First CMS Heavy-Flavour results at 13 TeV

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University and INFN Padova

14th International Workshop on
Meson Production, Properties and Interaction

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Outline

- Introduction
- Run-1 legacy
- $B^{\pm}$ production
- Quarkonia production
- Conclusions

Motivations

Motivations to study HF physics at CMS

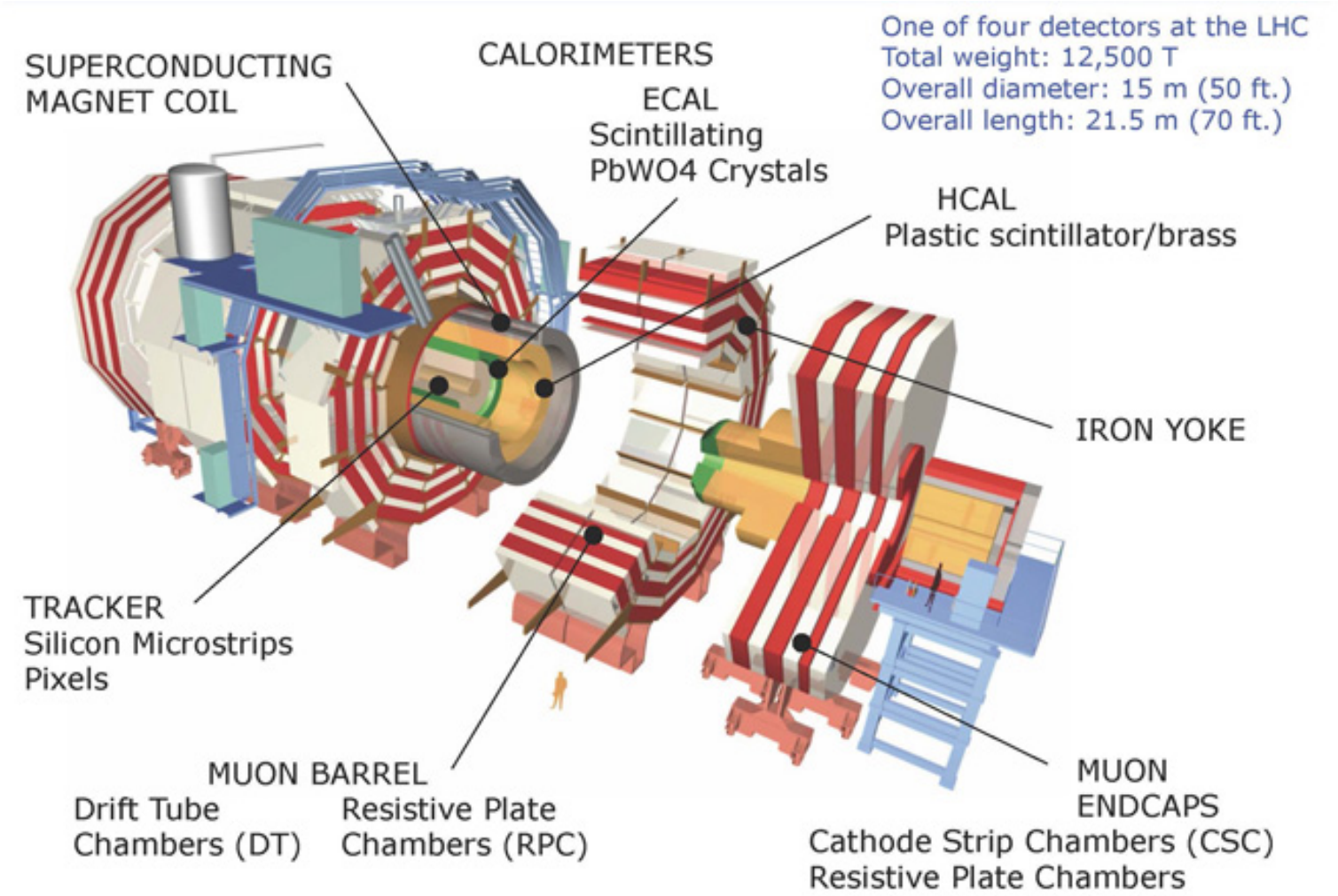
- Probe the underlying QCD processes:
  - measure production cross section,
  - measure quarkonia polarization,
  - look for new and exotic states.
- Look for effects of new physics beyond the Standard Model (not treated here):
  - study lifetime and decay properties of B hadrons,
  - look for new physics effects in rare decays.

