Spectroscopy of charm and beauty at CMS

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TWENTY-SECOND LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS August, 21-27, 2025
MOSCOW STATE UNIVERSITY

ФЕДЕРАЛЬНОЕ ГОСУДАРСТВЕННОЕ БЮДЖЕТНОЕ УЧРЕЖДЕНИЕ НАУКИ
Физический институт имени П.Н.Лебедева Российской академии наук
ФИАН

OUTLINE

- CMS triggers for flavour physics

- $T_{cc\bar{c}\bar{c}} \rightarrow J/\psi\ J/\psi$ with Run2+Run3 data (315 fb^{-1})
- $T_{cc\bar{c}\bar{c}} \rightarrow \psi(2S)\ J/\psi$ with Run2+Run3 data
- Spin and parity of $T_{cc\bar{c}\bar{c}}$

Public results link

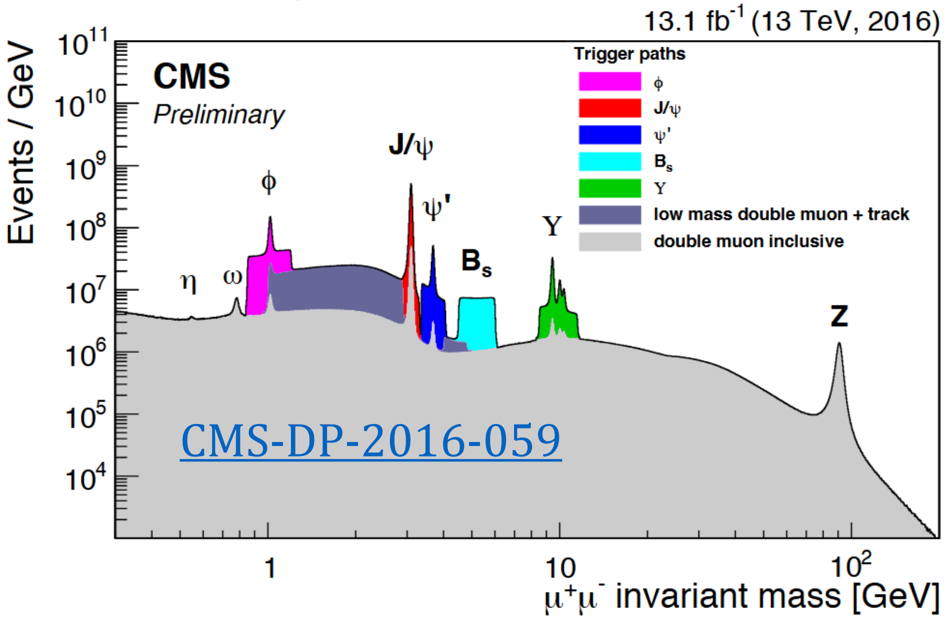
Preliminary results link

- First full reconstruction of B* mesons

CMS triggers for flavour physics

Majority of analyses rely on dimuon triggers
Significant acceptance improvement in Run-3!

Run-2



Run-3

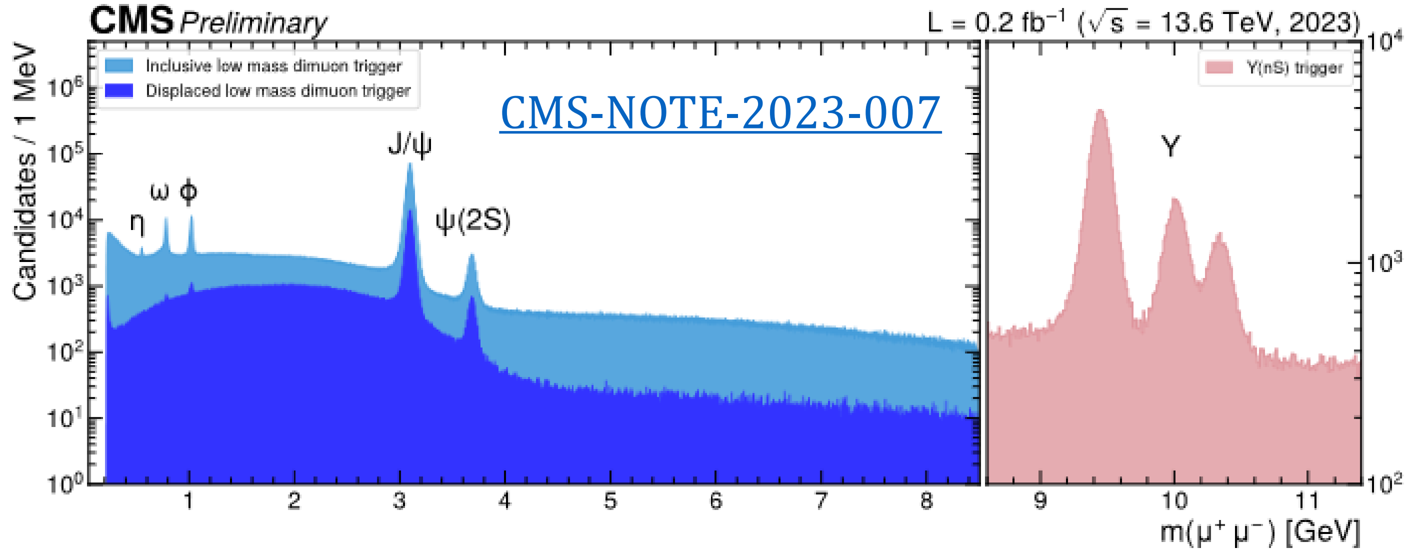


Figure 1: Dimuon mass distribution for data collected with inclusive, displaced, and Upsilon triggers.

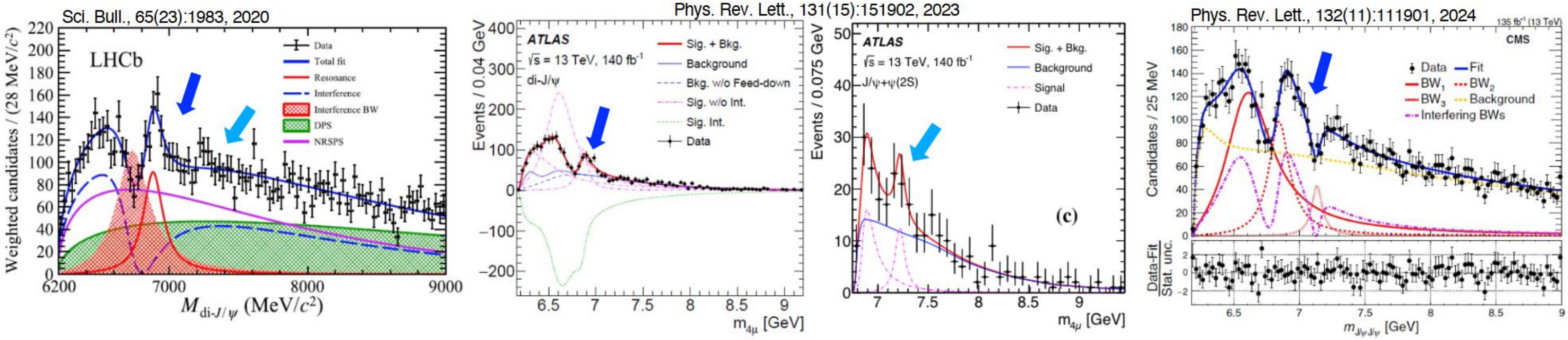
+ single-muon b-parking in 2018
  (single displaced muon with high rate)

+ trimuon triggers and some other

+ single-muon b-parking in 2022 and 2024-2025
  (single displaced muon)

+ trimuon triggers and some other

Fully charm tetraquarks



- LHCb observed X(6900), confirmed by ATLAS and CMS.
- A threshold excess, NOT explained! Classified as background
- The 3 experiments use interference, but in different ways

  LHCb: threshold BW interferes with SPS, but X(6900) is not interfering!

  ATLAS: interference among three “structures” – two for the threshold hump, one for X(6900)

  CMS: multi-resonance interference (3 resonances), threshold peak not interfering
- Only CMS claimed X(6600) and X(7100)

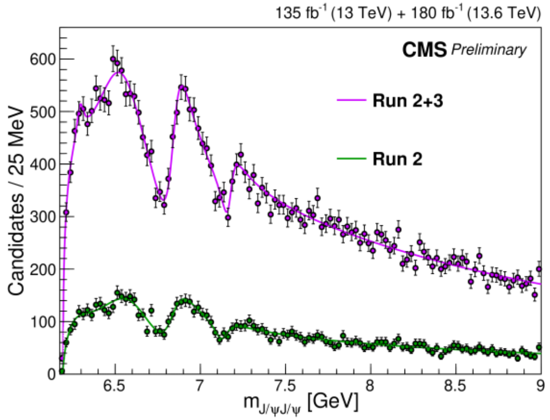
- **CMS follow-up: spin-parity analysis with Run-2, spectra analysis with Run 2 + Run 3, + ψ(2S)*J*/ψ**

Fully charm tetraquarks: J/ψ J/ψ, 315fb^{-1}

CMS-PAS-BPH-24-003

➢ Fit to m(J/ψ J/ψ) components:

- **Signal: sum of interfering Relativistic Breit-Wigner functions**
- Non-res SPS background
- Non-res DPS background
- Combinatorial background (non-J/ψ dimuons)
- Feed-down ($T_{cc\bar{c}\bar{c}} \rightarrow H_{c\bar{c}}\, J/\psi \rightarrow J/\psi\, J/\psi\, X$, where $X = \gamma, \pi, \pi\pi$, etc)
- Threshold enhancement "BW0"

