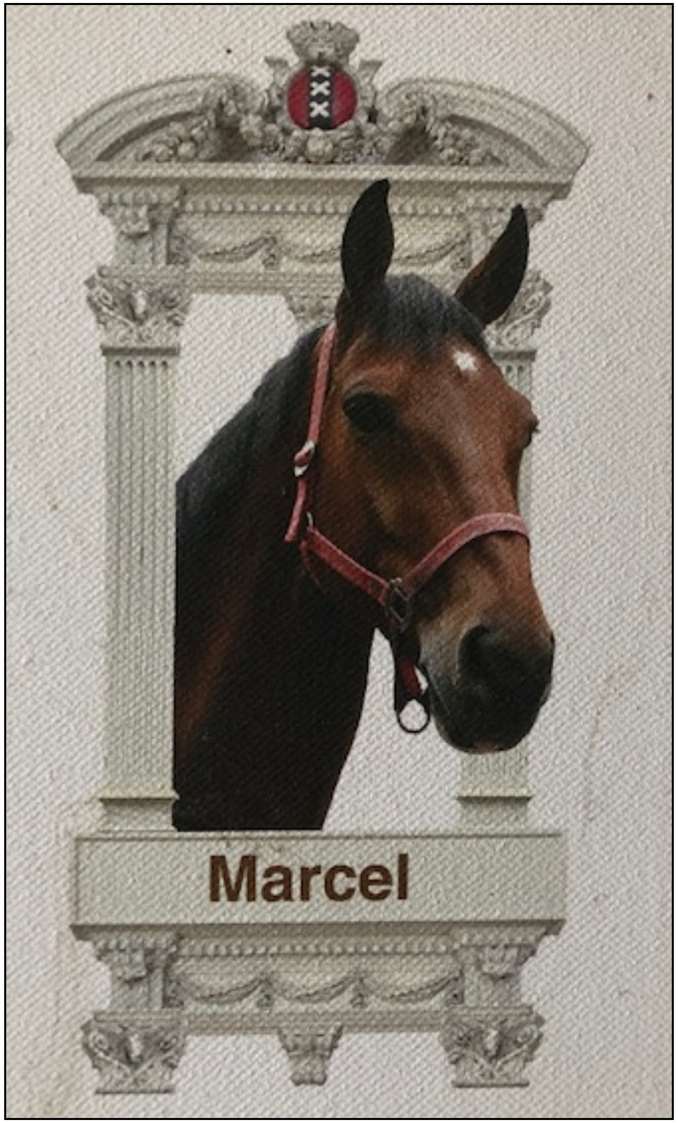
Physics Summary

Niels Tuning

Upgrade II workshop, 10 Apr 2019

Thanks to the organizers



Physics topics on the Agenda:

Overview of the flavour elements of the HL-LHC physics workshop	*Jorge Martin Camalich et al.*	
Vondelkerk, Amsterdam	13:35 - 14:00	
Rare decays and LFU tests at Upgrade II (Theory)	*Javier Fuentes-Martin*	
Vondelkerk, Amsterdam	14:05 - 14:30	
Rare decays and LFU tests at Upgrade II (LHCb)	*Paula Alvarez Cartelle*	
Vondelkerk, Amsterdam	14:35 - 14:55	
CP violation in Charm at Upgrade II (theory)	*Luca Silvestrini et al.*	
Vondelkerk, Amsterdam	08:45 - 09:10	
CP violation in Charm at Upgrade II (LHCb)	*Laurent Dufour*	
Vondelkerk, Amsterdam	09:15 - 09:35	
Heavy Ion physics in the HL-LHC era	*Laure Marie Massacrier*	
Vondelkerk, Amsterdam	09:40 - 10:05	
Physics with an upgraded Calorimeter	*Yasmine Sara Amhis et al.*	
Vondelkerk, Amsterdam	11:55 - 12:15	
TORCH Physics	*Tom Hadavizadeh*	
Vondelkerk, Amsterdam	14:25 - 14:45	
CP violation in beauty at Upgrade II (theory)	*Monika Blanke et al.*	
Vondelkerk, Amsterdam	16:40 - 17:05	
CP violation in beauty at Upgrade II (experiment)	*Francesca Dordei et al.*	
Vondelkerk, Amsterdam	17:10 - 17:30	

Where we come from…

- Letter-of-Intent 1995

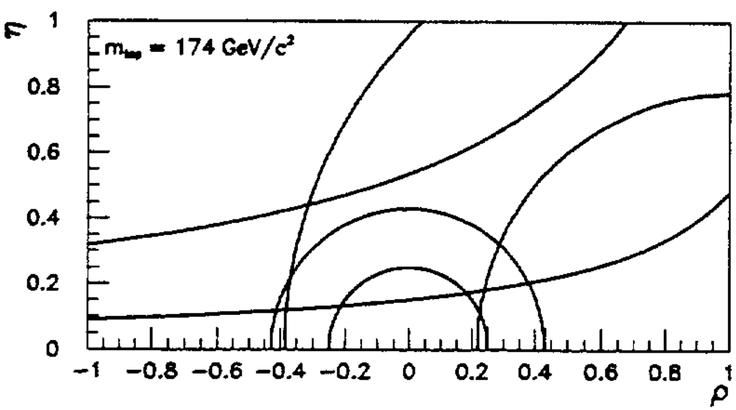


Figure 2.1: Limits on the CKM parameters (1σ) ρ and η for m_t = 174 GeV. The annular region cen-

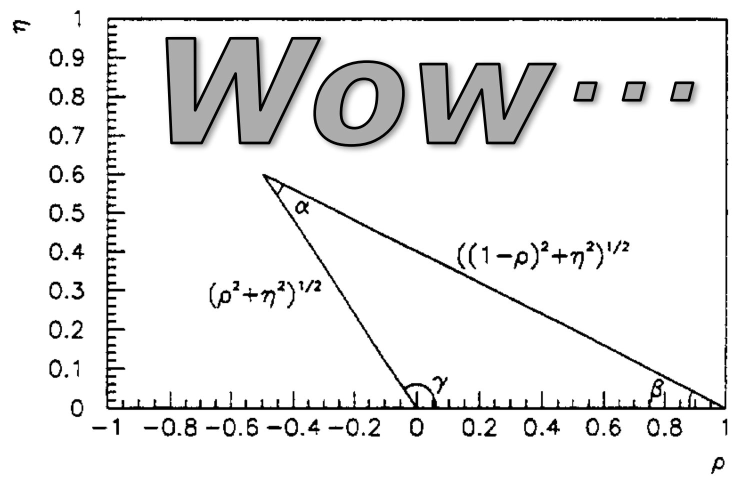
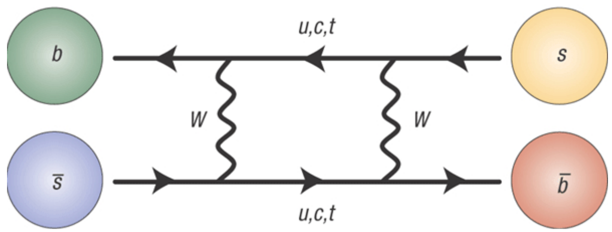


Figure 2.2: The Unitarity Triangle

J.Martin Camalich
on arXiv:1812.07638

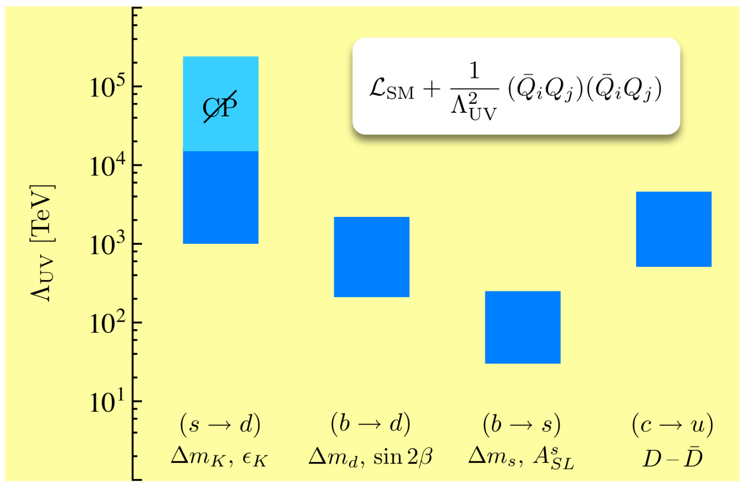
Flavour Physics in the HL-LHC era

- **Prototypical example:** FCNCs



$$\mathcal{M}_{\rm SM} \sim \overbrace{G_F}^{\text{Weak}} \underbrace{\overbrace{\frac{y_t^2}{16\pi^2}}^{\text{Loop}} \overbrace{(V_{ts}^* V_{tb})^2}^{\text{Flavor}}}_{\text{GIM}}$$

- Flavour observables probe (indirectly) very high energy scales!



Generic bounds without a flavor symmetry

M. Neubert at EPS 2011

What is the reach in Λ of flavour physics at HL(HE)-LHC?

Flavour physics has a track record…

c

GIM mechanism in $K^0 \rightarrow \mu\mu$

Weak Interactions with Lepton-Hadron Symmetry*

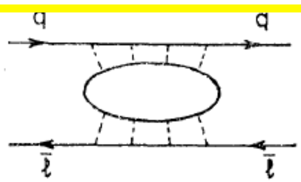
S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

splitting, beginning at order $G(G\Lambda^2)$, as well as contributions to such unobserved decay modes as $K_2 \rightarrow \mu^+ + \mu^-$, $K^+ \rightarrow \pi^+ + l + \bar{l}$, etc., involving neutral lepton

We wish to propose a simple model in which the divergences are properly ordered. Our model is founded in a quark model, but one involving four, not three, fundamental fermions; the weak interactions are medi-

new quantum number $\mathcal{C}$ for charm.



Glashow, Iliopoulos, Maiani,
Phys.Rev. D2 (1970) 1285

b

CP violation, $K_L^0 \rightarrow \pi\pi$

27 July 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have

three-body decays of the K_2^0. The presence of a two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP. Expressed as $K_2^0 = 2^{-1/2}[(K_0 - \bar{K}_0) + \epsilon(K_0 + \bar{K}_0)]$ then $|\epsilon|^2 \cong R_T \tau_1 \tau_2$

Christenson, Cronin, Fitch, Turlay,
Phys.Rev.Lett. 13 (1964) 138-140

t

$B^0 \leftrightarrow \bar{B}^0$ mixing

DESY 87-029
April 1987

OBSERVATION OF B^0-$\bar{B}^0$ MIXING

The ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson-lepton events on the $\Upsilon(4S)$ leads to the conclusion that B^0-$\bar{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ 90%CL	This experiment
$x > 0.44$	This experiment
$B^{\frac{1}{2}} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5$GeV$/c^2$	b-quark mass
$\tau_b < 1.4 \cdot 10^{-12}$s	B meson lifetime
$\lvert V_{td}\rvert < 0.018$	Kobayashi-Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [17]
$m_t > 50$GeV$/c^2$	t quark mass

ARGUS Coll.
Phys.Lett.B192:245,1987

Flavour physics has a track record…

Flavor physics was instrumental in **discovering** and **shaping** the SM

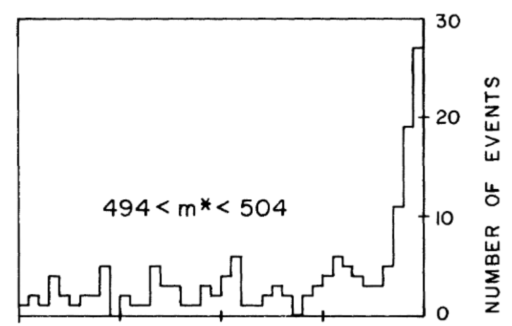
- **Nuclear β-decays:** Discovery **weak interactions** and **neutrino**
- **Rare Kaon-decays:** Discovery of the **charm quark**
- **Kaon decays:** Discovery of *CP* **violation** $\Longrightarrow$ Discovery of **3 generations**

- **Expect the unexpected ...**

J.Martin Camalich

observation of $K_L \to \pi^+\pi^-$ in 1964
$=$ first observation of CP violation

- prediction of third generation of fermions Kobayashi, Maskawa (1973)

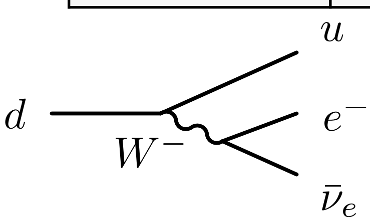


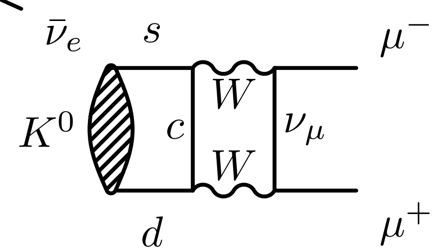
M. Blanke

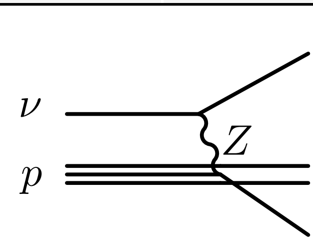
Precision physics!

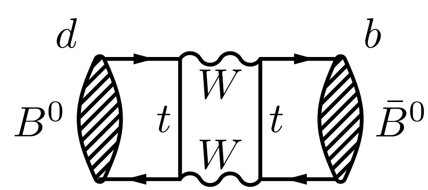
- Historical record of indirect discoveries:

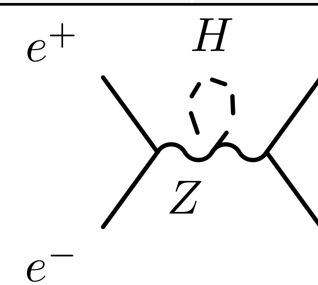
Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	$W \to e\nu$	UA1, UA2	1983
c	$K^0 \to \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \to \pi\pi$	CKM, 3rd gen	1964/72	Y	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \to e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \to Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \to 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?







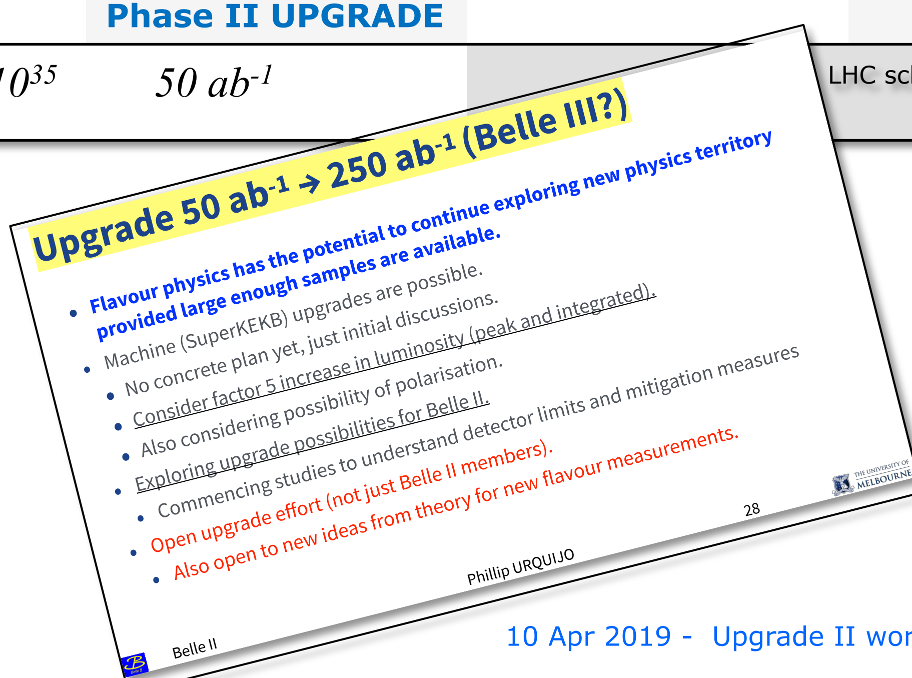




Timeline

2019 2020	2021 2022 2023	2024 2025 2026	2027 2028 2029	2030 2031	2032 203+
	Run III		Run IV		Run V
LS2		LS3		LS4	
LHCb 40 MHz **UPGRADE I**	$L = 2 \times 10^{33}$	**LHCb** **Consolidate: Upgr Ib**	$L = 2 \times 10^{33}$ $50\ fb^{-1}$	**LHCb** **UPGRADE II**	$L = 1.5 \times 10^{34}$ $300\ fb^{-1}$
ATLAS **Phase I Upgr**	$L = 2 \times 10^{34}$	**ATLAS** **Phase II UPGRADE**	**HL-LHC** $L = 5 \times 10^{34}$	**ATLAS**	**HL-LHC** $L = 5 \times 10^{34}$
CMS **Phase I Upgr**	$300\ fb^{-1}$	**CMS** **Phase II UPGRADE**		**CMS**	$3000\ fb^{-1}$
Belle II $5\ ab^{-1}$	$L = 8 \times 10^{35}$	$50\ ab^{-1}$			

LHC schedule: Frederick Bordry, Jun 2015



News!
Ph.Urquijo on **Belle III**,
Durham, 3 Apr 2019

Main results statistics limited!

Physics Case for an LHCb Upgrade II, CERN-LHCC-2018-027

Observable	Current LHCb	σ(stat)/σ(sys)	Largest source of systematic
EW Penguins			
R_K	$0.745 \pm 0.090 \pm 0.036$ [274]	2.5	Mass shape & trigger eff
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [275]	2.2	MC correction & residual bkgd
	–		
CKM tests			
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	3	Δm_s, time res, tagging, det asymmetry
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	-	
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	8	Decay time: bias and efficiency
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [44]	8	Angular efficiency
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	8	Decay time resolution
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	5	Acceptance (angular and time)
$a_{\rm sl}^s$	33×10^{-4} [211]	1.3	Track reco asymmetry
$\lvert V_{ub}\rvert / \lvert V_{cb}\rvert$	6% [201]	0.5	External BR(Λ_c)
$B_s^0, B^0 \to \mu^+\mu^-$			
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	6	f_d/f_s
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	9	Decay time acceptance
$S_{\mu\mu}$	–		
$b \to c\ell^-\bar{\nu}_l$ LUV studies			
$R(D^*)$	0.026 [215, 217]	1	MC sample size
$R(J/\psi)$	0.24 [220]	1	F($B_c \to J/\psi$) form factor
Charm			
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	2.7	Mass model
A_Γ ($\approx x \sin\phi$)	2.8×10^{-4} [240]	2.8	Contribution from sec b→D*X decays
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	2	Contribution from sec b→D*X decays

Run-1 ➔ Upgrade II: Order of magnitude in precision

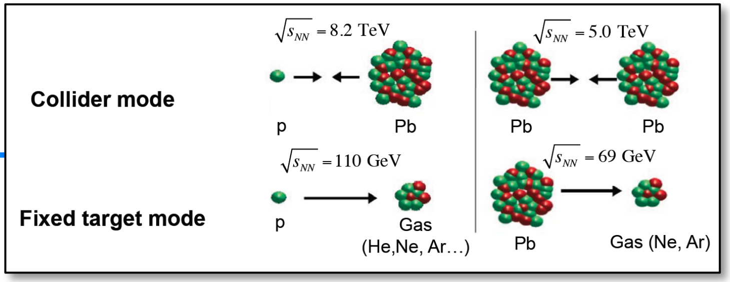
Observable	Current LHCb	Upgrade II
EW Penguins		
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [274]	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [275]	0.008
R_ϕ, R_{pK}, R_π	–	0.02, 0.02, 0.05
CKM tests		
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	1°
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	11 mrad
a_{sl}^s	33×10^{-4} [211]	3×10^{-4}
$\lvert V_{ub}\rvert / \lvert V_{cb}\rvert$	6% [201]	1%
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$		
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	2%
$S_{\mu\mu}$	–	0.2
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**		
$R(D^*)$	0.026 [215, 217]	0.002
$R(J/\psi)$	0.24 [220]	0.02
Charm		
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	3.0×10^{-5}
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	1.0×10^{-5}
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	8.0×10^{-5}

Physics Case for an LHCb Upgrade II, CERN-LHCC-2018-027

Outline

- Rare Decays
  - Very rare: $B_{(s)}^0 \rightarrow \mu^+\mu^-$
  - FCNC EWP: $b \rightarrow sll$
- CP violation in Charm
  - CPV in mixing: y_{CP}, A_Γ
  - CPV in decay: ΔA_{CP}
- CP violation in Beauty
  - Time dependent: $\sin 2\beta$, φ_s
  - Time integrated: γ
- Heavy Ions

Heavy Ions



E(Z TeV)	$\sqrt{s_{NN}}$											
	pp		p-^{208}Pb		^{208}Pb-^{208}Pb		^{129}Xe-^{129}Xe		p-^{16}O		^{16}O-^{16}O	
	$\sqrt{s}=2E$		$\sqrt{s}=2E\sqrt{r}$		$\sqrt{s}=2Er$, $r=82/208$		$\sqrt{s}=2Er$, $r=54/129$		$\sqrt{s}=2E\sqrt{r}$		$\sqrt{s}=2Er$, $r=8/16$	
1.38	2.76	2013										
2.51	5.02	2015 2017										
3.5	7	2011	4.40		2.76	2010 LHCb off						
4	8	2012	5.02	2013 2016	3.15							
6.37			8.00		5.02	2015 2018						
6.5	13	2015-2018	8.16	2016	5.12		5.44	2017				
2.75	5.5	50 pb^{-1}										
4.4	8.8	200 pb^{-1}										
7	14		8.8	0.6 pb^{-1} 2023	5.5	2 nb^{-1} 2021, 22			9.9	200ub^{-1}	7	500ub^{-1}

