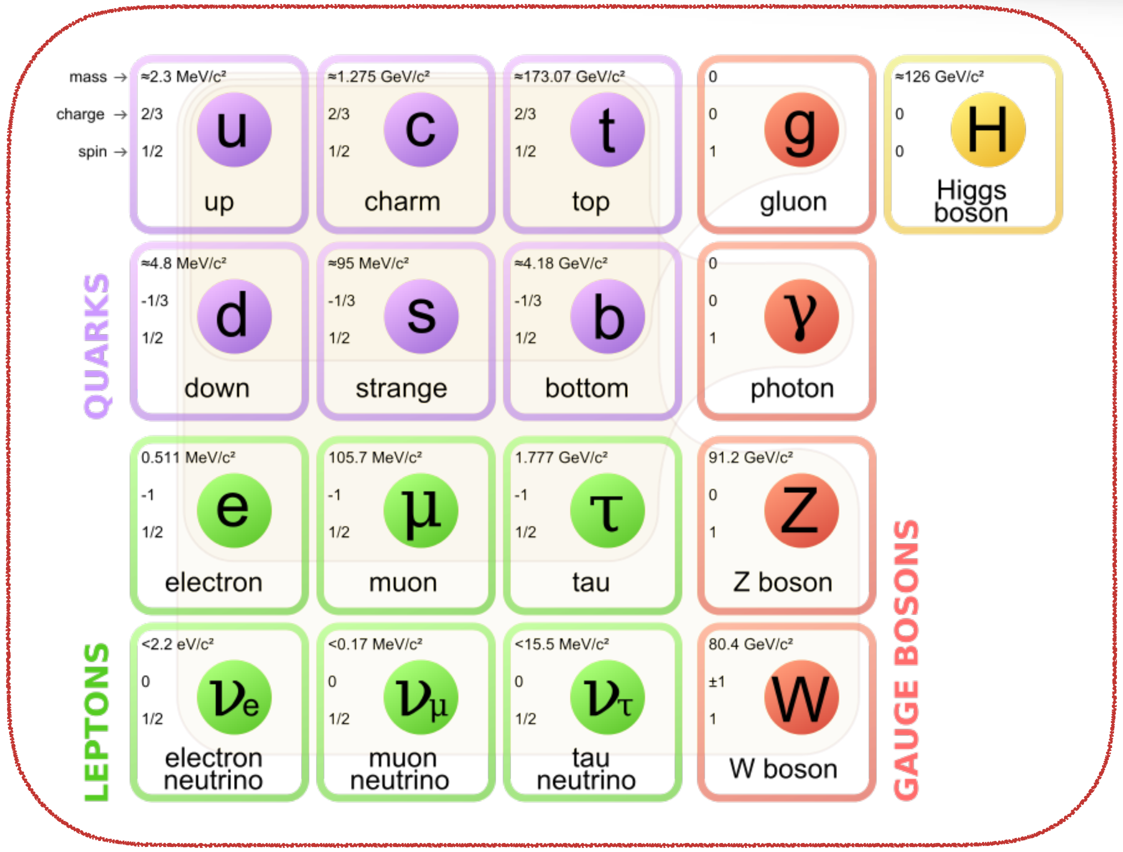
Search for New Physics with B-decays using CMS data

Niladribihari Sahoo
Tata Institute of Fundamental Research

on behalf of the CMS collaboration
2017/12/11

- Introduction
- Results for $B_s \rightarrow \mu^+\mu^-$
- Results for $B_d \rightarrow K^{*0}\mu^+\mu^-$
- Conclusion

Introduction: search for New Physics (NP)



Standard Model(SM):

most successful theory in particle physics

Deficiencies of SM:

dark matter, gravity etc..

Two ways to search for New Physics (NP)

- **Direct Search:**

  Produce the new heavy particles beyond the standard model (SM).

  The production cross-section are usually very small.

  (heavier is the mass, smaller is the cross-section)

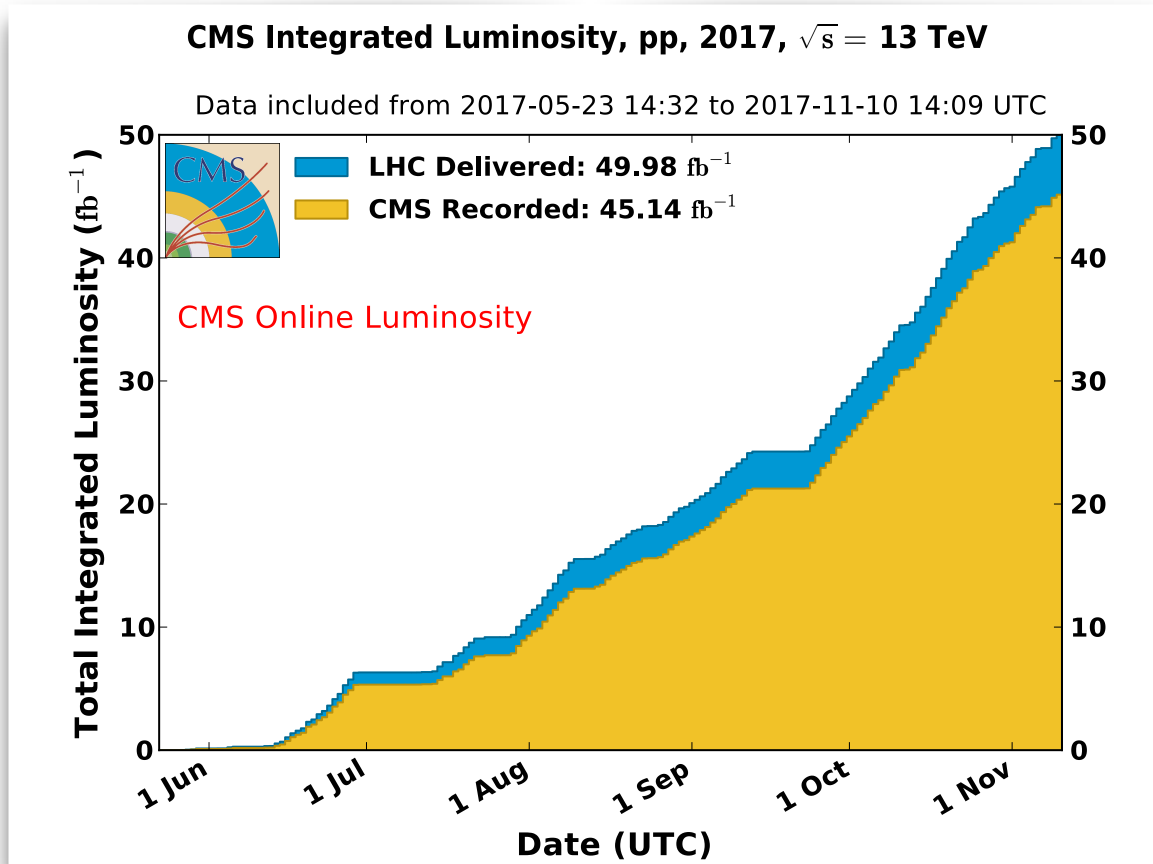
- **Indirect Search:**

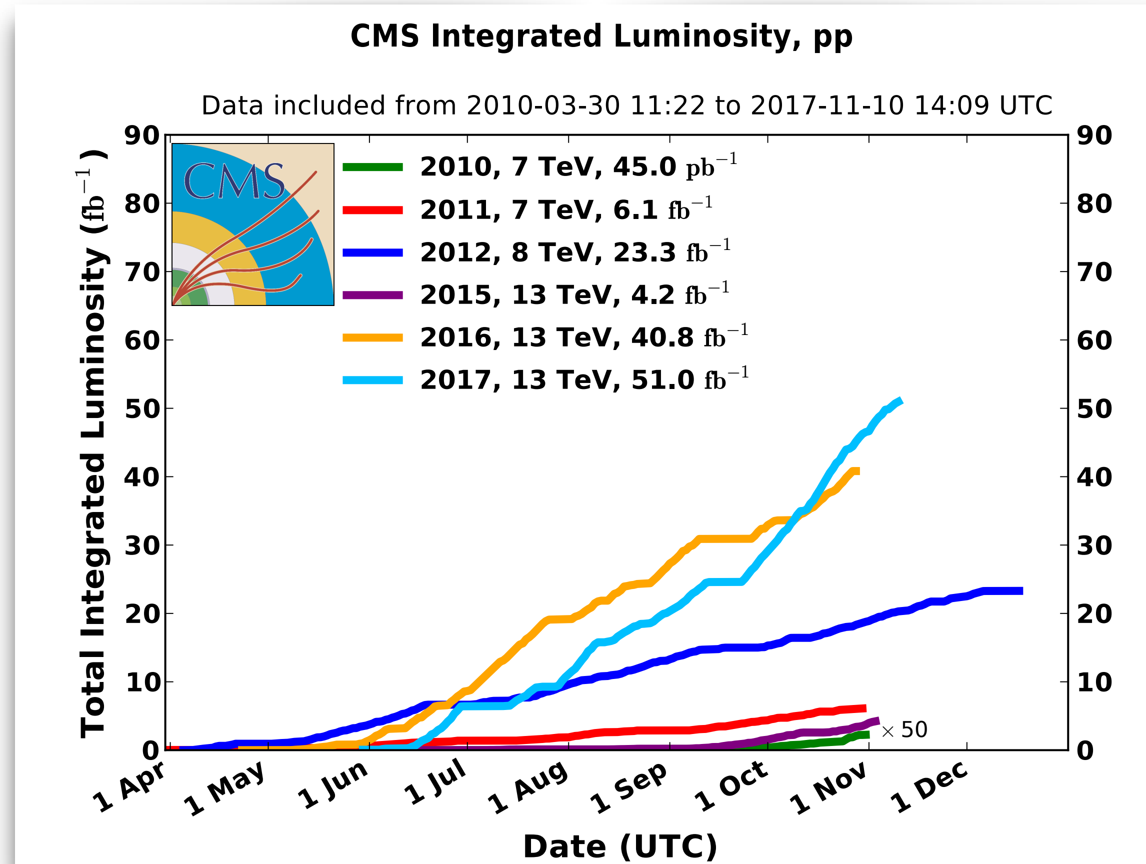
  Measure observables of SM processes (mainly **rare decay** processes).

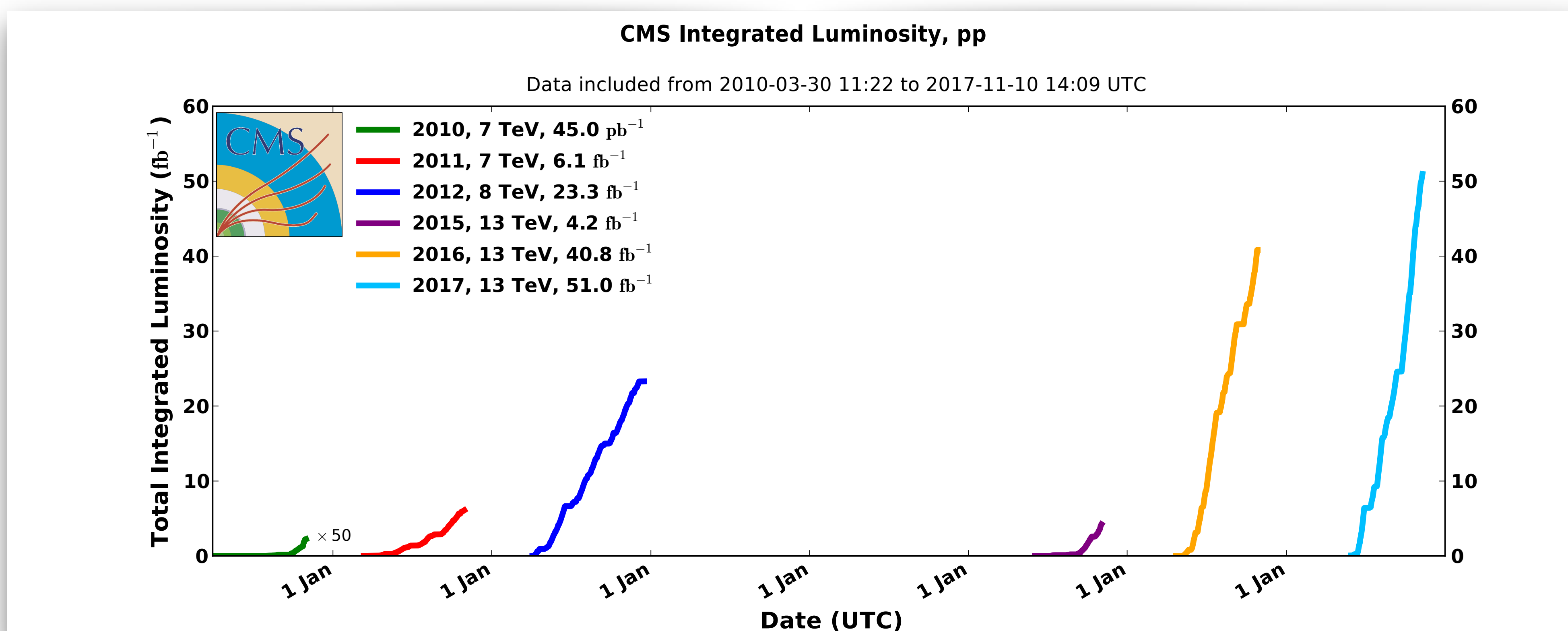
  Any significant deviation from SM prediction would be a hint of NP.

