April Flavor/Collider Workshop, April 2-3, 2019

$B \to \mu^+\mu^-$ & Top CPV

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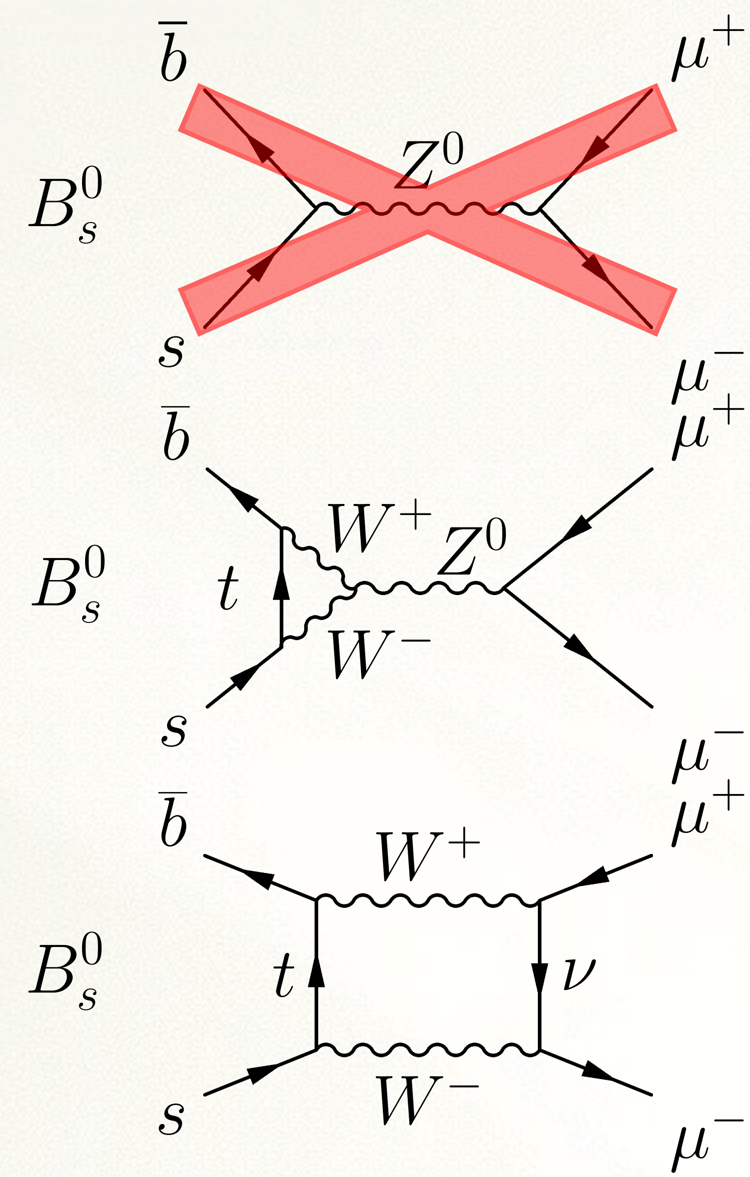
Measurement of $B_{s,d} \to \mu^+\mu^-$

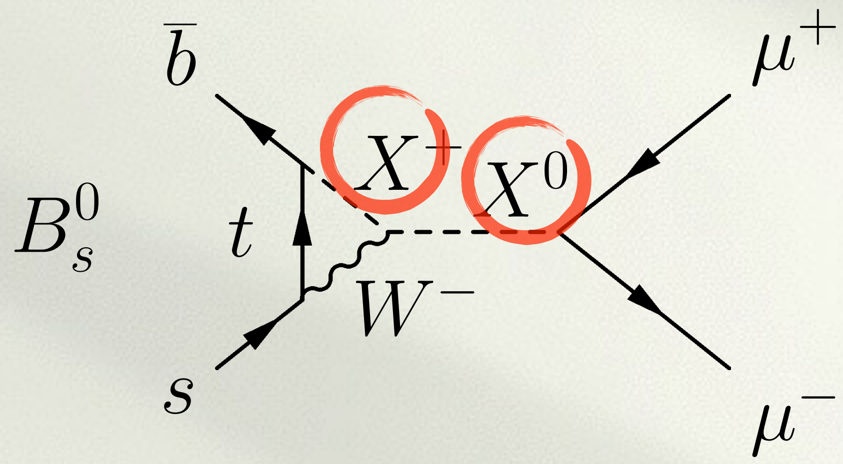
- **$B\to\mu\mu$** is one of the most typical/ important searches for rare bottom decays!
- $B\to\mu\mu$ are <u>highly suppressed</u> in SM:
  - FCNC processes, only proceed through Z-pengiun, and box diagrams (suppressed by $[m_W/mt]^2$).
  - Cabibbo suppressed: $|V_{tq}|^2$
  - Helicity suppressed: $[m_\mu/m_B]^2$
- Resulting **tiny branching fractions**, but rather *robust*:



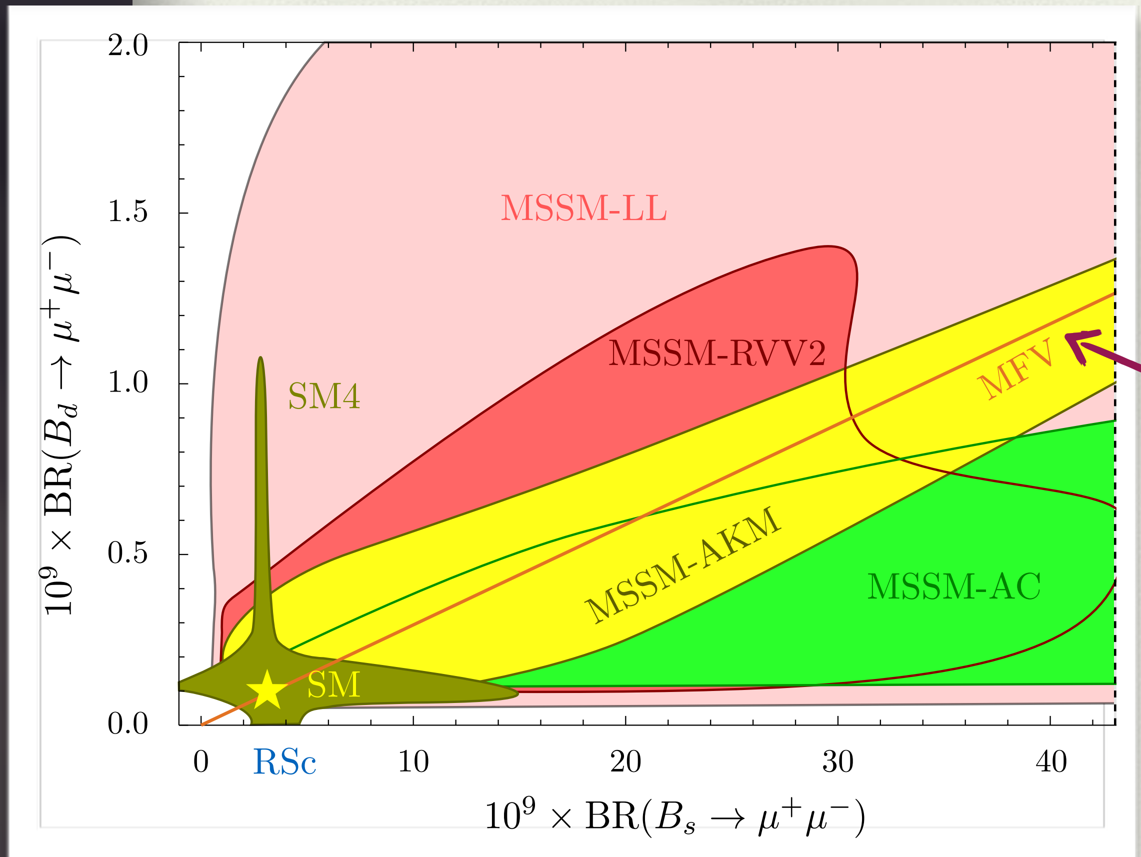
$$\mathcal{B}(B_s\to\mu^+\mu^-) = (3.57 \pm 0.17)\times10^{-9}$$
$$\mathcal{B}(B_d\to\mu^+\mu^-) = (1.06 \pm 0.09)\times10^{-10}$$

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

Measurement of $B_{s,d} \to \mu^+\mu^-$ (cont.)



