2nd ECFA

HIGH LUMINOSITY LHC Experiments Workshop

Physics and technology developments

21st - 23rd
OCTOBER 2014

Aix-les-Bains | France

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Registration and further information at https://indico.cern.ch/event/315626/
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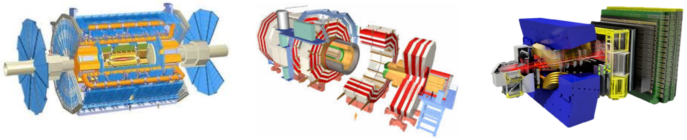
Heavy Flavour prospects at the HL-LHC

Vincenzo Vagnoni
INFN Bologna
LHCb Collaboration

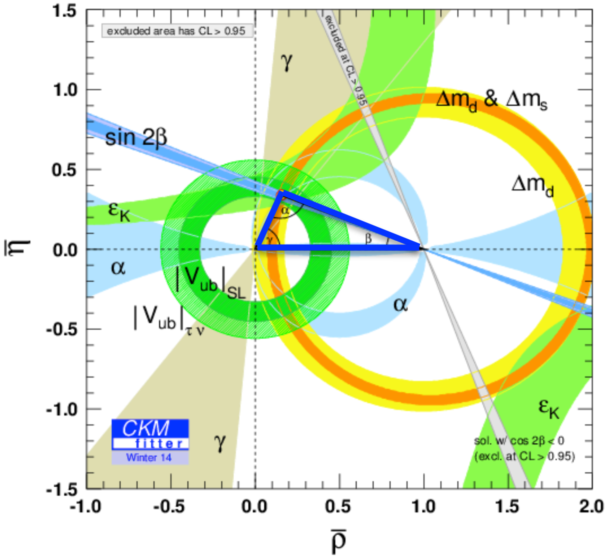
on behalf of

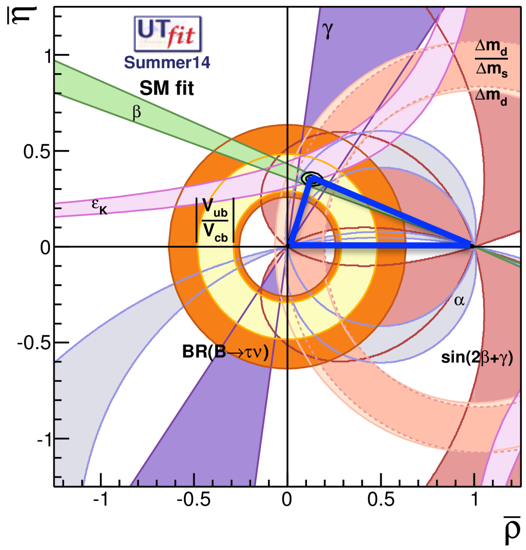


Material provided by
Alessandro Cerri, Kai-Feng Chen, Tim Gershon, Nuno Leonardo, Fabrizio Palla, Darren Price, Pavel Řezníček

Consistency of global CKM fits

- Tremendous success of the CKM paradigm!
  - All of the measurements agree in a highly profound way





- The quark flavour sector is well described by the CKM mechanism
  - need to go to high precision measurements to probe theoretically clean observables

Perspectives for luminosity growth

	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (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}

- Note that beauty production cross section is roughly doubled passing from 7 TeV to 14 TeV *pp* collisions
- Sensitivity projections are updated incorporating knowledge emerging from physics analyses performed with the full Run I data set
  - in any case, keep in mind that these extrapolations are based on a certain number of assumptions
- Reminder: LHCb upgrade comes already in LS2, whereas the HL ATLAS and CMS upgrades come in LS3

Physics prospects

- Focus on a few key channels where far-future prospects have been studied in some detail

$B_{d,s} \rightarrow \mu\mu$

$B_d \rightarrow K^*\mu\mu$

Mixing-induced CP violation in B_s

Tree-level determination of γ

- **There is however a plethora of observables to be studied, ways beyond this simple list!!!**

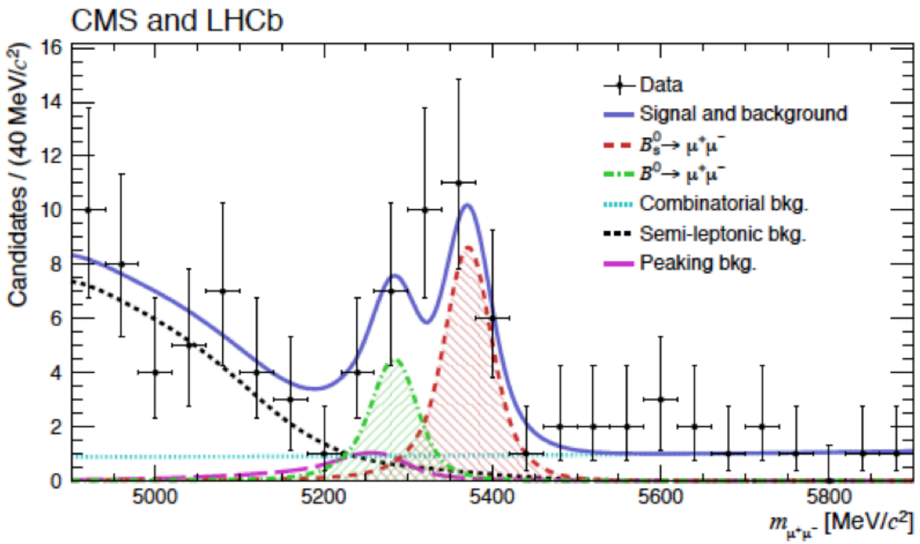
Combined CMS and LHCb results

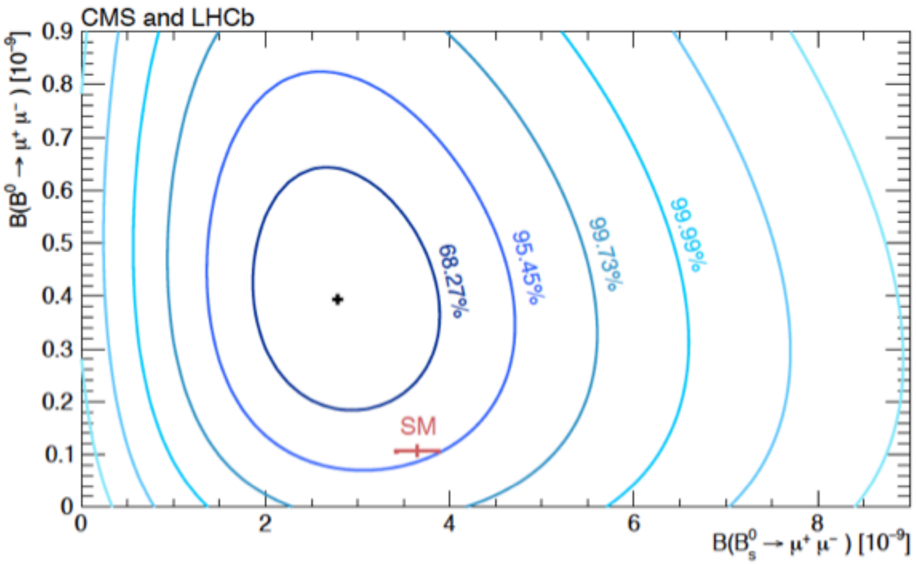
- CMS and LHCb have now performed a combined fit to their full Run 1 data sets

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

- Significance of $B_s \to \mu\mu$ 6.2σ: **first observation!**
  - Compatibility with the SM at 1.2σ
- Excess of events at the 3σ level observed for the $B^0 \to \mu\mu$ hypothesis with respect to background-only
  - Compatible with SM at 2.2σ
- ATLAS analysis is ongoing





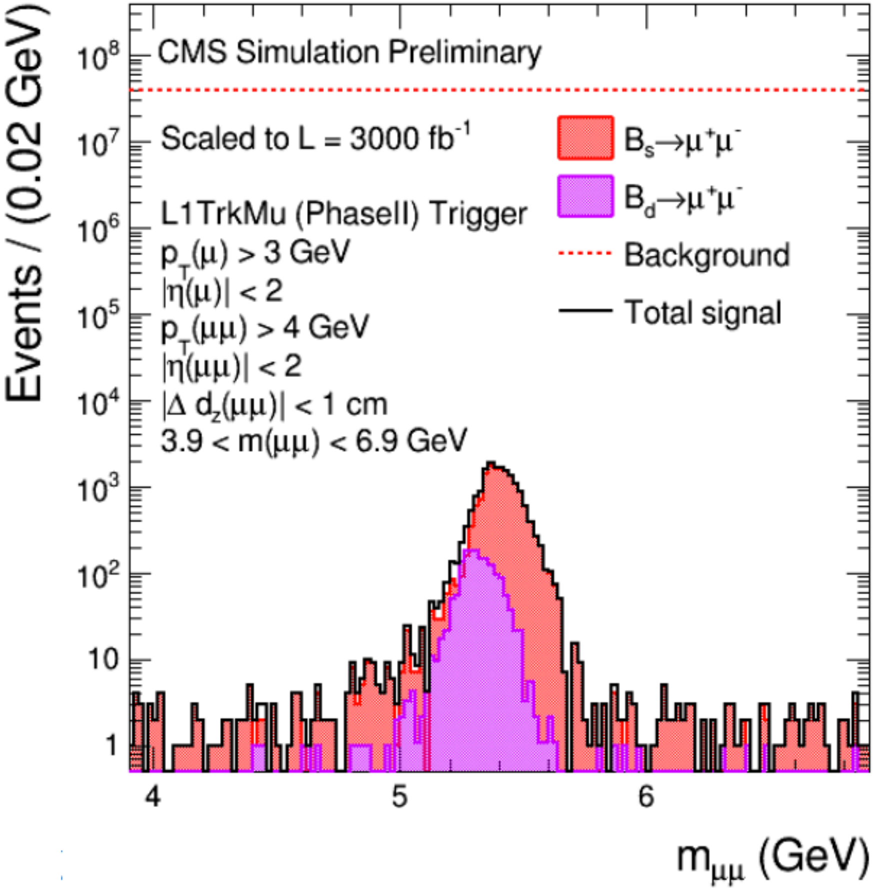
CMS-BPH-13-007, LHCb-PAPER-2014-049: to be submitted to Nature

Case study at CMS: $B \rightarrow \mu^+\mu^-$

- Benchmark channel studied for assessing the B-physics performance of the CMS Phase-2 upgraded detector
- Focus on two aspects of the analysis
  - Implementation and performance of a L1 track trigger
  - Effect of CMS upgrades to the final analysis performance
- In particular, two CMS upgrades are more relevant
  - L1 Trigger: especially through the new track trigger machinery
  - Tracker: through the reduced material budget and increased resolution

Case study at CMS: B→$\mu^+\mu^-$

- Simulation of a low-p_T di-muon L1 trigger algorithm exploiting the upgraded CMS tracker
  - Mass resolution at L1 is determined to be 70 MeV
  - Trigger rate in the HL-LHC conditions (average of 140 PU events) is estimated to be a few hundred Hz



- The expected performances of the upgraded CMS L1 trigger are found to be more than sufficient to implement the trigger algorithm for B→$\mu^+\mu^-$

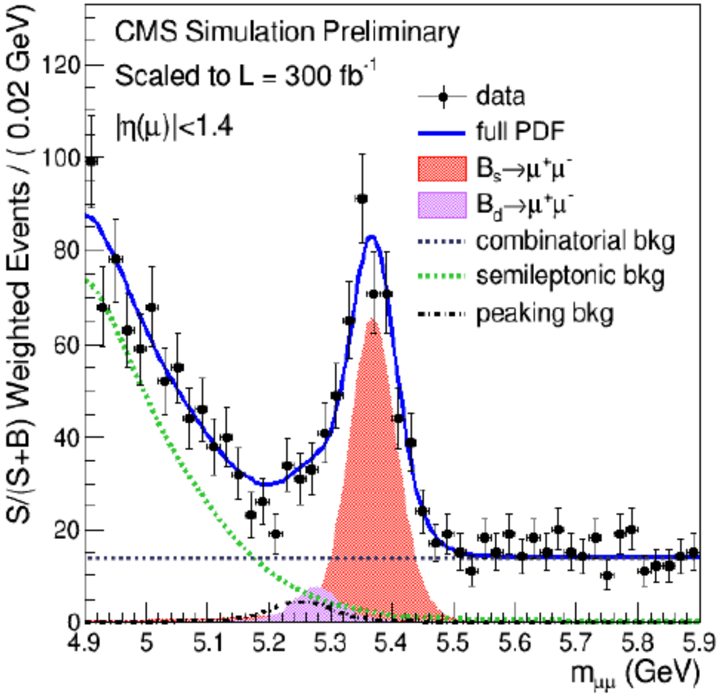
Case study at CMS: $B\rightarrow\mu^+\mu^-$

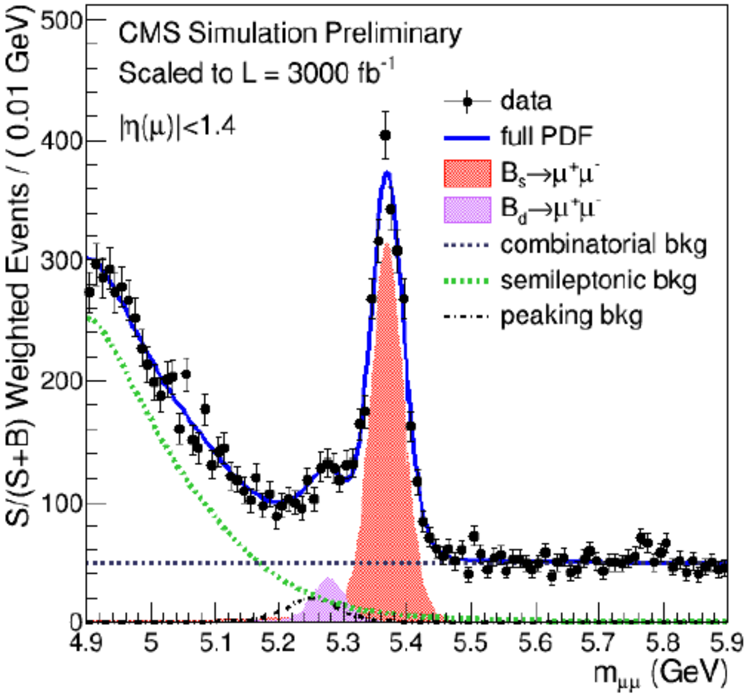
Pre HL-LHC at 300 fb^{-1}

- $\delta\mathcal{B}/\mathcal{B}$ ($B_s\rightarrow\mu\mu$) = 13%
- $\delta\mathcal{B}/\mathcal{B}$ ($B_d\rightarrow\mu\mu$) = 48%
- $\delta\mathcal{R}/\mathcal{R}$ = 50%
- $B_d\rightarrow\mu\mu$ significance ≈2.2σ

HL-LHC at 3000 fb^{-1}

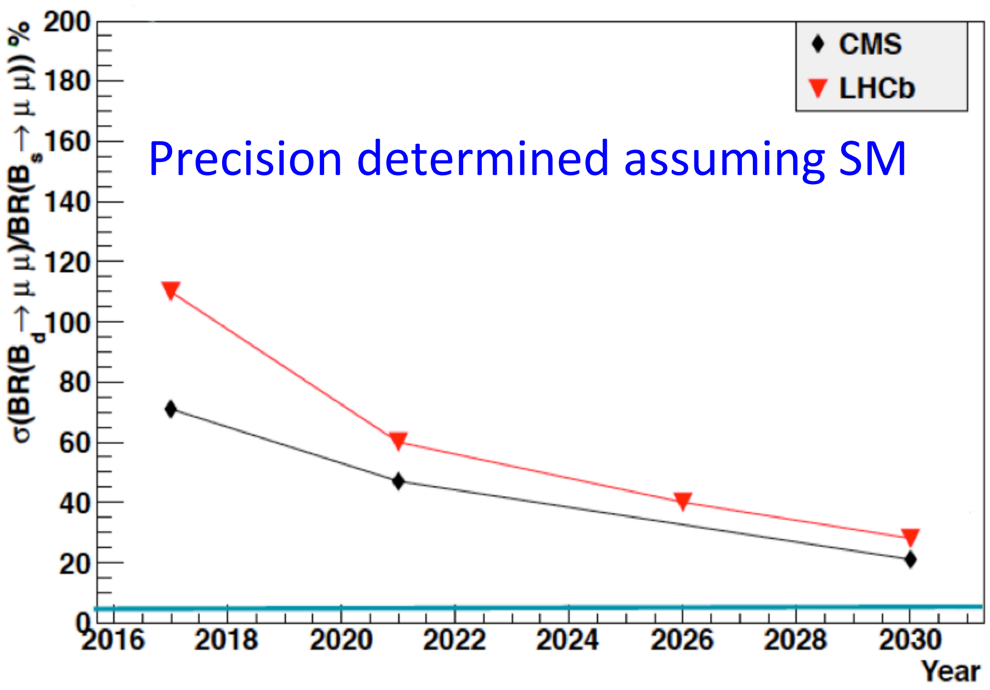
- $\delta\mathcal{B}/\mathcal{B}$ ($B_s\rightarrow\mu\mu$) = 11%
- $\delta\mathcal{B}/\mathcal{B}$ ($B_d\rightarrow\mu\mu$) = 18%
- $\delta\mathcal{R}/\mathcal{R}$ = 21%
- $B_d\rightarrow\mu\mu$ significance ≈6.8σ





Prospects with $B_{d,s} \to \mu^+\mu^-$

- The ratio $BR(B_d \to \mu^+\mu^-)/BR(B_s \to \mu^+\mu^-)$ is known with better theoretical uncertainty
- Measurement will still be dominated by experimental uncertainty by 2030

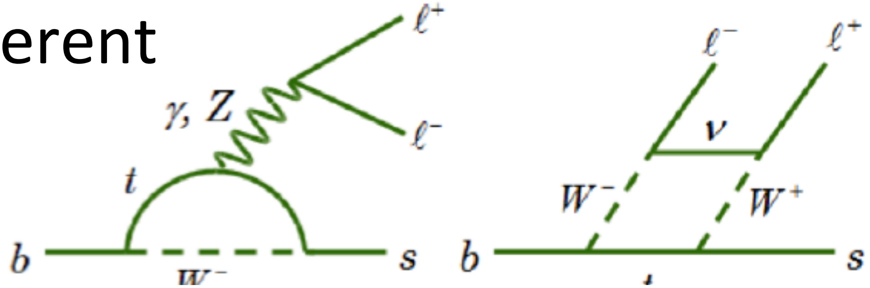


Precision determined assuming SM

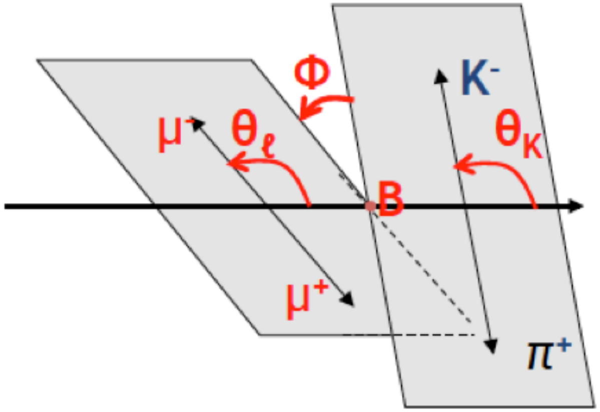
- With increased statistics, the measurement of effective $B_s \to \mu^+\mu^-$ lifetime and possibly time-dependent CP violation will become possible
  - New observables sensitive to NP effects in very rare B decays

