Rare decays at ATLAS and CMS

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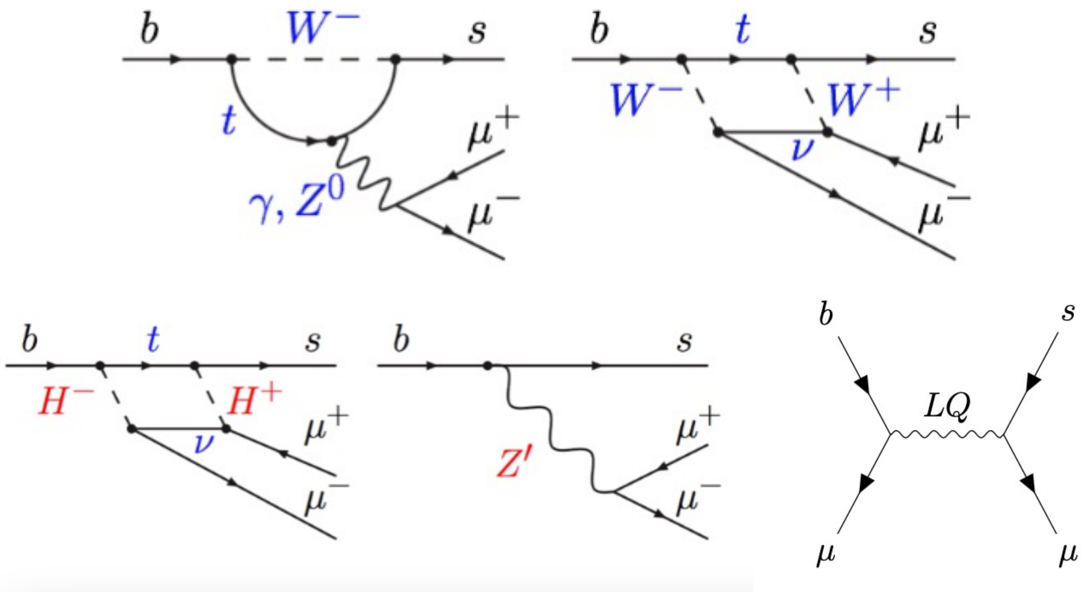
Probing CLF anomalies at ATLAS and CMS

- **b→s$\ell^+\ell^-$ suppressed at tree level in the SM,** further suppression by CKM and helicity
- Rare decay but theoretical predictions extremely precise
- **Ideal playground for NP, that can show up in**
  - Enhancement/suppression of BR
  - Modification of the angular distributions of the decay products



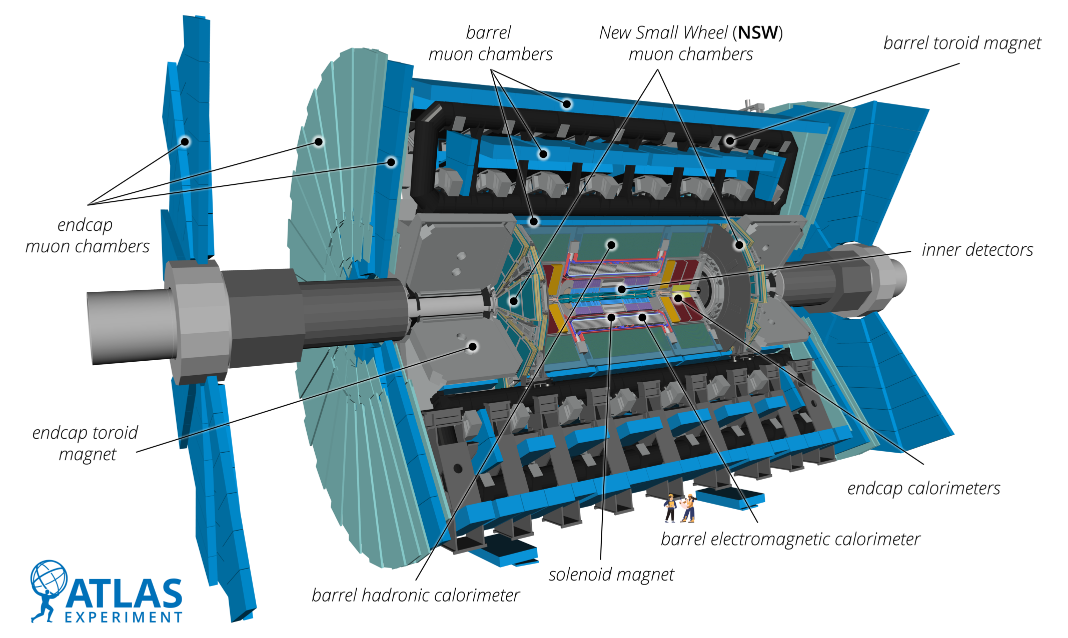
- **Up to 2022,** combining the results of B decays involving muon pairs**: preference for NP of 5-7σ compared to the SM, mostly driven by LHCb.**

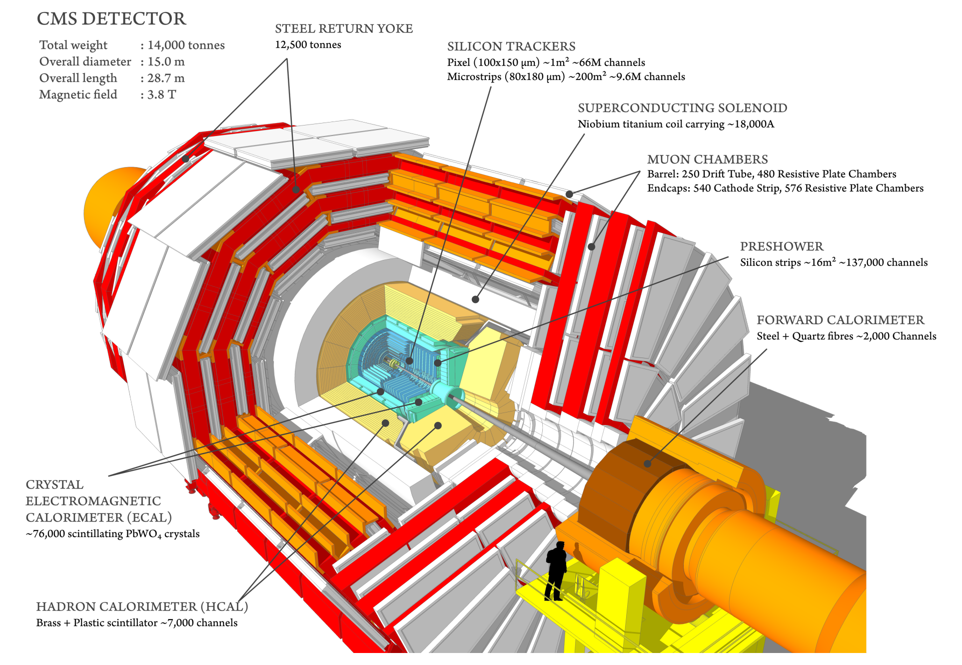
- **Anomalous magnetic moment of the muon** has been argued to possibly have a joint origin with the anomalies in B-meson decays (arXiv:2103.13991)

ATLAS and CMS studies:

- ➢ $B^0_{(s)}$ BR and lifetime
- ➢ B→K$\mu\mu$ angular distributions
- ➢ η →4μ decay

ATLAS and CMS Features & Techniques



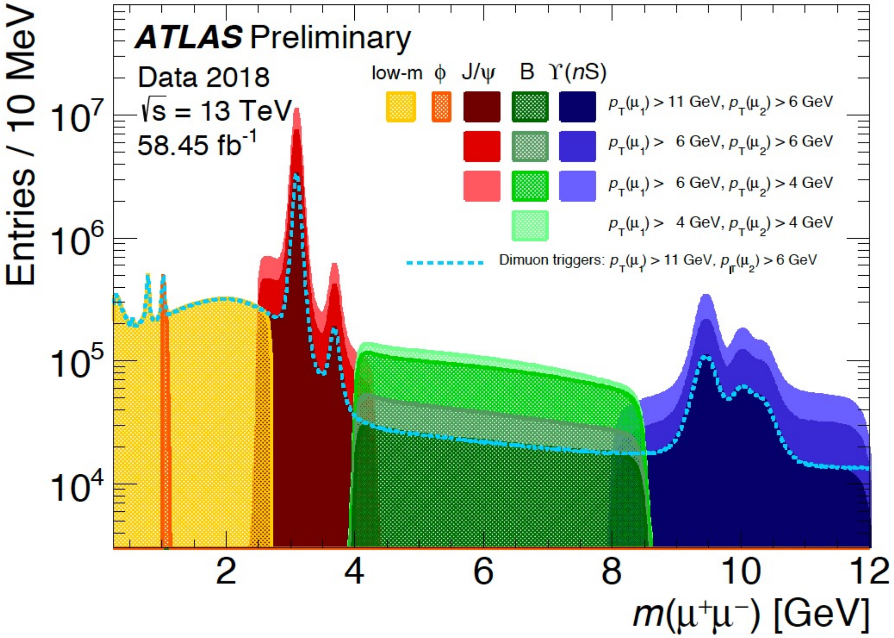


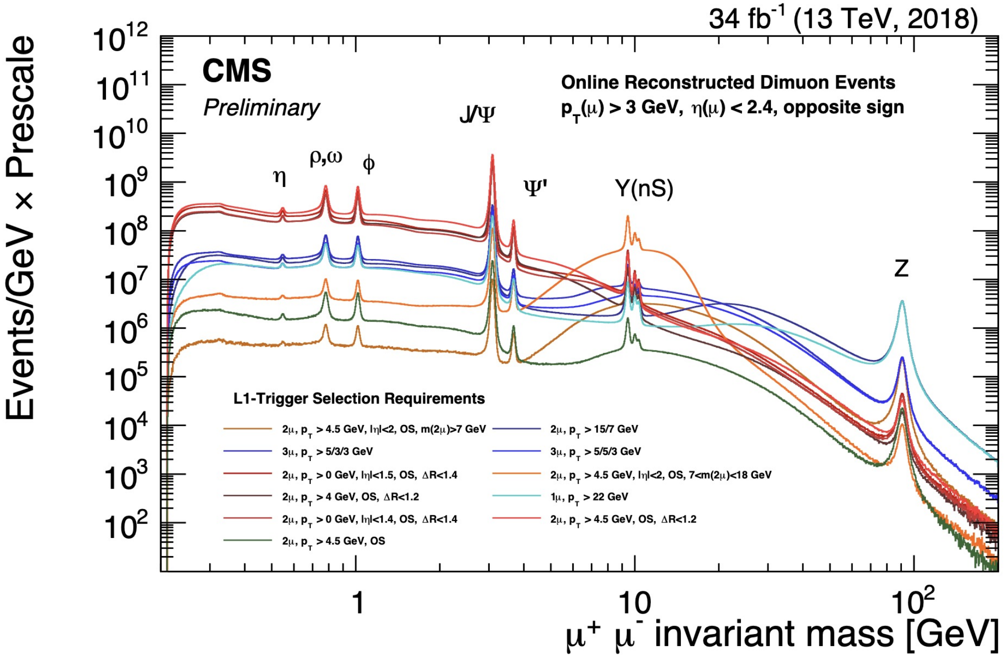
Compared to Belle, BaBar: Copious production of B_s, B_c, Λ_b → **high statistics** for searches for rare decays

Compared to LHCb:
- – central acceptance for tracks ($|\eta| \lesssim 2.5$)
- – Operated at full LHC pileup rate (up to ~60 collisions/BX) → higher lumi but complex environment
- – Weak-to-nonexistent hadron particle ID
- – Kinematic acceptance effectively puts pT cut on parent hadrons

B-Physics programme at ATLAS & CMS

- Data: Run 2 $\mathscr{L}\sim 140\ \mathrm{fb}^{-1}$ pp collisions at $\sqrt{s} = 13$ TeV (2016-18)
- «**Standard**» **trigger** program focused mostly on muon final states
- «**Scouting**» **triggers** collecting events with a set of loose-selection and high-rate
- Other approaches:
  - CMS B-parking Run 2 data collecting huge unbiased ($\sim 10^{10}$) b-hadron events
  - Di-electron triggers in Run 2 at ATLAS





Nevertheless … Some results still based on Run 1 dataset

Selected results for rare decay searches

- **Measurement of the $B_s^0 \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu^+\mu^-$**
  - Full Run2 (New, arXiv:2212.10311)
  - Run 1+ 2015, 2016 (JHEP 04 (2019) 098)

Covered in this talk

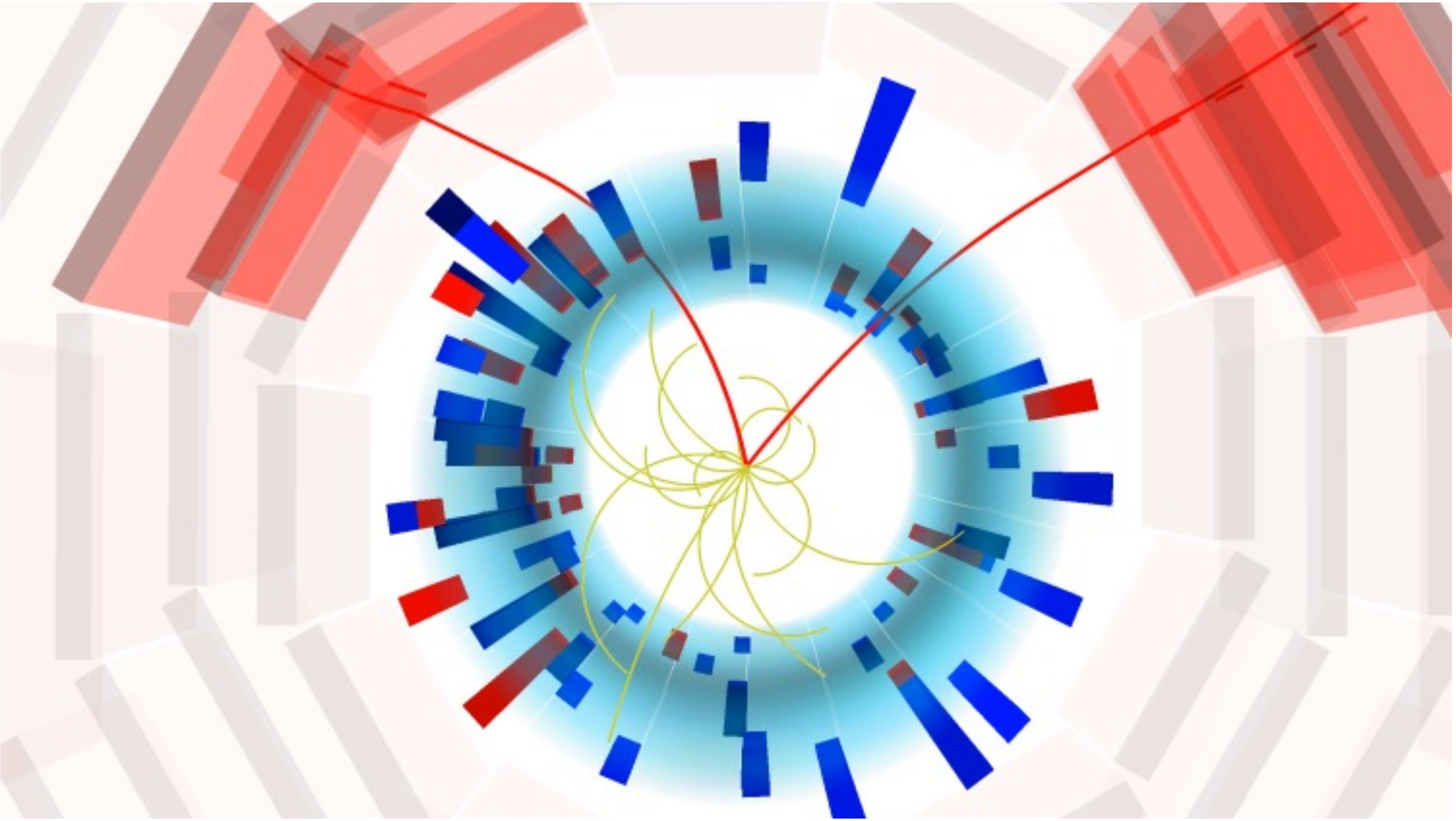
- **Angular analysis of B→Kμμ decays in *pp* collisions at $\sqrt{s}$=8 TeV**
  - $B^0 \to K^*\mu^+\mu^-$: JHEP 10 (2018) 047
  - $B^0 \to K^*\mu^+\mu^-$ PLB 781 (2018) 517 (P_1, P'_5), PLB 753 (2016) 424 (A_{FB} , F_L)
  - $B^+ \to K^+\mu^+\mu^+$ PRD 98 (2018) 112011
  - $B^+ \to K^{*+}\mu^+\mu^-$ JHEP 04 (2021) 124

Covered in this talk

- **First observation of the rare 4μ decay of the η meson**
  - Full Run2 (New, arXiv:2305.04904)

Covered in this talk

Measurement of the $B_s^0 \longrightarrow \mu^+\mu^-$ decay properties and search for the $B^0 \longrightarrow \mu^+\mu^-$

