12th Large Hadron Collider Physics Conference,
3-7 Jun 2024, Northeastern Univ., Boston

LEPTON FLAVOR VIOLATION & RARE HEAVY FLAVOR DECAYS

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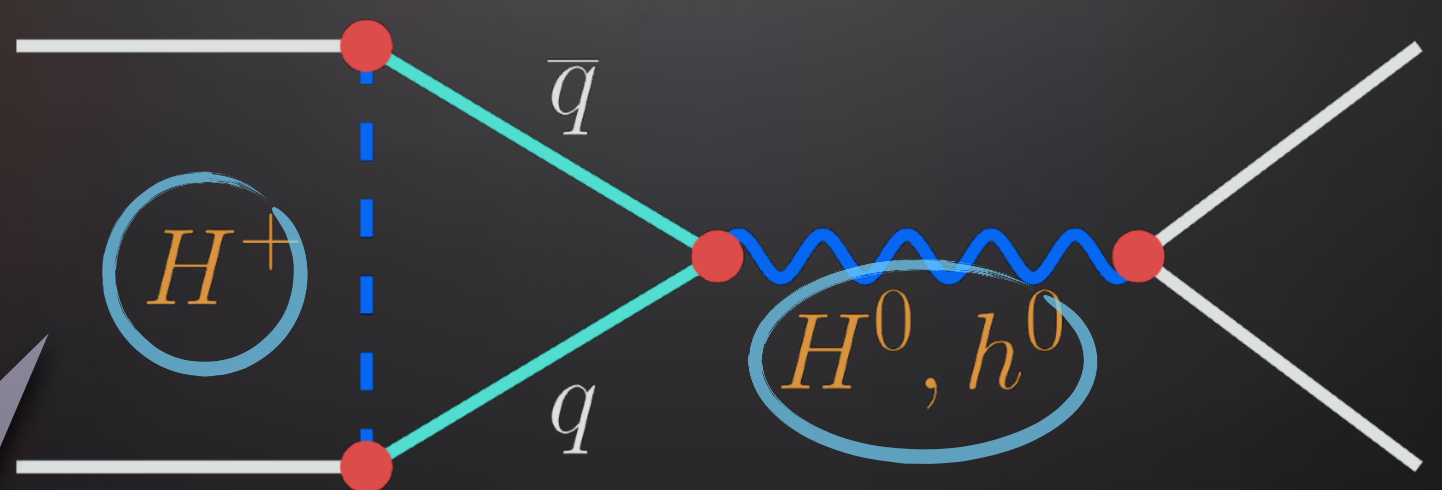
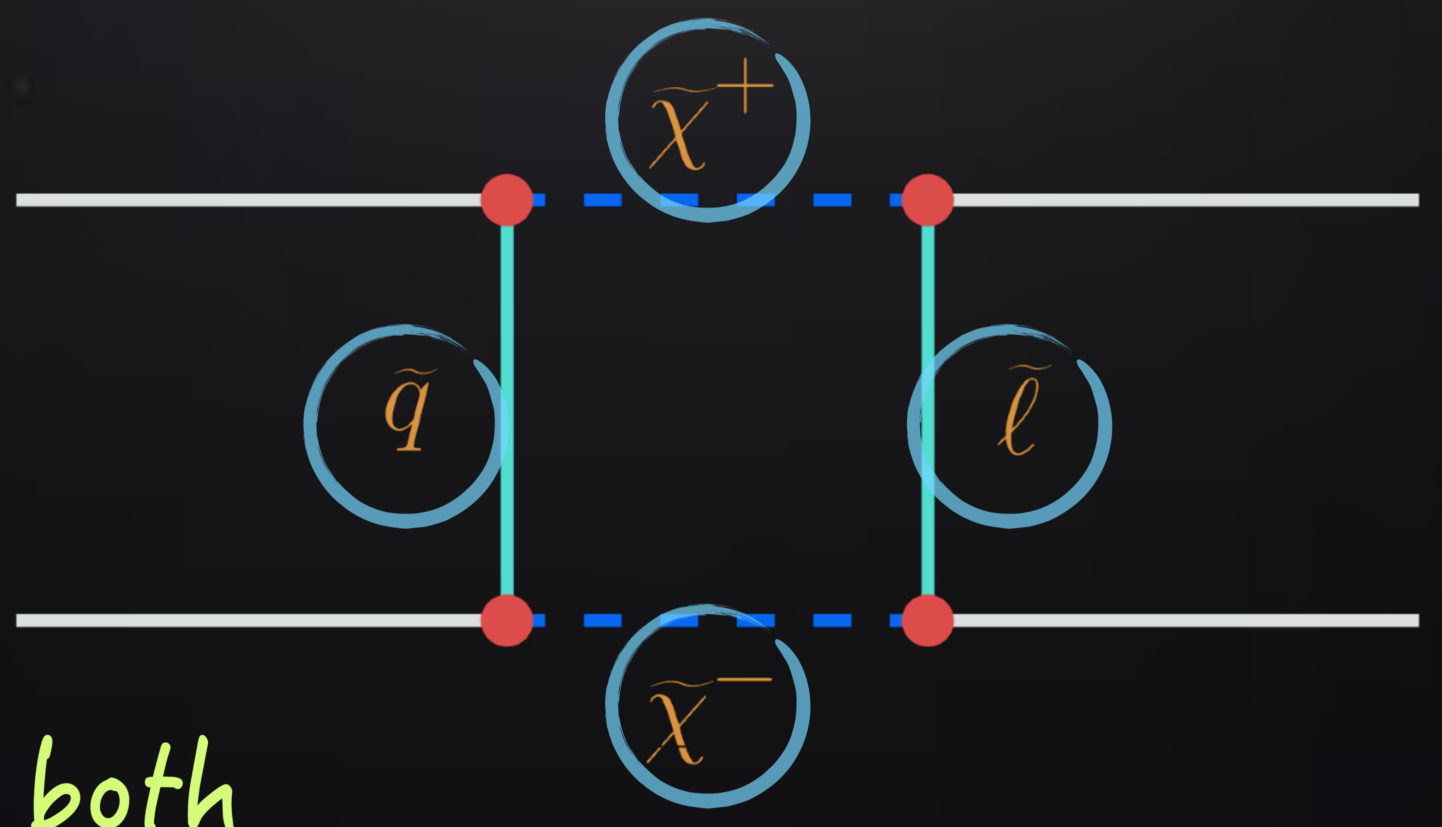
On Behalf of the ATLAS, CMS & LHCb Collaborations

WHY LOOKING FOR RARE PROCESSES?

- Finding rare and peculiar events itself is already fascinating!
- Probing New Physics through indirect searches:
  - "Virtual" new particles can participate in the **LOOP/RARE PROCESSES** and modify the decay.
  - By detecting deviations from the predictions will guide the way how the SM should be extended!

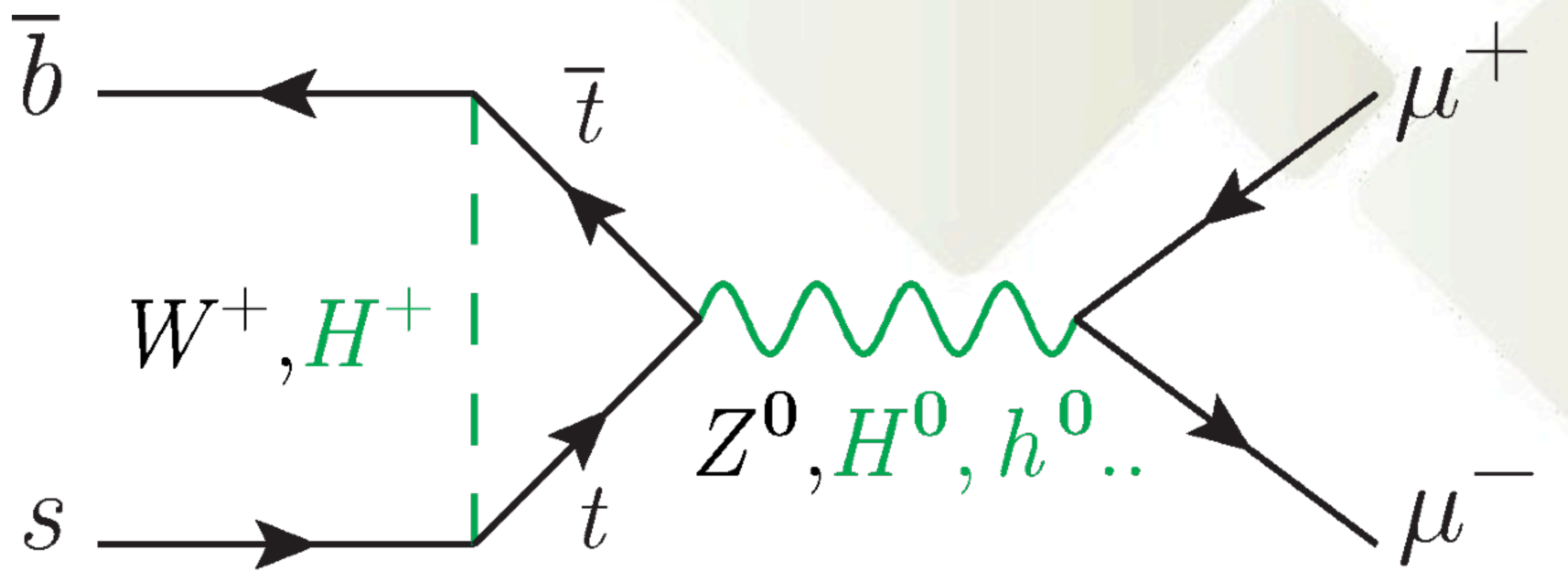


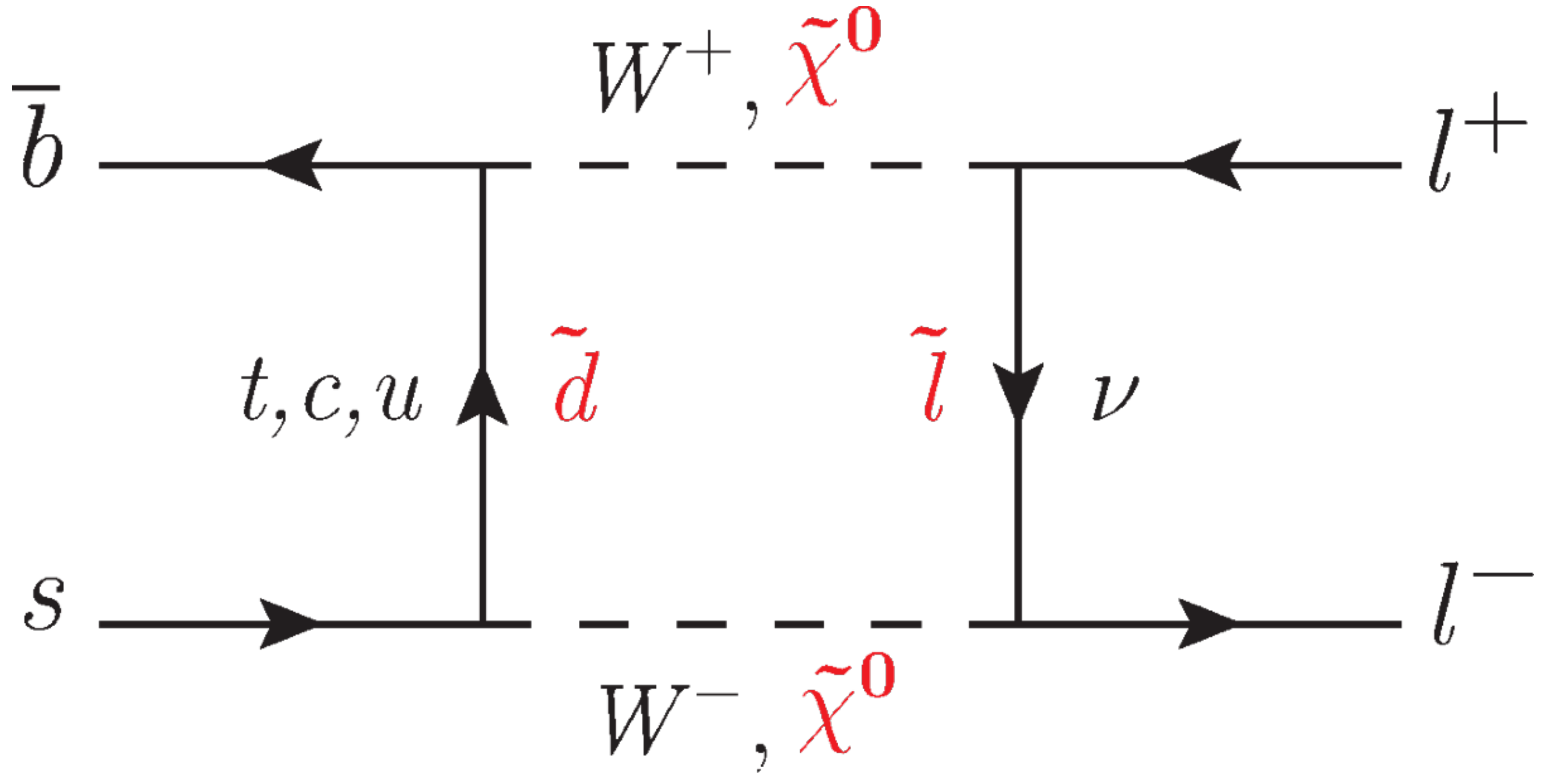
If new particles cannot be observed in the direct searches, here is the place we shall dig in!



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

A TYPICAL RARE DECAY TOPIC: $B \to \mu^+\mu^-$





- $B \to \mu^+\mu^-$ 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.

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

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

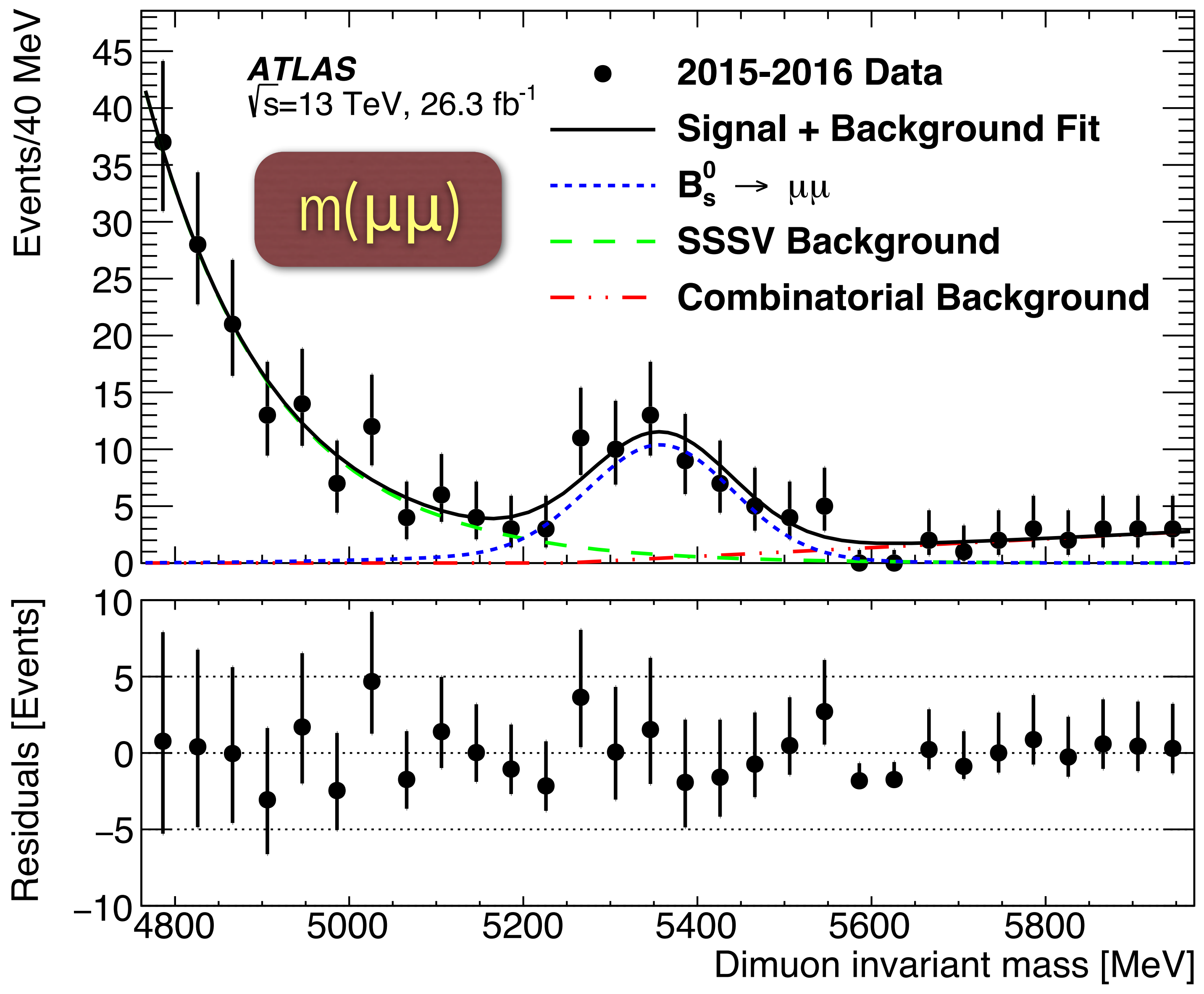
- Branching fraction $B_s \to \mu\mu$ has been well measured:

Channel	ATLAS+CMS+LHCb
$B_s \to \mu^+\mu^-$	$(2.69^{+0.37}_{-0.35}) \times 10^{-9}$
$B^0 \to \mu^+\mu^-$	$< 1.9 \times 10^{-10}$ @ 95% CL

Ref. ATLAS/CMS/LHCb 2020 Combination
LHCb PRL 128 (2022) 041801
CMS PLB 842 (2023) 137955
(updated measurements)

$B_s \to \mu^+\mu^-$ EFFECTIVE LIFETIME

Ref. ATLAS
JHEP 09 (2023) 199

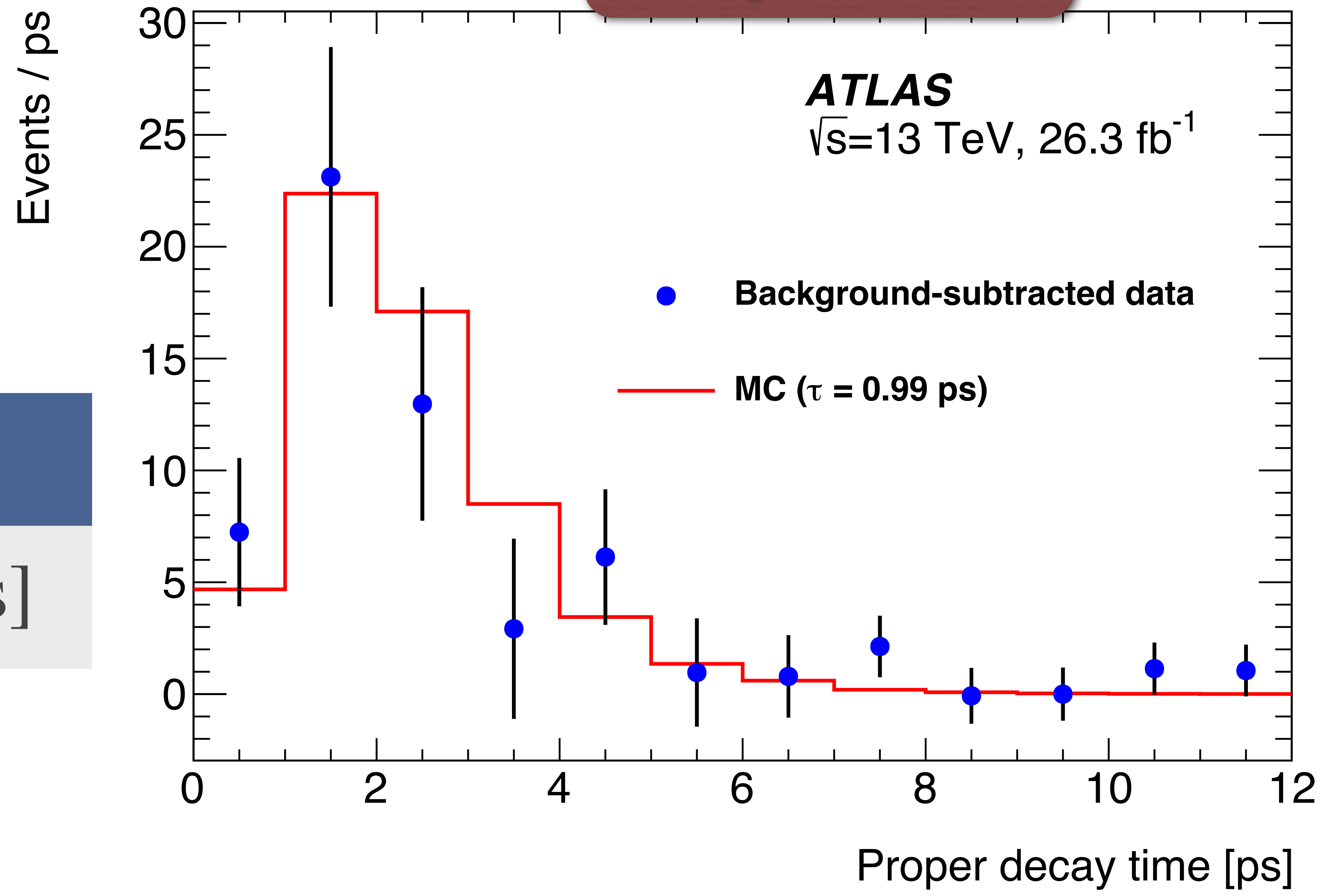


- ATLAS performed a measurement of $B_s \to \mu\mu$ effective lifetime with 26.3 fb^{-1} data at 13 TeV.
- 58±13 background-subtracted (*sPlot method*) signal candidates included in the fit.
- Uncertainties are extracted with **Neyman construction**; major systematics: data-MC discrepancies.

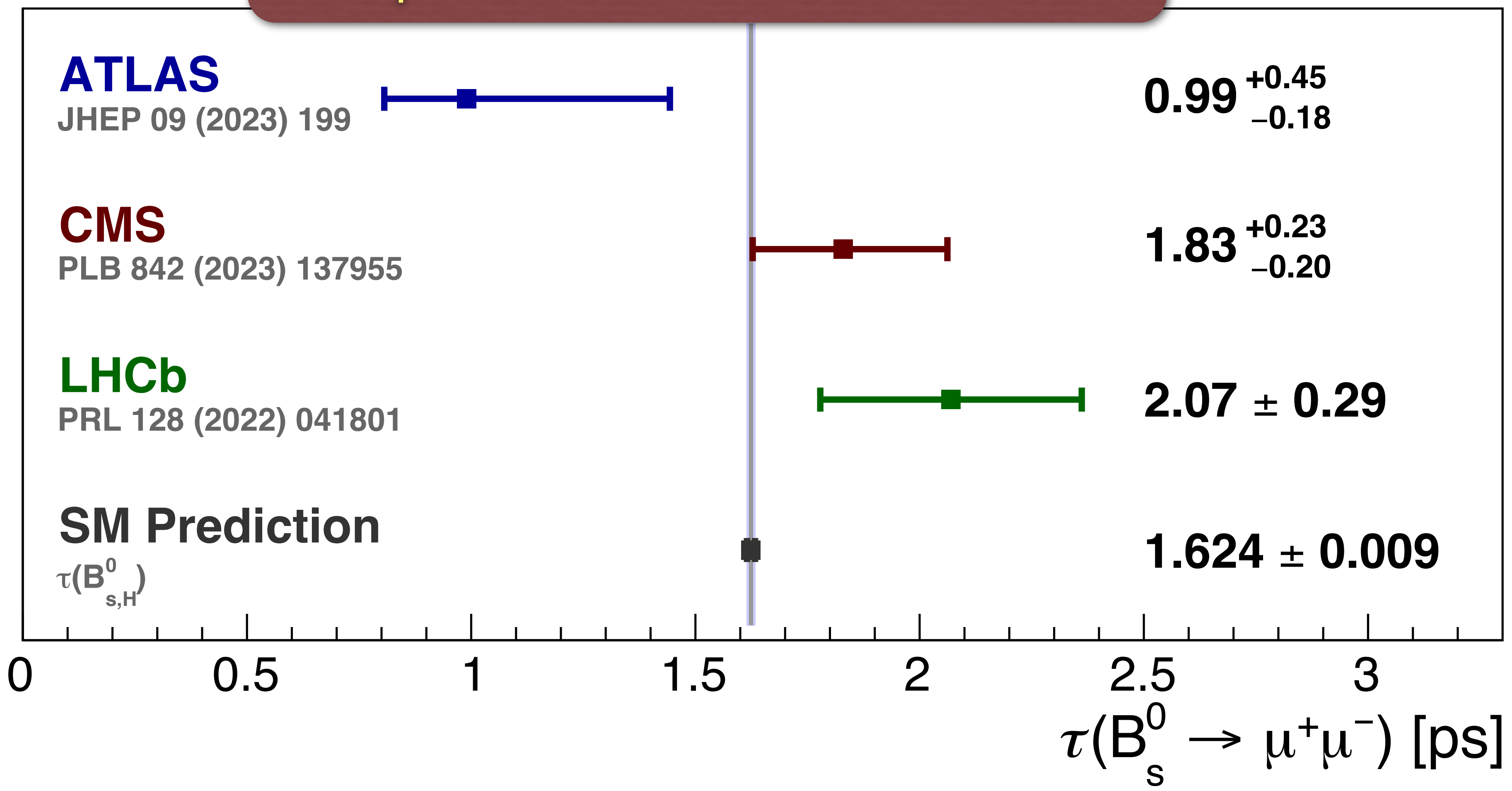
Result is consistent with SM and other measurements

$B_s \to \mu^+\mu^-$ Effective Lifetime
$\tau = 0.99^{+0.42}_{-0.07}\,(\text{stat}) \pm 0.17\,(\text{syst})\ [\text{ps}]$