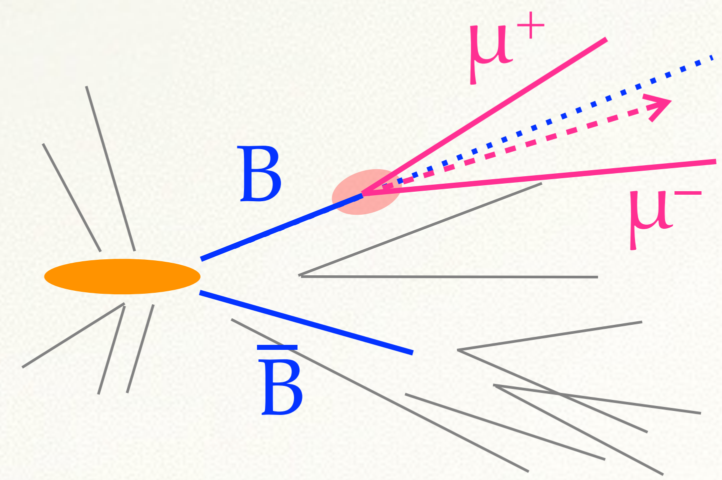
Ref: D. M. Straub, arXiv: 1012.3893



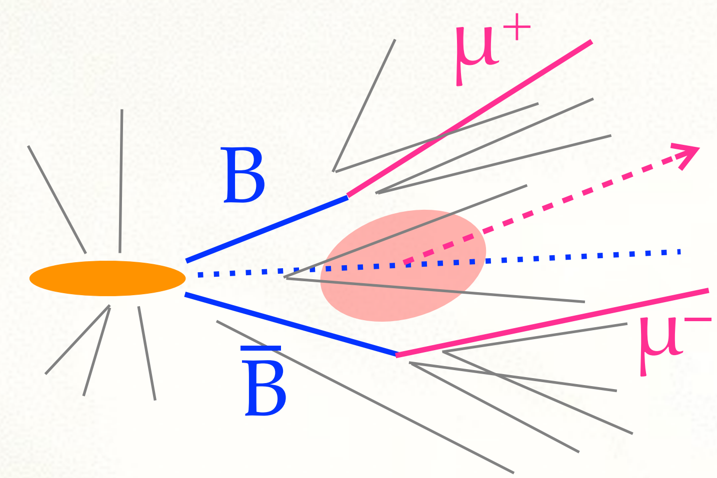
- Loop diagram + Suppressed SM + Theoretically clean = ***An excellent place to look for new physics*** (*or, constraining NP parameter space instead!*).
- Some of the new physics scenarios may boost the $B \to \mu\mu$ decay rates easily, for example:
  - **2HDM:** $\mathcal{B} \propto \tan^4\beta$ & $m(H^+)$
  - **MSSM:** $\mathcal{B} \propto \tan^6\beta$
- **B_s/B_d ratio** – a stringent test of minimal flavor violation (MFV) hypothesis.
- Light and heavy B_s eigenstates are characterised by a large $\Delta\Gamma$; only the heavy state can decay into dimuon in the SM. ***Different effective lifetime is allowed in BSM.***

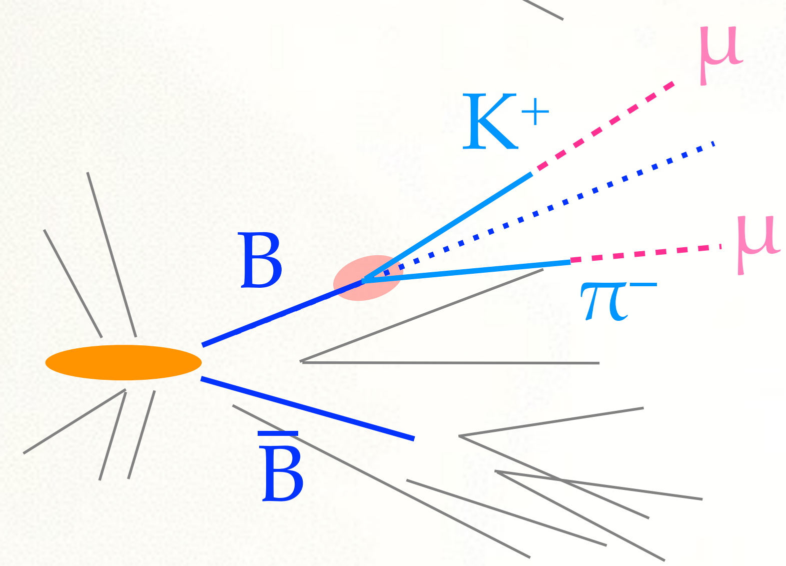
Analysis Aspects

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



- **Background sources**
  - two semileptonic B decays
  - one semileptonic B + a misidentified hadron
  - rare background from single B meson decays: e.g. **$B \to K\pi/KK$** *(peaking)*, **$B_s \to K^-\mu^+\upsilon$**, **$\Lambda_b \to p\mu\upsilon$** *(not peaking)*





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

Analysis Aspects (2)

- Machine learning algorithms (*mostly BDT nowadays*) are introduced to suppress combinatorial background as well as misidentified muons from charged hadrons.
- Calibrations/validations with $B^+ \to J/\psi K^+$, $B^0 \to K^- \pi^+$ and $B_s \to J/\psi \phi$.
- Normalized to the reference channel $B^+ \to J/\psi(\to \mu^+\mu^-) K^+$ (LHCb also takes $B^0 \to K\pi$ as normalization):

$$\mathcal{B}(B_{s,d} \to \mu^+\mu^-) = \frac{N_S}{N(B^\pm \to J/\psi K^\pm)} \times \mathcal{B}(B^\pm \to J/\psi K^\pm) \times \frac{A(B^\pm)}{A(B_s)} \frac{\varepsilon^{ana}(B^\pm)}{\varepsilon^{ana}(B_s)} \frac{\varepsilon^{\mu}(B^\pm)}{\varepsilon^{\mu}(B_s)} \frac{\varepsilon^{trig}(B^\pm)}{\varepsilon^{trig}(B_s)} \frac{f_u}{f_s}$$

Acceptance

Selection efficiency

muon identification

Trigger efficiency

B-hadronization composition, for B_s only (LHCb+ATLAS average: 0.250±0.012)

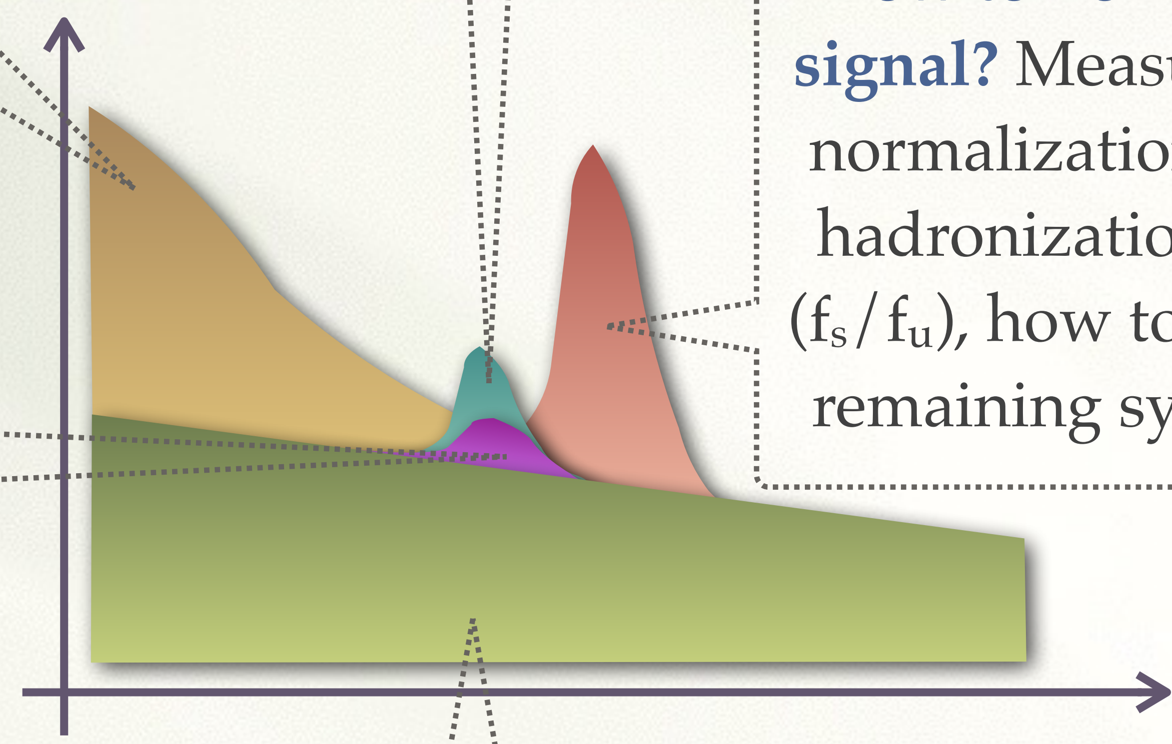
Similar **trigger & selection** for reducing systematics

(Many) Analysis Issues

$B_{s,d} \to \mu^+\mu^-$ is a **SM measurement** after observation!

How to **model the major semileptonic background** channels, and their mass distributions and decay branching fractions?

