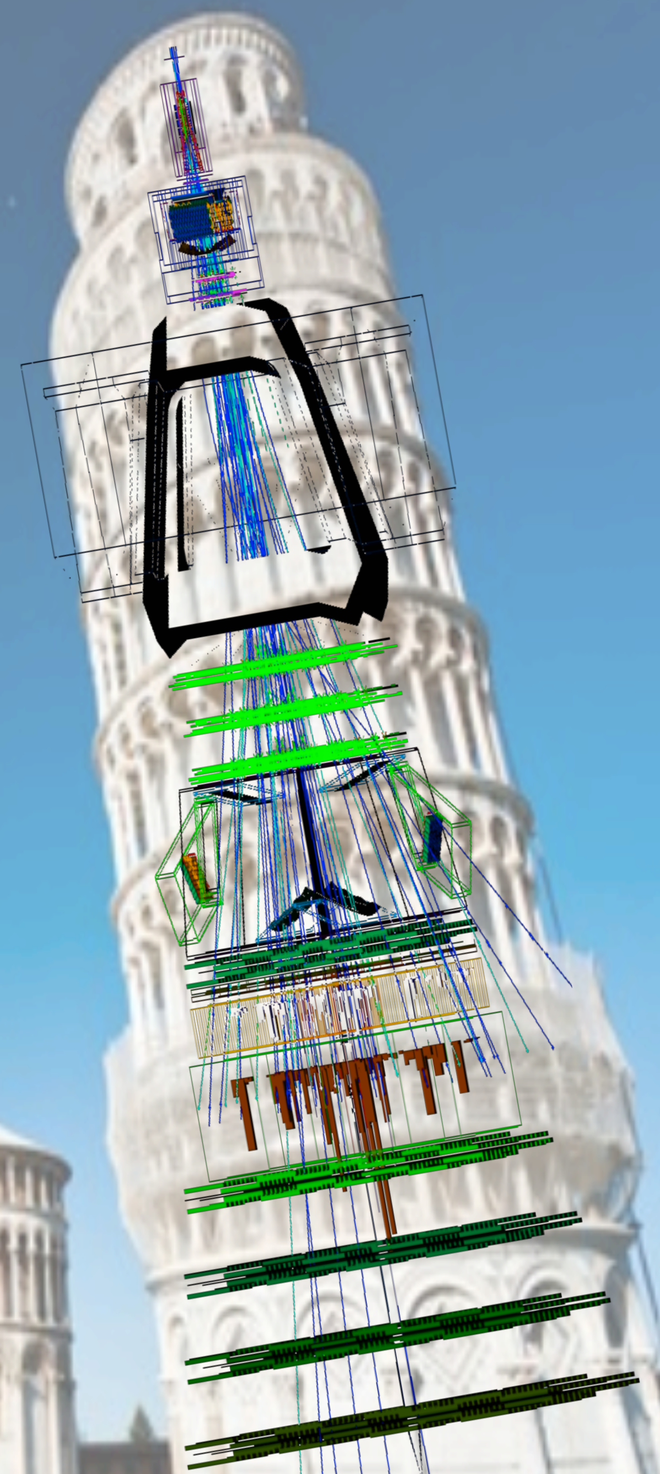
An "extreme" heavy flavour experiment?

(beyond LHCb and Belle II)

V. VAGNONI

INFN BOLOGNA

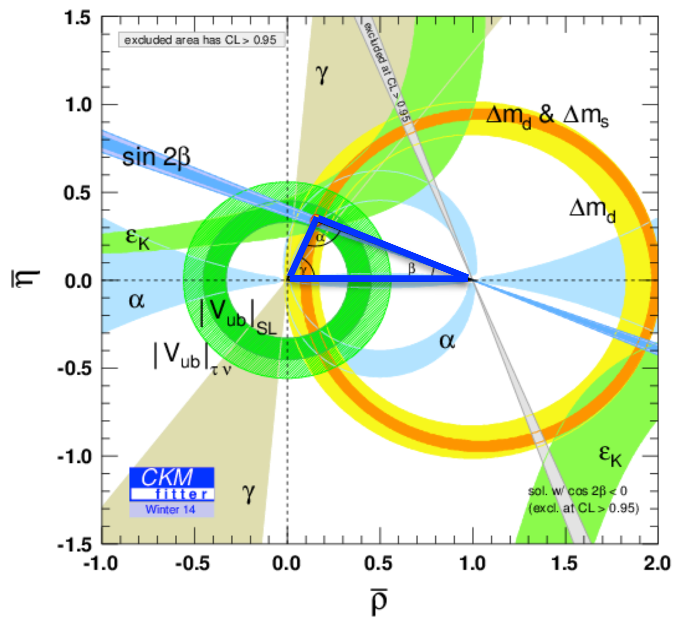


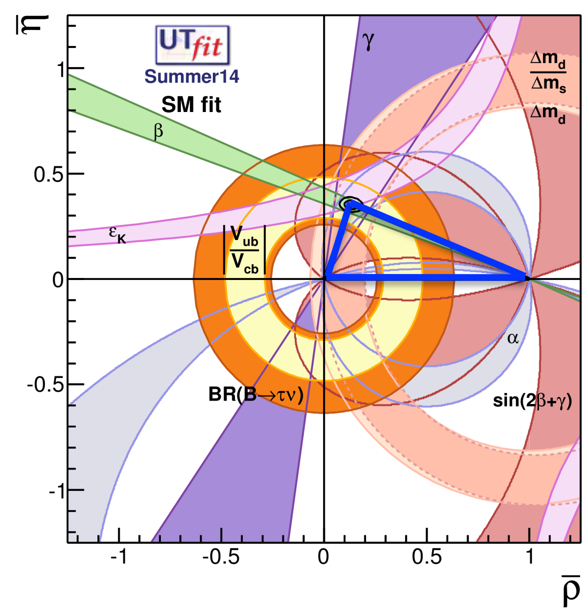
THE LANDSCAPE OF FLAVOUR PHYSICS TOWARDS THE HIGH INTENSITY ERA

9-10 December 2014
Scuola Normale Superiore, Pisa

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

Consistency of global CKM fits

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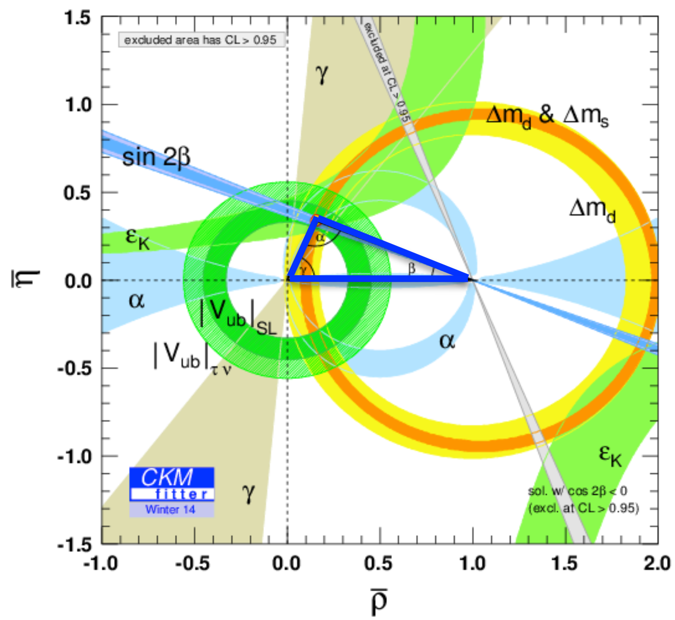
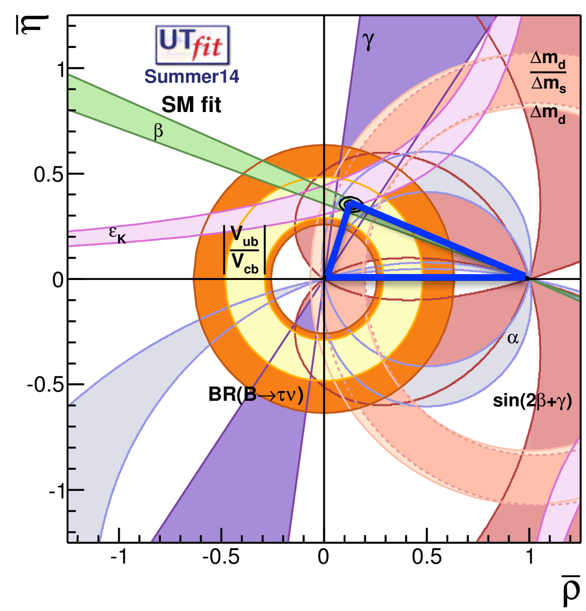


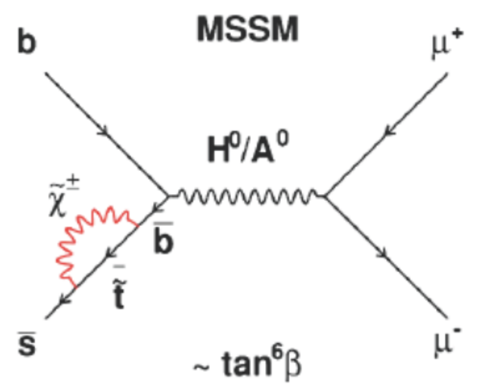


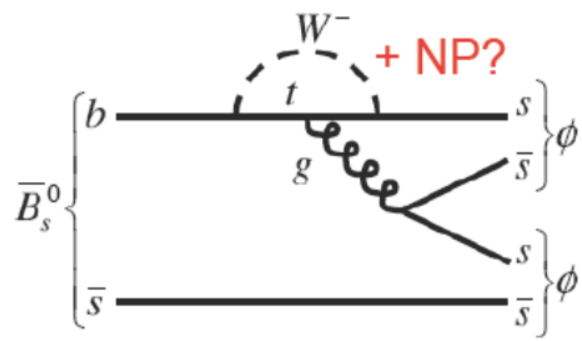
- We are leaving in a strange era
  - on the one hand we have been achieving great experimental success
  - on the other hand, we feel depressed as everything looks consistent with what we already knew

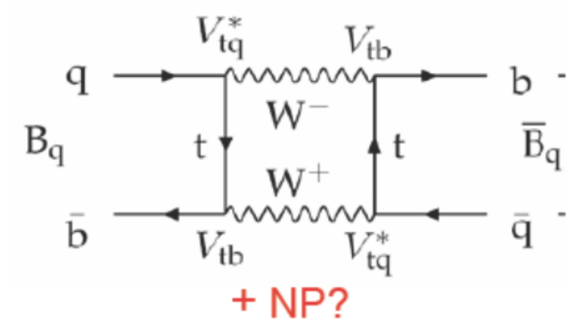
However...

- There are good reasons to believe that the SM is incomplete
  - hierarchy
  - unification of gauge couplings
  - dark matter
  - matter-antimatter asymmetry
  - ...
- Unfortunately these arguments do not provide stringent quantitative predictions, apart from hints that the NP scale should be "close" to the EW scale
- By studying *CP*-violating and flavour-changing processes we can accomplish two fundamental tasks
  - Identify new symmetries (and their breaking) beyond the SM
  - Probe mass scales not accessible directly

Precision measurements of *CP* violation and rare decays







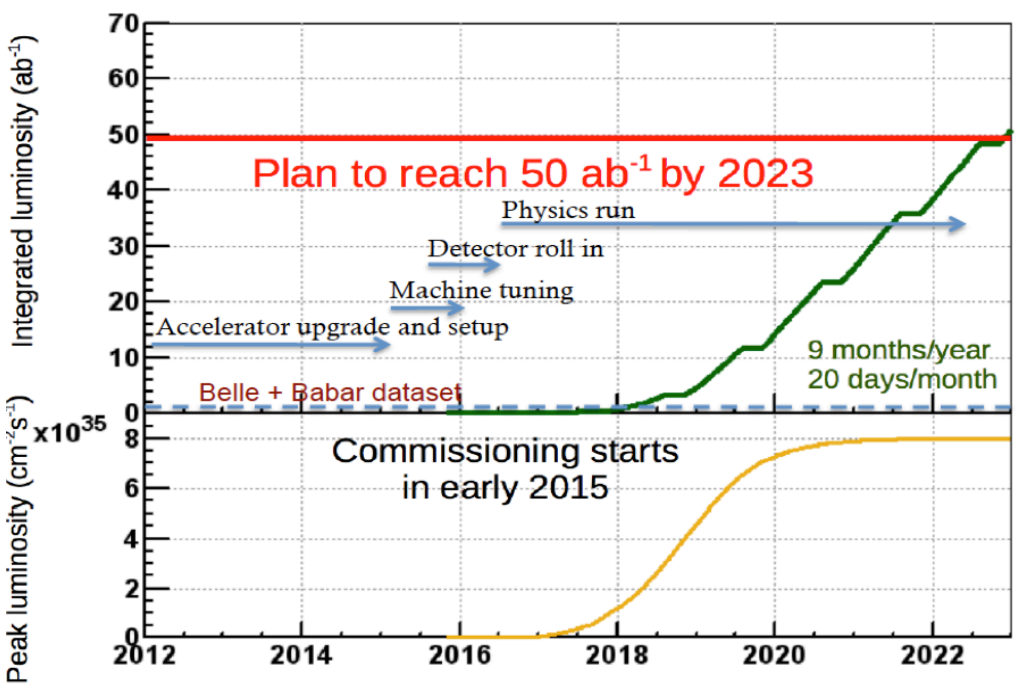
- General decomposition in terms of couplings and scales

$$A = A_0 \left[c_{SM} \frac{1}{M_W{}^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

- If the SM contribution is not negligible, uncertainties on the SM coupling can hide NP effects
  - Need to go to high precision measurements of theoretically clean observables

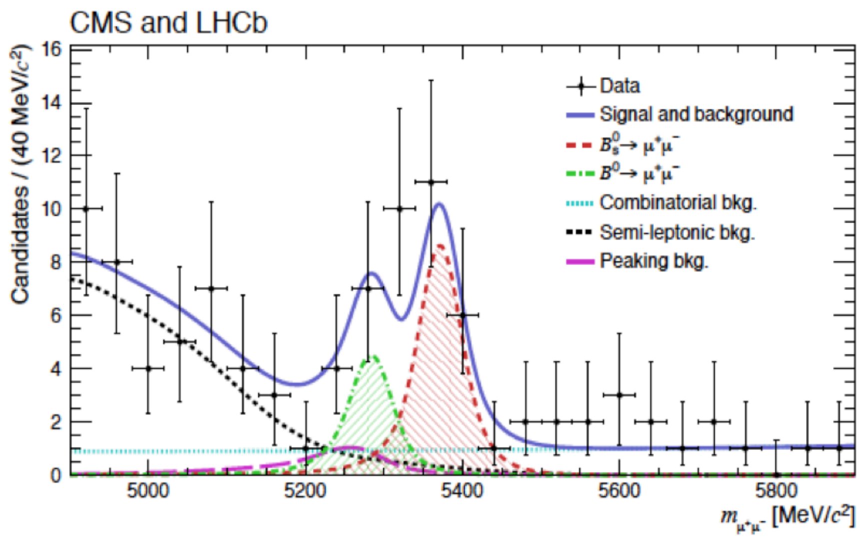
LHC and Belle II runs

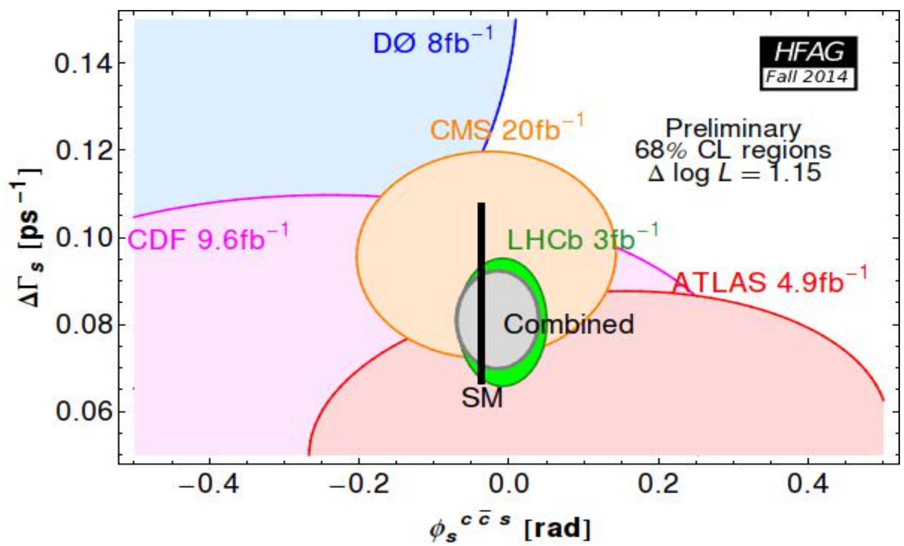
	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)
ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	⟶	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

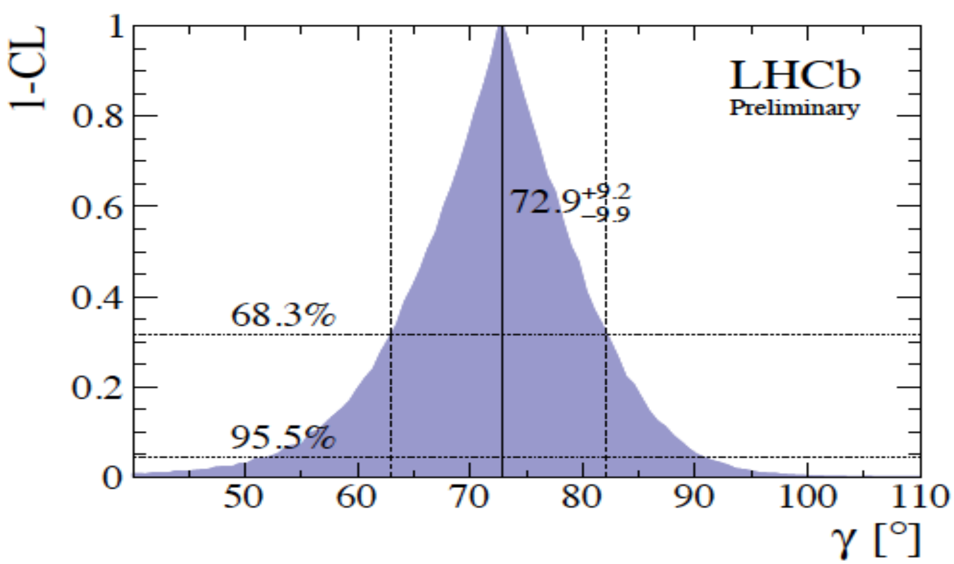


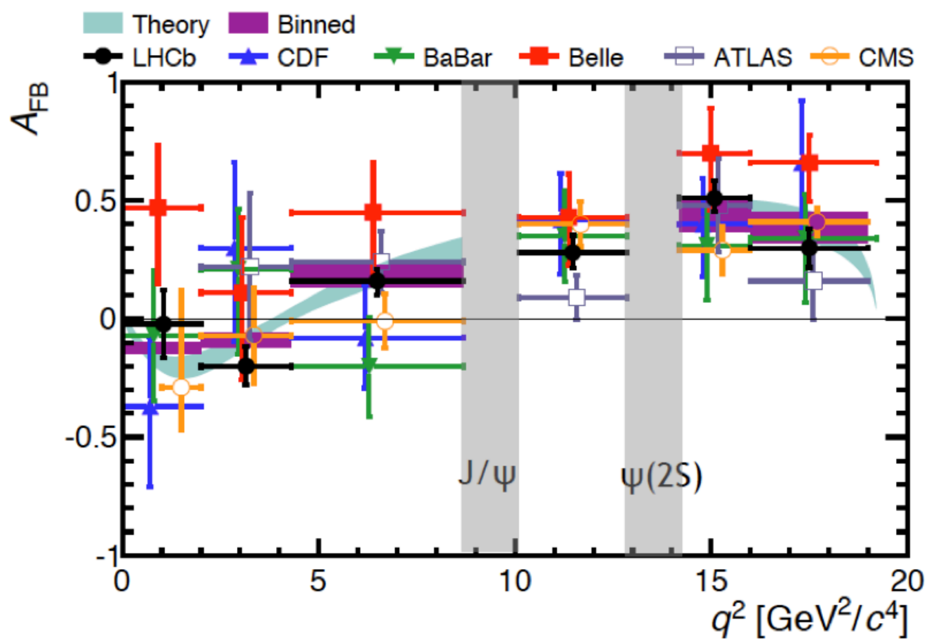
- Physics run expected around 2018, but will start deploying the full potential by 2020
  - Integrating 50 ab^{-1} in about 5 years

