Challenging the CKM picture of CP violation at LHCb

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on behalf of the LHCb Collaboration

PASCOS 2016
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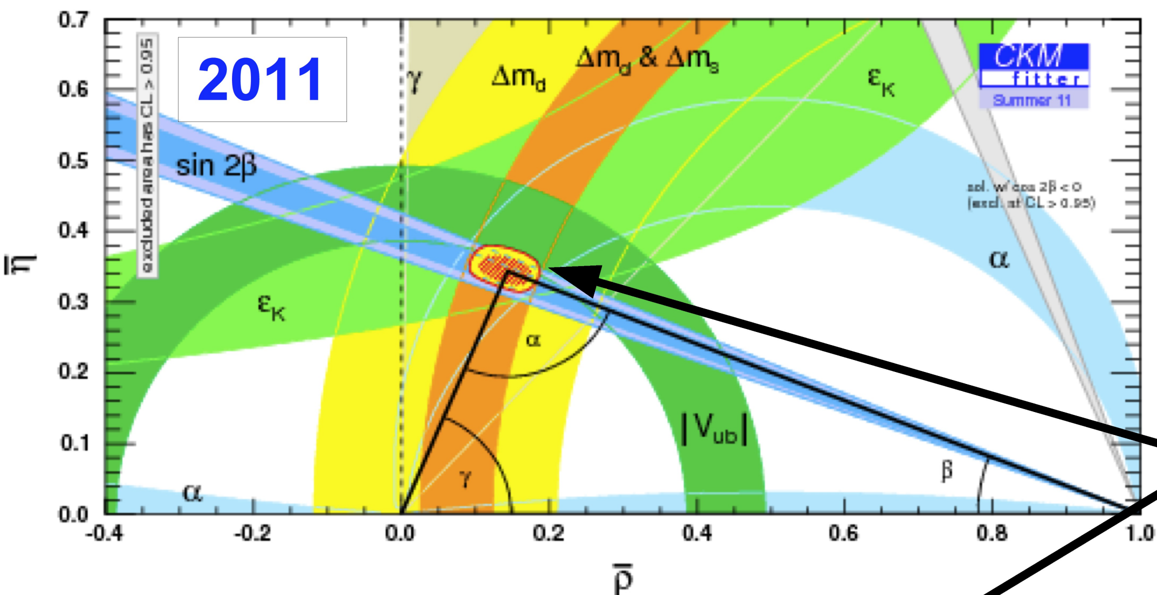
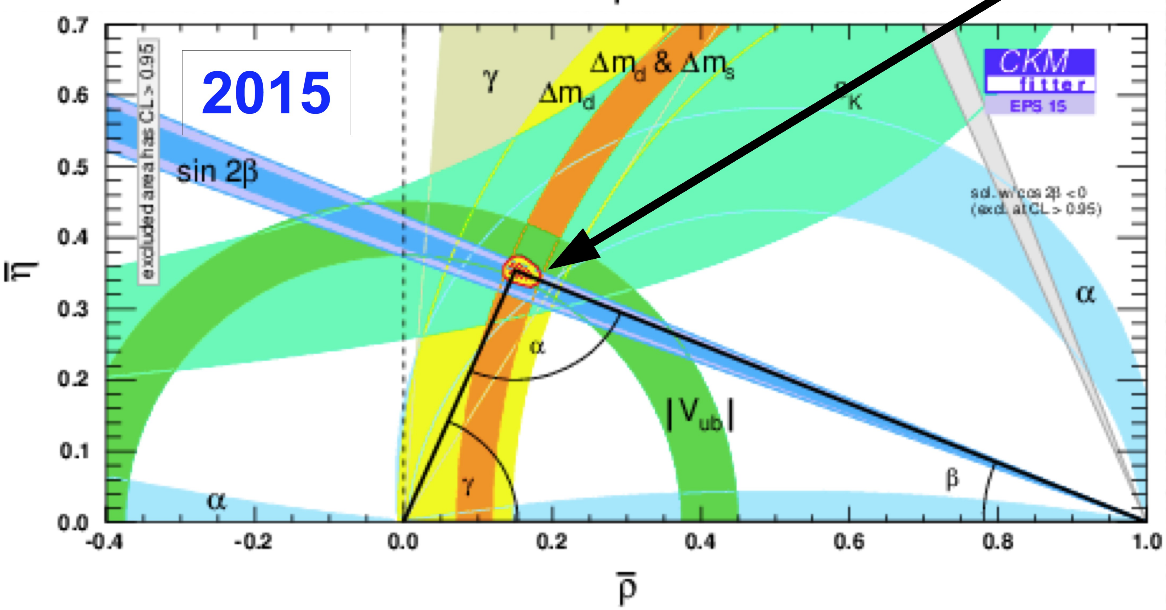
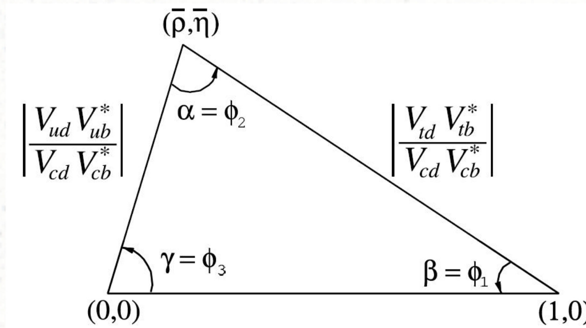
UNIVERSITÀ DI PISA

CKM: before & after LHC







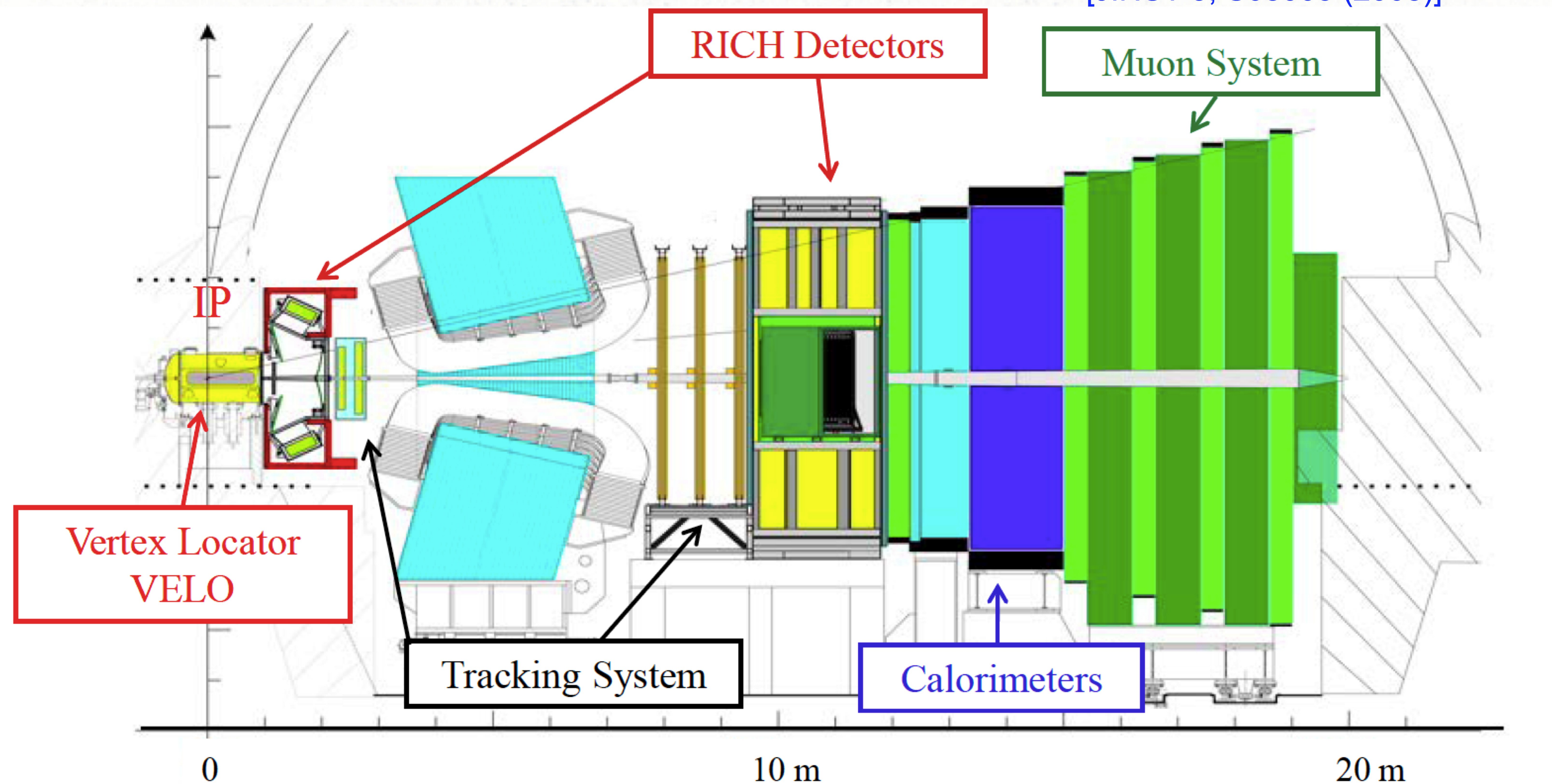
- 4x smaller area
- 4x better σ(J)
- 2x on angles (4x on γ)

Most of the improvement due to LHCb !

Further improvements after this plot (EPS'15)

The LHCb experiment

[JINST 3, S08005 (2008)]



- Large LHC yields in hi-η region ~100μb
- Great mass/momentum resolution
- Great I.P. resolution resolves Bs oscillations
- Great K/π/p/μ separation
- Lum. Leveling and L0 *μ/h/γ* trigger
- Large online PC farm and high rate to storage

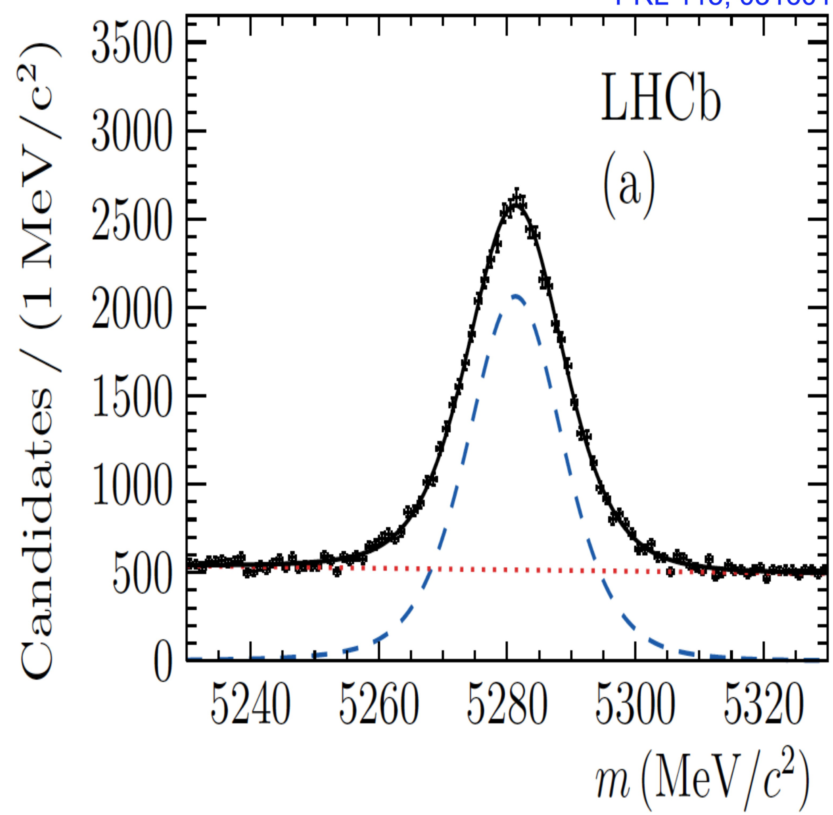
LHCb signals

LHCb's large yields balance the larger background and worse tagging power relative to e+e- experiments
→ today's similar sensitivity on tagged measurements: e.g. $B^0 \rightarrow J/\psi\ K_s$

(LHCb even better positioned for untagged measurements, and time-dependent B_s)

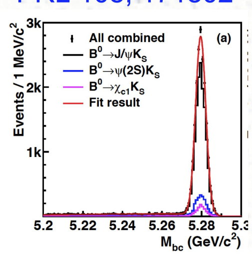
LHCb 41,500 (J/psi Ks only)

