LHCb perspectives on flavour physics

Agnieszka Obłąkowska-Mucha
AGH UST Kraków

on behalf of LHCb Collaboration

"Collider Physics"
2nd Symposium of the Division for Physics of Fundamental Interactions of the Polish Physical Society

May 2016 Katowice

Outline

I. Why Flavour Physics?

II. LHCb spectrometer in Run II and Upgrade

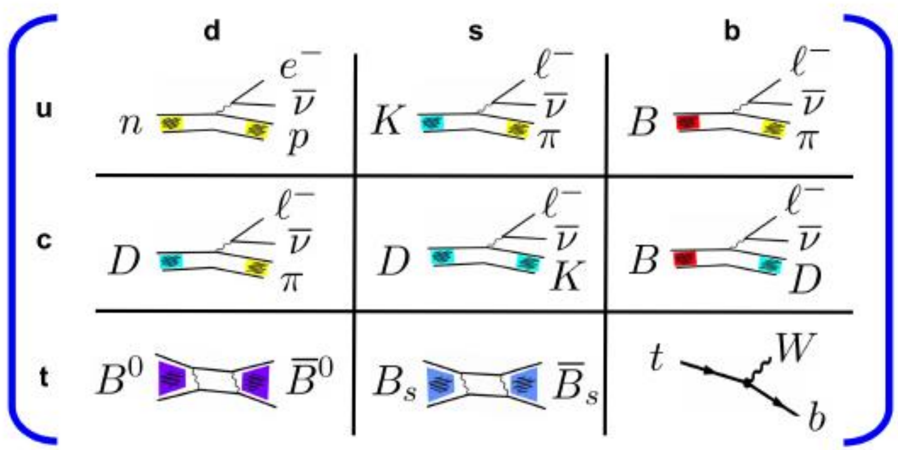
III. Prospects for selected results from LHCb:

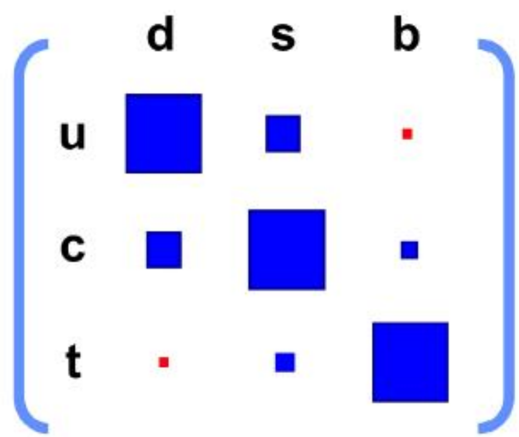
1. Standard Model benchmarks:
   - CKM γ angle with $B \to DK$
   - CP violation in charm
2. Probing New Physics:
   - $B \to \mu\mu$
   - Weak phase ϕ_S

IV. Summary

for the current LHCb results follow the talk of Marcin Chrząszcz on this Symposium

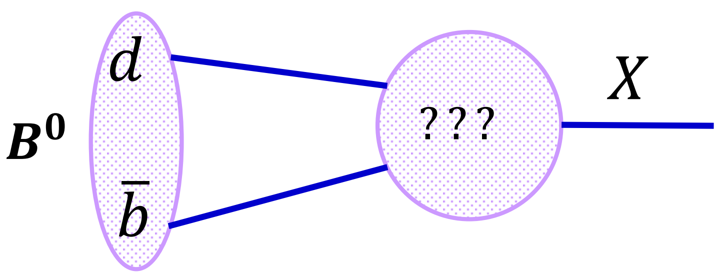
V =





Flavour Physics for precise measurements

1. **Direct** searches for production of new objects (higher and higher energies, luminosities – ATLAS, CMS)
2. **Indirect** searches (a low energy „window" for discoveries) – LHCb
   a) test the SM with high precision measurements, especially processes which are very well predicted and calculated, if disagreements are found – this is a sign of the existence of new objects via indirect method
   b) virtual effects allow probing energies much higher than LHC. **New Physics** may enter in boxes and in penguin contributions
   c) very successful in the past (charm and top quarks predictions)



Even heavy particles can make significant contributions via:

- increase of amplitudes,
- different weak or/and strong phases

$$A = A_{SM} + A_{BSM}$$

LHCb time-line

	Run I (2010-12)	Run II (2015-18)	Run III (2021-23)	Run IV-V (2025-28, >30)
Integrated Luminosity	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	150 fb^{-1}
Energy $\sqrt{s}$	7-8 TeV	13-14 TeV	14 TeV	14 TeV

Upgrade of LHCb during LS2

LHCb up to 2018 ≥ 8 fb^{-1} @ 14 TeV:

- find or rule out the evidences of New Physics and sources of flavour symmetry breaking
- searches of rare decays and exotic states,
- physics in the forward region.

LHCb Upgrade + HL LHC ≥ 50 fb^{-1} @ 14 TeV:

- increase precision on quark flavour observables,
- aim – experimental sensitivities comparable to theoretical uncertainties.

LHCb sensitivity to flavour observables

Eur. Phys. J. C73 (2013) 2373

Type	Observable	LHC Run 1	RUN II	LHCb upgrade	Theory
B_s^0 mixing	$\phi_S(B_s^0 \to J/\psi\phi)$	0.050	0,025	0.009	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	0.012	~ 0.01
	$A_{sl}(B_s^0)$ (10^{-3})	2.8	1.4	0.5	0.03
Gluonic penguin	$\phi_s^{eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	0.023	0.02
	$\phi_s^{eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	0.029	< 0.02
	$2\beta^{eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	0.04	0.02
Right-handed currents	$\phi_s^{eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	0.030	< 0.01
	$\tau^{eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	0.8%	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.04	0.020	0.007	0.02
	$q_0^2\, A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	1.9%	$\sim 7\%$
	$A_I(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.09	0.05	0.017	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	2.4%	$\sim 10\%$
Higgs penguin	$B(B_S \to \mu\mu)10^{-9}$	1.0	0,5	0.19	0.3
	$BR(B_S \to \mu\mu)/B(B_S \to \mu\mu)$)	220%	110%	40%	$\sim 5\%$
Unitarity triangle angles	$\gamma(B^0 \to D^{(*)}K^{(*)})$	7°	4°	1.1°	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	2.4°	negligible
	$\beta(B^0 \to J/\psi K_S^0)$	1.7°	0.8°	0.31°	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)10^{-4}$	3.4	2.2	0.5	–
	ΔA_{CP} (10^{-3})	0.8	0.5	0.12	–

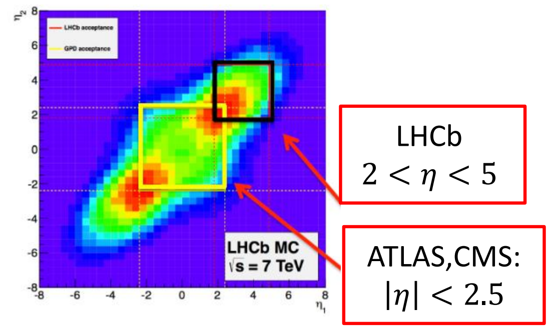
Aim: increase the statisctic to overconstrain SM, find or exclude New Physics

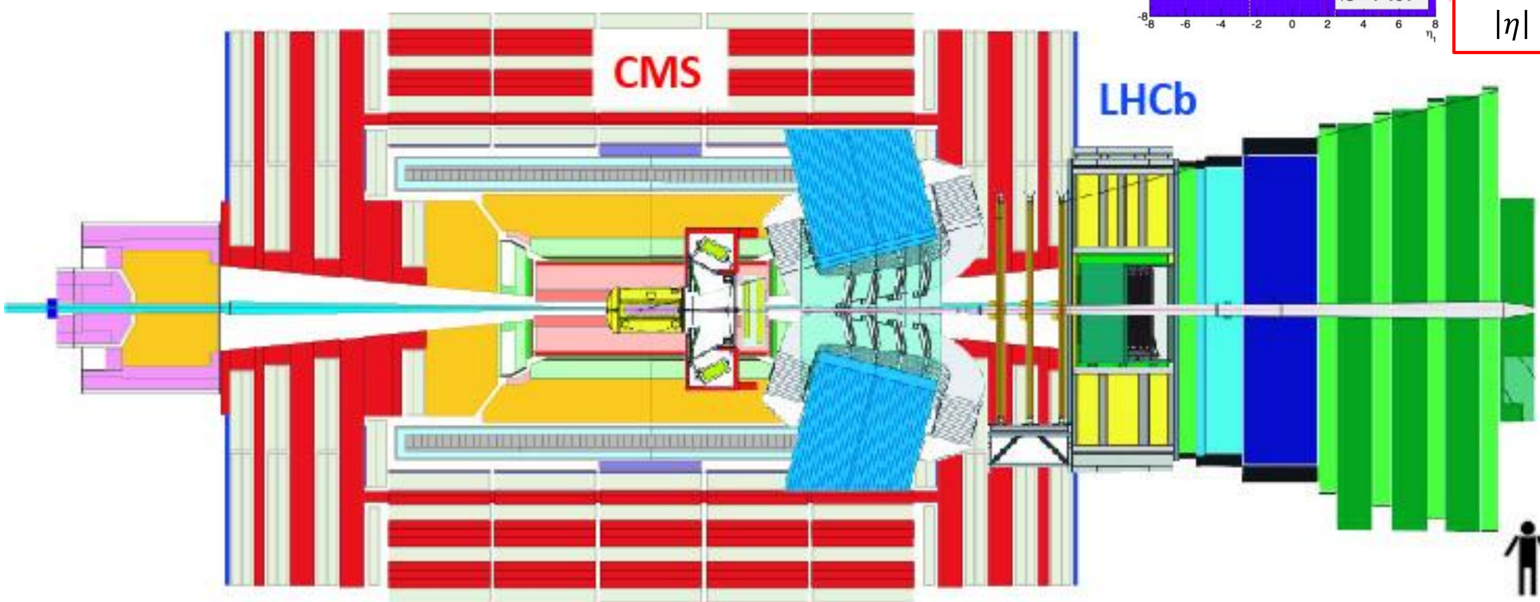
The apparatus – Run I and II

The detector dedicated for studying flavour physics at LHC. Especially CP violation and rare decays of beauty and charm mesons.

