HEAVY FLAVOUR PHYSICS IN ATLAS AND CMS

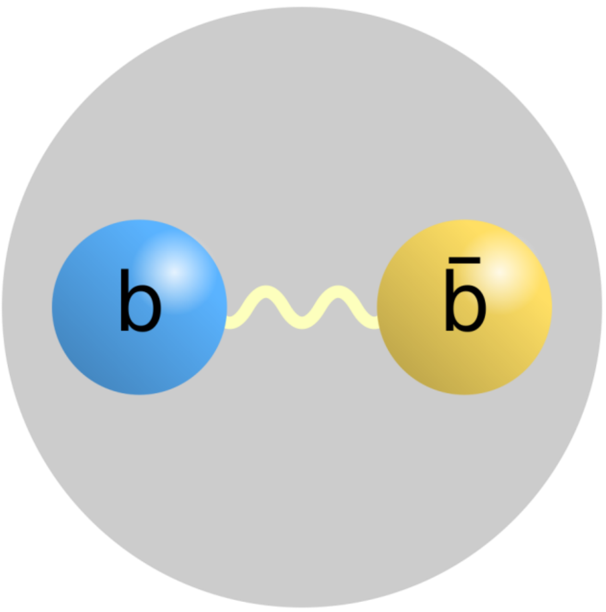
Edwin Chow (ATLAS)

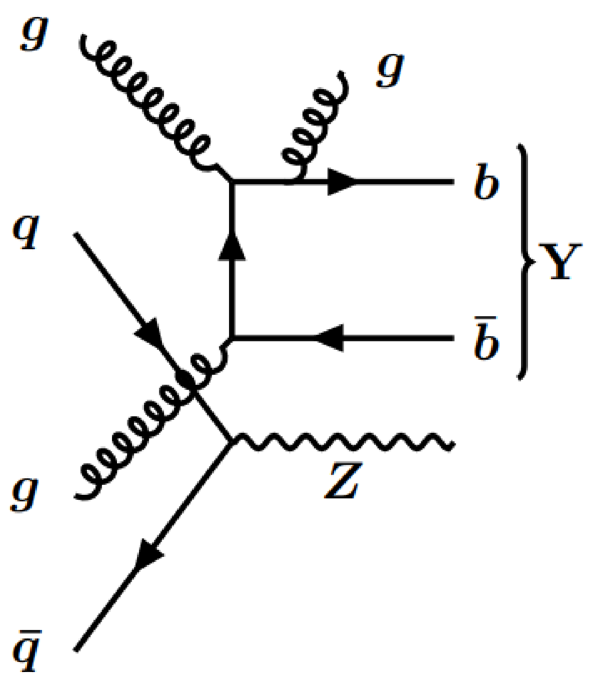
MORIOND EW
16TH MAR, 2026

Content

$\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ production

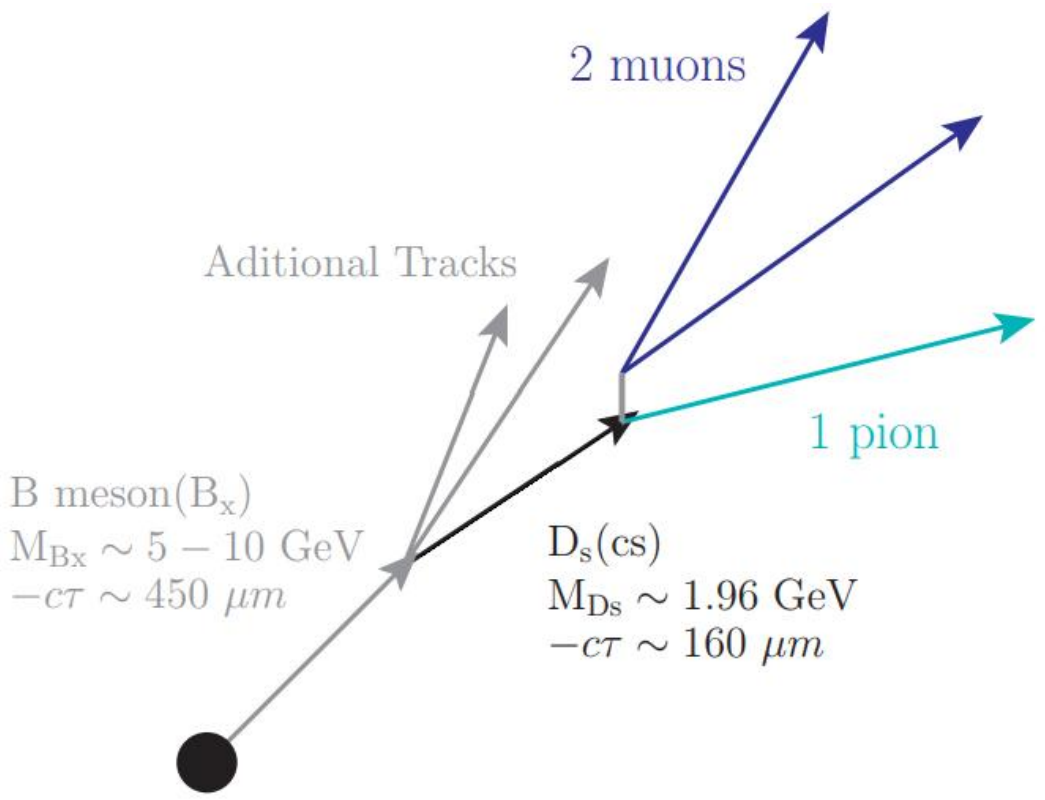
- $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ differential cross sections (CMS-BPH-24-004 arxiv)
- $\Upsilon(1S) + Z$ associated production and effective double-parton scattering (CMS-BPH-23-007 arxiv)





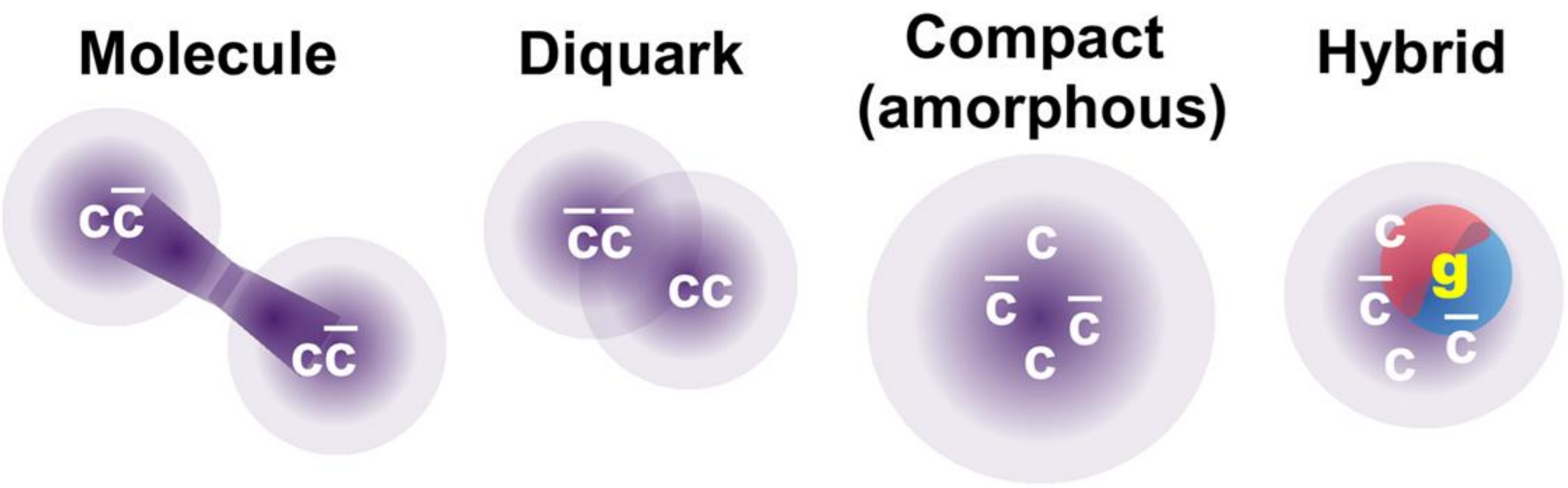
B and D meson production

- B^0 lifetime precision measurement (ATLAS-BPHY-2020-09 arxiv erratum)
- Exclusive reconstruction of B^* mesons (CMS-BPH-24-011 arxiv)
- D meson production measurements (ATLAS-BPHY-2018-10 arxiv)



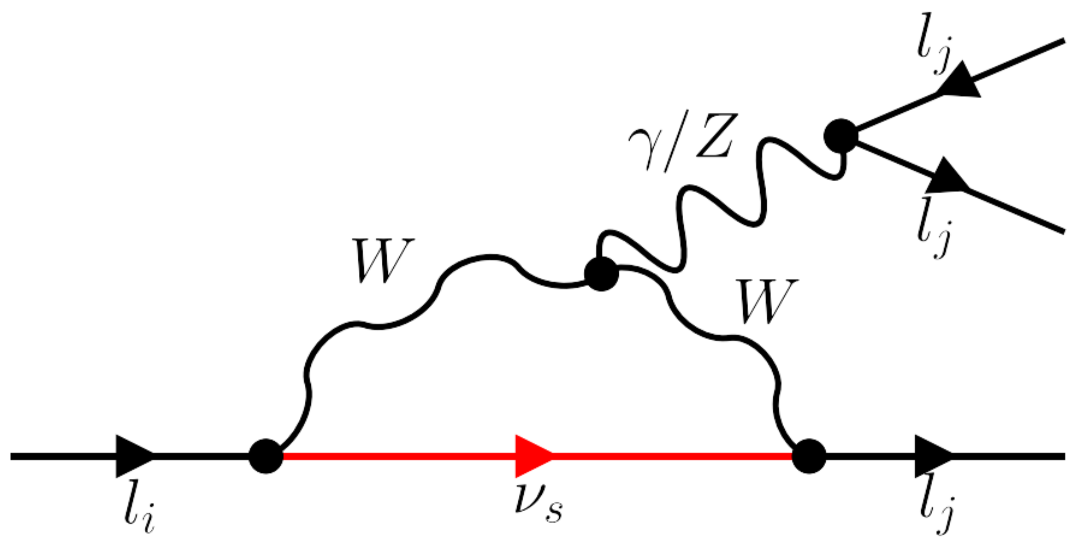
Tetra quarks

- All-charm tetraquarks (CMS-BPH-24-003 arxiv and CMS-BPH-24-002 arxiv)
- $J/\psi + \psi(2S)$ resonance (ATLAS-BPHY-2023-01 arxiv)



Rare decay and searches

- LFV $\tau \to 3\mu$ (ATLAS – New Results)
- Rare $\eta \to \mu\mu ee$ (CMS-BPH-24-001 cds)



$\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$

CMS-BPH-24-004

$\Upsilon \rightarrow \mu^{+}\mu^{-}$

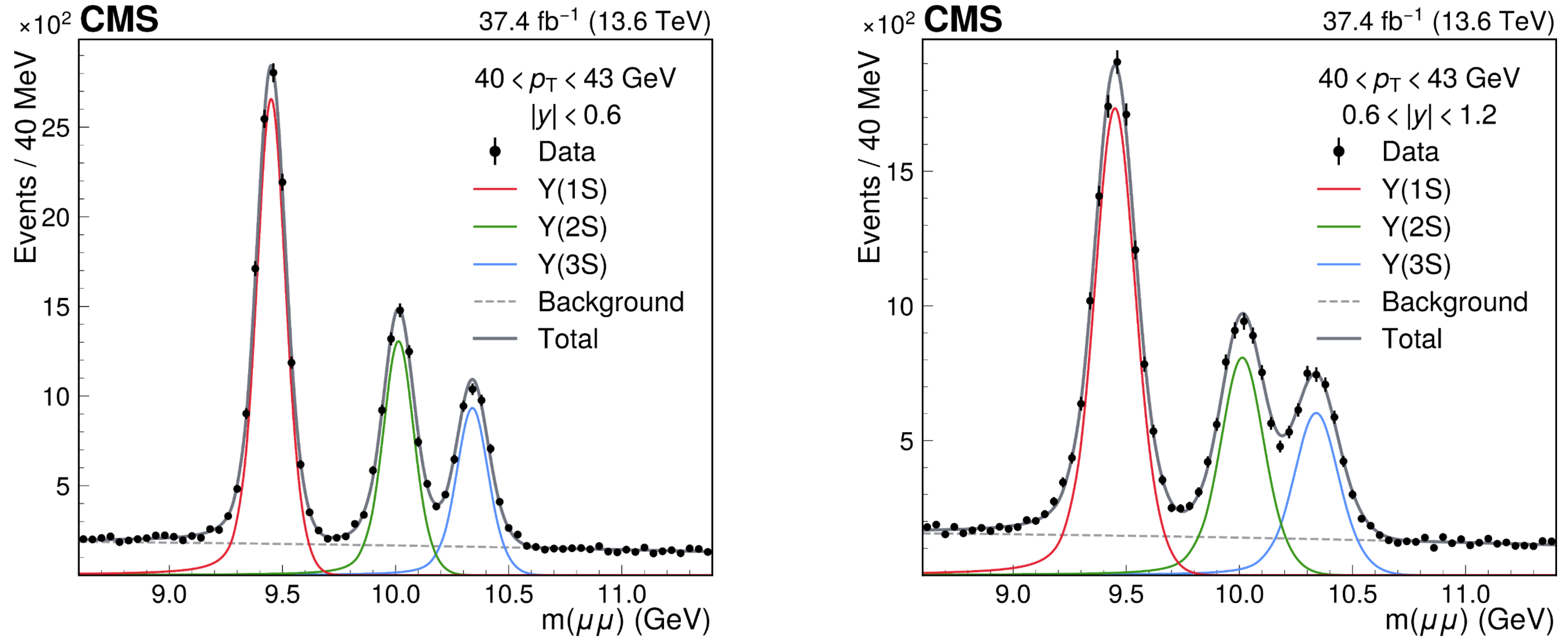
- Early run-3 result at 13.6 TeV
- Probe of quarkonium production

Fit and result

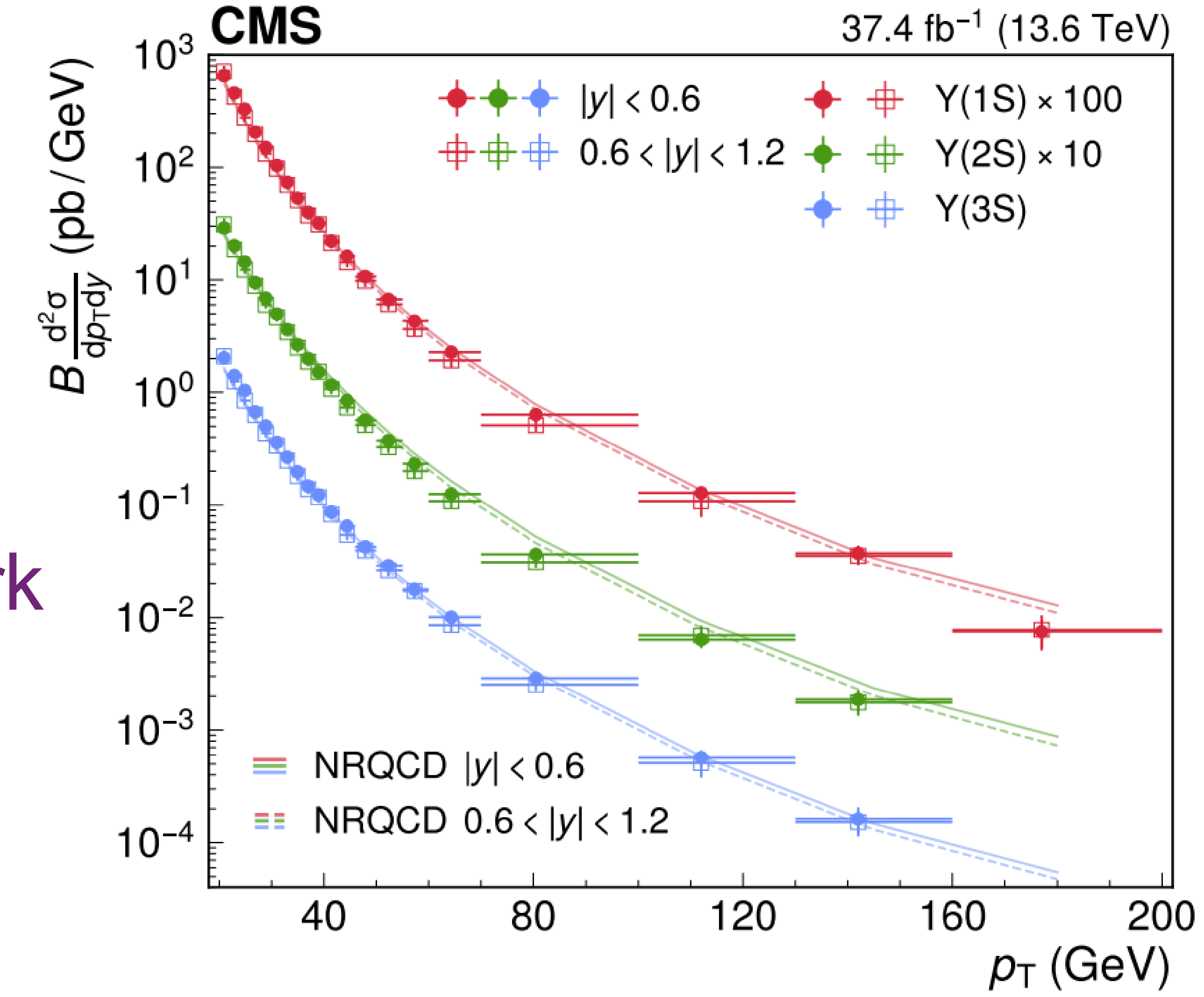
- Beautifully resolved 3 peaks for 1S, 2S and 3S
- Showcasing good muon resolution

Double differential cross sections

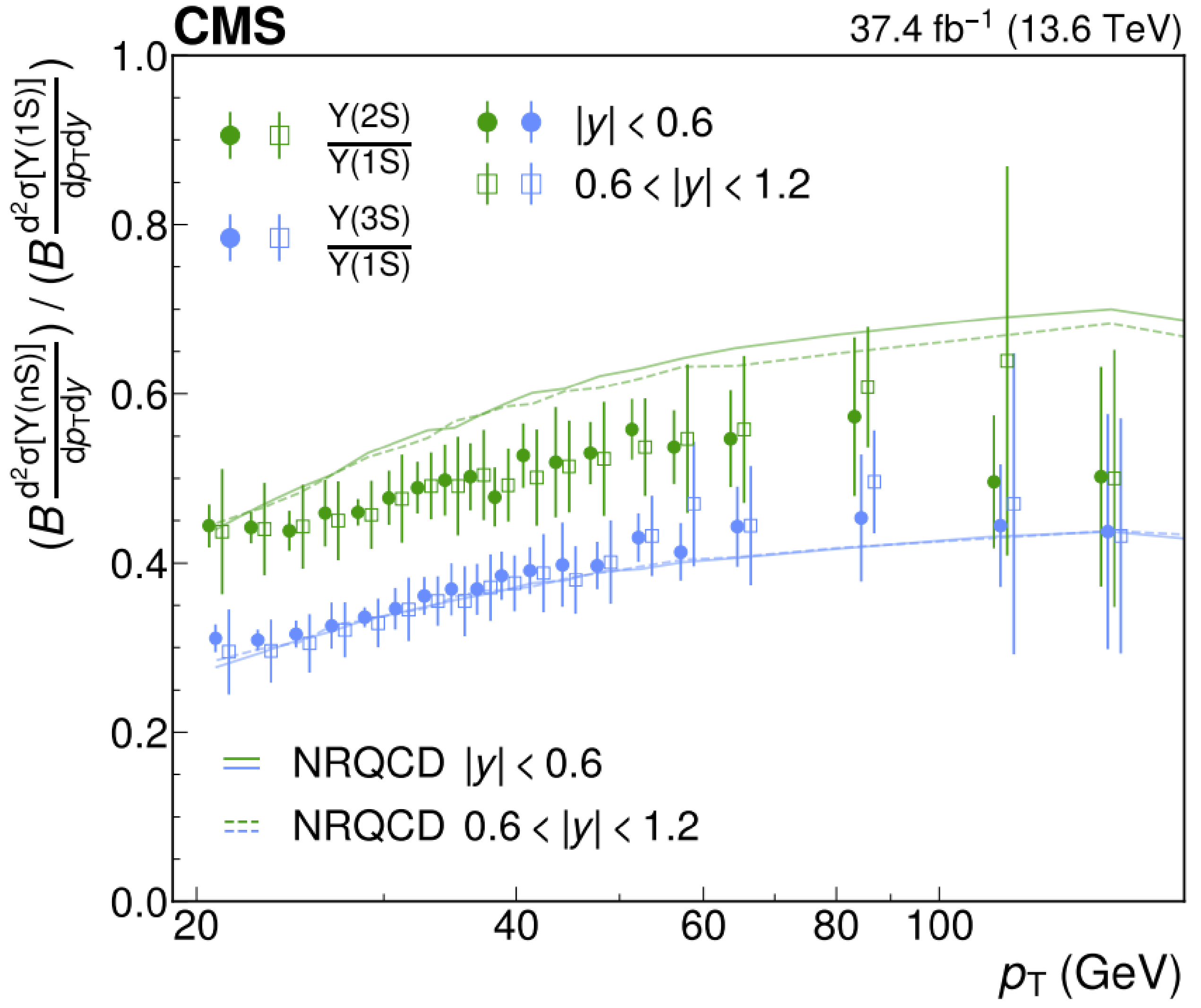
- Measured $\frac{d^2\sigma}{dp_T dy}$ from 20 to 200 GeV
- 19 bins in p_T from 20 to 200GeV
- 2 bins in $|y|$: $|y| < 0.6$, $0.6 < |y| < 1.2$
- Good overall agreement with NRQCD, but ratio shows otherwise
  → important input to global fits to improve such framework



