ICNFP 2016 - Crete - 6-14 July 2016

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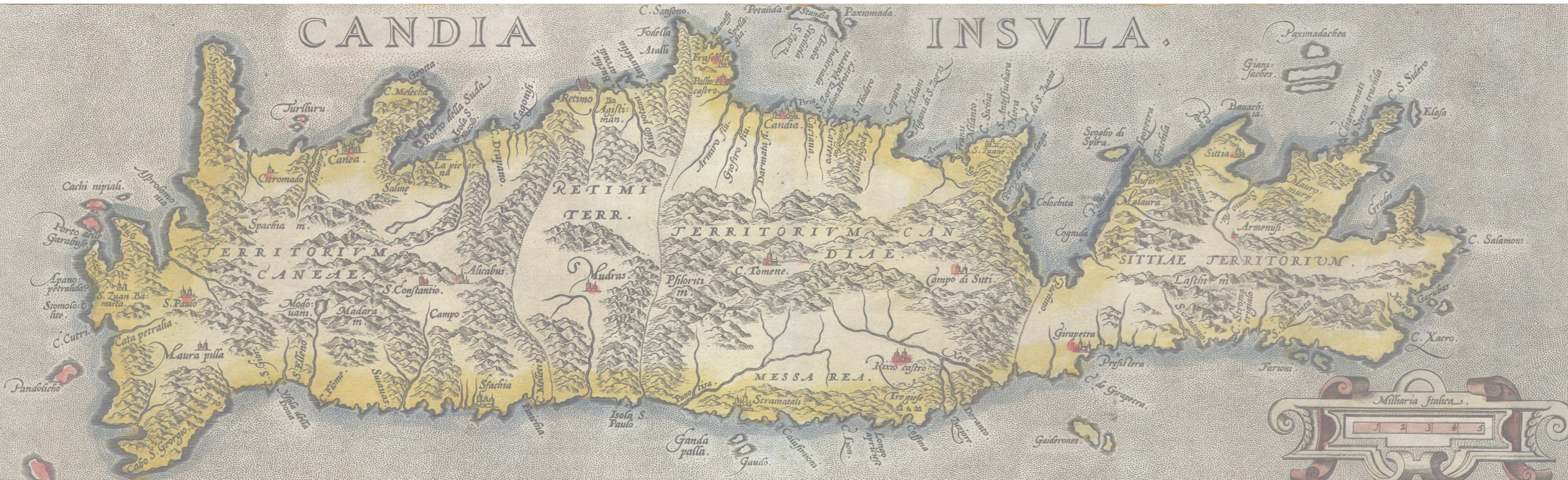
on behalf of
CMS Collaboration

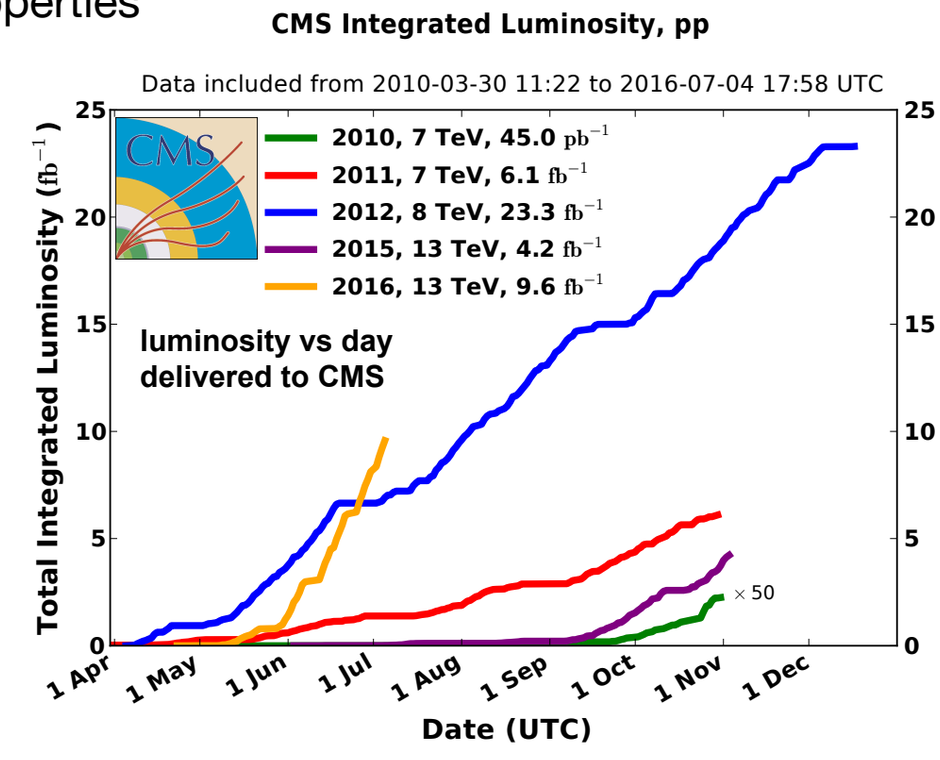
B physics and Quarkonia in CMS



Flavor physics @CMS

- The CMS experiment at the LHC has a rich and competitive heavy flavor program
- CMS flavour physics objectives:
  - understand the underlying **QCD processes**:
    - measuring the spectrum of heavy flavour production (x-sections and polarizations of quarkonia and other states)
    - looking for new exotic quarkonia states and new mesons/baryons
  - test the **Standard Model** predictions with **high precision** measurements:
    - studying decay rates, lifetimes, CPV and other b hadron properties
  - look for **New Physics indications** in the rare decays

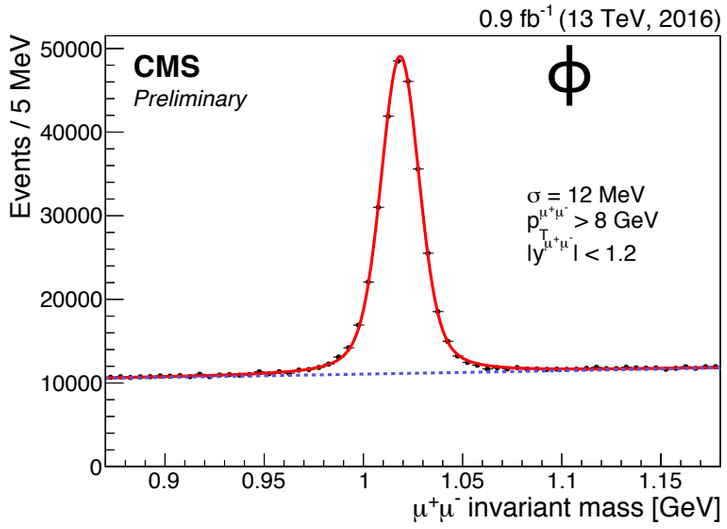
- **Only selected recent results are presented in this talk**
  - measurements based on 8 and 13 TeV data collected during 2012, 2015 and 2016

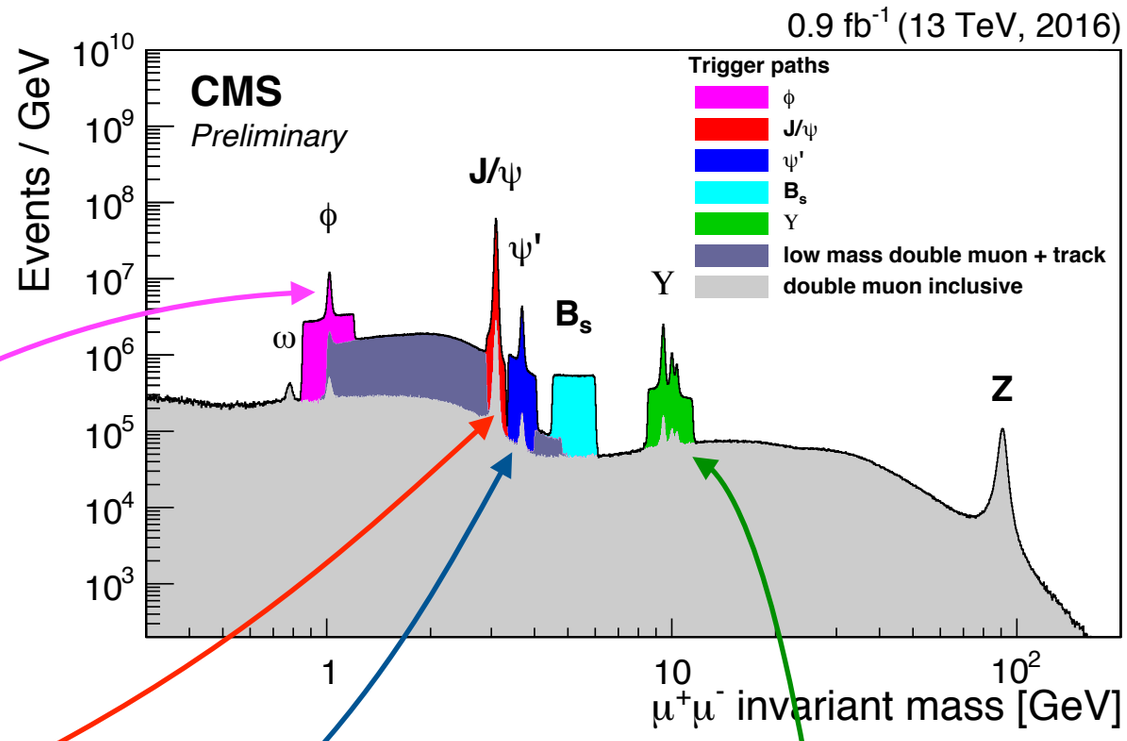


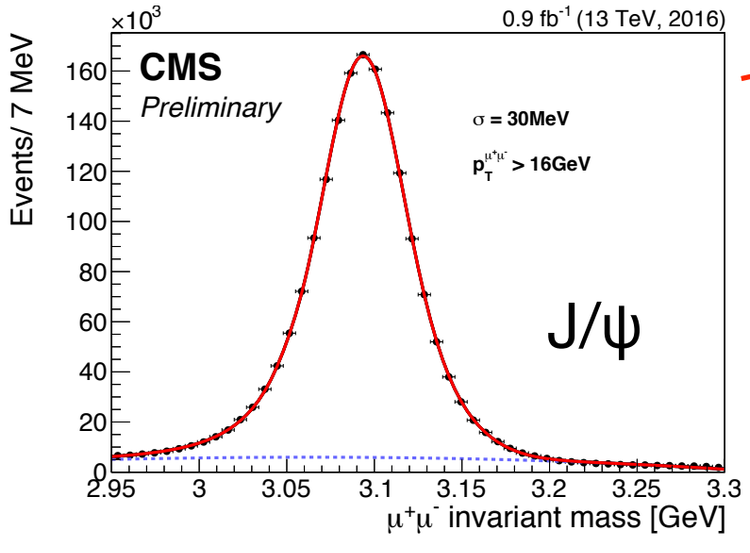
CMS B-physics triggers

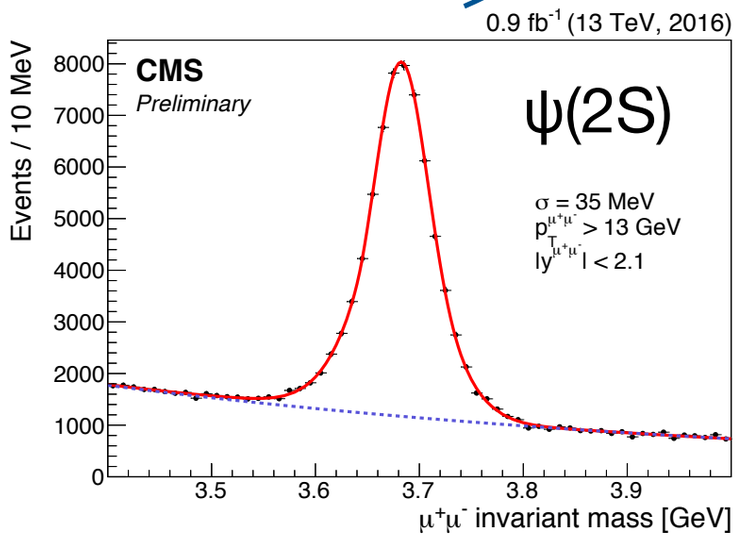
https://cds.cern.ch/record/2161025
https://cds.cern.ch/record/2160343