PRL 115, 031601



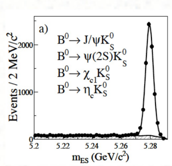
Belle 15,500

PRL 108, 171802

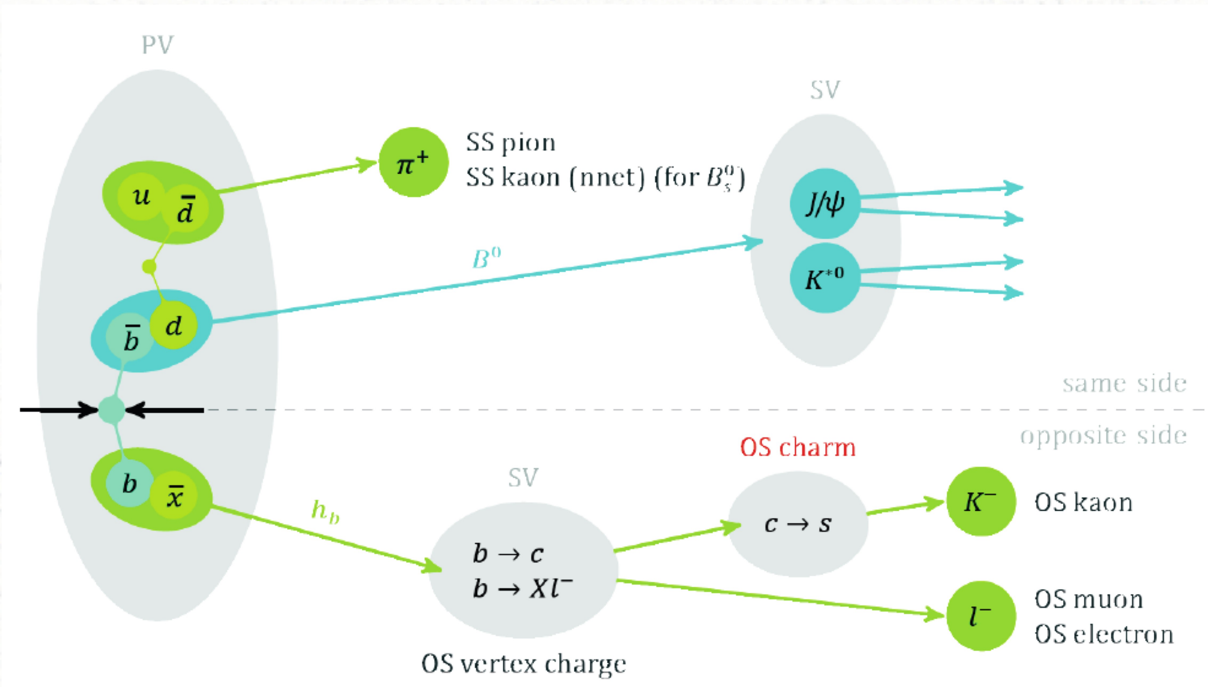


BaBar 8,400

PRD 79, 072009



Flavor Tagging @ LHCb



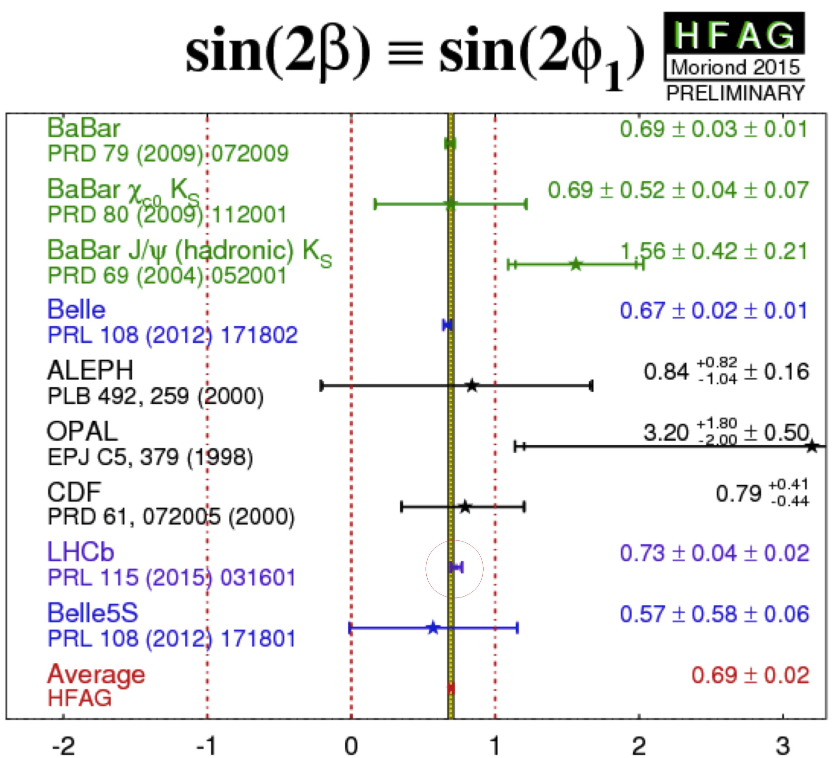
- Same-side *pion (kaon for Bs)*
- Opposite side *Vertex Charge, lepton, kaon, or charm*
- Total performance εD^2 = *3÷5%* depending on channel
  - Compare to ~30% at "B-factories"

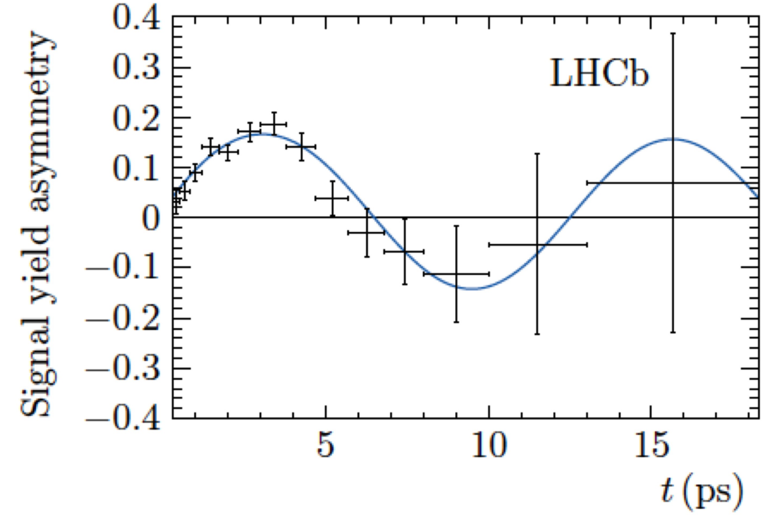
Status of $\sin(2\beta)$ @ LHCb

Phys. Rev. Lett. 115, 031601 – Published 14 July 2015

Tagged time-dependent analysis

- Exploit OS and for first time SSπ tag. $\epsilon D^2 = 2.99 \pm 0.03\%$





$$S = 0.731 \pm 0.035 \pm 0.020$$

$$S^{\rm Belle}_{J/\psi K^0_S} = 0.670 \pm 0.029 \pm 0.013$$

$$S^{\rm BaBar}_{J/\psi K^0_S} = 0.662 \pm 0.039 \pm 0.012$$

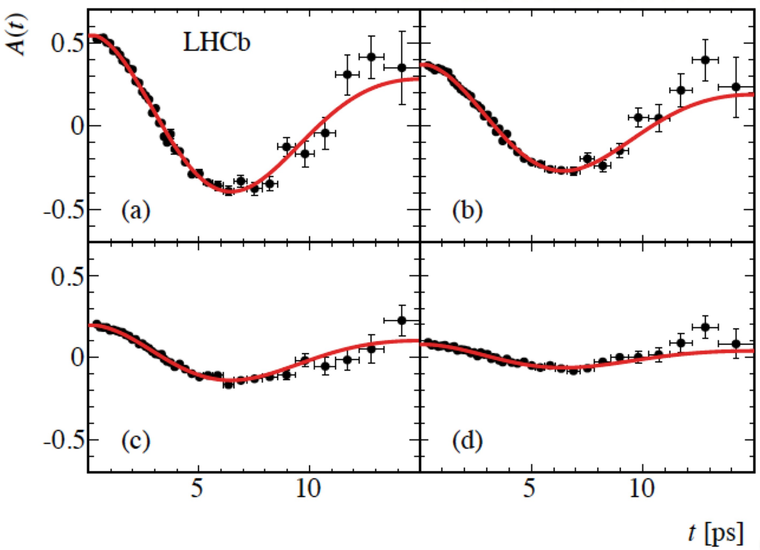
- Precision of LHCb 3fb^{-1} result ~ Babar/Belle

NEW: Best measurement of Δm_d

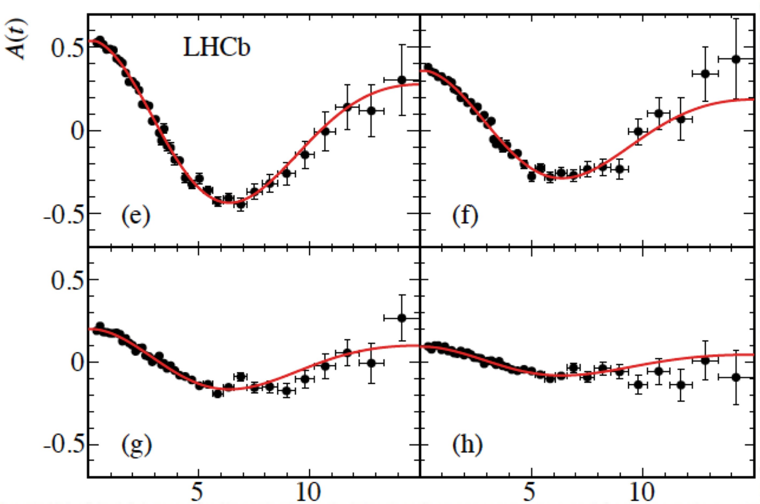
Submitted Apr 12, 2016

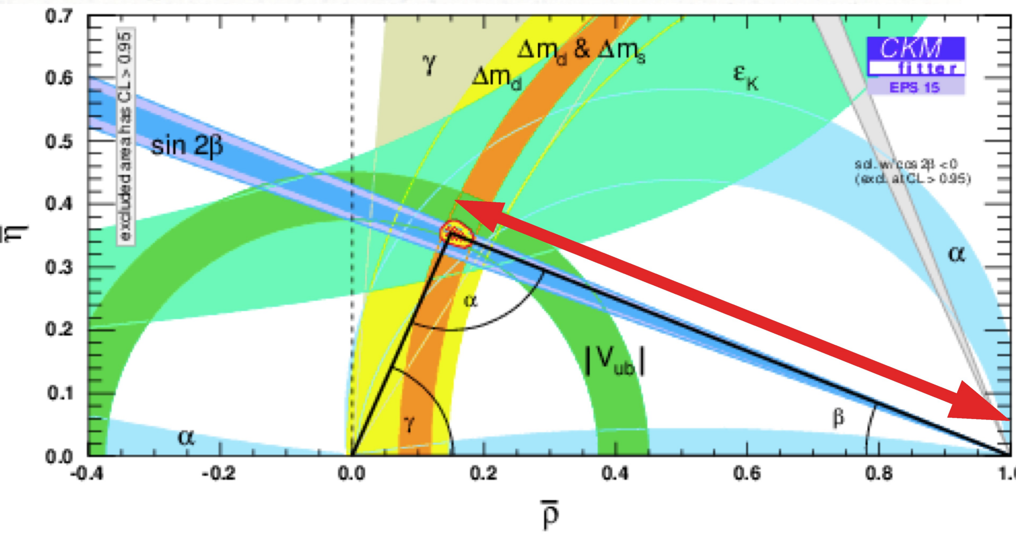
D^-

ArXiv:1604.03475



D^{*-}



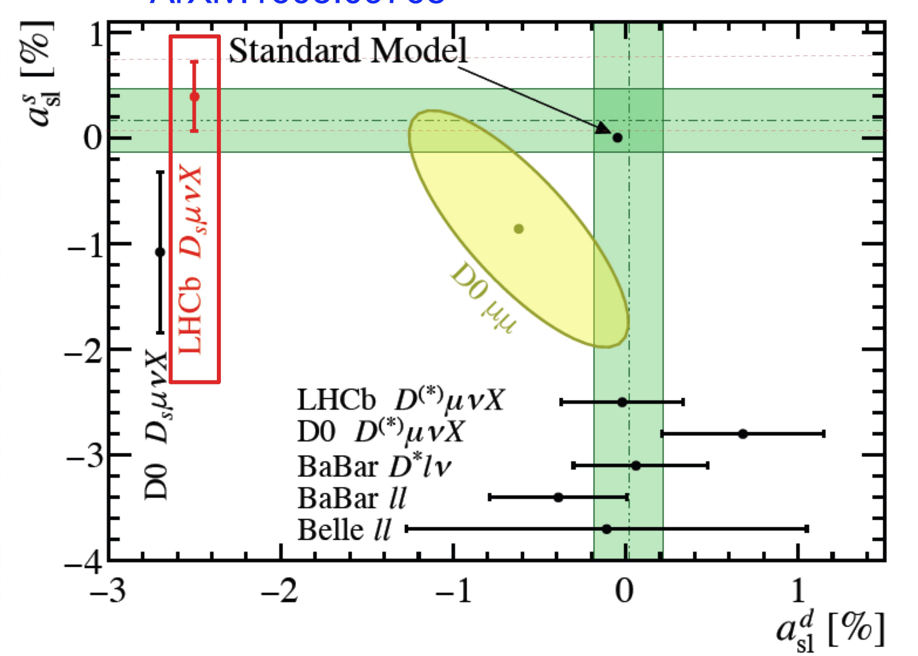


- Use semileptonic (self-tagging) decays
  $B^0 \rightarrow D^{(*)-} \mu X$
- Δm_d = 505.0 ± 2.1 ± 1.0 ns^{-1}
- This measurement alone improves the WA from 510 ± 3 → 506.4 ± 1.9 [HFAG]

Another new semileptonic result: a_{SL}

Submitted June 1, 2016

ArXiv:1605.09768



- Use semileptonic (self-tagging) decays $B_s^0 \to D_s^{(*)-}\mu X$ to measure mixing CPV

