Exotics (non-SUSY) searches at LHC

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on behalf of the CMS and ATLAS collaborations

2023年第九届中国LHC物理年会
The 9th China LHC Physics Workshop (CLHCP2023)
2023年**11月16日至11月20日**

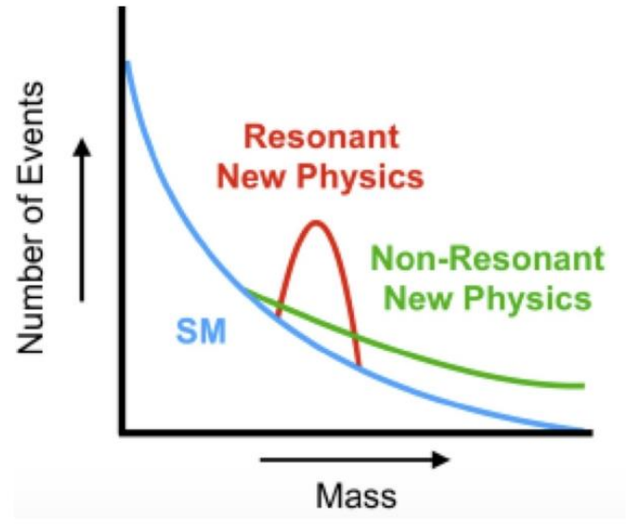
Heavy resonance search at collider experiments

- **Standard Model (SM) is successful for particle physics**
- **SM shortcomes (Hierarchy problem, Unific.of Gravity, Dark Matter/Energy) indicate the existence of New Physics → Beyond Standard Model (BSM) theories**

Heavy resonance search is a good way to probe new physics

➢ **Heavy resonances are predicted in many new physics models:**

- **Two-Higgs-doublet model (A, $H^{\pm}$, …)**
- **Heavy Vector triplet (W', Z')**
- **Many more…**



➢ **A straight-forward way to observe new physics/particles:**

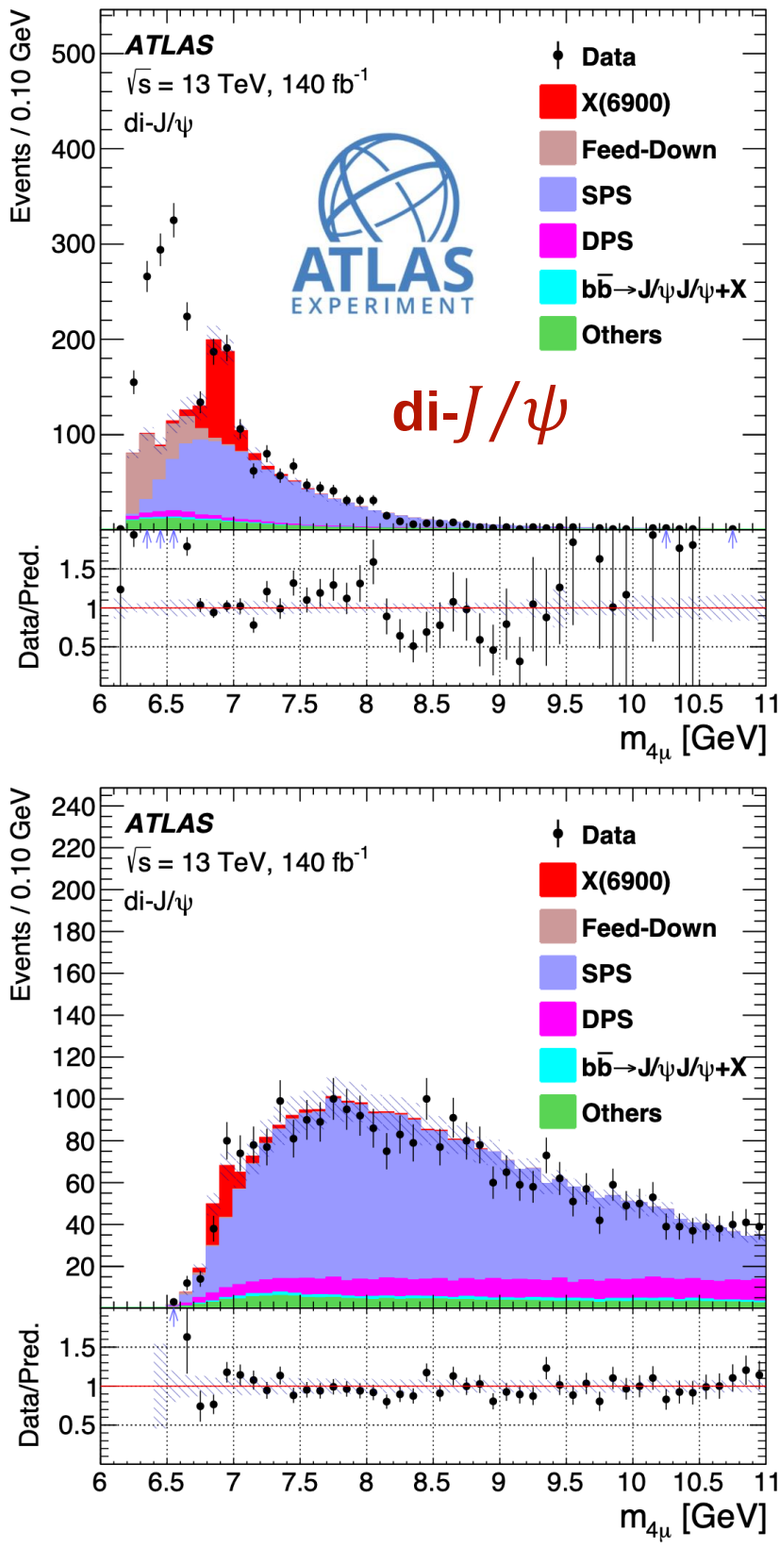
- **Featured kinematics (e.g., "invariant mass") could make a bump on a rather flat SM background spectrum, indicating an unknown resonance particle**
- **High energy collider like LHC makes it possible to search for "heavy" resonances at high energy**

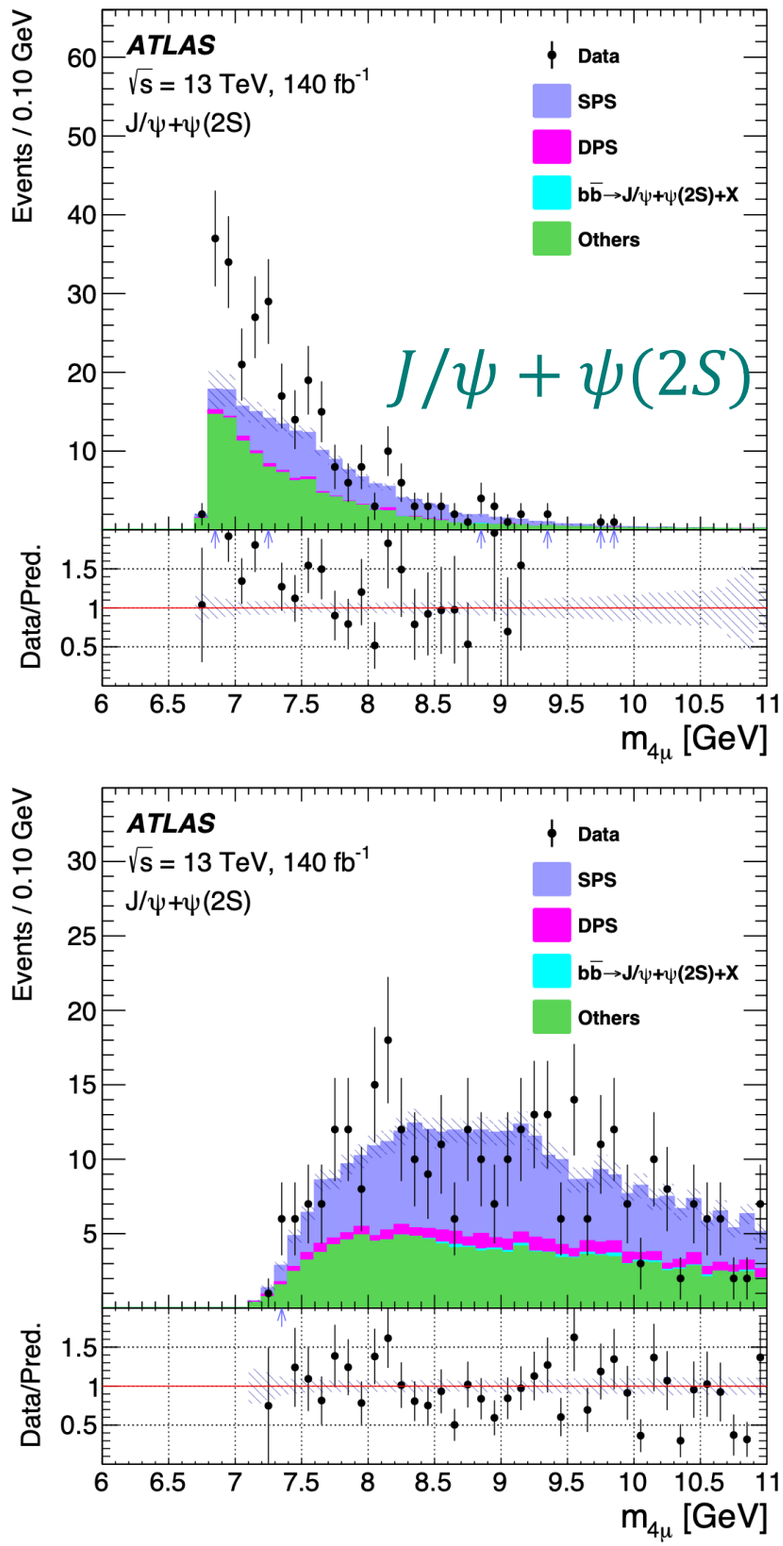
Today I just focus those in which China group has obvious contributions

Phys. Rev. Lett. 131 (2023) 151902

double charmonium distributions (ATLAS)

- Di-muon and tri-muon triggers are used
- Event selections:
  - $p_T > 4,4,3,3$ GeV and $|\eta| < 2.5$ for the four muons
  - J/ψ and $\psi(2S)$ mass window requirement
  - Vertex fit quality and L_{xy} requirements to reduce non-prompt background
- Signal region (top two plots): $\Delta R(angular\ distance) < 0.25$ between charmonia
- Control region (bottom two plots): $\Delta R \geq 0.25$ between charmonia