➠ Studying both processes are important and complementary to each other

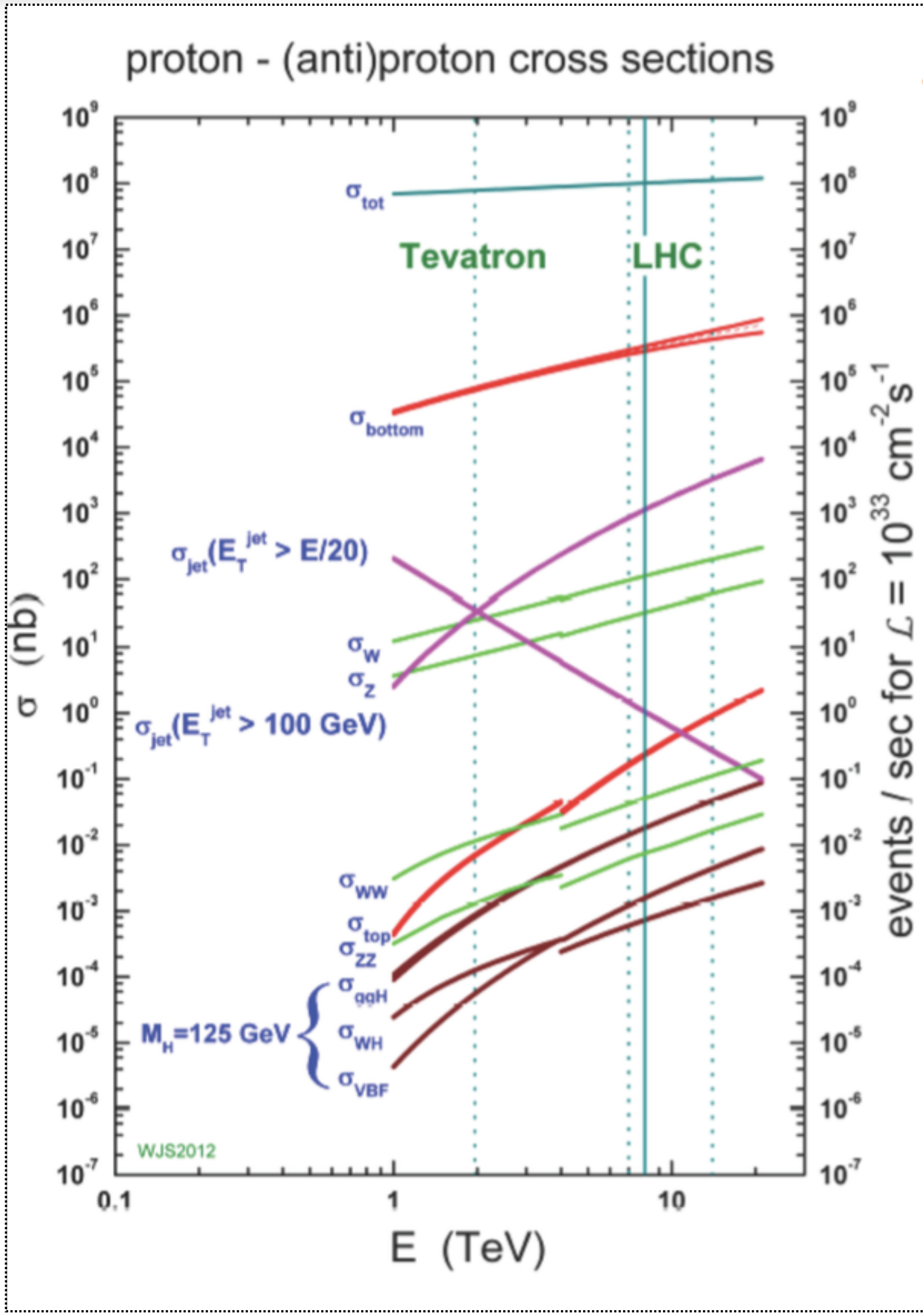
LHC and CMS performance



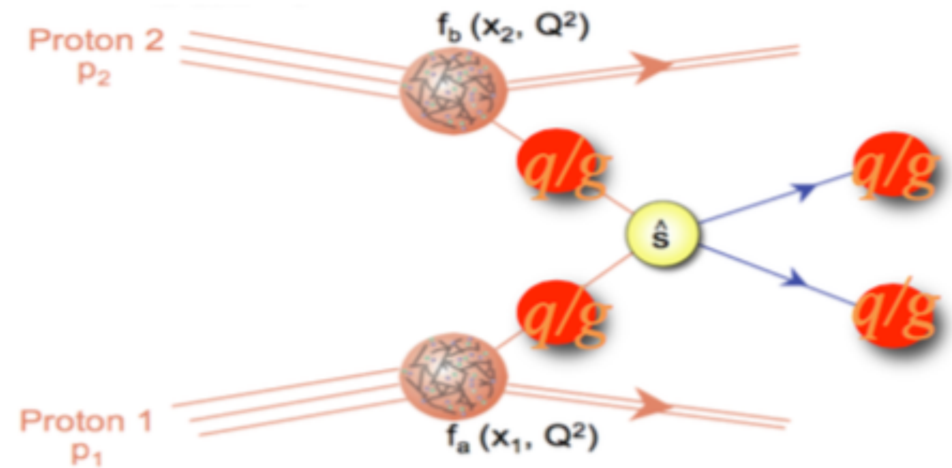




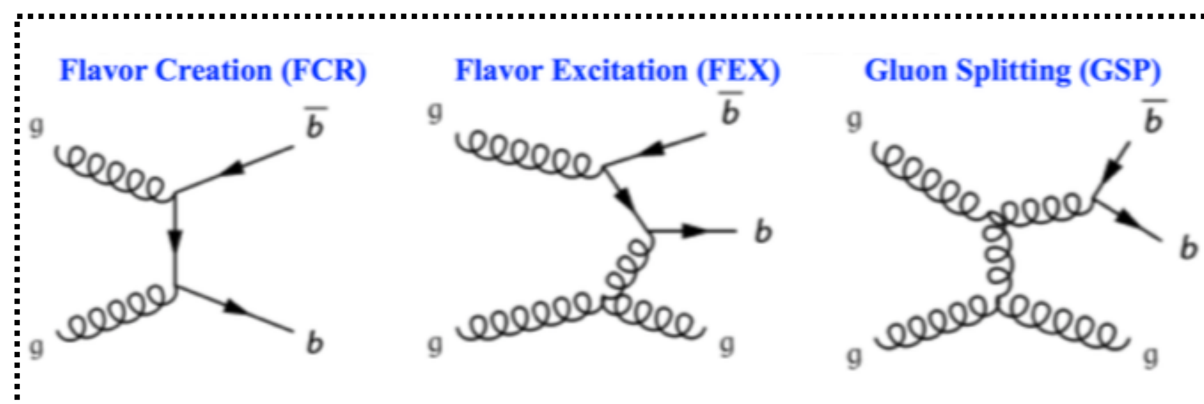
Why we can do better at higher energy ?



- because of large production rate



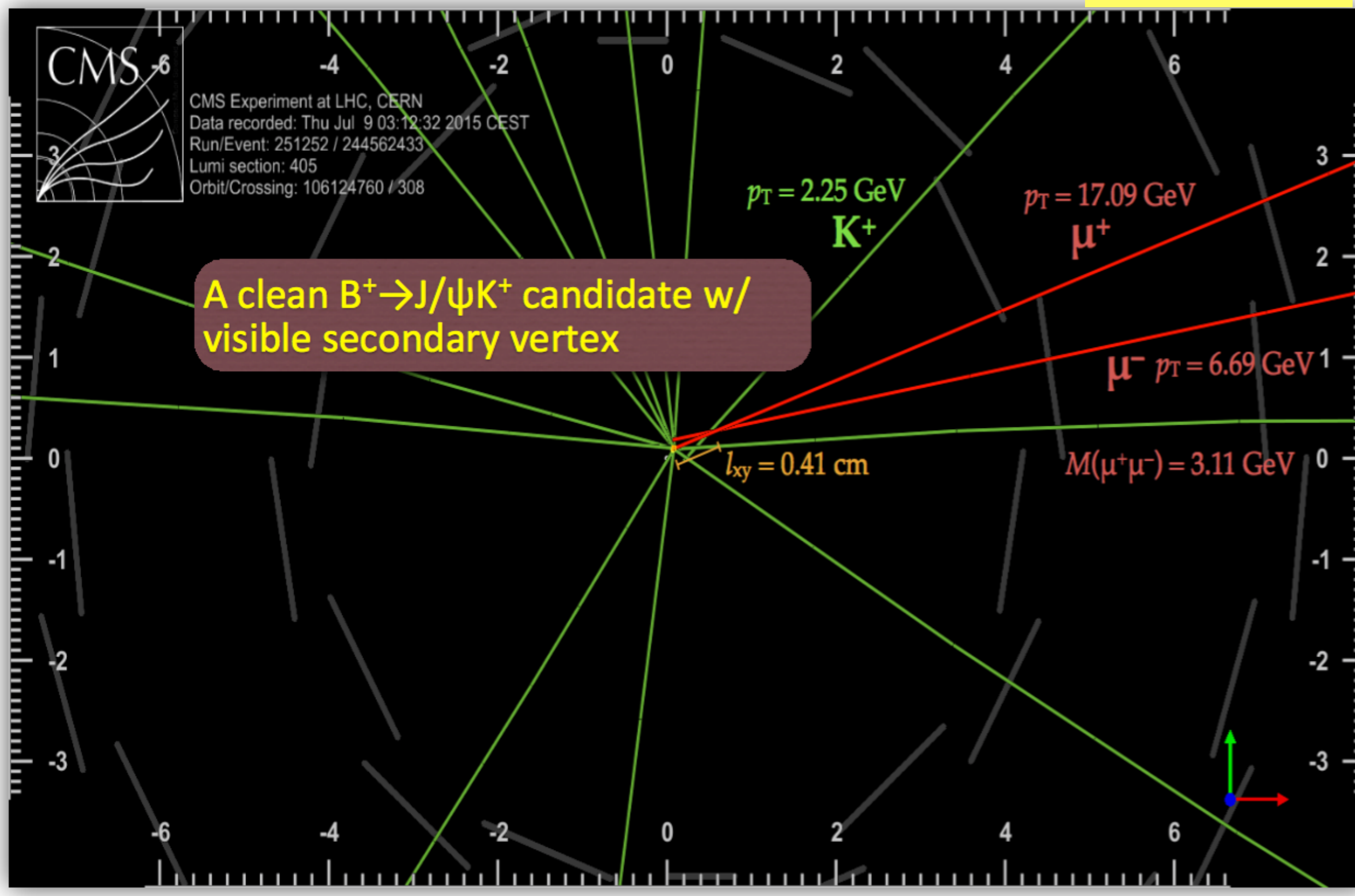
- B production cross-section goes up by almost one order of magnitude higher compared to Tevatron [in LHC ~ O(100μb)]



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

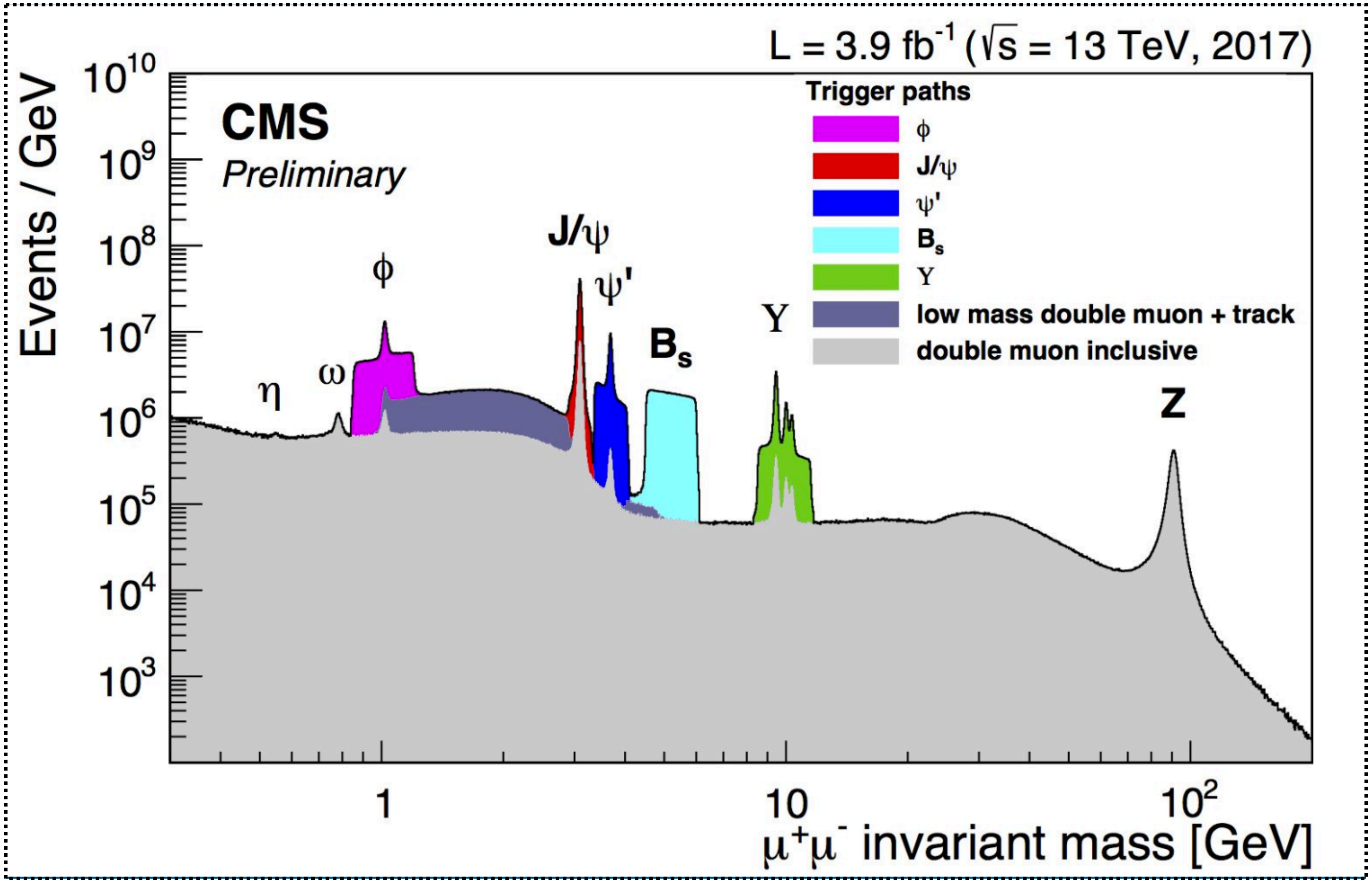
Events with dimuons from CMS @ 13 TeV

CMS DP-2015/018



Events with dimuons from CMS @ 13 TeV

CMS DP-2017/029



- Many flavor physics analyses depend upon the prompt and displaced quarkonium triggers.
- The trigger requirements are tightened due to increased luminosity.
- ~15% bandwidth is given to flavor physics.