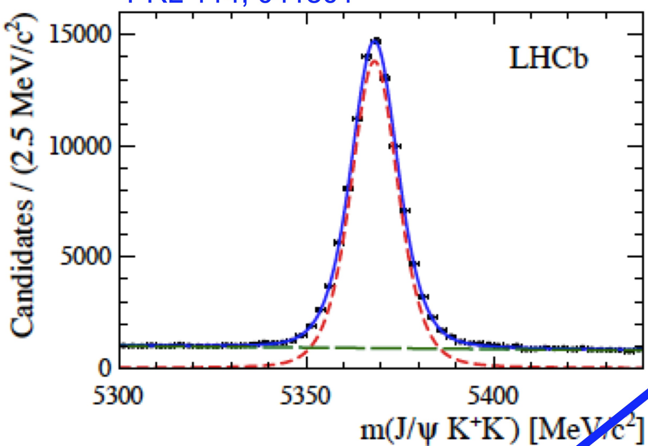
$$a_{sl} = \frac{N(\bar{B}\to B \to f) - N(B\to\bar{B} \to \bar{f})}{N(\bar{B}\to B \to f) + N(B\to\bar{B} \to \bar{f})} = \frac{1-|q/p|^4}{1+|q/p|^4}$$

- Fast B_s oscillations wash out effects of the production asymmetry
- World's best single measurement: $a_{sl} = 0.43 \pm 0.26(stat) \pm 0.20(syst)$ %

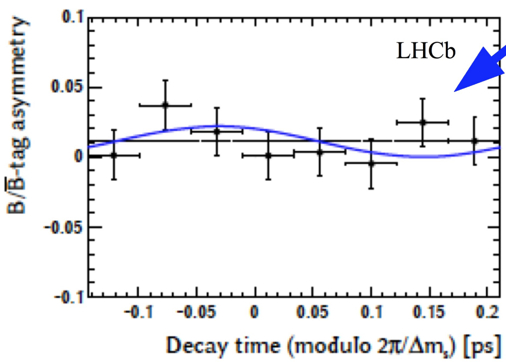
Brings the WA back towards the SM !

No need to ask about Bs mixing

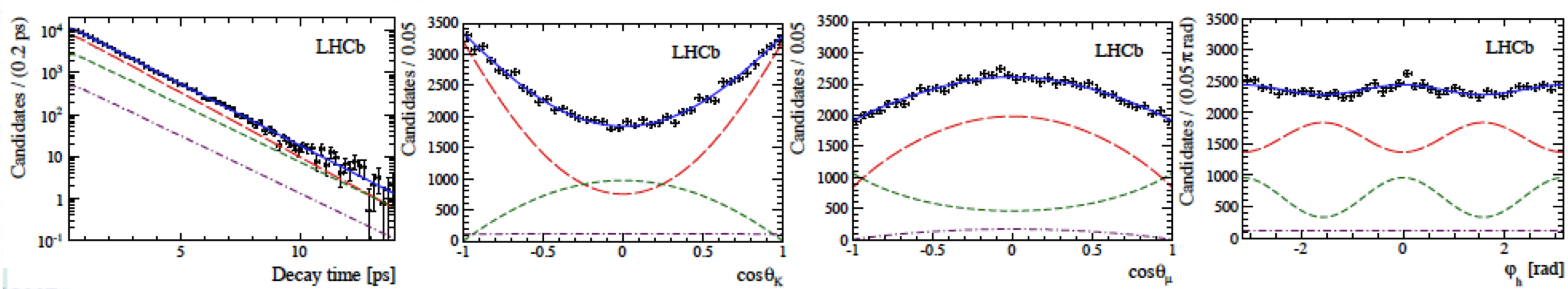
PRL 114, 041801



- Measuring the CP-violating phase $\varphi_s^{c\bar{c}s}$: $-2\beta_s \equiv -2\arg\left(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*\right) = -0.0363 \pm 0.0013$ in SM
- 100x zoom relative to B0 plot (**50 fs** bins)... (thanks to the VELO)



$$
\begin{aligned}
\varphi_s &= -0.058 \pm 0.049 \pm 0.006\,\text{rad},\\
|\lambda| &= 0.964 \pm 0.019 \pm 0.007,\\
\Gamma_s &= 0.6603 \pm 0.0027 \pm 0.0015\,\text{ps}^{-1},\\
\Delta\Gamma_s &= 0.0805 \pm 0.0091 \pm 0.0033\,\text{ps}^{-1}
\end{aligned}
$$



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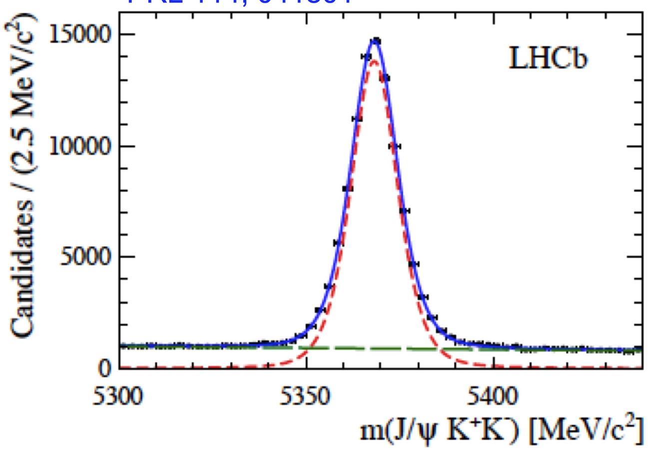
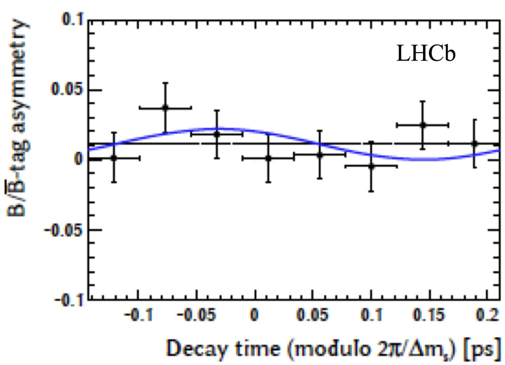
PRL 114, 041801





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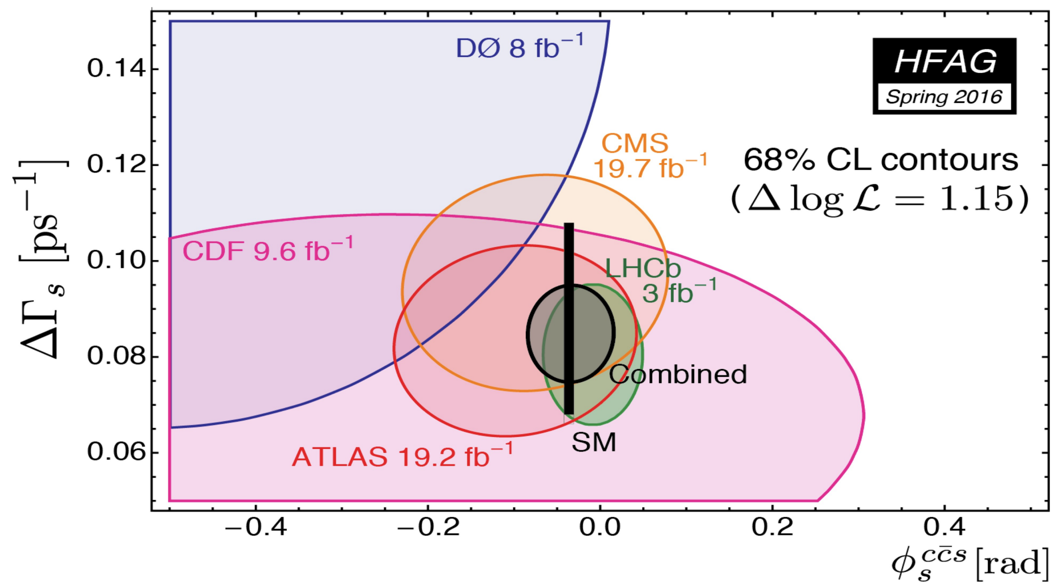
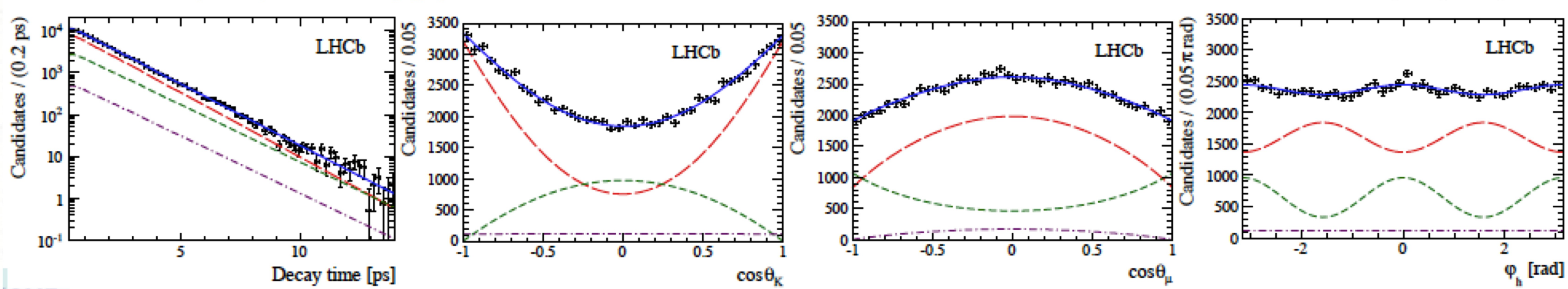




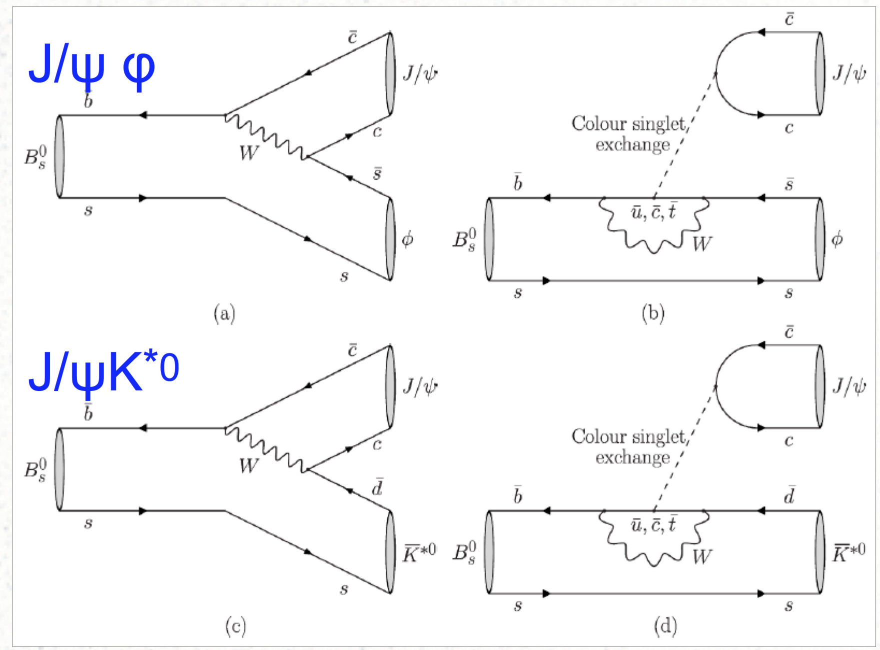
ϕ_s penguin corrections from data

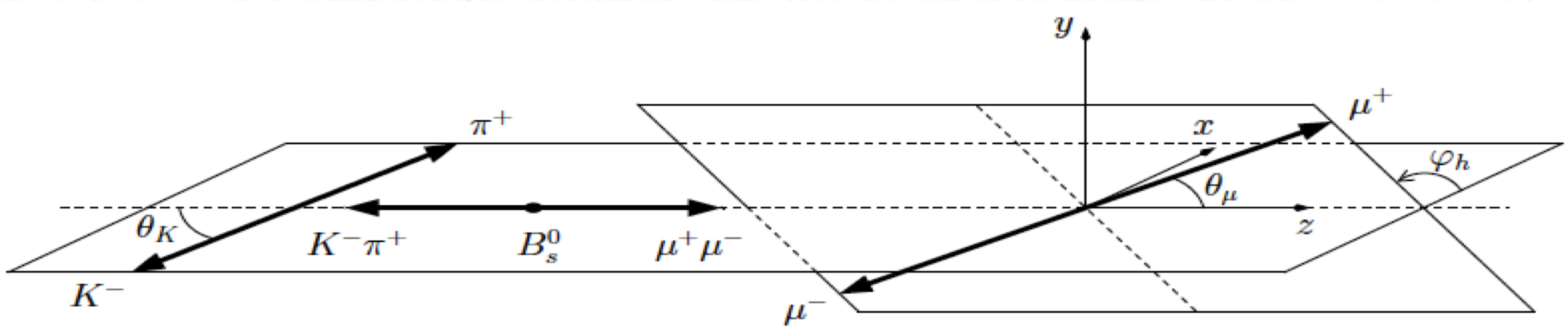
- With increasing levels of precision, cannot anymore neglect contribution of penguin diagrams

- It is however possible to obtain corrections from Bs →J/ψ K^{*0} data, by measuring BR/polarization

