Rare B-decays at CMS

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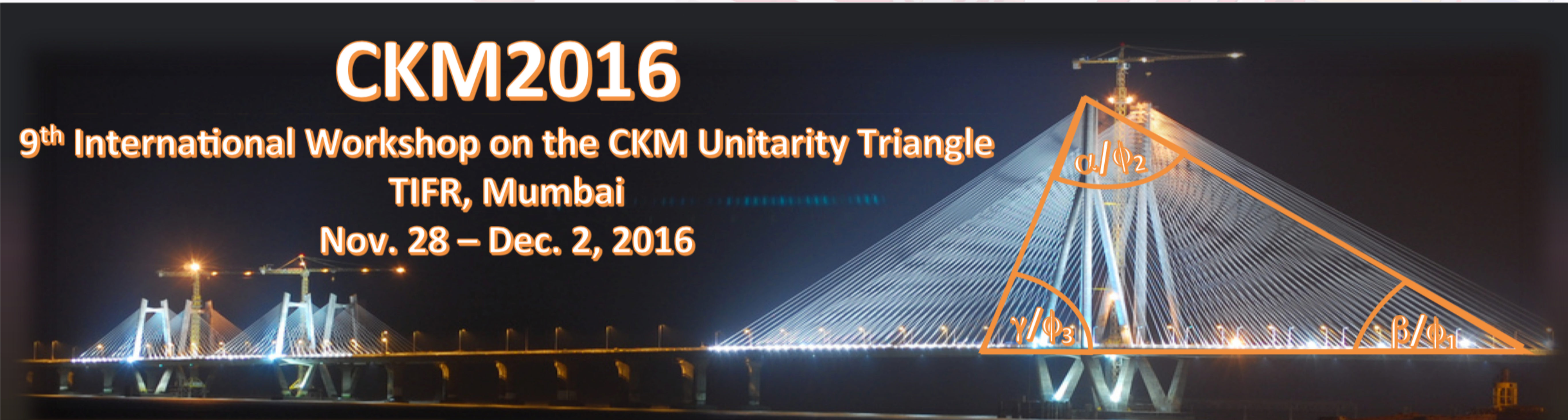
for the CMS collaboration

2016/11/28

- Introduction
- Initial B results with 13 TeV 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 in particle physics.

There are many unsolved questions in this sector (listing here 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 ?

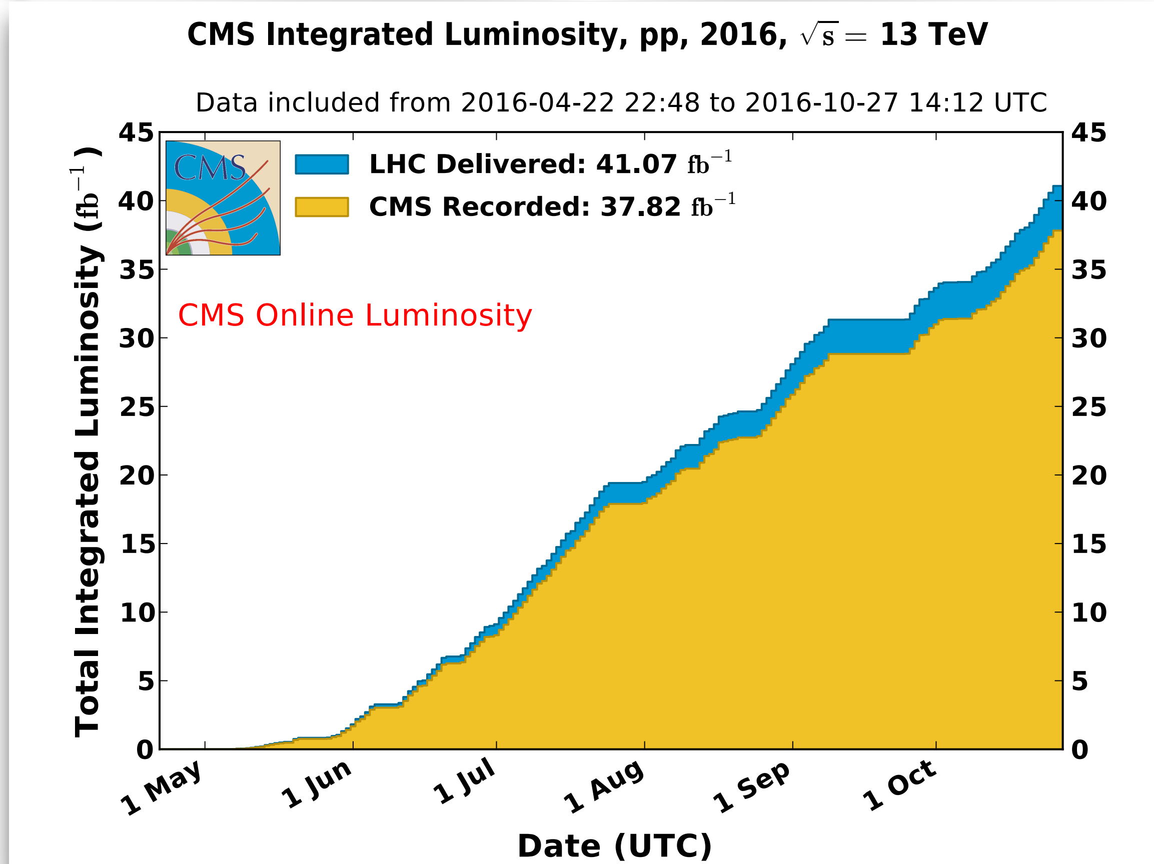
LHC era is very important to pin down some of the flavor questions.

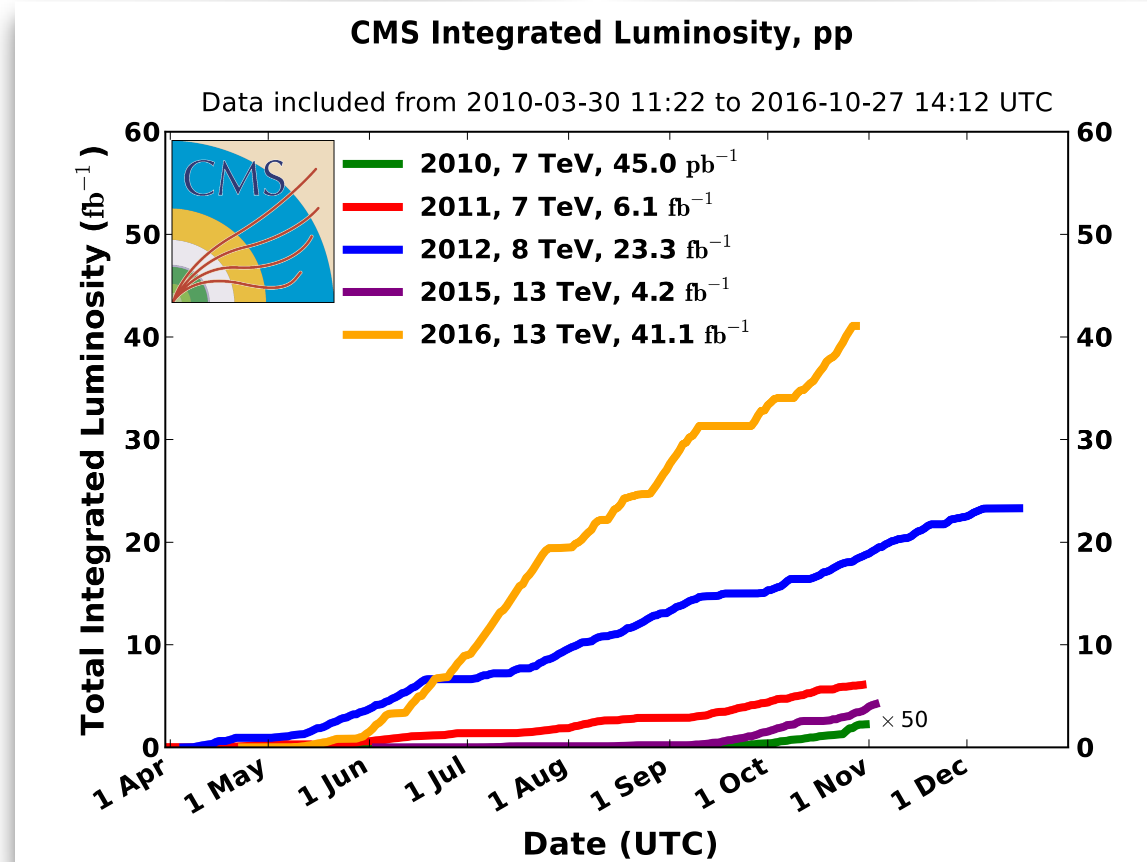
Two ways to probe the New Physics (NP):

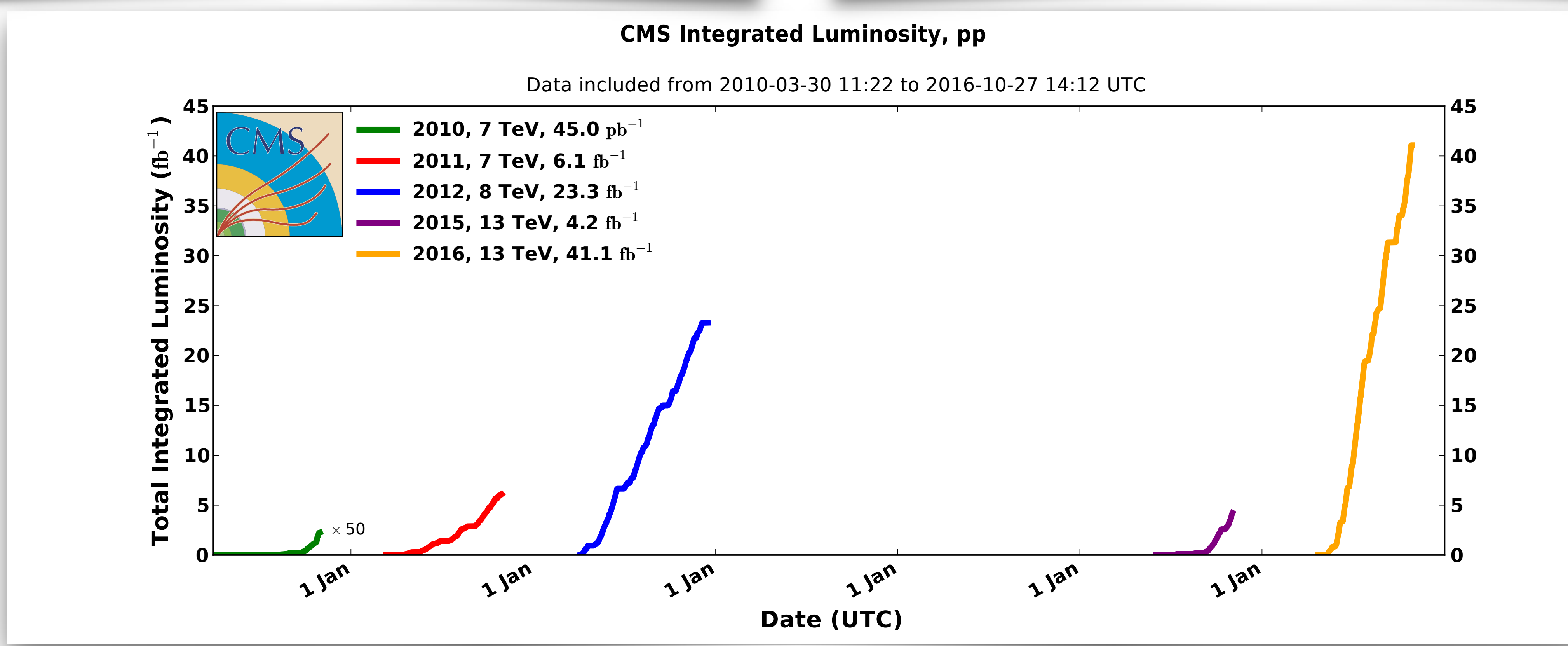
- ☞ Direct Search:
  produce the new heavy particles beyond the standard model (**SM**).
  The production cross-section are usually very small.

- ☞ Indirect Search:
  measure observables of SM processes (mainly **rare decay** processes).
  any significant deviation from SM prediction would be a hint of NP.

