Workshop on High Luminosity LHC and Hadron Colliders

Flavour physics at HL-LHC with ATLAS and CMS

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On behalf of ATLAS and CMS

LNF - Frascati
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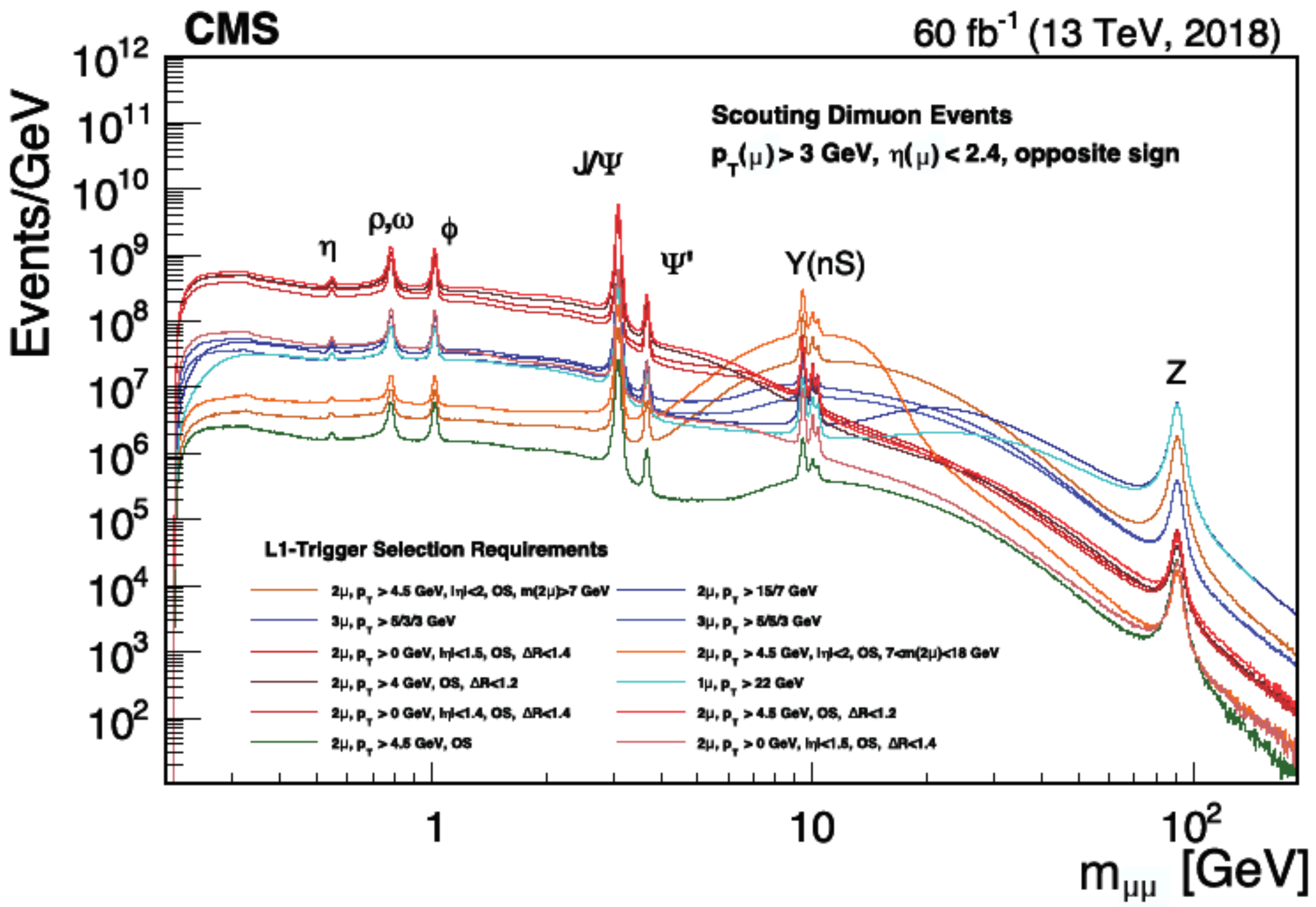
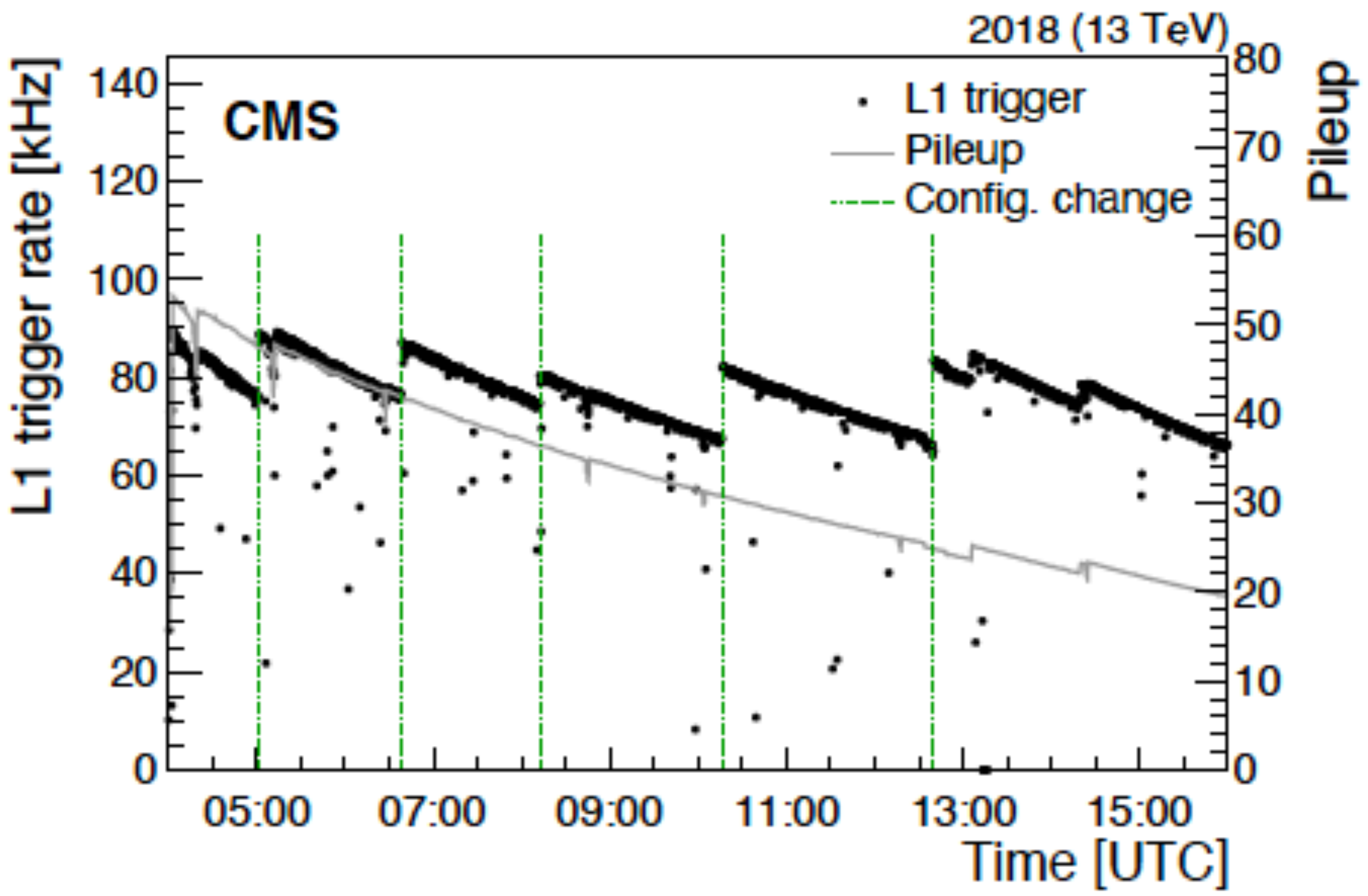
Introduction

- Already in the first phase of the LHC operations ATLAS and CMS have contributed with many measurements to the physics of the flavour at the LHC
  - B hadron production high cross section even in the central region ~O(500 mb)
  - Triggering on muon final states (especially double muon triggers) allows to cover many final states
    - Dedicated triggers
      - J/ψ
      - Double muons with "high-p_T" thresholds (4-6 GeV)
      - Inclusive di-muons (3-4 GeV) up to below the $\Upsilon(1S)$ mass
    - B-Parking:
      - 10^{10} events





Opportunities of B-physics at Phase-2

- Improved detectors
  - Trackers
    - Higher granularity to cope with higher pileup due to instantaneous luminosity increase
    - Smaller material budget
    - Increased angular coverage
    - Tracking at L1
  - Muon systems
    - Allow lowering muon p_T thresholds in L1 trigger and have larger angular coverage
  - Timing detectors (NEW!)
    - Allow particle identification
  - Higher Trigger bandwidth
    - L1 acceptance 100 kHz—> 750 kHz / HLT output 7.5 kHz (instead of 1kHz in Run3)
- Increased luminosity
  - Up to 4000 fb^{-1} per experiment (x10 wrt Run 3)

ATLAS Phase–2 Upgrades

Legacy detectors

New detectors

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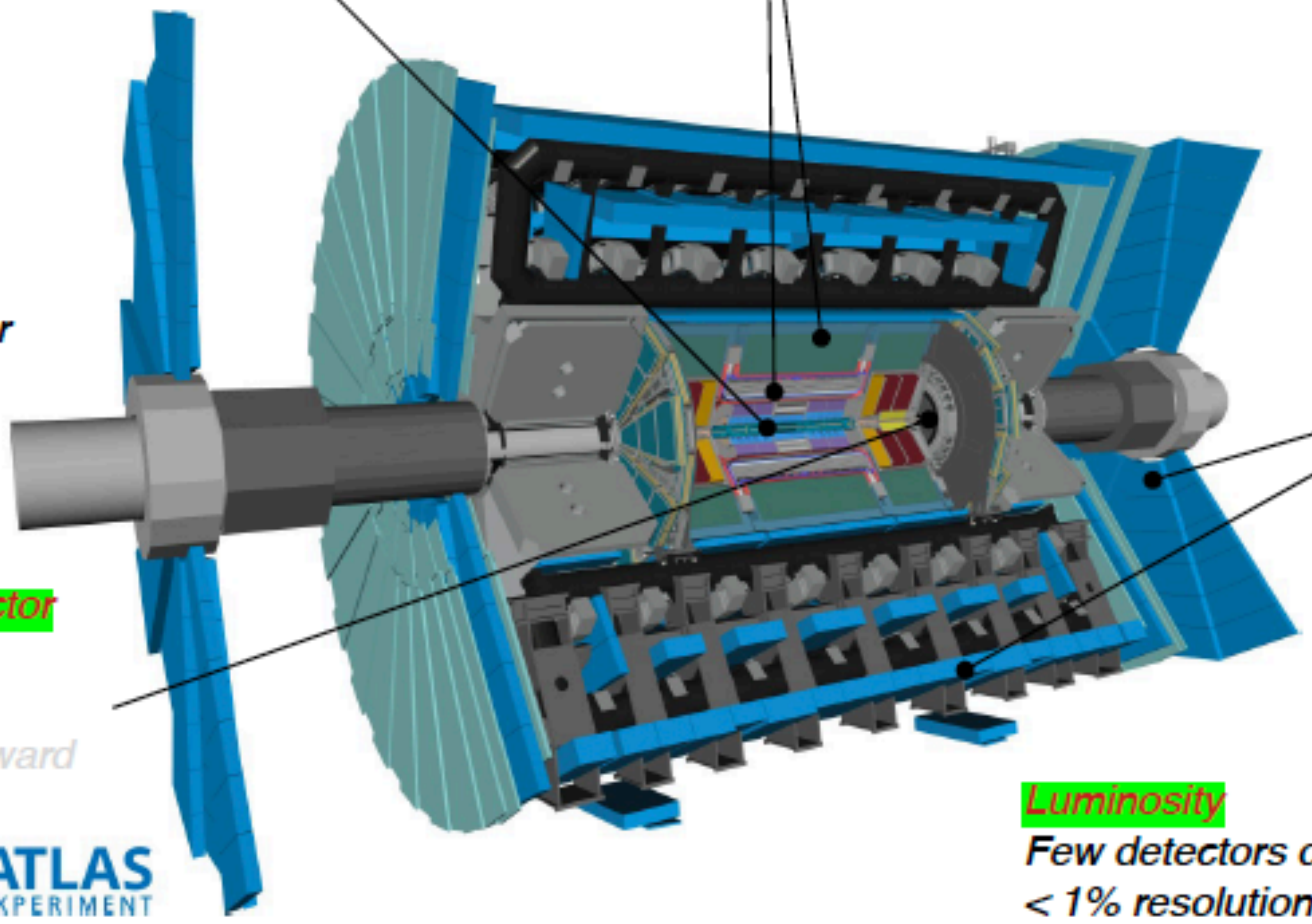
New Inner Tracker (ITk)
All silicon with 9 layers up to |η|=4
Less material finer segmentation
Improve vertexing, tracking, b-tagging

Calorimeter Electronics
On-detector electronics upgrades of LAr and Tile Calorimeters
Provide 40 MHz readout for triggering

Beyond the upgrades, consolidating of the legacy systems

Trigger and DAQ Upgrade
Single level Trigger with 1 MHz output (x 10 current)
Improved DAQ system with faster FPGAs



Muon Detector
Upgrade of the detector electronics for new T/DAQ system
Upgrade of inner barrel chambers with new RPC and sMDT (outer where Inner does not fit)
Improve trigger efficiency and momentum resolution, and reduced fakes

New High Granularity Timing Detector
Precision track timing (30 ps) with LGAD in the forward region.
Improve pile-up rejection in the forward region

ATLAS EXPERIMENT

Luminosity
Few detectors devoted to luminosity to get < 1% resolution as ATLAS has in Run2: LUCID-3, ITk-BCM', HGTD

2

CMS Phase-2 detector

L1-Trigger

https://cds.cern.ch/record/2714892

- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting

DAQ & High-Level Trigger

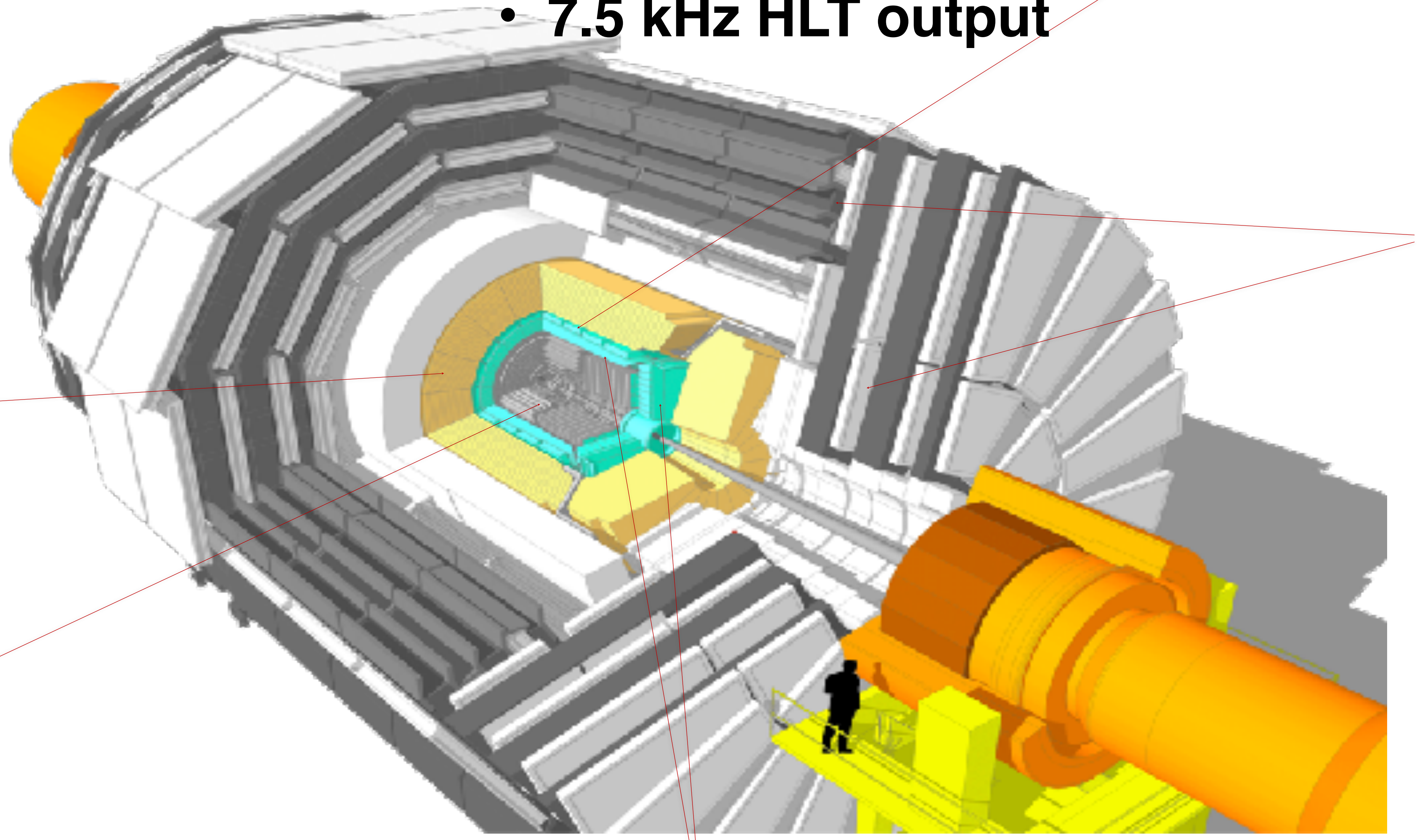
https://cds.cern.ch/record/2759072

- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

Barrel Calorimeters

https://cds.cern.ch/record/2283187

- ECAL single crystal granularity at L1 trigger
  with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards



