Results on Production of B-hadrons and Onia at CMS

GRANT RILEY

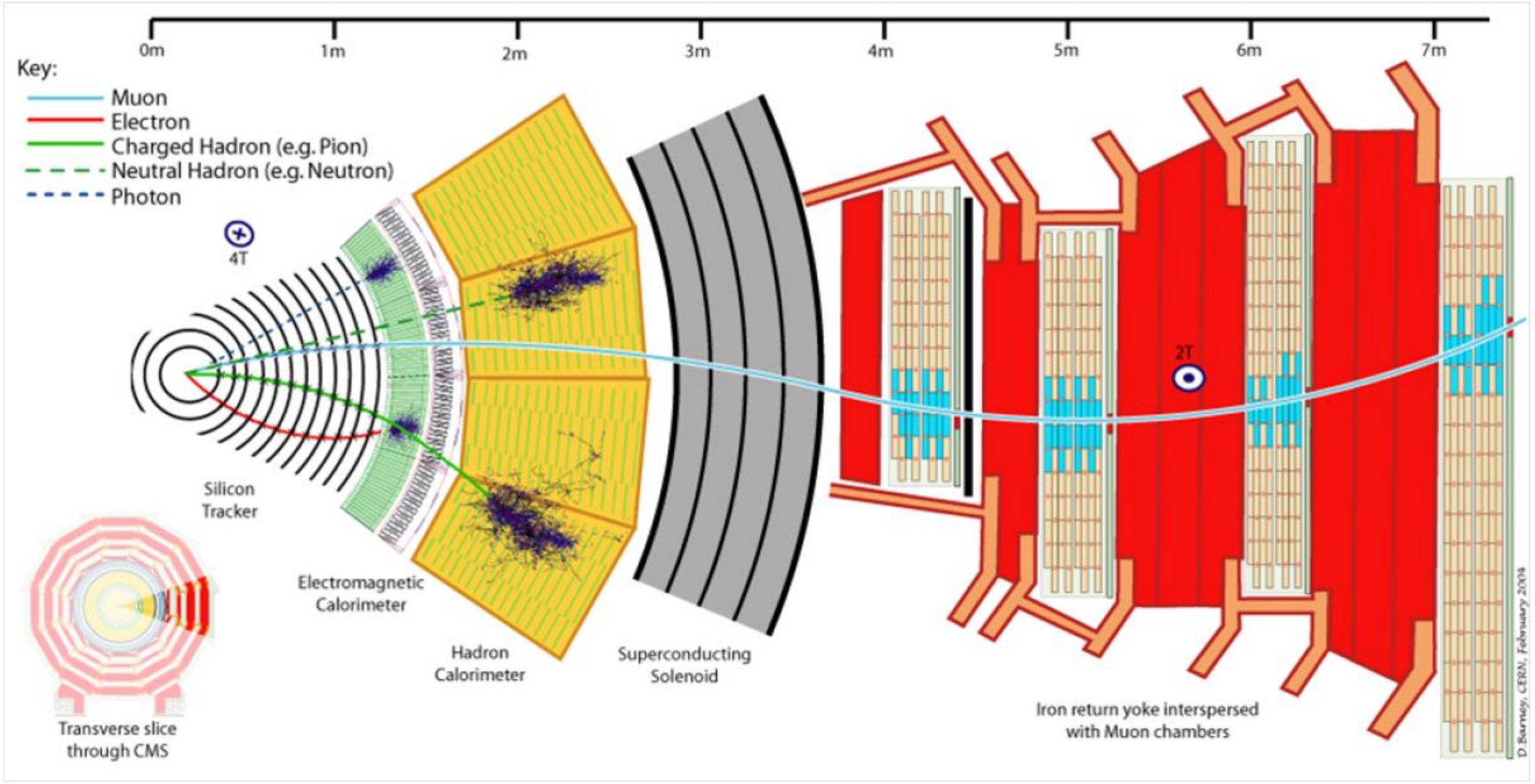
REPRESENTING CMS AND THE CMS B-PHYSICS GROUP

Outline

- CMS Detector and Triggers
- Quarkonia overview
- J/ψ, $\Upsilon(\mathrm{nS})$ production
- B, B_s, B_c production
- X and Y resonances
- Double Quarkonia cross section

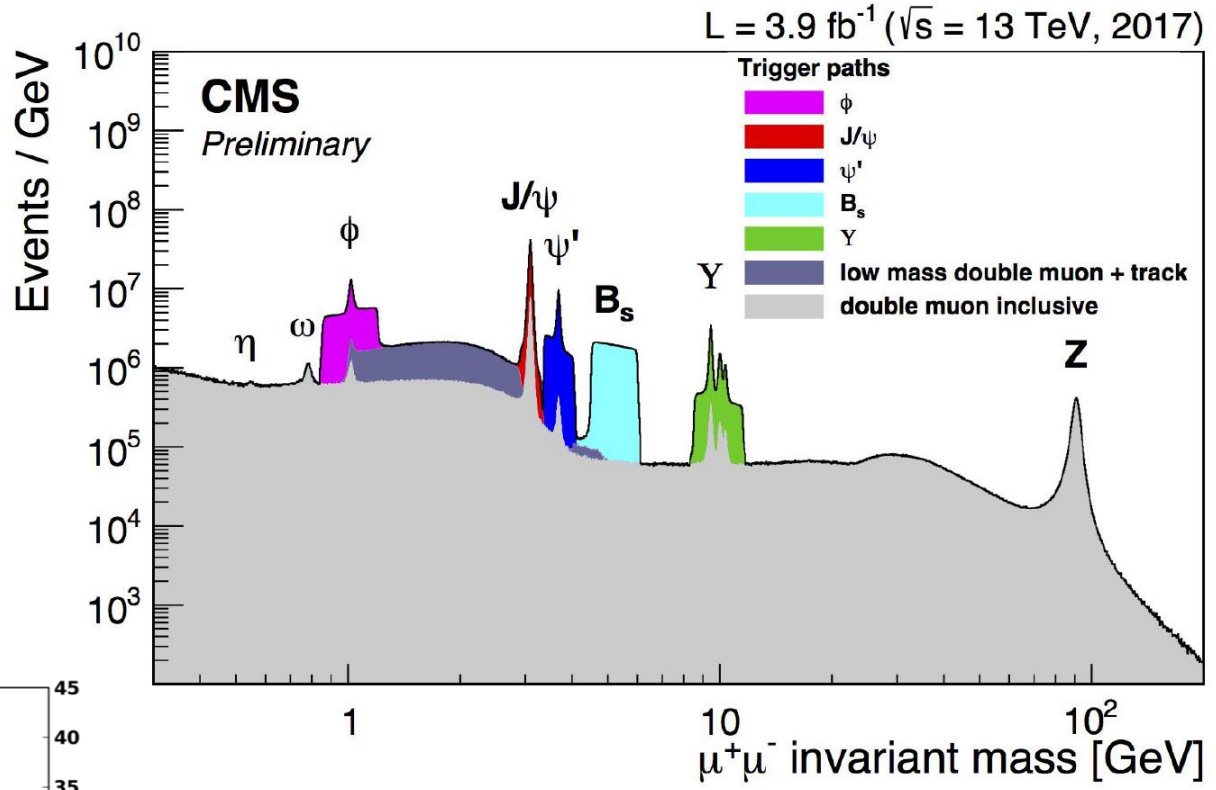
- Summary

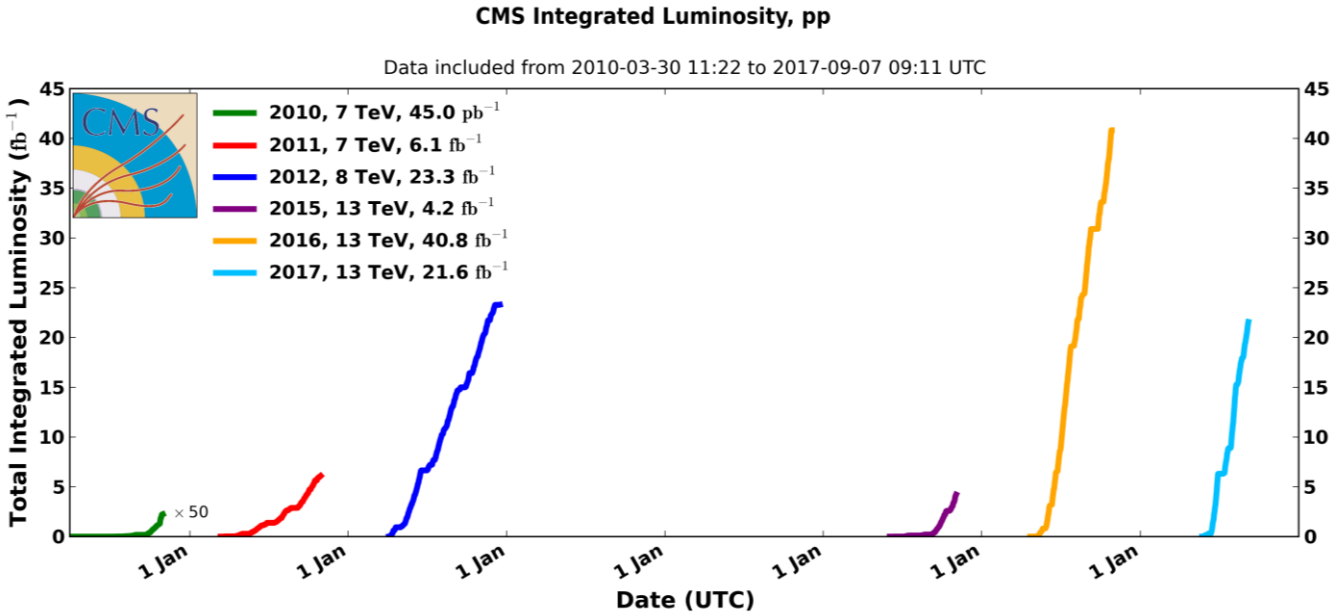
Compact Muon Solenoid



CMS Trigger System for Quarkonia

- CMS has collected data for 6 years at 7, 8 and 13 TeV
- Increasing instantaneous luminosity
- Triggers essential to measure specific final states in hadronic collision
  - B-Physics specific triggers
  - Double, triple and quad muon selectors
  - Vertexing and vertex displacement
  - Dimuon mass windows



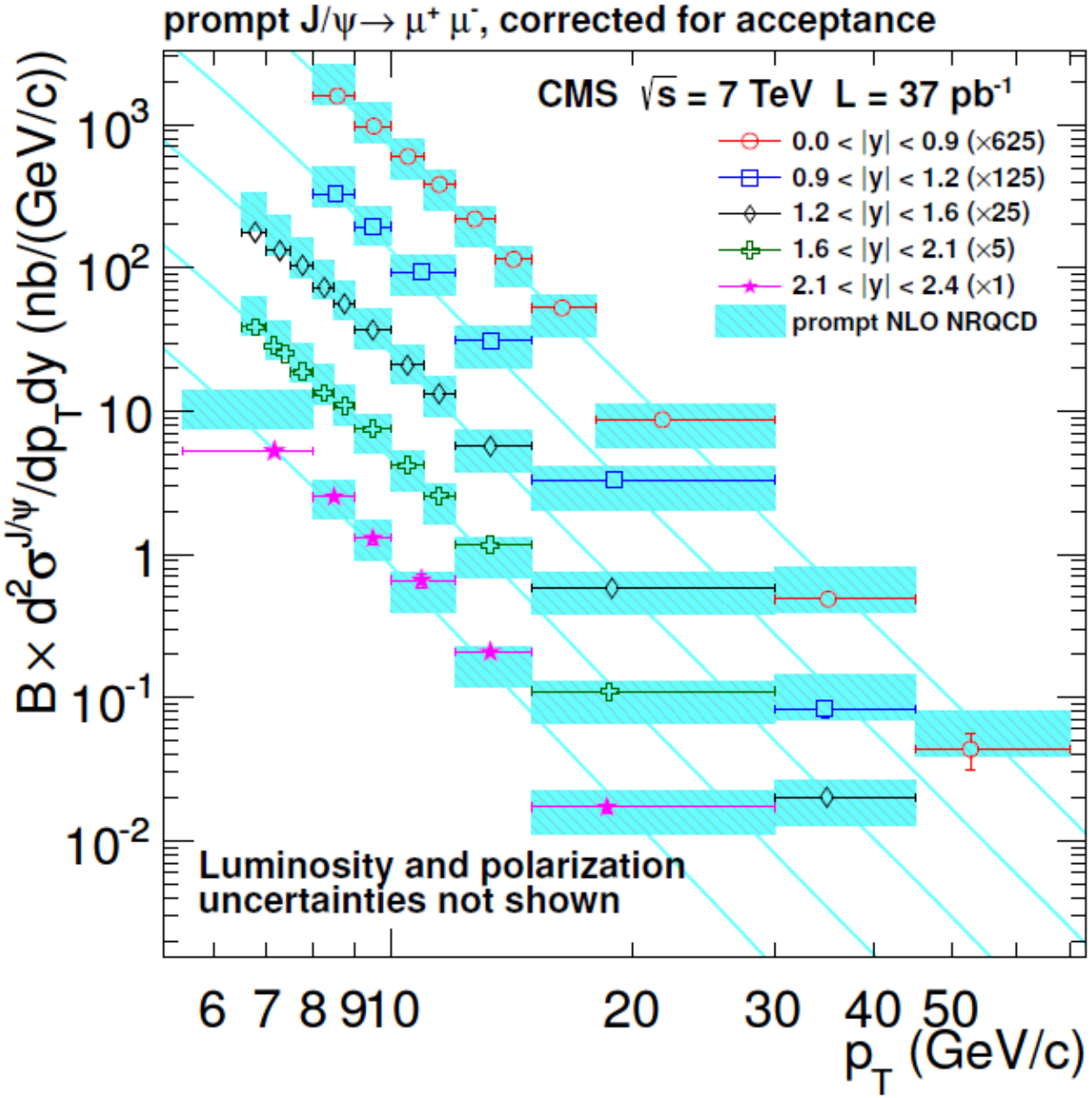


J/ψ, ψ(2S) Cross Sections at 7 TeV

- Measure J/ψ and ψ(2S) xsec in bins of p_T, up to p_T ~ 50 GeV

- High precision measurement
  ➔Compare with model
- Test of NRQCD
  - short-distance terms governed by parton distribution functions (PDFs)
  - long-distance matrix-elements (LDMEs), fits to data
- Good agreement

- Several Questions
  - Does the scaling with energy work?
  - When do NNLO corrections become necessary
  - Higher pT, do the models still agree?