K. De Bruyn and R. Fleischer, JHEP 03 (2015)

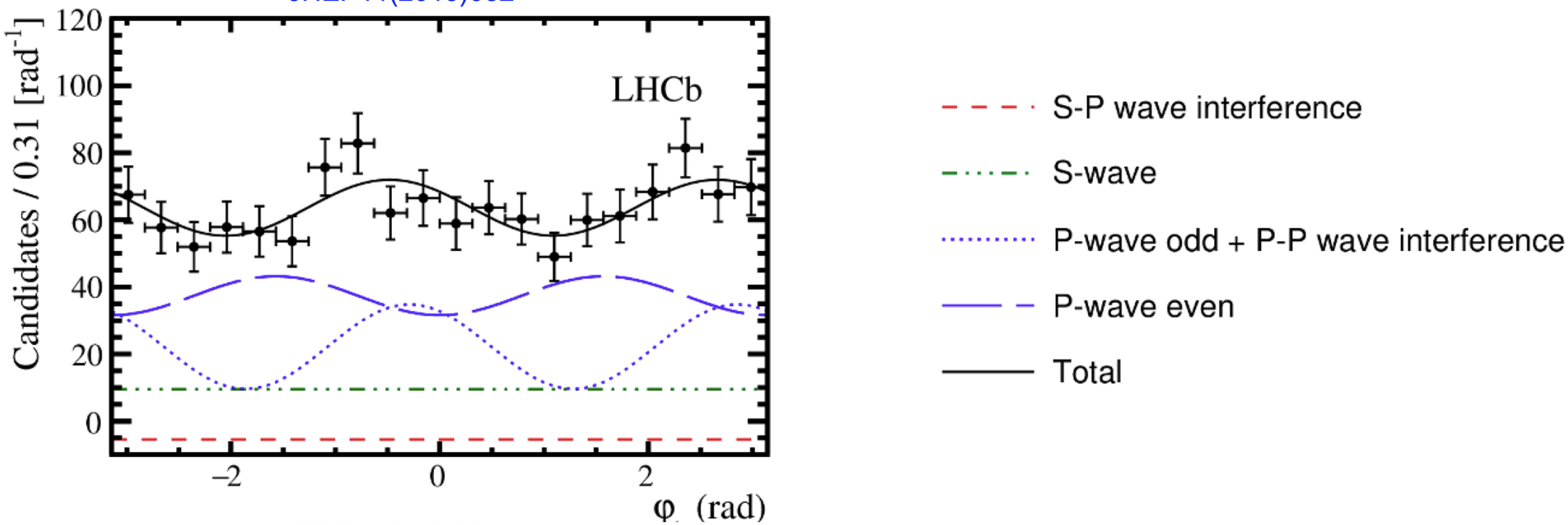
tree penguin



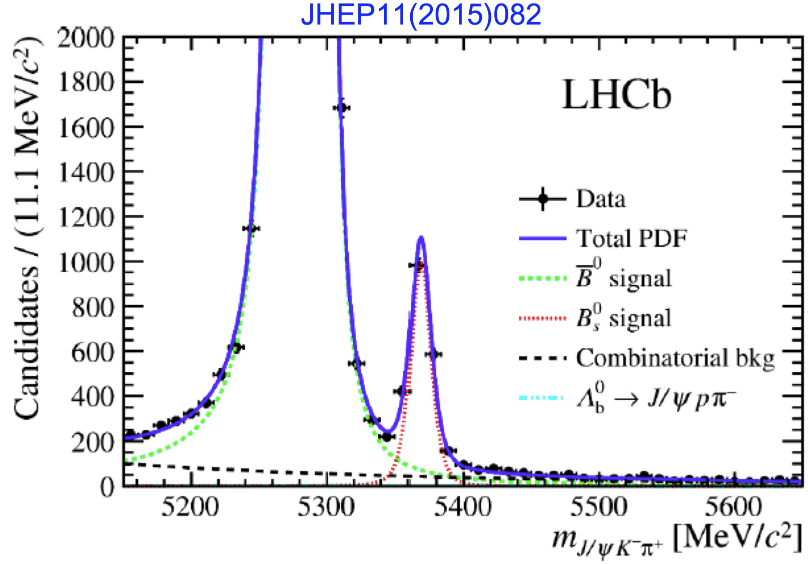


ϕ_s penguin corrections from data

JHEP11(2015)082



JHEP11(2015)082



→ Obtained that shifts from penguin pollution are small:

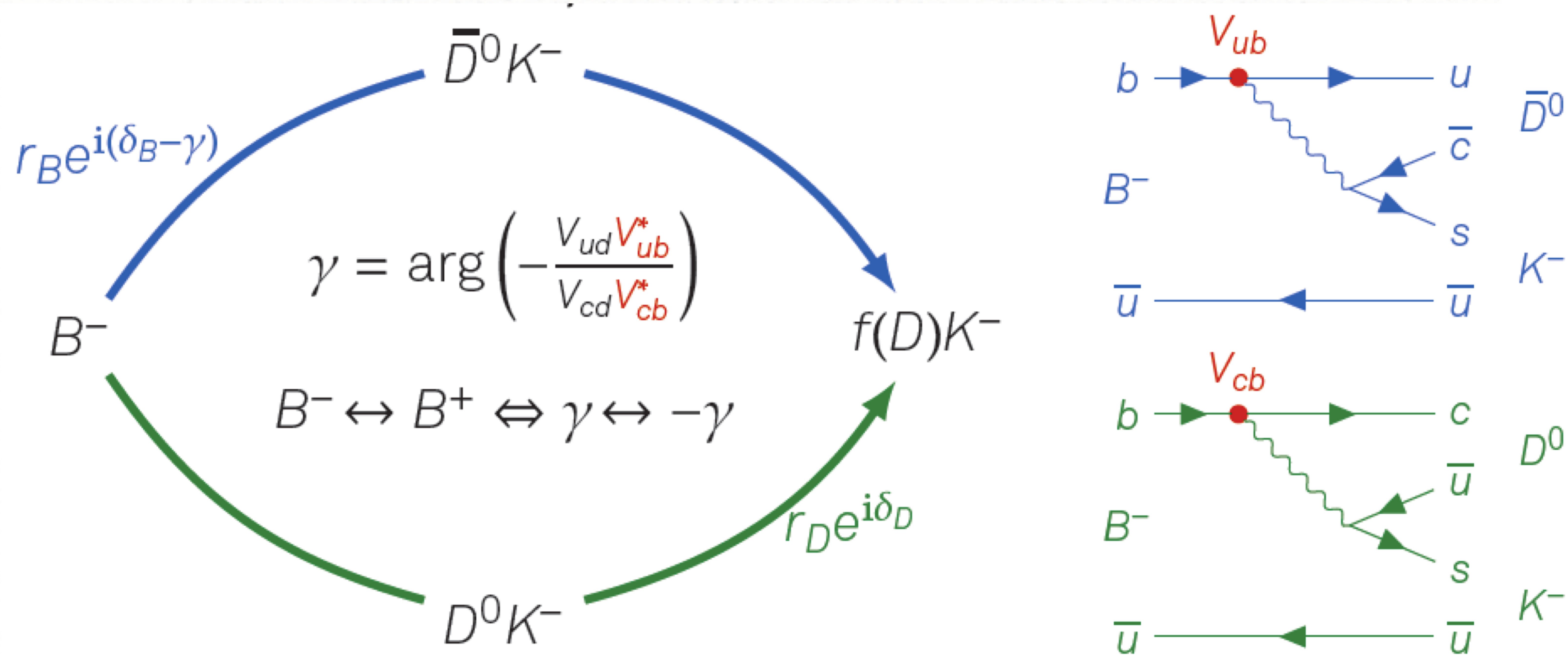
$$\Delta\phi_{s,0}^{J/\psi\phi} = 0.000^{+0.009}_{-0.011}\,(\mathrm{stat})\ {}^{+0.004}_{-0.009}\,(\mathrm{syst})\,\mathrm{rad}\,,$$

$$\Delta\phi_{s,\parallel}^{J/\psi\phi} = 0.001^{+0.010}_{-0.014}\,(\mathrm{stat})\ \pm 0.008\,(\mathrm{syst})\,\mathrm{rad}$$

$$\Delta\phi_{s,\perp}^{J/\psi\phi} = 0.003^{+0.010}_{-0.014}\,(\mathrm{stat})\ \pm 0.008\,(\mathrm{syst})\,\mathrm{rad}$$

Recent developments on CKM Angle Gamma

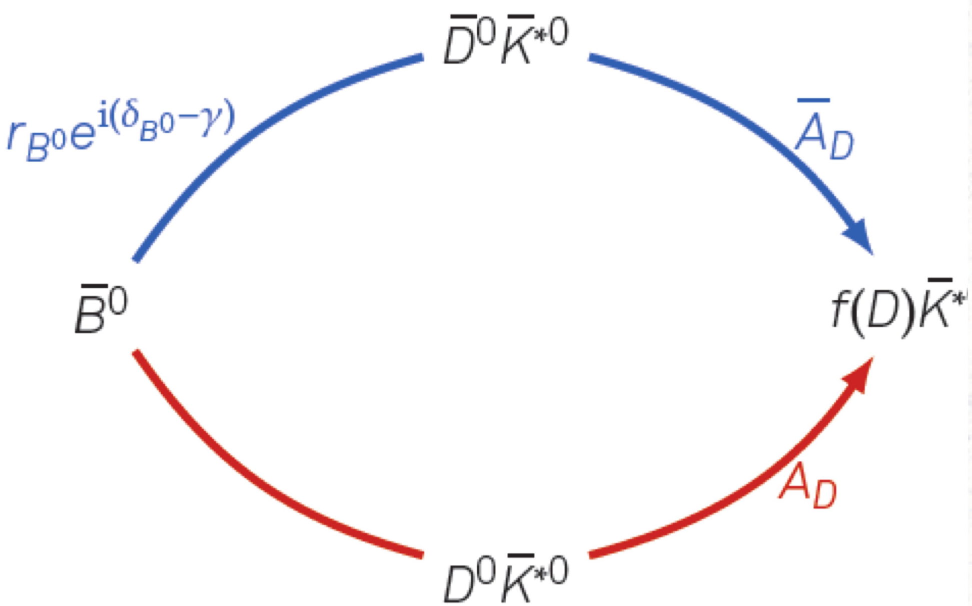
γ from tree-level processes



- A family of B → D K decays receive contributions from both $b \to u$ and $b \to c$ tree-level processes.
- Interference (A_{CP}) measures γ cleanly – different ways:
  - GLW: D → CP eigenstates [PLB 265 (1991) 172]
  - ADS: D → DCS mode [PRL 78 (1997) 3257]
  - GGSZ: D → n-body, via Dalitz [PRD 68 (2003) 054018]

Still least known CKM angle

D^0K^{*0} GGSZ



- B sign tagged by flavor-specific decay $K^{*0} \rightarrow K^+\pi^-$
- $D^0 \rightarrow$ 3-body Dalitz amplitude
  - $A_D = |A_D(m_-, m_+)|\, e^{i\delta_D}$
- Parametrize interference with
  $x_\pm = r_{B^0} \cos(\delta_{B^0} \pm \gamma)$
  $y_\pm = r_{B^0} \sin(\delta_{B^0} \pm \gamma)$

Recent results from LHCb

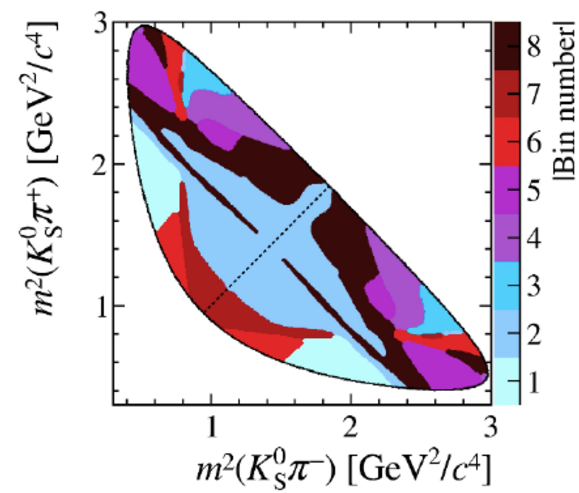
- JHEP06(2016)13
- ArXiv:1605.0108

Hot from the press: $D^0 K^{*0}$ GGSZ

JHEP06(2016)131, published 21/6/2016

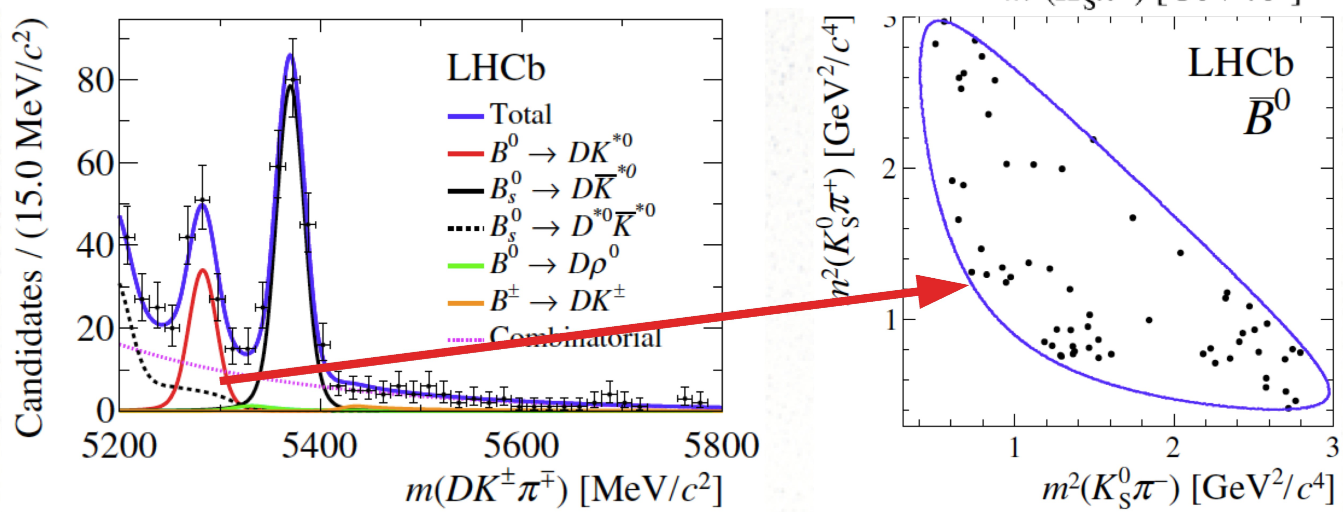
Model-independent fit of Dalitz plot of $D^0 \to K_S \pi^+\pi^-$ (+ K_S KK)

$$N_i(B^0) = n_{\bar{B}^0}\left[F_i + (x_-^2 + y_-^2)F_{-i} + 2\kappa\sqrt{F_i F_{-i}}(x_- c_i + y_- s_i)\right]$$