Some selected topics from LHC Run 1

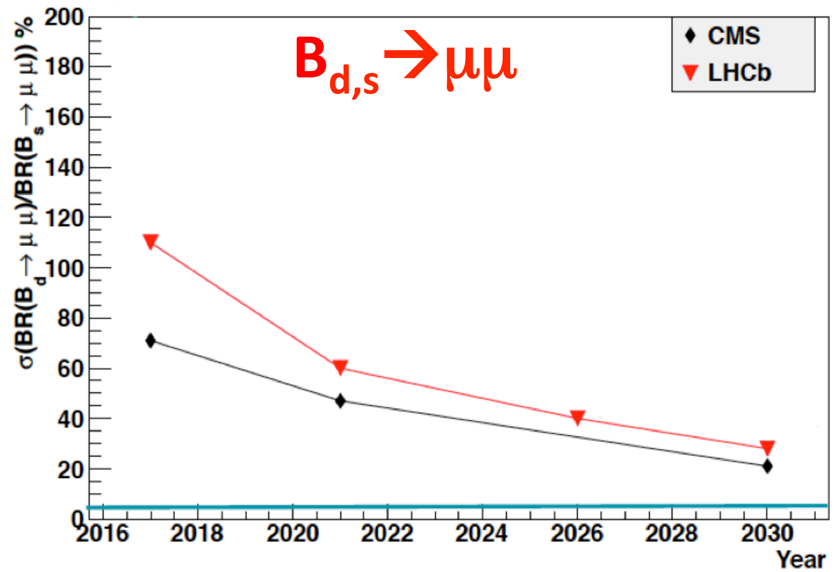


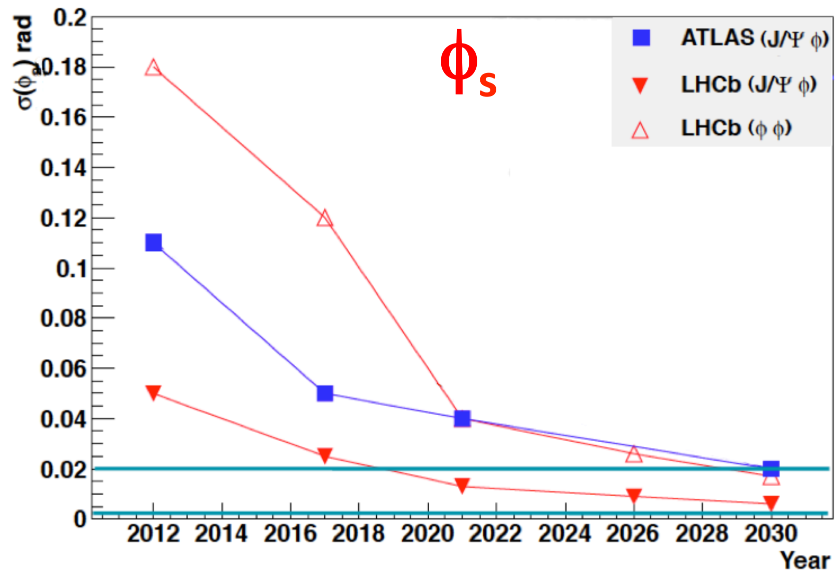


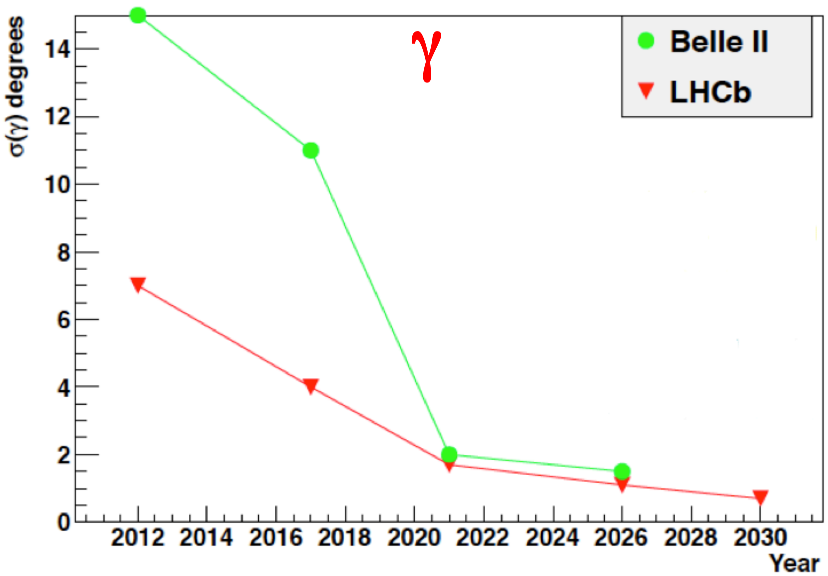


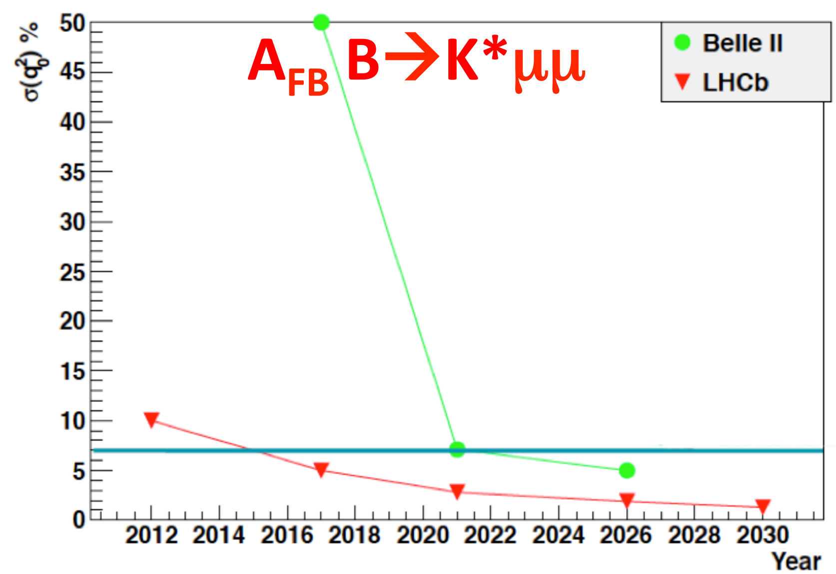


Very nice prospects

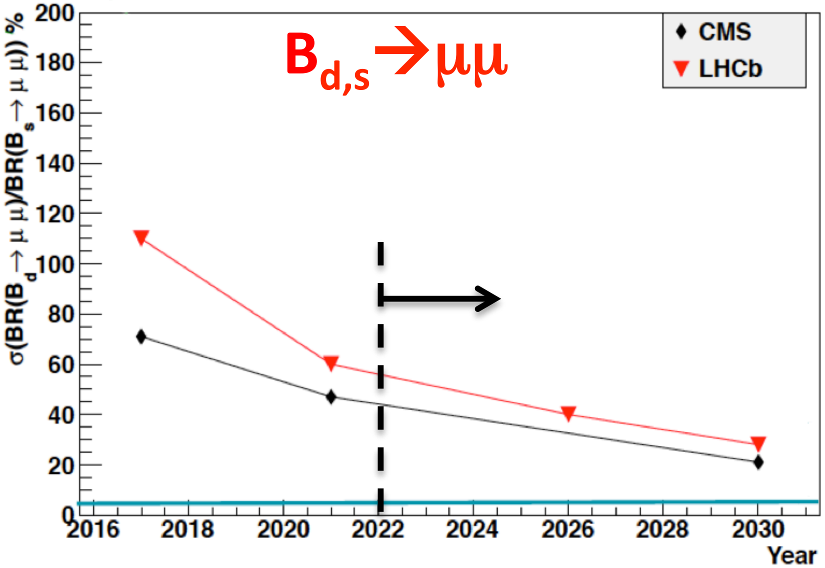


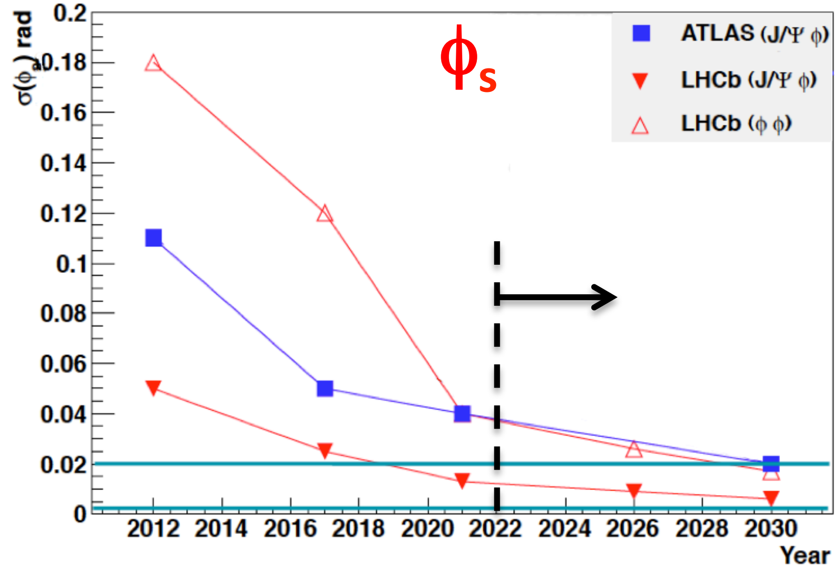


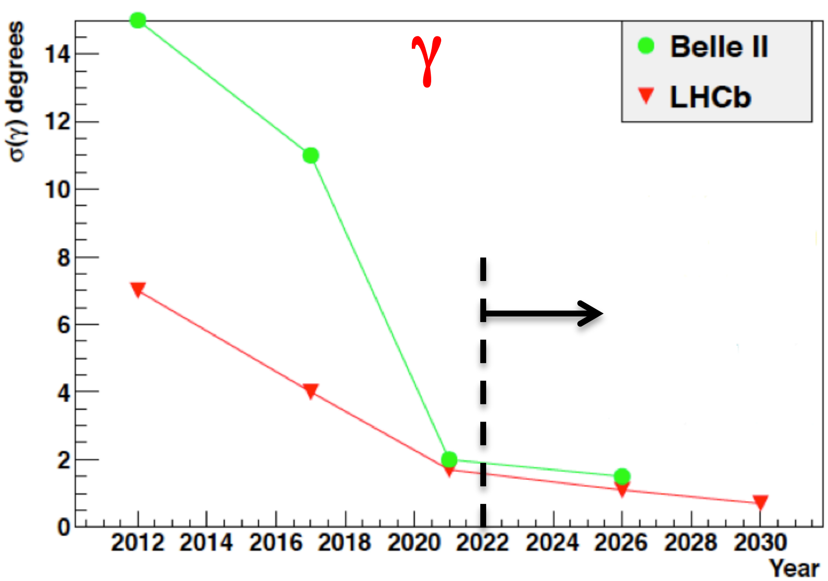


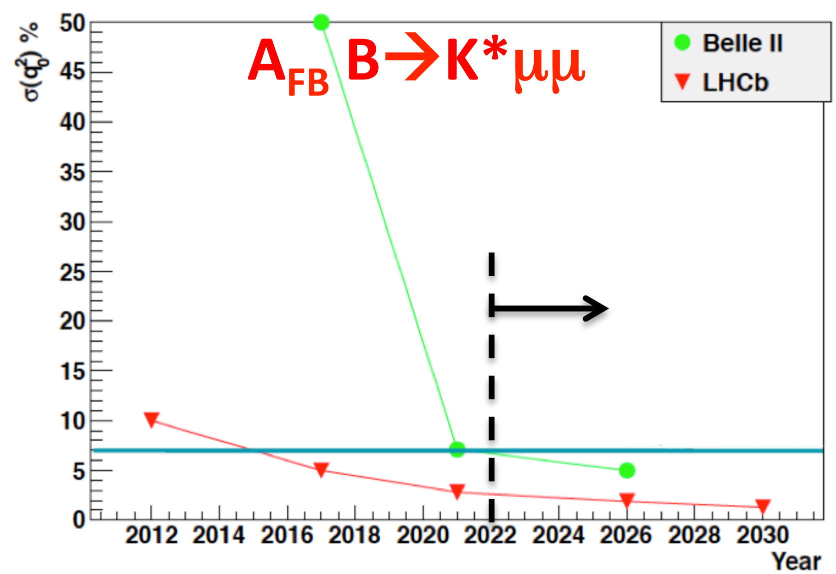


But...









- Marginal improvements in the 2020's

An "Extreme Flavour" experiment?

- Currently planned experiments at the HL-LHC will only exploit a small fraction of the huge rate of heavy-flavoured hadrons produced
  - ATLAS/CMS: full LHC integrated luminosity of 3000 fb^{-1}, but limited efficiency due to lepton high p_T requirements
  - LHCb: high efficiency, also on charm events and hadronic final states, but limited in luminosity, 50 fb^{-1} vs 3000 fb^{-1}
- Would an experiment capable of exploiting the full HL-LHC luminosity for flavour physics be conceivable?
  - Aiming at collecting O(100) times the LHCb upgrade luminosity → 10^{14} b and 10^{15} c hadrons in acceptance at $L=10^{35}$ $cm^{-2}s^{-1}$

An “Extreme Flavour” experiment?

- Very difficult to give an answer, but if we want anything like that to happen at some point, we need to start discussing
  - The European Strategy Group recommended to achieve "full exploitation of the LHC", but no plans currently exist in the flavour sector, unless descoping what “full” means
- In parallel to the experimental discussion, a detailed study of the physics impact should be carried out as well
- Some exploratory work ongoing in the framework of the “What’s Next?” INFN initiative

Challenges

- There are good reasons why such a discussion has not started
- On the experimental side: processing and storing such a huge amount of interesting events is a difficult technological endeavour, even when projected a decade into the future
  - Such an experiment would require an improvement of a factor 10^4 to 10^5 both in permanent storage capacity and computing power with respect to the state-of-the-art, we might achieve a factor 10^2-10^3 maybe
  - Need a shift of paradigm to perform data analysis in real time, rather than much later offline
- On the theoretical side: can such a sample of bottom and charm mesons be fully exploited?
  - O(100x) limits, O(10x) resolutions
    - E.g.: UT angles at 0.1°, charm CPV at 10^{-5}, $B_d/B_s \to \mu\mu$ at 3%, $t \to \mu\mu\mu$ at 10^{-11}
  - Can theoretical uncertainties be brought down to the projected experimental ones for a large enough number of interesting observables?

Concept

- If we could identify the interesting heavy-flavour decays in real time and record only the information that is relevant to the study of each particular process, we would achieve a large reduction in the amount of data to be transmitted and stored permanently
- In this way we would gain orders of magnitude in the number of decays collected per unit time with respect to what could be done with a traditional approach
  - thus alleviating the size of the data storage and at the same time the amount of computing power required for the final analysis

Requirements

- Readout at 40 MHz
  - we are already there (e.g. LHCb upgrade), but much larger throughput
- Strong tracking capabilities at high luminosity
- Real time event reconstruction at 40 MHz
  - Get tracks and other complex primitives straight out of the detector
    - Need for specialized processors?
- Particle identification
  - muon (mandatory), hadronic (very important), calorimeter (useful?)
- Offline-like calibration in real time
- Physics analysis in "real time"
  - Ability to do precision measurements from reduced data formats
  - Need superior real time detector calibration, and well-chosen control samples
  - Need clever methods to control systematics
    - Understanding of systematic uncertainties at that required level of precision will be yet another challenge

Reading out the detector

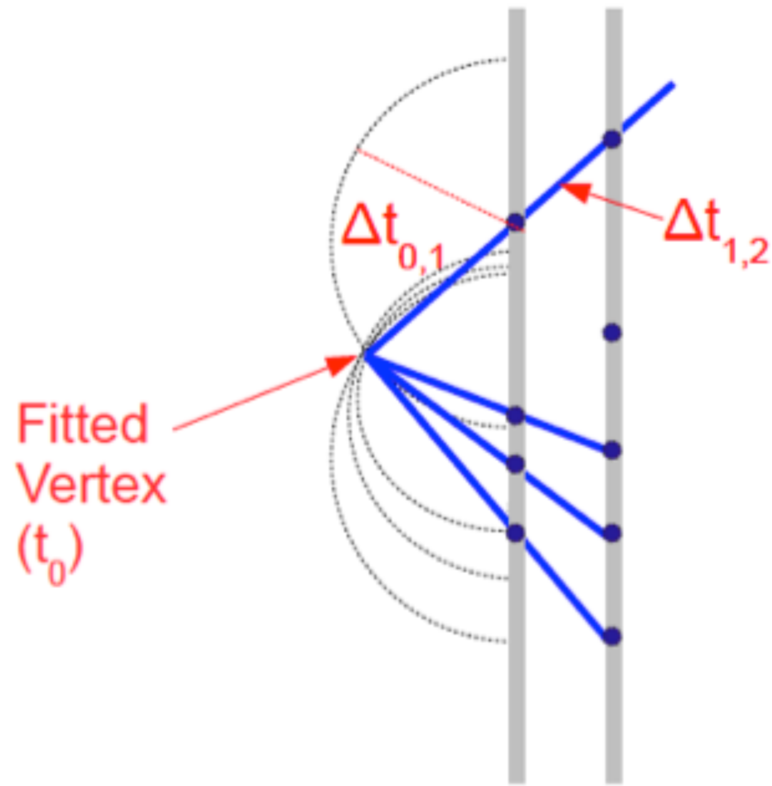
- LHCb upgrade plans to readout 40 Tb/s → about 10^4 serial links
  - ~4 Gb/s sustained by a current GBT device
  - Estimated cost is about 1.5 MCHF
- How to increase by a factor 100?
- A first obvious challenge arises from the required number of serial links with present technology → 10^6 links
  - A new radiation-hard serialiser chip characterised by a much higher bandwidth than the GBT would be needed to have a manageable number of links (no more than few 10^4)
- State-of-the-art commercial FPGAs provide serial I/O link components covering a range between 10 Gb/s to 40 Gb/s
  - However, they are not radiation-hard devices
  - Current radiation-hardened FPGAs are generally equipped with transceivers of limited bandwidth (of the order of few Gb/s)
- The feasibility of such a new generation high-speed radiation-hard device for data transmission needs to be investigated

