Rare and semileptonic decays of b-baryons and B_c meson

Flavor Physics with b-Baryons and B_c Mesons
Opportunities for Discoveries
Mainz 26-29 May 2026

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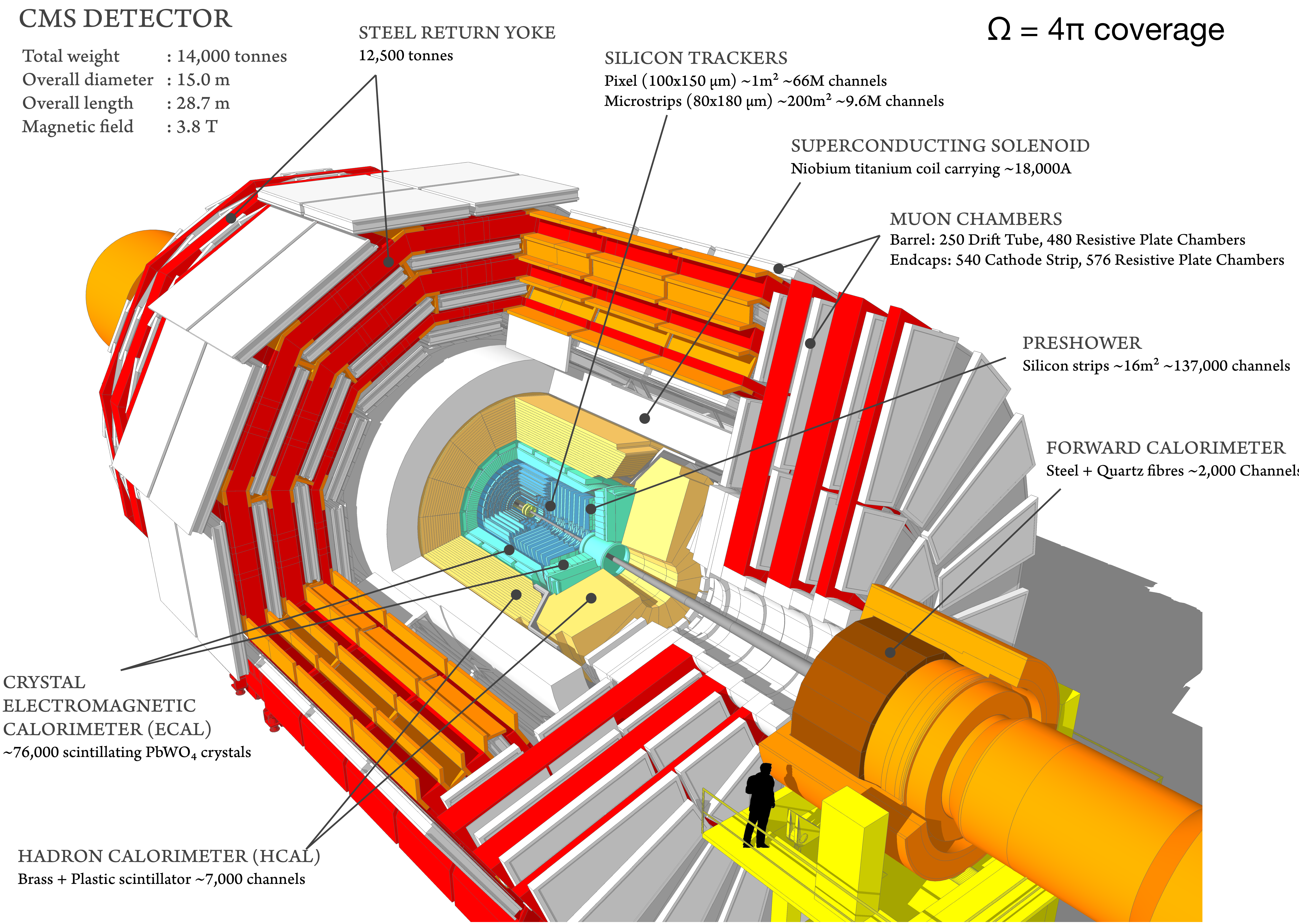
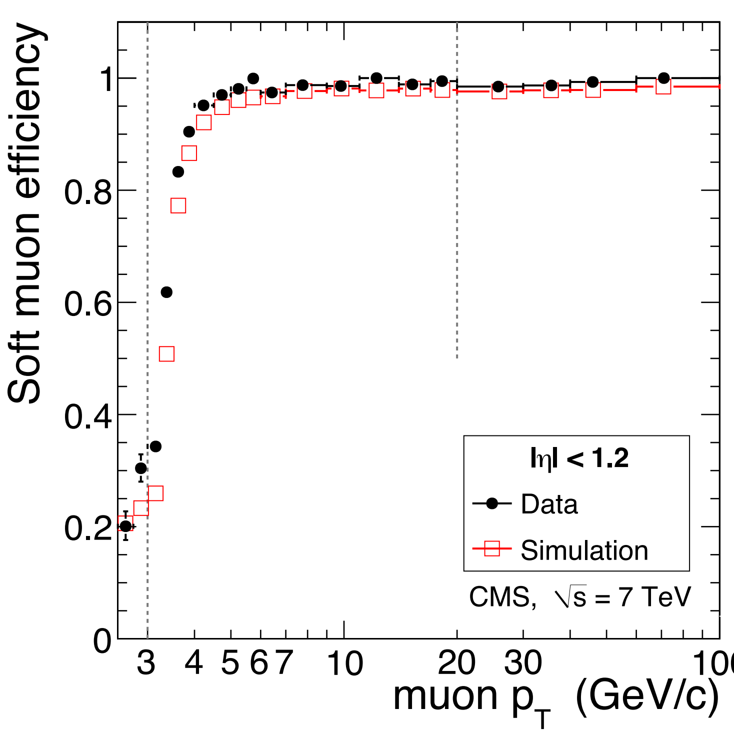
CMS
Compact Muon Solenoid

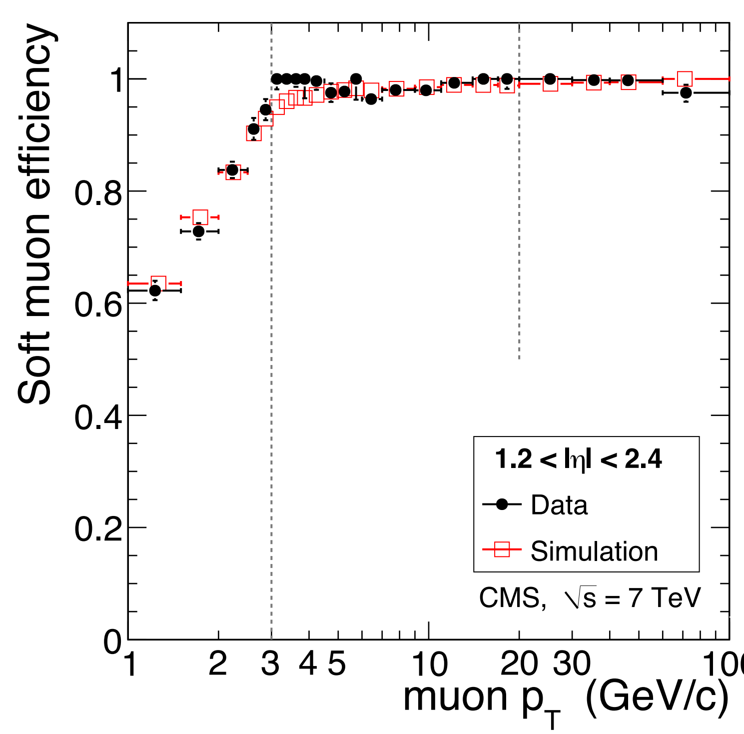
$\Omega = 4\pi$ coverage

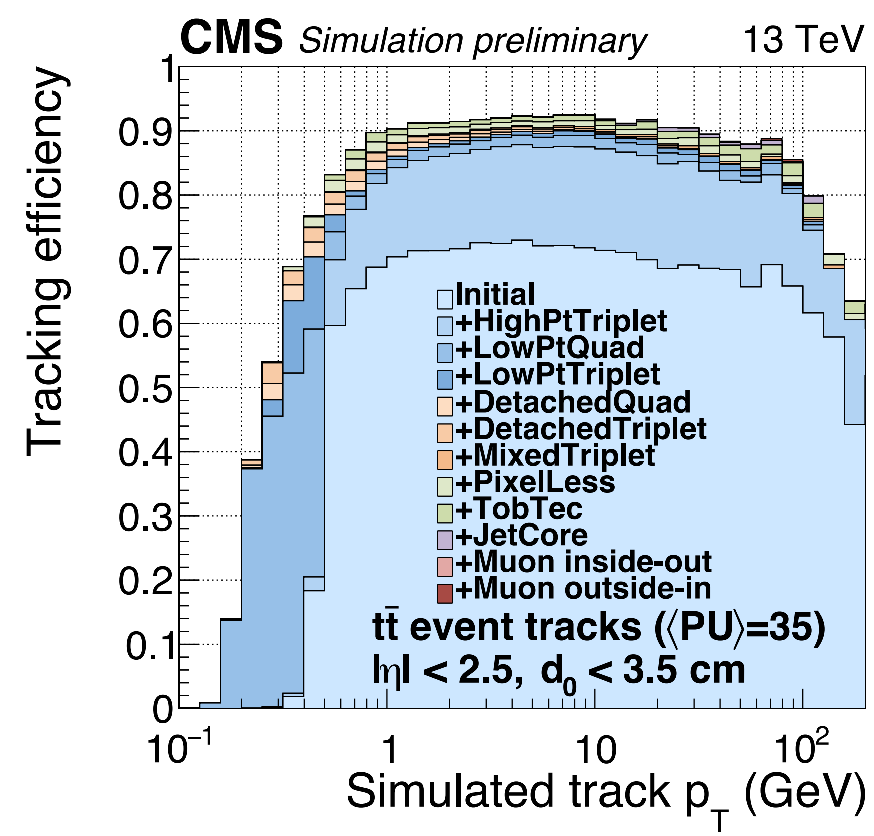


Muons and tracks for B-Physics

- **muon and track acceptance up to |η| < 2.5**
- **muons from p_T > 3.5 (1.5) GeV in central (forward) region**
  determined by radius of muon system and 3.8T
- **viable track efficiency from 300 MeV**
- excellent mass resolution
- **no PID** (sometimes can circumvent)
- primary (secondary) vertex position resolution ~10 μm (~few 10 μm)







credit Andrea Bocci

architecture of the CMS Trigger

Trigger System

- reduce the number of events from the **LHC collision rate (40 MHz)** to the data rate that can be stored, reconstructed and analysed **Offline ~~(~1 kHz)~~ O(few kHz)**
- maximising the physics reach of the experiment

L1 Trigger

- coarse readout of the Calorimeters and Muon detectors
- implemented in custom electronics, ASICs and FPGAs
- **3 event types, 128 “physics” bits + 64 “technical” bits**
- output rate limited to ~~100 kHz~~ by the readout electronics

>100 kHz in Run3

High Level Trigger

- readout of the whole detector with full granularity
- based on the CMSSW software, running on **O(15k) Xeon cores**
- organised in **O(2500) modules, O(400) trigger paths, O(10) streams**
- output rate limited to an average of ~~~1 kHz~~ by the Offline resources

O(few kHz)

LHC

40 MHz

L1 Trigger

full readout

100 kHz

High Level Trigger

Offline

~~~1 kHz~~

O(few kHz)

2015.04.16 Gion, Kyoto 3

trigger often the bottleneck for “soft” physics at CMS
~~~

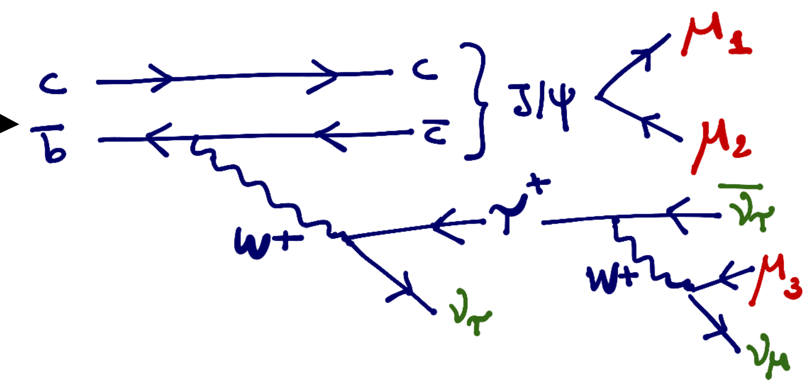
CMS results on b-baryons and B_c

	Publication / PAS	Title
B_c	JHEP 01 (2015) 063	Measurement of the ratio $B(B_c^+ \to J/\psi\pi^+\pi^+\pi^-)/B(B_c^+ \to J/\psi\pi^+)$ and the production cross sections times branching fractions of $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ in pp collisions at $\sqrt{s}$ = 7 TeV
	EPJC 78 (2018) 457 [Erratum]	Measurement of b hadron lifetimes in pp collisions at $\sqrt{s}$= 8 TeV
	PRL 122 (2019) 132001	Observation of two excited B_c^+ states and measurement of the $B_c^+(2S)$ mass in pp collisions at $\sqrt{s}$= 13 TeV
	PRD 102 (2020) 092007	Measurement of $B_c(2S)^+$ and $B_c^*(2S)^+$ cross section ratios in proton-proton collisions at $\sqrt{s}$= 13 TeV
	PRD 111 (2025) L051102	Test of lepton flavor universality in semileptonic B_c^+ meson decays in proton-proton collisions at $\sqrt{s}$= 13 TeV
	arXiv:2510.21559	Measurement of the ratio of the $B_c^+ \to J/\psi\tau^+\nu\tau$ and $B_c^+ \to J/\psi\mu^+\nu\mu$ branching fractions using three-prong τ lepton decays
Λ_b	PLB 714 (2012) 136-157	Measurement of the Λ_b cross section and the \bar{Λ}b to Λ_b ratio with $J/\psi\Lambda$ decays in pp collisions at $\sqrt{s}$ = 7 TeV
	JHEP 07 (2013) 163	Measurement of the Λb^0 lifetime in pp collisions at $\sqrt{s}$ = 7 TeV
	PRD 97 (2018) 072010	Measurement of the Λ_b polarization and angular parameters in $\Lambda_b \to J/\psi\Lambda$ decays from pp collisions at $\sqrt{s}$= 7 and 8 TeV
	PLB 802 (2020) 135203	Observation of the $\Lambda_b^0 \to J/\psi\Lambda\phi$ decay in proton-proton collisions at $\sqrt{s}$= 13 TeV
	PLB 803 (2020) 135345	Study of excited Λ_b^0 states decaying to $\Lambda_b^0\,\pi^+\pi^-$ in proton-proton collisions at $\sqrt{s}$= 13 TeV
	EPJC 84 (2024) 1062	Observation of the $\Lambda_b^0 \to J/\psi\Xi^- K^+$ decay
Ξb, Ξb*	PRL 108 (2012) 252002	Observation of a New Ξ_b Baryon
	PRD 110 (2024) 012002	Observation of the $\Xi_b^- \to \psi(2S)\Xi^-$ decay and studies of the Ξ^{*0}_b baryon in proton-proton collisions at $\sqrt{s}$= 13 TeV
Exotic / pentaquark searches	PRL 126 (2021) 252003	Observation of a new excited beauty strange baryon decaying to $\Xi_b^-\pi^+\pi^-$

