Rare decays: ATLAS / CMS

F. Tresoldi
on behalf on the ATLAS and CMS collaborations

HL-LHC workshop

18 June 2018

ATLAS EXPERIMENT

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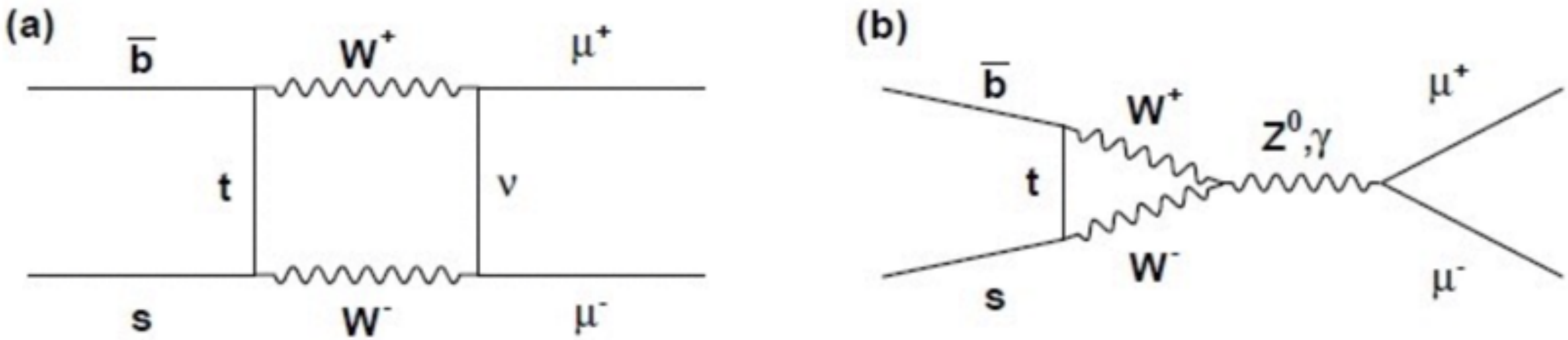
Outline

- why rare decays?
- HL-LHC studies from ATLAS and CMS
- ATLAS and CMS projections for $B_{(s)} \rightarrow \mu^+\mu^-$
- conclusions

why study rare decays?

- B-physics rare and semi-rare processes are mediated by flavour changing neutral current (FCNC)



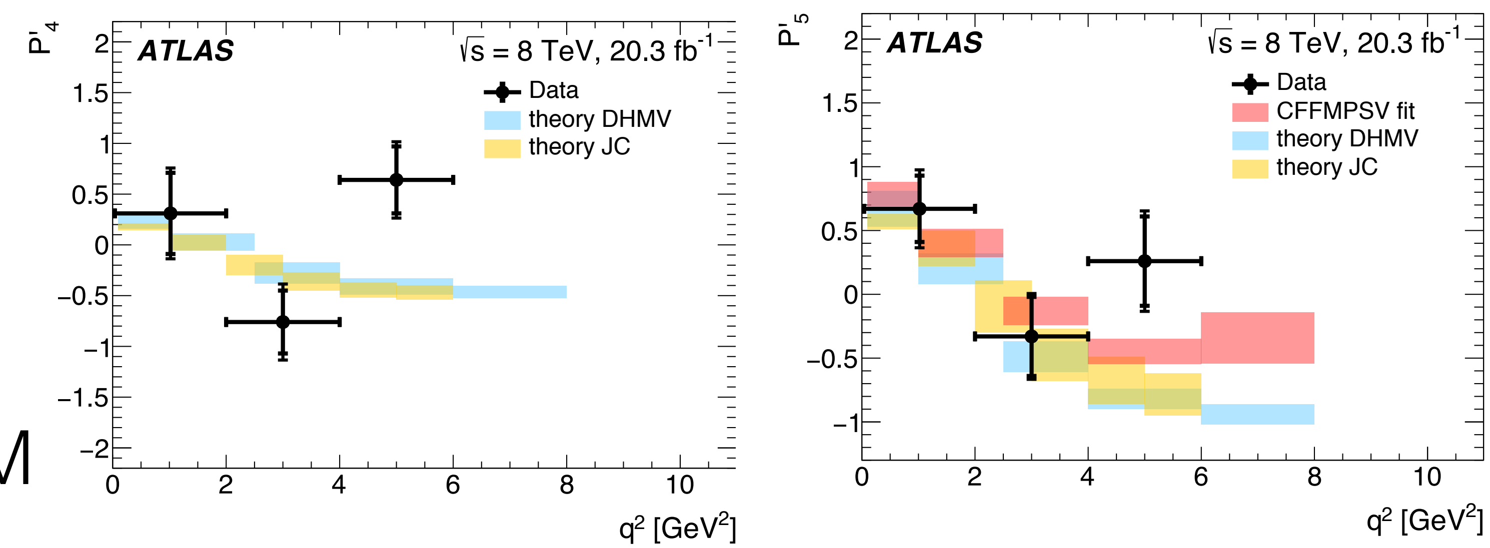
- suppressed SM amplitudes → sensitive to small effects from NP loop contributions
  - We can indirectly search for new physics at scales beyond the reach of the LHC
  - **sensitive probe for beyond standard model physics**

- HL-LHC will be a powerful test bench for B physics predictions
  - high collected luminosity → study rare processes at a sensitivity level never reached before
  - simple projection: 10^{15} $b\bar{b}$ pairs in 3000 fb^{-1} (HL-LHC)
  - possibility to cover new interesting channels —> B → τμ, B → μe, B → ττ

$B \to K^* \mu^+\mu^-$ from ATLAS and CMS

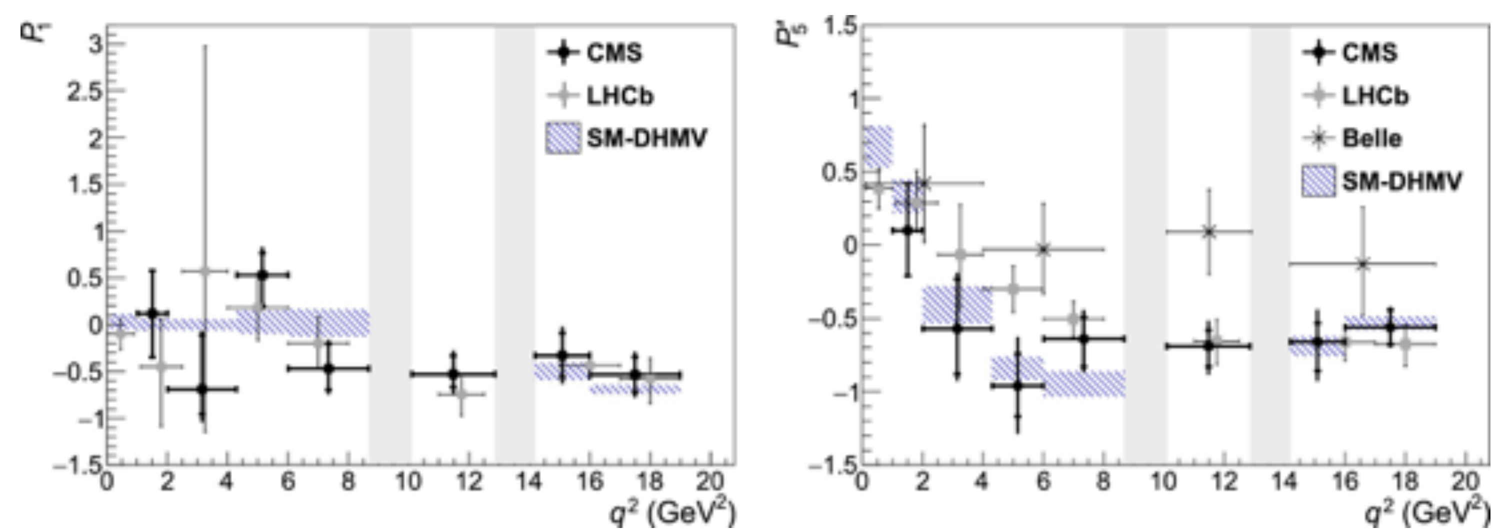
- new physics entering the loop can be detected by looking at the angular distributions of the decay
- Run 1 ATLAS and CMS analysis public

[CERN-EP-2017-161]



- ATLAS —> deviation in P_4' and P_5'
- CMS —> in agreements with SM
- LHCb —> deviation in P_5'

- ATLAS and CMS show great potential in this hot topic



[Phys.Lett. B781 (2018) 517-541]