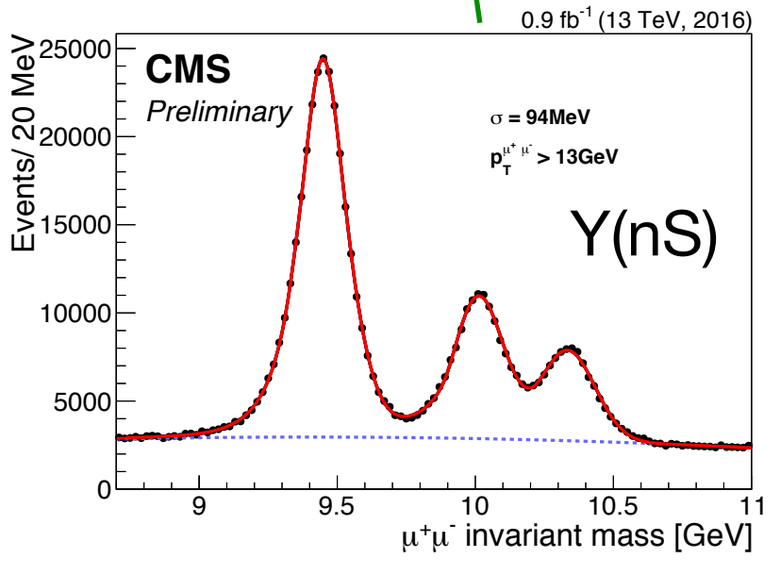
- Flavor physics analyses rely on dimuon triggers
  - **displaced/non-displaced quarkonia (ϕ, J/ψ, ψ(2S), Υ)**







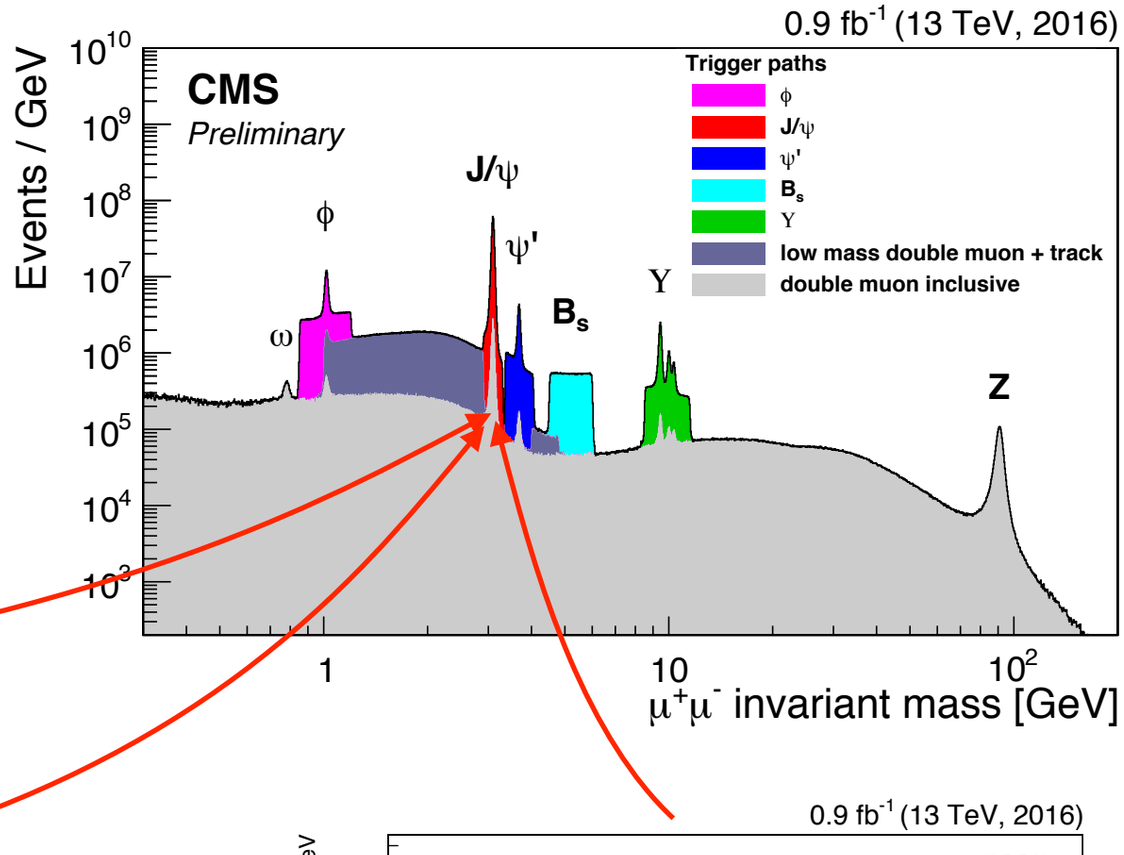


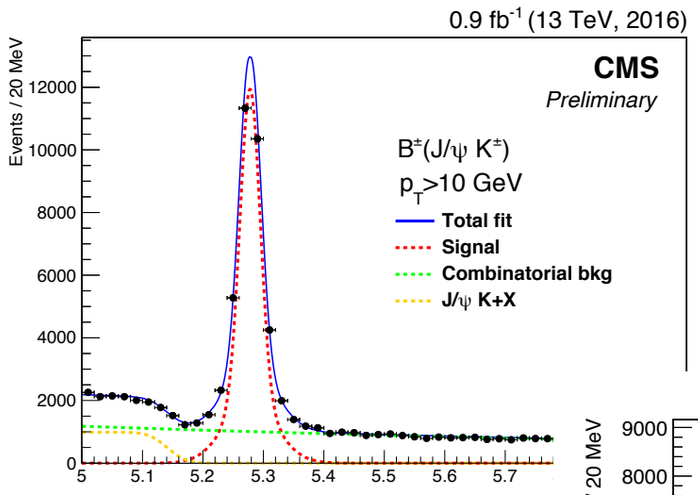


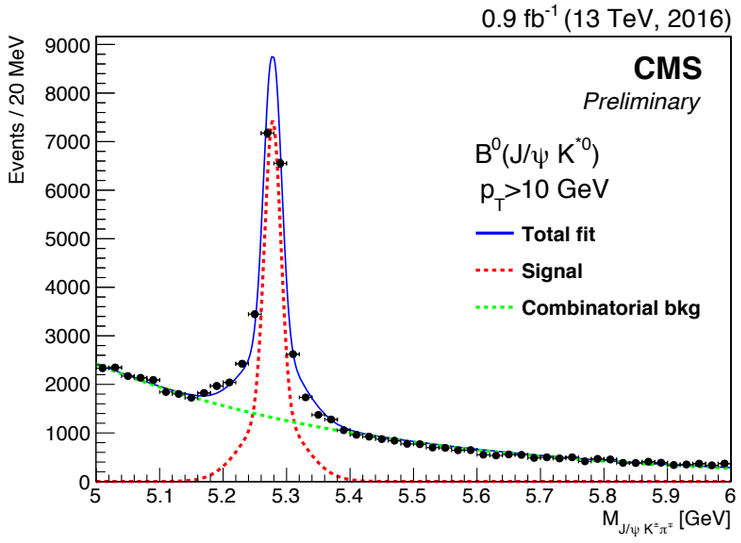
CMS B-physics triggers

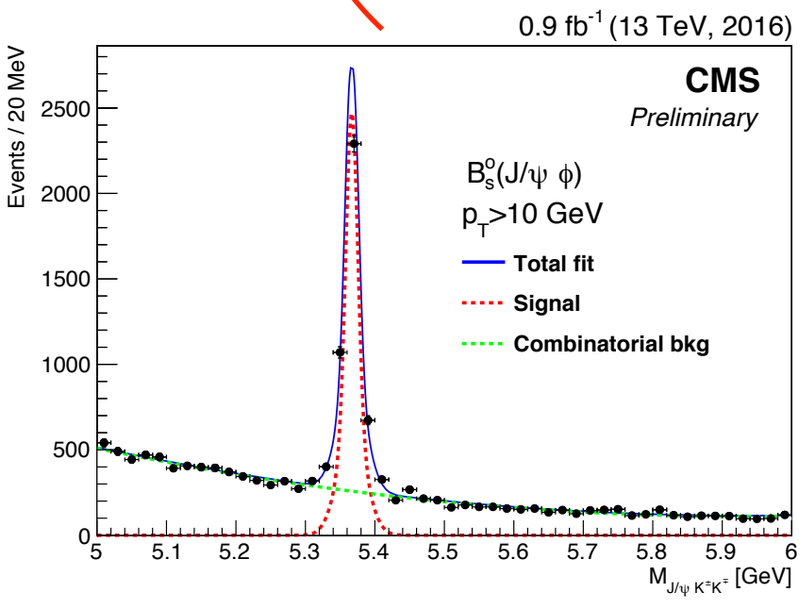
https://cds.cern.ch/record/2161025
https://cds.cern.ch/record/2160343

- Flavor physics analyses rely on dimuon triggers
  - displaced/non displaced quarkonia (ϕ, J/ψ, ψ(2S), Υ)
  - non resonant dimuon
  - **dimuon + track triggers**









