Sixth Workshop on Theory, Phenomenology and Experiments in Flavour Physics - FPCapri2016

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Recent Results on Flavor Physics by CMS

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on behalf of the CMS Collaboration

- Production cross sections:
  - B^+ & Quarkonium (13 TeV), $\Upsilon(1S)\Upsilon(1S)$ (8 TeV)
- FCNC Measurements:
  - $B \to K^* l^+l^-$
  - $t \to Zq$, $t \to Hq$ & single $t + \gamma$

Production Cross Sections

Preliminary Results @ 13 TeV:

- "Measurement of the B^+ hadronic production cross section in pp collisions at 13 TeV" [$L=50.8\ pb^{-1}$]
- "Quarkonium production cross section in pp collisions at 13 TeV" [$L=2.7\ fb^{-1}$]

Preliminary Results @ 8 TeV:

- "Observation of $\Upsilon(1S)$ pair production at CMS" [$L=20.7\ fb^{-1}$]

$\sigma(pp \to B^+X)$ @ 13 TeV

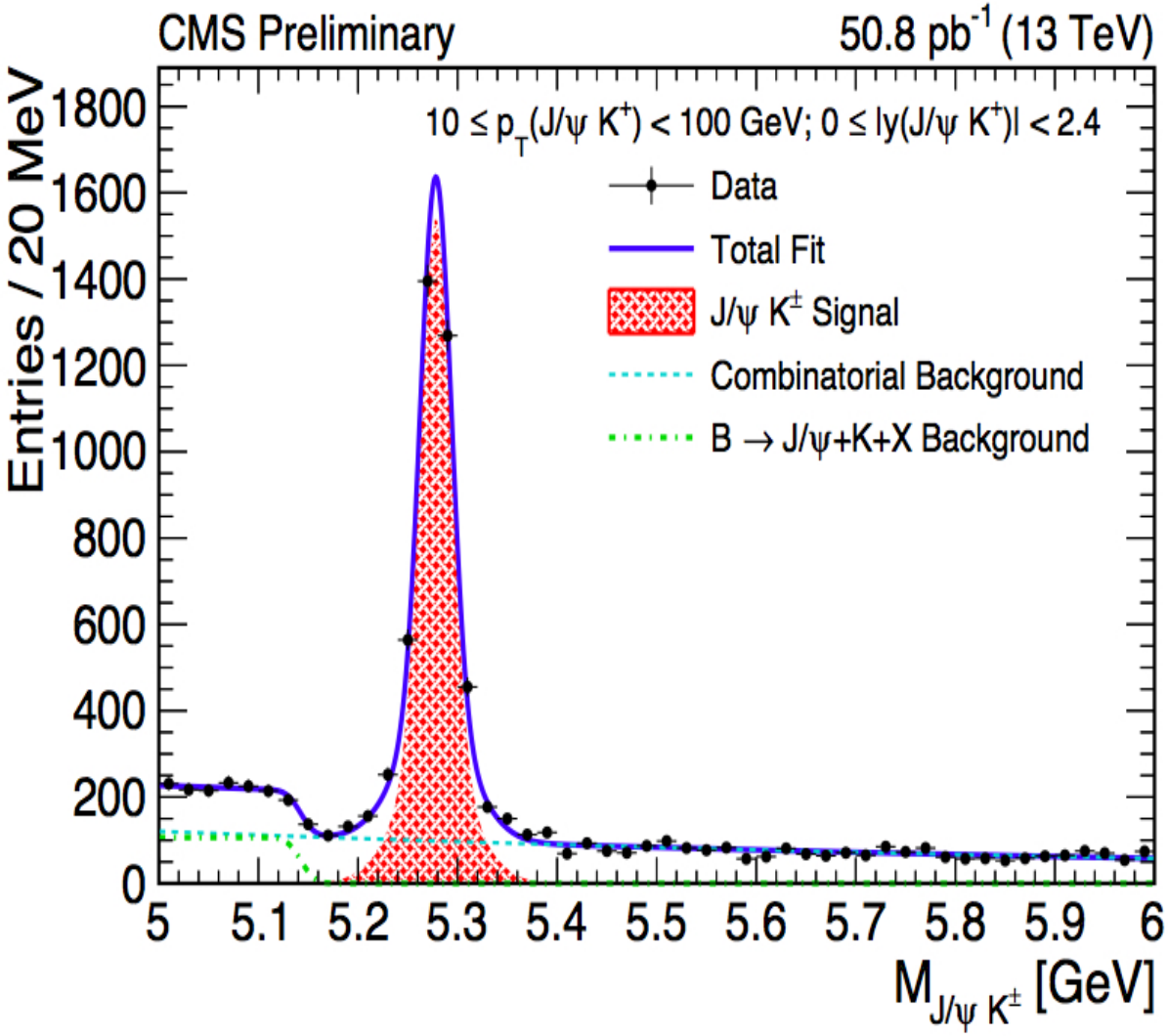
- Measurements of b-hadron production cross sections at the highest energy provide crucial test of QCD calculations
- Strategy:
  - Measurement performed using $B^+ \to J/\psi\, K^+$, ($J/\psi \to \mu\mu$ & K^+ from the same vertex)
  - Kinematic fit performed constraining m($\mu\mu$) to the J/ψ mass
  - Differential cross sections as a function of transverse momentum and rapidity in the range 10 GeV < P^B_T < 100 GeV; $|y^B| < 2.4$

$$\frac{d\sigma(pp \to B^+X)}{dp_T^B} = \frac{n_{sig}(p_T^B)}{2\,A\cdot\epsilon(p_T^B)\,\mathcal{B}\,\mathcal{L}\,\Delta p_T^B}, \qquad \frac{d\sigma(pp \to B^+X)}{dy^B} = \frac{n_{sig}(|y^B|)}{2\,A\cdot\epsilon(|y^B|)\,\mathcal{B}\,\mathcal{L}\,\Delta y^B}$$

- Acceptance x Efficiency jointly evaluated from simulated B^+ sample
- Trigger & Muon efficiencies from data inclusive $J/\psi \to \mu\mu$ decays

$\sigma(pp \to B^+X)$ @ 13 TeV

- Signal yields extracted in the different bins from a $m(J/\psi\, K^+)$ fit

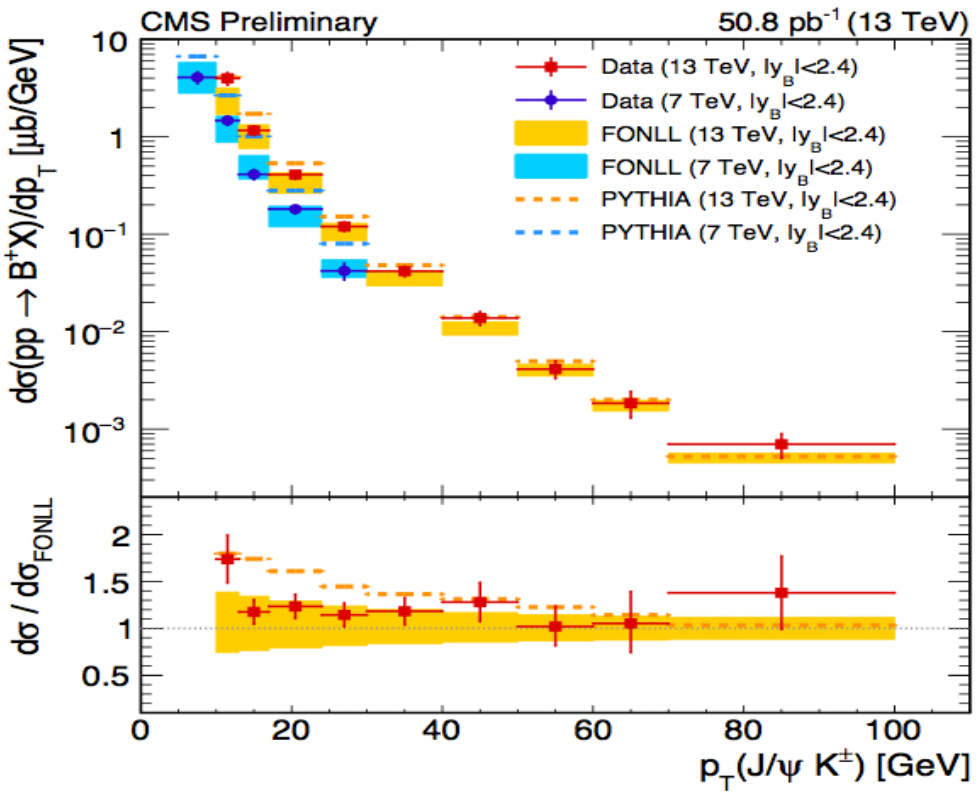


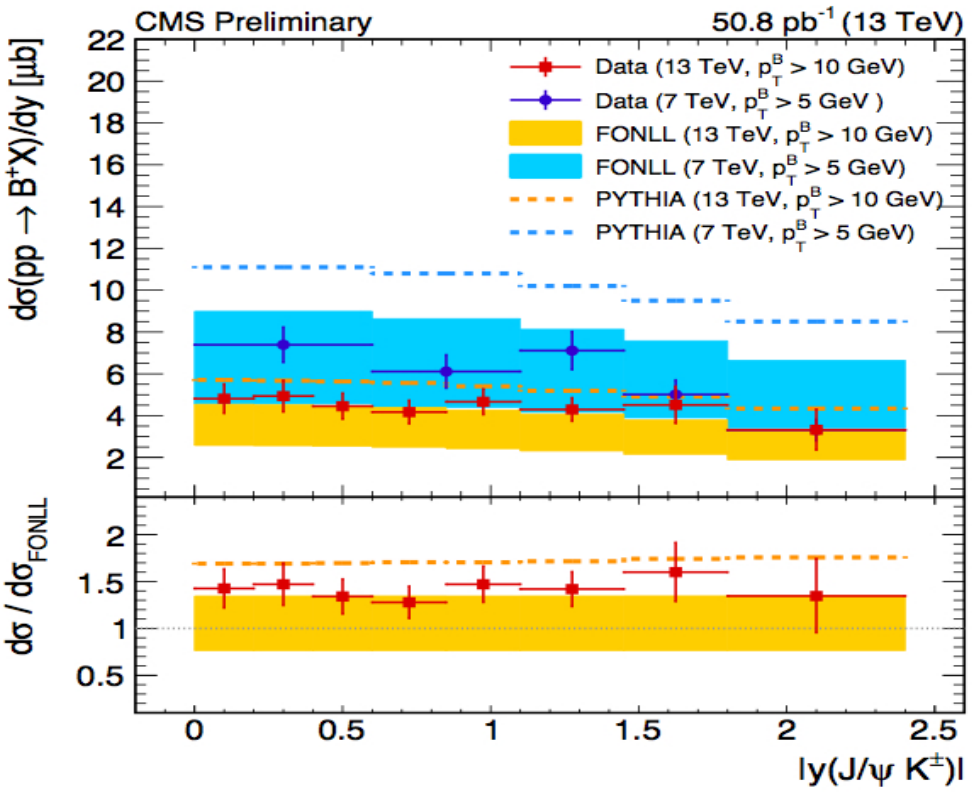
$m(J/\psi\, K^+)$ PDF:

- Signal: sum of two Gaussians (relative fraction from MC)
- Combinatorial: Exponential function (from inclusive J/ψ)
- Mis-reconstructed B → J/ψ KX: Error function
- Negligible contribution from $B^+ \to J/\psi\, \pi^+$

$\sigma(pp \rightarrow B^+X)$ @ 13 TeV

- Differential cross sections:

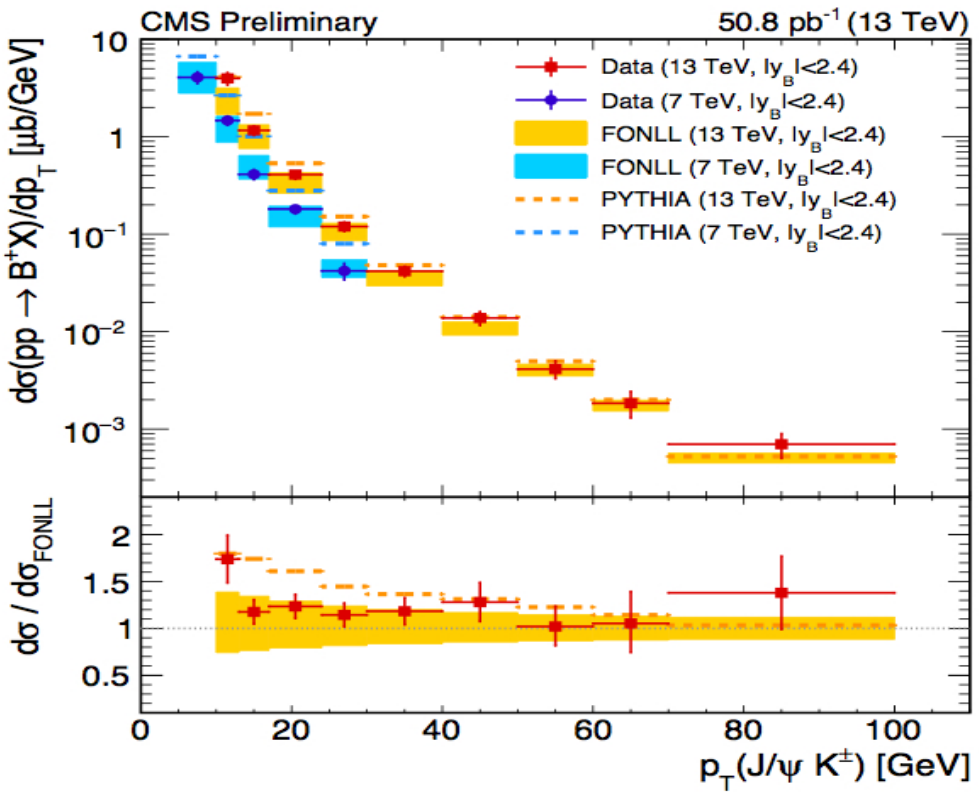


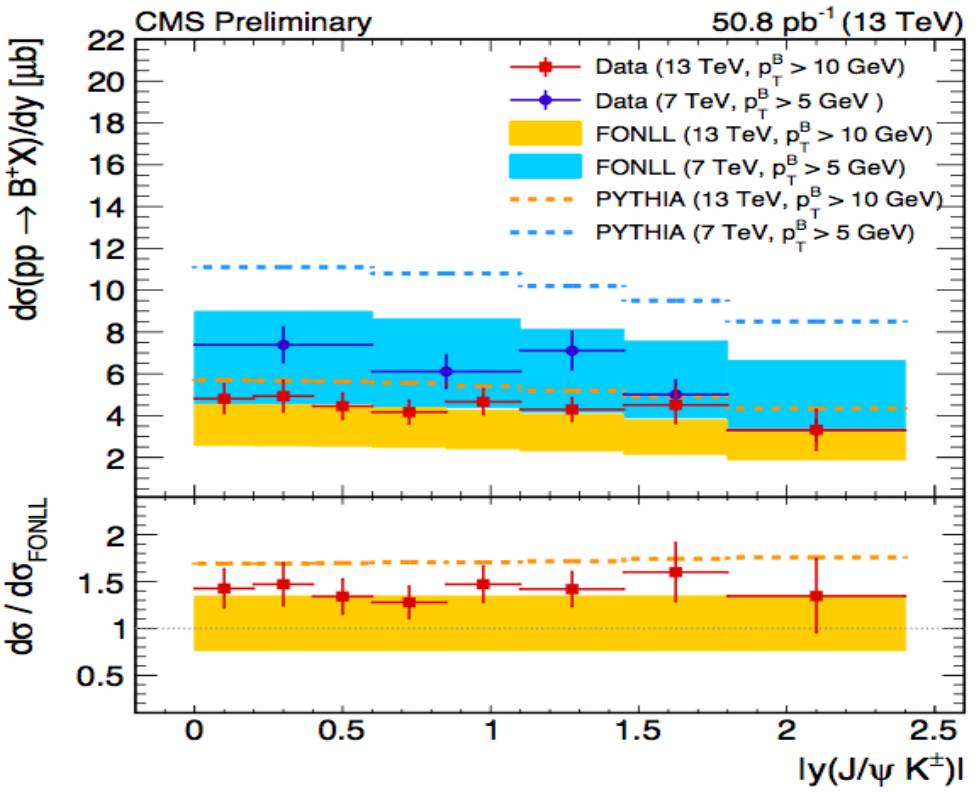


- Systematics from muon identification & reconstruction, signal & BKG PDFs, P^B_T & y^B prediction & resolution, track reconstruction, luminosity and BR($B^+ \rightarrow J/\psi\ K^+ \rightarrow \mu\mu\ K^+$)

$\sigma(pp \to B^+X)$ @ 13 TeV

- Differential cross sections:





- Measured values show reasonable agreement with predicted shapes and normalizations by PYTHIA [Comput. Phys. Commun. 178, 852 (2008)] & FONNL [JHEP 0103, 006 (2001)]

σ(pp → Quarkonium) @ 13 TeV

- Quarkonium production described by Non-Relativistic QCD using factorization of perturbative & hadonization processes
  - Comparison of cross sections at 7 TeV and 13 TeV provides a test of the factorization hypotheses

- Measure pp → J/ψ, ψ, Υ(nS) double differential cross sections as a function of transverse momentum and rapidity in the range $P_T > 20$ GeV; $|y| < 1.2$:

$$BR(q\bar{q} \to \mu^+\mu^-) \times \frac{d^2\sigma^{q\bar{q}}}{dp_T dy} = \frac{N^{q\bar{q}}(p_T, y)}{\mathcal{L}\Delta y \Delta p_T} \cdot \left\langle \frac{1}{\epsilon(p_T, y)\mathcal{A}(p_T, y)} \right\rangle$$

- Acceptance evaluated event-by-event using a simulated sample with flat rapidity and realistic P_T distribution assuming no polarization

σ(pp → Quarkonium) @ 13 TeV

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  - Comparison of cross sections at 7 TeV and 13 TeV provides a test of the factorization hypotheses

- Measure pp → J/ψ, ψ, Υ(nS) double differential cross sections as a function of transverse momentum and rapidity in the range

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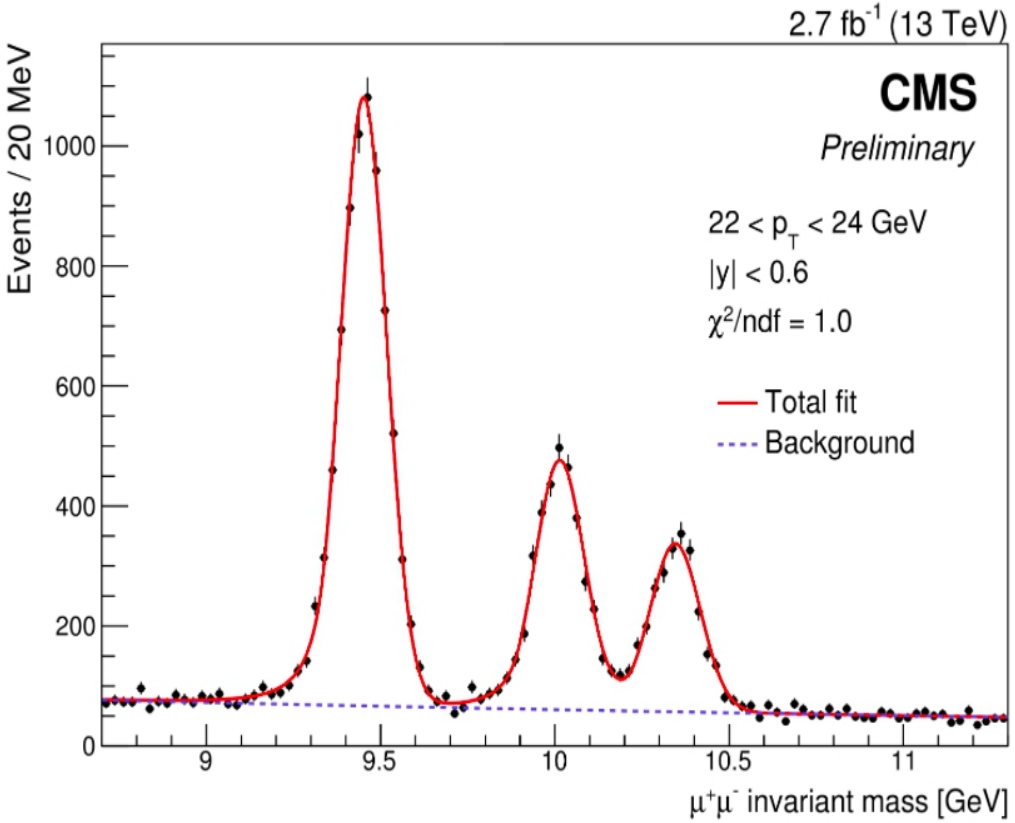
  - Efficiency from data-driven studies using Tag & Probe technique on inclusive J/ψ → μμ decays

σ(pp → Quarkonium) @ 13 TeV

- Strategy:
  - Vertex of opposite charge muons fitted in high acceptance region

    $P_T(\mu) > 4.5$ GeV for $|\eta(\mu)| < 0.3$

    $P_T(\mu) > 4.0$ GeV for $0.3 < |\eta(\mu)| < 1.4$
- Signal yields extracted in the different bins from invariant mass fit



Mass PDFs:

Signal:

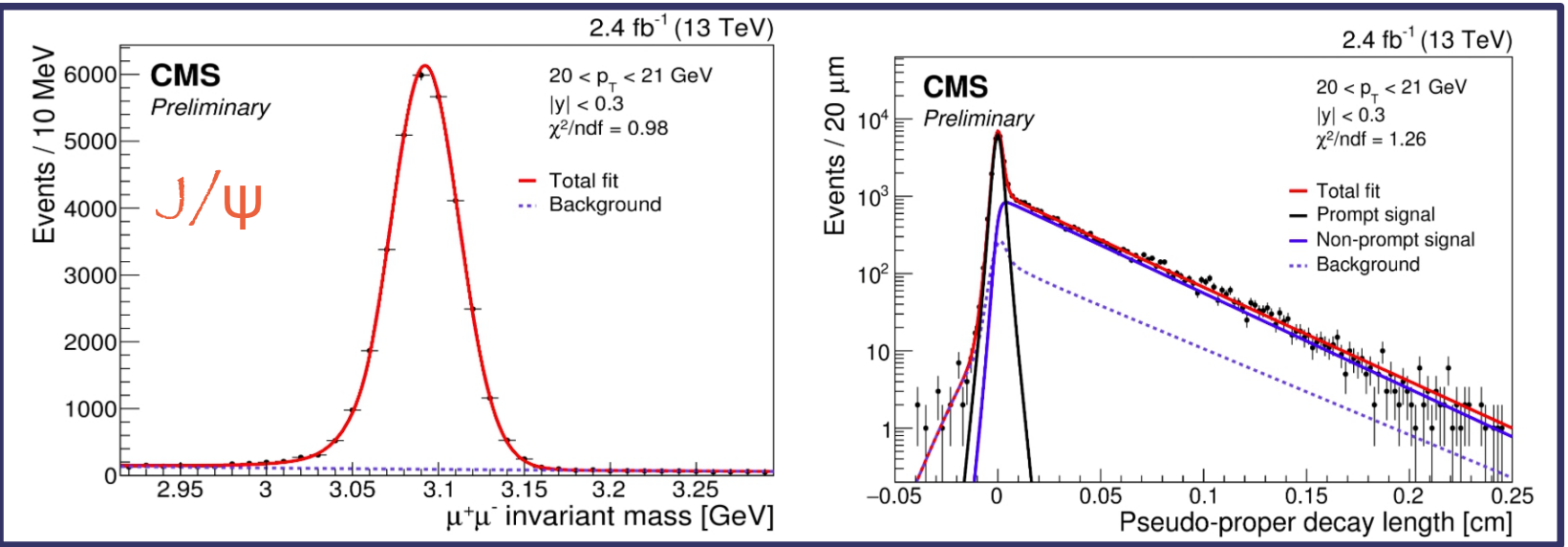
- ψ, Υ: Crystal Ball
- J/ψ: Crystal Ball+Gaussian

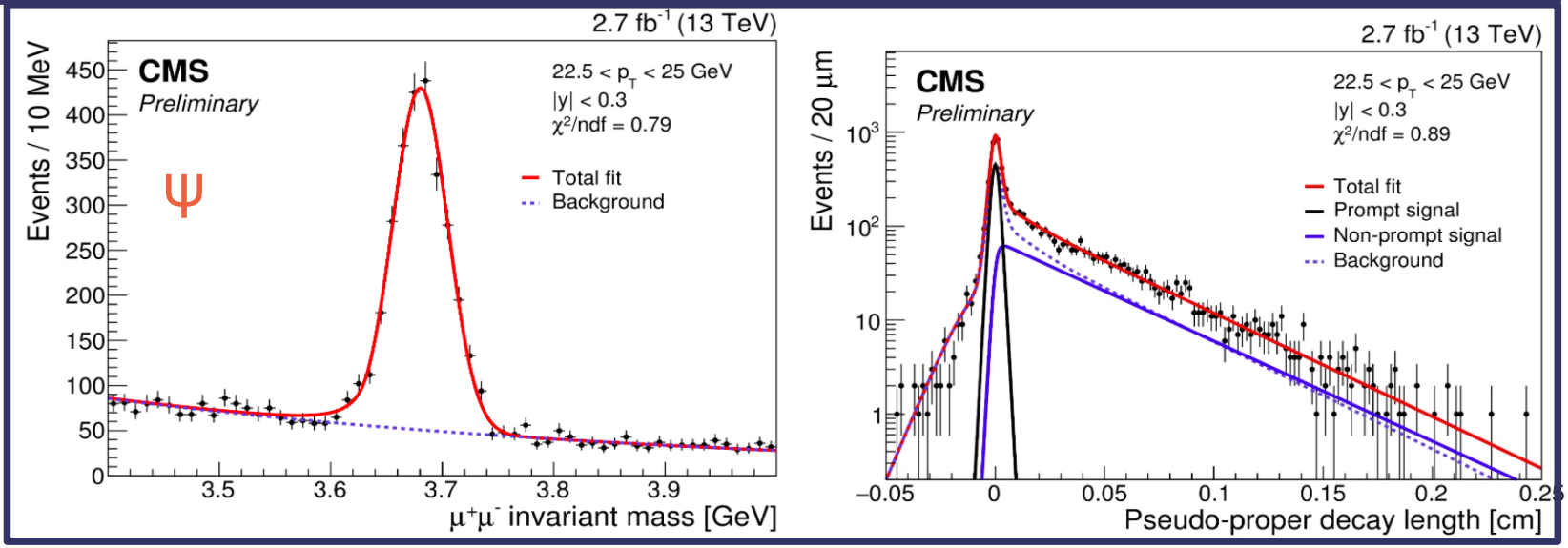
Combinatorial:

- Exponential function

σ(pp → Quarkonium) @ 13 TeV

- Non-prompt charmonium fraction from B decays extracted from a simultaneous 2D (m, decay lenght) fit:



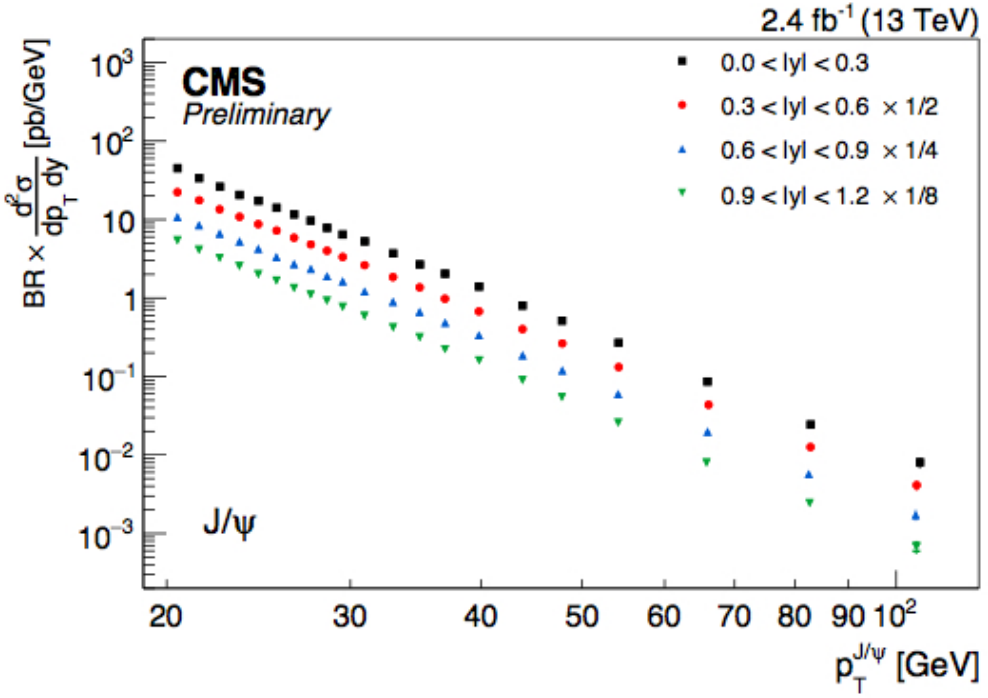


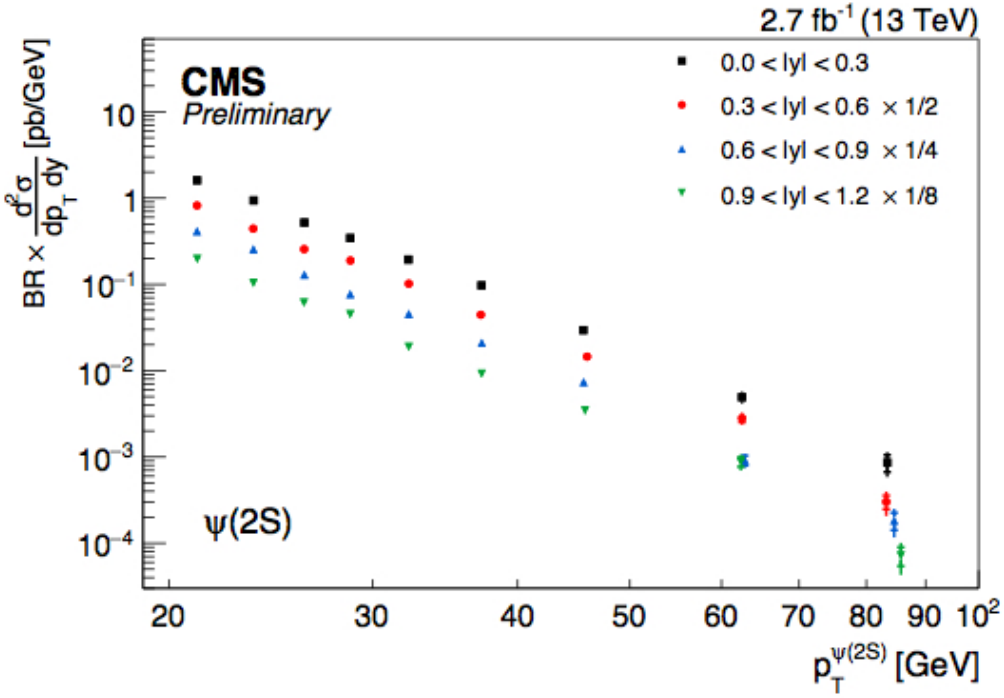
PDL PDFs

- Prompt: Resolution function
- Non-prompt: Exponential ⊗ resolution
- Combinatorial: 2 Gaussians centered at zero + Exponential

σ(pp → Charmonium) @ 13 TeV

- Double differential charmonium cross sections:

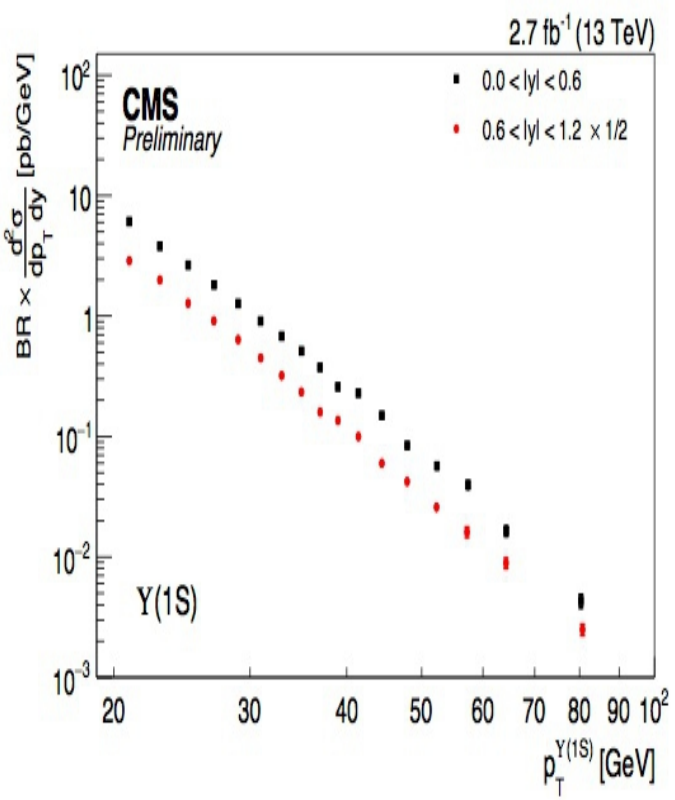


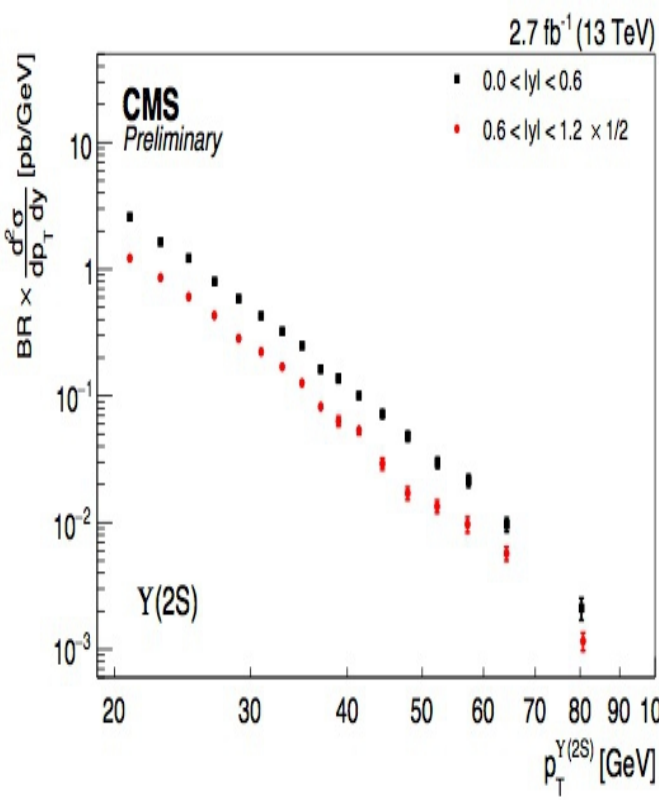


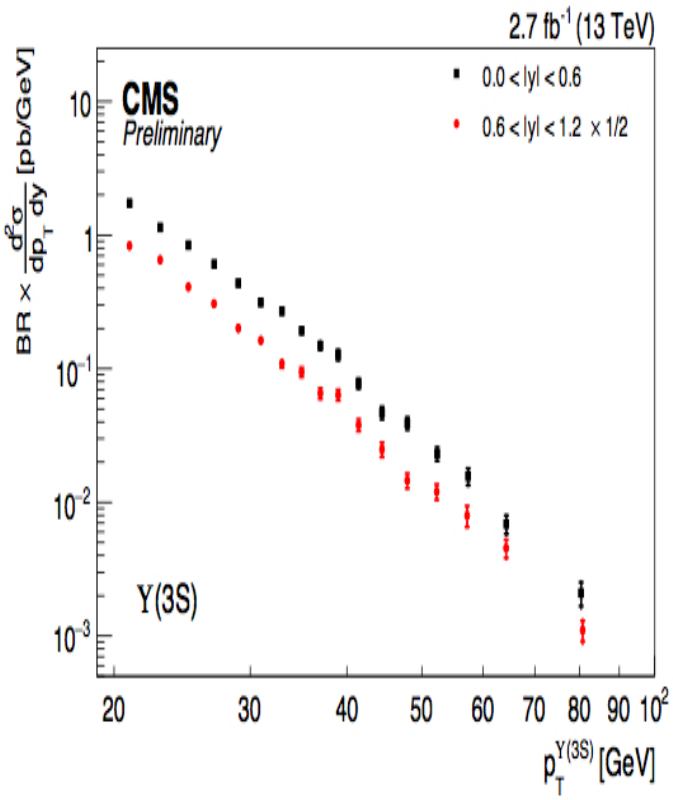
- Systematics include: Signal & BKG PDFs, resolution function, muon efficiency, limited MC statistics, non-prompt fraction (primary vertex choice, decay lenght PDFs)

σ(pp → Bottomonium) @ 13 TeV

- Double differential bottomonium cross sections:



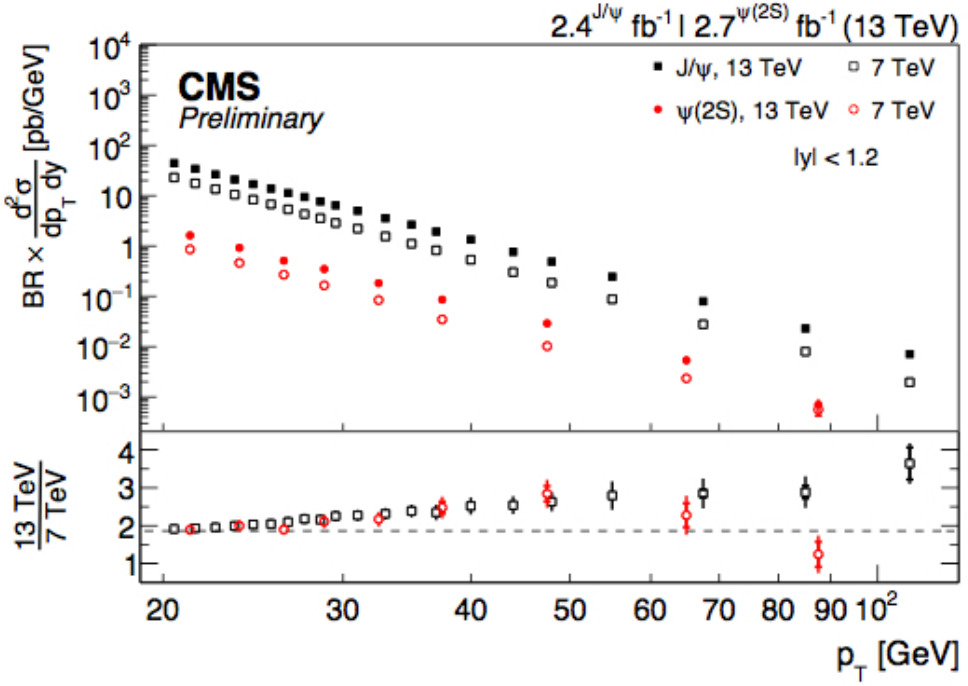


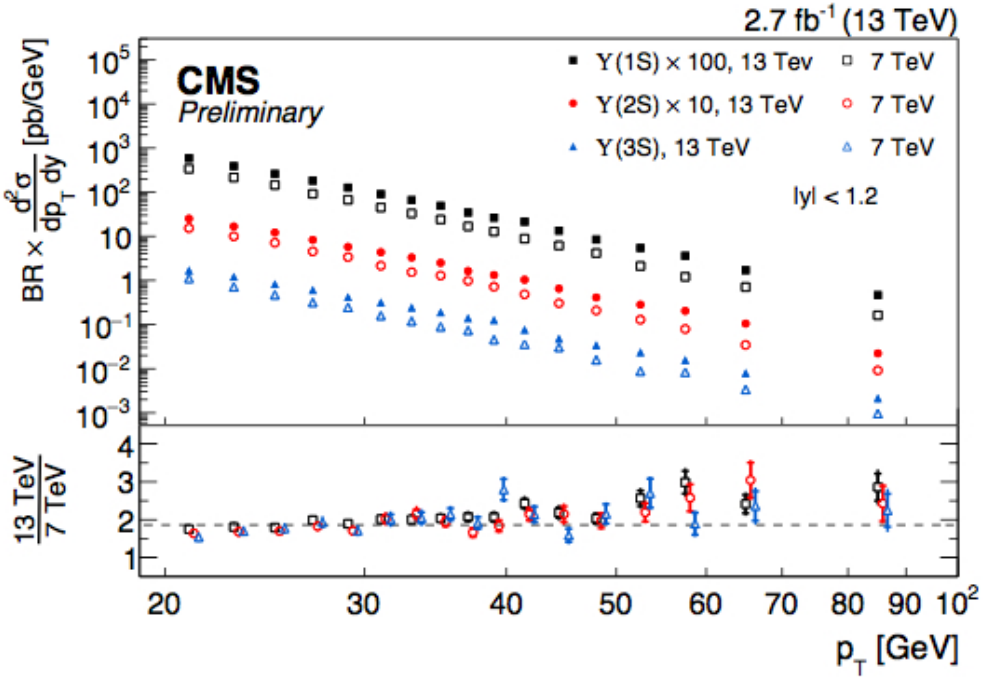


- Systematics include: Signal & BKG PDFs, resolution function, muon efficiency, limited MC statistics

σ(pp → Quarkonium) @ 13 TeV

- Comparison between different energies:

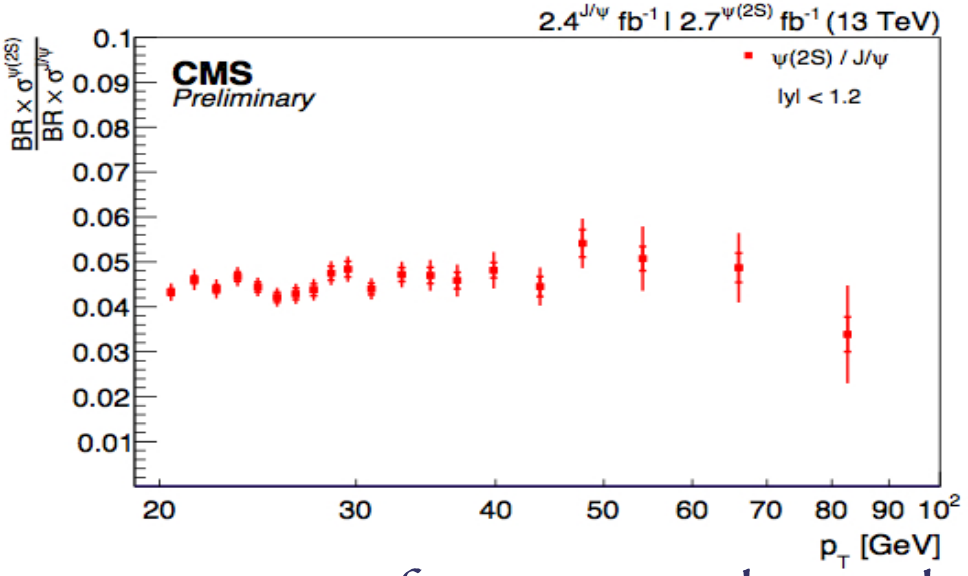


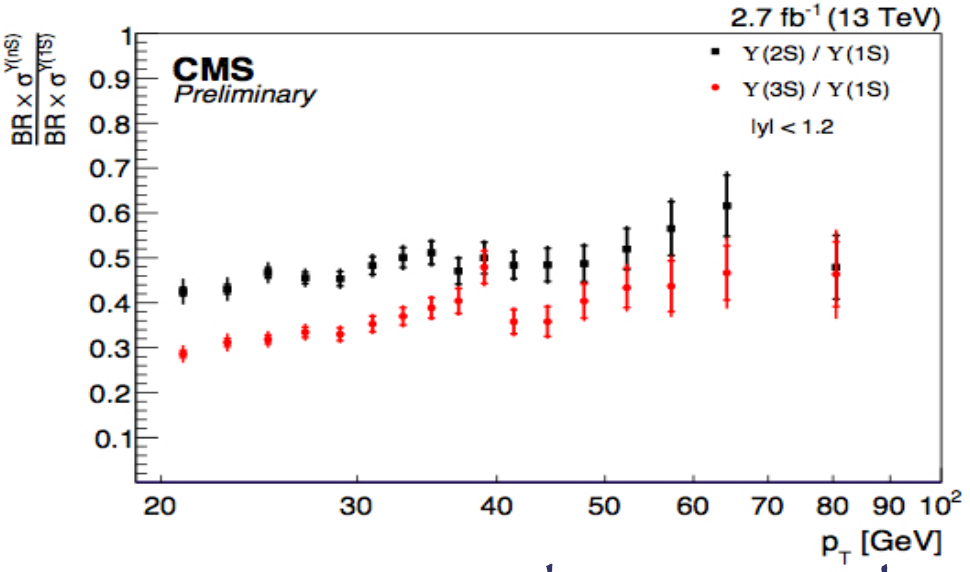


- Results for | y |<1.2 from weighted averages of different rapidity bins
- Cross section ratios ~ 2-3 with slow P_T dependence (expected from evolution of parton distribution function)
- NRQCD prediction @ 13 TeV to be updated

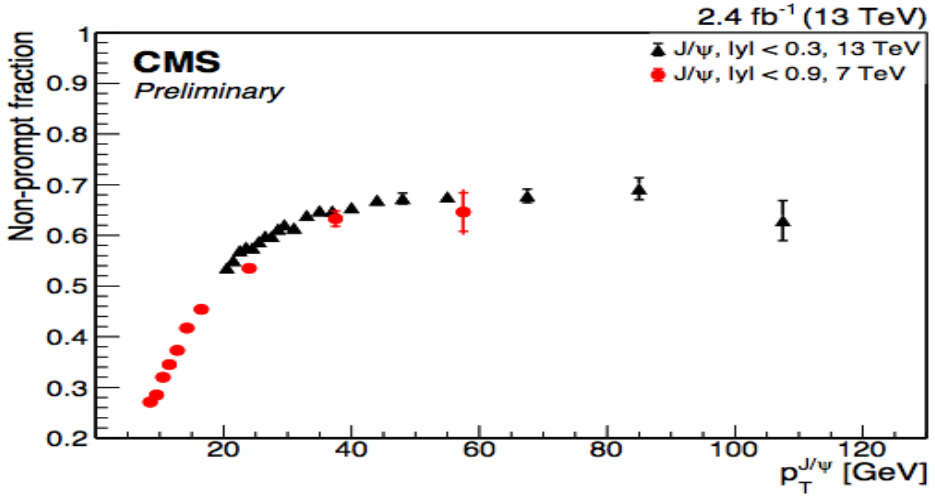
σ(pp → Quarkonium) @ 13 TeV

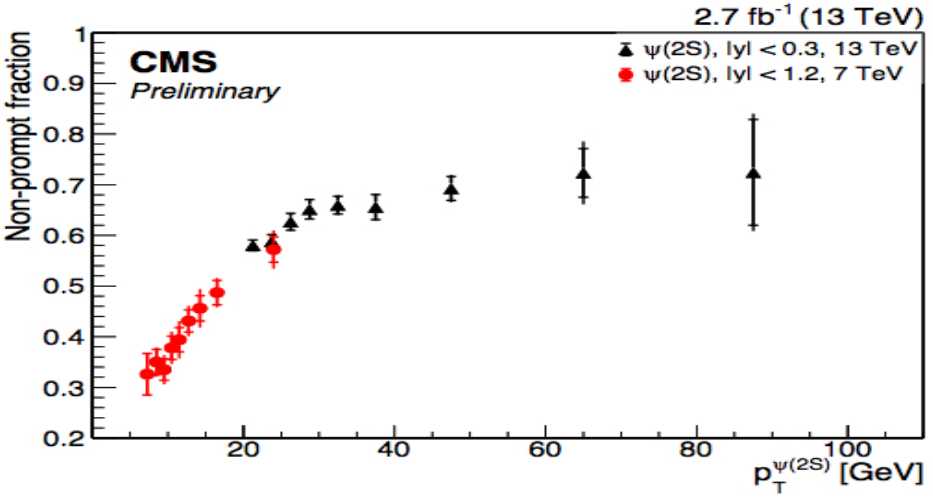
- Excited vs ground prompt fraction states :





- Non-prompt fraction P_T dependence in agreement with 7 TeV results





Υ(1S) pair production

- Quarkonia pair production measurements provide important tests of single(double)-parton-scattering mechianisms and tetra-quark states decays
- Measure pp → Υ(1S) Υ(1S) total cross section in the range P_T (Υ) < 50 GeV; |y (Υ)| < 2.0 :

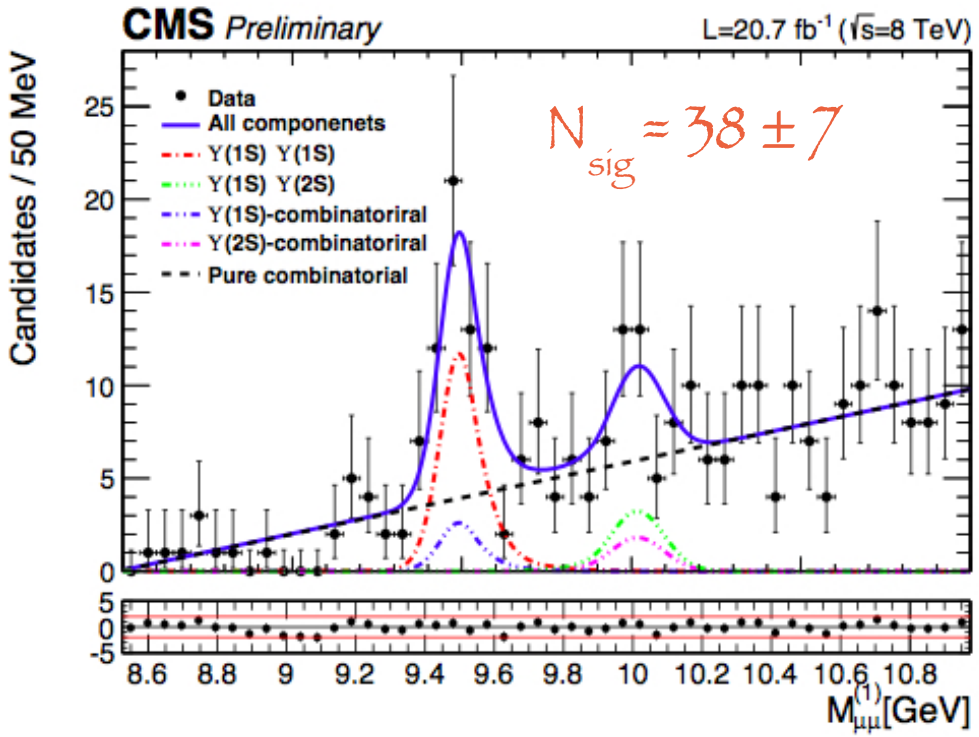
$$\sigma(pp \to YY) = \frac{N^{YY}}{BR(Y \to \mu\mu)^2 \cdot \mathcal{L}} \cdot \left\langle \frac{1}{\epsilon \cdot \mathcal{A}} \right\rangle$$

- Efficiency and Acceptance computed event-by-event on a MC sample using the measured Υ and muon momenta
- Υ mesons assumed to decay isotropically