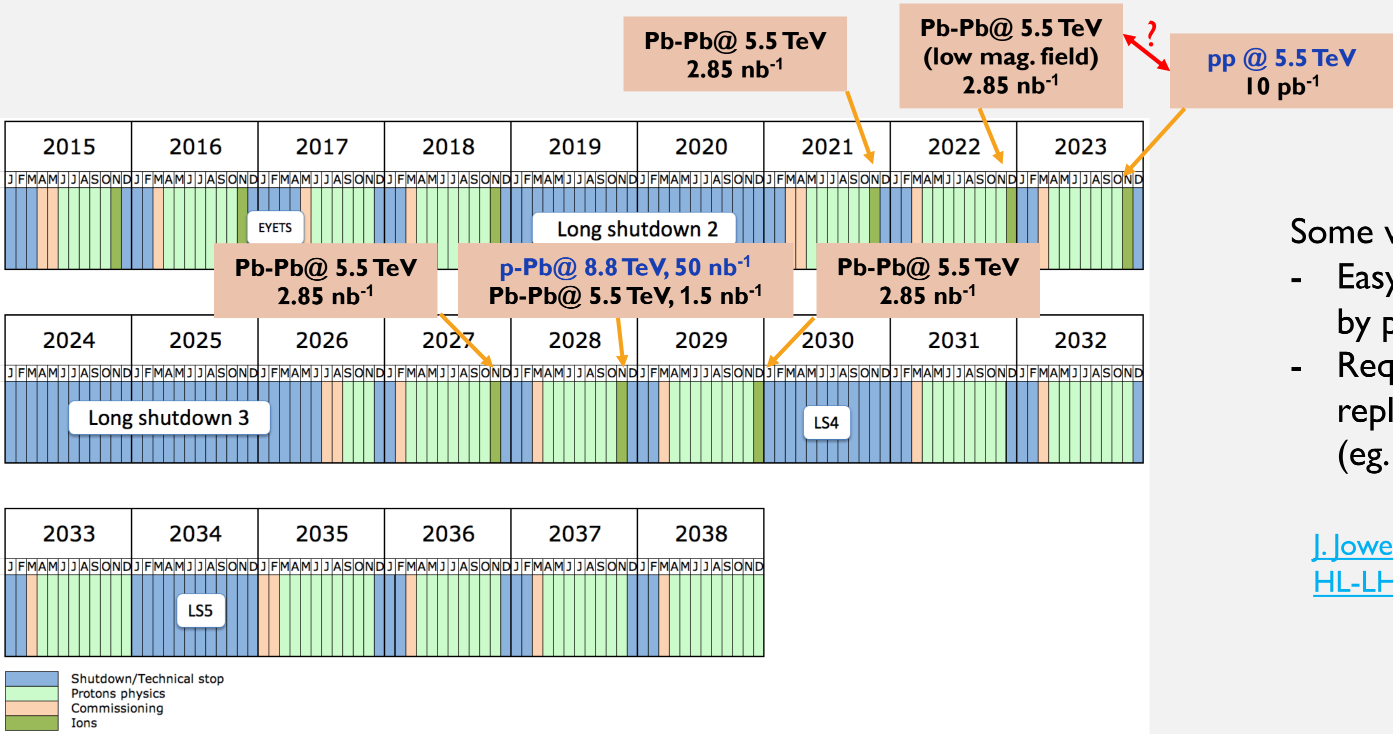
Requested luminosity taken from HL-LHC WG5 arXiv:1812.06772

❑ ***Need for pp reference at $\sqrt{s}$ = 5.5 TeV***

L. Massacrier

L. Massacrier

Heavy Ions in the LHC

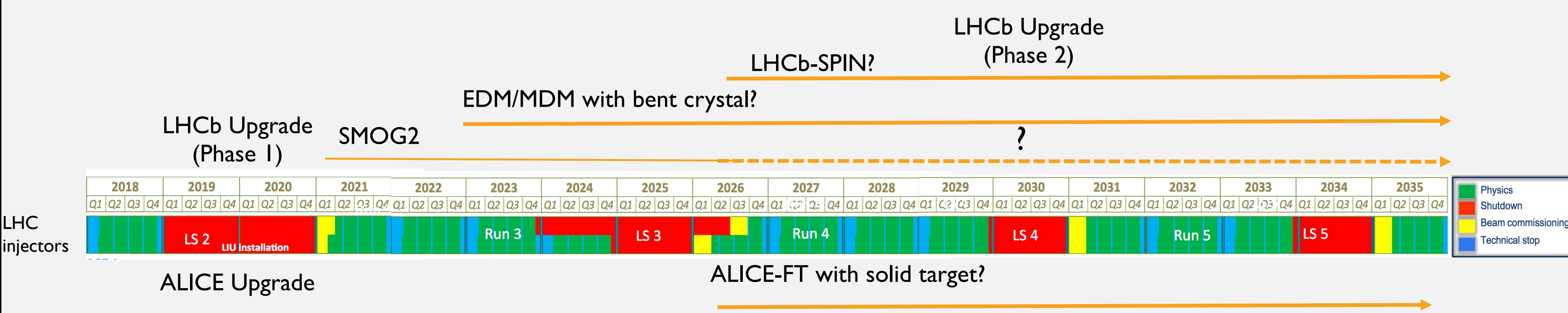


Some variations possible:

- Easy modification: replace Pb-Pb by p-Pb or pp ref
- Requiring more preparation: replace Pb-Pb by other specie (eg. Ar-Ar)

[J. Jowett, Workshop on the physics of HL-LHC, oct. 2017]

Proposal in ALICE to install a fixed-target setup (solid target or gas-jet) during LS3



L. Massacrier

LHCb strenght w.r.t ALICE in the forward region after the upgrades

- First observation by ALICE of an excess in the yield of J/ψ at very low-p_T in peripheral AA collisions
  - → attributed to coherent photoproduction of J/ψ in collisions with nuclear overlap
  - → could potentially become a new golden probe of the QGP
- Run 3&4, measurement in most central AA collisions still challenging (~ 15% uncertainty on the yield)
- Excellent p_T resolution (LHCb) to study the p_T shape (and confirm the mechanism)
- Also needs large statistics : polarization measurement, Ψ(2S) and Υ vector mesons to study medium in

- X_c measurement challenging in AA
- Complementary to J/Ψ, Ψ(2S) to understand the charmonia suppression/regeneration pattern
- Only LHCb can measure X_c → J/Ψ+γ at forward y (down to low p_T)
- Interesting new channel X_c → J/Ψ+$\mu^+\mu^-$ requires large stat (LHCb, ALICE)
  - → 5 fb^{-1} in pp ~ 100 nb^{-1} Pb-Pb

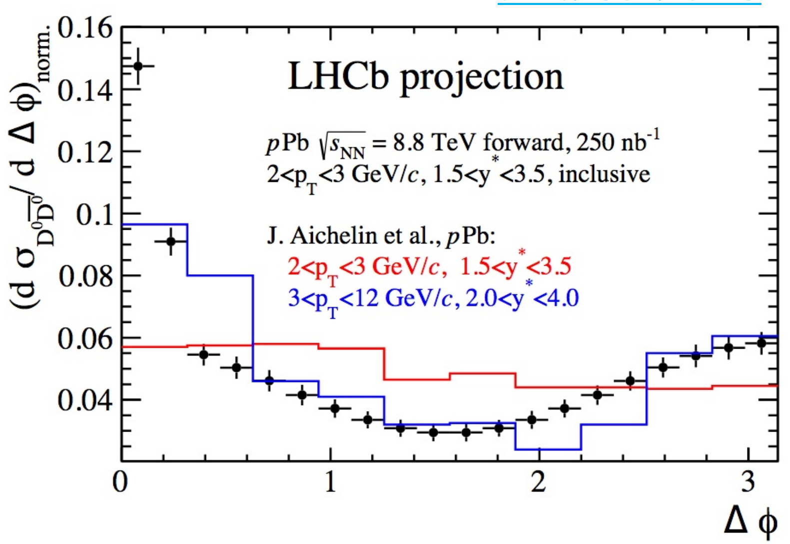
Jets

Heavy Flavour

Quarkonia

Low-mass dileptons

arXiv:1902.10229



Correlation of fully reconstructed HF hadrons only possible in LHCb in the forward region

Rare decays: very rare $B_{(s)}^0 \to l^+ l^-$

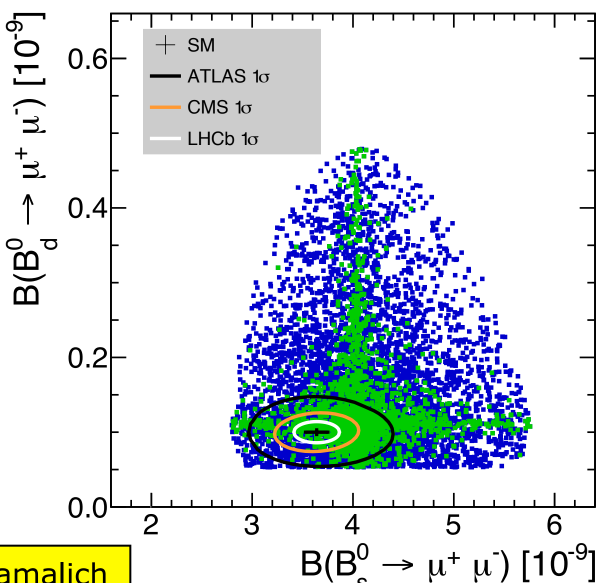
Helicity suppression

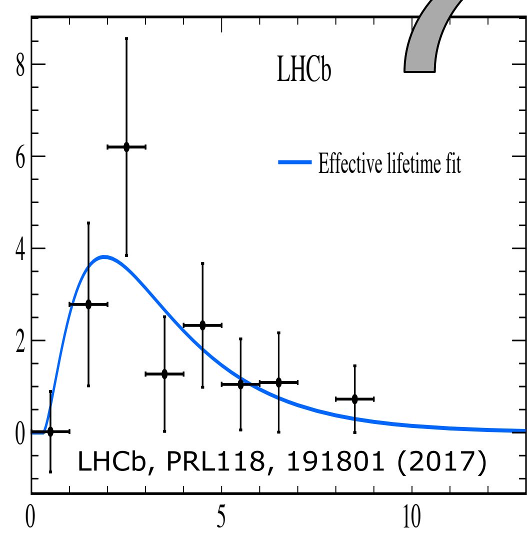
Cabibbo suppression

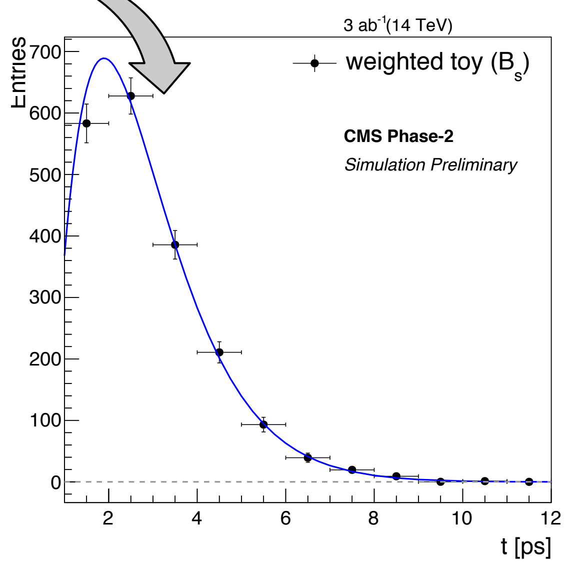
meson type	Lepton type e	μ	τ
B^0	$(2.48 \pm 0.21)10^{-15}$	$(1.06 \pm 0.09)10^{-10}$	$(2.22 \pm 0.19)10^{-8}$
B^0_s	$(8.54 \pm 0.55)10^{-14}$	$(3.65 \pm 0.23)10^{-9}$	$(7.73 \pm 0.49)10^{-7}$

From M.Bona, Ref. Bobeth et al., PRL 112 (2104) 101801

- **Branching fr.** (SM pred. by $|V_{cb}|$)
- **Effective lifetime**





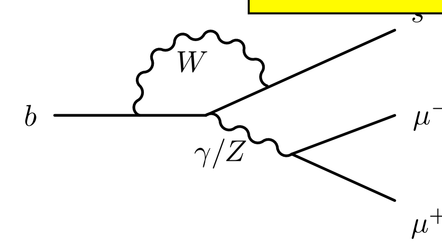


J.Martin Camalich

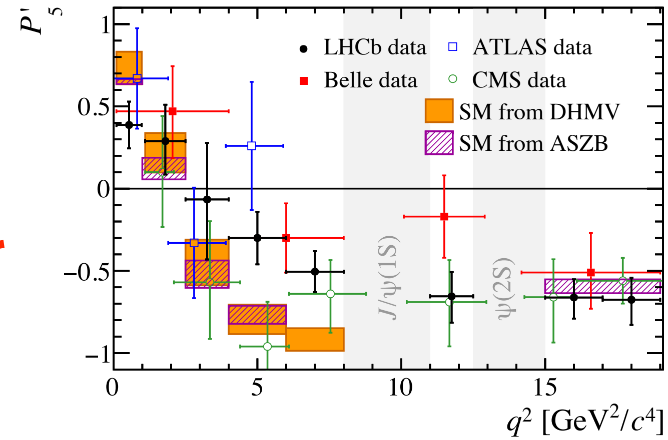
P.Alvarez Cartelle

P.Alvarez Cartelle

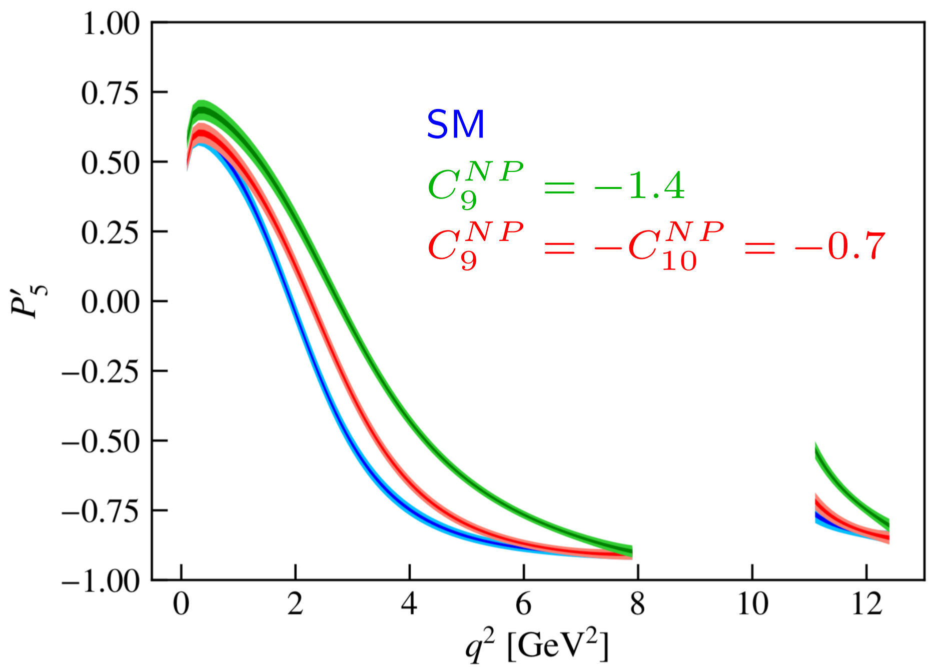
Rare Decays: FCNC EWP b→sll

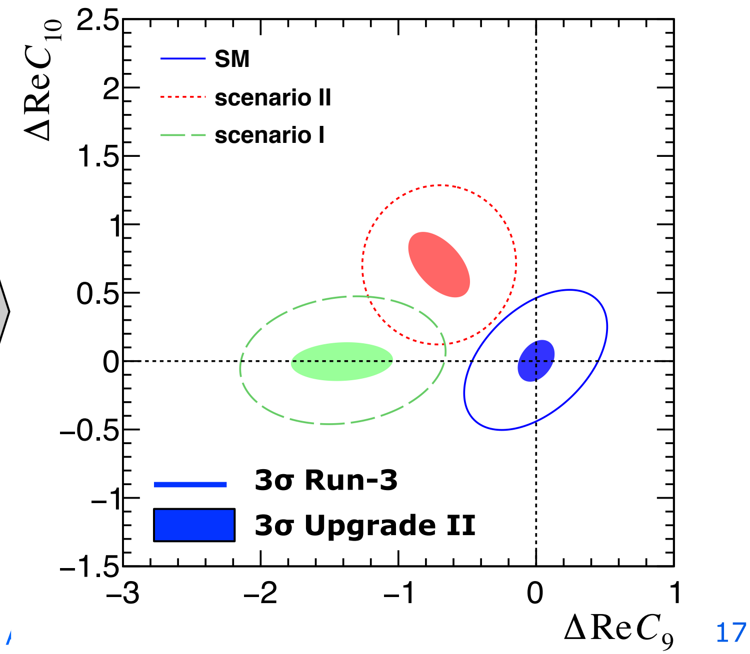


- Angular analysis
  - 440k $B^0 \to K^{0*}\mu^+\mu^-$



[LHCb-PUB-2018-009]





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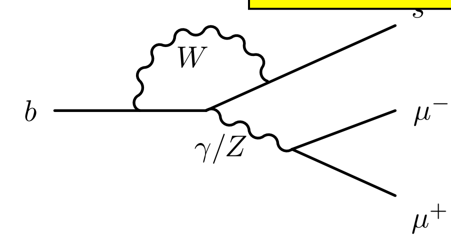
P.Alvarez Cartelle

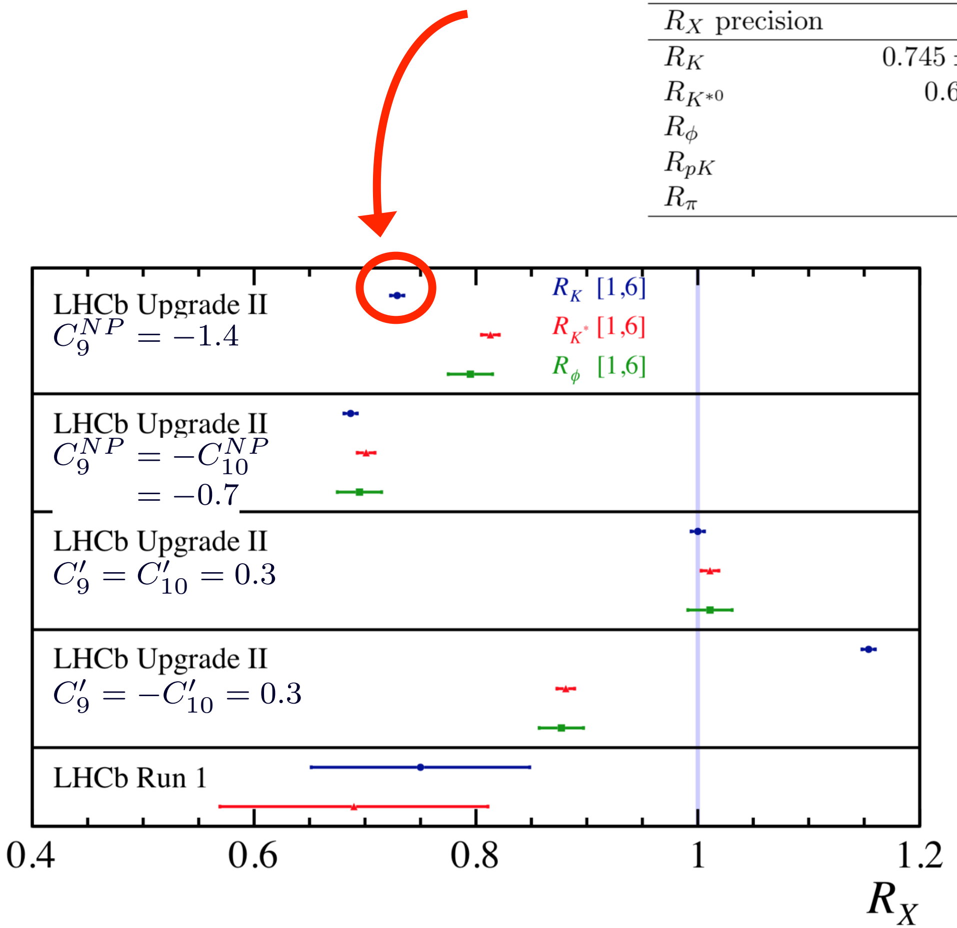
Rare Decays: FCNC EWP b→sll



- Event yield prospects
  - 46k $B^+ \to K^+ e^+ e^-$

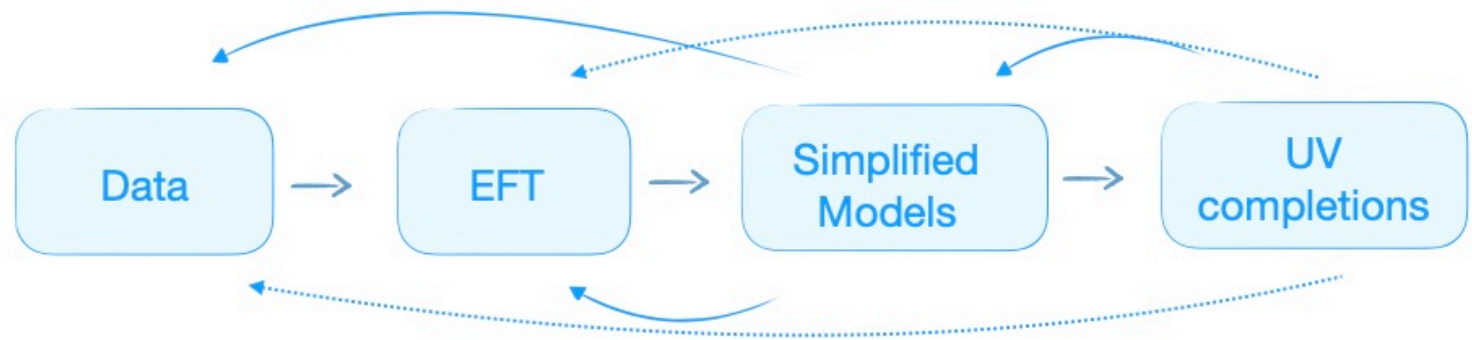
[Upgrade II physic

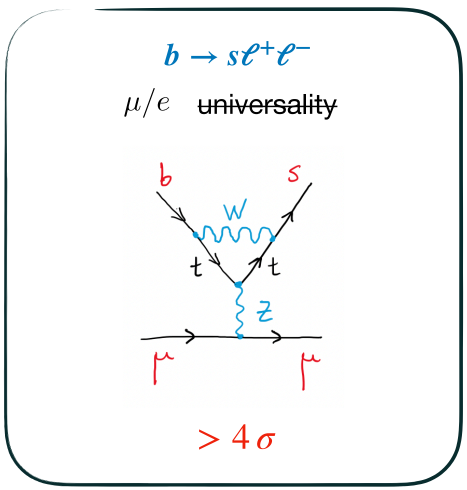
Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \to K^+ e^+ e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0} e^+ e^-$	111 ± 14 [275]	490	1 400	3 300	20 000
$B^0_s \to \phi e^+ e^-$	–	80	230	530	3 300
$\Lambda^0_b \to pK e^+ e^-$	–	120	360	820	5 000
$B^+ \to \pi^+ e^+ e^-$	–	20	70	150	900
R_X precision	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
R_K	0.745 ± 0.090 ± 0.036 [274]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	0.69 ± 0.11 ± 0.05 [275]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