Calorimeter Endcap

https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

Tracker

https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

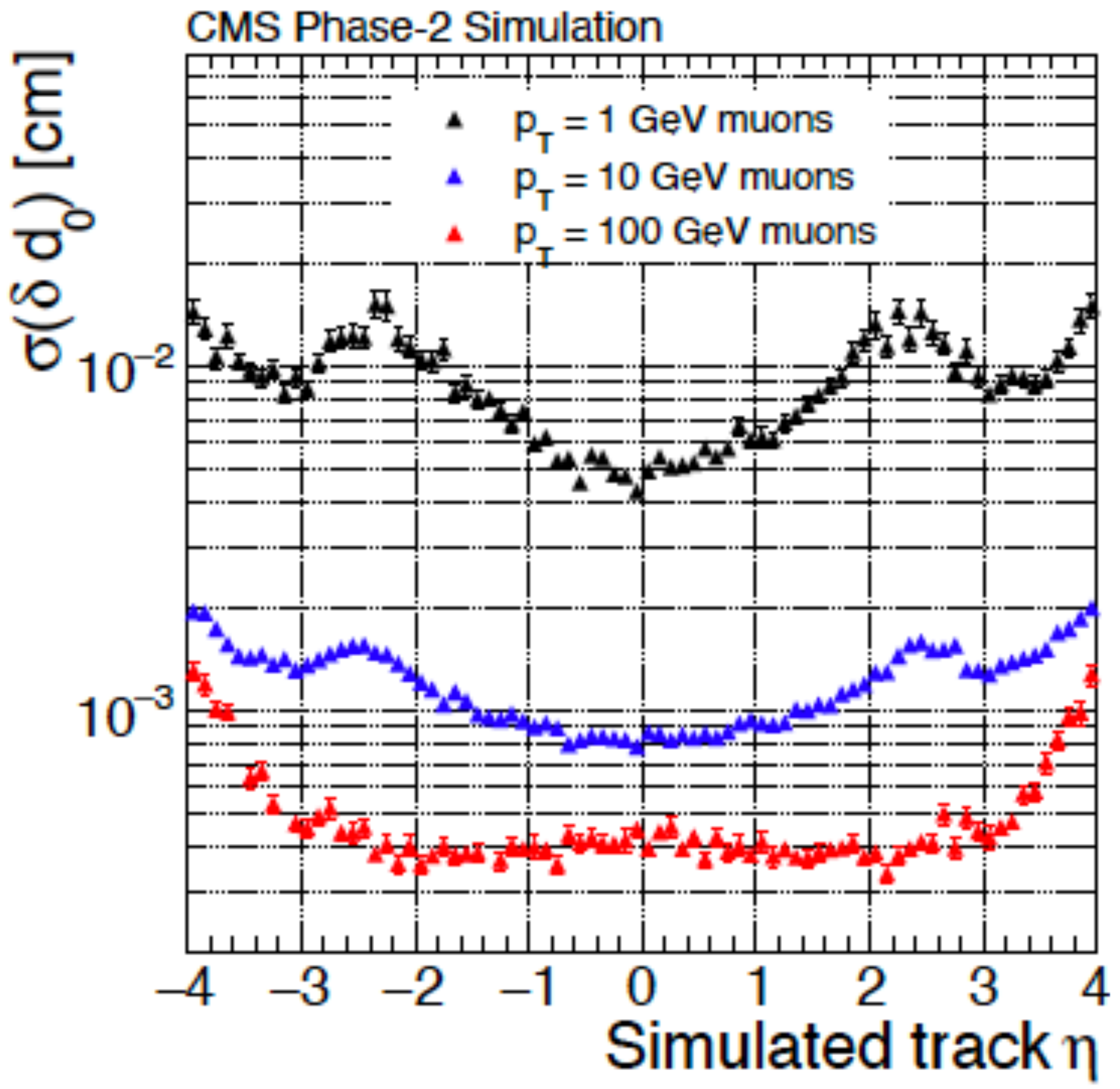
MIP Timing Detector

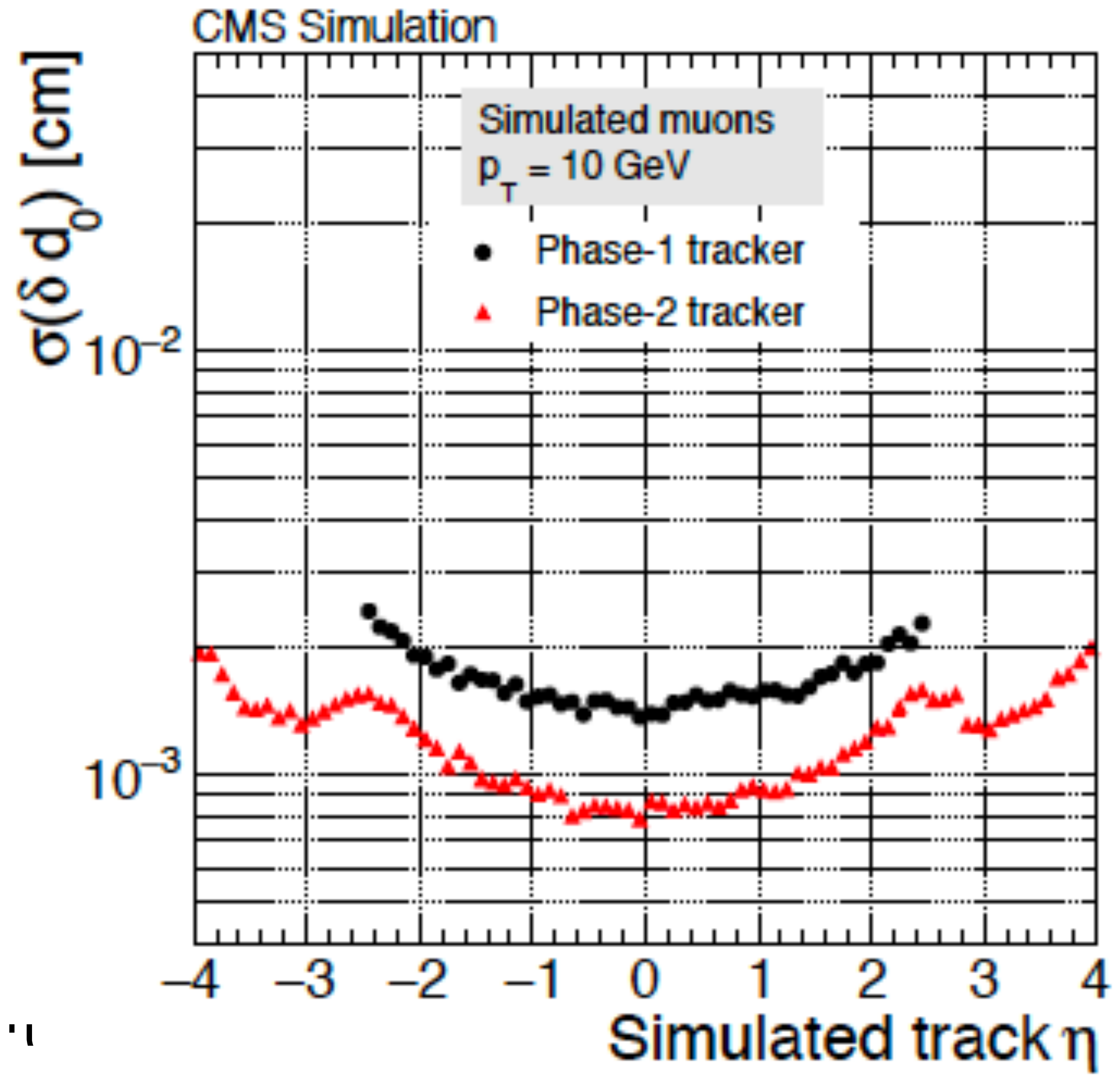
https://cds.cern.ch/record/2667167

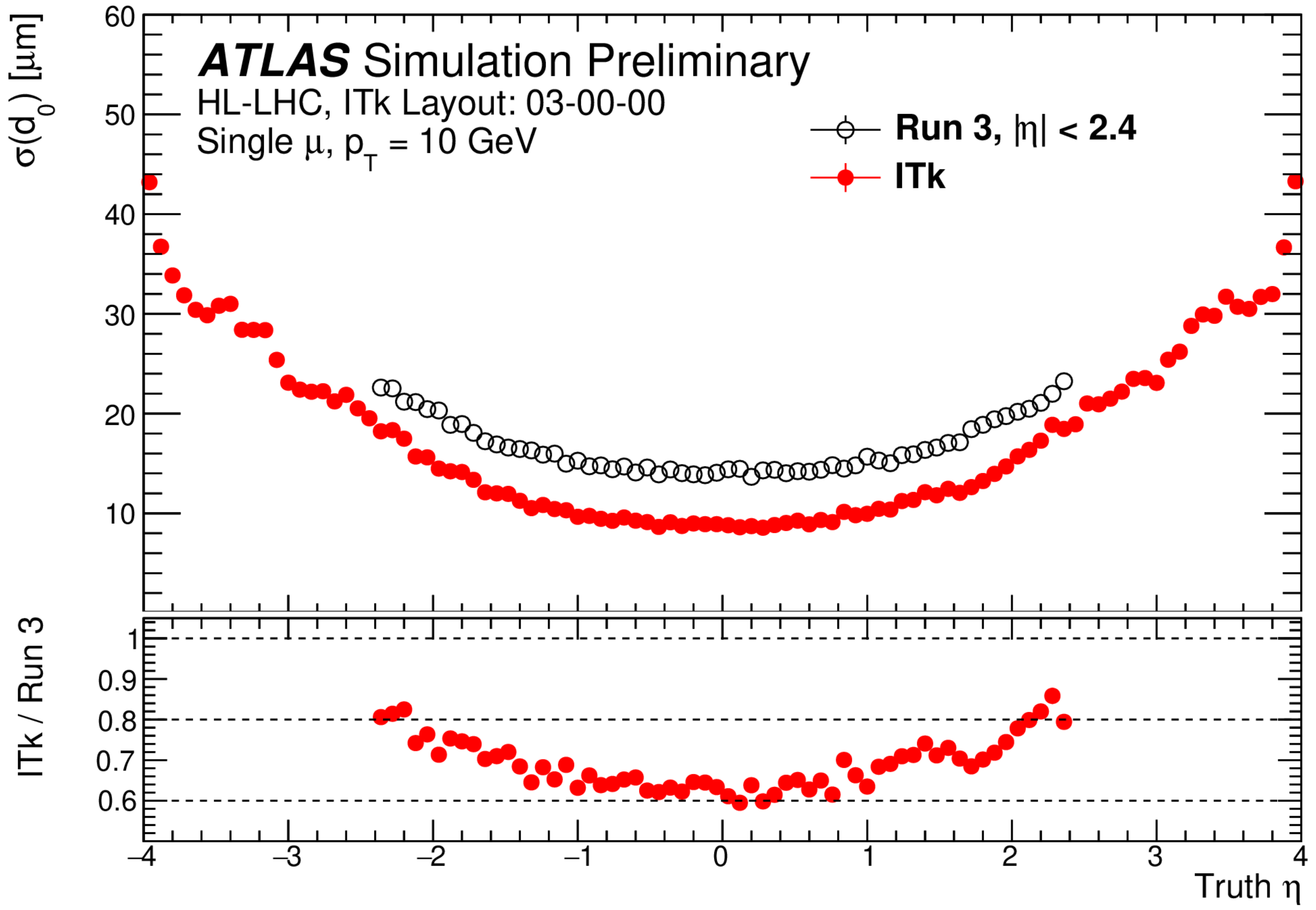
Precision timing with:

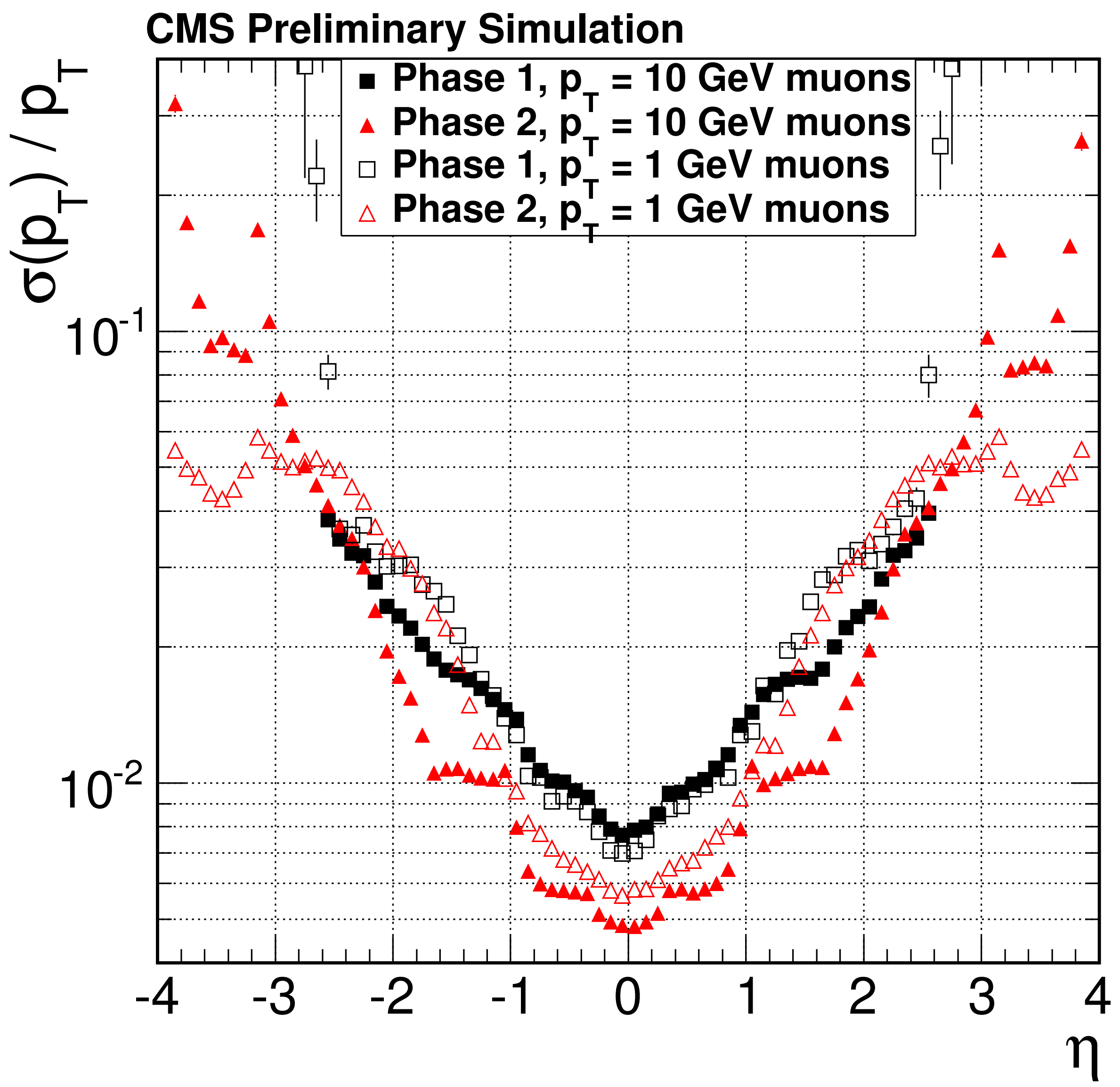
- Barrel layer: Crystals + SiPMs
- Endcap layer:
  Low Gain Avalanche Diodes

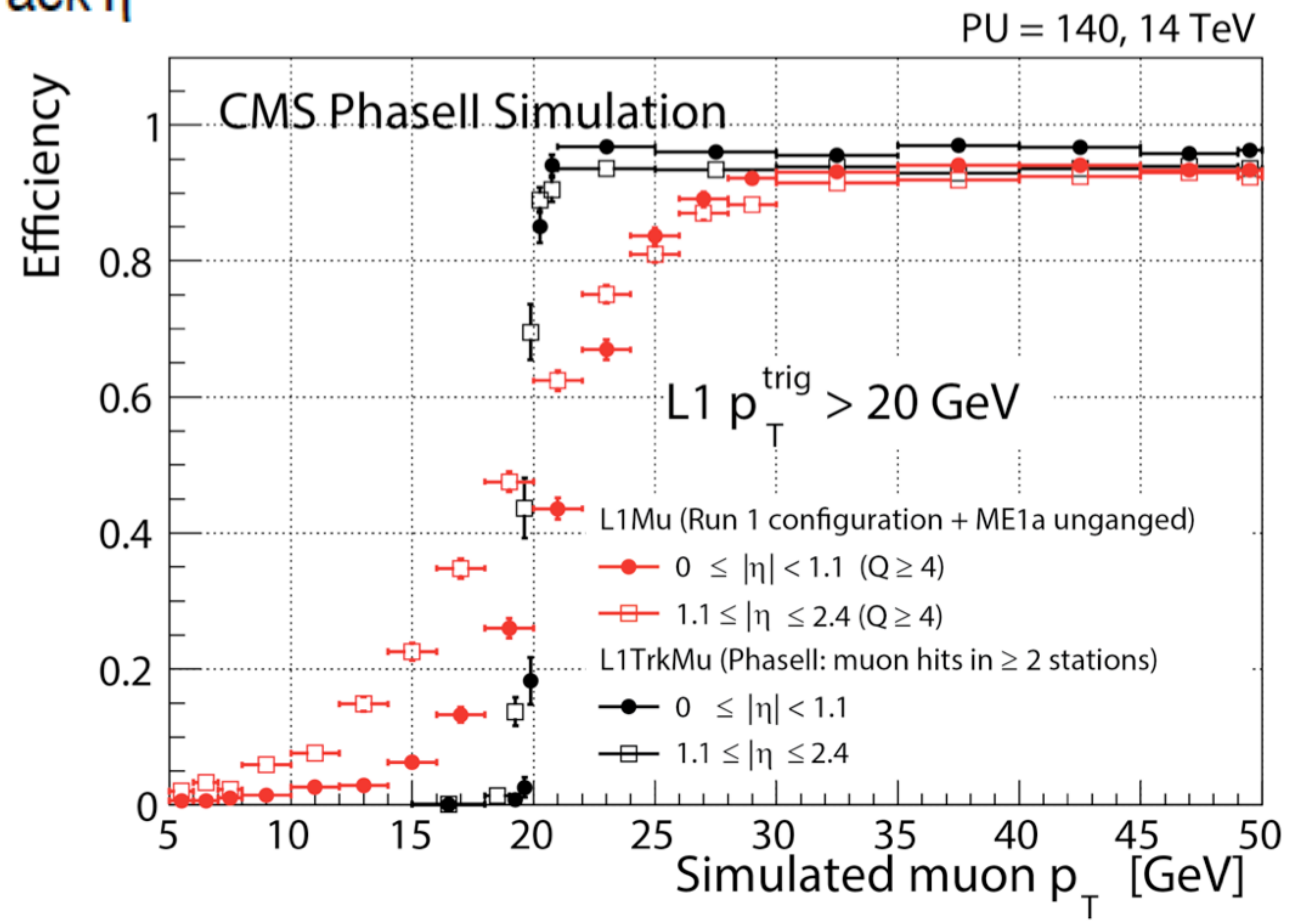
Tracking and Muon reconstruction











CP violation in $B_s \to J/\psi\, \phi$ decays

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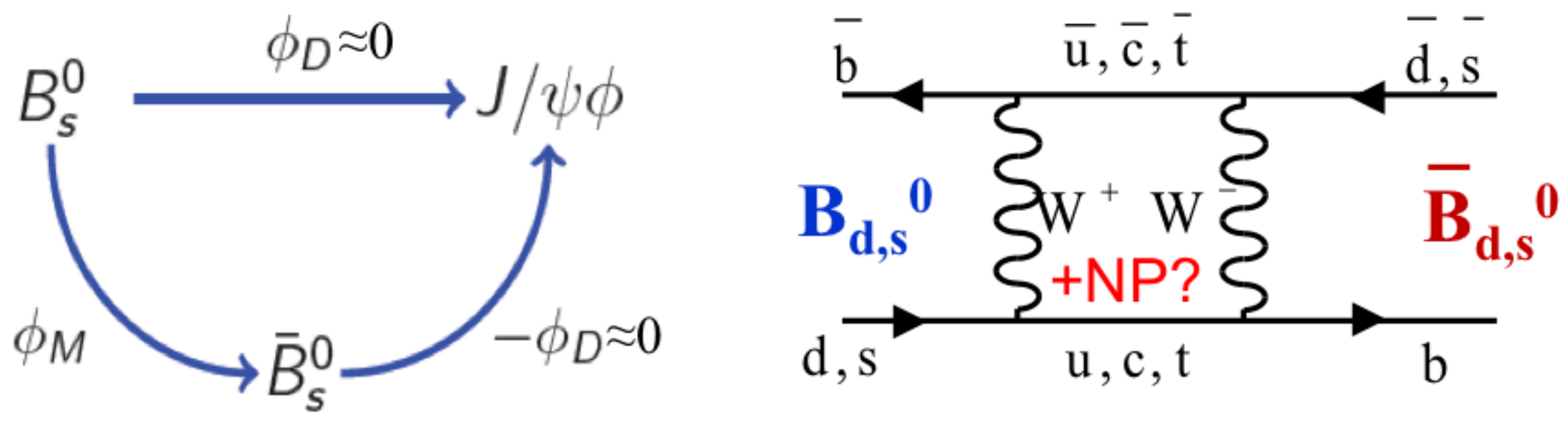
- CP violating phase in B_s mesons decays arises from interference between direct $B_s \to J/\psi\, \phi$ decay amplitude with its mixed amplitude.