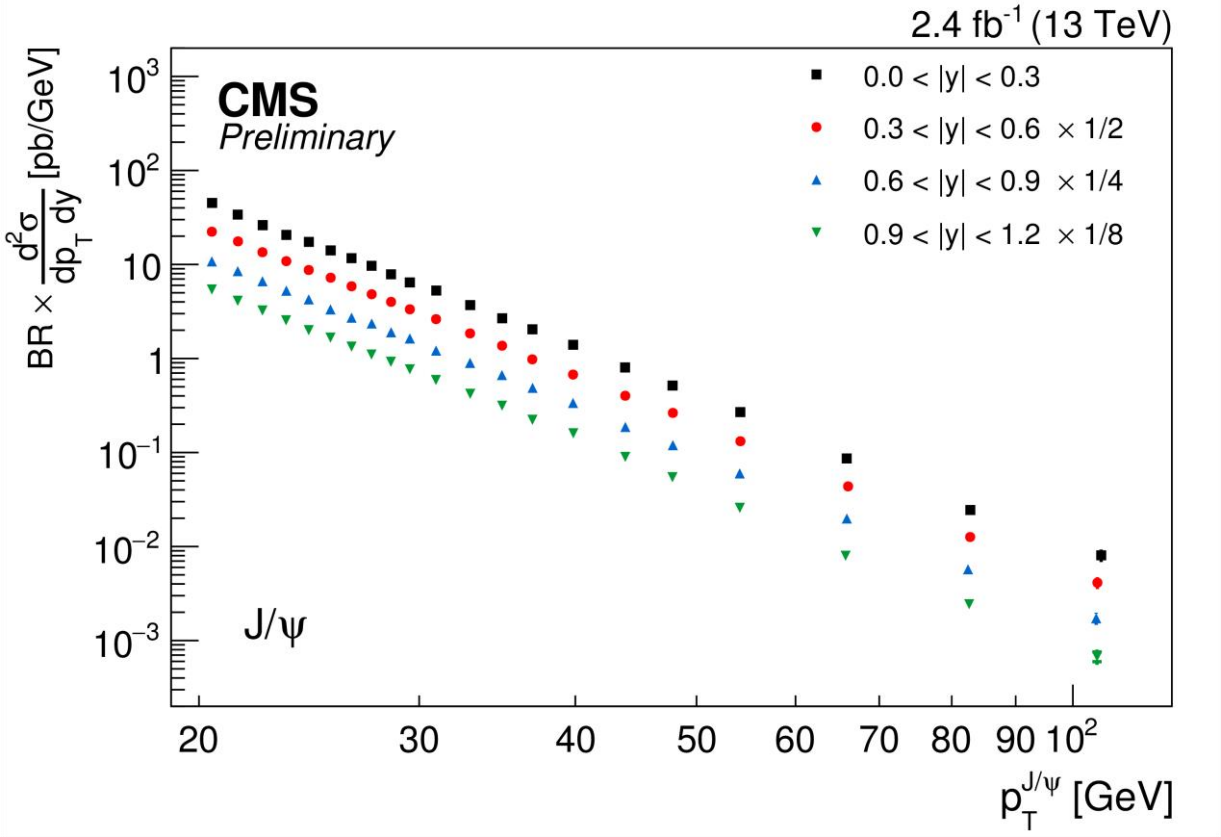


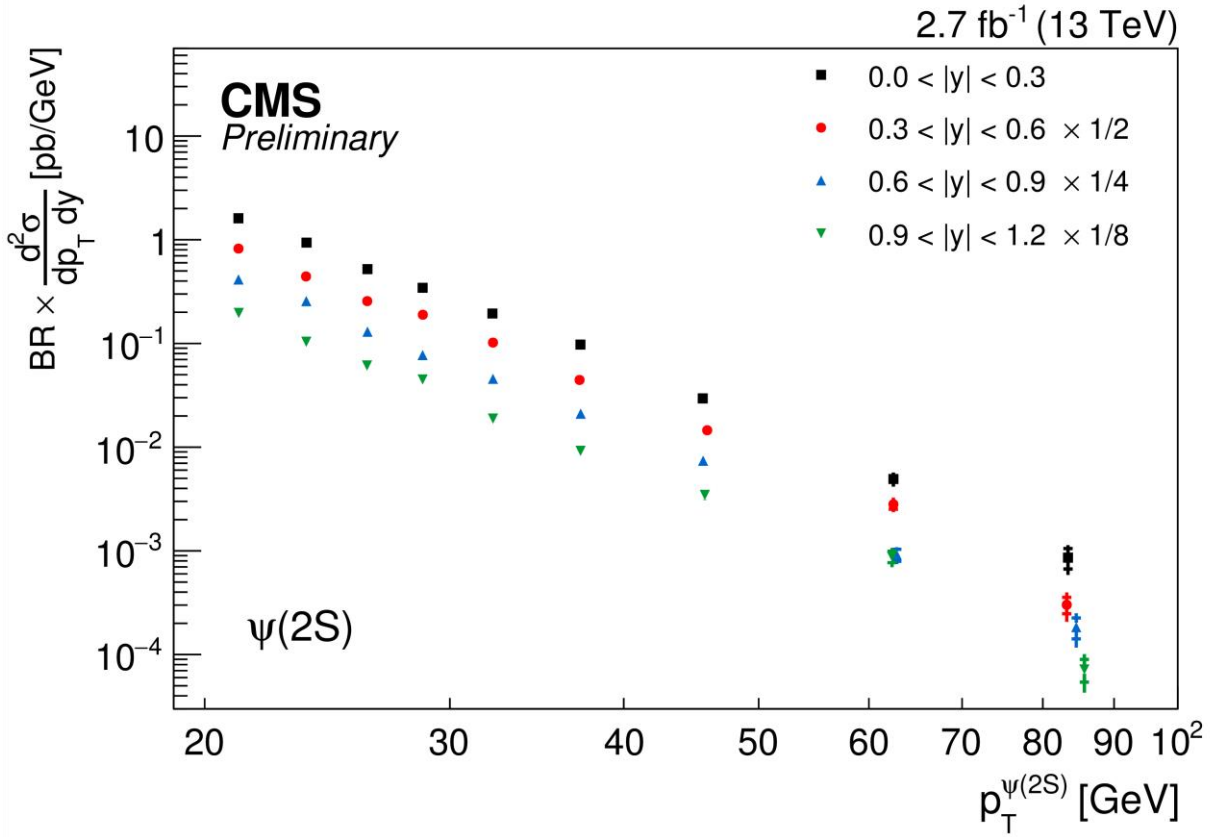
JHEP 02 (2012) 011

J/ψ, ψ(2S) Cross Sections at 13 TeV

- Measure J/ψ and ψ(2S) xsec in bins of p_T, up to p_T ~ 100 GeV
- Improves on prior reach of 50 GeV at CMS
- Do the models still work?

- Dimuon final state
- Vertex probability and pT requirements on dimuons at HLT level
- Detailed J/ψ & muon acceptances and quality cuts applied after reconstruction





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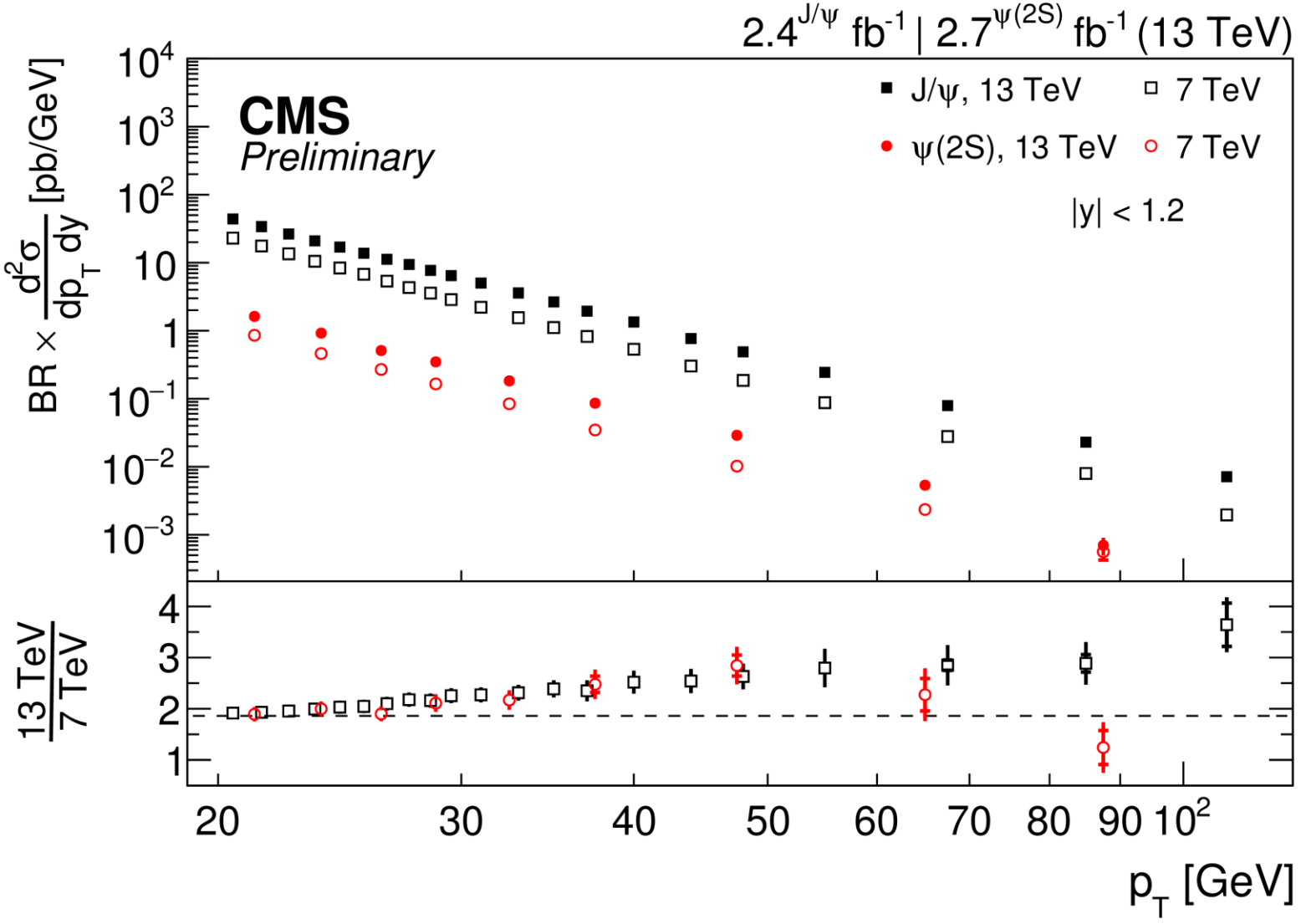
J/ψ, ψ(2S) Cross Sections

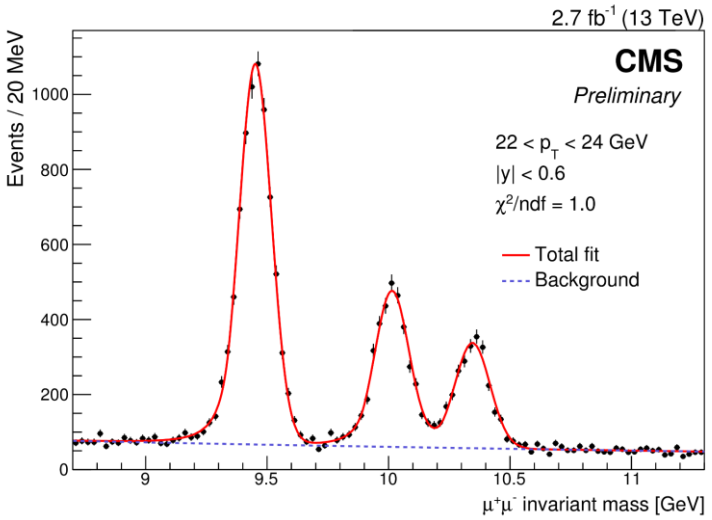
- Find scaling in total cross section due to CoM energy increase
- Input to models
- Used as a baseline measurement
  - Cross section ratios
  - Multi-parton interactions