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

- These FCNC decays are highly suppressed in SM

  ➟ helicity suppressed, by a factor of $(m_\mu/m_B)^2$

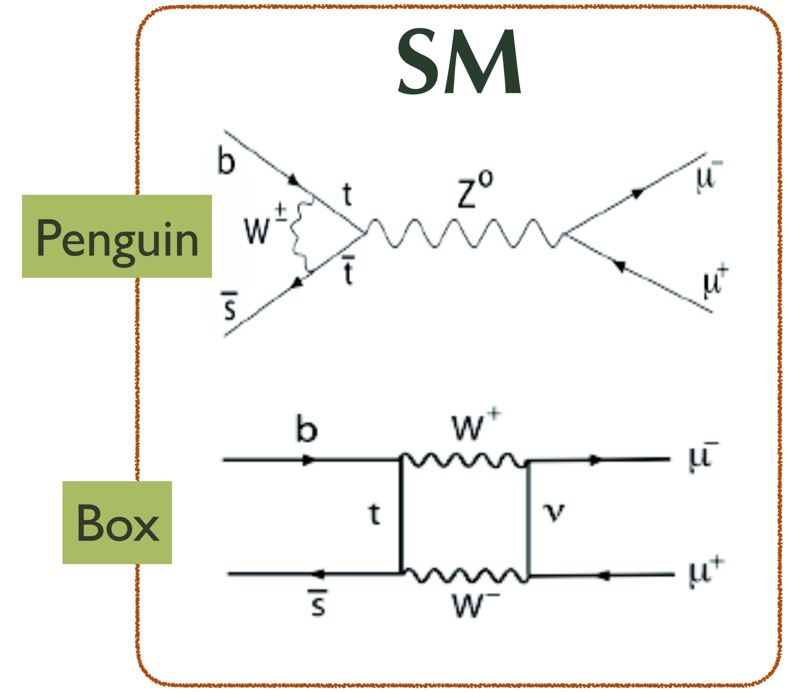
  ➟ forbidden at the tree level in SM, only can proceed through higher order loop diagrams

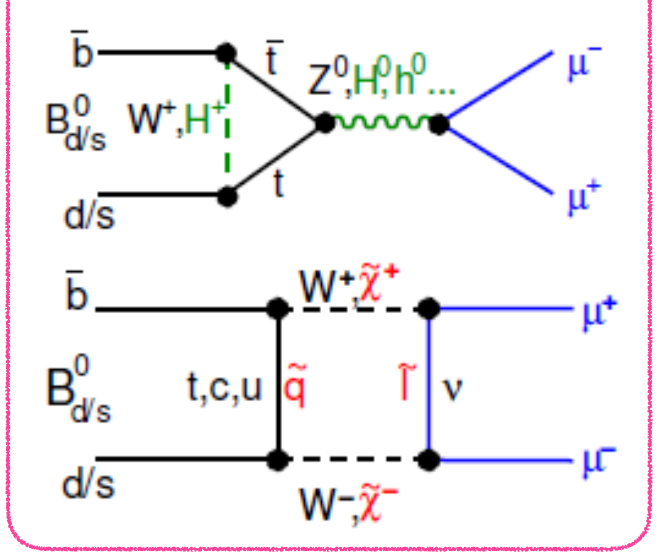
  ➟ Cabibbo suppressed $|V_{tb(ts)}|^2$

- Possible new particles in the loops

  ➟ may enhance or suppress the decay rates !

- Probably the cleanest rare decay both experimentally and theoretically



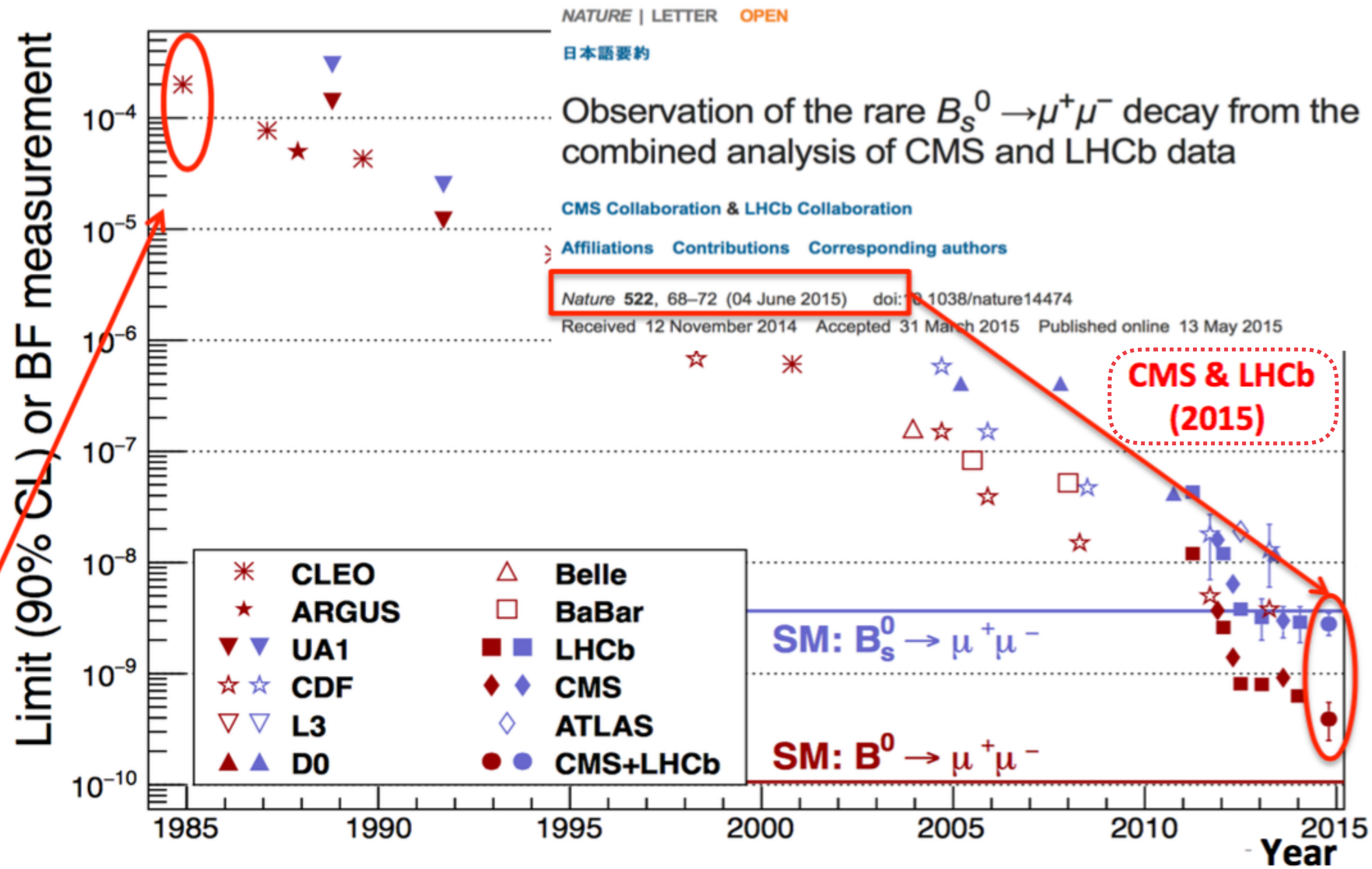


SM Predictions:

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

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

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 $B_d \to \mu\mu$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \frac{n^{obs}_{B_s^0}}{\varepsilon_{B_s^0} N_{B_s^0}} = \frac{n^{obs}_{B_s^0}}{\varepsilon_{B_s^0} \mathcal{L}\, \sigma(pp \to B_s^0)}$$
$$= \frac{N_S}{N^{B^+}_{obs}} \frac{f_u}{f_s} \frac{\varepsilon^{B^+}_{tot}}{\varepsilon_{tot}} \mathcal{B}(B^+)$$

Data split in two categories:
- Barrel: 2 μ in barrel |η|<1.4
  - ➟ better sensitivity, σ_M~40MeV
- Endcap: ≥1 μ in endcap |η|>1.4
  - ➟ more events, σ_M~60MeV

Normalization Sample: $B^\pm \to J/\psi K^\pm \to \mu^+ \mu^- K^\pm$

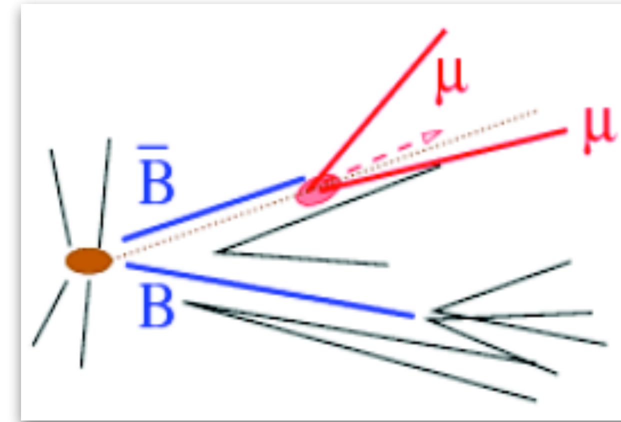
- measure $B_s \to \mu\mu$ relative to the normalization channel (minimize uncertainty due to b production cross section and integrated luminosity)
- ➟ nearly identical selection cuts to reduce systematic uncertainties

Control Sample: $B_s \to J/\psi\, \varphi \to \mu^+ \mu^- K^+ K^-$

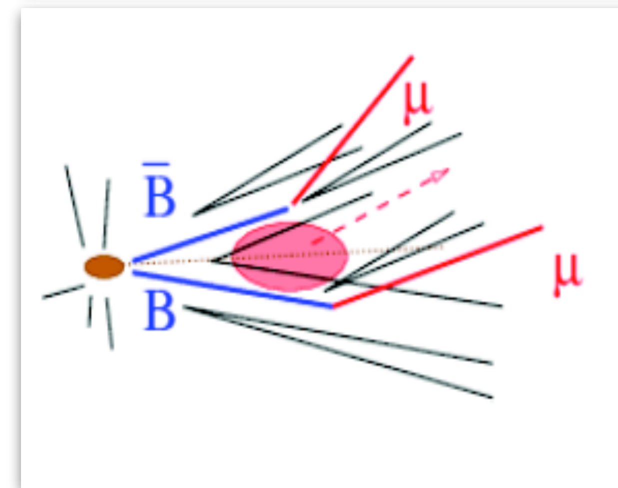
- ➟ calibrate and validate MC

Signal and Backgrounds

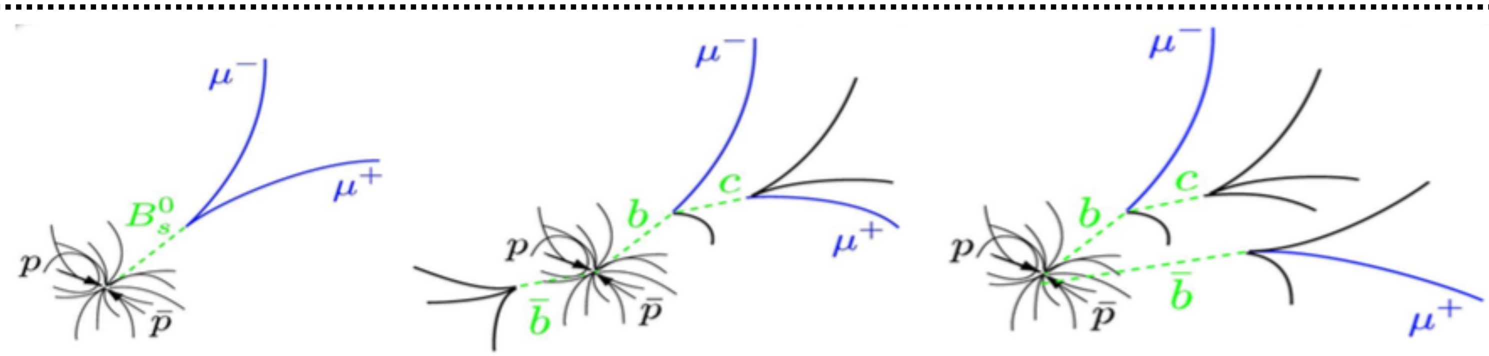
- Signal: $B_{s(d)} \rightarrow \mu\mu$
  - ➟ two muons from a decay vertex
  - ➟ well reconstructed secondary vertex
  - ➟ momentum aligned w/ flight direction
  - ➟ invariant mass around $m(B_{s(d)})$
  - ➟ blind analysis



- 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, $B_s \rightarrow K^+K^-$
  - ➟ non peaking background, e.g, $B_s \rightarrow K^-\mu^+\nu$, $\Lambda_b \rightarrow p\mu^+\nu$