- $B \to K^* \mu^+\mu^-$ —> expected HL-LHC studies from ATLAS and CMS

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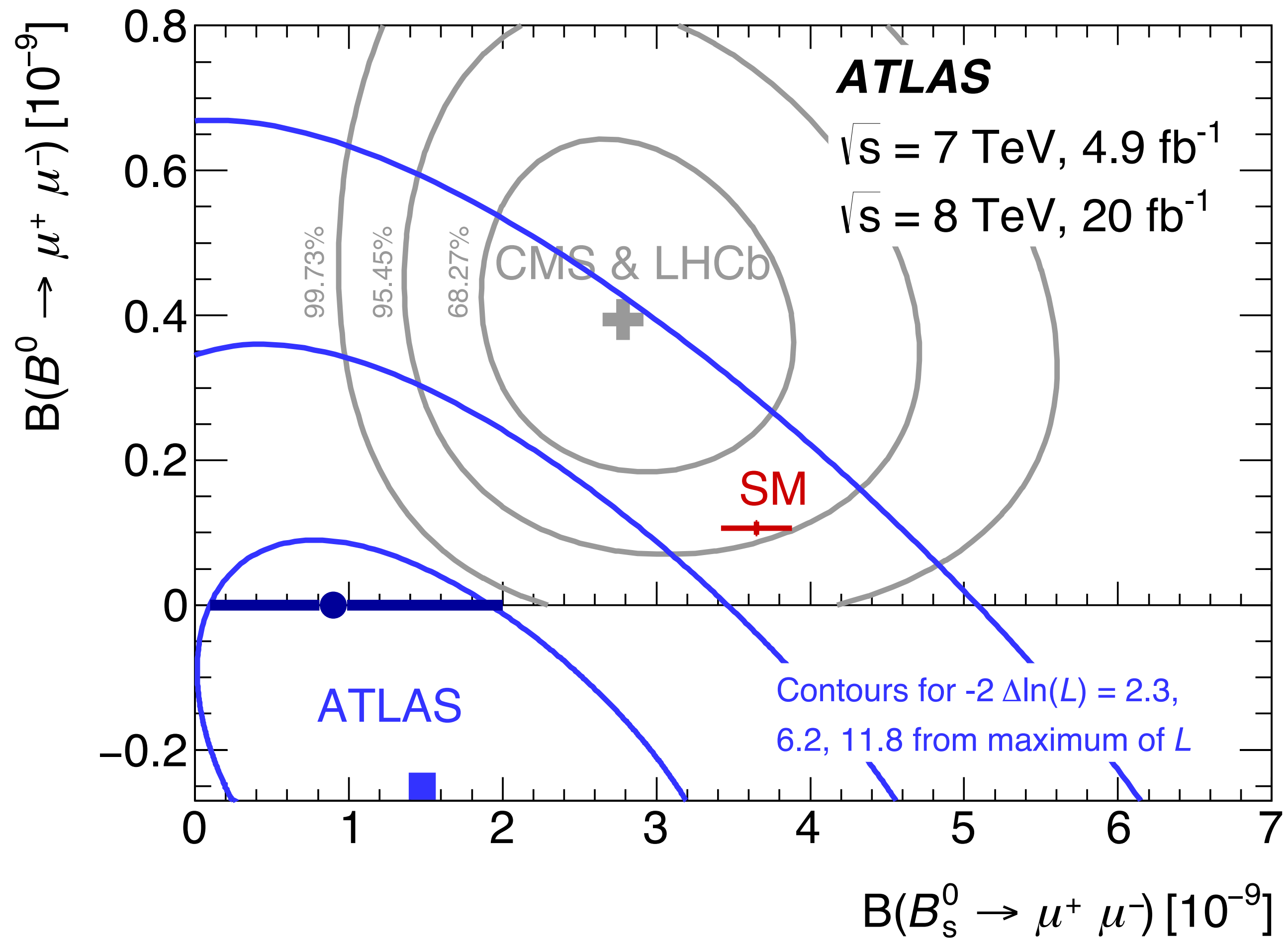
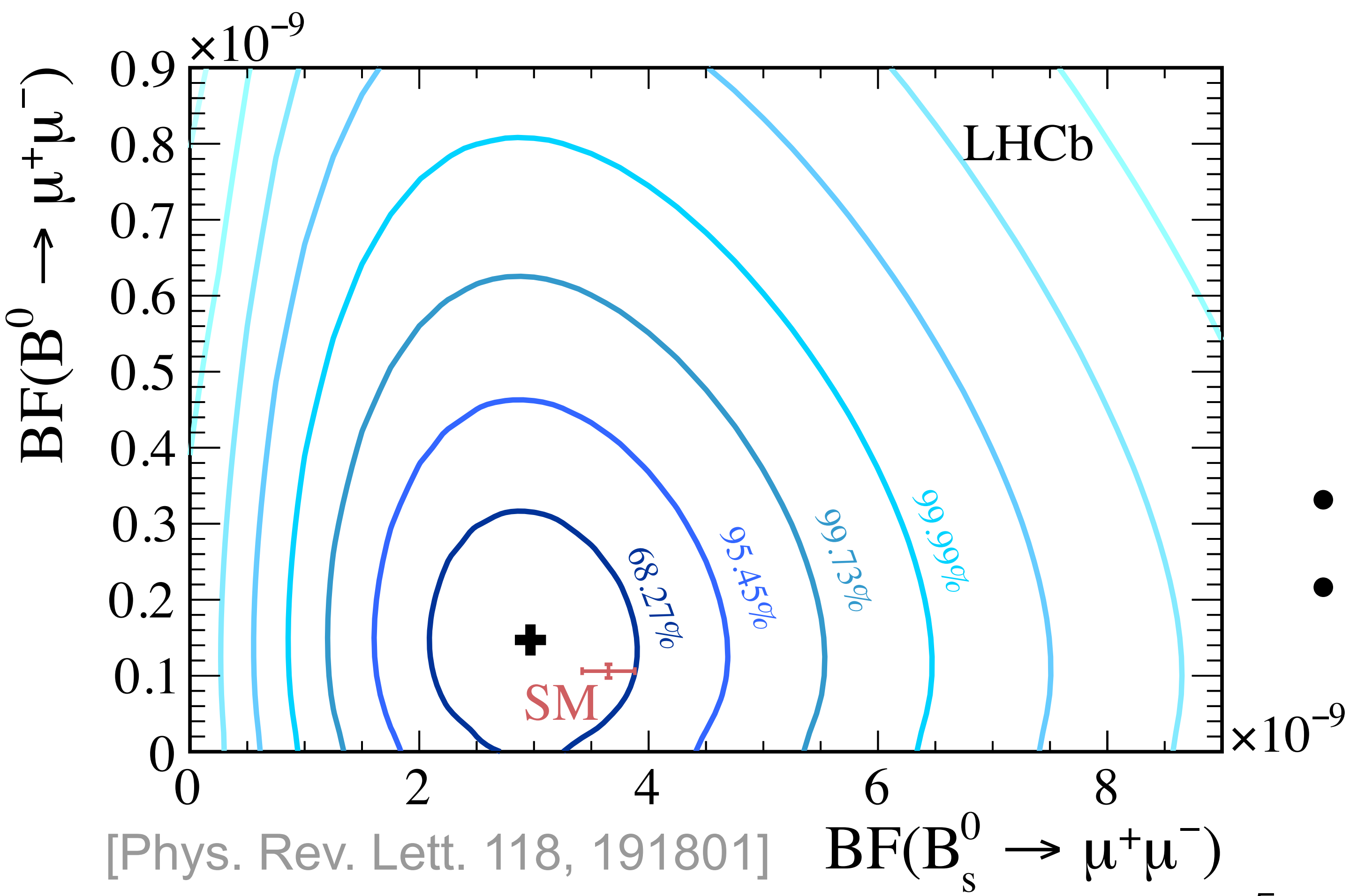
$B_{(s)} \to \mu^+\mu^-$ from ATLAS and CMS

- $B_{(s)} \to \mu^+\mu^-$:
  - studies published from both ATLAS and CMS
  - use these processes as benchmark for flavour physics at HL-LHC
  - additional studies on effective lifetime estimate from CMS ongoing

[Eur. Phys. J. C76 (2016) 513]





[Phys. Rev. Lett. 118, 191801]

- LHCb studies also available
- see Christoph's talk

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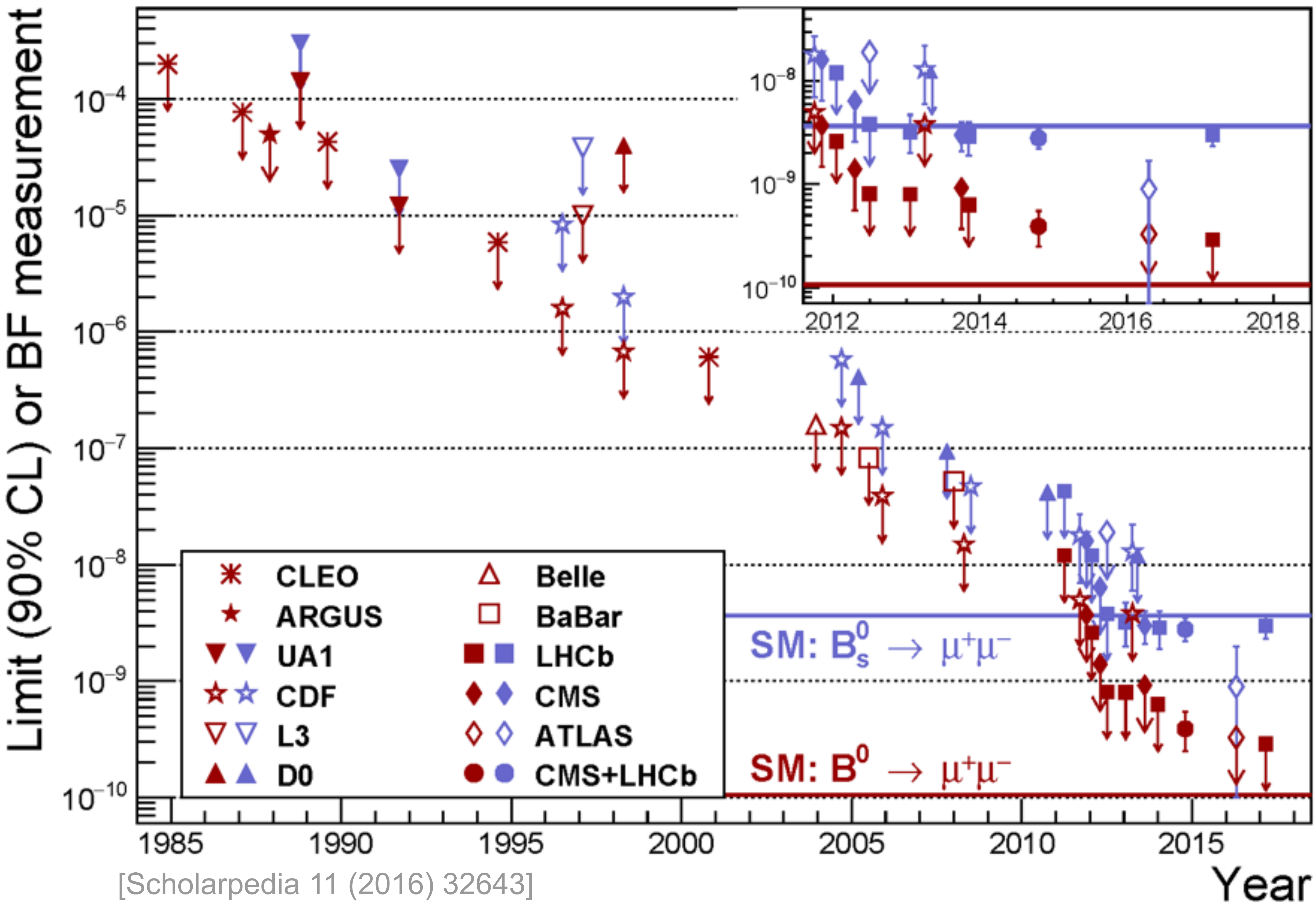
$B_{(s)} \to \mu^+\mu^-$ state of the art