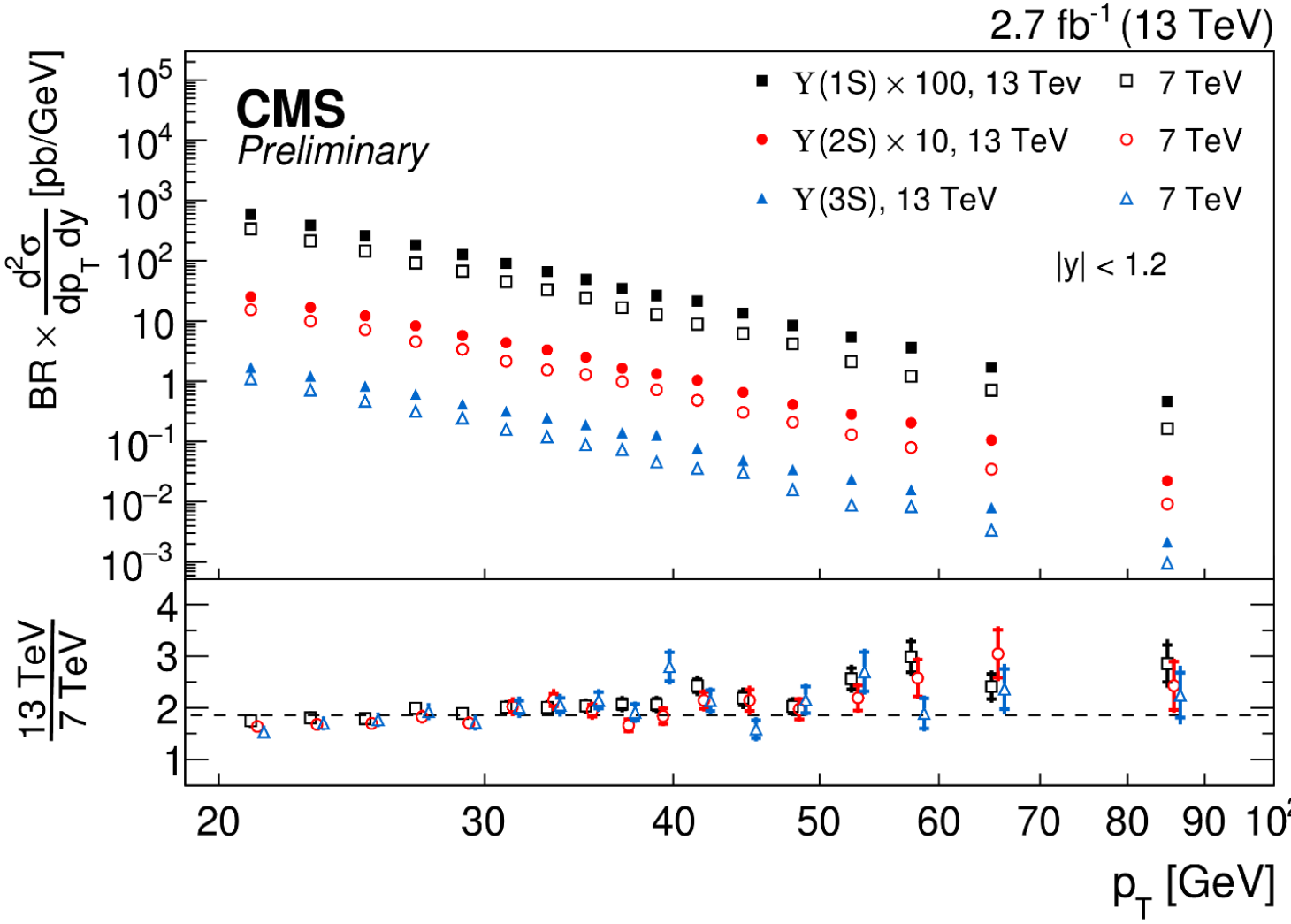


Υ(1S), Υ(2S), Υ(3S) Cross Sections

- Υ trigger accepts 1S, 2S and 3S states
- Dimuon decay channel
- Υ(nS) 13 TeV compared to 7 TeV measurement

- CoM cross section scaling similar to J/ψ





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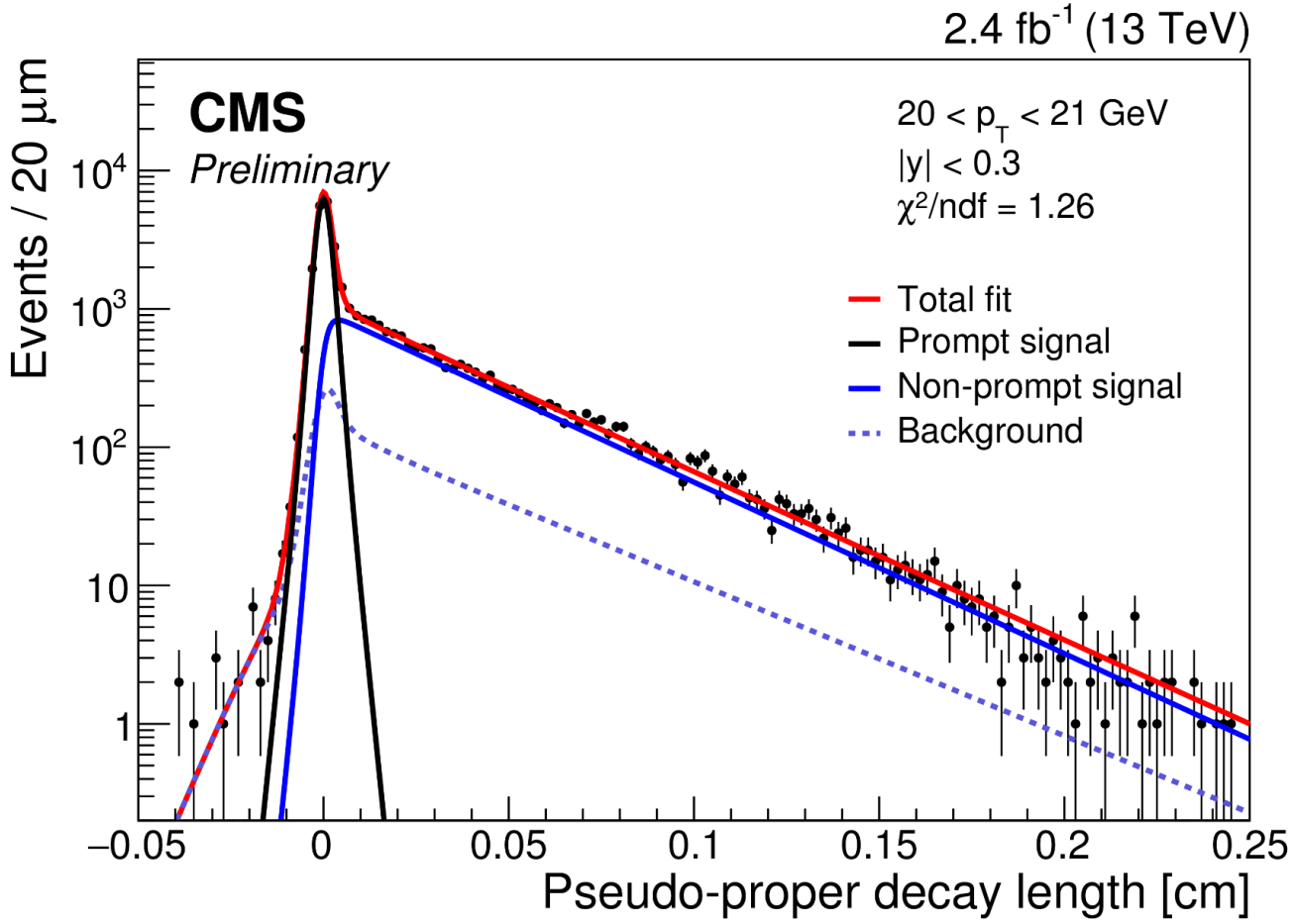
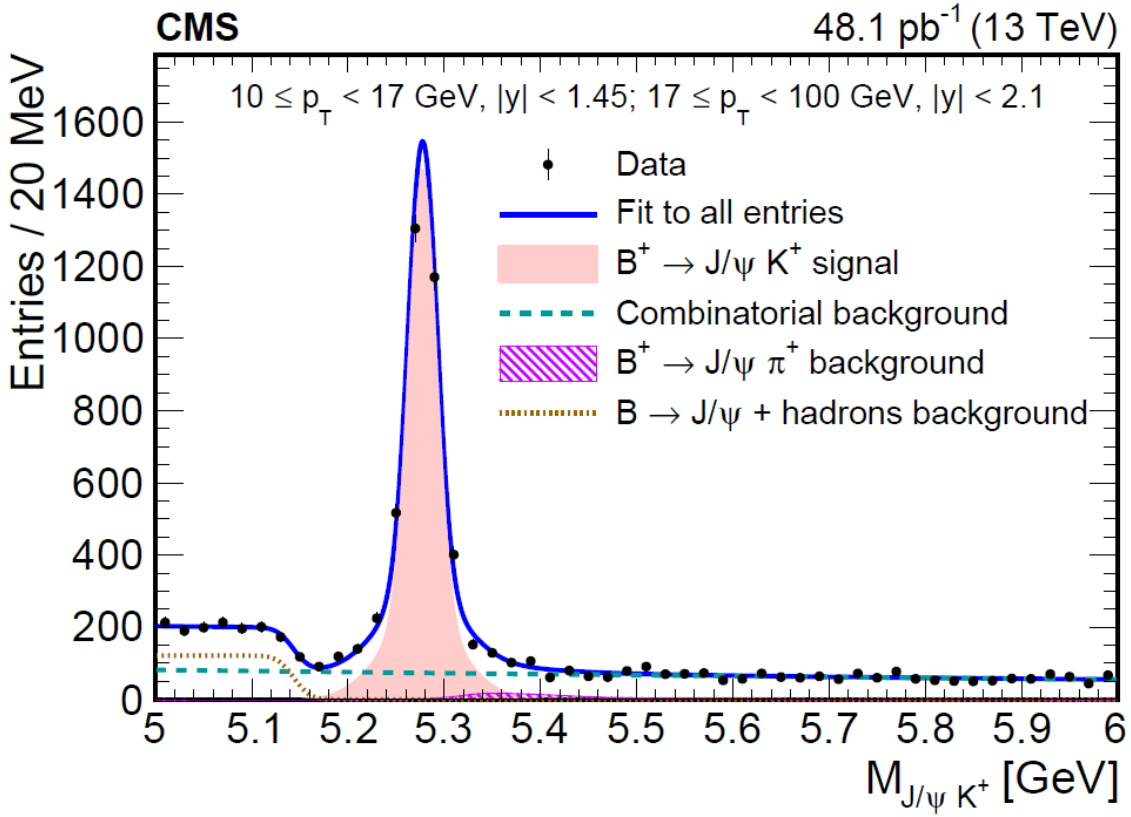
Prompt Quarkonia

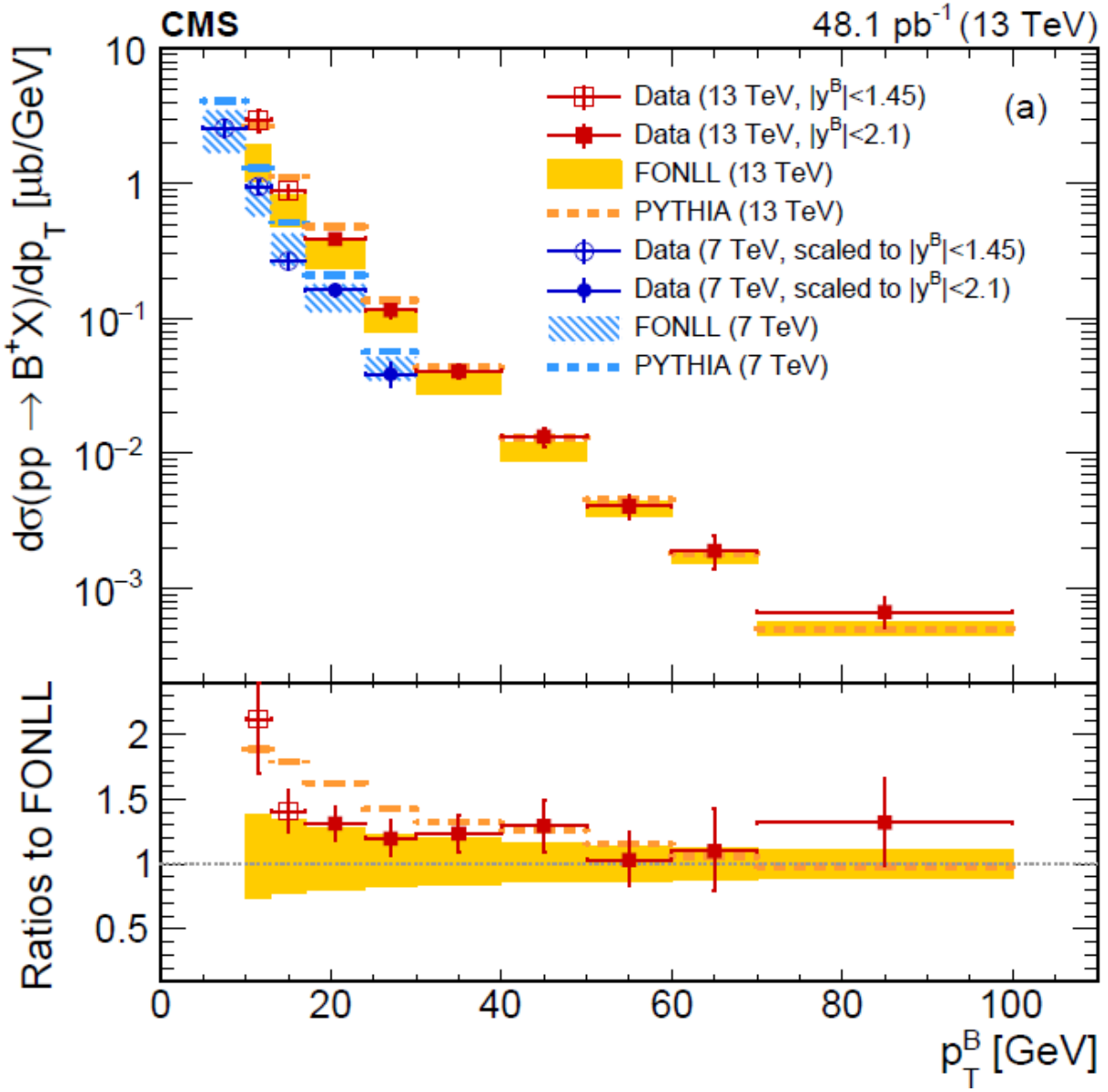
- Prompt and non-prompt contributions to J/ψ
- Maximum likelihood fit to measure non-prompt fraction
- Non prompt J/ψ can be from B decays
- Pseudo proper decay length $l_{xy} = \frac{d_{xy} * m_x}{pT}$
- Displaced vertex measurement available to triggers