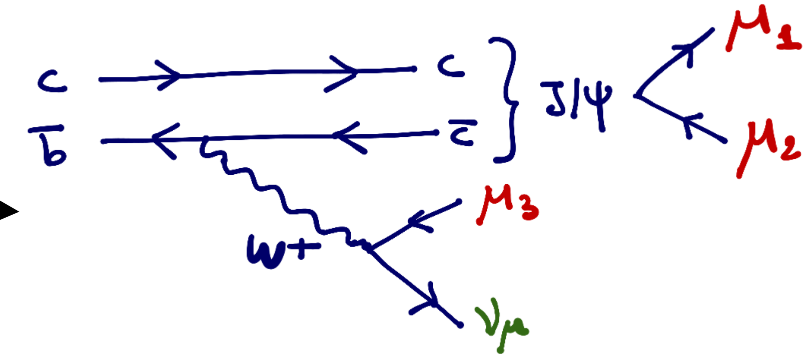
all CMS B-Physics results here

Phys. Rev. D 111 (2025) L051102

LFUV test: measurement of $R(\mathrm{J}/\psi)$



$$R(\mathrm{J}/\psi) = \frac{\mathscr{B}(\mathrm{B_c} \to \mathrm{J}/\psi\, \tau\, \nu_\tau)}{\mathscr{B}(\mathrm{B_c} \to \mathrm{J}/\psi\, \mu\, \nu_\mu)}$$



- B_c **only accessible at LHC,** $R(\mathrm{J}/\psi)$ **complementary to** $R(D^{(*)})$
- **SM prediction** $R(\mathrm{J}/\psi) = 0.26$ Phys. Rev. Lett. 125, 222003
- **recently updated LHCb** $R(\mathrm{J}/\psi) = 0.51 \pm 0.12\,(\mathrm{stat.}) \pm 0.08\,(\mathrm{syst.})$ Phys. Rev. Lett. 120, 121801

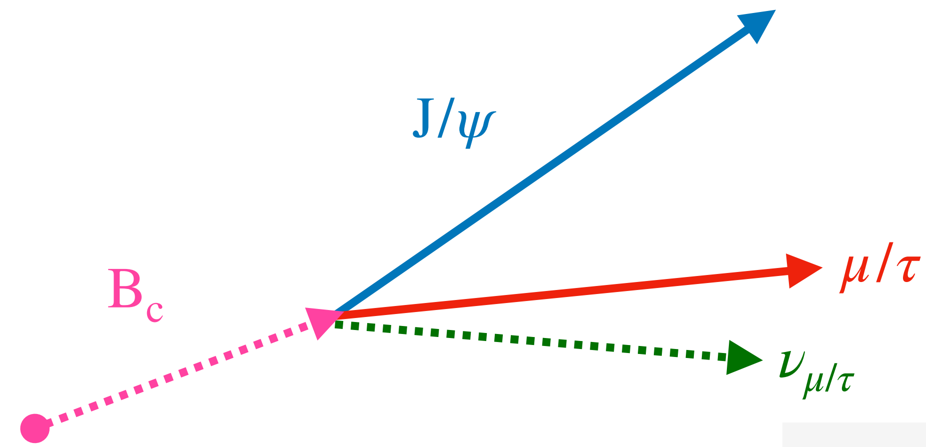
2σ deviation

- **three muon final state,** $\mathrm{J}/\psi \to \mu\mu$ **and** $\tau \to \mu\nu_\mu\nu_\tau$

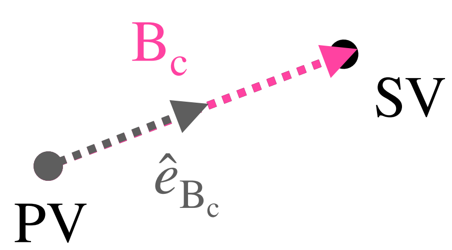
Analysis at a glance

- **2018 dataset** $\mathscr{L} = 59.7\,\mathrm{fb}^{-1}$
- **same** 3μ **+** $1(3)\nu$ **final state for numerator** τ **(denominator** μ**)**
  undetected neutrino(s) → missing momentum
- **simultaneous ML binned template fit**
  parameter of interest $R(\mathrm{J}/\psi)$
- ***collinear approximation*** **to infer full** B_c **momentum**
  $p_{B_\mathrm{c}} = m_{B_\mathrm{c}}^{\mathrm{PDG}} / m_{3\mu}^{\mathrm{vis}} \cdot p_{3\mu}^{\mathrm{vis}}$
- **distinguish** $1\,\nu$ **vs.** $3\,\nu$ **via kinematic variables e.g.**
  $q^2 = (p_{B_\mathrm{c}} - p_{\mathrm{J}/\psi})^2$ mass of the leptonic system
- **J/Ψ + μ trigger**, **basic kinematic/ID selections on 3μ candidate**
  μ_3 also required to be isolated

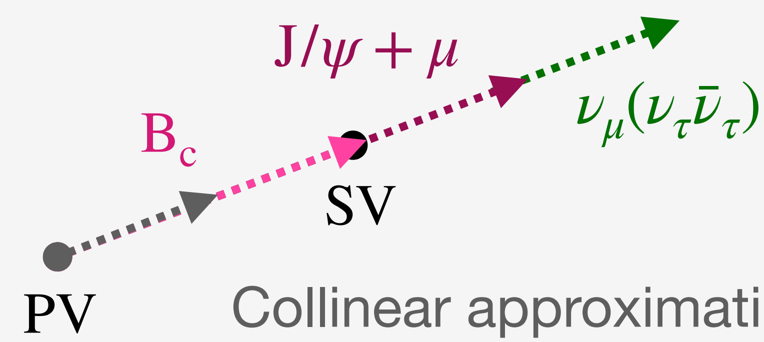
$\mathrm{B_c}$ momentum reconstruction



(circa) à la LHCb



$$\vec{p}_{\mathrm{B_c}} = |\vec{p}_{\mathrm{J}/\psi+\mu}| \cdot \frac{m_{\mathrm{B_c}}}{m_{\mathrm{J}/\psi+\mu}} \cdot \hat{e}_{\mathrm{B_c}}$$



Collinear approximation

$$p_{\mathrm{B_c}} = \frac{m_{\mathrm{B_c}}}{m_{\mathrm{J}/\psi+\mu}} \cdot p_{\mathrm{J}/\psi+\mu}$$

- **two options considered, opted for collinear approximation**
  - better tau/mu discrimination (but other disadvantages, see later)
- $p_{\mathrm{B_c}}$ four momentum crucial to define key kinematic observables e.g. $q^2 = (p_{\tau/\mu} + p_{\nu_\tau/\nu_\mu})^2$

LFUV test: measurement of $R(J/\psi)$

Signal and background processes

- **signals**

  $B_c \to J/\psi\tau\nu$ (num)

  $B_c \to J/\psi\mu\nu$ (den)

- ***fake muon* background**

  J/ψ + misID had

  (mostly $K \to \mu\nu$)

  data driven

- **H_b background**

  J/ψ from b-hadron + μ

  (98% combinatorial)

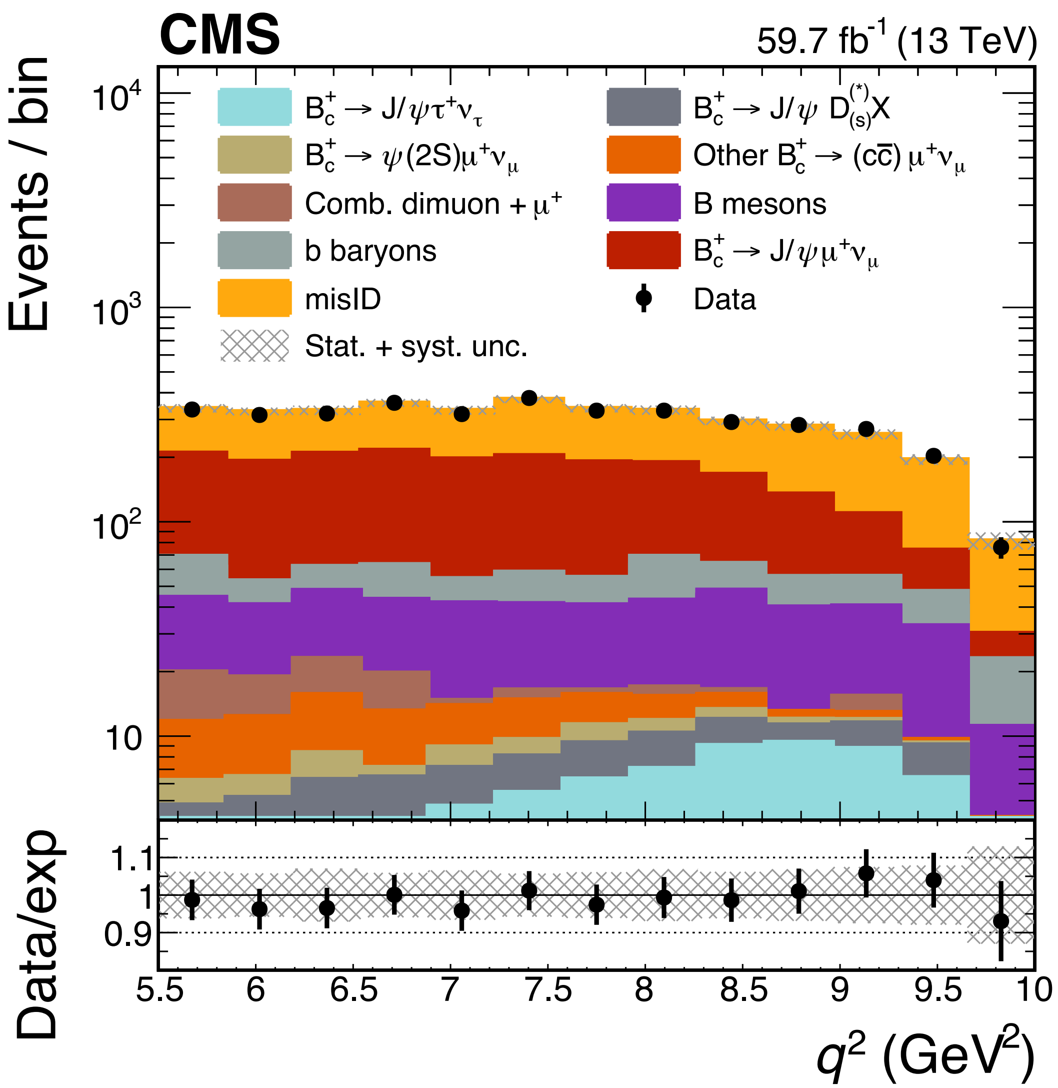
  simulation + control region

- $B_c \to J/\psi + D_{(s)}^{(*)}$, $B_c \to (c\bar{c})\mu\nu$, $B_c \to \psi(2S)\mu\nu$

  simulation

- **combinatorial dimuon + X**

  data driven



Signal and background processes

- signals

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  (mostly $K \to \mu\nu$)