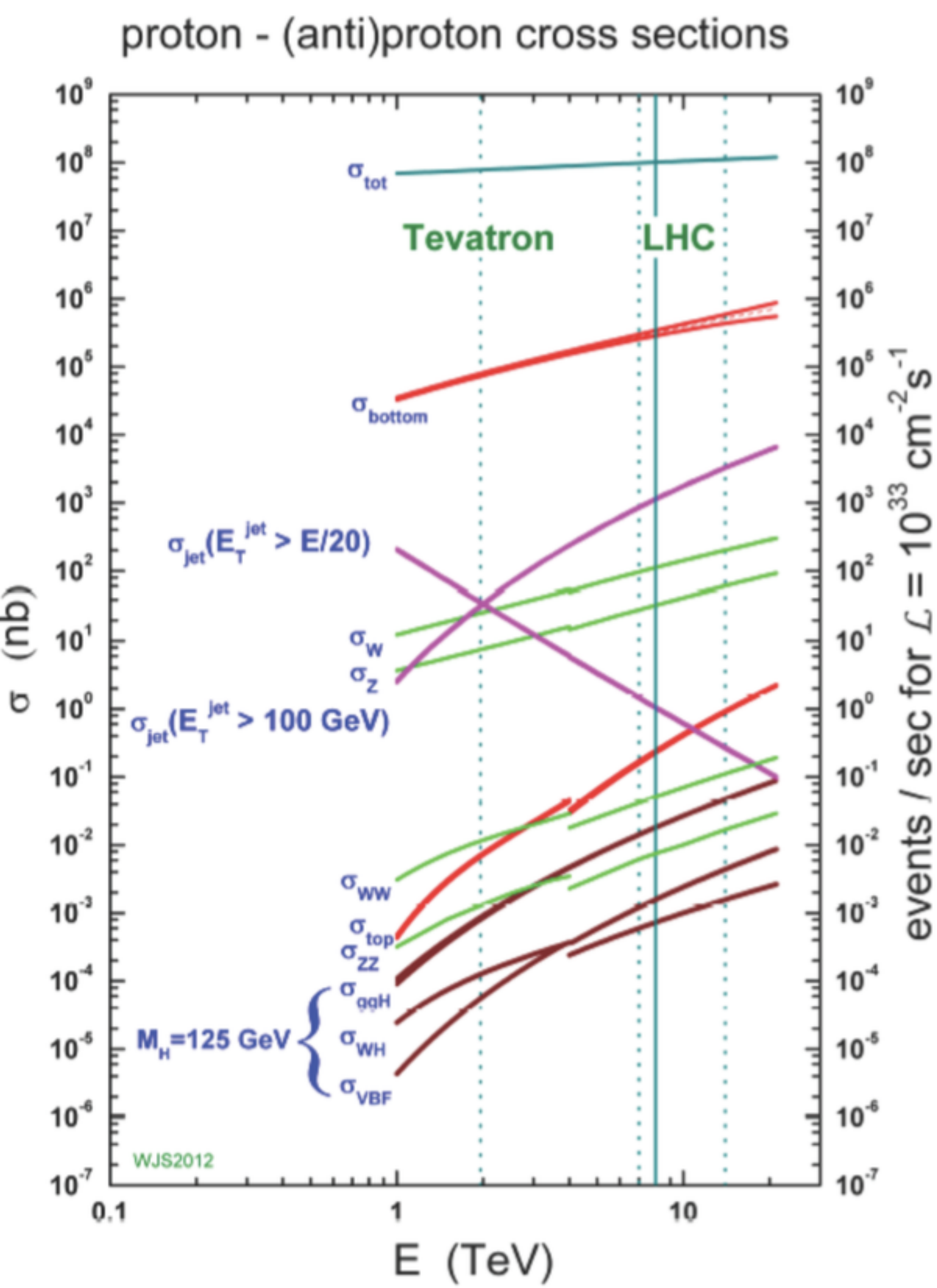
LHC and CMS performance



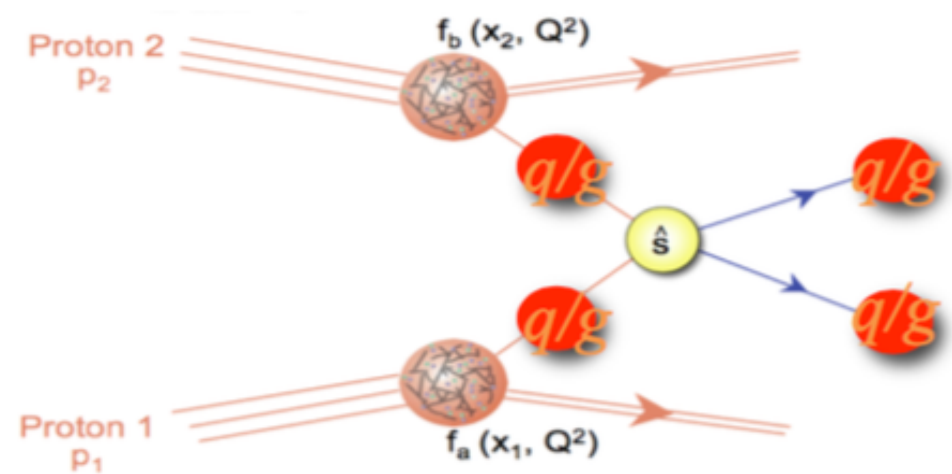




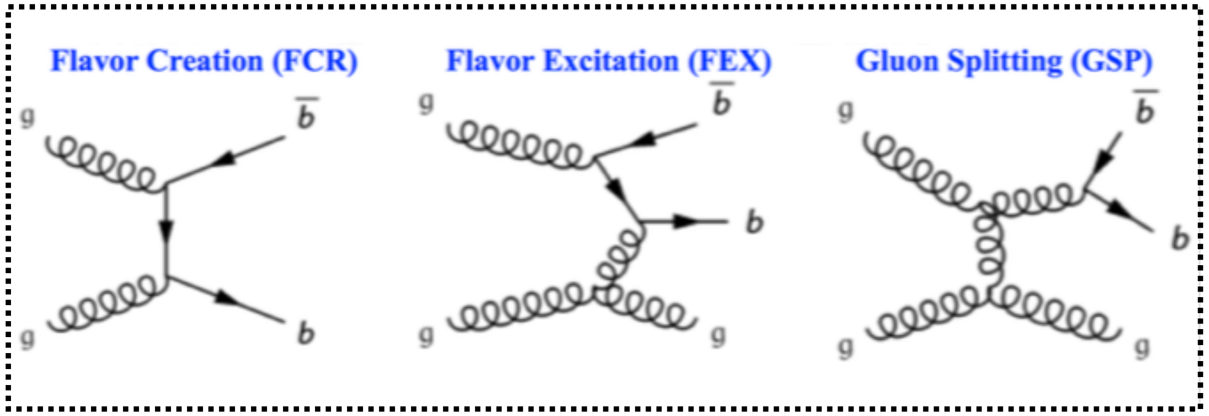
Why we can do better at higher energy ?



- because of large production rate



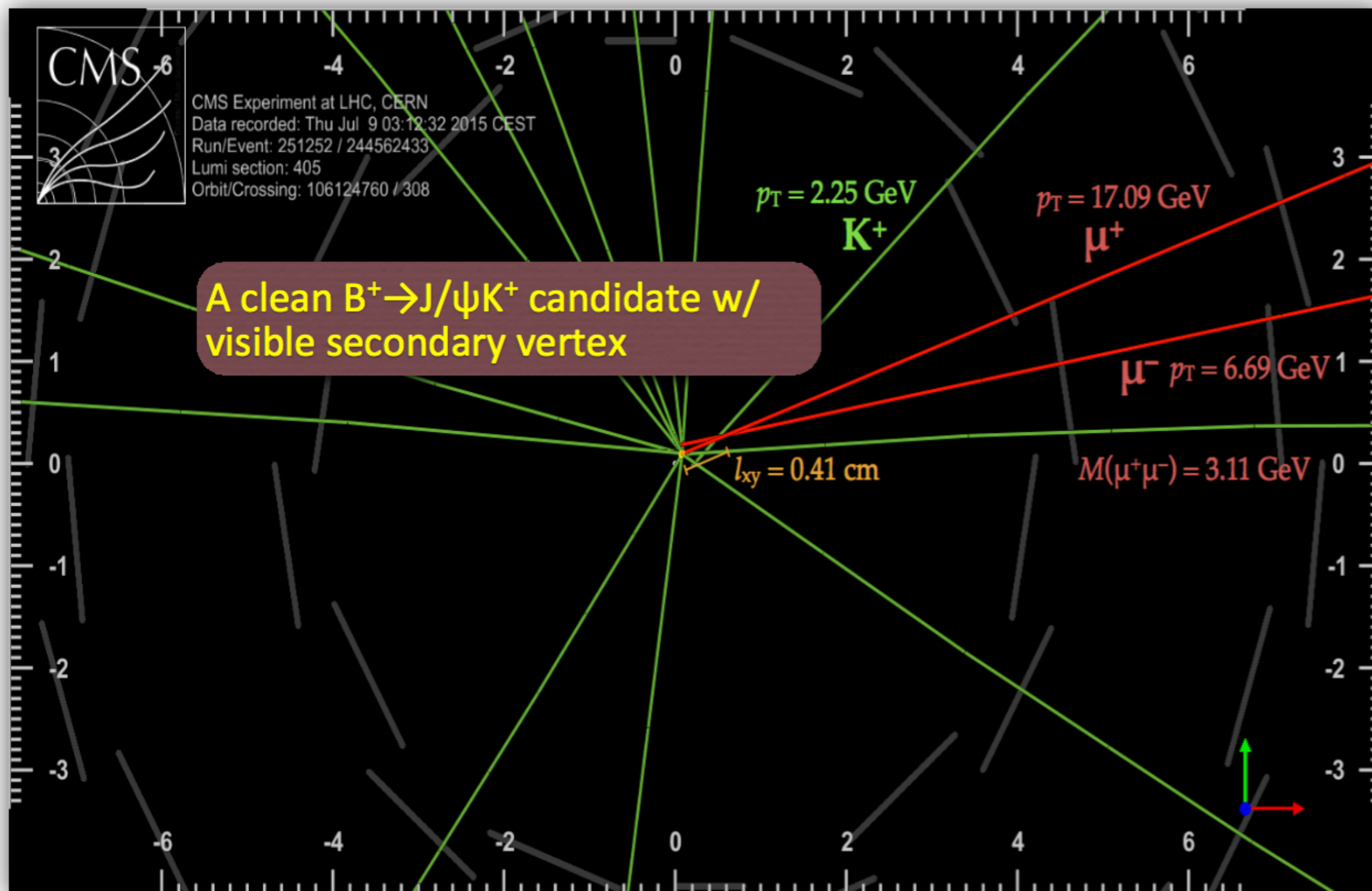
- B production cross-section goes up by almost one order of magnitude higher compared to Tevatron [in LHC ~ O(100μb)]



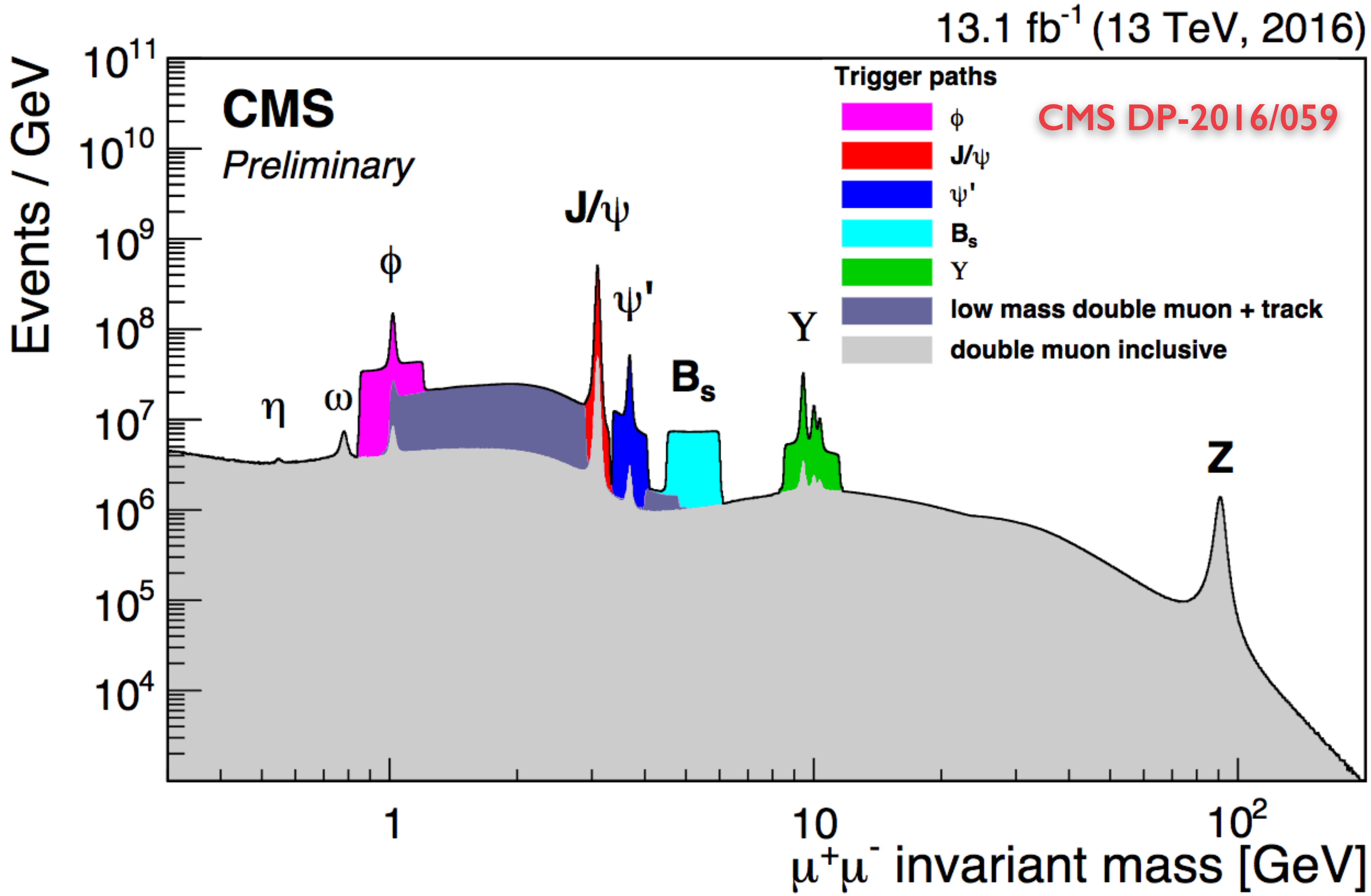
- not only the production, but also the final state is important.

Events with dimuons from CMS @ 13 TeV

CMS DP-2015/018



Physics with dimuons from CMS @ 13 TeV



- Many flavor physics analyses depend upon the prompt and displaced quarkonium triggers.
- The trigger requirements are tightened due to increased luminosity.
- ~10% bandwidth is given to flavor physics.