Tracking capabilities

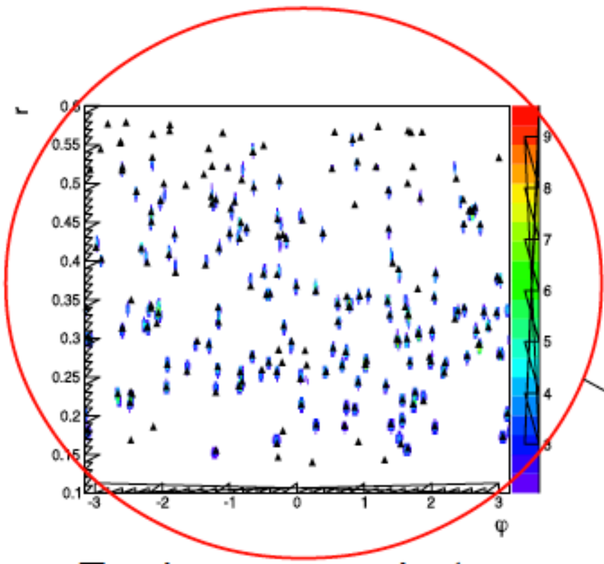
- A good tracking system is crucial to handle a pileup with 100 vertexes
- Pattern recognition is certainly challenging, but can be helped in various ways
  - Double-layer detectors (a la CMS)
    - local measurement of track angle
  - Time-tagged silicon pixel detectors
    - e.g. UFSD project (R&D by N. Cartiglia, INFN Torino), aim at 50 μm and 10 ps from a single pixel
- Resolving primary vertexes is an issue, but maybe not strictly necessary
  - May measure decay lengths by intersecting trajectories with the beam line as a linear source of tracks
  - Identify a few tracks of interest, and then analyze all remaining tracks that have a value of the z-intercept compatible with provenience from a common vertex

Tracking in a time-tagged detector

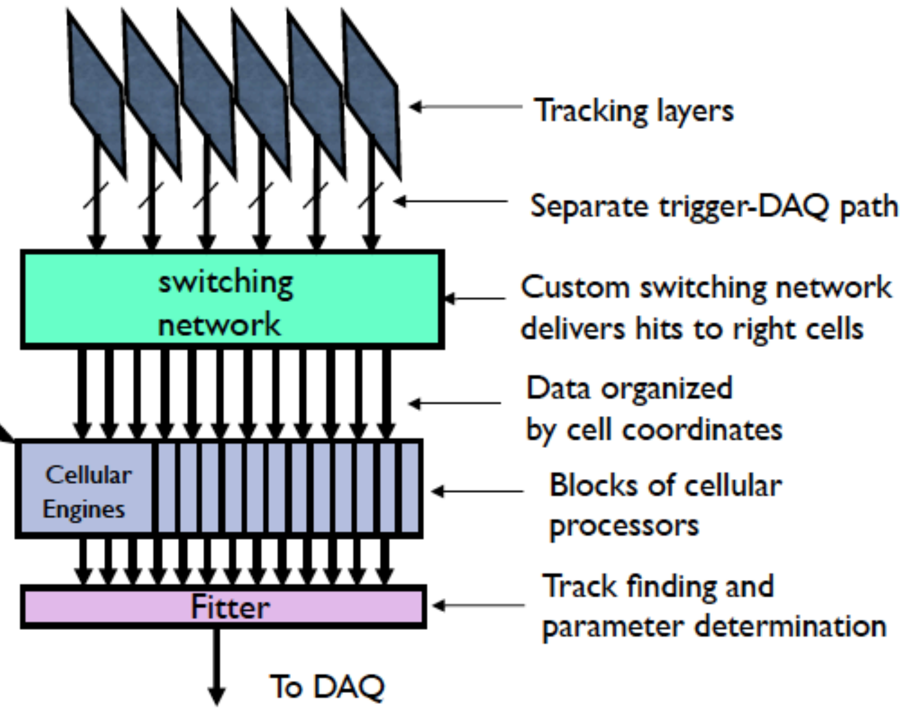
- Timing constraint allow vertex reconstruction even from a single layer
- Also strict constraints to hit association between layers
- If feasible, could be of great help for local data reduction



Example of parallel low-latency tracking



Tracks seen as clusters
("retina algorithm")



- Feasibility studies done in the context of the LHCb upgrade using today's FPGA (LHCb-INT-2014-019)
  - Offline-quality tracking with sub-μs latency and 40 MHz rate at $L=3*10^{33}$
- Electronics progress + ASIC + specially-designed detector → $L\sim 10^{35}$
  - Hardware scales linearly with amount of input data
- See talk by G. Punzi @INSTR-2014 (Novosibirsk) + related talks @WIT-2014

Muon PID

- Due to the high rate and to the harsh radiation environment, the employment of gaseous detectors is not straightforward
  - more reliable, robust and fast solutions are needed
- A possible choice involves large area scintillator bars with WLS fibers and SiPM readout
  - Detector occupancies should be reduced by designing high-granularity detectors, e.g. bars a few centimeters wide with each active plane consisting of orthogonal layers of scintillator bars, providing both coordinates at the same time
- Given the very high luminosity and, as a consequence, the high level of background radiation, one of the most critical issues is to understand the radiation damage of the sensitive components

Hadron PID

- The ability to distinguish hadrons is extremely important to cover a wide range of measurements and considerably simplify the analysis
  - see LHCb physics results
- Could Cherenkov detectors cope with very high track density?
  - limited by photodetector pixel density?
  - how far can we go?
- An alternative possibility that has been suggested is the use of a thick TRD
  - is it conceivable?

Calorimetry?

- The LHCb calorimeter system is perfectly functional
  - it is very important in particular for the hadronic trigger
- However, hard to make physics analyses with calorimeters at LHCb so far
  - large background
  - lower mass resolution
- Unclear whether calorimetry is really mandatory and how useful it could be in the harsh environment of an extreme flavour experiment
  - how much physics do we loose forgetting radiative decays and final states with electrons and π^0s?

Detector geometry

- The best detector geometry cannot be determined without dedicated studies, only some considerations here
- The detector does not need to be hermetic
  - The experiment will work only on a part of the collision data, it is not expected that global event variables, like the missing E_T, could play a useful role
  - A tracking volume for containing K_S decays is very desirable
- Forward or central configuration?
- Some trade-offs to be worked out
  - A forward configuration has the advantage of an easier access to the data, easier cabling etc. and allows room for large detectors, like those that may be required for PID purposes
  - It is likely to require a smaller number of channels and be therefore less expensive
  - It may however suffer from larger radiation-resistance issues, and the high track density may be an issue to pattern recognition

Analysis model

- The huge size of data samples involved and the required precision level mean that an extreme flavor experiment requires a different model of data analysis from the traditional paradigm in use in HEP
  - there is no way to store the entire event information for so many events
  - different methodology from the usual: "trigger, storage, calibration, offline analysis”
  - Need to move towards “real time” physics analysis
- Even taking only a specific piece of data from each interesting crossing may be too much for some high-rate processes
  - e.g. D mixing and CPV
- Ability to do precision measurements from stored samples of reduced size
- Go beyond the “event” concept: only save statistical summaries
  - whose sizes grow less than linearly with the amount of collected data

Real time calibration

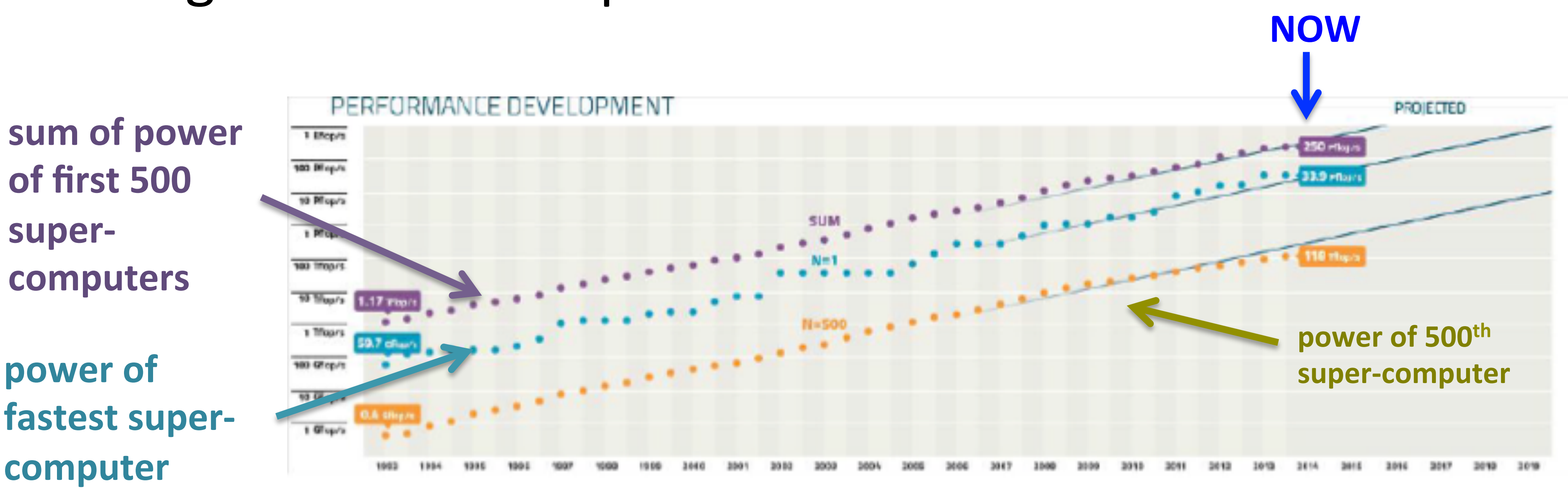
- An important aspect will be to demonstrate that a system for high-precision calibration in real time is possible
  - calibration process should have high level of reliability as there is no way to perform a second pass
  - If the calibration for a certain chunk of data is diagnosed to be defective, there is probably no way to recover → discard it
- On-detector reconstruction system with embedded calibration making extensive use of local information and performing corrections on the fly
- A substantial development effort will be needed to produce a detailed design
  - The availability of large samples of data from existing LHC runs may be of great help in the process of designing the system, allowing to perform realistic tests

Extreme theory

- A significant experimental progress requires an analogous improvement of theoretical accuracies
- A crucial ingredient from the theory side is the ability to determine hadronic matrix elements with sufficient precision from Lattice QCD
- Lattice QCD has witnessed a very important progress in the last 15 years, mainly for two reasons
  - increase of the computational power
  - improvements in the algorithms
- The computational power can be predicted with rather good reliability, since it is found to follow a simple scaling law

LQCD extrapolations

- Typical computer systems that are available today for Lattice QCD simulations have performances in the range 0.1-0.5 PFlops, that is within the lower part of the top 500 list
- By extrapolating the available computer power for Lattice QCD simulations, in 2025 we should be in the range 100-500 PFlops



Projections to 2025

Hadronic Parameter	2002 [432]	2013 [433]	What Next Era (2025)
$f_+^{K\pi}(0)$	-	0.4%	0.1%
B_K	17%	1.3%	0.1 – 0.5%
f_{B_s}	13%	2%	0.5%
f_{B_s}/f_B	6%	1.7%	0.5%
B_{B_s}	9%	7%	0.5 – 1%
B_{B_s}/B_B	3%	10%	0.5 – 1%
$F_{D^*}(1)$	3%	2%	0.5%
$B \to \pi$	20%	10%	$\geq$ 1%

0.1% precision does not look impossible

- Estimates below 1% are to be taken *cum grano salis*
- At that level of precision, small effects that are typically neglected have to be considered
  - E.g. isospin breaking and electromagnetic effects are at the 1% level
- However, in principle they can be included
  - First lattice studies of isospin breaking and electromagnetic effects have been performed in the last years leading to promising results
- But remember: this is not for free! Need to be sustained with appropriate funding → millions, not peanuts

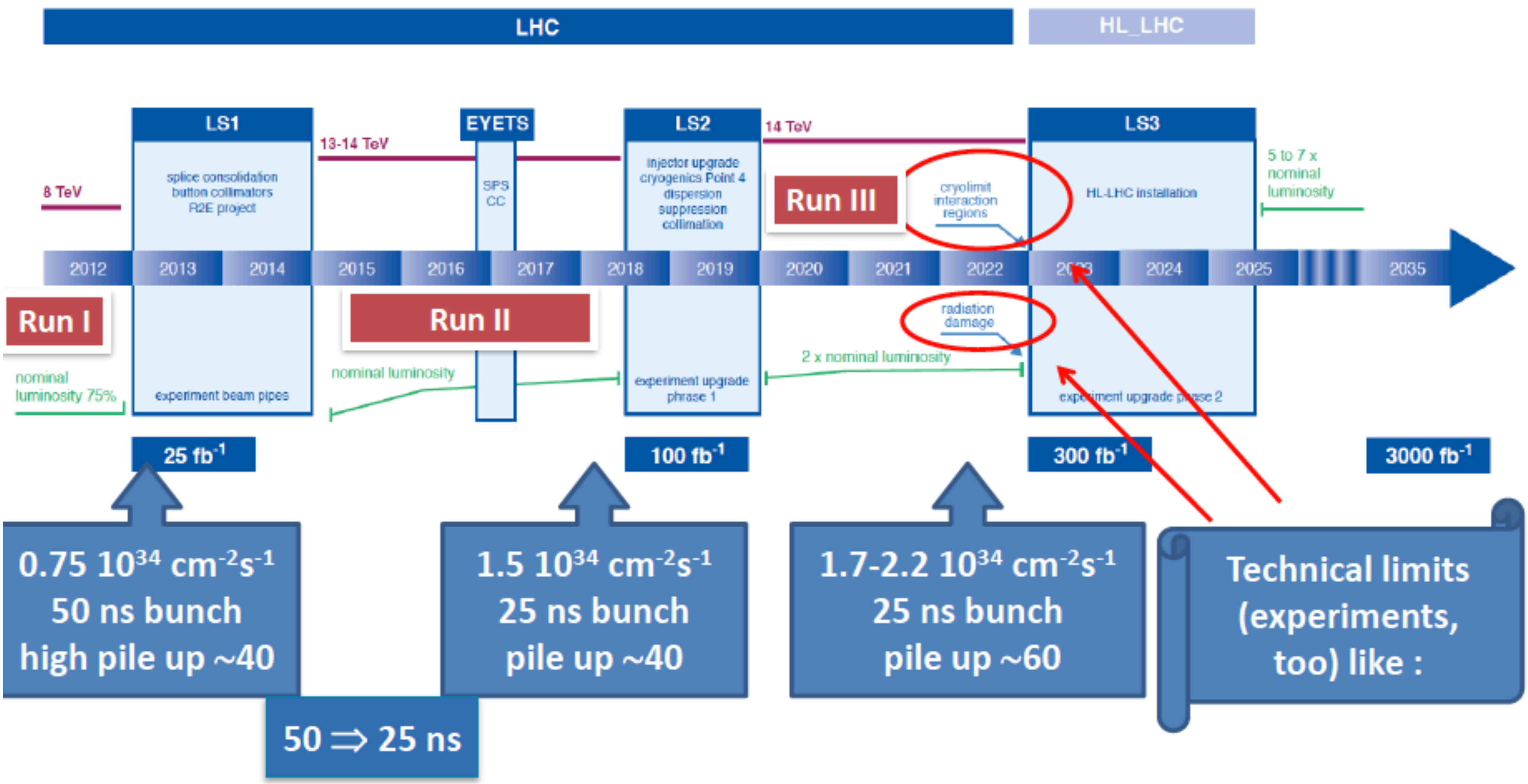
Conclusions

- With planned detector improvements, we expect marginal gains in flavour physics from 2022 onwards
- The potential offered by the huge heavy flavour production at HL-LHC needs something new on the experimental side to be thoroughly exploited
- Is an extreme flavour experiment conceivable?
  - certainly challenging, but might be worth exploring its feasibility
- Lot of studies are needed to turn seminal concepts into a concrete design phase, including studies of the physics impact for the definition of an extreme physics case
- Along with the experimental progress, improvements on the theoretical side (including LQCD, but not only) are extremely important

Backup

Abandon hope all ye who enter here

New LHC / HL-LHC Plan



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

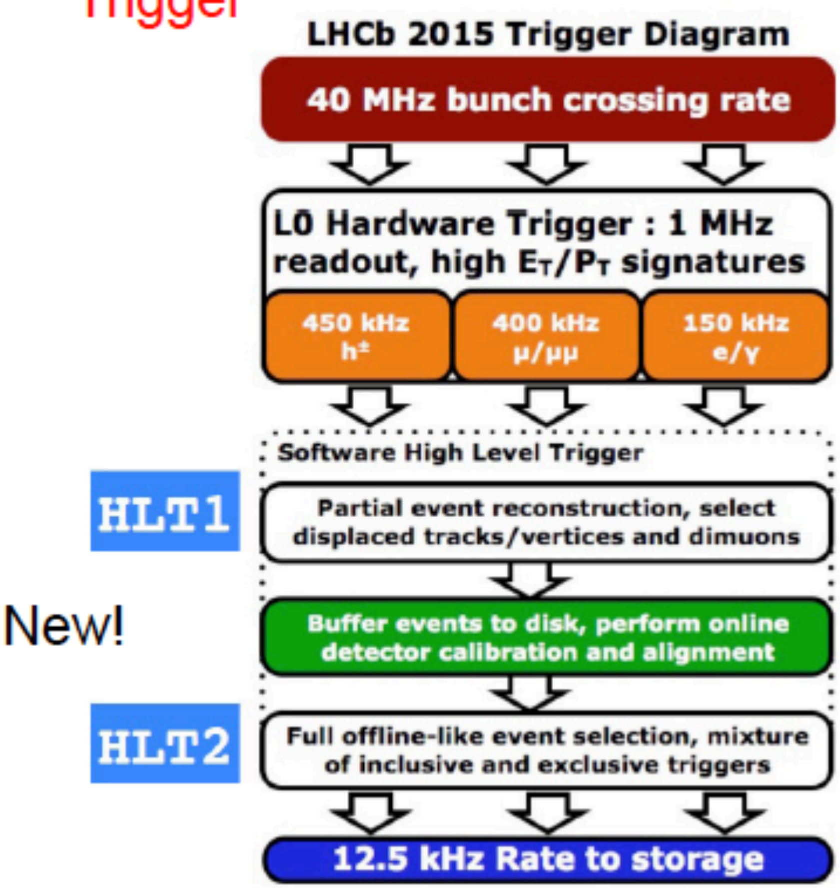
Huge increase in precision, in many cases to the theoretical limit, and the ability to perform studies beyond the reach of the current detector.