- Divide Dalitz plot in wide bins
- Correct for local efficiency F_i using semileptonic B data
  - B0 → D*+ μX
- D0 decay phase shifts from CLEO data [PRD 82 112006]

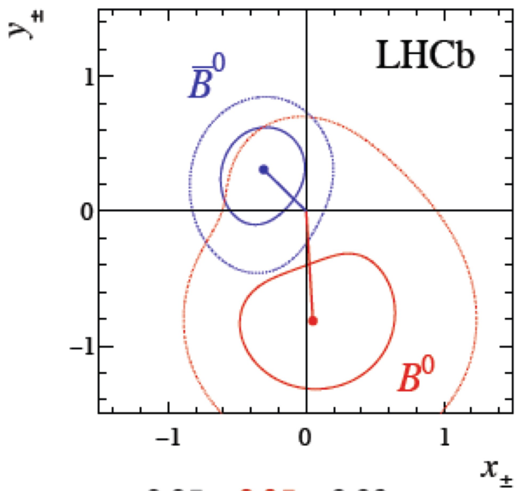
  → fit for x± y±



Hot from the press: D^0K^{*0} GGSZ

model-independent

JHEP06(2016)131, published 21/6/2016



$x_+ = 0.05 \pm 0.35 \pm 0.02$

$x_- = -0.31 \pm 0.20 \pm 0.04$

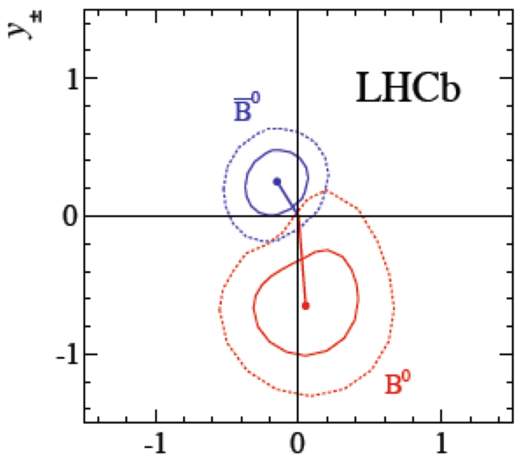
$y_+ = -0.81 \pm 0.28 \pm 0.06$

$y_- = 0.31 \pm 0.21 \pm 0.05$

$\gamma = 71 \pm 20$ deg

model-dependent

ArXiv:1605.01082 posted 1/7/2016



$x_+ = 0.05 \pm 0.24 \pm 0.04 \pm 0.01$

$x_- = -0.15 \pm 0.14 \pm 0.03 \pm 0.01$

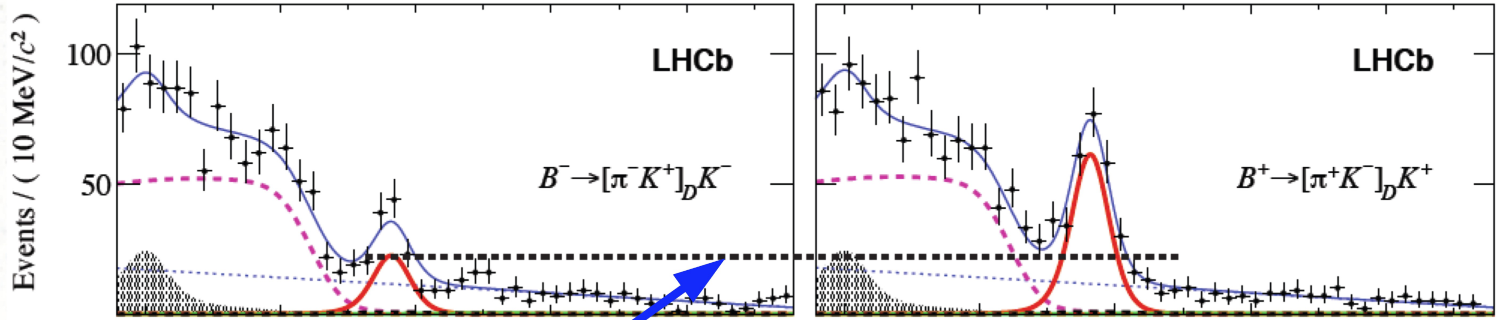
$y_+ = -0.65\ ^{+0.24}_{-0.23} \pm 0.08 \pm 0.01$

$y_- = 0.25 \pm 0.15 \pm 0.06 \pm 0.01$

$\gamma = 80\ ^{+21}_{-20}$ deg

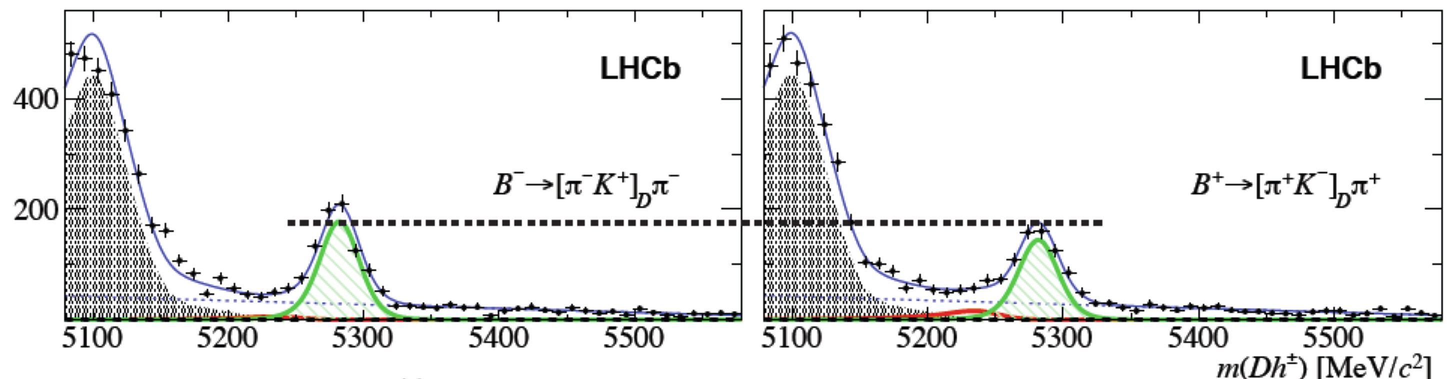
Other recent results: ADS

ArXiv:1603.08993 submitted 29/3/2016



Note large asymmetry (first >**5σ** effect in a single mode)

$$A^{\pi K}_{\mathrm{ADS}(K)} = -0.403 \pm 0.056 \pm 0.011$$

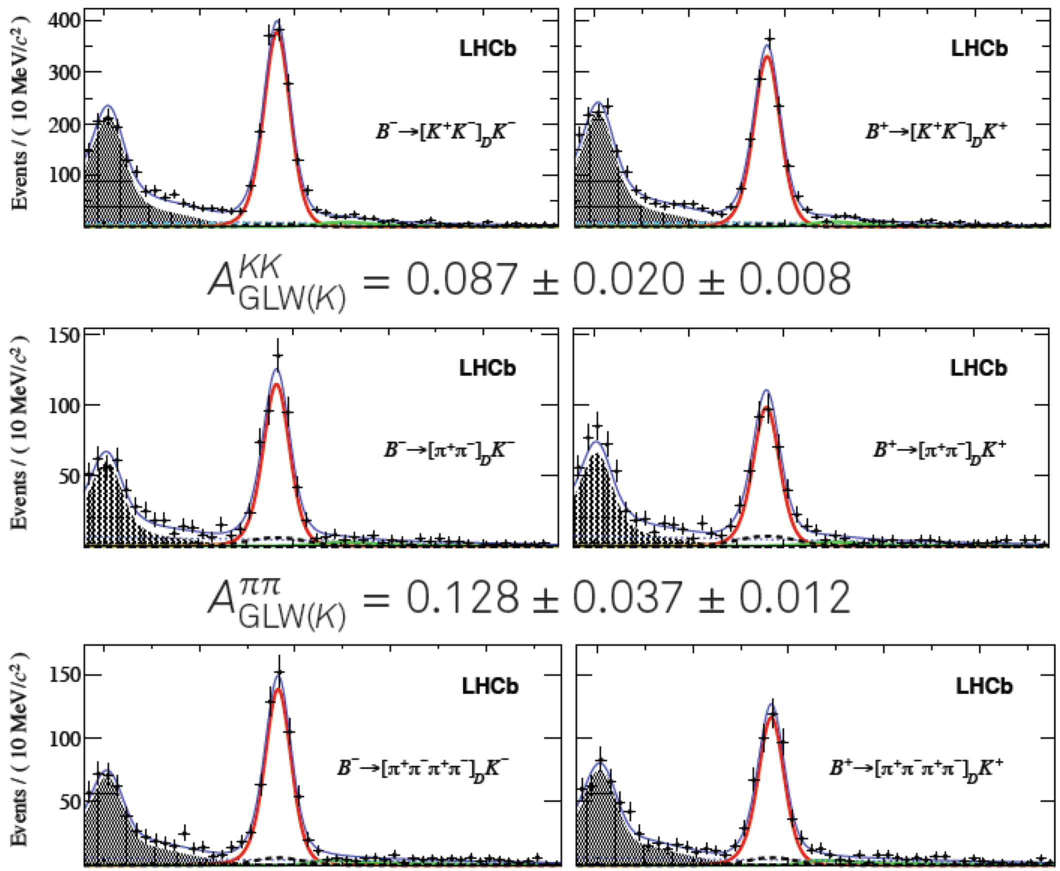


$$A^{\pi K}_{\mathrm{ADS}(\pi)} = 0.100 \pm 0.031 \pm 0.009$$

Analysis also performed in 4-body D^0 final states

Other recent results: GLW

ArXiv:1603.08993 submitted 29/3/2016



$$A^{KK}_{\mathrm{GLW}(K)} = 0.087 \pm 0.020 \pm 0.008$$

$$A^{\pi\pi}_{\mathrm{GLW}(K)} = 0.128 \pm 0.037 \pm 0.012$$

$$A^{\pi\pi\pi\pi}_{\mathrm{GLW}(K)} = 0.100 \pm 0.034 \pm 0.018$$

Novelty: $D^0 \to 4\pi$ final state

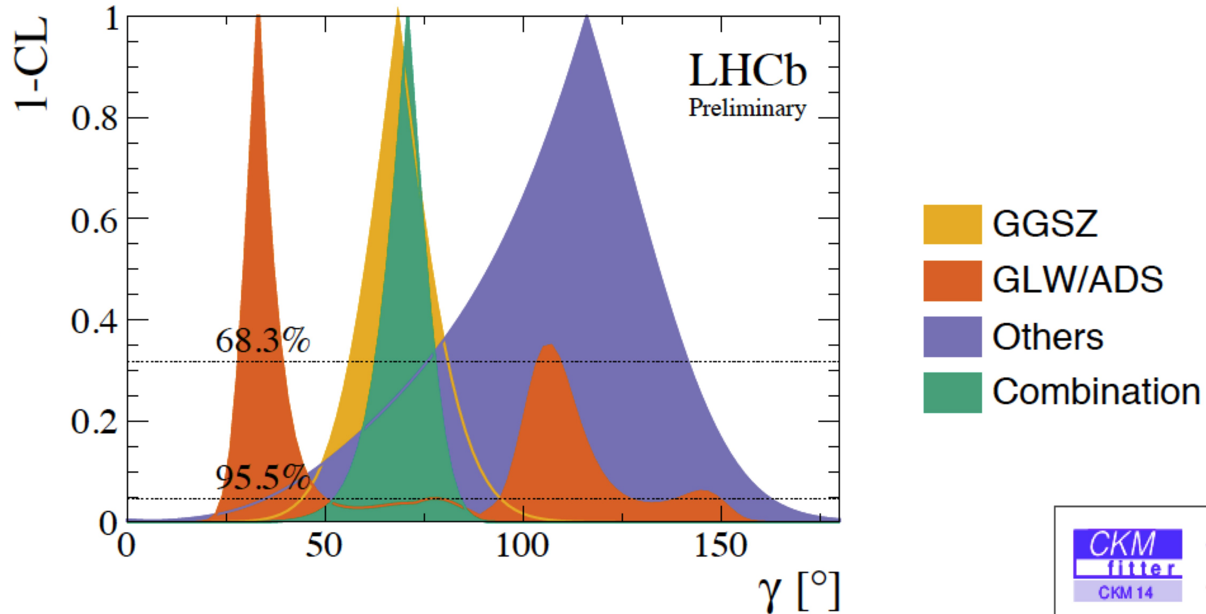
LHCb Gamma combination

LHCb-CONF-2016-001 (Mar 14, 2016)