Mass fits in differen |y| bins



Differential cross-sections



Ratio $\Upsilon(3S)$ and $\Upsilon(3S)$ to $\Upsilon(1S)$

$\Upsilon(1S) + Z$ associated production

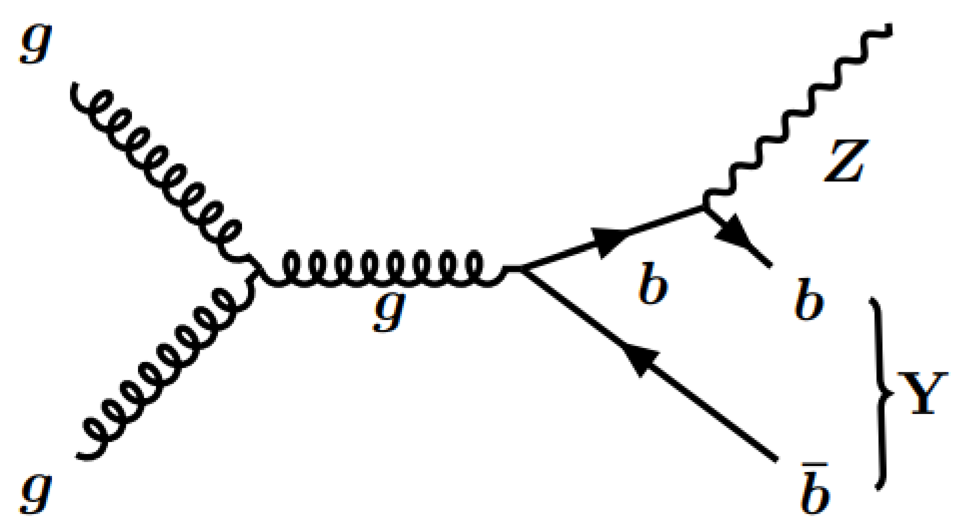
CMS-BPH-23-007

$\Upsilon(1S) + Z \rightarrow \mu^+\mu^-\mu^+\mu^-$

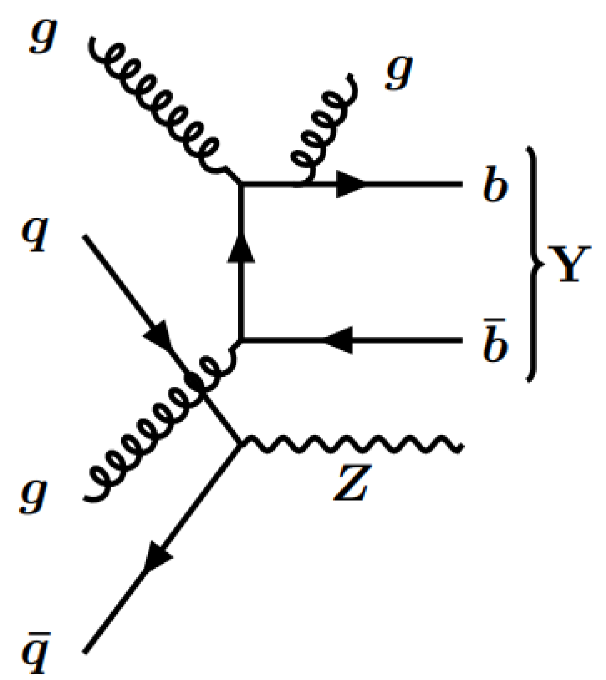
- First study of such production
- Can be produced in SPS or DPS
- Contribution of DPS can be expressed in σ_{eff}

Reconstruction and selection

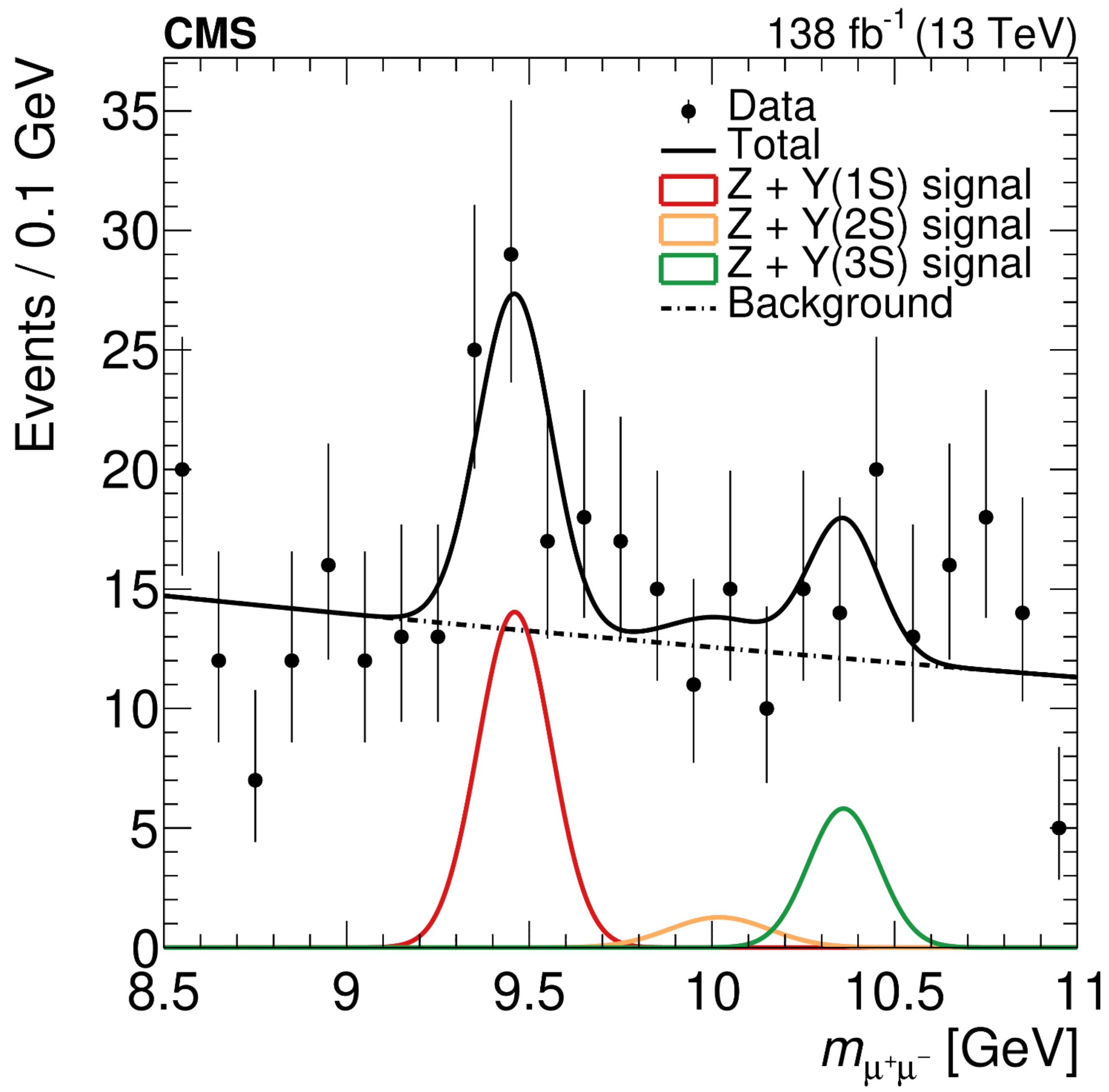
- Key variable: $m_{\mu\mu}$ of $\Upsilon(nS)$ and Z candidates
  Match muon pairs to lie near $\Upsilon(nS)$ and Z mass
- Dedicated selection on vertex variables
- Signal just resolvable given the statistics
- $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances gives < 3 s.d.
  → Focus on $\Upsilon(1S)$



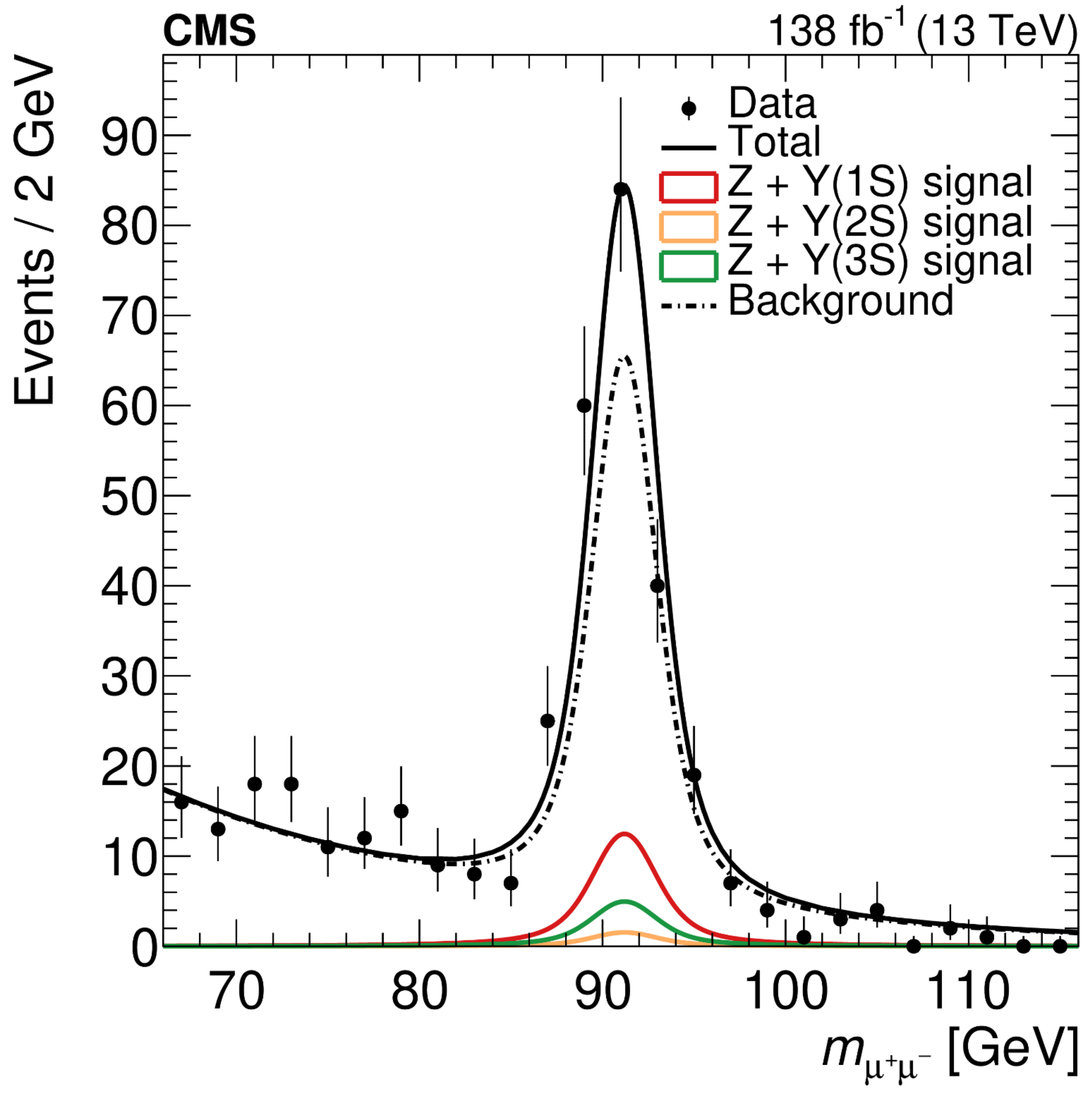
Single parton scattering



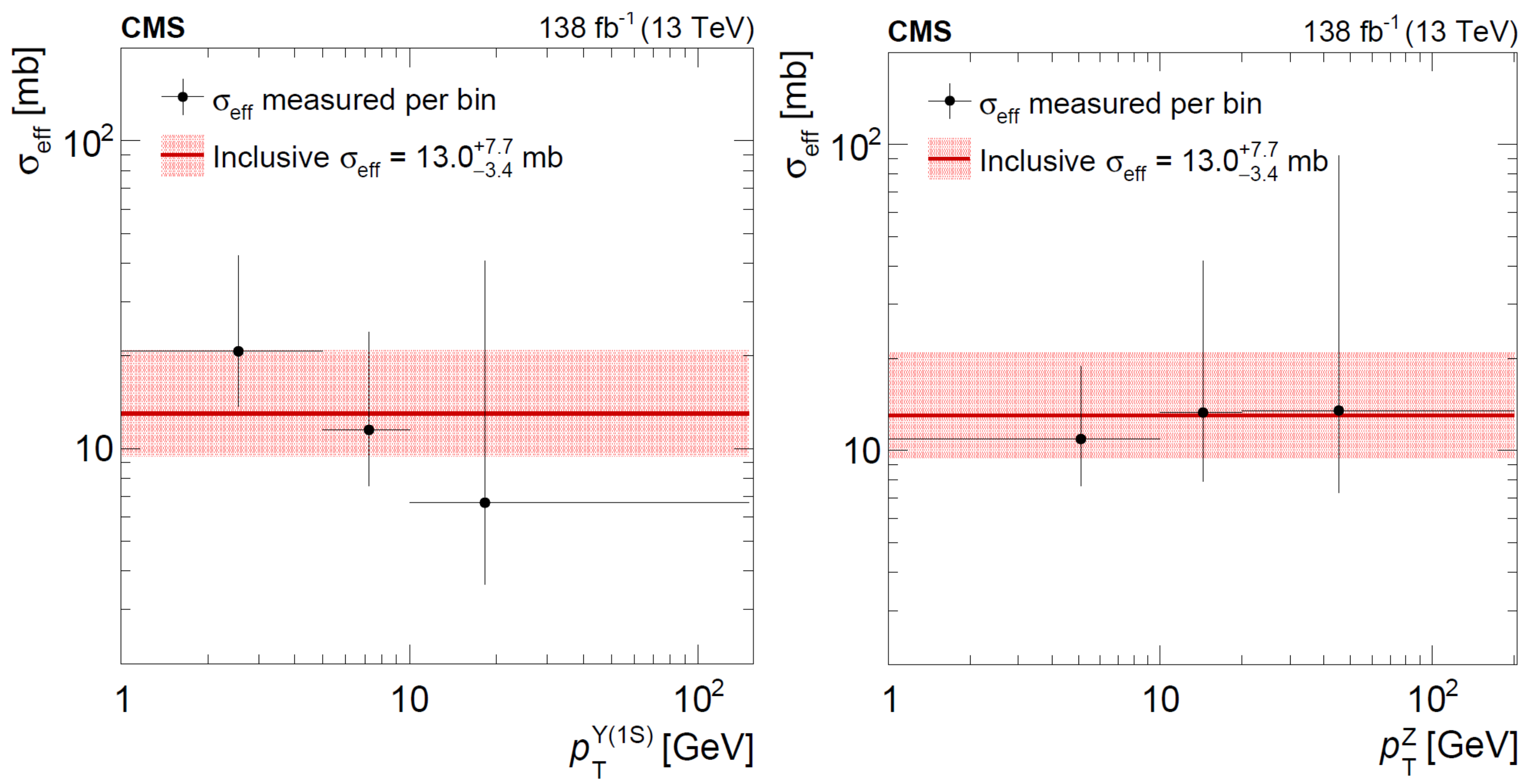
Double parton scattering



Muon pairs from $\Upsilon(nS)$



Muon pairs from Z



First σ_{eff} measured in bins of Υ and Z momenta

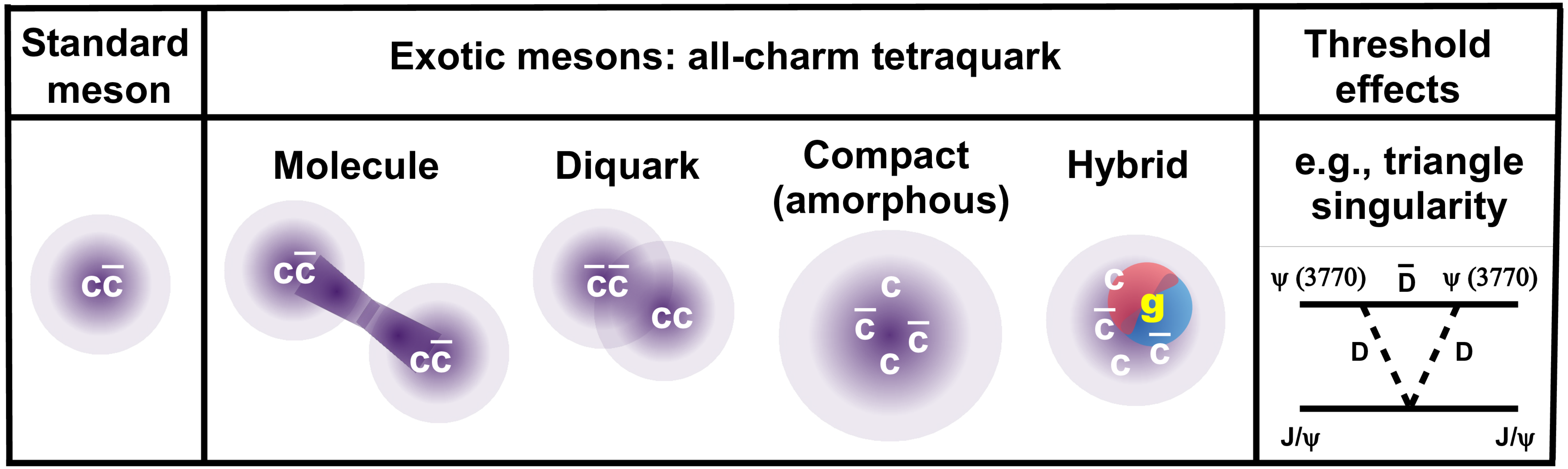
A family of all-charm tetraquarks

CMS-BPH-24-003

LHC has revealed tetraquark candidates, but fundamental questions still unanswered..
If I have 4 charm quarks, how do I get a tetraquark?
What are <u>tetraquark states</u> and their <u>substructure</u>?

- Molecule: Two distinct mesons loosely in orbit
- Diquark: Tightly bound pairs of charms and anti-charm
- Amorphous: No substructure
- Hybrid: Involvement of valence gluon
- Non-resonant dynamic effects

To start with: Do we have enough <u>statistics</u> to test the models?



