22nd Conference on Flavor Physics and CP Violation, May 27th, 2024

SEARCHES FOR RARE DECAYS @CMS

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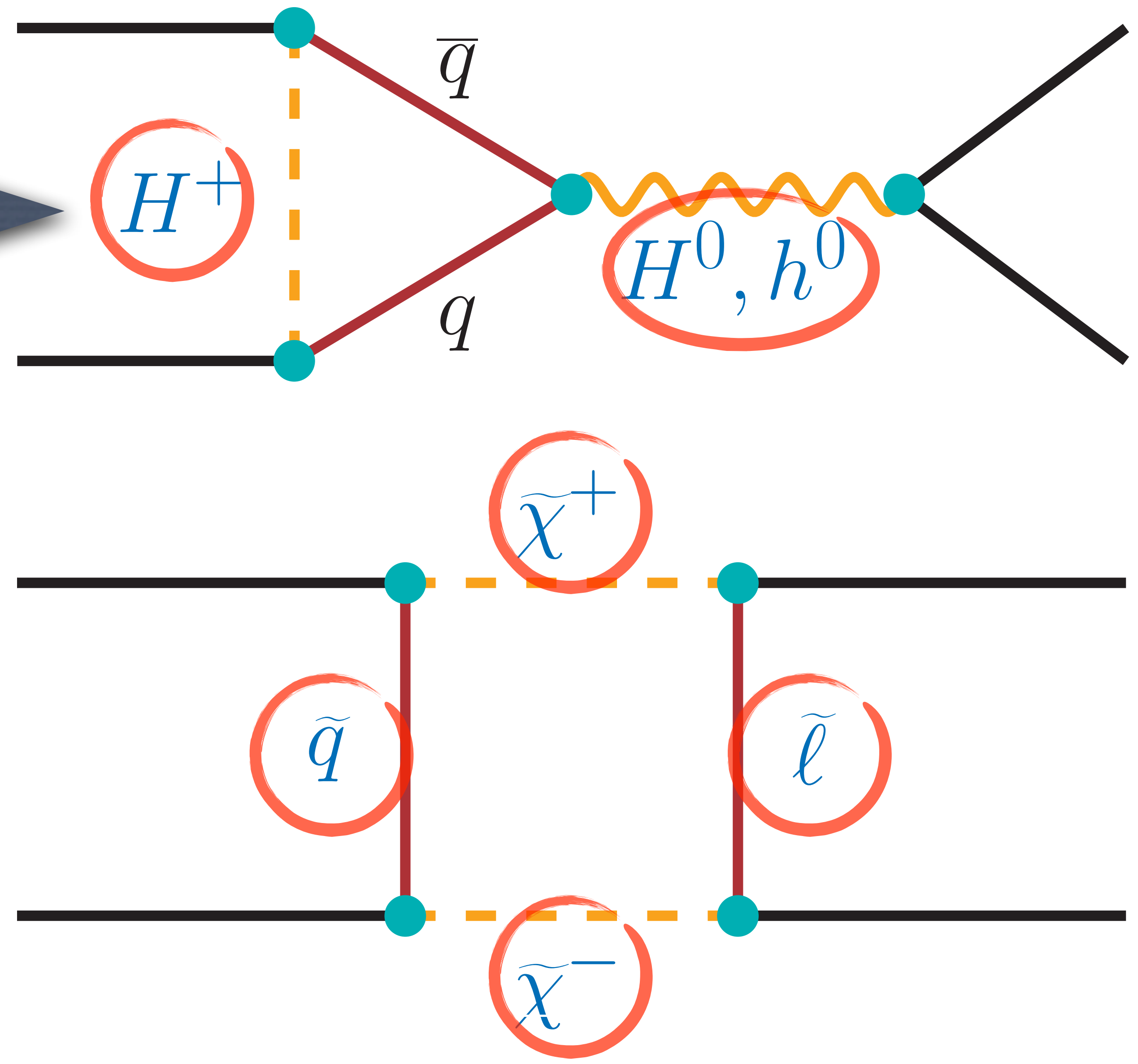
On Behalf of the CMS Collaboration

PROBE FOR NEW PHYSICS?

- **Through direct searches:**
  - Produce "real" new particles at high energy and discovery via their decays or interactions with the detectors.
- **Through indirect searches:**
  - "Virtual" new particles participating in the **RARE PROCESSES** and detecting any deviations from the SM predictions.

If new particles cannot be observed in the direct searches, here is the place we shall dig in!



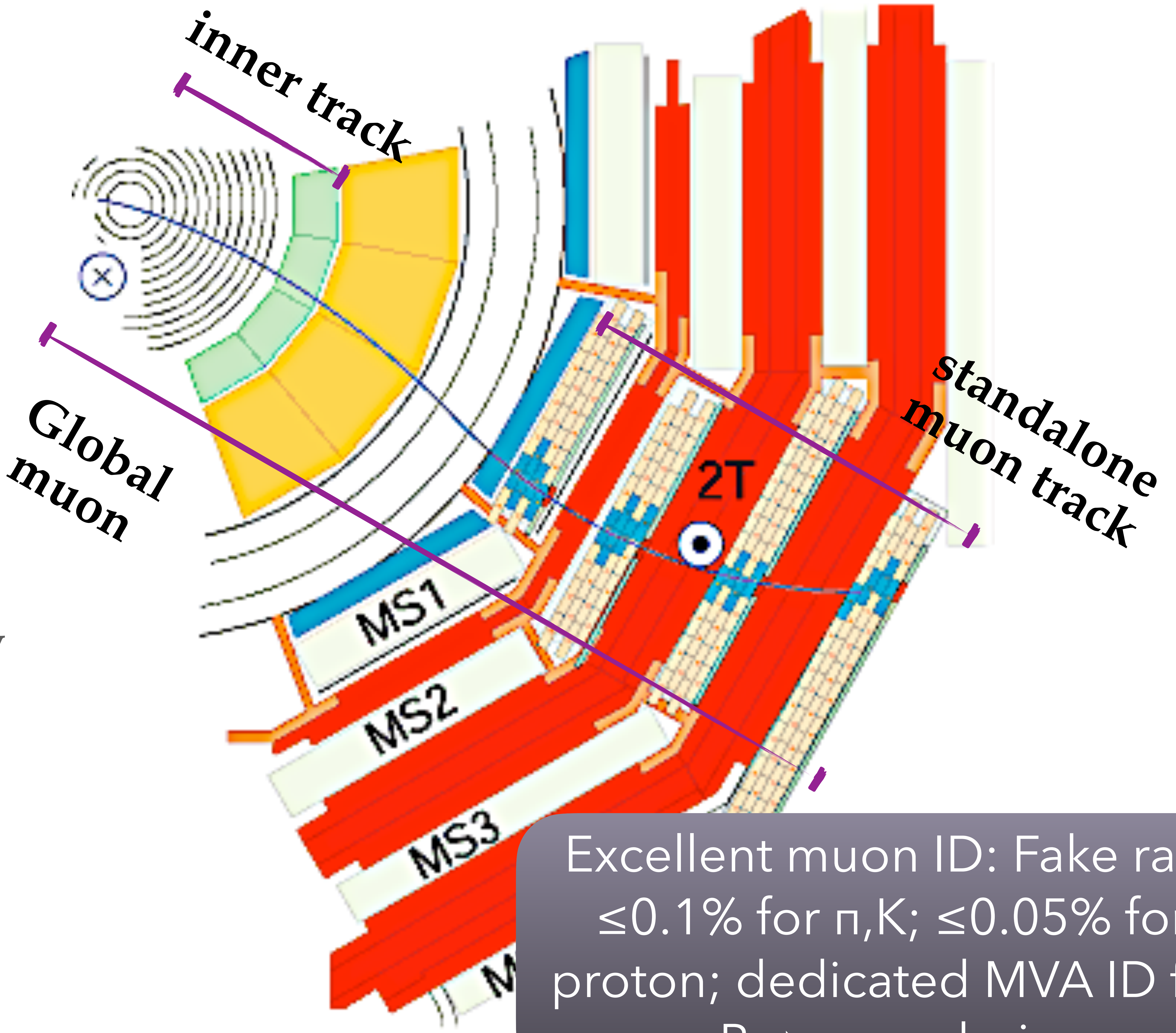
Direct and indirect searches are both necessary and complement each other!

Measurement of $B_s \to \mu^+\mu^-$ & Search for $B^0 \to \mu^+\mu^-$	Search for the LFV $\tau \to 3\mu$ decay	Observation of rare $\eta \to 4\mu$ decay	Observation of the rare $J/\psi \to 4\mu$ decay
Ref. PLB 842 (2023) 137955	PLB 853 (2024) 138633	PRL 131 (2023) 091903	CMS BPH-22-006 Accepted by PRD

CMS MUON RECONSTRUCTION

As muon in the name of the detector, CMS does have an excellent muon system!

- **CMS muon system**:
  - 3 different devices, with a large coverage up to $|\eta|<2.4$.
  - Good dimuon mass resolution: ~0.6-1.5% (depending on $|y|$).
- **Reconstruction algorithms**:
  - **Standalone muon**: reconstructed in muon system only
  - **Global muon**: standalone muon ⇒ inner track
  - **Tracker muon**: inner track ⇒ muon system

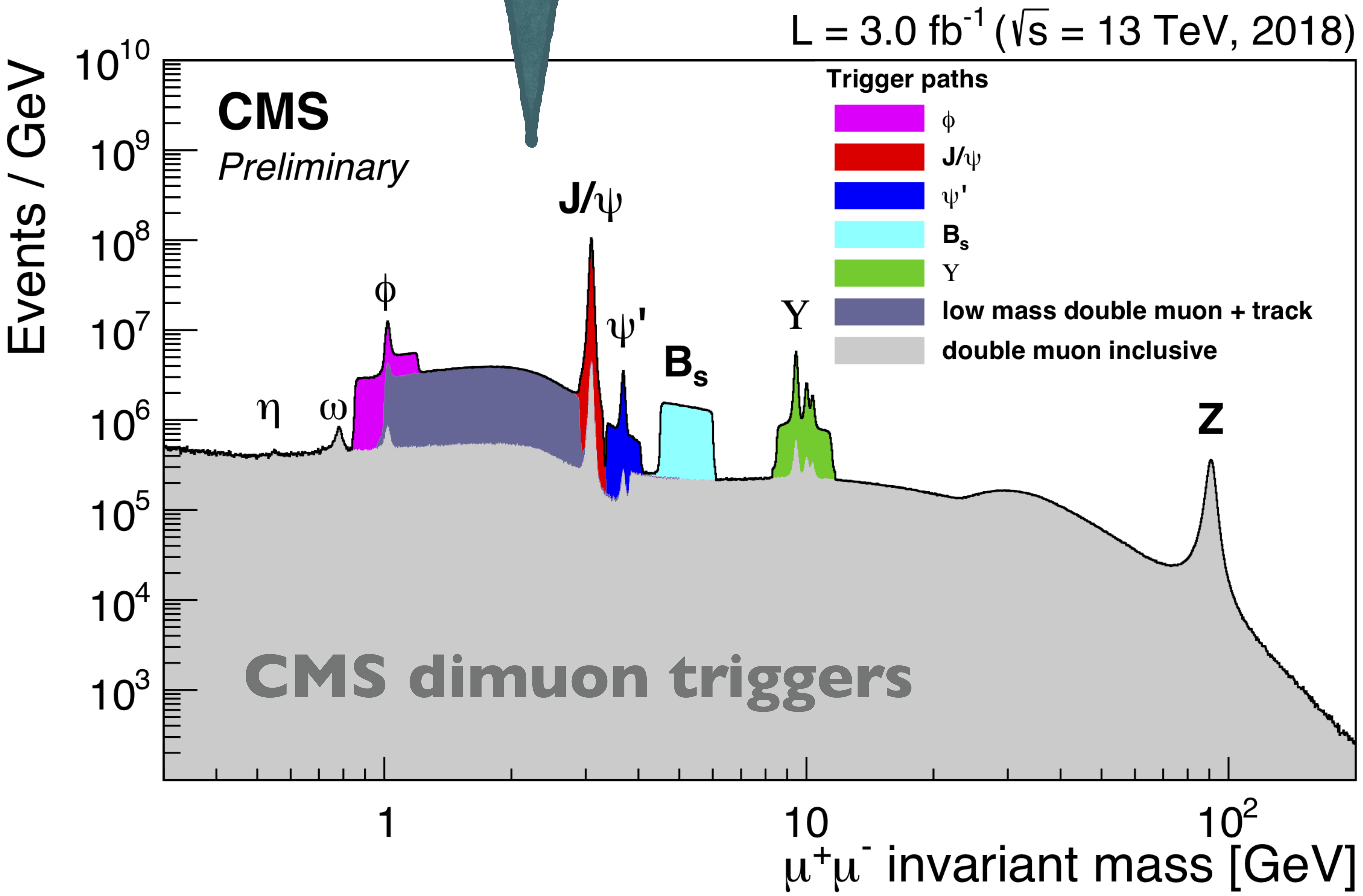


Excellent muon ID: Fake rate ≤0.1% for π,K; ≤0.05% for proton; dedicated MVA ID for B→μμ analysis.

CMS HEAVY FLAVOR TRIGGERS

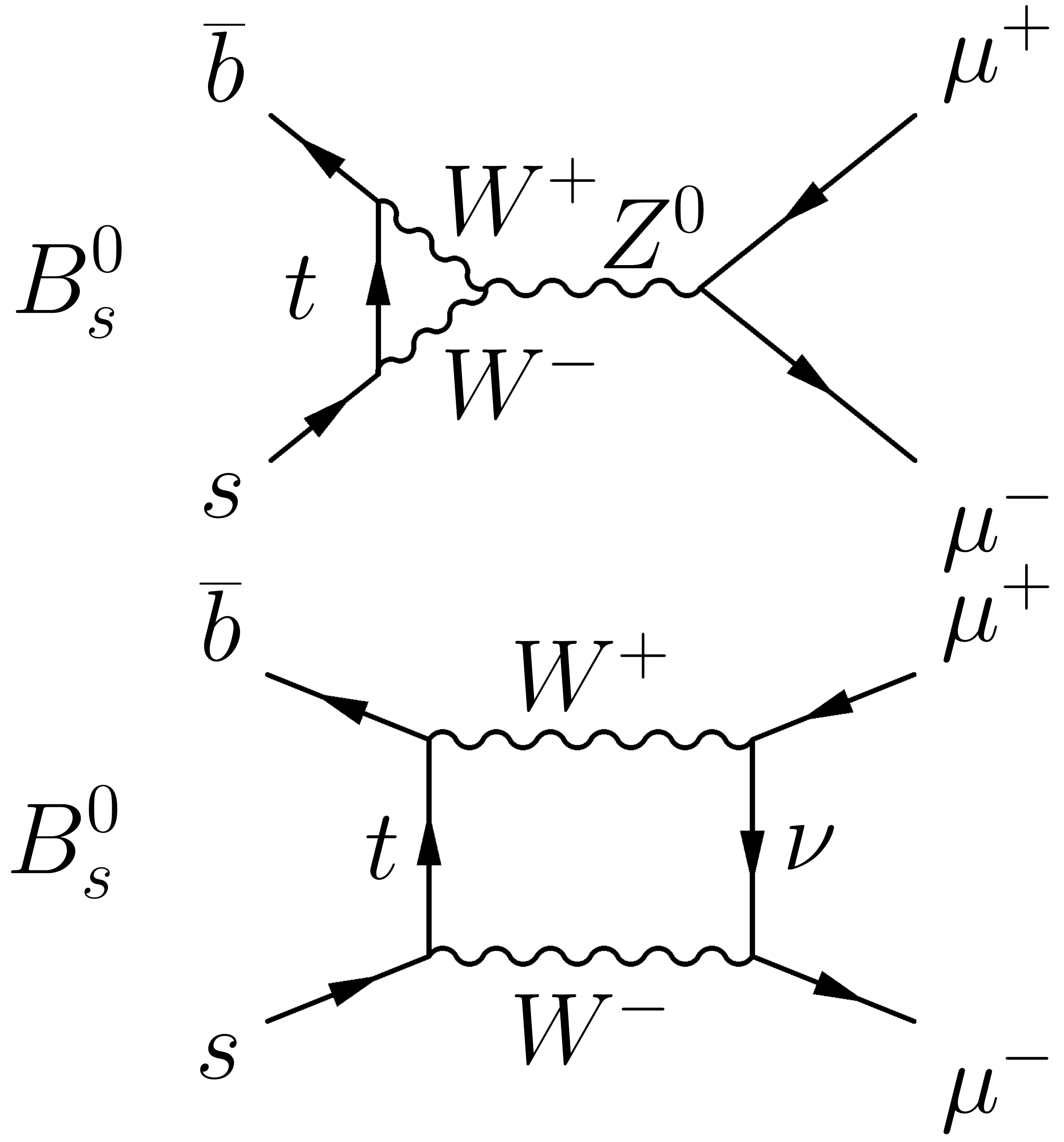
- **CMS trigger system**:
  - Fast hardware trigger (L1) @ 100 kHz
  - Software trigger with full tracking & vertex reconstruction (HLT) @ 1.5 kHz.
  - Specific triggers were developed for various analyses.
  - Trigger requirements tightened with increased luminosity.
  - ~15% of bandwidth is given to flavor physics; **"scouting"** & **"parking"** streams for extended capabilities.