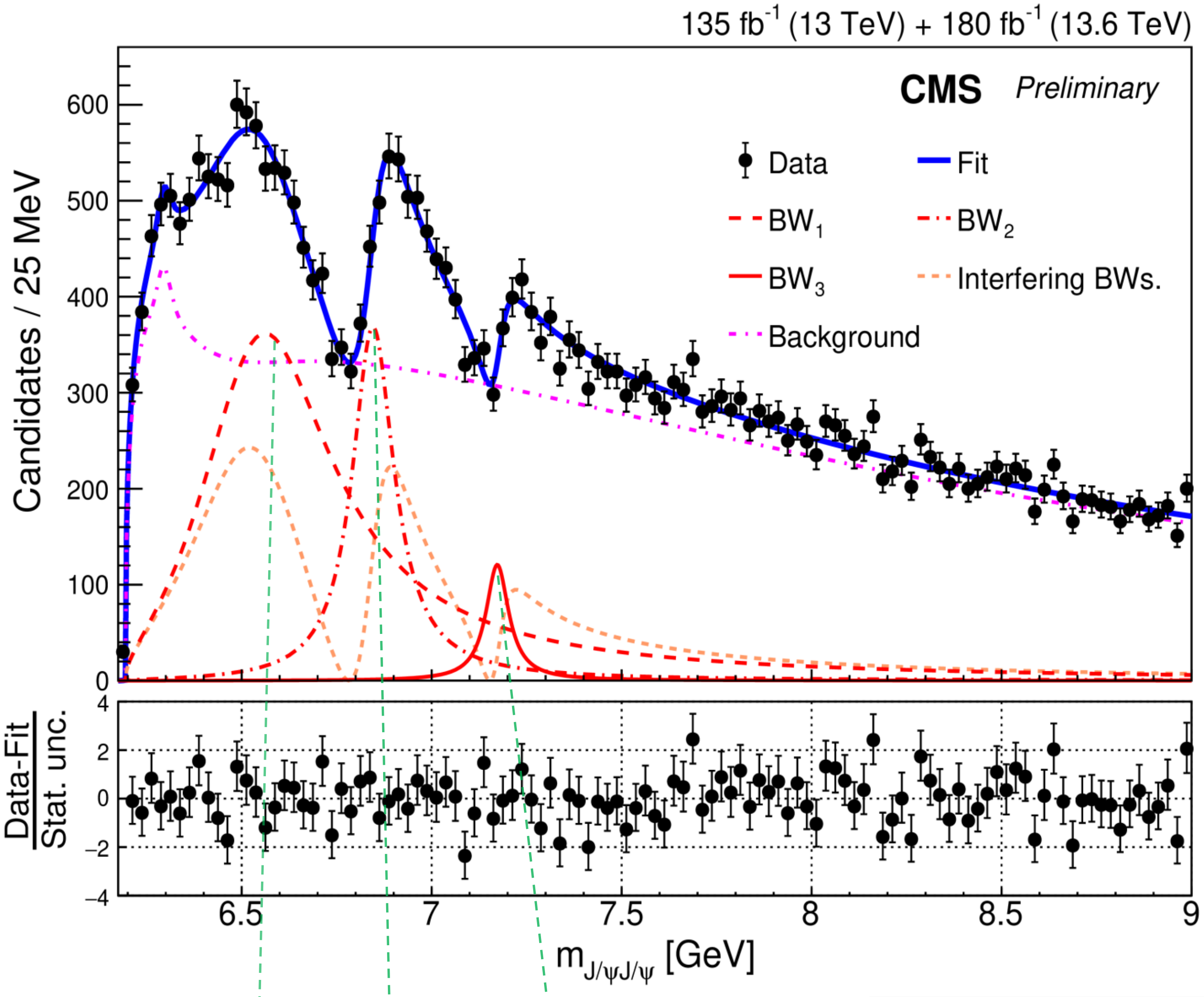


➢ Run II+III ***J/ψJ/ψ yield*** is *3.6X* of Run II

➢ Run II+III ***luminosity*** is *2.3X* of Run II

Fully charm tetraquarks: $J/\psi\, J/\psi$

CMS-PAS-BPH-24-003



$T_{cc\bar{c}\bar{c}}(6600)$ $T_{cc\bar{c}\bar{c}}(6900)$

$T_{cc\bar{c}\bar{c}}(7100)$

Significances:

$T_{cc\bar{c}\bar{c}}(6600)$: **15σ**

$T_{cc\bar{c}\bar{c}}(6900)$: **17σ**

$T_{cc\bar{c}\bar{c}}(7100)$: **8σ (observation!)**

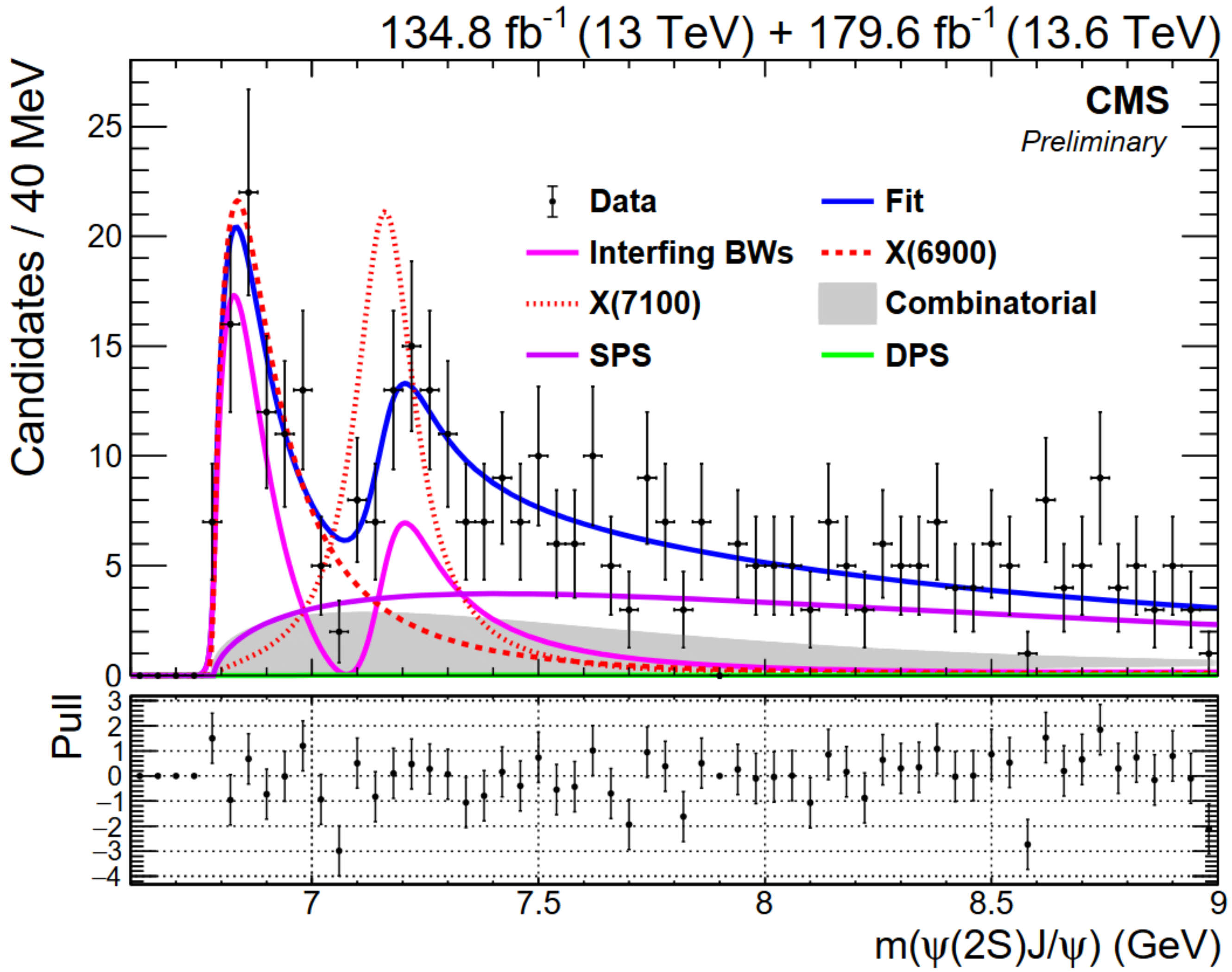
Dip at 6.8 GeV: **10σ**

Dip at 7.1 GeV: **8σ**

Interference observed with high significance → likely 3 states have same JPC

		BW_1	BW_2	BW_3
Interference	m (MeV)	$6593\,^{+15}_{-14} \pm 25$	$6847\,^{+10}_{-10} \pm 15$	$7173\,^{+9}_{-10} \pm 13$
(Run 2+Run 3)	Γ (MeV)	$446\,^{+66}_{-54} \pm 87$	$135\,^{+16}_{-14} \pm 14$	$73\,^{+18}_{-15} \pm 10$

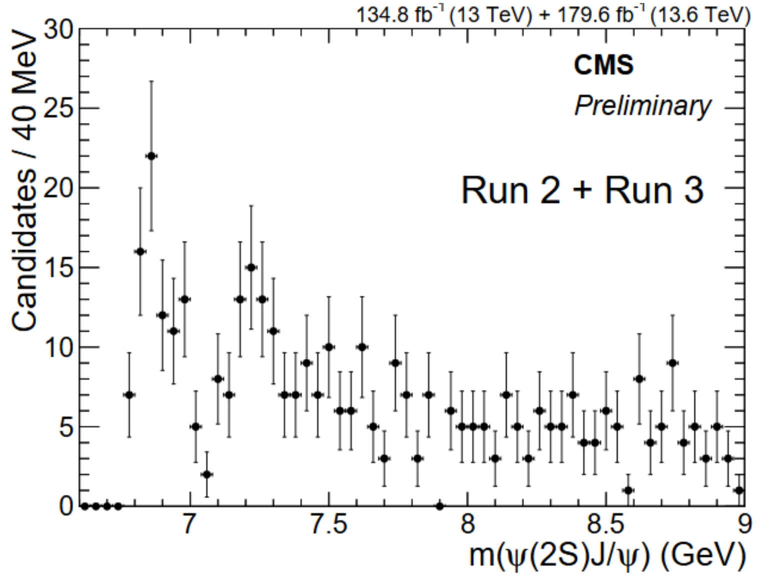
Fully charm tetraquarks: $J/\psi\ \psi(2S)$, 315 fb^{-1}



