Study of Rare B-decays with CMS

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Sept 14th, 2016

- ✓ Introduction
- ✓ Initial B-results with 13TeV data
- ✓ Results for $B_s \rightarrow \mu^+\mu^-$
- ✓ Results for $B_d \rightarrow K^{*0}\ \mu^+\mu^-$
- ✓ conclusion

Introduction

- **Flavor production and study of its properties is one of the most interesting areas among the particle physics community.**
- **There are many unsolved questions in this sector (listing only few):**

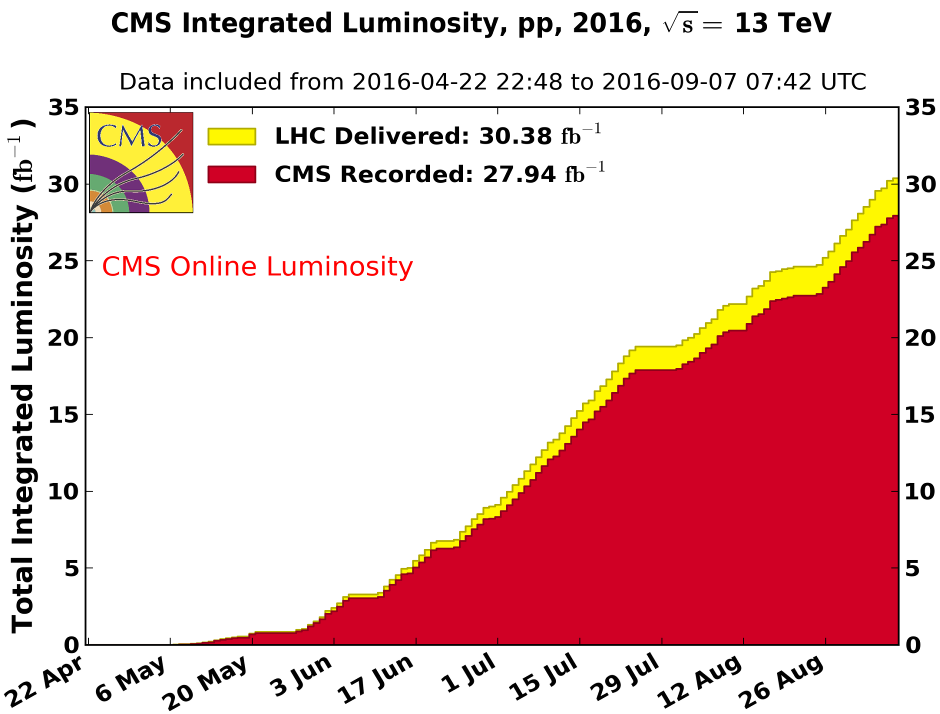
  -> What are the principles for the observed pattern of fermion mass and mixing angles ?
  -> Are there any new sources of flavor symmetry breaking apart from SM Yukawa couplings at TeV scale ?
  -> Are there new sources of CP violation to explain the observed matter-antimatter asymmetry of universe ?

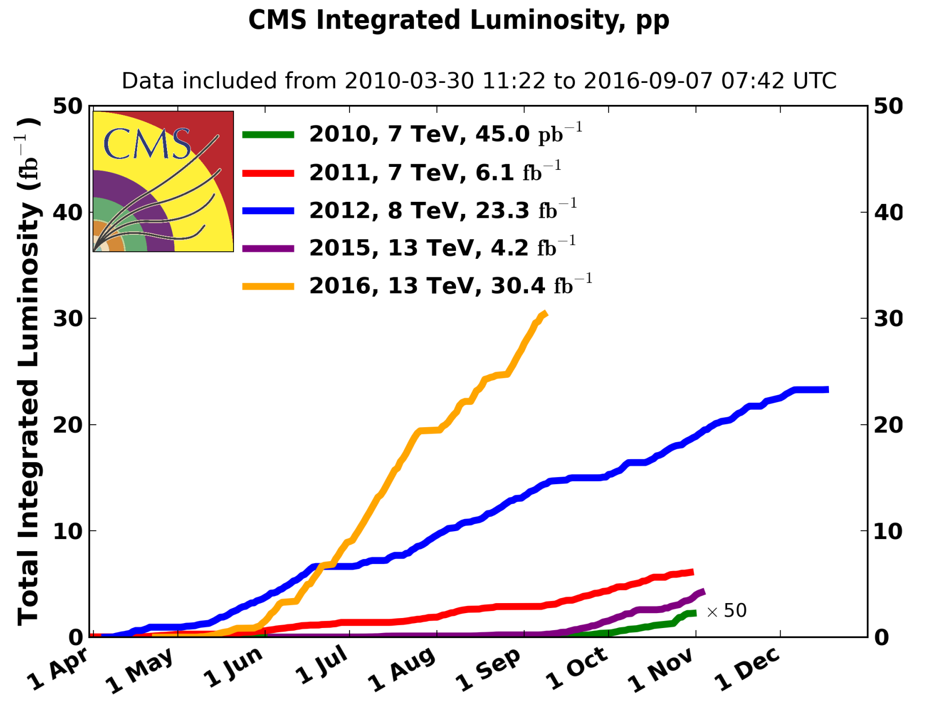
- **LHC era is very important pin down some of the flavor questions.**

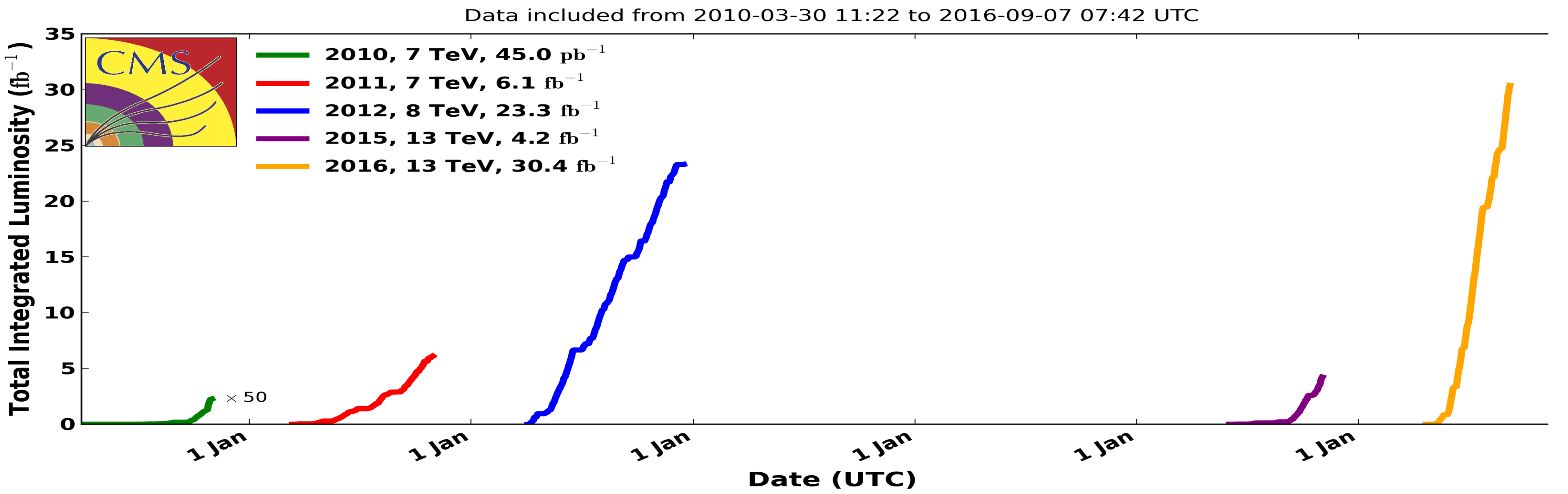
It allows us to probe the NP in two ways:

- **Produce heavy particles beyond SM. The production cross-section of those particles is usually small.**
- **Measure the observables/parameters of SM processes (*specifically rare decay modes*). Any significant deviation from SM prediction might be hint of NP.**

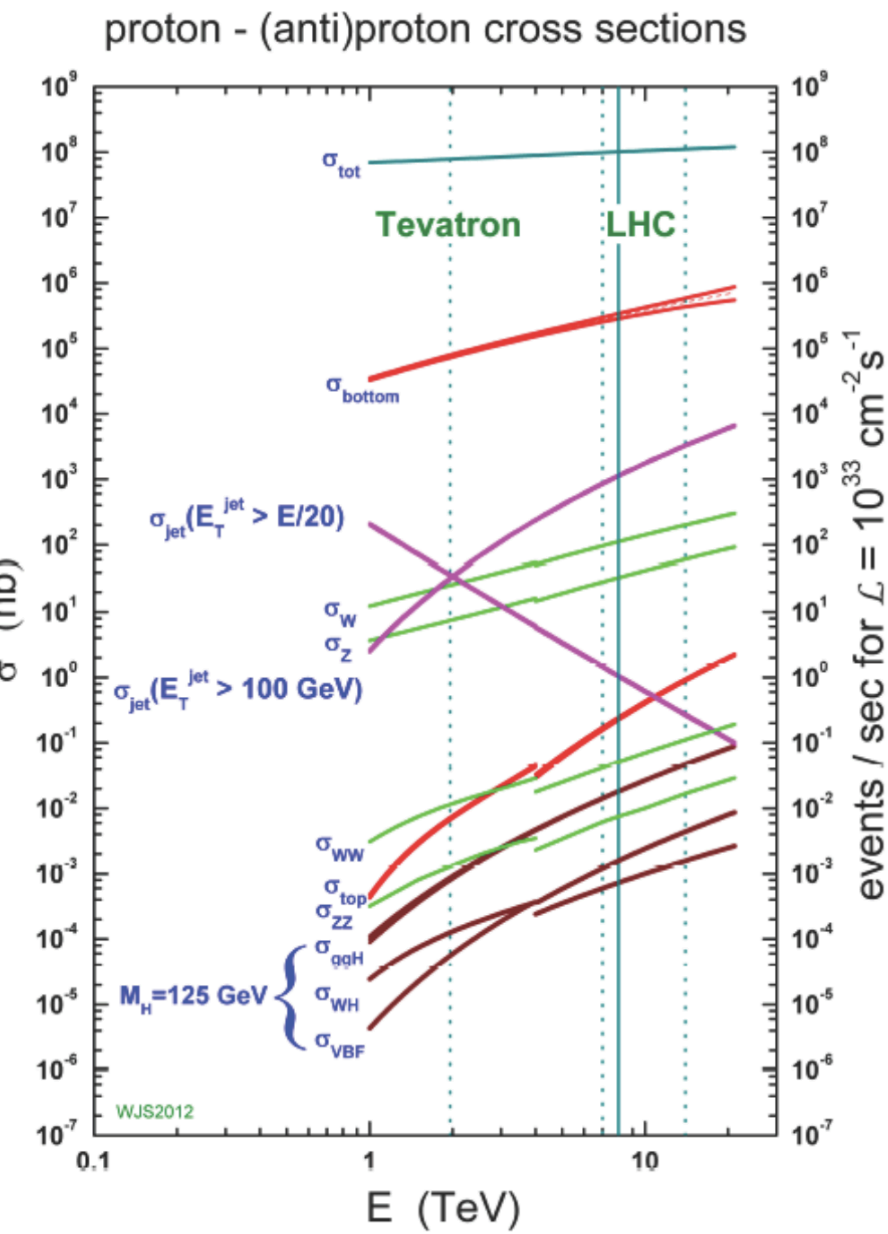
LHC & CMS performance



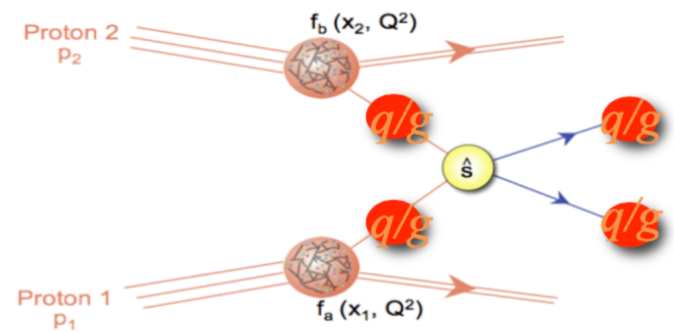




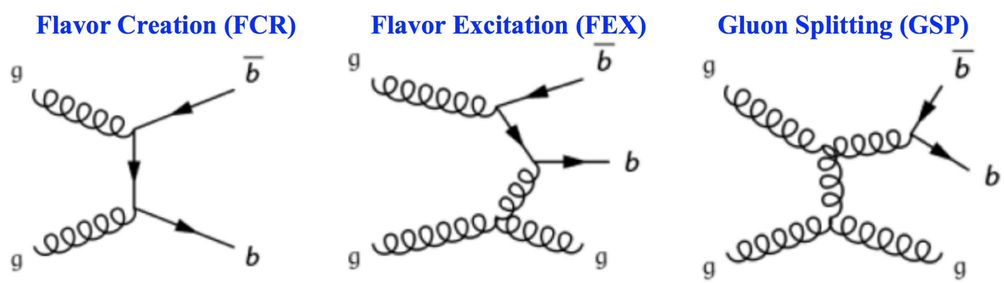
Why we can do better at higher energy ?



