HEAVY-FLAVOR SPECTROSCOPY IN ATLAS & CMS

Greg Landsberg

54th Rencontres de Moriond QCD, 26.03.2019

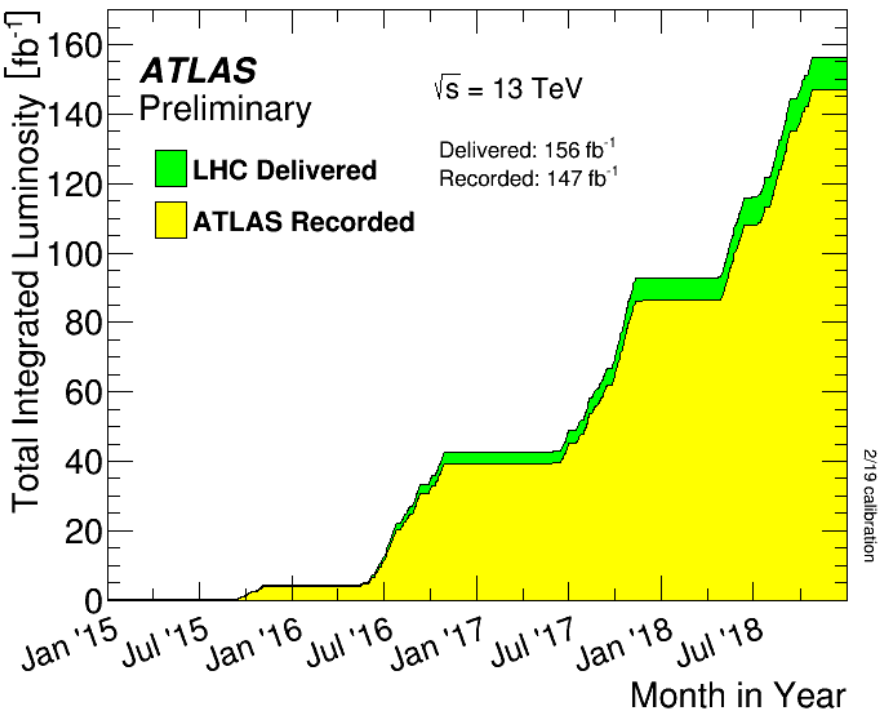
Outline

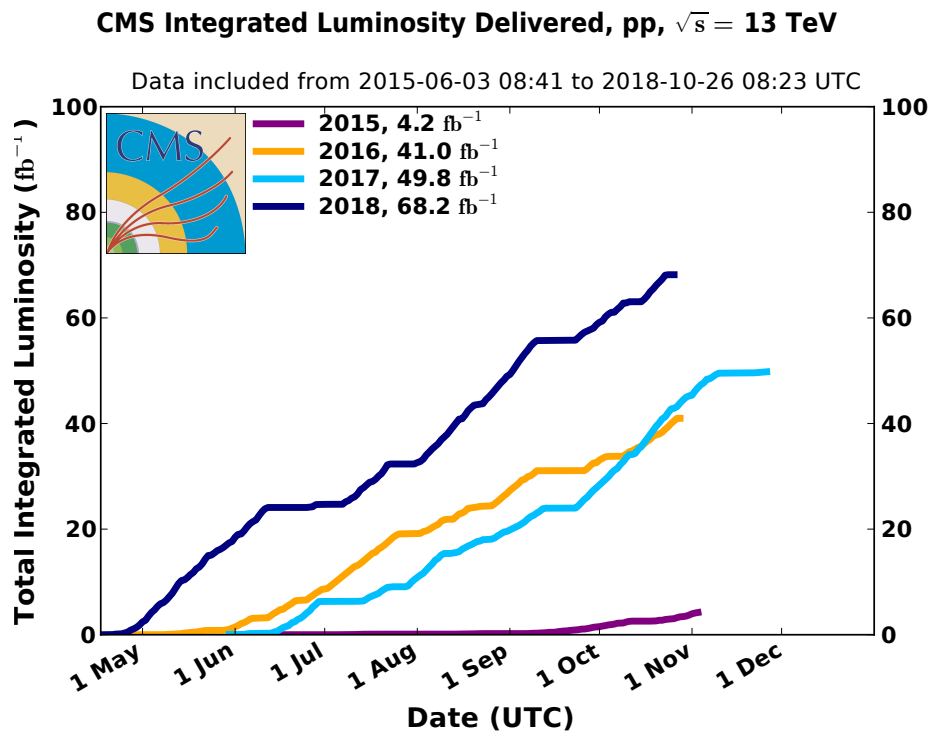
- $B \to K^* \mu\mu$ angular analysis and prospects
- CP Violation in the $B_s \to J/\psi\phi$ decay
- Angular analysis of the $B \to J/\psi \Lambda p$ decay
- Spectroscopy of excited B_s and B_c mesons
- Conclusions

- N.B. All the references are clickable links

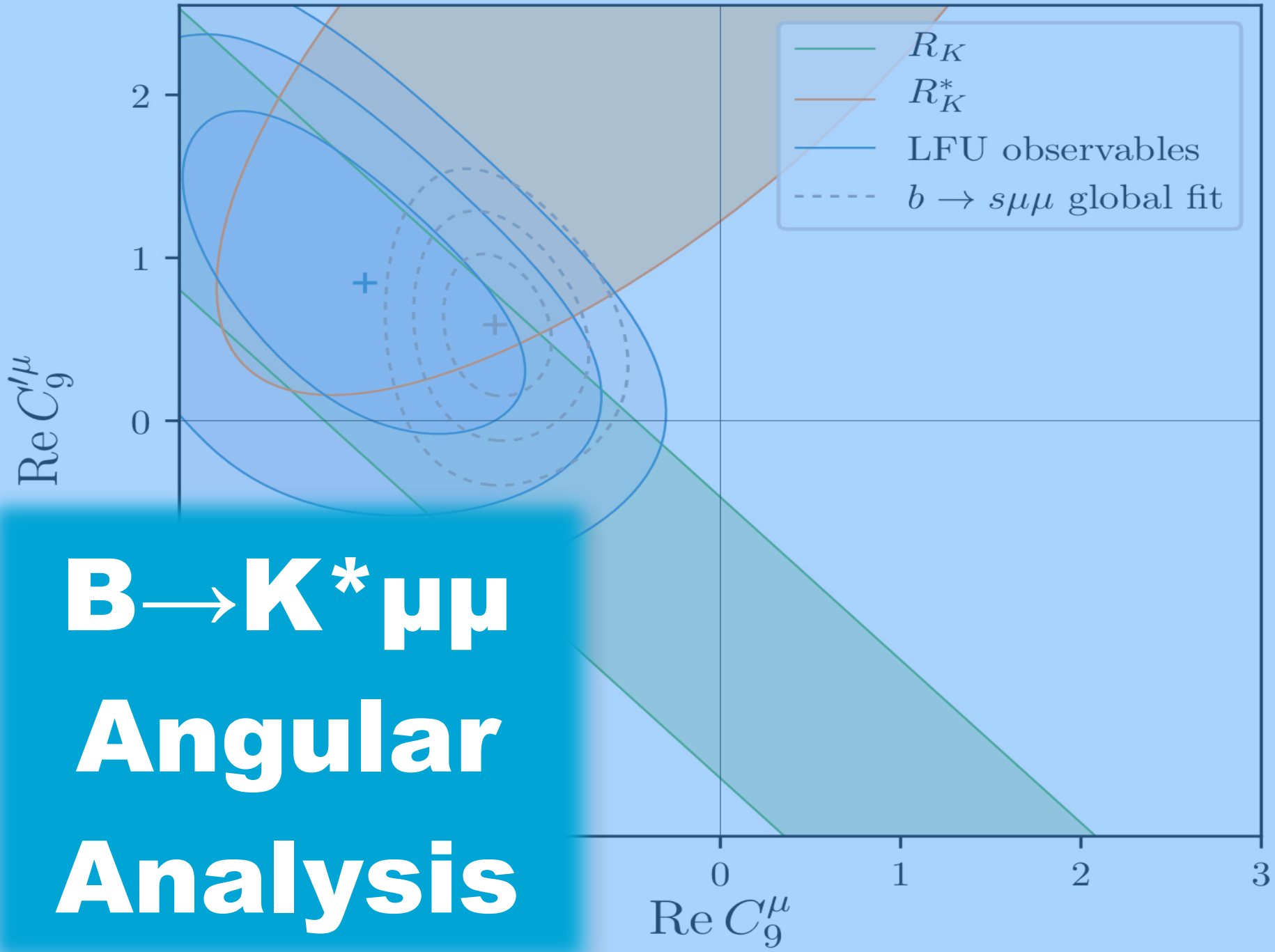
LHC Run 2: Big Success

- 160 fb^{-1} has been delivered by the LHC in Run 2 (2015–2018), at a c.o.m. of 13 TeV, exceeding the original integrated luminosity projections
- Over 140 fb^{-1} of physics-quality data recorded by ATLAS/ CMS
- Thank you, LHC, for a spectacular run!



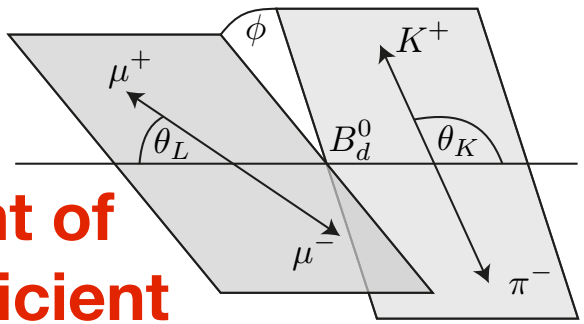


B→K*μμ Angular Analysis

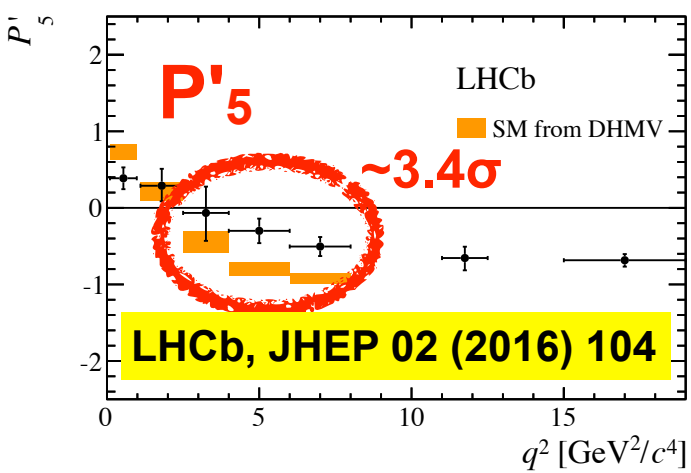


Angular Analysis B→K*μμ

- **Recent ATLAS measurement, aimed at P'_5 and other angular coefficients**
  - ★ **Based on 2012 8 TeV data, 20 fb^{-1}**
  - ★ **Inspired by recent LHCb ~3.4σ hint of a discrepancy in P'_5 angular coefficient**
  - ★ **Possible connection to the $b \to s\ell^+\ell^-$ flavor anomalies**