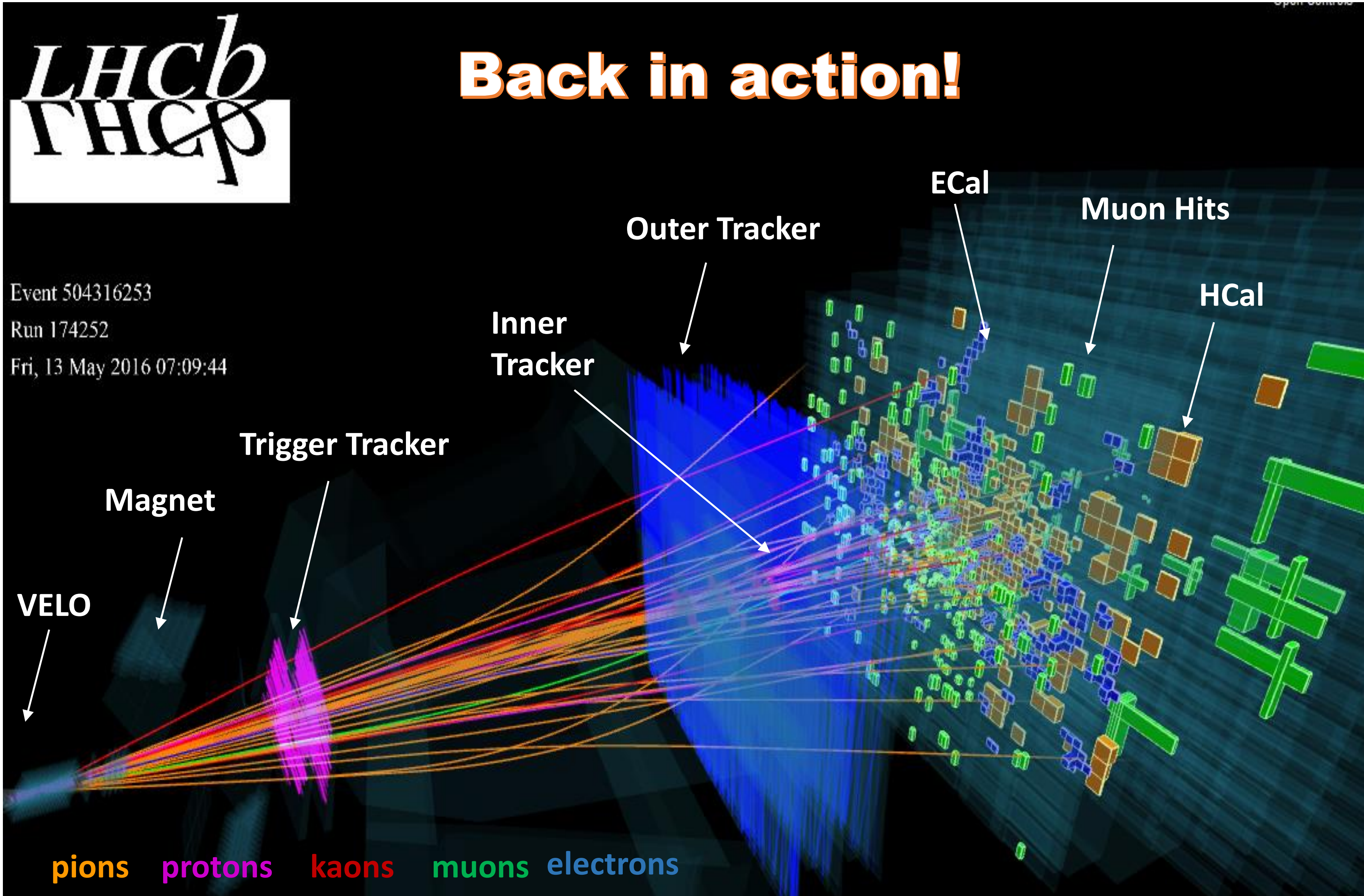
- excellent decay time resolution $\sim 50 fs$
- precise tracking: $\delta p/p \sim 0.4 - 0.6\%$, trigger on low p_t, low mass
- particle identification $2 - 100\ GeV/c$

Complimentary kinematical coverage to CMS and ATLAS





Back in action!



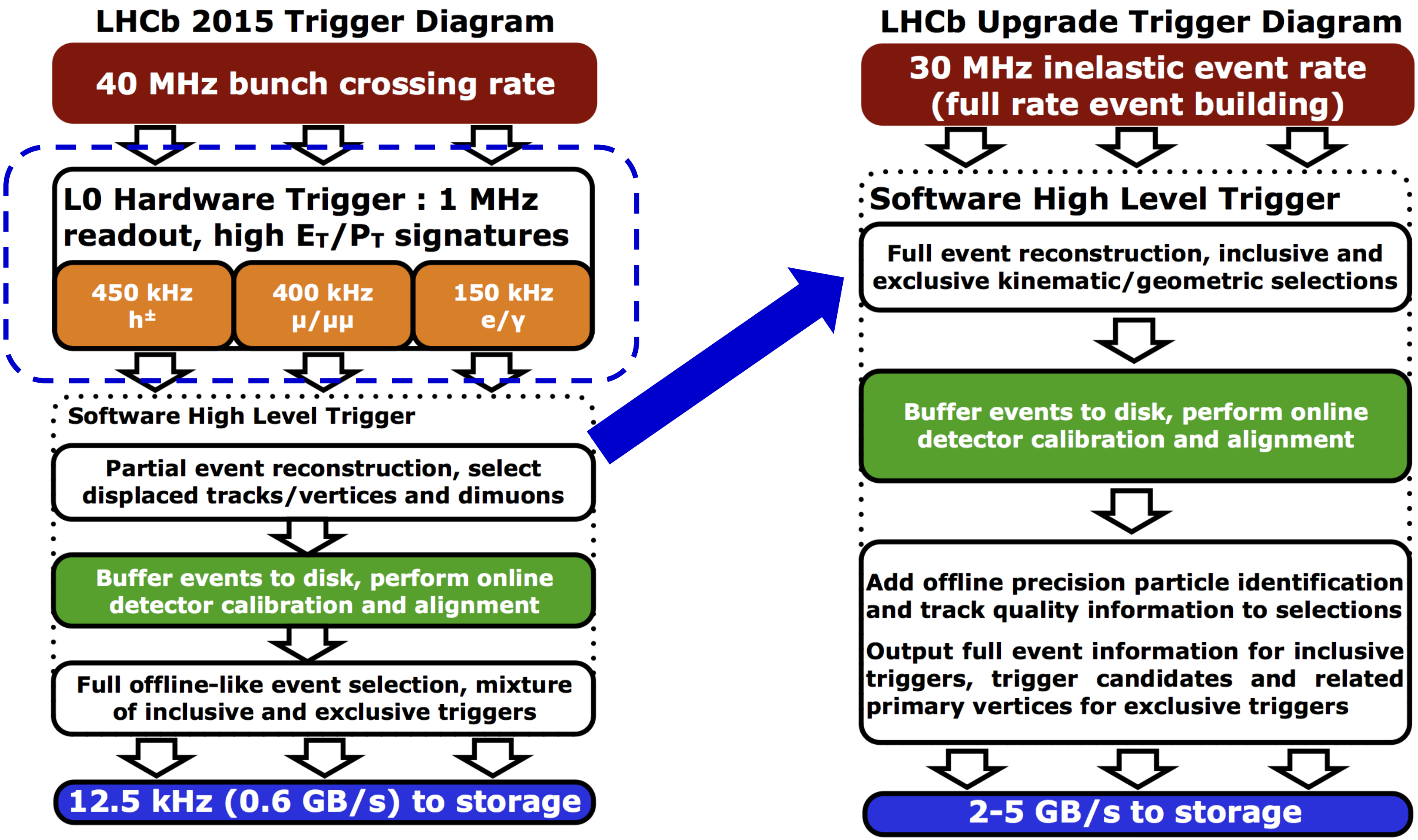
LHCb sensitivity to flavour observables

Eur. Phys. J. C73 (2013) 2373

Type	Observable	LHC Run 1	LHCb 2018	UPGRADE	Theory
B_s^0 mixing	$\phi_S(B_s^0 \to J/\psi\phi)$	0.050	0.025	0,009	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.023**	0.02
	$\phi_s^{eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\ A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_I(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$B(B_S \to \mu\mu)10^{-9}$	1.0	0.5	0.19	0.3
	$BR(B_S \to \mu\mu)/B(B_S \to \mu\mu)$	220%	110%	40%	$\sim 5\%$
Unitarity triangle angles	$\gamma(B^0 \to D^{(*)}K^{(*)})$	7°	4°	1.1°	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	2,4°	negligible
	$\beta(B^0 \to J/\psi\ K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)10^{-4}$	3.4	2.2	0.5	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

Experimental precision with upgraded detector comparable to theoretical uncertainties!