The flavor physics analyses rely on displaced/non-displaced quarkonia (J/ψ, ψ' & Υ), B(s), non-resonant dimuon triggers.



PHYSICS MOTIVATION: $B \to \mu^+\mu^-$

- $B \to \mu^+\mu^-$ decays only proceed through FCNC processes and are highly suppressed in SM.
- Loop diagram + Suppressed SM + Theoretically clean = **an excellent place to look for NP**.
- What to measure:
  - **Branching fractions**: $B_s \to \mu\mu$ may start to enter precision regime, while first evidence of $B^0 \to \mu\mu$ might emerge.
  - **Effective lifetime**: only the heavy B_s state can decay into dimuon in the SM; different composition of states may be allowed by NP.



$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\,\Gamma(B_s(t) \to \mu^+\mu^-)\,dt}{\int_0^\infty \Gamma(B_s(t) \to \mu^+\mu^-)\,dt} = \frac{\tau_{B_s^0}}{1-y_s^2}\left(\frac{1+2\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-}y_s + y_s^2}{1+\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-}y_s}\right)$$

$$\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-} \equiv -\mathcal{R}(\lambda)/(1+|\lambda|^2)$$
$$y_s \equiv \tau_{B_s^0}\Delta\Gamma_s/2$$

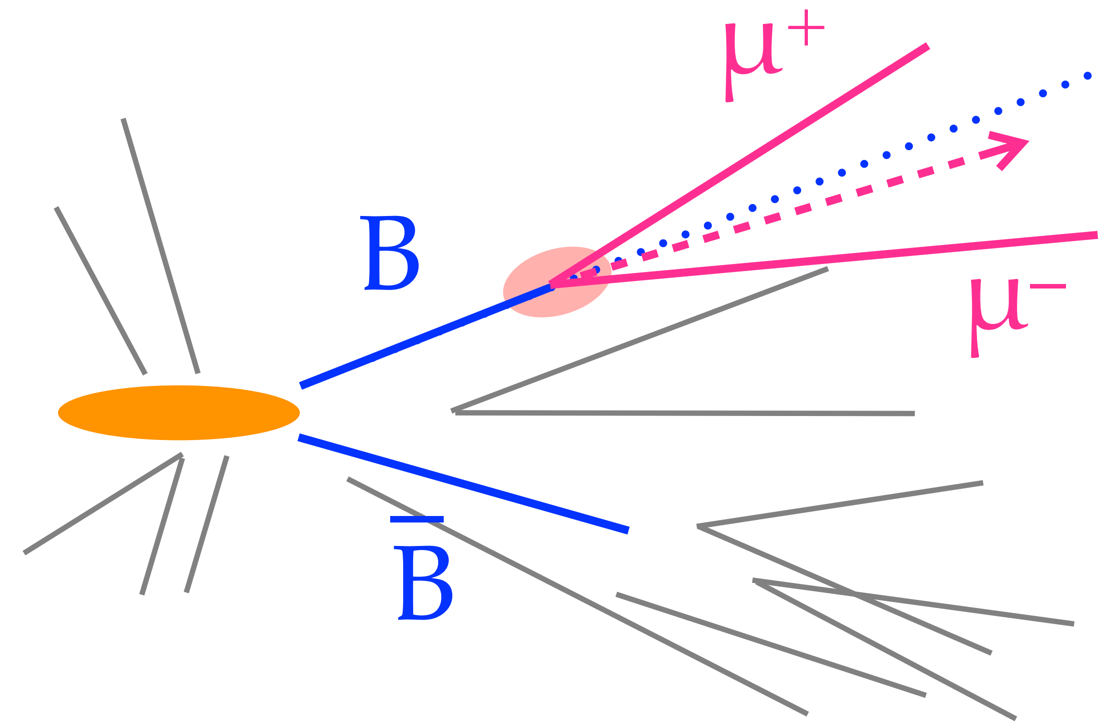
- SM predictions:

$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.66 \pm 0.14)\times 10^{-9}$
$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05)\times 10^{-10}$
$\tau(B_s \to \mu^+\mu^-) = 1.624 \pm 0.009$ ps

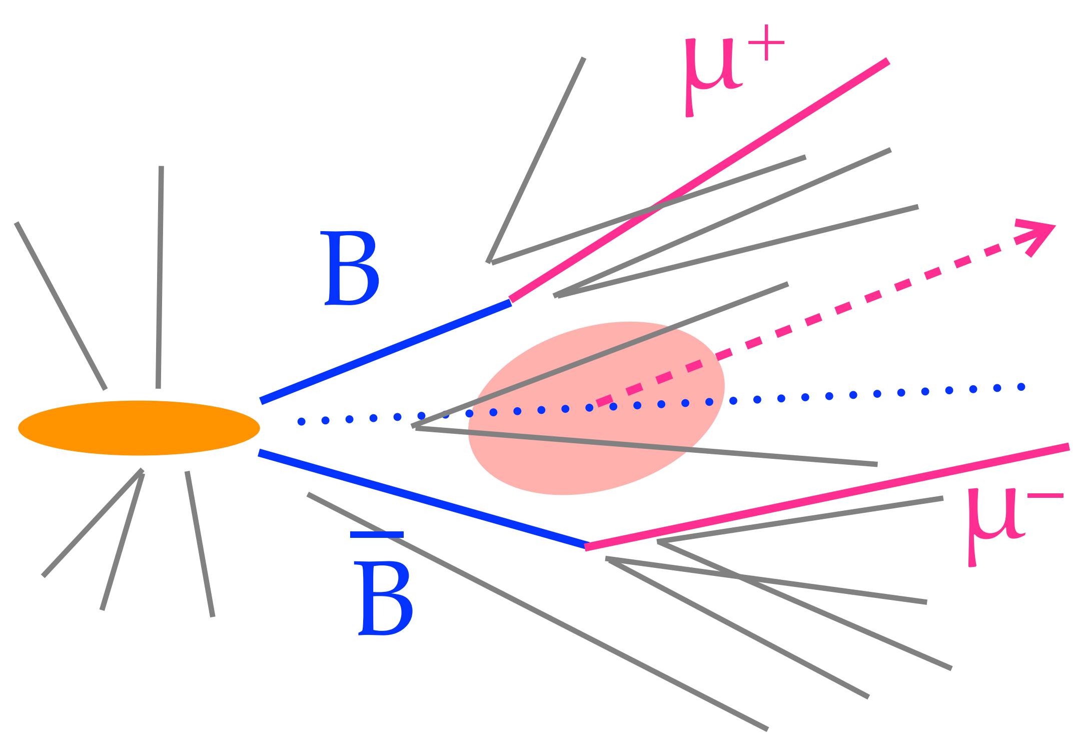
Ref: Beneke et al, JHEP 10 (2019) 232
Beneke et al, PRL 120, 011801 (2018)
Bobeth et al, PRL 112, 101801 (2014)

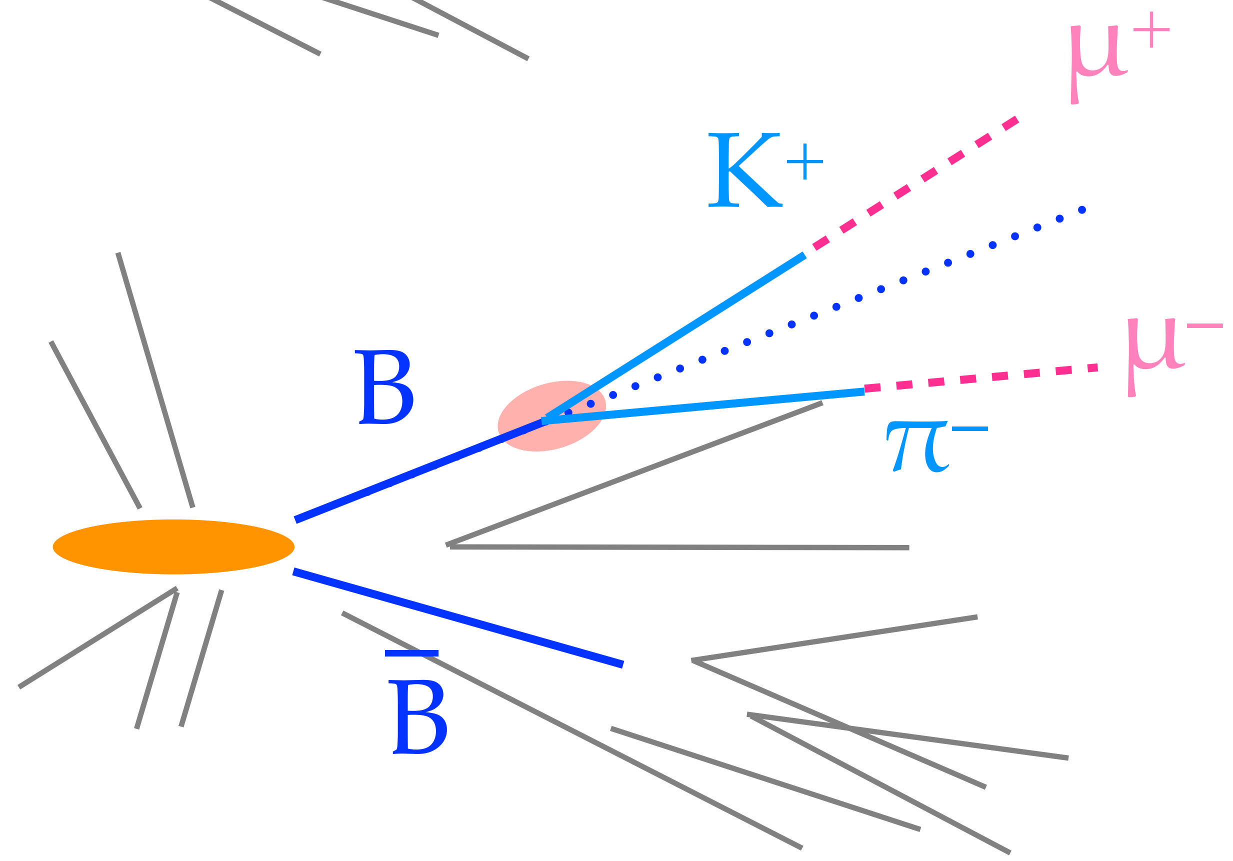
ANALYSIS ASPECTS

- **$B_{s,d} \to \mu^+\mu^-$ signal signature:**
  - two muons from one displaced vertex; isolated from other activities; momentum aligned with its flight direction; invariant mass peaking at $M(B_{s,d})$.



- **Background sources:**
  - **Combinatorial background** consists of
    - two semileptonic B decays
    - one semileptonic B + a misidentified hadron
  - **Rare background** from single B meson decays:
    e.g. $B \to K\pi/KK/\pi\pi$ *(peaking)*,
    $B \to h^-\mu^+\nu$, $B \to h\mu^+\mu^-$ *(not peaking)*





Powerful background suppression reached by muon quality, well-reconstructed secondary vertex, isolation, pointing angle, and $M(\mu\mu)$ resolution.

ANALYSIS ASPECTS (CONT.)

- Background suppression achieved by
  - Strict **BDT muon identification** requirement, including tracking and muon related detector information, fake rates ≲0.1%.
  - An improved **event classification BDT**, which includes topological and kinematical variables.
- Branching fractions are normalized with **$B^+ \to J/\psi K^+$** or **$B_s \to J/\psi \varphi$**:

External b hadronization fraction ratio

Allow first order cancellation of systematics; rare backgrounds normalized in a similar manner.

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

$$\text{or } \left\{ = \mathcal{B}(B_s^0 \to J/\psi\phi) \times \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{B_s^0 \to J/\psi\phi}} \times \frac{\epsilon_{B_s^0 \to J/\psi\phi}}{\epsilon_{B_s^0 \to \mu^+\mu^-}} \right\}$$

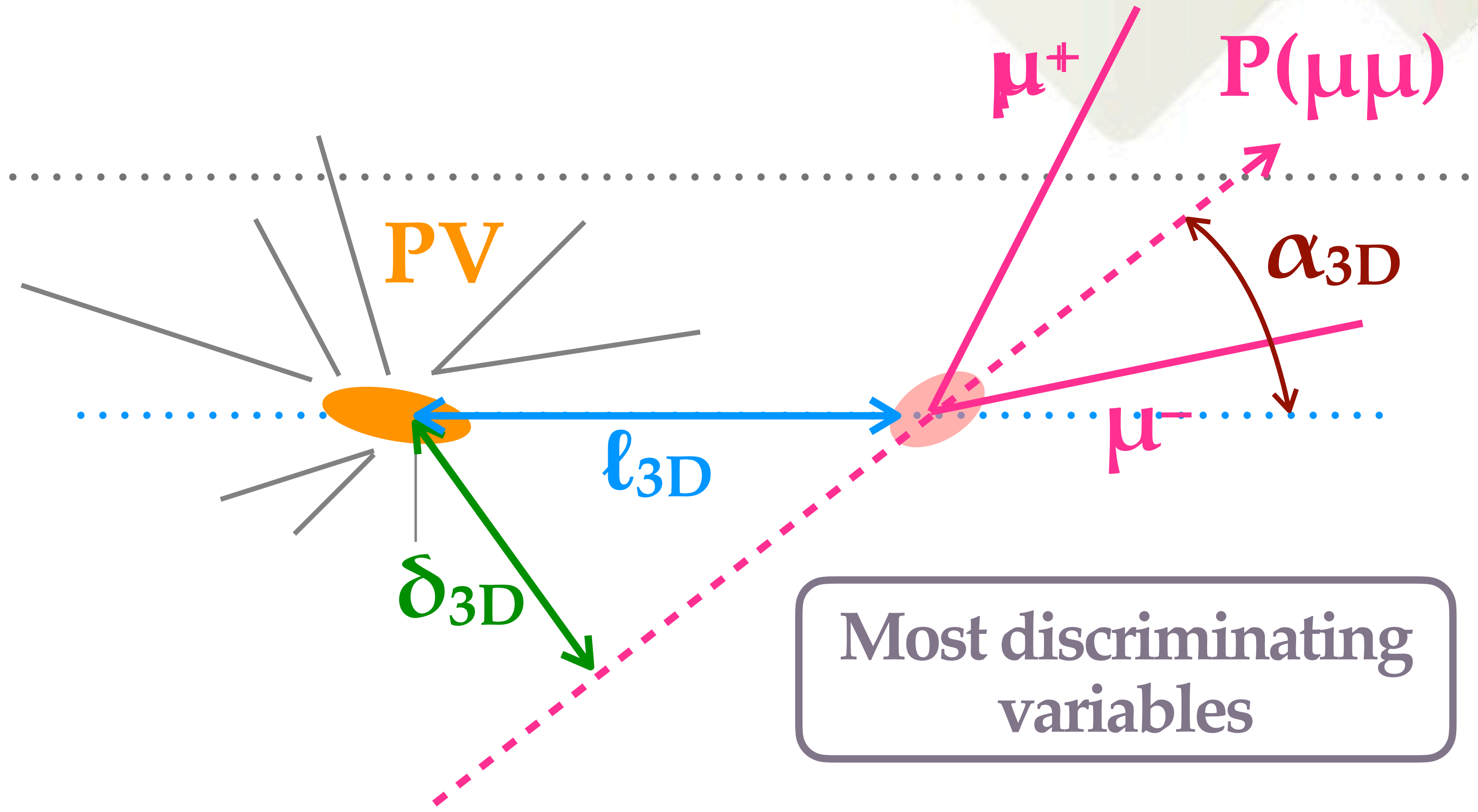
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \times \frac{N_{B^0 \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \times \frac{\epsilon_{B^+ \to J/\psi K^+}}{\epsilon_{B^0 \to \mu^+\mu^-}} \times \frac{f_u}{f_d}$$