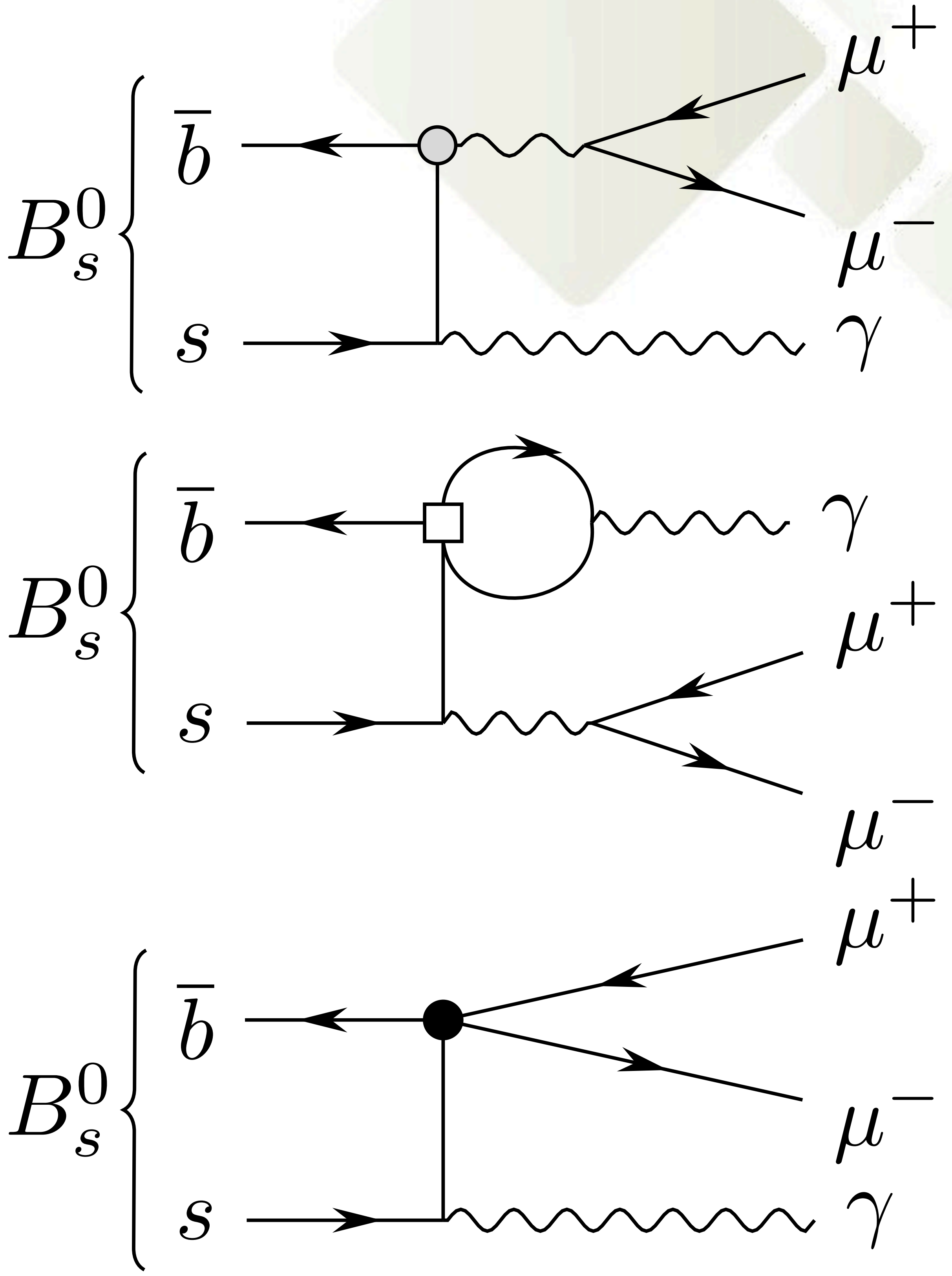
decay time sPlot



Comparison w/ other measurements

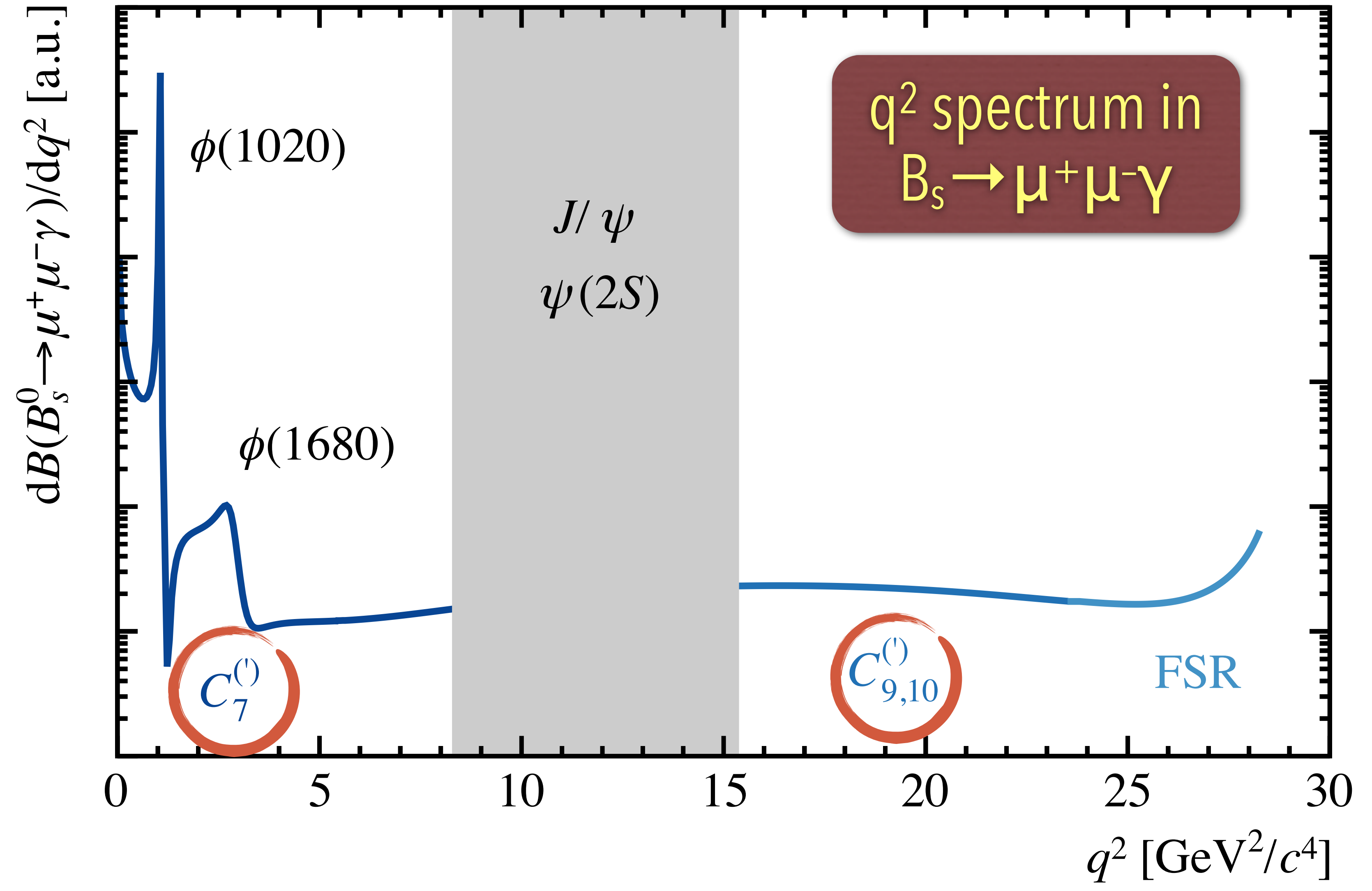


LHCb SEARCH FOR $B_s \to \mu^+\mu^-\gamma$



- A powerful probe for investigating any deviations from the SM, with sensitivity to a wider set of operators.
  - The chiral suppression in $B_s \to \mu\mu$ is relaxed with the additional photon, compensating the addition of the QED vertex.
- First studied as the partial reconstructed background for the $B_s \to \mu\mu$ analysis and the first upper limit for high q^2 region was reported (**ref. LHCb PRL 128 (2022) 041801**).
- A dedicated analysis in **three q^2 regions of interests**:

q^2 bin	I	II	III
q^2 [GeV²]	$[4m^2_\mu, 2.89]$	[2.89, 8.29]	$[15.37, m^2_{Bs}]$
$m(\mu\mu)$ [GeV]	$[2m_\mu, 1.70]$	[1.70, 2.88]	$[3.92, m_{Bs}]$
$10^{10} \times \mathcal{B}(B_s \to \mu^+\mu^-\gamma)$	82±15	2.54±0.34	9.1±1.1



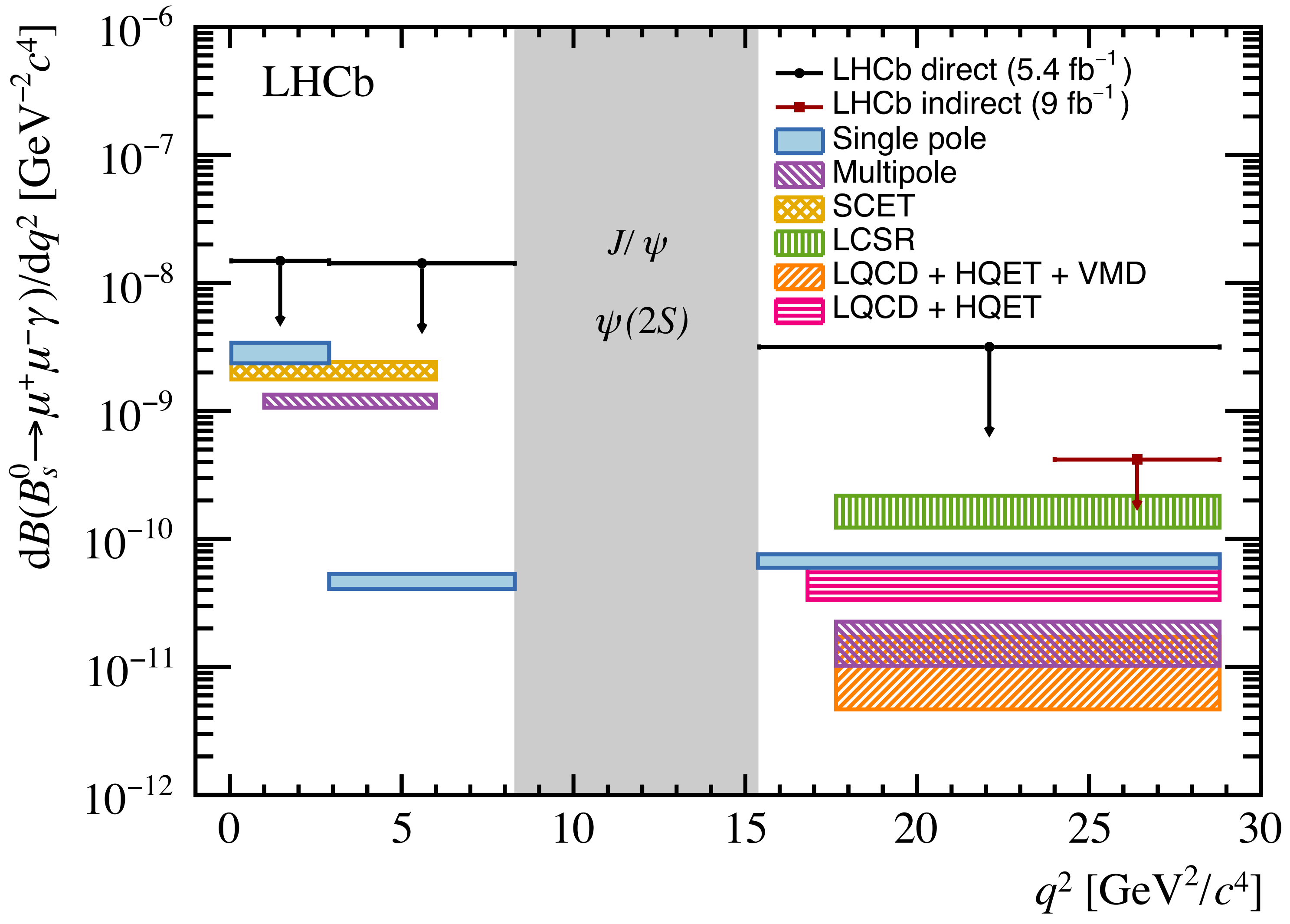
Ref. LHCb arXiv:2404.03375, submitted to JHEP

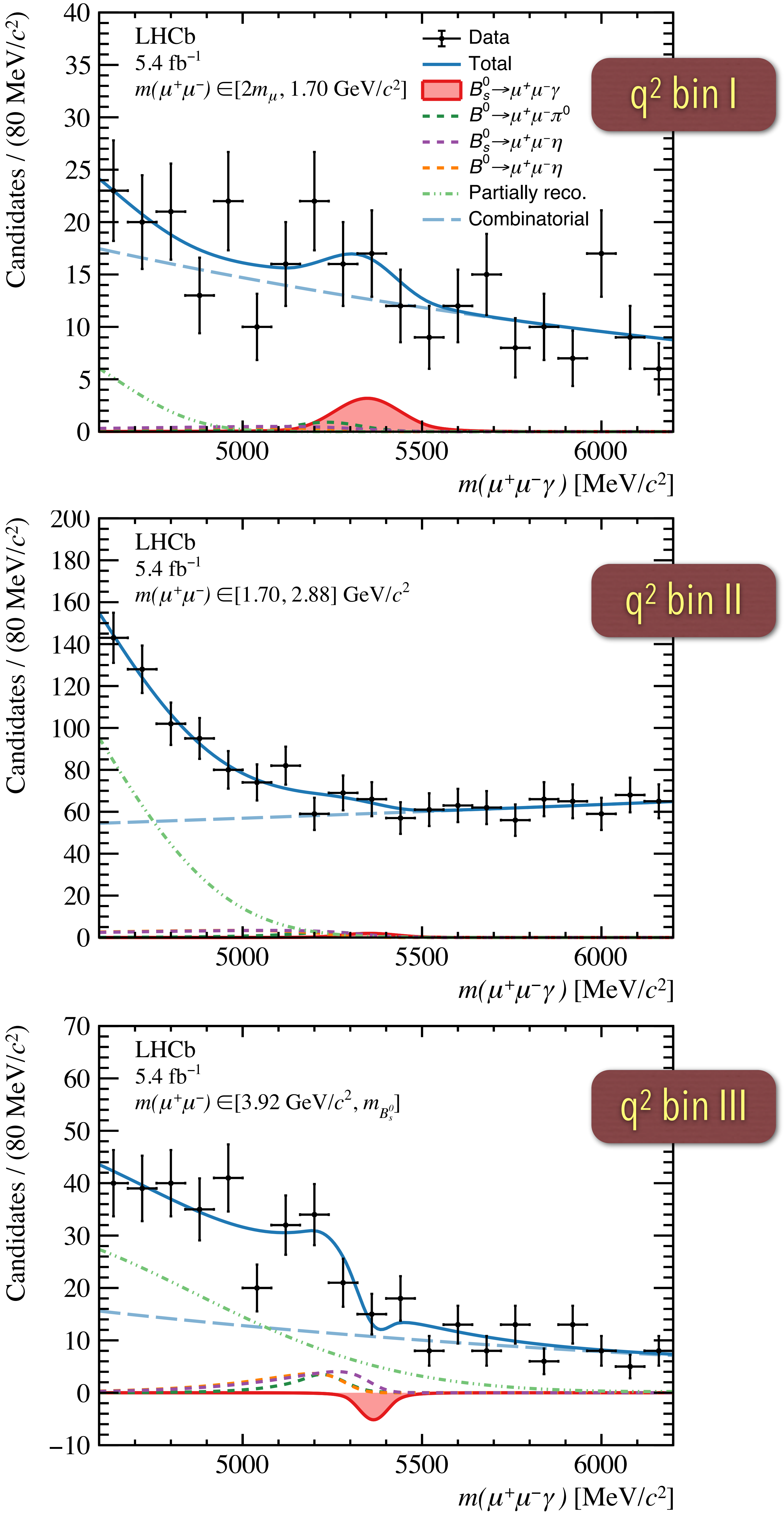
LHCb SEARCH FOR $B_s \to \mu^+\mu^-\gamma$

Ref. LHCb arXiv:2404.03375, submitted to JHEP

- Analysis is performed in three q^2 bins.
- Branching fractions are normalised to the well-known decay: $B_s \to J/\psi\eta$, and the $B_s \to \varphi(\to K^+K^-)\gamma$ decay is used as control channel to assess data/MC agreement.
- Two MLP classifiers are introduced to reduce the combinatorial background.
- Extended UML fits to the final-state mass distributions; **no significant signal found yet.**

q^2 bin	Upper Limit @ 95% CL
I (w/ ϕ veto)	$<4.2(3.4)\times10^{-8}$
II	$<7.7\times10^{-8}$
III	$<4.2\times10^{-8}$
Combined	$<2.8\times10^{-8}$





LHCb SEARCH FOR RARE B→Dμ⁺μ⁻ DECAYS

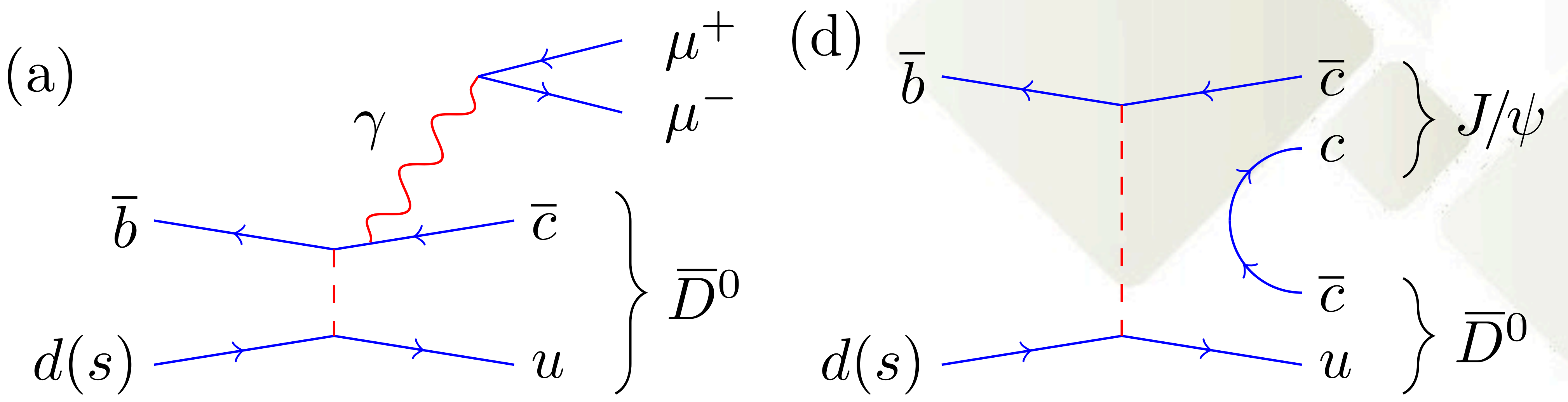
- The $B \to D\mu^+\mu^-$ decays proceed via an internal scatter process, specifically a W-exchange.
- Theoretical expectations:
  $\mu^+\mu^-$ from J/ψ ($10^{-8} \sim 10^{-7}$), non-resonant: 3×10^{-9}.
- Only $B_c^+ \to D_s^+ J/\psi$ is seen from LHCb 9 fb^{-1} data:

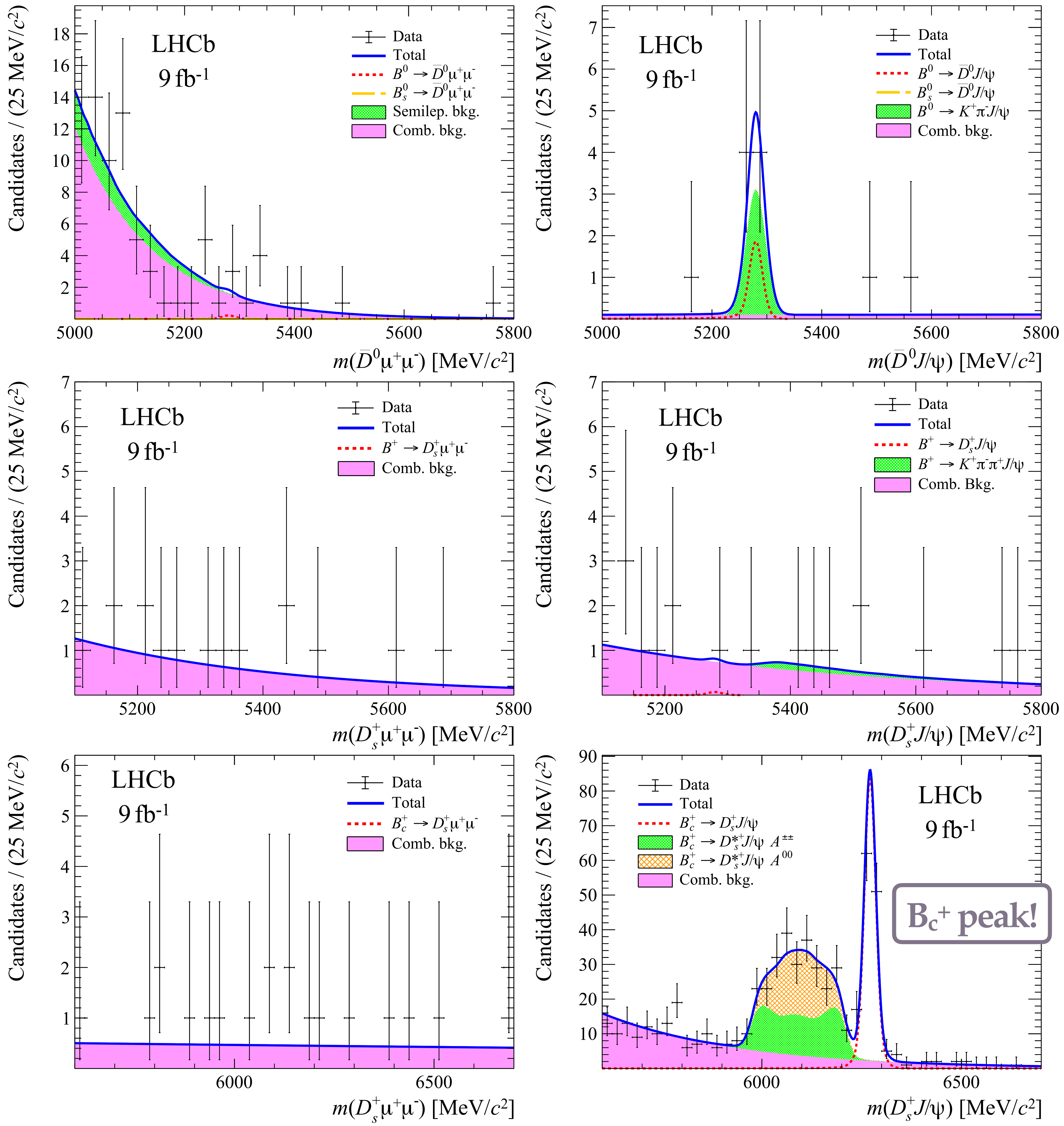
$$\frac{f_c}{f_u}\cdot\mathcal{B}(B_c^+\to D_s^+ J/\psi) = (1.63\pm0.15\pm0.13)\times10^{-5}$$

Observable	UL @ 95% CL
$\mathcal{B}(B^0\to D^0\mu^+\mu^-)$	$<5.1\times10^{-8}$
$\mathcal{B}(B^+\to D_s^+\mu^+\mu^-)$	$<3.2\times10^{-8}$
$\mathcal{B}(B_s\to D^0\mu^+\mu^-)$	$<1.6\times10^{-7}$
$f_c/f_u \cdot \mathcal{B}(B_c^+\to D_s^+\mu^+\mu^-)$	$<9.6\times10^{-8}$
$\mathcal{B}(B^0\to D^0 J/\psi)$	$<1.1\times10^{-6}$
$\mathcal{B}(B^+\to D_s^+ J/\psi)$	$<3.5\times10^{-7}$
$\mathcal{B}(B_s\to D^0 J/\psi)$	$<1.5\times10^{-6}$

Ref. LHCb JHEP 02 (2024) 032

Either the first such measurement or an improvement by 3 orders of magnitude!





