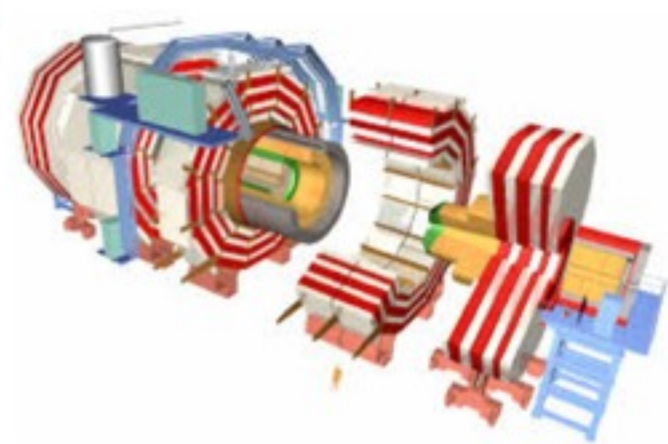
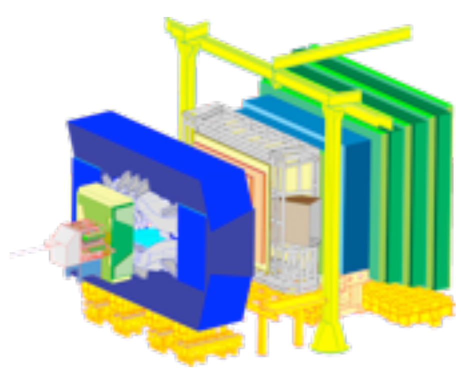
Heavy Flavor Physics results from LHC Run I

& prospects for Run II





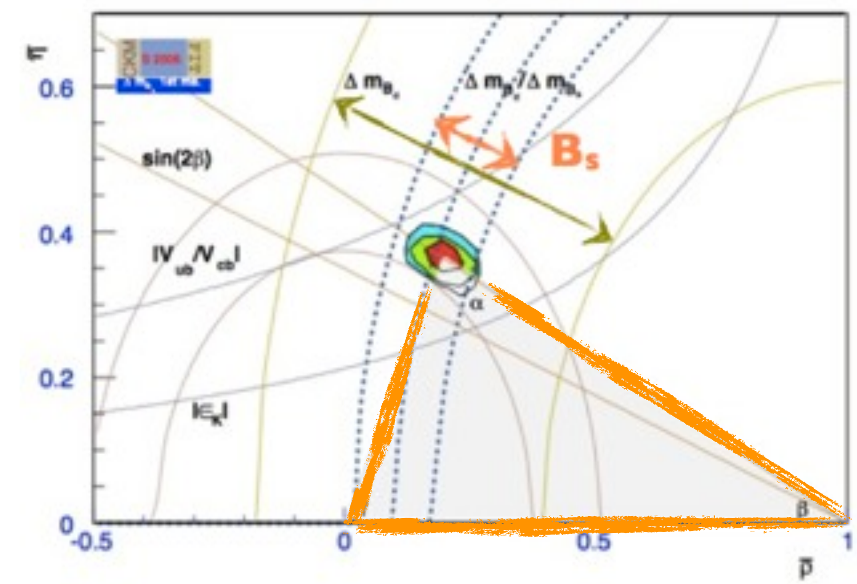
Nuno Leonardo, LIP
CMS B Physics co-convener

LIP seminar
January 8, 2015

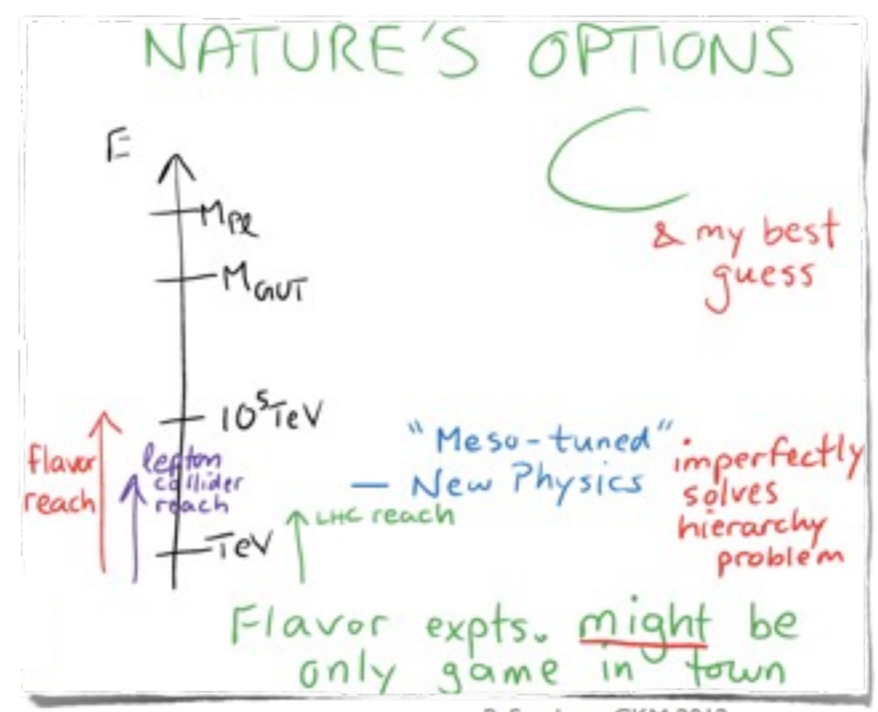
COMPETE
QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL
UNIÃO EUROPEIA
Fundo Europeu de Desenvolvimento Regional
FCT
Fundação para a Ciência e a Tecnologia

Heavy flavor physics goals

- probe Standard Model
  - both strong and electroweak sectors, through production and decay of heavy hadrons in different media
  - understand flavor structure
  - understand why SM appears so fundamental: no BSM detected in Run I yet

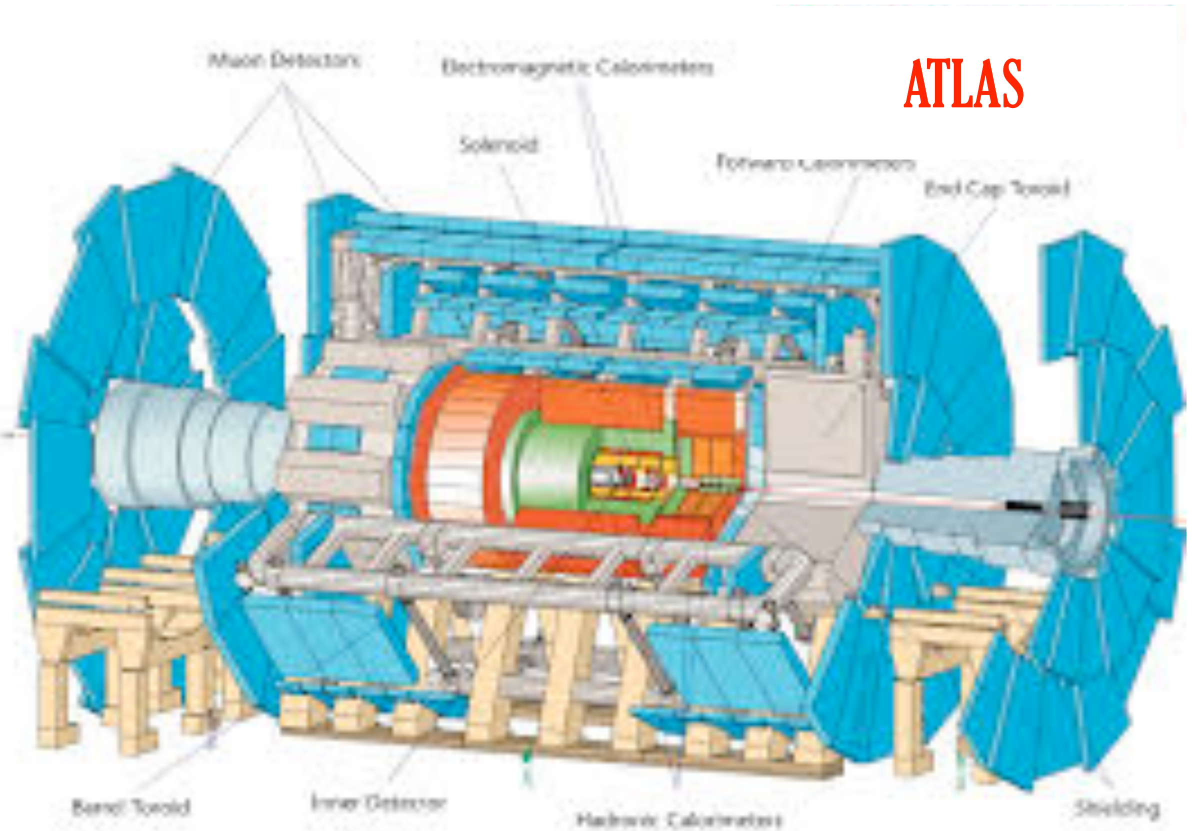


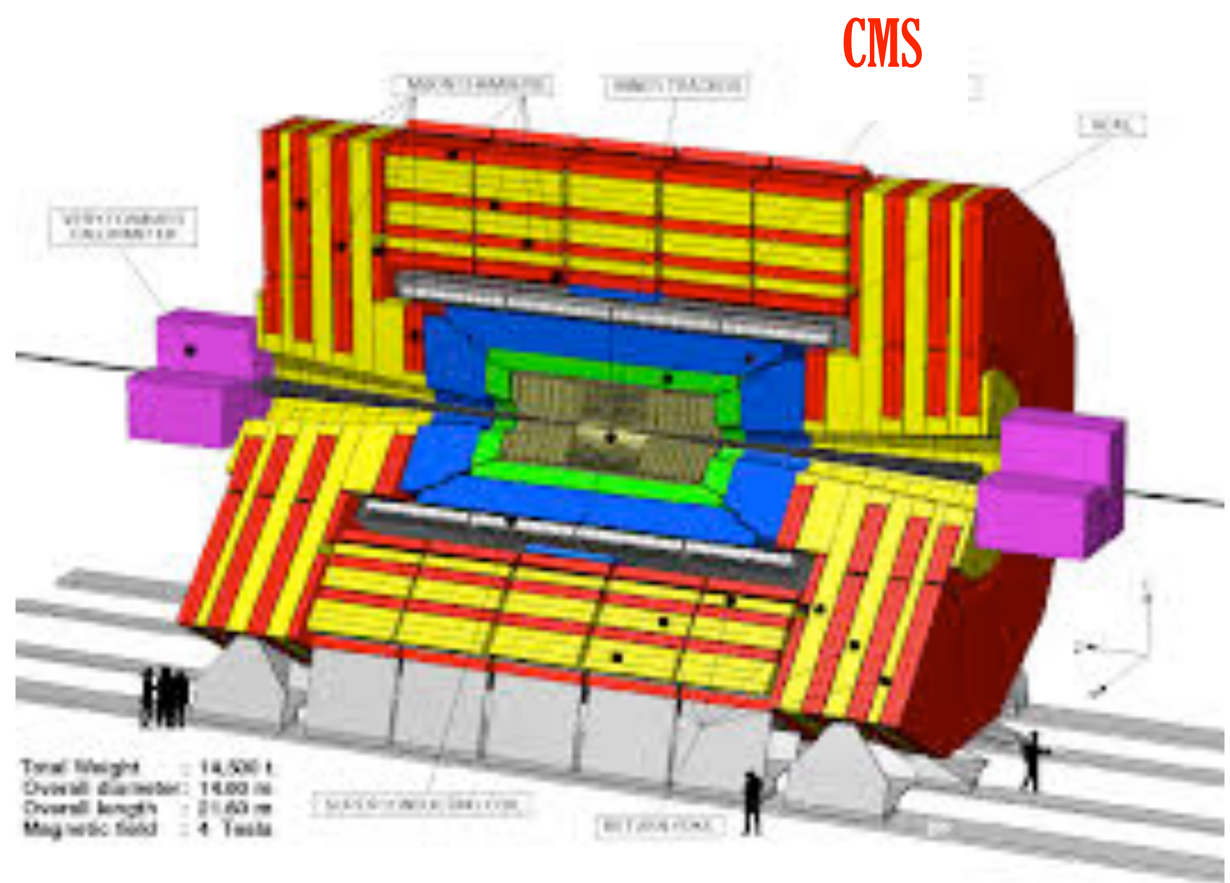
- search for New Physics
  - flavor asymmetries and rare decays can open door to physics BSM
  - complementary to direct searches
  - sensitivity reach to multi-TeV mass scales through loop processes

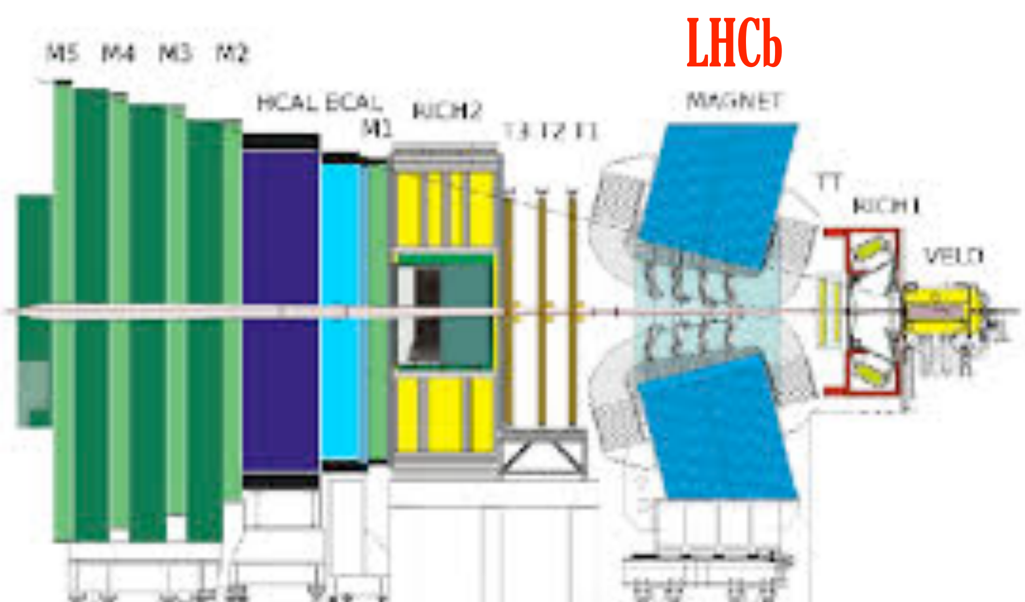


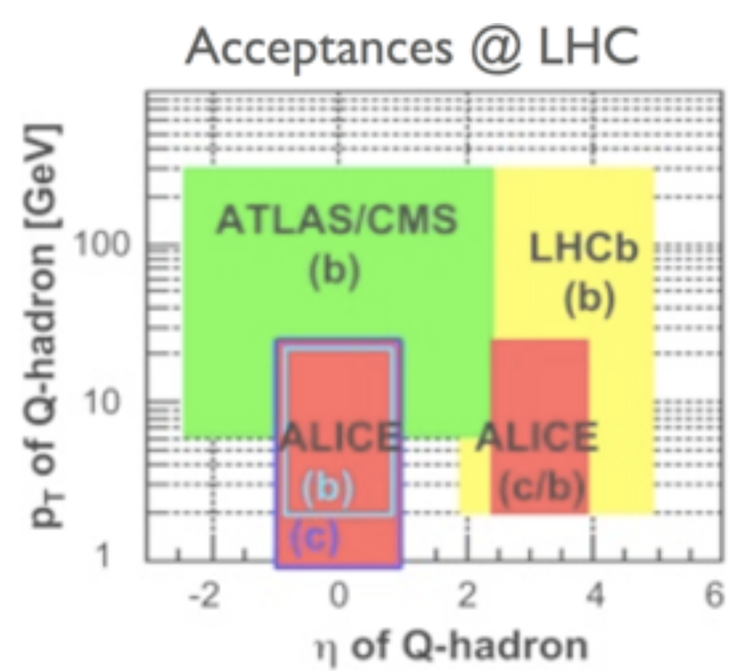
R. Sundrum-CKM 2012

Detectors


ATLAS
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding


CMS
Total Weight : 14,500 t
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

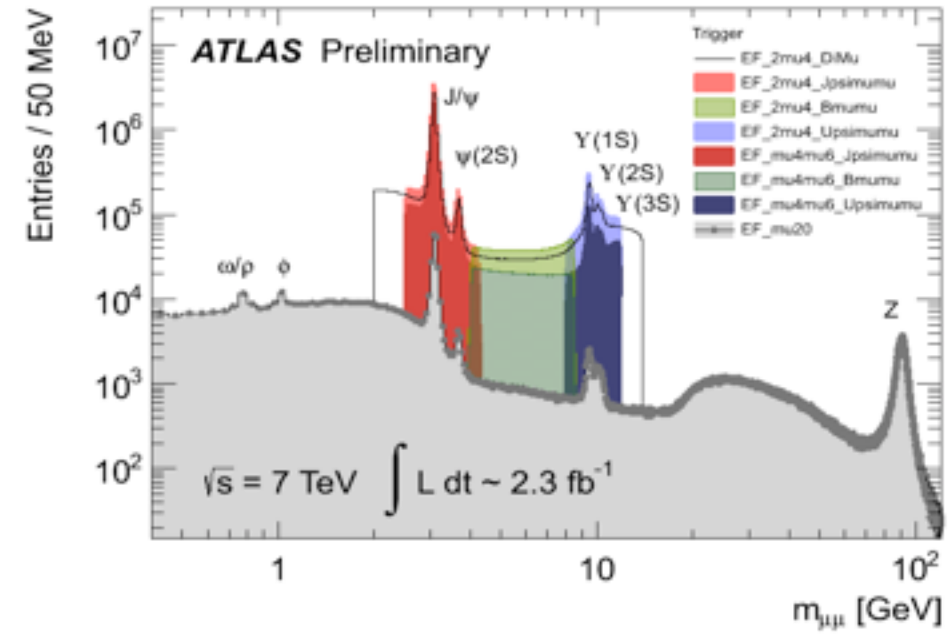

LHCb
M5 M4 M3 M2
HCAL ECAL
M1
RICH2
T3 T2 T1
MAGNET
TT
RICH1
VELO

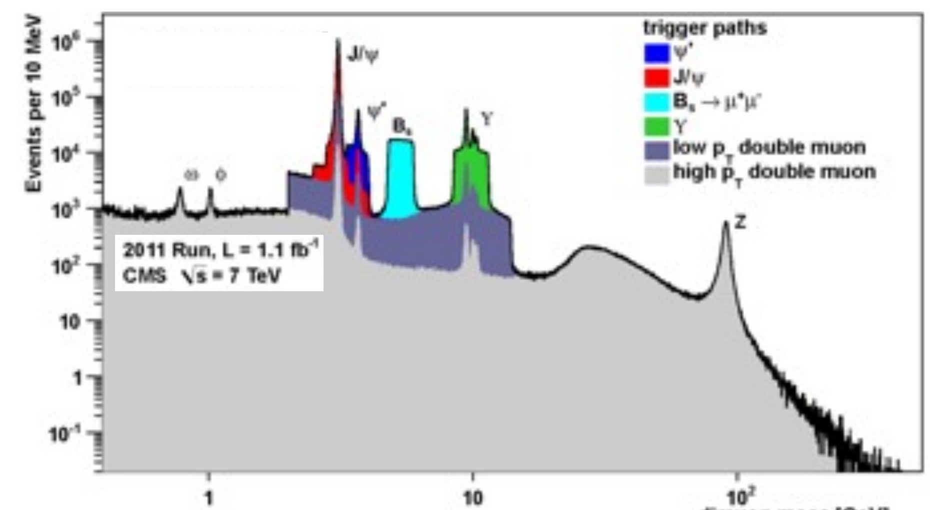

Acceptances @ LHC
ATLAS/CMS (b)
LHCb (b)
ALICE (b) (c)
ALICE (c/b)
p_T of Q-hadron [GeV]
1
10
100
-2
0
2
4
6
η of Q-hadron

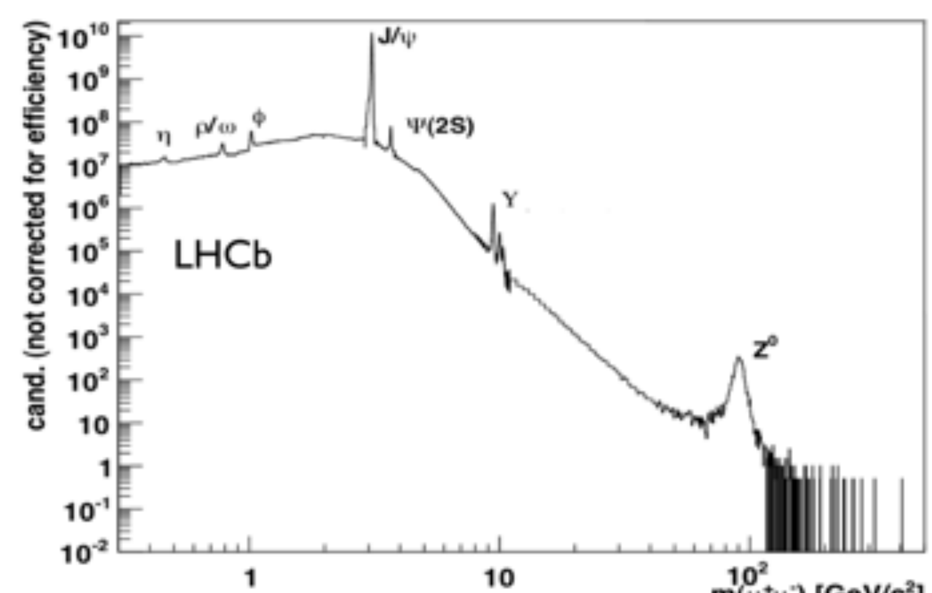
Performance

- precision tracking
  - good momentum, impact parameter and vertex resolutions
  - good b-tagging capabilities
- robust muon identification
  - muon detection down to low p_T, low mis-identification rates
- flexible trigger
  - high rates imply very selective requirements to store interesting b and c decays
  - majority of HF analyses @ ATLAS and CMS based on single and double muon triggers

- specialization versus general-purpose approaches
  - LHCb benefits from hadron identification detectors, allow to distinguish K vs π vs p, needed to reconstruct hadronic b and c decays
  - ATLAS and CMS have the ability to explore high multiplicity (high-pileup pp, Pb-Pb) collisions, and integrate larger luminosities



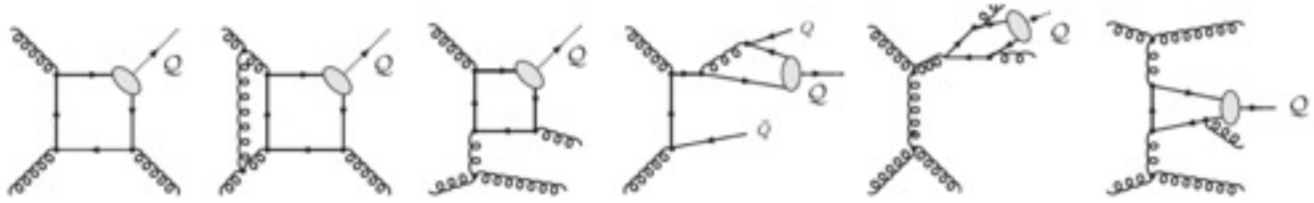




Outline

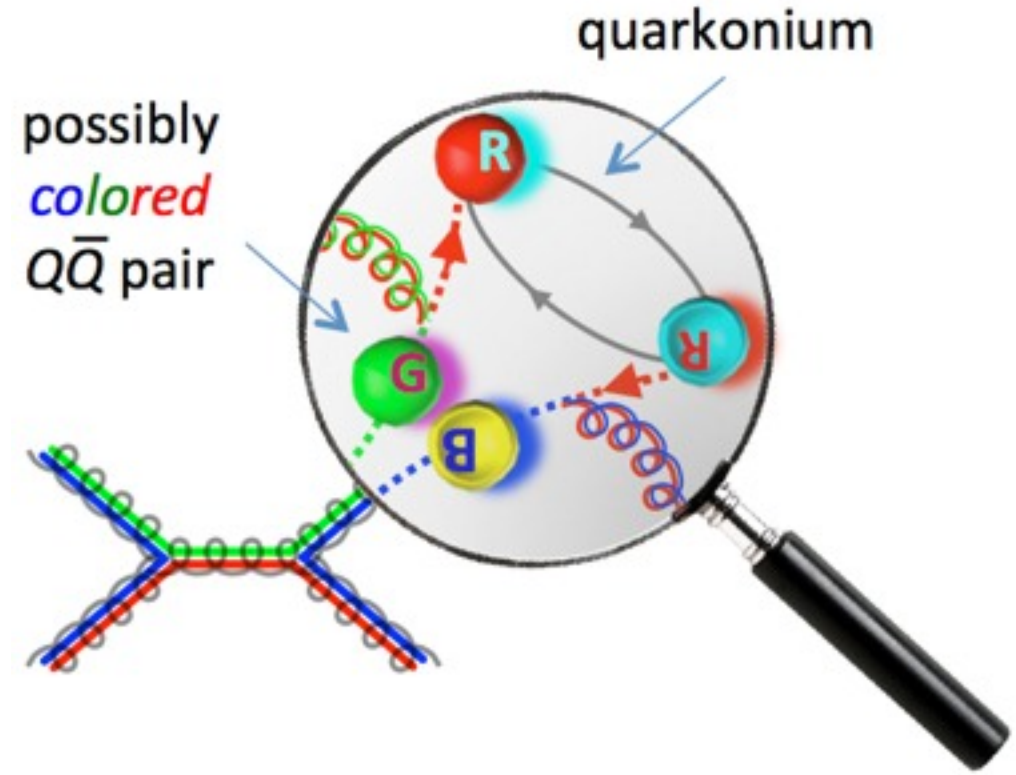
- production (and suppression)
  - quarkonia and b-hadrons as QCD probes in different media
- spectroscopy
  - new states and new decays
- properties
  - lifetime, flavor tagging, CP violation
- rare decays
  - highly suppressed processes with high sensitivity to new physics
- prospects
  - flavor physics into high-luminosity LHC running

Production



Quarkonia

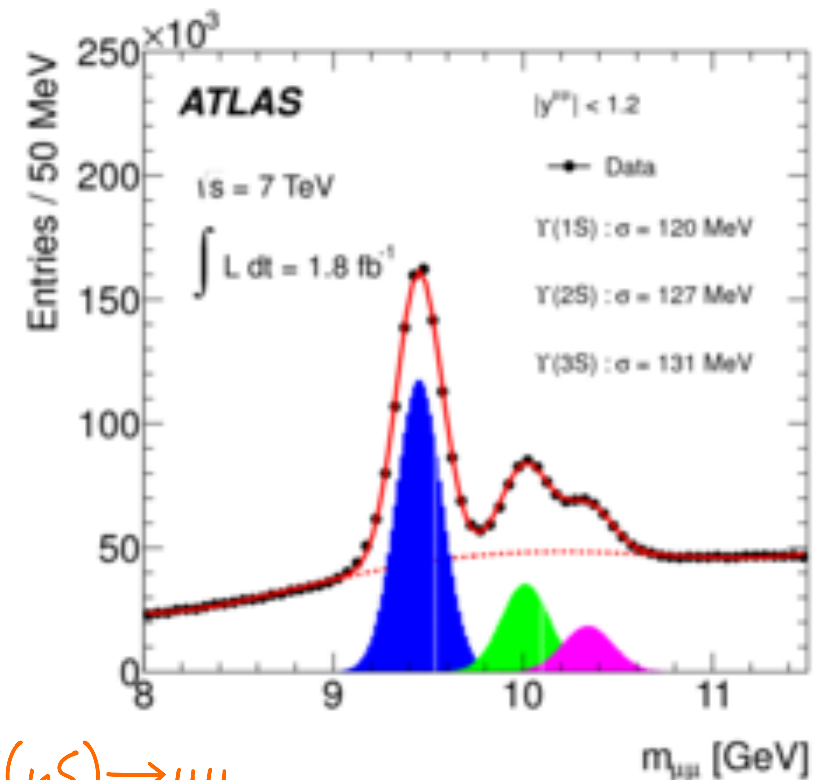
- LHC is a heavy-quark(onia) factory
- heavy quark-antiquark states are an ideal system in which to study how strong interaction binds quarks into hadrons
- cross section and polarization calculations up to NLO
  - estimate contributions from color singlet and color octet terms



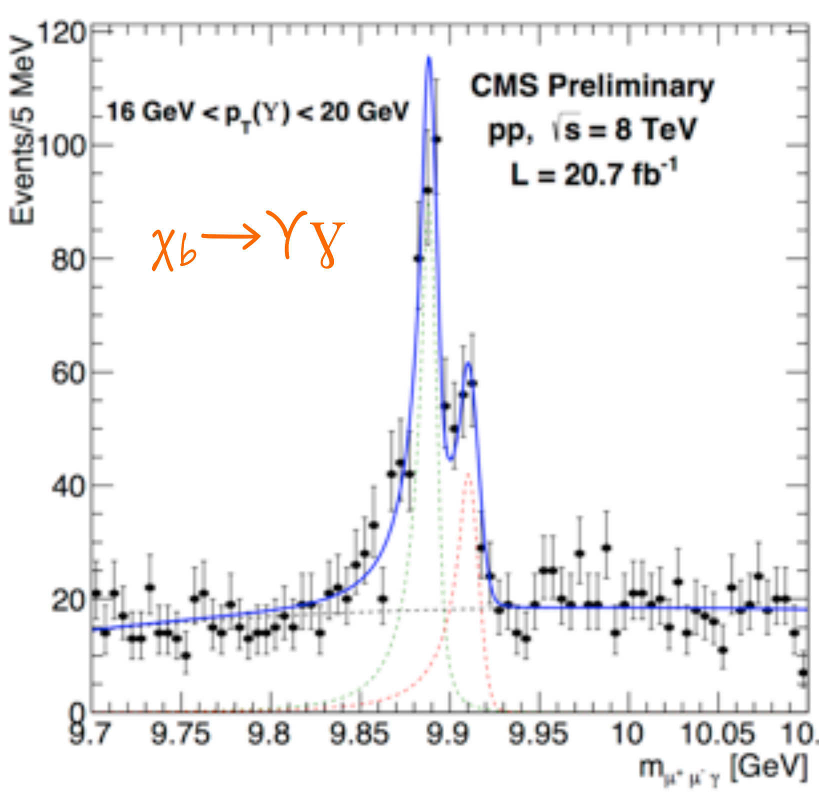
➡ theory-data comparisons are more reliable at high-p_T, making ATLAS and CMS measurements particularly important

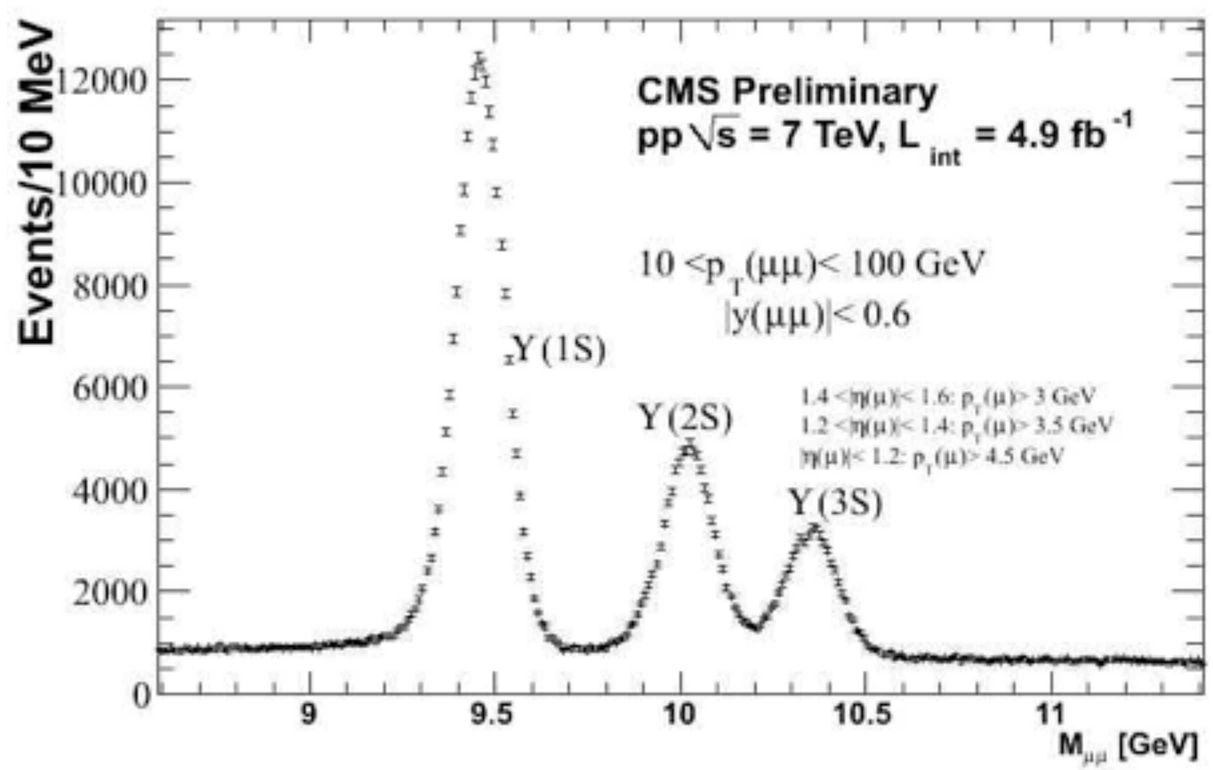
Bottomonia

- good dimuon mass resolution
  - allow to resolve S-wave states
- accurate reconstruction of low-energy photons
  - allow to resolve P-wave decays
  - explore $\gamma \to e^+e^-$ conversions
  - detect χ states w/ ~5MeV resolution



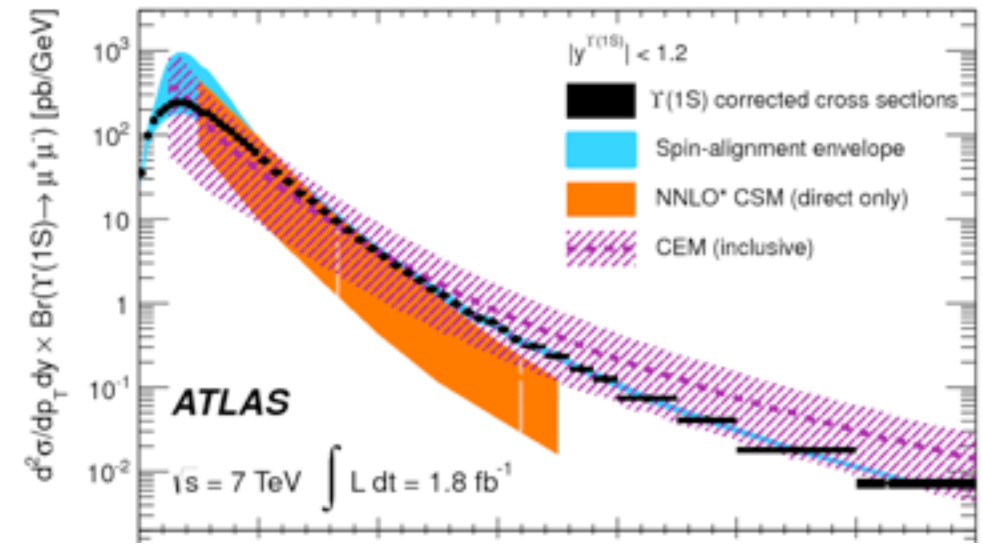
ϒ(nS)→μμ



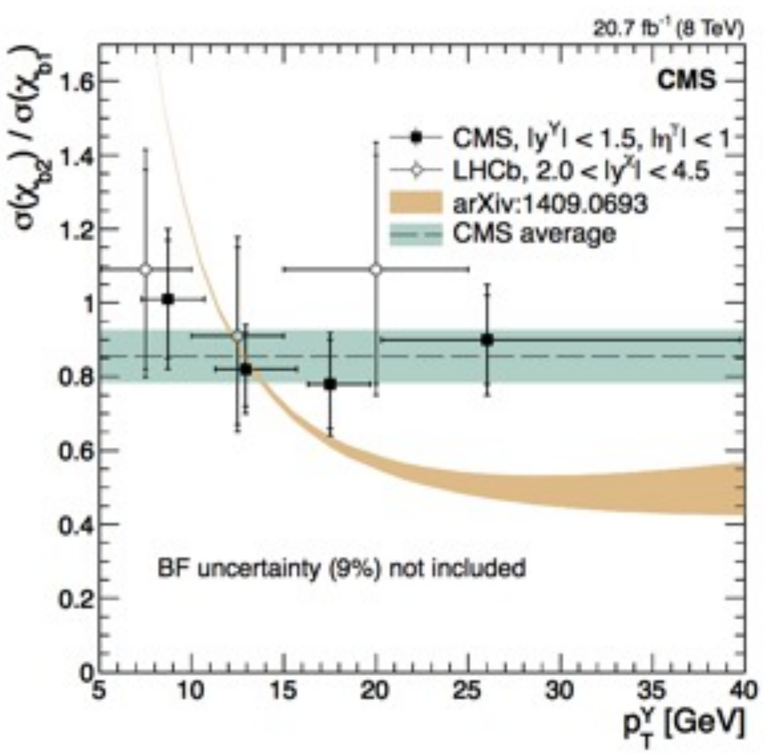


Bottomonium cross sections

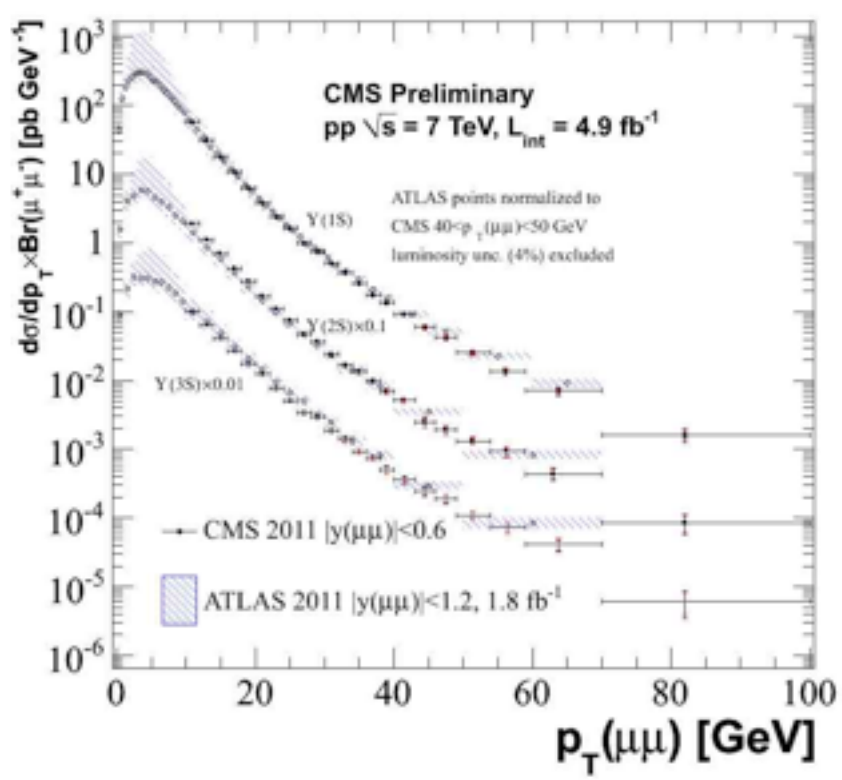
- S-wave measurements up to p_T of 100 GeV
  - Tevatron and LHCb data limited to $p_T < 15$GeV
  - further extension with 2012 data and Run 2
- high-p_T reach allows to probe models with increasing precision
- P-wave cross-section ratios