B Hadron Inclusive Cross Section at 13TeV

- Measured using $B^+ \to J/\psi K^+$
- $\sigma = 15.3 \pm 0.4(stat) \pm 2.1(syst) \pm 0.4(lumi)\mu b$
- Reasonable agreement with FONLL[1] and PYTHIA predictions





[1] JHEP 03 (2001) 006

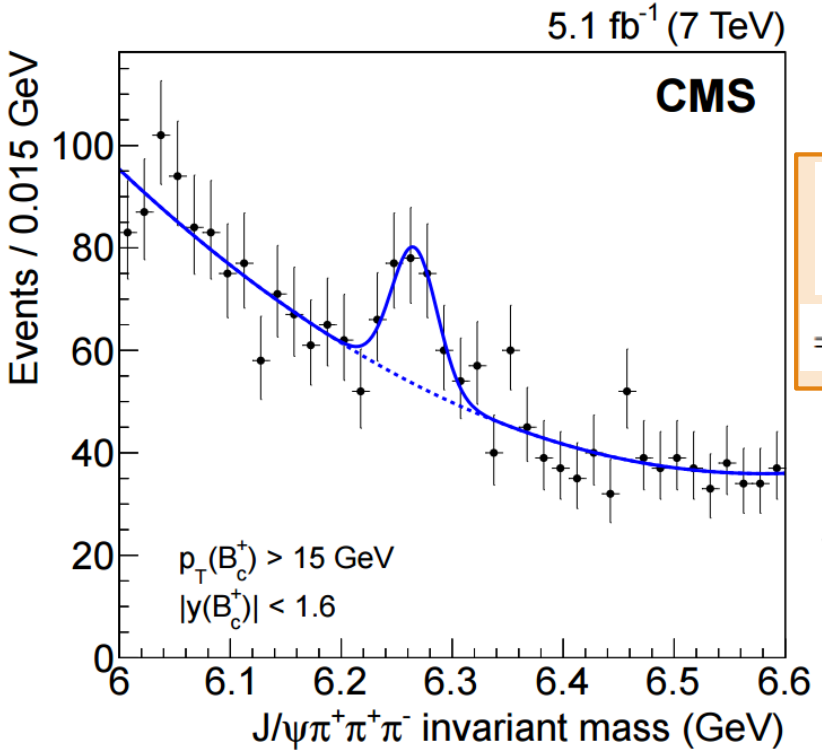
PLB 771 (2017) 435

Observation of B_c Properties via Branching Ratios

- B_c cross section ratio with B measured at 7 TeV
- $B_{(c)}$ $pT > 15$ and $|y| < 1.6$

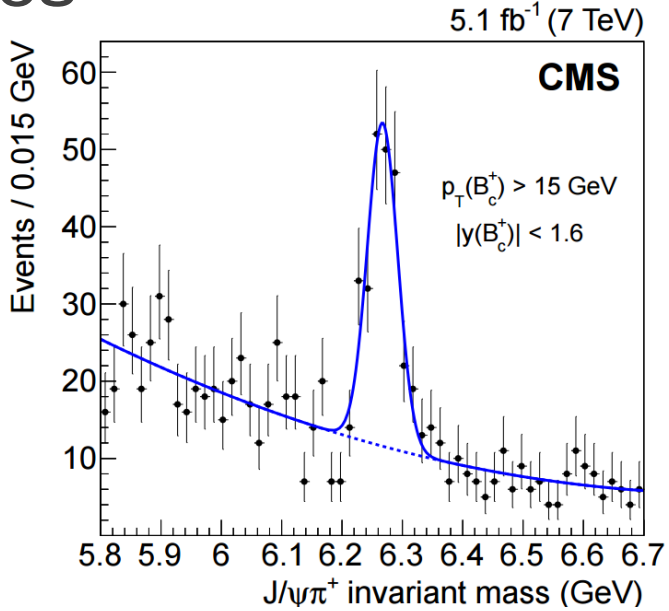
$$\frac{\sigma(B_c^{\pm}) \times Br(B_c^{\pm} \to J/\psi\pi^{\pm})}{\sigma(B^{\pm}) \times Br(B^{\pm} \to J/\psi K^{\pm})} = [0.48 \pm 0.05\,(\text{stat}) \pm 0.03\,(\text{syst}) \pm 0.05\,(\tau_{B_c})]\%$$

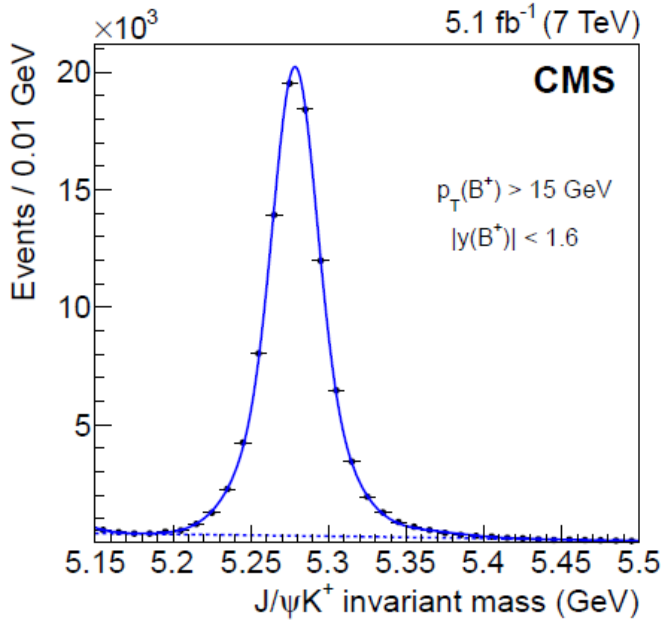
- Observation of decay to J/ψ + 3 π



$$\frac{BR(B_c^{\pm} \to J/\psi\pi^{\pm}\pi^{\pm}\pi^{\mp})}{BR(B_c^{\pm} \to J/\psi\pi^{\pm})} = 2.55 \pm 0.80\,(\text{stat}) \pm 0.33\,(\text{syst})^{+0.04}_{-0.01}\,(\tau_{B_c})$$

- Agrees with LHCb result [1]





[1] Phys. Rev. Lett. 108 (2012) 251802

JHEP 01 (2015) 063

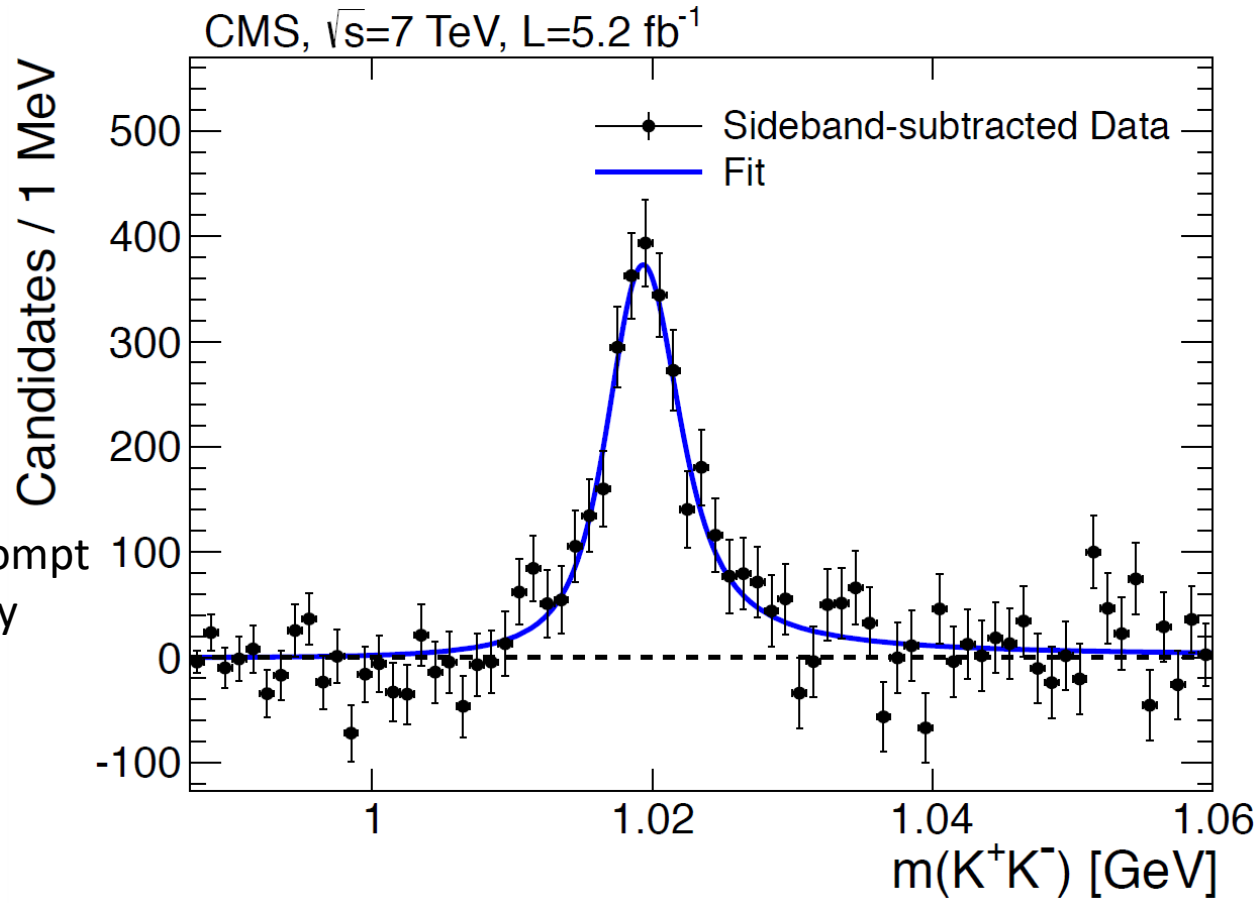
Studies of Charmonium Like States

- Several states named “X” or “Y” recently found
- Many unknowns
- Some decay through J/ψ + quarkonia
- Add information to the puzzle
- J/ψ reconstructed through $\mu^+\mu^-$ in these analyses
- ϕ reconstructed through K^+K^-

$X(3872) \rightarrow J/\psi\pi^+\pi^-$: Cross section ratio, non prompt fraction, compare to theory

$X(5568) \rightarrow B_s^0\pi^\pm$: Search
$B_s^0 \rightarrow J/\psi\phi$
$\phi \rightarrow K^+K^-$