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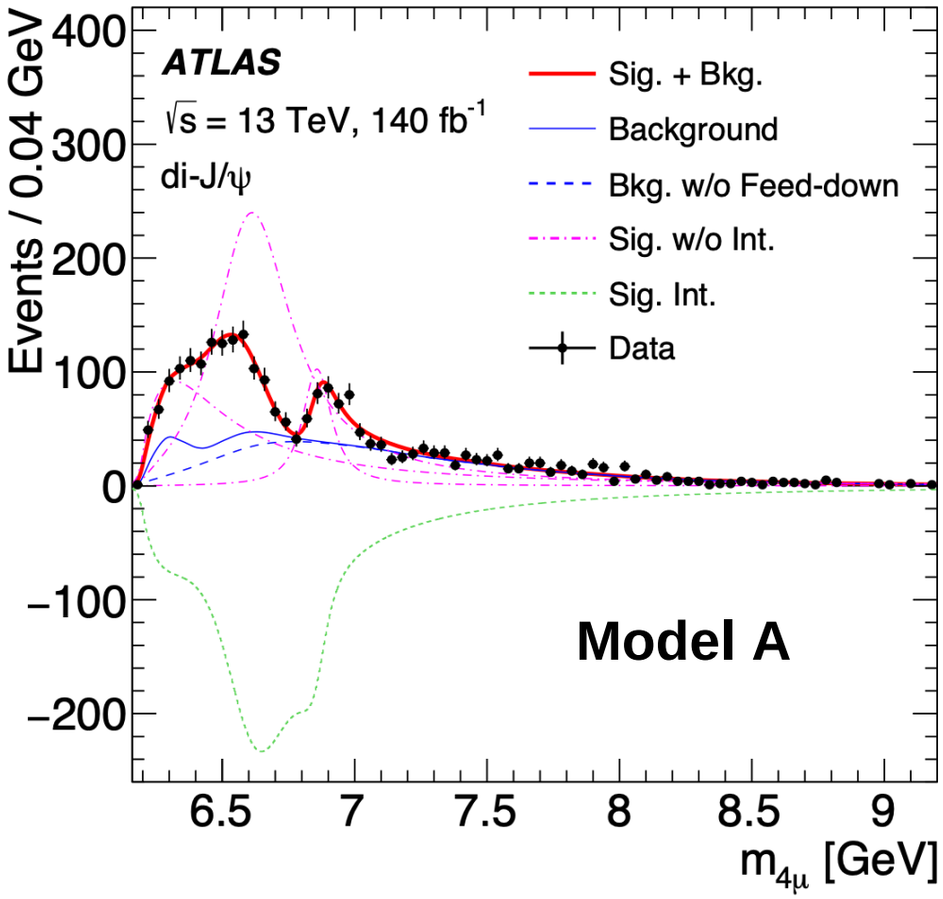
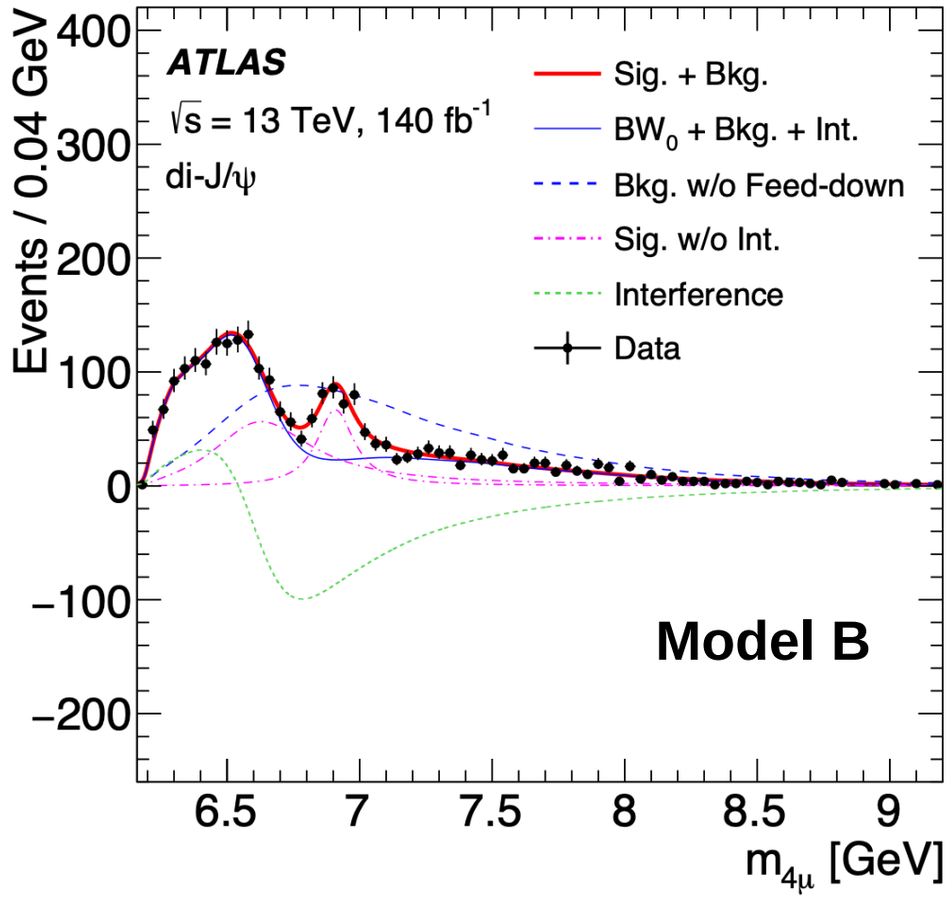
Fit results — $di\text{–}J/\psi$ channel





- In the di-J/ψ channel, two signal models are tested:
  - **Model A**: three interfering signal peaks
  - **Model B**: two signal peaks
- The peak around **6.9 GeV** is consistent with the LHCb observed X(6900) (arXiv:2006.16957), with significance far above 5σ

X(6900) > 5σ

di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—

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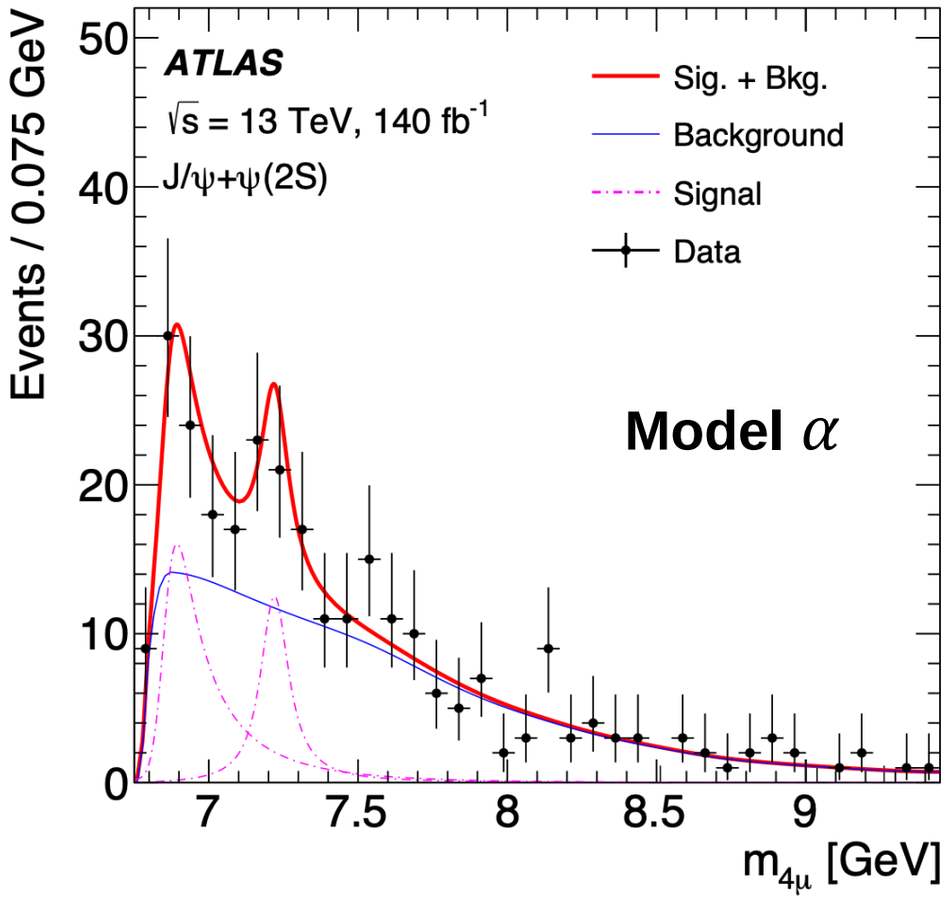
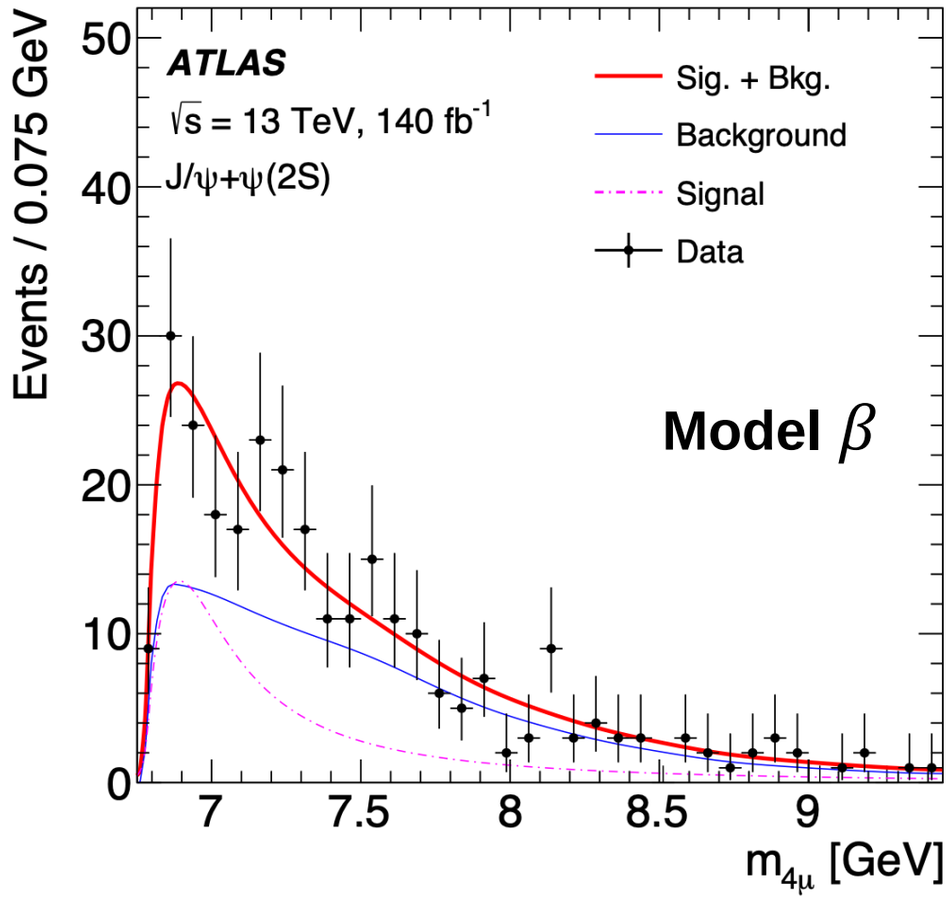
Fit results — $J/\psi + \psi(2S)$ channel



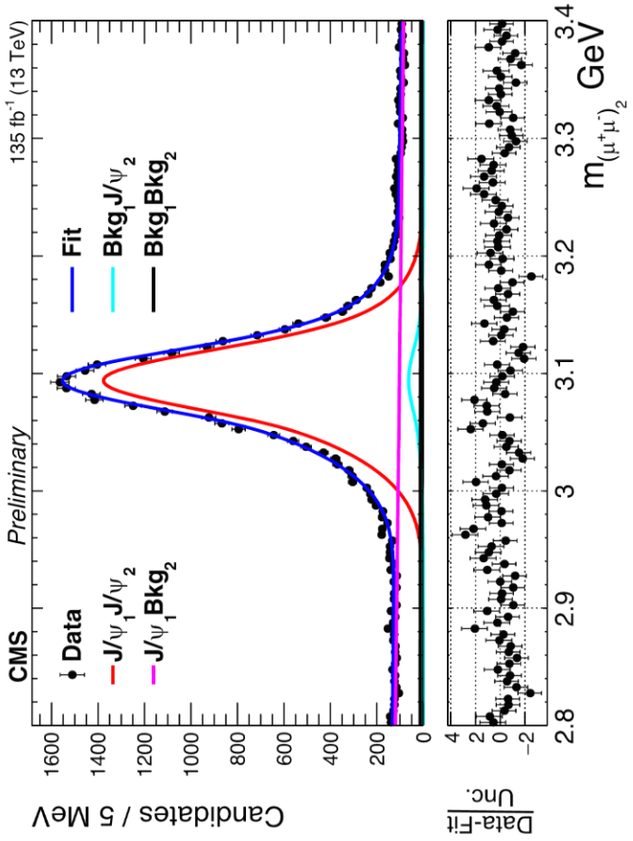


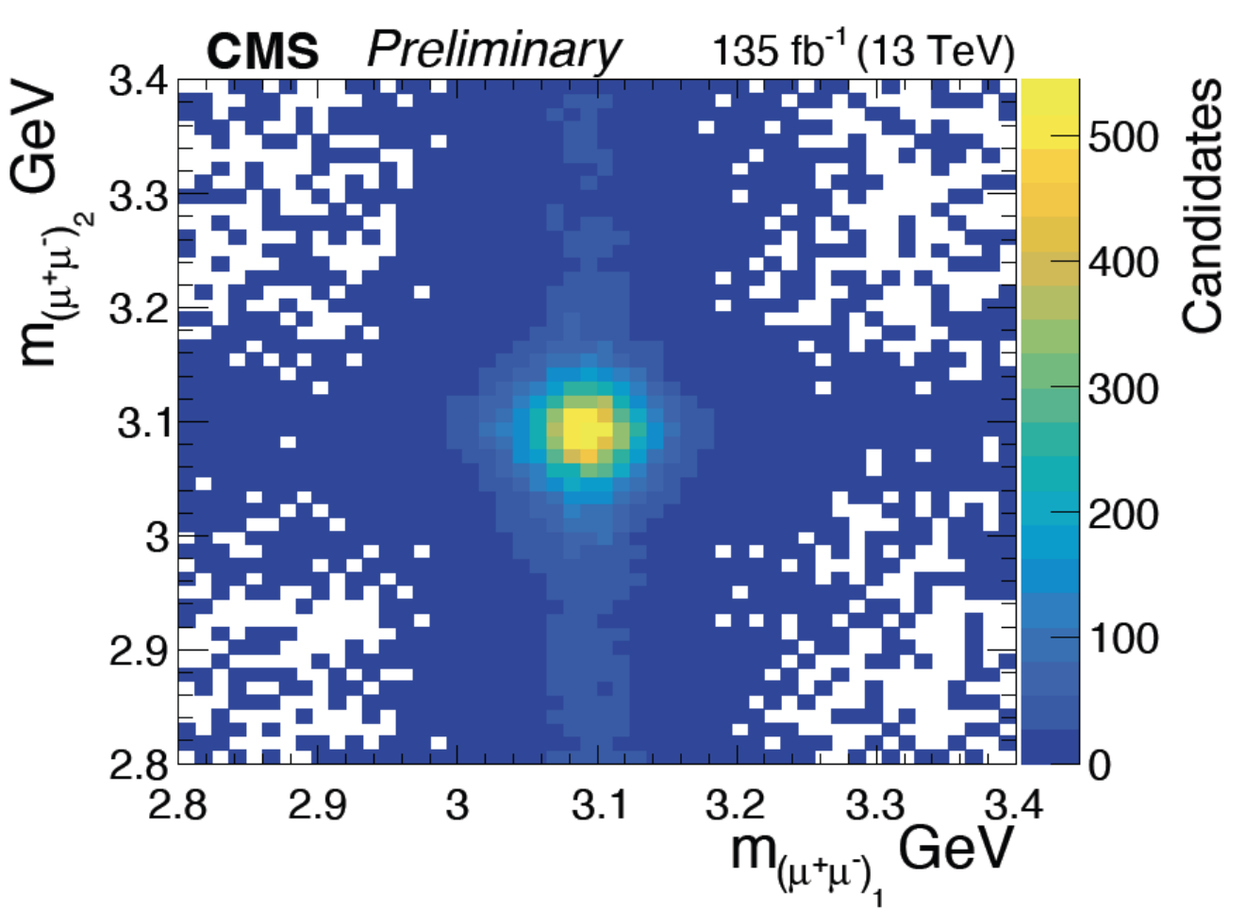
- In the $J/\psi + \psi(2S)$ channel, also two signal models are tested:
  - **Model** α: the same peaks observed in the di-J/ψ channel also decaying into $J/\psi + \psi(2S)$ plus a standalone peak.
  - **Model** β: only one signal peak

