All charm tetraquarks and recent heavy flavor results at CMS

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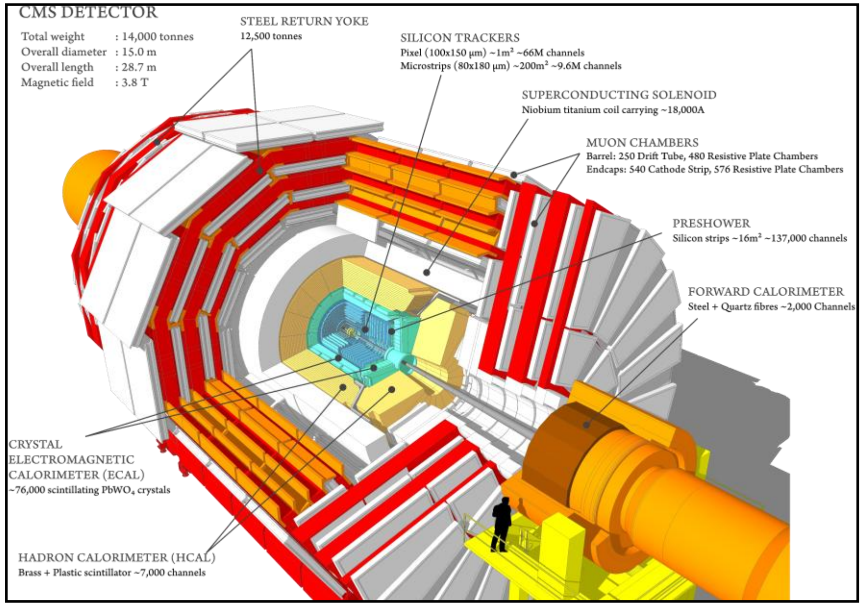
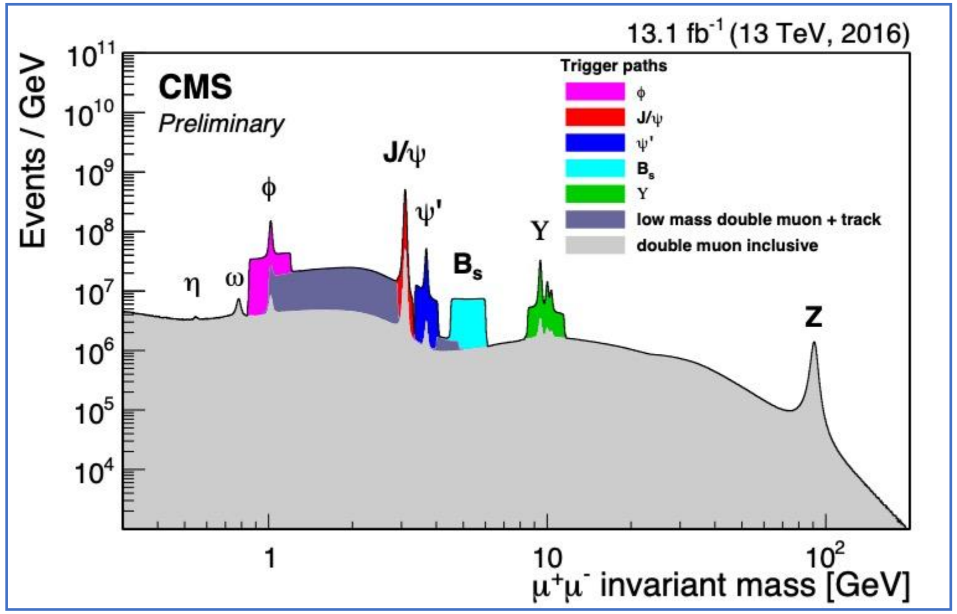
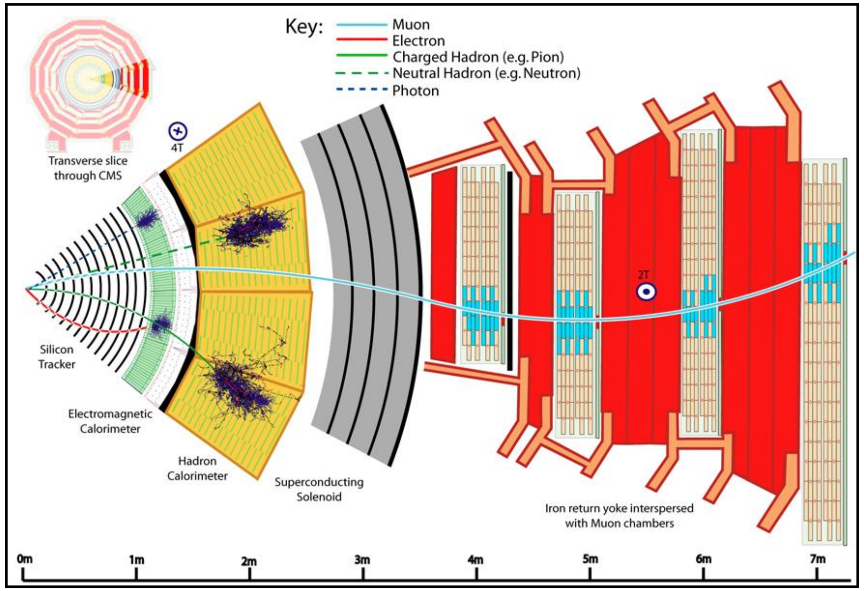
Outline

- Introduction
- All charm tetraquarks
- Other heavy flavor results
- Summary

CMS detector

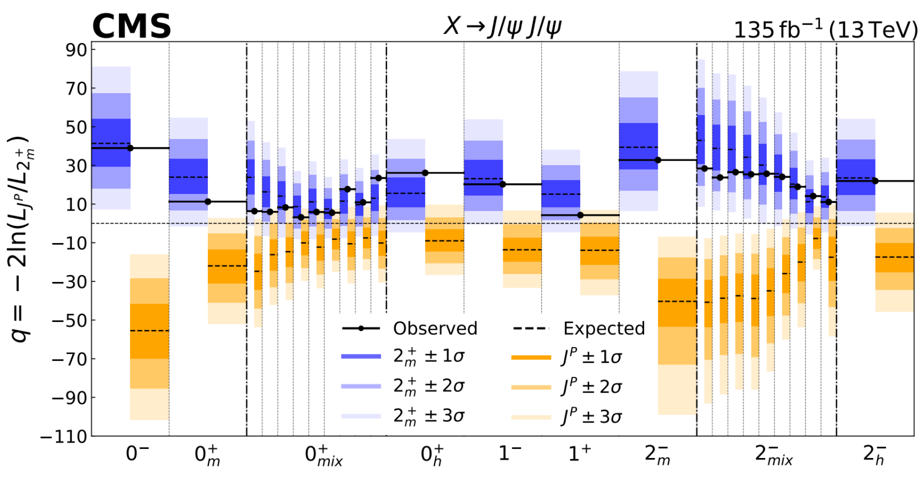




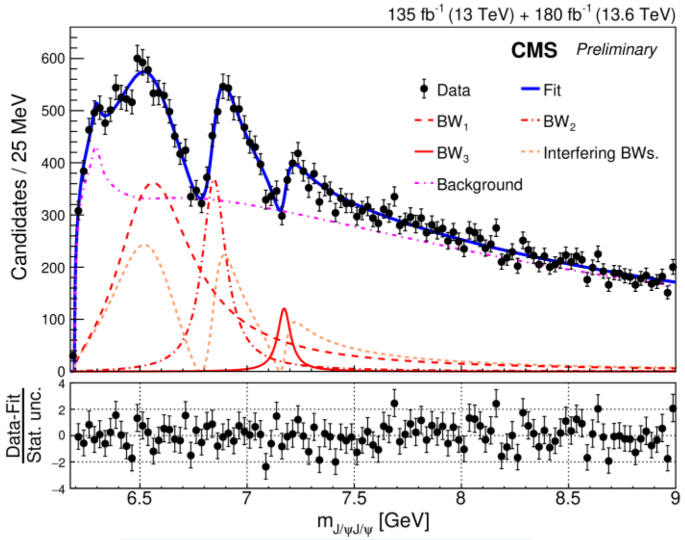


- Excellent detector for physics program
- Good muon system
  - High-purity muon ID, $\frac{\Delta m}{m} \sim 0.6\%$ for J/ψ
- Silicon tracking detector
  - $\mathrm{B} = 3.8\ \mathrm{T}, \frac{\Delta p_T}{p_T} \sim 1\%$ & good vertex resolution
- Triggers for different physics programs