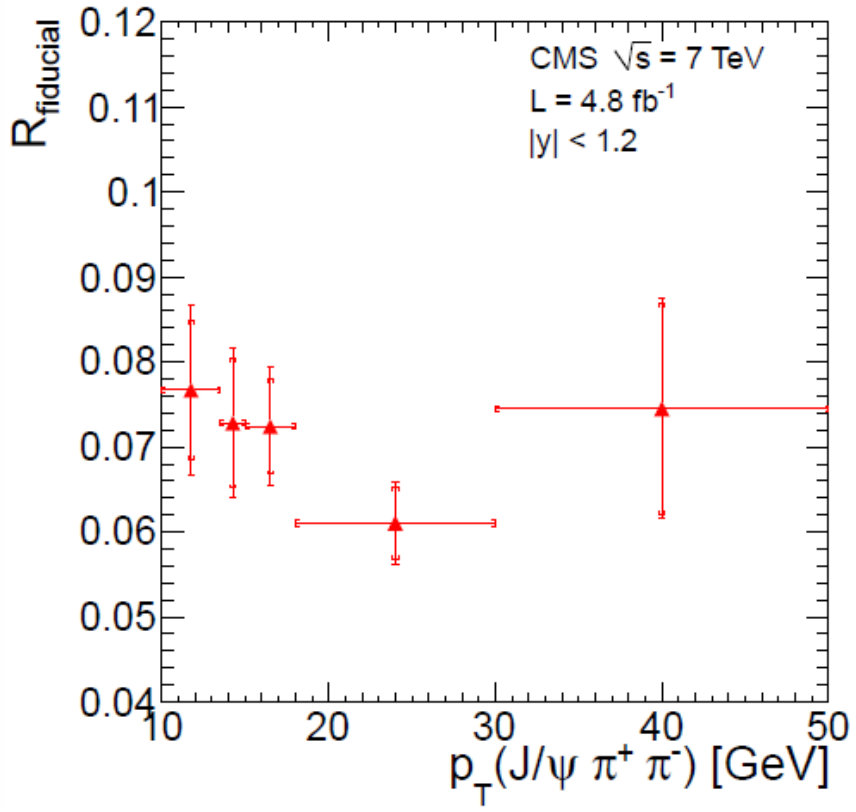
$Y(4140) \rightarrow B^\pm \rightarrow J/\psi\phi K^\pm$: Mass, width
$\phi \rightarrow K^+K^-$



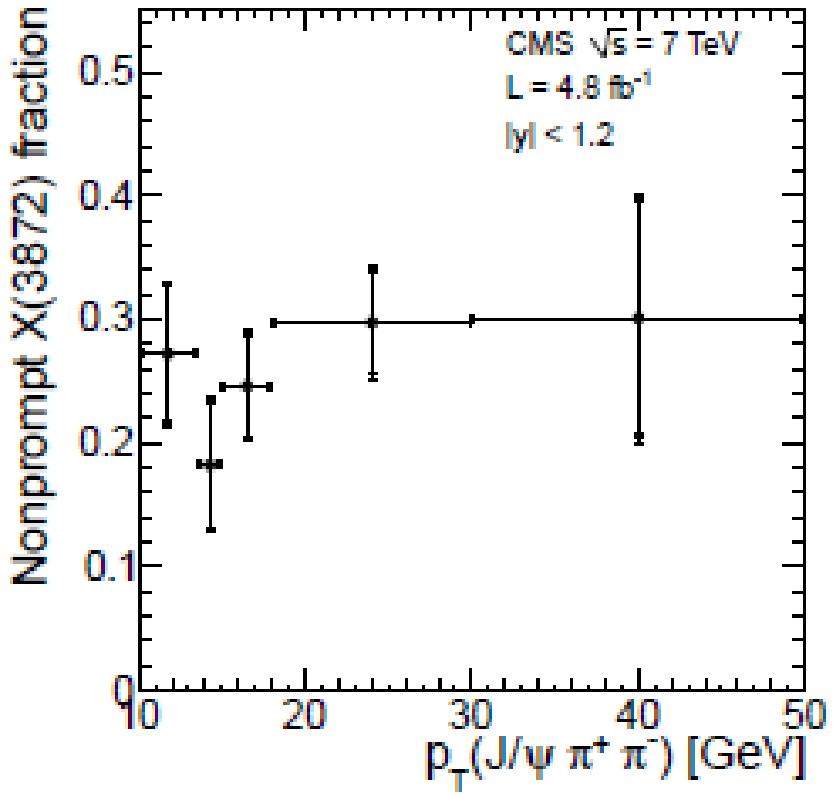
Phys.Lett.B 734 (2014) 261

X(3872) → $J/\psi\,\pi^+\pi^-$

- Cross section ratio measured on 7TeV data
- R = X(3872)/ψ(2S) cross section ratio
  - Assumed unpolarized
  - Polarization variation up to 90%



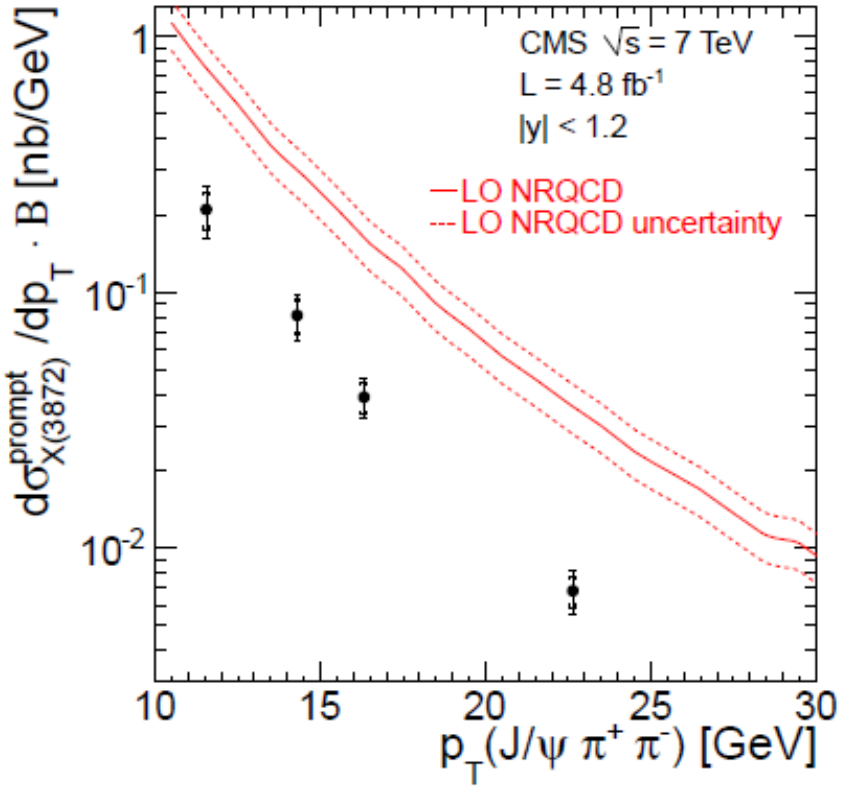
- Decays from B-hadrons found by measuring non-prompt fraction based on $l_{xy} > 100\mu m$



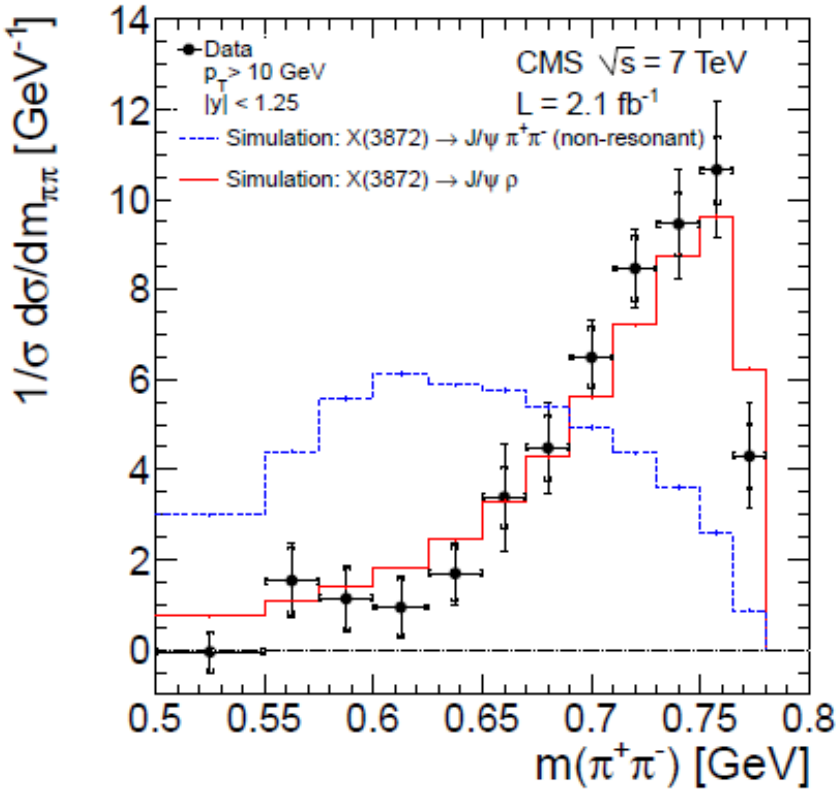
JHEP 1304 (2013) 154

X(3872) → $J/\psi\,\pi^+\pi^-$

- Prompt cross section measured at 7 TeV
- Compared to NRQCD model [1]
- Predictions describe pT shape well, however significantly exceed measured value



- Di-pion invariant mass spectrum compared to simulation
- Resonant $\rho^0 \to \pi\pi$ intermediate state (red)
- Non-resonant (blue)
- Intermediate ρ^0 better agrees with data



[1] Phys.Rev.D. 81 (2010) 114018

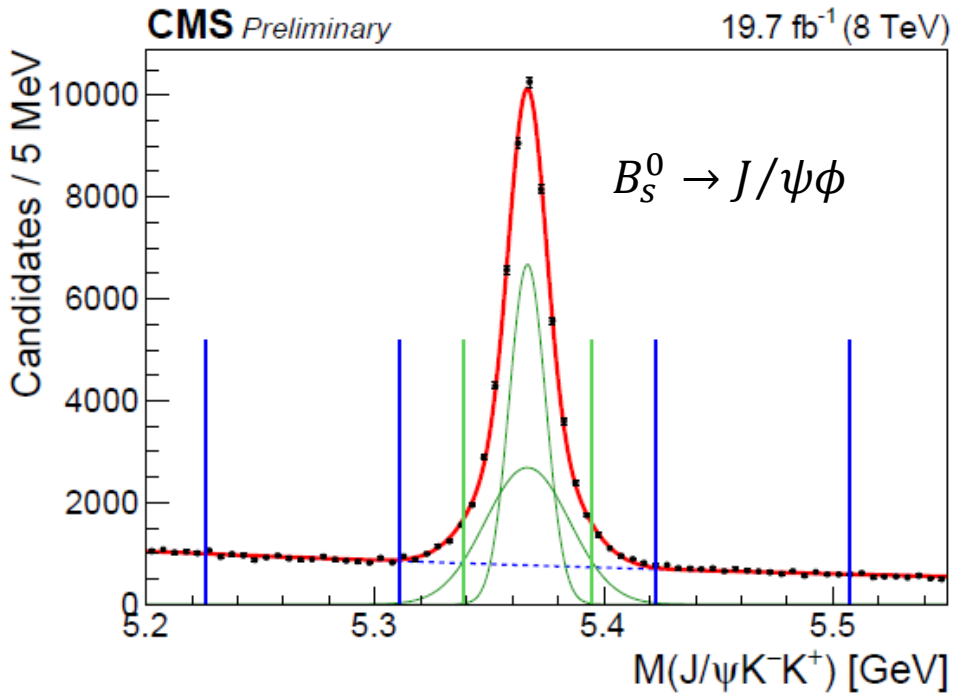
JHEP 1304 (2013) 154

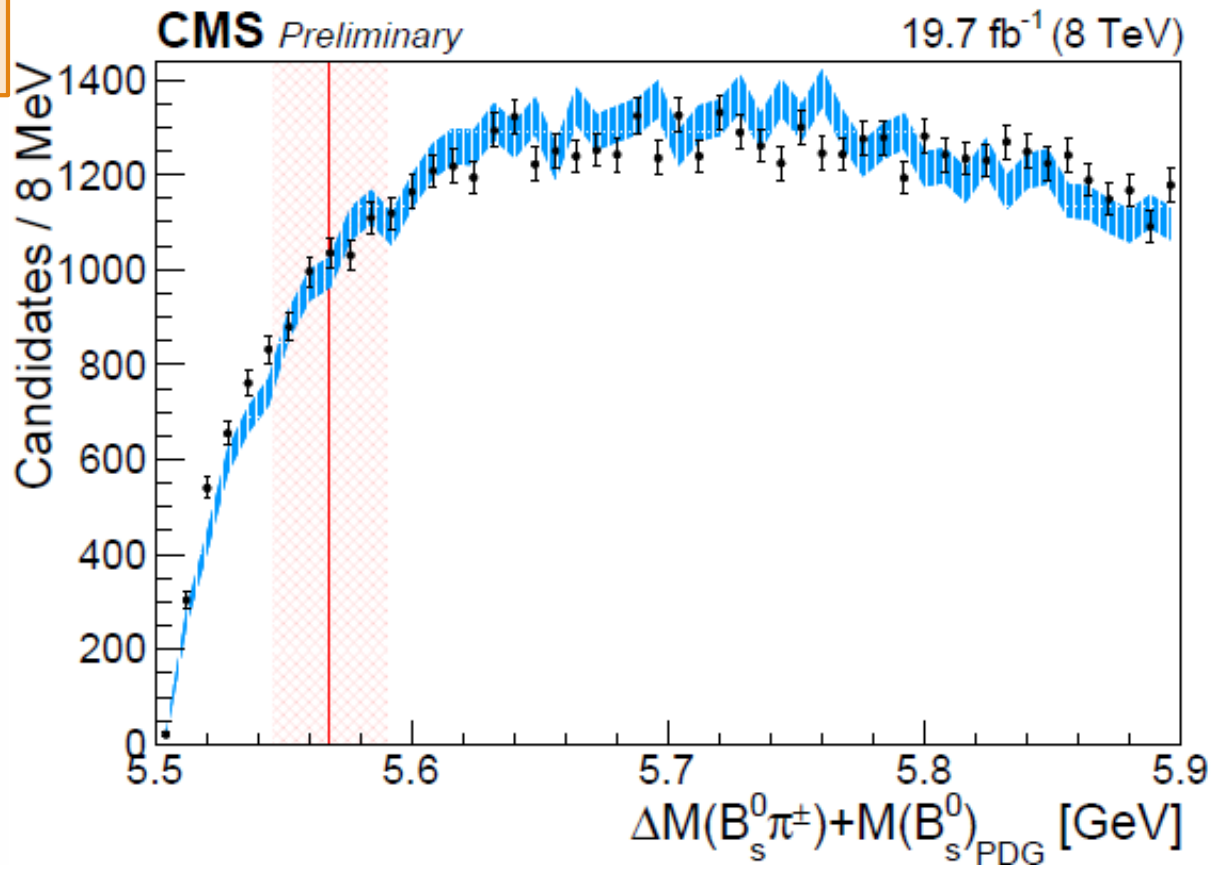
Search for X(5568) → $B_s^0\ \pi^{\pm}$

- Evidence for 5588 MeV X state from D0 [1]
- CMS searches at 8TeV using 19.7 fb^{-1}
- $B_s^0\ pT > 10\ GeV$