A family of all-charm tetraquarks

CMS-BPH-24-003

Considers X(6600), X(6900) and X(7100)
"3-way interference" between these states
→holds tetraquark structural information

- $X \rightarrow J/\psi\, J/\psi$ *or* $J/\psi\, \psi(2S)$

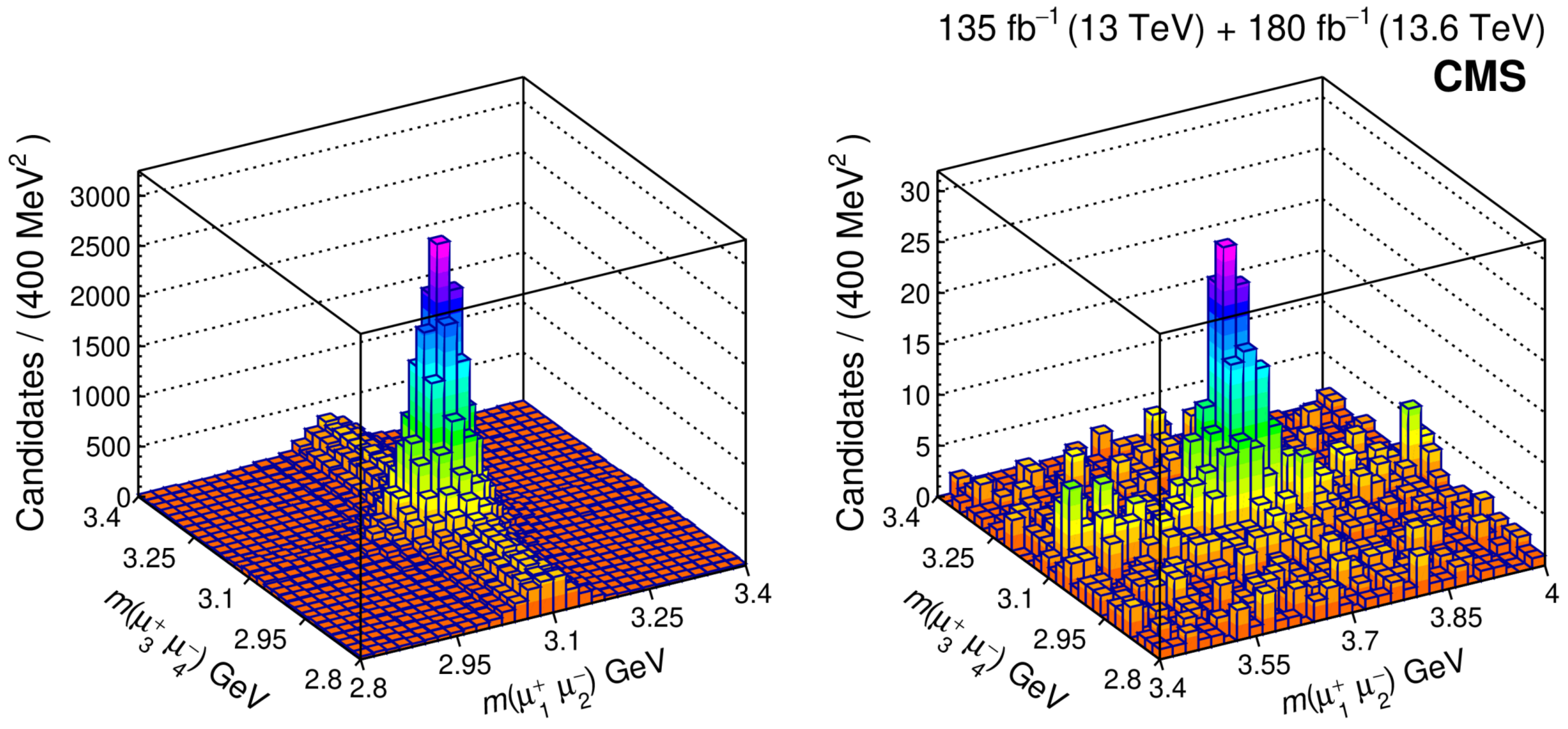
$J/\psi\, J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$
- $m_{\mu\mu}$ near $m_{J/\psi} = 3.7\ \mathrm{GeV}$

$J/\psi\, \psi(2S) \rightarrow \mu^+\mu^-\mu^+\mu^-$
- $m_{\mu_1\mu_2}$ near $m_{\psi(2S)} = 3.1\ \mathrm{GeV}$
- $m_{\mu_3\mu_4}$ near $m_{J/\psi} = 3.7\ \mathrm{GeV}$

Fit model
- Breit-Wigner as core for the signal
- Interference term added

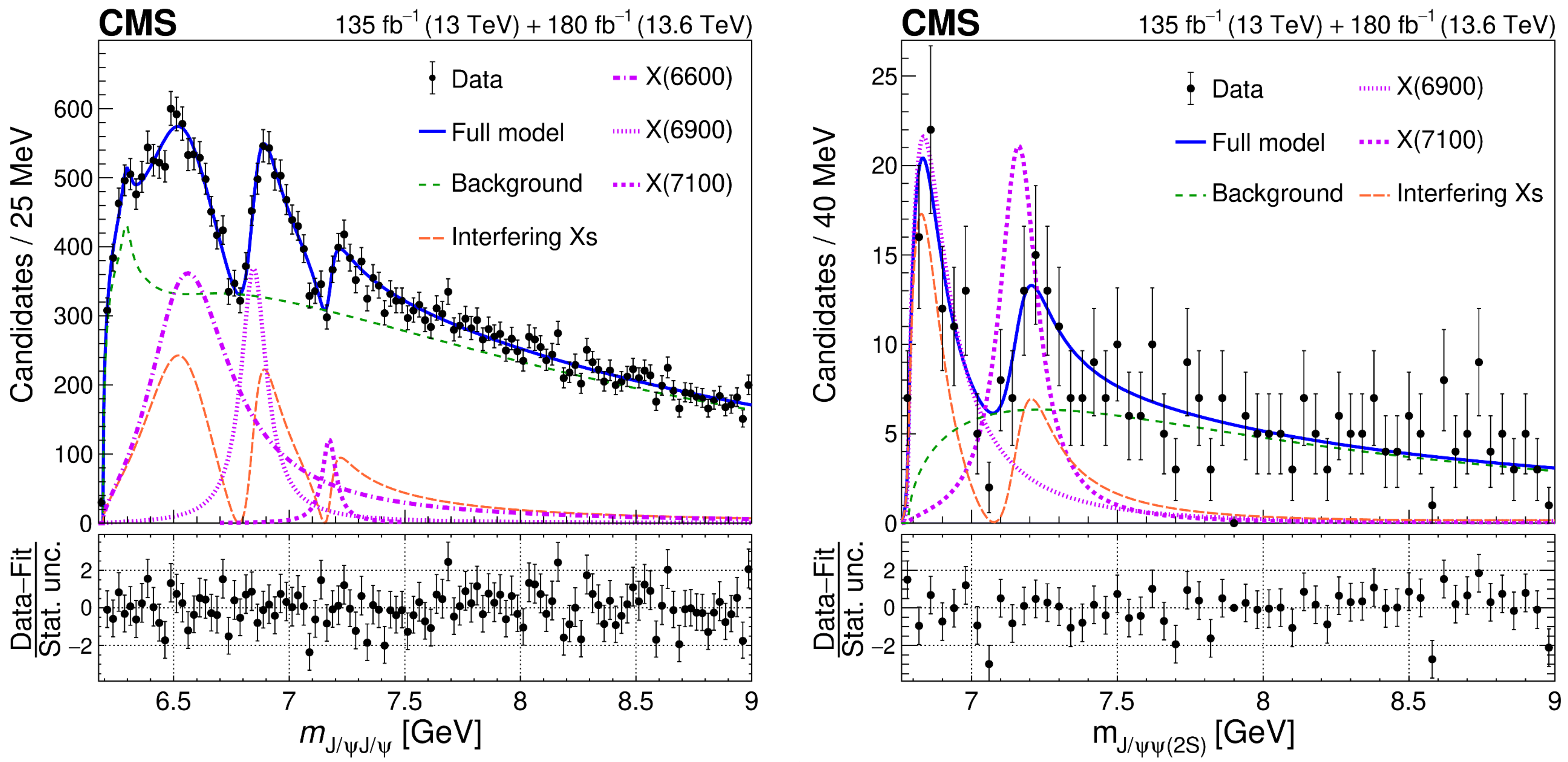
$$|M|^2 = \left|r_1 e^{i\phi_1} BW_{6600} + BW_{6900} + r_3 e^{i\phi_3} BW_{7100}\right|^2$$

- r *and* ϕ are the relative amplitude and phase angles



$J/\psi\ \ J/\psi$ channel

$J/\psi\ \ \psi(2S)$ channel



A family of all-charm tetraquarks

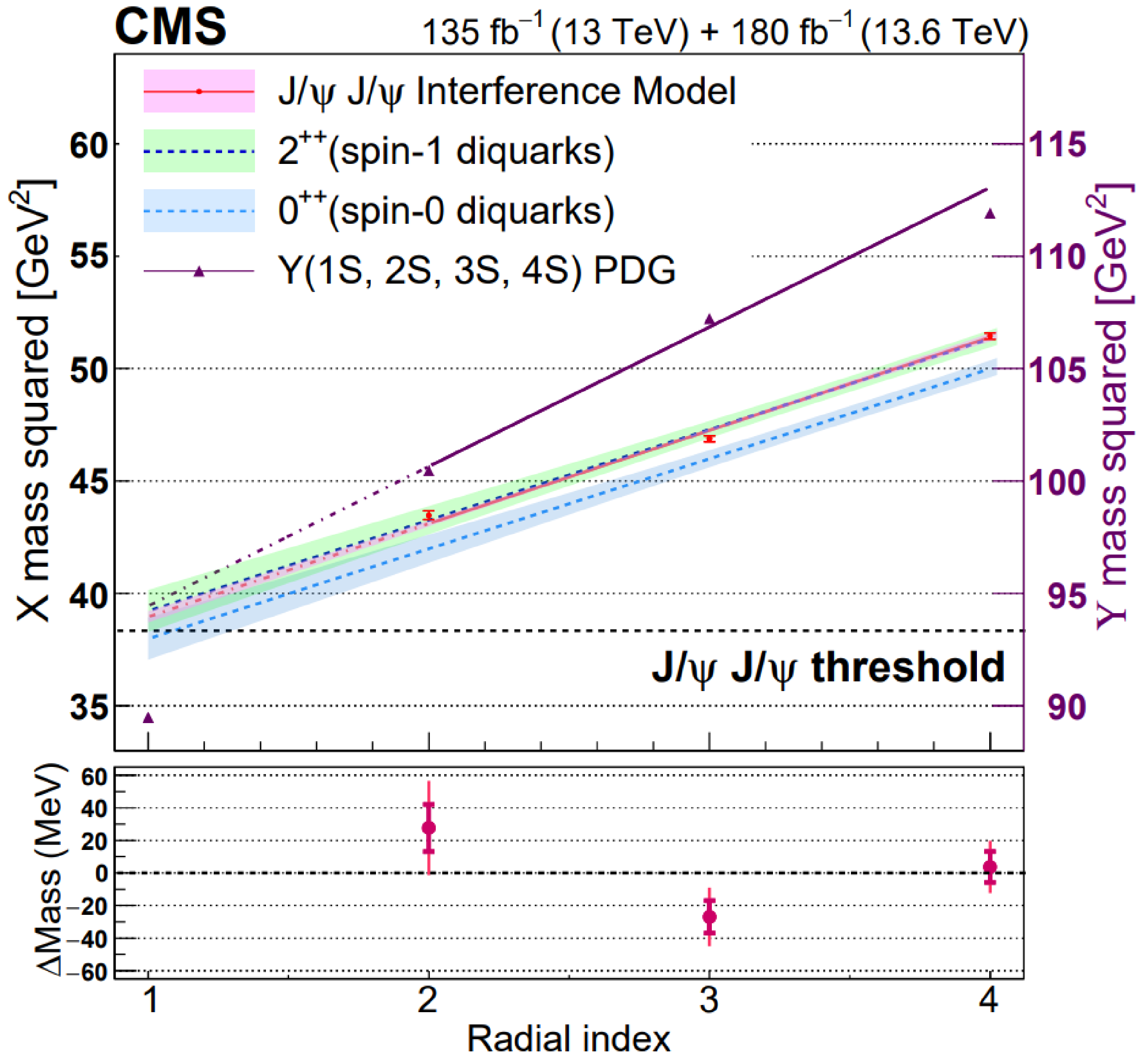
CMS-BPH-24-003

$J/\psi\, J/\psi$ pairs

- 4 times more $J/\psi\, J/\psi$ pairs than previously available
- X (6600) X(6900) X(7100) all observed at $> 5\sigma$
- Interference is also $> 5\sigma$

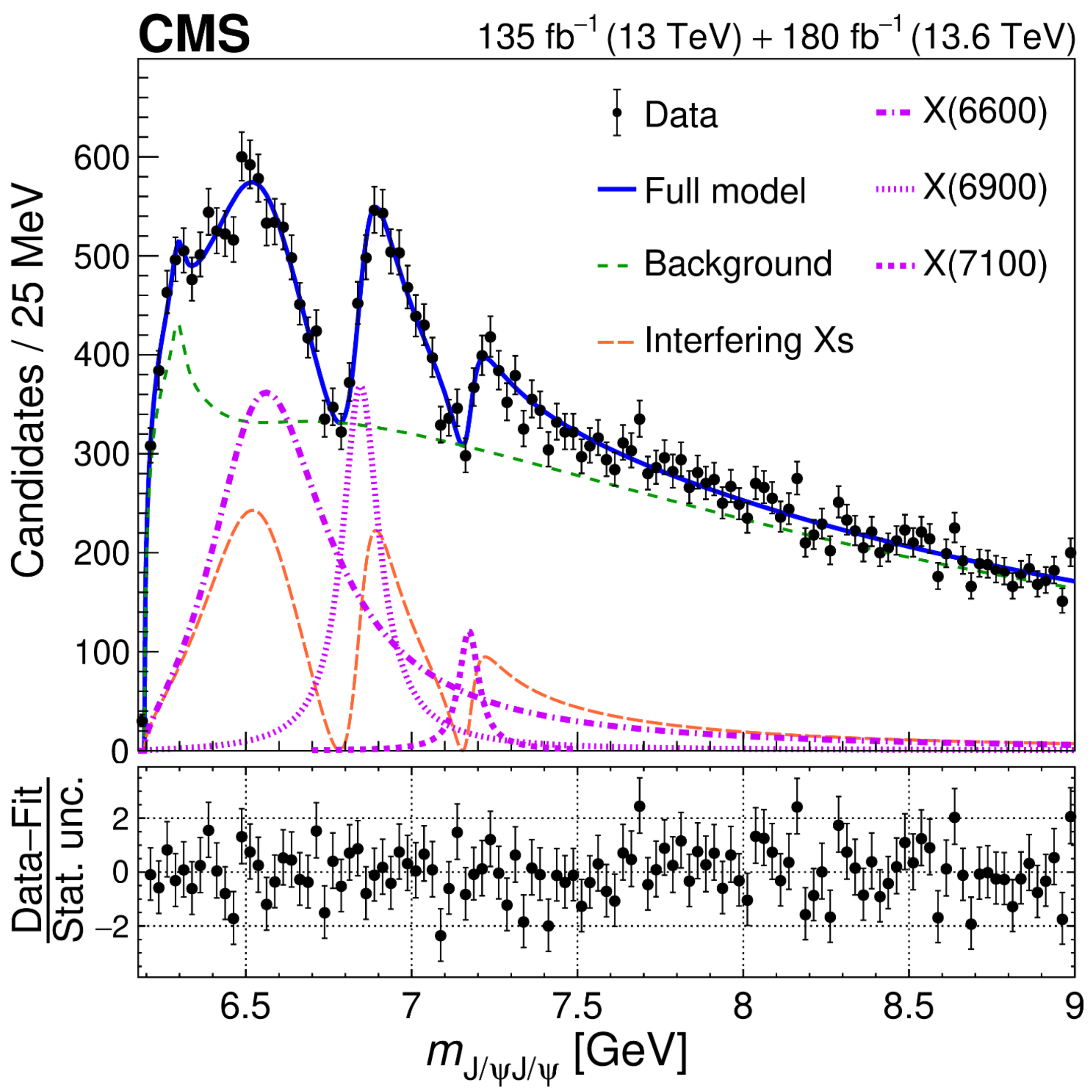
$J/\psi\, \psi(2S)$pairs

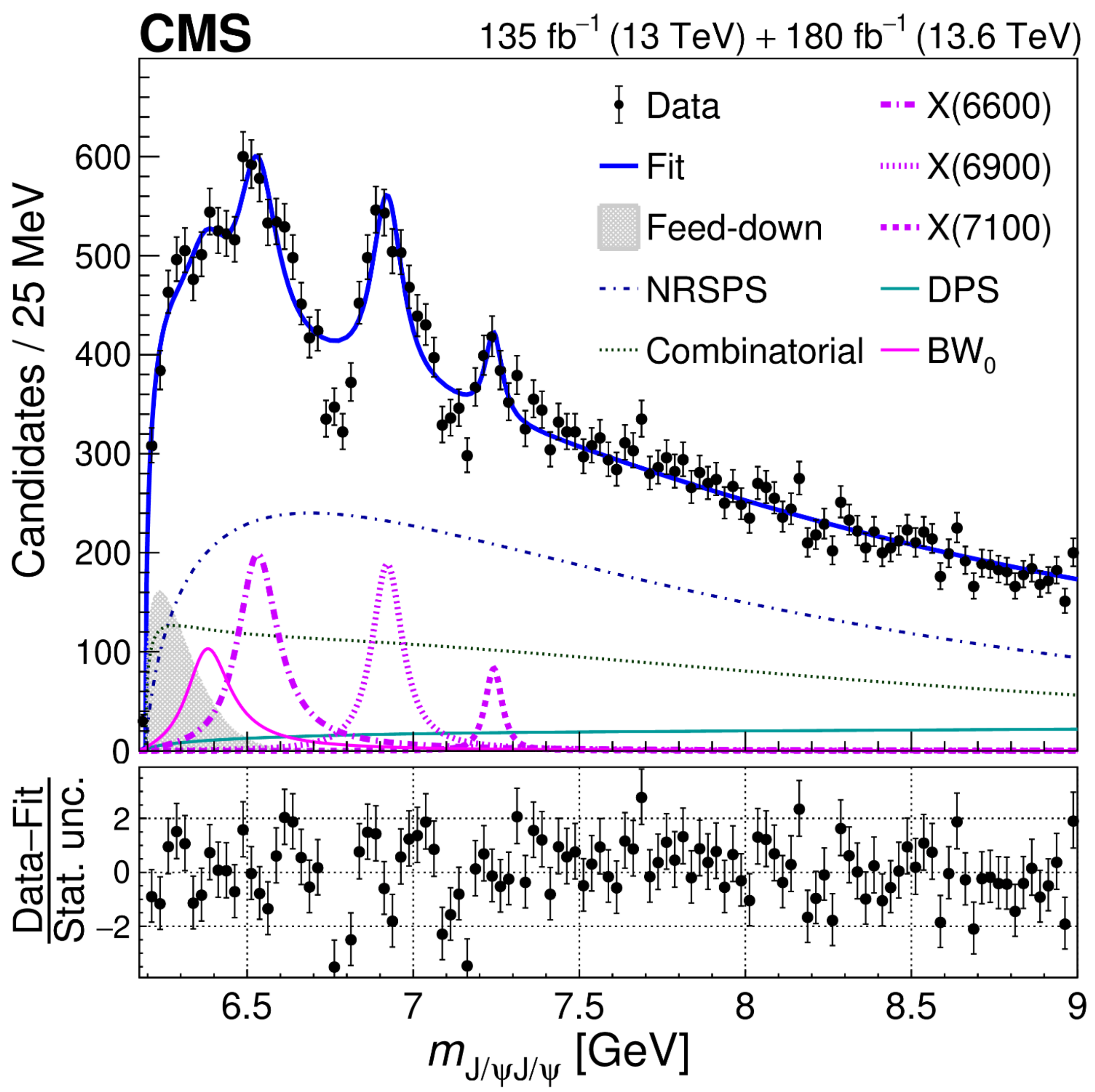
- X(6900) X(7100) observed at 8σ and 4σ, respectively
- Interference is also $> 2.5\sigma$



Comparing to $\Upsilon(nS)$

Testing interfering vs non-interfering





First 5σ observation of X(7100) and "three-way" interference
Consistent with spin-1 diquark model
The 3 resonances could be most naturally explained by a family excitation