The trigger – Run II and Upgrade



Physics selections obtained in trigger

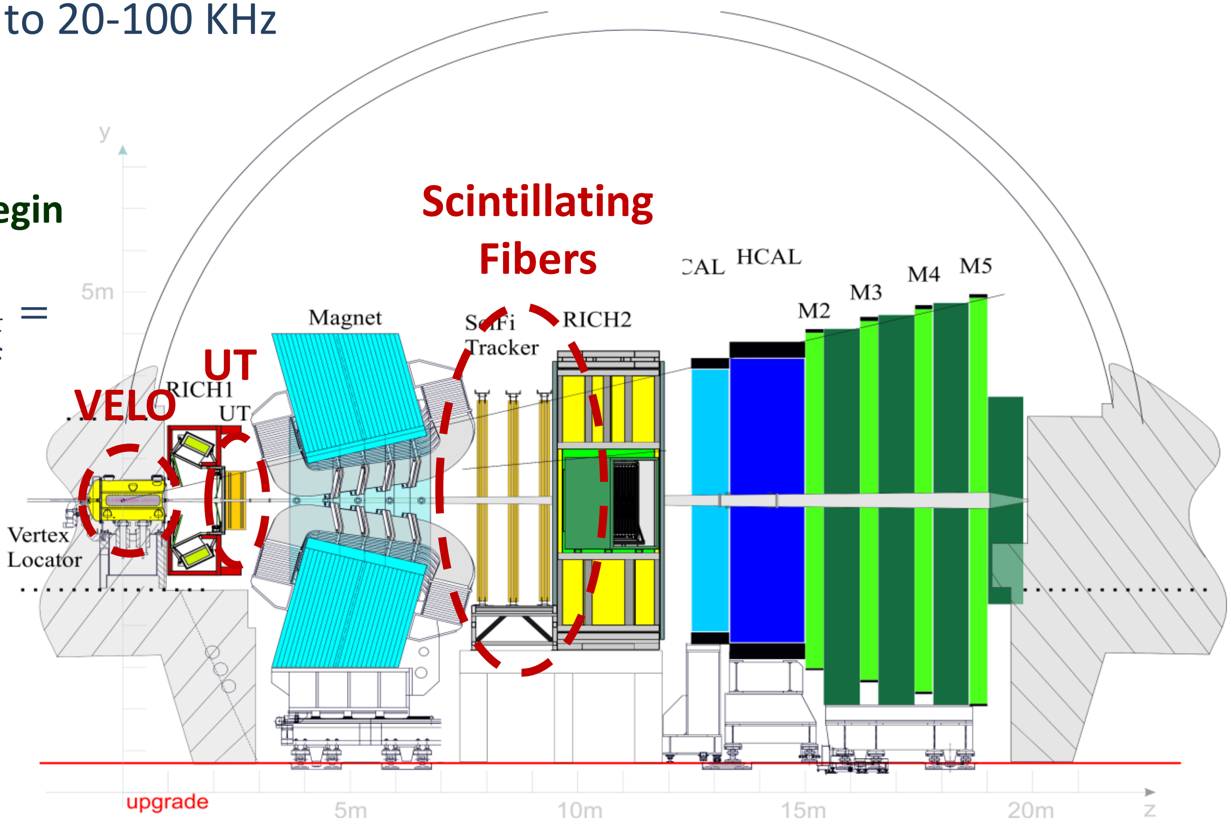
Upgraded LHCb

Installation is foreseen between 2018-19

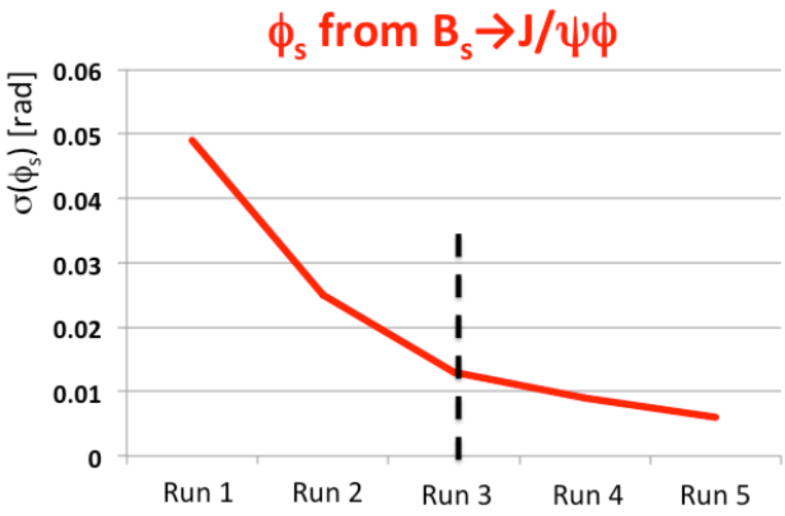
- New **tracking system**.
- Full event readout at 40 MHz.
- Upgraded trigger (fully software).
- Increase of the output rate to 20-100 KHz
- New PID system.

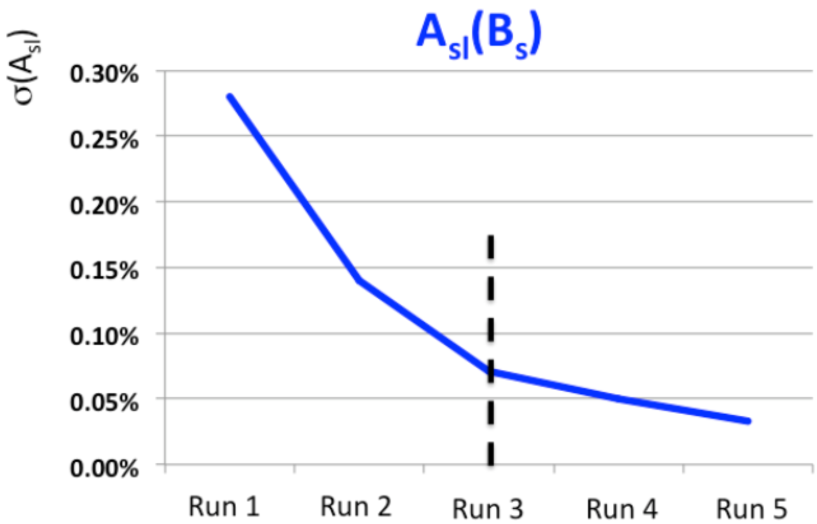
Run III of the LHC scheduled to begin in 2020:

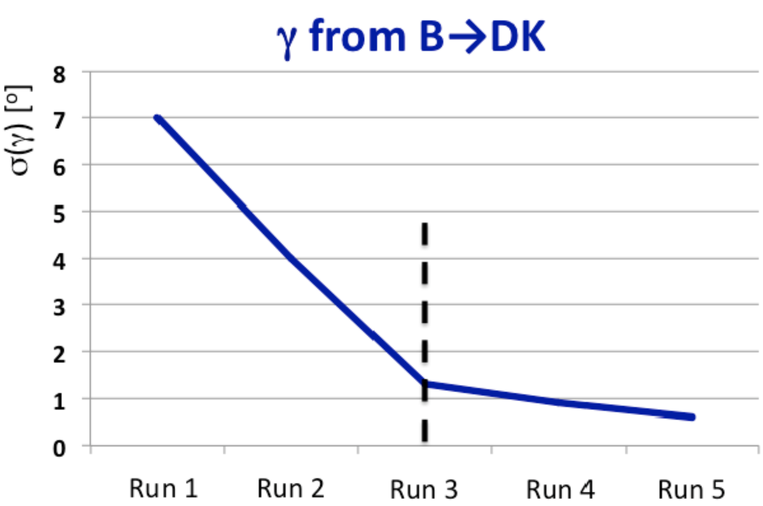
- Instantaneous luminosity: $\mathcal{L}_{inst} = 2 \times 10^{33}\ cm^{-2}s^{-1}$ (increase of factor 5),
- LHCb plans to collect 50 fb^{-1} of integrated luminosity @ √s=14 TeV,
- 25 ns of bunch time spacing,
- Average number of visible interaction μ≈5.2

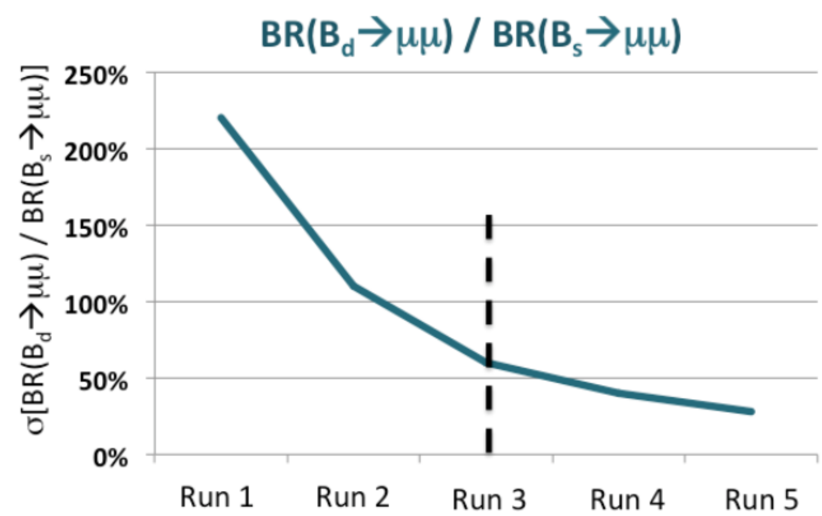


Prospects for key observables









inputs from LHCb-PUB-2014-040

CKM γ angle

1. γ angle is the only one that can be determined from tree only processes,
2. Theoretically clean: $\delta\gamma/\gamma \leq \mathcal{O}(10^{-7})$
3. So far has the worst precision:

$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

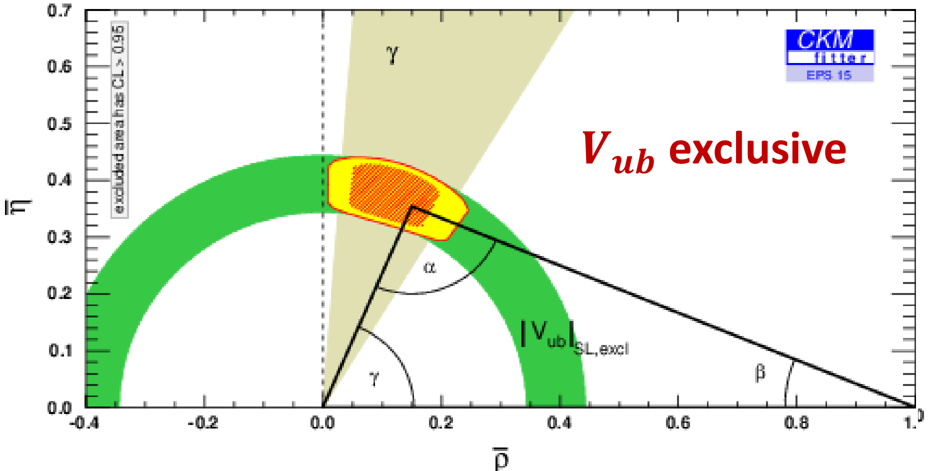
   a) direct measurements:

   BaBar: $\gamma = (69 \pm 17)^\circ$ PRD 87 (2013) 052015 , Belle: $\gamma = (68 \pm 15)^\circ$ CKM2012 preliminary