- No significant resonance found
- Data (points) compared to sideband B_s^0 (blue)
- Upper limit set on ρ_X the production rate times branching fraction B

$$\rho_X \equiv \left(\frac{\sigma\left(pp \to X + anything * \mathrm{B}\left(X \to B_s^0 \pi^{\pm}\right)\right)}{\sigma\left(pp \to B_s^0 + anything\right)}\right) < 3.9\% \text{ at } 95\% \text{ CL}$$





[1] Phys.Rev.Lett 117 (2016) 022003

CMS BPH 16 002 PAS

Search for Y(4140) in the $B^{\pm} \rightarrow J/\psi\phi K^{\pm}$ Decay

- Observation (>5σ) in 7TeV data 5.2fb^{-1}

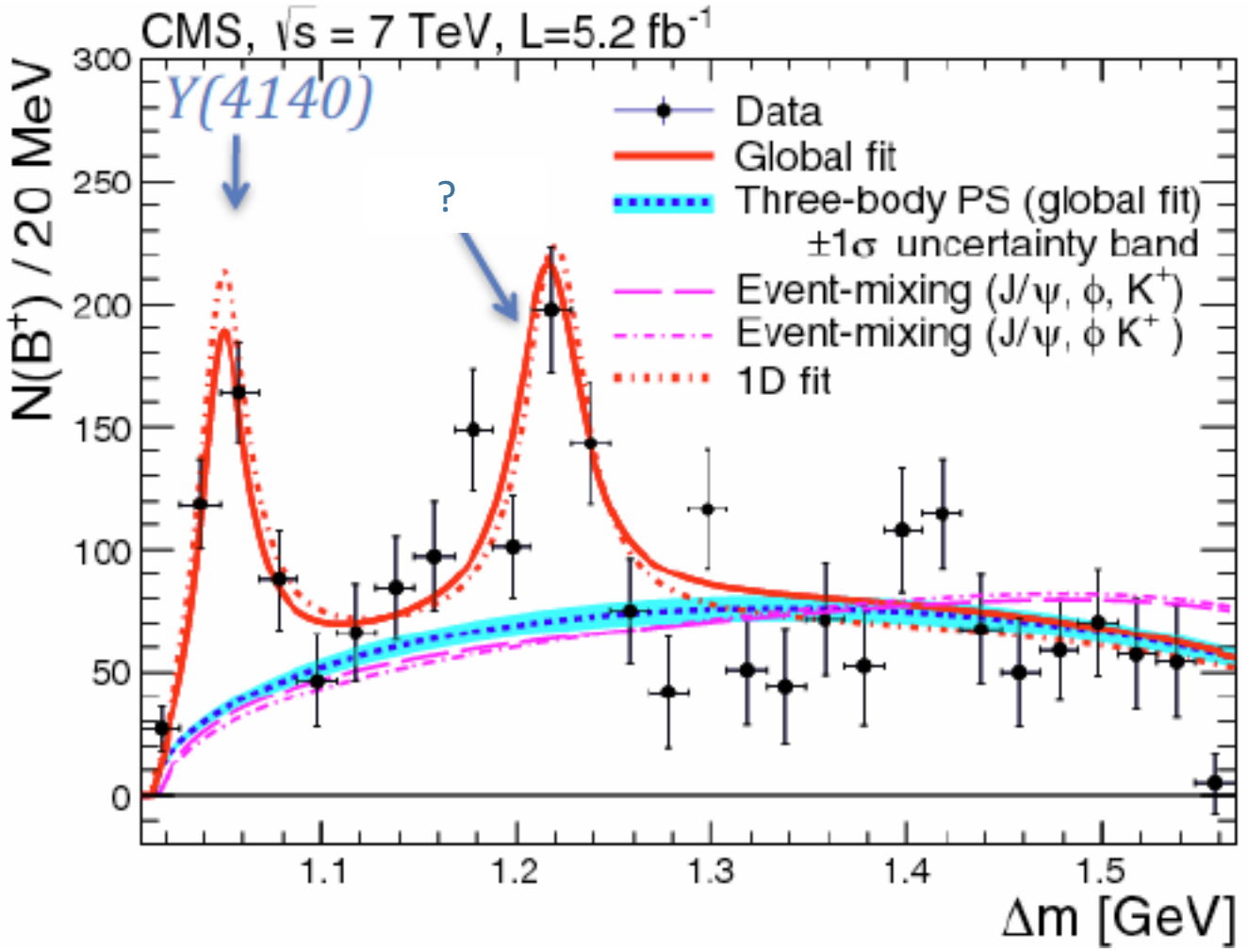
$M_{Y(4140)} = 4148.0 \pm 2.4(stat) \pm 6.3(syst)MeV$

$\Gamma_{Y(4140)} = 28^{+15}_{-11}(stat) \pm 19(syst)MeV$

- Additional mass peak not established
- Possible reflection
- $M_{peak2} = 4313.8 \pm 5.3(stat) \pm 7.3(syst)MeV$
- $\Gamma_{peak2} = 38^{+30}_{-15}(stat) \pm 16(syst)MeV$

- $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$

- Seen by CDF[1], and LHCb[2]
- Not seen by Belle[3], BaBar[4]



[1] Phys.Rev.Lett. 102 (2009) 242002
[2] Phys. Rev. D 95 (2017) 012002
[3] Phys.Rev.Lett. 104 (2010) 112004
[4] Phys. Rev. D 91 (2015) 012003

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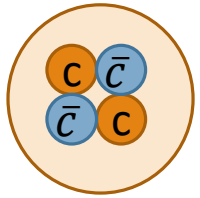
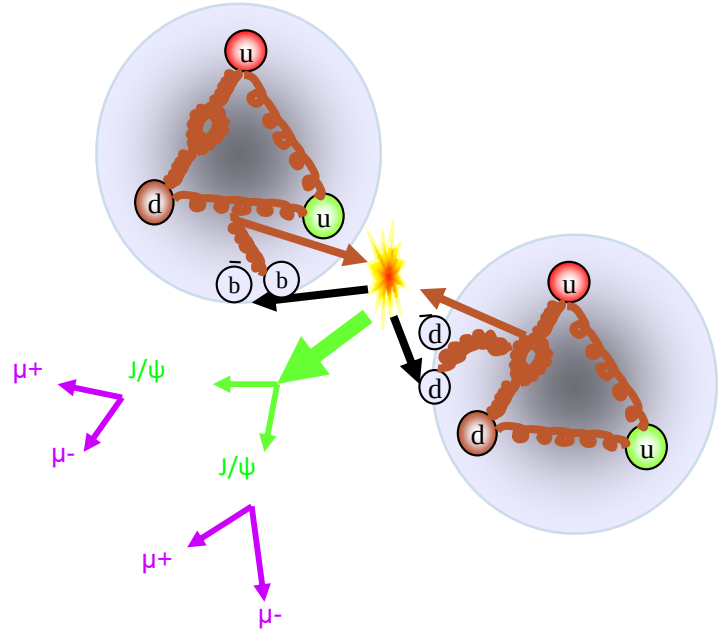
Prompt Double Quarkonia Production

$$\mu^+\mu^-\mu^+\mu^- \begin{cases} J/\psi \\ \psi(2S) \\ \Upsilon(nS) \end{cases}$$

- Double quarkonia production phase space @ CMS nicely complements LHCb
- 4 muon final state accesses many decay channels
- Muon reconstruction in CMS
  - Good resolution ($\frac{\Delta m}{m} \sim 0.6\%$) for J/ψ
  - High purity Muon ID
- Silicon tracking
  - pT resolution ~1% , 3.8 T magnetic field
  - Good vertex reconstruction
- Potential grounds for discovery
  - η_b (highly suppressed by current predictions)
  - Pseudo-scalar Higgs (NMSSM)
  - Tetraquark bound state
- Non-trivial contribution from double parton-scattering (DPS)
  - Cannot be modeled by current NRQCD predictions
- Non-trivial contributions from Next-to-Leading Order(NLO) SPS as well
  - Models released recently begin to approach NLO and NNLO



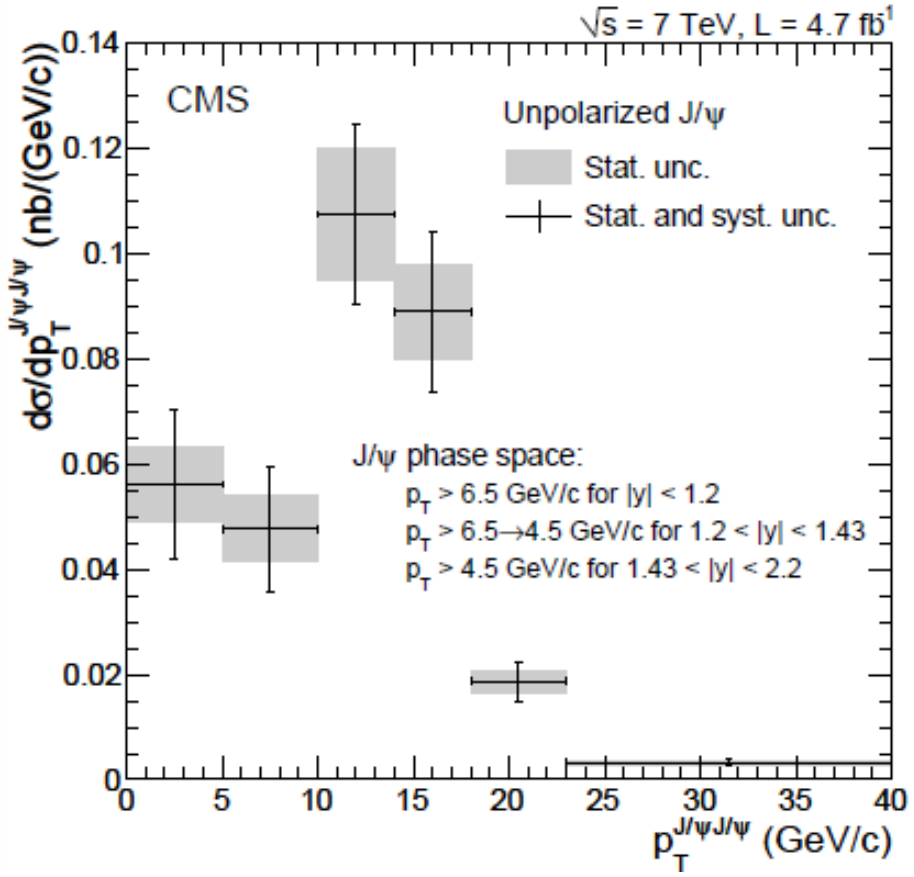
Tetraquark?