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

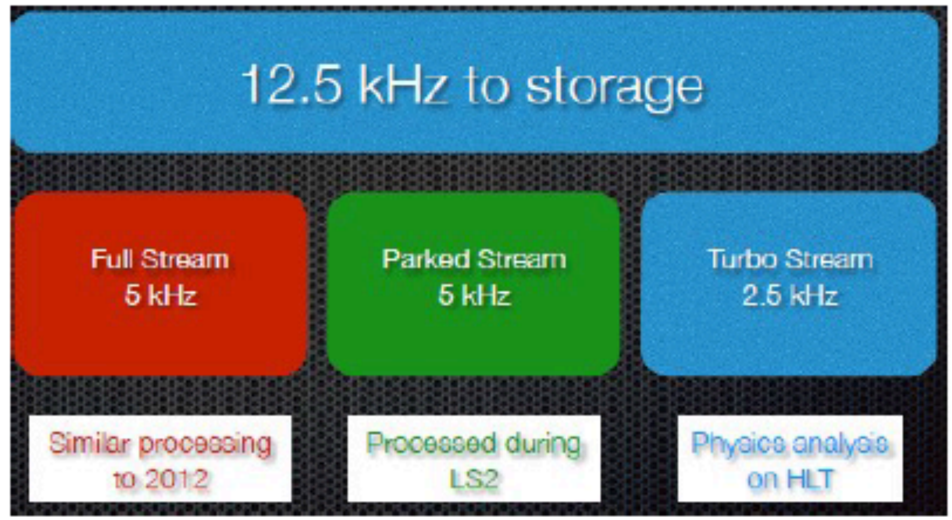
Run II operation

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

Trigger



Output streams



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

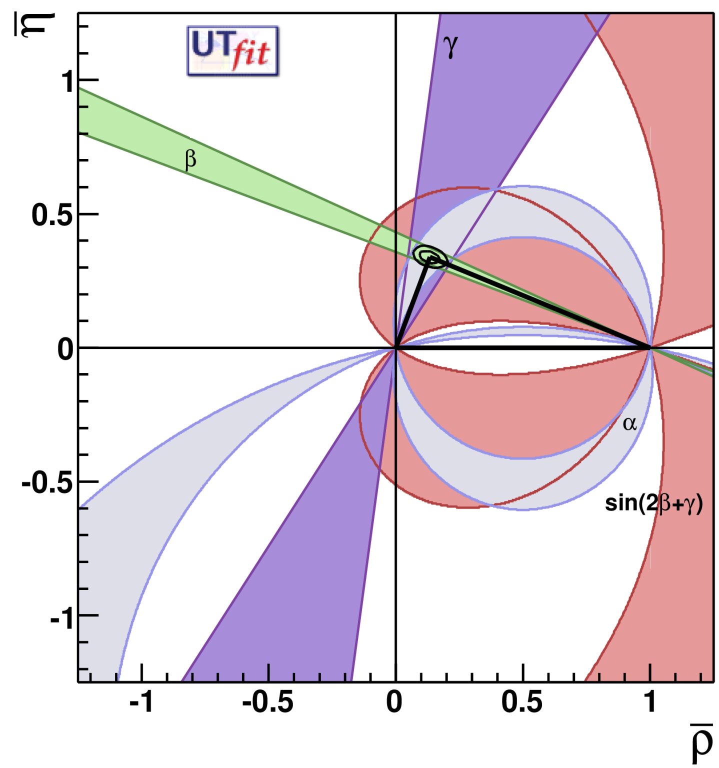
This splitting of HLT into two steps enables more info to be used in HLT2 (*e.g.* RICH) → improved signal-to-background separation (and helps test ideas we wish to use in Upgrade trigger)

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



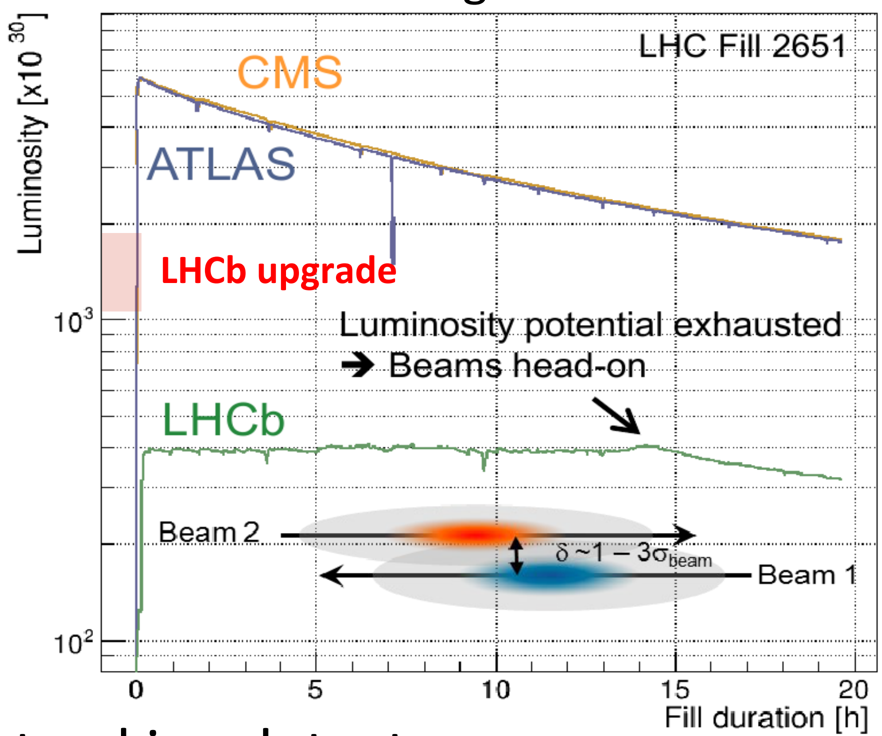
- Measurements can be affected by NP at different levels
  - γ from tree-level is basically unaffected
  - β (β_s) can be affected in B_d (B_s) mixing
  - α can be affected both in mixing and decay (loops in penguin diagrams)

Luminosity in LHCb upgrade

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

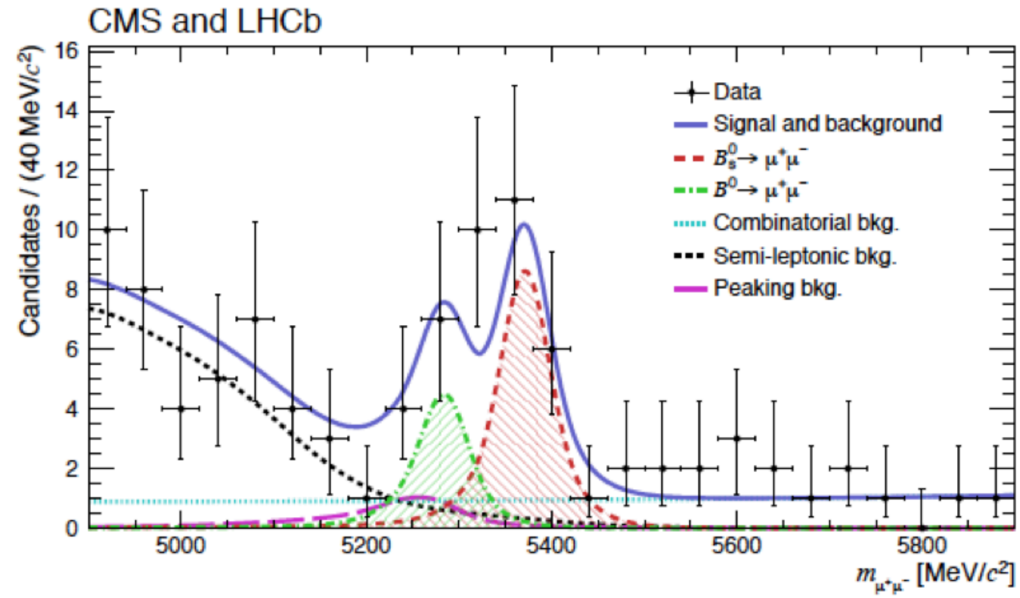
Status of $B_{d,s} \to \mu^+\mu^-$

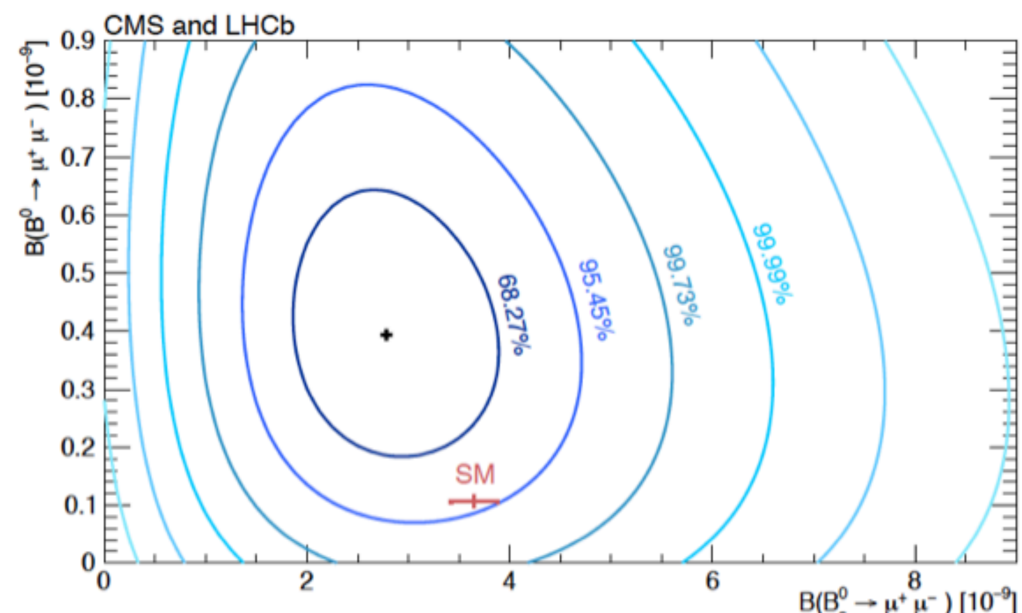
- CMS and LHCb have now performed a combined fit to their full Run 1 data sets

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

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

- 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: Submitted to Nature

Theory (2)

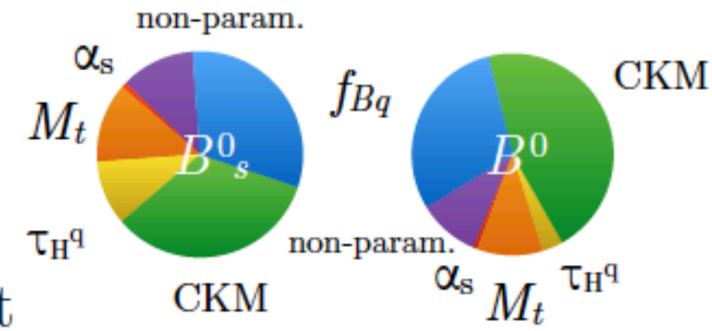
- Untagged time integrated branching fraction predictions:

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

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

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

error budgets



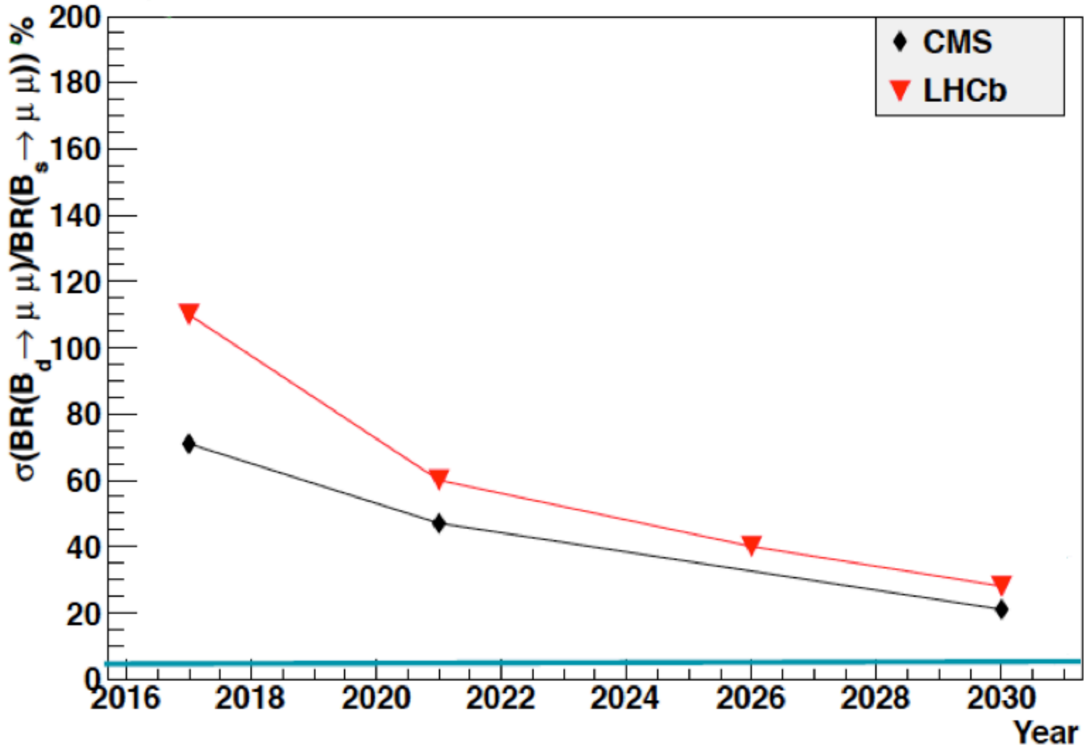
- Ratio of branching fractions of two modes powerful to discriminate among models beyond the SM. Precisely predicted in SM:

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

➡ stringent test of Minimal Flavour Violation hypothesis

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

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



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

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

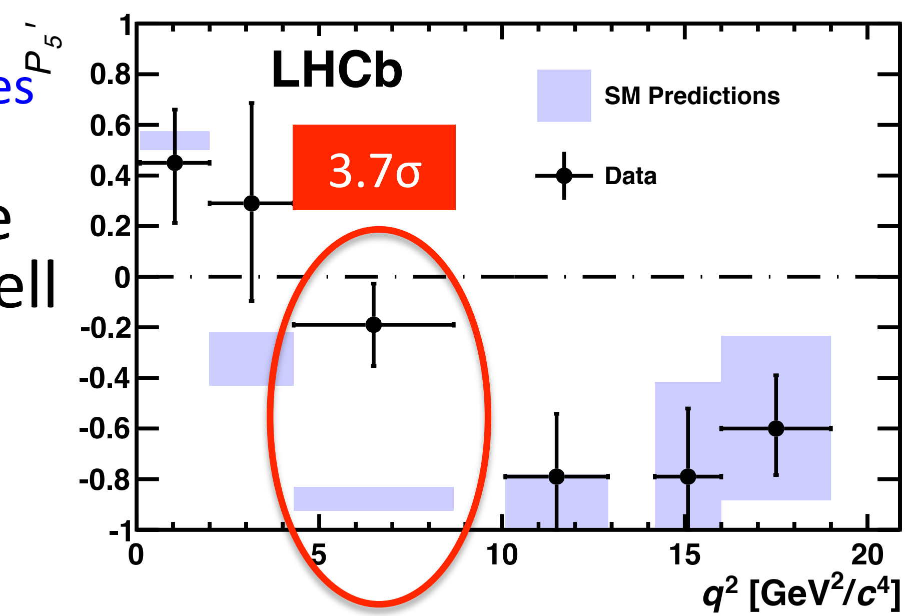
Differential decay rate

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

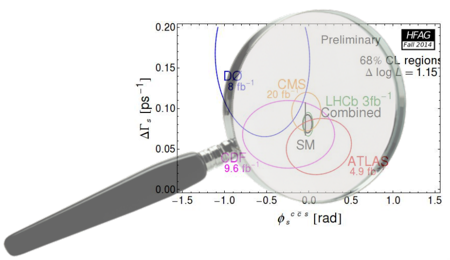
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}.$$

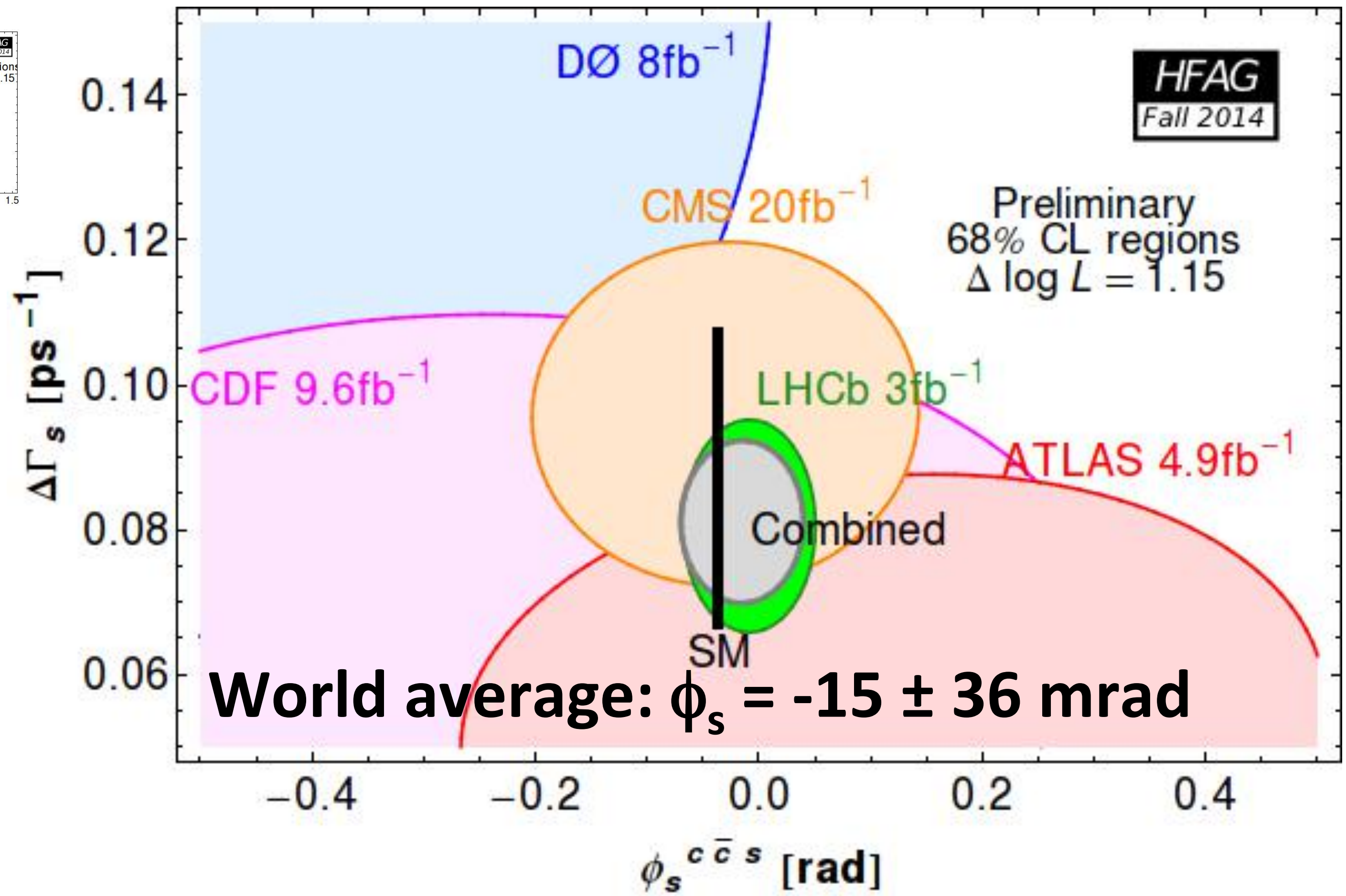
- Interesting feature in one of the observables (P'_5)
  - No definitive conclusion yet
  - Additional statistics and theoretical studies are needed
- LHCb has great potential to improve in this sector, ATLAS and CMS (as well as Belle II) are expected to play an important role too
- On the long run,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