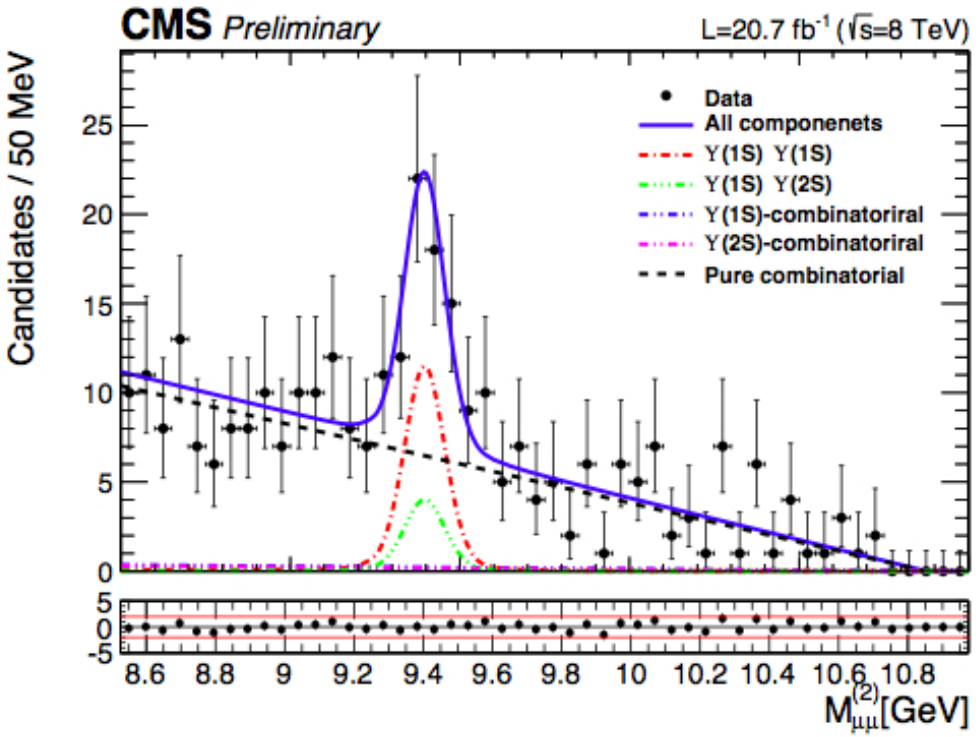
Υ(1S) pair production

- Υ pairs candidates reconstructed in events with four muons with total zero charge from the same vertex (P_T (μ) > 3.5 GeV; |y (μ)| < 2.4)
- Signal yields extracted from 2D ($m(\mu\mu)_{High}$, $m(\mu\mu)_{Low}$) invariant mass fit

Higher m(μμ)



Lower m(μμ)

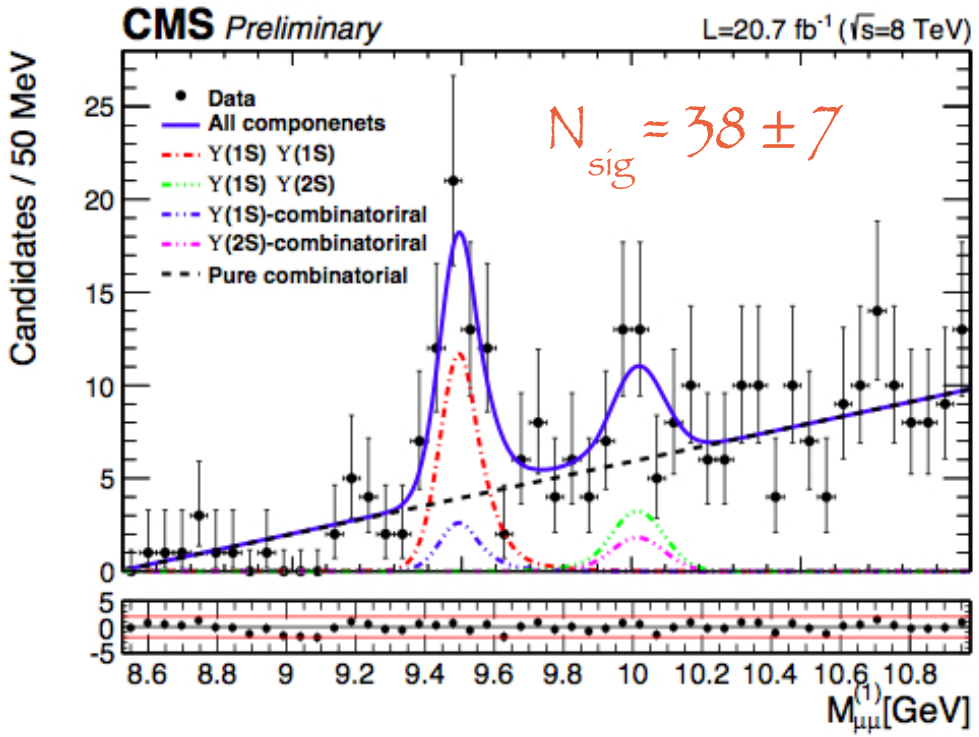


Υ(1S) pair production

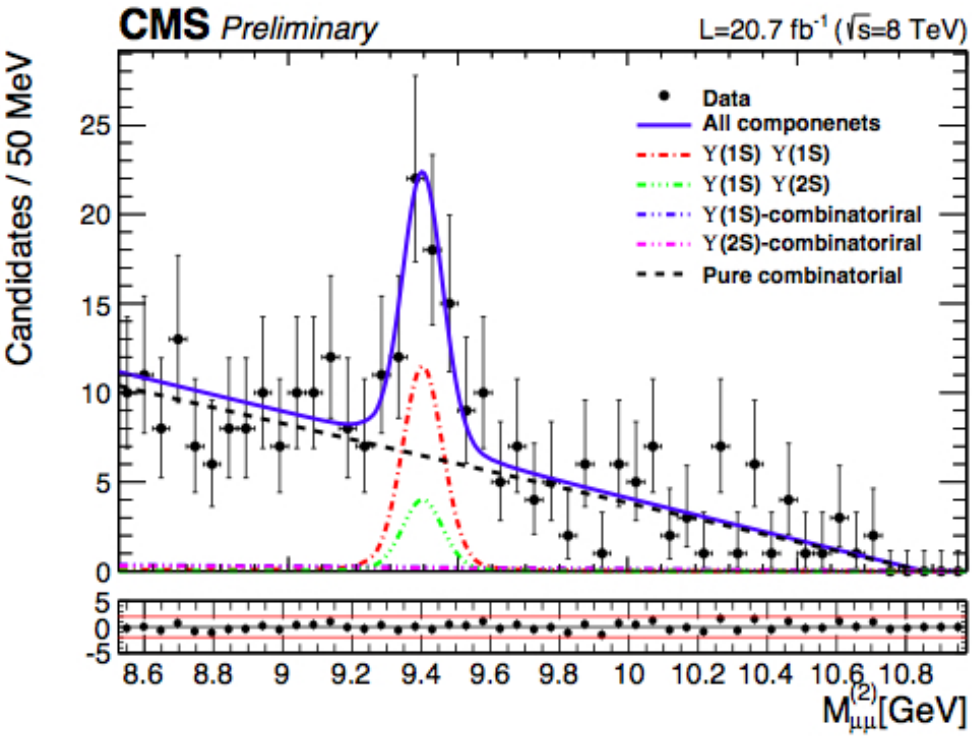
- Five components considered:

  Υ(1S) Υ(1S), Υ(1S) Υ(2S), Υ(1S) BKG, Υ(2S) BKG, Pure BKG
- Non-prompt Υ production negligible

Higher m(μμ)



Lower m(μμ)



Υ(1S) pair production

Result:

$$\sigma_{Tot} = 68.8 \pm 12.7 \pm 7.4 \pm 2.8\ (BR_{\Upsilon \to \mu\mu})\ pb$$

- Systematics from: signal & BKG PDF shapes, muon efficiency & acceptance, luminosity

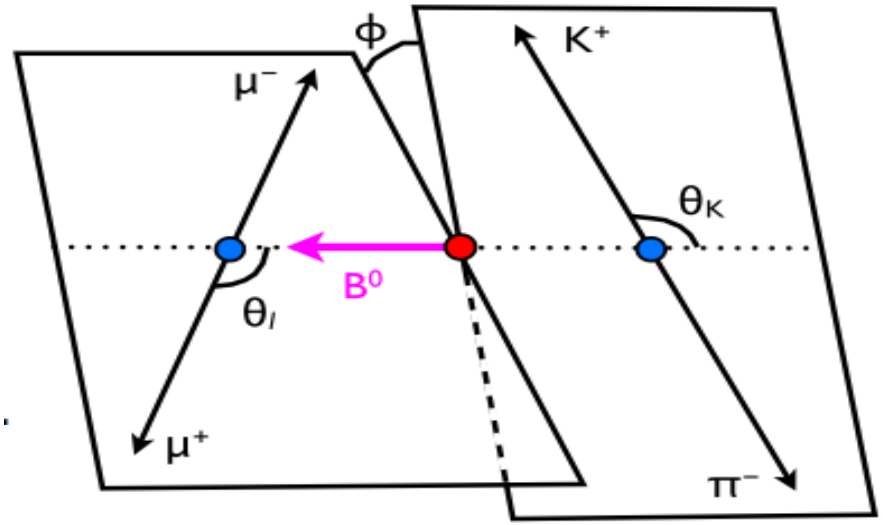
- Accepance sensitivity on Υ decay angular distribution checked for extreme scenarios of 100% longitudinal (transverse) Υ polarization
  - Total cross section variation fom -38% to +36%

FCNC in B Decays

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

- "Angular analysis of the decay $B^0 \to K^{*0}\mu\mu$ from pp collisions at $\sqrt{s} = 8$ TeV" [$L=20.5\ fb^{-1}$]
  Phys. Lett. B753, 424 (2016)

$B \to K^* \mu^+ \mu^-$



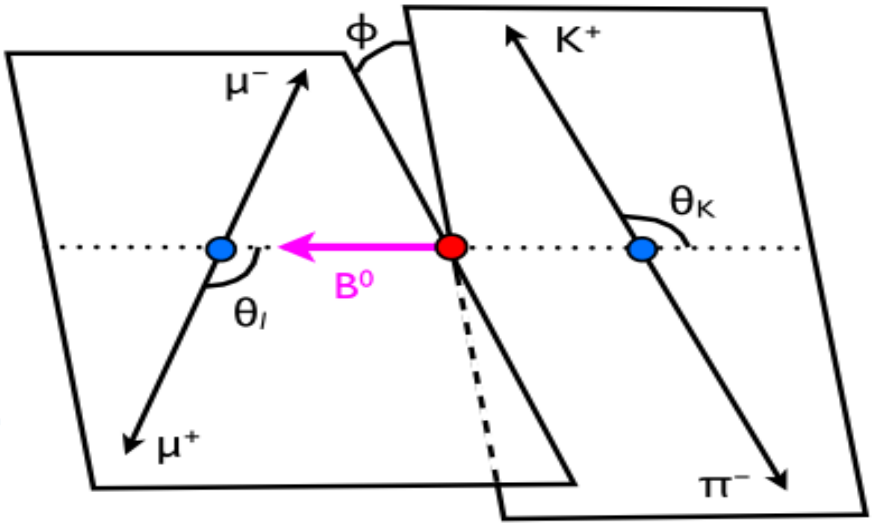
- Kinematics of the decay $B \to V \mu^+ \mu^-$ ($V=K^*, \varphi, \rho$) determined by three angles:
  - θ_l, θ_K, ϕ
- Event Yields reconstructed in bins of $q^2=m^2(\mu^+\mu^-)$
- ϕ integrated out in the current analysis

- Differential Amplitude:

$$\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_K\, d\cos\theta_l\, dq^2} = \frac{9}{16}\left\{\left[\frac{2}{3}F_S + \frac{4}{3}A_S\cos\theta_K\right](1-\cos^2\theta_l) + (1-F_S)\left[2F_L\cos^2\theta_K(1-\cos^2\theta_l) + \frac{1}{2}(1-F_L)(1-\cos^2\theta_K)(1+\cos^2\theta_l) + \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_l\right]\right\}.$$

- Observables Include:
  - Differential Branching Ratio dB/dq^2
  - A_{FB} (forward-backward muon asymmetry)
  - F_L (fraction of longitudinally polarized K^*)

$B \to K^* \mu^+ \mu^-$



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- F_S Fraction of spinless $K\pi$ (S-wave) combination
- A_S: Interference amplitude between S-wave and P-wave decays
- Small contributions (F_S <0.03, A_S ~-0.3/0.3 depending on the q^2 bin)

$B \to K^* \mu^+ \mu^-$

- Strategy:
  - Measure event yield Y_S, A_{FB} and F_L from an unbinned simultaneous fit to $M(K\pi\mu\mu)$, $\cos(\theta_K)$ and $\cos(\theta_l)$ in bins of q^2

$$PDF(m,\theta_K,\theta_l) = Y_S^C \left[S^C(m) S^a(\theta_K,\theta_l) \epsilon^C(\theta_K,\theta_l) \right.$$ Correctly Tagged Signal

$$\left. + \frac{f^M}{1-f^M} S^M(m) S^a(-\theta_K,-\theta_l) \epsilon^M(\theta_K,\theta_l) \right]$$ Mistagged Signal