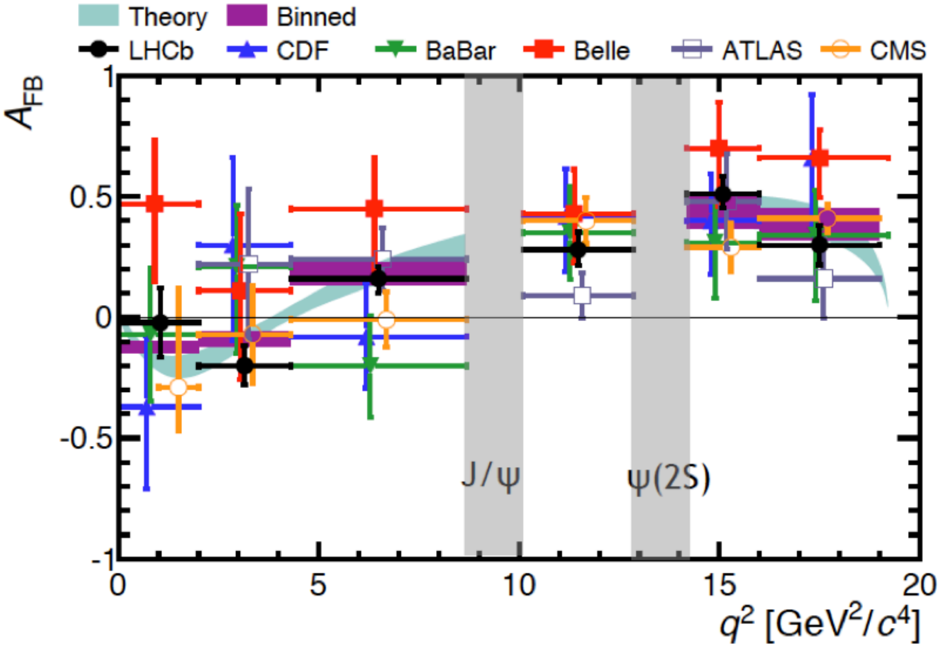
Status of $B_d \rightarrow K^{*}\mu^{+}\mu^{-}$

- Observables are q^2 (dimuon mass squared) and 3 angles
  - distributions are quite precisely predicted in the SM
- A_{FB}: LHC experiments have different sensitivities in the various bins
  - LHCb presently giving the most precise results



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





- A_{FB} is not necessarily the best variable
- Phenomenological work ongoing to define observables where hadronic uncertainties are partially cancelled

$B_d \rightarrow K^{*0}\mu^+\mu^-$: new observables

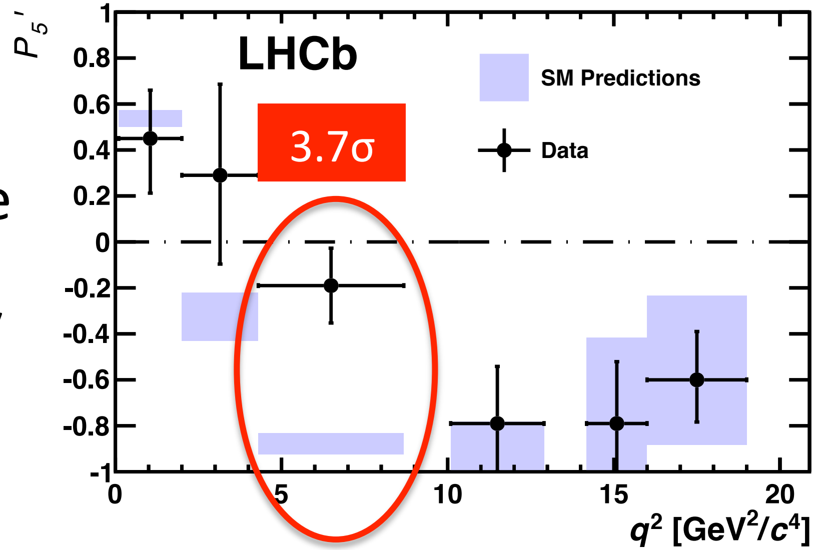
Differential decay rate

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

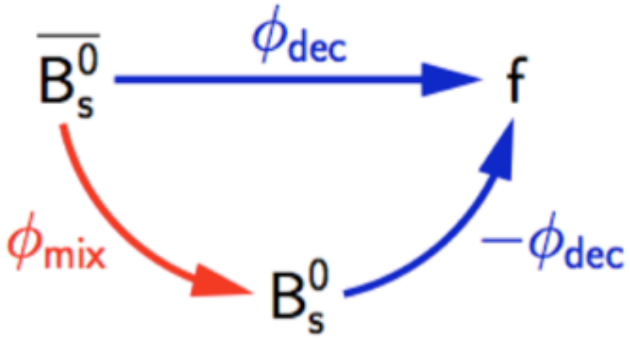
$$\boxed{P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}.}$$

- Interesting feature in one of the observables (P'_5)
  - No definitive conclusion yet
  - Additional statistics and theoretical studies are needed
- LHCb has great potential to improve in this sector, ATLAS and CMS (as well as Belle II) are expected to play an important role too
- On the long run, progresses on the theory side are needed for a clean interpretation of the measurements

Phys. Rev. Lett. 111 (2013) 191801



CP violation induced by B_s mixing



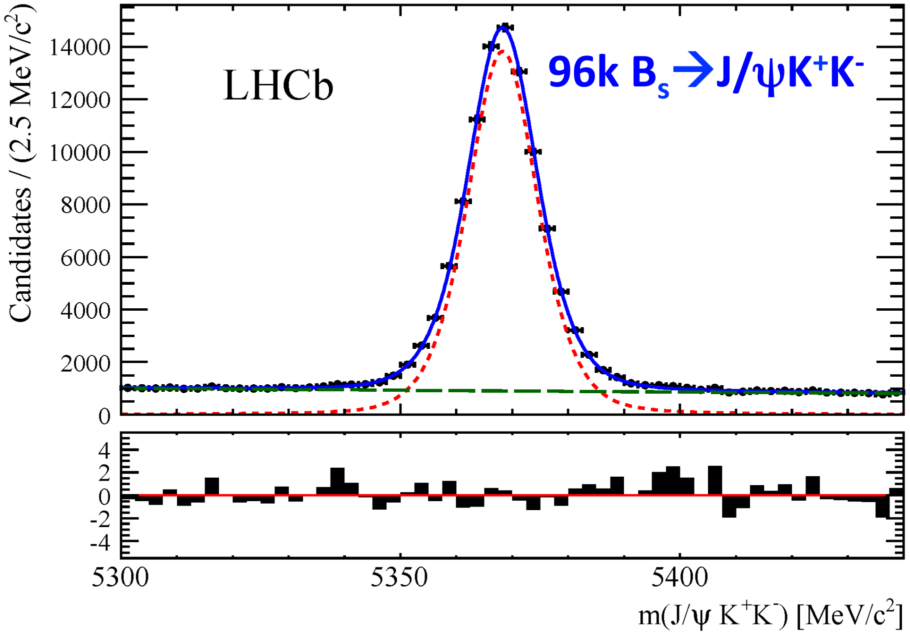
SM: $\phi_s \approx 36$ mrad

- CP violation due to interference between mixing and decay
- $B_s \rightarrow J/\psi\phi$ proceeds (mostly) via a $b \rightarrow c\bar{c}s$ tree diagram
  - NP can show up in the mixing

- $B_s \rightarrow \phi\phi$ is $b \rightarrow s\bar{s}s$ penguin-dominated
  - NP can show up in the mixing and/or in the decay
- P→VV decays
  - Full angular analysis is needed to disentangle *CP*-even and *CP*-odd amplitude components
- This is the case of an observable with an asymptotic experimental uncertainty comparable with the theoretical uncertainty → effort needed to improve theoretical control in conjunction with data-driven methods

Latest LHCb measurements of ϕ_s

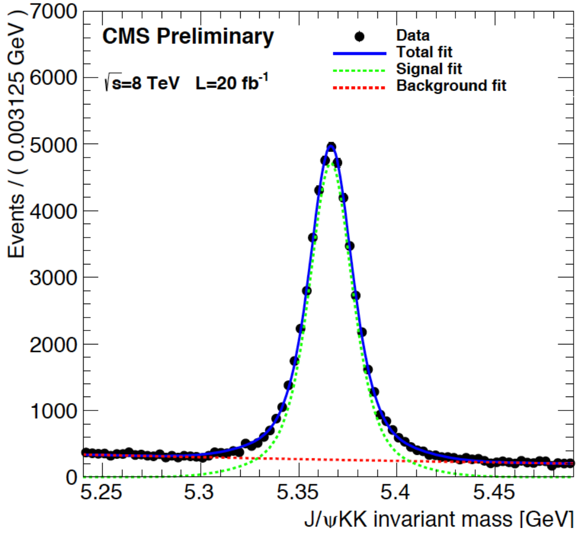
- Using **$B_s \rightarrow J/\psi K^+K^-$** (3 fb^{-1})
  - LHCb-PAPER-2014-059: **ϕ_s = -58 ± 49 ± 6 mrad**



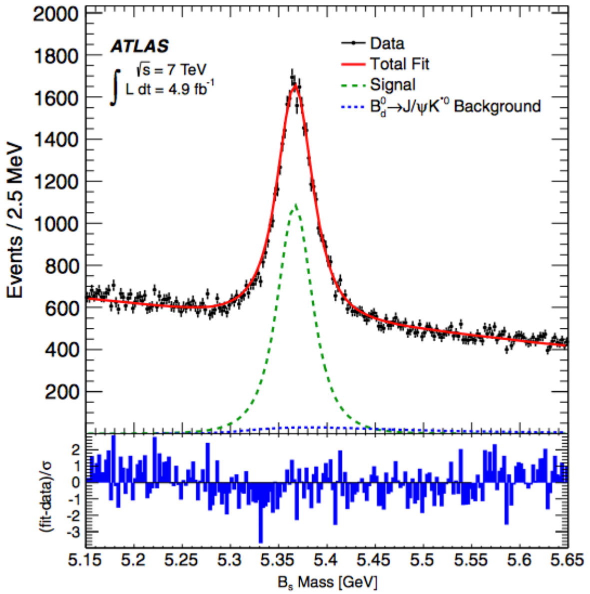
- Using **$B_s \rightarrow J/\psi \pi^+\pi^-$** (3 fb^{-1})
  - Phys. Lett. **B736** (2014) 186: **ϕ_s = 70 ± 68 ± 8 mrad**
- Using **$B_s \rightarrow D_s^+D_s^-$** in 3 fb^{-1}
  - arXiv 1409.4619: **ϕ_s = 20 ± 170 ± 20 mrad**
- Using **$B^0 \rightarrow \pi^+\pi^-$** and **$B_s \rightarrow K^+K^-$** (U-spin) in 1 fb^{-1}
  - arXiv 1408.4368: **$\phi_s = -120 ^{+140}_{-150}$ mrad**

Latest ATLAS and CMS measurements of ϕ_s

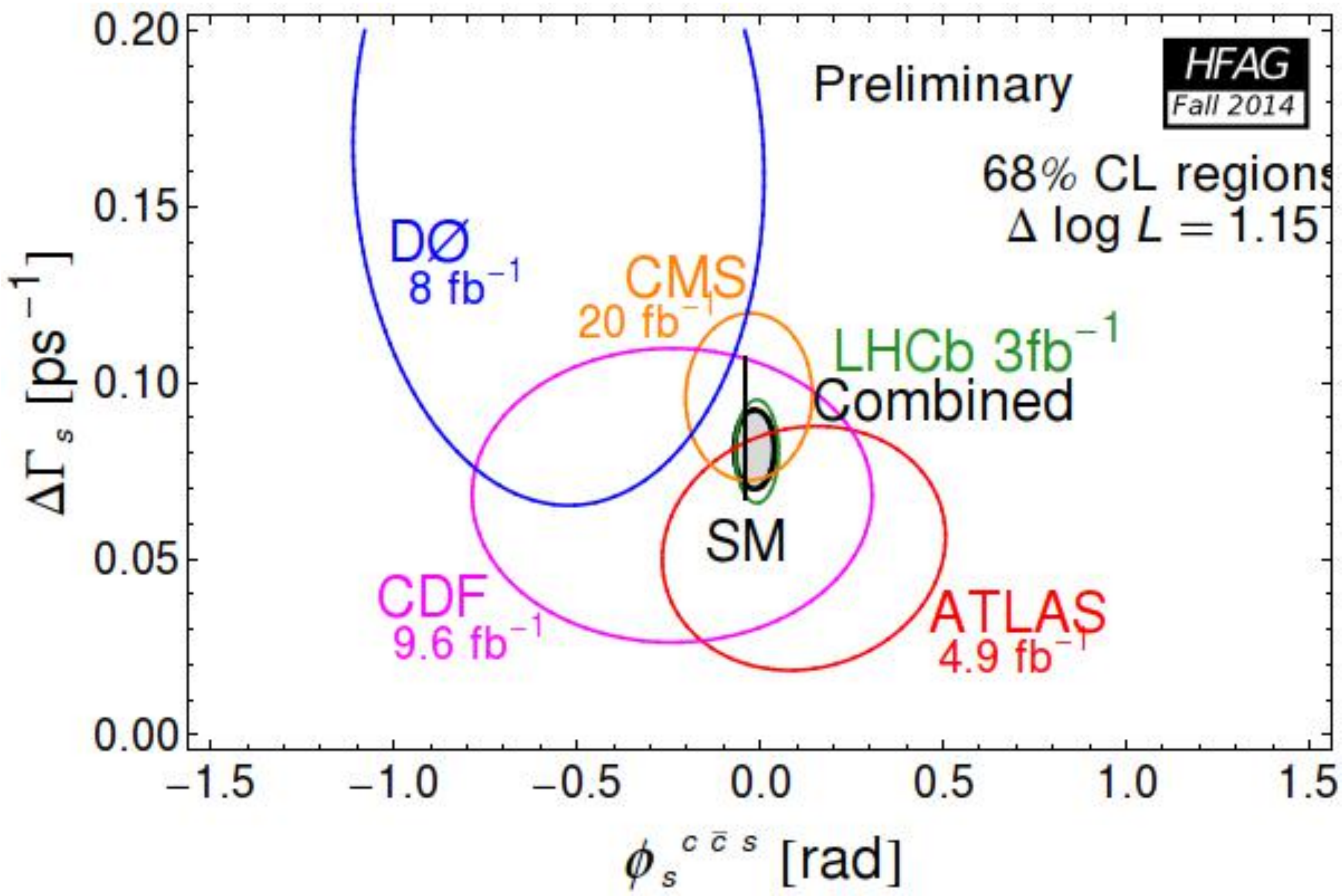
- Preliminary result from CMS using $B_s \rightarrow J/\psi\phi$ decays in 20 fb^{-1} of 2012 data
  - CMS-PAS-BPH-13-012: **ϕ_s= -30 ± 110 ± 30 mrad**



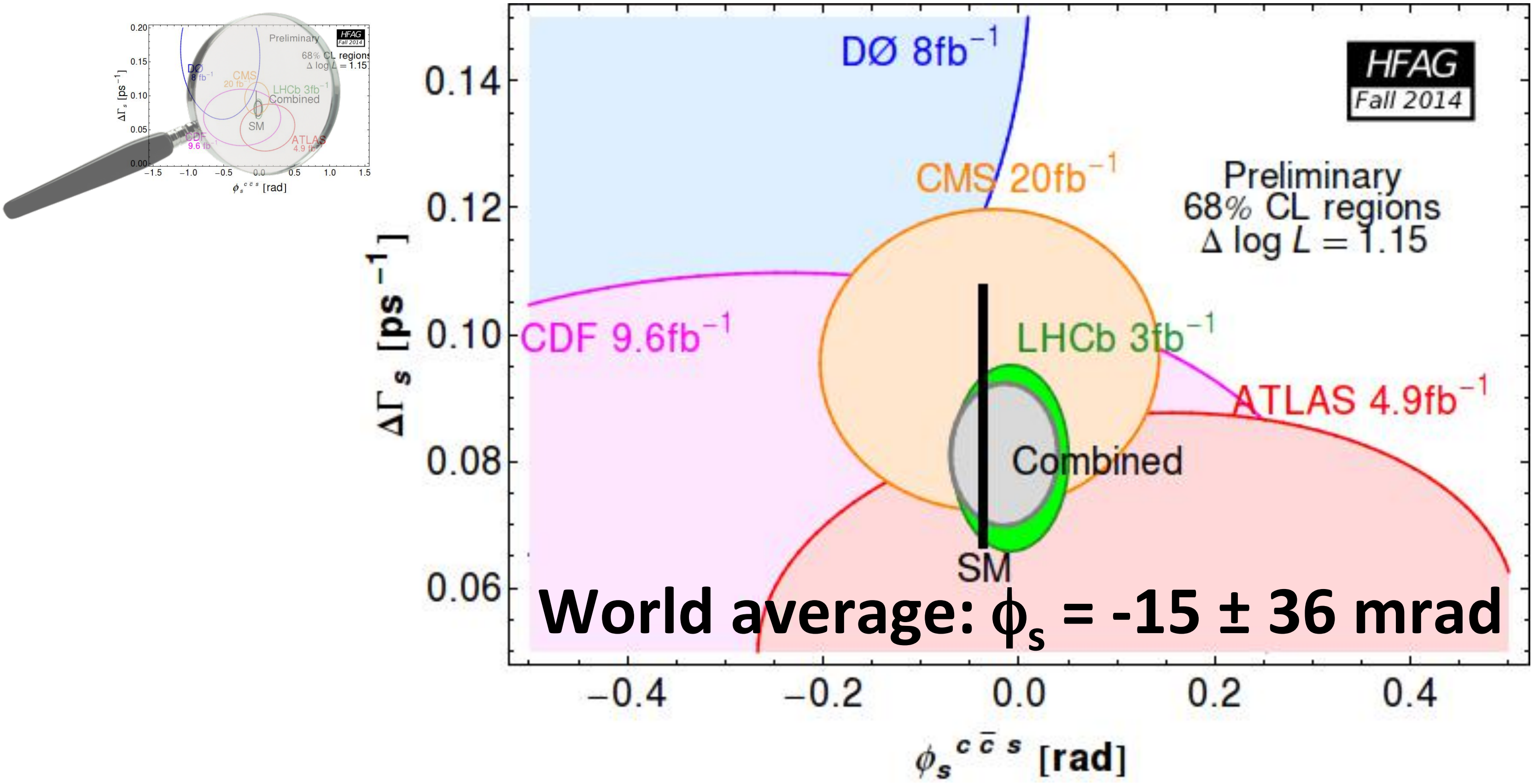
- Measurement from ATLAS using $B_s \rightarrow J/\psi\phi$ decays in 4.9 fb^{-1} of 2011 data
  - Phys. Rev. **D90** (2014) 052007: **ϕ_s= 120 ± 250 ± 50 mrad**
  - ATLAS update to full Run 1 statistics is ongoing



Combination of measurements



Combination of measurements

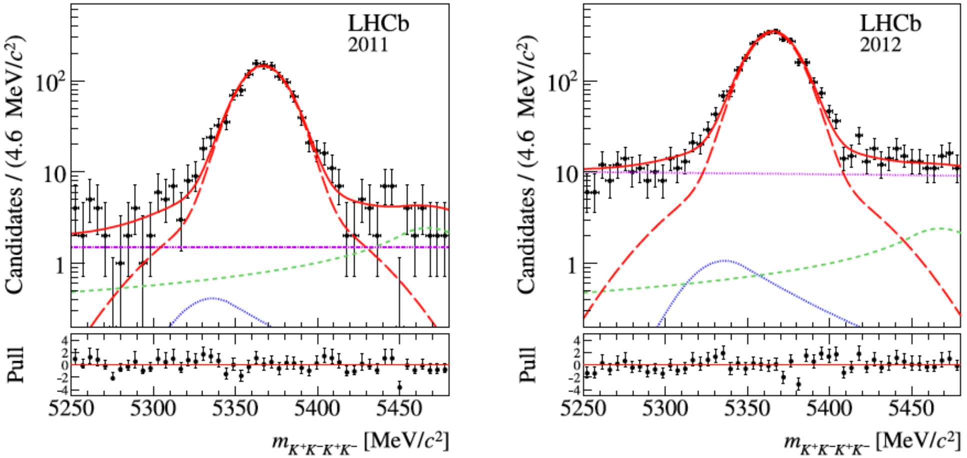


World average: ϕ_s = -15 ± 36 mrad

- Present uncertainty is dominated by LHCb
  - LHCb-only average: ϕ_s = -10 ± 40 mrad
- Not yet signs of discrepancy with SM expectation

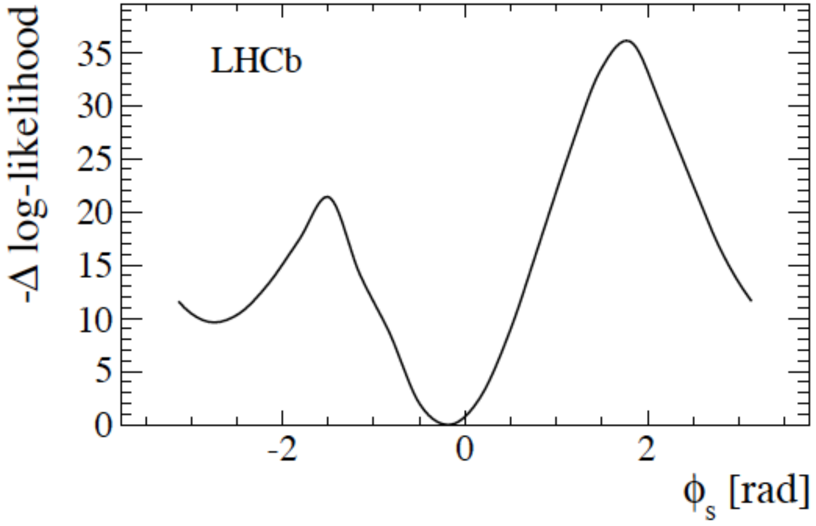
CP violation in $B_s \to \phi\phi$

- Decay forbidden at tree level in the SM
  - proceeds predominantly via a gluonic $b \to s\bar{s}s$ penguin
  - Provides an excellent probe of new heavy particles entering the penguin quantum loops