Same signal model, without 6600 peak

$T_{cc\bar{c}\bar{c}}$ (6900) : 7.9σ

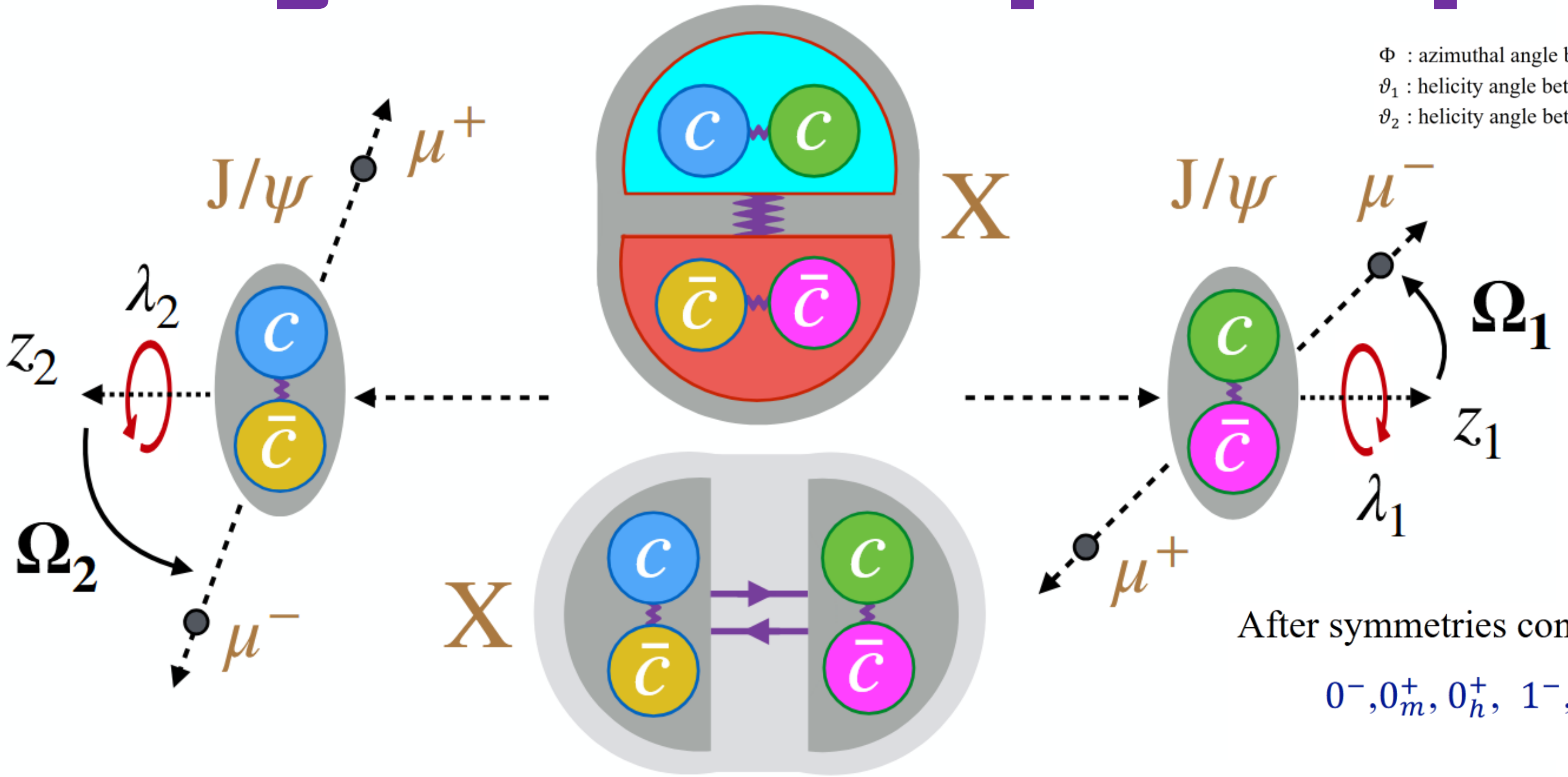
$T_{cc\bar{c}\bar{c}}$ (7100) : **4σ**



	$X(6900)$	$X(7100)$
M, MeV	$6876^{+46+110}_{-29-110}$	7169^{+26+74}_{-52-70}
Γ, MeV	$253^{+290+120}_{-100-120}$	$154^{+110+140}_{-82-160}$

CMS-PAS-BPH-22-004

Fully charm tetraquarks: spin-parity



Φ : azimuthal angle between two l^+l^- decay planes defined in X rest frame

ϑ_1 : helicity angle between opposite of J/ψ_2 momentum and l momentum defined in J/ψ_1 rest frame

ϑ_2 : helicity angle between opposite of J/ψ_1 momentum and l momentum defined in J/ψ_2 rest frame

CMS-BPH-24-002, arXiv:2506.07944

After symmetries conditions, **8 models of J_x^P** to test:

$0^-, 0_m^+, 0_h^+, 1^-, 1^+, 2_m^-, 2_h^-, 2_m^+$

m: *minimal dimension operators*
h: *higher-dimension operators*

To determine JPC, one needs to analyze distributions of production and decay angles

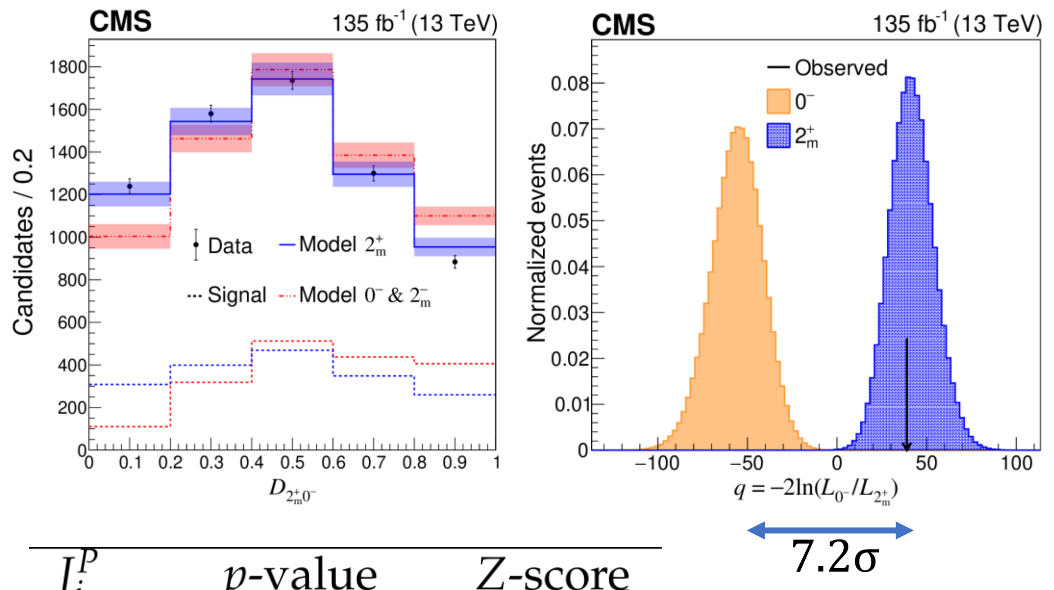
Instead of implementing a many-dimensional analysis, a different approach is utilized:
similar to the Higgs JPC measurement, a **discriminant** is built **for each pair of hypotheses** such that its distribution "differs as much as possible" for the two hypotheses.

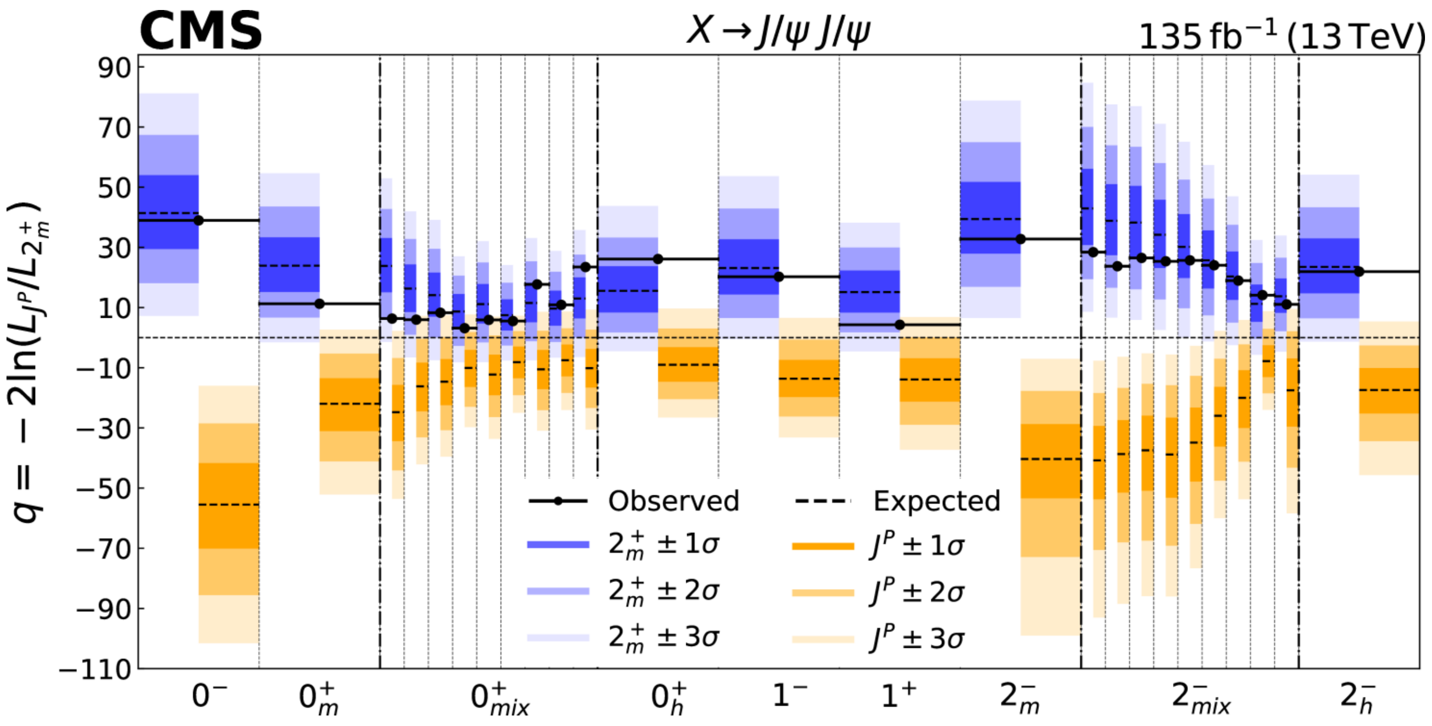
Input variables are the decay angles of $T_{cc\bar{c}\bar{c}}$ and the two J/ψ (no production angles; polarization was estimated to be small/irrelevant)

Fully charm tetraquarks: spin-parity

After many pairwise statistics tests, it is evident that **2^{++} model** survives all comparisons and is preferred by the data.