$J/\psi+\psi(2S)$	model α	model β
m_3	$7.22 \pm 0.03^{+0.01}_{-0.04}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3	$0.09 \pm 0.06^{+0.06}_{-0.05}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\%^{+25\%}_{-15\%}$	$\pm 20\% \pm 12\%$

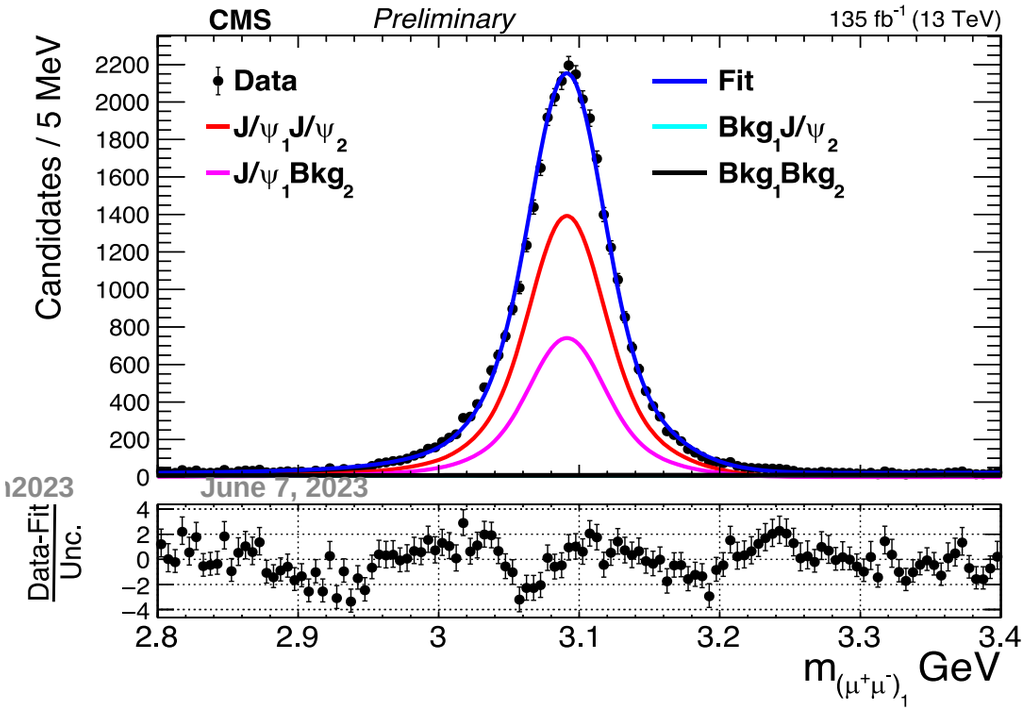
- The signal significance is 4.7σ (4.3σ) for model α (β). The significance of the **2nd peak** (7.2 GeV) reaches **3.0**σ, also hinted by LHCb and CMS (arXiv:2306.07164) in the di-J/ψ spectrum

CMS J/ψJ/ψ candidates at 13 TeV

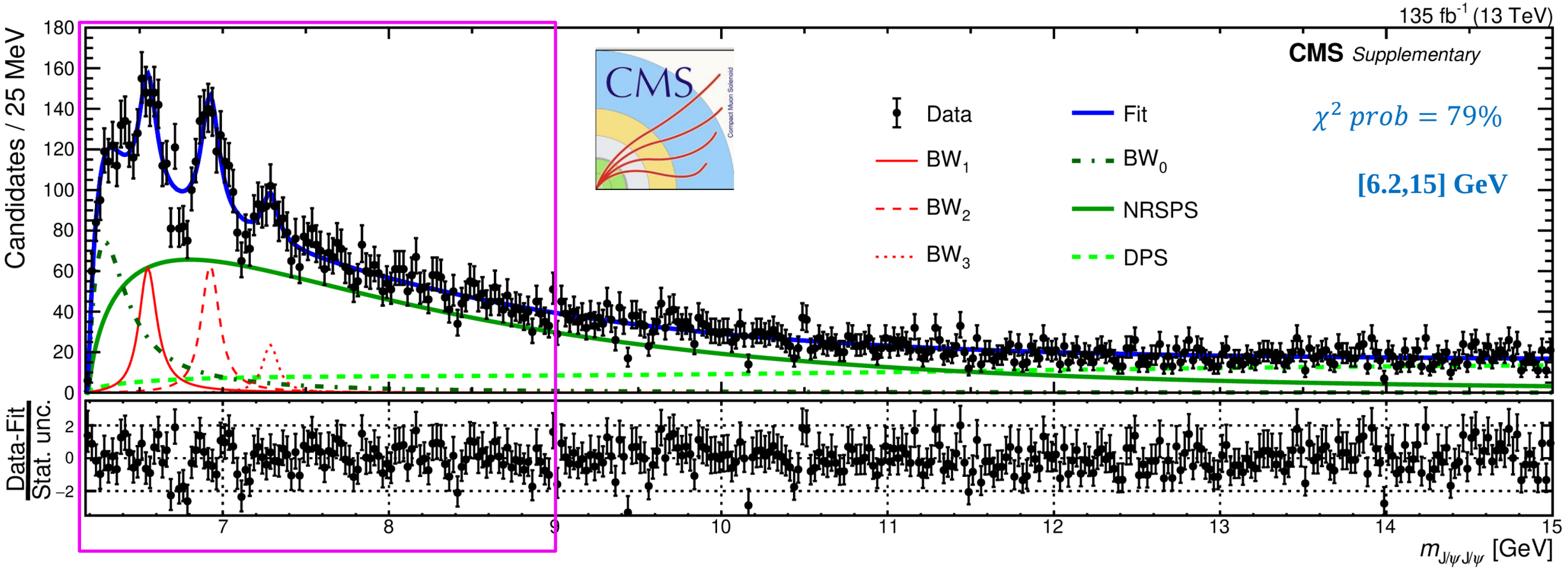




- **CMS data: 135 fb^{-1}, taken in 2016, 2017 and 2018 LHC runs**
- **J/ψ mass and vertex related cuts removed**
- **Clean J/ψ signals are seen**



CMS background (SPS + DPS + BW0)



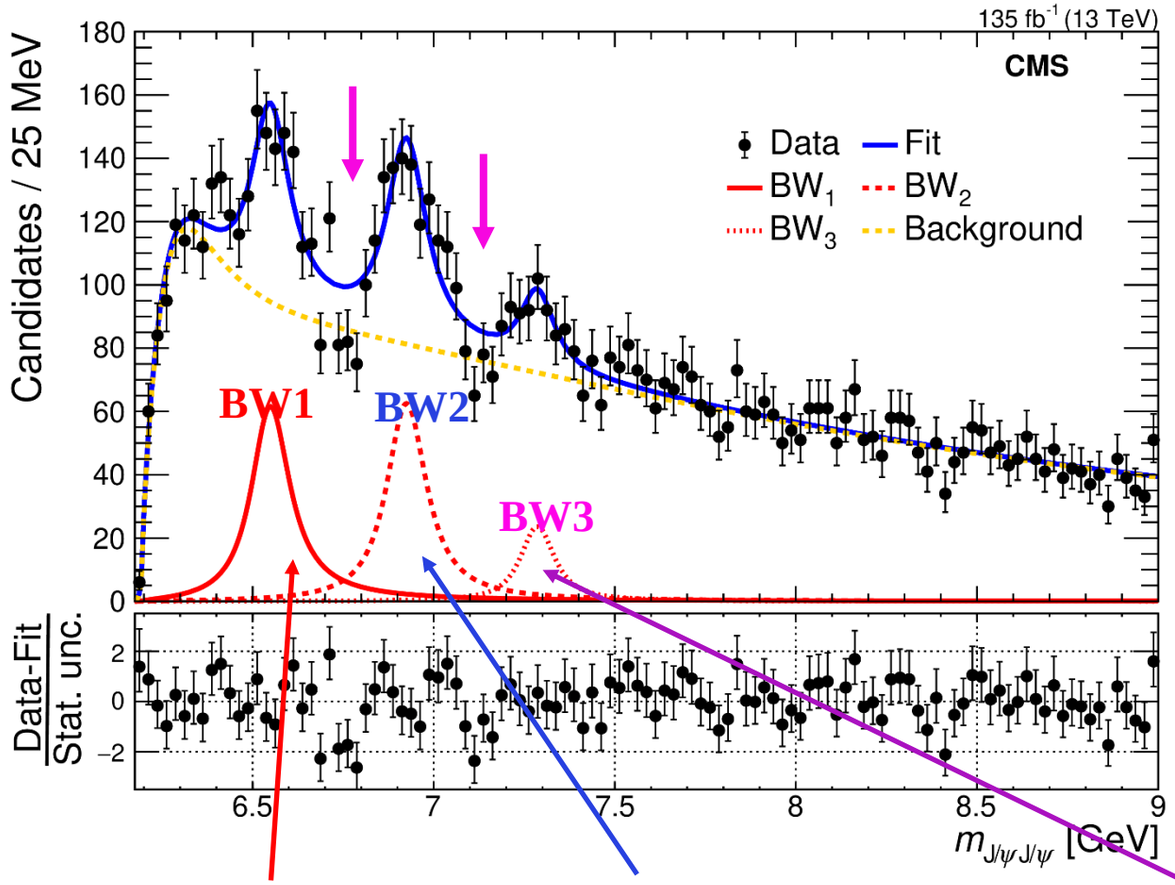
- **Most significant structure is a BW at threshold, BW0--what is its meaning?**
- **Treat BW0 as part of background due to:**
  - **BW0 parameters very sensitive to SPS and DPS model assumptions**
  - **A region populated by feed-down from possible higher mass states**
  - **Possible coupled-channel interactions, pomeron exchange processes…**
- **SPS+DPS+BW0 as our background**

CMS model: 3 BWs + Background

arXiv:2306.07164

χ^2 **Prob. = 1%**

[6.2,7.8] GeV



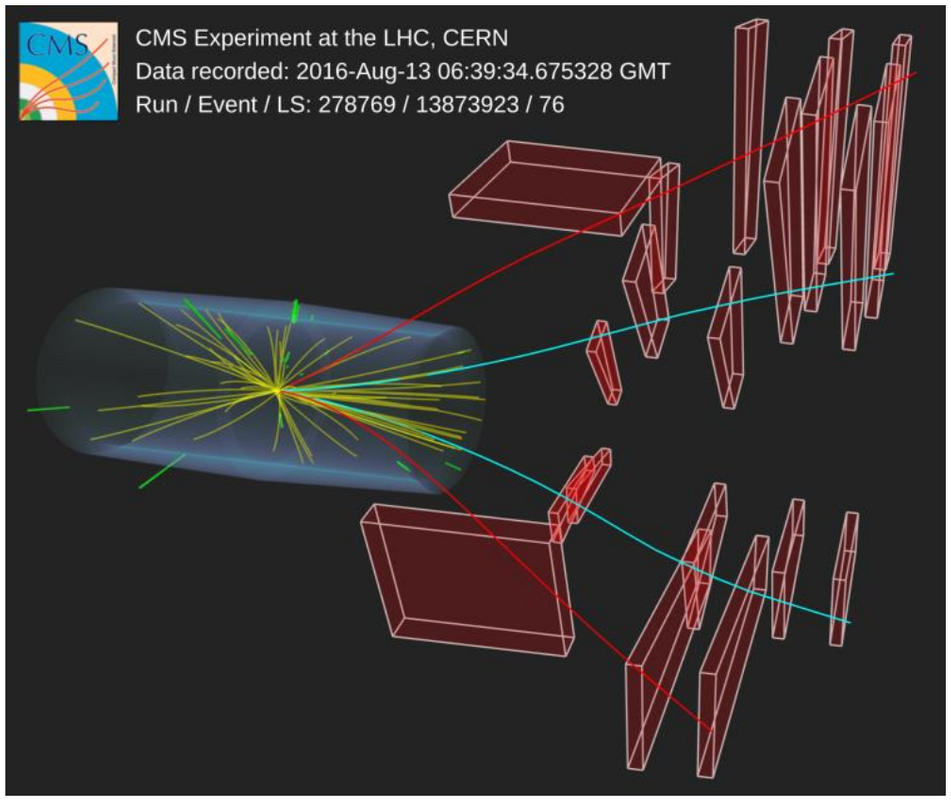
Statistical significance based on: 2 ln(L0/Lmax)

