HEAVY-FLAVOR PHYSICS IN CMS

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2020 Lake Louise Winter Institute in Particle Physics

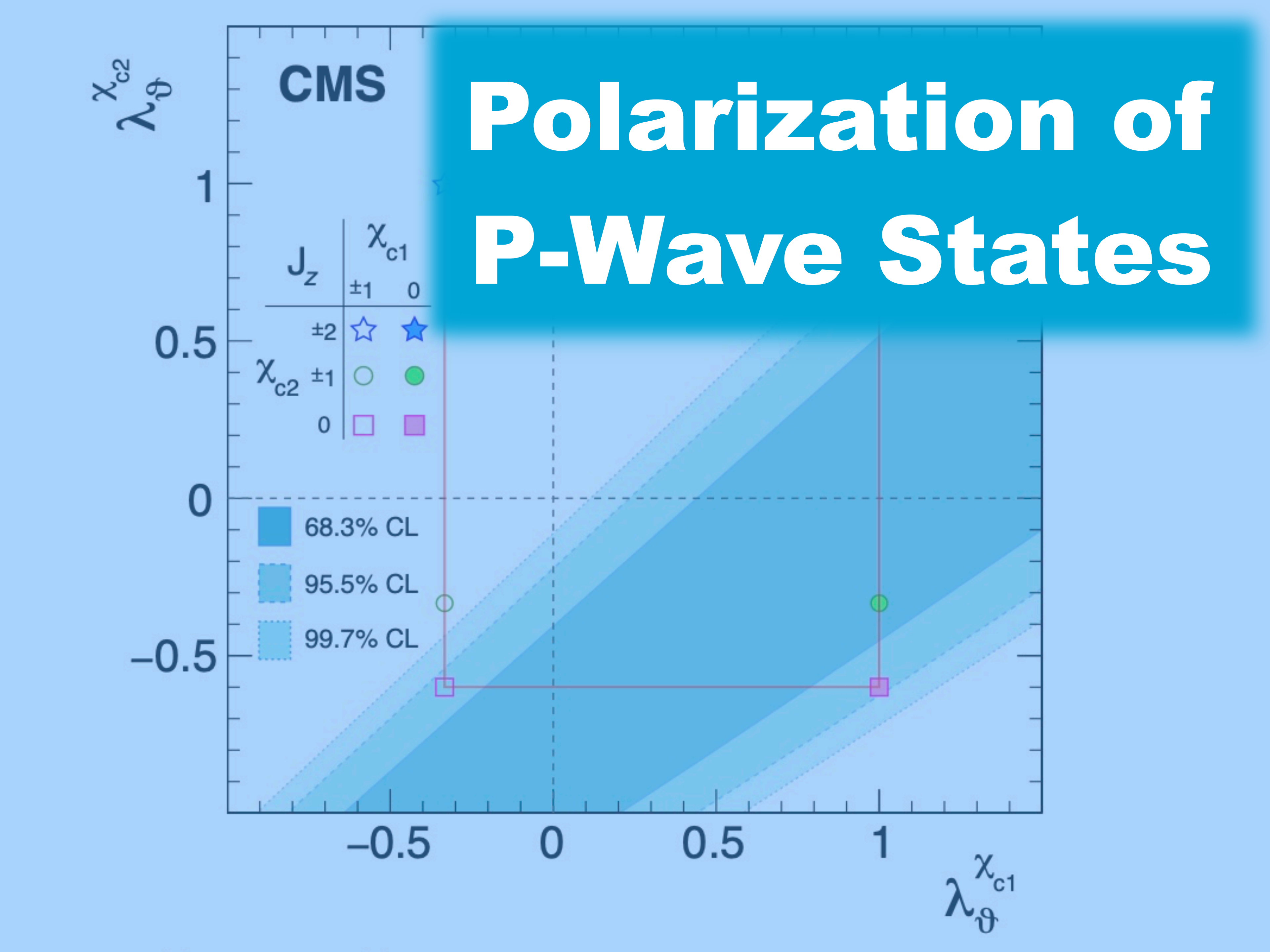
Outline

- Polarization measurements
- Rare decays in CMS
- Study of excited Λ_b baryons
- CMS B physics parked data
- Conclusions

- N.B. All the references are clickable links

CMS and Flavor Physics

- CMS has NOT been designed with flavor physics in mind
  - ★ Nevertheless, the large redundancy of the detector systems, excellent solid angle coverage, state-of-the-art all-silicon tracker, strong magnetic field, and flexible trigger system make it suitable for a number of heavy-flavor measurements, particularly ones involving centrally produced muons
- Large integrated luminosity (nearly 20 times the LHCb) compensates for mainly central coverage and generally higher trigger thresholds
  - ★ This makes CMS competitive with LHCb and B factories in ***selected*** heavy-flavor measurements
- Some of the analyses still explore the wealth of Run 1 data, with generally lower trigger thresholds than sustainable in Run 2
- The 2018 data parking campaign made CMS even more competitive by allowing to study all-hadronic heavy-flavor decays, as well as decays with electrons, V^0's, and τ leptons


Polarization of P-Wave States
CMS
$\lambda_\vartheta^{\chi_{c2}}$
$\lambda_\vartheta^{\chi_{c1}}$
J_z
χ_{c1}
±1
0
χ_{c2}
±2
±1
0
68.3% CL
95.5% CL
99.7% CL
1
0.5
0
−0.5
−0.5
0
0.5
1

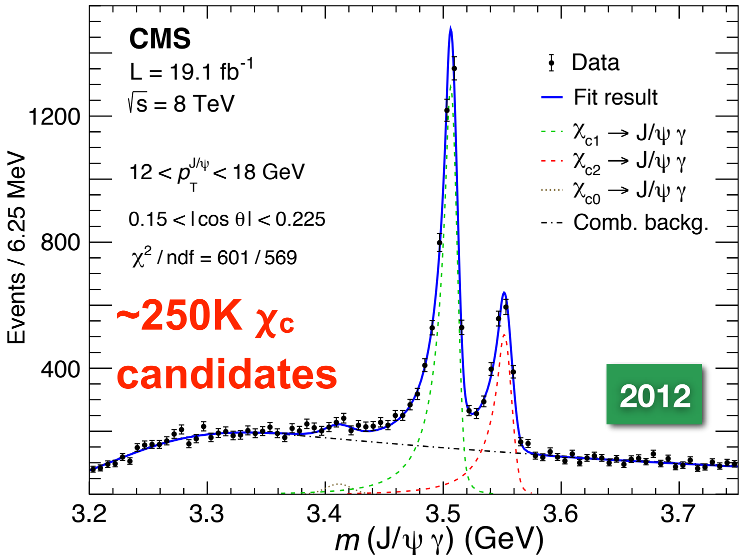
Polarization of $\chi_{c1,2}$ States

- Contrary to naive NRQCD expectations, S-wave spin-1 states are produced largely unpolarized at the LHC:
  - Tested in J/ψ, ψ(2S), Υ(nS) [n = 1-3] production
  - Can be explained by fine-tuning of LDME in NRQCD
- However, there have been no measurements of P-wave spin-1 state polarization so far
  - The recent global fits to the cross section and available polarization data predict strong and opposite polarizations for the P-wave χ_{c1} and χ_{c2} states
- First such measurement of the *relative* polarization for these two states has been just accomplished by CMS

Polarization of χ_c states

- The analysis uses 8 TeV data (19.1 fb^{-1}), which has more suitable triggers
- The χ_c states are observed via radiative decays to $J/\psi\gamma$, with low-p_T photons reconstructed via conversions
- Measurement of polarization difference is significantly simpler than measurement of individual polarizations, as the results are insensitive to the efficiency variations and other systematic effects

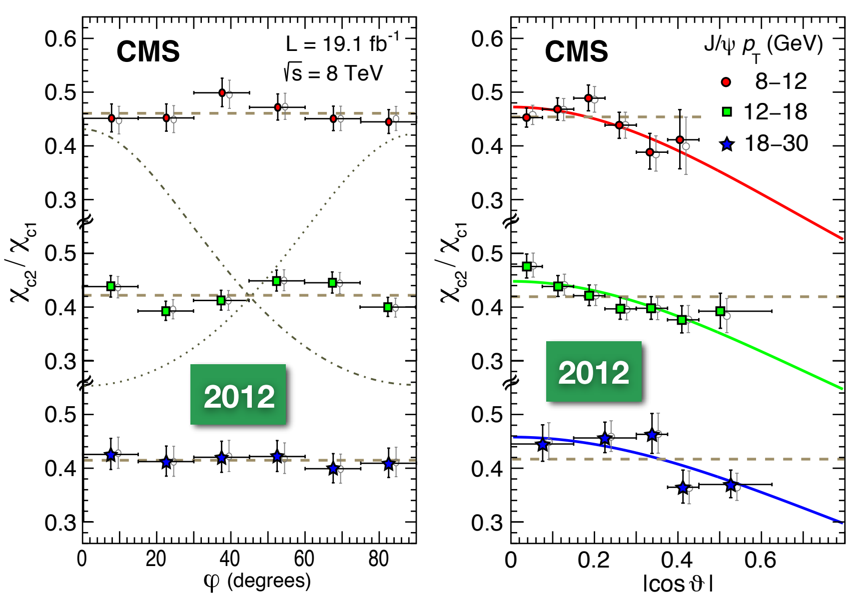
CMS arXiv:1912.07706



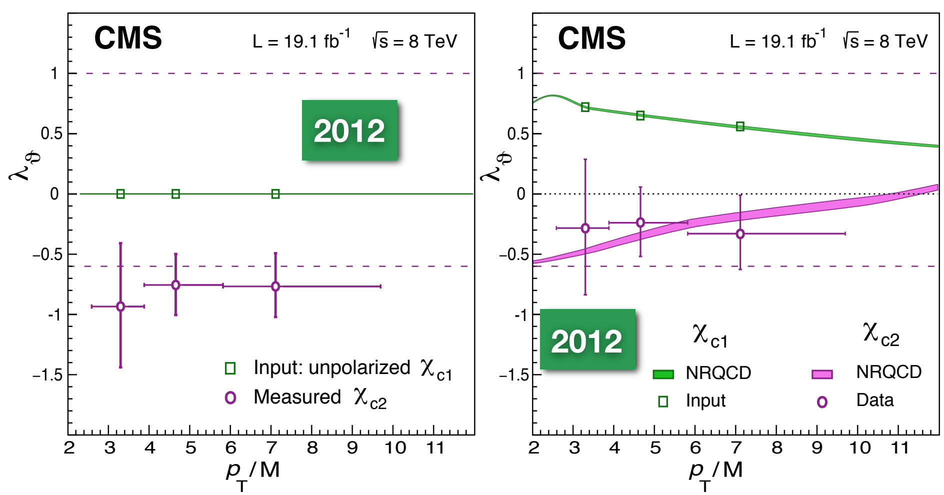
- The measurement is accomplished by comparing the yields of χ_c states as functions of helicity angles ϑ and φ