-> Because of large production rate

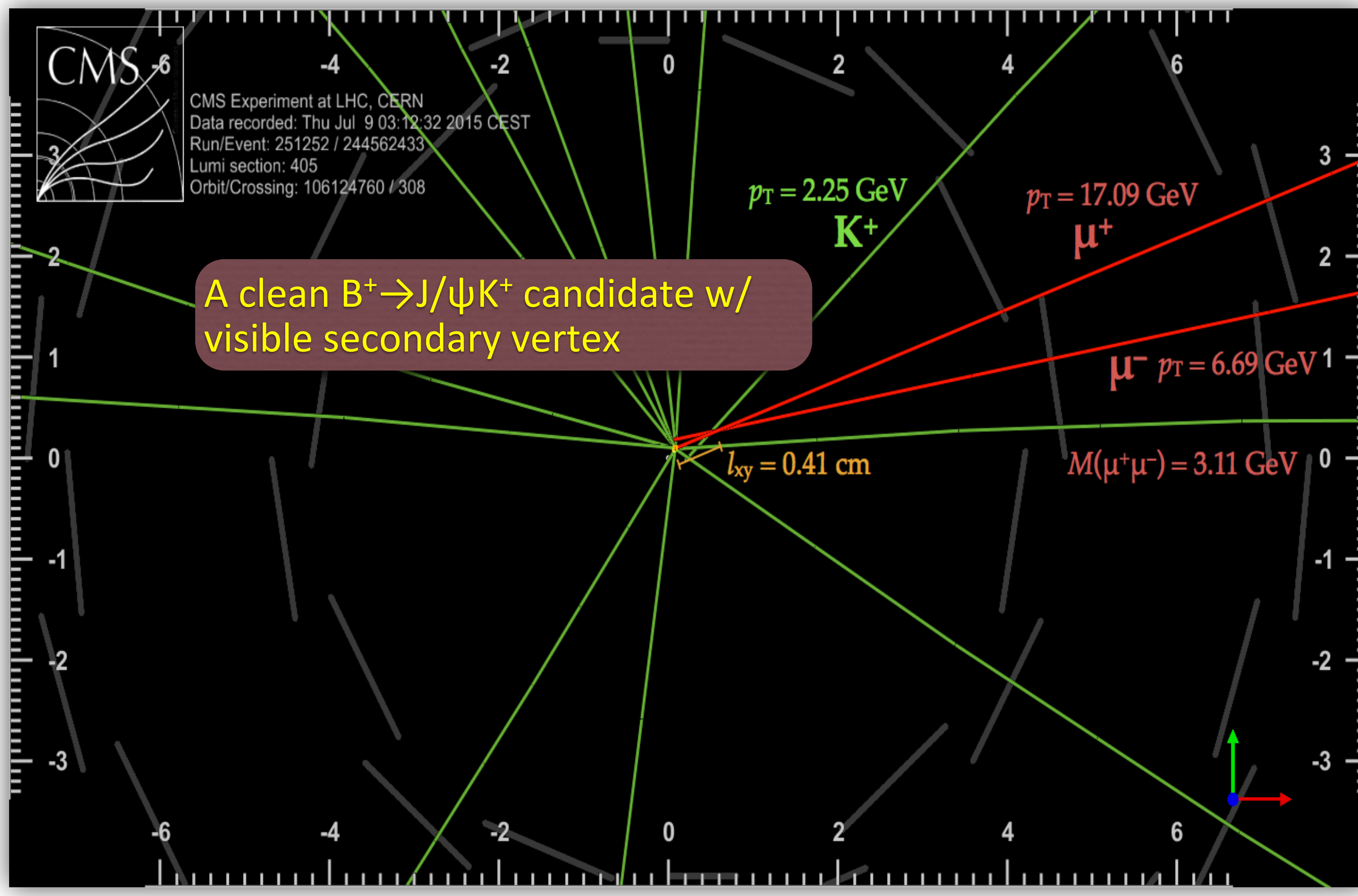


b-production cross-section goes up by almost one order of magnitude higher compared to Tevatron [in LHC ~O(100μb)]



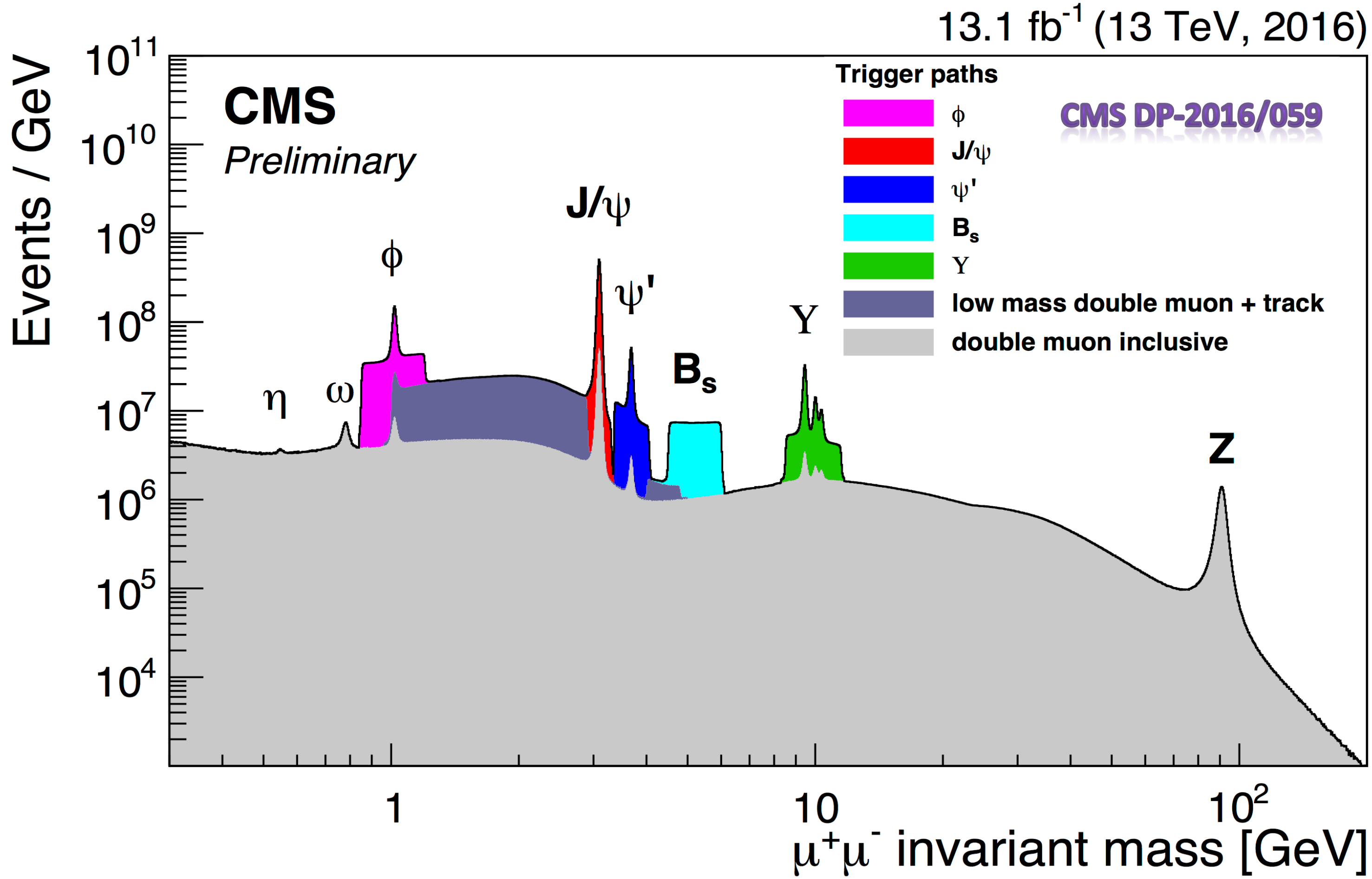
But its not the production only, also the type of final state is important

Event with di-muon from CMS @13TeV



CMS DP-2015/018

Physics with dimuons from CMS @13TeV



- Many flavor physics analysis depends on the prompt and displaced quarkonia triggers.
- The trigger requirements are tightened due with increased luminosity and higher production rate
- ~10% bandwidth is given to flavor physics

B^+ production cross section @13TeV from CMS

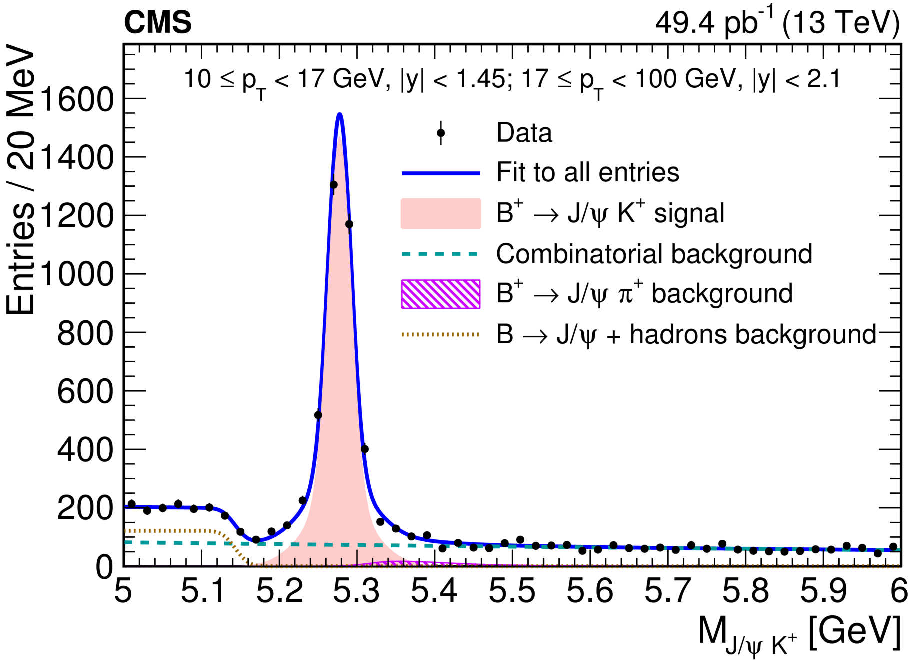
ARXIV: 1609.00873

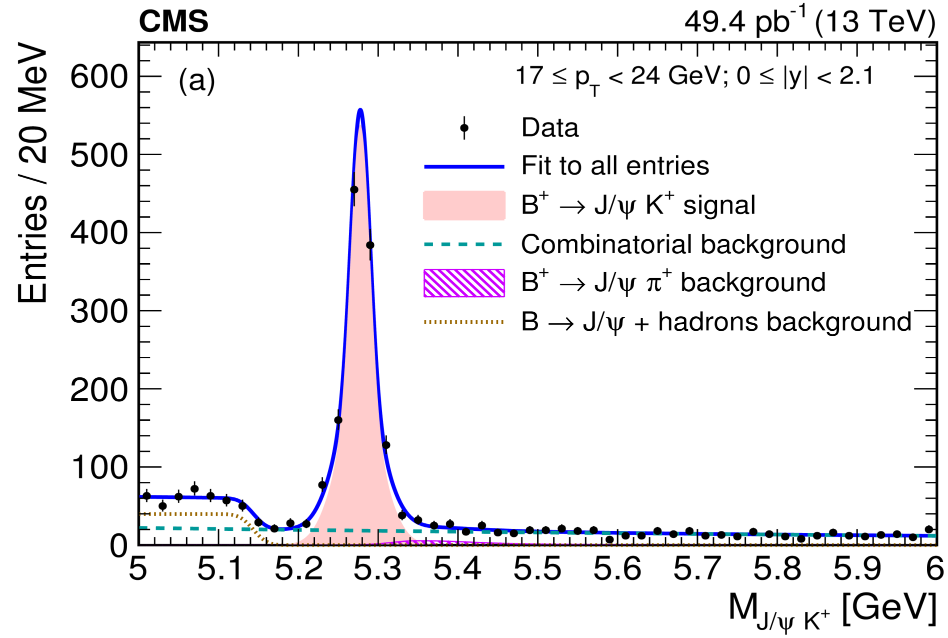
- Provides important information to understand particle interactions.
- B^+ differential production cross section as function of B transverse momentum and rapidity
- Uses exclusive decay mode $B^+ \to J/\Psi K^+$ ($J/\Psi \to \mu^+\mu^-$) [$pp \to B^+X \to J/\Psi K^+ X$]
- Both muons must be within $|\eta| < 1.6$ or one of the muons must have $P_T > 11$ GeV.
- J/Ψ candidates must have $P_T > 8$GeV and minimum χ^2 probability for vertex fit.
- Combined with charged track (considered to be kaon) with $P_T > 1$GeV
- The cut in decay length significance in transverse plane (distance between secondary vertex and beam spot in transverse plane divided by its uncertainty)
- The signal is obtained by extended maximum likelihood fit to the B^+ invariant mass distribution in bins of B^+ P_T and $|\eta|$.
- The differential cross-section is calculated to be

$$\frac{d\sigma(pp \to B^+X)}{dp_T^B} = \frac{n_{sig}(p_T^B)}{2\,A \cdot \epsilon(p_T^B)\,\mathcal{B}\,\mathcal{L}\,\Delta p_T^B}, \quad \frac{d\sigma(pp \to B^+X)}{dy^B} = \frac{n_{sig}(|y^B|)}{2\,A \cdot \epsilon(|y^B|)\,\mathcal{B}\,\mathcal{L}\,\Delta y^B}$$