LHCb SEARCH FOR RARE $B_c^+ \to \pi^+\mu^+\mu^-$ DECAYS

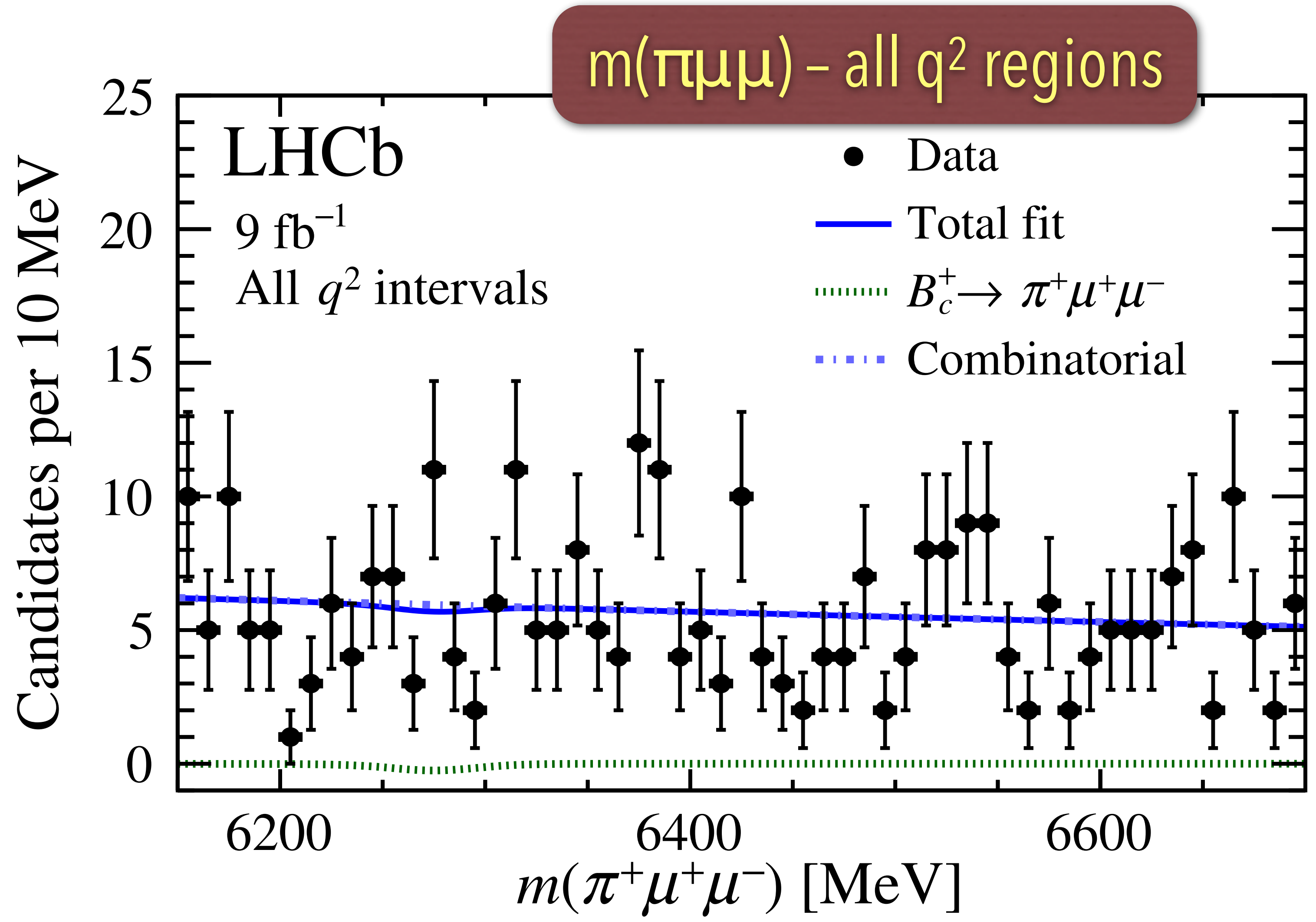
Ref. LHCb EPJC 84, 468 (2024)

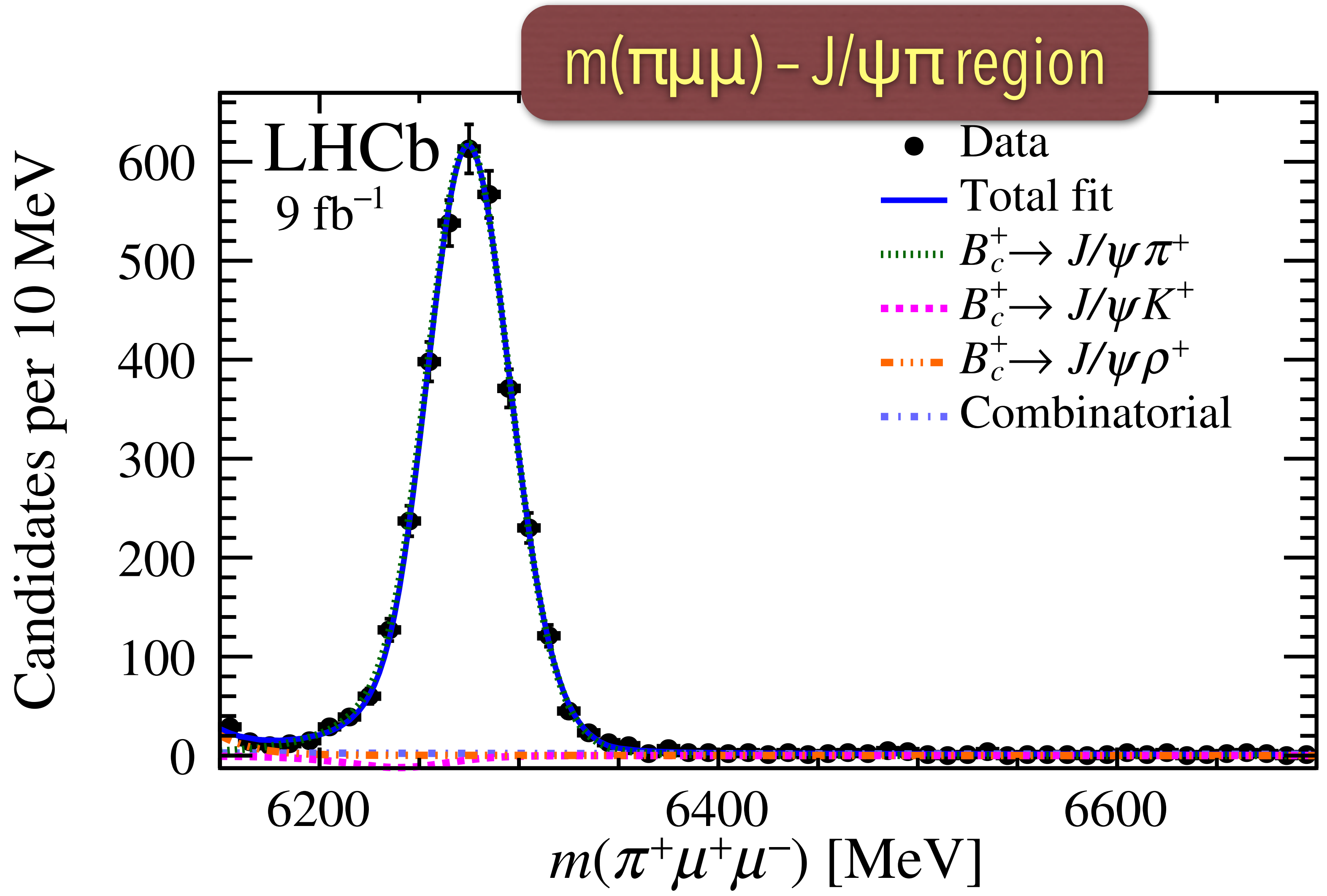
- B_c^+ meson can decay through the annihilation of the b and c quarks into a virtual W boson, resulting $D_s^+\mu^+\mu^-$ and $\pi^+\mu^+\mu^-$ (*⇒probe for the first time!*) decays.
- Can be the "parent" of $B_s^* \to \mu\mu$ via $B_c^+ \to (B_s^*)\pi^+ \to (\mu\mu)\pi^+$.
- No evidence for signal; upper limit is set on the branching fraction ratios w.r.t. $J/\psi\pi$.

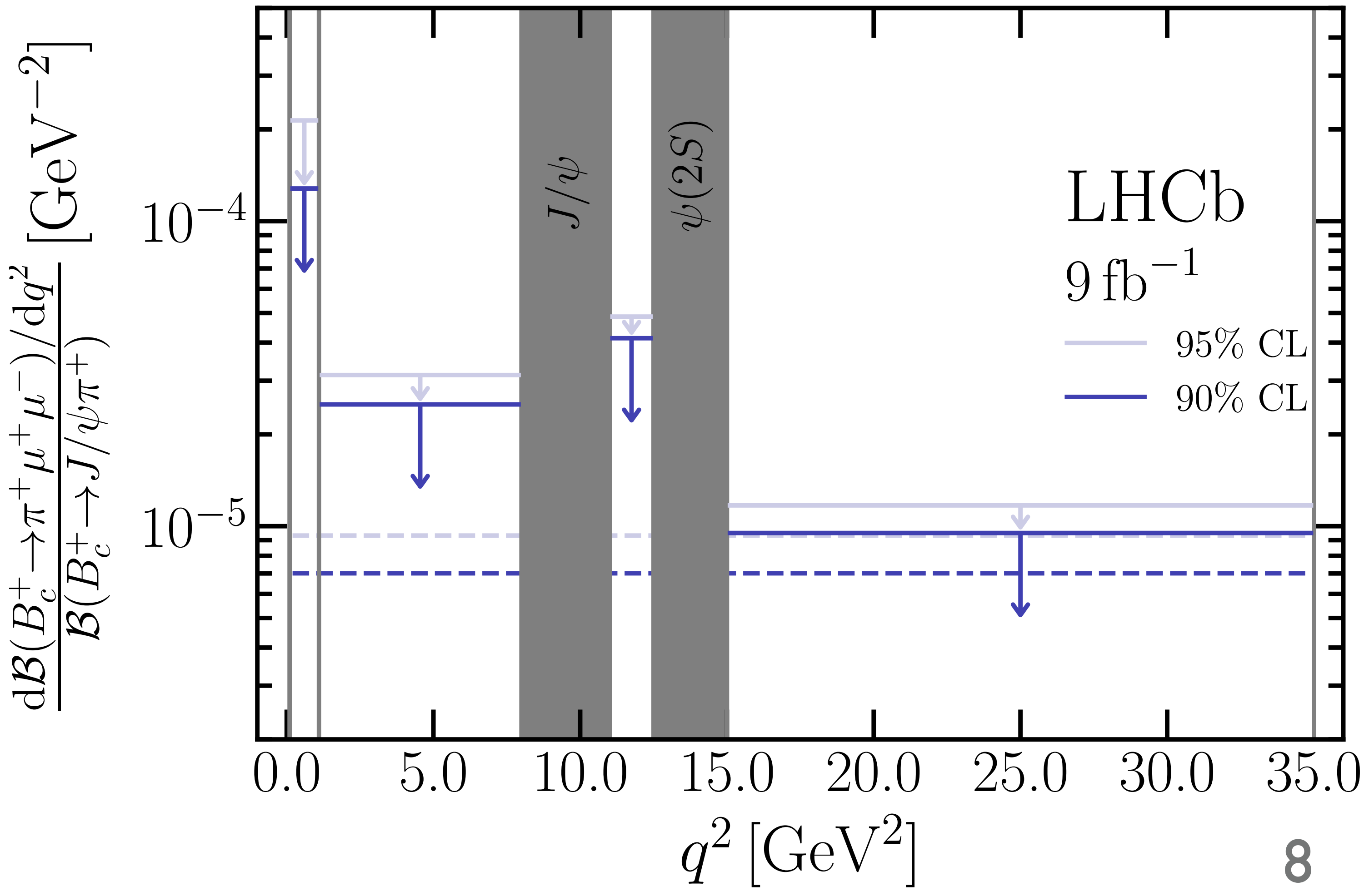
$R_{\pi^+\mu^+\mu^-/J/\psi\pi^+}$

q^2 interval	UL @ 95% CL
$0.1<q^2<1.1$ GeV^2	$<2.1\times10^{-4}$
$1.1<q^2<8.0$ GeV^2	$<2.2\times10^{-4}$
$11.0<q^2<12.5$ GeV^2	$<0.7\times10^{-4}$
$15.0<q^2<35.0$ GeV^2	$<2.3\times10^{-4}$
All	$<2.7\times10^{-4}$

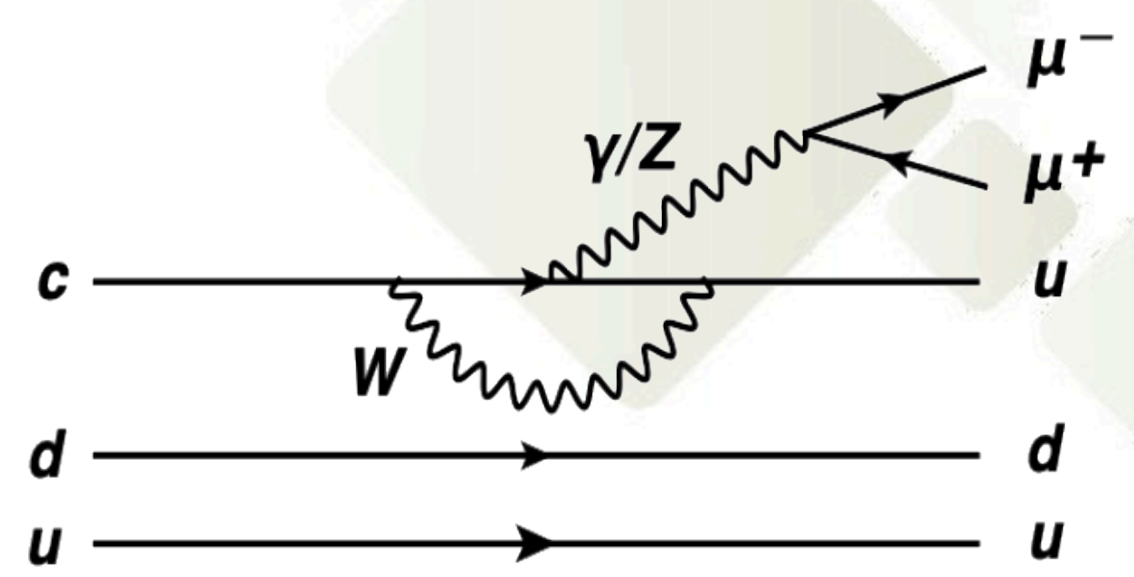
Also the best result on the $\psi(2S)\pi/J/\psi\pi$: $R_{\psi(2S)\pi^+/J/\psi\pi^+} = 0.254 \pm 0.018 \pm 0.003 \pm 0.005$



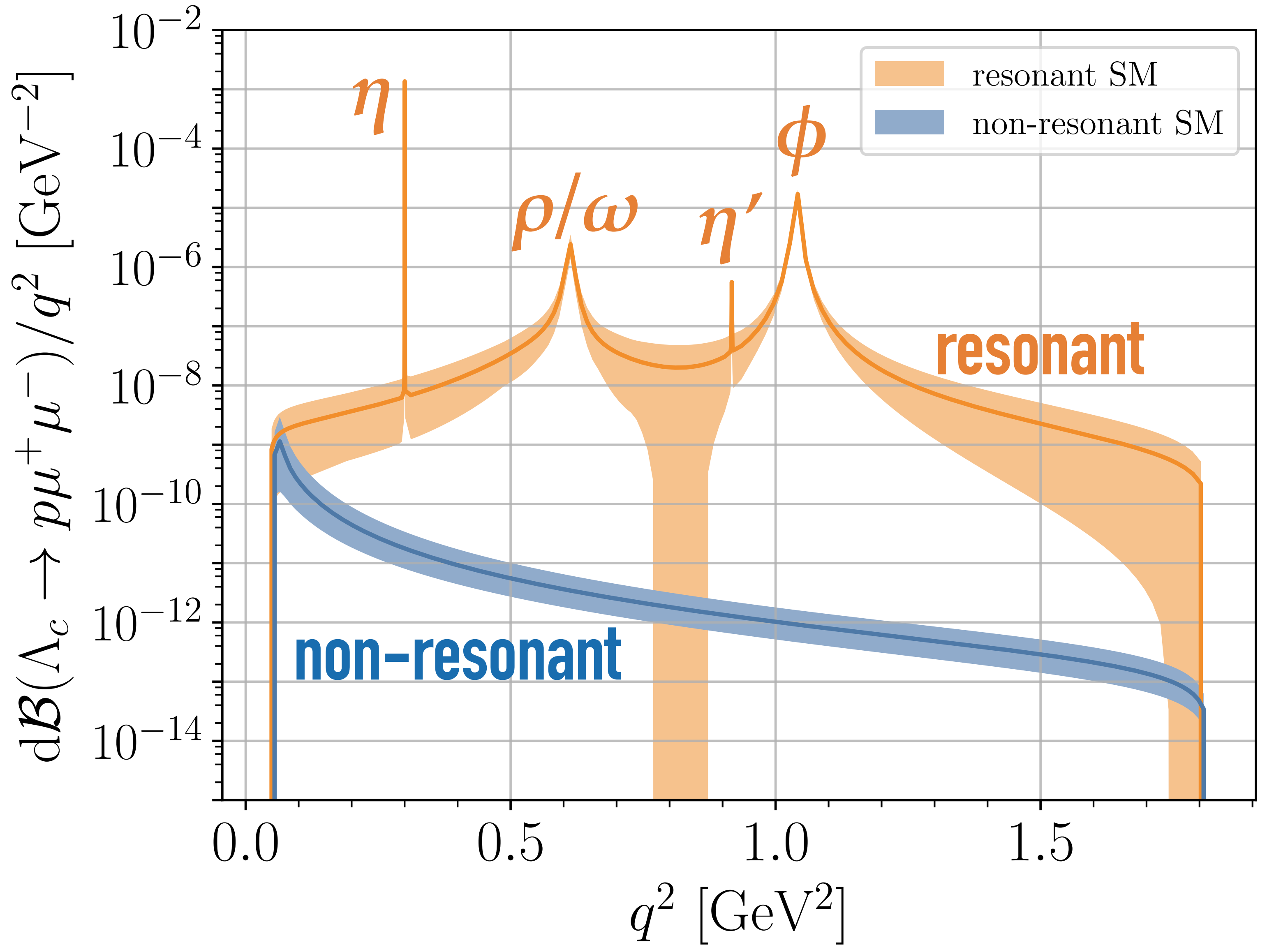




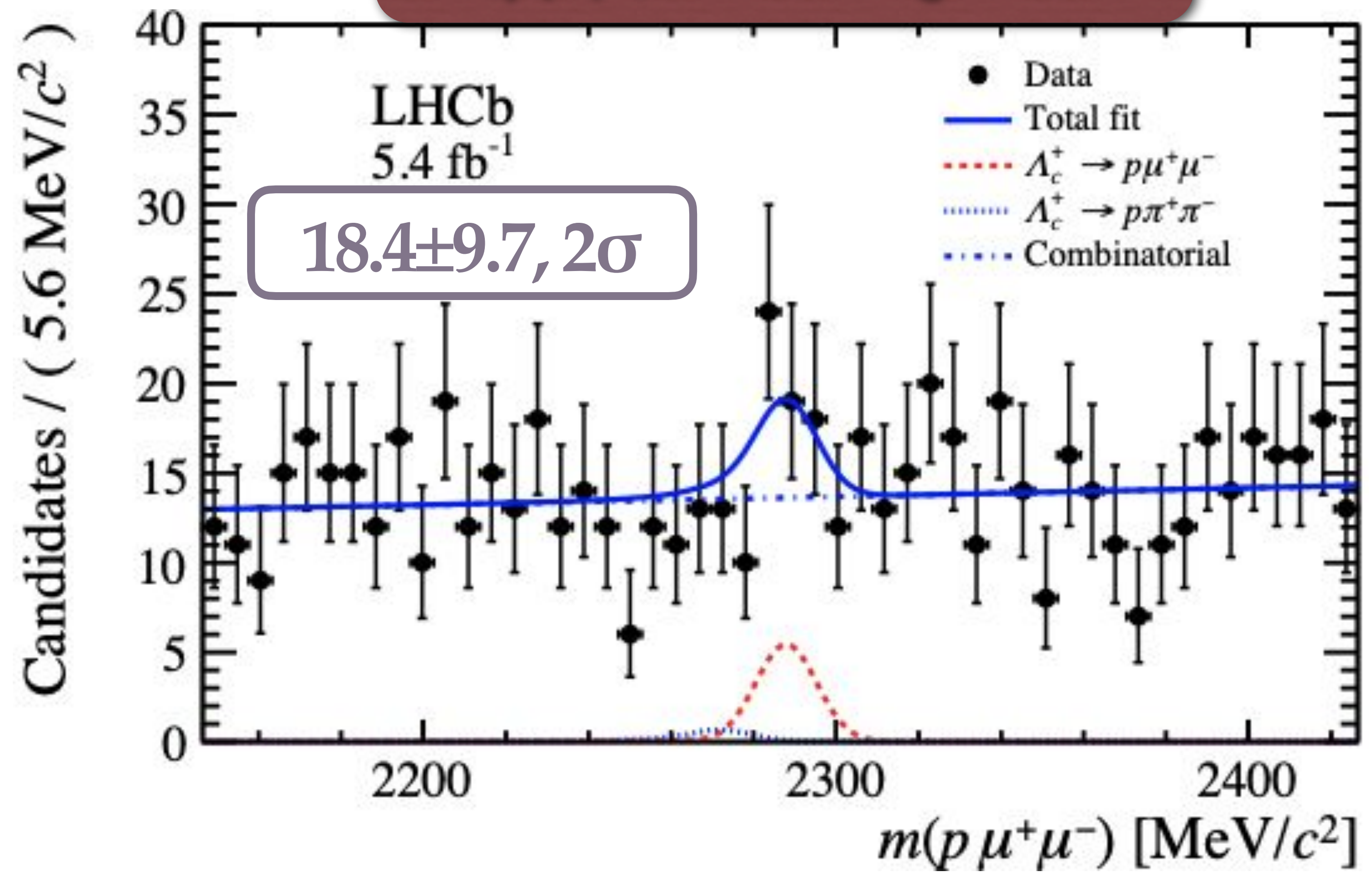
LHCb SEARCH FOR RARE $\Lambda_c^+ \to p\mu^+\mu^-$ DECAYS



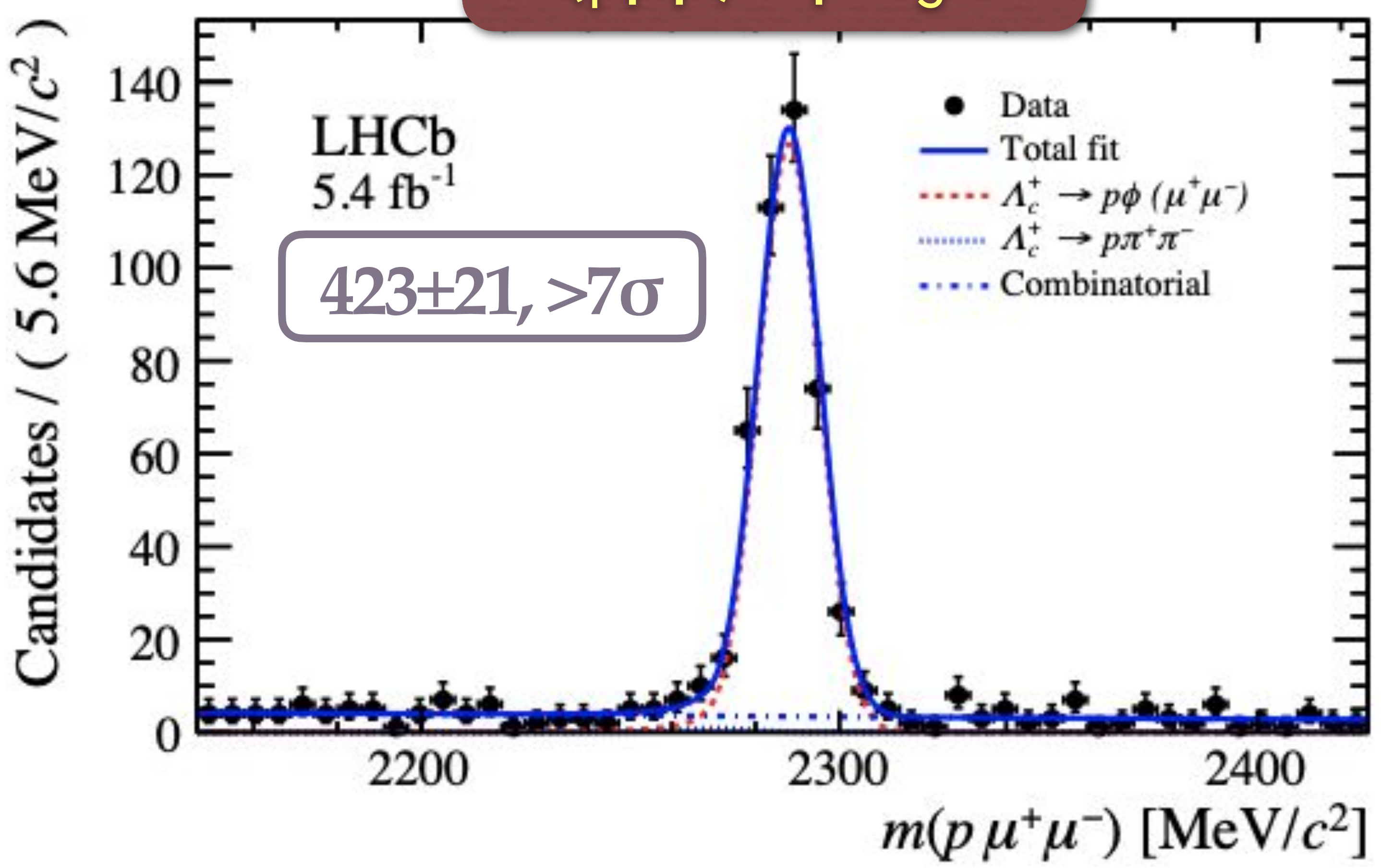
- In the SM short-distance contributions give $\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) \sim 10^{-8}$
- Including long-distance contributions from resonant $V \to \mu^+\mu^-$
  - Enhanced $\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) \sim 10^{-6}$ but hard to estimate precisely (*relative strong phases unknown!*)
  - Resonance tails across full q^2, hard to disentangle short-distance part.
- LHCb look for **non-resonant signal** in low-mass (<508 MeV) and high-mass (>1060 MeV) regions.
- **No significant signal found**, set the UL using the CLs method.



m(pμμ) – low+high mass



m(pμμ) – ϕ region

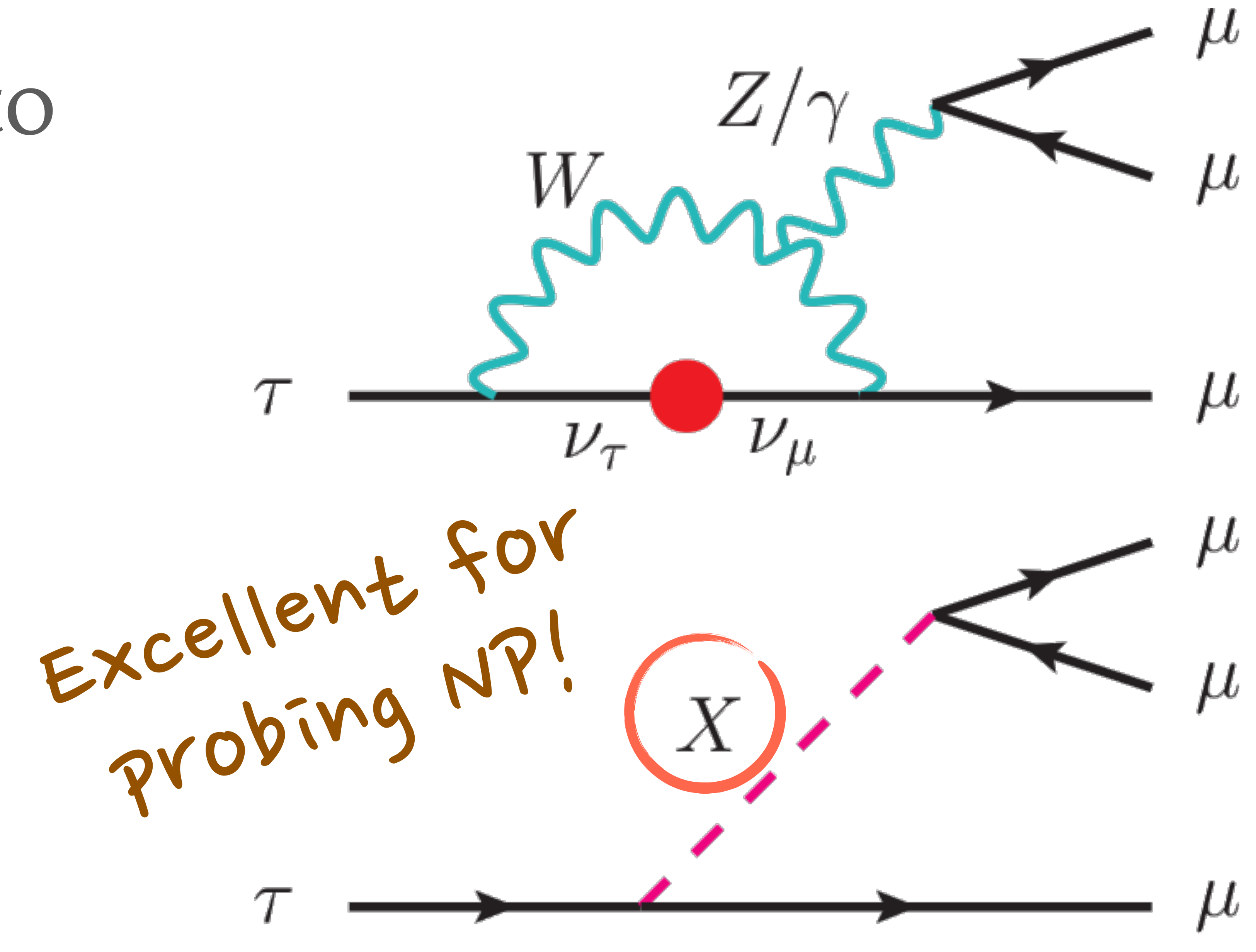


Ref. LHCB-PAPER-2024-005

Regions	UL @ 95% CL
low+high mass combined	$<3.24\times10^{-8}$
extrapolated to full m(μμ) region	$<8.2\times10^{-8}$

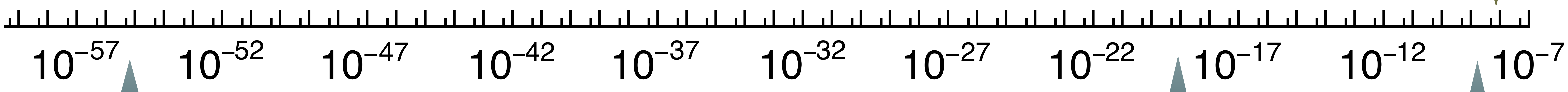
SEARCH FOR τ→3μ: INTRODUCTION

- 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.