Mass position and resolution of two nearby signal peaks



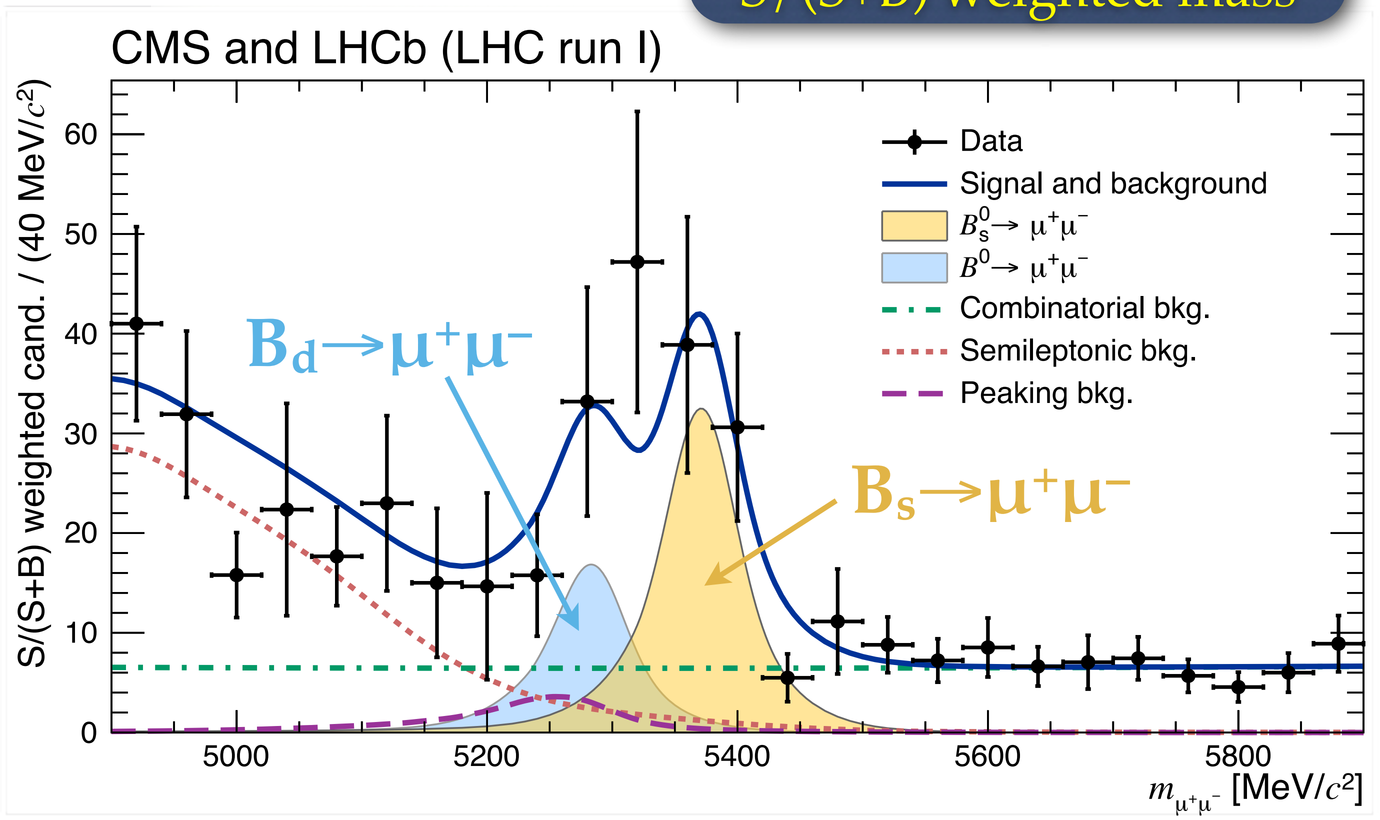
How to normalize the signal? Measurement of normalization channel, hadronization fraction (f_s / f_u), how to cancel the remaining systematics.

How to **control the peaking background** from rare 2-body B decays; how to calibrate the fake rate of muon ID with data; potential trigger performance difference between signal and background muon pairs.

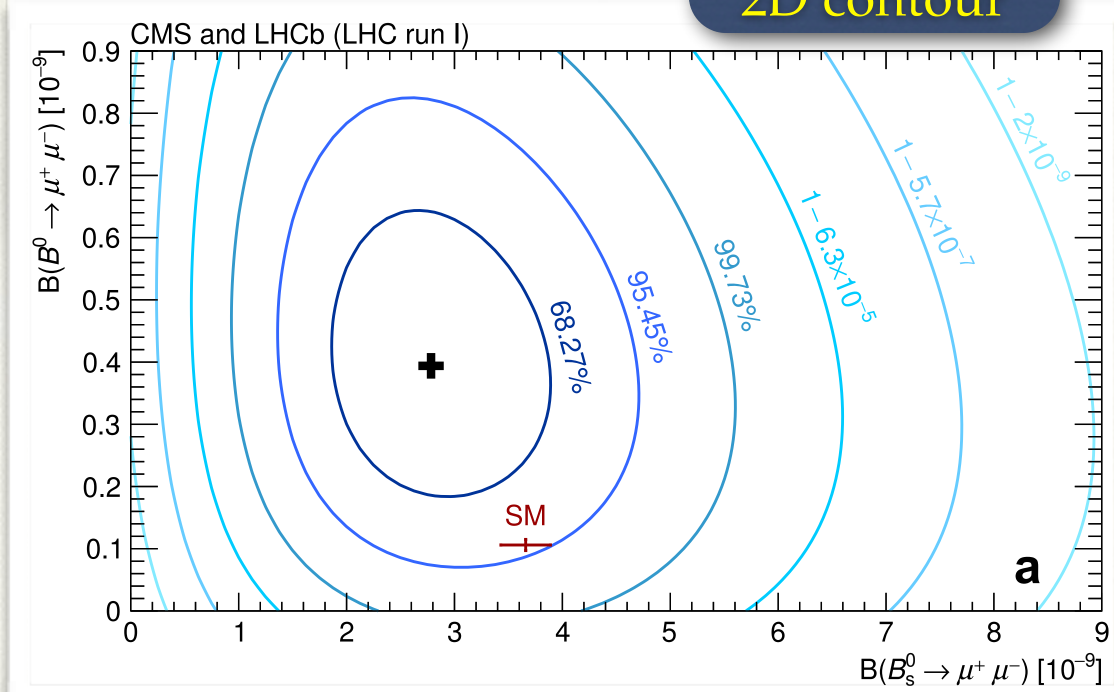
How to reduce the dominant background from combinatorics; how to verify the MVA/BDT performance with data.