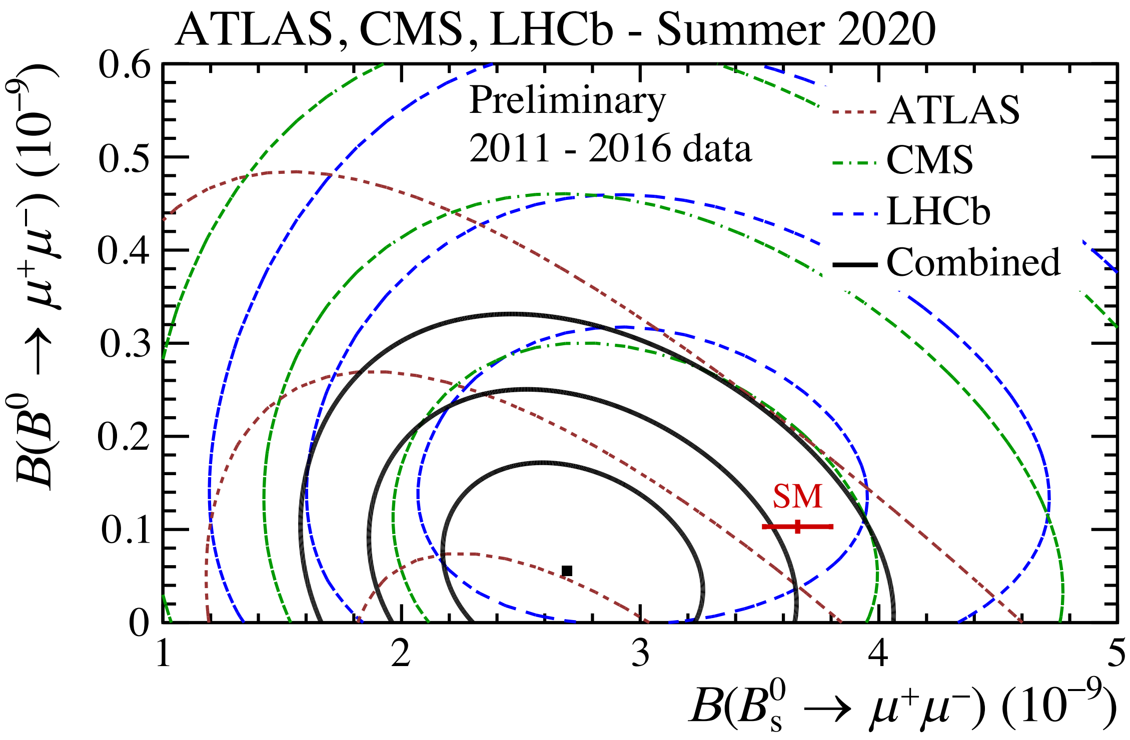


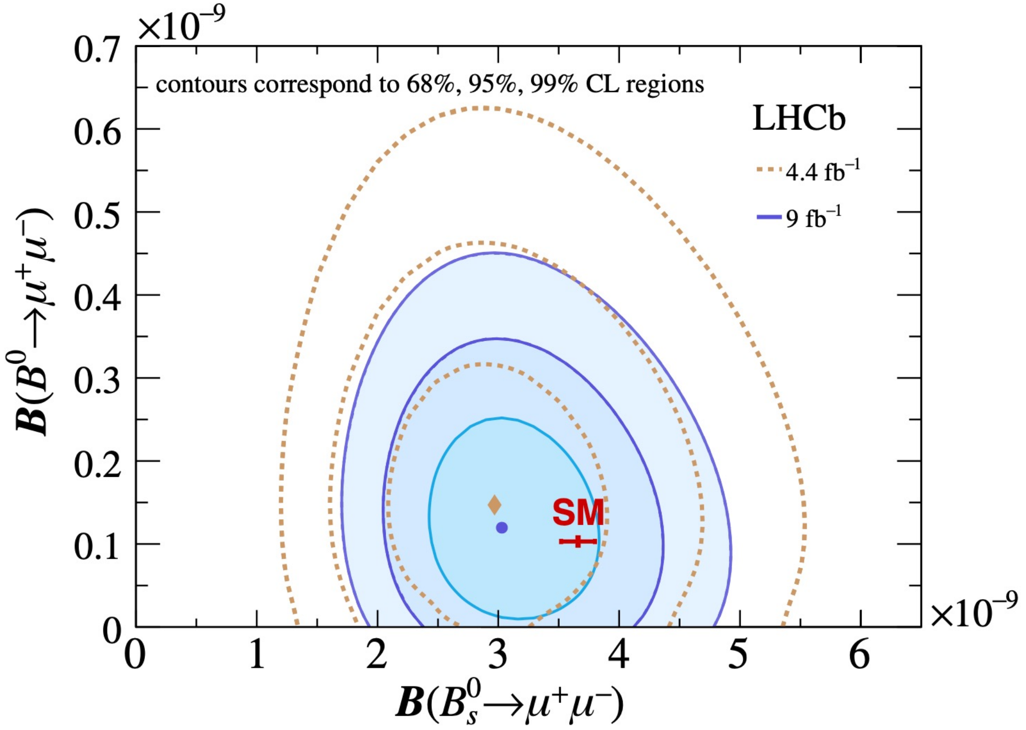
ATLAS and CMS have same analysis strategy, most recent analysis updated (CMS) reported here

$B_s^0 \to \mu^+\mu^-$ state of the art

2020 ATLAS, CMS, LHCb combination: ~2σ tension w.r.t. the SM prediction
New LHCb result based on full 9/fb data set reduces the tension to ~1σ

CMS PAS BPH-20-003





LHCb PRL 128 (2022) 041801

$B_s^0 \longrightarrow \mu^+\mu^-$ analysis strategy

- BR normalized using $B^+ \longrightarrow J/\psi\, K^+$ or $B_s^0 \longrightarrow J/\psi\phi$ to reduce uncertainties

$$\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = \mathcal{B}(\mathrm{B^+} \to \mathrm{J}/\psi\mathrm{K^+}) \frac{N_{\mathrm{B_s^0}\to\mu^+\mu^-}}{N_{\mathrm{B^+}\to\mathrm{J}/\psi\mathrm{K^+}}} \frac{\varepsilon_{\mathrm{B^+}\to\mathrm{J}/\psi\mathrm{K^+}}}{\varepsilon_{\mathrm{B_s^0}\to\mu^+\mu^-}} \frac{f_\mathrm{u}}{f_\mathrm{s}},$$

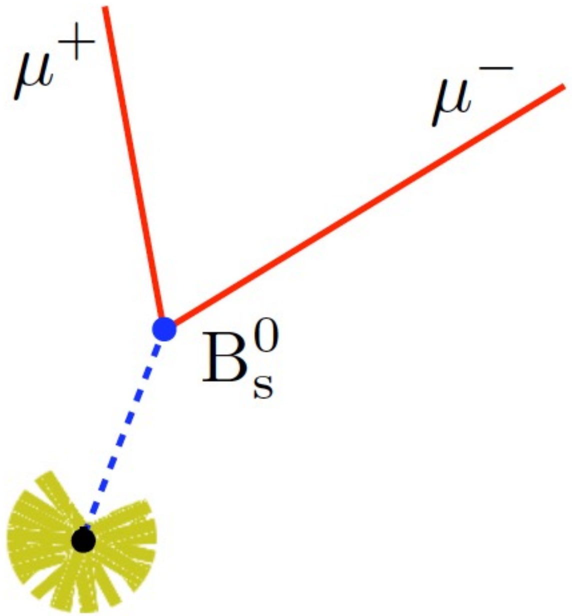
external input

alternative

$$\left(\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = \mathcal{B}(\mathrm{B_s^0} \to \mathrm{J}/\psi\phi(1020)) \frac{N_{\mathrm{B_s^0}\to\mu^+\mu^-}}{N_{\mathrm{B_s^0}\to\mathrm{J}/\psi\phi(1020)}} \frac{\varepsilon_{\mathrm{B_s^0}\to\mathrm{J}/\psi\phi(1020)}}{\varepsilon_{\mathrm{B_s^0}\to\mu^+\mu^-}},\right)$$

$$\mathcal{B}(\mathrm{B^0} \to \mu^+\mu^-) = \mathcal{B}(\mathrm{B^+} \to \mathrm{J}/\psi\mathrm{K^+}) \frac{N_{\mathrm{B^0}\to\mu^+\mu^-}}{N_{\mathrm{B^+}\to\mathrm{J}/\psi\mathrm{K^+}}} \frac{\varepsilon_{\mathrm{B^+}\to\mathrm{J}/\psi\mathrm{K^+}}}{\varepsilon_{\mathrm{B^0}\to\mu^+\mu^-}} \frac{f_\mathrm{u}}{f_\mathrm{d}},$$

external input

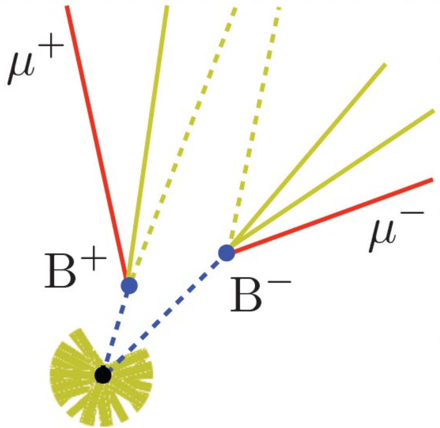


- Dimuon triggers, loose selections applied (SV requirements, invariant mass)
- MVA for background suppression and categorization.

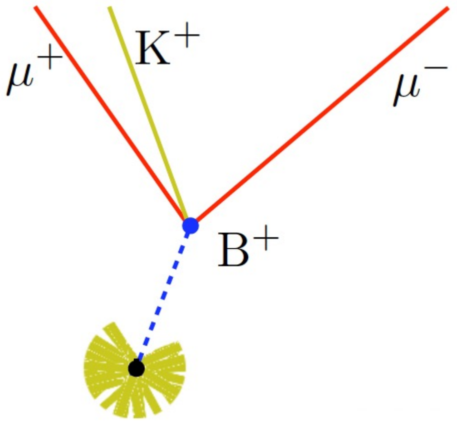
- BR and lifetime measurement extracted from simultaneous unbinned ML fits.

$B_s^0 \longrightarrow \mu^+\mu^-$ background contaminations

Combinatorial background *(two muons from two different heavy quarks)*



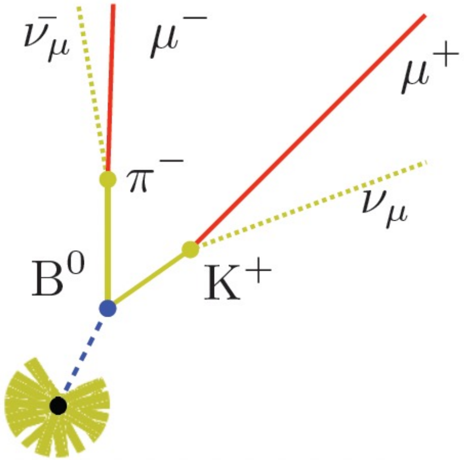
Partially reconstructed semileptonic decays *(both muons from the same B meson)*



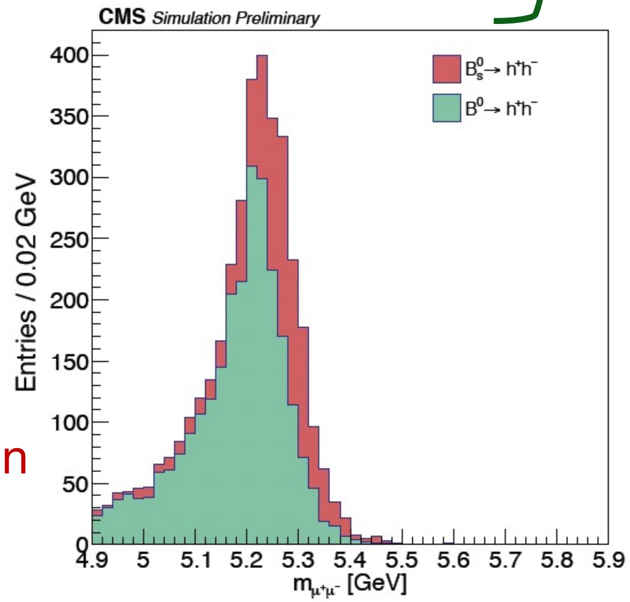
MVA to suppress dominant backgrounds

Peaking background from $\mu \rightarrow \pi/K$ misidentification

$(B^0 \longrightarrow K^+\pi^-,\ B_s^0 \longrightarrow K^+K^-)$



- mostly decays in flight $\mathrm{K}/\pi \longrightarrow \mu\nu_\mu$
- fake rates measured in $K_s \longrightarrow \pi\pi$ and $\phi \longrightarrow KK$ control samples
- used MVA-based muon identification



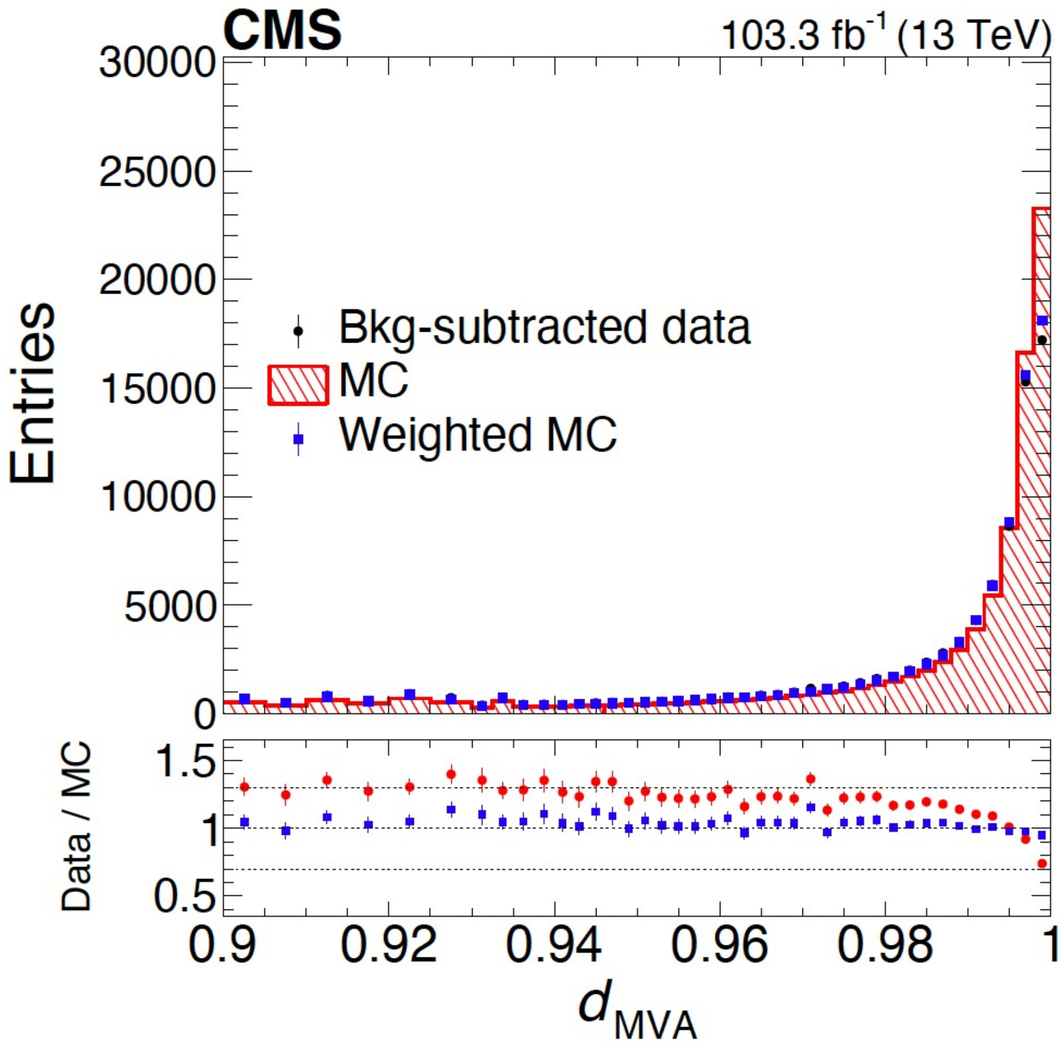
$B_s^0 \longrightarrow \mu^+\mu^-$: multivariate analysis

- Exploit several weak discrimination variables with a BDT (XGBoost)

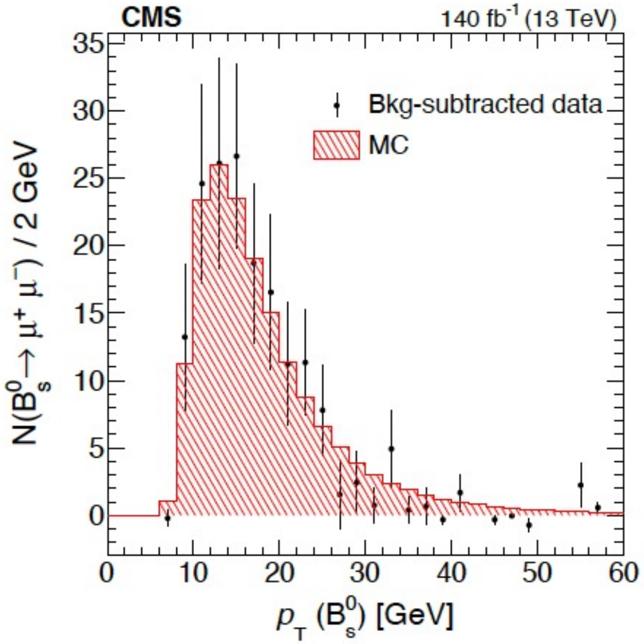
- Features:
  - **pointing angles** (2D and 3D)
    → all non-two-body backgrounds
  - **SV** (quality and displacement)
    → combinatorial
  - **isolation** (sum of p_T surrounding the signal)
    → semi-leptonic decays

- Training: MC signal sample, data from mass sidebands

- **BDT score validated on $B^+ \longrightarrow J/\psi\, K^+$**
  - Corrections factors derived with two different techniques and applied to $B_s \longrightarrow \mu^+\mu^-$ MC

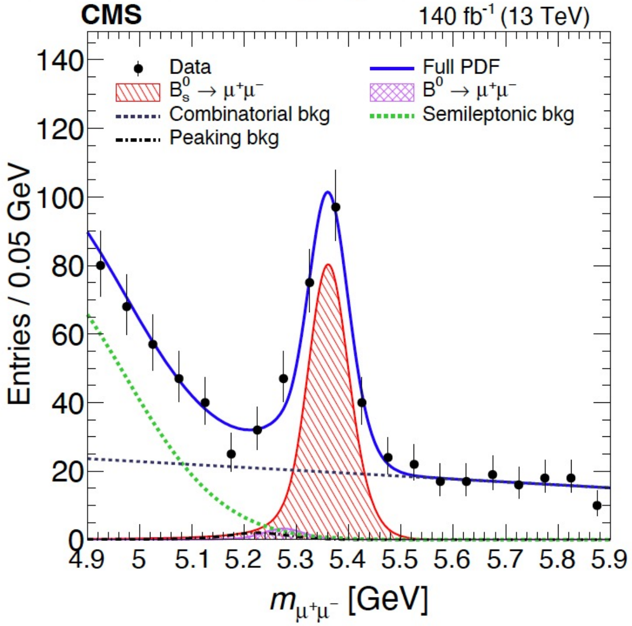


$B_s^0 \longrightarrow \mu^+\mu^-$ systematics and fit



Signal extracted by a 2D fit of the di-muon mass and its uncertainty.