For 0^{++} and 2^{-+}, there are two amplitudes → scan their mix with different relative magnitude





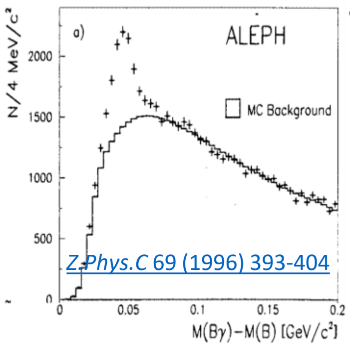
J_i^P	p-value	Z-score reject J_i^P
0^-	2.7×10^{-13}	7.2
0^+_m	4.3×10^{-5}	3.9
0^+_{mix}	1.4×10^{-2}	2.2
0^+_h	3.1×10^{-9}	5.8
1^-	8.0×10^{-8}	5.2
1^+	4.7×10^{-3}	2.6
2^-_m	4.1×10^{-12}	6.8
2^-_{mix}	6.5×10^{-4}	3.2
2^-_h	2.2×10^{-8}	5.5

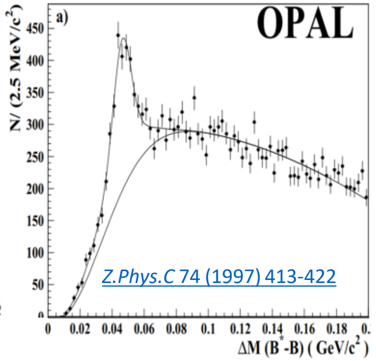
CMS-BPH-24-002, arXiv:2506.07944

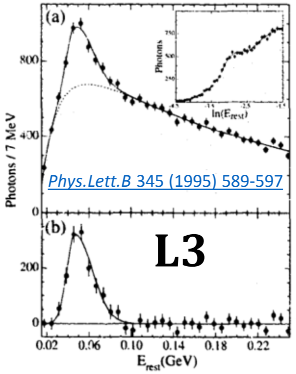
History of B* meson studies

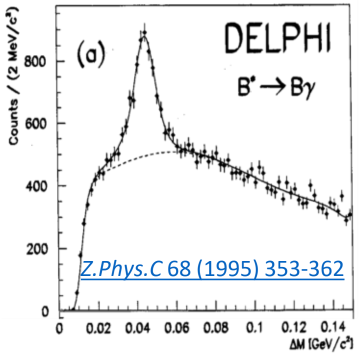
LEP experiments L3, DELPHI, OPAL, ALEPH
using $Z \to b\bar{b}$ process, inclusively reconstruct B meson as **b-jet**
combine **b-jet** with a converted photon (calibrated via π^0)

Measure **averaged between B^{*+}, B^{*0}, and B_s^{*0}** mass difference
$m(B^*)-m(B)$









Assumes $\Delta m = m(B^{*0})-m(B^0)=m(B^{*+})-m(B^+)$
for D mesons such Δm are different by 1.5 MeV!

$m_{B^*}-m_B$

VALUE (MeV)		EVTS	DOCUMENT ID		TECN
45.21 ± 0.21	OUR FIT				
45.42 ± 0.26	OUR AVERAGE includes data from $m_{B^*}-m_B$				
46.2 ±0.3 ±0.8			[1] ACKERSTAFF	1997M	OPAL
45.3 ±0.35 ±0.87		4227	[1] BUSKULIC	1996D	ALEP
45.5 ±0.3 ±0.8			[1] ABREU	1995R	DLPH
46.3 ±1.9		1378	[1] ACCIARRI	1995B	L3

28+ year-old measurements!

Mass differences also measured via P-wave B_s^0 states

PDG still has a single "entry" for B^{*+} and B^{*0}!

$m(B^{*+})-m(B^+)$ measured by LHCb using the difference between $B^*_{s2}(5840)^0 \to B^{*+} K^-$ and $B^*_{s2}(5840)^0 \to B^+ K^-$ peak positions

$m(B^{*+})-m(B^{*0})$ was measured by CMS (BPH-16-003) via the difference between $B_{s1}(5830)^0 \to B^{*0} K^0_S$ and $B_{s1}(5830)^0 \to B^{*+} K^-$ peak positions

$B^\pm$	1/2(0−)
B^0	1/2(0−)
$B^\pm/B^0$ ADMIXTURE	
$B^\pm/B^0/B_s^0/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
B^*	1/2(1−)
$B_1(5721)$	1/2(1+)

B^* MASS	5324.71 ± 0.21 MeV
$m_{B^*}-m_B$	45.21 ± 0.21 MeV
$m_{B^{*+}}-m_{B^+}$	45.37 ± 0.21 MeV
$\lvert(m_{B^{*+}}-m_{B^+})-(m_{B^{*0}}-m_{B^0})\rvert$	< 6 MeV CL=95.0%
$m_{B^{*0}}-m_{B^{*+}}$	0.91 ± 0.26 MeV

Main challenge: very low-energy photons emitted in $B^* \to B\gamma$

B_s^{*0} measurements at B-factories

B_s^{*0} mass difference w.r.t. B_s^0 was previously measured at B-factories via the energy spectrum of reconstructed B_s^0 mesons assumed to be produced in Υ(5S) decays:

- $\Upsilon(5S) \to B_s^0 \overline{B}_s^0$
- $\Upsilon(5S) \to B_s^{*0} \overline{B}_s^0$
- $\Upsilon(5S) \to B_s^0 \overline{B}_s^{*0}$
- $\Upsilon(5S) \to B_s^{*0} \overline{B}_s^{*0}$

However, the results were not in a good agreement with each other (PDG scale factor 2.9)

Central value of the mass difference is larger in comparison to B^+ & B^0

$m_{B_s^*} - m_{B_s}$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
$48.5^{+1.8}_{-1.5}$	OUR FIT Error includes scale factor of 2.9.		
46.1 ± 1.5	OUR AVERAGE		
45.7 ±1.7 ±0.7	[1] AQUINES 2006	CLEO	$e^+ e^- \to \Upsilon(5S)$
47.0 ±2.6	[2] LEE-FRANZINI 1990	CSB2	$e^+ e^- \to \Upsilon(5S)$

B_s^* MASS

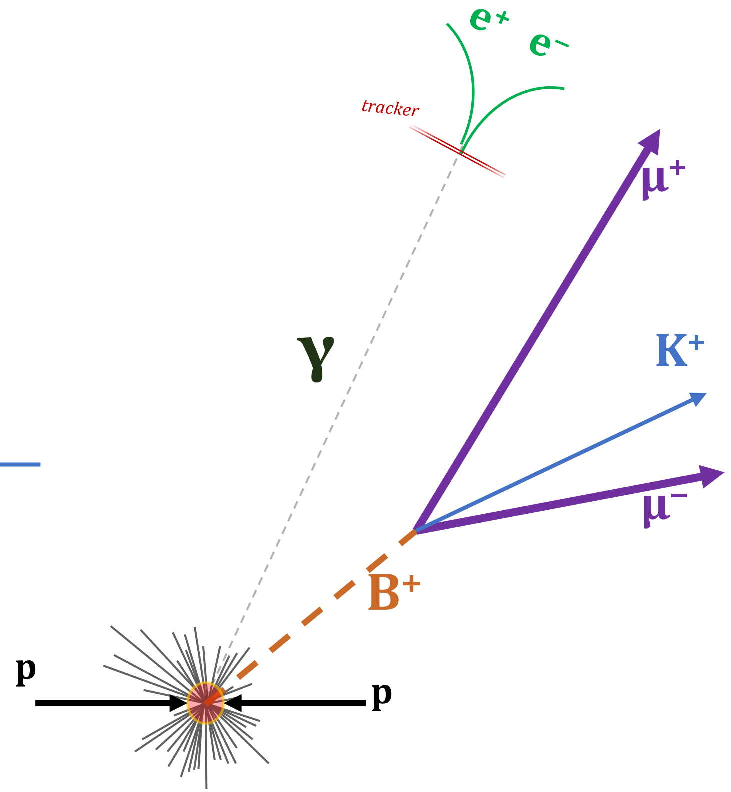
From mass difference below and the B_s^0 mass.

