Rare decays in CMS

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on behalf of the CMS Collaboration

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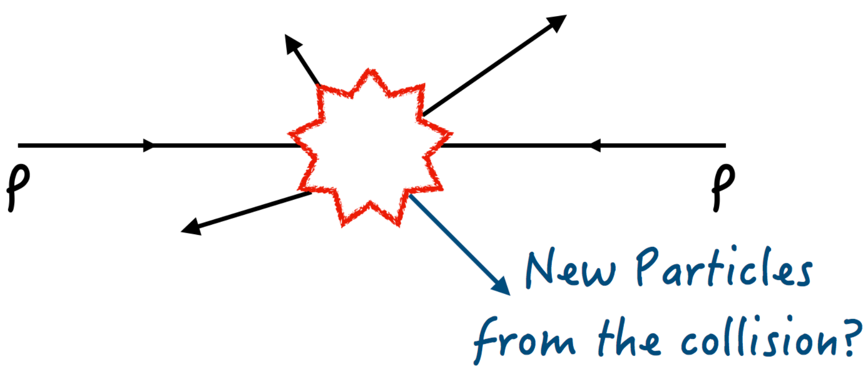
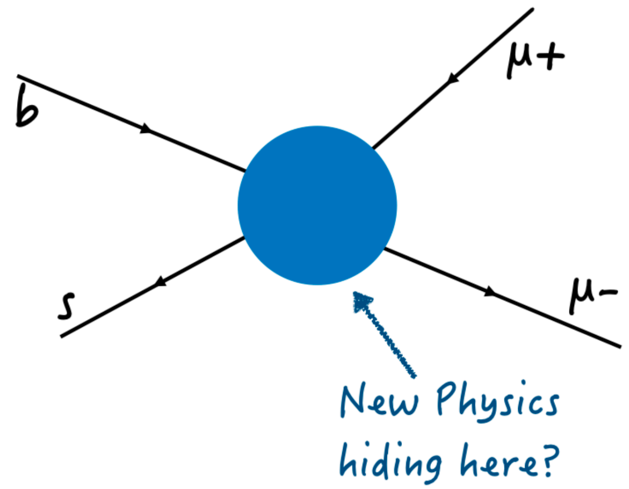
Why rare decays ?

- **Complementary approach to direct New Physics searches**





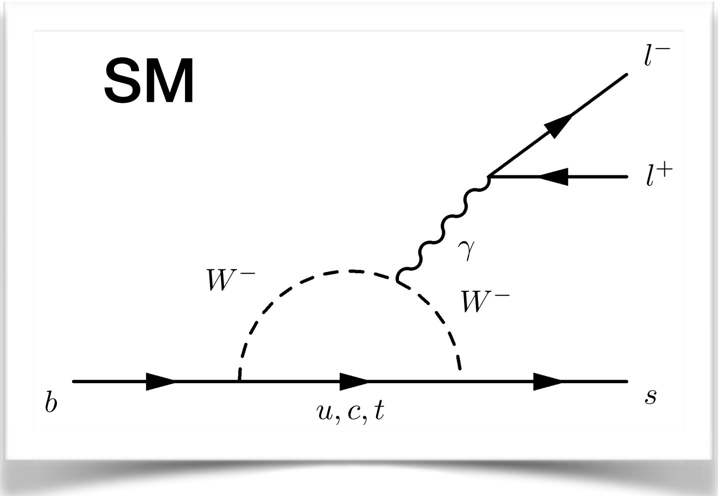
- Processes through loop diagrams or CKM suppressed in the Standard Model
  - typical branching ratios < 10^{-6}
- Impact of New Physics could be easier to spot
  - search for virtual contributions of new heavy particles
  - could impact branching ratios or angular distribution
- Allow to reach **sensitivity to higher mass scales than direct searches**
- Clean experimental and theoretical probes, precise SM predictions available

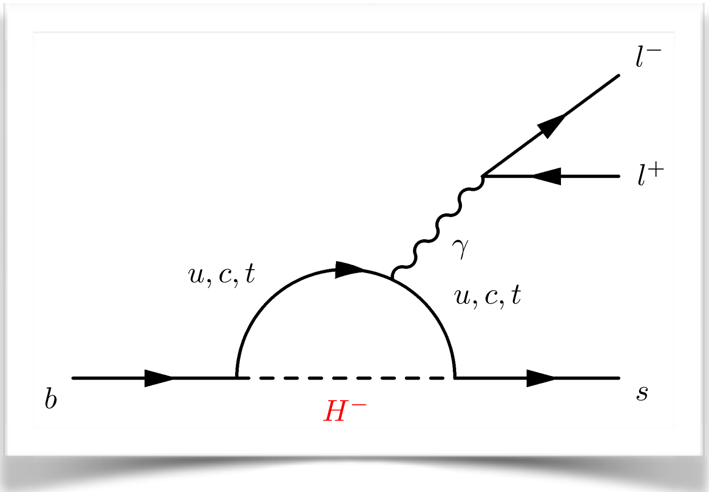
Outline

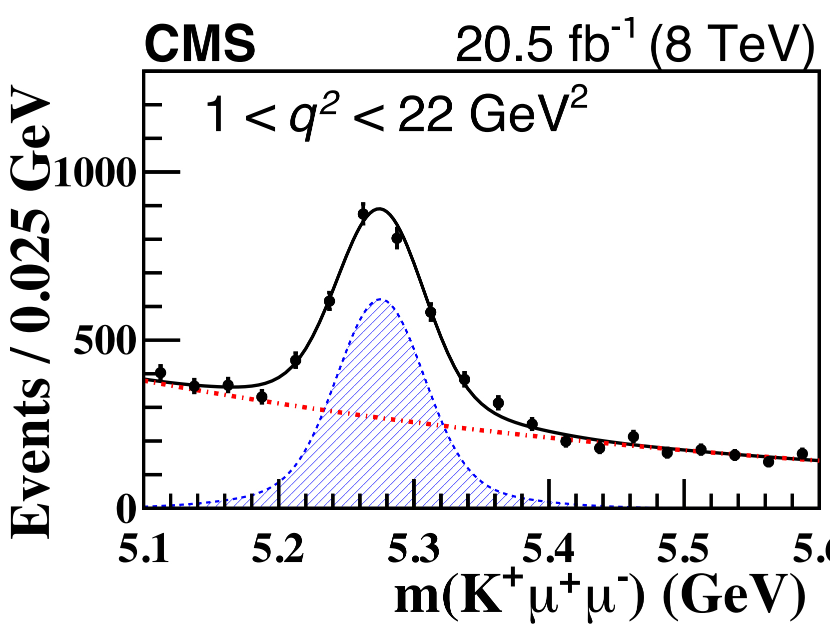
- Angular analysis of the $B^+ \to K^+ \mu\mu$ decay — Phys. Rev. D 98 (2018) 112011
- Search for $\tau \to 3\mu$ decays — CMS-PAS-BPH-17-004
- Prospects for selected rare decays measurements in CMS at the HL-LHC — CERN-LPCC-2018-06

$B^+ \to K^+\mu\mu$ decay: overview

- The decay $B^+ \to K^+\mu\mu$ is a **FCNC process of the type b → $s\ell\ell$**
    - forbidden at tree level in the SM (BR ~ 4.4×10^{-7})
- New heavy particles from NP can appear in competing diagrams, **affecting the differential angular distributions**
- Previously studied by *BABAR* , *Belle, CDF, and LHCb*
    - no hints of beyond SM physics
- **CMS analysis is based on Run 1 data at 8 TeV (20.5 fb^{-1})**
    - events selected by a displaced dimuon trigger
    - cut-based selection determined to optimise signal significance
    - 2286 ± 73 signal events with $1 < q^2 < 22$ GeV^2





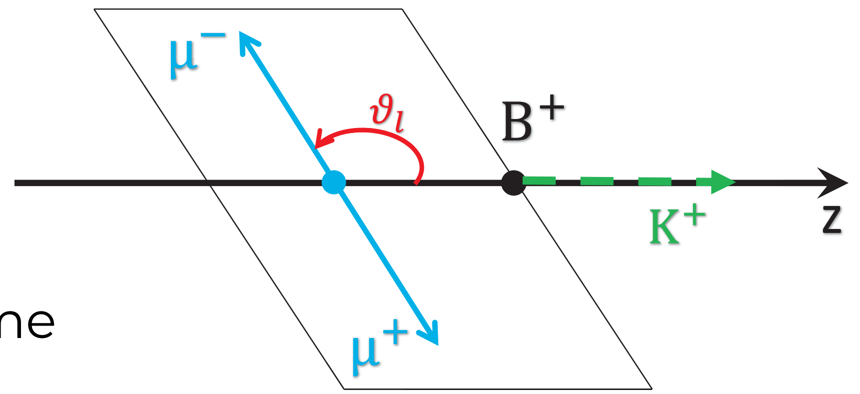


Phys. Rev. D 98 (2018) 112011

Angular analysis of the $B^+ \to K^+\mu\mu$ decay

- Decay rate is completely described as a function of the two variables q^2 and $\cos\theta_\ell$

$$\frac{1}{\Gamma_\ell}\frac{d\Gamma_\ell}{d\cos\theta_\ell} = \frac{3}{4}(1-F_H)(1-\cos^2\theta_\ell) + \frac{1}{2}F_H + A_{FB}\cos\theta_\ell$$