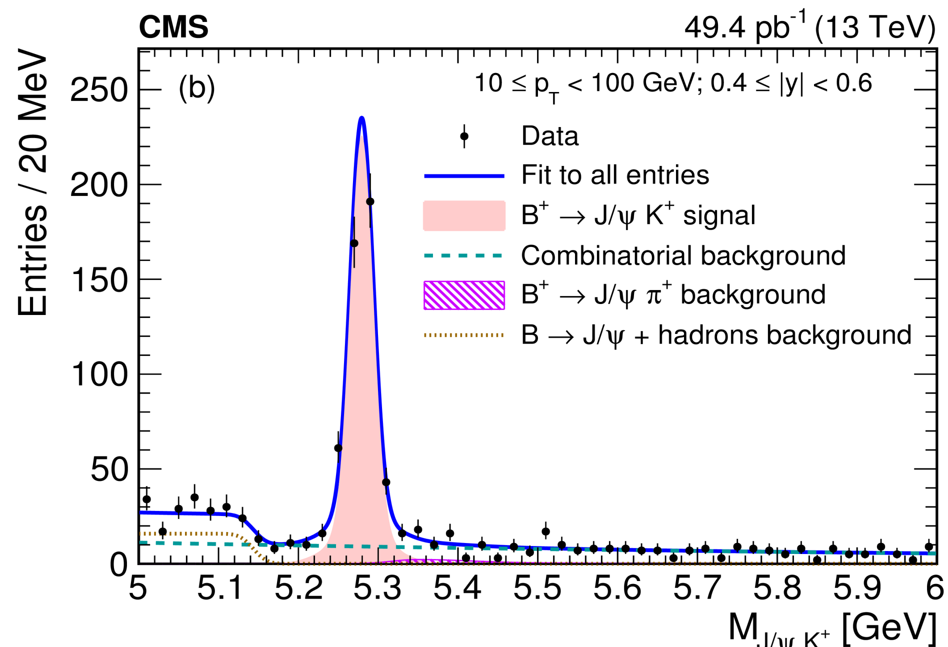
- Result shown is based on 49.4 pb^{-1} data collected at 13TeV

B+ production cross section @13TeV from CMS



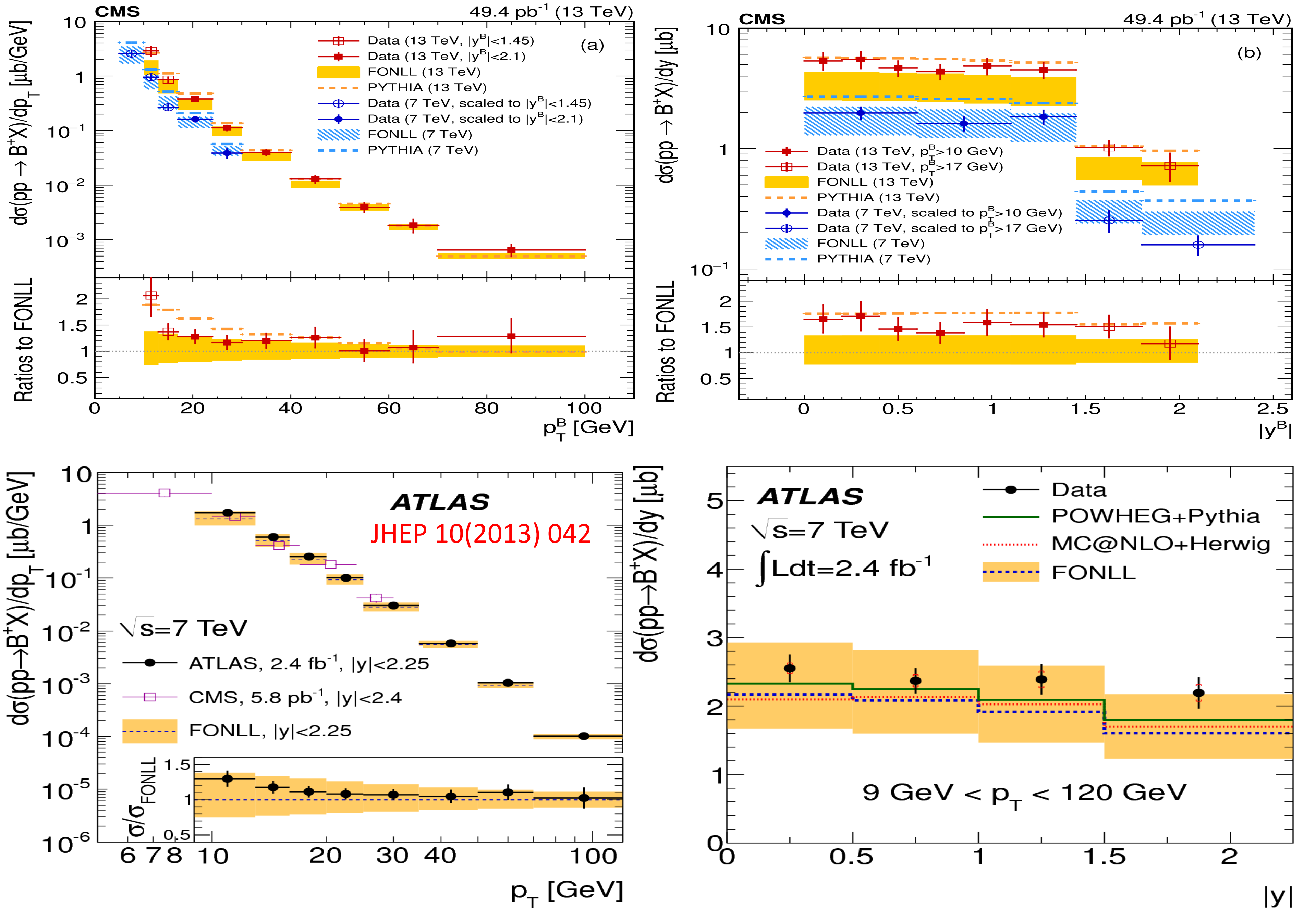


- **B Invariant mass distribution for different P_T and η regions.**
- **Signal -> Two Gaussian**
- **The mean of two Gaussians fixed, while the width and normalization are free (excep for some Pt bins where it is fixed from MC)**



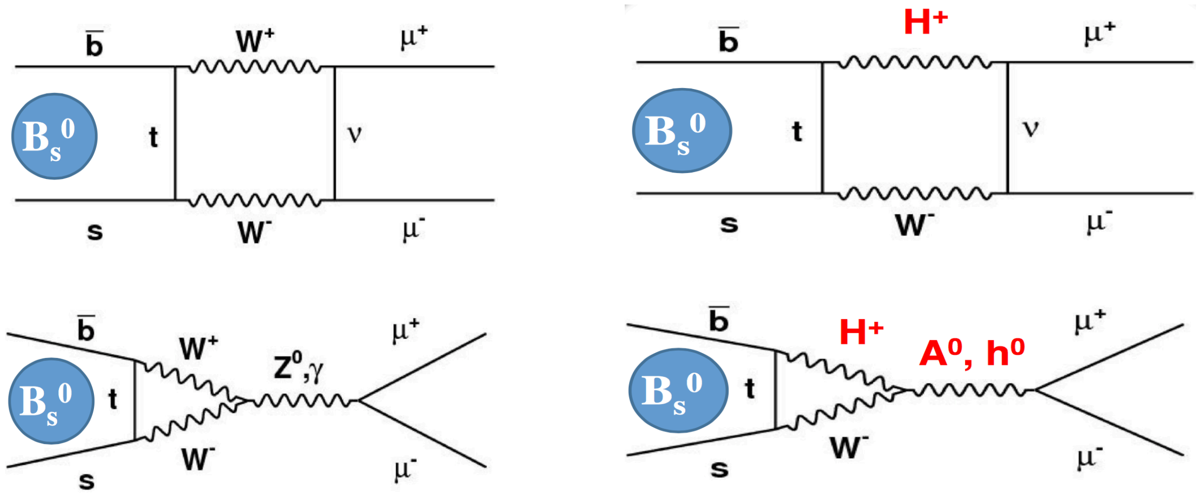
ARXIV: 1609.00873

B^+ production cross section from CMS & ATLAS

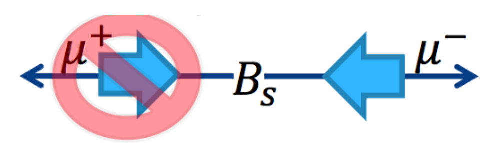


Facts about $B_s \to \mu^+\mu^-$

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

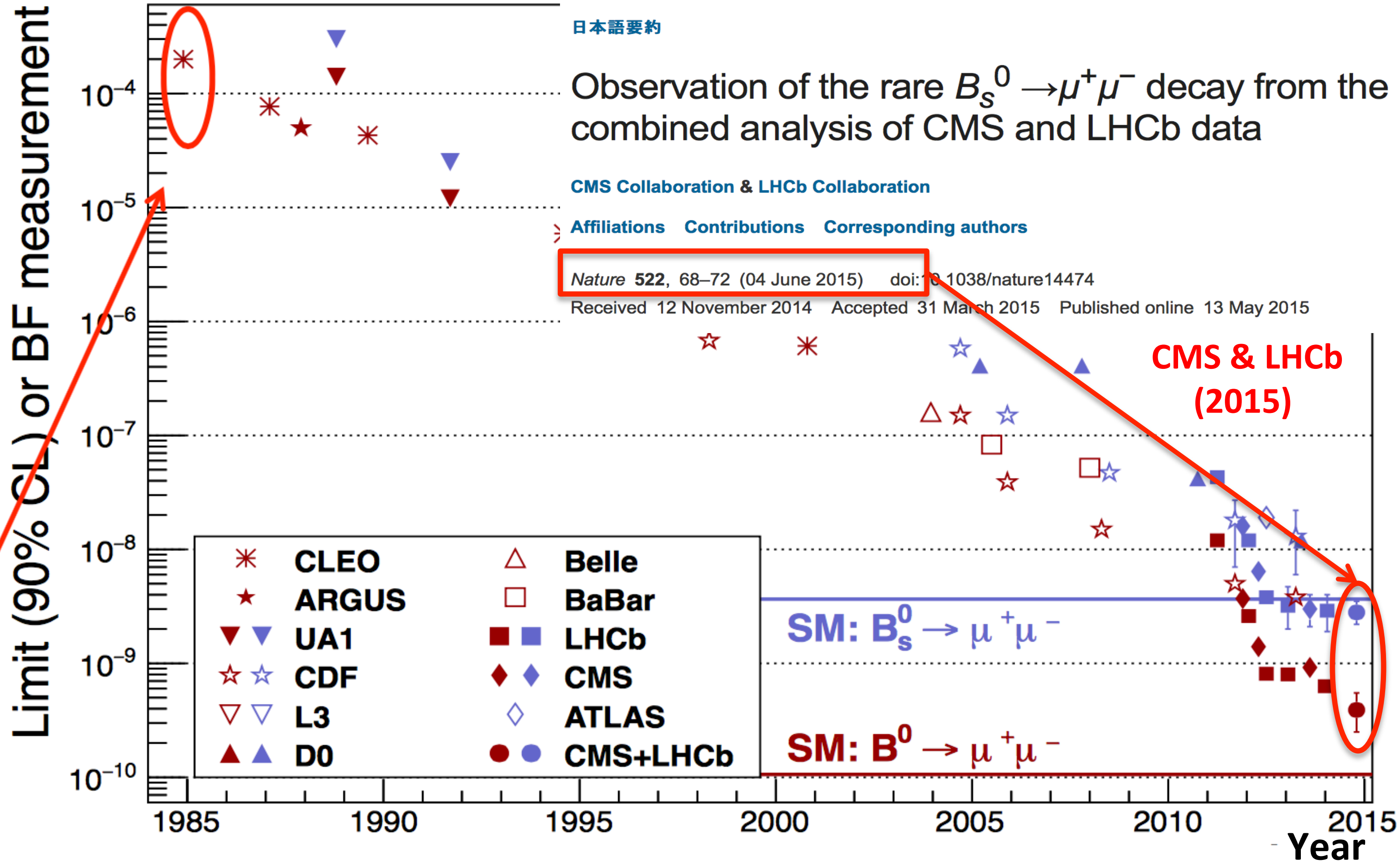


- The process is helicity suppressed by factor $(m_\mu/m_B)^2$ (forces one of the muons to have wrong helicity direction)



- $B_d \to \mu^+\mu^-$ is further suppressed compared to $B_s \to \mu^+\mu^-$ as $|V_{td}| < |V_{ts}|$
- Sensitive to pseudo-scalar and scalar couplings
- 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.