  dominant background

- **H_b background**

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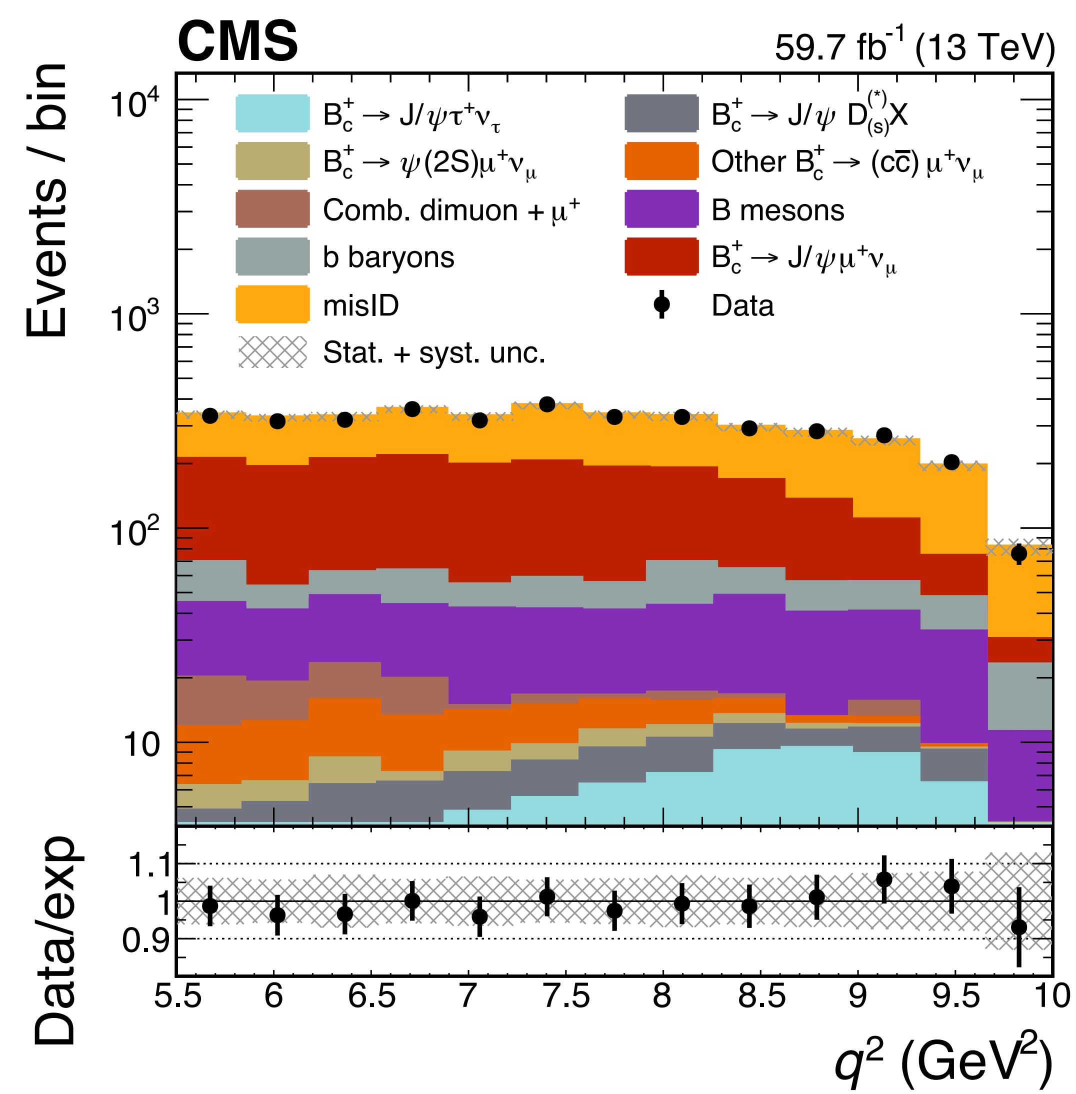
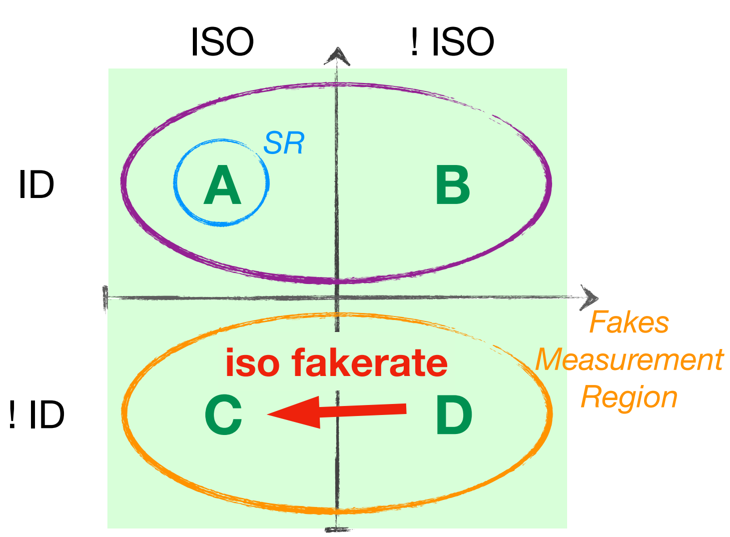
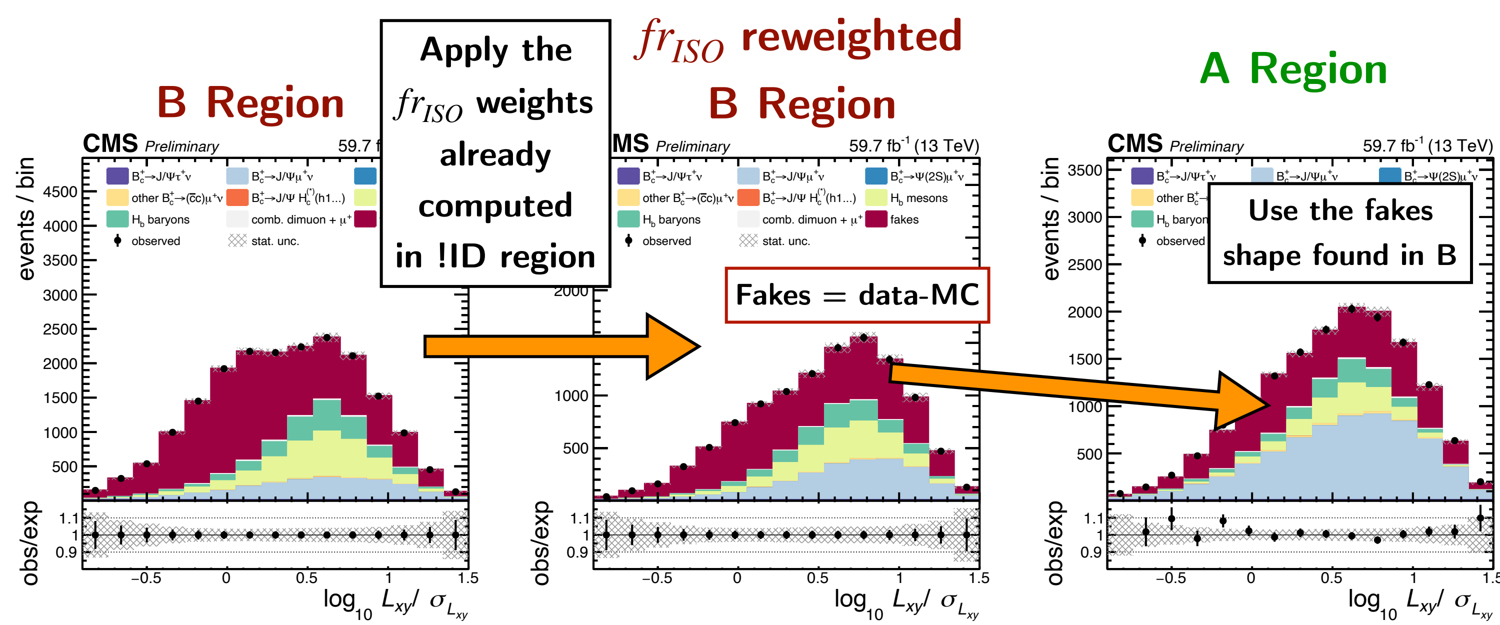


MisID muon background estimate

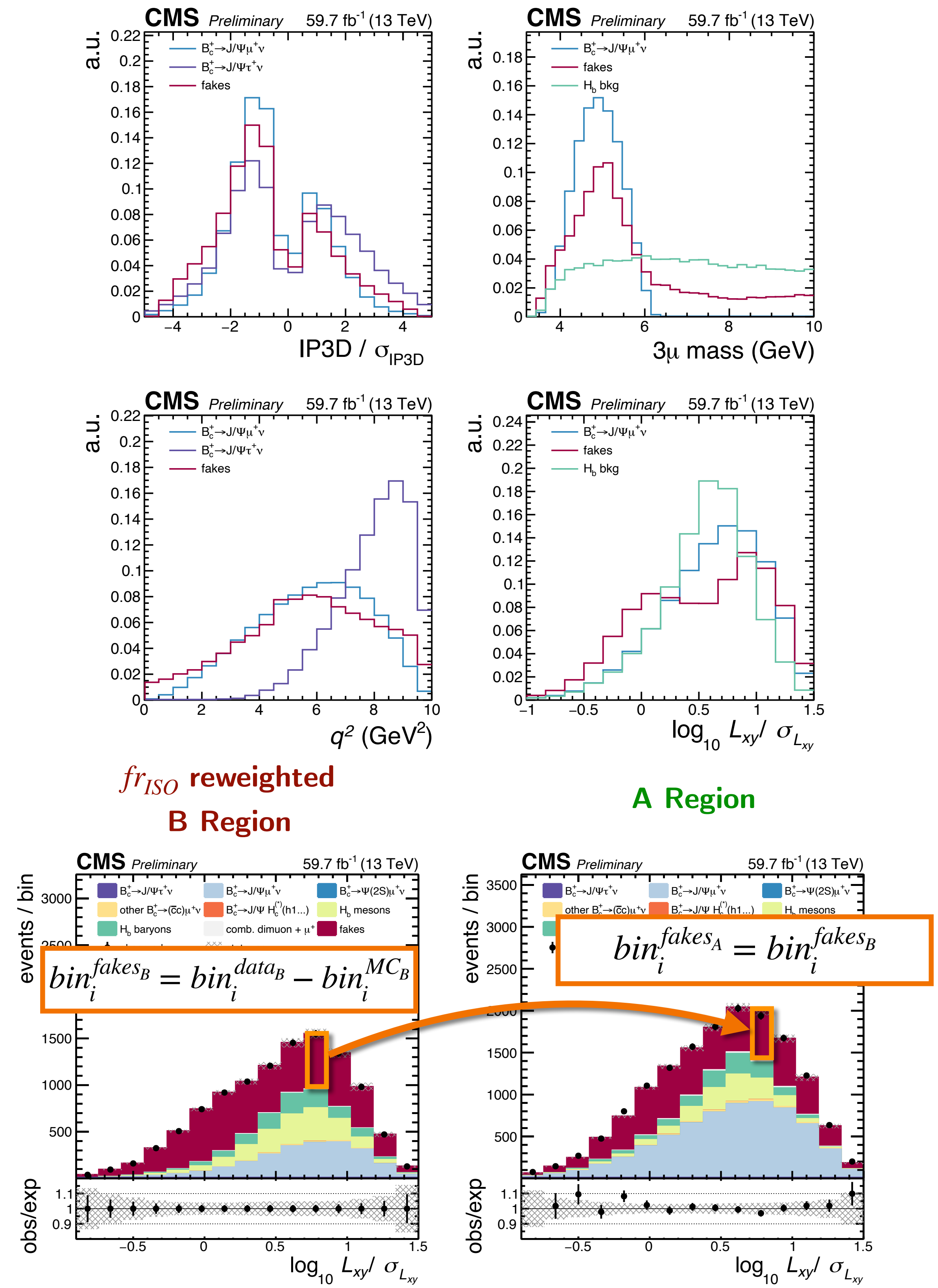
- **fake-rate probability fr_{ISO} measured in region adjacent to signal region** (inverted μ_3 ID)
- fr_{ISO} **fitted using NN classifiers to model multidimensional dependencies** (kinematics, topology…)
- ***in situ*** estimate, incorporated in the final ML fit





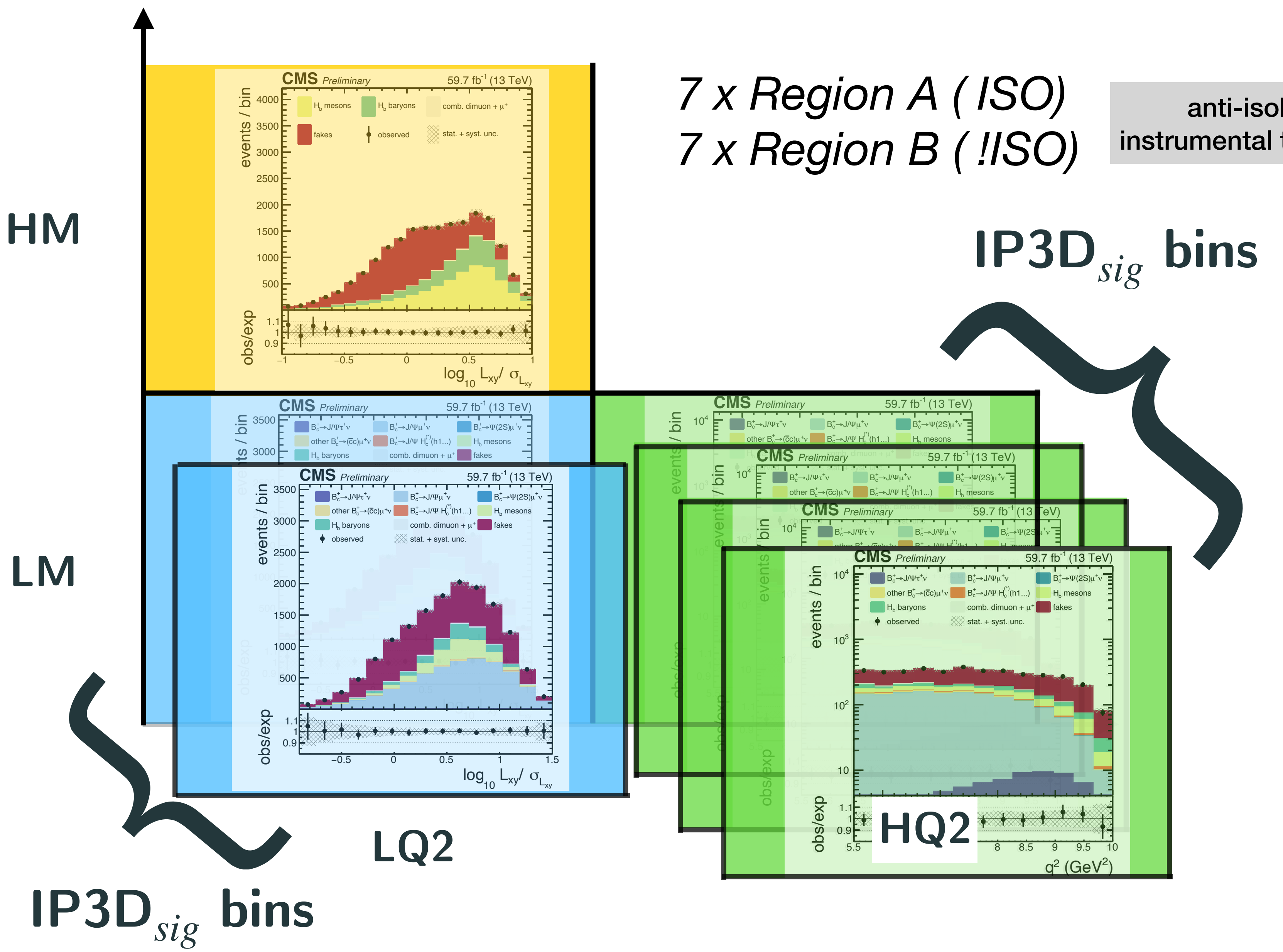
Fit model

- **binned maximum likelihood template fit**
  7(x2) categories
- $R(J/\psi)$ **parameter of interest**
- **fit to four observables, distinguish** $B_c \to J/\psi\tau\nu$, $B_c \to J/\psi\mu\nu$, H_b **and fakes**
- ***in situ*** **estimate of fake muon background**



Fit model

constrain H_b



7 x Region A (ISO)
7 x Region B (!ISO)

anti-isolated categories
instrumental to fakes bkg estimate

signal enriched

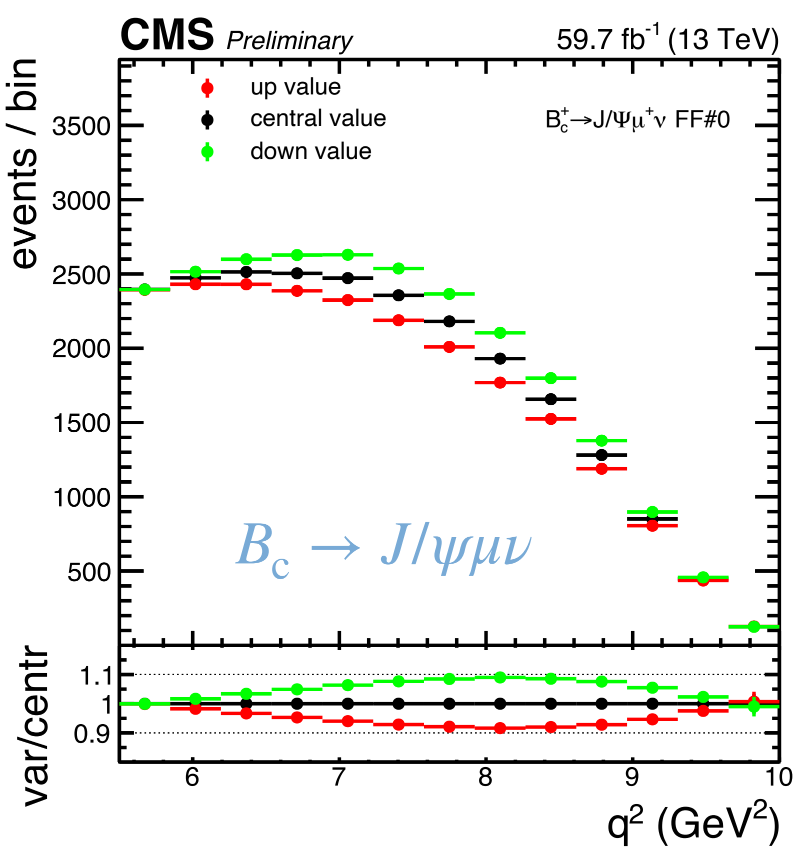
constrain
$B_c \to J/\psi \mu \nu$
and fakes

