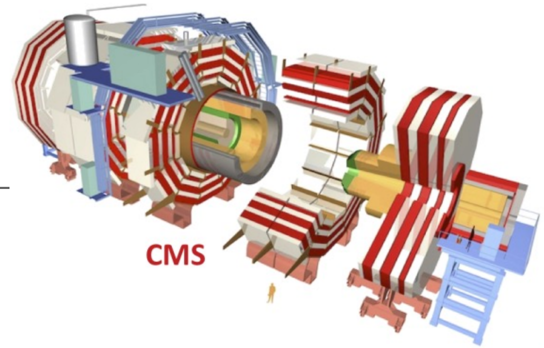
CMS B-Physics Results



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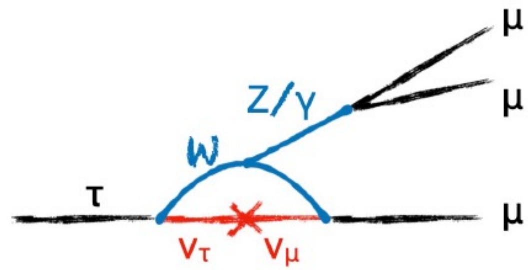
on behalf of the CMS Collaboration

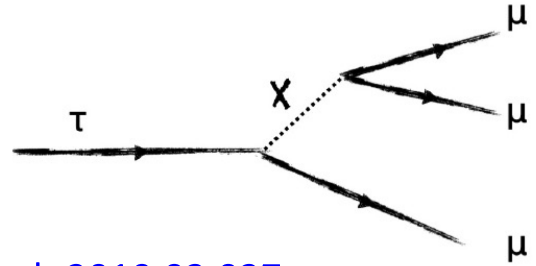
20/07/2023

Outline

- $\tau \rightarrow 3\mu$ LFV decay
- Observation of $\Lambda_b^0 \rightarrow J/\psi\ \Xi^- K^+$ decay
- Fragmentation fraction ratios
- Rare double-Dalitz decay of $\eta \rightarrow 4\mu$
- Study of di-charmonium spectrum
- Study of $B_{s/d} \rightarrow \mu^+\mu^-$ decay

Search for Lepton Flavor Violating(LFV) decay $\tau \to 3\mu$





- LFV decay, $\tau \to 3\mu$, is strongly suppressed in the SM
- Allowed via neutrino oscillation with BF ~ 10^{-55}
- Good place to look for New Physics(NP) as the predicted BF goes to as big as 10^{-9}
- The mode has been searched previously by B-factory as well as
- LHC experiments and the UL is set as:

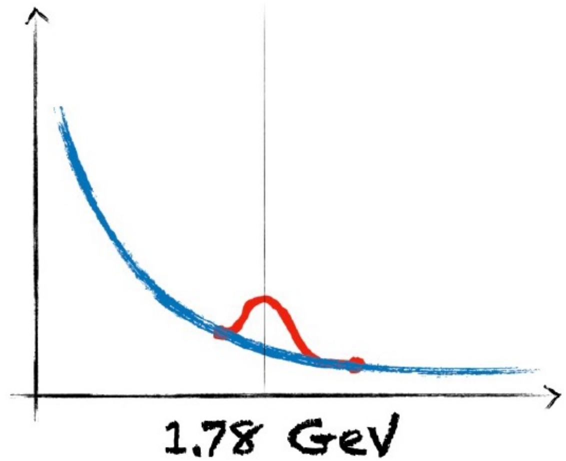
Observed Upper Limit @90% CL

Belle ($e^+e^- \to \tau^+\tau^-$):	BF ($\tau \to 3\mu$) < 2.1×10^{-8}	https://doi.org/10.1016/j.physletb.2010.03.037
BaBar ($e^+e^- \to \tau^+\tau^-$):	BF ($\tau \to 3\mu$) < 2.1×10^{-8}	https://doi.org/10.1103/PhysRevD.81.111101
LHCb Run1 (HF->τ):	BF ($\tau \to 3\mu$) < 4.6×10^{-8}	https://doi.org/10.1007/JHEP02(2015)121
ATLAS Run1 (W->τ):	BF ($\tau \to 3\mu$) < 38×10^{-8}	https://doi.org/10.1140/epjc/s10052-016-4041-9
CMS 2016 (HF +W ->τ):	BF ($\tau \to 3\mu$) < 8.0×10^{-8}	https://doi.org/10.1007/JHEP01(2021)163

- Heavy Flavor decays (~10^{11} τ's/fb) : signal process => $D_s^+ \to \tau\nu$, $B^+ \to \tau X$, $B^0 \to \tau X$
  -> Most abundant source of τ's ($Ds^+ \to \phi(\mu^+\mu^-)\pi^+$ as control channel)
  -> low P_T, high $|\eta|$, fake muons from pions and kaons.
- W-decays (10^7 τ's/fb): $W \to \tau\nu$
  -> High P_T , more central decays,
  -> Property of W bring additional handle to suppress backgrounds

Analysis strategy with Heavy Flavor decays

- CMS uses 2017 (38 fb^{-1})+ 2018 (59.7 fb^{-1}) data
- Look for three muons with peak around 1.78 GeV
- Three muons with total charge = ± 1
- Good common vertex along with other selection criteria
- Veto $\phi(\mu^+\mu^-)$ events
- Use BDT for the rest of the background reduction
- The dataset is split into 3 parts (called A,B,C) each year based on dimuon resolution.
- Each part is further subdivided based on BDT score.
- Knowledge of D or B meson cross-section etc not needed

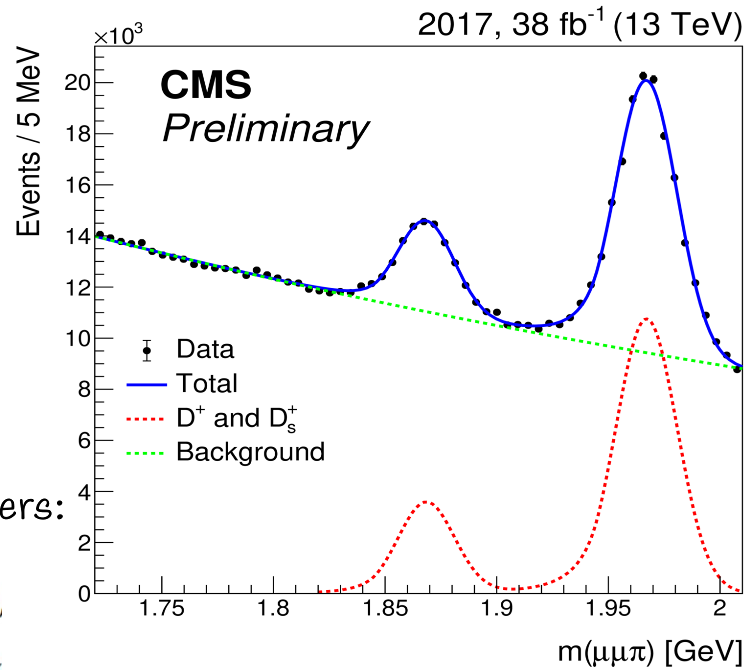


The number of $\tau\to3\mu$ signals events in D_s^+ decays that pass dimuon triggers:

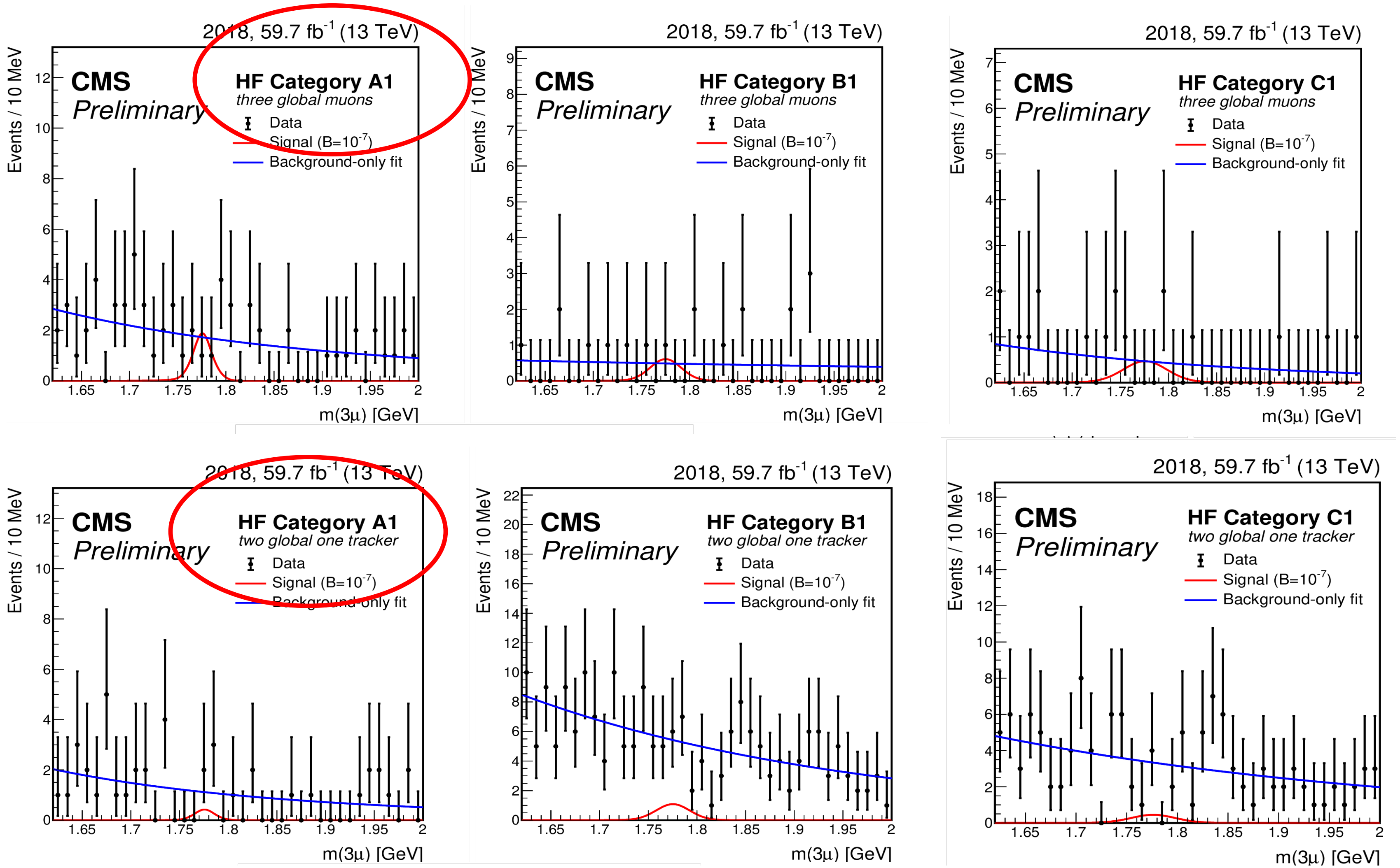
$$N_{3\mu(\mathrm{D})} = N_{\mu\mu\pi} \frac{\mathcal{B}(\mathrm{D_s^+}\to\tau^+\nu)}{\mathcal{B}(\mathrm{D_s^+}\to\phi\pi^+\to\mu^+\mu^-\pi^+)} \frac{\mathcal{A}_{3\mu(\mathrm{D})}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{\mathrm{reco}}_{3\mu(\mathrm{D})}}{\epsilon^{\mathrm{reco}}_{\mu\mu\pi}} \frac{\epsilon^{2\mu\mathrm{trig}}_{3\mu(\mathrm{D})}}{\epsilon^{2\mu\mathrm{trig}}_{\mu\mu\pi}} \mathcal{B}(\tau\to3\mu),$$