History of B →$\mu^+\mu^-$ search



NATURE | LETTER OPEN

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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CLEO, 1985:

VOLUME 53, NUMBER 14 PHYSICAL REVIEW LETTERS 1 OCTOBER 1984

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

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)]
Cornell University, Ithaca, New York 14853

SM branching fractions for $B \rightarrow \mu^+\mu^-$

- The SM branching fraction for $B_s \rightarrow \mu^+\mu^-$ can be written as

$$\mathcal{B}^{t=0}(B_s \to \mu^+\mu^-) = \frac{G_F^4 M_W^4}{\pi^2} \tau_{B_s} f_{B_s}^2 m_{B_s} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} |V_{tb}V_{ts}^*|^2 |C_{10}|^2$$

- To compare with experimental result, which is time integrated, a correction due to the B_s-mixing need to be taken into account (De Bruyn et al. [PRL 109, 041801], [PRL 108 (2012) 101803)

$$\mathcal{B}(B_s \to \mu^+\mu^-) = \frac{1}{1-y_s} \mathcal{B}(B_s(t=0) \to \mu^+\mu^-), \qquad y_s = \frac{\Delta\Gamma_s}{2\Gamma_s}$$

- Most recent time integrated predictions:

$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$
$\mathcal{B}(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

Ref: Bobeth et al, PRL 112, 101801 (2014), and with full electroweak 2 loop corrections and 3 loop QCD correction [Bobeth et al. [1311.1348 [Hermann et al. [1311.1347])

- Main uncertainties from f_{Bs} and CKM factor $|V_{tb}V_{ts}^*|$

	f_{B_q}	CKM	τ_H^q	M_t	α_s	other param.	non-param.	$\sum$
$\overline{\mathcal{B}}_{s\ell}$	4.0%	4.3%	1.3%	1.6%	0.1%	< 0.1%	1.5%	6.4%
$\overline{\mathcal{B}}_{d\ell}$	4.5%	6.9%	0.5%	1.6%	0.1%	< 0.1%	1.5%	8.5%

- Sensitive to NP e.g. BF $(B_s \rightarrow \mu^+\mu^-)$ α $\tan^6 \beta$ where $\beta = v_2/v_1$, ratio of neutral Higgs field vacuum expectation values

Analysis methodology

- Measure $B_s \to \mu^+\mu^-$ relative to the normalization channel (cancel uncertainty due to $b\bar{b}$ production cross-section and integrated luminosity)
  -> $B^+ \to J/\psi\, K^+$ with very precise branching fraction
  -> nearly identical selection to reduce systematic uncertainties

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \frac{n^{\rm obs}_{B_s^0}}{\varepsilon_{B_s^0} N_{B_s^0}} = \frac{n^{\rm obs}_{B_s^0}}{\varepsilon_{B_s^0} \mathcal{L}\, \sigma(pp \to B_s^0)}$$

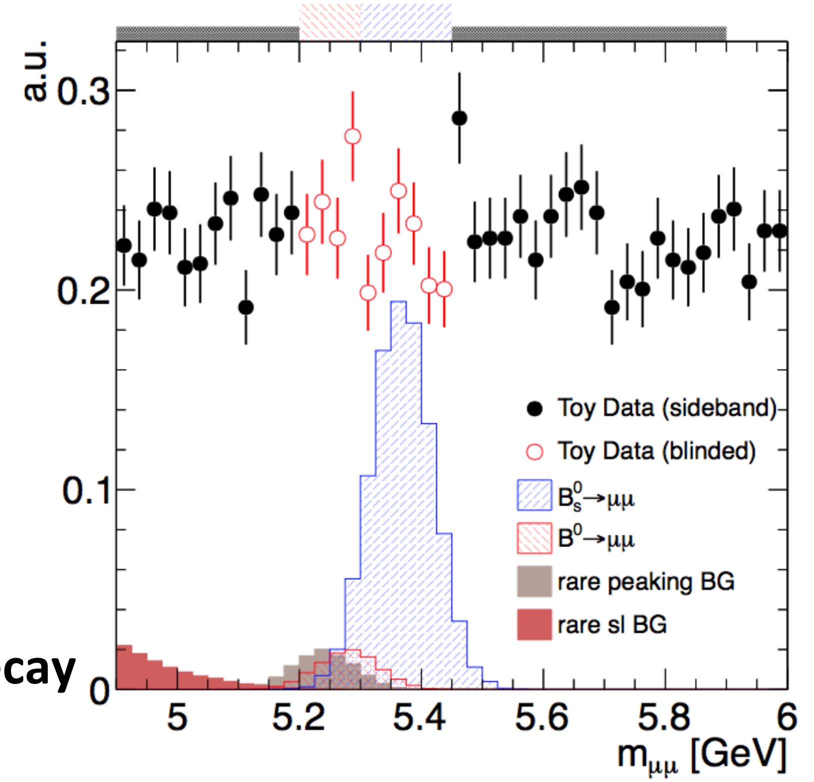
$$= \frac{N_S}{N^{B^+}_{\rm obs}} \frac{f_u}{f_s} \frac{\varepsilon^{B^+}_{\rm tot}}{\varepsilon_{\rm tot}} \mathcal{B}(B^+)$$

(N_s is same as $n^{obs}{}_{Bs}$)

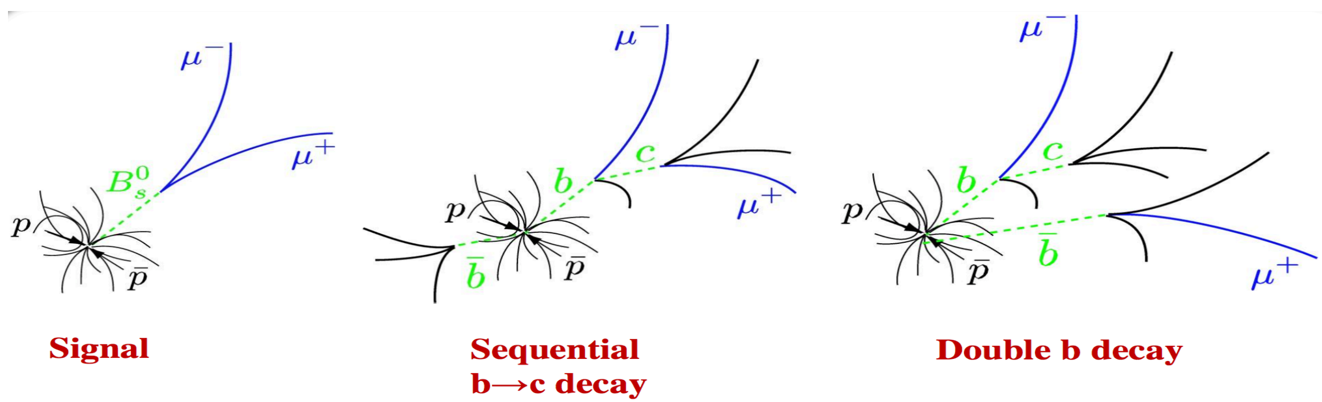
- Calibrate MC with reconstructed exclusive decays
  -> $B^+ \to J/\psi\, K^+$: normalization with high
  $B_s^0 \to J/\psi\, \phi$: B_s^0 signal MC: Used to validate MC simulation and to evaluate effects from differences in fragmentation between B^+ and B_s^0
- The efficiencies of all samples including detector acceptance are studied using MC
- Finally, the total data sample is split into sub-samples based on different criteria, e.g. in CMS the data are separated based on whether it is barrel or end cap event

Analysis strategy

- **Signal $B_s \rightarrow \mu^+\mu^-$:**
  - -> Two muons from one decay vertex
  - -> well reconstructed secondary vertex
  - -> momentum aligned with flight direction
  - -> mass around m ($B_{s/d}$)
  - -> blind analysis

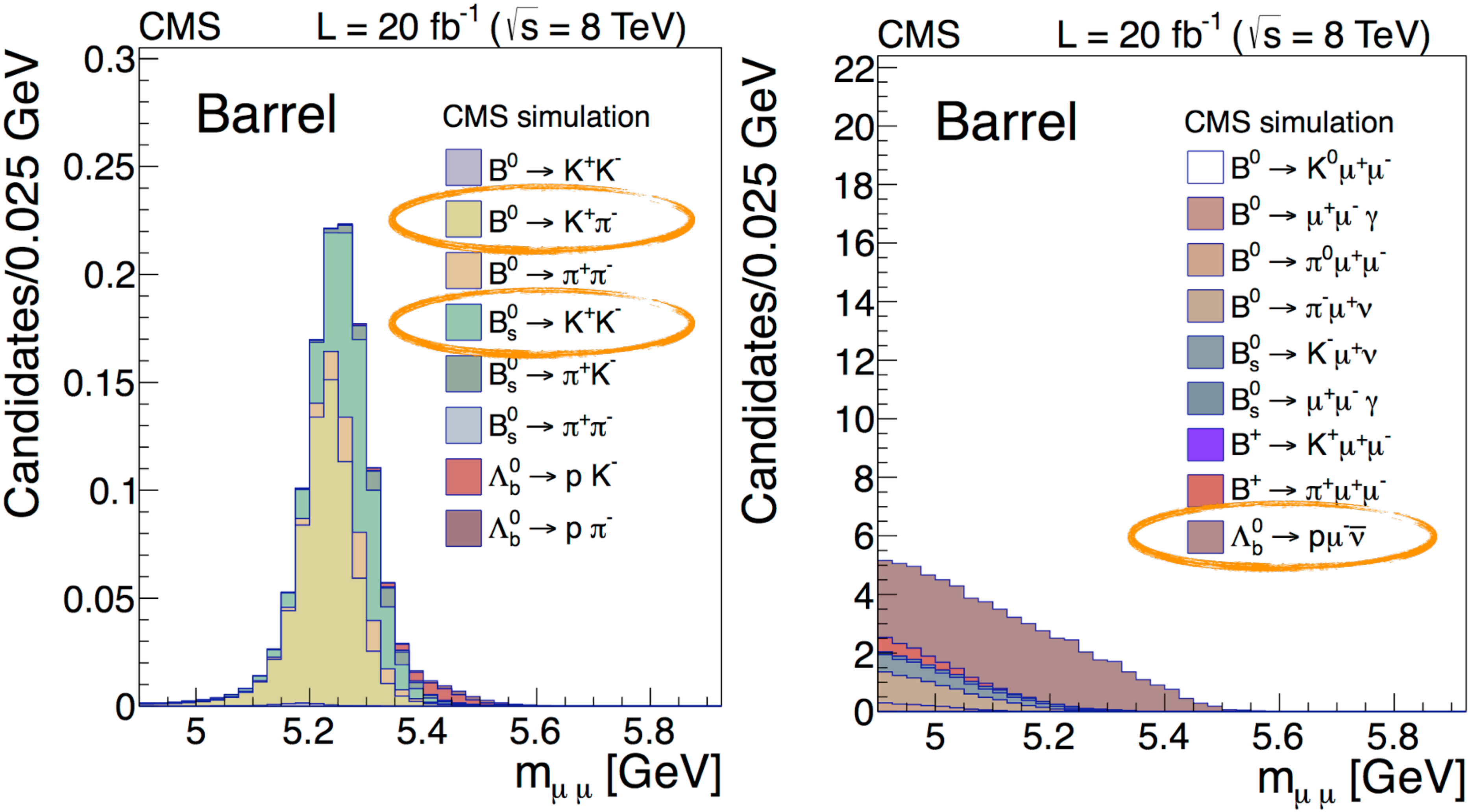


- **Background:**
  1. Combinatorial (from sideband of $B_{s/d}$-mass)
     - -> two semi-leptonic B-decays
     - -> One semi-leptonic and one hadronic B-decay
  2. Rare single B-decays (from MC simulation)
     - -> peaking background, e.g. $B_s^0 \rightarrow K^+K^-$
     - -> non-peaking background, e.g. $B_s^0 \rightarrow K^-\mu^+\nu$, $\Lambda_b \rightarrow p\mu^+\nu$