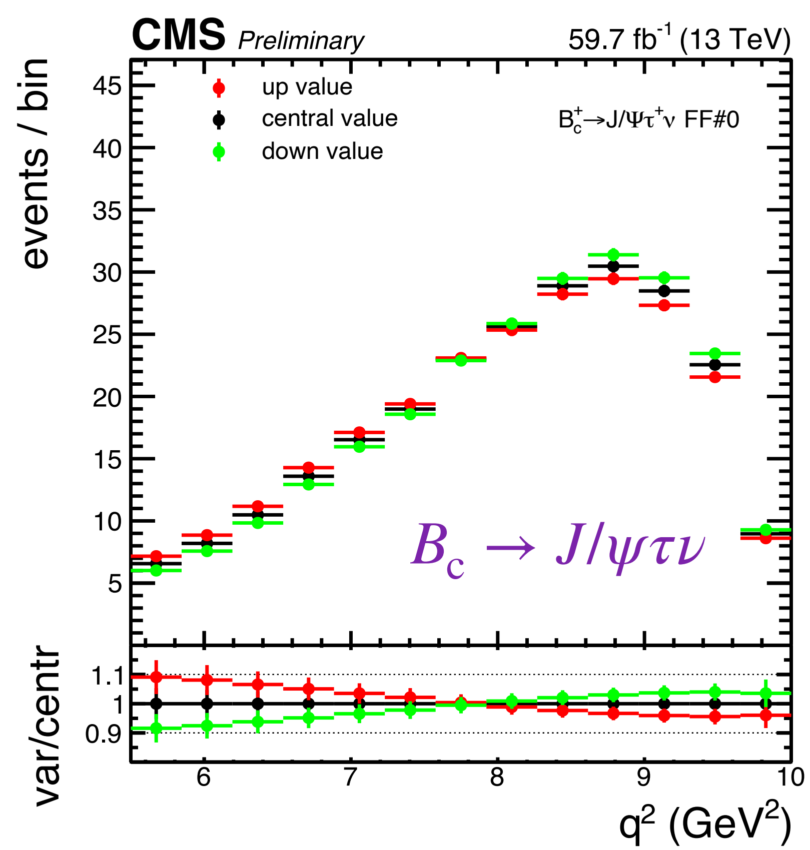
Uncertainties

uncertainties incorporated in ML fit as nuisance parameters, profiled

H_b and B_c norm. free floating, constrained in control regions

Contribution	Uncertainty type	Rel. uncertainty	$\Delta R(J/\psi) \cdot 10^{-2}$
B_c^+ form factors	10 shapes	–	18.2
fakes stat. non closure	bin-by-bin shapes	–	11.3
fakes background	2 shapes	–	4.2
fakes background	norm.	13.0%(+5% HM cat.)	2.5
finite MC size	bin-by-bin shapes	–	5.3
$IP3D/\sigma_{IP3D}$, $L_{xy}/\sigma_{L_{xy}}$ corr.	2 shapes	–	4.4
muon ID, iso, trigger	norm.	6.6%	2.5
J/ψ comb. norm.	norm.	20.0%	1.3
B_c^+ bkg. BRs	norm.	10.0 – 38.0%	0.7
H_b sample composition	norm.	10.0% for each H_b^i	0.5
Other	norm.	–	< 0.1

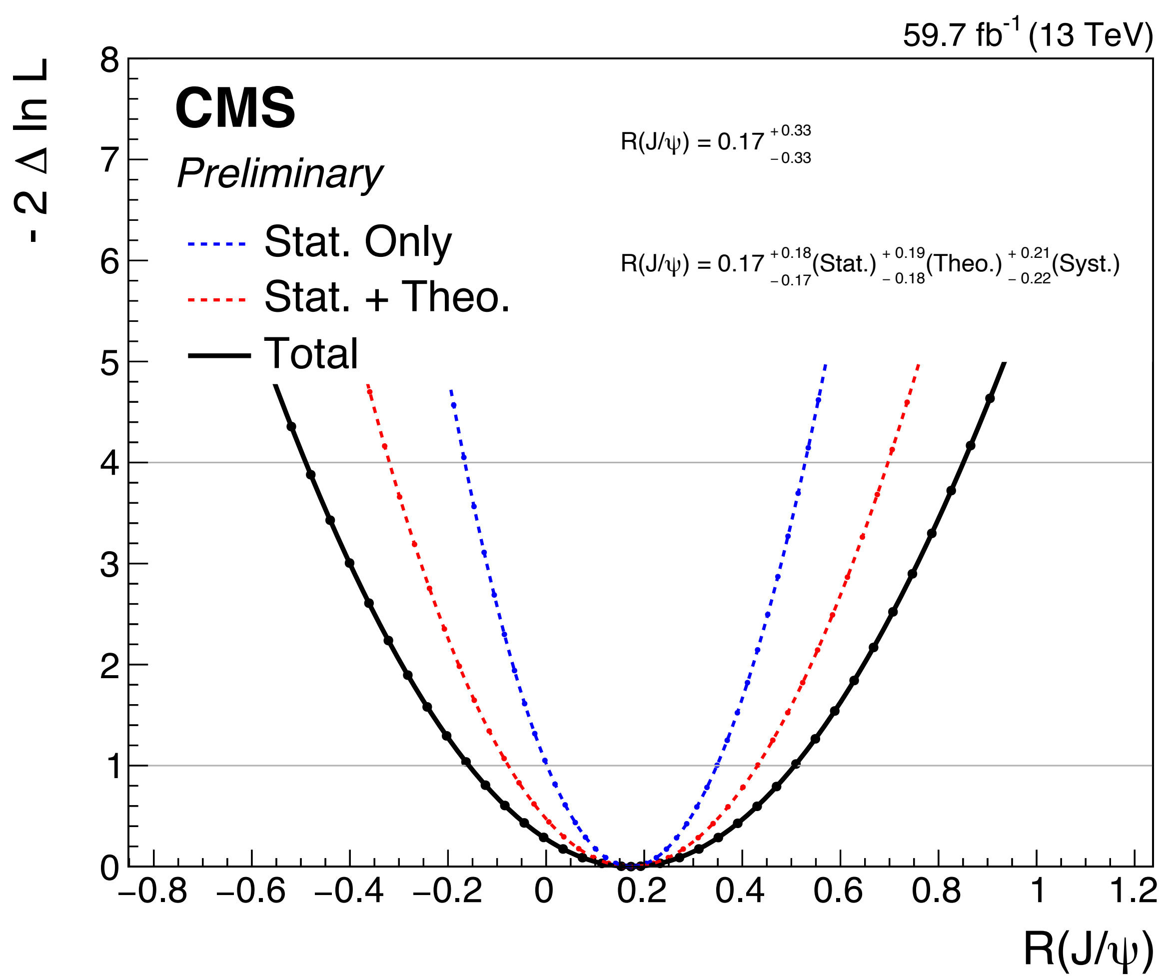




form factors [1] [2] dominant uncertainty

large impact on key kinematic observable q^2

Results



$$R(J/\psi) = 0.17\,^{+0.18}_{-0.17}\,(\text{stat.})\,^{+0.19}_{-0.19}\,(\text{theo.})\,^{+0.21}_{-0.22}\,(\text{syst.})$$

$$R(J/\psi) = 0.17 \pm 0.33$$

- **first LFUV result in $b \to c\ell\nu$ transitions at CMS**
  on partial Run2 dataset
- in agreement with both SM 0.26 and LHCb 0.51 ± 0.12 ± 0.08 within less than 1σ
- **sensitivity expected to significantly improve in coming iterations**

Leptonic $R(J/\psi)$ prospects

$$R(J/\psi) = 0.17\,^{+0.18}_{-0.17}\,(\text{stat.})\,^{+0.19}_{-0.19}\,(\text{theo.})\,^{+0.21}_{-0.22}\,(\text{syst.})$$

current result statistically and systematically limited
where to go from here?

- **statistical uncertainty**
  320 fb^{-1} collected in Run3, 80 fb^{-1} still not analyzed from Run2 → potentially 6-7x data for full Run2 + Run3
  (trigger, acceptance, efficiency vary year by year)

- **systematic uncertainty**
  fake background estimate uncertainties *extremely* conservative
  several systematic uncertainties scale with stats

- **theory uncertainty (form factors)**
  we used Phys. Rev. D 100, 094503, more recent LQCD FF available now
  (LHCb uses Harrison 2503.15090)

Leptonic $R(\mathrm{J}/\psi)$ prospects - segue

$$R(\mathrm{J}/\psi) = 0.17\,^{+0.18}_{-0.17}\,(\mathrm{stat.})\,^{+0.19}_{-0.19}\,(\mathrm{theo.})\,^{+0.21}_{-0.22}\,(\mathrm{syst.})$$

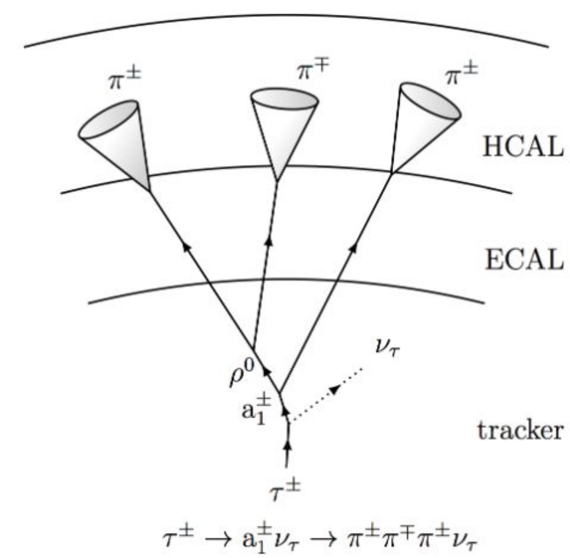
- **collinear approximation for $\mathrm{B_c}$ momentum reconstruction**
  pros: chosen because of higher $\mathrm{B_c}$ boost in CMS and better μ/τ separation in q^2
  cons: all $\mathrm{B_c}$ kinematic variables, e.g. q^2, m^2_{miss}, E^*_μ, ...
  100% correlated, no gain in combining them / multidim fit

- **simultaneous fit of pass/fail μ_3 isolation region**
  pros: in situ estimate, let data constrain fakes, robust and reliable
  cons: too much leeway, penalises performance
  introduces strong correlations between uncertainties

Hadronic $R(J/\psi)$

$$R(J/\psi) = \frac{\mathcal{B}(B_c \to J/\psi \tau_{\rm had} \bar{\nu})}{\mathcal{B}(B_c \to J/\psi \mu \bar{\nu})} = \frac{\mathcal{B}(B_c \to J/\psi \pi\pi\pi(+\pi^0)\bar{\nu})}{\mathcal{B}(B_c \to J/\psi \mu \bar{\nu})}$$

Decay mode	Meson resonance (MeV)	$\mathcal{B}[\%]$
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other hadronic decays		3.2
All hadronic decays		64.8