- $B^+ \to DK^+$, $D \to h^+h^-$, GLW/ADS, $3\,\mathrm{fb}^{-1}$ [ArXiv:1603.0899]
- $B^+ \to DK^+$, $D \to h^+\pi^-\pi^+\pi^-$, quasi-GLW/ADS, $3\,\mathrm{fb}^{-1}$ [ArXiv:1603.0899]
- $B^+ \to DK^+$, $D \to h^+h^-\pi^0$, quasi-GLW/ADS, $3\,\mathrm{fb}^{-1}$ [PRD 91 (2015) 112014]
- $B^+ \to DK^+$, $D \to K^0_\mathrm{S}h^+h^-$, model-independent GGSZ, $3\,\mathrm{fb}^{-1}$ [JHEP 10 (2014) 097]
- $B^+ \to DK^+$, $D \to K^0_\mathrm{S}K^+\pi^-$, GLS, $3\,\mathrm{fb}^{-1}$ [PLB 733 (2014) 36]
- $B^0 \to DK^+\pi^-$, $D \to h^+h^-$, GLW-Dalitz, $3\,\mathrm{fb}^{-1}$ [PRD 93 (2016) 112018]
- $B^0 \to DK^{*0}$, $D \to K^+\pi^-$, ADS, $3\,\mathrm{fb}^{-1}$ [PRD 90 (2014) 112002]
- $B^0 \to DK^{*0}$, $D \to K^0_\mathrm{S}\pi^+\pi^-$, model-dependent GGSZ, $3\,\mathrm{fb}^{-1}$ [ArXiv:1605.0108]
- $B^+ \to DK^+\pi^+\pi^-$, $D \to h^+h^-$, GLW/ADS, $3\,\mathrm{fb}^{-1}$ [PRD 92 (2015)]
- $B^0_s \to D^\mp_s K^\pm$, time-dependent, $1\,\mathrm{fb}^{-1}$ [JHEP 11 (2014) 060]

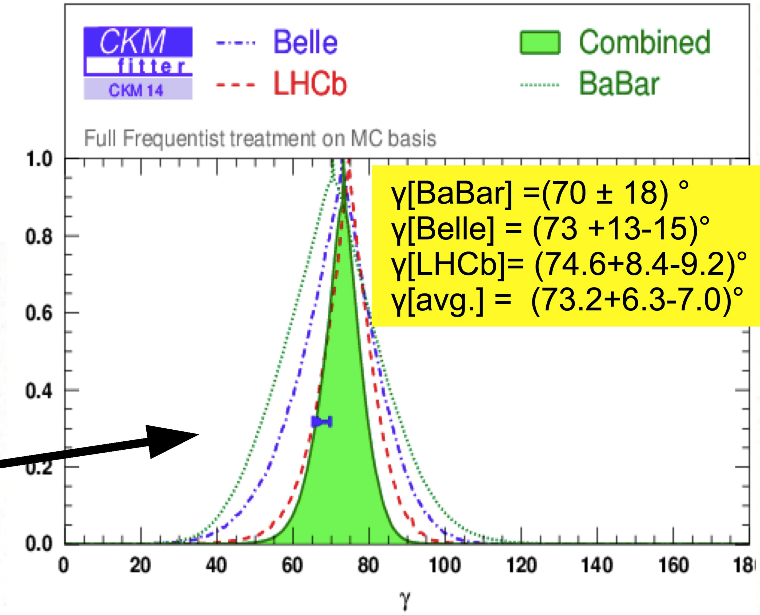
LHCb angle γ combination

LHCb-CONF-2016-001



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

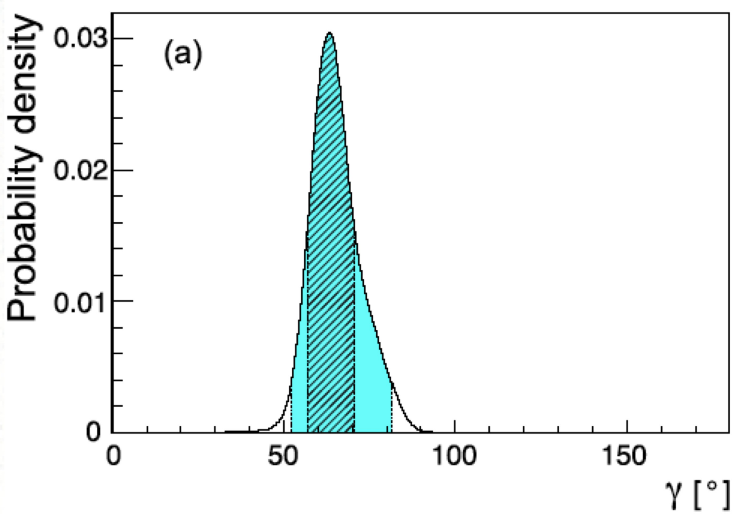
- Most precise measurement from a single experiment !
- Latest: not yet in this plot

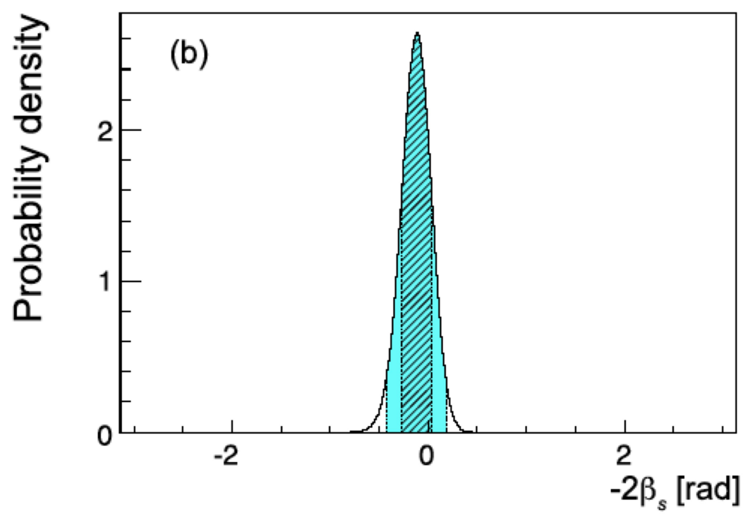


Angle γ "beyond the trees"

- Results from tree-level measurements can be compared to gamma (and β_s) results from penguin processes in search for deviations
- Analysis of 1fb^{-1} of $B^0 \to \pi^+\pi^-$ and $B_s \to KK$ data already provide interesting sensitivity (in agreement with tree-level).

Physics Letters B 741 (2015) 1–11



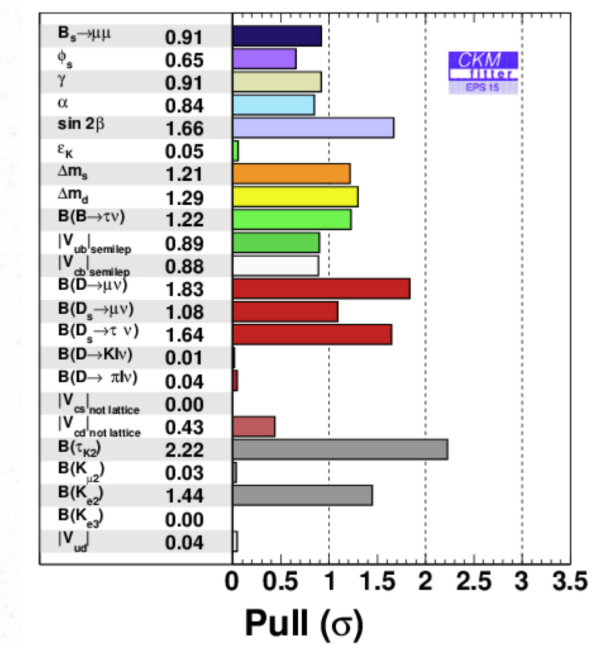


$$\gamma = (63.5^{+7.2}_{-6.7})^\circ$$

$$-2\beta_s = -0.12^{+0.14}_{-0.16} \text{ rad}$$

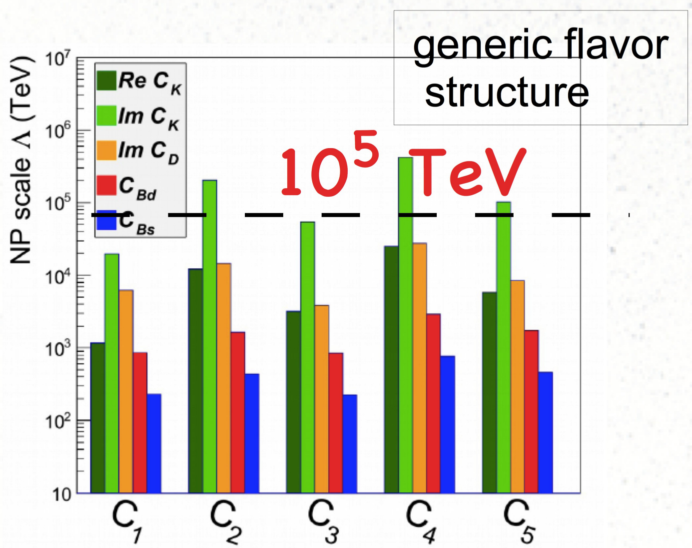
Prospects

CKM: does it fit the SM ?

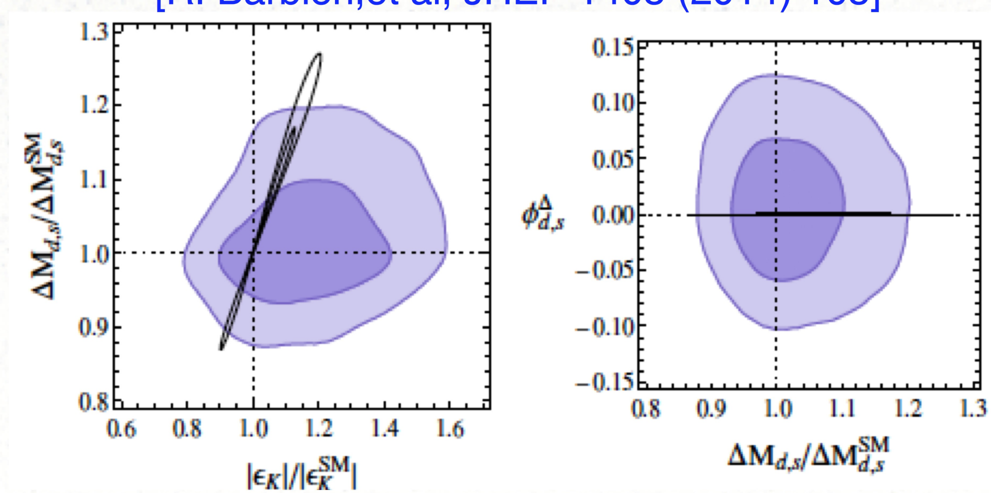


- As of today, no statistically significant deviation from CKM scheme has been seen
- Still there are good reasons to *expect* CPV effects beyond the SM/CKM scheme
- Potentially sensitive to very high E scales - while, in spite of the accuracy of current CKM fit, O(20%) NP effects could still be hiding in data

