CMS实验上的B物理研究进展

第六届重味物理与量子色动力学研讨会

清華大學
Tsinghua University

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The **Large Hadron Collider** (**LHC**) at CERN is the world's largest particle collider. It lies in a tunnel 27 kilometres in circumference and as deep as 175 metres beneath the France–Switzerland border near Geneva.

Home page: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

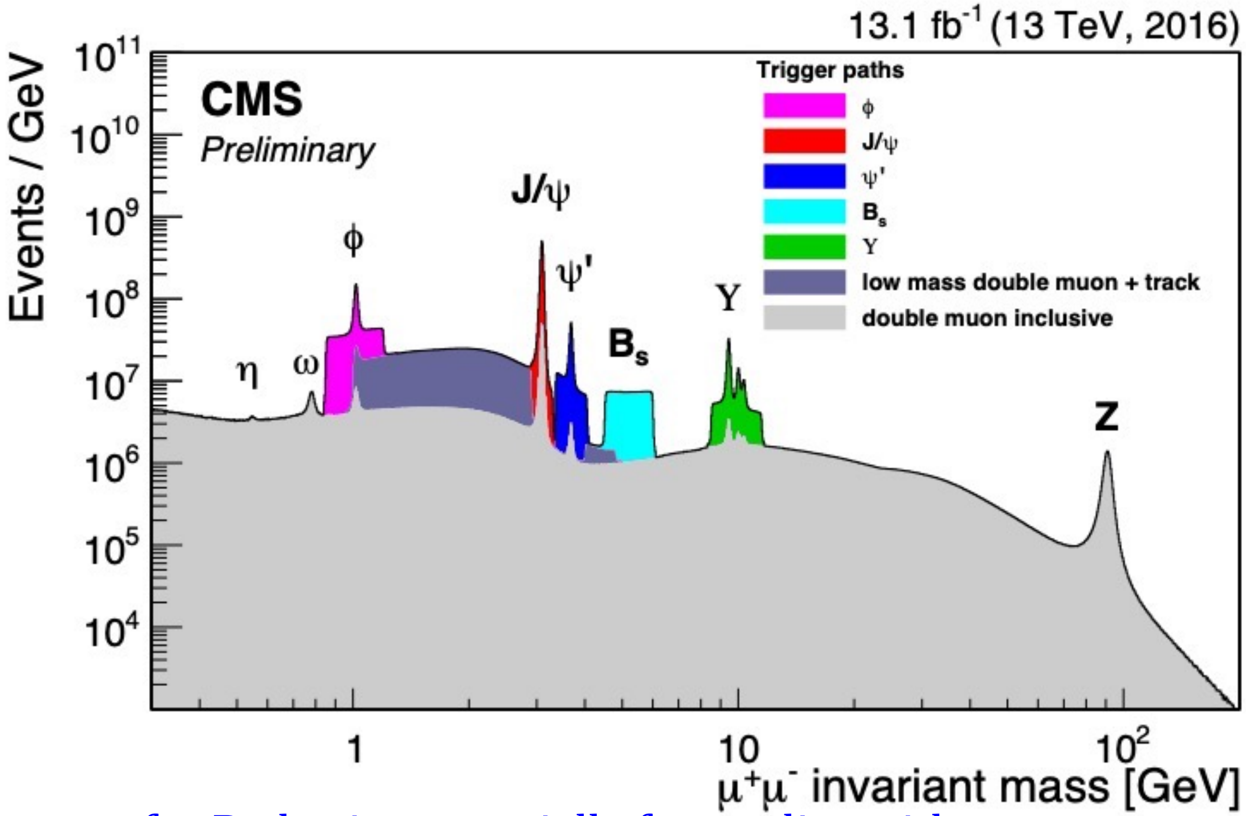
72 publications: https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH/index.html

- Quarkonium Production
  - Bottomium States
  - Charmonium States
- B and BB Production
  - Inclusive Measurements
  - B^0 and B^+ Production
  - B_s^0 Production
  - B_c^+ Production
- B Meson Decays
  - $B \to K^{(*)}\mu^+\mu^-$
  - $B_s^0 \to \mu^+\mu^-$
- CP Violation
- Baryons
- Spectroscopy, Exotic States

BPH

Production and Properties	Rare Decays
Violation of Fundamental Symmetries	Spectroscopy Exotic states

CMS dimuon & trigger



Excellent detector for B physics, especially for studies with muons

- Muon system
  - High-purity muon ID, $\Delta m/m \sim 0.6\%$ for J/ψ
- Silicon Tracking detector, B=3.8T
  - $\Delta p_T/p_T \sim 1\%$ & excellent vertex resolution
- Special triggers for different analyses at increasing Inst. Lumi.
  - μ p_T, $(\mu\mu)$ p_T, $(\mu\mu)$ mass, $(\mu\mu)$ vertex, and additional μ

2023 & 2024 public results

Purely muon final states

- Observation of $\eta \to \mu^+\mu^-\mu^+\mu^-$
- Upper limits of $\tau \to 3\mu$
- Observation of $J/\psi \to \mu^+\mu^-\mu^+\mu^-$
- Observation of new structure in $J/\psi\ J/\psi \to \mu^+\mu^-\mu^+\mu^-$
- Observation of $J/\psi\ J/\psi\ J/\psi \to \mu^+\mu^-\mu^+\mu^-\mu^+\mu^-$
- Measurement of $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

Muon + hadron final states

- Observation of $\Xi_b^- \to \psi(2S)\Xi^-$ and measurement of Ξ_b^{*0}
- Observation of $\Lambda_b^0 \to J/\psi\,\Xi^- K^+$
- Measurement of f_s/f_u through $B_s^0 \to J/\psi\,\phi$ and $B^+ \to J/\psi\,K^+$.
- Measurement of $R(K)$ through $B^\pm \to K^\pm\mu^+\mu^-$ $B^\pm \to K^\pm e^+e^-$
- Measurement of B_s^0 effective lifetime through $B_s^0 \to J/\psi\,K_S^0$
- Measurement of CPV through $B_s^0 \to J/\psi\,\phi(1020)$
- Search for CPV through $D^0 \to K_S^0 K_S^0$

2024 newly submitted

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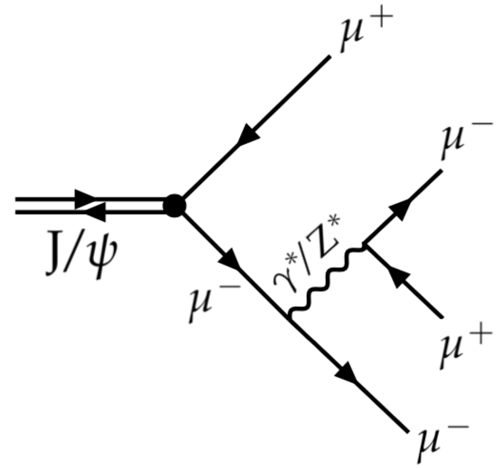
Moriond 2024

- Measurement of B_s^0 effective lifetime through $B_s^0 \to J/\psi K_S^0$
- Measurement of CPV through $B_s^0 \to J/\psi\phi(1020)$
- Search for CPV through $D^0 \to K_S^0K_S^0$