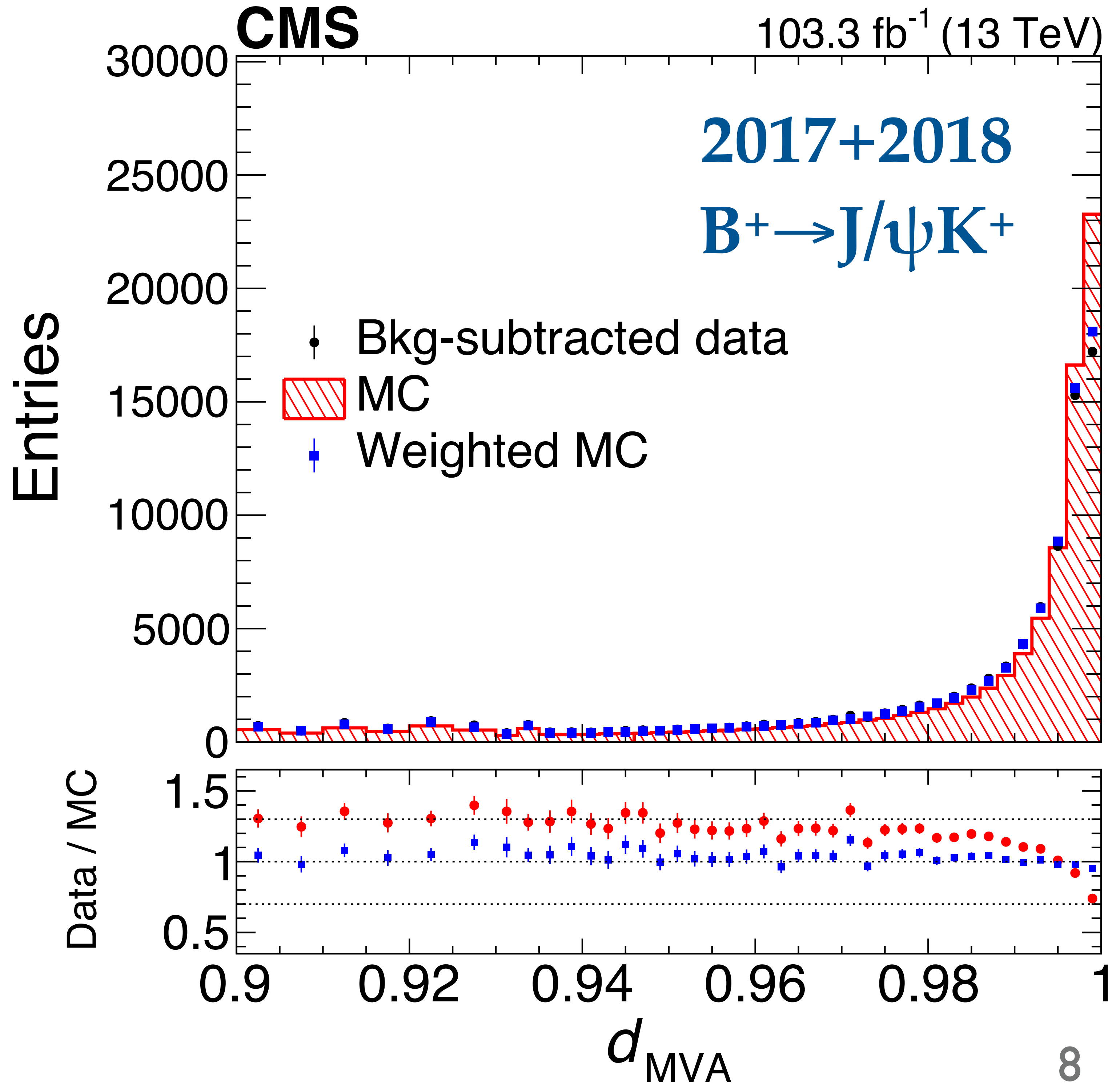
$=1$

EVENT CLASSIFICATION MVA

- New event classification MVA (denoted as **d_{MVA}**) to suppress the combinatorial backgrounds.
- Training with signal MC and mass sideband data with the XGBoost package (*advanced gradient boosting algorithm*).
- **Use $B^+ \to J/\psi K^+$ to calibrate MVA performance**; to make the d_{MVA} closer to signal $B \to \mu\mu$:
  - Require soft kaon $p_T < 1.5$ GeV;
  - Scale flight-length significance by 1.6;
  - Train a XGBoost classifier to reweight MC to match to the data.

only introduced here, not for the normalization!





~2 times higher signal efficiency for the same background level w.r.t. previous analysis

FRAGMENTATION RATIO: f_s/f_u

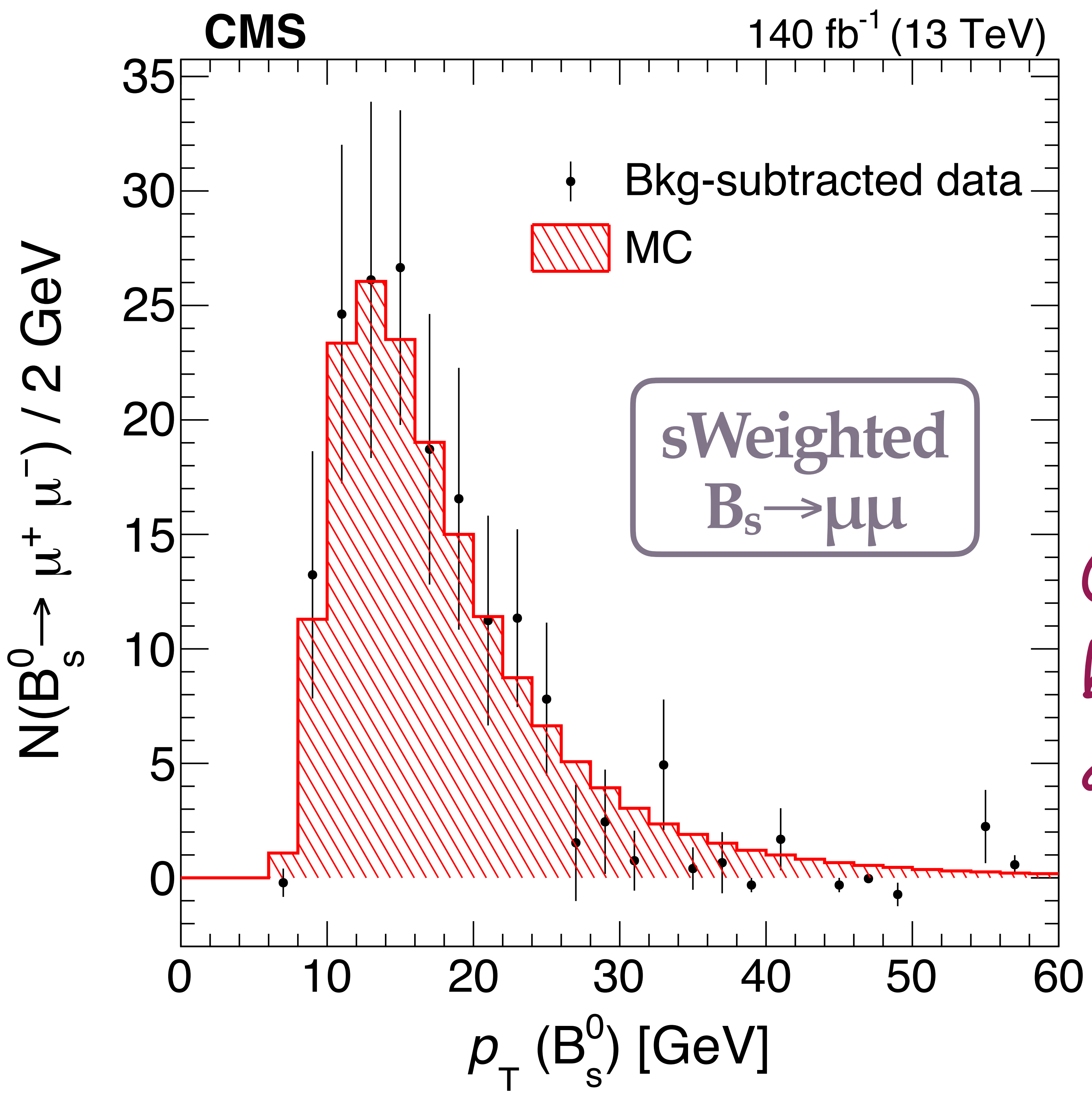
- The ratio of fragmentation fraction **f_s/f_u is a key external input** to this measurement:

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

Our evaluation:

$f_s/f_u = 0.231 \pm 0.008$

- This value is derived from the p_T-dependent results from **LHCb PRD 104 (2021) 032005**:
  - Integrate with the effective p_T distribution from the CMS analysis.
  - Verified with $J/\psi K^+$ and $J/\psi\varphi$ data.
- **Resulting BF can be rescaled**:
  - Can plug in a different value afterwards!
  - Treated as an **external uncertainty** *(not as a constrained nuisance parameter)*.



Good agreement between data and MC!

SYSTEMATIC UNCERTAINTIES BREAKDOWN

Branching fractions

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

Effective Lifetime

Effect	2016-A	2016-B	2017	2018
Efficiency modeling	0.01 ps			
Scanning over different gen lifetime sample	0.01 ps			
Decay time distribution mis-modeling	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**

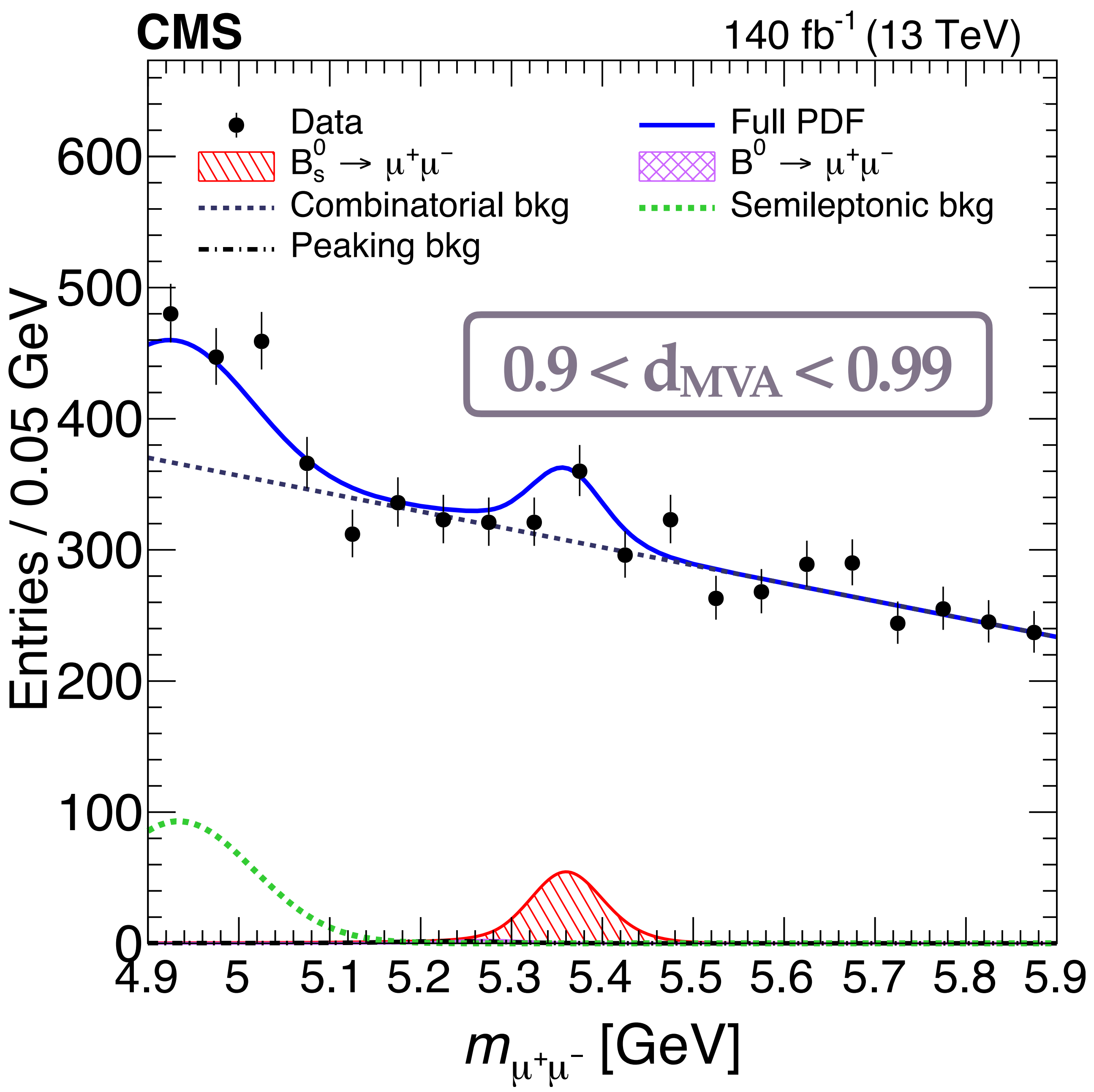
Still dominated by statistical uncertainty!