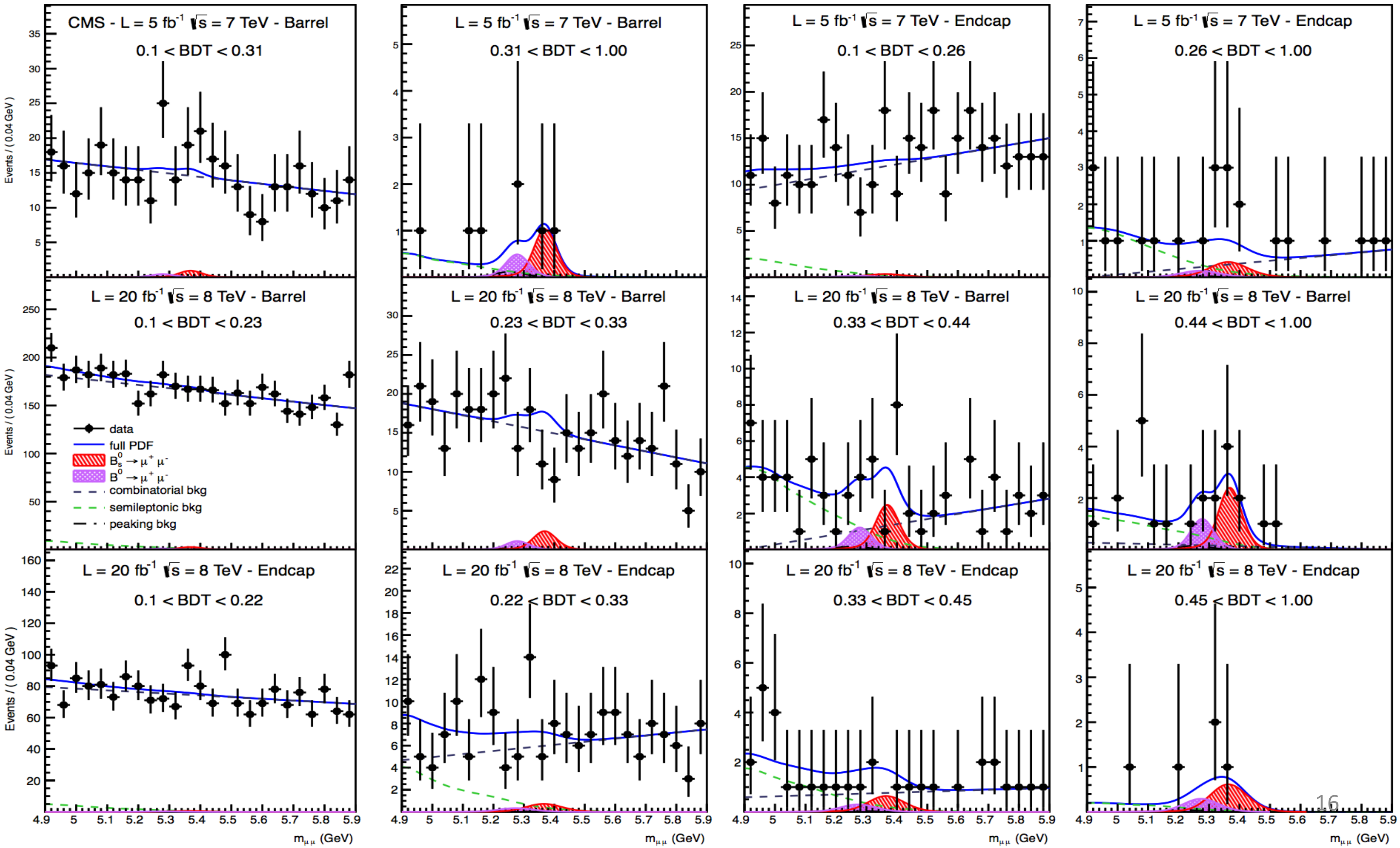
Backgrounds for $B \to \mu^+\mu^-$

- Understanding the background is very important to this kind of rare decay mode
- Plots below show peaking and non-peaking backgrounds



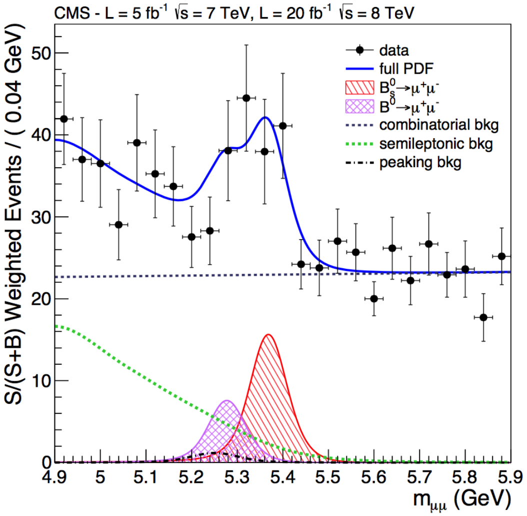
Invariant $\mu^+\mu^-$ mass

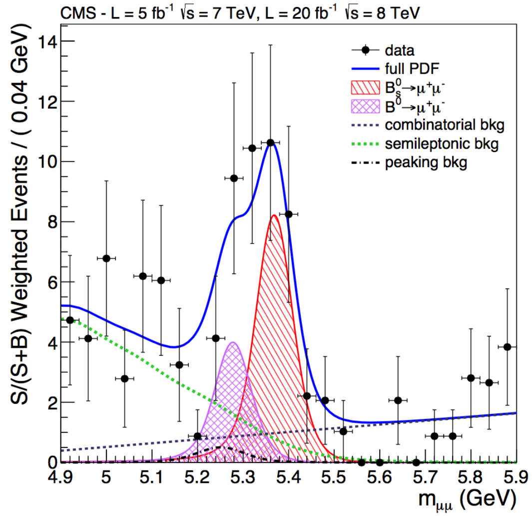
- The dimuon mass is further sub-divided into (apart from barrel and end cap in 7 TeV & 8 TeV) bins of BDT (boosted decision tree) discriminant. Uses 5fb^{-1} with 7 TeV and 20fb^{-1} with 8 TeV data.

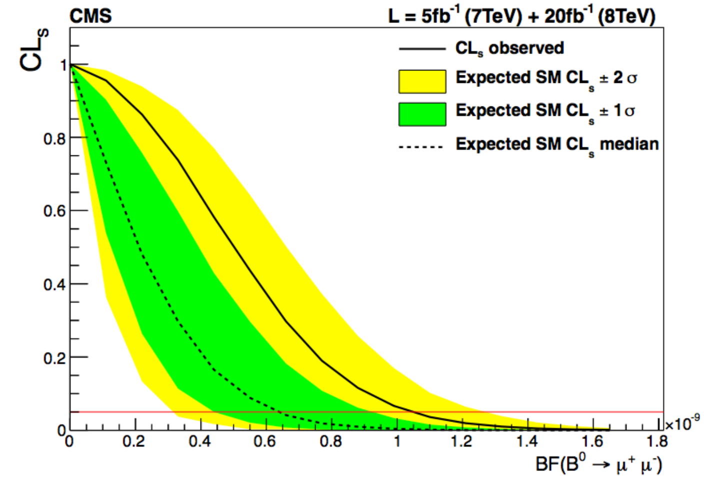


CMS results for $B \to \mu^+\mu^-$

PRL 111 (2013) 101804







		$\varepsilon_{tot}[10^{-2}]$	N^{exp}_{signal}	N^{exp}_{total}	N_{obs}
7 TeV	B^0 Barrel	(0.33 ± 0.03)	0.27 ± 0.03	1.3 ± 0.8	3
	B^0_s Barrel	(0.30 ± 0.04)	2.97 ± 0.44	3.6 ± 0.6	4
	B^0 Endcap	(0.20 ± 0.02)	0.11 ± 0.01	1.5 ± 0.6	1
	B^0_s Endcap	(0.20 ± 0.02)	1.28 ± 0.19	2.6 ± 0.5	4
8 TeV	B^0 Barrel	(0.24 ± 0.02)	1.00 ± 0.10	7.9 ± 3.0	11
	B^0_s Barrel	(0.23 ± 0.03)	11.46 ± 1.72	17.9 ± 2.8	16
	B^0 Endcap	(0.10 ± 0.01)	0.30 ± 0.03	2.2 ± 0.8	3
	B^0_s Endcap	(0.09 ± 0.01)	3.56 ± 0.53	5.1 ± 0.7	4

$B_s \to \mu\mu$ significance: 4.3 σ

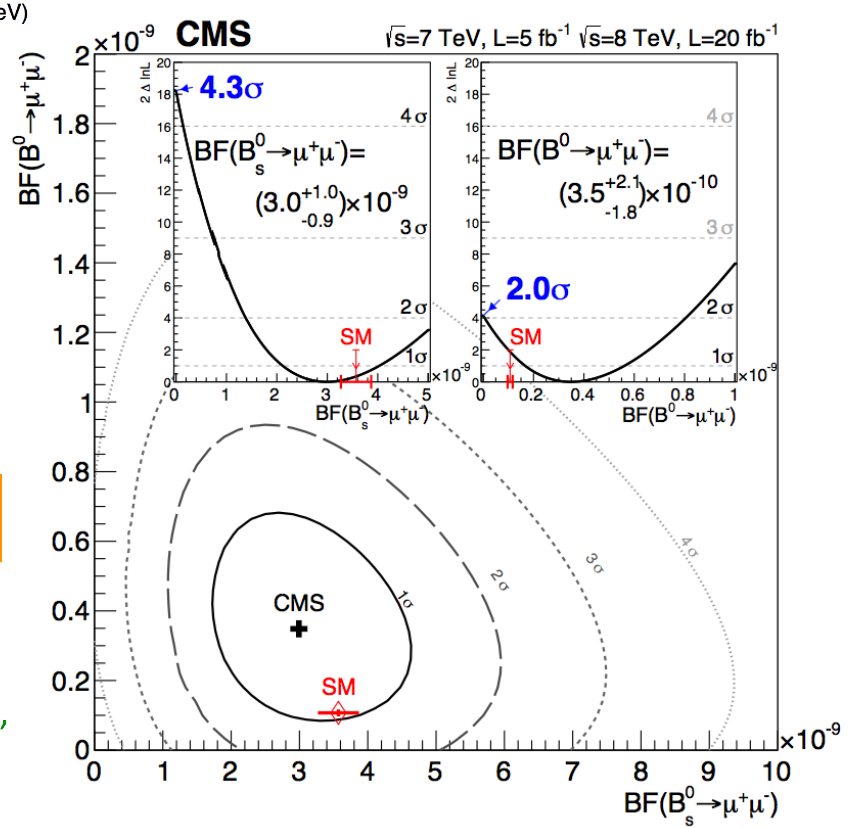
$$BR(B_s \to \mu\mu) = \left(3.0^{+0.9}_{-0.8}\ (\text{stat})^{+0.6}_{-0.4}\ (\text{syst})\right) \times 10^{-9}$$

$B_d \to \mu\mu$ significance: 2.0 σ

$$BR(B_d \to \mu\mu) = \left(3.5^{+2.1}_{-1.8}\ (\text{stat+syst})\right) \times 10^{-10}$$

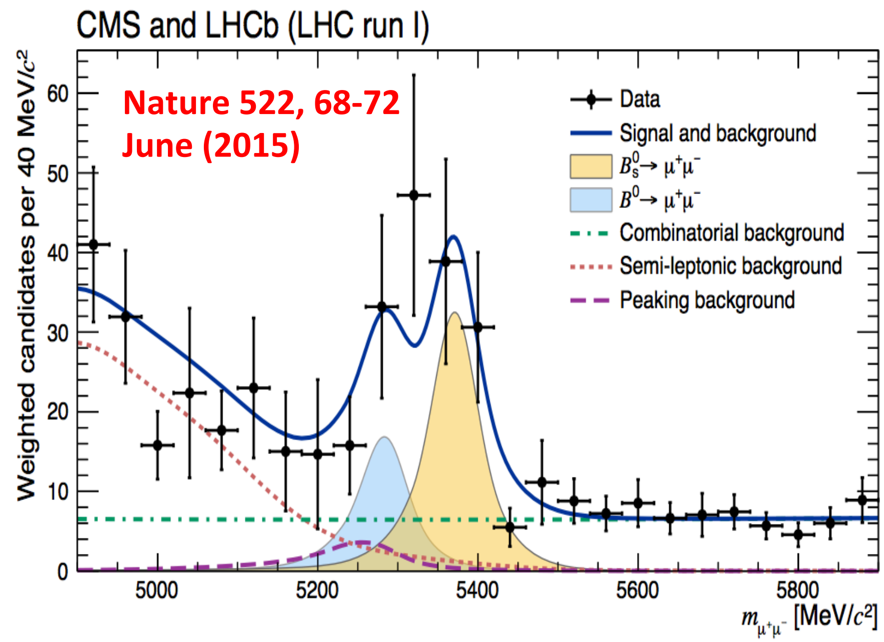
$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$
$\mathcal{B}(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

Ref: Bobeth et al, PRL 112, 101801 (2014)



CMS & LHCb combination for $B \to \mu^+\mu^-$

- **Both CMS & LHCb data are simultaneously fitted with BFs as common free parameters**
- **An un-binned maximum likelihood fit to the di-muon invariant mass is done over all BDT bins (12 bins for CMS and 8 bins for LHCb)**