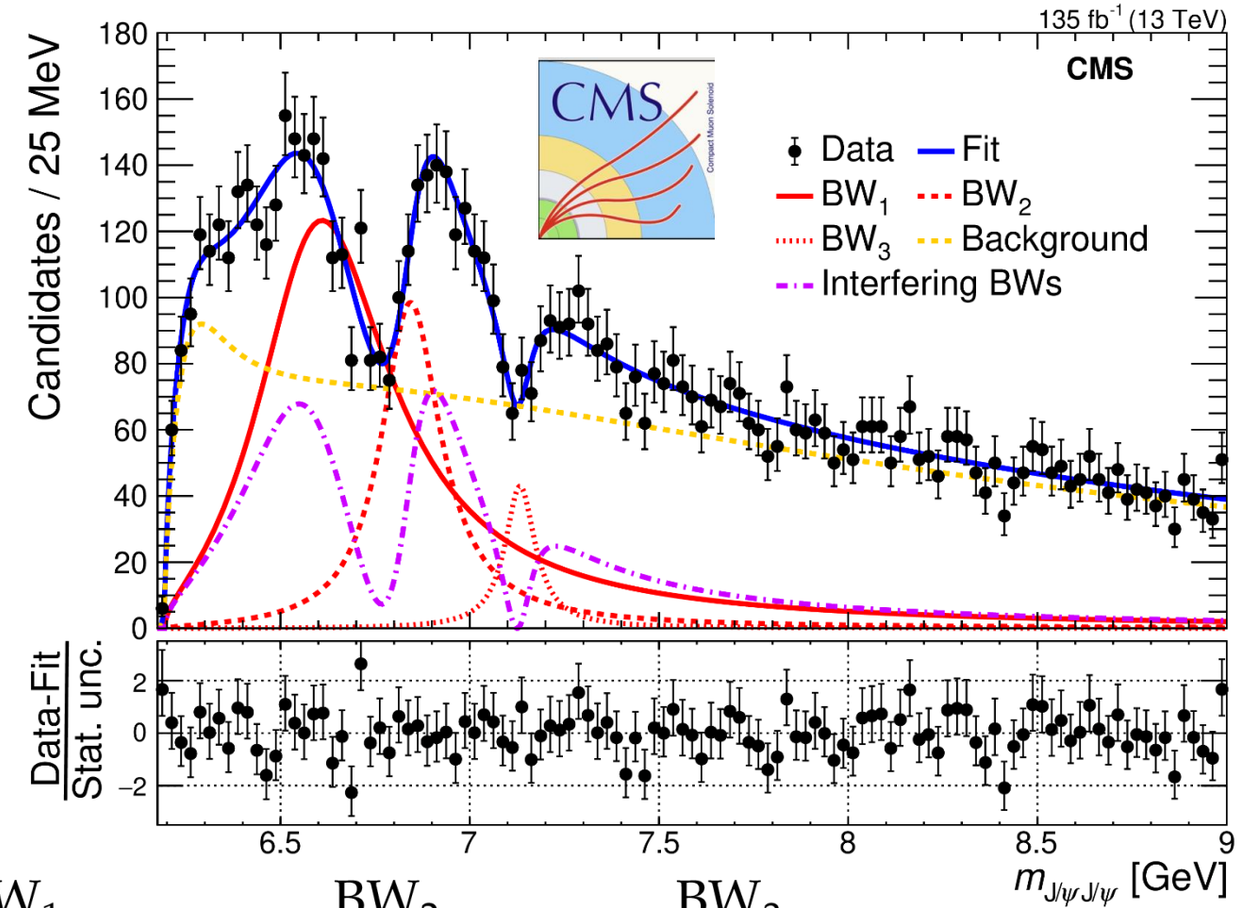
	BW1 (MeV)	BW2 (MeV)	BW3 (MeV)
m	6552 ± 10 ± 12	6927 ± 9± 4	7287 ± 19 ± 5
Γ	124 ± 29± 33	122 ± 22 ± 18	95 ± 46 ± 19
N	474 ± 113	492± 75	156± 56
σ(stat.)	6.5	9.4	4.1
σ(stat. + syst.)	5.7	9.4	4.1
	First observation	Confirmation of X(6900) from LHCb	Evidence

CMS interference fit

- **Fit with interf. among BW1, BW2, and BW3 describes data well**

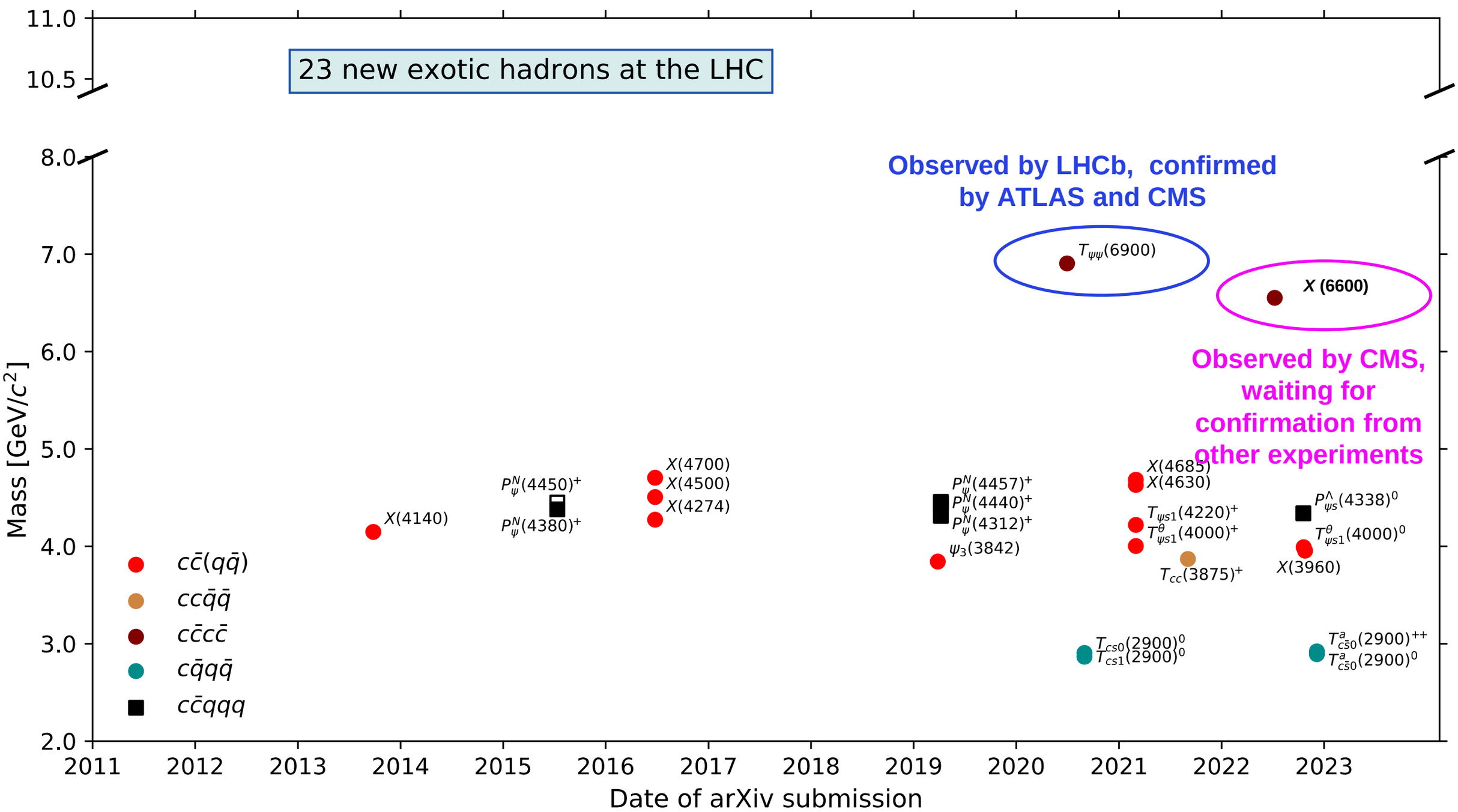
arXiv:2306.07164





		BW_1	BW_2	BW_3
No-interference	m [MeV]	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
	Γ [MeV]	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
	N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}
Interference	m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
	Γ [MeV]	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

New exotic hadrons at LHC



https://www.nikhef.nl/~pkoppenb/particles.html

Low-mass Z' boson

JHEP 07 (2023) 90

- Could address the g-2 anomaly through the Z' loop corrections without contradicting other existing data.
- Ideally suited to address the lepton flavour anomalies measured with the ratio of B-meson decays to muons and electrons.

Search for a new Z' gauge boson in 4μ events [arXiv:2301.09342]

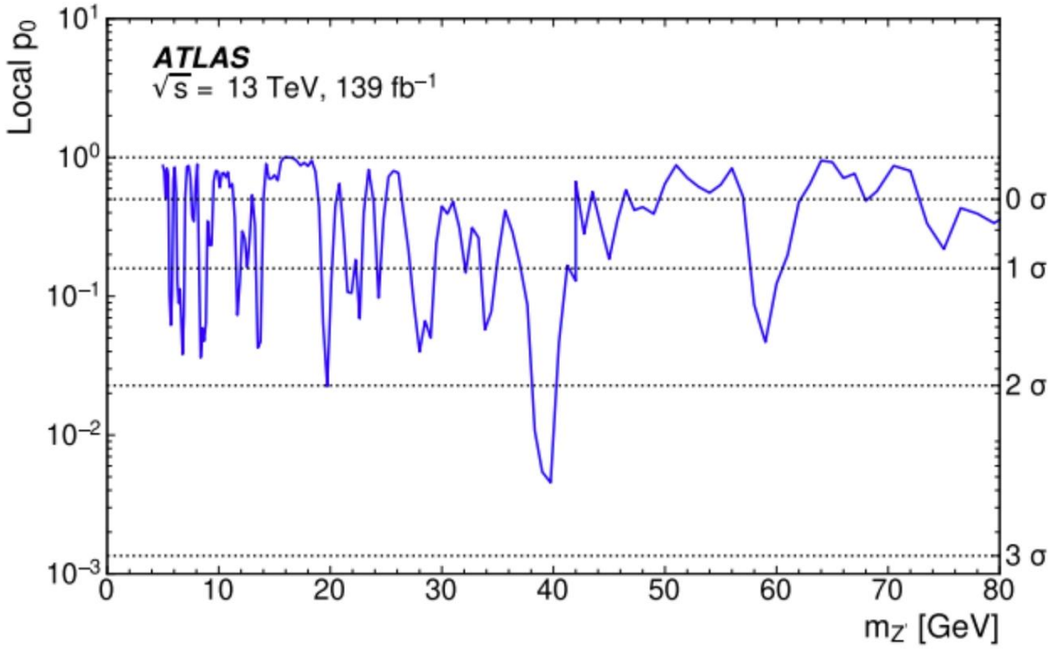
- **Signal:** low-mass Z' boson produced from FSR of Drell-Yan process.
- **Channel:** $\mu^+\mu^-\mu^+\mu^-$
- **Reconstruction:** Z_1 = pair of muons with invariant mass closest to m_Z.
  Z_2= pair of remaining muons with largest invariant mass.