VALUE (MeV)	DOCUMENT ID	TECN
$5415.4^{+1.8}_{-1.5}$	OUR FIT Error includes scale factor of 2.9.	
5415.8 ± 1.5	OUR AVERAGE Error includes scale factor of 2.6.	
5416.4 ±0.4 ±0.5	LOUVOT 2009	BELL
5411.7 ±1.6 ±0.6	[1] AQUINES 2006	CLEO

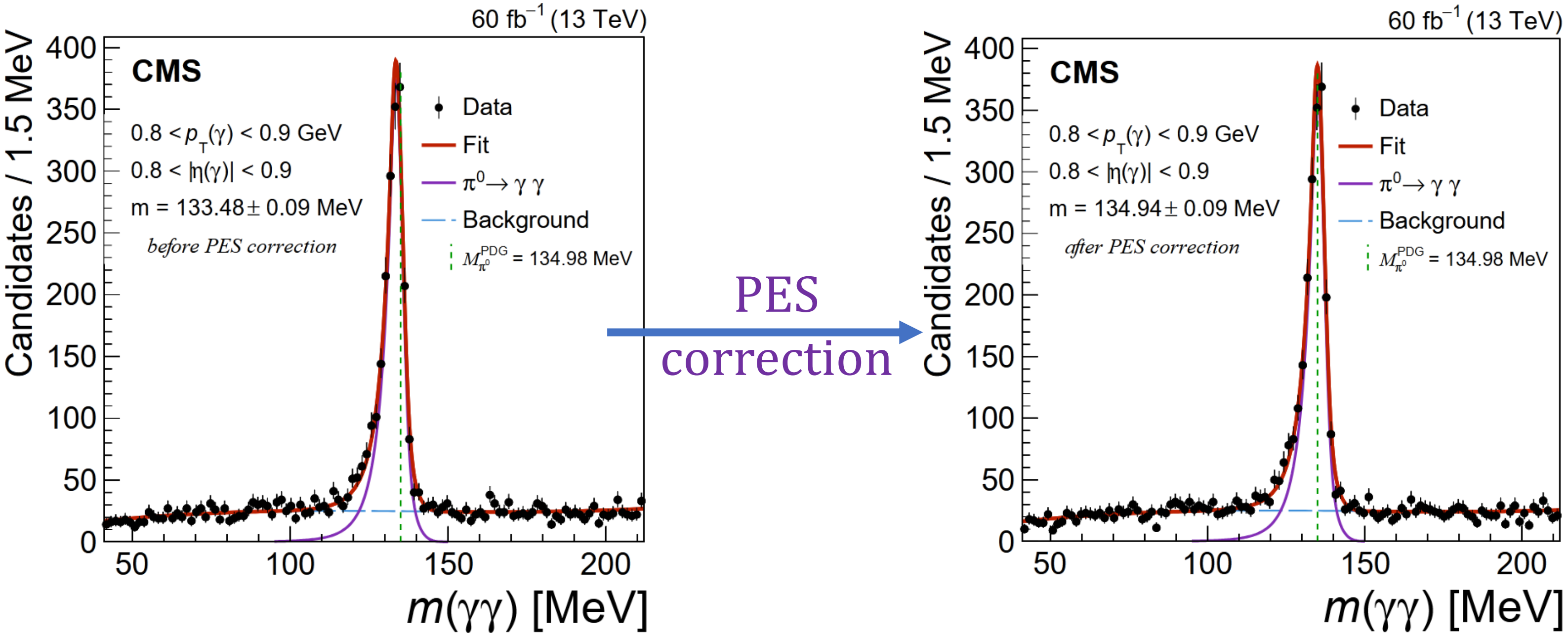
Do we have enough data in CMS to exclusively reconstruct B^{*+}, B^{*0}, and B_s^{*0} mesons via J/ψ modes and provide separate measurements of the respective Δm?

Reconstruction with Run-2 data

- No selection of a single trigger, use all
- Standard reconstruction of charmonium decays
  - $B^+ \to \psi K^+$, $B^0 \to \psi K^*(892)^0$ $[K^+\pi^-]$, $B^0_s \to \psi\, \varphi$ $[K^+K^-]$, J/ψ or $\psi(2S)$ $\to \mu^+\mu^-$
- Add a **photon conversion**, refit e^+e^- tracks with m=0 constraint, Fit Bγ vertex
- Refit Bγ into PV to improve the mass resolution



Photon energy scale calibration with π^0

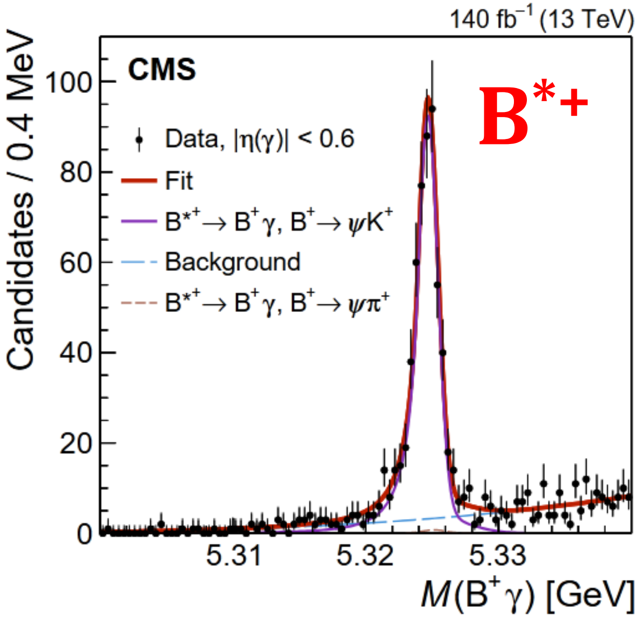


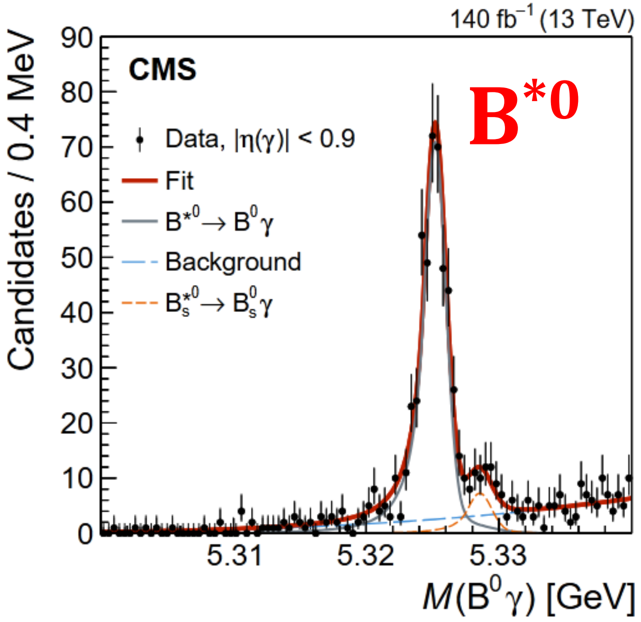
PDG π^0 mass: 134.9768 ± 0.0005 MeV

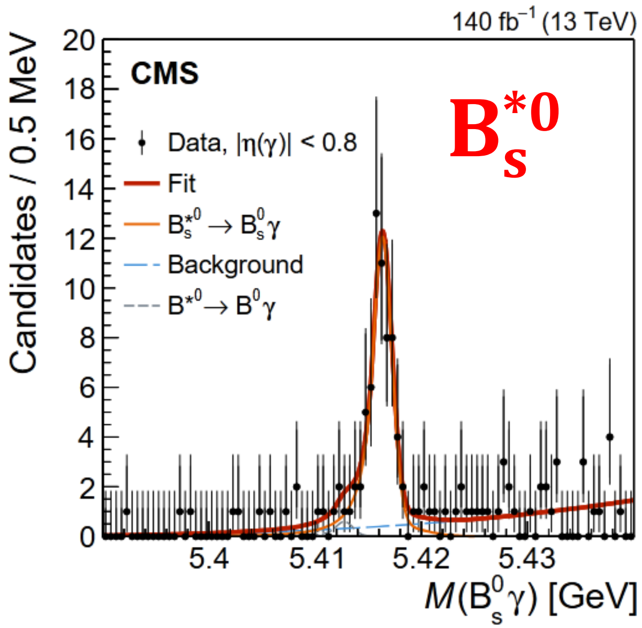
Photon energy from conversions is underestimated out of the box, developed a dedicated correction

$\pi^0 \to \gamma\gamma$ signal from two conversions, in a number of p_T and η ranges,

B* signals in Run 2 data







Simultaneous fit in the 7 categories

Most sensitive 3 are shown here, the other 4 in backup

Signals are described by DCB shapes fixed to MC except a common (for all) resolution scaling factor

Mass differences are shared (within B flavour)

$B^+ \to J/\psi\pi^+$ fixed shape and relative normalization

$B^{*0} \Leftrightarrow B_s^{*0}$ cross-feed: shifted signal shapes, for B^{*0} fixed relative normalization