θ_ℓ: angle between the μ^- and the K^+ in the dimuon rest frame

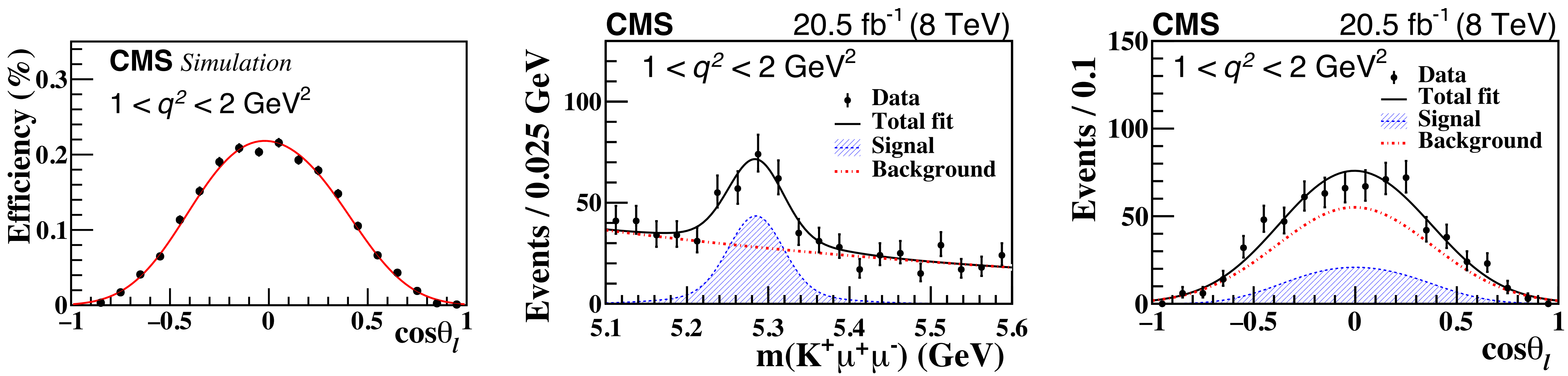
A_{FB}: forward-backward asymmetry of the dimuon system

F_H: contribution from the (pseudo)scalar and tensor amplitudes to the decay width

- Theoretical predictions are available for both parameters; in the SM
  - A_{FB} is expected to be zero (up to small corrections)
  - F_H is also small

Parameter extraction

- A_{FB} and F_H are extracted from a 2D extended **unbinned maximum-likelihood fit to the angular distribution** of the selected B^+ meson candidates, in various q^2 intervals
    - PDF built on angular decay rate and efficiency parametrisation (obtained from simulation)



Phys. Rev. D 98 (2018) 112011

- Total systematic uncertainty driven by uncertainties in
    - background distribution
    - fitting procedure
    - efficiency description

Systematic uncertainty	A_{FB} ($\times 10^{-2}$)	F_H ($\times 10^{-2}$)
Finite size of MC samples	0.4–1.8	0.9–5.0
Efficiency description	0.1–1.5	0.1–7.8
Simulation mismodeling	0.1–2.8	0.1–1.4
Background parametrization model	0.1–1.0	0.1–5.1
Angular resolution	0.1–1.7	0.1–3.3
Dimuon mass resolution	0.1–1.0	0.1–1.5
Fitting procedure	0.1–3.2	0.4–25
Background distribution	0.1–7.2	0.1–29
Total systematic uncertainty	1.6–7.5	4.4–39

Results

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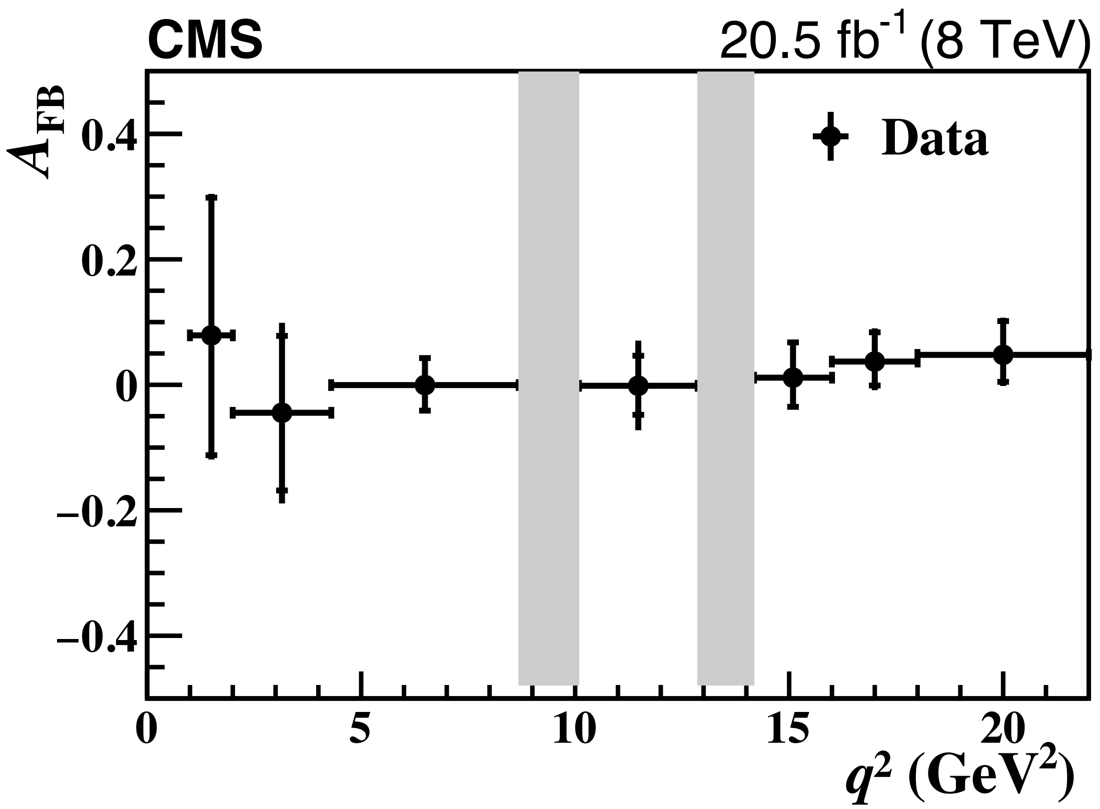
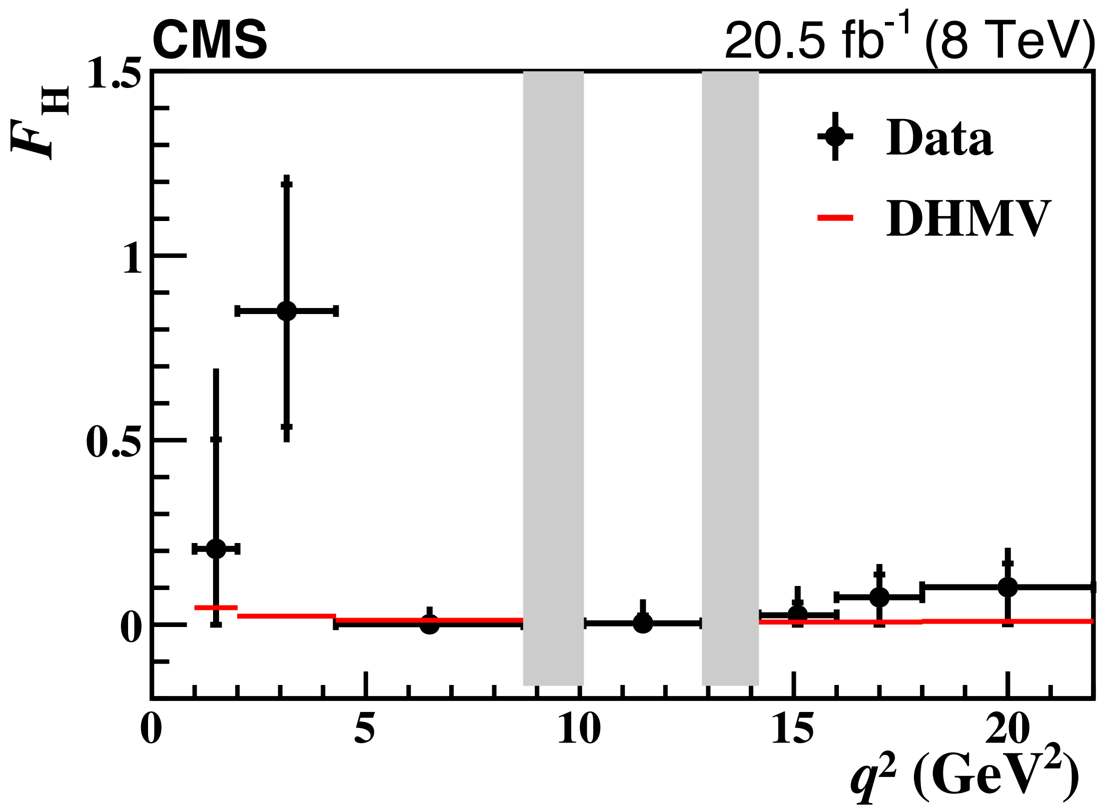


