Flavour-physics prospects in Run3 and HL-LHC at ATLAS and CMS

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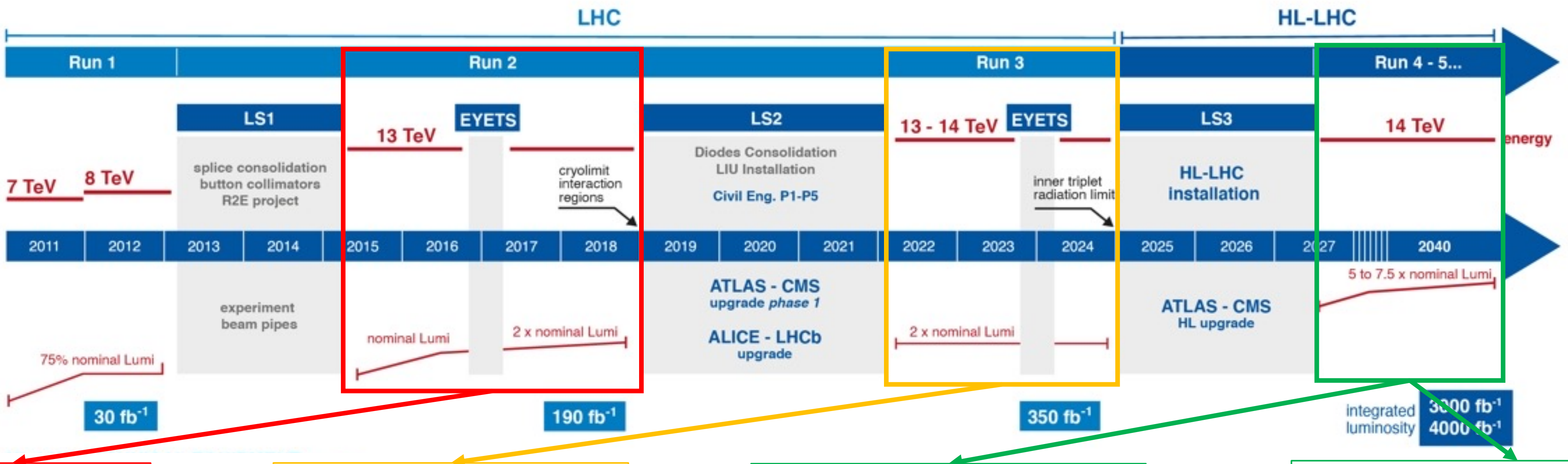
On behalf of CMS & ATLAS collaborations



Run2
$\mathcal{L} = 1\times10^{34} Hz/cm^2$
$\mathcal{L}_{int} = 150 fb^{-1}$

Run3
$\mathcal{L} = 1.3 \div 2\times10^{34} Hz/cm^2$
$\mathcal{L}_{int} = 150 fb^{-1}$

Nominal Run4
$\mathcal{L} = 5\times10^{34} Hz/cm^2$
$\mathcal{L}_{int} = 3000 fb^{-1} < PU >\sim 140$

Ultimate Run4
$\mathcal{L} = 7.5\times10^{34} Hz/cm^2$
$\mathcal{L}_{int} = 4000 fb^{-1} < PU >\sim 200$

- **Run 3** will take place from 2022 to 2024 at CM energy between 13 and 14 TeV :
  - pilot Beam Test Oct. 21, start of Run-3 2022 (stable beams expected in May);
  - expected to more than double the integrated luminosity of Run 2;
  - detector and reconstruction improvements;

- **Run 4** will take place after the LS3 at CM energy of 14 TeV :
  - <PU> of 140-200, highly dense environment;
  - Major detector & software upgrade;
  - aims to x10 the integrated luminosity of Run3;
  - Peak luminosity @ 5-7.5 x 10^{34} Hz/cm^2 ;

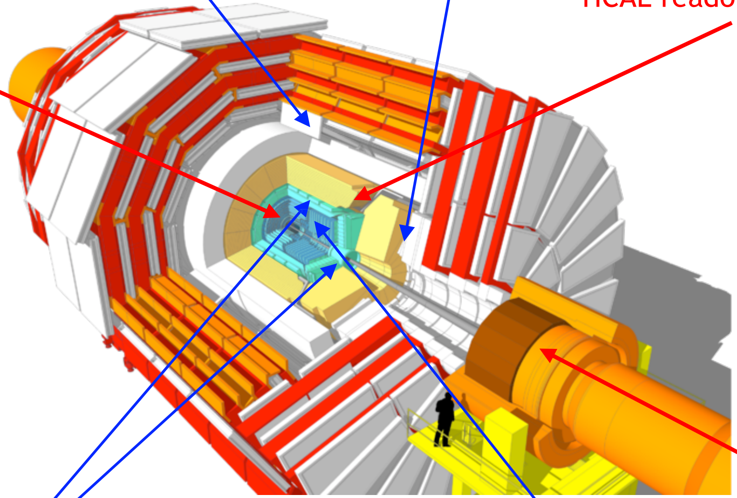
CMS & ATLAS detectors – Run 3 & Phase II Upgrades

Improved muon system
new RPC coverage (1.5 < |η| < 2.4)
new electronics
GEM up to |η| = 2.8

New endcap calorimeters (HGCAL)
high granularity
4D showers

New Barrel Pixel Layer 1 installed

HCAL readout upgrade



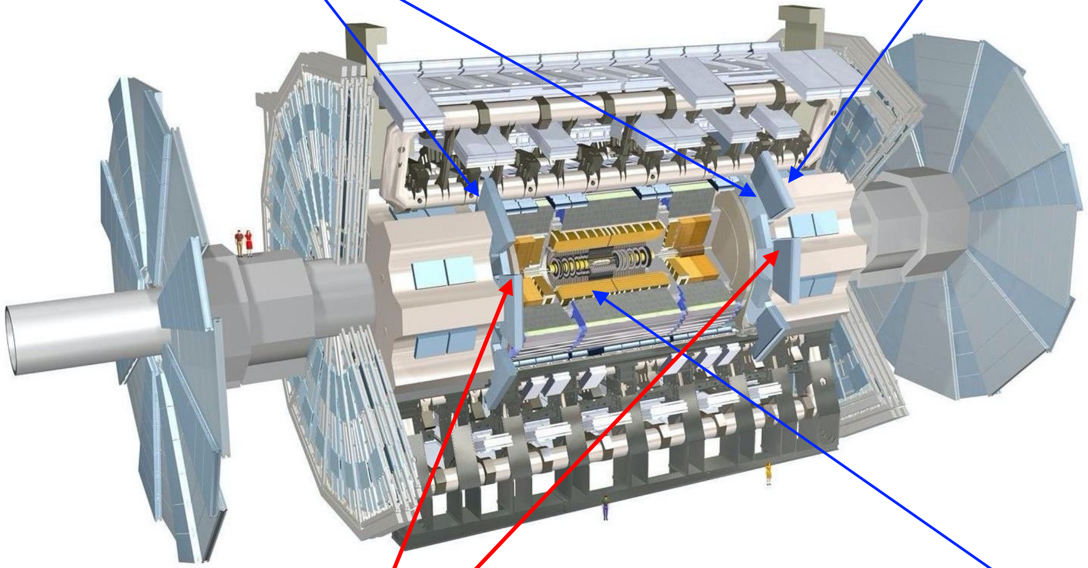
New precision timing detector
Timing resolution of 30-40 ps for MIPs
full coverage of |η| < 3.0

New inner tracker
all silicon tracker
track-trigger @ 40 MHz
coverage to |η| < 4

New beam pipe installed

Improved muon coverage and trigger
new RPCs in innermost layer
new MDT readout

New endcap high-granularity timing detector
30 ps/track in 2.4 < |eta| < 4.0
resolution of time dimension of beam spot



New Small Wheel (NSW) for the muon spectrometer

New inner tracker
all silicon tracker
coverage to |η| < 4

Run3
Phase II

Upgrade to trigger and DAQ
L1 rate increased to 750 kHz High Level trigger rate to 7.5 kHz Track information at L1

Upgrade to trigger and DAQ
L1 rate increased to 1 MHz
High Level trigger rate to 10 kHz

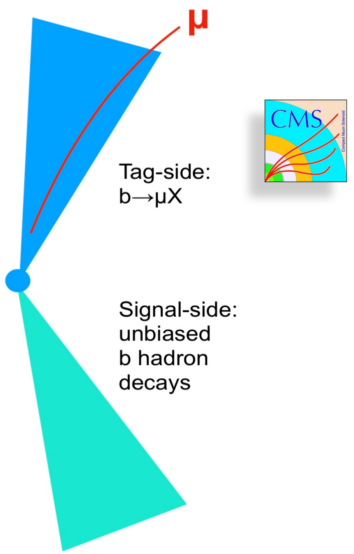
N.B. not all the planned upgrades to the detector are listed here

Statistics

- All analyses **could be repeated with up to twice** the integrated luminosity. Additional improvements in sensitivity from further developments, including ML techniques, and reduction of the systematic uncertainties.