B^+ production cross-section @ 13 TeV from CMS

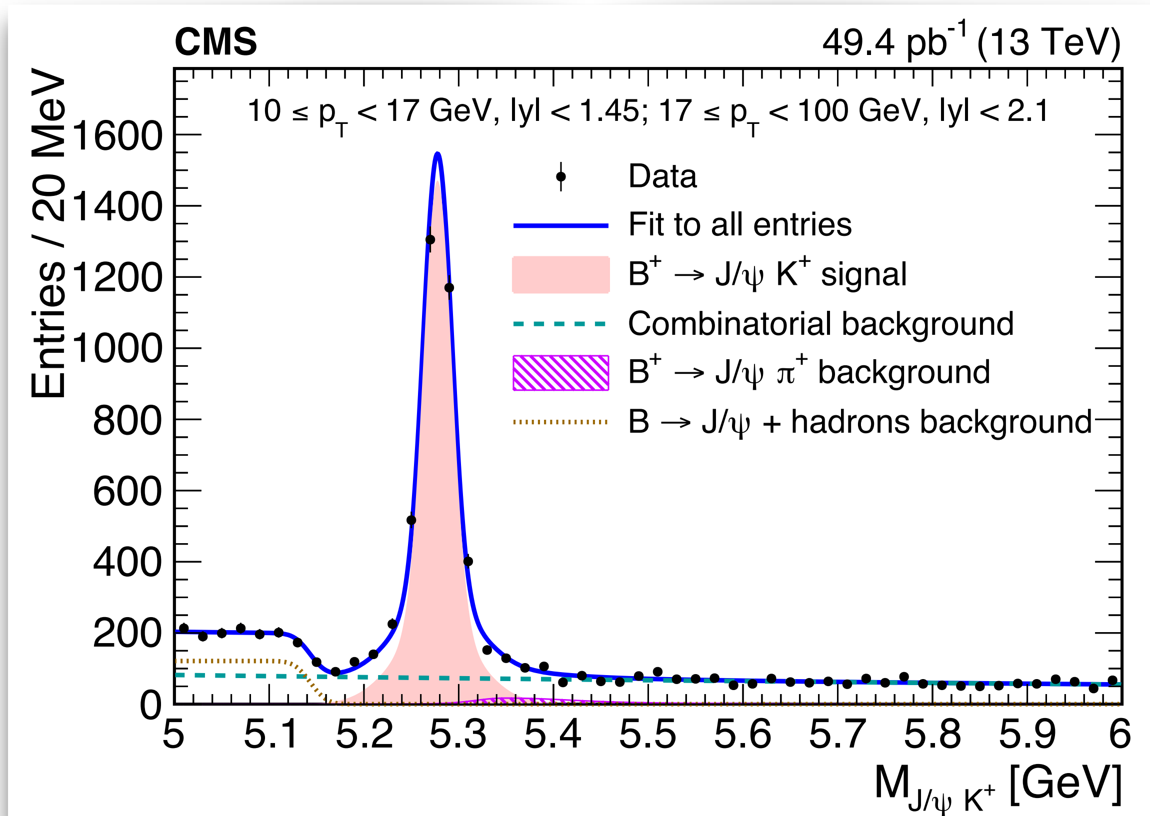
arXiV: 1609.00873

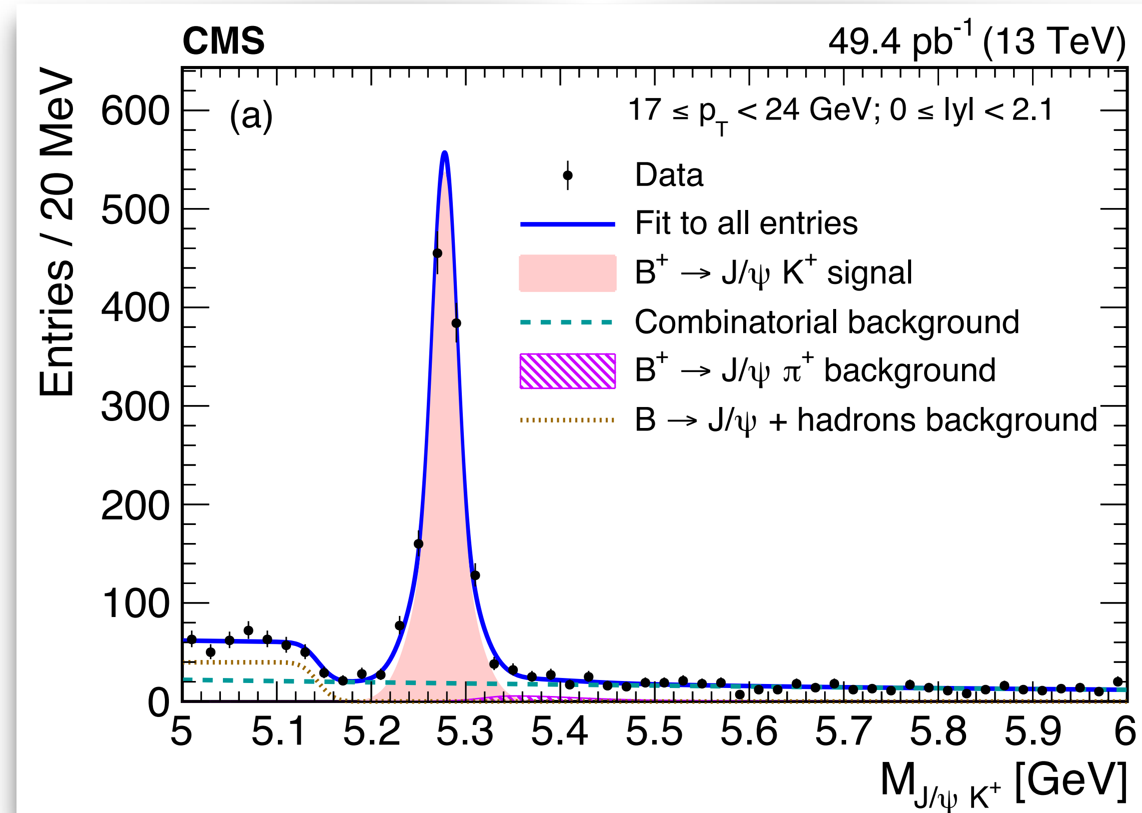
- Provides important information to understand particle interactions.
- B^+ differential production cross-section presented as a function of B^+ transverse momentum and rapidity
- Uses exclusive decay mode $B^+ \to J/\psi K^+$ ($J/\psi \to \mu\mu$) [$pp \to B^+X \to J/\psi X$]
- both muons must be within $|\eta| < 1.6$ 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.
- J/ψ candidate is combined with charged track (considered to be kaon) with $p_T > 1$ GeV
- The decay length significance cut is applied in transverse plane (distance between secondary vertex and beam spot in transverse plane divided by its uncertainty)
- The signal is obtained by extended likelihood fit to the B^+ invariant mass distribution in bins of B^+ p_T and $|\eta|$
- The differential cross-section is calculated to be

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

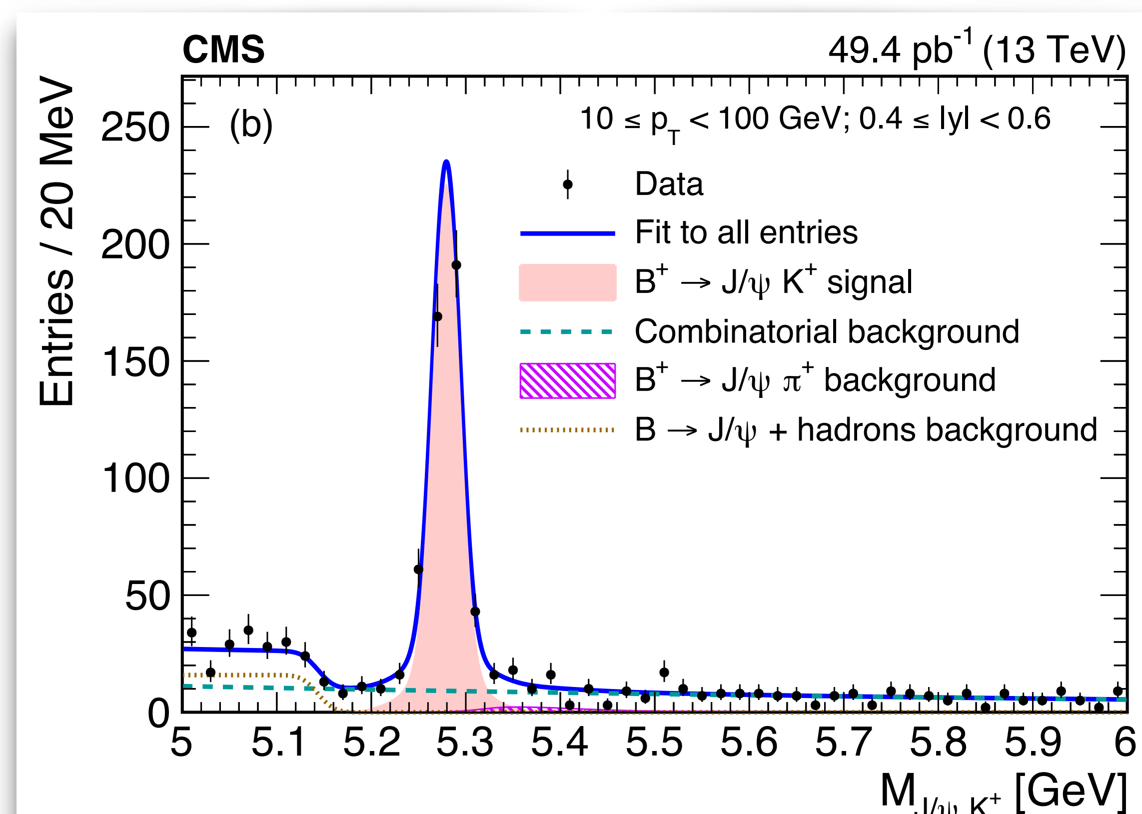
- Result shown is based on 49.4 pb^{-1} data collected @ 13TeV

B^+ production cross-section @ 13 TeV from CMS





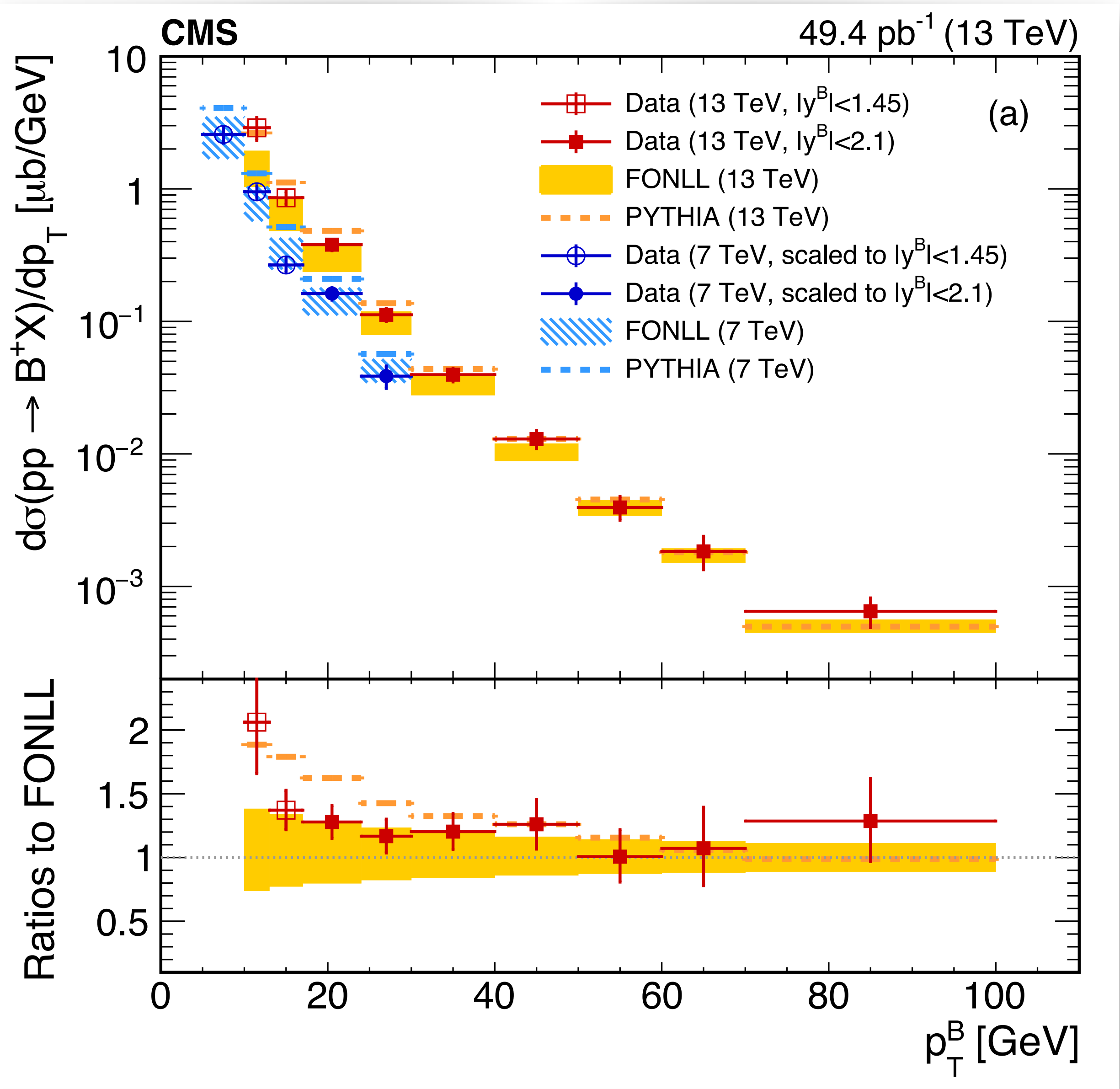
- B invariant mass distribution for different p_T and η regions.
- Signal: two gaussians
- The mean of the two gaussians fixed while the width and normalization are free (except for some p_T bins where it's fixed from MC)