B^+ production cross section at 13 TeV

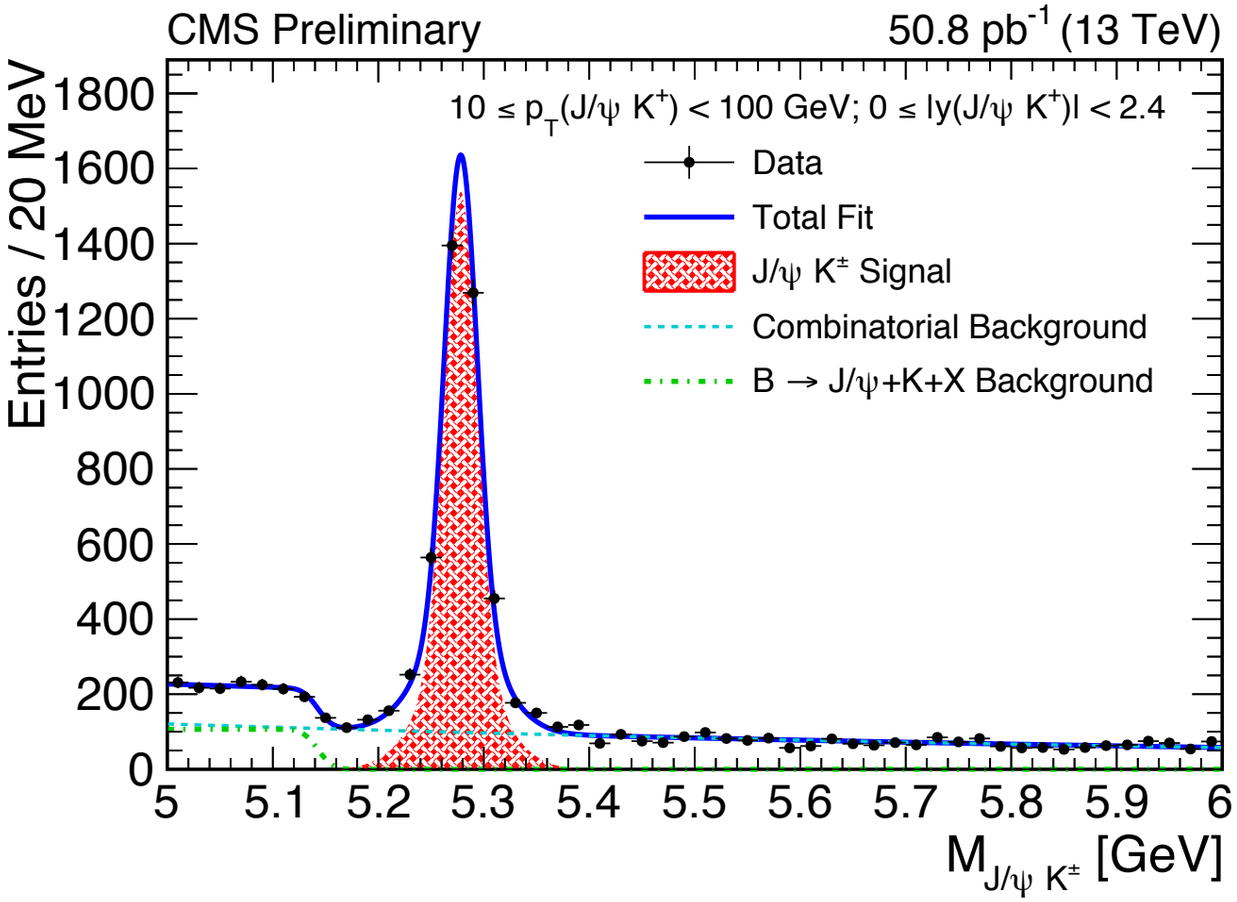
CMS-PAS-BPH-15-004

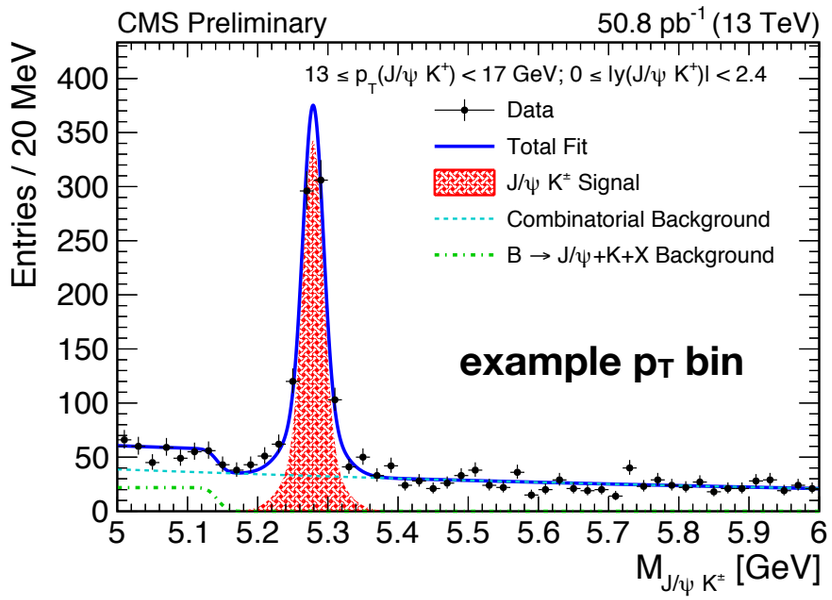
- Measurement at 13 TeV complements the cross section measurements already pursued during Run I
- Provides new important tests of theoretical calculations at higher energy
- **First 13 TeV B^+ production cross section measurement**
  - exploiting the exclusive decay channel $B^+ \rightarrow J/\psi K^+$, with $J/\psi \rightarrow \mu^+\mu^-$
  - differential cross section as a function of B transverse momentum and rapidity
  - based on 50.8 pb^{-1} at 13 TeV from 2015 dataset with 50 ns bunch spacing
    - collected with displaced dimuon trigger
    - phase space region $10 < p^B_T < 100$ GeV and $|y^B| < 2.4$

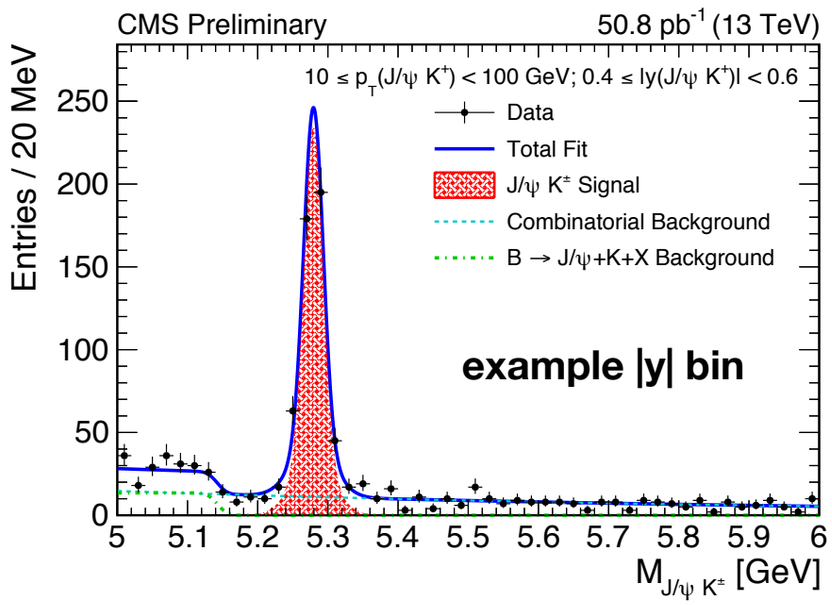
Signal extraction

CMS-PAS-BPH-15-004

- The signal yield is extracted with an extended unbinned maximum likelihood fit to the invariant mass distribution of the B^+ candidates, in p^B_T or $|y^B|$ bins
  - signal model: sum of two gaussians
  - combinatorial background: exponential function
  - mis-reconstructed B → J/ψ + track + X decays: error function







Cross section measurement

CMS-PAS-BPH-15-004

- Differential cross sections as a function of p_T for $|y^B| < 2.4$ and as a function of absolute rapidity for $10 < p^B_T < 100$ GeV are measured

signal yield in the given bin

$$\frac{\mathrm{d}\sigma(\mathrm{pp} \to \mathrm{B}^+ X)}{\mathrm{d}p_\mathrm{T}^\mathrm{B}} = \frac{n_\mathrm{sig}(p_\mathrm{T}^\mathrm{B})}{2\,A \cdot \epsilon(p_\mathrm{T}^\mathrm{B})\,\mathcal{B}\,\mathcal{L}\,\Delta p_\mathrm{T}^\mathrm{B}}$$

Bin width

cross section for single charge

Acceptance
as evaluated on the simulation

Efficiencies
are measured on data

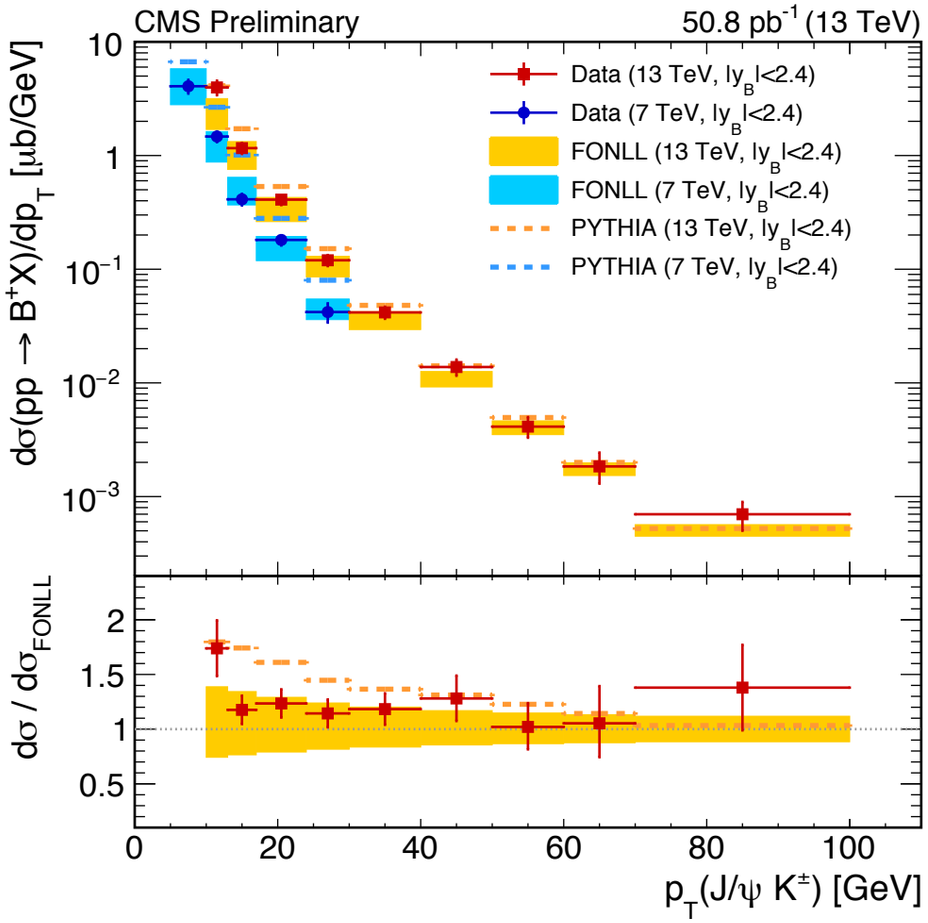
$\mathcal{B} = \mathcal{B}(B^+ \to J/\psi K^+) * \mathcal{B}(J/\psi \to \mu^+\mu^-)$

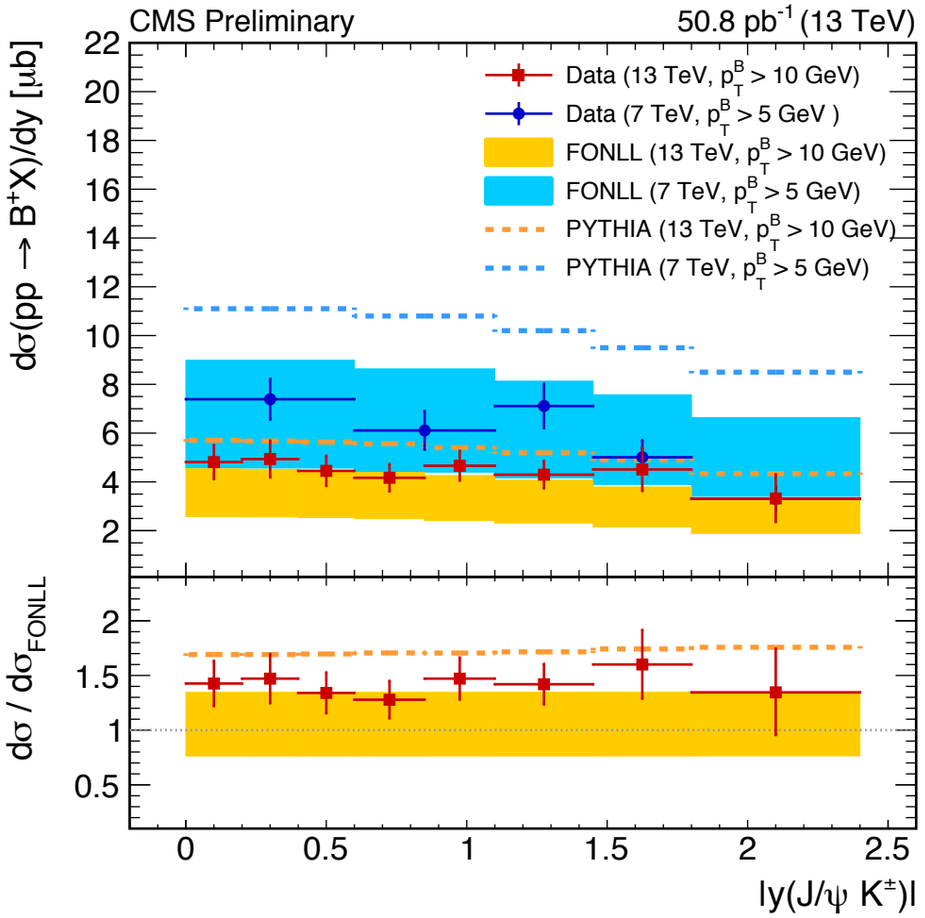
- Systematic uncertainties related to signal and background models, p_T and y resolution, generator distributions, B^+ lifetime, trigger and muon/track reconstruction, size of the simulation and luminosity have been evaluated

B^+ cross section results

CMS-PAS-BPH-15-004

- Differential measurements are compared to FONLL and PYTHIA calculations
  - reasonable agreement, both in terms of shape and of normalization, with FONNL calculations and PYTHIA simulation
- 7 TeV measurements are also shown for completeness