Polarization Results

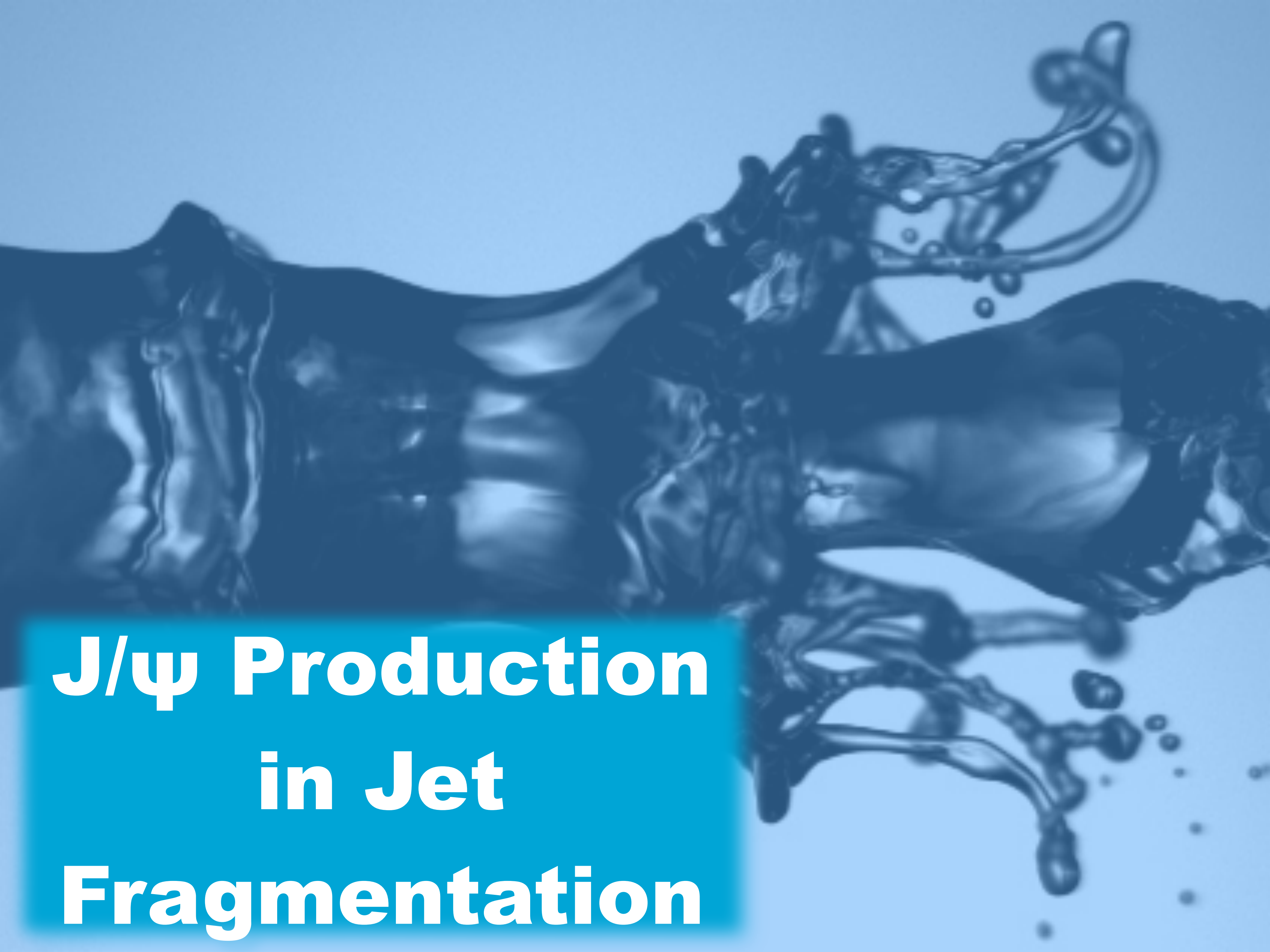
- **The results essentially rule out unpolarized production and favor NRQCD predictions with the LDME from the global fits**
- **Low pT dependence of the polarization difference λ_ϑ observed is consistent with the NRQCD predictions**
- **This is the first observation of non-zero polarization of vector quarkonia in hadronic collisions!**



CMS arXiv:1912.07706



J/ψ Production in Jet Fragmentation



J/ψ Mesons in Jets

- As discussed before, unpolarized production of J/ψ mesons in NRQCD requires rather precise cancellation of various terms
- The relative contributions of these terms is determined from global LDME fits to various J/ψ meson production data
- A sensitive measurement is production of J/ψ mesons within jets, as functions of the fraction of jet energy they carry (z), as well as jet p_T
- This measurement was carried for the first time by CMS using 8 TeV Run 1 data in three z bins of [0.40,0.45], [0.50,0.55], and [0.60,0.65] and the jet p_T range [56,120] GeV

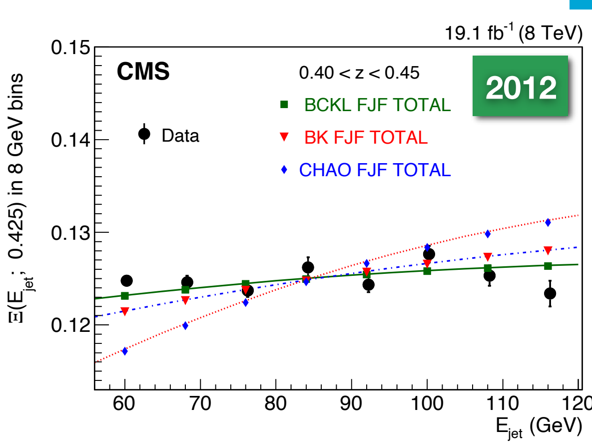
Theory Comparison

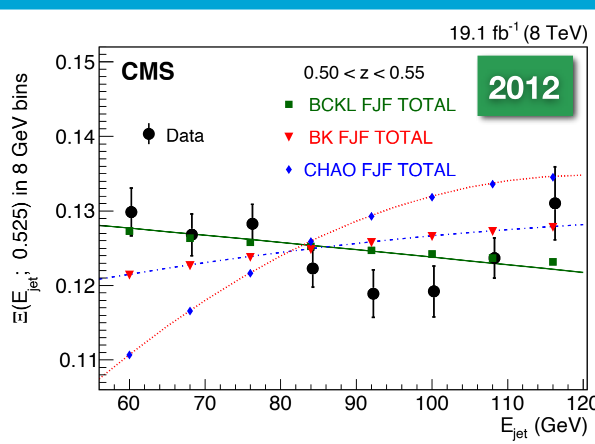
- Out of four NRQCD (non-interfering) terms $^{2S+1}L^{n}_{J}$: $^{1}S^{8}_{0}$, $^{3}S^{1}_{1}$, $^{3}S^{8}_{1}$, $^{3}P^{8}_{J}$, the $^{3}S^{1}_{1}$ color-singlet term is only important at low p_T, so we could ignore it
- The relative energy dependence of the other three terms is determined by a particular LDME set
- The fragmentation jet function (FJF) approach [Baumgart et al., JHEP 11 (2014) 003] allows to fit the ratio of differential cross section in a particular bin to that for the $0.3 < z < 0.8$ range of the analysis
- The results strongly prefer BCKL LDME set, as the only one providing reasonable data description, particularly at large z

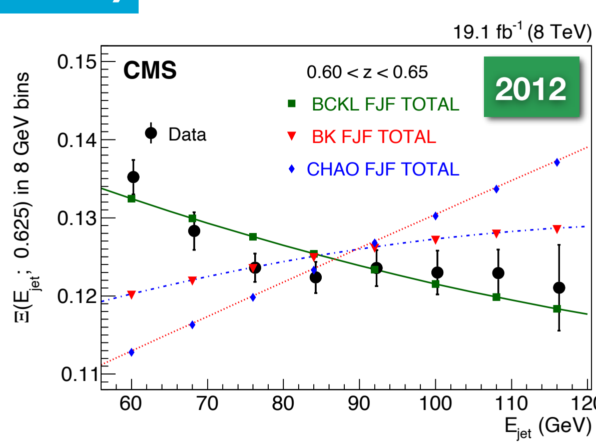
BCKL Predictions

- In the BCKL [Bodwin et al., PRL 113 (2014) 022001] LDME, the two S = 1 color octet terms have opposite signs and nearly identical energy behavior, and thus nearly cancel each other, making the $^1S^8_0$ term to dominate the total in the entire z and p_T range and providing good description of data
- In the BK [Butenschoen & Kniehl, Mod. Phys. Lett. A 28 (2013) 1350027] LDME, the $^1S^8_0$ and $^3S^8_0$ terms are similar and small, and the result does not describe the data anywhere in the phase space studied
- In the Chao [Chao, PRL 108 (2012) 242004] LDME, all three terms are similar, and the result also does not describe the data anywhere in the phase space studied

CMS arXiv:1910.01686 (updated)