$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_L d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi}\Big[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_L$$
$$-F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Big]. \quad (1)$$



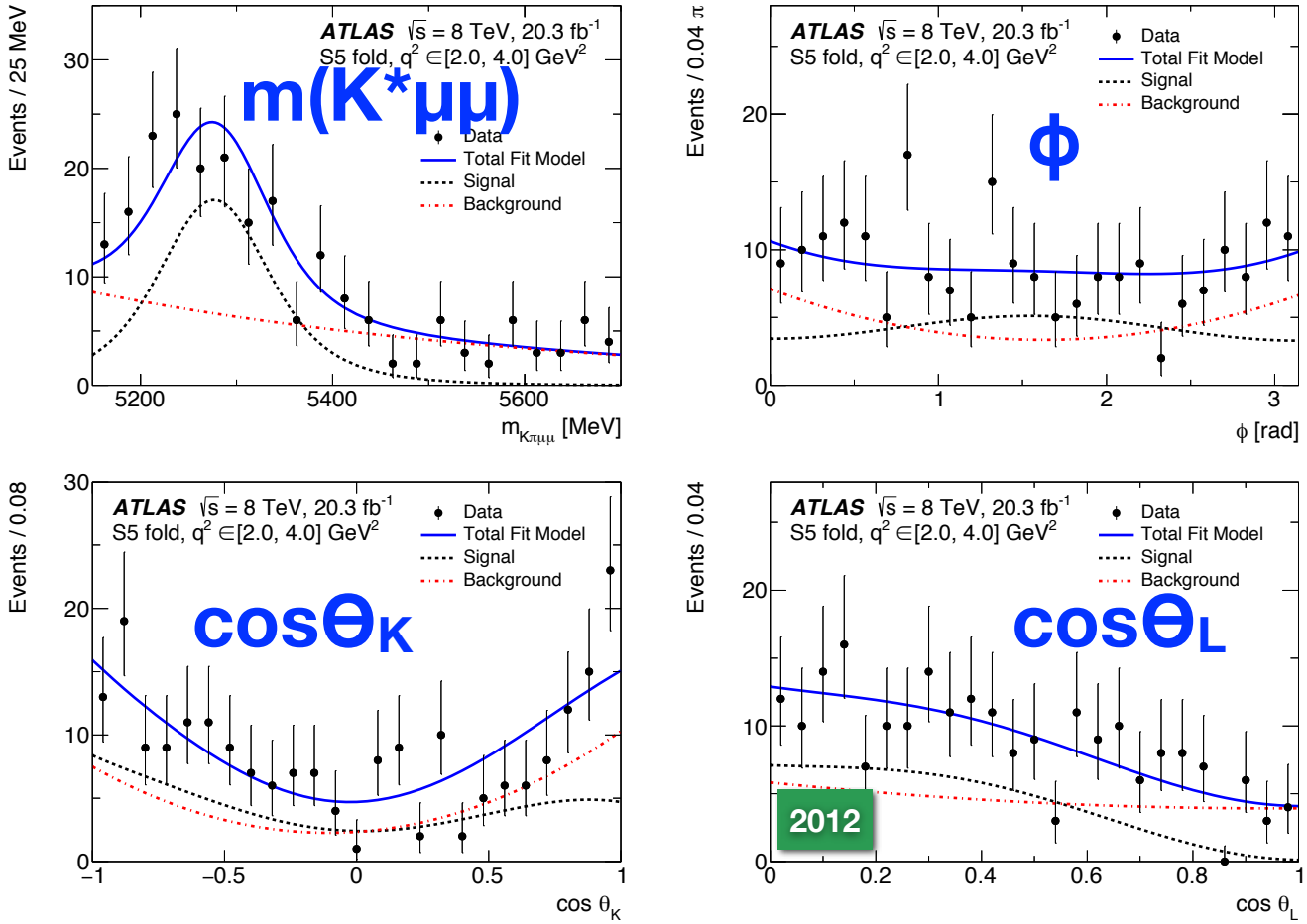
$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

Fit Projections

- Four-dimensional fits in the m(K*μμ), ϕ, cosΘ$_K$, and cosΘ$_L$ variables

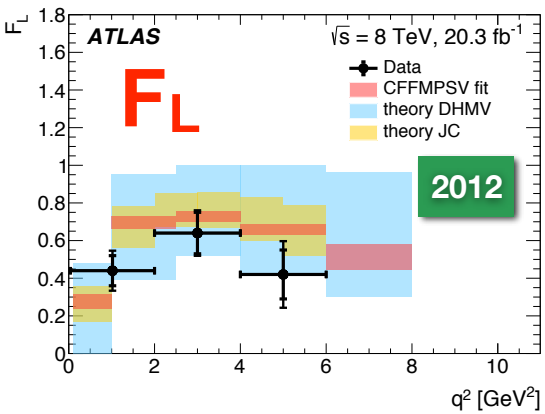
$2 < q^2 < 4$ GeV^2

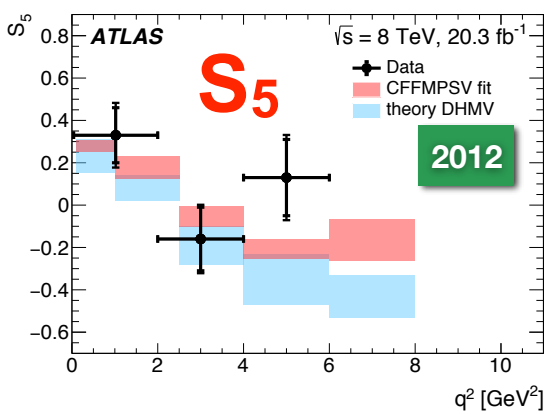
ATLAS, JHEP 10 (2018) 047



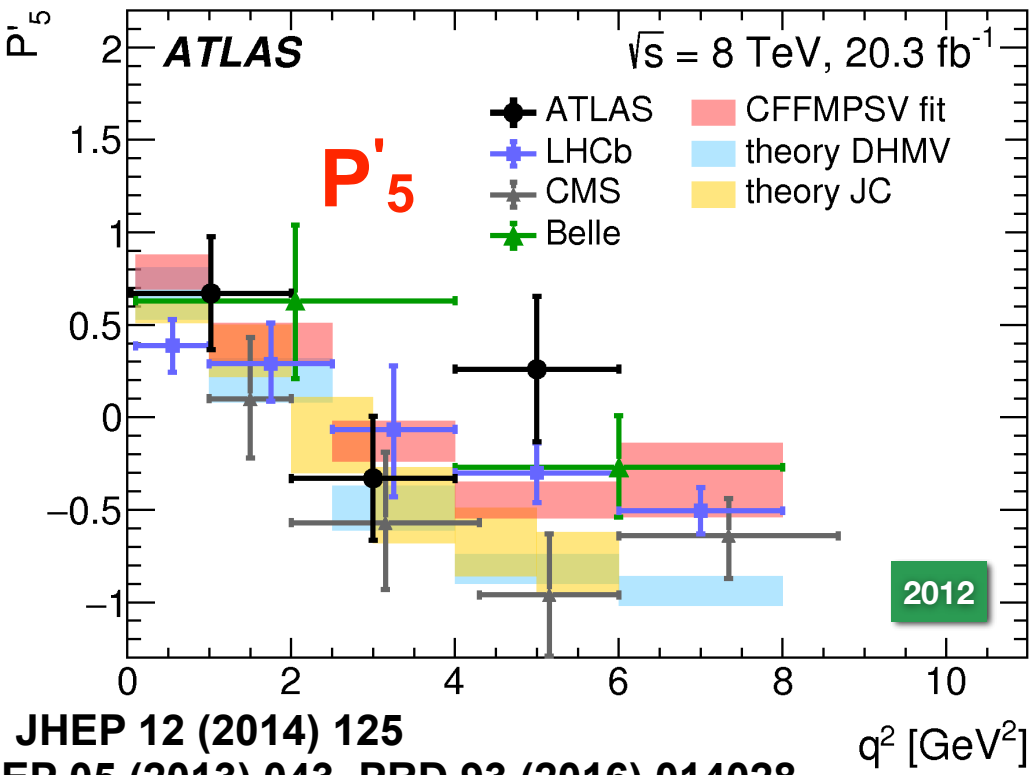
Results vs. Theory

- P'_5 results are in agreement with other experiments and theory in the $q^2 < 6$ GeV^2 range
  - ★ Deviation from the DHMV predictions is 2.7σ in the $4 < q^2 < 6$ GeV^2 bin





ATLAS, JHEP 10 (2018) 047

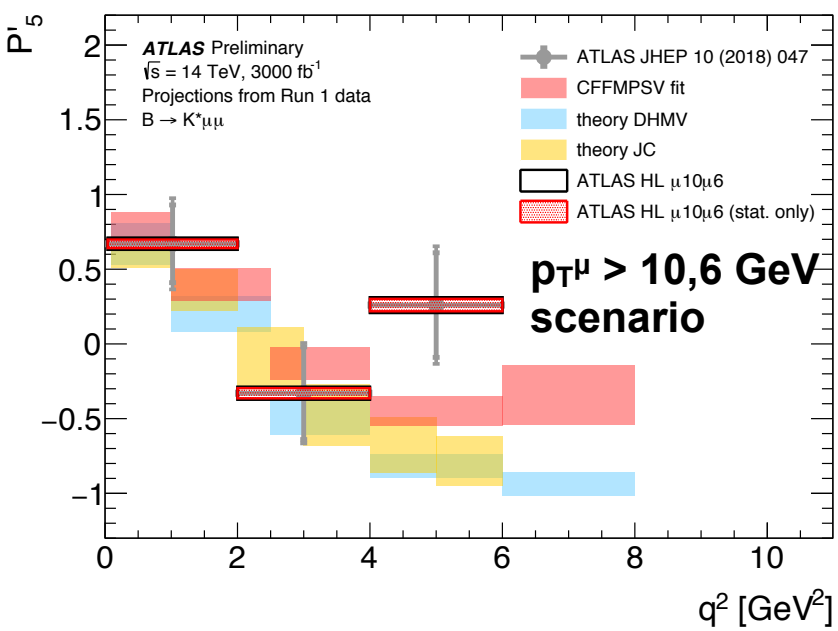


DHMV: JHEP 12 (2014) 125
JC: JHEP 05 (2013) 043, PRD 93 (2016) 014028
CFFMPSV: JHEP 06 (2016) 116

HL-LHC Projections

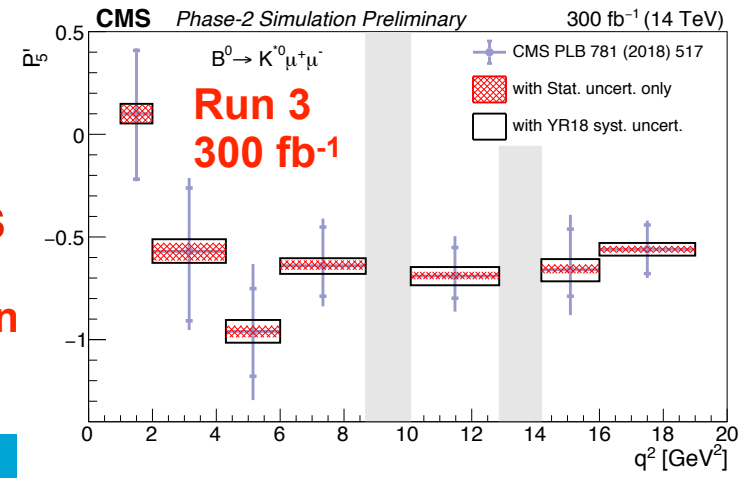
- **Both ATLAS and CMS have projected for the HL-LHC**
  - ★ **CMS also has Run 3 projections**