Bkg: $(m-m^0)^\beta$ with common β

3 states reconstructed fully exclusively for the 1st time

Precision order of magnitude better than PDG

Systematics much smaller than stat. uncertainty

$M(X\gamma) = m(X\gamma) - m(X) + M^{PDG}(X)$

Results

	Parameter	Value
1	$\Delta m(\mathrm{B}^{*+}) \equiv m(\mathrm{B}^{*+}) - m(\mathrm{B}^{+})$	$45.277 \pm 0.039 \pm 0.027$ MeV
2	$\Delta m(\mathrm{B}^{*0}) \equiv m(\mathrm{B}^{*0}) - m(\mathrm{B}^{0})$	$45.471 \pm 0.056 \pm 0.028$ MeV
3	$\Delta m(\mathrm{B}_s^{*0}) \equiv m(\mathrm{B}_s^{*0}) - m(\mathrm{B}_s^{0})$	$49.407 \pm 0.132 \pm 0.041$ MeV
4	$m(\mathrm{B}^{*+})$	$5324.69 \pm 0.04 \pm 0.03 \pm 0.07$ MeV
5	$m(\mathrm{B}^{*0})$	$5325.19 \pm 0.06 \pm 0.03 \pm 0.08$ MeV
6	$m(\mathrm{B}_s^{*0})$	$5416.34 \pm 0.13 \pm 0.04 \pm 0.10$ MeV
7	$m(\mathrm{B}^{*0}) - m(\mathrm{B}^{*+})$	$0.50 \pm 0.07 \pm 0.01 \pm 0.05$ MeV
8	$m(\mathrm{B}_s^{*0}) - m(\mathrm{B}^{*+})$	$91.66 \pm 0.14 \pm 0.03 \pm 0.12$ MeV
9	$m(\mathrm{B}_s^{*0}) - m(\mathrm{B}^{*0})$	$91.15 \pm 0.14 \pm 0.03 \pm 0.12$ MeV
10	$m(\mathrm{B}_s^{*0}) - \frac{1}{2}\left[m(\mathrm{B}^{*0}) + m(\mathrm{B}^{*+})\right]$	$91.40 \pm 0.13 \pm 0.03 \pm 0.12$ MeV
11	$\Delta m(\mathrm{B}^{*0}) - \Delta m(\mathrm{B}^{*+})$	$0.19 \pm 0.07 \pm 0.01$ MeV
12	$\Delta m(\mathrm{B}_s^{*0}) - \Delta m(\mathrm{B}^{*+})$	$4.13 \pm 0.14 \pm 0.03$ MeV
13	$\Delta m(\mathrm{B}_s^{*0}) - \Delta m(\mathrm{B}^{*0})$	$3.94 \pm 0.14 \pm 0.03$ MeV
14	$\Delta m(\mathrm{B}_s^{*0}) - \frac{1}{2}\left[\Delta m(\mathrm{B}^{*0}) + \Delta m(\mathrm{B}^{*+})\right]$	$4.03 \pm 0.13 \pm 0.03$ MeV
15	$\Delta m(\mathrm{B}^{*0}) / \Delta m(\mathrm{B}^{*+})$	$1.0043 \pm 0.0015 \pm 0.0002$
16	$\Delta m(\mathrm{B}_s^{*0}) / \Delta m(\mathrm{B}^{*+})$	$1.0912 \pm 0.0031 \pm 0.0007$
17	$\Delta m(\mathrm{B}_s^{*0}) / \Delta m(\mathrm{B}^{*0})$	$1.0866 \pm 0.0031 \pm 0.0007$
18	$2\,\Delta m(\mathrm{B}_s^{*0}) / \left[\Delta m(\mathrm{B}^{*+}) + \Delta m(\mathrm{B}^{*0})\right]$	$1.0889 \pm 0.0030 \pm 0.0007$

PDG 2024 [MeV]

45.34 ± 0.20

45.34 ± 0.20

48.5 ± 1.4

Main result: hyperfine splittings in B system

Order of magnitude precision improvement!

Adding PDG B masses

"B* mass" 5324.75±0.20 MeV

B_s^{*0} mass 5415.4±1.4 MeV

Mass differences between vector states

CMS-BPH-16-003

$M_{\mathrm{B}^{*0}} - M_{\mathrm{B}^{*+}} = 0.91 \pm 0.24 \pm 0.09 \pm 0.02$ MeV

In agreement, 3 times more precise

first measurements

Differences between hyperfine splittings: ***first measurements***

Ratios between hyperfine splittings: ***first measurements***

Uncertainties: ±stat ±syst ±PDG

Comparison with theory: see backup

charm and beauty mass differences

Charm mesons

$m(D^0) < m(D^+) < m(D_s^+)$

$\Delta m(D^{*+}) < \Delta m(D^{*0}) < \Delta m(D_s^{*+})$

$m_u < m_d < m_s$

$\Delta m_d < \Delta m_u < \Delta m_s$

Beauty mesons

$m(B^+) < m(B^0) < m(B_s^0)$

$\Delta m(B^{*+}) < \Delta m(B^{*0}) < \Delta m(B_s^{*0})$

$m_u < m_d < m_s$

$\Delta m_u < \Delta m_d < \Delta m_s$

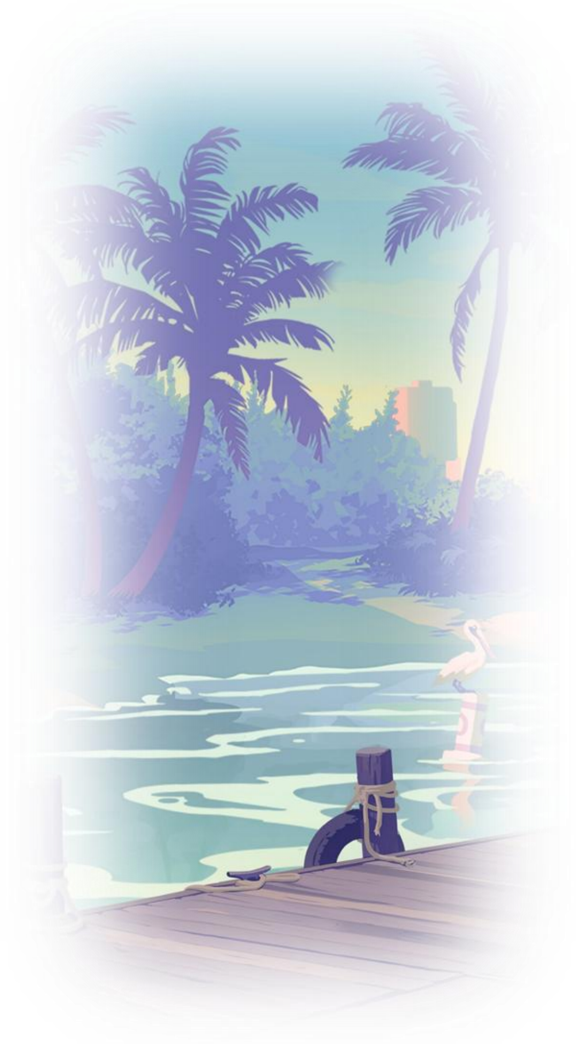
?

Summary

- CMS experiment paints a consistent picture of **fully-charm tetraquarks:**
  - Measurement of masses with Full Run2+3 data (first LHC analyses!)
  - Measurement of spin-parity reveal their $J^{PC} = 2^{++}$
- We **fully exclusively reconstruct**, for the first time, **B^{*+}, B^{*0}, and B_s^{*0} signals**
  - **Order of magnitude precision improvement in the Δm values!**
  - 18 various measurements, including differences and ratios, are provided for completeness
    both experimental and theoretical uncertainties partially cancel in their evaluations

- **Stay tuned for more results including those with much larger Run-3 dataset!**

Thank you!

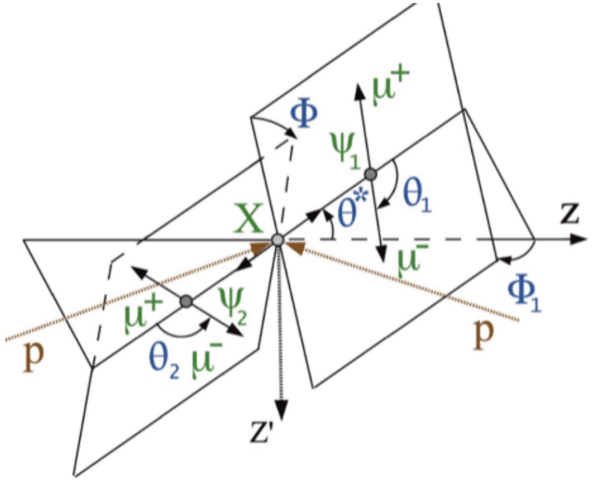


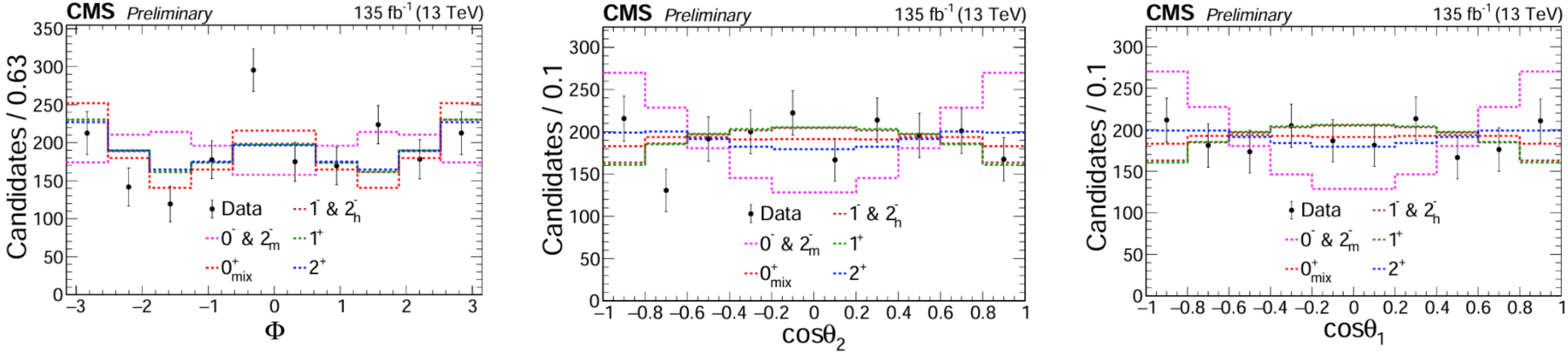
BACKUP

Angular distributions

❖ Decay angles *background-subtracted*

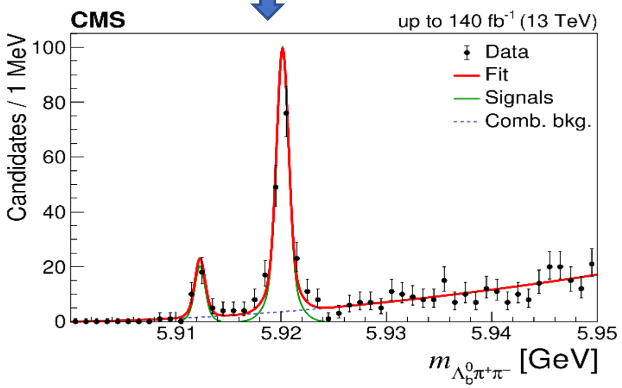
- 1D projections
- Limited information
  - see 0^- not align
  - hard distinguish $1^{\mp}$