Quarkonia cross section at 13 TeV

CMS-PAS-BPH-15-005

- Run I experiments at the LHC provided precise measurements of cross sections and polarizations for five quarkonium states: J/ψ, ψ(2S), and Υ(nS) (n= 1, 2, 3)
- Comparison of the 13 TeV to 7 TeV results offers a good opportunity to test NRQCD factorization hypotheses
- Also, the extended p_T reach at 13 TeV and the improved statistical precision can provide further comparisons with theoretical calculations
- Quarkonium states reconstructed in the dimuon decay channel, for dimuon rapidity $|y| < 1.2$
- based on 2.4 (2.7) fb^{-1} from 2015 dataset for J/ψ (other mesons)

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

signal yield in the given bin

Bin width

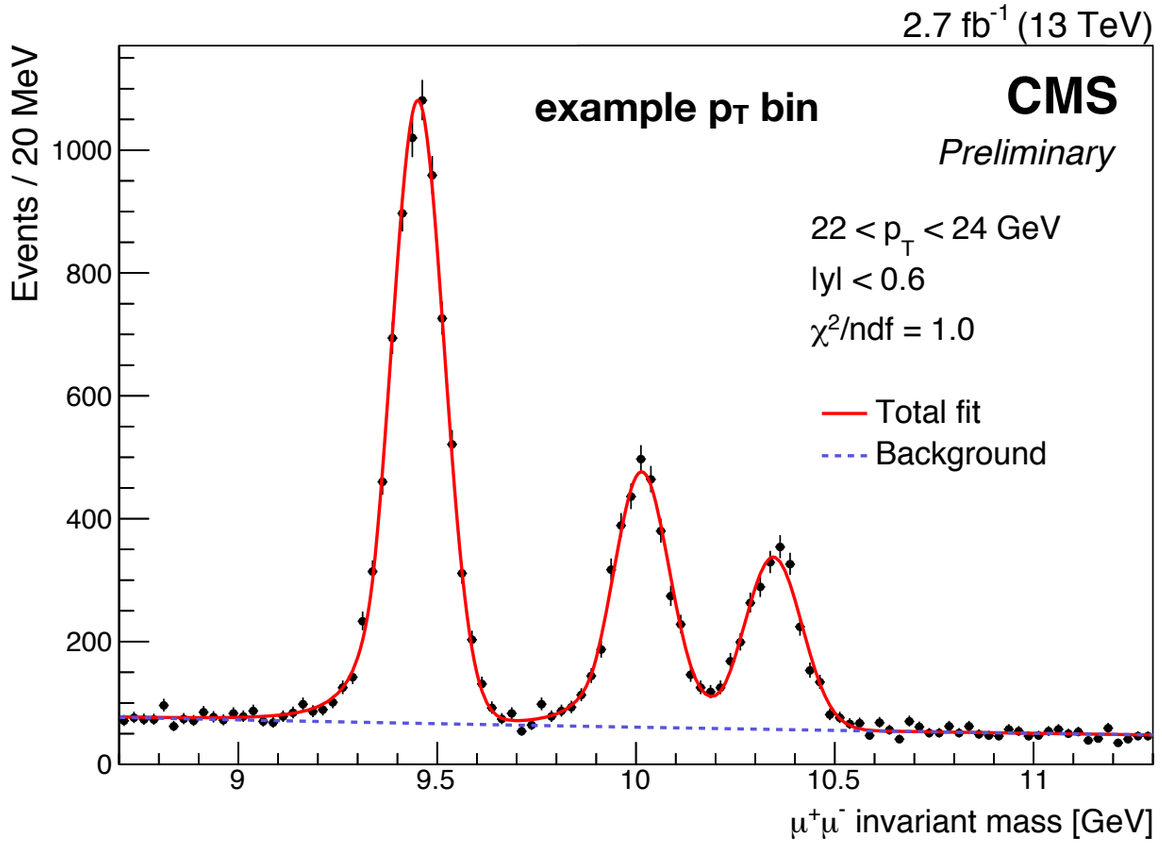
Acceptance
as evaluated on a particle gun MC

Efficiencies
measured through data-driven methods vs p_T and y

Bottomonium signal extraction

CMS-PAS-BPH-15-005

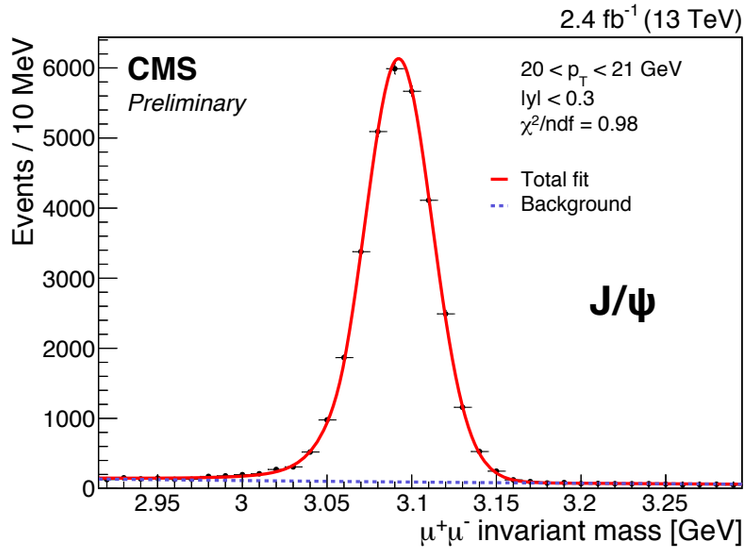
- For Y(nS) states, yields are extracted through maximum likelihood fits to the invariant mass spectra
  - three signal peaks modeled with Crystal Ball functions
  - background described by an exponential function

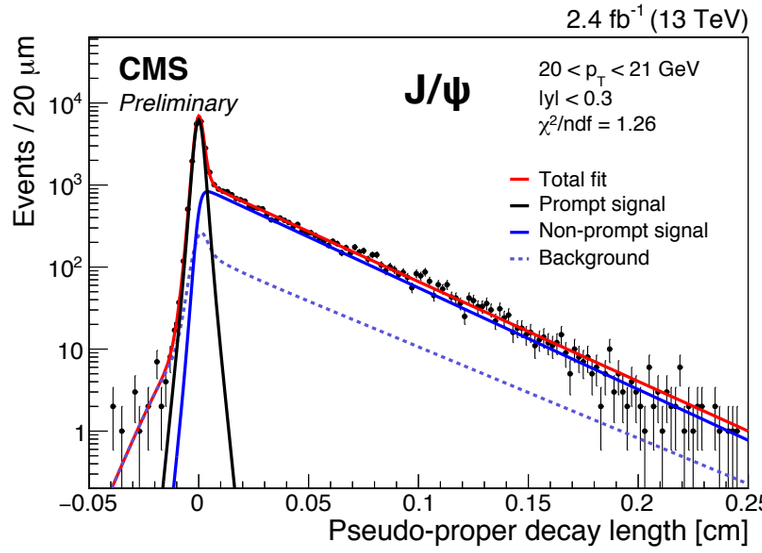


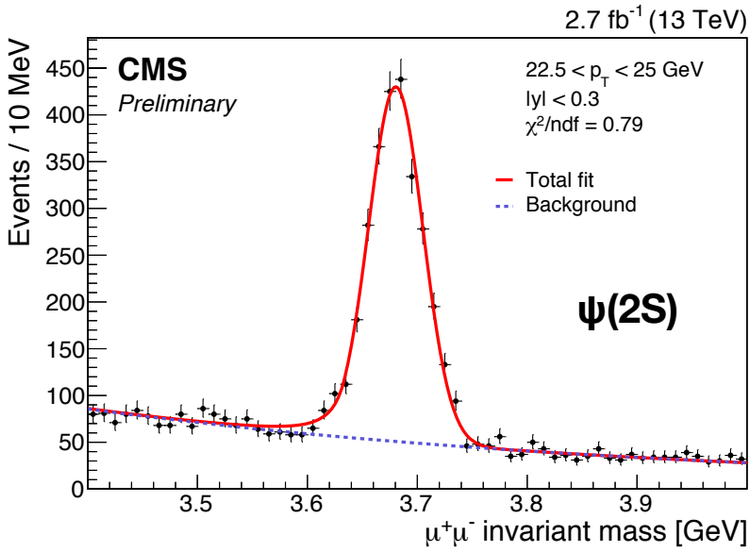
Charmonium signal extraction

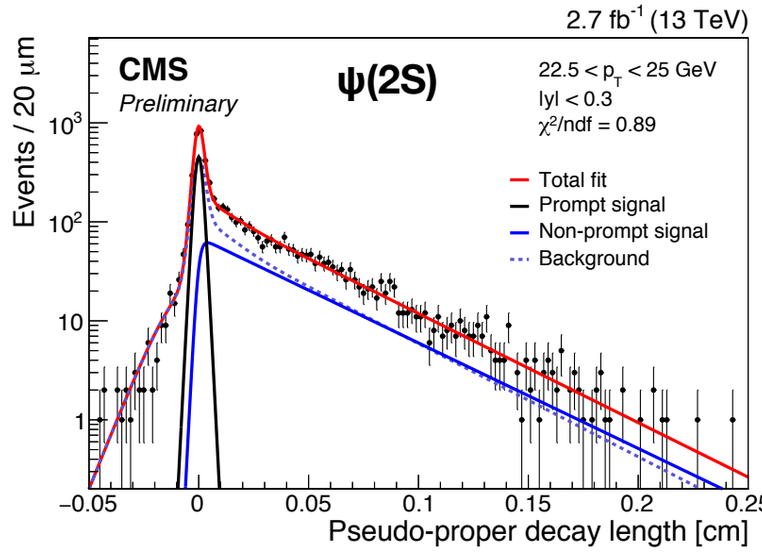
CMS-PAS-BPH-15-005

- Additional non-prompt component originating from the decay of *b*-hadrons is taken into account for charmonium states
  - prompt and non-prompt yields measured by simultaneous fits to the mass and pseudo-proper decay length distributions