- Standard Model prediction
  - $\phi_s = -2\beta_s + P \sim 2\arg(V_{ts} V^*_{tb}/V_{cs} V^*_{cb}) + P = -37.6^{+0.6}_{-0.5} + (2 \pm 10)$ mrad

    [J. Charles et al. (CKMfitter), Phys. Rev. D91, 073007 (2015), updated with Summer 2023 results]
  - where β_s is the B_s unitarity CKM triangle CP violating phase and P the penguin $(2 \pm 10$ mrad) contribution [Marten Z Barel et al 2021 J. Phys. G: Nucl. Part. Phys. 48 065002]

Ingredients for a measurement

- Time dependent angular analysis of differential decay rate

$$\frac{d^4\Gamma}{d\Theta d(t)} = f(\Theta, t, \alpha) \propto \sum_{i=1}^{10} \varepsilon(\Theta)\varepsilon(t) \cdot \tilde{O}_i(\alpha, t) \cdot g_i(\Theta)$$

$$\tilde{O}_i(\alpha, t) = \int O_i(\alpha, t')R(t-t')\mathrm{d}t'$$

- where O_i are time dependent functions, g_i are angular functions, and α a set of parameters, and R a the per-event resolution function

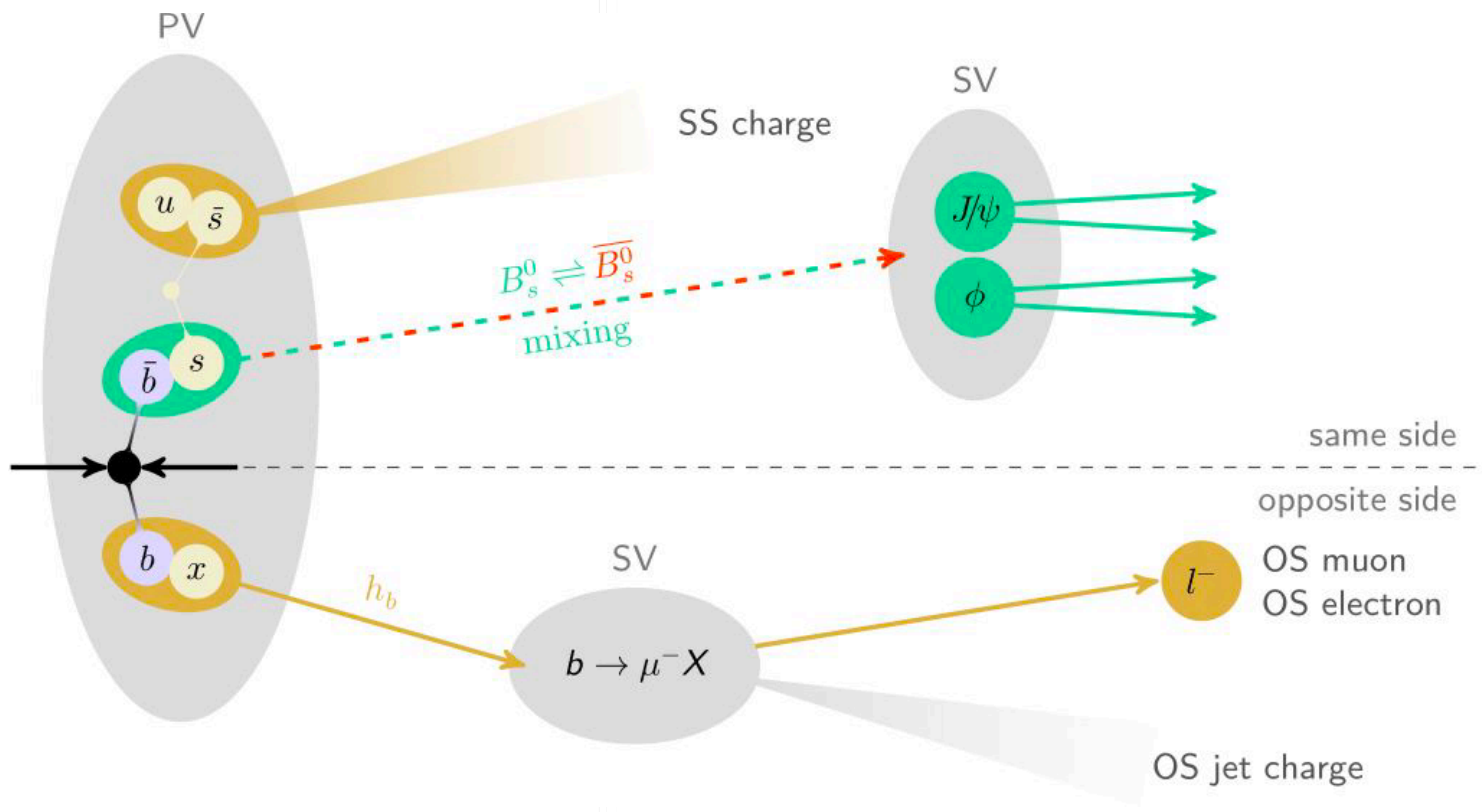
$$\alpha = \{\Delta\Gamma_s, c\tau, \phi_s, \Delta m_s, |A_0|^2, |A_\perp|^2, |A_\parallel|^2, |A_S|^2, \delta_\parallel, \delta_\perp, \delta_S, \delta_0\}$$

$$O_i(\alpha, t) = N_i e^{-ict/c\tau}\left[a_i \cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + b_i \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) + c_i\, \xi(1-2\omega)\cdot\cos(\Delta m_s t) + d_i \xi(1-2\omega)\cdot\sin(\Delta m_s t)\right]$$

- where ξ=0,±1 if tag is present or not, and ω is the fraction of mistagged events
  - Untagged events also contribute!
- b_i and d_i coefficients are sensitive to cos(ϕ_s) and sin(ϕ_s)

Flavour tagging

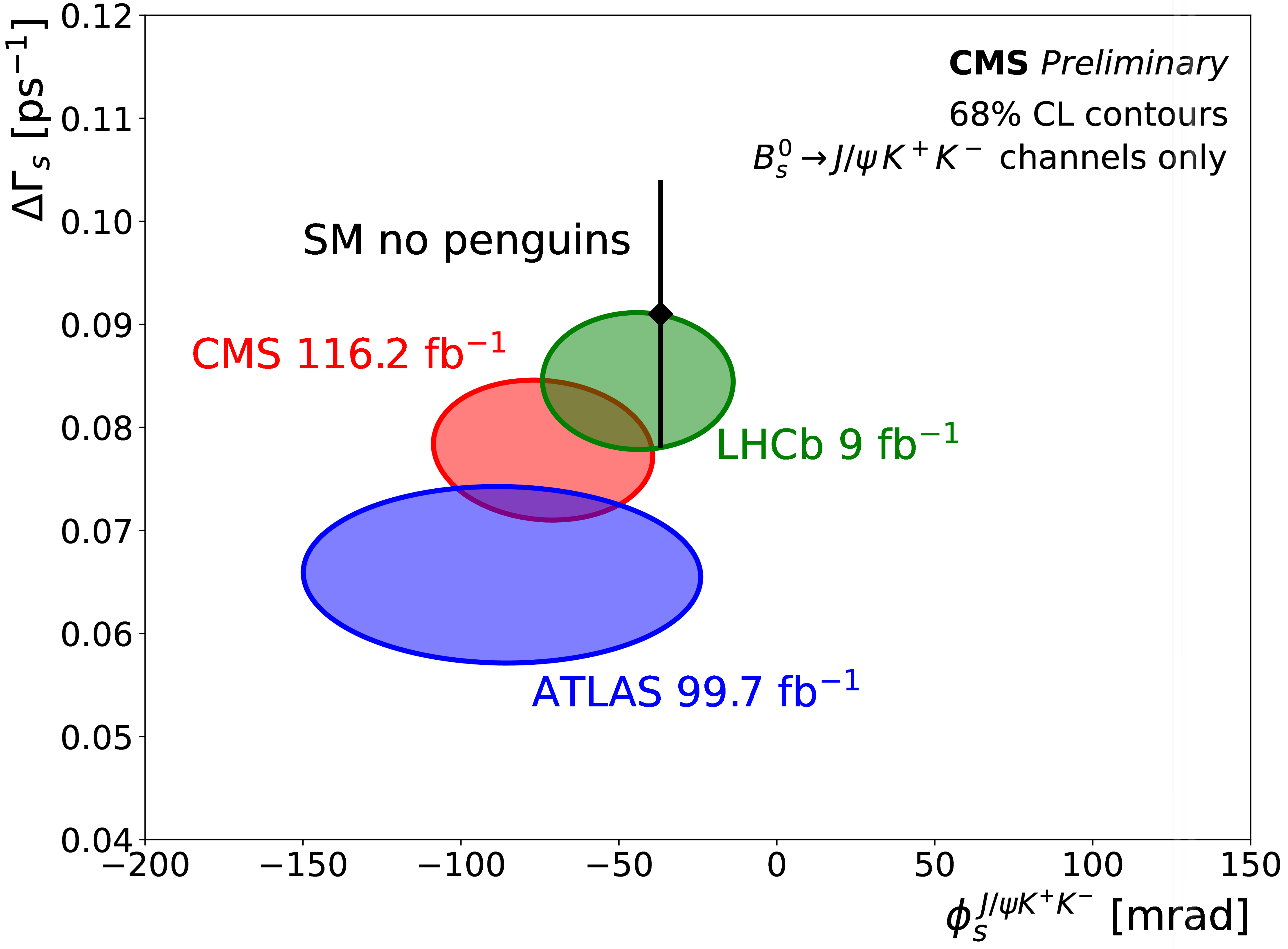
- Innovative Flavour Tagging algorithms based on machine learning techniques
  - Latest CMS tagging power using leptons+OS taggers: $\hat{P}_{tag} = \epsilon(1-2\omega)^2$ ~5.6% to be compared to ~4.2% of LHCb (which also uses SS and particle ID)



Category	ε_{tag} [%]	$\mathcal{D}^2_{eff}$	P_{tag} [%]
Only OS muon	6.07 ± 0.05	0.212	1.29 ± 0.07
Only OS electron	2.72 ± 0.02	0.079	0.214 ± 0.004
Only OS jet	5.16 ± 0.03	0.045	0.235 ± 0.003
Only SS	33.12 ± 0.07	0.080	2.64 ± 0.01
SS + OS muon	0.62 ± 0.01	0.202	0.125 ± 0.003
SS + OS electron	2.77 ± 0.02	0.150	0.416 ± 0.005
SS + OS jet	5.40 ± 0.03	0.124	0.671 ± 0.006
Total	55.9 ± 0.1	0.100	5.59 ± 0.02

Current ϕ_s measurements

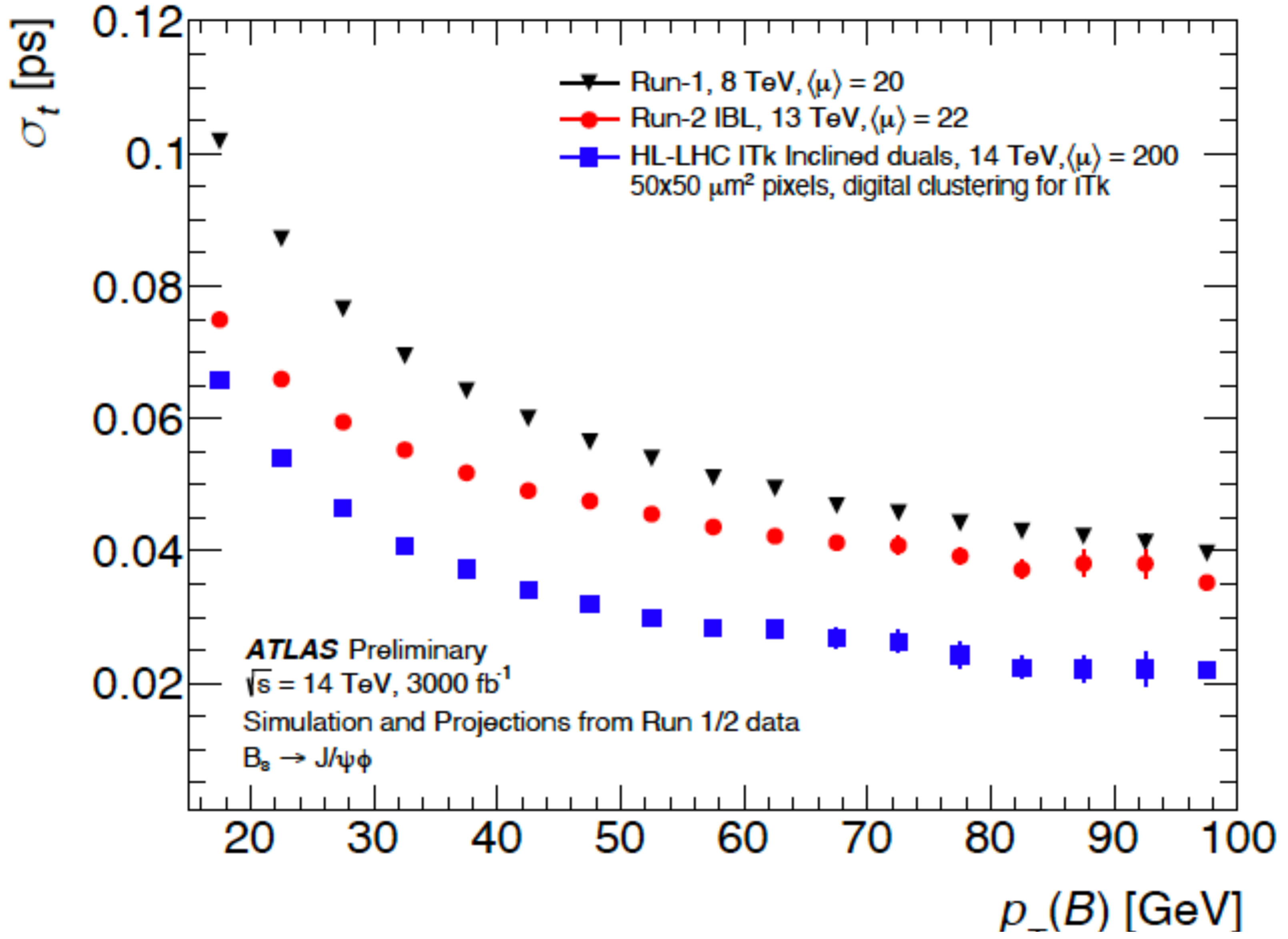
- LHCb exploited full Run1and Run2 statistics
- ATLAS 2015-17
- CMS 2017-18



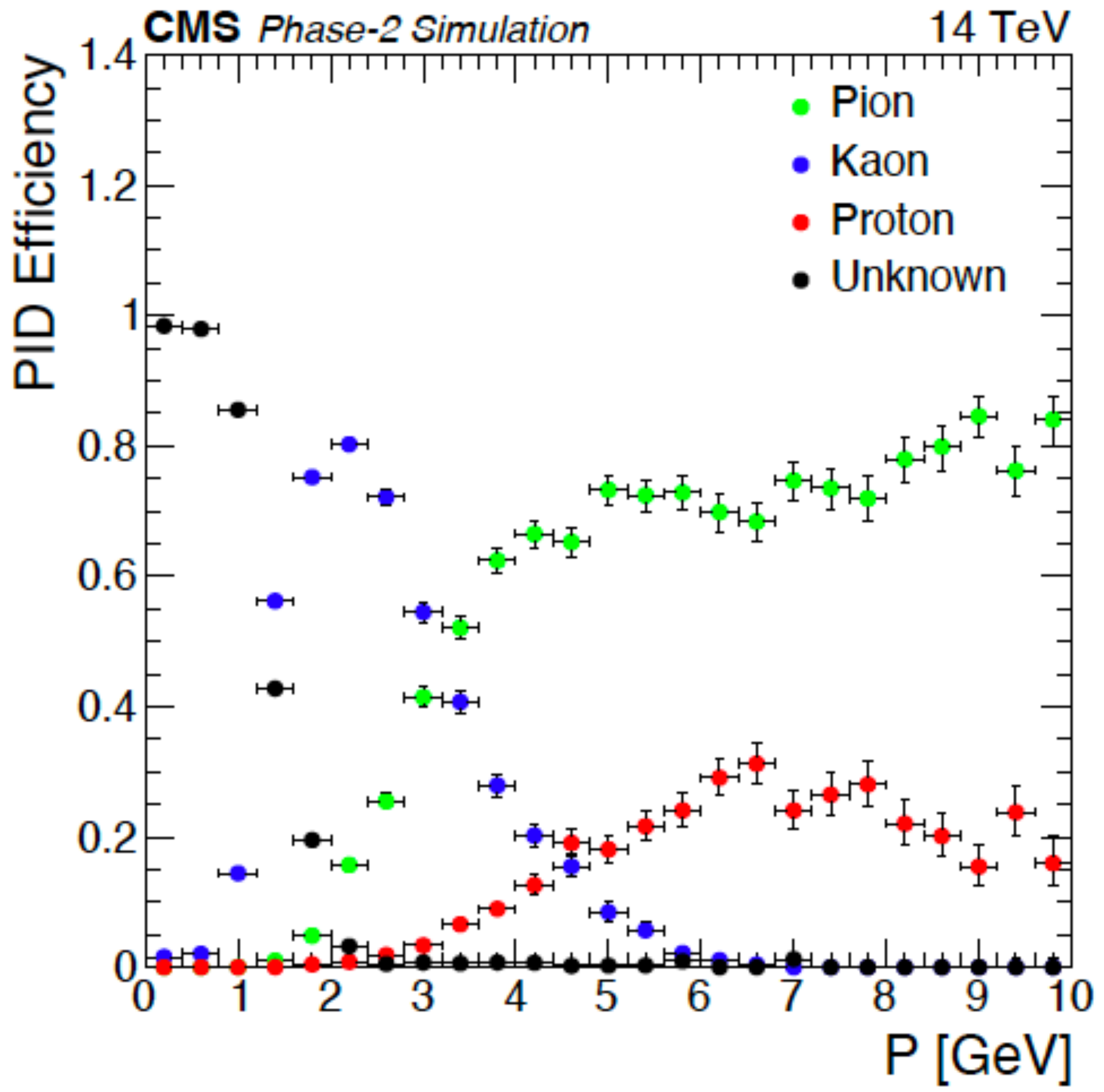
HL-LHC ϕ_s prospects - Detector improvements

- Improved muon systems
  - Extended forward coverage, better timing and trigge capabilities

- Improved Tracker systems
  - Less material budget, L1 track reconstruction
    - Sensitivity scales as $\exp[-0.5(\Delta m_s \cdot \sigma_t)^2]$



- Timing Detectors for TOF particle ID
  - Offer capabilities to discriminate pileup and good K/π separation between~1.5 to 4 GeV
  - Combined with other techniques will improve significantly the flavour tagging



[CERN-CMS-DP-2022-025]

HL-LHC ϕ_s prospects - II

- Extrapolated CMS tagging power with Same-Side tag, using Kaon ID

$$\hat{P}_{tag} = \epsilon(1-2\omega)^2 \sim 7.2(6.7)\,\%\ \text{for 40 (70) ps resol.}$$