ATLAS EXPERIMENT

中科大，南大

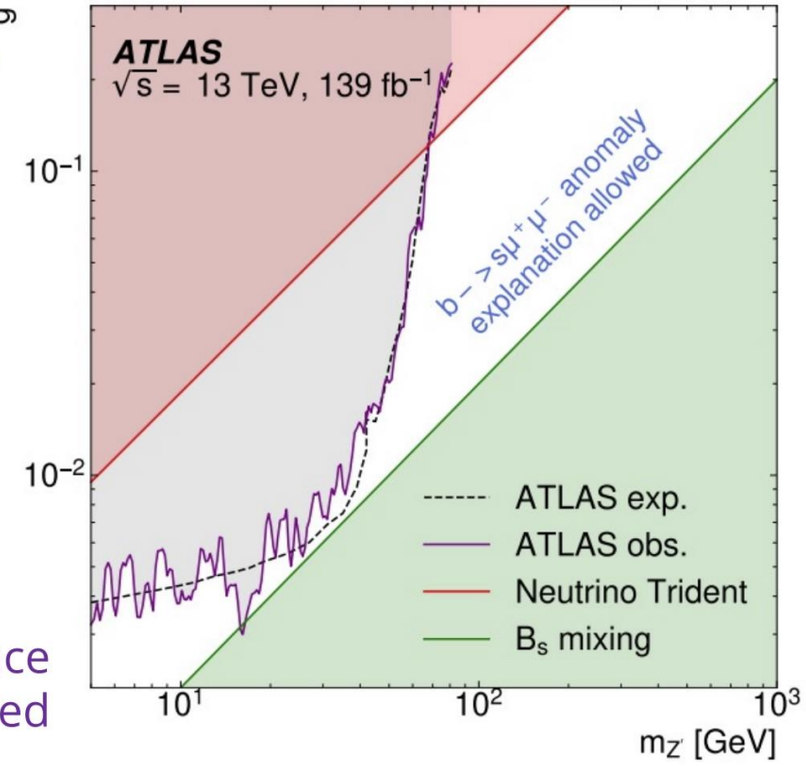
- **Fit:** Profile likelihood fit with m_{Z1} (for $m_{Z'} > 42$ GeV) or m_{Z2} (for $m_{Z'} < 42$ GeV) as discriminating variable.

p_0-value scan across the Z' mass signal regions



coupling strength of the Z' boson to 2nd and 3rd generation leptons

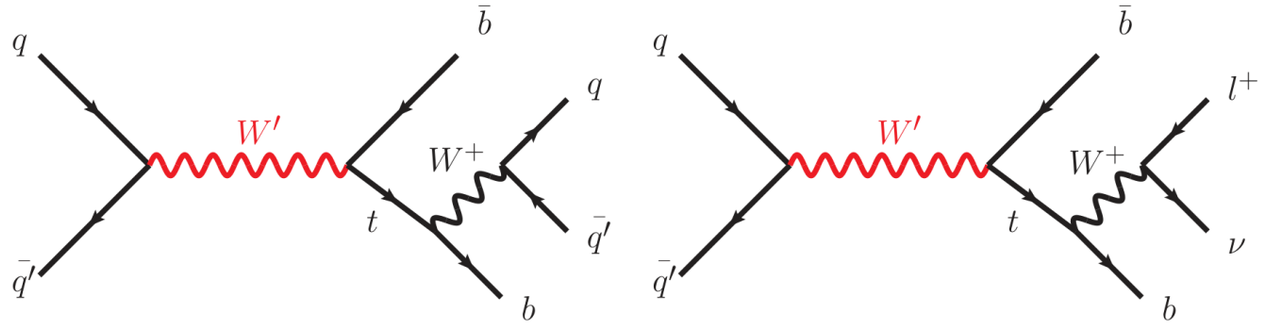
Gap in parameter space now largely excluded



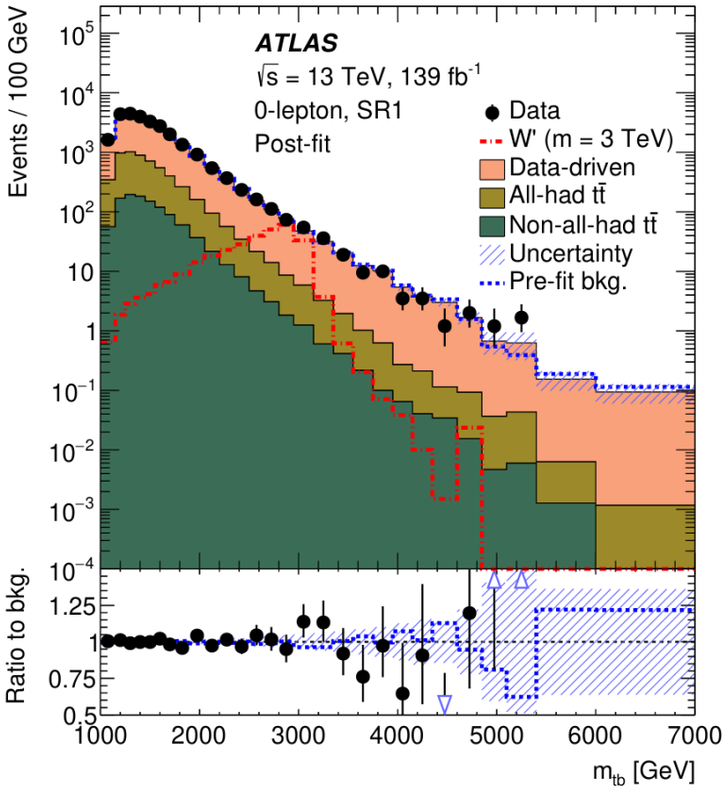
Search for vector-boson resonances decaying into a top quark and a bottom quark

- The W' boson is the mediator of a new charged vector current and can be massive enough to decay into a top quark and a bottom quark[PRD 19 (1979) 1277, PRD 20 (1979) 2619].
- Two chirality scenarios are considered for the W' boson: right-handed chirality and left-handed chirality

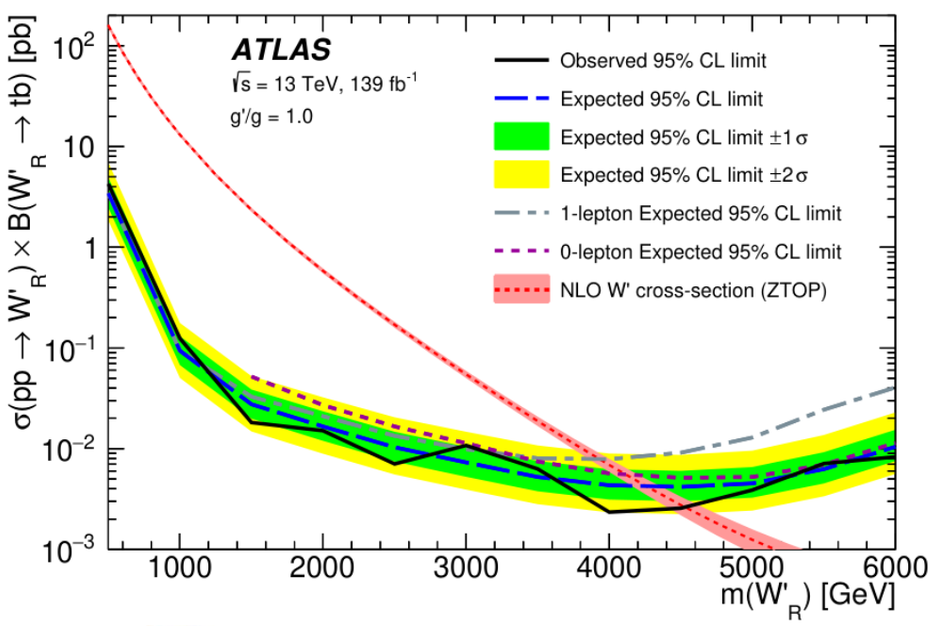
the reconstructed mass of the tb system is used to search for the W'-boson signal with two channels: the 0-lepton channel and 1-lepton channel.



(a)



(b)



- No significant deviation from the background prediction is observed.
- The results are expressed as upper limits on the $W' \to tb$ production cross-section times branching ratio as a function of the W'-boson mass

arXiv:2308.08521 山大

Search for the Zγ decay mode of resonances

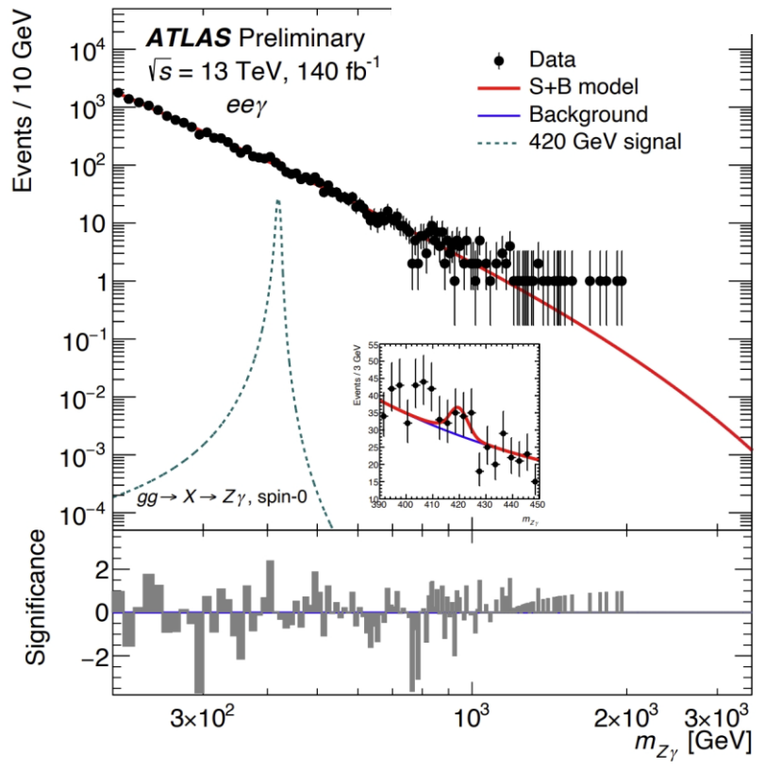
arXiv:2309.04364

Trigger

- Combination of single and dilepton triggers + single photon

Object selection

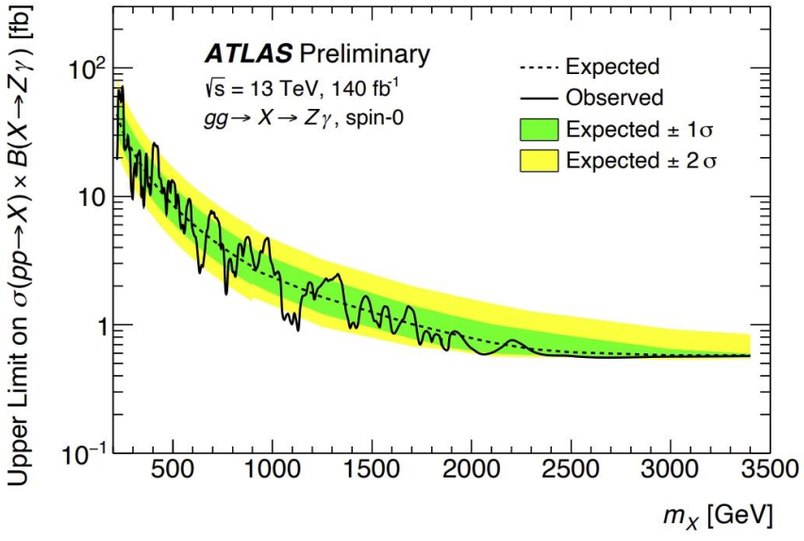
- Opposite sign same flavour leptons with $|m_{ll} - m_Z| < 15$ GeV
- Standard identification and isolation + **special treatment for boosted topologies** (MVA)
  - Relies on shape of the EM shower in the calorimeter and tracking information to identify close-by electron showers

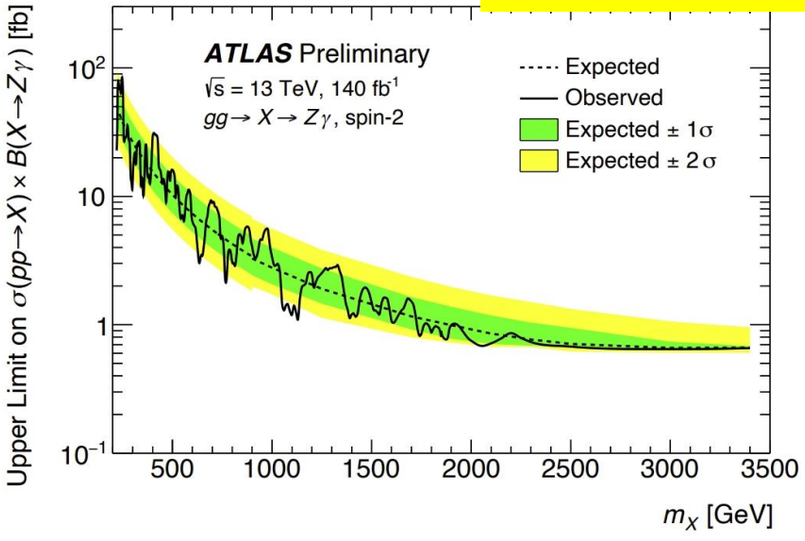


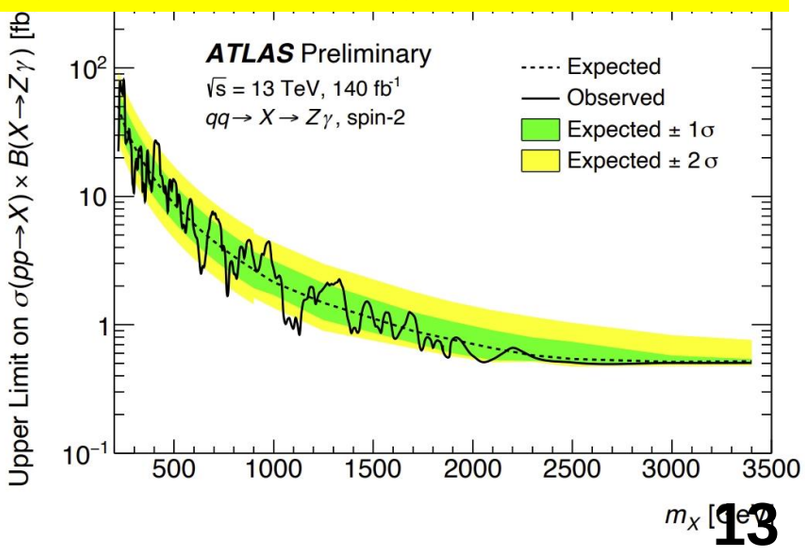
No significant excess observed

X mass (220 GeV-3400 GeV)