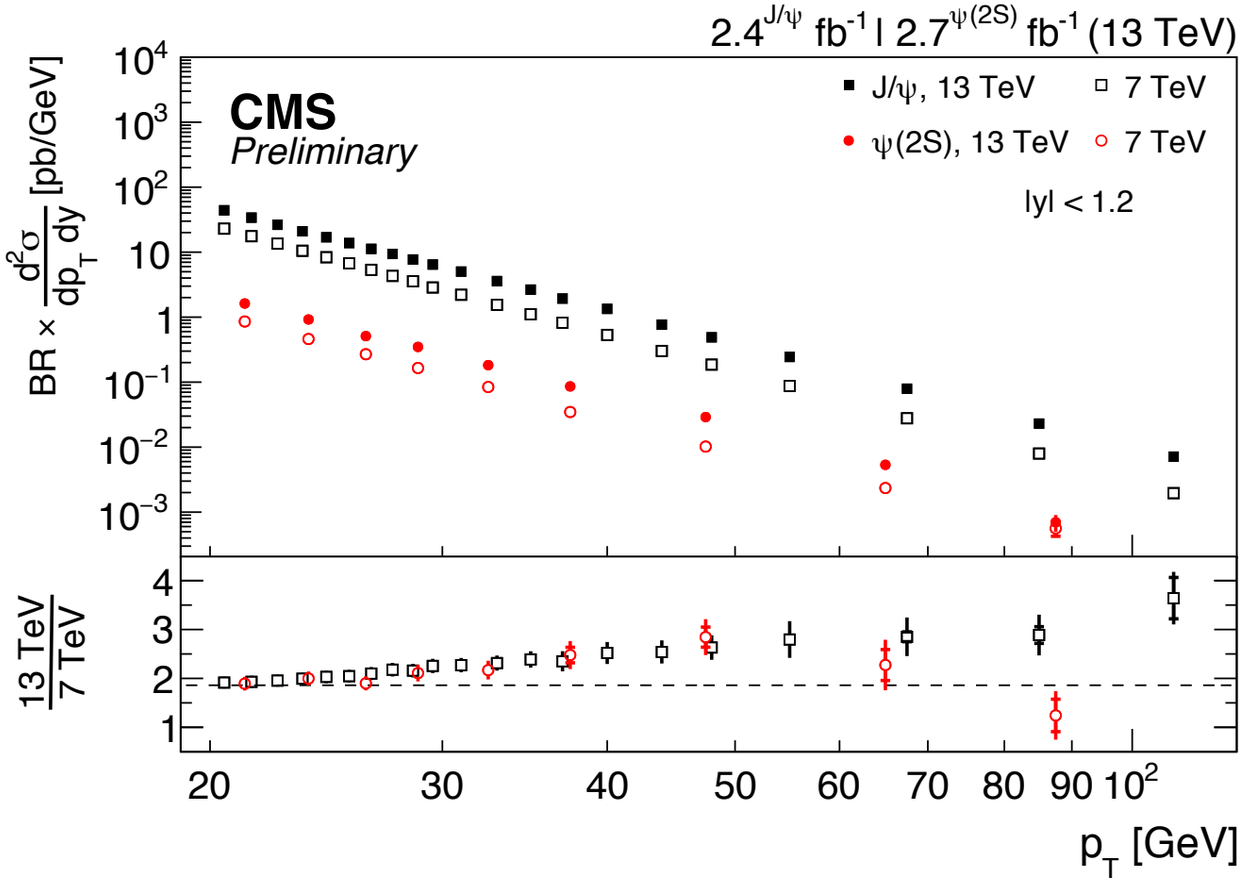


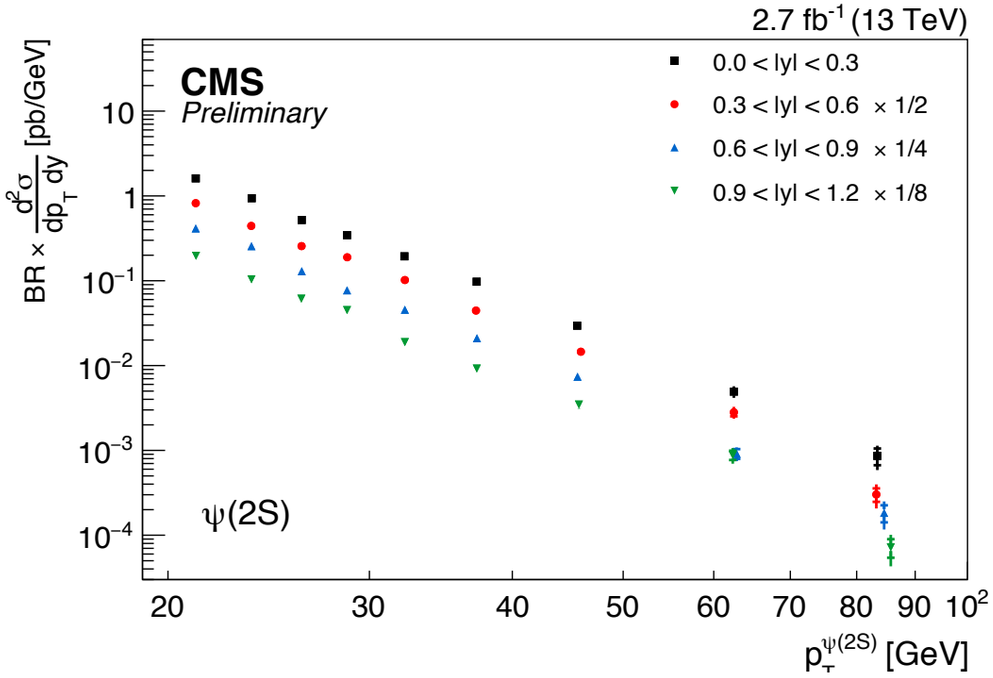


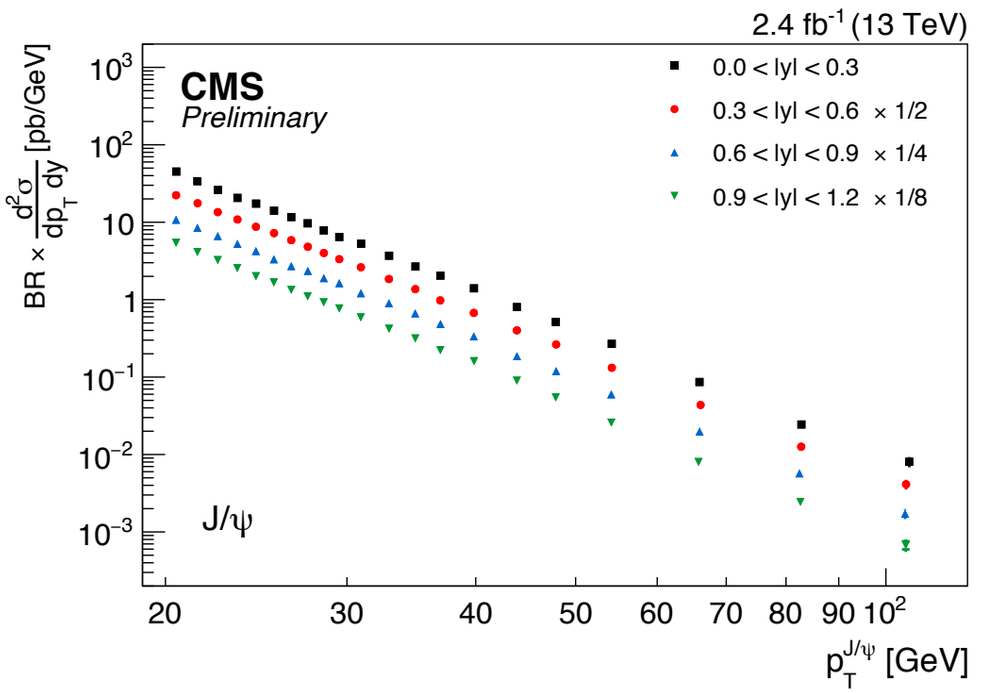


Charmonium results

CMS-PAS-BPH-15-005



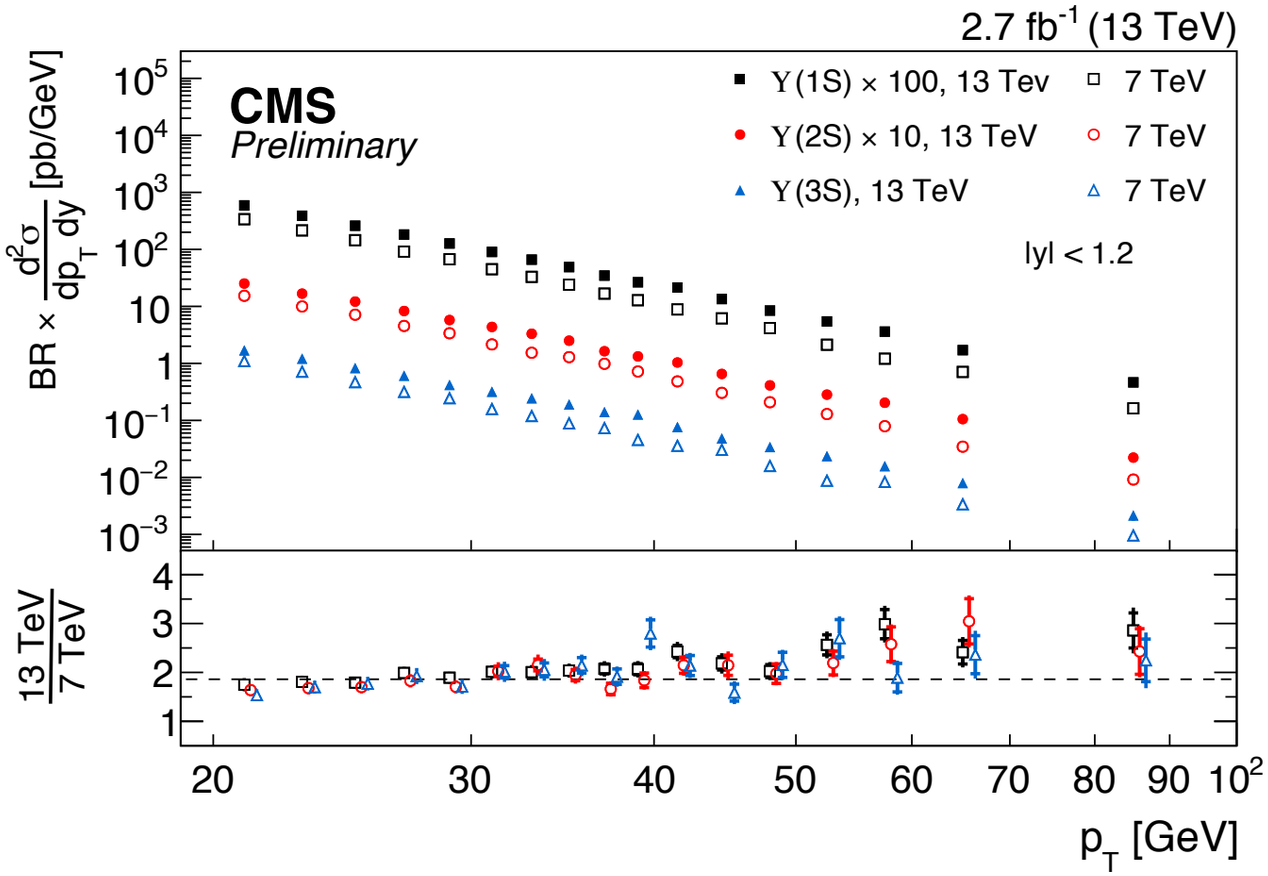




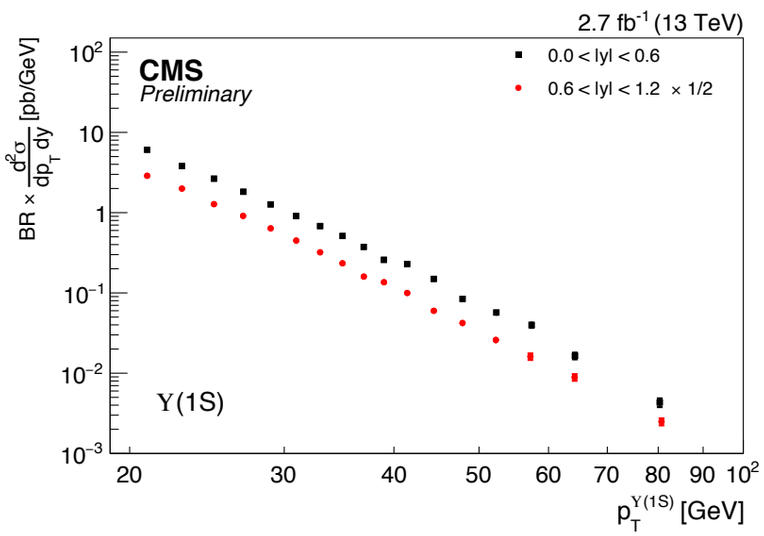
- The 13 TeV cross sections are factors of 2 to 3 larger than the corresponding 7 TeV cross sections, changing slowly as a function of dimuon p_T
- An increase of this order is expected from the evolution of parton distribution functions, as verified using Pythia 8

