

Heavy Flavour Physics at HL-LHC

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LHCb Collaboration

On behalf of the Heavy Flavour subgroup

<https://twiki.cern.ch/twiki/bin/view/ECFA/PhysicsGoalsPerformanceReachHeavyFlavour>

Thanks to Tancredi Carli , Alex Cerri, John Yuan Chao, Jack Kai-Feng Chen, Maria Jose Costa, Roger Forty, Tim Gershon, Bostjan Golob, Martijn Mulder, Sandro Palestini, Pavel Reznicek, Flera Rizatdinova, Maria Smizanska, Roberto Tenchini, Karim Trabelsi and Guy Wilkinson

Inputs from ATLAS, CMS, LHCb and Belle II collaborations



**ECFA High Luminosity LHC
Experiments Workshop
Physics and technology challenges
1st – 3rd October
Aix-les-Bains
France**

<https://indico.cern.ch/conferenceDisplay.py?confId=252045>

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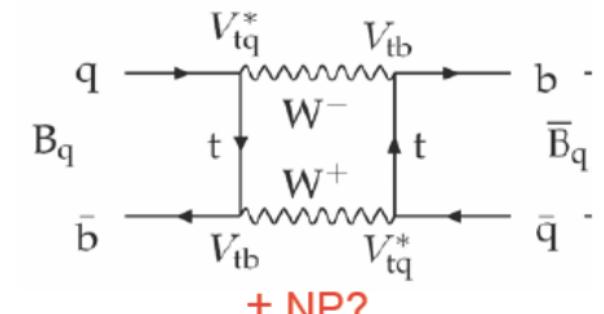
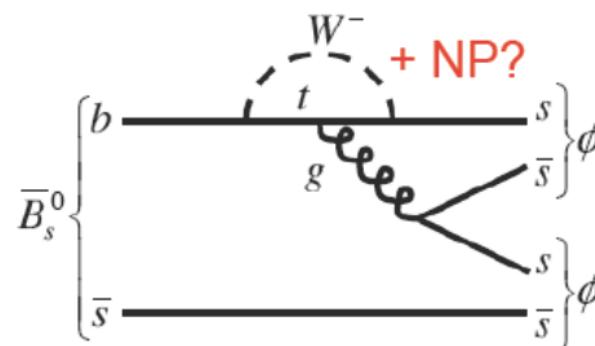
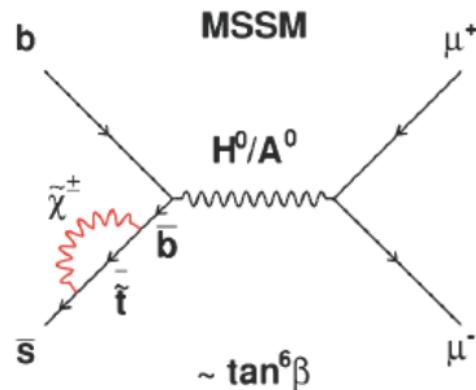
P. Allport, D. Contardo, D. Hudson, E. Potter



Picture Credit: OT Aix-les-Bains / Gilles Lansard

Motivation

- Precision measurements of CP asymmetries and rare decays



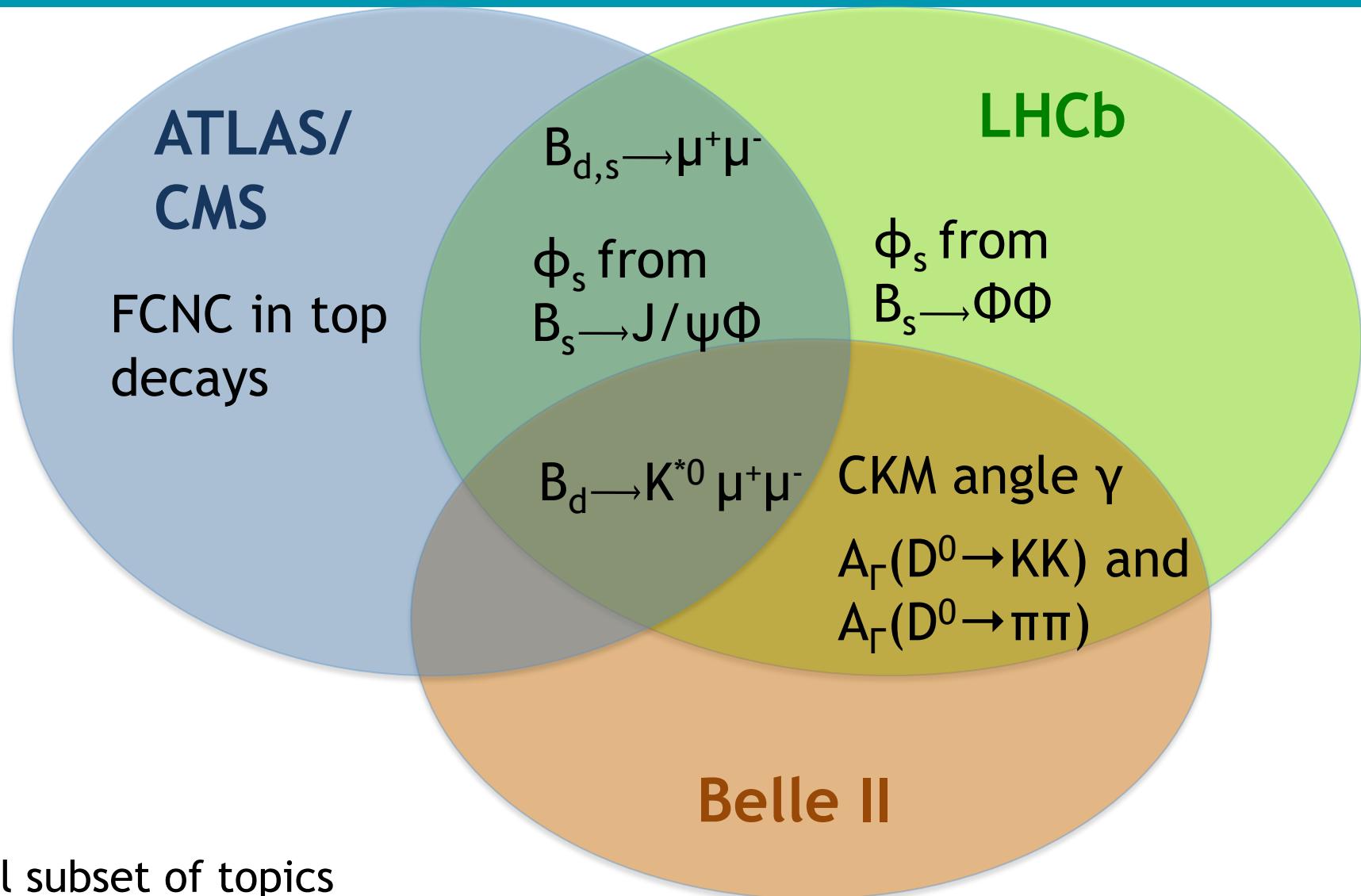
- A game of coupling and scale :

$$\frac{|\delta|}{\Lambda_{eff}^2}$$

NP scale
(mass of new particles)

- Clean predictions from the SM
 - Precise measurements (including control channels)

General framework : physics topics



small subset of topics

not all topics have been studied in every experiment

Belle II-only topics not mentioned

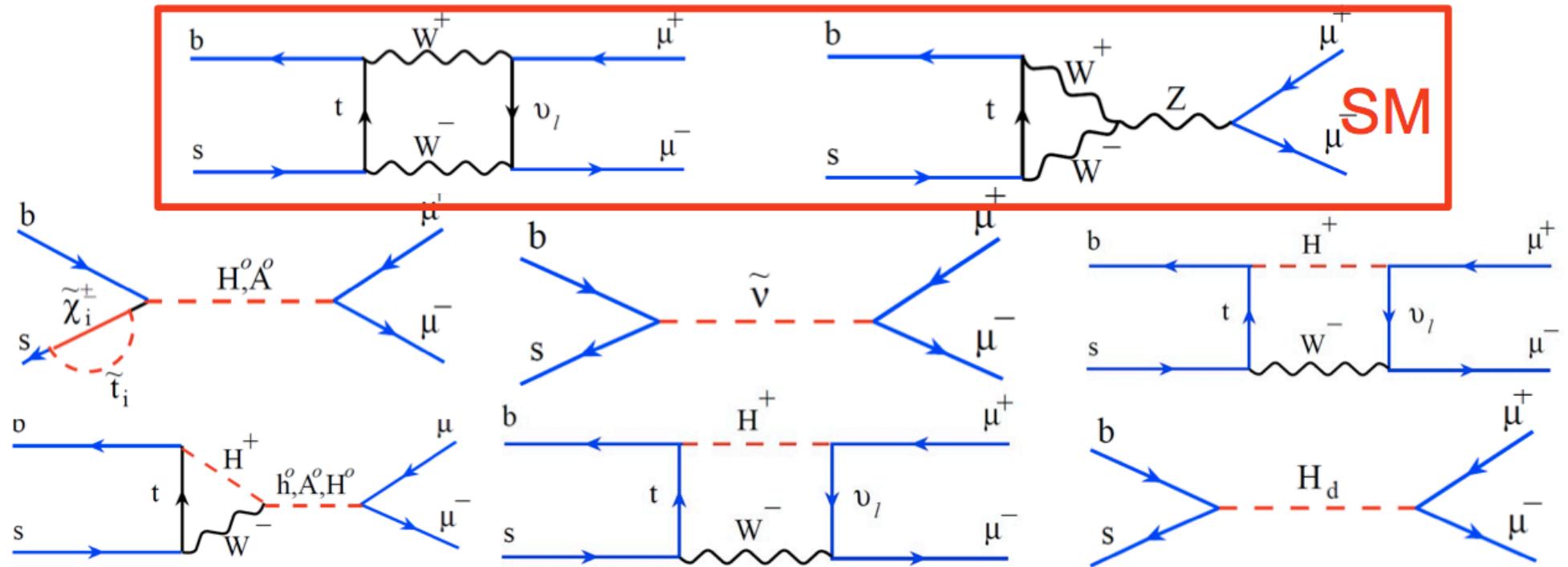
General framework : working hypotheses

- Current results used + improved detectors
- Simulation of running conditions (energy, pile-up)
- $\sigma(b\bar{b})^{14 \text{ TeV}} = 2 \times \sigma(b\bar{b})^{7 \text{ TeV}}$
- integrated luminosities :

	LHC era		HL-LHC era		
	2010-2012	2015-2017	2019-2021	2024-2026	2028-2030+
ATLAS & CMS	25 fb ⁻¹	100 fb ⁻¹	300 fb ⁻¹	→	3000 fb ⁻¹
LHCb	3 fb ⁻¹	8 fb ⁻¹	23 fb ⁻¹	46 fb ⁻¹	100 fb ⁻¹
Belle II	-	0.5 ab ⁻¹	25 ab ⁻¹	50 ab ⁻¹	-

The LHCb upgrade design is qualified for an integrated luminosity of 50fb⁻¹ but it is anticipated that LHCb will continue to be operational throughout the HL-LHC era

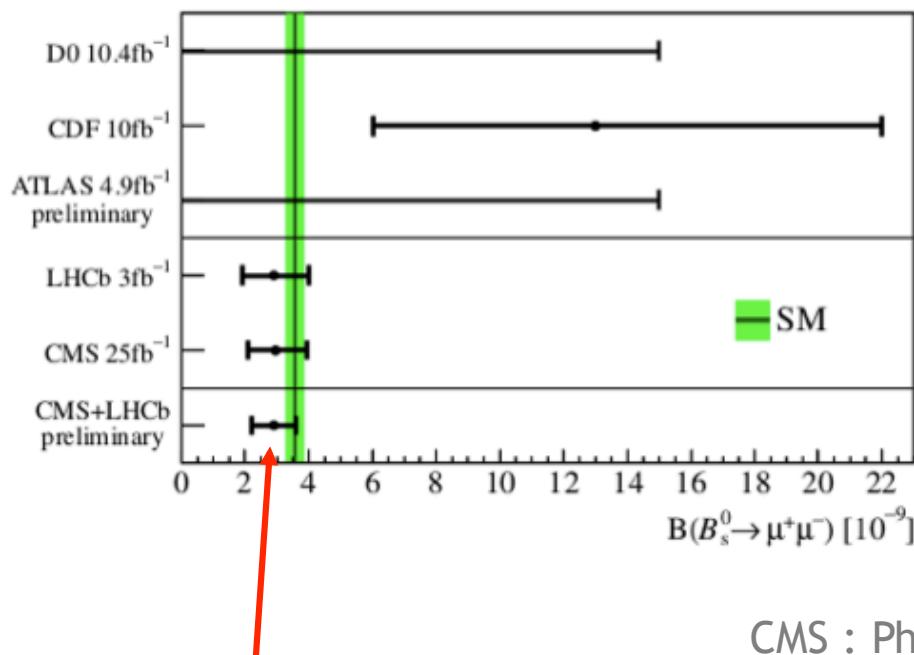
$B_{d,s} \rightarrow \mu^+ \mu^-$



SM : very rare (V_{tq} , helicity suppression)