Effect	$B_s^0 \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$
f_s/f_u ratio of the B meson production fractions	3.5%	—
d_{MVA} correction	2–3%	
Tracking efficiency (per kaon)	2.3%	
Trigger efficiency	2–4%	
Fit bias	2.2%	4.5%
Pileup	1%	
Vertex quality requirement	1%	
$B^+ \to J/\psi K^+$ shape uncertainty	1%	
$B^+ \to J/\psi K^+$ branching fraction	1%	



External inputs in the BF measurement:

- $\mathcal{B}(B^+ \to J/\psi K^+) = (1.020 \pm 0.019) \times 10^{-3}$,
- $\mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.961 \pm 0.033) \times 10^{-2}$,
- $f_s/f_u = 0.231 \pm 0.008$

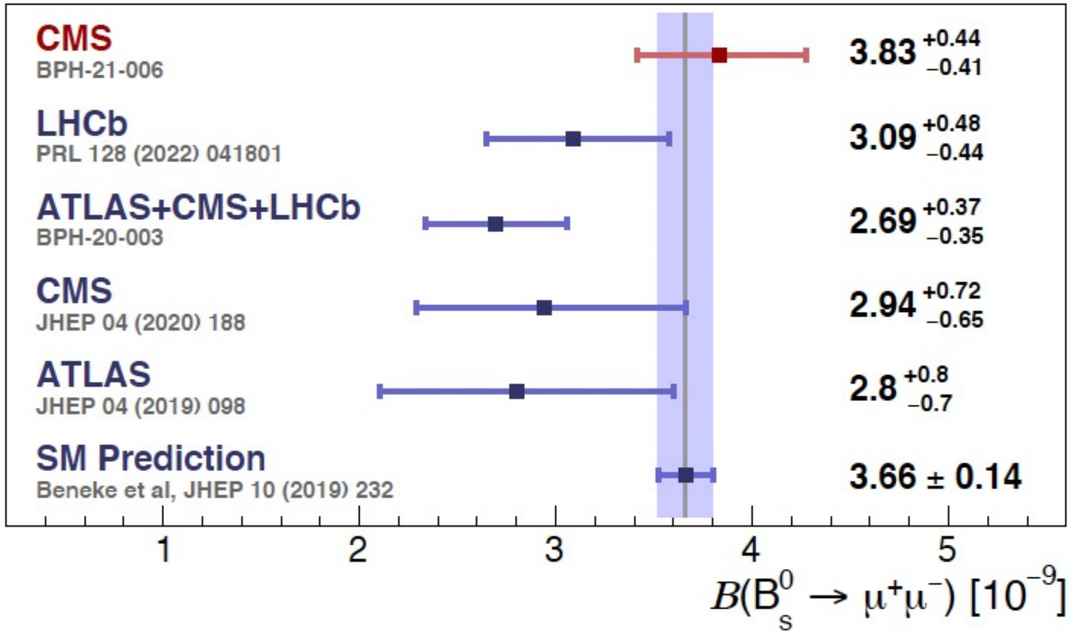
from LHCb: PRD 104 (2021) 032005
fs/fu measured by CMS is in agreement: https://arxiv.org/abs/2212.02309 (submitted to PRL)

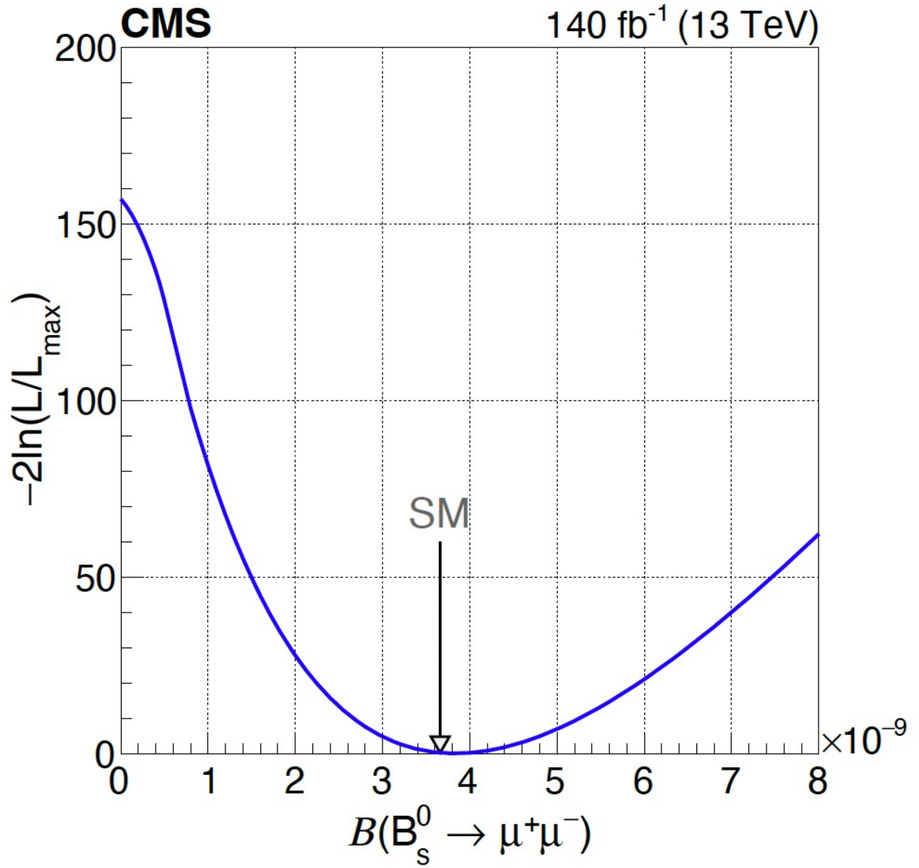
$B_s^0 \longrightarrow \mu^+\mu^-$ branching fraction

$$\boxed{\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\ (\mathrm{stat})\ ^{+0.19}_{-0.16}\ (\mathrm{syst})\ ^{+0.14}_{-0.13}\ (f_\mathrm{s}/f_\mathrm{u})\right] \times 10^{-9}}$$

Alternative using $B_s^0 \longrightarrow J/\psi\phi$:

$$\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = \left[4.02^{+0.40}_{-0.38}\ (\mathrm{stat})\ ^{+0.28}_{-0.23}\ (\mathrm{syst})\ ^{+0.18}_{-0.15}\ (\mathcal{B})\right] \times 10^{-9}$$

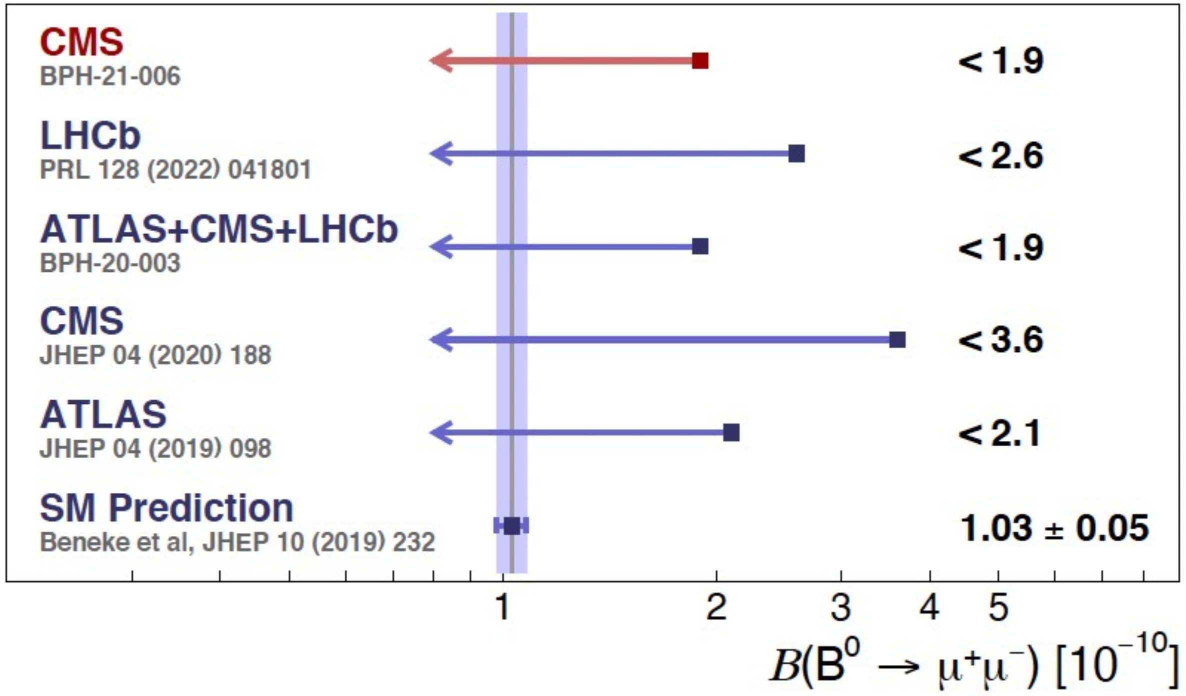


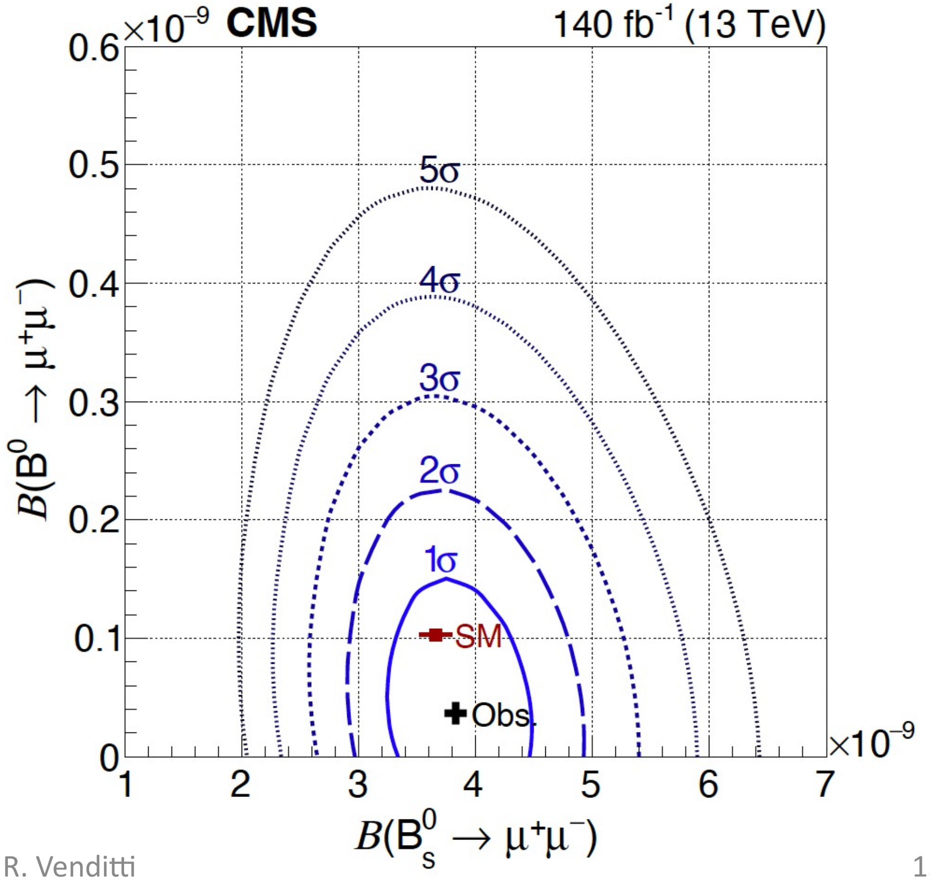


Upper limits on $B^0 \longrightarrow \mu^+\mu^-$ branching fraction

$$\boxed{\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at } 95\% \text{ CL}}$$

$$\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-) < 1.5 \times 10^{-10} \text{ at } 90\% \text{ CL}$$

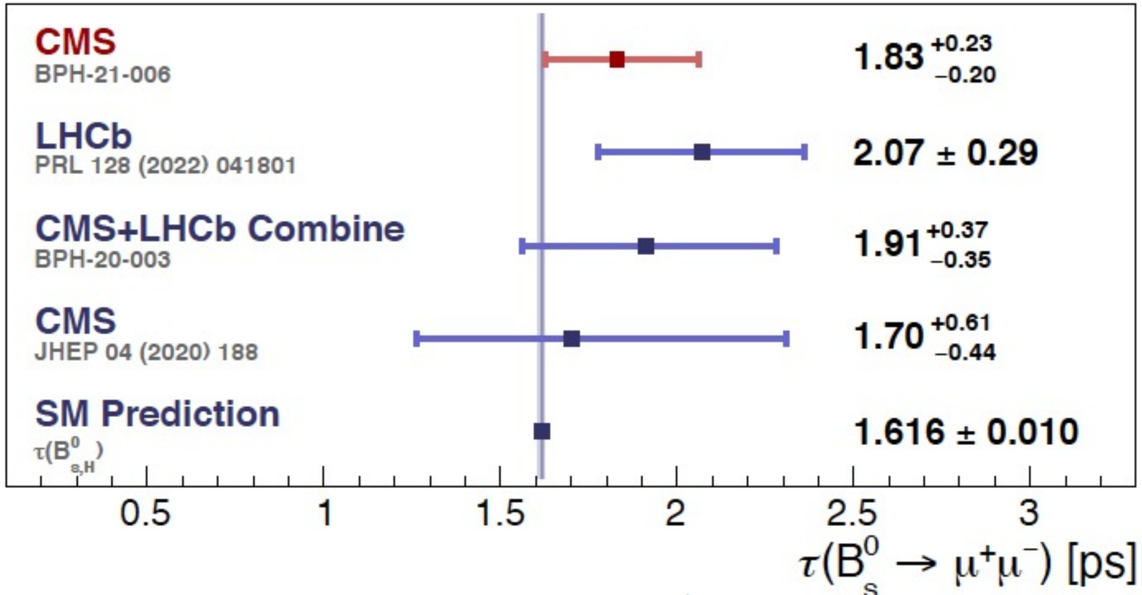




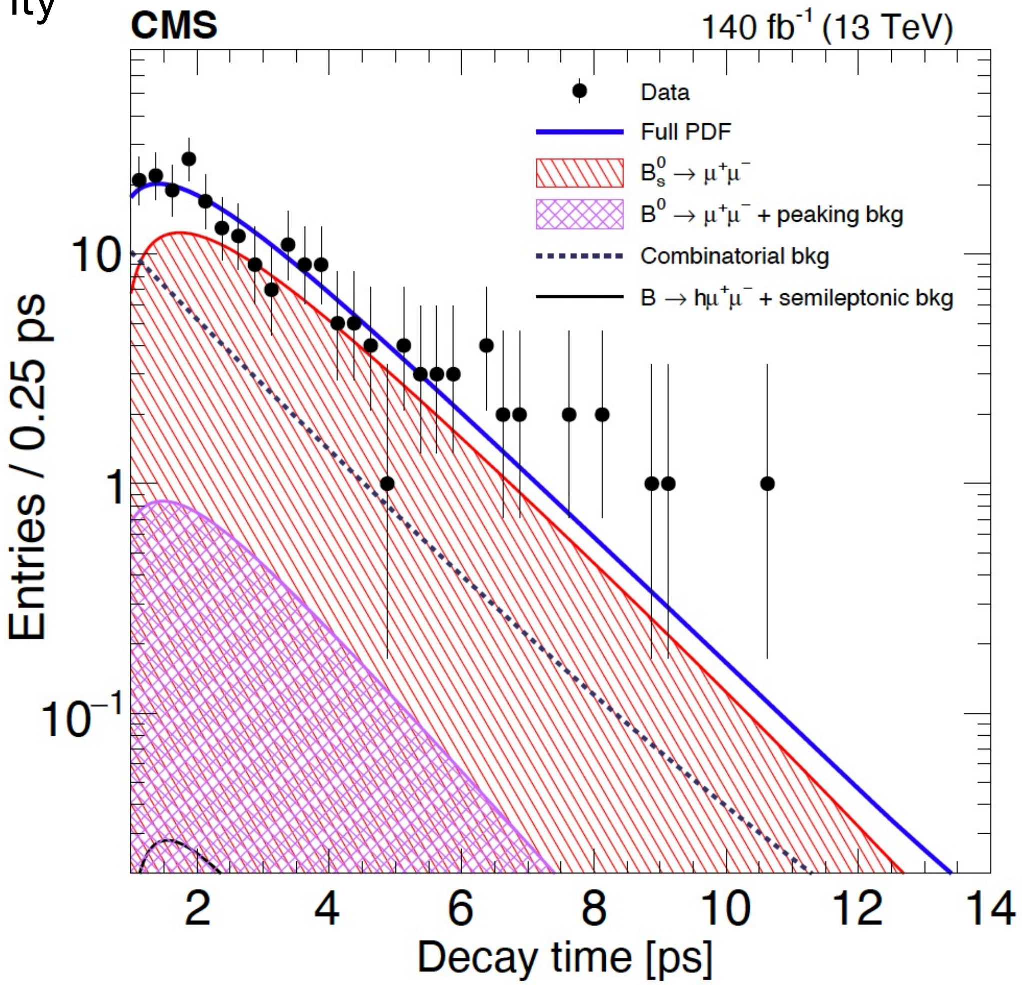
B_s^0 lifetime measurement

Signal extracted from 3D fit in mass, decay time and its uncertainty

Effect	2016a	2016b	2017	2018
Lifetime fit bias	0.04	0.04	0.05	0.04
Decay time distribution mismodeling	0.10	0.06	0.02	0.02
Efficiency modeling	0.01			
Lifetime dependence	0.01			
Total	0.11	0.07	0.05	0.04



Precision comparable to the B_s^0 mass eigenstates separation!

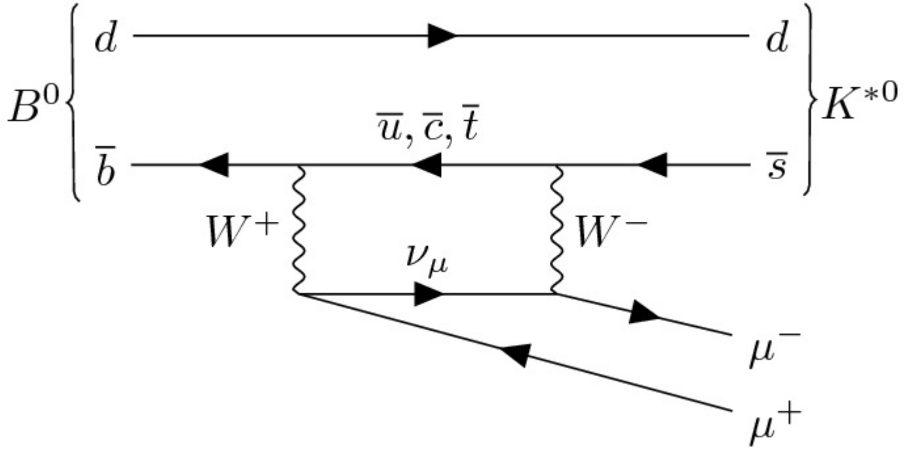


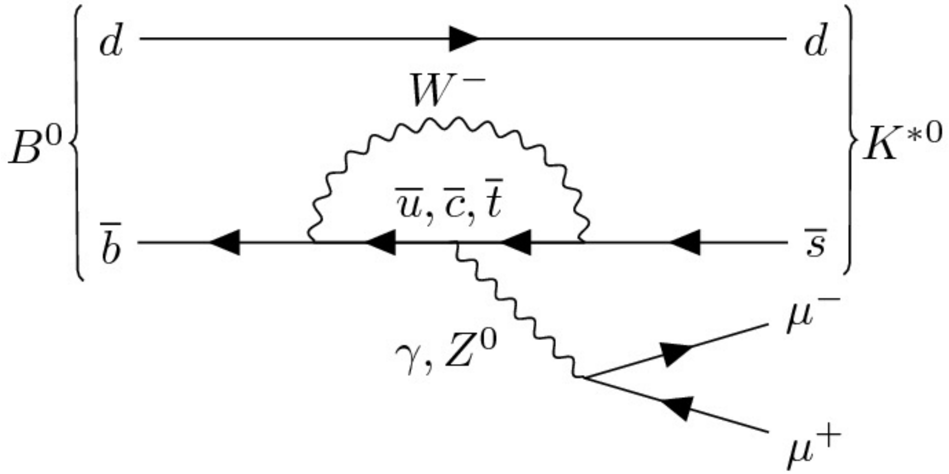
$$\boxed{\tau = 1.83\,^{+0.23}_{-0.20}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{syst})\text{ ps}}$$