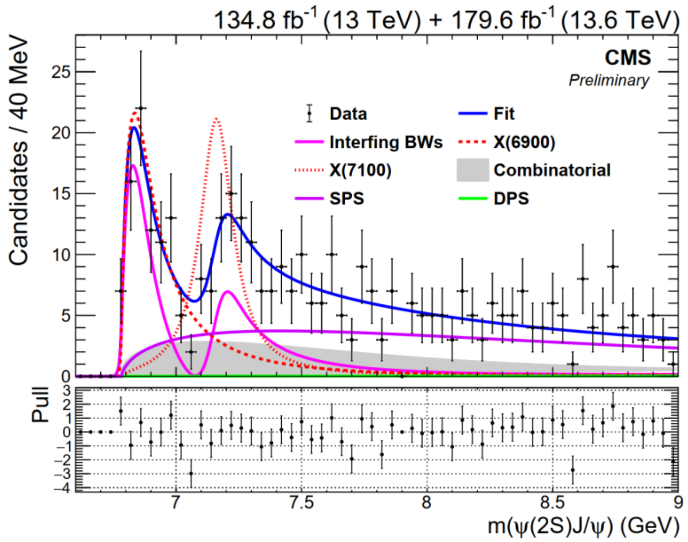
All charm tetraquark candidates at CMS



arxiv:2506.07944
Accepted by Nature



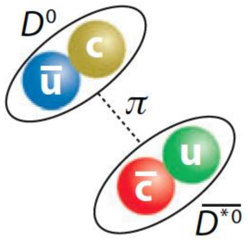
CMS-PAS-BPH-24-003



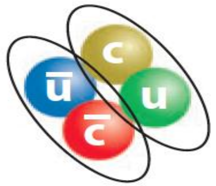
CMS-PAS-BPH-22-004

All charm tetraquark candidates at CMS

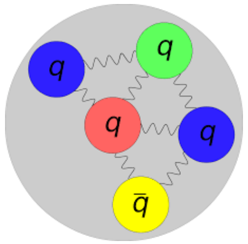
- Exotic hadrons allowed in QCD



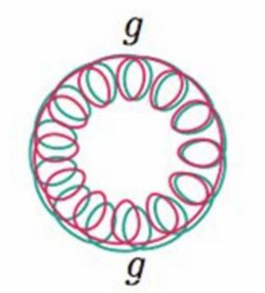
D^0–$\overline{D}^{*0}$ "molecule"



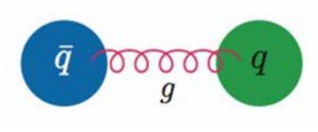
Diquark–diantiquark



pentaquark

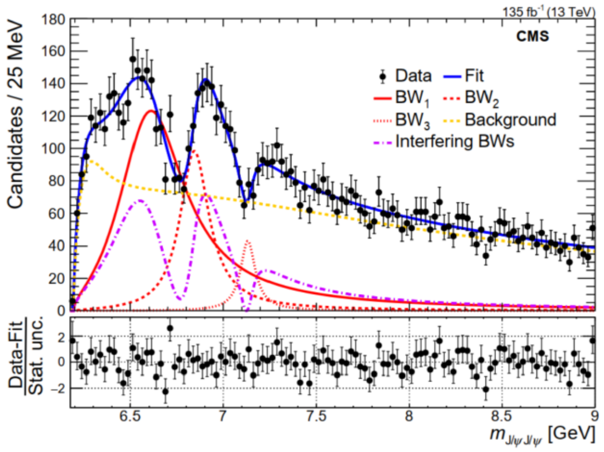


glueball

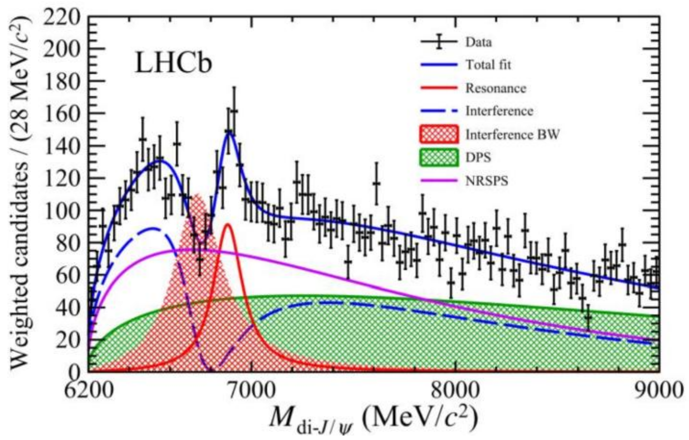


hybrid

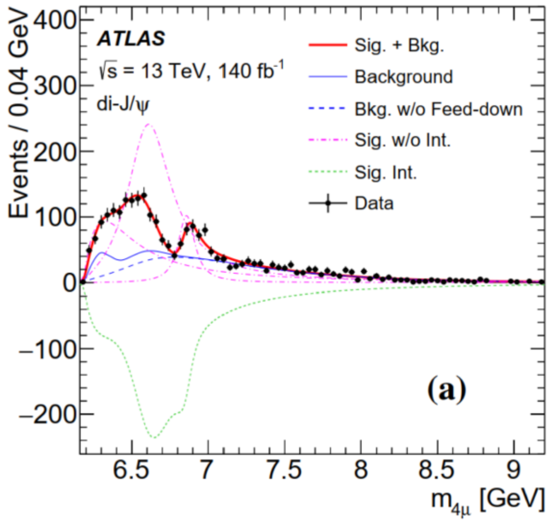
- All charm tetraquark candidates at LHC in past few years



[PhysRevLett132.111901(2024)]



[Sci.Bull.65(2020)23,1983-1993]

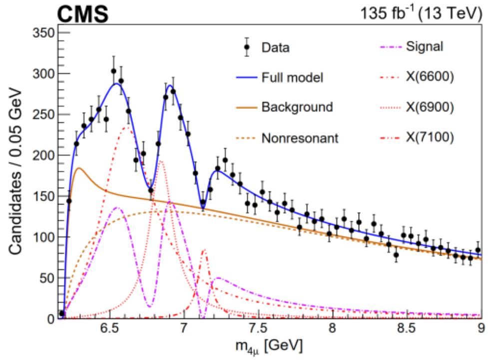


[PhysRevLett131.151902(2023)]

- Properties & Nature: further studies needed!

Spin-parity of the tetraquark candidates

arxiv:2506.07944



- Tetraquark candidates observed in $J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ channel
  - Mass spectrum implying interference
- Infer the spin-parity from their decays

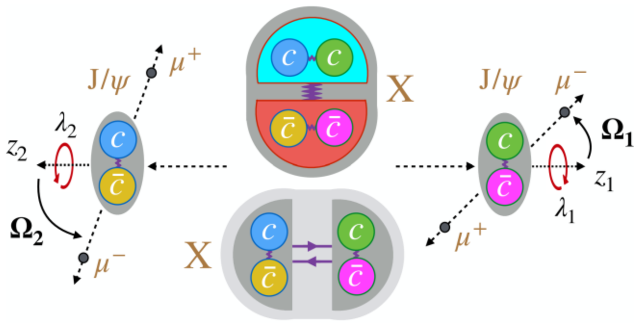
➢Theory

- $J_X = 0$:

$$A(X_{J=0} \to V_1 V_2) = a_1(q^2) m_V^2 \epsilon_1^* \epsilon_2^* + a_2(q^2) f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3(q^2) f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

$\mathbf{0_m^+}$ $\mathbf{0_h^+}$ $\mathbf{0^-}$

- …



➢Experiment

- Same properties of 3 resonances:

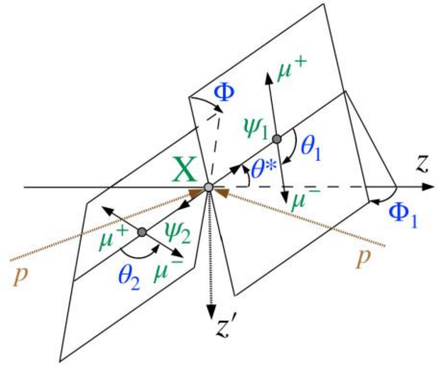
$$\mathcal{P}(m_{4\mu}, \Phi, \theta_1, \theta_2) = \mathcal{P}(m_{4\mu}) \cdot T\left(\vec{\Omega}\middle| m_{4\mu}\right) \propto |A|^2$$

- Pairwise tests of J_X^P hypotheses i and j:

$$\mathcal{D}_{ij}\left(\vec{\Omega}\middle| m_{4\mu}\right) = \frac{\mathcal{P}_i(\vec{\Omega}|m_{4\mu})}{\mathcal{P}_i(\vec{\Omega}|m_{4\mu}) + \mathcal{P}_j(\vec{\Omega}|m_{4\mu})}$$

- Final 2D model:

$$\boldsymbol{\mathcal{P}_{ijk}(m_{4\mu}, \mathcal{D}_{ij}) = \mathcal{P}_k(m_{4\mu}) \cdot T_{ijk}(\mathcal{D}_{ij}|m_{4\mu})}$$

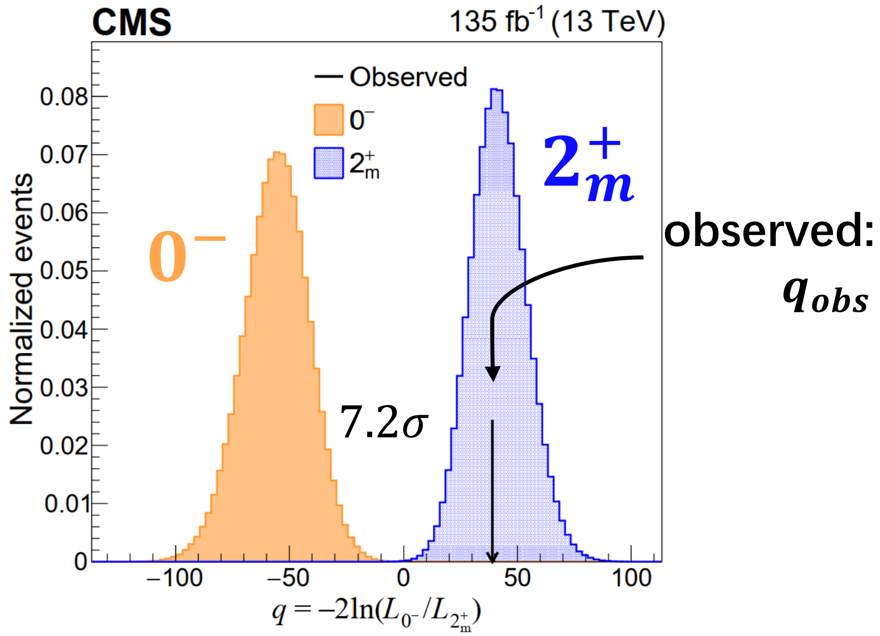


Spin-parity of the tetraquark candidates

arxiv:2506.07944

- Data analysis
  - Dataset, event selection, $m_{4\mu}$ shape from PhysRevLett132.111901(2024) (observation paper)
  - Background: data sideband & MC simulation with Pythia
  - Decay angles Φ, θ_1, θ_2 to identify $D_{ij}(\Phi, \theta_1, \theta_2; m_{4\mu})$