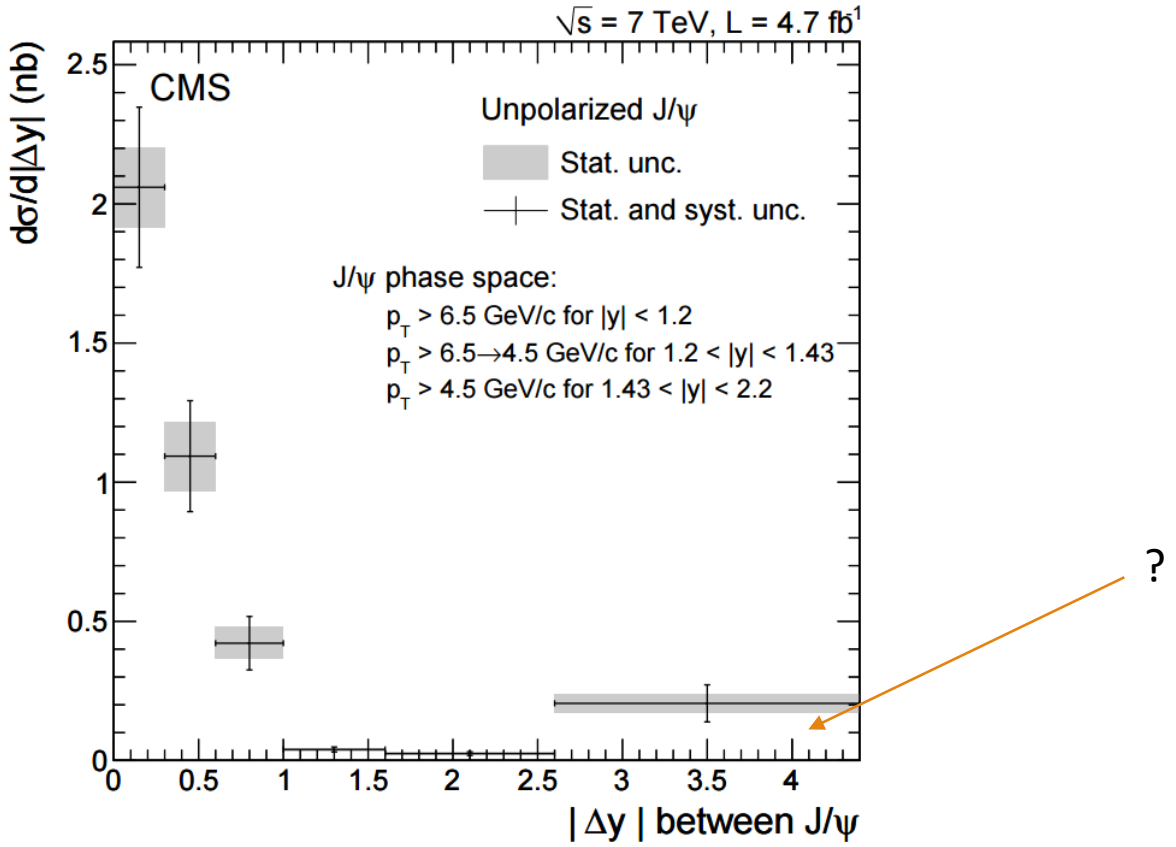


Prompt Double J/ψ Production

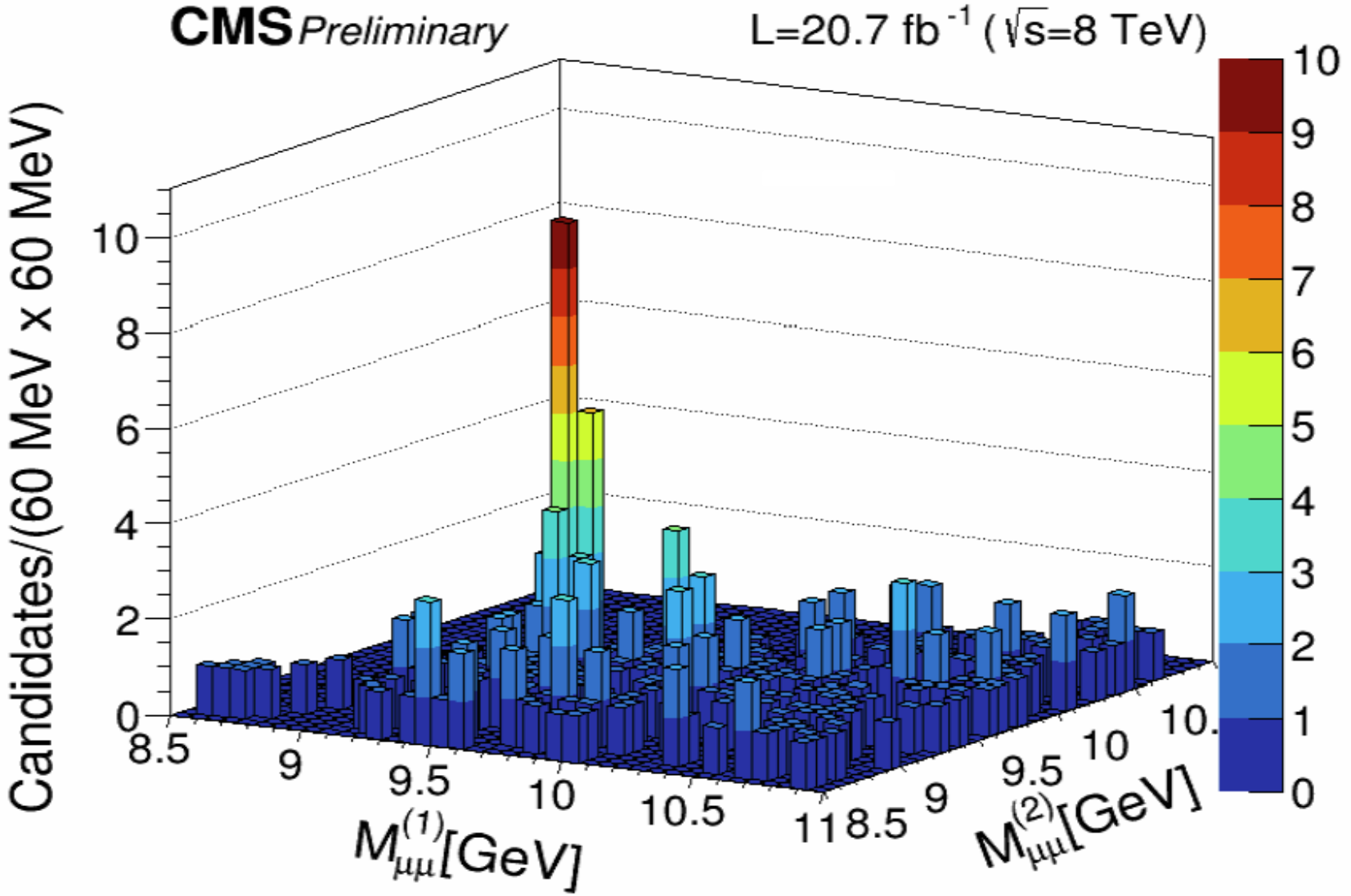
- Use 3-muon trigger
- 2 dimuon candidates compatible with J/ψ
- Dimuon and 4-muon vertex probability requirements
- Assuming unpolarized J/ψ

- J/ψ acceptance critical
- CMS gives access to high pT regime
- Complemantary to LHCb
- New model produced based on this measurement





Prompt Double Υ Observation



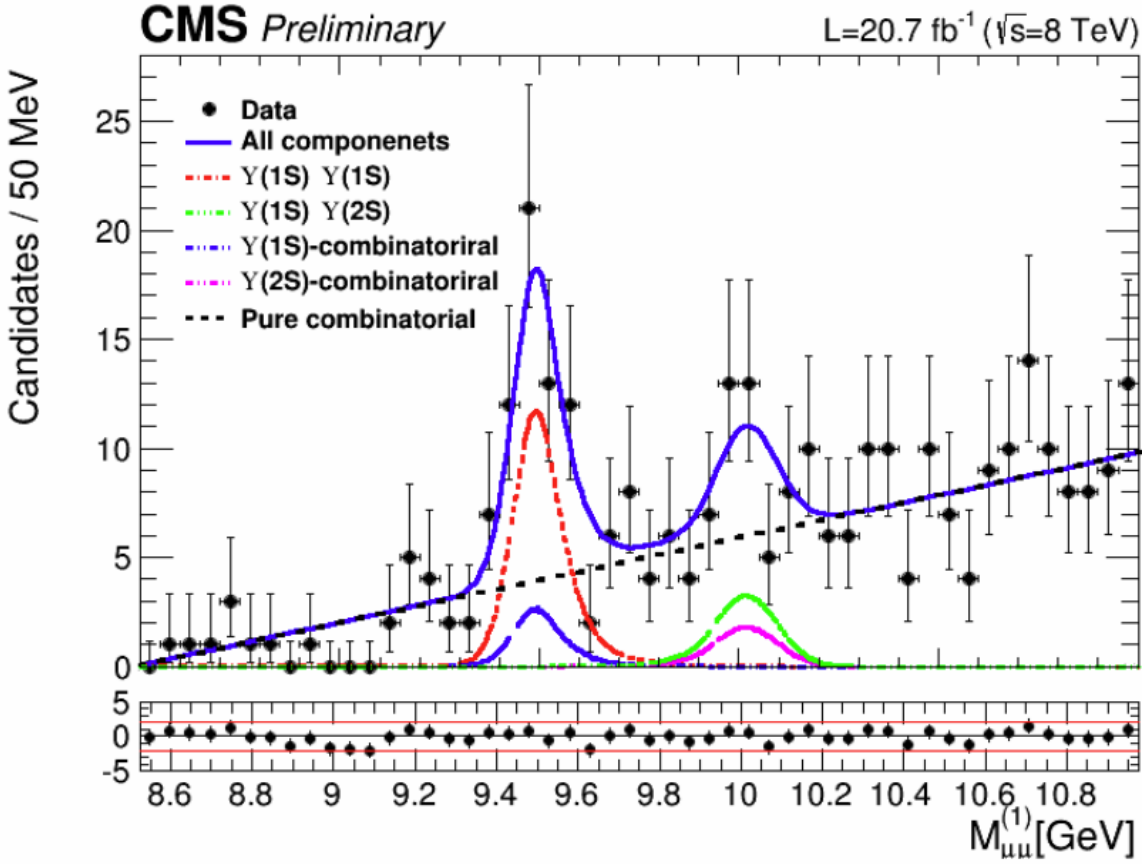
- 2d scatter plot of selected $\Upsilon\Upsilon \rightarrow 4\mu$ events
- Observation of Υ pair production >5σ

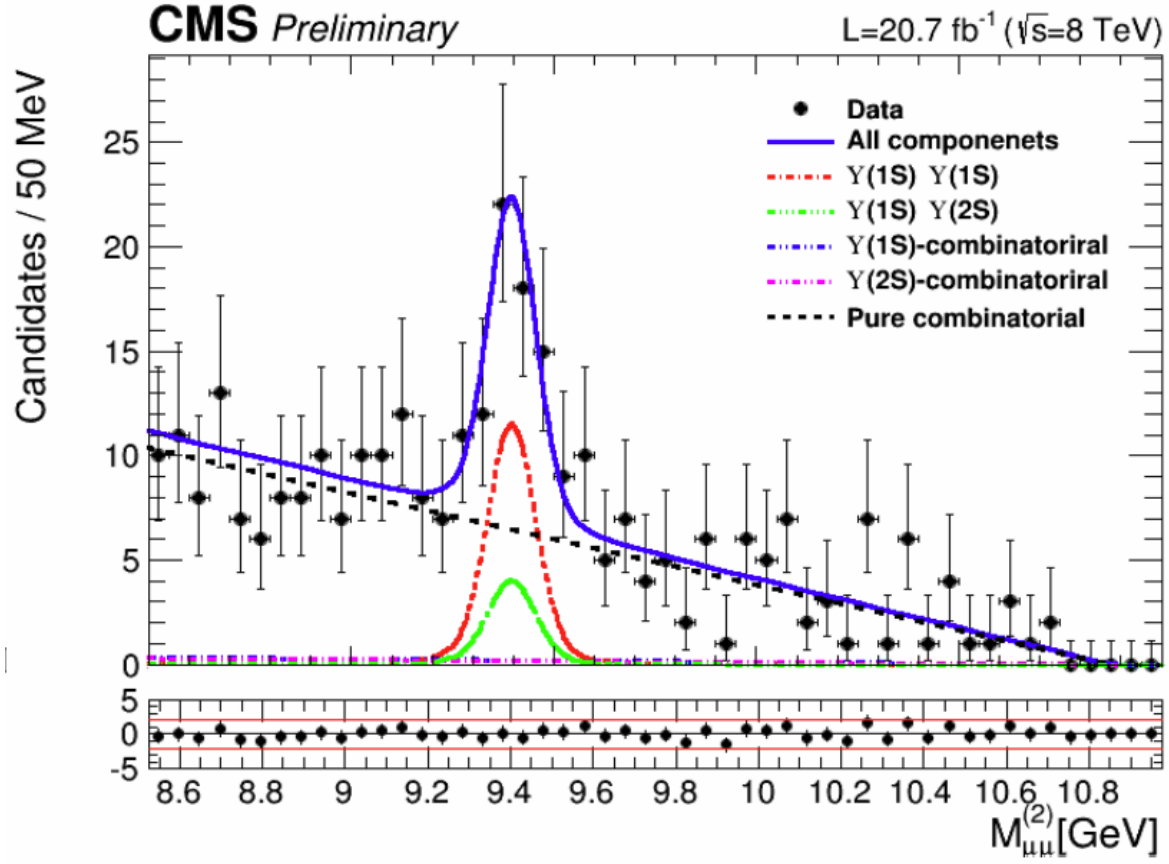
Prompt Double Υ Observation

- Yield extracted with 2D maximum likelihood fit
- Signal is modeled by 2 Crystal-ball functions
- Background is 1st order polynomial

- 38 ± 7 signal events for $\Upsilon(1S)\Upsilon(1S)$
- Small hint of $\Upsilon(1S)\Upsilon(2S)$
- Not enough statistics to extract DPS/SPS fraction

$$\sigma(pp \to \Upsilon\Upsilon) = 68.8 \pm 12.7(stat) \pm 7.4(syst) \pm 2.8(BR)\ pb$$