Angular analysis in semi-muonic rare B decays

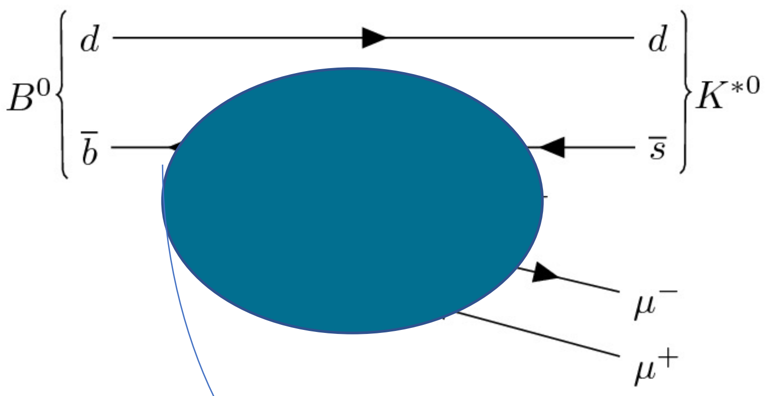
- **Angular analysis of B →K*ℓℓ is an ideal playground to test FCNC**
  - large range of observables with reduced theory uncertainties wrt BR measurements
- Higher statistics for $K^{*0} \to K^+\pi^-$ over $K^{*+} \to K^0_S\pi^+$
  - More complete **K^{*0} μμ** angular analyses done by both experiments
  - High statistics but less angular information available for $K^+\mu\mu$

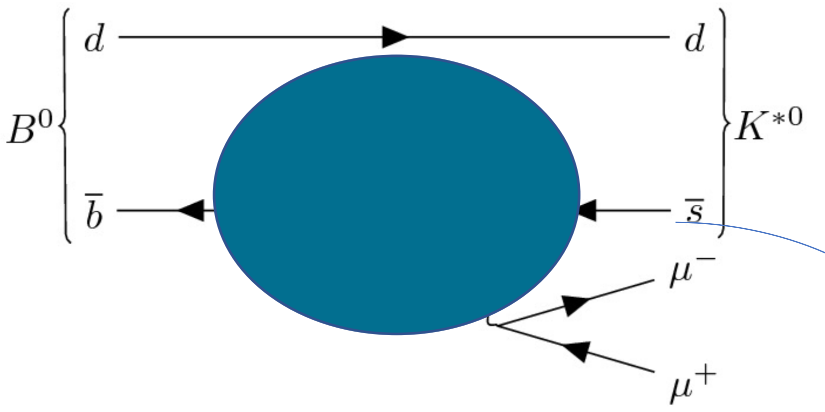
CMS and ATLAS performed similar measurements in semi-muonic final state in Run 1 dataset
(20 fb^{-1}@ $\sqrt{s}$=8 TeV)





Angular analysis in semi-muonic rare B decays

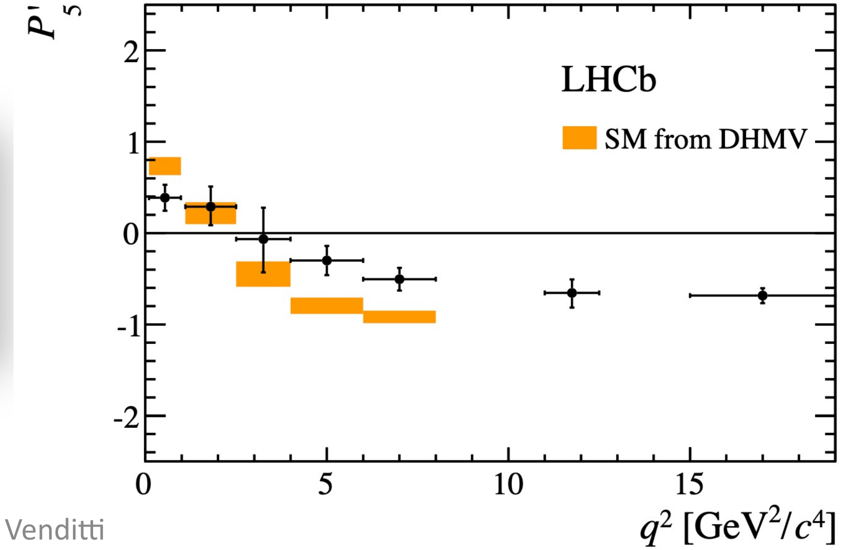




Angular coefficients of the final state amplitude are extracted in the Pi’ and Si’ basis to assess deviations of the (predicted Wilson coefficients) to the SM

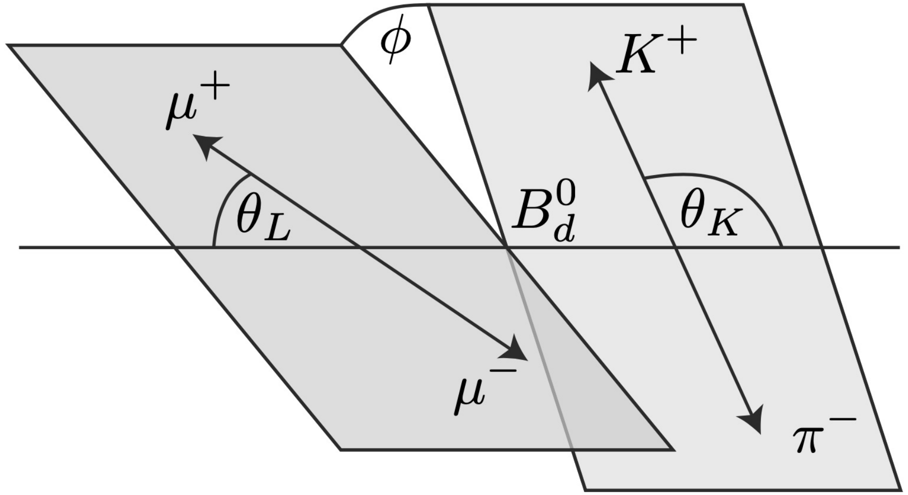
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{e^2}{16\pi^2} \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i') + h.c.$$

O(~3σ) discrepancy in P’$_5$ wrt SM in LHCb and Belle results



JHEP02 (2016) 104

$B^0 \to K^*\mu^-\mu^+$ angular analysis strategy



$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_L\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Bigg[\frac{3(1-\boxed{F_L})}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_L$$
$$-F_L\cos^2\theta_K\cos 2\theta_L + \boxed{S_3}\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+\boxed{S_4}\sin 2\theta_K\sin 2\theta_L\cos\phi + \boxed{S_5}\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+\boxed{S_6}\sin^2\theta_K\cos\theta_L + \boxed{S_7}\sin 2\theta_K\sin\theta_L\sin\phi$$
$$+\boxed{S_8}\sin 2\theta_K\sin 2\theta_L\sin\phi + \boxed{S_9}\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Bigg].$$

F_L: fraction of longitudinally polarised K^* mesons

S_i :angular coefficients.

$$P_1 = \frac{2S_3}{1-F_L}$$
$$P_2 = \frac{2}{3}\frac{A_{FB}}{1-F_L}$$
$$P_3 = -\frac{S_9}{1-F_L}$$
$$P'_{j=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

- UML fit in bins of $q^2 \in [0.04, 6.0]$ GeV^2 to extract the signal parameters of interest (F_L , S_i or P'_i)
- Veto on $q^2 \in [0.98, 1.1]$ GeV^2 to remove ϕ(1020) contamination

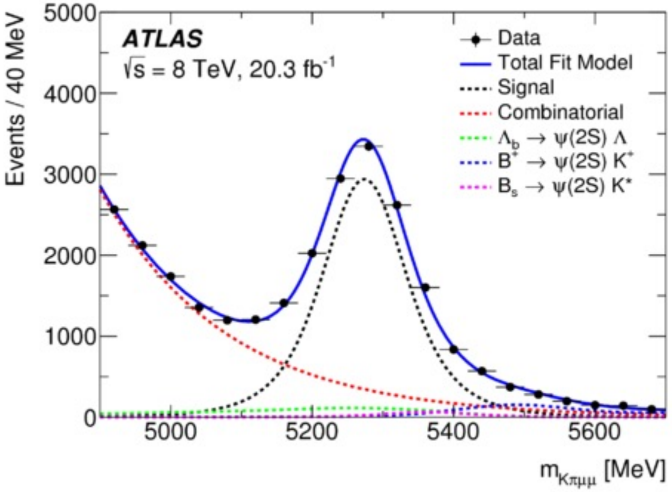
$B^0 \to K^* \mu^- \mu^+$ signal and background model

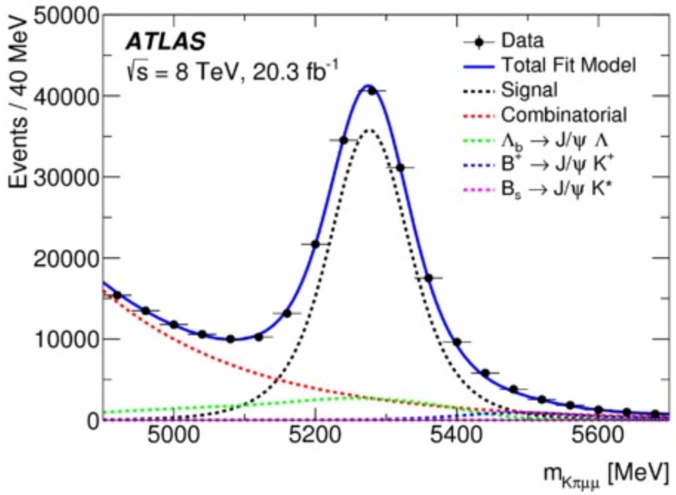
Signal Model

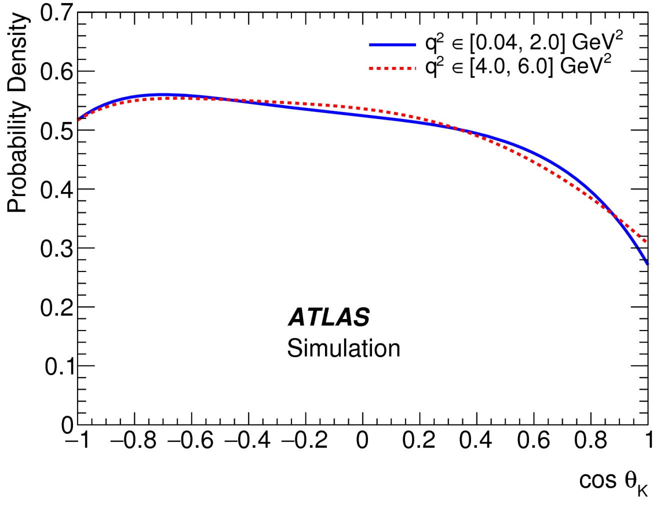
- Gaussian with width and mean extracted from Kcc control region
  - $B^0 \to K^* J/\psi$ ($q^2 \in [8, 11]$ GeV^2)
  - $B^0 \to K^* \psi(2S)$ ($q^2 \in [12, 15]$ GeV^2)
- Acceptance function modeled from MC
  - q^2 and angular distributions sculpted by the trigger and reconstruction efficiencies

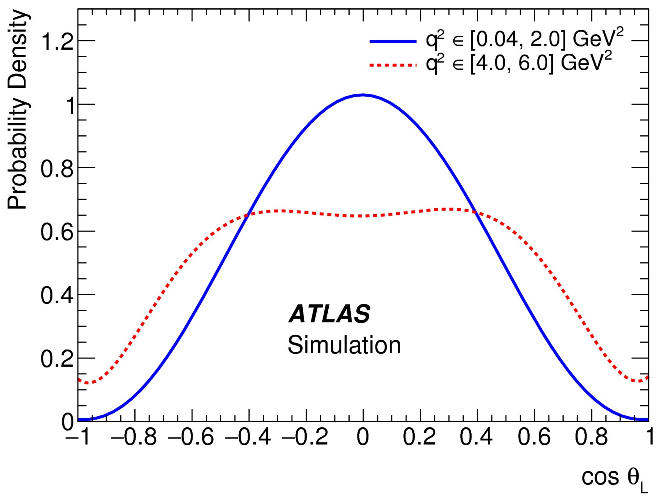
Background Model

- Mainly from combinatorial
  - Expo for the mass
  - Polynomial for the angular distributions
- Exclusive decays ($\Lambda_b \to \Lambda(1520)\mu\mu$, $\Lambda_b \to pK\mu\mu$, $B^+ \to K^{(*)+}\mu^+\mu^-$ and $B^0_s \to \phi\mu\mu$) accounted in the systematics









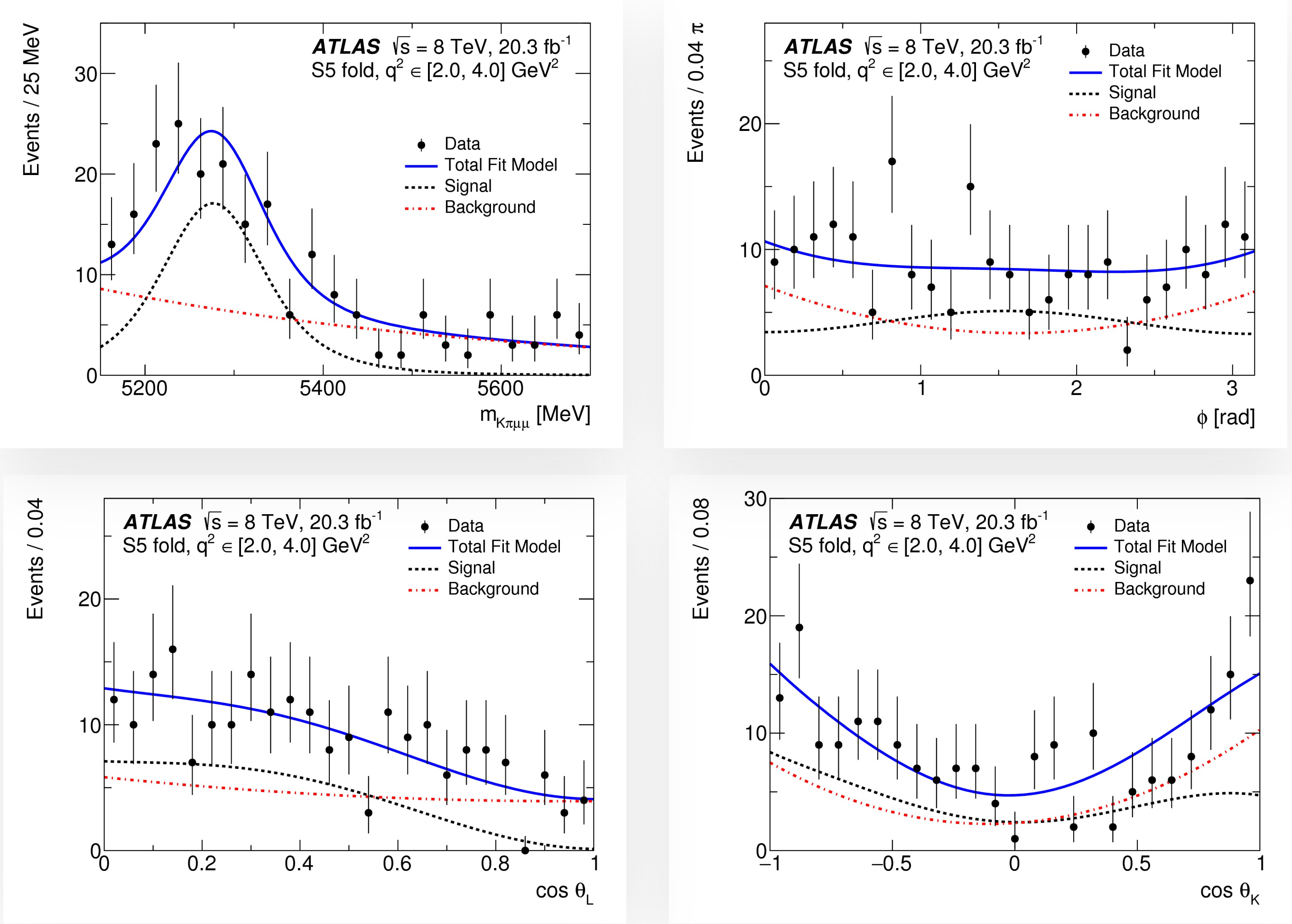
$B^0 \to K^*\mu^-\mu^+$ fit and systematics

Main systematics

- fake K* background and misrecontructed $B^+ \to K^+(\pi^+)\mu\mu$: Peak in $\cos\theta_K \sim 1$
- background from partially reconstructed $B \to D^0/D^+/D^+_s\ X$ decays → accumulation of events at $|\cos\theta_L| \sim 0.7$

Source	F_L	S_3	S_4	S_5	S_7	S_8
Combinatoric $K\pi$ (fake K^*) background	0.03	0.03	0.05	0.04	0.06	0.16
D and B^+ veto	0.11	0.04	0.05	0.04	0.01	0.06
Background pdf shape	0.04	0.04	0.03	0.03	0.03	0.01
Acceptance function	0.01	0.01	0.07	0.01	0.01	0.01
Partially reconstructed decay background	0.03	0.05	0.02	0.08	0.05	0.06
Alignment and B field calibration	0.02	0.04	0.05	0.04	0.04	0.04
Fit bias	0.01	0.01	0.02	0.03	0.01	0.05
Data/MC differences for p_T	0.02	0.02	0.01	0.01	0.01	0.01
S-wave	0.01	0.01	0.01	0.01	0.01	0.03
Nuisance parameters	0.01	0.01	0.01	0.01	0.01	0.01
Λ_b, B^+ and B_s background	0.01	0.01	0.01	0.01	0.01	0.01
Misreconstructed signal	0.01	0.01	0.01	0.01	0.01	0.01
Dilution	–	–	-	< 0.01	–	< 0.01

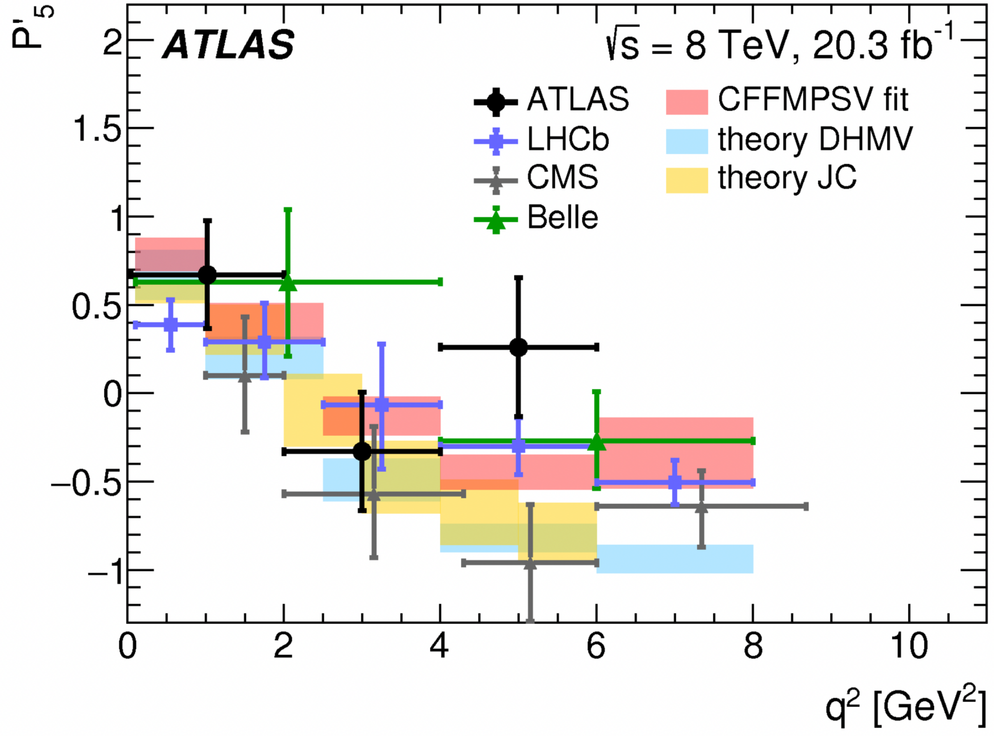
Example of fit results in the S_5 folding scheme