$\mathcal{B}(\tau\to3\mu)$

Best limit from Belle-II: $\mathcal{B}<1.9\times10^{-8}$ @ 90% CL



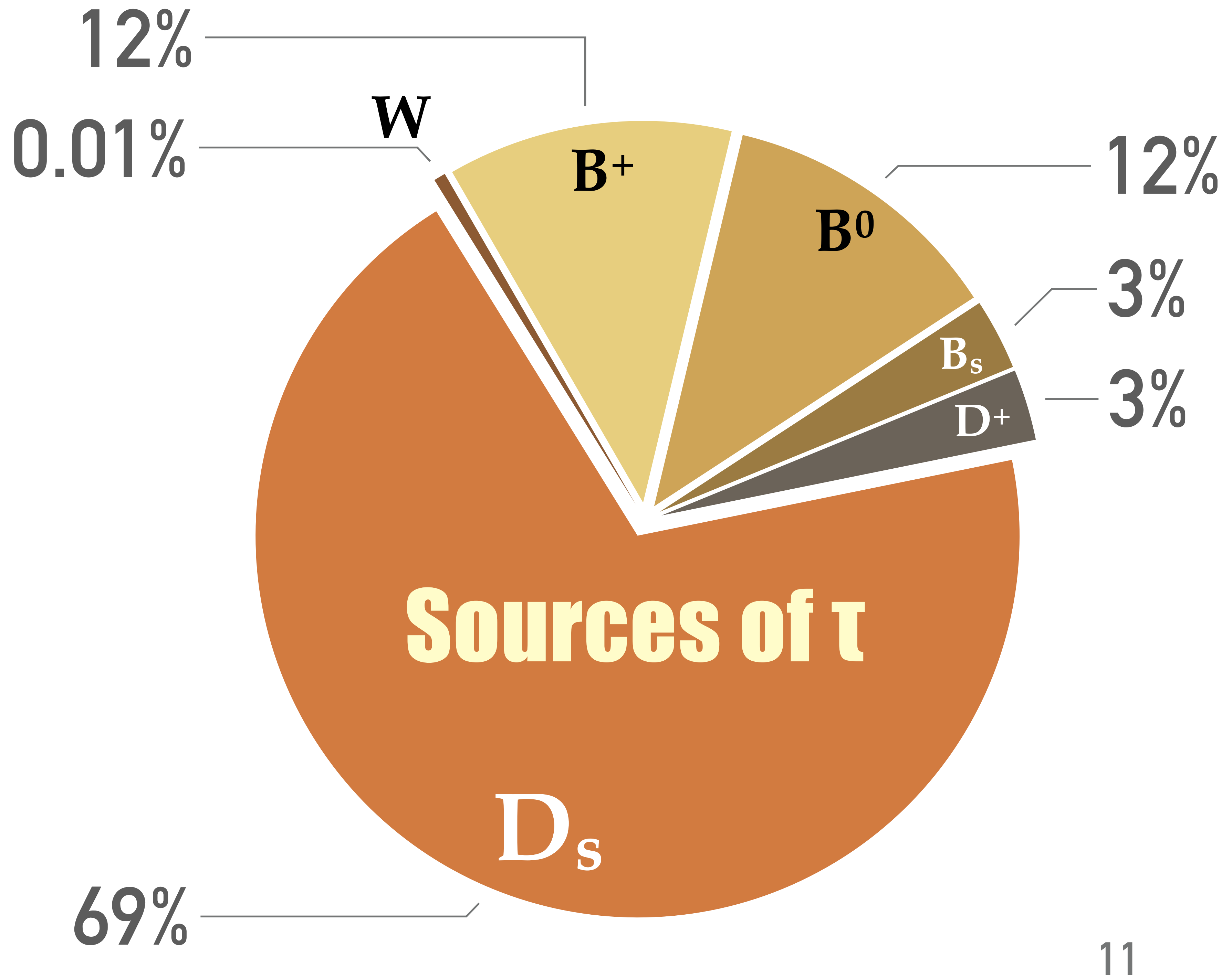
SM prediction: 10^{-53}~10^{-56}

SM + RH Dirac neutrino: 10^{-18}

SUSY: 10^{-7}~10^{-10}

CMS ANALYSIS OVERVIEW

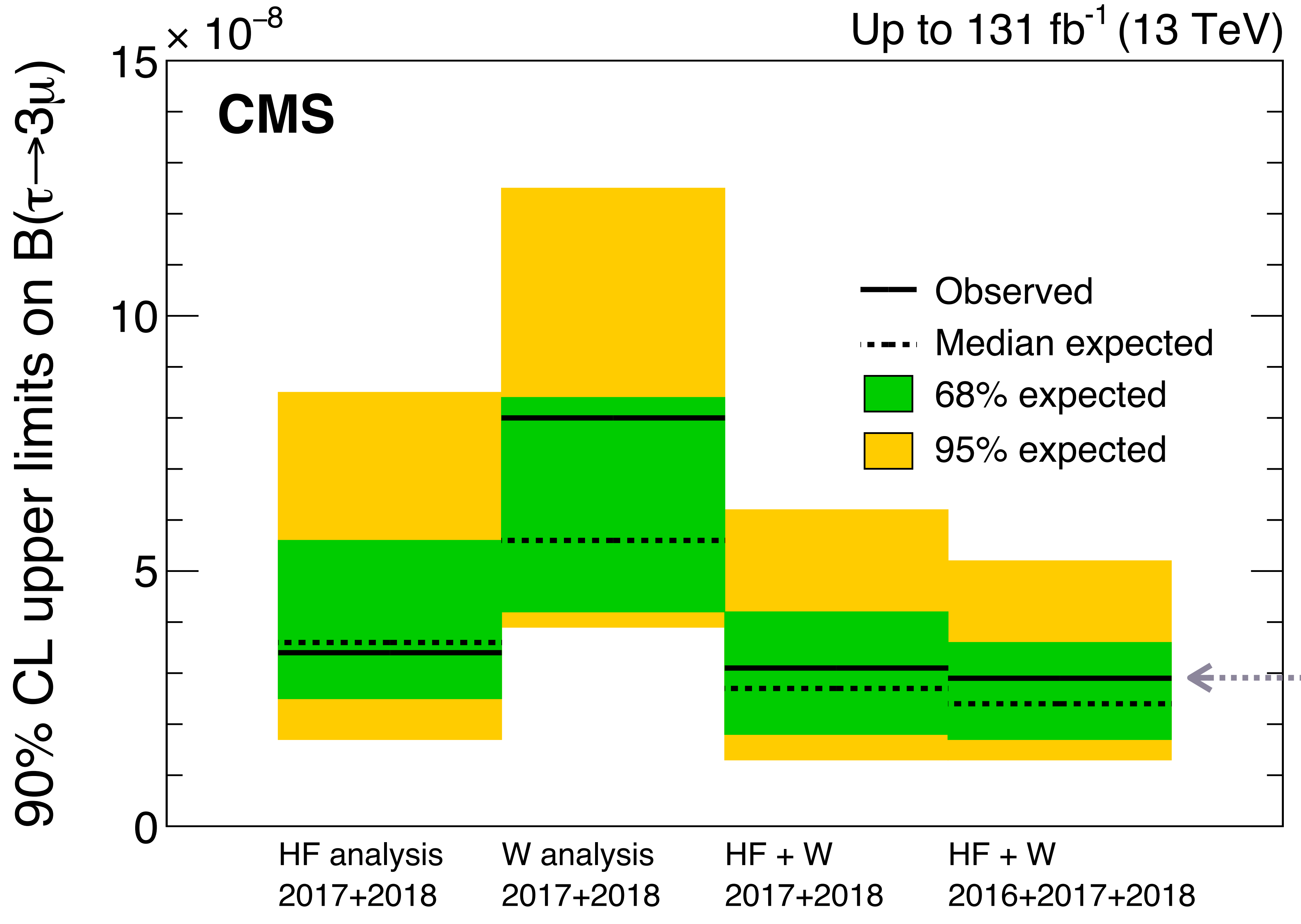
- 2016 data result is already published: Ref. CMS JHEP 01 (2021) 163.
- Extended to full Run-2 data, investigating both the **Heavy flavor** and **W-boson** channels:
  - HF decay: dominant source($\sim 10^{11}$ τ's per fb^{-1}), lower in p_T, more forward.
  - τ from W decay is much less ($\sim 10^{7}$ τ's per fb^{-1}), but higher in p_T and central; W kinematics provides additional handles!
- **Signal candidate is reconstructed with 3 muons, with sum of the charge = ±1**:
  - Signal extraction with simultaneous UML fit to 3μ invariant masses;
  - Events categorized with invariant mass resolution: 3 categories / year / production channel.
  - Background suppression by BDT discriminators.

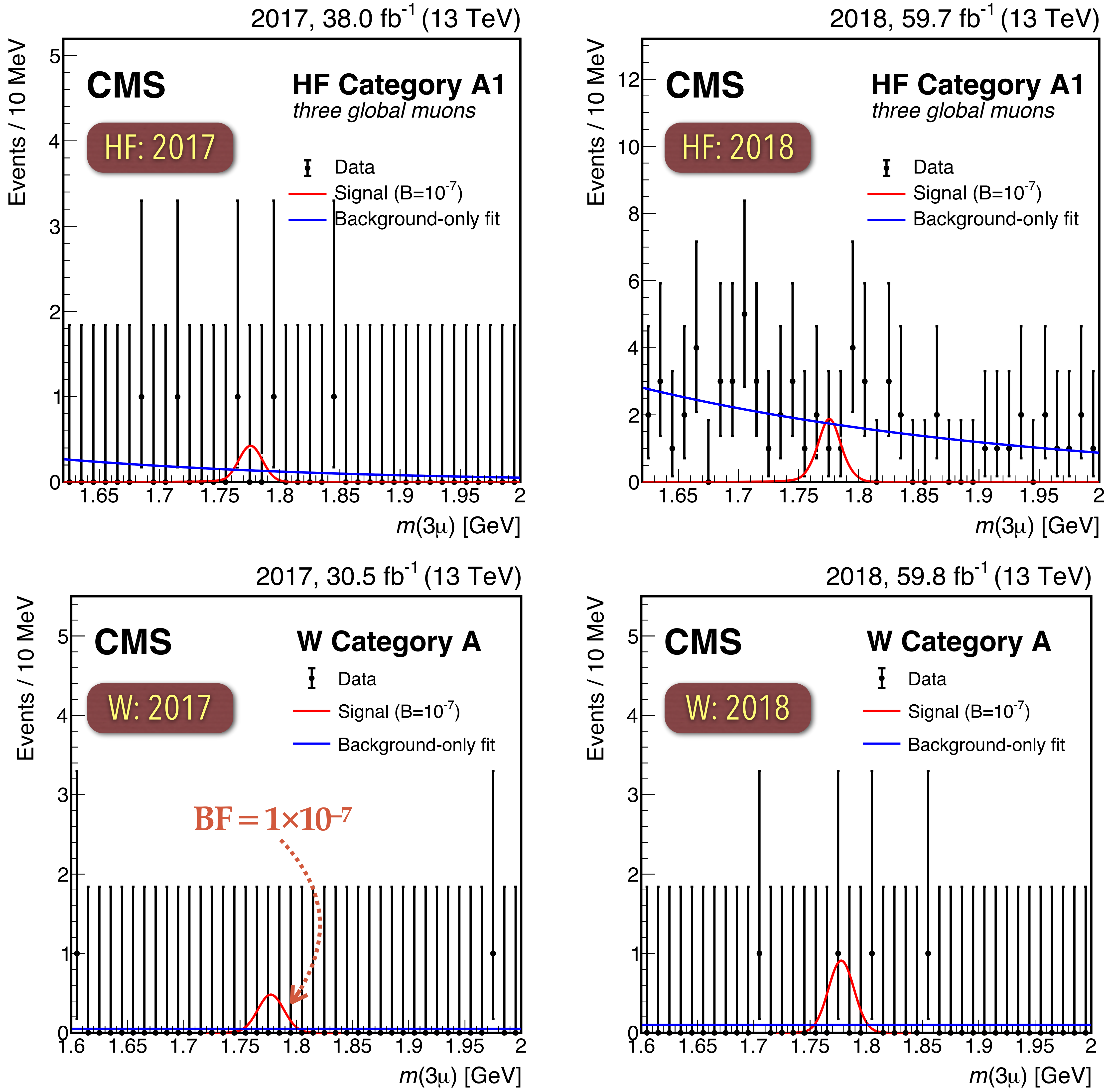


CMS RESULTING UPPER LIMIT

Ref. CMS PLB 853 (2024) 138633

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





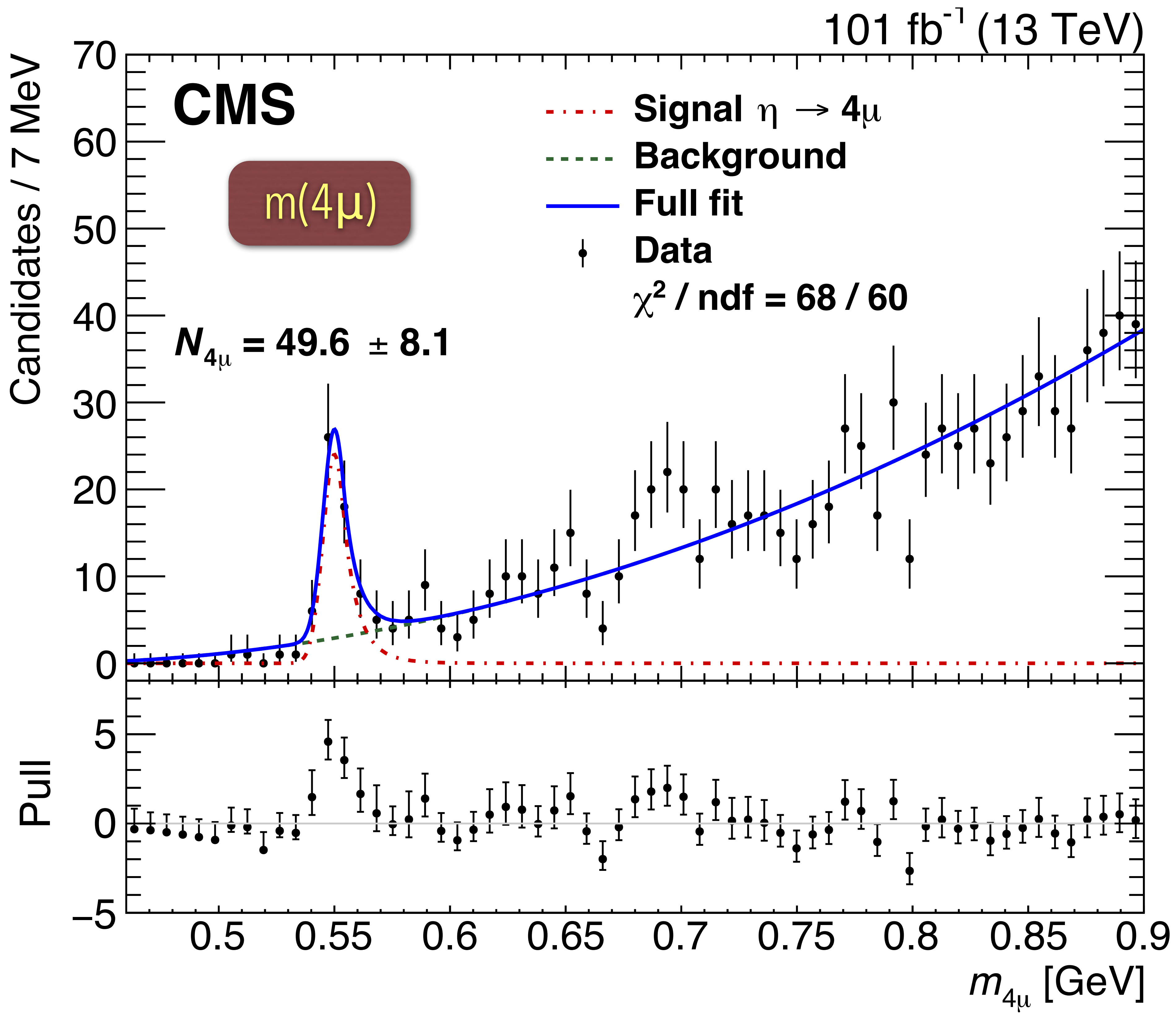
New analysis of 2017+2018 data combined with 2016 for the full Run-2 result:

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

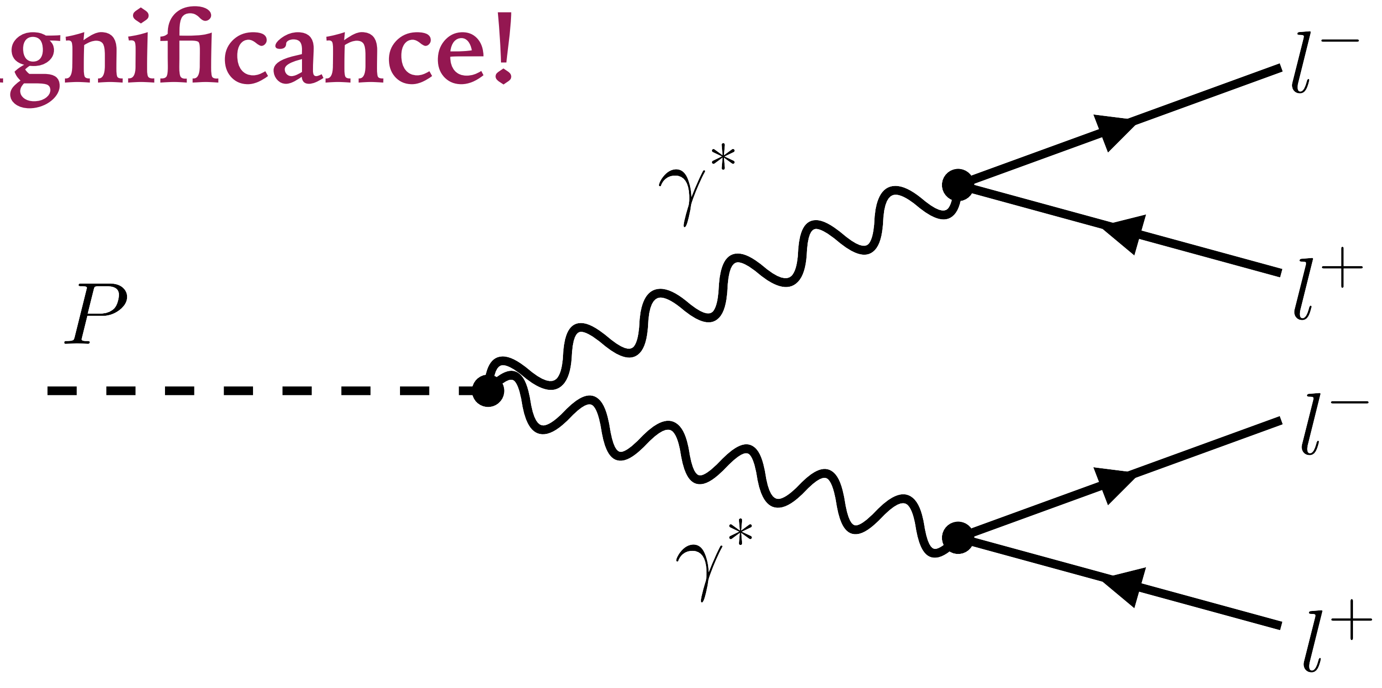
CMS OBSERVATION OF VERY RARE $\eta \to 4\mu$

More on scouting & parking: CMS arXiv:2403.16134, submitted to Physics Reports

Ref. CMS PRL 131 (2023) 091903



- In SM $\eta \to 4\mu$ decay predicted with a very low branching fraction of $O(10^{-9})$
  - Sensitive to new physics scenarios + precision test of the SM.
- Only feasible with **"data scouting"** scenario:
  - Reduce event size (Mb→kB) to speed up DAQ!
  - Save reconstruction at HLT and skip the standard prompt event processing.
- **~50 signal events observed from 101 fb^{-1} data, clearly a discovery of >5σ significance!**



Resulting branching fraction

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

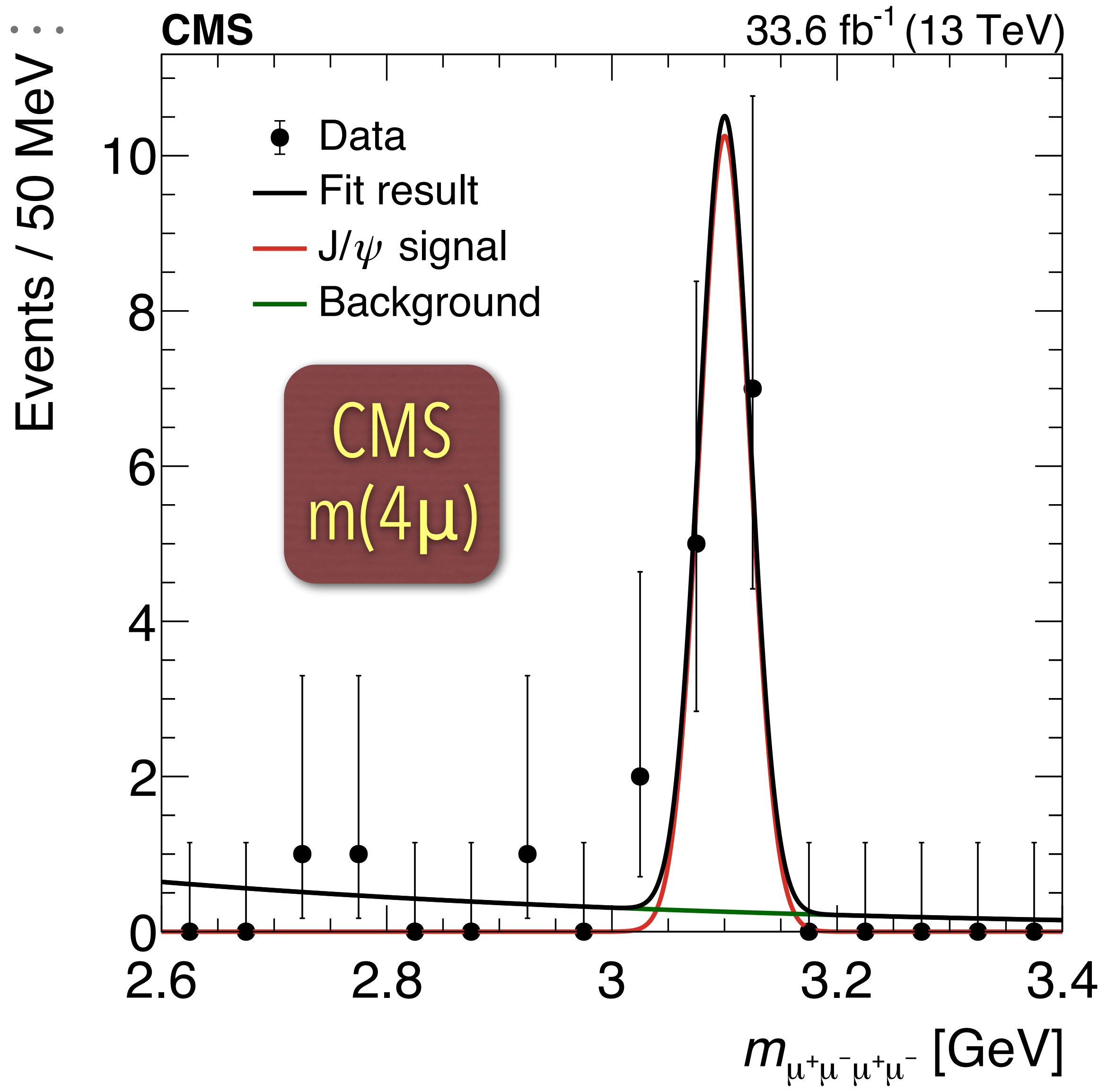
in agreement with SM prediction: $3.98 \pm 0.15 \times 10^{-9}$