Signal

Sequential b→c decay

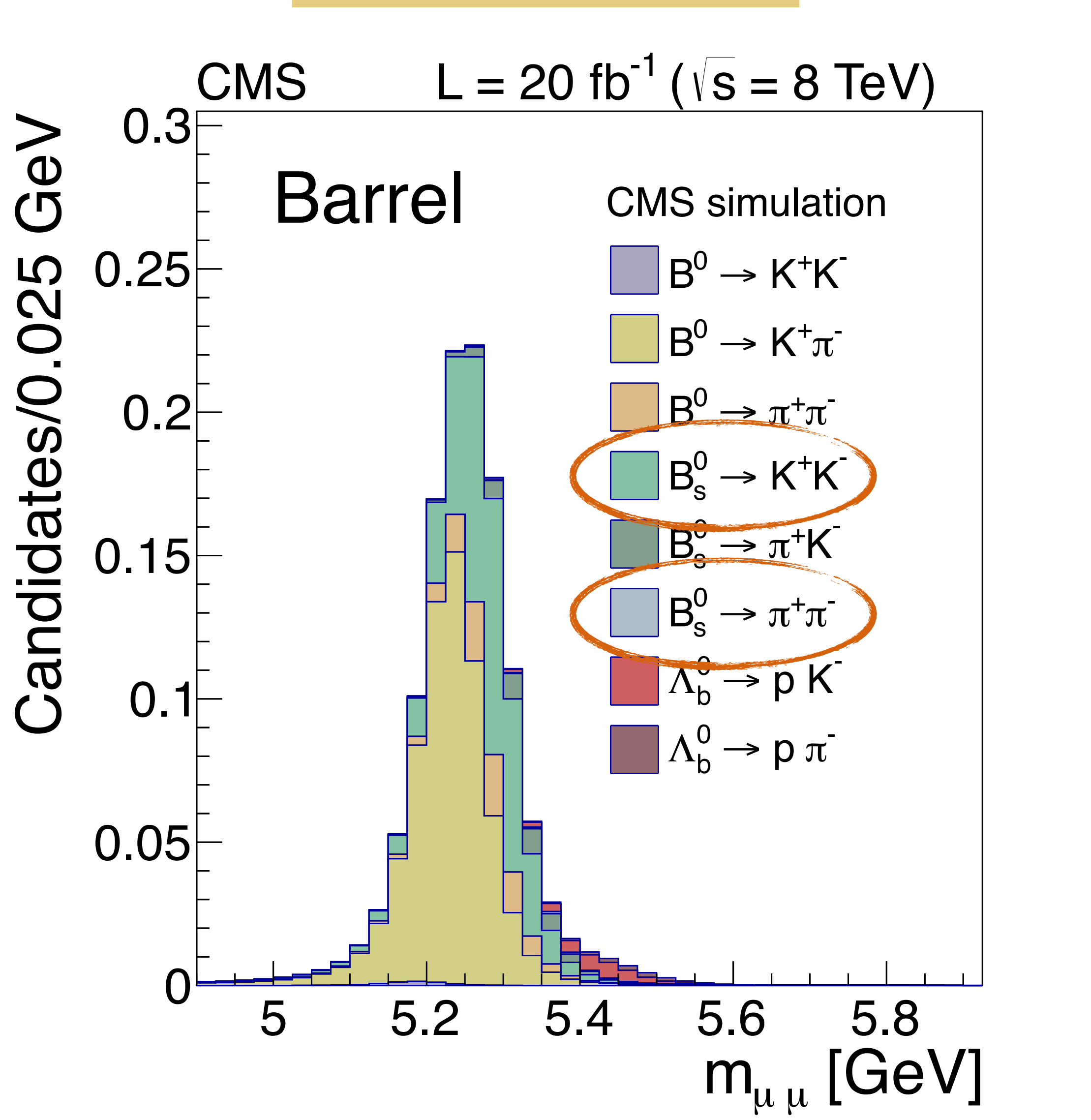
Double b decay

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

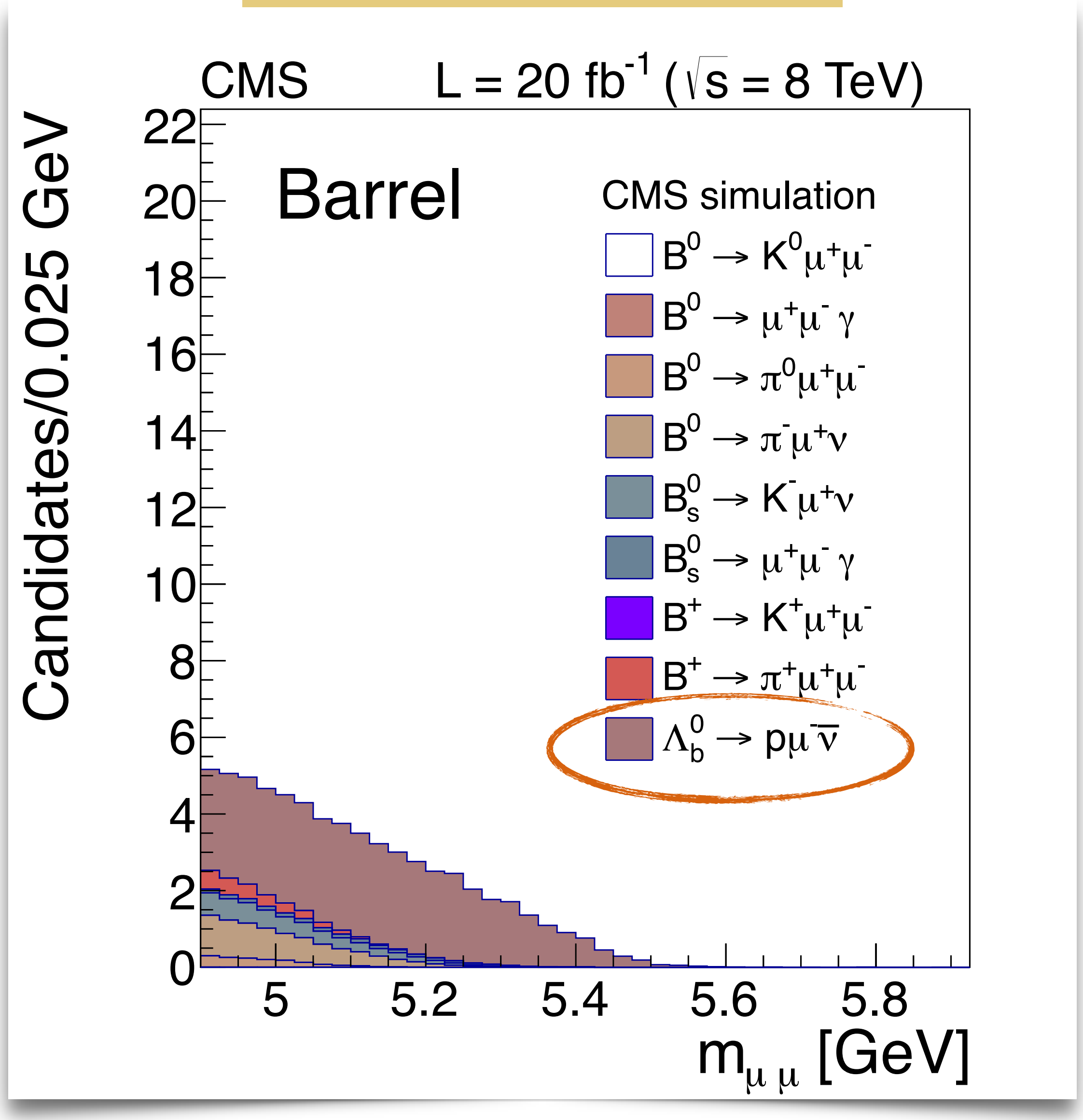
PRL 111(2013) 101804

- 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



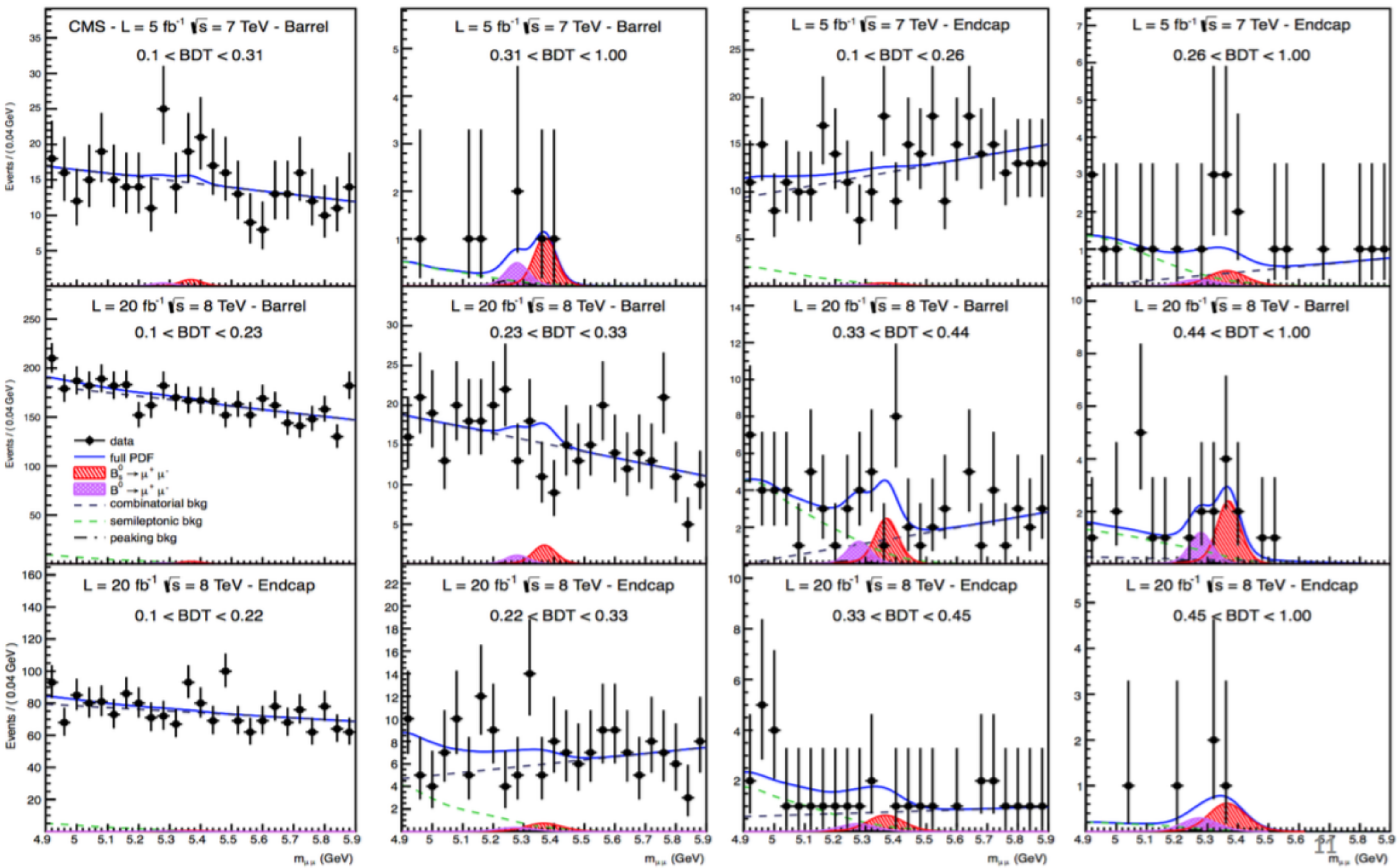
non-peaking backgrounds



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

PRL 111(2013) 101804

- The dimuon mass is further sub-divided into (apart from barrel and endcap 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

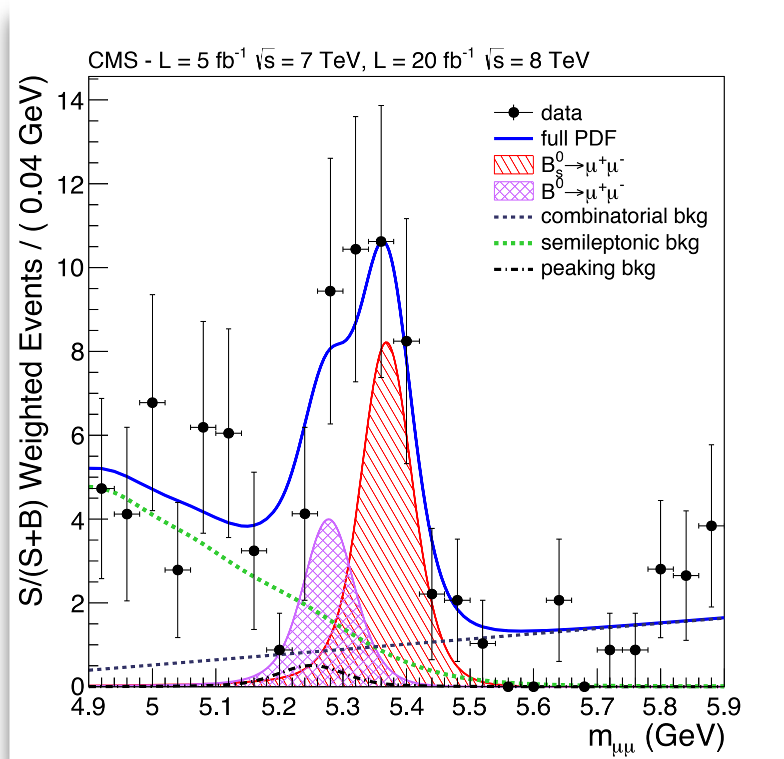
Experimental Result:

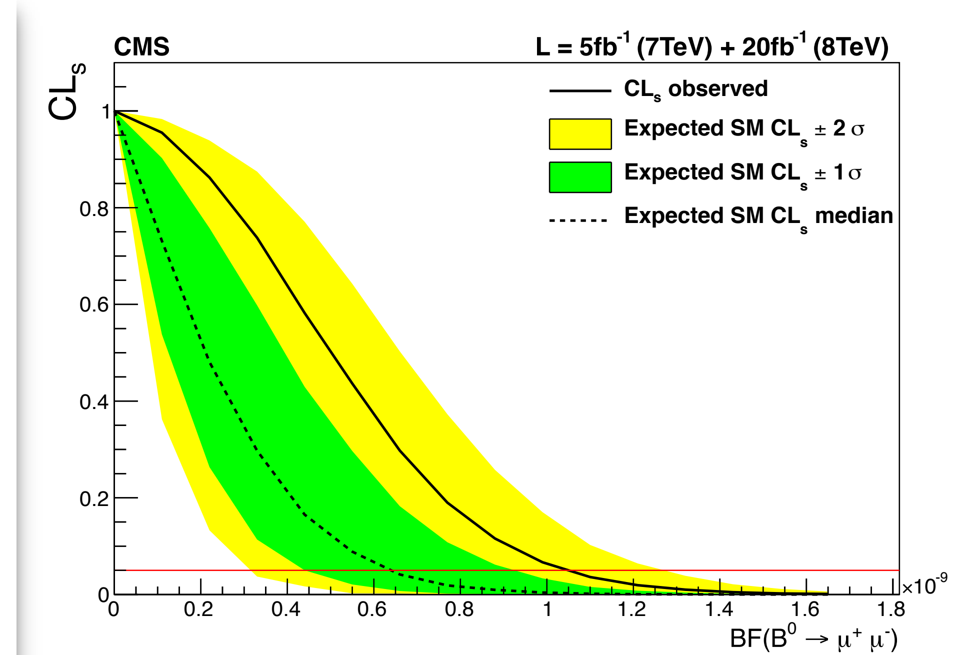
$BR(B_s \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$
$BR(B_d \to \mu^+\mu^-) < 1.1 \times 10^{-9}$ @ 95% CL

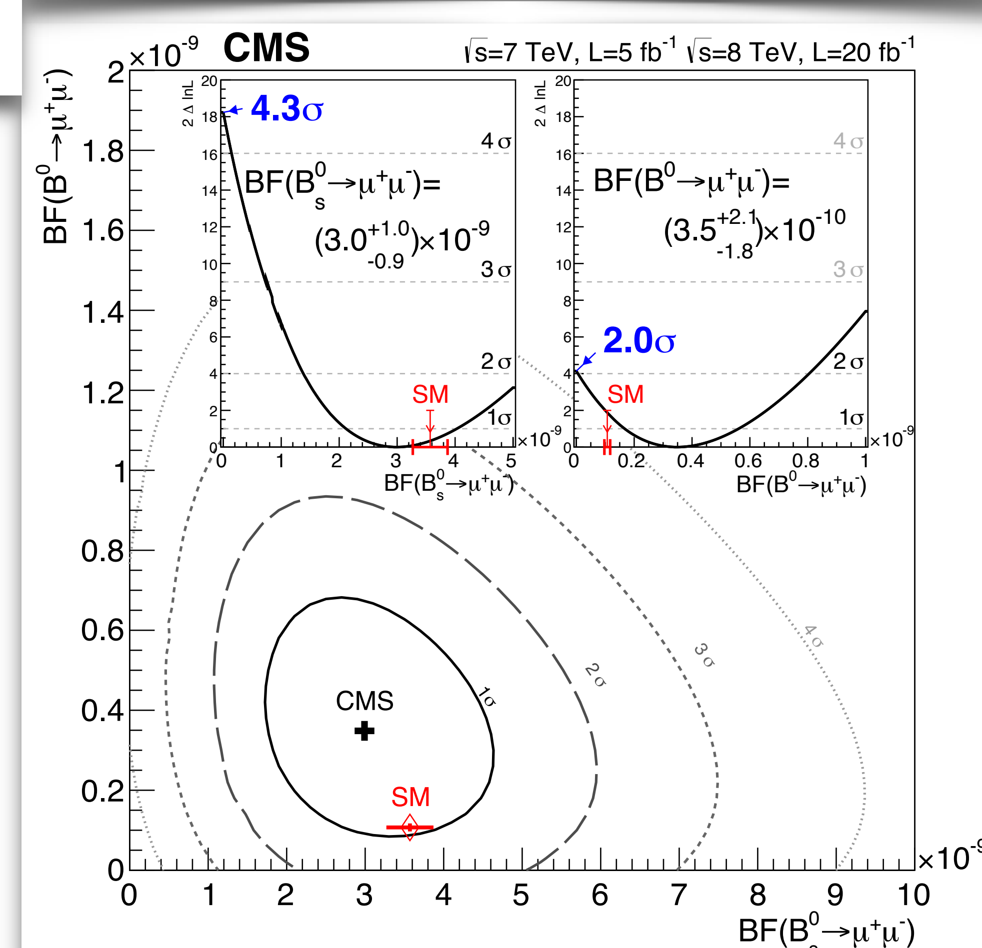
Theoretical Prediction:

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

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







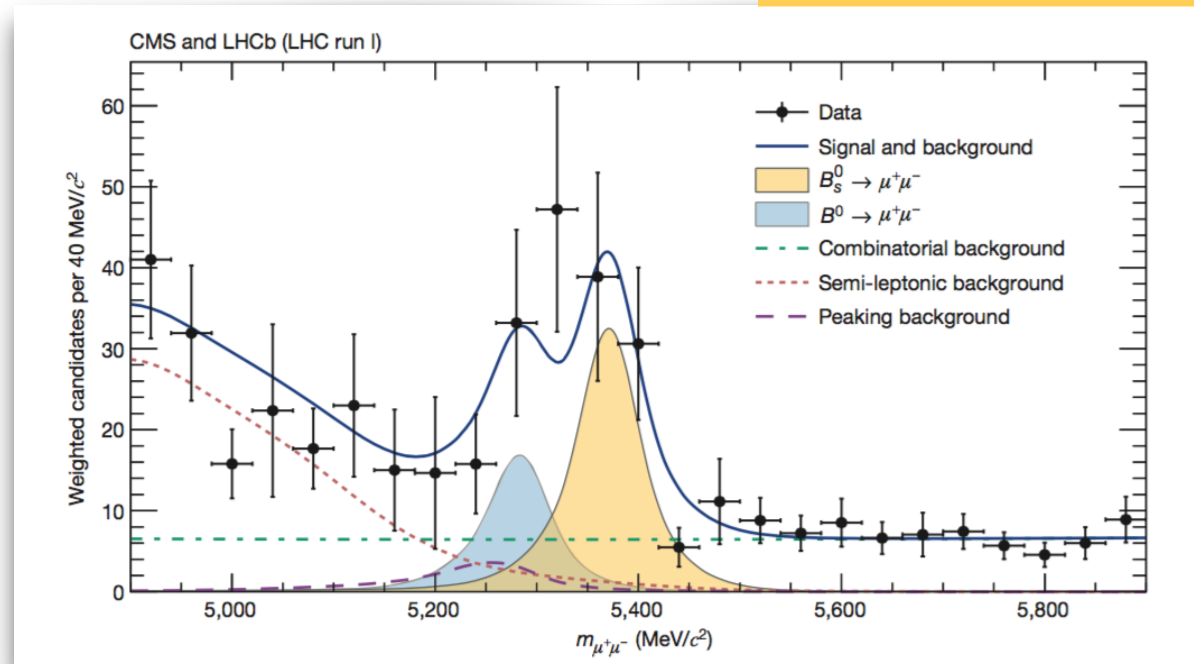
		$\varepsilon_{tot}[10^{-2}]$	N^{exp}_{signal}	N^{exp}_{total}	N_{obs}
7 TeV	B^0 barrel	0.33 ± 0.03	0.27 ± 0.03	1.3 ± 0.8	3
	B^0_s barrel	0.30 ± 0.04	2.97 ± 0.44	3.6 ± 0.6	4
	B^0 end cap	0.20 ± 0.02	0.11 ± 0.01	1.5 ± 0.6	1
	B^0_s end cap	0.20 ± 0.02	1.28 ± 0.19	2.6 ± 0.5	4
8 TeV	B^0 barrel	0.24 ± 0.02	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 $B_{s/d} \to \mu^+\mu^-$

Nature 522, 68-72

- 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)

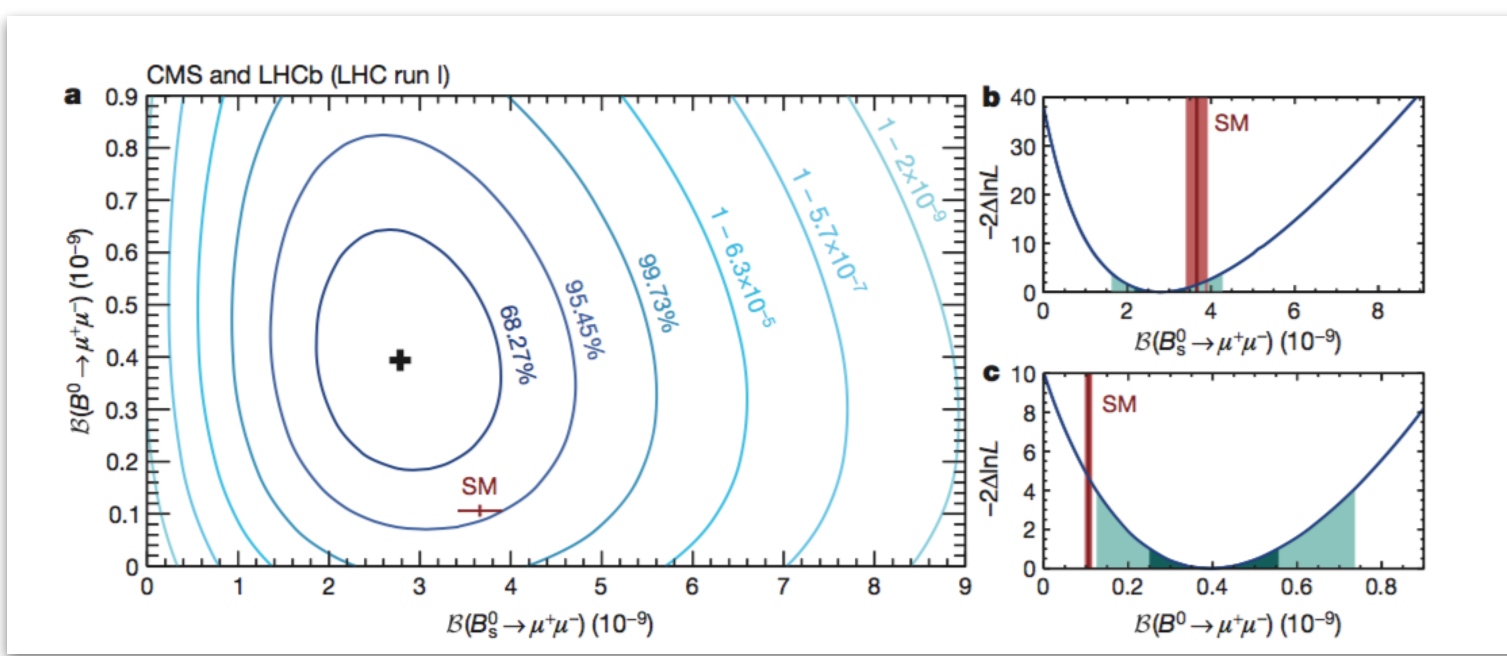


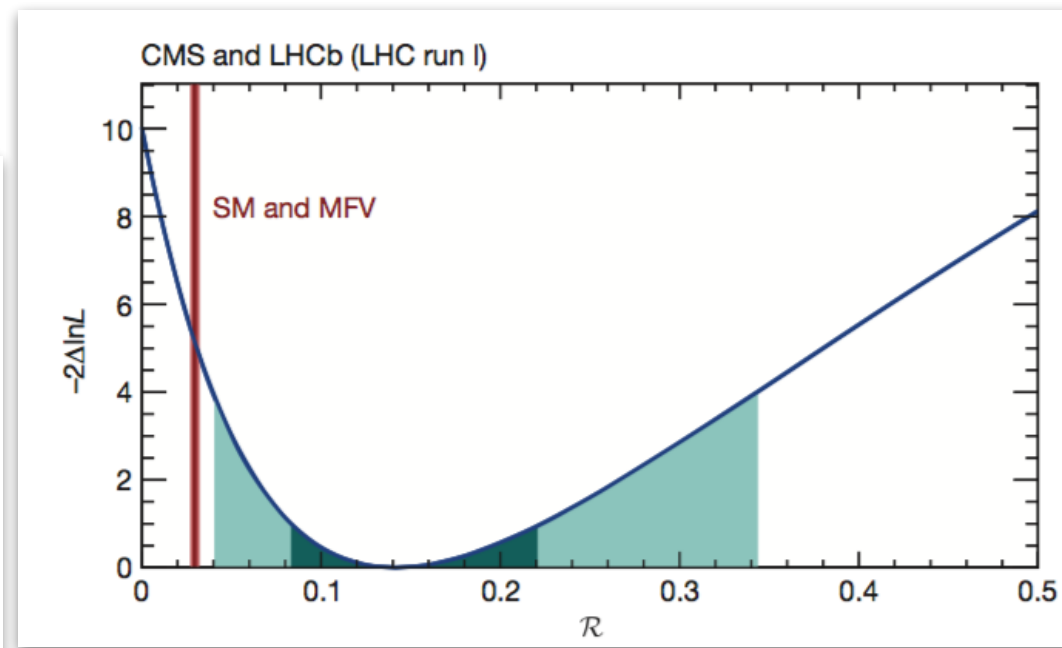
observed branching fraction:

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



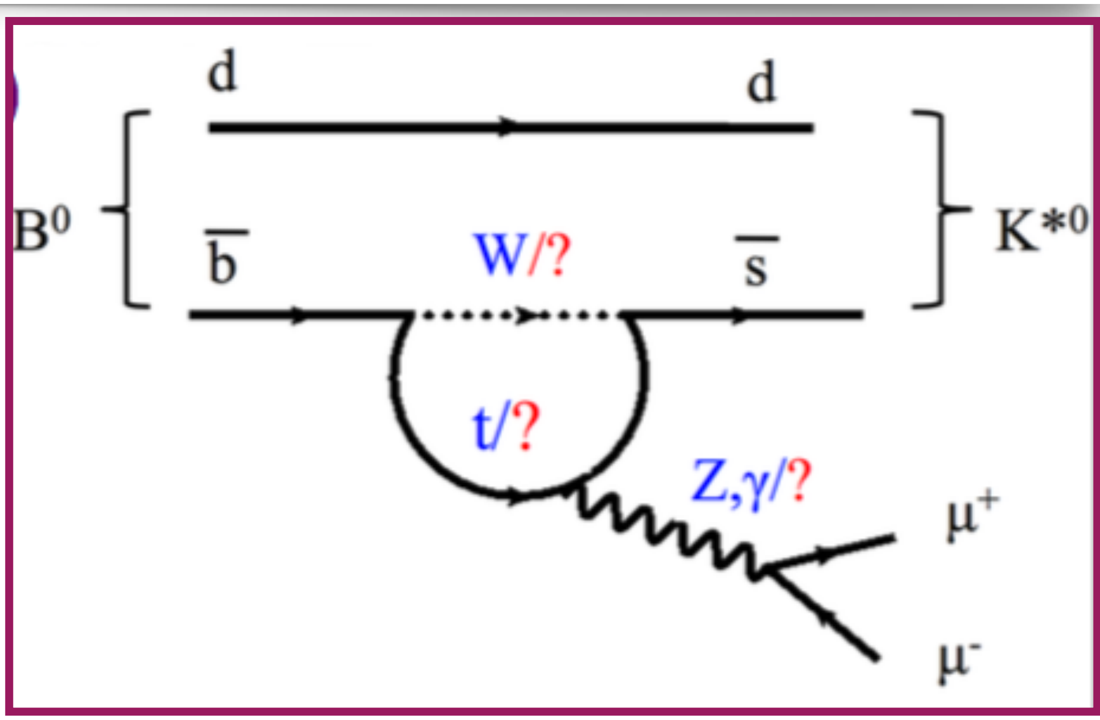


$$\mathcal{R} \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)_{\rm SM}/\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = 0.0295^{+0.0028}_{-0.0025}$$

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

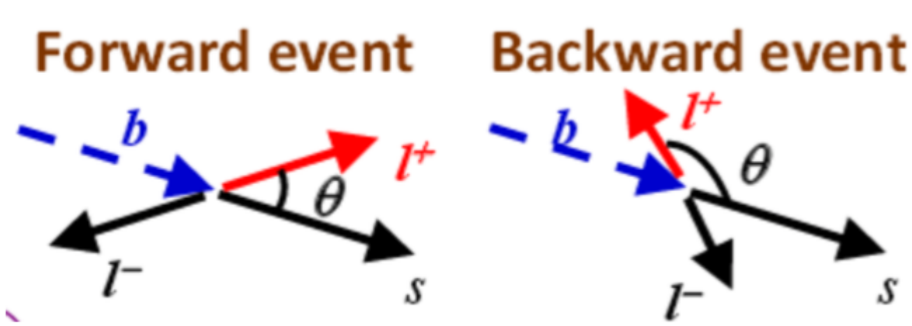
Angular analysis of $B^0 \to K^{*0} \mu^+\mu^-$ in CMS

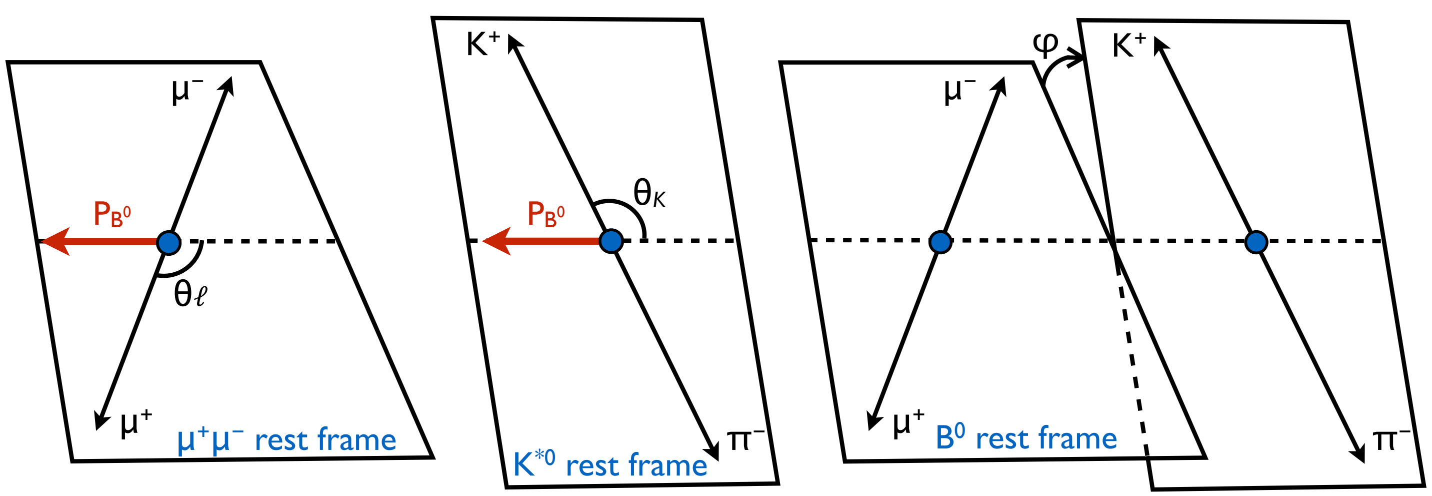
- $B^0 \to K^{*0} \mu^+\mu^-$ ➡ a FCNC process
- Forbidden at tree level, but allowed via loop diagrams (as shown on the right)
- Sensitive to NP through BSM particle in the loop
- Small branching fraction ($\sim 10^{-6}$)
- Fully described by three angles θ_K, θ_L, φ and $q^2 = m^2_{\mu\mu}$
- B^0 and $\bar{B}^0$ are identified by K and π charges
- Observables to be compared with SM predictions :
  - Forward backward asymmetry of muons, A_{FB}
  - Longitudinal polarization fraction of K*, F_L
  - Combination of angular co-efficients, P_i and P_i'



arXiv: 1710.02846

➡ Discrepancy of the angular parameters vs q^2 w.r.t SM might be a hint for NP.