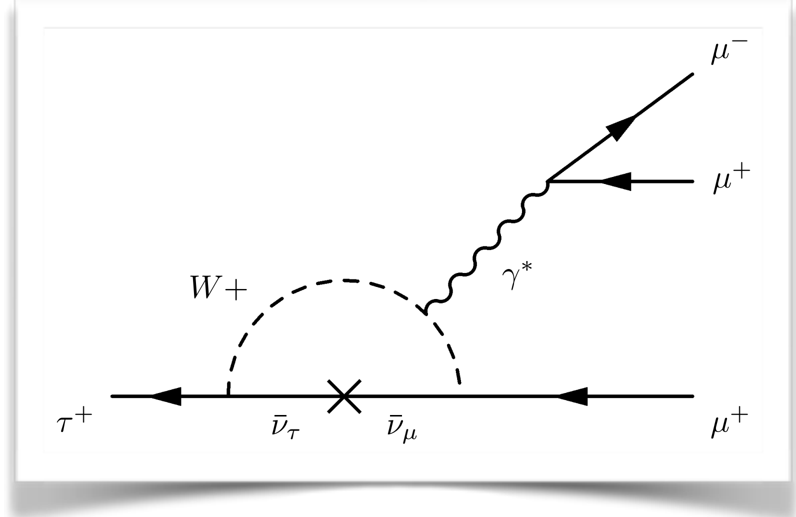


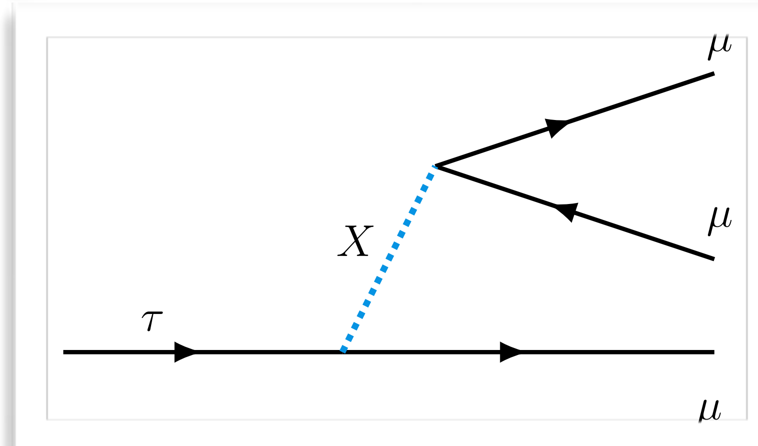
The measured values of A_{FB} are consistent with the SM expectation of no asymmetry

Generally good agreement between F_H results and theoretical predictions, as well as with previous measurements

Search for τ→3μ decays

- Charged lepton flavour violating (CLFV) decay of τ to 3 muons, with no missing neutrinos
  - in the SM, allowed by neutrino oscillations, but branching fractions beyond current experimental accessibility (BF ~ 10^{-14})
- The rate can be strongly enhanced in New Physics scenarios
- Experimentally the three-muon final state is accessible and clean
- Searches have been performed by *Belle, BaBar, LHCb, ATLAS*
  - no hint of signal yet
- Best limit from Belle: < 2.1×10^{-8} (@ 90% CL)



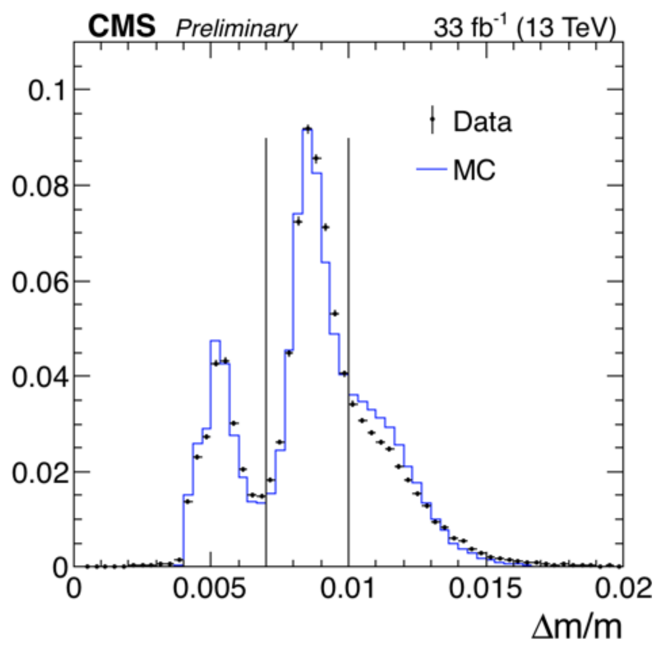


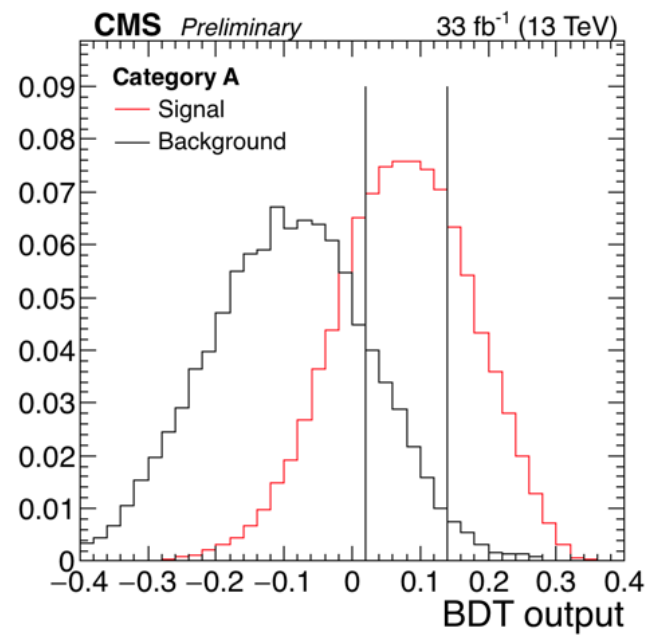
CMS has performed a search with 2016 data (33 fb^{-1}) using τ leptons produced in D and B hadron decays

CMS-PAS-BPH-17-004

Search strategy

- Select a τ (trimuon) candidate
  - trigger demands 2 muons plus a track, fitting to a common vertex
  - 3 offline muons with ∑charge = ±1.
- A **BDT is trained to separate signal from background**
  - inputs related to goodness of muon reconstruction and to the 3μ candidate properties
  - background inferred from data sidebands
- Selected events are divided in **categories** based on:
  - m(3μ) resolution, which depends on muon rapidity → 3 categories
  - in turn, each is split into 3 categories based on BDT score
    - only the two subcategories with highest S/B ratio are retained
- **Resulting in 6 categories which will be included in the fit**



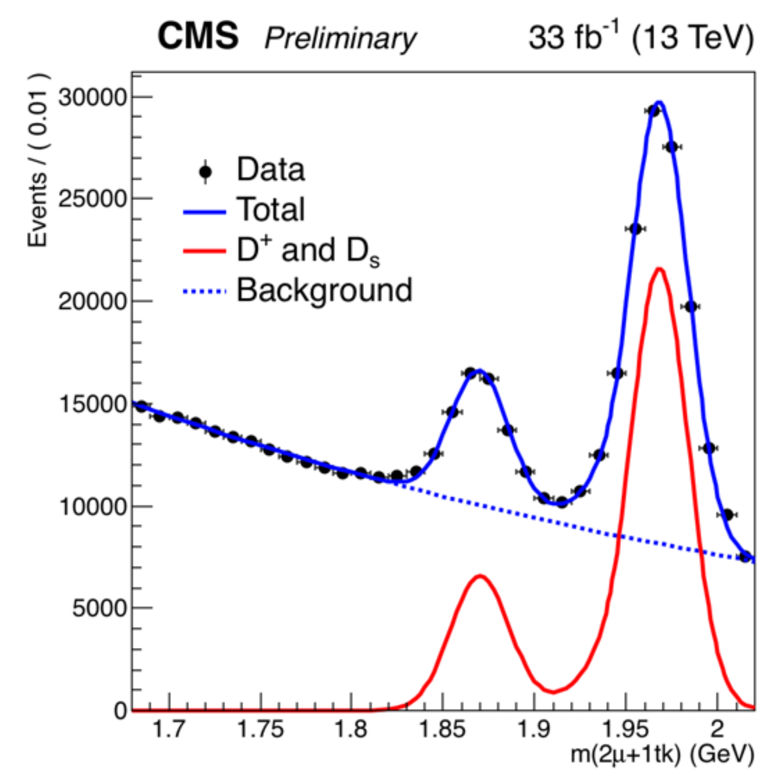


Results

- **$D_s \to \phi\pi^+ \to \mu\mu\pi^+$ events are used for normalisation**

$$N_{sig} = N_{D_s} \frac{\mathcal{B}(D_s \to \tau\nu)}{\mathcal{B}(D_s \to \phi\pi)} \frac{\epsilon_{sig}}{\epsilon_{\phi\pi}} \mathcal{B}(\tau \to 3\mu)$$

  - same trigger and very similar momentum spectra
  - fraction of (non-)prompt D_s estimated from a fit to the proper decay length distribution