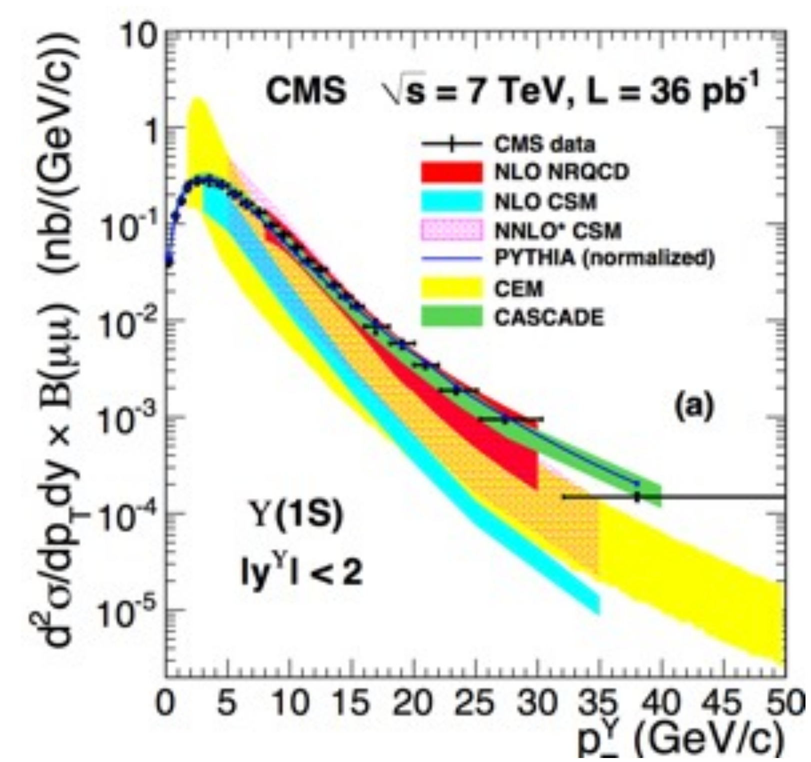


χ_b



$\Upsilon(nS)$

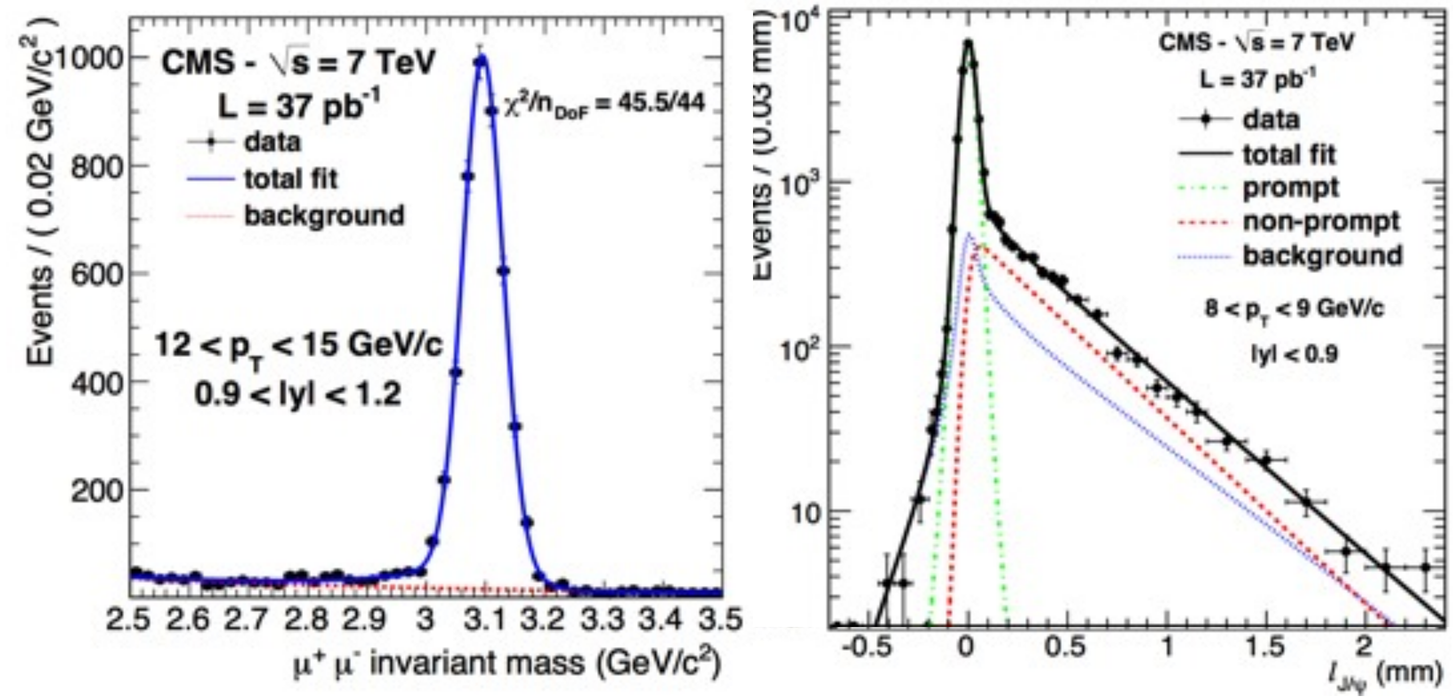




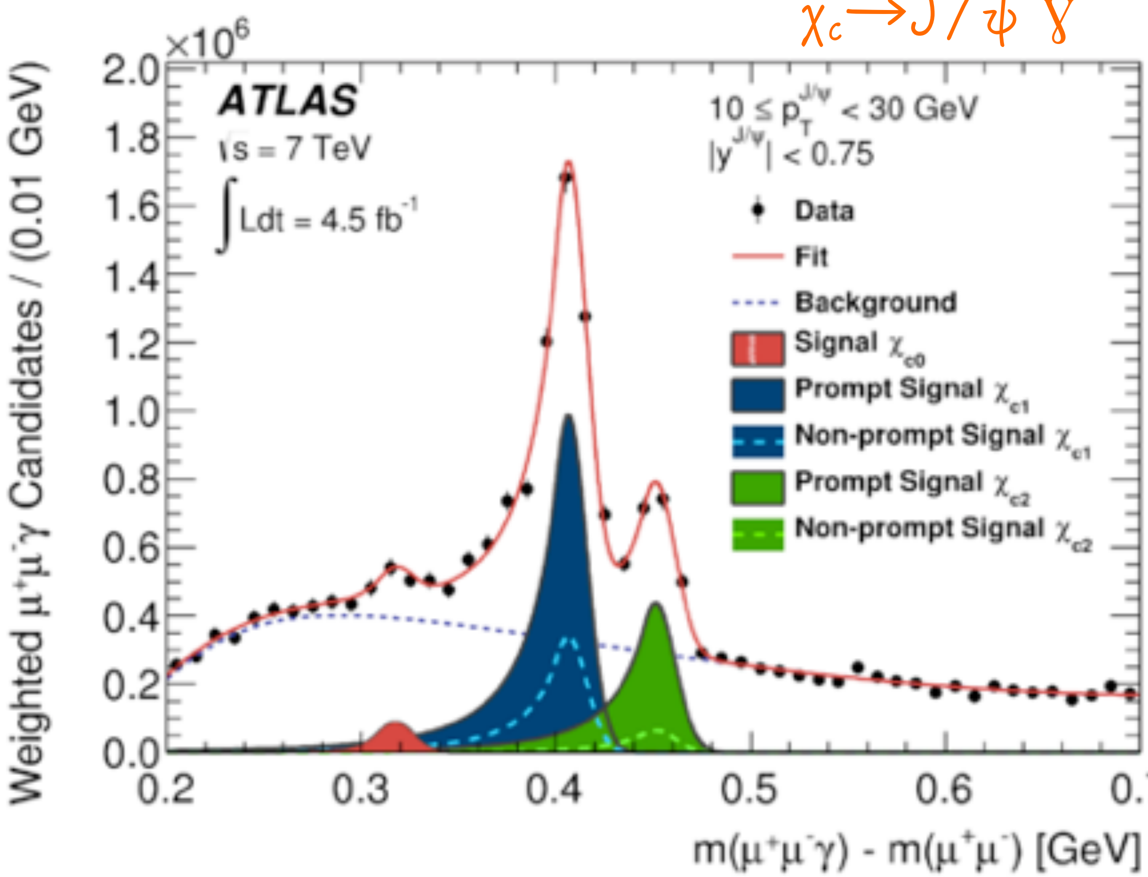
Charmonia

- very good dimuon mass resolution
- accurate reconstruction of low-energy γ crucial to detect radiative decays of P-wave states
- excellent secondary vertexing
  - crucial for separating prompt and non-prompt components via (pseudo) proper decay time analysis

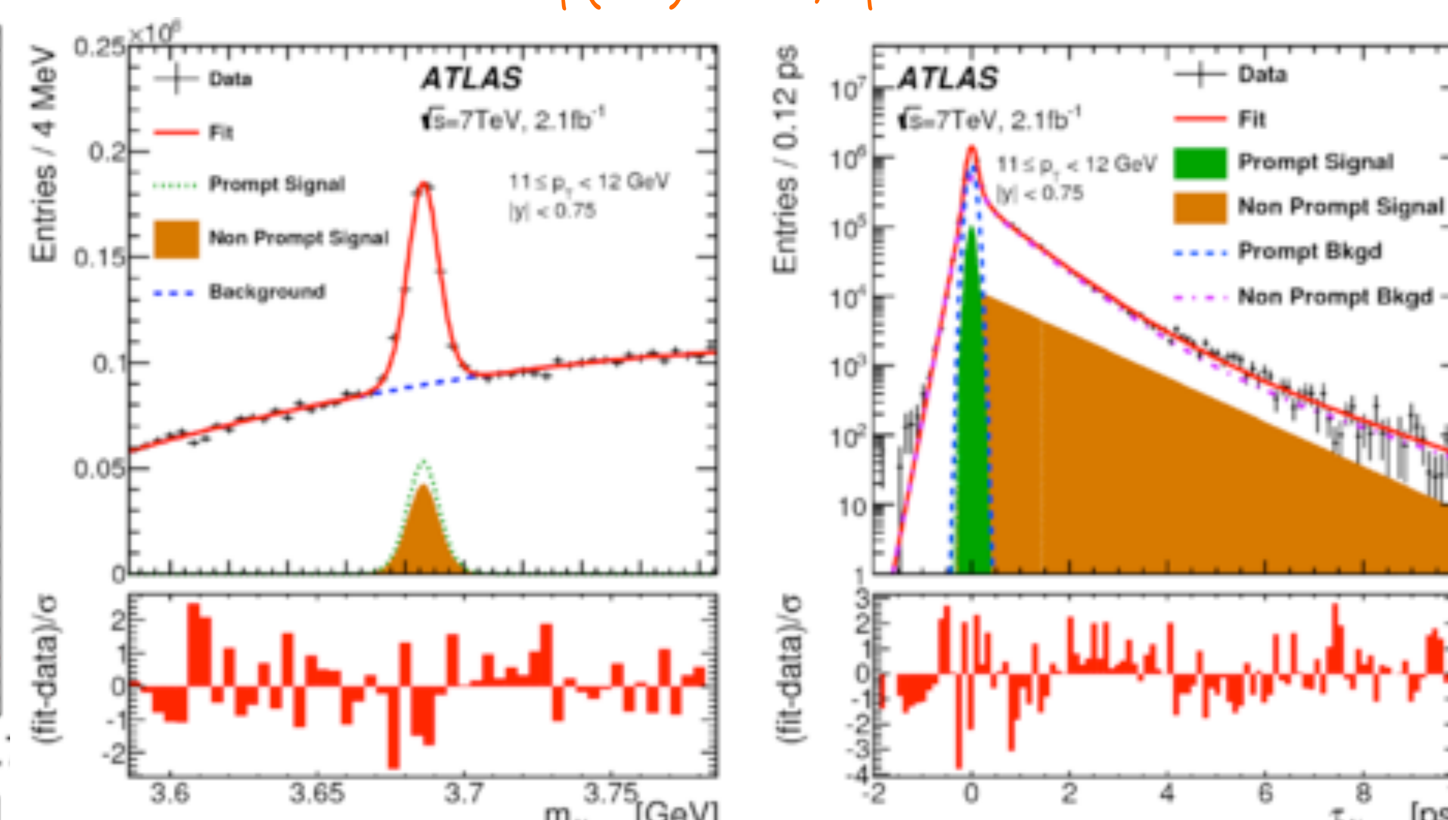
$J/\psi \to \mu\mu$



$\chi_c \to J/\psi\ \gamma$

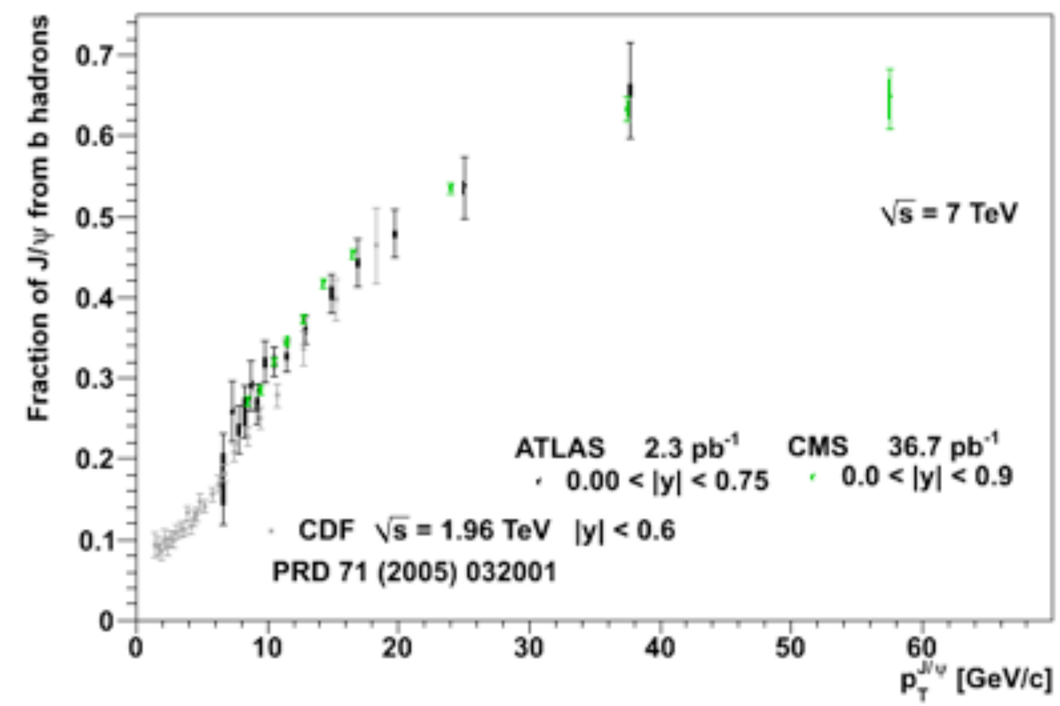


$\psi(2S) \to J/\psi\ \pi\pi$

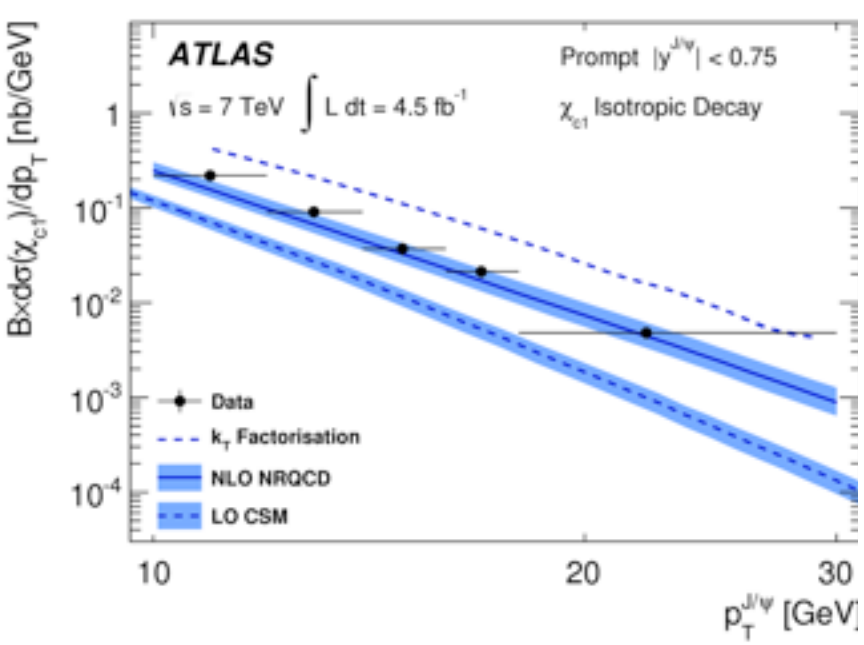


Charmonium cross sections

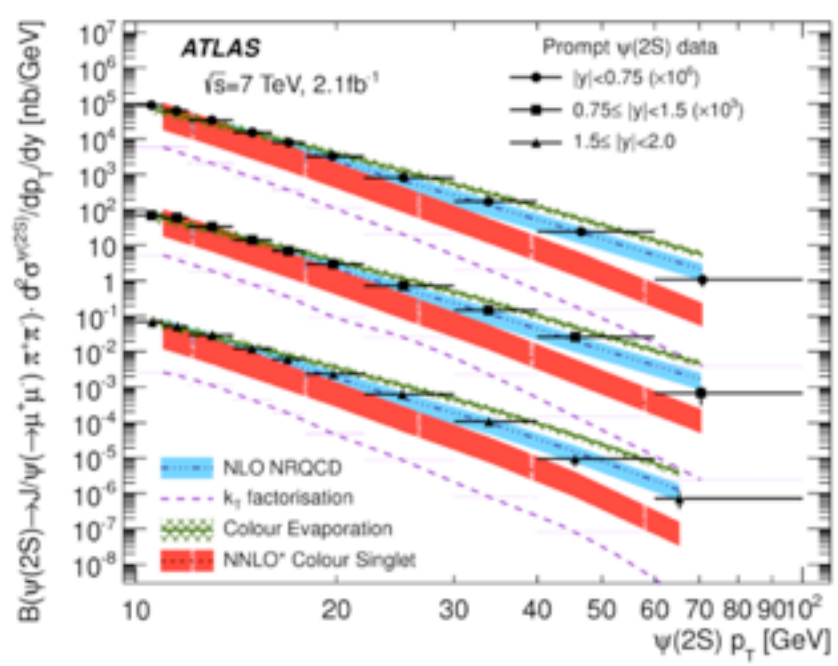
- S-wave and P-wave measurements
  - extension to unprecedented p_T provides precise input for testing theory predictions
- measurements provided for both prompt and non-prompt production
- disentangle feed-down contributions
  - b-hadron decays (non-prompt)
  - 2S to 1S state
  - P to S states



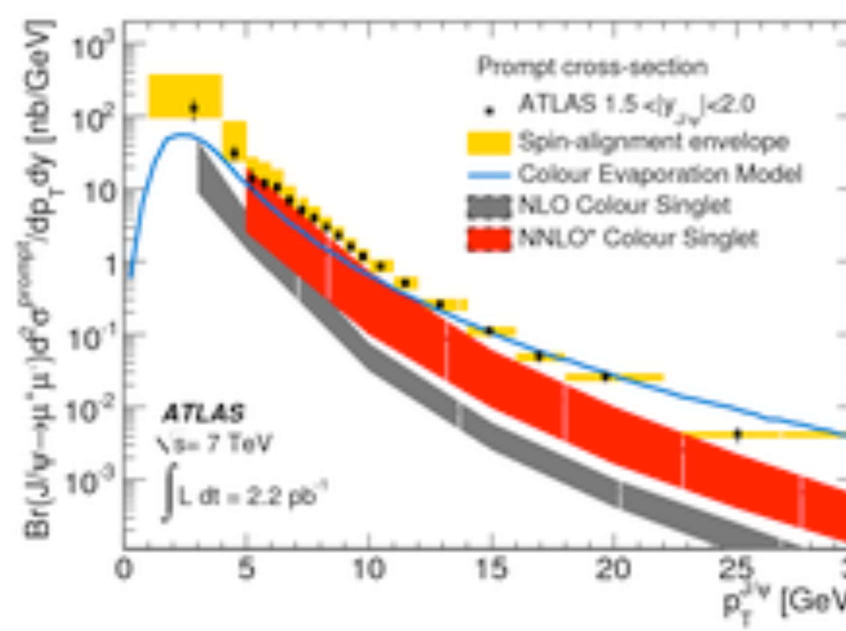
χ_c



$\psi(2S)$



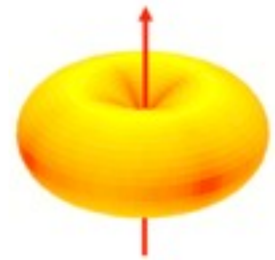
J/ψ

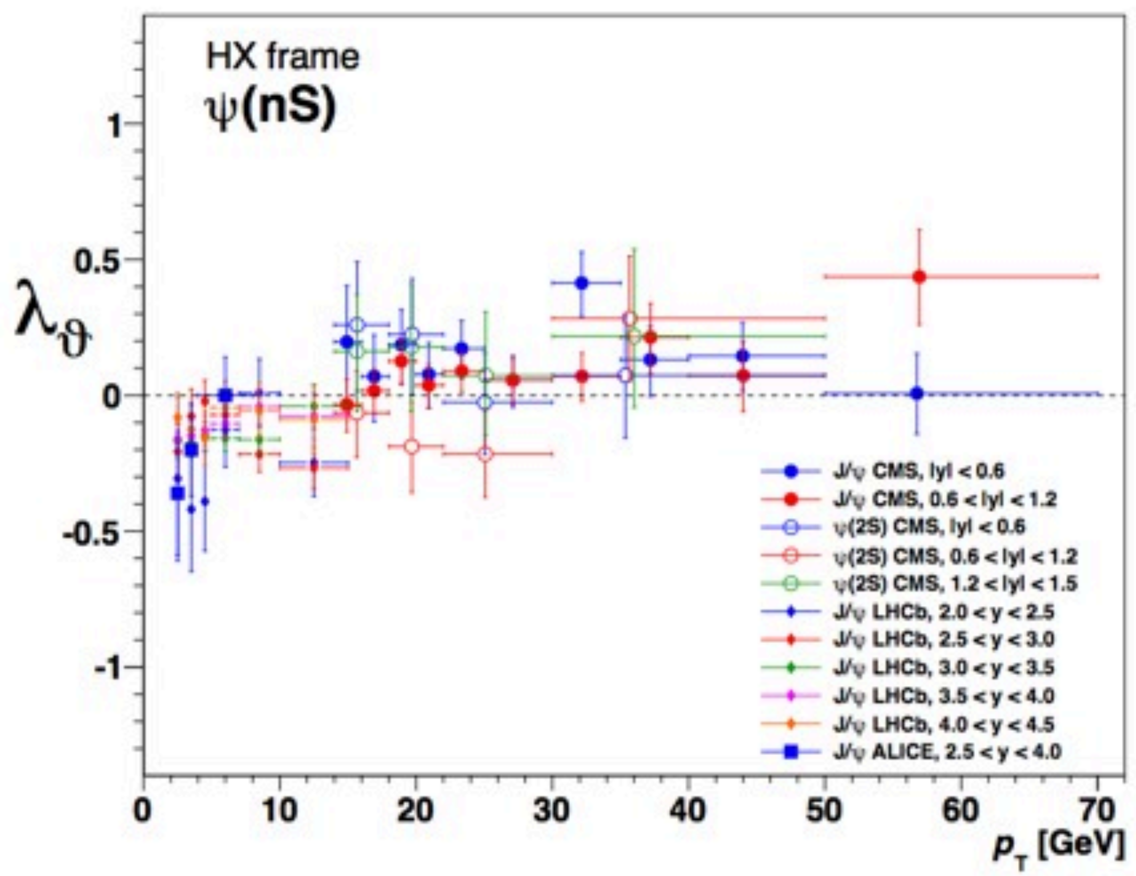


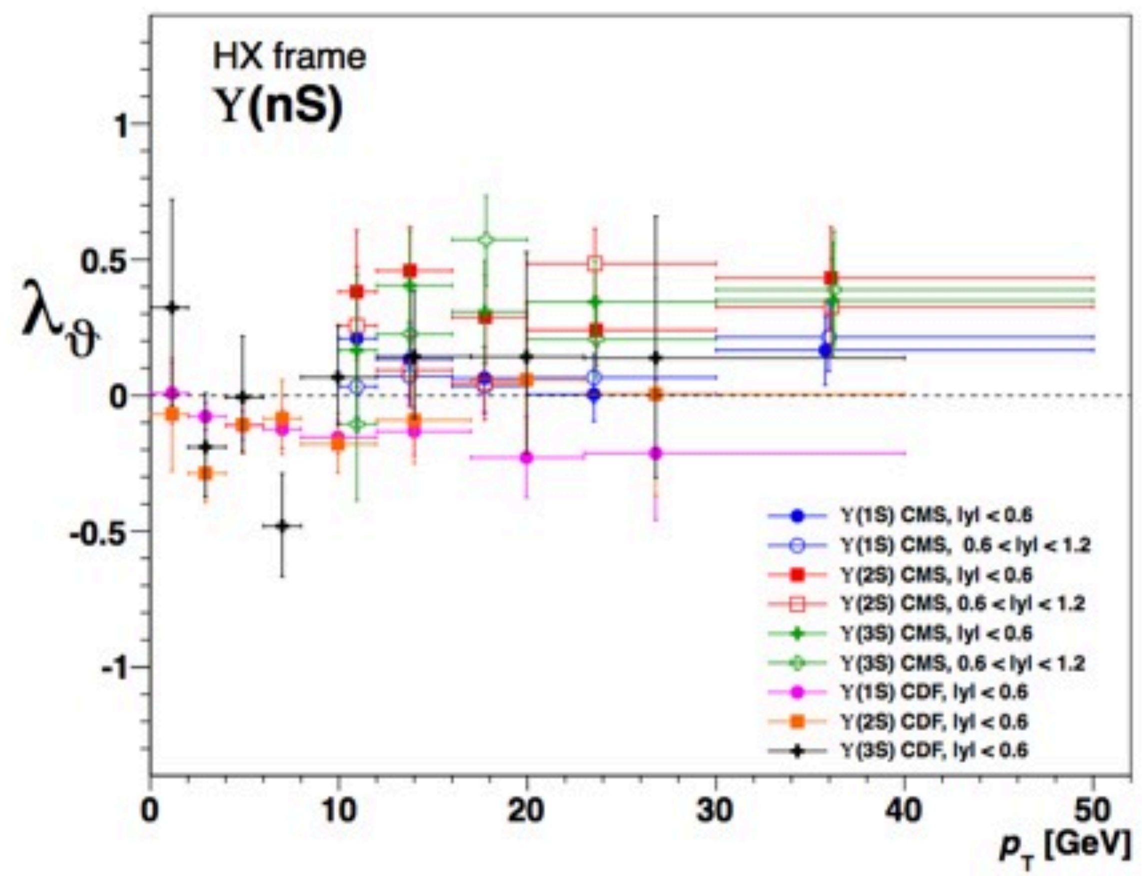
Quarkonium polarization

- CMS measured polarizations for all S-wave states
  - using the full dimuon angular decay distributions
  - in complementary reference frames
- S-wave results cluster around the unpolarized limit
- P-wave polarizations to be pursued next

$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi$$

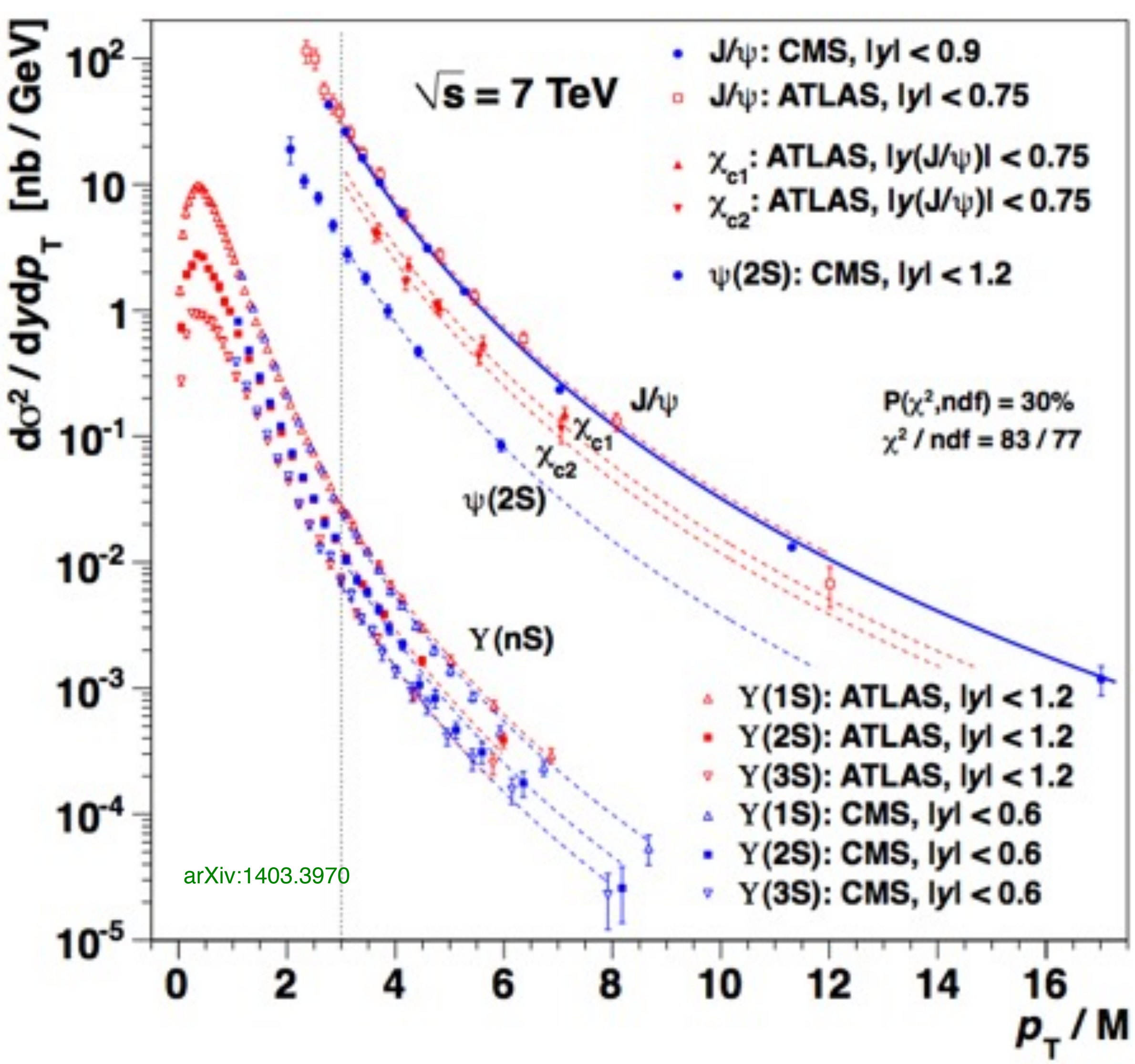




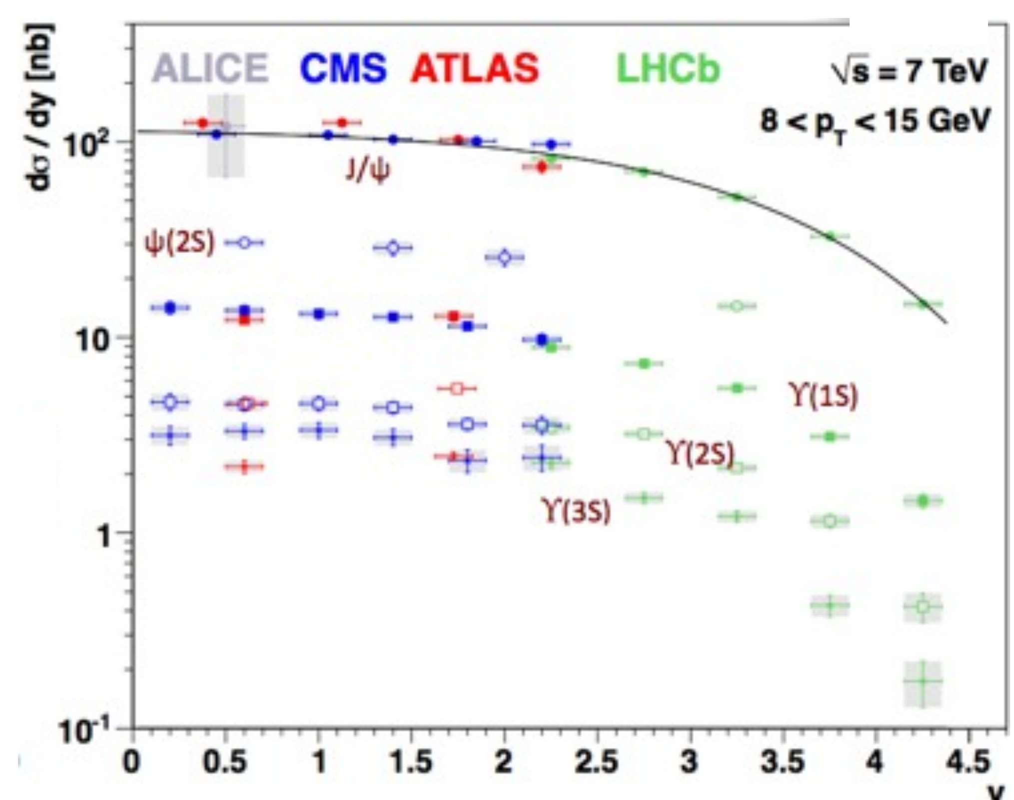


Quarkonium production

- cross sections for 7 quarkonia have similar p_T/m shapes (for $p_T/m>3$)
- polarizations for 5 quarkonia tend similarly to unpolarized limit
  - Ockham hints: all quarkonia dominantly produced by a single mechanism? (e.g. $^1S_0^{[8]}$)



- results from different experiments, covering different phase space, facilitates a more complete picture



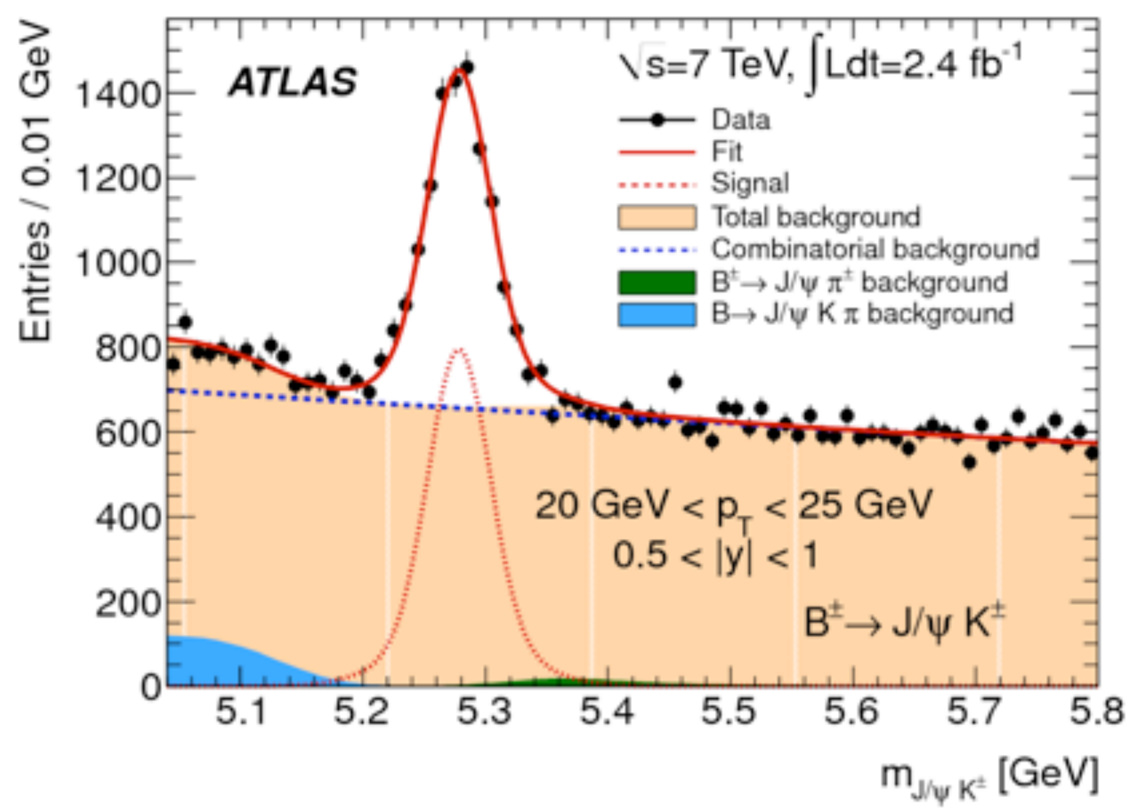
➡ LHC Run I brought about a thorough set of measurements in extended phase space contributing enormously to a clarification of the quarkonium sector

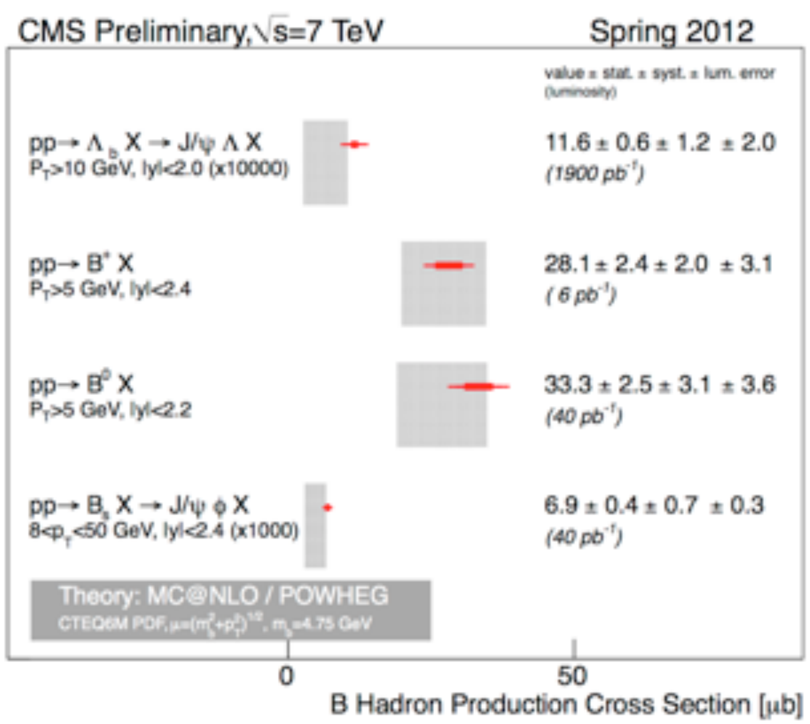
(open-flavor) b-hadron production

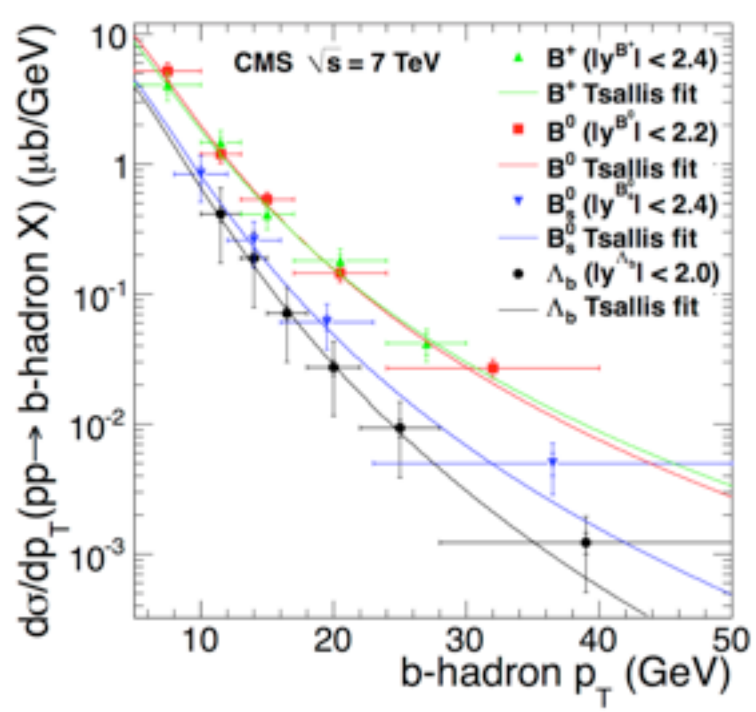
- measured production cross sections of various exclusive b-hadron decays: B_u, B_d, B_s, Λ_b
- measurements in good agreement with NLO predictions
- baryon spectra seems to fall faster then meson spectra