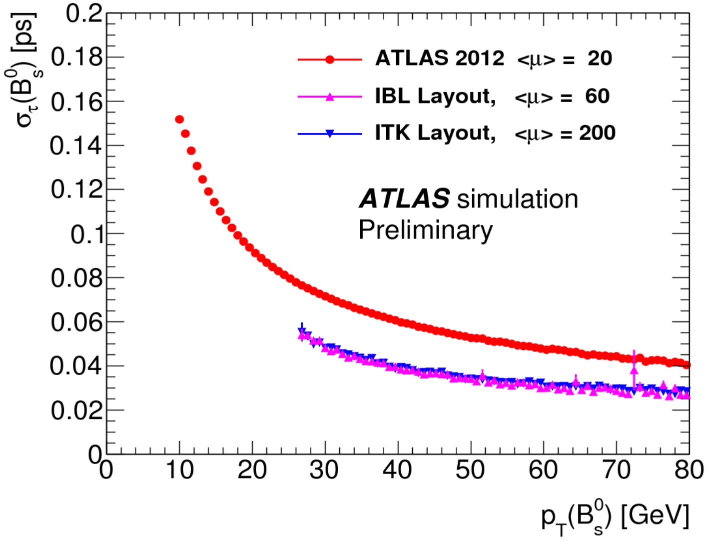
- Latest LHCb result with full Run 1 data set
  - Phys. Rev. **D90** (2014) 052011

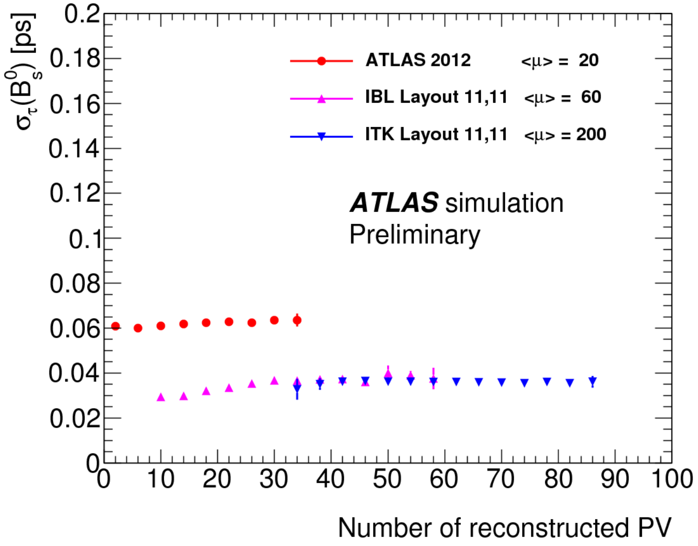
$\phi_s^{\phi\phi}$ = -170 ± 150 ± 30 mrad



- No sign of discrepancy yet, but overall precision comparable to golden $b \to c\bar{c}s$ modes!

Case study at ATLAS: $B_s \rightarrow J/\psi\phi$

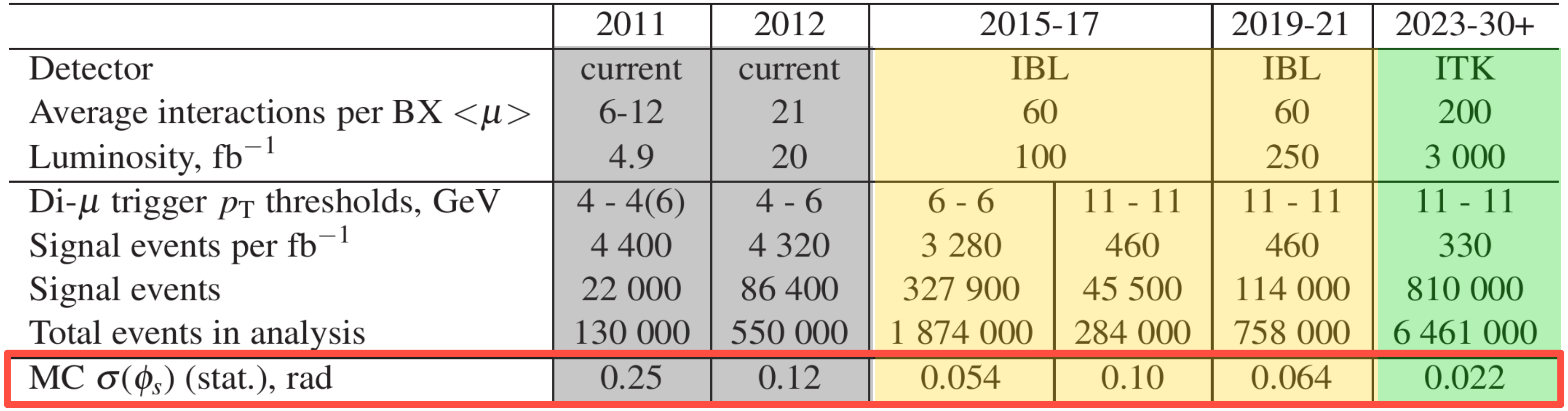




- New ID layouts IBL and ITK improve decay time resolution σ_t by 30% w.r.t. Run 1
- Higher p_T improves σ_t and signal purity on the account of lower efficiency
- σ_t stable in Run 1
  - – low p_T, dominated by material
- Slight σ_t (~14%) increase in Run 2 with number of PVs
  - – but stable at n. PV > 40

Case study at ATLAS: $B_s \rightarrow J/\psi\phi$

- Trigger settings of muon p_T thresholds for dimuons
  - Run 2/3: 6+6 GeV (nominal) or 11+11 GeV (pessimistic)
  - HL-LHC: 11+11 GeV
- Potential in Run 2/3 will strongly depend on the trigger thresholds
  - 7x less B_s events in the pessimistic trigger configuration

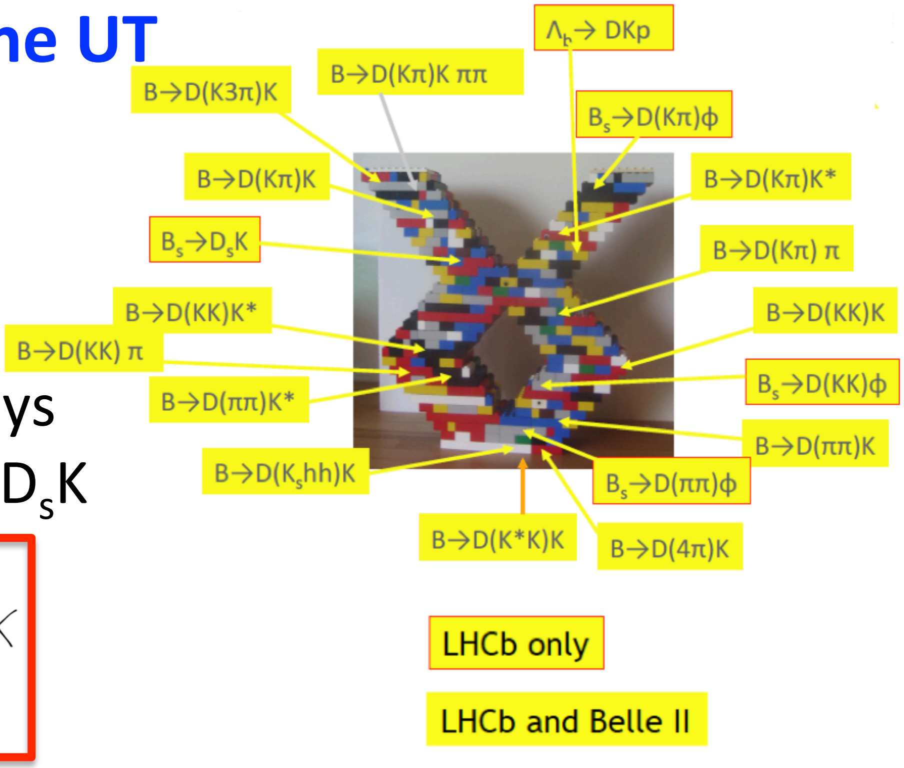


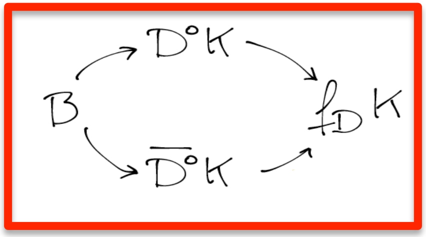
	2011	2012	2015-17		2019-21	2023-30+
Detector	current	current	IBL		IBL	ITK
Average interactions per BX $<\mu>$	6-12	21	60		60	200
Luminosity, fb^{-1}	4.9	20	100		250	3 000
Di-μ trigger p_T thresholds, GeV	4 - 4(6)	4 - 6	6 - 6	11 - 11	11 - 11	11 - 11
Signal events per fb^{-1}	4 400	4 320	3 280	460	460	330
Signal events	22 000	86 400	327 900	45 500	114 000	810 000
Total events in analysis	130 000	550 000	1 874 000	284 000	758 000	6 461 000
MC $\sigma(\phi_s)$ (stat.), rad	0.25	0.12	0.054	0.10	0.064	0.022

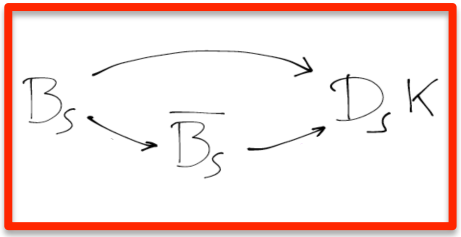
- Room for further improvements
  - Developments of the L1-topological trigger
  - Take into account flavour tagging and fit improvements developed in analysis of 8 TeV data of 2012

Tree-level determination of γ

- **γ is the least known angle of the UT**
  - sensitivity comes from the interference between b→u and b→c transitions
- Two main paths to γ
  - Time-independent, B→DK decays
  - Time-dependent, e.g. with $B_s \to D_sK$



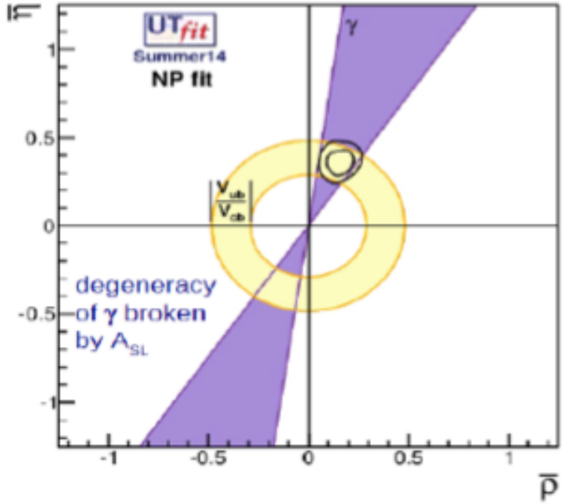




- Possible interplay with charmless *B* decays
  - Also sensitive to γ, but including penguin diagrams → NP could show up, but much more difficult to control theoretically
- **Combining several independent decay modes is the key to achieve the ultimate precision**

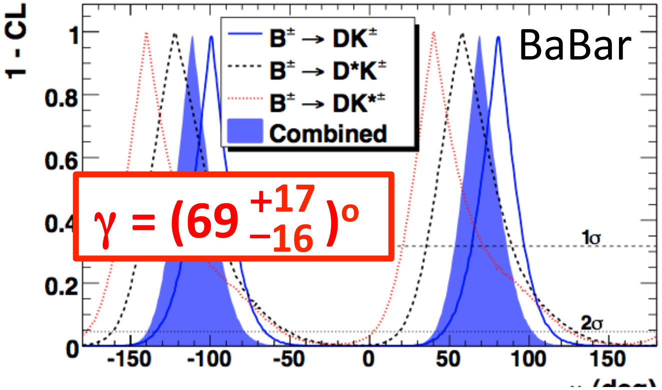
Experimental status for γ

- Measured by BaBar, Belle and LHCb using ADS, GLW and GGSZ (Dalitz) methods
  - **LHCb is now starting to dominate the world average**

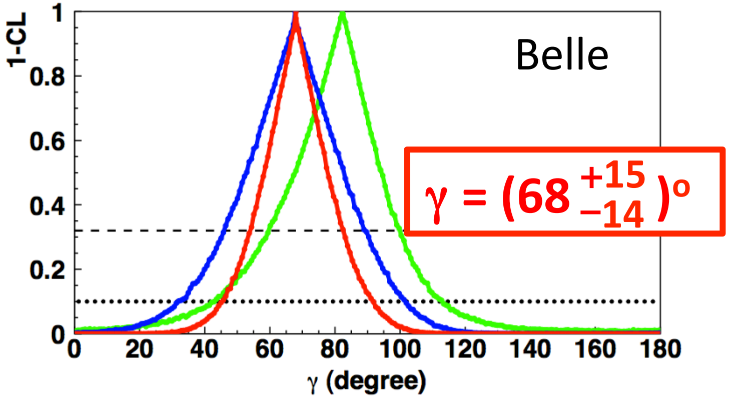


Measurements from tree-level decays are assumed to be almost insensitive to NP effects

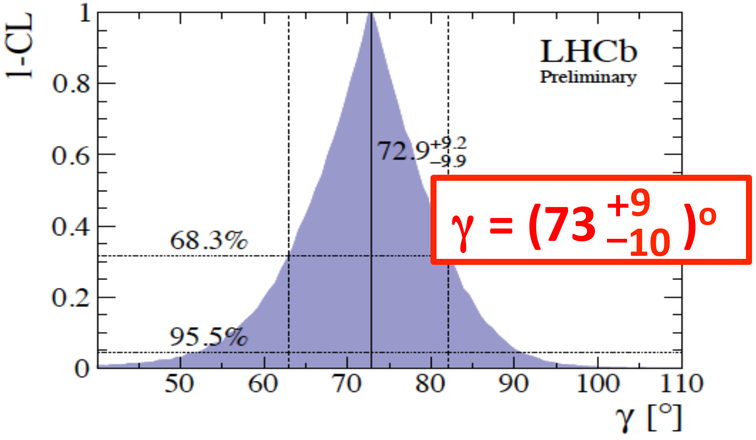
Standard candle for the SM, crucial to distinguish between genuine SM and BSM in UT fits



$\gamma = (69\,^{+17}_{-16})^{\circ}$



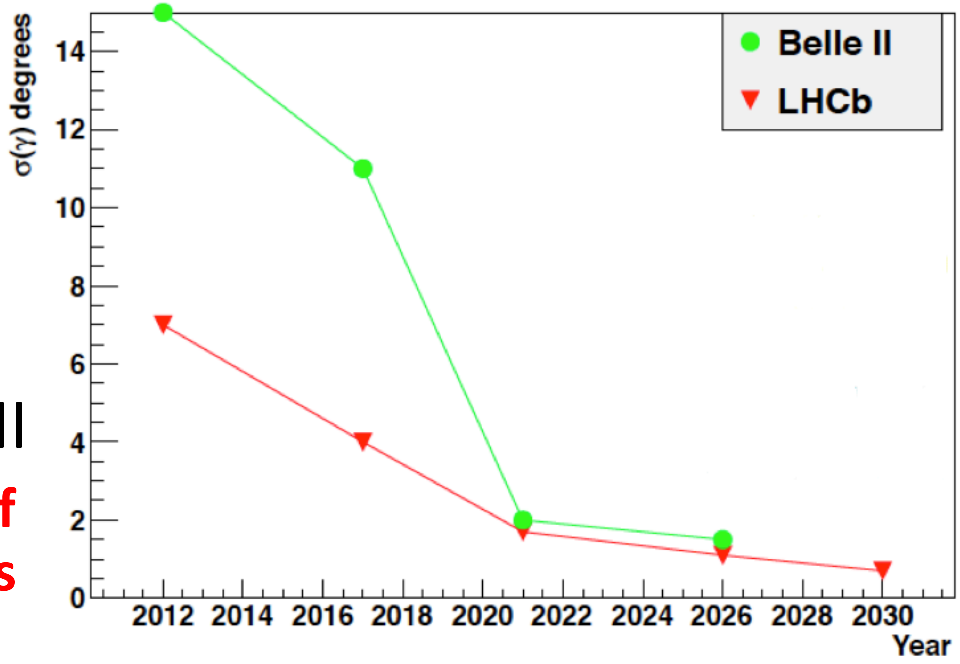
$\gamma = (68\,^{+15}_{-14})^{\circ}$



$\gamma = (73\,^{+9}_{-10})^{\circ}$

Prospects for γ

- Many analyses still to be completed with Run 1 data
  - ~7° precision achievable by exploiting the full power of current data set
- Comparable precision expected at LHCb and Belle II
  - **Sub-degree level by the end of the experimental programmes**
  - Small systematic uncertainties

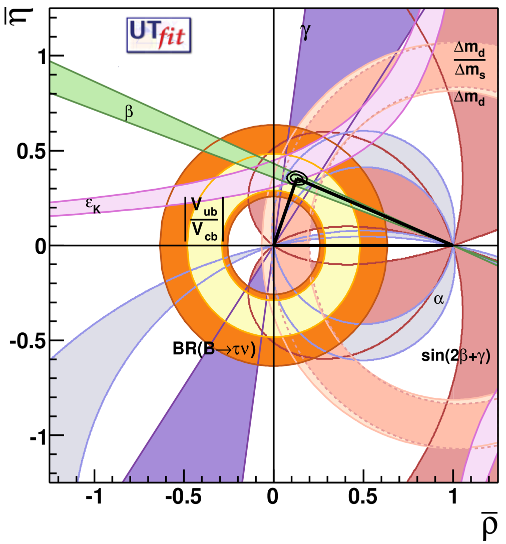


(Almost) vanishing theoretical uncertainty

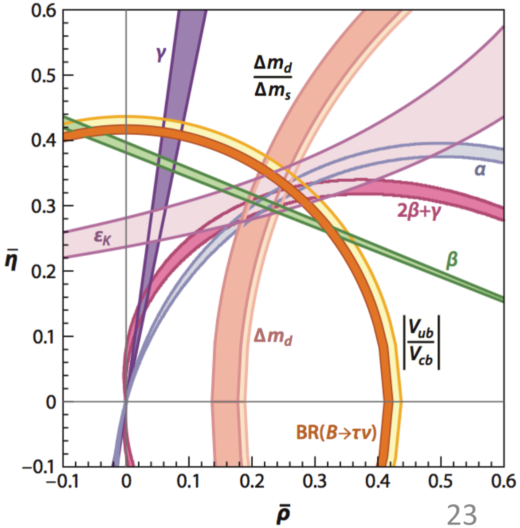
Conclusions

- Flavour physics has large room for improvements in many key measurements
  - **and there is a huge number of physics observables to be studied, well beyond the few ones mentioned in this talk**
    - charm physics, radiative *B* decays, charmless *B* decays, semileptonic asymmetries, charm and beauty spectroscopy, ...
- ATLAS, CMS and LHCb are developing a programme extending over the next 15 years
- Note: Belle II is expected to roll in 2017 with the first physics run
  - Rich complementarity (and some competition) between LHC and Belle II physics programmes is anticipated