Another crucial result CMS presented:
Determination of the spin and parity of all-charm tetraquarks
(CMS-BPH-24-002; Nature; arxiv)

Structures in $J/\psi + \psi(2S)$

ATLAS-BPHY-2023-01

Similar final state and similar fit range as CMS

- di-J/ψ and $J/\psi + \psi(2S)$ decay to 4μ are studied
- With the addition of $J/\psi + \psi(2S) \to 4\mu + 2\pi$ where $\psi(2S) \to 2\mu + 2\pi$ (focus of this slide)

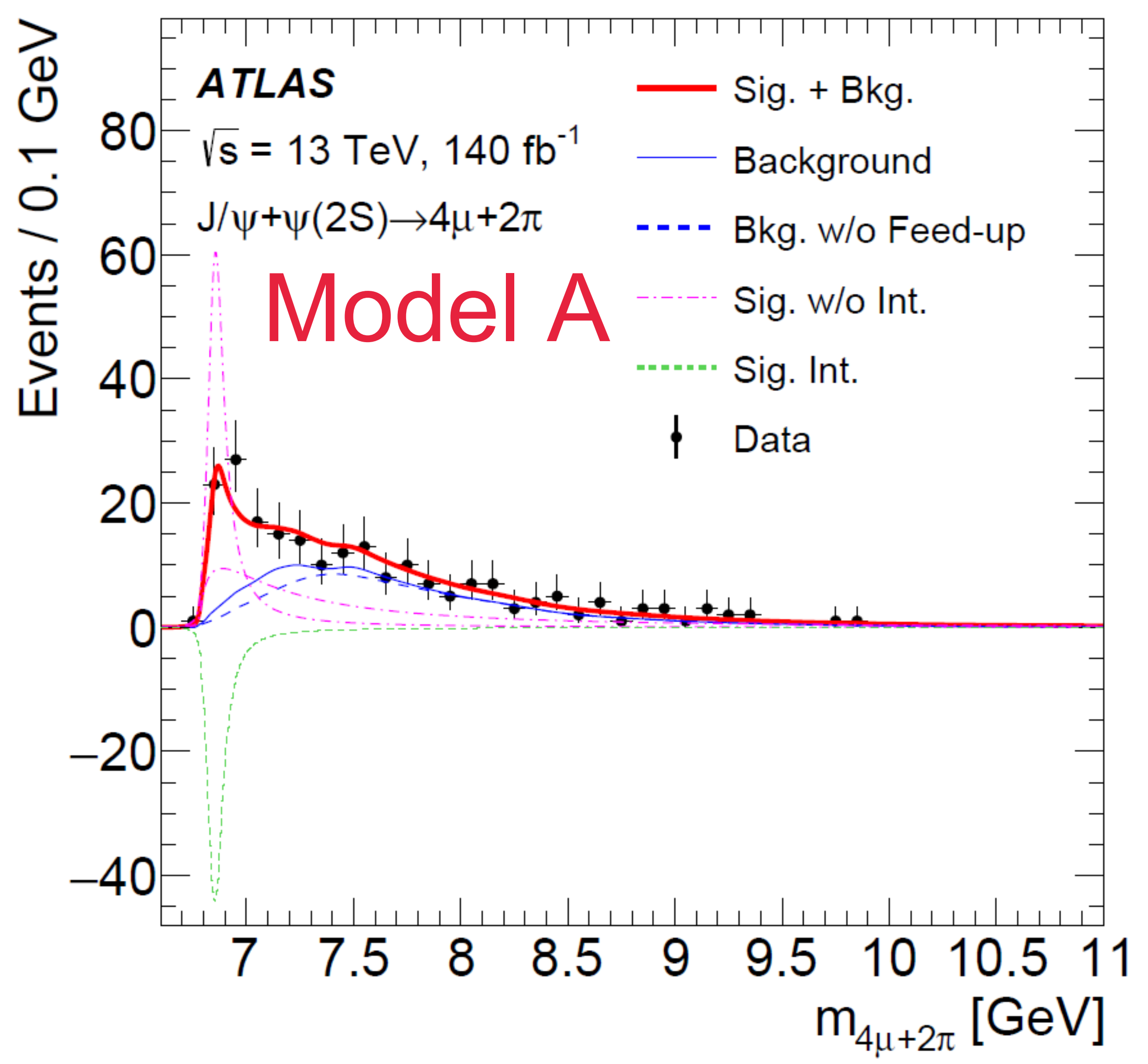
Main contribution

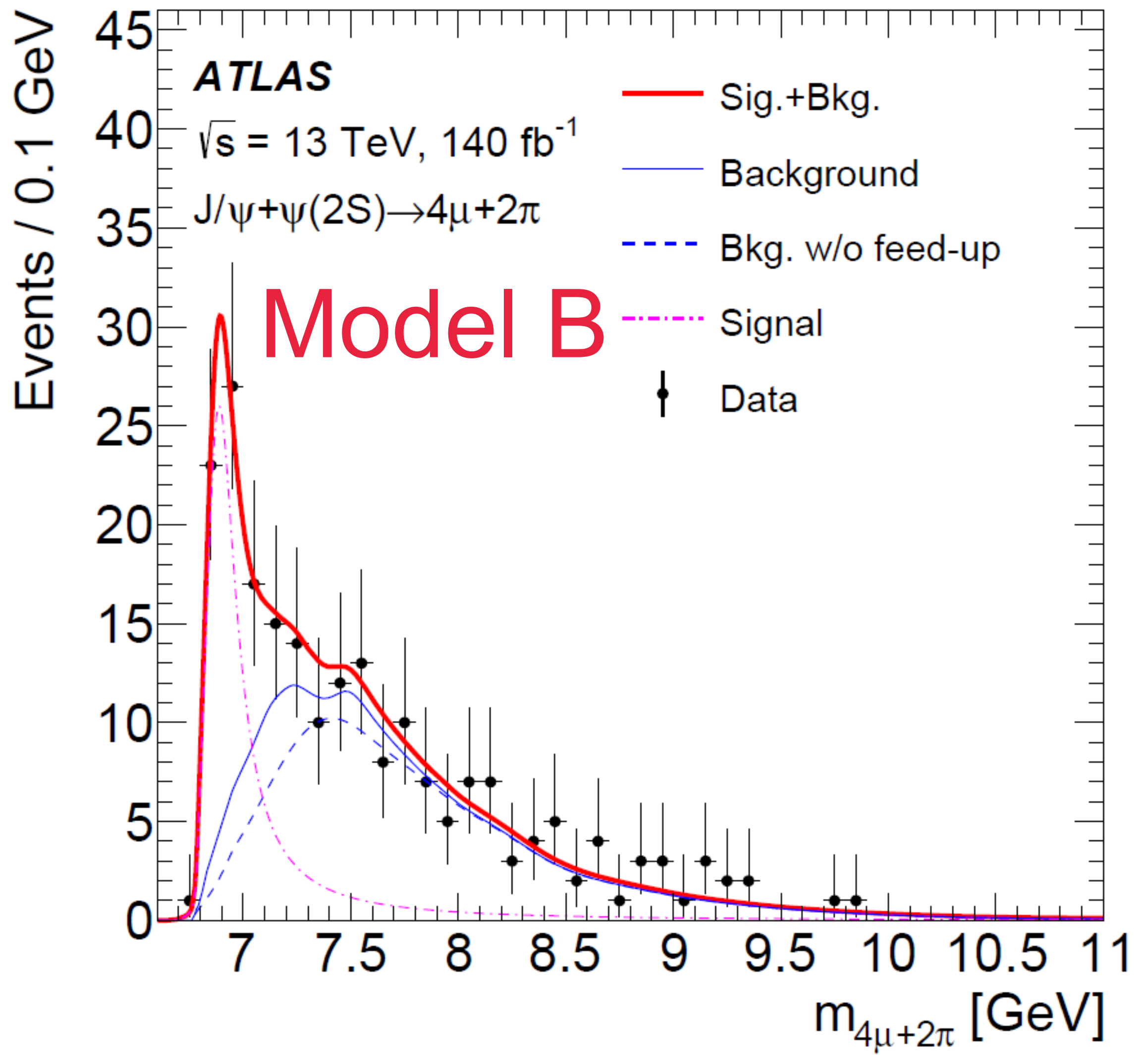
- Consider X(6900) and X(7200)
- Background of low-mass (LM) and SPS
- Consider signal cross feed of di-J/ψ and $J/\psi + \psi(2S)$ channels

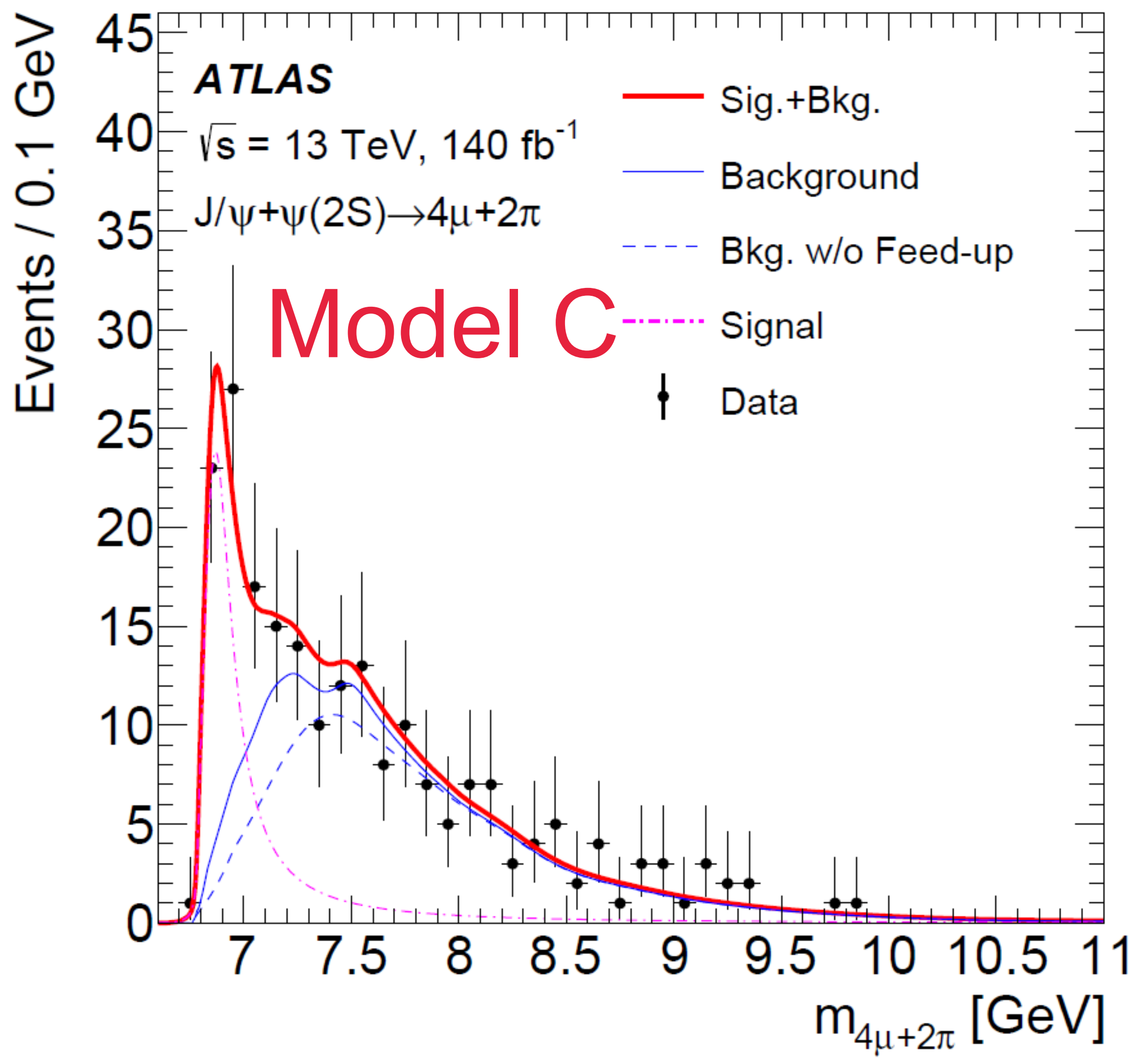
Emphasize on testing 3 models

- Model A: Xs, LM, SPS all interfering
- Model B: Xs are standalone, but LM interfering with SPS bkg
- Model C: Non-interfering

Confirms excess of X(6900) at 8.9σ
Excess at 6900MeV is significant regardless of model choice
Not enough significance for X(7200)







B^0 lifetime precision measurement ATLAS-BPHY-2020-09

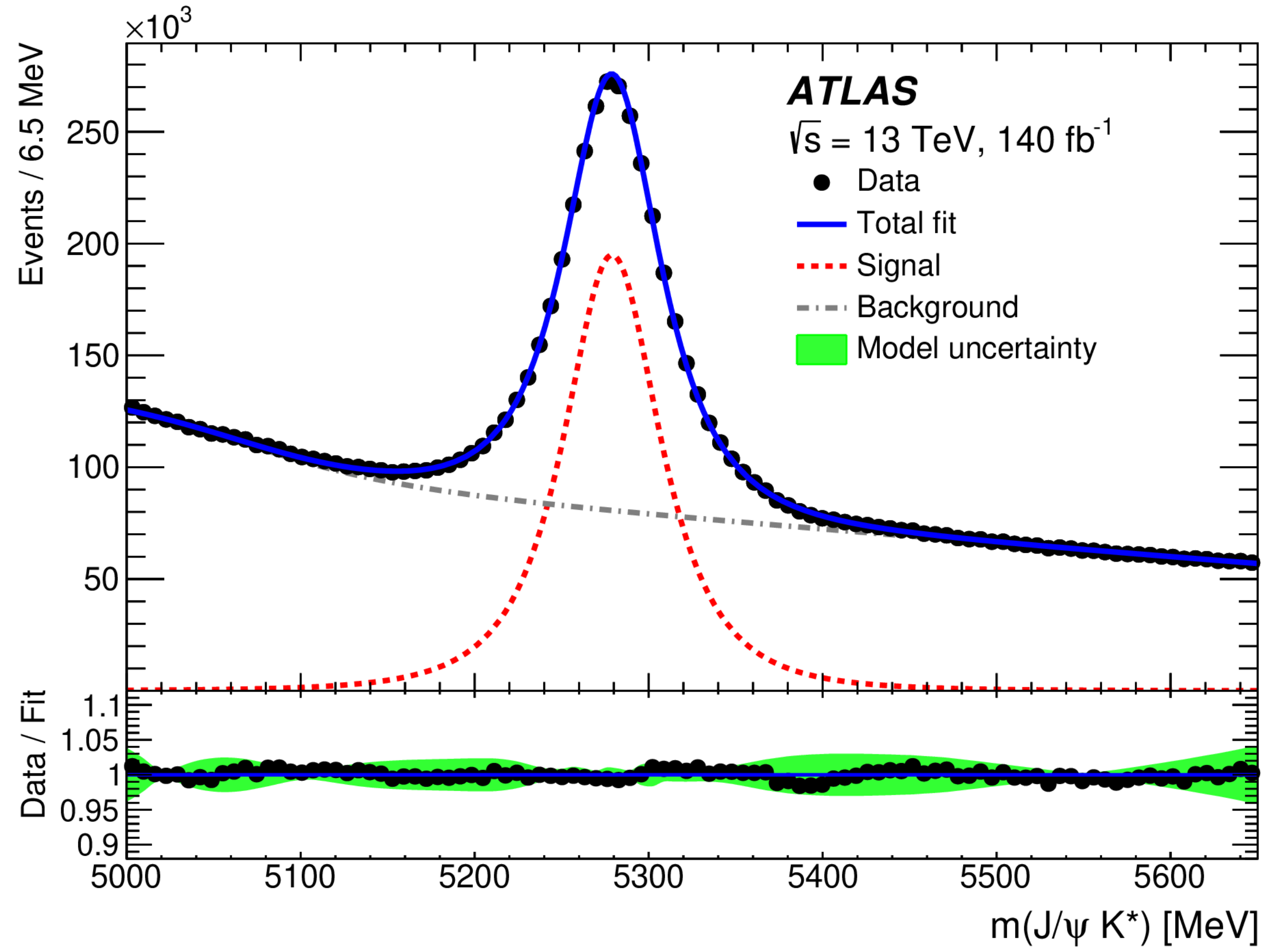
$B^0 \to J/\psi\, K^{*0} \to \mu^+\mu^- K^+\pi^-$

Fit

- mass-lifetime 2D pdf

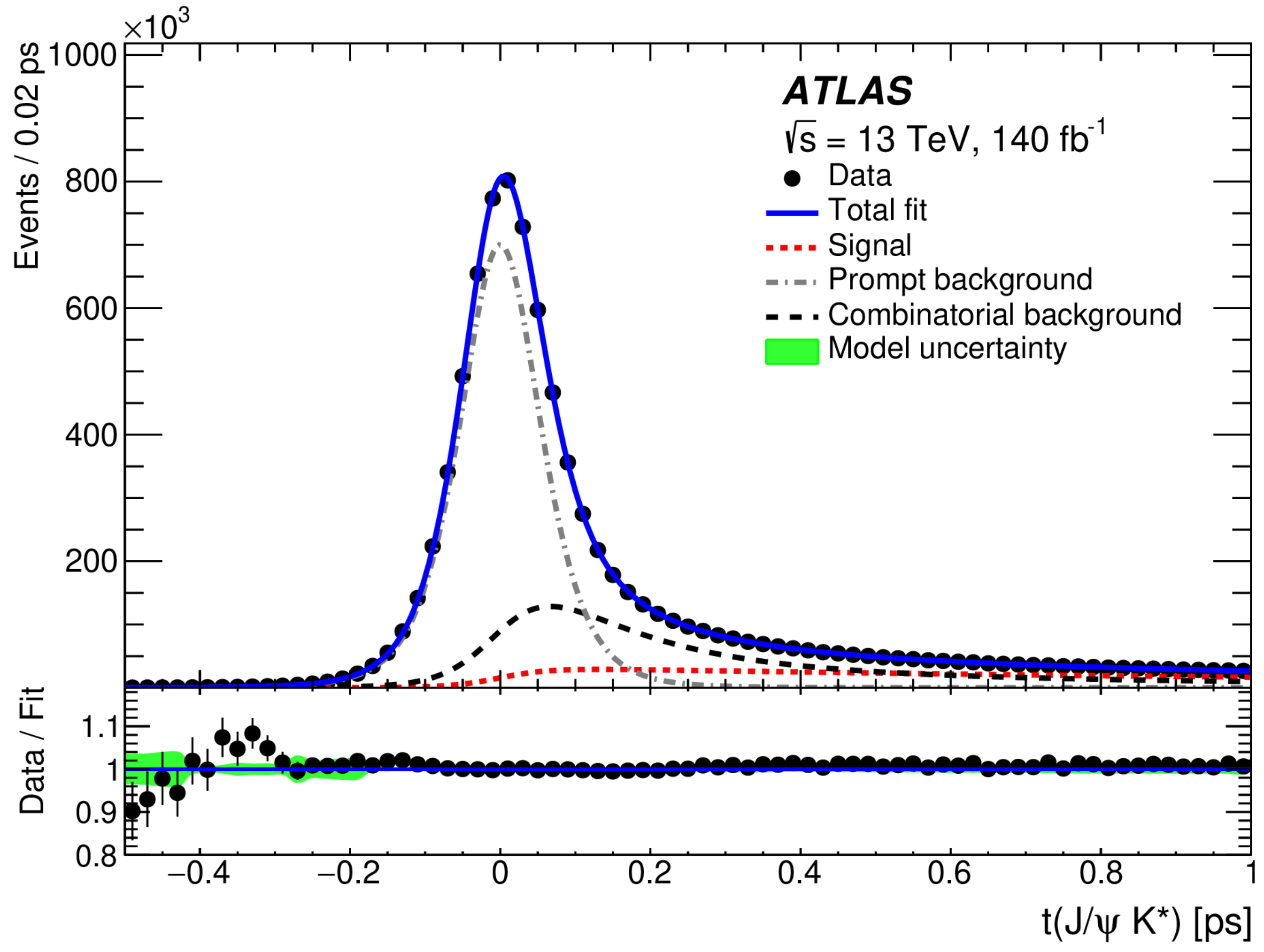
$$\ln L = \sum_{i=1}^{N} w(t_i) \ln[f_{\text{sig}}\mathcal{M}_{\text{sig}}(m_i)\mathcal{T}_{\text{sig}}(t_i, \sigma_{t_i}, p_{\text{T}_i}) + (1 - f_{\text{sig}})\mathcal{M}_{\text{bkg}}(m_i)\mathcal{T}_{\text{bkg}}(t_i, \sigma_{t_i}, p_{\text{T}_i})]$$