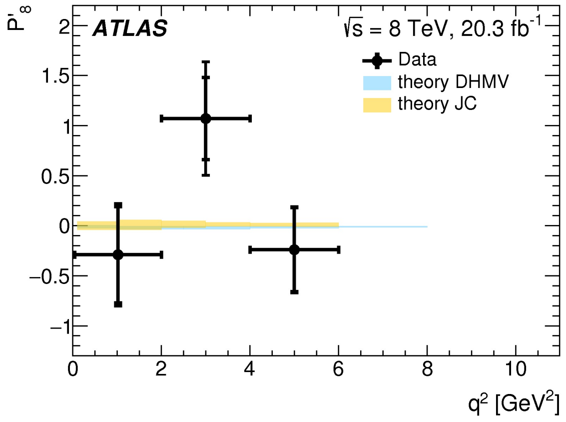


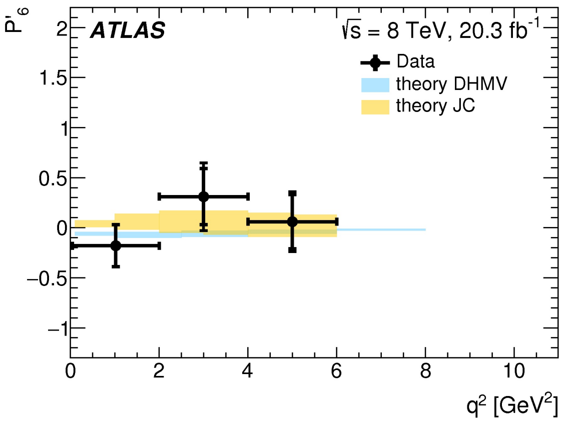
$B^0 \to K^* \mu^- \mu^+$ angular analysis results

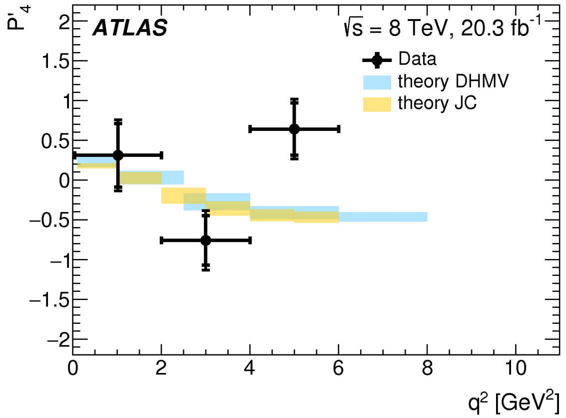
(Almost) consistent with SM predictions …

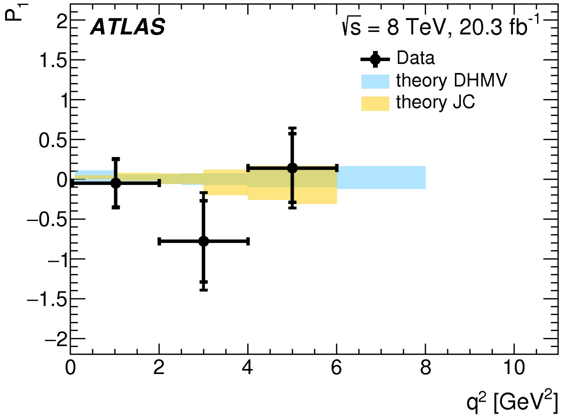
- 2.7 deviation from the SM prediction (DHMV, less significant for the other models) but still compatible with SM in 3σ in
  - P'_4 and P'_5 in [4.0, 6.0] GeV^2
  - P'_8 in $q^2 \in [2.0, 4.0]$ GeV^2





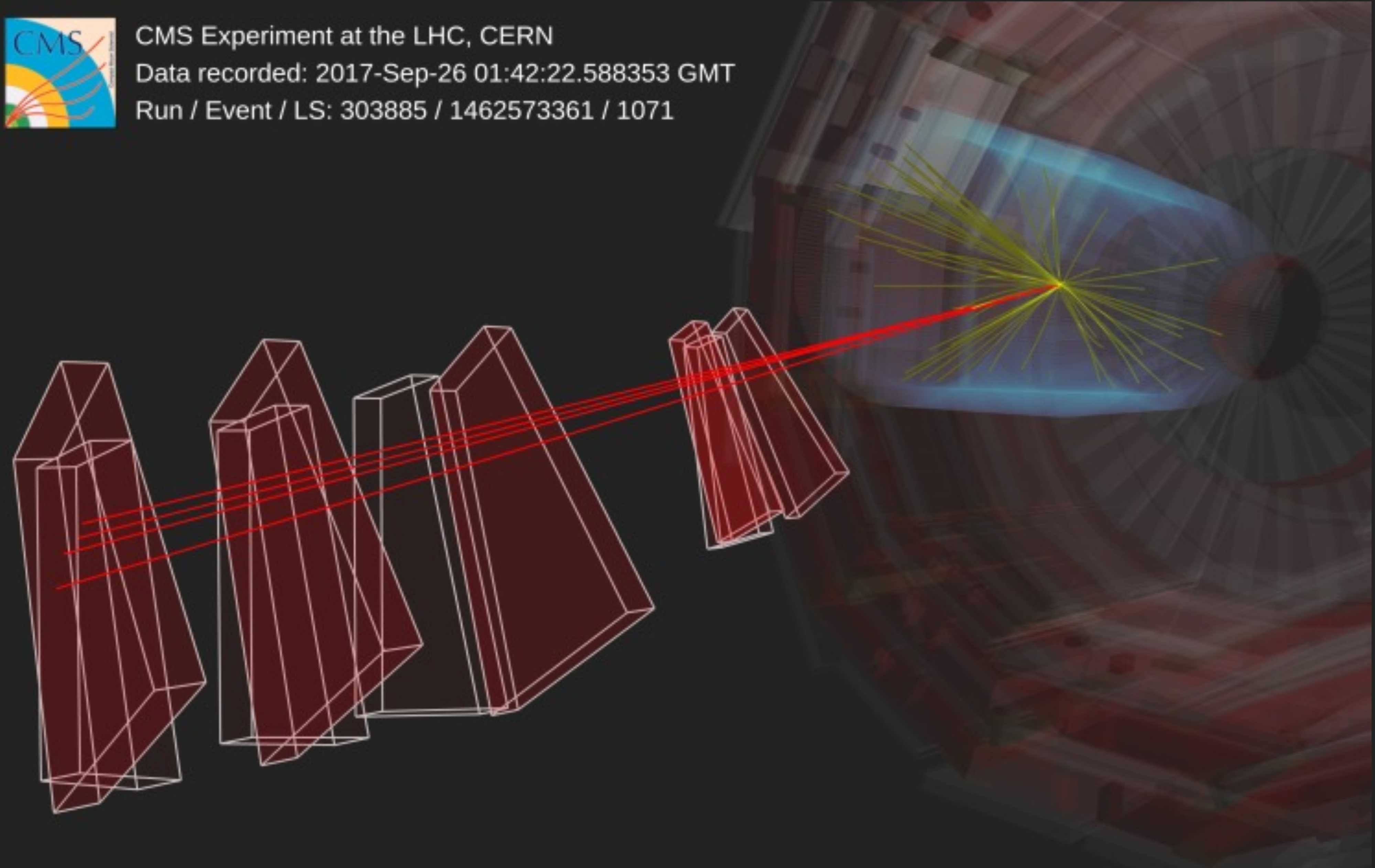






… and CMS and LHCb

First observation of the rare 4μ decay of the η meson

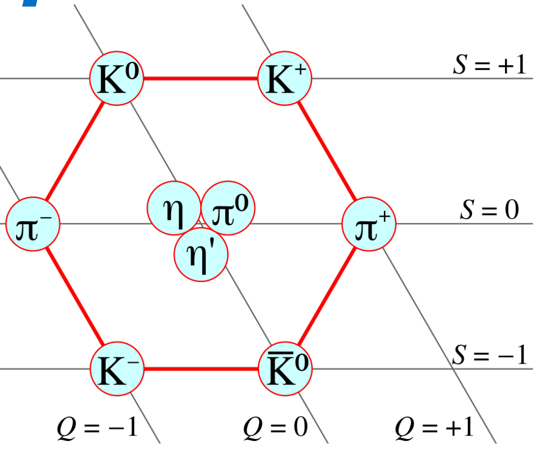


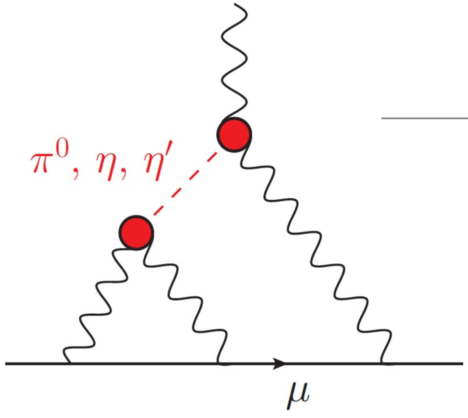
Leptonic radiative decays of the neutral pseudoscalars η and η'

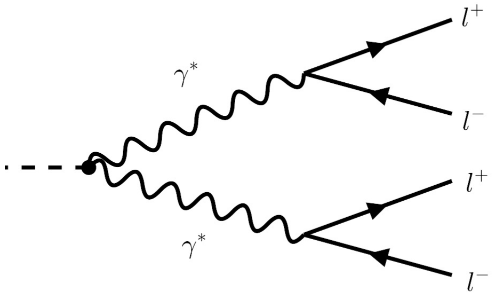
- Double Dalitz decays modes **not yet observed**

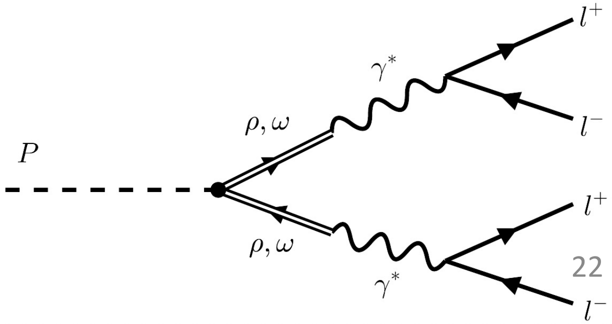
- **Important tests of the SM** (*Phys.Rept.* 945 (2022) 1)
  - light quark mass ratios,
  - $\eta - \eta'$ mixing parameters,
  - hadronic contributions to the anomalous magnetic moment of the muon (*Phys.Lett.B* 787 (2018) 111)

- **Sensitive to BSM** theories (*Rept.Prog.Phys.* 86 (2023) 1)
  - searches for hidden photons, light Higgs scalars, and axion-like particles
    - complementary to worldwide efforts to detect new light particles below the GeV mass scale
  - tests of discrete symmetry violation



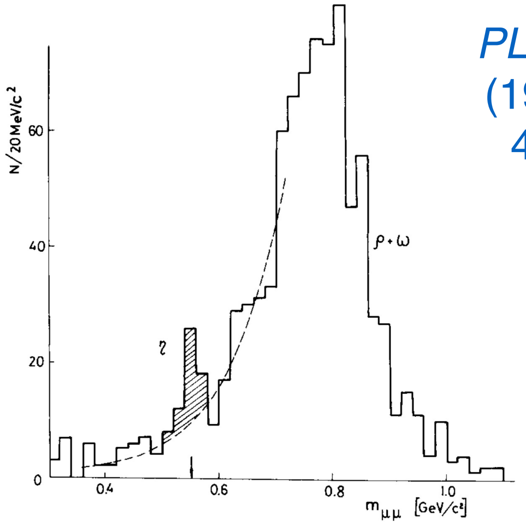






η leptonic decays: state of the art

SEPR $\eta \to 2\mu$ observation (1980)
$\sim 2\times10^7$ η's produced

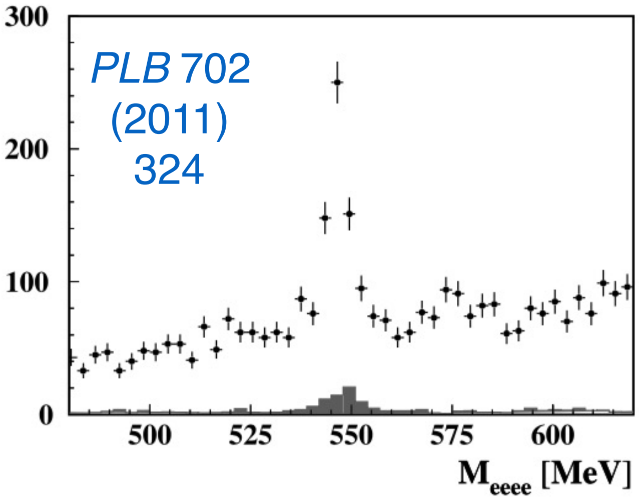


PLB 97 (1980) 471

Charged modes PDG 2022

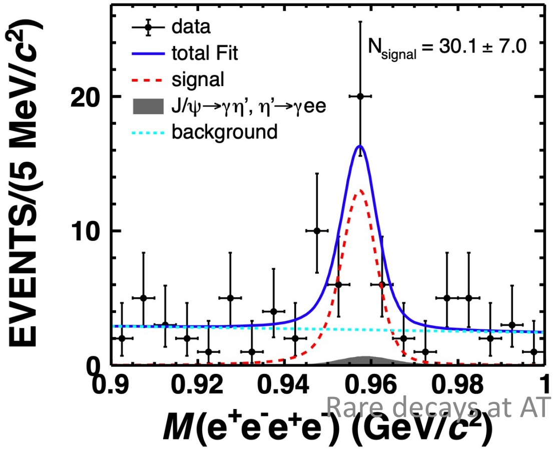
Γ_8	charged modes	(27.89 ± 0.29) %	S=1.2
Γ_9	$\pi^+\pi^-\pi^0$	(22.92 ± 0.28) %	S=1.2
Γ_{10}	$\pi^+\pi^-\gamma$	(4.22 ± 0.08) %	S=1.1
Γ_{11}	$e^+e^-\gamma$	$(6.9\pm0.4)\times10^{-3}$	S=1.3
Γ_{12}	$\mu^+\mu^-\gamma$	$(3.1\pm0.4)\times10^{-4}$	
Γ_{13}	e^+e^-	$< 7\times10^{-7}$	CL=90%
Γ_{14}	$\mu^+\mu^-$	$(5.8\pm0.8)\times10^{-6}$	
Γ_{15}	$2e^+2e^-$	$(2.40\pm0.22)\times10^{-5}$	
Γ_{16}	$\pi^+\pi^-e^+e^-(\gamma)$	$(2.68\pm0.11)\times10^{-4}$	
Γ_{17}	$e^+e^-\mu^+\mu^-$	$< 1.6\times10^{-4}$	CL=90%
Γ_{18}	$2\mu^+2\mu^-$	$< 3.6\times10^{-4}$	CL=90%

$\eta \to 4e$ (KLOE 2011, BESIII 2022)
$\sim 5\times10^7$ η's produced



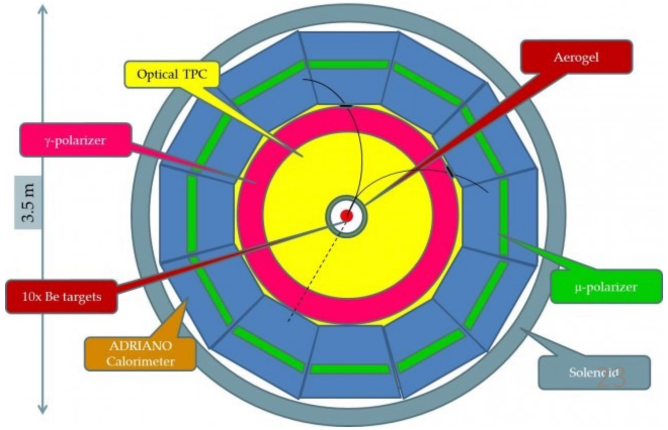
PLB 702 (2011) 324

Phys.Rev.D 105 (2022) 11



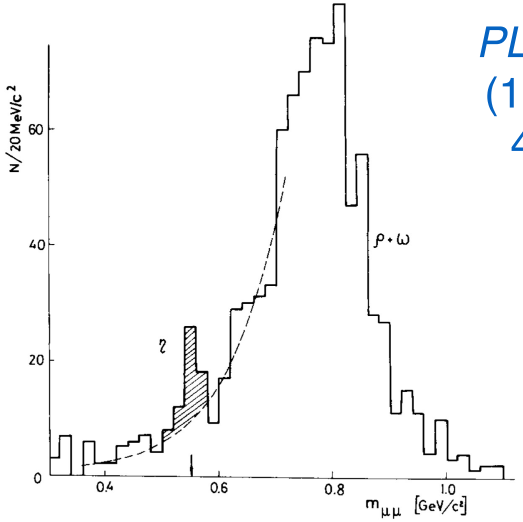
proposed experiment
2022 Snowmass Summer Study

REDTOP at Fermilab
Rare Eta Decays To Observe new Physics
$\sim 10^{13}$ η's/year



η leptonic decays: state of the art

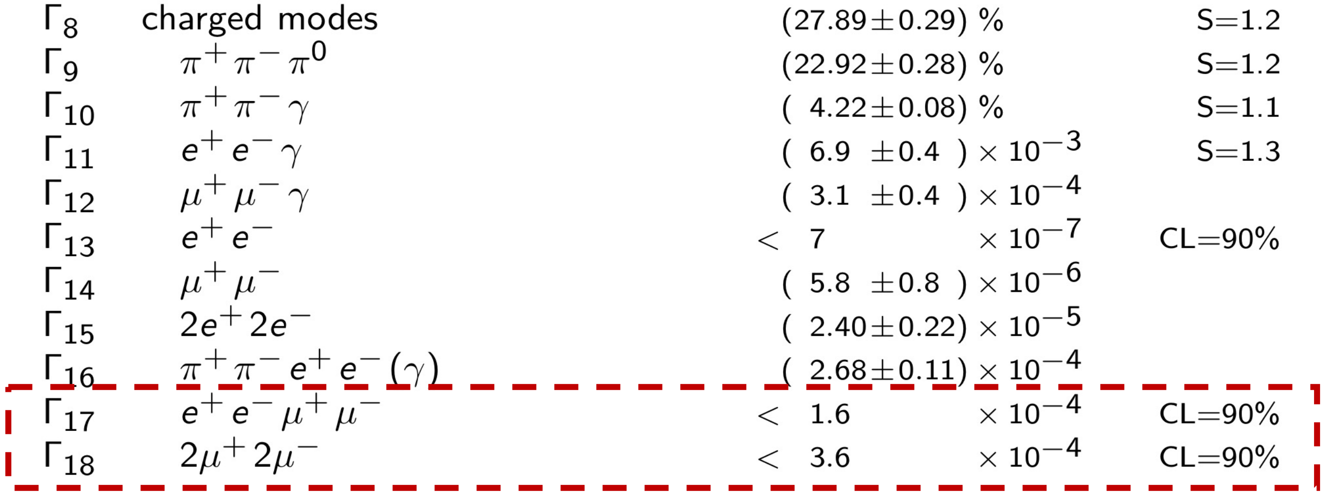
SEPR $\eta \to 2\mu$ observation (1980)
$\sim 2\times10^{7}$ η's produced