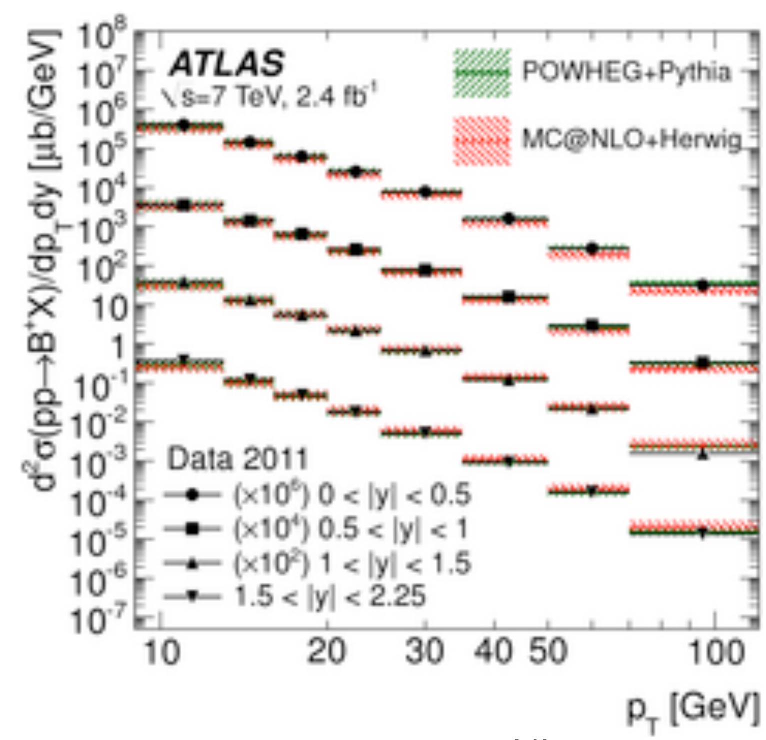
arXiv:1307.0126

$B_u \to J/\psi K^+$

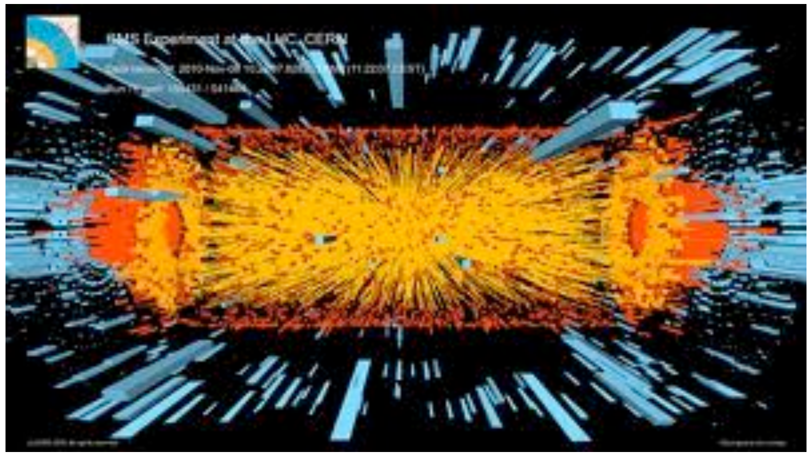






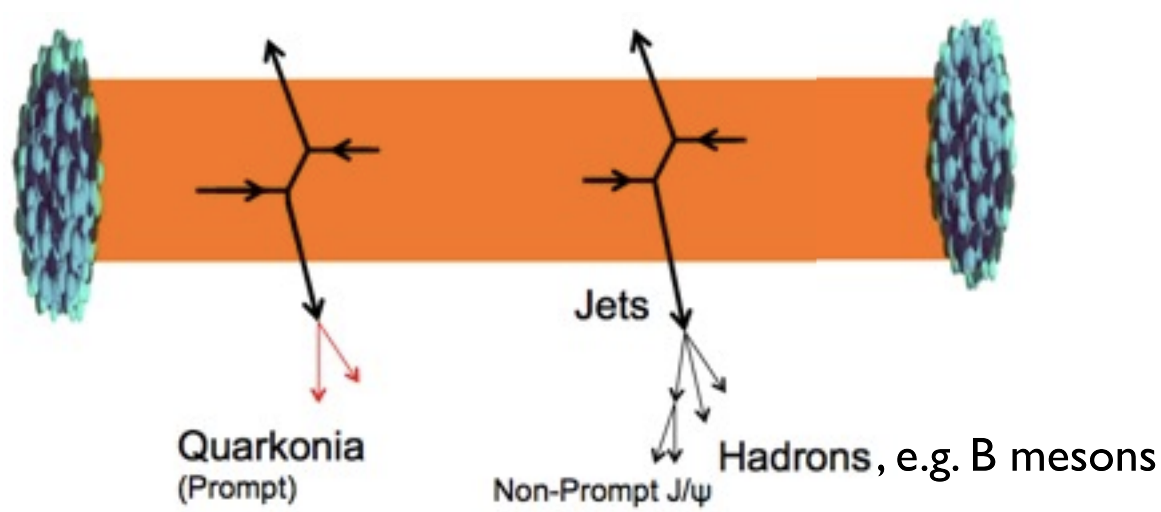


Suppression

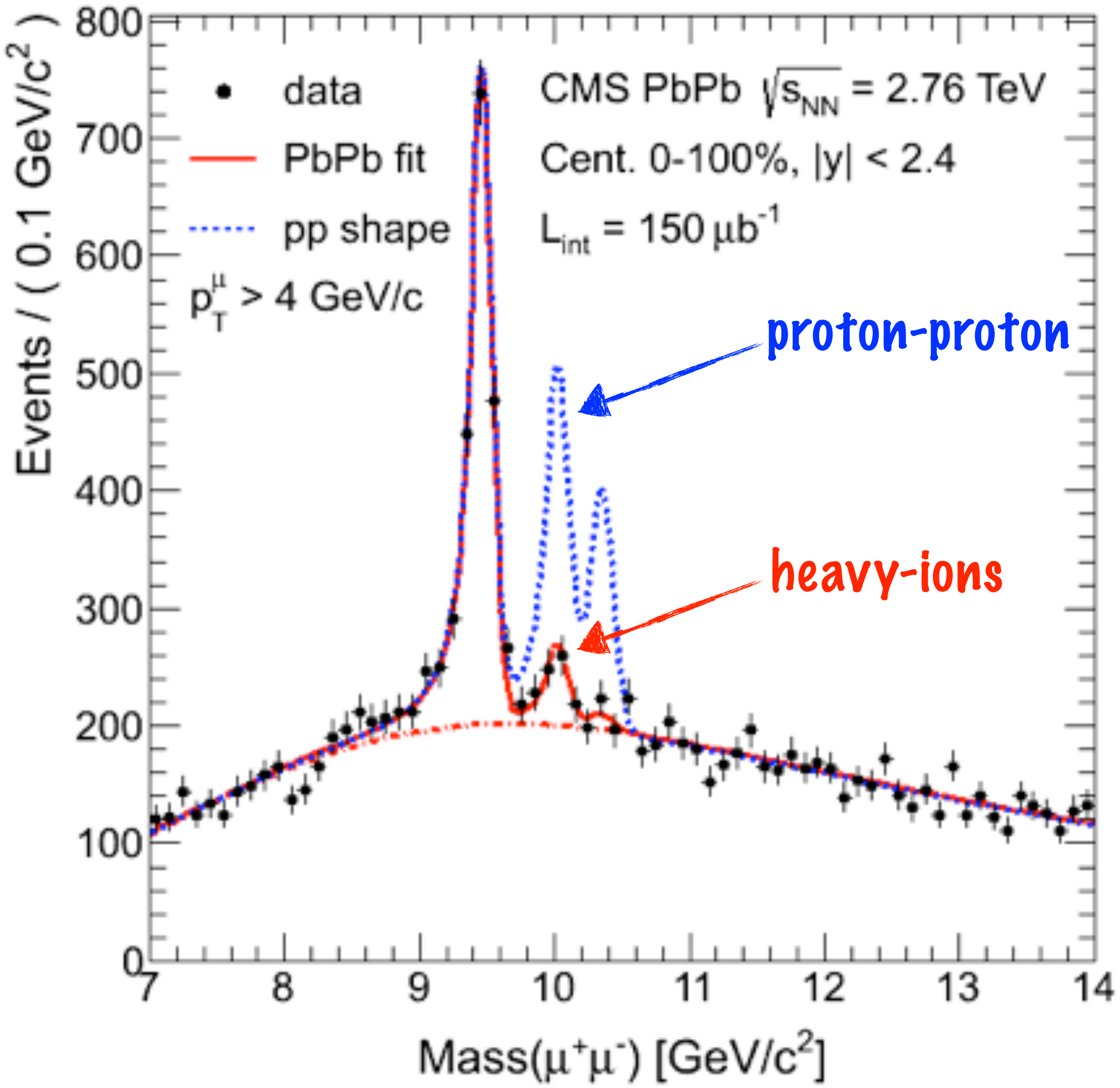


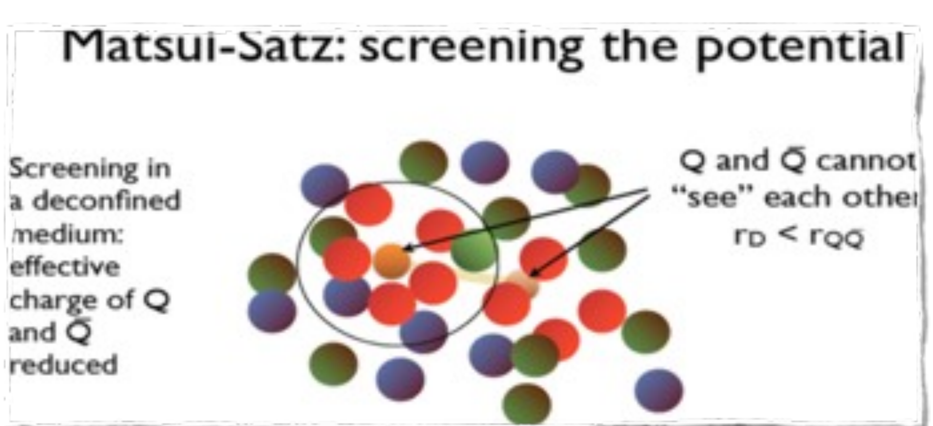
Heavy flavor in media

- in addition to p-p, the LHC collides Pb-Pb and p-Pb
- at large energy densities, QCD predicts the existence of a deconfined state of hadronic matter, the quark-gluon plasma
- heavy-flavor states are ideal "hard probes" for studying the properties of medium created in heavy-ion collisions at the LHC
  - Quarkonia expected to undergo *melting* due to color screening
  - Jets expected to undergo *energy loss*, relevant to study its flavor dependence



Bottomonia in Pb-Pb



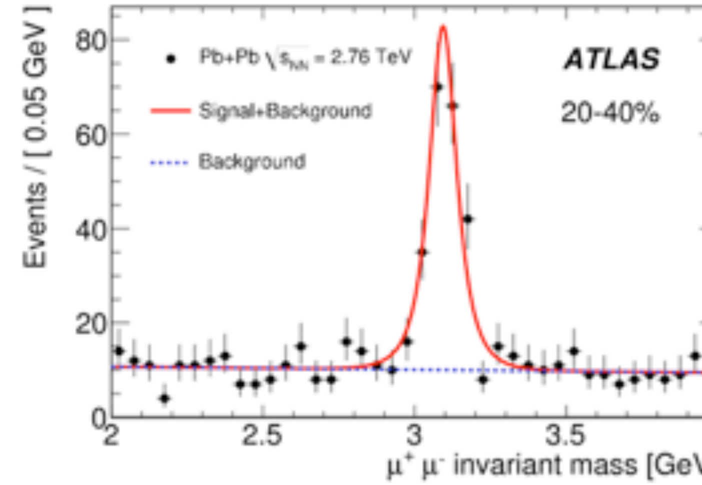


- CMS has reconstructed the 3 Y(nS) states for the *first time* in heavy-ion collisions
- all 3 states are suppressed in PbPb compared to pp
  - with the excited states, Y(2S) and Y(3S) being more suppressed than the ground state Y(1S)
- self-calibrating double ratio

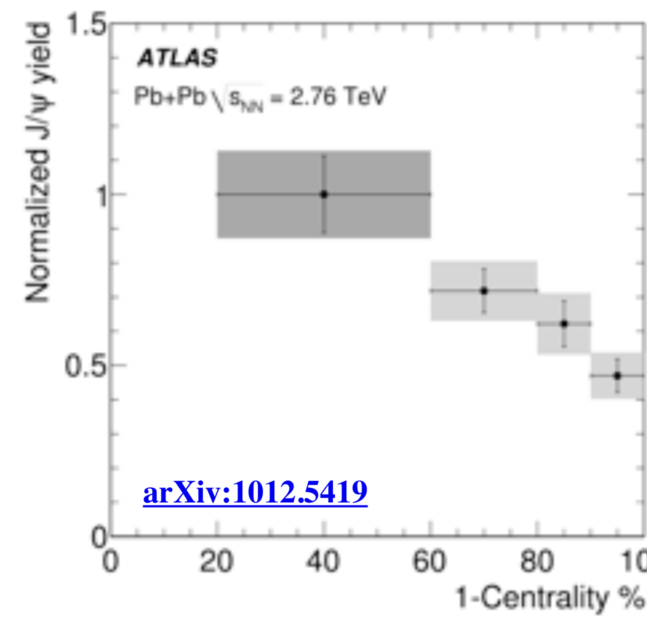
$$\frac{\Upsilon(2S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S)/\Upsilon(1S)|_{pp}} = 0.21 \pm 0.07\,(\text{stat.}) \pm 0.02\,(\text{syst.}) < 1$$

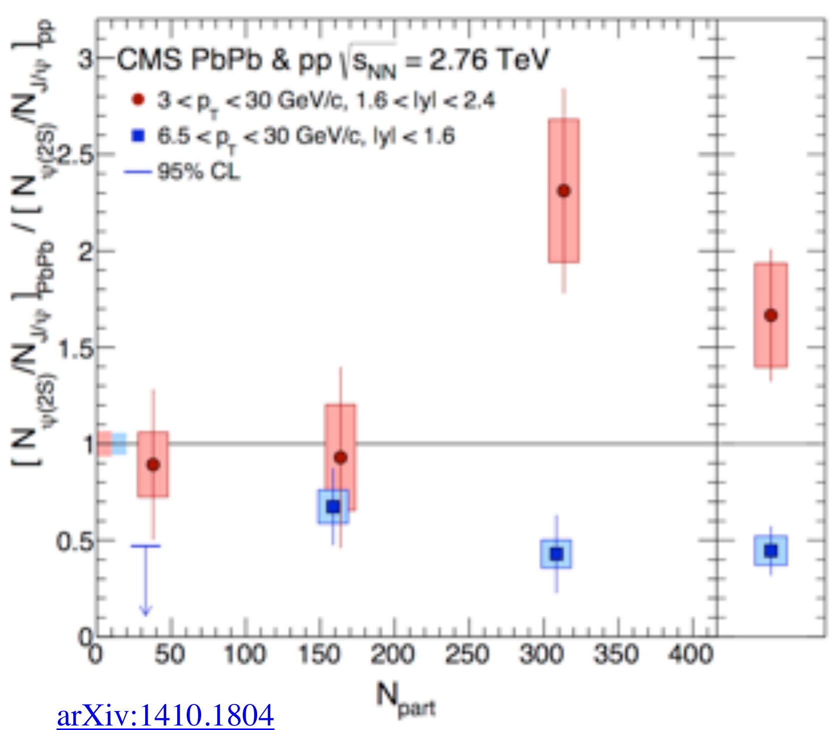
  - relative suppression observed (>5σ)
  - as expected in presence of QGP

Charmonia in Pb-Pb

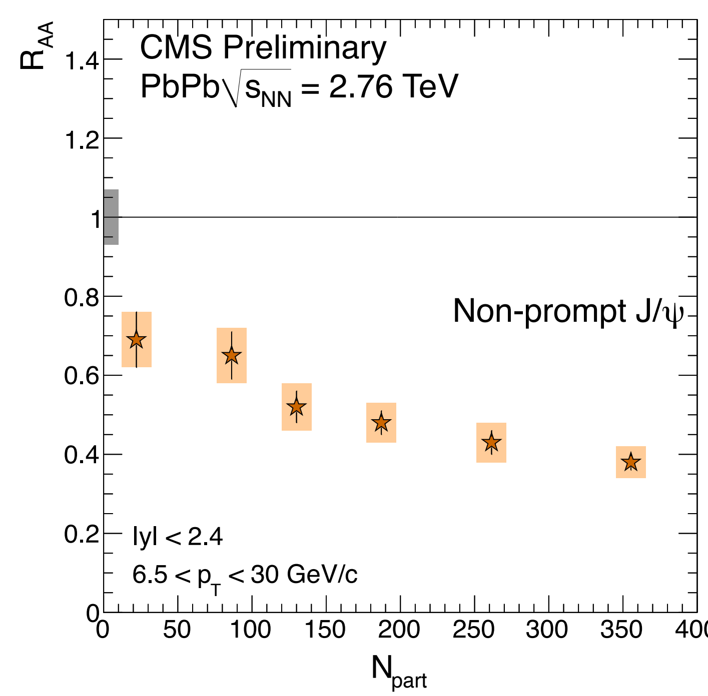


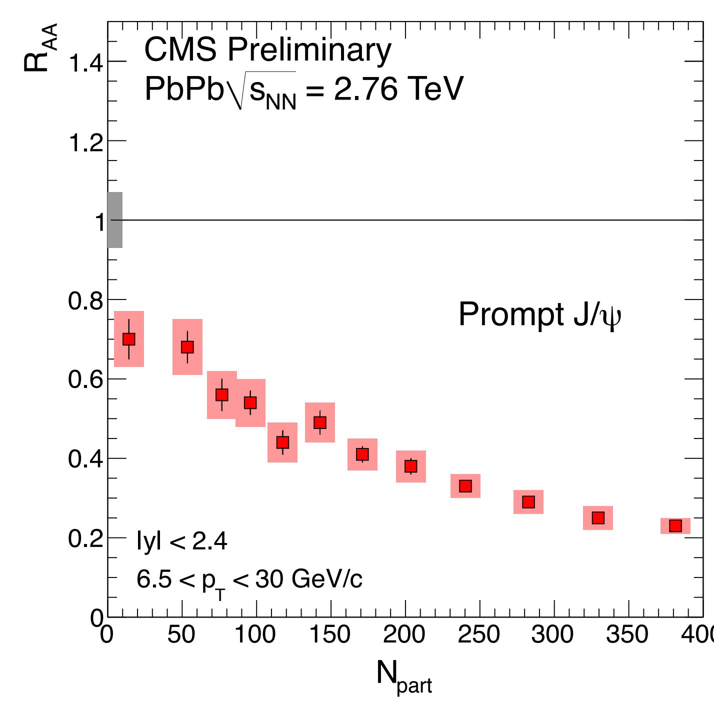
- prompt and non-prompt charmonia separated for the first time in heavy-ion collisions
  - prompt: suppression due to melting
  - non-prompt: suppression due to energy loss
- ψ(2S) vs J/ψ double ratio indicate
  - suppression for central, high-p_T
  - possible enhancement for forward, low-p_T
  - not significant (<3σ), but could be hint of *recombination*



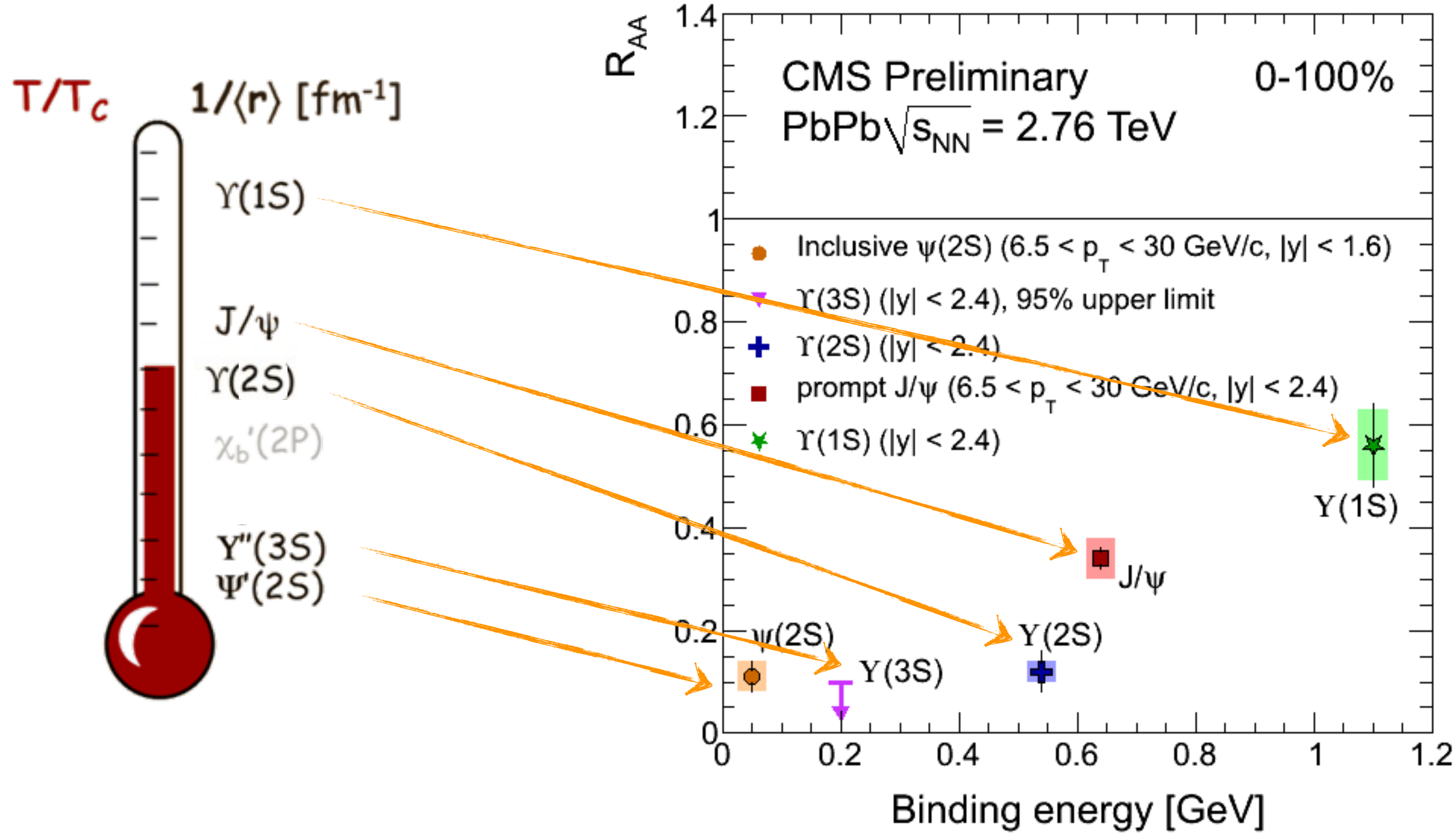


arXiv:1410.1804





Quarkonium sequential suppression in Pb-Pb



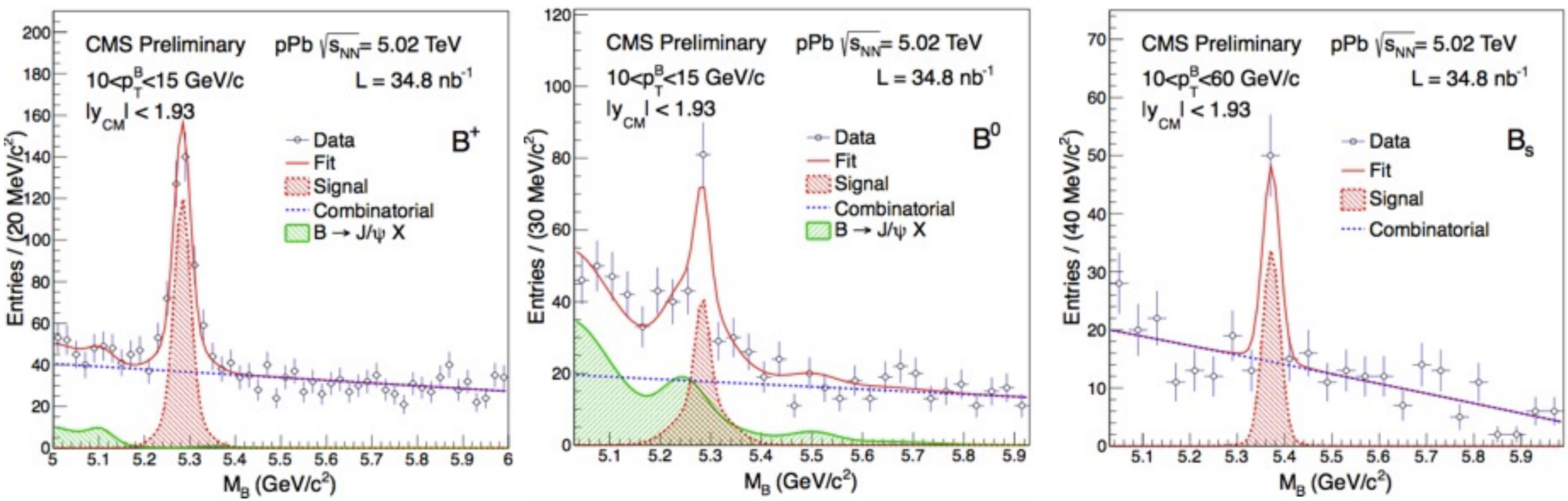
- CMS observes quarkonium sequential melting
- suppression pattern of S-wave states experimentally established:

  less tightly bound states are most suppressed in the hot medium

Exclusive B meson production in p-Pb

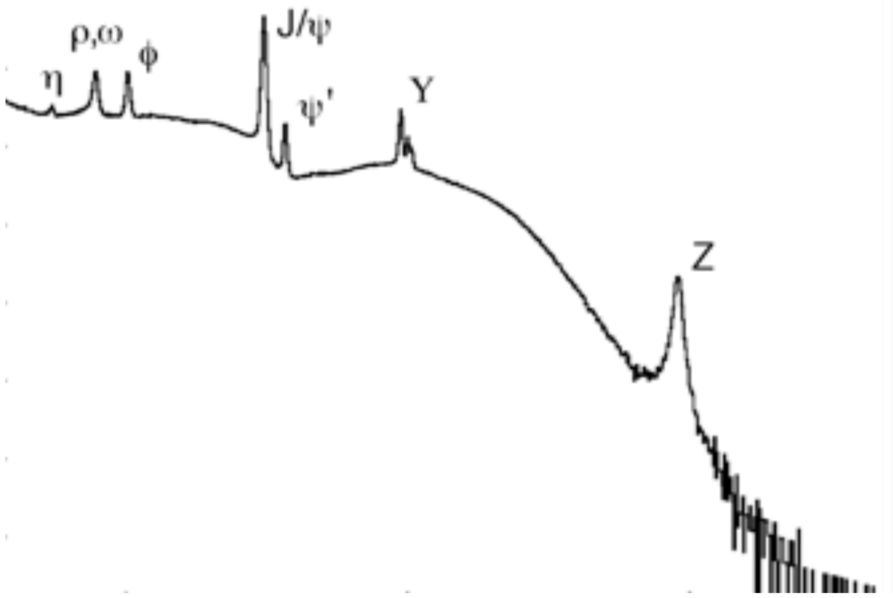
- B meson peaks reconstructed for the first time in collisions involving heavy ions

$B_u \rightarrow J/\psi K^+$ $B_d \rightarrow J/\psi K^{*0}$ $B_s \rightarrow J/\psi \Phi$



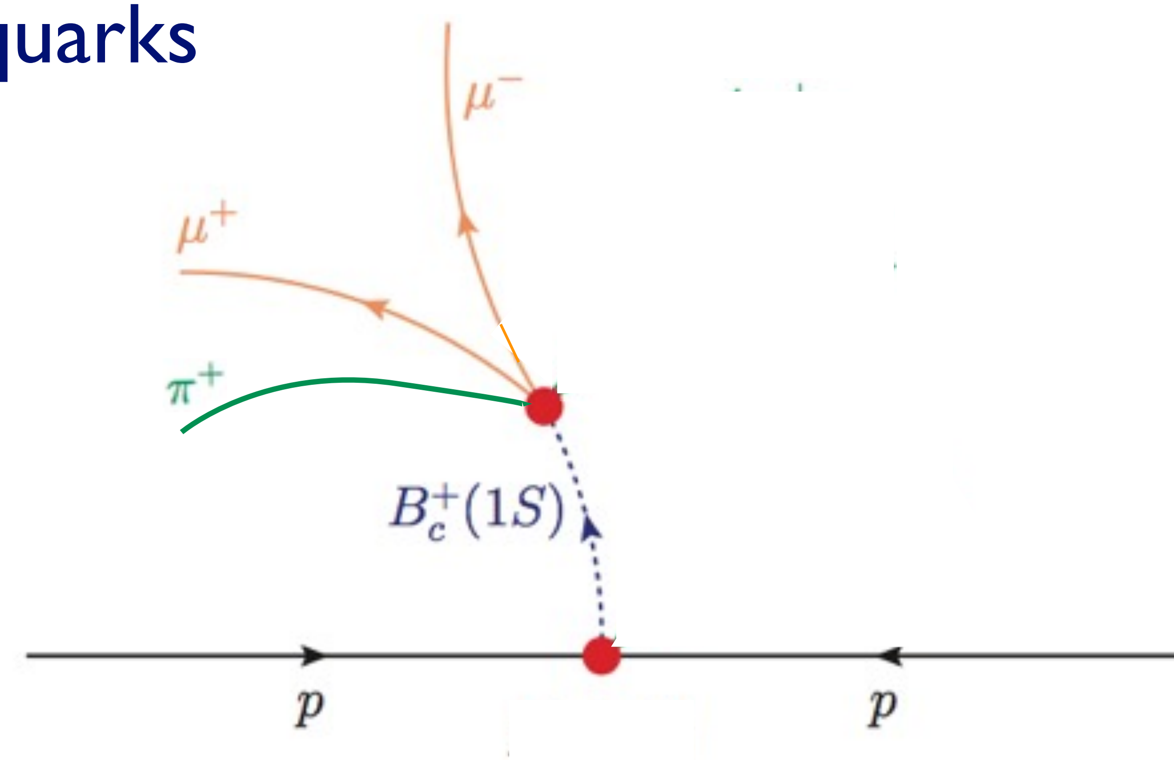
- new exclusive probes to study mechanisms of energy loss and its energy dependence
- next: attempt to reconstruct B peaks in Pb-Pb (to come in Run II)

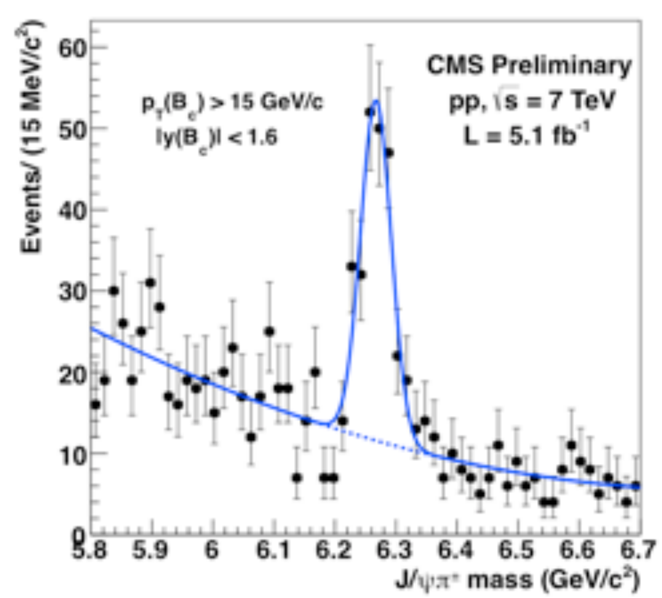
Spectroscopy

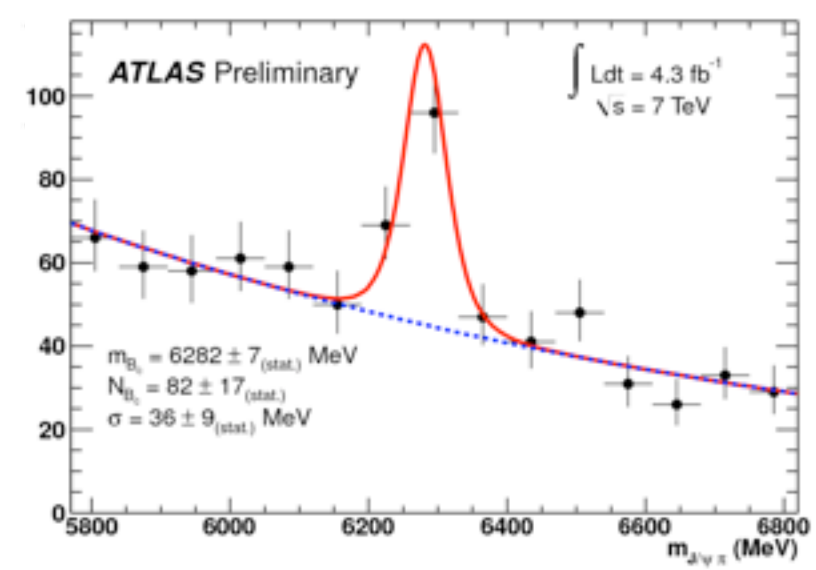


$J/\psi + \pi^+$ $[B_c(1S)]$

- B_c unique system of 2 different heavy quarks
  - in which to study heavy-quark dynamics

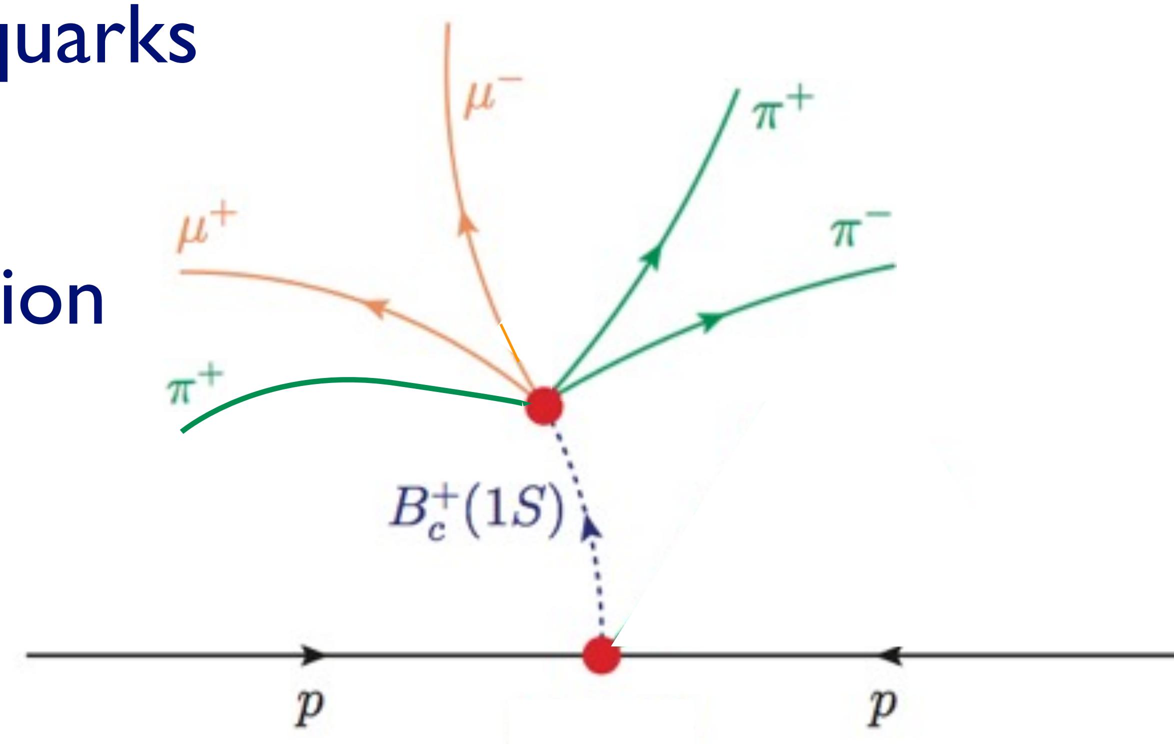






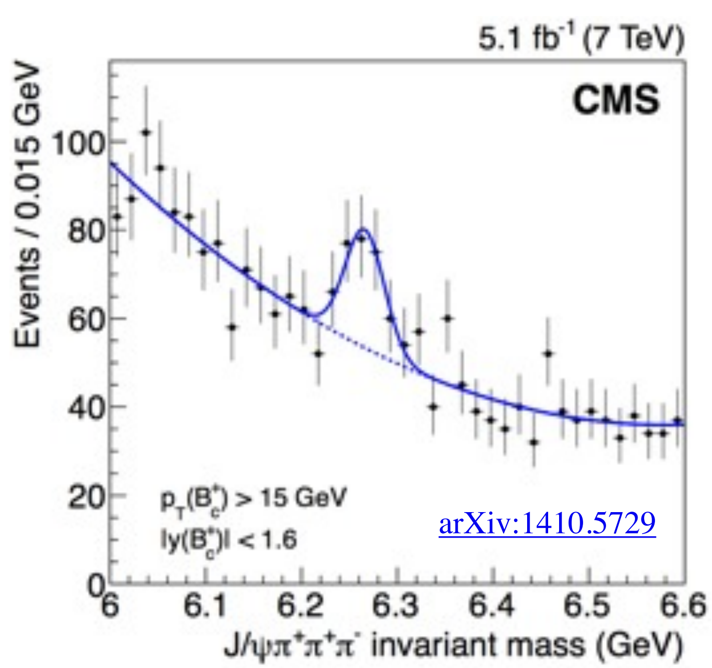
$J/\psi + \pi^+\pi^+\pi^-$ $[B_c(1S)]$

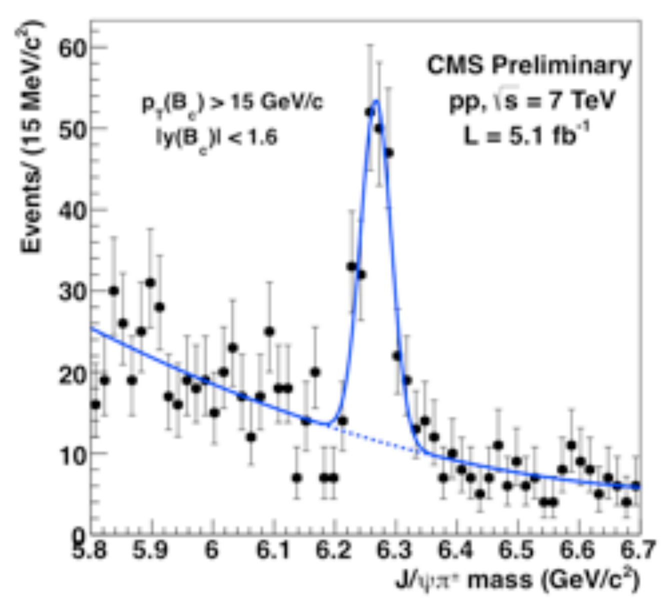
- B_c unique system of 2 different heavy quarks
  - in which to study heavy-quark dynamics
- CMS measures relative branching fraction
  - $B_c \to J/\psi\pi\pi\pi$ *vs* $B_c \to J/\psi\pi$