Non-conventional data taking methods

- **CMS B-parking:** in 2018 low p_T displaced triggers to save a sample of **unbiased B** hadron decays recoiling wrt the **triggered muon** (rate ~2kHz). Reconstructed after the end of the run. **Enables several analyses on LFU violation. Studying how to further optimize the trigger in Run 3.**



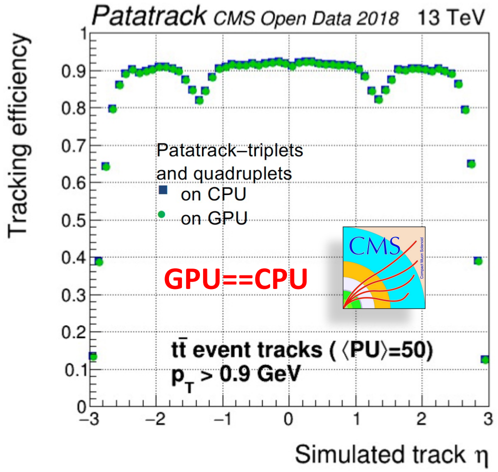
Collected billions of unbiased B decays

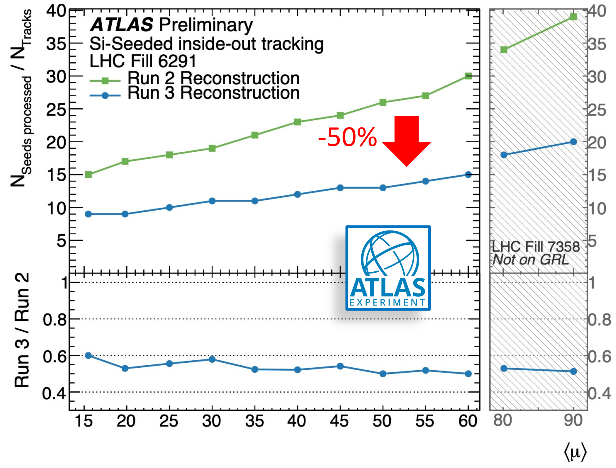
Mode	N_{2018}	f_B	$\mathcal{B}$
Generic b hadrons			
B^0_d	4.0×10^9	0.4	1.0
$B^\pm$	4.0×10^9	0.4	1.0
B_s	1.2×10^9	0.1	1.0
b baryons	1.2×10^9	0.1	1.0
B_c	1.0×10^7	0.001	1.0
Total	1.0×10^{10}	1.0	1.0
Events for R_K and R_{K^*} analyses			
$B^0 \to K^* \ell^+ \ell^-$	2600	0.4	6.6×10^{-7}
$B^\pm \to K^\pm \ell^+ \ell^-$	1800	0.4	4.5×10^{-7}

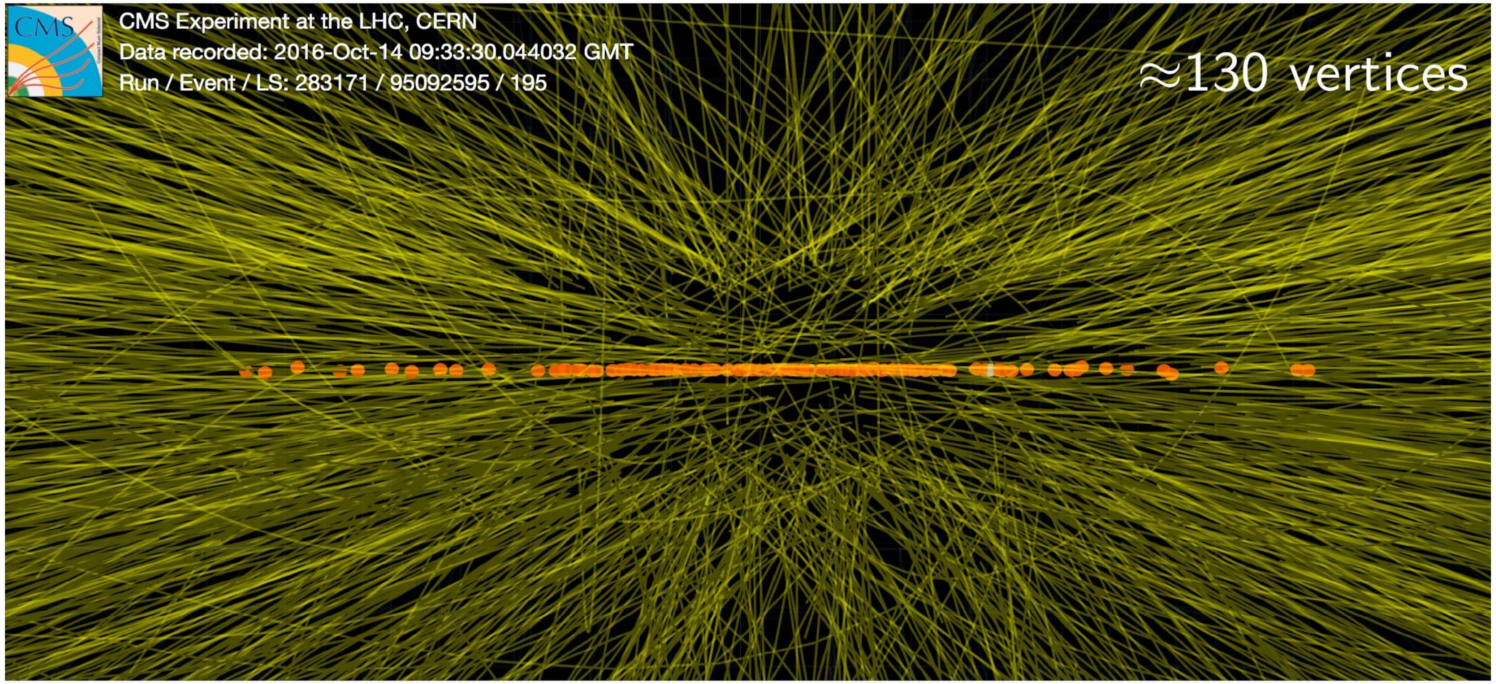
Event reconstruction improvements

- **CMS: Developed heterogeneous event reconstruction at HLT** (CPU + GPU) Already offload ~30% of reconstruction to GPUs: ECAL & HCAL local reconstruction, pixel reconstruction and tracking.
  - **Important gains in performance at HLT.**
  - **Current baseline for Run 3** HLT farm.

- **ATLAS: Increased performance of software algorithms**. E.g. timing of Run3 tracking time reduced by a factor **4** w.r.t. Run2.
  - **Fake rate drastically reduced (-50%) while efficiency untouched.**
  - **Increased availability of tracking at HLT.**





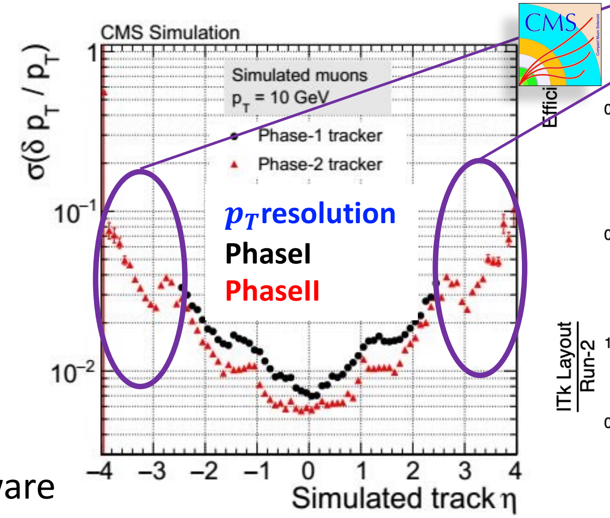


- Extremely harsh environment:
  - expected average pileup interactions of 140-200;
  - increase of particle density;
  - radiation damage to the detector;

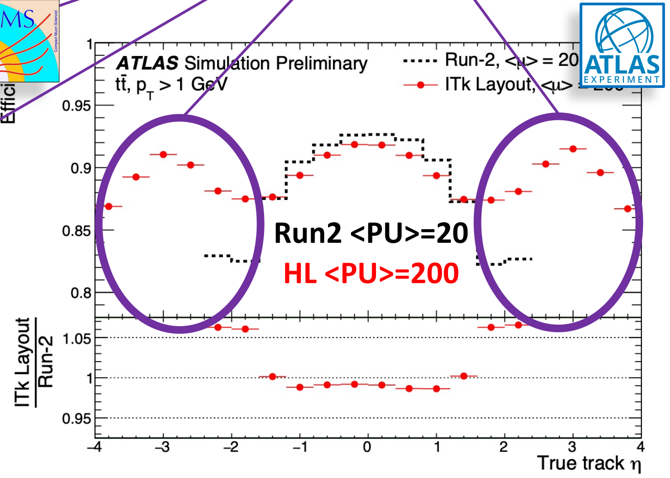
- B physics potential will be affected by the HL-LHC pileup conditions:
  - low p_T signature;
  - requirement of very high precision measurements;

- Both ATLAS & CMS will undergo a major upgrade in both hardware and software to cope with these new challenges maintaining or improving Phase I performance.