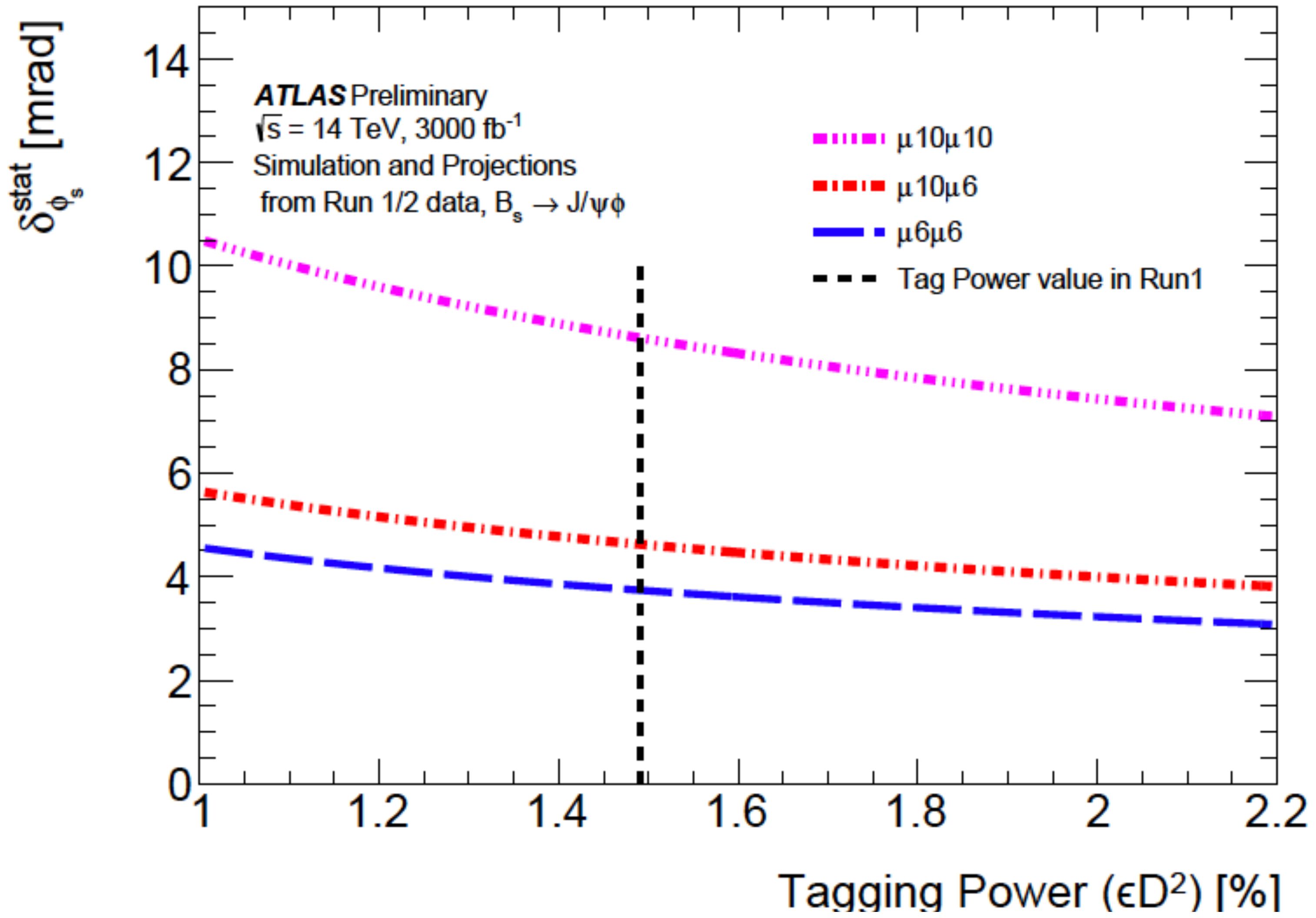
- Statistical precision scales as

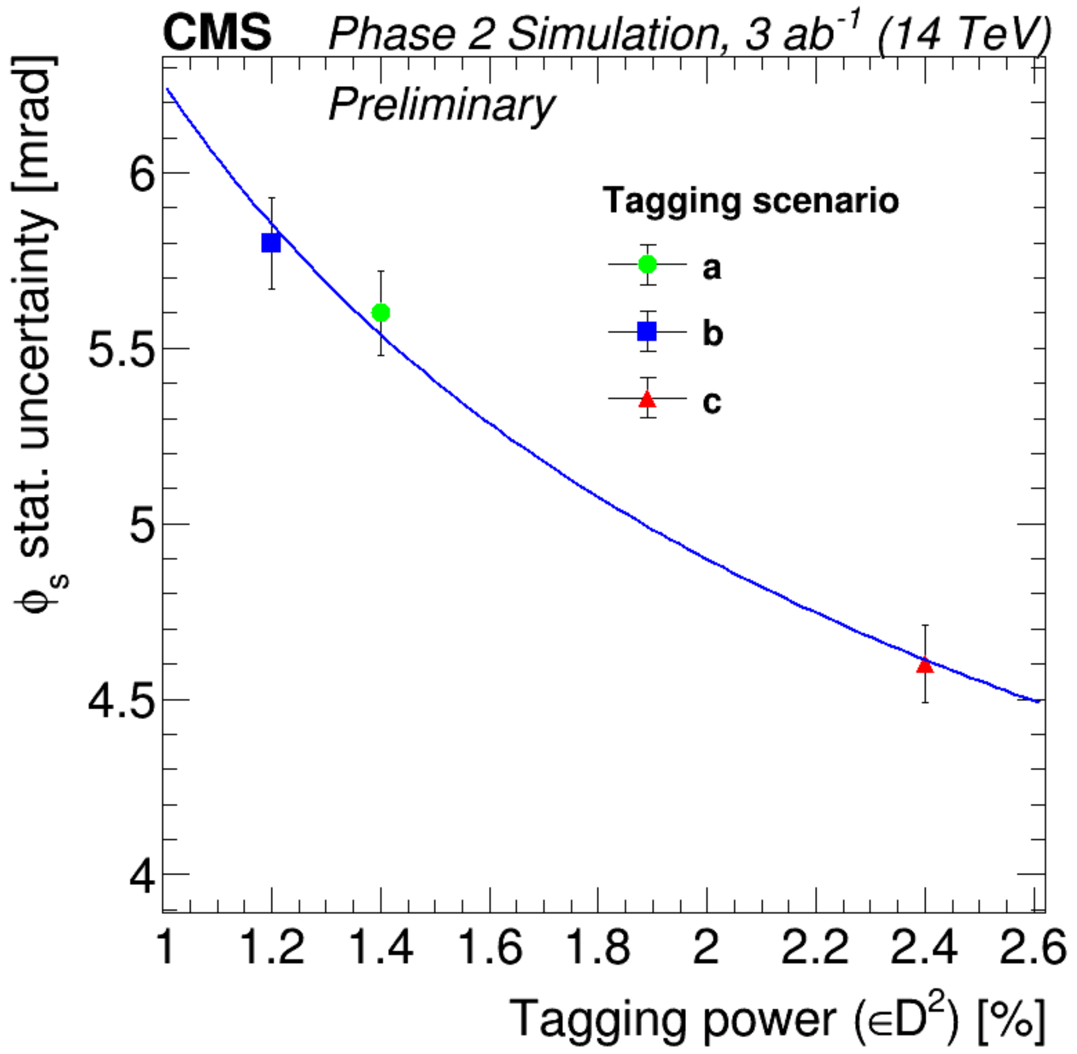
$$\sigma_{\phi_s}(\text{stat}) \propto \frac{1}{\sqrt{\epsilon}(1-2\omega)}$$

expect individual experiment reach $\sigma_{\phi_s}(stat) \sim 3$ mrad

- Current systematics (~7 mrad) dominated by statistics in tag calibration tag with $B^{\pm} \rightarrow J/\psi K^{\pm}$ and modelling: reaching 3 mrad seems doable

- Penguin contributions have similar size and must be measured and subtracted



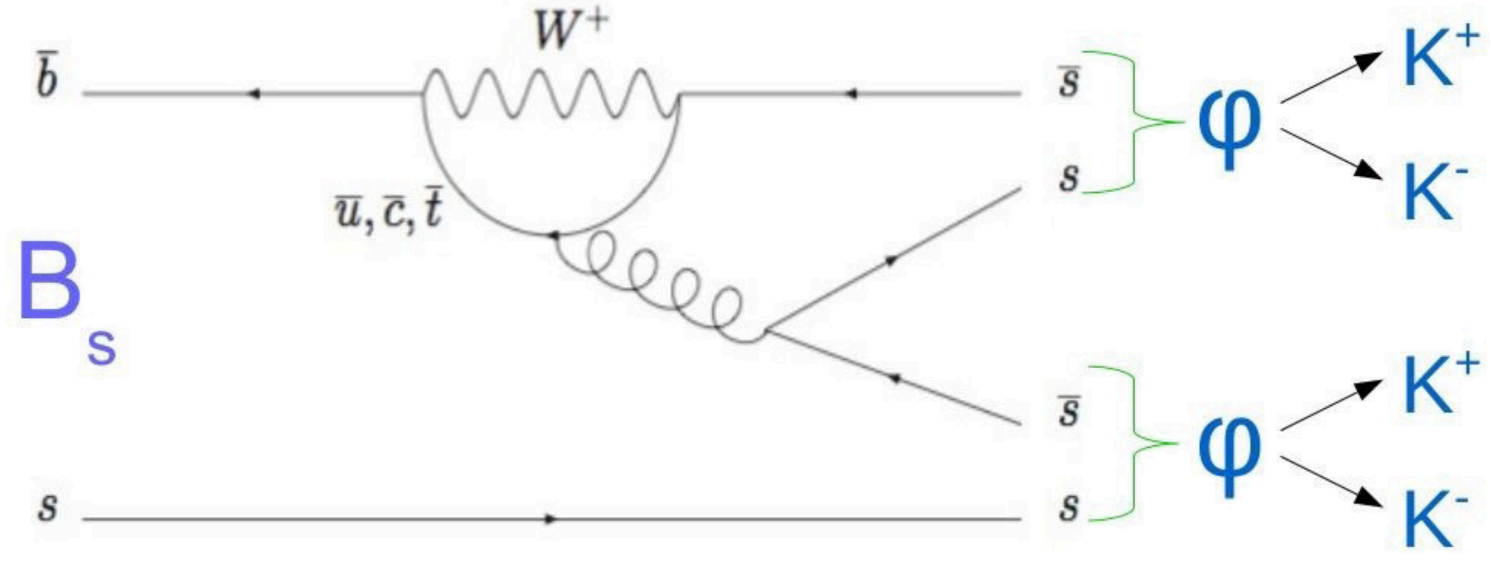


Period	L_{int} [fb^{-1}]	N_{sig}	f_{sig}	Tag Power [%]	$\sigma(\tau)$ [ps]	$\delta^{stat}_{\phi_s}$ [rad] measured (extrapolated)	$\delta^{stat}_{\Delta\Gamma_s}$ [ps^{-1}] measured (extrapolated)
2012	14.3	73693	0.20	1.49	0.091	0.082	0.013
2011	4.9	22690	0.17	1.45	0.100	0.25 (0.22)	0.021 (0.023)
						$\delta^{stat}_{\phi_s}$ [rad] extrapolated	
HL-LHC	3000						
Trigger μ6μ6		$9.72 \cdot 10^6$	0.17	1.49	0.048	0.004	0.0011
Trigger μ10μ6		$5.93 \cdot 10^6$	0.17	1.49	0.044	0.005	0.0014
Trigger μ10μ10		$1.75 \cdot 10^6$	0.15	1.49	0.038	0.009	0.003

Measuring the penguin pollution through $B^0_{d,s} \rightarrow J/\psi K^0_S$ and $B^0_s \rightarrow J/\psi \rho^0$ [De Bruyn, Fleisher JHEP 1503 (2015) 145]

ϕ_s through $B_s \to \phi\phi \to K^+K^-K^+K^-$

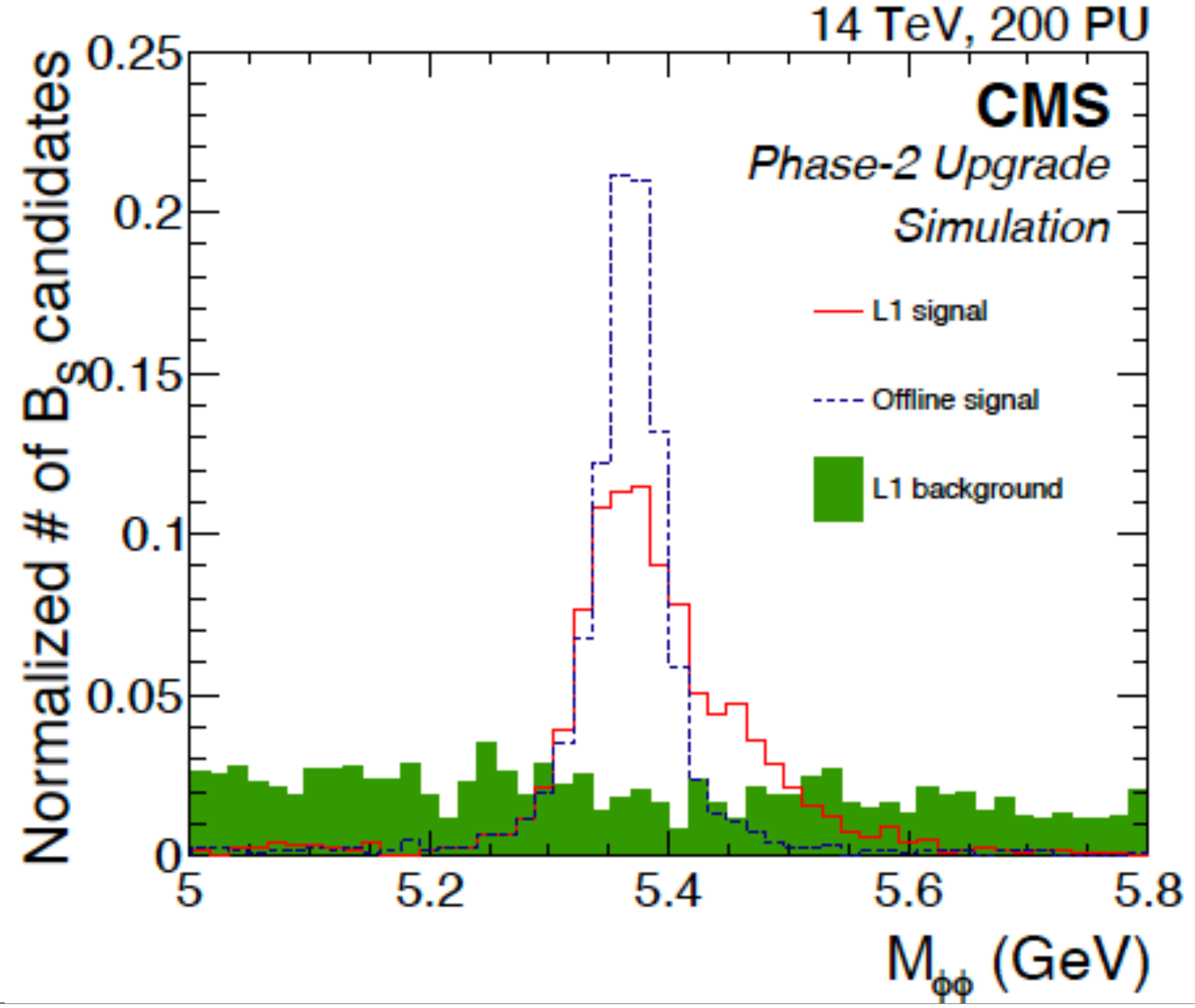
- Forbidden at tree level in SM, proceeds predominantly through gluonic penguins



- Promising number of events
- Signal can be triggered using L1 track reconstruction
  - 10 kHz at L1, 30% signal efficiency

Baseline	Efficiency (%)		Rate (kHz)
	L1	Offline	$< PU > = 200$
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

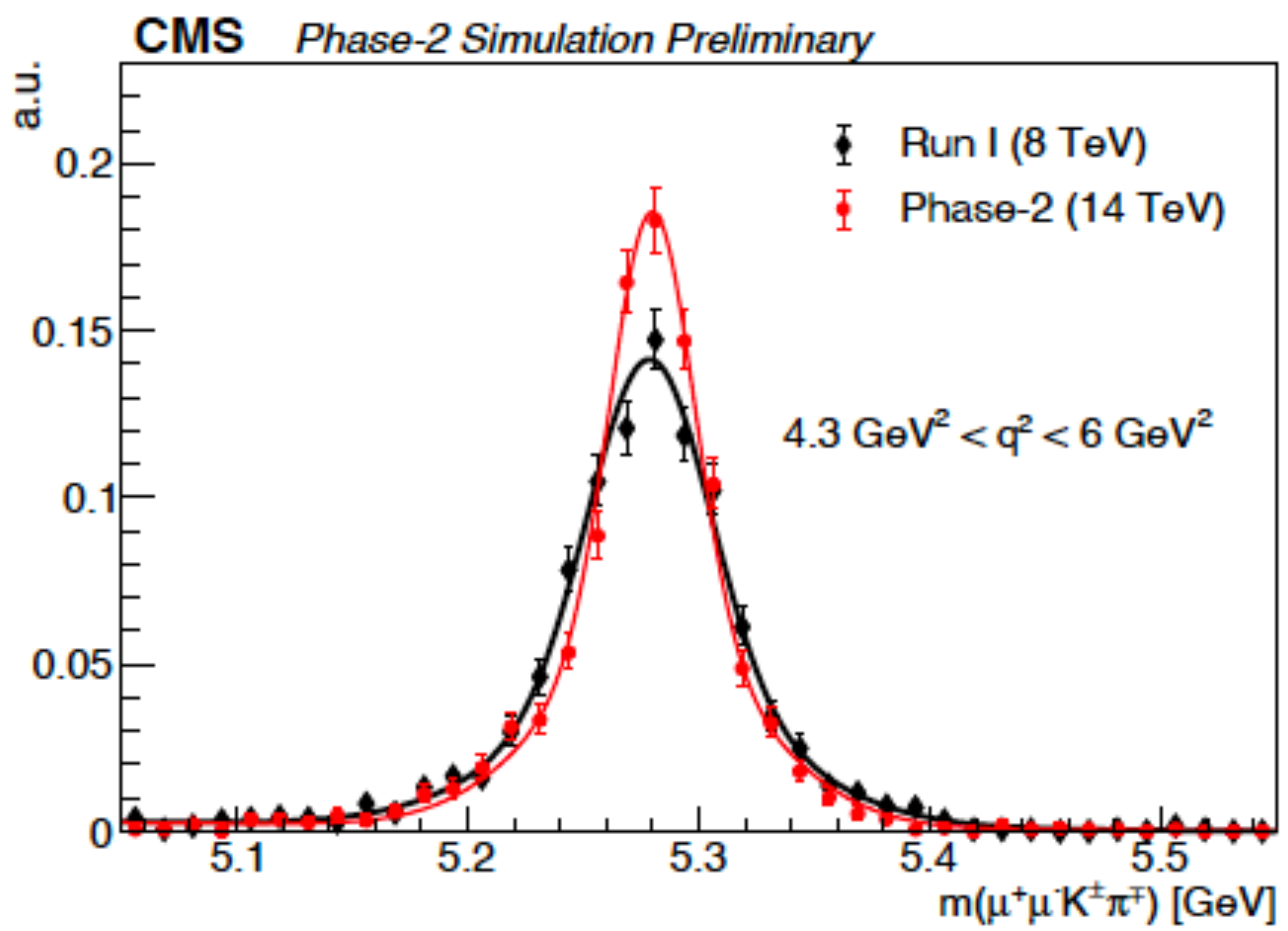
CERN-LHCC-2020-004 ; CMS-TDR-021

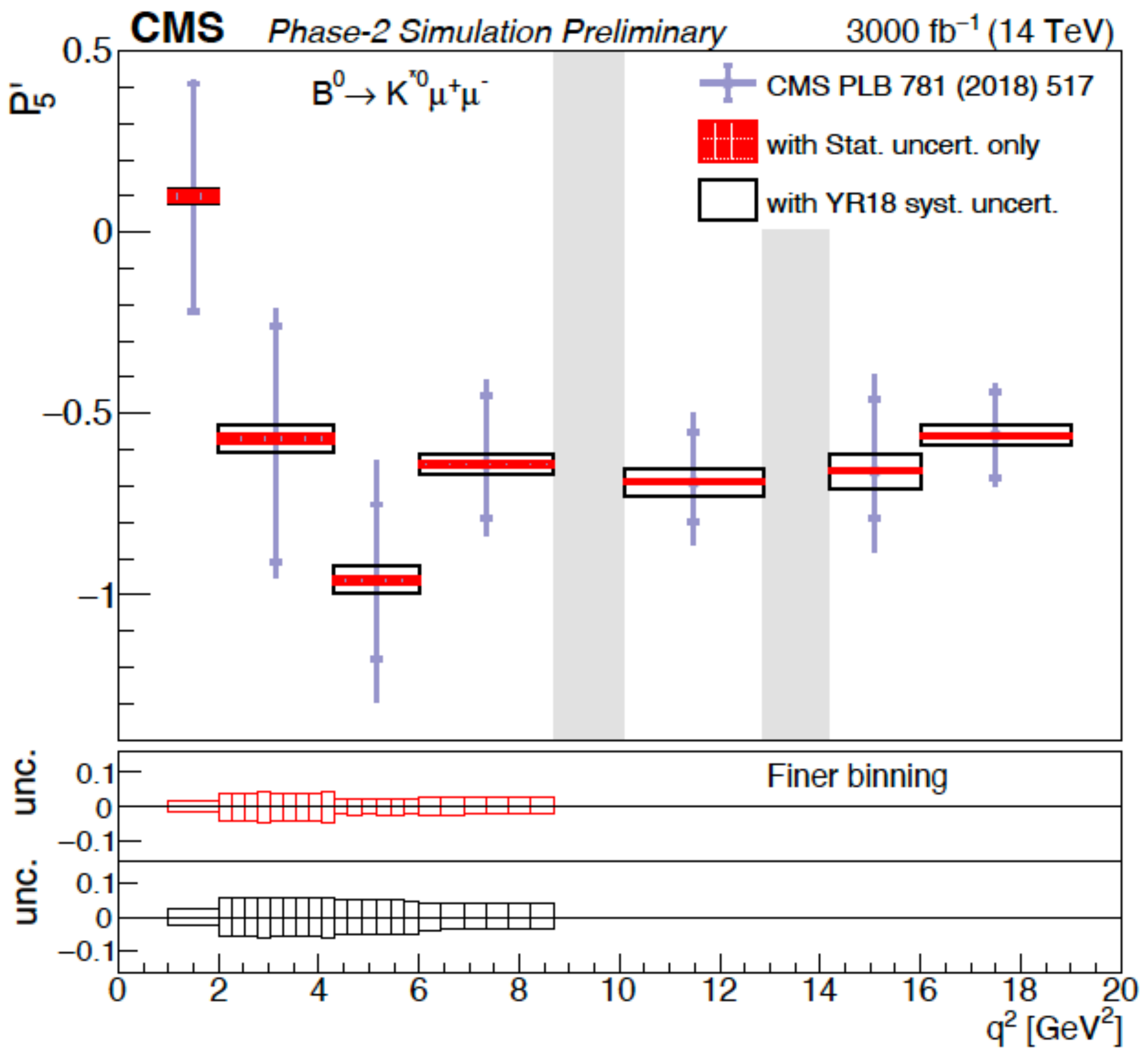


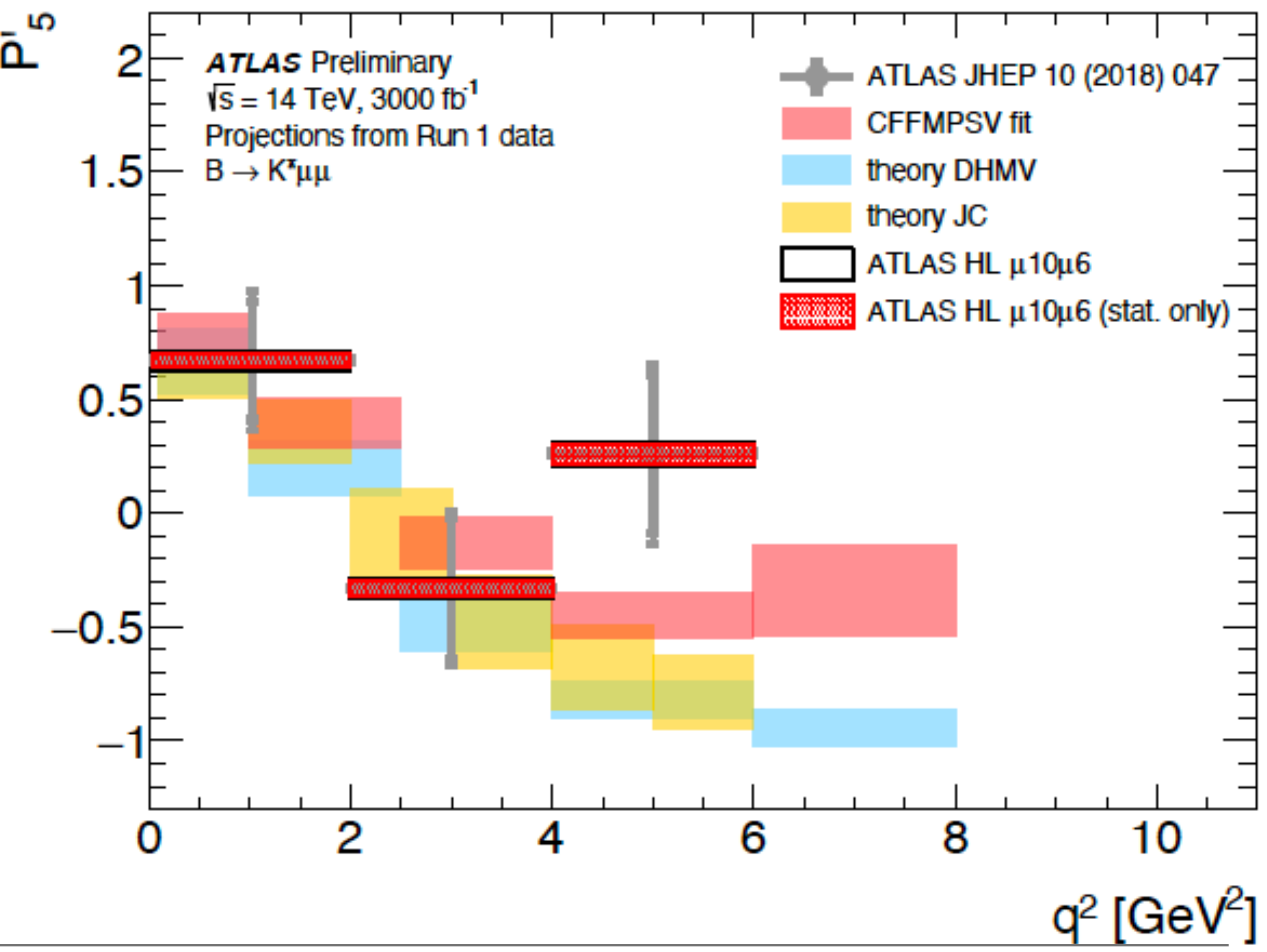
- Expect offline analysis to benefit from MTD particle ID