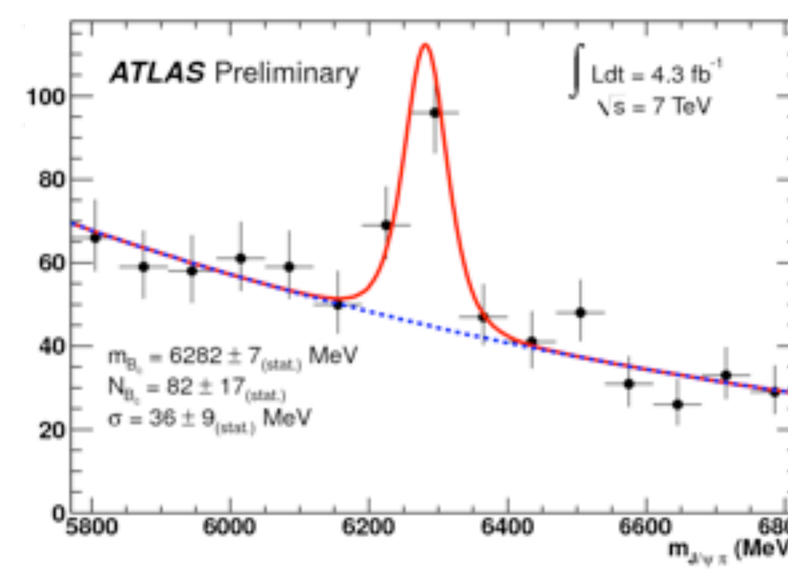


$$R_{B_c} = \frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+\pi^+\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$$

$$= 2.55 \pm 0.80\,(\text{stat}) \pm 0.33\,(\text{syst})\,^{+0.04}_{-0.01}\,(\tau_{B_c})$$

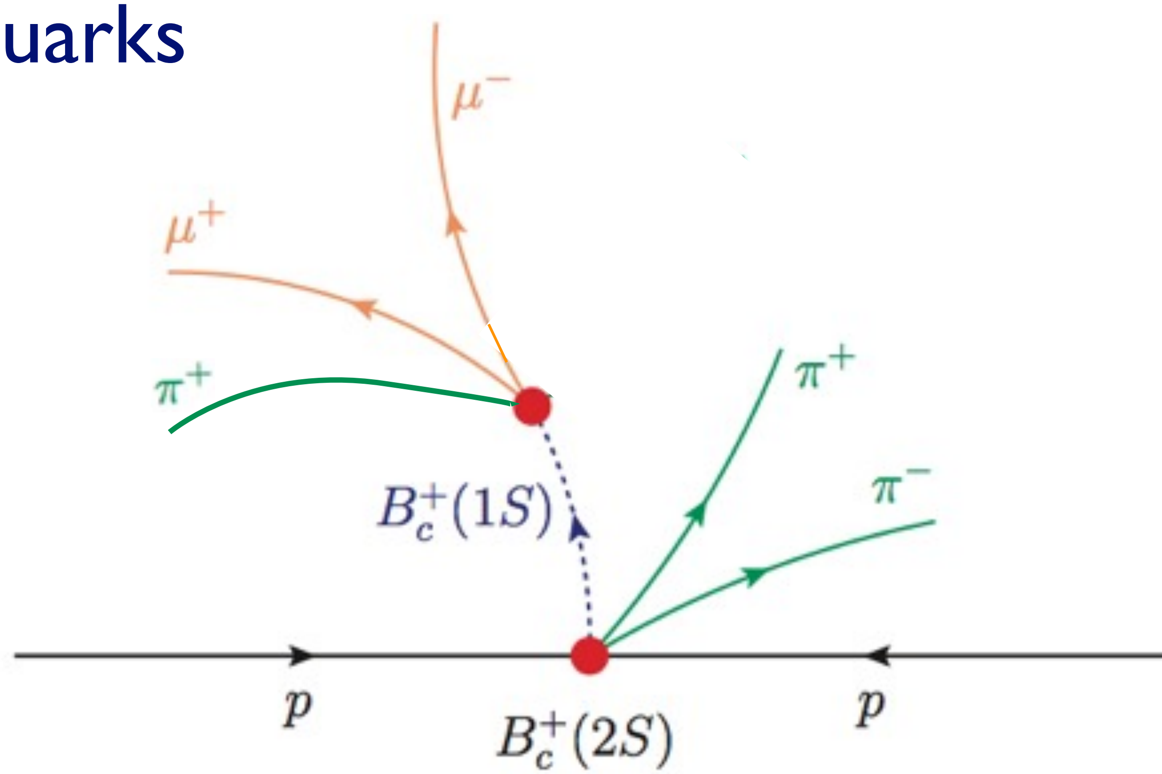




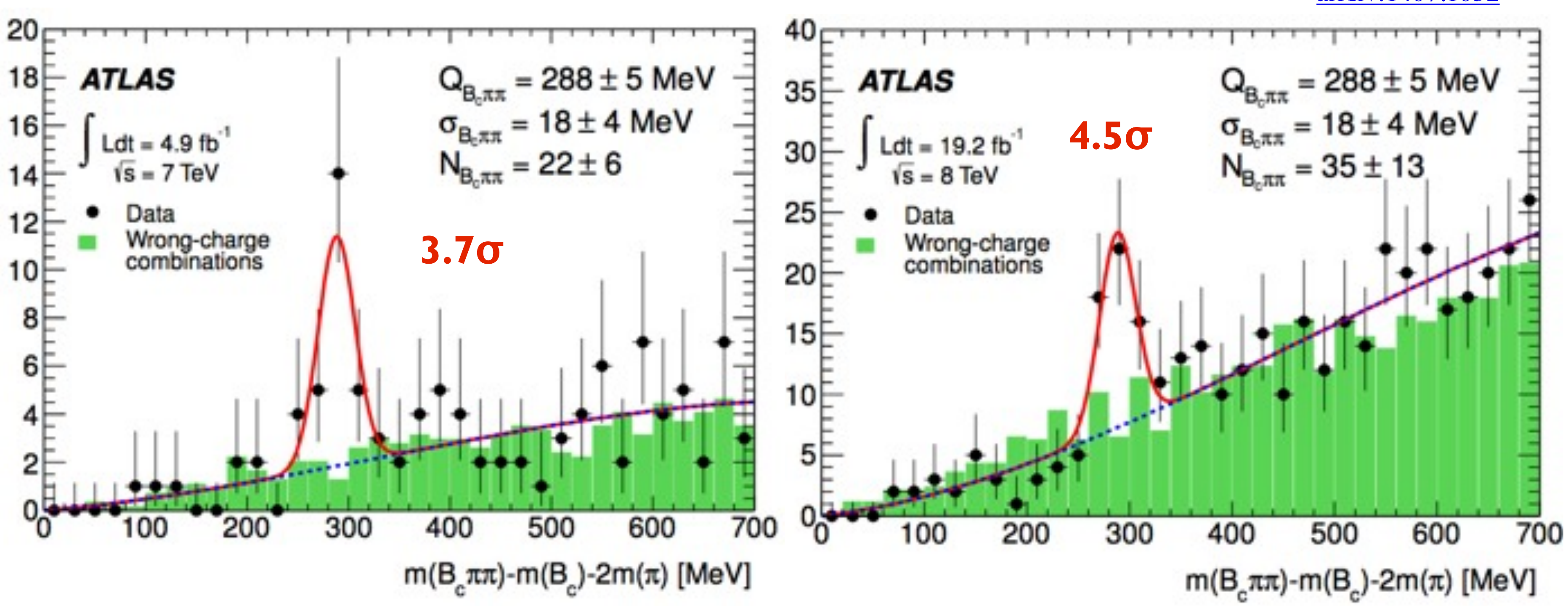


$J/\psi + \pi^+\pi^+\pi^-$ [$B_c(2S)$]

- B_c unique system of 2 different heavy quarks
  - in which to study heavy-quark dynamics
- ATLAS observes new state: $B_c^+(2S)$
  - $B_c(2S) \rightarrow B_c\pi\pi \rightarrow J/\psi\pi\ \pi\pi$ (signif. 5.2σ)
  - M = 6842 ± 4$_{(stat.)}$ ± 5 $_{(syst.)}$ MeV
  - compatible with $B_c(2S)$ predicted mass



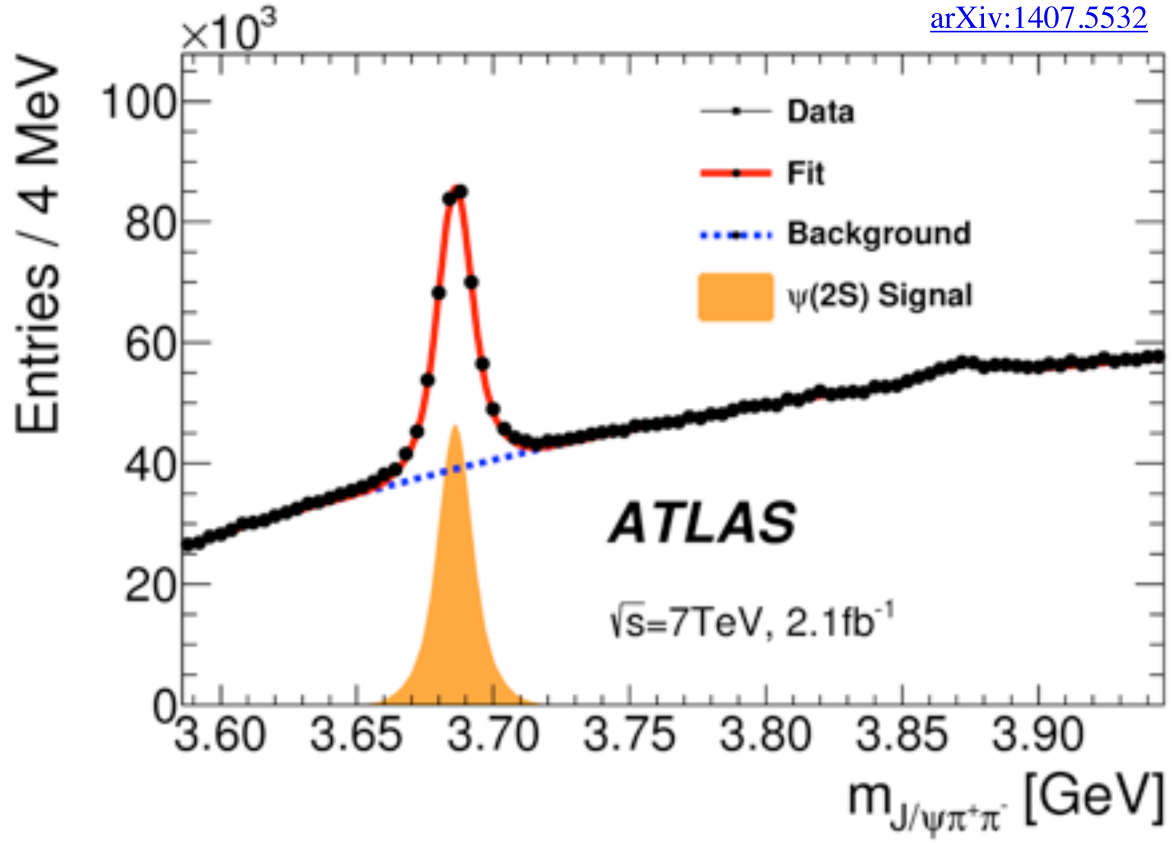
arXiv:1407.1032



$J/\psi + \pi^+\pi^-$ [$\psi(2S), X(3872)$]

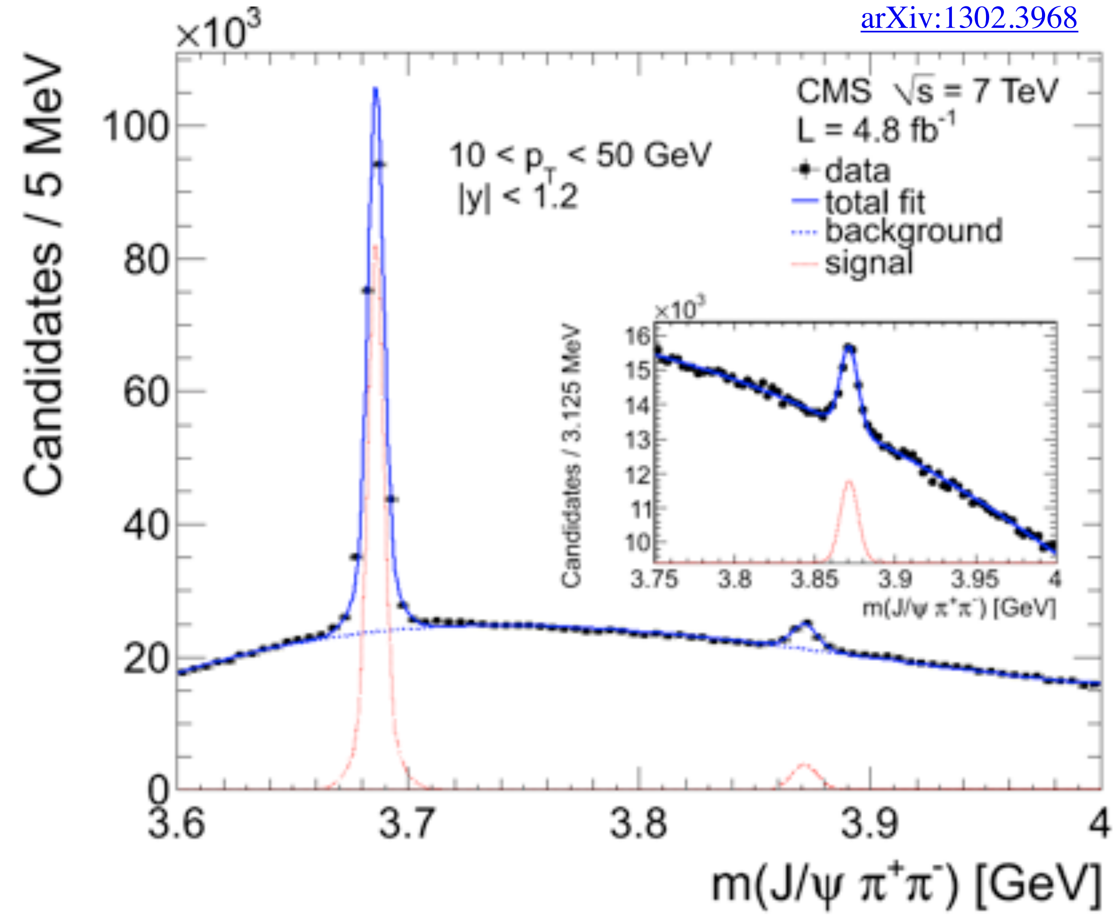
$\psi(2S) \to J/\psi\ \pi\pi$

arXiv:1407.5532



$X(3872) \to J/\psi\ \pi\pi$

arXiv:1302.3968

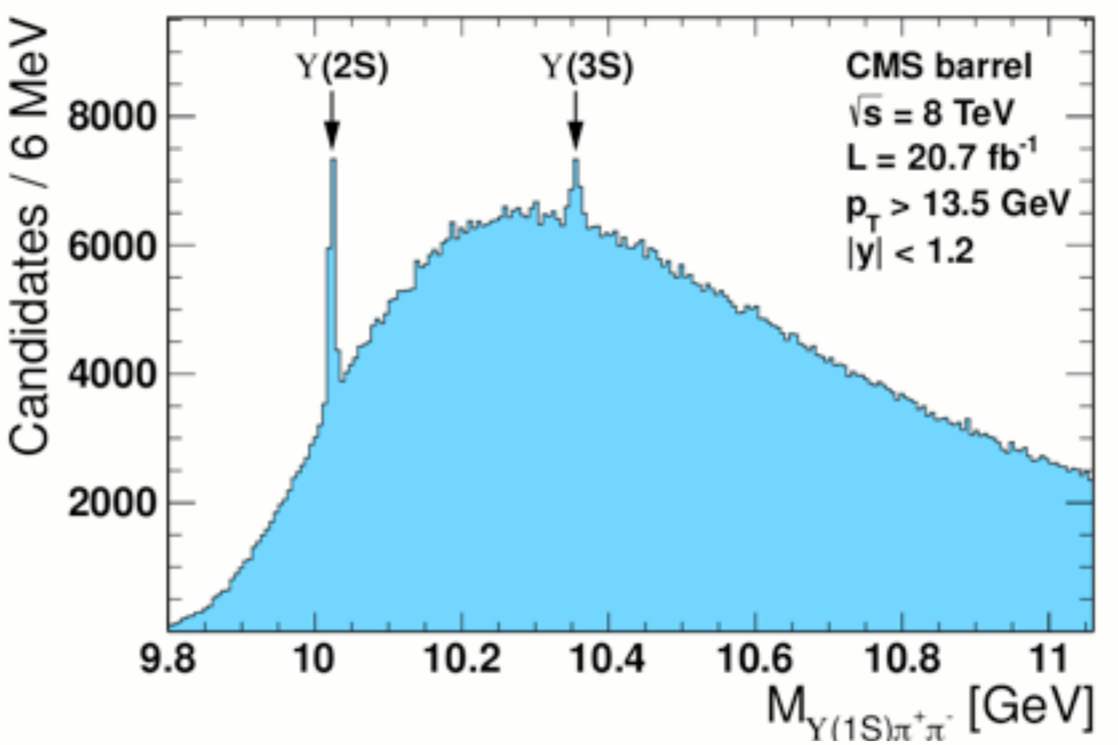


- CMS measures the the production cross section of the exotic quarkonium state $X(3872)$ reconstructed in the $J/\psi\ \pi\pi$ final state.
  - prompt and non-prompt components are separately extracted
- ATLAS performs corresponding measurements for the $\psi(2S)$ state

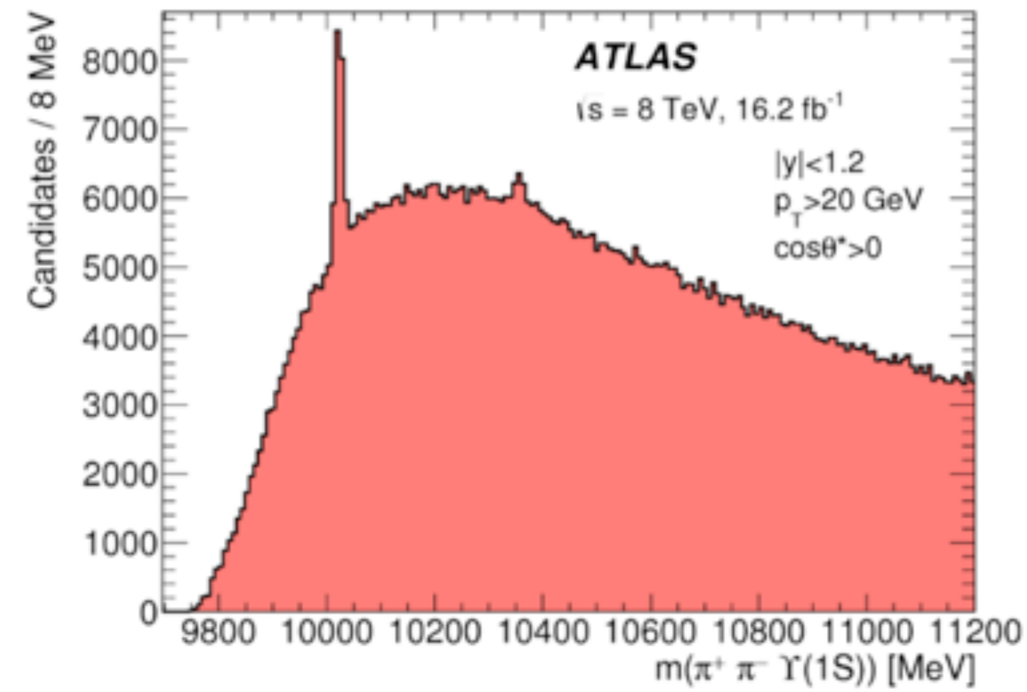
$\Upsilon + \pi^+\pi^-$ $[X_b]$

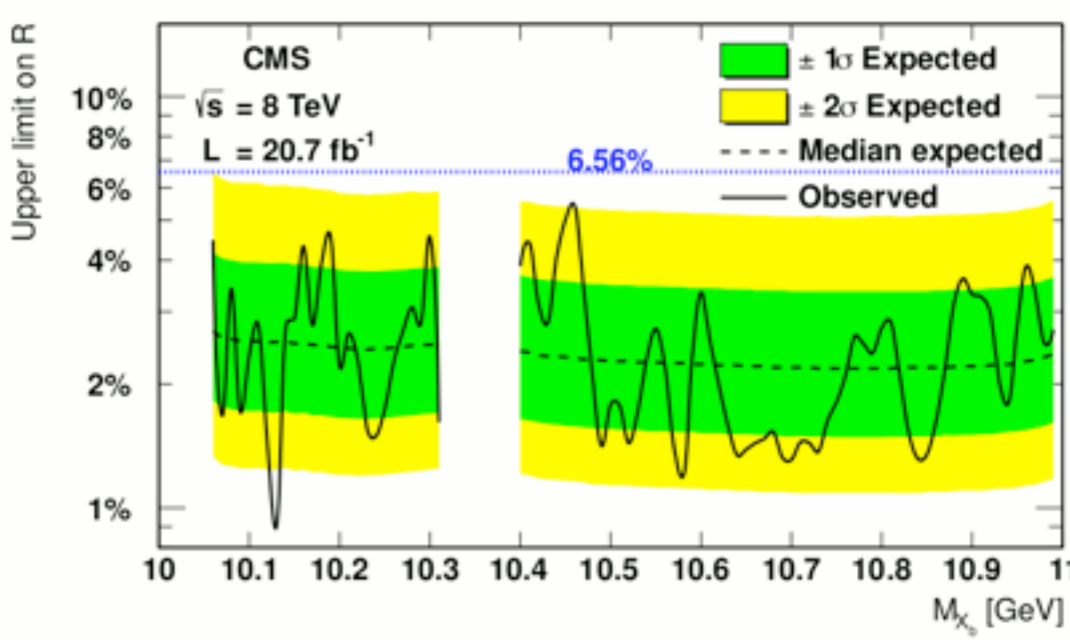
- CMS and ATLAS search for potential new resonances in $\Upsilon\pi\pi$ final state. No excess observed ⇒ exclusion limits.

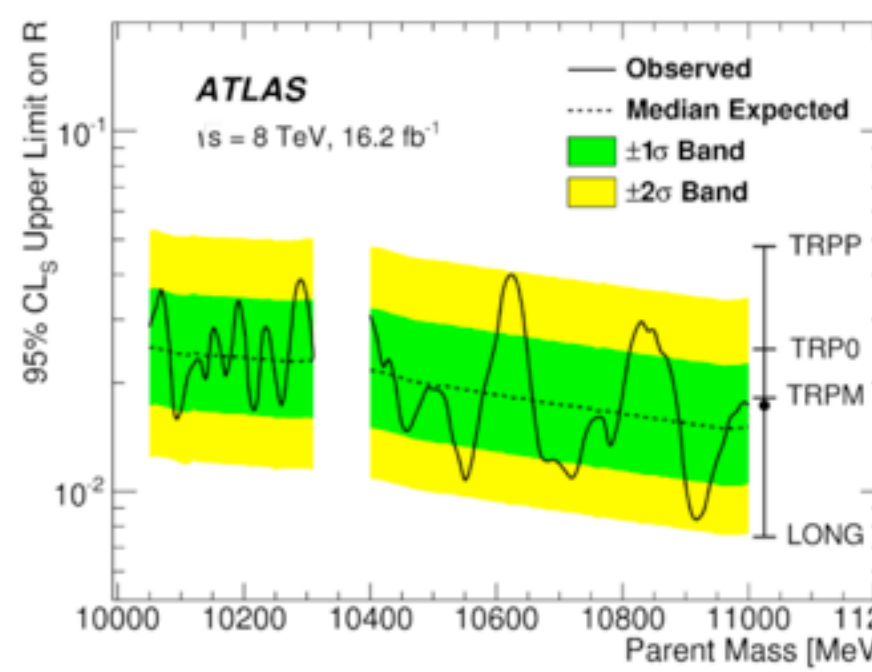
arXiv:1309.0250



arXiv:1410.4409

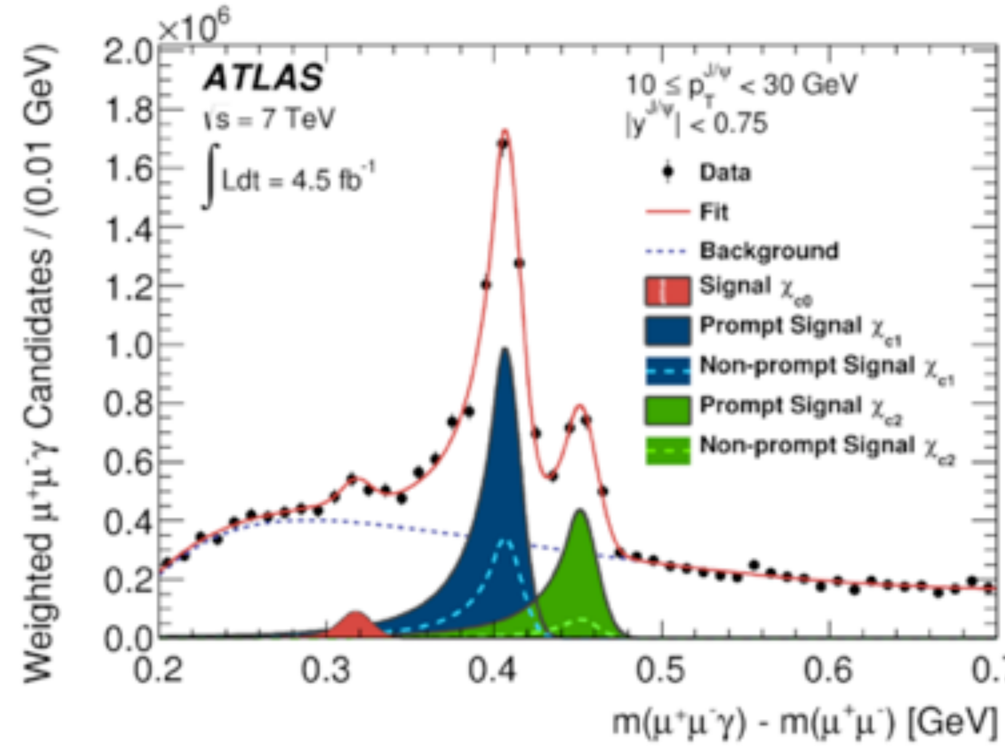




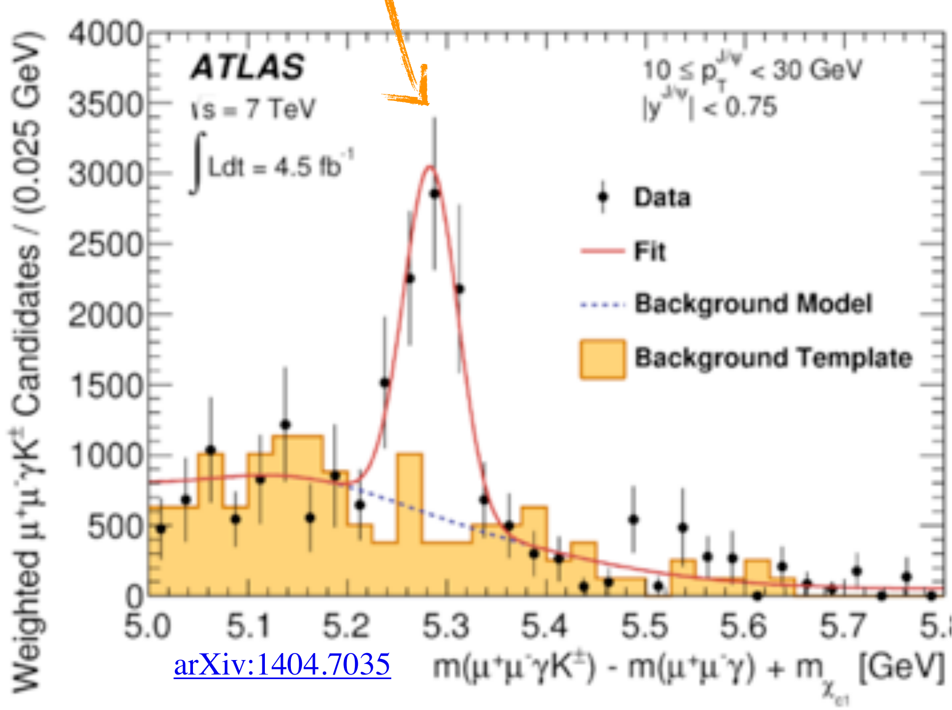


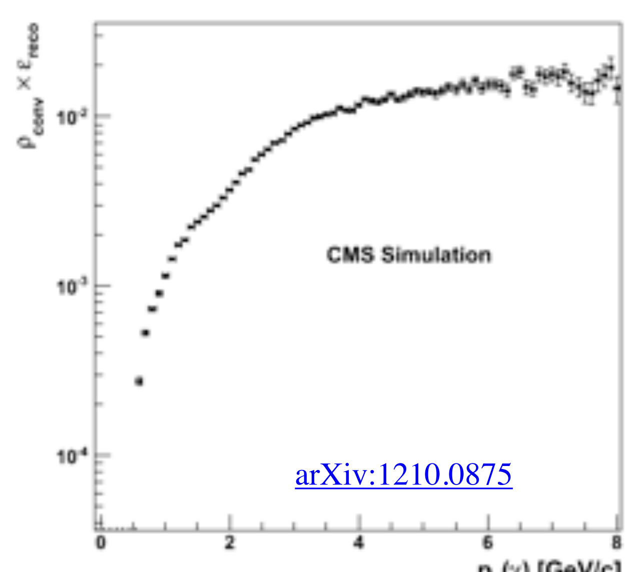
$J/\psi + \gamma(e^+e^-)$ $[\chi_c]$

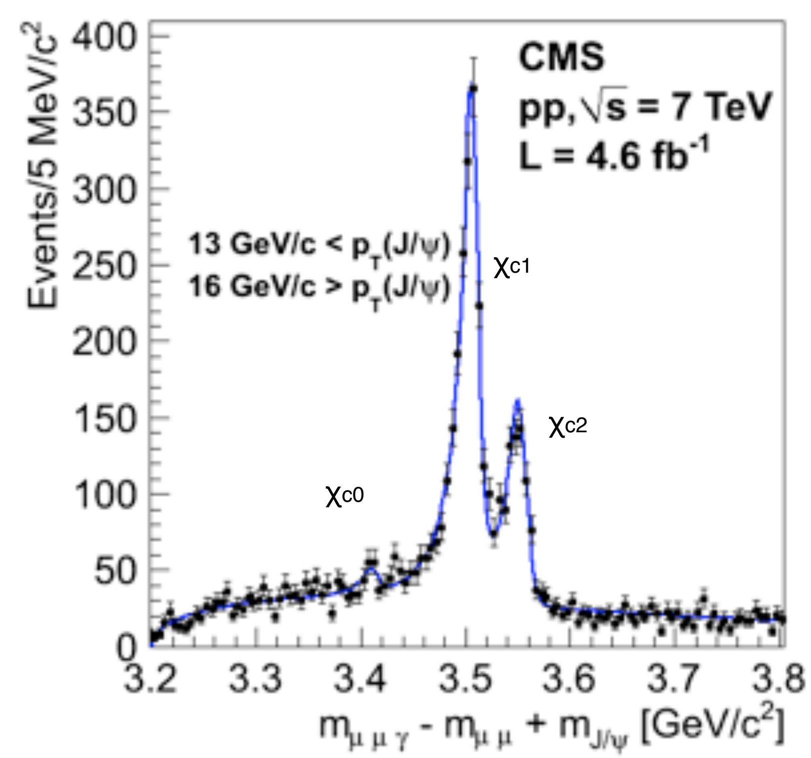
- radiative decays are explored to reconstruct P-wave charmonia in the $\psi+\gamma$ final state
- ATLAS measure the prompt and non-prompt production cross sections of $\chi_{c1}(1P)$ and χ_{c2} $(1P)$
- CMS also measures the relative prompt production of the 2 states
- ATLAS also measures the branching fraction of $B_u \to \chi_{c1} K^+$ relative to $B_u \to J/\psi K^+$



arXiv:1210.0875

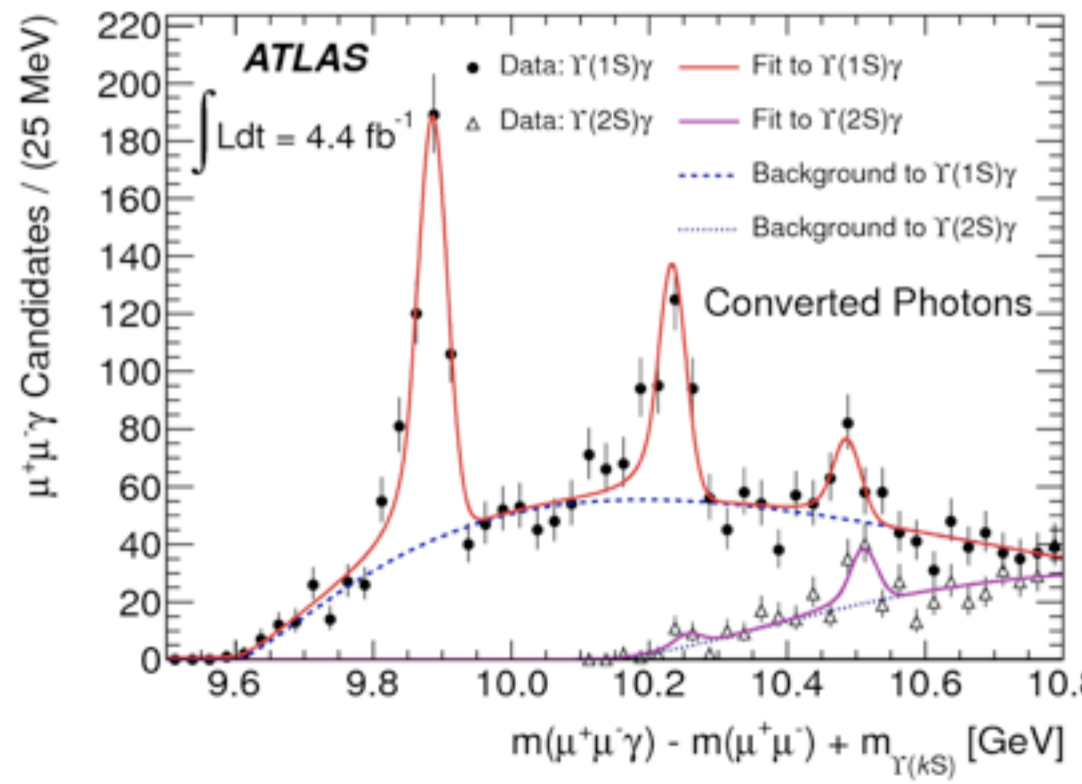




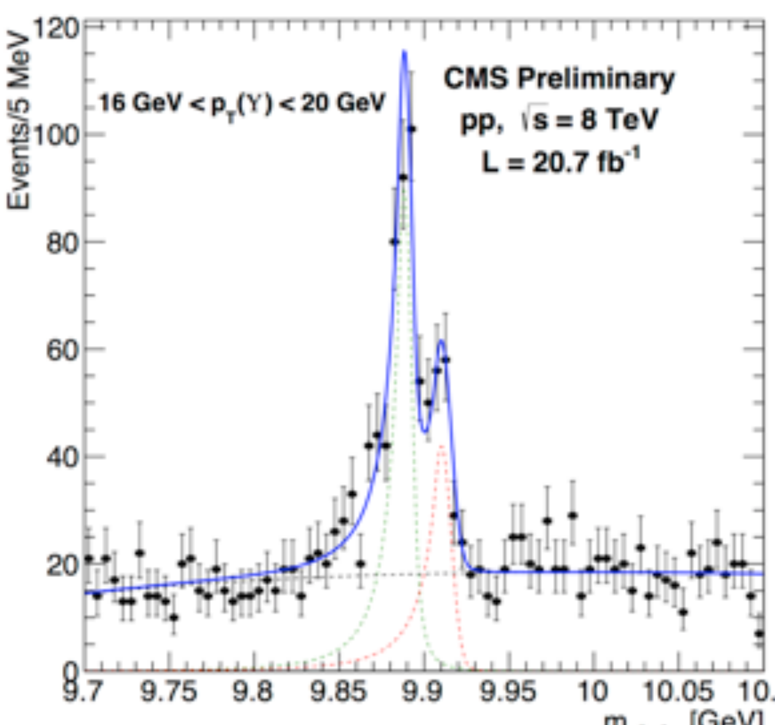


$\Upsilon + \gamma(e^+e^-)$ $[\chi_b(3P)]$

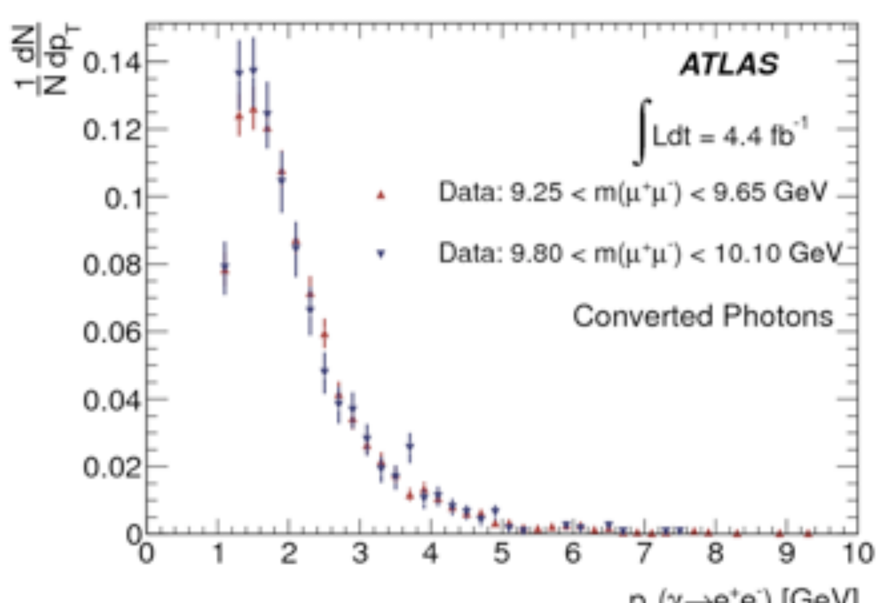
- radiative decays are explored to reconstruct P-wave bottomonia in the $\Upsilon+\gamma$ final state
- ATLAS observes new state: $\chi_b(3P)$
- CMS measures the production cross section of $\chi_{b1}(1P)$ and $\chi_{b2}(1P)$