[Scholarpedia 11 (2016) 32643]

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$B_{(s)} \rightarrow \mu^+\mu^-$ projections to Run 2/3 and HL-LHC

- similar strategy for ATLAS and CMS
  - studies based on latest published result —> Run1 analyses
  - do not consider improvements in analysis strategy —> conservative approach
  - maintain same PDFs and S/B ratio
    - scale yields with available statistics
    - modify PDFs parameters if needed

- common choices:
  - production X-section and signal BRs as predicted by the SM

  - total collected luminosity:

Run 2:
ATLAS: 130 fb^{-1}
CMS: 100 f fb^{-1}

Run 3:
CMS: 300 fb^{-1}

HL-LHC:
3 ab^{-1} (3000 fb^{-1})

- trigger strategy
  - crucial in HL-LHC environment
  - different strategies from ATLAS and CMS —> next slides

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ATLAS $B_{(s)} \to \mu^+\mu^-$ studies

- assumptions:
  - **$\sigma_{b\bar{b}}$ and BR based on SM predictions**
  - **collected luminosity** —> Run2 130 fb^{-1}, HL-LHC 3 ab^{-1}
  - **di-muon trigger efficiencies** —> various scenarios

- Run2
  - admixtures of di-muon triggers with different thresholds
    - 2mu6, mu6_mu4, their topological variations

- HL-LHC
  - 3 scenarios studied:
    - 2mu6 —> high-yield
    - mu10_mu6 —> intermediate
    - 2mu10 —> conservative

ATLAS $B_{(s)} \to \mu^+\mu^-$ studies

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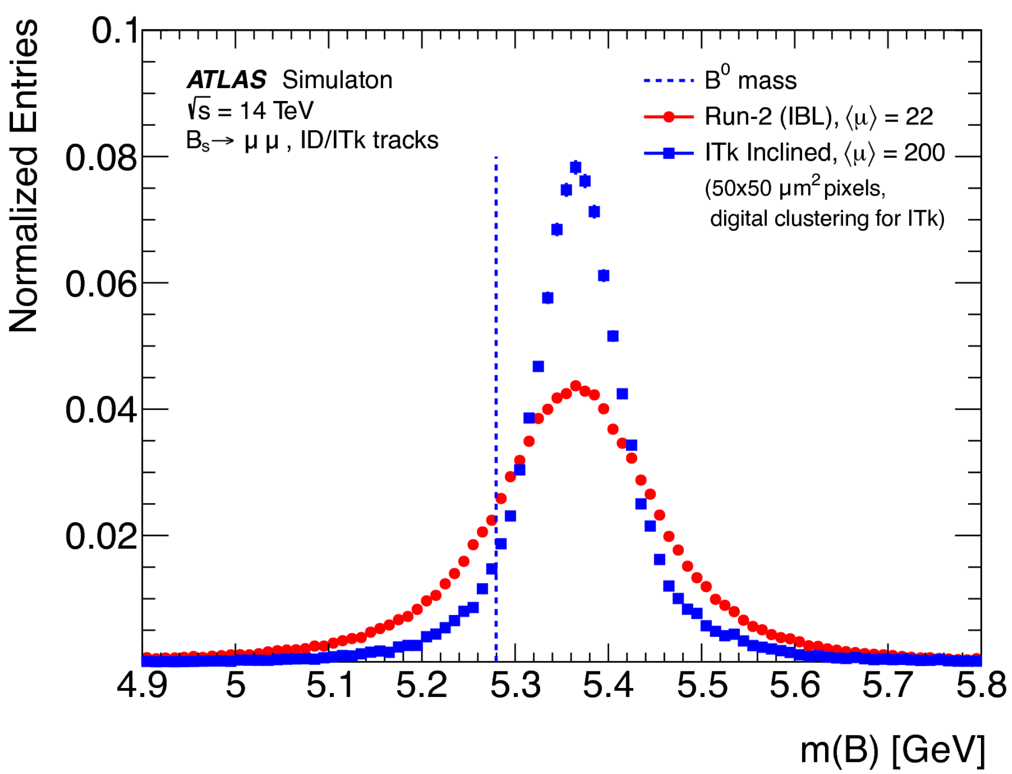
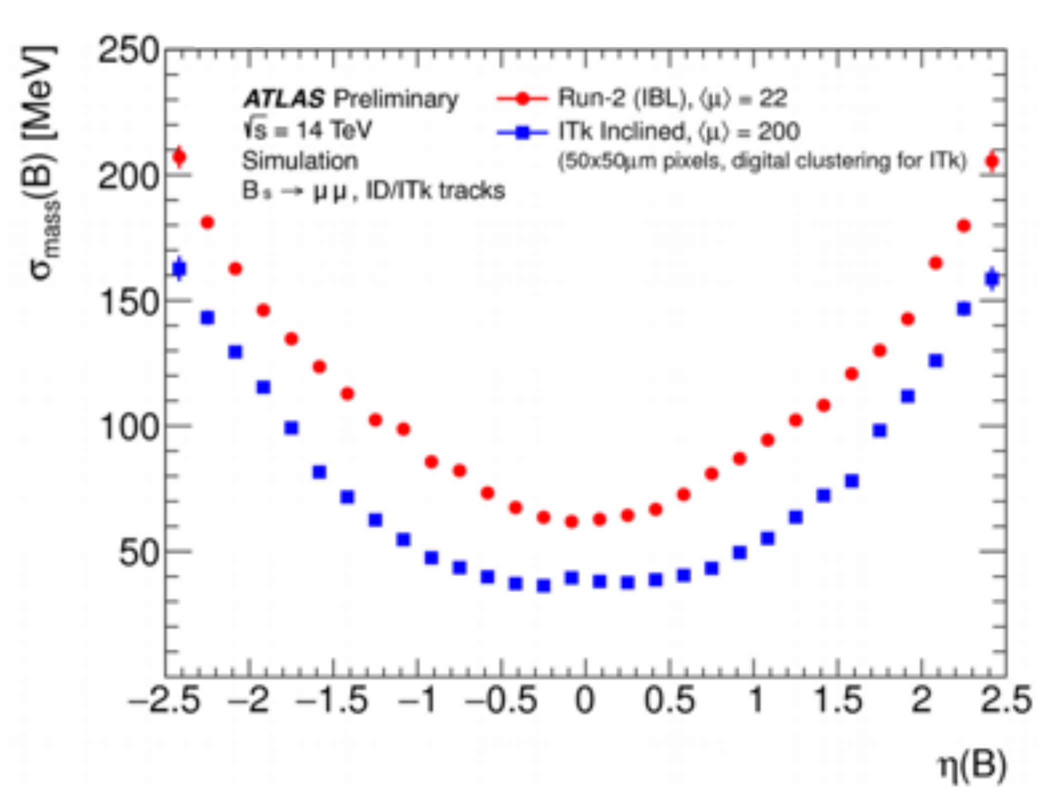
  - **collected luminosity** —> Run2 130 fb^{-1}, HL-LHC 3 ab^{-1}
  - **di-muon trigger efficiencies** —> various scenarios
  - **dimuon mass resolution** —> improvement in phase 2





improve bkg rejection and B_s-B_d separation

[CERN-LHCC-2017-021, ATLAS-TDR-030]

ATLAS $B_{(s)} \to \mu^+\mu^-$ studies

- assumptions:
  - **$\sigma_{b\bar{b}}$ and BR based on SM predictions**
  - **collected luminosity** —> Run2 130 fb^{-1}, HL-LHC 3 ab^{-1}
  - **di-muon trigger efficiencies** —> various scenarios
  - **dimuon mass resolution** —> improvement in phase 2
  - **systematics** —> conservative approach

- external systematics:
  - e.g. f_s/f_d, BR($B^\pm \to J/\psi K^\pm$)
  - same as Run1
- internal systematics:
  - e.g. data-MC discrepancies, triggering modelling, background extrapolation, …
  - scale with statistics