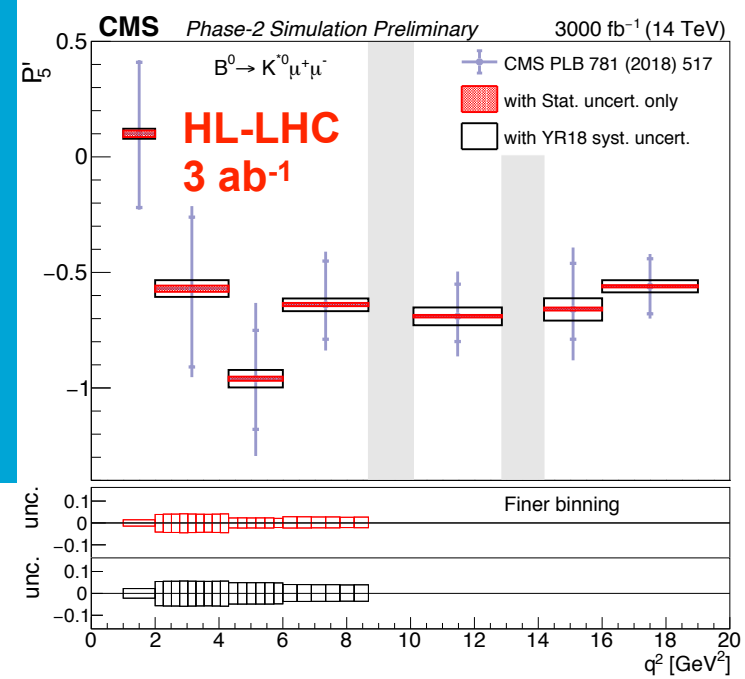
ATLAS: x5-9 improvement in precision, depending on the trigger scenario (p_T^μ > 6,6; 10,6; and 10,10 GeV)



ATL-PHYS-PUB-2019-003

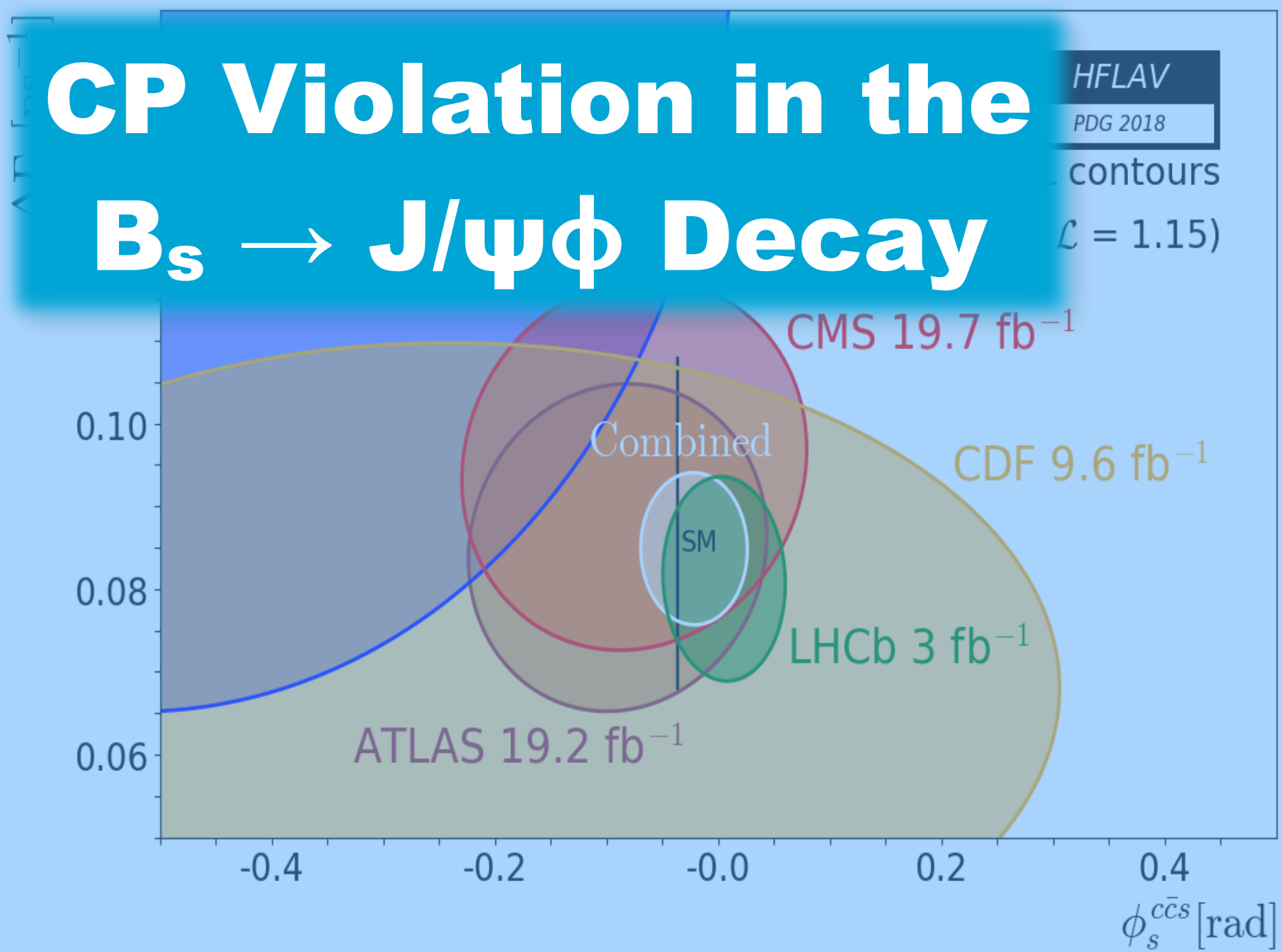
CMS PAS FTR-18-033





CMS: Up to x15 improvement w/ 3 ab^{-1} compared to the 8 TeV CMS result [PLB 781 (2018) 517]

CP Violation in the $B_s \rightarrow J/\psi\phi$ Decay



CP Violation in $B_s \to J/\psi\phi$

- New analysis from ATLAS based on 2016+2017 13 TeV data (80.5 fb^{-1}) taken with a dimuon J/ψ trigger, combined with an earlier 7+8 TeV result
  - ★ The trigger has been corrected for the time-time-dependence of the efficiency for muons with large displacement
- Use opposite-side tagging (based on a combination of the lepton and track-in-cone charge), calibrated with self-tagging $B^{\pm} \to J/\psi K^{\pm}$ decays
  - ★ A tagging efficiency of ε = 14.7% with an effective dilution of D = 33.4% and tagging power εD^2 = 1.7% has been achieved
  - ★ 3.2M Bs → $J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ candidates, 0.5M remains after tagging
- A maximum likelihood fit to data with 9 parameters, including ϕ_s, Γ_s, $\Delta\Gamma_s$ is performed

$$\phi_s = -0.076 \pm 0.034\ (\text{stat.}) \pm 0.019\ (\text{syst.})\ \text{rad}$$
$$\Delta\Gamma_s = 0.068 \pm 0.004\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1}$$
$$\Gamma_s = 0.669 \pm 0.001\ (\text{stat.}) \pm 0.001\ (\text{syst.})\ \text{ps}^{-1}$$

-0.021 ±0.031 (HFLAV)

0.083 ±0.006 (PDG)

0.664 ±0.004 (PDG)

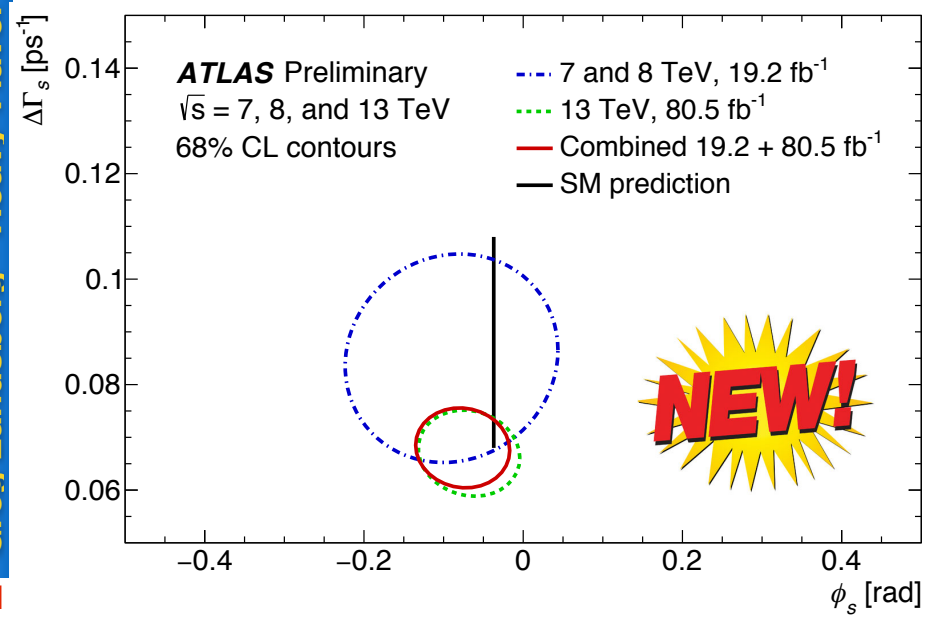
NEW!