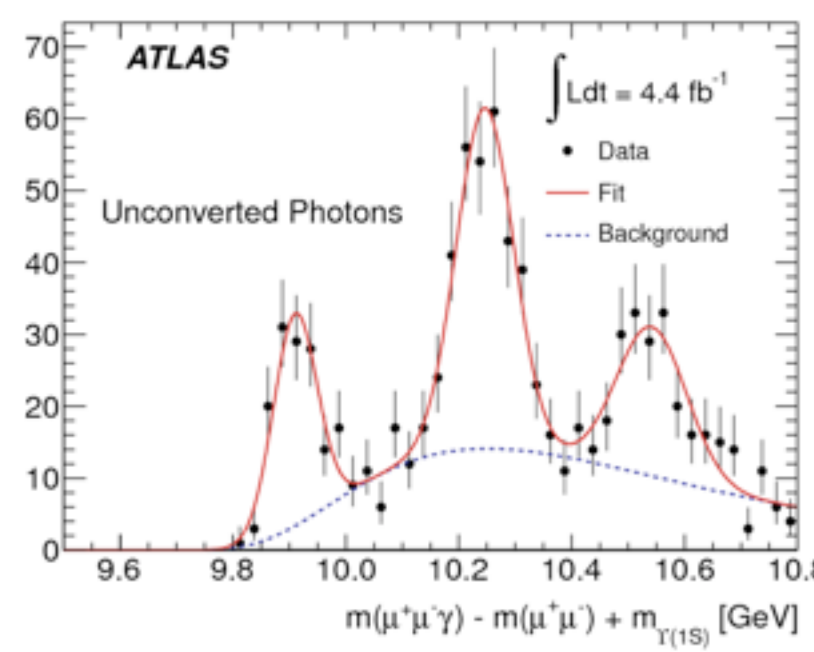


arXiv:1409.5761



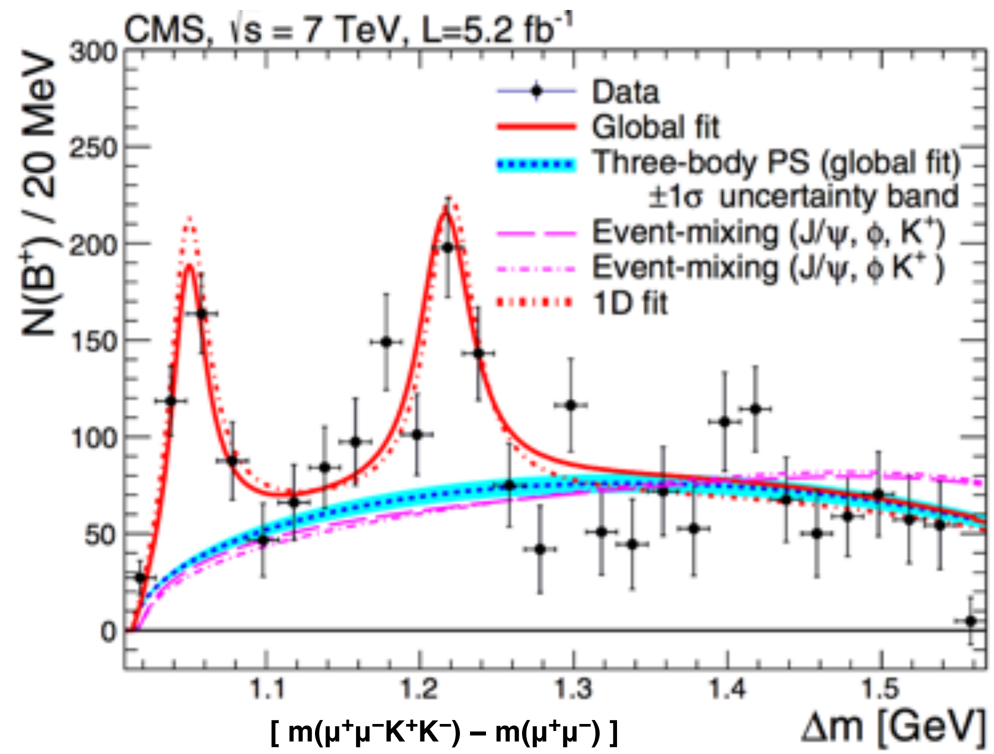
arXiv:1112.5154



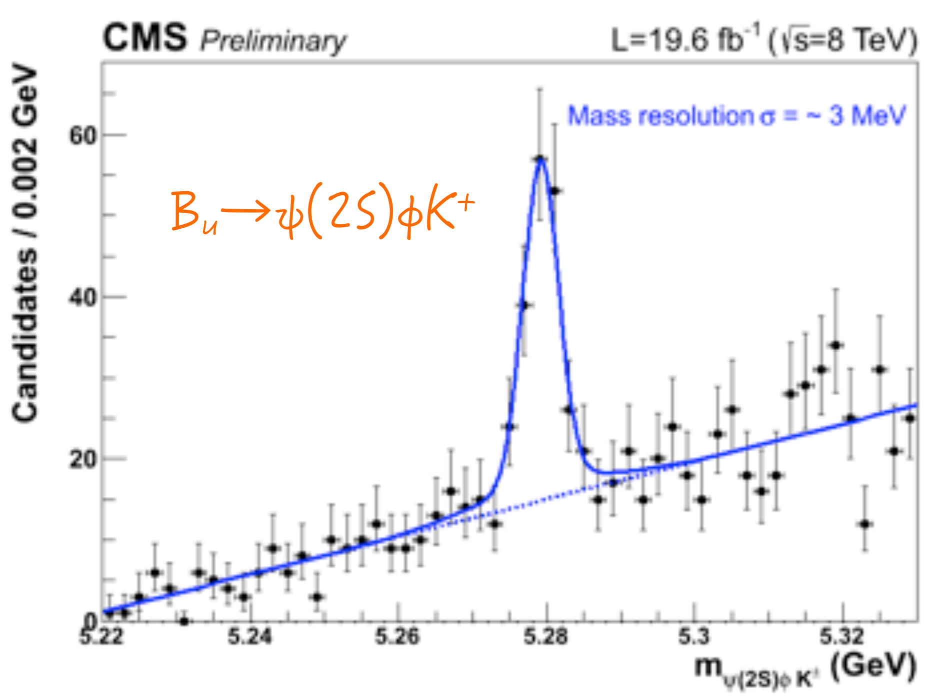


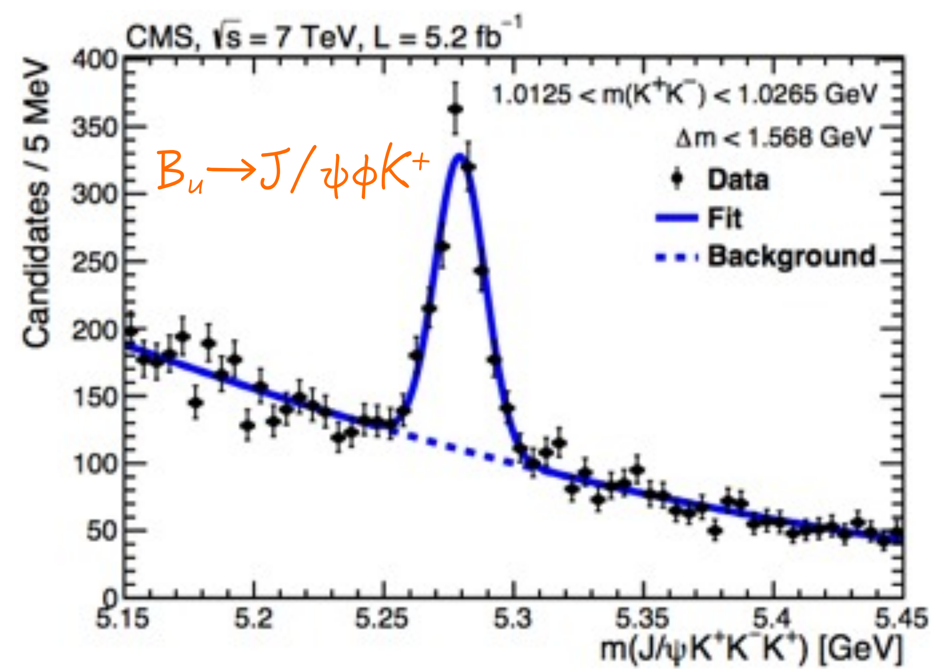
$J/\psi + \phi(K^+K^-)$ $[Y(4140)]$

- Explore the B decay: $B_u \to Y[J/\psi\phi]K$
- CMS observes two new structures in the $J/\psi\phi$ mass spectrum
  - 1st peak: $M_1 = 4148.0 \pm 2.4 \pm 6.3$ MeV, $\Gamma_1 = 28 \pm 15 \pm 19$ MeV
  - 2nd peak: $M_2 = 4313.8 \pm 5.3 \pm 7.3$ MeV, $\Gamma_2 = 38 \pm 30 \pm 16$ MeV
- Nature of these structures still under investigation



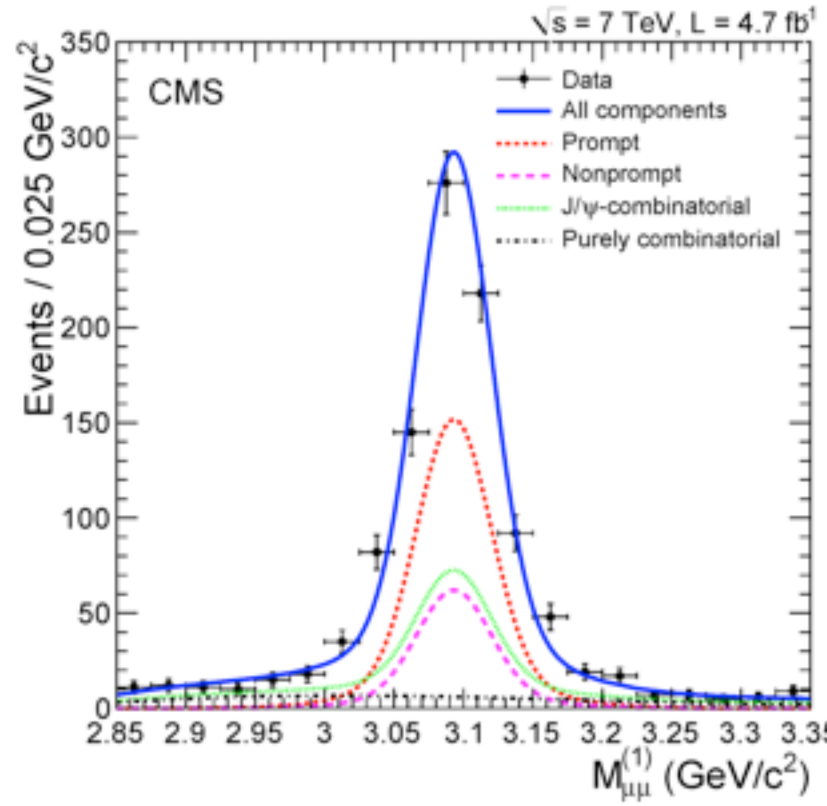
- CMS observes new decay mode $B_u \to \psi(2S)\phi K^+$



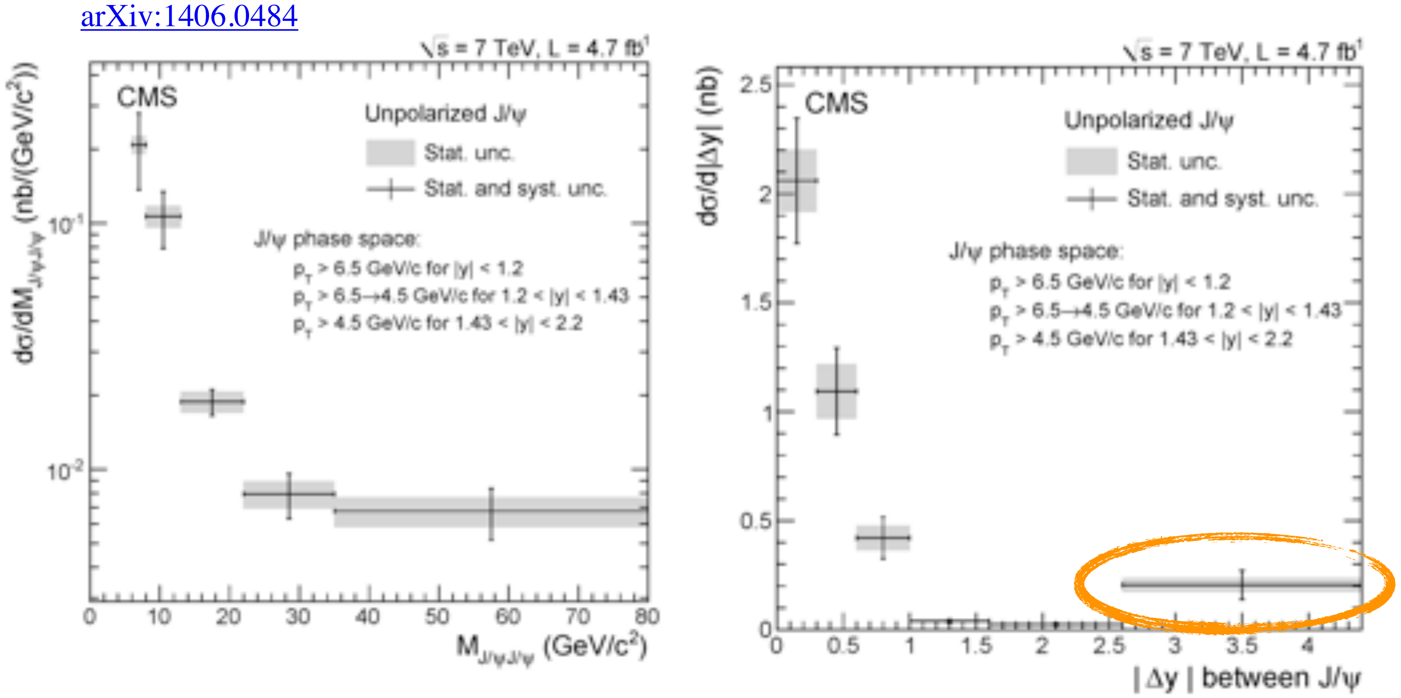


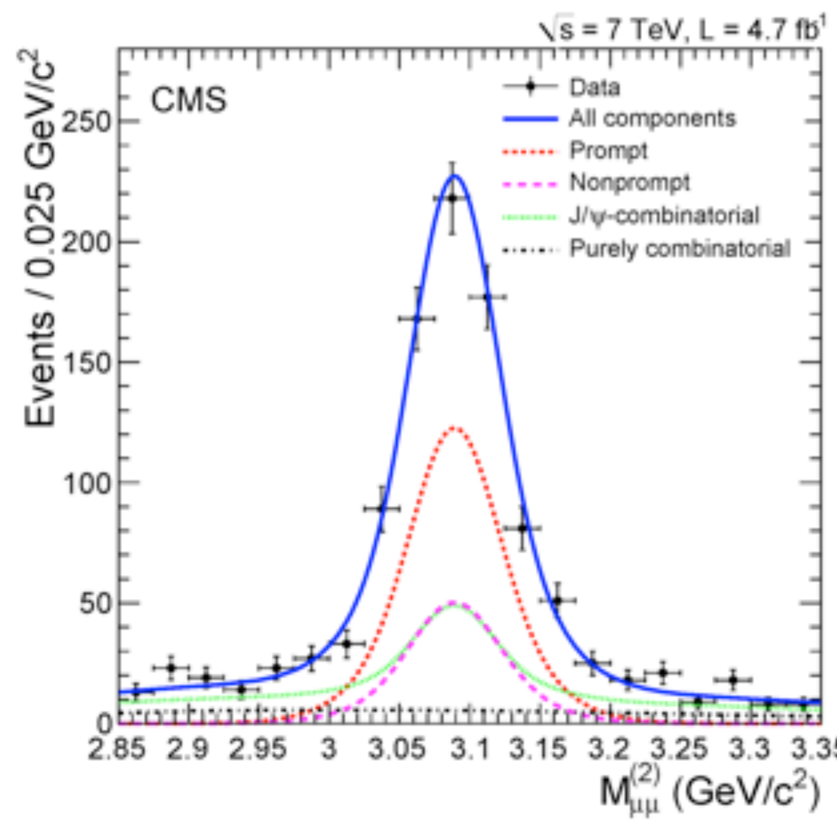
$J/\psi + J/\psi$

- CMS measures prompt J/ψ pair production
- multi-parton scattering ⇒ difficult to address in QCD ⇒ experimental input essential
- total and differential cross section measured
  - $\sigma = 1.49 \pm 0.07_{stat.} \pm 0.014_{syst.}$ nb
- evidence of excess at $|\Delta y|>2.6$ predicted to have a large Double Parton Scattering contribution



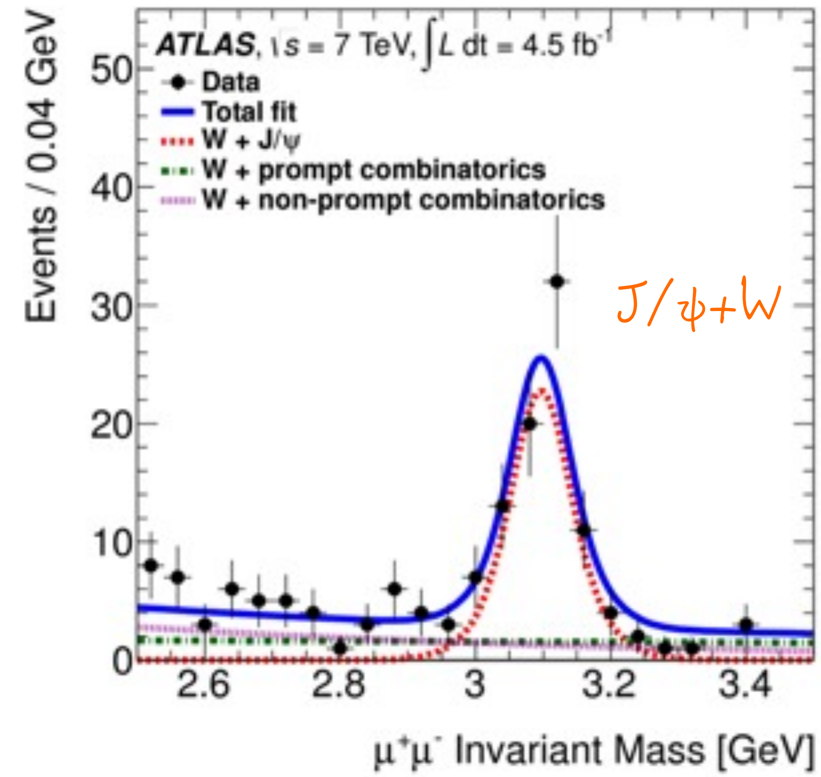
arXiv:1406.0484



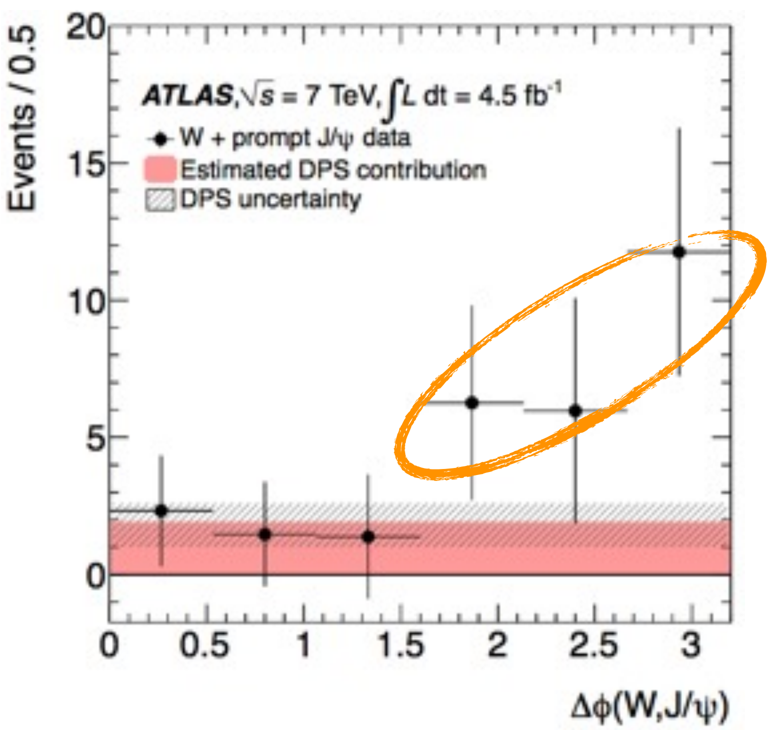


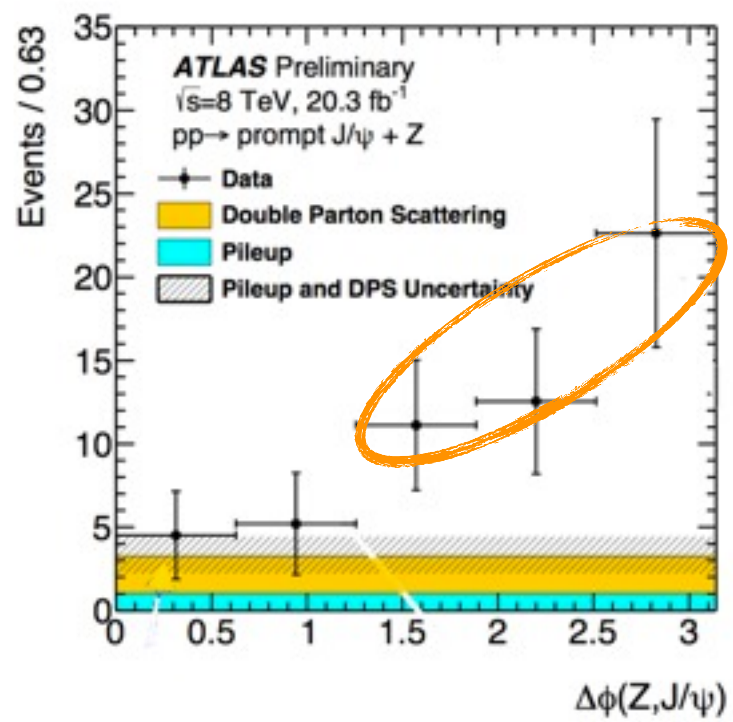
J/ψ + W/Z

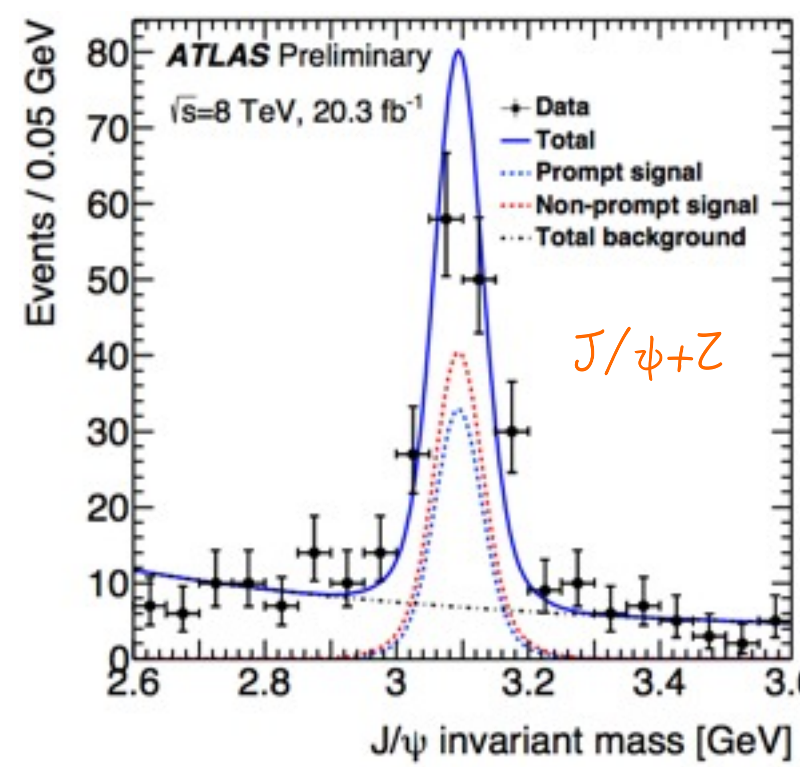
- measure J/ψ + V associated production
  - single- and double-parton scattering contribute
  - relative color singlet/octet contributions may differ from inclusive production
  - possibility of resonant production from Higgs or NP



- ATLAS observes J/ψ+W and J/ψ+Z (significance >5σ)







- similar pattern seen in the azimuthal opening angle indicating DPS (+SPS) J/ψ + V production
  (flat azimuthal distribution o.w. expected from uncorrelated processes)

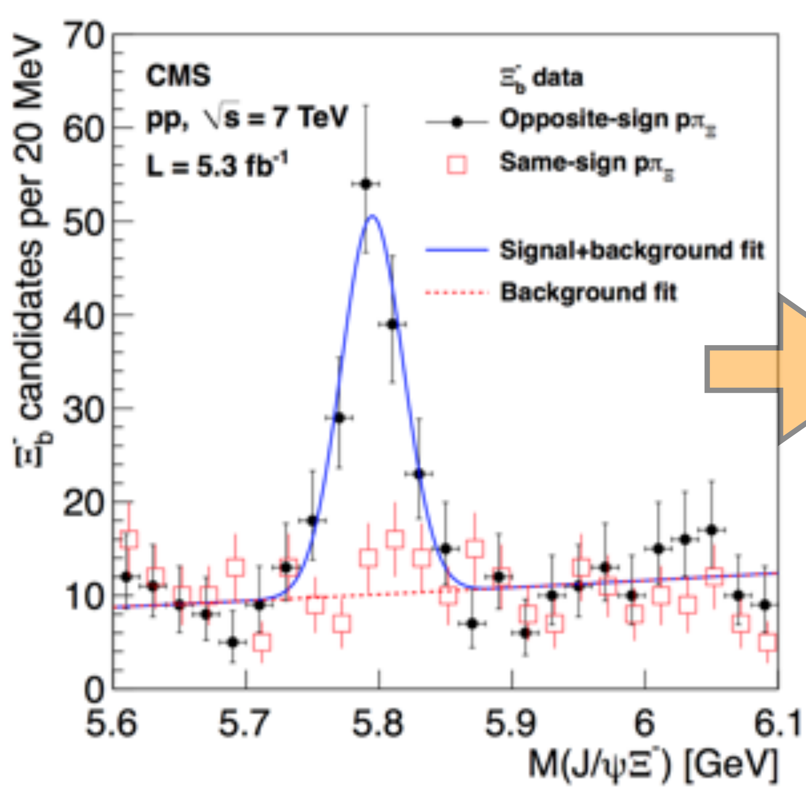
$J/\psi + \Xi$ $[\Xi_b^{0*}]$

$\Xi_b^{*0} \to \Xi_b^- \pi^+$
$\to \Xi_c^- J/\psi\ \pi^+$
$\to \Lambda^0\ \pi^-\ J/\psi\ \pi^+$
$\to \mu^+\mu^- p^+ \pi^- \pi^- \pi^+$

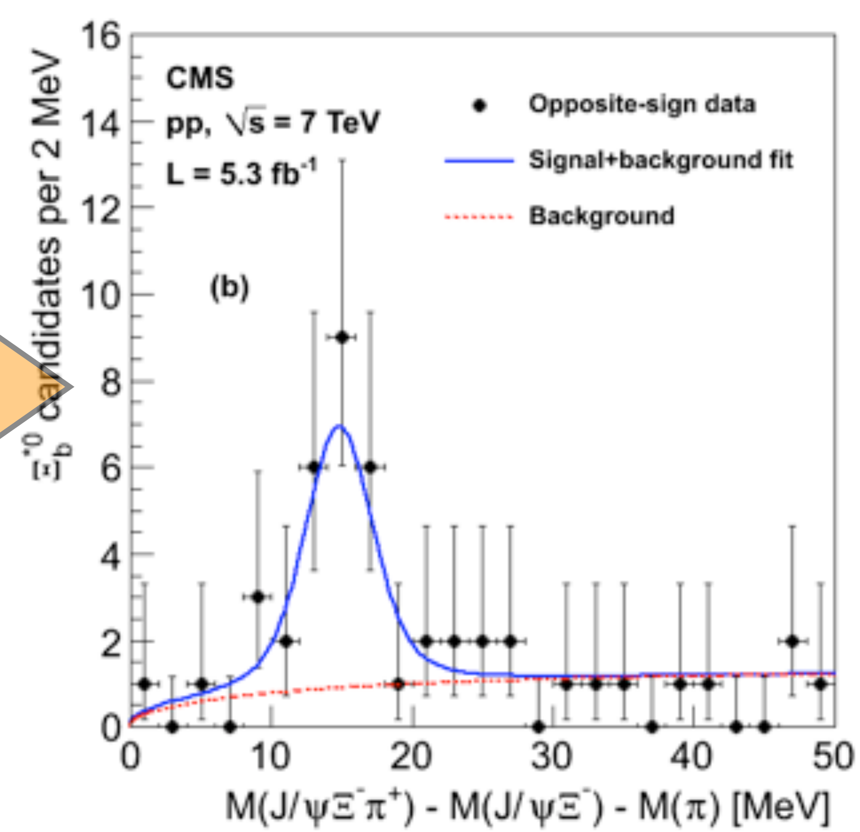
- exploring more complex, multi-vertex, multi-resonance topologies
- CMS observes new baryon state: Ξ_b^{0*}
  - *neutral* excited Ξ_b state

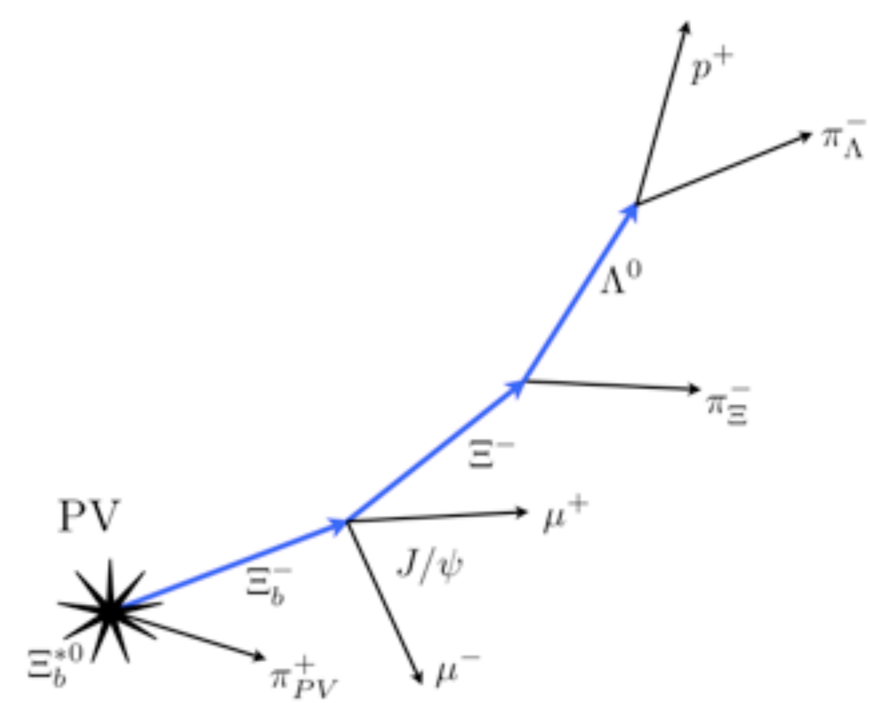
complex cascade decay topology
- 4 displaced vertices
- 6 final state tracks

Ξ_b^-



Ξ_b^{0*}





arXiv:1204.5955

$\Xi + \pi\pi$

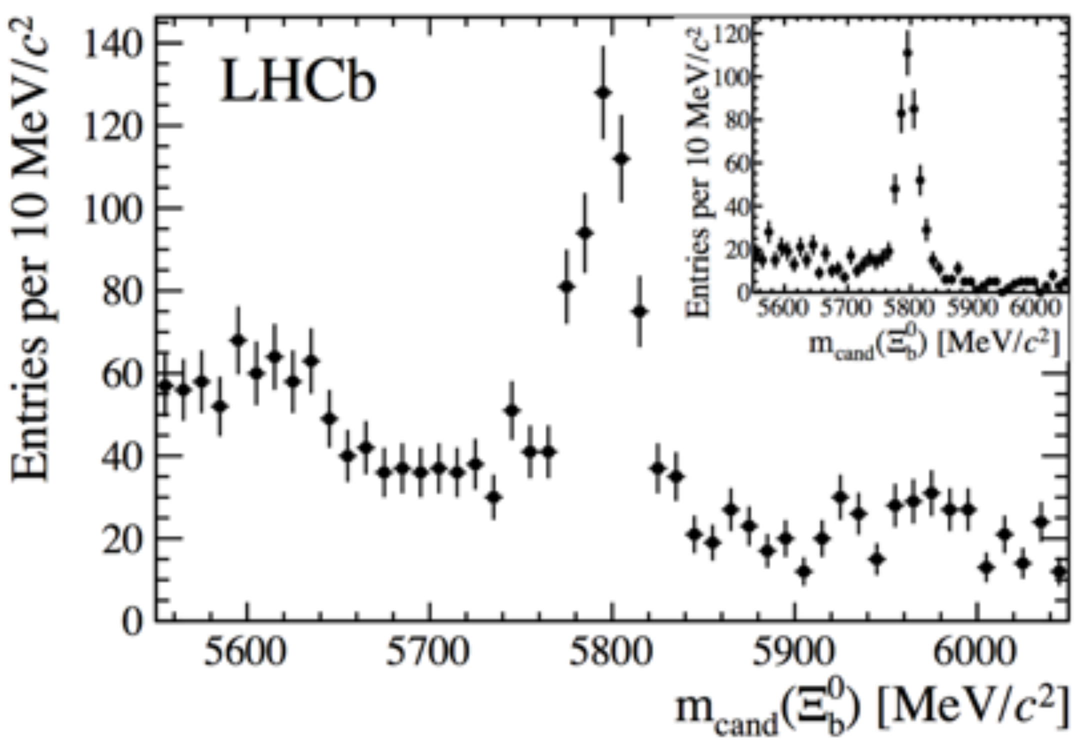
$[\Xi_b^{-*}]$

- exploring complex topologies
  - *without* final state di-muon resonance
- LHCb observes new baryon states: $\Xi_b'^-$, Ξ_b^{-*}
  - two new *charged* additions to the Ξ_b family

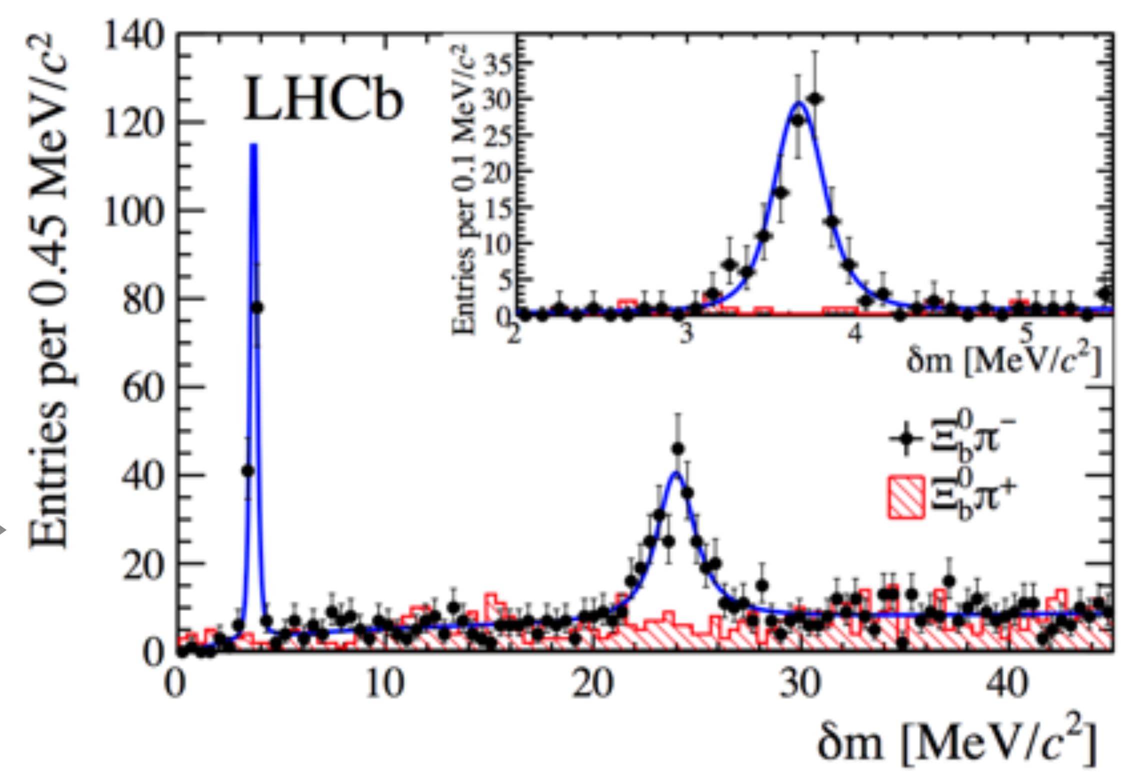
$$\Xi_b^{*-} \to \Xi_b^0 \pi^-$$
$$\to \Xi_c^+ \pi^- \pi^-$$
$$\to p K^- \pi^+ \pi^- \pi^-$$

complex cascade decay topology
- 3 displaced vertices
- 5 final state tracks

Ξ_b^0



Ξ_b^{-*}



arXiv:1411.4849

CP violation

b-hadron lifetimes [Λ_b]