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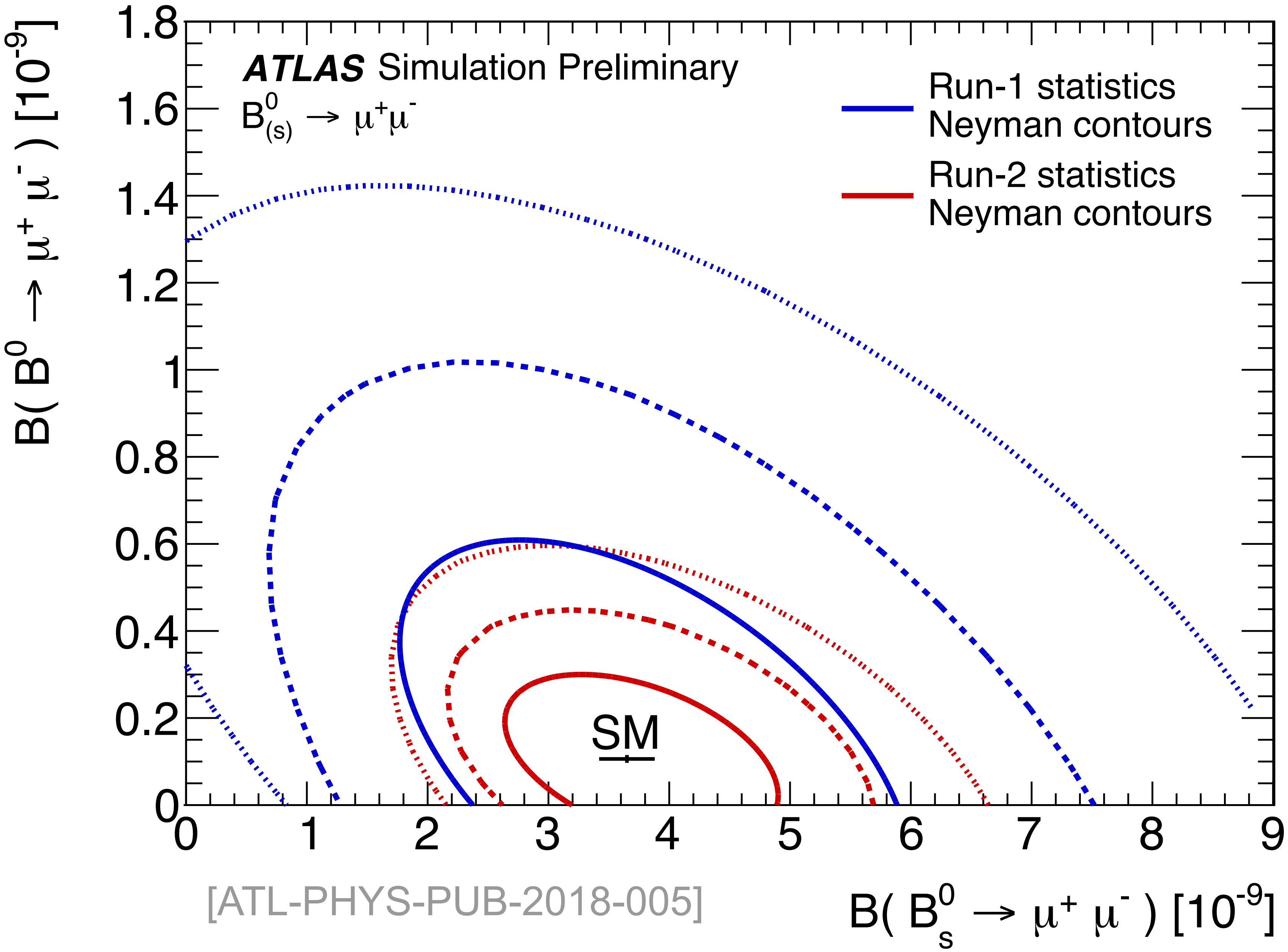
ATLAS Run 2

- test of extrapolation procedure with Full Run 2 statistics prediction
- projected Run2 statistics: ~x7 Run1 statistics



[ATL-PHYS-PUB-2018-005]

- stat+syst contours based on 2D Neyman belt construction
- depending on statistical regime:
  - "low statistics": full-fledged Neyman belt approach
  - asymptotically: likelihood contours
- Neyman contours close to likelihood ones already for expected run 2 statistics —> approximate HL extrapolations with likelihood

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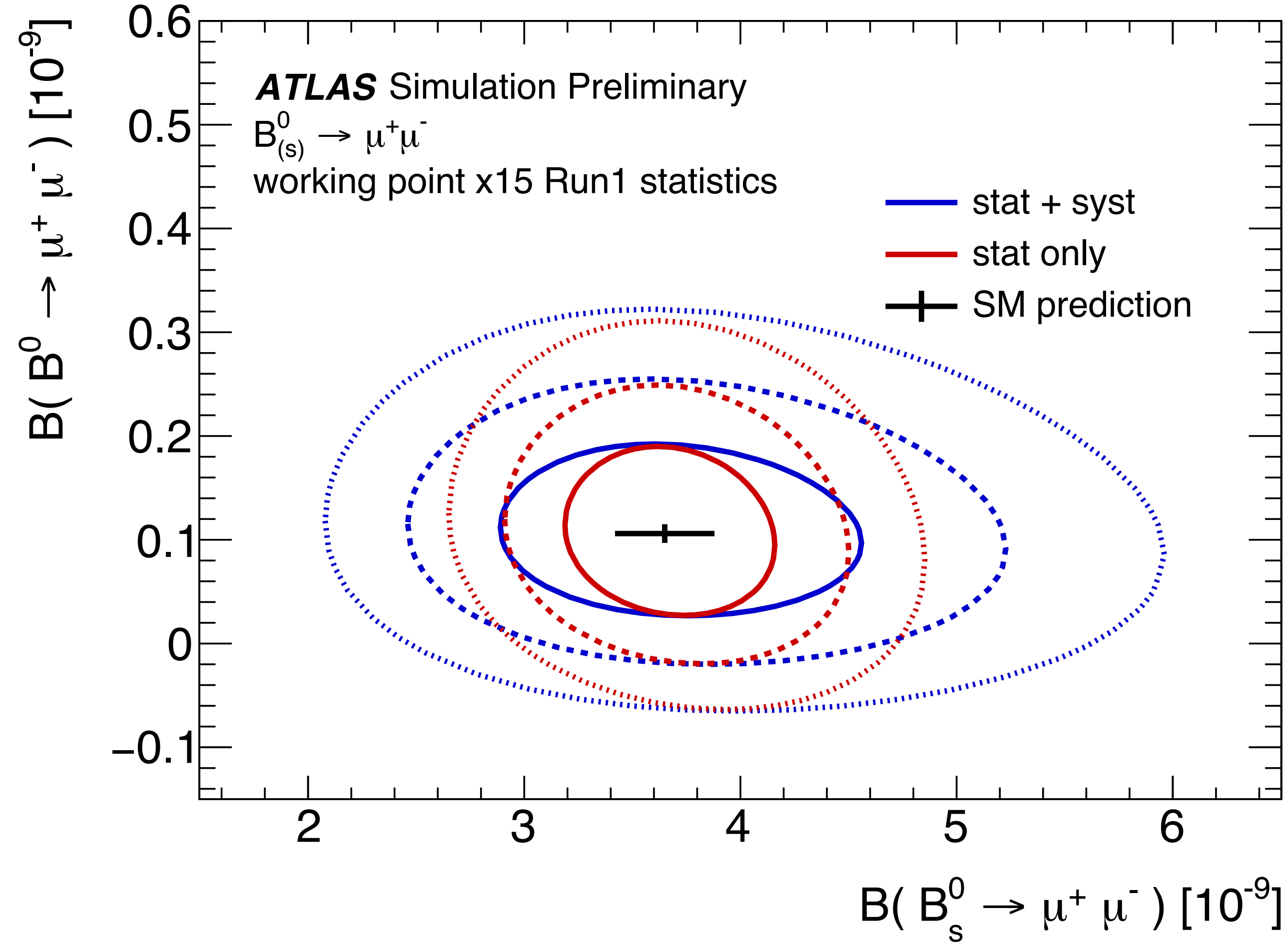
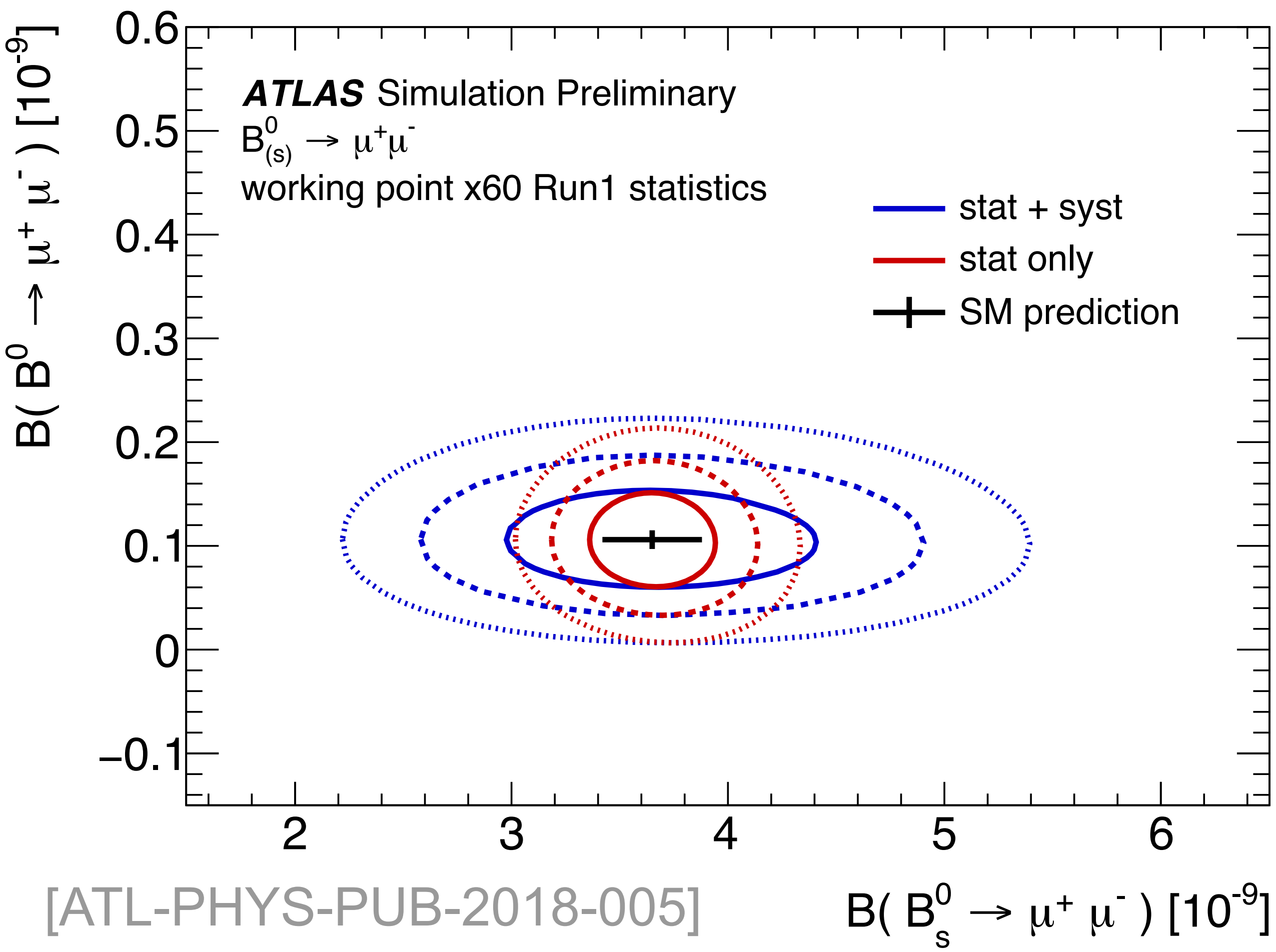
ATLAS HL-LHC