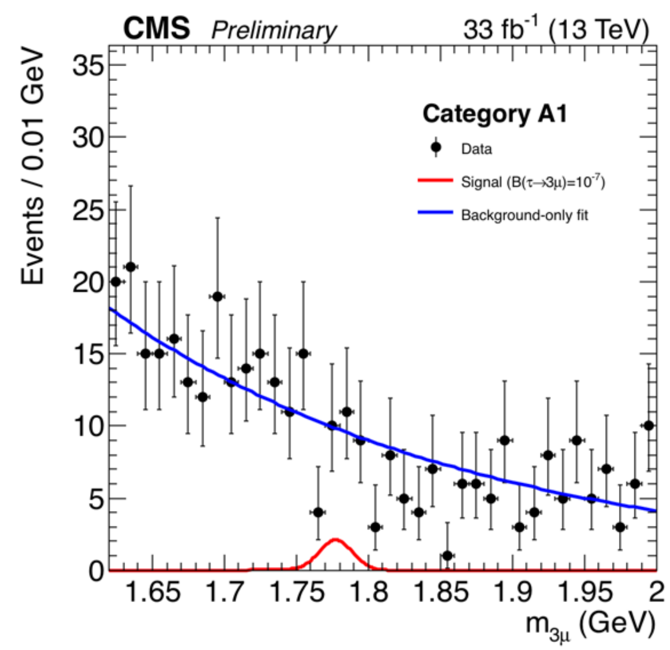


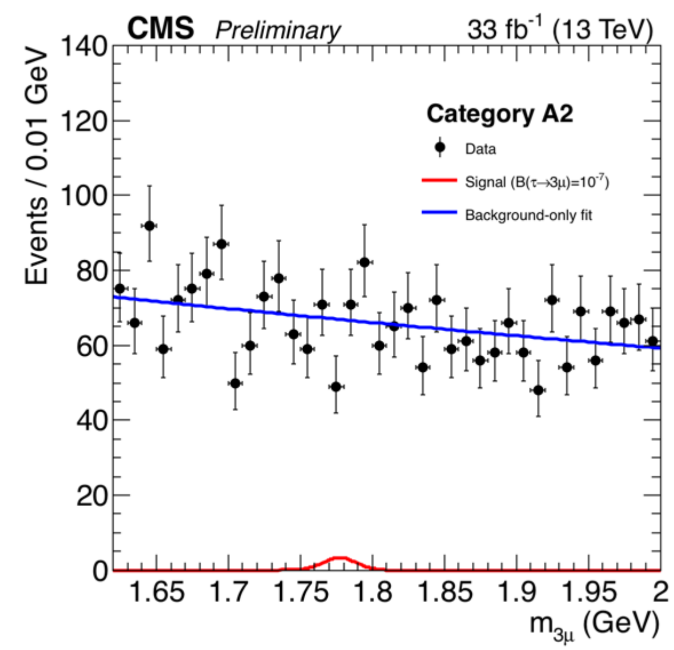
- Limit is finally extracted through a **simultaneous maximum likelihood fit to the 6 categories**

- Dominant systematic uncertainties:
  - D_s normalization (10%)
  - $D_s \to \Phi\pi$ branching fraction (8%)

No excess found

Observed (expected) limits at 90% CL:
$B(\tau \to 3\mu) < 8.8(9.9) \times 10^{-8}$



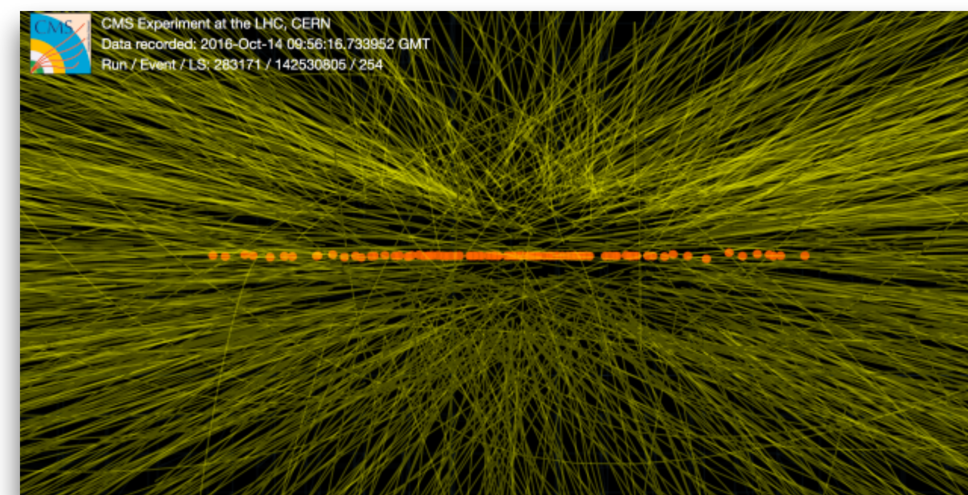


CMS-PAS-BPH-17-004

Prospects @HL-LHC

- The prospects at HL-LHC for experimental sensitivities of selected measurements in rare decay processes have been studied, assuming 3000 fb^{-1} recorded
- However, harsh operating conditions will make it difficult to exploit this potential:
    - expected **average pileup of 200,** with resulting increase of particle density
    - **radiation damage** to the detector

http://cds.cern.ch/record/2231915



- B-physics is among the physics topics that might suffer more from the HL-LHC conditions
    - relative low momenta of the typical signatures
    - high precision required by the measurements
- On the other hand, the **Phase-II upgrades of the CMS detector promise to recover a good detection ability and even give better performances than those of the current detector**
    - Lifetime of detectors
    - Increased readout bandwidth
    - PU mitigation

→ replace inner tracker & forward calorimeter
→ replacing electronics
→ higher detector granularity to reduce occupancy
→ improved trigger capabilities
→ precision timing

$B_{(s)} \to \mu\mu$: current status

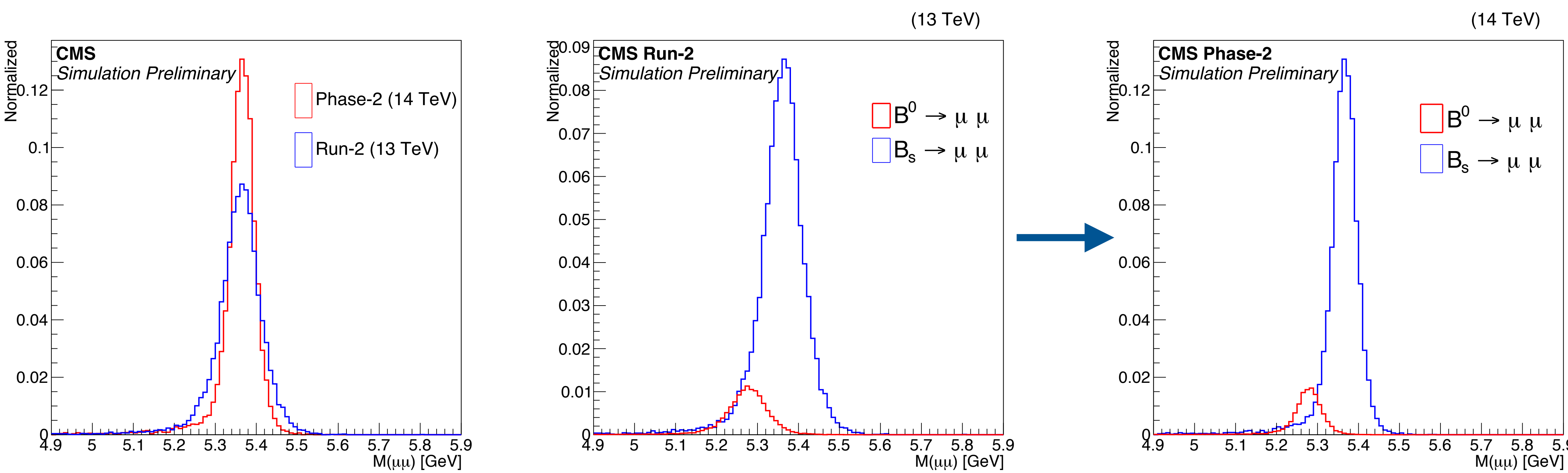
- $B_{(s)} \to \mu\mu$ decays only proceed via FCNC processes forbidden at tree level
  - highly suppressed in SM but enhancements/further suppressions of the BRs predicted in several SM extensions
- Current experimental results all in agreement with the SM, though statistically limited

	$\mathcal{B}(B_s \to \mu\mu)$	$\mathcal{B}(B^0 \to \mu\mu)$	
SM	**$(3.66 \pm 0.23) \times 10^{-9}$**	**$(1.06 \pm 0.09) \times 10^{-10}$**	
Run I (CMS)	$(3.0^{+1.0}_{-0.9}) \times 10^{-9}$	$< 1.1 \times 10^{-9}$ @95% CL	PRL 111 (2013) 101804
Run I (CMS+LHCb)	$(2.8^{+0.7}_{-0.6}) \times 10^{-9}$	$(3.9^{+1.6}_{-1.4}) \times 10^{-10}$	Nature 522 (2015) 68
Run I + 2015/16 (ATLAS)	$(2.8^{+0.8}_{-0.7}) \times 10^{-9}$	$< 2.1 \times 10^{-10}$ @95% CL	JHEP 1904 (2019) 098
Run I + Run II (LHCb)	$(3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$	$< 3.4 \times 10^{-10}$ @95% CL	Phys.Rev.Lett. 118 (2017)