Phys. Rev. Lett. 111 (2013) 191801



Status of ϕ_s



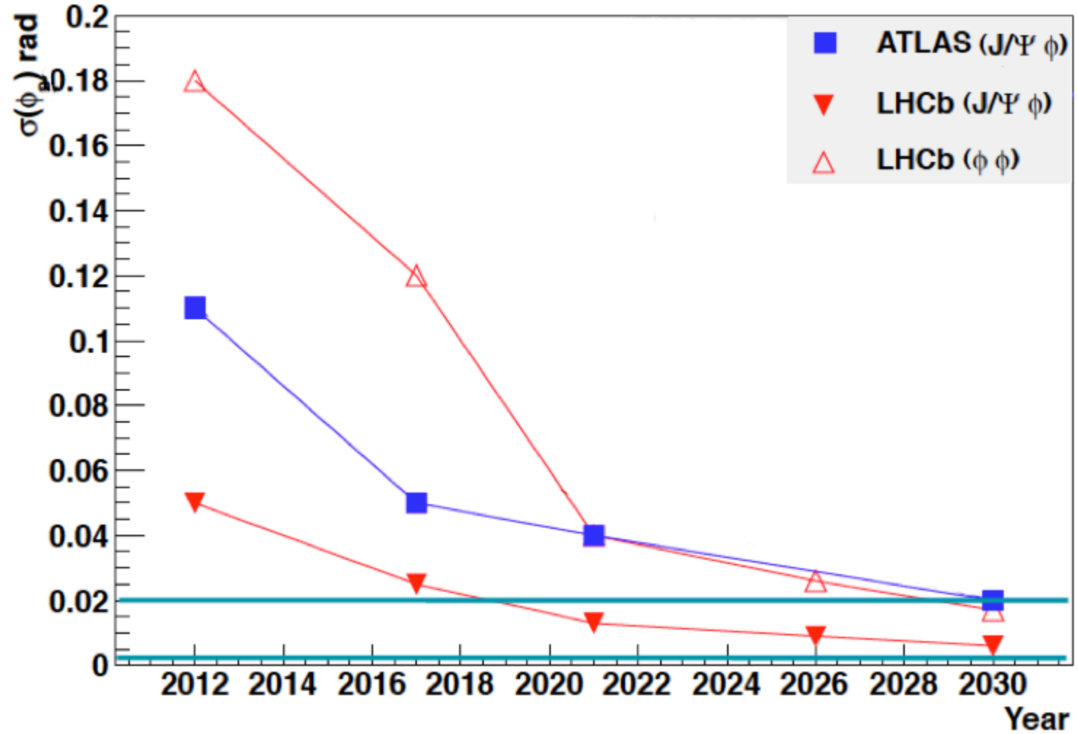


World average: ϕ_s = -15 ± 36 mrad

- Present uncertainty is dominated by LHCb
  - LHCb-only average: ϕ_s = -10 ± 39 mrad
- Not yet signs of discrepancy with SM expectation

Perspectives for ϕ_s

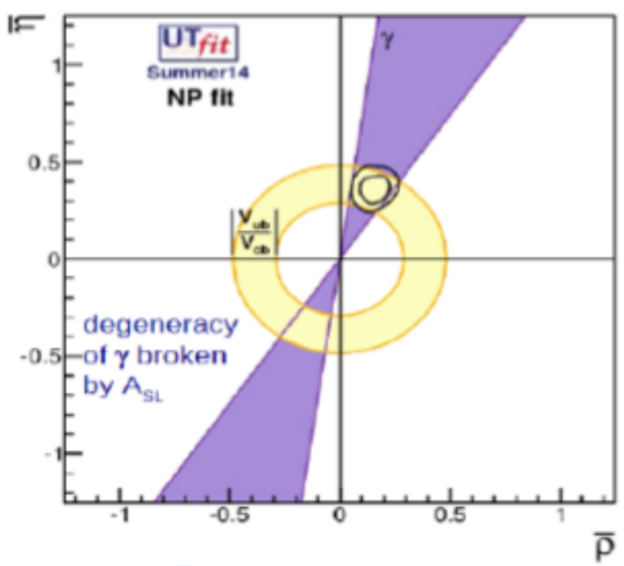
- This is the case of an observable with an asymptotic experimental uncertainty comparable with the theoretical uncertainty
  - $\sigma_{th}(\phi\phi) \approx 0.02$
  - $\sigma_{th}(J/\psi\phi) \approx 0.003$



- For $J/\psi\phi$ in particular, the uncertainty, due to the presence of subleading contributions to the tree-level amplitude, can be quantified with data-driven methods
- Improvements from theory would be certainly welcome

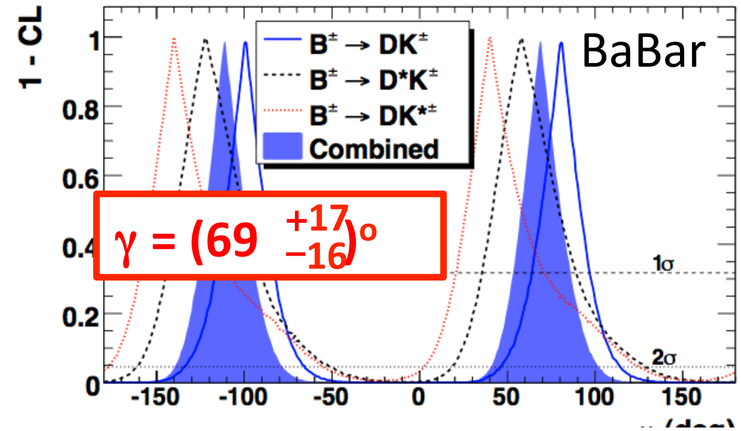
Status of γ

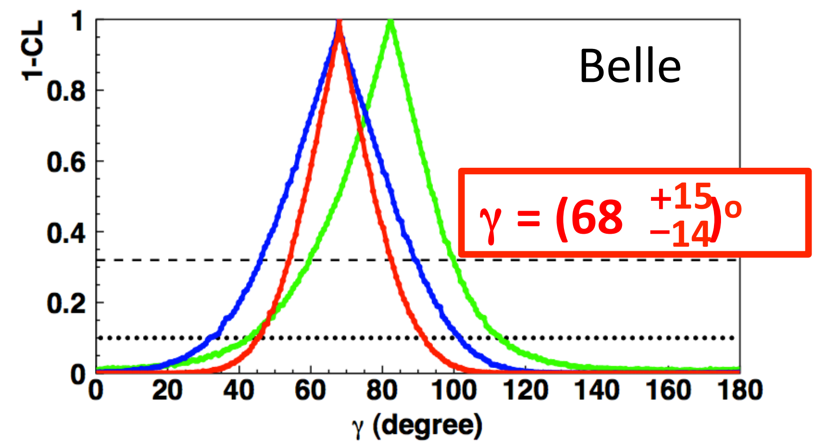
- Measured by BaBar, Belle and LHCb using ADS, GLW and GGSZ (Dalitz) methods
  - **LHCb is now starting to dominate the world average**

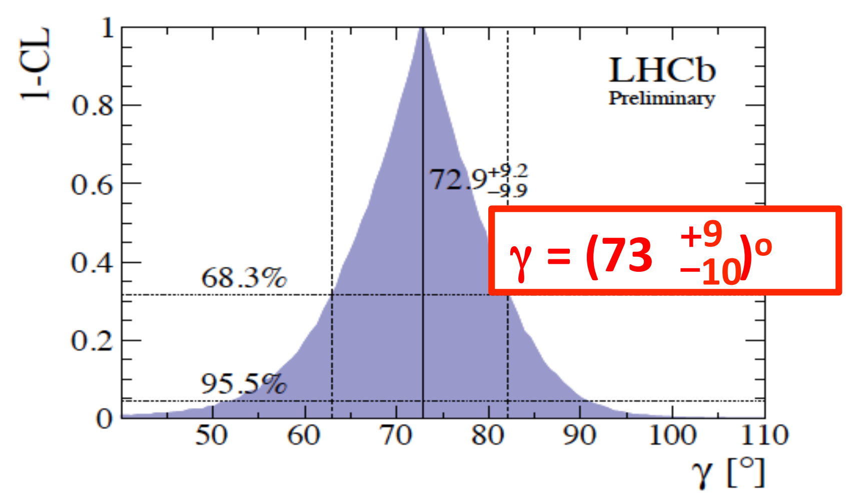


Measurements from tree-level decays are assumed to be almost insensitive to NP effects

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

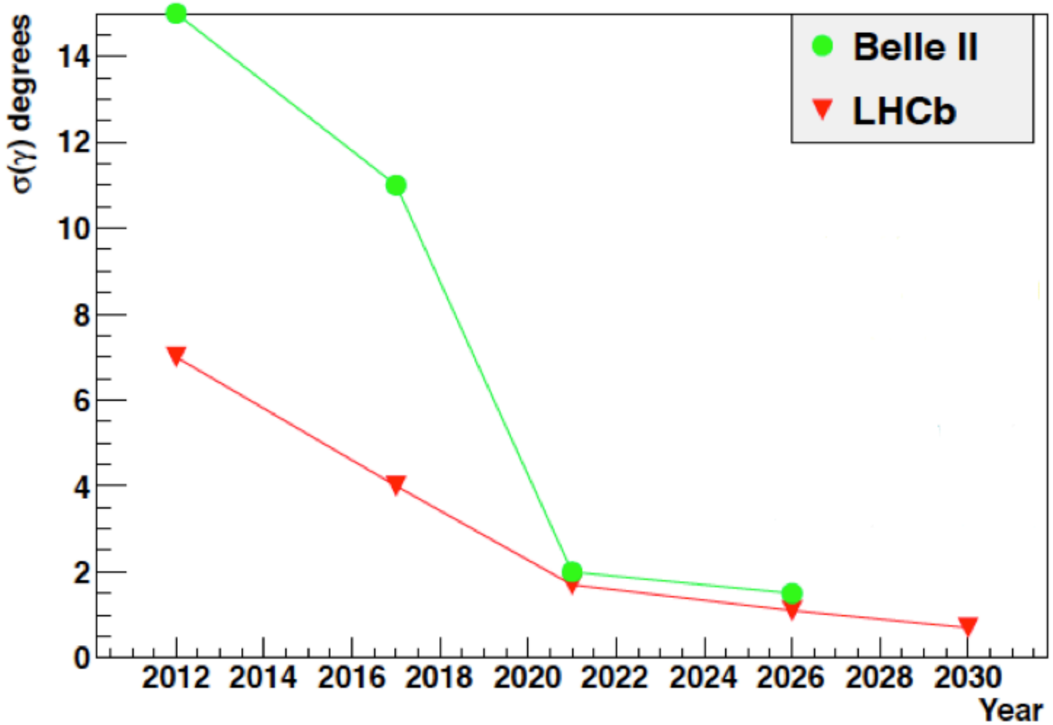






Prospects for γ

- 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

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
    - $B_s \to J/\psi\phi$, $\Lambda_b \to J/\psi\Lambda$, …, $B_{(s)} \to \mu\mu$, $b \to s\mu\mu$
  - 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

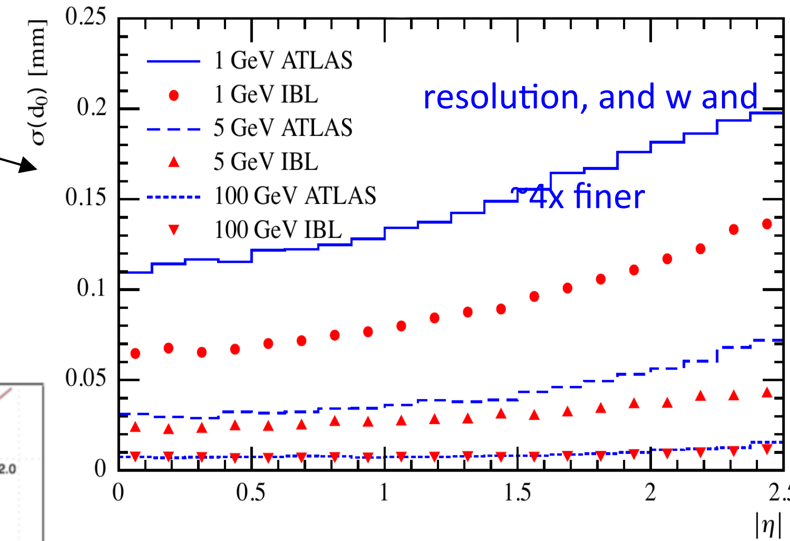
- To make that possible and keep similar or better performance, we need:
  - **trigger strategies** and
  - **detector upgrades** (namely tracking)

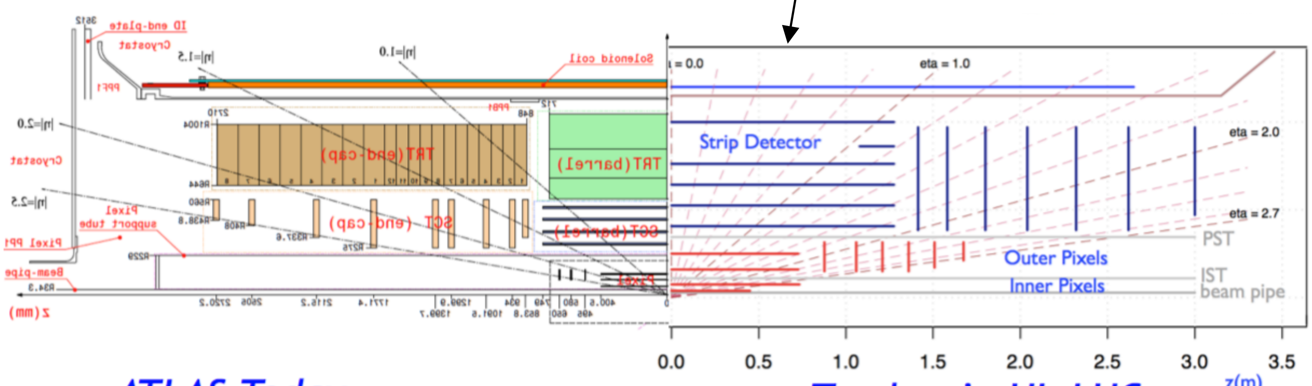
  able to face the harsher environment of the future Runs

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

Relevant ATLAS Detector Upgrades

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

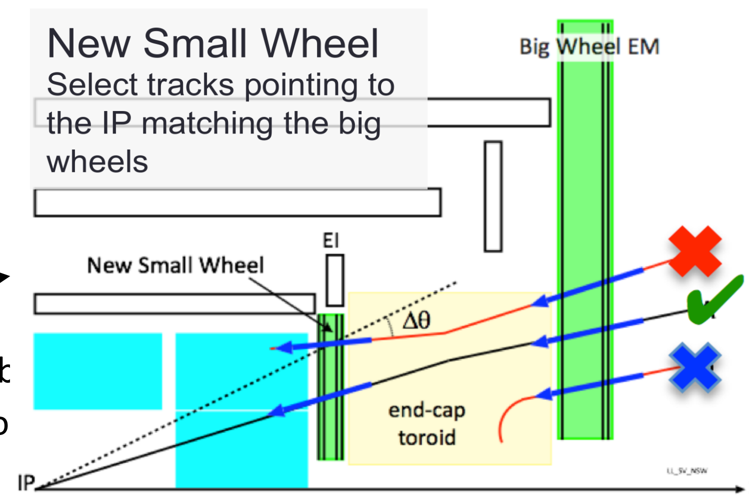




ATLAS Today

Tracker in HL-LHC

- 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 comb
  - Run-2/3: Fast Tracking (FTK) – a HW-based track finder at "offline precisio trigger and the next SW-based trigger levels



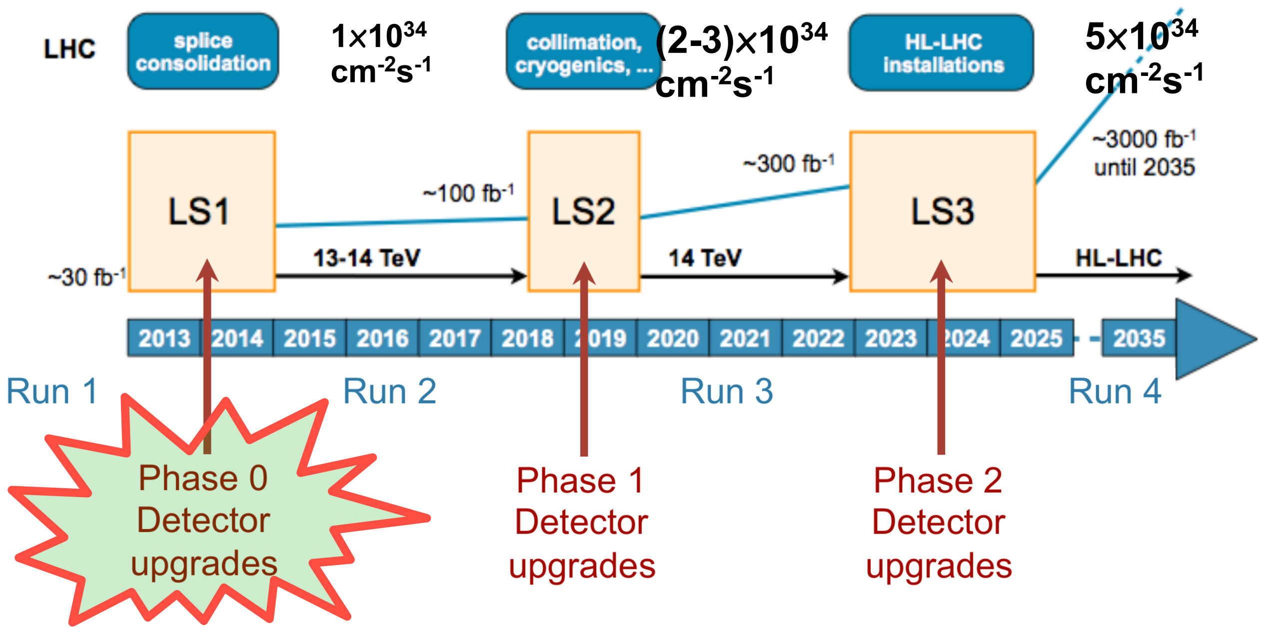
Trigger Strategies for ATLAS B-physics

- 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

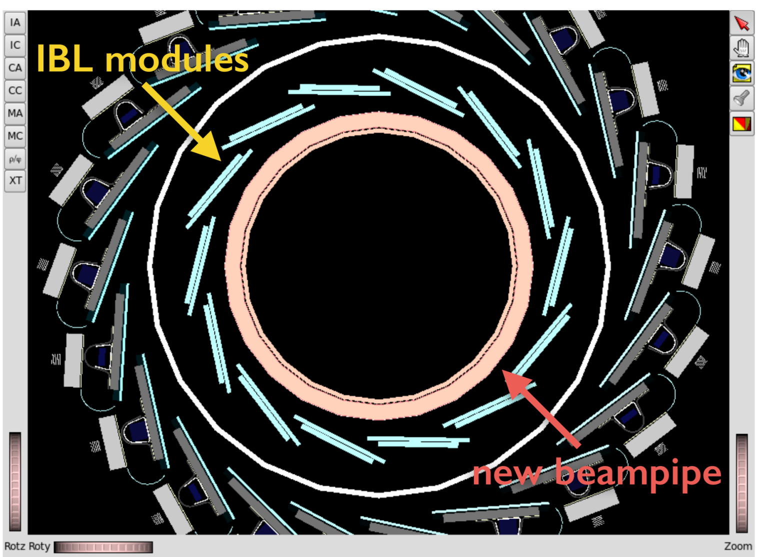
- Level 1 trigger rate control:
  - Increasing the **muon p_T thresholds** or collecting signal in the **barrel detectors only** (this was Run-1 approach for peak luminosity) → in Run-2 would lead to significant signal loss
  - From Run-2 , additional **topological selections** will be possible at HW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