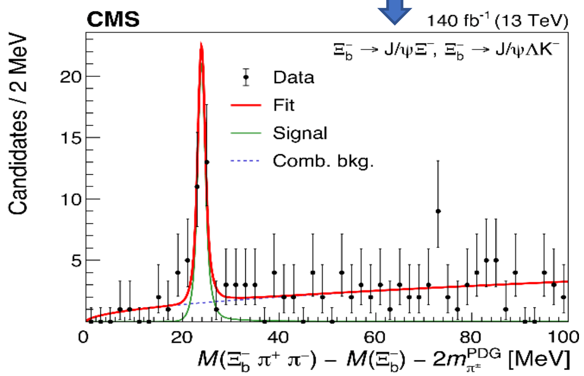




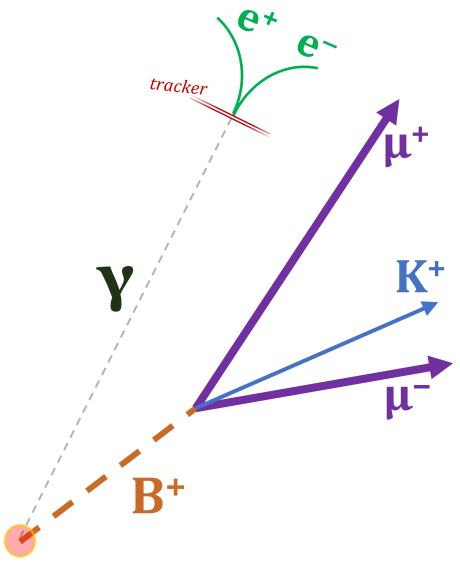
PV refit to improve the resolution

We are using the PV refit, developed and pioneered in BPH-19-003 ($\Lambda_b^0\pi^+\pi^-$), and used in BPH-20-004 ($\Xi_b^-\pi^+\pi^-$)

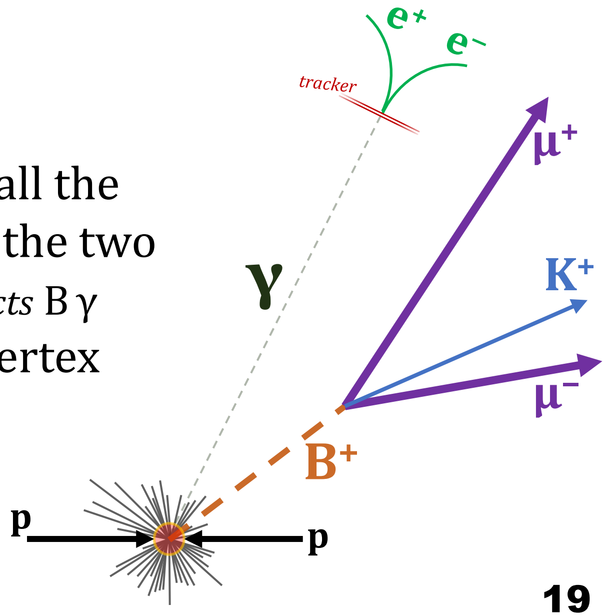




B γ vertex fit:
Fit 2 *KinematicObjects* into same vertex



PV refit: fit all the PV tracks + the two *KinematicObjects* B γ into same vertex



PV refit improves mass resolution

Peaking contributions

$B^0 \to J/\psi K^+\pi^-$ During reconstruction, pion may be swapped with kaon

(well-known feature from many analyses with B^0, the same P5' BPH-21-002, etc)

We obtain the fraction of swapped component w.r.t. "correctly-tagged" to be about 9%

However, the observed **shape in *M(Bγ)* is consistent with the correct component**, with no shift or broadening

→ We ignore this, since swapped candidates will give the same signal shape

Since we have no hadron ID, $B^0 \to J/\psi K^+\pi^-$ can look like $B^0_s \to J/\psi K^+K^-$ and vice versa

To suppress these, we have anti-φ cut in B^0 selection and a narrow $\varphi \to K^+K^-$ mass cut in B^0_s selection

Still, some fraction of events passes through

The shapes was studied in MC (removing φ and anti-φ cuts to increase stats) and we found that

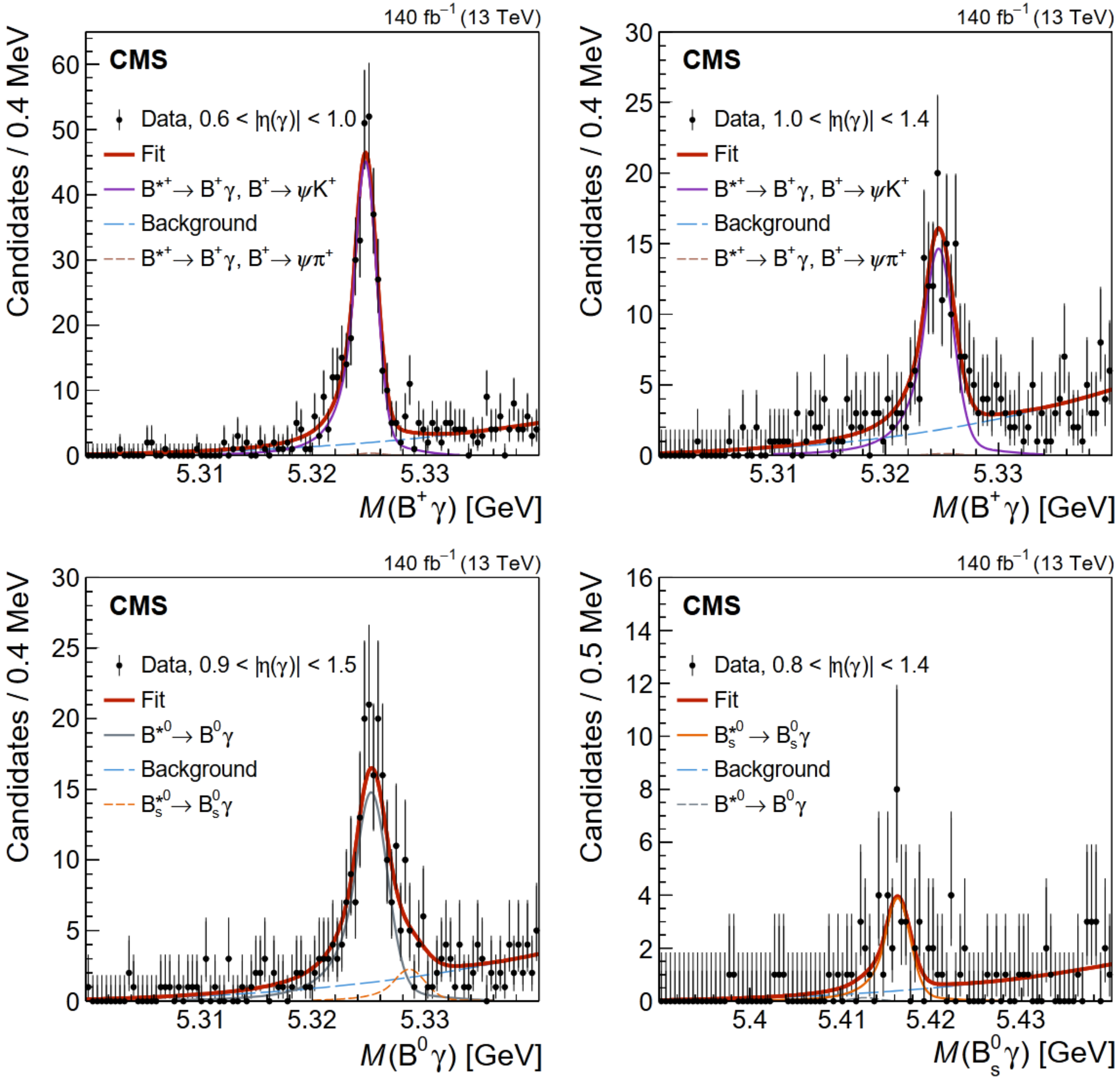
- $B^{*0} \to B^0\gamma \to J/\psi K^+\pi^-\gamma$ reflection in $M(B^0_s\,\gamma)$ has the **same shape as $B^{*0} \to B^0\gamma$ signal, just shifted** by 87.54 MeV
- $B^{*0}_s \to B^0_s\gamma \to J/\psi K^+K^-\gamma$ reflection in $M(B^0\,\gamma)$ has the **same shape as $B^{*0}_s \to B^0_s\gamma$ signal, just shifted** by −87.78 MeV

For the normalization, B^0_s is not reliable due to significant contribution of $B^0_s \to J/\psi K^+K^-$ decays not through φ resonance

For the B^{*0} reflection in $M(B^0_s\,\gamma)$, it is estimated to be ~0.67% of the B^{*0} signal

Projections in additional fit categories

CMS-BPH-24-011, arXiv:2508.05820



The $B\gamma$ mass resolution is found to depend strongly on $|\eta(\gamma)|$, ranging from about 0.7 MeV at $|\eta(\gamma)|$ close to zero to about 2 MeV at $|\eta(\gamma)|$ around 1.5. To improve the accuracy of the B^* meson mass measurements, a simultaneous fit of the $B\gamma$ mass distributions in several categories, defined by ranges of $|\eta(\gamma)|$, is performed. Pseudo-experiments were used to obtain a set of optimal $|\eta(\gamma)|$ ranges for each meson flavor. The resulting simultaneous fit structure includes: three $|\eta(\gamma)|$ ranges with boundaries at 0, 0.6, 1.0, and 1.4 for the B^{*+} signal; two $|\eta(\gamma)|$ ranges with boundaries at 0, 0.9, and 1.5 for the B^{*0} signal, and two $|\eta(\gamma)|$ ranges with boundaries at 0, 0.8, and 1.4 for the B_s^{*0} signal.