Extended η coverage



CMS-TDR-014

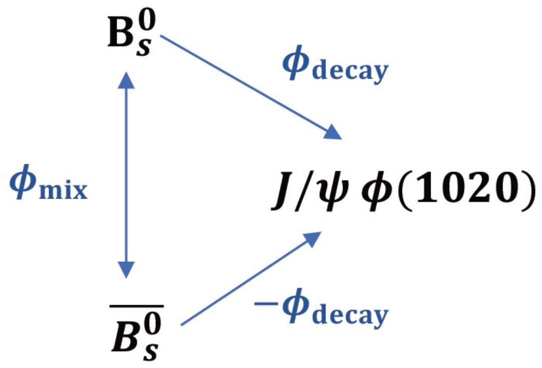


ATL-PHYS-PUB-2019-014

$$B_s^0 \to J/\psi\phi$$

$\boldsymbol{\phi_s}$: CPV phase arises from interference between direct B_s^0 decays to a CP eigenstate and decays through $B_s^0 - \overline{B_s^0}$.

- **SM:** $\phi_s \simeq -2\beta_s = -2arg\left(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -36.96^{+0.72}_{-0.84}\text{mrad}$.
- **BSM:** modification up to $\sim 10\%$ (new particles contribute to mixing).



$\phi_s = \phi_{mix} - 2\,\phi_{decay}$

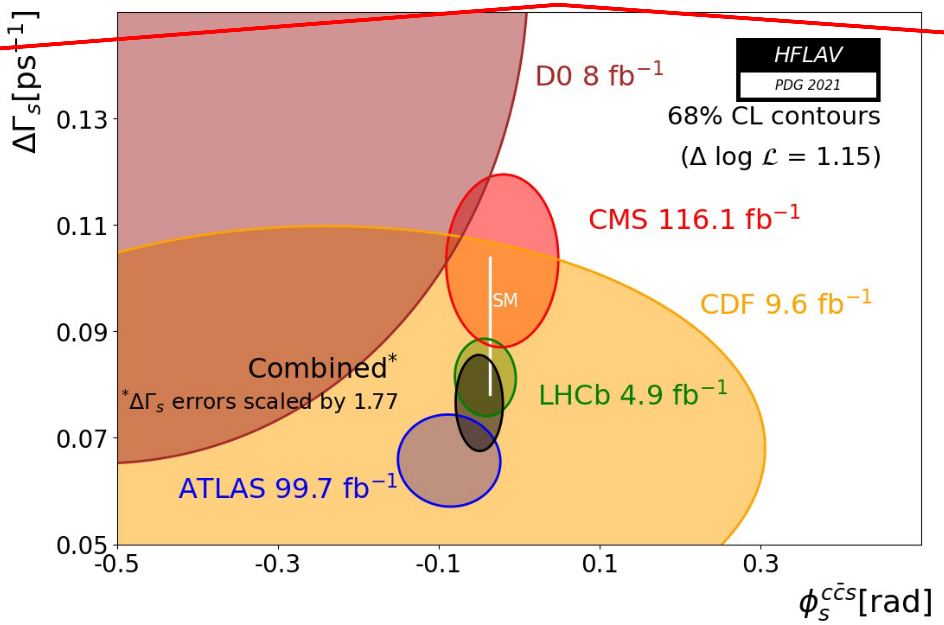
State of the art: some tension between the experiments.

Perspectives: potentially new physics hidden discoverable as uncertainties shrinks.

For both experiments statistical uncertainties still play an important role: room for improvement for Run3&HL.

ATLAS — EPJ C81(2021)342

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.081	0.041	0.022
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0043
Γ_s [ps^{-1}]	0.6687	0.0015	0.0022
$\lvert A_\parallel(0)\rvert^2$	0.2213	0.0019	0.0023
$\lvert A_0(0)\rvert^2$	0.5131	0.0013	0.0038
$\lvert A_S(0)\rvert^2$	0.0321	0.0033	0.0046
$\delta_\perp - \delta_S$ [rad]	−0.25	0.05	0.04
	Solution (a)		
$\delta_\perp$ [rad]	3.12	0.11	0.06
$\delta_\parallel$ [rad]	3.35	0.05	0.09
	Solution (b)		
$\delta_\perp$ [rad]	2.91	0.11	0.06
$\delta_\parallel$ [rad]	2.94	0.05	0.09

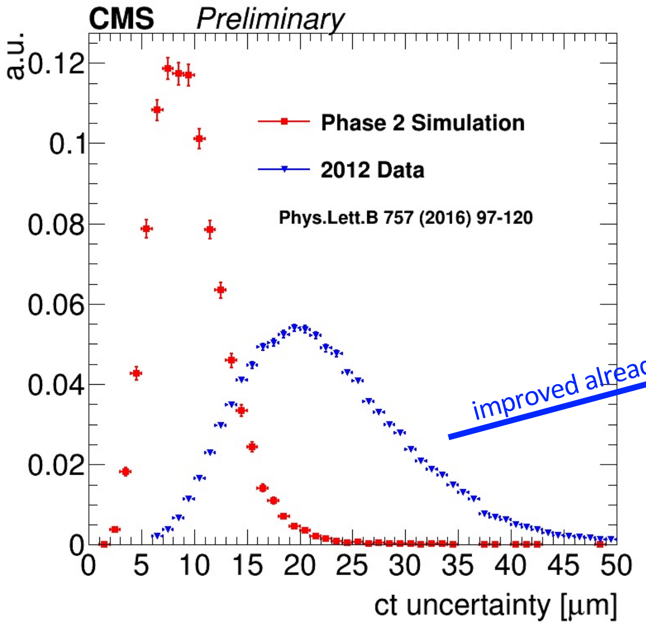


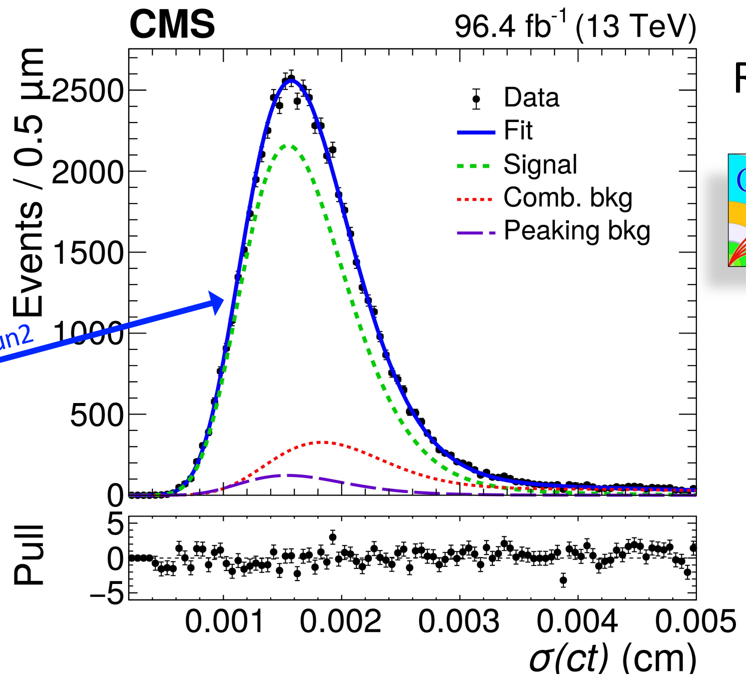
CMS — PLB 816(2021)136188

Parameter	Fit value	Stat. uncer.	Syst. uncer
ϕ_s [mrad]	−11	± 50	± 10
$\Delta\Gamma_s$ [ps^{-1}]	0.114	± 0.014	± 0.007
Δm_s [$\hbar$ps^{-1}]	17.51	$^{+0.10}_{-0.09}$	± 0.03
$\lvert\lambda\rvert$	0.972	± 0.026	± 0.008
Γ_s [ps^{-1}]	0.6531	± 0.0042	± 0.0024
$\lvert A_0\rvert^2$	0.5350	± 0.0047	± 0.0048
$\lvert A_\perp\rvert^2$	0.2337	± 0.0063	± 0.0044
$\lvert A_S\rvert^2$	0.022	$^{+0.008}_{-0.007}$	± 0.016
$\delta_\parallel$ [rad]	3.18	± 0.12	± 0.03
$\delta_\perp$ [rad]	2.77	± 0.16	± 0.04
$\delta_{S\perp}$ [rad]	0.221	$^{+0.083}_{-0.070}$	± 0.048