CMS+LHCb Run-1 Combination

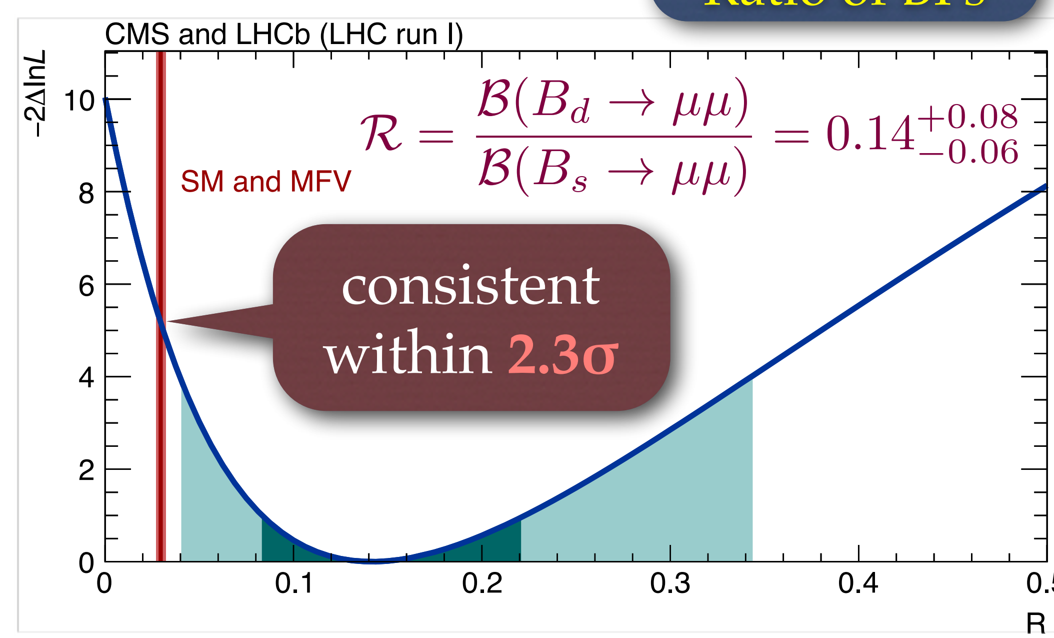
S/(S+B) weighted mass



2D contour



Ratio of BFs



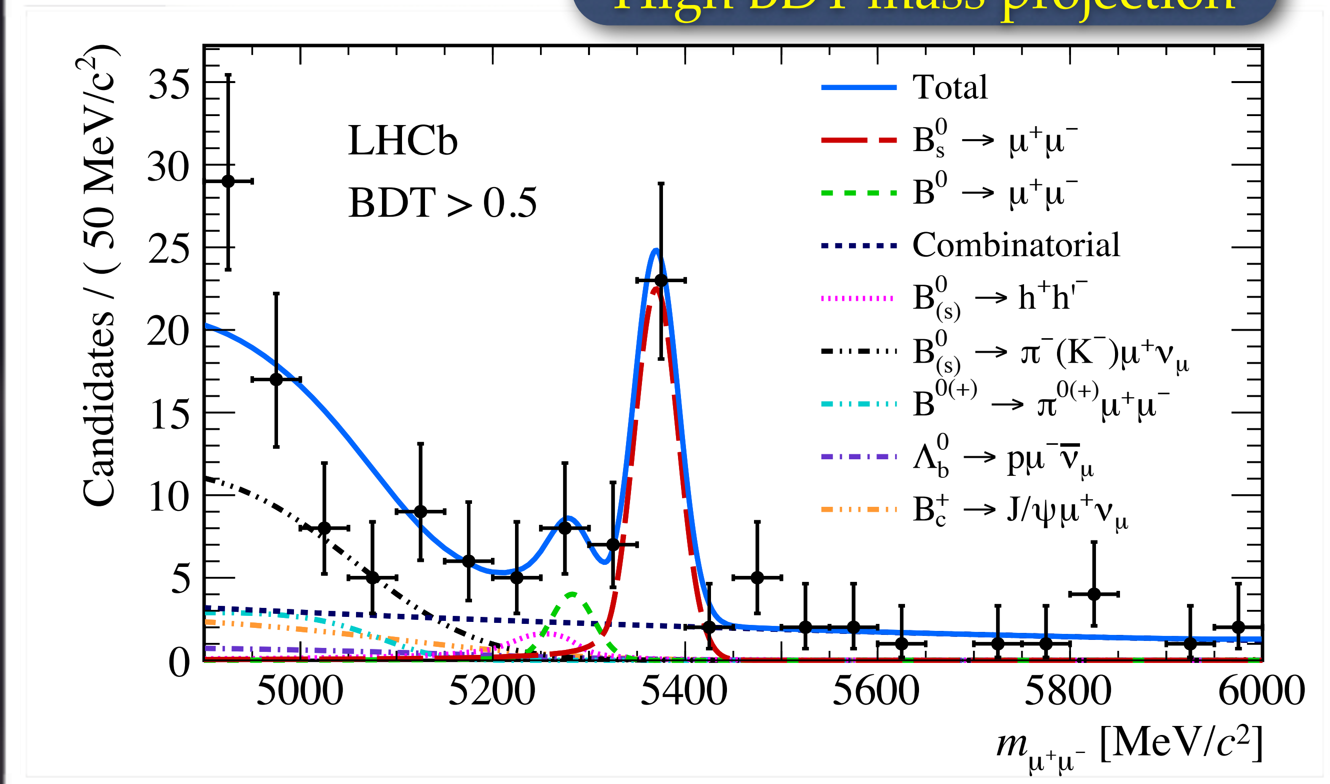
Ref: Nature 522, 68-72

Channel	Branching fraction	Signif.
$B_s \to \mu^+\mu^-$	$(2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$	6.2σ [7.4σ]
$B_d \to \mu^+\mu^-$	$(3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$	3.2σ [0.8σ]

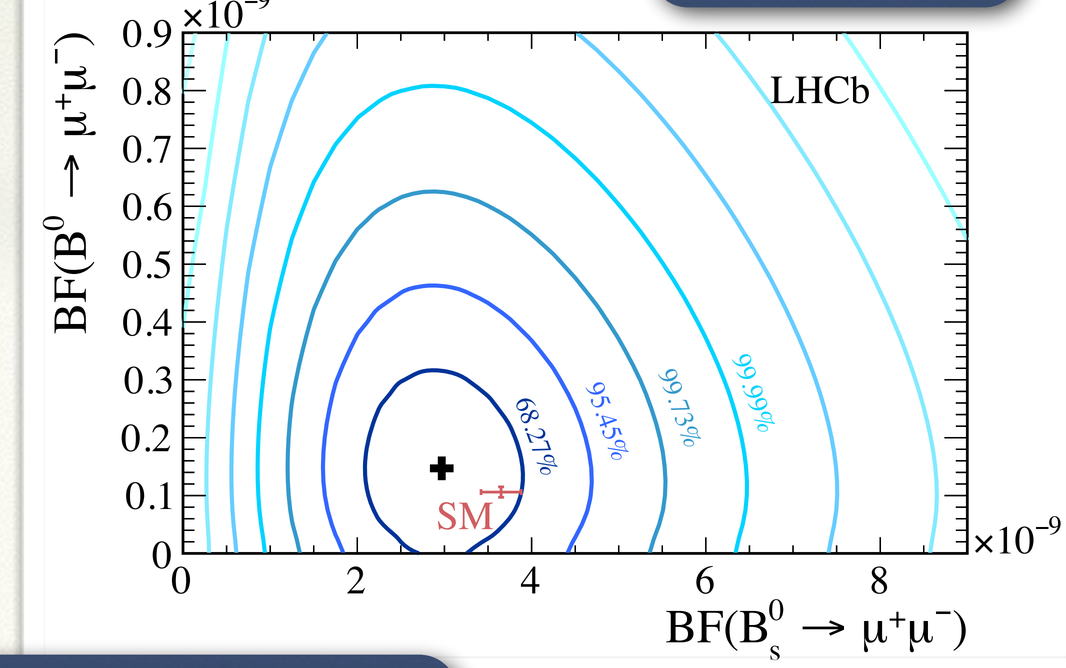
Expected significances are estimated with SM branching fractions.

LHCb Run 1+2$^{(partial)}$ Results

High BDT mass projection



2D contour

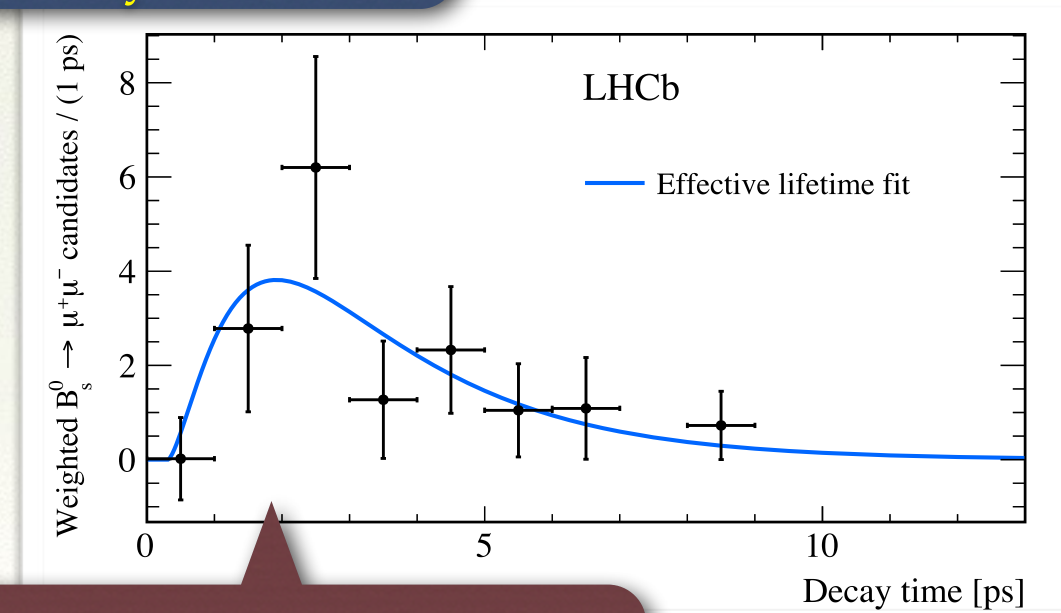


Ref: LHCb PRL 118, 191801 (2017)

Channel	Branching fraction	Signif.
$B_s \to \mu^+\mu^-$	$(3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$	7.8σ
$B_d \to \mu^+\mu^-$	$(1.5^{+1.2}_{-1.0}) \times 10^{-10}$	1.6σ

$[\mathcal{B}(B_d \to \mu^+\mu^-) < 3.4 \times 10^{-10}]$

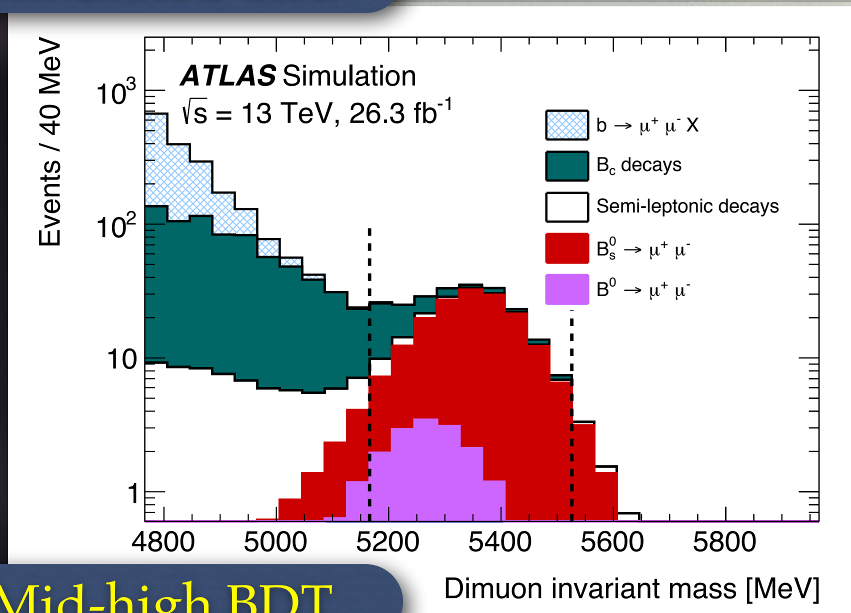
Decay time sPlot



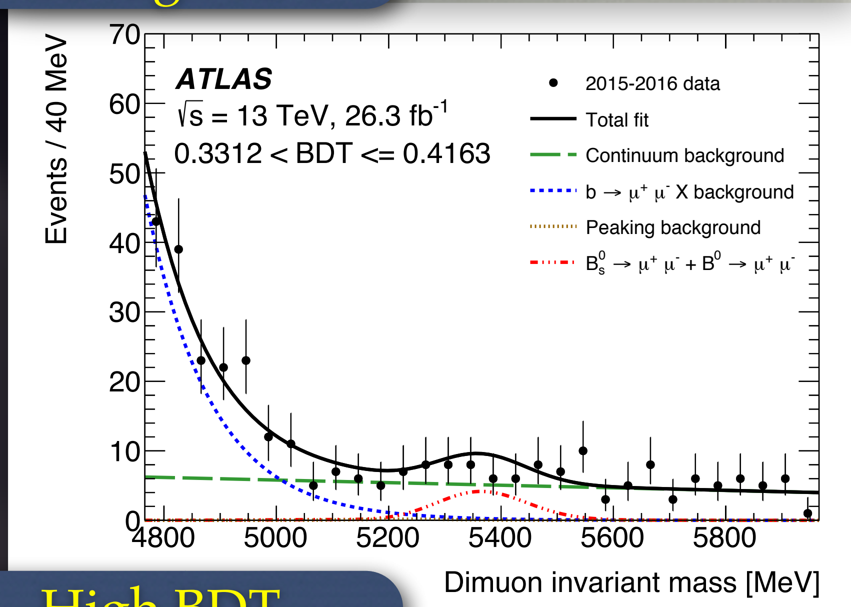
Resulting $\tau(\mu\mu)$
$2.05 \pm 0.44 \pm 0.05$ ps