The number of $\tau\to3\mu$ signals events in $B_s^+\to\tau + X$ decays that pass dimuon triggers:

$$N_{3\mu(\mathrm{B})} = N_{\mu\mu\pi}\, f \frac{\mathcal{B}(\mathrm{B}\to\tau+\mathrm{X})}{\mathcal{B}(\mathrm{D_s^+}\to\phi\pi^+\to\mu^+\mu^-\pi^+)\mathcal{B}(\mathrm{B}\to\mathrm{D_s^+}+\mathrm{X})} \frac{\mathcal{A}_{3\mu(\mathrm{B})}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{\mathrm{reco}}_{3\mu(\mathrm{B})}}{\epsilon^{\mathrm{reco}}_{\mu\mu\pi}} \frac{\epsilon^{2\mu\mathrm{trig}}_{3\mu(\mathrm{B})}}{\epsilon^{2\mu\mathrm{trig}}_{\mu\mu\pi}} \mathcal{B}(\tau\to3\mu),$$



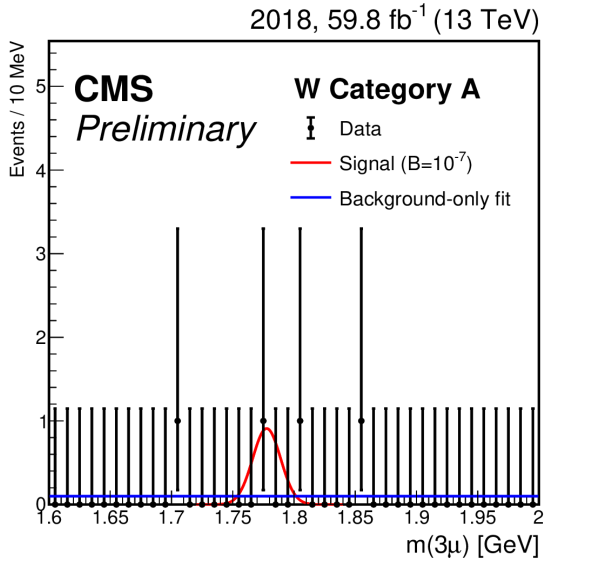
τ invariant mass from Heavy Flavor decays

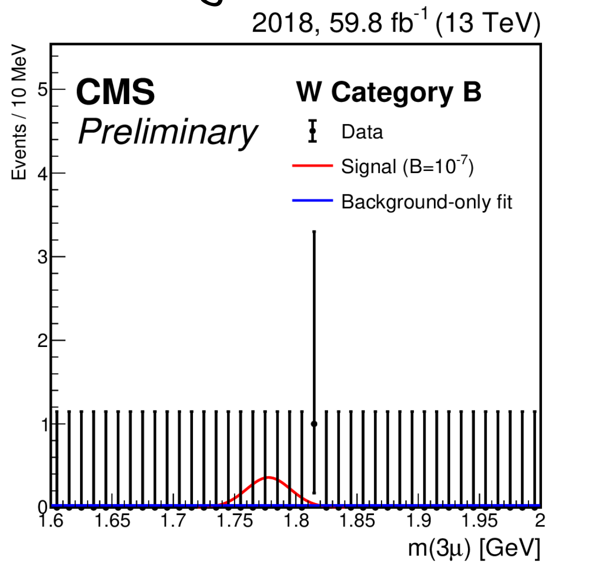


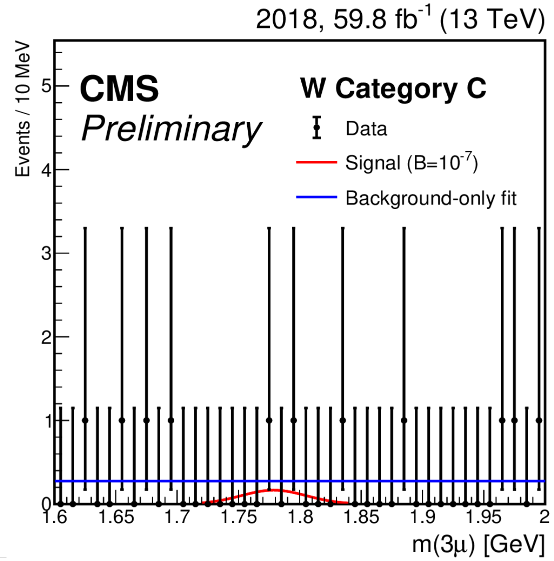
- The top shows with three global muons and bottom plots are for two global + 1 tracker muon.
- The blue line shows the background only fit whereas the red gaussian curve shows the signal component assuming the tau decay branching fraction as 10^{-7}. No signal excess.

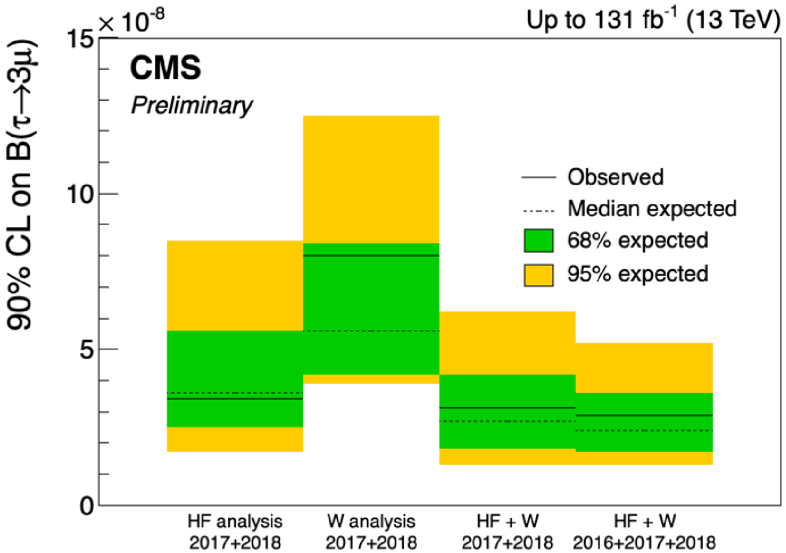
τ invariant mass from W-decay mode and BF measurement

- Three collimated muons with relatively high P_T. Large missing momentum.
- ϕ and ω vetoed. Residual backgrounds reduced with BDT





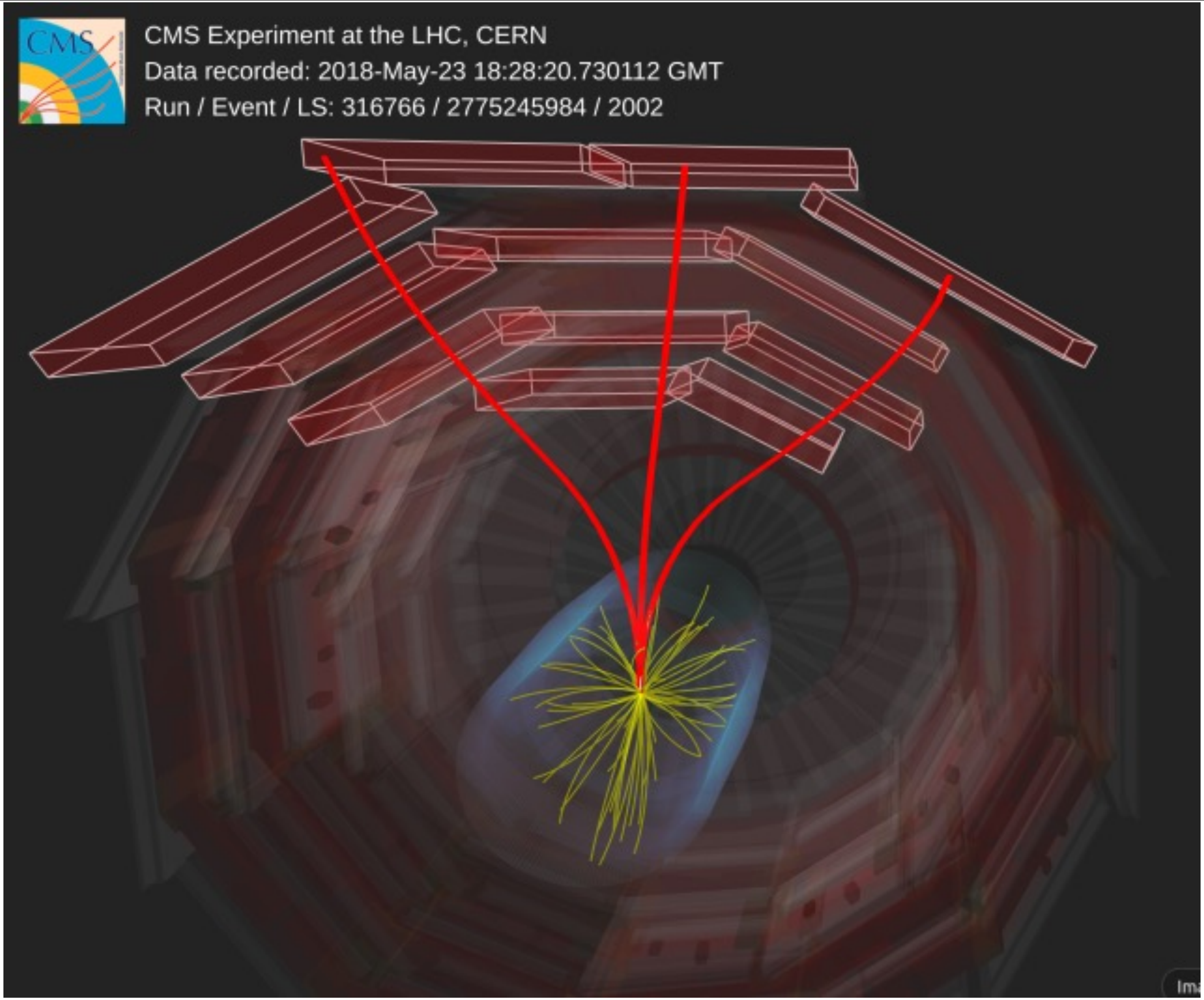




The branching fraction is obtained with UML fit to all 36 event categories in heavy flavor and W channels.
The observed (expected) upper limit at 90% CL on branching fraction of $\tau \to 3\mu$ using Run-2 CMS data is 2.9 (2.4) x 10^{-8}

CMS-PAS-BPH-21-005

A random three muon event with CMS data



Observation of the decay $\Lambda_b^0 \to J/\psi\, \Xi^- K^+$ decay

- Multibody decays of beauty hadrons allows to search for intermediate resonances in the decay products, specifically, decay products containing charmonium states. For example, b-hadron decaying to a charmonium along with a baryon allows to look for pentaquarks in J/ψ + baryon system in the intermediate resonance structure.
- LHCb reported significant $J/\psi p$ pentaquark like structure in the decay of $\Lambda_b^0 \to J/\psi\, p\, K^-$

PRL 115 (2015) 072001

- One such decay is $\Lambda_b^0 \to J/\psi\, \Xi^- K^+$ and $\Lambda_b^0 \to \psi(2S)\, \Lambda$ used as normalization channel

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi \Xi^- K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = \frac{N(\Lambda_b^0 \to J/\psi \Xi^- K^+)}{N(\Lambda_b^0 \to \psi(2S)\Lambda)} \frac{\epsilon_{\psi(2S)\Lambda}}{\epsilon_{J/\psi \Xi^- K^+}} \times \frac{\mathcal{B}(\psi(2S) \to J/\psi \pi^+\pi^-)}{\mathcal{B}(\Xi^- \to \Lambda\pi^-)}$$