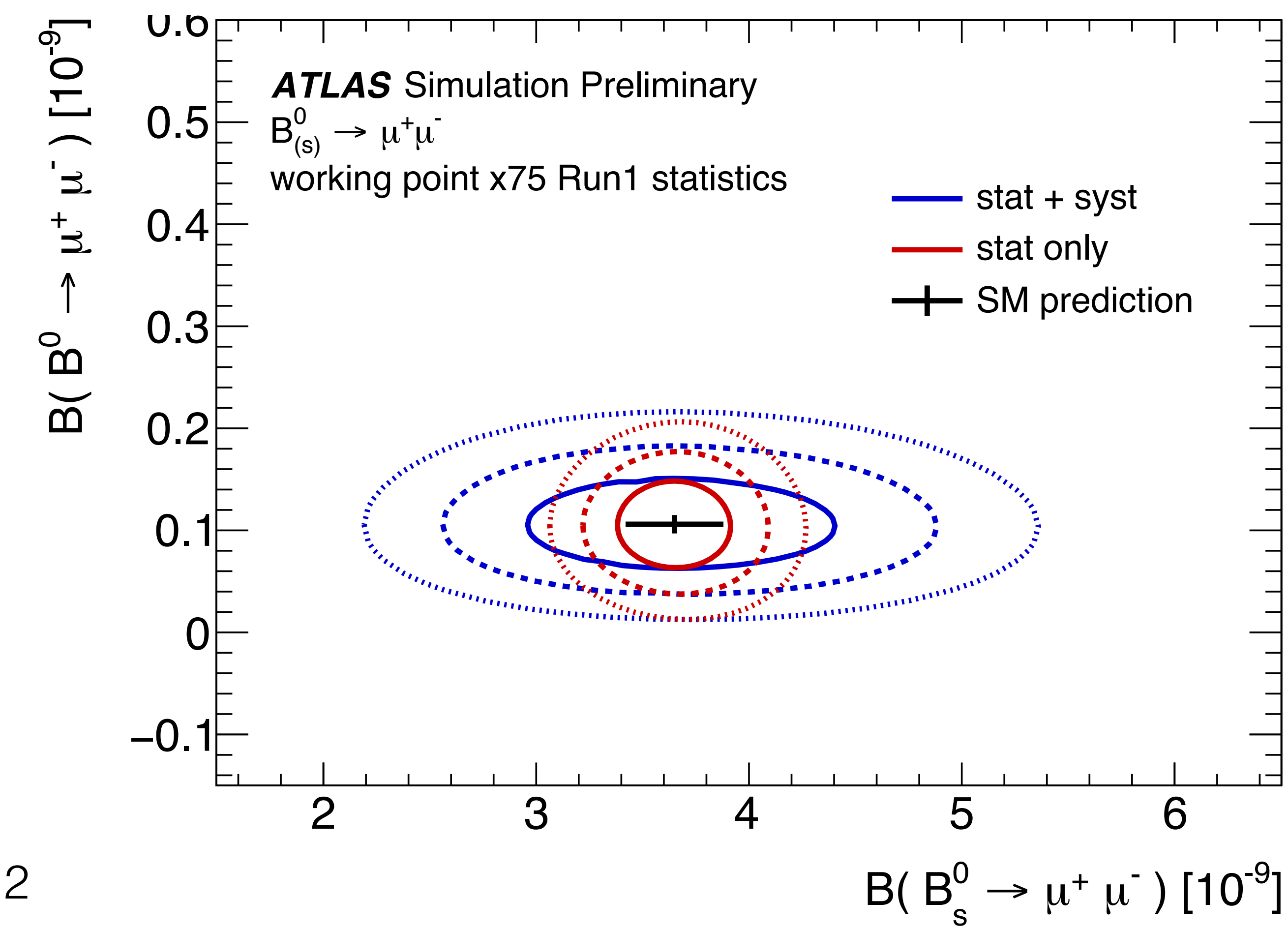
- 3 trigger scenarios:
  - 2mu10
    - conservative: ~x15 Run1 stat
  - mu6_mu10
    - intermediate: ~x60 Run1 stat
  - 2mu6
    - high yield: ~x75 Run1 stat

- profiled likelihood contours
  - **red**: stat only
  - **blue**: stat + syst

- dominant systematic on BR(Bs): f_s/f_d



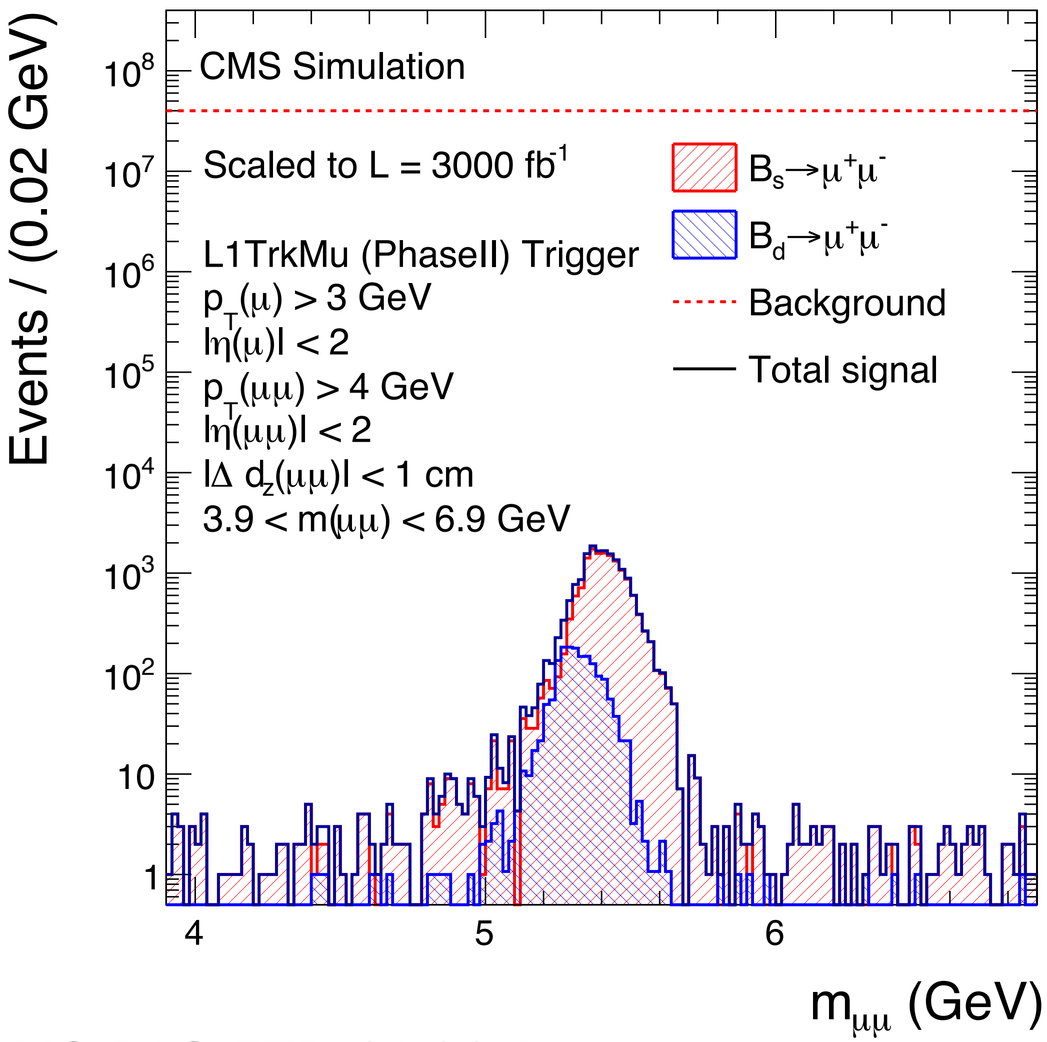




[ATL-PHYS-PUB-2018-005]