- Hypothesis test
  - Test statistics: $q = -2\ln(\mathcal{L}_{J_i^P}/\mathcal{L}_{J_j^P})$
  - Confidence level: $CL_s = \dfrac{P(q \geq q_{\text{obs}} \mid J_j^P + \text{bkg})}{P(q \geq q_{\text{obs}} \mid J_i^P + \text{bkg})}$
  - Example: $j = 0^- \text{ vs.} \, i = 2_m^+$



Spin-parity of the tetraquark candidates

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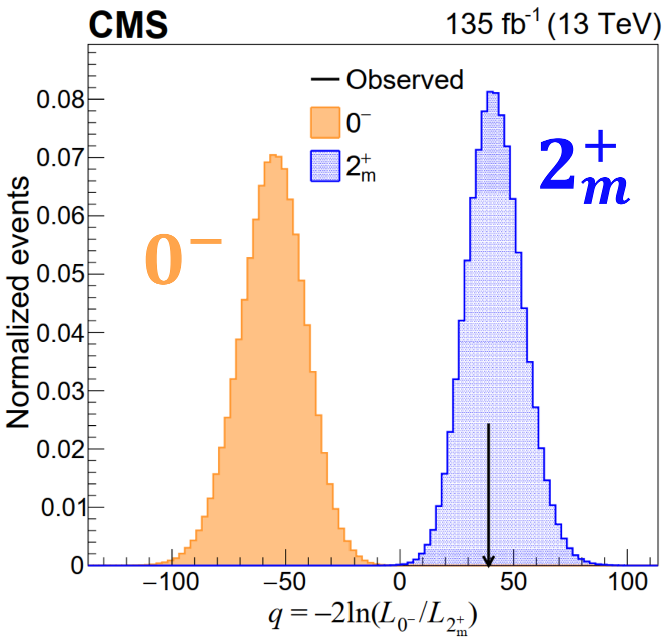
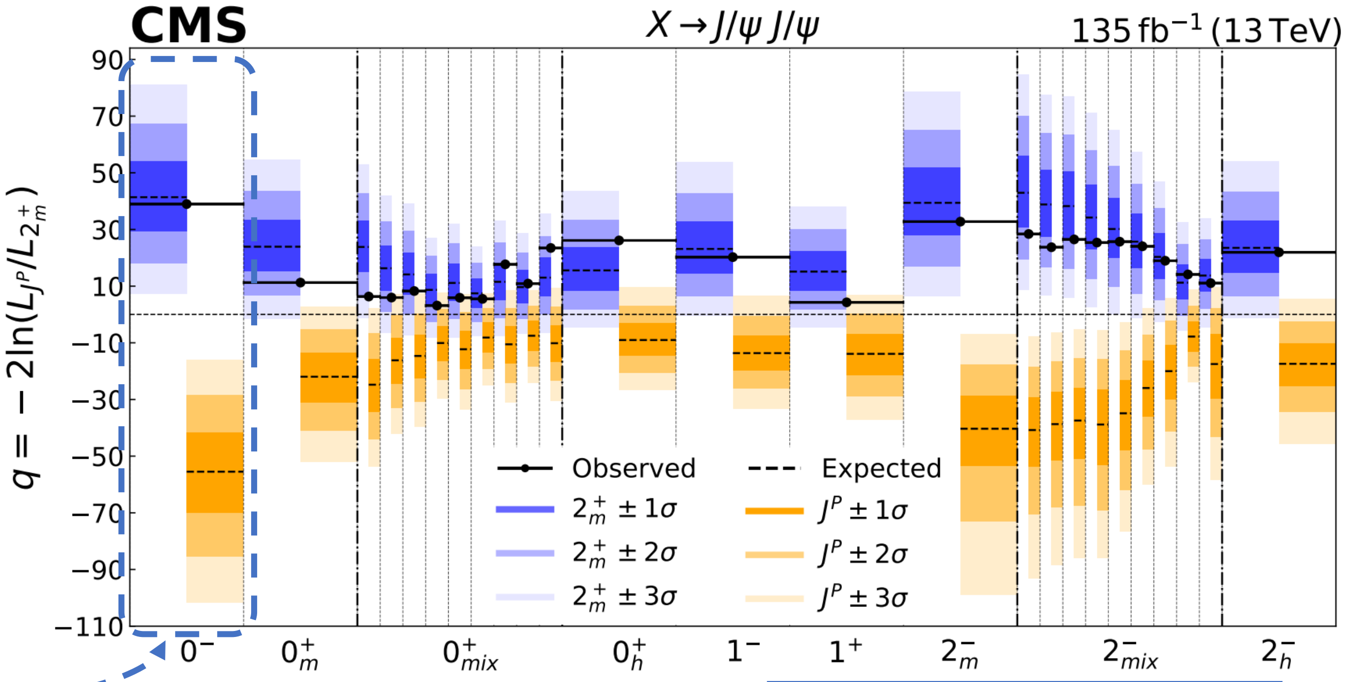
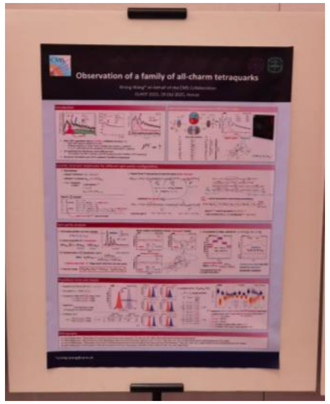




- **Data consistent with** 2^{++}, inconsistent with **others**
- JPC of the three tetraquark candidates X(6600), X(6900), X(7300)
  - $PC = ++$
  - $J \neq 1$ at > 99% CL; $J \neq 0$ at 95% CL
  - $J > 2$ possible, but highly unlikely, require $L \geq 2$
  - **$J = 2$ consistent**, naively expected $J = 0$

More details see Xining Wang's poster

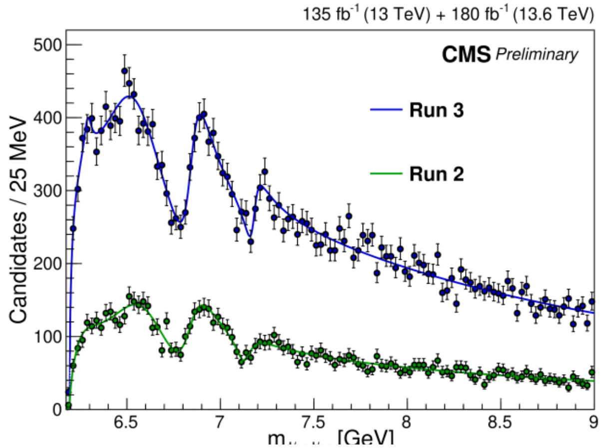


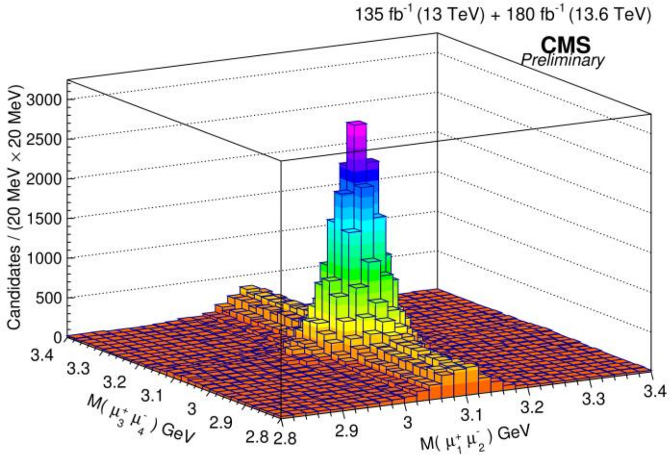
Accepted by Nature

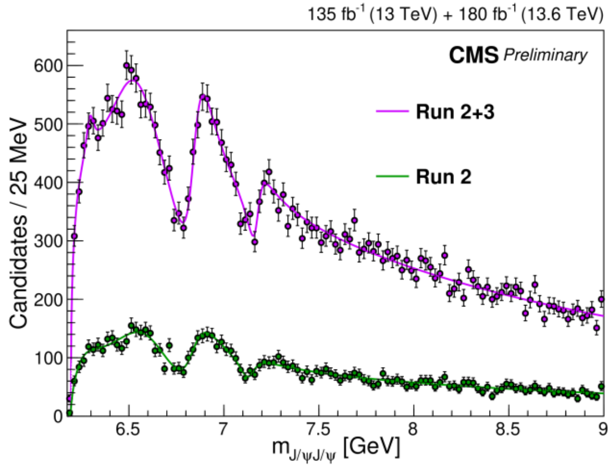
All-charm tetraquarks candidates at CMS

CMS-PAS-BPH-24-003

- Tetraquark candidates observed in $J/\psi J/\psi$ mass at CMS
  - J/ψ reconstructed via its $\mu^+\mu^-$ decays
- Data ($314\ fb^{-1}$)
  - 2016-2018 (run 2): 13 TeV, 134.8 fb^{-1}
  - 2022-2024 (run 3): 13.6 TeV, **179.6** fb^{-1}
- Trigger
  - Run 2: 3 muons, pT > 5, 3, 3 GeV
  - Run 3: 2muons, pT > 4, 3 GeV