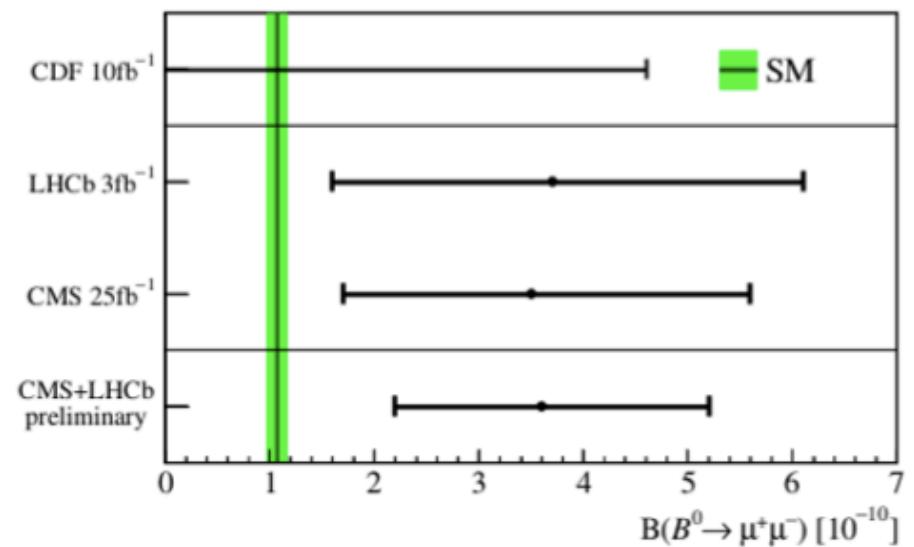
Large sensitivity to NP, eg : $\text{Br}_{\text{MSSM}}(B_q \rightarrow \ell^+ \ell^-) \propto \frac{M_b^2 M_\ell^2 \tan^6 \beta}{M_A^4}$

$\text{BR}(B_s \rightarrow \mu^+ \mu^-)$



measured with 25%
precision

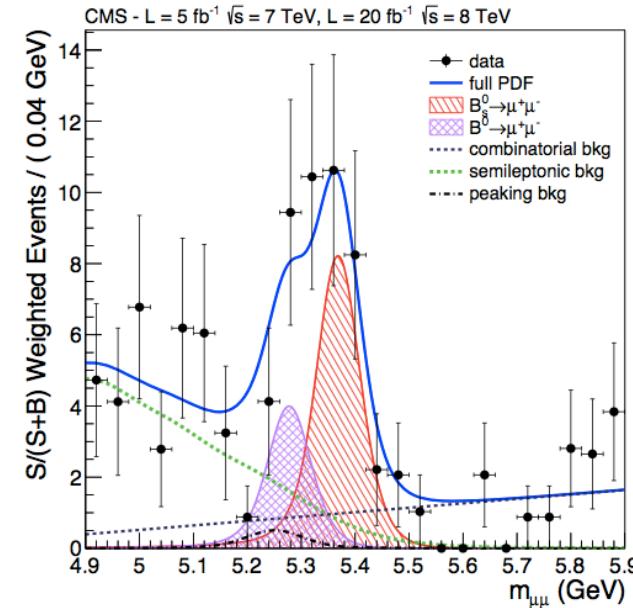
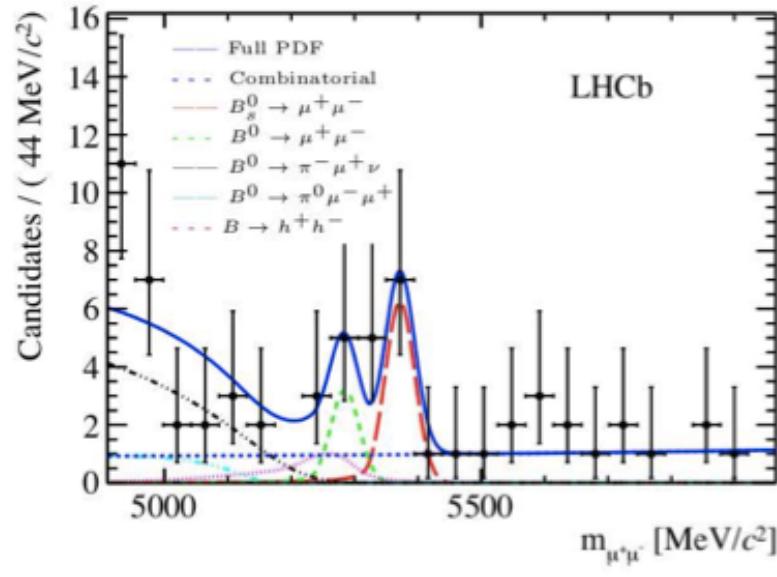
$\text{BR}(B_d \rightarrow \mu^+ \mu^-)$



CMS : Phys. Rev. Lett. 111 (2013) 101804, arXiv:1307.5025.
 LHCb : Phys. Rev. Lett. 111 (2013) 101805, arXiv:1307.5024.
 Combination : CMS-PAS-BPH-13-007 ; LHCb-CONF-2013-012

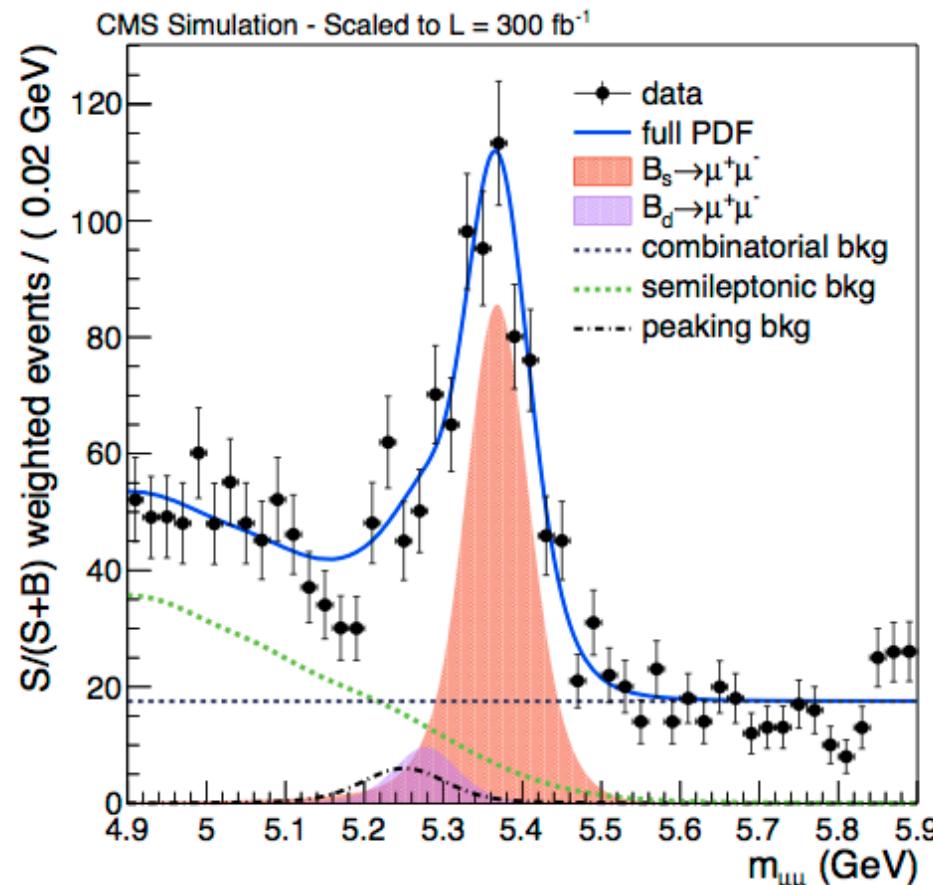
From theory : BRs known to 10% (can be improved with refined lattice QCD calculations)

$B_{d,s} \rightarrow \mu^+ \mu^-$: what's next ?

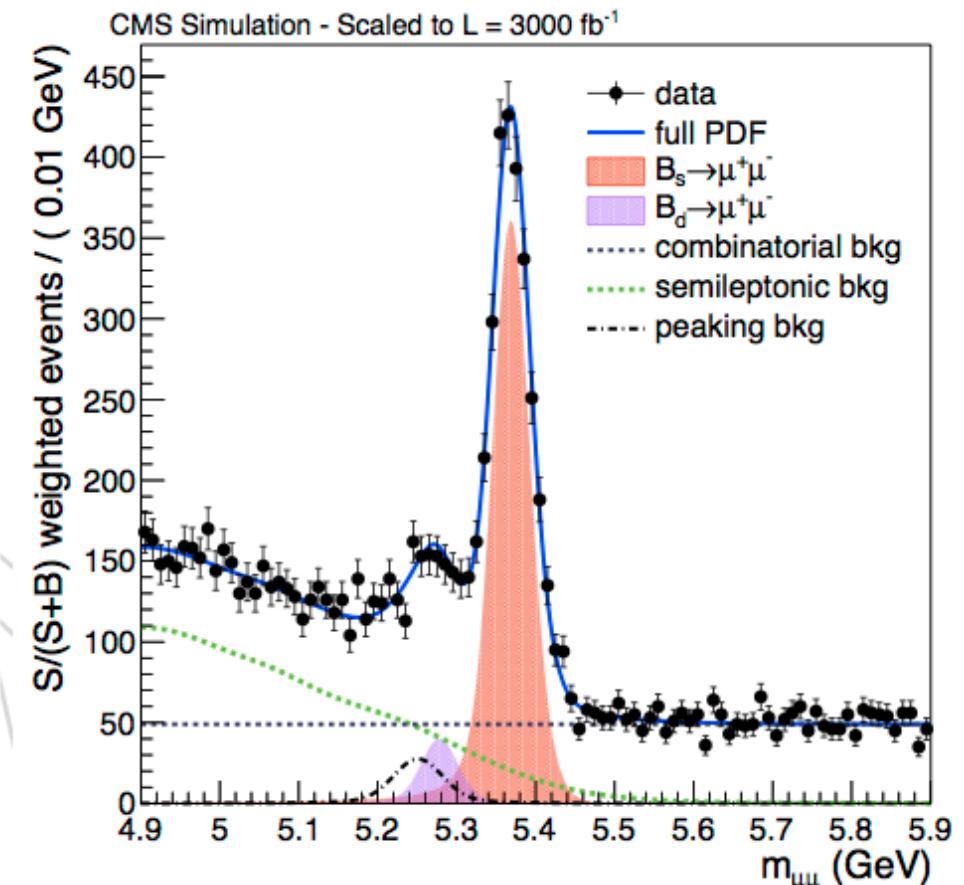


- Measure B_d and B_s : NP effects can be different
- HL-LHC : $\text{BR}(B_s)$ will be limited (theory, f_d/f_s or B_s absolute BR)
- Use B_d !
- B mass resolution is crucial :
 - CMS and LHCb can do it.
 - ATLAS mass resolution has to be improved.
 - $B_d \rightarrow \mu^+ \mu^-$ suffers from $B_d \rightarrow K\pi$ background