CMS $B_{(s)} \to \mu^+\mu^-$ studies

- assumptions:
  - **$\sigma_{b\bar{b}}$ and BR based on SM predictions**
  - **collected luminosity** —> Run2 100 fb^{-1}, Run3 300 fb^{-1}, HL-LHC 3 ab^{-1}
  - **di-muon trigger** —> L1 track trigger for Phase 2



- Phase I: standard di-muon trigger
- Phase 2: L1 track trigger
  - invariant mass resolution at L1: 70 MeV
  - preliminary rate estimates: few hundred Hz at L1

[CMS-PAS-FTR-14-015]

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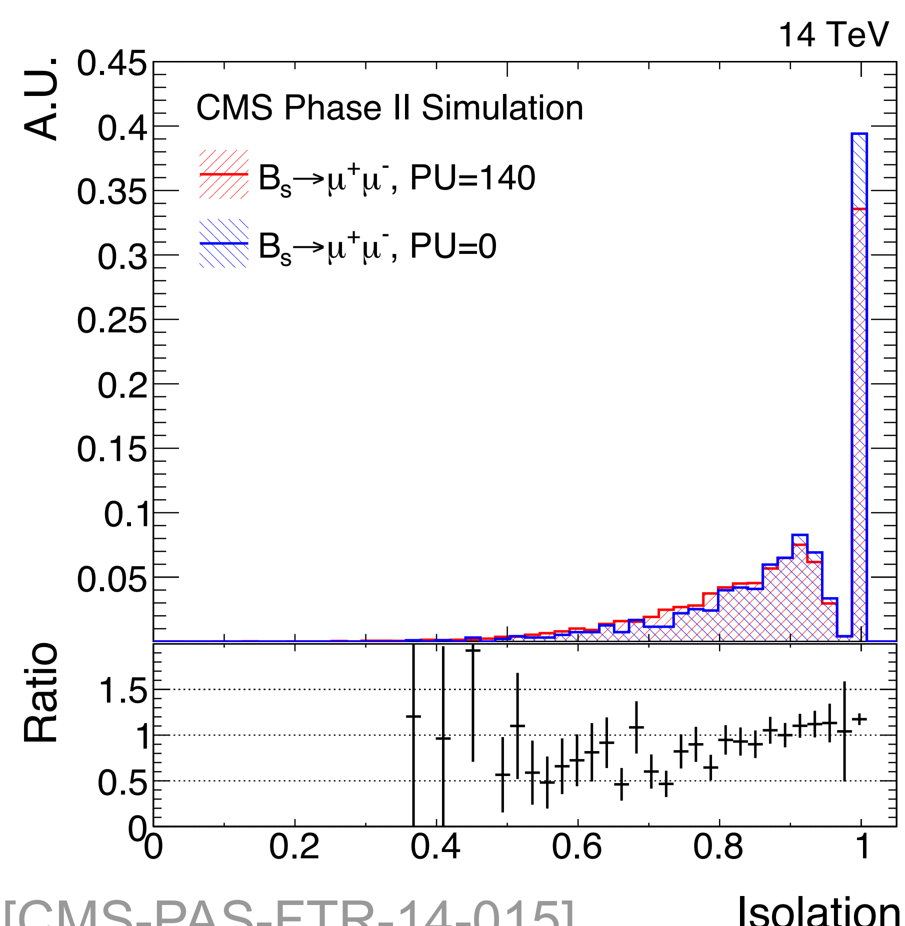
CMS $B_{(s)} \rightarrow \mu^+\mu^-$ studies

- assumptions:
  - **$\sigma_{b\bar{b}}$ and BR based on SM predictions**
  - **collected luminosity** —> Run2 100 fb^{-1}, Run3 300 fb^{-1}, HL-LHC 3 ab^{-1}
  - **di-muon trigger** —> L1 track trigger for Phase 2
  - **pile-up effects** —> impact on discriminating variables



[CMS-PAS-FTR-14-015]

- due to high HL-LHC luminosity
  - efficiency loss in discriminating variables due to pile-up
  - tighter μ cuts to maintain fake rate as Run1
- overall efficiency loss: 30%
  - conservative estimation

CMS $B_{(s)} \rightarrow \mu^+\mu^-$ studies

- assumptions:
  - **$\sigma_{b\bar{b}}$ and BR based on SM predictions**
  - **collected luminosity** —> Run2 100 fb^{-1}, Run3 300 fb^{-1}, HL-LHC 3 ab^{-1}
  - **di-muon trigger** —> L1 track trigger for Phase 2
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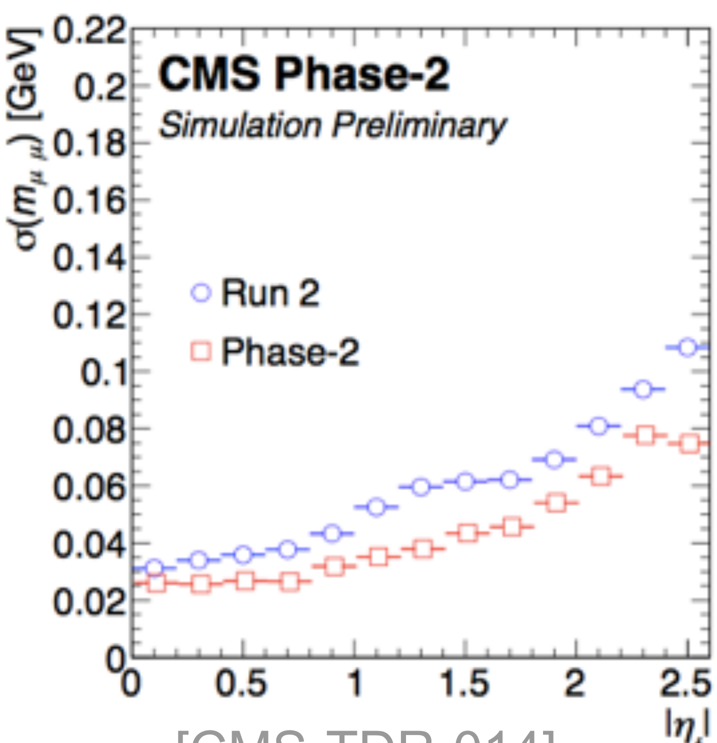
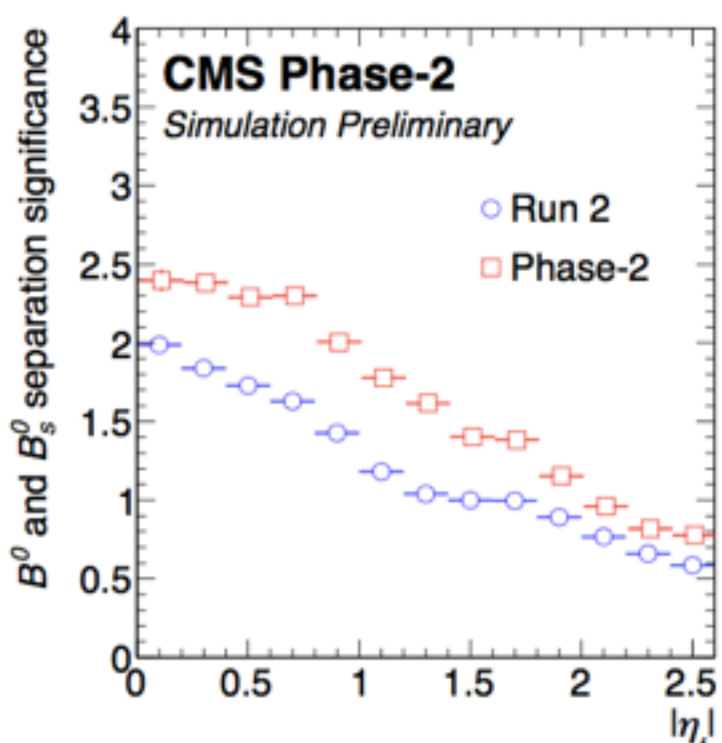
  - **dimuon mass resolution** —> improvement in phase 2





- improve bkg rejection and B_s-B_d separation

[CMS-TDR-014]