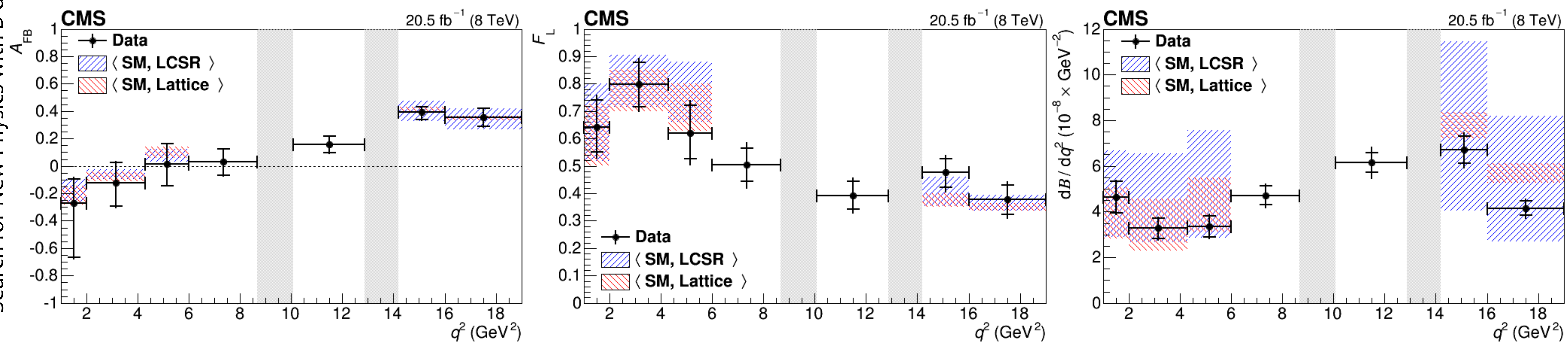




Analysis history

- First iteration of the analysis @ 8 TeV, 20 fb^{-1} [PLB 753 (2016) 424]
- Measured A_{FB}, F_L and dB/dq^2 vs q^2
- Signal Yield ~ 1400 events
- 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
- No deviation from SM prediction

Experiment	F_L	A_{FB}	$d\mathcal{B}/dq^2$ $(10^{-8}\,\mathrm{GeV}^{-2})$
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)	$0.73^{+0.08}_{-0.10}$	$-0.03^{+0.04}_{-0.03}$	$3.8^{+1.2}_{-1.0}$



- > 3σ tension from SM seen by LHCb on P'_5 observable at $q^2 < 6$ GeV^2 [JHEP 02 (2016) 104]
- Second iteration with the same dataset dedicated to measure P'_5 and P_1 with CMS data

Measurement of P'$_5$ and P$_1$ in $B^0 \to K^{*0} \mu^+\mu^-$

- Final state has contribution from P-wave (K*) and S-wave
- The PDF has 14 parameters in total: fold about $\varphi = 0$ and $\theta_L = \pi/2$ to reduce them

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2 d\cos\theta_l d\cos\theta_K d\phi} = \frac{9}{8\pi}\left\{\frac{2}{3}\left[(F_S + A_S\cos\theta_K)\left(1-\cos^2\theta_l\right) + A_S^5\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right.$$
$$+ (1-F_S)\left[2F_L\cos^2\theta_K\left(1-\cos^2\theta_l\right) + \frac{1}{2}(1-F_L)\left(1-\cos^2\theta_K\right)\left(1+\cos^2\theta_l\right)\right.$$
$$+ \frac{1}{2}P_1(1-F_L)(1-\cos^2\theta_K)(1-\cos^2\theta_l)\cos 2\phi$$
$$\left.\left. + 2P_5'\cos\theta_K\sqrt{F_L(1-F_L)}\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right\}$$

- 6 parameters left: statistics not enough to perform a fully floating fit
- F_L, F_S and A_s fixed from previous CMS measurement [PLB 753 (2016) 424]
- P'$_5$ and P$_1$ measured

☞ 4-dimensional unbinned maximum likelihood fit is used to extract P'$_5$ and P$_1$ in 7 q² bins.

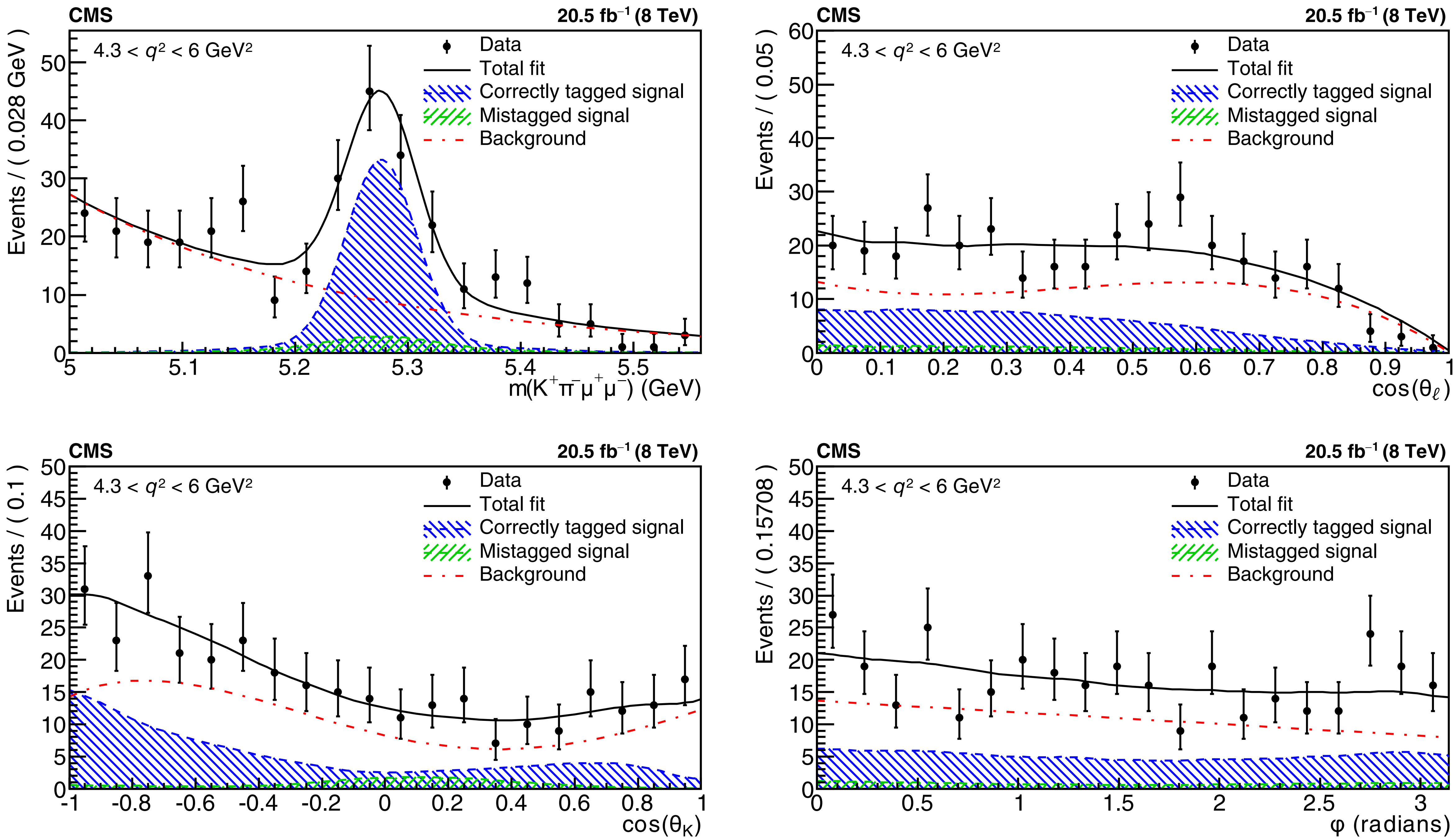
The fit includes:
1. signal, background and mistag component
2. 3D efficiency function
3. Background fixed from sidebands

$$\text{p.d.f.}(m,\cos\theta_K,\cos\theta_l,\phi) = Y_S^C\cdot\left(S_i^R(m)\cdot S_i^a(\cos\theta_K,\cos\theta_l,\phi)\cdot\epsilon_i^R(\cos\theta_K,\cos\theta_l,\phi)\right.$$
$$\left.+\frac{f_i^M}{1-f_i^M}\cdot S_i^M(m)\cdot S_i^a(-\cos\theta_K,-\cos\theta_l,-\phi)\cdot\epsilon_i^M(-\cos\theta_l,-\cos\theta_K,-\phi)\right)$$
$$+ Y_B\cdot B_i^m(m)\cdot B_i^{\cos\theta_K}(\cos\theta_K)\cdot B_i^{\cos\theta_l}(\cos\theta_l)\cdot B_i^{\phi}(\phi).$$

Measurement of P'_5 and P_1 in $B^0 \rightarrow K^{*0} \mu^+\mu^-$
(contd.)

Fit projection in 3rd bin $4.30 < q^2 < 6.00$ GeV^2

arXiv: 1710.02846



See the backup for projection plots in other q^2 bins

Measurement of P'_5 and P_1 in $B^0 \rightarrow K^{*0} \mu^+\mu^-$ (contd.)

arXiv: 1710.02846

Systematic uncertainties

Source	$P_1 (\times 10^{-3})$	$P'_5 (\times 10^{-3})$
Simulation mismodeling	1–33	10–23
Fit bias	5–78	10–120
Finite size of simulated samples	29–73	31–110
Efficiency	17–100	5–65
$K\pi$ mistagging	8–110	6–66
Background distribution	12–70	10–51
Mass distribution	12	19
Feed-through background	4–12	3–24
F_L, F_S, A_S uncertainty propagation	0–210	0–210
Angular resolution	2–68	0.1–12
Total	100–230	70–250

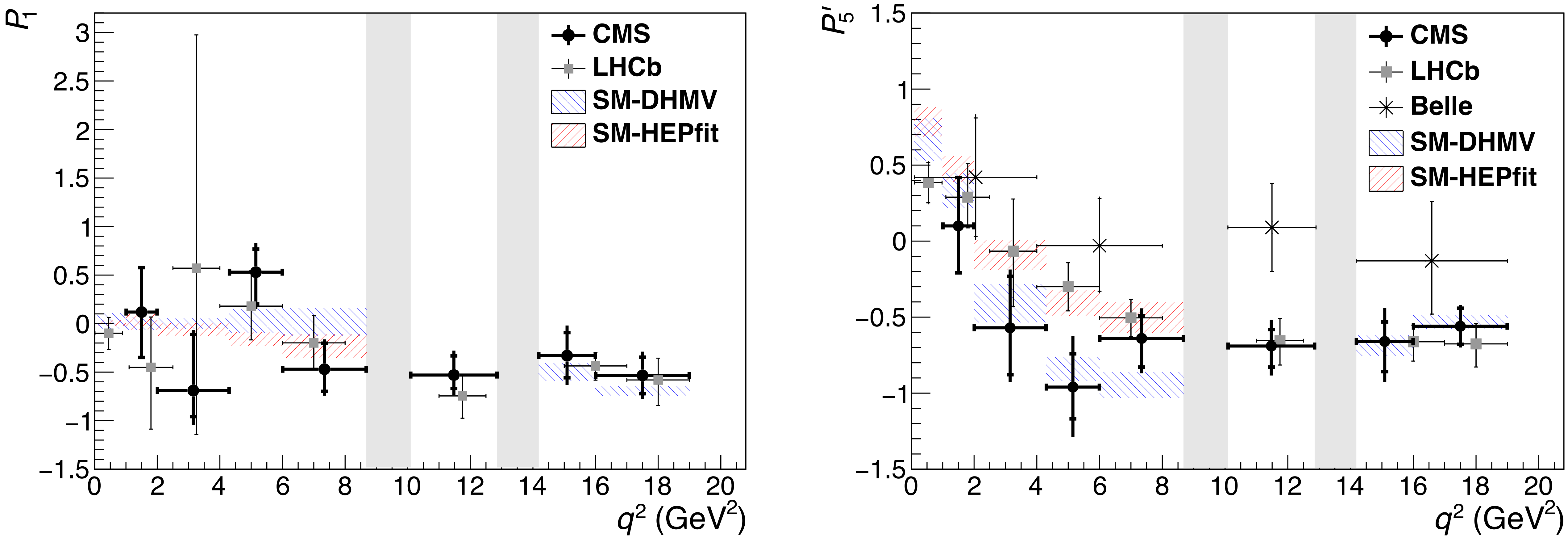
Results in each q^2

q^2 (GeV^2)	Signal yield	P_1	P'_5
1.00–2.00	80 ± 12	$+0.12\,^{+0.46}_{-0.47} \pm 0.10$	$+0.10\,^{+0.32}_{-0.31} \pm 0.07$
2.00–4.30	145 ± 16	$-0.69\,^{+0.58}_{-0.27} \pm 0.23$	$-0.57\,^{+0.34}_{-0.31} \pm 0.18$
4.30–6.00	119 ± 14	$+0.53\,^{+0.24}_{-0.33} \pm 0.19$	$-0.96\,^{+0.22}_{-0.21} \pm 0.25$
6.00–8.68	247 ± 21	$-0.47\,^{+0.27}_{-0.23} \pm 0.15$	$-0.64\,^{+0.15}_{-0.19} \pm 0.13$
10.09–12.86	354 ± 23	$-0.53\,^{+0.20}_{-0.14} \pm 0.15$	$-0.69\,^{+0.11}_{-0.14} \pm 0.13$
14.18–16.00	213 ± 17	$-0.33\,^{+0.24}_{-0.23} \pm 0.20$	$-0.66\,^{+0.13}_{-0.20} \pm 0.18$
16.00–19.00	239 ± 19	$-0.53 \pm 0.19 \pm 0.16$	$-0.56 \pm 0.12 \pm 0.07$

CMS results vs SM prediction & other measurements

LHCb: JHEP 02 (2016) 104
Belle: PRL 118 (2017) 111801
ATLAS: ATLAS-CONF-2017-023 (not shown here)

arXiv: 1710.02846



Results are well in agreement with the SM predictions and previous measurements.

Summary

☞ Two main measurements discussed today:

- $B_s \to \mu^+\mu^-$:
  - The very rare decay $B_s \to \mu^+\mu^-$ has been clearly observed and the measured BF is compatible with SM prediction (within 1.2σ).
  - It provides stringent constraints on New Physics models. More data are required for $B_d \to \mu^+\mu^-$ observation soon.