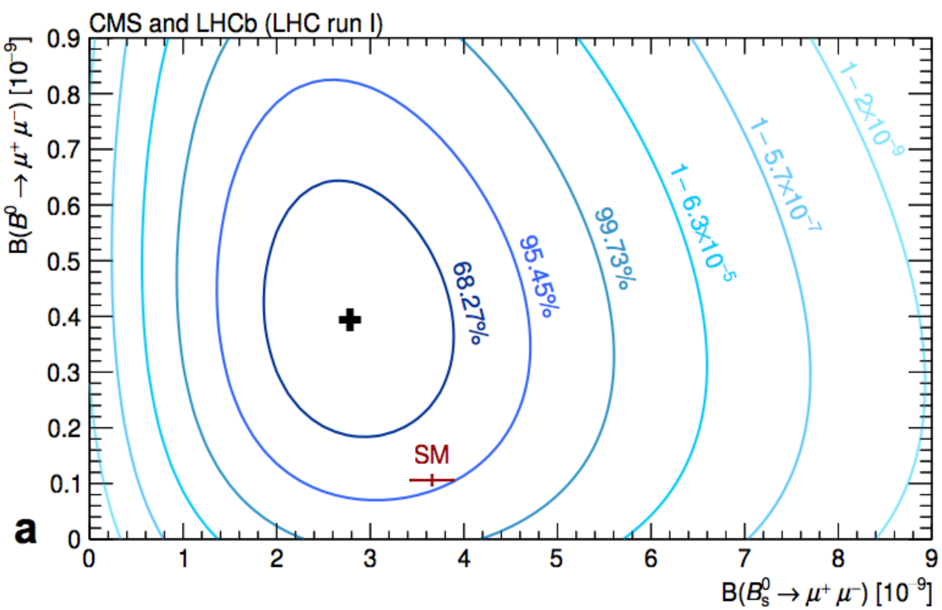


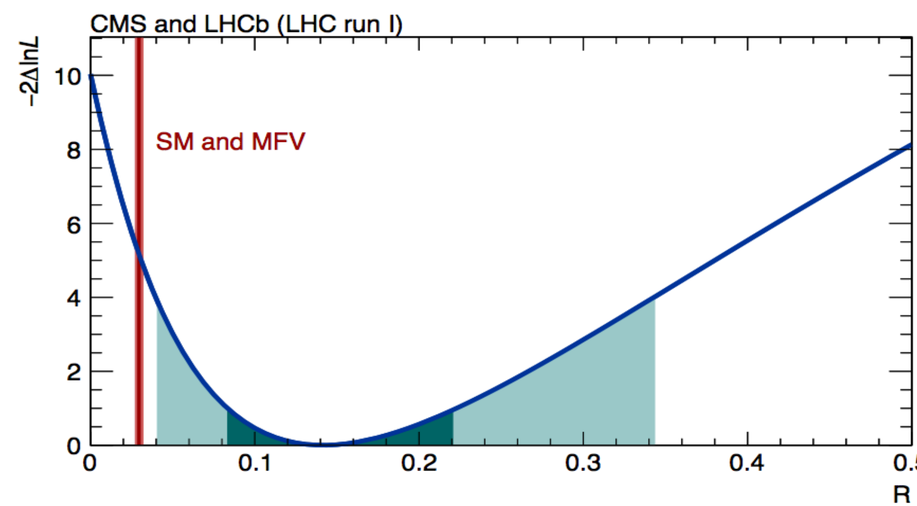
Observed branching fraction:

$BR(B^0_s) = (2.8^{+0.7}_{-0.60}) \times 10^{-9}$ (35% syst) 6.2σ observed

$BR(B^0) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$ (18% syst) 3.0σ **evidence**

SM compatibility: 1.2σ for B_s and 2.2σ for B^0

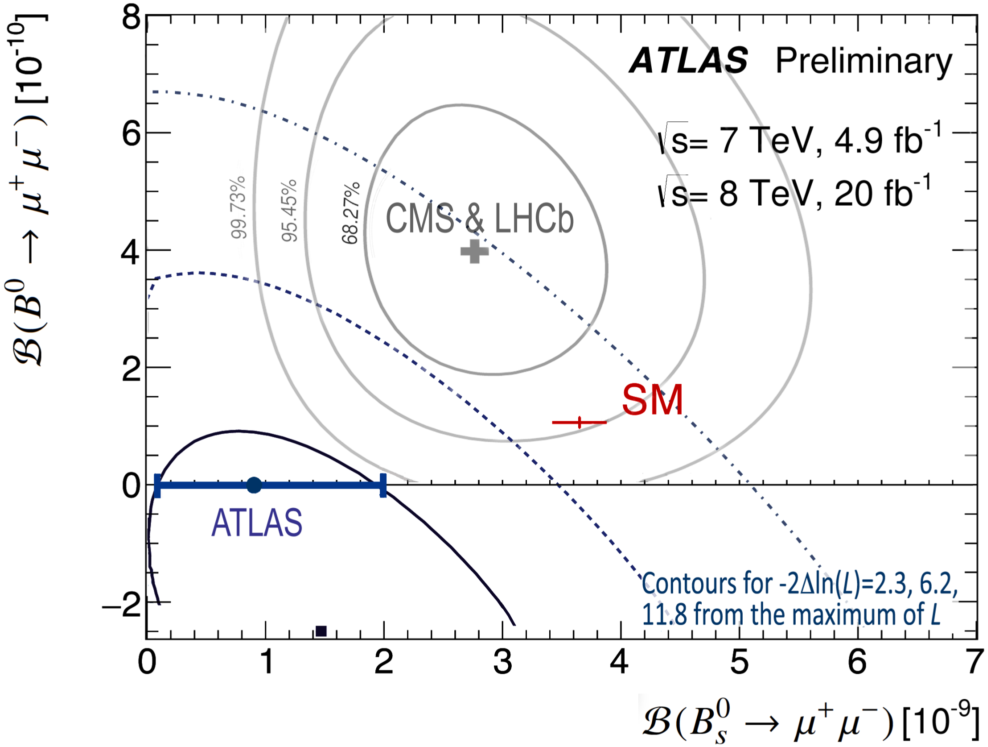




$\mathcal{R} \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)_{SM}/\mathcal{B}(B^0_s \to \mu^+\mu^-)_{SM} = 0.0295^{+0.0028}_{-0.0025}$

Experiment $\mathcal{R} = 0.14^{+0.08}_{-0.06}$ **(2.3σ away from SM)**

ATLAS result on $B_s \rightarrow \mu^+\mu^-$



Using the data collected in Run-1, ATLAS showed preliminary results on the rare decays of B^0_s and B^0 into muon pairs.

For B^0_s:

- $BR(B^0_s \to \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9}$
- $< 3.0 \times 10^{-9}$ at 95% CL (from CL_s)

For B^0:

- $BR(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10}$ at 95% CL (from CL_s)
- The limit is above the SM prediction
- and reaches the central value of the CMS & LHCb combination $BR(B^0)_{CMS\&LHCB} = (3.9^{+1.6}_{-1.4})\times 10^{-10}$.

The compatibility with the SM, for the simultaneous fit, is 2.0 σ .

NP constraints with $B \to \mu^+\mu^-$

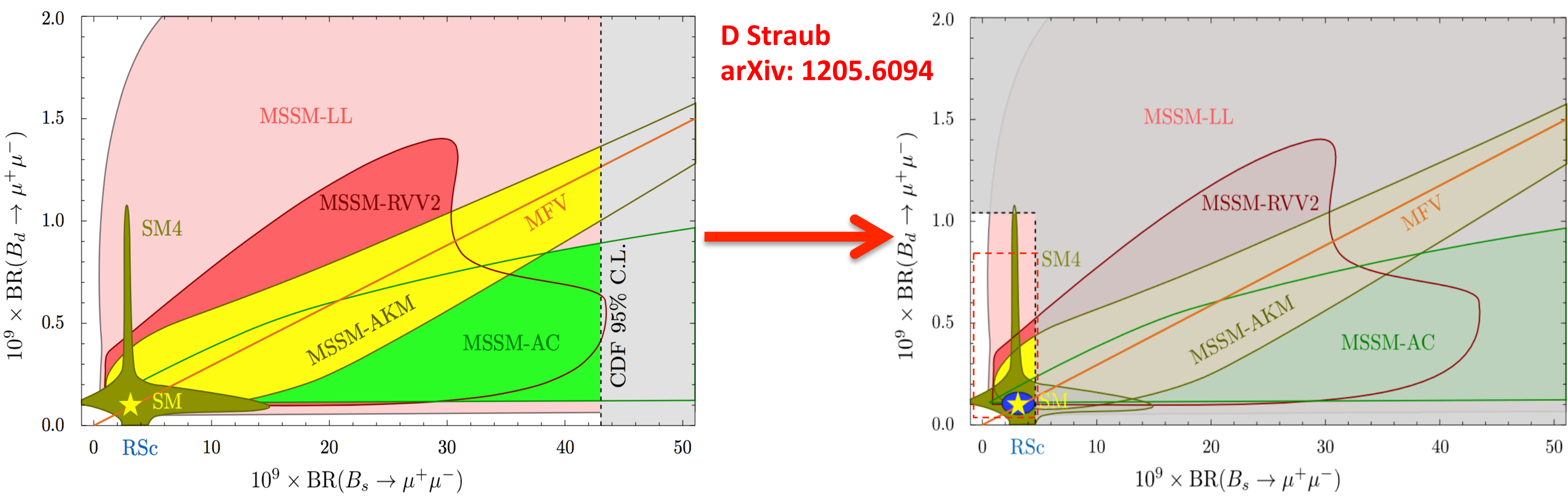
- NP can enter through the Wilson coefficient (C_i's) of operators in effective Hamiltonian

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

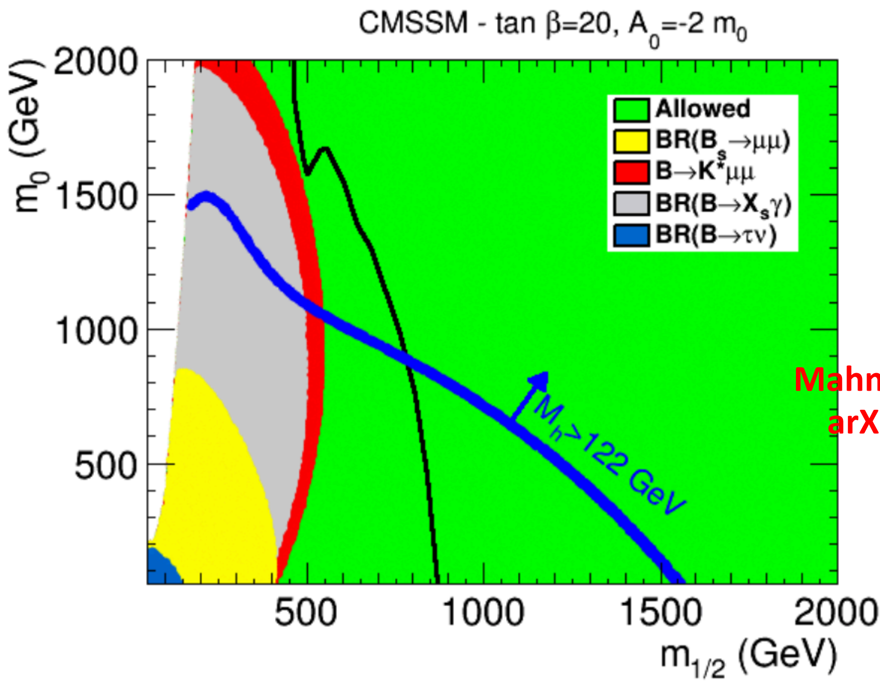
$$O_S^{(\prime)} = \frac{m_b}{m_{B_s}} (\bar{s} P_{R(L)} b)(\bar{\ell}\ell)$$

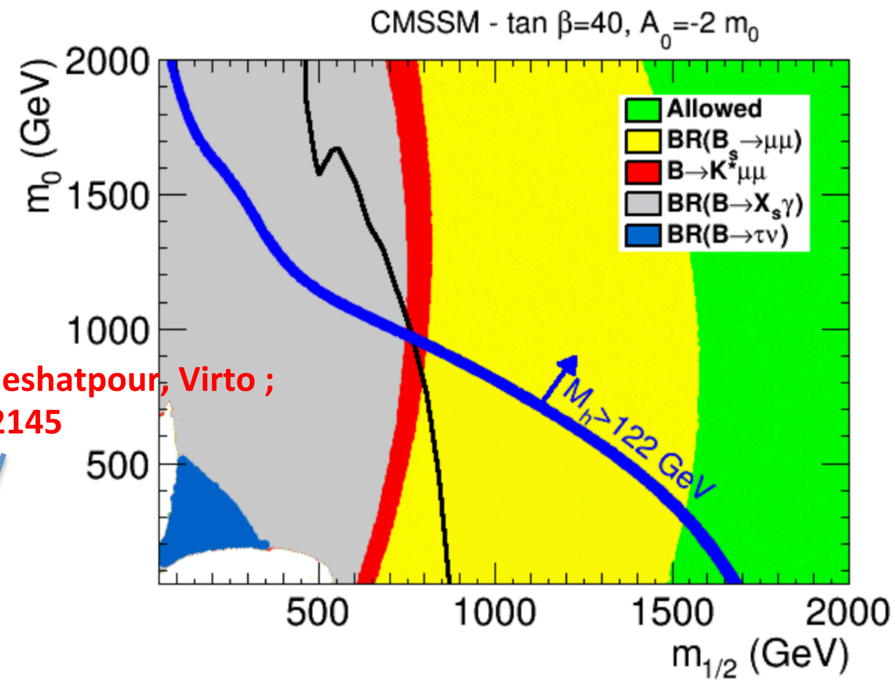
$$O_P^{(\prime)} = \frac{m_b}{m_{B_s}} (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell)$$

- The BF for $B \to \mu^+\mu^-$ can be enhanced in the presence of NP in the scalar or pseudoscalar operators, which can lift the helicity suppression.
- Can create some correlation among different decay modes such as $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$
- A large part of parameter space of SUSY models with large tanβ are ruled out.
- However, SM4 or RSc or SUSY models with low tanβ is to be probed now.
- For example, SM4 is ruled out if enhancement in both $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ is observed.