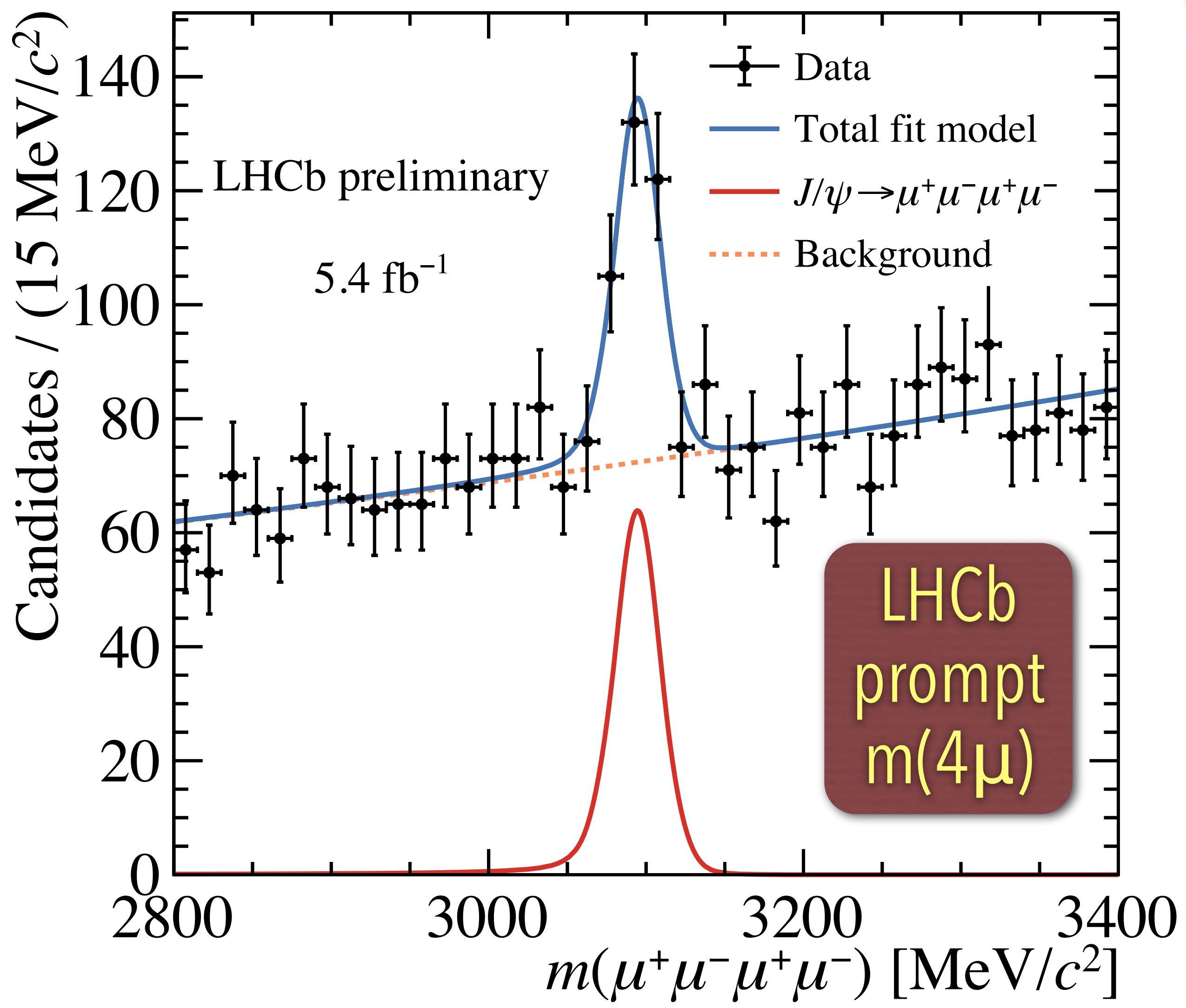
OBSERVATION OF J/ψ→4μ DECAYS

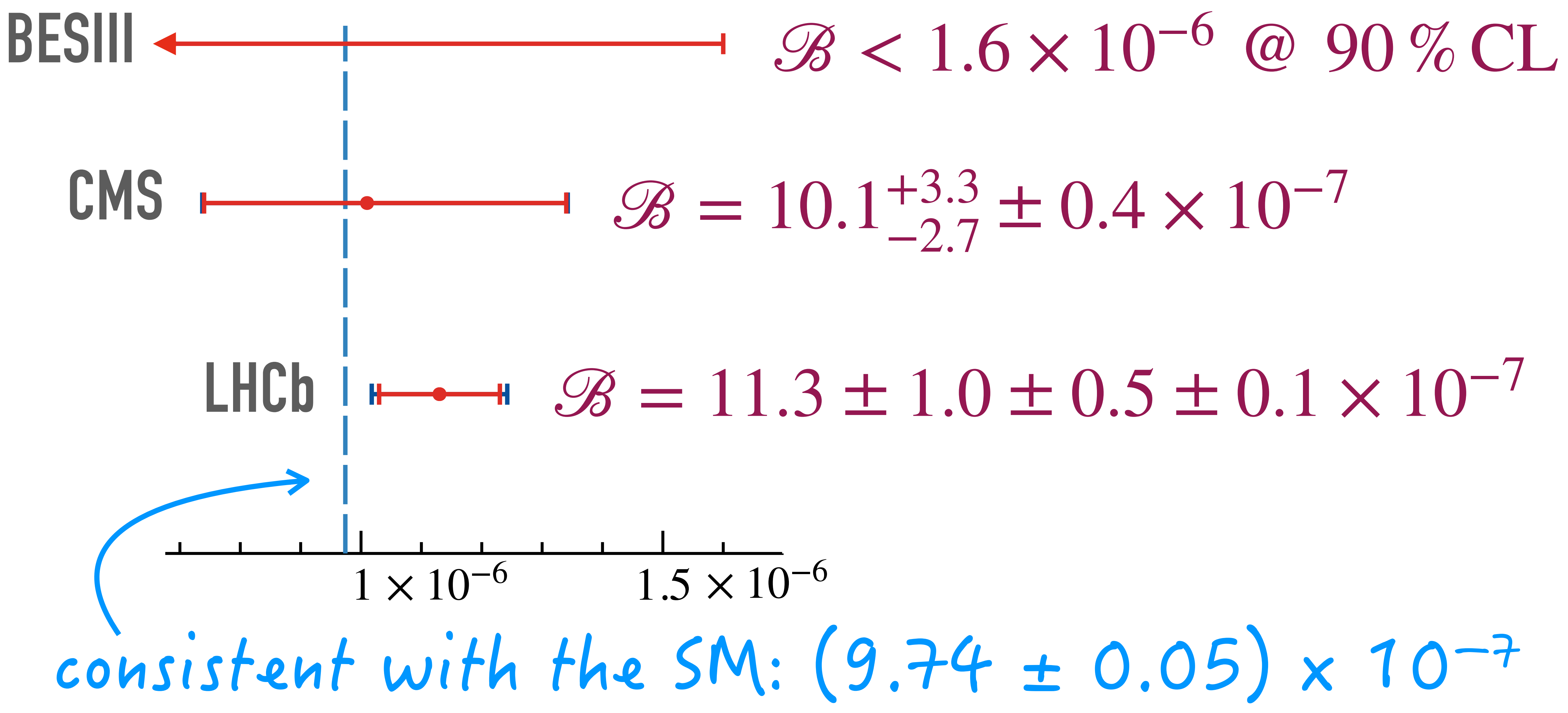
CMS BPH-22-006
Accepted by PRD

LHCb-CONF-2024-001

- Thanks to the large production rate at LHC, 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.**
- CMS exploits the **"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 observed plenty of candidate events too: **further studies allowed** (*e.g. checking the underlying structures!*)



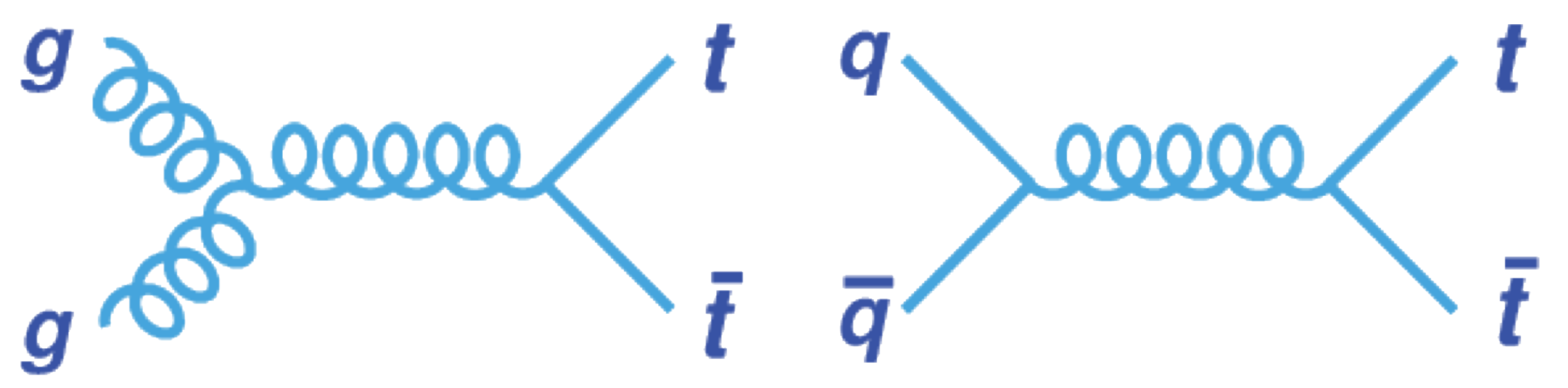




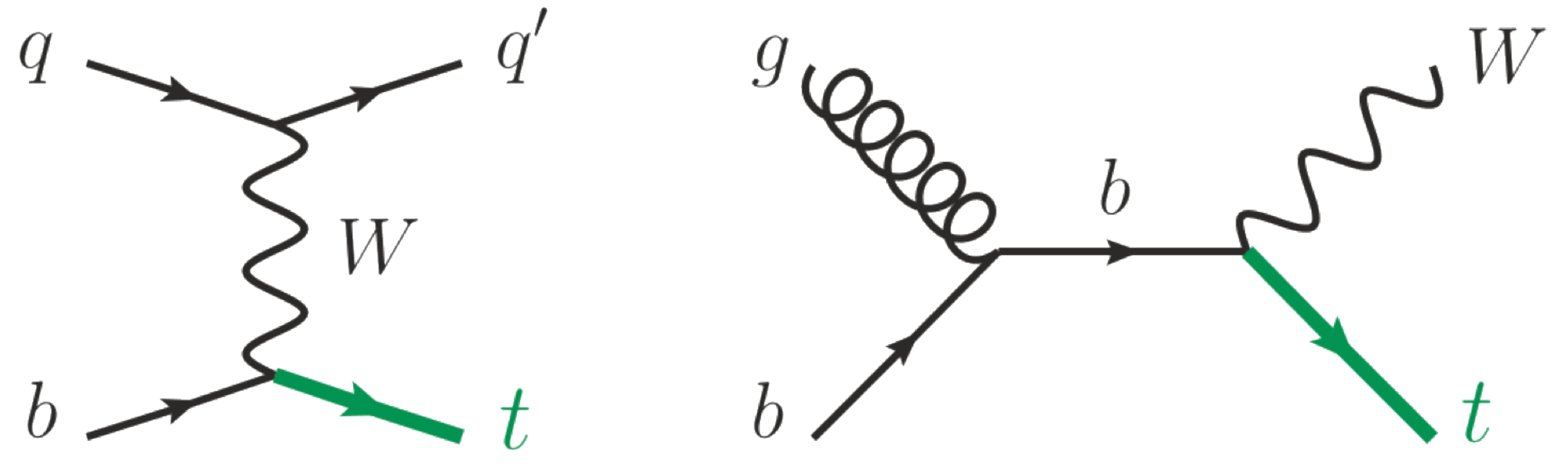
CLIMB TO TOP AND BEYOND!

TOP QUARK @ LHC

- Top quark is heavy and short lived:
  - Heaviest known point-like particle, ~36 times heavier than the bottom quark, why?
  - Large Yukawa coupling to the Higgs boson, essential in EW symmetry breaking.
  - Decays before hadronization –– allow to probe bare quark properties!
- LHC is a **TOP QUARK FACTORY**! Large production cross sections provided by high center-of-mass energy:
  - 120M of top pairs produced at ATLAS/CMS during Run-2, more are coming at Run-3!
  - **An excellent place to search for new physics with rare decays!**



$t\bar{t}$ pair via strong interactions: dominant production (mostly gluon), sensitive to PDF

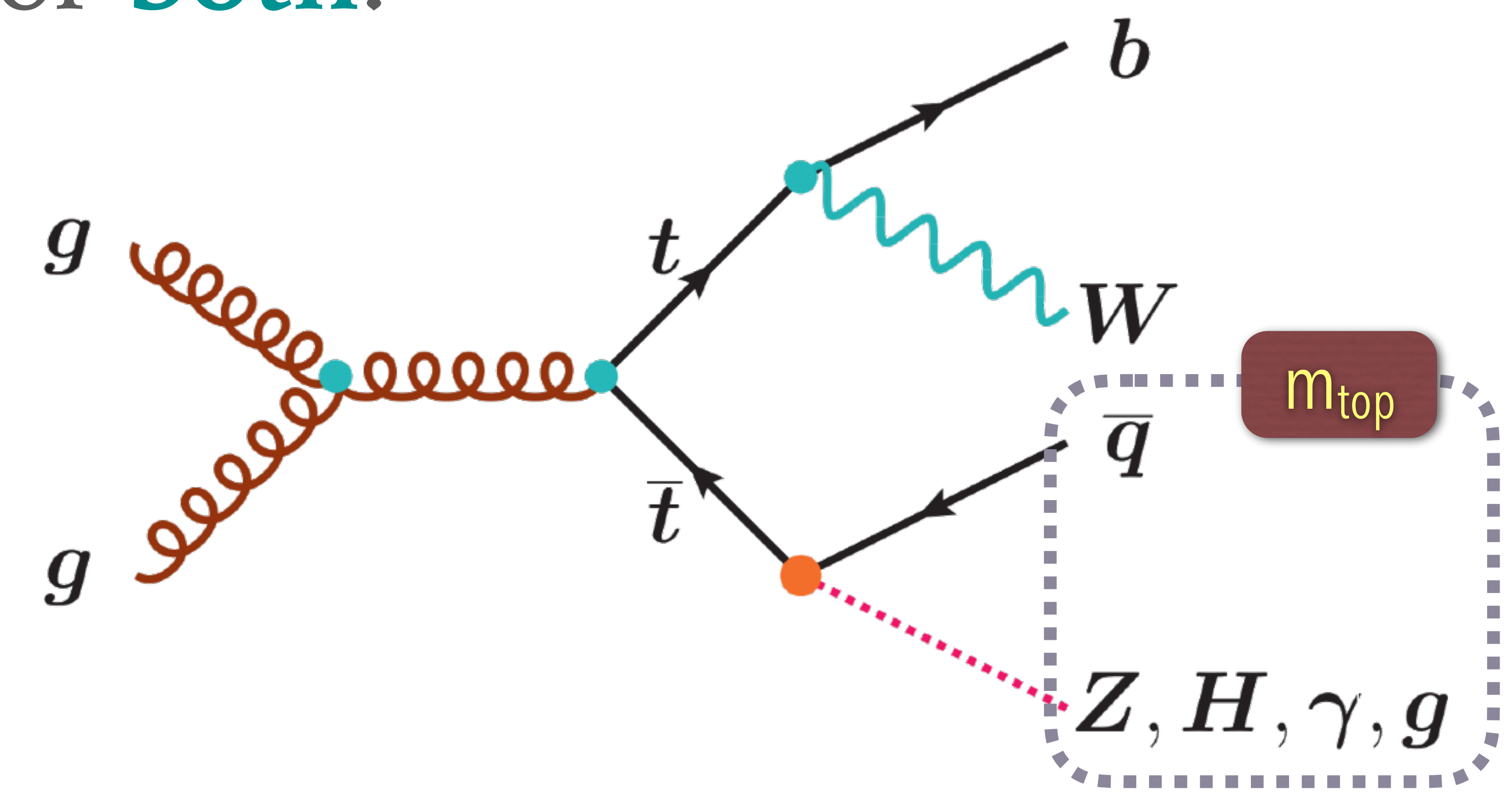


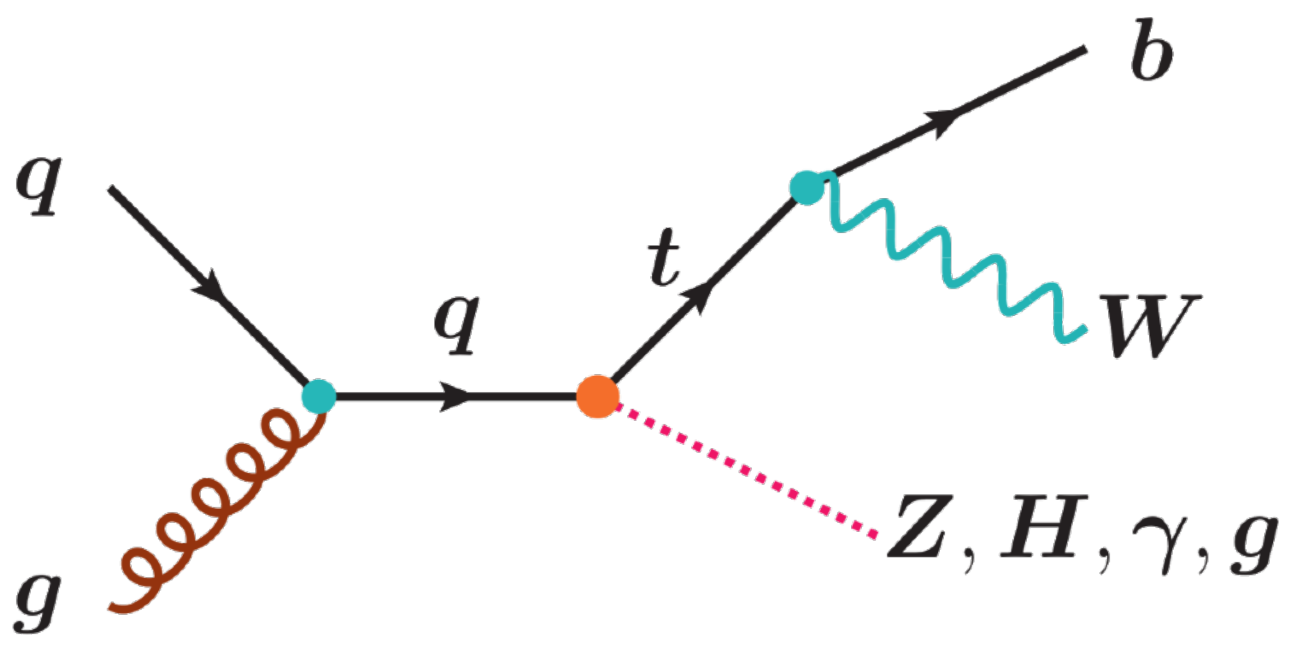
Single top via charged weak current: Wtb vertex in the production, sensitive to Vtb

SEARCHES FOR TOP FCNC • TOP CLFV

- **Flavor-changing neutral current/coupling (FCNC)** transitions are forbidden at tree level. BSM could enlarge the couplings — introducing possible tree diagrams or with relaxed GIM suppression.
- **Charged Lepton Flavor Violation (CLFV)** via neutrino oscillations is highly suppressed due to the tiny neutrino masses; NP models can enhance the rates too!
- These processes usually contain distinctive event signatures, e.g. with Z/isolated photon/multiple leptons. Searches can be performed either with **$t\bar{t}$ decay**, or through **single t production**, or **both**.

Large production rate; similar sensitivities for q=u,c



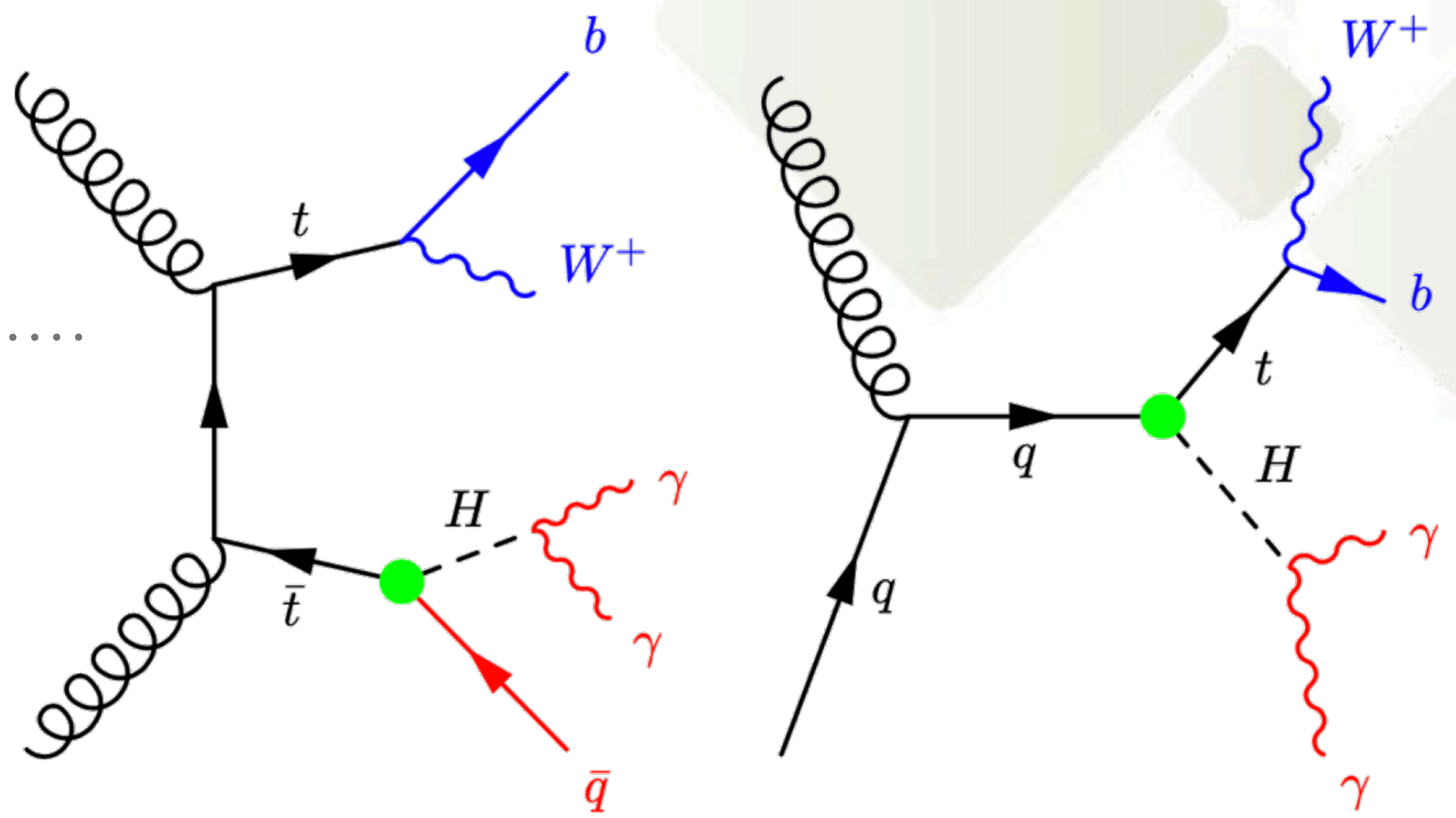


direct probe at the production; require normalization to x-section; q=u is flavored due to incoming parton.

Final state only differs by a jet!

ATLAS FCNC BETWEEN TOP & H(γγ)

SM pred.: 10^{-15}~10^{-17}

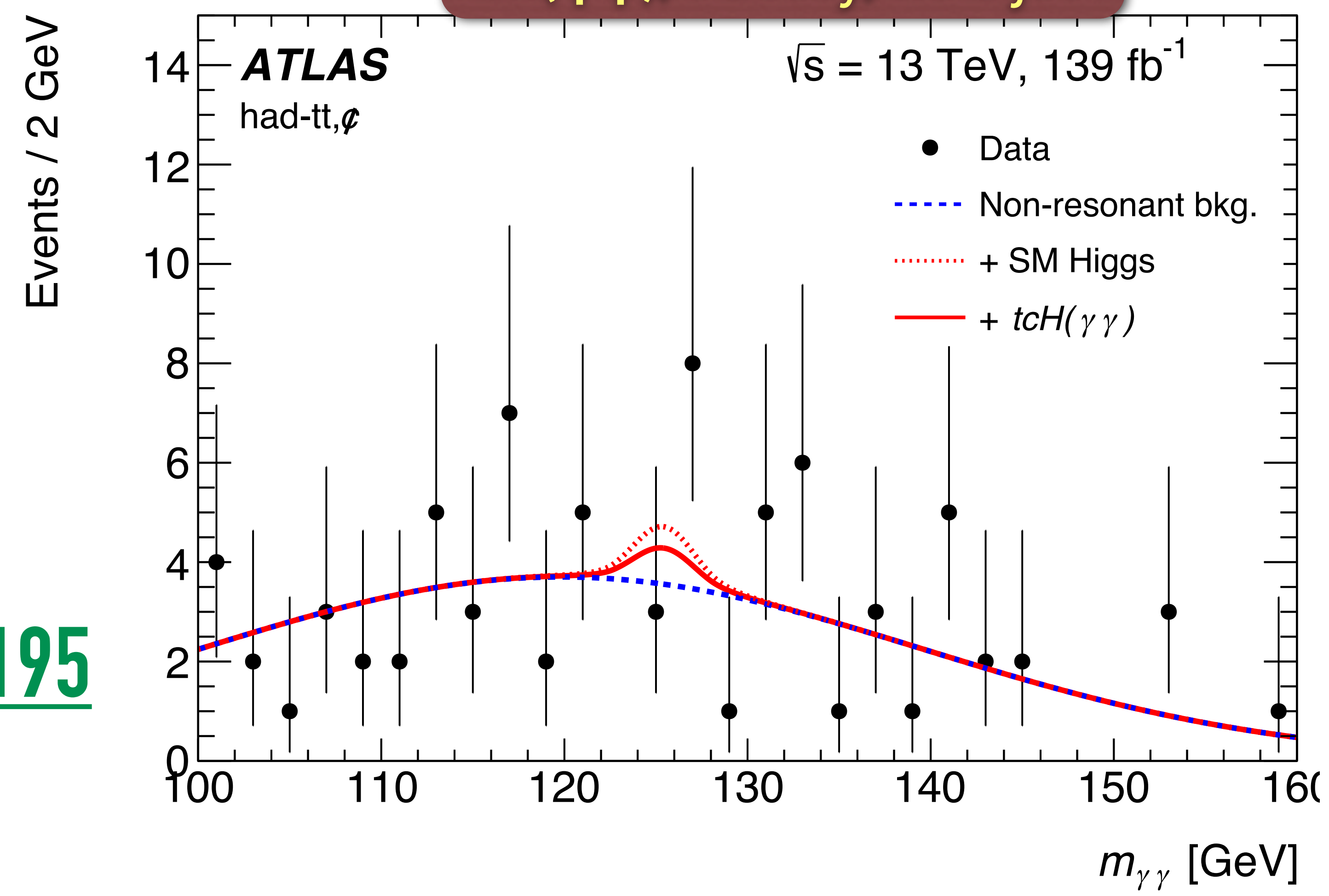


- Two final states, tH and tqH, arising from single and tt decay considered.
- Fits are performed in several regions that target **events with H→γγ (*clean signature!*)**, 0 or 1 lepton, plus charm tagging and top reconstruction.
- Better categorisation + additional MVA background rejection, resulted in a significant gain compared with previous study.