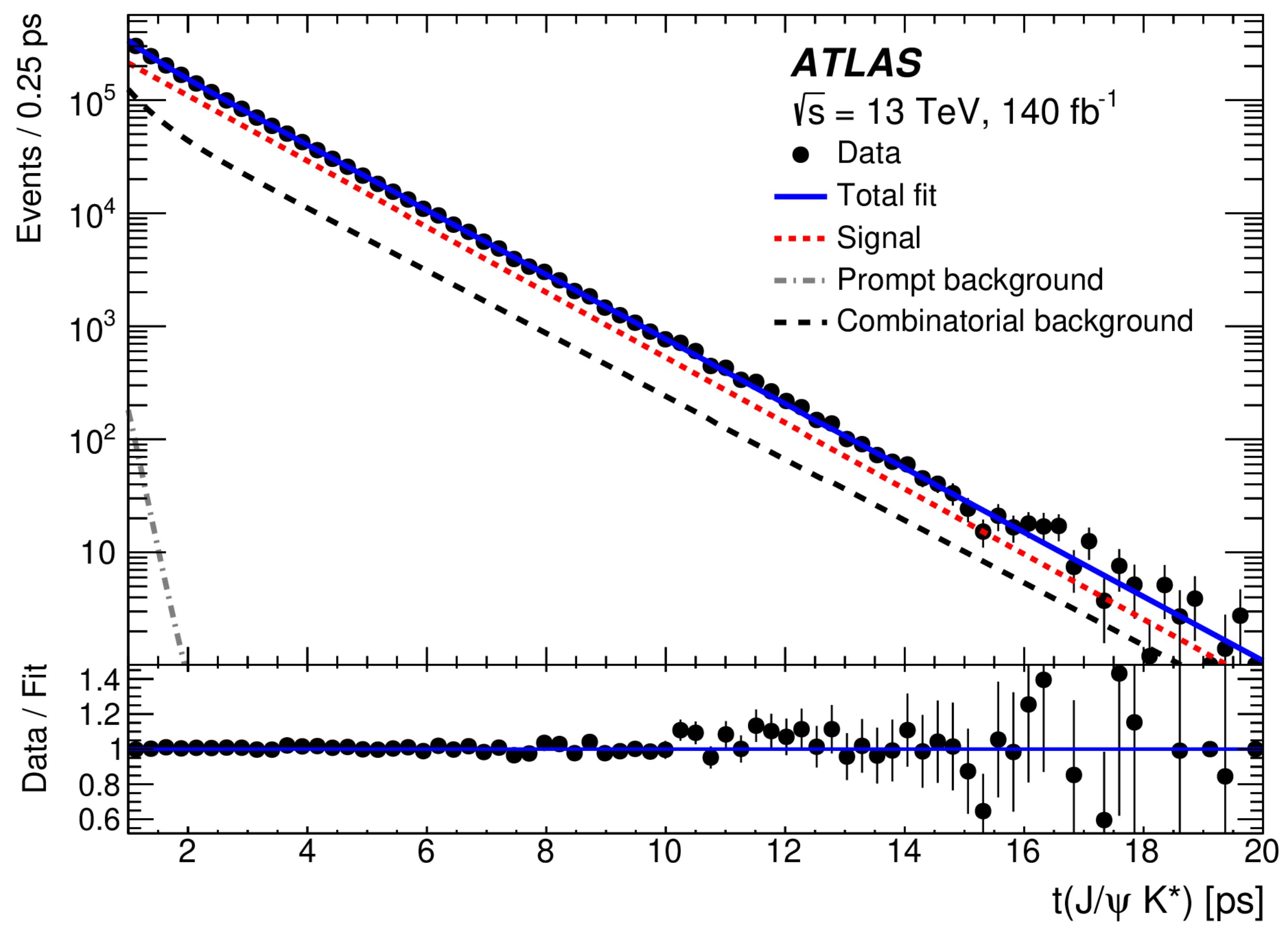
- Effective at distinguishing prompt and combinatorics backgrounds



Systematics

- Lifetime calculated by $\frac{L_{XY}\, m}{p_T}$
  Affected by track parameter uncertainties
- Specifically collaborate with vertexing/tracking groups
- Tackle tracker misalignment, propagate such impact to final B-vertex as systematics





Fits performed in 2D, these are projections

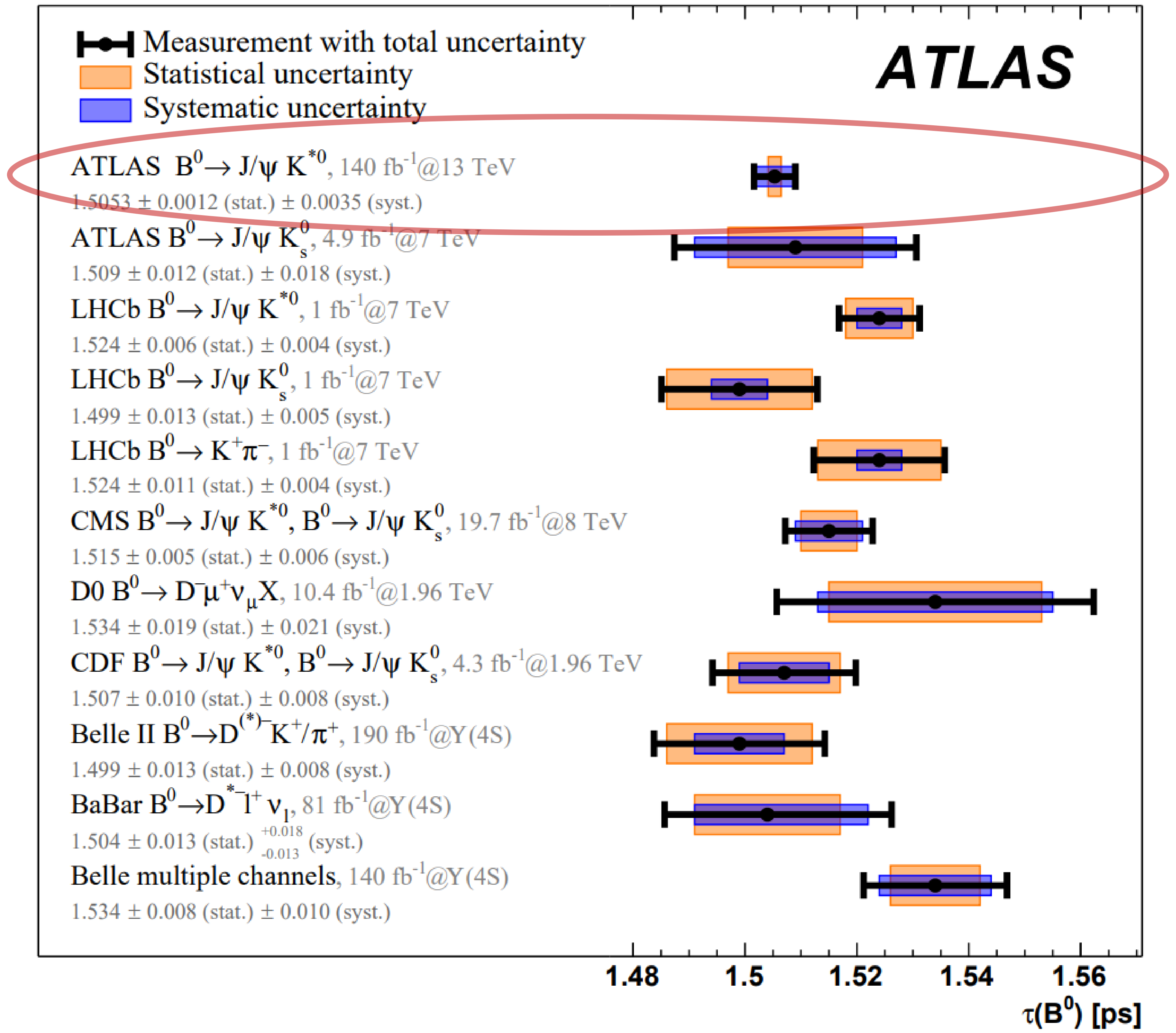
B^0 lifetime precision measurement

ATLAS-BPHY-2020-09

Systematics
- For background, mass and lifetime was found to be correlated
- Time part of background pdf studied with mass dependence

Result
- Smallest stat. uncertainty to-date
- τ: 1.5053 ± 0.0012 (stat) ± 0.0035 (syst) ps
  → total uncertainty of 0.0037 ps or 0.5%
- The best lifetime by a single experiment
- Valuable input to prediction models

Source of uncertainty	Systematic uncertainty [ps]
ID alignment	0.00108
Choice of mass window	0.00104
Time efficiency	0.00135
Best-candidate selection	0.00041
Mass fit model	0.00152
Mass-time correlation	0.00229
Proper decay time fit model	0.00010
Conditional probability model	0.00070
Fit model test with pseudo-experiments	0.00002
Total	0.0035



Model	Γ_d/Γ_s
HQE [16]	1.003 ± 0.006
Lattice QCD [17]	1.00 ± 0.02

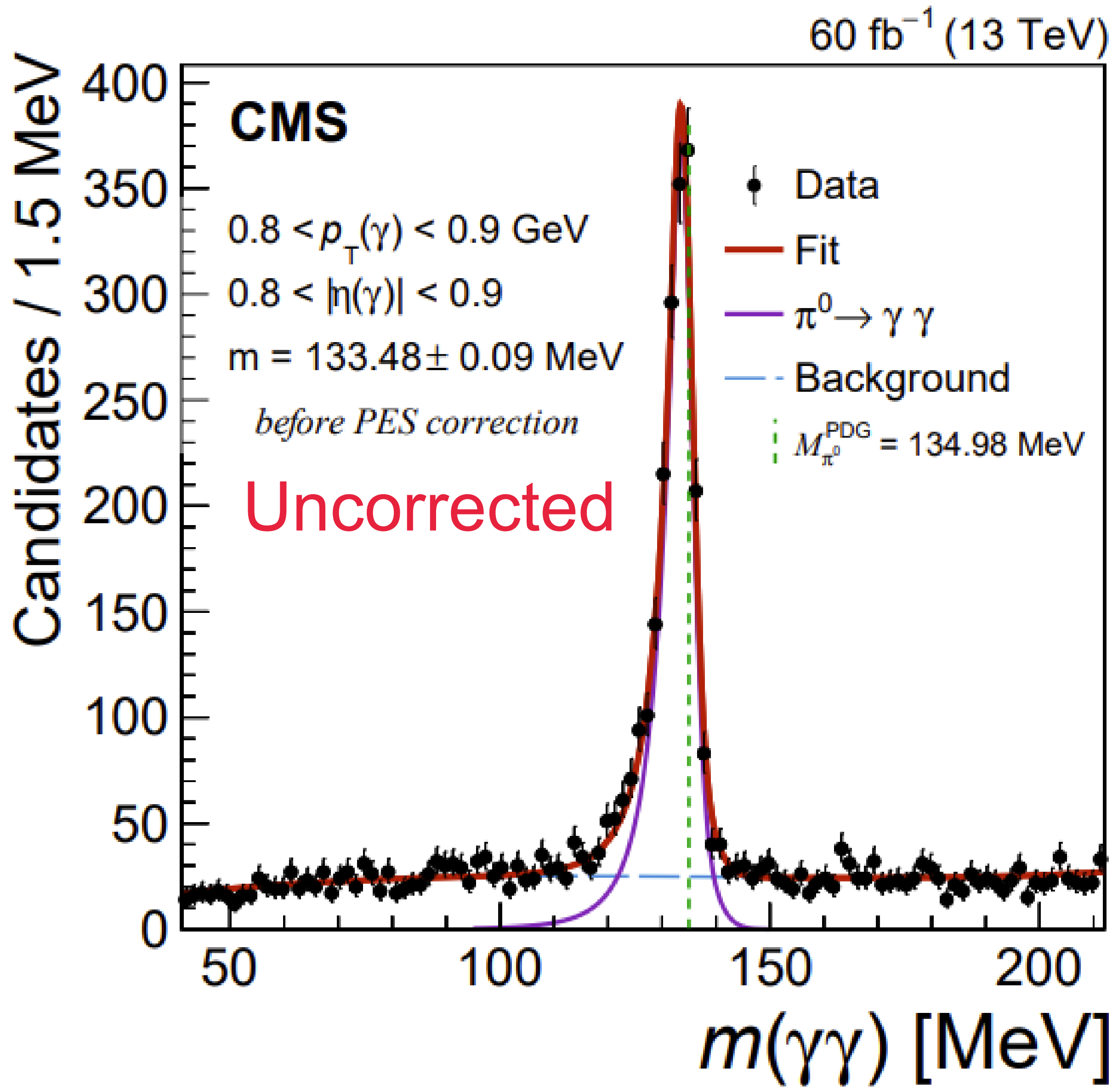
Theoretical predictions for B^0 to $B_S{}^0$ width ratio
ATLAS: 0.9910 ± 0.0022 (STAT) ± 0.0036 (SYST)

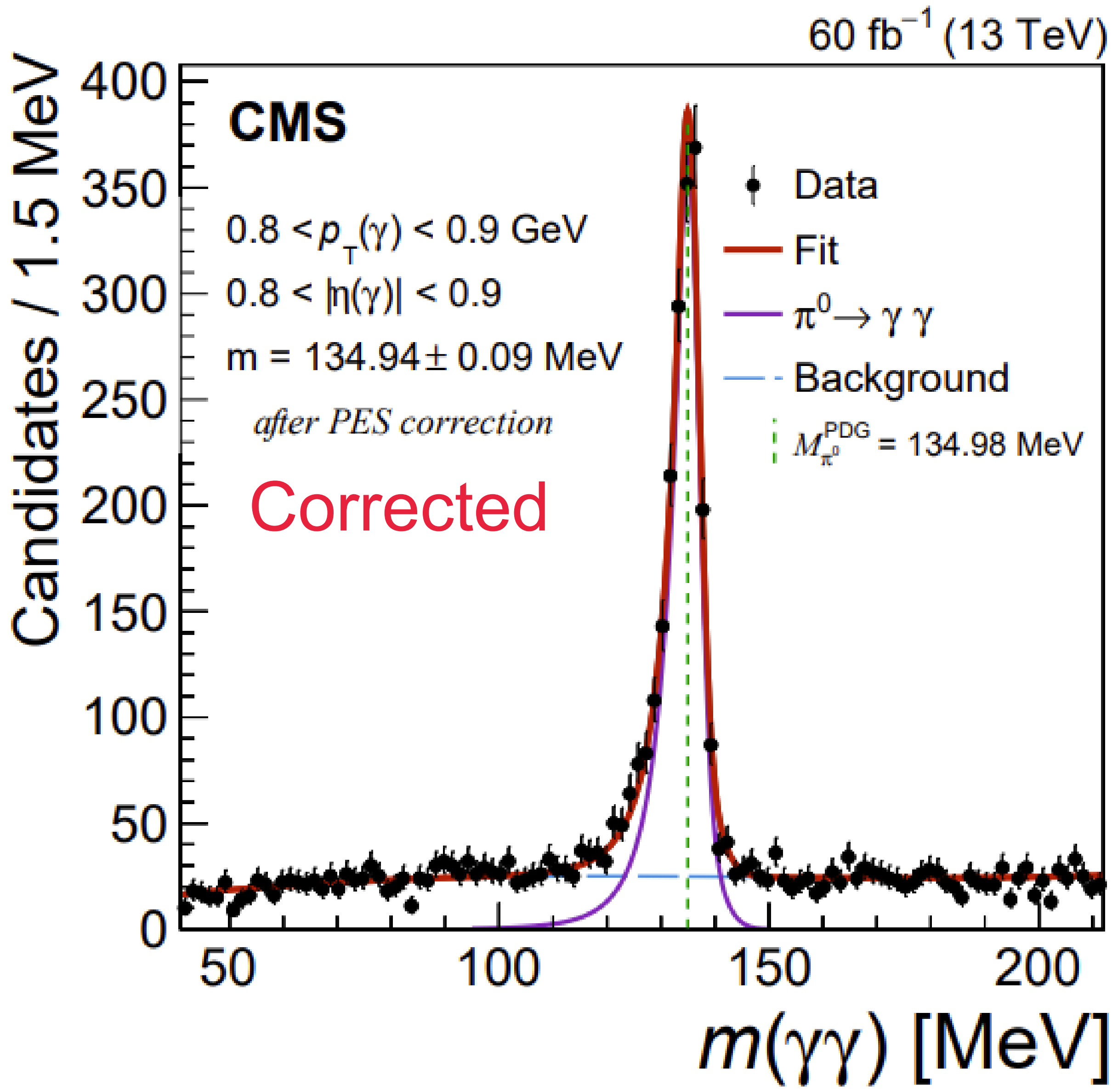
Exclusive reconstruction of B^* mesons CMS-BPH-24-011

Excited B mesons
- B^+, B^0 and B_S^0 are in general extensively studied
- B^{*+}, B^{*0} and B_S^{*0} are much less explored
- Mass difference $m(B^*) - m(B)$ is crucial to quark models

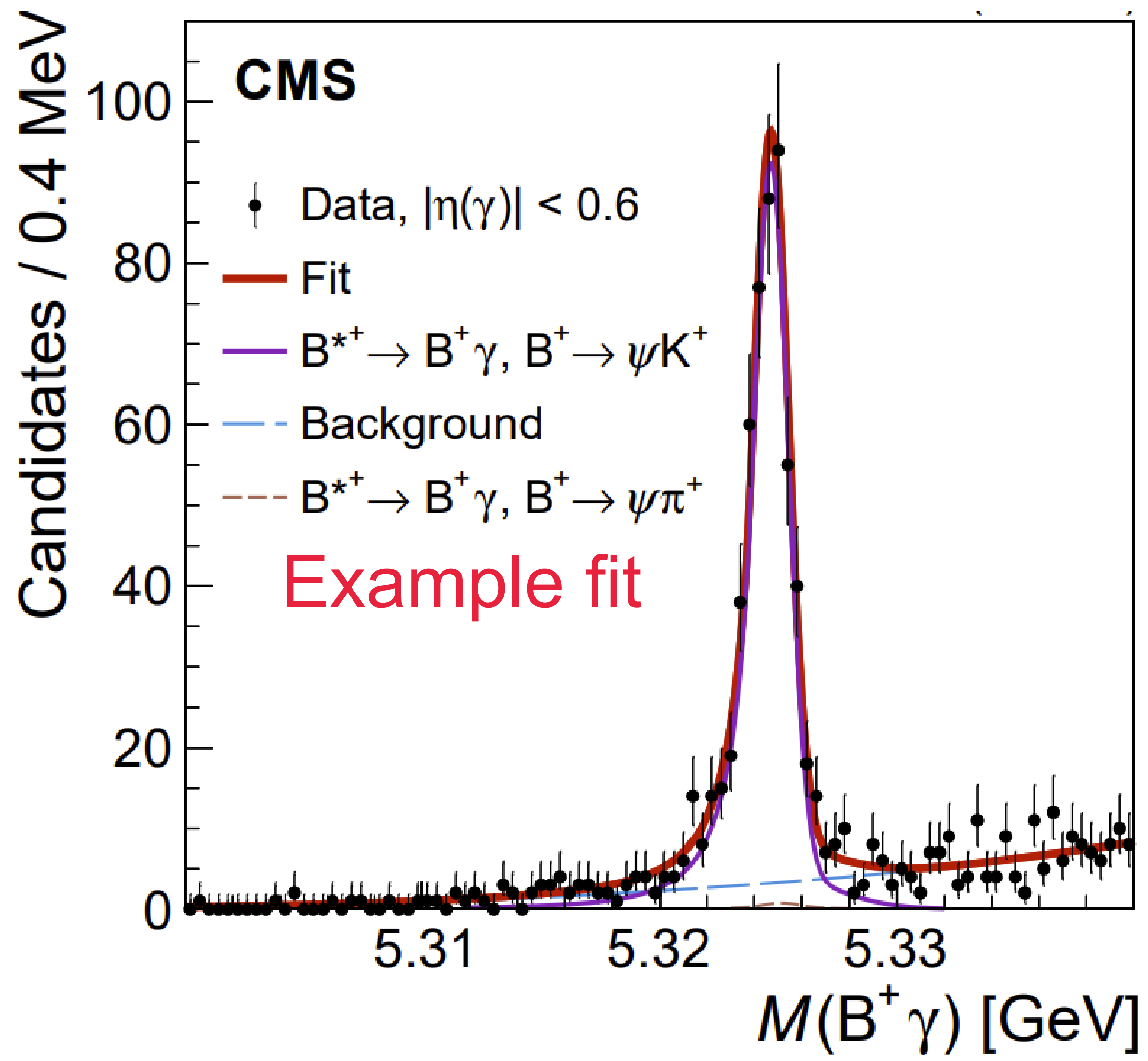
Challenge
- In $B^* \to B\gamma$ decays, the photon is 40-50 MeV (B^* frame)
  → Use conversion electrons
  → Photon candidates > 300MeV
- True photon energy; electrons lose energy in the detector
  → Photon energy scale correction algorithm
  Tuned per bins of p_T and $|\eta|$, using $\pi^0 \to \gamma\gamma$ decay