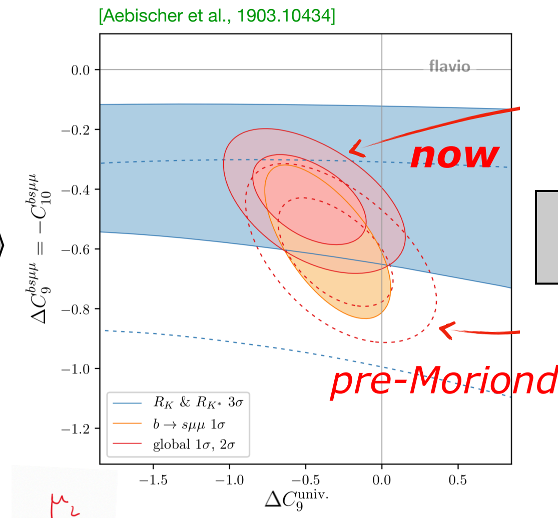


Rare Decays: FCNC EWP b→sll

The general approach







★ New R_K measurement by LHCb and R_{K^*} by Belle

Faroughi @ CKM18

	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Scalars	$S_1 = (\mathbf{3}, \mathbf{1})_{-1/3}$	✗	✓	✗
	$R_2 = (\mathbf{3}, \mathbf{2})_{7/6}$	✗	✓	✗
	$\widetilde{R}_2 = (\mathbf{3}, \mathbf{2})_{1/6}$	✗	✗	✗
	$S_3 = (\mathbf{3}, \mathbf{3})_{-1/3}$	✓	✗	✗
Vector	$U_1 = (\mathbf{3}, \mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3}, \mathbf{3})_{2/3}$	✓	✗	✗

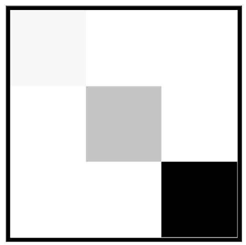
Angelescu, Becirevic, DAF, Sumensari [1808.08179]

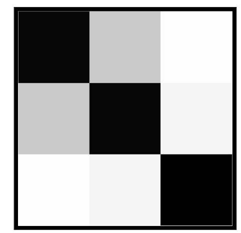
A NP hint to the SM flavor puzzle?

J.Fuentes Martin

The SM Yukawa sector

… whose values do not look at all accidental

$M_{u,d,e} \sim$ 

$V_{\mathrm{CKM}} \sim$ 

Remember Tuesday meeting 17 Feb 2009 ?

LHCb Tuesday Meeting

Tuesday 17 Feb 2009, 14:00 → 18:00 Europe/Zurich

160-1-009 (CERN)

Andreas Schopper, Andrey Golutvin

Description Meeting Access Information:
- Meeting URL : Click here
- Phone Bridge
  see e-mail to the lhcb-general

14:00 → 14:15 **News**

Speaker: Andreas Schopper

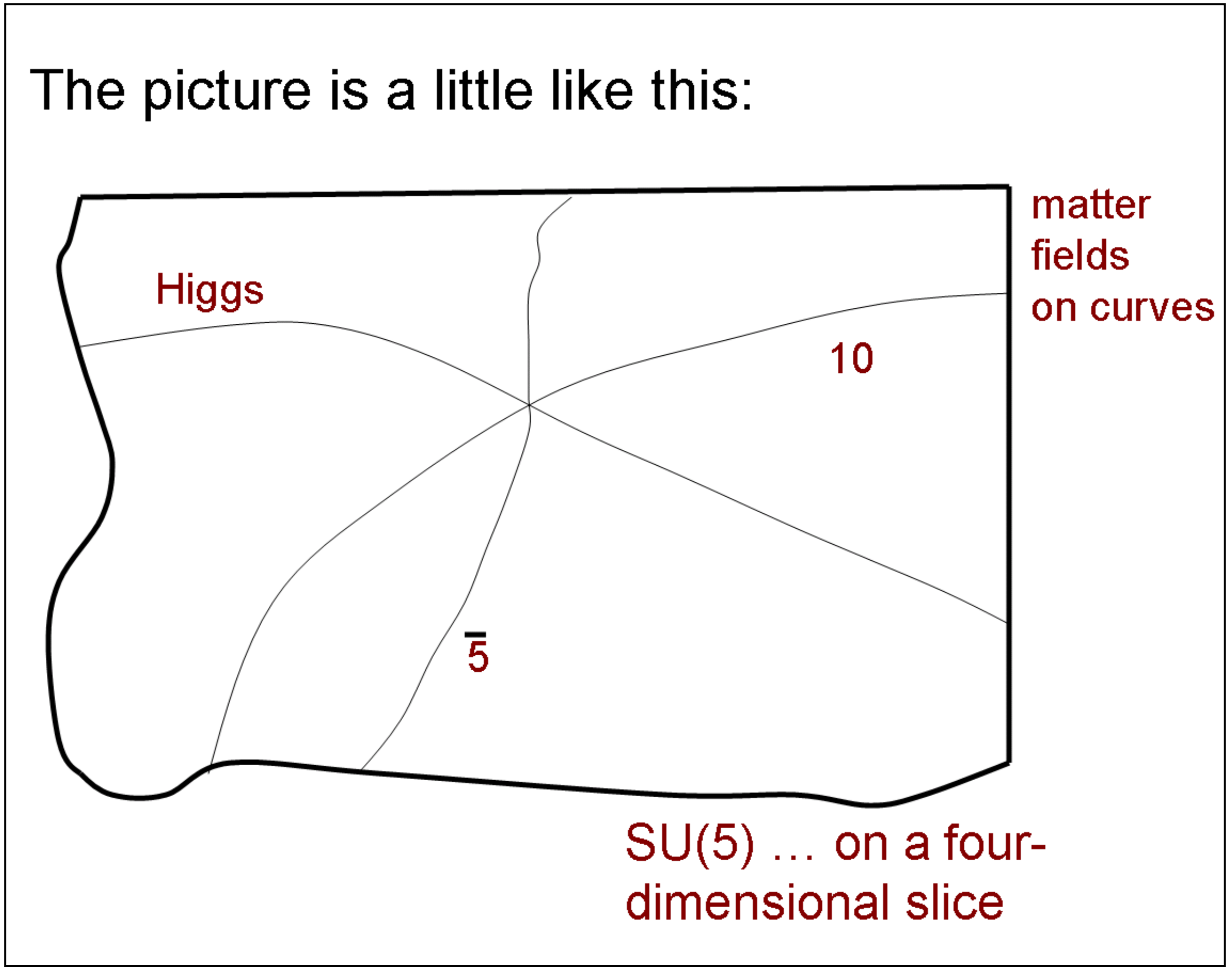
14:15 → 15:00 **The Problem Of Flavor**

Speaker: Edward Witten

Slides

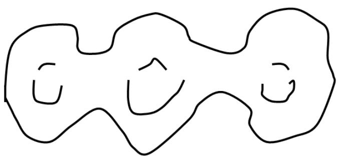
In 2004, Time magazine stated that Witten was widely thought to be the **world's greatest living** theoretical physicist.

"The picture is a little like this" ?



"The picture is a little like this"

In this approach, the ordinary Higgs field is a wavefunction on K, as are the quark and lepton fields



Quark and lepton masses and the CKM matrix are determined by the overlaps of these wavefunctions.

Higgs fields and quarks and leptons are supported on the three curves, and the Yukawa couplings that gives masses to down quarks and charged leptons come from the intersection drawn. (Up quark masses come from a similar intersection.)

In the leading approximation, only one particle of each type (i.e. the third generation particles – top, bottom, tau) get masses. The others have wavefunctions that vanish at the intersection point.

E. Witten, Tue meeting 17 Feb 2009, https://indico.cern.ch/event/51958/

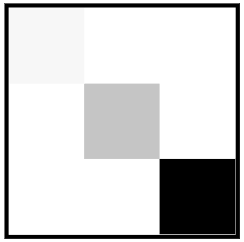
Vafa&Heckman, "*From F-Theory GUT's to the LHC*" arXiv:0809.3452

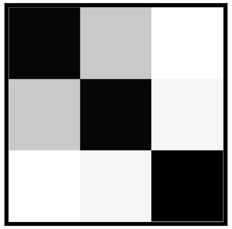
A NP hint to the SM flavor puzzle?

The SM Yukawa sector is characterized by 13 parameters

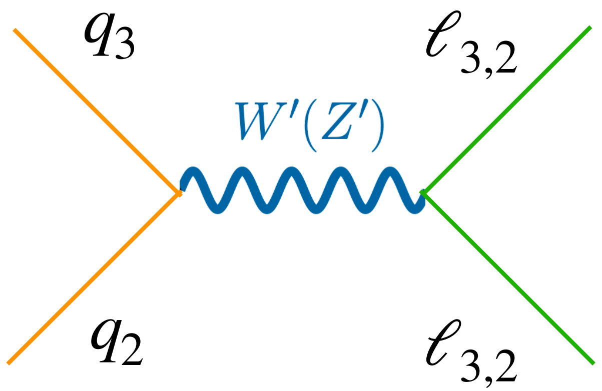
[3 lepton masses + 6 quark masses + 3+1 CKM parameters]

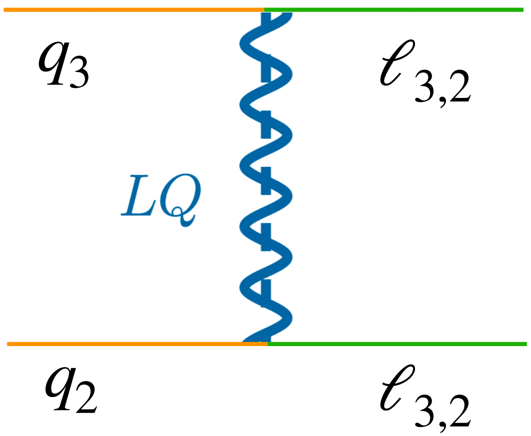
… whose values do not look at all accidental

$M_{u,d,e} \sim$ 

$V_{\text{CKM}} \sim$ 

✔ The flavor anomalies seem to suggest a similar trend: large NP effects in 3rd generation, gradually smaller effects in the light generations





The U_1 leptoquark solution

$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta^L_{i\alpha}(\bar{q}^i_L \gamma_\mu \ell^\alpha_L) - \beta^R_{i\alpha}(\bar{d}^i_R \gamma_\mu e^\alpha_R)\right] + \mathrm{h.c.}$$

Flavor structure$^{(*)}$

$$\beta^L = \begin{pmatrix} 0 & 0 & \beta^L_{d\tau} \\ 0 & \beta^L_{s\mu} & \beta^L_{s\tau} \\ 0 & \beta^L_{b\mu} & \beta^L_{b\tau} \end{pmatrix} \qquad \beta_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta^R_{b\tau} \end{pmatrix}$$

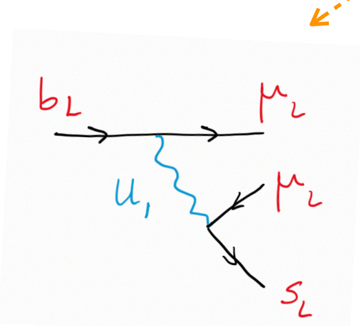
$\beta^L_{b\tau} = 1$

$\beta^R_{b\tau} \sim \mathcal{O}(1)$

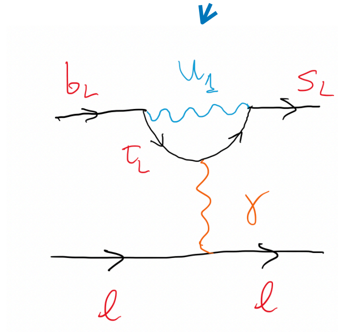
$\beta^L_{s\tau}, \beta^L_{b\mu} \sim \mathcal{O}(0.1)$

$\beta^L_{s\mu}, \beta^L_{d\tau} \sim \mathcal{O}(0.01)$

C_{V_L} $\qquad$ C_{S_R}

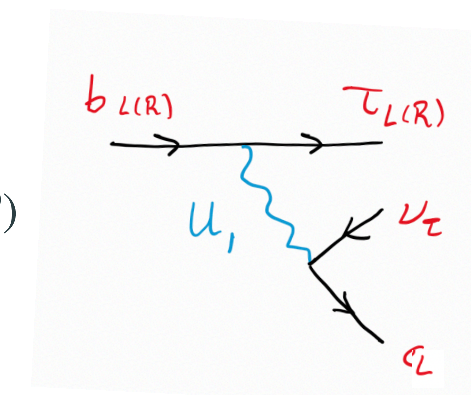


$\Delta C_9^\mu = -\Delta C_{10}^\mu$



$\Delta C_9^{e,\mu,\tau}$

$b \to s\ell\ell \ll R(D^{(*)})$



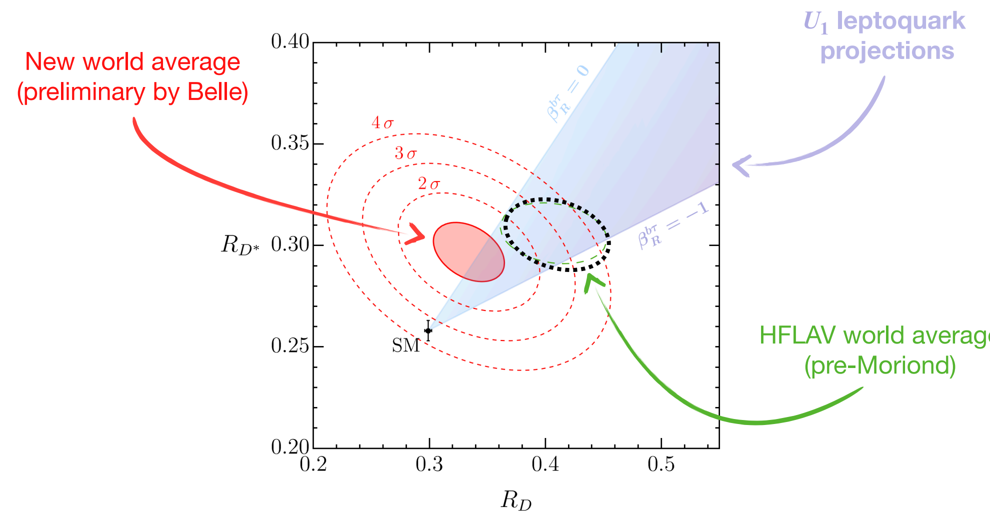
[Crivellin et al., 1807.02068]

$^{(*)}$ N.B.: Deviations from this structure highly constrained by low-energy flavor data

J.Fuentes Martin

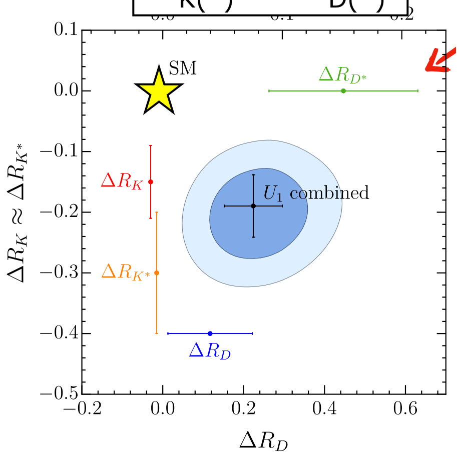
Low-energy fit results

- U_1 leptoquark projections:

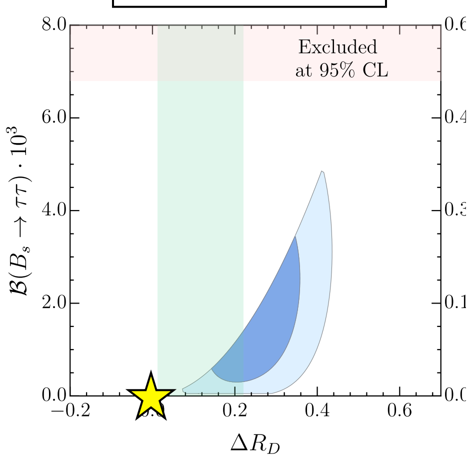


- U_1 leptoquark predictions:

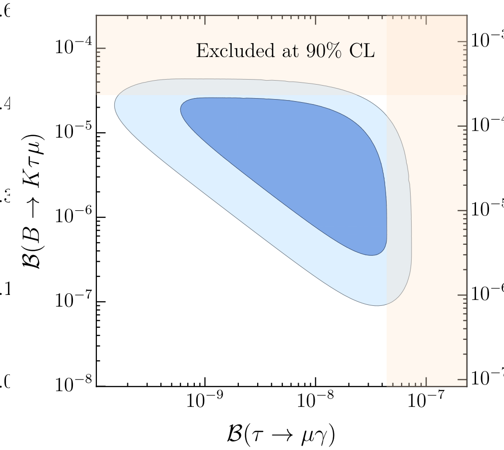
$R_{K(*)}$ vs $R_{D(*)}$



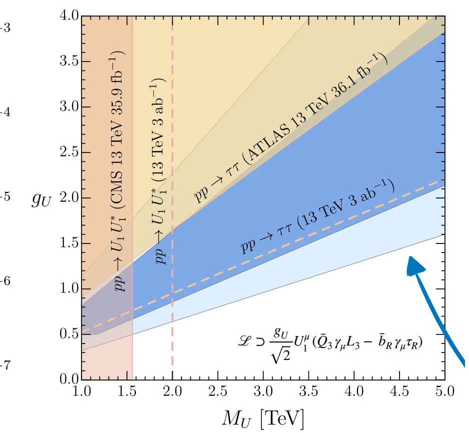
$B_s \to \tau\tau$ vs R_D



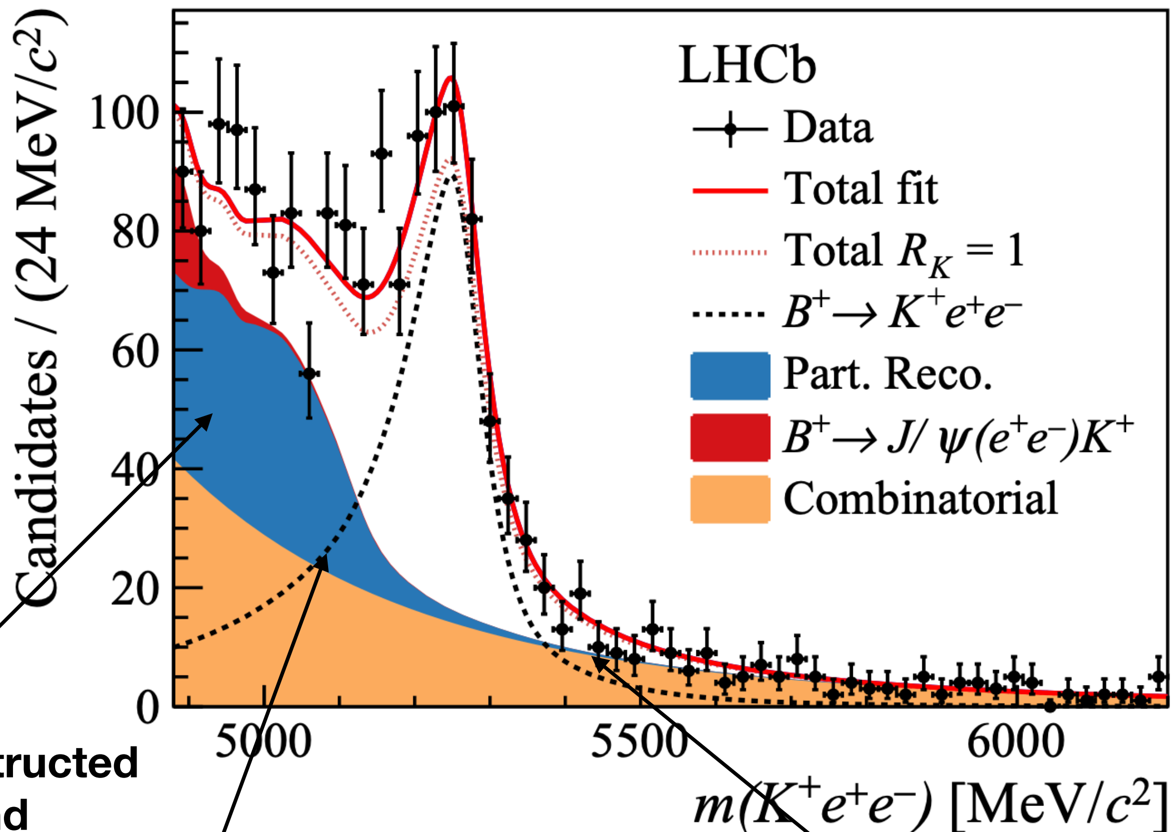
$B \to (K)\mu\tau$ vs $\tau \to \mu\gamma$