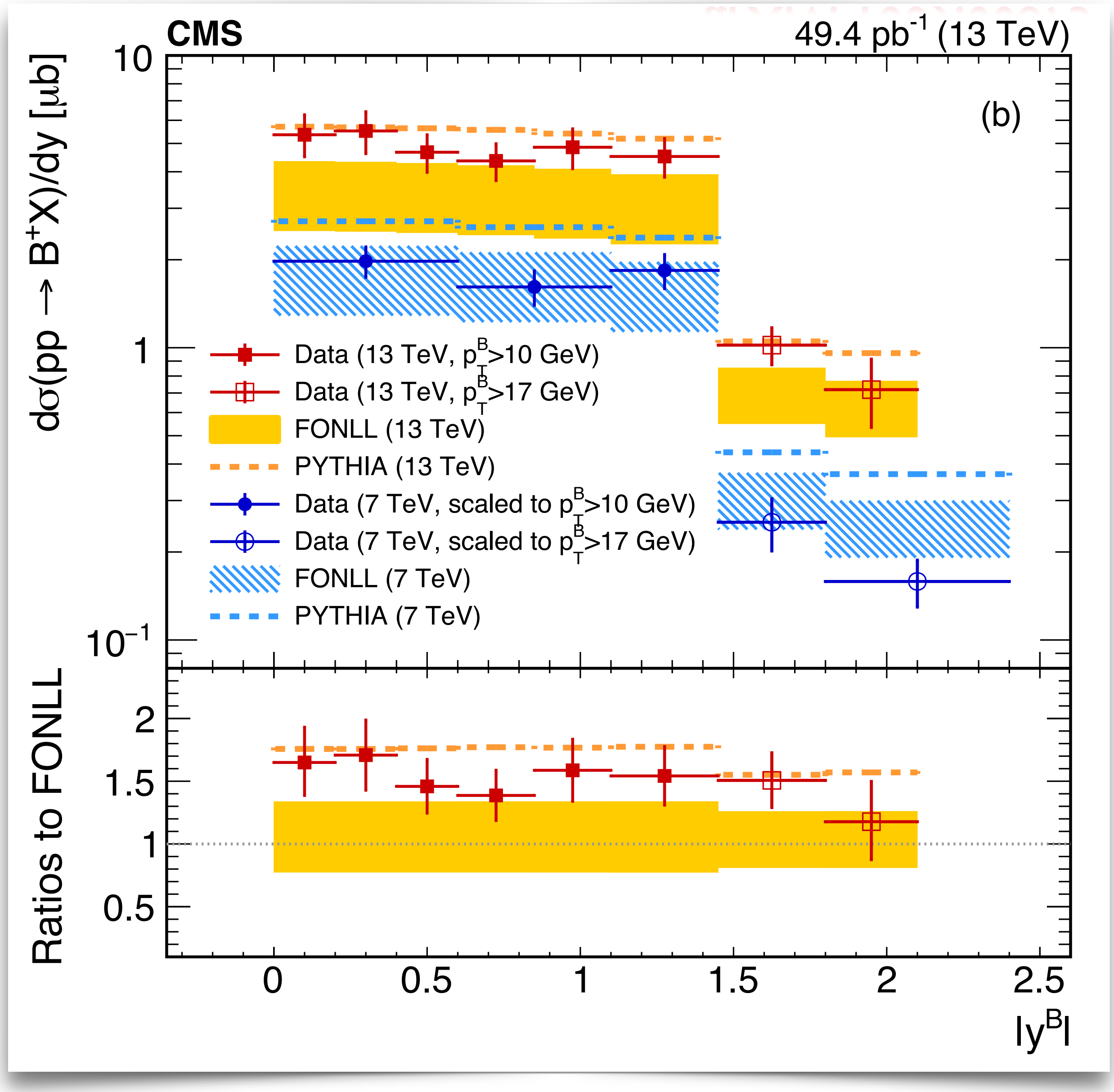


arXiV: 1609.00873

B^+ production cross-section from CMS

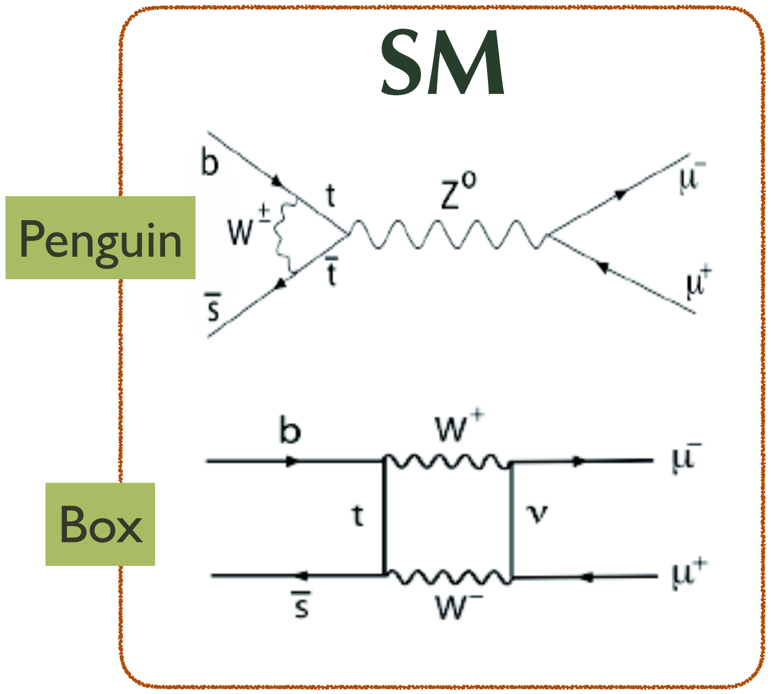
arXiV: 1609.00873



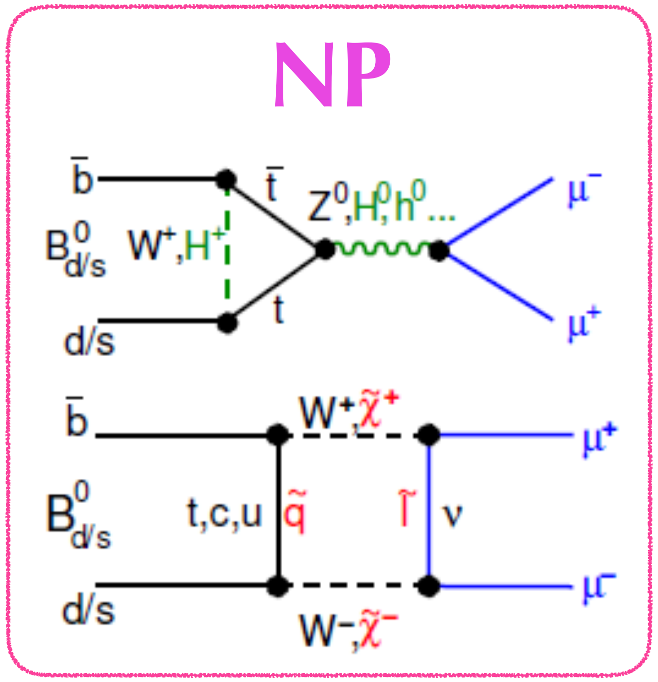


Facts about $B_{s/d} \to \mu^+\mu^-$

- **These FCNC decays are highly suppressed in SM**
  - ➟ **helicity suppressed**, by a factor of $(m_\mu/m_B)^2$
  - ➟ forbidden at the tree level in SM, only can proceed through higher order loop diagrams
  - ➟ Cabibbo suppressed $|V_{tb(ts)}|^2$



- **Possible new particles in the loops**
  - ➟ may enhance or suppress the decay rates !



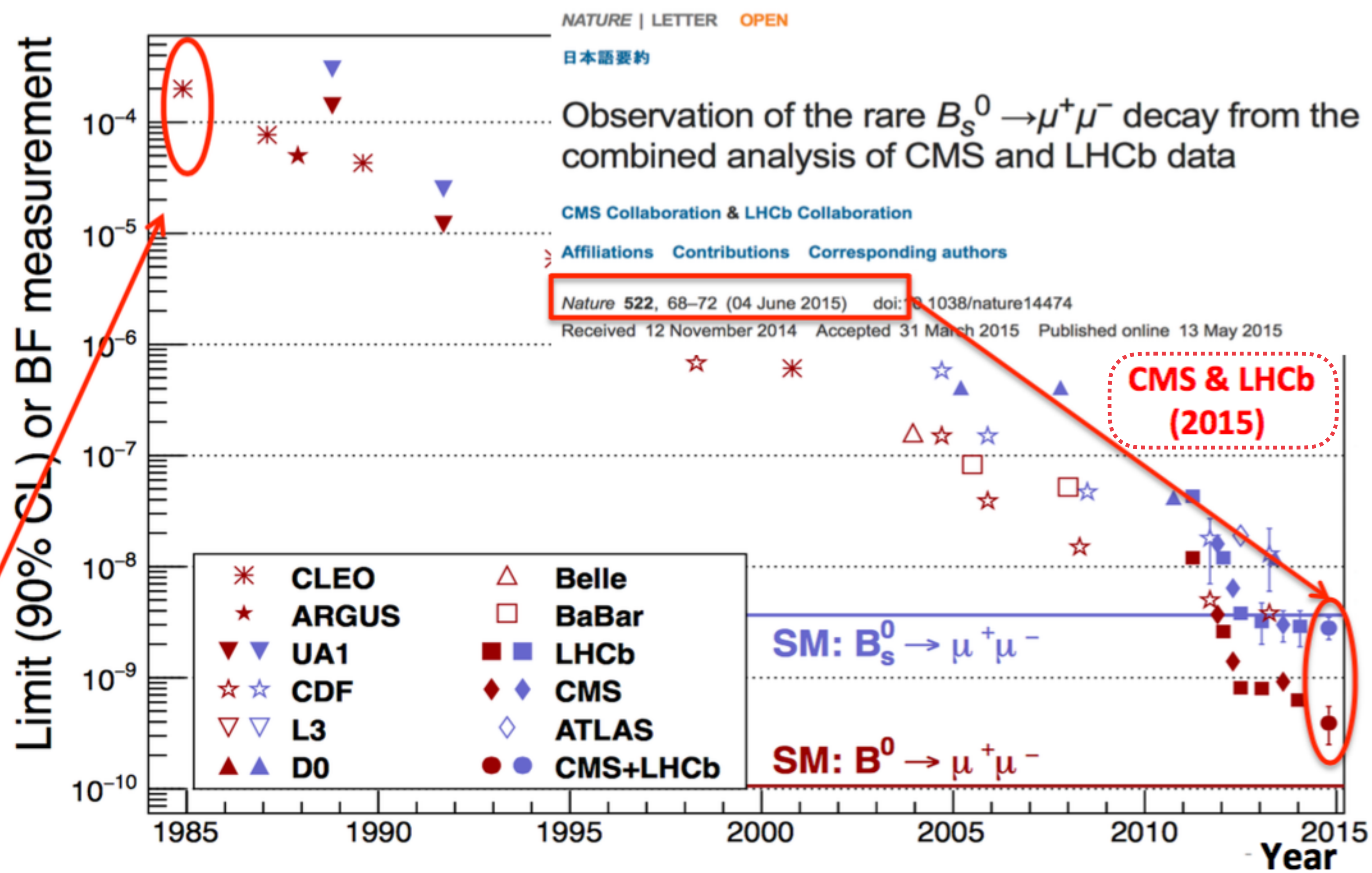
- **Probably the cleanest rare decay both experimentally and theoretically**

SM Predictions:

$BR(B_s \to \mu\mu) = (3.66 \pm 0.23) * 10^{-9}$
$BR(B_d \to \mu\mu) = (1.06 \pm 0.09) * 10^{-10}$

Bobeth et al, PRL 112, 101801 (2014)

History of $B_{s/d} \to \mu^+\mu^-$ search



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

Analysis Methodology

- **Full LHC Run 1 datasets**
  - $5fb^{-1}(\sqrt{s} = 7TeV, 2011)$ and $20fb^{-1}(\sqrt{s} = 8TeV, 2012)$
- blind signal region until selection is fixed
- multivariate candidate selection(BDT)

Region definitions	Invariant mass (GeV)
overall window	$4.90 < m_{\mu1\mu2} < 5.90$
blinding window	$5.20 < m_{\mu1\mu2} < 5.45$
$B^0 \to \mu^+\mu^-$ window	$5.20 < m_{\mu1\mu2} < 5.30$
$B_s \to \mu^+\mu^-$ window	$5.30 < m_{\mu1\mu2} < 5.45$

- **Unbinned maximum likelihood fit to dimuon invariant mass**
  - fit simultaneously both $B_s \to \mu\mu$ and $B_d \to \mu\mu$

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

$$= \frac{N_S}{N_{obs}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{tot}^{B^+}}{\varepsilon_{tot}} \mathcal{B}(B^+)$$

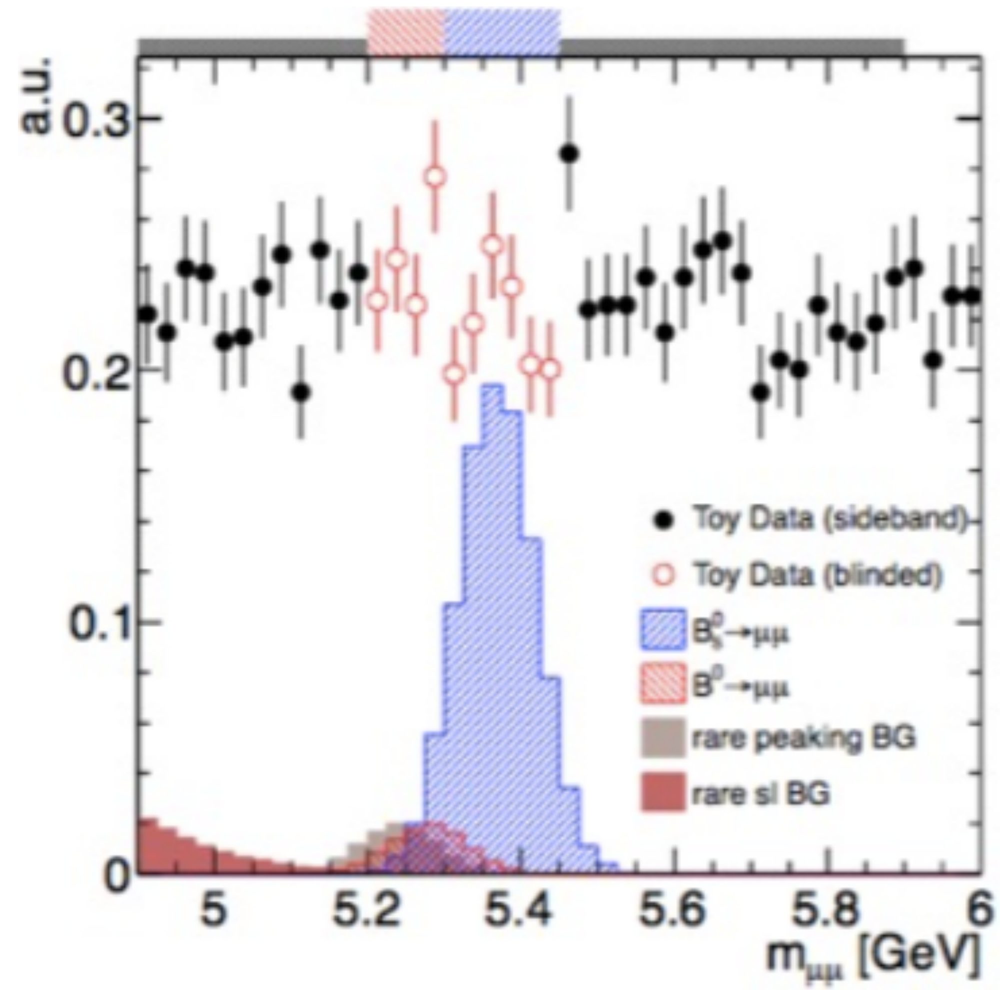
Data split in two categories:
- Barrel: 2 μ in barrel $|\eta|<1.4$
  - better sensitivity, $\sigma_M \sim 40$MeV
- Endcap: $\gtrsim 1$ μ in endcap $|\eta|>1.4$
  - more events, $\sigma_M \sim 60$MeV

- **Normalization Sample:** $B^\pm \to J/\psi K^\pm \to \mu^+ \mu^- K^\pm$
  - measure $B_s \to \mu\mu$ relative to the normalization channel (minimize uncertainty due to b production cross section and integrated luminosity)
  - nearly identical selection cuts to reduce systematic uncertainties

- **Control Sample:** $B_s \to J/\psi\, \varphi \to \mu^+ \mu^- K^+ K^-$
  - calibrate and validate MC

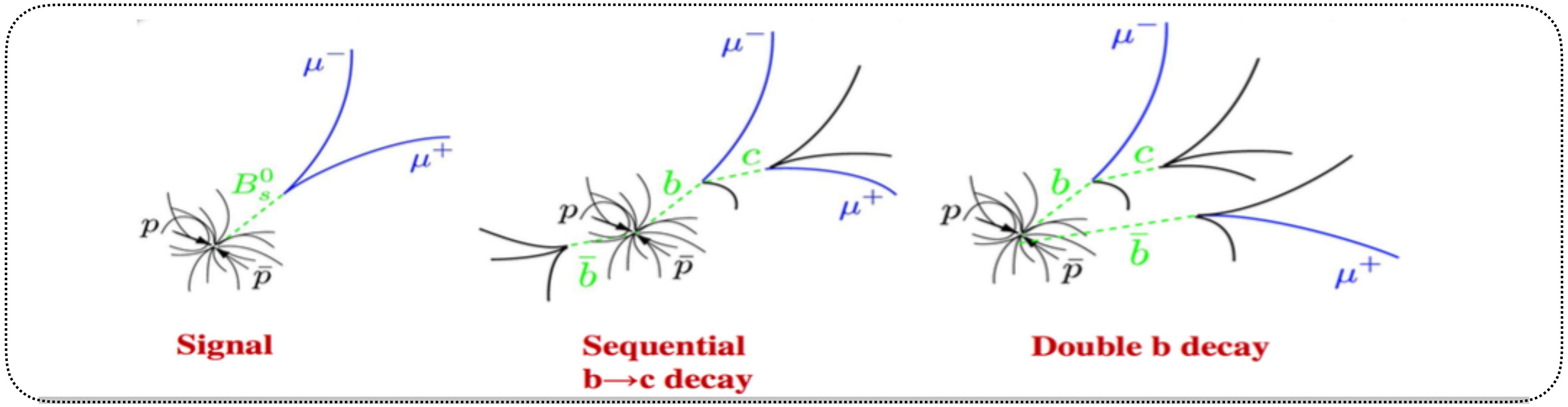
Analysis Strategy

- Signal: $B_{s(d)} \to \mu\mu$
  - ➟ two muons from a decay vertex
  - ➟ well reconstructed secondary vertex
  - ➟ momentum aligned w/ flight direction
  - ➟ invariant mass around $m(B_{s(d)})$
  - ➟ blind analysis



- Backgrounds:
- *combinatorial* (from sideband of $B_{s(d)}$ mass)
  - ➟ two semi-leptonic B decays
  - ➟ one semi-leptonic and one hadronic B decay

- *rare single B decays* (from MC simulations)
  - ➟ peaking background, e.g, $B_s \to K^+K^-$
  - ➟ non peaking background, e.g, $B_s \to K^-\mu^+\nu$, $\Lambda_b \to p\mu^+\nu$