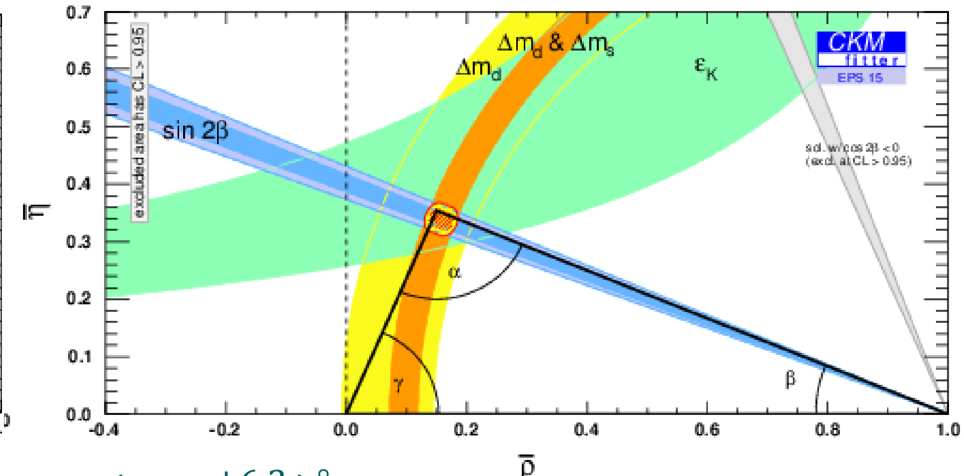
   b) indirect measurements (dominated by loops): $(66.9^{+1.0}_{-3.7})^\circ$

some tension between direct and indirect methods- need better precision from trees measurements

trees - direct



no trees - indirect



CKM fitter 2015: $\gamma = (73.2^{+6.3}_{-7.0})^\circ$

CKM γ angle

1. $\boldsymbol{\gamma}$ angle is the only one that can be determined from tree only processes,
2. Theoretically clean: $\delta\gamma/\gamma \leq \mathcal{O}(10^{-7})$
3. So far has the worst precision:

$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)$$

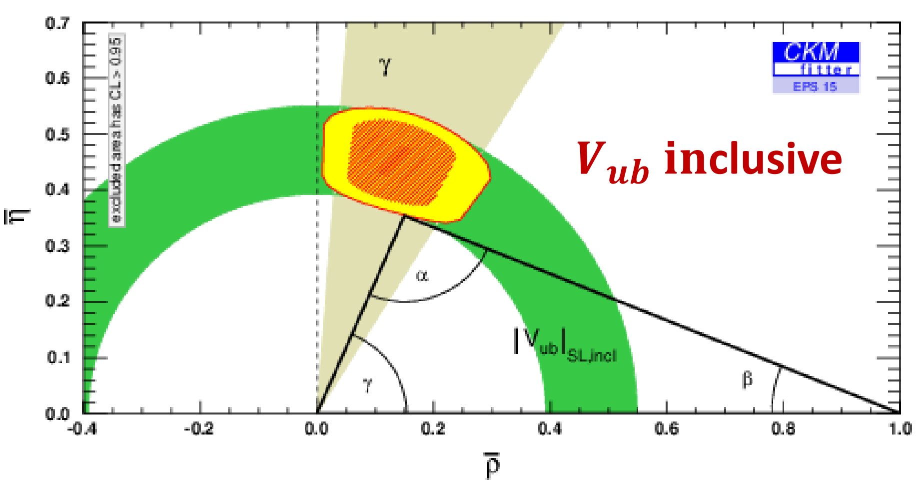
   a) direct measurements:

   BaBar: $\gamma = (69 \pm 17)^{\circ}$ PRD 87 (2013) 052015 , Belle: $\gamma = (68 \pm 15)^{\circ}$ CKM2012 preliminary

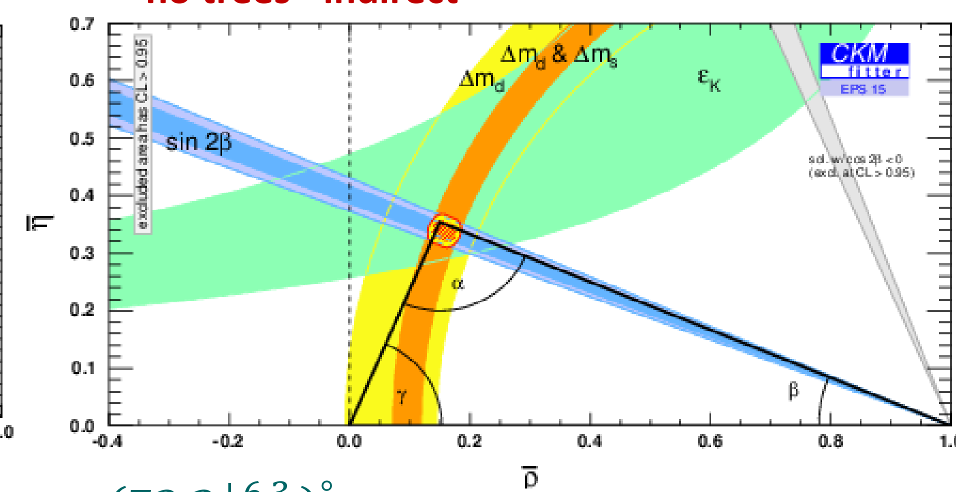
   b) indirect measurements (dominated by loops): $(66.9^{+1.0}_{-3.7})^{\circ}$

> some tension between direct and indirect methods- need better precision from trees measurements

trees - direct



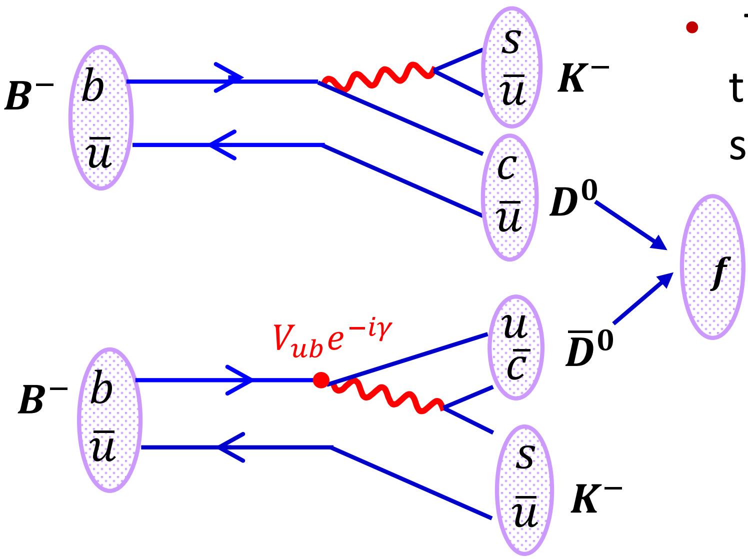
no trees - indirect



CKM fitter 2015: $\gamma = (73.2^{+6.3}_{-7.0})^{\circ}$

CKM γ angle from $B^{\pm} \to DK^{\pm}$

$$B^{\pm 0} \to D^0 K^{\pm * 0}$$



$$A_{CP} = \frac{\Gamma\{B^- \to D^0 K^-\} - \Gamma\{B^+ \to D^0 K^+\}}{\Gamma\{B^- \to D^0 K^-\} + \Gamma\{B^+ \to D^0 K^+\}} \propto \sin\gamma$$

- Sensitive to the γ when D^0 and $\overline{D^0}$ decay to the same final state.
- The interference of these two amplitudes depends on their relative magnitudes - one of them is usually suppressed.

$$A(B^- \to K^- f) \sim A(D \to f) + r_B e^{i(\delta_B - \gamma)} A(\bar{D} \to f)$$

$$r_B e^{i\delta_B} = \frac{A(B^- \to \bar{D} K^-)}{A(B^- \to D K^-)}$$

- Hadronic unknows: r_B and δ_B
- Different experimental techniques (GLW, ADS, GGSZ).
- Plenty (>16) of final states :

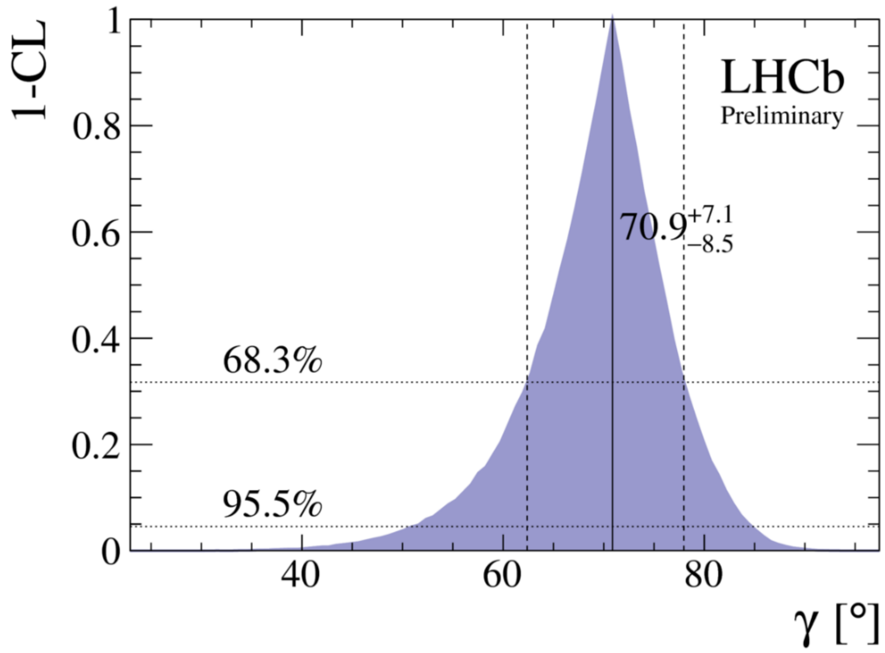
new!