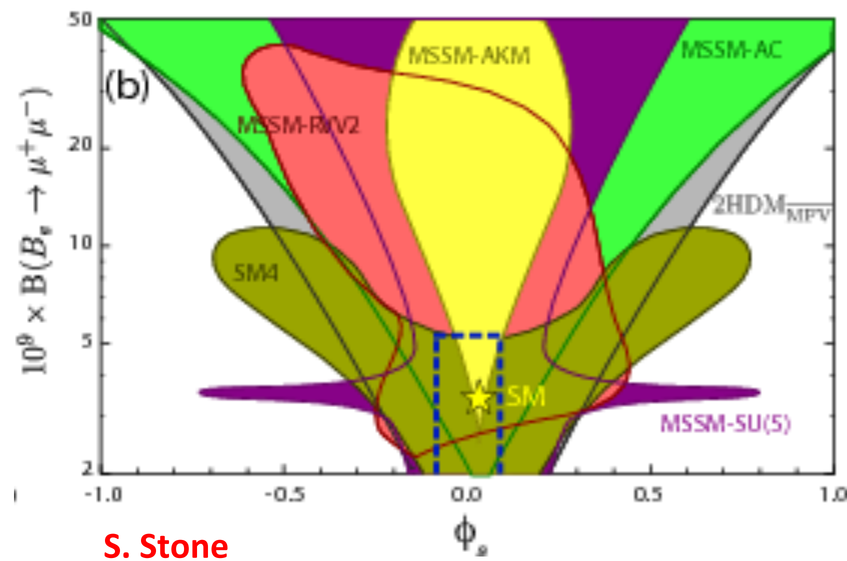
NP constraints with $B \to \mu^+\mu^-$





Mahmoudi, Neshatpour, Virto ; arXiv1401.2145

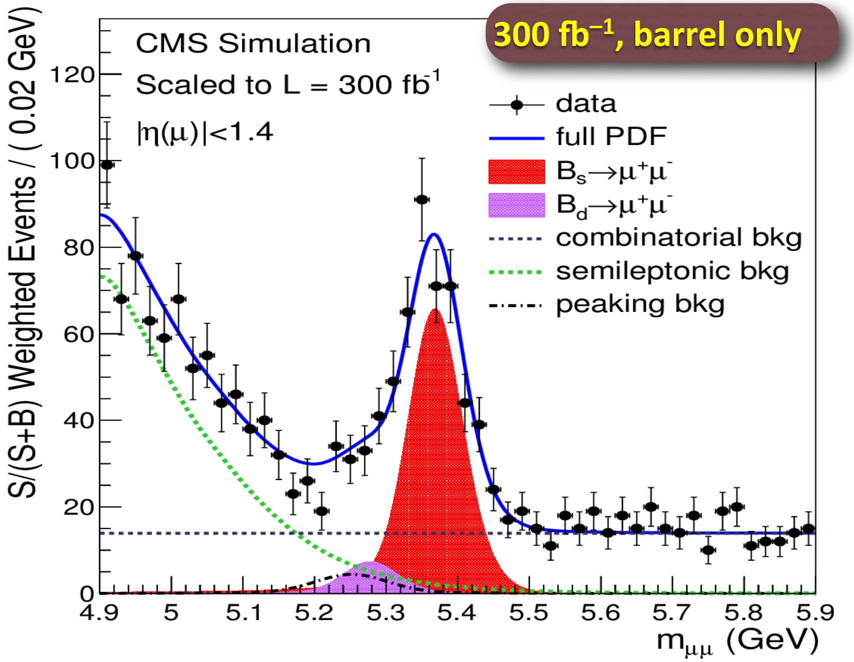
- Takes different experimental measurements
- Constrains $m_{1/2}$ and m_0 SUSY parameter space
- Trilinear soft breaking parameter $A_0 = -2m_0$ is chosen to keep consistency with observed Higgs mass
- Constraints from $B_s \to \mu^+\mu^-$ at large tanβ are stronger than lower tanβ (also to direct search)
- Plot on the right shows the allowed region by $B_s \to \mu^+\mu^-$ BF measurement and the mixing induced CP asymmetry (ϕ_s)

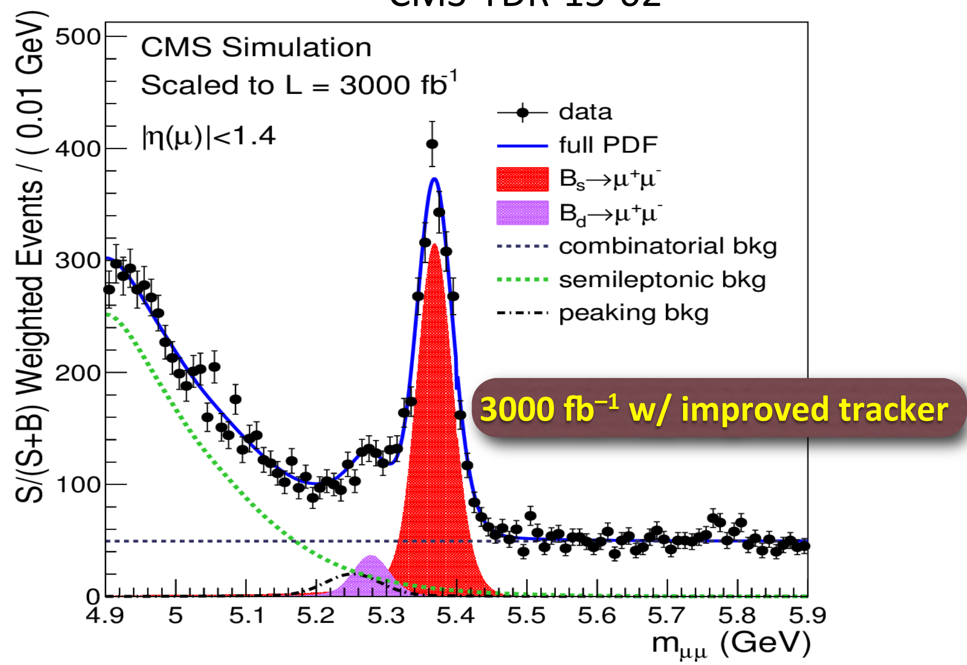


S. Stone
arxiv: 1212.6374

CMS future prediction

CMS-PAS-FTR-14-015
CMS-TDR-15-02





$\mathcal{L}(fb^{-1})$	$N(\mathrm{B}_s)$	$N(\mathrm{B}^0)$	$\delta\mathcal{B}(\mathrm{B}_s \to \mu\mu)$	$\delta\mathcal{B}(\mathrm{B}^0 \to \mu\mu)$	B^0 sign.	$\delta\frac{\mathcal{B}(\mathrm{B}^0 \to \mu\mu)}{\mathcal{B}(\mathrm{B}_s \to \mu\mu)}$
20	18.2	2.2	35%	>100%	0.0-1.5 σ	>100%
100	159	19	14%	63%	0.6-2.5 σ	66%
300	478	57	12%	41%	1.5-3.5 σ	43%
300 (barrel)	346	42	13%	48%	1.2-3.3 σ	50%
3000 (barrel)	2250	271	11%	18%	5.6-8.0 σ	21%

- **Expectation assuming SM branching fraction and planned detector upgrade.**
- **Large pile up will affect detection efficiency, tightening selection criteria, reduce background, better determination of peaking background.**

Measurement of B->$K^{*0}\mu^+\mu^-$ at CMS

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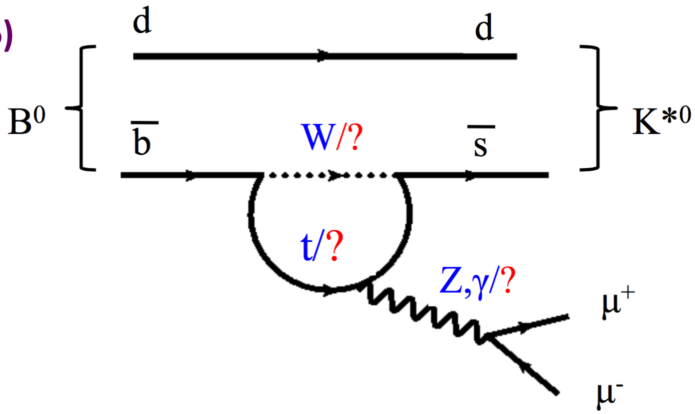
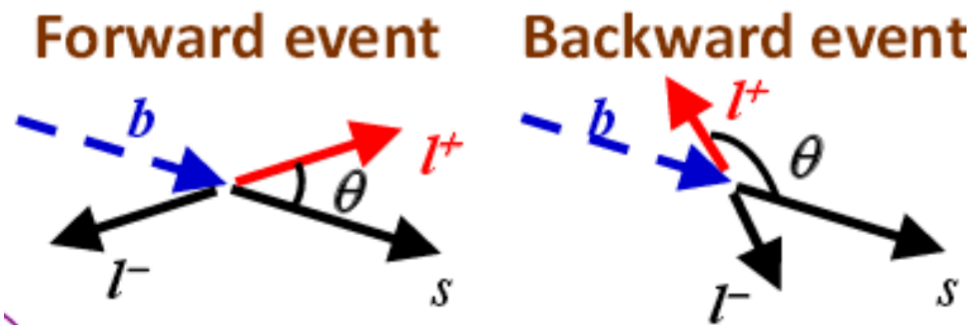
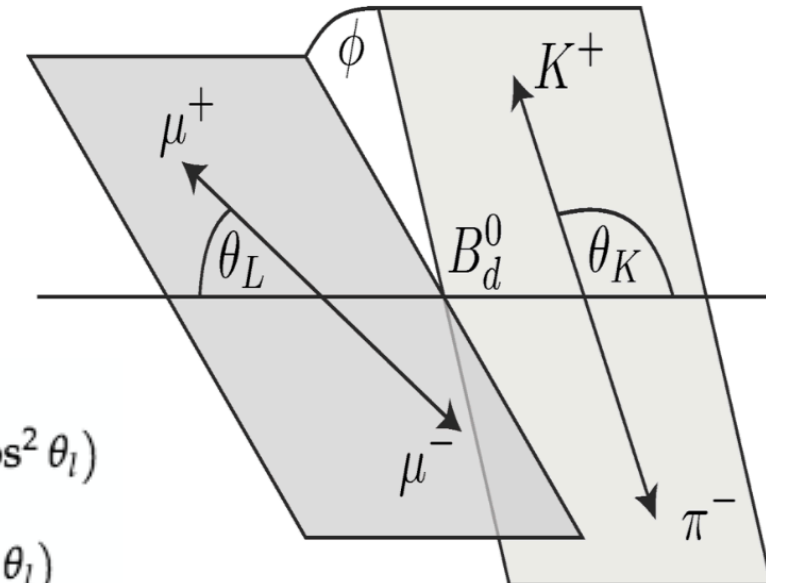
- Forbidden at tree level, but allowed via loop diagrams (as shown on the right)
- Sensitive to NP through BSM particles in the loop
- Small branching fraction (10^{-6}) .
- Observables to compare with SM predictions: differential BF, A_{FB}, A_{CP}, P_5', Isospin asymmetry…







$$\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_K\, d\cos\theta_l\, dq^2} = \frac{9}{16}\Big\{\frac{2}{3}\left[F_S + A_S\cos\theta_K\right]\left(1-\cos^2\theta_l\right) + (1-F_S)\left[2F_L\cos^2\theta_K\left(1-\cos^2\theta_l\right) + \frac{1}{2}(1-F_L)\left(1-\cos^2\theta_K\right)\left(1+\cos^2\theta_l\right) + \frac{4}{3}A_{FB}\left(1-\cos^2\theta_K\right)\cos\theta_l\right]\Big\}.$$