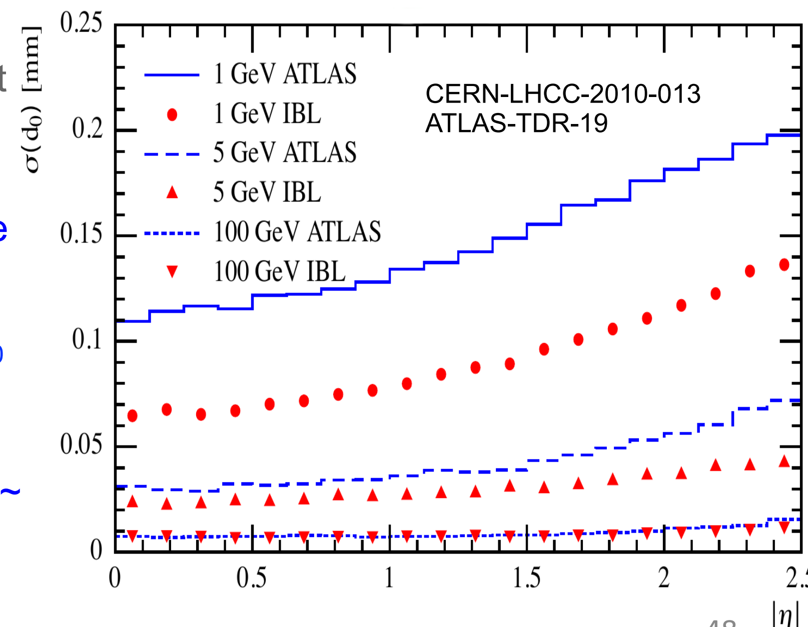
Detector & Trigger Upgrades – Phase 0



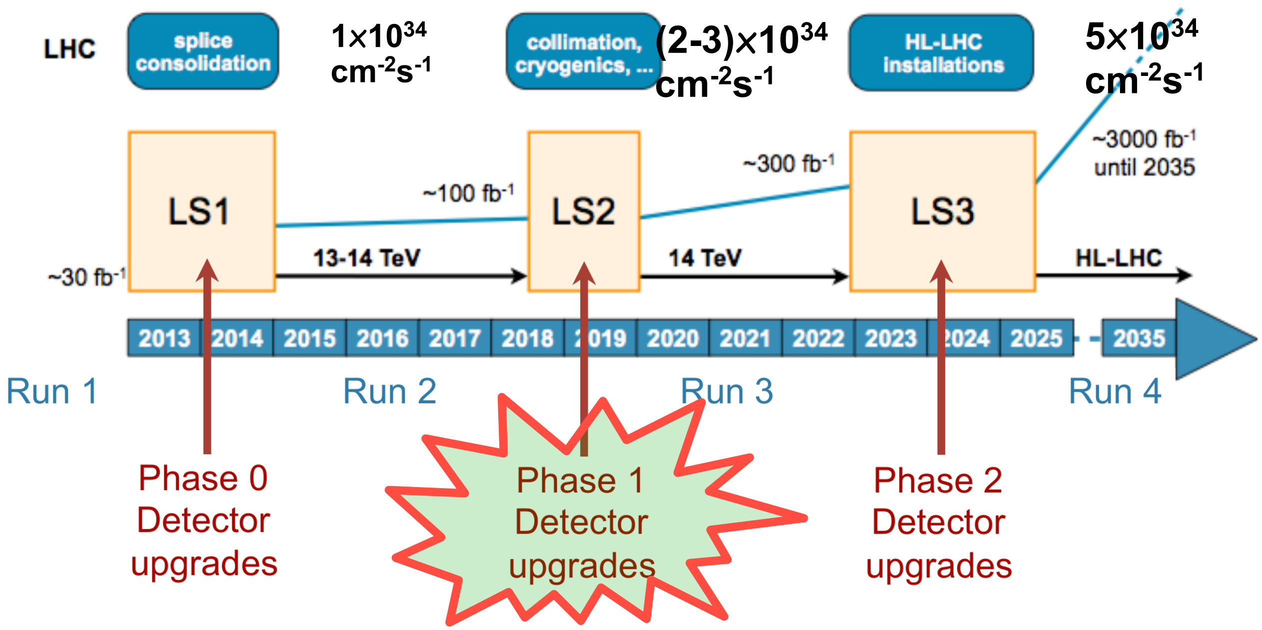
- Long Shutdown (LS) 1 almost over, LHC starts providing physics data in Spring 2015
- Additional Pixel Layer (IBL) and Be small radius beam pipe
- Topological L1 trigger
- Improved coverage of Muon spectrometer ($1.0 < |\eta| < 1.3$)
- Diamond Beam Monitor, consolidation of some parts of the detector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



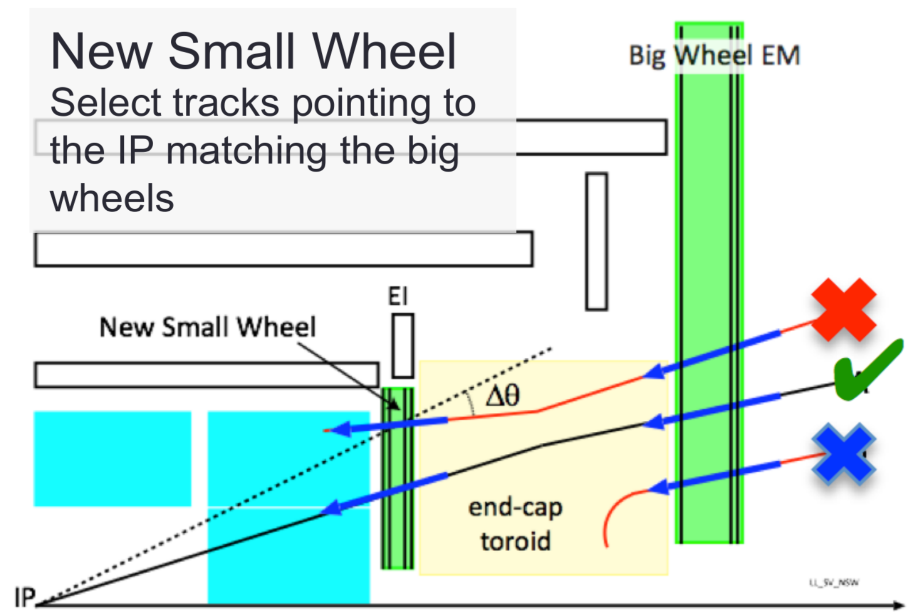
Detector & Trigger Upgrades – Phase 1



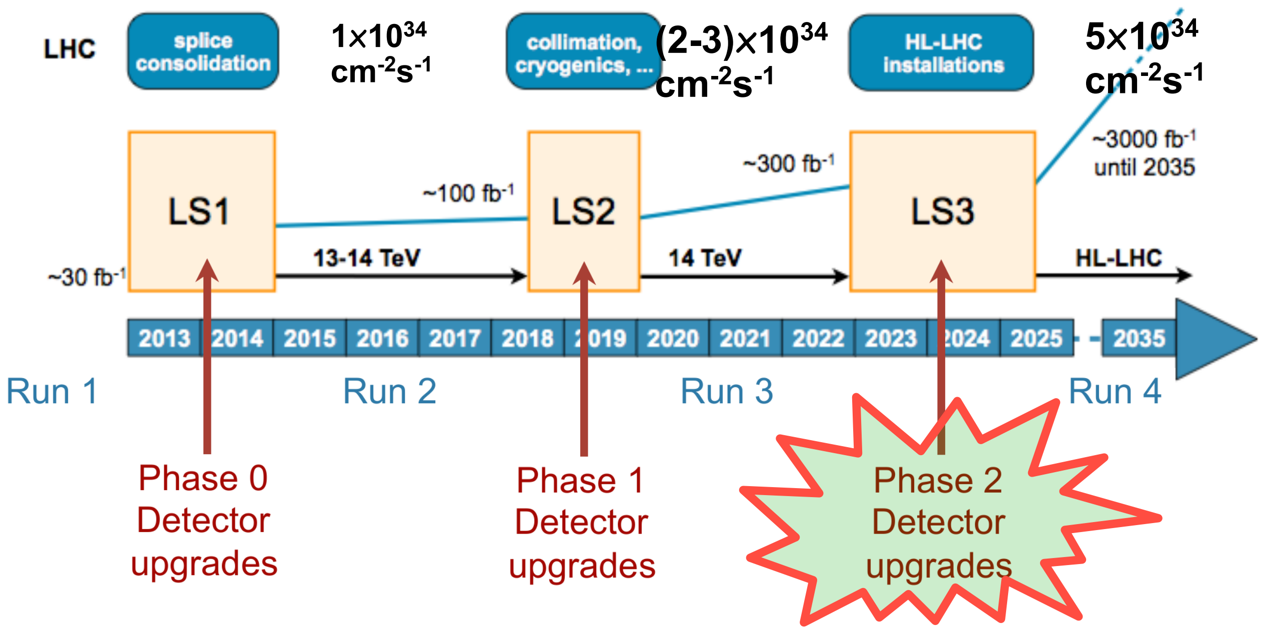
- Goal: no loss of performance when going above LHC nominal luminosity
- New small muon wheel
- New fast-tracking (FTK) at trigger level 1.5. Gradually implemented already during Run 2
- Higher granularity and precision L1 trigger for calorimeter
- TDAQ improved performance

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

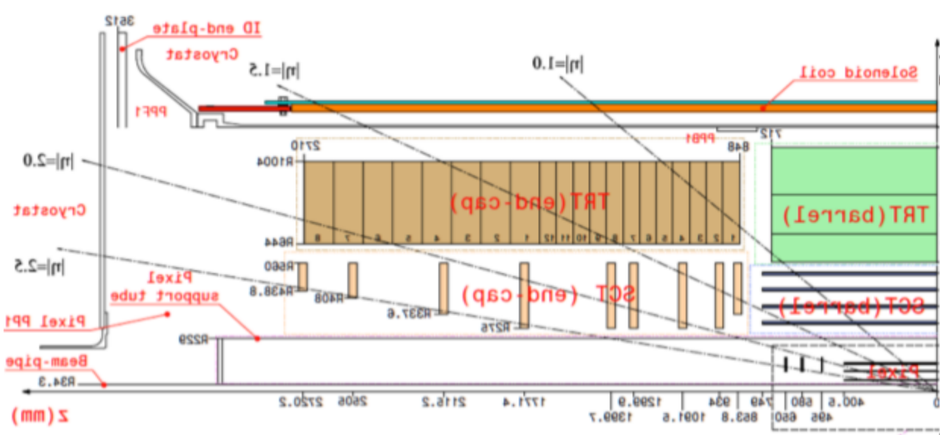


Detector & Trigger Upgrades – Phase 2

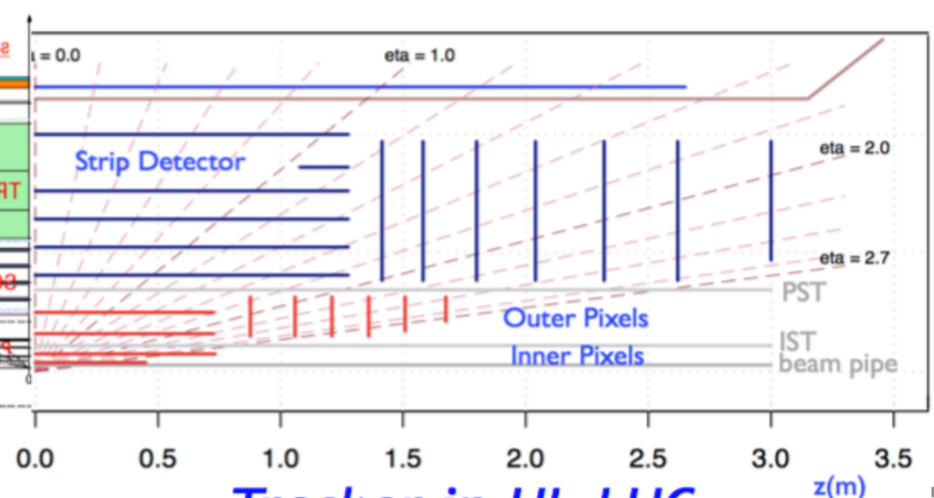


- Goal: maintain/improve performance despite high lumi.
- Completely new Si based tracking (ITK)
- New trigger system – possibly will include HW-based L1 track trigger
- Full granularity calorimetry information
- Upgrade part of the muon systems, fast trigger

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)

Potential for Run 2,3 and HL-LHC

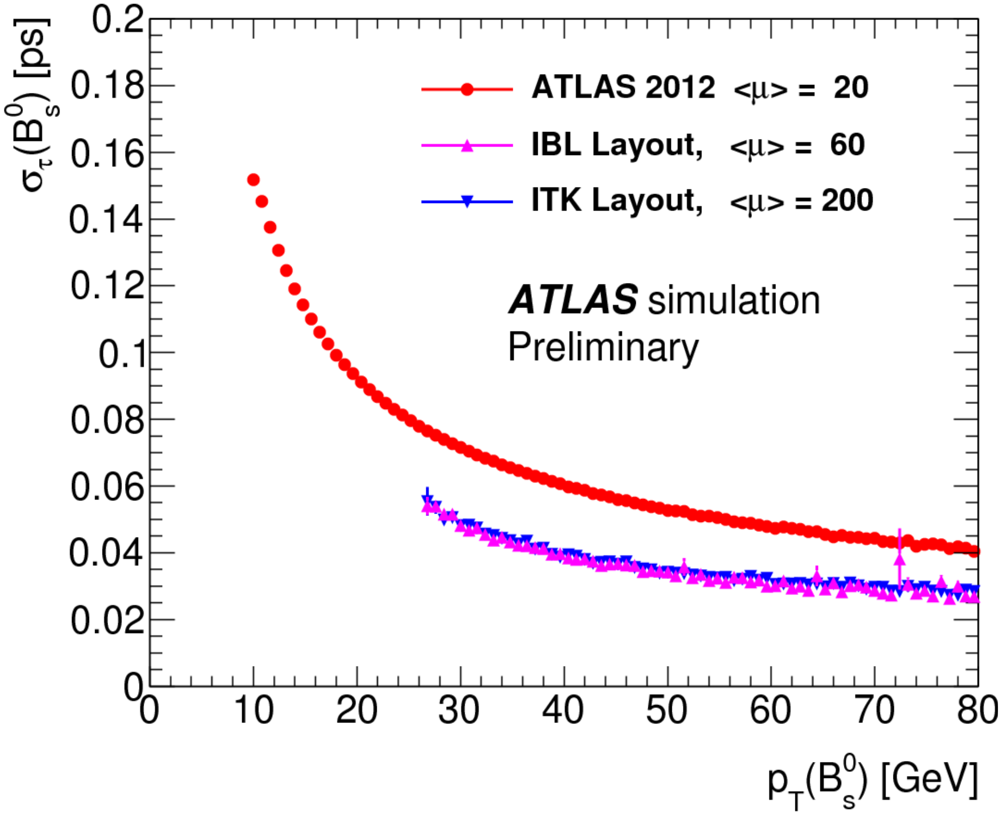
- Key factors with new detectors and high luminosity:
  - Lifetime precision: namely time resolution σ_τ – with new Inner Detectors
  - Performance stability in high pileup
  - Statistics: efficiency decrease is unavoidable; higher trigger thresholds, stronger track selections. Compensation: bigger cross-section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

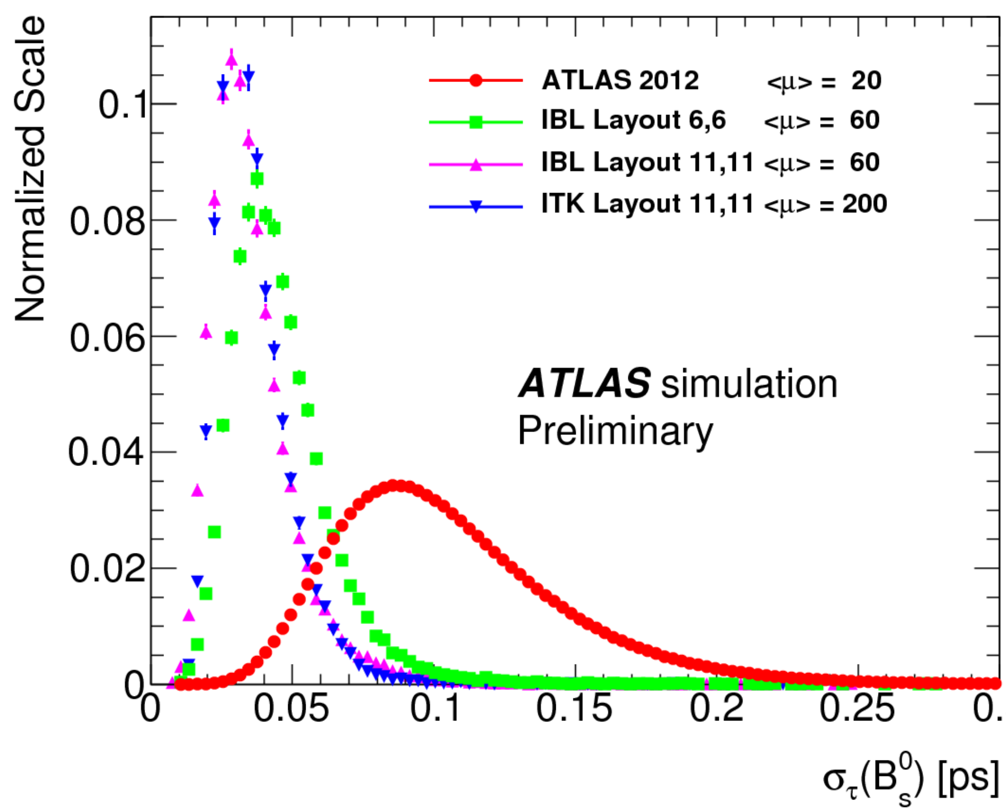
Process	MC cuts	Geometry	$<\mu>$	MC events
$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	$p_T(\mu^\pm) > 3.5$ GeV	2012	20	$40 \cdot 10^6$
$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	$p_T(\mu^\pm) > 6$ GeV	IBL	60	$50 \cdot 10^3$
$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	$p_T(\mu^\pm) > 11$ GeV	IBL	60	$50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