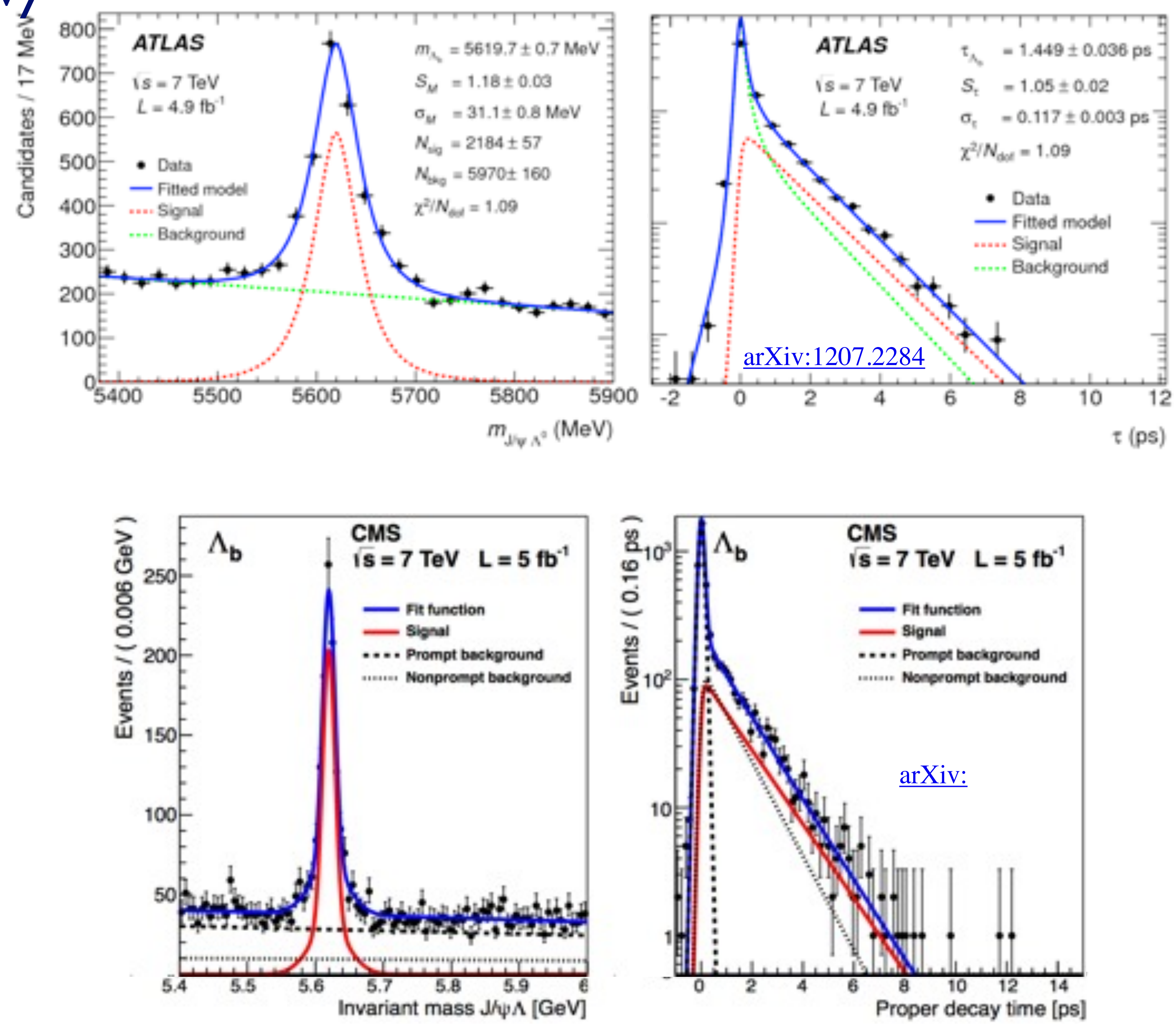
$\Lambda_b \to J/\psi(\mu\mu)\Lambda^0(p\pi)$

- accurate description of the proper decay time dimension crucial for heavy flavor measurements
  - used to separate prompt from non-prompt production
  - a required ingredient for study of time-dependent CP asymmetries
- Λ_b lifetime has large experimental uncertainty
  - both experiments provide lifetime measurements for this baryon

ATLAS
τ = 1.449 ± 0.036 ± 0.017 ps
m = 5619.7 ± 0.7 ± 1.1 MeV

CMS
τ = 1.503 0.052 ± 0.031 ps

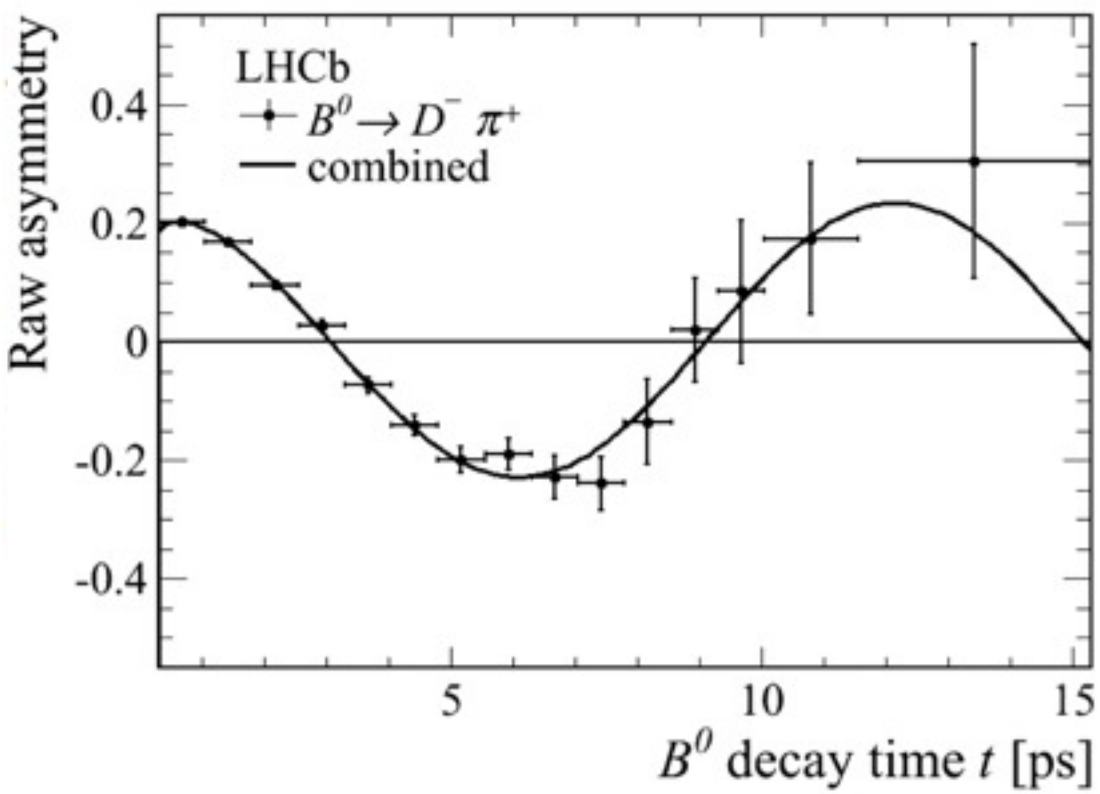
(PDG: τ = 1.451±0.013 ps)

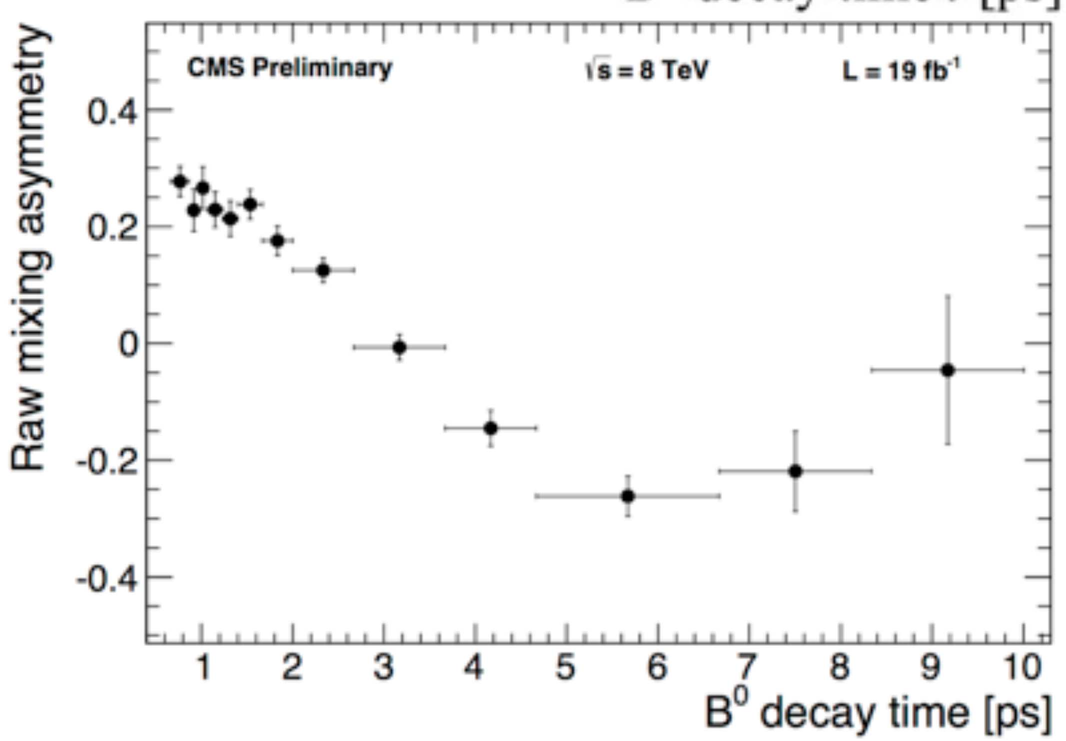


- effective lifetime measurements for other b-hadron states and decays also being pursued

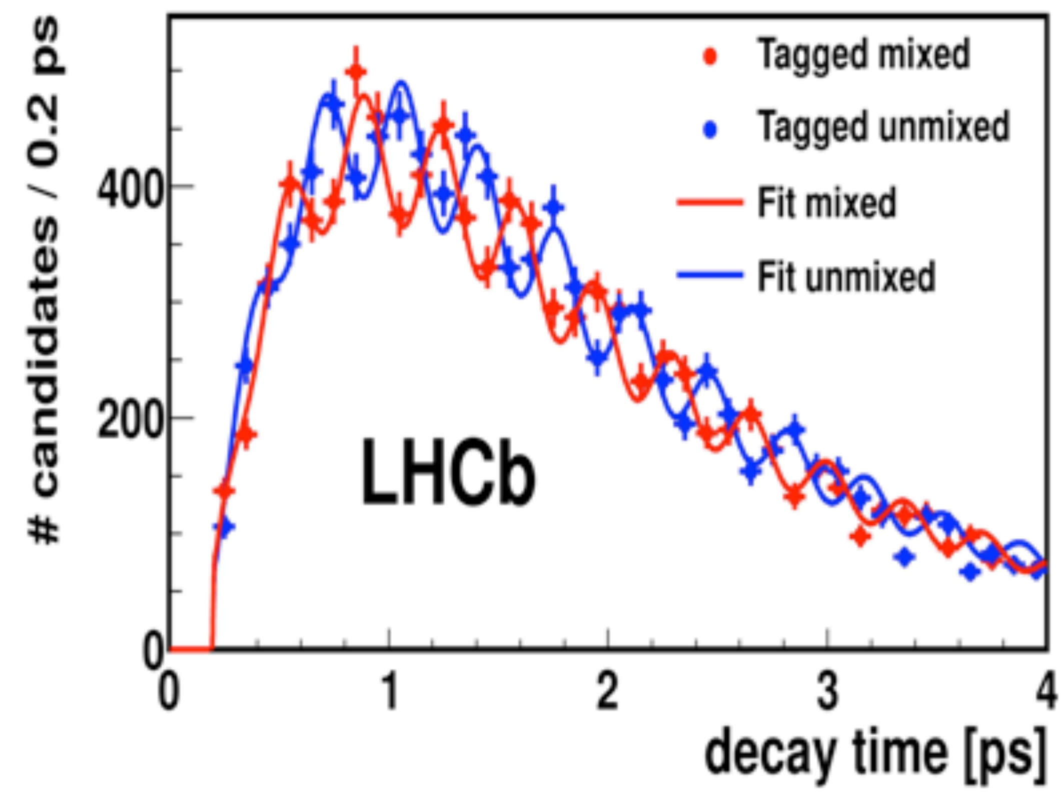
B-$\overline{B}$ mixing

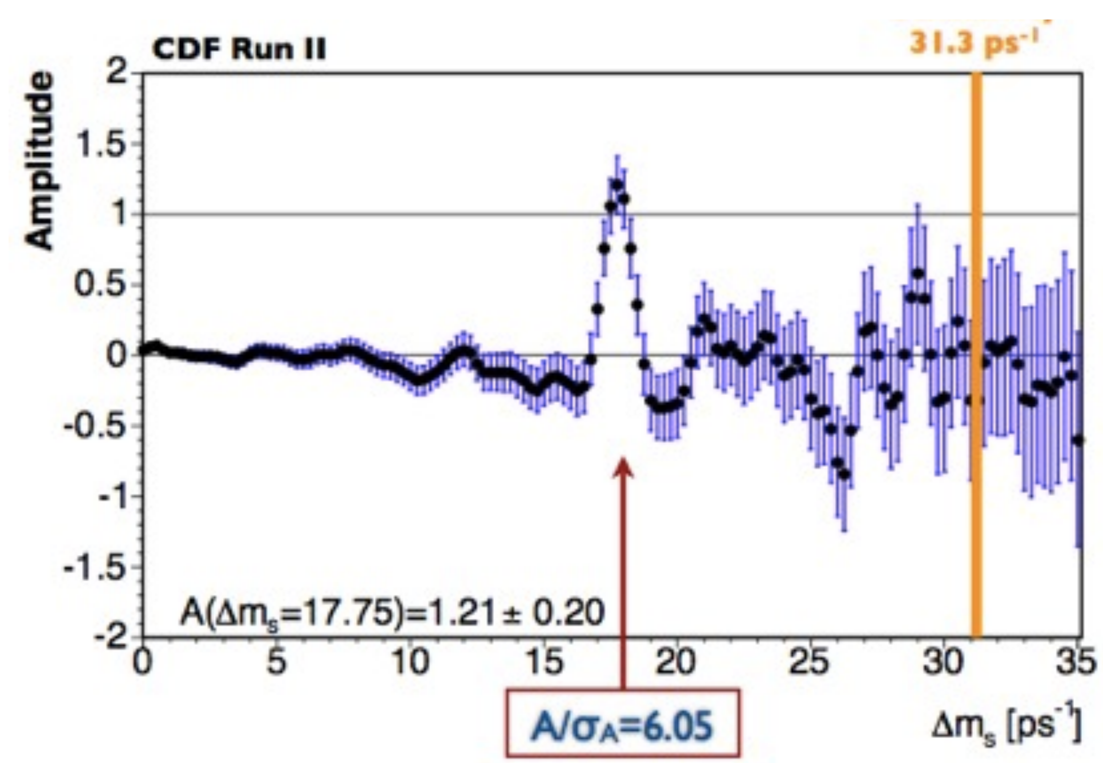
B_d





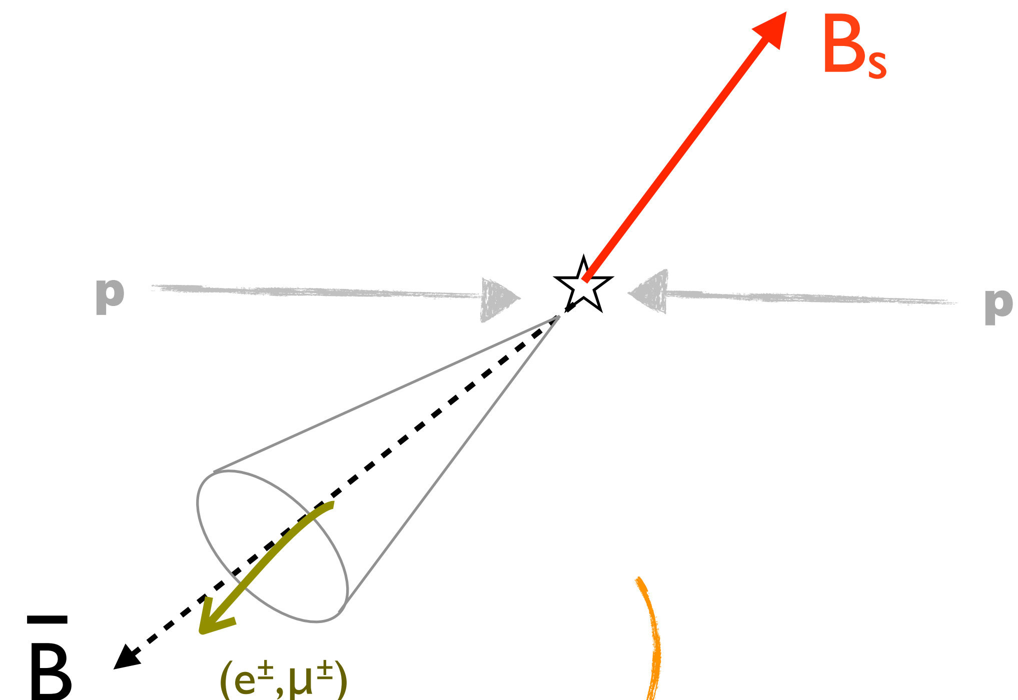
B_s





Flavor tagging

- identification of the B vs $\underline{\mathrm{B}}$ flavor at production
  - a required ingredient to study CP asymmetries
- all experiments have developed opposite-side tagging methods (OST), based on lepton and jet charges
- tagging power (quantifying the method's efficiency and purity)
  - ATLAS: εD^2=1.45 ± 0.05 % (muon+electron+jet)
  - CMS: εD^2= 0.97 ± 0.03 % (muon+electron)
  - LHCb: εD^2= 1.19 ± 0.06 % (muon+electron+jet+kaon)
- same-side tagging (SST) has been explored in addition at LHCb
  - LHCb: εD^2= 0.84 ± 0.11% (kaon)



$$\left(\begin{array}{c}\text{mixing}\\ \text{significance}\end{array}\right)^2 \sim \frac{\epsilon \mathcal{D}^2 S}{2}\cdot\frac{S}{S+B}\cdot e^{-\sigma_t^2 w^2}$$

CP violation

- time-dependent asymmetry

direct CPV

CPV in decay-mixing interference

$$\mathcal{A}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f\cos(\Delta m_{d(s)}t) + S_f\sin(\Delta m_{d(s)}t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2}t\right) - A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_{d(s)}}{2}t\right)}$$

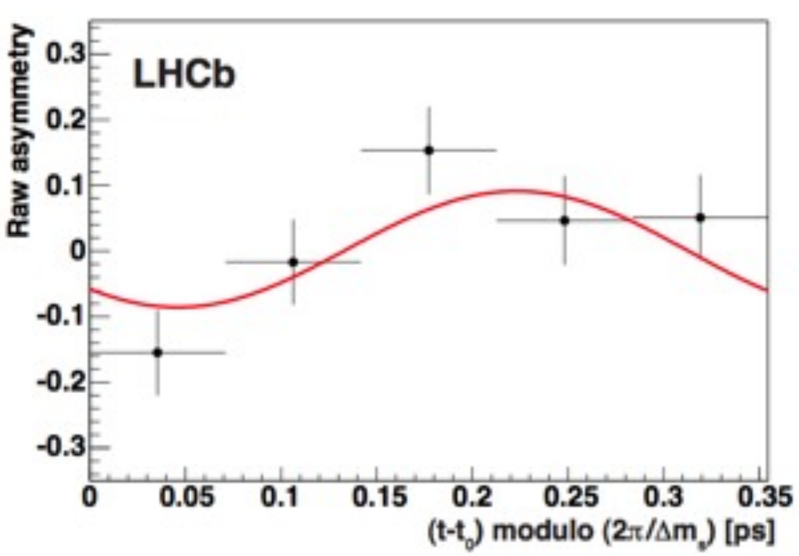
A_{CP}

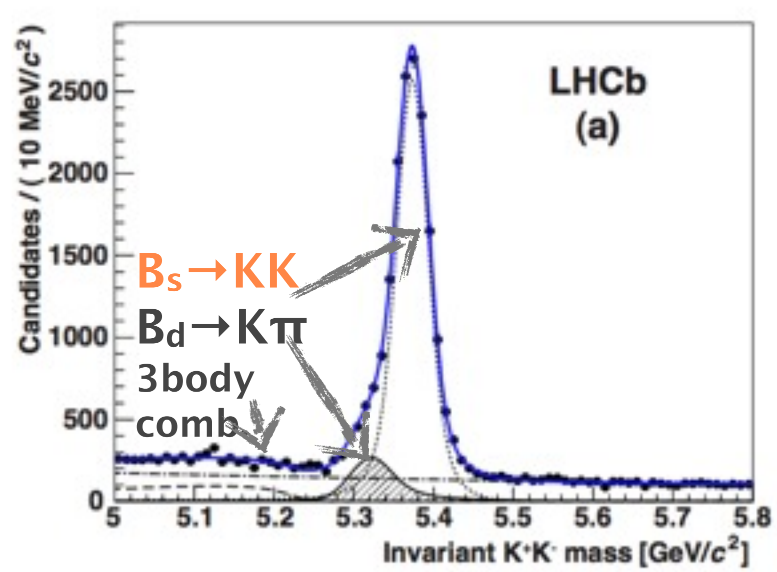
- LHCb explores hadronic B decays
  - B→ππ, Kπ,KK
- first observation of CPV in B_s system

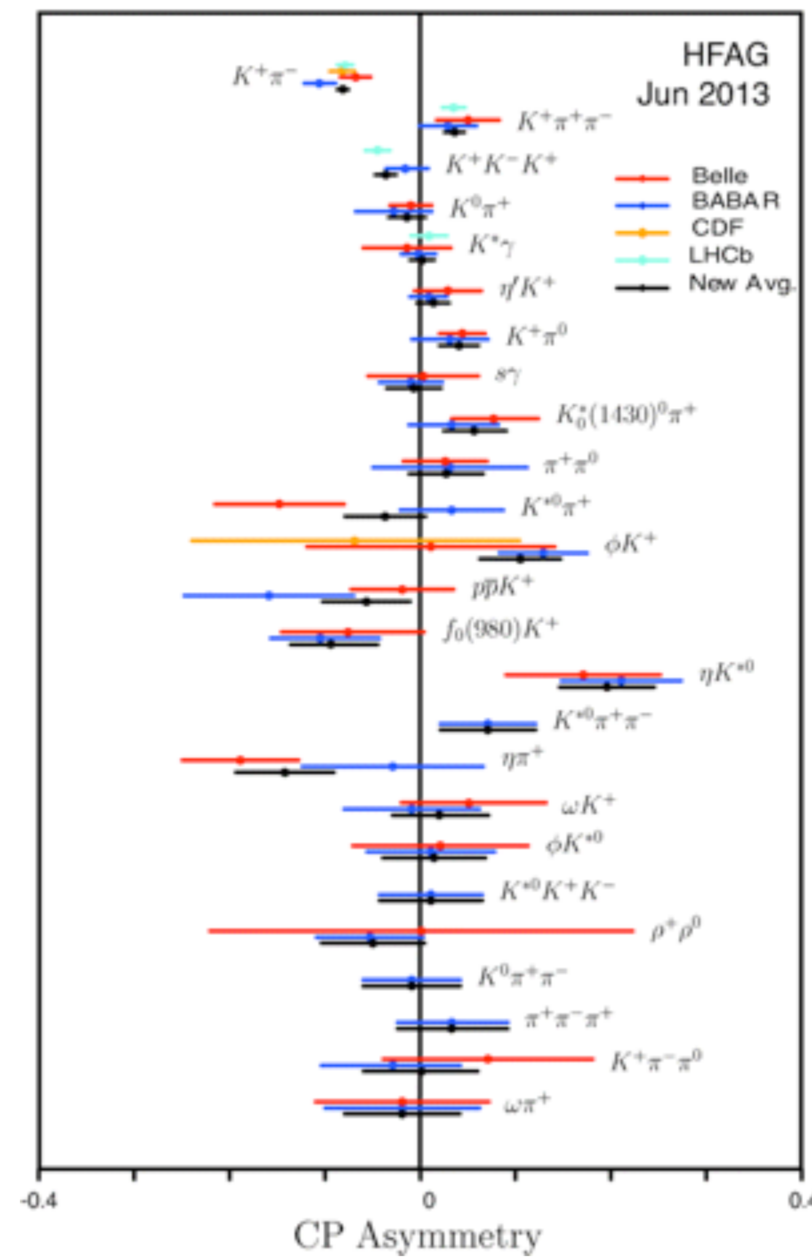
arXiv:1304.6173

- first time-dependent CPV measurement in B_s→KK decays

arXiv:1308.1428



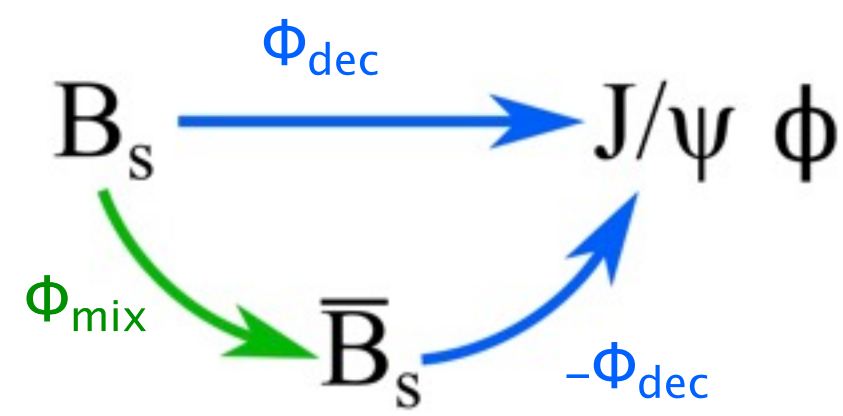




$B_s \rightarrow J/\psi\Phi$

- B_s mesons undergo fast particle-antiparticle flavor oscillations (Δm_s), with non-negligible width difference ($\Delta\Gamma_s$)
- flavor-unspecific final states (such as $J/\psi\Phi$) are accessible by both B_s and $\underline{B}_s$:
- weak phase Φ_s arises from the quantum interference between direct and mixing-mediated decays
- the 'golden' channel $B_s \rightarrow J/\psi\Phi$
  - provides an experimentally clean final state ($\mu\mu KK$)
  - 2 vector mesons final state ⇒ mixture of CP-even and CP-odd states
- precise SM predictions for Φ_s (4% uncertainty)

CP violation in the interference of decay and mixing



$$\Phi_s = \Phi_{mix} - 2\,\Phi_{dec}$$

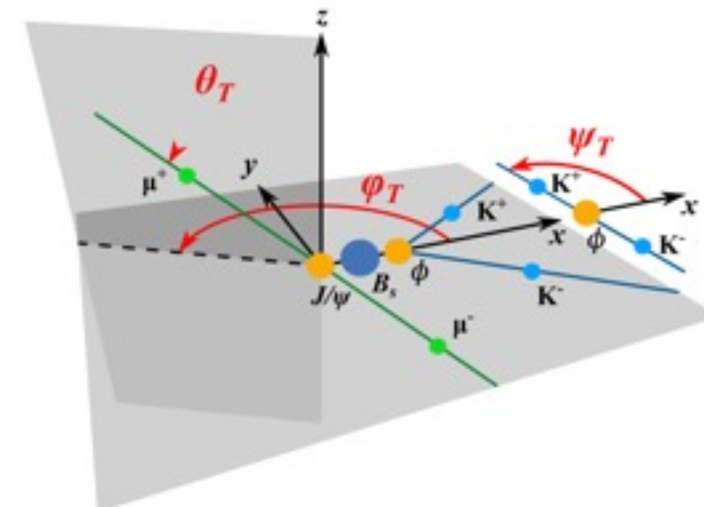
$\phi_{SM} \sim -0.04$

NP can add large phases

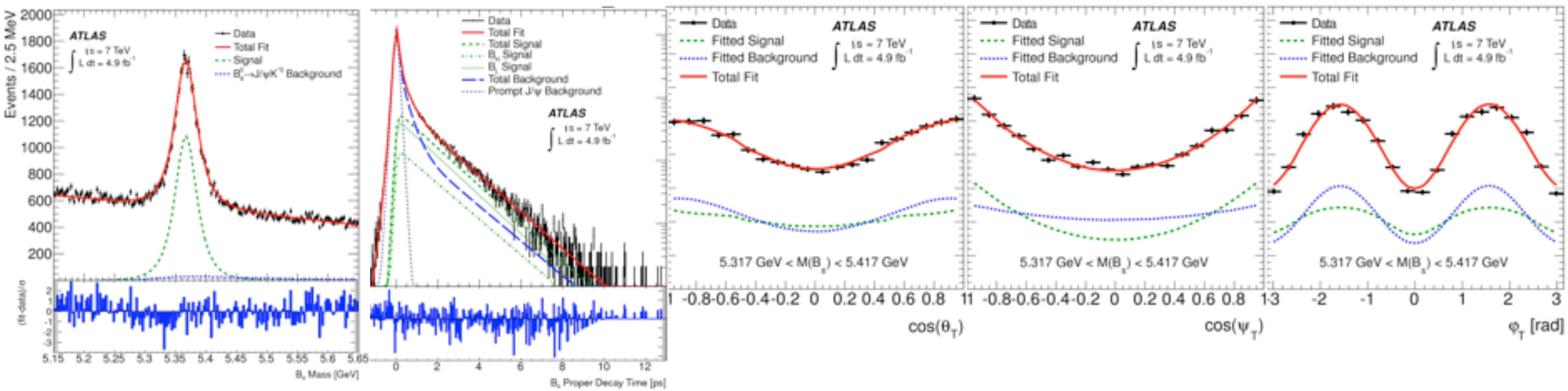
$$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$

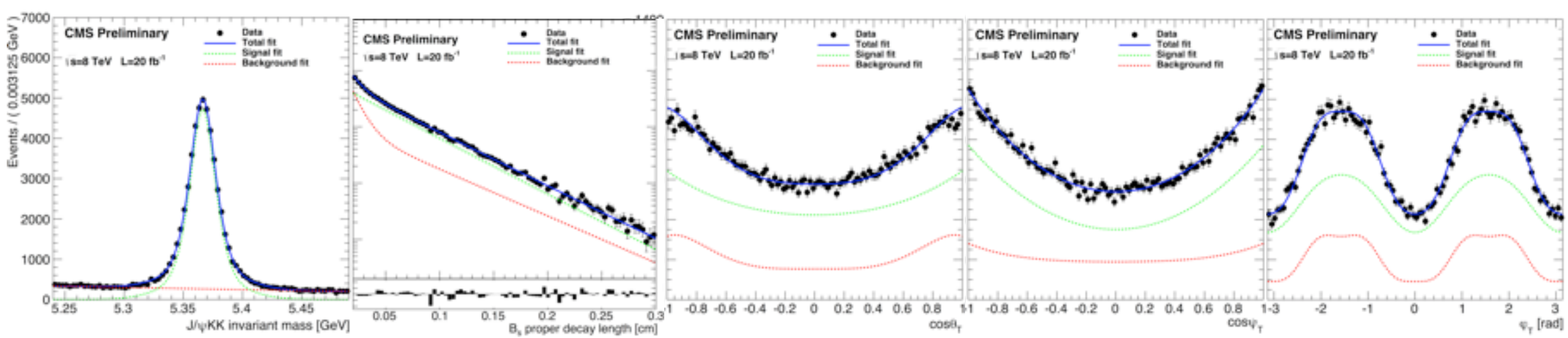
- several new physics scenarios predict enhanced values for Φ_s relative to SM prediction

$B_s \to J/\psi\phi$

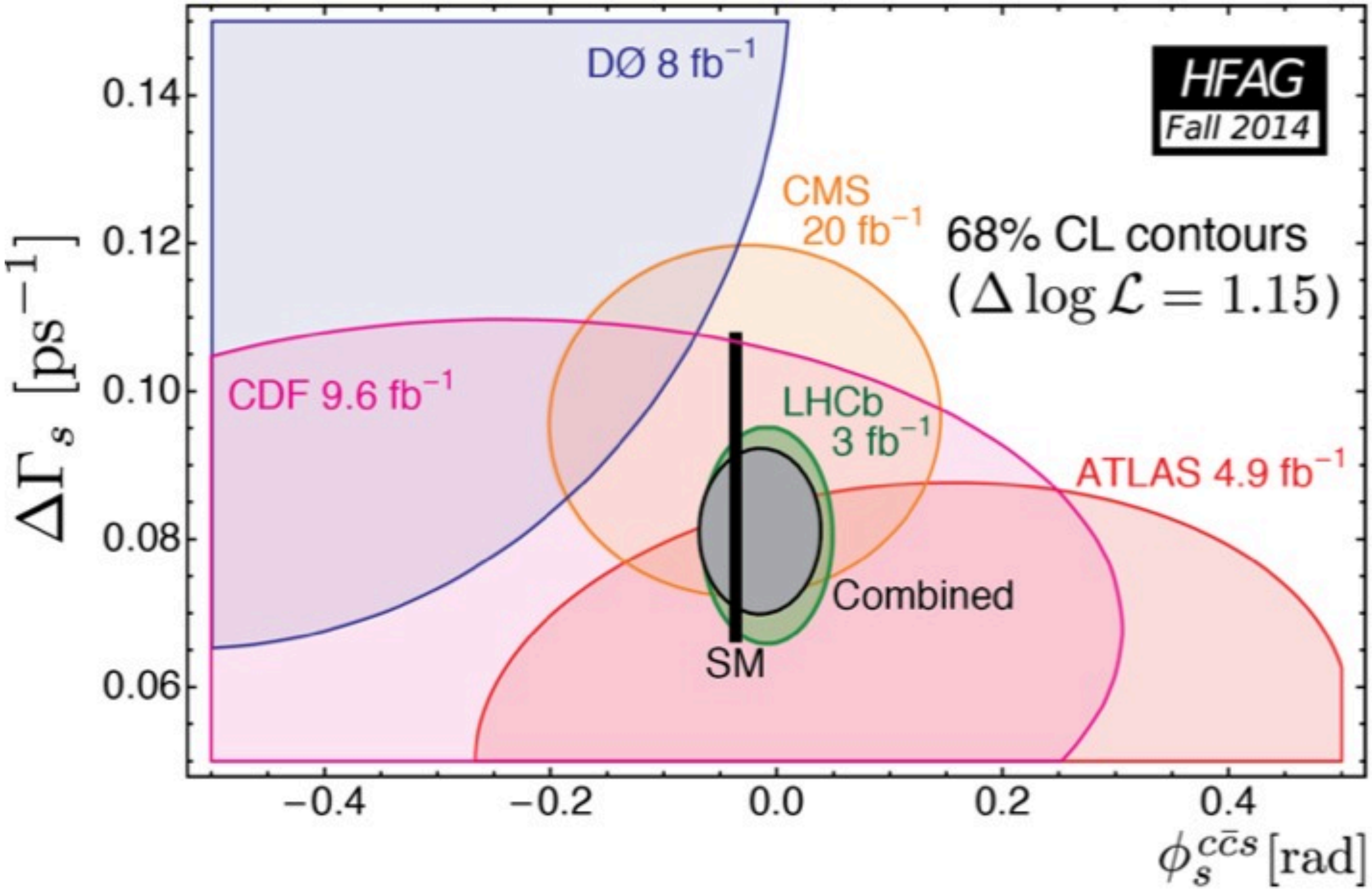


- analysis ingredients:
  - mass and proper decay time
  - flavor tagging
  - angular analysis





ϕ_s [world summary]

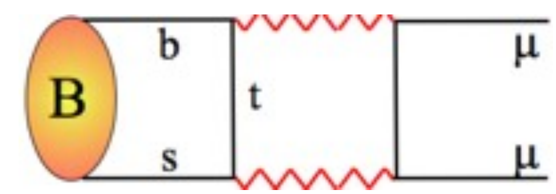


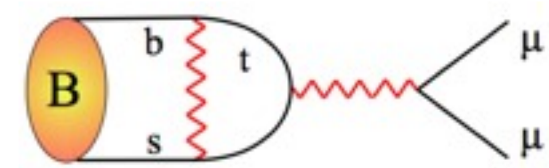
Experiment	$\Delta\Gamma_s$ (ps^{-1})	ϕ_s (rad)
ATLAS (4.9/fb)	0.053±0.021±0.010	0.12±0.25±0.05
CMS (20/fb)	0.096±0.014±0.007	−0.03±0.11±0.03
LHCb (3/fb)	0.0805±0.0091±0.0032	−0.058±0.049±0.006

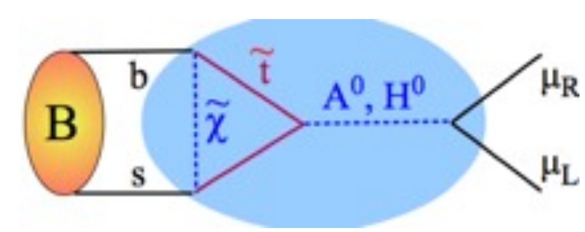
rare decays

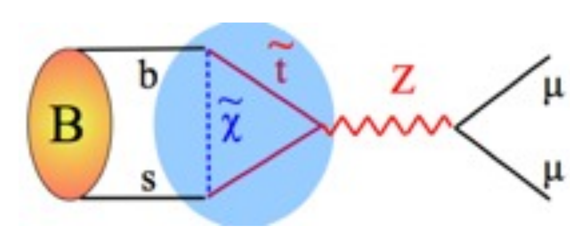
rare beauty decays

- processes highly suppressed and precisely predicted in the SM
- complementary to direct searches for new physics
  - access multi-TeV scales through loop contributions
- $B_d \to K^* \mu\mu$
  - effective FCNC process
  - allow measurements of many sensitive kinematic variables and asymmetries
- $B_{s,d} \to \mu\mu$
  - both decays are very suppressed in SM: effective FCNC, helicity suppression
  - branching fractions may be sizably enhanced by NP scenarios: extended Higgs sectors and high-tanβ SUSY