Results from 2015 data taking at $\sqrt{s} = 13$ TeV :

- $B^{\pm}$ production cross section
- Quarkonia production cross sections

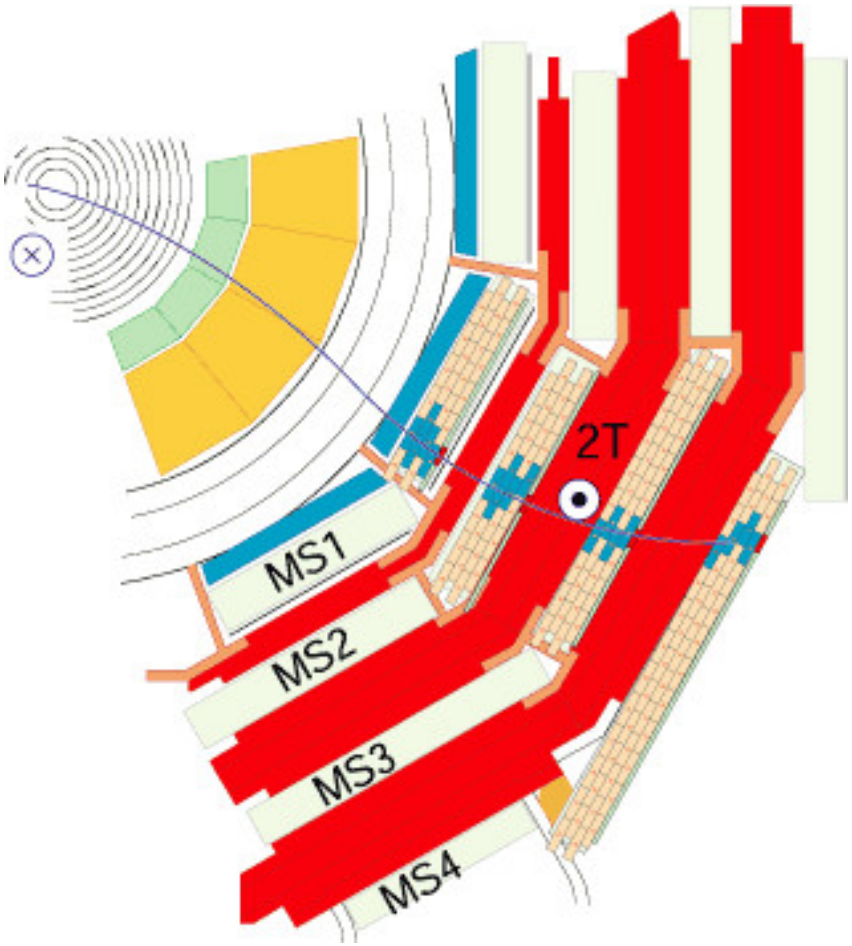
Experiment

The CMS experiment



JINST 03 (2008) S08004

Muon reconstruction



- 3 detectors dedicated to muon trigger and reconstruction
- Stand-alone reconstruction capability by muon detectors
- Tracker-muon match:
  - inside-out: more efficient at low p_T
  - outside-in: more efficient at high p_T