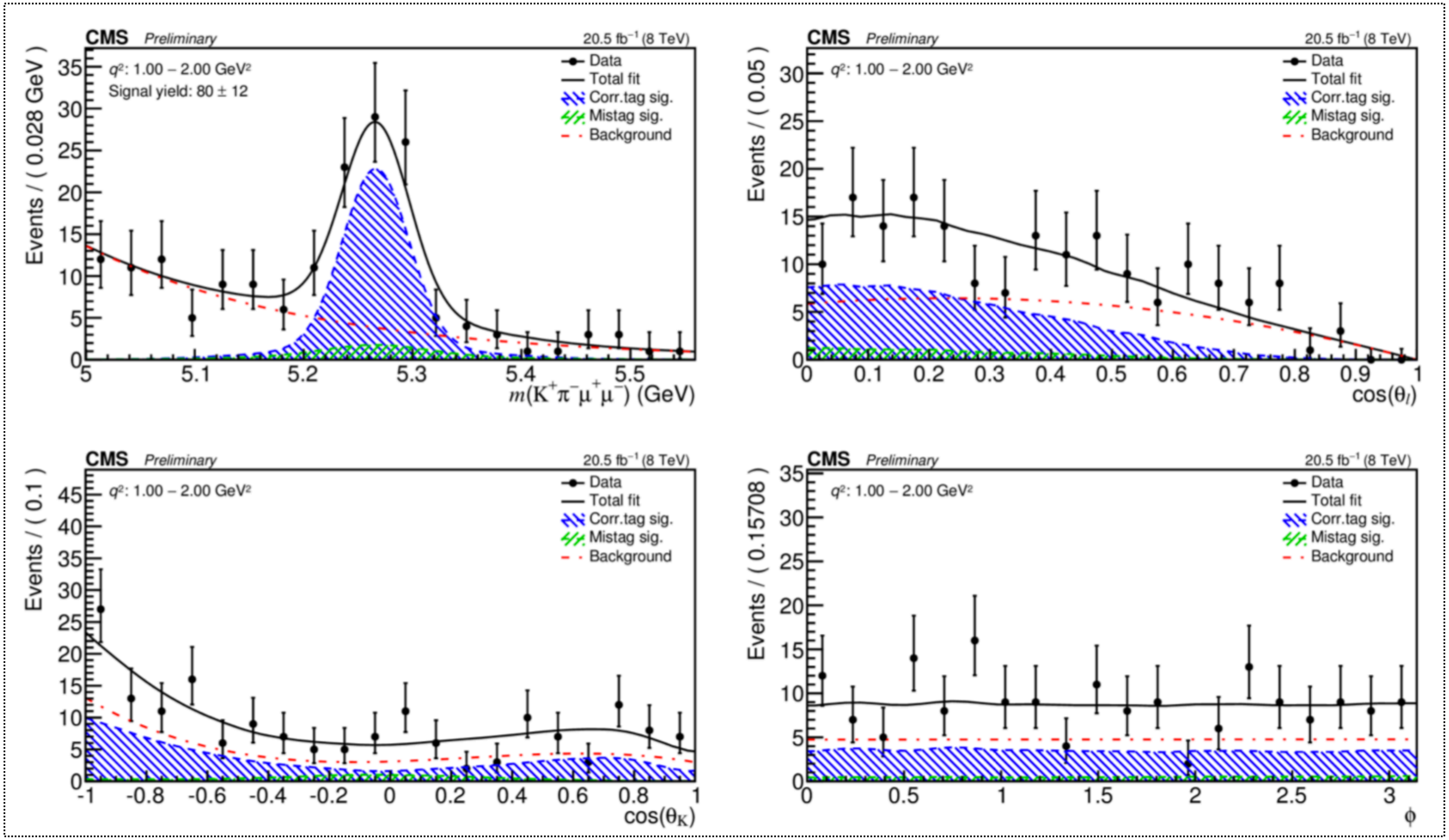
- $B^0 \to K^{*0}\mu^+\mu^-$:
  - Extended measurements are carried out for $B^0 \to K^{*0}\mu^+\mu^-$ decay modes. Most of the observables are found to be consistent with SM predictions.
  - More data in next few years would be very crucial for LHC to look something beyond SM.

Rare decays play an important role in search of physics beyond the SM.
No clear striking signals about NP yet, more data will help to clarify them.

Back Up

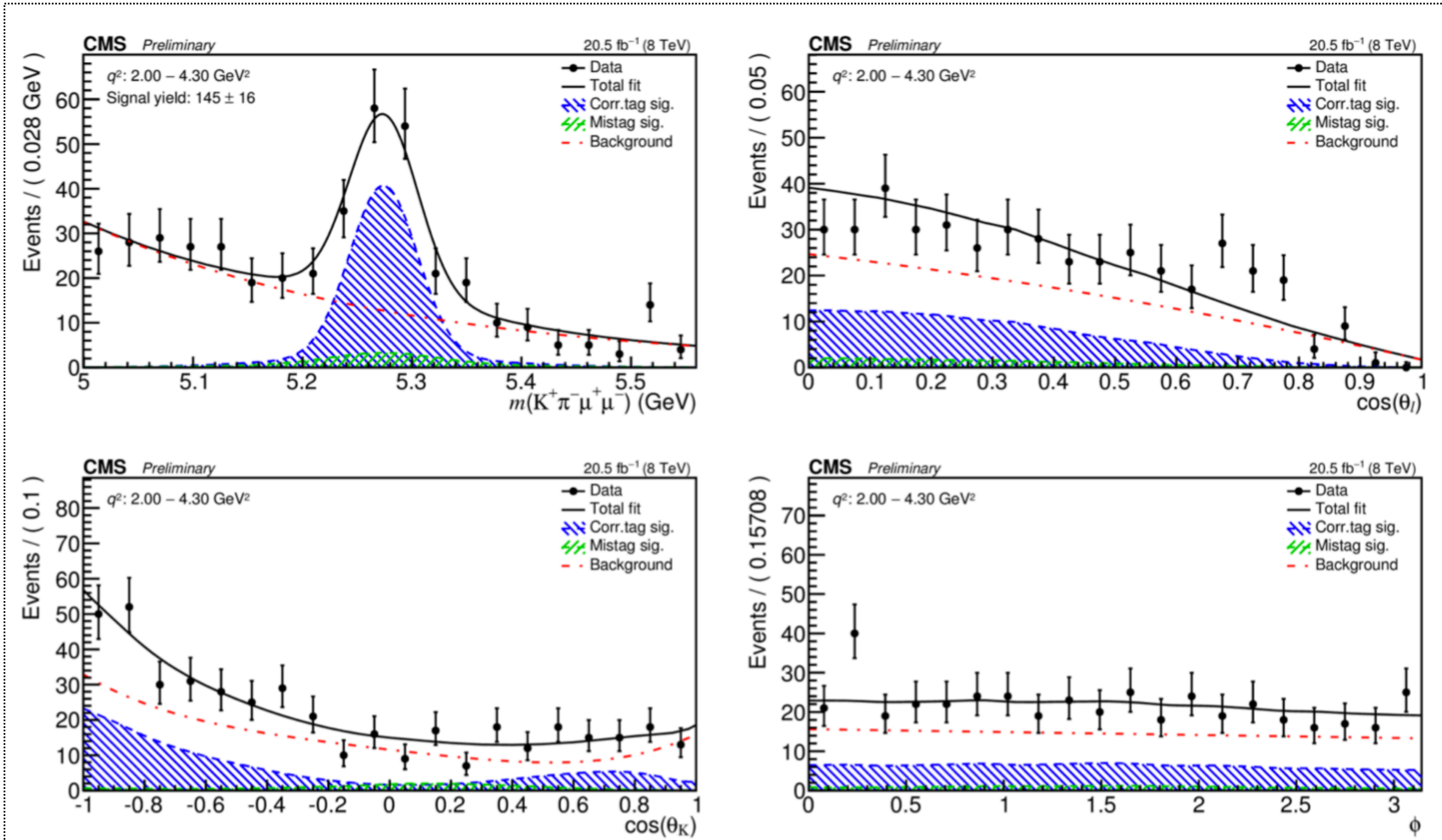
Measurement of P'_5 and P_1 in $B^0 \to K^{*0} \mu^+\mu^-$ (contd.)

Fit projection in 1st bin $1.00 < q^2 < 2.00$ GeV^2



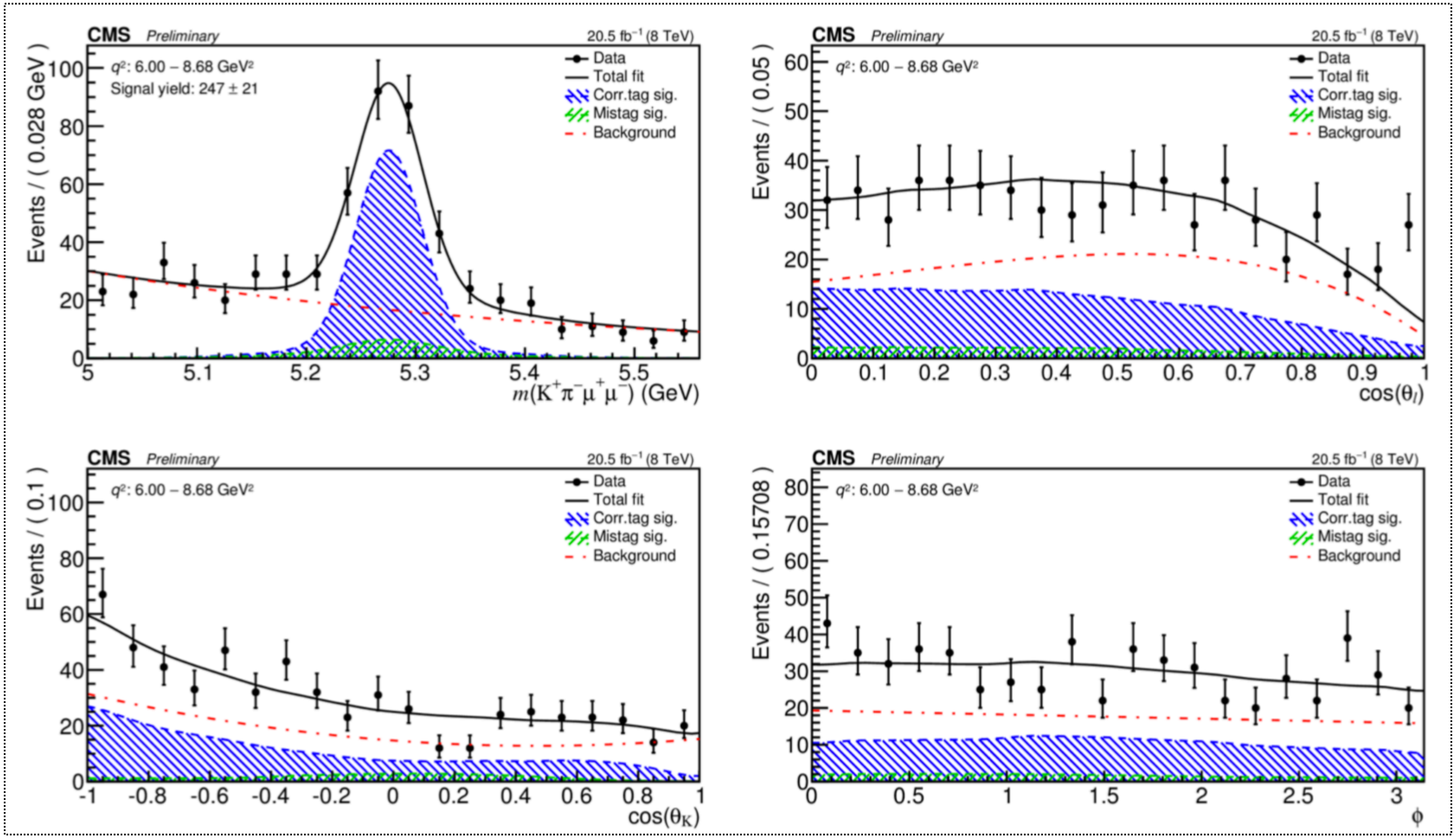
Measurement of P'_5 and P_1 in $B^0 \to K^{*0} \mu^+\mu^-$ (contd.)

Fit projection in 2nd bin $2.00 < q^2 < 4.30$ GeV^2



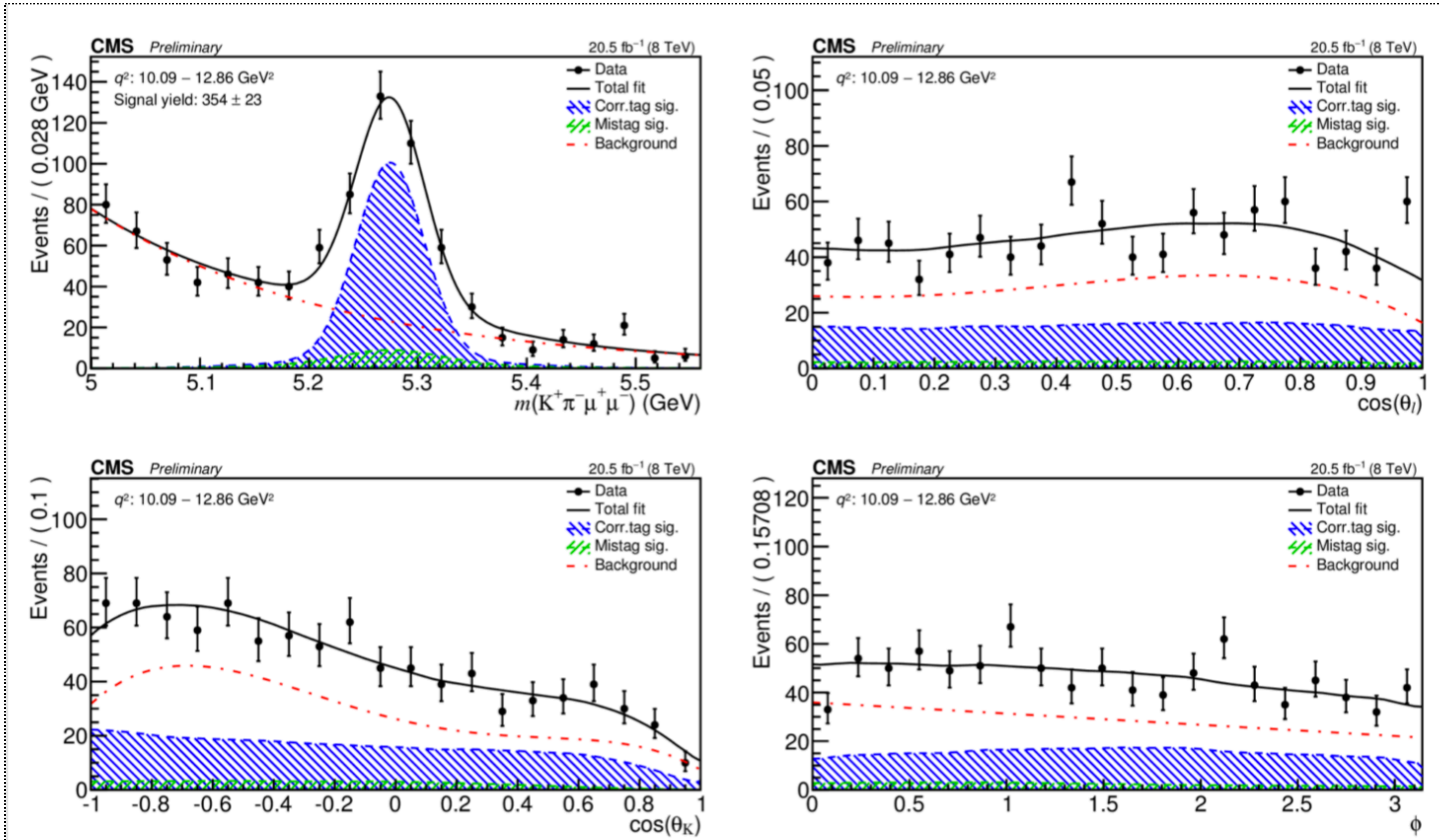
Measurement of P'_5 and P_1 in $B^0 \rightarrow K^{*0} \mu^+\mu^-$ (contd.)