- $D \to CP$ eigenstates: $K^+K^-, \pi^+\pi^-, K^+K^-\pi^0, \pi^+\pi^-\pi^0$
- $D \to CP$ flavour specific: $K^+\pi^-$, $K^+\pi^-\pi^+\pi^-, K_S K^+\pi^-$
- $D \to$3 body self-conjugated: $K_S\pi^+\pi^-, K_S K^+ K^-$

γ combination in LHCb

6. Direct, time integrated measurements: $B^{\pm 0} \to D^0 K^{\pm * 0}$
7. Mixing induced, time dependent analysis: $B_S^0 \to D_S^{\mp} K^{\pm}$

The 2016 combination for γ measurement (LHCb-CONF-2016-001)



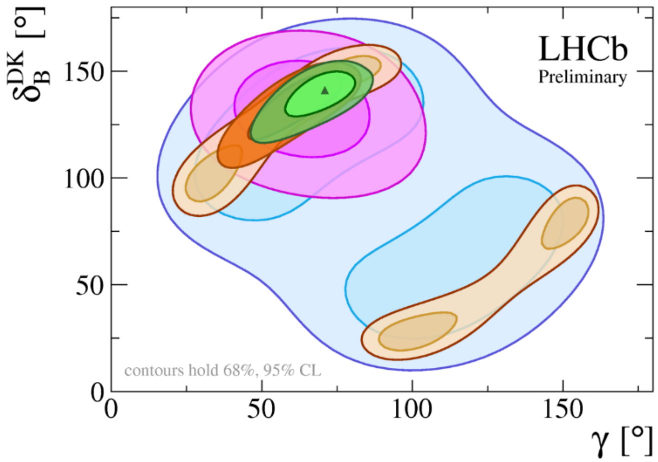
$$\gamma = \left(70.9^{+7.1}_{-8.5}\right)^{\circ}$$

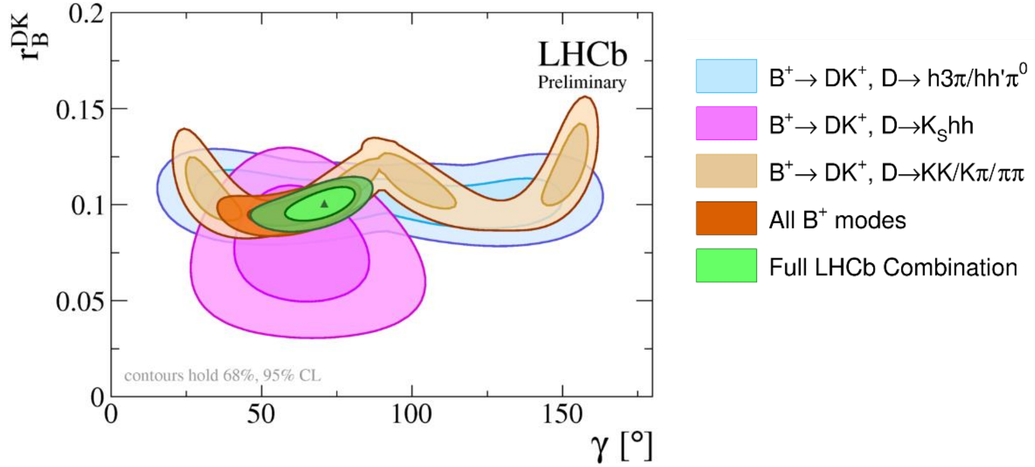
The most precise determination of angle γ

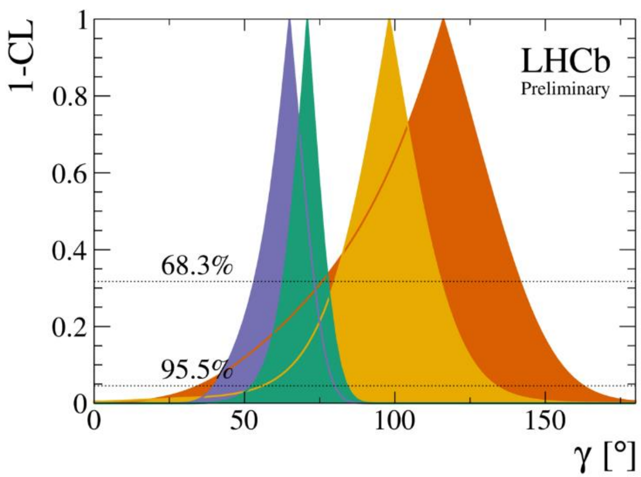
CKM γ angle - differenet modes

LHCb-CONF-2016-001

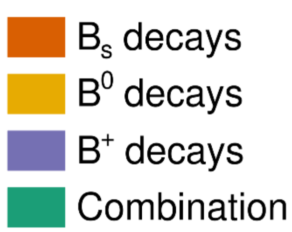
The result depends on hadronic unknowns: r_B and δ_B and other parameters (δ_D)…





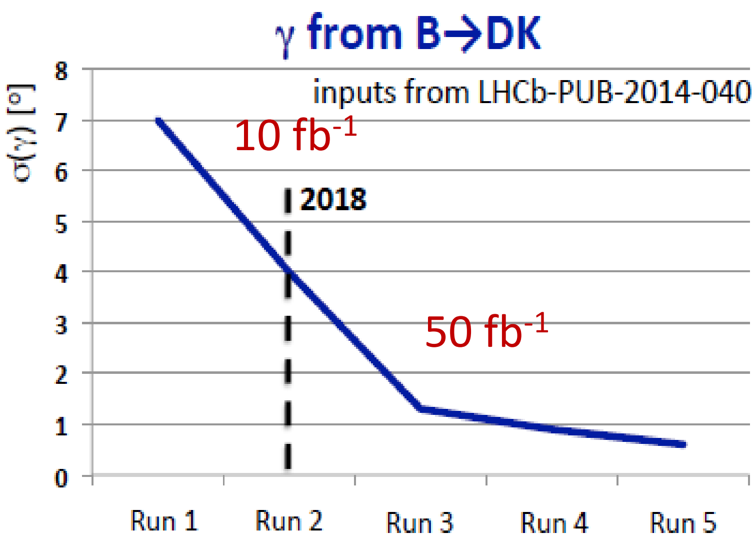


… and varies between different modes



Prospects for γ in Run II

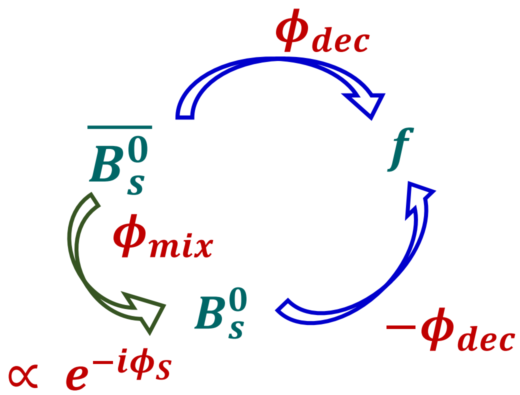
1. To perform time dependent analysis - more signal events of $B_S^0 \to D_S^{\mp} K^{\pm}$ and more challenging channels as $B_S^0 \to D_S^{\mp *} K^{\pm *}$.
2. The angle γ can be also measured from charmless B decays: $B \to h^+ h^-$, $B^+ \to K^+ h^+ h^-$ (loops sensitive to NP).
3. The time-dependent $B_S^0 \to D_S^{\mp} K^{\pm}$ can be also sensitive to NP because of mixing.



- We expect close to 10 fb^{-1} of data Run II (2016-18)
- The precision for γ of the order of $\sigma(\gamma) \sim 4°$
- The sensitivity on γ with 50 pb^{-1} is expected as $1°$.
- It is possible mainly due to major improvements with the software trigger in Upgrade.

Weak phase ϕ_s

CP violation induced by B_s^0 mixing

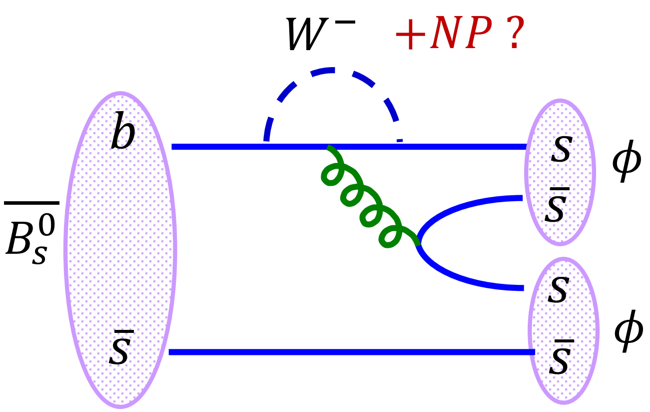


$$\phi_s = \phi_{mix} - 2\phi_{dec}$$

1. CP violation due to interference between direct B_s^0 decay and decay after oscillation $B_s^0 \leftrightarrow \overline{B_s^0}$.
2. Different analyses:
   - $B_s^0 \to J/\psi\phi(KK)$ – proceeds mostly via $b \to c\bar{c}s$ tree diagram – NP can show up in the mixing

$$\phi_s = -0.058 \pm 0.049(stat) \pm 0.006(syst)$$

Phys.Rev.Lett. 114 041801 (2015)



   - $B_s^0 \to \phi\phi$ – is penguin- dominated $b \to ss\bar{s}$ process, excellent probe of new heavy particles entering the quantum loops

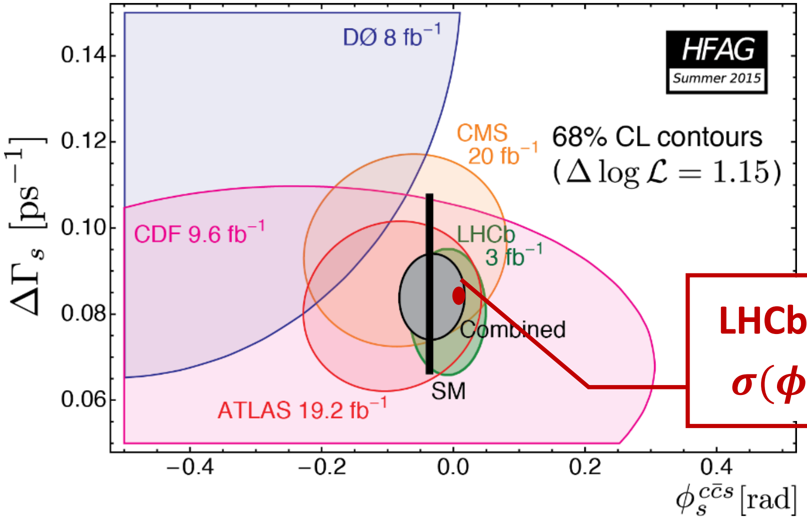
$$\phi_s(\phi\phi) = -0.17 \pm 0.15(stat) \pm 0.03(syst)$$