Observation of $J/\psi \longrightarrow 4\mu$

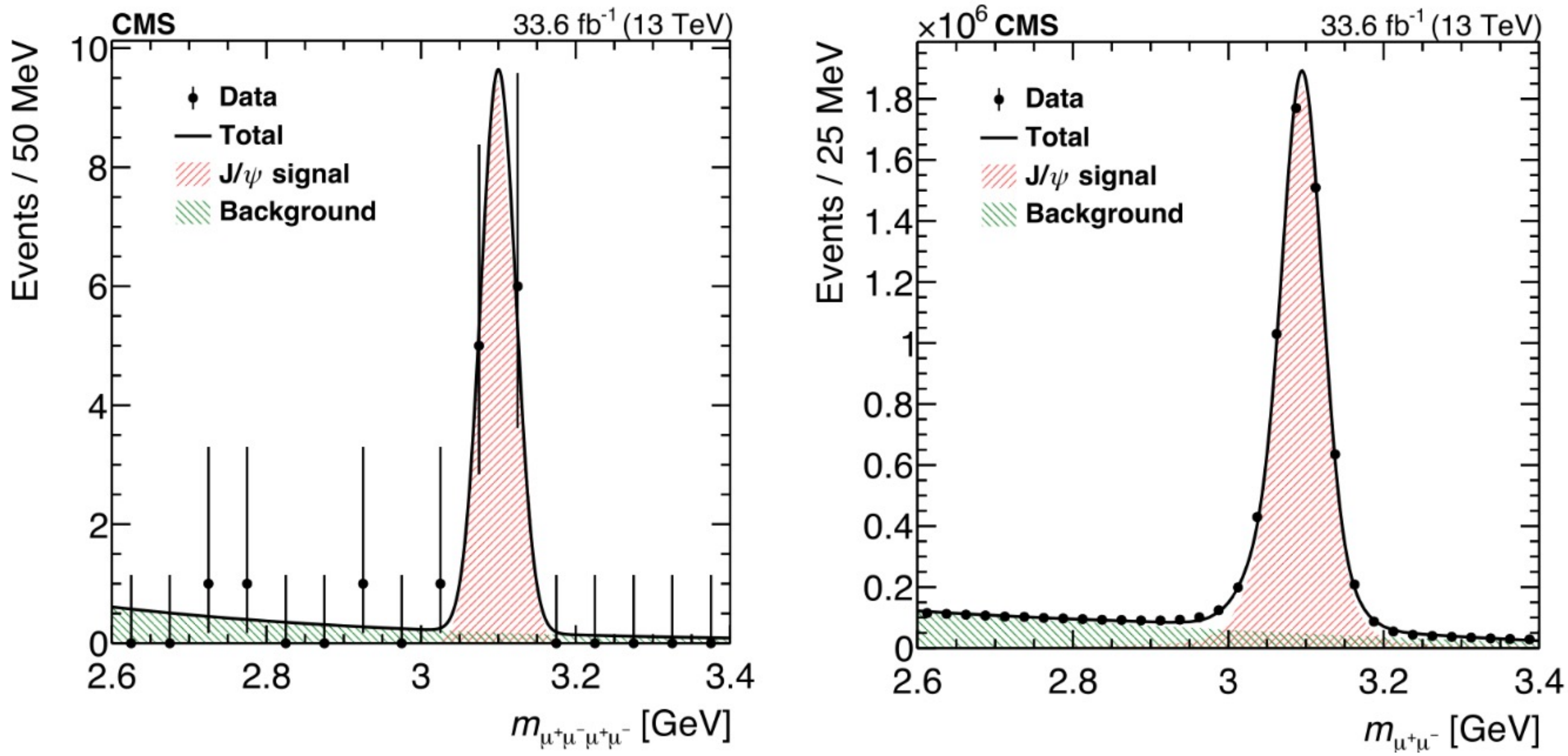
- SM: proceeds via virtual photon or Z with predicted $\mathcal{B}(J/\psi \rightarrow 4\mu) = 9.74 \pm 0.05 \times 10^{-7}$
  - BSM particles can contribute & affect the rates
  - Novel testing ground for QED predictions



- Using the "B-parking" datasets
  - Single muon trigger:
    - Minimum p_T requirement， minimum signed d_0 significance
    - Thresholds and pre-scales adjusted based on instantaneous luminosity to level the trigger rate，high level trigger rate < 5 kHz
  - 10 billion events saved to tape and reconstructed when computing resources become available
  - Opposite side jets provide an unbiased sample of b-decays
    - 60-90% purity estimated by reconstructing $B \rightarrow D^{*+}\mu^{-}\bar{\nu}_{\mu}$
  - *Now possible to reconstruct fully hadronic B decays*

Observation of J/ψ ⟶ 4μ

- First observation of J/ψ ⟶ 4μ



$$B(J/\psi \to 4\mu) = B(J/\psi \to \mu\mu) \times \frac{N_{4\mu}}{N_{2\mu}} \times \frac{\epsilon_{2\mu}}{\epsilon_{4\mu}}$$

$$B(J/\psi \to 4\mu) = [9.4^{+3.2}_{-1.7}(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-7}$$

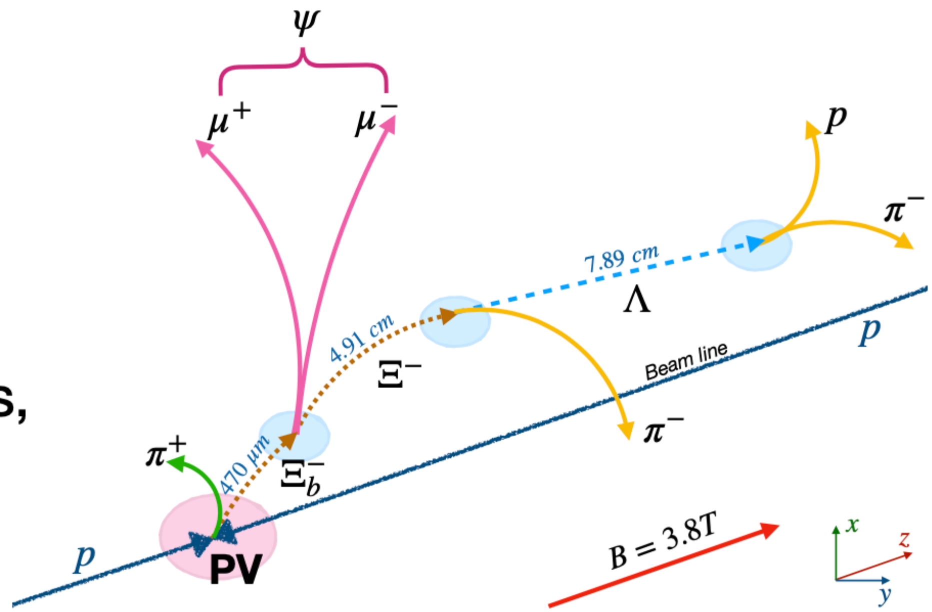
- Consistent with SM prediction $(9.74 \pm 0.05) \times 10^{-7}$

$\Xi_b \to \psi(2S)\Xi$ observation and Ξ_b^{*0} studies

Increasing data statistics @LHC allows **exploration of ground and excited Ξ_b states**

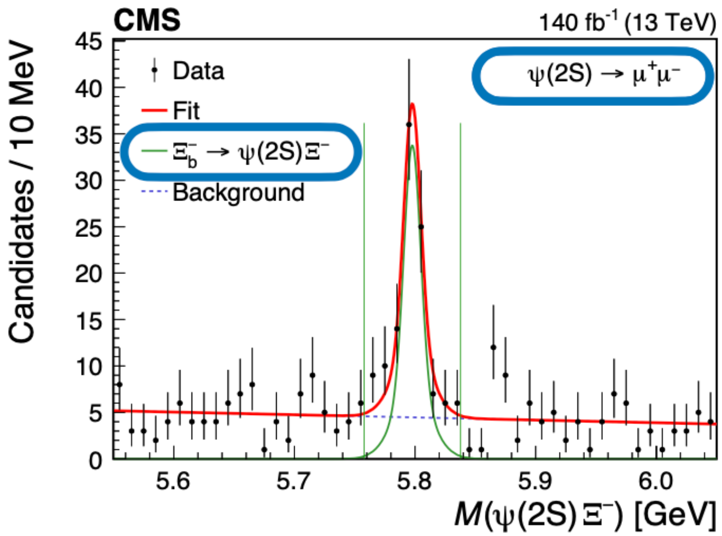
- Weak ground Ξ_b decays: possible intermediate resonances or CP violation
- Measurements of both ground and excited (Ξ_b^*) state properties constrain heavy quark EFT → **better understanding of quark dynamics and hadronization**