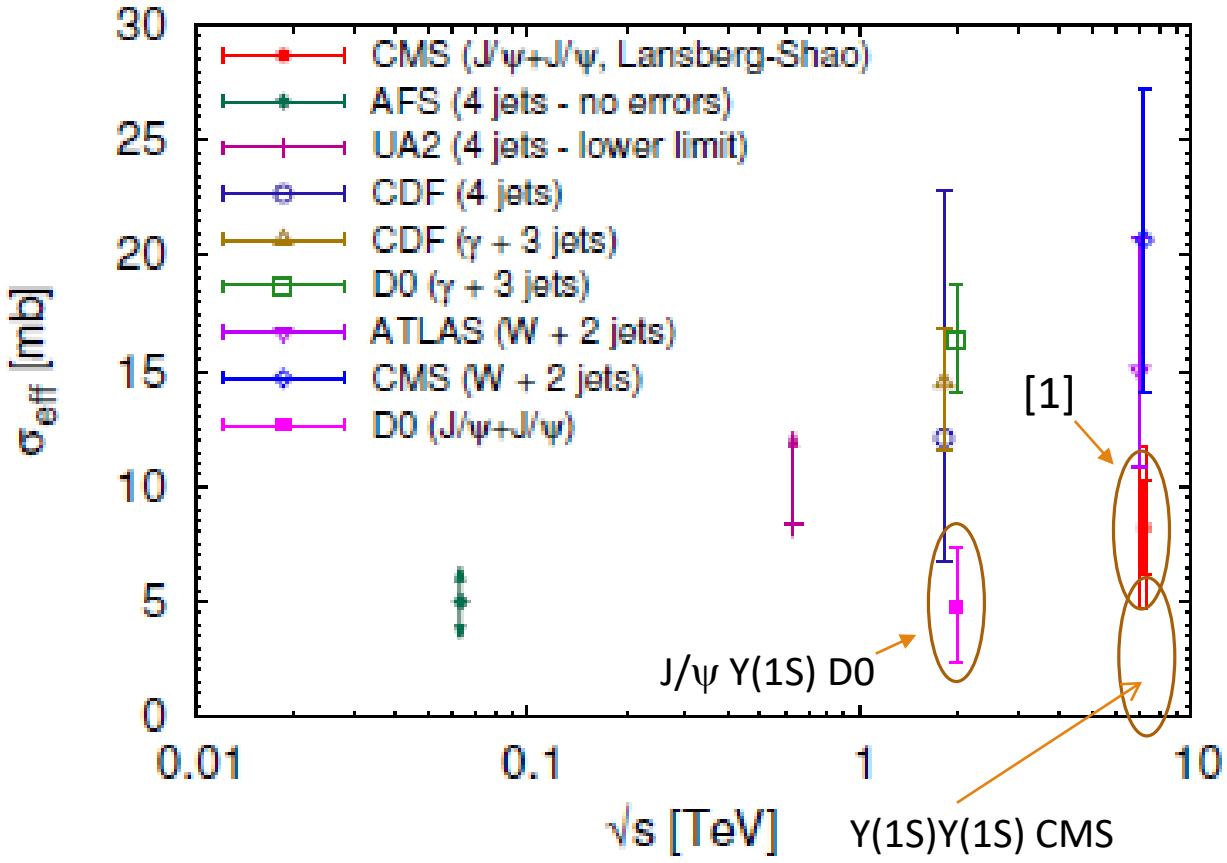
JHEP 05 (2017) 013

Effective Cross Section of DPS

- σ_{eff} represents the effective size of partonic interaction in the proton, should be independent of $\sqrt{s}$
- Jet measurements so far show higher values than quarkonia
- DPS contribution from quarkonia is predicted for CMS based on 7TeV cross section measurements
- CMS can provide several more points in runs with higher statistics

$$\sigma_{eff} = \frac{1}{2}\frac{\sigma^2_{single\ J}}{\sigma_{dps}}$$

Estimate [1]: 13 % SPS LO
60 % SPS NLO
27 % DPS



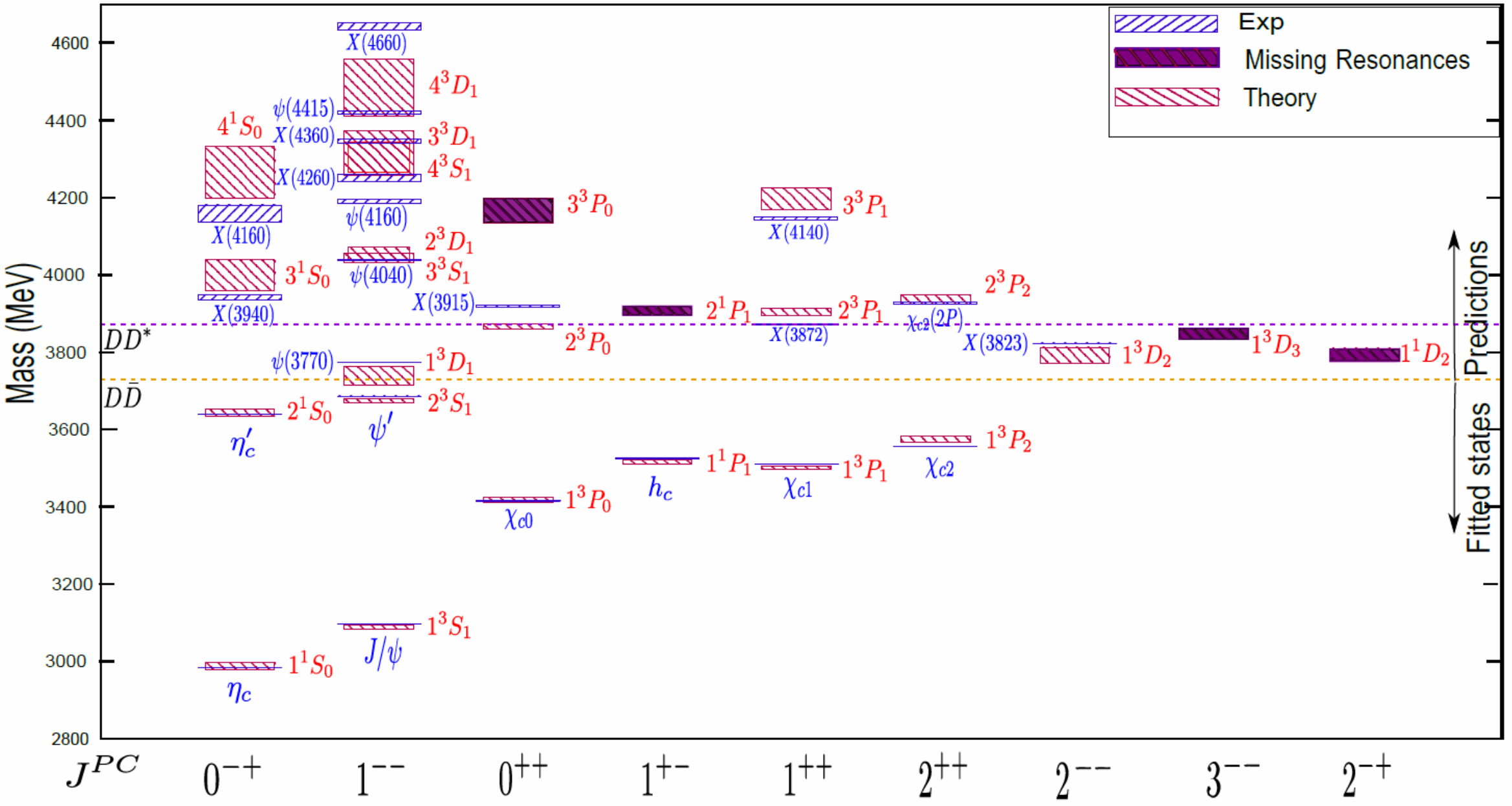
[1] Phys.Lett.B 751 (2015) 479

Conclusion

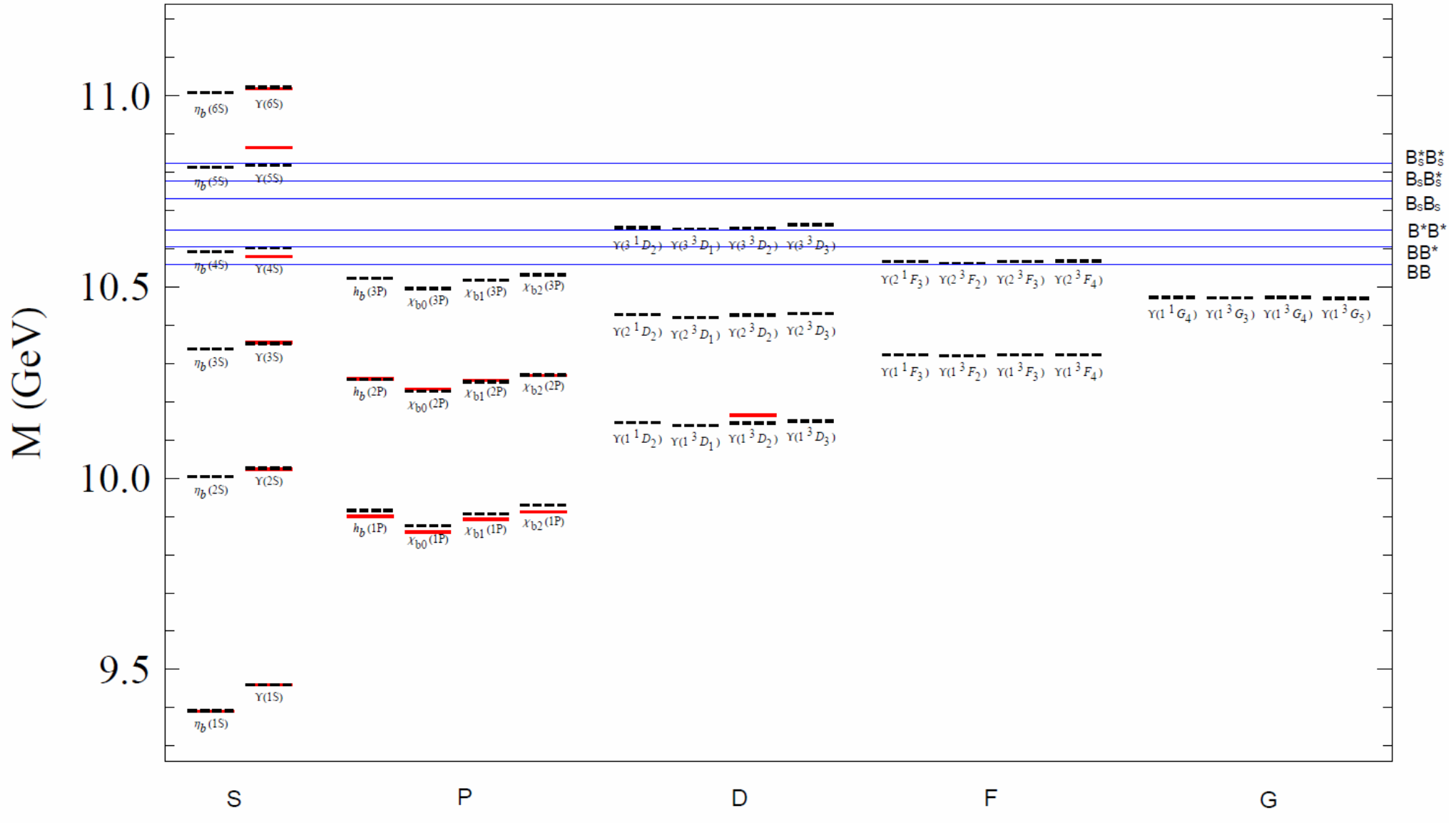
CMS is contributing in many different quarkonia measurements

Stay tuned for exciting results in the future!

Backup


Exp
Missing Resonances
Theory
Mass (MeV)
4600
4400
4200
4000
3800
3600
3400
3200
3000
2800
J^{PC}
0^{-+}
1^{--}
0^{++}
1^{+-}
1^{++}
2^{++}
2^{--}
3^{--}
2^{-+}
$D\bar{D}^*$
$D\bar{D}$
η_c
1^1S_0
η_c'
2^1S_0
J/ψ
1^3S_1
ψ'
2^3S_1
h_c
1^1P_1
χ_{c0}
1^3P_0
χ_{c1}
1^3P_1
χ_{c2}
1^3P_2
1^3D_1
1^3D_2
1^3D_3
1^1D_2
2^1P_1
2^3P_0
2^3P_1
2^3P_2
3^1S_0
3^3S_1
3^3P_0
3^3P_1
2^3D_1
3^3D_1
4^1S_0
4^3S_1
4^3D_1
$X(3940)$
$X(4160)$
$\psi(4040)$
$\psi(4160)$
$X(4260)$
$X(4360)$
$\psi(4415)$
$X(4660)$
$X(3915)$
$X(4140)$
$X(3872)$
$\chi_{c2}(2P)$
$X(3823)$
Predictions
Fitted states

Quarkonia spectrum: Bottom



Prompt double J/ψ non-resonant production

JHEP 1409 (2014) 094

- Non-resonant prompt model at 7TeV consists of DPS and LO SPS
- Non-prompt is B model, combinatorial background

- Prompt & non-prompt shapes derived from MC
- Combinatorial shapes from sideband analysis

- Good understanding of non-prompt production is critical to search for resonances
- SPS+DPS does not well describe cross section measurement
  - ➔ new models were developed to include NNLO SPS