→ We are definitely NOT at the end of this game

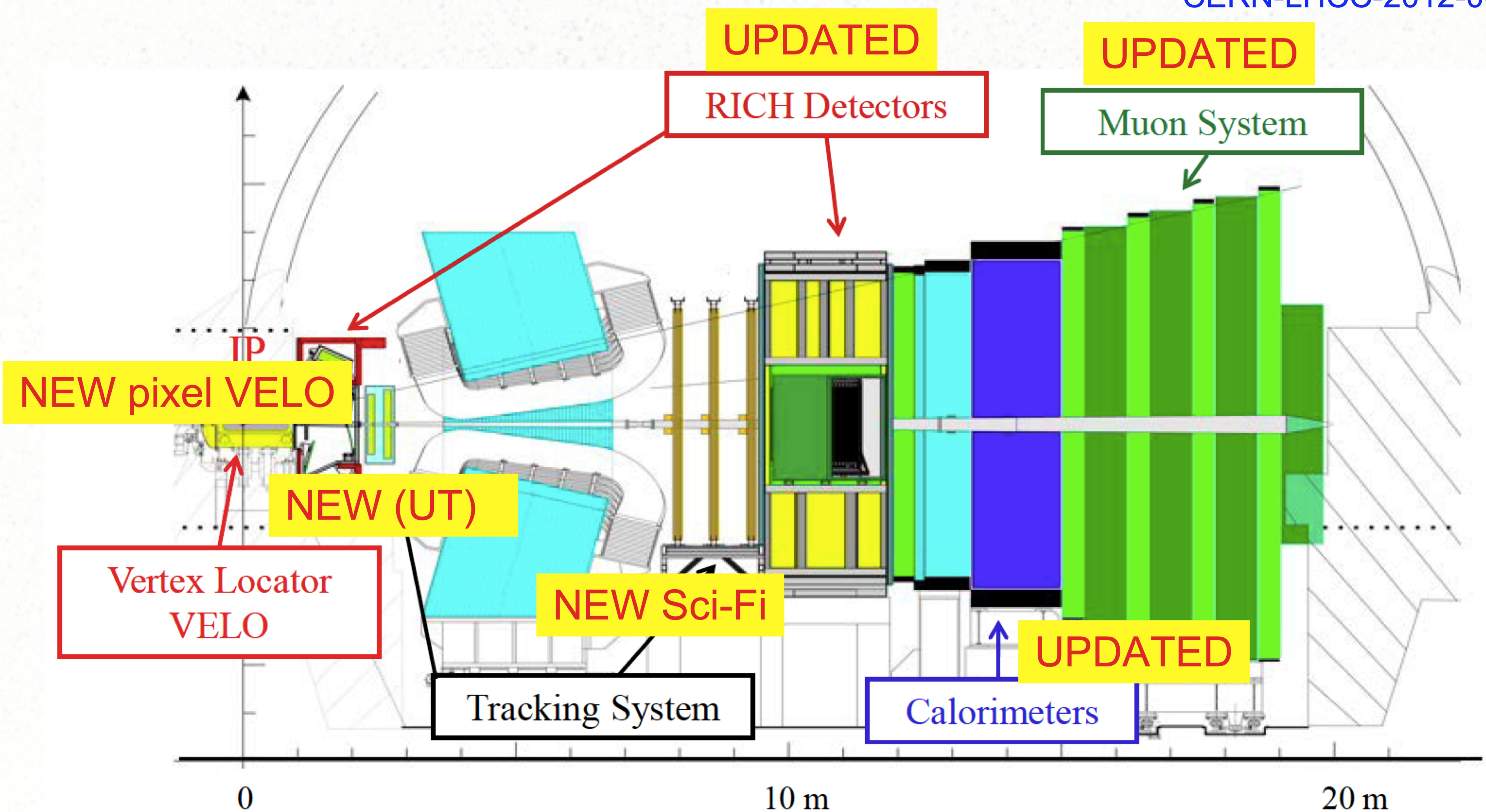


[R. Barbieri,et al, JHEP 1405 (2014) 105]



The LHCb upgrade: detector

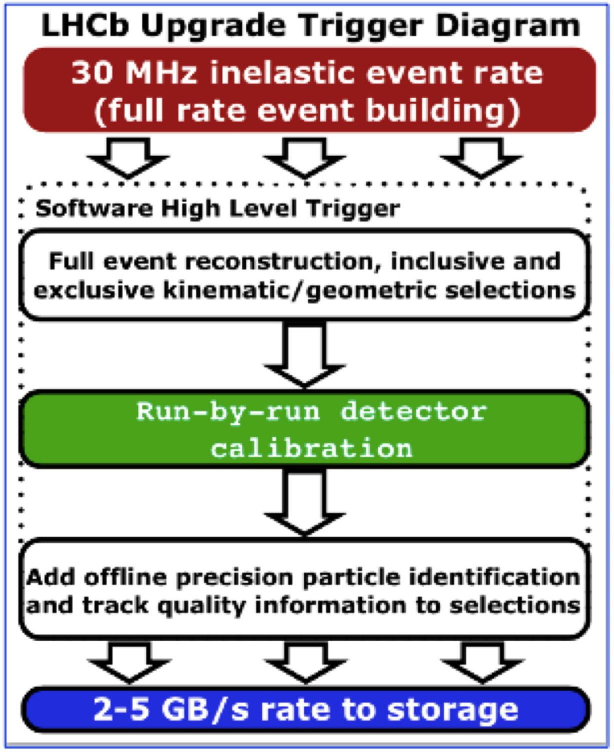
CERN-LHCC-2012-007

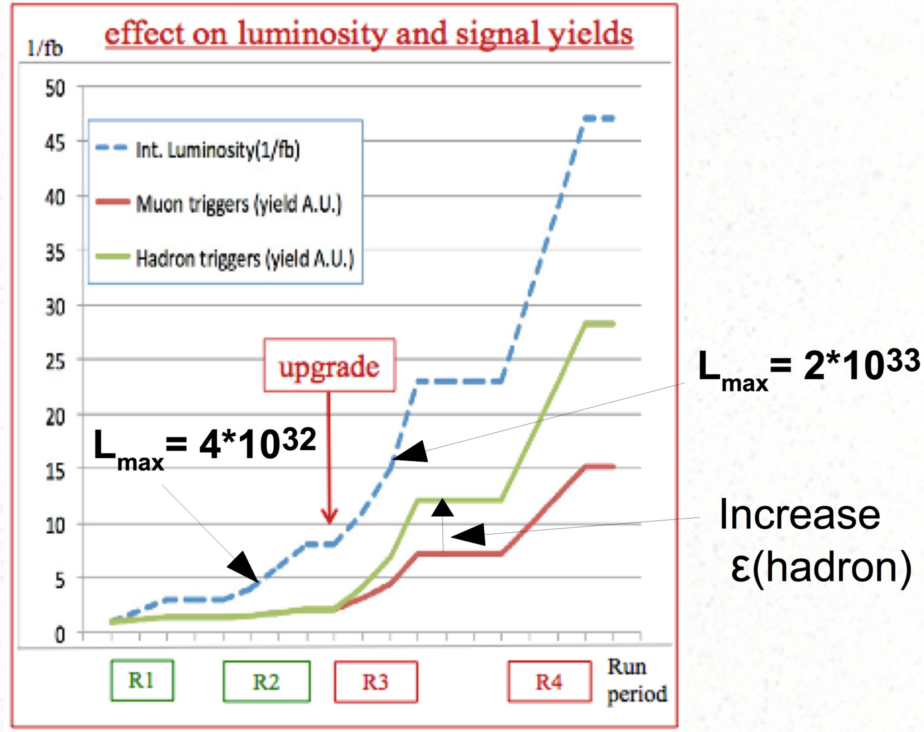


- Substantial upgrades to most detectors
- Higher granularity + faster electronics to handle higher L

The LHCb DAQ upgrade

CERN-LHCC-2014-016

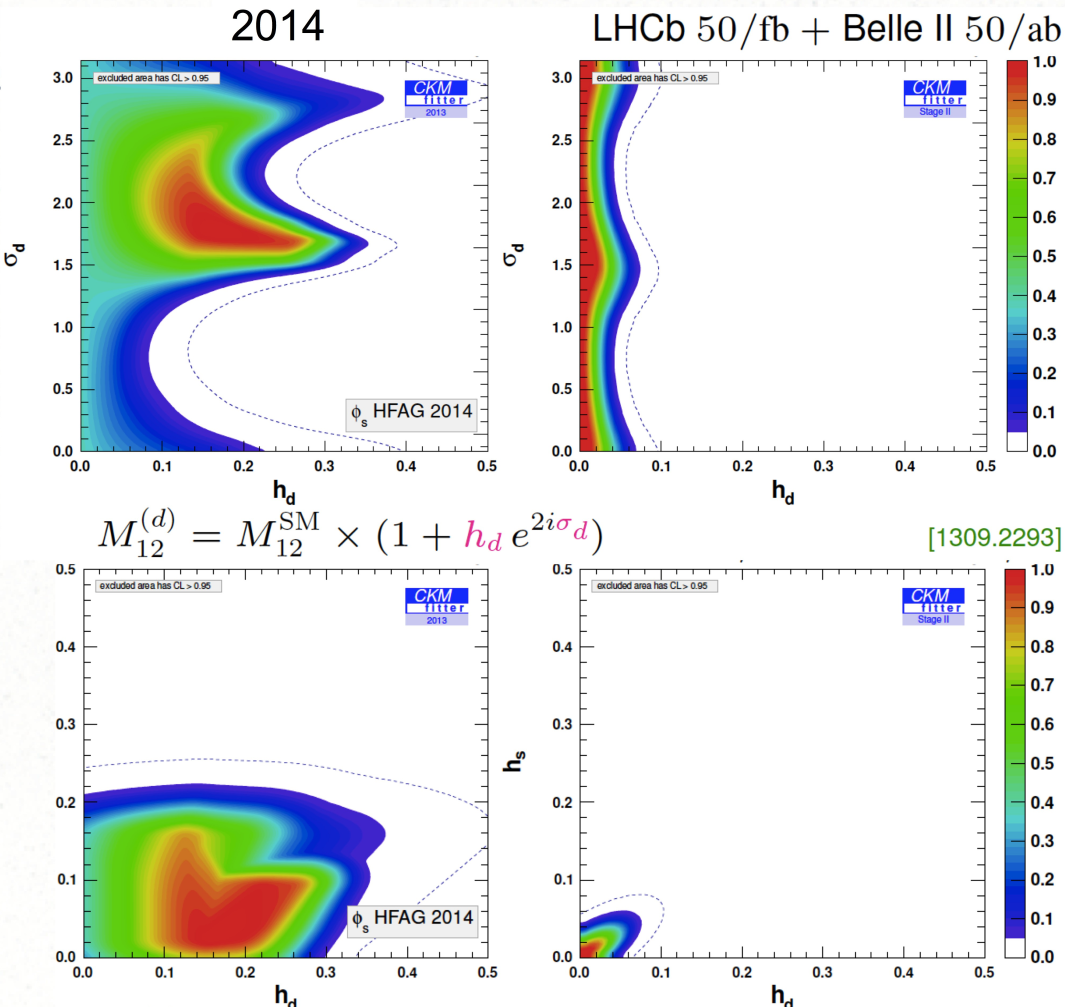




- Detector readout and trigger at 40 MHz + higher rate to storage will be the drivers to handle 5x luminosity and collect larger samples
    - Plan for **50 fb^{-1}** integrated luminosity by the end of Run 4 (2028)
- Based on new front-end electronics, large PC-based event-builder network, and large expansion of online CPU farm
- Real-time data calibration and reconstruction

Future NP sensitivity in B-mixing

[J.Charles et al.,, Phys. Rev. D 89, 033016 (2014)]



$$M_{12}^{(d)} = M_{12}^{\rm SM} \times (1 + h_d\, e^{2i\sigma_d})$$

$$M_{12}^{(q)} = M_{12}^{\rm SM} \times (1 + h_q\, e^{2i\sigma_q})$$

- LHCb with 50 fb^{-1} will continue to dominate in HL-LHC era: $\sigma(\phi_s)$= 0.045 → 0.009

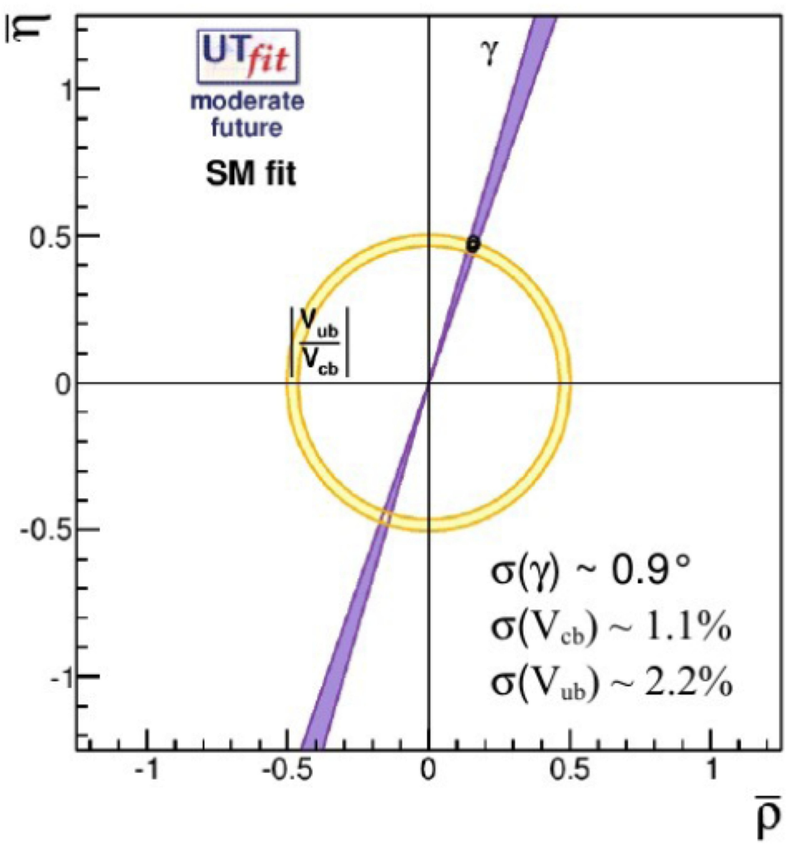
  Also extrapolate: $\sigma(\beta)$= 0.2 deg (~Belle II)