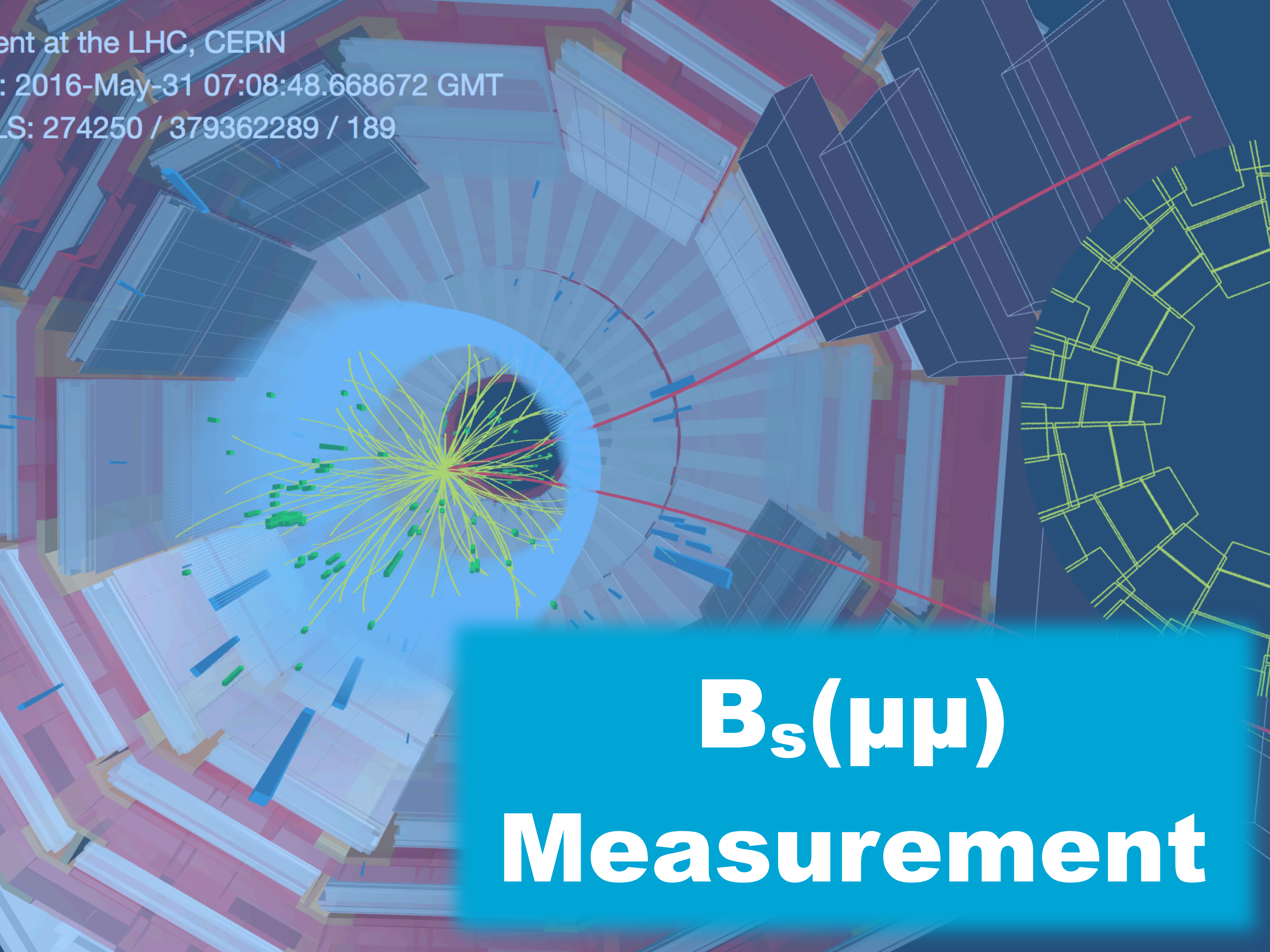




Why Does it Matter?

- The result may have a profound connection to the J/ψ [lack of] polarization puzzle
- The $^1S^8_0$ term is the only one that has both S and J equal to zero, implying that J/ψ mesons do not have any polarization in production
- The fact that it dominates in jet fragmentation into J/ψ mesons at all momentum fractions and p_T for the only set of LDME, which provides an adequate description of the jet data, may explain the lack of polarization in J/ψ meson production
- It also implies that the other two LDME sets miss crucial information in the global fit, which results in their failure to describe differential jet fragmentation data

$B_s(\mu\mu)$ Measurement



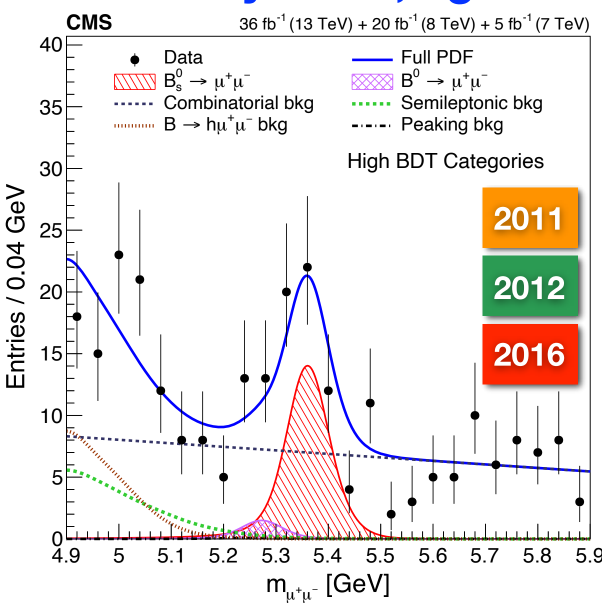
$B_s/B^0 \to \mu\mu$ Results

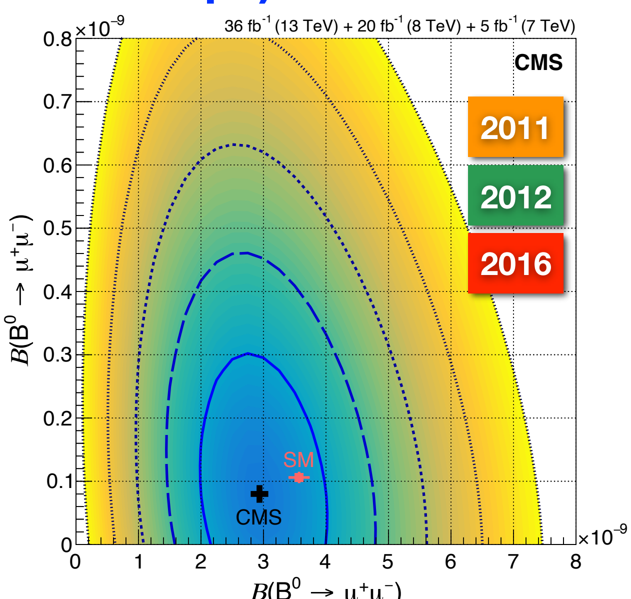
- New $B_s(\mu\mu)$ measurement and a search for $B^0(\mu\mu)$ with Run 1 + 2016 Run 2 data
- Superseded the earlier Run 1 analysis, which became a basis of the combination with LHCb claiming the first observation of the $B_s(\mu\mu)$ decay [Nature 522 (2015) 68]
- Main improvements:
  - ★ Added partial Run 2 data @ 13 TeV
  - ★ More tight muon ID to reduce misidentified hadron background
  - ★ Addition of the lifetime measurement
  - ★ More detailed treatment of the fragmentation function ratio