PLB 97 (1980) 471

Charged modes

PDG 2022



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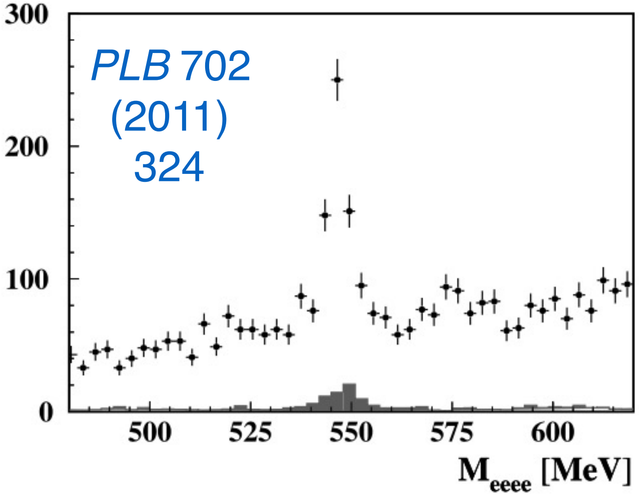
Γ_{18}	$2\mu^+2\mu^-$	$< 3.6\times10^{-4}$	CL=90%

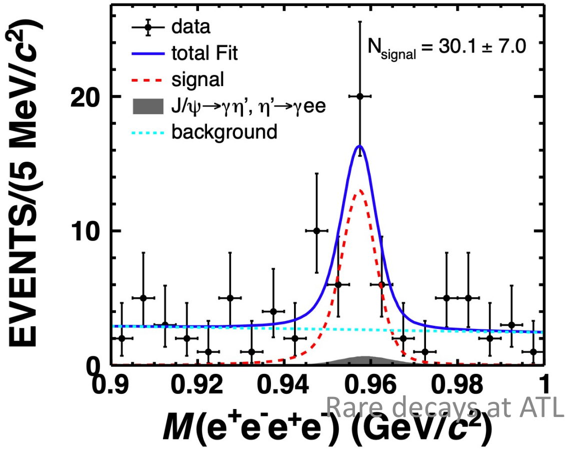
CMS: 4.5 M $\eta \to 2\mu$ events / 101 fb^{-1}
$\sim 10^{12}$ η's recorded!

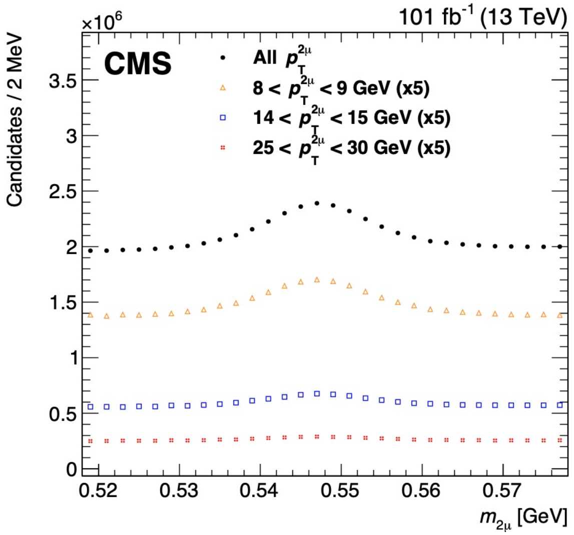
$\eta \to 4e$ (KLOE 2011, BESIII 2022)
$\sim 5\times10^{7}$ η's produced



PLB 702 (2011) 324

Phys.Rev.D 105 (2022) 11



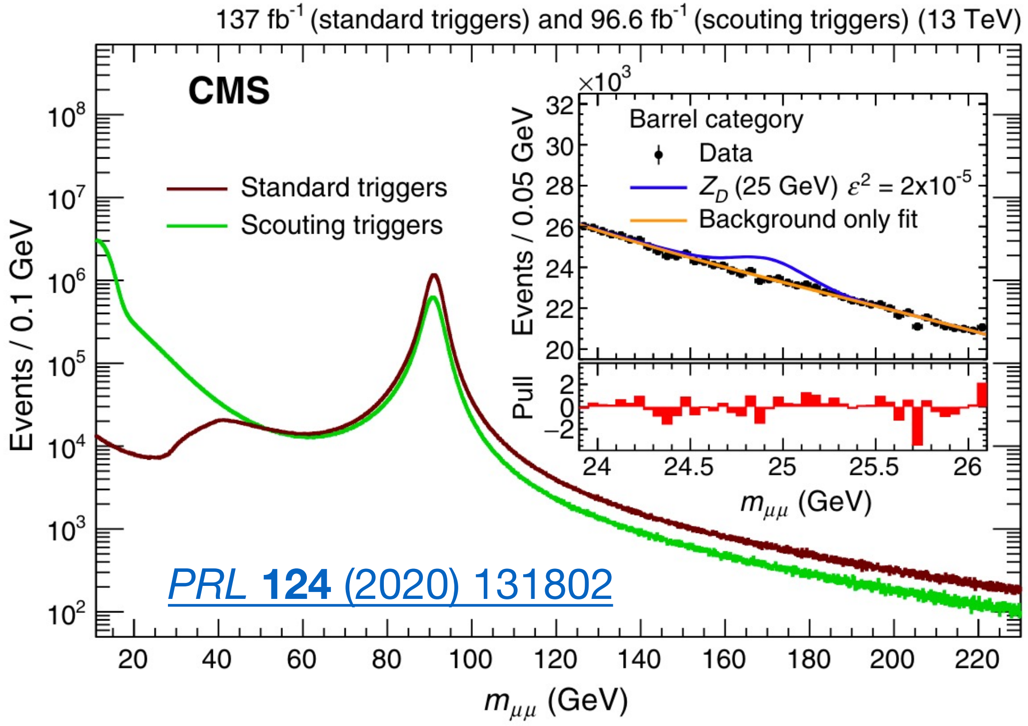


$\eta \longrightarrow 4\mu$: trigger strategy

Trigger – the Muon Scouting stream:

- Loose-selection, high-rate triggers
- Store only a limited amount of information per event
    - Track parameters and muon quality

- In 2017 and 2018, collected ~100 fb^{-1}

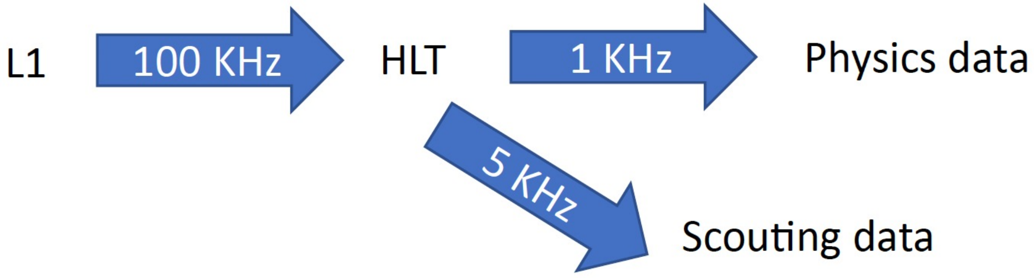


PRL **124** (2020) 131802

L1 Muon Scouting triggers for $\eta \longrightarrow 4\mu$

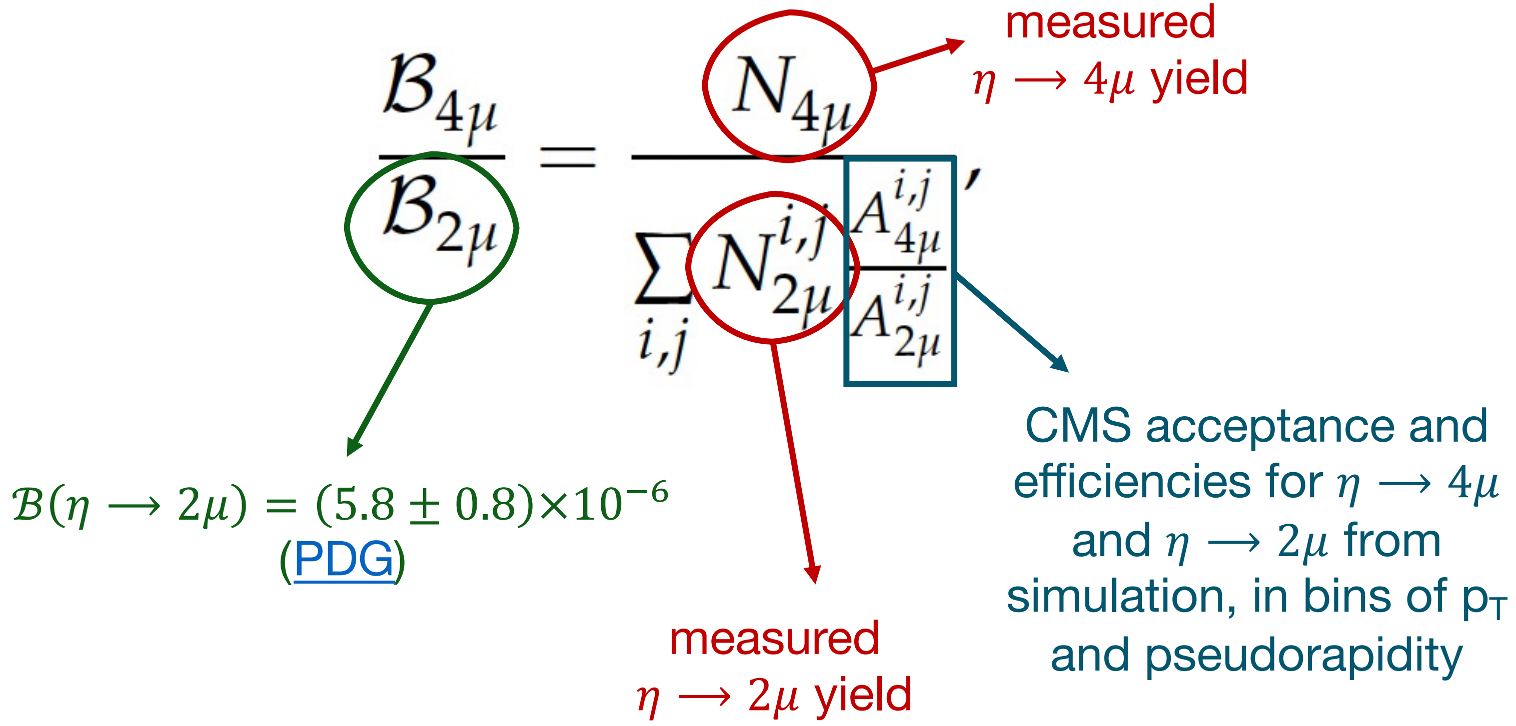
L1 path	p_T [GeV]	$\|\eta\|$	ΔR	$m_{\mu\mu}$ [GeV]	Efficiency
#1	$> 4, 4.5$	–	< 1.2	–	83%
#2	–	< 1.5	< 1.4	–	44%
#3	$> 15/7$	–	–	–	42%
#4	> 4.5	< 2.0	–	7–18	8%

Overall 92% efficiency on signal



$\eta \longrightarrow 4\mu$: analysis strategy

- $\eta \longrightarrow 4\mu$ BF determined relative to $\eta \longrightarrow 2\mu$
- Offline selections: total charge, common vertex
- Acceptance and efficiencies from MC simulation



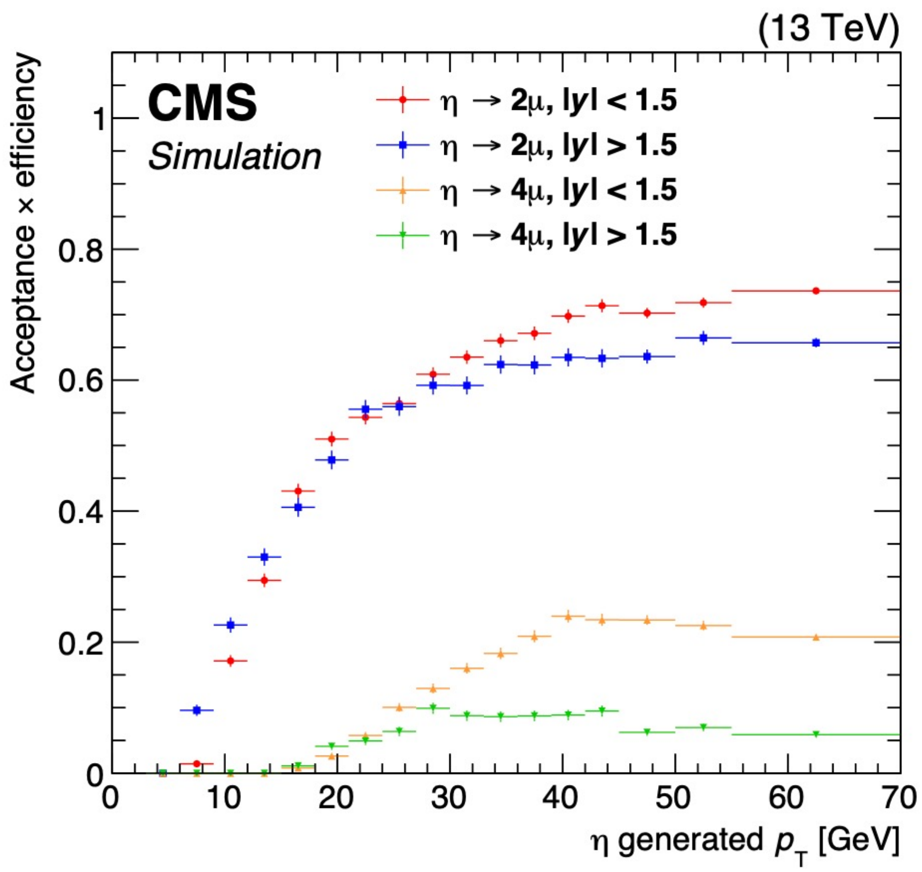
$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}},$$

measured $\eta \longrightarrow 4\mu$ yield

$\mathcal{B}(\eta \longrightarrow 2\mu) = (5.8 \pm 0.8) \times 10^{-6}$ (PDG)

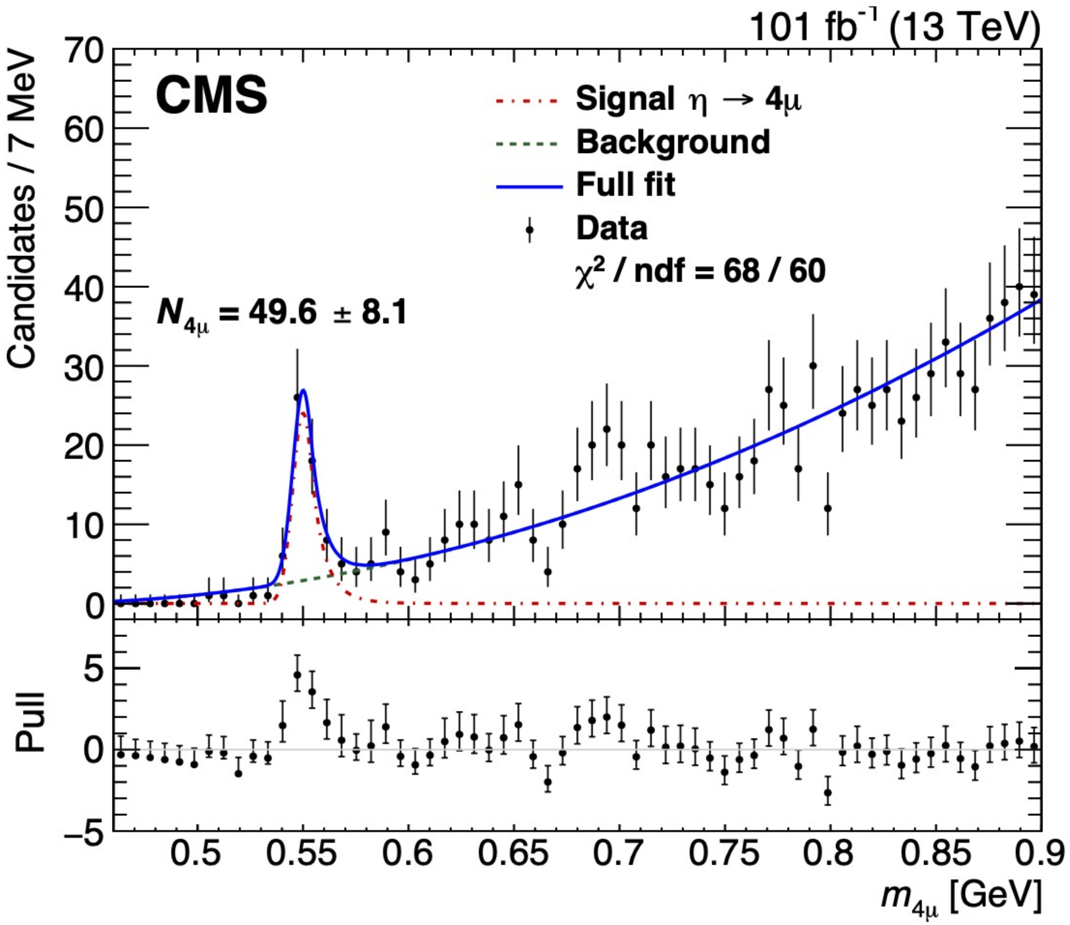
measured $\eta \longrightarrow 2\mu$ yield

CMS acceptance and efficiencies for $\eta \longrightarrow 4\mu$ and $\eta \longrightarrow 2\mu$ from simulation, in bins of p_T and pseudorapidity



- Modeling of Acceptance x efficiency function is the main source of systematics O(10%)
  - including muon trigger and reconstruction efficiency and data-MC difference

$\eta \longrightarrow 4\mu$: observation and fit result



- Clear peak in the 4μ spectrum
- Statistical significance > 5 standard deviations

- Possible background contaminations studied from simulation
  - contamination of misidentified hadrons is negligible in the signal region

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = (0.9 \pm 0.1\,(\text{stat}) \pm 0.1\,(\text{syst})) \times 10^{-3}.$$

$$\mathcal{B}(\eta \to 4\mu) = (5.0 \pm 0.8\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.7\,(\mathcal{B})) \times 10^{-9}.$$