1. **spin-0 gg→X: 95% C.L., 65.5-0.6 fb**
2. **spin-2 gg(qq)→X: 95% C.L., 77.4(76.1)-0.6(0.5) fb（高能所，南大）**



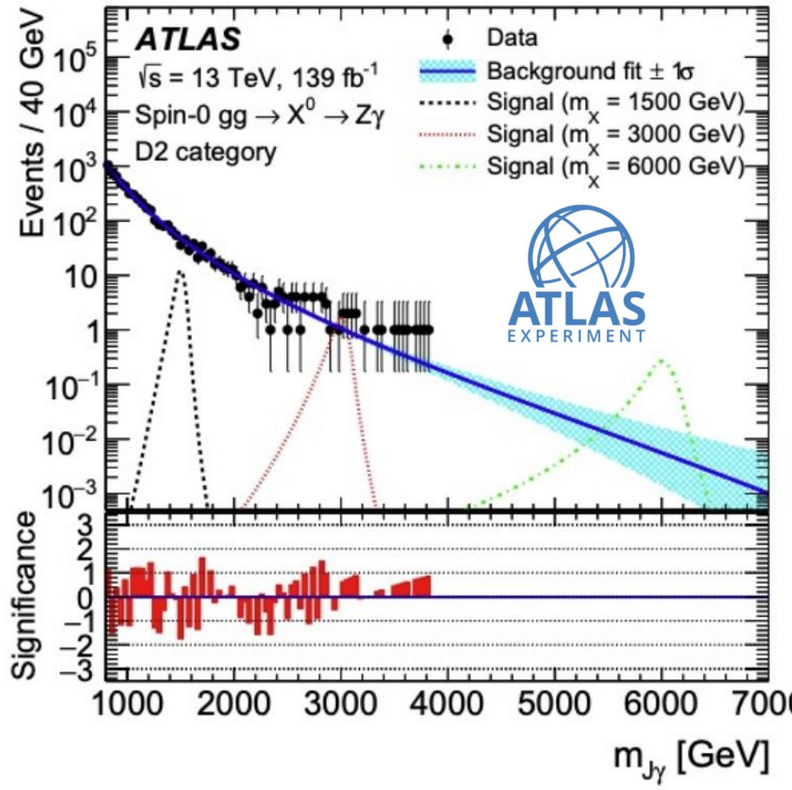




Heavy resonances decaying to bosons

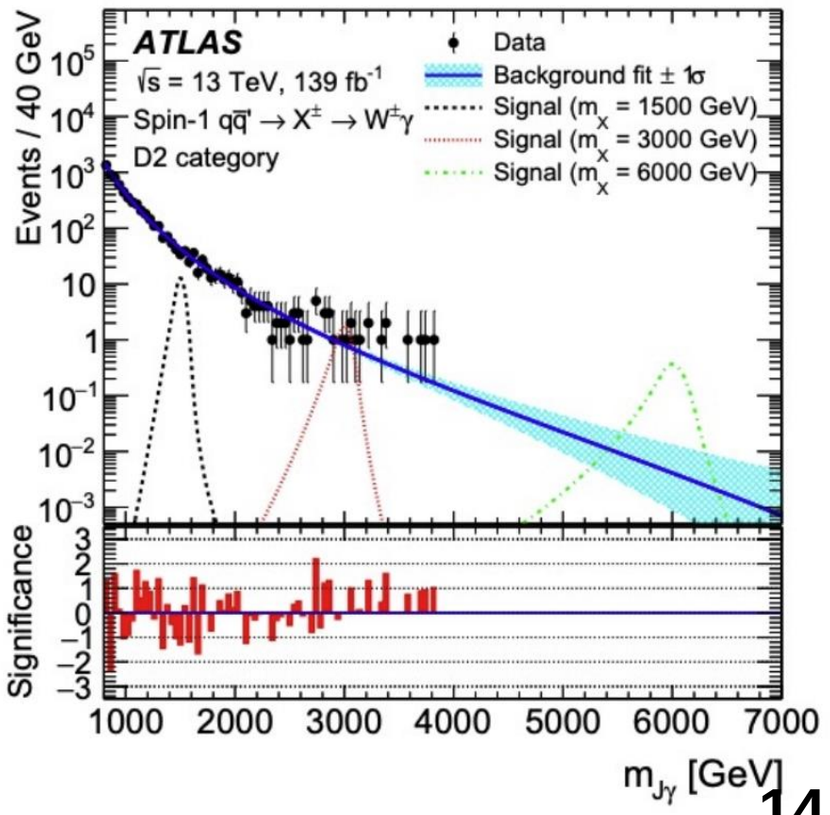
Search for high-mass $W\gamma$ and $Z\gamma$ resonances using hadronic W/Z boson decays [arXiv:2304.11962]

- **Signal:** Generic high-mass boson: spin-1 $X^{\pm}$ or spin-0/2 X^{0}. Assume decay width small compared to experimental resolution.
- **Channel:** $W\gamma/Z\gamma$ with hadronic decays of W and Z.
- **Reconstruction:** large-R jets with 2-pronged substructure for boosted W and Z.
- **Trigger and event selection:** single photon trigger, ≥ 1 photon and ≥ 1 jet with kinematic requirements.



Largest local signal significance (2.5σ) for spin-0 $gg \rightarrow X^{0} \rightarrow Z\gamma$ at $m_X = 3640$ GeV.

Dominant uncertainties for signal come from jet mass/energy/resolution.



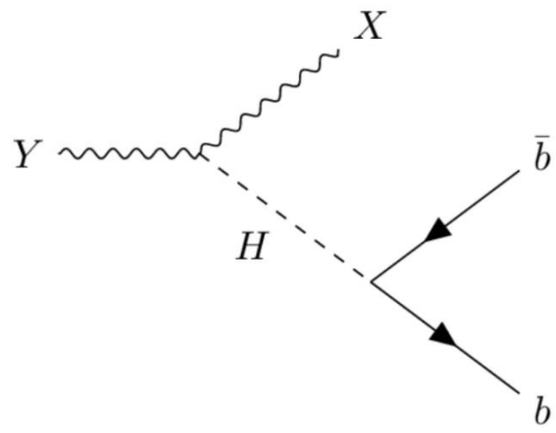
高能所、李所、清华

New Resonance Y → XH→qqbb

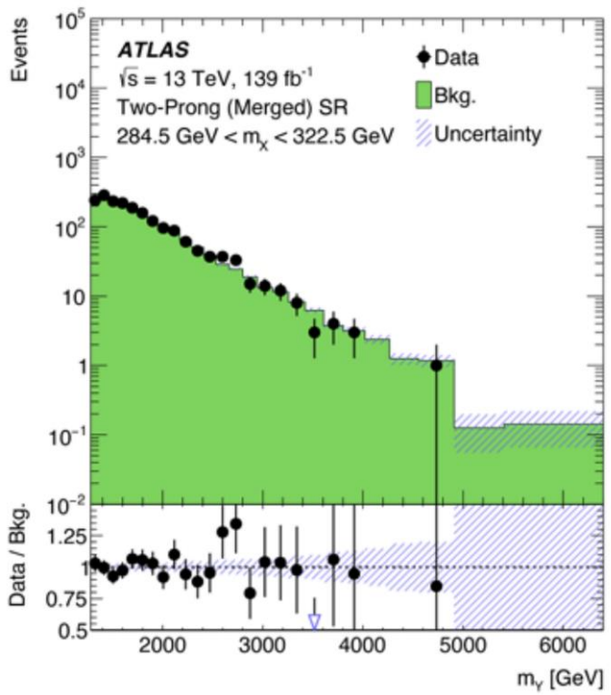
PRD 108 (2023) 052009

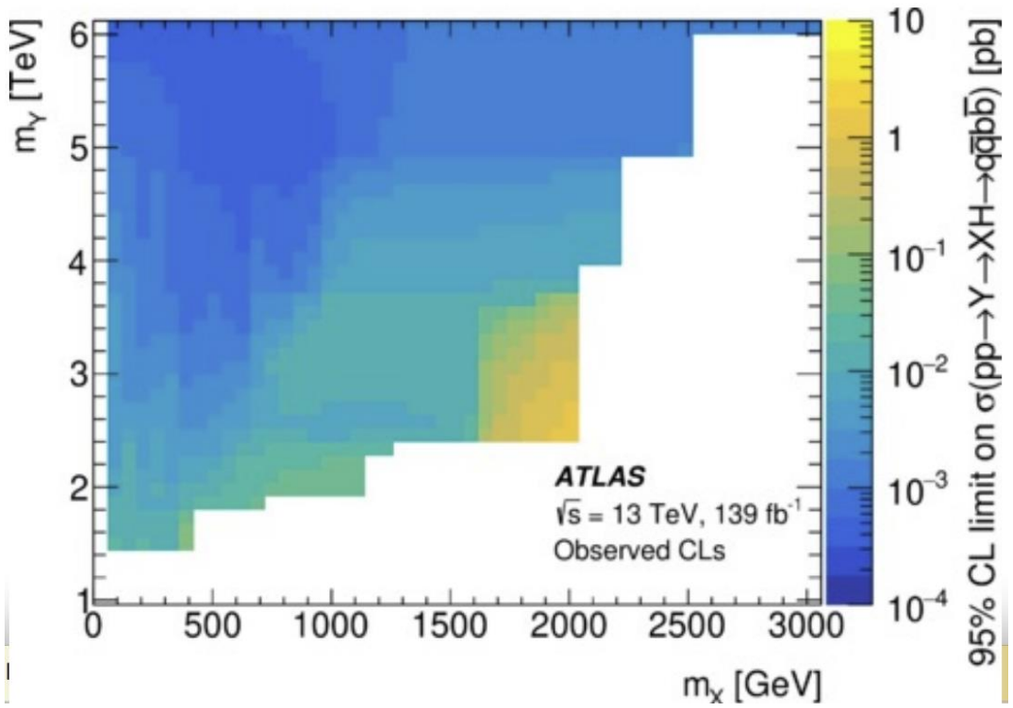
New heavy resonances Y decaying into a Standard Model Higgs boson H and a new boson X.

- Final states defined by a Higgs decays in to bb and the X to light quark resulting in a **fully hadronic final state.**
- Heavy Vector Triplet HVT model used as benchmark for **cross section upper limits**



- Three Signal Regions SR:
  - **SR (Merged):** X and H are reconstructed as a large radius jet.
  - **SR (Resolved):** an orthogonal resolved region where the X is reconstructed as two small radius jets.
  - **SR (Anomaly):** Additional anomaly detection, which selects the *X* particle based solely on its substructural incompatibility with background jets (not orthogonal to the other SRs).