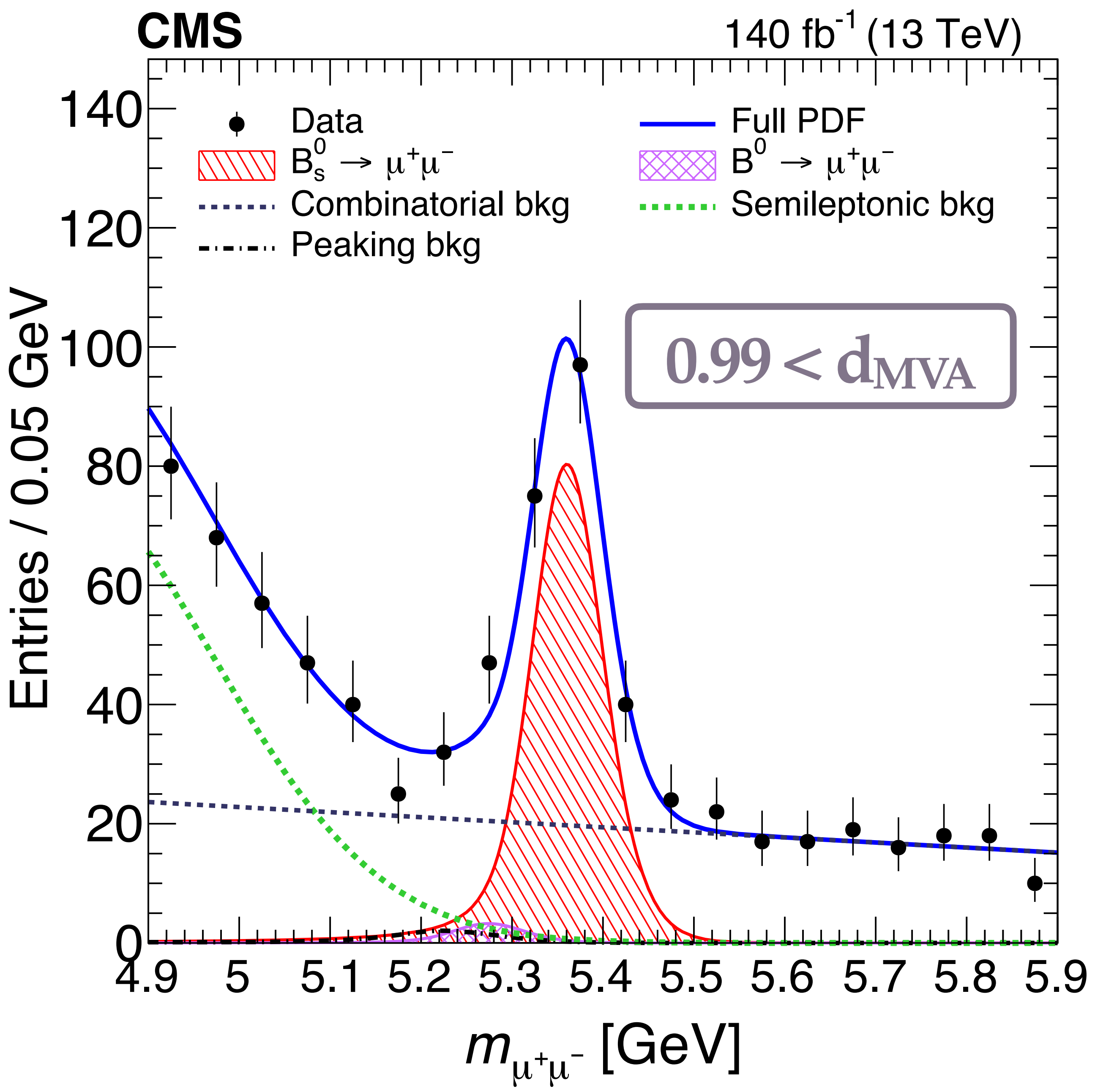
- **BF dependency on lifetime assumption**: scale factors on branching fraction for alternative lifetime hypothesis (τ in ps): $\alpha_{BF} = 1.577 - 0.358\tau$
- Lifetime bias is caused by the correlation between decay time and d_{MVA}.

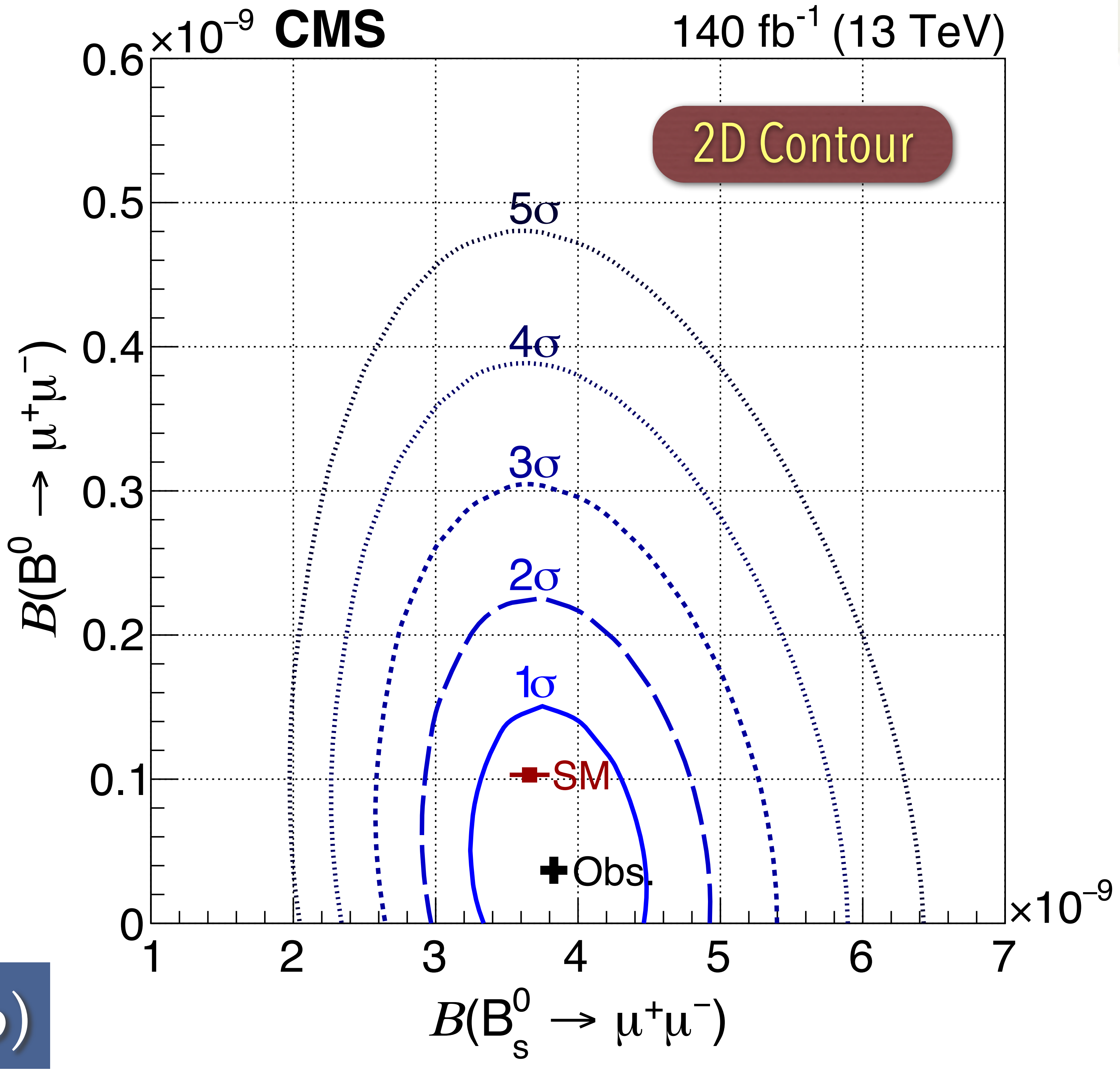
RESULTS: BRANCHING FRACTIONS

Ref. CMS
PLB 842 (2023) 137955

Combined projections for low/high dMVA categories







Channel	Branching fraction	Sign. (obs)	Sign. (exp)
$B_s \to \mu^+\mu^-$	$[3.83^{+0.38}_{-0.36}\,(\text{stat})^{+0.19}_{-0.16}\,(\text{syst}) \pm 0.13\,(f_s/f_u)] \times 10^{-9}$	12.5σ	13.1σ
$B^0 \to \mu^+\mu^-$	$[0.37^{+0.75}_{-0.67}\,(\text{stat})^{+0.08}_{-0.09}\,(\text{syst})] \times 10^{-10}$	0.5σ	1.7σ

This is the best single measurement on BF($B_s \to \mu\mu$) to date!

If normalized by $B_s \to J/\psi\phi$: $\mathscr{B}(B_s \to \mu^+\mu^-) = [3.95^{+0.39}_{-0.37}\,(\text{stat})^{+0.29}_{-0.24}\,(\text{syst})] \times 10^{-9}$

Remark: BF($B_s \to J/\psi\phi$) itself still depends on f_s/f_u!

RESULTS:LIMITS & EFFECTIVE LIFETIME

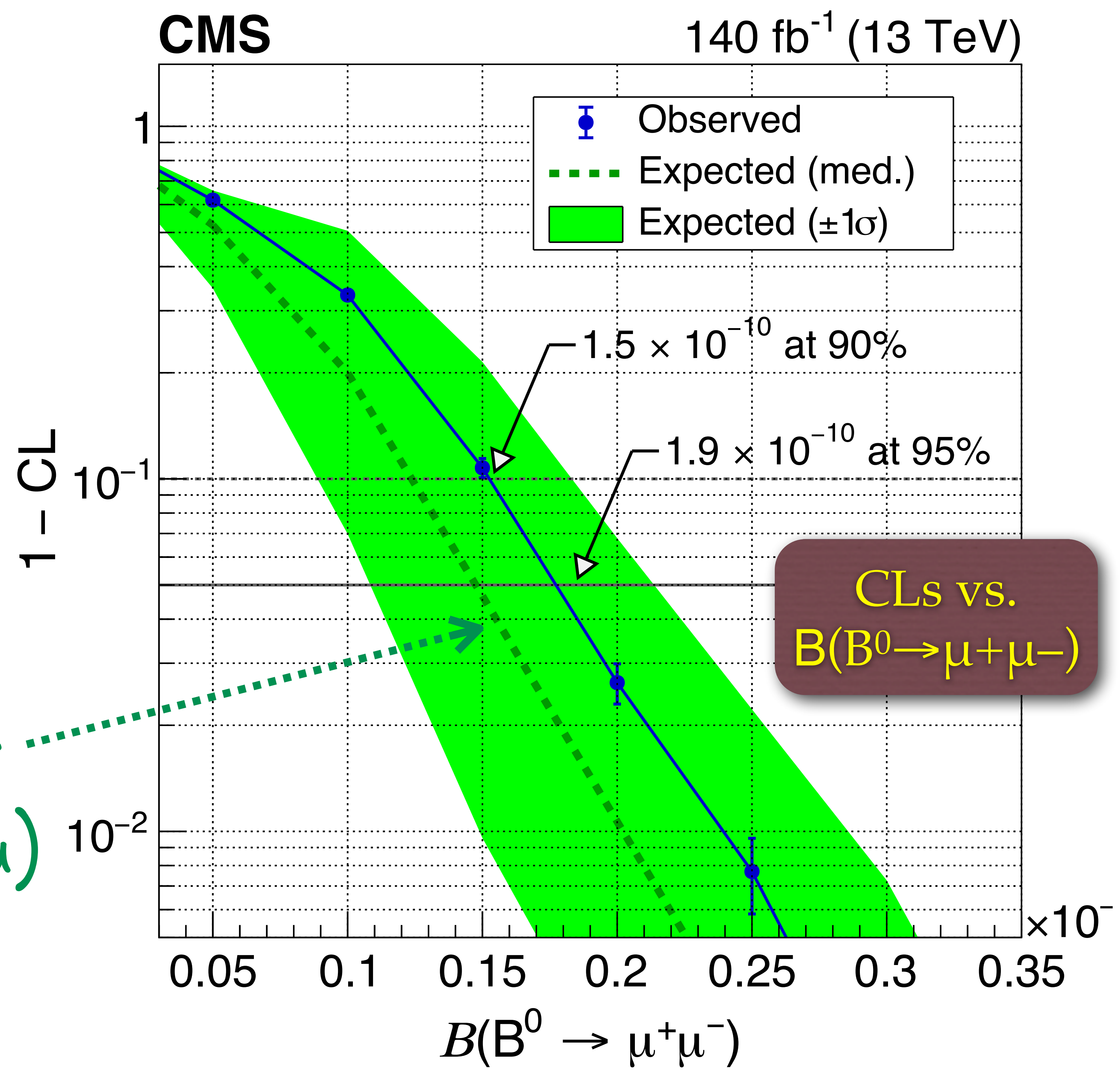
Ref. CMS
PLB 842 (2023) 137955

- Upper limit with full CLs prescription, using *LHC-style profile likelihood* as the test statistic.
- Effective lifetime extract with 3D ML fit to mass, decay time, and decay time uncertainty.

Result is consistent with SM and previous/other studies

$B_s \to \mu^+\mu^-$ Effective Lifetime
$\tau = 1.83^{+0.23}_{-0.20}\,(\text{stat}) \pm 0.03\,(\text{syst})$ [ps]

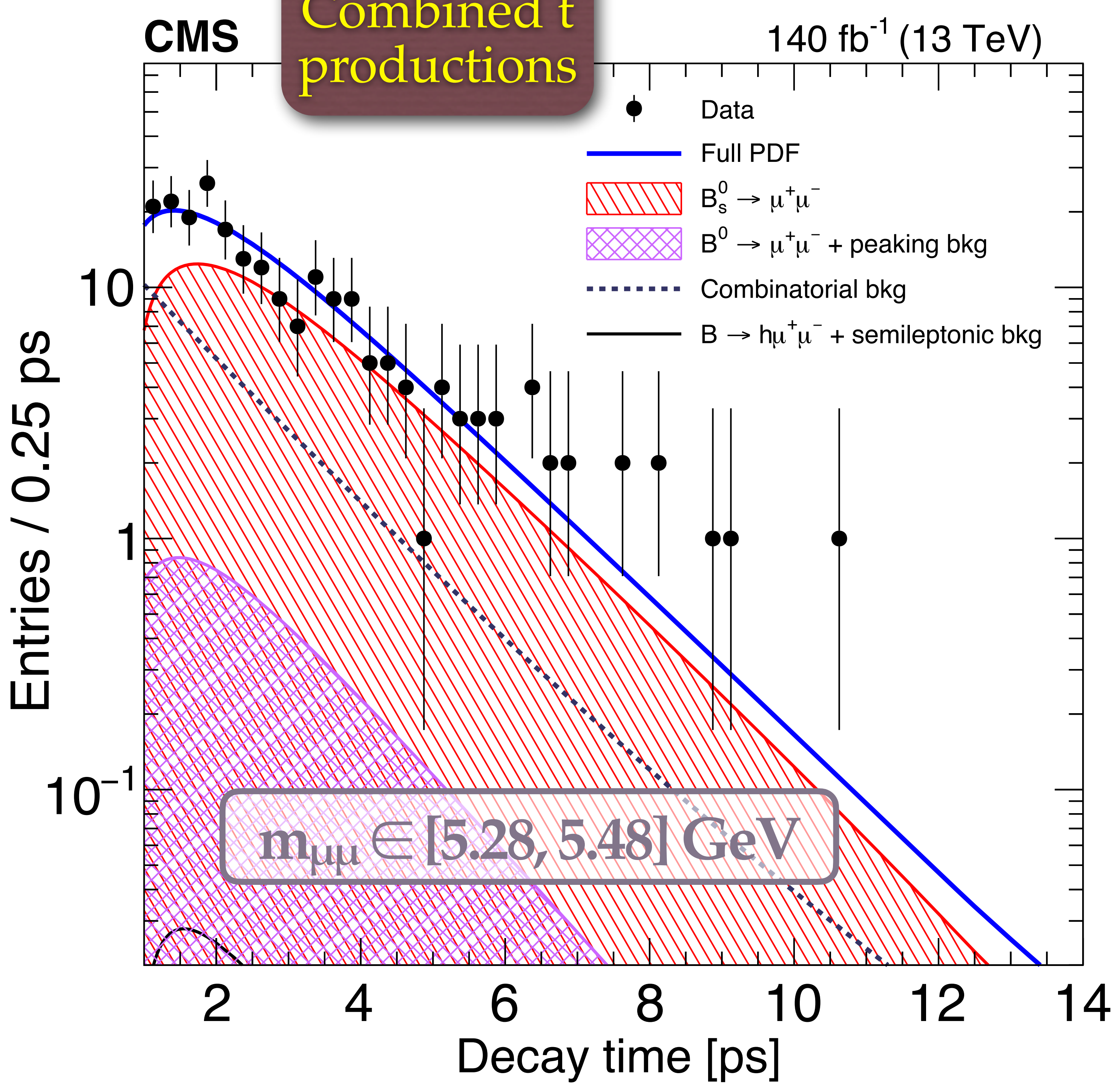
C.L.	UL on $B^0 \to \mu^+\mu^-$
95%	$<1.9 \times 10^{-10}$
90%	$<1.5 \times 10^{-10}$