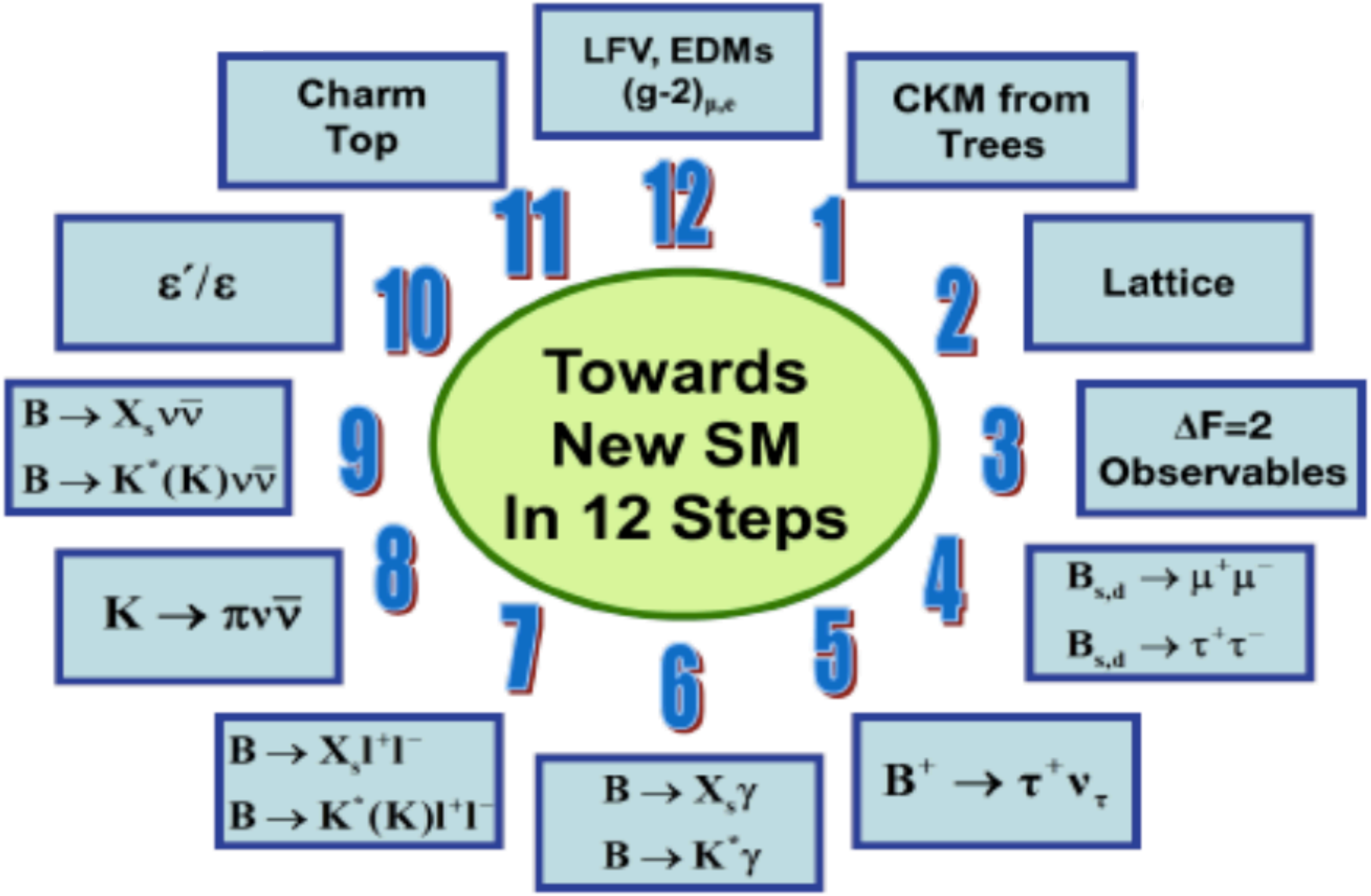
Today



Tomorrow?



The Flavour Clock cannot stop!



Towards New SM In 12 Steps

12 LFV, EDMs $(g-2)_{\mu,e}$

1 CKM from Trees

2 Lattice

3 $\Delta F=2$ Observables

4 $B_{s,d} \to \mu^+\mu^-$ $B_{s,d} \to \tau^+\tau^-$

5 $B^+ \to \tau^+\nu_\tau$

6 $B \to X_s\gamma$ $B \to K^*\gamma$

7 $B \to X_s l^+l^-$ $B \to K^*(K)l^+l^-$

8 $K \to \pi\nu\bar{\nu}$

9 $B \to X_s\nu\bar{\nu}$ $B \to K^*(K)\nu\bar{\nu}$

10 ε'/ε

11 Charm Top

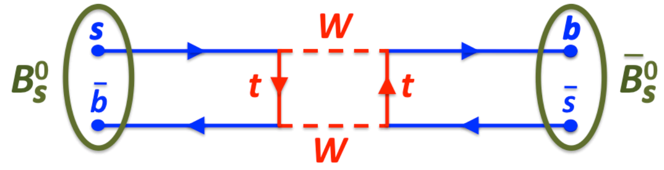
Buras *et al.*

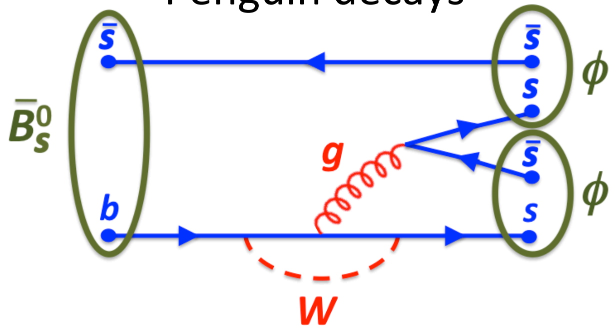
Backup

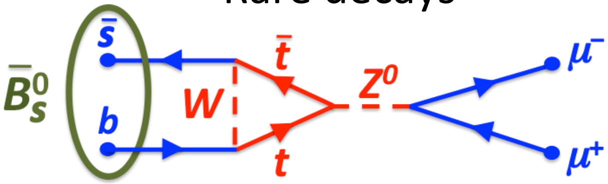
Abandon hope all ye who enter here

Flavour Physics

searching for new particles through their virtual effects


Mixing


Penguin decays


Rare decays

- Precision measurements of *CP* violation and rare decays
- If the SM contribution is not negligible, uncertainties on the SM coupling can hide NP effects
  - – Need to focus on theoretically clean processes
- Who will win the reality vs virtuality race?

The Upgrade in a nutshell

Indirect search strategies for New Physics, *e.g.* precise measurements & the study of suppressed processes in the flavour sector become ever-more attractive following the experience of LHC 1 run that direct signals are elusive

Our knowledge of flavour physics has advanced spectacularly thanks to LHCb. Maintaining this rate of progress beyond run II requires significant changes.

The LHCb Upgrade

1) Full software trigger
- Allows effective operation at higher luminosity
- Improved efficiency in hadronic modes

2) Raise operational luminosity to 2×10^{33} cm^{-2} s^{-1}

Necessitates redesign of several sub-detectors & overhaul of readout

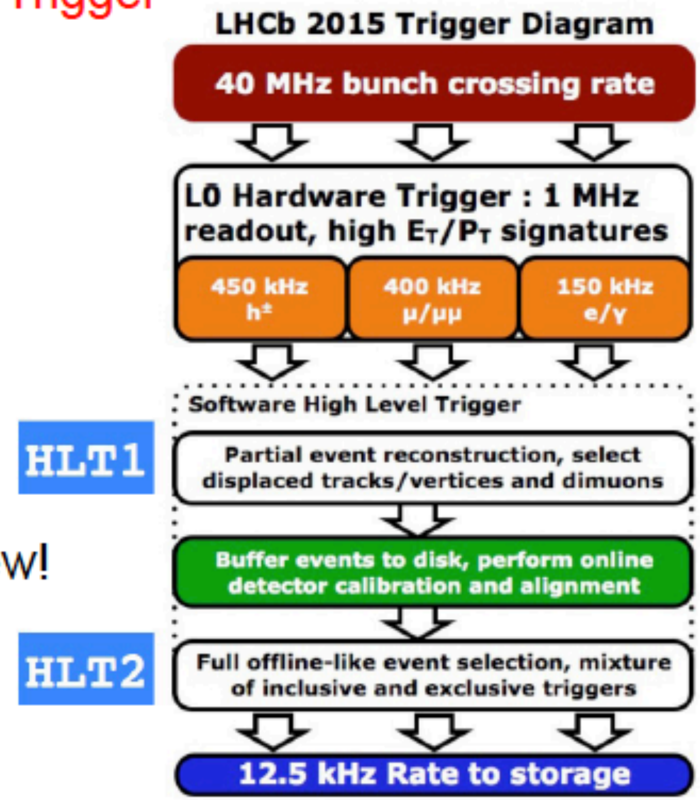
Huge increase in precision, in many cases to the theoretical limit, and the ability to perform studies beyond the reach of the current detector.

Flexible trigger and unique acceptance also opens up opportunities in other topics apart from flavour ('a general purpose detector in the forward region')

Run II operation

Several ambitious changes planned for operation during run II aimed at increasing physics output and making optimal use of resources

Trigger



LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz	400 kHz	150 kHz
$h^\pm$	$\mu/\mu\mu$	e/γ

Software High Level Trigger

HLT1

Partial event reconstruction, select displaced tracks/vertices and dimuons

New!

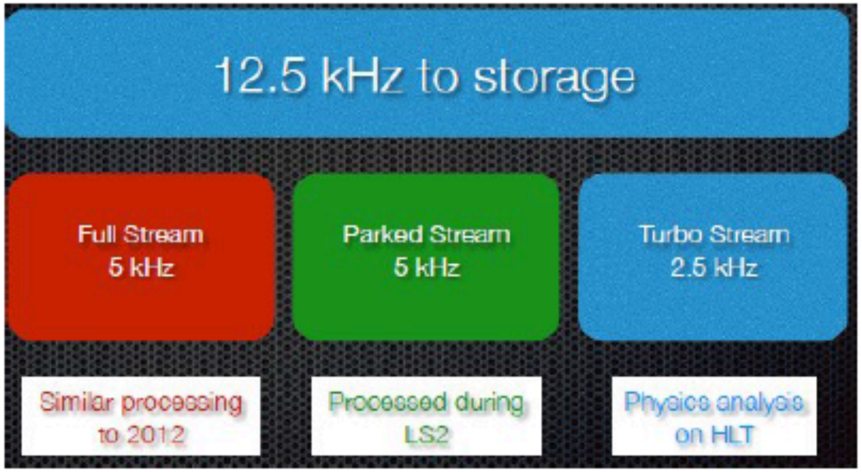
Buffer events to disk, perform online detector calibration and alignment

HLT2

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz Rate to storage

Output streams



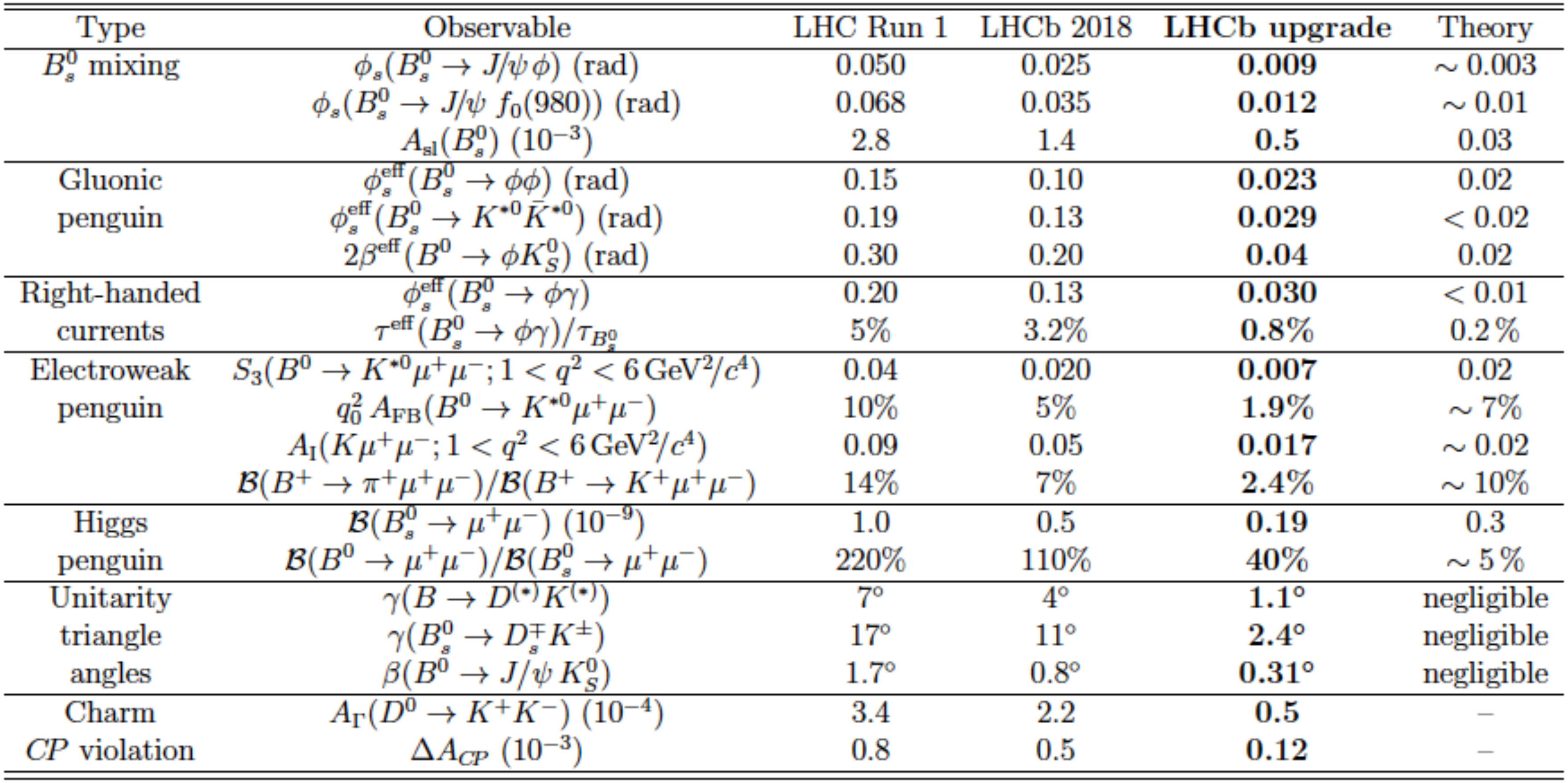
12.5 kHz to storage

Full Stream 5 kHz	Parked Stream 5 kHz	Turbo Stream 2.5 kHz
Similar processing to 2012	Processed during LS2	Physics analysis on HLT

Turbo-stream will needs no offline processing. If this works well then it has important implications for Upgrade.

This splitting of HLT into two steps enables more info to be used in HLT2 (*e.g.* RICH) → improved signal-to-background separation (and helps test ideas we wish to use in Upgrade trigger)

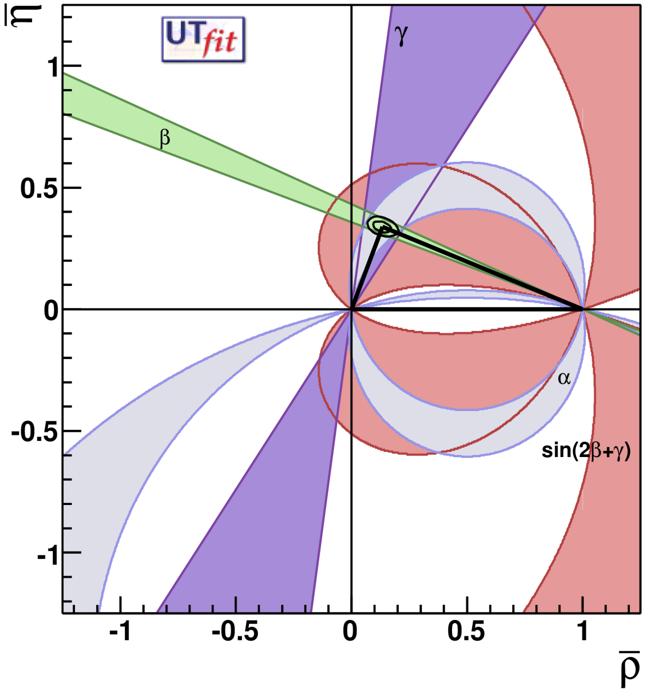
Today: latest sensitivity table



Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.050	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.023**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2%
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

Measurements of UT angles

- Interpretation in terms of CKM matrix elements does not depend on strong theory inputs
  - $\sigma_{th}(\gamma)$ negligible from tree-level decays
    - Brod and Zupan, JHEP 01 (2014) 051
  - $\sigma_{th}(\beta)$ small and controllable with data-driven methods
    - Ciuchini *et al.*, PRL 95 (2005) 221804
    - Faller *et al.*, PRD 79 (2009) 014030
  - $\sigma_{th}(\beta_s)$ small and controllable with data-driven methods
    - Faller et al., PRD 79 (2009) 014005
  - $\sigma_{th}(\alpha) \approx 1^o$
    - Gronau *et al.*, PRD 60 (1999) 034021
    - Botella *et al.*, PRD 73 (2006) 071501
    - Zupan, Nucl. Phys. Proc. Suppl. 170 (2007) 33



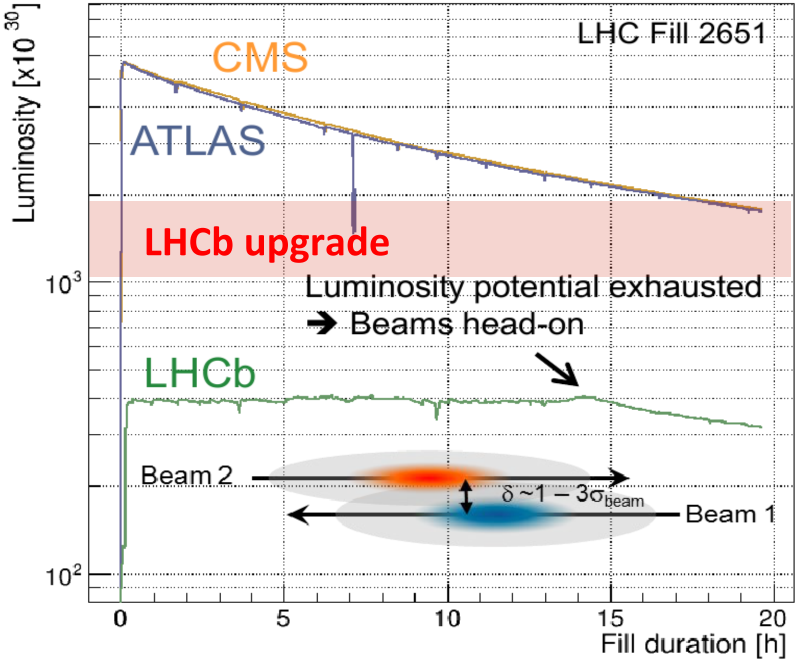
- Measurements can be affected by NP at different levels
  - γ from tree-level is basically unaffected
  - β (β_s) can be affected in B_d (B_s) mixing
  - α can be affected both in mixing and decay (loops in penguin diagrams)

How to increase LHCb statistics

Up to LS2

- running at levelled luminosity of $4 \cdot 10^{32}$ cm^{-2}s^{-1}
- software trigger running at 1 MHz after hardware trigger
- record 3-5 kHz

2012 running conditions



LHCb upgrade

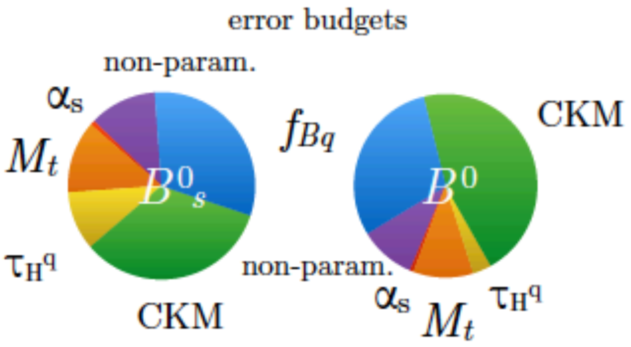
- running at $1\text{-}2 \cdot 10^{33}$ cm^{-2}s^{-1}
- replace R/O, RICH photodetectors and tracking detectors
- full software trigger, running at 40 MHz
- record 20 kHz

Large improvements in physics yields due to lower p_T and E_T cuts

- x10 in muonic *B* decays
- x20 in charm and hadronic *B* decays

Theory (2)

Bobeth et al. [PRL 112 (2014) 101801]



- Untagged time integrated branching fraction predictions:

$$\begin{aligned}\mathcal{B}(B^0_s \to \mu^+\mu^-) &= (3.66 \pm 0.23) \times 10^{-9}\\ \mathcal{B}(B^0 \to \mu^+\mu^-) &= (1.06 \pm 0.09) \times 10^{-10}\end{aligned}$$

updated with the latest top mass measurement (Tevatron+LHC combination) [hep-ex/1403.4427]

- Ratio of branching fractions of two modes powerful to discriminate among models beyond the SM. Precisely predicted in SM:

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B^0_s \to \mu^+\mu^-)} = \frac{\tau_{B_d}}{1/\Gamma^s_H}\left(\frac{f_{B_d}}{f_{B_s}}\right)^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{M_{B_d}\sqrt{1-\frac{4m_\mu^2}{M_{B_d}^2}}}{M_{B_s}\sqrt{1-\frac{4m_\mu^2}{M_{B_s}^2}}} = 0.0295^{+0.0028}_{-0.0025}$$

➡ stringent test of Minimal Flavour Violation hypothesis

Fit result

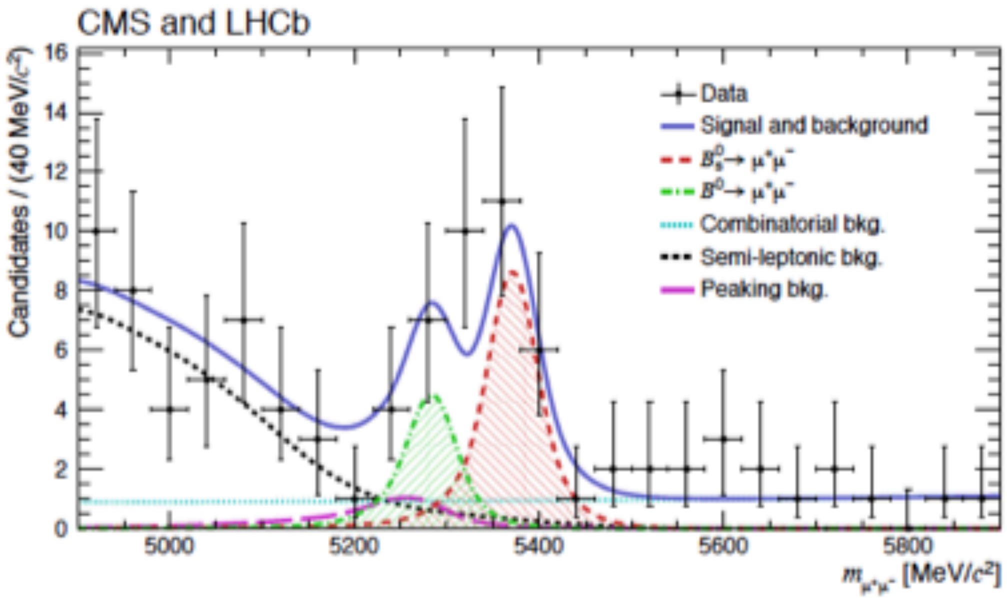
from the simultaneous fit we get:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

Using the Wilks' theorem the statistical significance from the likelihood is:

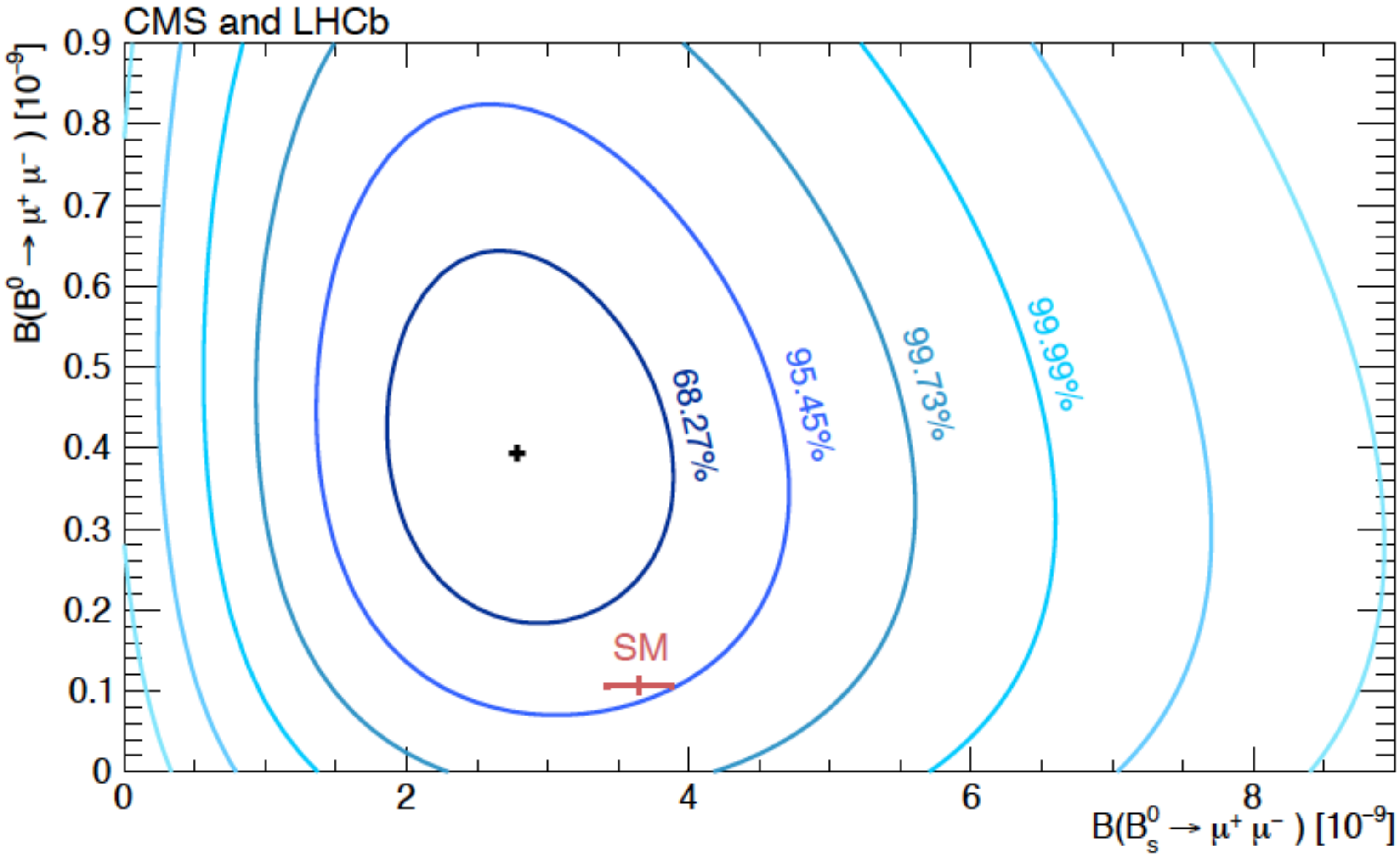
- 6.2 σ for the $B^0{}_s \to \mu^+\mu^-$ (Expected SM 7.6 σ)
  - ✦ First **observation**
- 3.2 σ for the $B^0 \to \mu^+\mu^-$ (Expected SM 0.8 σ)



projection of invariant mass of best 6 categories selected through S/(S+B) value

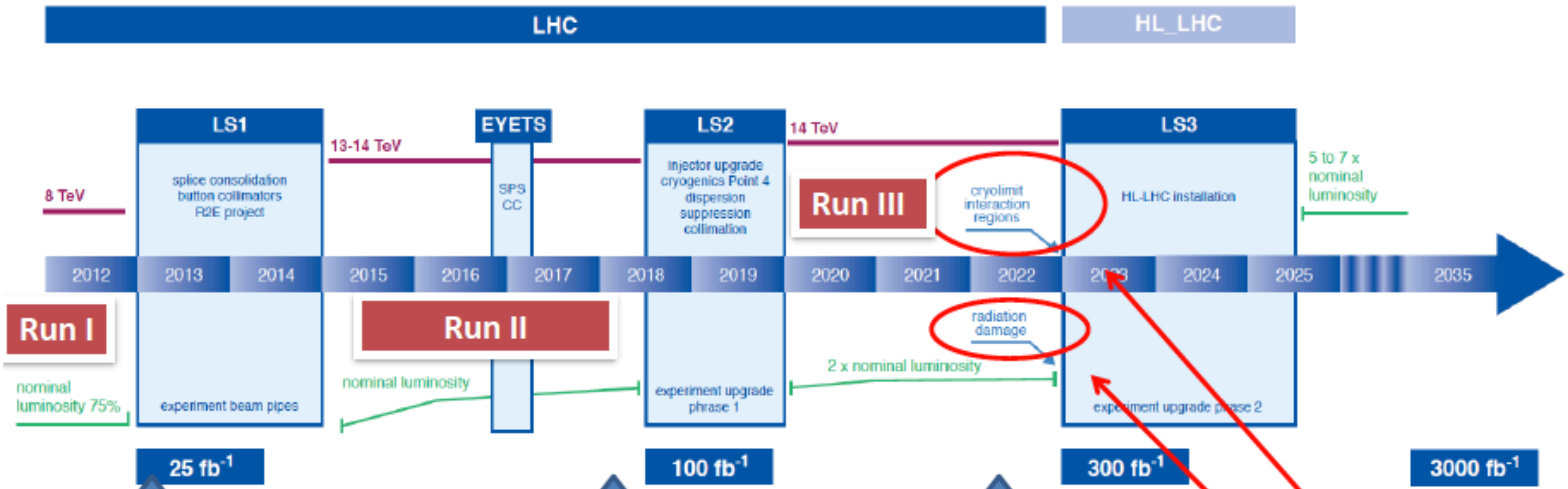
Wilks' theorem assumes asymptotic behaviour, Feldman-Cousin approach is used for $B^0 \to \mu^+\mu^-$

2D likelihood scan of Branching Fractions



Probability contours plot from 2D likelihood scan

New LHC / HL-LHC Plan



0.75 10^{34} cm^{-2}s^{-1}
50 ns bunch
high pile up ~40

50 ⇒ 25 ns

1.5 10^{34} cm^{-2}s^{-1}
25 ns bunch
pile up ~40

1.7-2.2 10^{34} cm^{-2}s^{-1}
25 ns bunch
pile up ~60

Technical limits
(experiments,
too) like :

ATLAS B-Physics Programme

- The B-physics programme in Run 2 and beyond will follow the current Run 1 approach:
  - Precision measurements and rare processes that most benefit from high integrated luminosity and/or are inaccessible at B-factories. Focus on those with potential in beyond-SM effects
    - $B_s \rightarrow J/\psi\phi$, $\Lambda_b \rightarrow J/\psi\Lambda$, …, $B_{(s)} \rightarrow \mu\mu$, $b \rightarrow s\mu\mu$
  - Heavy flavour production at 14TeV
    - B-hadron and D-meson production x-section, prompt/non-prompt quarkonia production, quarkonia spin alignment
  - Heavy flavour production in association with other physics objects
    - Vector boson + J/ψ, double J/ψ production etc.
  - Searches for new/exotic states and new decay modes
    - χ_b, B_c decays, $B_c(2S)$, heavy baryons, exotic quarkonia etc.

- Trigger still ties us to muonic final states

B-Physics Programme cont.

- The Run 1 of LHC experiments showed: in B-physics a sensitivity to potential effects beyond SM is only possible if the measurements are accomplished at unprecedentedly high precision => need the future LHC Runs

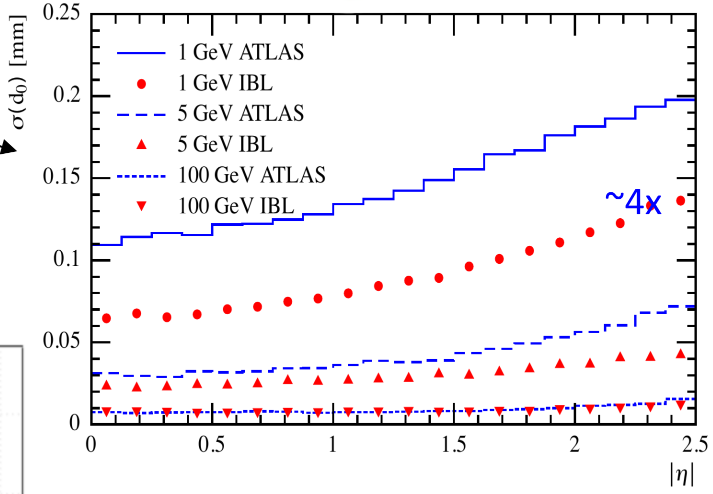
- To make that possible and keep similar or better performance, we need:
  - **trigger strategies** and
  - **detector upgrades** (namely tracking)

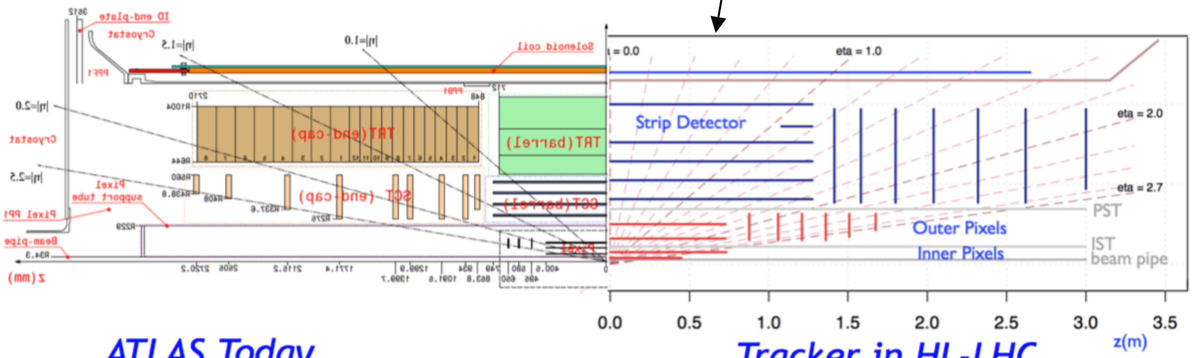
  able to face the harsher environment of the future Runs

- 2nd part of the talk => study of the impact of the detector & trigger changes on $B_s \rightarrow J/\psi\phi$ measurement precision

Relevant ATLAS Detector Upgrades

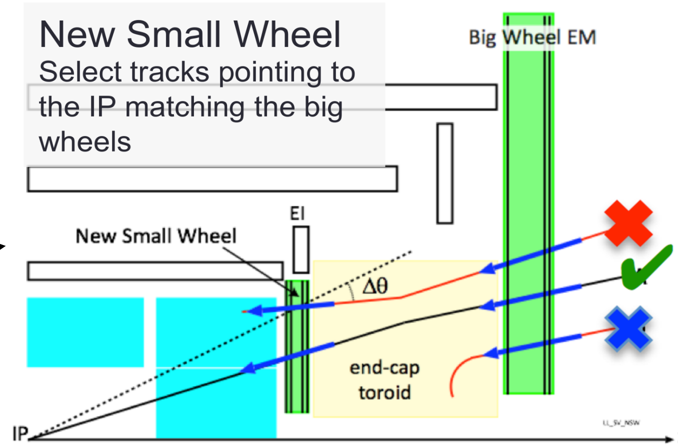
- Inner Tracker upgrade:
  - Run-2: Additional Pixel Layer (IBL), better d0 and z0 resolution, and w and f resolution at low-pT
  - HL-LHC: Completely new Si based tracking (ITK), finer granularity





ATLAS Today

Tracker in HL-LHC



New Small Wheel

Select tracks pointing to the IP matching the big wheels

- Muon detector upgrades:
  - Run-2: Improved coverage in 1.0<|η|<1.3
  - Run-3: Installed New Small Wheel
  - HL-LHC: Upgrade of the muon systems, fast trigger
- Trigger upgrades:
  - Run-2: Topological L1 trigger (selection based on rought topology of combined objects at L1)
  - Run-2/3: Fast Tracking (FTK) – a HW-based track finder at “offline precision”; installed between HW based level-1 trigger and the next SW-based trigger levels

Trigger Strategies for ATLAS B-physics

- Triggers remain based on single/di/multi-muon signatures, but can be combined with other objects (e.g. hadronic tracks)
- The rates of the passing events must fit the limits of the trigger system at each stage:
  - Run-1: the total maximum output rates from the L1, L2 and EF: 75 kHz, 6-7kHz, 400 Hz
  - Run-1 limitations on B-physics triggers mainly from the restriction on the **L1** rate
  - In upcoming runs, both HW-based **L1** and SW-based **L2+EF** will have to be tightened to fit within the allowed limits

- Level 1 trigger rate control:
  - Increasing the **muon p_T thresholds** or collecting signal in the **barrel detectors only** (this was Run-1 approach for peak luminosity) → in Run-2 would lead to significant signal loss
  - From Run-2 , additional **topological selections** will be possible at HW level: rough selections based on di-muon **opening angle, invariant mass** etc.

- Level 2 trigger & Event Filter rate control:
  - The available tools allow offline-analysis like selections. Can thus reconstruct complicated objects (**whole B-decay trees**) and make selections based on that
  - CPU resources will be saved by the **Fast Tracking Trigger**

Current ATLAS Detector

Muon Specrometer

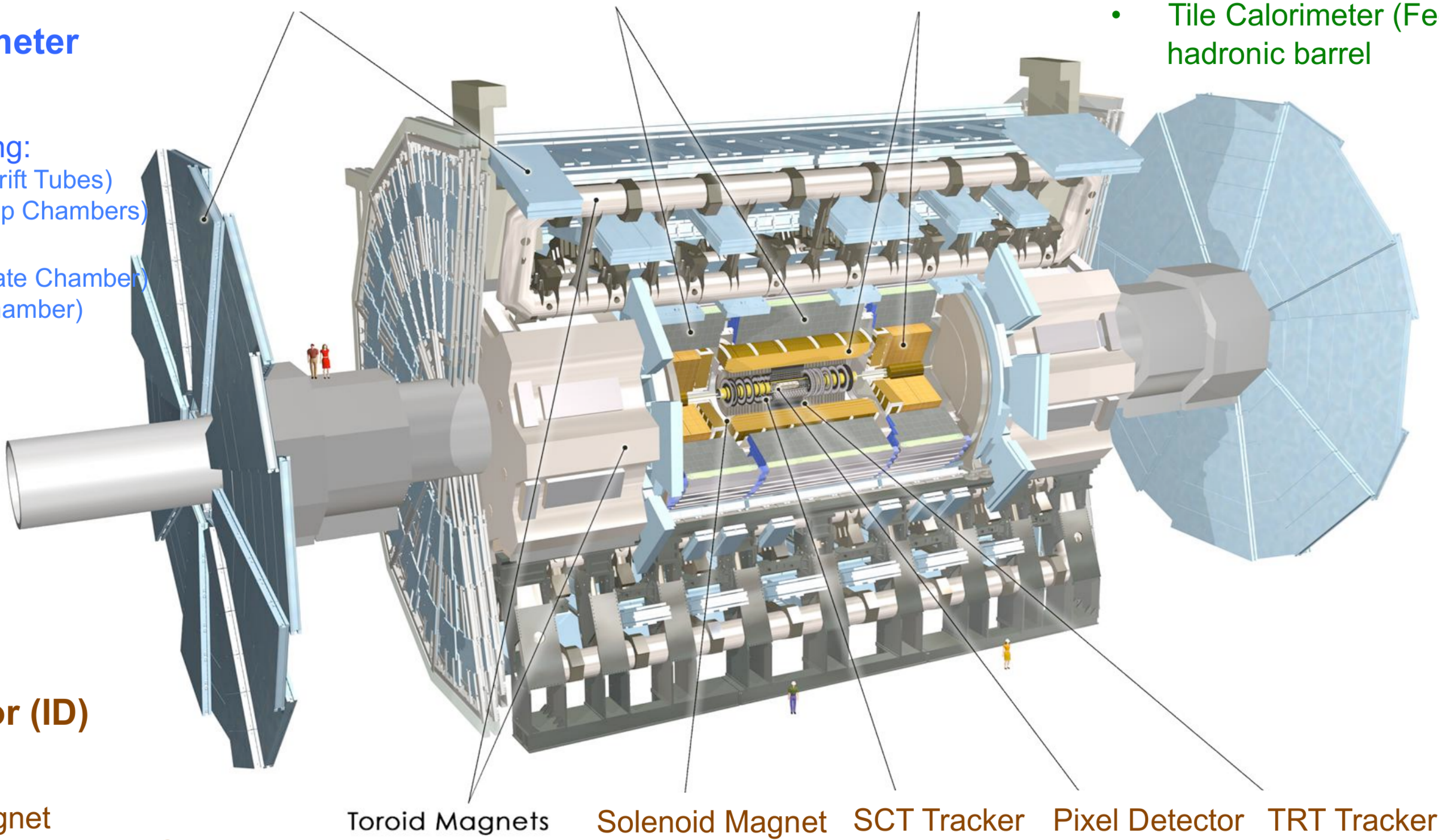
Toroid Magnets

Precision μ tracking:

- MDT (Monitored Drift Tubes)
- CSC (Cathode Strip Chambers)

Trigger:

- RPC (Resistive Plate Chamber)
- TGC (Thin Gas Chamber)



Calorimeter System

EM and Hadronic energy

- LAr EM barrel and EC
- LAr Had. Barrel
- Tile Calorimeter (Fe-Scin.) hadronic barrel

Inner Detector (ID)

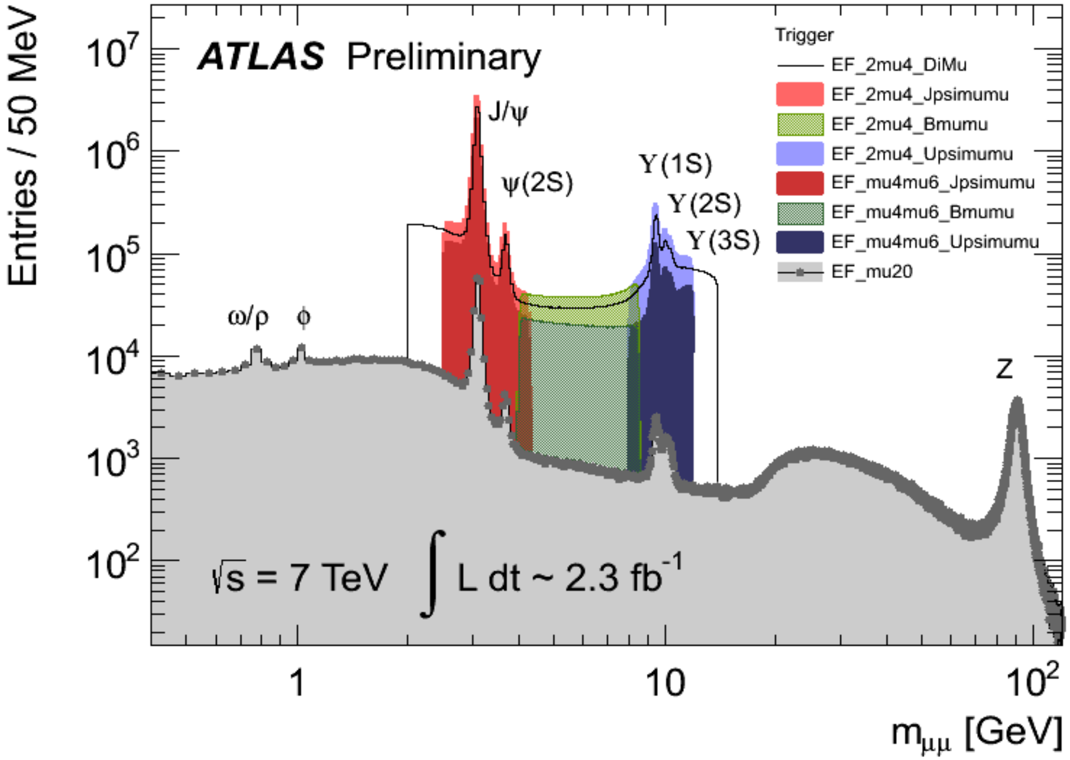
Tracking

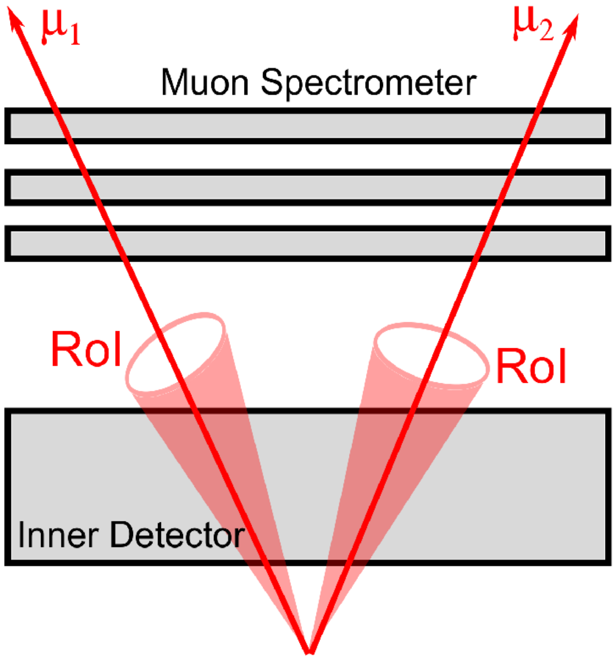
2T Solenoid Magnet

- Silicon Pixels, 50x400 μm^2
- Silicon Strips (SCT), 80 μm stereo
- Transition Ratiation Tracker (TRT) 36 points/track

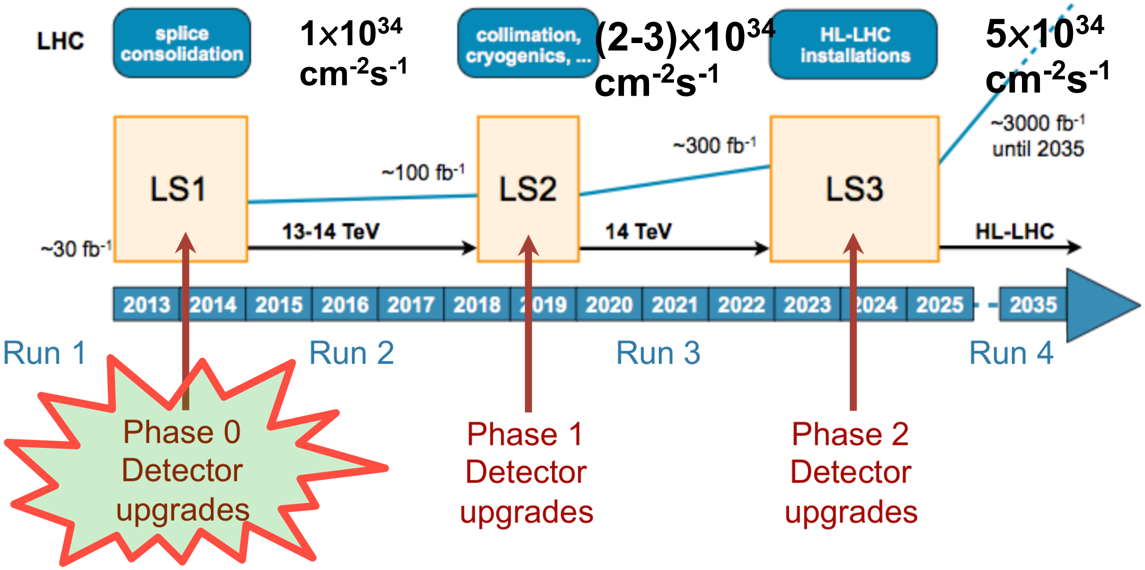
Current (Run 1) B-Physics Triggers

- Mostly based on di-muon signature (e/γ or hadronic B-decays lost in background), some analyses using single-muon based or multi-muon triggers
- Whole trigger chain 3-level based:
  - Level1 (L1) – HW based, fast muon detectors, di-muons with $p_T > 4$ GeV
  - Level2 (L2)/Event Filter (EF) – SW based, precise confirmation of the muons by Inner Detector tracks reconstruction, di-muon vertex construction (inv. mass cut), and possibly search for other hadronic tracks of requested B-





Detector & Trigger Upgrades – Phase 0



LHC

splice consolidation

1×10^{34} $cm^{-2}s^{-1}$

collimation, cryogenics, …

$(2\text{-}3)\times10^{34}$ $cm^{-2}s^{-1}$

HL-LHC installations

5×10^{34} $cm^{-2}s^{-1}$

~30 fb^{-1}

LS1

~100 fb^{-1}

13-14 TeV

LS2

~300 fb^{-1}

14 TeV

LS3

~3000 fb^{-1} until 2035

HL-LHC

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2035

Run 1

Run 2

Run 3

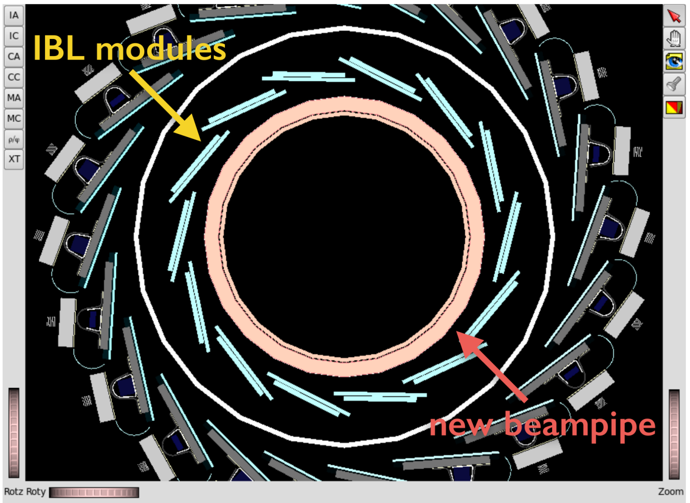
Run 4

Phase 0 Detector upgrades

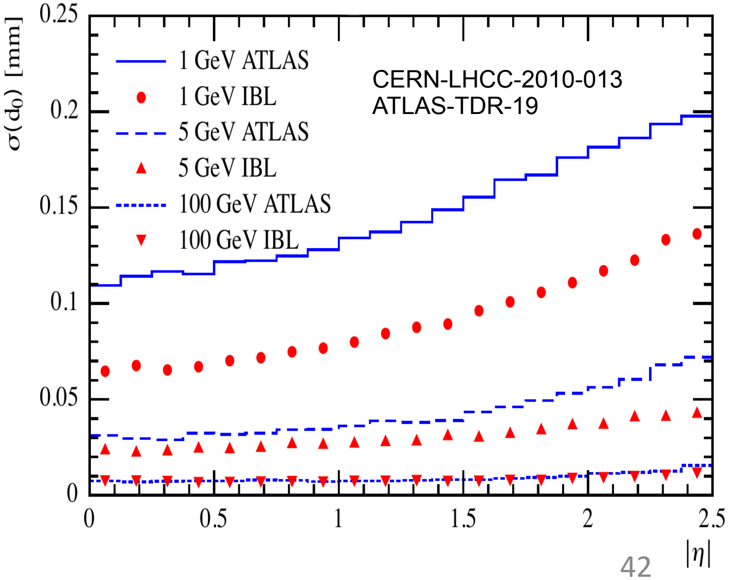
Phase 1 Detector upgrades

Phase 2 Detector upgrades

- Long Shutdown (LS) 1 almost over, LHC starts providing physics data in Spring 2015
- Additional Pixel Layer (IBL) and Be small radius beam pipe
- Topological L1 trigger
- Improved coverage of Muon spectrometer ($1.0 < |\eta| < 1.3$)
- Diamond Beam Monitor, consolidation of some parts of the detector (cooling etc.)

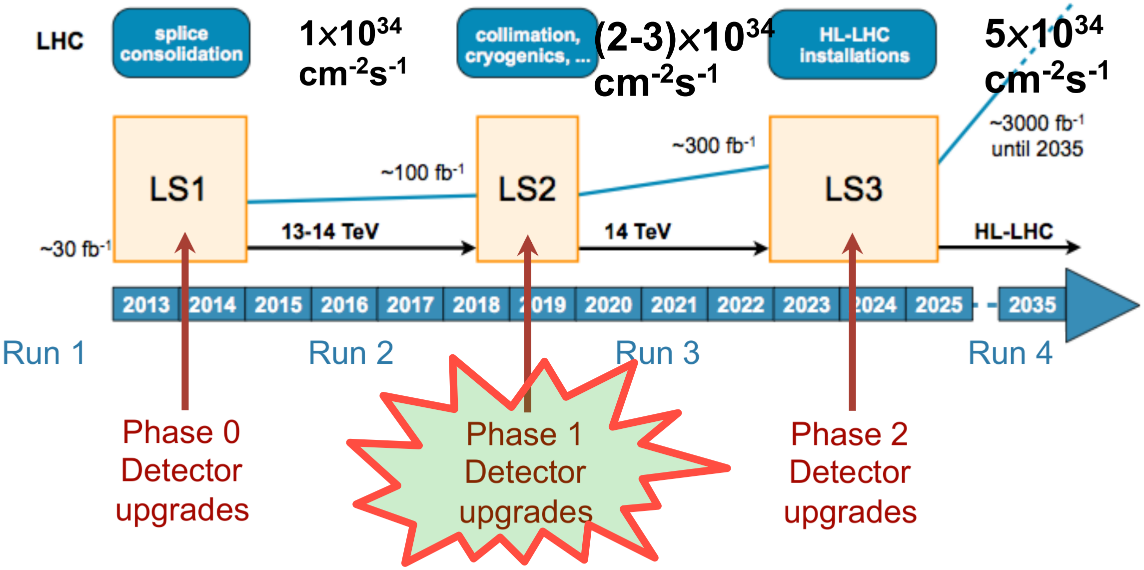


- Small radius (32-38 mm; current B-layer at 50.5 mm), small material budget
- 4th pixel layer => more robust track reconstruction, better impact parameter d_0 and z_0 resolution
- Better θ and ϕ resolution at low p_T ~ 1 GeV



CERN-LHCC-2010-013
ATLAS-TDR-19

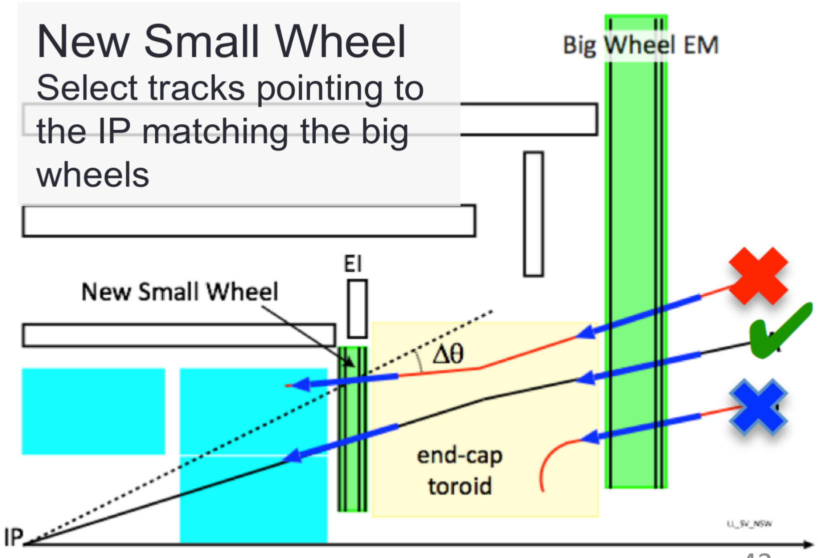
Detector & Trigger Upgrades – Phase 1



- Goal: no loss of performance when going above LHC nominal luminosity
- New small muon wheel
- New fast-tracking (FTK) at trigger level 1.5. Gradually implemented already during Run 2
- Higher granularity and precision L1 trigger for calorimeter
- TDAQ improved performance

Fast tracking trigger:

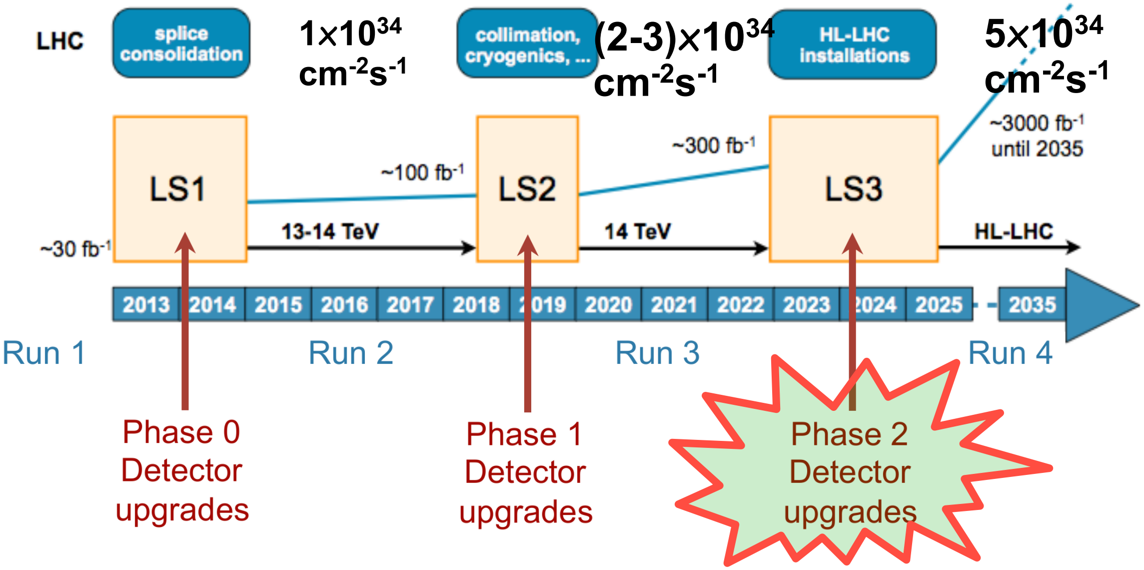
- HW based track finder in the Inner Detector silicon layers at "offline precision"
- Provides tracks already before the L2 trigger (first SW based trigger layer)
- Two-step processing: hit pattern matching & subsequent linear fitting in FPGAs



New Small Wheel

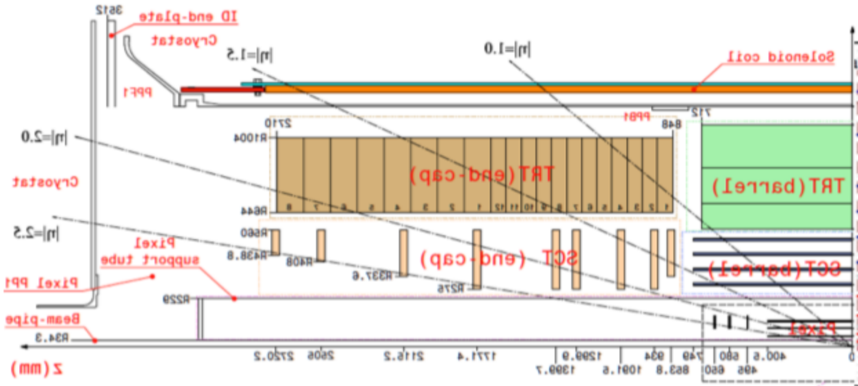
Select tracks pointing to the IP matching the big wheels

Detector & Trigger Upgrades – Phase 2

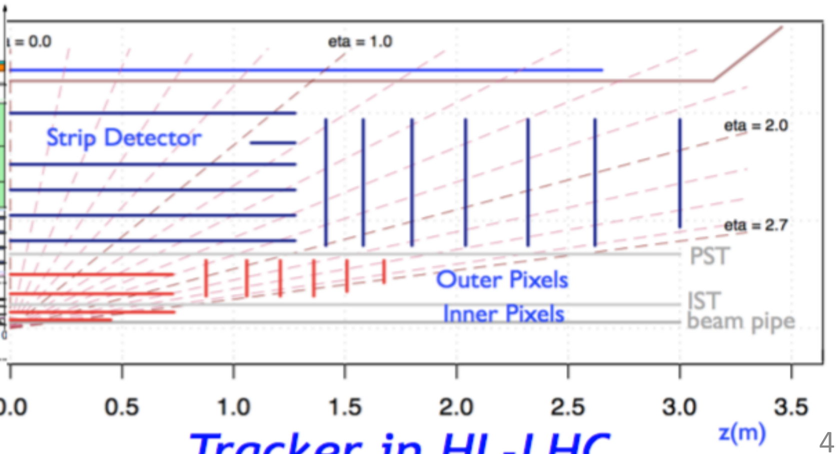


- Goal: maintain/improve performance despite high lumi.
- Completely new Si based tracking (ITK)
- New trigger system – possibly will include HW-based L1 track trigger
- Full granularity calorimetry information
- Upgrade part of the muon systems, fast trigger

Phase 2 Inner Tracker: current ID will become inefficient due to radiation damage; too high occupancy in TRT; high granularity (~4x better) required to cope with high pileup (~up to 200)