Yields from data fit

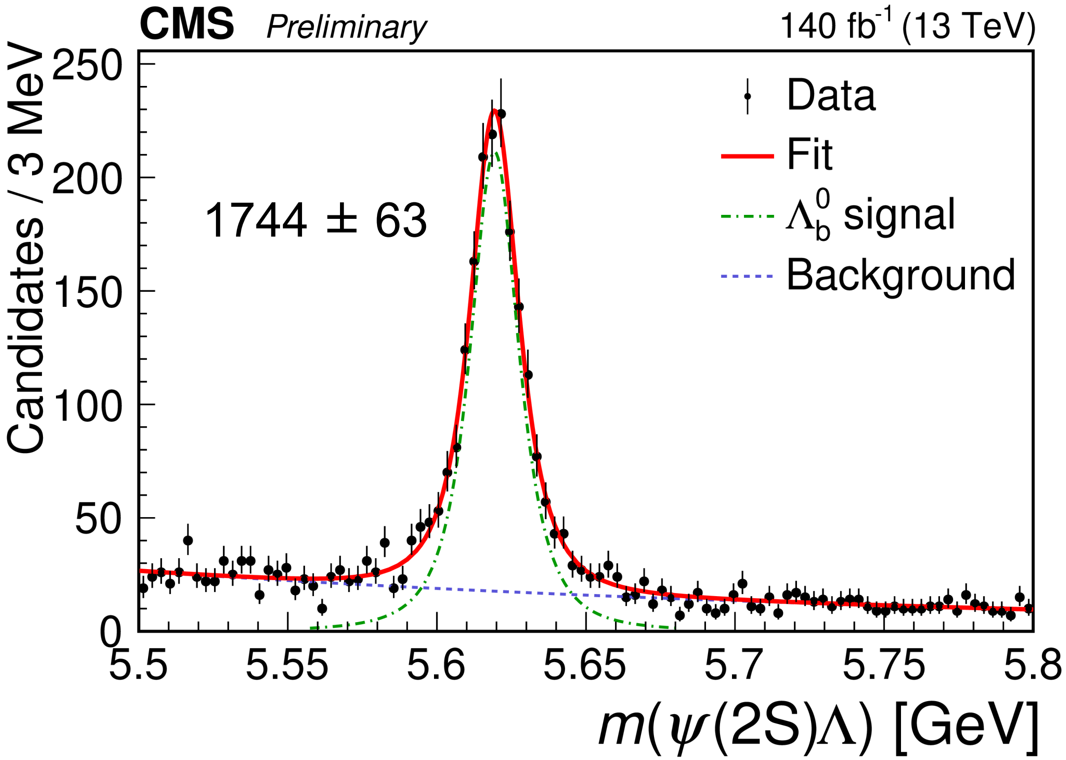
Eff ratio from MC

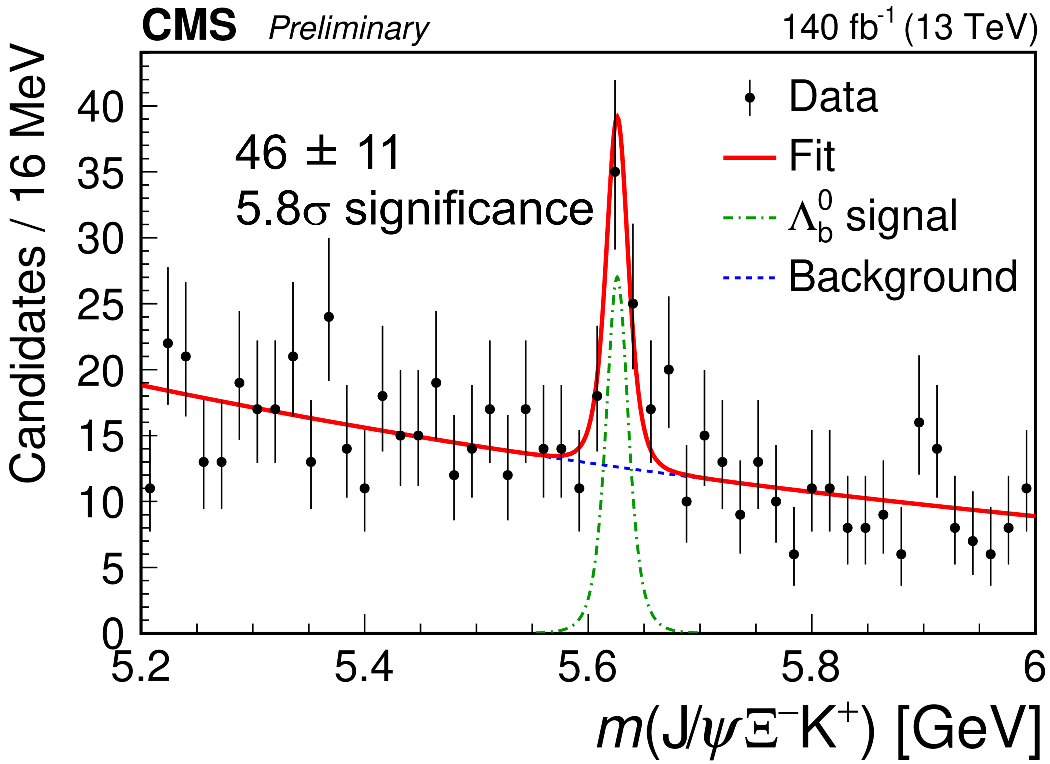
BF ratio from PDG

where $J/\psi \to \mu^+\mu^-$, $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$

- Allows to look for doubly or triply strange pentaquarks.

Observation of the decay $\Lambda_b^0 \to J/\psi\, \Xi^- K^+$ decay





Source	Uncertainty (%)
Signal model	3.9
Background model	6.7
Non-$\psi(2S)$ contribution	2.5
Finite size of MC samples	5.6
Tracking efficiency	2.3
Alternative selection criteria	33.5
Total	35.0

- First observation of $\Lambda_b^0 \to J/\psi\, \Xi^- K^+$
- First decay to have $J/\psi\, \Xi^-$ system in products.
  No significant narrow peaks in $J/\psi\, \Xi^-$ distribution

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi \Xi^- K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = [2.5 \pm 0.8\,(\text{stat}) \pm 0.9\,(\text{syst})]\%,$$

CMS-PAS-BPH-22-002

Ratio of fragmentation fractions (f_s/f_u, f_d/f_u) with CMS data

- The fragmentation fractions: f_u, f_d, and f_s -> probability of b-quark to hadronize to B-mesons or b-baryons such as B^+ (f_u), B_d^0(f_d), B_s^0 (f_s), Λ_b(udb) etc.

- Since in the fragmentation process, the color force fields create quark-antiquark pairs that combine with a bottom quark (bq, bq_1q_2) to create B-meson or b-baryon, it can not be reliably calculated by perturbative QCD, so must be determined empirically.

- Very useful when measuring branching fraction of B_s^0 (e.g., $B_s^0 \to \mu^+\mu^-$) relative to other B-mesons (most often use B^0 or B^+ to cancel the effect of b-hadron production cross section, integrated luminosity and other systematic uncertainties).

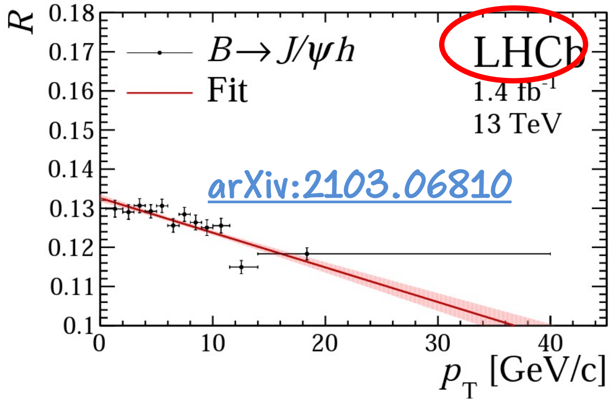
- However, f_u/f_s is one of the major uncertainties for measurement of branching fraction of $B_s^0 \to \mu^+\mu^-$:

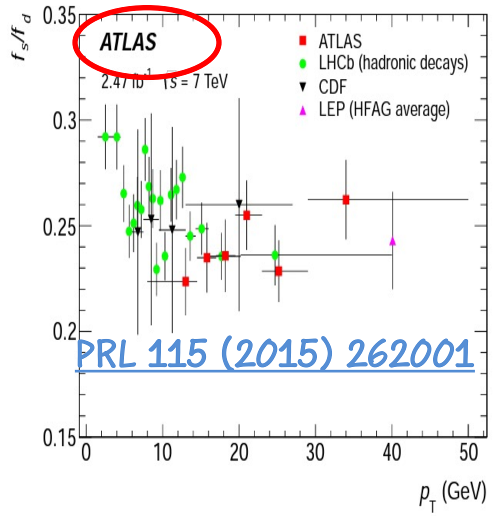
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \frac{\varepsilon_{B^+ \to J/\psi K^+}}{\varepsilon_{B_s^0 \to \mu^+\mu^-}} \frac{f_u}{f_s}$$

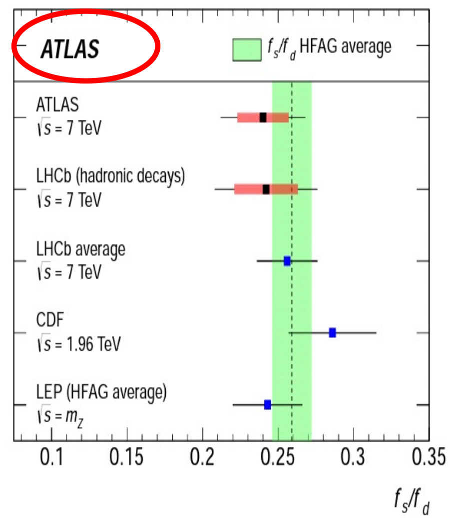
- So, precise measurement of fragmentation ratio is important. However, the ratio depends on kinematic variables such as transverse momentum, and pseudo-rapidity of the b-hadron.

Previous results on fragmentation fraction ratio

- LHCb and ATLAS have measured these parameters: LHCb has seen P_T dependence whereas ATLAS didn't observe such P_T dependency (although measured in different P_T range).







$$\frac{f_s}{f_u} = \frac{n_{\rm corr}(B_s^0 \to J/\psi\phi)}{n_{\rm corr}(B^+ \to J/\psi K^+)} \frac{\mathcal{B}(B^+ \to J/\psi K^+)}{\mathcal{B}(B_s^0 \to J/\psi\phi)\mathcal{B}(\phi \to K^+K^-)} = \frac{\mathcal{R}}{\mathcal{F}_R}$$

- CMS measures R_s (f_s/f_u) and f_d/f_u using the decays $B_s^0 \to J/\psi\ (\mu^+\mu^-)\ \phi\ (K^+K^-)$, $B^+ \to J/\psi\ (\mu^+\mu^-) K^+$ .and $B^0 \to J/\psi\ K^{*0}(K^-\pi^+)$. To be precise CMS measures