Phys.Rev.D 90 052011 (2014)

this channel will benefit from the new LHCb trigger in Run II and expected precision will be comparable to golden $b \to c\bar{c}s$ mode

Prospects for ϕ_s

ϕ_s is very sensitive to NP, but no NP effects have been seen, yet…



LHCb Upgrade

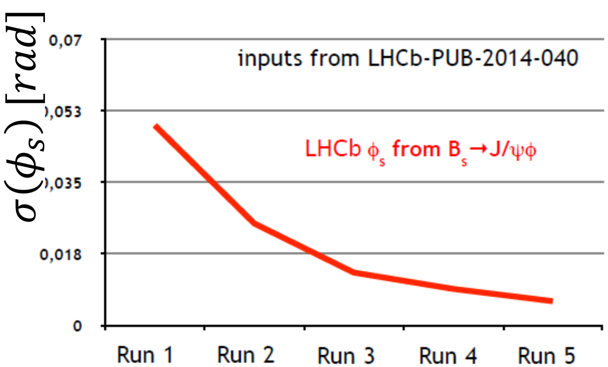
$\sigma(\phi_s) \sim 0.01$

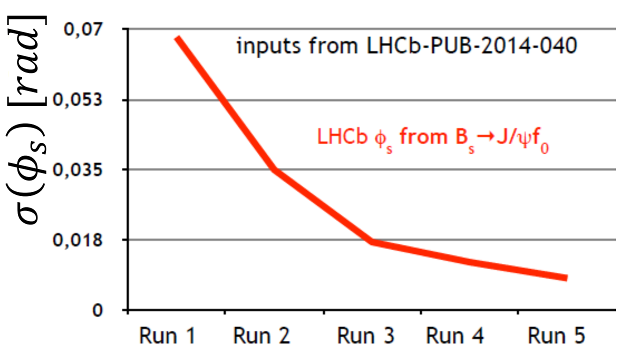
SM: $\phi_s^{SM} = -0.0363^{+0.0014}_{-0.0012}$

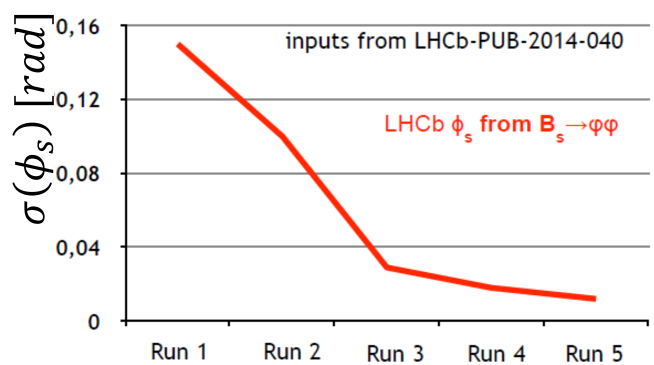
Experiments (HFAG combined):

$$\phi_s^{exp} = -0.034 \pm 0.033$$

Great progress after RunI but still plenty of possibilities for NP. The main task is to obtain better precision.







Quest for New Physics: $B_{(s)} \to \mu^+\mu^-$

Nature 13 May 2015 doi:10.1038/nature14474

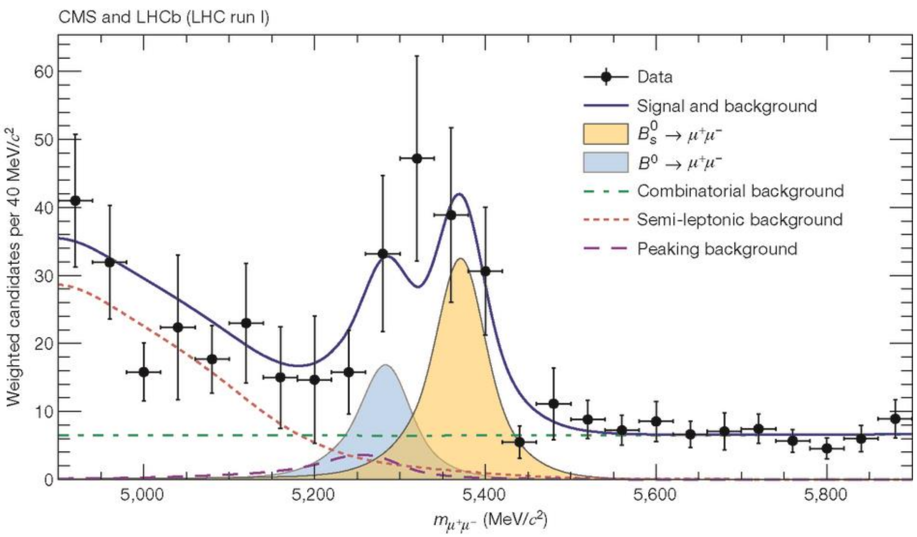
- CMS & LHCb – first observation of the decay $B_S \to \mu\mu$
- Statistical significance above $\boldsymbol{6\sigma}$
- The best measurement of branching fraction to date
- $\boldsymbol{3\sigma}$ evidence for $\boldsymbol{B \to \mu\mu}$

$$\boldsymbol{BR(B_S \to \mu\mu) = \left(2.8^{+0.7}_{-0.6}\right) \times 10^{-9}}$$

$$BR(B_S \to \mu\mu)SM = (3.66 \pm 0.23) \times 10^{-9}$$

$$\boldsymbol{BR(B \to \mu\mu) = \left(3.9^{+1.6}_{-1.4}\right) \times 10^{-10}}$$

$$BR(B \to \mu\mu)SM = (1.06 \pm 0.09) \times 10^{-10}$$

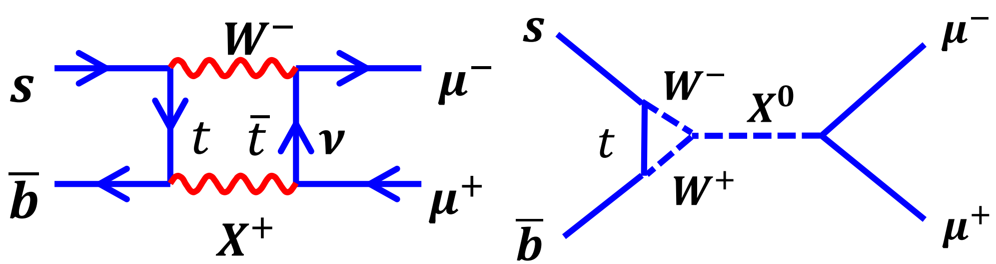


- Both results are statistically compatible with the Standard Model predictions
- Stringent constraints on theories beyond SM

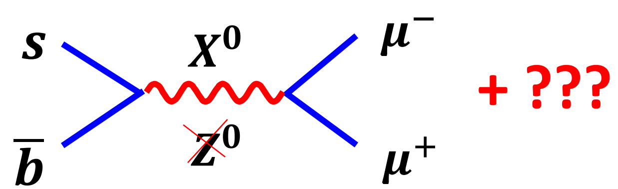
$B_{(s)} \to \mu^+\mu^-$

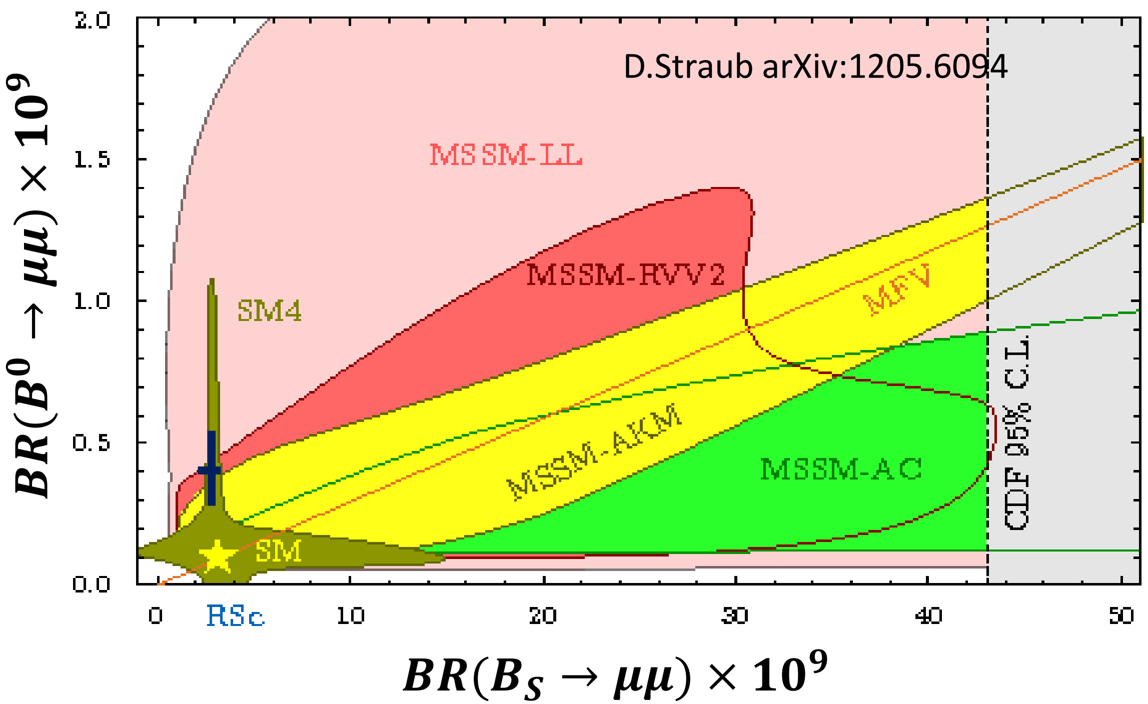
In the SM flavour-changing neutral currents are GIM and CKM suppressed.