- **The high statistics available at the HL-LHC will allow to perform precise measurements of the BRs and of the effective lifetime of the $B_s \to \mu\mu$ decay**

Perspectives for $B_{(s)} \to \mu\mu$

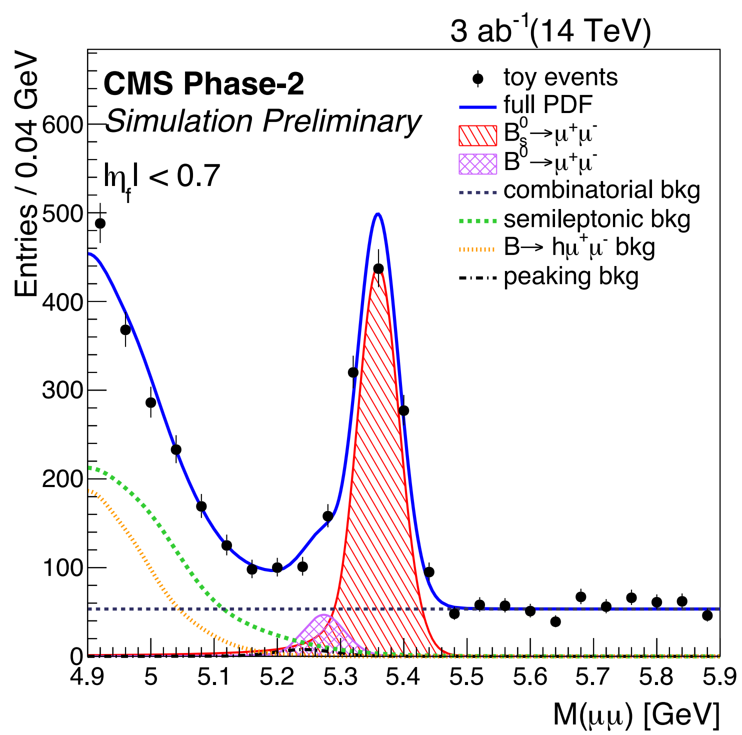
- Starting point for the projections is CMS Run-2 analysis (not public yet)
- Sensitivity to the effective lifetime and BRs measurements is evaluated on pseudo-experiments based on the Run-2 PDF for the signal and background components
- **Improvements in the invariant mass reconstruction of the dimuon system** from the new tracking system are included
  - in the barrel region improvement of ~40-50% wrt Run-2 scenario
  - it will result in a substantial reduction of semileptonic background contribution into the signal regions and improved separation of the B_s^0 and B^0

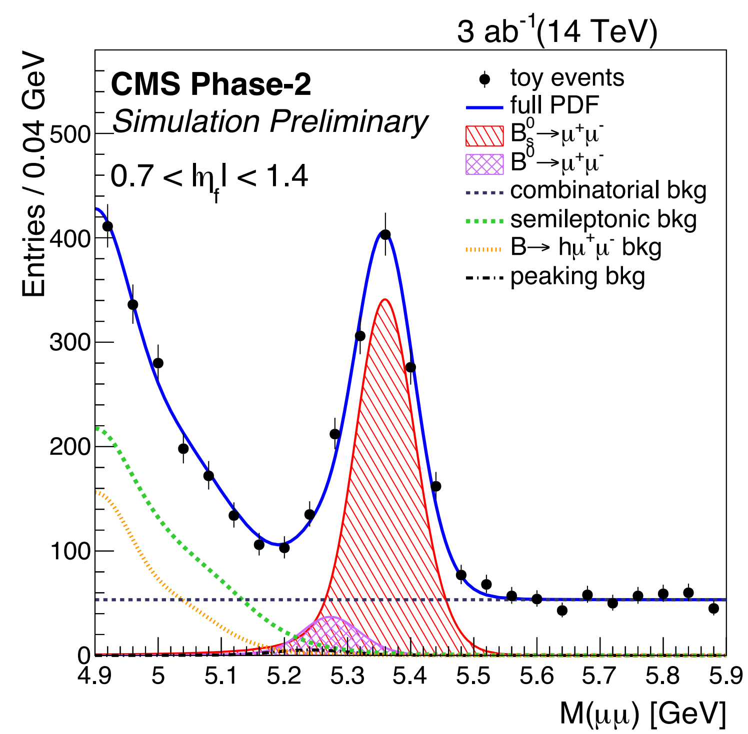


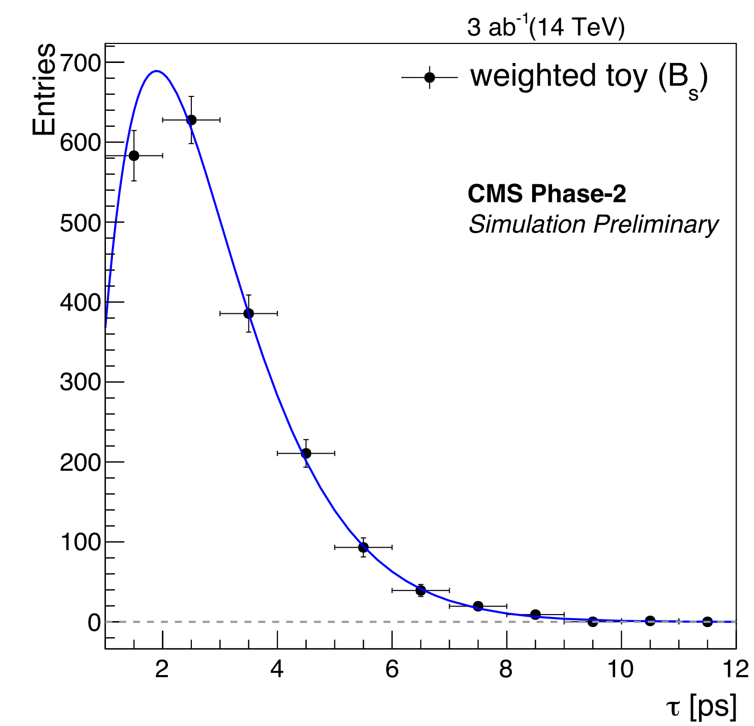
CMS-PAS-FTR-18-013

$B_{(s)} \to \mu\mu$ projections: results

- BRs extracted via unbinned maximum likelihood fit to the dimuon invariant mass distribution in bins of the BDT discriminant variable
- Lifetime measured through binned ML fit to sPlot produced with mass fit likelihood