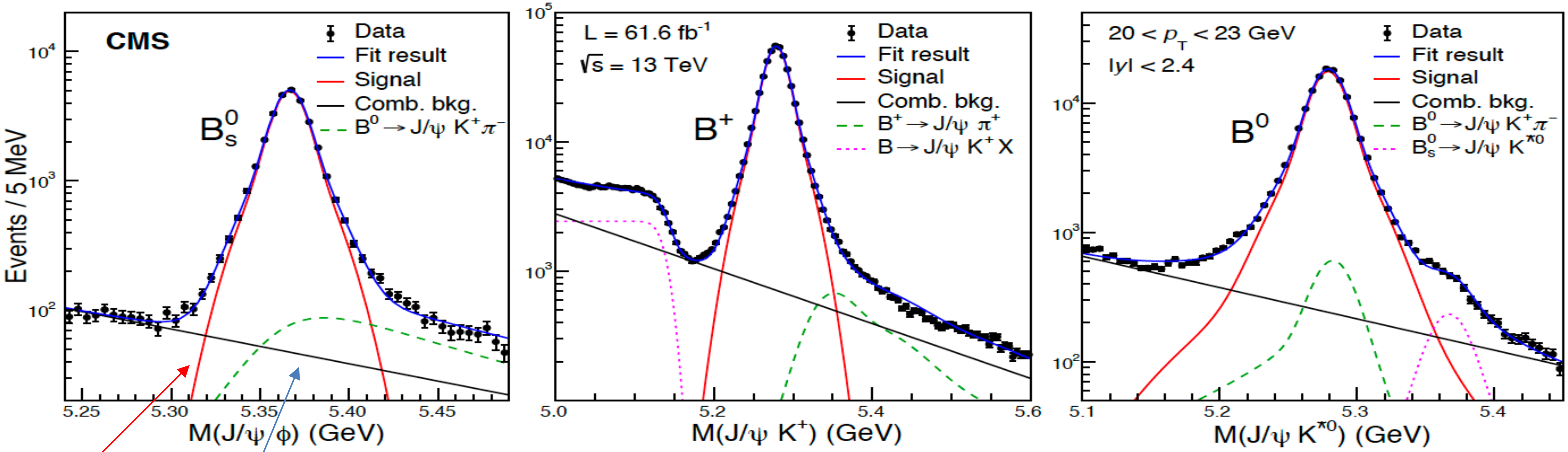
$$\mathcal{R}_s = (N_{B_s^0}/\epsilon_{B_s^0})\ /\ (N_{B^+}/\epsilon_{B^+}) = f_s/f_u\ \frac{\mathcal{B}(B_s^0 \to J/\psi\,\phi)\mathcal{B}(\phi \to K^+K^-)}{\mathcal{B}(B^+ \to J/\psi\,K^+)}$$

$$\mathcal{R}_d = \frac{N_{B^0}}{\epsilon_{B^0}} \Big/ \frac{N_{B^+}}{\epsilon_{B^+}} = f_d/f_u\ \frac{\mathcal{B}(B^0 \to J/\psi\,K^{*0})\mathcal{B}(K^{*0} \to \pi^-K^+)}{\mathcal{B}(B^+ \to J/\psi\,K^+)}$$

- In the ratio J/ψ branching fraction cancels out. We measure R_s (instead of f_s/f_u) as available measurement of $B_s^0 \to J/\psi\phi$ branching fraction and of f_s are correlated.

- CMS uses 61.6 fb^{-1} data collected during 2018 with COM energy 13TeV.

Signal yields for B_s^0, B^+, and B^0

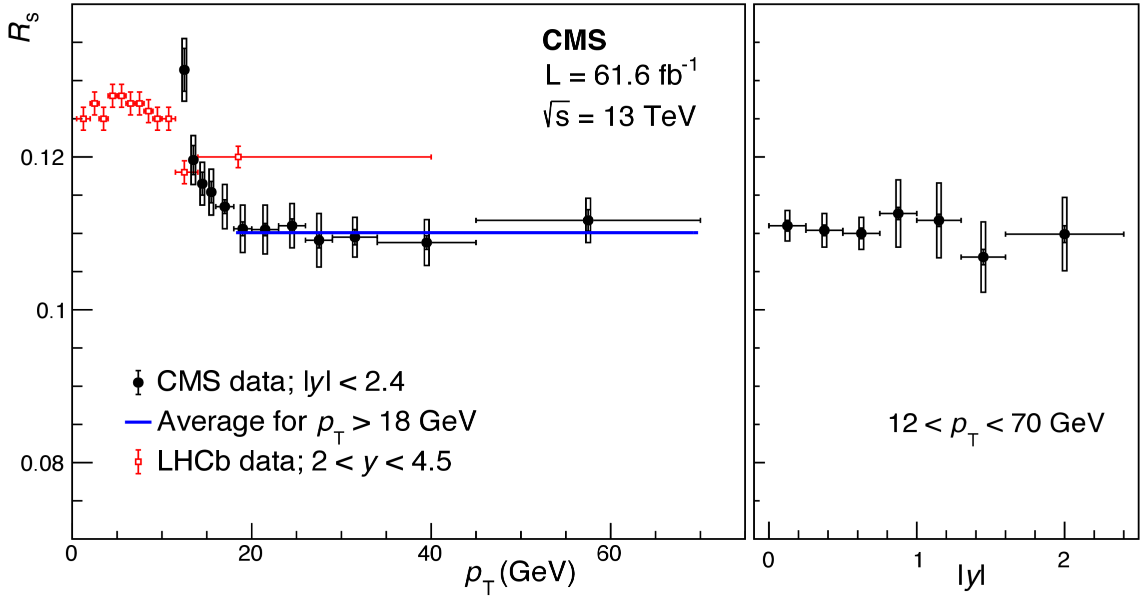


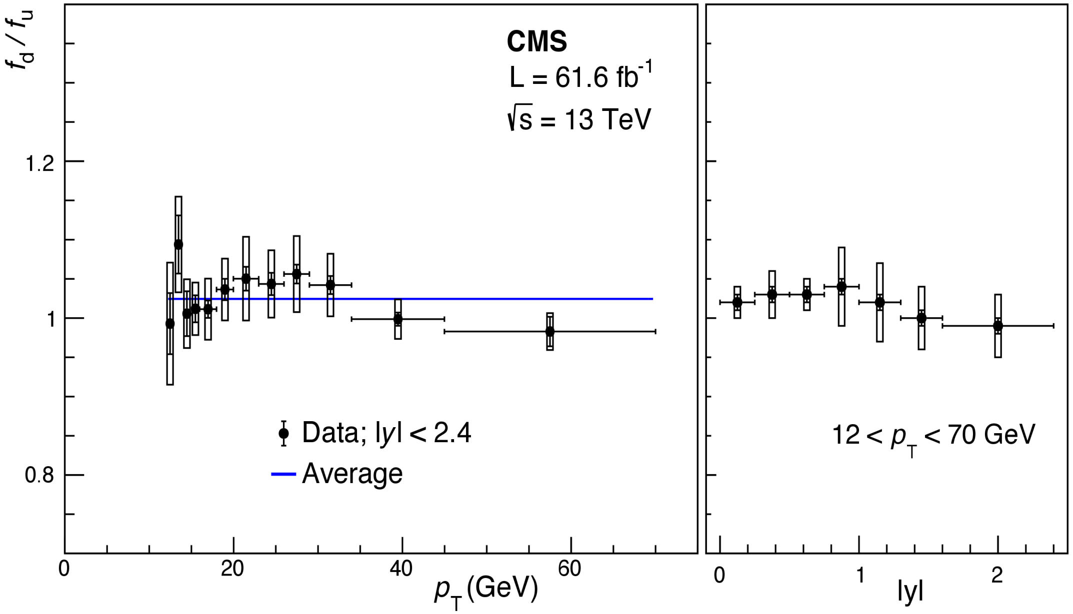
- Signal pdf: Double Gaussian with common mean, independent widths
- Combinatorial background: Exponential
- The other peaking/non-peaking background normalizations/pdfs are either fixed/floated depending on kind of background and information available, e.g.:

- $B^0 \to J/\psi K^+\pi^-$ (where pion can be misidentified as kaon) is Johnson function, with normalization fixed w.r.t signal yield.
- $B \to J/\psi K^+X$ is error function with free shape parameters
- $B^+ \to J/\psi\pi^+$, triple gaussian, normalization fixed to signal yield and scaled by BF ratios
- $B^0 \to J/\psi K^+\pi^-$, shape and relative normalization w.r.t. unswapped fixed from MC.
- $B_s \to J/\psi K^{*0}$ shape fixed from MC, normalization fixed to signal yield.

R_s and f_d/f_u results with CMS data

- The measured R_s does not show any |y| dependence, although there is clear dependence on P_T at low P_T followed by flat shape in high P_T.
- Similar dependency observed by LHCb.
- Averaging the P_T> 18 GeV, the value of Rs= 0.1102± 0.0027

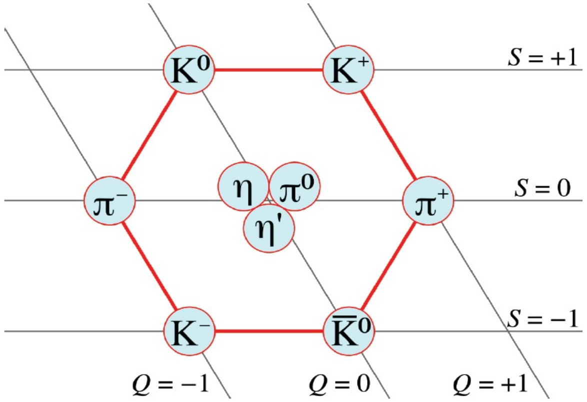




arXiv:2212.02309 (accepted by PRL)

- The ratio f_d/f_u shows no dependency on either P_T or |y|.
- The average over all P_T points given the value: 1.015 ± 0.051. This is consistent with unity as expected from strong isospin symmetry.
- This result will be crucial in the measurement $B_s^0 \to \mu^+\mu^-$ in future.

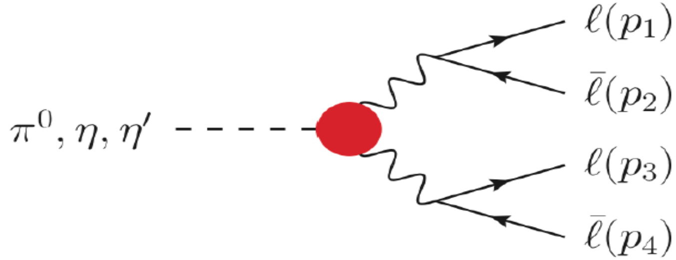
The rare decay of η –> μ⁺μ⁻μ⁺μ⁻ with CMS Data



- Neutral Meson – Pseudoscalar, like π^0, with Strangeness(S)=0 and Charge (Q)=1. $J^{PC}= 0^{-+}$
- Mixture of light quark states:

$$\eta = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$$

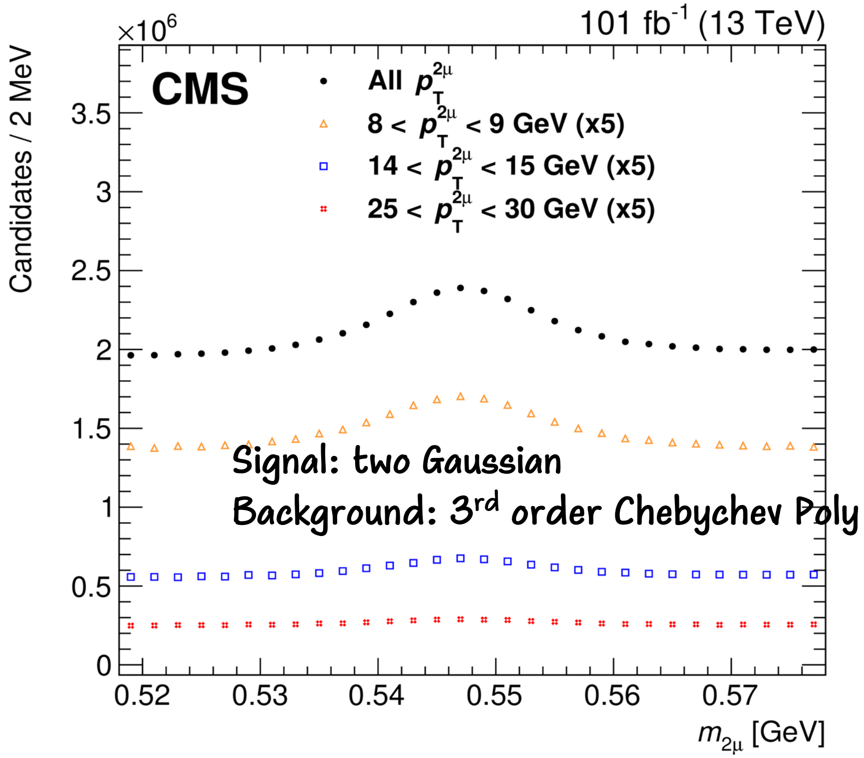
- Mass: 547.9MeV, Width= 0.0013MeV
- η decays to 4 leptons through radiative double Dalitz decays where two virtual photons internally convert to leptons pairs.