Rare $b \to s\mu^+\mu^-$ decays

- Angular analysis and dB/d_{q^2} of $B^0 \to K^{*0}\mu^+\mu^-$
  - K^{*0} or $\bar{K}^{*0}$ determine the CP state of the B0
- HL-LHC projection
  - Conservatively use same trigger, background
    - Simply rescale for integrated luminosity ~ one order of magnitude better wrt Run1
  - Better mass resolution
  - Systematically limited
  - Possible further improvements not ye taken into account
    - Level-1 Track Trigger
    - Particle ID with MTD

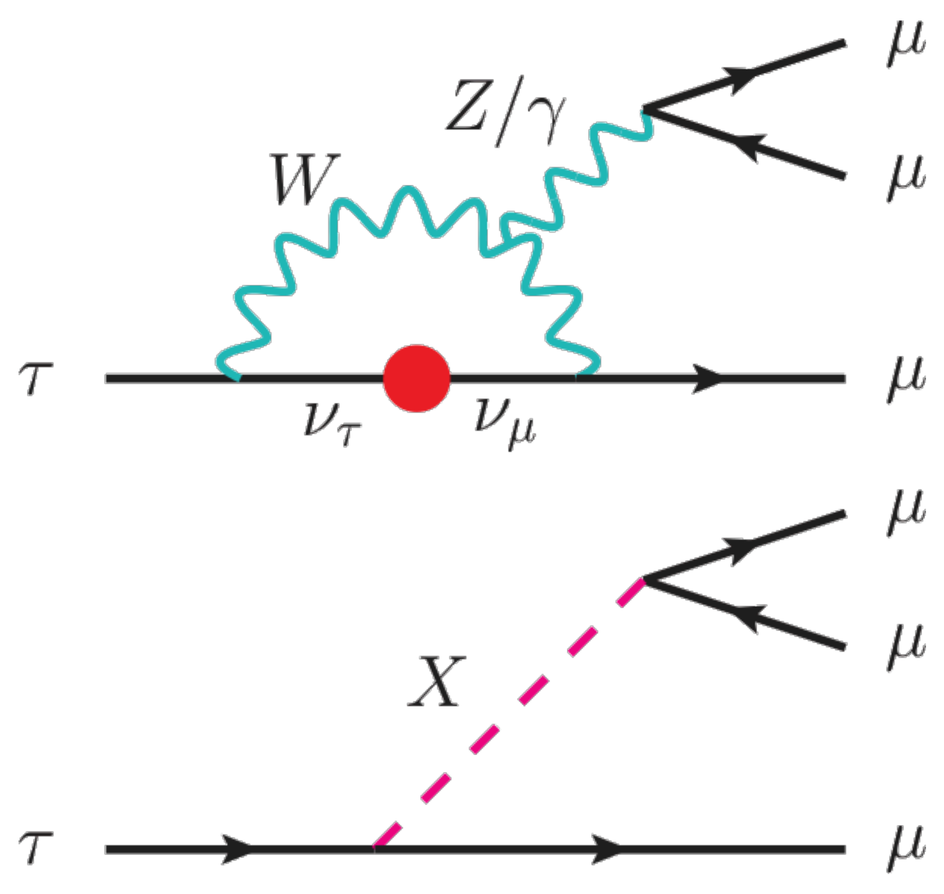


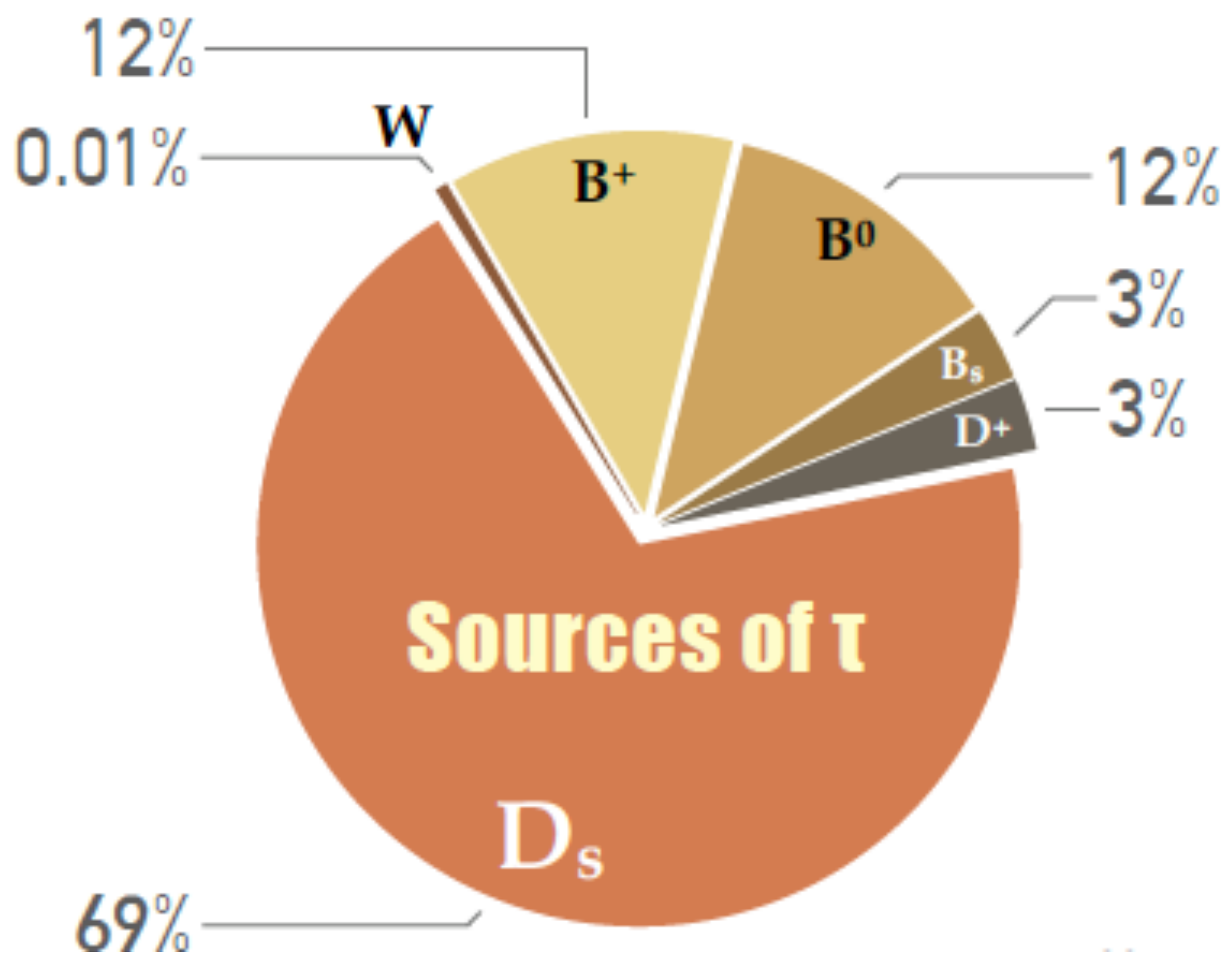




CLFV using $\tau \to 3\mu$

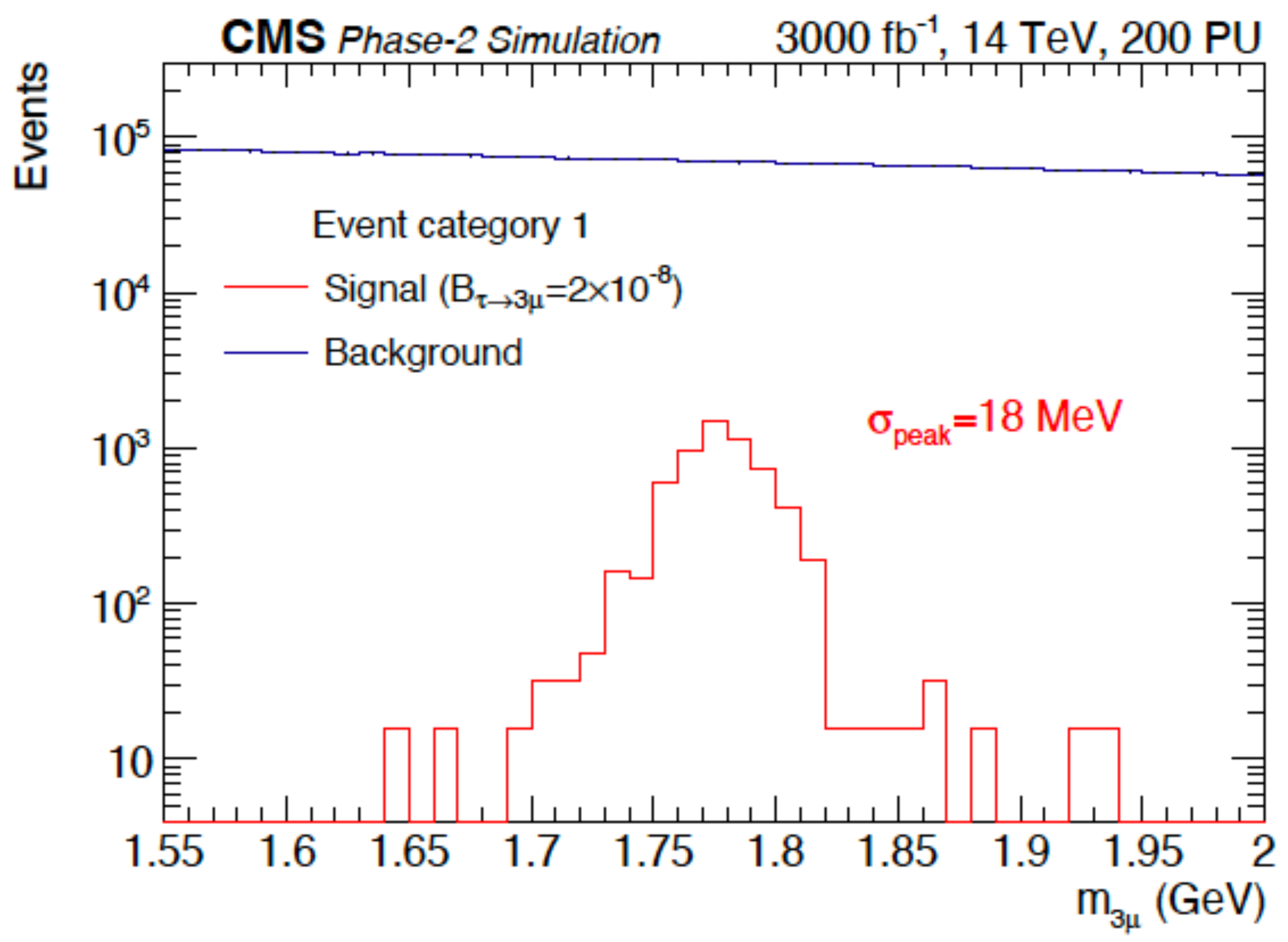
- Practically forbidden in the SM (BR~10^{-56}-10^{-53})
  - Excellent for probing New Physics
  - Experimentally very clean
  - Two main sources of τ leptons at the (HL-)LHC
    - Heavy Flavours (dominant source) ~$10^{11}\tau$/fb-1
      - $b \to \tau X$ and $D_s^+ \to \tau\nu_\tau$
      - Low p_T, less central in pseudo-rapidity
    - W bosons (~$10^7\tau$/fb-1)
      - Higher p_T, more central in pseudo-rapidity
    - Relatively simple analysis (3 muons invariant mass)
      - Backgrounds from mis-id pions and combinatorics
- Most precise result at LHC<2.9 10^{-8} @90% CL from CMS with 131 fb^{-1}

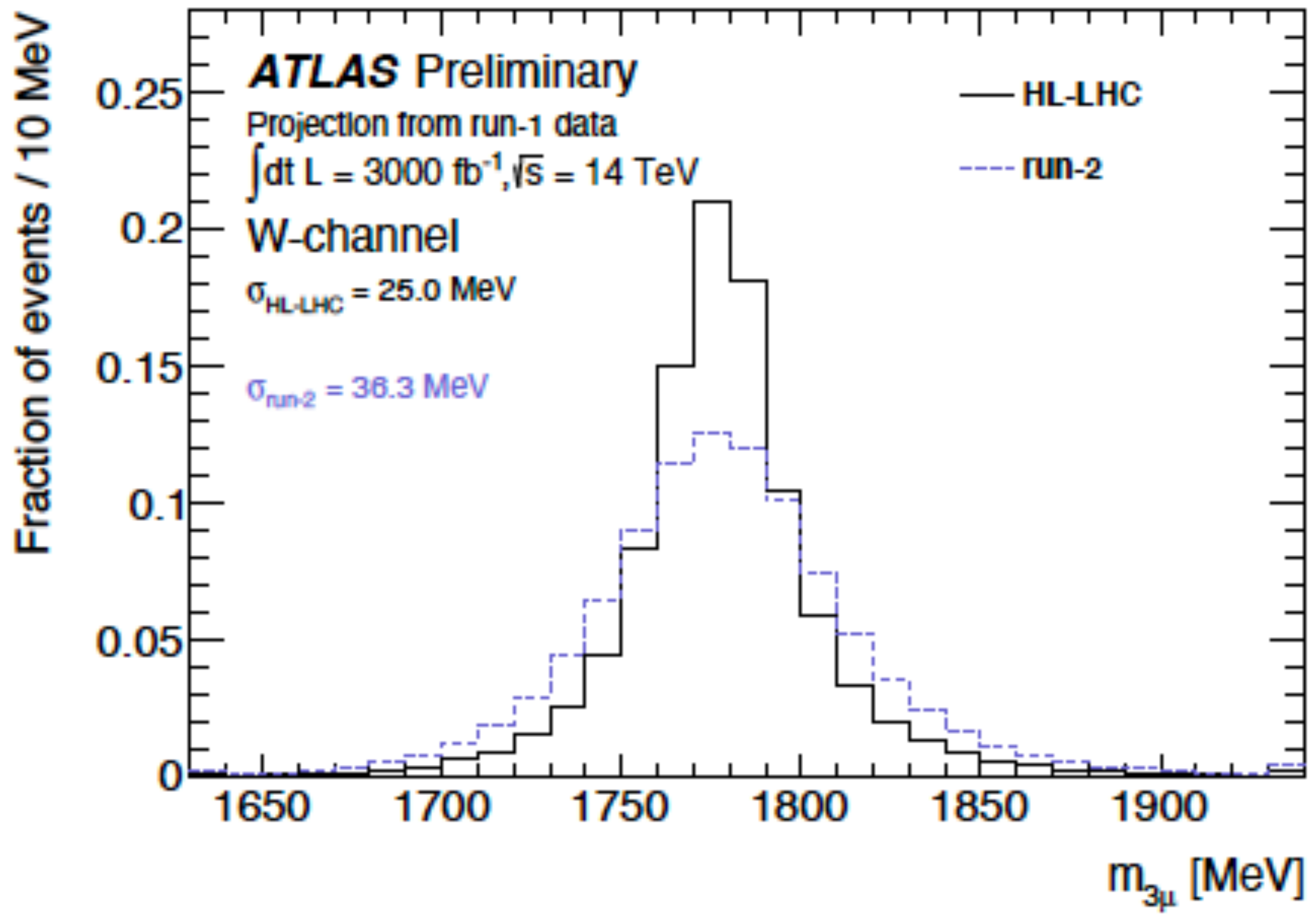


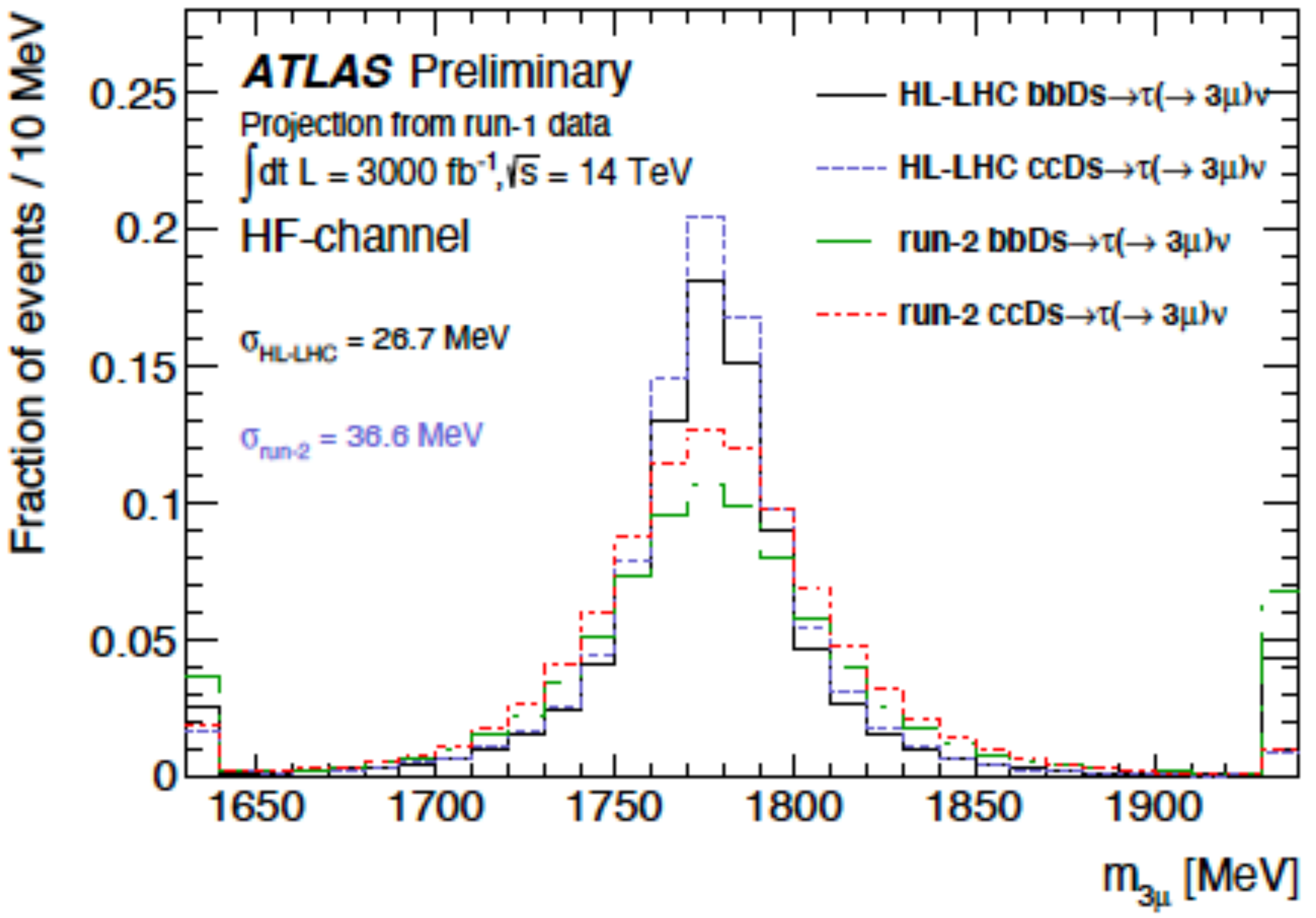


HL-LHC $\tau \to 3\mu$ predictions

- Improved mass resolutions thanks to lighter and higher granularity trackers
- Better muon identification with new improved detectors
  - ATLAS reach <1-6 10^{-9} @90% CL depending on the background levels
  - CMS projection
    - HF search <0.6 10^{-9} @90% CL
    - W channel potentially background free with <0.2 10^{-9} @90% CL