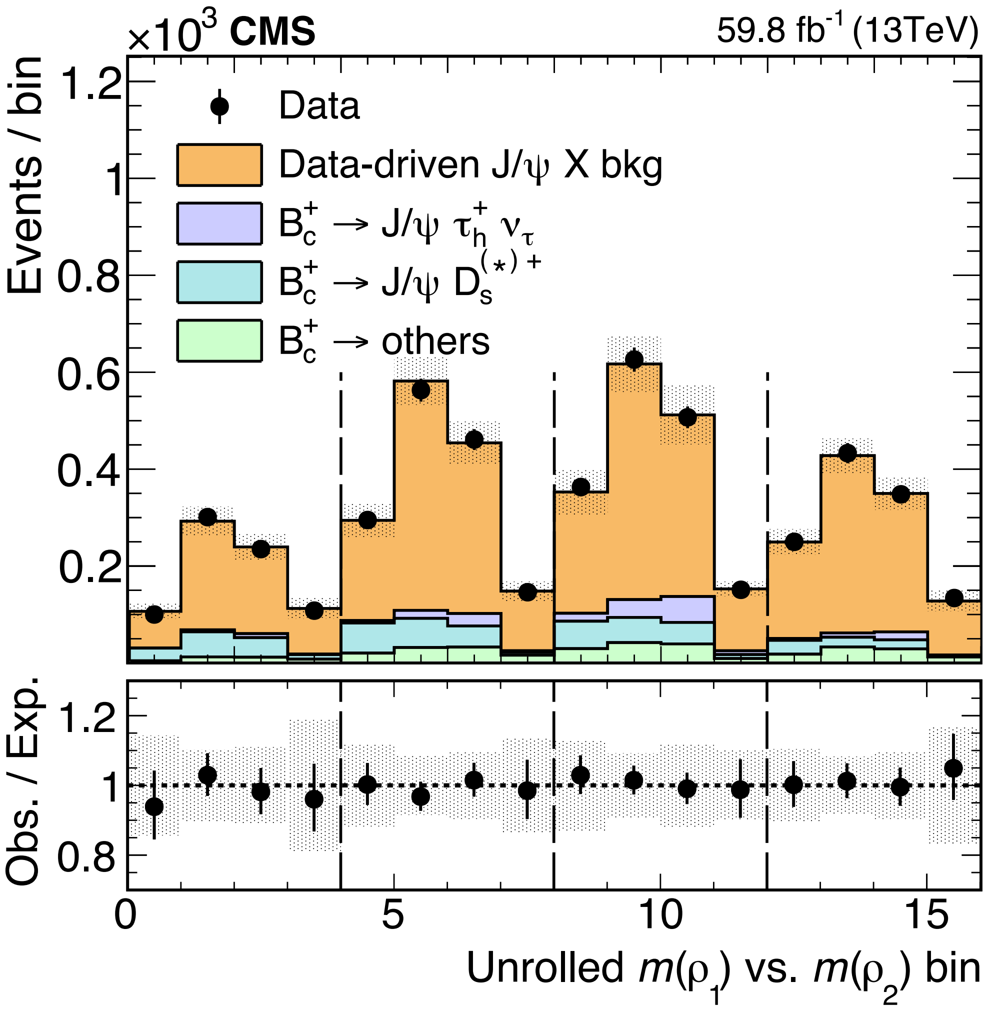


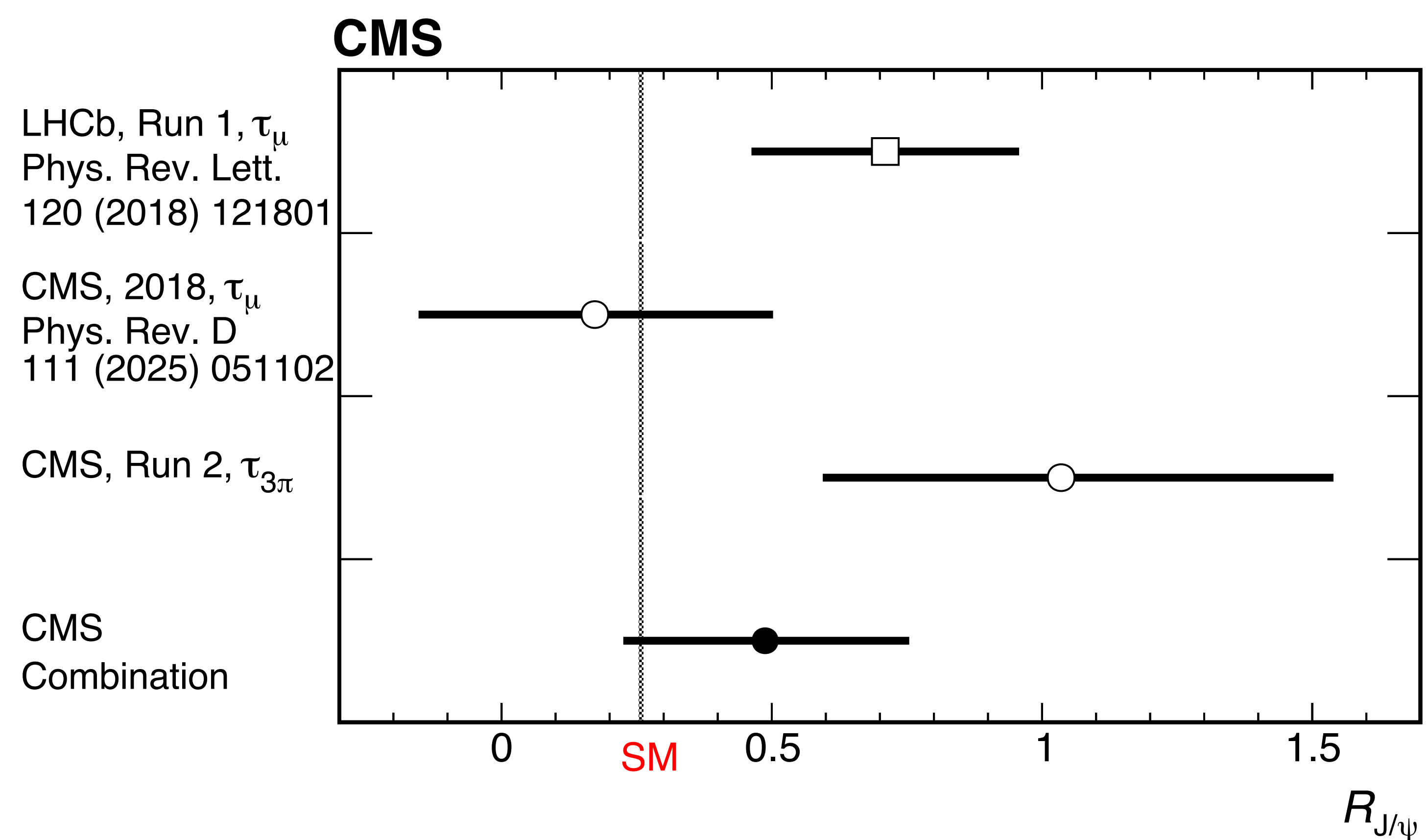
- **focus on $\tau^+ \to \pi^+\pi^+\pi^-$ hadronic tau decays**
  inclusive wrt additional π^0
- **combine with leptonic analysis** (with appropriate correlations) **to share common denominator**
- **in this analysis, full Run2 dataset ~137 fb^{-1}**

Analysis strategy

- **dedicated low p_T tau reconstruction**
- BDT to suppress backgrounds, mostly J/Ψ from B decay plus combinatorial 3 tracks
- J/Ψ + X background estimated from data
- $\mathrm{B_c} \rightarrow \mathrm{J}/\psi + \mathrm{D}_{(s)}^{(*)}$ background from simulation plus generous uncertainty
- **dominant decay** $\tau \rightarrow a_1(1260) \rightarrow \rho^0(\rightarrow \pi^+\pi^-)\pi^+$
- **signal extraction from binned ML fit to "unrolled" 2D** $m(\rho_1) \times m(\rho_2) = m(\pi_1^+\pi^-) \times m(\pi_2^+\pi^-)$ **distribution**

Results





combined

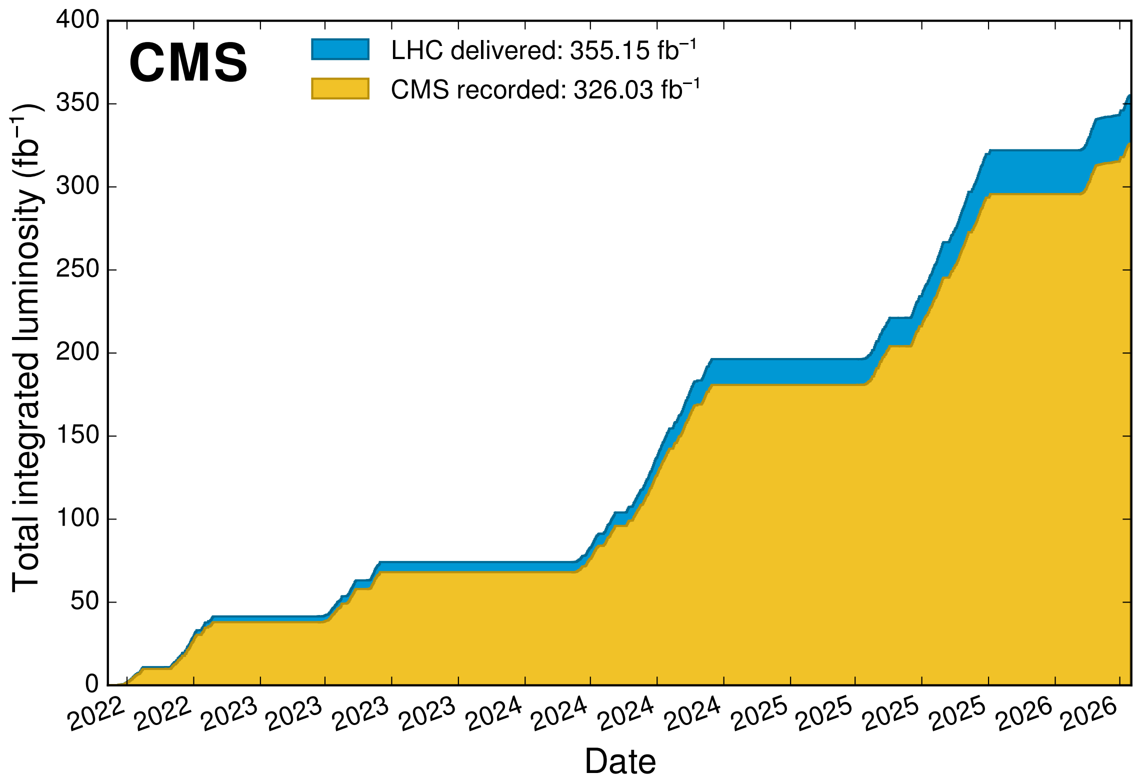
$$R(\mathrm{J}/\psi) = 0.49 \pm 0.25\,(\mathrm{syst.}) \pm (0.09)\,(\mathrm{stat.})$$

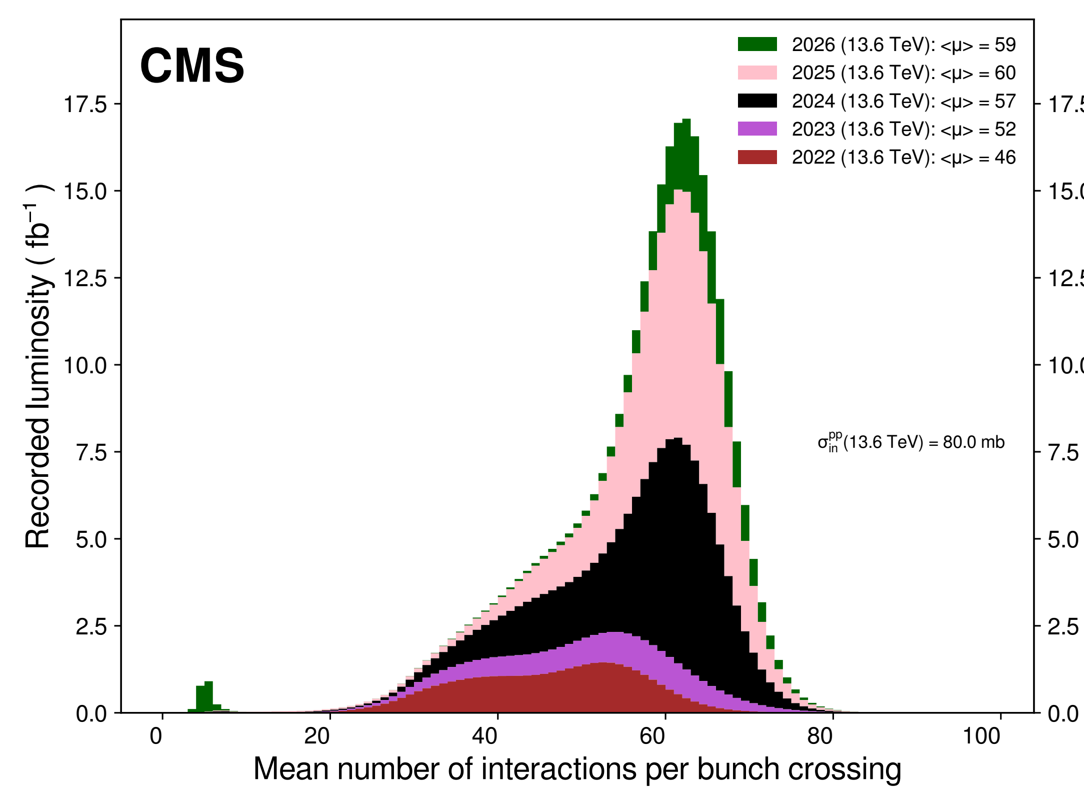
Hadronic $R(\mathrm{J}/\psi)$ prospects

- **significantly better triggers in Run3**
  inclusive dimuon, as opposed to dimuon plus track with vertex conditions (works against tau decay being displaced)
- **in light of the above, increase in statistics much larger that Run3 / Run2 luminosity ratio of about 2**
- **less sensitive to form factors**
- … but large combinatorial bkg challenging

Run3 luminosity and pileup

- **2022-2026 collected 326 fb^{-1}** (vs 140 fb-1 in Run2)
- higher PU than Run2 $<\mu> = 54$ vs $<\mu> = 34$
  (not an insurmountable problem)

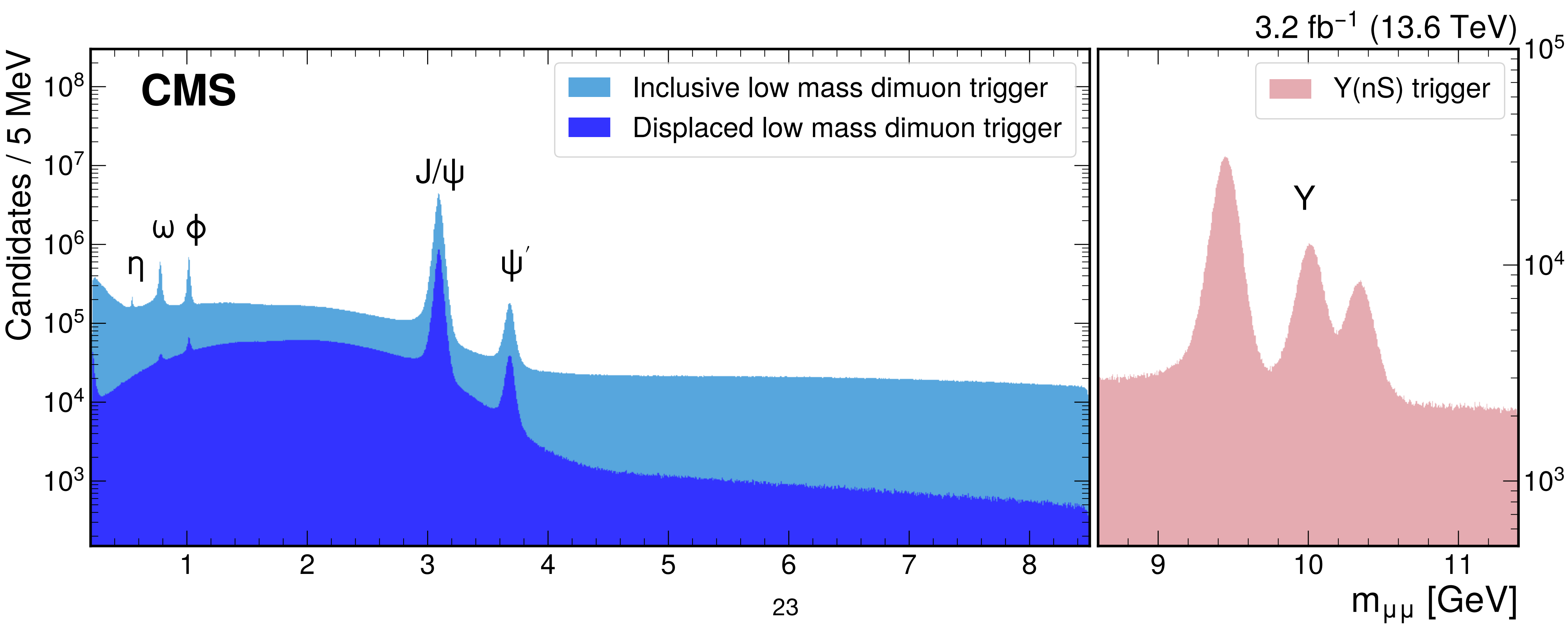




PR 1115 (2025) 678

Inclusive dimuon triggers

- **inclusive di-muon trigger up to $m_{\mu\mu} < 8\,\mathrm{GeV}$**
  p_T > 3,4 GeV, ~full pseudorapidity coverage
  - in Run2, either di-mu + track low p_T + displacement, or di-mu inclusive high p_T
  - significant increase in acceptance, (re-)opens new avenues