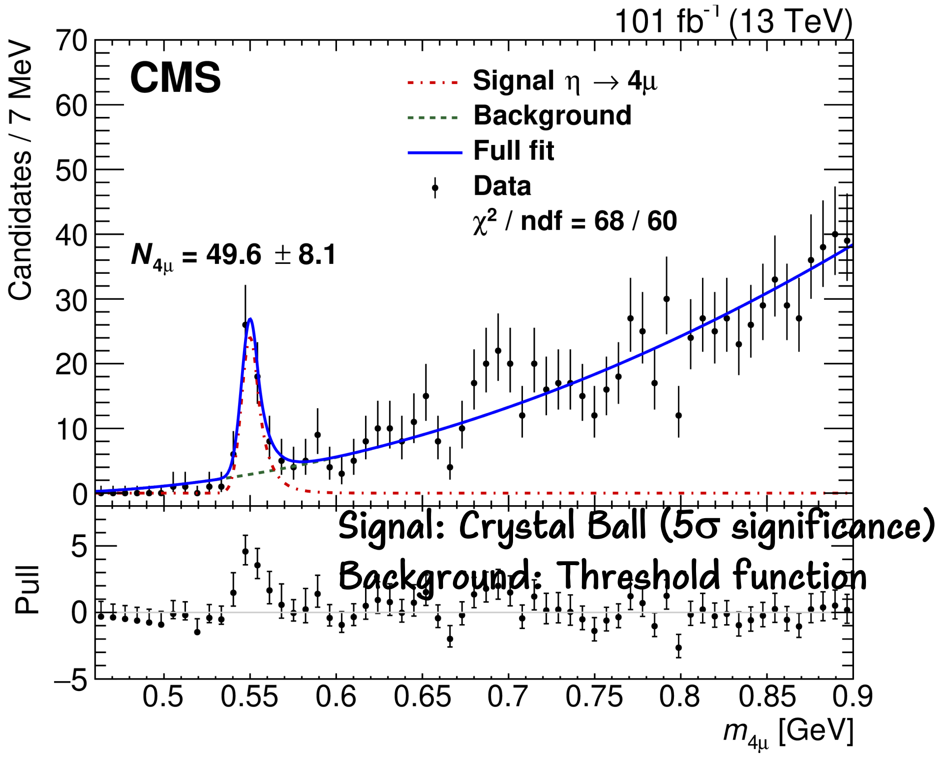


- No Hadrons among decay products -> Matrix element directly sensitive to the η meson transition form factor.
- The knowledge of η meson coupling to the virtual photons is important for calculation of anomalous magnetic moment of muon.
- Study of this process provide a sensitive probe to new Physics, e.g., dark photons, light Higgs scalars, axion-like particles which is complementary to detect new particles below GeV mass scale.

Analysis strategy

- CMS uses 13 TeV data (101 fb^{-1}) collected during 2017 and 2018.
- Use $\eta \to \mu^+\mu^-$ [where $B(\eta \to \mu^+\mu^-) = (5.8 \pm 0.8) \times 10^{-6}$] as the reference channel.
- Dedicated set of high-rate triggers are developed to improve the efficiency at low mass [low P_T muon threshold and keeps only limited information(<10kB)/event].
- Two/Four muons to come from same vertex. About 4.5M $\eta \to 2\mu$ signals and ~50 $\eta \to 4\mu$ signal events found.





Branching fraction measurement for η–>4μ

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

- $\mathcal{B}_{4\mu}$: BF of η–>4μ
- $\mathcal{B}_{2\mu}$: BF of η–>2μ
- $N_{4\mu}$: #of 4μ signal yield
- $N^{i,j}_{2\mu}$: #of 2μ signal yield
- $A^{i,j}_{4\mu}$: Acceptance x Efficiency for 4μ events
- $A^{i,j}_{2\mu}$: Acceptance x Efficiency for 2μ events

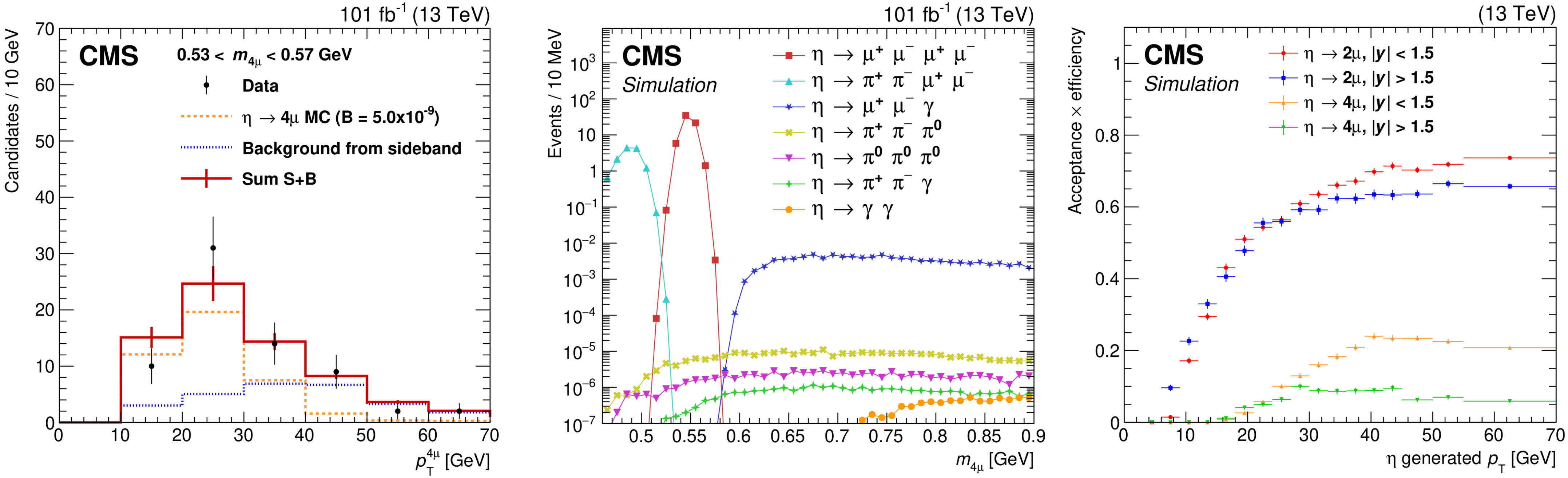
Here ***i*** and ***j*** runs over the P_T and pseudo-rapidity of η mesons

- Using the signal yields and acceptance values, we get $\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = (0.9 \pm 0.1\,(\text{stat}) \pm 0.1\,(\text{syst})) \times 10^{-3}$
- However, using the world average value of BF of η–>2μ, $\mathcal{B}(\eta \to 2\mu) = (5.8 \pm 0.8) \times 10^{-6}$

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

- The expected theoretical value of η to 4μ decay is $(3.98 \pm 0.15) \times 10^{-9}$.
- The observed central value 25% more than prediction, however consistent given large error.

η–> 4μ result with CMS data



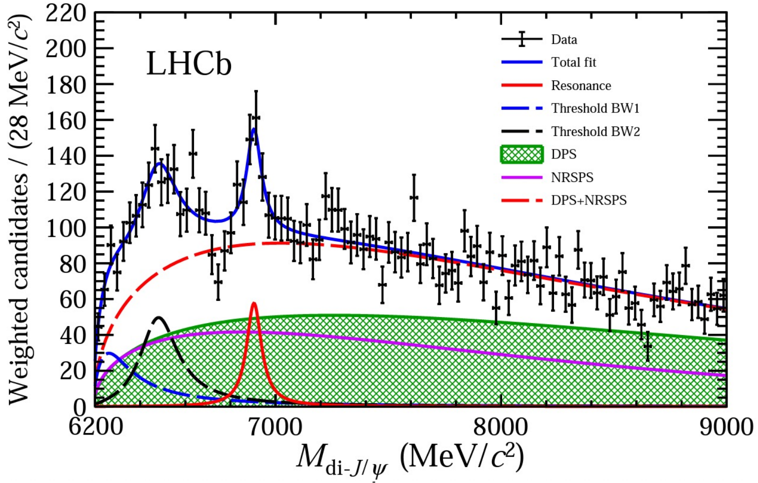
- Main Source of syst shown below: (Several sources already cancels out in the ratio)
  track PT threshold: 9%, trigger PT threshold: 8.4%,
  efficiency plateau 3.2%, fit model (alternate signal and background models): 6.6%
  Overall syst. Uncertainty on BF is ~ 14%

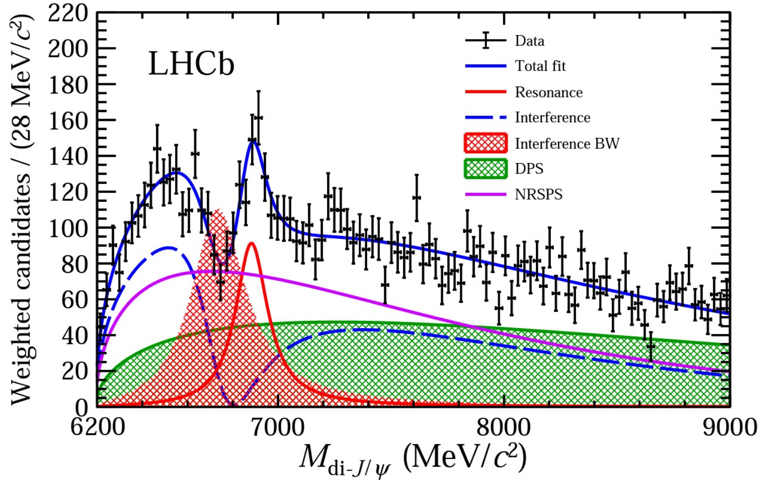
- This is first observation of the double Dalitz decay η–>4μ with high-rate muon trigger.
- It is very important to measure the reference channel precisely.

CMS-PAS-BPH-22-003 (accepted by PRL)

Di-charmonium excess in 4μ final state

- Apart from conventional mesons(two quark states) and baryons(three quark states) many tetraquarks and several pentaquarks candidates are observed in experiment but their theoretical interpretation remain contested.
- The first experimental evidence for exotic hadron was $\chi_{c1}(3872)$ observed by Belle Collaboration in 2003 [PRL 91 (2003) 262001].
- In 2020, LHCb reported evidence of narrow resonance in di-J/ψ (-> 4μ) spectrum, at around 6.9 GeV, which can be interpreted as tetraquark consisting of four charm quarks.