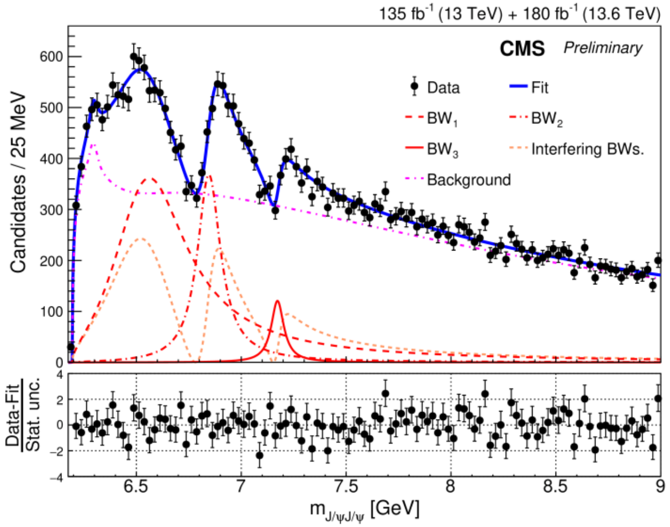


All-charm tetraquark candidates at CMS

CMS-PAS-BPH-24-003

- X(6600), X(6900), X(7100) in $J/\psi J/\psi$ at CMS
  - Data fit
    - Signal: Coherent sum of X(6600), X(6900), X(7100)
    - BKG: NRSPS, DPS, combinatorial contribution, feeddown
  - Significance
    - $> 5\sigma$ **for each** of X(6600), X(6900), and **X(7100) [first observation]**
    - $> 5\sigma$ **for interference (two dips)**

      $> 5\sigma$ **for each single dip**: 6750 MeV dip, and 7150 MeV dip



		X(6600)	X(6900)	X(7100)
		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)	$446\ ^{+66}_{-54} \pm 87$	$135\ ^{+16}_{-14} \pm 14$	$73\ ^{+18}_{-15} \pm 10$
Interference	m (MeV)	$6638\ ^{+43+16}_{-38-31}$	$6847\ ^{+44+48}_{-28-20}$	$7134\ ^{+48+41}_{-25-15}$
(Run 2 [12])	Γ (MeV)	$440\ ^{+230+110}_{-200-240}$	$191\ ^{+66+25}_{-49-17}$	$97\ ^{+40+29}_{-29-26}$

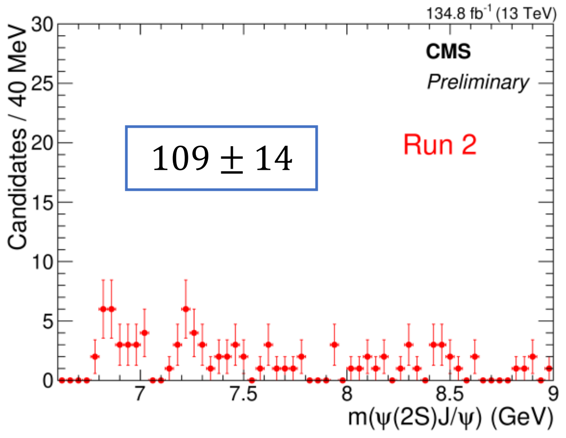
More details see
Yilin Zhou's talk yesterday

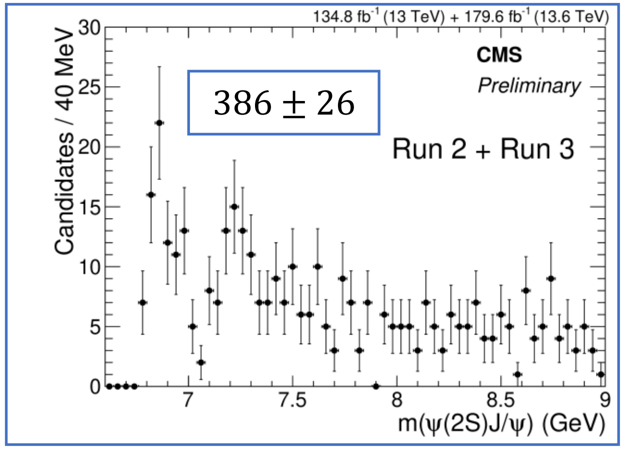
Feeddown: e.g., $X \to J/\psi\psi(2S) \to J/\psi J/\psi\pi\pi$ is reconstructed as $J/\psi J/\psi$ instead of $J/\psi J/\psi\pi\pi$

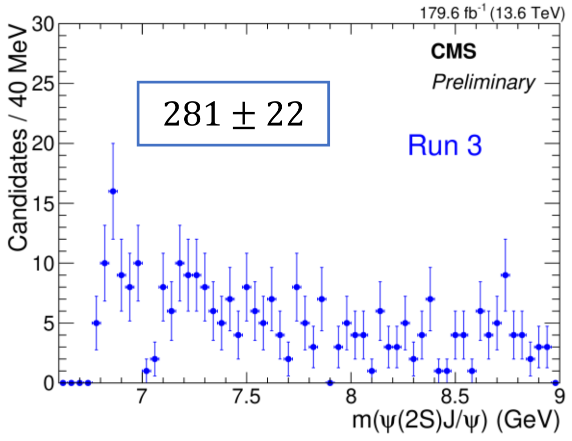
X(6900) and X(7100) in $J/\psi\psi(2S)$ at CMS

CMS-PAS-BPH-22-004

- J/ψ and $\psi(2S)$ reconstructed via $\mu^{+}\mu^{-}$
- Data (314 fb^{-1}):
  - 2016-2018 (run 2): 13 TeV, 134.8 fb^{-1}
  - 2022-2024 (run 3): 13.6 TeV, **179.6** fb^{-1}
- Trigger:
  - Run 2: 3 muons, pT > 5, 3, 3 GeV
  - Run 3: 2muons, pT > 4, 3 GeV



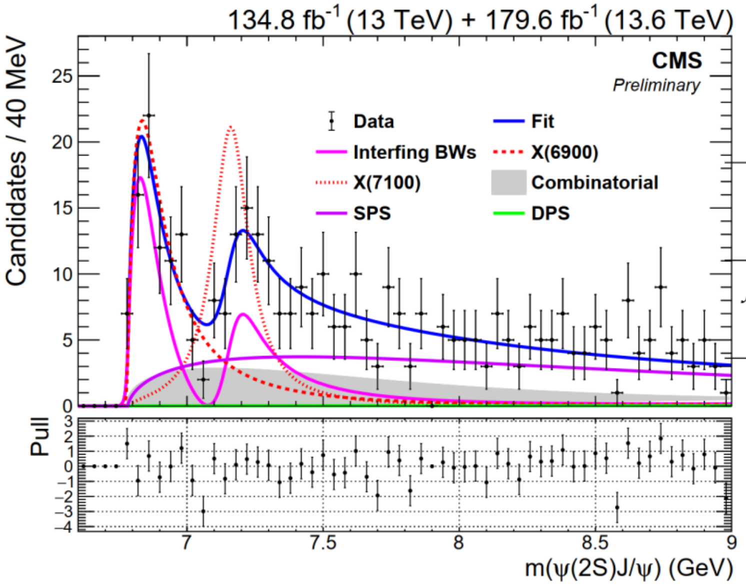




X(6900) and X(7100) in $J/\psi\psi(2S)$ at CMS

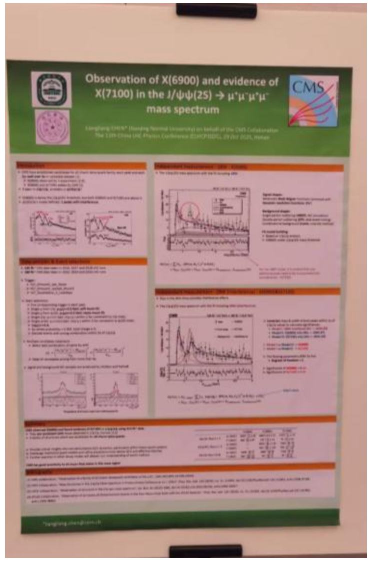
CMS-PAS-BPH-22-004

- X(6900) and X(7100) in $J/\psi\psi(2S)$
  - Data fit
    - Signal: X(6900), X(7100) and their interference
    - Background: NRSPS, DPS, combinatorial contribution
  - **$> 5\sigma$ for X(6900) [first observation in this channel], 4.0σ for X(7100)**
  - Impact from X(6600) [below threshold] considered in systematic uncertainty