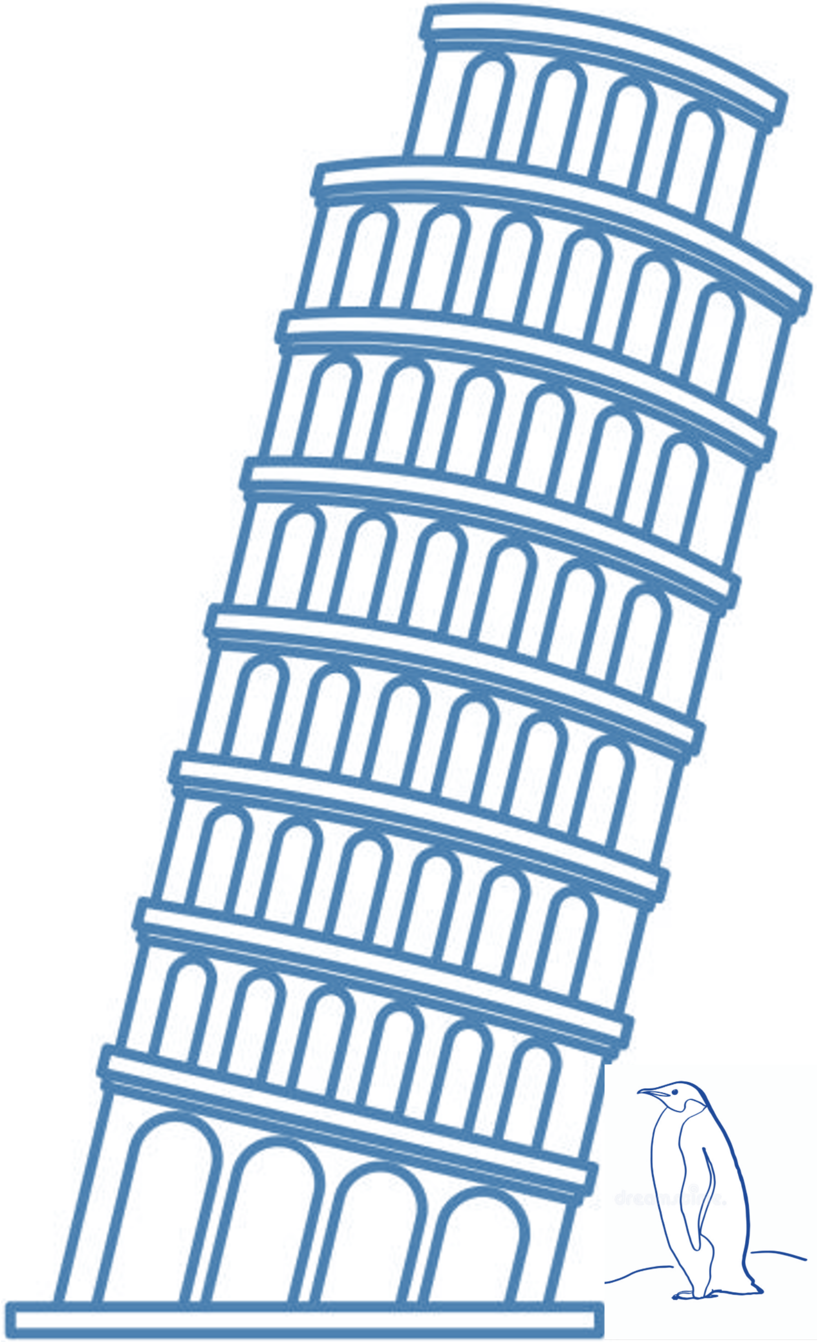
SM expectation:
$\mathcal{B}(\eta \longrightarrow 4\mu) = (3.98 \pm 0.15) \times 10^{-9}$
(*Chinese Phys. C* **42** (2018) 023109)

Conclusions

b→sμμ transitions deeply studied at ATLAS and CMS

- Measurement of the $B_s^0 \longrightarrow \mu^+\mu^-$ decay properties and search for the $B^0 \longrightarrow \mu^+\mu^-$ decay at CMS (arXiv:2212.10311)
  - Analysis on full Run 2 dataset (140 fb^{-1})
  - All results are consistent with the SM
  - Best *single* measurement of $\mathcal{B}(B_s^0 \longrightarrow \mu^+\mu^-)$ to date
- Angular analysis in B→Kμμ shows no deviations from SM (within the limited experimental precision)

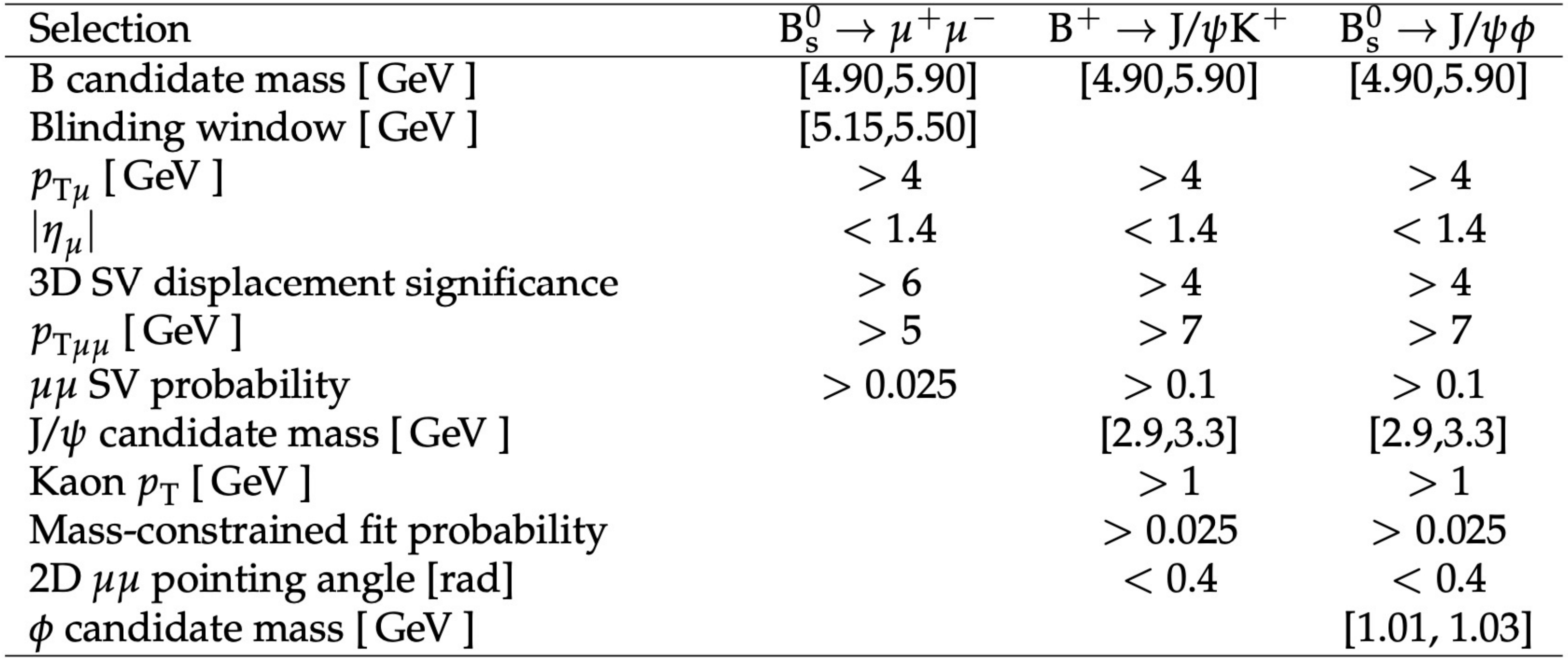
- **First observation of the rare 4μ decay of the η meson at CMS** (arXiv:2305.04904)
  - Observation made possible by use of high-rate triggers, collecting 100 fb^{-1} in 2017 and 2018
  - The measured value of $\mathcal{B}(\eta \longrightarrow 4\mu)$ is 25% higher than the SM expectation
  - Still in agreement within uncertainties



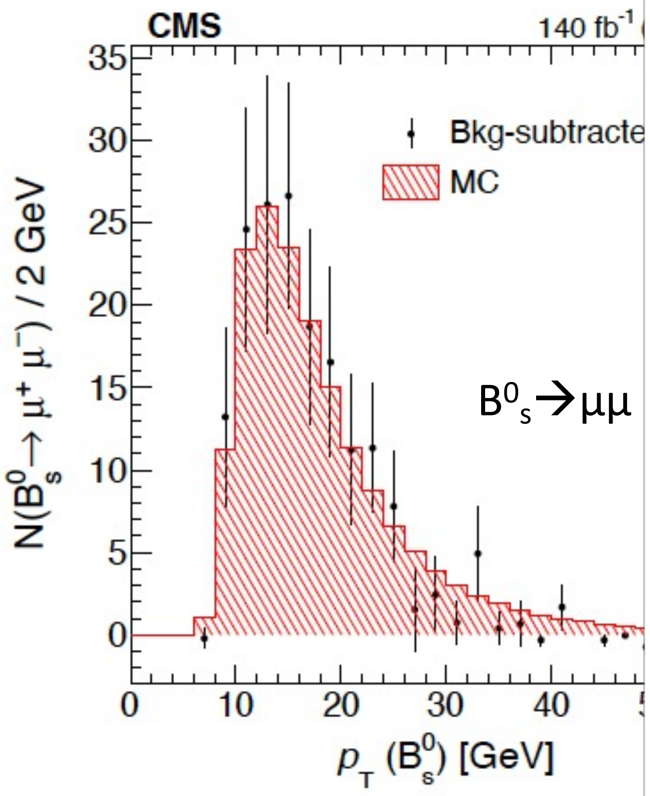
Thanks for your attention!

Backup

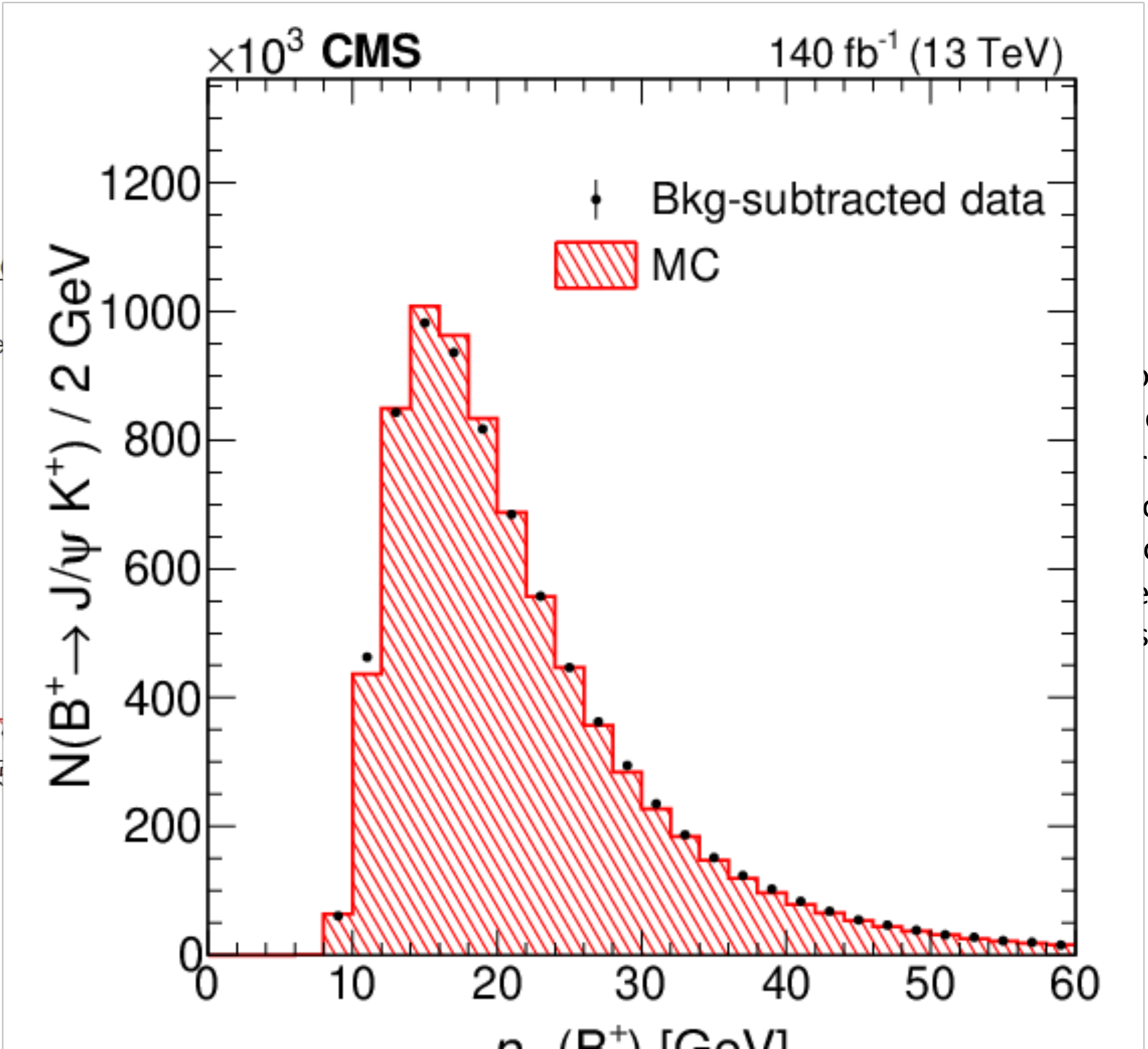
$B_{(s)} \longrightarrow \mu^+\mu^-$ selections



Selection	$\mathrm{B_s^0} \to \mu^+\mu^-$	$\mathrm{B^+} \to \mathrm{J}/\psi \mathrm{K^+}$	$\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$
B candidate mass [GeV]	[4.90,5.90]	[4.90,5.90]	[4.90,5.90]
Blinding window [GeV]	[5.15,5.50]		
$p_{\mathrm{T}\mu}$ [GeV]	> 4	> 4	> 4
$\lvert\eta_\mu\rvert$	< 1.4	< 1.4	< 1.4
3D SV displacement significance	> 6	> 4	> 4
$p_{\mathrm{T}\mu\mu}$ [GeV]	> 5	> 7	> 7
$\mu\mu$ SV probability	> 0.025	> 0.1	> 0.1
J/ψ candidate mass [GeV]		[2.9,3.3]	[2.9,3.3]
Kaon p_T [GeV]		> 1	> 1
Mass-constrained fit probability		> 0.025	> 0.025
2D $\mu\mu$ pointing angle [rad]		< 0.4	< 0.4
ϕ candidate mass [GeV]			[1.01, 1.03]



$B^0_s \to \mu\mu$



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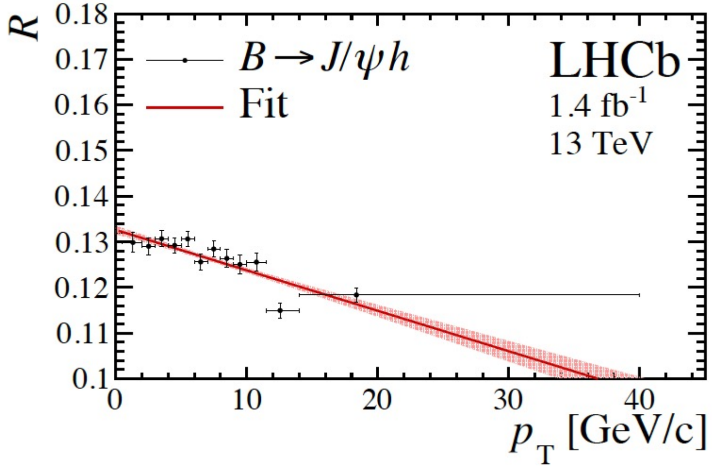
fs/fd ratio, LHCb measurement

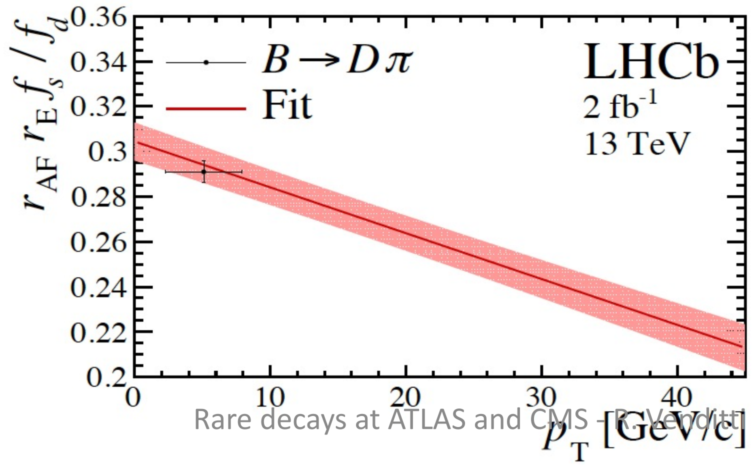
B^0 and B_S^0 production cross section ratio (fragmentation fraction) extrapolated from LHCb result [arXiv:2103.06810]

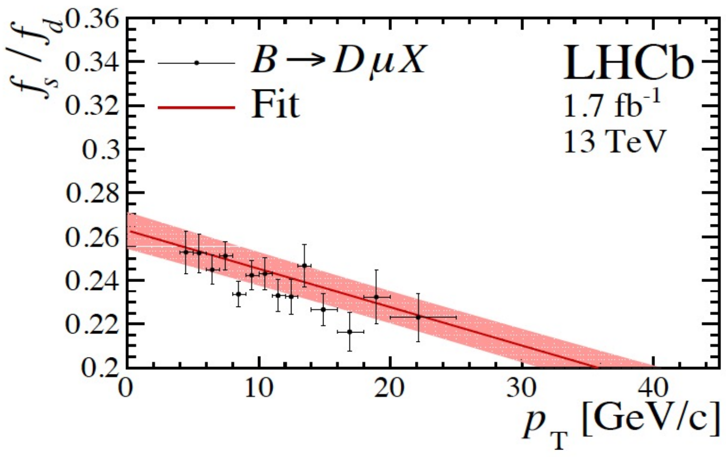
$$\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-) = \mathcal{B}(\mathrm{B^+} \to \mathrm{J}/\psi \mathrm{K^+}) \frac{N_{\mathrm{B_s^0}\to\mu^+\mu^-}}{N_{\mathrm{B^+}\to\mathrm{J}/\psi\mathrm{K^+}}} \frac{\varepsilon_{\mathrm{B^+}\to\mathrm{J}/\psi\mathrm{K^+}}}{\varepsilon_{\mathrm{B_s^0}\to\mu^+\mu^-}} \boxed{\frac{f_\mathrm{u}}{f_\mathrm{s}}},$$

fs/fd is the ratio of the B_S^0 and B^0 production cross sections.
LHCb has shown several times that this ratio depends on the B meson pT, the most recent measurement combines several previous results. Some channels allow direct extraction of fs/fd but are limited by statistics, other channels have branching fractions tied to fs/fd but allow to estimate pT and η dependence of fs/fd.
All the information was combined in simultaneous global fit:

$$\boxed{f_s/f_d \quad (p_\mathrm{T}, 13\,\mathrm{TeV}) \quad = (0.263 \pm 0.008) + ((-17.6 \pm 2.1) \times 10^{-4}) \cdot p_\mathrm{T}\ ,}$$