CMS 300 fb^{-1}

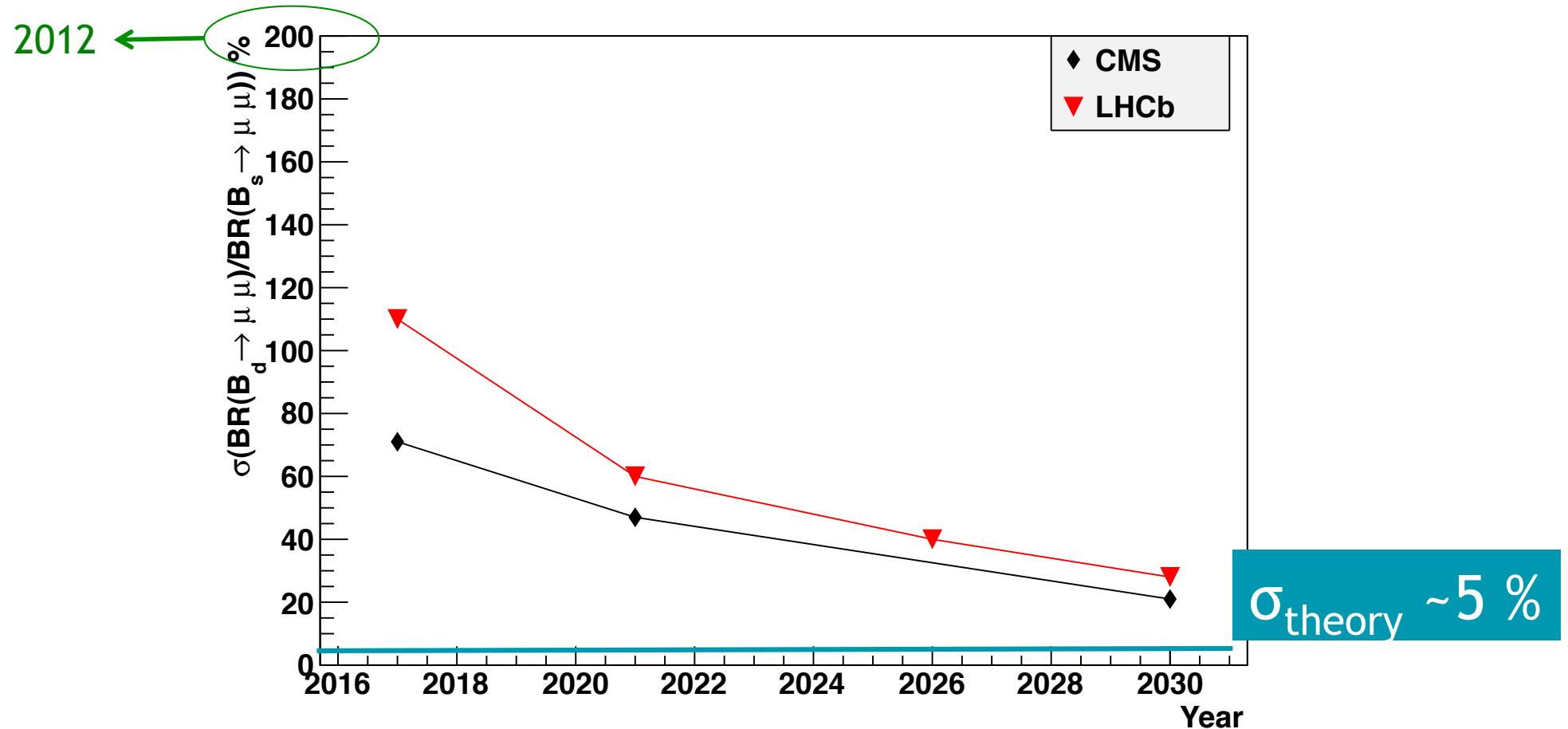


CMS 3000 fb^{-1}



improved inner tracker system and
removal of the endcap candidates

Expected precision on $\text{BR}(B_d \rightarrow \mu^+\mu^-)/\text{BR}(B_s \rightarrow \mu^+\mu^-)$

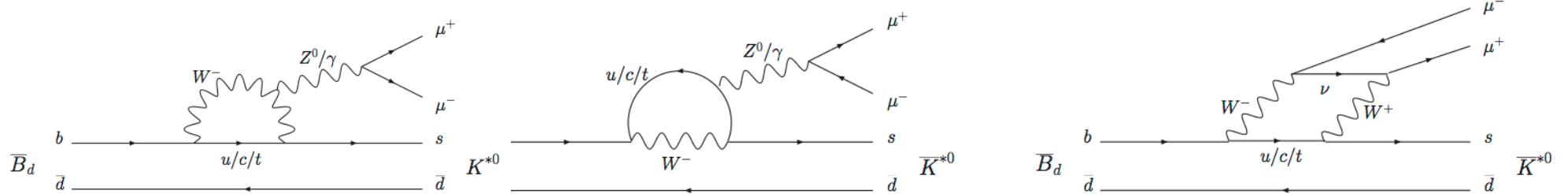


Precision computed assuming the SM BR

But also : measurement of the $B_s \rightarrow \mu^+\mu^-$ effective lifetime (clean test of NP) with ~2000 events

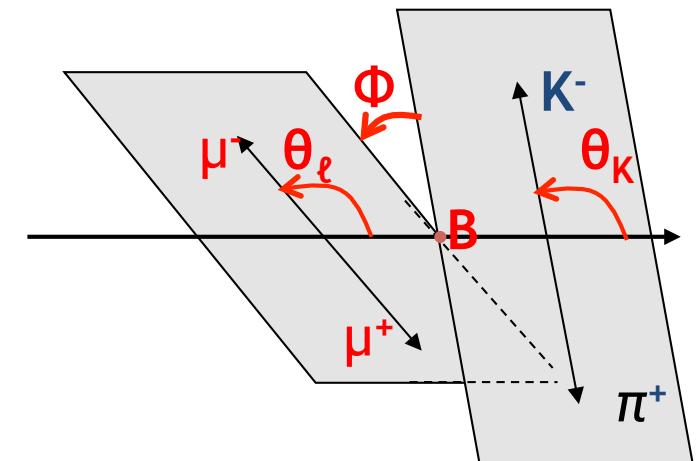
Angular observables in $B_d \rightarrow K^{*0} \mu^+ \mu^-$

SM :



System described by

- $q^2 = M^2(\ell\ell)$
- 3 angles



Distributions of the angular variables precisely predicted in the SM

Deviations expected from NP

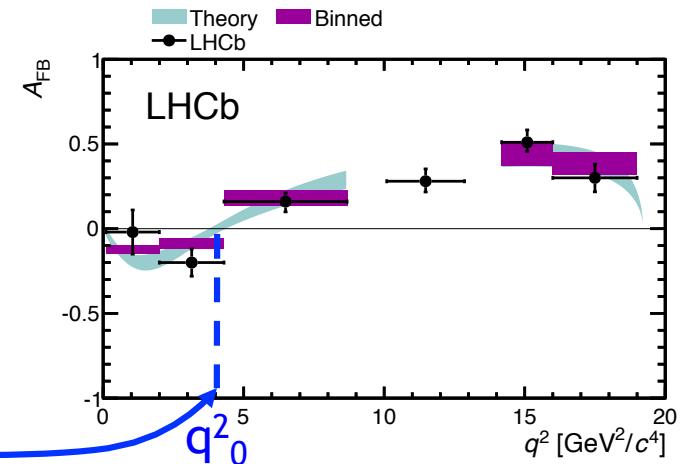
Probe the NP structure if any effect observed :

eg in the low q^2 region the Φ distribution is sensitive to the photon polarization

$$A_{FB} = \frac{\Gamma(\cos\theta_{B\ell^+} > 0) - \Gamma(\cos\theta_{B\ell^+} < 0)}{\Gamma(\cos\theta_{B\ell^+} > 0) + \Gamma(\cos\theta_{B\ell^+} < 0)}$$

$$A_{FB}(q^2_0) = 0$$

used as a reference



Important phenomenological work to construct observables with low theoretical uncertainties

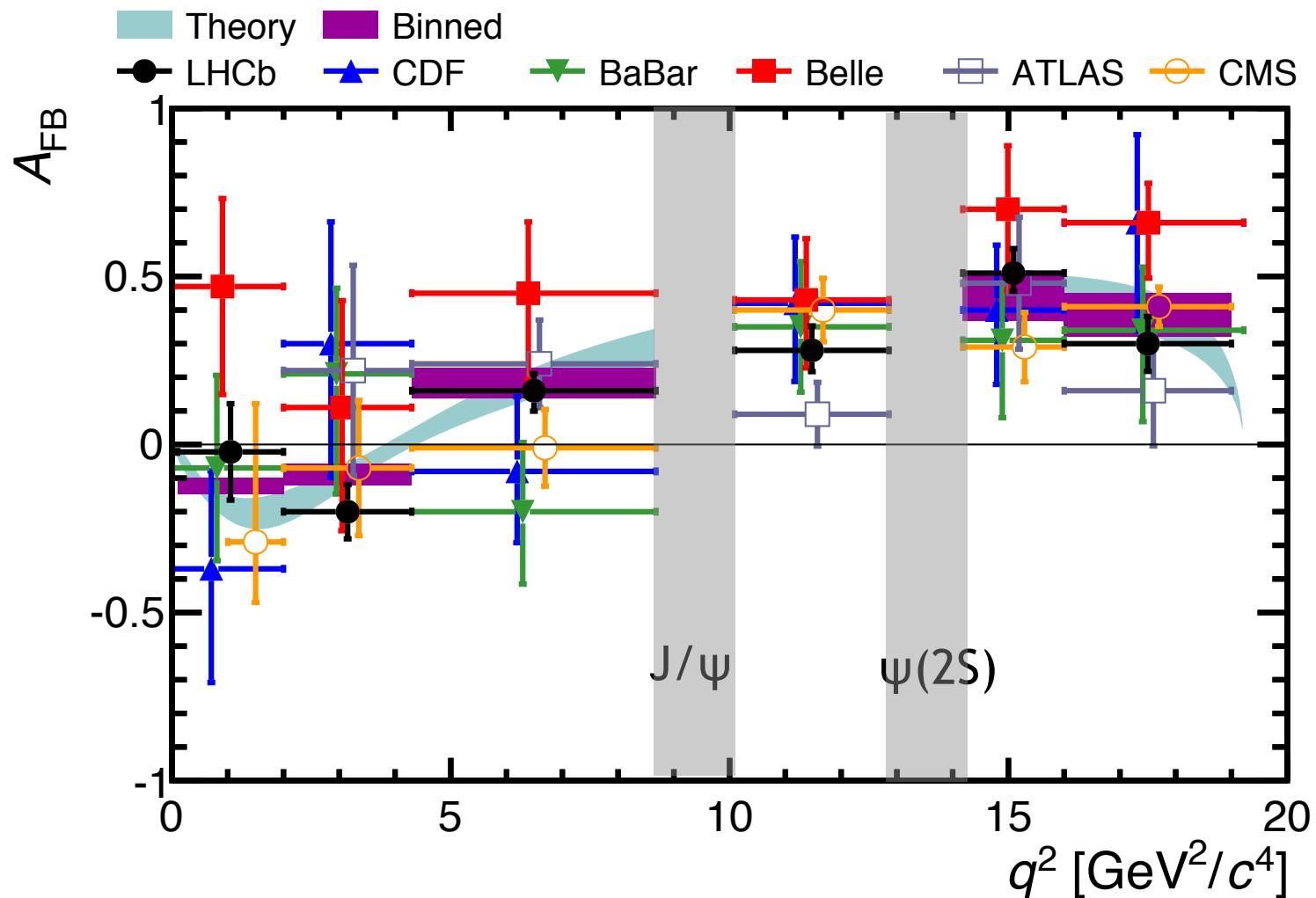
$$A_T^{(2)}(q^2) = \frac{|A_\perp(q^2)|^2 - |A_\parallel(q^2)|^2}{|A_\perp(q^2)|^2 + |A_\parallel(q^2)|^2}$$

sensitive to RH-couplings ($C_7^{'}$) at low q^2

$$A_T^{(2)}(0) = \frac{2 \operatorname{Re}[C_7^{\text{eff}} C_7^{' \text{eff}*}]}{|C_7^{\text{eff}}|^2 + |C_7^{' \text{eff}*}|^2}$$

Current results :