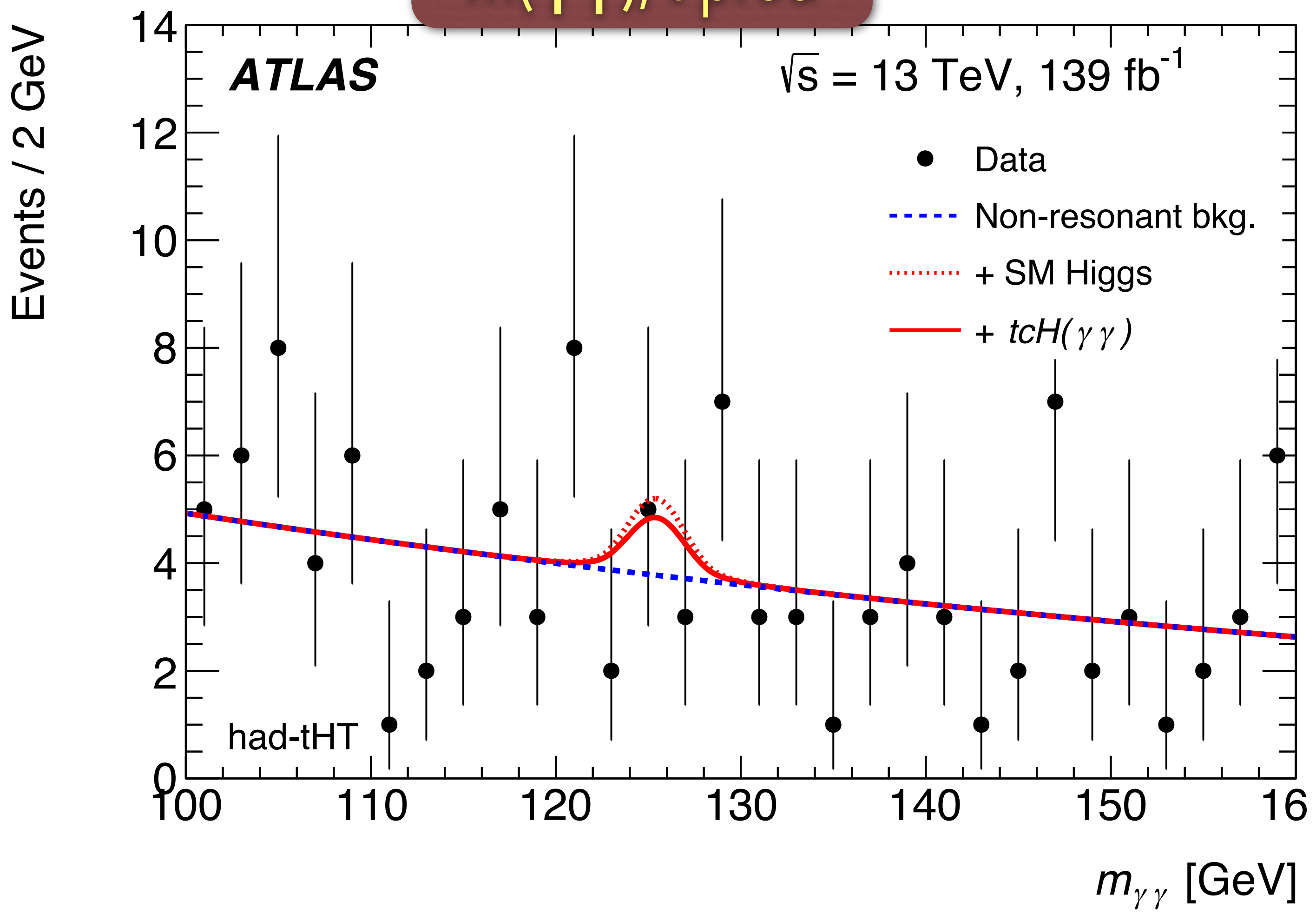
Observable	Obs. limit	Exp. limit
$\mathcal{B}$(t→u+H)	**3.8×10^{-4}**	3.9×10^{-4}
$\mathcal{B}$(t→c+H)	**4.3×10^{-4}**	4.7×10^{-4}

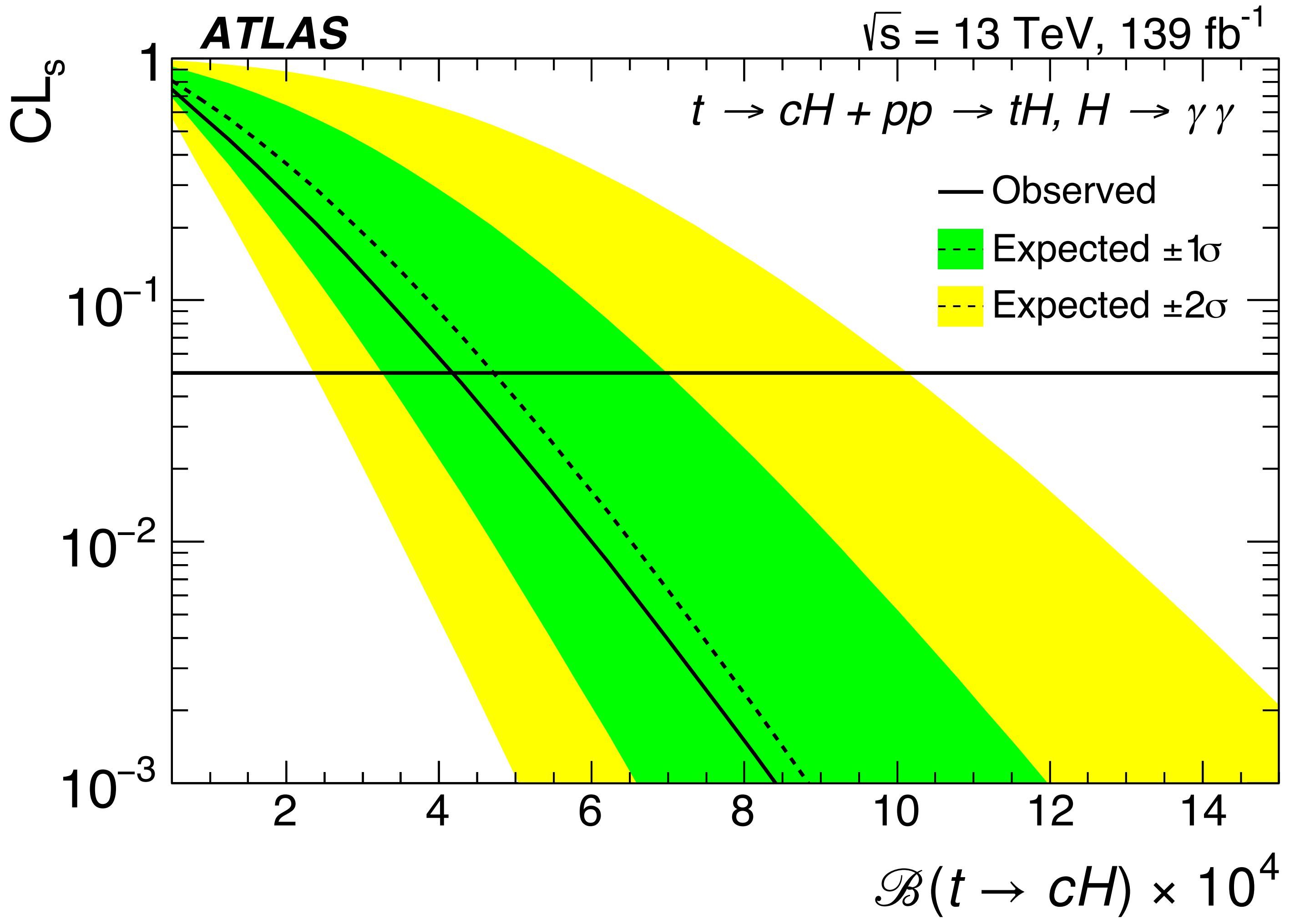
Ref. ATLAS
JHEP 12 (2023) 195

m(γγ), t decay, no c-jet

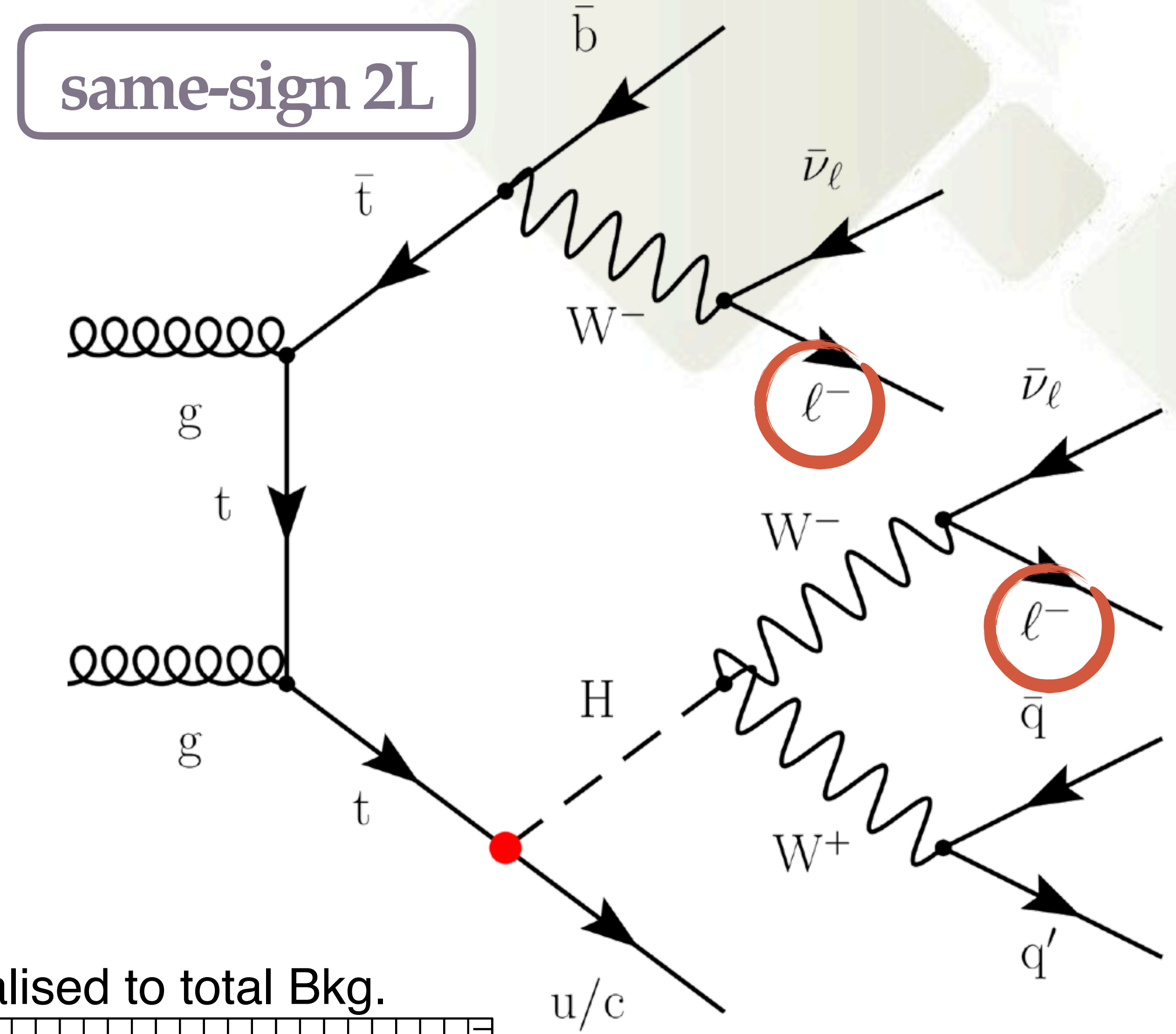


m(γγ), t prod





ATLAS FCNC BETWEEN TOP & H(MULTILEPTONS)



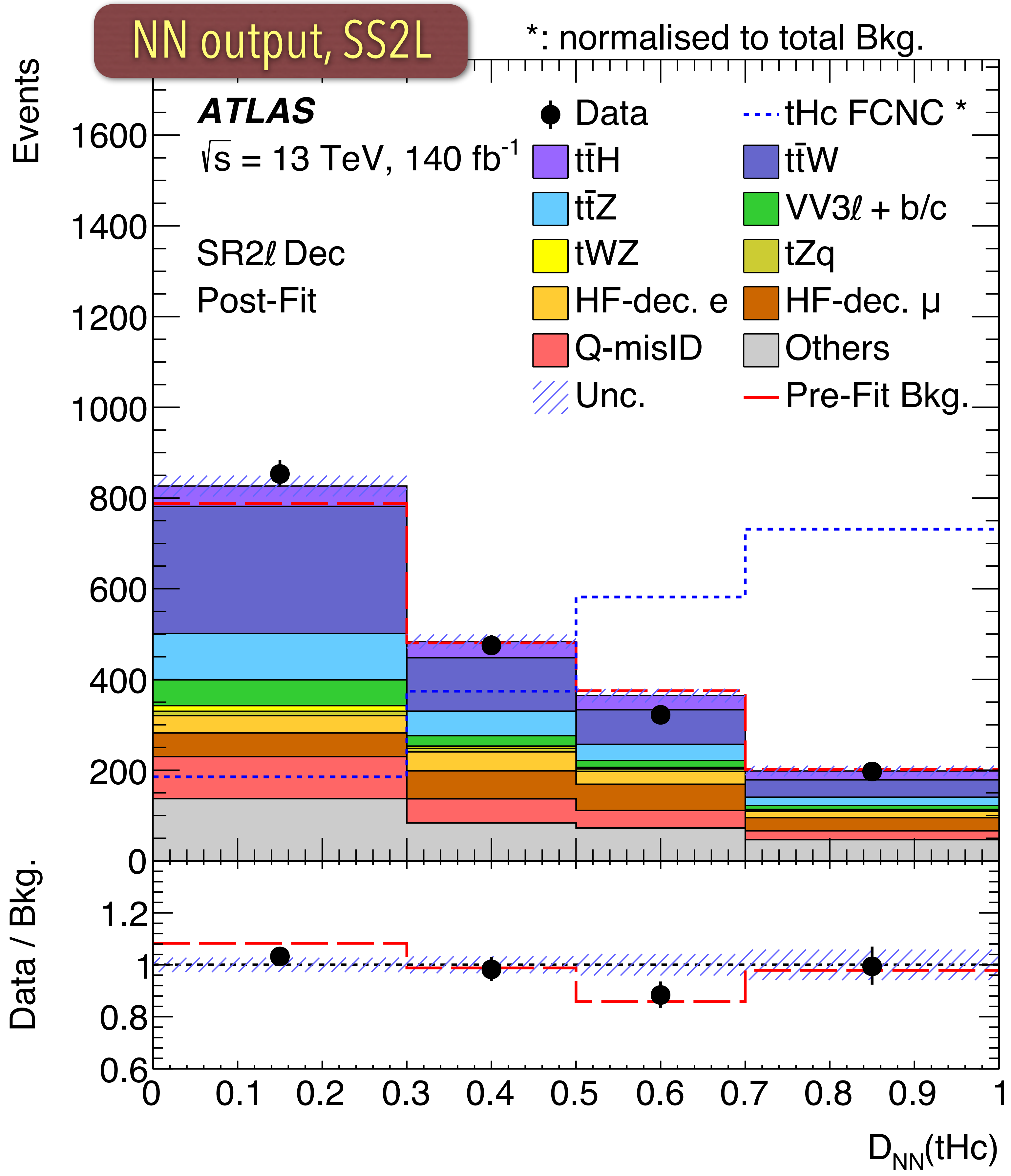
- Analysis conducted with **same-sign dilepton** or **trilepton** final states, covering $H \to ZZ^{(*)}$, $WW^{(*)}$, ττ decays.
- Both top pair or single tH productions are considered.
- Dedicated neural networks targeting production and decay to enhance significance. Output used in the signal extraction fitting.

This analysis

Observable	Obs. limit	Exp. limit
$\mathcal{B}(t \to u+H)$	2.8×10^{-4}	3.0×10^{-4}
$\mathcal{B}(t \to c+H)$	3.3×10^{-4}	3.8×10^{-4}

Combining with $H \to \gamma\gamma/bb/\tau\tau$

Observable	Obs. limit	Exp. limit
$\mathcal{B}(t \to u+H)$	2.6×10^{-4}	1.8×10^{-4}
$\mathcal{B}(t \to c+H)$	3.4×10^{-4}	2.3×10^{-4}

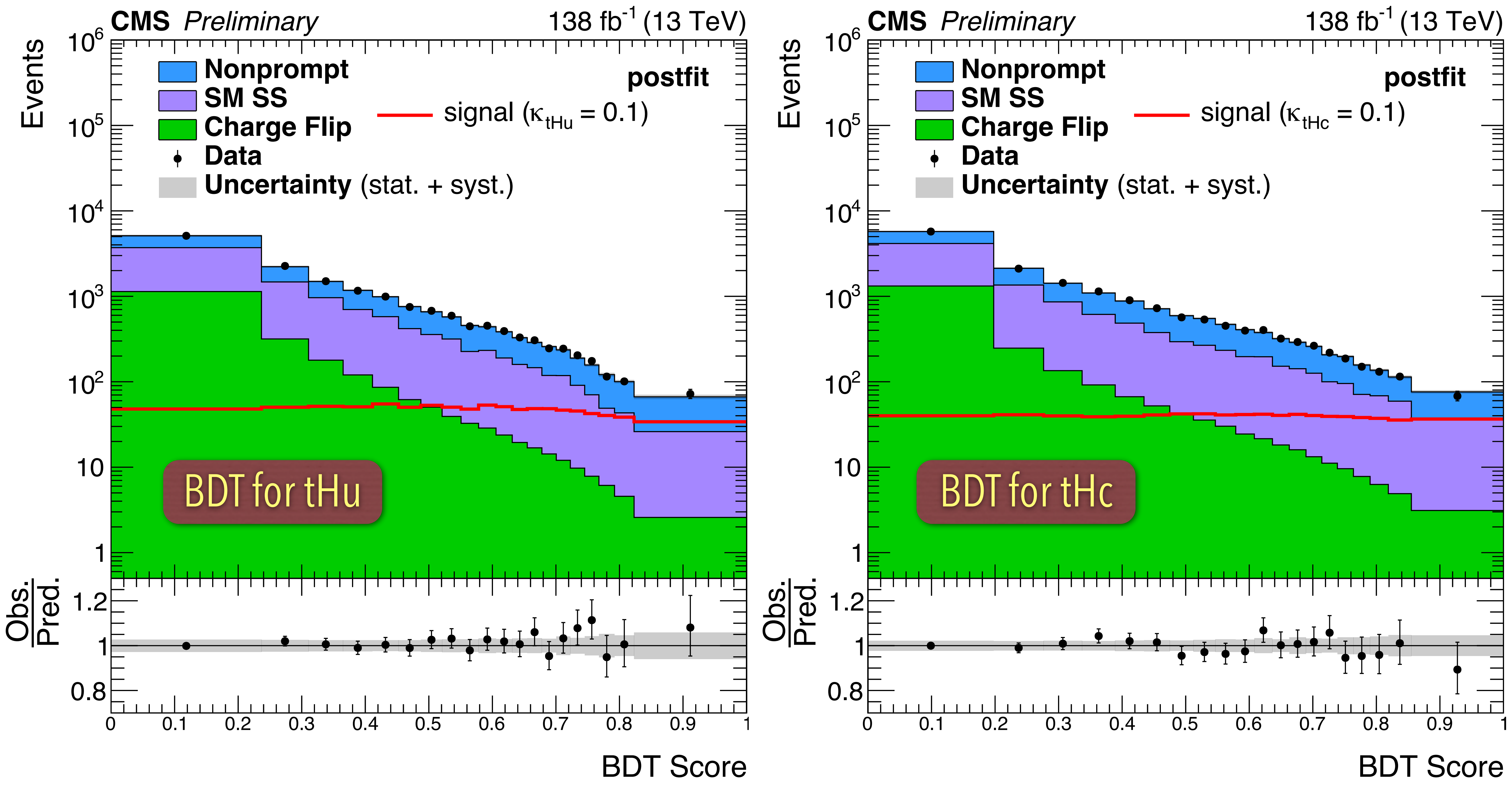


Ref. ATLAS arXiv:2404.02123 submitted to EPJC

CMS FCNC BETWEEN TOP & H(MULTILEPTONS)

Ref. CMS-PAS-TOP-22-002

- Exploit the **same-sign dilepton** (e,μ) + ≥1jet final state to cover $H\to ZZ^{(*)}$, $WW^{(*)}$, $\tau\tau$ decays.
- Both top pair and single top productions are considered too.
- Two separated BDTs, trained to identify the tuH and tcH signals, are introduced to evaluate and classify each event.



This analysis

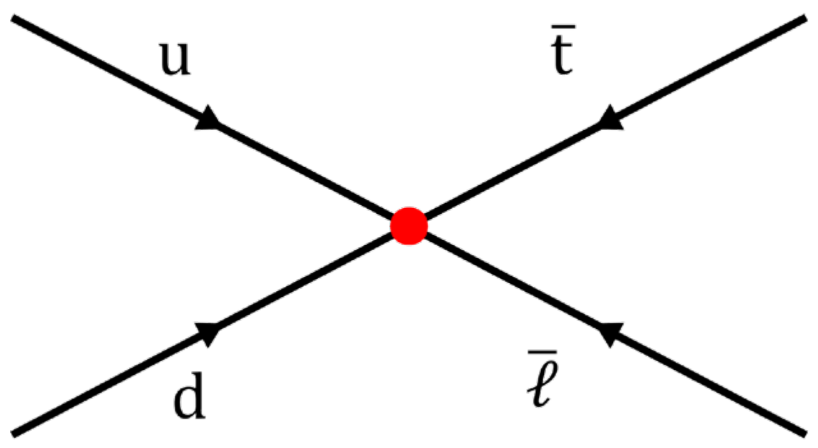
Observable	Obs. limit	Exp. limit
$\mathcal{B}(t\to u+H)$	**7.2×10^{-4}**	5.9×10^{-4}
$\mathcal{B}(t\to c+H)$	**4.3×10^{-4}**	6.2×10^{-4}

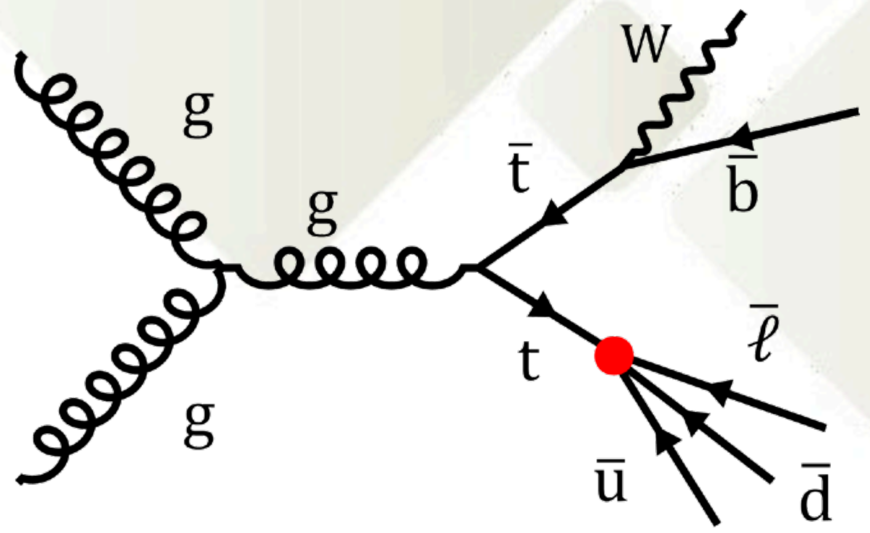
Combining with $H\to\gamma\gamma/bb/\tau\tau$

Observable	Obs. limit	Exp. limit
$\mathcal{B}(t\to u+H)$	**1.9×10^{-4}**	2.7×10^{-4}
$\mathcal{B}(t\to c+H)$	**3.7×10^{-4}**	3.5×10^{-4}

Comparable CMS & ATLAS limits on tcH/tuH couplings!

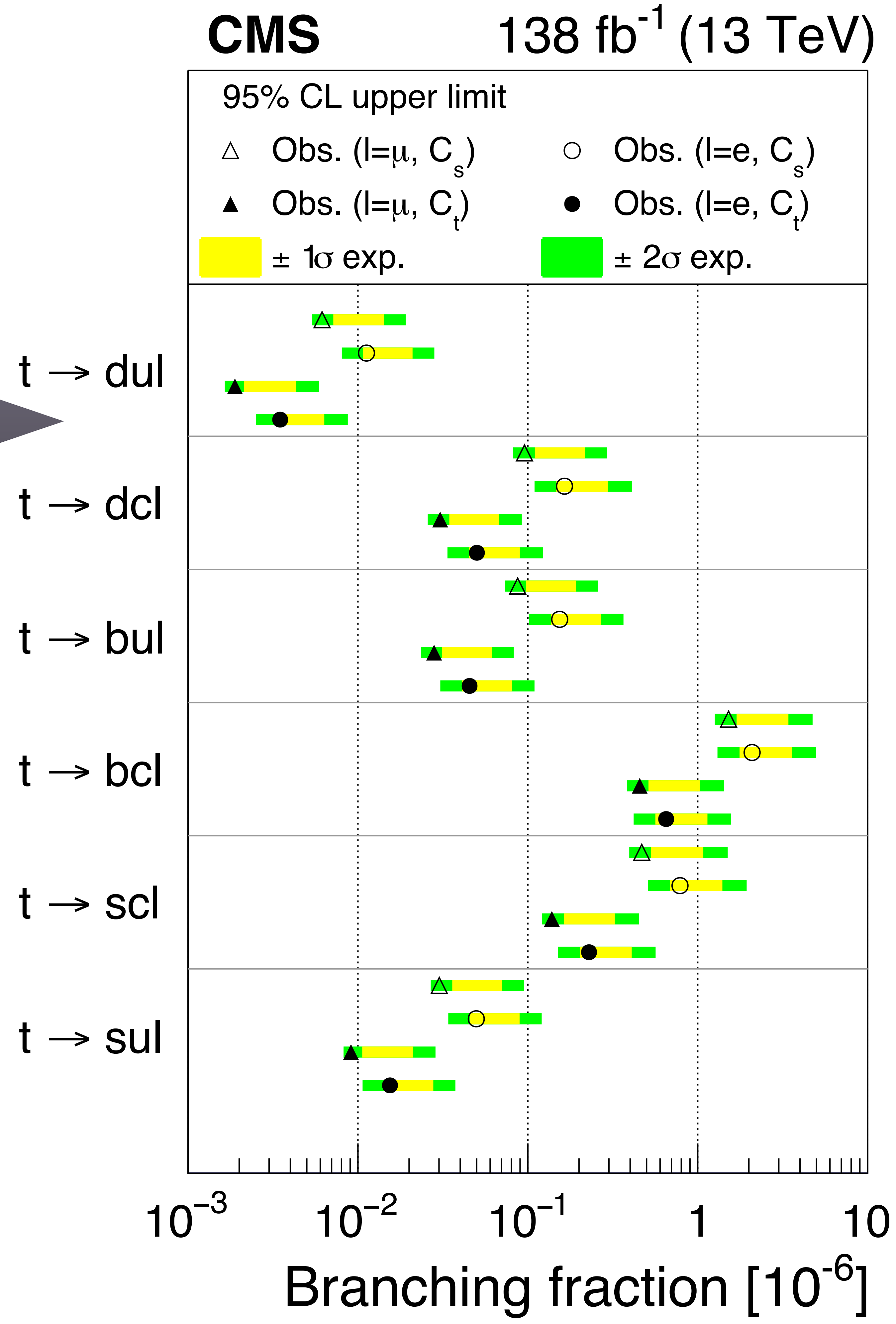
CMS SEARCH FOR TOP BARYON NUMBER VIOLATION