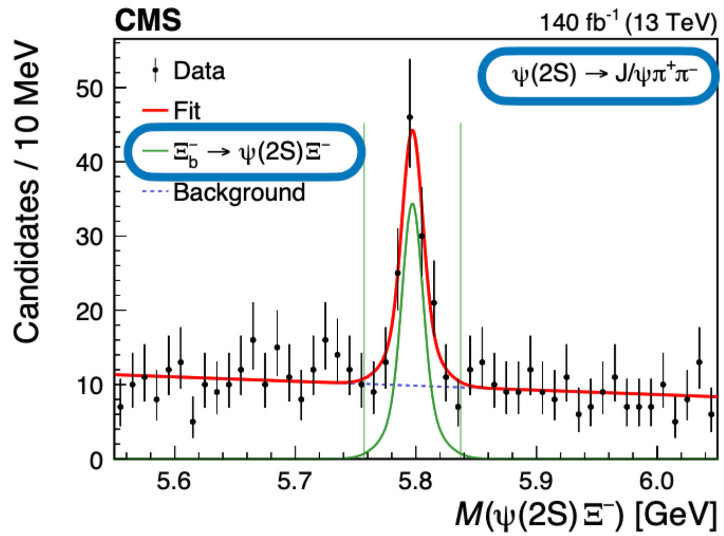
- Full Run 2 140 fb^{-1}
- Ξ_b^- reconstructed via: $\Xi_b^- \to J/\psi\Xi^-$, $\Xi_b^- \to \psi(2S)(\to J/\psi\pi\pi)\Xi^-$, $\Xi_b^- \to \psi(2S)(\to \mu\mu)\Xi^-$, $\Xi_b^- \to J/\psi\Lambda^0K^-$ with $J/\psi \to \mu\mu$ and $\Xi^- \to \Lambda^0(p\pi)\pi^-$
- Ξ_b^{*0} from fitting Ξ_b^- virtual track and $\pi^\pm$ from PV
- **rich topology:** leverage vertex refit, long Ξ and Λ lifetime, mass constraints, mass differences



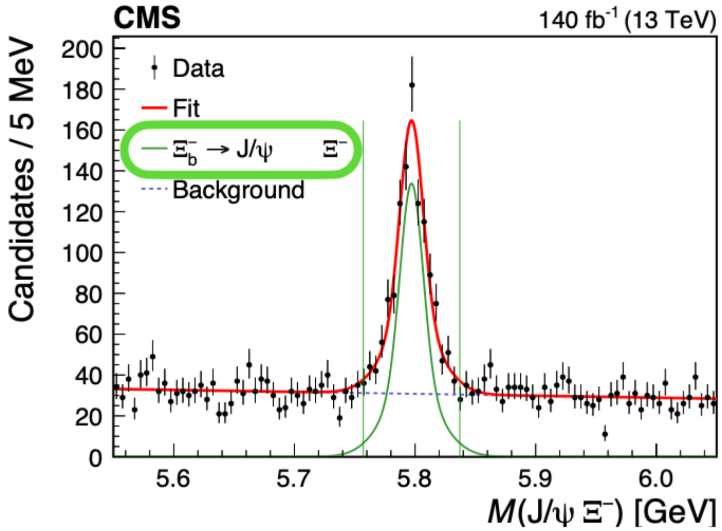
$\Xi_b \to \psi(2S)\Xi$ observation and Ξ_b^{*0} studies

- First observation of $\Xi_b \to \psi(2S)\Xi$





obs. > 5σ



Decay channel	N	$m^{\text{fit}}_{\Xi_b^-}$ (MeV)	σ_{eff} (MeV)
$\Xi_b^- \to J/\psi\Xi^-$	846 ± 40	5797.1 ± 0.6	16.3 ± 1.0
$\Xi_b^- \to J/\psi\Lambda K^-$	920 ± 98	5798.8 ± 0.9	11.9 ± 1.5
$\Xi_b^- \to J/\psi\Sigma^0 K^-$	880 ± 170	—	—
$\Xi_b^- \to \psi(2S)\Xi^-$ (with $\psi(2S) \to \mu^+\mu^-$)	74 ± 11	5797.7 ± 1.4	11.1 ± 2.0
$\Xi_b^- \to \psi(2S)\Xi^-$ (with $\psi(2S) \to J/\psi\pi^+\pi^-$)	90 ± 14	5797.2 ± 1.7	13.1 ± 2.8

bkup

$$R = \frac{\mathcal{B}(\Xi_b^- \to \psi(2S)\Xi^-)}{\mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)} = 0.84\,^{+0.21}_{-0.19}\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.02\,(\mathcal{B})$$

R measured in tighter fiducial volume

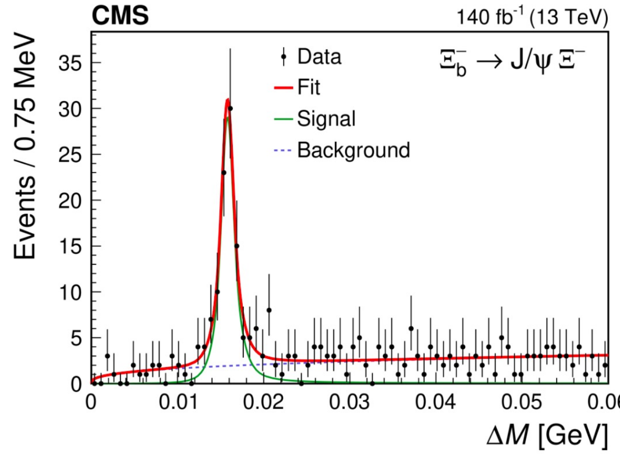
$\Xi_b \to \psi(2S)\Xi$ observation and Ξ_b^{*0} studies

- Novel measurements of b-baryon properties

Properties of Ξ_b^{*0}

- Using $\Xi_b^{*0} \to \Xi_b^- \pi^+$ with multiple Ξ_b^- decays ($\psi(2S)\Xi^-, J/\psi\,\Xi^-, J/\psi\,\Lambda K^-, J/\psi\,\Sigma^0 K^-$)
- Ξ_b^{*0} mass and decay width extracted in a fit to $\Delta M = M(\Xi_b^-\pi^+) - M(\Xi_b^-) - m_{\pi^+}^{PDG}$
  → **Improved mass resolution** wrt. $M(\Xi_b^-\pi^+)$

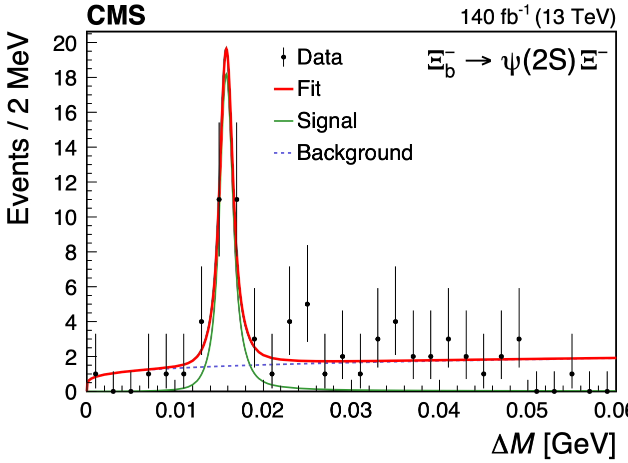
$$m_{\Xi_b^{*0}} = 5952.4 \pm 0.1(\text{stat} + \text{syst}) \pm 0.6(m_{\Xi_b^-})\ \text{MeV}$$
$$\Gamma_{\Xi_b^{*0}} = 0.87^{+0.22}_{-0.20}(\text{stat}) \pm 0.16(\text{syst})\ \text{MeV}$$