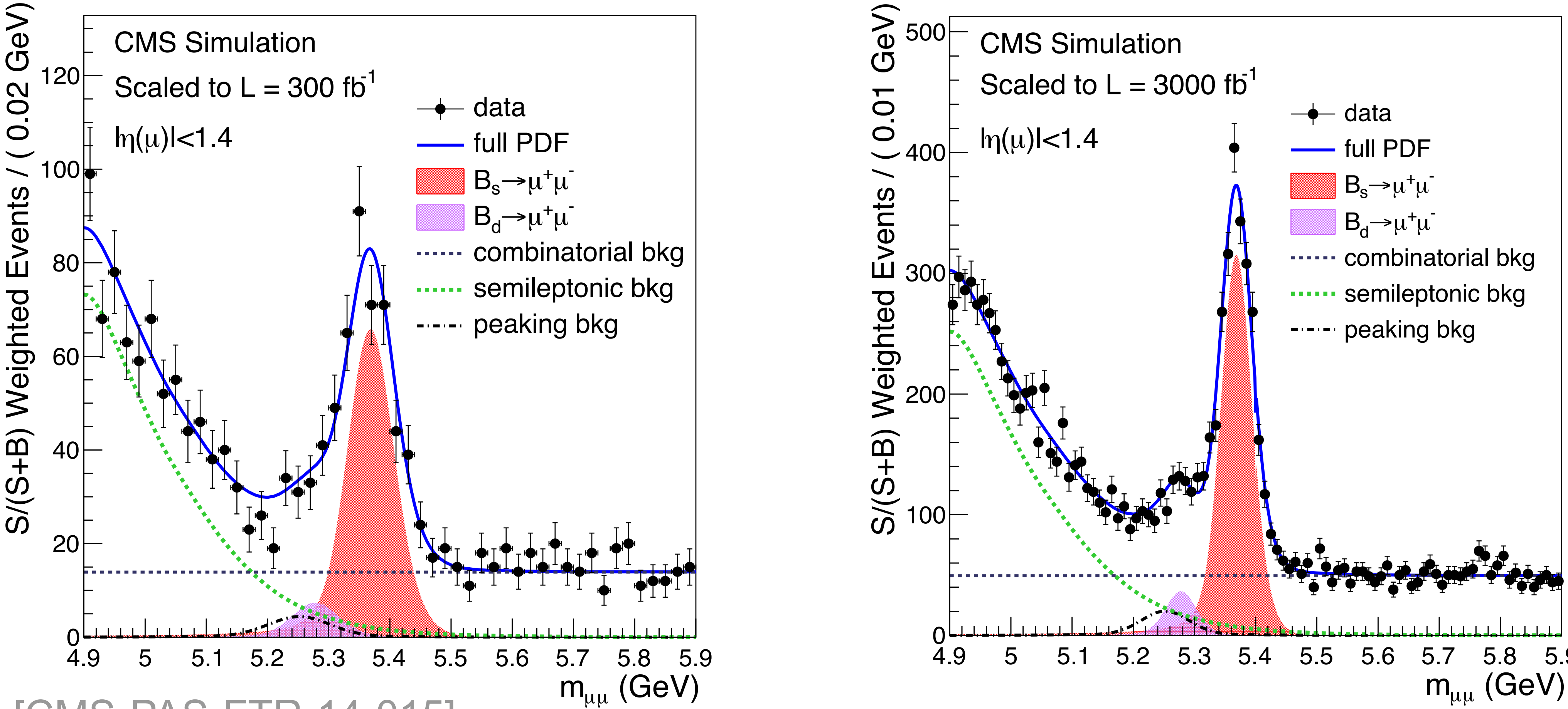
CMS $B_{(s)} \to \mu^+\mu^-$ studies

- assumptions:
  - **$\sigma_{b\bar{b}}$ and BR based on SM predictions**
  - **collected luminosity** —> Run2 100 fb^{-1}, Run3 300 fb^{-1}, HL-LHC 3 ab^{-1}
  - **di-muon trigger** —> L1 track trigger for Phase 2
  - **pile-up effects** —> impact on discriminating variables
  - **dimuon mass resolution** —> improvement in phase 2
  - **systematics** —> scale with statistics

	Run I	Phase I	Phase II
f_s/f_d	9%	5%	5%
norm yield	5%	5%	3%
peaking bkg	60%	20%	10%
semileptonic decays	50%	25%	20%

[CMS-PAS-FTR-14-015]

CMS Run 3 and HL-LHC



[CMS-PAS-FTR-14-015]

$\mathscr{L}$ (fb^{-1})	$\delta BR(B_s)$	$\delta BR(B_d)$	$BR(B_d)$ sign.	$\delta[BR(B_s) / BR(B_d)]$
100	14%	63%	0.6-2.5σ	66%
300	12%	41%	1.5-3.5σ	43%
300 (barrel)	13%	48%	1.2-3.3σ	50%
3000 (barrel)	11%	18%	5.6-8.0σ	21%

uncertainty on BRs

$BR(B_d)$ statistical significance

uncertainty on BRs ratio

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ATLAS - CMS comparison at HL-LHC

- compare ATLAS and CMS expected uncertainties on signal BRs
  - ATLAS uncertainties from: ATL-PHYS-PUB-2018-005
  - CMS uncertainties derived from: CMS-PAS-FTR-14-015
- including systematics

	σ(BR(B_s)) [10^{-9}]	σ(BR(B_d)) [10^{-9}]
CMS	0.40	0.019
ATLAS high-yield	0.46	0.028
ATLAS intermediate	0.47	0.031
ATLAS conservative	0.55	0.054

SM predictions: BR(B_s) = (3.65 ± 0.23) x 10^{-9}, BR(B_d) = (1.06 ± 0.09) x 10^{-10}

- on B_s CMS slightly better than ATLAS intermediate and high-yield
  - ATLAS systematics conservatively over-estimated
- on B_d CMS shows smaller uncertainty than ATLAS
- both experiments have great potential
  - possibility to measure both BRs at 5 sigma

conclusions

- HL-LHC will be a powerful test bench for B physics predictions

- ongoing HL-LHC studies on several processes
  - $B \to K^* \mu^+\mu^-$ (P5' parameter)
- $B_{(s)} \to \mu^+\mu^-$ studies ready

- projections to Run2/3 and HL-LHC performed by ATLAS and CMS
  - rather conservative assumptions
  - increment in luminosity and B production X-section
  - major detector improvements considered

- both ATLAS and CMS show great potential
  - possibility to measure $BR(B_{(s)} \to \mu^+\mu^-)$ at 5 sigma

BACKUP

ATLAS - CMS comparison at HL-LHC

- compare ATLAS and CMS expected uncertainties on signal BRs
  - ATLAS uncertainties from: ATL-PHYS-PUB-2018-005
  - CMS uncertainties calculated from: CMS-PAS-FTR-14-015

	σ BR(B_s) [10^{-9}]		σ BR(B_d) [10^{-9}]	
	stat+sys	stat only	stat+sys	stat only
CMS	0.40		0.019	
ATLAS high-yield	0.46	0.18	0.028	0.027
ATLAS intermediate	0.47	0.19	0.031	0.030
ATLAS conservative	0.55	0.32	0.054	0.053

SM predictions: BR(B_s) = $(3.65 \pm 0.23) \times 10^{-9}$, BR($B_d$) = $(1.06 \pm 0.09) \times 10^{-10}$