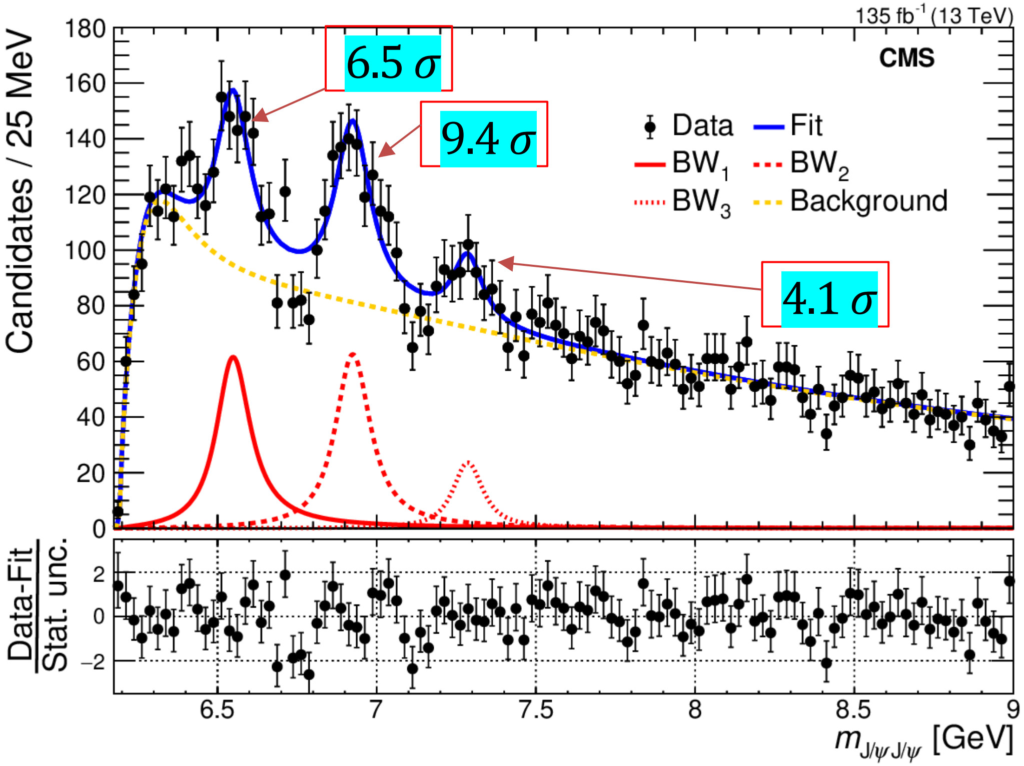




Science Bulletin 65 (2020) 1983

LHCb model I: no interference	LHCb model II: with interference
$m[X(6900)] = 6905 \pm 11 \pm 7\,\text{MeV}/c^2$ $\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\text{MeV}$	$m[X(6900)] = 6886 \pm 11 \pm 11\,\text{MeV}/c^2$ $\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\text{MeV}$

di-J/ψ spectrum without interference model using CMS data



Fit model building:

- Sequential fit starting from background-only hypothesis to increasingly complex ones.
- Add new features if their local significance exceeds 3 standard deviations.

Signal shapes are relativistic S-wave Breit-Wigner functions convolved with double Gaussian resolution functions (BW):

- BW_1 -> structure at ≃ 6600 MeV
- BW_2 -> $X(6900)$
- BW_3 -> structure at ≃ 7200 MeV

Background shapes based on MC simulations:

- **Non-resonant single-parton scattering** (NRSPS)

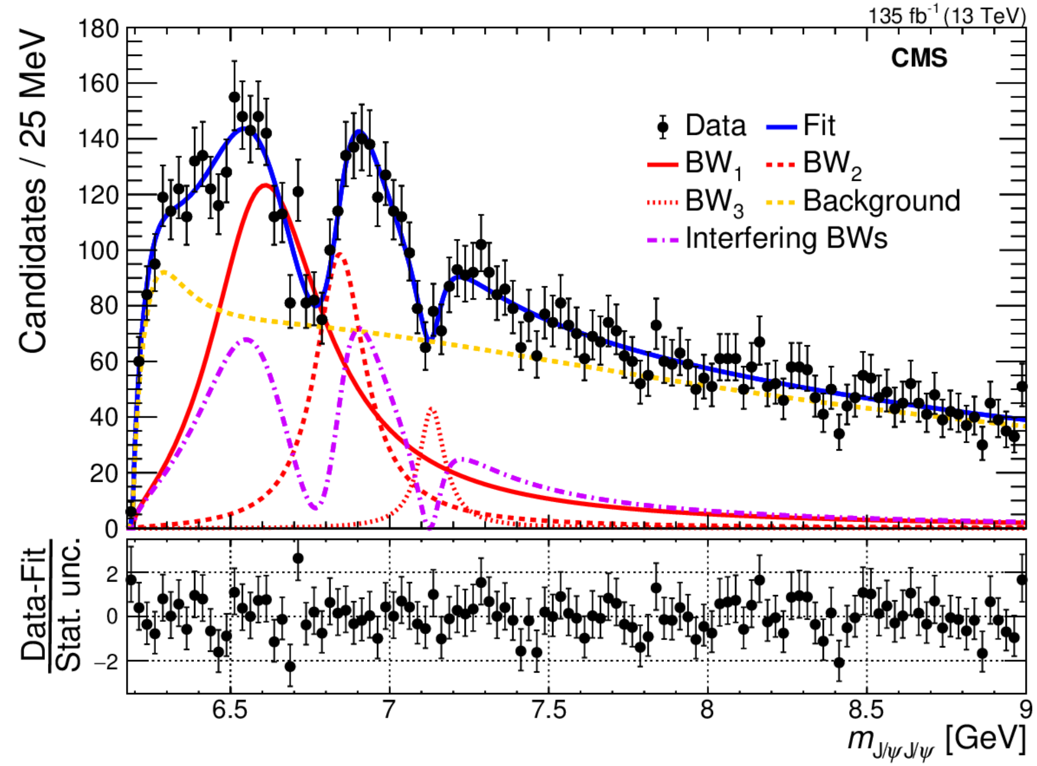
$$f_{SPS}(x, x_0, \alpha, p_1, p_2, p_3) = (x - x_0)^{\alpha} \times \left(1 - \left(\frac{1}{(15 - x_0)^2} - \frac{p_1}{10}\right)(15 - x)^2\right) \times \exp\left(-\frac{(x - x_0)^{p_3}}{2p_2^{p_3}}\right)$$

where $x_t = x - x_0$ and $x_0 = 2M_{J/\psi}$

- **Non-resonant double-parton scattering** (NRDPS):

$$f_{DPS}(x) = \sqrt{x_t} \times \exp(-a x_t) \times (p_0 + p_1 x_t + p_2 x_t^2) \quad \text{where } x_0 = 2M_{J/\psi}$$

di-J/ψ spectrum with interference model using CMS data



- The region around 6750 MeV and 7150MeV are poorly modeled.
- Consider the interference model, between BW_1, BW_2 and BW_3. The term is proportional to

$$|r_1 \exp(i\phi_1)\mathrm{BW}_1 + \mathrm{BW}_2 + r_3 \exp(i\phi_3)\mathrm{BW}_3|^2.$$

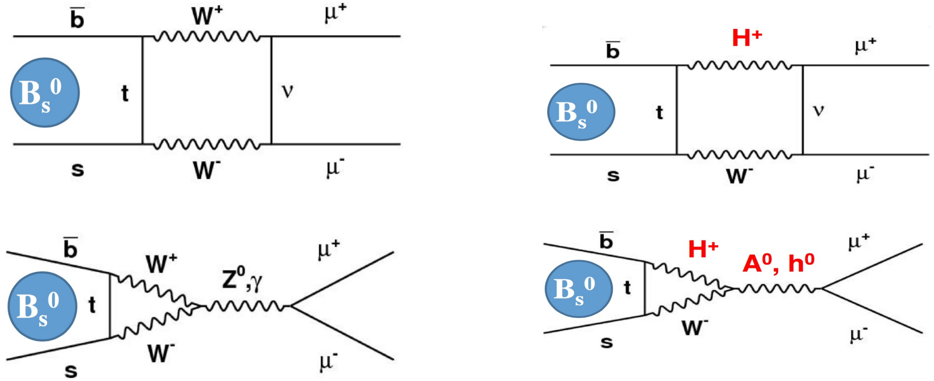
- As per recent theoretical calculations of $cc\bar{c}\bar{c}$ spectrum, these three structures may be a family of radical excitation of the same J^{PC}.

CMS-PAS-BPH-21-003 (submitted to PRL)

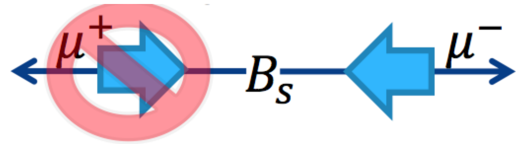
		BW_1	BW_2	BW_3
No-interference	m [MeV]	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
	Γ [MeV]	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
	N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}
Interference	m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
	Γ [MeV]	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

Introduction to $B_s \to \mu^+\mu^-$ decay

- It's a flavor changing neutral current (FCNC) process. Tree level contribution is forbidden in Standard Model.
- Only occurs via loop diagram as shown below.



- The process is helicity suppressed by factor $(m_\mu/m_B)^2$ (forces one of the muons to have wrong helicity direction)



- $B_{s/d} \to \mu^+\mu^-$ is further suppressed compared to $B_{s/d} \to \mu^+\mu^-$ as $|V_{td}| < |V_{ts}|$
- Any new physics could change the branching fraction (extra amplitudes will contribute to the decay process).
- Probably the cleanest rare decay both experimentally and theoretically.

$B(B_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$
$B(B_d \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$

Ref: Bobeth et al, PRL 112, 101801 (2014), and with full electroweak 2 loop corrections and 3 loop QCD correction [
M Beneke et al. JHEP 10(2019) 232

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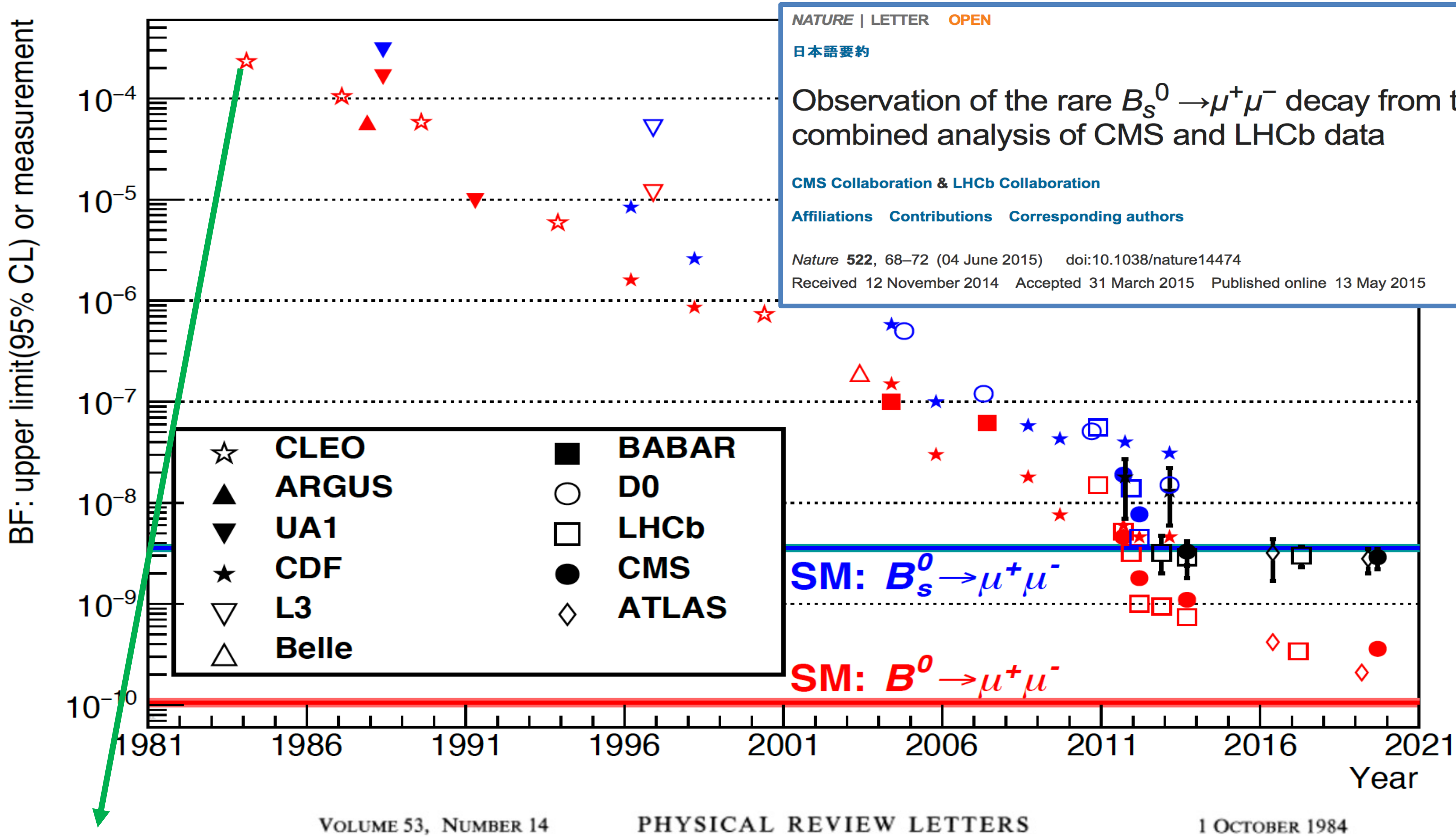
History of $B_s \to \mu^+\mu^-$ search