loops – New Particles but not FV



tree – requires FV

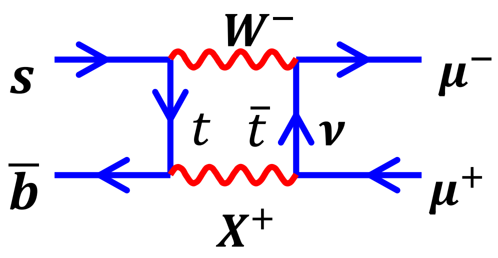


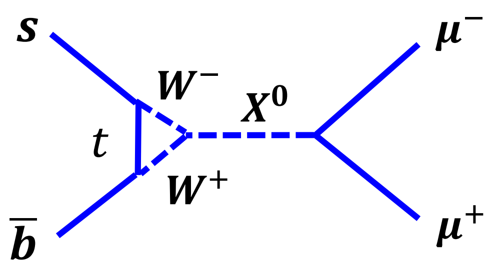


$B_{(s)} \to \mu^+\mu^-$

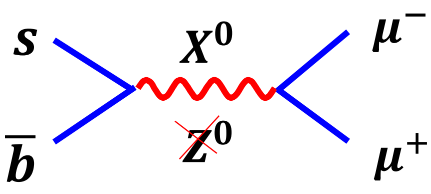
In the SM flavour-changing neutral currents are GIM and CKM suppressed.

loops – New Particles but not FV



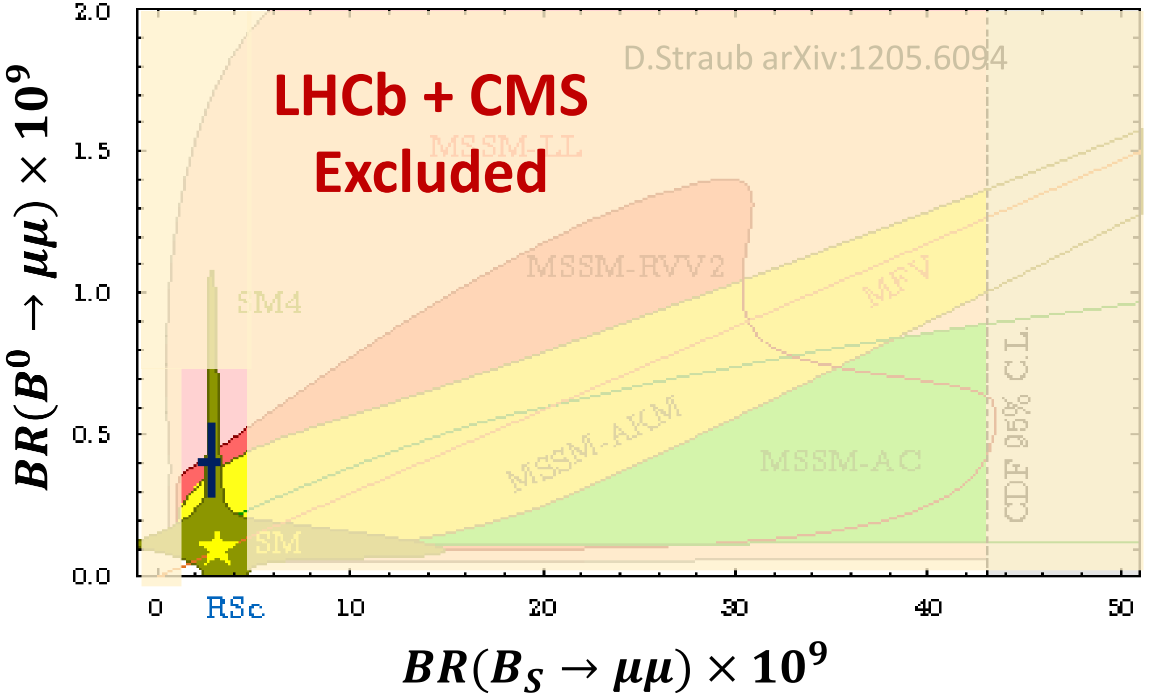


tree – requires FV



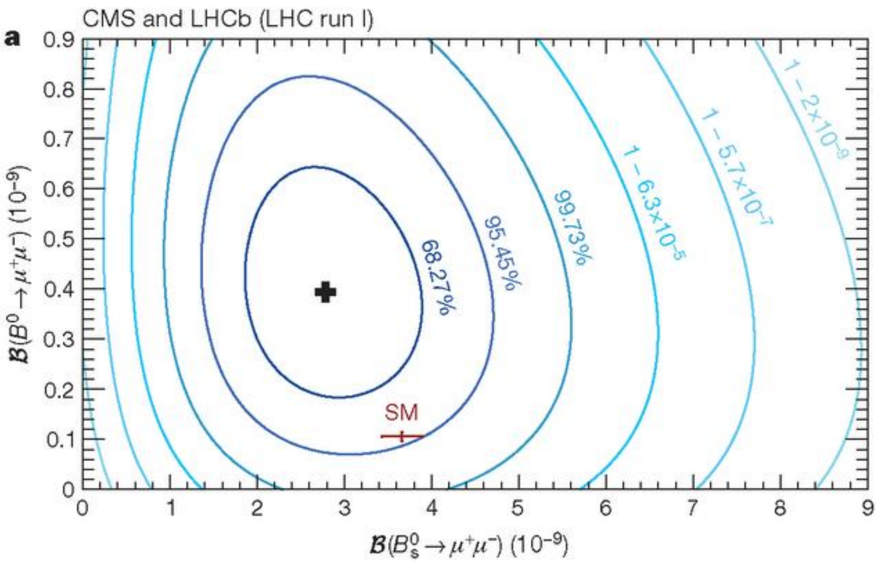
+ ???

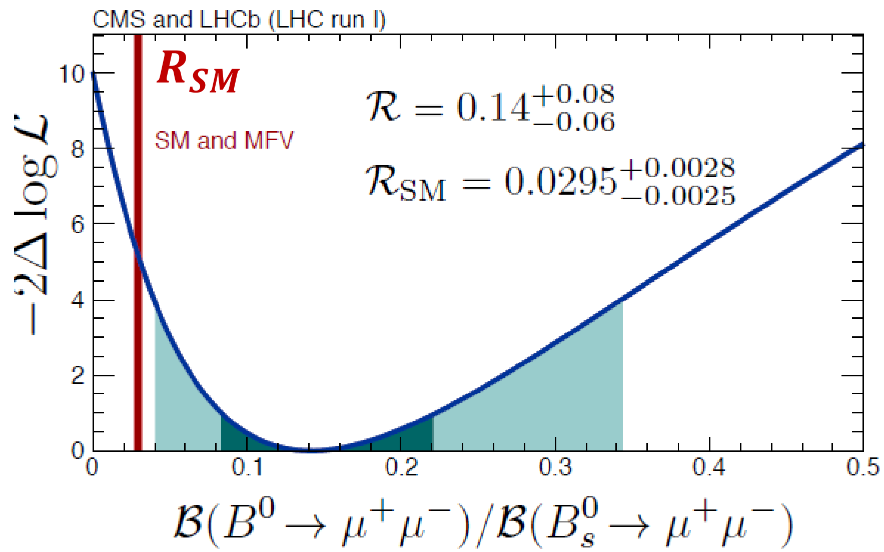
Impact on SUSY models



$B_{(s)} \to \mu^+\mu^-$ - BR

The BRs ratio: $R = \frac{BR(B \to \mu\mu)}{BR(B_S \to \mu\mu)}$ is also predicted in the SM:



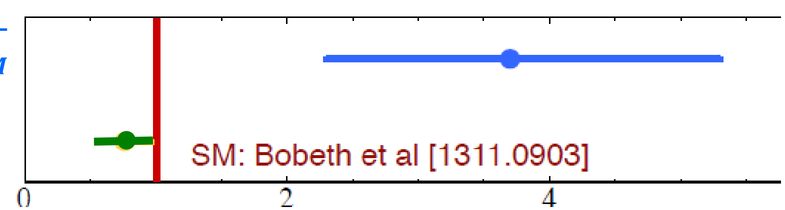


There is a small tension in the branching fraction ratio, especially in $B \to \mu\mu$:

Looking forward to Run 2 data!

$\frac{BR(B \to \mu\mu)}{BR(B \to \mu\mu)_{SM}}$

$\frac{BR(B_s \to \mu\mu)}{BR(B_s \to \mu\mu)_{SM}}$

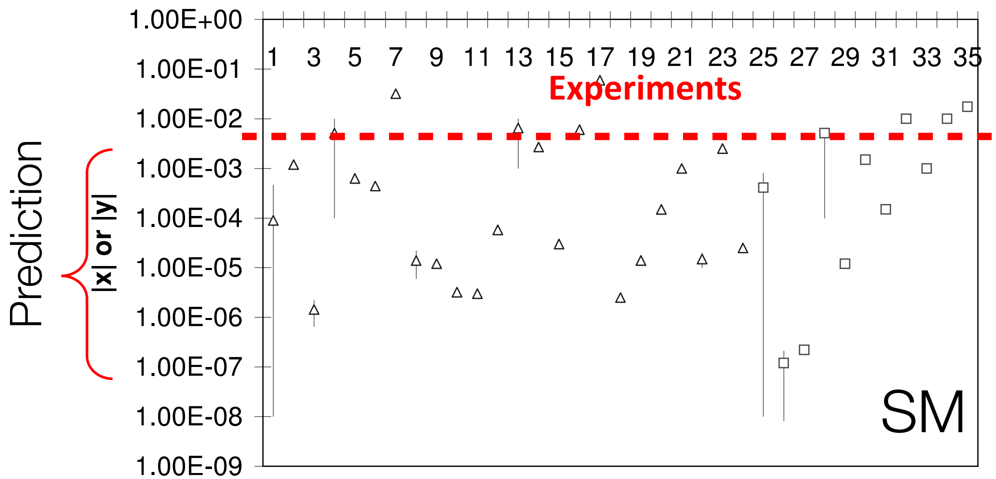


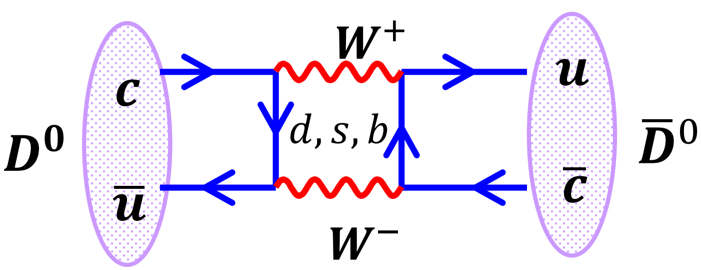
CPV in charm- hope

In the Standard Model:

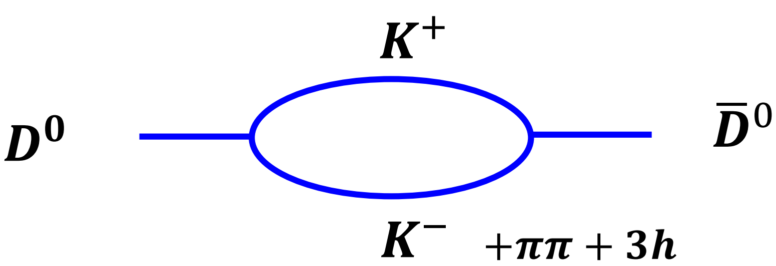
- expected CPV in charm sector is small: 10^{-3},
- SM predictions vary widely
- New Physics contribution can enhance up to 10^{-2}.
- Perfect place for New Physics searching (small background from SM)

Int.J.Mod.Phys.A21(2006)5686





Mixing via box-diagram



Mixing via hadronic intermediate states (difficult to calculate)

CPV in charm - measurements

1. Searches for direct CP violation in charm: plenty of methods with 2- and multibody D^0 final states. No CP violation has been observed with whole Run I data set.

2. The search of indirect (in mixing) time-integrated CP asymmetry in two body decays: $D^0 \to K^+K^-, D^0 \to \pi^+\pi^-$ is based on measurement of the A_Γ asymmetry

$$A_\Gamma \equiv \frac{\Gamma(D^0 \to K^+K^-) - \Gamma(\bar{D}^0 \to K^+K^-)}{\Gamma(D^0 \to K^+K^-) + \Gamma(\bar{D}^0 \to K^+K^-)} \approx \left(\frac{1}{2}A_m + A_d\right) y \cos\phi - x \sin\phi$$

$$A_m \equiv \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$

in the mixing

in the decay amplitudes

$$A_d \equiv \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2}$$

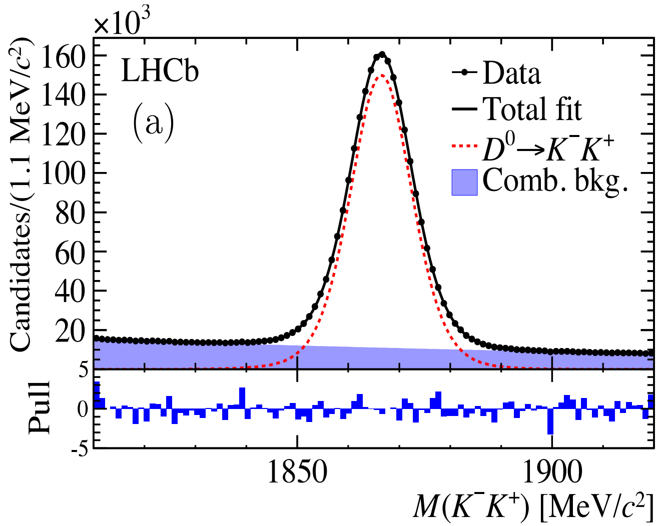
A_Γ is a measure of indirect CPV, since the contribution from direct CPV is considered as very small.

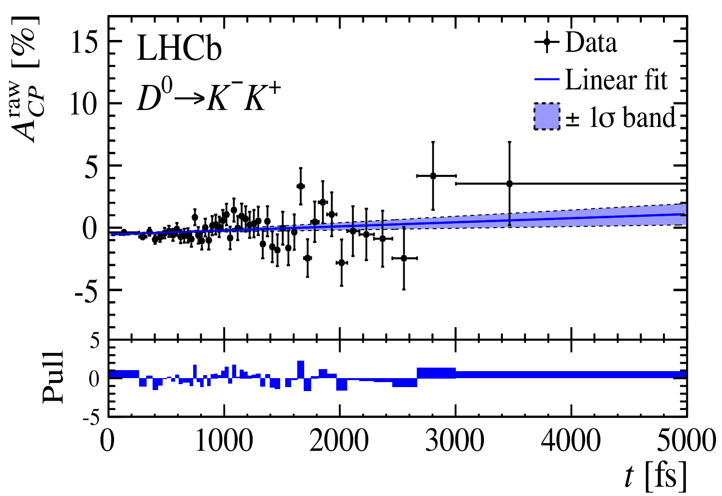
A_Γ asymmetry

JHEP 04 (2015) 043, 3 fb^{-1}

The asymmetry of the decay frequencies of D^0 and $\bar{D}^0$ to CP- eigenstates $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$

$B^0 \to D^0\mu^- X$ and $B^0 \to \bar{D}^0\mu^- X$





2.3 M events of K^+K^-

$$A_\Gamma(K^+K^-) = (-0.134 \pm 0.077^{+0.026}_{-0.034})\%$$

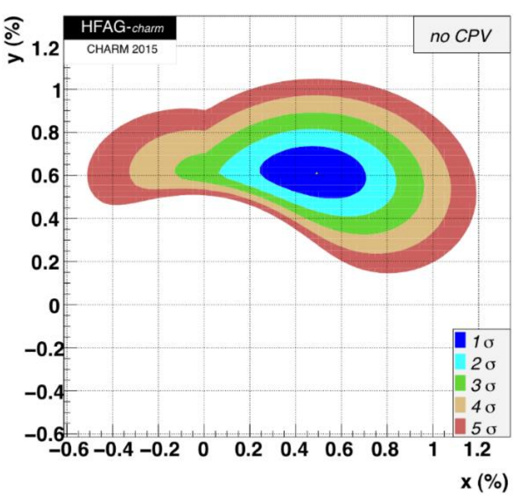
$$A_\Gamma(\pi^+\pi^-) = (-0.092 \pm 0.145^{+0.025}_{-0.033})\%$$

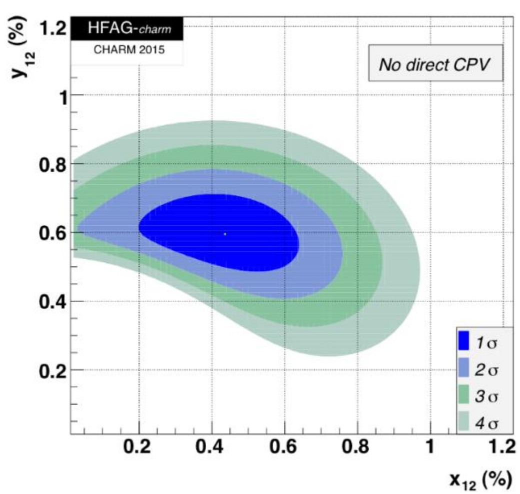
No evidence for indirect CPV in charm within 1 per mil.

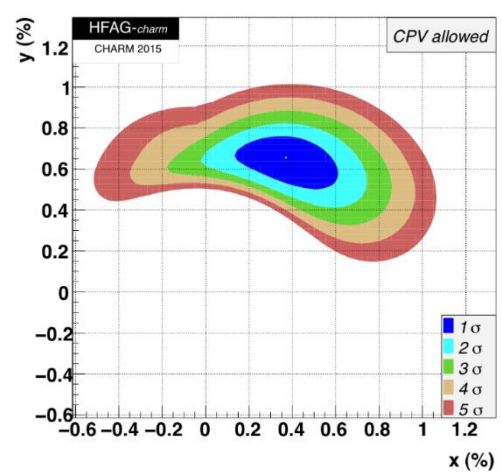
CPV in charm - prospects

1. We expect a great increase in charm events during Run II mainly due to dedicated trigger settings.
2. While any significant evidences of CP violation in charm is observed, it would be possible to distinguish CPV effects coming from charm mixing and from decay.
3. The level of CPV in charm is really small, so exploring the new data one should be aware of New Physics effects.

Parameter	No CPV	No direct CPV in DCS decays	CPV allowed
$x[\%]$	$0.49^{+0.14}_{-0.15}$	$0.44^{+0.14}_{-0.15}$	0.37 ± 0.16
$y[\%]$	0.61 ± 0.08	0.60 ± 0.07	$0.66^{+0.07}_{-0.10}$







Summary

1. During Run I data taking LHCb spectrometer proved that flavour physics can be successfully studied in the hadron collider.

2. In Run II started in 2015 with an increased energy to 13 TeV, the $\boldsymbol{\sigma(b\bar{b})}$and $\boldsymbol{\sigma(c\bar{c})}$ is larger by about 60%.

3. The novel approach to trigger system increased an output bandwidth from 5 kHz to 12 kHz which allows to record more data.

4. In the era of Run II, we expect about twice as much $\boldsymbol{b\bar{b}}$ and $\boldsymbol{c\bar{c}}$ pair per fb^{-1}.

5. All this would benefit better precision on key measurements ($\delta\phi_s$ ~0.025, $\delta\gamma \sim 4^0$) and/or new exclusion limits or New Physics discoveries (i.e. CPV in Charm).

6. In the forthcoming Run III (Upgrade) due to even more precise measurements, the sensitivity to a large number of key observables can be improved by an order of magnitude.

Backup

		LHC era		HL-LHC era	
	Run 1	Run 2	Run 3	Run 4	Run 5+
$\phi_s(B_s^0 \to J/\psi\phi)$	0.05	0.025	0.013	0.009	0.006
$\phi_s(B_s^0 \to \phi\phi)$	0.15	0.10	0.029	0.018	0.012
$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}$	220%	110%	60%	40%	28%
$q_0^2\ A_{\rm FB}(K^{*0}\mu^+\mu^-)$	10%	5%	2.8%	1.9%	1.3%
γ	7°	4°	1.3°	0.9°	0.6°
$A_\Gamma(D^0 \to K^+K^-)$	3.4×10^{-4}	2.2×10^{-4}	0.7×10^{-4}	0.4×10^{-4}	0.3×10^{-4}