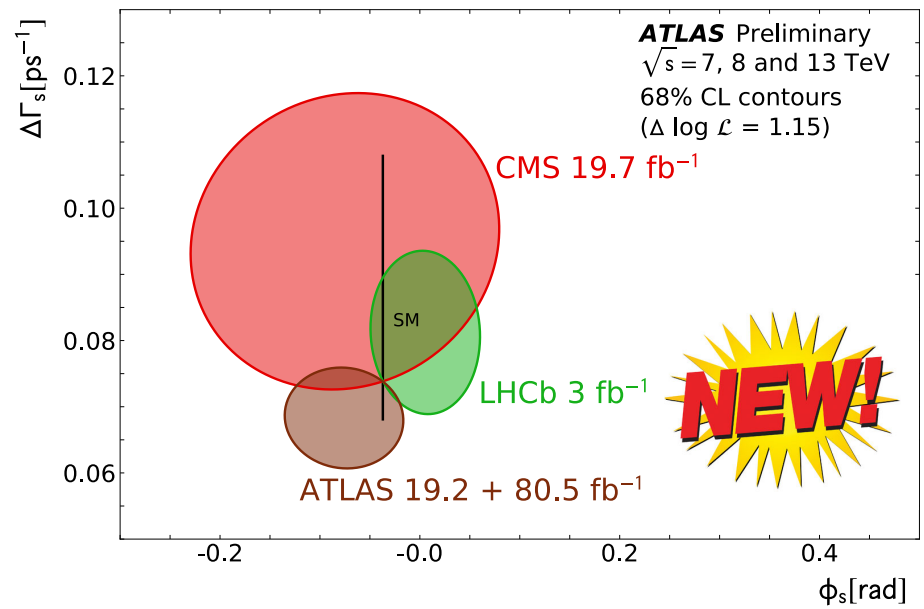
ATLAS-CONF-2019-009

ATLAS CPV Results

- The new data are consistent with an earlier ATLAS result
- The results are consistent within 2σ with the HFLAV/PDG world-average values for these parameters
  - ★ A significant improvement in the precision in Γ_s is achieved
- At 1σ level the new result it is also consistent with the LHCb and CMS measurements

ATLAS-CONF-2019-009





Observation of $B^- \to J/\psi \Lambda \bar{p}$ and Searches for $B^- \to J/\psi \Sigma^0 \bar{p}$ and $B^0 \to J/\psi p \bar{p}$ Decays

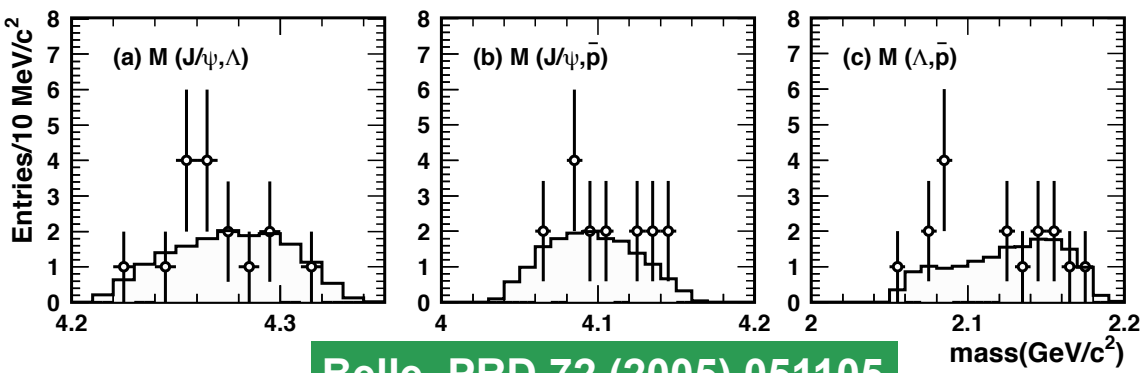
Q. L. Xie,[8,*] K. Abe,[6] K. Abe,[39] I. Adachi,[6] H. Aihara,[41] Y. Asano,[45] T. Aushev,[10] S. Bahinipati,[4] A. M. Bakich,[36] E. Barberio,[17] M. Barbero,[5] I. Bedny,[1] U. Bitenc,[11] I. Bizjak,[11] S. Blyth,[20] A. Bondar,[1] A. Bozek,[23] M. Bračko,[6,16,11] J. Brodzicka,[23] T. E. Browder,[5] Y. Chao,[22] A. Chen,[20] W. T. Chen,[20] B. G. Cheon,[3] R. Chistov,[10] Y. Choi,[35] A. Chuvikov,[31] S. Cole,[36] J. Dalseno,[17] M. Danilov,[10] M. Dash,[46] L. Y. Dong,[8] A. Drutskoy,[4] S. Eidelman,[1] Y. Enari,[18] S. Fratina,[11] N. Gabyshev,[1] T. Gershon,[6] A. Go,[20] G. Gokhroo,[37] B. Golob,[15,11] A. Gorišek,[11] J. Haba,[6] K. Hayasaka,[18] H. Hayashii,[19] M. Hazumi,[6] L. Hinz,[14] T. Hokuue,[18] Y. Hoshi,[39] S. Hou,[20] W.-S. Hou,[22] Y. B. Hsiung,[22] T. Iijima,[18] K. Ikado,[18] A. Imoto,[19] A. Ishikawa,[6] R. Itoh,[6] M. Iwasaki,[41] Y. Iwasaki,[6] J. H. Kang,[47] J. S. Kang,[13] P. Kapusta,[23] S. U. Kataoka,[19] N. Katayama,[6] H. Kawai,[2] T. Kawasaki,[25] H. R. Khan,[42] H. Kichimi,[6] J. H. Kim,[35] S. M. Kim,[35] K. Kinoshita,[4] P. Krokovny,[1] C. C. Kuo,[20] Y.-J. Kwon,[47] G. Leder,[9] S. E. Lee,[33] T. Lesiak,[23] J. Li,[32] D. Liventsev,[10] F. Mandl,[9] T. Matsumoto,[43] A. Matyja,[23] W. Mitaroff,[9] K. Miyabayashi,[19] H. Miyake,[28] H. Miyata,[25] Y. Miyazaki,[18] R. Mizuk,[10] G. R. Moloney,[17] T. Nagamine,[40] Y. Nagasaka,[7] E. Nakano,[27] Z. Natkaniec,[23] S. Nishida,[6] O. Nitoh,[44] T. Nozaki, H. Ozaki,[6] P. Pakhlov, N. Satoyama,[34] K. Sayee N. Soni,[29] S. Stanič,[26] Y. Teramoto,[27] X. Y. Unno,[6] S. Uno,[6] Y. Watanabe,[42] E. S. L. Zang,[8] C. C. Zhang,[8] J. Zhang,[6] L. M. Zhang,[32] Z. P. Zhang,[32] V. Zhilich,[1] and T. Ziegler[31]

(The Belle Collaboration)

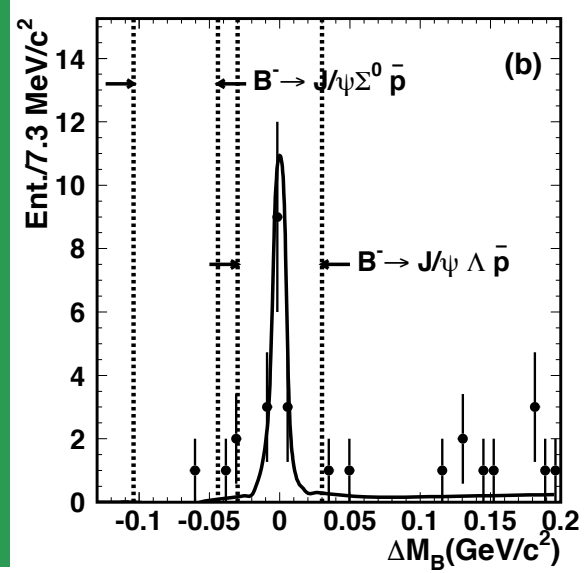
Study of the B→J/ψΛp Decay

Baryonic B Decays

- $B \to J/\psi \Lambda p$ is a rare baryonic decay of the B^+ meson, observed in 2005 by Belle with a handful (17.2 ± 4.1) of events:
  - ★ $B(B^- \to J/\psi \Lambda p) = (11.6 \pm 2.8^{+1.8}_{-2.3}) \times 10^{-6}$
- Attempted to study the three two-body masses, but the results were inconclusive because of a low signal yield
- Historically, rich potential way of looking for new resonances: the X, Y particles were discovered in the $B \to J/\psi + X$ decays
  - ★ More recently LHCb saw two pentaquark candidates (P^+_c) in the $\Lambda_b \to J/\psi + X$ decays