$B_s^0 \to J/\psi\phi$ performance improvement @ HL-LHC

CMS-PAS-FTR-18-041

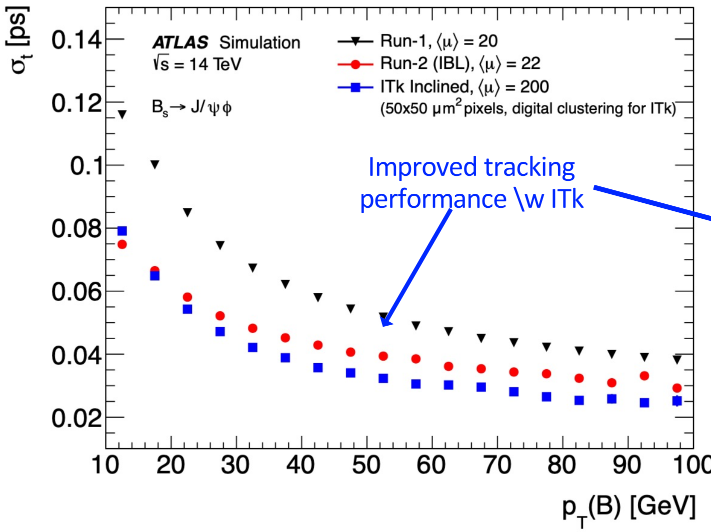


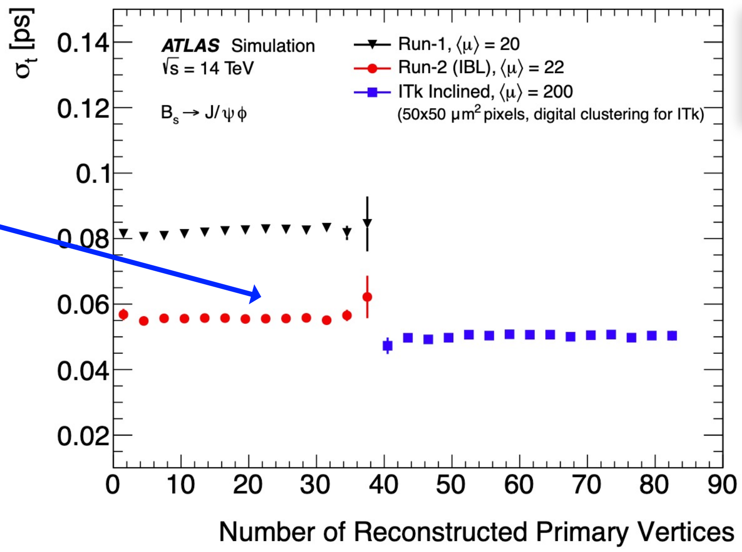


Run1-like. Dedicated MCs @ <PU>=200. 3000 fb^{-1}

- new silicon tracker: better resolution, coverage up to $|\eta| = 4$;
- $c\tau$ uncertainty greatly reduced;
- multiple tagging scenarios considered influence ϕ_s uncertainties;

ATL-PHYS-PUB-2018-041

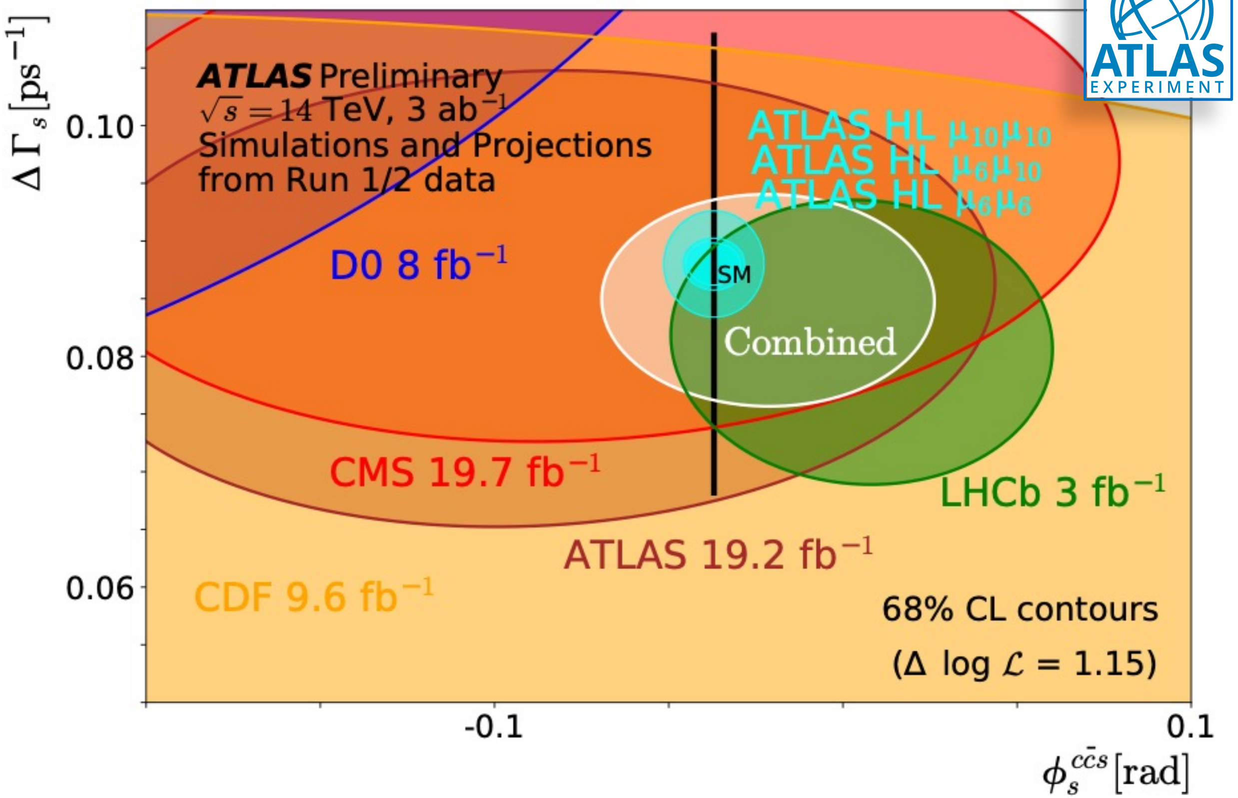


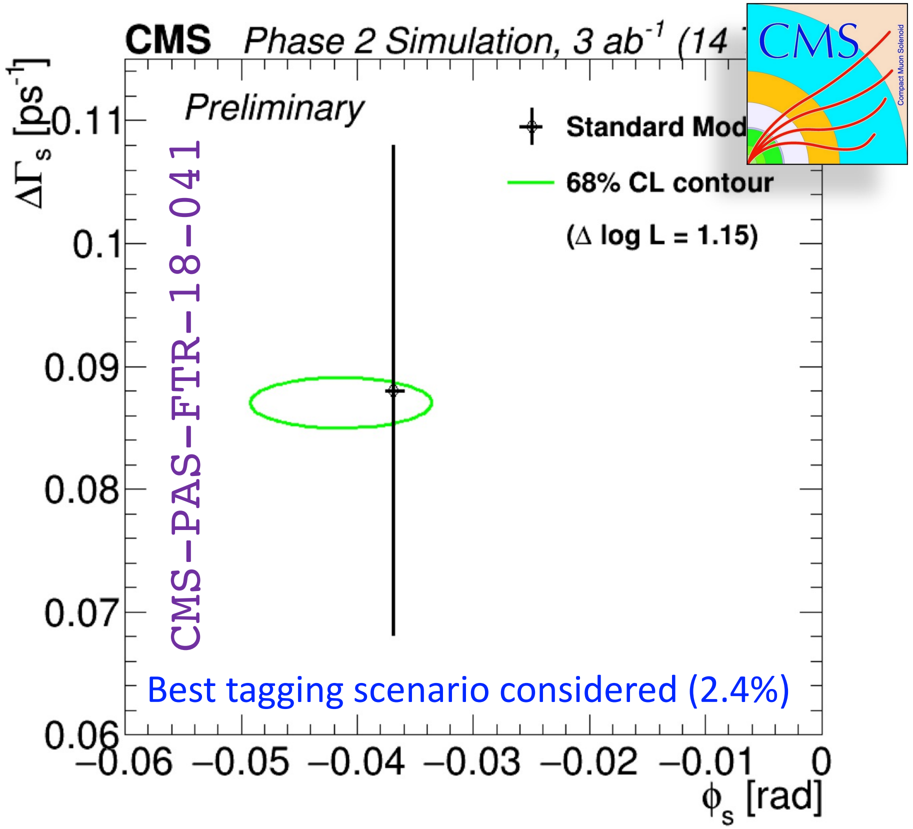


- ITk $50\times50\ \mu m^2$;
- σ_τ resoluton improves over Run2 IBL, improves with p_T;
- could improve further with analogue digital pixel clustering;

- Systematic errors are based on conservative assumptions.
- Combining the increased statistics and the improved detector performance ATLAS and CMS would reach enough precision to be comparable with SM: **uncertainties reduced by a factor $4 \div 6$.**
- Further improvements with cross-experiment results combination.