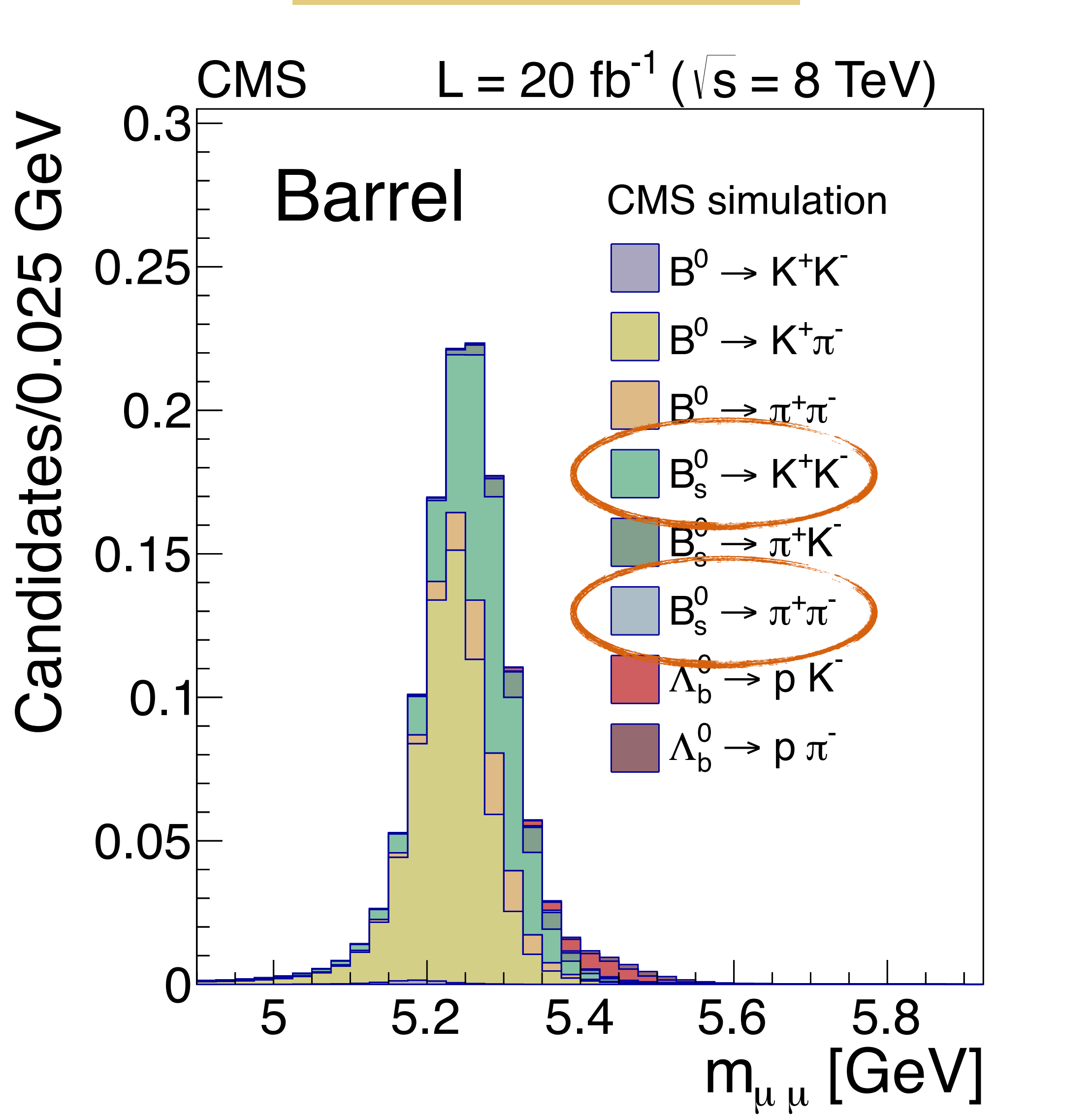


Backgrounds for $B_{s/d} \rightarrow \mu^+\mu^-$

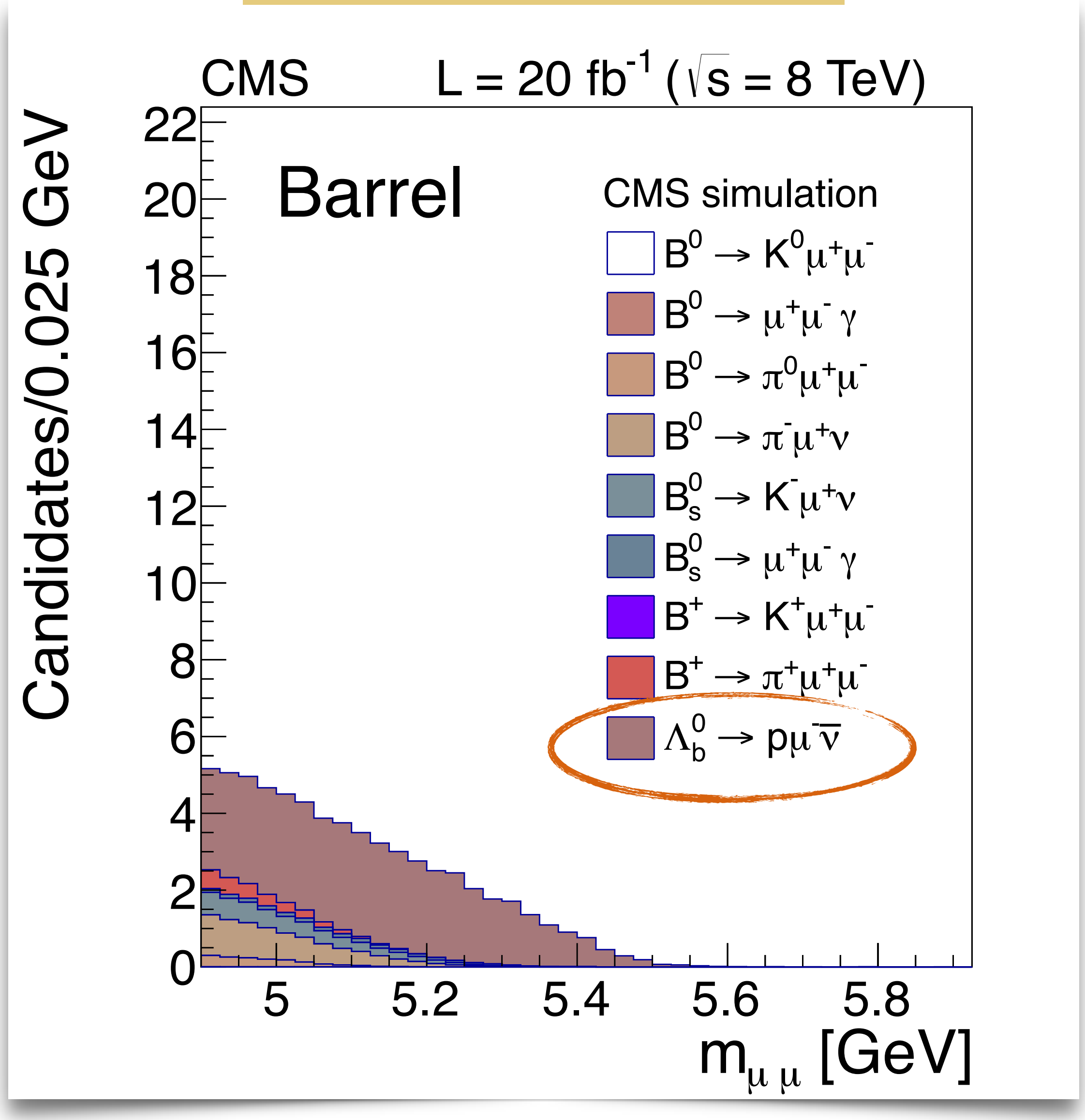
PRL 111(2013) 101804

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

peaking backgrounds



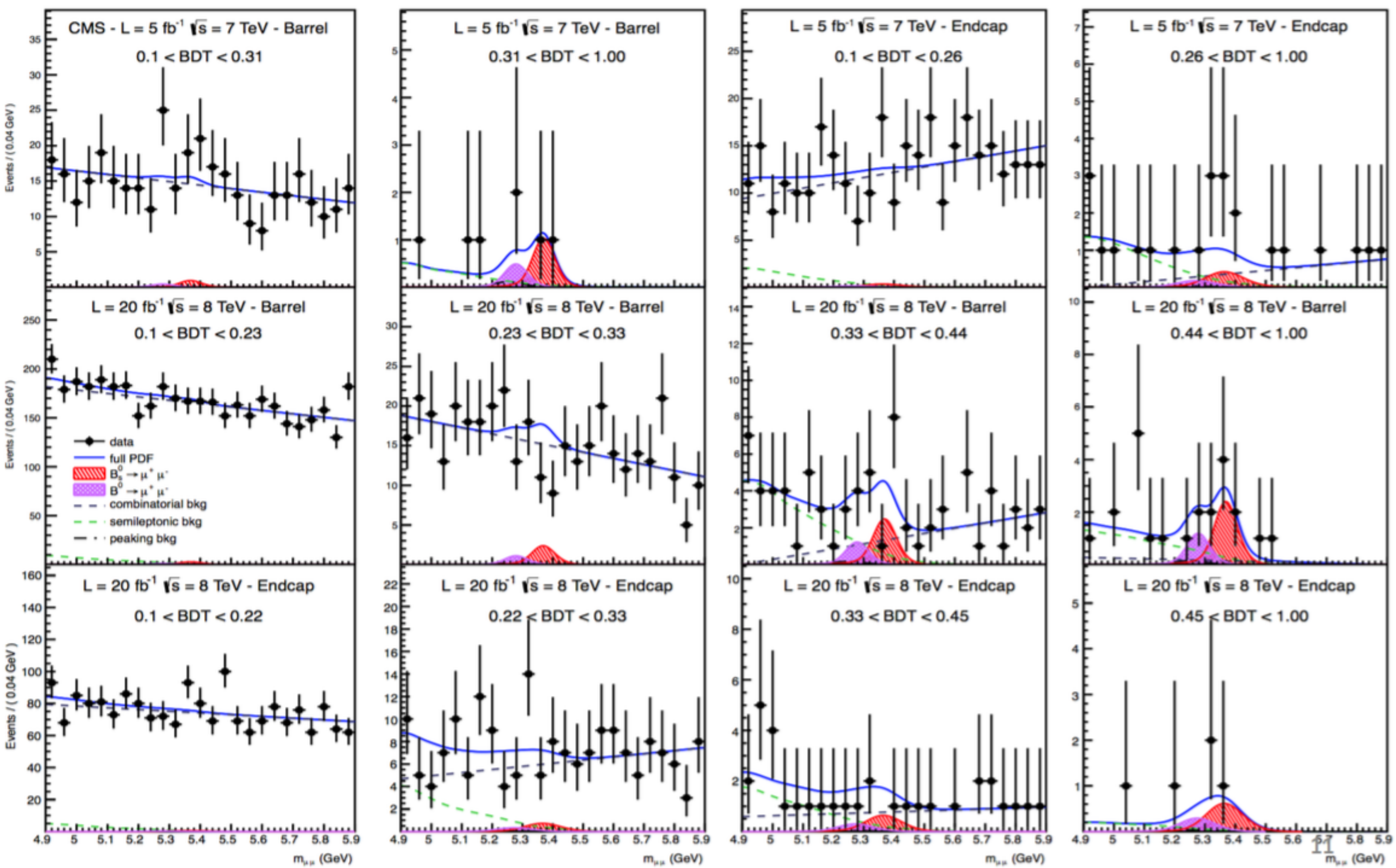
non-peaking backgrounds



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

PRL 111(2013) 101804

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



CMS results for $B_{s/d} \to \mu^+\mu^-$

PRL 111(2013) 101804

Experimental Result:

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

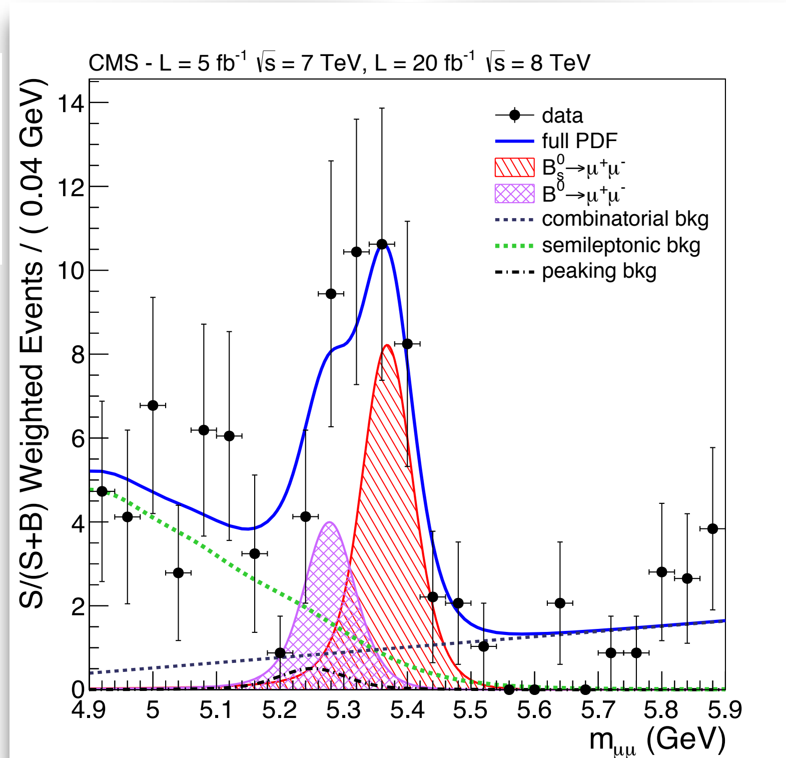
$$BR(B_d \to \mu\mu) = \left(3.5^{+2.1}_{-1.8}\ (\text{stat+syst})\right) \times 10^{-10}$$

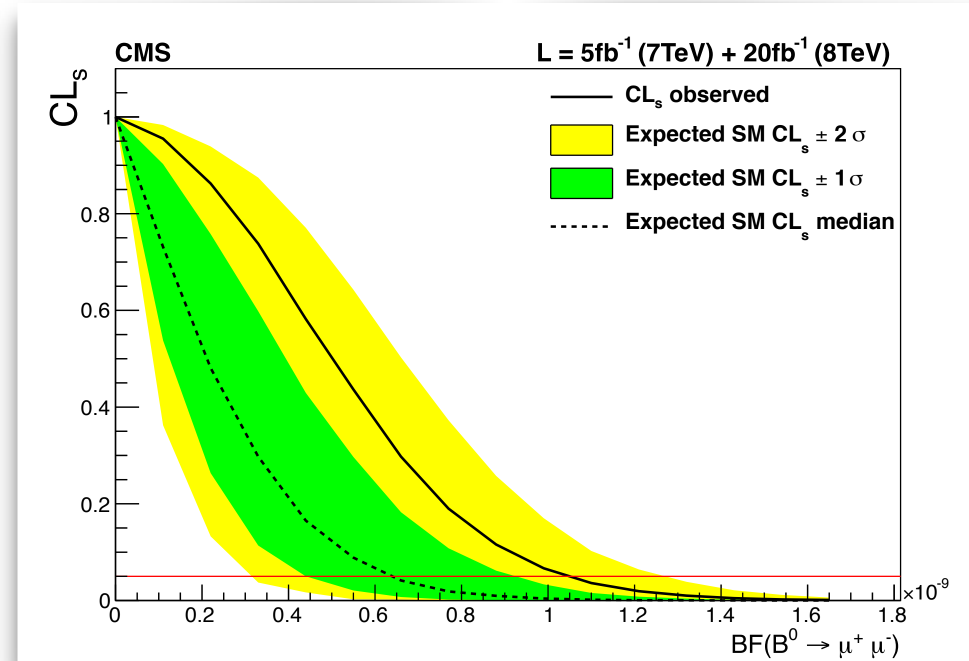
Theoretical Prediction:

$BR(B_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$

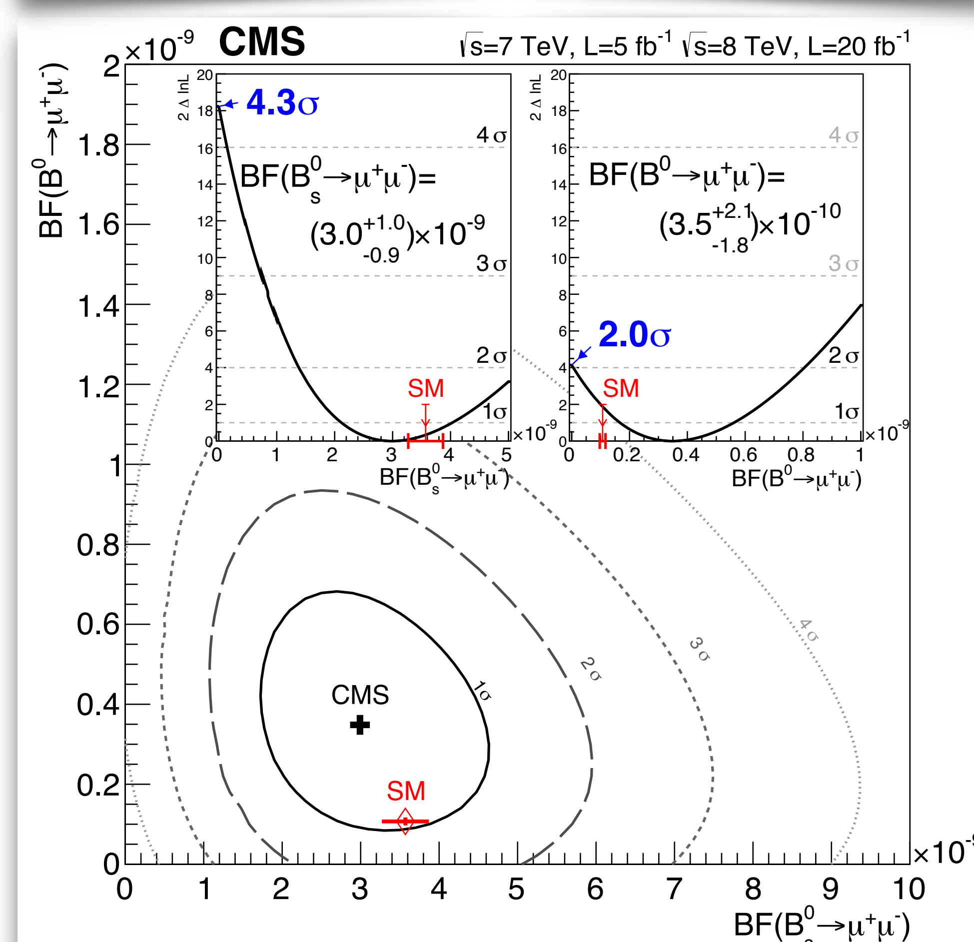
$BR(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

- $B_s \to \mu\mu$ significance: 4.3σ
- $B_d \to \mu\mu$ significance: 2σ





		$\varepsilon_{tot}[10^{-2}]$	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 end cap	0.20 ± 0.02	0.11 ± 0.01	1.5 ± 0.6	1
	B^0_s end cap	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 end cap	0.10 ± 0.01	0.30 ± 0.03	2.2 ± 0.8	3
	B^0_s end cap	0.09 ± 0.01	3.56 ± 0.53	5.1 ± 0.7	4

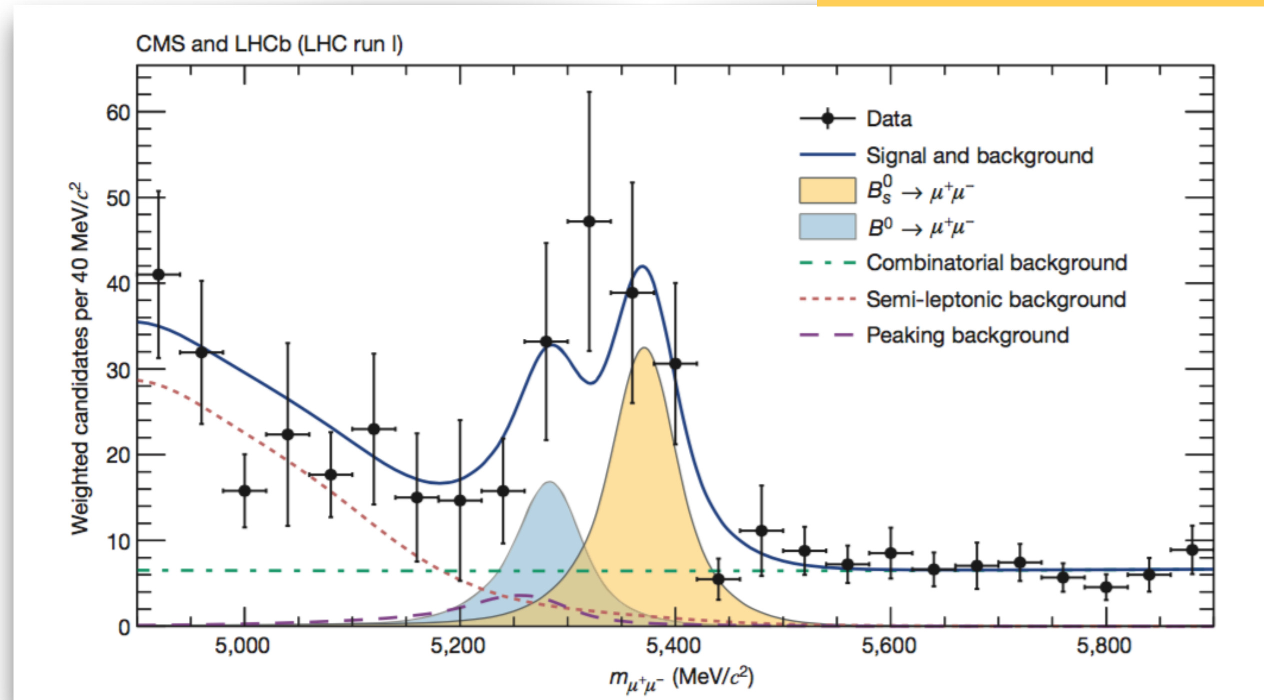


The results are compatible with SM expectations.

CMS and LHCb combination for $B_{s/d} \to \mu^+\mu^-$

- both CMS and LHCb data are simultaneously fitted with BFs as common free parameters
- an unbinned maximum likelihood fit to the dimuon invariant mass is done over all BDT bins (12 bins for CMS and 8 bins for LHCb)

Nature 522, 68-72

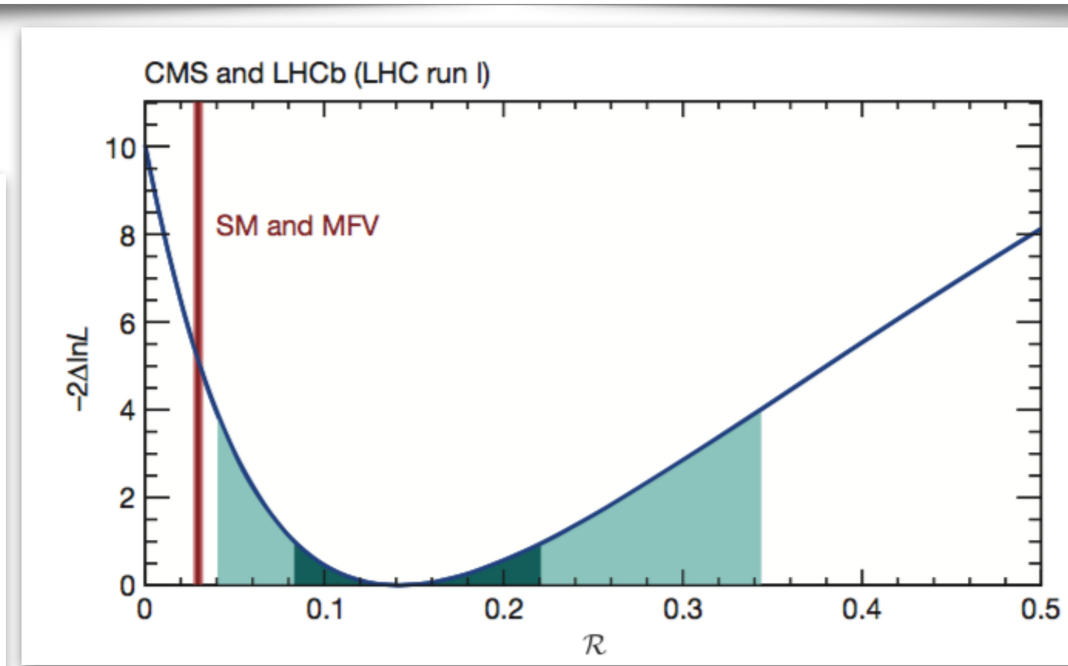


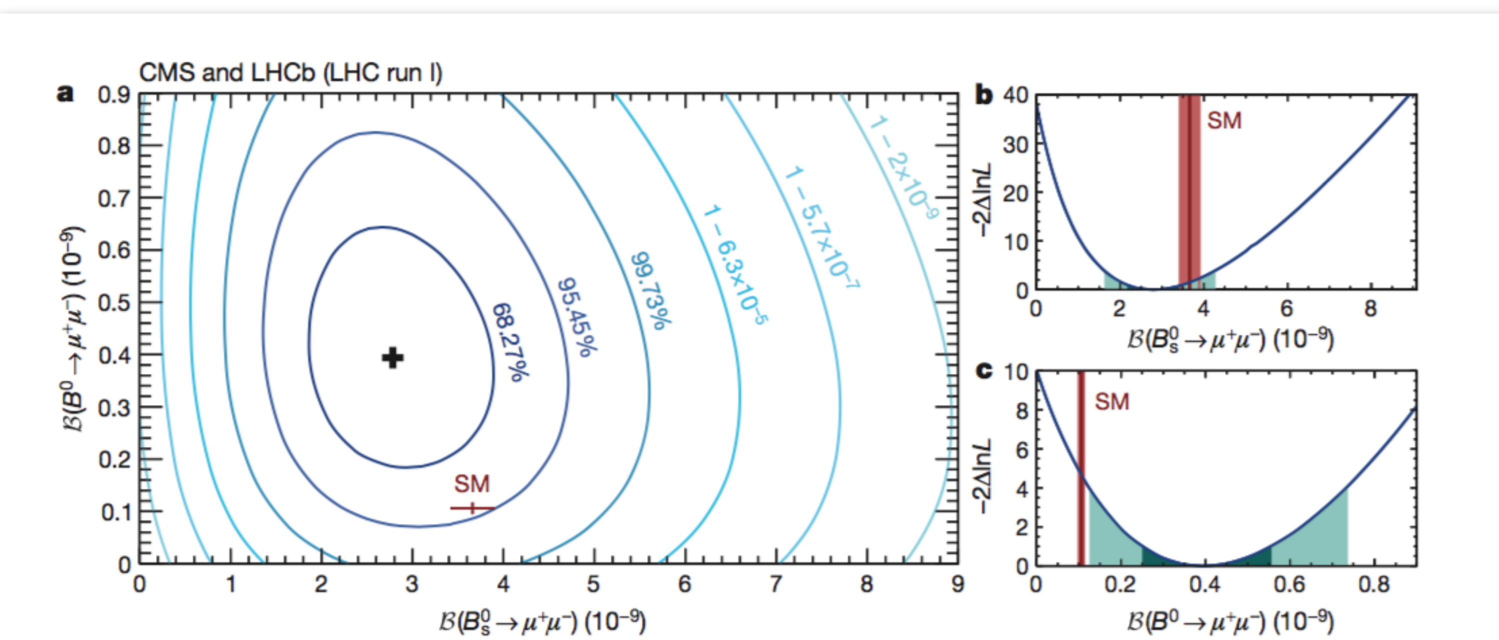
observed branching fraction:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$ 6.2σ observed