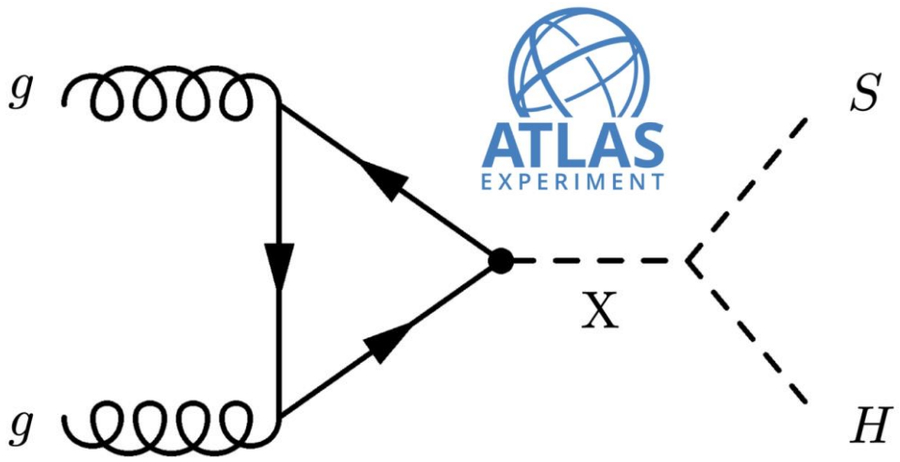




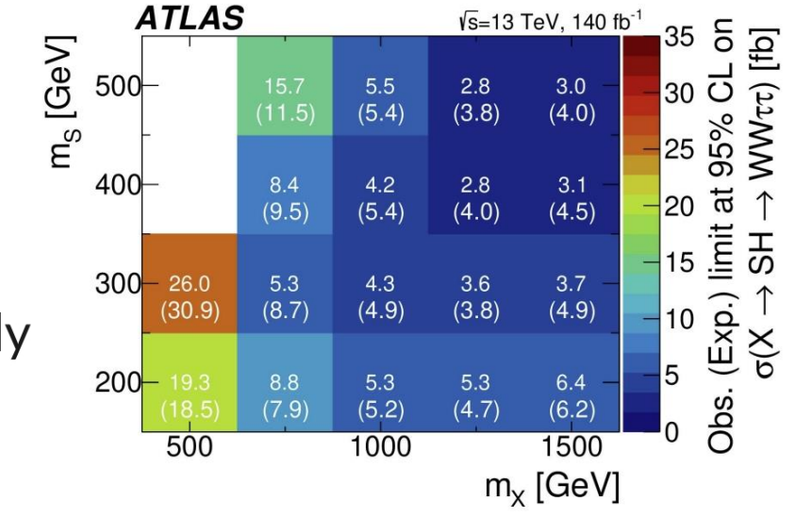
No significant excess of data over the expected background is observed. The observed limits range for the cross section from 0.34 fb to 1.22 pb. (中科大)

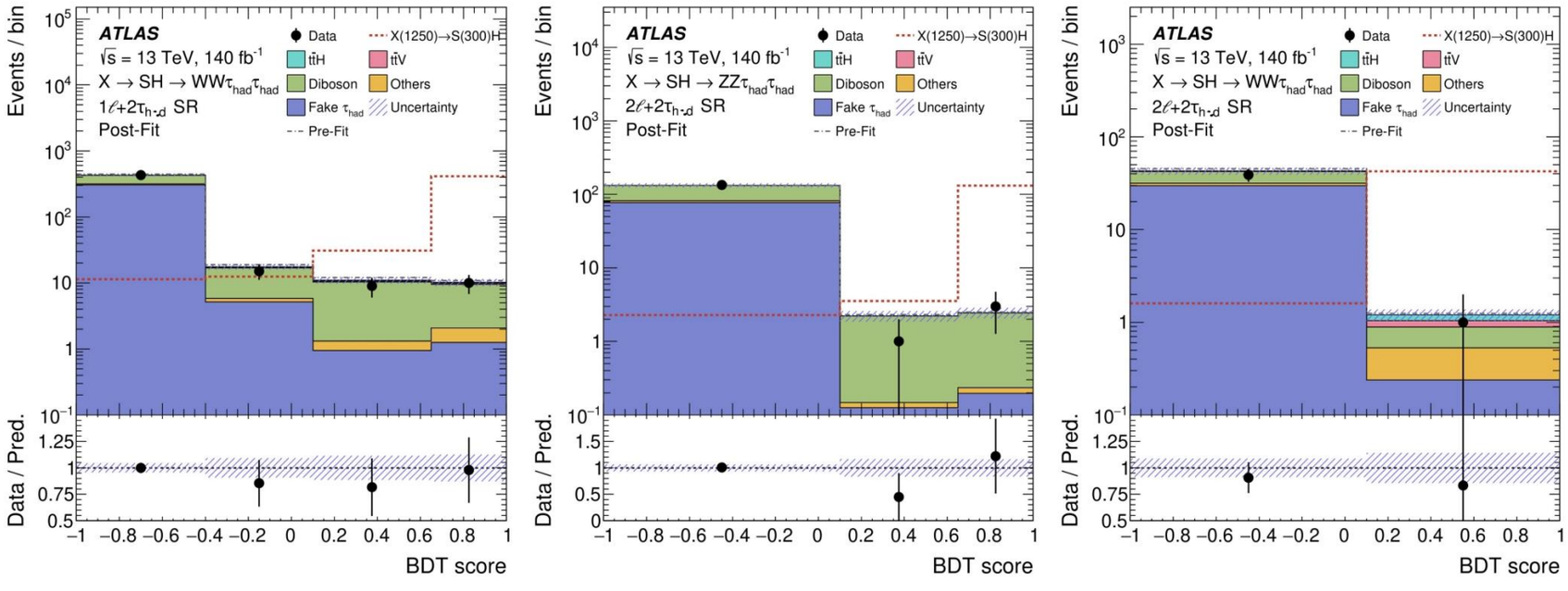
Search for a new heavy scalar particle $X \rightarrow SH$

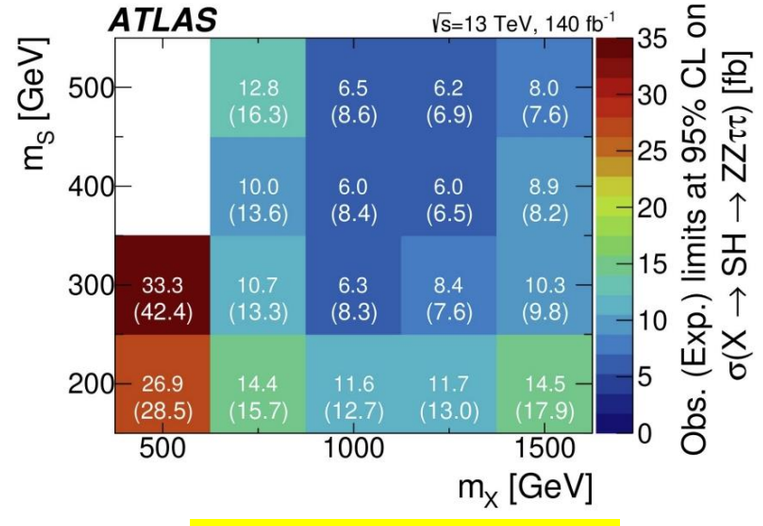
➢ Selecting events containing two hadronically decaying τ-lepton candidates (τ_{had}) from $H \rightarrow \tau^+\tau^-$ decays and one or two light leptons ($\ell = e, \mu$) from $S \rightarrow WW, ZZ$ decays.



- Three signal regions ZZ2l2τ, WW2l2τ, WW1l2τ
  - Distinguished by number of light leptons and m(ll)
- Separate signal and background using boosted decision trees
  - split in signal regions and mass of S
  - m_X provided as a parameter, background gets assigned m_X randomly
- Exclusion fit performed on BDT output distributions







JHEP 10 (2023) 009

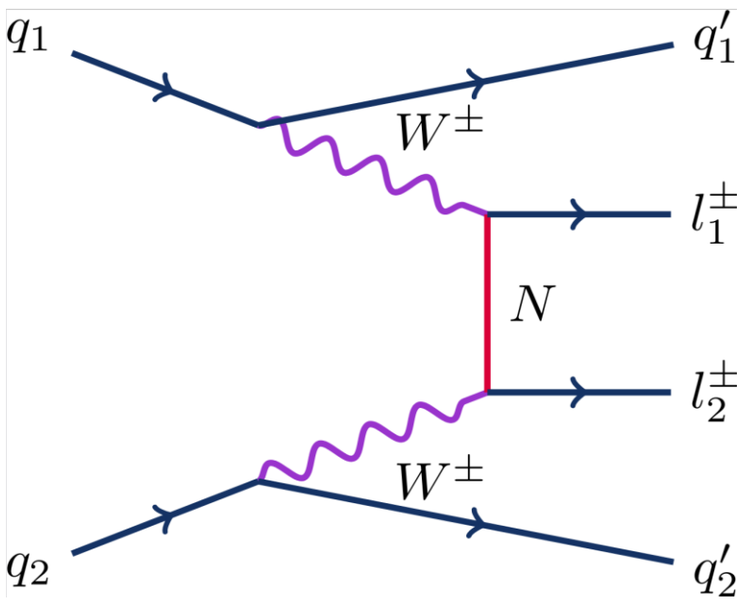
高能所

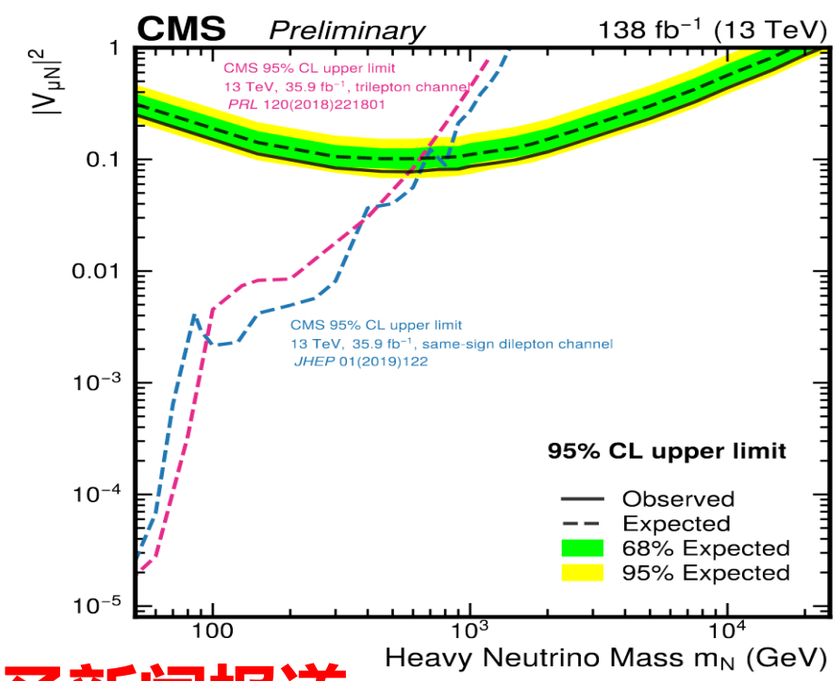
Probing Heavy Majorana Neutrinos

➢ **The first search exploiting the vector boson fusion process to probe heavy Majorana neutrinos and the Weinberg operator, which produced either a pair of muons or a pair of antimuons.**

➢ **No evidence of lepton number violation in the muon data. For heavy Majorana neutrinos, constraints on the squared mixing element between the muon and the heavy neutrino are derived in the heavy neutrino mass range 50 GeV–25 TeV; for masses above 650 GeV these are the most stringent constraints**

➢ **A first test of the Weinberg operator provides an observed upper limit at 95% C.L. on the effective μμ Majorana neutrino mass of 10.8 GeV.**





Upper limits on the heavy neutrino mixing element $|V_{\mu N}|^2$ at the 95% C.L. as a function of the heavy neutrino mass m_N.

CERN和《中国科学报》给予新闻报道

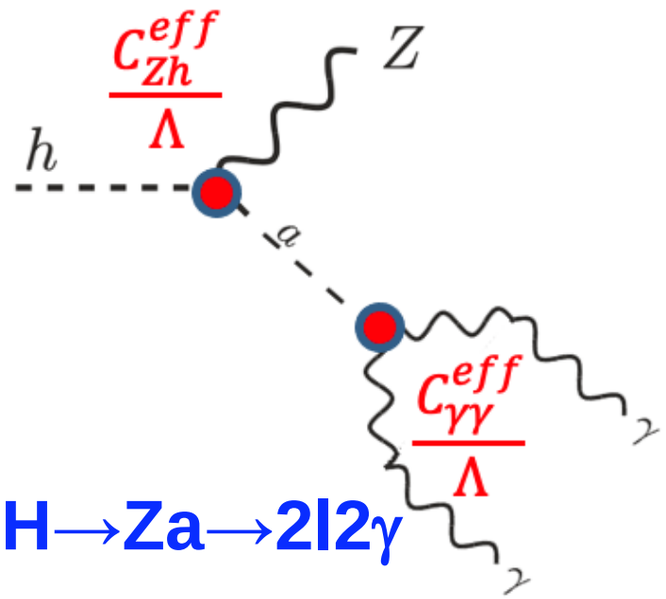
CMS北大组主导

Phys. Rev. Lett. 131 (2023) 011803, Editors' suggestion & Featured in Physics

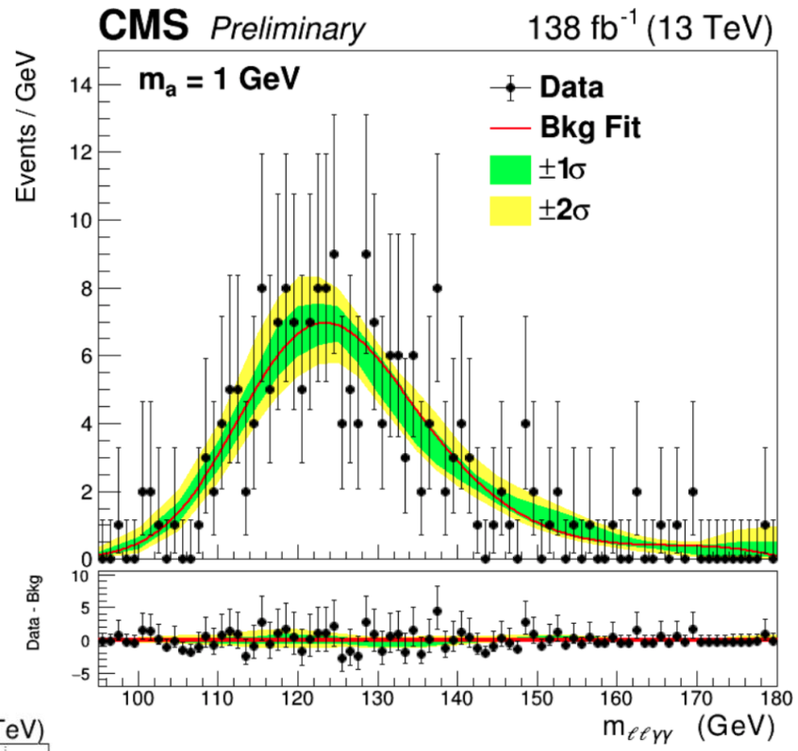
Search for the exotic decay of the Higgs boson into a Z boson and a light pseudoscalar

➢ First search for the exotic decay of the Higgs boson to an ALP and a Z boson, where the ALP decays to a pair of photons: an evidence of BSM.