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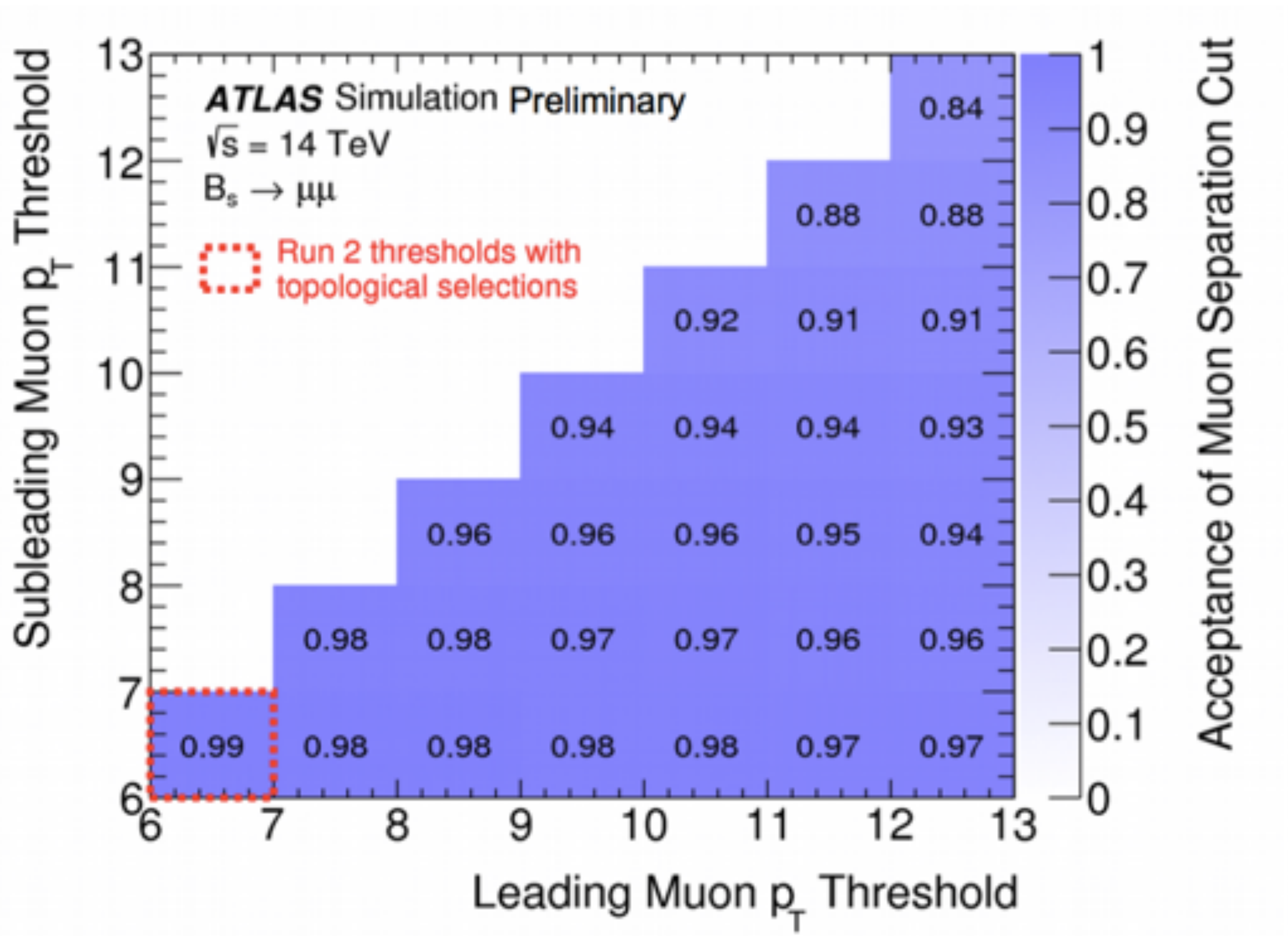
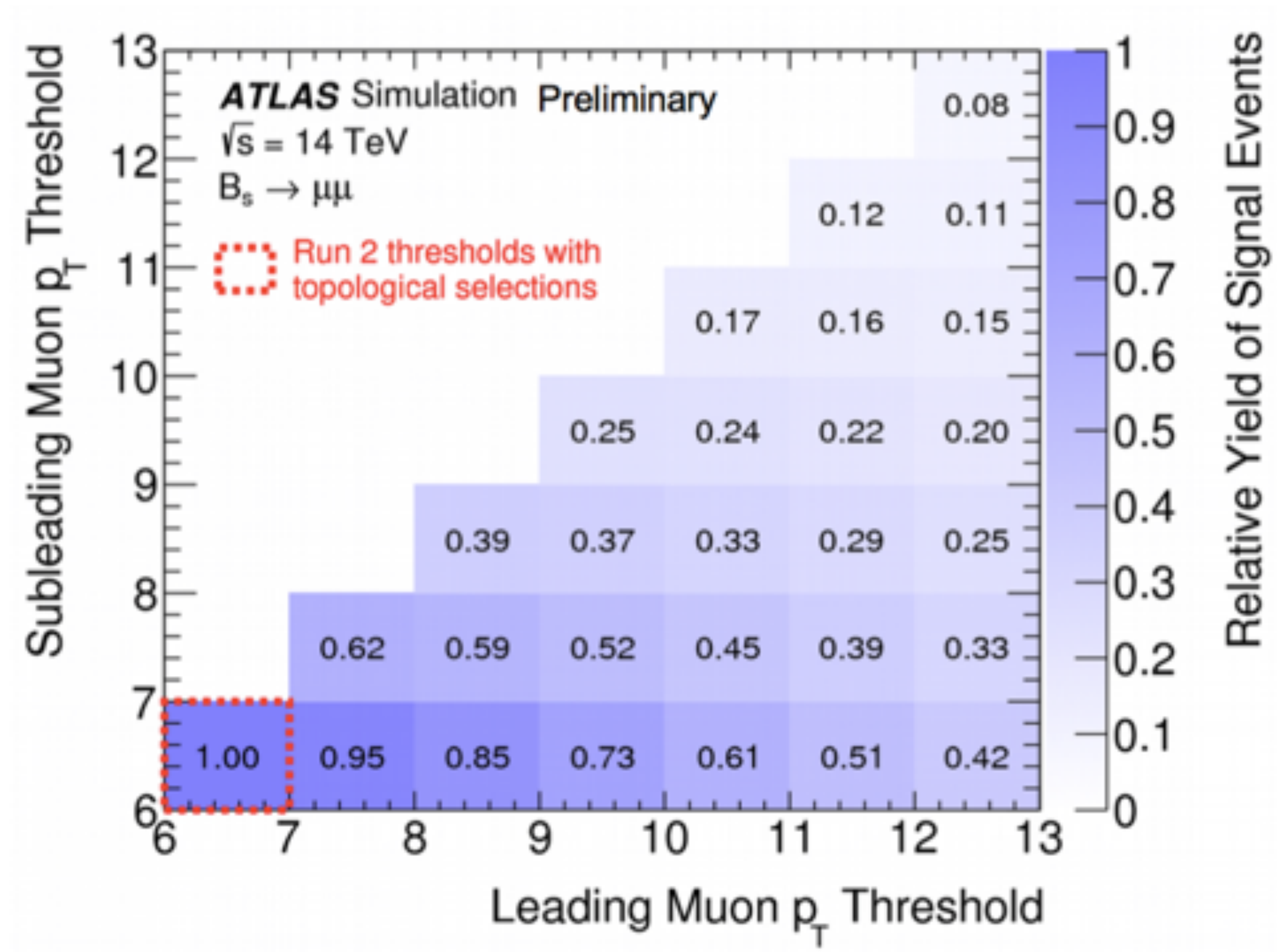
ATLAS di-muon trigger yields

- Run 1⁄2 baseline offline cuts applied

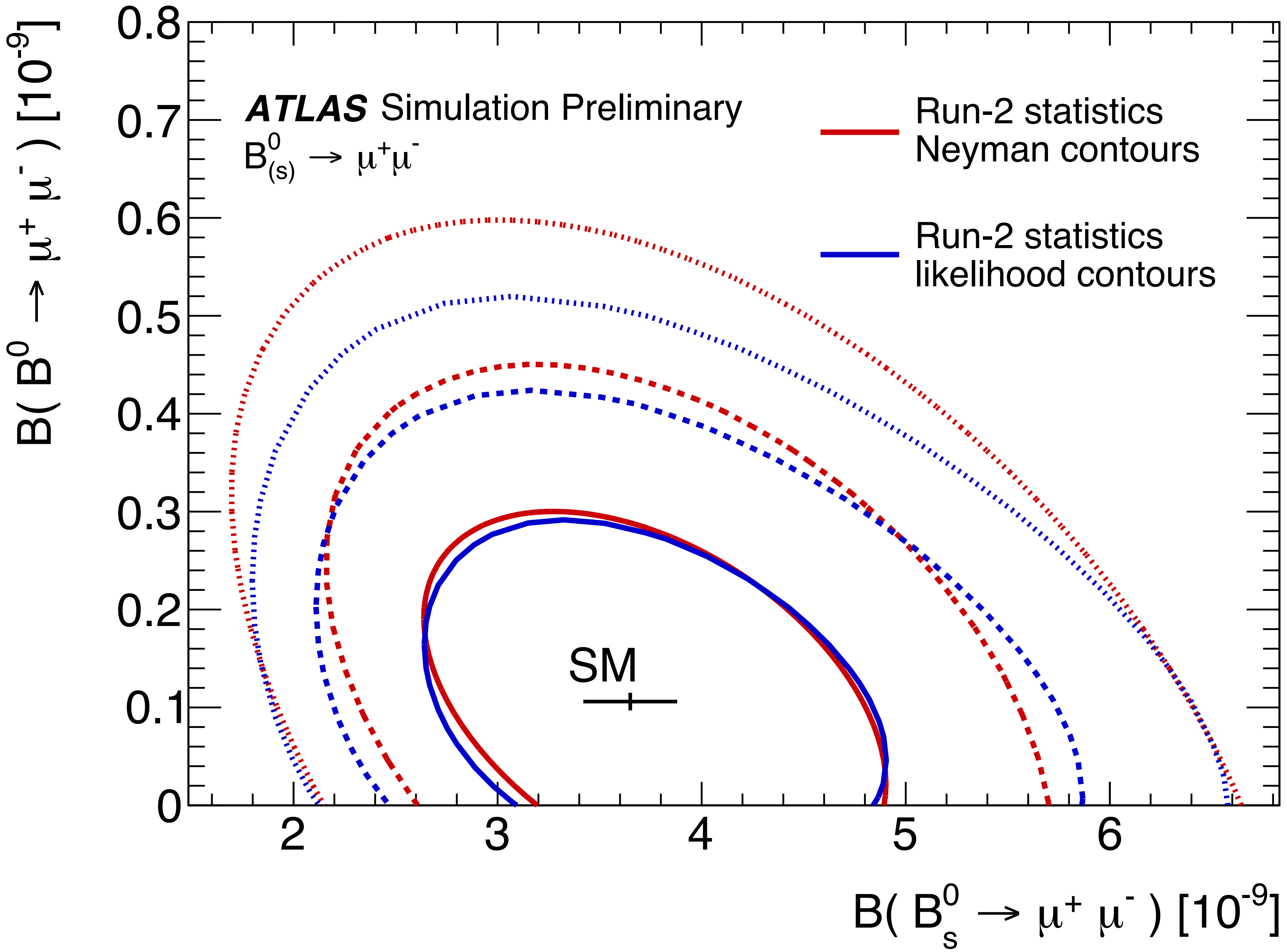




- separation of muons by either $|\Delta\eta(\mu^+,\mu^-)| > 0.2$ rad or $|\Delta\phi(\mu^+,\mu^-)| > 0.2$ rad (typical L1 muon trigger granularity)
- normalized to $pT(\mu1) > 6$ GeV & $pT(\mu2) > 6$ GeV
- work ongoing to improve trigger acceptance for near-by muons

- normalized to $pT(\mu1) > 6$ GeV & $pT(\mu2) > 6$ GeV (lowest unprescaled di-μ trigger in Run 2)

ATLAS Run 2 projection



Comparison of the 68.3% (solid), 95.5% (dashed) and 99.7% (dotted) stat.+syst. confidence regions for the extrapolated Run 2 statistics. Red contours are obtained exploiting the 2D Neyman belt construction based on pseudo-MC experiments, while blue contours are drawn at constant Δ logL in the gaussian maximum approximation. The Run 2 pseudo-MCs reproduce the expected signal mass resolution and have been scaled with respect to their Run 1 counterpart according to the triggers available in Run 2, the different integrated luminosity and the different B production cross section. The black point shows the SM theoretical prediction and its uncertainty