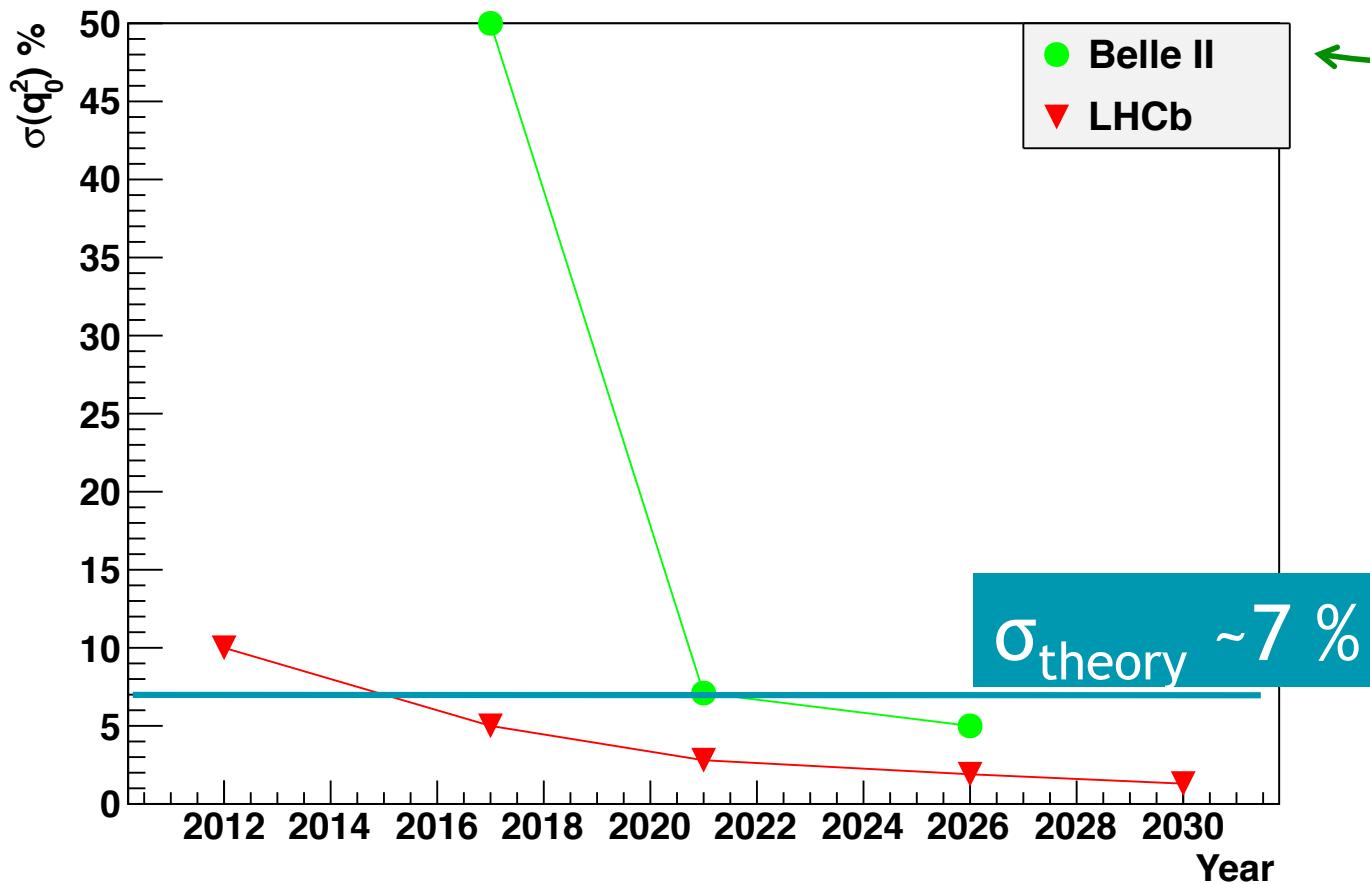
ATLAS : ATLAS- CONF-2013-038.
 CMS : arXiv:1308.3409.
 LHCb : JHEP 08 (2013) 131



Relative weights of the LHC experiments depend on the q^2 bin
 ‘cleanliness’ varies with bins (resonances in $M(\mu^+\mu^-)$)

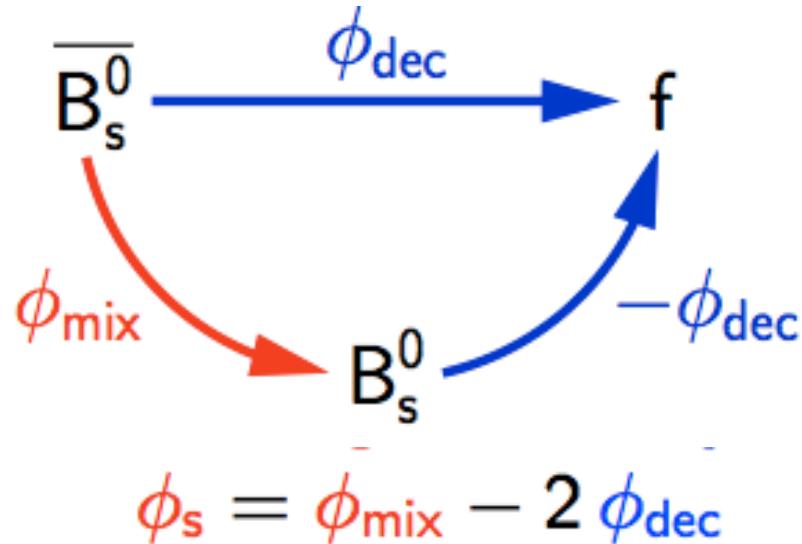
Expected precision on q^2_0

$K^* l^+ l^-$, where $l = e$ or μ and
 K^* includes both K^{*0} and K^{*+}



- triggering at low muon p_T is mandatory
- A_{FB} is not the best variable (contains hadronic uncertainties)
- much more than that in $B_d \rightarrow K^{*0} \mu^+ \mu^-$ analyses

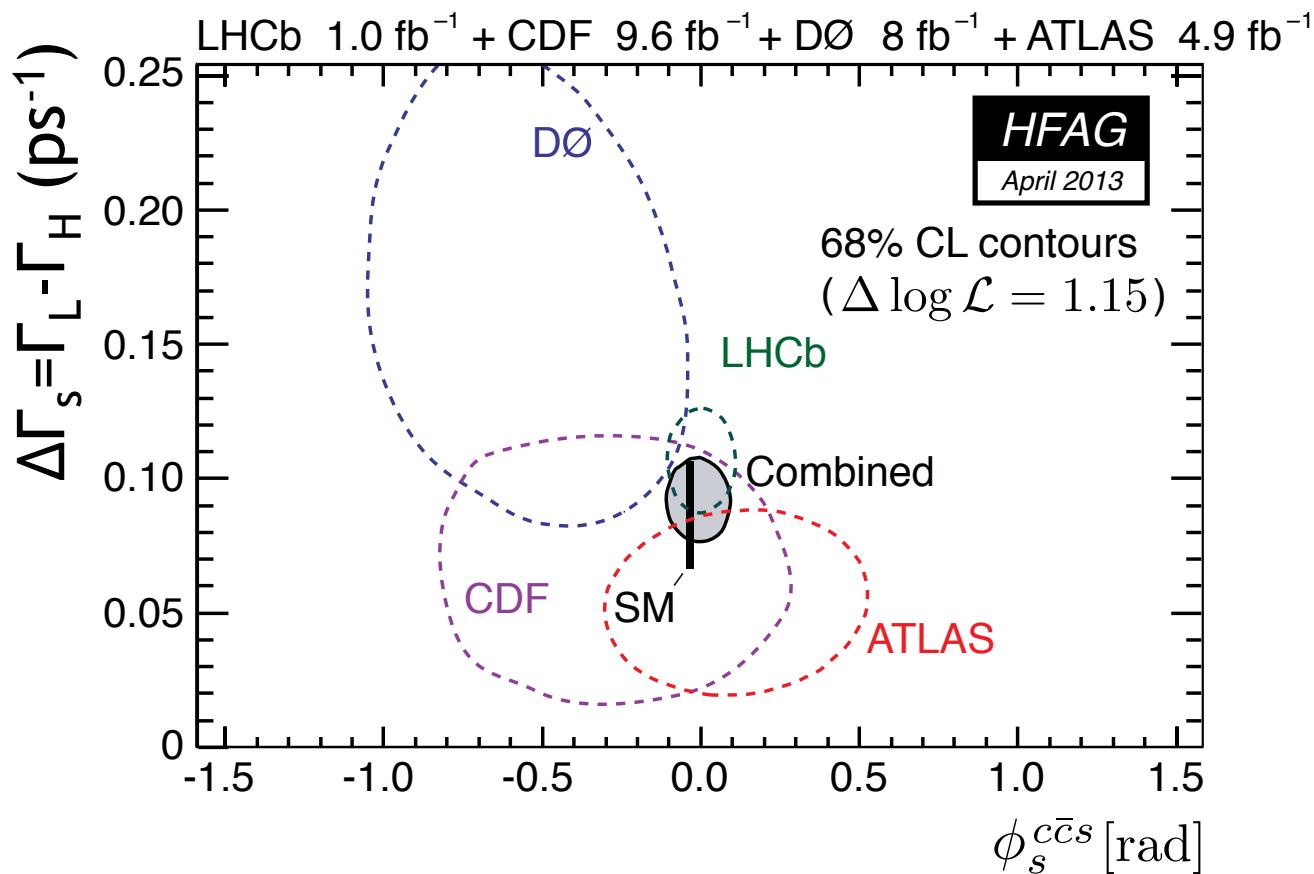
ϕ_s from $B_s \rightarrow J/\psi\Phi$ and $B_s \rightarrow \Phi\Phi$



CP violation due to the interference between mixing and decay

- Requires :
 - initial state tagging
 - time measurement
 - angular analysis (VV final state) to disentangle CP-even and CP-odd contributions
 - measurement of $\Delta\Gamma_s$

$B_s \rightarrow J/\psi \Phi$ current results



ATLAS (2011) $\varphi_s = 0.12 \pm 0.25(\text{stat.}) \pm 0.11(\text{syst.})$ rad

LHCb(2011) $\varphi_s = 0.01 \pm 0.07(\text{stat.}) \pm 0.01(\text{syst.})$ rad

ATLAS : ATLAS-CONF-2013-039.

LHCb : Phys. Rev. D87 (2013) 112010

$B_s \rightarrow J/\psi \Phi$ $b \rightarrow c\bar{c}s$

tree diagram

NP can show up in the mixing

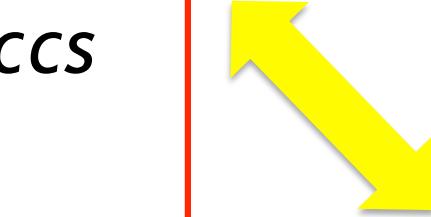
$B_s \rightarrow \Phi\Phi$ $b \rightarrow s\bar{s}s$

penguin diagram

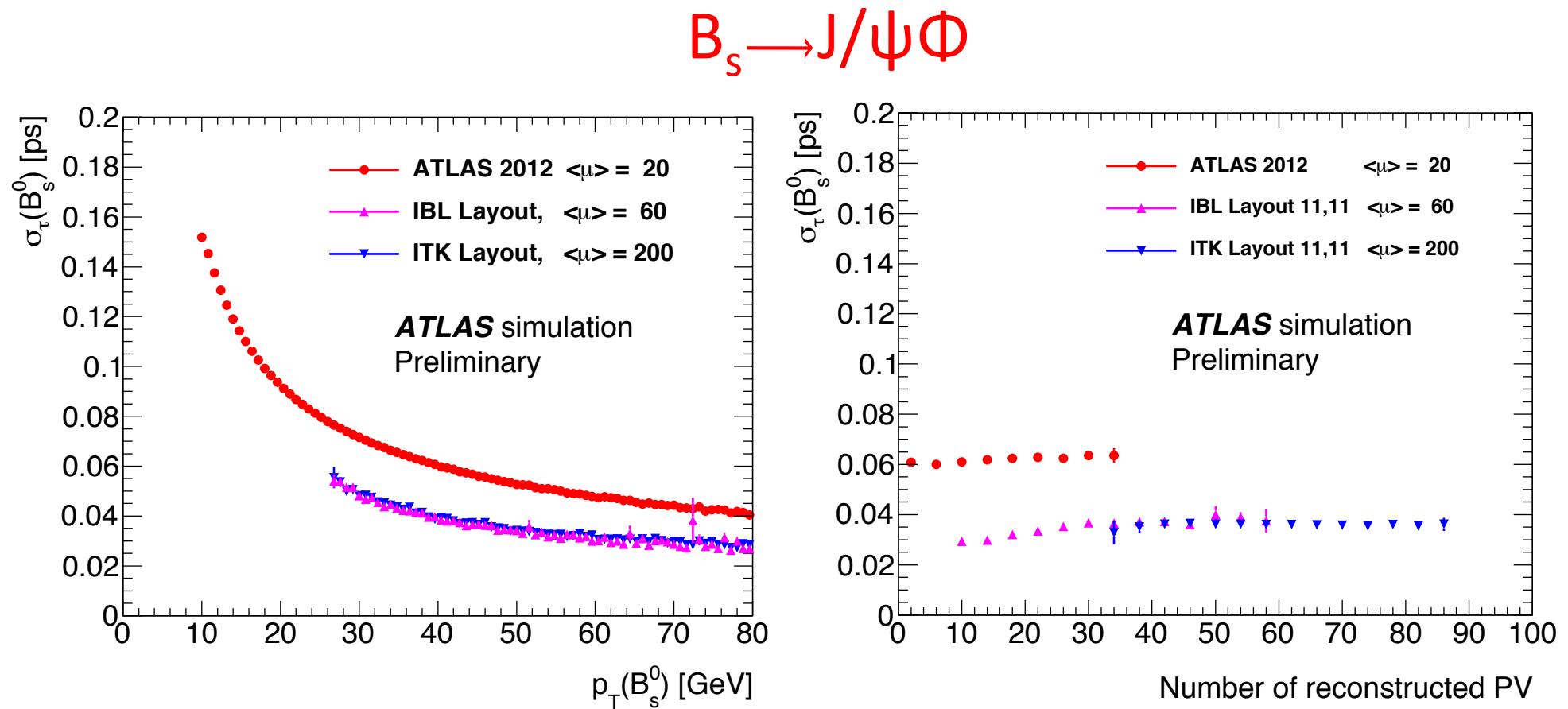
NP can show up in the mixing
or in the decay (penguin loops)