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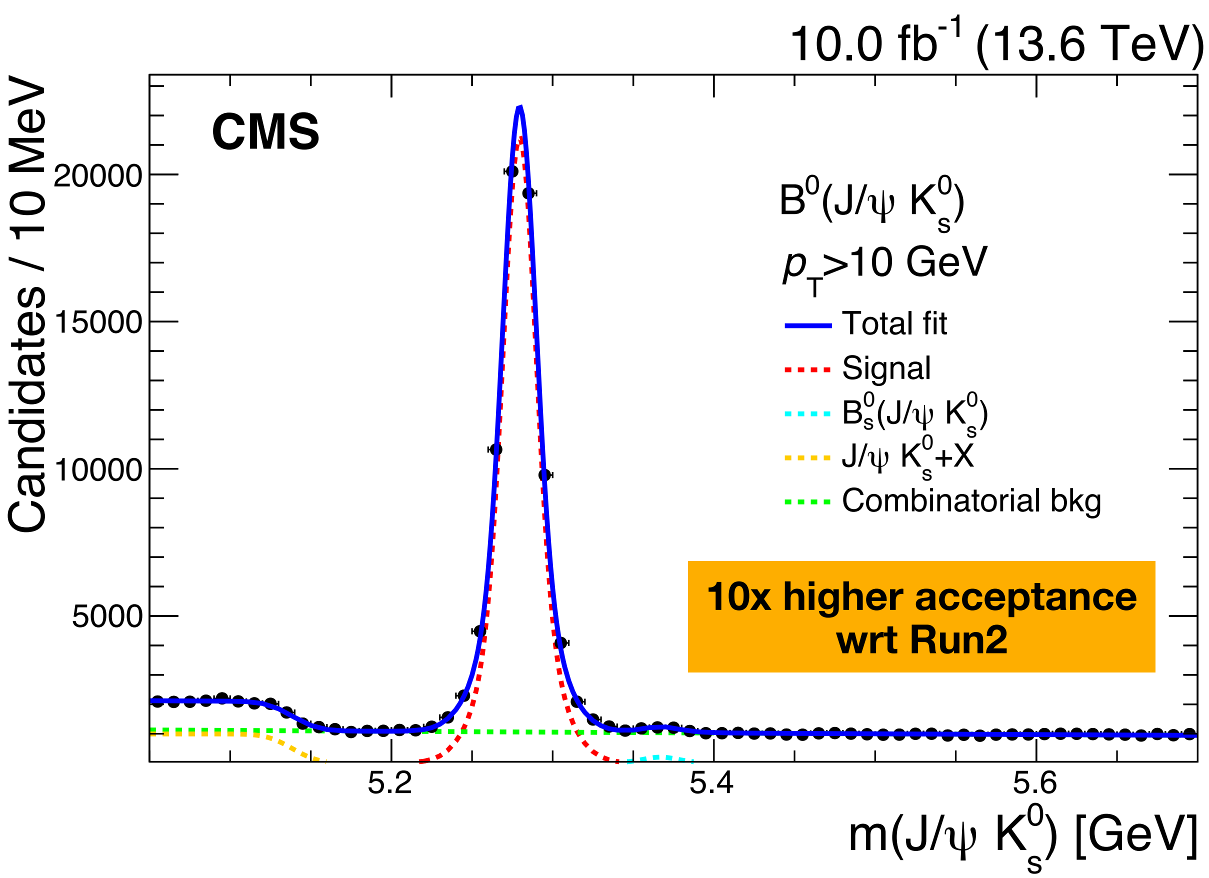
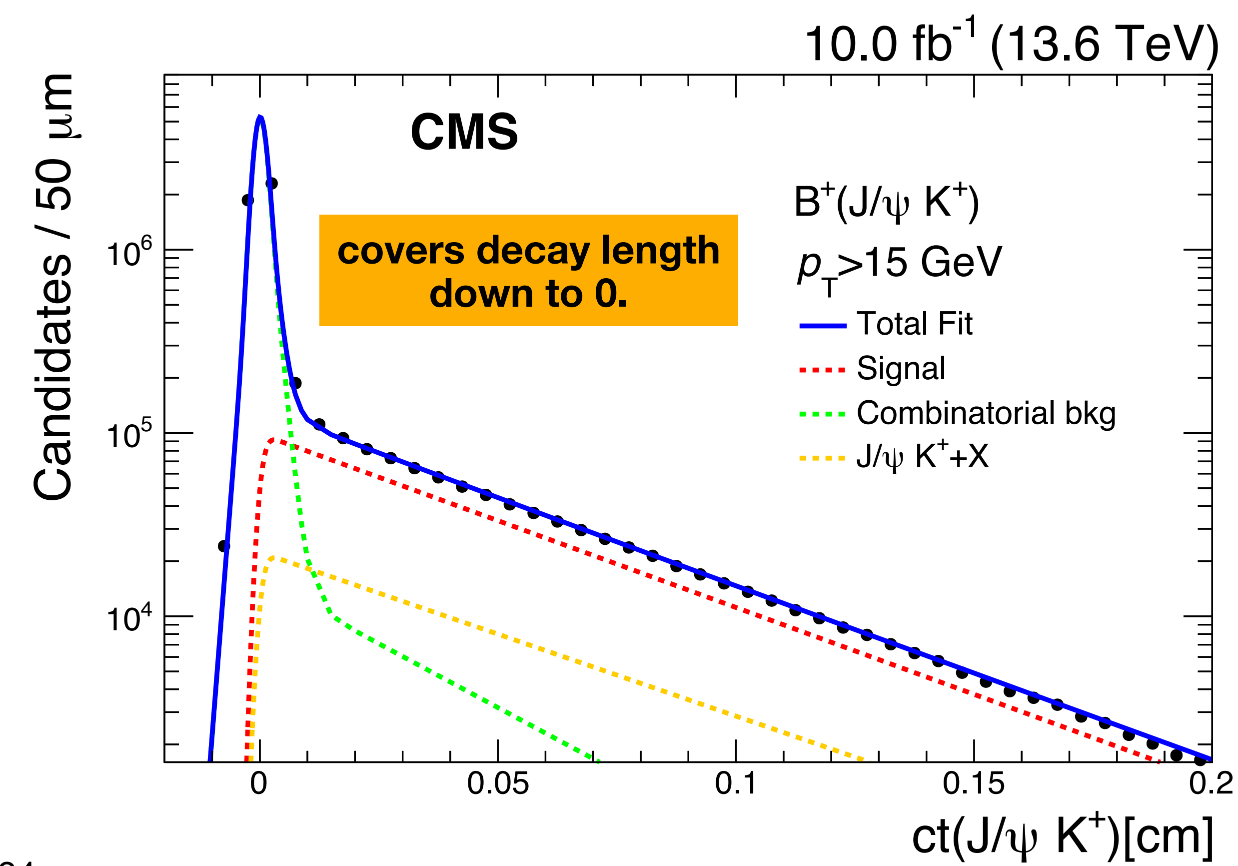
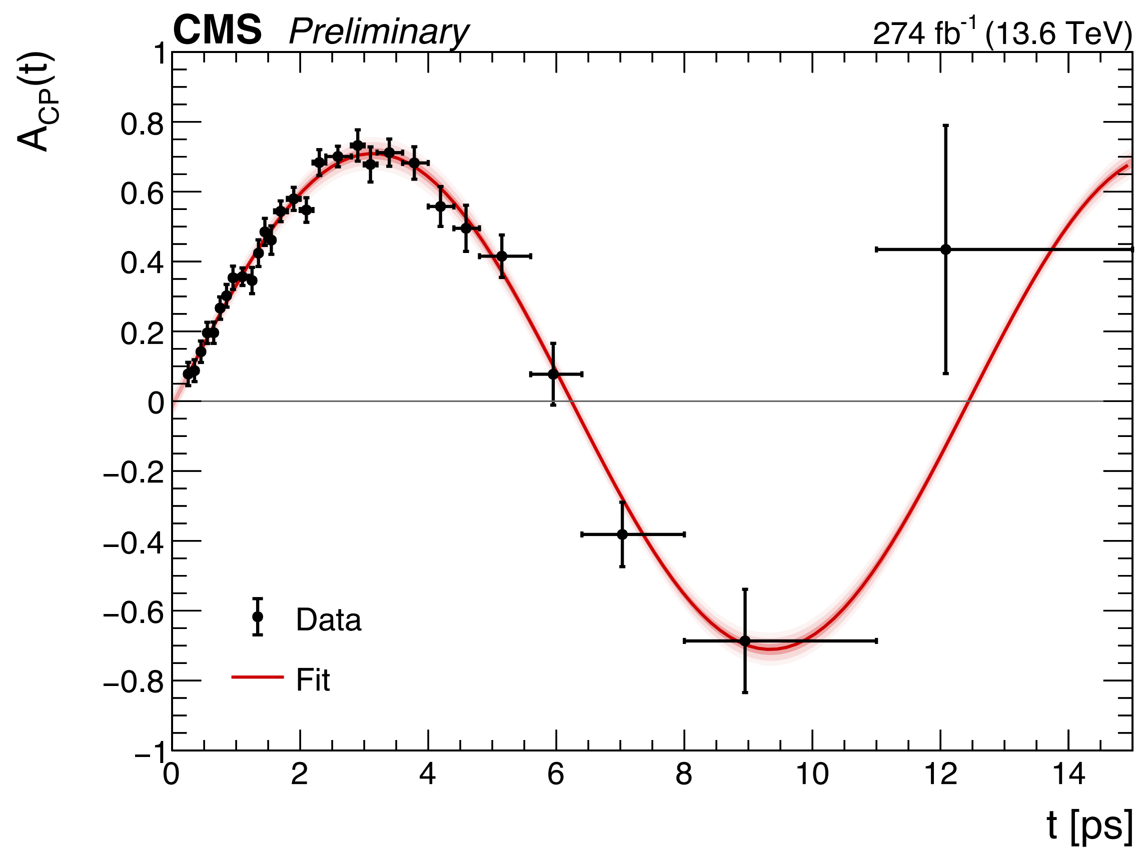
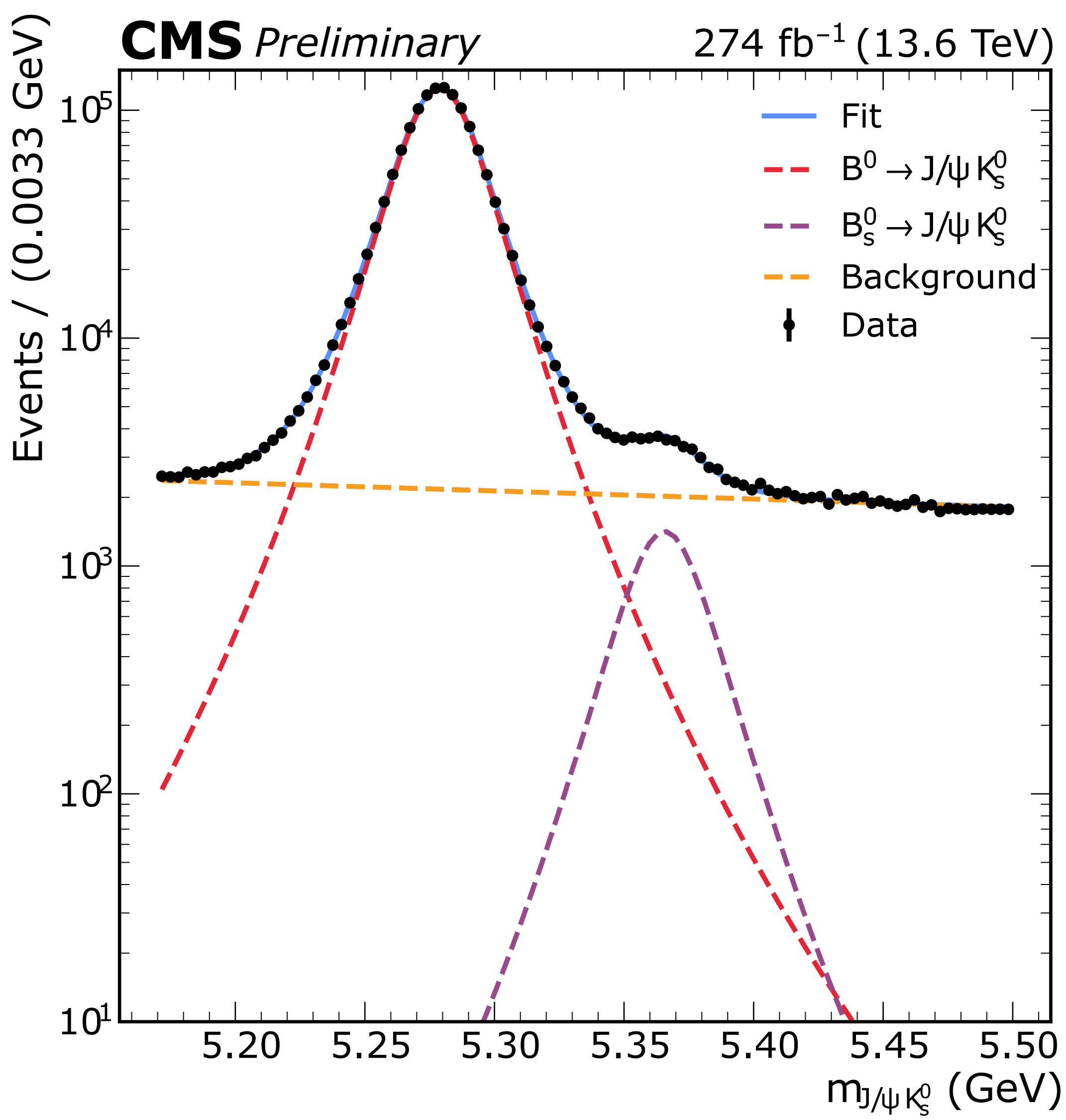