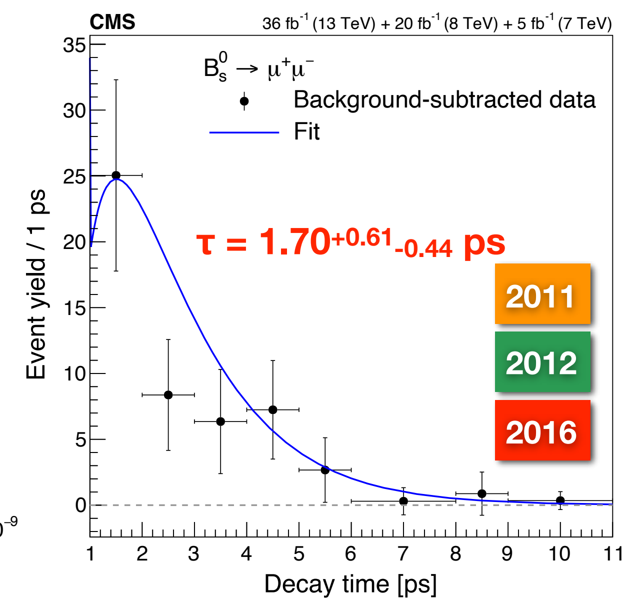
$B_{[s]}^0(\mu\mu)$ in CMS

CMS arXiv:1910.12127

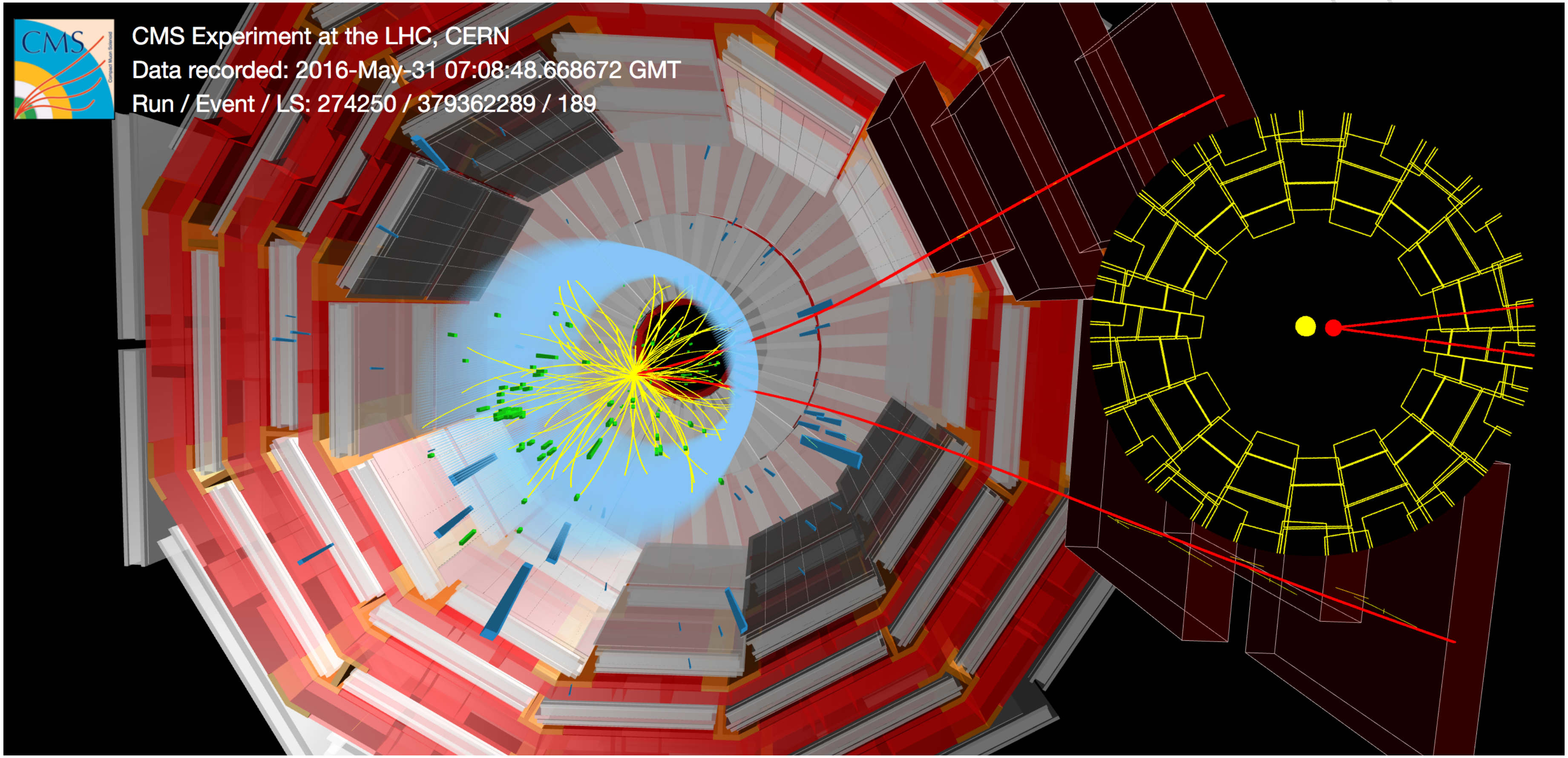
- $B(B_s \to \mu\mu) = [2.9^{+0.7}_{-0.6}$ (exp.) +0.2 (frag.)] x 10^{-9}
  - ★ Observed (expected) significance 5.6 (6.5) s.d.
- $B(B \to \mu\mu) < 3.6\ (3.1) \times 10^{-10}$ @ 95 (90)% CL
- Theory prediction: $B(B_s \to \mu\mu) = (3.63 \pm 0.11) \times 10^{-9}$ (including effects of mixing and the latest form factors from lattice QCD calculations)
- Naive 1D average: $2.92\ ^{+0.42}_{-0.38}$, i.e.,1.64σ below the SM prediction; 2D average ~ 2σ below the prediction; the LHC average is coming shortly
- Effective lifetime measurement: $\tau = 1.70^{+0.61}_{-0.44}$ ps (expect: 1.615 ± 0.004 ps for the heavy state; light state: 1.415 ps)







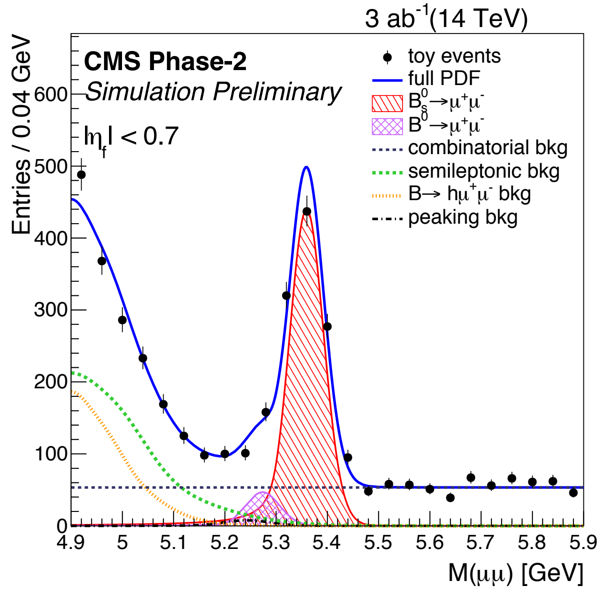
$B_s(\mu\mu)$ Candidate Event

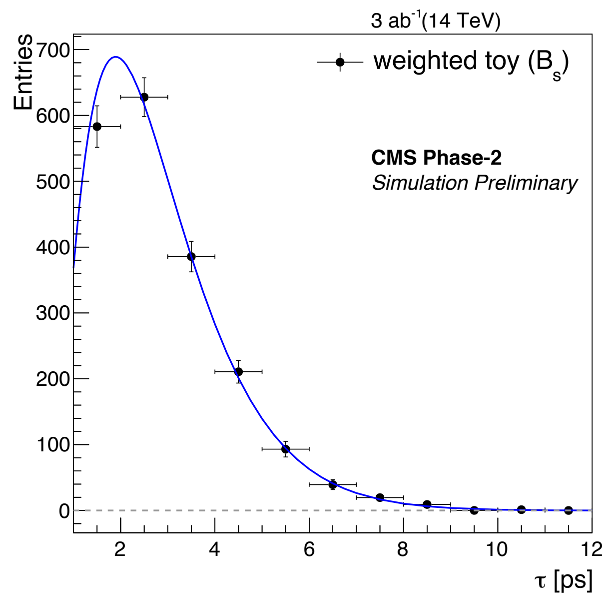


$B_s(\mu\mu)$ Prospective

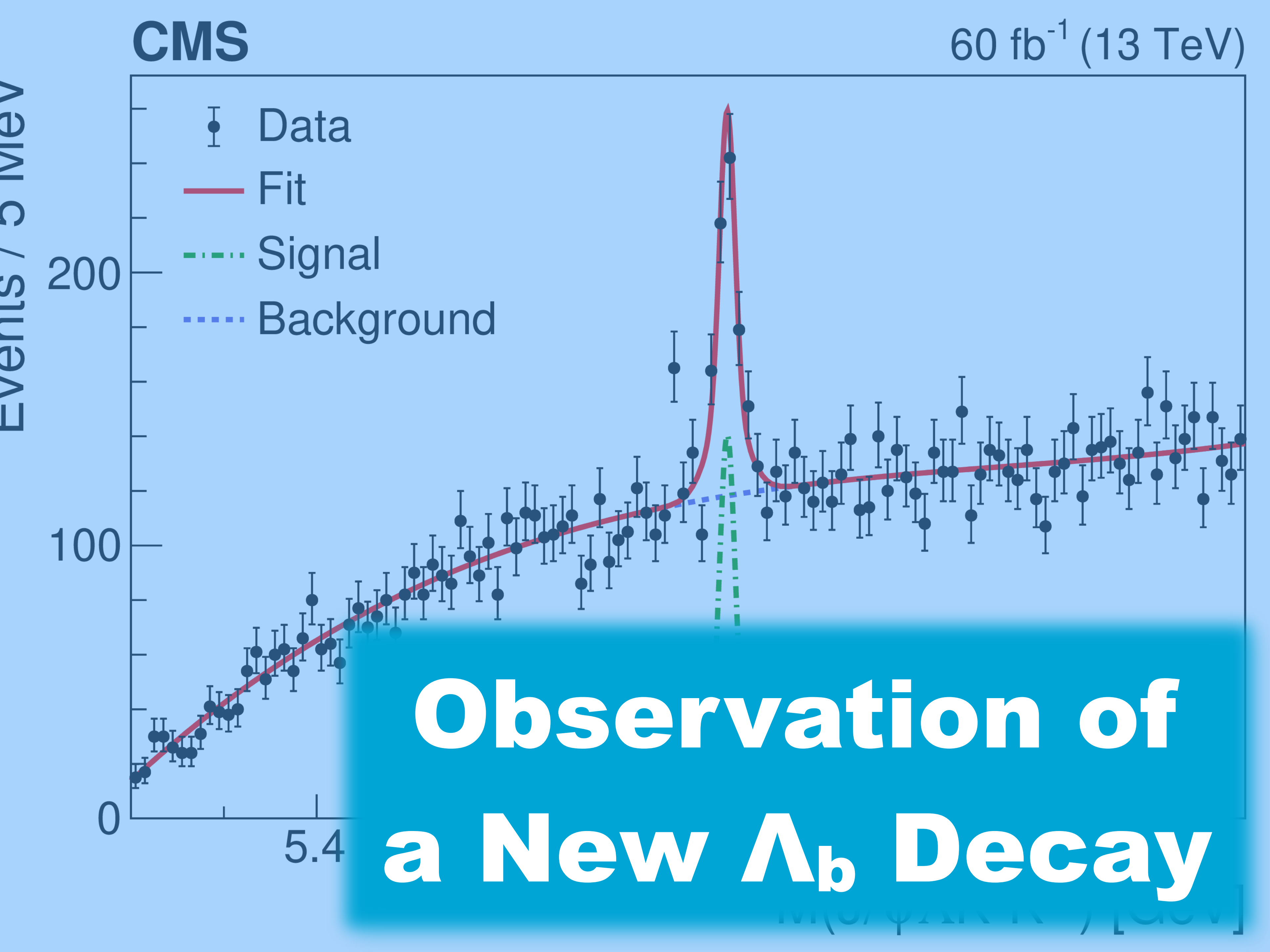
- 3x more Run 2 data is yet to be analyzed - expect a significant improvement!
- For the $B(\mu\mu)$ discovery, need HL-LHC; will also be able to probe the lifetime with sufficient enough precision to resolve the two B_s states

CMS PAS FTR-18-013





$\mathcal{L}$ (fb^{-1})	$N(B_s)$	$N(B^0)$	$\delta\mathcal{B}(B_s \to \mu\mu)$	$\delta\mathcal{B}(B^0 \to \mu\mu)$	$\sigma(B^0 \to \mu\mu)$	$\delta[\tau(B_s)]$(stat-only)
300	205	21	12%	46%	$1.4 - 3.5\sigma$	0.15 ps
3000	2048	215	7%	16%	$6.3 - 8.3\sigma$	0.05 ps