ATL-PHYS-PUB-2018-041



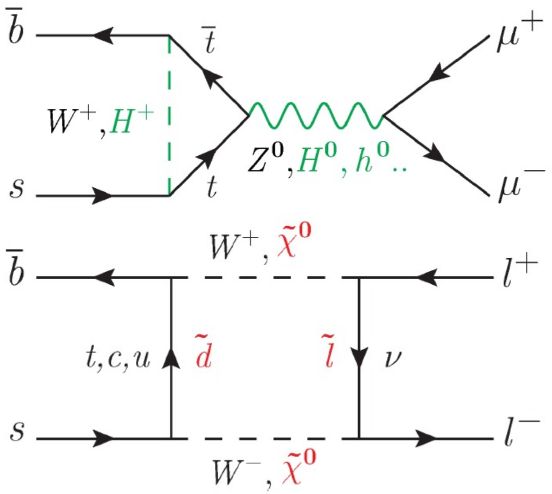


Best tagging scenario considered (2.4%)

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

- **SM: suppressed decay [loop + helicity]:**
  - high precision branching fractions (4-5%);
  - only heavy eigenstate B^0_{sH} contribute.

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.005) \cdot 10^{-10}$$

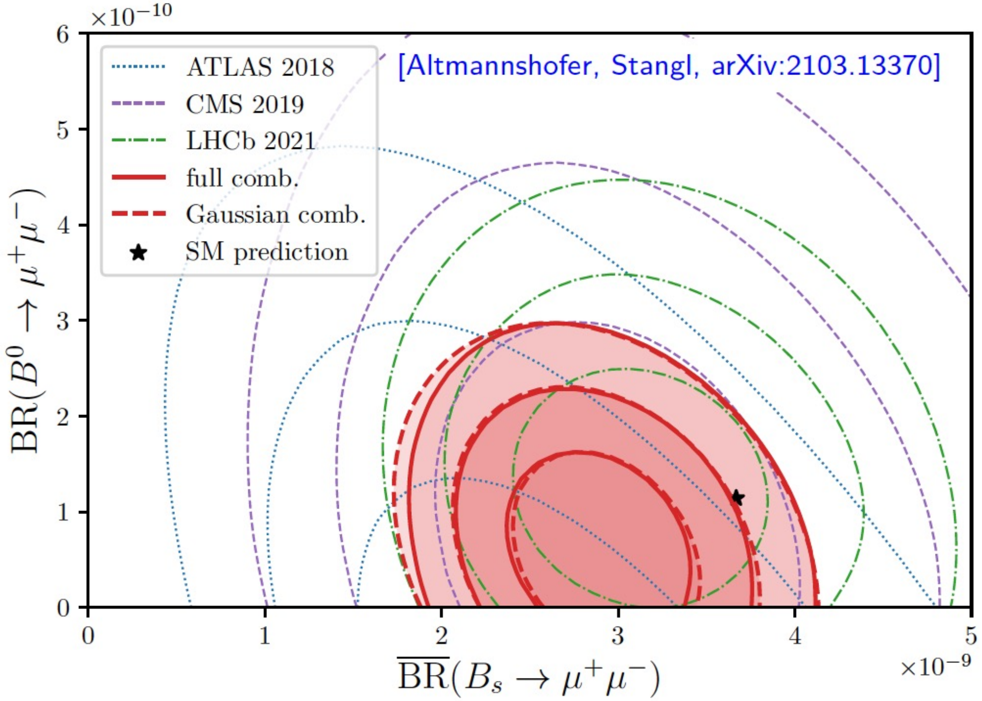


- **BSM:**

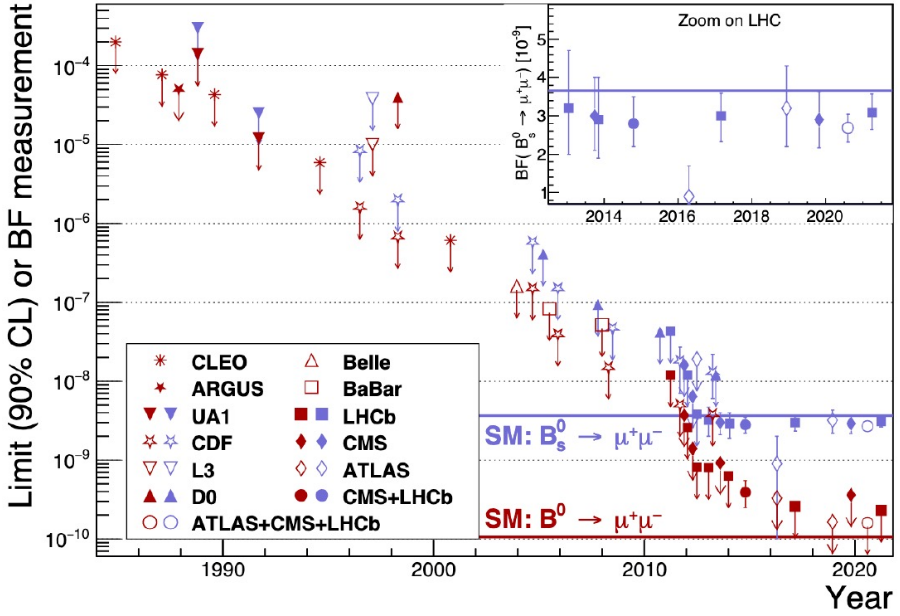
  non-SM heavy particles (2 higgs doublet, MF Violation, SUSY,…) may affect the branching fractions or affect $\tau_{\mu\mu}$.

State of the art: consistent measurements across experiments agree with S.M.

Perspectives: potentially new physics hidden discoverable as uncertainties shrinks.

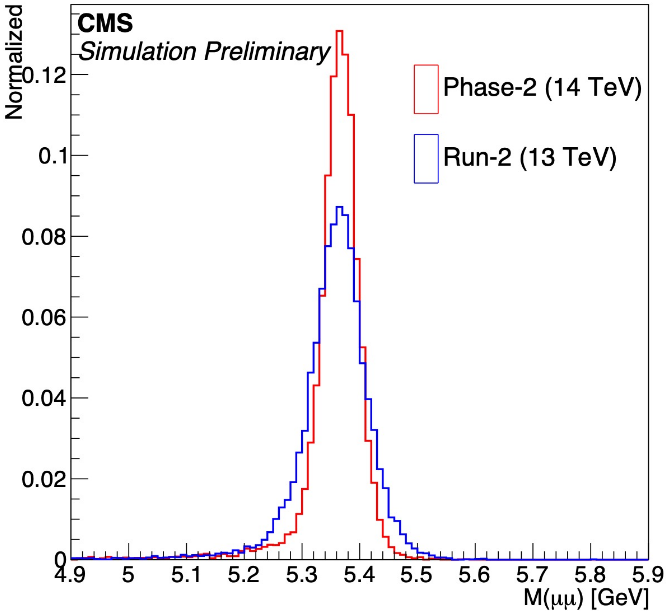


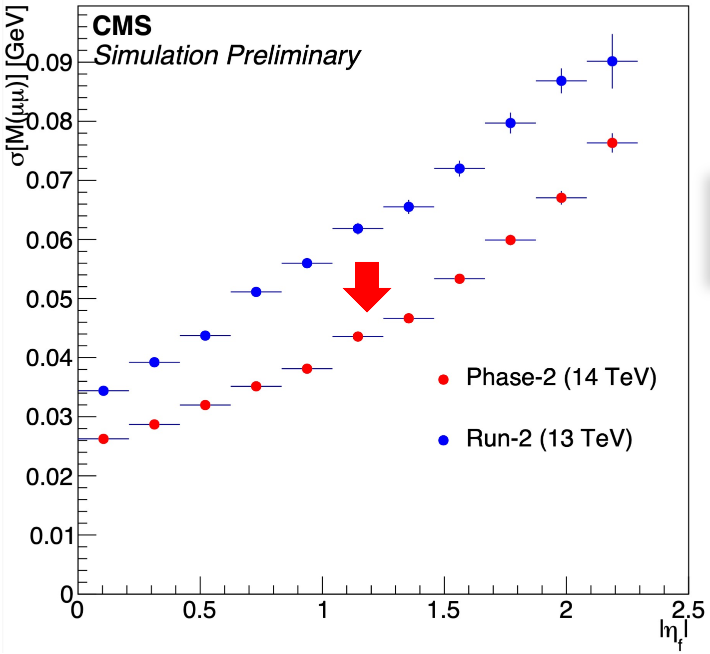
A 30+ year long quest



Still statistics from full Run2/3 to be explored fully & in Run 4 we expect better mass separation and highly increased statistics