- Ξ_b^{*0} and Ξ_b^- **production cross-section ratio**

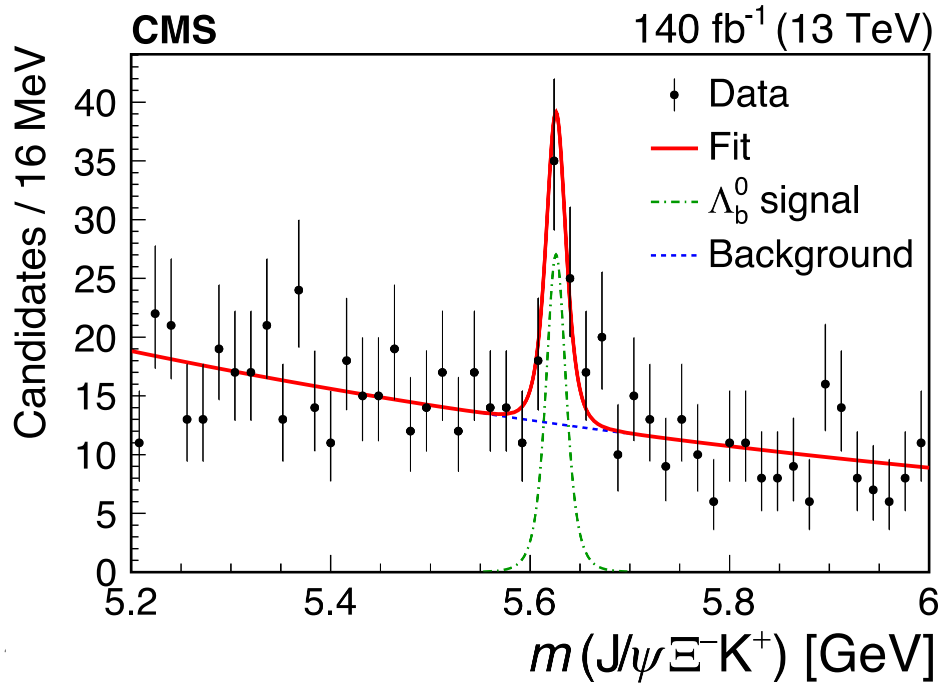
$$\frac{\sigma(pp \to \Xi_b^{*0}X)B(\Xi_b^{*0} \to \Xi_b^-\pi^+)}{\sigma(pp \to \Xi_b^- X)} = 0.23 \pm 0.04\ (\text{stat}) \pm 0.02\ (\text{syst})$$

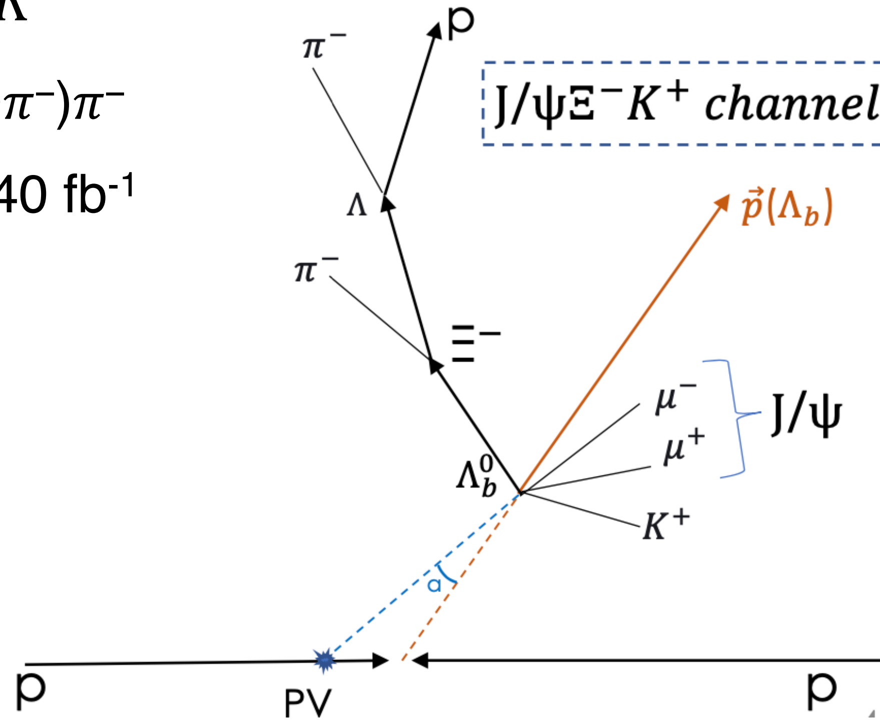
→ $\sim {}^1/_4$ of Ξ_b^- are produced in $\Xi_b^{*0} \to \Xi_b^-\pi^+$
→ $\sim {}^1/_3$ of Ξ_b^- coming from Ξ_b^{*0} decays



Observation of $\Lambda_b \to J/\psi\, \Xi^- K^+$

- Multi-body decays of b-hadrons may proceed through exotic intermediate resonances
  - E. g. pentaquark $J/\psi\, p$ structure in $\Lambda_b \to J/\psi\, p\, K^-$ observed by LHCb
  - $\Lambda_b \to J/\psi\, \Xi^- K^+$ final state can unveil yet-unobserved (e. g. doubly-strange) pentaquarks
- First-time observation of $\Lambda_b \to J/\psi\, \Xi^- K^+$
  - In final states with $J/\psi \to \mu\mu$, $\Xi^- \to \Lambda(\to p\pi^-)\pi^-$
  - **$5.8\,\sigma$** significance with full Run-2 data 140 fb^{-1}





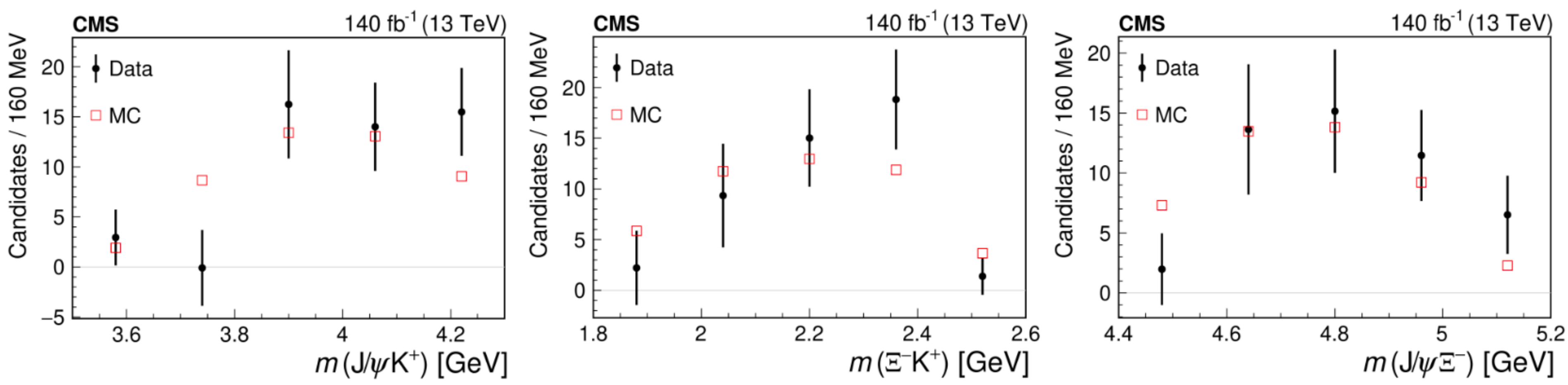
Observation of $\Lambda_b \to J/\psi\, \Xi^- K^+$