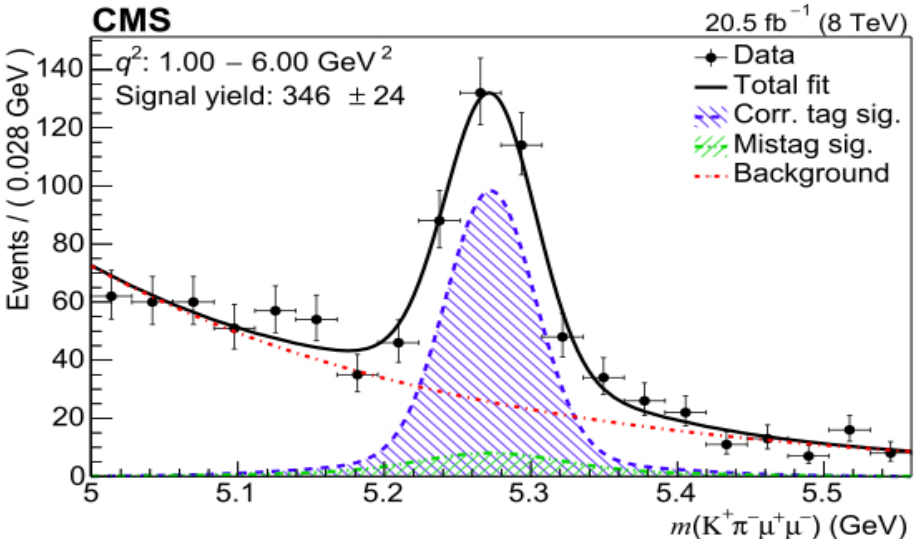
$$+ Y_B B^m(m) B^{\theta_K}(\theta_K) B^{\theta_l}(\theta_l)$$ BKG

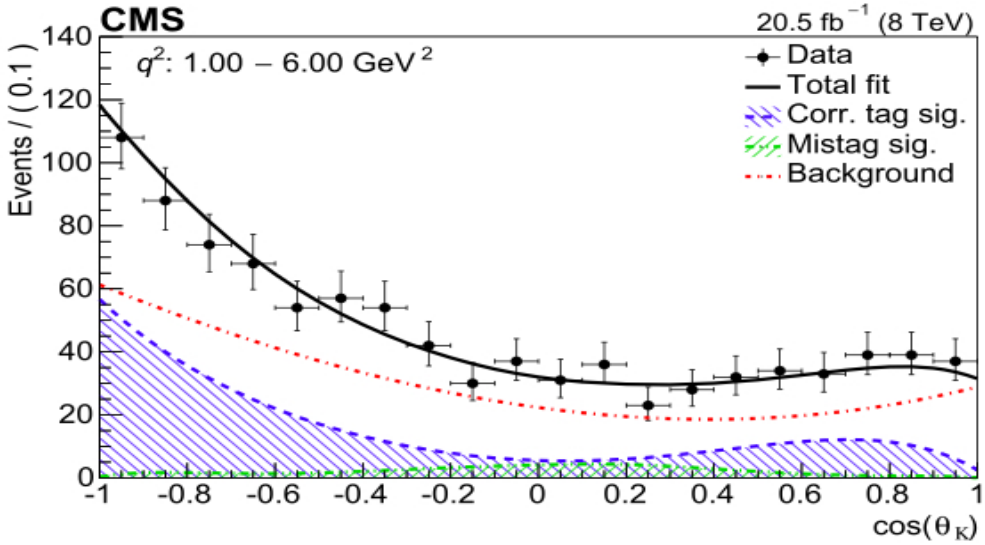
Y_S^C, Y_B	Event Yields
f^M	Fraction of mistagged signal events
$S^a(\theta_K,\theta_l), \epsilon^C(\theta_K,\theta_l), \epsilon^M(\theta_K,\theta_l)$	Signal angular shape and efficiency
$S^C(m), S^M(m), B(m)$	Mass PDFs
$B(\theta_{K(l)})$	Angular BKG PDFs from Data Side Bands

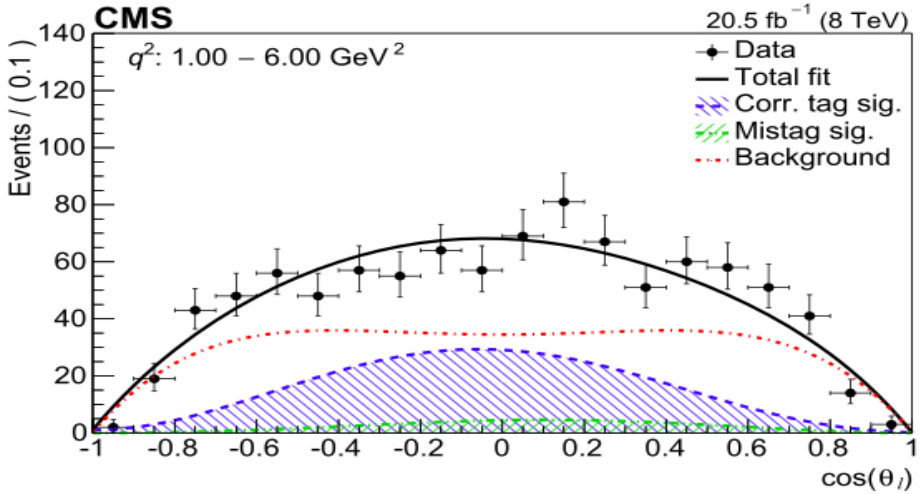
  - dB/dq^2 obtained relative to the normalization channel $B^0 \to K^* J/\psi$

$B \to K^* \mu^+ \mu^-$

- Strategy:
  - Measure event yield Y_S, A_{FB} and F_L from an unbinned simultaneous fit to $M(K\pi\mu\mu)$, $\cos(\theta_K)$ and $\cos(\theta_l)$ in bins of q^2





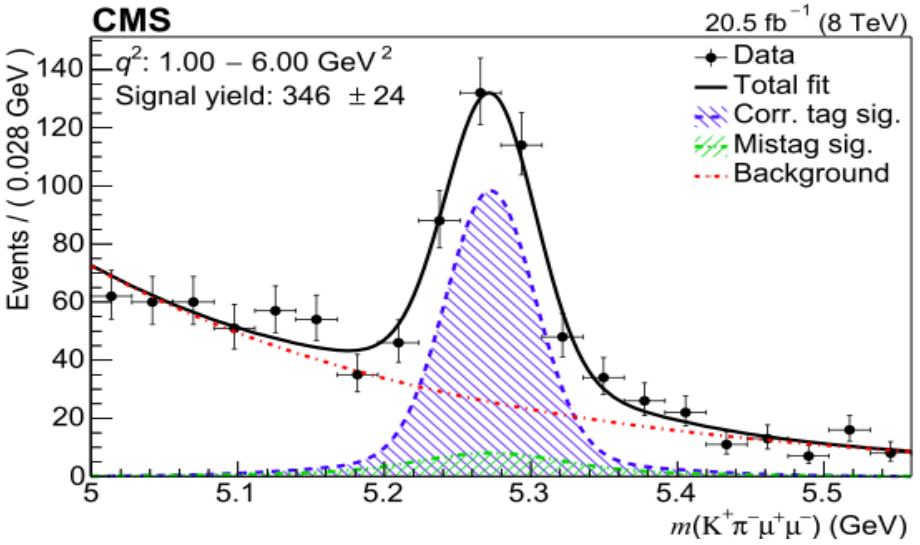


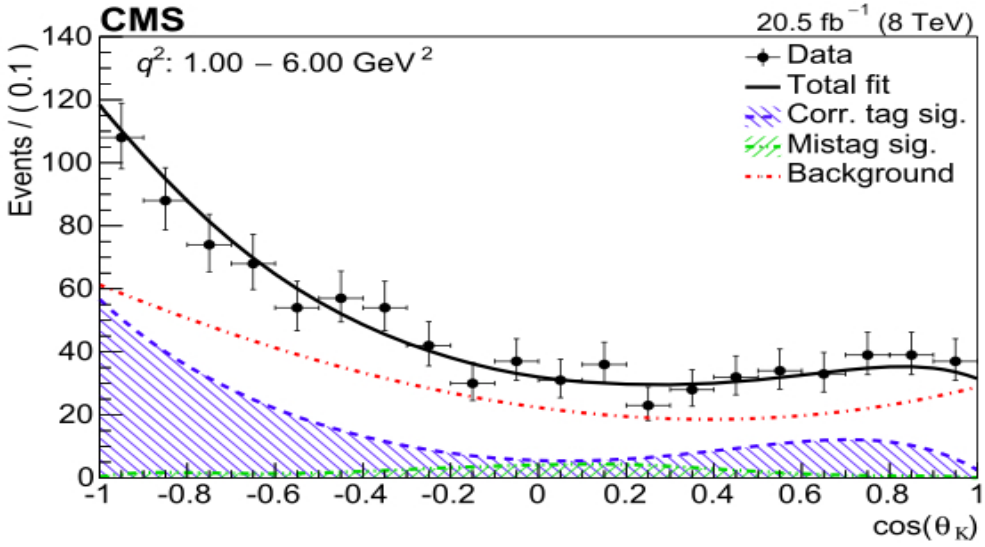
Example: $1 < q^2 < 6$ GeV^2

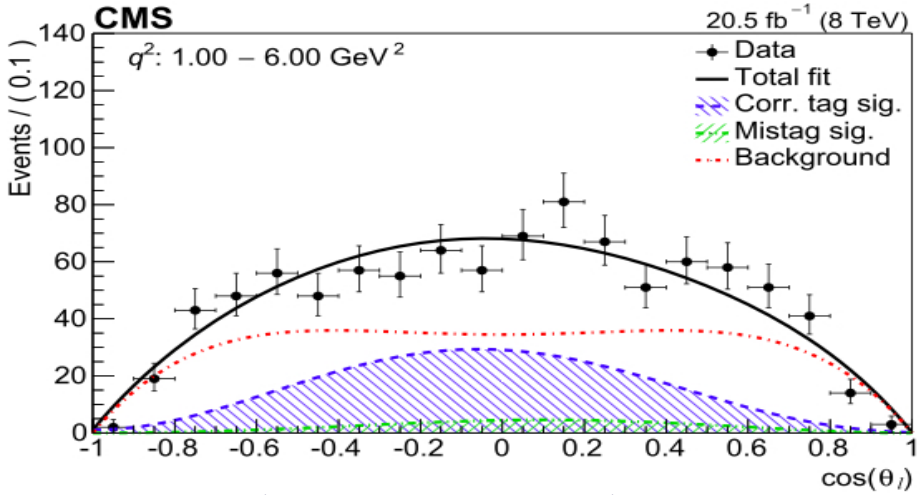
q^2 perturbative window with theory error under good control, away from $q^2 \to 0$ photon pole and $c\bar{c}$ resonances at higher q^2

$B \to K^* \mu^+ \mu^-$

- Strategy:
  - Measure event yield Y_S, A_{FB} and F_L from an unbinned simultaneous fit to $M(K\pi\mu\mu)$, $\cos(\theta_K)$ and $\cos(\theta_l)$ in bins of q^2