Performances

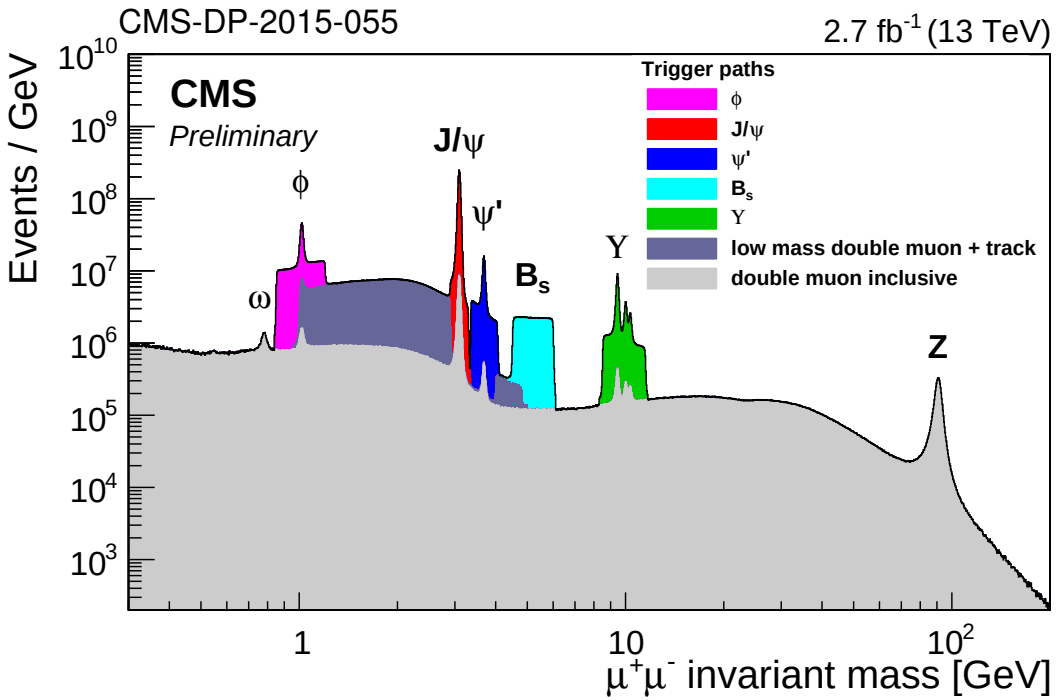
JINST 7 (2012) P10002

- Misidentification probability $P_{\text{mis}} < 1\%$
- Momentum resolution $\sigma(p_T) \sim 1 \div 6\%$ for $p_t < 100$ GeV

Trigger

- High luminosity
- Limited bandwidth

$\Rightarrow$ Di-muon triggers
possibly plus other tracks



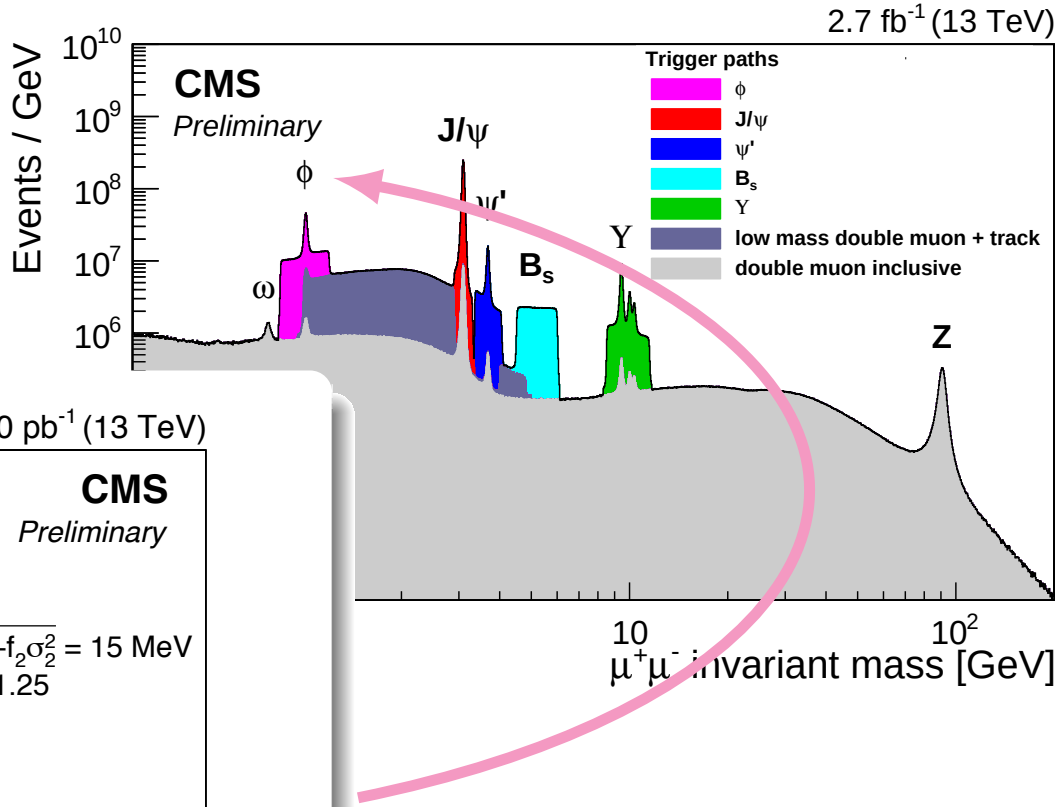
- L1: hardware
  (fast, rate $\sim$ 100 kHz)
- HLT: software
  (full track reconstruction,
  rate $\sim$ 1 kHz)