LHCb only

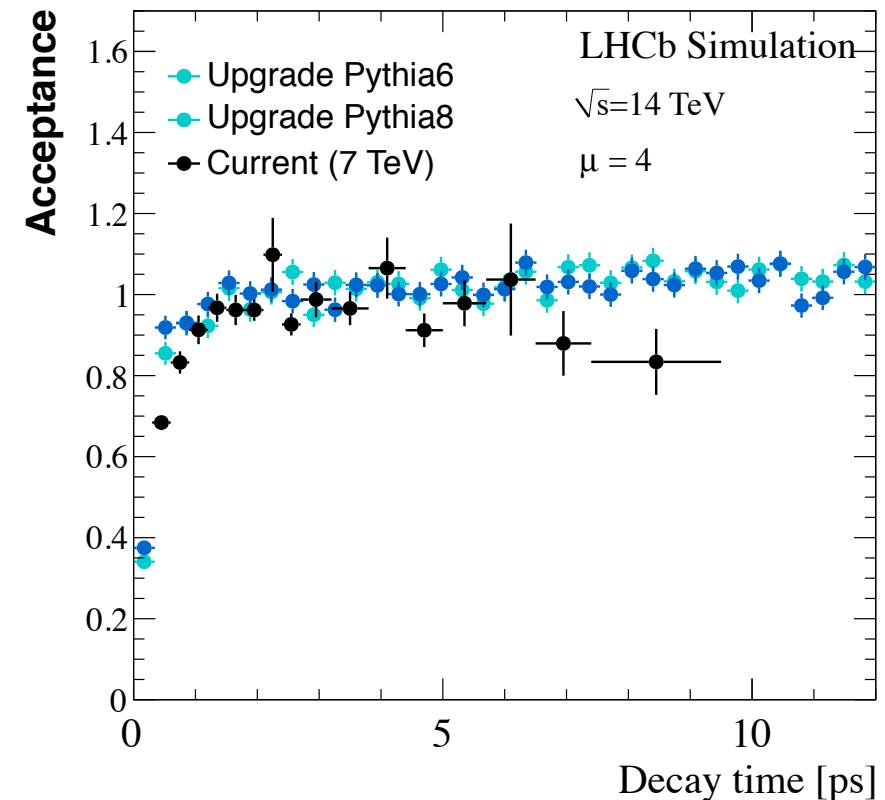
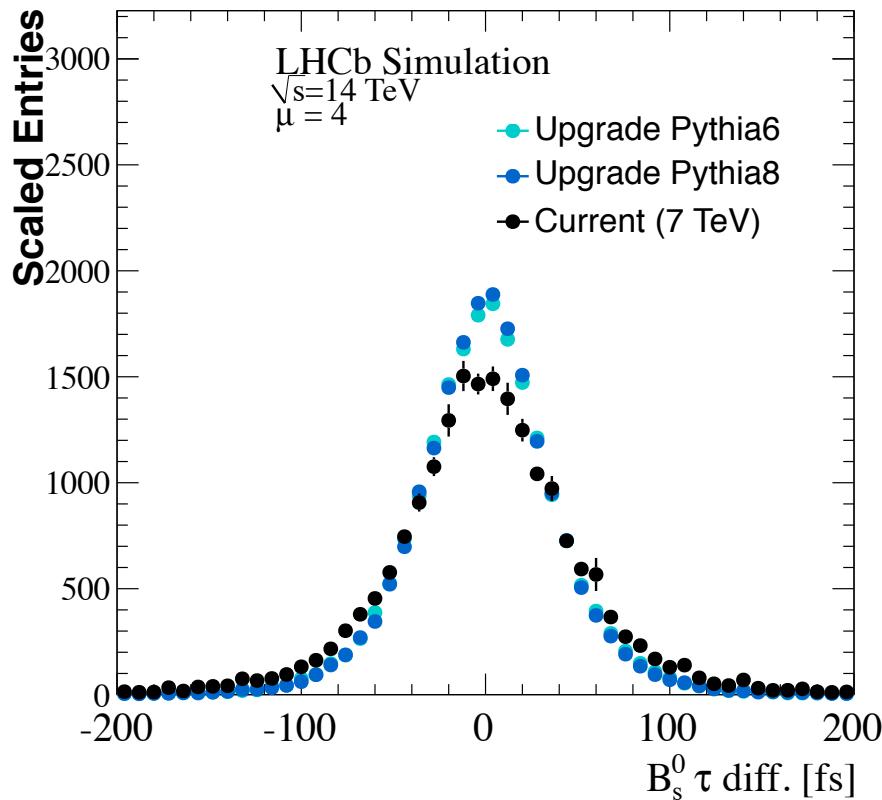
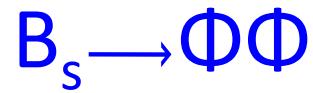
SM



Knowledge of the time resolution is crucial for ϕ_s measurements
 Under control even in tough conditions !



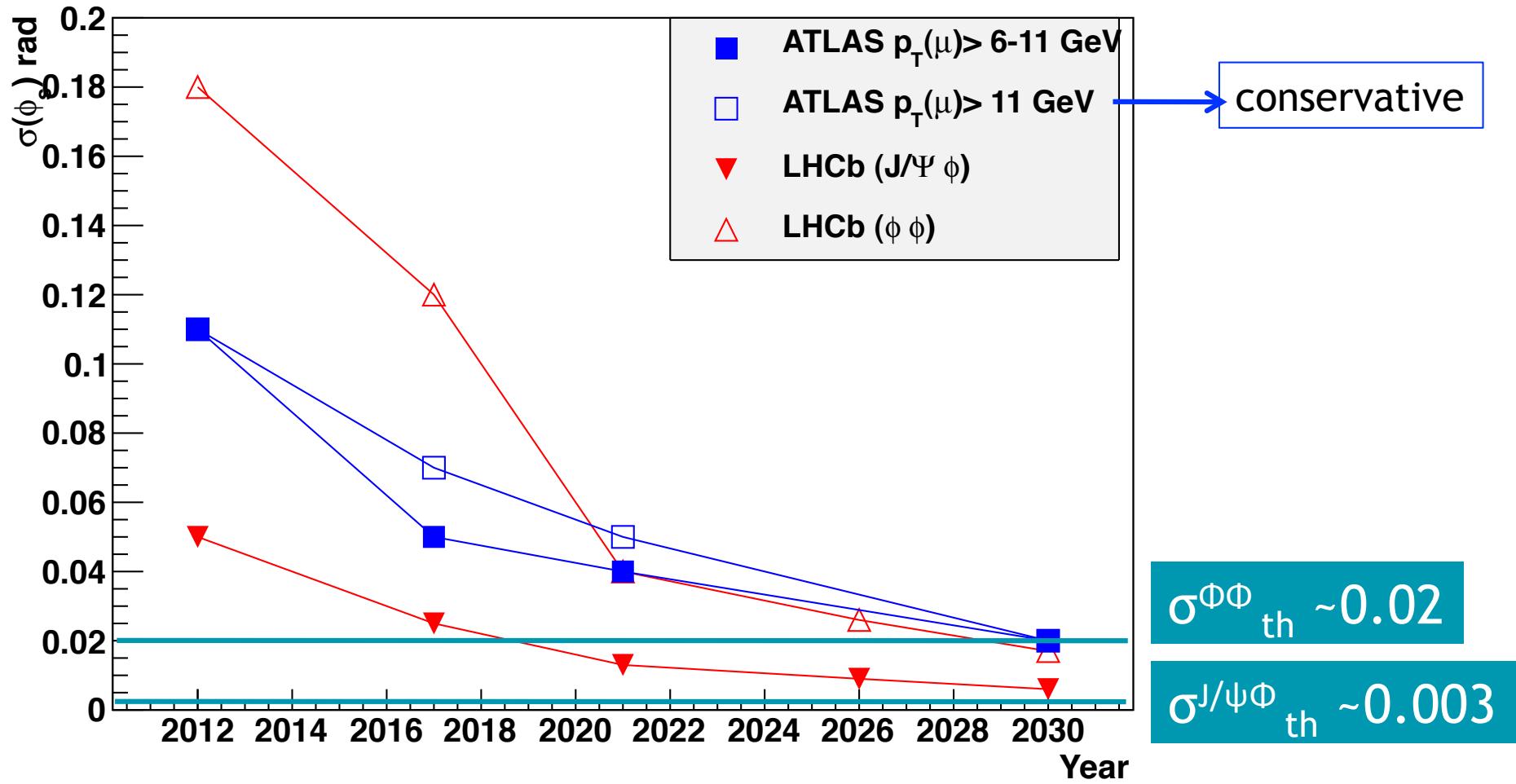
Improvements wrt 2012 due to detector change and to tighter p_T cuts



Better decay time resolution and increased decay time acceptance due to the improved IP resolution

Similar performances at $\mu=8$ ($2 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ with 25 ns : $v=7.6$)

Expected precision on ϕ_s (rad)



- A crucial ingredient is the effective tagging efficiency and its knowledge
- Importance of the J/ψ trigger

The CKM angle γ

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

Interferences between $b \rightarrow c$ and $b \rightarrow u$ transitions

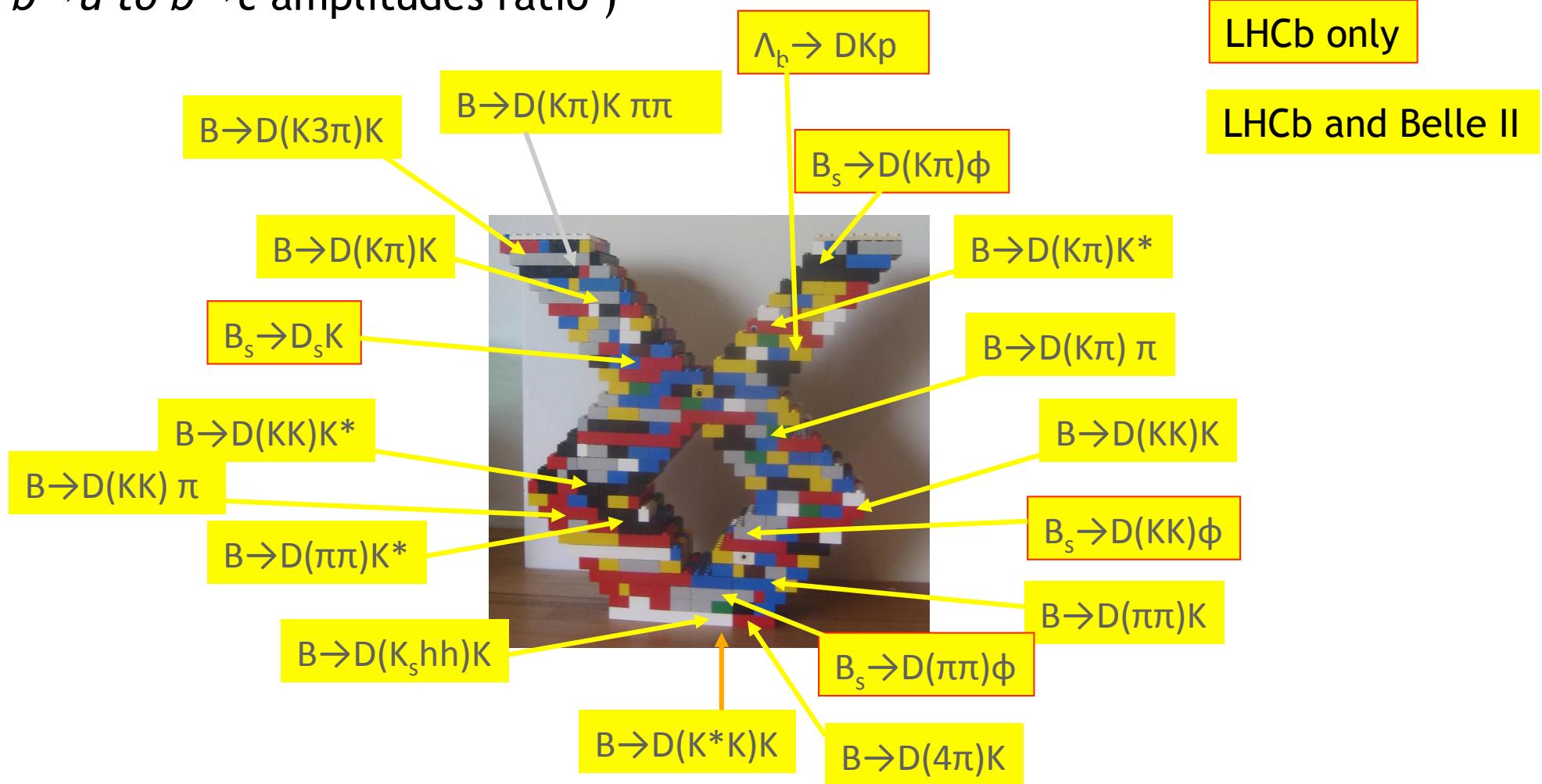
Time independent measurements
 $(B \rightarrow D K^{(*)}$ large family)
Tree diagrams
SM reference point