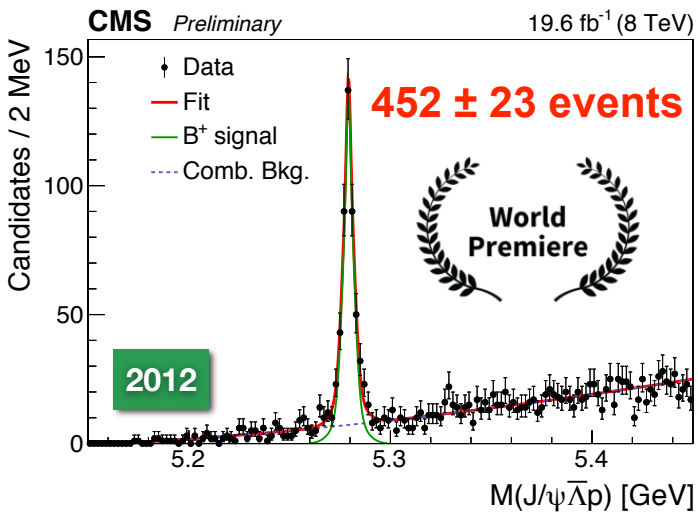
Belle, PRD 72 (2005) 051105

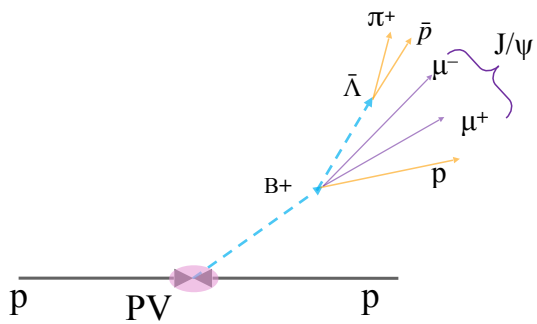


Belle, PRD 72 (2005) 051105

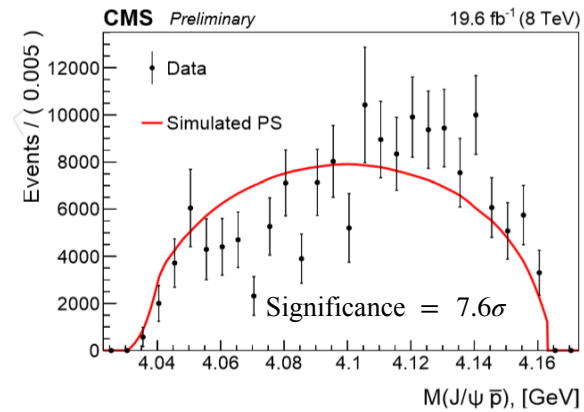
B → J/ψΛp Decay in CMS

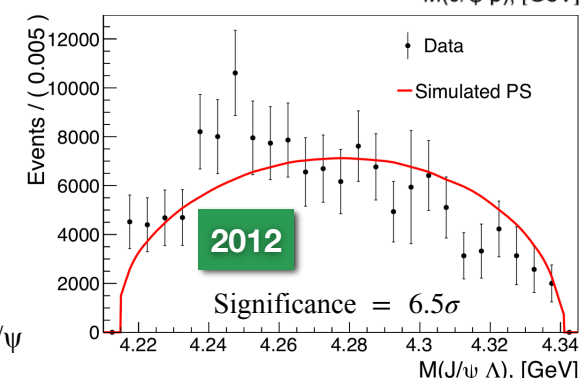
- The analysis is based on 8 TeV 2012 data, 19.6 fb^{-1}
- Use $B \to J/\psi K^* \to J/\psi K^0_S \pi$ as the normalization channel, which has a similar efficiency
  - ★ Measured branching fraction is: $(15.07 \pm 0.81\ (stat) \pm 0.40\ (syst) \pm 0.86\ (Br)) \times 10^{-6}$
  - ★ Most precise to date & consistent with Belle
- Large signal yield allowed to study the two-body masses in more detail than Belle
  - ★ Phase-space fit fails pretty badly in all three two-body mass distributions

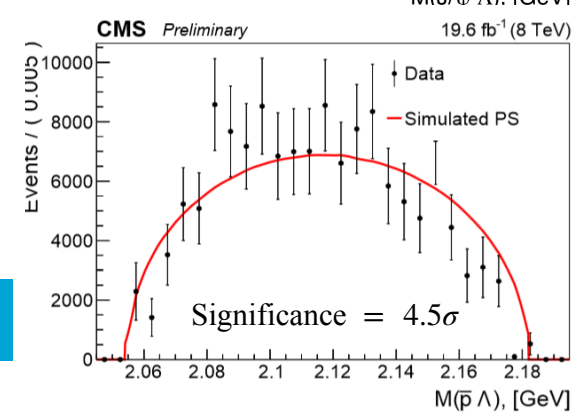




CMS PAS BPH-18-005







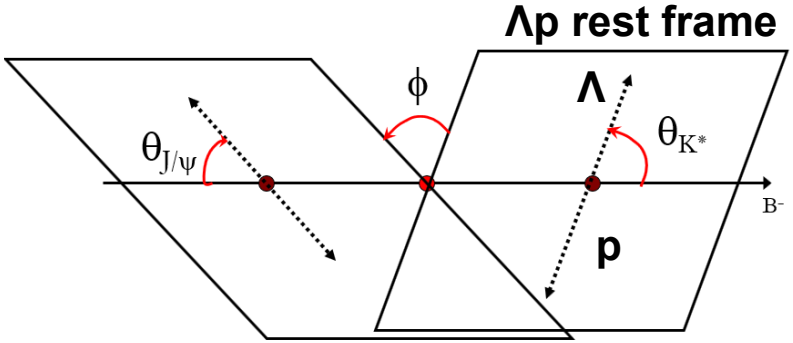
Method of Moments

- Before assuming new resonances, must exclude non-exotic scenarios
- Use model-independent method of moments, invented by BaBar [PRD 79 (2009) 112001] and further refined by LHCb [PRD 92 (2015) 112009; PRL 117 (2016) 082002]
- Attempt to take into account the potential reflection from several K* resonances, which can decay in Λp
  - ★ In each M(Λp) bin, fit the angular distribution with a sum of Legendre polynomials in cos of the K*(Λp) decay helicity angle, defined as the angle between the Λ and B in the Λp rest frame:

$$\frac{dN}{d\cos\theta_{K^*}} = \sum_{j=0}^{l_{max}} \langle P_j^U \rangle P_j(\cos\theta_{K^*})$$

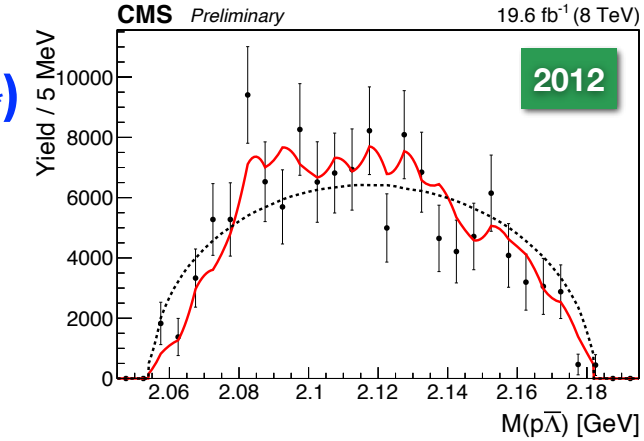
  - ★ For ℓ_{max} equal to *twice* the spin of the highest-spin resonance, can describe all the resonances and their interference
  - ★ Use ℓ_{max} = 2 x 4 = 8 and weight the distributions with the $\langle P_j^U \rangle$ moments

Resonance	Mass, [MeV]	Width, [MeV]	J^P
$K_4^{-*}(2045)$	2045±9	198±30	4^+
$K_2^{-*}(2250)$	2247±17	180±30	2^-
$K_3^{-*}(2320)$	2324±24	150±30	3^+