High p_T



Physics with ECAL



Partially reconstructed background

non trivial signal shape from simulation

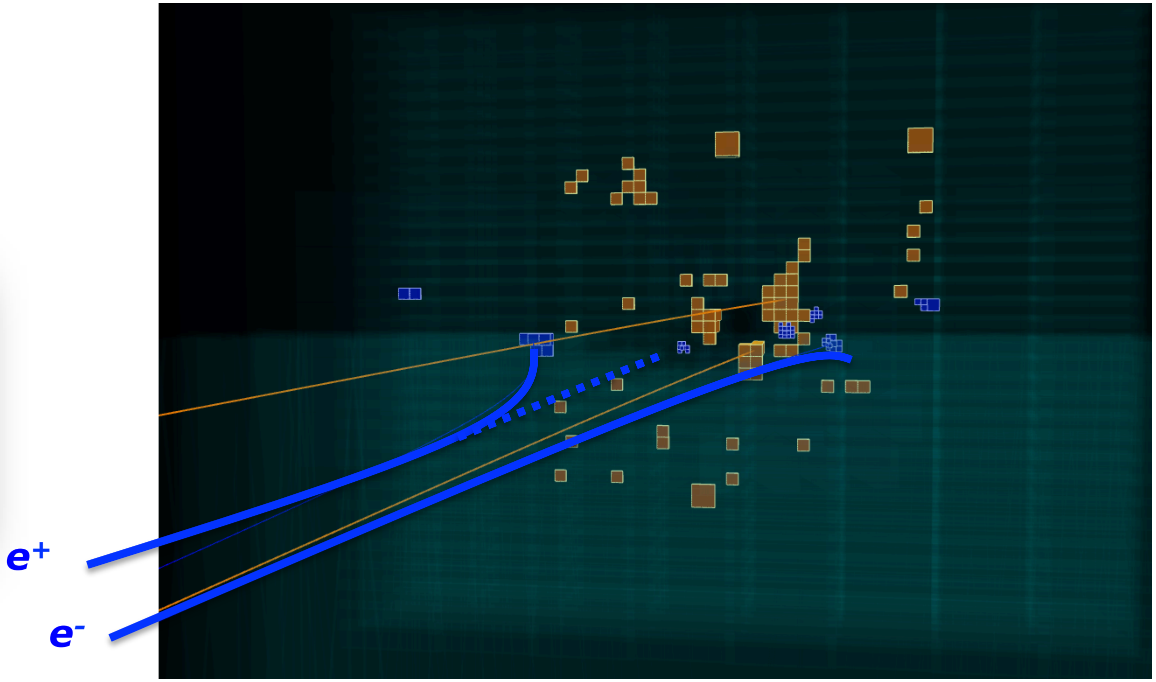
When bremsstrahlung photons are added.

12

Physics with ECAL

Wishlist

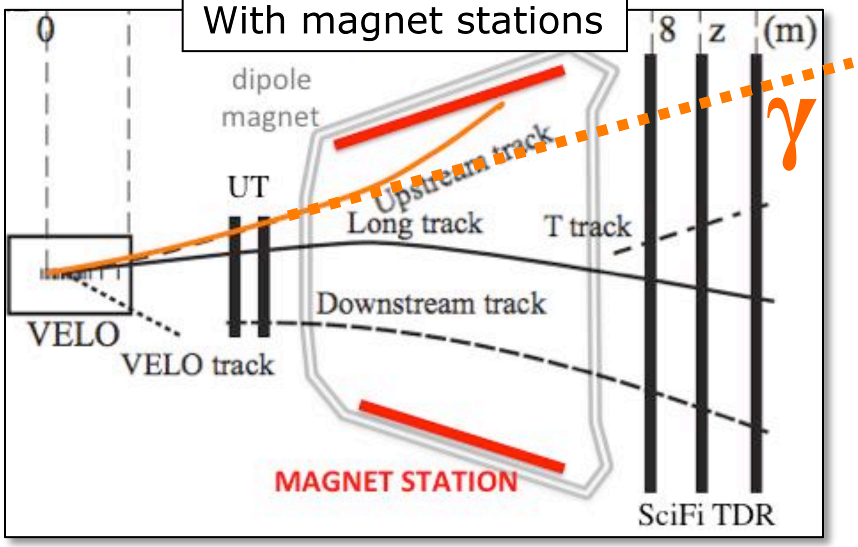
Important to keep a light detector and to be able to reconstructed the bremsstrahlung photons.
Could we improve/rethink the identification of bremsstrahlung photons using “timing” ?



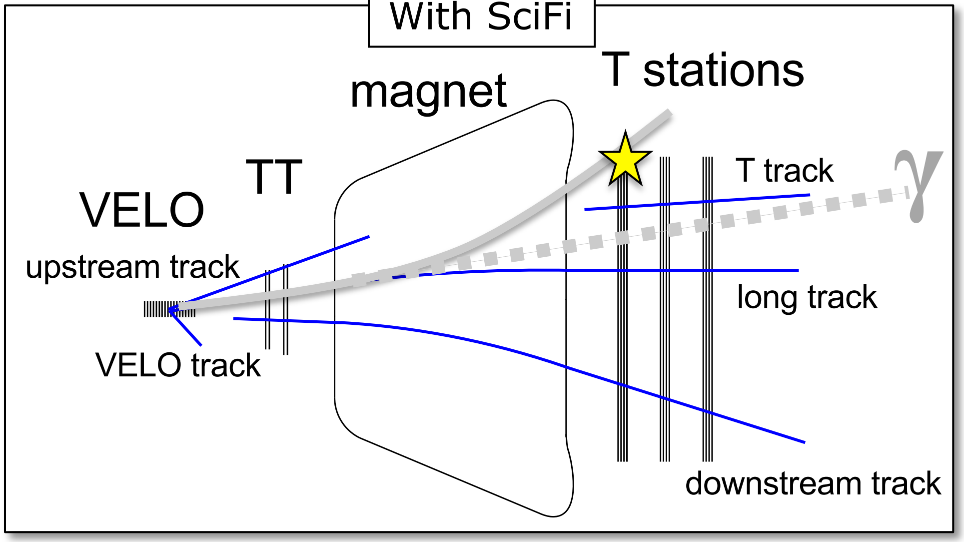
Physics with ECAL

- Reconstruct photons
- Electrons that lost most of their energy
  - Magnet chambers?!
  - Improve upstream tracks by adding SciFi hit?!
  - Use photon as tag to identify electron

With magnet stations

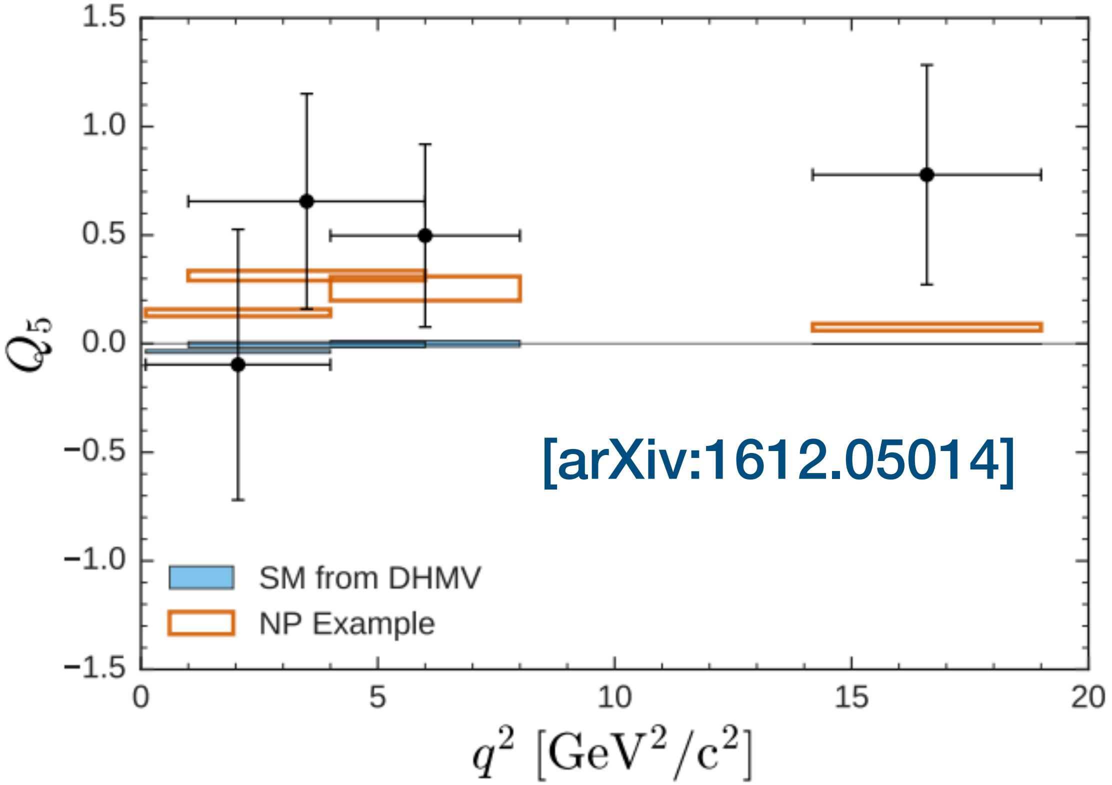


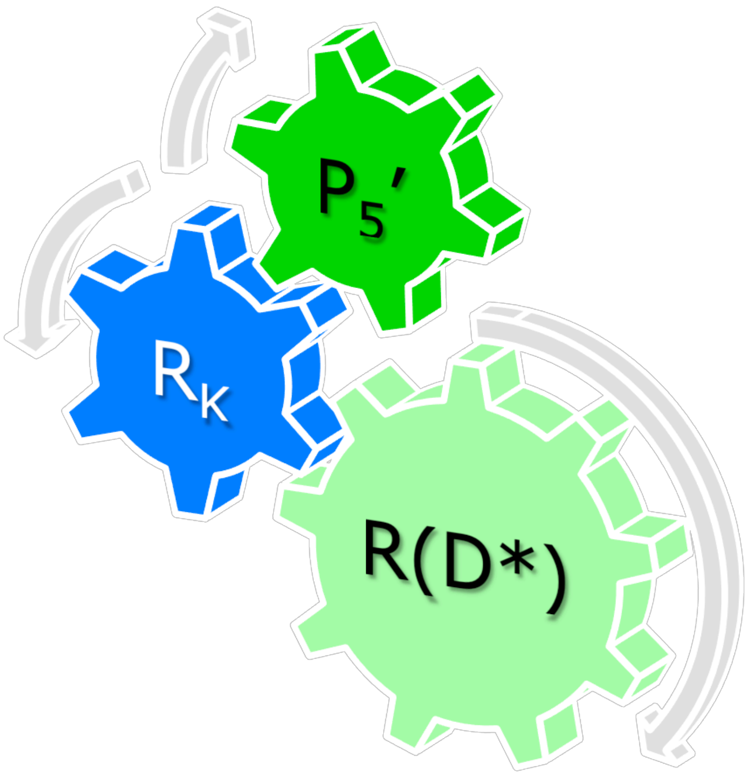
With SciFi



Idea from Patrick Koppenburg

Rare decays: b→sll





$$Q_i = P_i^{\mu} - P_i^{e}$$

Y. Amhis

Outline

- Rare Decays
  - Very rare: $B_{(s)}^0 \to \mu^+\mu^-$
  - FCNC EWP: $b \to sll$
- CP violation in Charm
  - CPV in mixing: y_{CP}, A_Γ
  - CPV in decay: ΔA_{CP}
- CP violation in Beauty
  - Time dependent: $\sin 2\beta$, φ_s
  - Time integrated: γ
- Heavy Ions

Charm

- Mixing: x, y (or y_{CP})

$$x = \Delta m / \Gamma \qquad y' \equiv y\cos\delta - x\sin\delta$$
$$y = \Delta\Gamma / 2\Gamma \qquad x' \equiv x\cos\delta + y\sin\delta$$

$$y_{CP} \equiv \frac{\Gamma_{CP\pm}}{\Gamma} - 1 \qquad y_{\rm CP} = \frac{\Gamma(D_+) - \Gamma(D_-)}{\Gamma(D_+) + \Gamma(D_-)}$$
$$y_{\rm CP} = \frac{y}{2}\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - \frac{x}{2}\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)$$

- CPV in mixing: q/p, φ, A_Γ

$$y_{CP} \equiv \frac{\Gamma_{\overline{D}^0\to K^+K^-} + \Gamma_{D^0\to K^+K^-}}{2\Gamma} - 1$$
$$A_\Gamma \equiv \frac{\Gamma_{D^0\to K^+K^-} - \Gamma_{\overline{D}^0\to K^+K^-}}{2\Gamma}$$

difference of decay widths affected implies |q/p|≠1, ie. CPV in mixing

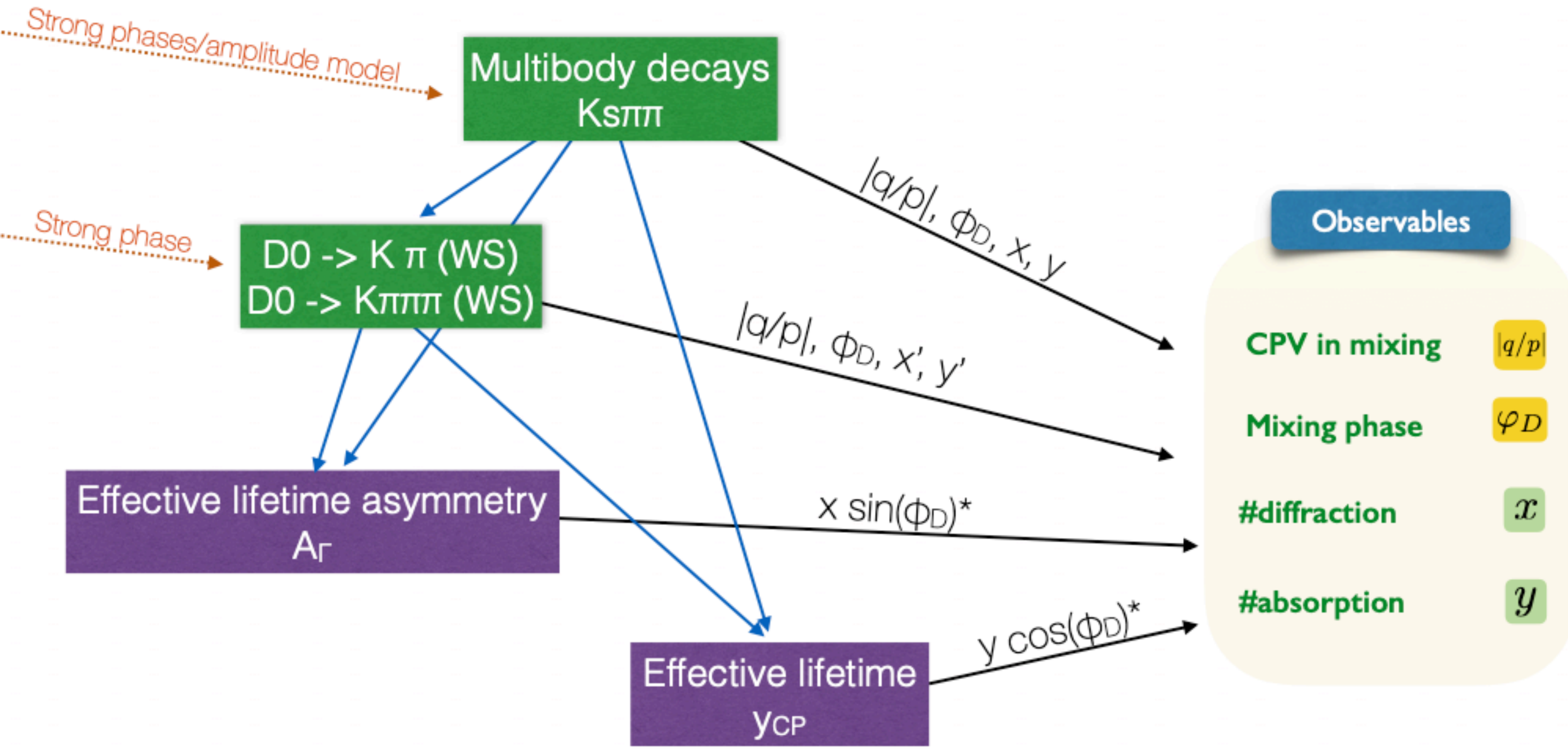
$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M^0}\rangle$$
$$\tan\phi = \left(1 - \left|\frac{q}{p}\right|\right)\frac{x}{y} = -\frac{a_{\rm SL}}{2}\frac{x}{y}$$

- CPV in decay: ΔA_{CP}

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = A(K^+K^-) - A(\pi^+\pi^-)$$

See e.g.: A.Kagan and M.Sokoloff,
On Indirect CP Violation and Implications for D^0–D^0 and B_s–B_s mixing, arXiv:0907.3917

Charm mixing



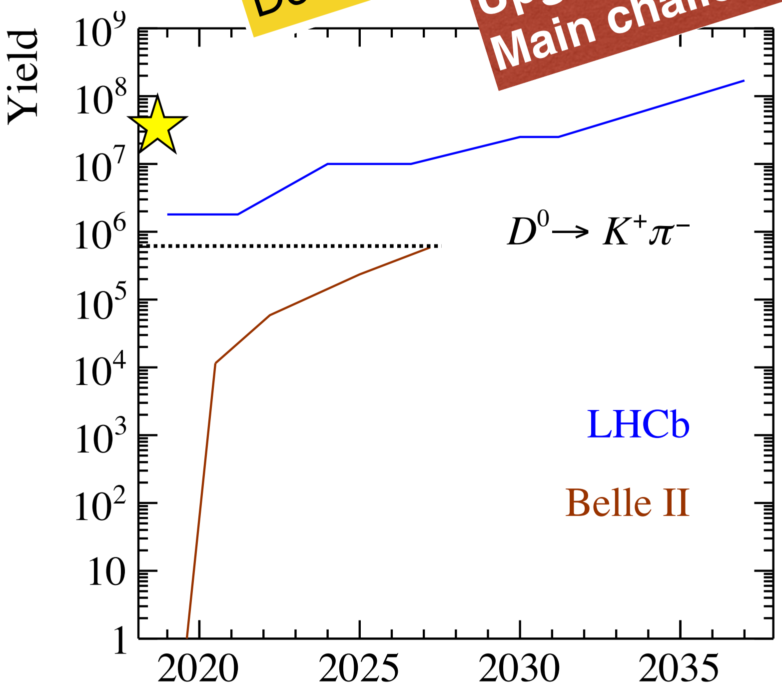
*: if |q/p|≠1, then more complex

Charm

- Loads…

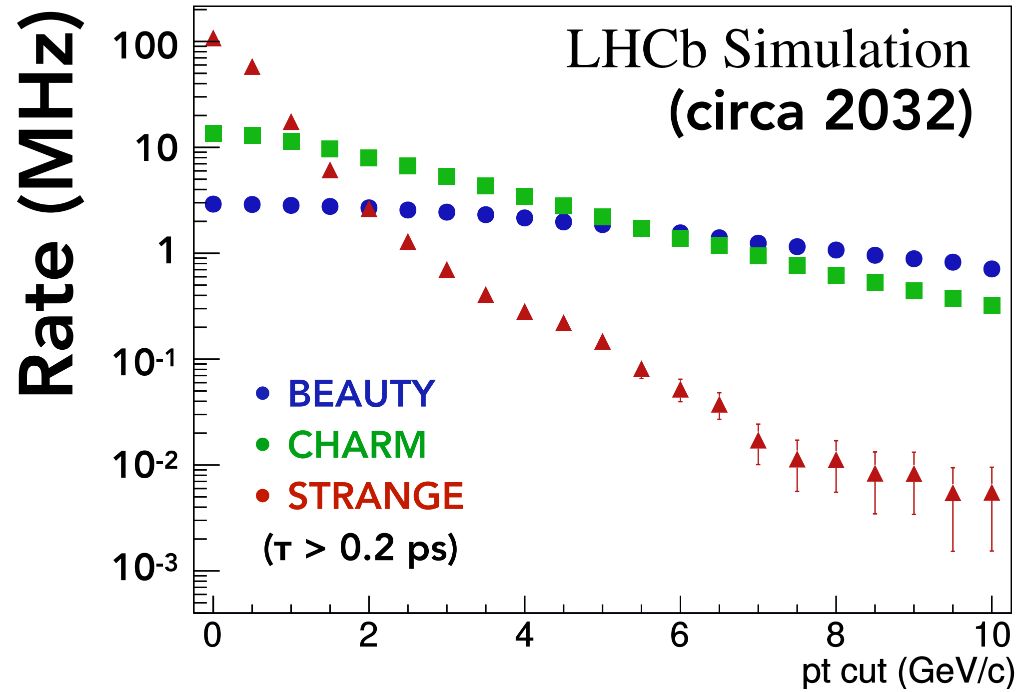
Development in detector calibration essential