Fit projection in 4th bin $6.00 < q^2 < 8.68$ GeV^2



Measurement of P'_5 and P_1 in $B^0 \to K^{*0} \mu^+\mu^-$ (contd.)

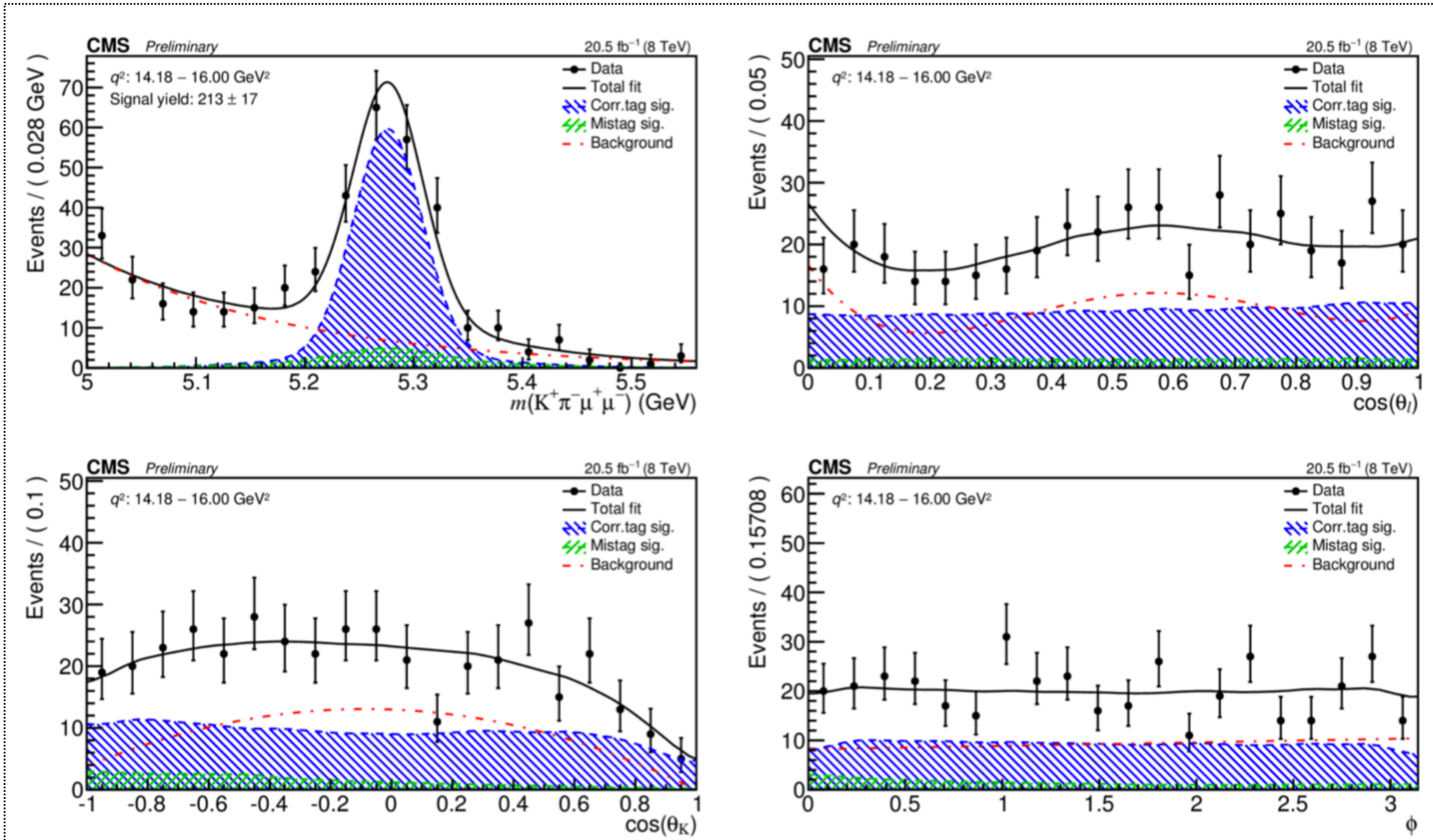
Fit projection in 6th bin $10.09 < q^2 < 12.86$ GeV^2



Measurement of P'_5 and P_1 in $B^0 \rightarrow K^{*0} \mu^+\mu^-$

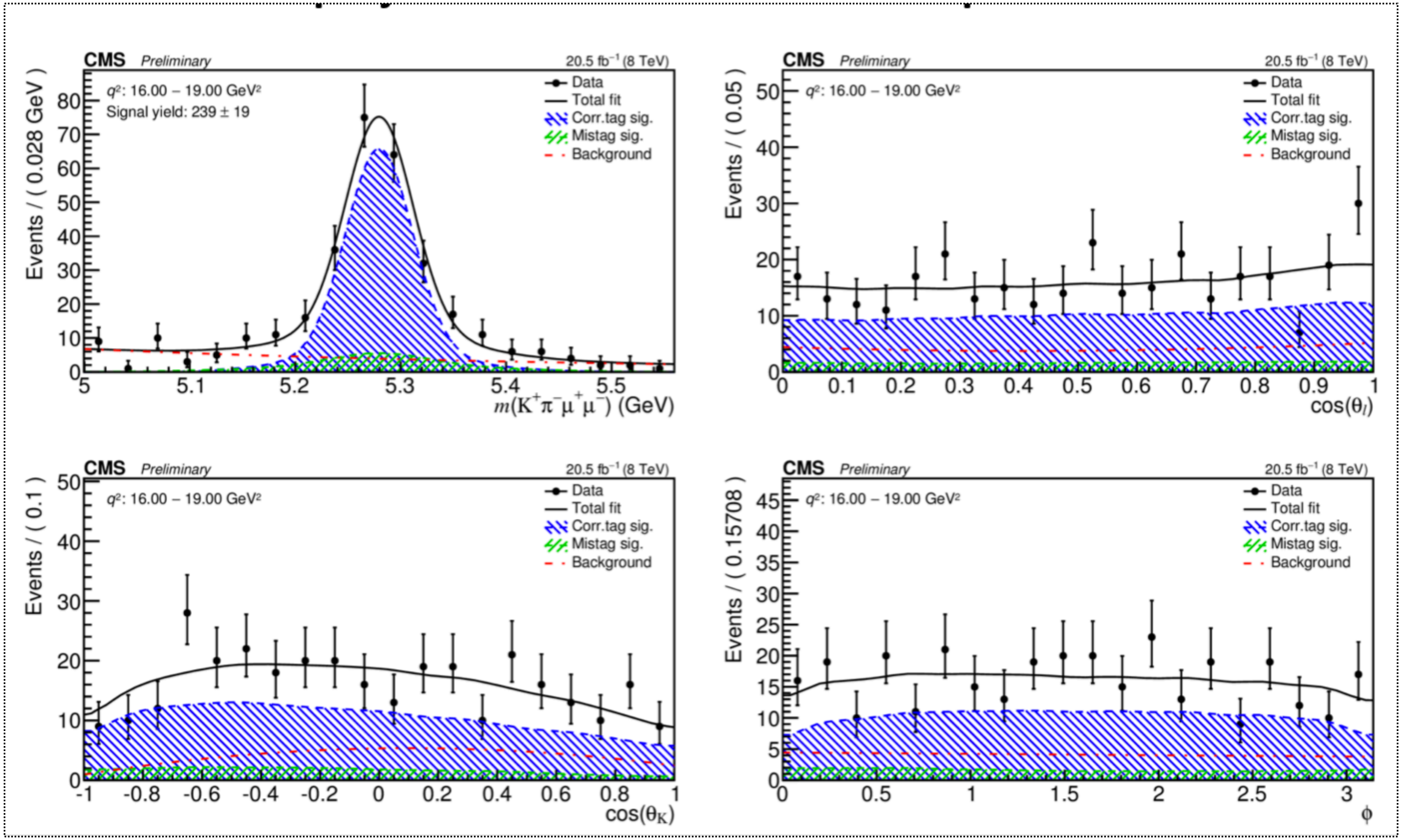
(contd.)

Fit projection in 8th bin $14.18 < q^2 < 16.00$ GeV^2

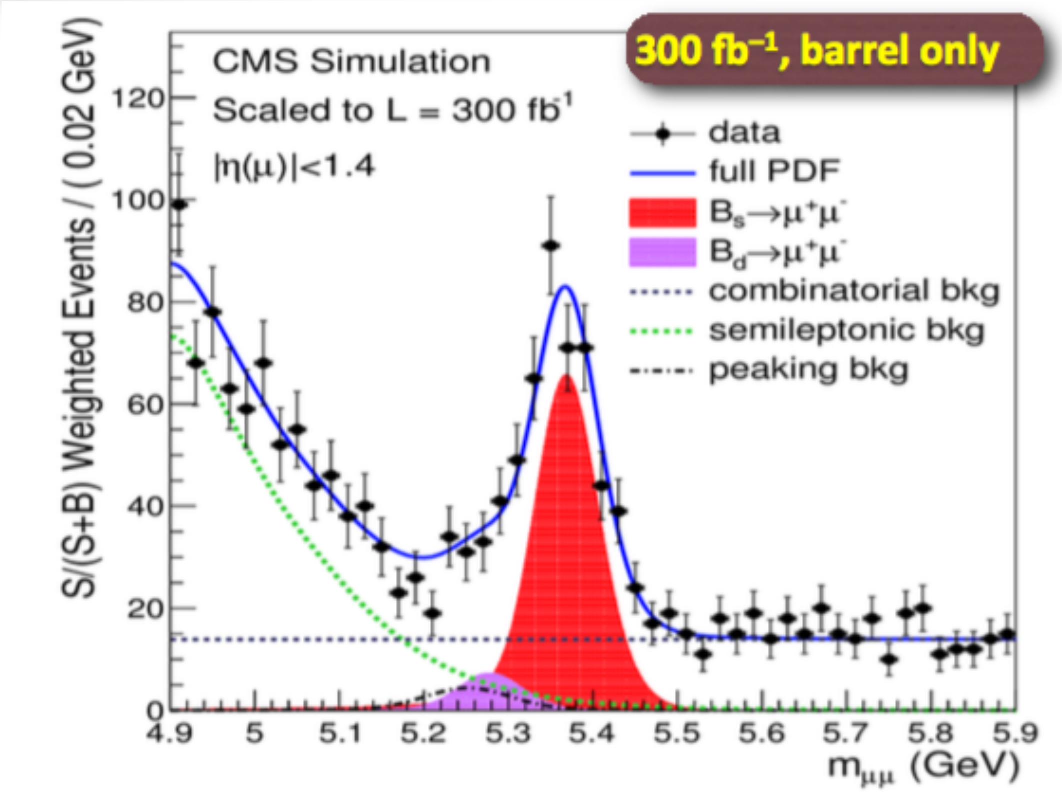


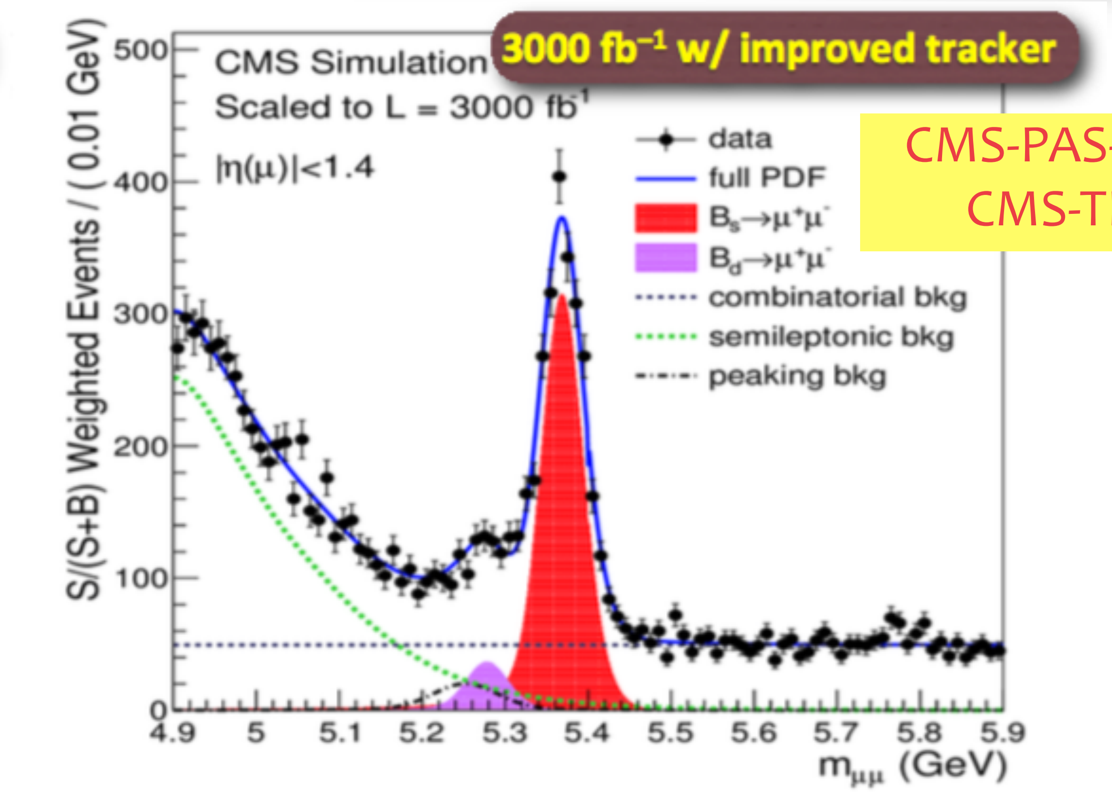
Measurement of P'_5 and P_1 in $B^0 \to K^{*0} \mu^+\mu^-$ (contd.)

Fit projection in 9th bin $16.00 < q^2 < 19.00$ GeV^2



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.