Time dependent measurements
 $(B_s \rightarrow D_s K)$
tree (decay) + box (mixing) diagrams
sensitive to NP in mixing $(B_s \rightarrow J/\psi \Phi)$

charmless decays
box/loops diagrams
sensitive to NP

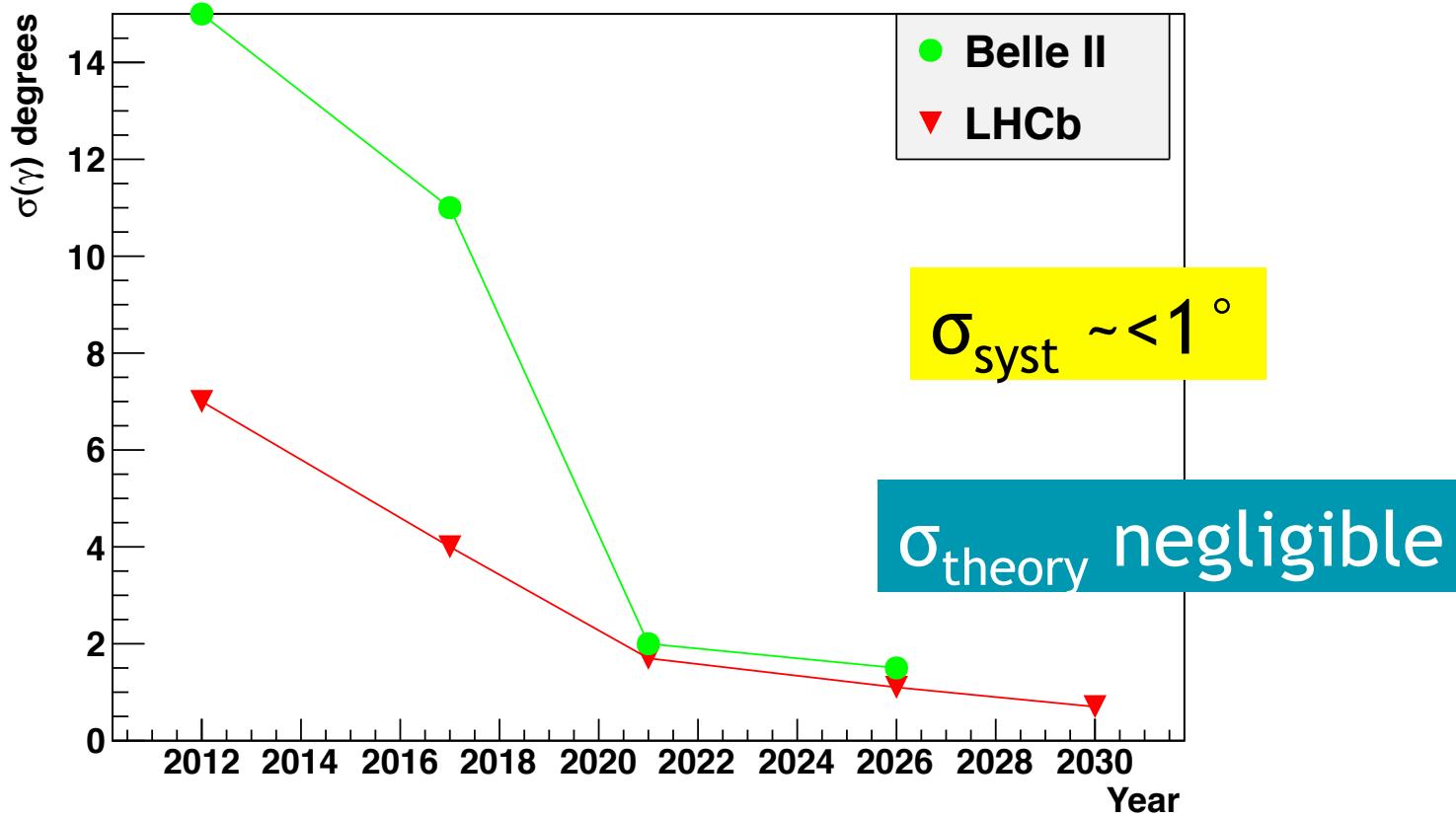


The “ultimate” γ -from tree-decays precision will be reached through many individual measurements, with very different sensitivities (due to different $b \rightarrow u$ to $b \rightarrow c$ amplitudes ratio)



Some of them are challenging at the LHC (many tracks, low p_T , hadronic trigger)

Expected precision on γ from tree decays



Precise measurements : comparison with loop measurements
possible to a very good level

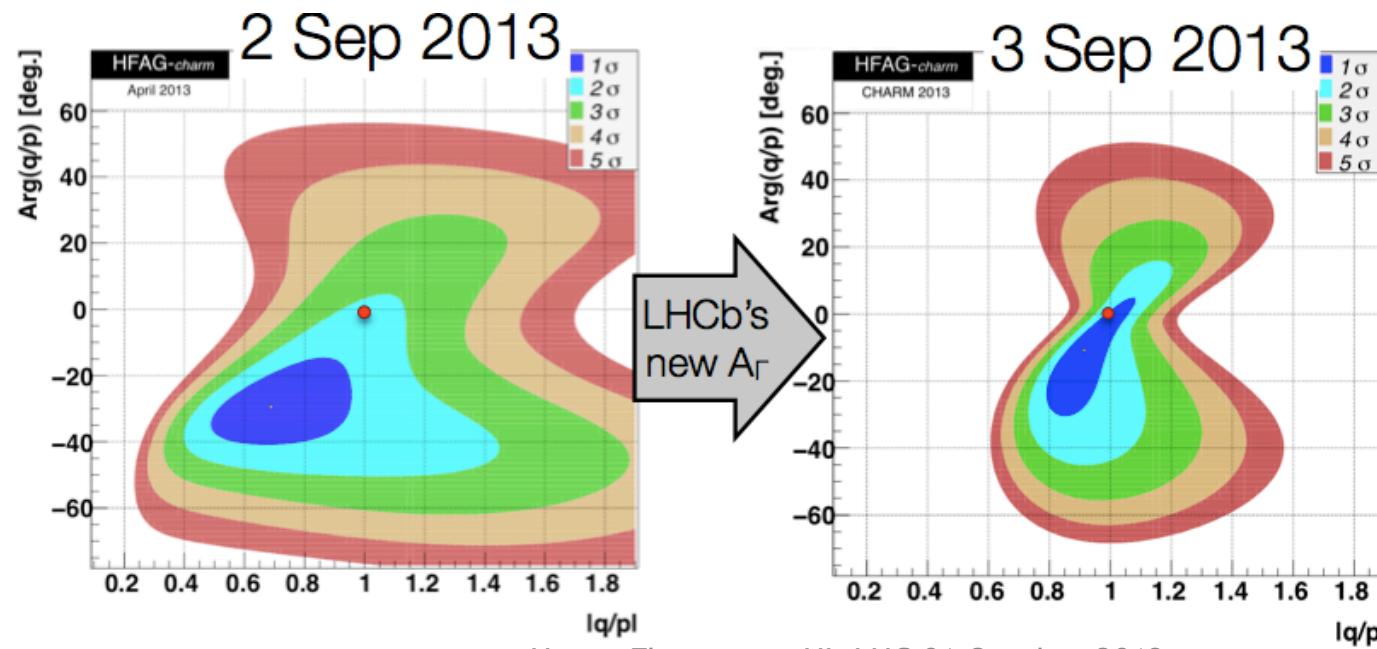
$A_\Gamma(D^0 \rightarrow KK)$ and $A_\Gamma(D^0 \rightarrow \pi\pi)$

FCNC decays for up-type quarks : a different place to look for NP

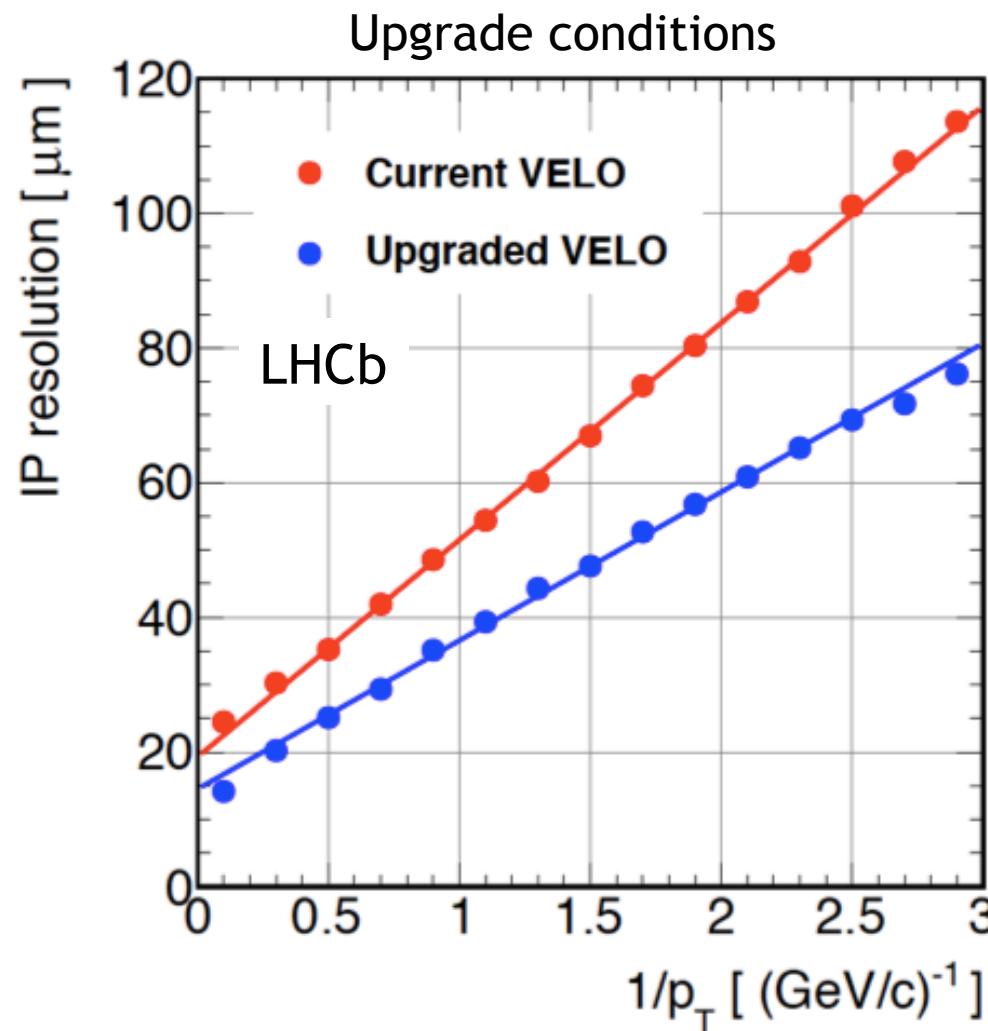
A_Γ taken as a reference :

$$A_\Gamma = \frac{\tau(\overline{D^0} \rightarrow h^+ h^-) - \tau(D^0 \rightarrow h^+ h^-)}{\tau(\overline{D^0} \rightarrow h^+ h^-) + \tau(D^0 \rightarrow h^+ h^-)}$$