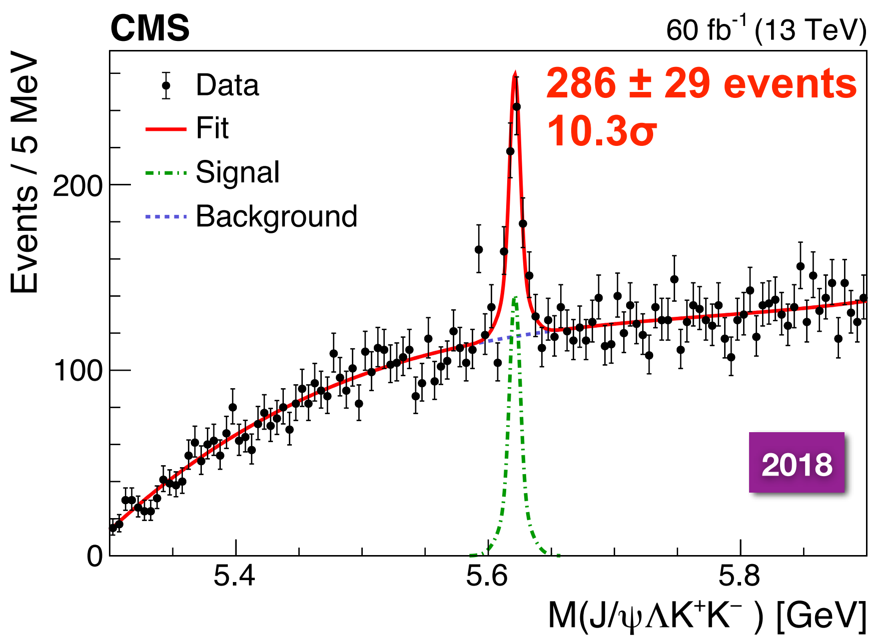

CMS
60 fb-1 (13 TeV)
Data
Fit
Signal
Background
200
100
0
5.4
Observation of
a New Λb Decay

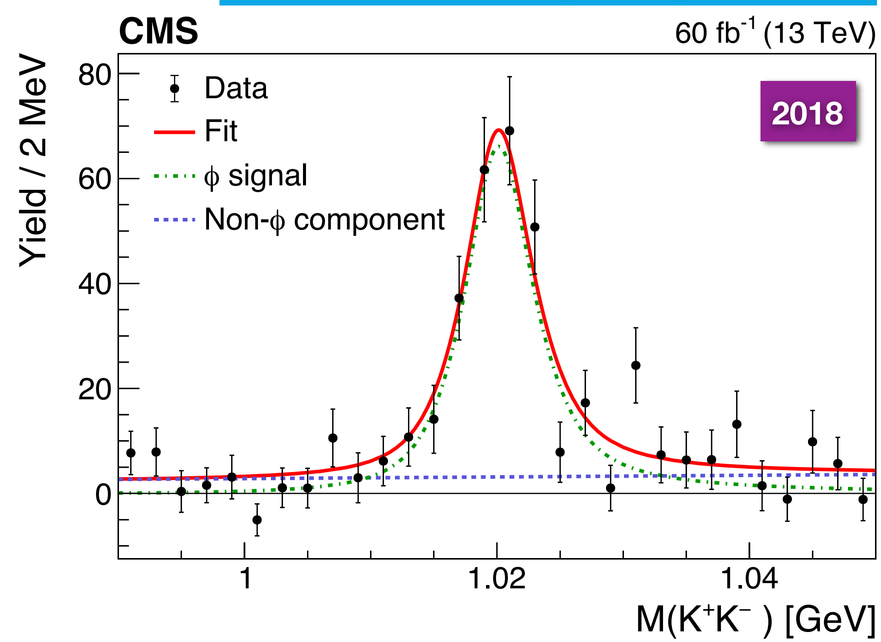
Observation of a Rare Λ_b Decay

- Search for a new rare Λ_b decay: $\Lambda_b \to J/\psi\Lambda\phi$ in 2018 data (60 fb^{-1}) motivated by the observation of exotic narrow pentaquark candidates in the $J/\psi p$ spectrum in the $\Lambda_b \to J/\psi pK$ decay by LHCb [PRL 122 (2019) 222001]
- Use the $\Lambda_b \to \psi(2S)\Lambda \to J/\psi\Lambda\pi^+\pi^-$ decay as the normalization channel (similar topology and track multiplicity)

$$\frac{\mathcal{B}(\Lambda_b \to J/\psi\Lambda\phi)}{\mathcal{B}(\Lambda_b \to \psi(2S)\Lambda)} = (8.26 \pm 0.90\ (\text{stat}) \pm 0.68\ (\text{syst}) \pm 0.11\ (\mathcal{B}))\%$$

CMS PLB 802 (2020) 135203





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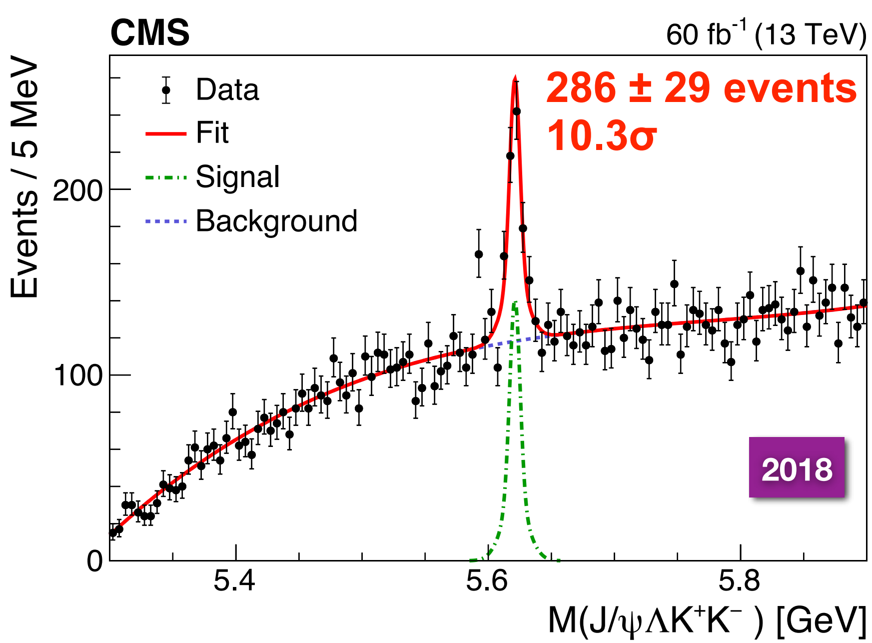
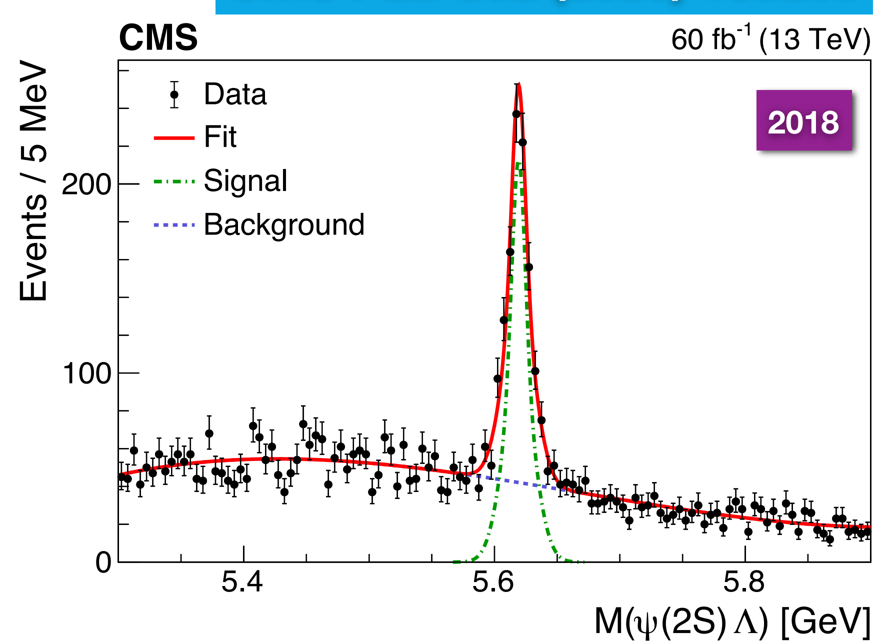
CMS PLB 802 (2020) 135203



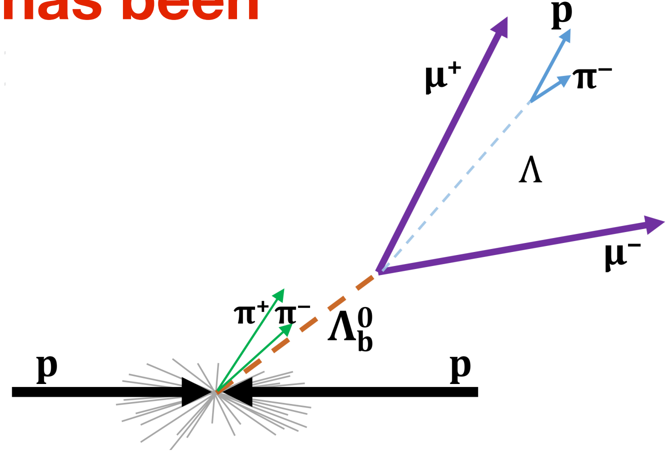


Greg Landsberg - Heavy-Flavor Physics in CMS - February 2020

Mass (in GeV)
6.6
6.4
6.2
6.0
5.8
5.6
3S
2P
1D
2S
1P
1S
Λb(5920)0
Λb(5912)0
Λb(5620)0
Λb
3S
2P
1D
2S
1P
Σb(6097)
Excited Λb Baryons