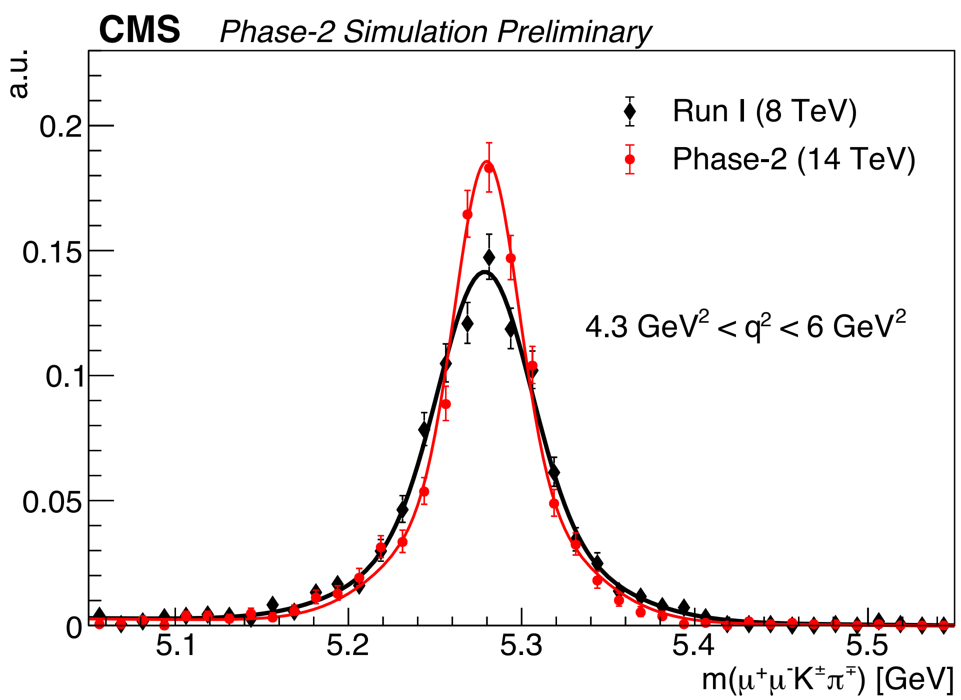
CMS-PAS-FTR-18-013

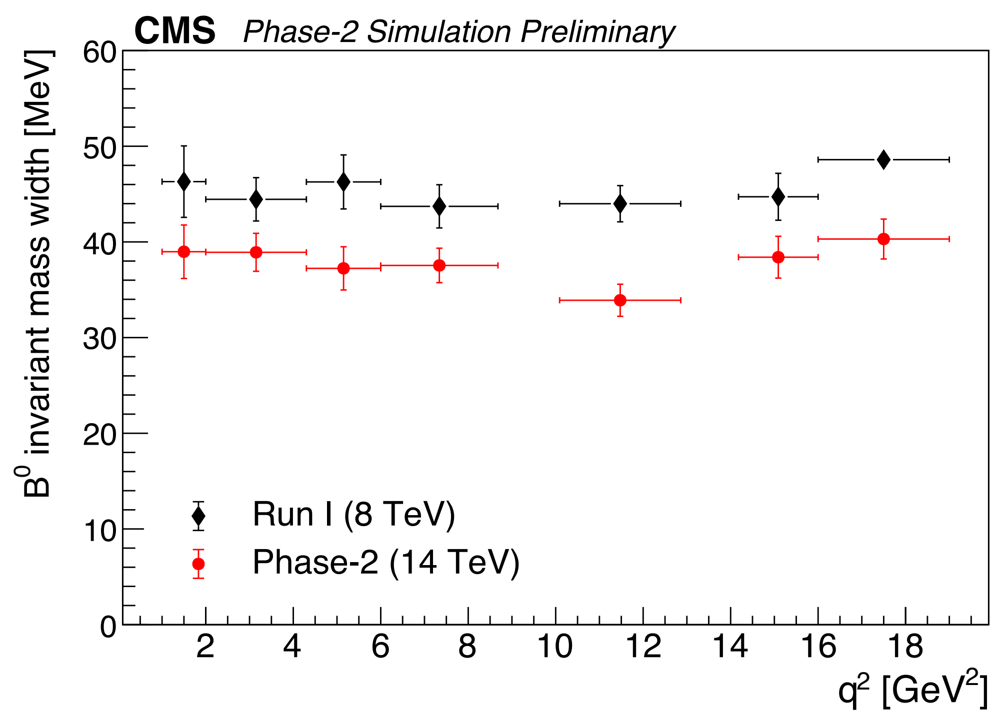
$\mathcal{L}$ (fb^{-1})	$N(B_s)$	$N(B^0)$	$\delta\mathcal{B}(B_s \to \mu\mu)$	$\delta\mathcal{B}(B^0 \to \mu\mu)$	$\sigma(B^0 \to \mu\mu)$	$\delta[\tau(B_s)]$(stat-only)
300	205	21	12%	46%	$1.4 - 3.5\sigma$	0.15 ps
3000	2048	215	7%	16%	$6.3 - 8.3\sigma$	0.05 ps

Perspectives for P_5' in the $B^0 \to K^* \mu\mu$ decay

- Angular analysis of the FCNC $B^0 \to K^* \mu\mu$ decay gives access to NP-sensitive observables
  - deviation from SM expectation observed by LHCb and Belle in the P_5' parameter
  - consistency with SM from CMS Run-1 measurement (stat. limited)

- The **expected precision on the P_5' parameter is extrapolated to the int. lumi of 3000 fb^{-1}**, starting from CMS Run-1 results
  - no improvements in the analysis strategy or in the trigger performance are considered
  - same signal-to-background ratio is assumed for the projections
  - visible improvements in the mass resolution thanks to the upgraded tracker

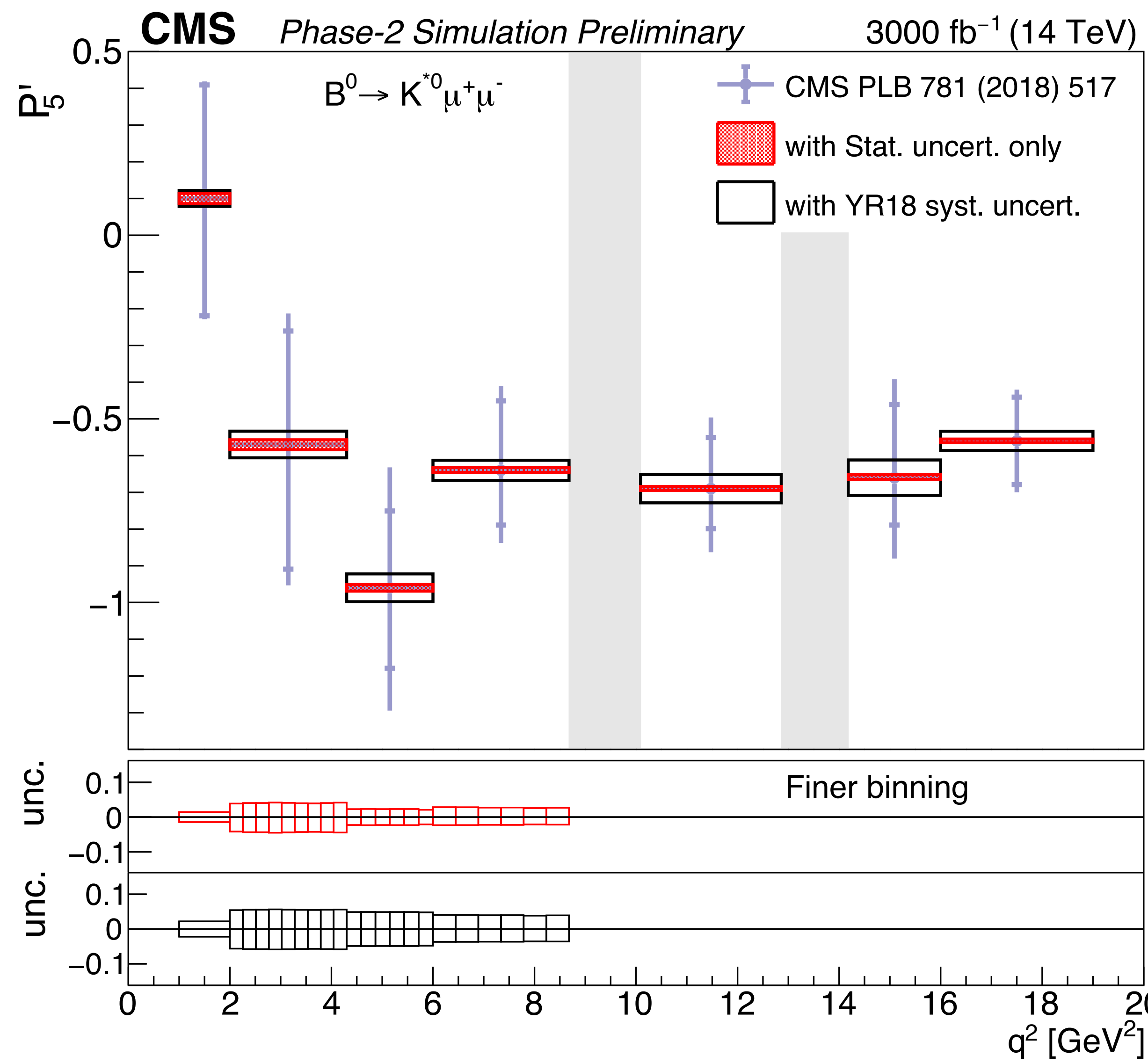




CMS-PAS-FTR-18-033

Perspectives for P_5': results

- For each q^2 bin, expected yields obtained from events simulated with Phase-2 scenario and 200 pileup, and scaled to the luminosity of 3000 fb^{-1}
  - ~700k signal events expected over the full q^2 range
- Statistical uncertainty obtained by scaling the Run-1 stat. uncertainty to the expected number of signal events
- Systematic uncertainties scaled by a factor 2 or according to the increase of statistics of the control samples
- **Uncertainties are estimated to improve up to a factor of 15 compared to the Run-1 result**
- The large available statistics will allow to to use a finer q^2 binning



CMS-PAS-FTR-18-033

Summary

- The **angular analysis of the $B^+ \to K^+ \mu\mu$ decay** has allowed to measure the angular observables A_{FB} and F_H which are consistent with the SM predictions

- **A search for the $\tau \to 3\mu$ decay** using a sample of τ's from D and B meson has been performed
    - no excess is observed
    - upper limit on $B(\tau \to 3\mu)$ is set at 8.9×10^{-8} @90% CL

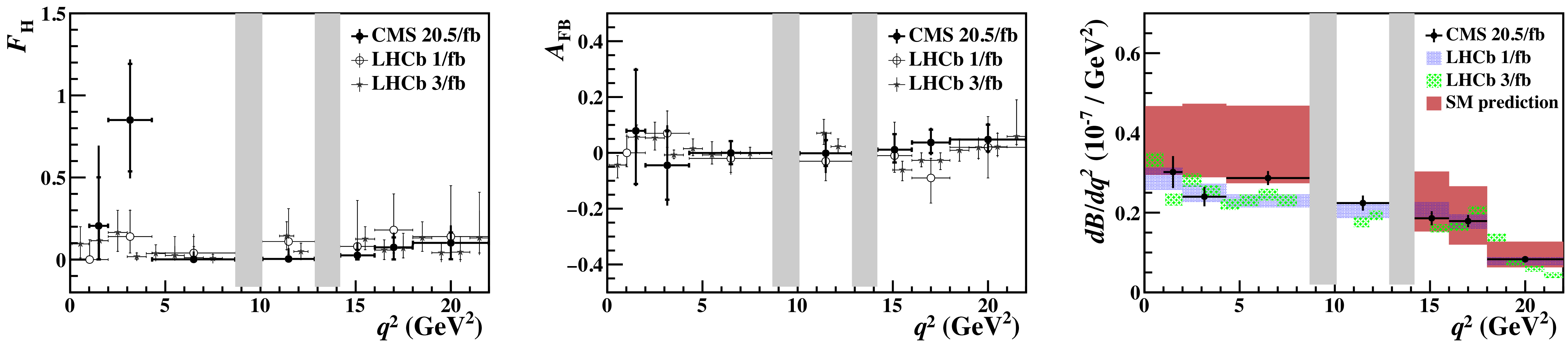
- **Prospects for measurements of selected rare decays process in the HL-LHC scenario** have been presented
    - the observation of $B^0 \to \mu^+\mu^-$ in excess of 5σ is possible with 3000 fb^{-1}
    - CMS will have the capability to measure the $B_s \to \mu\mu$ effective lifetime with an uncertainty of ~0.05 ps
    - the uncertainties on P_5' in the $B^0 \to K^*\mu\mu$ decay are estimated to improve up to a factor of 15 compared to the Run-1 result