CERN-LHCC-2020-004

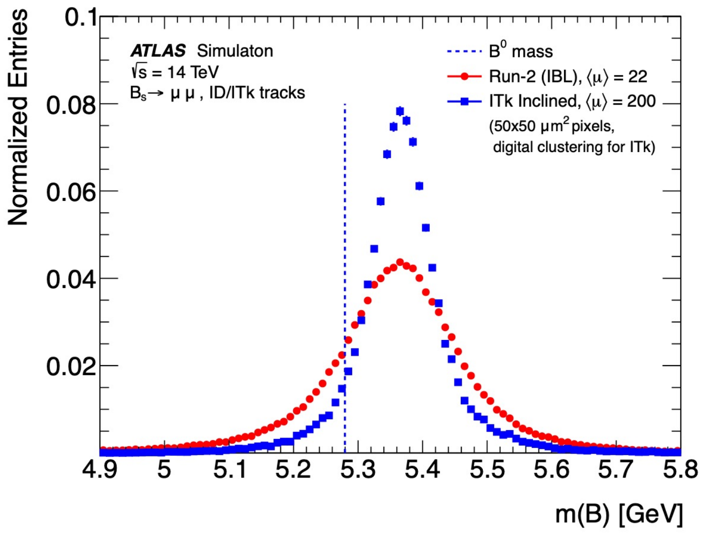


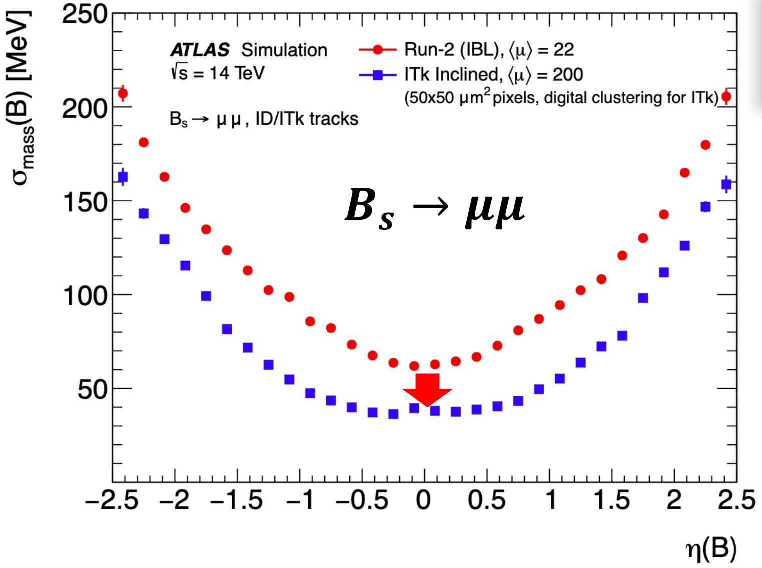


Run1-like. Dedicated MCs @ <PU>=200. 3000 fb^{-1}

- most of the impact from new silicon tracker improved performance;
- up to ~ 25 % improvement in mass peak separation (η dependent);
- cross-feed and backgrounds reduced;

CERN-LHCC-2020-007





- ITk 50×50 μm^2;
- improved mass resolution for B_s:
  - barrel x 1.65: $1.4\sigma \rightarrow 2.3\sigma$;
  - endcaps x 1.5: $0.85\sigma \rightarrow 1.3\sigma$;
- multiple triggering scenarios:

  $\mu_{10}\ \mu_{10}$ - $\mu_{10}\mu_6$ - $\mu_6\mu_6$;

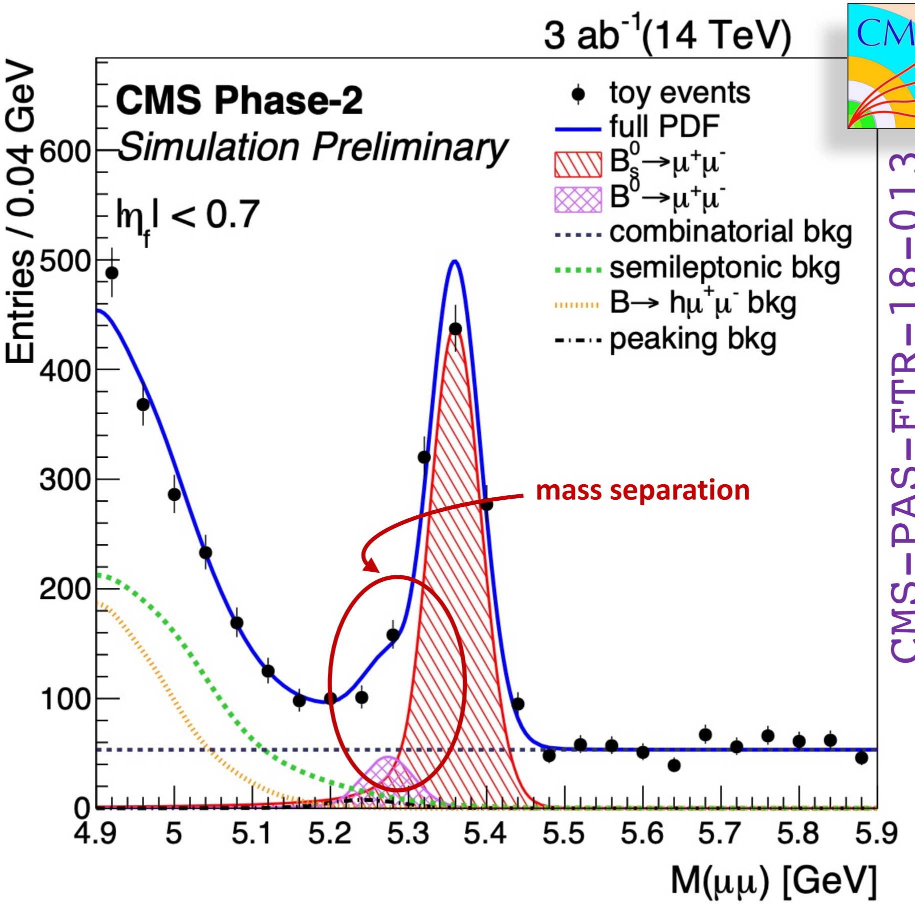
$B_s^0 \to \mu\mu$ @ HL-LHC

- Observation of $B_d \to \mu\mu$ with significance estimated by CMS.
- Much more precise measurements of the $\mathcal{B}s$ and $\tau(B_s)$.

6.3 ÷ 8.3σ@ HL-LHC

< 5σ @ Run3

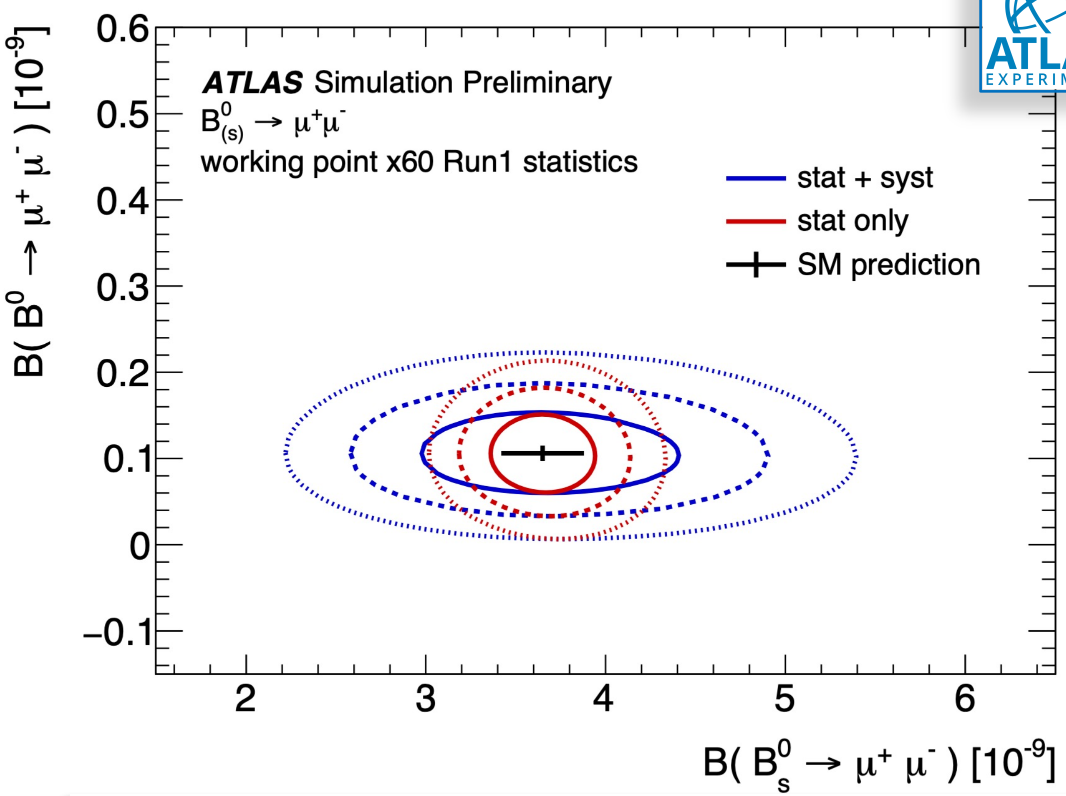
	$\mathcal{L}$ (fb^{-1})	$N(B_s)$	$N(B^0)$	$\delta\mathcal{B}(B_s \to \mu\mu)$	$\delta\mathcal{B}(B^0 \to \mu\mu)$	$\sigma(B^0 \to \mu\mu)$	$\delta[\tau(B_s)]$(stat-only)
Run3	300	205	21	12%	46%	$1.4 - 3.5\sigma$	0.15 ps
HL	3000	2048	215	7%	16%	$6.3 - 8.3\sigma$	0.05 ps