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$$ 3.0σ evidence

SM compatibility: 1.2σ for B_s and 2.2σ for B_d



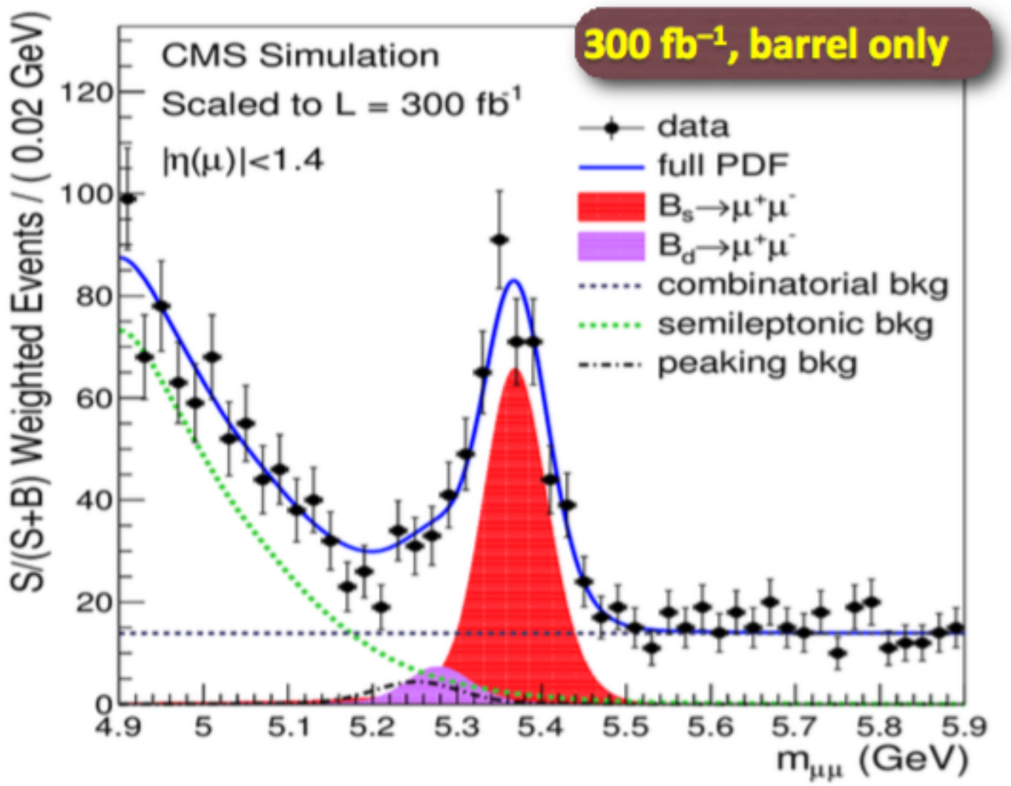


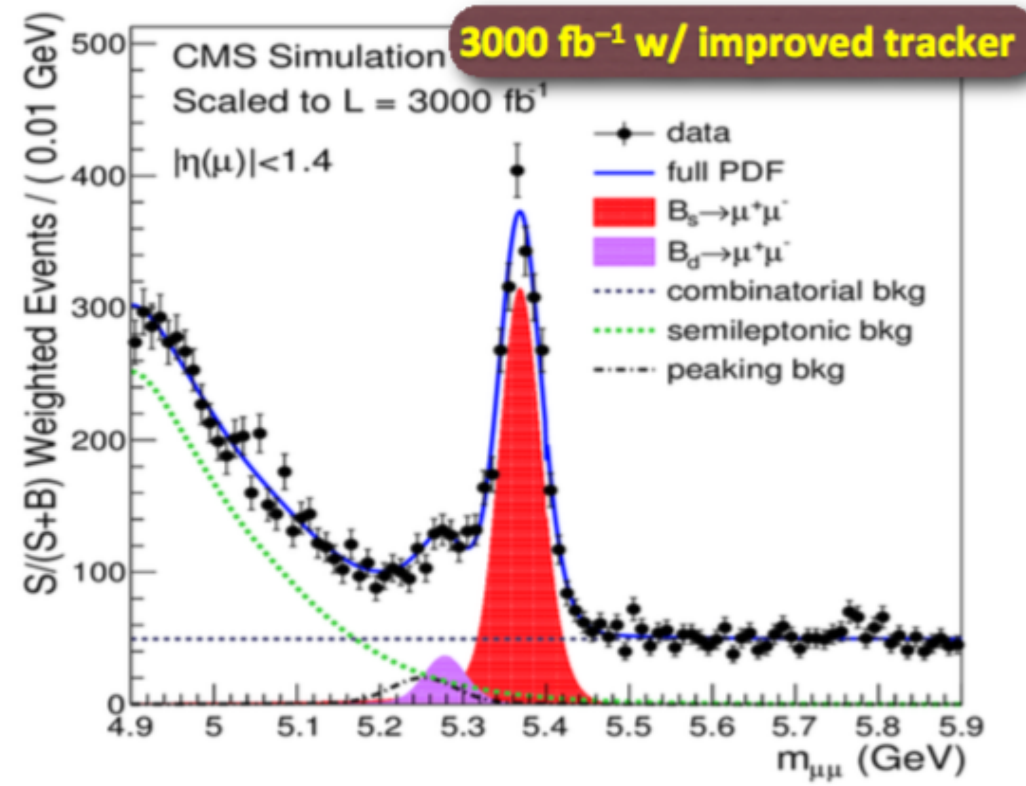
$$\mathcal{R} \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)_{\rm SM}/\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = 0.0295^{+0.0028}_{-0.0025}$$

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

CMS future prediction

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





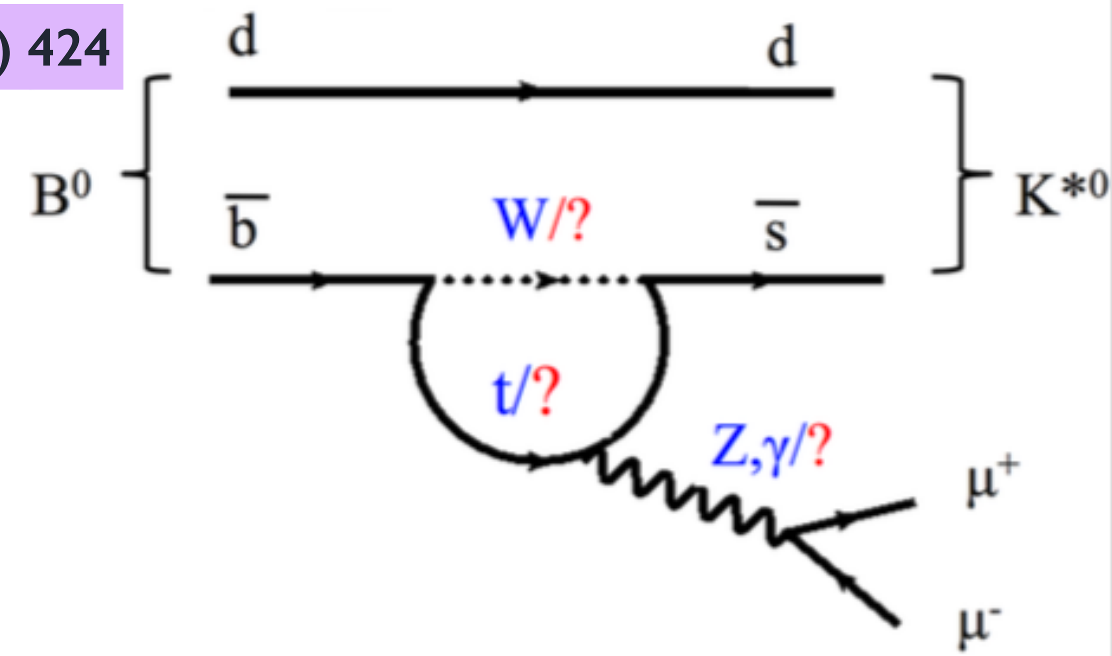
$\mathcal{L}(fb^{-1})$	$N(B_s)$	$N(B^0)$	$\delta\mathcal{B}(B_s \to \mu\mu)$	$\delta\mathcal{B}(B^0 \to \mu\mu)$	B^0 sign.	$\delta\frac{\mathcal{B}(B^0 \to \mu\mu)}{\mathcal{B}(B_s \to \mu\mu)}$
20	18.2	2.2	35%	>100%	0.0-1.5 σ	>100%
100	159	19	14%	63%	0.6-2.5 σ	66%
300	478	57	12%	41%	1.5-3.5 σ	43%
300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

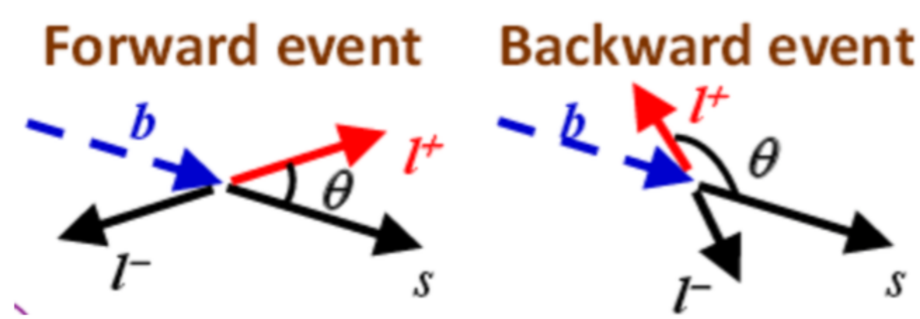
- Expectation assuming SM branching fraction and planned detector upgrade
- Large pile up will affect detection efficiency, tightening selection criteria, reduce background, better determination of peaking background.

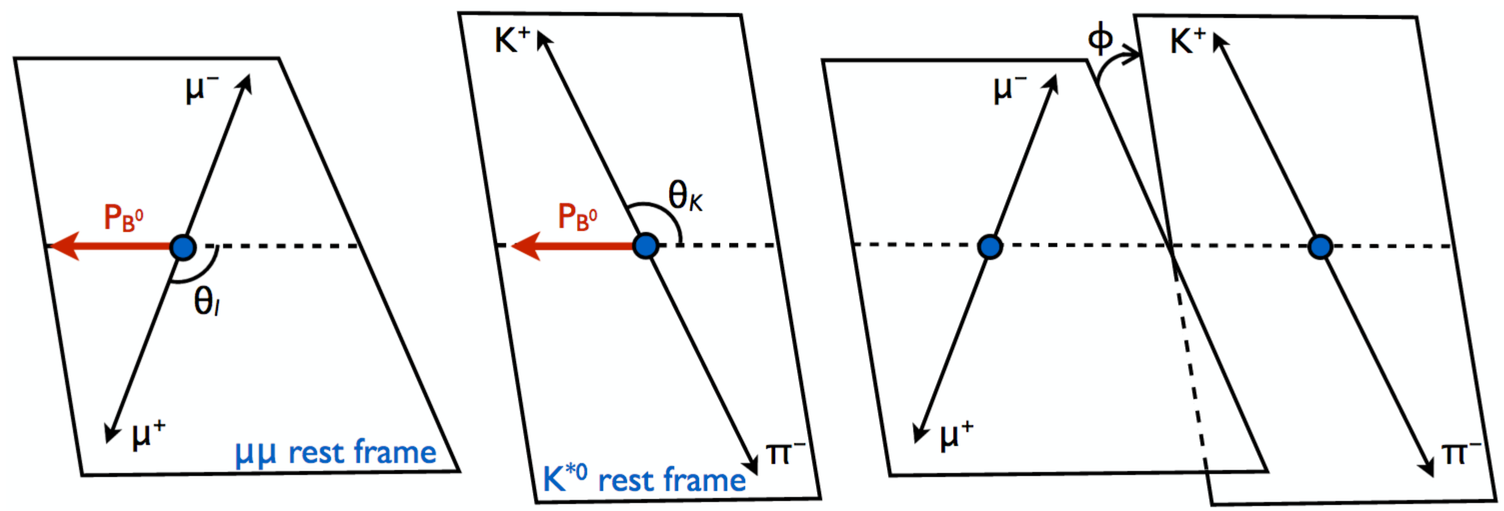
Measurement of $B^0 \to K^{*0} \mu^+\mu^-$ in CMS

PLB 753 (2016) 424

- forbidden at tree level, but allowed via loop diagrams (as shown on the right)
- sensitive to NP through BSM particle in the loop
- small branching fraction ($\sim 10^{-6}$)
- observable to be compared to SM predictions : differential BF, A_{FB}, F_L, A_{CP}, P_5', Isospin asymmetry…







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

Measurement of $B^0 \rightarrow K^{*0} \mu^+\mu^-$ in CMS (cont.)

- Unbinned maximum likelihood fit to three variables: $m(K^+\pi^-\mu^+\mu^-)$, and two angular variables θ_K, θ_L in each q^2 bin.
- Signal (correctly tagged)
- Signal (wrongly tagged)
- Combinatorial background
- we are interested in p-wave components