CLs vs. $B(B^0 \to \mu^+\mu^-)$

Background only hypothesis (no SM $B^0 \to \mu\mu$)

Combined t productions

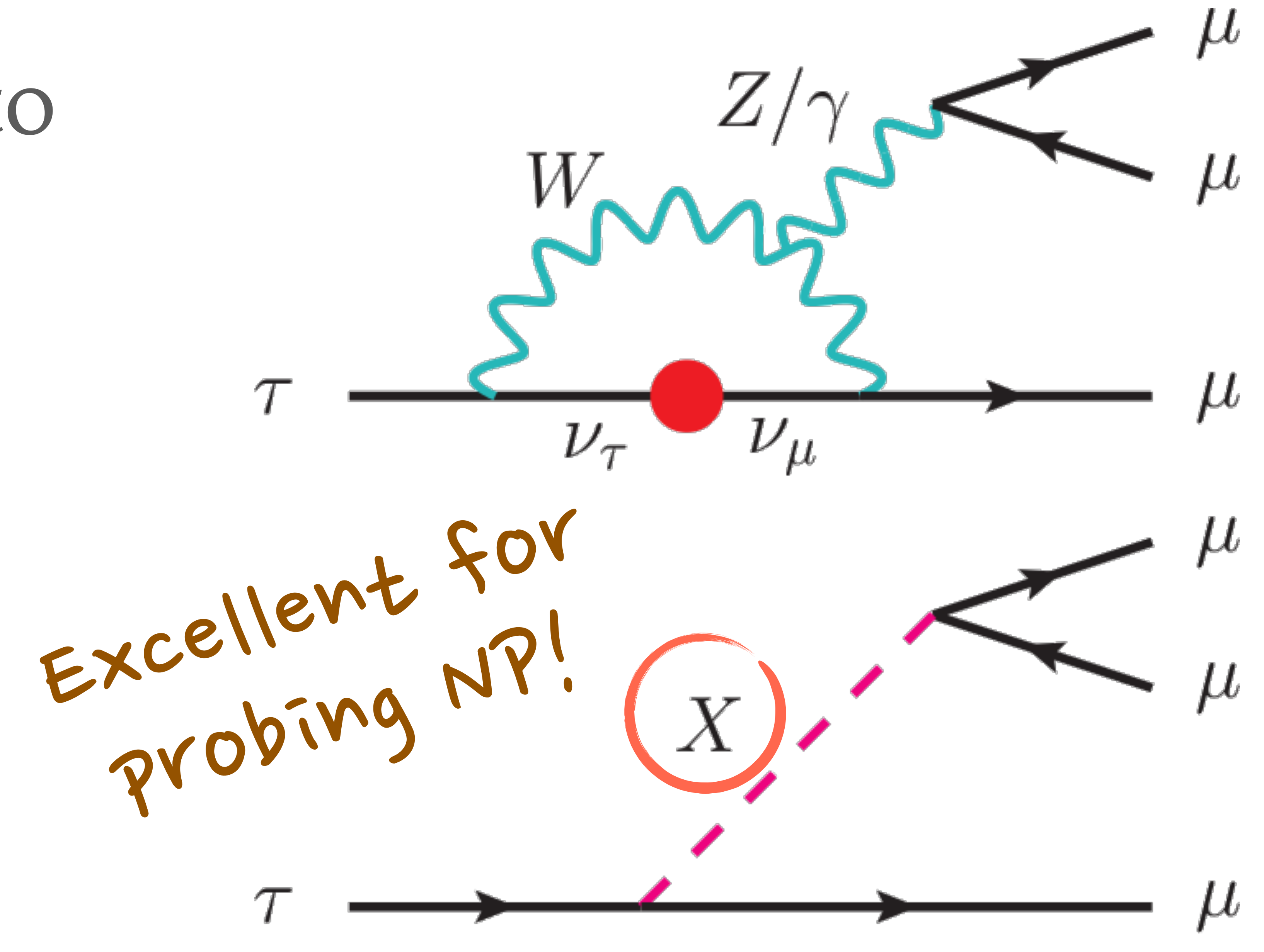


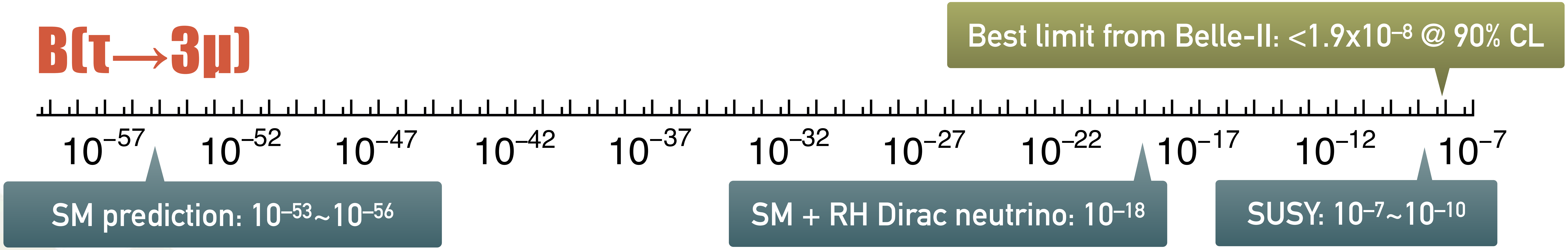
Best single measurement on effective lifetime as well!

A $B_s \to \mu^+\mu^-$ Candidate From 2018 Data

SEARCH FOR τ→3μ: INTRODUCTION

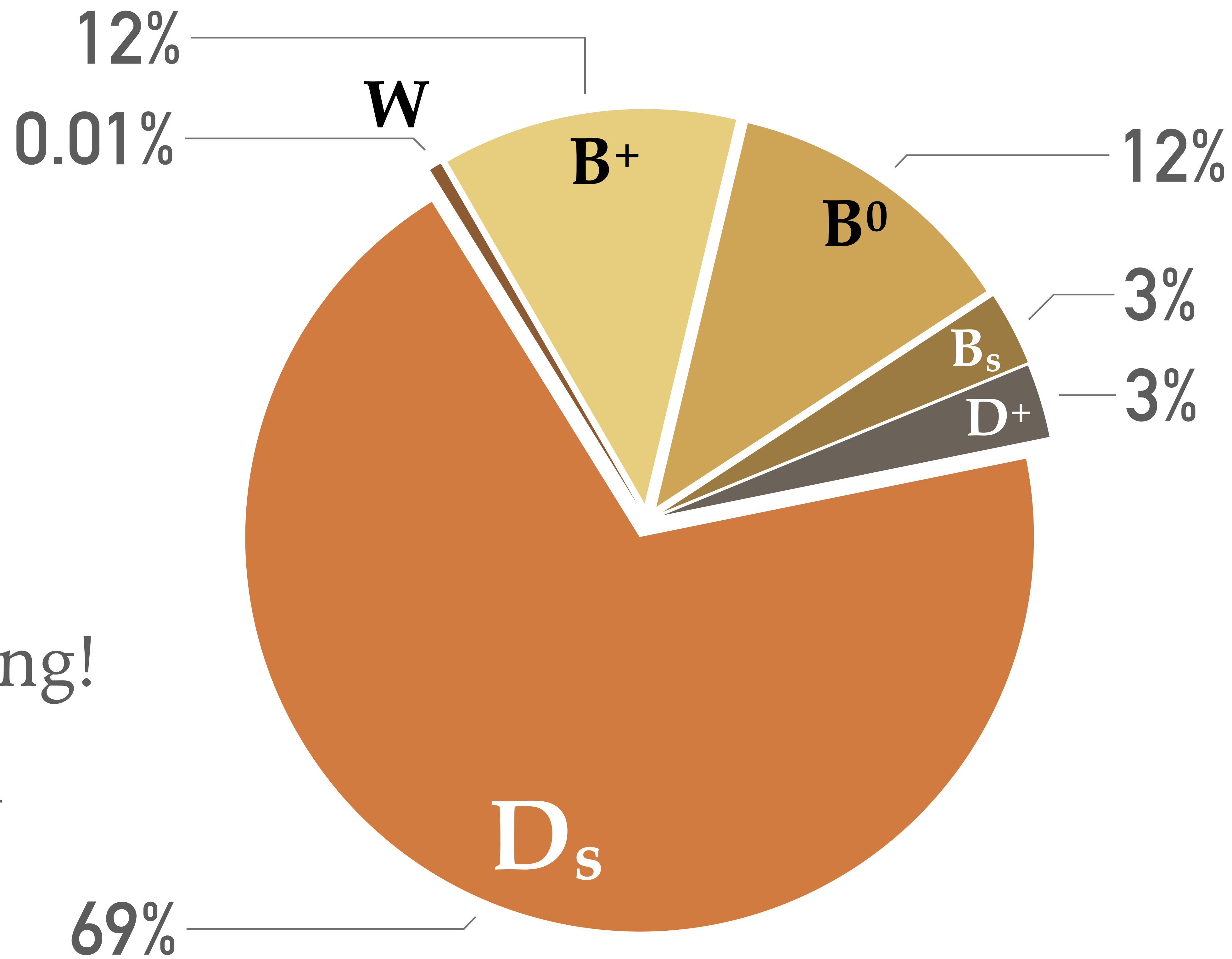
- A **charged lepton flavor violating (CLFV)** decay of τ to 3 muons, no missing neutrinos.
- Allowed by neutrino oscillations in SM, but with extraordinarily small branching fractions beyond experimental accessibility!
- The rate can be **strongly enhanced with New Physics scenarios**; experimentally the three-muon final state is accessible and clean.





SOURCES OF τ LEPTONS IN PROTON COLLISIONS

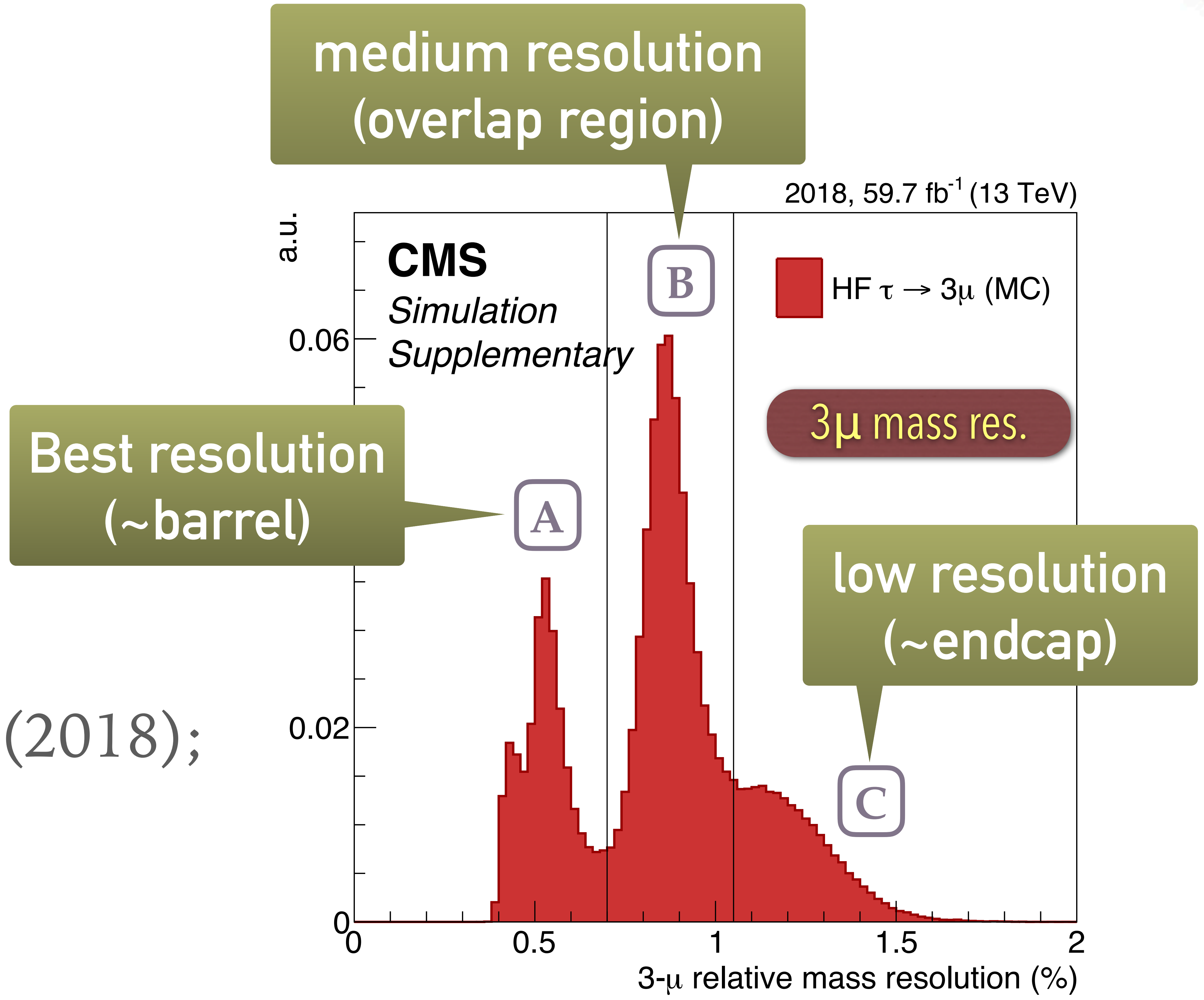
- Two major sources of τ leptons are considered: **heavy flavor** and **W-boson**:
- Decaying of heavy flavor mesons is the dominant source of τ leptons ($\sim 10^{11}$ τ's per fb^{-1}):
  - Lower p_T, more forward (larger $|\eta|$) ⇒ lower trigger efficiency.
  - Easier to pick up fake μ from hadrons.
- Rate for τ leptons from W-boson decay is much smaller ($\sim 10^{7}$ τ's per fb^{-1}), but:
  - Higher p_T and central in barrel ⇒ easier triggering!
  - Kinematic information of W provides additional handles for background suppression: large missing E_T, lower hadronic activities, etc.