➢ The mass range of $1 < m_a < 30$ GeV is considered for $H \rightarrow Za$ decay.

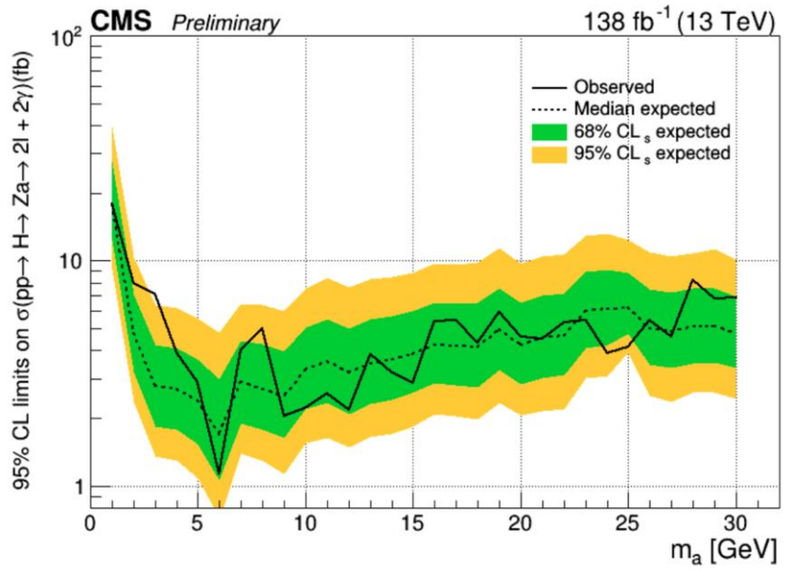


H→Za→2l2γ



No significant deviation from the standard model expectation is observed.

CMS-PAS-HIG-22-003
已投稿PLB, 高能所



Expected and observed 95% CL limits on σ(pp → H) × B(H → Za → 2l2γ). The observed (expected) limits range from 17.8 (17.9) fb for m_a = 1 GeV to 4.7 (6.9) fb for m_a = 30 GeV.

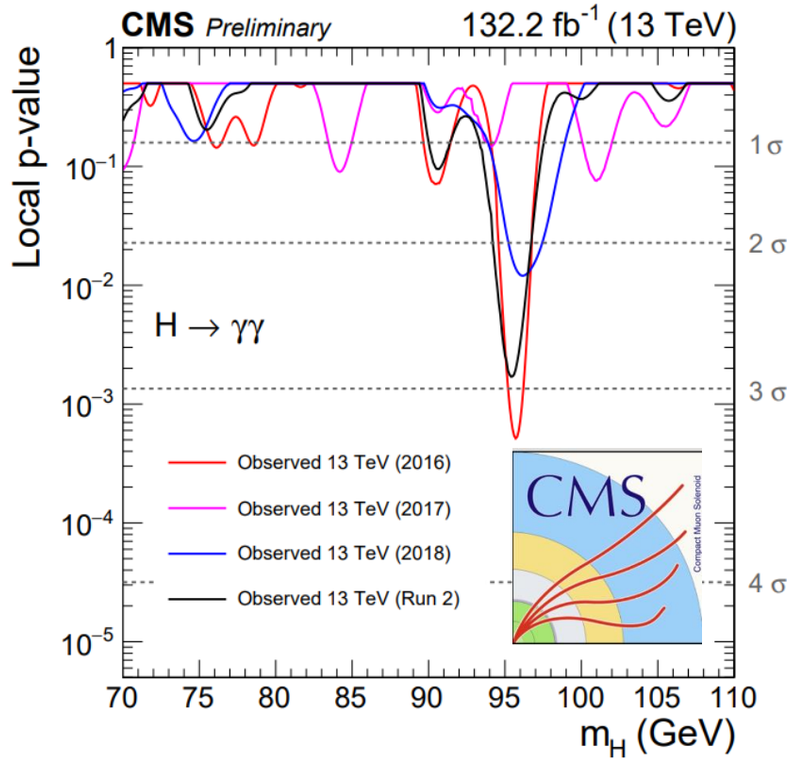
Search for standard model-like Higgs boson h→γγ

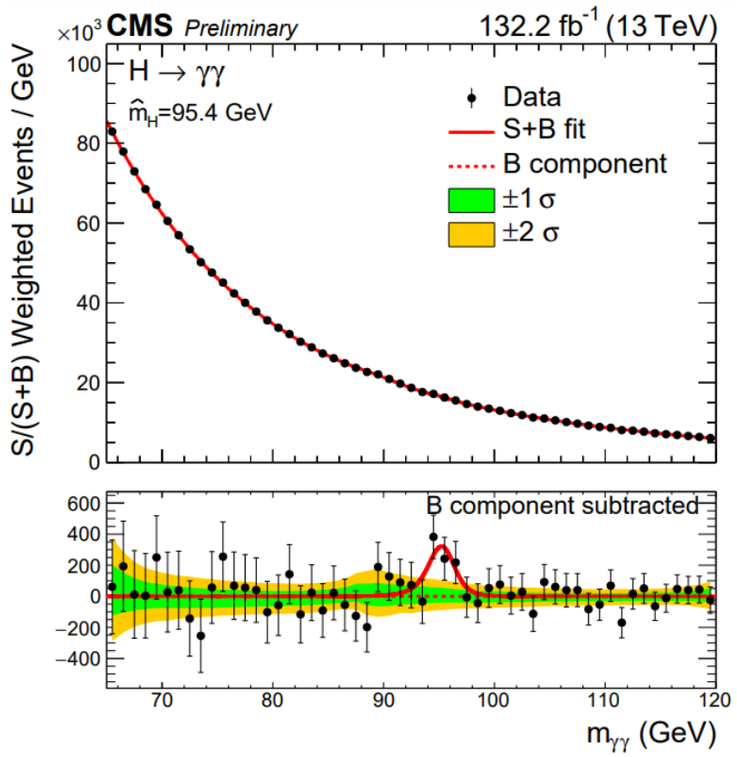
CMS-PAS-HIG-20-002，高能所

- **The extended parameter space of several BSM models predicted the presence of additional Higgs bosons with masses below 125GeV**

- **Good motivation for extending searches for Higgs bosons to masses as far below m_H = 110 GeV as possible, where H refers to an additional Higgs boson which is "SM-like"**

- **A mass hypothesis of 95.4 GeV with a local (global) significance of 2.9 (1.3) standard deviations.**

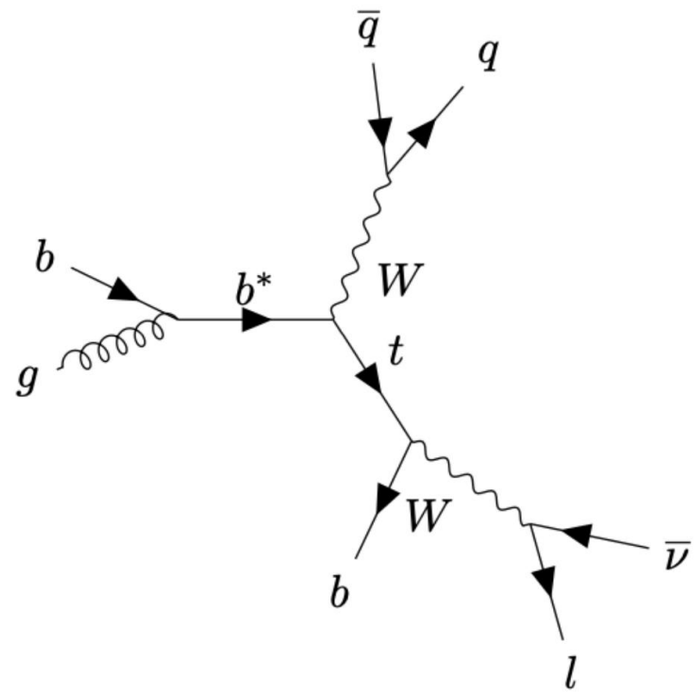


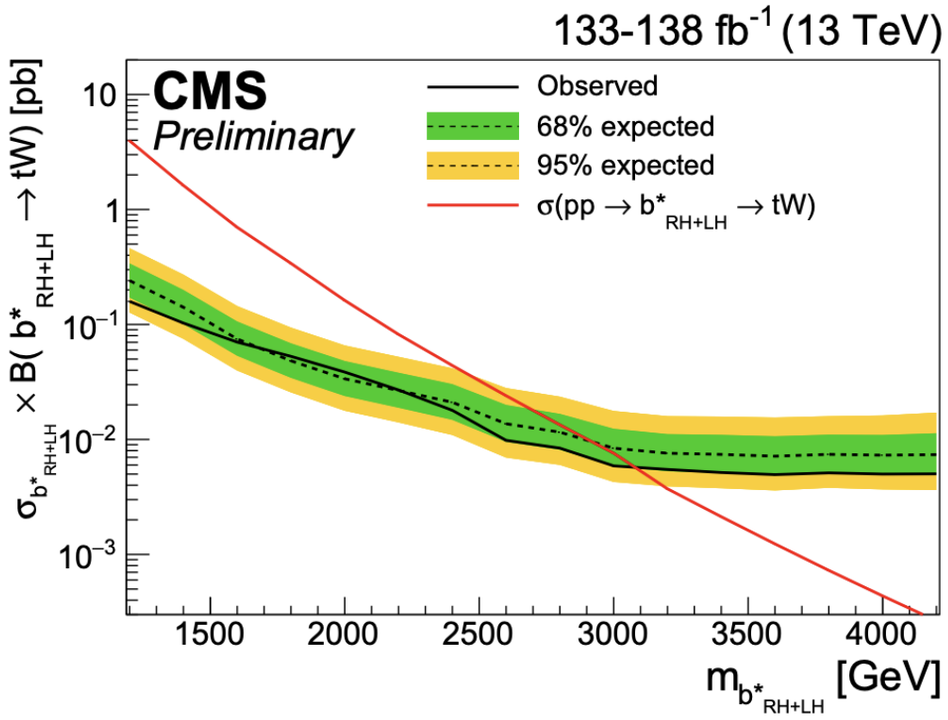


Search for a heavy resonance decaying into a top quark and a W boson

CMS-PAS-B2G-21-005，高能所

- **Excited quarks can interact with the SM particles through gauge mediation, such that a gauge boson and a SM quark is produced in their decay.**
- **For b∗ masses m(b∗) > 700 GeV, the decay to tW is predicted to be dominant**
- **The tW system is reconstructed from the semileptonic t decay, t → Wb → lνb, and the hadronic W boson decay, W → $q\bar{q}'$.**
- **No statistically significant excess over the expected background is found.**
- **b∗ quarks with left-handed, right-handed, and vector-like chiralities are excluded at 95% C.L. for masses below 2.4, 2.8, and 3.1 TeV, respectively.**





Summary

- CMS and ATLAS studied the di-J/ψ mass spectrum and found X(6900); First observation of X(6600) and evidence of X(7300) by CMS; Evidence of new structures in the J/ψ+ψ(2S) channel by ATLAS. A family of structures which are candidates for all-charm tetra-quarks!

- Heavy resonance search remains an active area of research

✓ New models and particles beyond the Standard Model explored at ATLAS and CMS, yet no significant deviation beyond Standard Model is observed

✓ New techniques such as Machine Learning are developed and implemented in the analyses Extended exclusion limits on BSM theories

Backup

Exploration of possible interference among BWs

- Explored fit with interference among various combinations of BWs
- Pdf for three BW interference

$$Pdf(m) = N_{X_0} \cdot |BW_0|^2 \otimes R(M_0)$$
$$+ N_{X\ and\ interf} \cdot |r_1 \cdot \exp(i\phi_1) \cdot BW_1 + BW_2 + r_3 \cdot \exp(i\phi_3) \cdot BW_3|^2$$
$$+ N_{NRSPS} \cdot f_{SPS}(m) + N_{NRDPS} \cdot f_{DPS}(m)$$

Interf. term

- Studied many ways interference due to possible J^{PC} and quantum coherence
  - 2-object-interference among BW0, BW1, BW2, BW3
  - 3-object-interference among BW0, BW1, BW2, BW3
  - 4-object-interference among BW0, BW1, BW2, BW3

Final CMS choice: interference among BW1, BW2, BW3