CMS-BPH-24-011, arXiv:2508.05820

Measured observables: ratios and differences

1. $\Delta m(B^{*+}) \equiv m(B^{*+}) - m(B^{+})$, directly
2. $\Delta m(B^{*0}) \equiv m(B^{*0}) - m(B^{0})$, directly
3. $\Delta m(B_s^{*0}) \equiv m(B_s^{*0}) - m(B_s^{0})$, directly

Discussed in previous slides

4. $m(B^{*+})$, using 1. and PDG B^{+} mass
5. $m(B^{*0})$, using 2. and PDG B^{0} mass
6. $m(B_s^{*0})$, using 3. and PDG B_s^{0} mass
7. $\Delta m(B^{*0}) - \Delta m(B^{*+})$, directly
8. $\Delta m(B_s^{*0}) - \Delta m(B^{*+})$, directly
9. $\Delta m(B_s^{*0}) - \Delta m(B^{*0})$, directly
10. $\Delta m(B_s^{*0}) - \frac{\Delta m(B^{*0}) + \Delta m(B^{*+})}{2}$, directly
11. $m(B^{*0}) - m(B^{*+})$, using 7. and PDG mass difference $m(B^{0}) - m(B^{+})$
12. $m(B_s^{*0}) - m(B^{*+})$, using 8. and PDG mass difference $m(B_s^{0}) - m(B^{+})$
13. $m(B_s^{*0}) - m(B^{*0})$, using 9. and PDG mass difference $m(B_s^{0}) - m(B^{0})$
14. $m(B_s^{*0}) - \frac{m(B^{*0}) + m(B^{*+})}{2}$, using 10. and PDG mass difference $m(B_s^{0}) - \frac{m(B^{0}) + m(B^{+})}{2}$
15. $\Delta m(B^{*0}) / \Delta m(B^{*+})$, directly
16. $\Delta m(B_s^{*0}) / \Delta m(B^{*+})$, directly
17. $\Delta m(B_s^{*0}) / \Delta m(B^{*0})$, directly
18. $\frac{2 \cdot \Delta m(B_s^{*0})}{\Delta m(B^{*+}) + \Delta m(B^{*0})}$, directly

7 out of 18: 4,5,6,11,12,13,14 – are just shifted by a PDG value w.r.t. another observable

(Statistical and) **systematic uncertainties of 1,2,3 are correlated** and can cancel in difference/ratio →
extract all 11 values in each test/variation and evaluate systematics "separately" for the 11 observables

Theory/model uncertainties are also expected to be reduced in the difference/ratio predictions

CMS-BPH-24-011, arXiv:2508.05820

Systematic uncertainties

Source	$m(B^{*+}) - m(B^+)$	$m(B^{*0}) - m(B^0)$	$m(B_s^{*0}) - m(B_s^0)$
Signal model	4	8	21
Signal shape parameters	15	15	18
Yield ratios of $\lvert\eta(\gamma)\rvert$ ranges	1	2	10
Background shape	2	<1	7
Cross-feed $B_s^{*0} \leftrightarrow B^{*0}$	<1	1	10
Photon energy scale, statistical	12	14	16
Photon energy scale, systematic	18	18	19
Total	27	28	41

in keV

In all cases systematic uncertainties are much smaller than statistical ones

Source	$\Delta m(B^{*0}) - \Delta m(B^{*+})$	$\Delta m(B_s^{*0}) - \Delta m(B^{*+})$	$\Delta m(B_s^{*0}) - \Delta m(B^{*0})$	$\Delta m(B_s^{*0}) - \frac{\Delta m(B^{*0})+\Delta m(B^{*+})}{2}$
Measured value	194	4130	3936	4033
Statistical uncertainty	68	138	139	134
Signal model	4	23	23	23
Signal shape parameters	1	3	3	3
Yield ratios of $\lvert\eta(\gamma)\rvert$ ranges	3	11	7	9
Background shape	3	9	6	8
Cross-feed $B_s^{*0} \leftrightarrow B^{*0}$	1	10	12	11
Photon energy scale, statistical	4	11	11	11
Photon energy scale, systematic	<1	2	2	2
Total systematic uncertainty	7	31	30	30

in keV

Source	$\Delta m(B^{*0}) / \Delta m(B^{*+})$	$\Delta m(B_s^{*0}) / \Delta m(B^{*+})$	$\Delta m(B_s^{*0}) / \Delta m(B^{*0})$	$\frac{2\,\Delta m(B_s^{*0})}{\Delta m(B^{*+})+\Delta m(B^{*0})}$
Measured value	1.00428	1.09122	1.08656	1.08888
Statistical uncertainty	0.00151	0.00306	0.00309	0.00297
Signal model	0.00009	0.00050	0.00052	0.00052
Signal shape parameters	0.00002	0.00003	0.00004	0.00003
Yield ratios of $\lvert\eta(\gamma)\rvert$ ranges	0.00008	0.00023	0.00016	0.00020
Background shape	0.00005	0.00020	0.00014	0.00017
Cross-feed $B_s^{*0} \leftrightarrow B^{*0}$	0.00003	0.00023	0.00025	0.00015
Photon energy scale	0.00009	0.00025	0.00024	0.00024
Total systematic uncertainty	0.00016	0.00067	0.00066	0.00065

comparison with theory

CMS-BPH-24-011, arXiv:2508.05820

*Most predictions we found have no uncertainties; have no fractions of MeV (while experimental precision is ~0.1 MeV); don't discuss presented here ratios or differences; and they **all** don't distinguish B^+ and B^0* ☹

Only few (lattice) theory papers provide uncertainties and comment on mass differences between vector and ground states, i.e. hyperfine splitting in B system.

Parameter	Measurement, MeV	Theory, MeV
$\Delta m(B^{*+})$ $m(B^{*+}) - m(B^+)$	$45.277 \pm 0.039 \pm 0.027$	50 ± 3 [10] 39 ± 2 [24] 41.7 ± 5.3 [25]
$\Delta m(B^{*0})$ $m(B^{*0}) - m(B^0)$	$45.471 \pm 0.056 \pm 0.028$	
$\Delta m(B_s^{*0})$ $m(B_s^{*0}) - m(B_s^0)$	$49.407 \pm 0.132 \pm 0.041$	52 ± 3 [10] 38 ± 1 [24] 37.8 ± 6.7 MeV [25]

[10] Phys.Rev.D 86 (2012) 094510

[24] JHEP 01 (2025) 123

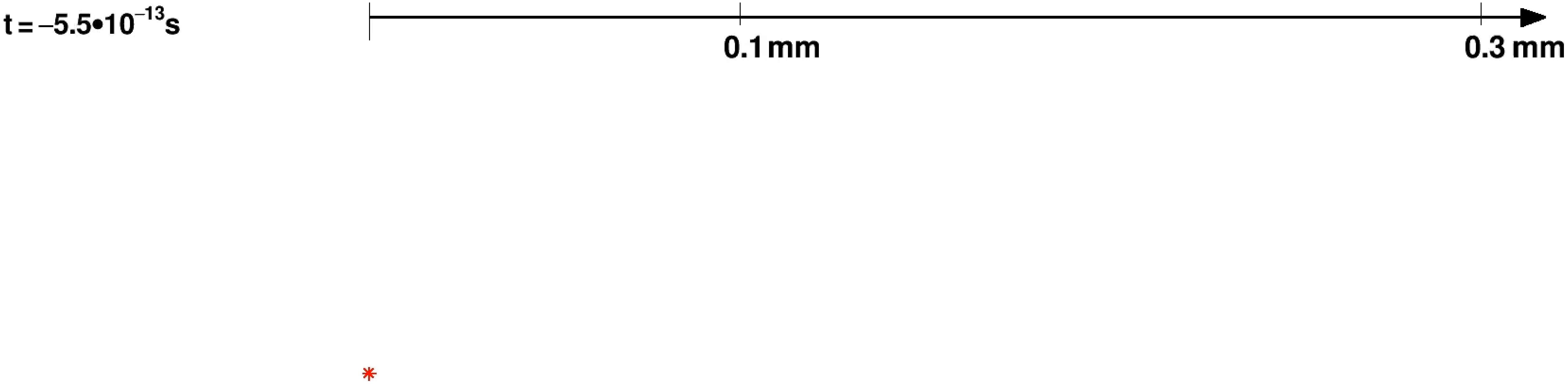
[25] Phys.Rev.D 92 (2015) 5, 054509

One paper [10] comments that the ratio of hyperfine splittings $\Delta m(B_s)/\Delta m(B)$ can be predicted with lower uncertainty:

Parameter	Measurement	theory
$\Delta m(B^{*0})/\Delta m(B^{*+})$ $\frac{m(B^{*0})-m(B^0)}{m(B^{*+})-m(B^+)}$	$1.0043 \pm 0.0015 \pm 0.0002$ —	———
$\Delta m(B_s^{*0})/\Delta m(B^{*+})$ $\frac{m(B_s^{*0})-m(B_s^0)}{m(B^{*+})-m(B^+)}$	$1.0912 \pm 0.0031 \pm 0.0007$	1.007 ± 0.034 [10]
$\Delta m(B_s^{*0})/\Delta m(B^{*0})$ $\frac{m(B_s^{*0})-m(B_s^0)}{m(B^{*0})-m(B^0)}$	$1.0866 \pm 0.0031 \pm 0.0007$	
$\frac{2\cdot\Delta m(B_s^{*0})}{\Delta m(B^{*+})+\Delta m(B^{*0})}$	$1.0889 \pm 0.0030 \pm 0.0007$	

[10] Phys.Rev.D 86 (2012) 094510

R. J. Dowdall, C. T. H. Davies, T. C. Hammant, and R. R. Horgan, "Precise heavy-light meson masses and hyperfine splittings from lattice QCD including charm quarks in the sea"


t = −5.5•10^−13 s
0.1 mm
0.3 mm