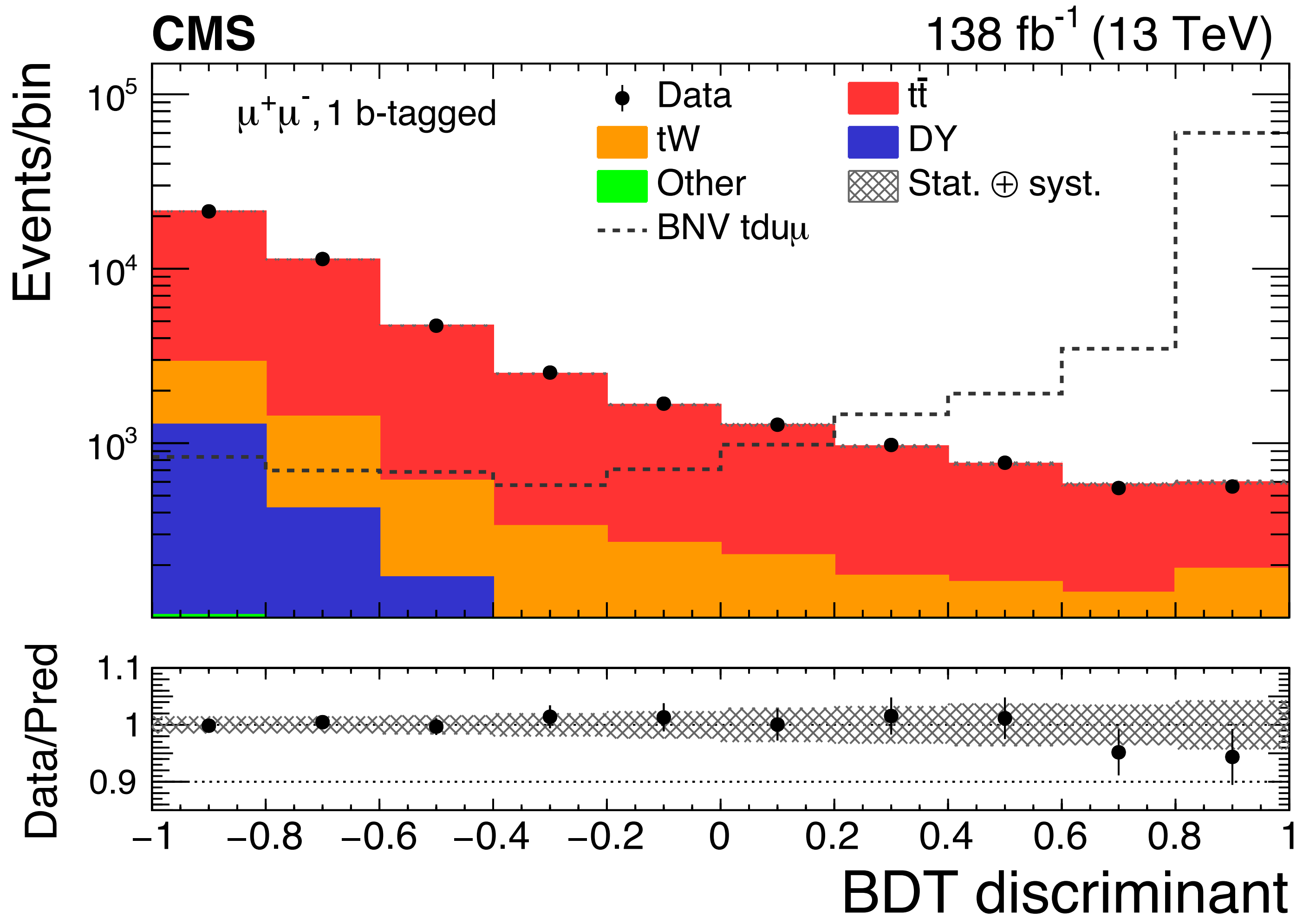


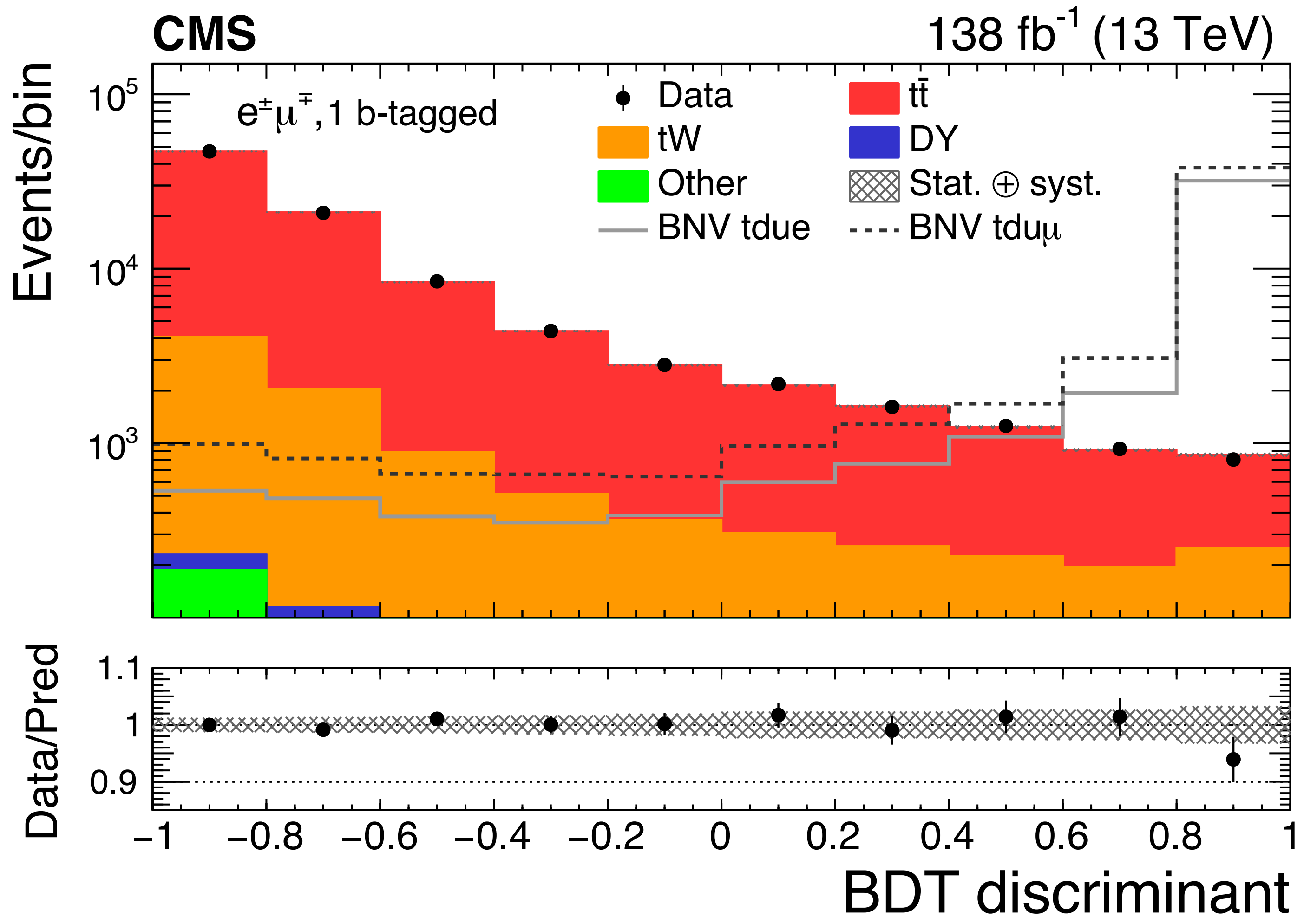


- **Baryon number violation (BNV)** is included in the BSM scenarios to provide a mechanism to explain the large matter-antimatter asymmetry in the universe.
- Possible search though top decay & production is feasible; select opposite-sign dilepton with one of the leptons from BNV interaction.
- BDT discriminators are trained and used in the ML fit for signal extraction.

Branching fraction limits very from 2×10^{-9} to 2×10^{-6}, depending on the couplings.



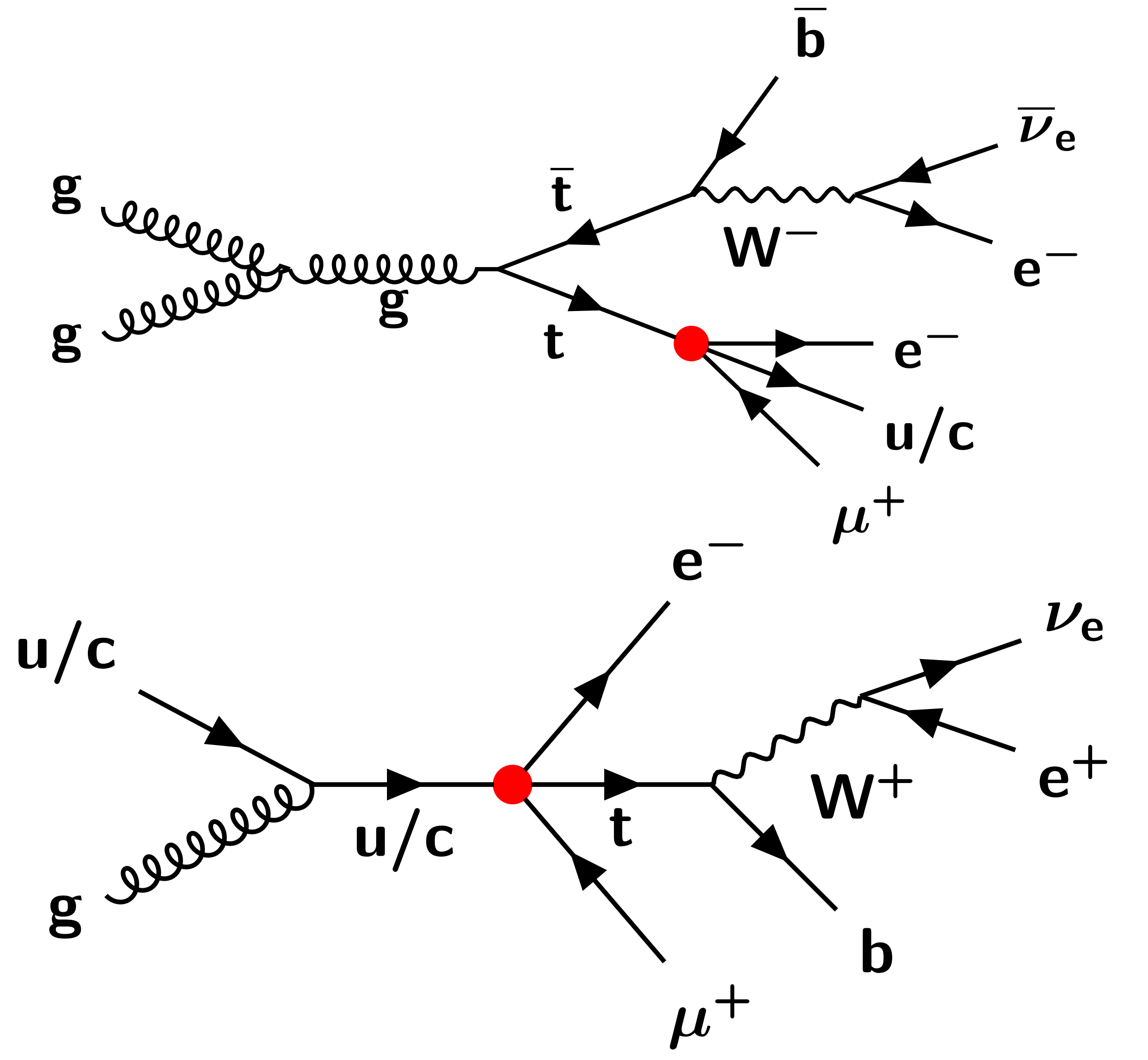


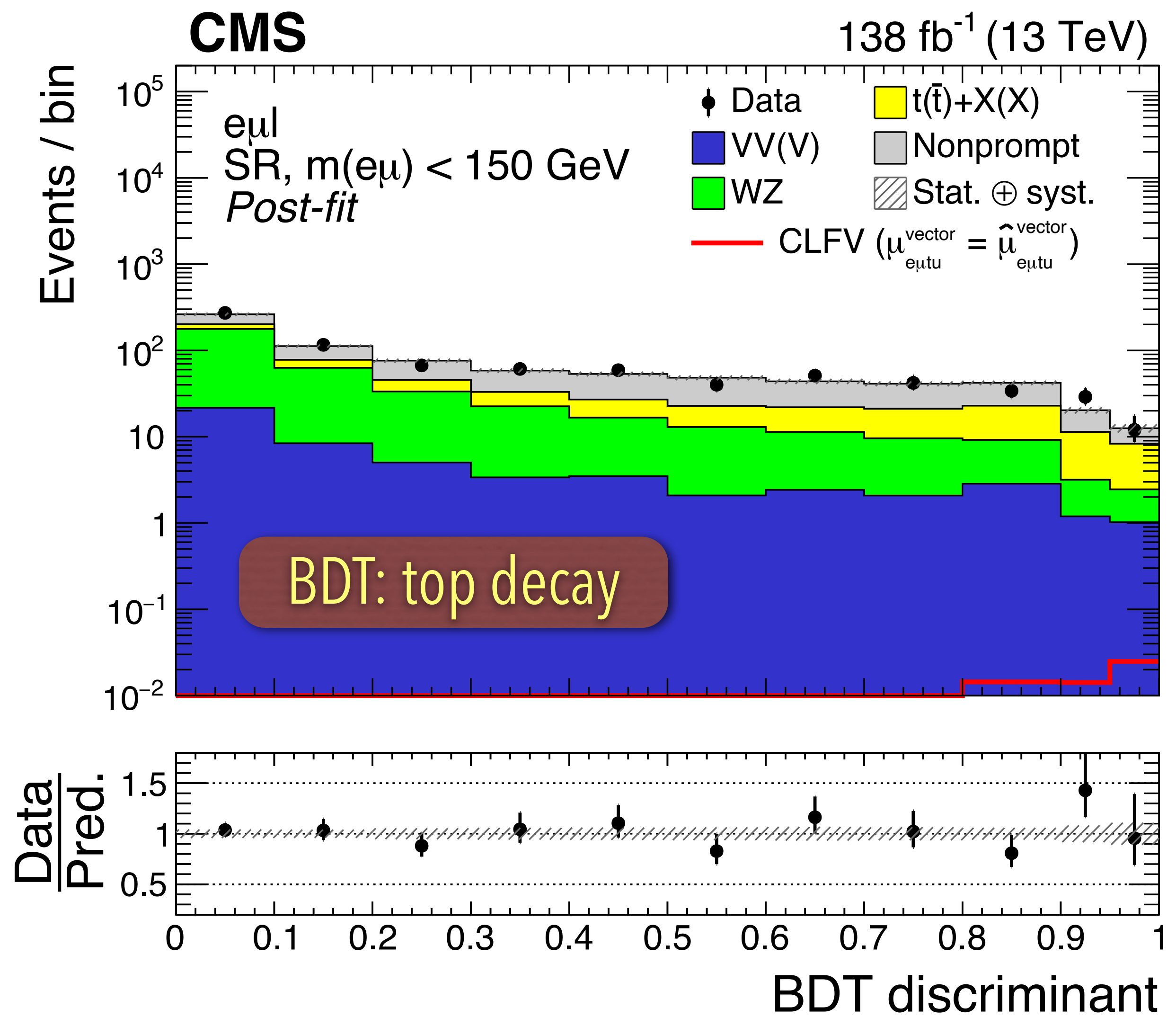


Ref. CMS arXiv:2402.18461 accepted by PRL

CMS TOP LEPTON FLAVOR VIOLATION: e-μ

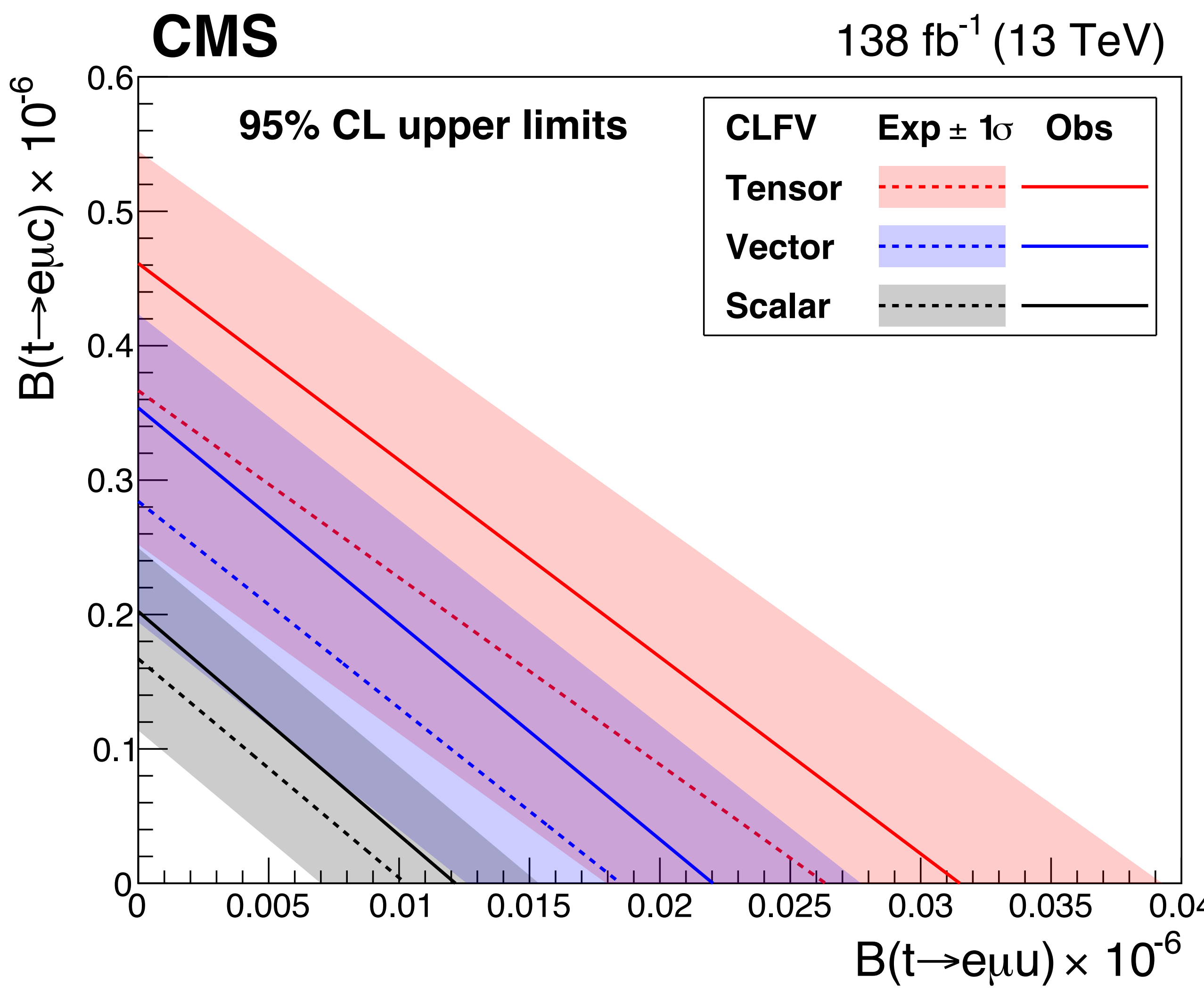
- Search for CLFV **eμtu** and **eμtc** interactions in decay and production, based on a very clean **3-lepton+jet** signature.
- BDT trained for each signal region.
- No significant excess is observed, limits extracted from fits to BDTs:

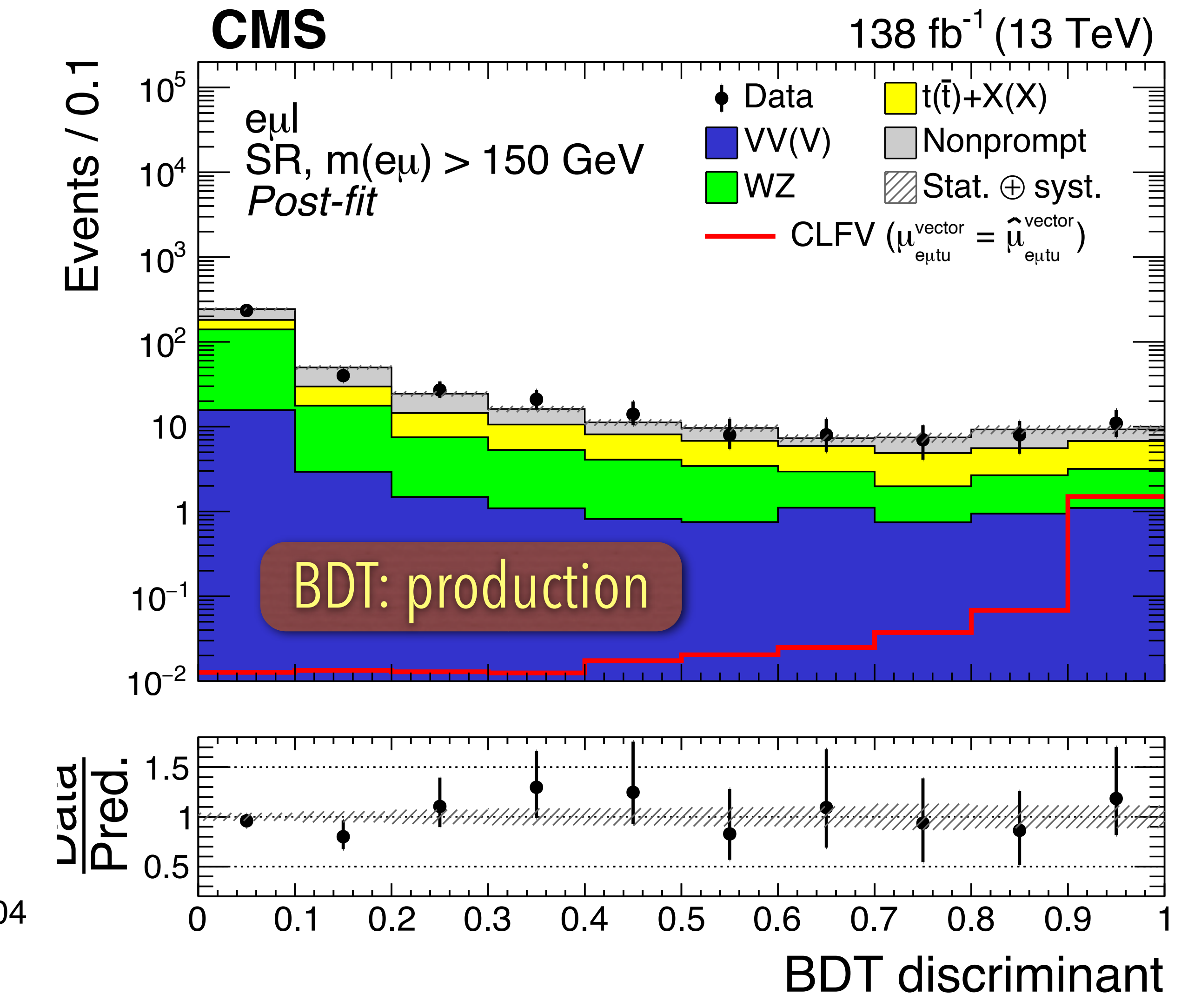




Ref. CMS arXiv:2312.03199, submitted to PRD

Coupling	Lorentz structure	Obs. limit
eμtu	tensor	3.2×10^{-8}
	vector	2.2×10^{-8}
	scalar	1.2×10^{-8}
eμtc	tensor	4.98×10^{-7}
	vector	3.69×10^{-7}
	scalar	2.16×10^{-7}

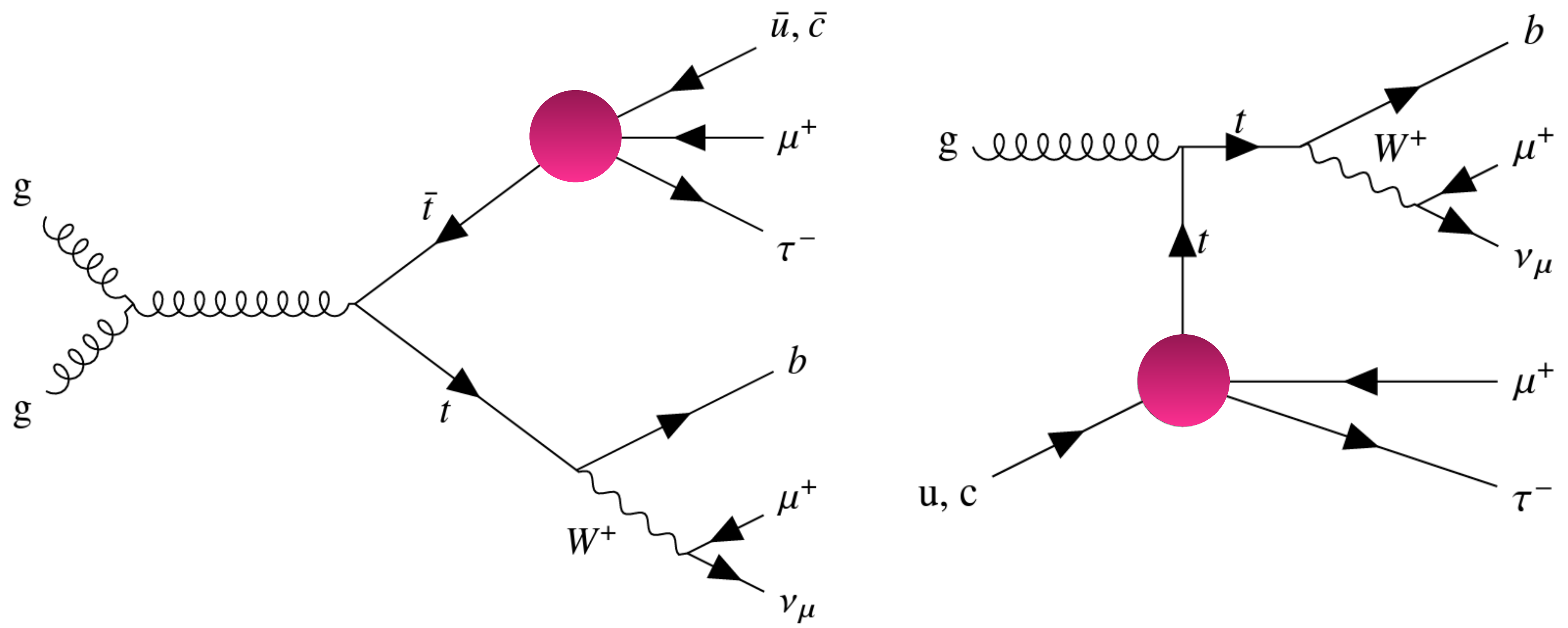




Most stringent limits on t→eμq to date!

ATLAS TOP LEPTON FLAVOR VIOLATION: μ-τ

- Search for CLFV in **μτqt** (q=u,c) interactions, in both decay and production with an event signature of **same-sign 2μ + 1 hadronic τ + 1 b-jet**.
- The signal in the SR is estimated with a binned profile-likelihood fit to the HT, with CR included for background normalisation determination.
- **No signal excess found** – upper limits are derived for the decay branching fractions & corresponding Wilson coefficients.