- $\Lambda_b \to J/\psi\, \Xi^- K^+$ branching fraction ratio measurement
  - Large systematics cancellation in the measured ratio R
  - Result dominated by low signal statistics

$$R = \frac{B(\Lambda_b \to J/\psi\, \Xi^- K^+)}{B(\Lambda_b \to \psi(2S)\Lambda)} = \frac{N_{signal}}{N_{ref.}} \times \frac{\epsilon_{signal}}{\epsilon_{ref.}} \times \frac{B(\psi(2S) \to J/\psi\, \pi^- \pi^+)}{B(\Xi^- \to \Lambda \pi^-)}$$

$$= [\mathbf{3.38} \pm \mathbf{1.02}\ (\boldsymbol{stat.}) \pm \mathbf{0.61} (\boldsymbol{syst.}) \pm \mathbf{0.03}\ (\boldsymbol{B})]\ \%$$

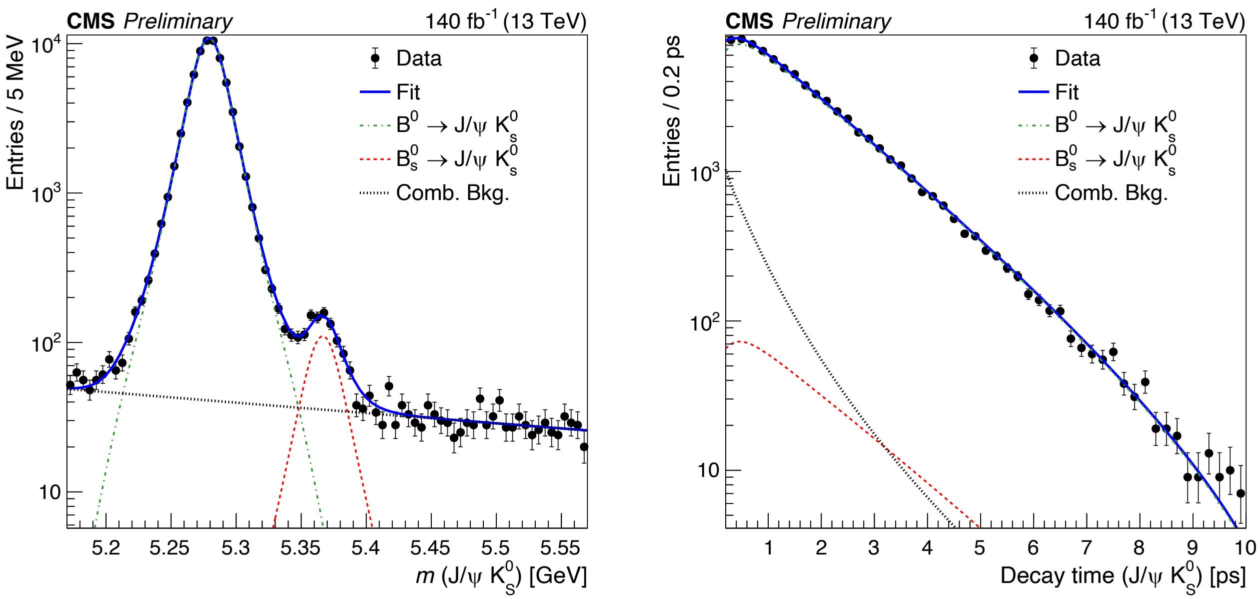
- Search for intermediate resonances

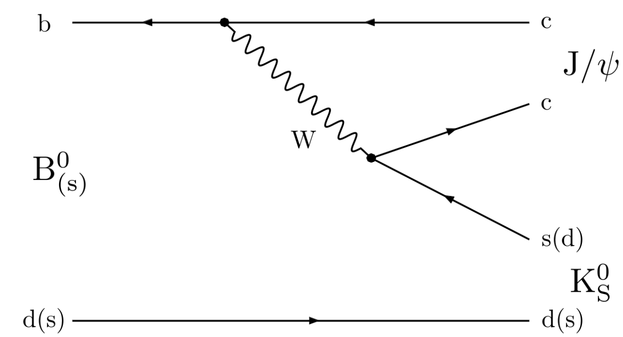


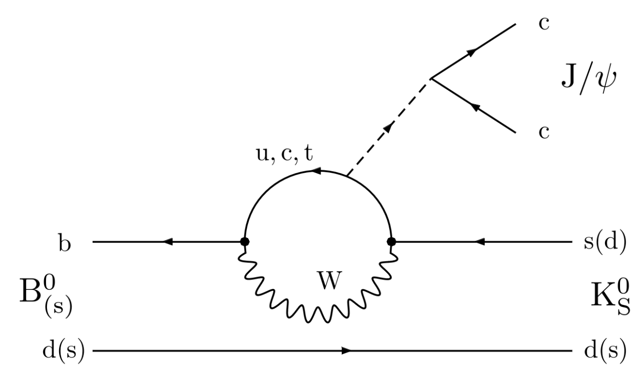
No evidence of resonant structures at this signal statistics

$B_s^0 \to J/\psi K_s^0$ effective lifetime

- Full Run-2 dataset at 13 TeV, 140 fb^{-1}
  - Using $J/\psi \to \mu\mu$ high p$_T$ trigger, $K_s^0 \to \pi\pi$
- 2D UML fit to mass and decay length







$$\tau^{obs}_{J/\psi K_s} = 1.59 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst})\ \text{ps}$$

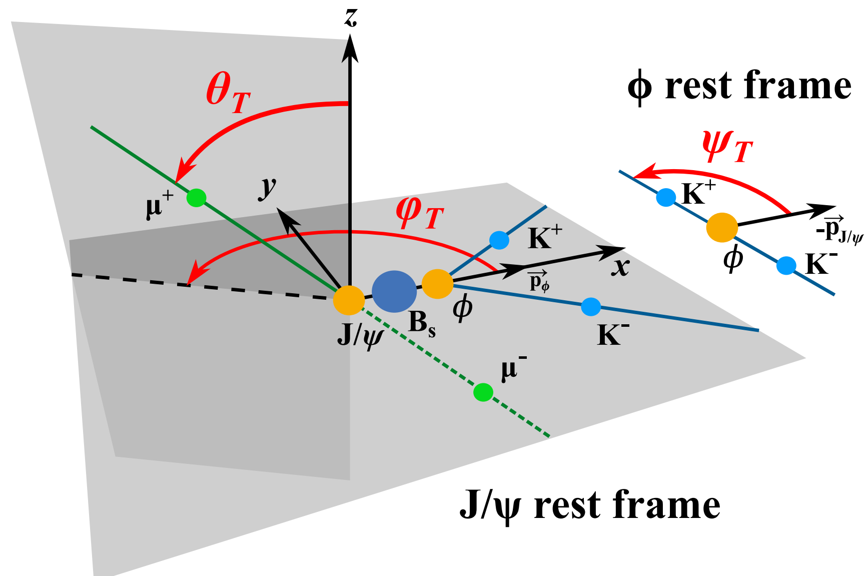
Compatible within 2.1σ with LHCb, improved accuracy
Strong agreement with the SM prediction of 1.62 ± 0.02 ps.