CMS-PAS-FTR-18-013

Run2 latest
- $> 30\%$ for B_s
- $> 100\%$ for B^0

CMS-PAS-BPH-20-003



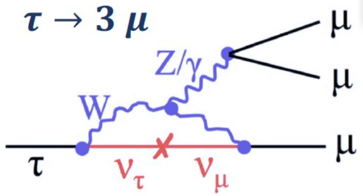
ATL-PHYS-PUB-2018-005

	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ stat [10^{-10}]	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ stat + syst [10^{-10}]	$\mathcal{B}(B^0 \to \mu^+\mu^-)$ stat [10^{-10}]	$\mathcal{B}(B^0 \to \mu^+\mu^-)$ stat + syst [10^{-10}]
Run 2	7.0	8.3	1.42	1.43
HL-LHC: Conservative	3.2	5.5	0.53	0.54
HL-LHC: Intermediate	1.9	4.7	0.30	0.31
HL-LHC: High-yield	1.8	4.6	0.27	0.28

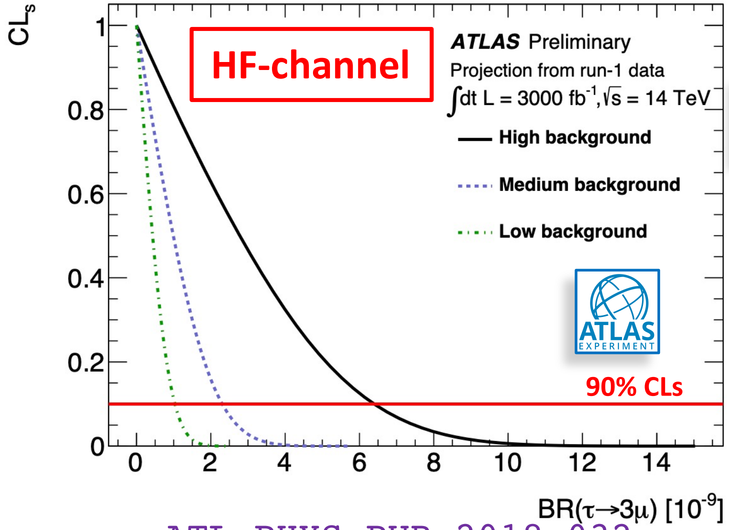
÷ 4 (stat, B_s^0); ÷ 5 (stat, B^0)

Further Studies

The $\tau \rightarrow 3\mu$ decay has never been observed so far.



- **SM:**
  1. no symmetry than enforces the conservation of the lepton flavour;
  2. charged LFV decays are possible in SM with neutrino oscillations $\mathcal{B}(\tau \rightarrow 3\mu) \sim 10^{-54}$.
- **BSM:**
  some BSM theories predict $\mathcal{B}(\tau \rightarrow 3\mu) < 10^{-8} \div 10^{-9}$ (observable at present-day experiments);

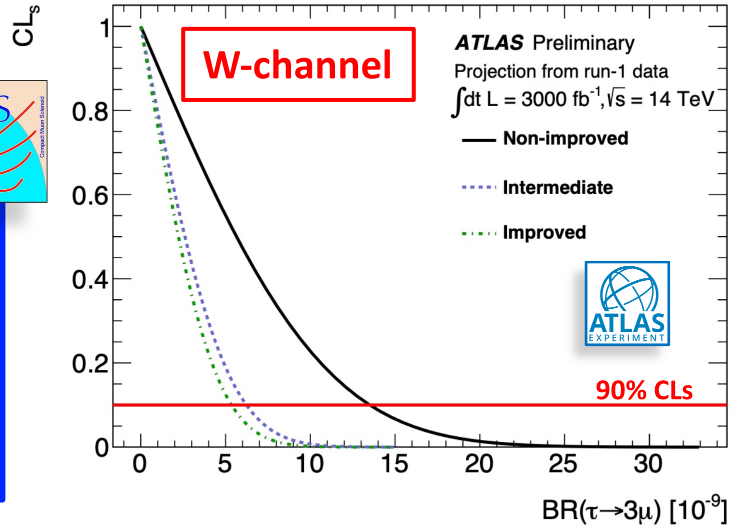


ATL-PHYS-PUB-2018-032

Testing HL potential with dedicated MCs @ <PU>=200. $3000\ \text{fb}^{-1}$. Multiple scenarios:

- W-channel: **non-improved (~Run1 scaled)**, **intermediate (~Run2 scaled)**, **improved (\w ITk).**
- HF-channel: **low (~W)**, **medium (3×W)**, **high (10×W)** backgrounds.

In all cases huge improvement w.r.t. Run1 (for W) and important contribution to the search.



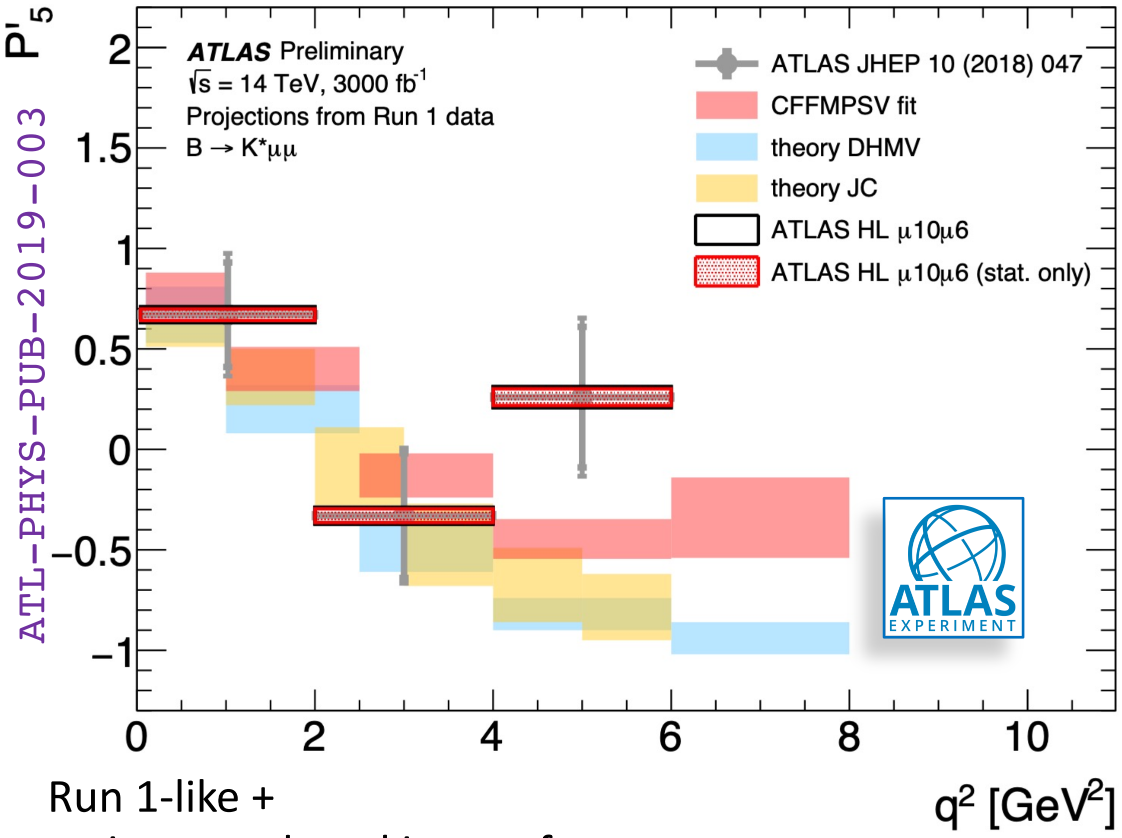
- **New 2016 data** result [JHEP01(2021)163]

$$\mathcal{B}(\tau \rightarrow 3\mu) < 8.0 \cdot 10^{-8} \text{ @ } 90\%\ \text{C.L.} \quad \text{(from W + HF)}$$

- **Run3 (+full Run2)**: increased statistics and new triggering options
- **HL**: will gain from extended muon coverage and L1 trackin (and statistics, of course).