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日本語要約

Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

CMS Collaboration & LHCb Collaboration

Affiliations Contributions Corresponding authors

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Upper Limit on Flavor-Changing Neutral-Current Decays of the *b* Quark 21

P. Avery, C. Bebek, K. Berkelman, D. G. Cassel, J. W. DeWire, R. Ehrlich, T. Ferguson, R. Galik, M. G. D. Gilchriese, B. Gittelman, M. Halling, D. L. Hartill, S. Holzner, M. Ito, J. Kandaswamy, D. L. Kreinick, Y. Kubota, N. B. Mistry, F. Morrow, E. Nordberg, M. Ogg, A. Silverman, P. C. Stein, S. Stone, D. Weber, and R. Wilcke[a]

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Signal normalization

- Two parameters to be measured from data
  - $B_s \rightarrow \mu\mu$ branching fraction and lifetime
  - Search for $B_d \rightarrow \mu\mu$
- The signal branching fractions are calculated by normalizing to another decay channel: $B \rightarrow J/\psi K$ (primary), $B_s \rightarrow J/\psi\phi$ (alternate)
- Master formula followed for branching fraction estimation:

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = \mathcal{B}(B^+ \rightarrow J/\psi K^+) \frac{N_{B_s^0 \rightarrow \mu^+\mu^-}}{N_{B^+ \rightarrow J/\psi K^+}} \frac{\varepsilon_{B^+ \rightarrow J/\psi K^+}}{\varepsilon_{B_s^0 \rightarrow \mu^+\mu^-}} \frac{f_u}{f_s},$$

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = \mathcal{B}(B_s^0 \rightarrow J/\psi \phi) \frac{N_{B_s^0 \rightarrow \mu^+\mu^-}}{N_{B_s^0 \rightarrow J/\psi \phi}} \frac{\varepsilon_{B_s^0 \rightarrow J/\psi \phi}}{\varepsilon_{B_s^0 \rightarrow \mu^+\mu^-}},$$

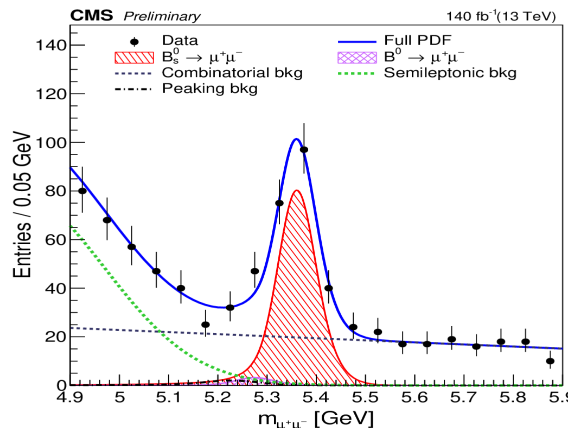
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = \mathcal{B}(B^+ \rightarrow J/\psi K^+) \frac{N_{B^0 \rightarrow \mu^+\mu^-}}{N_{B^+ \rightarrow J/\psi K^+}} \frac{\varepsilon_{B^+ \rightarrow J/\psi K^+}}{\varepsilon_{B^0 \rightarrow \mu^+\mu^-}} \frac{f_u}{f_d},$$

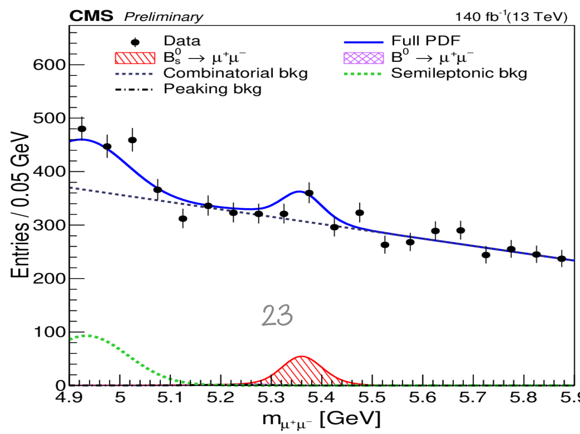
  - $\varepsilon = \varepsilon_{Acc.} \times \varepsilon_{Reco.}$ is total efficiency from the MC.
  - N_{mode} is the normalization of the corresponding decay mode of data fit.
  - f_u , f_s , f_d are the b-quark fragmentation fractions
- Allows the first order cancellation of most systematics

Extraction of $B_{s/d} \rightarrow \mu^+\mu^-$ signal yield

- Signal yield (needed for branching fraction estimation) is obtained via 2-dimensional un-binned maximum likelihood fit to the dimuon invariant mass and its uncertainty
- Events are split into 16 non overlapping categories
  - ⇒ Pseudo-rapidity of the forward muon (2 categories): [0, 0.7] and [0.7, 1.4]
  - ⇒ Data taking period (4 periods): 2016 [split into two parts], 2017, 2018
  - ⇒ MVA (two categories based on signal purity): [0.9, 0.99] and [0.99, 1.0]

<table>
<tr><th>Effect</th><th>$B_s{}^0 \rightarrow \mu^+\mu^-$</th><th>$B^0 \rightarrow \mu^+\mu^-$</th></tr>
<tr><td>Trigger efficiency</td><td colspan="2">2.4 – 3.7%</td></tr>
<tr><td>Pileup</td><td colspan="2">1%</td></tr>
<tr><td>Vertex quality</td><td colspan="2">1%</td></tr>
<tr><td>MVA correction</td><td colspan="2">2 – 3%</td></tr>
<tr><td>Tracking efficiency</td><td colspan="2">2.3%</td></tr>
<tr><td>$J/\psi K^+$ shape (BF)</td><td colspan="2">1% (1%)</td></tr>
<tr><td>Fit bias</td><td>2.2%</td><td>4.5%</td></tr>
<tr><td>f_s/f_u ratio</td><td>3.5%</td><td>-</td></tr>
</table>



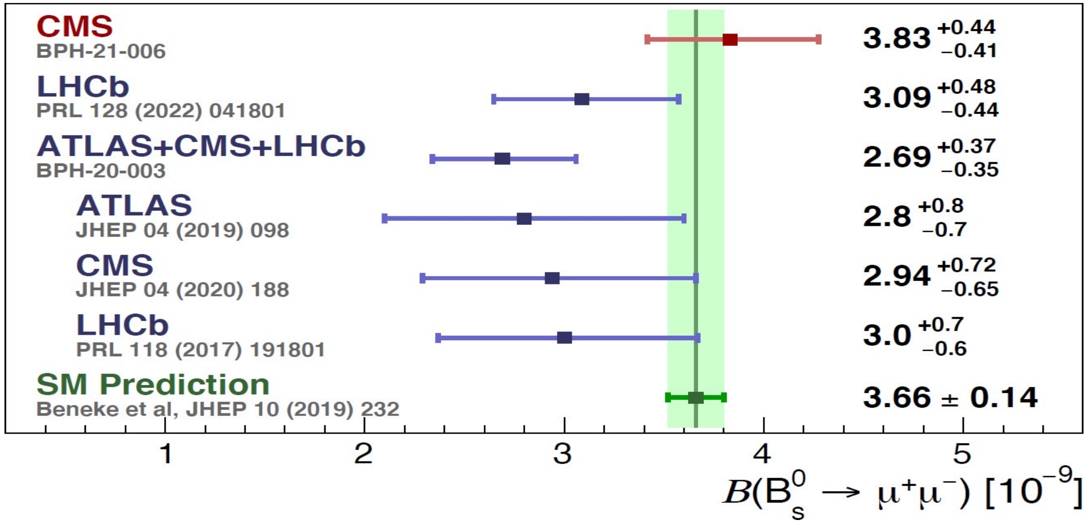


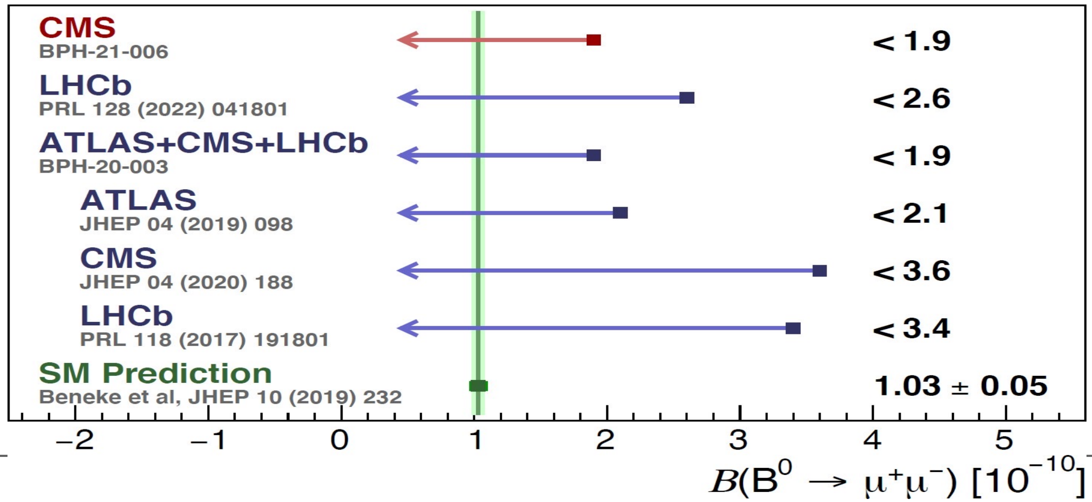
- Main challenge for $B^0 \rightarrow \mu^+\mu^-$ is combinatorial background
- Need lot more data and improved analysis method to reach discovery level.