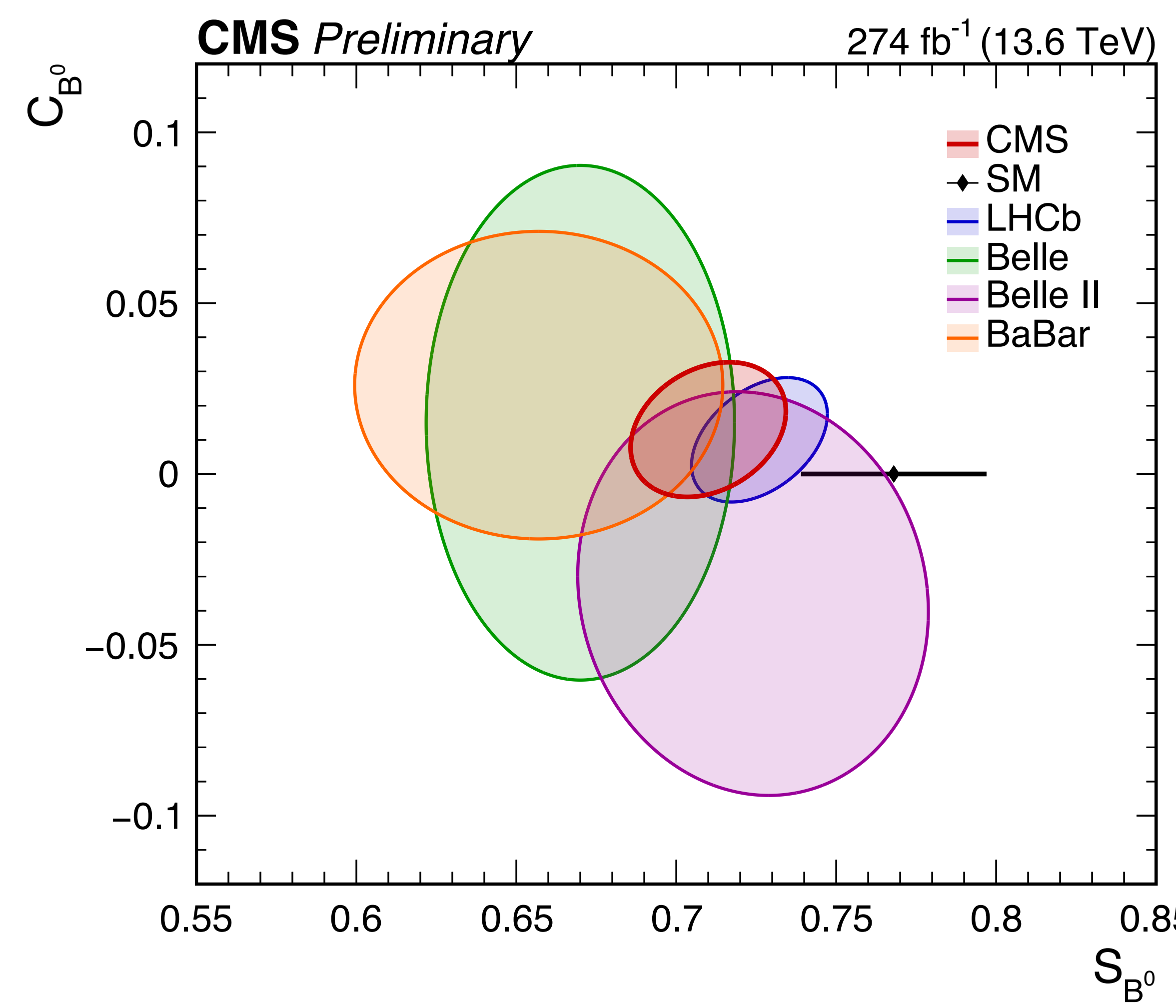


Intermezzo
CKM β in $B^0 \to J/\psi K_s$

- made possible by di-muon triggers

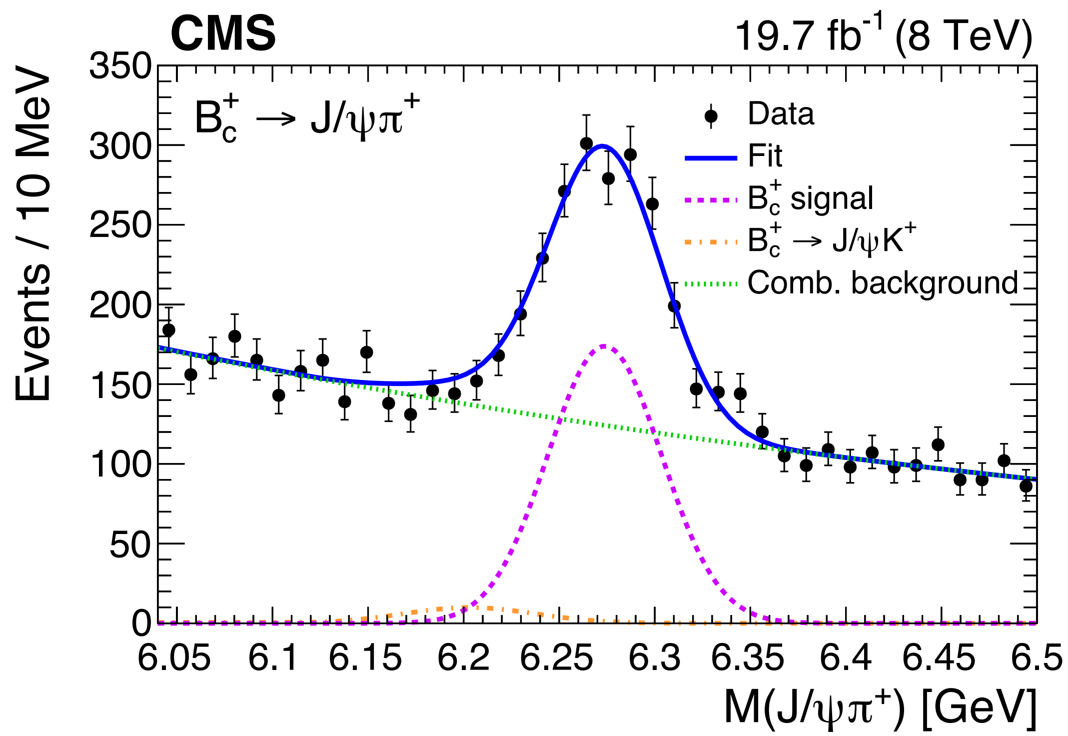


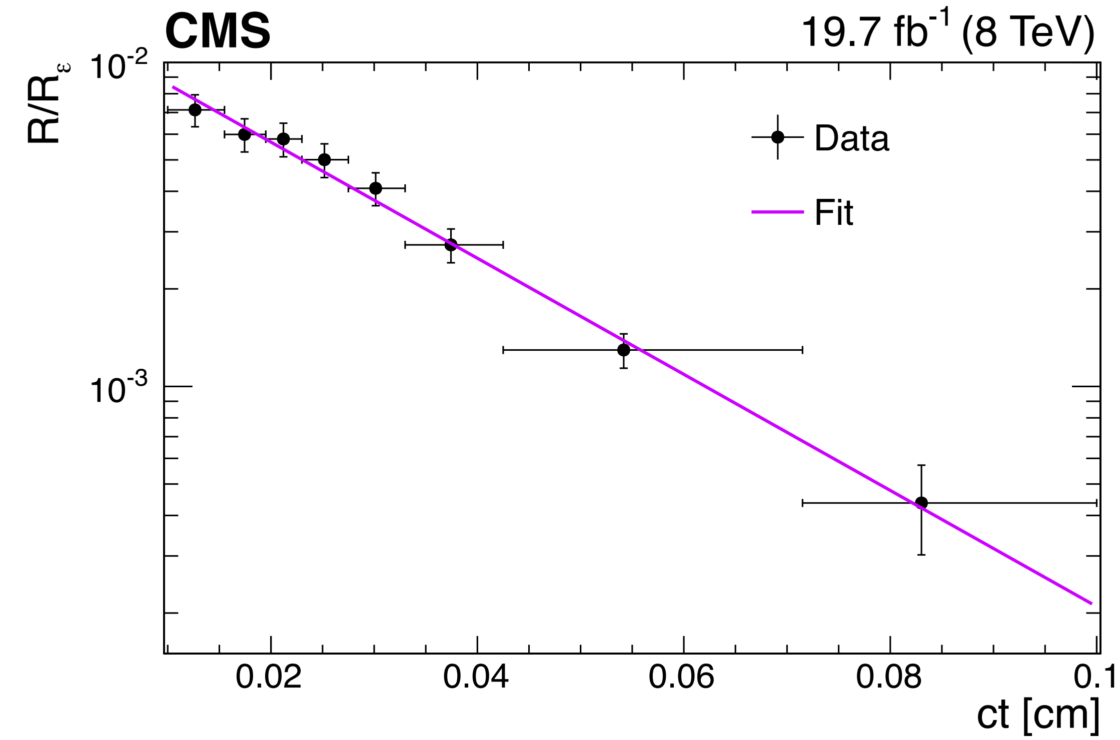




[EPJC 78 (2018) 457](#) [[Erratum]](#)

B_c lifetime



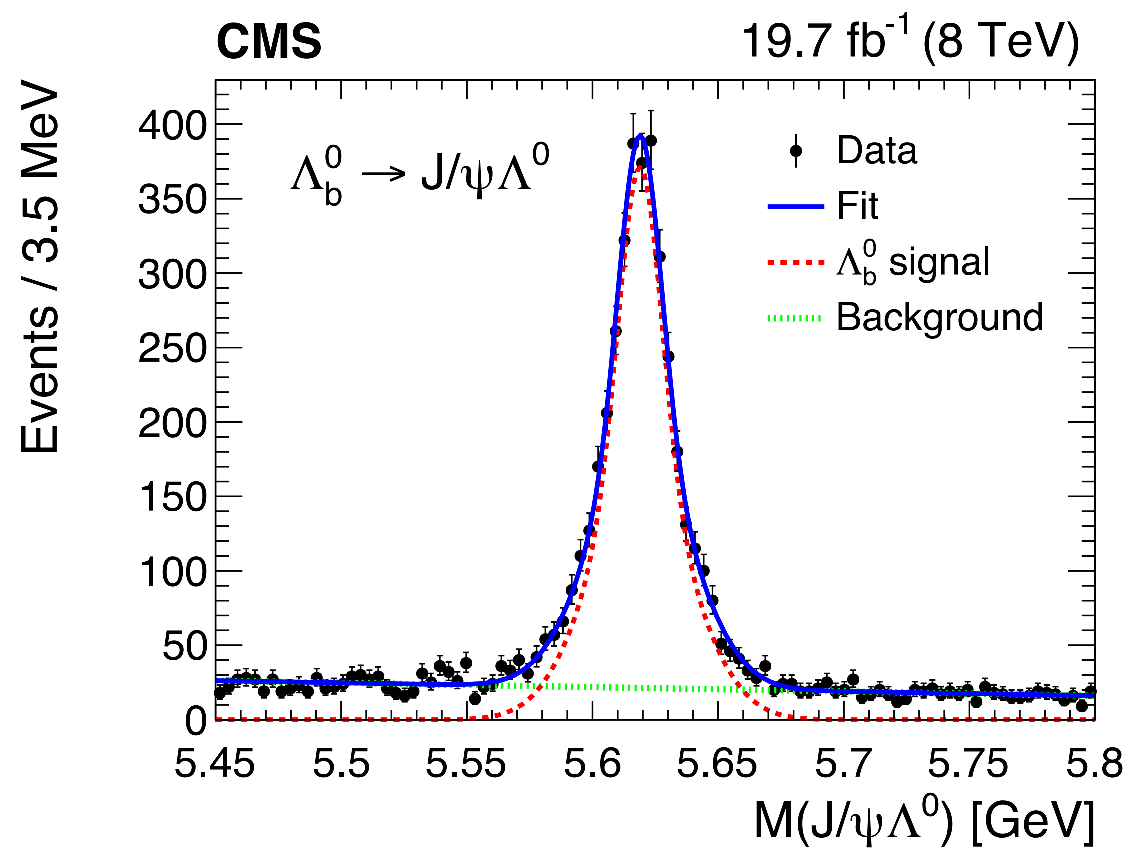


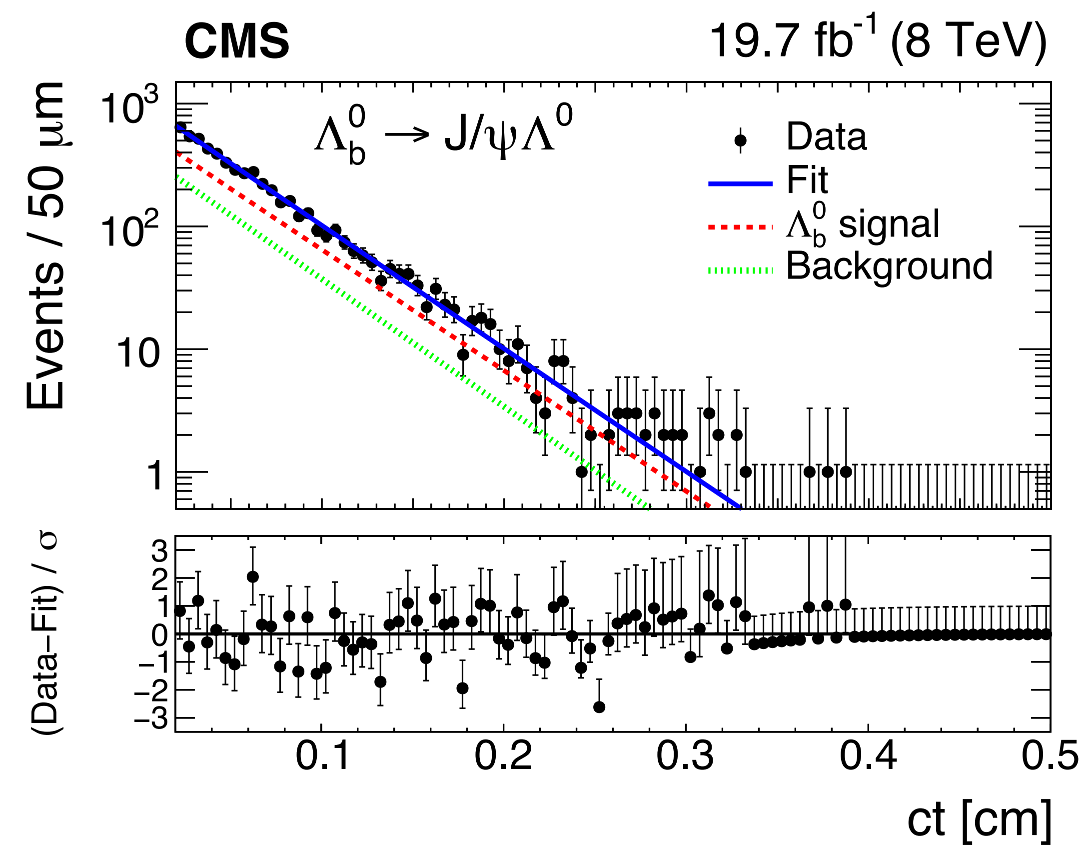
- CMS (and LHCb) most precise measurements from Run2
- CMS Run3 statistics 15x, cross section 2x
  - potential breakthrough

B_c^+ MEAN LIFE PDGID:S091T JSON (beta)