backup

Angular analysis of the $B^+ \to K^+ \mu\mu$ decay

q^2 (GeV^2)	Y_S	A_{FB}	F_H	F_H(EOS)	F_H(DHMV)	F_H(FLAVIO)
1.00–2.00	169 ± 22	$0.08\ ^{+0.22}_{-0.19} \pm 0.05$	$0.21\ ^{+0.29}_{-0.21} \pm 0.39$	0.047	0.046	0.045
2.00–4.30	331 ± 32	$-0.04\ ^{+0.12}_{-0.12} \pm 0.07$	$0.85\ ^{+0.34}_{-0.31} \pm 0.14$	0.024	0.023	0.022
4.30–8.68	785 ± 42	$0.00\ ^{+0.04}_{-0.04} \pm 0.02$	$0.01\ ^{+0.02}_{-0.01} \pm 0.04$	—	0.012	0.011
10.09–12.86	365 ± 29	$0.00\ ^{+0.05}_{-0.05} \pm 0.05$	$0.01\ ^{+0.02}_{-0.01} \pm 0.06$	—	—	—
14.18–16.00	215 ± 19	$0.01\ ^{+0.06}_{-0.05} \pm 0.02$	$0.03\ ^{+0.03}_{-0.03} \pm 0.07$	0.007	0.007	0.006
16.00–18.00	262 ± 21	$0.04\ ^{+0.05}_{-0.04} \pm 0.03$	$0.07\ ^{+0.06}_{-0.07} \pm 0.07$	0.007	0.007	0.006
18.00–22.00	226 ± 20	$0.05\ ^{+0.05}_{-0.04} \pm 0.02$	$0.10\ ^{+0.06}_{-0.10} \pm 0.09$	0.008	0.009	0.008
1.00–6.00	778 ± 47	$-0.14\ ^{+0.07}_{-0.06} \pm 0.03$	$0.38\ ^{+0.17}_{-0.21} \pm 0.09$	0.025	0.025	0.020
1.00–22.00	2286 ± 73	$0.00\ ^{+0.02}_{-0.02} \pm 0.03$	$0.01\ ^{+0.01}_{-0.01} \pm 0.06$	—	—	—

Phys. Rev. D 98 (2018) 112011



$B_{(s)} \to \mu\mu$ projections

- Systematic uncertainties

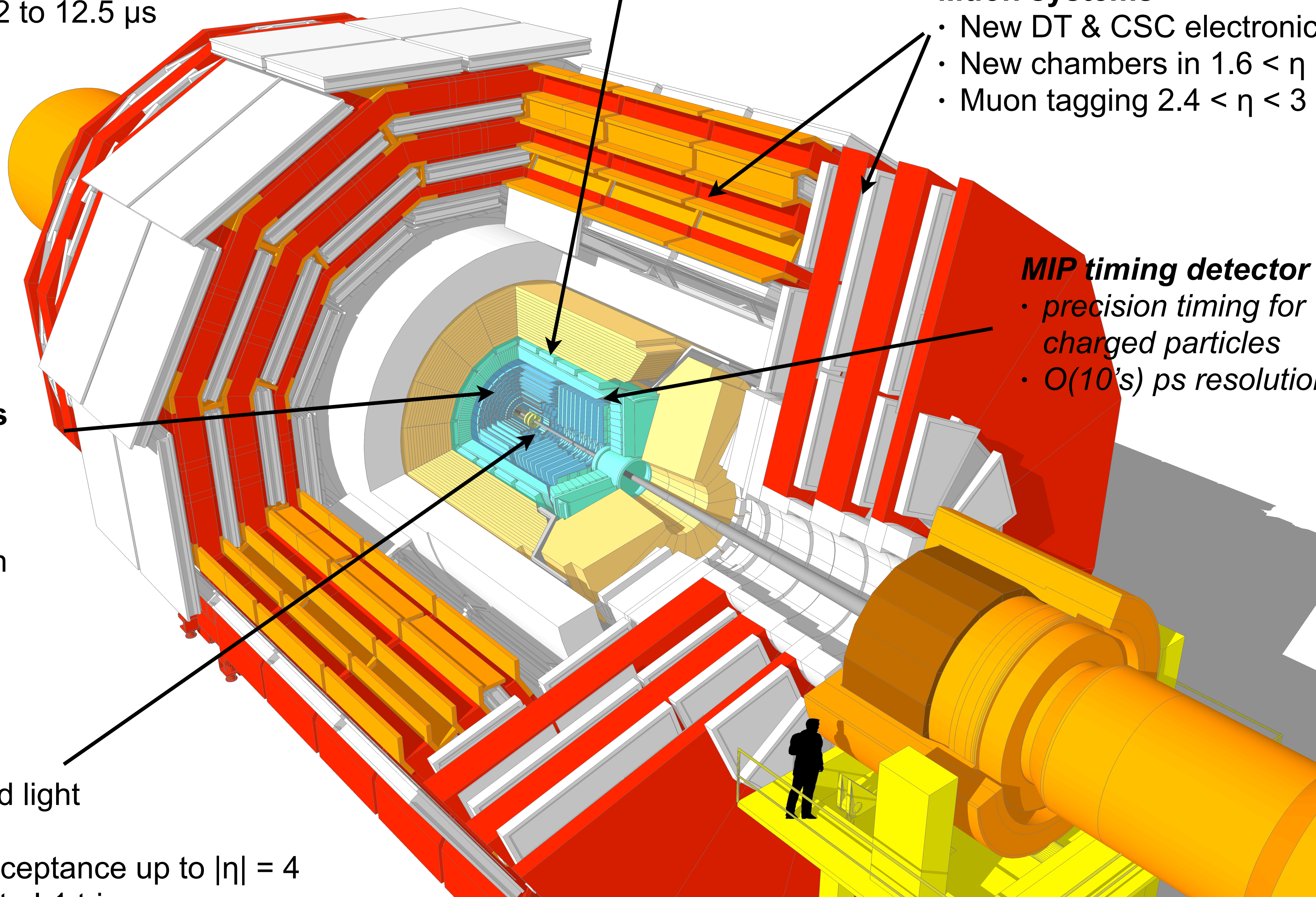
Source	Input uncertainties	$\delta\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\delta\mathcal{B}(B^0 \to \mu^+\mu^-)$
Muon ID efficiency ratio	1%	1%	1%
B^+ normalization yield	1.4%	1.4%	1.4%
f_u/f_s ratio	3.5%	3.5%	-
Effective lifetime	2%	2%	-
Trigger efficiency	1.5%	1.5%	1.5%
Other sources	3%	3%	3%
Peaking background yield	10%	0.5%	2.7%
Semileptonic background yield	7.5%		

CMS Phase II upgrades overview

Trigger/HLT/DAQ
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered
- latency increased from 3.2 to 12.5 μs

Barrel EM Calorimeter
- New electronics
- Low operating temperature = 10°

Muon systems
- New DT & CSC electronics
- New chambers in $1.6 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$



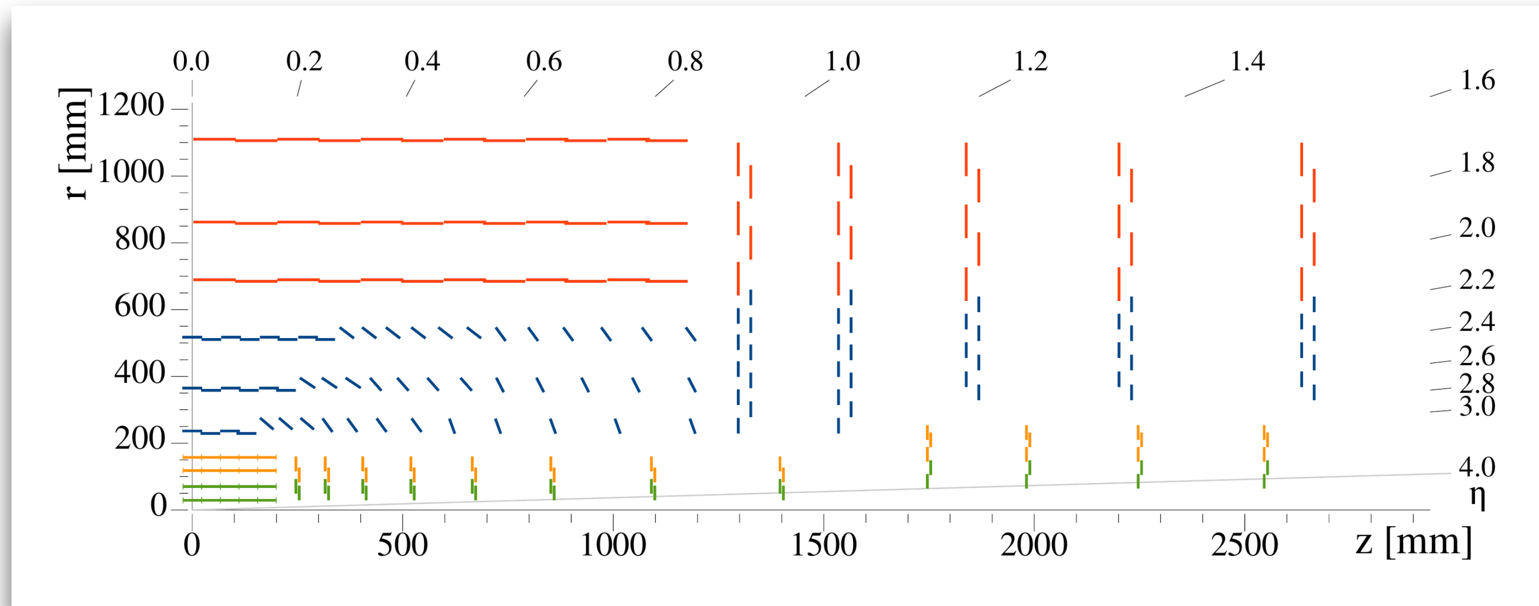
MIP timing detector
- *precision timing for charged particles*
- *O(10's) ps resolution*