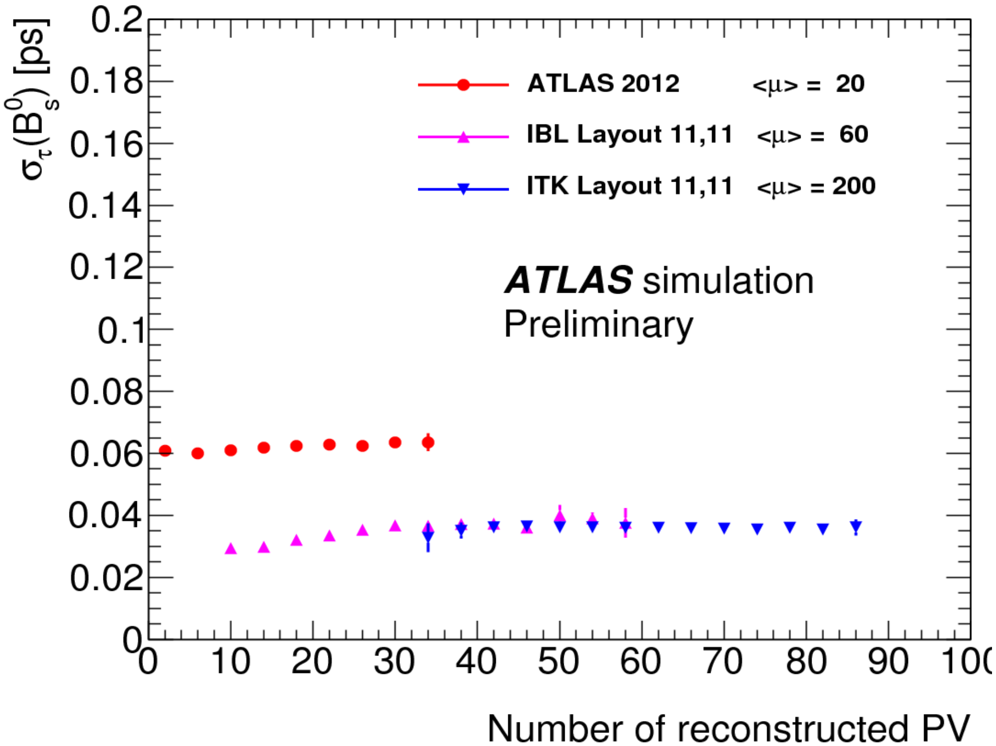
Time Resolution: ITK, IBL w.r.t Run 1

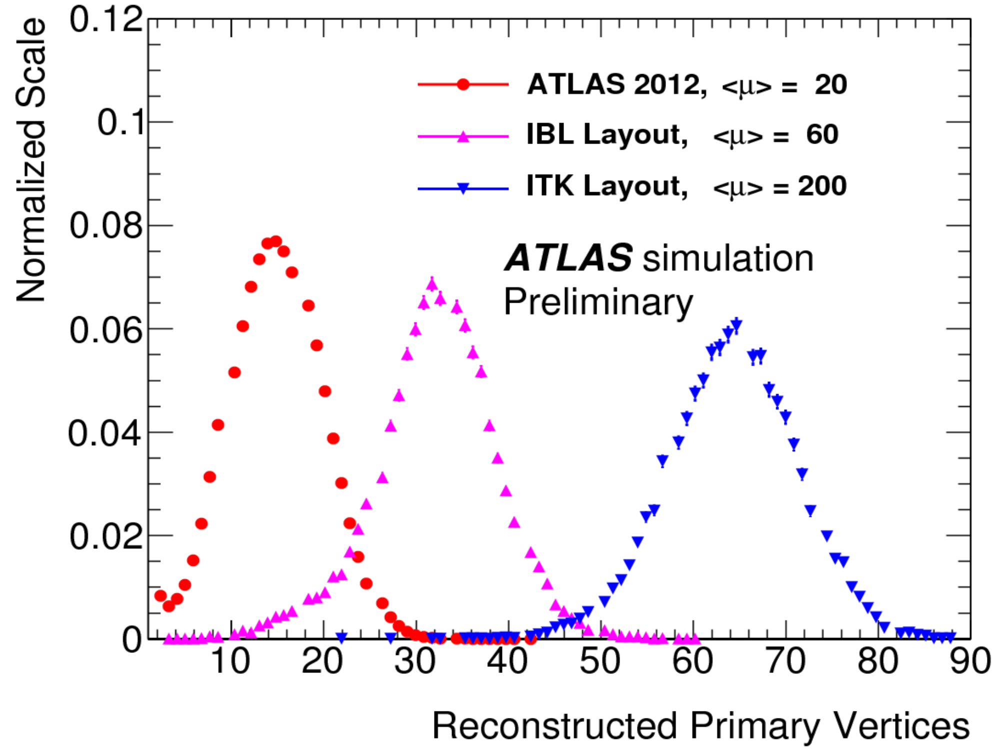




- Time resolution is important for precise measurement of CPV of fast oscillating B_s mesons
  - in 2011 data taking the LHCb $<\sigma_\tau>$ ~40 fs^{-1}, ATLAS $<\sigma_\tau>$ ~100 fs^{-1}
  - with equal statistics @ 2011: LHCb $\sigma(\phi_s) = 0.10$ rad, ATLAS $\sigma(\phi_s) = 0.25$ rad
- New ID 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 number of primary vertices (#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

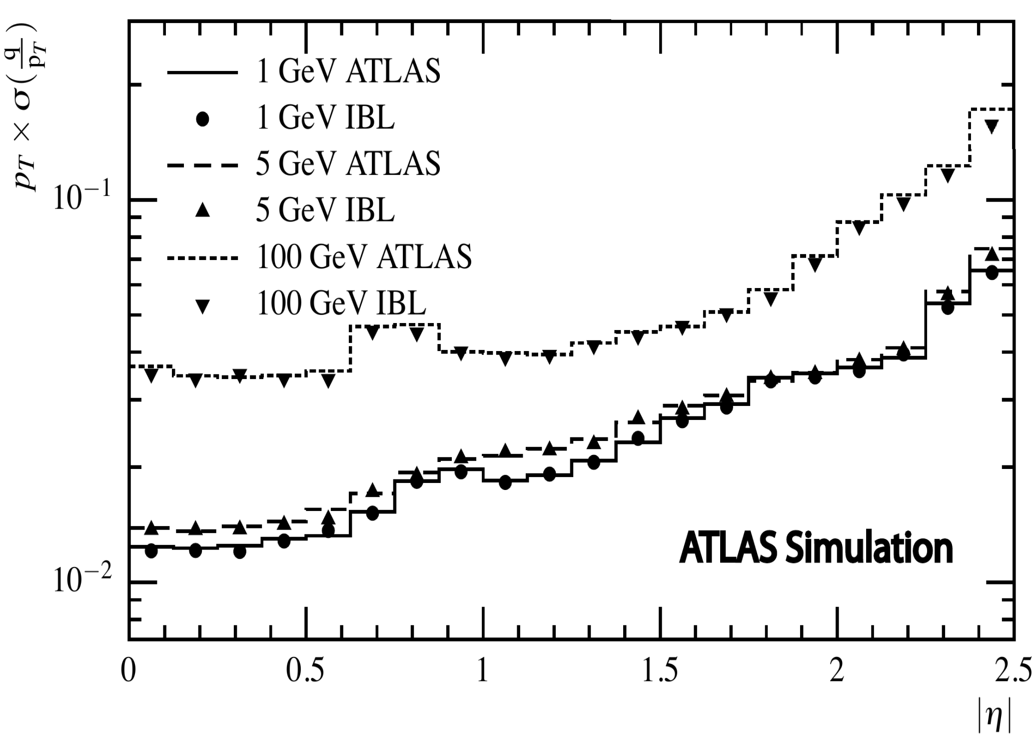
- *) 2011 Toy-MC fit driven by 2011 data, result is consistent with real 2011 data analysis (arXiv:1407.1796, W. Dearnaley talk on Monday), background estimates from 2012 data sidebands
- 2012 is also a result of Toy-MC model, driven by 2012 data
- Muon p_T thresholds 11+11 GeV substantially (7×) decrease 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

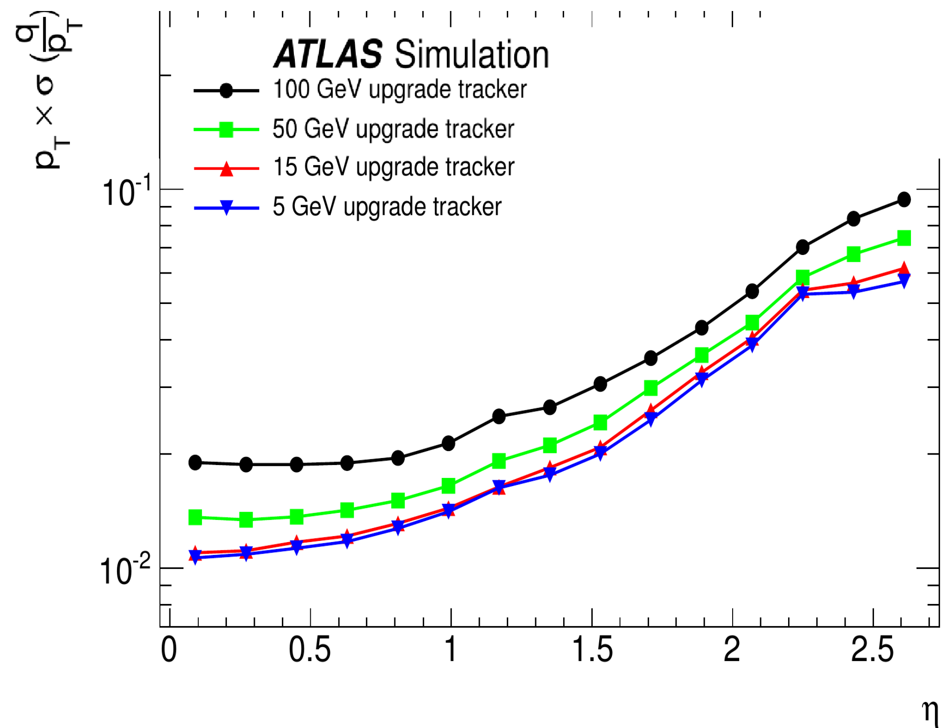
Conclusions

- 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

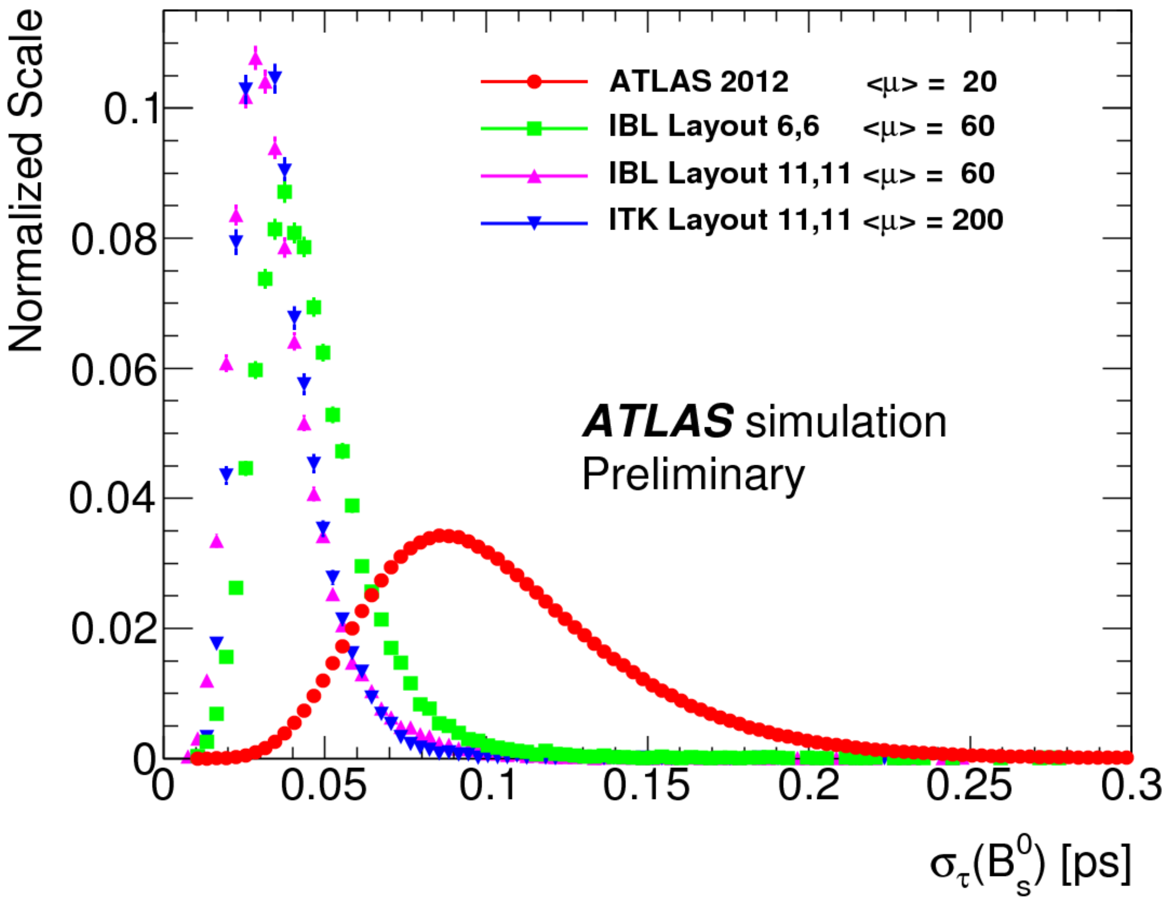
IBL & ITK p_T Resolution

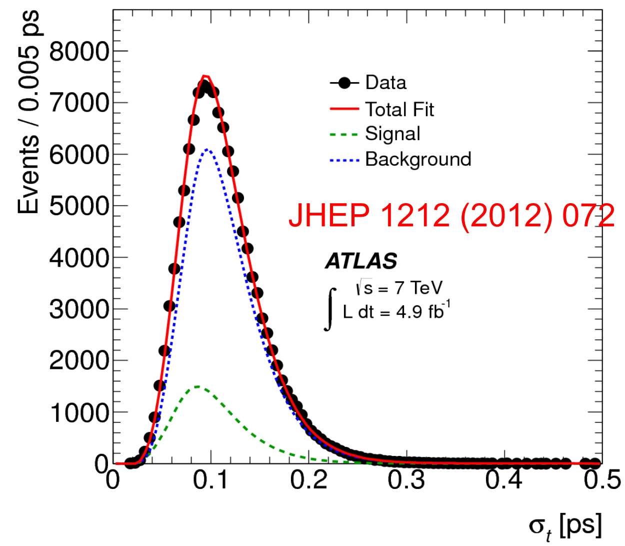
CERN-LHCC-2012-022 ; LHCC-I-023

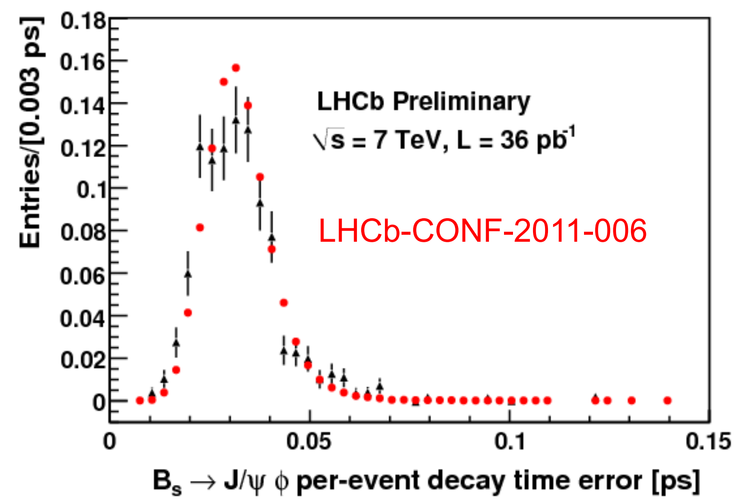




Time Resolution: ITK, IBL w.r.t Run 1







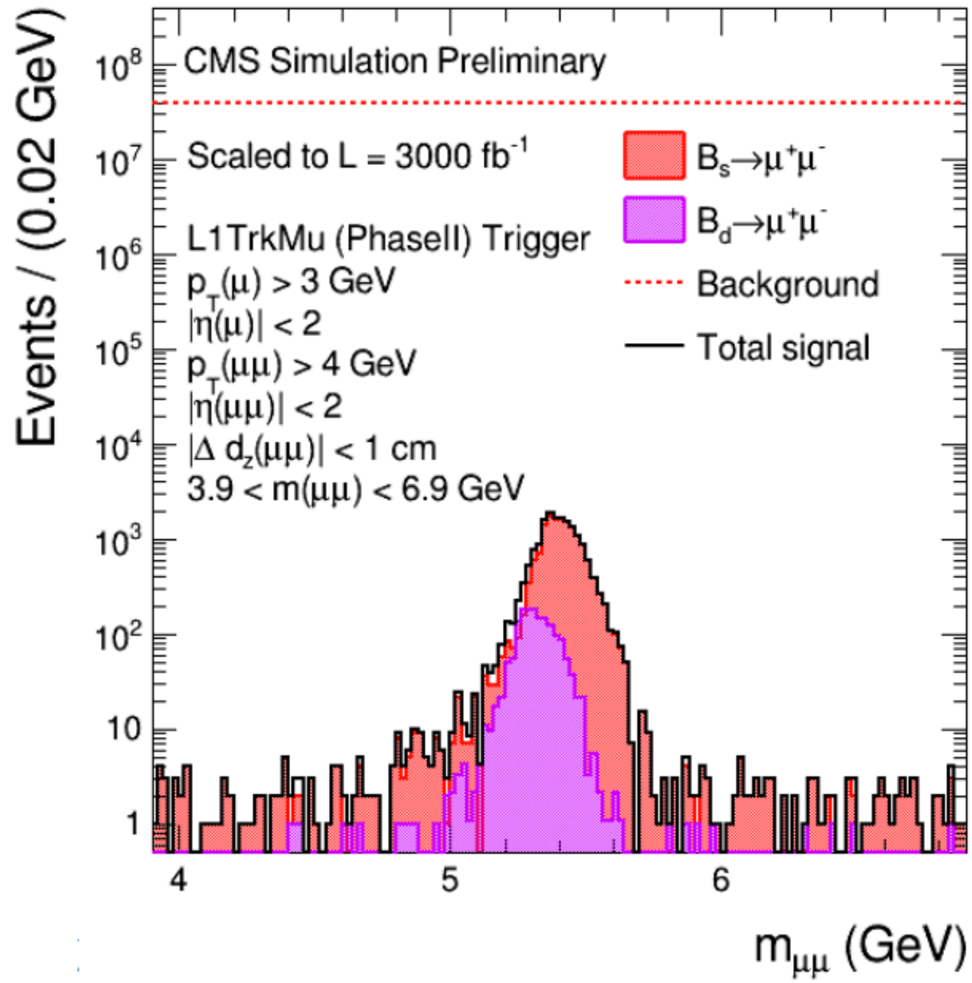
- Improvement of an average time resolution <σ_τ> in future runs will also be connected with increased p_T thresholds
- On the other side, the increase of the thresholds will reduce efficiency with improved trigger purity