Measurement of B->$K^{*0}\mu^+\mu^-$ at CMS

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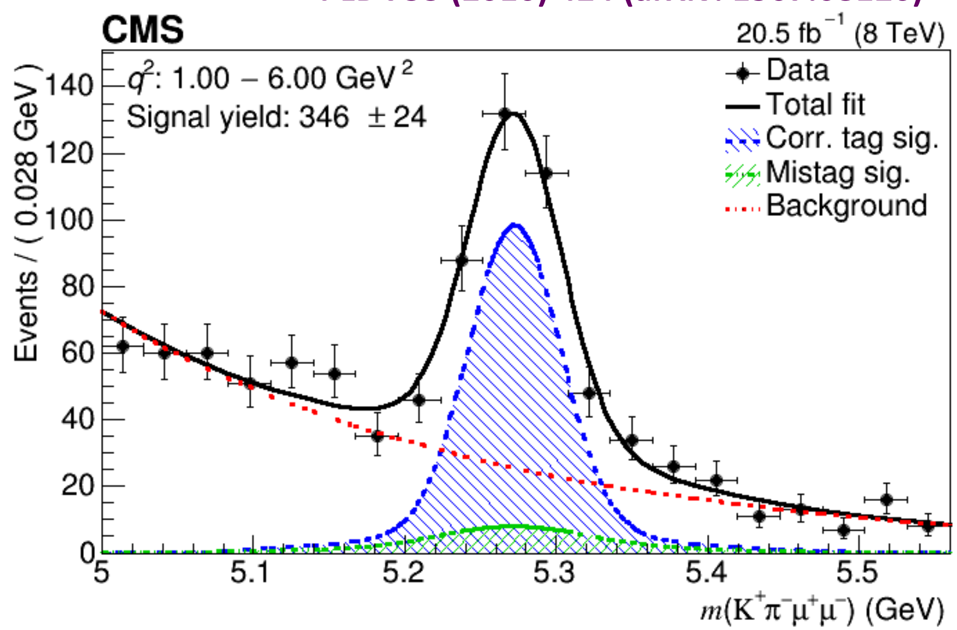
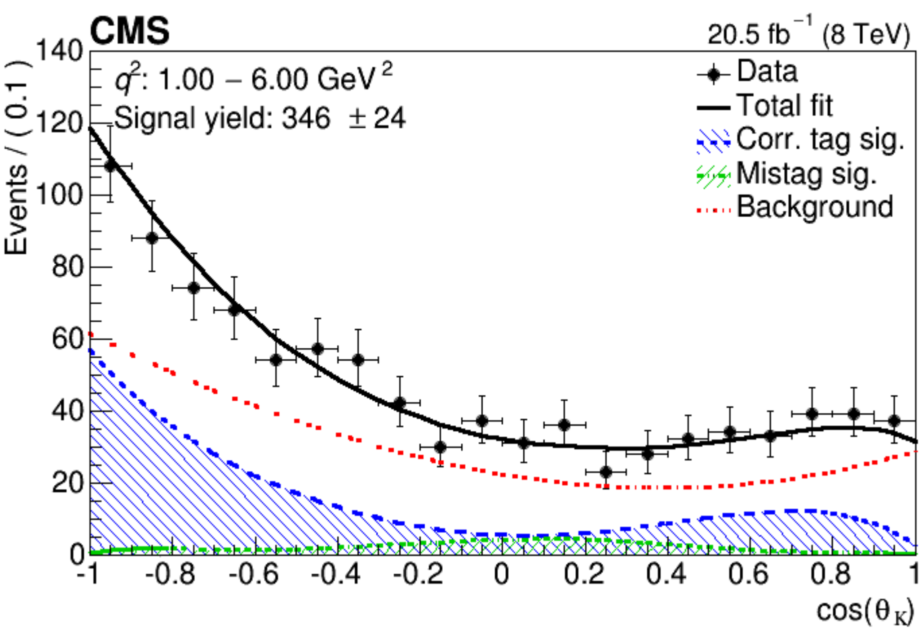
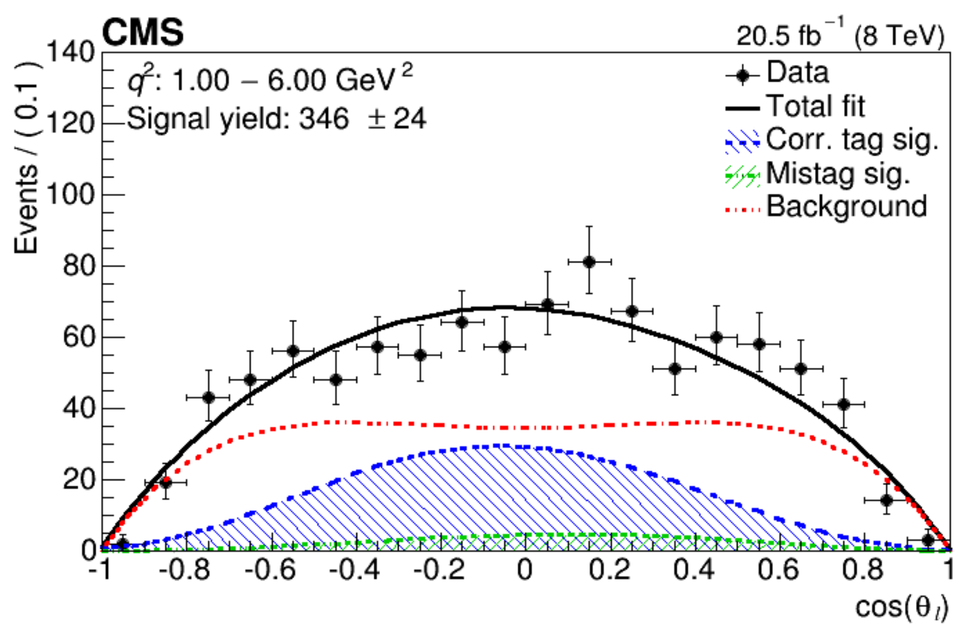
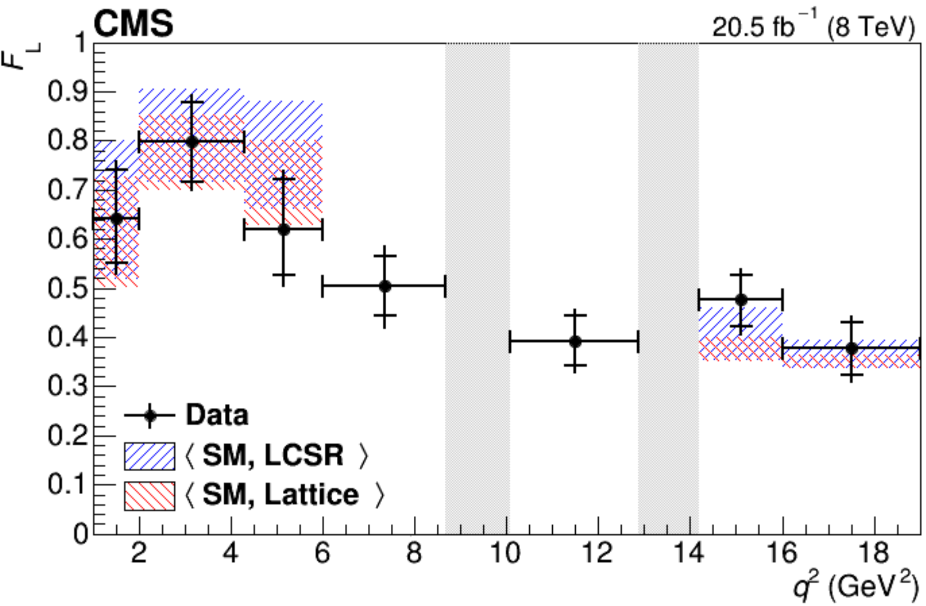
- Unbinned maximum likelihood fit to three variables: $m(K^+\pi^-\mu^+\mu^-)$ and two angular variables θ_K and θ_L in each q2 bins.
- Signal (correctly tagged)
- Signal (wrongly tagged)
- Combinatorial background
- we are interested in p-wave components

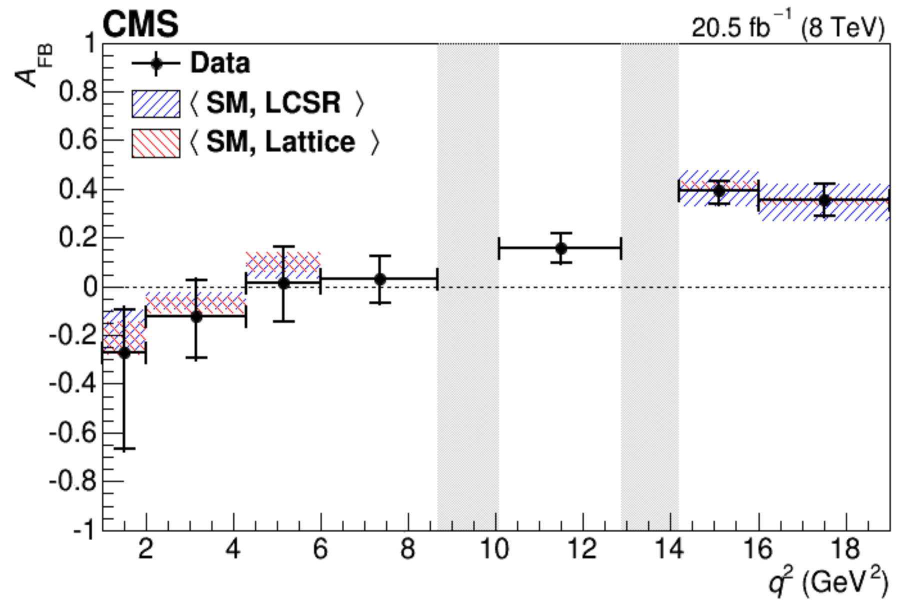




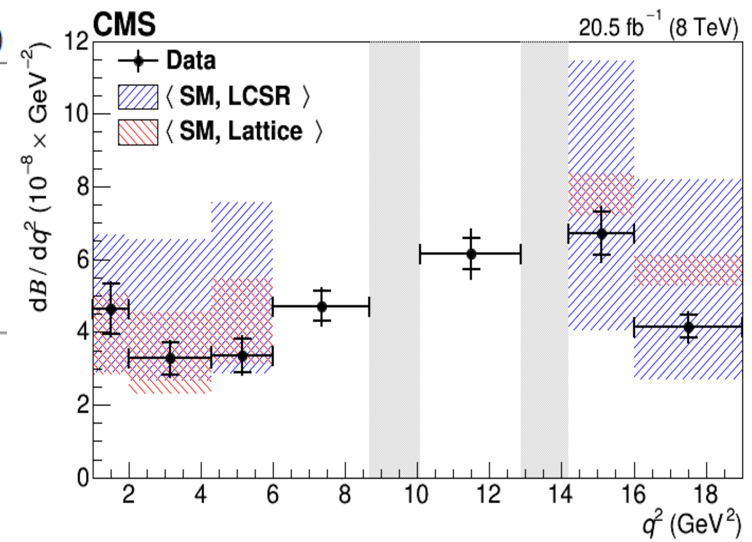


B->$K^{*0}\mu^+\mu^-$ at CMS (cont.)





Experiment	F_L	A_{FB}	$d\mathcal{B}/dq^2$ (10^{-8} GeV^{-2})
CMS (7 TeV)	$0.68 \pm 0.10 \pm 0.02$	$-0.07 \pm 0.12 \pm 0.01$	$4.4 \pm 0.6 \pm 0.4$
CMS (8 TeV, this analysis)	$0.73 \pm 0.05 \pm 0.04$	$-0.16^{+0.10}_{-0.09} \pm 0.05$	$3.6 \pm 0.3 \pm 0.2$
CMS (7 TeV + 8 TeV)	0.72 ± 0.06	-0.12 ± 0.08	3.8 ± 0.4
LHCb	$0.65^{+0.08}_{-0.07} \pm 0.03$	$-0.17 \pm 0.06 \pm 0.01$	$3.4 \pm 0.3^{+0.4}_{-0.5}$
BaBar	—	—	$4.1^{+1.1}_{-1.0} \pm 0.1$
CDF	$0.69^{+0.19}_{-0.21} \pm 0.08$	$0.29^{+0.20}_{-0.23} \pm 0.07$	$3.2 \pm 1.1 \pm 0.3$
Belle	$0.67 \pm 0.23 \pm 0.05$	$0.26^{+0.27}_{-0.32} \pm 0.07$	$3.0^{+0.9}_{-0.8} \pm 0.2$
SM (LCSR)	$0.79^{+0.09}_{-0.12}$	$-0.02^{+0.03}_{-0.02}$	$4.6^{+2.3}_{-1.7}$
SM (Lattice)	$0.73^{+0.08}_{-0.10}$	$-0.03^{+0.04}_{-0.03}$	$3.8^{+1.2}_{-1.0}$



CMS results consistent with theory prediction as well as other experimental results.

Summary

- The 13/8TeV results from CMS are consistent with theory prediction.
- CMS and LHCb reported a first observation of $B_s \to \mu^+\mu^-$ (6.2σ from combined data). The measured BF is compatible with SM prediction (within 1.2σ)
- Combined result reported first evidence of $B^0 \to \mu^+\mu^-$. The measurement is compatible with SM within 2.2σ
- The result provides strong constraint to the NP parameter spaces.
- However, we look forward for new (13 TeV & 14 TeV) datasets to give us $B^0 \to \mu^+\mu^-$ observation soon.
- B->$K^{*0}\mu^+\mu^-$ results are consistent with theory prediction as well as other experiments.
- The next few years would be very crucial for LHC to look for something beyond SM.