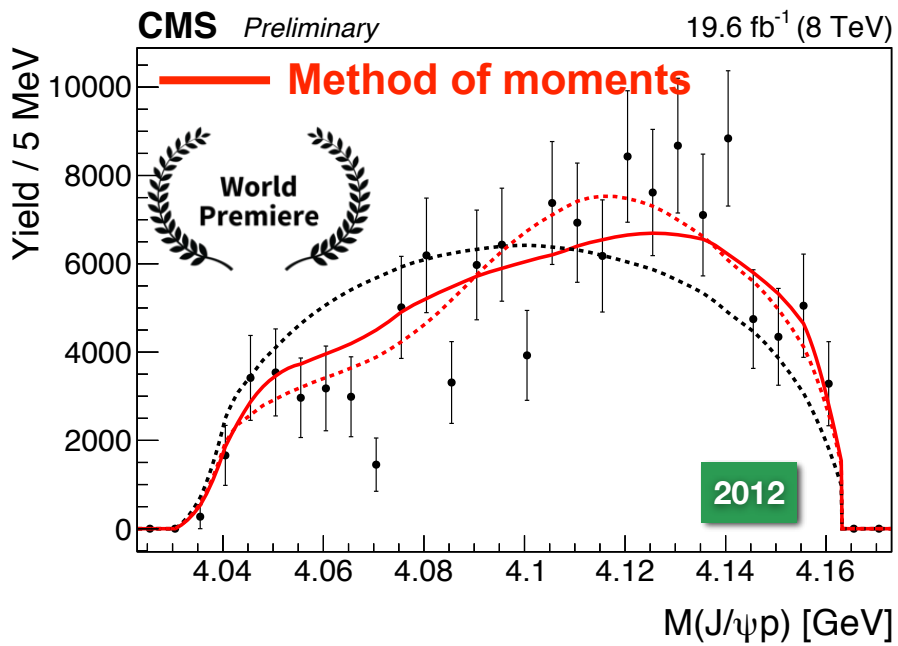


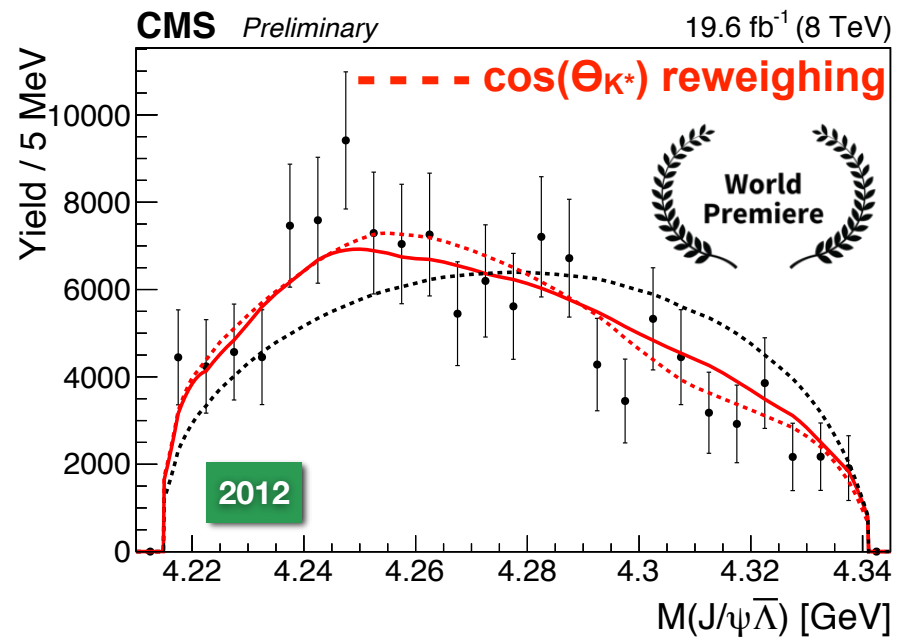
Reweighted Results

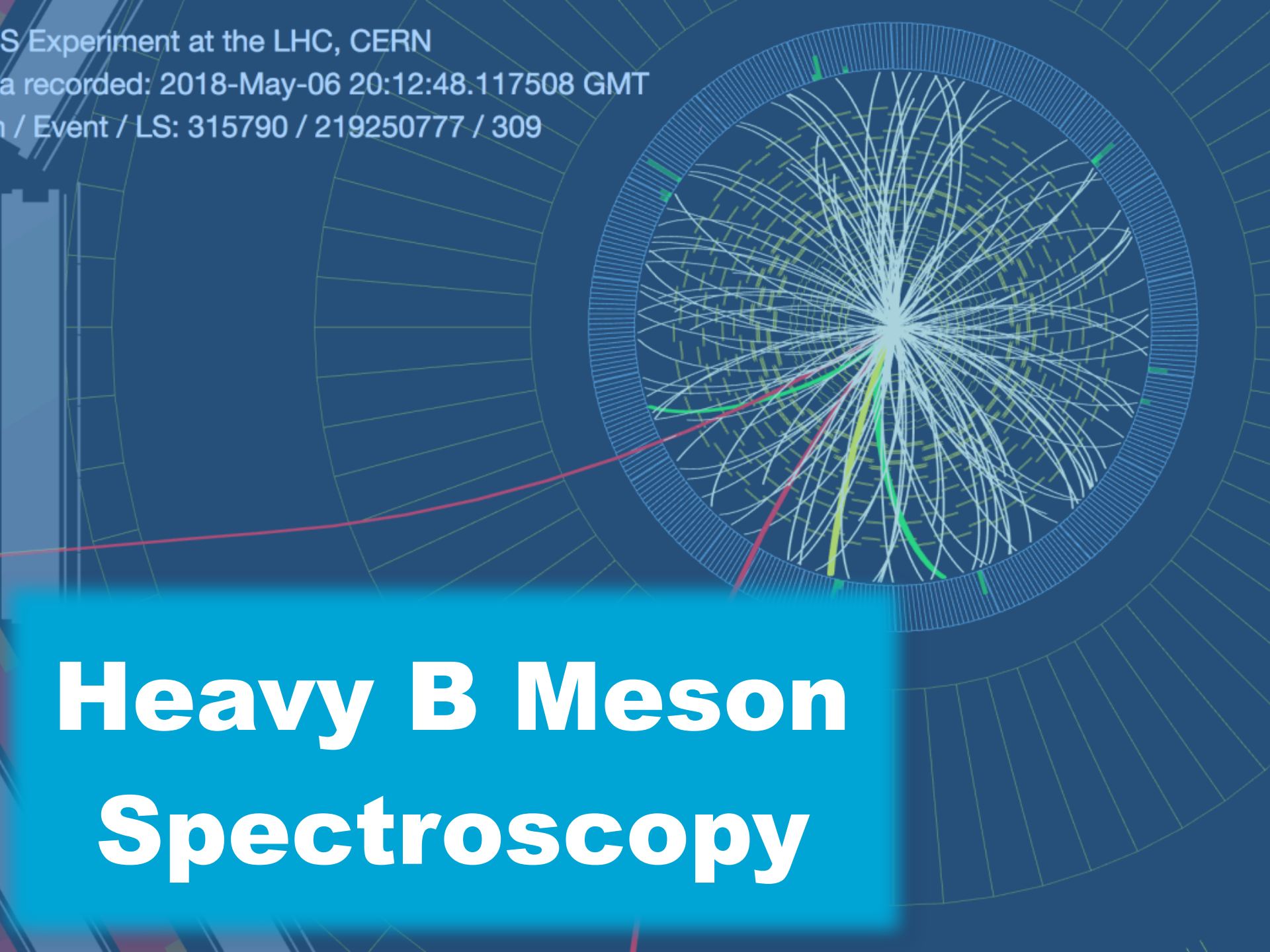
- This model-independent approach is more powerful than simply reweighting the $\cos(\Theta_{K^*})$ distribution according to the observed one in data
- Drastically improves the agreement w/ the phase space decay model
- Compatibility with data is now within ~2.3σ, eliminating the need for new resonances!



CMS PAS BPH-18-005



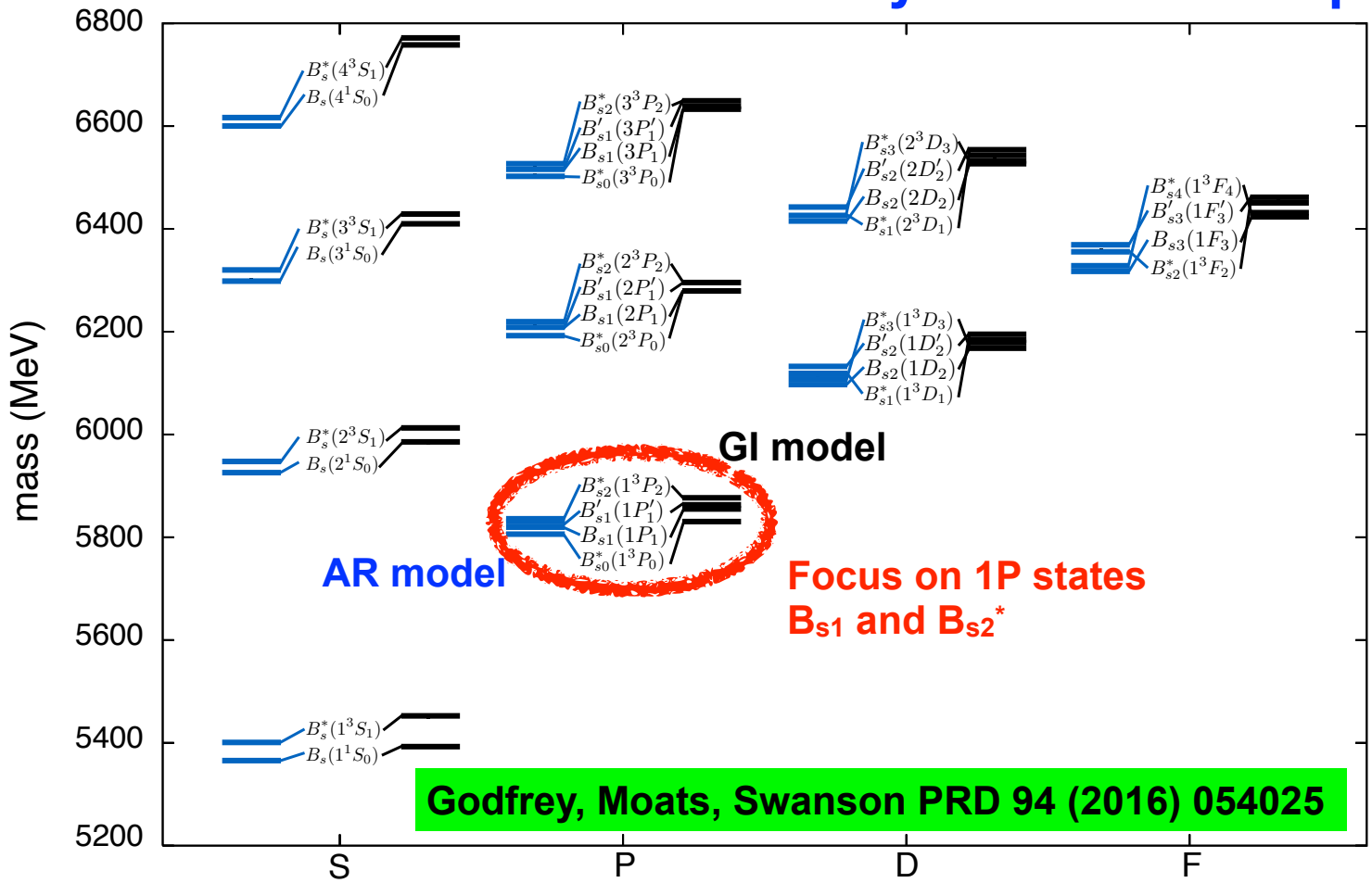




Heavy B Meson Spectroscopy

B_s Spectroscopy

- Only a few excited B_s states have been observed so far: $B^*_s(5416)$, $B_{s1}(5830)$, $B^*_{s2}(5840)$, possibly X(5568); theory predictions are not exact either - very rich field for exploration



Study of Excited B_s States

- CMS analysis based on 2012 data @ 8 TeV studying p-wave excitations, in particular B_{s1} ($j_s = 3/2$, $J^P = 1^+$) and B^*_{s2} ($j_s = 3/2$, $J^P = 2^+$) [observed by CDF, D0, and later LHCb]
  - ★ First observation of $B^*_{s2} \to B^0 K_s^0$ with 6.3σ significance; a 3.9σ evidence for $B_{s1} \to B^{*0} K_s^0$ is also seen
  - ★ The following branching fraction ratios were measured:

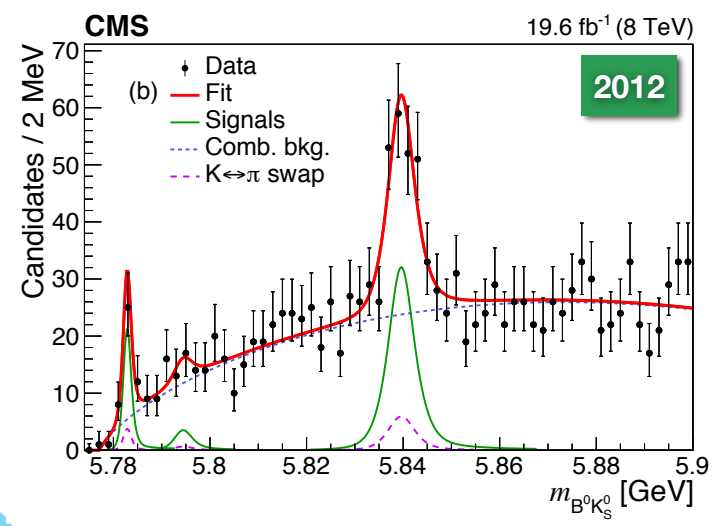
$$R_2^{0\pm} = \frac{\mathcal{B}(B^*_{s2} \to B^0 K^0_S)}{\mathcal{B}(B^*_{s2} \to B^+ K^-)} = 0.432 \pm 0.077 \pm 0.075 \pm 0.021,$$

$$R_1^{0\pm} = \frac{\mathcal{B}(B_{s1} \to B^{*0} K^0_S)}{\mathcal{B}(B_{s1} \to B^{*+} K^-)} = 0.49 \pm 0.12 \pm 0.07 \pm 0.02,$$

$$R_{2*}^{\pm} = \frac{\mathcal{B}(B^*_{s2} \to B^{*+} K^-)}{\mathcal{B}(B^*_{s2} \to B^+ K^-)} = 0.081 \pm 0.021 \pm 0.015,$$

$$R_{2*}^{0} = \frac{\mathcal{B}(B^*_{s2} \to B^{*0} K^0_S)}{\mathcal{B}(B^*_{s2} \to B^0 K^0_S)} = 0.093 \pm 0.086 \pm 0.014.$$

CMS EPJC 78 (2018) 939



- ★ Also measured mass differences:

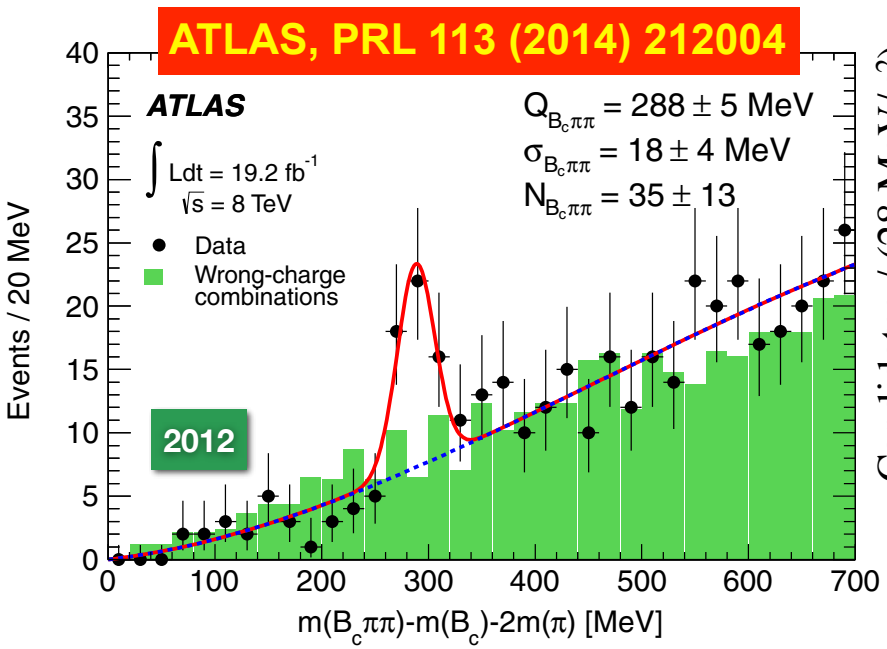
First meas. →

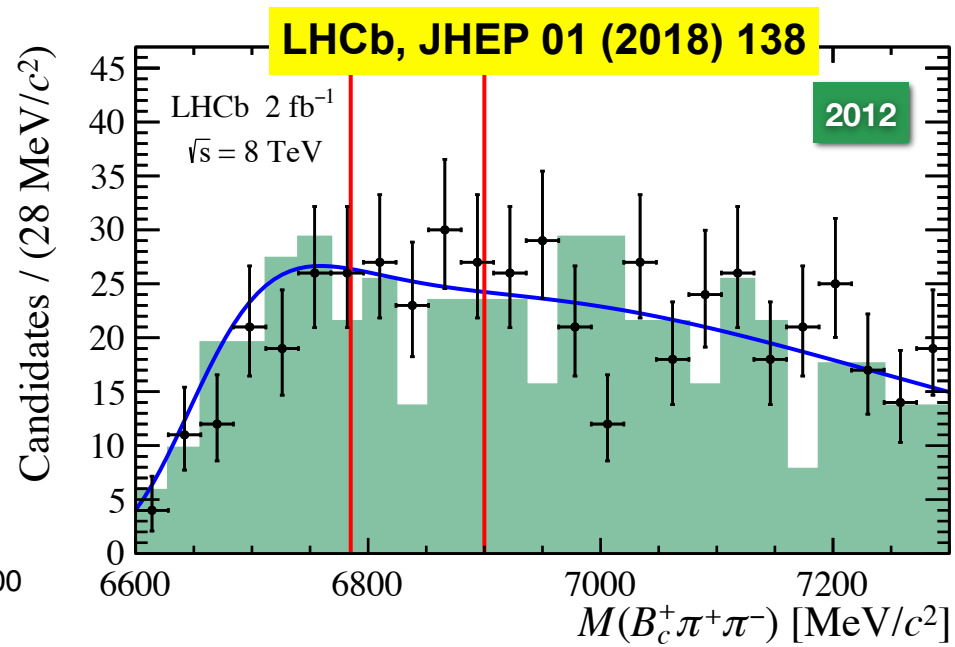
$$M_{B^0} - M_{B^+} = 0.57 \pm 0.49 \pm 0.10 \pm 0.02\,\text{MeV},$$
$$M_{B^{*0}} - M_{B^{*+}} = 0.91 \pm 0.24 \pm 0.09 \pm 0.02\,\text{MeV}.$$

$$M(B^*_{s2}) = 5839.86 \pm 0.09 \pm 0.07 \pm 0.15\,\text{MeV},$$
$$M(B_{s1}) = 5828.78 \pm 0.09 \pm 0.06 \pm 0.28\,\text{MeV}.$$

Excited B_c Mesons

- The B_c spectroscopy is even less studied
- The only observed excited state so far was $B_c(2S)$ at the mass of 6842 MeV
  - ★ Seen by ATLAS at 5.2σ; not confirmed by LHCb in 8 TeV data

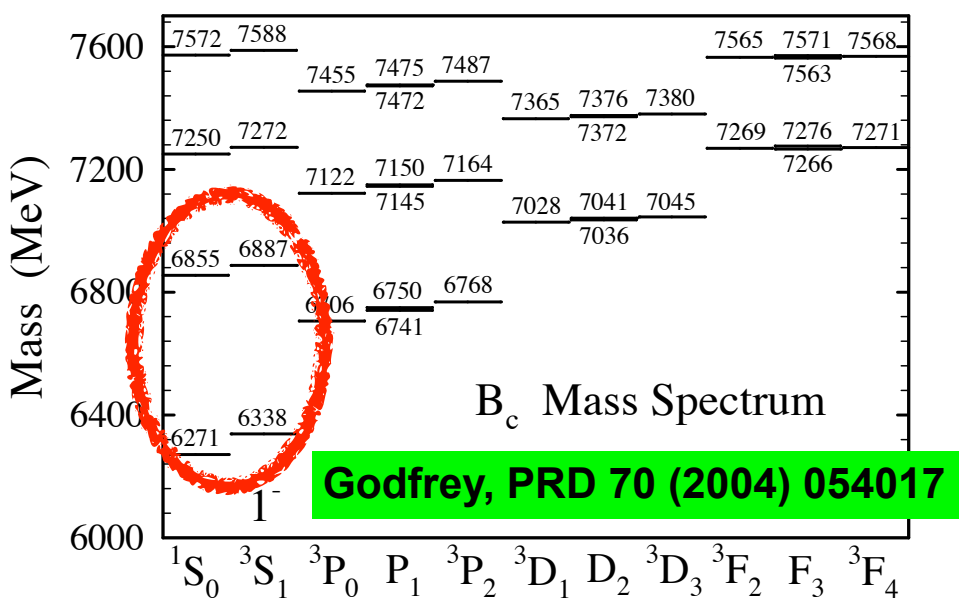




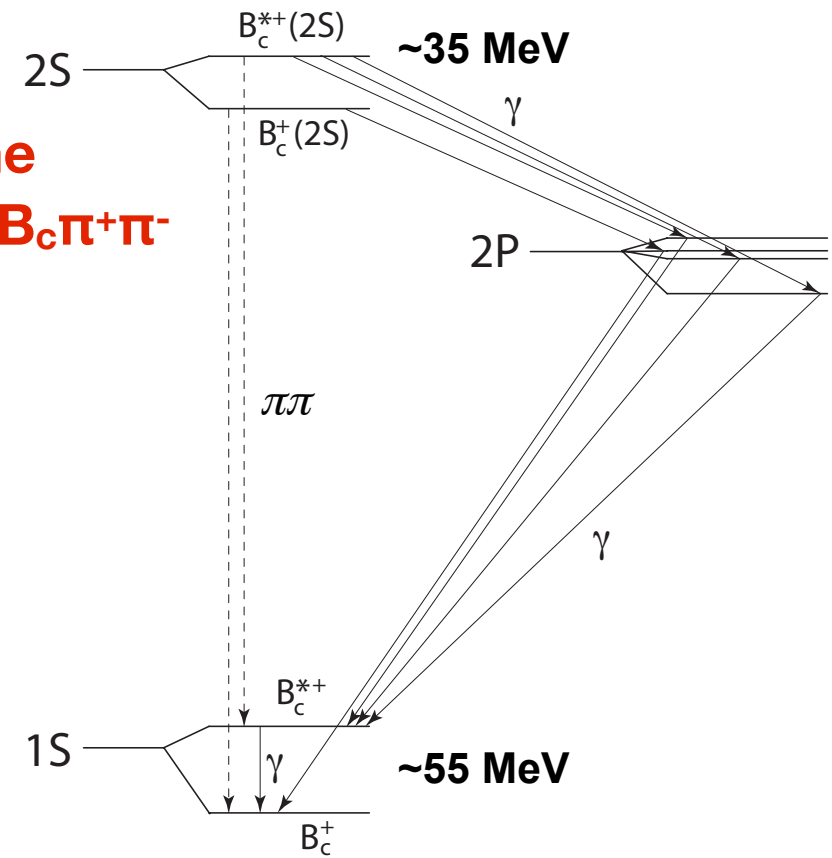
- Enter CMS: the first LHC paper based on the entire 13 TeV Run 2 data (2015-2018), 143 fb^{-1}

$B_c(2S)$ Spectrum and Transitions

- **Focus on the s-wave excitations: $B_c(2S)$ and $B^*_c(2S)$**
  - ★ **Expect smaller mass splitting than for B_c and B^*_c**
  - ★ **Main decay modes: $B_c(2S) \to B_c\pi^+\pi^-$, $B^*_c(2S) \to B^*_c\pi^+\pi^- \to B_c\gamma\pi^+\pi^-$, with a lost soft photon**
  - ★ **Can observe both states via the same experimental signature: $B_c\pi^+\pi^-$**