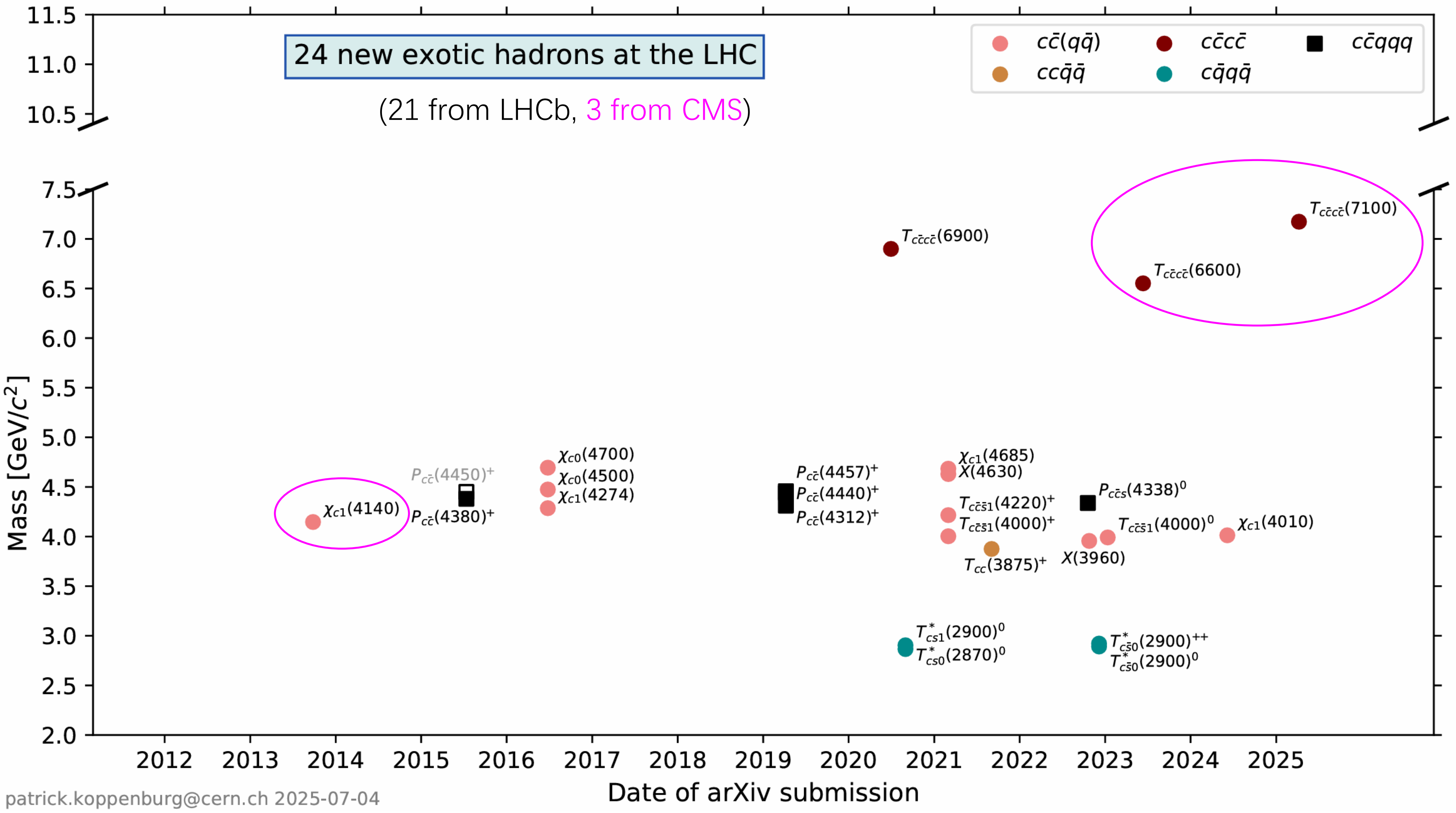


Fit	Sample	Interf.		$X(6600)$	$X(6900)$	$X(7100)$
f_{i23}	$J/\psi\psi(2S)$	BW_2, BW_3	m :	—	$6876^{+46+110}_{-29-110}$	7169^{+26+74}_{-52-70}
			Γ :	—	$253^{+290+120}_{-100-120}$	$154^{+110+140}_{-82-160}$
f_{JJ} [1]	$J/\psi J/\psi$	BW_1, BW_2, BW_3	m :	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
			Γ :	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

More details see Liangliang Chen's poster

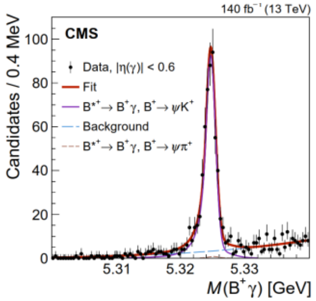


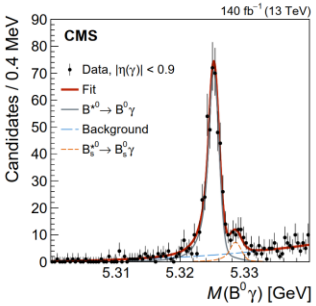
Exotic hadrons at LHC

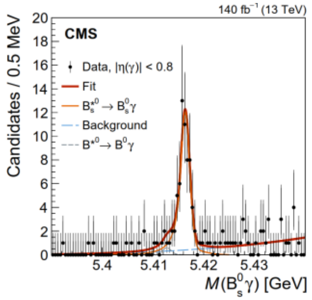


https://www.koppenburg.ch/particles.html

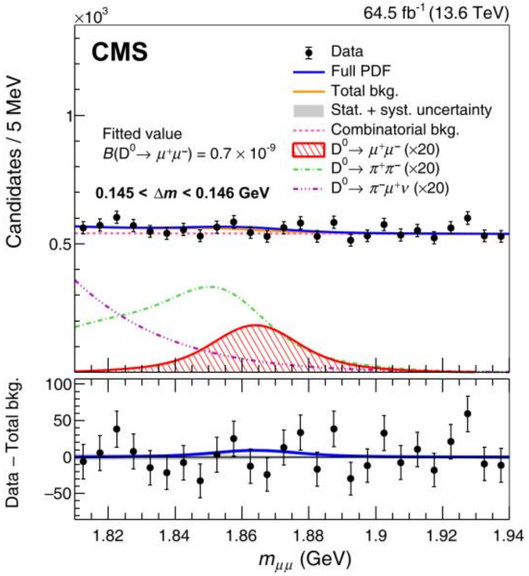
Other heavy flavor results



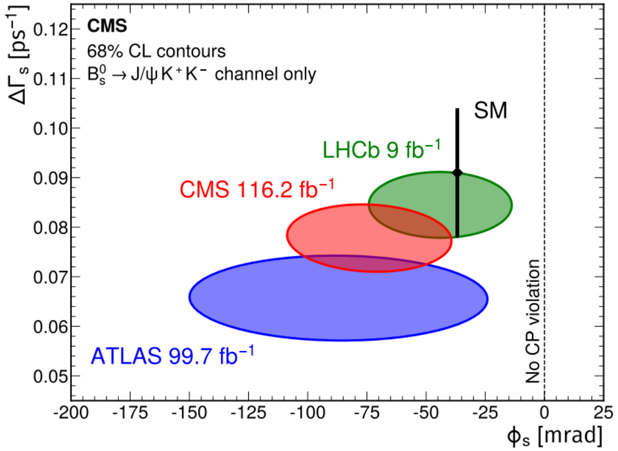




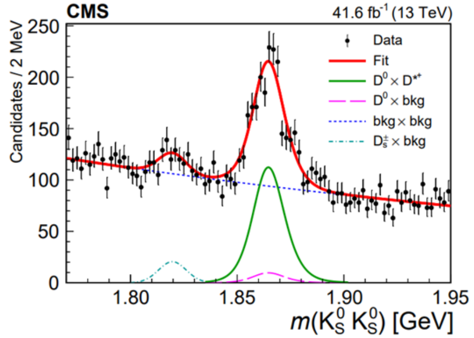
arxiv:2508.05820
Submitted to PRL

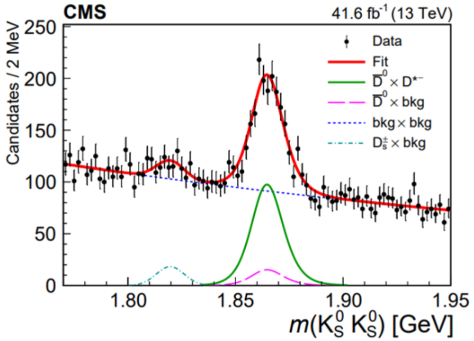


PhysRevLett135,151803(2025)



arxiv:2412.19952
Submitted to PRL





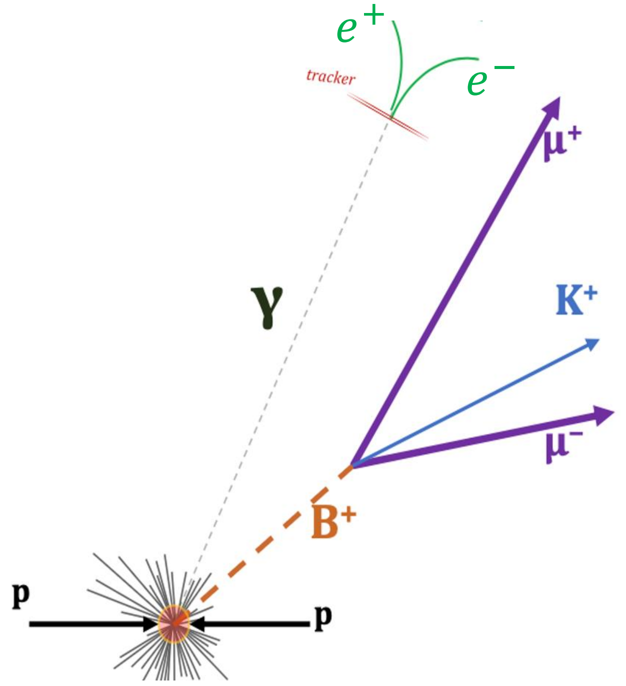
EPJC84(2024)1264

Precise mass measurement of $\mathrm{B}^{*+}, \mathrm{B}^{*0}$, and B_s^{*0}

arxiv:2508.05820

- Mass measurement of $\mathrm{B}^{*+}, \mathrm{B}^{*0}, \mathrm{B}_s^{*0}$
  - Hyperfine splits in the B meson system are important input for quark models
  - Tension in indirect mass measurements: LHCb, CMS vs. CLEO, Belle
  - ➢Calls for precise measurement