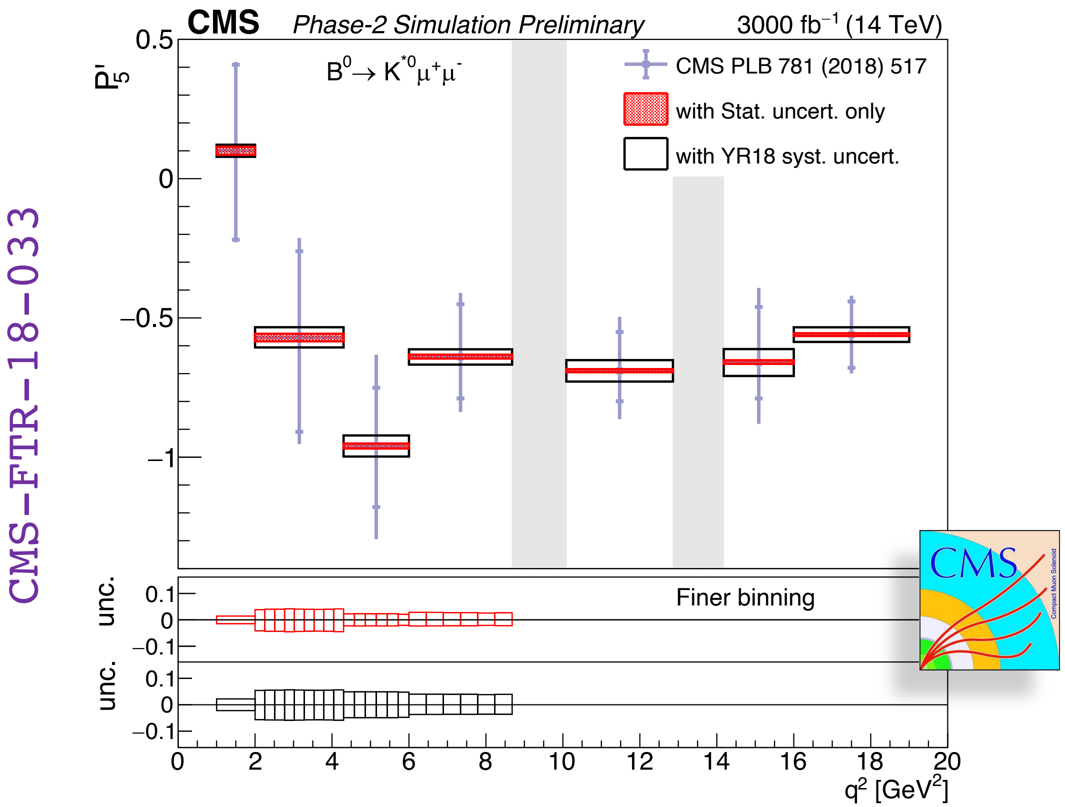
$b \to sll$ processes are an **excellent laboratory** to probe new physics phenomena:

- suppressed in SM (FCNC, forbidden tree-level);
- new phyisics phenomena can affect BR or angular distributions of final state,



Run 1-like +

- improved tracking performance
- 3 trigger scenarios $\mu_{10}\ \mu_{10}$ - $\mu_{10}\mu_6$ - $\mu_6\mu_6$
- P_5' precision improved by $\sim\times 5, \sim\times 8, \sim\times 9$

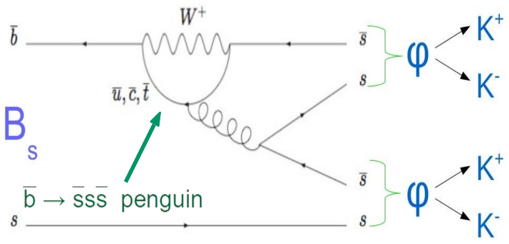


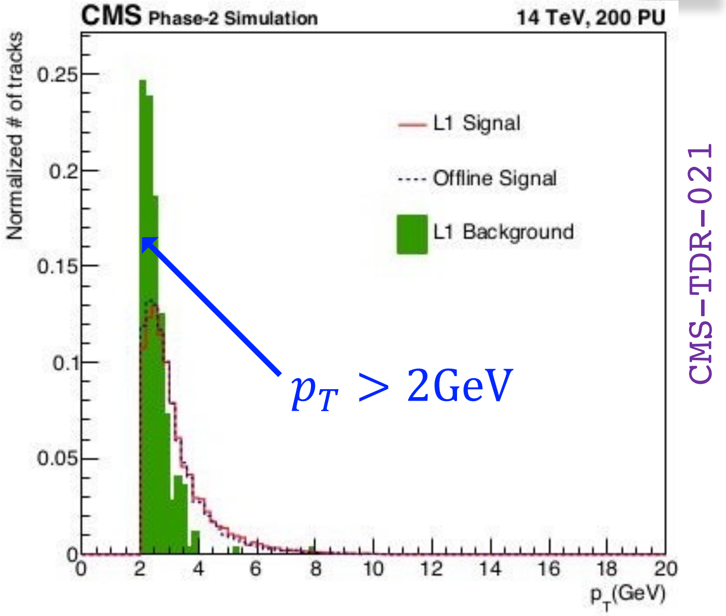
Run 1-like +

- improved tracking: higher mass resolution
- P_5' precision improve by a $\sim\times 15$
- capability to perform a full angular analysis

$B_s^0 \to \phi\phi \to 4K$ @ HL-LHC

- **SM:** FCNC process forbidden at tree level.
- **BSM:** b quark decaying through a penguin diagram.
  - Contributions from heavy particles, beyond the direct reach of LHC.
  - Provide new insight to the CP violating phase in the B_s system.



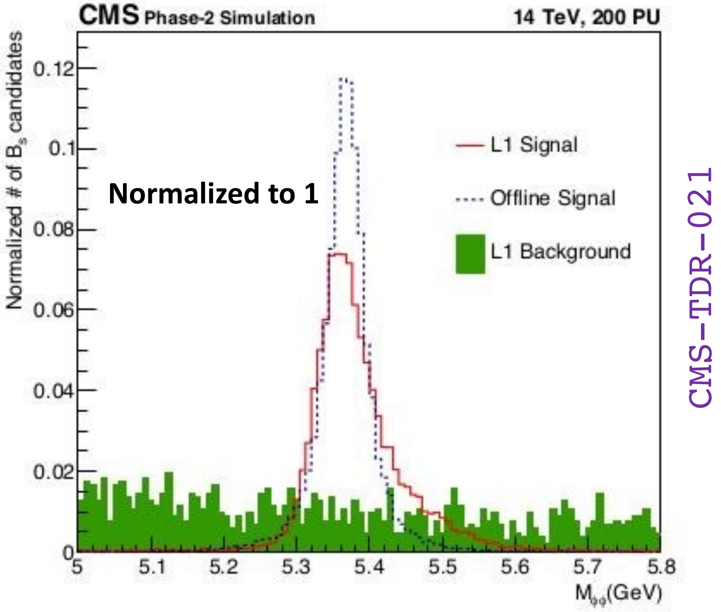


L1 tracking opens new opportunities for the L1 trigger, such as the reconstruction of light meson candidates from hadronic decays : **$B_s^0 \to \phi\phi$ used as case of study.**

To optimize signal efficiency and event rate, three different working points for event selection used: loose, medium and tight. Differing mainly for $p_T(B_s^0)(\geq 10 \text{ or } \geq 12\text{GeV})$ and $M_{\phi\phi}$window.

Baseline	Efficiency (%) L1	Efficiency (%) Offline	Rate (kHz) $< PU > = 200$
Loose	36.15 ± 0.37	60.78 ± 0.50	44.70 ± 1.65
Medium	30.28 ± 0.33	50.04 ± 0.44	15.00 ± 0.95
Tight	30.25 ± 0.33	49.96 ± 0.43	10.02 ± 0.78

(stat only unc.)



@ <PU> = 200:
- $\sim \mathbf{30}\%$ signal efficiency **achievable already at L1** at a rate $\sim 15\ kHz$;
- computation made possible by FPGAs;

Summary & conclusions

Dummy Summary

- **Run3** is coming with interesting prospects, **new triggering** and **data-taking** techniques and **doubled** statistics.
- **Extensive upgrade** program for CMS & ATLAS for **HL-LHC** together with $\times$**10 statistics**.
- $B_s^0 \to J/\psi\phi$:
  - will benefit from HL-LHC 3000fb^{-1} to shrink statistical uncertainties (still dominant);
  - much more precise $c\tau$ measurement thanks to the improved tracking performance;
- $B_{d/s} \to \mu\mu$:
  - significant improvement in mass resolution leads to better separation;
  - observation of $B_d \to \mu\mu$ at 5σ or more;
  - much more precise measurement of the branching fractions and other observables;
- $\tau \to \mu\mu\mu$:
  - full Run2 & Run3 statistics awaits;
  - at HL-LHC extensive studies from ATLAS show;
  - will take advantage of extended $|\eta|$ coverage (up to 4);
- $B_s^0 \to \phi\phi$:
  - interesting showcase for L1 tracking: @<PU>=200 signal already visible at L1;
- $B^0 \to K^{*0}\mu\mu$:
  - will benefit from HL-LHC 3000fb^{-1} and improved tracking: P_5' precision improved up to ~order of magnitude for both ATLAS & CMS;

The HL-LHC and CMS & ATLAS Phase-2 upgrade will extend the physics reach of both experiments significantly.

***Thanks*!**

“I am putting myself to the fullest possible use, which is all I think that any conscious entity can ever hope to do”