ATLAS Run-1+2 (partial)

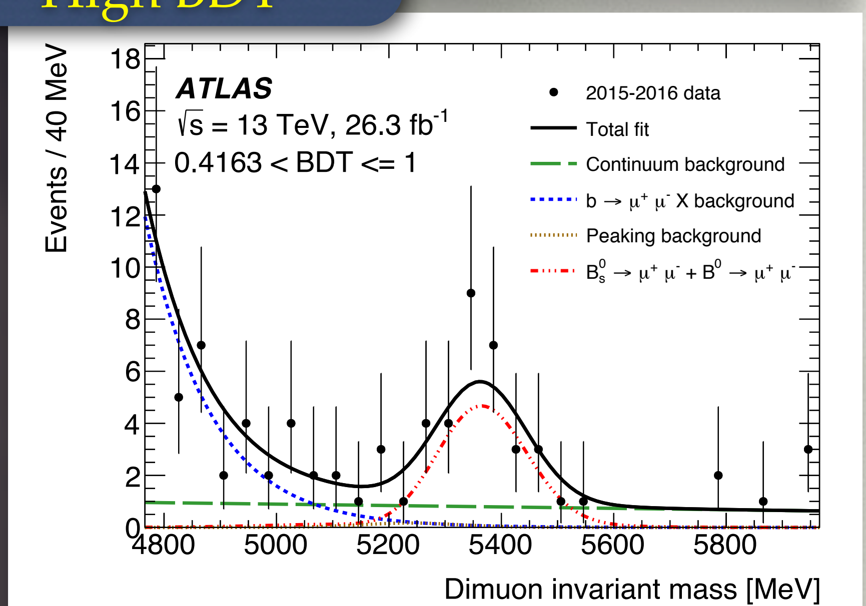
Simulated dist.