- **First exclusive reconstruction** of $\mathrm{B}^{*+}, \mathrm{B}^{*0}$, and B_s^{*0} via $\mathrm{B}^* \to \mathrm{B}\gamma$
  - Dataset: $140\ fb^{-1}$ in 2016-2018 at $\sqrt{s} = 13$ TeV
  - Low-energy photon reconstruction (challenge!): e^+e^- pair from photon conversion
  - Ground-state B mesons reconstruction: $B^+ \to \psi K^+, B^0 \to \psi K^{*0}, B_s^0 \to \psi\phi$
  - $\psi[J/\psi, \psi(2S)] \to \mu^+\mu^-$, $K^{*0}(892) \to K^+\pi^-$, $\phi(1020) \to K^+K^-$

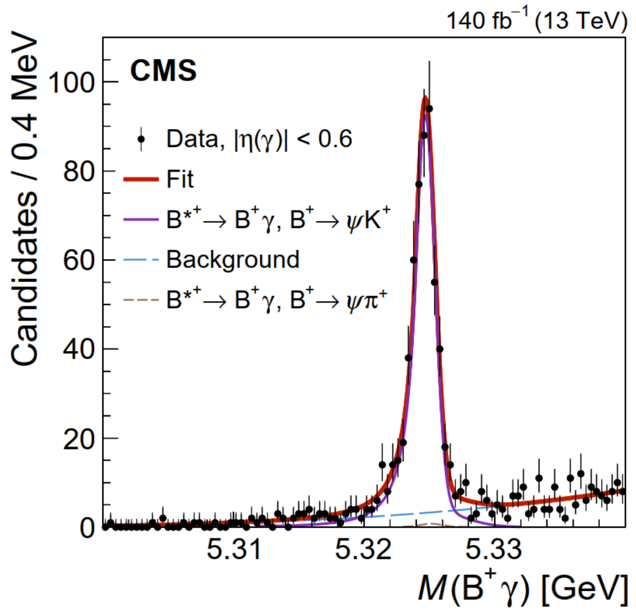


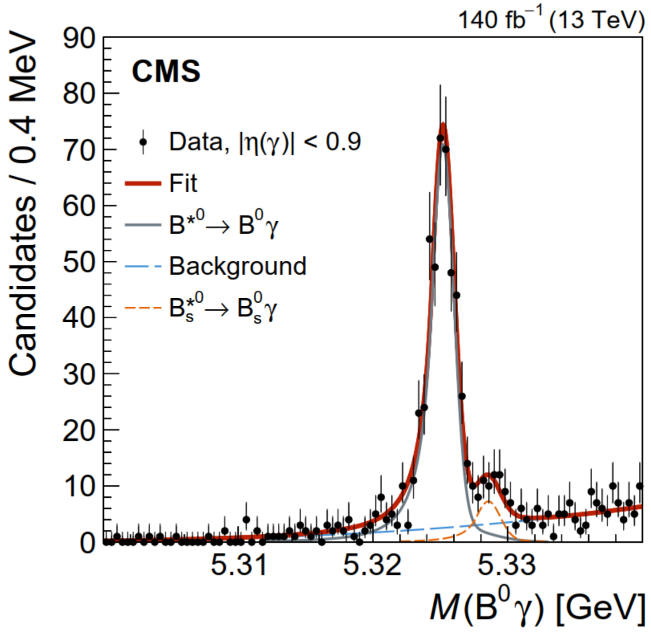
Precise mass measurement of B^{*+}, B^{*0}, and B_s^{*0}

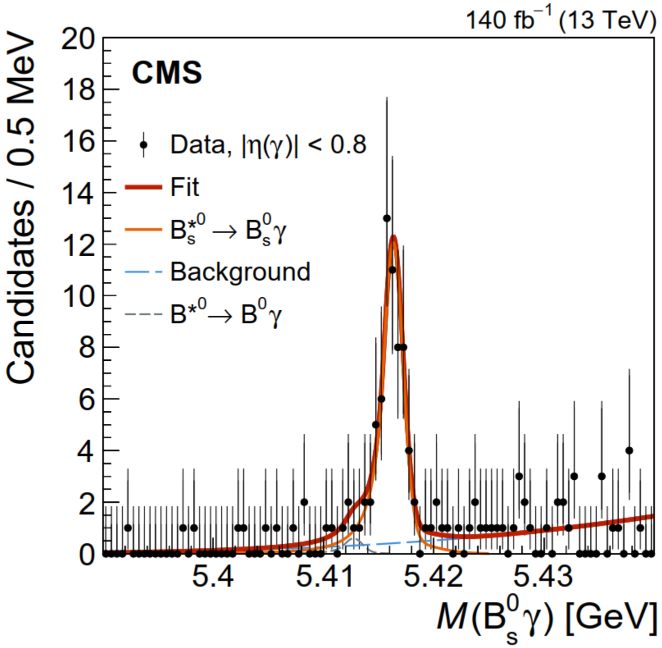
arxiv:2508.05820

Submitted to PRL

- Simultaneous fit in the 7 categories of $|\eta(\gamma)|$
  - Signal shapes are double crystal ball functions
  - To better constrain peaking contribution from the other two B^*
  - Fit projections in best resolution region in below







- To improve resolution: $M(\mathrm{B}\gamma) = m(\mathrm{B}\gamma) - m(\mathrm{B}) + M_{\mathrm{B}}^{\mathrm{PDG}}$

Precise mass measurement of B^{*+}, B^{*0}, and B_s^{*0}

arxiv:2508.05820

	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

$\mathrm{B_s^{*0}}$ mass 5415.4±1.4 MeV

Mass differences between vector states

In agreement, 3 times more precise

CMS-BPH-16-003

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

first measurements

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

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

Submitted to PRL

Search for the rare decay $D^0 \to \mu^+\mu^-$ in pp collisions

PhysRevLett135,151803(2025)

- $D^0 \to \mu^+\mu^-$ a FCNC process
  - Highly suppressed in SM 3×10^{-13}
  - Sensitive to new physics

    Significant enhancement in many new physics models:

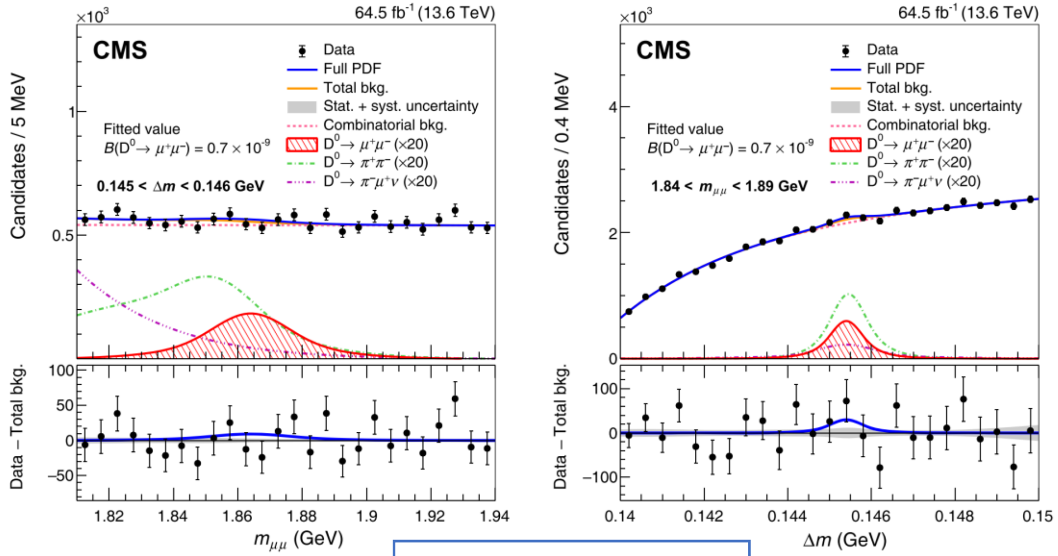
    leptoquarks, R-parity violating supersymmetry, extra fermions or gauge bosons
- UL $< 3.1 \times 10^{-9}$ @ 90% CL from LHCb, still allows NP contributions

- $D^0 \to \mu^+\mu^-$ search at CMS
  - pp collision dataset in 2022-2023 at $\sqrt{s} = 13.6$ TeV, 64.5 fb^{-1}
  - New inclusive dimuon trigger
  - D^0 from $D^{*+} \to D^0\pi^+$ to suppress background
  - 2D UML fit on $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$

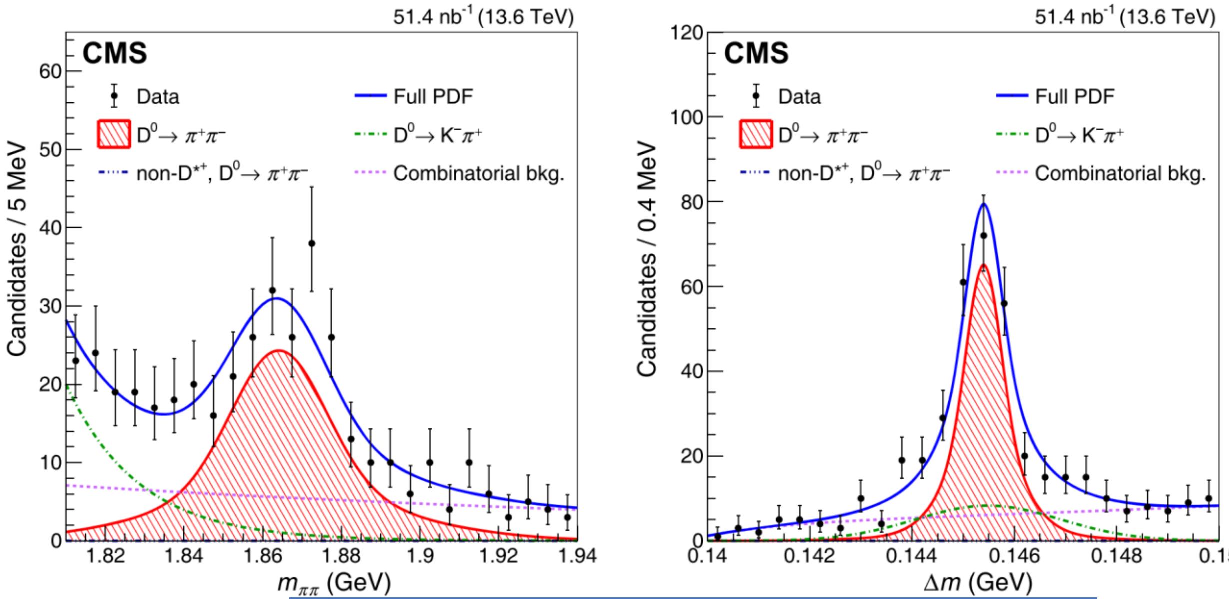
Search for the rare decay $D^0 \to \mu^+\mu^-$ in pp collisions