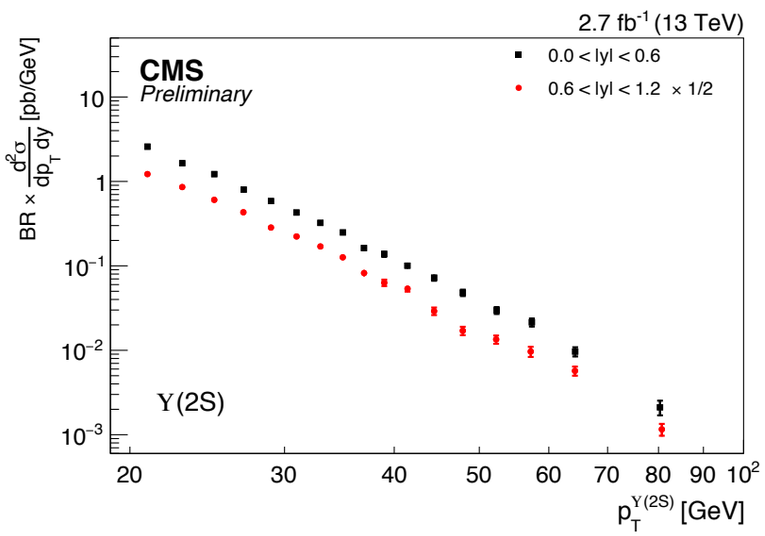
Bottomonium results

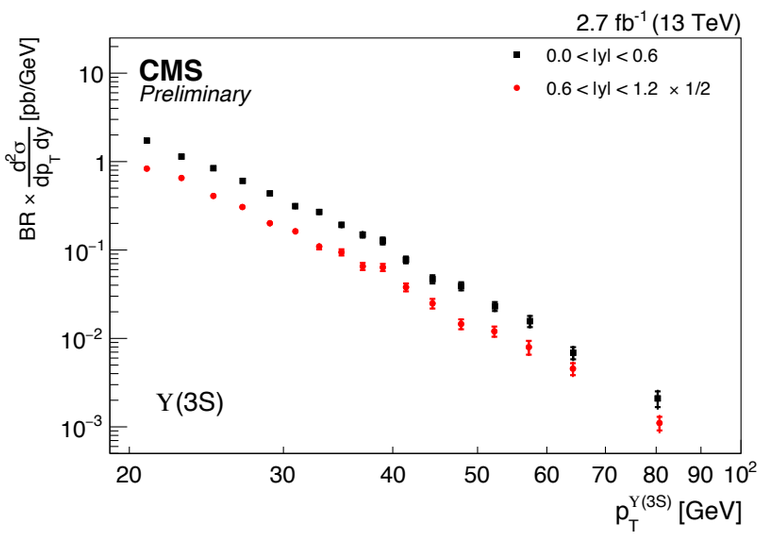
CMS-PAS-BPH-15-005



Also for bottomonium the 13 TeV cross sections are factors of 2 to 3 larger than the corresponding 7 TeV cross sections, with slow changes as a function of dimuon p_T



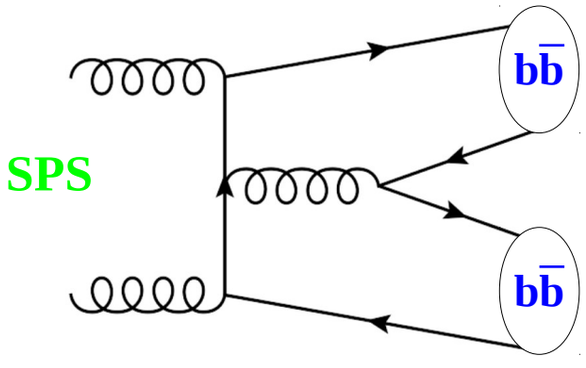


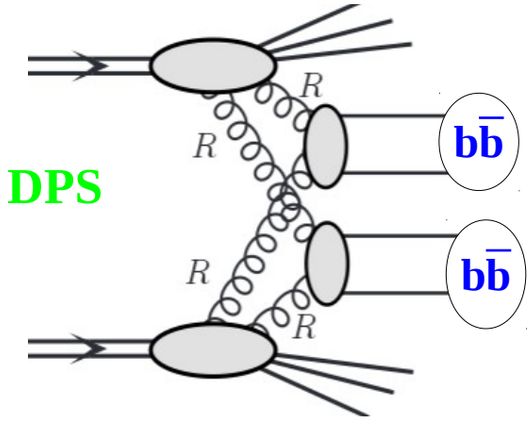


Observation of Y(1S) pair production

CMS-PAS-BPH-14-008

- **First observation** of the simultaneous production of Y(1S) pairs
  - measurements of quarkonia pair production are first step in the search for tetra-quark states
  - previous measurements from NA3, LHCb, D0 and CMS on J/ψ pairs and J/ψ/Y pairs
  - important tests of QCD predictions, complementary to single quarkonia production measurements
    - high statistics measurements could provide information about the production mechanism (Single or Double Parton Scattering)
- analysis is based on 20.7 fb^{-1} of data at 8 TeV from 2012 dataset

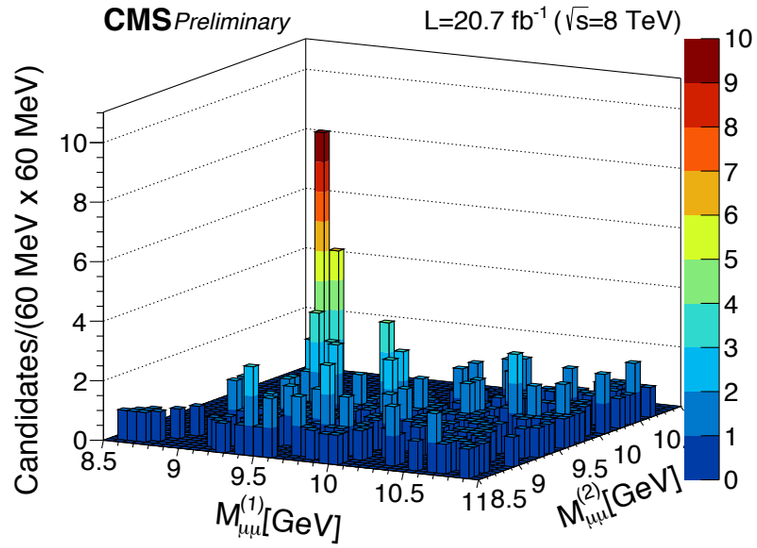


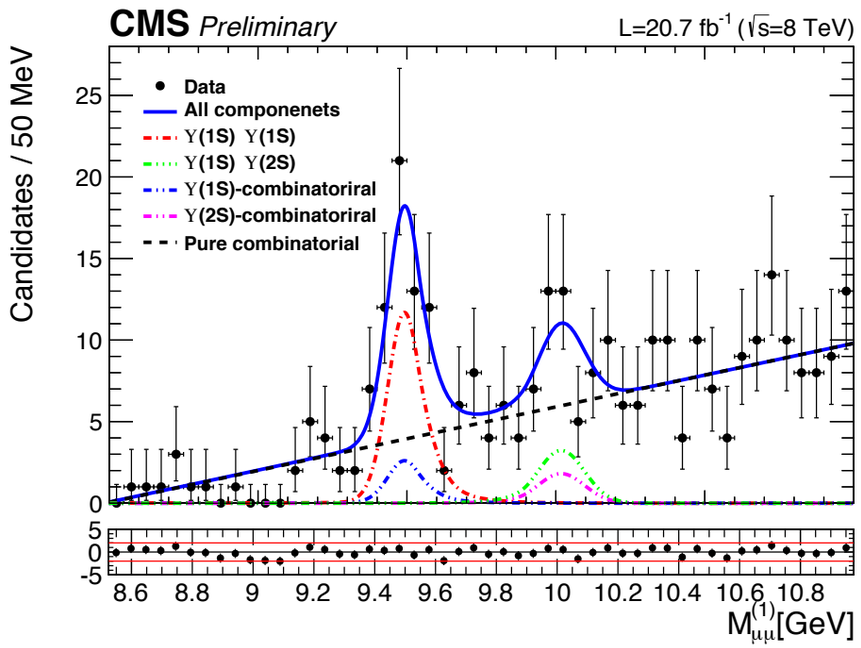


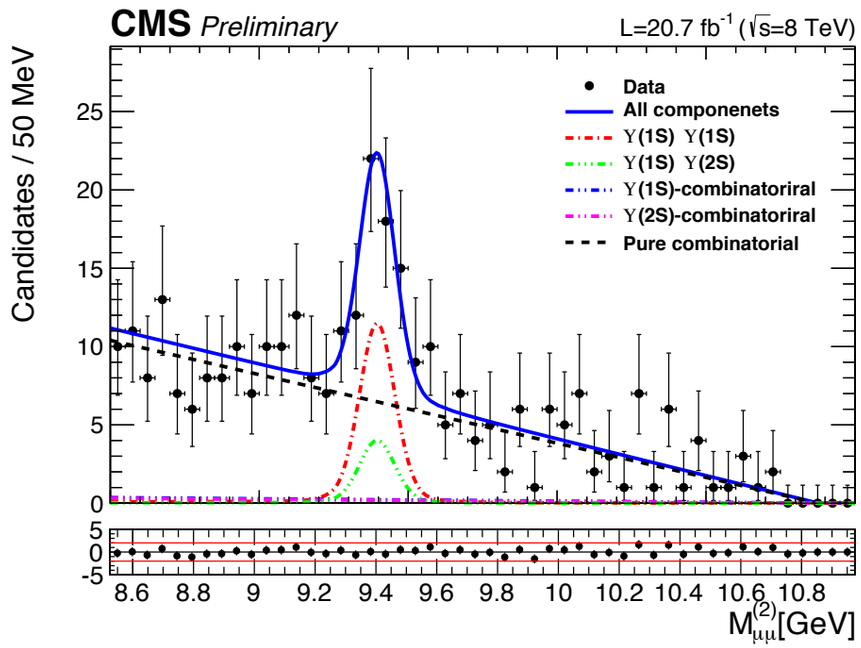
Signal extraction

CMS-PAS-BPH-14-008

- Events selected requiring four muons with zero total charge and muon $p_T > 3.5$ GeV
- Two kinematic variables defined: higher dimuon invariant mass $M^1_{\mu\mu}$ and lower dimuon invariant mass $M^2_{\mu\mu}$
- Yields are extracted through a 2D likelihood fit
  - each muon pair is modeled as signal + background contribution
  - signal model: sum of two Crystal Ball functions, parameters are extracted from signal MC samples and fixed
  - background: first order Chebyshev Polynomial







N_{sig} = 38 ± 7 events
local significance = 9.6σ

Cross section measurement

CMS-PAS-BPH-14-008

- Inclusive cross section is measured in the region |y(Y)| < 2.0 and p_T(Y) < 50 GeV

$$\sigma_T = \frac{N_{sig}}{\mathcal{B}(Y(1S) \to \mu^+\mu^-)^2 \cdot \mathcal{L}} \cdot < \frac{1}{\varepsilon(p_T, |y|)\mathcal{A}(p_T, |y|)} >$$

Component	Systematic Uncertainty
PDF Shape	7.9%
Simulation	4.9%
Efficiency	3.7%
Acceptance	2.8%
Integrated Luminosity	2.5%
Total Uncertainty	10.7%

Efficiency and acceptance corrections on event-by-event basis using data-embedding method to minimize model dependence of correction factors

- both corrections have been validated using signal MC SPS and DPS models

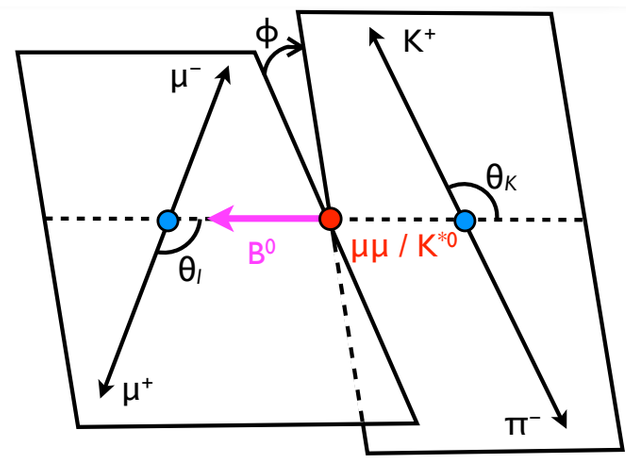
- Assuming unpolarized production of Y(1S) mesons, the cross-section at $\sqrt{s}$ = 8 TeV is measured to be

σ_T = 68.8 ± 12.7 (stat.) ± 7.4 (syst.) ± 2.8 (BR) pb

- Expected to change by up to +36% (longitudinal) or -38% (transverse) in case of extreme polarization scenarios