Upgrade-II essential!
Main challenge: event trigger



Belle II Physics Book

Partially reconstructed signals

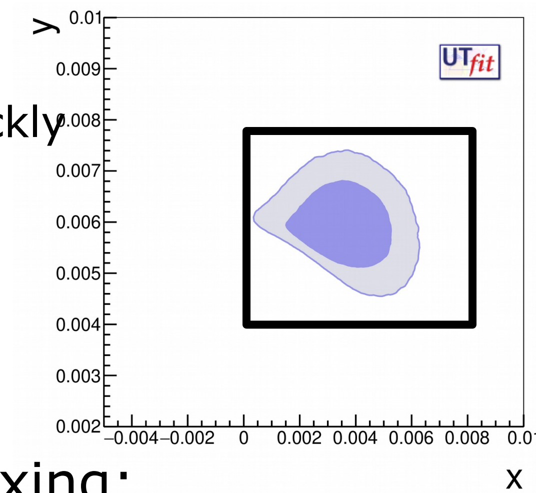


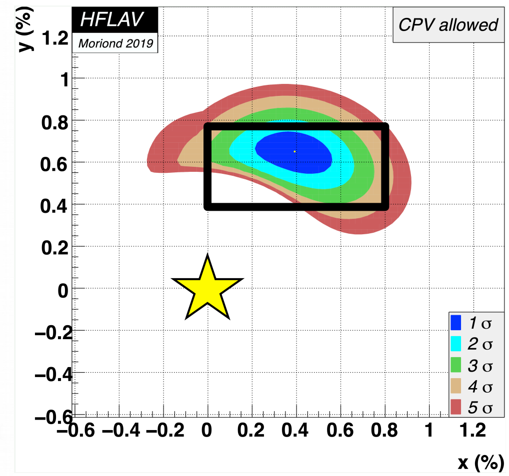
V.Gligorov, TUPiFP, Durham, 2 Apr 2019

L. Dufour

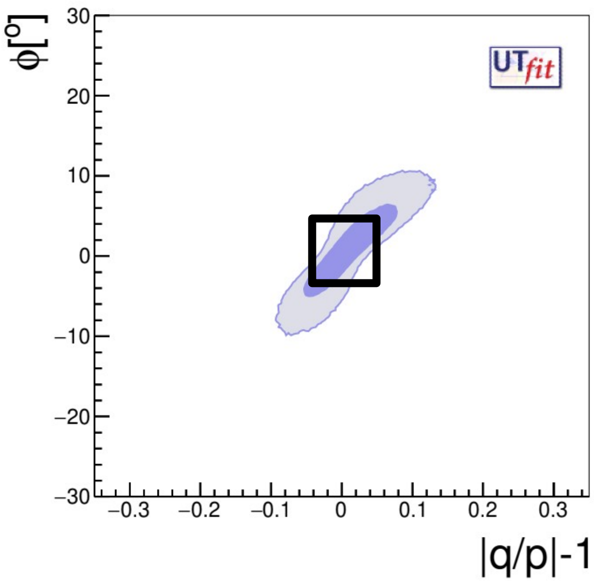
CP violation in mixing charm: q/p

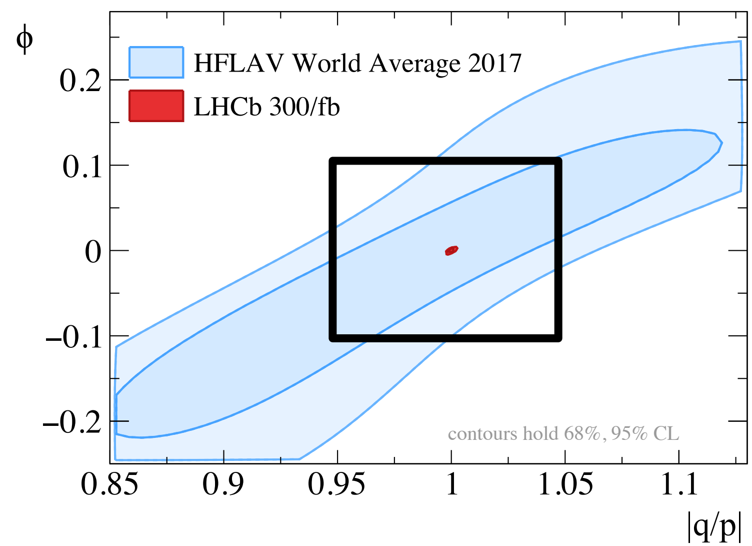
- D^0 mesons mix
  - Although they decay quickly





- Nailing down CPV in mixing:





L. Dufour, L. Silvestrini

CP violation in decaying charm: ΔA_{CP}

- Natural expectations in the SM:
  - $A_{CP} \sim O(r_{CKM} \langle \Delta U=0, I=0\rangle / \langle \Delta U=2, I=2\rangle \sin\delta) \sim r_{CKM}$
  - $\Delta A_{CP} \sim 2\, r_{CKM} \sim 0.13\ \%$

Brod, Kagan & Zupan '11
Franco, Mishima & L.S. '12

4th Workshop on LHCb Upgrade II
Amsterdam, 8-10 April 2019
Luca Silvestrini
5

It's SM

- LHCb obtained a fantastic observation of ΔA_{CP} in the ballpark of the SM expectation
- Not yet clear which theory approach can do best; most promising ones imho:
  - assume FSI dominance + dynamical info on rescattering
  - assume SU(3) + hierarchy in SU(3)-breaking
  - get some dynamical info from LQCD

L. Silvestrini

To be(yond the SM) or not to be(yond the SM)

From A. Di Canto. Durham, 2-4 Apr 2019,
Towards the Ultimate Precision in Flavour Physics

Charm Outlook

EXP. INPUTS:

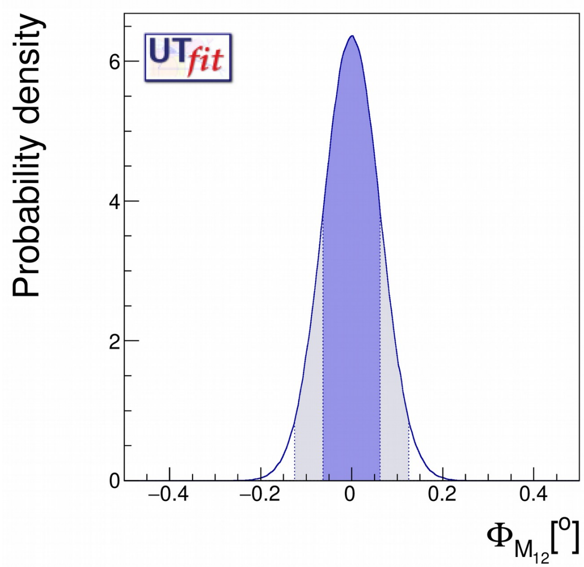
- $D \to K\pi$
- A_Γ
- $D \to K_S\pi\pi$
- $D \to K\pi\pi\pi$

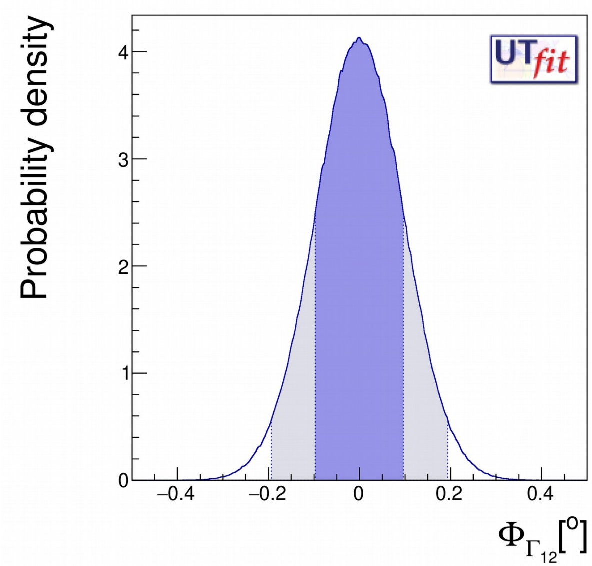
Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)_{K^+K^-}$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)_{\pi^+\pi^-}$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(x'_{K\pi\pi\pi})$	$\sigma(y'_{K\pi\pi\pi})$	$\sigma(\lvert q/p\rvert)$	$\sigma(\phi)$
Run 1-2 (9 fb^{-1})	0.22	2.3×10^{-4}	2.3×10^{-4}	0.020	1.2°
Run 1-3 (23 fb^{-1})	1.29	0.9×10^{-4}	0.9×10^{-4}	0.008	0.5°
Run 1-4 (50 fb^{-1})	3.36	0.6×10^{-4}	0.6×10^{-4}	0.005	0.3°
Run 1-5 (300 fb^{-1})	22.5	0.2×10^{-4}	0.2×10^{-4}	0.002	0.1°

Yields taken from HL-LHC WG4 arXiv:1812.07638

$\Phi_{12}=\arg(\Gamma_{12}/M_{12})=-\Phi_M$, $\phi_f=\phi=\arg(q/p)$





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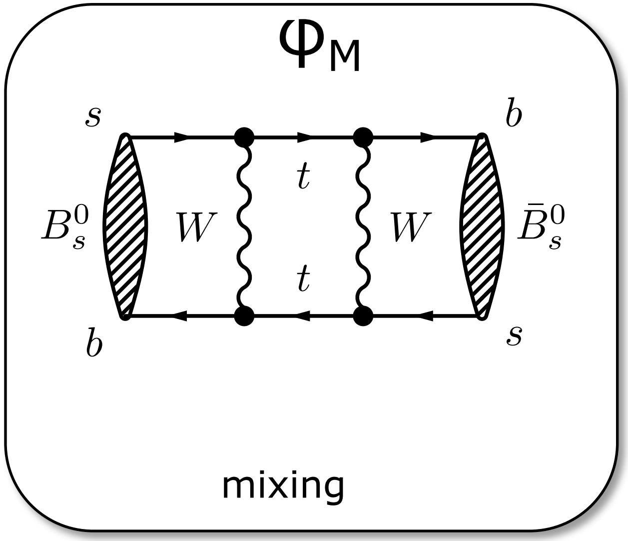
  - Time integrated: γ
- Heavy Ions

CP violation in beauty: Time dependent (φ_s, β)

- New physics in the box diagram?



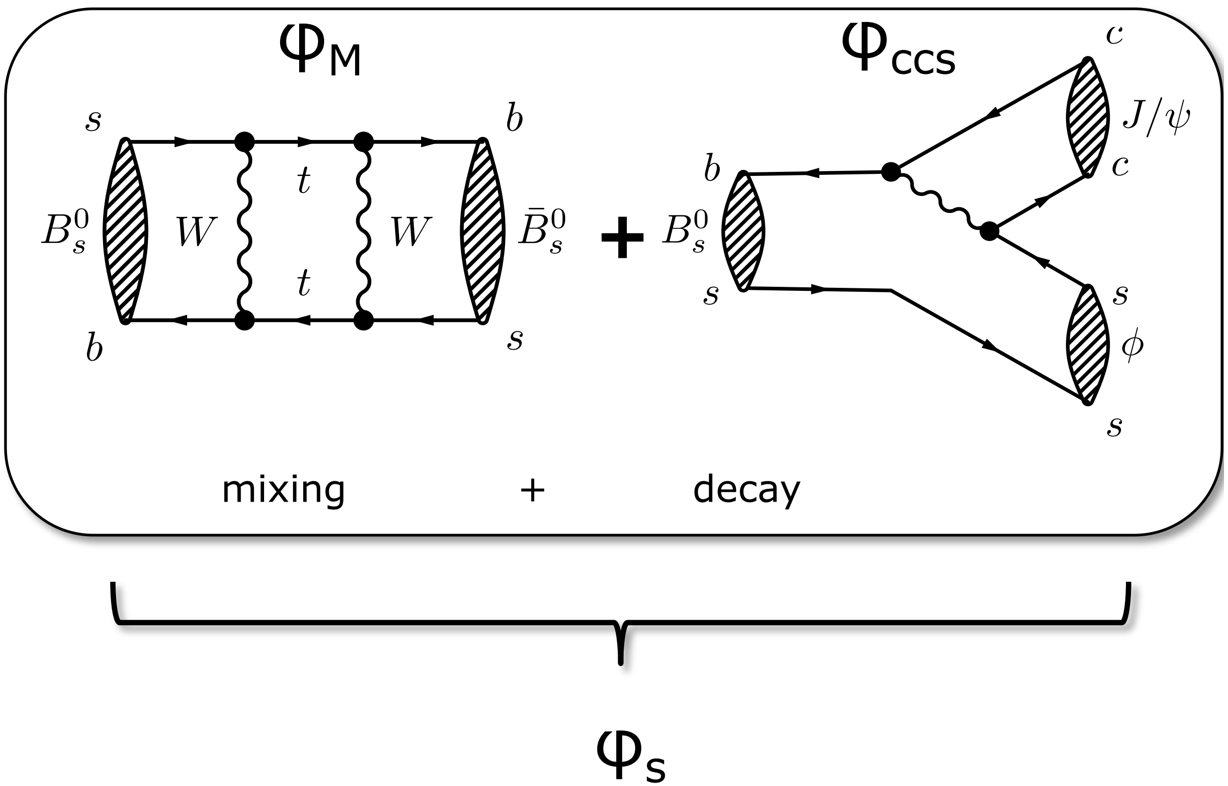
"Mixing" phase??

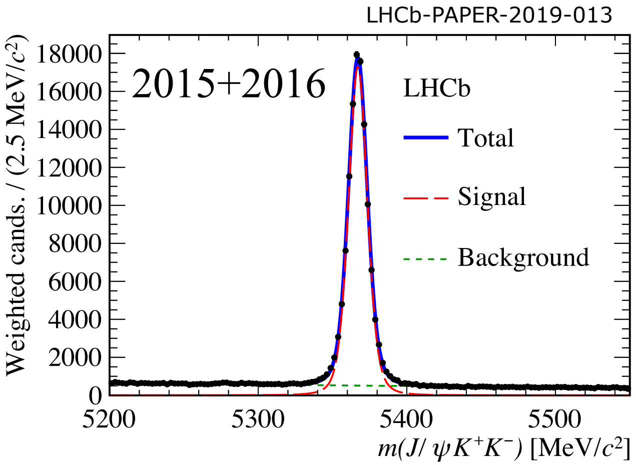
CP violation in mixing (semi-leptonic): $\phi_{\Gamma/M} = \phi_M - \phi_\Gamma$

CP violation in mixing and decay ($B_s^0 \rightarrow J/\psi\varphi$): $\phi_s = \phi_M - \phi_{ccs}$

CP violation in beauty: Time dependent (φ_s, β)

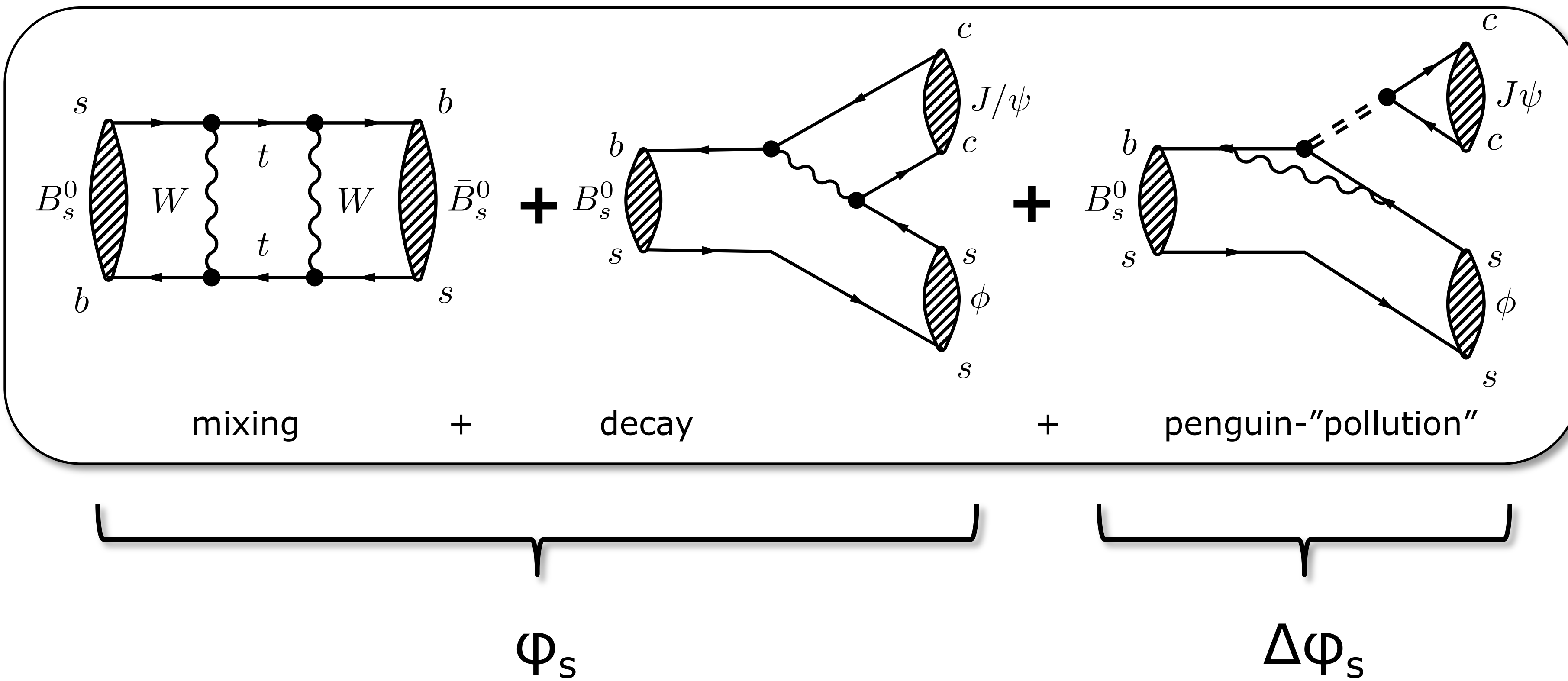
- New physics in the box diagram?





CP violation in beauty: Time dependent (φ_s, β)

- New physics in the box diagram?