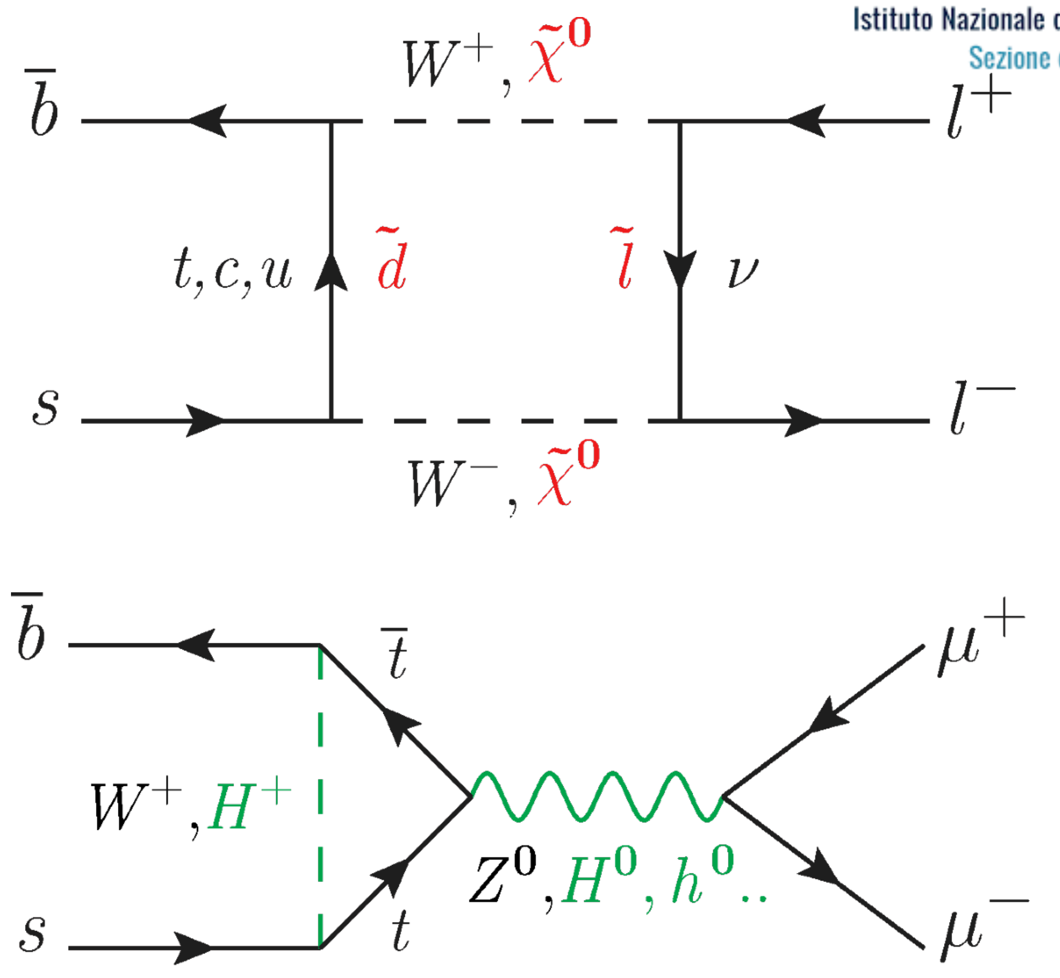






$B^0_{d,s} \to \mu^+\mu^-$ @ HL-LHC

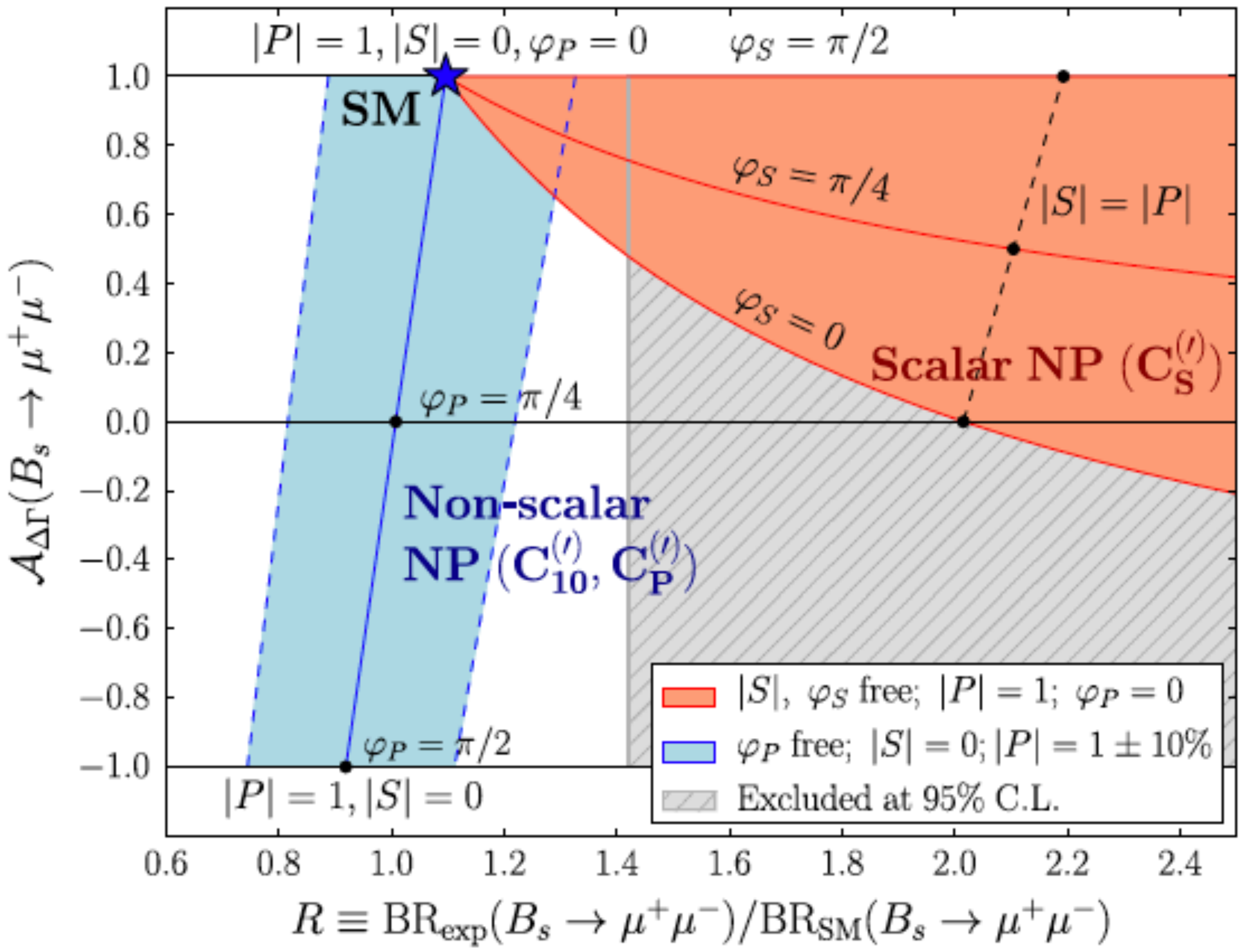
- Can only proceed via highly suppressed FCNC modes in SM
  - Theoretically clean to look for BSM physics [Beneke, M., Bobeth, C. & Szafron, R. J. High Energ. Phys. 2019, 232 (2019)]
    - $BR(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$
    - $BR(B^0_d \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$
  - In SM only B^0_s heavy mass eigenstate can decay into muons, in case of non CP violation
    - Any deviation could be hint of New Physics



$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{exp}}} = 2 - (1 - y_s^2)\frac{\tau_{\mu^+\mu^-}}{\tau_{B_s}}$$

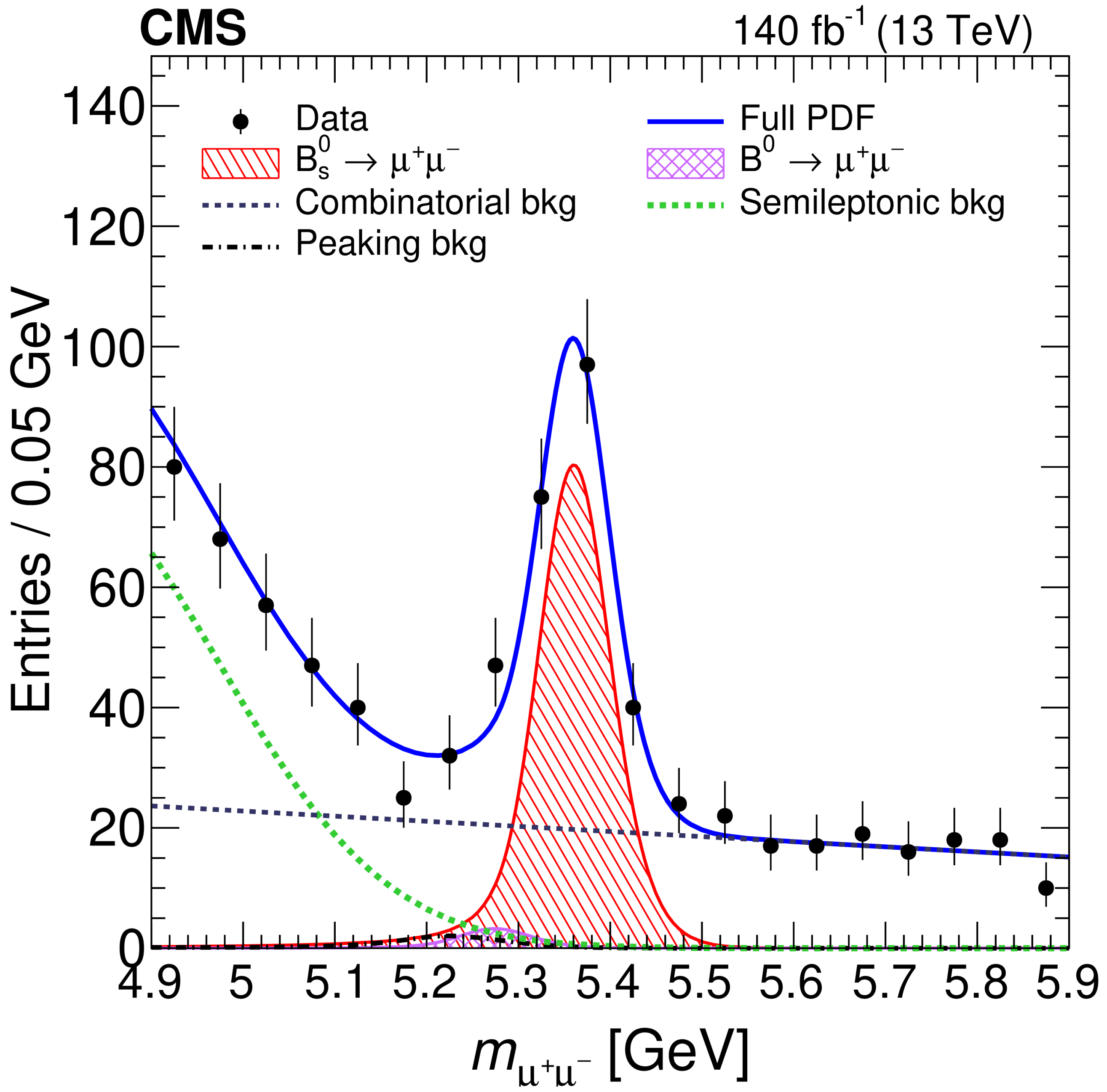
$$y_s = 0.5\Delta\Gamma_s/\Gamma_s = 0.0635 \pm 0.0035 \qquad \mathcal{A}_{\Delta\Gamma} y_s = \frac{(1-y_s^2)\tau_{\mu^+\mu^-} - (1+y_s^2)\tau_{B_s}}{2\tau_{B_s} - (1-y_s^2)\tau_{\mu^+\mu^-}}$$

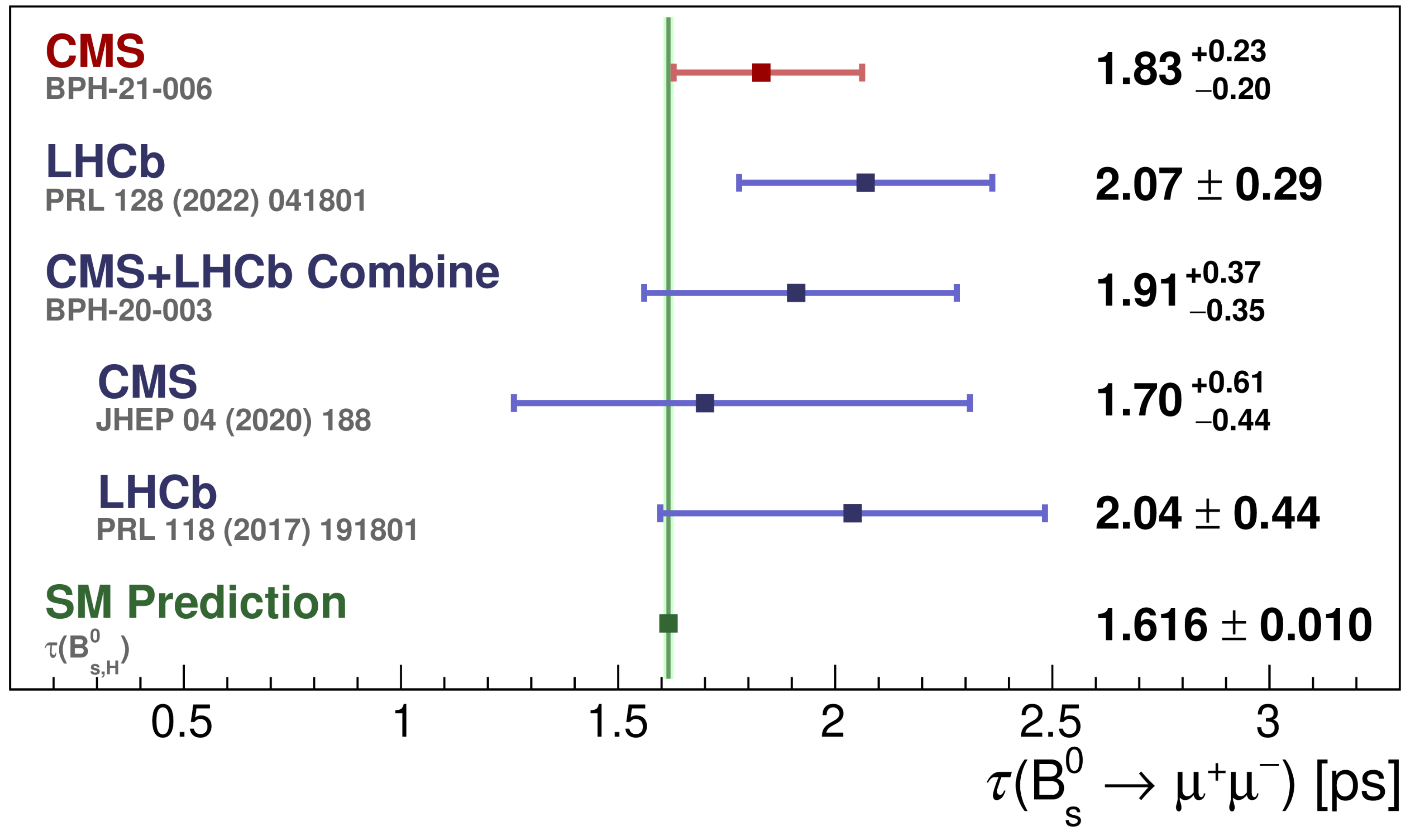
[K. De Bruyn et al. Phys. Rev. Lett. **109**, 041801]