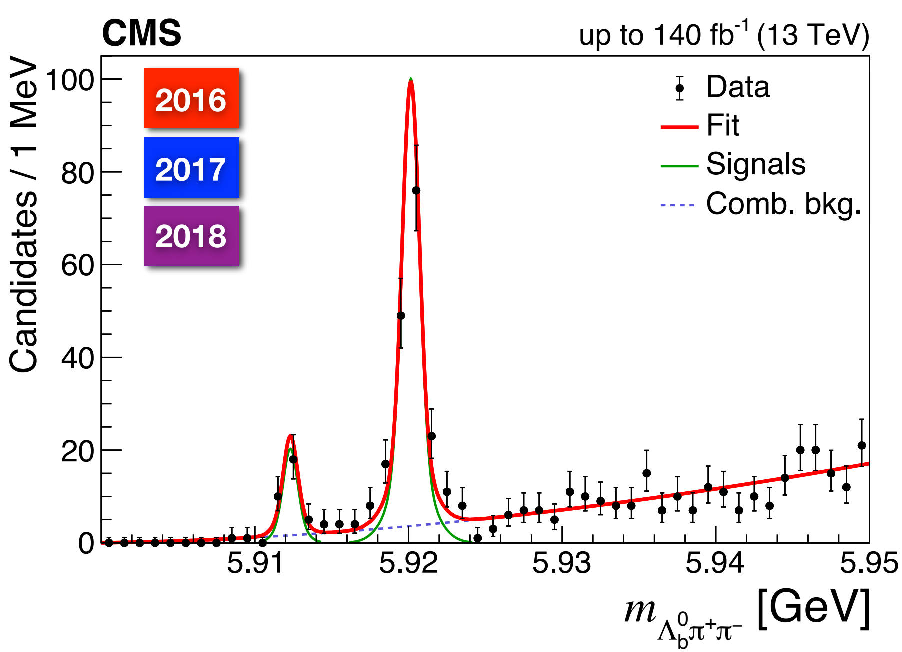
Excited Λ_b Baryons

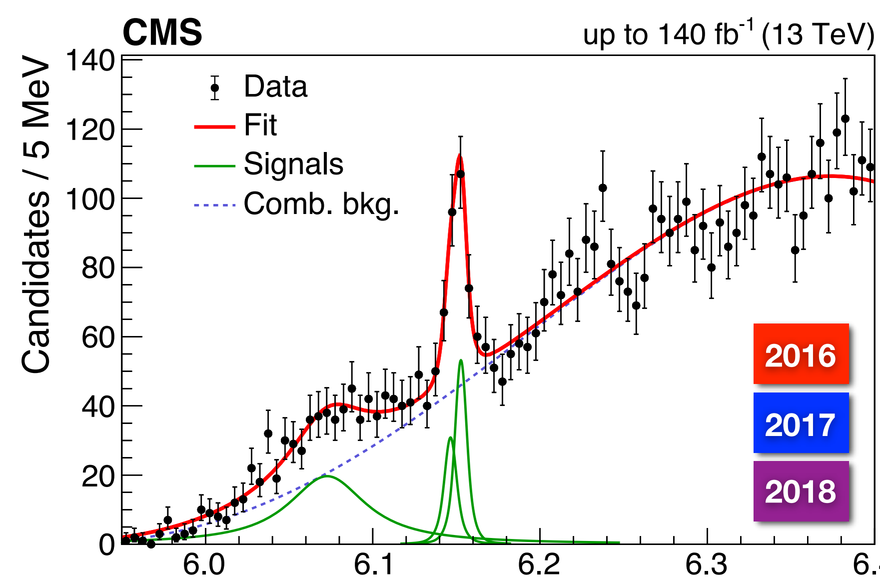
- Studies of heavy excited baryon mass spectra is an important test of HQET
  - ★ Predictions are all over the place and generally contradict each other
- New CMS study of excited Λ_b baryons in the $\Lambda_b\pi^+\pi^-$ mass spectrum in a wide mass range with Run 2 data, up to 140 fb^{-1}
  - ★ Triggered by the observation of $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ by LHCb in 2012 (only the 5920 state has been confirmed by CDF in 2013)
- The search uses a combination of various J/ψ + X triggers, as no dedicated trigger for the signal is available in Run 2



Two Mass Ranges

- The analysis has been optimized differently at low masses, near the $\Lambda_b\pi\pi$ mass threshold, and at high masses, where the background is generally large
- Low-mass spectrum clearly shows $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ resonances, with the masses consistent with the observed ones by LHCb/PDG
- High-mass spectrum shows an unresolved structure at 6150 MeV consistent with the $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ states very recently observed by LHCb [PRL 123 (2019) 152001]
- In addition, a wide bump around 6070 MeV is observed for the first time





CMS arXiv:2001.06533

Mass Measurements

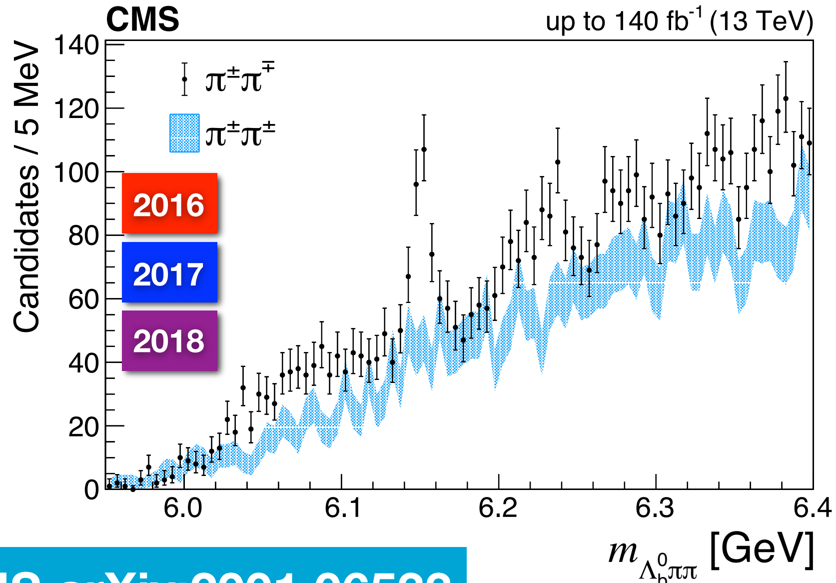
- The following parameters of the peaks have been obtained:

$$M(\Lambda_b(5912)^0) = 5912.32 \pm 0.12 \pm 0.01 \pm 0.17\,\text{MeV}, \quad 5.7\sigma$$
$$M(\Lambda_b(5920)^0) = 5920.16 \pm 0.07 \pm 0.01 \pm 0.17\,\text{MeV}, \quad > 6\sigma$$
$$M(\Lambda_b(6146)^0) = 6146.5 \pm 1.9 \pm 0.8 \pm 0.2\,\text{MeV},$$
$$M(\Lambda_b(6152)^0) = 6152.7 \pm 1.1 \pm 0.4 \pm 0.2\,\text{MeV}, \quad \Big\} > 5\sigma$$

  - ★ The last uncertainty is due to the Λ_b mass measurement
- The masses of the first two resonances have been measured to a precision comparable with the PDG
- The two higher-mass states are in agreement with the LHCb measurement, but measured with worse precision
  - ★ We thereby confirm the existence of $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ resonances

More on the Wide Excess

- More data are needed for a proper interpretation of the wide structure, as it could be not a single state, but a superposition of several nearby broad states
- Various reflections have been thoroughly studied and excluded as the nature of the bump
- If fit with a single broad resonance, the parameters are:
  - ★ M(X) = 6073 ± 5 MeV, Γ(X) = 55 ± 11 MeV, with the significance ~4σ
- The bump is not seen in the $\Lambda_b\pi^\pm\pi^\pm$ mass spectrum with same-sign dipions

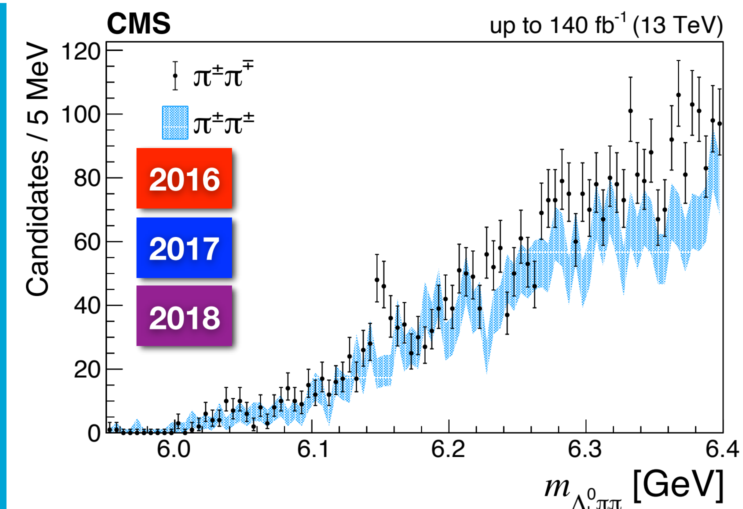


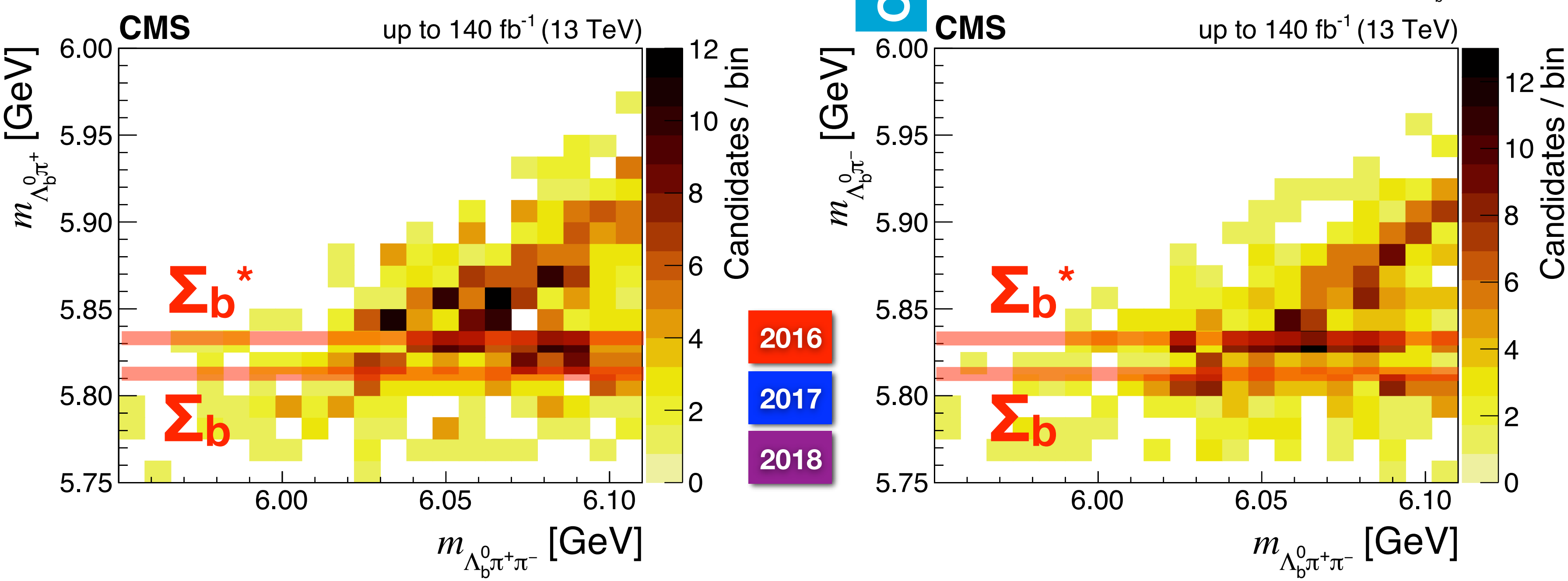
CMS arXiv:2001.06533

More on the Wide Bump

- The bump is consistent with originating from a resonance in the $\Sigma_b/\Sigma_b^* + \pi$ system, but no firm conclusion can be made with the present data set