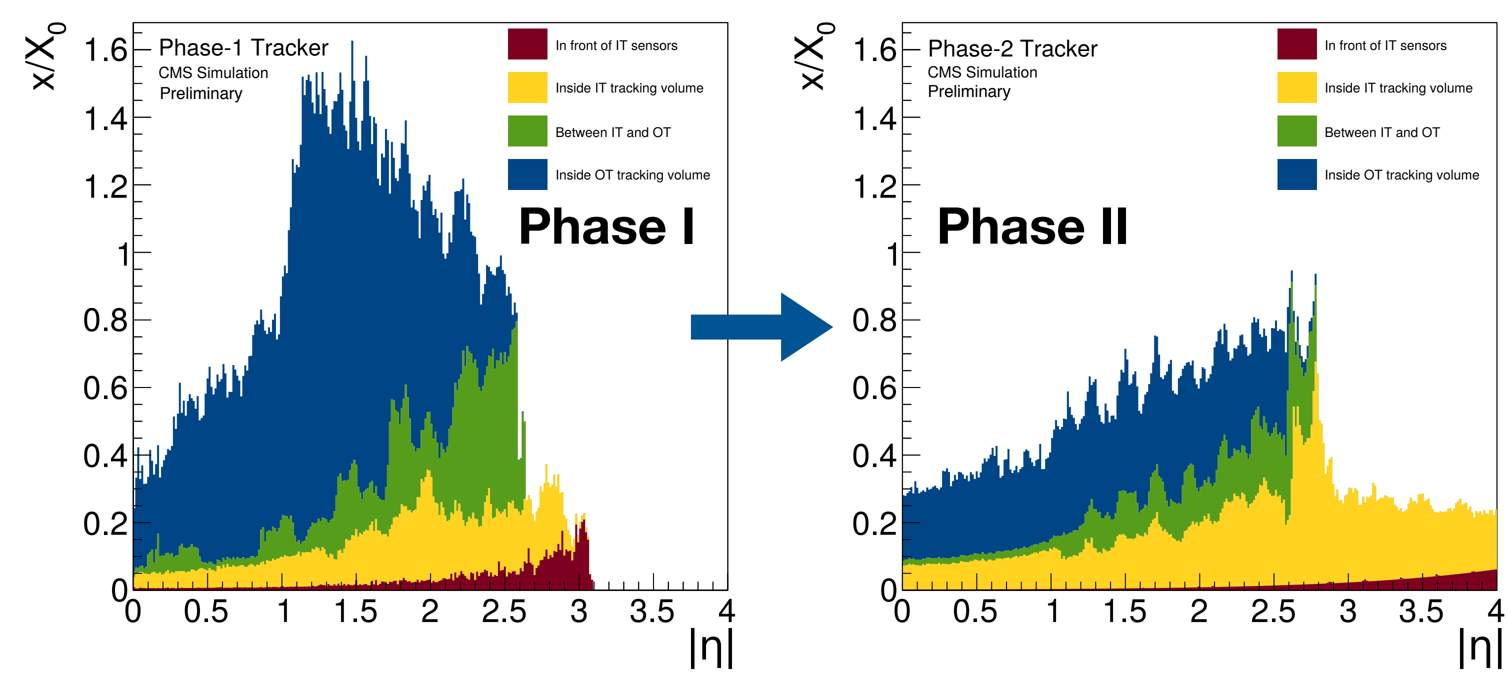
New endcap calorimeters
- Sampling calorimeter
- Radiation tolerant
- High granularity
- 3D shower reconstruction

New tracker
- Radiation tolerant and light
- Higher granularity
- Increased forward acceptance up to $|\eta| = 4$
- Tracking information to L1 trigger

Tracker upgrade

- Needed to deal with radiation damage and cope with higher pileup
- **Inner tracker:**
  - pixel sensors
  - narrower pitch than present pixel detector
  - increased granularity to limit the occupancy
  - coverage up to |η|~4
- **Outer tracker:**
  - design driven by addition of hardware track trigger capabilities
  - pixel-strip & 2-strip sensors
  - progressively tilted modules
- Substantial reduction of the material budget with respect to present detector

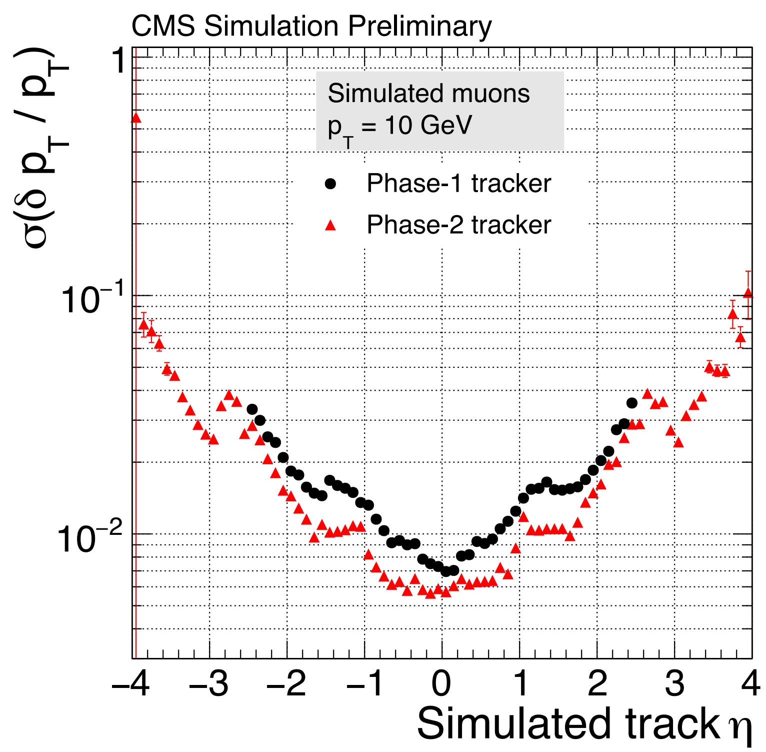


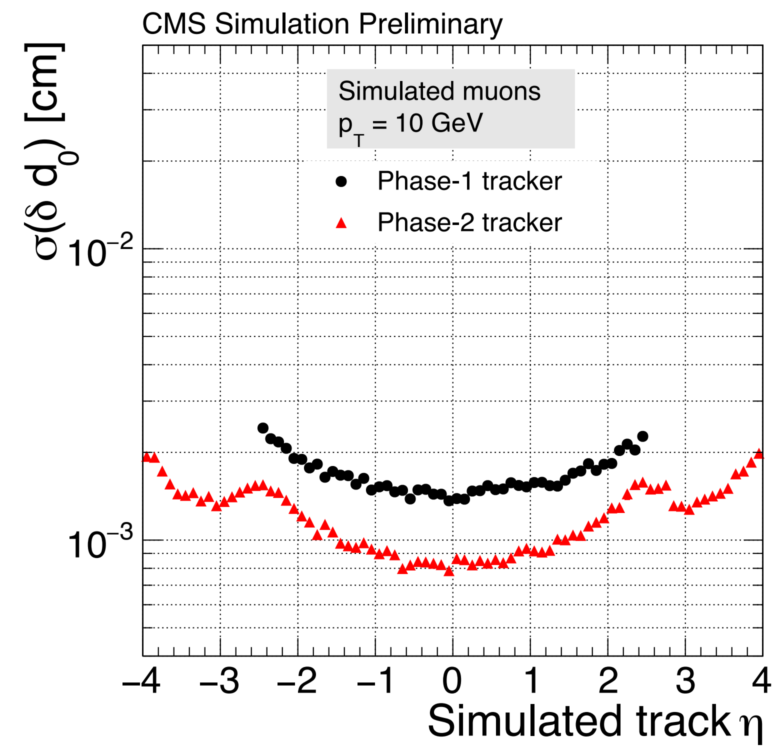


CMS-TDR-014

Tracker performance: resolution

CMS-TDR-014





- Significant improvements in transverse momentum and transverse impact parameter resolution with respect to current detector
  - thanks to better hit resolution and lower material budget