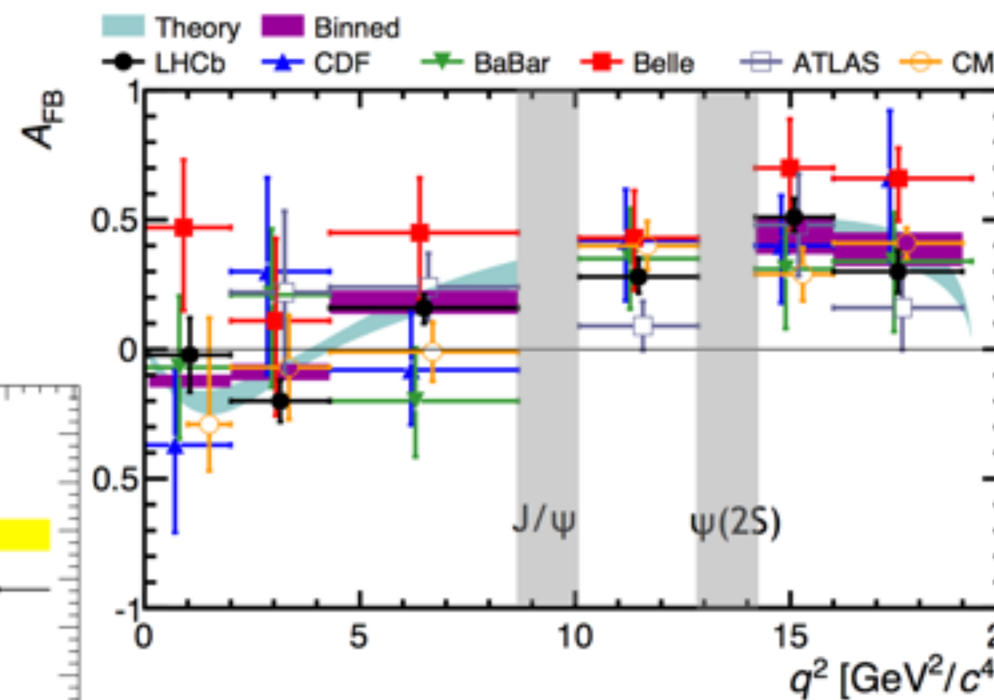


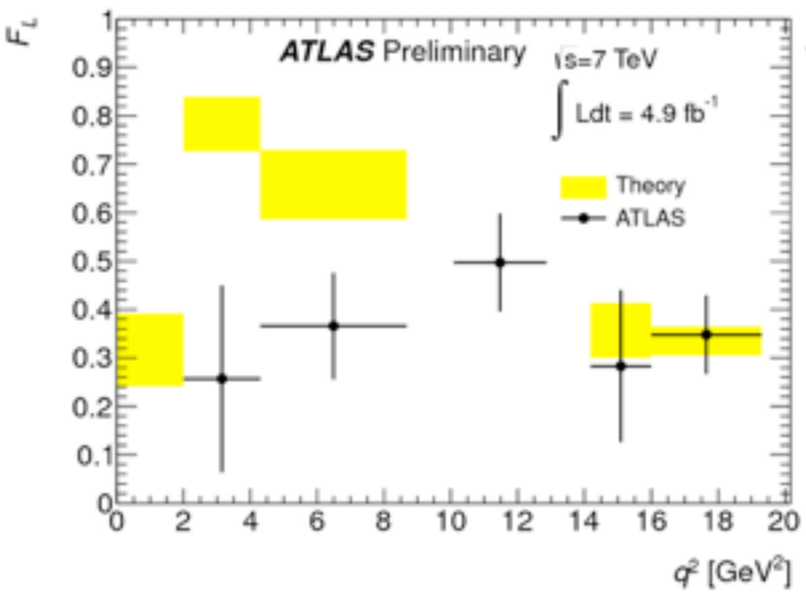


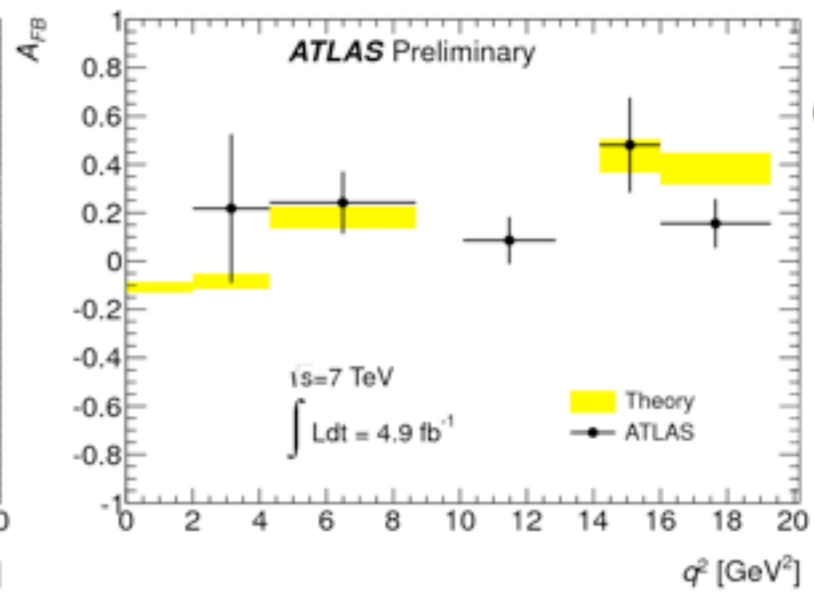


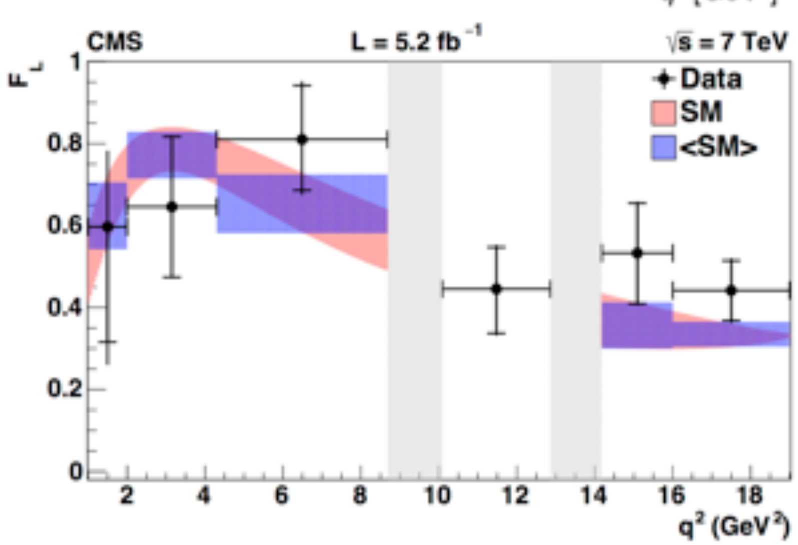
$B^0 \rightarrow K^* \mu\ \mu$

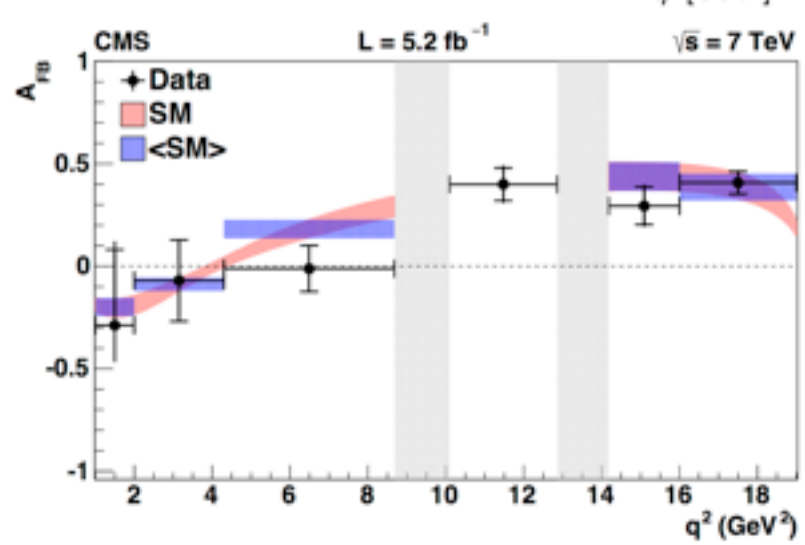
- strategy: fit for m(kπμμ), cos(Θ_l), cos(Θ_k) in bins of di-μ mass square (q^2), excluding (ψ) resonant region
- observables measured:
  - **A_{FB}**: forward-backward asymmetry of the muons
  - **F_L**: fraction of longitudinal polarization of the K^{0*}
  - **dB/dq^2**: differential branching fraction

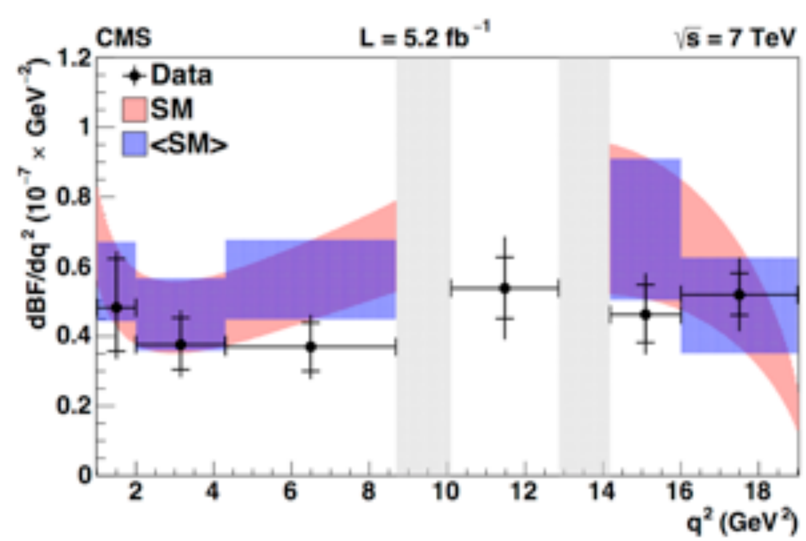




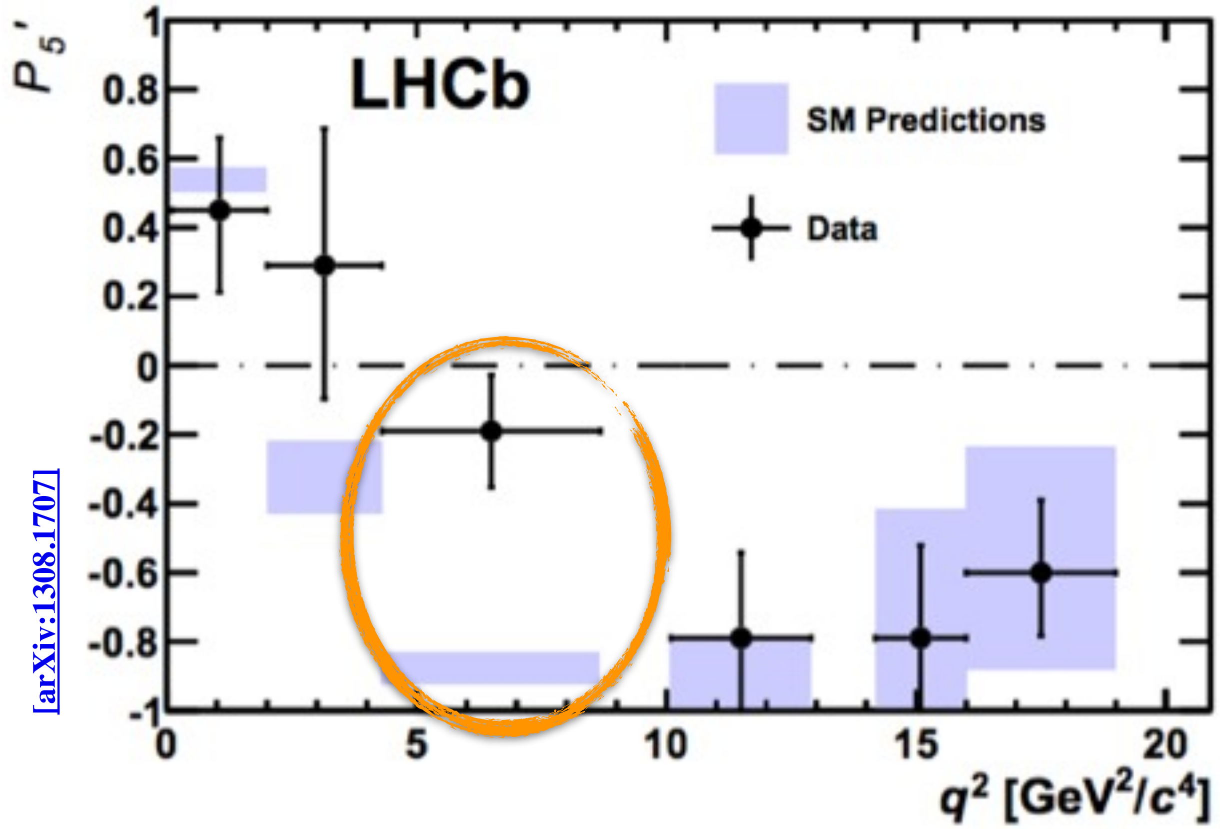


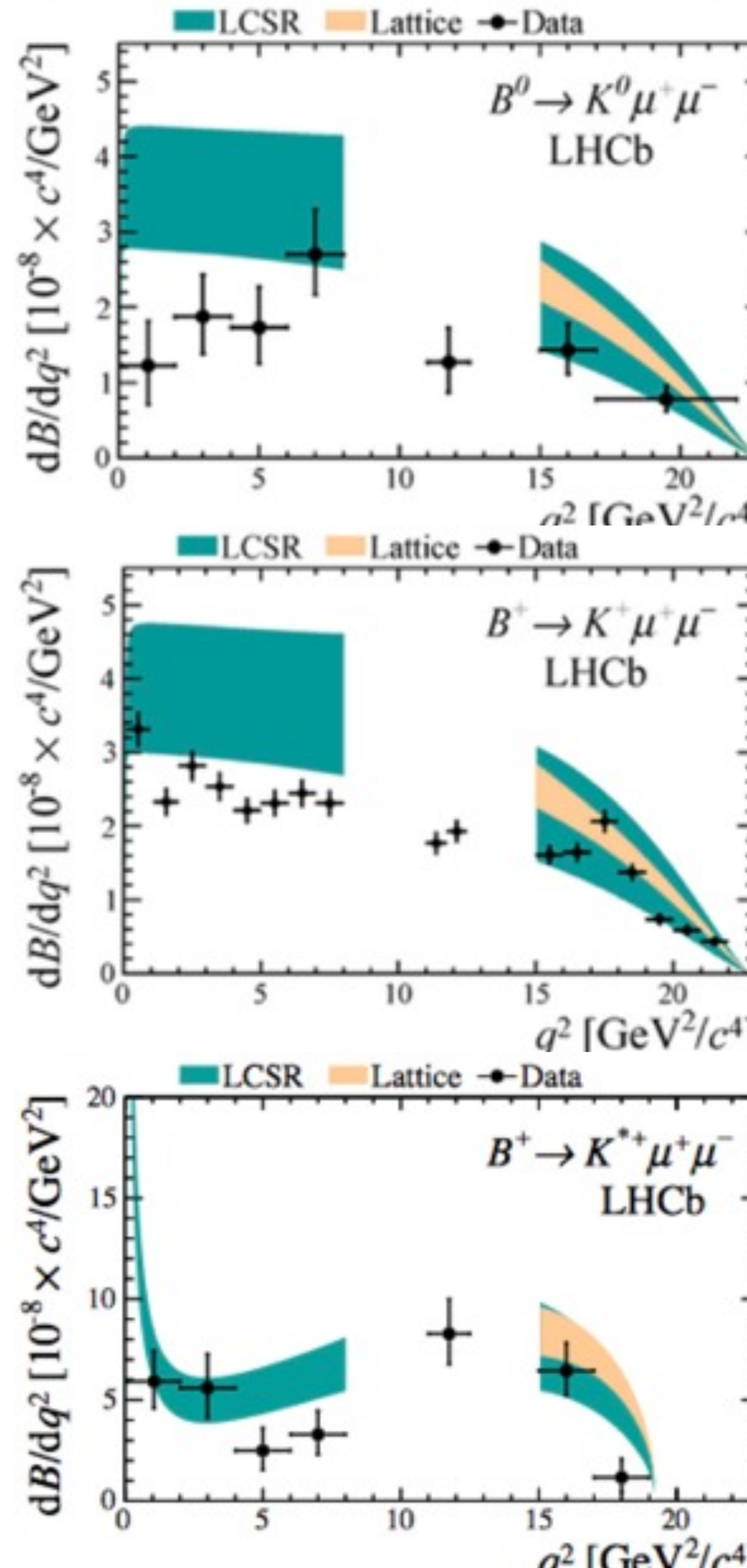






$B^0 \to K^* \mu\ \mu$

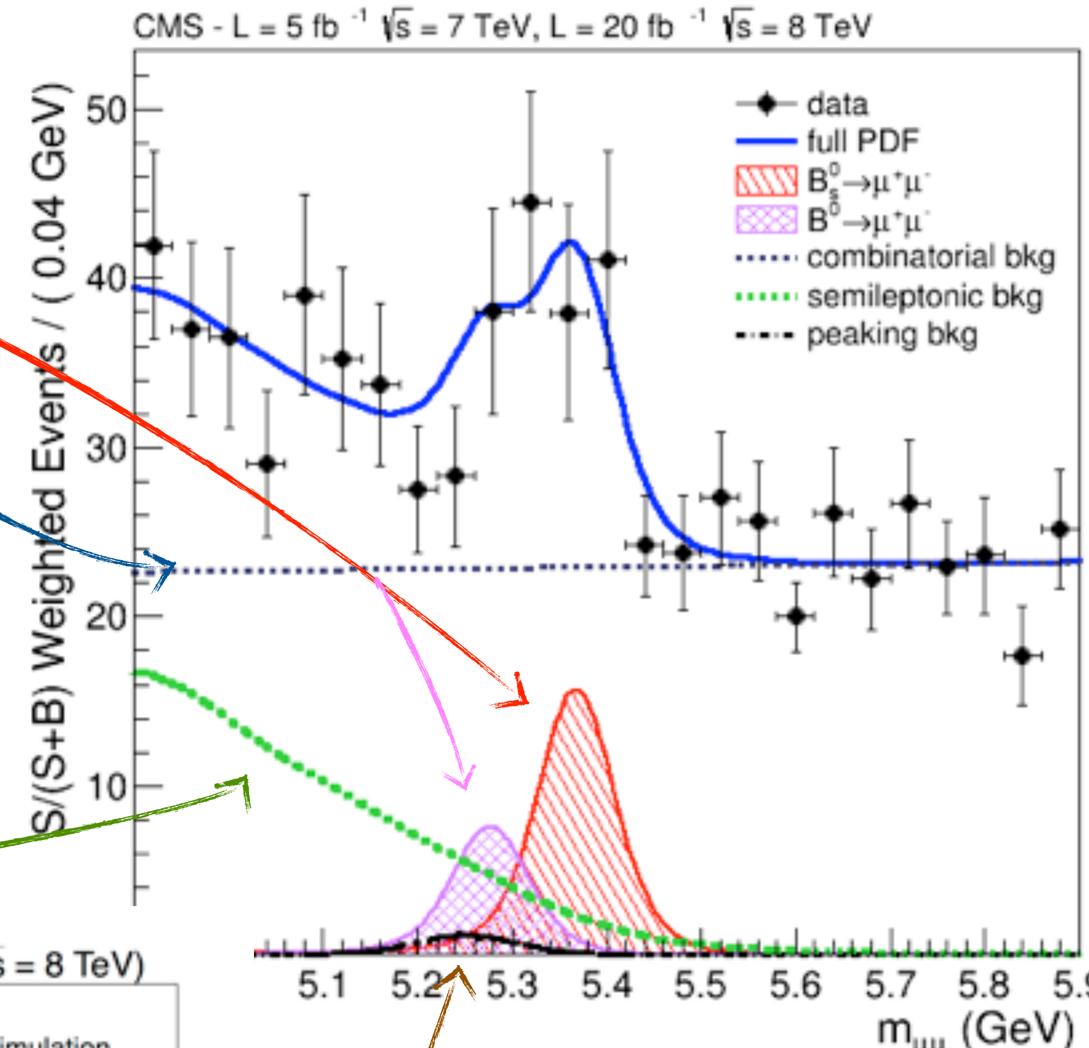


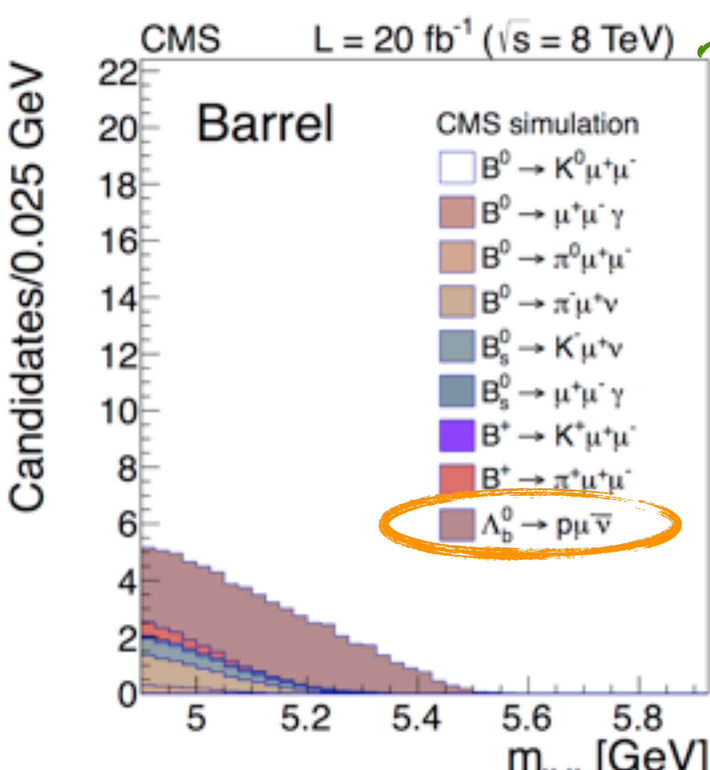


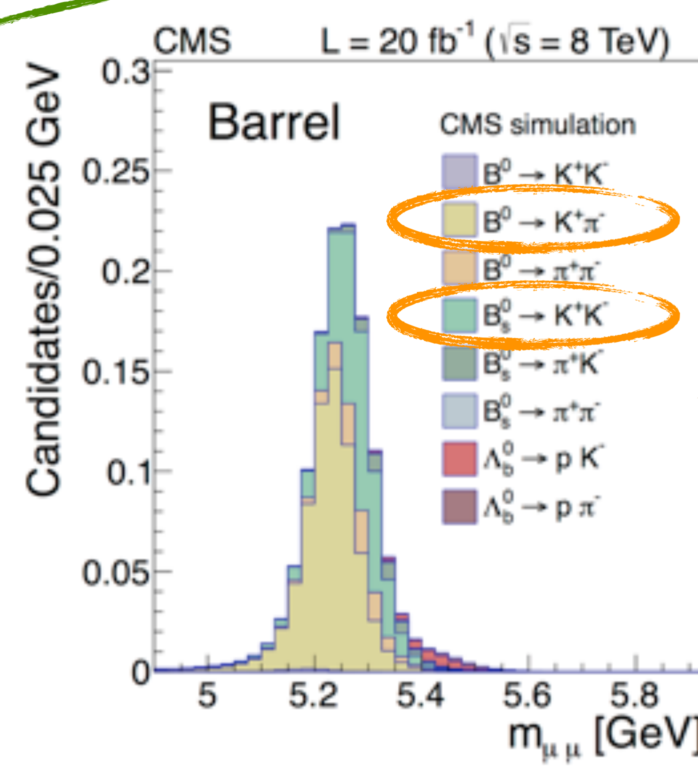
- new set of observables proposed ➠ less sensitive to hadronic form factors
- P_5': LHCb measures 4 new observables in 6 bins of q^2; one of the 24 measurements deviates from SM by 3.7σ, or 2.8σ accounting for all-bin fluctuations
- possible interpretation as a NP contribution to Wilson coefficient C_9
- interesting (correlated?) tensions with SM prediction
- ➠ to be explored with priority with more data and additional decays

$B_{s,d} \to \mu\mu$

- B_d and B_s signals
  - Crystal Ball, fixed shape,
  - normalization floating
- combinatorial background
  - first-degree polynomial
- rare semileptonic background ($b \to q\mu\nu$)
  - fixed shape, constrained normalization
- rare peaking background
  - constrained to expectation







- rare physics backgrounds normalized to B^+ yields in data, for each analysis channel

$B_{s,d} \to \mu\mu$

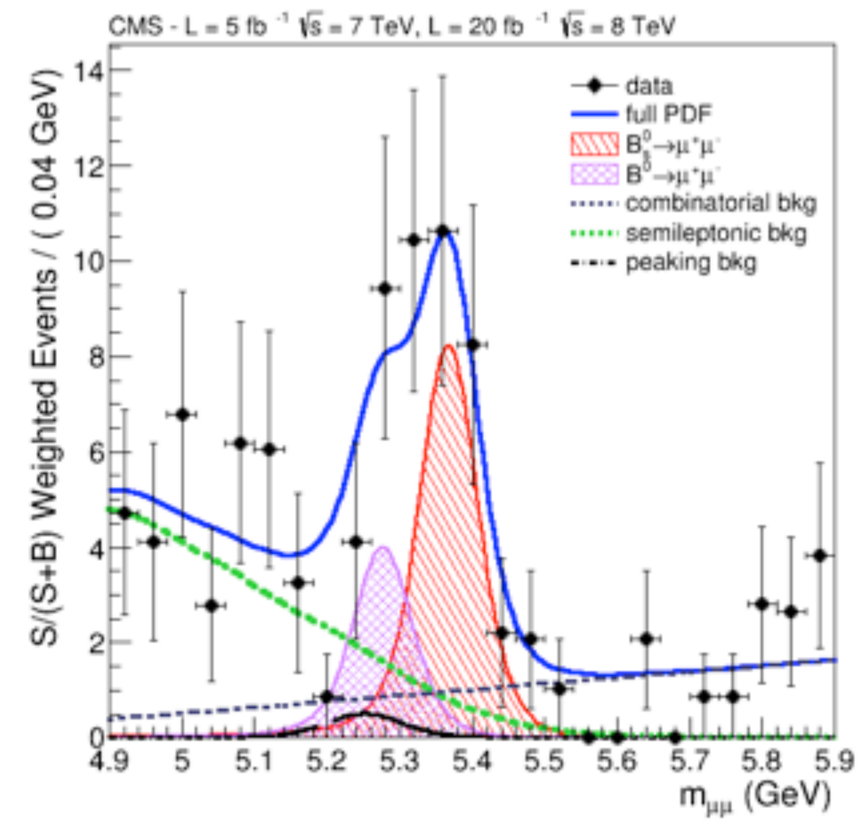
- selection implemented using multivariate methods (BDT)
- CMS observes the decay: $B_s \to \mu\mu$

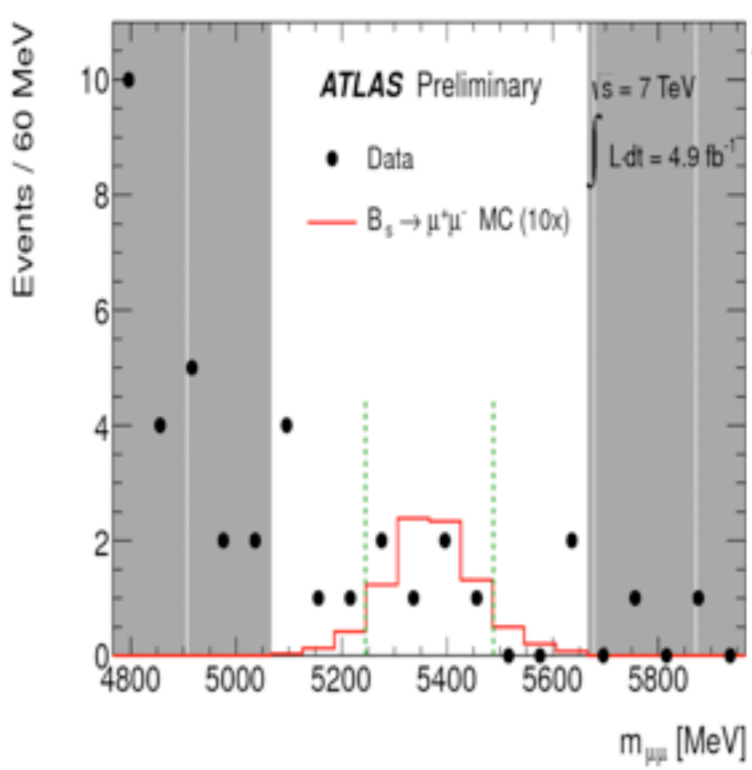
$$\mathrm{BR}(B_s \to \mu\mu) = \left(3.0^{+0.9}_{-0.8}\ (\mathrm{stat})^{+0.6}_{-0.4}\ (\mathrm{syst})\right) \times 10^{-9} \qquad (4.3\sigma)$$

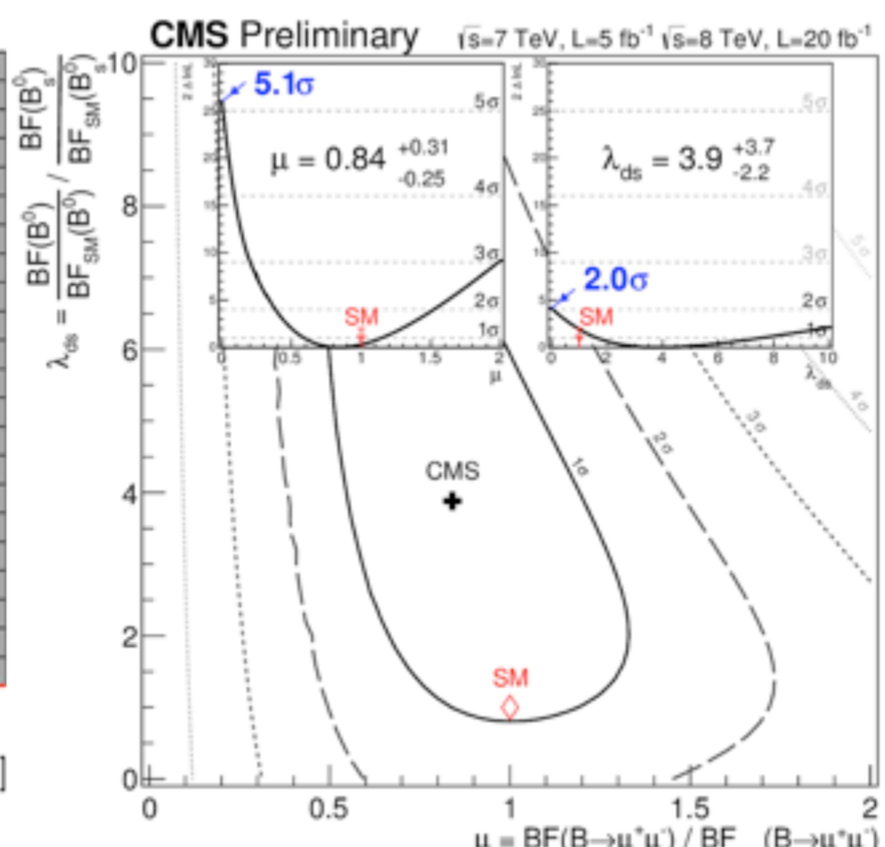
$$\mathrm{BR}(B_d \to \mu\mu) = \left(3.5^{+2.1}_{-1.8}\ (\mathrm{stat+syst})\right) \times 10^{-10} \qquad (2.0\sigma)$$

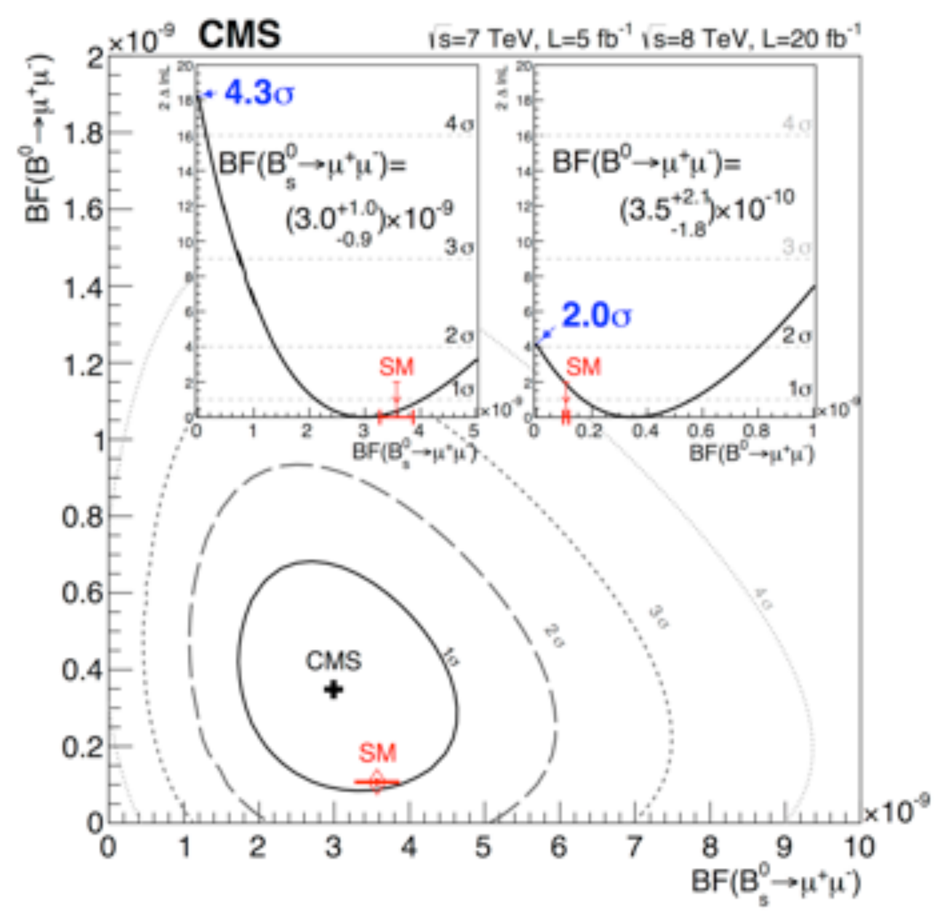
  - using the full Run I dataset, optimized muon identification, BDT discriminator, categorized unbinned likelihood method

- ATLAS with $5\mathrm{fb}^{-1}$ data analyzed places upper limit on B_s
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.5\ (1.2) \times 10^{-8}$ at 95% (90%) CL







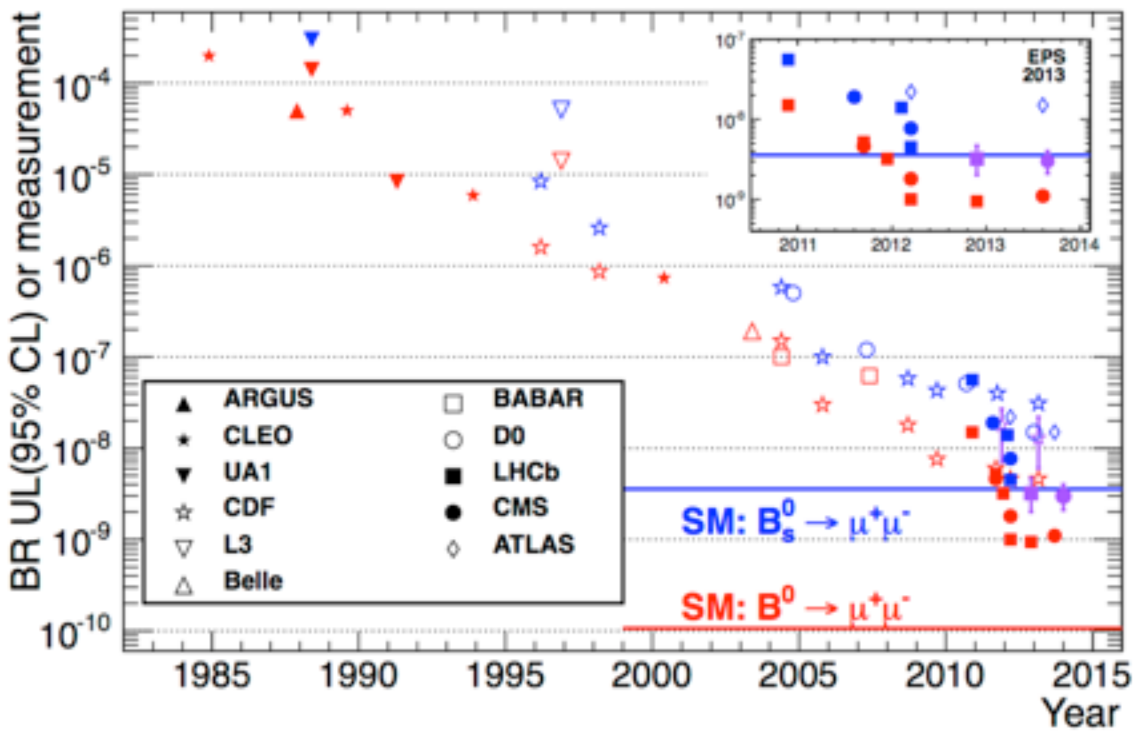


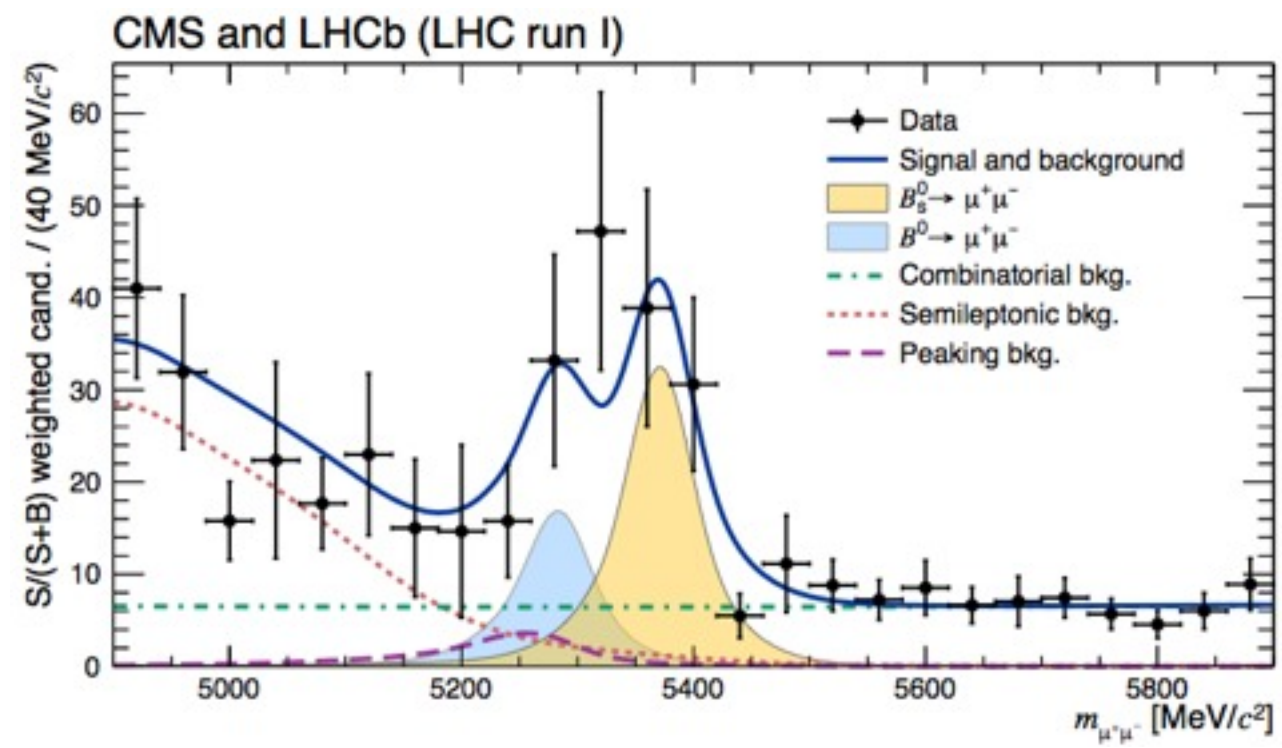
$B_{s,d} \to \mu\mu$ [LHC combination]