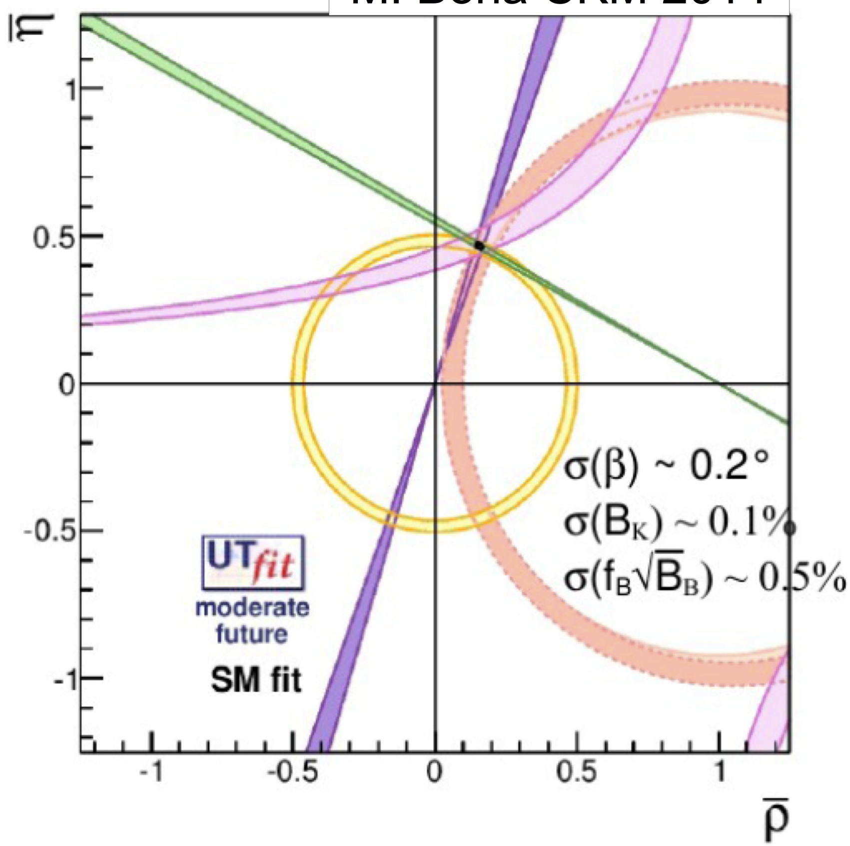
- Sensitivity to NP at 2 TeV (10^3 TeV) level, independent of phase

  → gluino sensitivity in the same ballpark of direct searches

CKM plots of the future

M. Bona CKM 2014

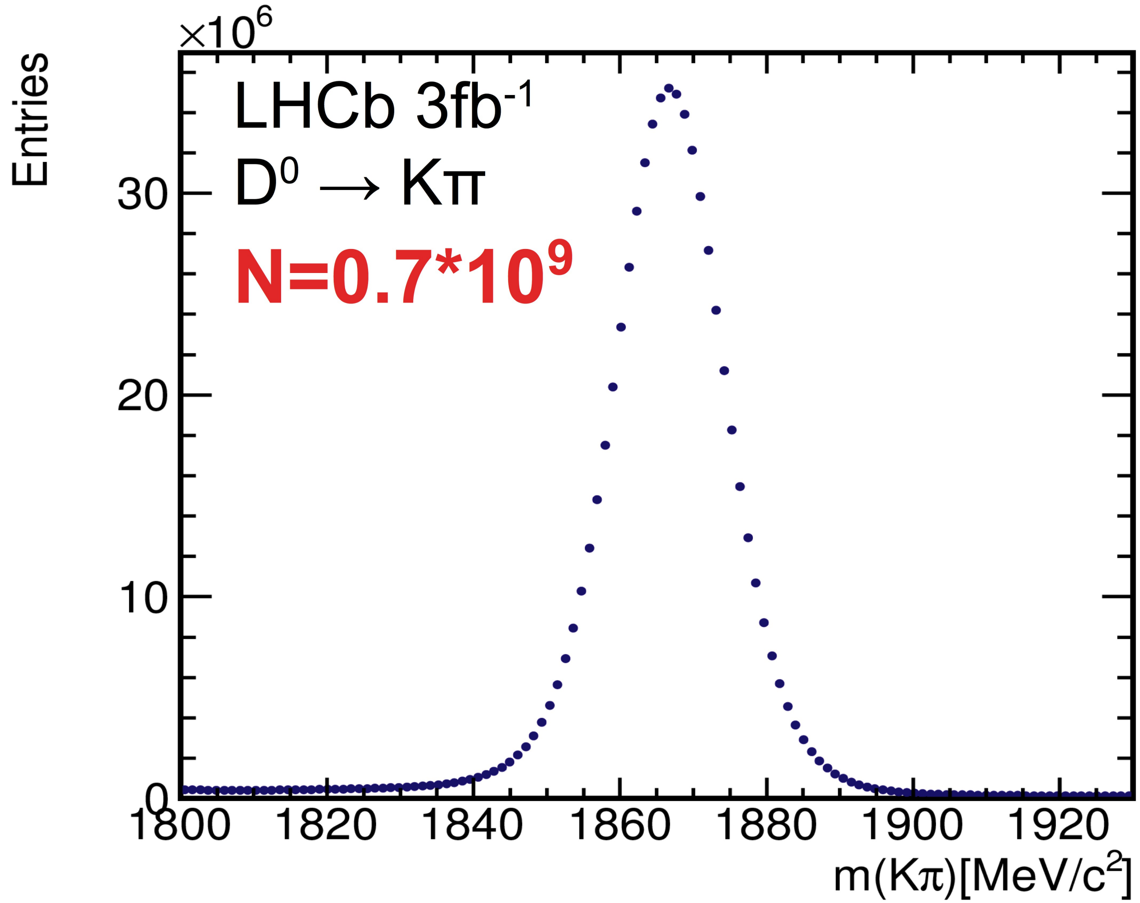




errors from tree-only fit on ρ and η:
σ(ρ) = 0.008 *[currently 0.051]*
σ(η) = 0.010 *[currently 0.050]*

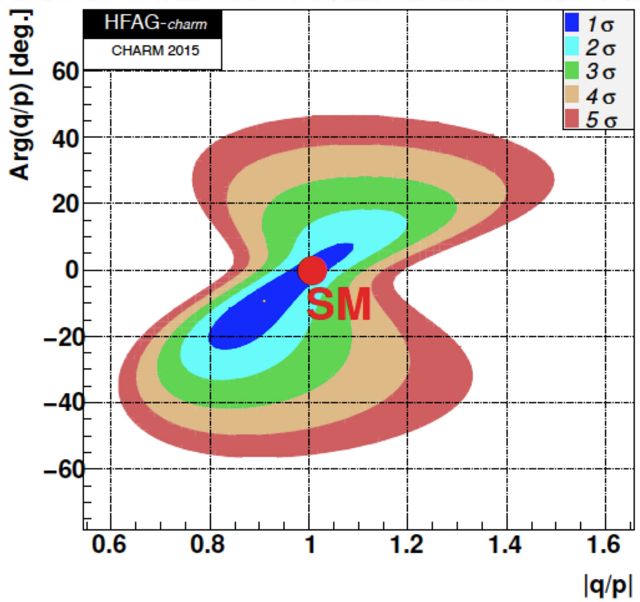
errors from 5-constraint fit on ρ and η:
σ(ρ) = 0.005 *[currently 0.034]*
σ(η) = 0.004 *[currently 0.015]*

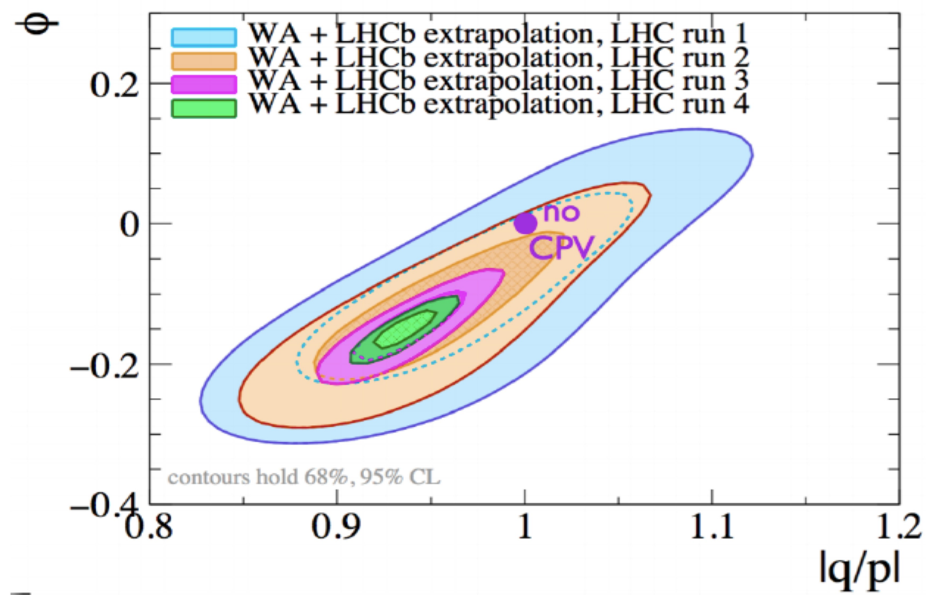
*LHC**b** is not just about Beauty...*



Unprecedented access to clean samples of ***Billions*** of charm hadron decays

Prospects in Charm CPV





- LHCb the first single experiment to observe D^0 mixing [PRL 110 (2013) 10180]
- **World best A_{CP}** measurements already from the first $1fb^{-1}$ →

Recently publ. $3fb^{-1}$ D→ππ/KK DCPV:

$$\Delta A_{CP} = [-0.10 \pm 0.08(\text{stat}) \pm 0.03(\text{syst})]\%$$

PRL 116, 191601 (2016)

- CPV in charm not yet observed. Indirect CPV not theory limited. Related to top FCNC.
- **50 fb^{-1}** yield interesting sensitivities → *unique probe of up-quark sector*

$\int \mathcal{L}\,dt$	Run-1 (2010-12)	LHC era Run-2 (2015-18)	Run-3 (2020-22)	HL-LHC era Run-4 (2025-28)	Run-5 (2030++)
x [10^{-3}]	1.22	0.92	0.42	0.25	0.18
y [10^{-3}]	0.53	0.37	0.15	0.09	0.06
$\|q/p\|$ [10^{-3}]	59	44	20	12	8
ϕ [mrad]	89	70	33	20	14

Mixing and indirect *CP* violation sensitivities

LHCb projections to 50 fb^{-1} – and still room for improvement…

[LHCb-PUB-2014-40]

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**		Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**		~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.068	0.035	**0.012**	x3	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**		0.03
Gluonic	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**		0.02
penguin	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**		< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**		0.02
Right-handed	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**		< 0.01
currents	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**		0.2 %
Electroweak	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**		0.02
penguin	$q_0^2\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	More	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	obs	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**		$\sim 10\%$
Higgs	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**		0.3
penguin	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	x8	$\sim 5\,\%$
Unitarity	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**		negligible
triangle	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	large	negligible
angles	$\beta(B^0 \to J/\psi\ K_S^0)$	1.7°	0.8°	**0.31°**		negligible
Charm	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	large	–
CP violation	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**		–

LHCb Future Upgrade Studies

- Due to the exciting prospects, LHCb recently started considering further improvements to its program:

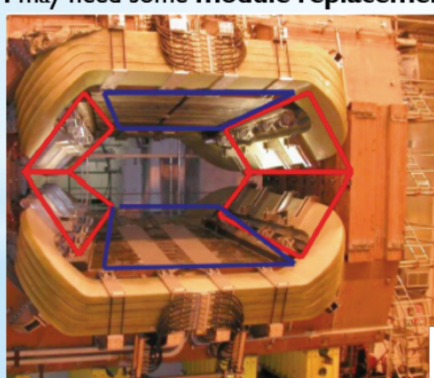
  - Small improvements/consolidations for Run 4 (“Phase-1B”)

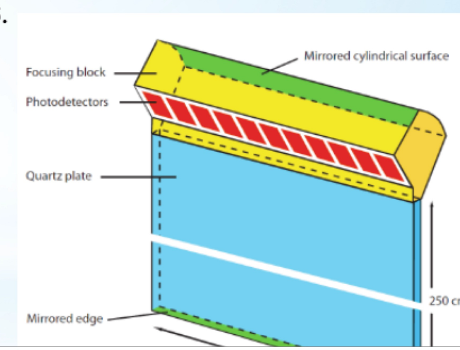
  - Further upgrades for Run 5, to accept up to L= 300 fb^{-1}

[→ see "Beyond the LHCb Phase-1 Upgrade" workshop, 6/4/2016]

LHCb Phase-Ib upgrade during **LS3** aims for **moderate cost** improvements on the Phase-I detector. Possible improvements being investigated which have the potential to extend LHCb physics capabilities:

- Improve **tracking acceptance** for **low momentum** particles by installing **tracking stations** on the **dipole magnet internal side**.
- Improve **muon acceptance** by adding **muon chambers around the dipole** magnet using the **magnet yoke as shielding**.
- **Replace HCAL with a new shielding** for the muon chambers.
- **Innermost ECAL** region needs to be replaced during LS3. Rather than using existing spares, use **new technologies (see later).**
- **TORCH:** as standalone **PID detector**, or as a **timing device**, perhaps embedded in ECAL.
- **SciFi** may need some **module replacement** during LS3.
- …





F. Teubert, BEAUTY 2016

Conclusions

- LHCb run I brought significant improvement to the precision of our CKM picture
- An exciting path to further results in the coming years at LHC