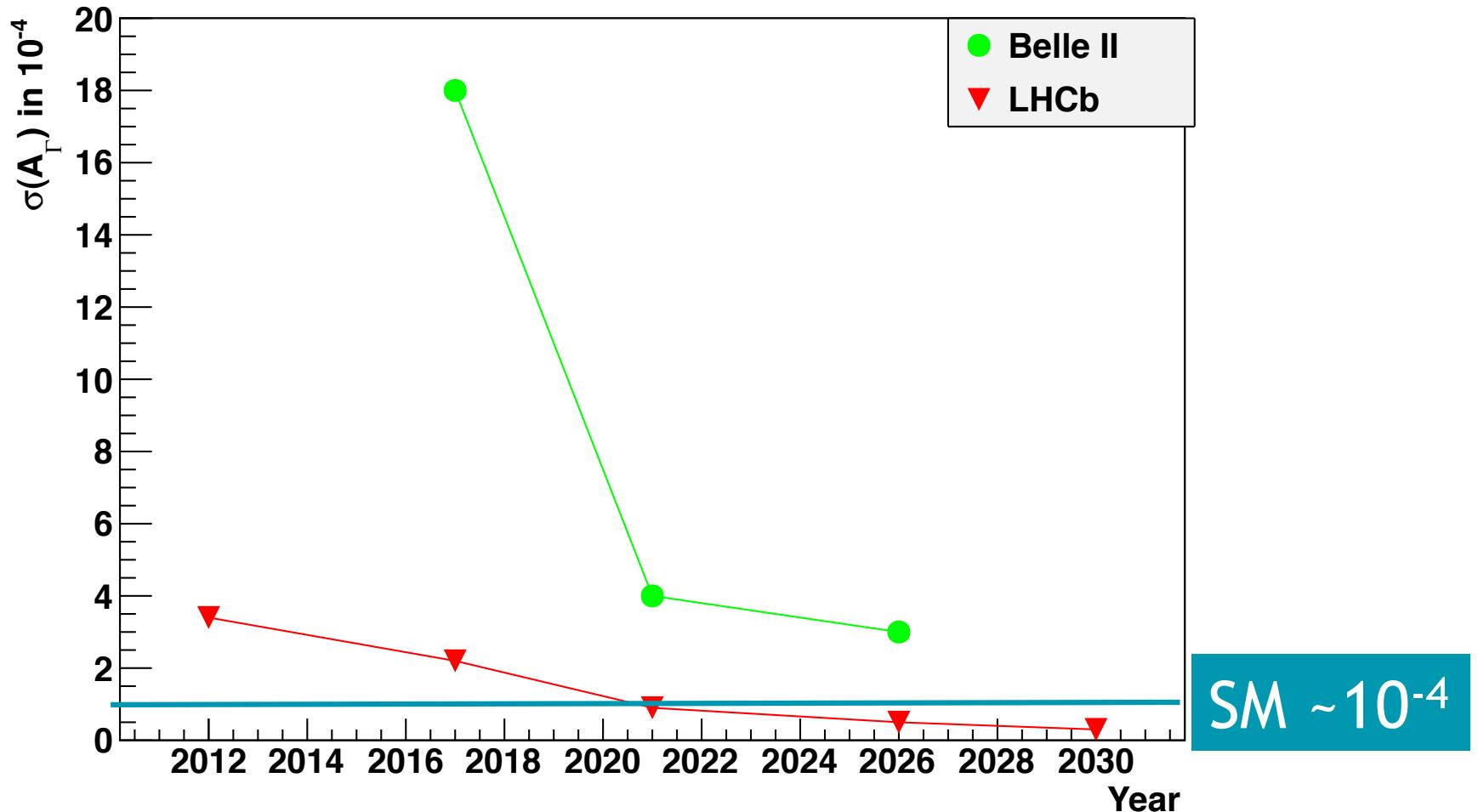
- $A_\Gamma \neq 0 \Rightarrow$ CPV in charm mixing (SM : $\sim 10^{-4}$)
- $A_\Gamma(D^0 \rightarrow KK) \neq A_\Gamma(D^0 \rightarrow \pi\pi) \Rightarrow$ direct CPV



A crucial ingredient for fully hadronic decays (trigger) and to be able to measure A_Γ to a very good precision : the impact parameter resolution



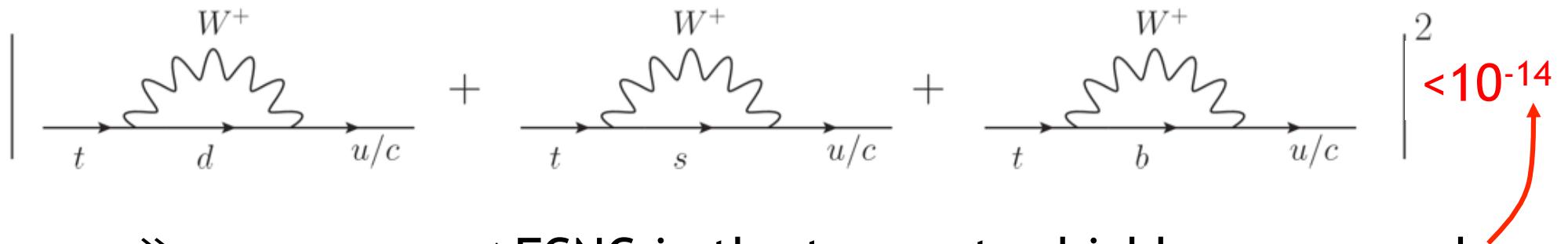
Expected precision on A_Γ



$\sigma_{\text{syst}} \sim 10^{-4}$ evaluated using data driven techniques

FCNC top decays

In the SM :



$m_{top} \gg m_{\text{other quarks}}$ \Rightarrow FCNC in the top sector highly suppressed

NP : can be increased up to 10^{-4}

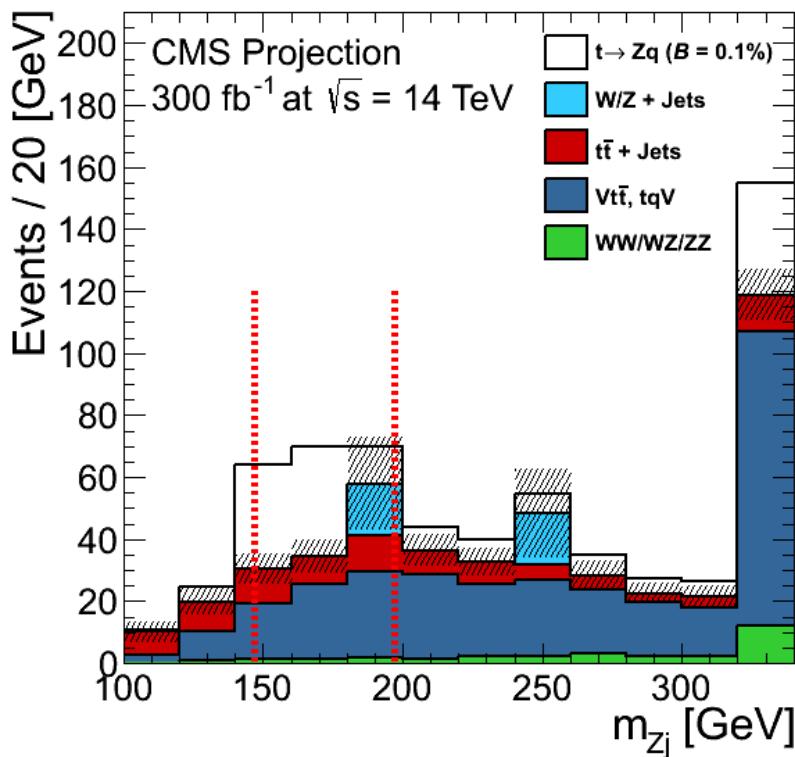
Search for

- $tt \rightarrow (Z^0 u/c)(W^- b)$, $Z^0 \rightarrow l^+ l^-$, $W^- \rightarrow l^- \nu$

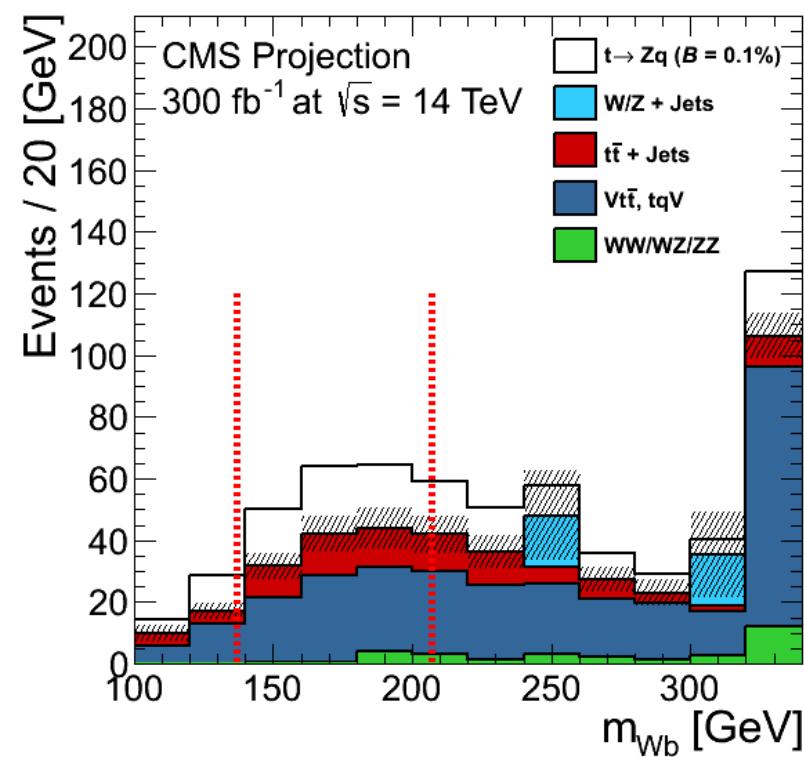
Three leptons in final state : high trigger efficiency

- $tt \rightarrow (\gamma u/c)(W^- b)$, $W^- \rightarrow l^- \nu$

$t\bar{t} \rightarrow (Z^0 + u/c)(W^- + b), (Z^0 \rightarrow l^+ l^- + q), (W^- \rightarrow l^- \nu + b)$

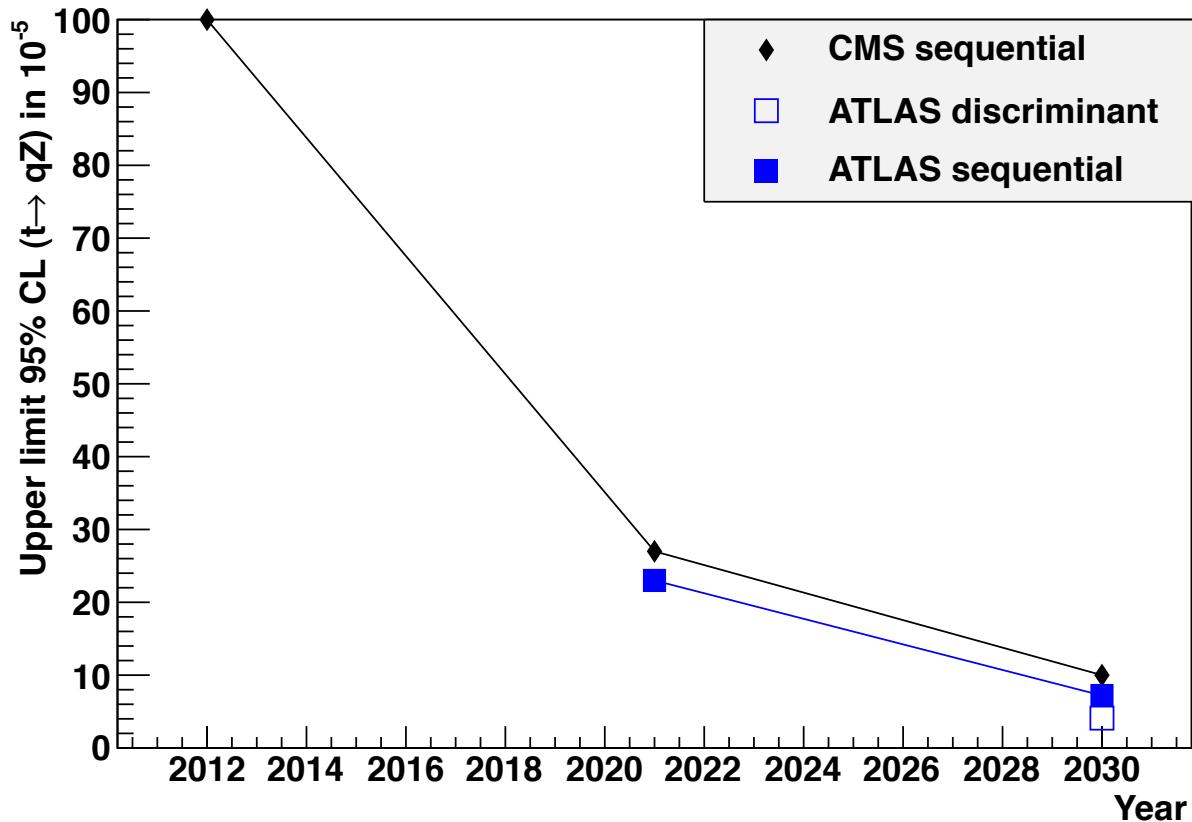


$M_{top}(Zq)$



$M_{top}(Wb)$

Expected upper limit (95 %CL) on $\text{BR}(t \rightarrow qZ)$



Expected upper limit (95 %CL) on $\text{BR}(t \rightarrow q\gamma)$

	2019-2021	2028-2030+
ATLAS	300 fb^{-1}	3000 fb^{-1}
	7.8×10^{-5}	$1.3 - 2.5 \times 10^{-5}$