Branching fraction measurement

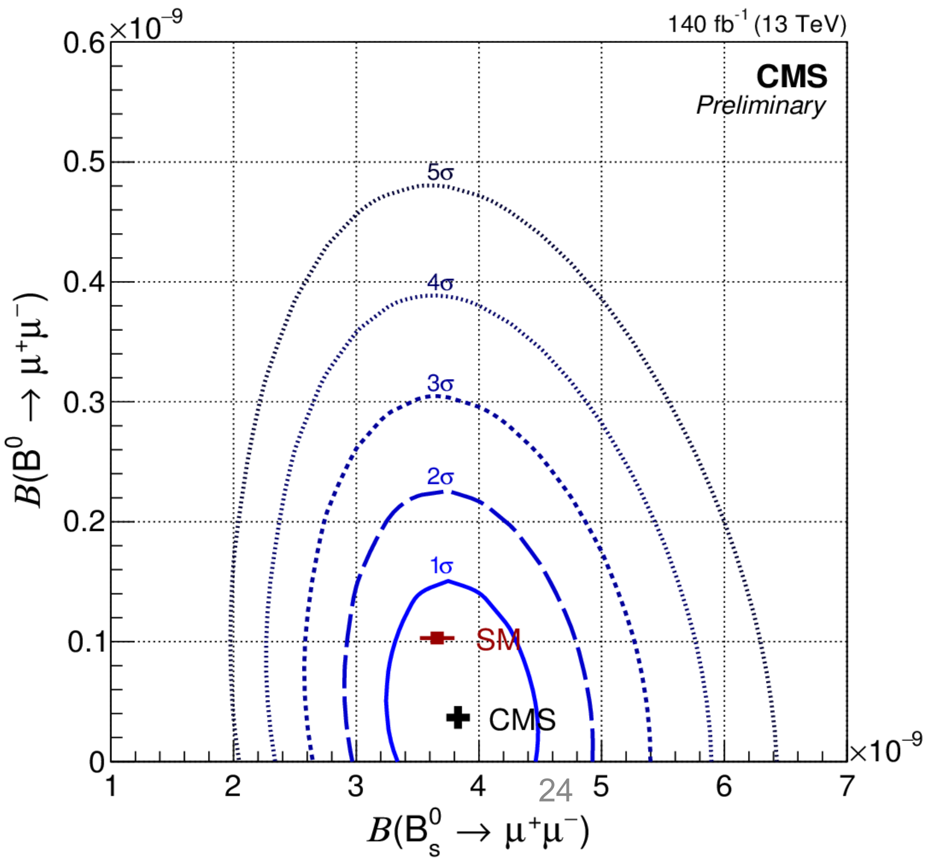
$$BR(B_s^0 \to \mu^+\mu^-) = [3.83^{+0.38}_{-0.36}\ (\mathrm{stat})^{+0.19}_{-0.16}\ (\mathrm{syst})^{+0.14}_{-0.13}(f_s/f_u)] \times 10^{-9}$$

$$BR(B^0 \to \mu^+\mu^-) = [0.37^{+0.75}_{-0.67}\ (\mathrm{stat})^{+0.08}_{-0.09}\ (\mathrm{syst})] \times 10^{-10}$$



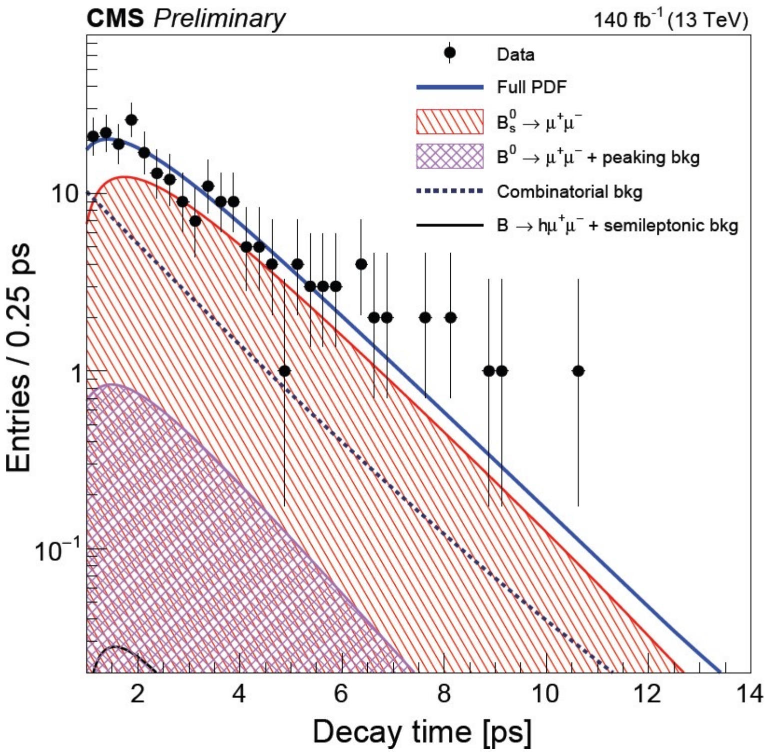


Best measurement by any experiment to date!



PLB 842 (2023) 137955

Effective of lifetime measurement

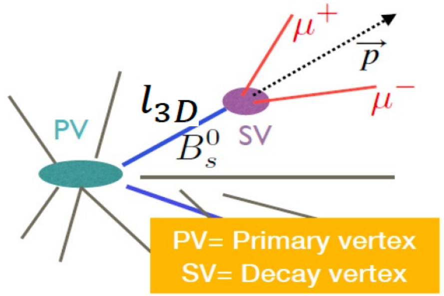


- The proper decay time (t):

$$t = m\frac{l_{3D}}{p}$$

  m: mass of B-meson

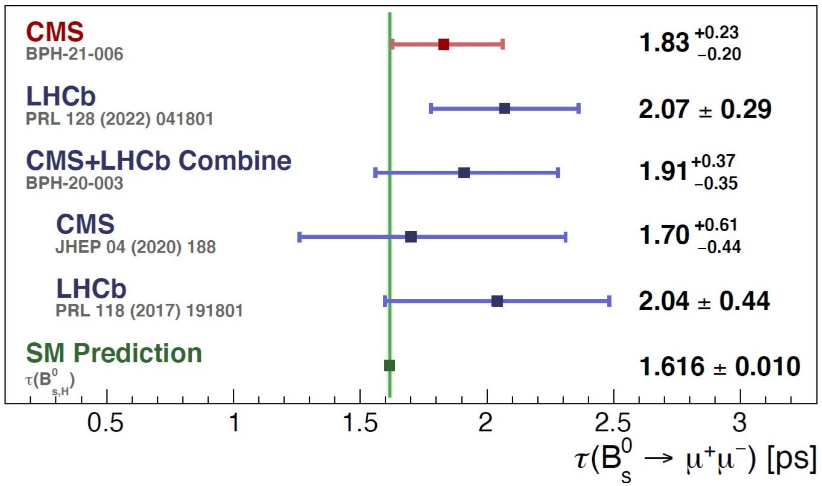
  p: momentum of B-meson



- Unbinned maximum likelihood fit to dimuon invariant mass, proper decay time and its uncertainty
- The dominant source of systematics comes from a strong correlation between MVA and decay time:
- Systematic uncertainties:

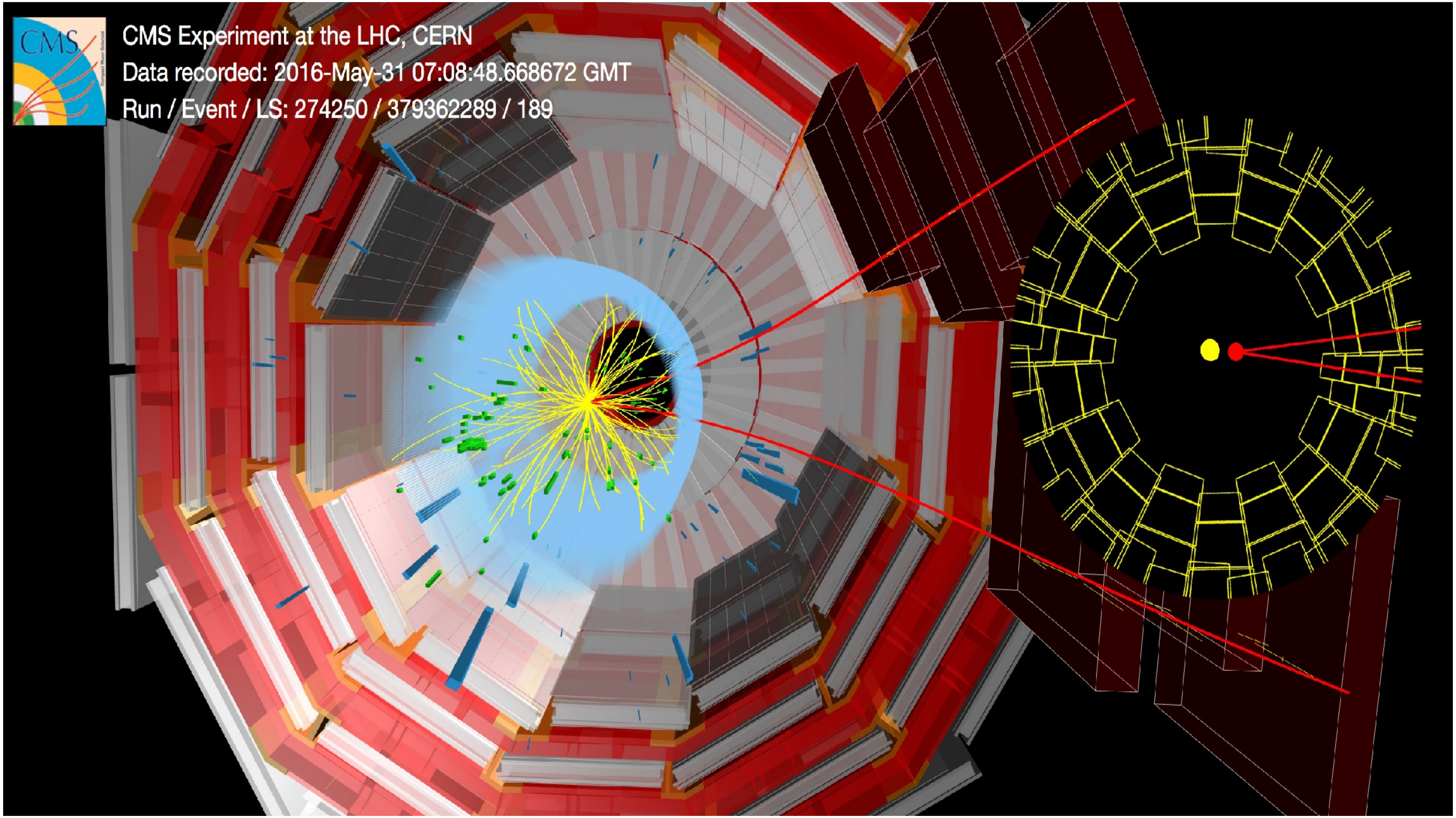
Effect	2016a	2016b	2017	2018
Efficiency modelling	0.01 ps			
Lifetime dependence	0.01 ps			
Decay time mismodeling	0.10 ps	0.06 ps	0.02 ps	0.02 ps
Lifetime bias	0.04 ps	0.04 ps	0.05 ps	0.04 ps
Total	**0.11 ps**	**0.07 ps**	**0.05 ps**	**0.04 ps**

$$\tau(B_s \to \mu^+\mu^-) = [1.83^{+0.23}_{-0.20}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{syst})]\ \text{ps}$$



Best measurement to date !

A random $B_s \rightarrow \mu^+\mu^-$ event with CMS detector



Summary and discussions

- CMS pursues broad spectrum of B-physics measurements.
- Better measurement on lepton flavor violating decay of $\tau \rightarrow 3\mu$ is reported.
- First observation of $\Lambda_b^0 \rightarrow J/\psi\ \Xi^- K^+$ decay is reported.
- The precision measurements of fragmentation fraction would be crucial input for the $B_s^0 \rightarrow \mu^+\mu^-$ branching fraction.
- The first observation of double Dalitz rare decay of $\eta \rightarrow 4\mu$ is reported.
- Di-charmonium mass spectrum was studied by CMS. The detailed interpretation of the structures (whether they are four charm tetra quark states) are yet to be confirmed.
- The results for $B_s^0 \rightarrow \mu^+\mu^-$ branching fraction and effective lifetime as best ones by any experiment so far.
- More results on Run2, as well as Run3 data (with COM energy of 13.6 TeV) coming soon.