VALUE (10^{-12} s)		DOCUMENT ID		TECN	COMMENT
0.510 ± 0.009	OUR EVALUATION (Produced by HFLAV)				
0.510 ± 0.009	OUR AVERAGE				
$0.541 \pm 0.026 \pm 0.014$		[1] SIRUNYAN	2018BY	CMS	pp at 8 TeV
$0.5134 \pm 0.0110 \pm 0.0057$		[2, 3] AAIJ	2015G	LHCB	pp at 7, 8 TeV
$0.509 \pm 0.008 \pm 0.012$		[4] AAIJ	2014G	LHCB	pp at 8 TeV

Λ_b lifetime





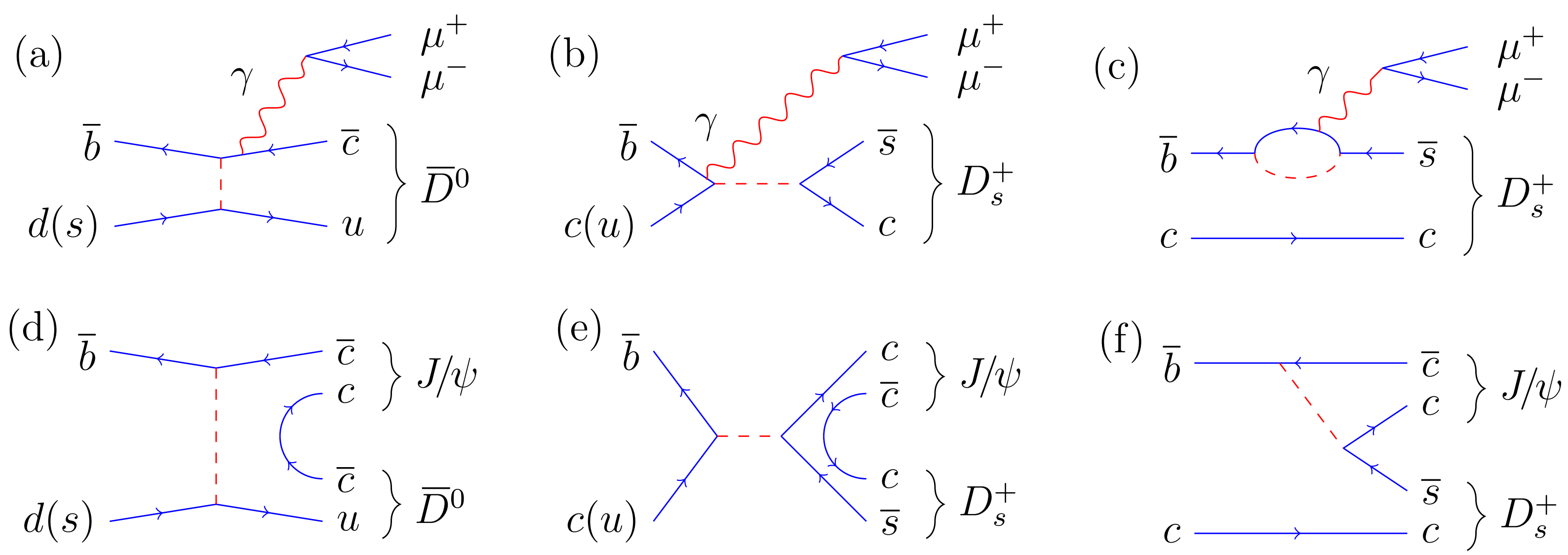
- CMS (and LHCb) most precise measurements from Run2
- CMS Run3 statistics 15x, cross section 2x
    - potential breakthrough

Λ_b^0 MEAN LIFE PDGID:S040T

See b-baryon Admixture section for data on b-baryon mean life average over species of b-bary

VALUE (10^{-12} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.468 ± 0.009	**OUR EVALUATION**	(Produced by HFLAV)			
1.477 ±0.027 ±0.009		1 SIRUNYAN	2018BY	CMS	pp at 8 TeV
1.415 ±0.027 ±0.006		2 AAIJ	2014E	LHCB	pp at 7 TeV
1.479 ±0.009 ±0.010		3 AAIJ	2014U	LHCB	pp at 7, 8 TeV

$b \to s\ell\ell$ in $B_c \to D_s\mu\mu$ decays

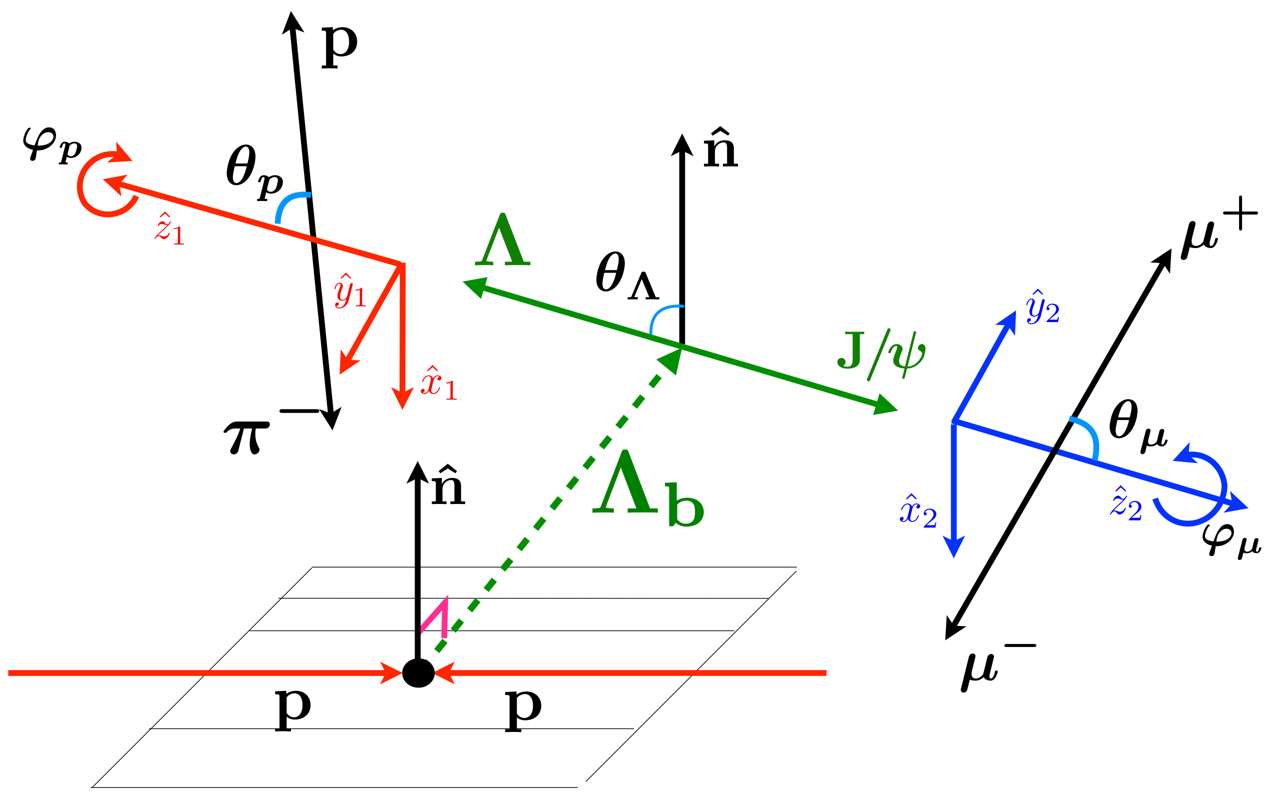


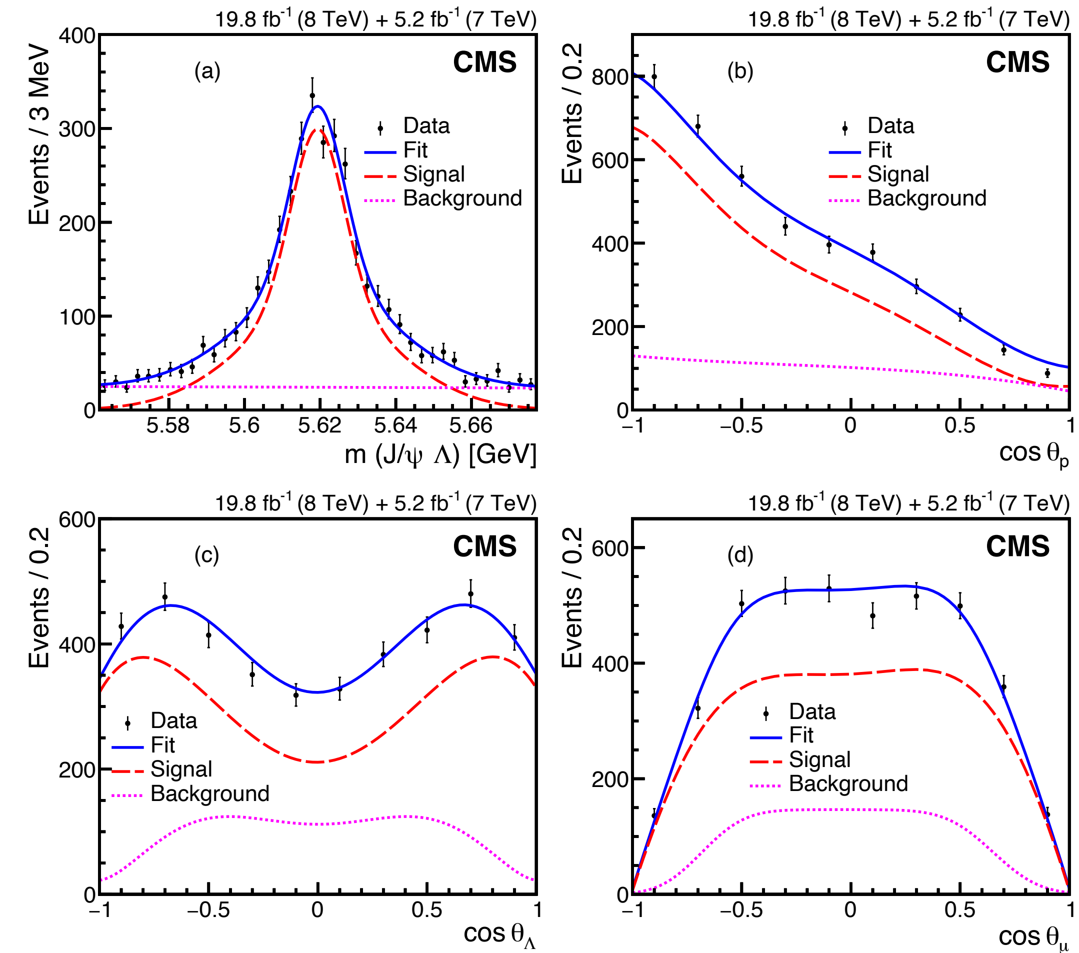
LHCb
10.1007/JHEP02(2024)032

- cited yesterday by Biplab
- LHCb exclusion already in the 10^{-7} - 10^{-8} range, close to SM exp.
- **with Run 3 data, CMS can access these decays, potentially competitive**

PRD 97 (2018) 072010

$\Lambda_b \to \Lambda^0 \mu\mu$ angular analysis and $d\mathscr{B}/dq^2$

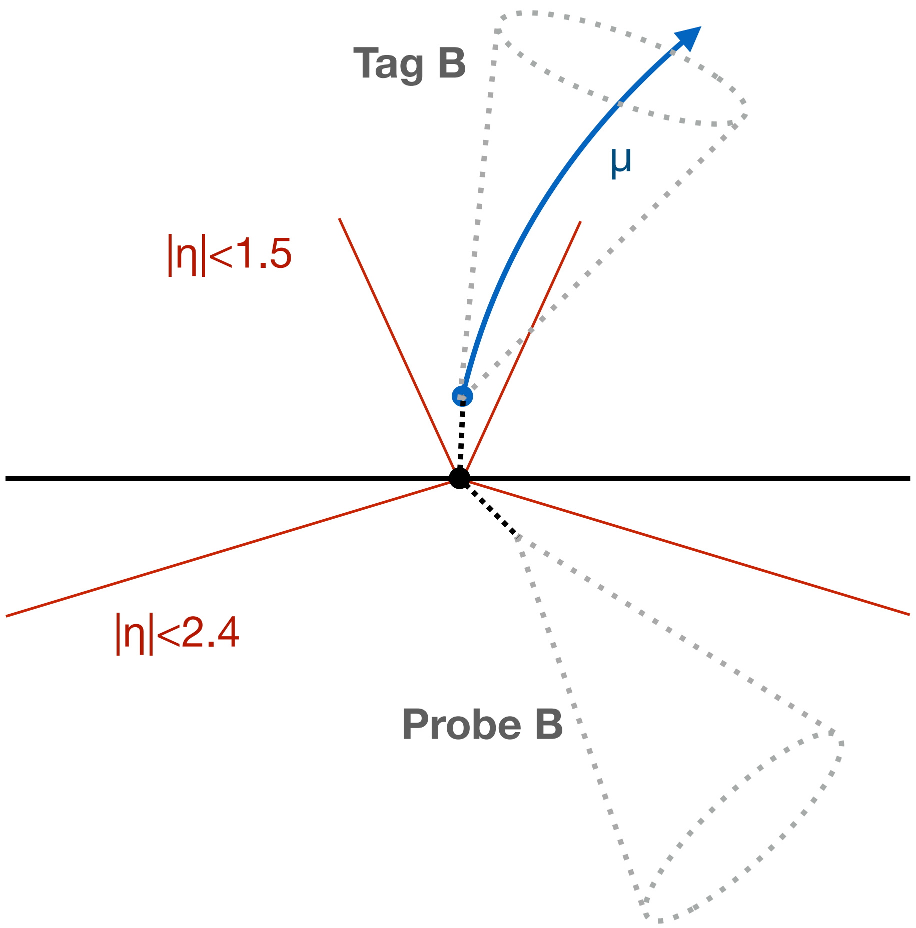




- $b \to \ell\ell$ **in baryons complementary to mesons**
- **CMS Run1**
  - stat limited (~6000 candidates), not full angular
  - as before, in Run3 15x lumi and 2x cross section

Other semileptonic?

- thanks to single muon triggers, CMS can also access e.g.
  - $\Lambda_b \rightarrow \Lambda_c^{(*)} \mu\nu$
  - $\Xi_b \rightarrow \Xi_c^{(*)} \mu\nu$
  - ...



- time an person power limited

Conclusions

- **CMS Run3 offers many opportunities for B_c and b-baryon** thanks to single-muon, dimuon (and dielectron parking dataset)
  - **B_c, Λ_b lifetimes (also omega b and differences between baryons)**
  - Λ_b differential branching fractions and angular observables
  - updated R(J/Ψ), with today's experimental know how and recent LQCD FF
  - semileptonic b-baryon decays
- rich spectroscopy program (not covered here)

Backup

PRL 122 (2019) 132001

PRD 102 (2020) 092007

Excited $B_c^{*+}(2S)$ and $B_c^{+}(2S)$