Channel of choice
- $B^* \to B\gamma(ee)$
- $B^+ \to \psi\, K^+$, $B^0 \to \psi\, K^{*0}$ and $B_S^0 \to \psi\phi$
  ($J/\psi \to \mu\mu$, $K^{*0} \to K^+\pi^-$ and $\phi \to K^+K^-$)





	CMS Measured Value [MeV]	PDG World Average [MeV]
$m(B^{*+}) - m(B^+)$	$45.277 \pm 0.039_{\text{stat}} \pm 0.027_{\text{syst}}$ MeV	45.37 ± 0.21 MeV
$m(B^{*0}) - m(B^0)$	$45.471 \pm 0.056_{\text{stat}} \pm 0.028_{\text{syst}}$ MeV	45.42 ± 0.26 MeV
$m(B_s^{*0}) - m(B_s^0)$	$49.407 \pm 0.132_{\text{stat}} \pm 0.041_{\text{syst}}$ MeV	$48.5^{+1.5}_{-0.4}$ MeV



First time exclusively reconstructed
An order of magnitude improvement over world average value

D meson production measurement

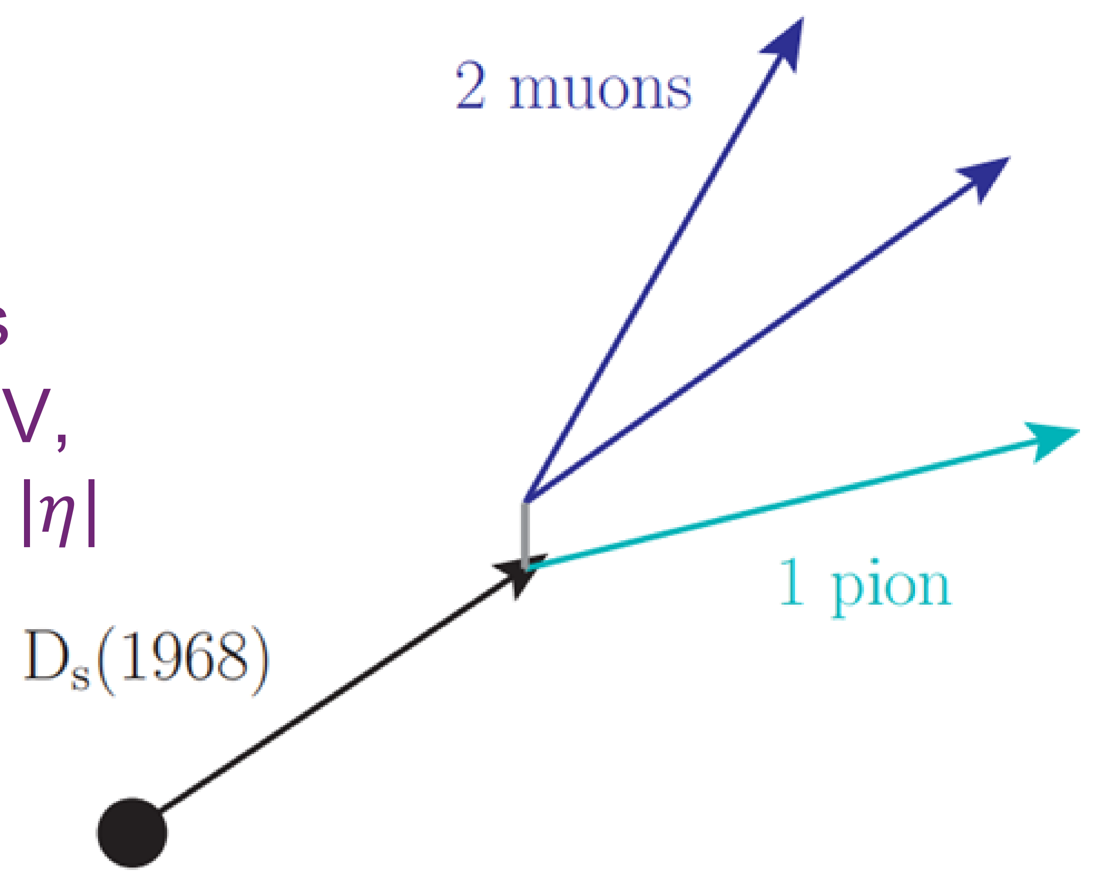
ATLAS-BPHY-2018-10

D meson production

- Directly related to charm production
- Normalization for works making use of D meson

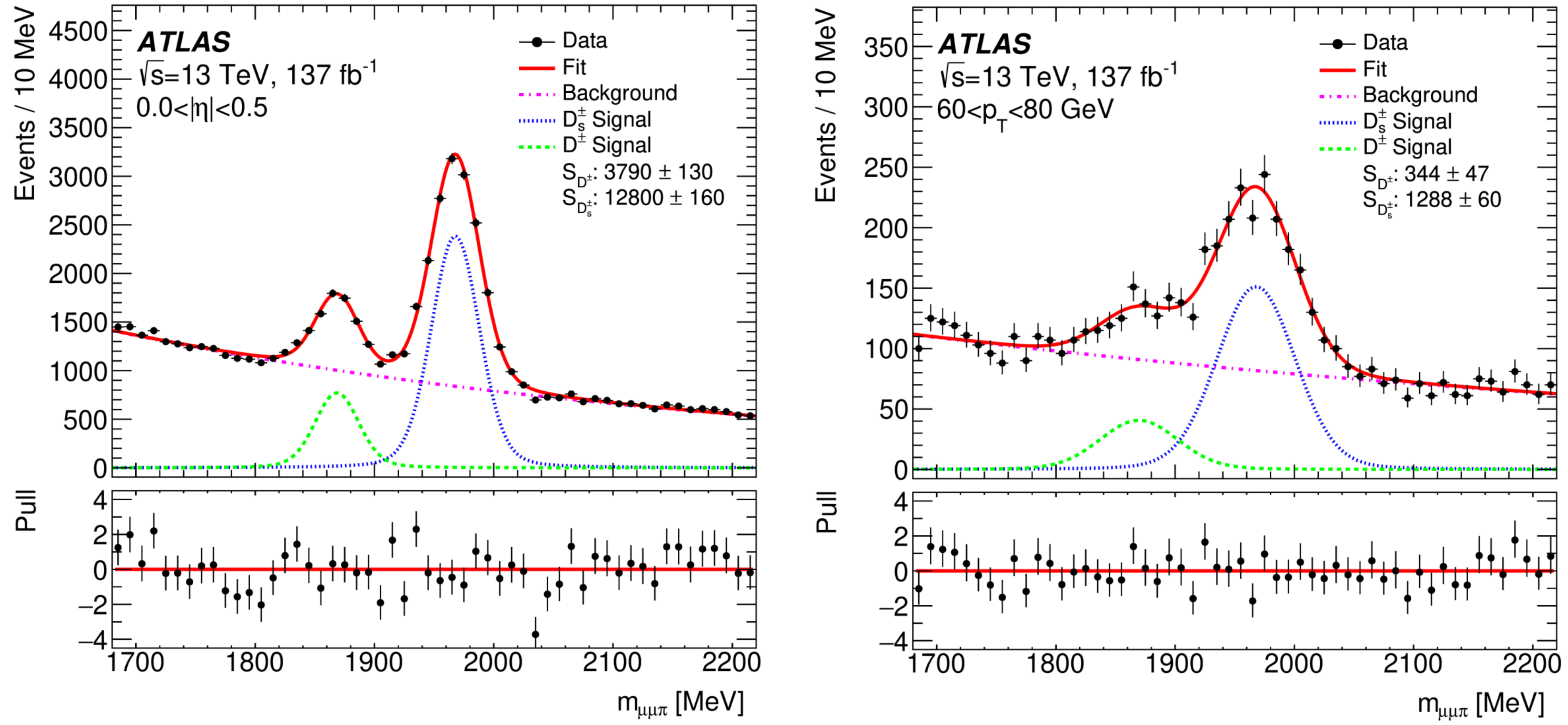
$D^{\pm}/D_s^{\pm} \rightarrow \phi\pi \rightarrow \mu\mu\pi$

- Cleaner compared to using K/π final states
- $D^{\pm}$ and $D_s^{\pm}$ have mass difference < 100MeV, extracted simultaneously, in bins of p_T and $|\eta|$
- Enhanced using $m_{\mu\mu}$ around ϕ mass
- Limited by muon trigger thresholds

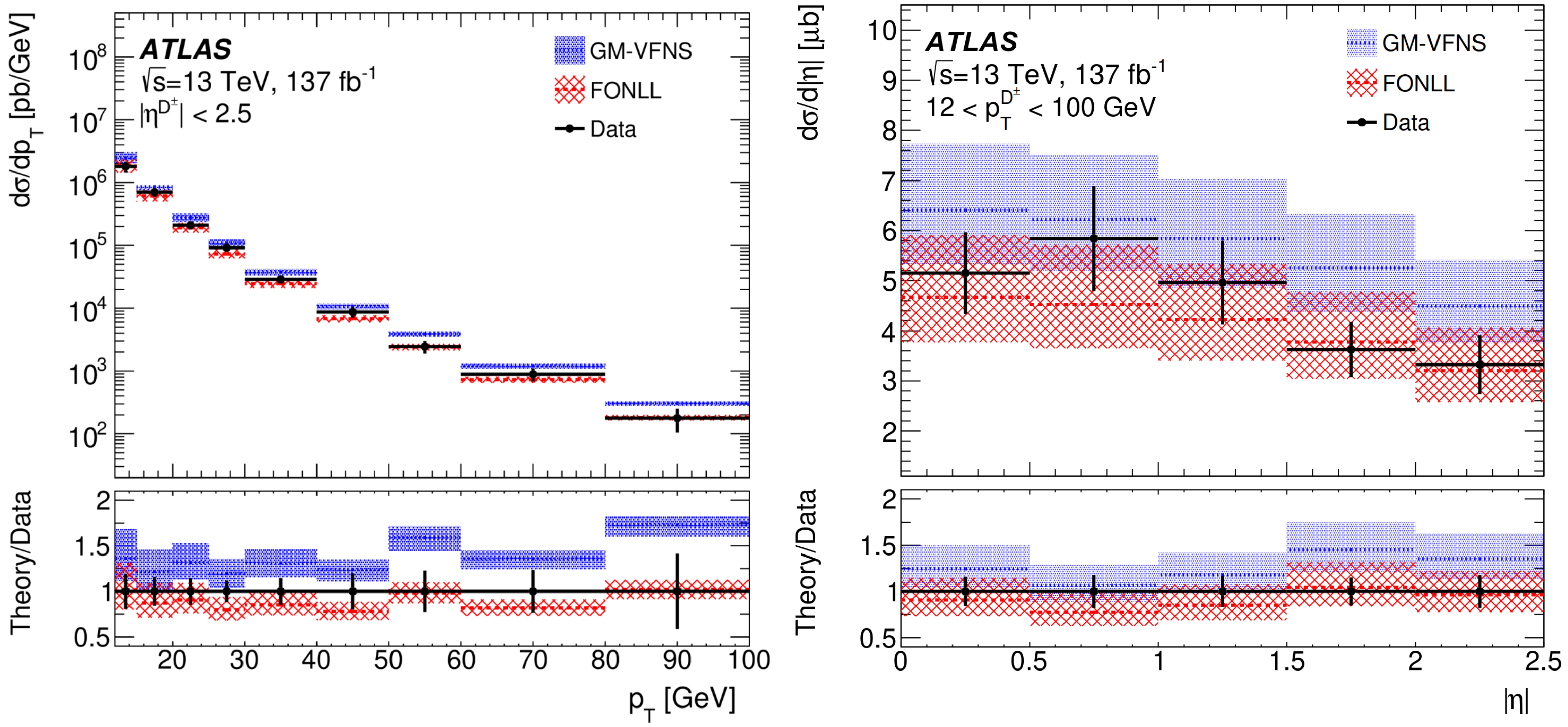


Result

- First differential measurement of $D_s^{\pm}$ meson in the LHC up to 100 GeV
- In agreement with FONLL and GM-VFNS with deviation at high p_T
- Input to NNPDF in improve PDF model



Unbinned fits to extract yield



Differential cross-sections

LFV $\tau \to 3\mu$ decay

ANA-BPHY-2020-09

BR($\tau \to 3\mu$) status

- Any signal is clear bSM physics
  MSSM : 10^{-10} - 10^{-8} (arxiv; 0801.1826)
  Standard Model: ~10^{-55} (arxiv; 1912.09862)
- ATLAS run-1: 3.76×10^{-7}
- Most stringent limit is by Belle-II at 1.9×10^{-8}

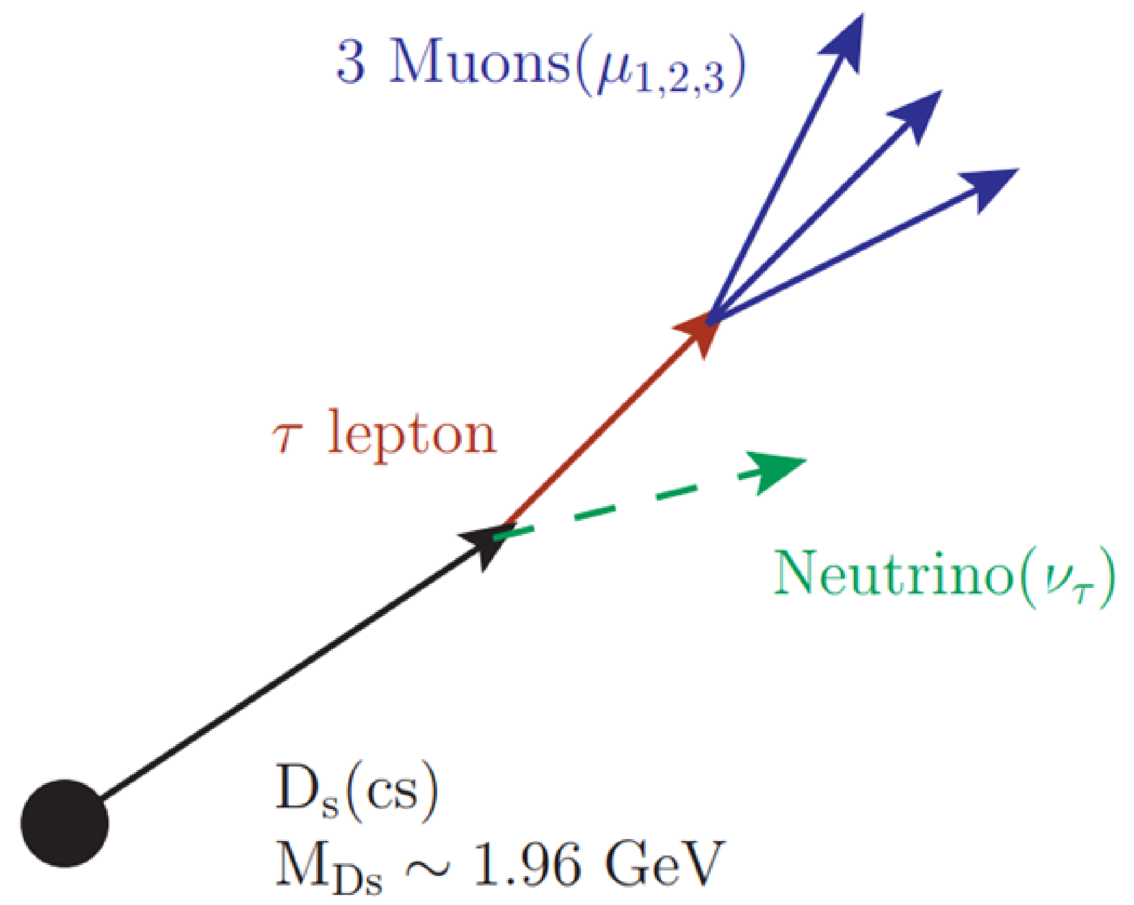
Channels accessible by LHC

- Challenging heavy flavour (HF) at lower energy
  $BR(D_s^{\pm} \to \tau + \nu_\tau)$~5.4%
  $BR(B \to \tau + X)$~3.4%
- Cleaner, W-boson (EW) at higher energy
  $BR(W \to \tau + \nu_\tau)$ ~10.8%
- Optimize primarily for W channel, include also HF result

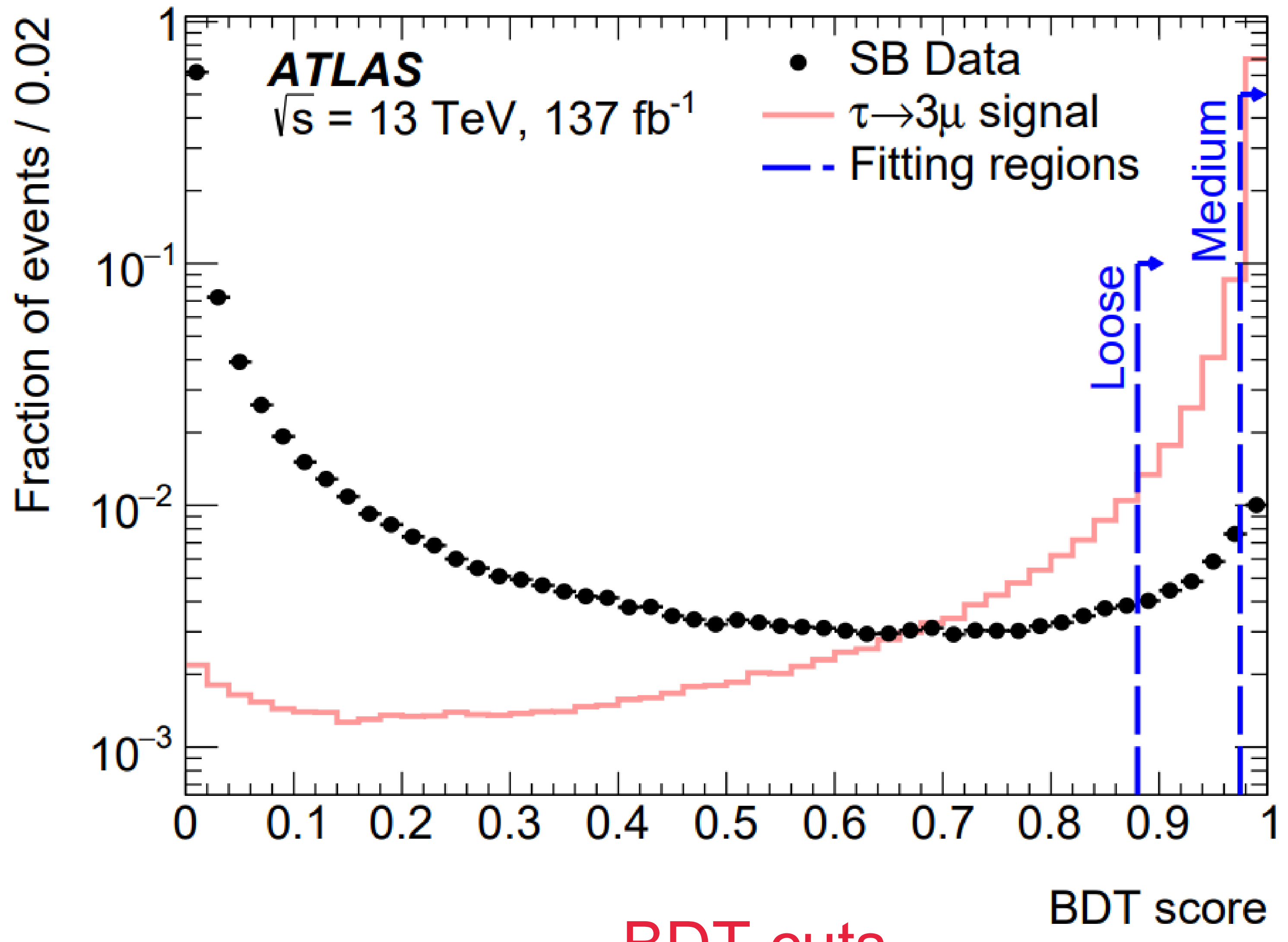
Analysis approach

- BDT cuts to define fit regions, fit around τ mass
- Focus on EW channel (better sensitivity over HF, due to trigger limitation)