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

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

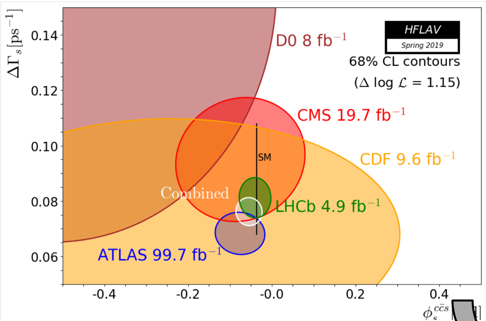
$$\Delta\phi_{s,\perp}^{J/\psi\,\phi} = 0.003^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\,\text{rad}$$

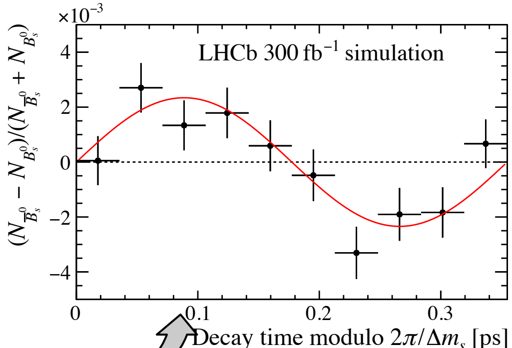
[JHEP 11 (2015) 082]

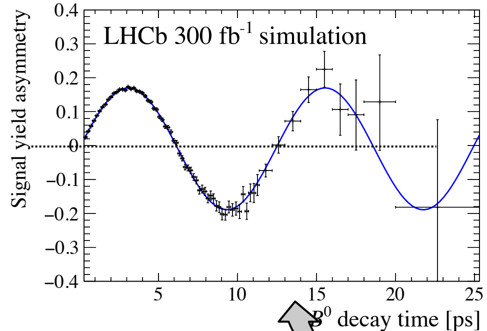
F. Dordei & L. Zhang

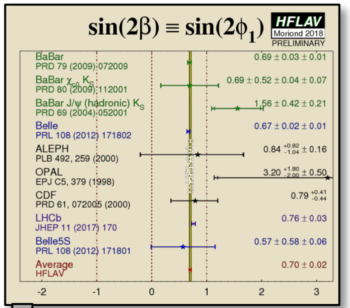
CP violation in beauty: Time dependent (φ_s, β)

$$\text{(left) } B_s^0 \to J/\psi\,\phi \text{ or (right) } B^0 \to J/\psi\,K_S^0$$



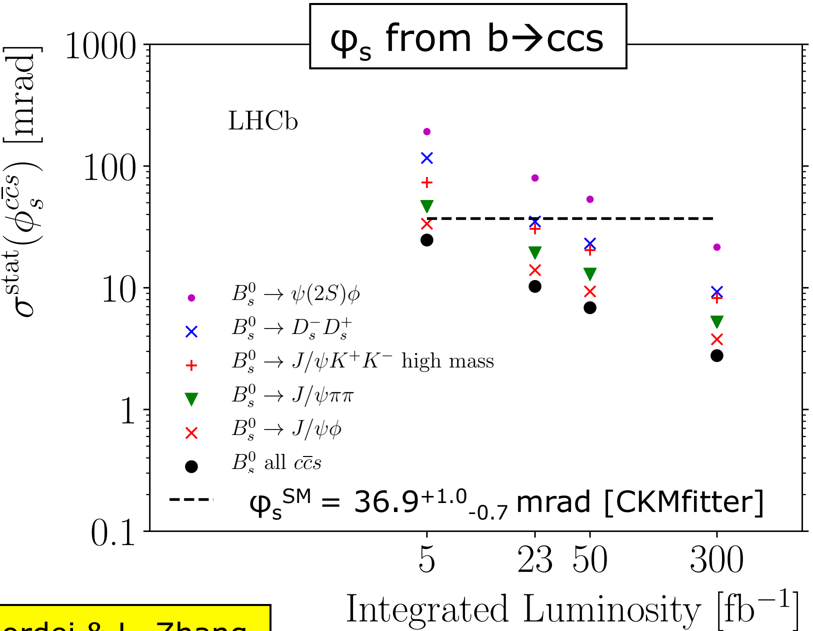


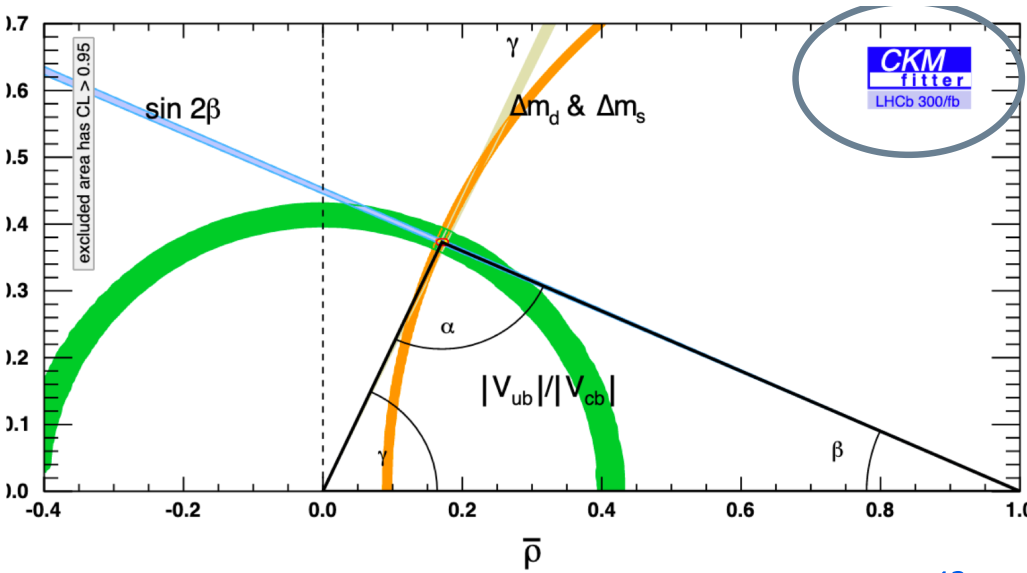




$\varphi_s = -0.054 \pm 0.021$ rad
$\Delta\Gamma_s = 0.0762 \pm 0.0034$ ps^{-1}

$S \equiv -\eta_{CP}\sin(2\beta) = 0.699 \pm 0.017$



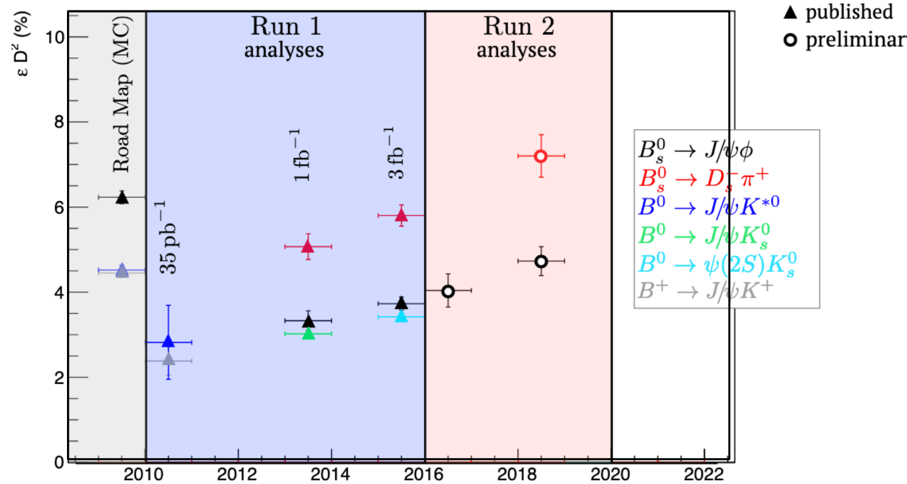


LHCb-PUB-2018-009, arXiv:1808.08865, Physics case for an LHCb Upgrade II

F. Dordei & L. Zhang

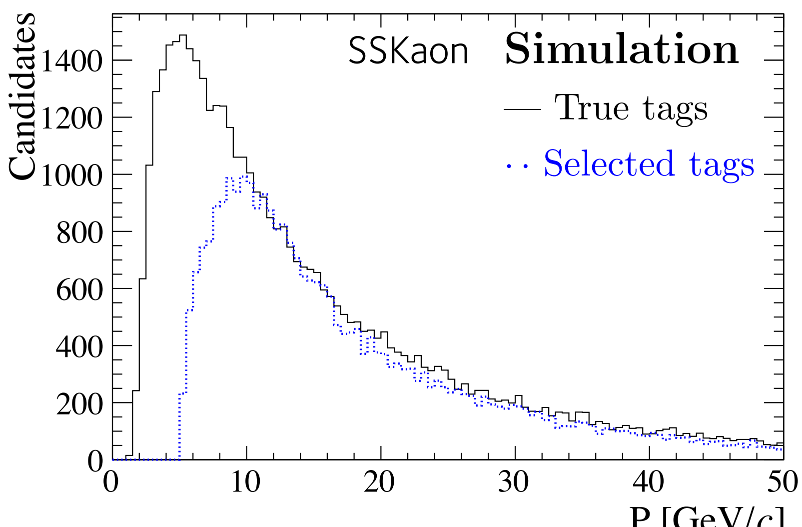
CP violation in beauty: Time dependent

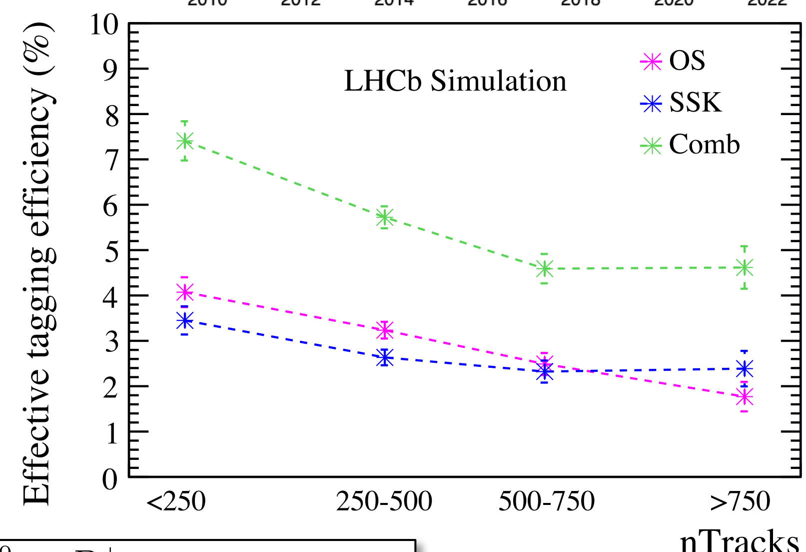
Plot from S. Akar



Tagging

- Great improvement
- Suffers from multiplicity
- TORCH will help



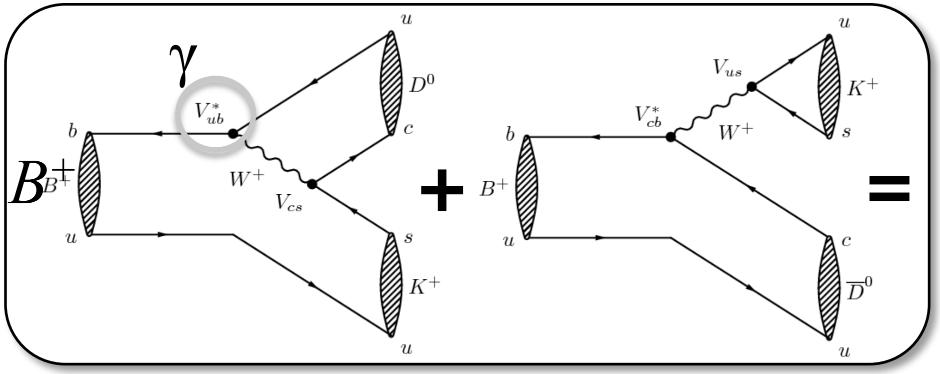


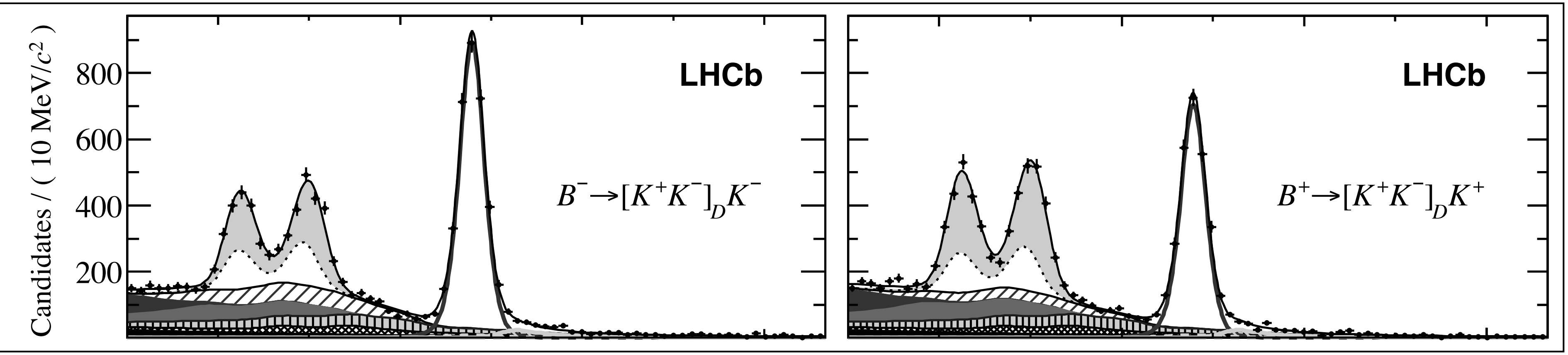
$B_s^0 \to D_s^+\pi^-$

Tagger	$B_s^0 \to D_s^+\pi^-$ Nominal	TORCH	Perfect
SSKaon	$1.20 \pm 0.05\%$	$1.52 \pm 0.05\%$	$1.61 \pm 0.05\%$
OSKaon	$1.29 \pm 0.05\%$	$1.73 \pm 0.06\%$	$1.80 \pm 0.06\%$

T.Hadavizadeh

CP violation in beauty: Time integrated (γ)





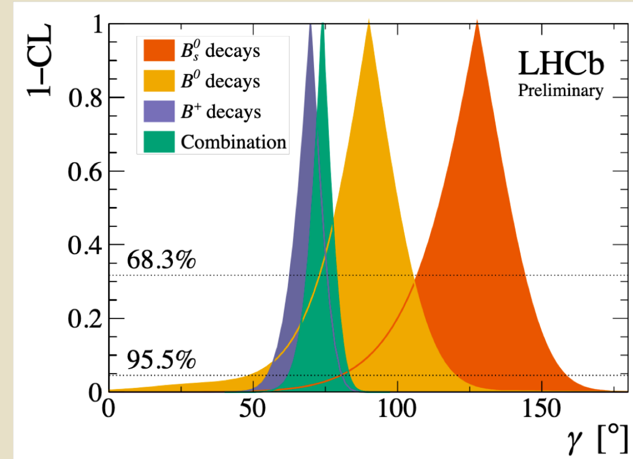
LHCb, PLB 777 (2018) 16

State of art of γ

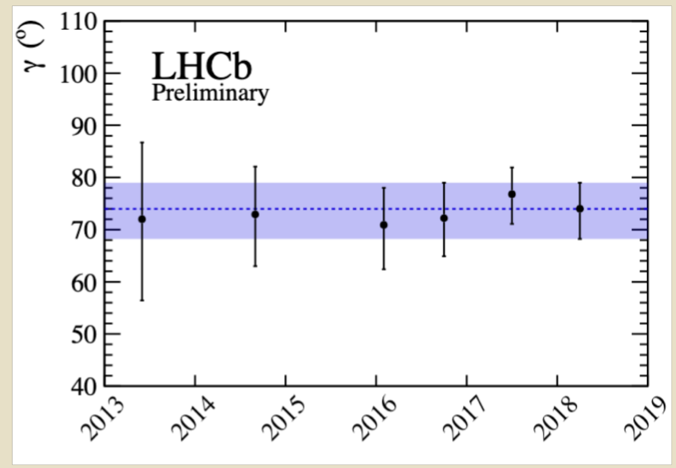
- Strategy similar to previous combinations: frequentist treatment.
- This combination includes new and updated measurements.

[LHCb-CONF-018-002]

B decay	D decay	Method	Ref.	Dataset[†]	Status since last combination [3]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2	New
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2	Updated results
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD	[25]	Run 1	Updated results
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1	New



[LHCb-CONF-018-002]



[LHCb-CONF-018-002]

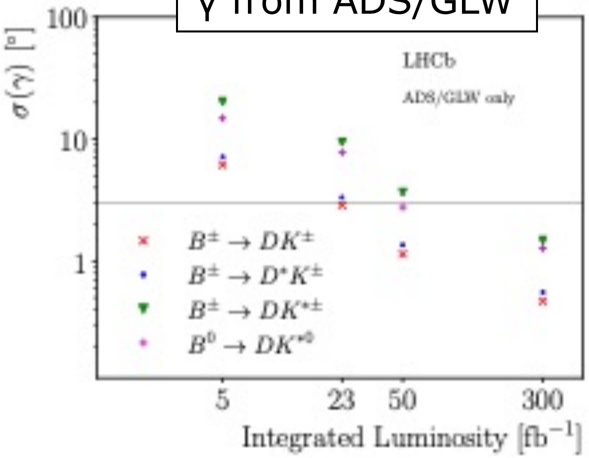
LHCb combination
$\gamma = (74.0^{+5.0}_{-5.8})^\circ$

In agreement with world averages
Supersedes the previous LHCb measurement.
Most precise determination of γ from a single experiment to date.

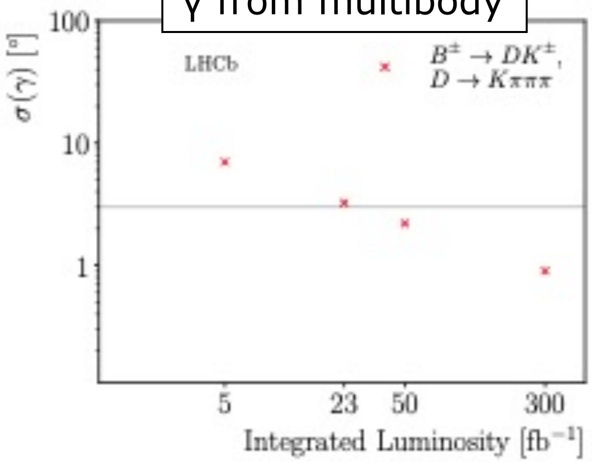
F. Dordei & L. Zhang

CP violation in beauty: Time integrated (γ)

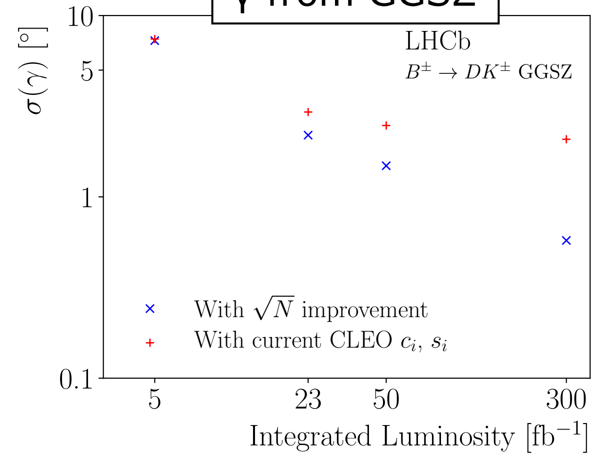
γ from ADS/GLW



γ from multibody



γ from GGSZ

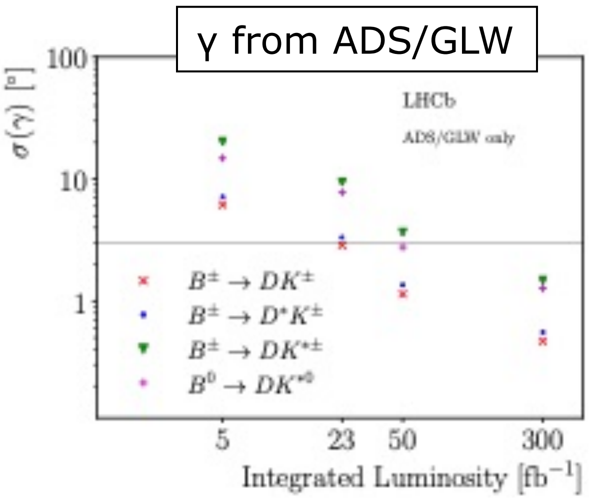


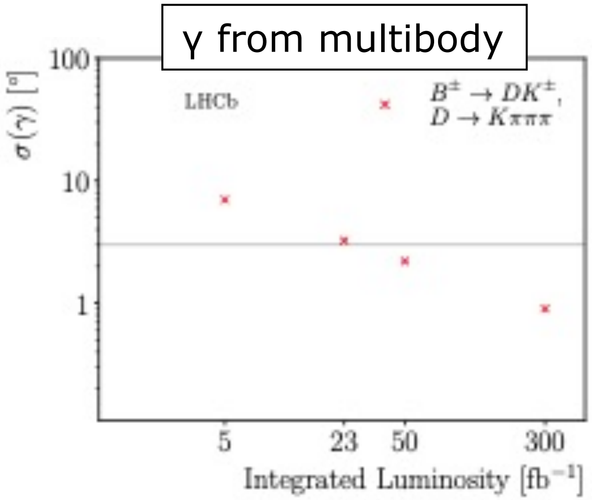
- Belle-II targets a precision of 1.5° at the end of data-taking (2025)

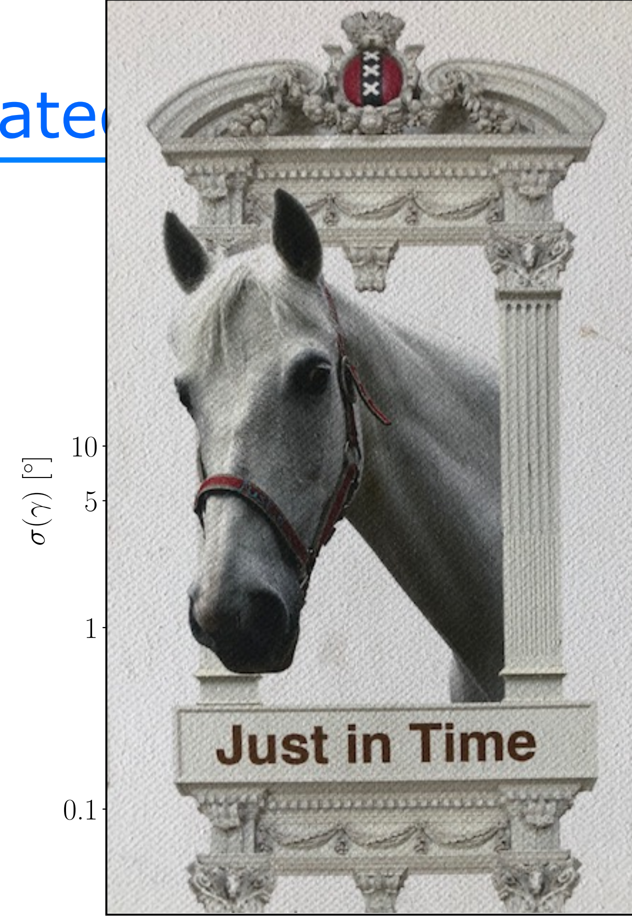
LHCb-PUB-2018-009, arXiv:1808.08865, Physics case for an LHCb Upgrade II