Sources of τ

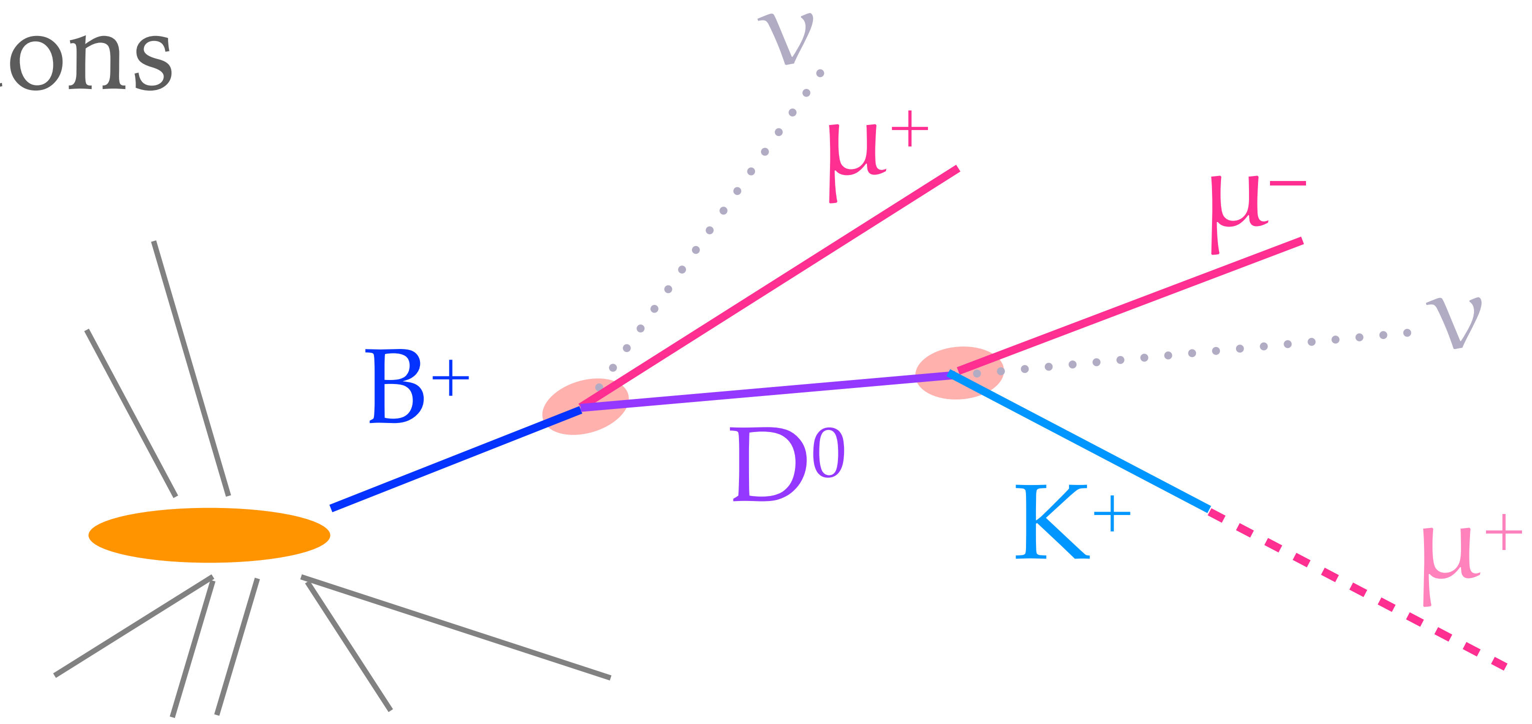
ANALYSIS OVERVIEW

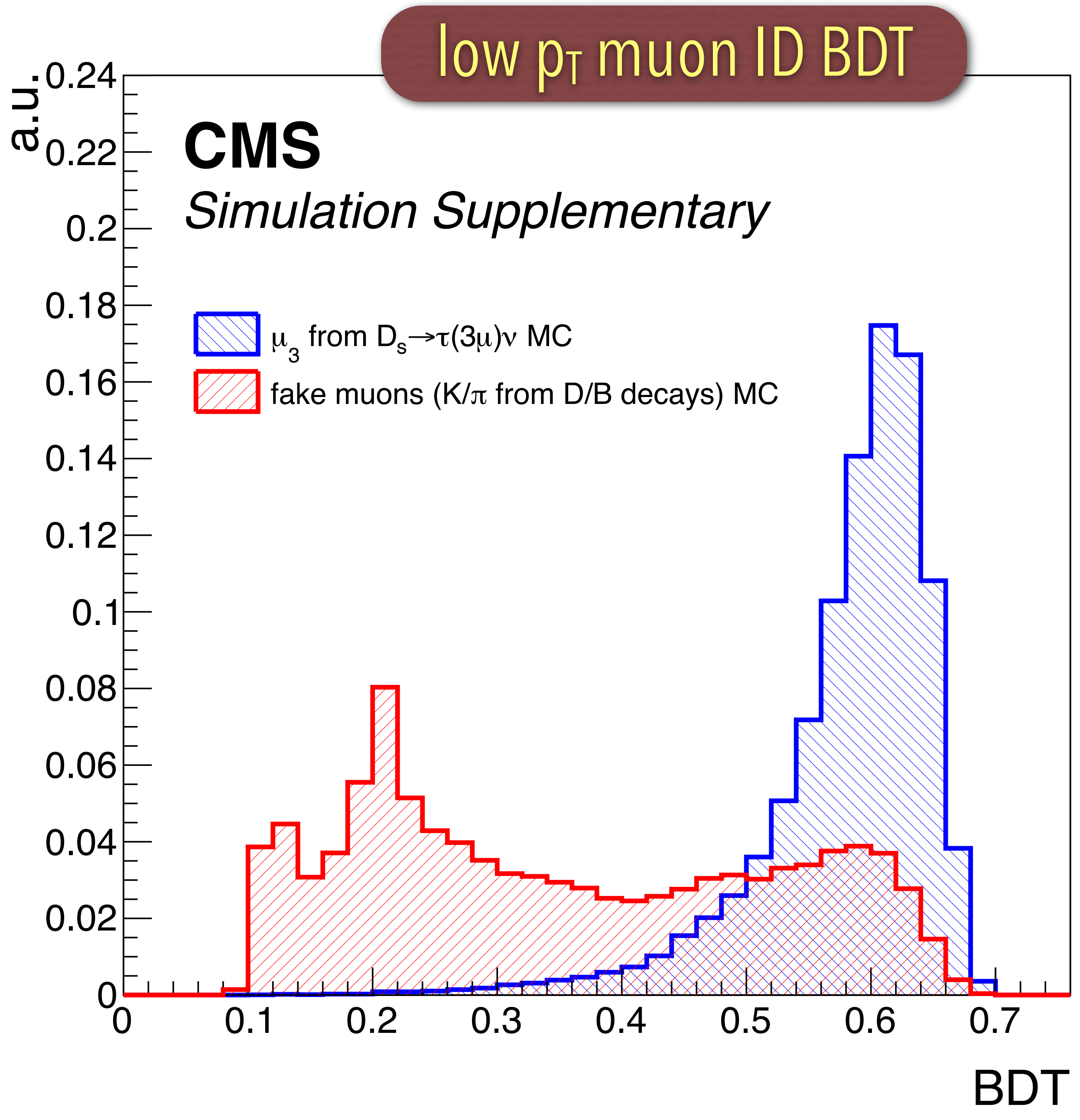
- The analysis incorporate 131 fb^{-1} pp collision data @ 13 TeV:
  - 2016 data result is already published:
    Ref. CMS JHEP 01 (2021) 163.
  - Extended to full Run-2 data, investigating both the heavy flavor and W production channels.
- **Dedicated HLT triggers are designed**:
  - **W-boson**: select three isolated muons;
  - **Heavy flavor**: 2 muons + 1 track (2017) or three muons (2018);
- **Signal candidate is reconstructed with 3 muons, with sum of the charge = ±1**:
  - Signal extraction with simultaneous UML fit to **3μ invariant masses**;
  - Events are categorized according to their invariant mass resolution ⇒ **3 categories per year per production channel**.



BACKGROUND SOURCES

- **Dominant background is combinatorial**, with two real muons plus one fake μ from hadrons (typically decay-in-flight):
  - A typical case is B→D cascade decays, e.g. **B→D+μ+X, D→μ+ν+K, K→μ**
  - A dedicated BDT used as low-p_T muon ID, trained on signal vs. fake muons from hadrons.
- Backgrounds with 3 genuine muons, with two of them coming from resonances: φ(1020)→μμ and ω(783)→μμ
  - Apply veto to those resonances
- **Further background suppression by event MVA discriminator.**
- Electroweak W→μν+FSR: produce 3μ+large missing E_T signature, removing by requiring on the displacement from the interaction point.

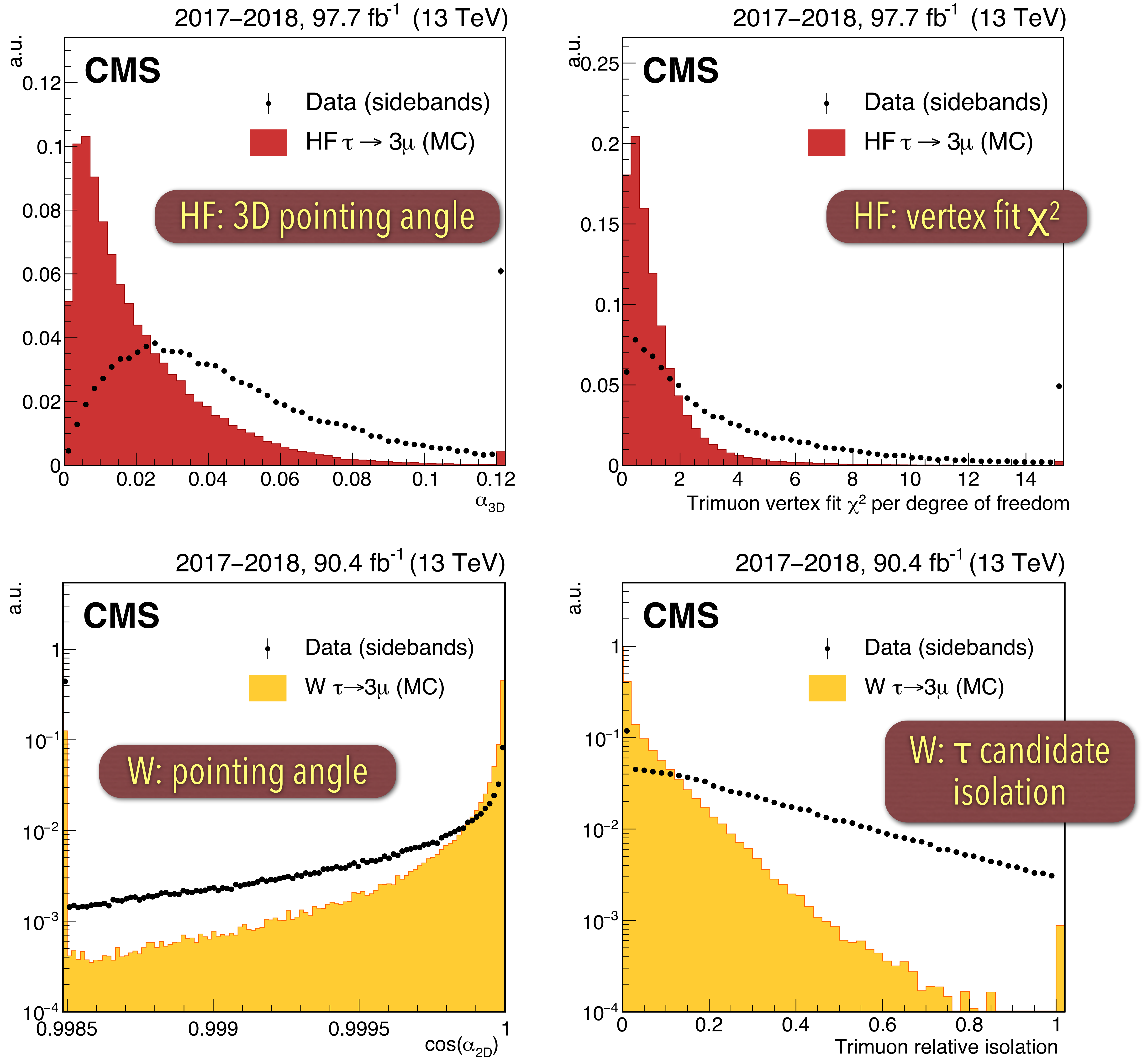




MULTIVARIATE ANALYSIS

- **Boosted Decision Tree** discriminators are trained to suppress background:
  - $\tau \to 3\mu$ MC as signal;
  - Data sideband events are used as proxies of background
  - Separated MVA for different channels.
- Scale factors applied to MC to match the data efficiencies and distributions.
- Key input features include: **kinematical information** (*momentum, missing energy*) and **topological** (*vertex finding, pointing angle, isolation variables*), **others** (*muon ID BDT*).