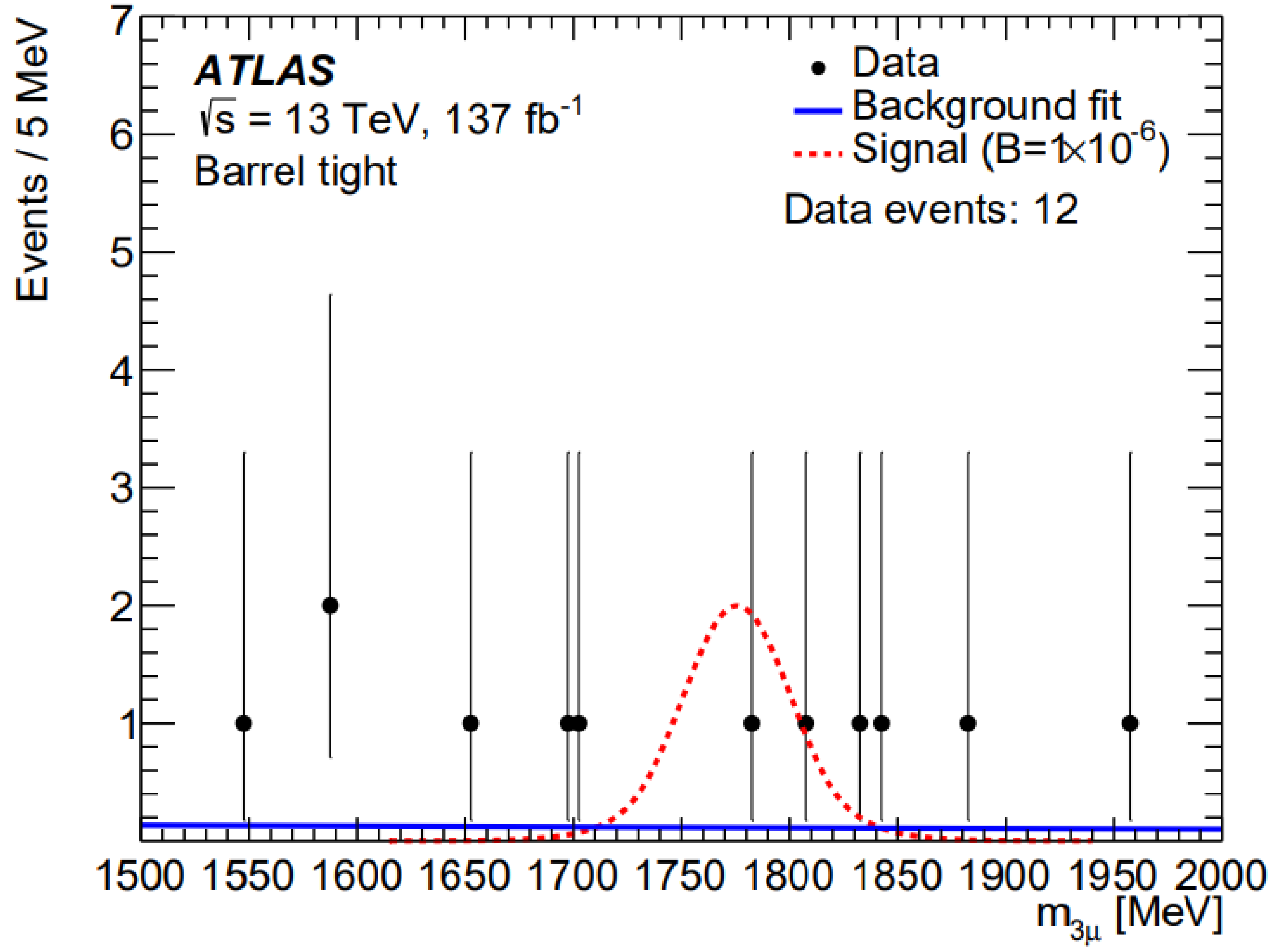
Limit of $\mathrm{BR}(\tau \to 3\mu) < 8.7 \times 10^{-8}$ at 90% CL



HF Channel



BDT cuts



Unbinned fit around τ mass

Rare $\eta \to \mu\mu ee$ decay

CMS-BPH-24-001

$\eta(\to \gamma^*\gamma^*) \to \mu\mu ee$

- Challenging prediction because of the two virtual photons
- Unknown transition form factors
- SM prediction: 2.3×10^{-6}
- Previous result: Upper limit at 9.7×10^{-5} (CELSIUS/WASA Collaboration 2008; arxiv)

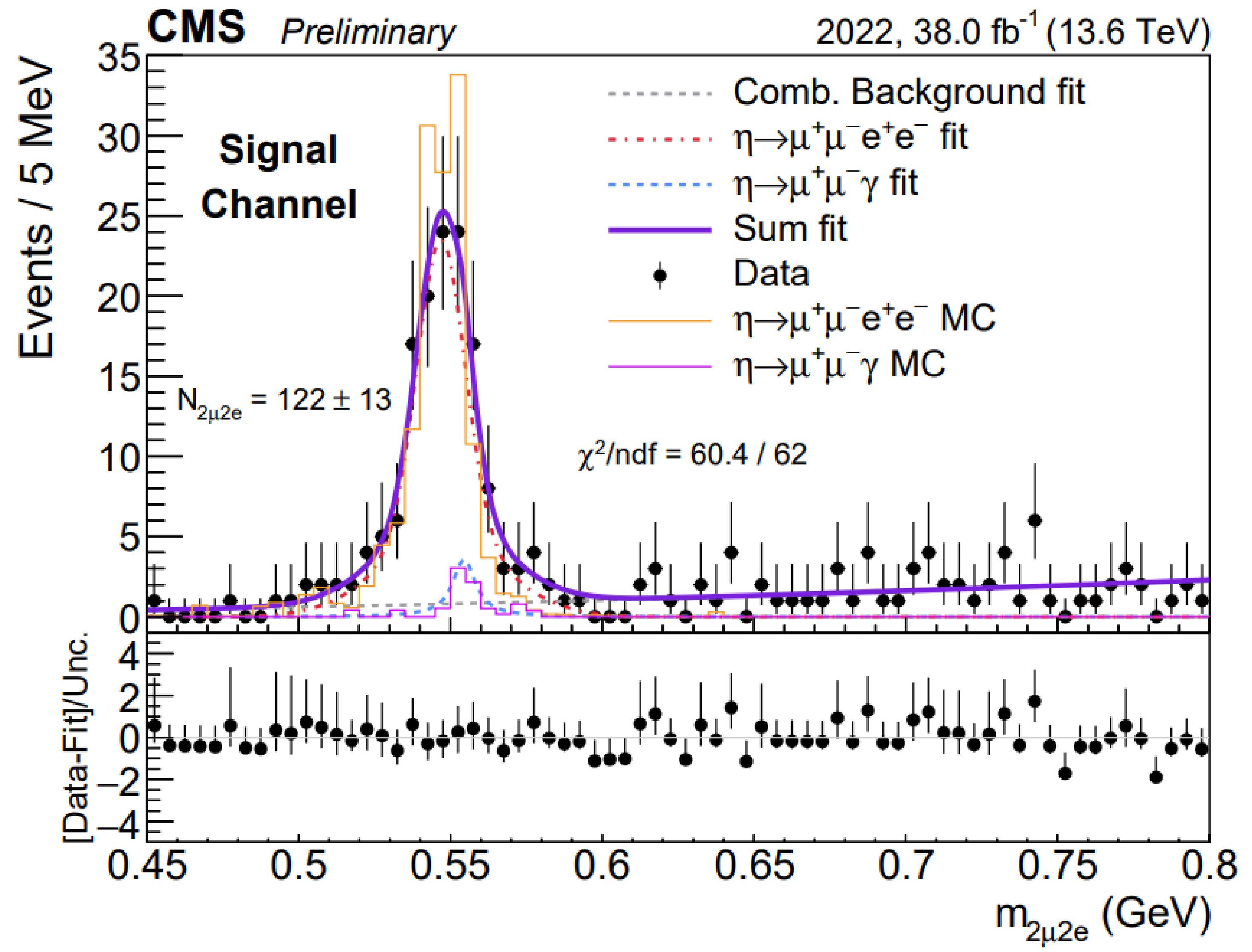
$\eta \to \mu\mu\gamma$

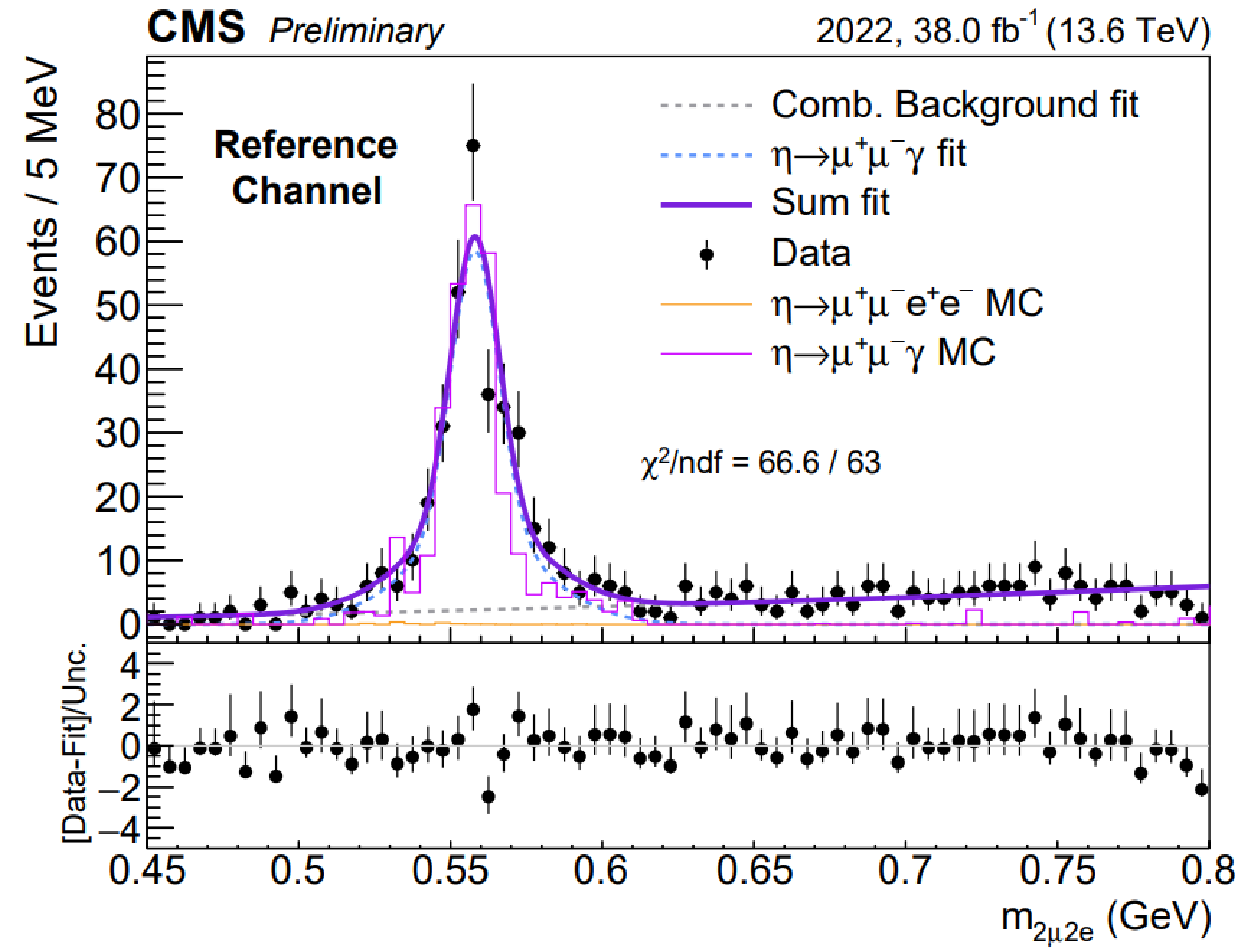
- Reference channel
- Known BR of $(3.1 \pm 0.4) \times 10^{-4}$

Challenges

- Very soft final states
  →Special dimuon trigger with threshold at 3 and 4 GeV
  →Electrons down to 2GeV
- Electron resolution
  →Electrons assumed to be from primary vertex,
  but real vertex can be in the first pixel layer
  → Peak at 554 MeV (world average 548 MeV)
- Photon conversion and reference channel contamination
  → Reference channel enhanced region designed to
  select electrons coming from photon conversion

Clear signal in the fit, fitted $N_{2e2\mu} = 122 \pm 13$, measured BR of $(2.1 \pm 0.7) \times 10^{-6}$
Consistent with SM, first observation of the decay





Summary

$\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ production

- $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ differential cross sections (CMS-BPH-24-004; arxiv)
  → Differential measurement over a broad kinematic range; strong input for global fits
- $\Upsilon(1S) + Z$ associated production and effective double-parton scattering (CMS-BPH-23-007; arxiv)
  → First study of the production; measuring DPS in kinematic bins

Tetra quarks

- Family of all-charm tetraquarks (CMS-BPH-24-003; arxiv)
  → Observation of 3 states and interference; interpretation of common underlying configuration
- $J/\psi + \psi(2S)$ resonance (ATLAS-BPHY-2023-01; arxiv)
  → Confirms observation of X(6900), strengthened by adding $4\mu + 2\pi$ mode

B and D meson production

- B^0 lifetime precision measurement (ATLAS-BPHY-2020-09; arxiv; erratum)
  → Best B^0 lifetime on to-date
- Exclusive reconstruction of B^* mesons (CMS-BPH-24-011 arxiv)
  → First exclusive reconstruction; mass difference 1 order of magnitude improvement
- D meson production measurements (ATLAS-BPHY-2018-10; arxiv)
  → First differential measurement for high p_T

Searches

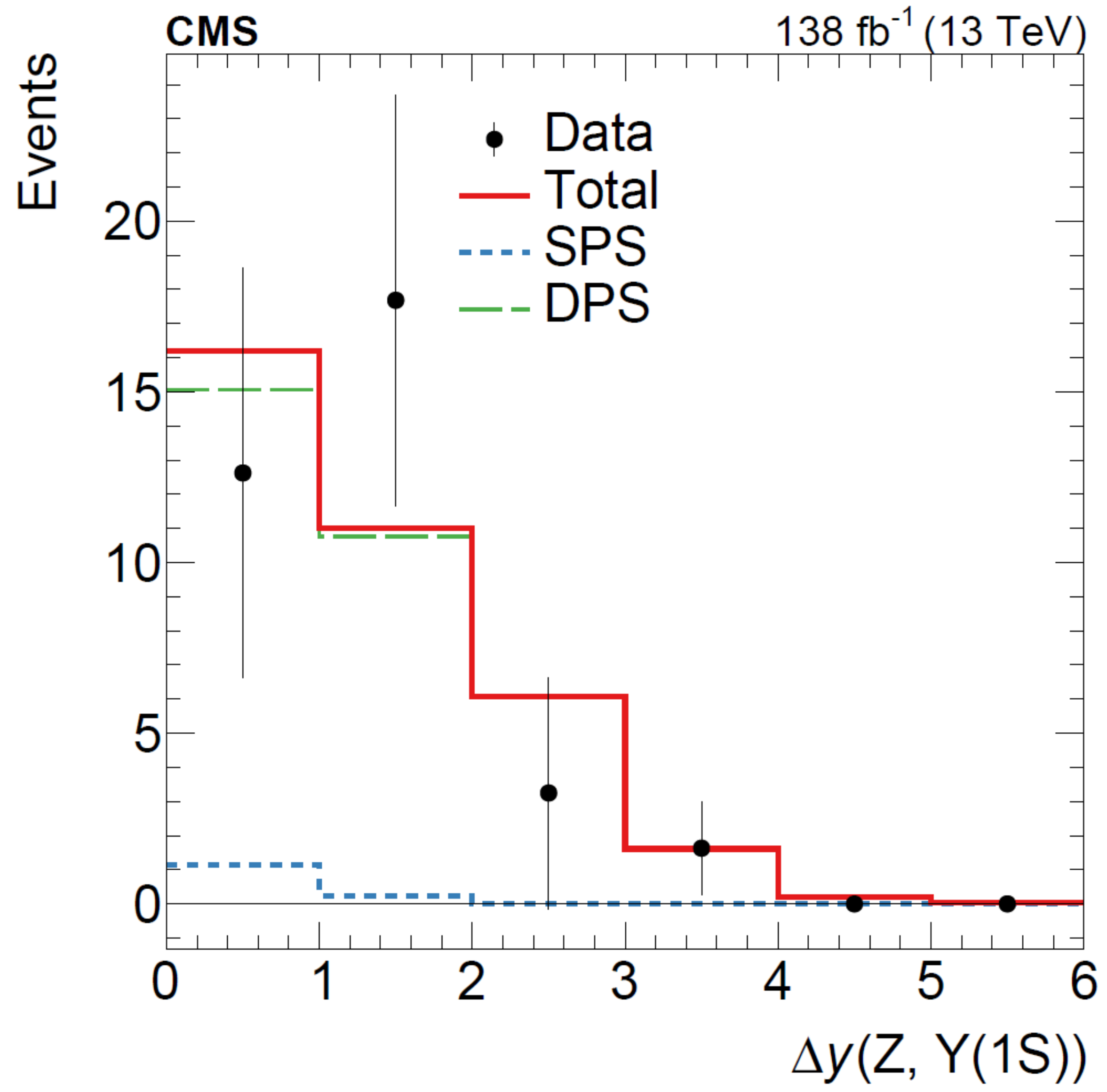
- LFV $\tau \to 3\mu$ (ATLAS – New Results)
  → Improved limit compared to ATLAS run-1 result; 4 times improvement
- Rare $\eta \to \mu\mu ee$ (CMS−BPH−24−001; cds)
  → First observation; almost 2 orders of magnitude improvement

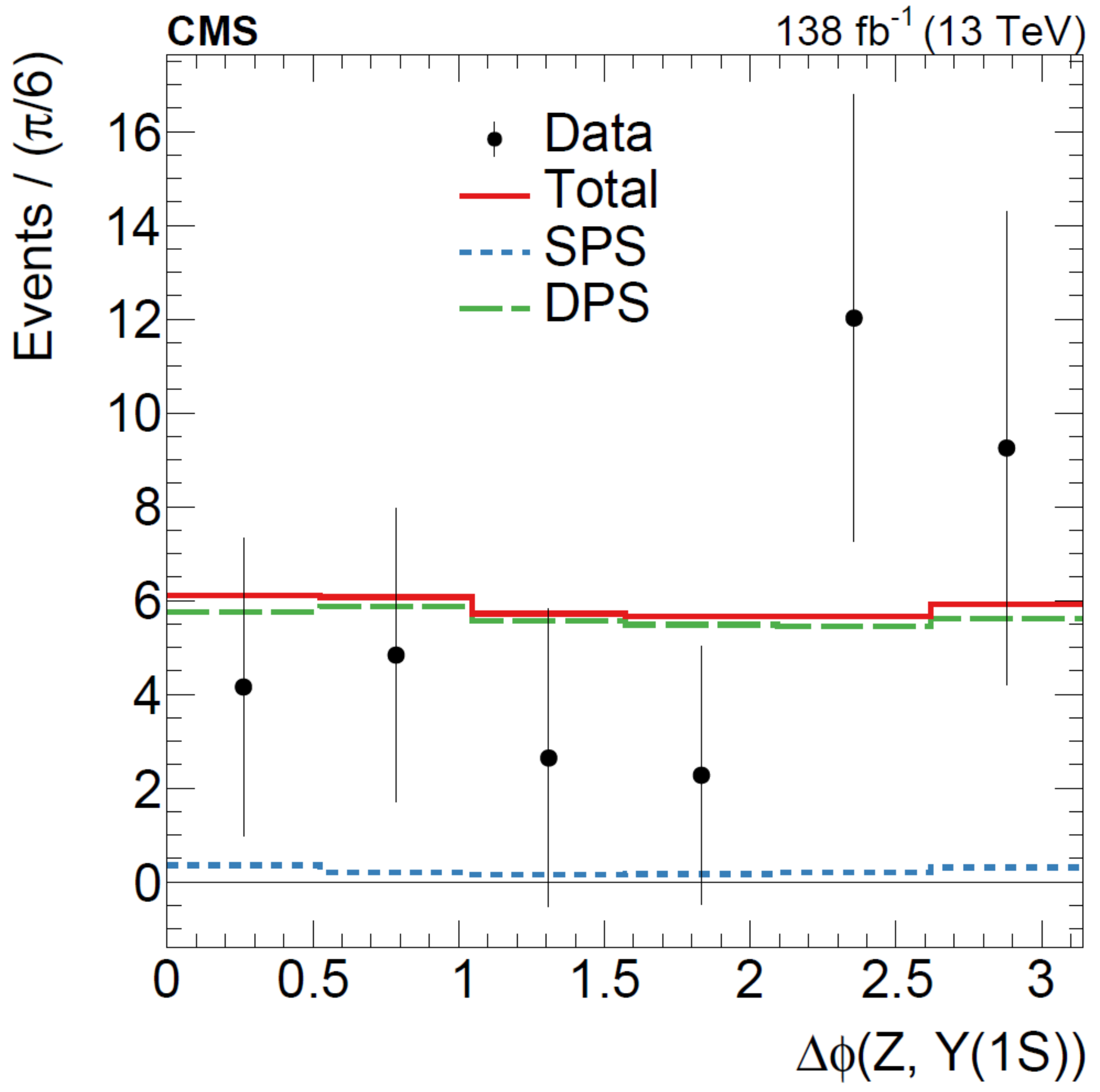

Thank You!
Tetraquarks?