F. Dordei & L. Zhang

CP violation in beauty: Time integrated







- Belle-II targets a precision of 1.5° at the end of data-taking (2025)

LHCb-PUB-2018-009, arXiv:1808.08865, Physics case for an LHCb Upgrade II

F. Dordei & L. Zhang

CP violation in beauty: Time integrated (γ)

by LHCb: $\gamma = (74.0^{+5.0}_{-5.8})^\circ$ LHCb (2018)

b & Belle II): precision $< 1^\circ$ expected!

lattice QCD

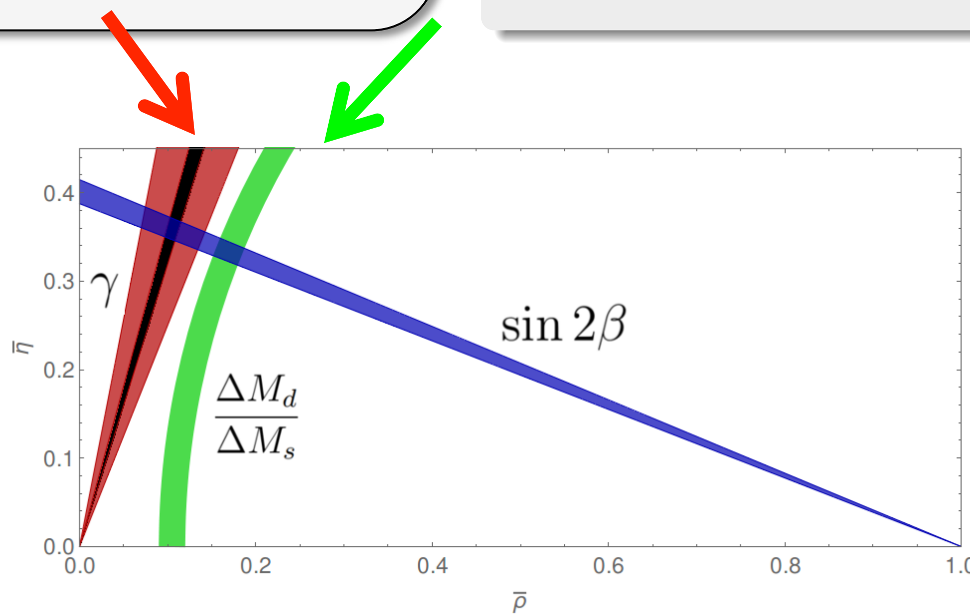
- Fermilab Lattice/MILC — Bazavov et al. (2016)
  $\xi = 1.206 \pm 0.019 \succ \gamma = (63.0 \pm 2.1)^\circ$
- RBC/UKQCD — Boyle et al. (2018)
  $\xi = 1.1853 \pm 0.0054^{+0.0116}_{-0.0156} \succ \gamma = (60.7 \pm 1.5)^\circ$

QCD sum rules — King, Lenz, Rauh (2019)

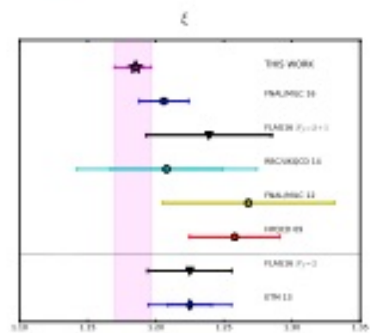
- $\xi = 1.2014^{+0.0065}_{-0.0072} \succ \gamma = (62.5 \pm 0.9)^\circ$

$$\xi^2 = \frac{f_{B_s}^2 \hat{B}_{B_s}}{f_B^2 \hat{B}_B} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{\Delta m_s}{\Delta m_d} \frac{m_B}{m_{B_s}}$$

M. Blanke and A. Buras
arXiv:1812.06963



Comparison to literature

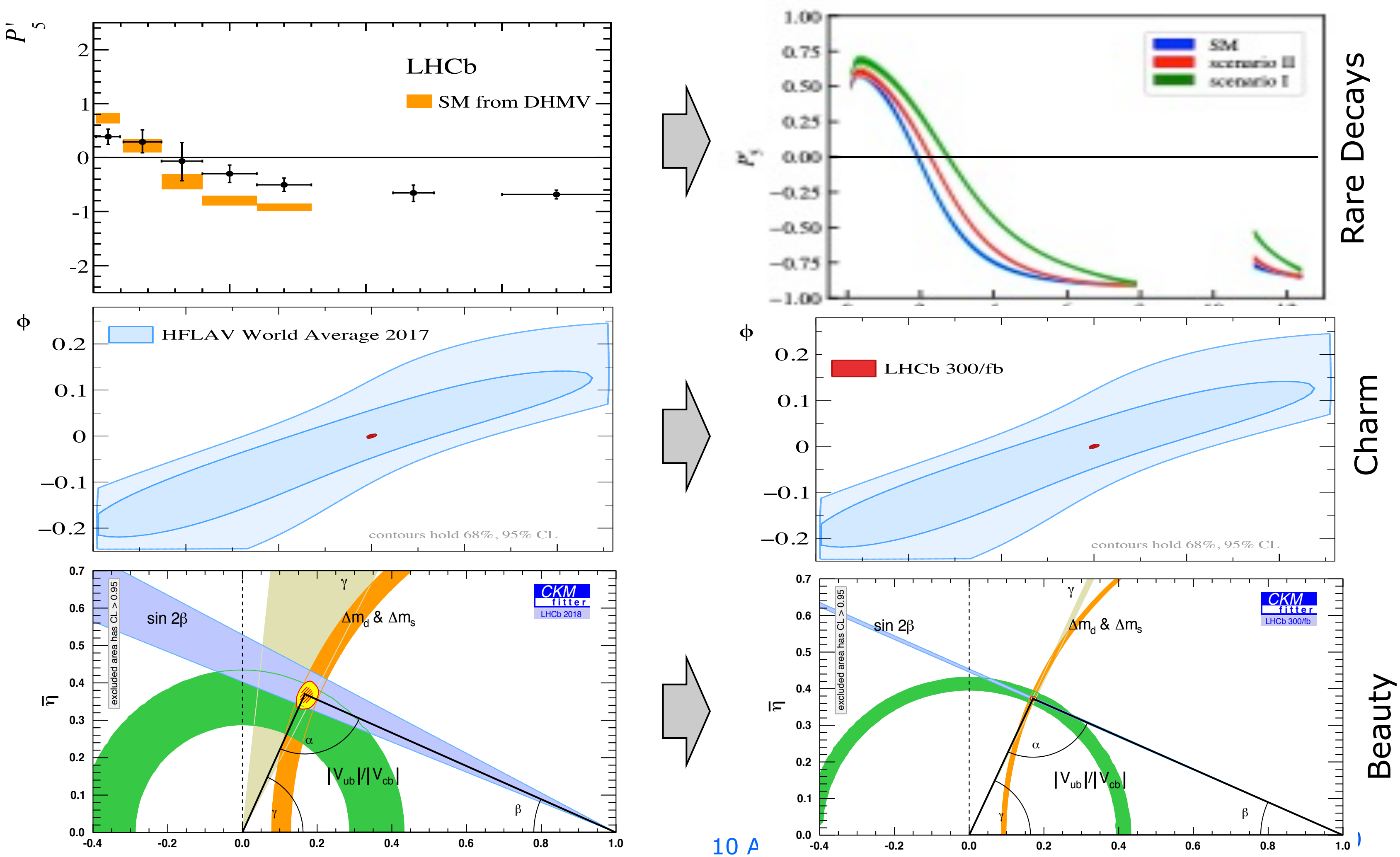


J. Tobias Tsang, Durham, Apr 2019

- tension currently at the 2σ level
- may become significant with improved experimental precision in γ

Summary

- Precision measurements to scrutinize the Standard Model
- Precision measurements only way to reach very high mass scales
- Precision measurements are not yet precise enough



10 A

Backup

Recommendations (physics)

- Magnet side stations
  - Improvement of mass resolution?
  - Track efficiency and computing time?
  - Check Geant parameters for low-p
- TORCH
  - Physics study with degraded performance
  - Effect on channels that do not use TORCH
- Mighty tracker
  - Re-evaluate target occupancy (2% ?)
  - Optimal z spacing?
  - Develop more realistic detector description, inc services
- MUON shielding
  - Efficiency for high-impact physics channels
  - Faster electronics to counter deadtime
  - Loss in physics when removing HCAL

LHCb-INT-2019-011
April 5, 2019

Recommendations from Upgrade Ib Review

J. Albrecht[1], F. Blanc[2], M. Charles[3], C. Fitzpatrick[4], M. Needham[5], C. Parkes[4,6], G. Passaleva[4,7], P. Perret[8], E. Thomas[4], U. Uwer[9], V. Vagnoni[10], D. Websdale[11], G. Wilkinson[12]

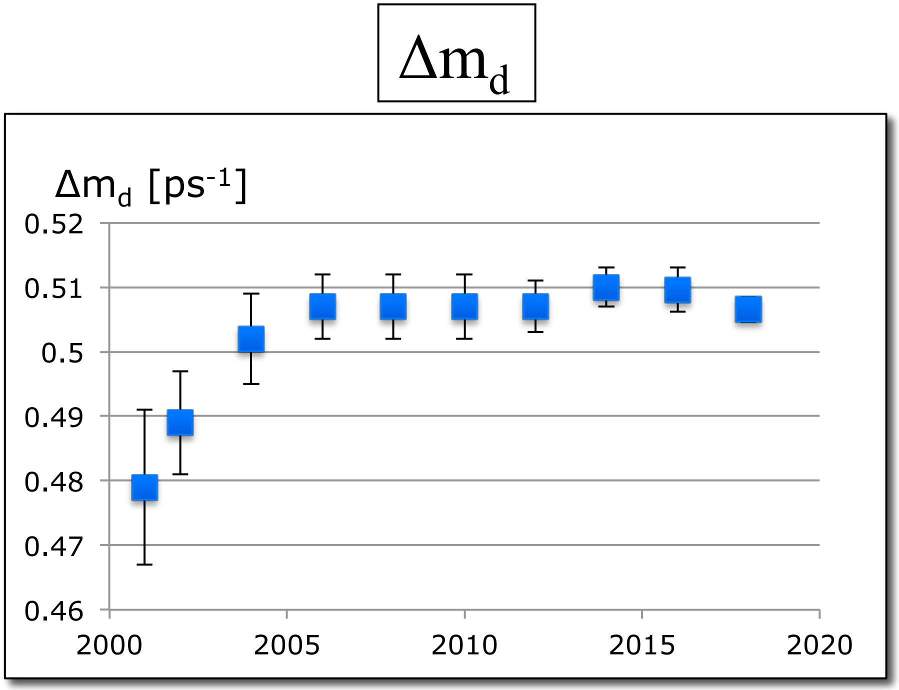
Still on the shelf!

Analysis	Run 1	Run 2	
	2011-2012	2015-2016	2017-2018
$B_{(s)} \rightarrow \mu\mu$	✔	✔	✗
P_5'	✔	✗	✗
R_K	✔	✔	✗
R_{K*}	✔	✗	✗
$R_{\phi, pK, K\pi\pi, \pi}$	✗	✗	✗
R_D	✗	✗	✗
R_{D*}	✔	✗	✗

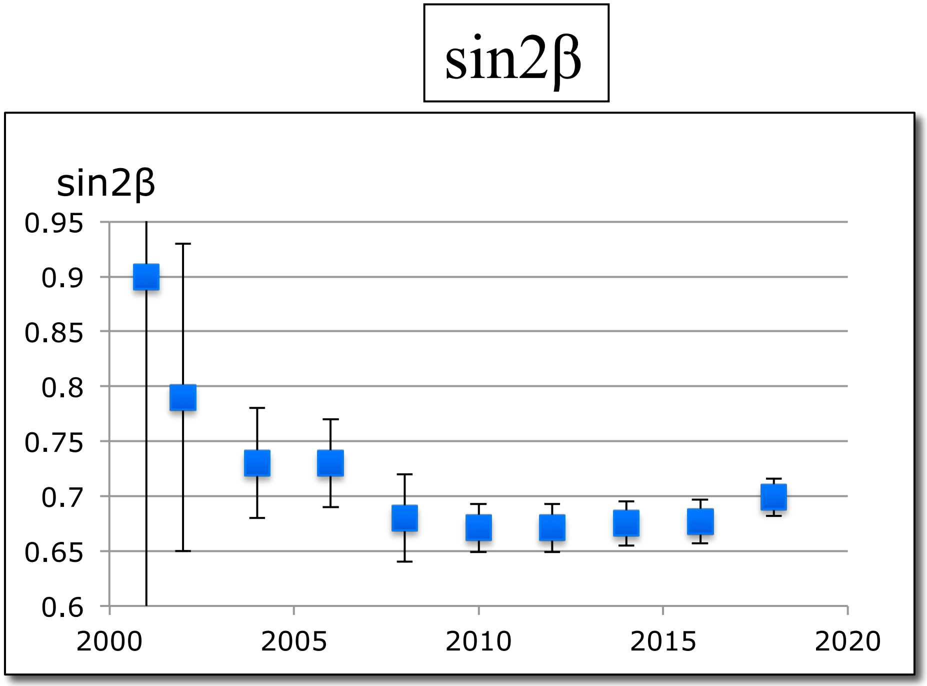
Disclaimer: not a complete list; e.g. searches not included

Progress

- B^0



Δm_d
Δm_d [ps^-1]
0.52
0.51
0.5
0.49
0.48
0.47
0.46
2000
2005
2010
2015
2020

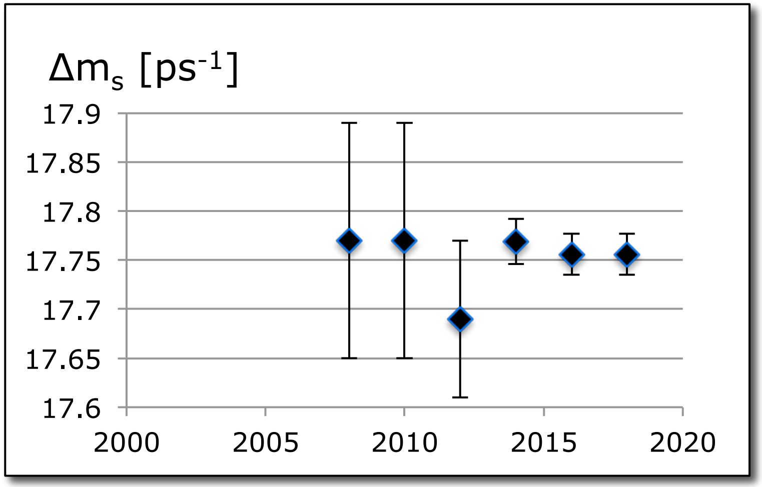


sin2β
sin2β
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
2000
2005
2010
2015
2020

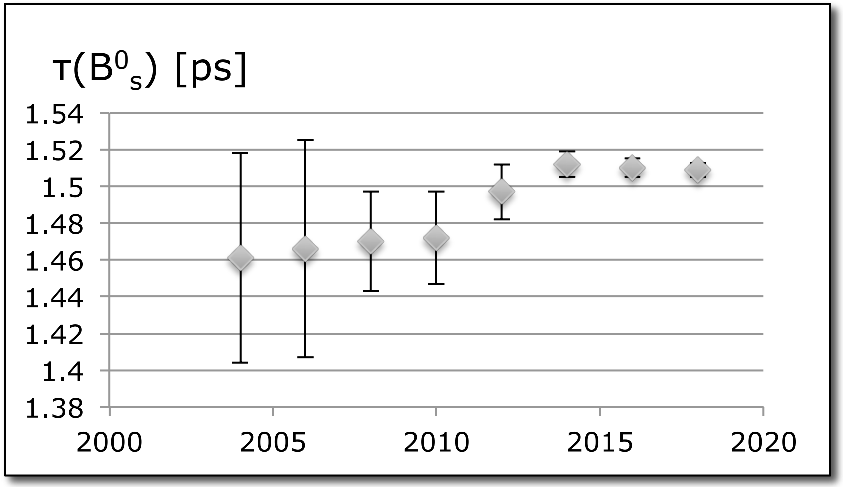
Progress

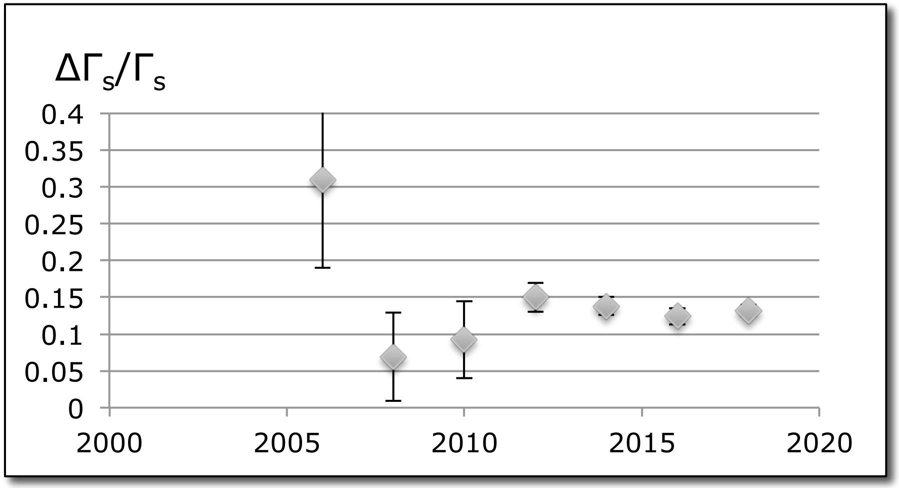
- B^0_s

Δm_s



τ_{Bs}





$\Delta\Gamma_s/\Gamma_s$

CP violation in kaons

Observation of direct CP violation in $K \to \pi\pi$ NA48, KTeV (2002)

$$(\varepsilon'/\varepsilon)_{\text{exp}} = (16.6 \pm 2.3) \cdot 10^{-4}$$

- reliable SM prediction difficult due to large cancellation between QCD and EW penguin contributions
- recent progress by lattice QCD — RBC/UKQCD (2015)
  supported by dual QCD methods — Buras, Gérard (2015ff)
- current SM prediction — Buras, Gorbahn, Jäger, Jamin (2015)

$$(\varepsilon'/\varepsilon)_{\text{SM}} = (1.9 \pm 4.5) \cdot 10^{-4}$$

➢ **New Physics in ε'/ε? Where else could we see it?**

M. Blanke

HL-LHC documents

[5] WG1: Standard Model Physics, arXiv:1902.04070;
WG2: Higgs Physics, arXiv:1902.00134;
WG3: Beyond the Standard Model Physics, arXiv:1812.07831;
WG4: Flavour Physics, arXiv:1812.07638;
WG5: High Density QCD Physics, arXiv:1812.06772

1. **Report on the Physics at the HL-LHC and Perspective**
ATLAS and CMS Collaborations. Feb 26, 2019. 1377 pp.
CERN-LPCC-2019-01, CMS-FTR-19-001, ATL-PHYS-PUB-2019-006
Conference: C19-03-01
e-Print: **arXiv:1902.10229** **[hep-ex]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNo
CERN Document Server; ADS Abstract Service
Detailed record - Cited by 1 record

2. **Standard Model Physics at the HL-LHC and HE-LHC**
HL-LHC Collaboration and HE-LHC Working Group (P. Azzi (INFN, Padua) *et al.*). Feb 11, 2019. 219 pp.
CERN-LPCC-2018-03
e-Print: **arXiv:1902.04070** **[hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; OSTI.gov Server
Detailed record - Cited by 7 records

3. **Higgs Physics at the HL-LHC and HE-LHC**
Physics of the HL-LHC Working Group (M. Cepeda (CERN & Madrid, CIEMAT) *et al.*). Jan 31, 2019. 364 pp.
CERN-LPCC-2018-04
e-Print: **arXiv:1902.00134** **[hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; OSTI.gov Server
Detailed record - Cited by 20 records

4. **Beyond the Standard Model Physics at the HL-LHC and HE-LHC**
X. Cid Vidal (Santiago de Compostela U., IGFAE) *et al.*. Dec 19, 2018. 279 pp.
CERN-LPCC-2018-05
e-Print: **arXiv:1812.07831** **[hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; OSTI.gov Server
Detailed record - Cited by 16 records

5. **Opportunities in Flavour Physics at the HL-LHC and HE-LHC**
A. Cerri (Sussex U.) *et al.*. Dec 18, 2018. 292 pp.
CERN-LPCC-2018-06
e-Print: **arXiv:1812.07638** **[hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; OSTI.gov Server
Detailed record - Cited by 18 records

6. **Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams**
Z. Citron (Ben Gurion U. of Negev) *et al.*. Dec 17, 2018. 207 pp.
CERN-LPCC-2018-07
Conference: C18-06-18.8
e-Print: **arXiv:1812.06772** **[hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service
Detailed record - Cited by 19 records

The need for more precision

Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed”

– A.Soni

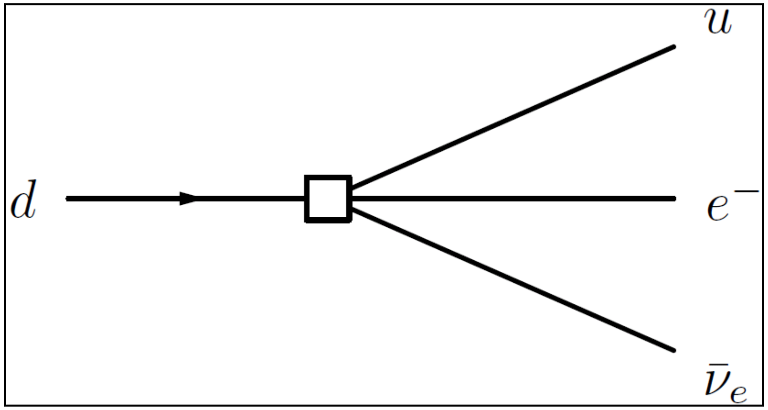
- “A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky.”