Angular analysis of $B^0 \rightarrow K^{*0} \mu^+\mu^-$

- FCNC decay that gives access to large number of observables: branching fractions, CP asymmetries and angular observable
  - SM branching fraction is about $4.5 \cdot 10^{-7}$
  - sensitive to new vector or axial-vector currents and virtual photon polarization
  - the decay is fully described by three angles (θ_l, θ_K, ϕ) and the dimuon invariant mass squared (q^2)
  - the observables depend on form-factors for the $B \rightarrow K^*$ transition plus the underlying short distance physics (Wilson coefficients)



$$\left.\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\right|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K +$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

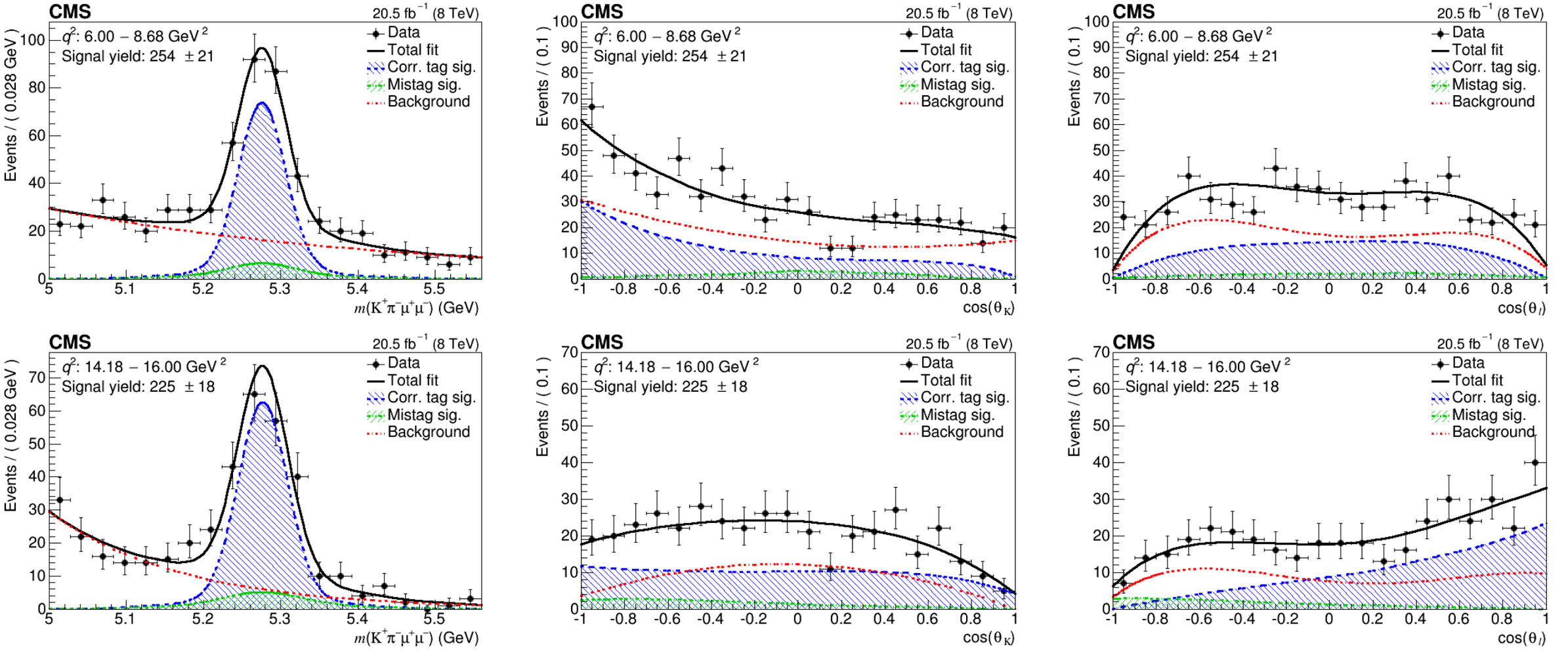
fraction of longitudinal polarisation of the K*

forward-backward asymmetry of the dilepton system

CMS analysis measures A_{FB}, F_L and differential branching fraction (dB/dq^2) in bins of q^2

Analysis details

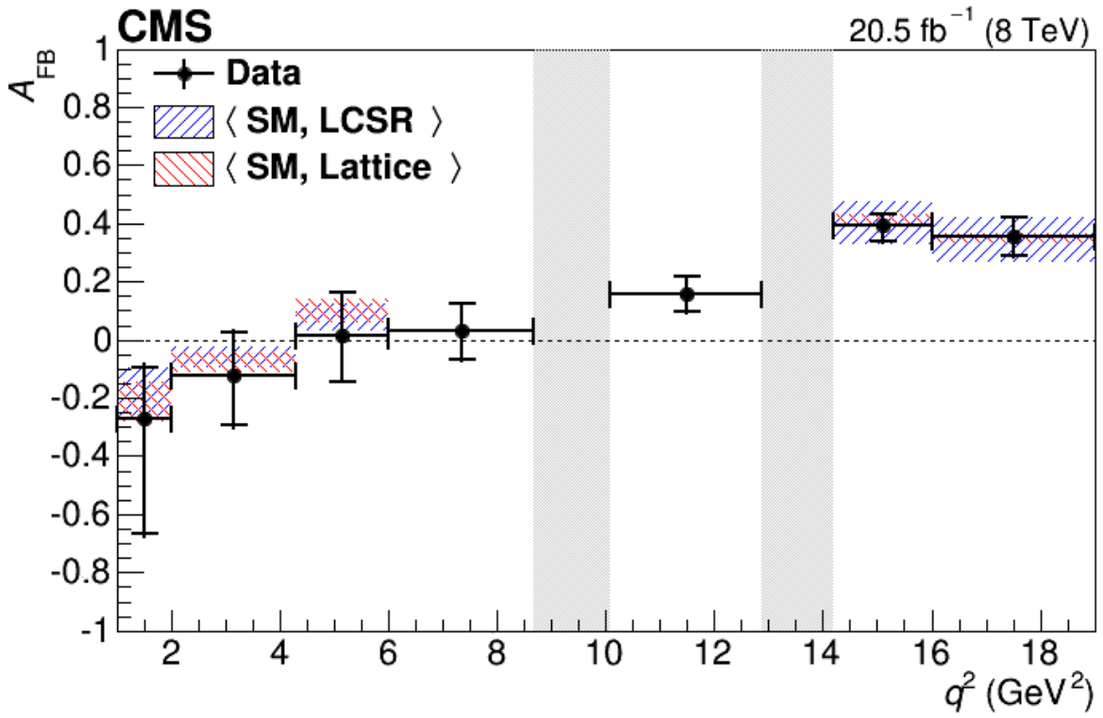
- Analysis is performed on a 20.5 fb^{-1} data sample from 8 TeV collisions
- Control channels: $B^0 \rightarrow J/\psi\, K^{*0}$ (also used as normalization) & $B^0 \rightarrow \psi(2S)\, K^{*0}$
- 1430 $B^0 \rightarrow K^{*0}\mu^+\mu^-$ signal events divided in 7 q^2 bins (excluding J/ψ & ψ' regions)
- Unbinned extended maximum likelihood fits to m(Kπμμ) and angular variables θ_K and θ_l in each q^2 bin

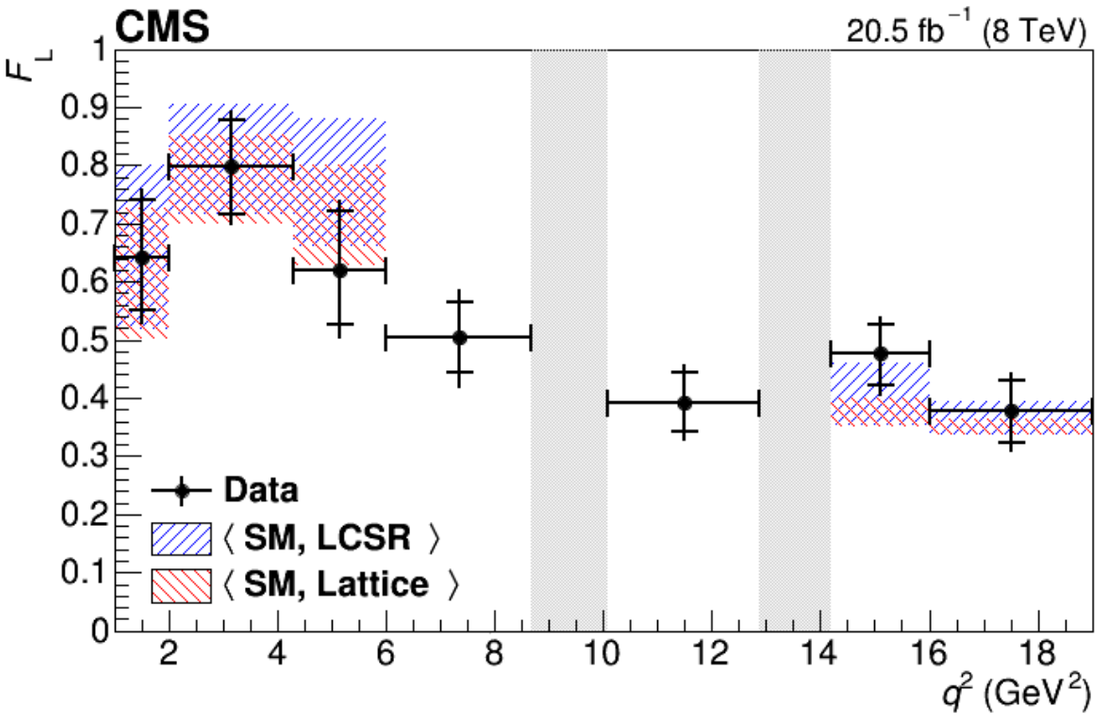


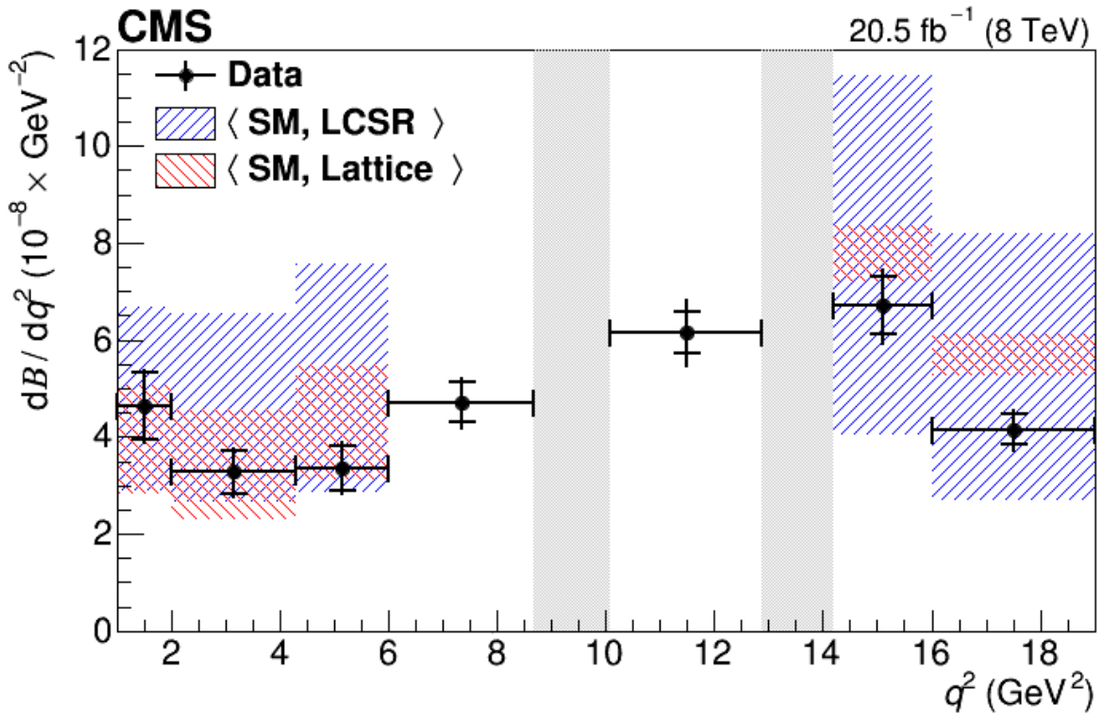
Results

PLB 753 (2016) 424

- Measurements are compared to two SM predictions, which differ in the calculator of the form factors
  - results are consistent with the predictions
- Measurement of A_{FB} and F_L with good precision at high q^2
- Analysis with more angular variables (P'5, etc) is in preparation