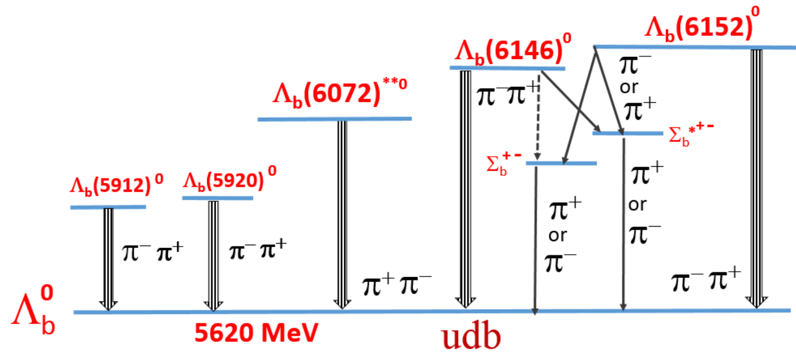
CMS arXiv:2001.06533

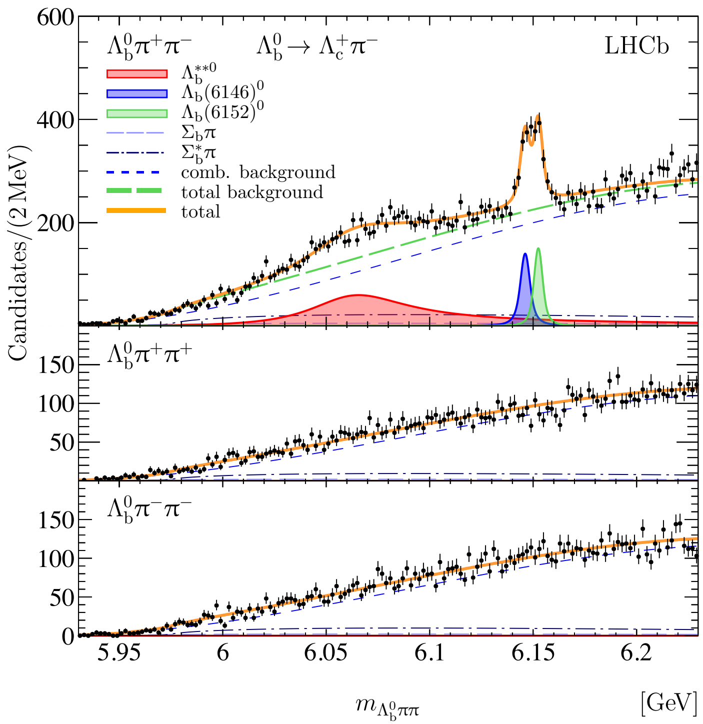




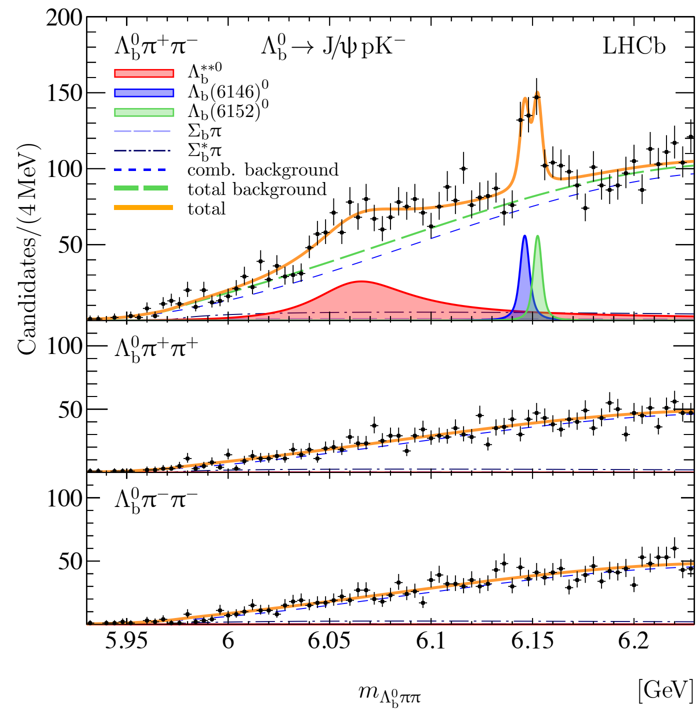
Hot off the Press

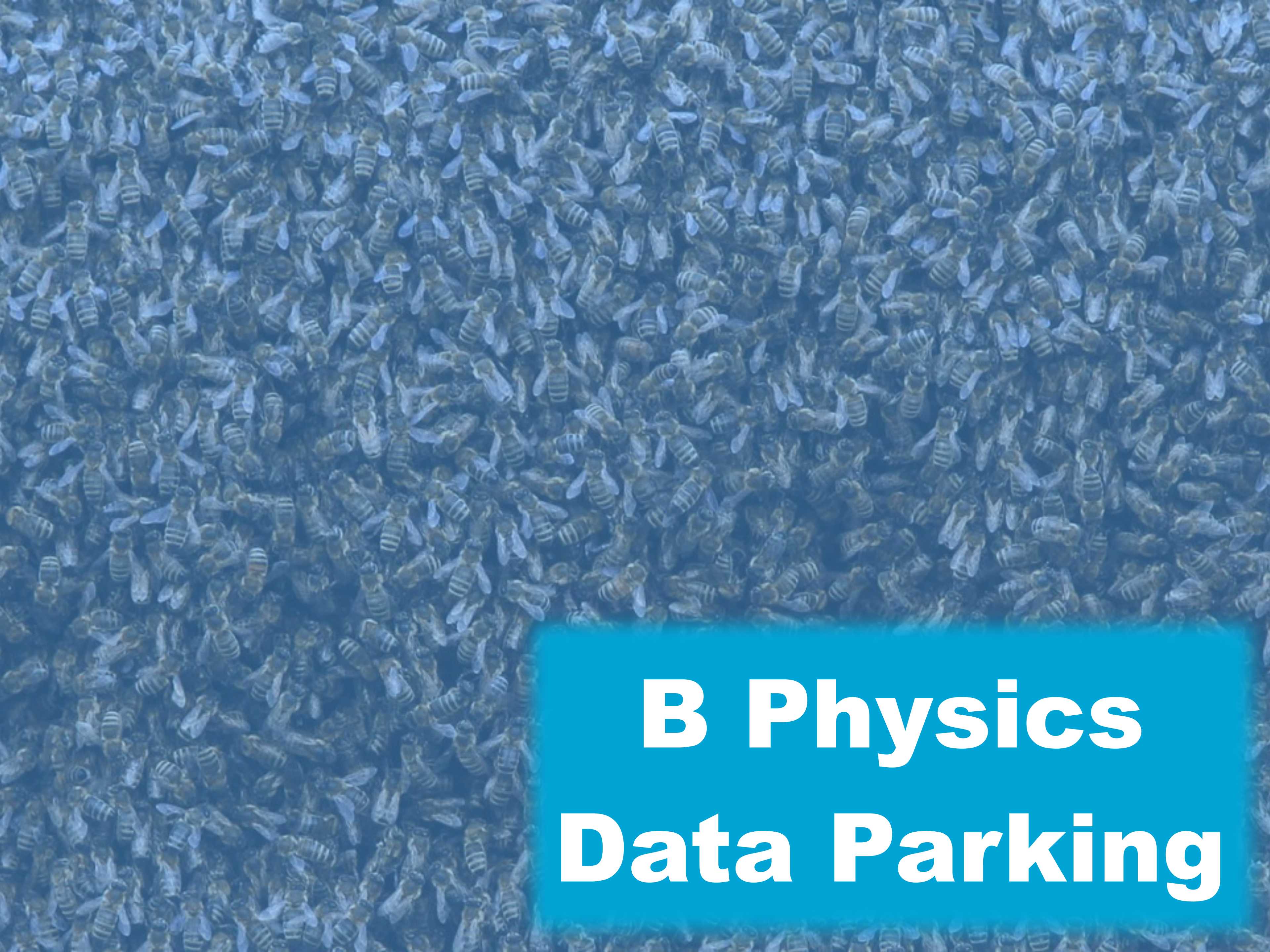
- Yesterday, LHCb confirmed the wide bump observed by CMS with similar parameters and interpreted it as Λ_b^{**}