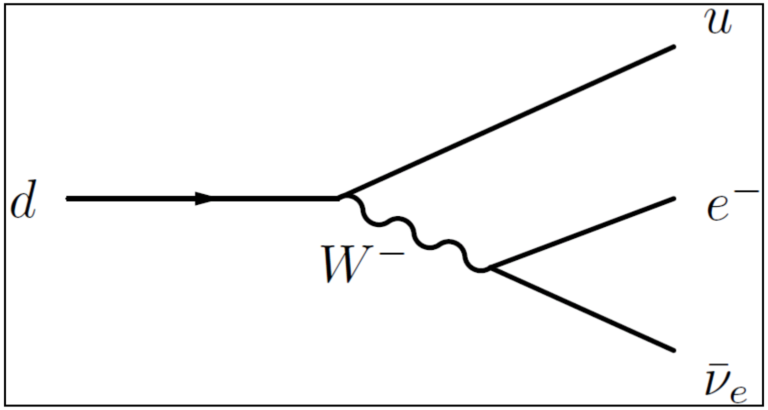
– L.Okun

(remember: $\mathcal{B}(K_L^0 \to \pi^+\pi^-) \sim 2\ 10^{-3}$)

Intermezzo: Effective couplings

- Historical example



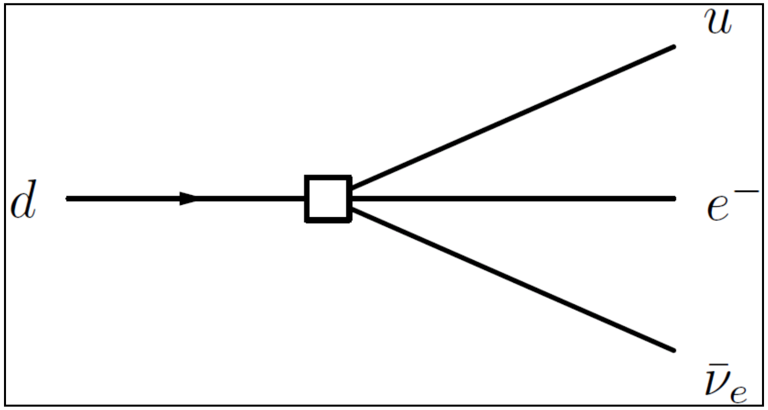


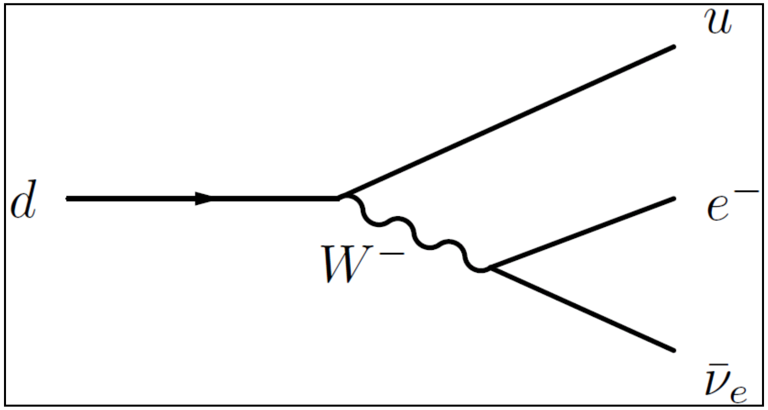
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

- Both are correct, depending on the energy scale you consider

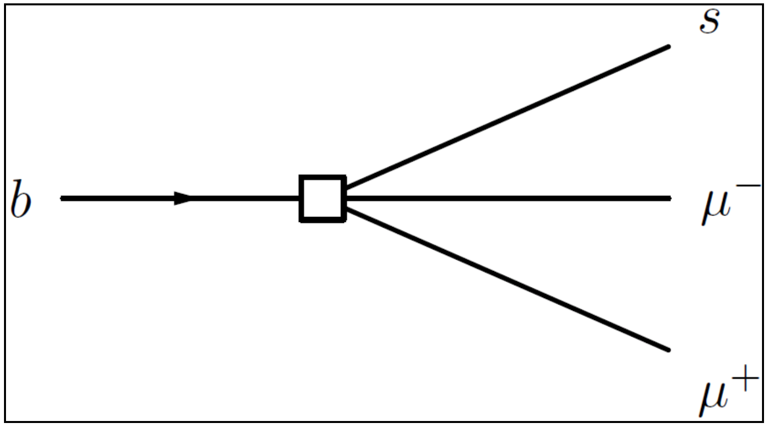
Intermezzo: Effective couplings

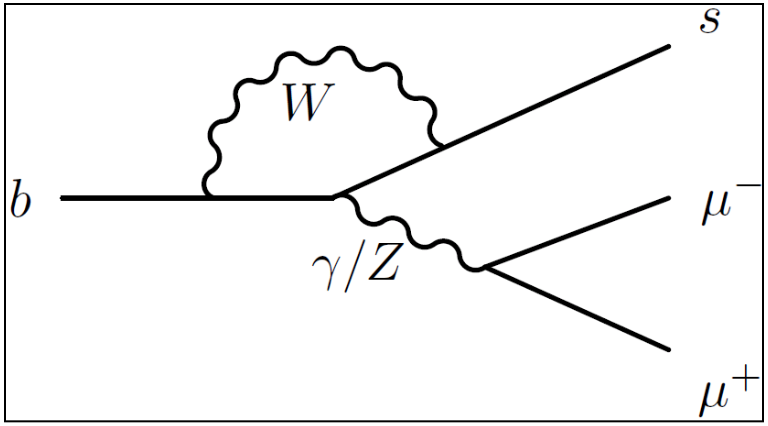
- Historical example





- Analog: *Flavour-changing neutral current*





Intermezzo: Effective couplings

- Effective coupling can be of various "kinds"
  - Vector coupling: C_9
  - Axial coupling: C_{10}
  - Left-handed coupling (V-A): C_9-C_{10}
  - Right-handed (to quarks): C_9', C_{10}', …
  - …

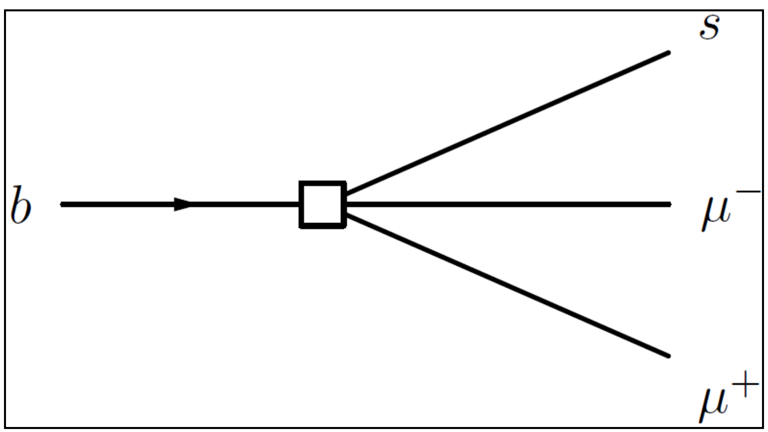
$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{\text{CKM}} \sum_i C_i(\mu) Q_i$$

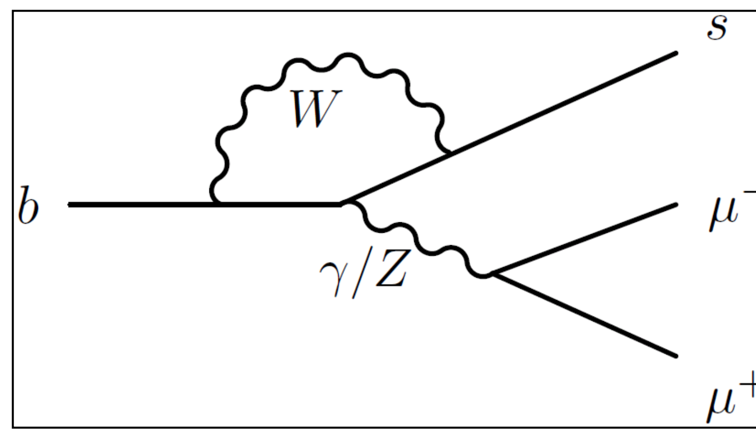
See e.g. Buras & Fleischer, hep-ph/9704376

Semi–Leptonic Operators (fig. 11f):

$$Q_{9V} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_V \qquad Q_{10A} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_A$$

- Analog: *Flavour-changing neutral current*



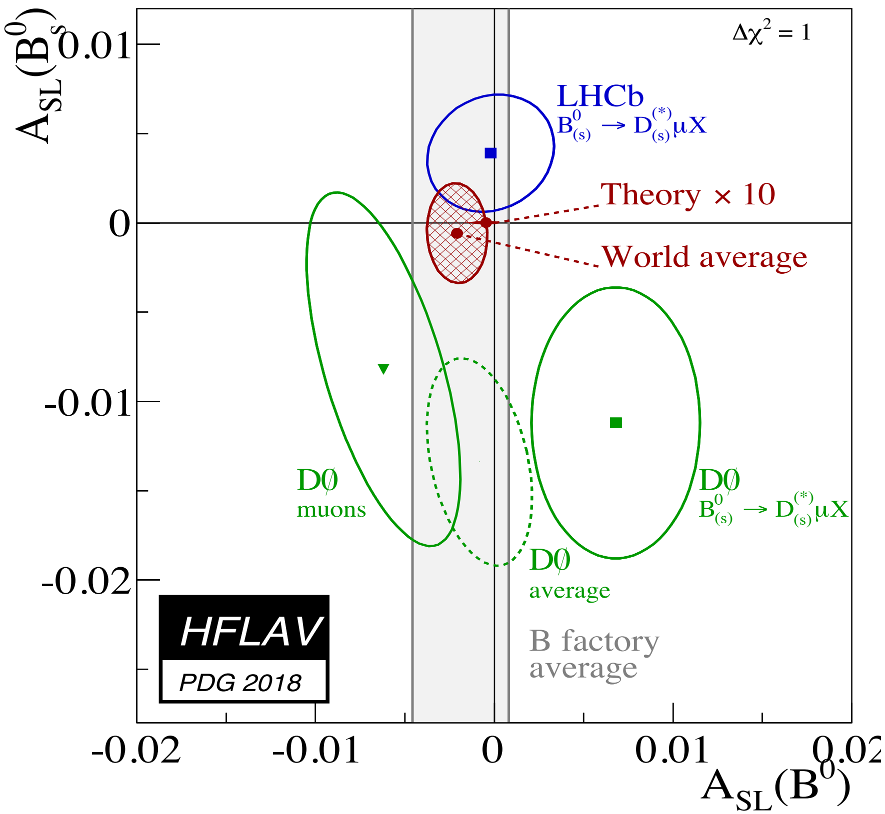


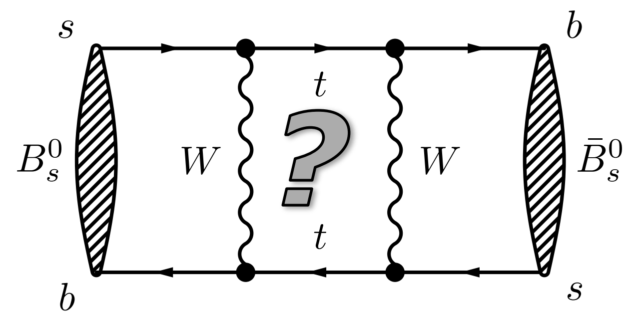
CP violation in beauty: A_{sl}

- Is there CP violation in mixing in $B_{(s)}$ system?
  - q, p "quantify" CP eigenstates
  - If $|q/p| \neq 1$ then

$$\left|B_H\right\rangle = p\left|B^0\right\rangle - q\left|\overline{B^0}\right\rangle$$

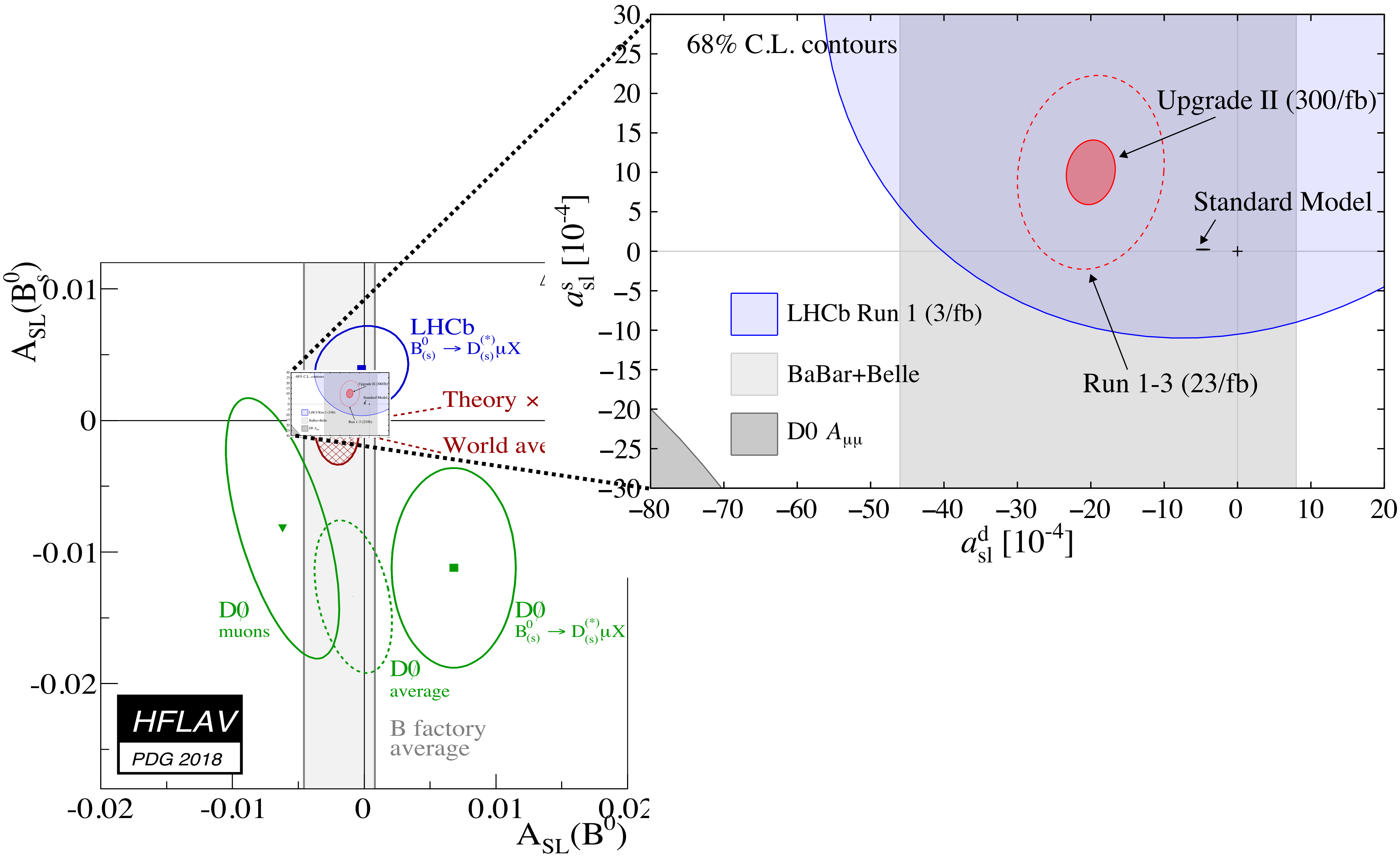
$$\text{Prob}\left(\overline{B}^0 \rightarrow B^0\right) \neq \text{Prob}\left(B^0 \rightarrow \overline{B}^0\right)$$





$$A_{sl} = \frac{\Gamma(\overline{B}^0 \rightarrow \overline{f}) - \Gamma(B^0 \rightarrow f)}{\Gamma(\overline{B}^0 \rightarrow \overline{f}) + \Gamma(B^0 \rightarrow f)} = \frac{1 - |q/p|^4}{1 + |q/p|^4} = \frac{\Delta\Gamma}{\Delta m}\tan\phi_{\Gamma/M}$$

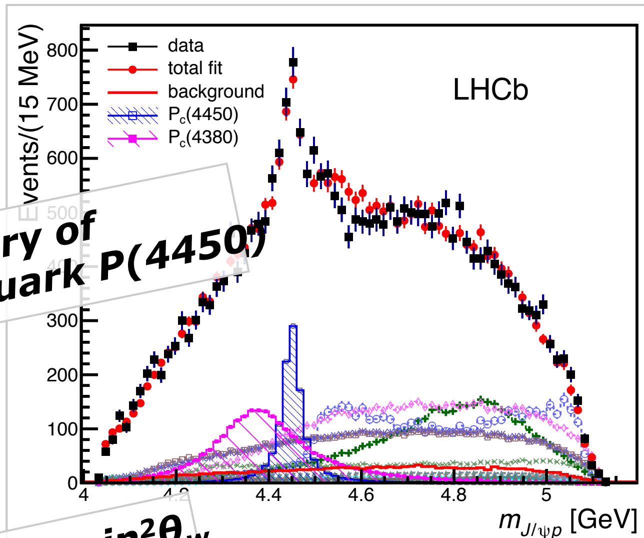
CP violation in beauty: A_{sl}



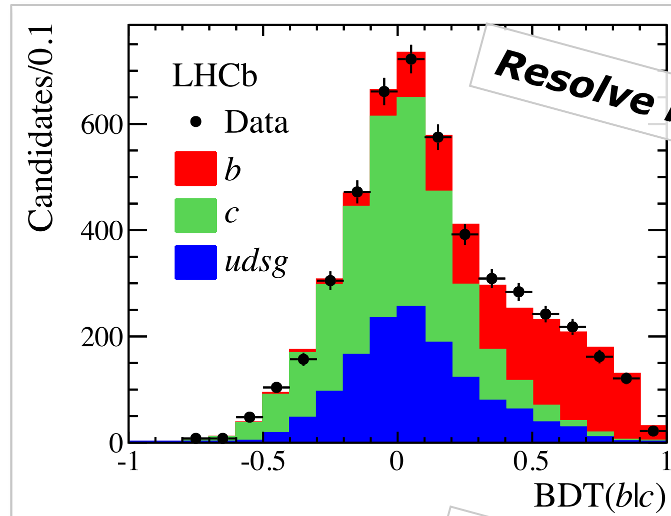
LHCb = more than flavour

pdfs, jets, heavy-ion, EW, exotic states…

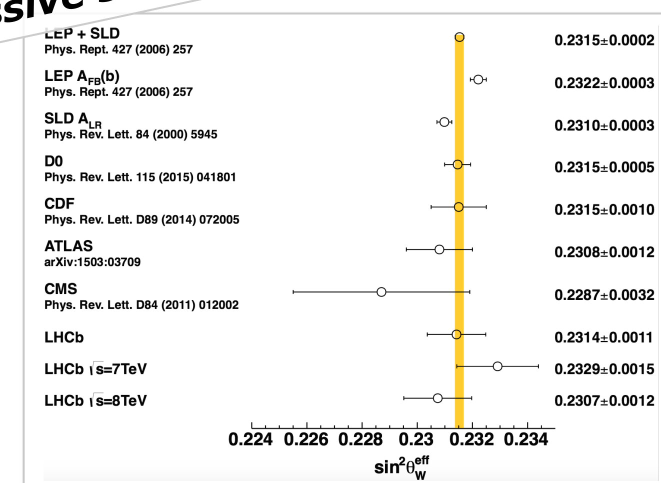
Discovery of pentaquark P(4450)



Resolve b and c jets



Impressive $\sin^2\theta_W$



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