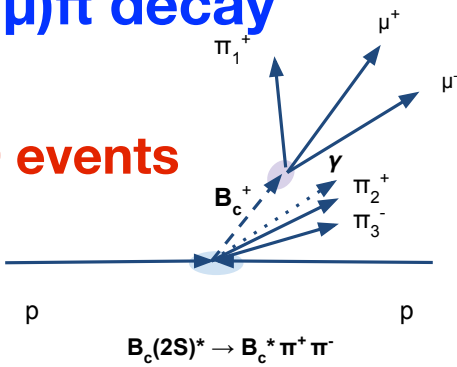


Godfrey, PRD 70 (2004) 054017

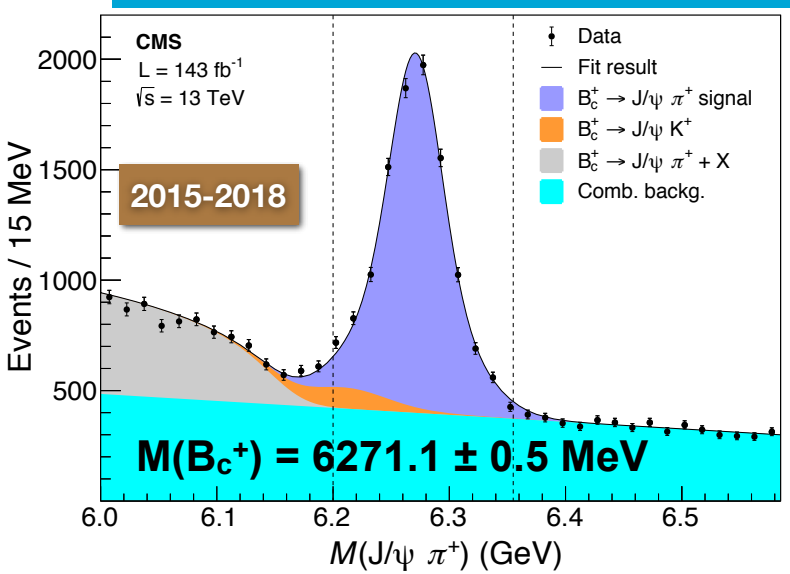


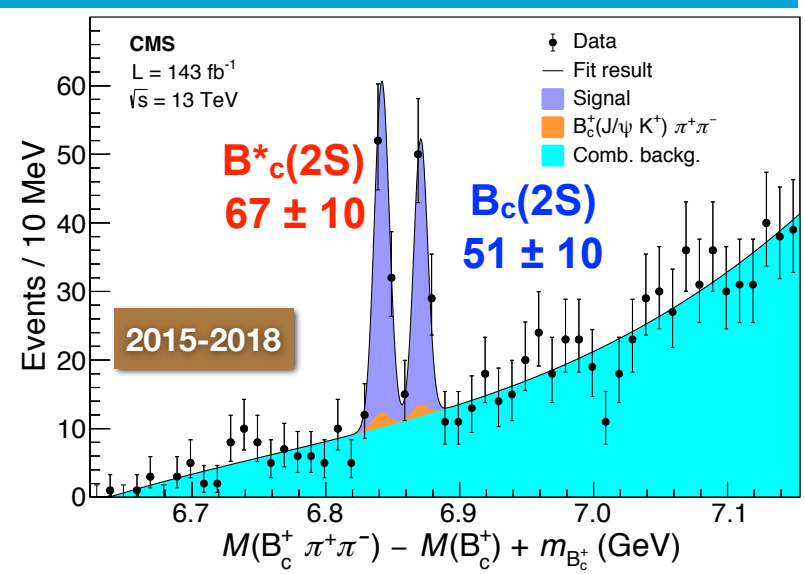
Observation of Resolved B_c States

- **Full Run 2 data set analysis, using the $B_c \to J/\psi(\mu\mu)\pi$ decay channel**
  - ★ **Relatively high-p_T (> 15 GeV) B_c candidates: ~7600 events**
  - ★ **Well-separated $B_c(2S)$ and $B^*_c(2S)$ peaks, both observed and resolved at >5σ level**
  - ★ **ΔM_{exp} = 29.1 ± 1.5 ± 0.7 MeV**
  - ★ **$M(B_c^+(2S))$ = 6871.0 ± 1.2 (stat) ± 0.8 (syst) ± 0.8 (B_c^+) MeV**

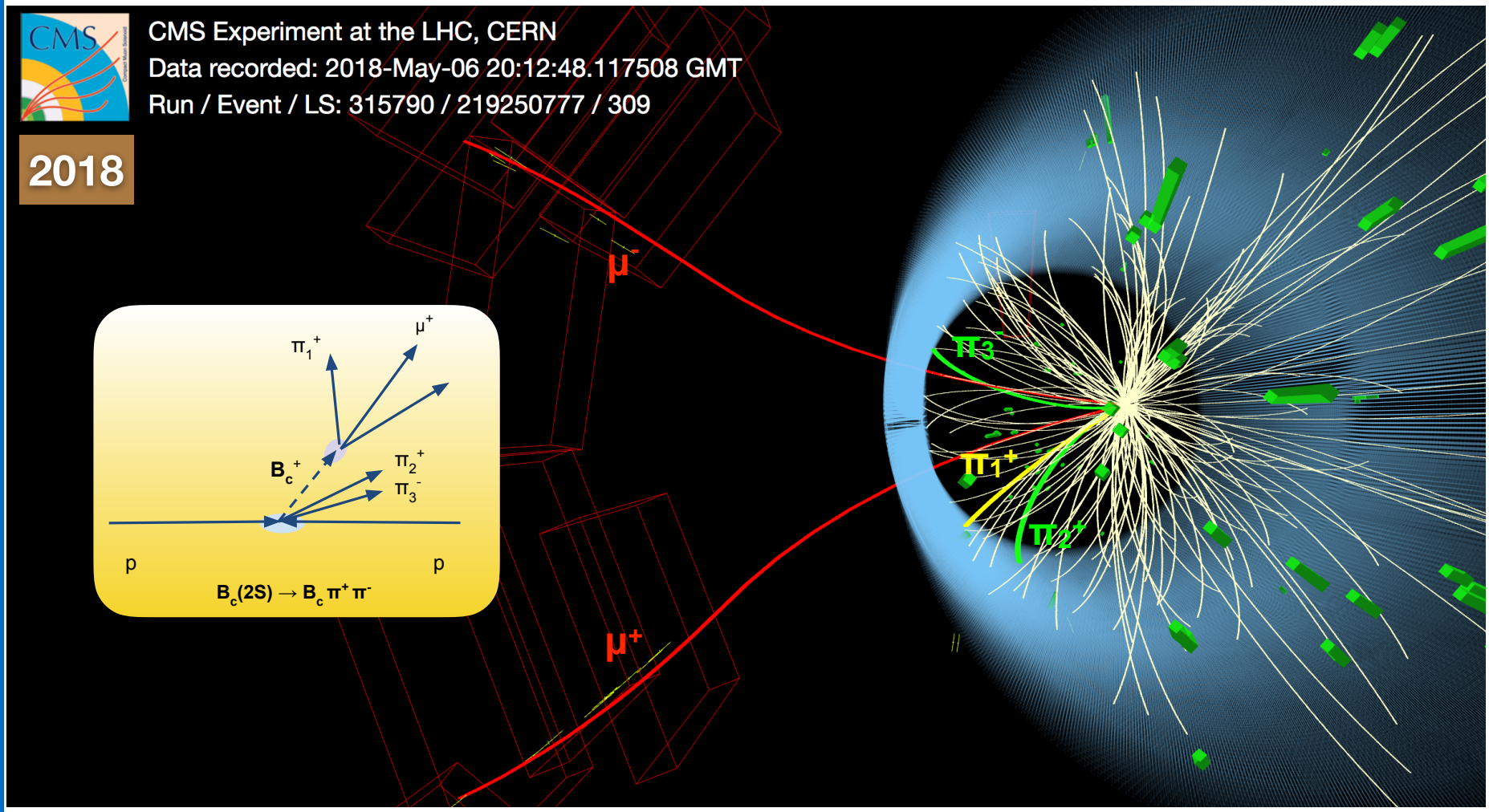


CMS, arXiv:1902.00571, to appear in PRL (also Editor's Suggestion)





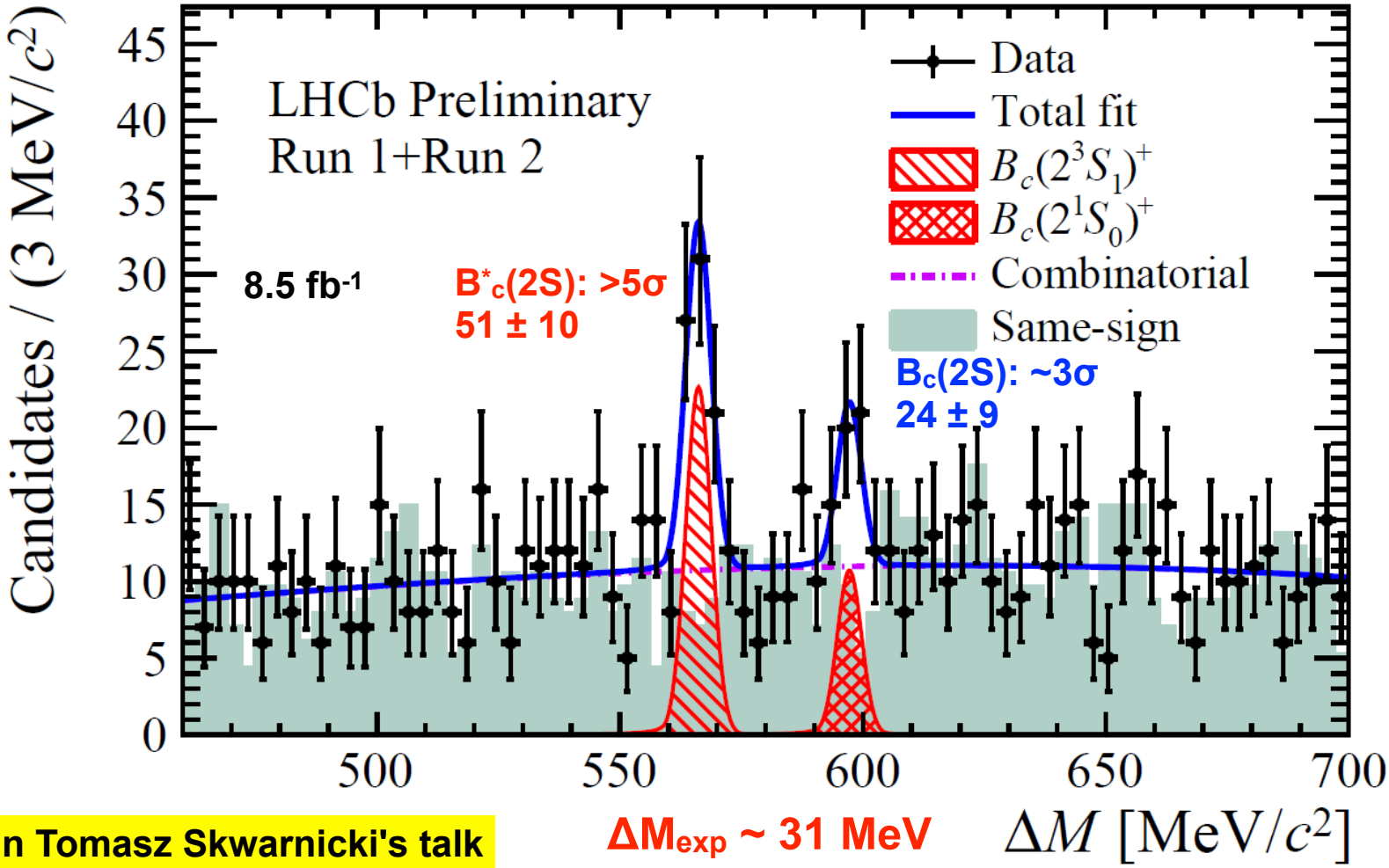
A $B_c(2S)$ Candidate



Hot off the Press

- **Now LHCb has also confirmed the two peaks!**

http://lhcb-public.web.cern.ch/lhcb-public/



ΔM_{exp} ~ 31 MeV

More in Tomasz Skwarnicki's talk

Conclusions

- Heavy-flavor spectroscopy continues to be very rich, both experimentally and theoretically
- Large LHC data sets collected in Run 2 by ATLAS and CMS allowed for the observation of new states and for precision studies of the properties of the already established decays
- Some of these studies may have direct impact on the possible claim of flavor anomalies seen in the $b \to s\ell^+\ell^-$ transitions
- Just started tapping into the full Run 2 potential - stay tuned for many more new results based on this unprecedented data set!