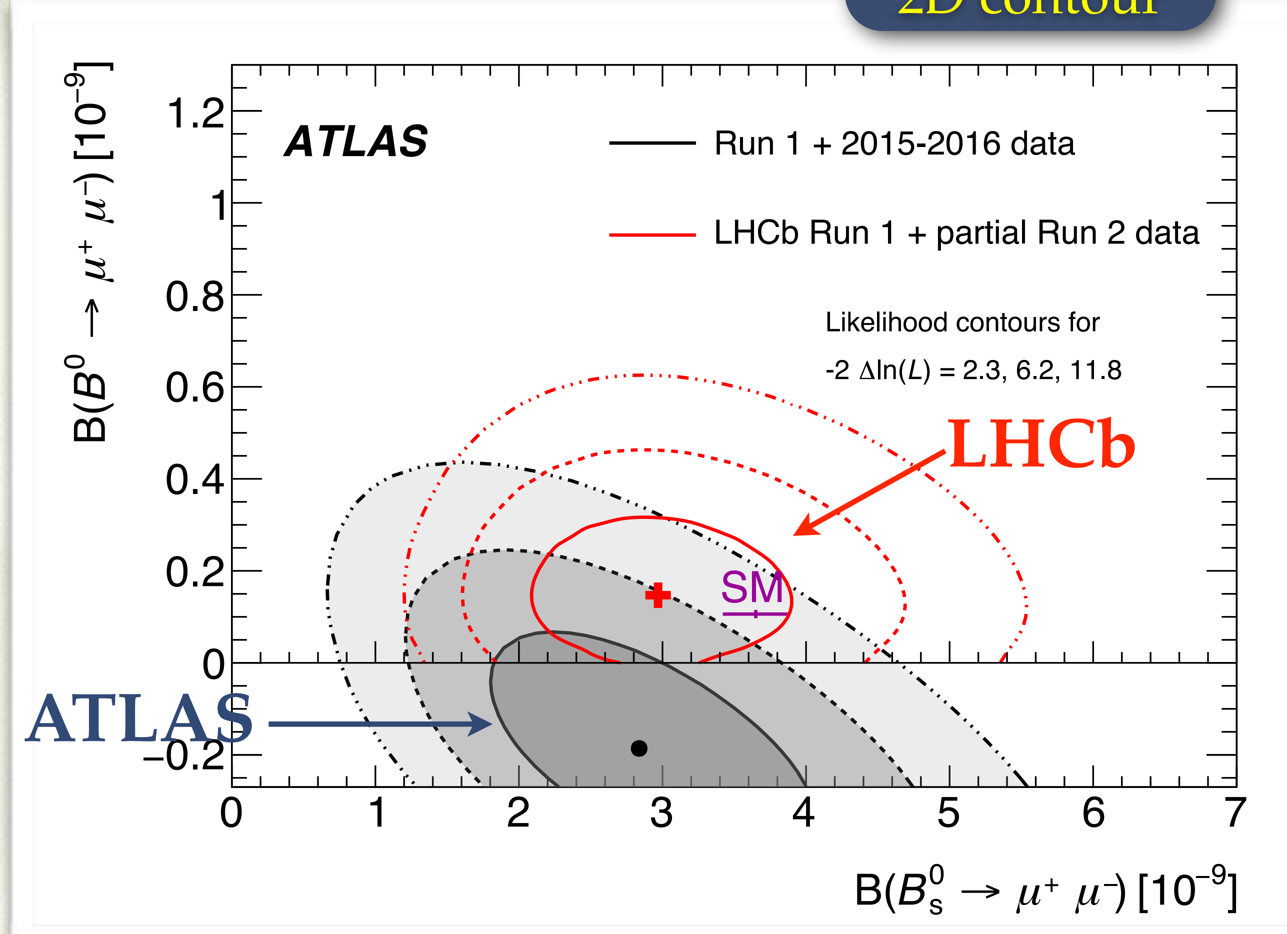
Mid-high BDT



High BDT



2D contour

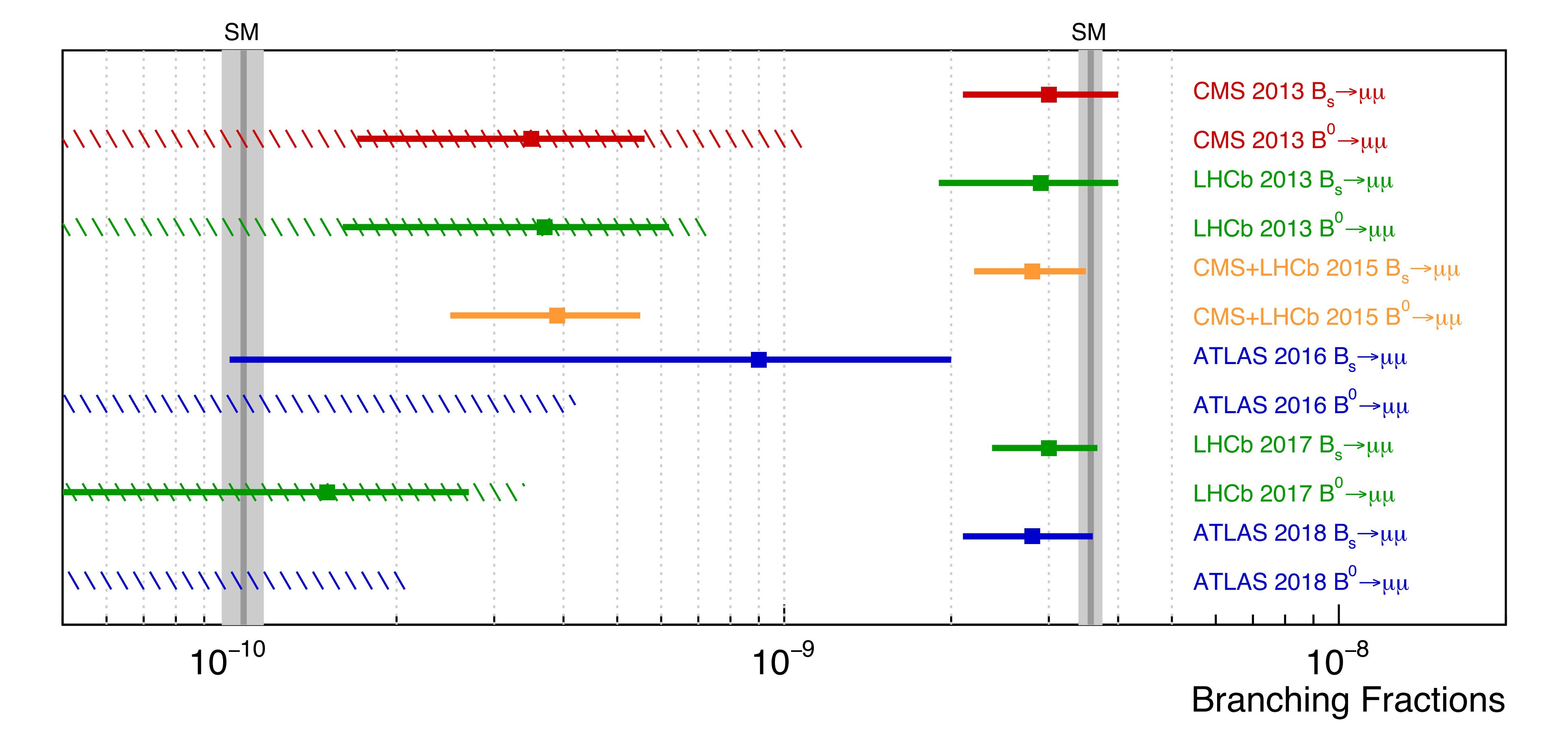


Ref: Submitted to JHEP, arXiv:1812.03017

Channel	Branching fraction
$B_s \to \mu^+\mu^-$	$(2.8\,^{+0.8}_{-0.7}) \times 10^{-9}$
$B_d \to \mu^+\mu^-$	$< 2.1 \times 10^{-10}$

Combined significance for $B_s \to \mu\mu$: 4.6σ; ~2.4σ from SM

Results Since 2013

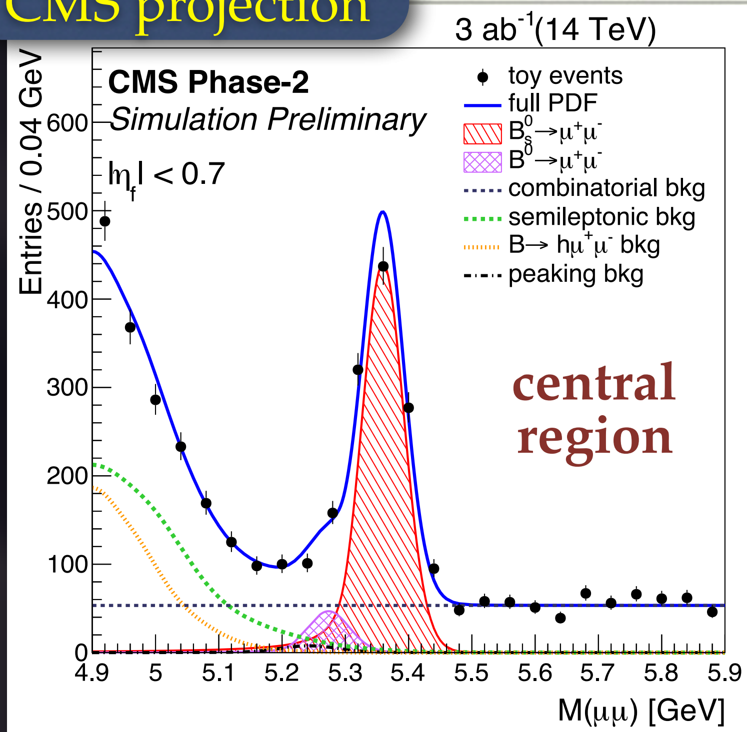


More Run-2 data to be added to the analysis!

- $B_s\to\mu^+\mu^-$ tends to be slightly smaller than the SM prediction (*~1 σ from each experiment*); the excess in $B^0\to\mu^+\mu^-$ drops since LHCb new measurement.
- CMS Run-2 analysis is still in the pipeline.
- Grand combination of ATLAS+CMS+LHCb is under discussion; not for a new paper but for a HFAV / PDG entry.

Future Prospects @ HL-LHC

CMS projection

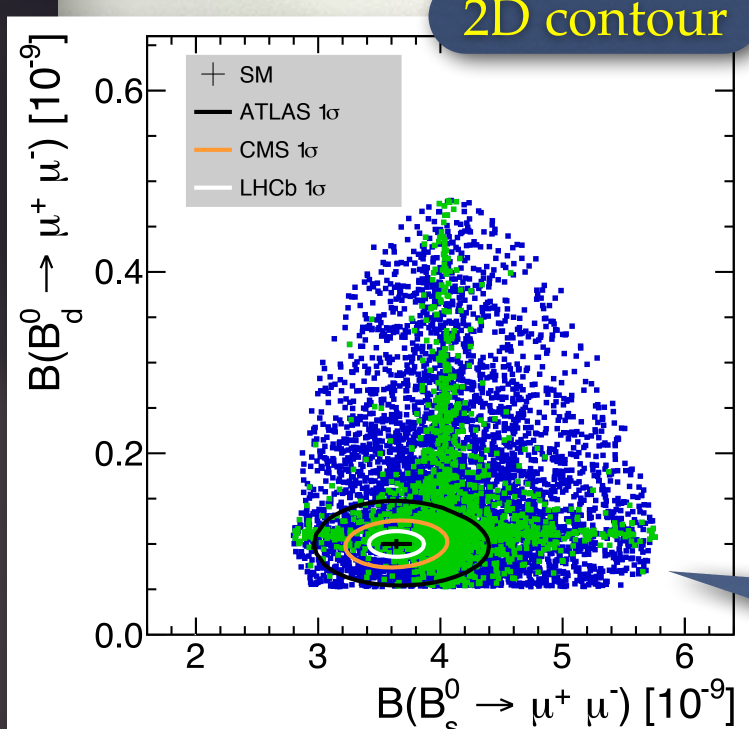


Ref: HL-LHC WG4 report arXiv:1812.07638

Experiment	Scenario	Error on $\mathcal{B}(B_s \to \mu^+\mu^-)$	Error on $\mathcal{B}(B_d \to \mu^+\mu^-)$
LHCb	23 fb^{-1}	8.2%	33%
LHCb	300 fb^{-1}	4.4%	9.4%
CMS	300 fb^{-1}	12%	46%
CMS	3 ab^{-1}	7%	16%
ATLAS	Run2	22.7%	135%
ATLAS	3 ab^{-1} Conservative	15.1%	51%
ATLAS	3 ab^{-1} Intermediate	12.9%	29%
ATLAS	3 ab^{-1} High-yield	12.6%	26%

- Other studies:
  LHCb effective lifetime: 8% (23 fb^{-1}) / 2% (300 fb^{-1})
  LHCb time-dependent CPV: 0.2 on $S_{\mu\mu}$.
  CMS effective lifetime error: 3% (3 ab^{-1})

2D contour



green-blue dots from
Dutta, Mimura, PRD 91 (2015) 095011

CP Violation with Top

- Top does play an important rule in the CPV of bottom section, but the CPV effect of itself is much less addressed so far.
- Top CPV in SM is negligible thanks to the “too effective” GIM cancellation.
- But it does not forbid the contributions from NP! **Any hit of CPV in top sector is definitely a call from NP**.
- Given the (over-)dominant t→bW decay, it is not so straightforward to find a good observable to probe top CPV effect! The usual trick used in bottom or strange does not work here.

CPV with Triple-Product

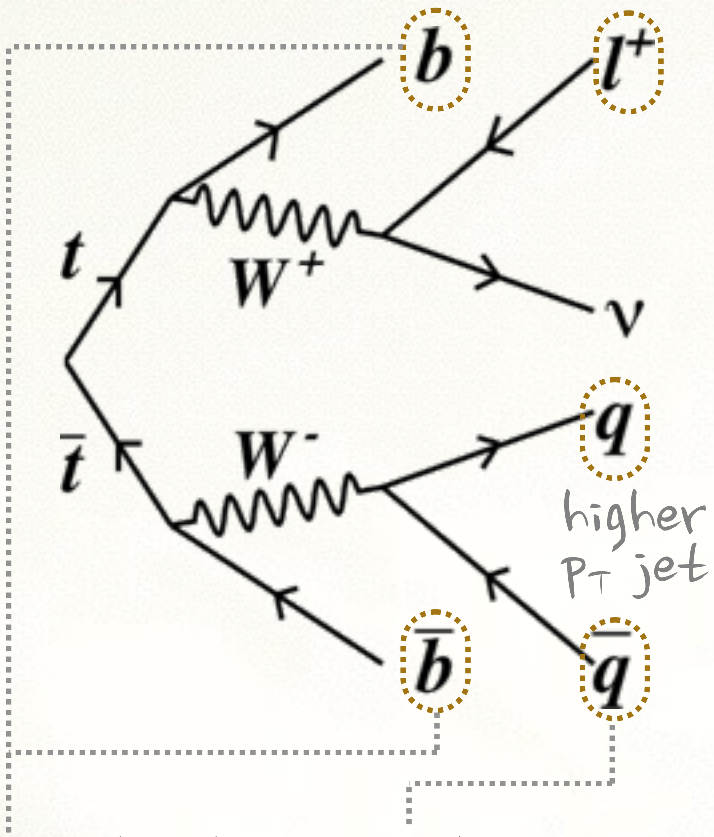
- Constructing **T-odd observables** (O_i) with 3 independent vectors in the form of $v_1 \cdot (v_2 \times v_3)$:
  - Typical choices of these vectors are the momentum or spin direction of decay daughters.
  - These observables are odd under time reversal, are also CP-odd if **CPT conservation** is assumed. (Sometimes this is also called *T-odd CPV* or *T violation*.)
- The CP violation can be probed by measuring a non-zero asymmetry:

$$A_{CP}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)}$$

- This is different from the generic decay rate asymmetry (e.g. Acp(Kπ)):
  - Decay rate Acp is generally proportional to **sinδ·sinϕ** (δ=strong CP-phase, ϕ=weak CPV phase);
  - T-odd Acp is proportional to **cosδ·sinϕ**. So one can also measure non-zero value even the strong phase is small.