LHCb, arXiv:2002.05112



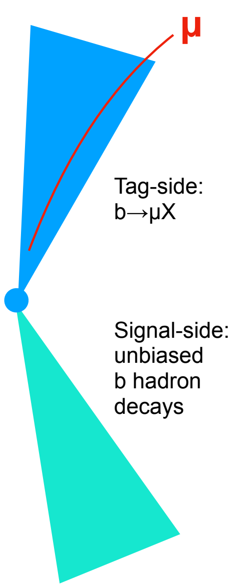

B Physics
Data Parking

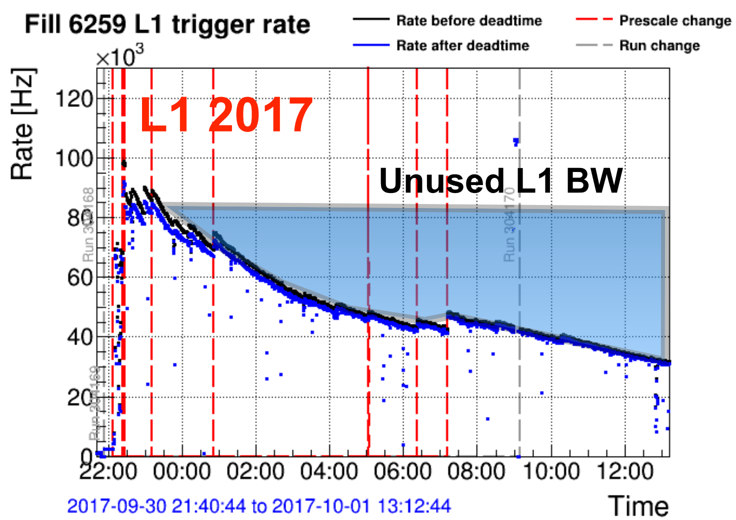
2018 Data Parking

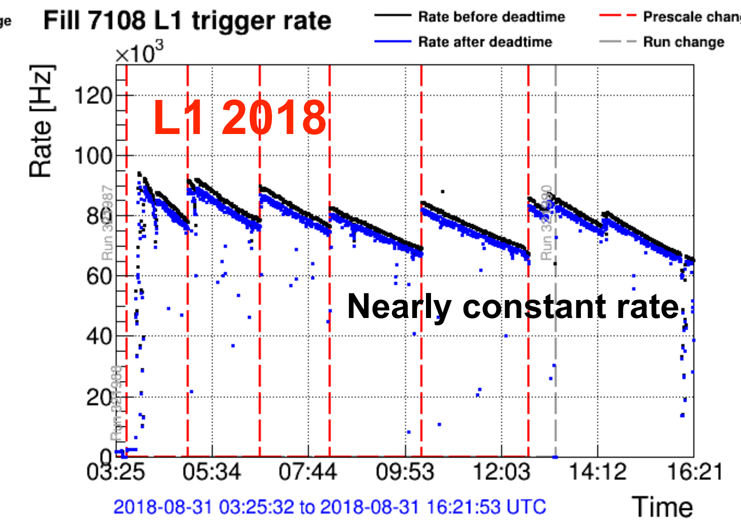
- The 2018 B physics parking campaign: the main goal was to make CMS competitive with LHCb in the R(K)/R(K*) measurements, which attracted a lot of attention in the last couple of years
- It also has a potential to enable a number of new measurements in the B physics sector, which were not thought possible before
- The goal was "simple": to record ~10^{10} unbiased B hadron decays in 2018, using the flexibility of the CMS data taking model
- Thanks to a lot of enthusiasm and help from the entire collaboration, we have accomplished this goal: 12B events recorded with b purity of ~75%

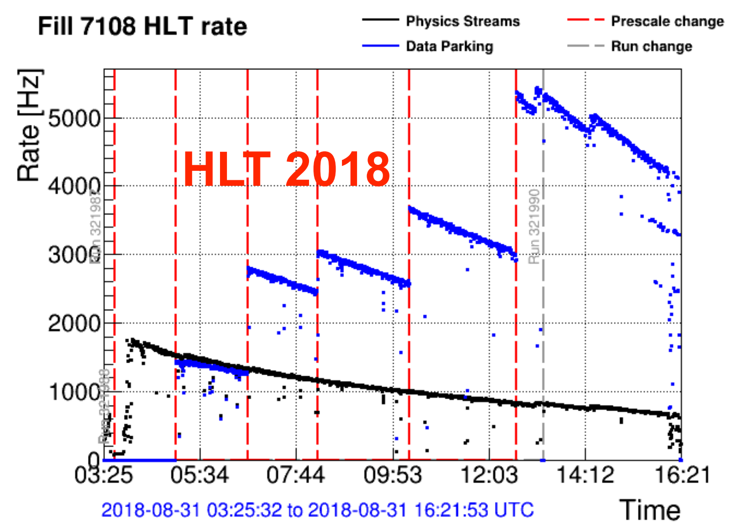
B Parking Trigger Strategy

- As the luminosity drops, turn on various single-muon |η|-restricted seeds, which allow to keep L1 rate constant and increase HLT rate toward the end of each fill









<PU> ~ 20; ~40/fb recorded

Settings	Peak $\mathcal{L}_{inst}$ [10^{34} cm^{-2} s^{-1}]	L1 μ p_T threshold [GeV]	HLT μ p_T threshold [GeV]	HLT μ IP_{sig} threshold	Trigger purity [%]	Peak rate [kHz]
1	1.7	12	12	6	92	1.5
2	1.5	10	9	6	87	2.8
3	1.3	9	9	5	86	3.0
4	1.1	8	8	5	83	3.7
5	0.9	7	7	4	59	5.4

What we Have on Tape

- **Here is what we have on tape:**

Mode	N_{2018}	f_B	$\mathcal{B}$
	Generic b hadrons		
$B^0_{\rm d}$	4.0×10^9	0.4	1.0
$B^\pm$	4.0×10^9	0.4	1.0
$B_{\rm s}$	1.2×10^9	0.1	1.0
b baryons	1.2×10^9	0.1	1.0
$B_{\rm c}$	1.0×10^7	0.001	1.0
Total	1.0×10^{10}	1.0	1.0
	Events for R_K and R_{K^*} analyses		
$B^0 \rightarrow K^*\ell^+\ell^-$	2600	0.4	6.6×10^{-7}
$B^\pm \rightarrow K^\pm\ell^+\ell^-$	1800	0.4	4.5×10^{-7}

More than 20x the entire BaBar B sample collected in just 6 months!

For other physics, the integrated luminosity of this sample is ~40 fb^{-1}

BROWN

What we Have on Tape

- **Here is what we have on tape:**

Mode	N_{2018}	f_B	$\mathcal{B}$
	Generic b hadrons		
B^0_{d}	4.0×10^9	0.4	1.0
$B^\pm$	4.0×10^9	0.4	1.0
B_{s}	1.2×10^9	0.1	1.0
b baryons	1.2×10^9	0.1	1.0
B_{c}	1.0×10^7	0.001	1.0
Total	1.0×10^{10}	1.0	1.0
	Events for R_K and R_{K^*} analyses		
$B^0 \rightarrow K^*\ell^+\ell^-$	2600	0.4	6.6×10^{-7}
$B^\pm \rightarrow K^\pm\ell^+\ell^-$	1800	0.4	4.5×10^{-7}

World's largest B_c sample!

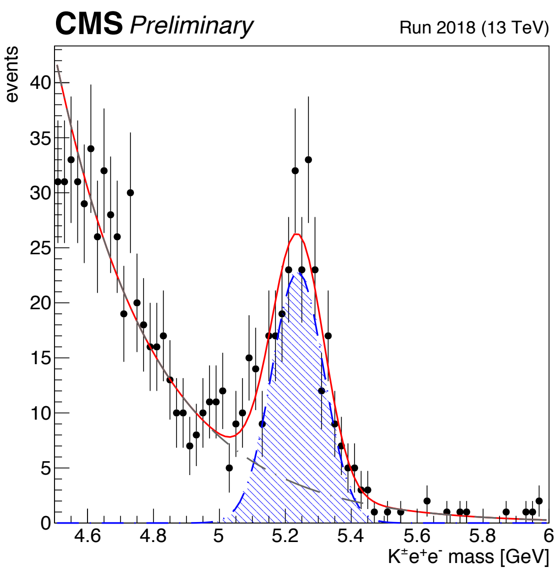
More than 20x the entire BaBar B sample collected in just 6 months!

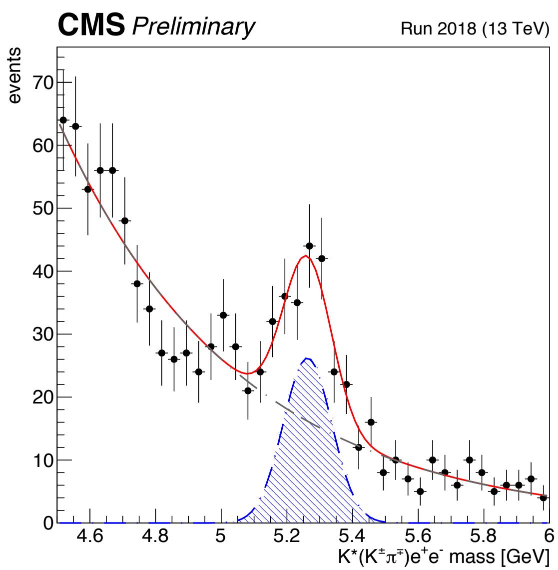
For other physics, the integrated luminosity of this sample is ~40 fb^{-1}

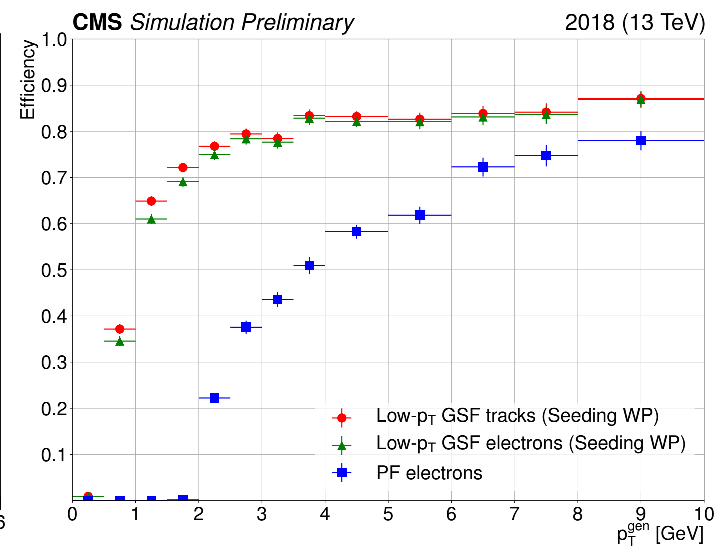
Toward R(K/K*) Measurement

- **Clearly see J/ψ(ee)K/K* peaks (plots below are "online", i.e., ~1% of data!)**
- **The main challenge is low-p_T electron reconstruction, which was never tuned below a few GeV in CMS**
- **Very good progress made; now have reliable ID down to <1 GeV, which allows us to start pursuing the actual analysis at full speed**

CMS DP-2019/043







What we Achieved So Far?

- Invested in the basic components of the R(K/K*/ϕ) analysis: robust electron reconstruction and ID, and the analysis infrastructure
- Developing low-energy τ ID and regression with the R(D/D*/J/ψ), $B_{(s)} \to \tau\tau$ goals in mind
- Had a number of very fruitful discussion with theoretical community on other uses of our parked data, e.g.:
  - ★ f_s/f_d and f_s/f_u fragmentation function ratios via hadronic B meson decays
  - ★ $R(\Lambda_b)$
  - ★ a number of rare decays

Conclusions

- CMS heavy-flavor program continues to be very rich, both experimentally and theoretically
- Large LHC data sets collected in Run 2 allowed for the observation of new states and decays, 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
- A 2018 B Physics parking campaign allowed us to collect world's largest sample of unbiased b hadron decays, offering a very rich physics program in months to come - stay tuned!