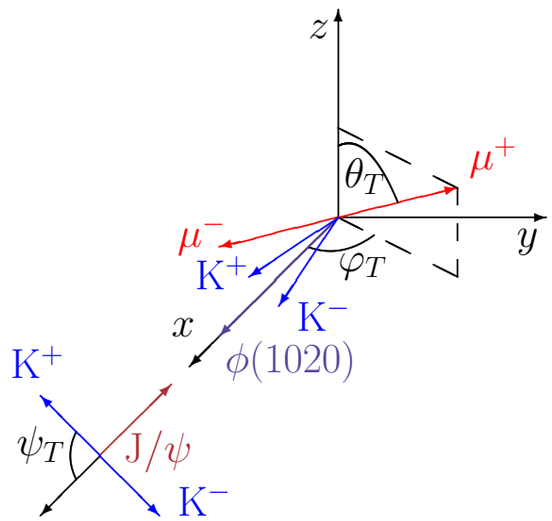




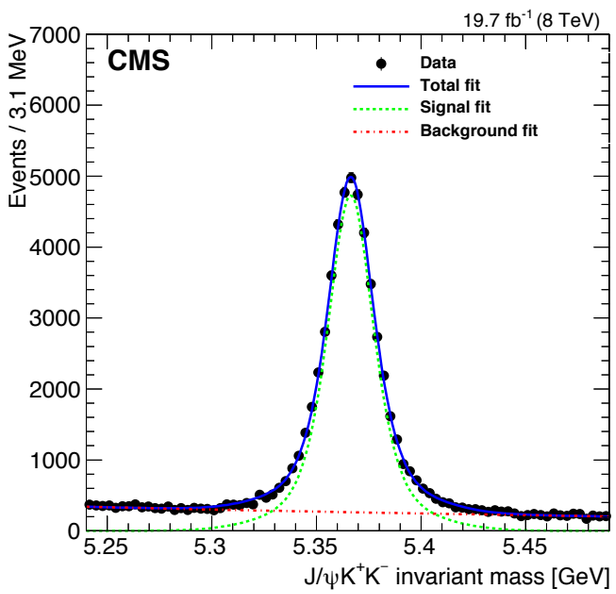
Measurement of φ_s and $\Delta\Gamma_s$

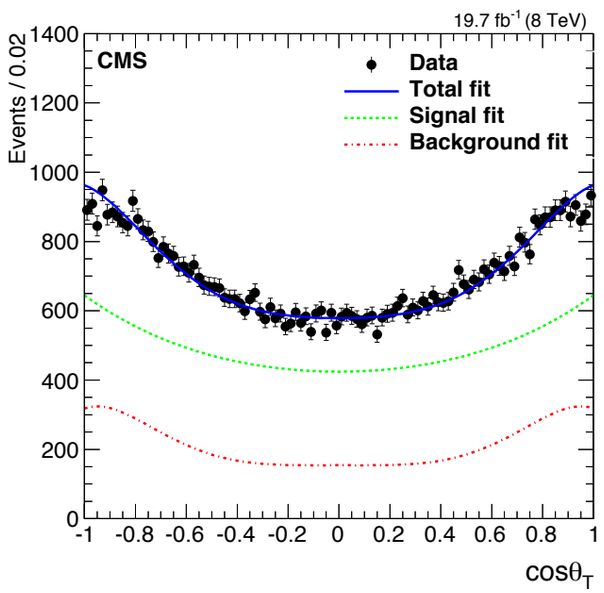
arXiv:1507.07527

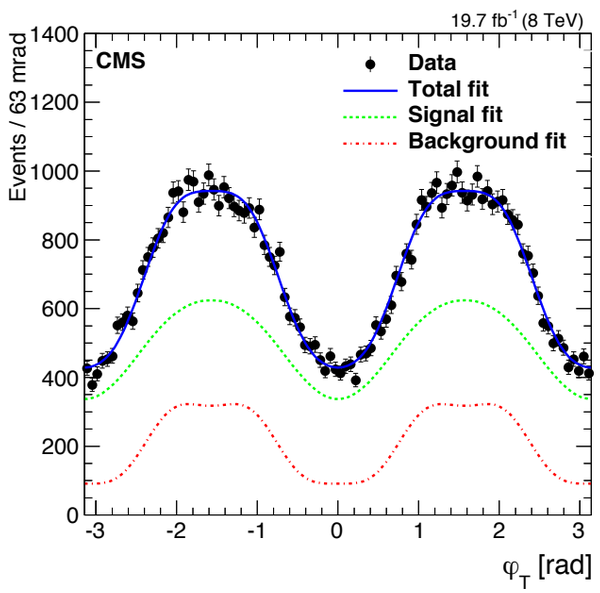
- Very precise predictions of the CP violating phase φ_S are available from the SM
  - any measured deviation would be an indication of New Physics contributions
- φ_S measured together with decay-width difference $\Delta\Gamma_s$ between light and heavy B_s mass eigenstates using the decay $B_s \rightarrow J/\psi\phi(1020) \rightarrow \mu^+\mu^-K^+K^-$
  - time-dependent and flavor-tagged angular analysis to disentangle the two CP final states



- three angles θ_T, ψ_T, and ϕ_T used to describe the decay topology
- OS lepton tagging implemented to determine the B_s flavor at production time
- UML fit to data performed using information on m_B, decay angles, tagging, ct and its uncertainty







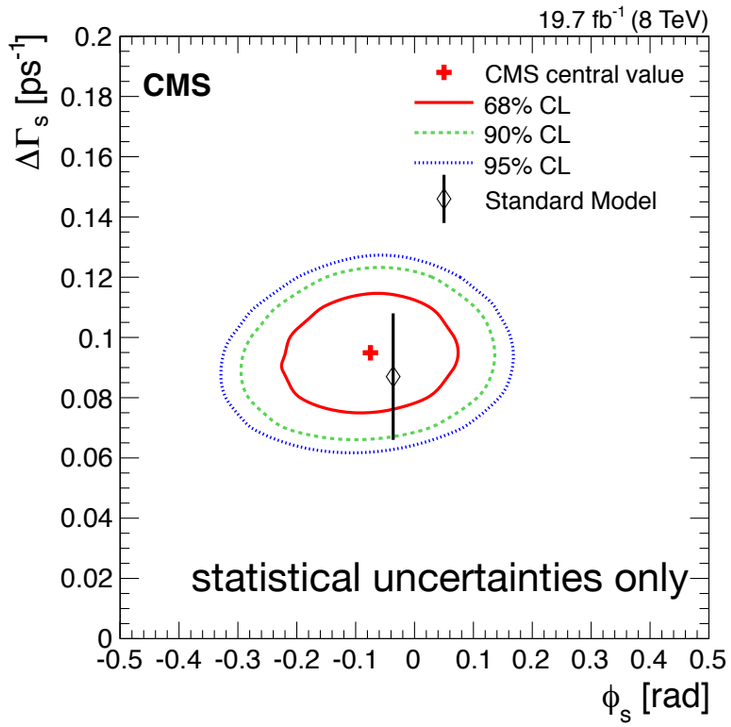
φ_s and $\Delta\Gamma_s$ results

arXiv:1507.07527

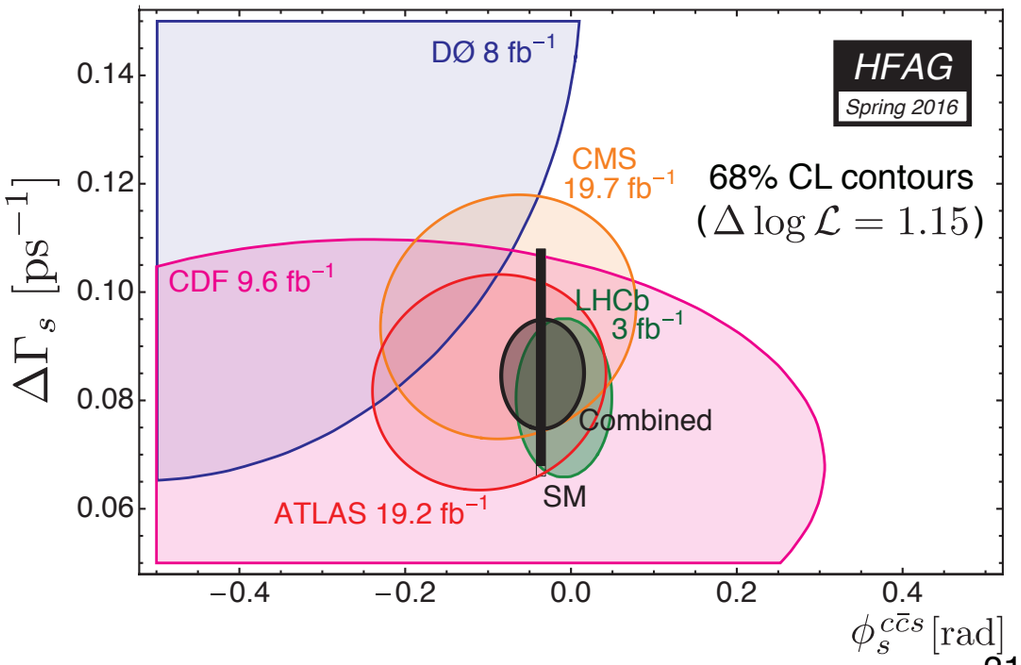
- Analysis exploits the 8 TeV data sample (19.7 fb^{-1}) collected in 2012
- Measured values for the weak phase φ_S and the decay width difference $\Delta\Gamma_s$ are:

$\varphi_S = -0.075 \pm 0.097\ (stat) \pm 0.031\ (syst)$ rad

$\Delta\Gamma_s = 0.095 \pm 0.013\ (stat) \pm 0.007\ (syst)\ ps^{-1}$



- **Results are consistent with SM predictions for φ_s and confirm non-zero values for $\Delta\Gamma_s$**
- Statistically limited measurement → significant improvement expected from analysis of Run II data
- Analysis of the $B_s \to J/\psi\, f_0$ decay mode (BR already measured in CMS PLB 756 (2016) 84) could further contribute to the determination of φ_s



Summary and outlook

- **The Run II of the LHC will provide a lot of interesting heavy flavor events**
  - analyses of 13 TeV data are promising and first results are appearing
    - differential cross section for B^+ production at 13 TeV has been measured up to 100 GeV in p_T
    - double differential production cross sections at 13 TeV for J/ψ, ψ(2S), Υ(nS) have been measured
  - improvements in precision are expected for analyses already pursued in Run I, eg. $B_{s(d)} \rightarrow \mu\mu$
    (Run I references: Phys.Rev.Lett. 111 (2013) 101804 and Nature 522 (2015) 68-72, not mentioned in this talk)

Estimate of analysis sensitivity CMS PAS FTR-14-015

$\mathcal{L}$ (fb^{-1})	$N(B_s^0)$	$N(B^0)$	$\delta\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	$\delta\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$	B^0 sign.	$\delta\frac{\mathcal{B}(B^0\rightarrow\mu^+\mu^-)}{\mathcal{B}(B_s^0\rightarrow\mu^+\mu^-)}$
20	18.2	2.2	35%	> 100%	$0.0-1.5\,\sigma$	> 100%
100	159	19	14%	63%	$0.6-2.5\,\sigma$	66%
300	478	57	12%	41%	$1.5-3.5\,\sigma$	43%
300 (barrel)	346	42	13%	48%	$1.2-3.3\,\sigma$	50%

- Interesting measurements still being carried out on Run I data
  - the most recent result on Run I has been shown today and is a first observation!

All CMS BPH results are available at
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

backup

Angular analysis results

- CMS measurement at 8TeV is combined with previous measurement at 7 TeV
- Results are compared to measurements from other experiments, showing comparable or higher precision