T-odd CPV with Top Events

- The trick is then to select some "measurable" vectors from top production and decay, and to form the triple product combinations.
- **Hayreter & Valencia PRD 93 (2016) 014020** proposed a list of 26 observables for leptonic and lepton+jets top pair events, and study the contribution of chromoelectric dipole moment (**CEDM**).
- CMS analysis picked up 4 observables which are practically accessible for lepton+jets top events:



Need to use (b-)jet and lepton directions; the A_{CP} value can be as large as few % with CEDM.

$$O_2 = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j_1}) \xrightarrow{\text{lab}} \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$

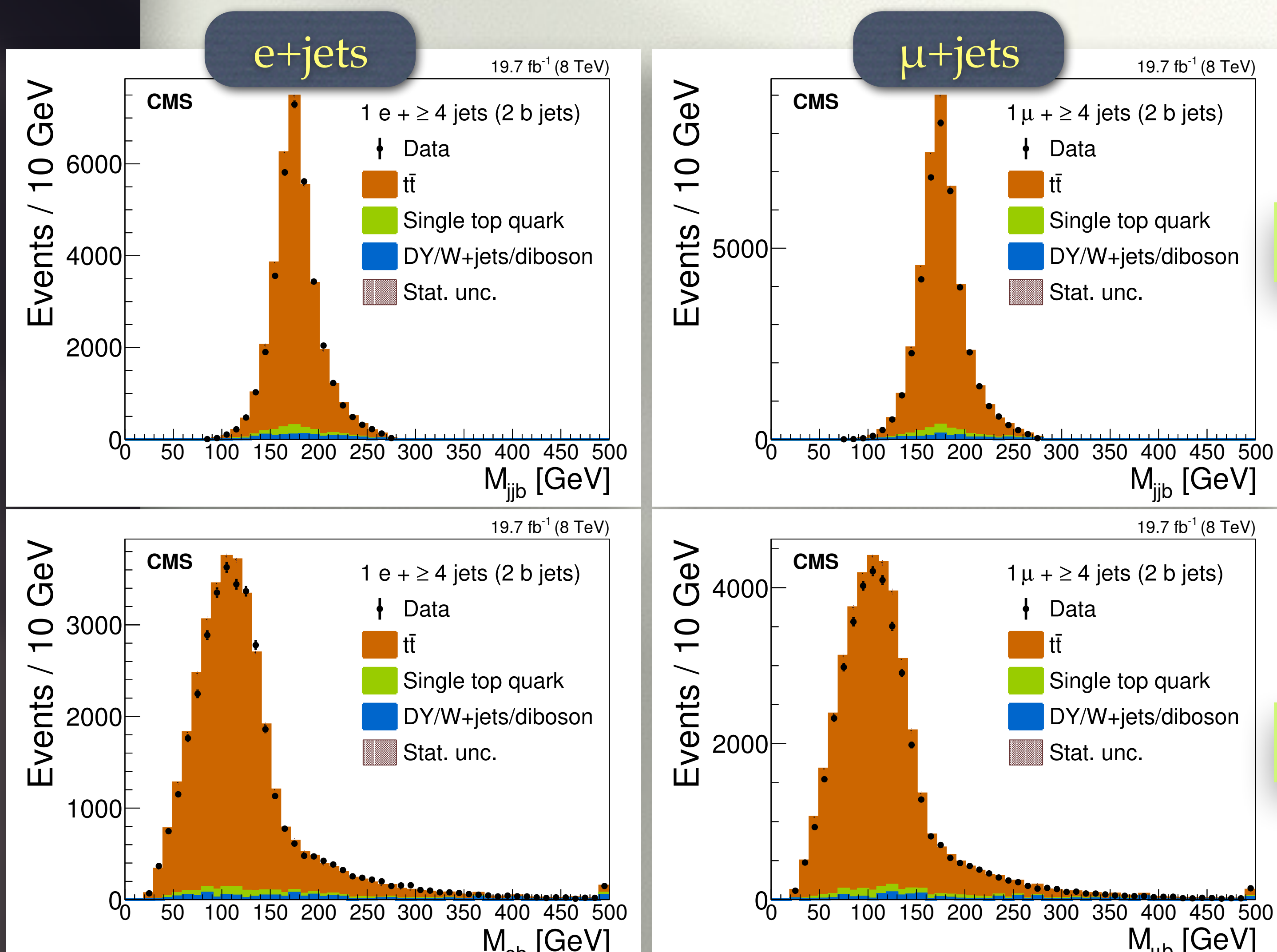
$$O_3 = Q_\ell\, \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j_1}) \xrightarrow{b\bar{b}\,\text{CM}} \propto Q_\ell\, \vec{p}_b \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$

$$O_4 = Q_\ell\, \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j_1}) \xrightarrow{\text{lab}} \propto Q_\ell\, (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$

$$O_7 = q \cdot (p_b - p_{\bar{b}})\, \epsilon(P, q, p_b, p_{\bar{b}}) \xrightarrow{\text{lab}} \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z (\vec{p}_b \times \vec{p}_{\bar{b}})_z.$$

Top CPV: Analysis Strategy

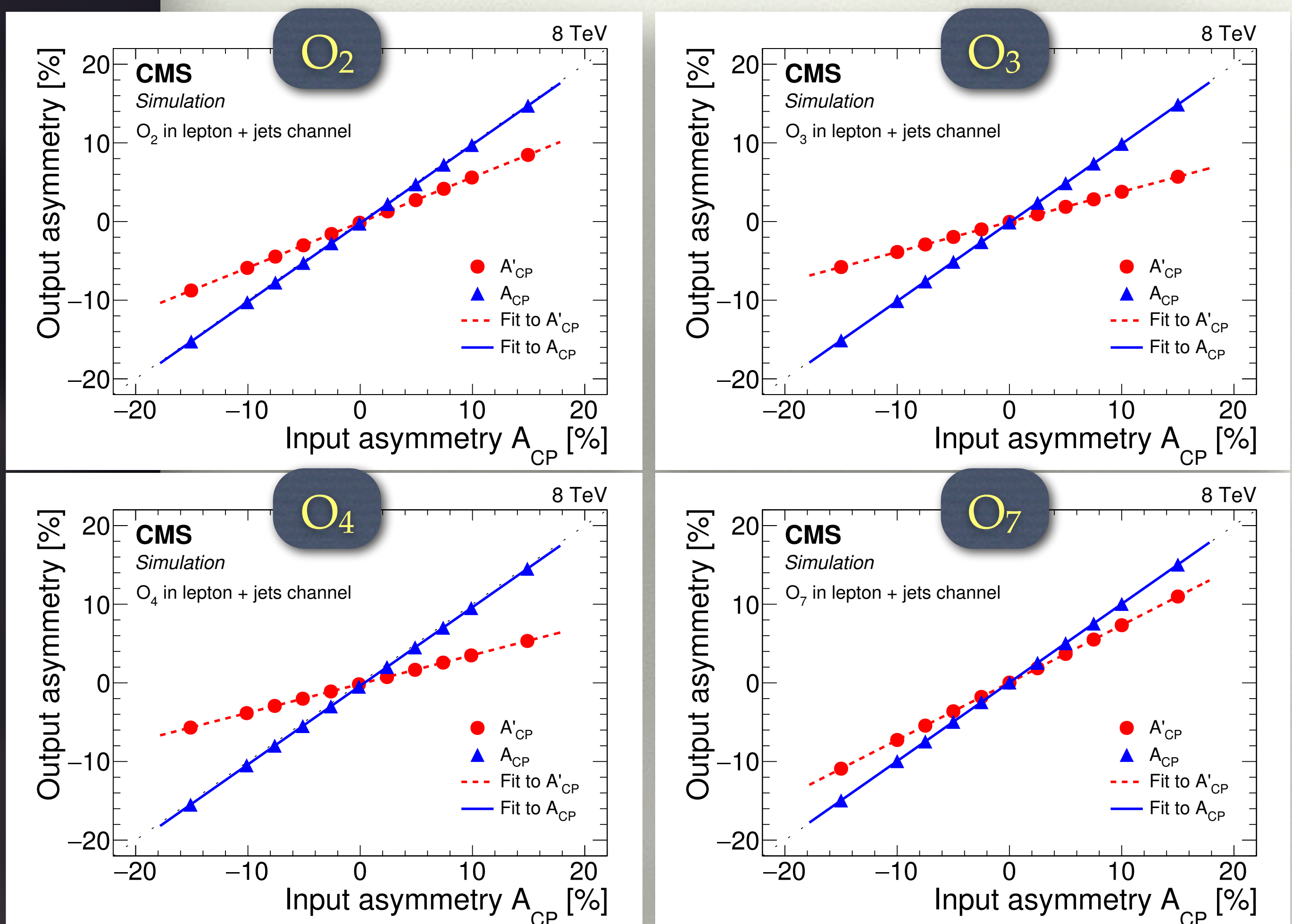
- Thanks to the large top pair production at the LHC, one can select very clean top events to start with.
- Selected **67K lepton+jets+2 b-tags candidates** from 8 TeV 20 fb^{-1} data:



Use W(2-jet) and Top(3-jet) invariant masses to resolve the permutation: need to know which jet is b and which is anti-b!