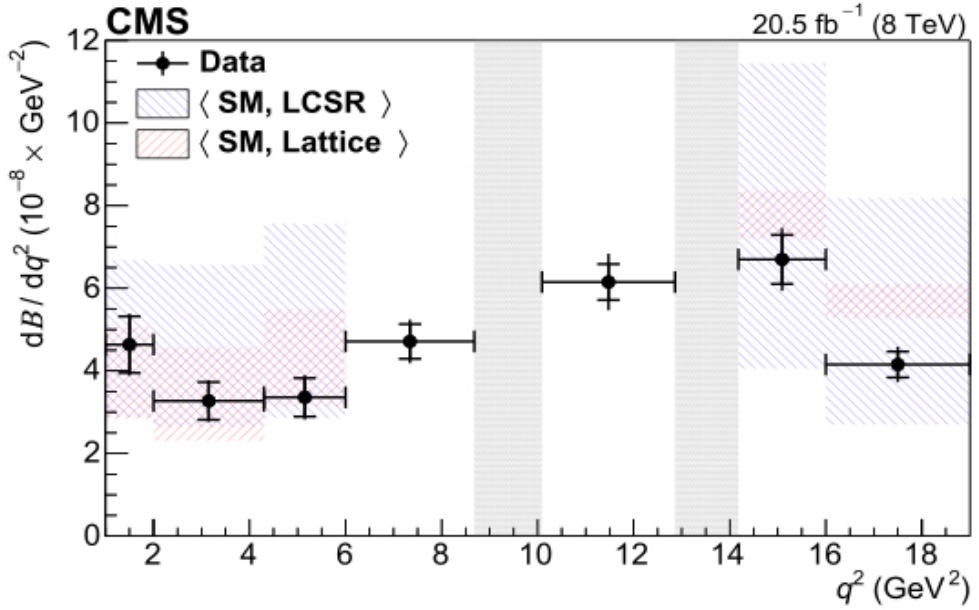


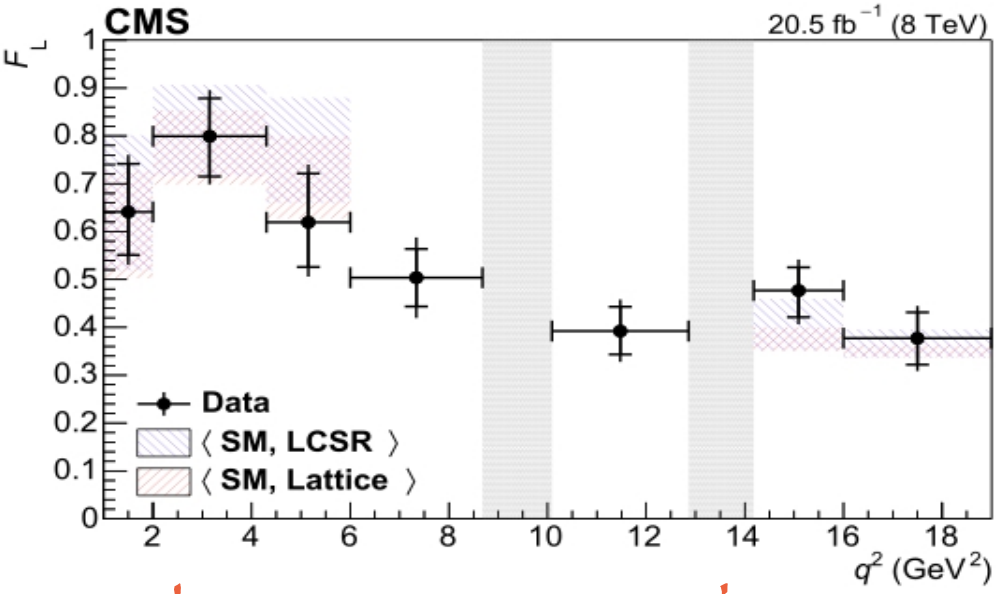


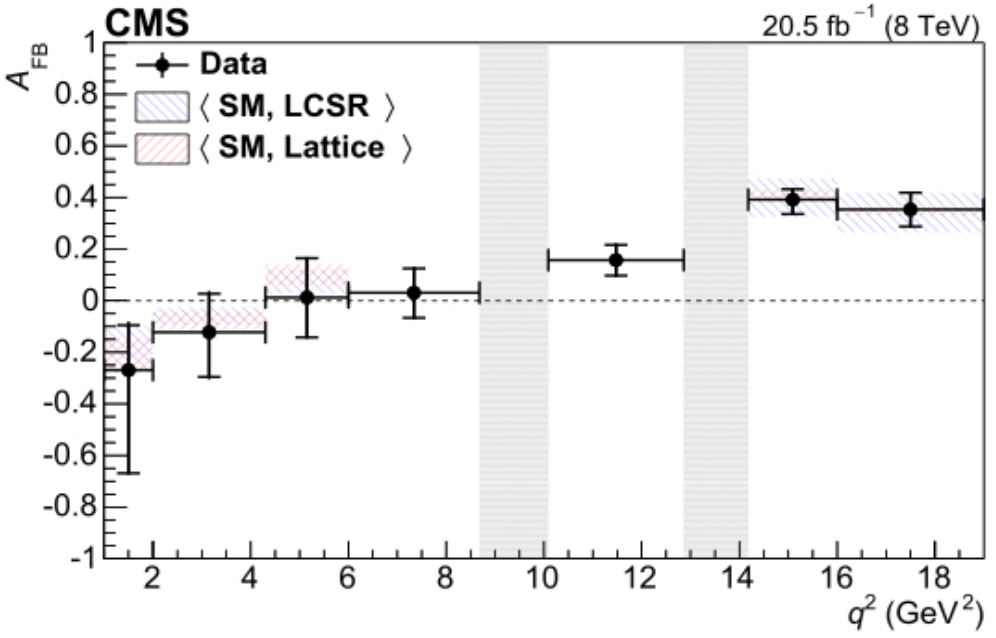


- Total of ~1400 signal evts reconstructed
- NO PID:
  - B flavor tagging from best m(Kπ)
  - Mistag fraction ≈ 12-14% from MC
- BKG PDFs from Data Side Bands

$B \to K^* \mu^+ \mu^-$: Results



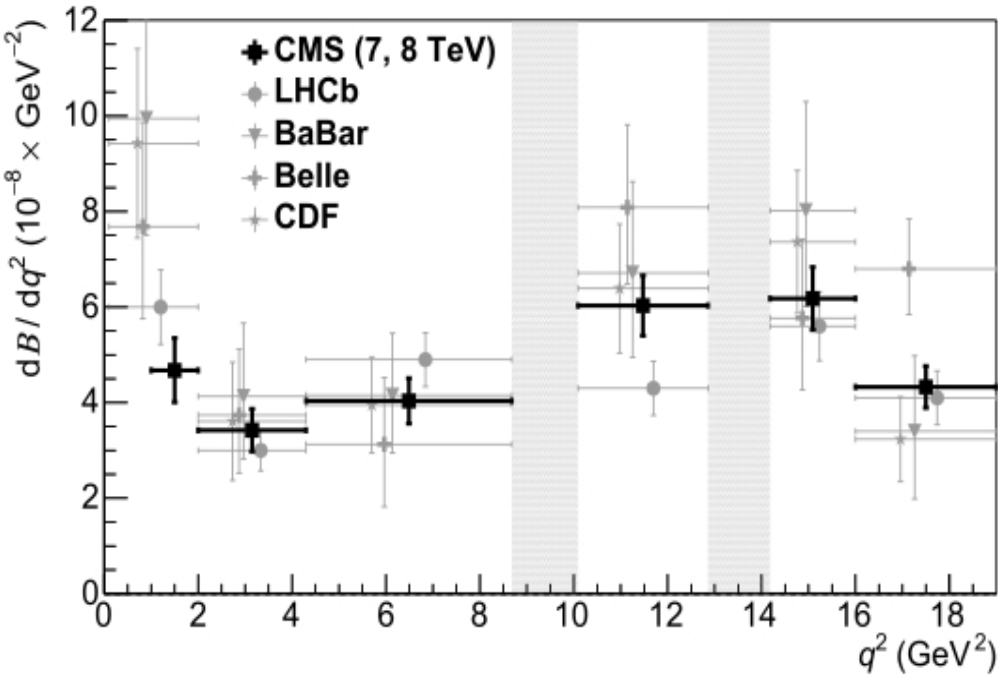


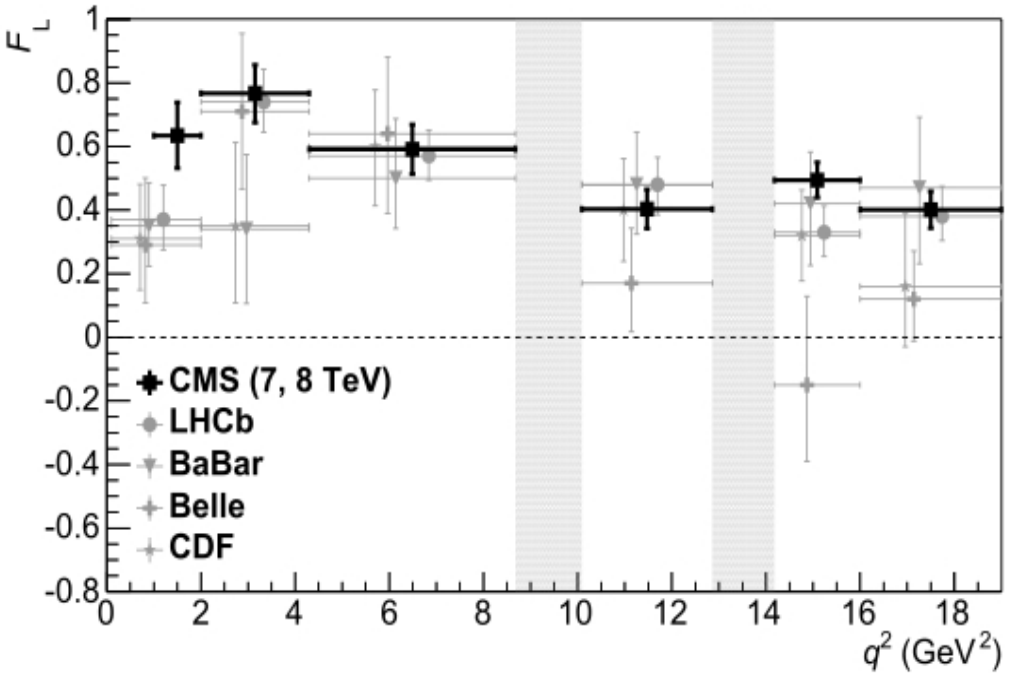


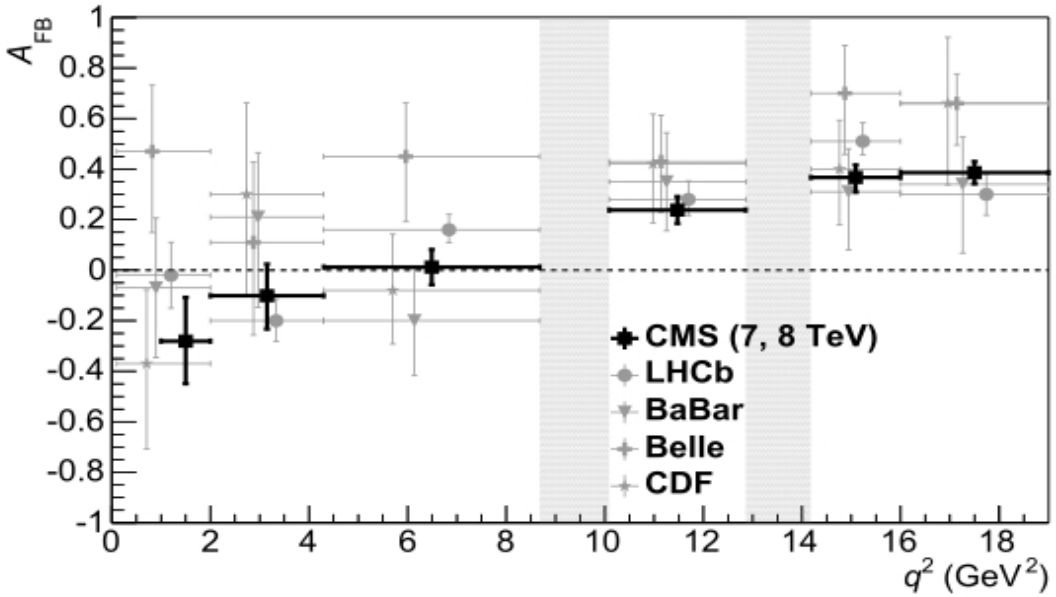
Results consistent with SM

- Systematics from BKG PDF shapes, efficiency, simulation mismodeling and fit bias.
- Theoretical predictions:
  - Light-cone sum rules at low q^2 and extrapolation at high q^2 [JHEP 09 089 (2010), JHEP 02 010 (2013)]
  - Lattice [Phys. Rev. D89 094501 (2014)]

Comparison with other experiments







What Next from CMS?