ATLAS Today



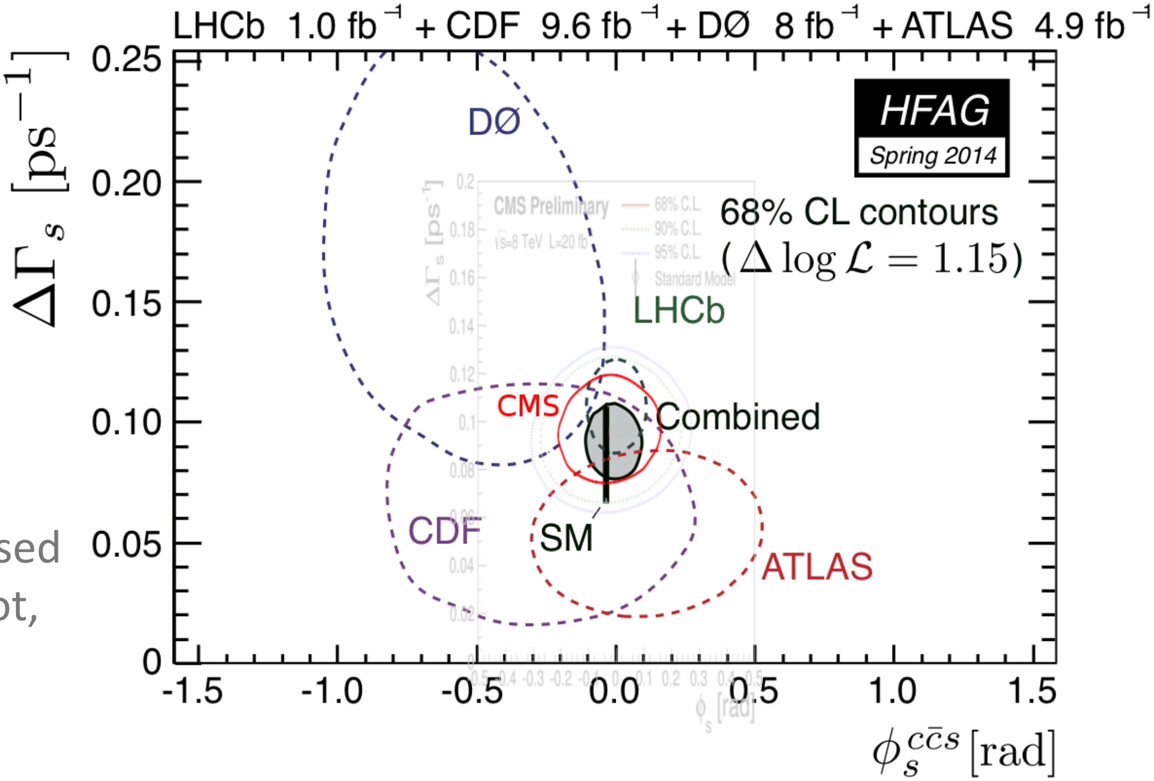
Tracker in HL-LHC

Future Potential for CPV Measurement in $B_s \rightarrow J/\psi\phi$ Decay

ATL-PHYS-PUB-2013-010
(prepared for ECFA High Luminosity LHC Experiments Workshop in 2013)

Physics Motivation

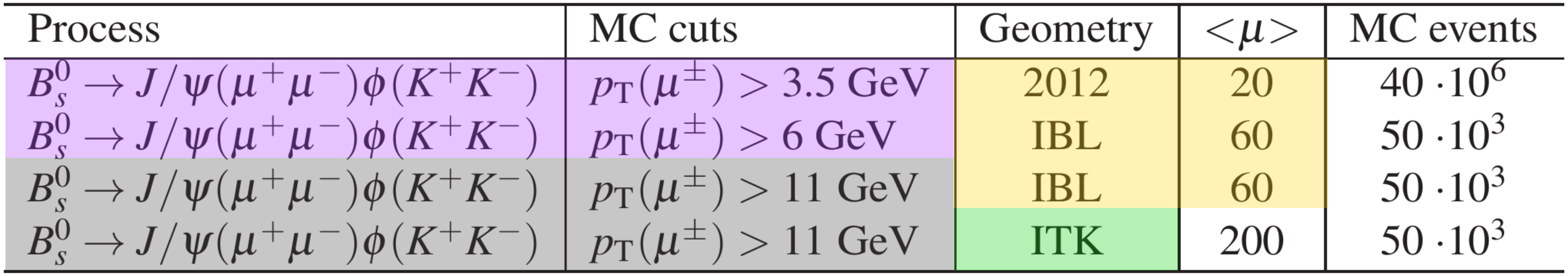
- Latest 2D sensitivity plot: CPV phase ϕ_s w.r.t. $\Delta\Gamma$ – full Tevatron data and the LHC measurements:
  - LHCb (1 fb^{-1}),
  - ATLAS (4.9 fb^{-1}),
  - CMS (20 fb^{-1})
    - fresh result, superimposed on the official HFAG plot, not included in the combination



- ATLAS result 3rd best. Analysis on the way for 8TeV data with 4× bigger statistics
- Measurements consistent with SM so far, but the SM $\phi_s = -0.0368 \pm 0.0018$ with very small uncertainty → any deviation would prove effects beyond SM
- LHC experiments will need Runs 2,3 and HL-LHC phase to achieve this sensitivity

Potential for Run 2,3 and HL-LHC

- Key factors with new detectors and high luminosity:
  - Lifetime precision: namely time resolution σ_τ – with new Inner Detectors
  - Performance stability in high pileup
  - Statistics: efficiency decrease is unavoidable; higher trigger thresholds, stronger track selections. Compensation: bigger cross-section at 14 TeV (~2 times) and high integrated luminosity at HL-LHC

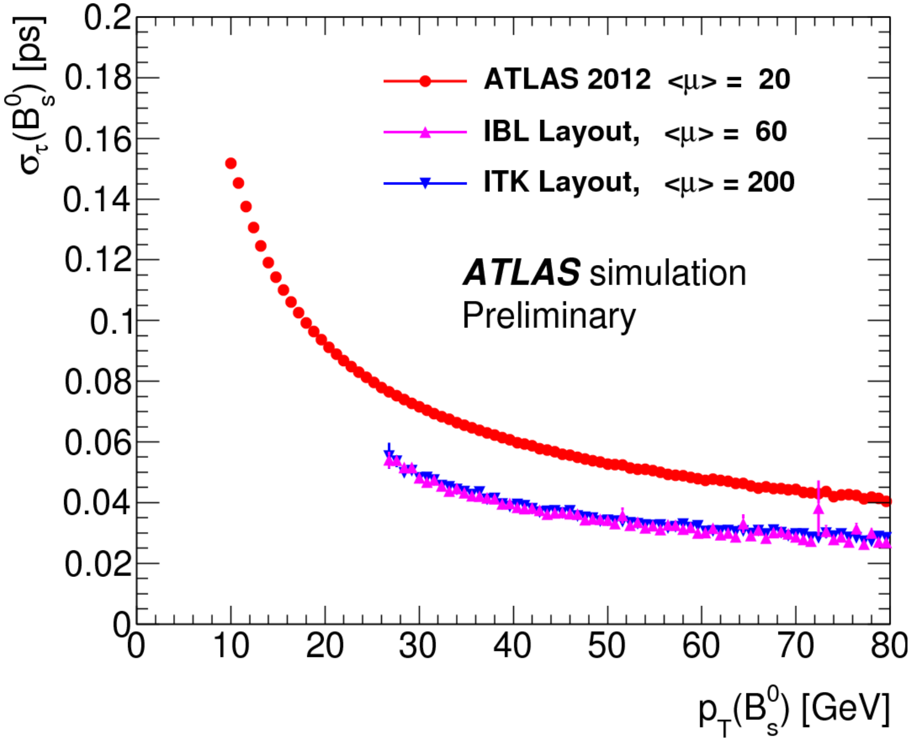


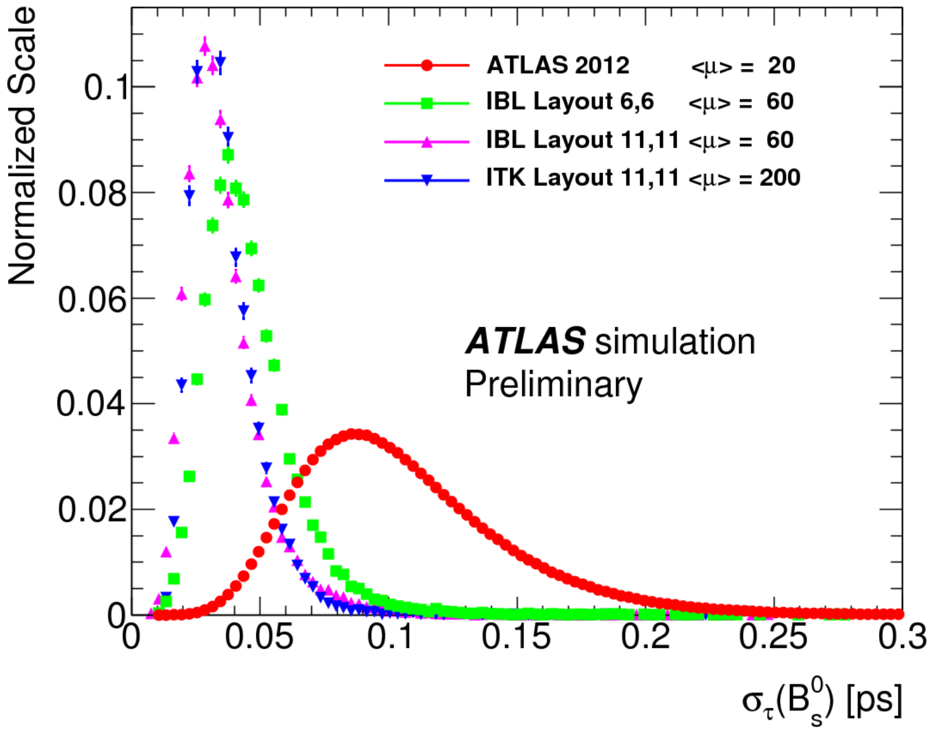
Process	MC cuts	Geometry	$<\mu>$	MC events
$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	$p_T(\mu^\pm) > 3.5$ GeV	2012	20	$40 \cdot 10^6$
$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	$p_T(\mu^\pm) > 6$ GeV	IBL	60	$50 \cdot 10^3$
$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	$p_T(\mu^\pm) > 11$ GeV	IBL	60	$50 \cdot 10^3$
$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	$p_T(\mu^\pm) > 11$ GeV	ITK	200	$50 \cdot 10^3$

model: MC events simulated with di-muon thresholds:

- p_T **6+6 GeV** or **11+11 GeV** for Run 2
- p_T **11+11 GeV** for Run 3 and HL-LHC

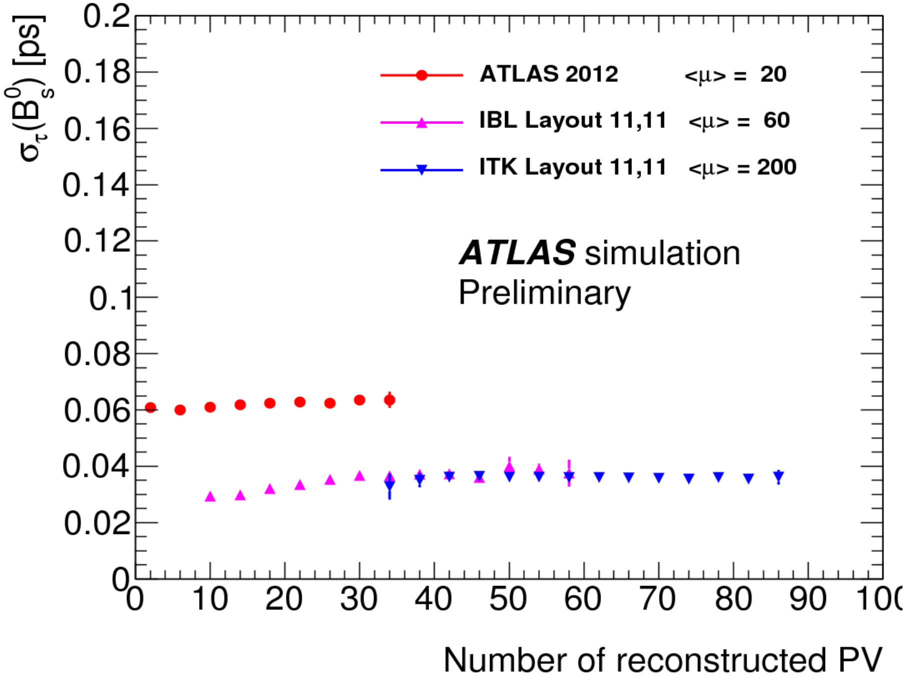
Time Resolution: ITK, IBL w.r.t Run 1

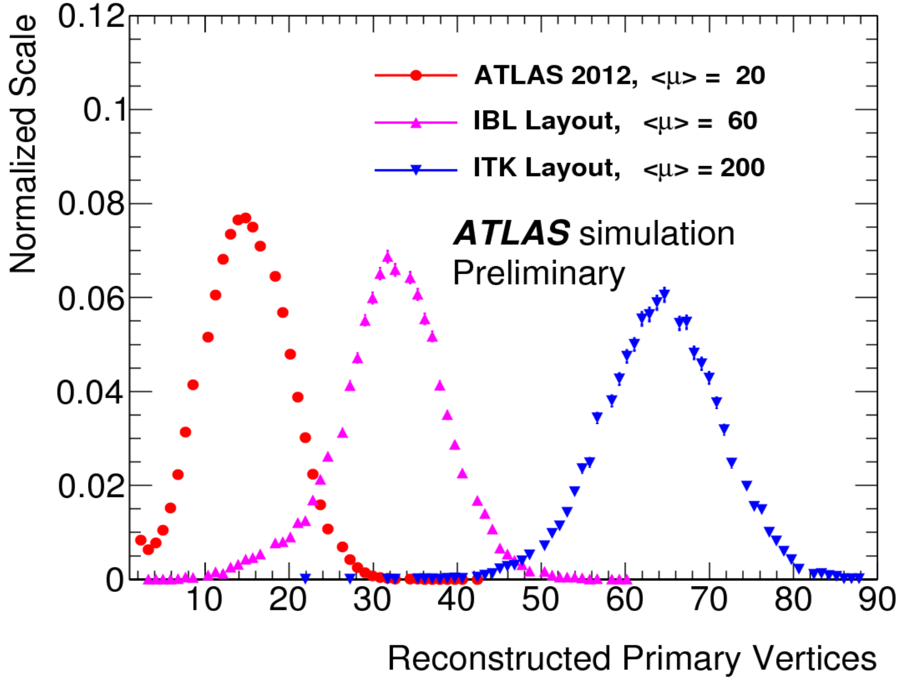




- Time resolution is important for precise measurement of CPV of fast oscillating B_s mesons
  - in 2011 data taking the LHCb $<\sigma_\tau>$ ~40 fs^{-1}, ATLAS $<\sigma_\tau>$ ~100 fs^{-1}
  - with equal statistics @ 2011: LHCb $\sigma(\phi_s)$ = 0.10 rad, ATLAS $\sigma(\phi_s)$ = 0.25 rad
- New ID layouts IBL and ITK improve σ_τ by factor of 30% compared to Run 1 performance (for the same p_T values)
- Higher p_T in future runs improves further σ_τ and signal purity on the account of lower efficiency

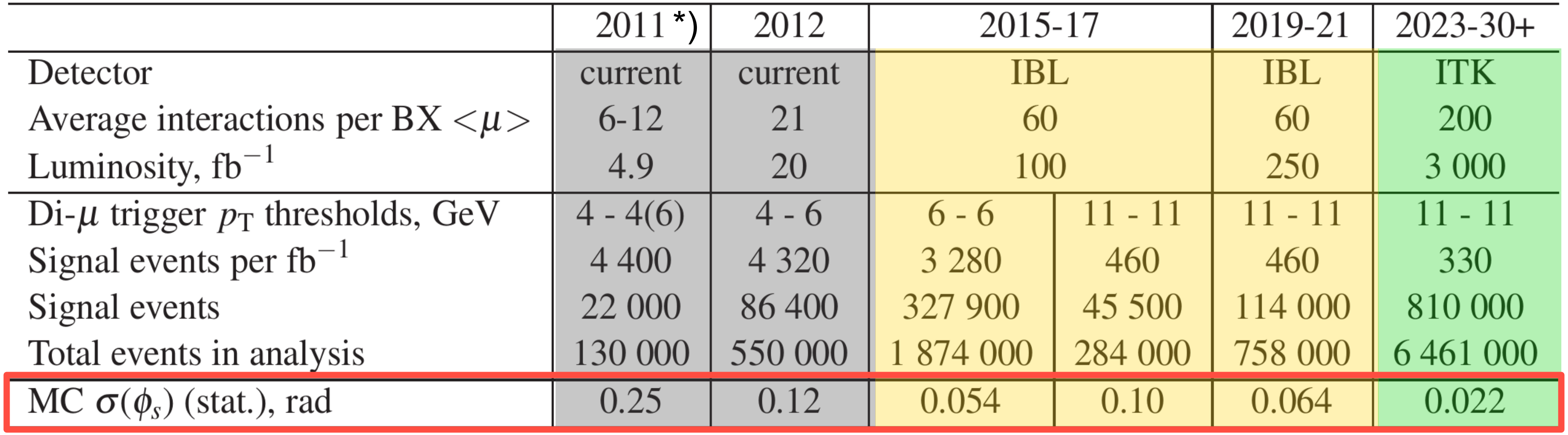
Time Resolution: Stability with #PV





- Concern: time resolution σ_τ may deteriorate with increasing <u>number of primary vertices</u> (#PV)
  - B_s decay time $\tau = L_{xy}M_B/p_T(B)$ where L_{xy} is displacement in xy plane of B_s vertex from PV
  - Best PV candidates chosen by a minimal 3D distance of $p_T(B)$ direction vector to PV
- Run 1: 8TeV (2012 data): high resolution σ_τ was low ~100 fs and dominated by material due to low p_T → σ_τ not sensitive to #PV
- IBL and ITK: high resolution σ_τ ~ 35 fs and also higher p_T used → σ_τ slightly grows (by ~14%) between #PV 10-40; then with ITK layout σ_τ becomes stable over all #PV range 40-90

Precision on CPV Phase ϕ_s from MC



	2011 *)	2012	2015-17		2019-21	2023-30+
Detector	current	current	IBL		IBL	ITK
Average interactions per BX $<\mu>$	6-12	21	60		60	200
Luminosity, fb^{-1}	4.9	20	100		250	3 000
Di-μ trigger p_T thresholds, GeV	4 - 4(6)	4 - 6	6 - 6	11 - 11	11 - 11	11 - 11
Signal events per fb^{-1}	4 400	4 320	3 280	460	460	330
Signal events	22 000	86 400	327 900	45 500	114 000	810 000
Total events in analysis	130 000	550 000	1 874 000	284 000	758 000	6 461 000
MC $\sigma(\phi_s)$ (stat.), rad	0.25	0.12	0.054	0.10	0.064	0.022

- *) 2011 Toy-MC fit driven by 2011 data, result is consistent with real 2011 data analysis (arXiv: 1407.1796, W. Dearnaley talk on Monday), background estimates from 2012 data sidebands
- 2012 is also a result of Toy-MC model, driven by 2012 data
- Muon p_T thresholds 11+11 GeV substantially (7×) decrease number of signal events per fb^{-1} w.r.t. 6+6 GeV thresholds
- Hence a potential in Runs 2 and 3 would depend on muon trigger thresholds applied
- Two given ϕ_s precision values for Run 2: 0.054 rad (11+11 GeV) and 0.10 rad (6+6 GeV) represent an optimistic and a rather conservative options

Conclusions

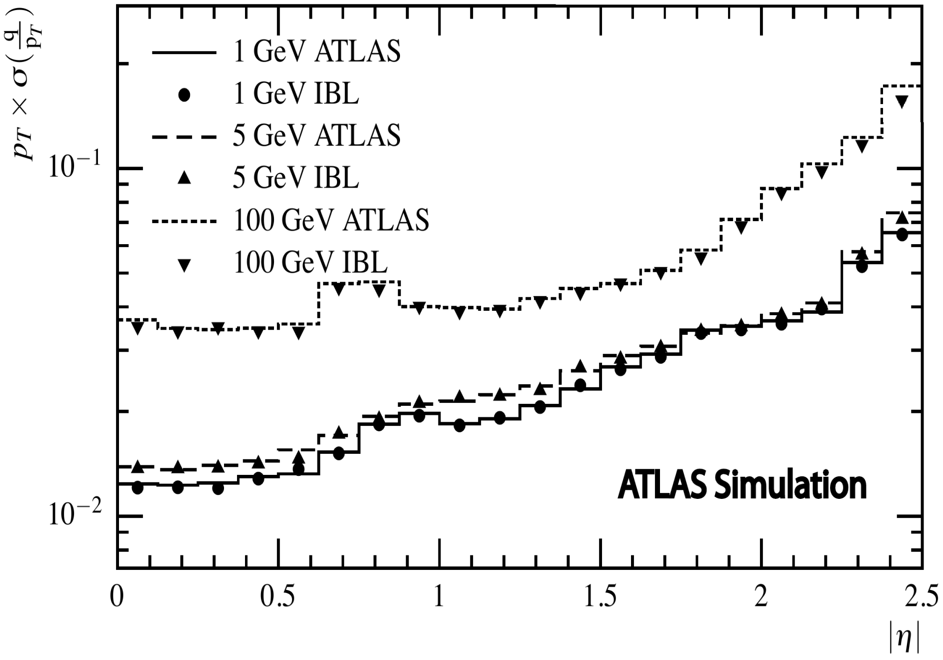
- ATLAS will continue its B-physics program in the Run 2,3 and the HL-LHC era, focusing on precision measurements, rare decays and heavy flavour production and spectroscopy