CPV in $B_s^0 \to J/\psi\, \phi(1020)$ decays

- 2017 + 2018 dataset, 13 TeV, 96.5 fb^{-1} (~ 491000 signal events)
  - passing $J/\psi + \mu$ or $J/\psi + \phi$ trigger
  - $J/\psi \to \mu\mu$, $\phi \to KK$
- Time-and flavour-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



CPV in $B_s^0 \to J/\psi\,\phi(1020)$ decays

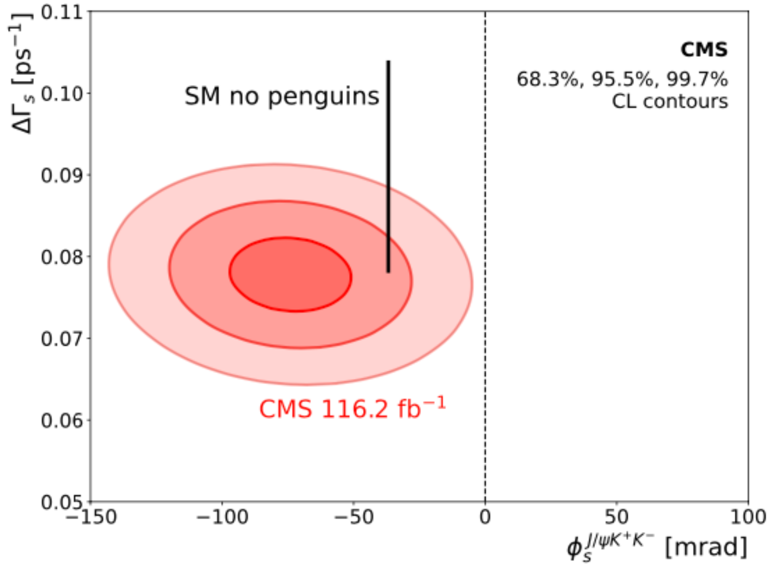
Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	-73	± 23	± 7
$\Delta\Gamma_s$ [ps^{-1}]	0.0761	± 0.0043	± 0.0019
Γ_s [ps^{-1}]	0.6613	± 0.0015	± 0.0028
Δm_s [$\hbar$ps^{-1}]	17.757	± 0.035	± 0.017
$\lvert\lambda\rvert$	1.011	± 0.014	± 0.012
$\lvert A_0\rvert^2$	0.5300	± 0.0016	± 0.0044
$\lvert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

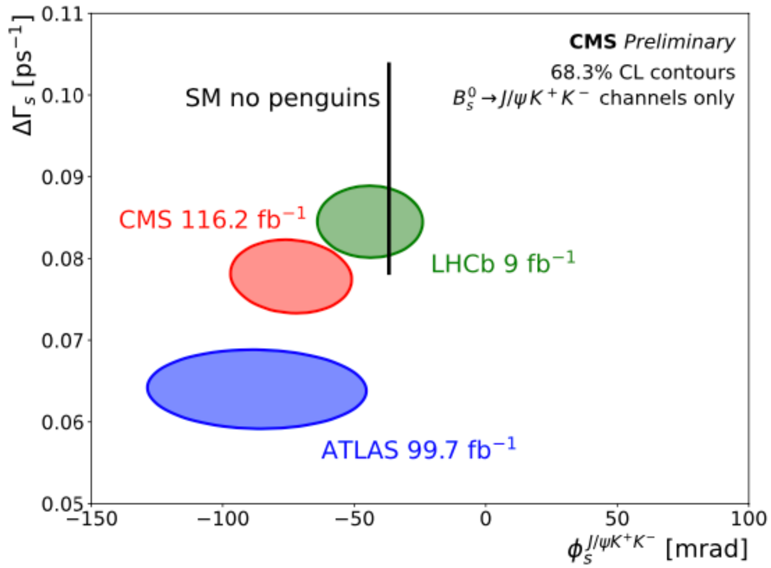
3.2 σ evidence of CP violation in $B_s^0 \to J/\psi\phi$ decays

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 $D^0 \to K_s^0 K_s^0$

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

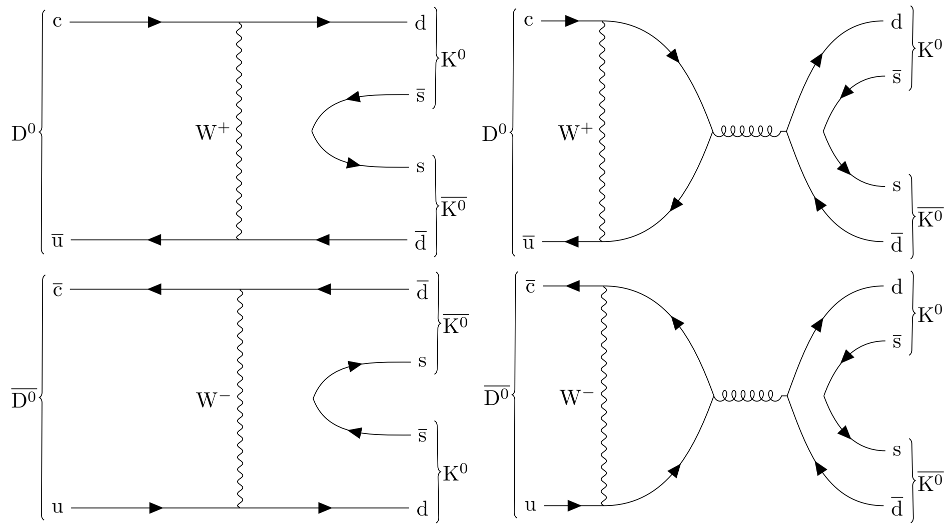
LHCb $A_{CP}(D^0 \to K_S^0 K_S^0) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\,\%$

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

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

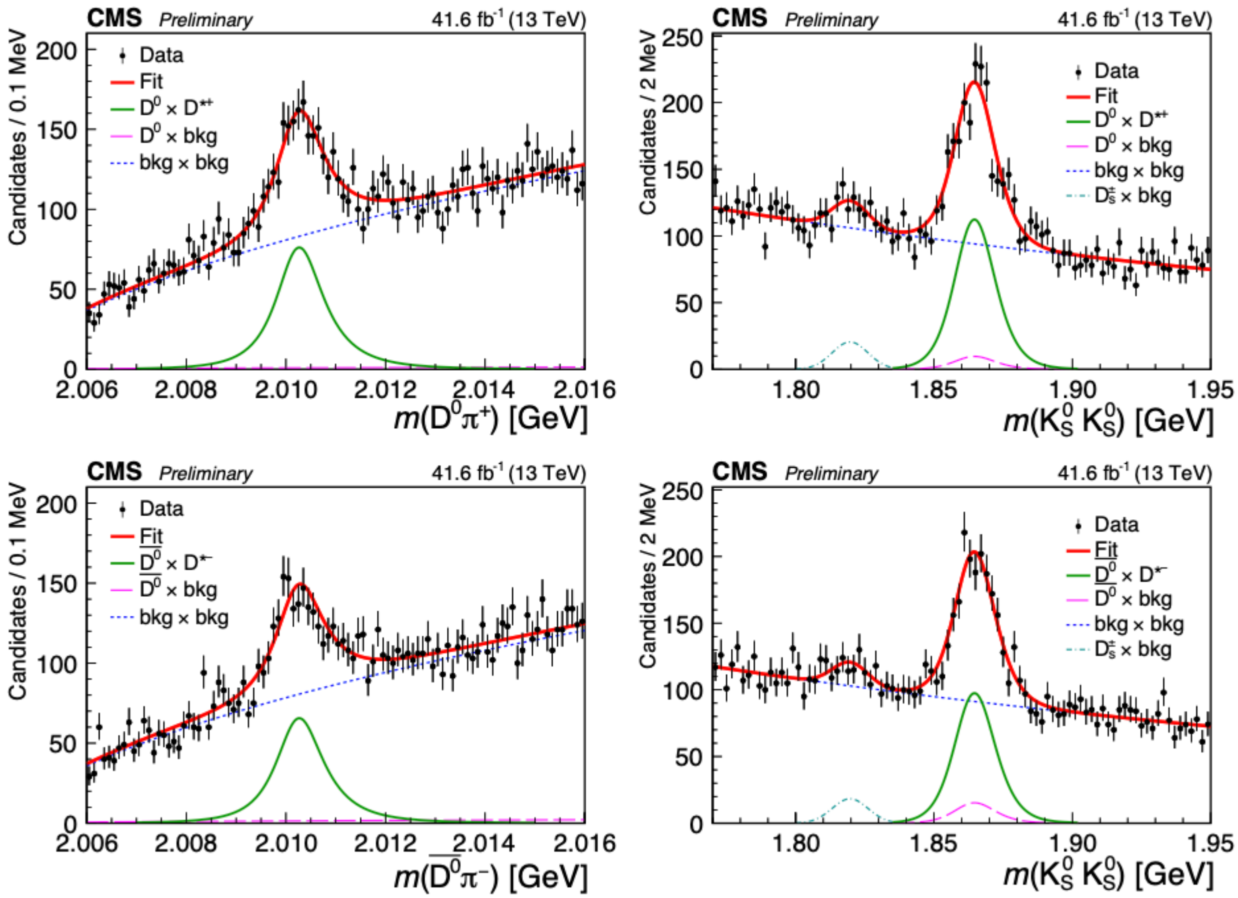
$$A_{CP} = A_{CP}^{\text{raw}} - A_{CP}^{\text{pro}} - A_{CP}^{\text{det}}$$