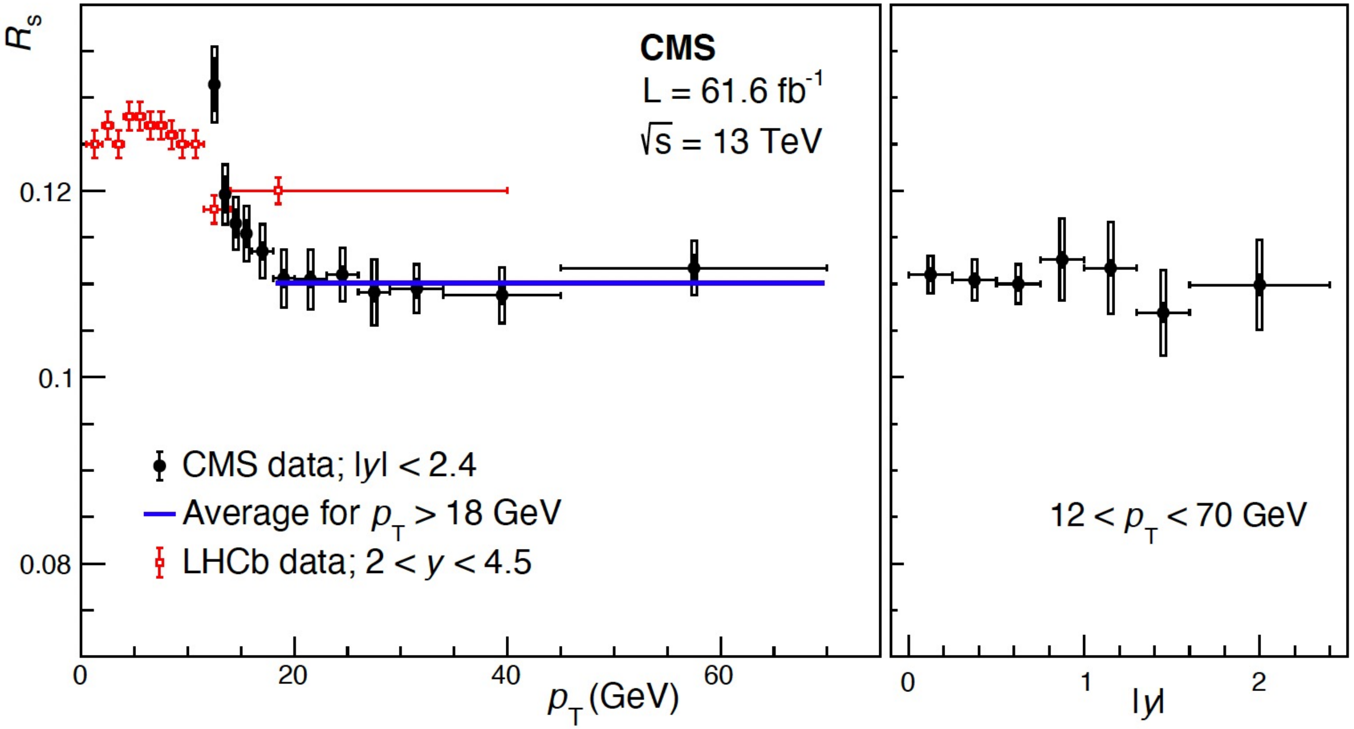


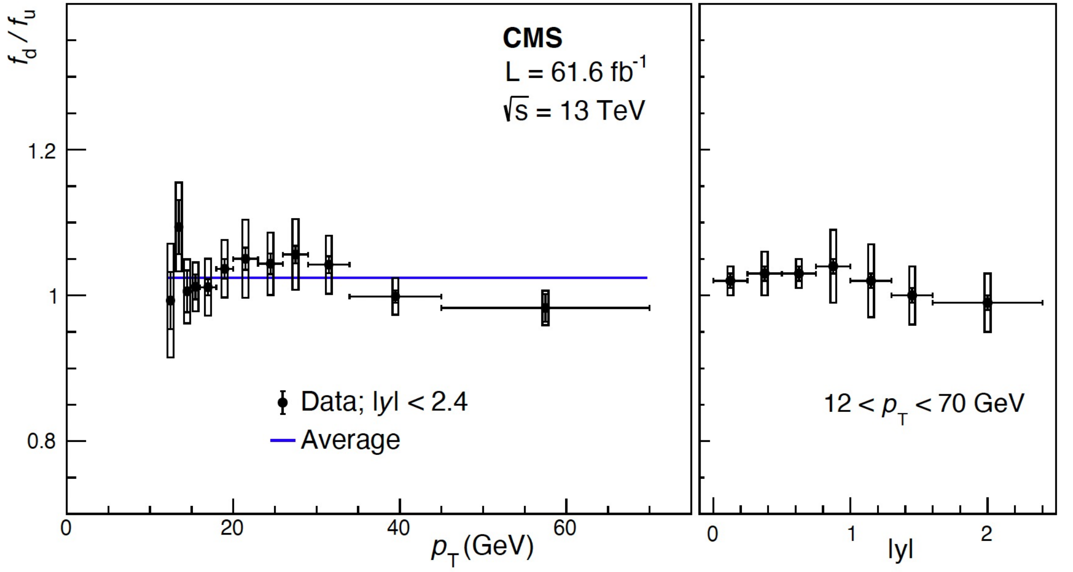


fs/fd ratio, CMS measurement

$$\mathcal{R}_{\mathrm{s}} = f_{\mathrm{s}}/f_{\mathrm{u}}\,\frac{\mathcal{B}(\mathrm{B}_{\mathrm{s}}^{0}\to \mathrm{J}/\psi\,\phi)\mathcal{B}(\phi\to \mathrm{K}^{+}\mathrm{K}^{-})}{\mathcal{B}(\mathrm{B}^{+}\to \mathrm{J}/\psi\,\mathrm{K}^{+})}$$

$$\mathcal{R}_{\mathrm{d}} = \frac{N_{\mathrm{B}^0}}{\epsilon_{\mathrm{B}^0}} \bigg/ \frac{N_{\mathrm{B}^+}}{\epsilon_{\mathrm{B}^+}} = f_{\mathrm{d}}/f_{\mathrm{u}}\,\frac{\mathcal{B}(\mathrm{B}^{0}\to \mathrm{J}/\psi\,\mathrm{K}^{*0})\mathcal{B}(\mathrm{K}^{*0}\to \pi^{-}\mathrm{K}^{+})}{\mathcal{B}(\mathrm{B}^{+}\to \mathrm{J}/\psi\,\mathrm{K}^{+})}.$$





https://arxiv.org/abs/2212.02309

Run 3 trigger strategies

- In 2022: inclusive dimuon trigger
  - designed to maximise $B^0 \longrightarrow \mu^+\mu^-$ efficiency
  - suitable for several $b \longrightarrow sll$ studies, charmonium and B spectroscopy, LFV $\tau \longrightarrow \mu\mu\mu$, exo-searches, search for $\eta \longrightarrow \mu^+\mu^-e^+e^-$

- In 2023 and beyond: more challenging data taking conditions
  - higher PU
  - limited bandwidth for dimuon triggers

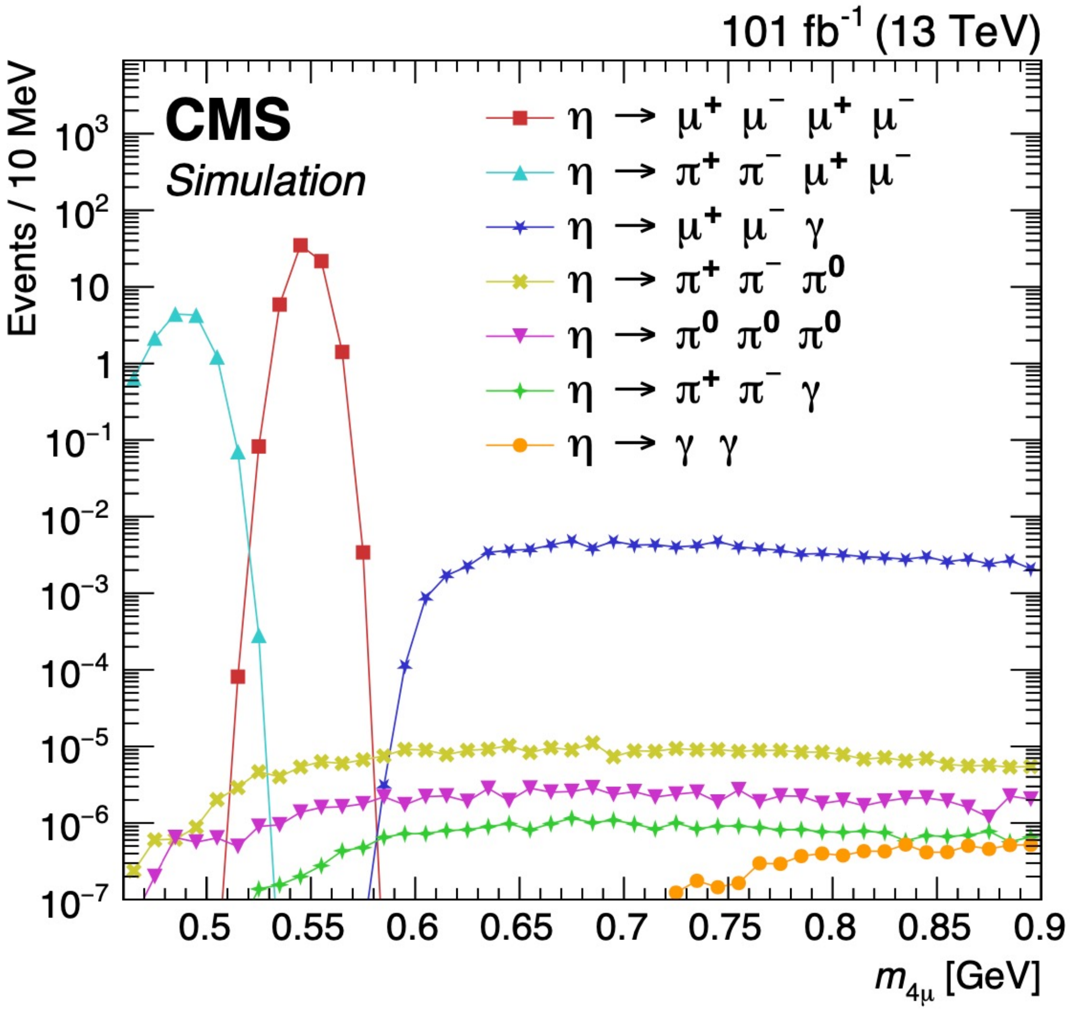
    → set up a strategy to keep the inclusive dimuon trigger

$\eta \longrightarrow 4\mu$: background studies

Cross check performed to check for possibility of rare η decay backgrounds using simulated samples

- $\eta \to \mu^+\mu^- \gamma$ with γ conversion in material non-peaking and shifted to higher m(4μ)
- $\eta \to \pi^+\pi^-\mu^+\mu^-$ with π→μ fake shifted to lower mass due to wrong mass hypothesis
  - Rate shown is for current experimental limit
    - $B(\eta \to \pi^+\pi^-\mu^+\mu^-) < 1.6 \times 10^{-4}$
    - SM Prediction 6.5×10^{-9}

No possibility of significant peaking background component



$\eta \longrightarrow 4\mu$: uncertainties

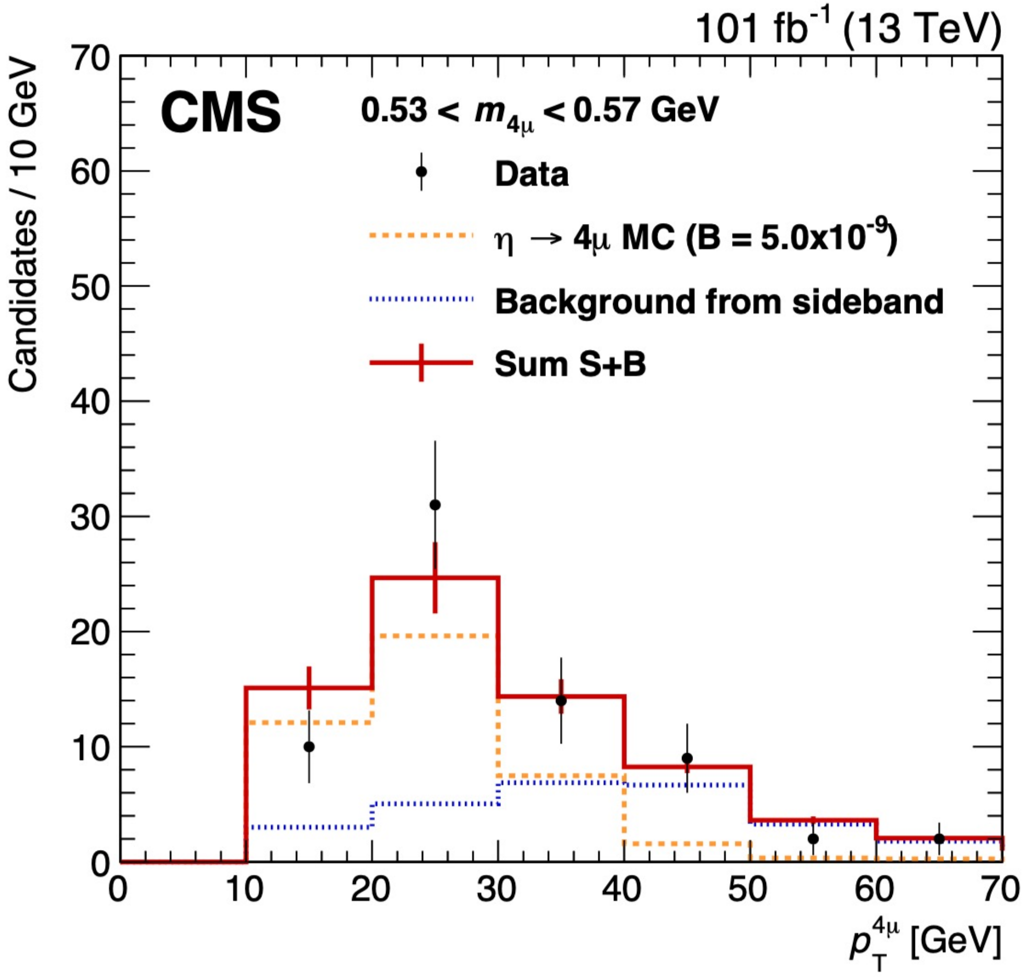
η→4μ differential event rate as a function of pT in excellent agreement with the simulation

Residual uncertainty due to the imperfect knowledge of Axε for η→2μ and η→4μ

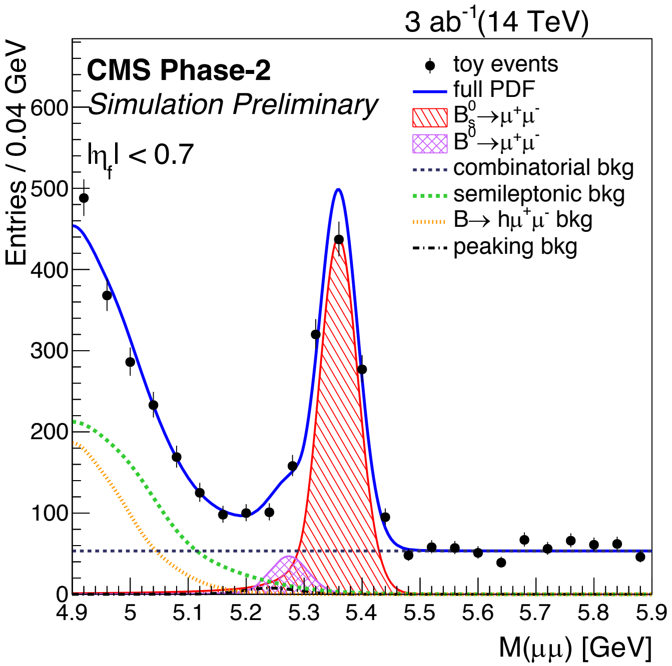
- Accounts for threshold effects determined η→2μ efficiency differences between data and MC (in total ~13%)

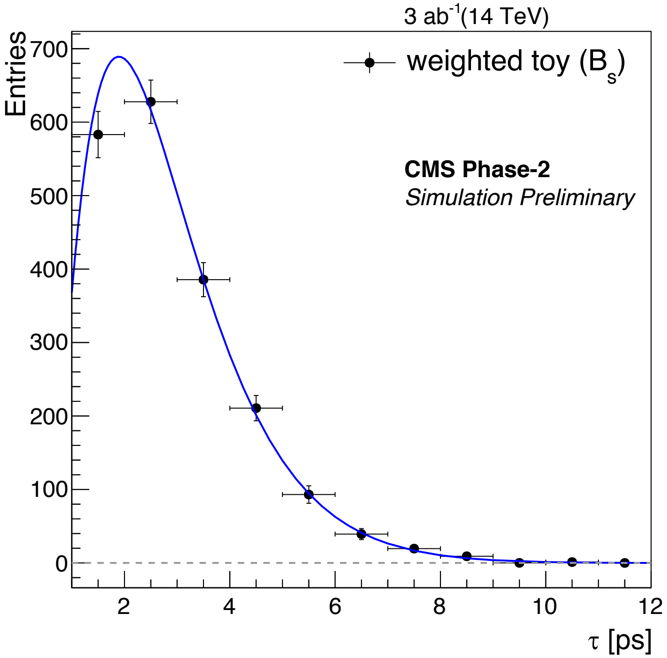
Uncertainty in normalization mode branching ratio (~14%)

$$\mathcal{B}(\eta \to 2\mu) = (5.8 \pm 0.8) \times 10^{-6}$$

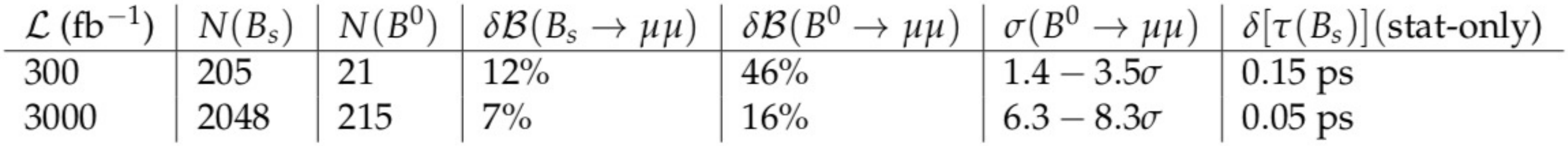


$B_s^0 \longrightarrow \mu^+\mu^-$ perspectives at HL-LHC





- Theory prediction limited by $|V_{cb}|$
- Experimental uncertainty on B_s^0 dominated by fs/fd
- Mass resolution improvements will help distinguishing the B_s^0 and B_d^0 peaks → B_d^0 discovery



$\mathcal{L}$ (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

$B_d^0 \to K^{*}\mu^+\mu^-$ in Run 3 and beyond

- Run3 data could allow to resolve the situation experimentally
- HL-LC Statistics would allow improvement in the precision by one order
  - ~(5–9) × for ATLAS
  - ~ 15× for CMS