PhysRevLett135,151803(2025)

- 2D UML fit on $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$
  - Sum of two/three Gaussians for signal component in $m(D^0)/\Delta m$



Signal channel



Normalization channel: $D^0 \to \pi^+\pi^-$

- No obvious excess of events
  - $B\left(D^0 \to \mu^+\mu^-\right) < 2.1(2.4) \times 10^{-9}$ at 90(95)% CL using the asymptotic $\mathrm{CL_s}$ method

Evidence for CP violation in $B_s^0 \to J/\psi\phi$ decays arxiv:2412.19952

- 2017 + 2018 dataset, 13 TeV, 96.5 fb^{-1} (~ 491000 signal events)
  - passing $J/\psi + \mu$ or $J/\psi + \phi$ trigger
  - $J/\psi \to \mu^+\mu^-, \phi \to K^+K^-$
- Time-and flavor-dependent angular analysis, 7D UML fit

$$m, ct, \sigma_{ct}, \omega_{tag}, \cos\theta_T, \cos\psi_T, \varphi_T$$

- **angular analysis**: to separate CP eigenstates

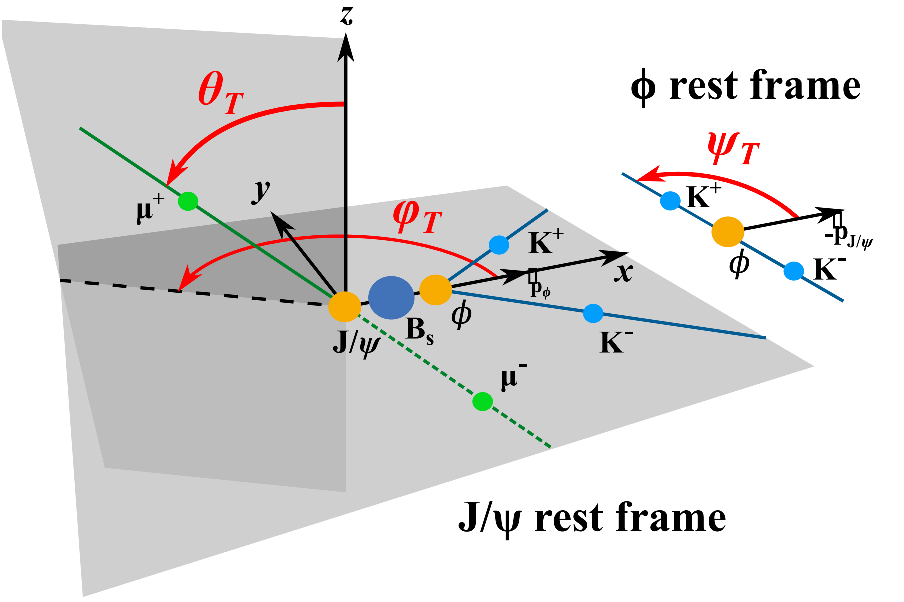
  angular efficiencies

- **flavour tagging**: to infer $B_s^0/\bar{B}_s^0$ flavour at production

  tagging decision and mistag probability

- **time analysis**: to model flavour oscillations

  time efficiency and resolution



Evidence for CP violation in $B_s^0 \to J/\psi\phi$ decays

arxiv:2412.19952

Submitted to PRL

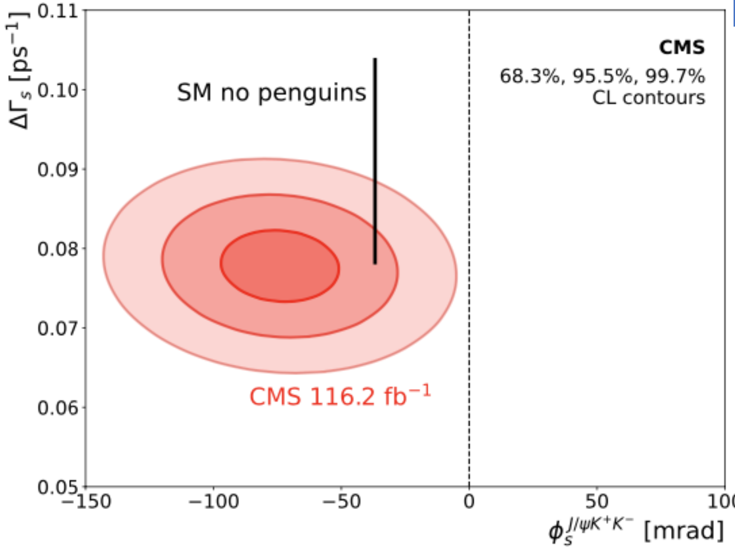
Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	-73	± 23	± 7
$\Delta\Gamma_s$ [ps^{-1}]	0.0761	$\pm$ 0.0043	$\pm$ 0.0019
Γ_s [ps^{-1}]	0.6613	$\pm$ 0.0015	$\pm$ 0.0028
Δm_s [$\hbar$ps^{-1}]	17.757	$\pm$ 0.035	$\pm$ 0.017
$\lvert\lambda\rvert$	1.011	$\pm$ 0.014	$\pm$ 0.012
$\lvert A_0\rvert^2$	0.5300	$\pm$ 0.0016	$\pm$ 0.0044
$\lvert A_\perp\rvert^2$	0.2409	$\pm$ 0.0021	$\pm$ 0.0030
$\lvert A_S\rvert^2$	0.0067	$\pm$ 0.0033	$\pm$ 0.0009
$\delta_\parallel$	3.145	$\pm$ 0.074	$\pm$ 0.025
$\delta_\perp$	2.931	$\pm$ 0.089	$\pm$ 0.050
$\delta_{S\perp}$	0.48	$\pm$ 0.15	$\pm$ 0.05

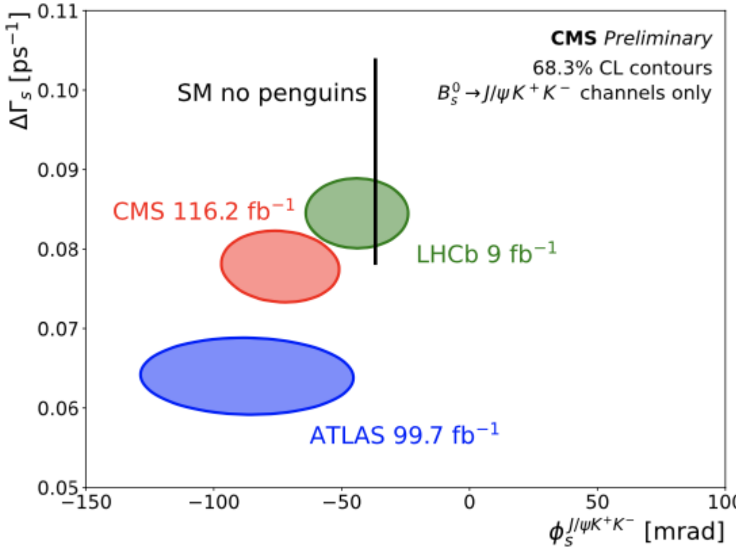
3.2 σ evidence of CP violation in $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ decays

results in agreement with SM and other experiments

still statistically limited, competitive with other measurements

combined with 8 TeV analysis





- Comparable in precision to the world's most precise single measurement by LHCb

Search for CPV in $D^0 \to K_S^0 K_S^0$

EPJC84(2024)1264

- CPV in up-quark (heavily suppressed) not as well studied as in down-quark
- First observation by LHCb $A_{CP}(D^0 \to KK) - A_{CP}(D^0 \to \pi\pi) = (-15.4 \pm 2.9) \times 10^{-4}$

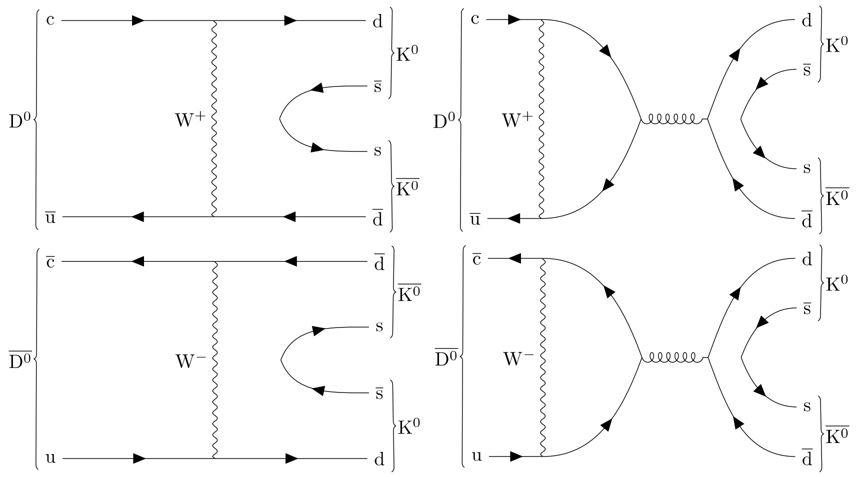
Belle $A_{CP}(D^0 \to K_S^0 K_S^0) = (-0.02 \pm 1.53 \pm 0.02 \pm 0.17)\,\%$