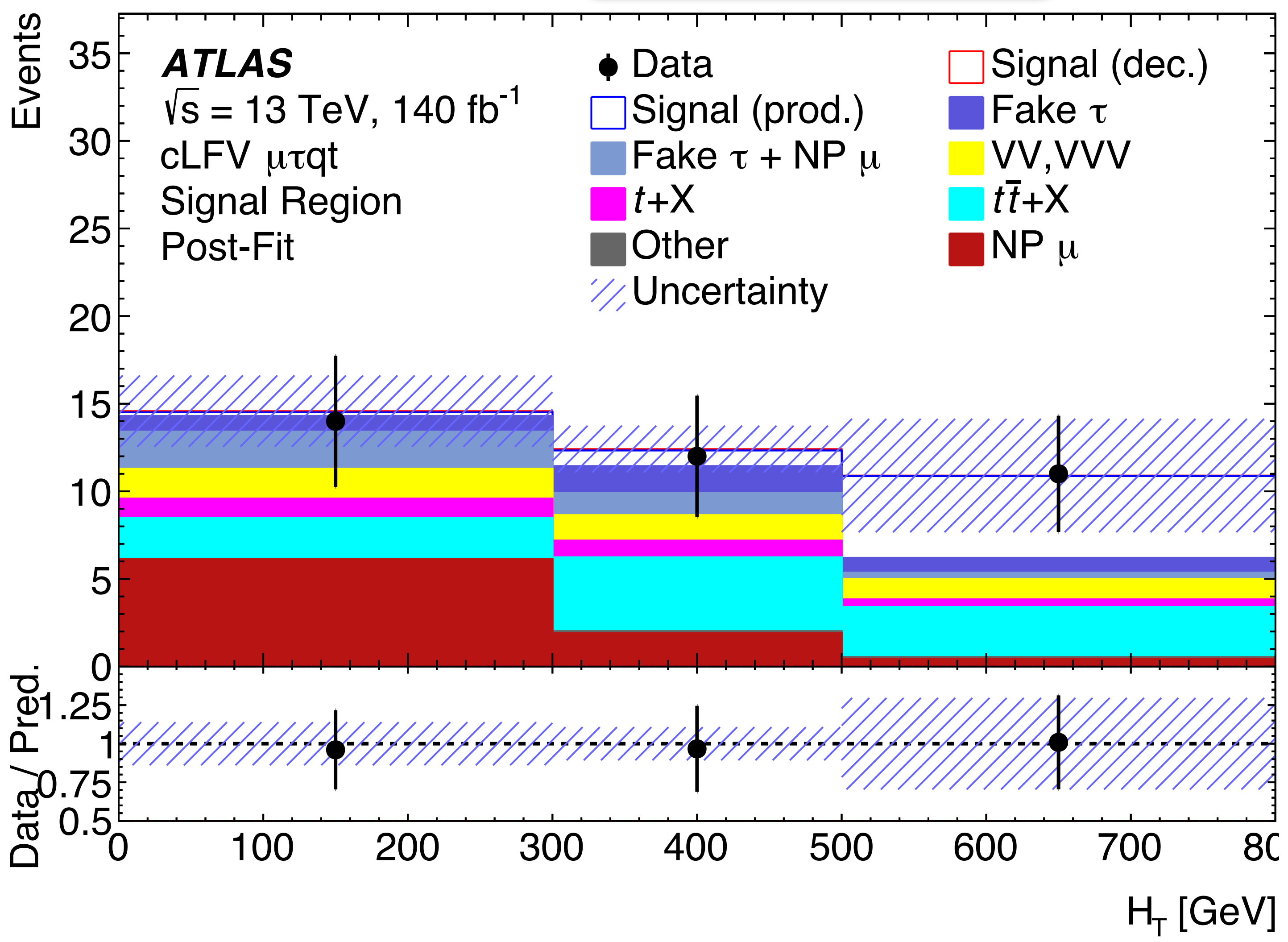
Ref. ATLAS arXiv:2403.06742, submitted to PRD

Observed: $\mathcal{B}(t \to \mu\tau q) < 8.7 \times 10^{-7}$

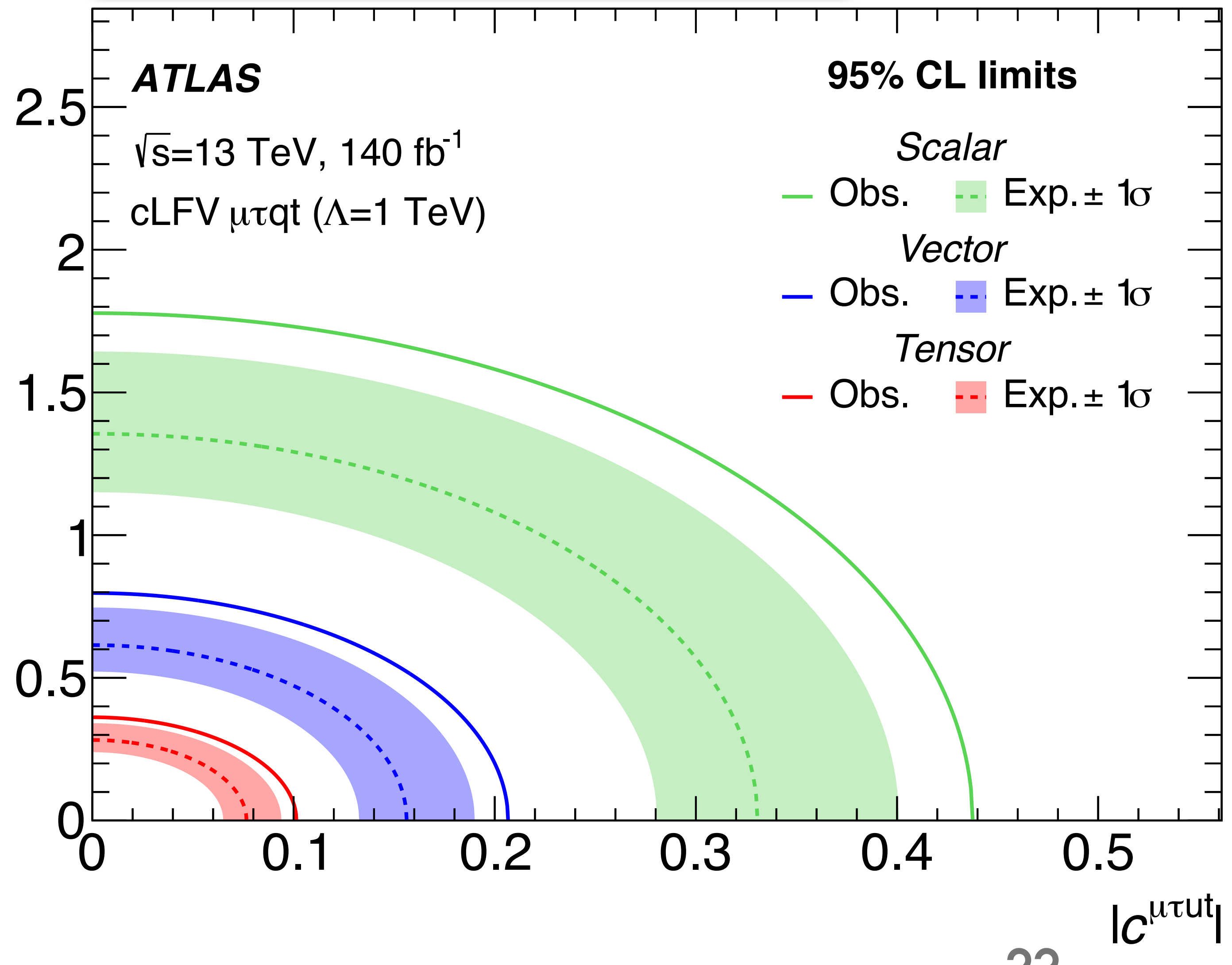
Expected: $\mathcal{B}(t \to \mu\tau q) < 5.0 \times 10^{-7}$

Complement to the CLFV in eμqt searches!

Postfit H_T in SR

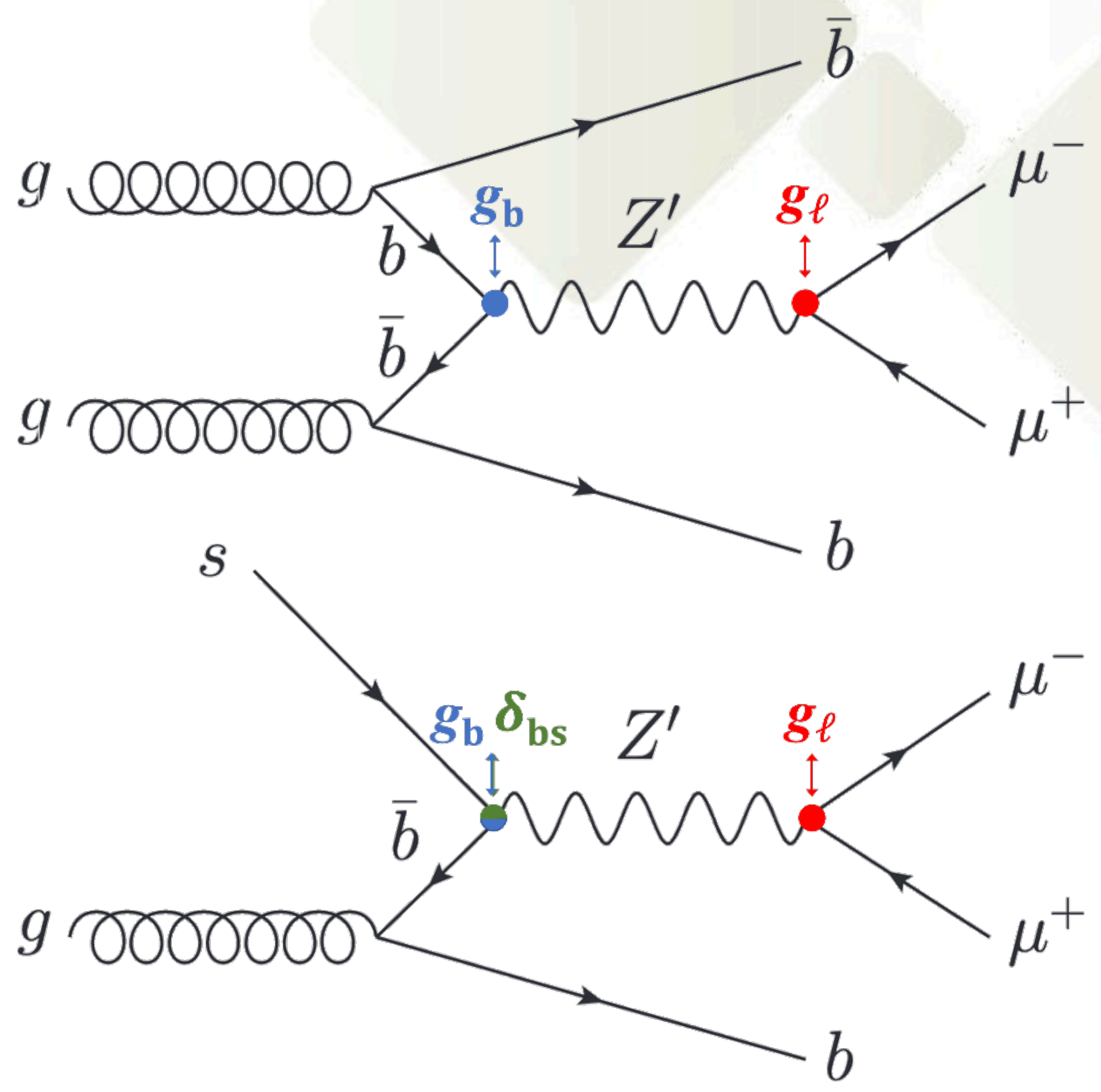


Limits on Wilson coefficients



LEPTON FLAVOR UNIVERSALITY AT HIGH PT

Ref. CMS JHEP 10 (2023) 043

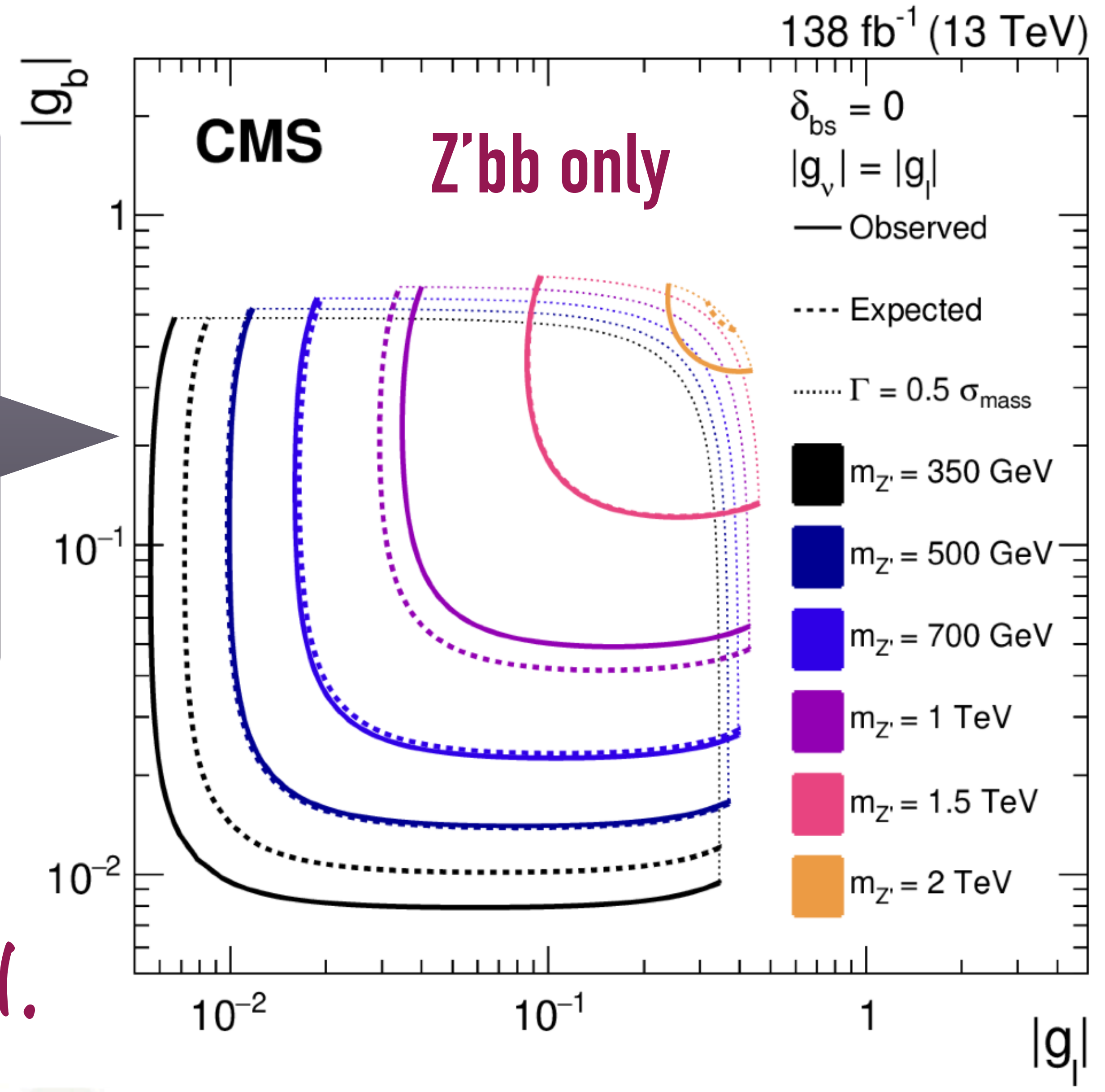


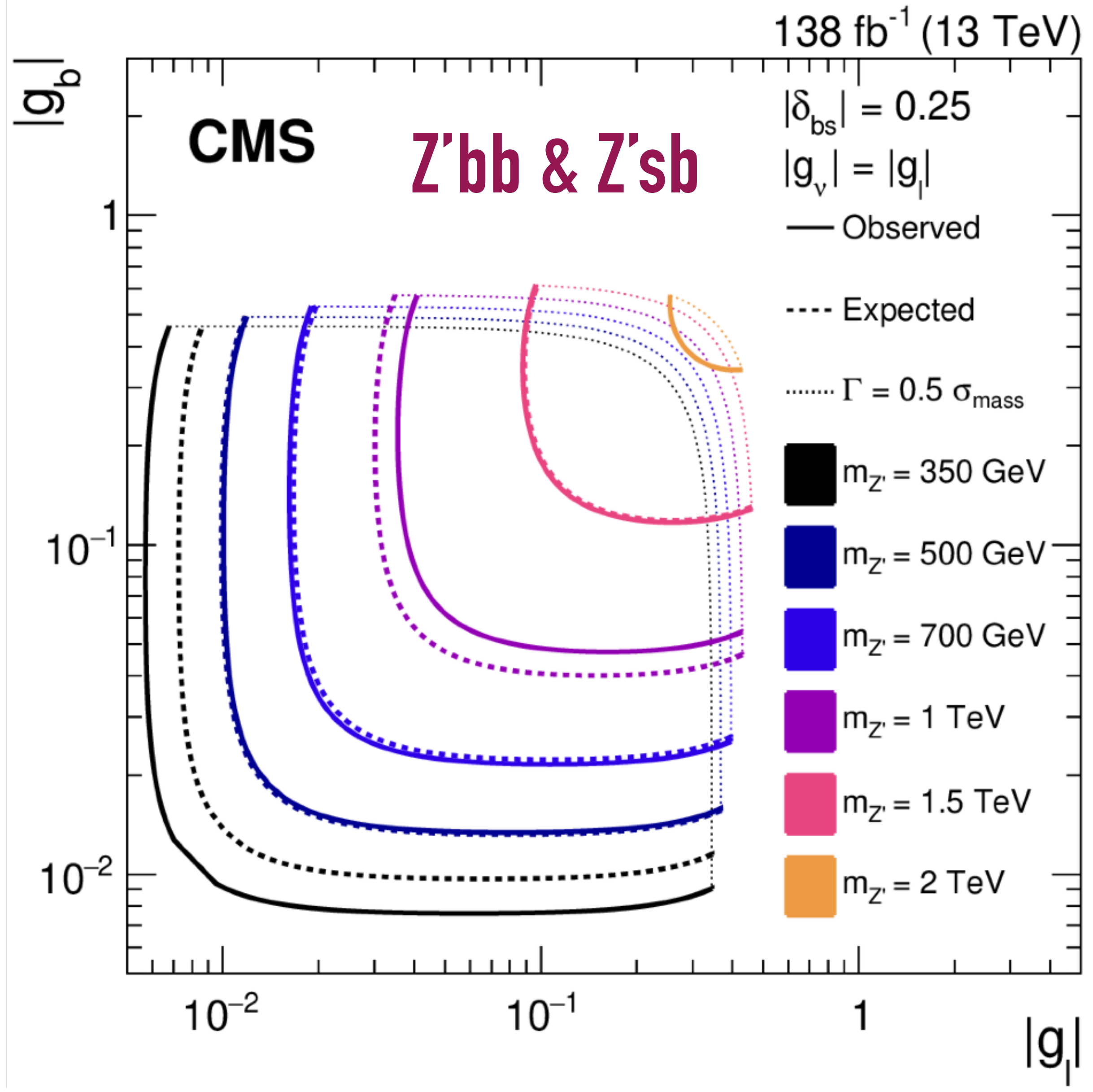
- **Probing b→sℓℓ transitions assuming a Z' near TeV scale!**
- Look for a narrow Z'→μ⁺μ⁻ (>350 GeV) plus at least one b-jet with 138 fb^{-1} data collected at 13 TeV.
- Events are categorized according to # of b-jets and the constraints are set on a simplified lepton-flavor-universal (LFU) model:

$$\mathscr{L} = Z'_\eta \left\{ g_\ell \sum \bar{\ell}\gamma^\eta P_L \ell + g_\nu \sum \bar{\nu}\gamma^\eta P_L \nu + g_b \left[\bar{b}\gamma^\eta P_L b + \delta_{bs}(\bar{s}\gamma^\eta P_b b + \mathrm{h.c.}) \right] \right\}$$

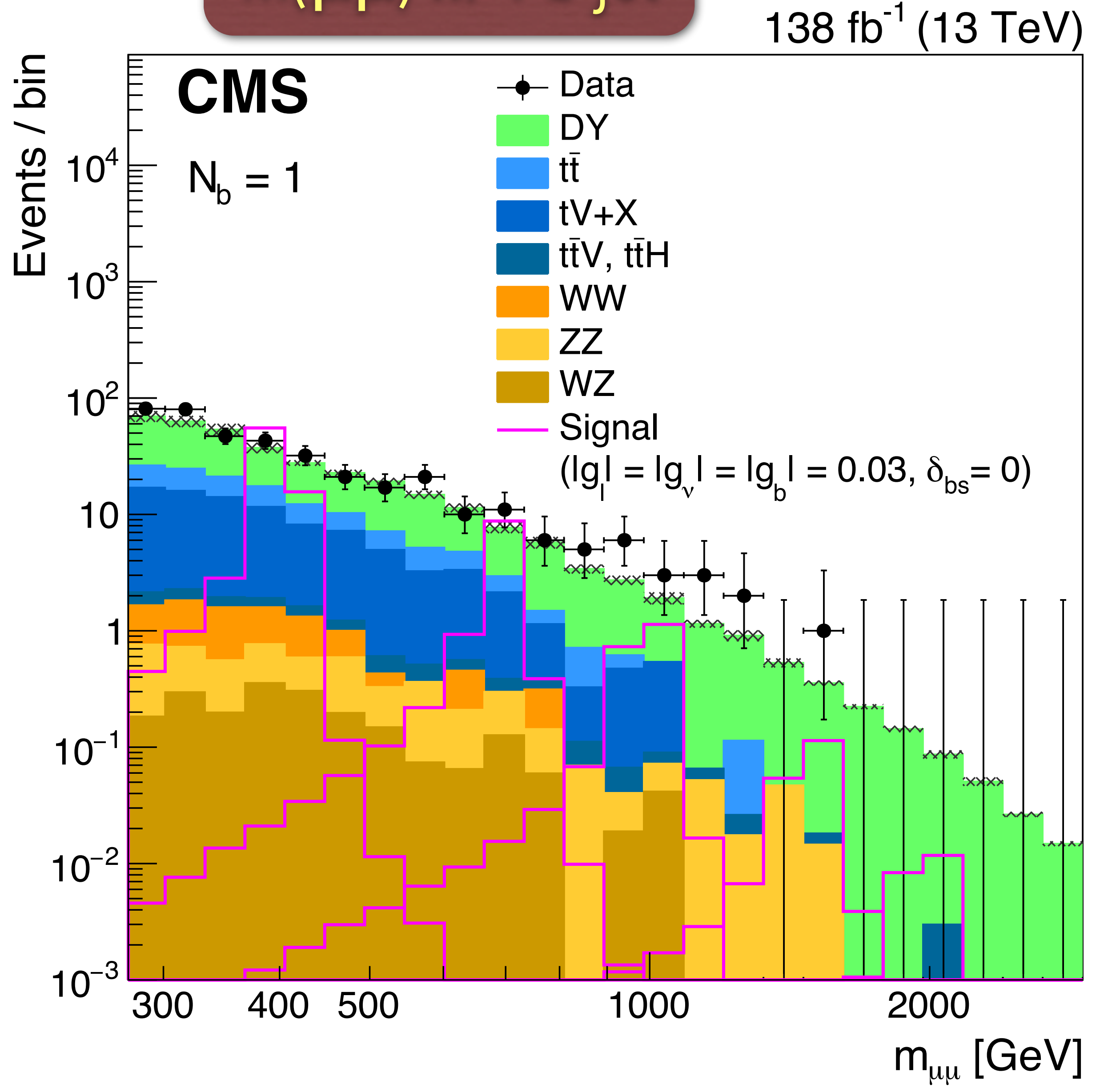
Depending on Z' mass – limits on Z' couplings to lepton(=neutrino), and to b(s) are set.

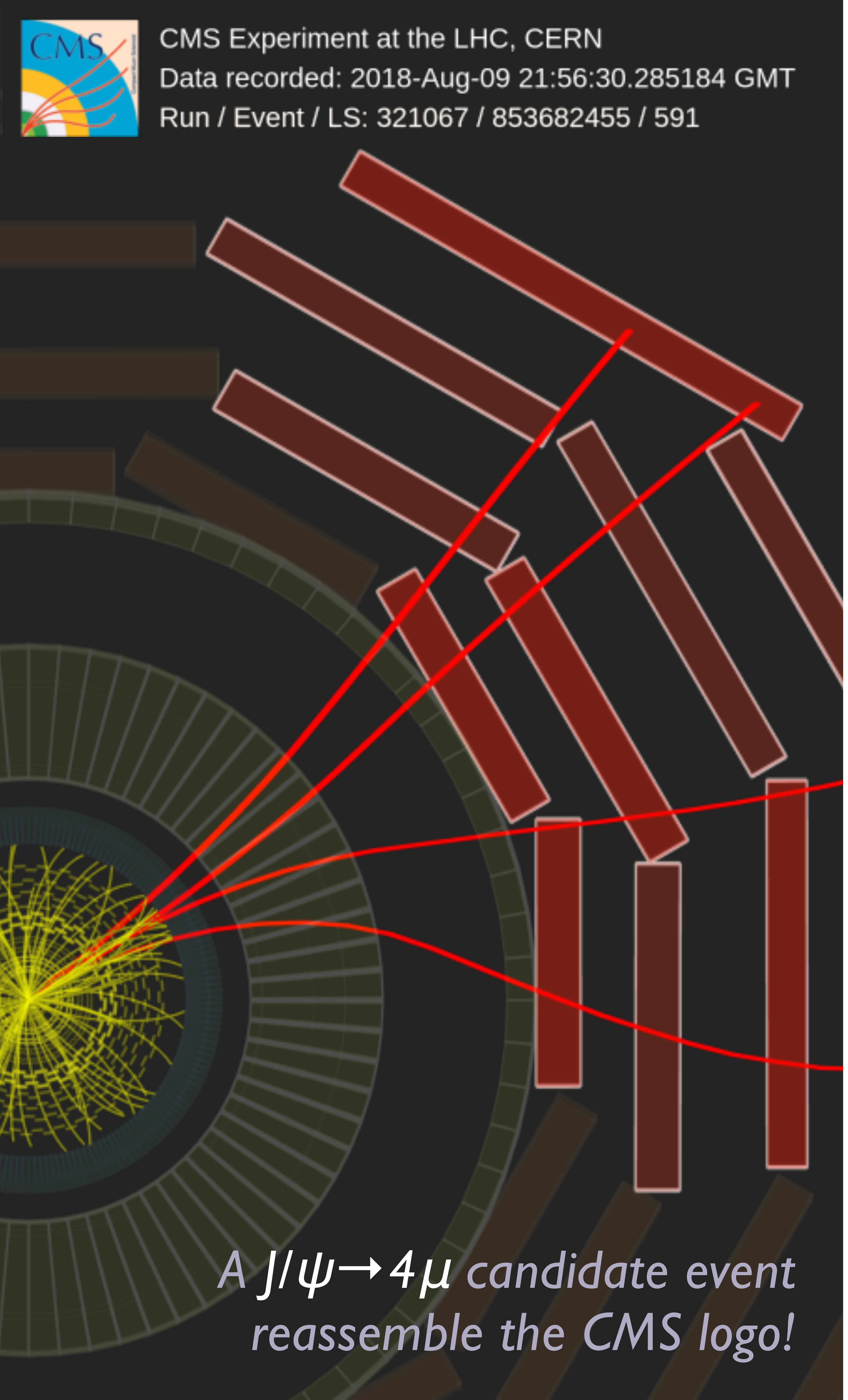
Also with the interpretations in a flavored B3-L2 model.





m(μμ) w/ 1 b-jet





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

SUMMARY

Looking for rare decays is an indirect probe for the physics beyond the SM! This is the place we should dig in if no observation of new heavy particles at the direct searches.

- Very rare B mesons or τ leptons decays have been probed by LHC experiments; results are consistent with the SM so far.
- Extended trigger capabilities allow the discovery of $\eta \to 4\mu$ & $J/\psi \to 4\mu$ decays.
- With large production cross sections of top, the searches for top rare decays are feasible; Limits on the branching fractions of $O(10^{-6})$ or even smaller have been derived.
- Possible to test lepton flavor violation with high p_T searches as well!

Stay tuned for upcoming Run-3 results, and maybe even a discovery in the near future!


BACKUP