Summary

- History : many breakthroughs in Flavour Physics !
(small CPV in K^0 mixing : 3rd family)
- Theory uncertainties will be quantified with data driven techniques

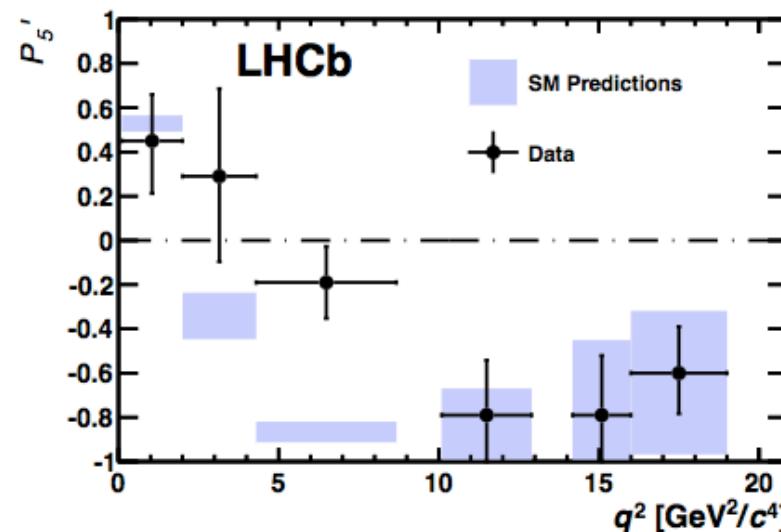
Experiments can do more than what is listed here !

		LHC era			HL-LHC era	
		Run 1	Run 2	Run 3	Run 4	Run 5+
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$	CMS	—	71%	47%	...	21%
	LHCb	—	110%	60%	40%	28%
$\phi_s(B_s^0 \rightarrow J/\psi \phi)$	ATLAS	0.11	—	0.04–0.05	...	0.020
	LHCb	0.05	—	0.013	0.009	0.006
$\phi_s(B_s^0 \rightarrow \phi \bar{\phi})$	LHCb	0.18	0.12	—	0.026	0.017
	LHCb	7°	4°	1.1°	—	0.7°
γ	Belle2	—	11°	2°	—	—
	LHCb	3.4×10^{-4}	2.2×10^{-4}	0.9×10^{-4}	0.5×10^{-4}	4×10^{-5}
$A_\Gamma(D^0 \rightarrow K^+ K^-)$	LHCb	—	18×10^{-4}	$4\text{--}6 \times 10^{-4}$	$3\text{--}5 \times 10^{-4}$	—
	Belle2	—	—	—	—	—
$q_0^2 A_{FB}(K^{*0} \mu^+ \mu^-)$	LHCb	10%	5%	2.8%	1.9%	1.3%
	Belle2	—	50%	7%	5%	—
$t \rightarrow qZ$	ATLAS	23×10^{-5}	...	$4.1\text{--}7.2 \times 10^{-5}$
	CMS	100×10^{-5}	...	27×10^{-5}	...	10×10^{-5}
$t \rightarrow q\gamma$	ATLAS	7.8×10^{-5}	...	$1.3\text{--}2.5 \times 10^{-5}$

Back up slides

Towards a full angular analysis of $B_d \rightarrow K^{*0} \mu^+ \mu^-$

$$\begin{aligned} \frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi} & \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K - F_L \cos^2 \theta_K \cos 2\theta_\ell \right. \\ & + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi \\ & + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + S_6 \sin^2 \theta_K \cos \theta_\ell \\ & \left. + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right] \end{aligned}$$



all bins (24) in q^2 in agreement with SM except 1

If all bins independent, the probability of having such deviation or greater is 0.5%
More data needed to clarify the picture

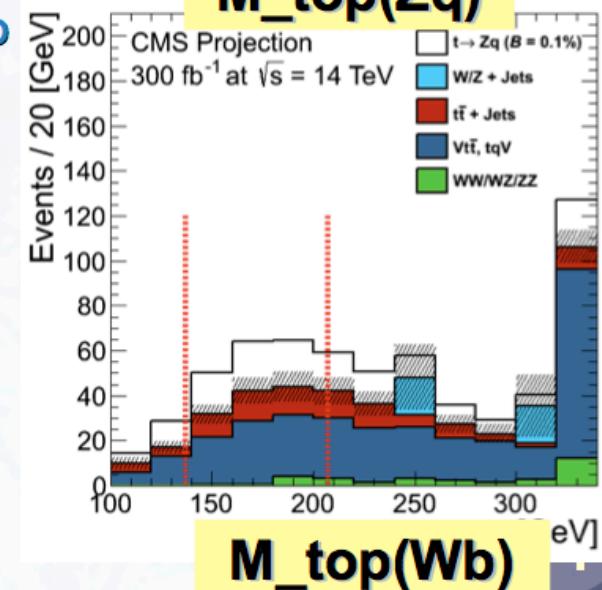
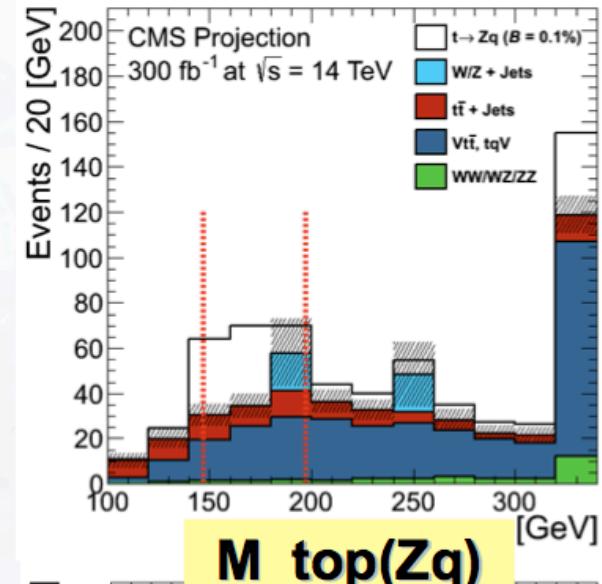


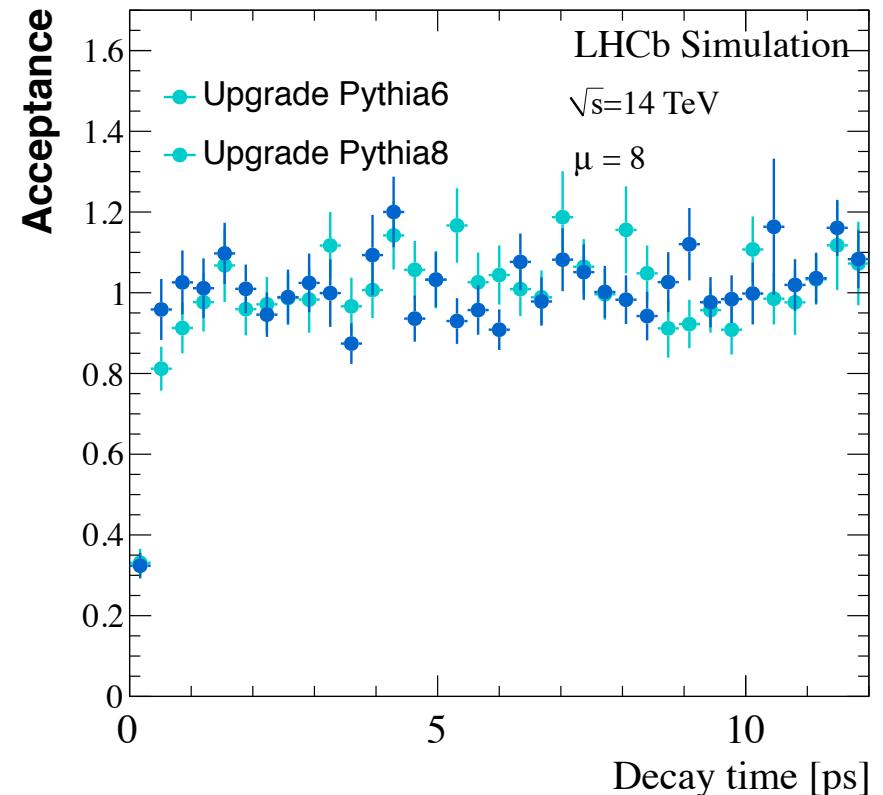
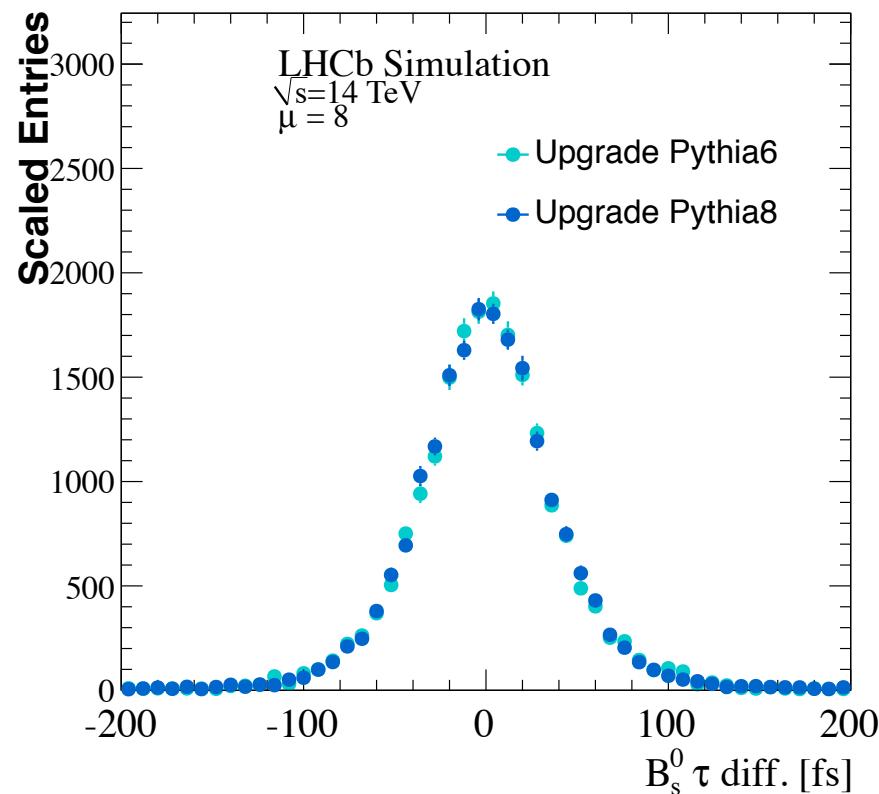
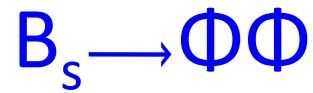
Projection on Top FCNC Search

- Loop process: suppressed in SM $O(10^{-14})$
 - SM extensions $\rightarrow O(10^{-4})$
- Simple projection
 - Based on 8 TeV study result
 - Assuming some syst. improve with $1/\sqrt{L}$
- DELPHES study
 - Using Phase II conf. 4, PU 140
 - Same syst. assumptions
 - Discovery scenarios:

$Br > 0.03\%$ for 3σ with $300/fb$, $Br > 0.02\%$ for 5σ with $3/ab$

$B(t \rightarrow Zq)$	19.5/fb @ 8 TeV	300/fb @ 14 TeV	3/ab @ 14 TeV
Simple Projection			
Exp. Limit	---	< 0.011 %	< 0.007 %
DELPHES FSIM Projection			
Exp. Limit	< 0.10 %	< 0.027 %	< 0.010 %
1 σ Bound	0.06 – 0.14%	0.018 – 0.038%	0.007 – 0.014%
2 σ Bound	0.05 – 0.20%	0.013 – 0.051%	0.005 – 0.020%





$\mu=8$ ($2 \cdot 10^{32}$ cm $^{-2}$ s $^{-1}$ with 25 ns : $\mu=7.6$)