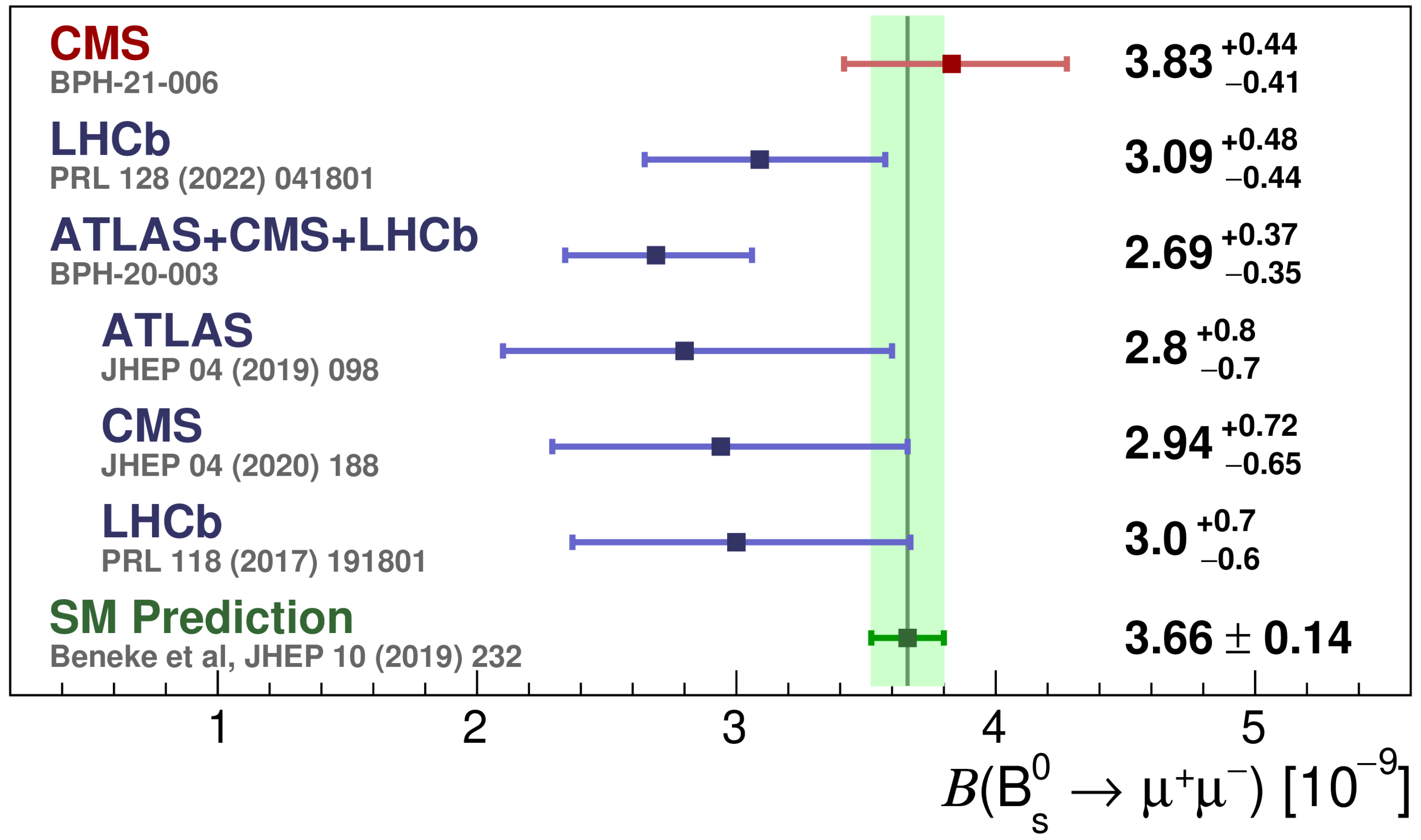


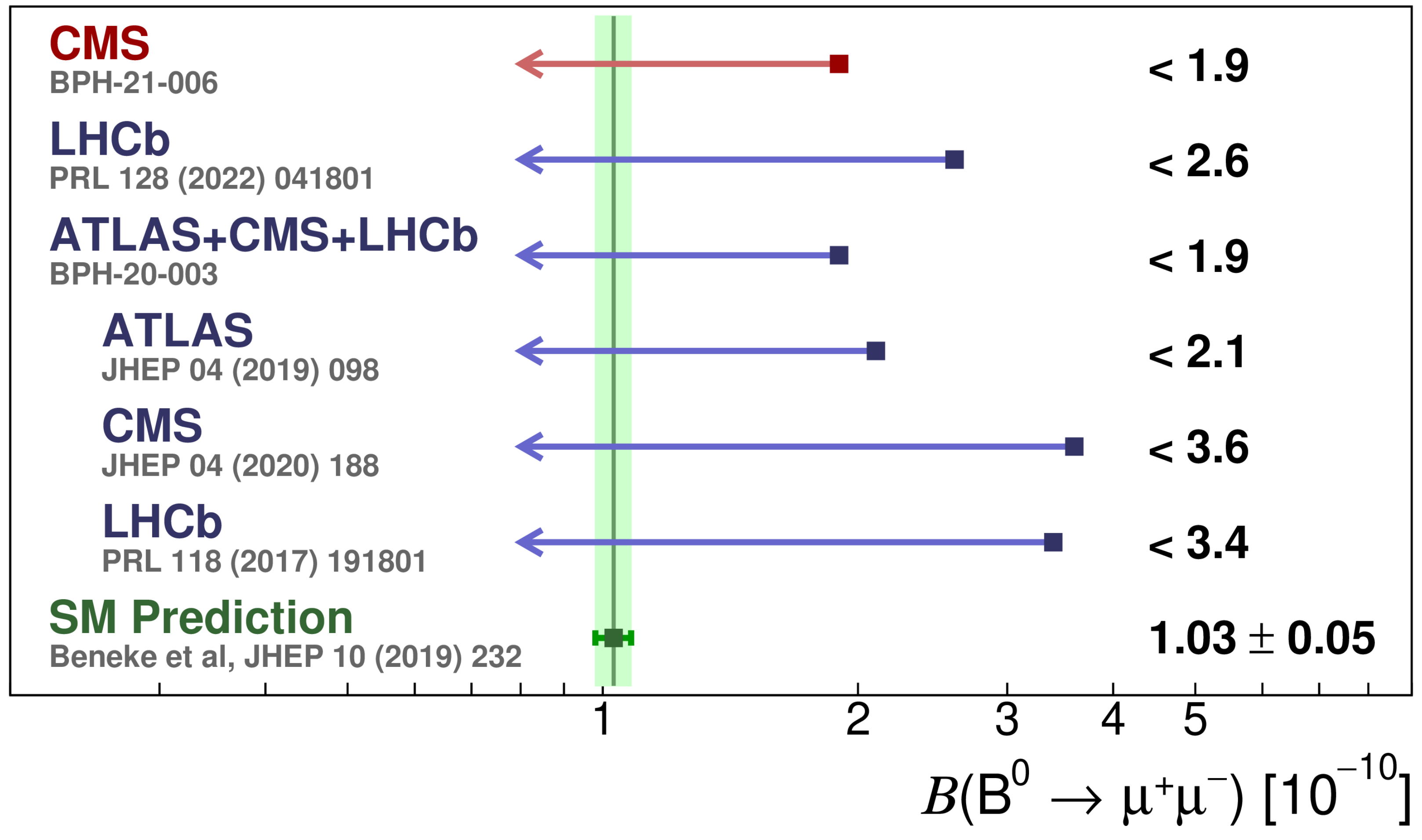
$B^0_{d,s} \to \mu^+\mu^-$ @ HL-LHC

- Measurements:
  - Branching fractions
    - B_s most precise from CMS: $\left[3.83^{+0.38}_{-0.36}(stat)^{+0.19}_{-0.16}(syst)^{+0.14}_{-0.13}(f_s)\right] \times 10^{-9}$
      - SM consistent
    - B_d not yet at evidence $< 1.9 \times 10^{-10} @ 95\,\%\, CL$
  - Effective lifetime:
    - Only heavy B_s eigenstate can decay in SM
    - Measurements so far consistent with SM but precision is still poor



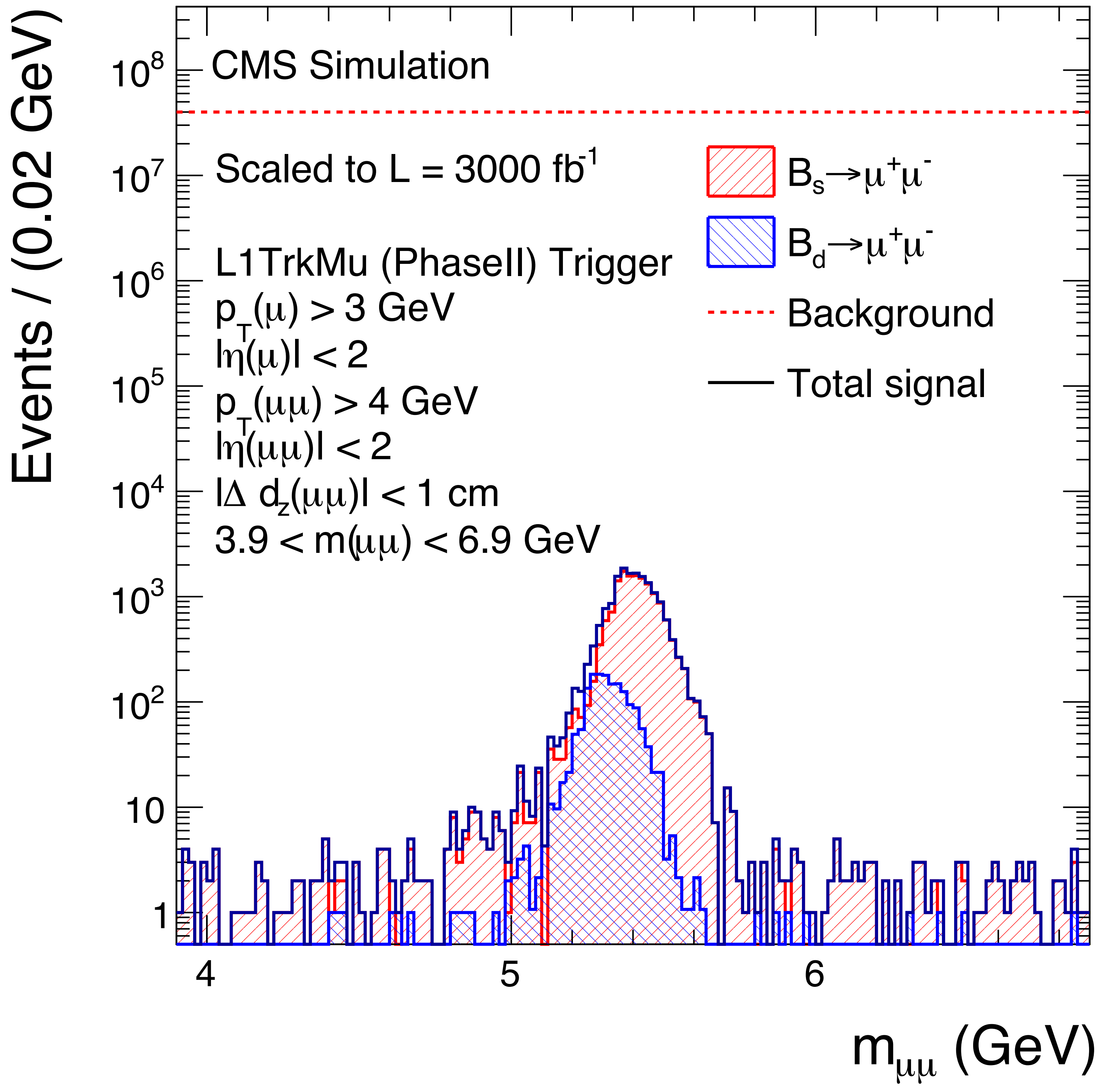






$B^0_{d,s} \to \mu^+\mu^-$ @ HL-LHC

Level-1 μ⁺μ⁻ reconstructed invariant mass distribution



Triggers:

CMS: Same trigger thresholds as the 2012 analysis

pT(μ)>3 GeV for |η|<2 at L1

Feasible only with the L1-Track Trigger: ~few hundred Hz @ L1

(stand-alone Muon trigger with 4 GeV thresholds the rate is ~300 KHz)

ATLAS trigger thresholds may vary from 6 GeV to 10 GeV.

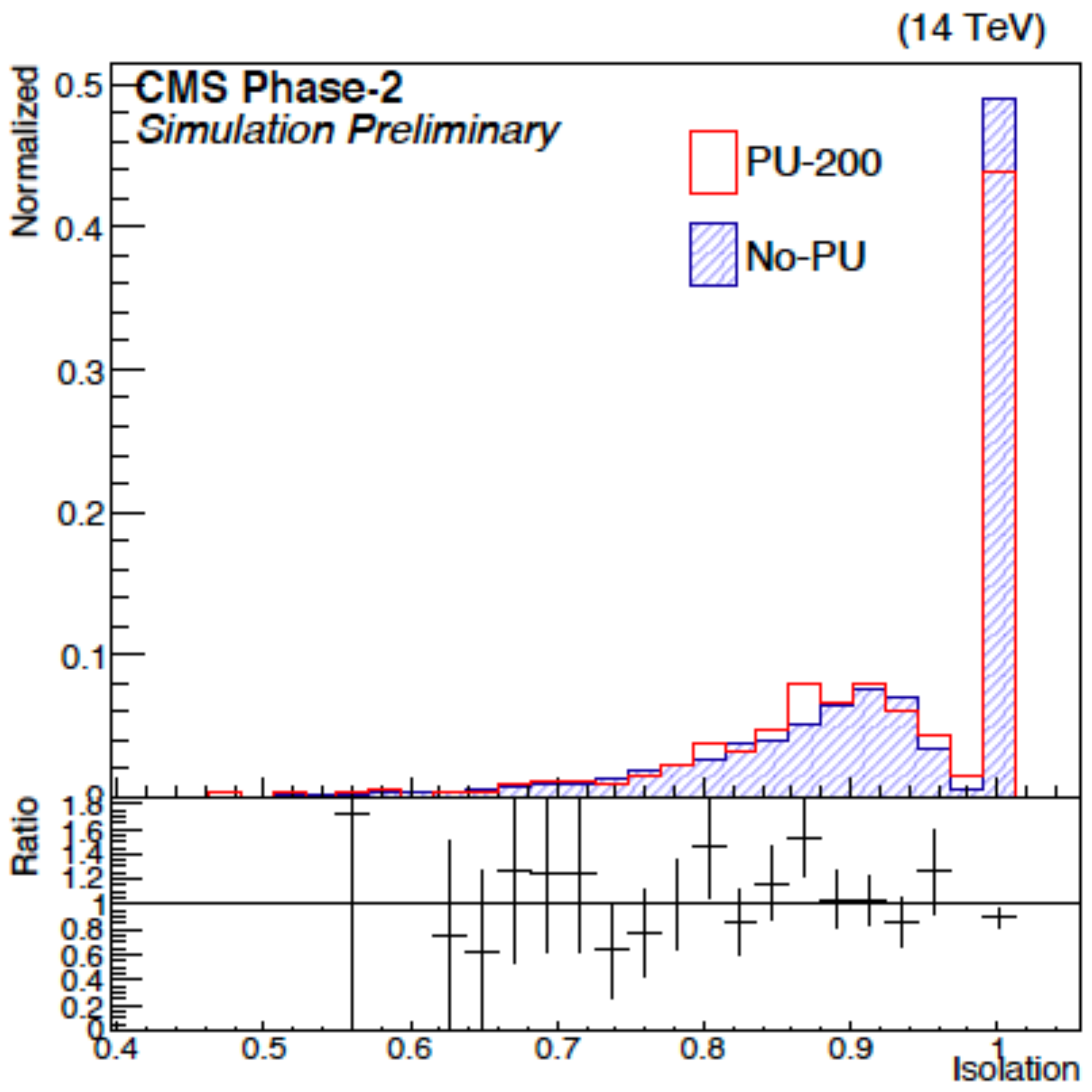
Sensitivity will depend crucially on that

Effects due to increased pileup

- Estimated loss of 2.5% in single μ tracking efficiency
- Assume conservative 30% loss in the isolation efficiency
  - checked with full simulation the effect on one isolation variable to be 16%