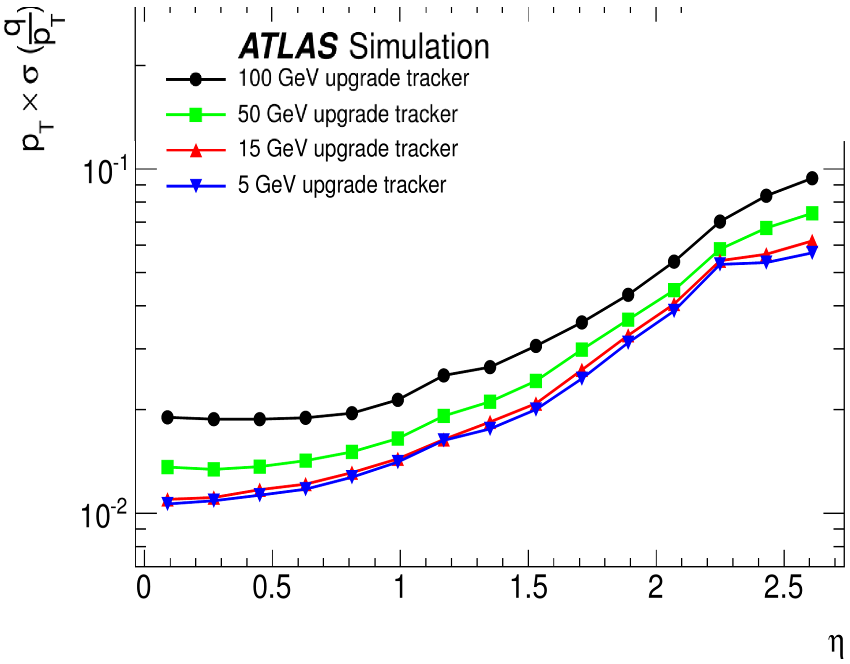
- Detector upgrades (namely in tracking and muon system) and new trigger strategies and tools will help to cope with the high-luminosity environment and achieve precision needed to examine possible beyond-SM effects in the heavy-flavour production and decays

- Pilot study of $B_s \rightarrow J/\psi\phi$ CPV analysis:
  - shown improvements in the precision coming from the tracking detectors upgrade (already those for Run 2)
  - demonstrated strong dependence of the precision on the trigger thresholds/ configurations
  - indicated weak effect on the analysis by the expected pile-up conditions in future LHC Runs

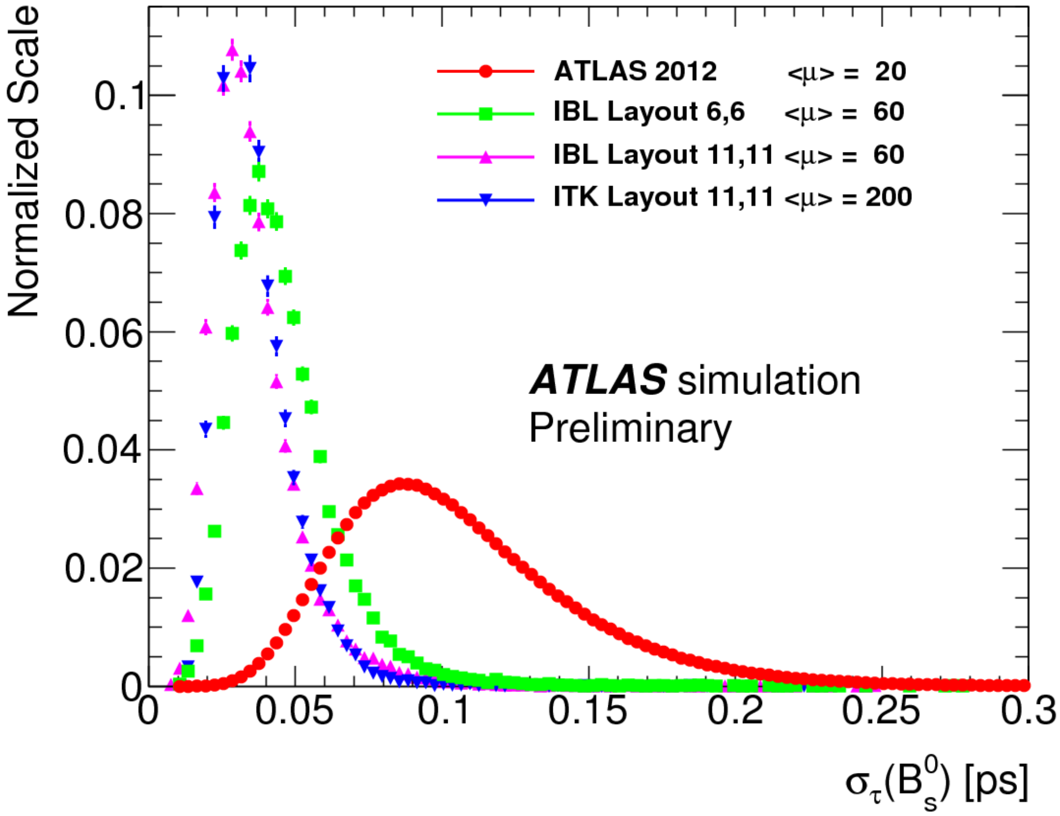
IBL & ITK p_T Resolution

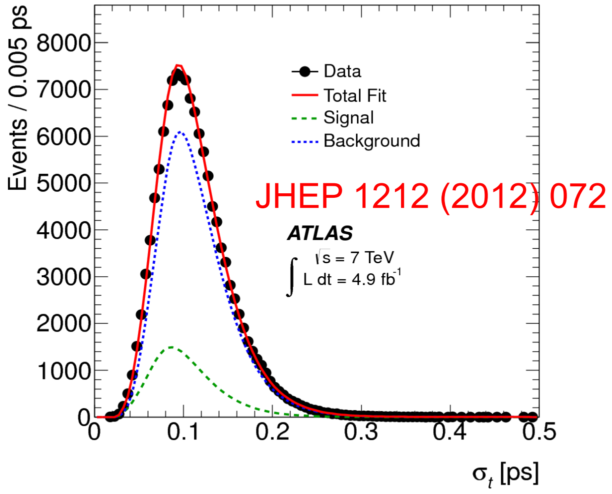
CERN-LHCC-2012-022 ; LHCC-I-023





Time Resolution: ITK, IBL w.r.t Run 1





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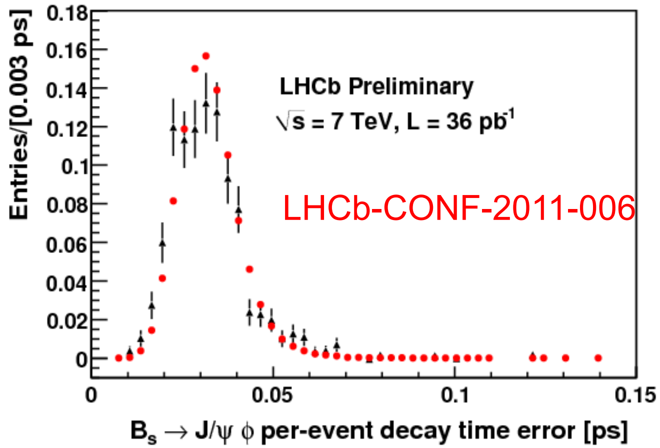


LHCb-CONF-2011-006

- Improvement of an average time resolution $<\sigma_\tau>$ in future runs will also be connected with increased p_T thresholds
- On the other side, the increase of the thresholds will reduce efficiency with improved trigger purity

Measurement Precision Using Toy-MC

- Performance parameters extracted from fully simulated signal events were used as input to Toy-MC to estimate precision on physics parameters of the B_s decay
- Background full simulation not done (too high rejection), so background properties derived from mass-sidebands of 2012 data; for future layouts after applying muon $p_T > 6$ GeV or $p_T > 11$ GeV cuts
- Generated Toy-MC events were then fit by the same program as used for real data
- Toy-MC model was validated against 2011 data conditions and the results on sensitivity to physics parameters found consistent with real data analysis

Study of the CMS Phase-2 upgrade performance for the B⟶μμ measurement

CMS Collaboration

B physics studies

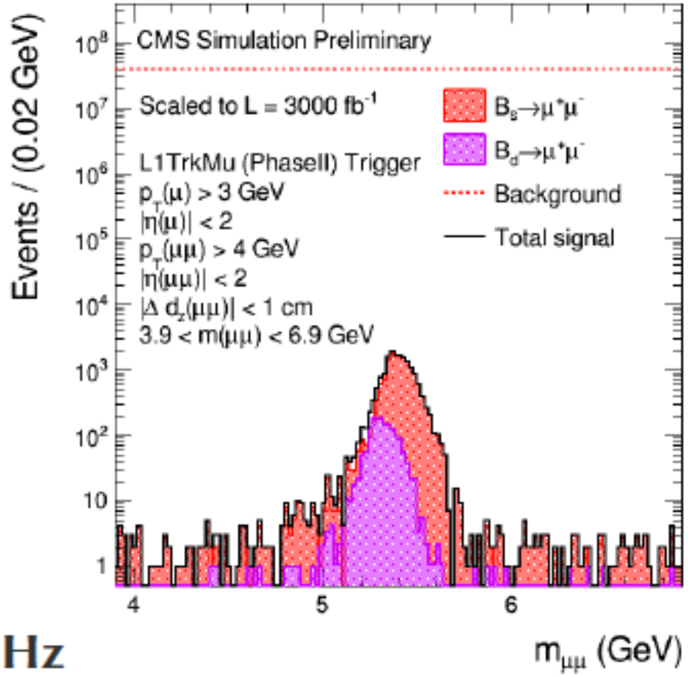
- One benchmark channel was studied for assessing the B-physics performance of the CMS Phase-2 upgraded detector: search for $B^0 \to \mu\mu$ decays and measurement of the $B^0_{(s)} \to \mu\mu$ branching fraction
  - Physics importance of the channel: the observation of the $B^0 \to \mu\mu$ decay and the precise determination of its branching fraction can pose stringent limits to new physics models
  - Other measurements are possible with the statistics collected at HL-LHC: cross section ratios, polarization, etc. Only some of them were considered in this study.

- For this study, we looked at two aspects of the analysis
  1) Implementation and performance of a L1 track trigger for the $B \to \mu\mu$ signal
  2) Effect of CMS upgrades to the final analysis performance

- The two CMS upgrades that affect more the analysis outcome are:
  - L1 Trigger: especially through the new track trigger machinery
  - Tracker: through the reduced material budget and increased resolution

L1 trigger for $B^{o}_{(s)}\rightarrow\mu\mu$

- We simulated a low-p_T di-muon L1 trigger algorithm exploiting the triggering capabilities of the upgraded CMS tracker
  - 2 opposite-charge L1 "Tk muons", reconstructed from a matching of the L1 tracks and L1 standalone muons
  - $p_T(\mu) > 3$ GeV
  - $|\eta(\mu)| < 2$
  - $p_T(\mu\mu) > 4$ GeV
  - $|\eta(\mu\mu)| < 2$
  - $\Delta d_z(\mu\mu) < 1$ cm
  - $3.9 < m(\mu\mu) < 6.9$ GeV



- Mass resolution at L1 is measured to be ≈ 70 MeV using Gaussian fits to the signal peaks
- Trigger rate in the HL-LHC conditions (average of 140 PU events) is estimated to be **a few hundred Hz**
  - It constitutes only a tiny fraction of the total L1 bandwidth
- This study shows that the expected performances of the upgraded CMS L1 trigger are more than sufficient to implement trigger algorithm for B⟶μμ having the same acceptance of the L1 trigger used in LHC Run 1

Setup of toy experiments to estimate CMS performance

- We run toy experiments to estimate the analysis performance in two scenarios:
  - The Phase-1 scenario, corresponding to the expected performance of the CMS detector after the Phase-1 upgrades and to 300 fb^{-1} of integrated luminosity
  - The Phase-2 upgrade scenario, corresponding to the expected performance of the CMS detector after the full Phase-2 upgrades and to 3000 fb^{-1} of integrated luminosity
- In both cases we are using the public results of the Run-1 $B_s \to \mu\mu$ analysis as a starting point, incorporating also the improvements present in the CMS-LHCb combination (under preparation). These improvements are:
  - Changes in the way the signal efficiency depends on proper life time (increases B_s signal yield)
  - Change in the shape of the semi-leptonic background due to the use of an improved theoretical model
- The toy experiments use the **invariant mass resolution coming from the full Geant4 simulation** of the CMS detector as input:
  - In the case of the Phase-1 scenario, this is roughly equal to the resolution measured with the current CMS detector, i.e. ≈ 42 MeV when both muons are in the barrel ($|\eta| < 1.4$)
  - In the case of the Phase-2 scenario, this is ≈ 28 MeV when both muons are in the barrel ($|\eta| < 1.4$), with **an improvement of a factor 1.5 with respect to the Phase-1 scenario**
- Other inputs to the toy experiments come from extrapolations from the Run-1 analysis (detailed in the next slides)
- Input signal branching fractions from Standard Model predictions are assumed everywhere

Other inputs to the toy experiments: 300 fb^{-1}

- These are the details of the extrapolations made in order to find the inputs to the toy experiments for the Phase-1 300 fb^{-1} scenario:
  - Barrel only (muon $|\eta| < 1.4$)
  - Muon efficiency & fate rate: the same as 8 TeV analysis
  - Uncertainty on B^+ normalization channel: 5%
  - Uncertainty of the peaking backgrounds: 20%
  - Uncertainty of the semileptonic backgrounds: 25%
  - Uncertainty of the f_s/f_u ratio: 5%
  - Trigger & PU performance: same as 8 TeV analysis

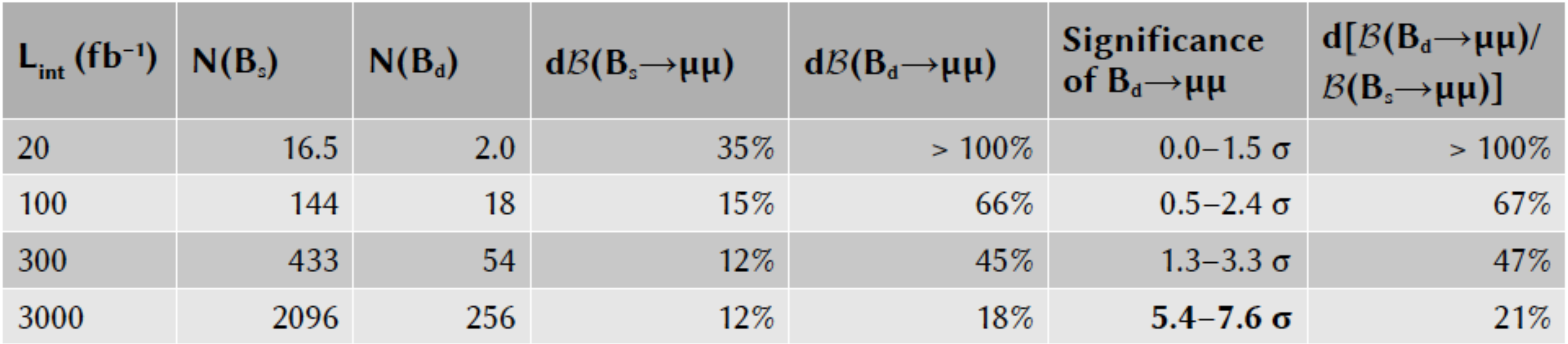
- As written in slide 4, in addition to these extrapolations, the invariant mass resolution coming from the full Geant4 simulation of the Phase-1 CMS detector is used ($\approx$ 42 MeV)

Other inputs to the toy experiments: 3000 fb^{-1}

- These are the details of the extrapolations made in order to find the inputs to the toy experiments for the Phase-2 3000 fb^{-1} scenario:
  - Barrel only (muon $|\eta| < 1.4$)
  - Muon efficiency & fate rate: the same as 8 TeV analysis
  - Uncertainty on B^+ normalization channel: 3%
  - Uncertainty of the peaking backgrounds: 10%
  - Uncertainty of the semileptonic backgrounds: 20%
  - Uncertainty of the f_s/f_u ratio: 5%
  - Trigger & PU performance:
    - 35% reduction of efficiency on signal and normalization channel
    - 30% reduction of efficiency on backgrounds

- As written in slide 4, in addition to these extrapolations, the invariant mass resolution coming from the full Geant4 simulation of the Phase-2 CMS detector is used (≈ 28 MeV)

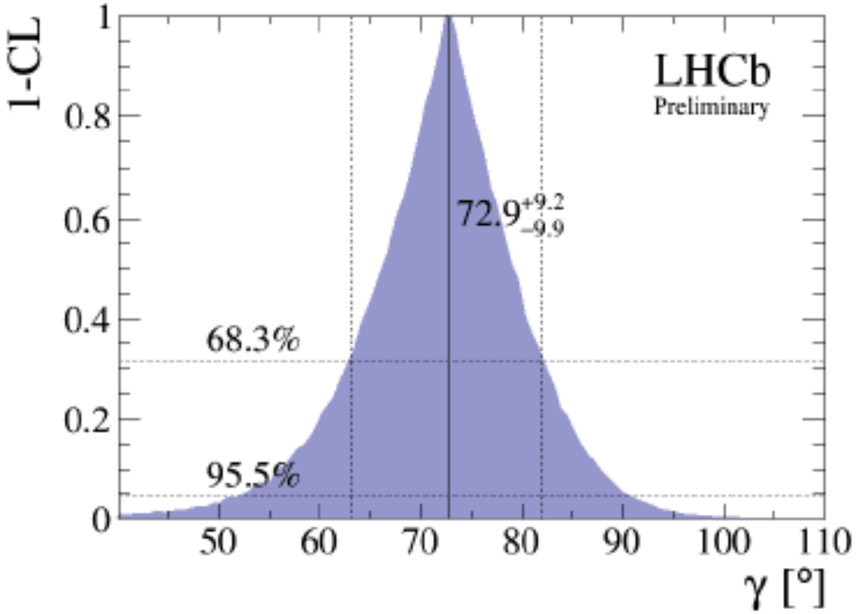
Reference results from PAS FTR-13-022



L_{int} (fb^{-1})	$N(B_s)$	$N(B_d)$	$d\mathcal{B}(B_s\rightarrow\mu\mu)$	$d\mathcal{B}(B_d\rightarrow\mu\mu)$	Significance of $B_d\rightarrow\mu\mu$	$d[\mathcal{B}(B_d\rightarrow\mu\mu)/\mathcal{B}(B_s\rightarrow\mu\mu)]$
20	16.5	2.0	35%	> 100%	0.0–1.5 σ	> 100%
100	144	18	15%	66%	0.5–2.4 σ	67%
300	433	54	12%	45%	1.3–3.3 σ	47%
3000	2096	256	12%	18%	**5.4–7.6 σ**	21%

γ from B → DK

- Sensitivity to γ from numerous channels
  - $B^+ \to DK^+$ ($D \to K_S hh$)
  - $B^+ \to DK^+$ ($D \to hh'$)
  - $B_s \to D_s K$
  - $B^0 \to DK^{*0}$ ($D \to hh'$)
    - $B^0 \to DK\pi$ ($D \to hh'$)
  - $B^+ \to DK^+$ ($D \to K_S K\pi$)
  - $B^+ \to DK^+$ ($D \to K3\pi$, 4h, $hh'\pi^0$)
  - $B^0 \to DK^{*0}$ ($D \to K_S hh'$)
  - $B^+ \to DK^+\pi\pi$ ($D \to hh'$, $K_S hh'$, etc.)
  - $B^+ \to D^*K^+$ ($D \to hh'$, $K_S hh'$, etc.) … and many, many more



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