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

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

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



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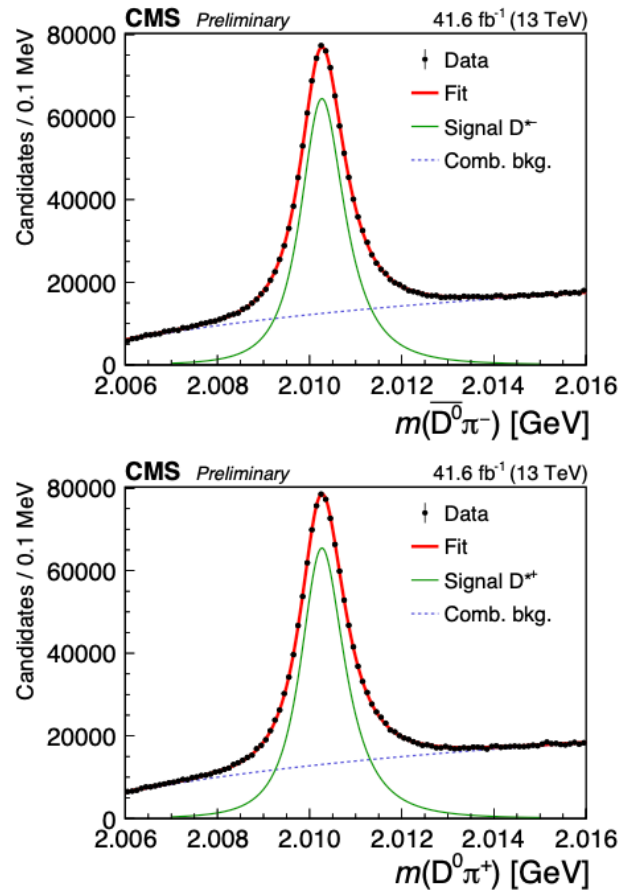
$A_{CP}^{raw}(K_S^0\pi\pi) = (0.78 \pm 0.10)\,\%$

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



$$A_{CP} = A_{CP}^{raw}(K_S^0K_S^0) - A_{CP}^{raw}(K_S^0\pi\pi) - A_{CP}(K_S^0\pi\pi)$$

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

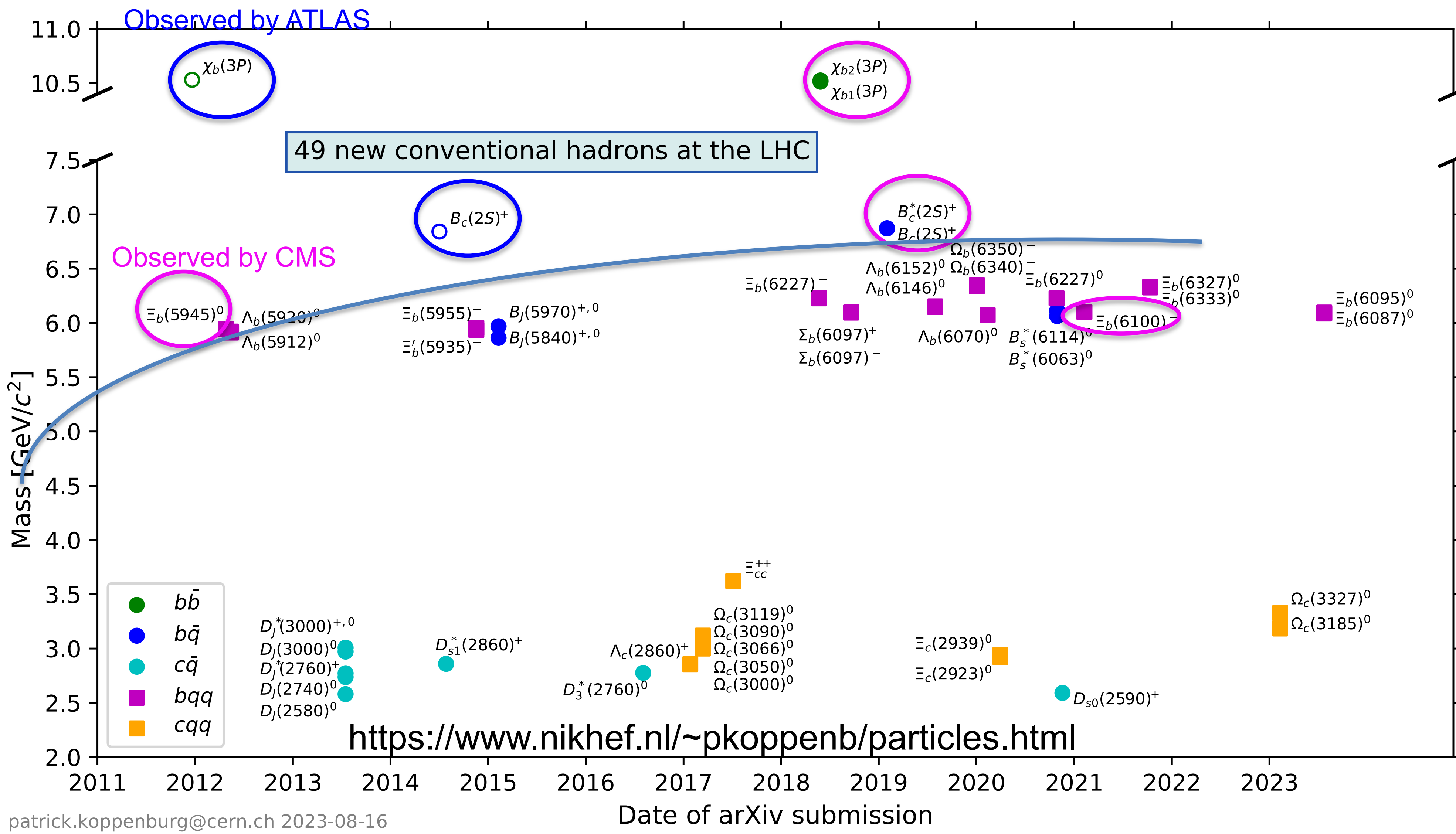
$$\Delta A_{CP} \equiv A_{CP}(\mathrm{K^0_S K^0_S}) - A_{CP}(\mathrm{K^0_S}\pi^+\pi^-) = 6.3 \pm 3.0\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst})\,\%.$$