$$I = \frac{p_T(B)}{p_T(B) + \sum_{trk} p_T}$$

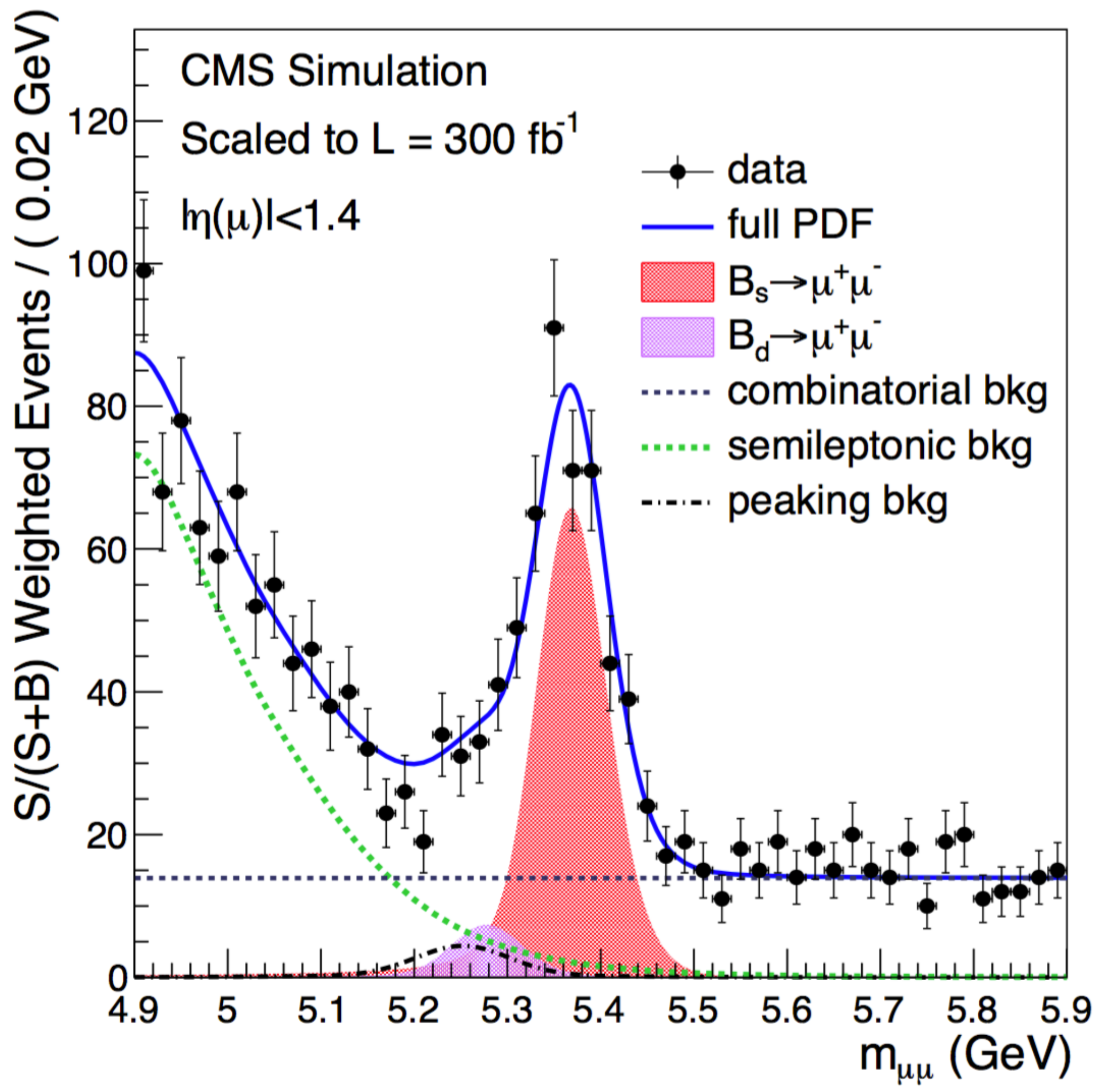
ΔR=0.7, p_T>0.9 GeV d_{ca}< 500

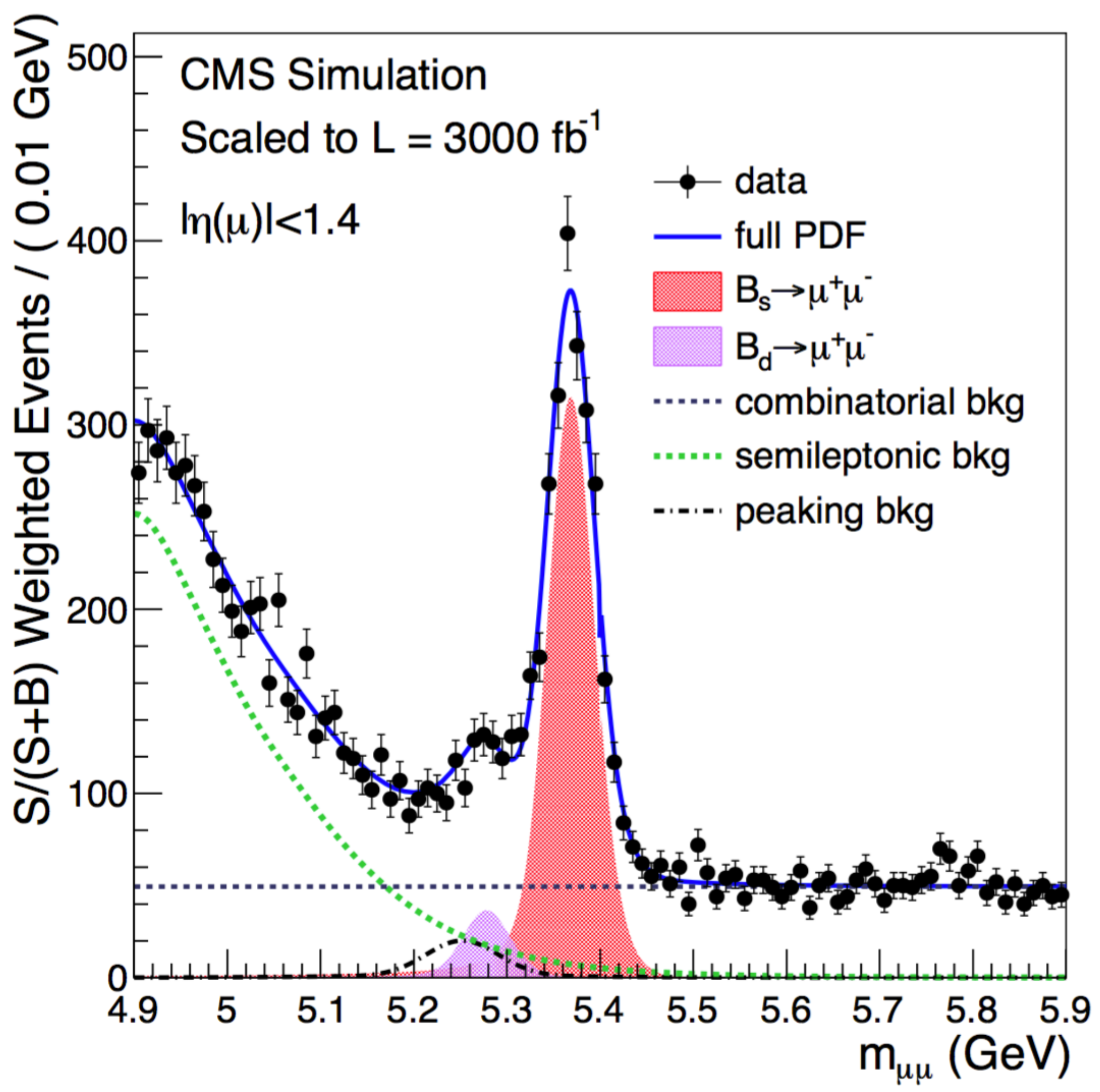


$B^0_{d,s} \to \mu^+\mu^-$ HL-LHC predictions

Improved mass resolutions

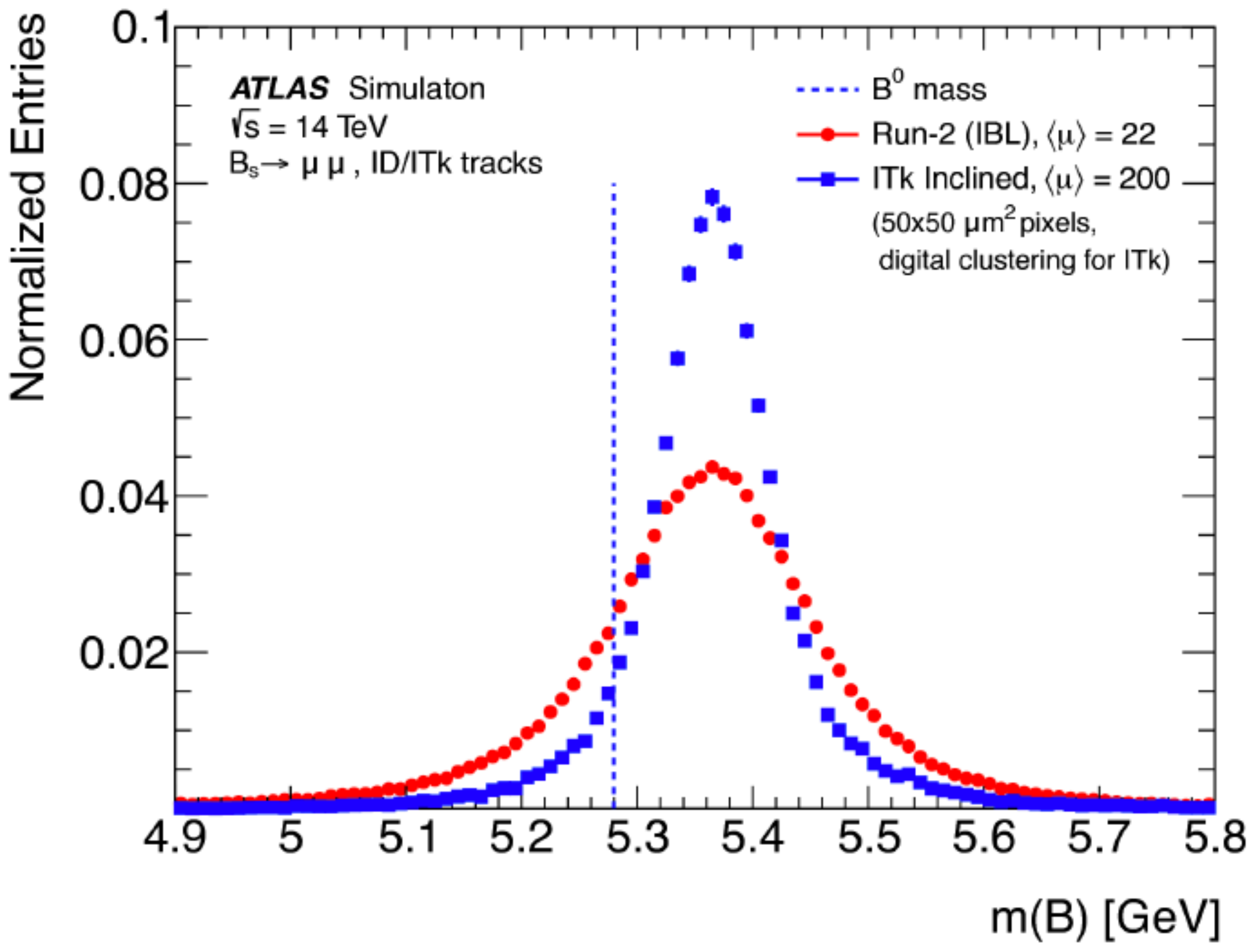
- Trackers with less material budget and more granularity
- CMS larger magnetic field (3.8 T) wrt ATLAS (2 T) gives better resolution





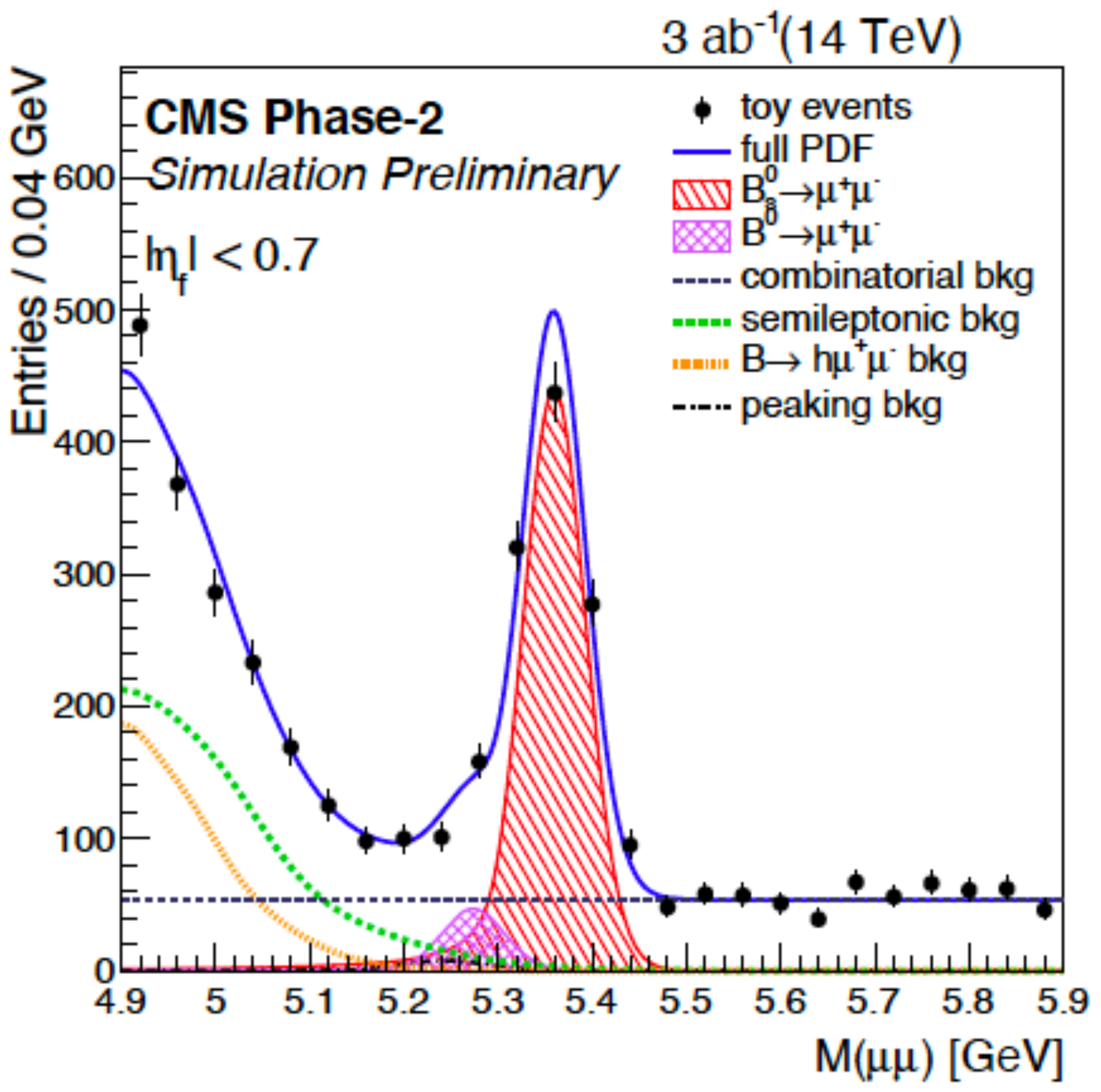
Improved Tracker

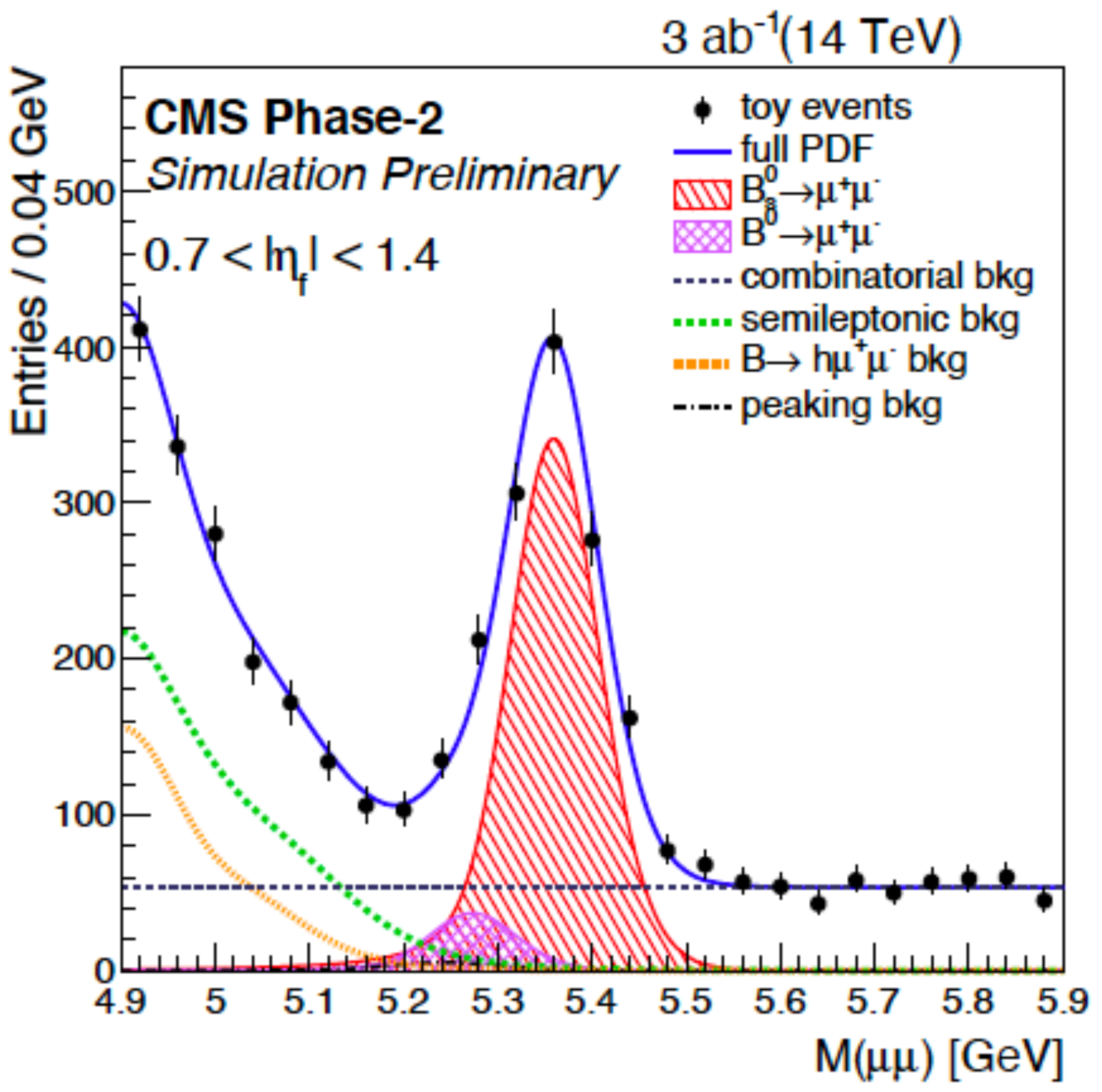
CMS PAS FTR-14-015



ATL-PHYS-PUB-2018-005

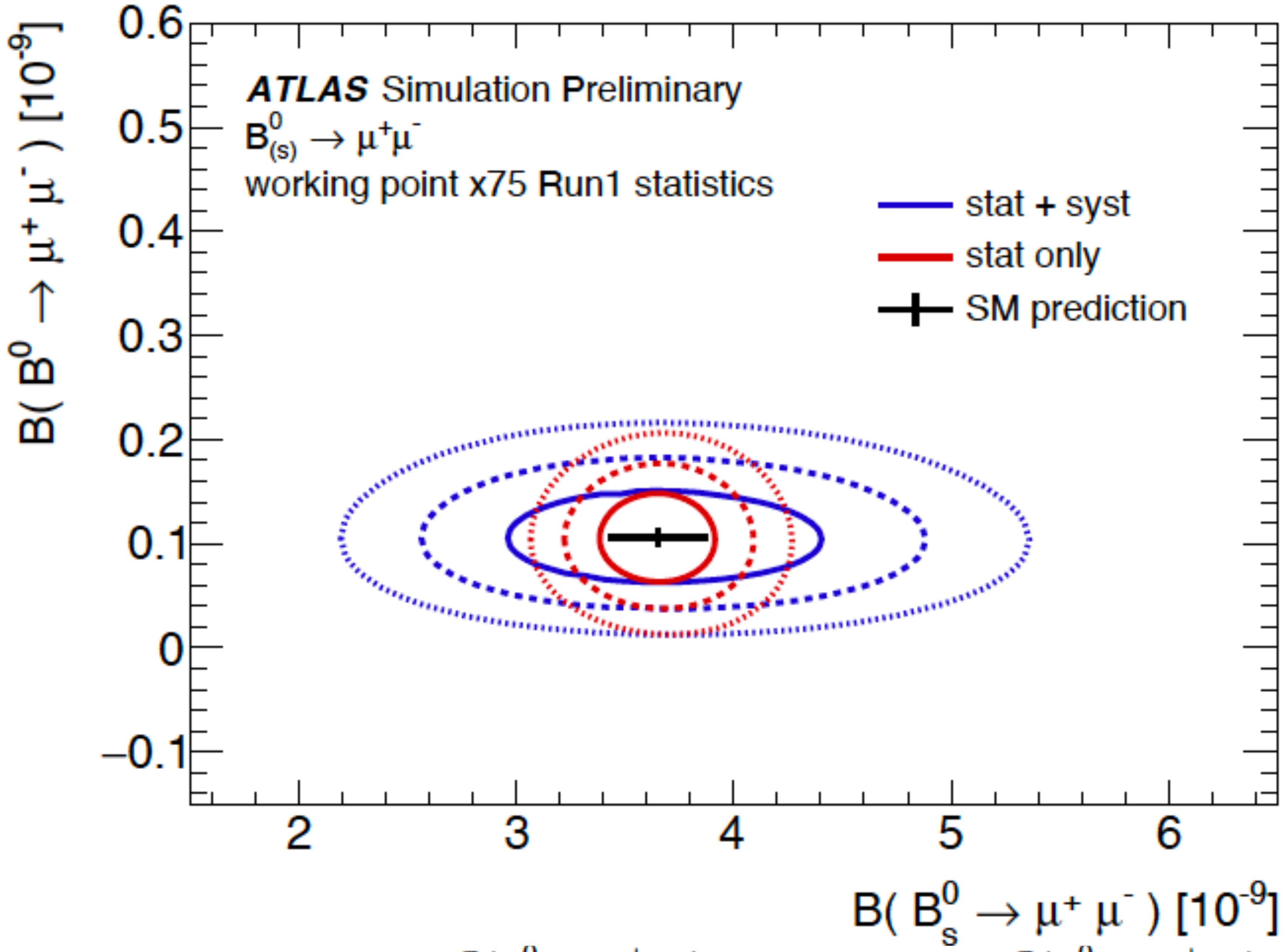
$B^0_{d,s} \to \mu^+\mu^-$ HL-LHC predictions





CMS PAS FTR-18-013

ATL-PHYS-PUB-2018-005



$\mathcal{L}$ (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
140	295.	12.	11%			0.23 ps

CMS Run2

	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$		$\mathcal{B}(B^0 \to \mu^+\mu^-)$	
	stat [10^{-10}]	stat + syst [10^{-10}]	stat [10^{-10}]	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

ATLAS 3000 fb-1 $\delta(\tau_{B_s}) \approx 0.04\ ps$ (stat)

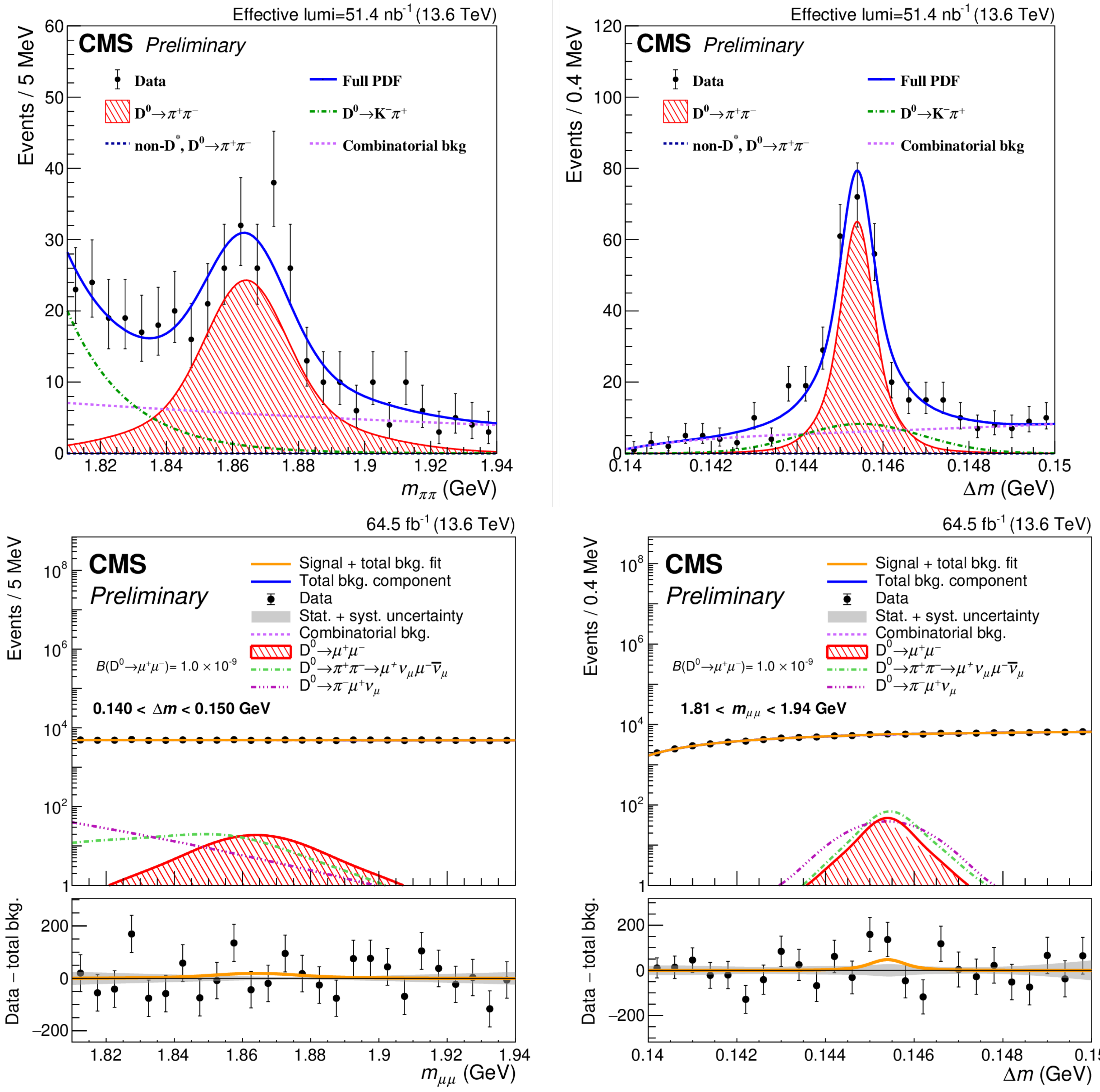
$D^0 \to \mu^+\mu^-$

- CMS measurement using $D^{*+} \to D^0\pi^+$ decays
  - Signal $D^0 \to \mu^+\mu^-$
  - Normalisation channel $D^0 \to \pi^+\pi^-$
  - Main background $B \to \mu D X \to \mu^+\mu^- X$ and combinatorial from two B semileptonic decays
  - Similar to $B \to \mu^+\mu^-$: isolation, pointing angle, vertexing

  - $BR(D^0 \to \mu^+\mu^-) < 2.6 \times 10^{-9} @ 90\,\%\,CL$ with 50 fb^{-1}
    - Best world limit

  - Extrapolation to 4 ab^{-1} simple statistical scaling
    - $BR(D^0 \to \mu^+\mu^-) < \approx 3 \times 10^{-10} @ 90\,\%\,CL$
    - It can be better thanks to better vertex resolution getting rid of the B hadron backgrounds

CMS-PAS-BPH-23-008



Conclusions

- The new ATLAS and CMS detectors will increase the detector performances at HL-LHC
  - Tenfold statistic wrt current LHC run will allow several B-Physics measurements at unprecedented levels of precision
    - CP violation in B decays will hit systematics limits and penguin contamination
      - $\phi_s \approx 3$ mrad within reach
    - $b \to s\mu^+\mu^-$ (P_5') will be limited by systematics
    - LFV $BR(\tau \to 3\mu)$ can be probed up to few 10^{-10}
    - $BR(B_d^0 \to \mu^+\mu^-)$ will be measured with a O(10%) precision
    - $BR(D^0 \to \mu^+\mu^-)$ limits ~10^{-10} within reach, competitive with LHCb
  - New analysis techniques will probably push these predictions even further
- These will let ATLAS and CMS to fiercely compete with LHCb and Belle-II on many decay channels in the search for new physics in heavy flavours decays