LHCb $A_{CP}(D^0 \to K_S^0 K_S^0) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\,\%$

- The current world average for the time-integrated CP asymmetry is $A_{CP}\left(K_S^0 K_S^0\right) = -1.9 \pm 1.1\,\%$ [19], which is dominated by results from the LHCb [25] and Belle [26] Collaborations.
- First CPV measurement in charm sector at CMS
  - 2018 data, 41.6 fb-1 BParking dataset
  - contains O(10^{10}) semileptonic B decays

$$A_{CP} = \frac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}$$

$$A_{CP} = A_{CP}^{raw} - A_{CP}^{pro} - A_{CP}^{det}$$

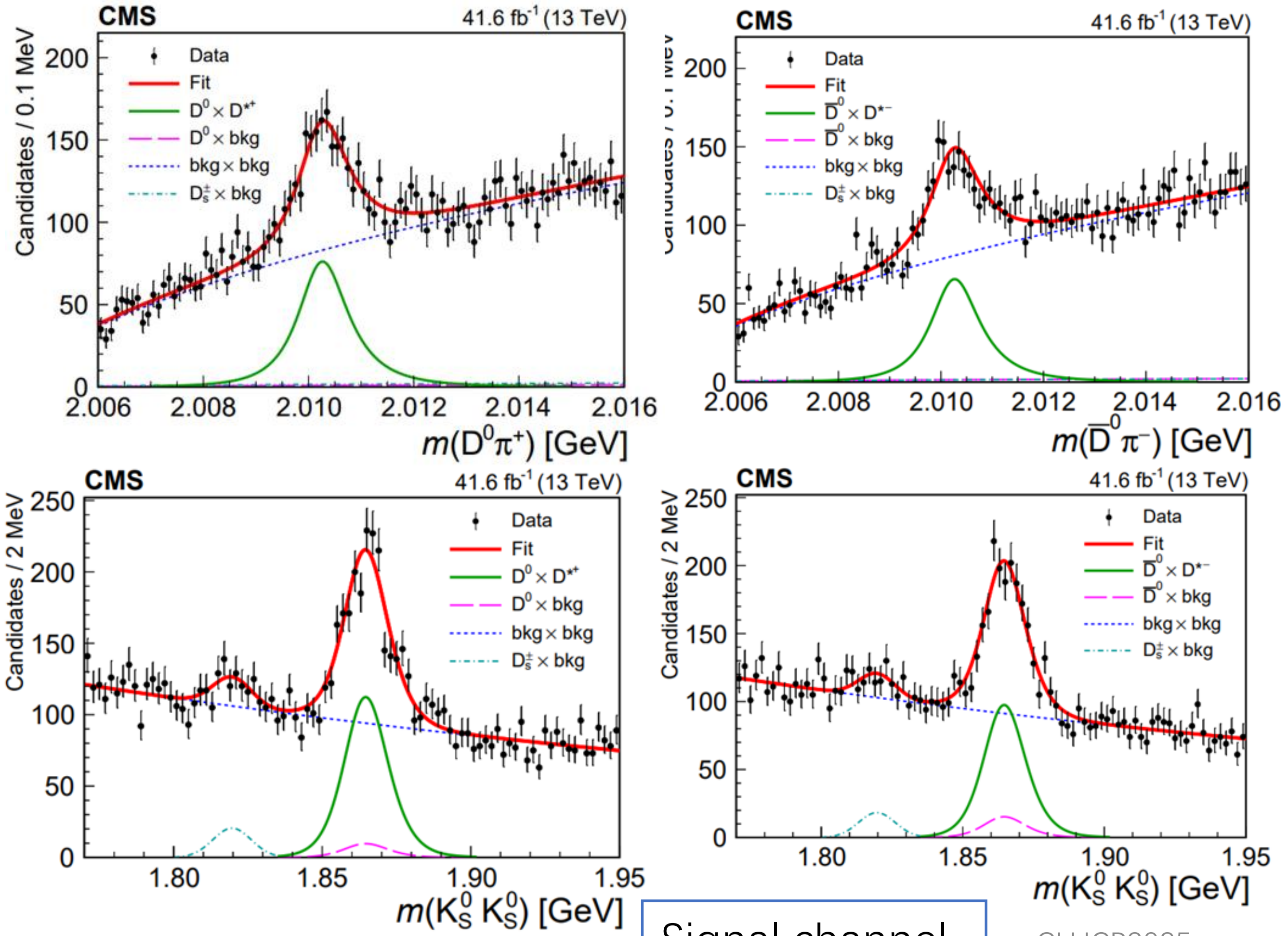


Search for CPV in $D^0 \to K_S^0 K_S^0$

EPJC84(2024)1264

$A_{CP}^{raw}(K_S^0 K_S^0) = (7.1 \pm 3)\,\%$

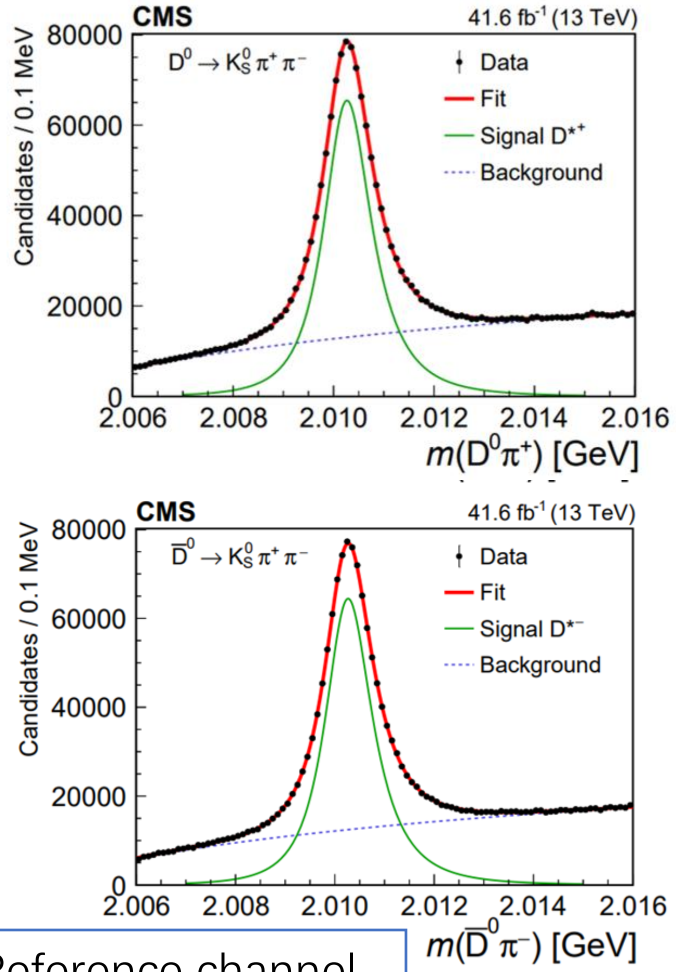
Pion charge	N	χ^2 (x axis)	χ^2 (y axis)
π^+	1095 ± 46	77	90
π^-	951 ± 44	93	62



Signal channel

$A_{CP}^{raw}(K_S^0 \pi\pi) = (0.78 \pm 0.10)\,\%$

Charge of pion	N	χ^2 with 100 bins
π^+	$944\,800 \pm 3\,500$	78
π^-	$930\,150 \pm 3\,400$	93



Reference channel

CLHCP2025

Search for CPV in $D^0 \to K_S^0 K_S^0$

EPJC84(2024)1264

- Direct measurement: $\Delta A_{CP} \equiv A_{CP}(\mathrm{K_S^0K_S^0}) - A_{CP}(\mathrm{K_S^0}\pi^+\pi^-) = 6.3 \pm 3.0\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst})\,\%.$

➢ $A_{CP}(\mathrm{K_S^0K_S^0}) = 6.2 \pm 3.0\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst}) \pm 0.8(A_{CP}(\mathrm{K_S^0}\pi^+\pi^-))\,\%$

Source	Uncertainty, %
$m(\mathrm{D}\pi^\pm)$ signal model	0.10
$m(\mathrm{D}\pi^\pm)$ background model	0.02
$m(\mathrm{K_S^0K_S^0})$ signal model	0.04
$m(\mathrm{K_S^0K_S^0})$ background model	0.02
$m(\mathrm{K_S^0K_S^0})$ fit range	0.04
Reweighting	0.09
ΔA_{CP} in MC	0.13
Total	0.20

- Compatible with no CPV at 2.0σ, with LHCb at 2.7σ, with Belle at 1.8σ
- Statistically limited; systematic primarily from fit models
- More details see Vladimir’s talk this afternoon

Summary

- Recent contributions in heavy flavor & (exotic) hadron physics at CMS
  - All-charm tetraquarks
  - Precise measurement of the mass of $\mathrm{B}^{*+}, \mathrm{B}^{*0}, \mathbf{and}\ \mathrm{B}_s^{*0}$
  - Rare decay of $D^0 \to \mu^+\mu^-$ to probe new physics
  - CPV search in $D^0 \to K_S^0 K_S^0$
- New data, new opportunities!
  - Working on & waiting for new results from run 3 data

Thanks