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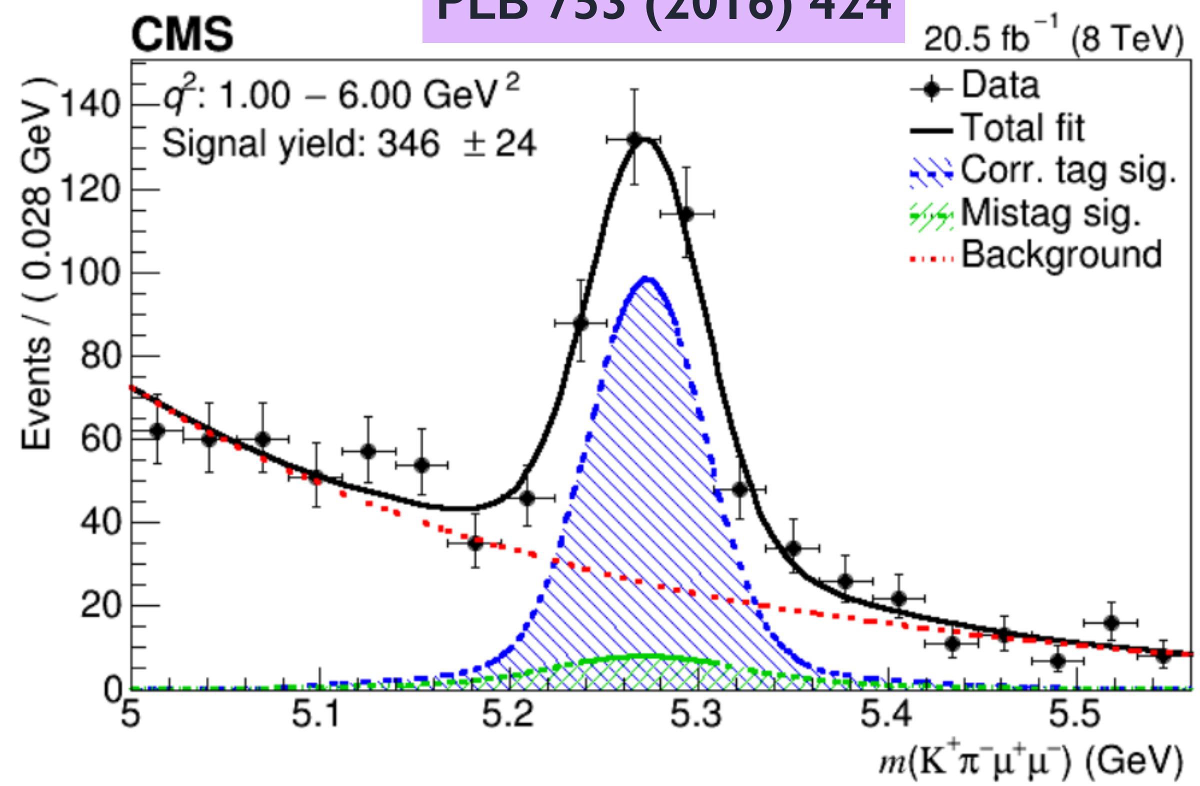
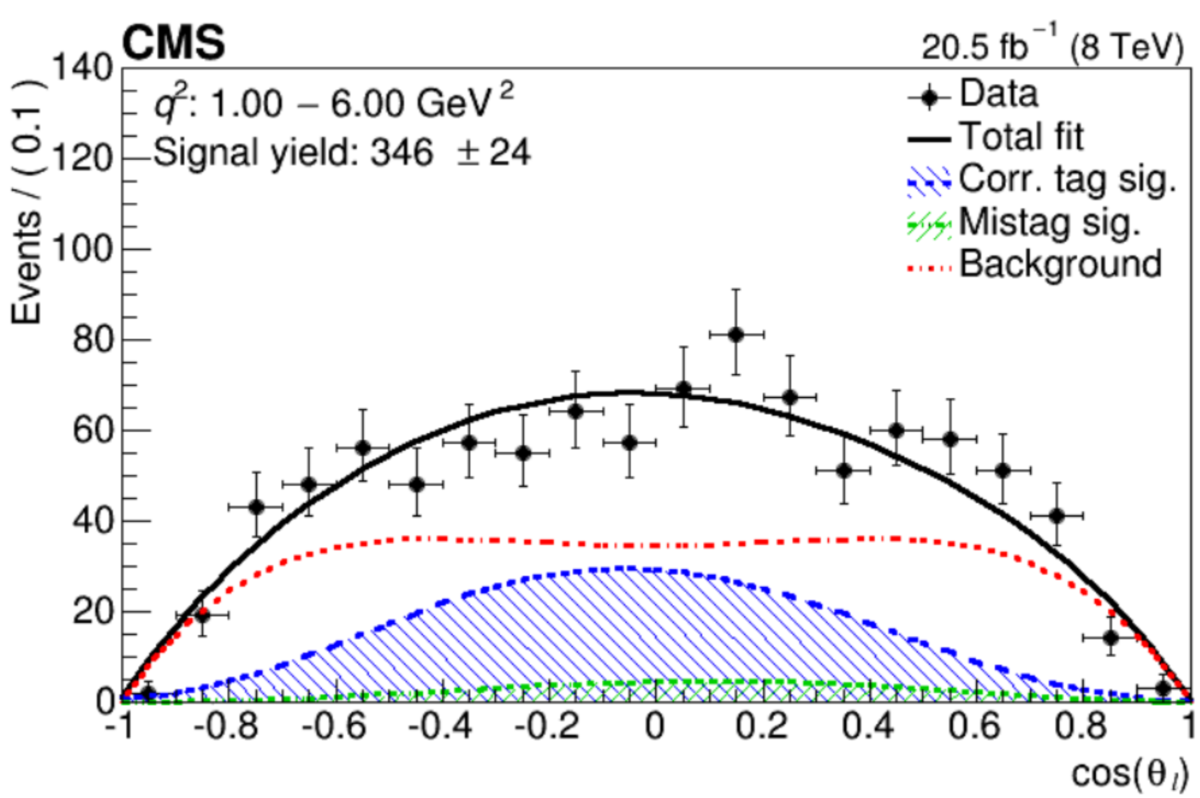
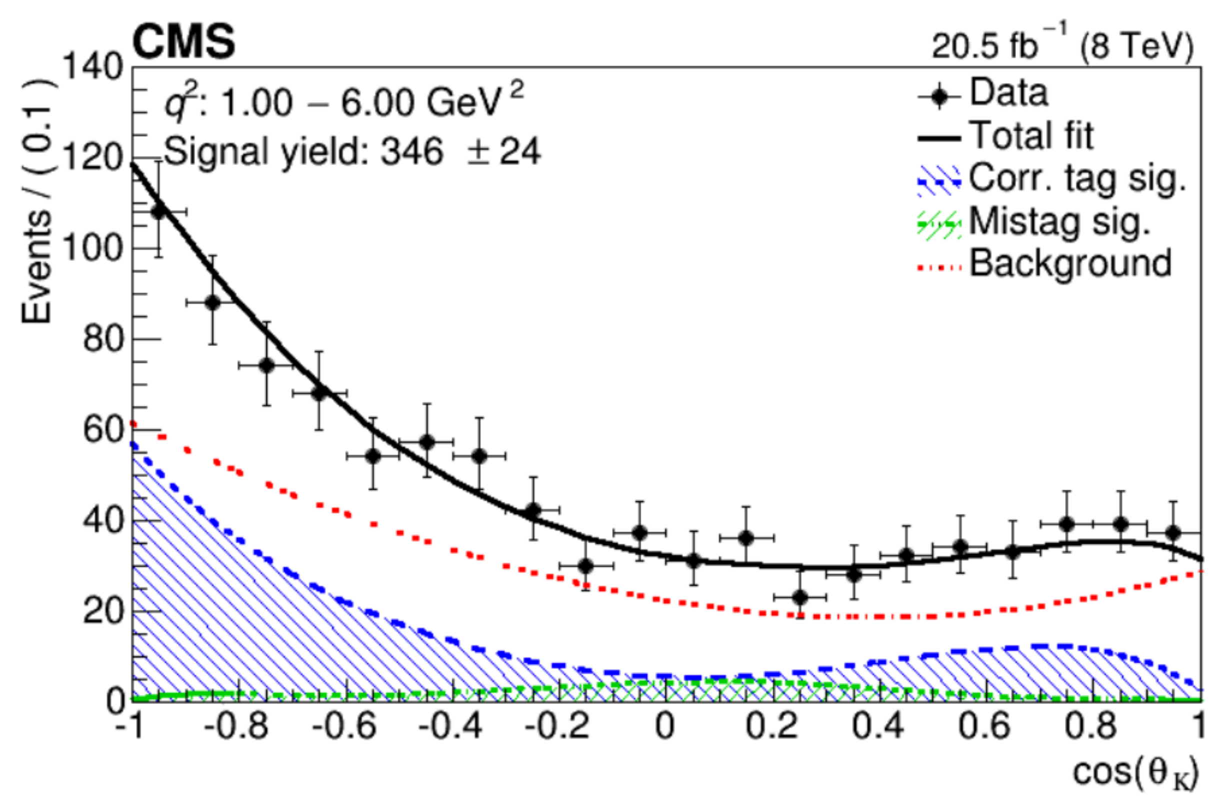
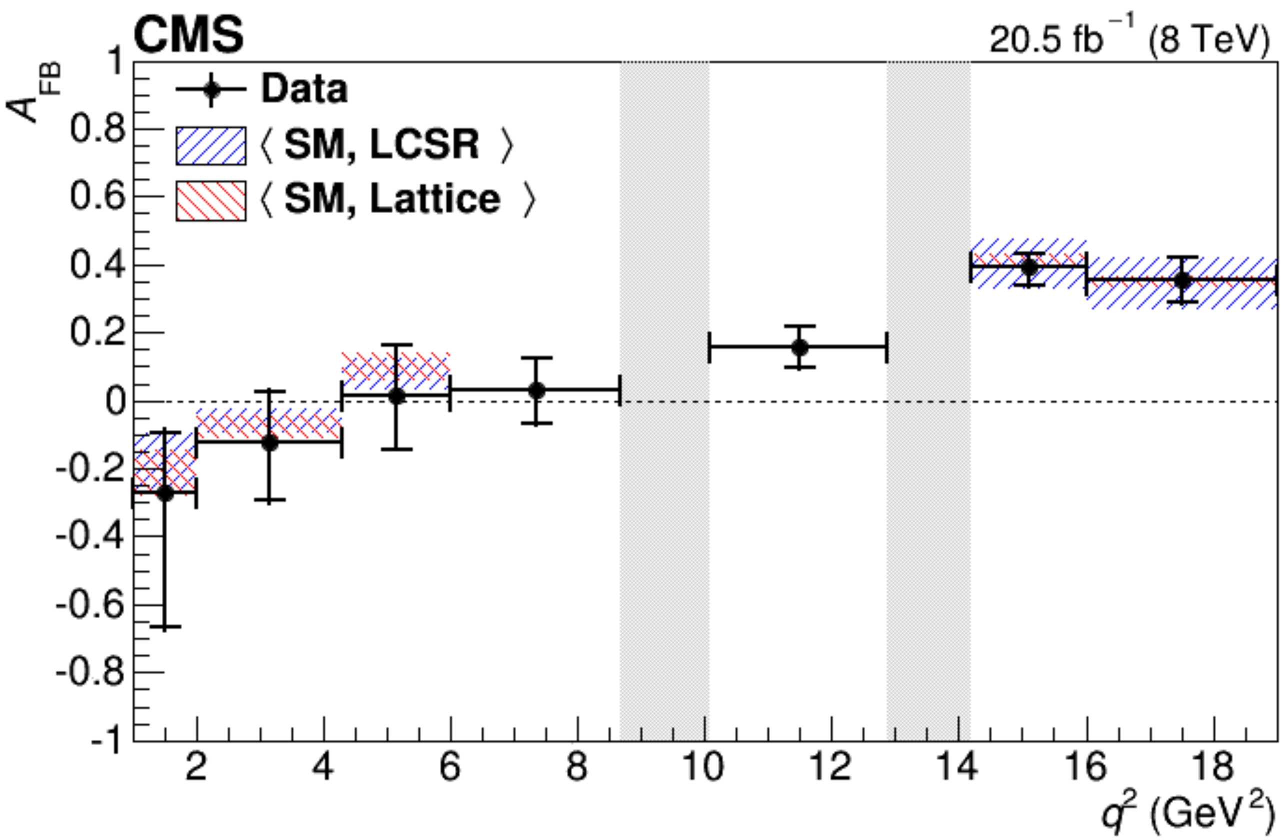
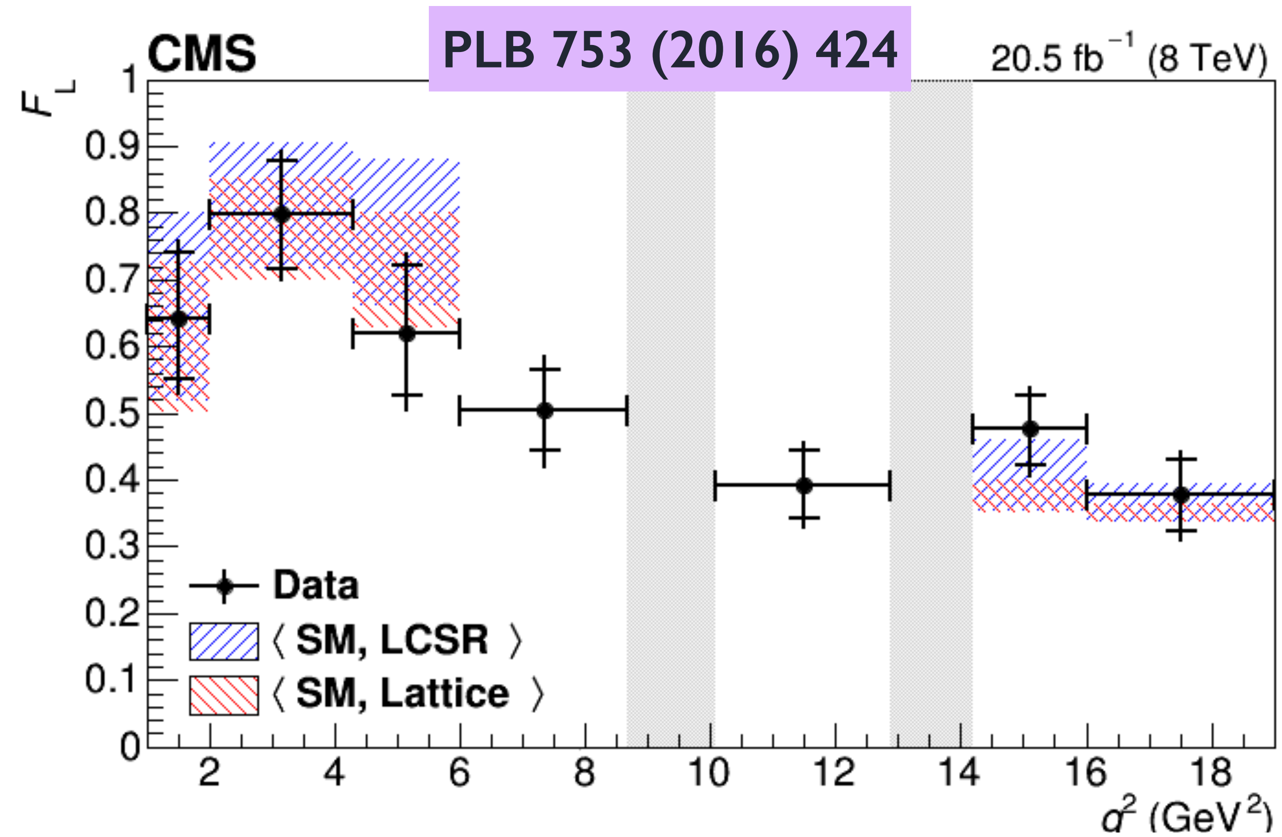




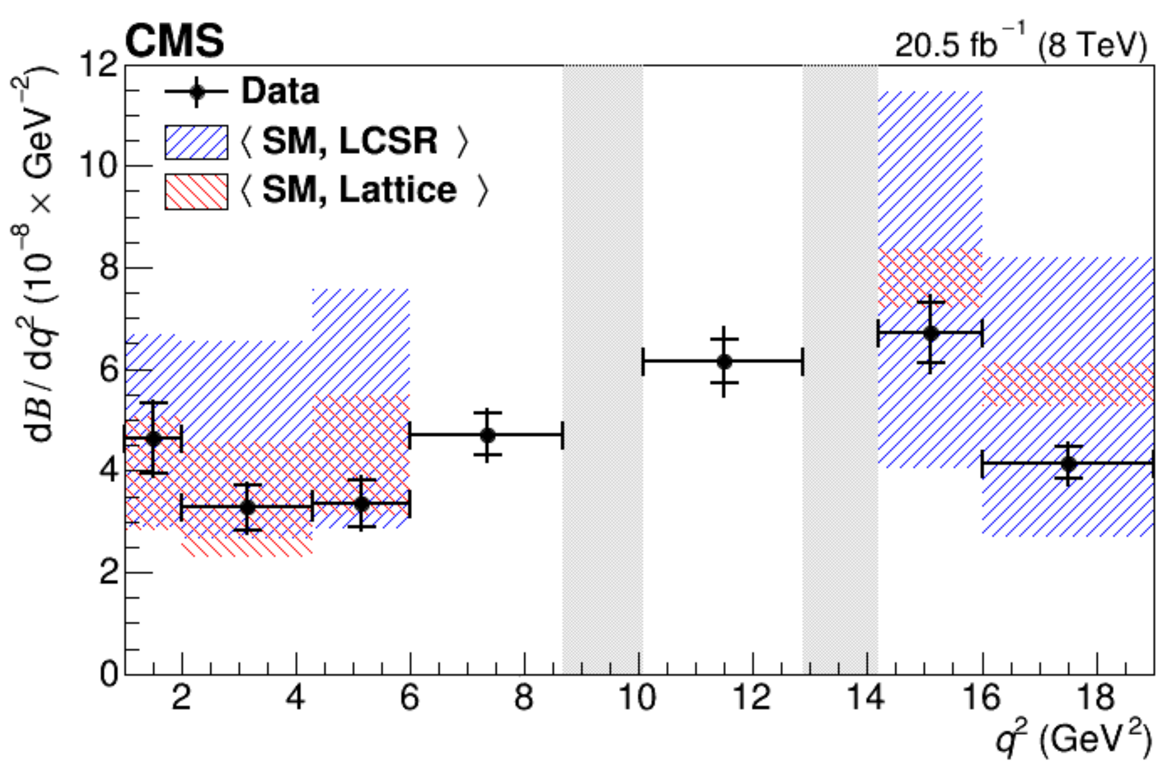


Measurement of $B^0 \to K^{*0}\,\mu^+\mu^-$ in CMS (cont.)





Experiment	F_L	A_{FB}	$d\mathcal{B}/dq^2$ $(10^{-8}\,\text{GeV}^{-2})$
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 are consistent with theory predictions as well as with experimental results.

Summary

- CMS and LHCb reported a first observation of $B_s \rightarrow \mu^+\mu^-$ (6.2σ from combined data). The measured BF is compatible with SM predictions (within 1.2σ).
- Both experiments reported the first evidence of $B_d \rightarrow \mu^+\mu^-$. The measurement is compatible with SM within 2.2σ.
- CMS + LHCb provides the most precise BF measurement for these decay modes.
- However, we look forward for the new(13 and 14TeV) data to give us $B_d \rightarrow \mu^+\mu^-$ observation soon.
- $B^0 \rightarrow K^{*0}\mu^+\mu^-$ 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.