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

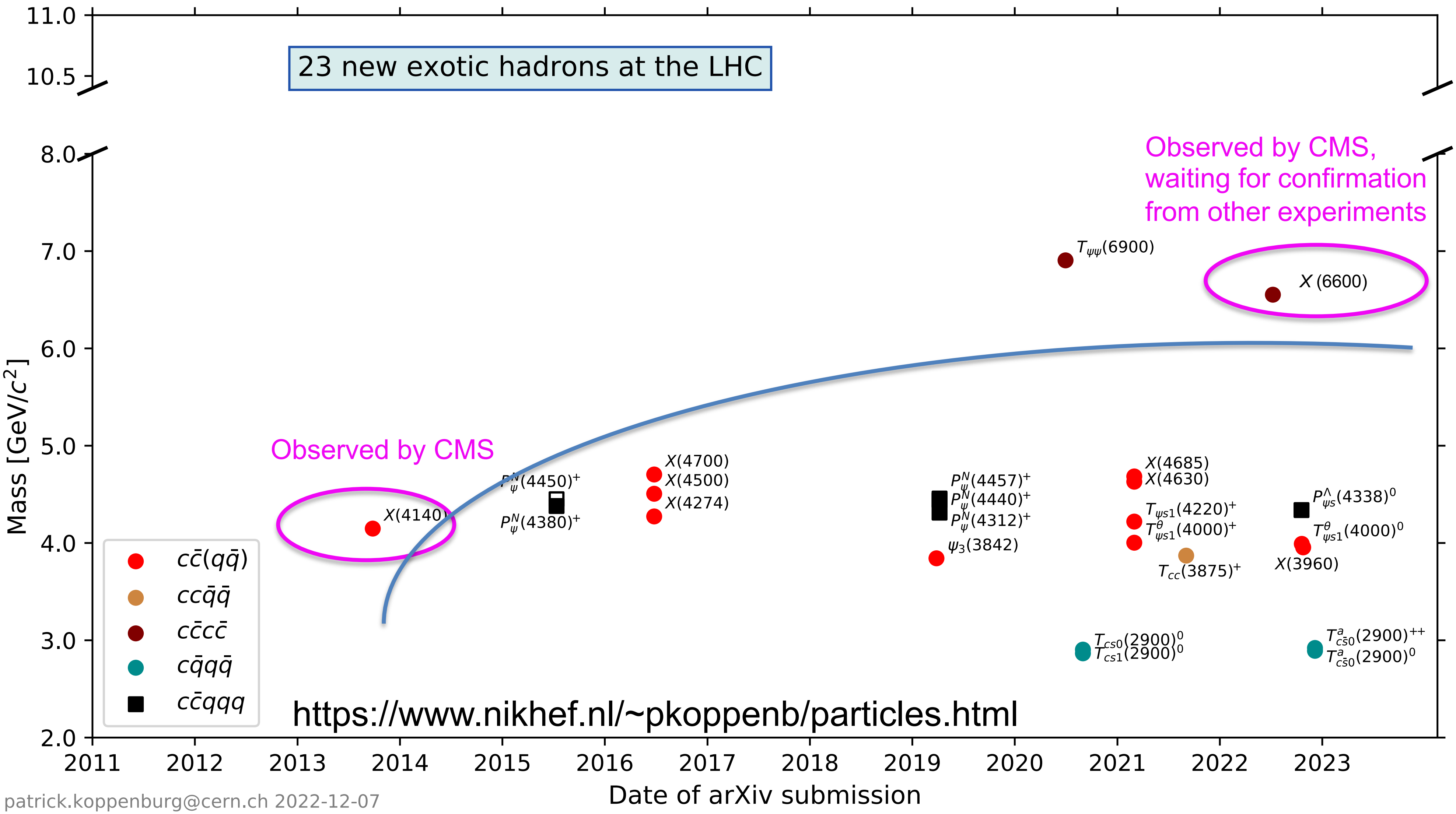
Source	Uncertainty, %
$m(\mathrm{D}\pi^\pm)$ signal model	0.10
$m(\mathrm{D}\pi^\pm)$ background model	0.02
$m(\mathrm{K^0_S K^0_S})$ signal model	0.04
$m(\mathrm{K^0_S K^0_S})$ background model	0.02
$m(\mathrm{K^0_S K^0_S})$ fit range	0.04
Reweighting	0.09
ΔA_{CP} in MC	0.13
Total	0.20

- Compatible with no CPV at 2σ, with LHCb at 2.7σ, with Belle at 1.8σ
- Statistically limited, systematic primarily from fit models
- Paves the way for future more accurate measurements

New conventional hadrons at LHC

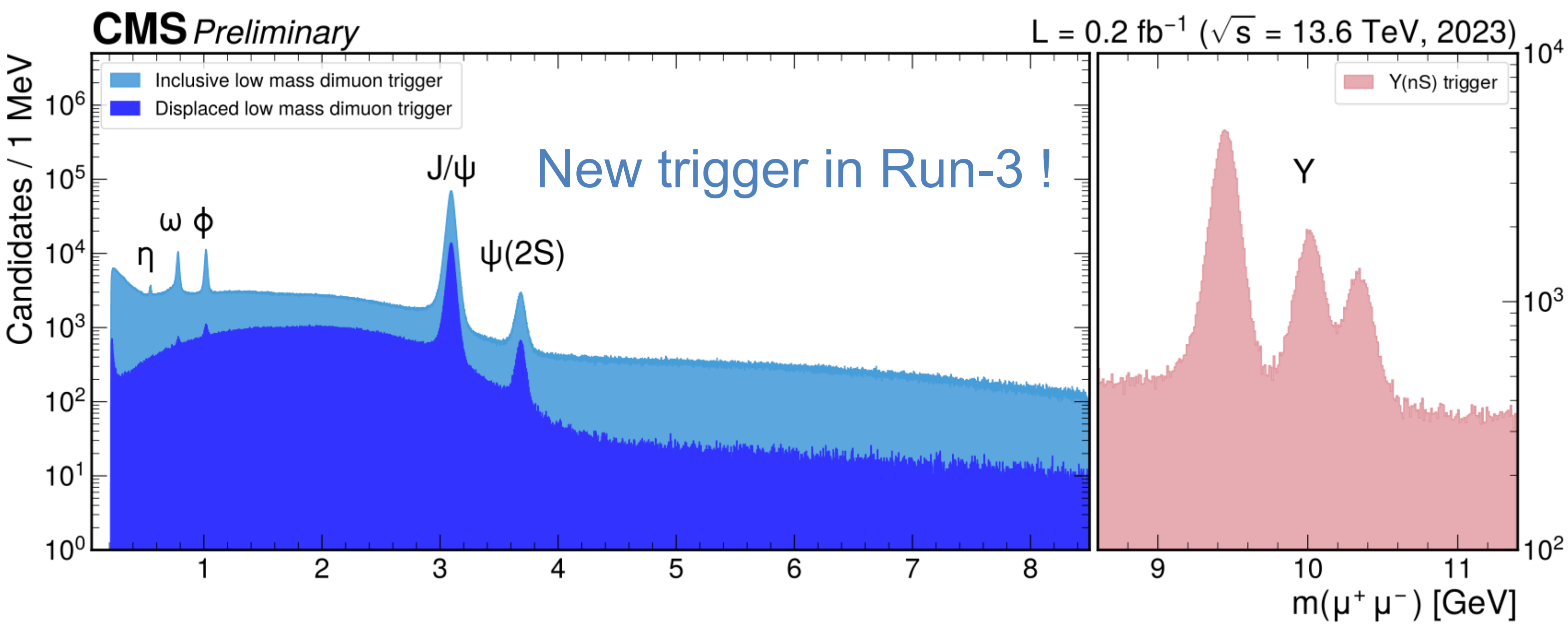


New exotic hadrons at LHC



Summary and outlook

- The general purpose experiment CMS at the LHC pursue an articulated B–Physics program
- Complementary to dedicated experiments:
  - Different phase space coverage
  - Competitive in many analyses (especially if based on muons)
- Developed ingenious data taking techniques to expand physics potential



Thank you!

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