- Result using new angular variable P5' with reduced Form-Factor dependence expected soon

FCNC in Top Decays

$t \rightarrow Zq$:

- "Search for Flavor-Changing Neutral Currents in Top-Quark Decays $t \rightarrow Zq$ in pp Collisions at $\sqrt{s} = 8$ TeV" [$L=19.7\ fb^{-1}$] Phys. Rev. L. 112, 171802 (2014)

$t \rightarrow Hq$:

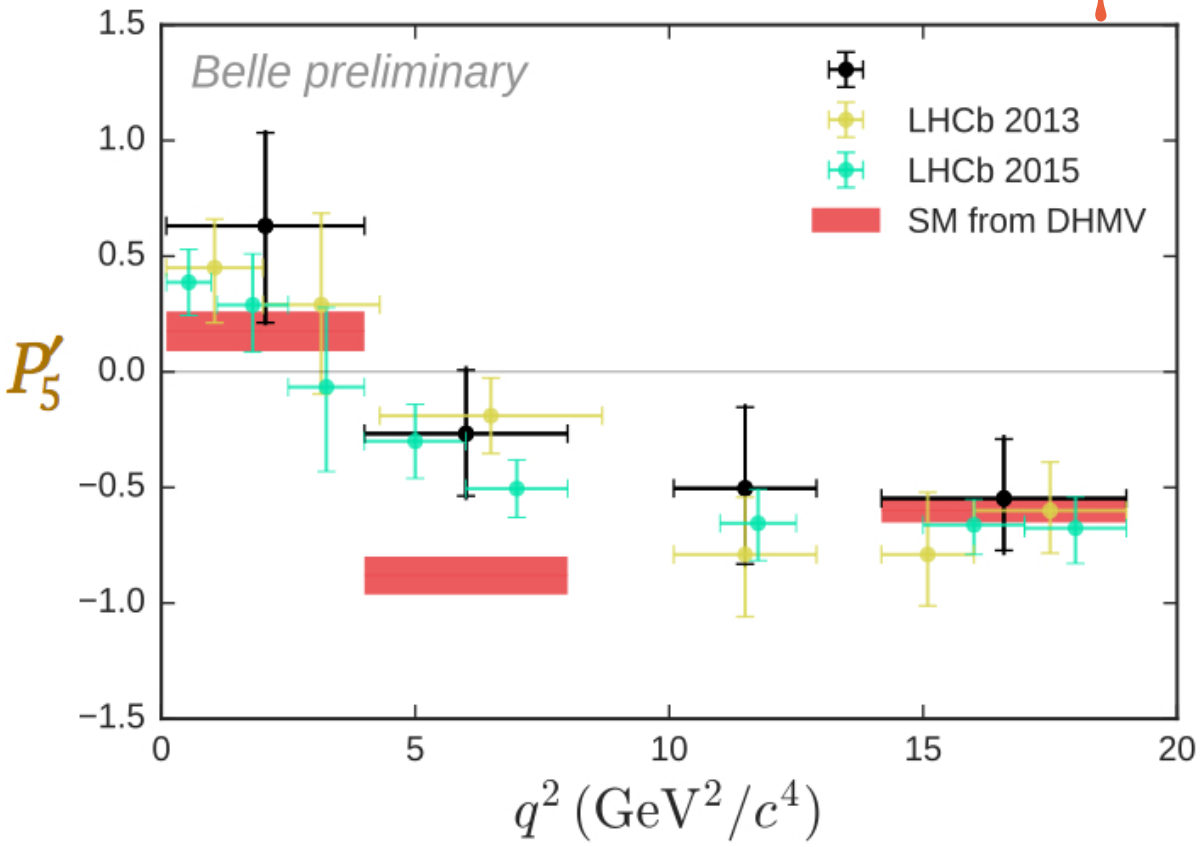
- "Search for top quark decays via Higgs-boson-mediated flavor changing neutral currents in pp collisions at $\sqrt{s} = 8$ TeV" [$L=19.7\ fb^{-1}$] Preliminary
- "Search for top quark decays $t \rightarrow qH$ with $H \rightarrow \gamma\gamma$ in pp collisions at $\sqrt{s} = 8$ TeV" [$L=19.7\ fb^{-1}$] Preliminary
- "Search for the Flavor-Changing Neutral Current Decay $t \rightarrow qH$ where the Higgs decays to bb Pairs at $\sqrt{s} = 8$ TeV" [$L=19.8\ fb^{-1}$] Preliminary

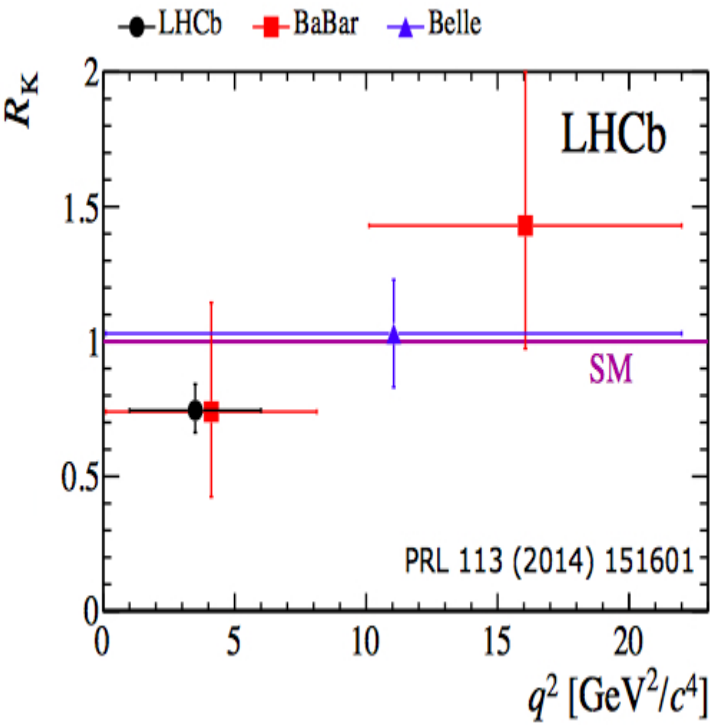
Single $t + \gamma$:

- "Search for anomalous single top quark production in association with a photon in pp collisions at $\sqrt{s} = 8$ TeV" [$L=19.8\ fb^{-1}$] JHEP 04, 035 (2016)

Backup

$B \to K^* \mu^+ \mu^-$

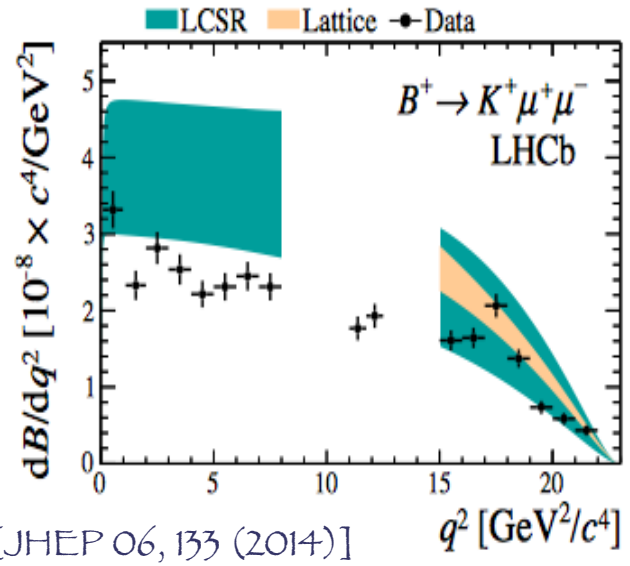


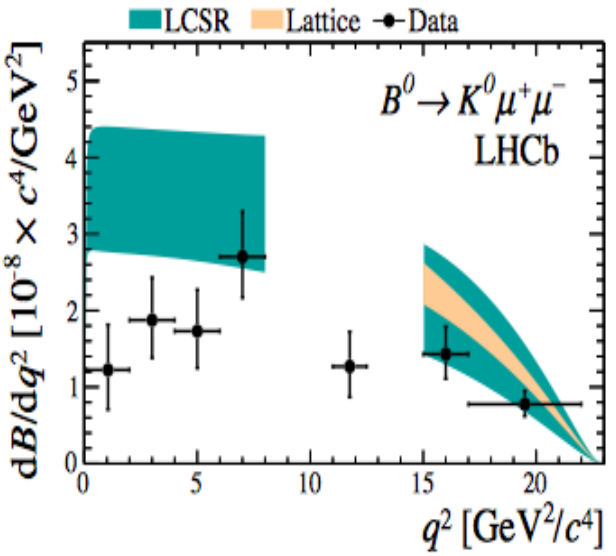


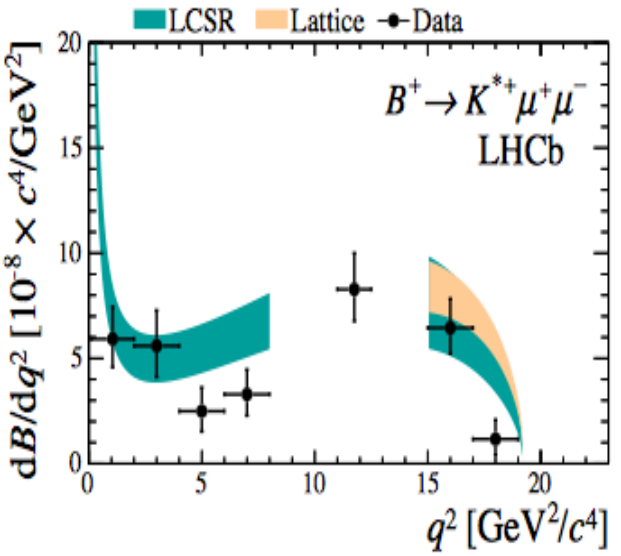
- LHCb full statistics result on P5': discrepancy at 3.4 σ level [JHEP 02, 104 (2016)]
- Belle confirms the tension at 2.1 σ level [arXiv:1604.04042]
- Need to control the charm penguin to disentangle SM from NP in C_7^{eff} and C_9^{eff}

B → K* ll Related quantities

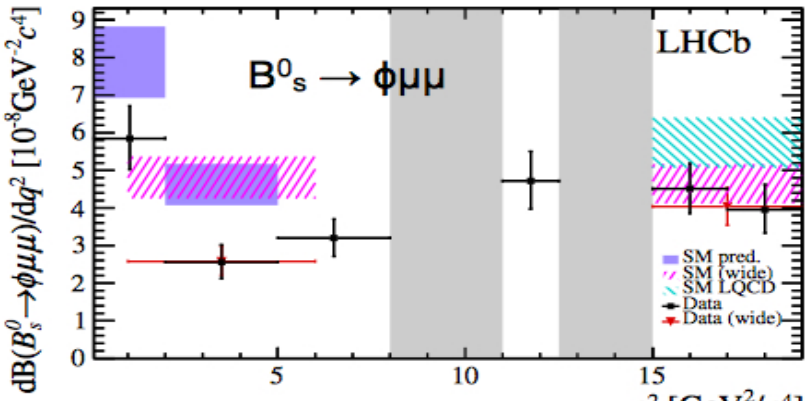
- K* μ⁺μ⁻ tension motivates studies of differential BRs



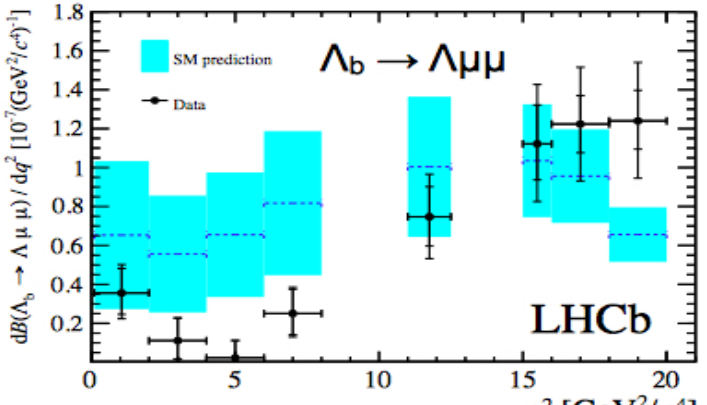




[JHEP 06, 133 (2014)]



[JHEP 09, 179 (2015)]

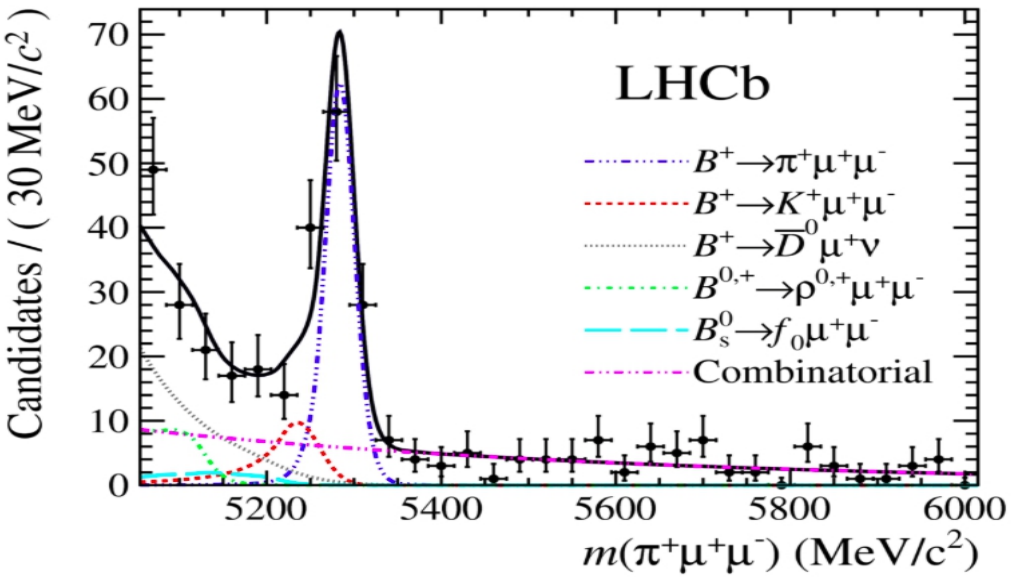


[JHEP 06, 115 (2015)]

- All the results are "consistent" with SM at <2.2 σ
- But all of them are lower than the predictions…

$B \to \pi\, l^+ l^-$

- Measurements of related b → dμμ channels very useful to reveal information on Minimal Flavor Violat nature of New Physics



LHCb [JHEP 10, 034 (2015)]:

$BR(B^+ \to \pi^+\mu^+\mu^-) = (1.83 \pm 0.24 \pm 0.05)\,10^{-8}$ in agreement with MFV

$BR(B^+ \to \pi^+\mu^+\mu^-)/BR(B^+ \to K^+\mu^+\mu^-) = 0.037 \pm 0.008 \pm 0.001$

$|V_{td}|/|V_{ts}| = 0.24^{+0.05}_{-0.04}$ in agreement with box processes ($\Delta m_s/\Delta m_d$) results