Use l+b invariant mass to determine the signal purity from data: 92.5% (e+jets), 92.4% (μ+jets)

Top CPV: Dilution

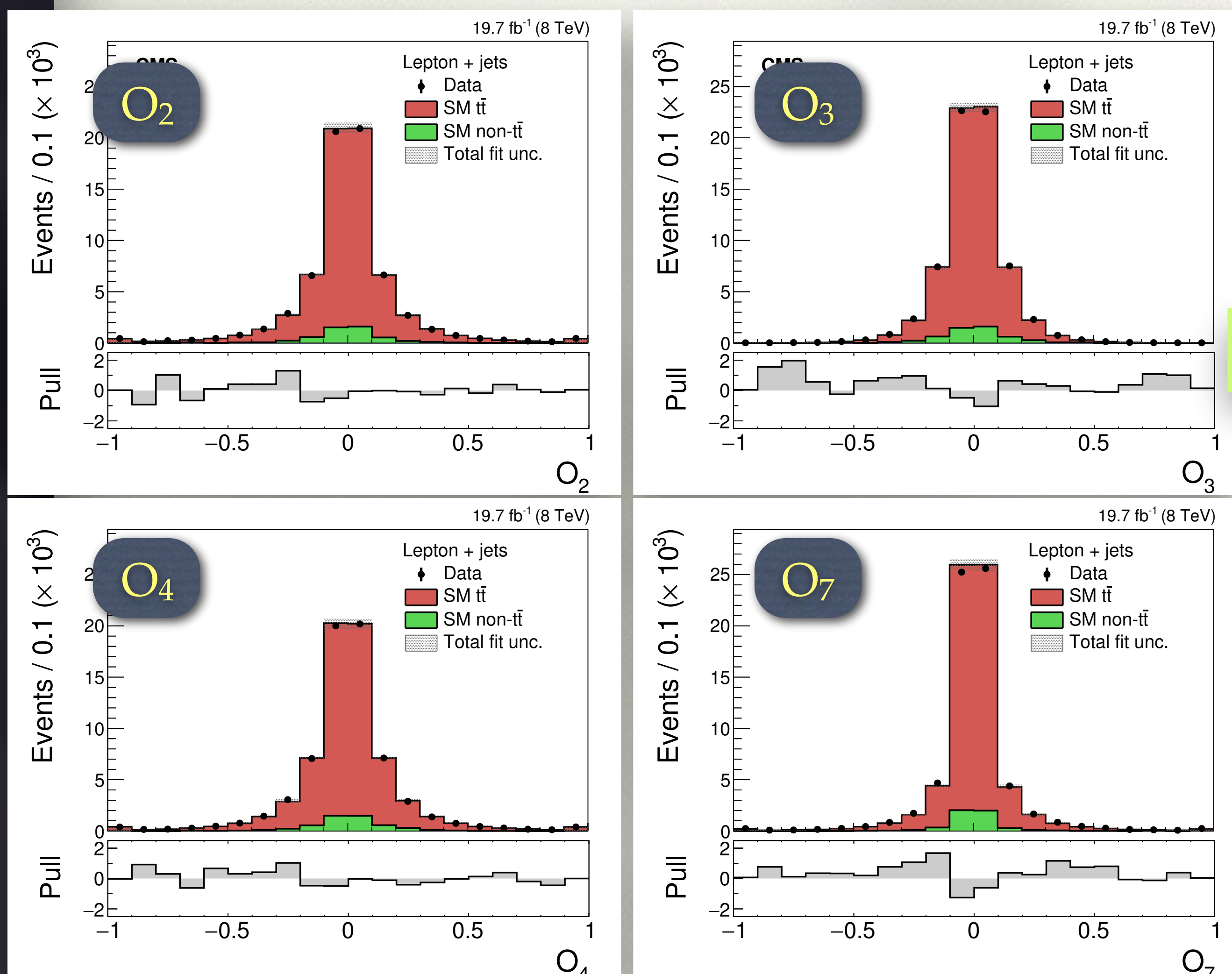


	wrong sign frac	Dilution factor
O_2	(21.3±1.0)%	0.575±0.019
O_3	(30.9±0.9)%	0.383±0.018
O_4	(31.7±1.0)%	0.367±0.020
O_7	(13.5±0.5)%	0.730±0.010

- The mis-reconstruction at the event (e.g. swap the two b-jets, direction resolution of the jets, etc) can wash out the asymmetry information.
- The measured (raw) A_{CP} is proportional to the true A_{CP} at generator, up to a **dilution factor**.
- The dilution factors should be different for different observables and can be effected by NP (*here SM MC is used*).

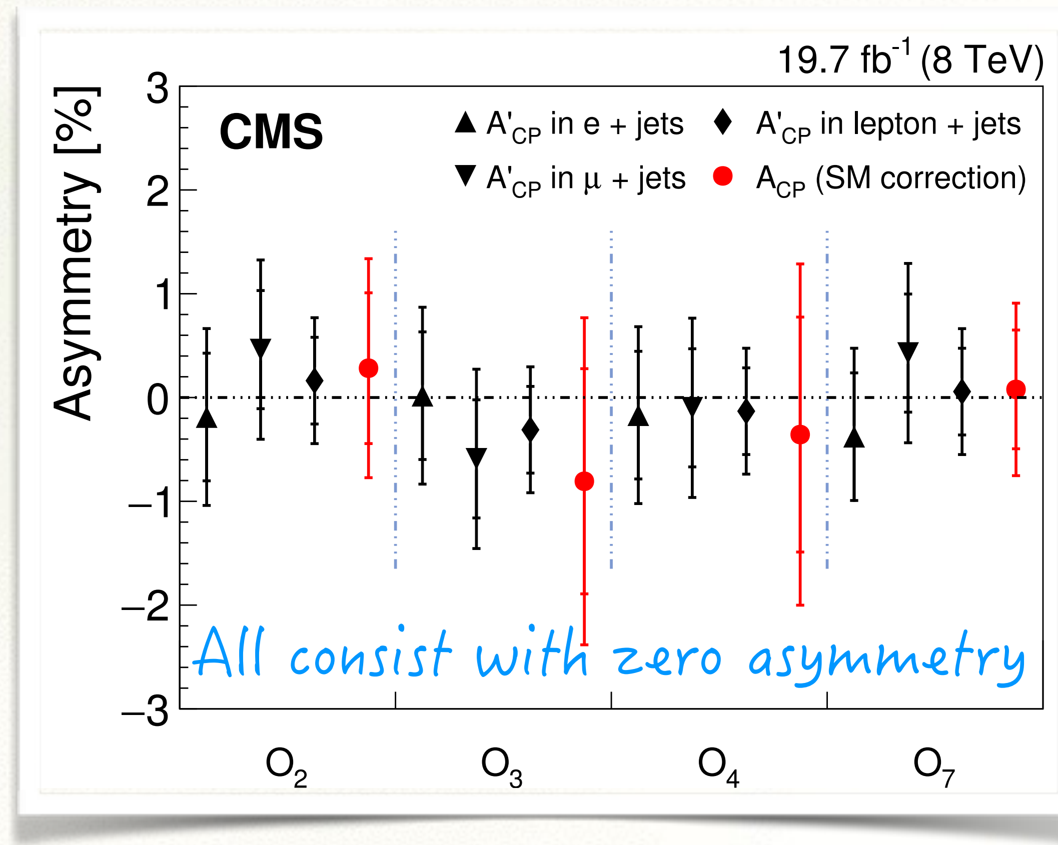
O3, O4 require a larger correction due to the possibility to swap two b-jets. O7 has no such an issue.

Top CPV: Results



Ref. JHEP 03 (2017) 101

	Raw A_{CP} (%)	Corr. A_{CP} (%)
O_2	+0.16±0.42±0.44	+0.3±1.1
O_3	−0.31±0.42±0.44	−0.8±1.6
O_4	−0.13±0.42±0.44	−0.4±1.7
O_7	+0.06±0.42±0.44	+0.1±0.8



- Precision ~0.6% for raw A_{CP}, already systematics dominant (*by detector bias measurement*).

Top CPV: What's the next?

- **CPV/CEDM tests though triple-products:**
  - Foreseeable 13 TeV measurements with improved systematics estimation. But adding full Run-2 data will take a long time.
  - Dilepton channel is also worked out by Korea university, to be released soon.
- **Big question — what can be carried out in addition to the existing studies?**
  - Chung Kao shown me a paper by C. Schmidt and M. Peskin, suggesting to compare the transverse energy distributions from leptons. But probably an update pheno study is also needed?

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Probe of *CP* Violation in Top Quark Pair Production at Hadron Supercolliders

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(Received 30 March 1992; revised manuscript received 24 June 1992)

We show that measurement of the difference in the transverse energy distribution of leptons and antileptons from $t\bar{t}$ events at hadron colliders provides an interesting probe of *CP* violation in the Higgs sector. We predict a *CP*-violating asymmetry at the 10^{-3} level.

Any other ideas?

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