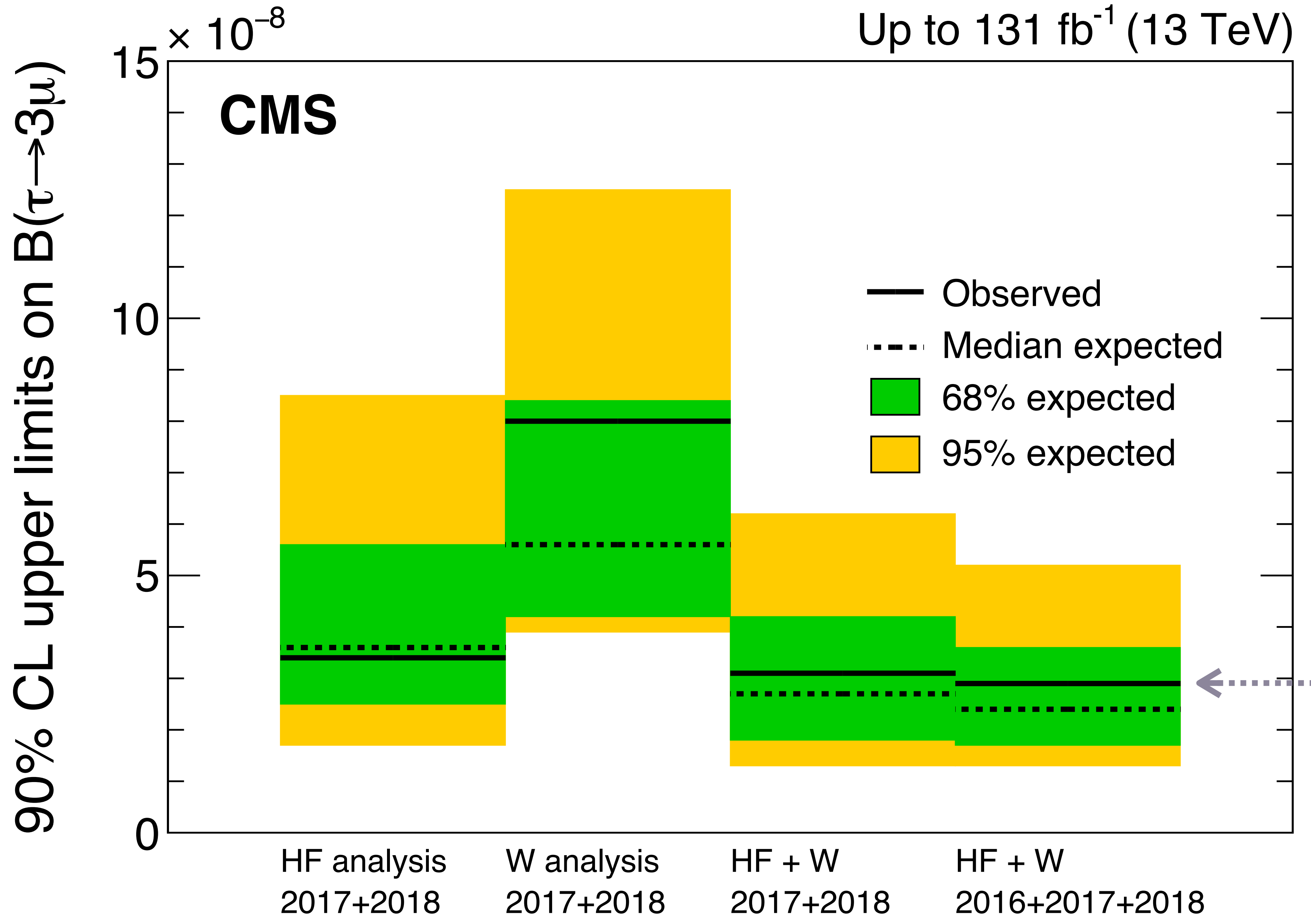
Most discriminating features



RESULTING UPPER LIMIT

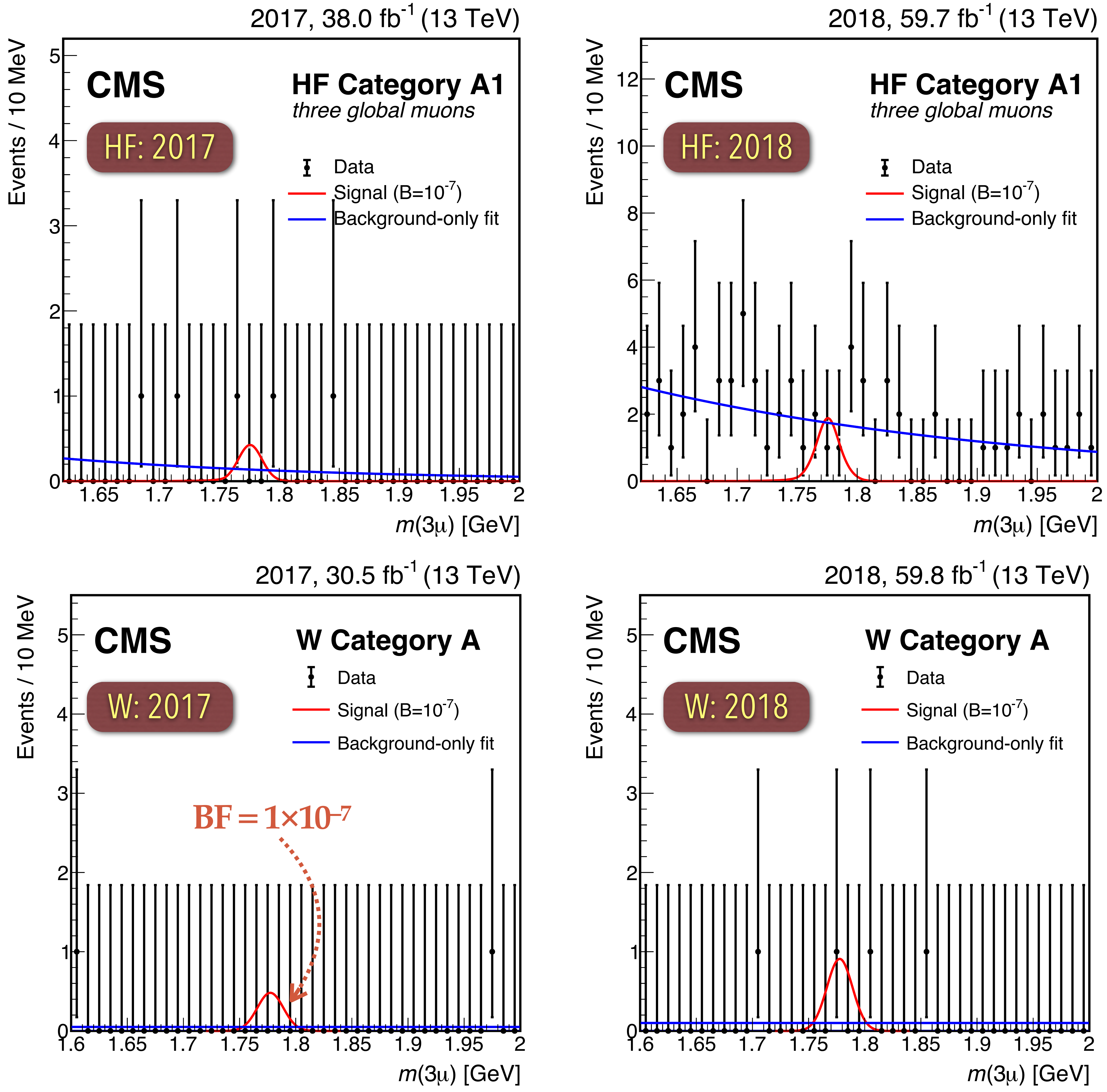
Ref. CMS
PLB 853 (2024) 138633

- **No hint of signal found**, upper limit set on the $\tau \to 3\mu$ branching fraction:



New analysis of 2017+2018 data combined with 2016 for the full Run-2 result:

C.L.	UL on B($\tau \to 3\mu$)
95%	$<3.6 \times 10^{-8}$
90%	$<2.9 \times 10^{-8}$

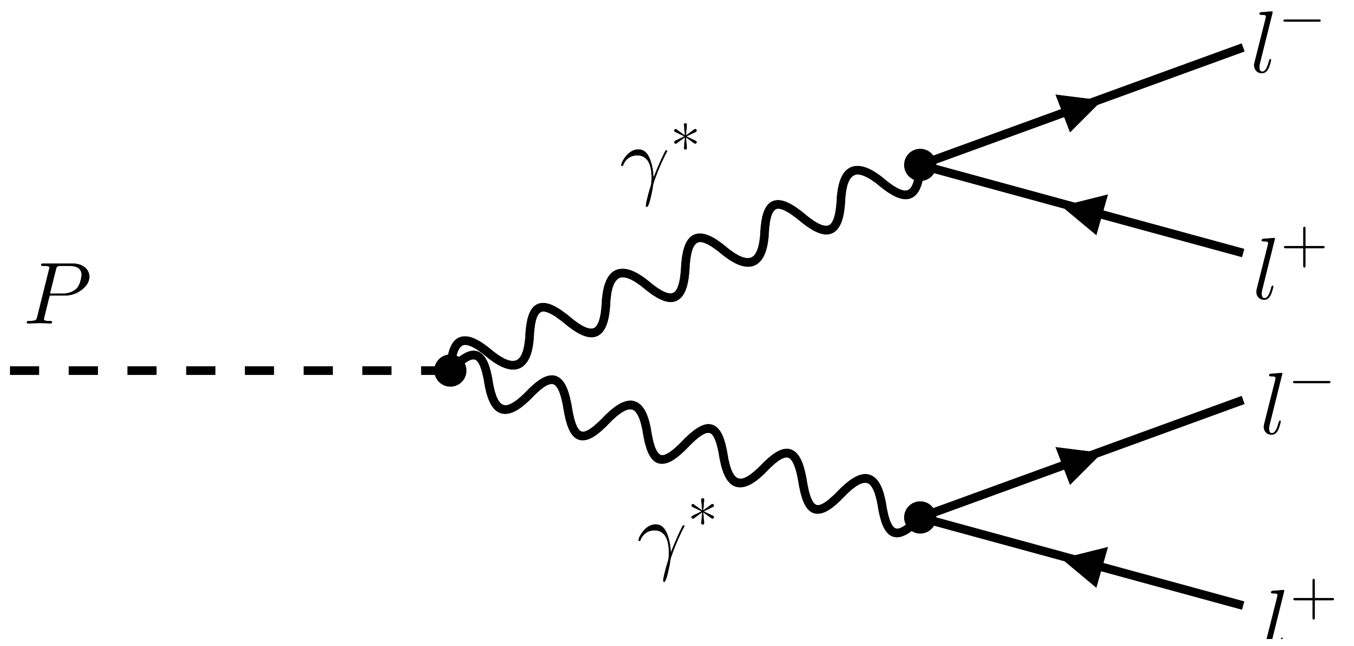


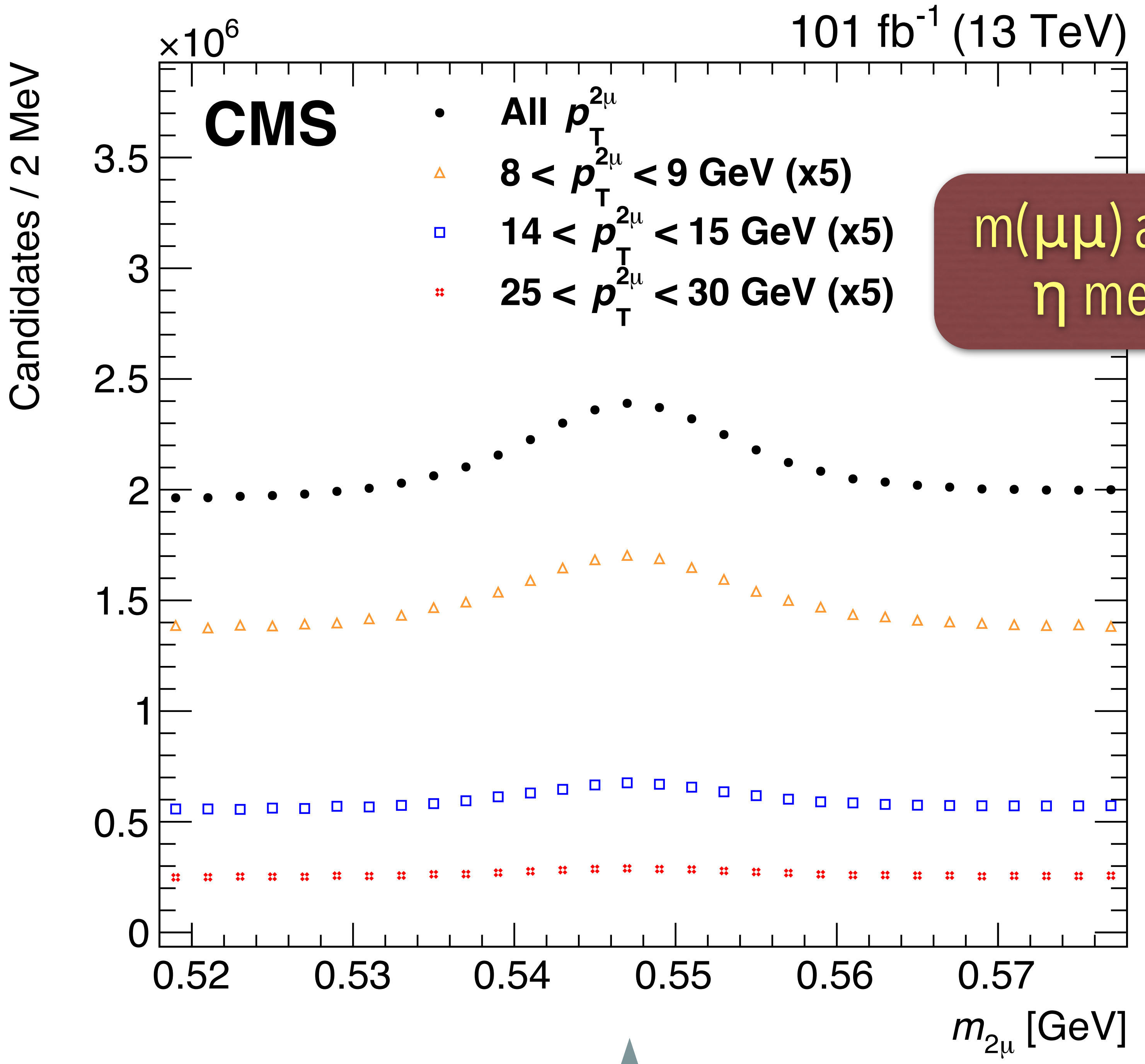
Analyses utilizing CMS extended trigger capabilities:
“scouting” & “parking” steams

More information in
CMS arXiv:2403.16134, submitted to Physics Reports

VERY RARE η→4μ DECAYS

- In SM η→4μ decay predicted with a very low branching fraction of $O(10^{-9})$:
  - Sensitive to new physics scenarios + precision test of the SM.
- This analysis is only feasible with **"data scouting"** scenario:
  - Regular trigger thresholds are limited by the computing power and bandwidth.
  - **Reduce event size to speed up data acquisition!**
  - Limit the amount of information to muon tracks
  - **Save high-level trigger reconstruction and skip the standard prompt event processing**
  - Reduced the typical event size from MB to few kB.
- With relaxed thresholds, it is **possible to explore rare decays in very low p_T regions!**