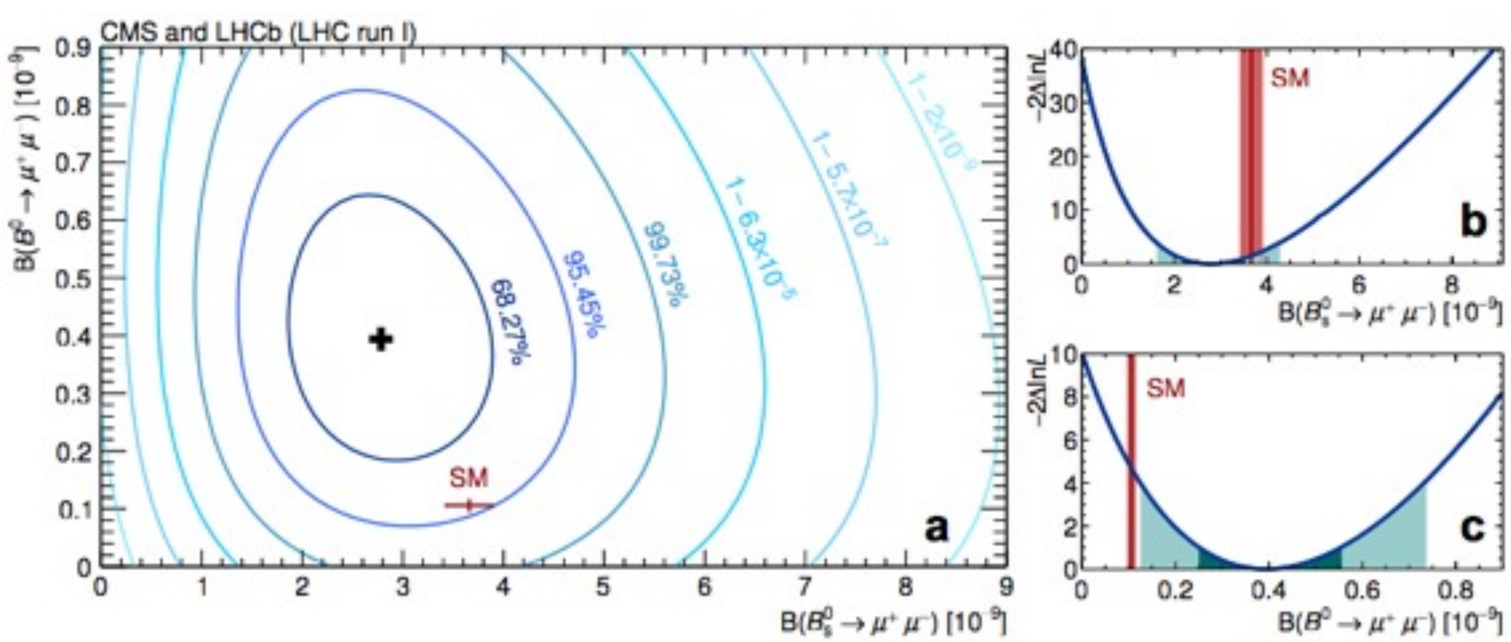
... a 30-years quest ➠

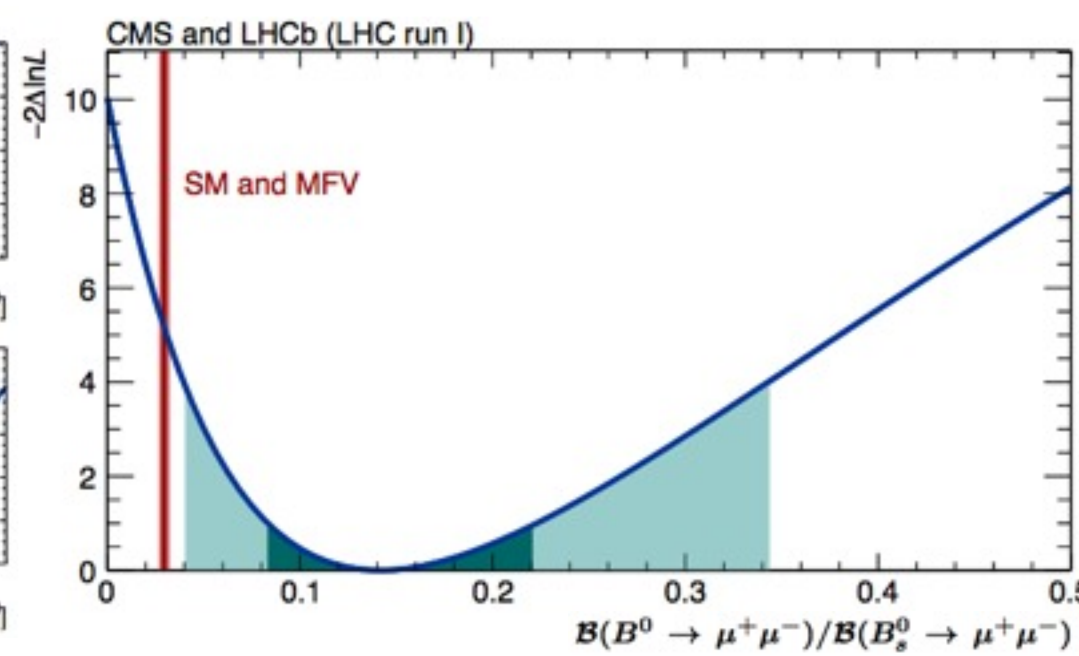
$$\boxed{\begin{aligned} \mathcal{B}(B_s^0 \to \mu^+\mu^-) &= \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9} \\ \mathcal{B}(B^0 \to \mu^+\mu^-) &= \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10} \end{aligned}}$$

(6.2σ)
(3.0σ)







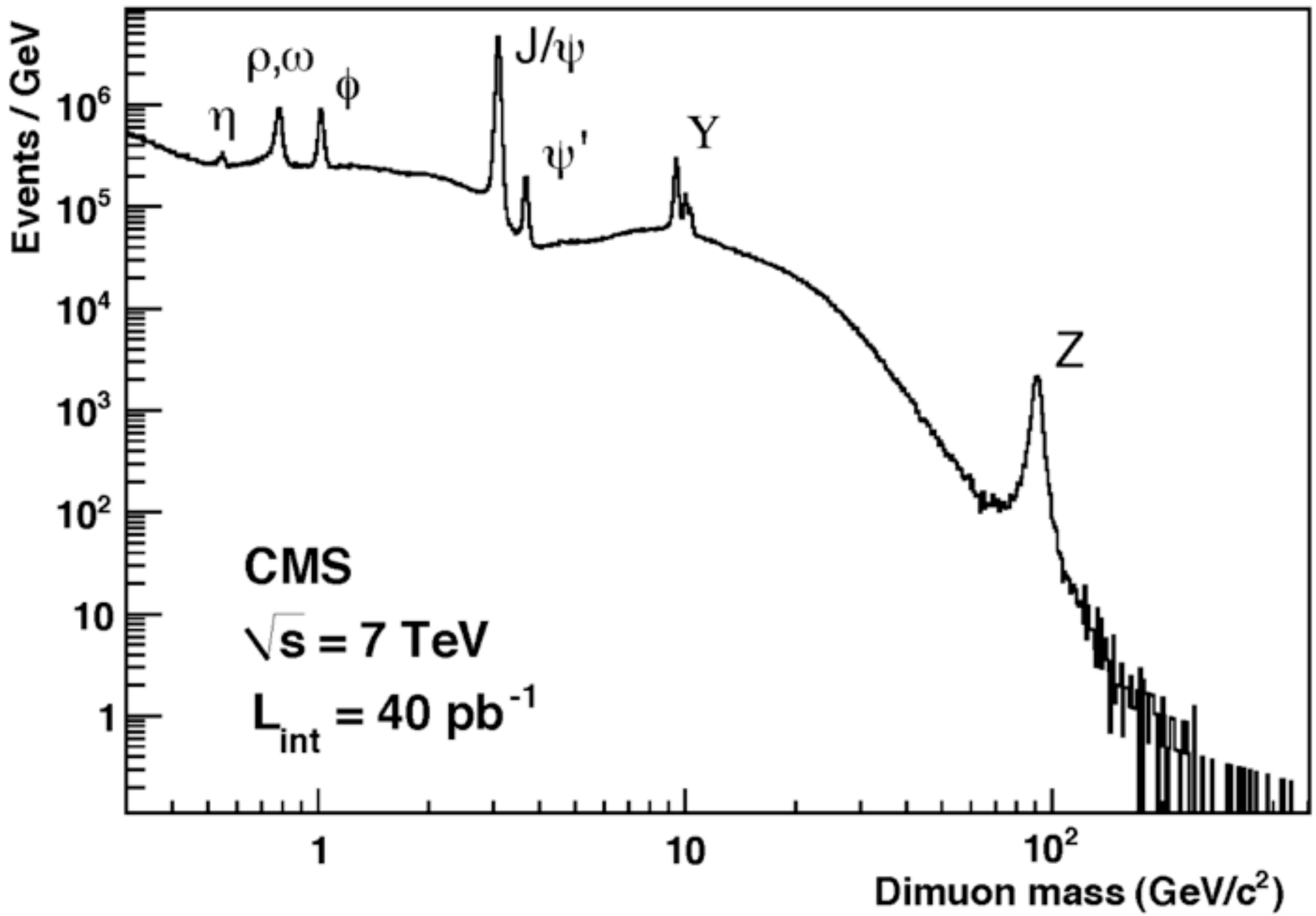


Summary

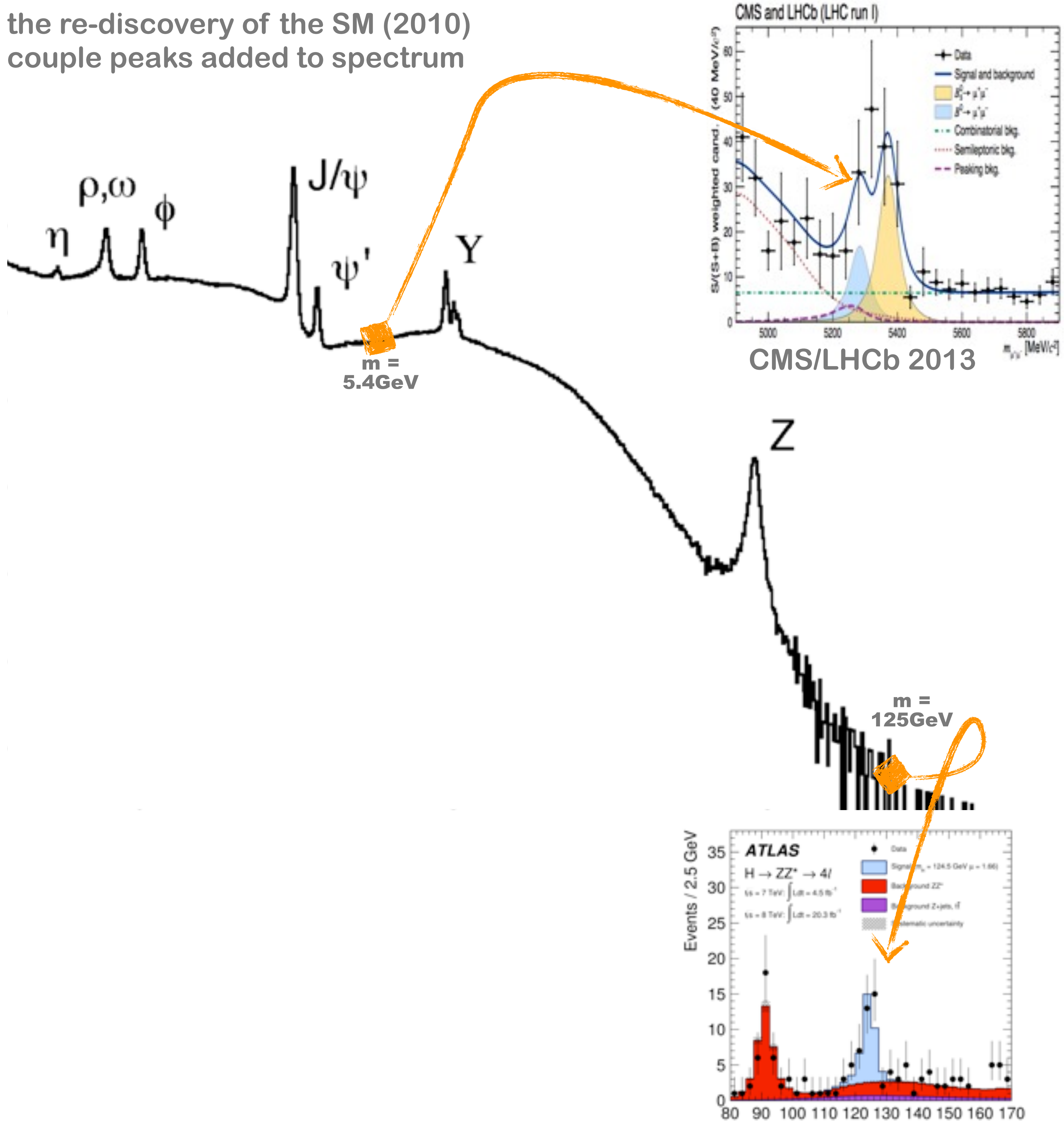
- presented a selection of heavy flavor results based on LHC Run I data
  - LHC's HF-specialized and general-purpose detectors provide access to complementary phase space: necessary for a complete picture of flavor physics
- Run I highlights include:
  - properties: precision measurements of b and c hadron production and decay
  - spectroscopy: observation of new meson and baryon states and decay modes
  - in media: observation of sequential quarkonium suppression
  - rare processes: observation of the long-sought $B_s \to \mu\mu$ decay
- All is in good agreement with standard model so far
  - new physics is becoming constrained in flavor sector
  - possible SM discrepancies and NP hints await more data
- higher energy, luminosity and pileup of coming LHC runs will bring both new possibilities and challenges to flavor physics measurements

Heavy flavor results @ ATLAS, CMS, LHCb in more details:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH
http://lhcbproject.web.cern.ch/lhcbproject/CDS/cgi-bin/index.php

• the re-discovery of the SM (2010)

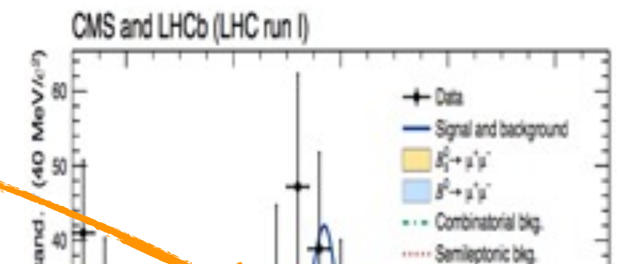


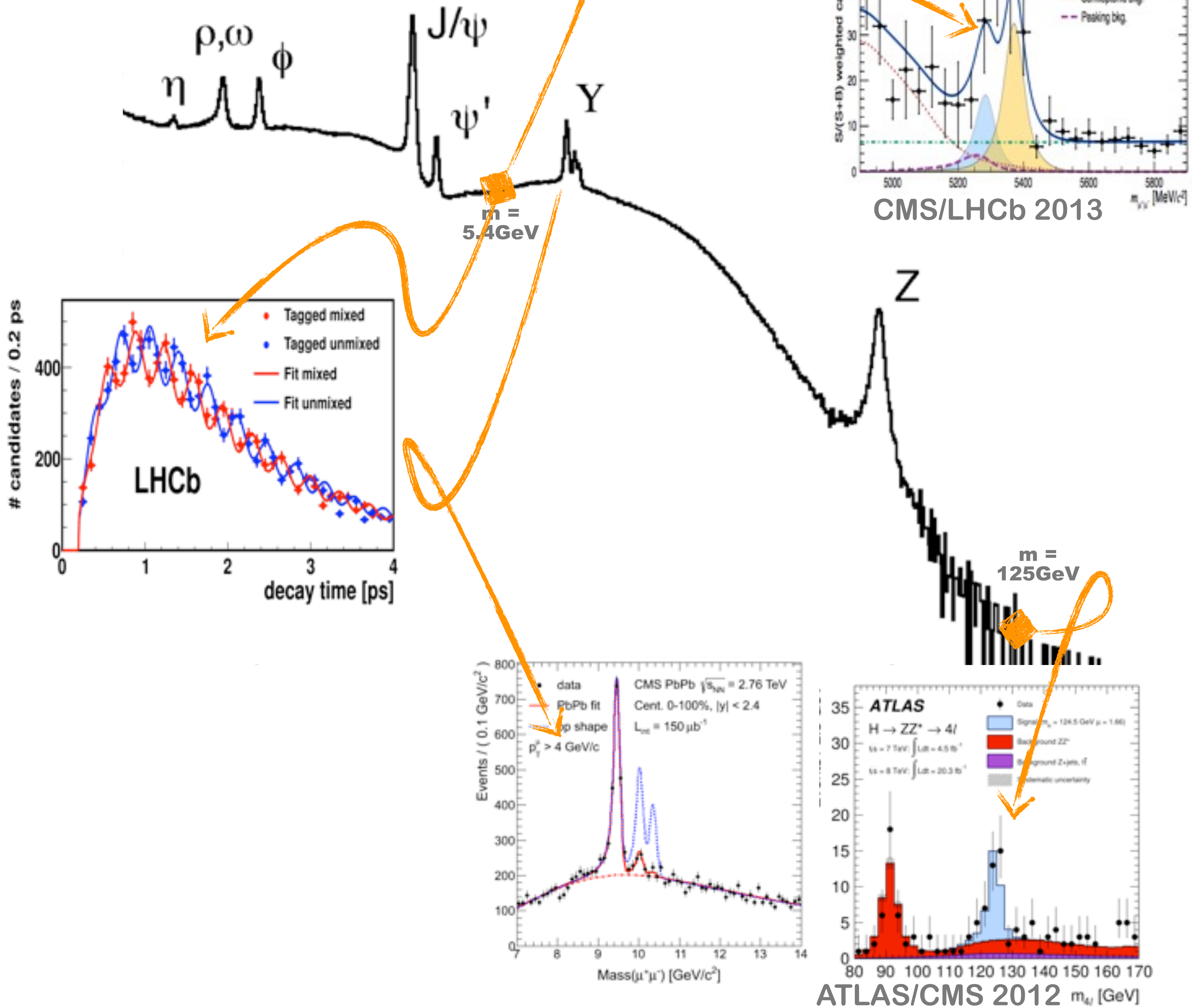
- the re-discovery of the SM (2010)
- couple peaks added to spectrum



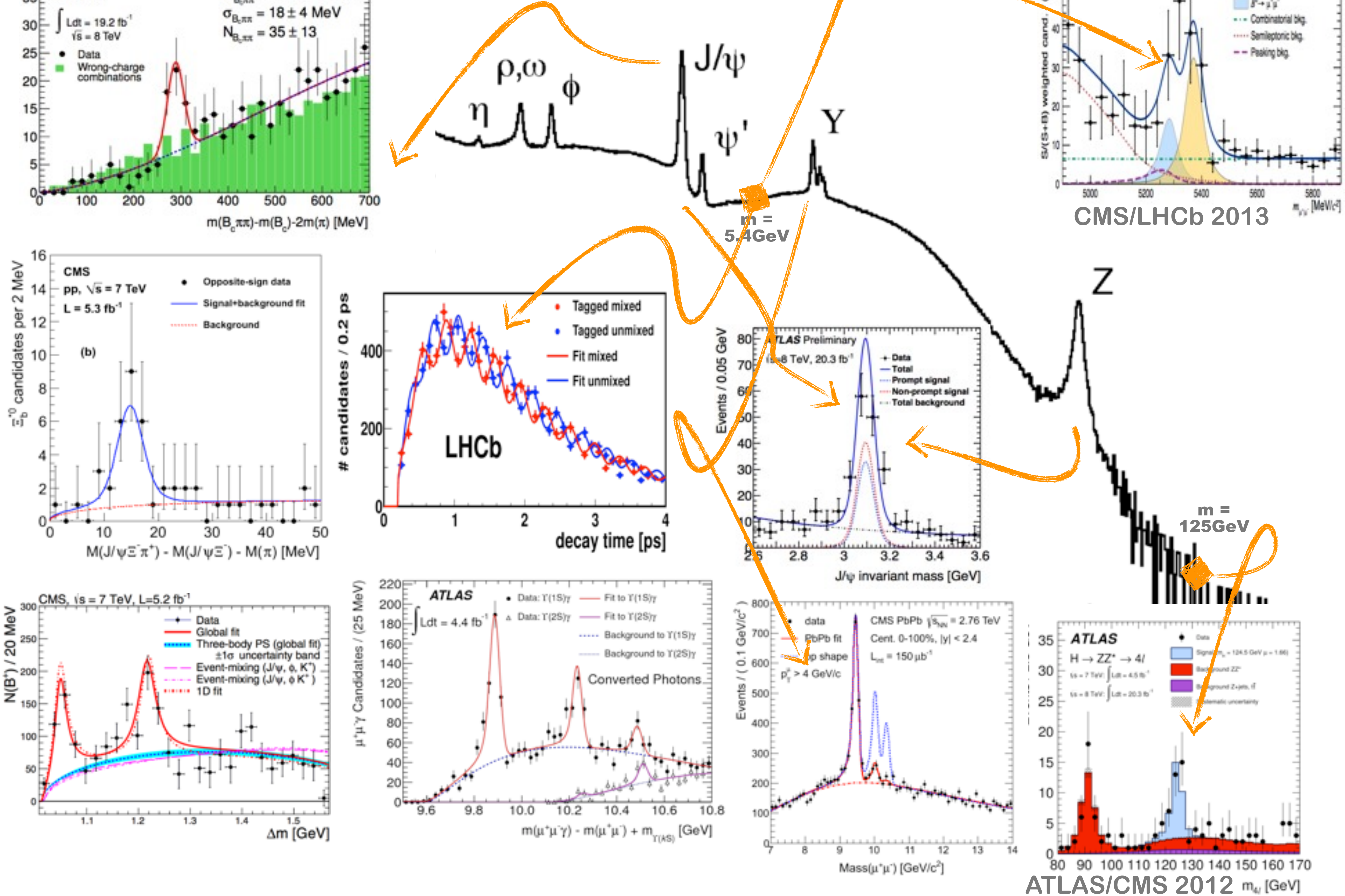
ATLAS/CMS 2012

• the re-discovery of the SM (2010)
• couple peaks added to spectrum

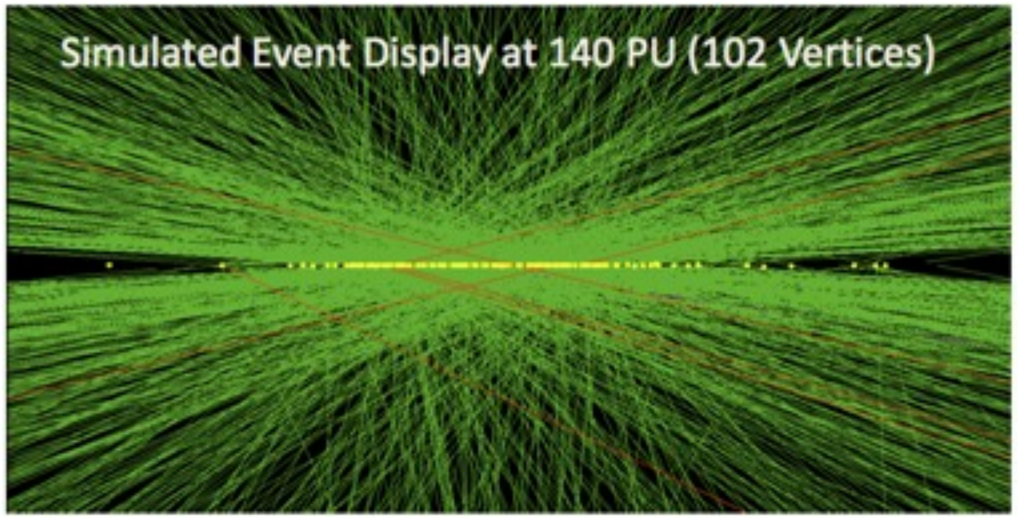




- the re-discovery of the SM (2010)
- couple peaks added to spectrum
- by 2015, various other observations



perspectives



LHC schedule

	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)
ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	$\longrightarrow$	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

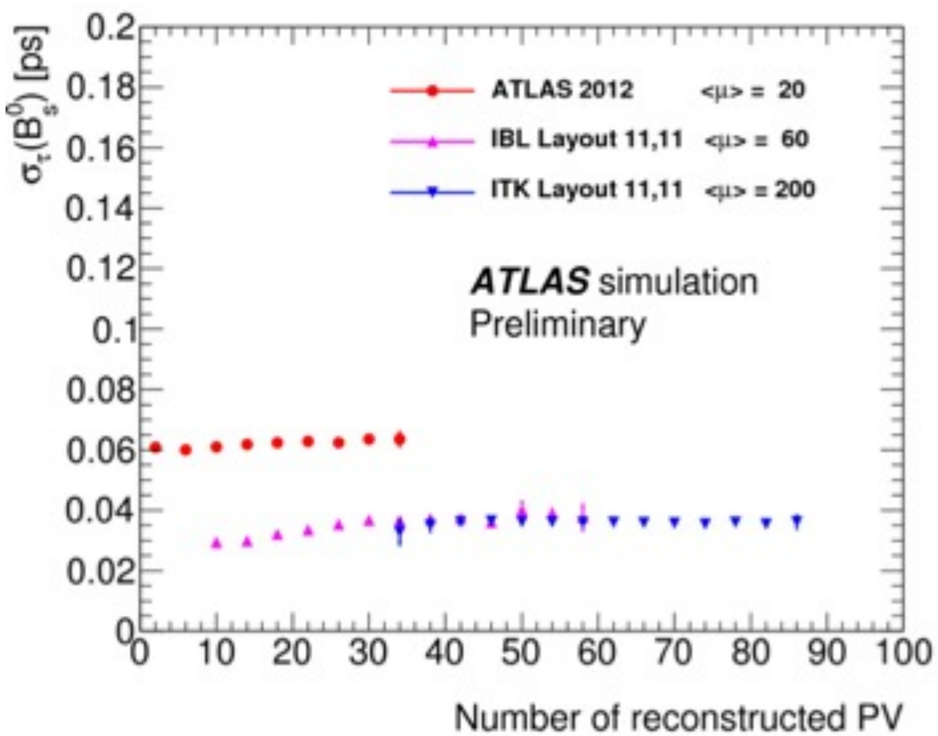
- LHC (2010-2022)
  - increase pp collision energy to 14 TeV ⇒ beauty cross-section increase x2
- HL-LHC (2025-2035)
  - enable a total integrated luminosity of 3 ab^{-1}
  - average pileup $<\mu>\sim 140$, peak luminosity $5\times10^{34}\ cm^{-2}\ s^{-1}$
- extreme inst. lumi. / pileup conditions ⇒ full detector upgrades
  - major ATLAS/CMS upgrades during LS3 (2023-2025) for HL-LHC

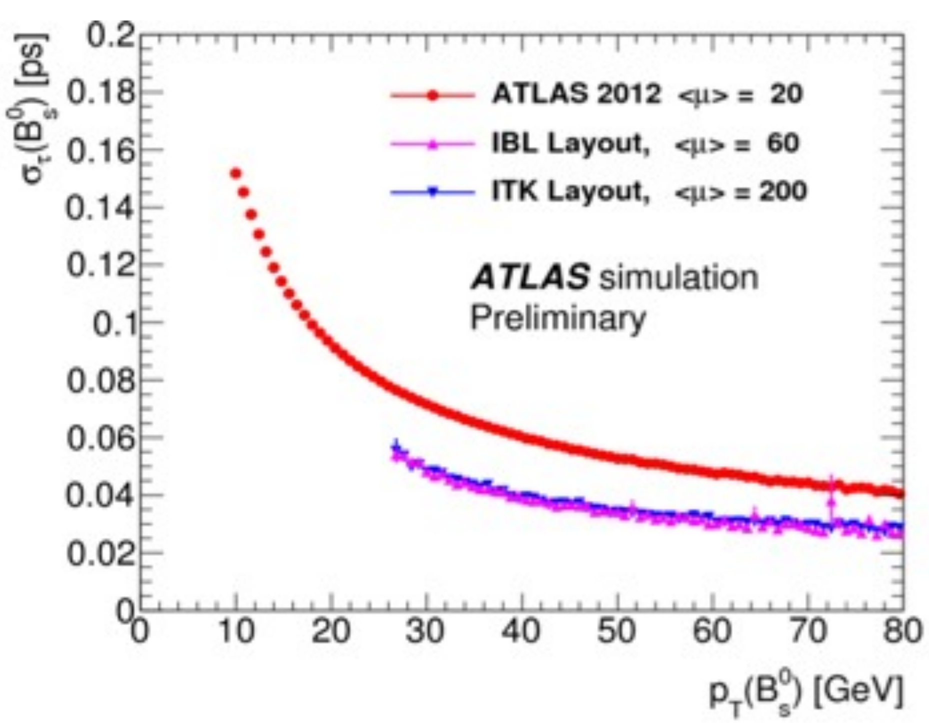
ATLAS & CMS upgrades

- detector upgrades for LHC phase
  - ATLAS fast tracking (FTK) input to HLT (deployment 2015; based on CDF's SVT, which was determining for CDF's B Physics Run II great success)
  - CMS improvements in muon and pixels ⇒ vertex resolution, mitigate pileup
- detector upgrades for HL-LHC phase
  - new inner tracking systems: high granularity, less material, high $\eta(\sim 4)$ coverage: ⇒ improve detector performance for low p_T, increased resolution
  - track-trigger capabilities: efficiently reconstruct at hardware trigger level tracks with p_T down to 2 GeV ⇒ open new avenues for the general purpose detectors to trigger on heavy flavor signals
  - DAQ: 750kHz @L1, 7.5kHz @HLT

sensitivity: $B_s \to J/\psi\Phi$

[ATLAS, LHCb]





- knowledge of decay time resolution σ_t crucial for Φ_s measurement

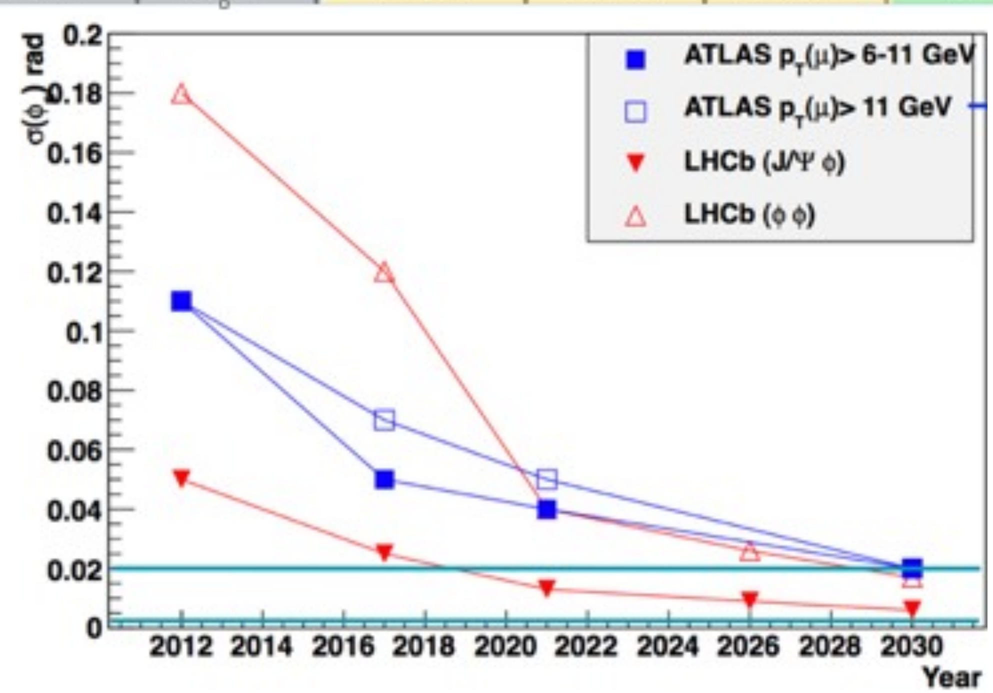
$$A_{CP} \approx (1-2w)e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2} \eta_f \sin\phi_s \sin(\Delta m_s t)$$

flavor tagging

angular analysis

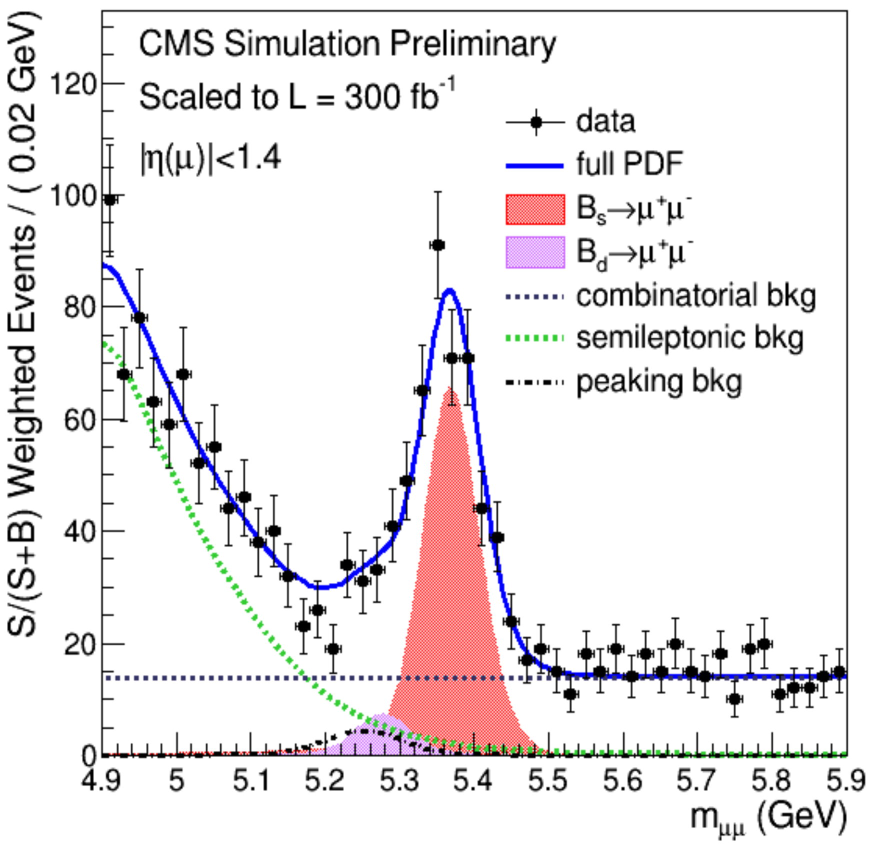
- ATLAS new ID layouts IBL / ITK
  - improve σ_t 30% wrt Run I
  - 14% increase σ_t in Run 2 due to # of PV
- potential will depend strongly on trigger thresholds Run2/3: 6+6GeV, HL-LHC: 11+11GeV

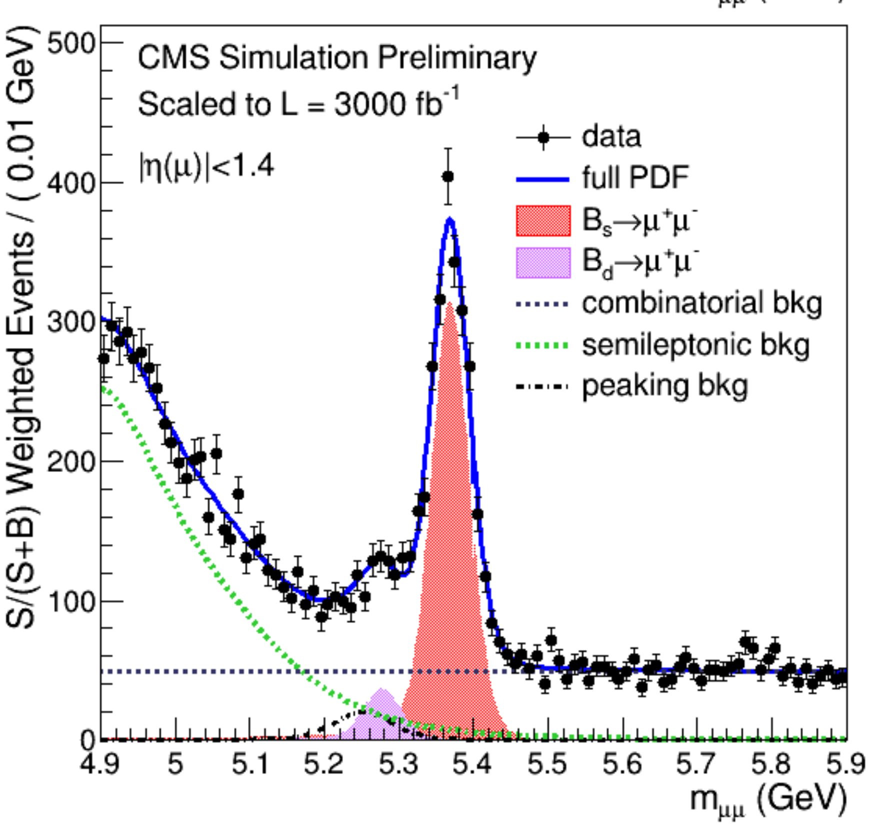
2011	2012	2015-17		2019-21	2023-30+
0.25	0.12	0.054	0.10	0.064	0.022



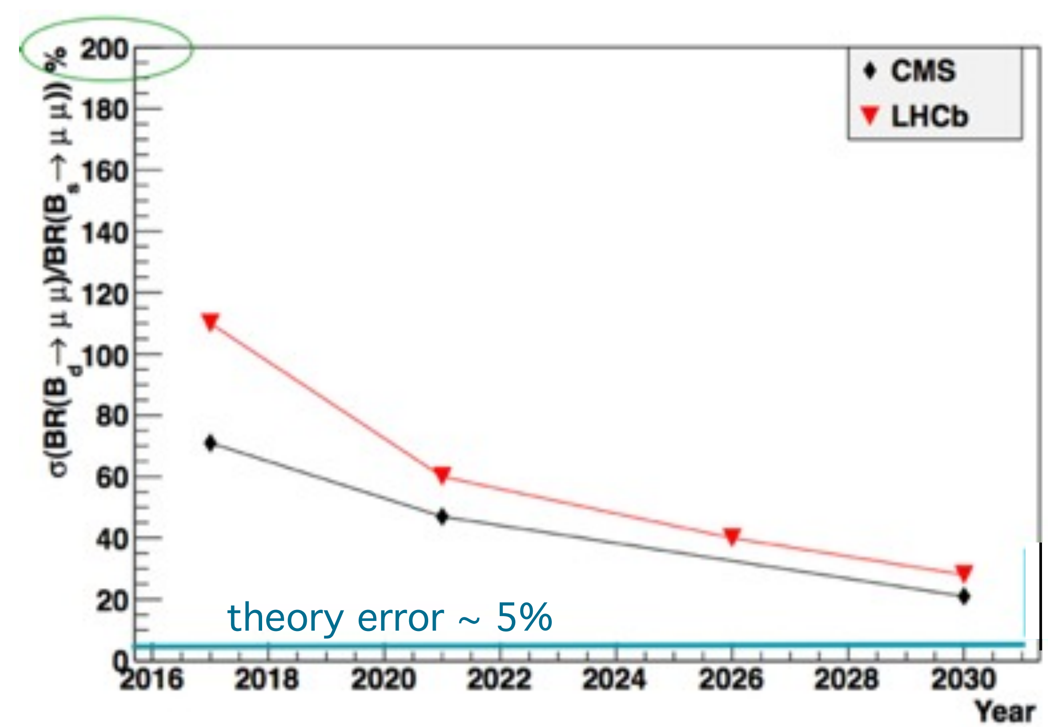
sensitivity: $B \to \mu\mu$

[CMS, LHCb]





- Sensitivity estimated based on expected detector performance by re-scaling results of Run I analysis
- SM prediction for B_d/B_s ratio assumed
- B_d observation (>5σ) within reach (HL-LHC)
- theory errors on branching fraction (ratio) will remain smaller than experimental sensitivity
- will explore additional observables with complementary sensitivity, e.g. effective lifetime and possibly time-dependent CP asymmetries



backup