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: $B \rightarrow \mu^+\mu^-$

- 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

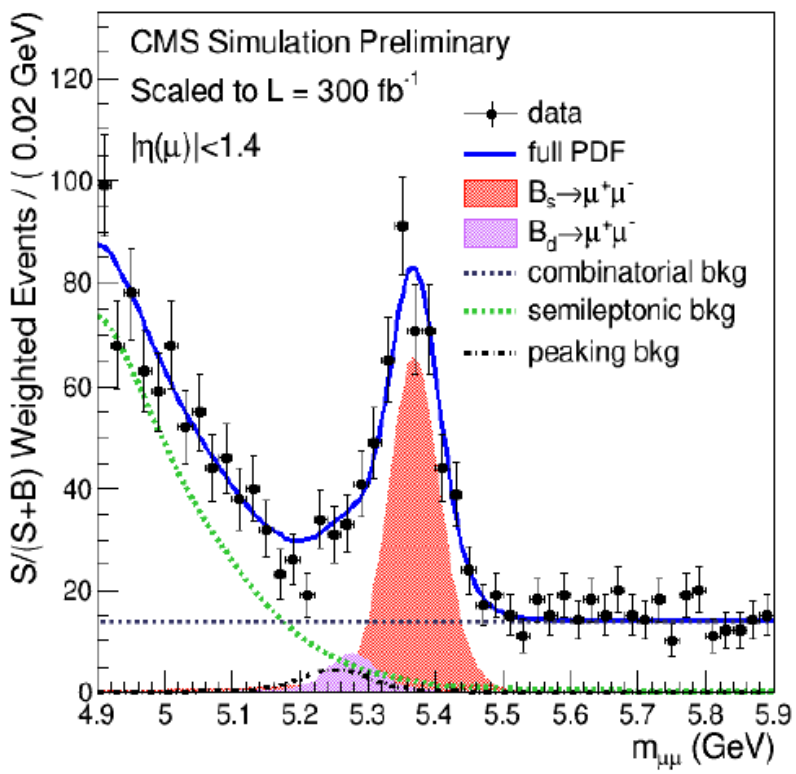


- The expected performances of the upgraded CMS L1 trigger are found to be more than sufficient to implement the trigger algorithm for $B \rightarrow \mu^+\mu^-$

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

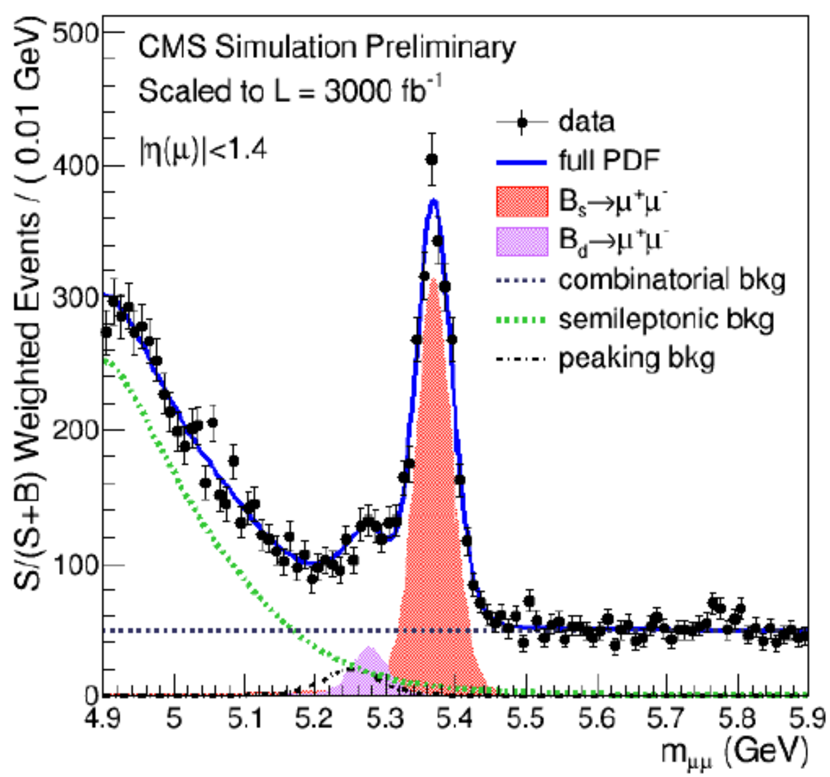
Pre HL-LHC at 300 fb^{-1}

- $\delta\mathcal{B}/\mathcal{B}$ ($B_s \rightarrow \mu\mu$) = 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



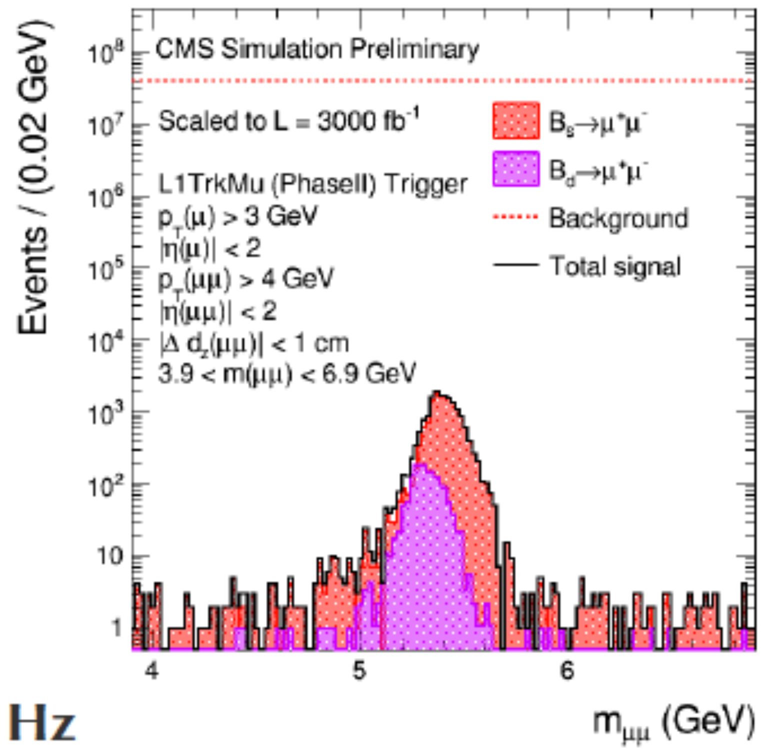
HL-LHC at 3000 fb^{-1}

- $\delta\mathcal{B}/\mathcal{B}$ ($B_s \rightarrow \mu\mu$) = 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



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 $B \rightarrow \mu\mu$ 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. $\approx$ 42 MeV when both muons are in the barrel ($|\eta| < 1.4$)
  - In the case of the Phase-2 scenario, this is $\approx$ 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

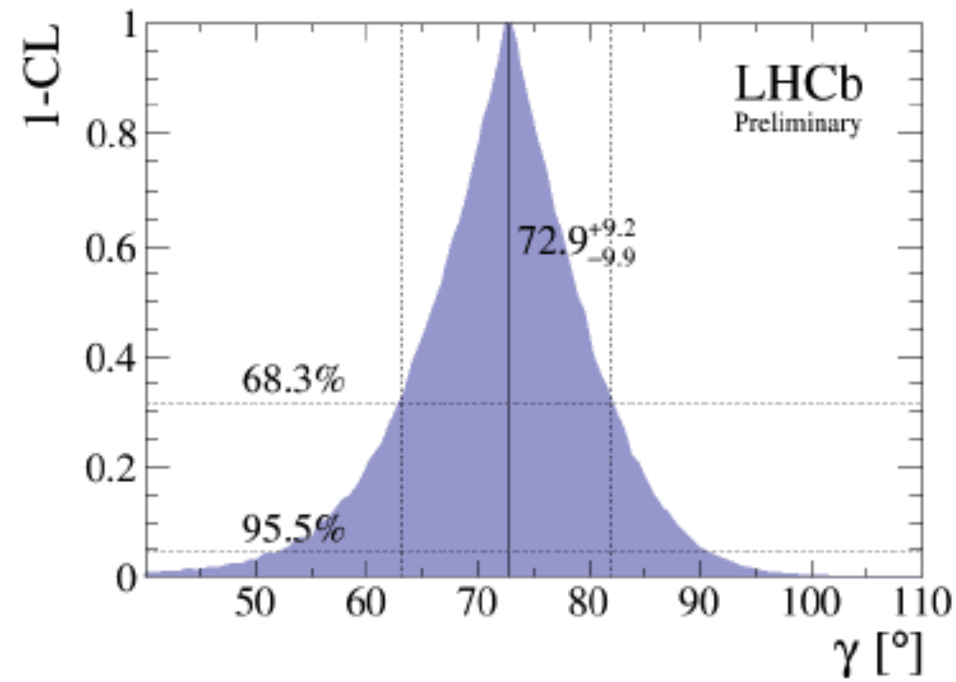
- As written in slide 4, in addition to these extrapolations, the invariant mass resolution coming from the full Geant4 simulation of the Phase-2 CMS detector is used ($\approx$ 28 MeV)

Reference results from PAS FTR-13-022

L_{int} (fb^{-1})	$N(B_s)$	$N(B_d)$	$d\mathcal{B}(B_s \to \mu\mu)$	$d\mathcal{B}(B_d \to \mu\mu)$	Significance of $B_d \to \mu\mu$	$d[\mathcal{B}(B_d \to \mu\mu)/\mathcal{B}(B_s \to \mu\mu)]$
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 $B \to DK$

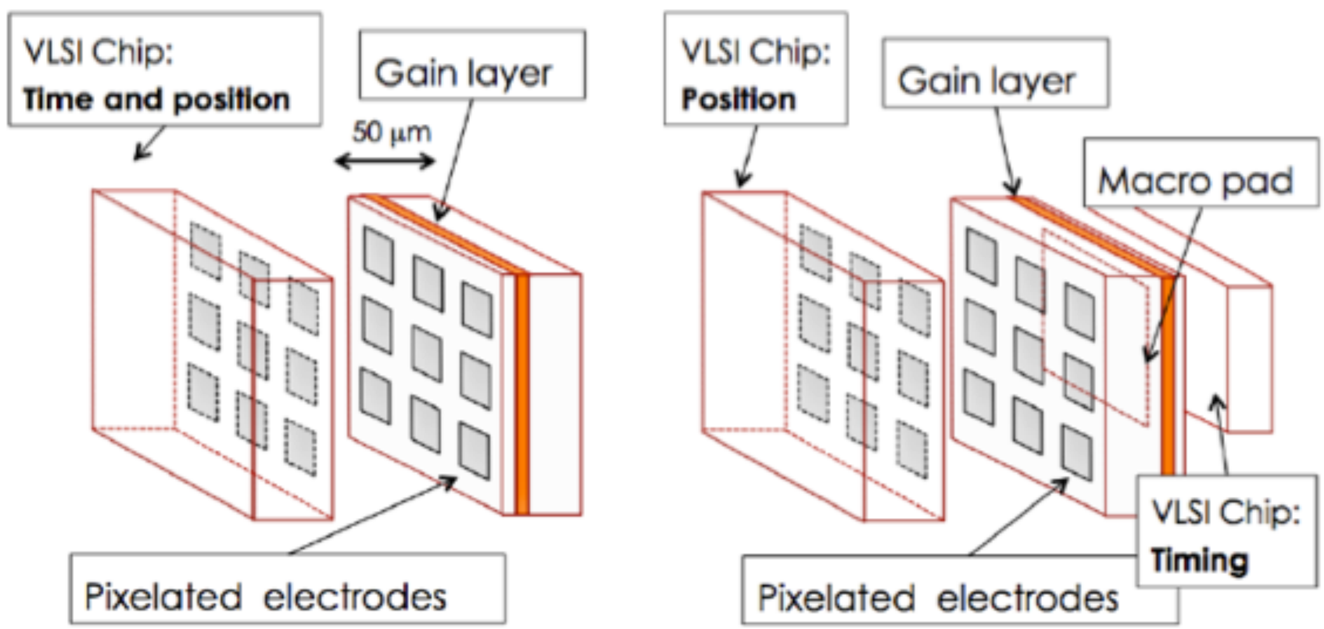
- Sensitivity to γ from numerous channels
  - $B^+ \to DK^+$ ($D \to K_S hh$)
  - $B^+ \to DK^+$ ($D \to hh'$)
  - $B_s \to D_s K$
  - $B^0 \to DK^{*0}$ ($D \to hh'$)
    - $B^0 \to DK\pi$ ($D \to hh'$)
  - $B^+ \to DK^+$ ($D \to K_S K\pi$)
  - $B^+ \to DK^+$ ($D \to K3\pi$, 4h, $hh'\pi^0$)
  - $B^0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



Colour code: 3/fb; 1/fb; not yet

Ultra-Fast Silicon Detectors

- The design of ultra-fast silicon detectors (UFSD) exploits the effect of charge multiplication in silicon to obtain detectors that can concurrently measure with high accuracy time and space



UFSD requirements

- Main set of requirements to obtain excellent timing resolution: (i) low noise, (ii) large signals and (iii) a short rise time
- These requirements are complemented by the additional request of having signals that are very uniform: if the signal shape changes a lot on an event-to event basis, than the timing accuracy is severely degraded
- The ultimate performance of UFSD depends critically on the combination of the sensors with the read-out electronics
- A highly pixelated UFSD requires a full custom ASIC read-out, bump bonded to the sensor
- The design of UFSD requires the optimization of many intertwined parameters. We are considering two distinct options for the realization of a highly pixelated UFSD system, Figure 39: (i) Left: a single read-out chip, able to measure position and time, or (ii) Right: a split design, where we use double side read-out to separate the position measurement from the time determination
- This second design is mechanically more challenging, however reduces the complexity of each read-out chip. Both designs assure (i) excellent timing capability, due to the enhanced signal and reduced collection time, and (ii) accurate position determination, due to the pixelated electrodes.

PicoSecond Tracking

Can we build a 4-D tracking system for concurrent time and position measurement?

Goal:
- **50 micron**
- **10 picosecond**

From the same Pixel
(many layers, better resolution)

Sensor:
- Fast and Large signal
- Low noise

Timing depends upon:
- Noise
- dV/dt
- Rise time

A possible solution:
Thin silicon sensor (50 micron) with low internal gain

→ This is traditional silicon sensor, with 10 x Signal
(not APD or SiPM-like, they don't go into breakdown)

And it should be:
- Radiation hard
- Low Mat. Budget
- Non-Magnetic
- Cheap
- Photon blind

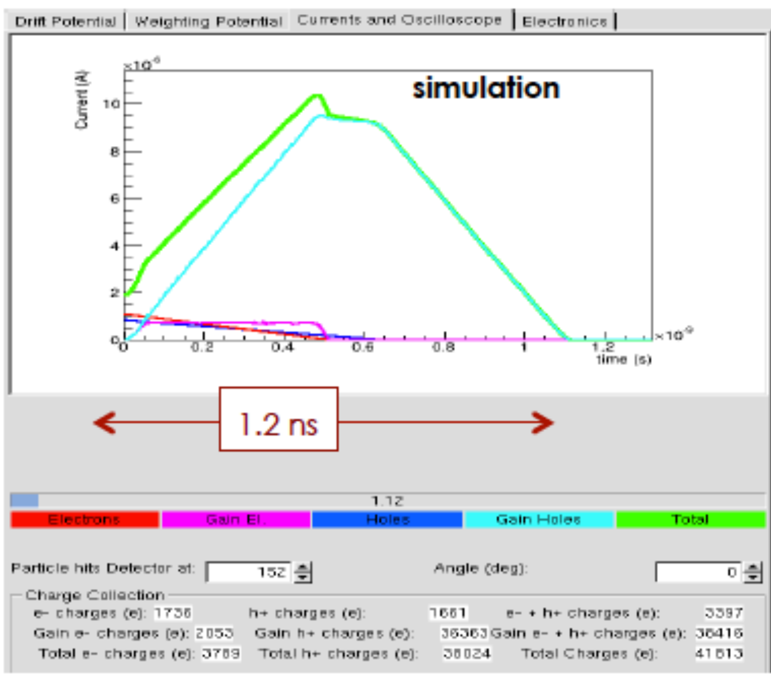
Ultra-Fast Silicon Detector (INFN - gruppo V)

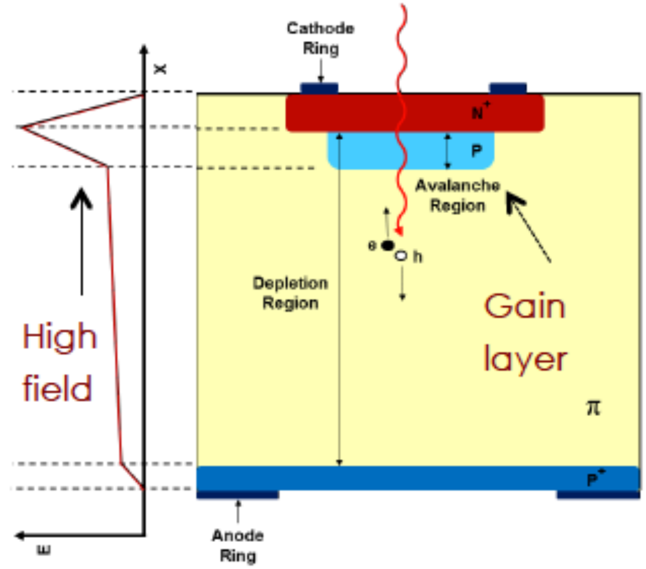
UFSD: pixelated silicon detector with low internal gain (LGAD)

UFSD gain: Add an extra deep p+ implant

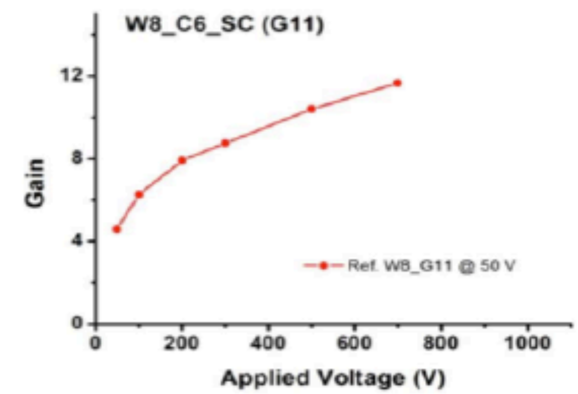
➔ High local field generates multiplications

- 50 μ thick Si. detector
- Large Signal: ~40k e/h (as in a 500 μ Si det.)
- Very short signal (~1 ns)





Prototype UFSD shows good gain (~ 10)



Nicolo Cartiglia, INFN, Torino - UFSD

Status and outlook

Status:

- UFSD Prototypes exist and show strong gain (5-20)
- New Collaboration with FBK started, design ready by summer
- Collaboration on electronics with CAEN and Saclay
- Production of 50 micron-thick, UFSD microstrips and small pixels under way

What can we do with Picosecond Tracking?

- Very good Time-of-Flight
  => Much lighter than Magnet on satellite for momentum measurements
- Fight background
  => New generation of NA62 (100 ps precision)
- Pile-up rejection
  => Help at HI-LHC in forward direction
- Resolve tracking ambiguities
  ⇒ More information always help in tracking..
- **Your ideas here…**