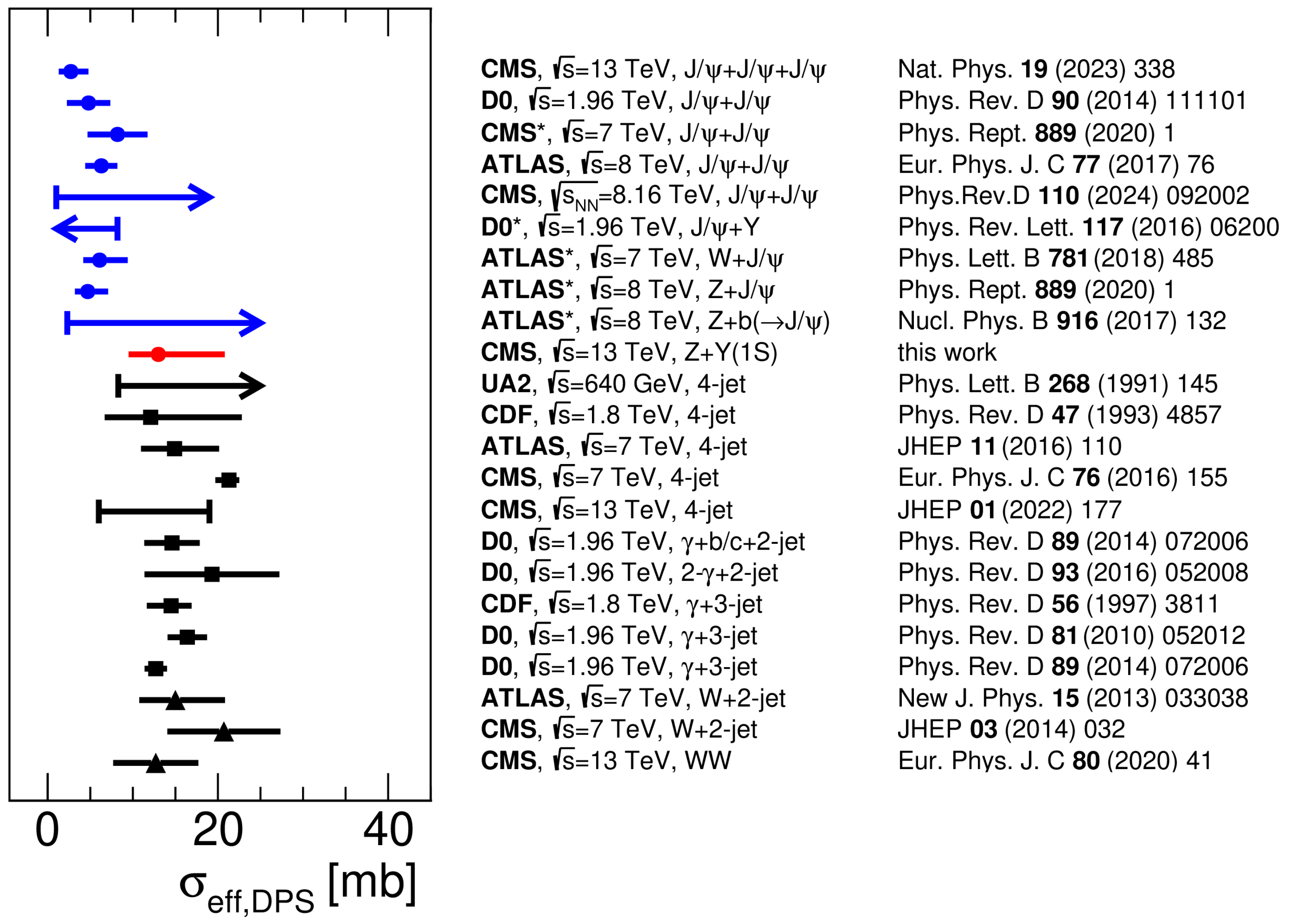
Effective double-parton scattering

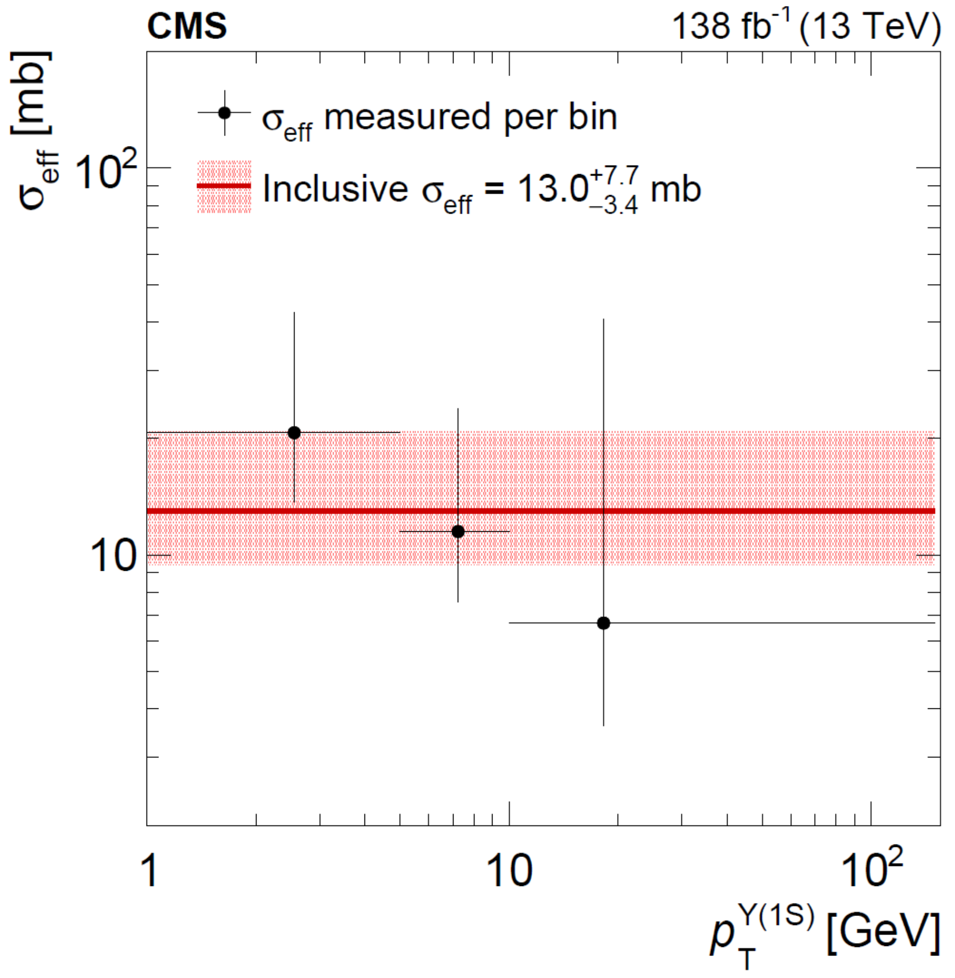
SPS DPS contribution

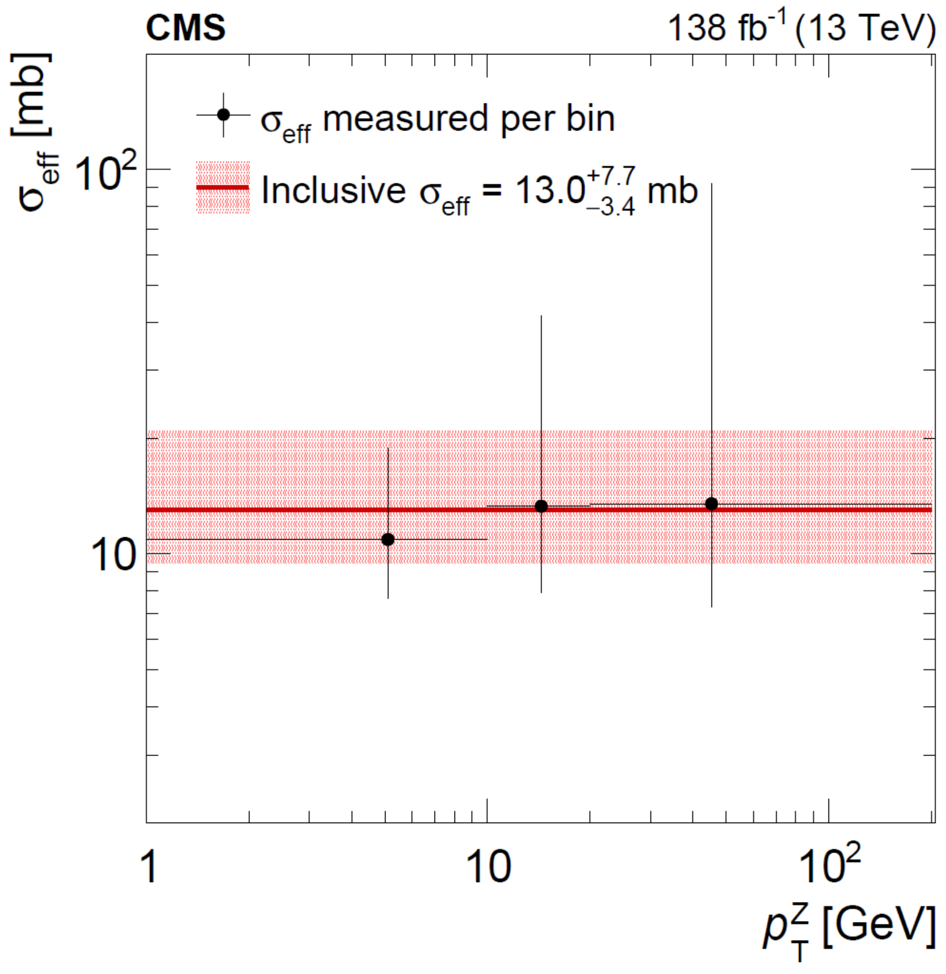
- Fit performed to extract per bin





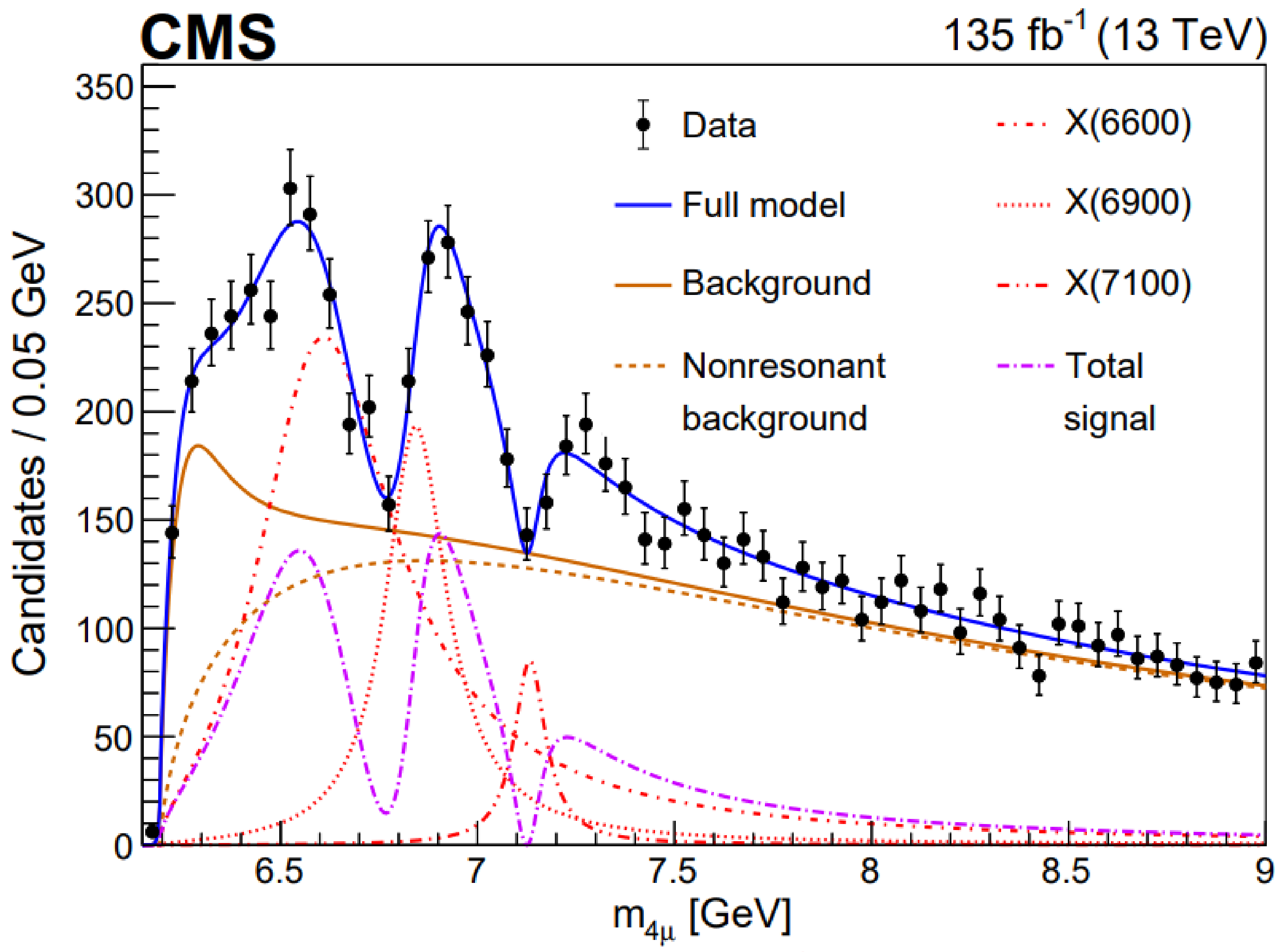




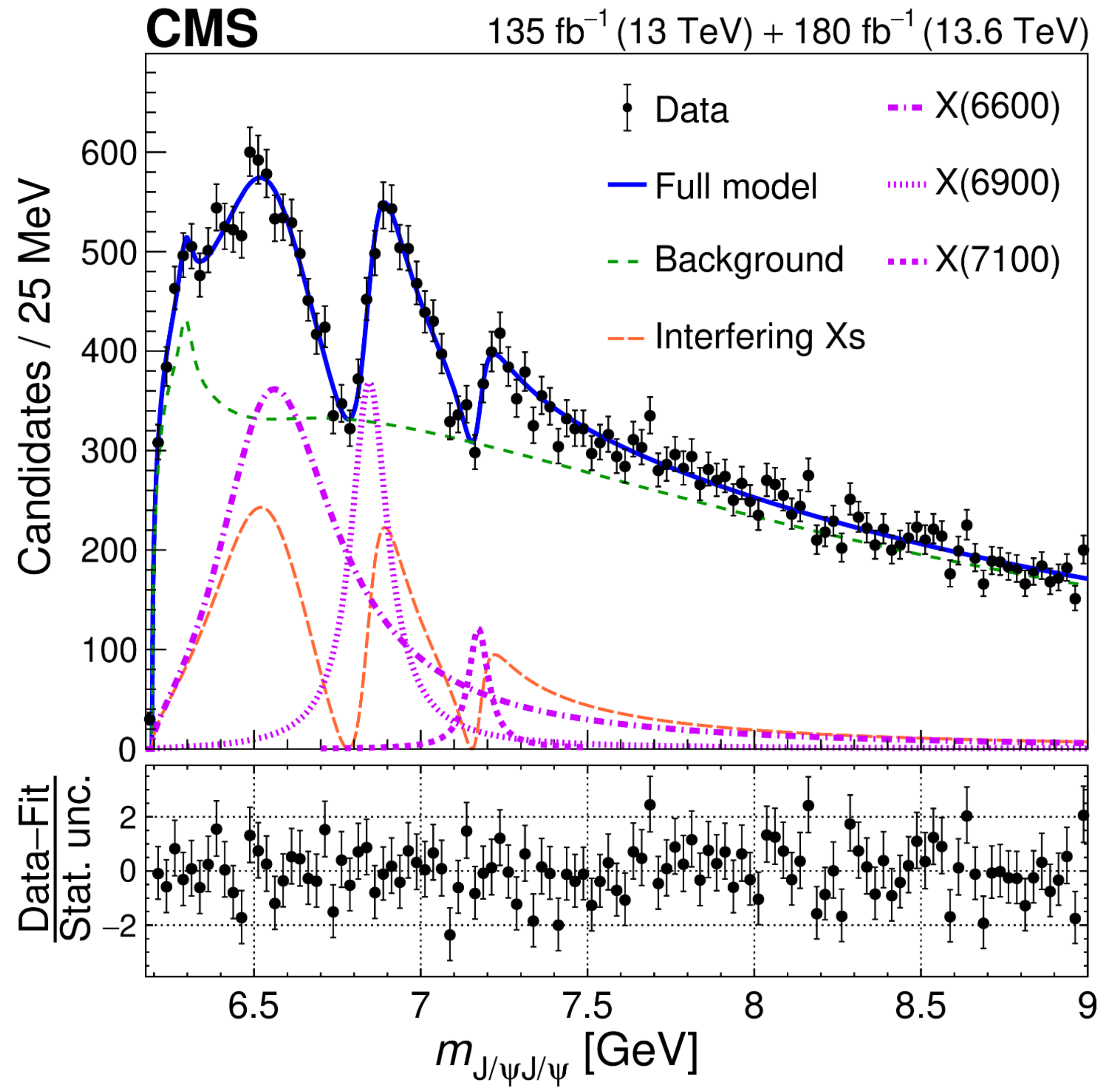


- For the first time σ_{eff} measured in bins of Υ and Z momenta
- Overall measurements are consistent with other experiments

Determination of the spin and parity of all-charm tetraquarks



Run 2



Run 2 + run 3