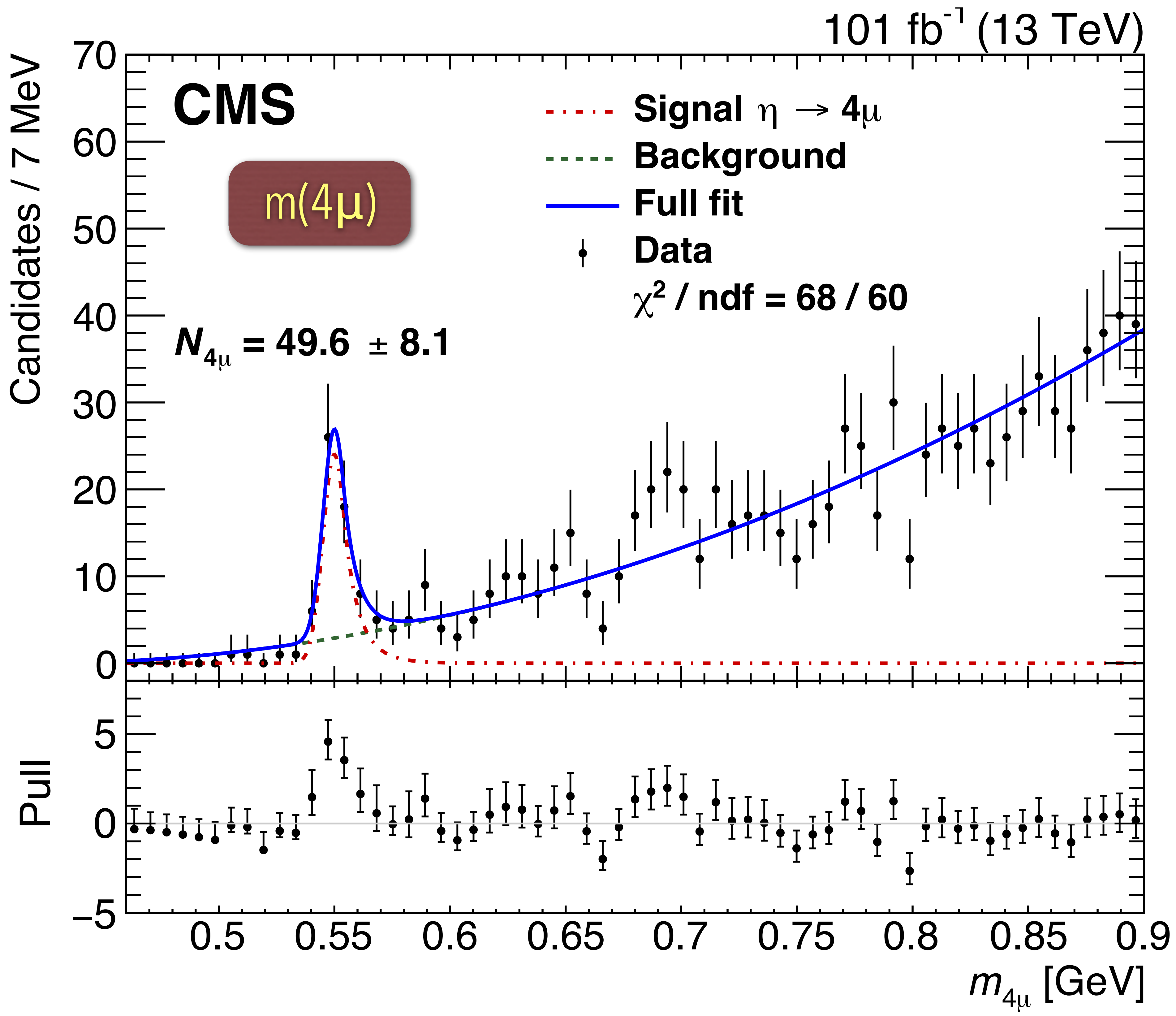


m(μμ) around η meson

4.5 M of η→2μ events recorded → billions of η mesons produced in the CMS acceptance!

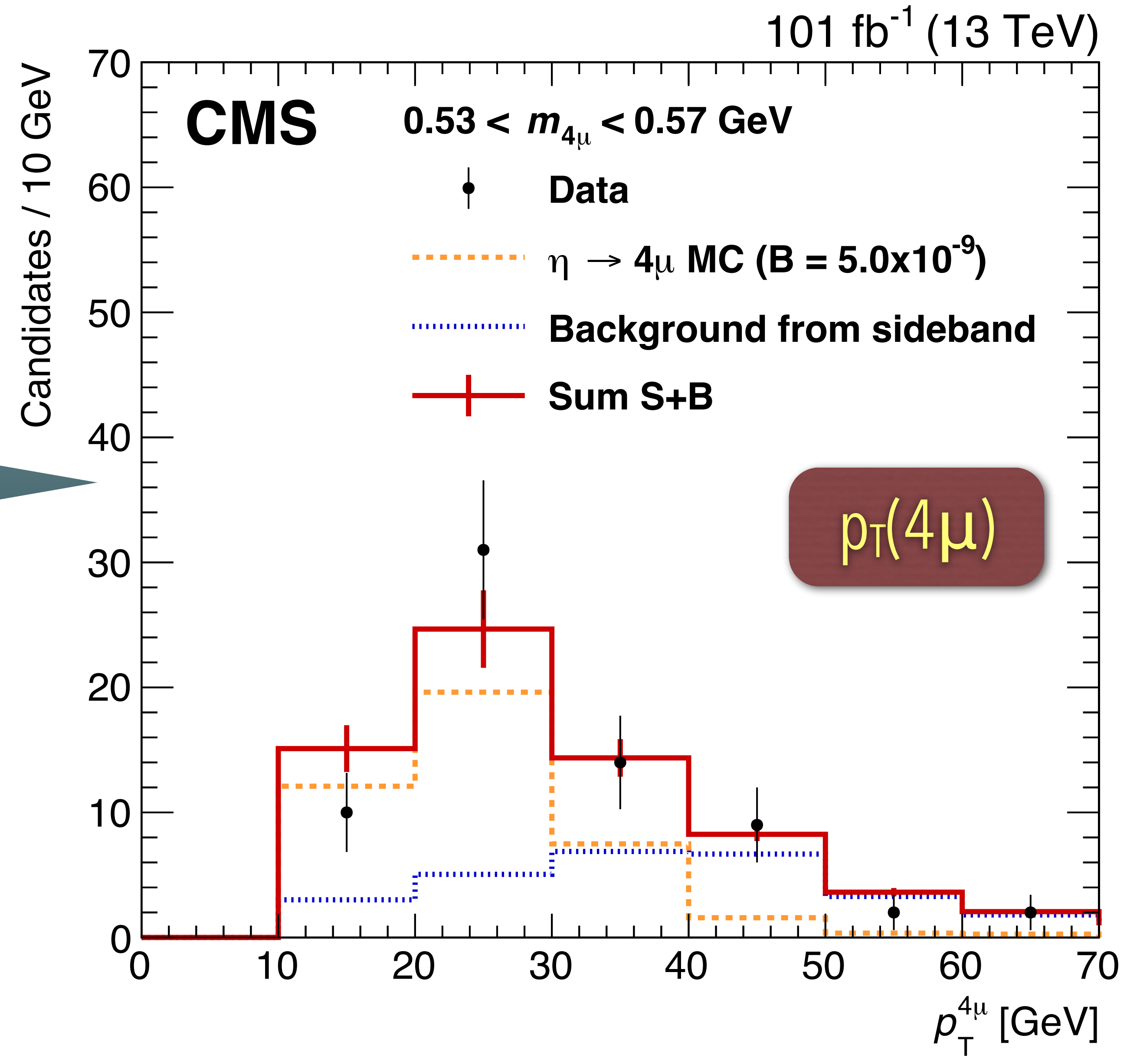
VERY RARE η→4μ DECAYS: RESULT

Ref. CMS PRL 131 (2023) 091903



- **~50 signal events observed from 101 fb^{-1} data, clearly a discovery of >5σ significance!**
- Normalized to the η→2μ yield as a relatively precise normalization strategy;
- Efficiency and acceptance corrections from MC for 2μ–4μ differences.

Good description of four-muon p_T spectrum for the events near signal peak.



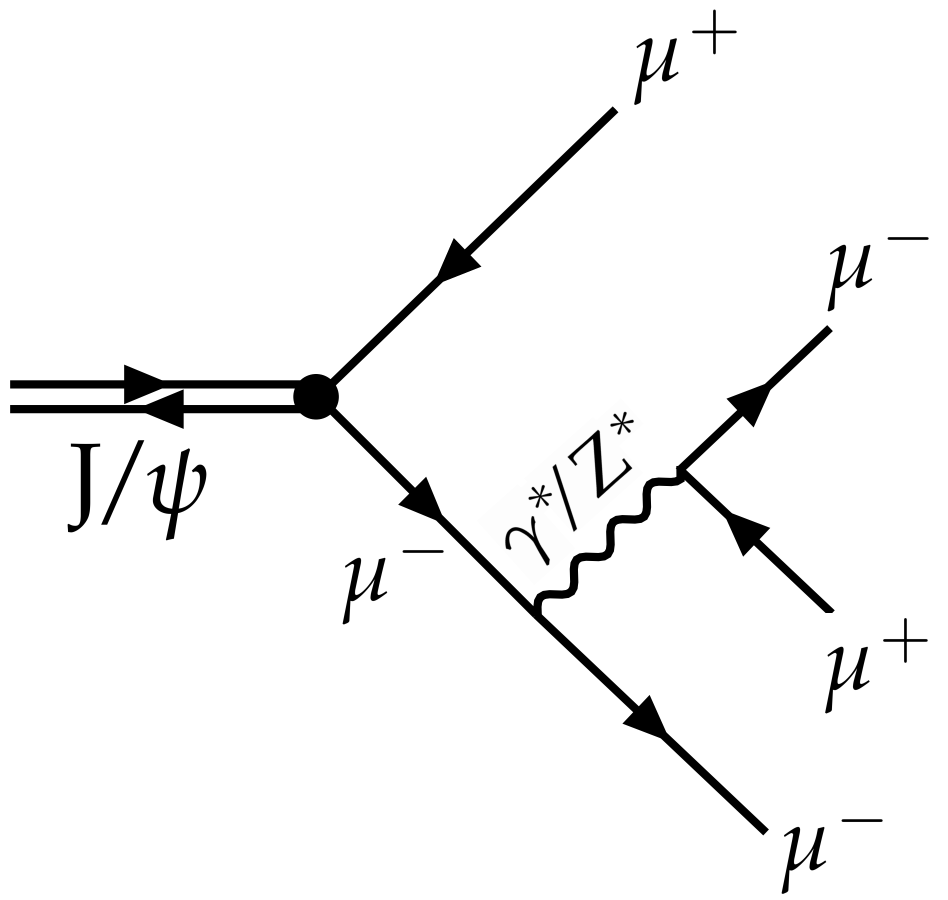
Resulting branching fraction

$B(\eta\to\mu^+\mu^-\mu^+\mu^-) = 5.0 \pm 0.8\ (\text{stat}) \pm 0.7\ (\text{syst}) \pm 0.7\ (B_{\eta\to\mu\mu}) \times 10^{-9}$

in agreement with SM prediction: $3.98\pm0.15\times10^{-9}$

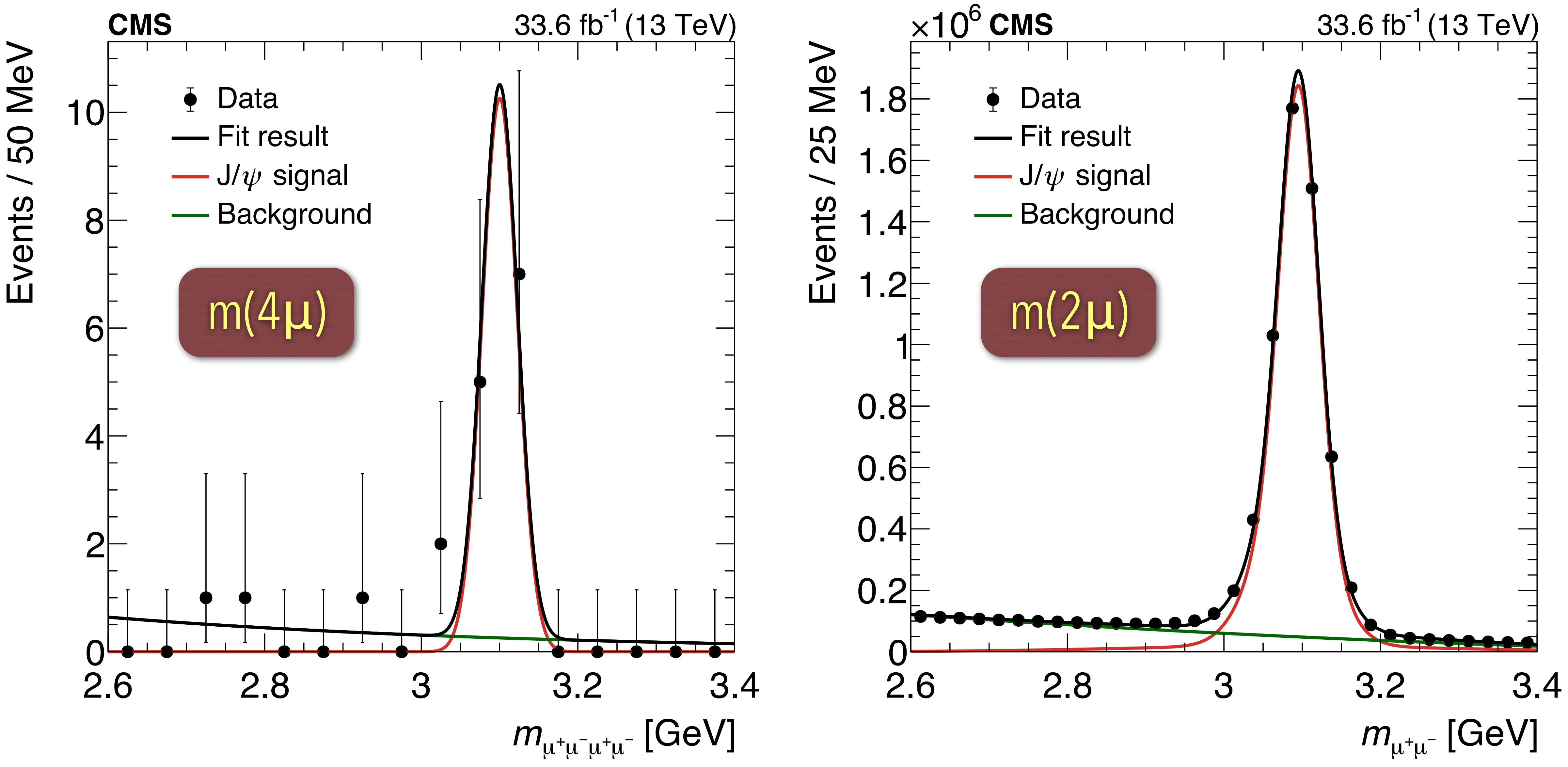
OBSERVATION OF RARE J/ψ→4μ DECAYS

- Thanks to the large production rate, an excellent opportunity to explore very rare decays to multiple muons.
- J/ψ→4e and 2e2μ have been found by BES III.
- **A novel testing ground for quantum electrodynamics predictions.**
- Exploits the **"B Parking"** scenario: a **specialized trigger** (*w/ just one muon!*) and **data storage strategy** (*no prompt reconstruction, only "park" the data for further analysis*) was implemented to assemble a b-hadron enriched data set in 2018.
- LHCb see this too: LHCb-CONF-2024-001.



CMS BPH-22-006
Accepted by PRD

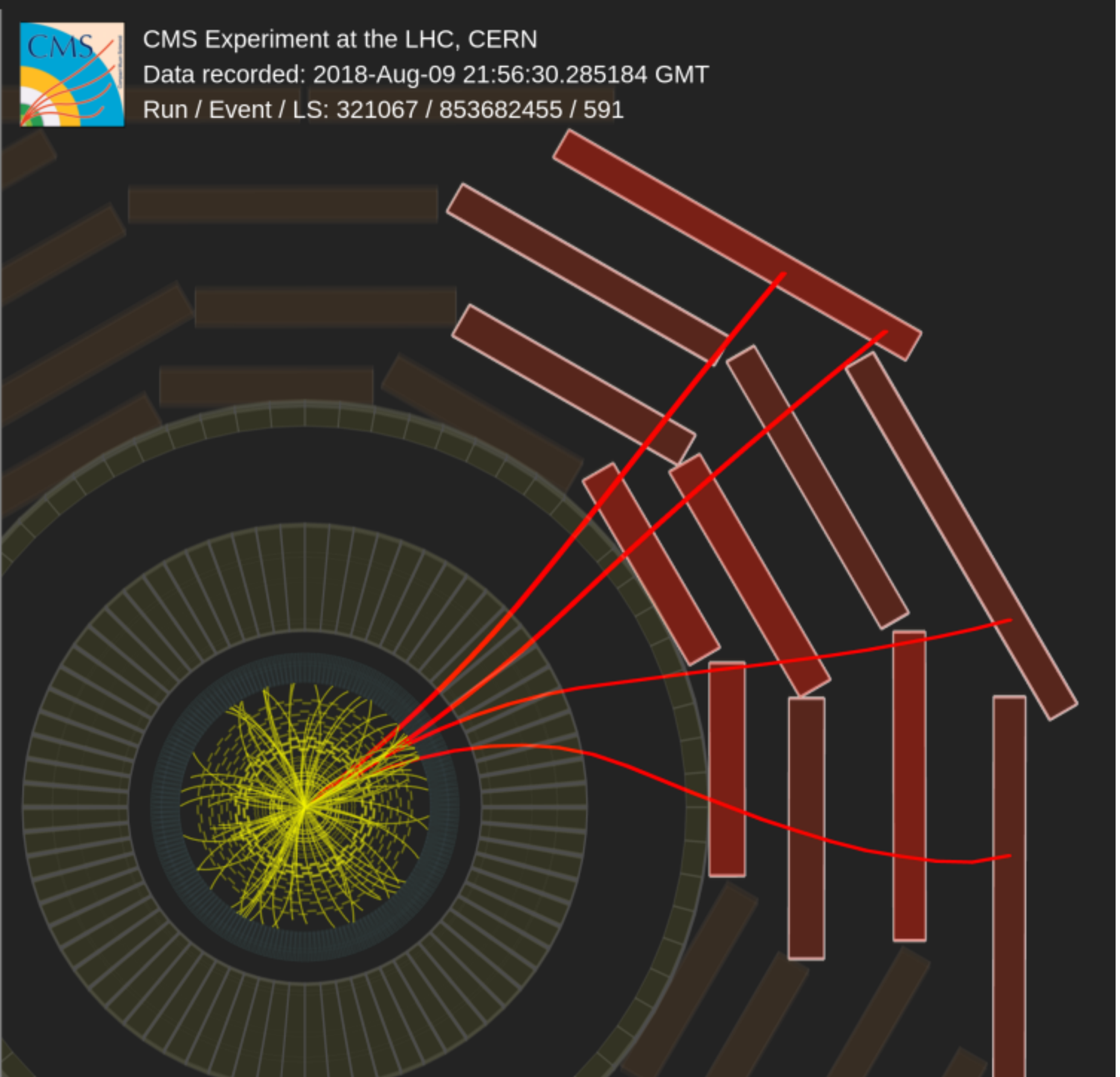
Around ~12 signals found.
Normalized by J/ψ→μμ



Resulting branching fraction

$$B(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-) = 10.1^{+3.3}_{-2.7}\,(\text{stat}) \pm 0.4\,(\text{syst}) \times 10^{-7}$$

consistent with the SM: $(9.74 \pm 0.05) \times 10^{-7}$



A $J/\psi \to 4\mu$ candidate event reassemble the CMS logo!

SUMMARY

- The studies of $B_{(s,d)} \to \mu\mu$ are presented. Results are consistent with the SM, **will pull BF($B_s \to \mu\mu$) average to be higher** / closer to SM value.
- By exploring both heavy flavor and W channels with full Run-2 samples, the upper limit on **$\tau \to 3\mu$ is getting closer the best result** from the B-factory.
- The extended trigger capabilities even allow the **observation of very rare $\eta \to 4\mu$ and $J/\psi \to 4\mu$ decays**!

Thanks to the great muon performance and dynamic trigger configurations, CMS can play a key role in rare decay searches!


BACKUP