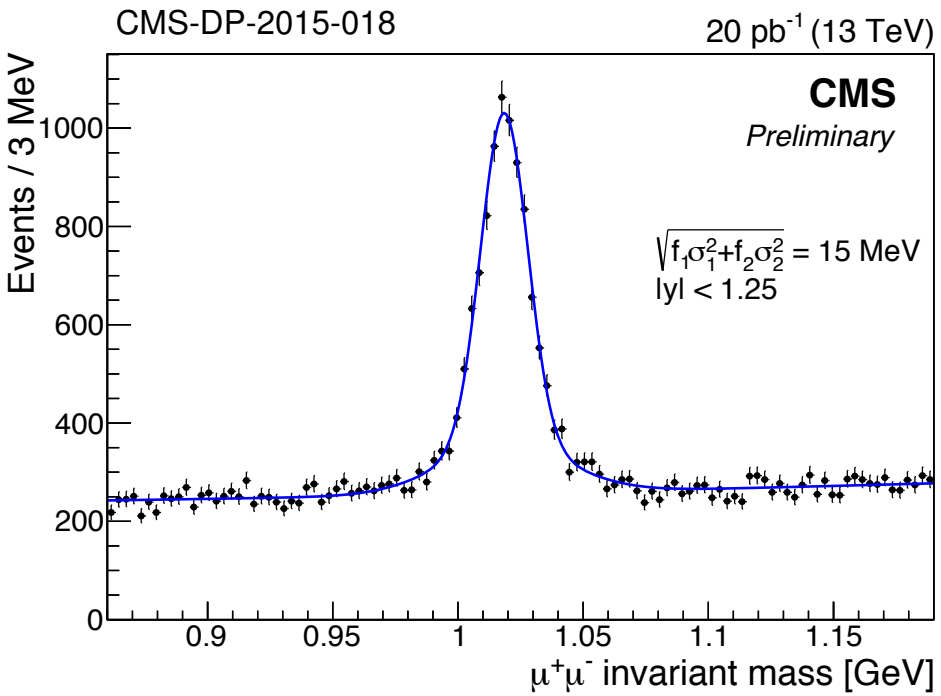
Specific triggers developed for different analyses

Cuts on
- transverse momentum, (pseudo)rapidity
- vertex χ^2 and displacement
- di-muon mass & pointing angles

Preliminary results

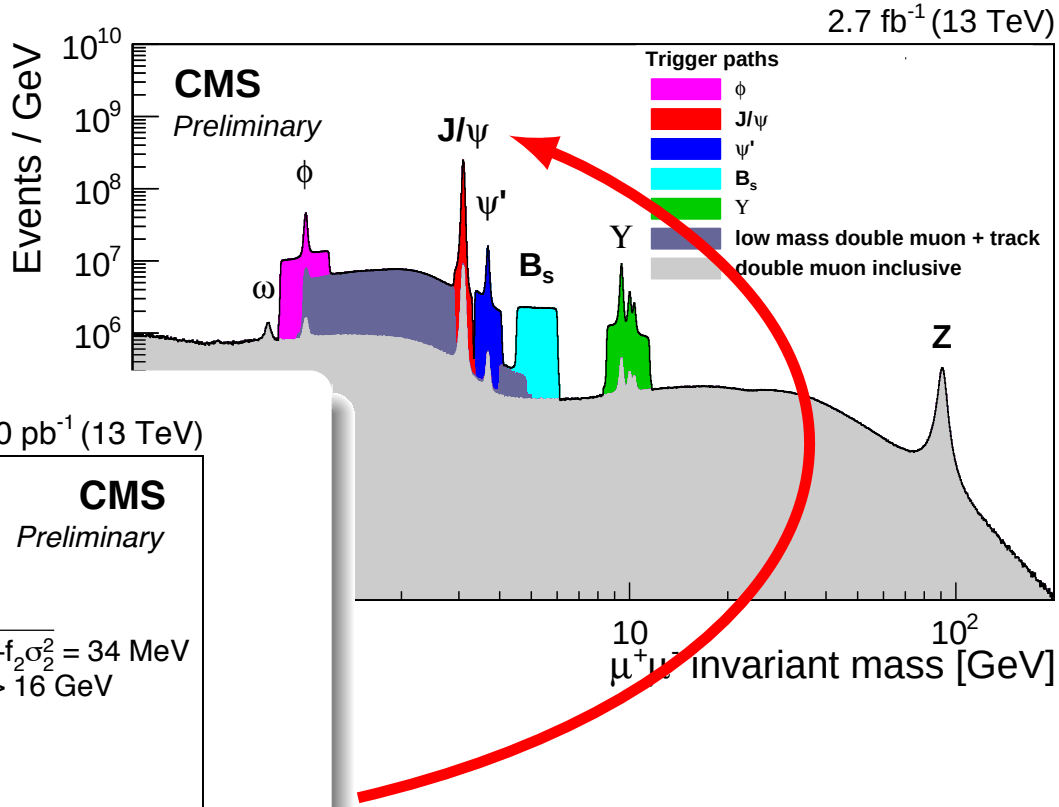
$$\phi \rightarrow \mu^+\mu^-$$

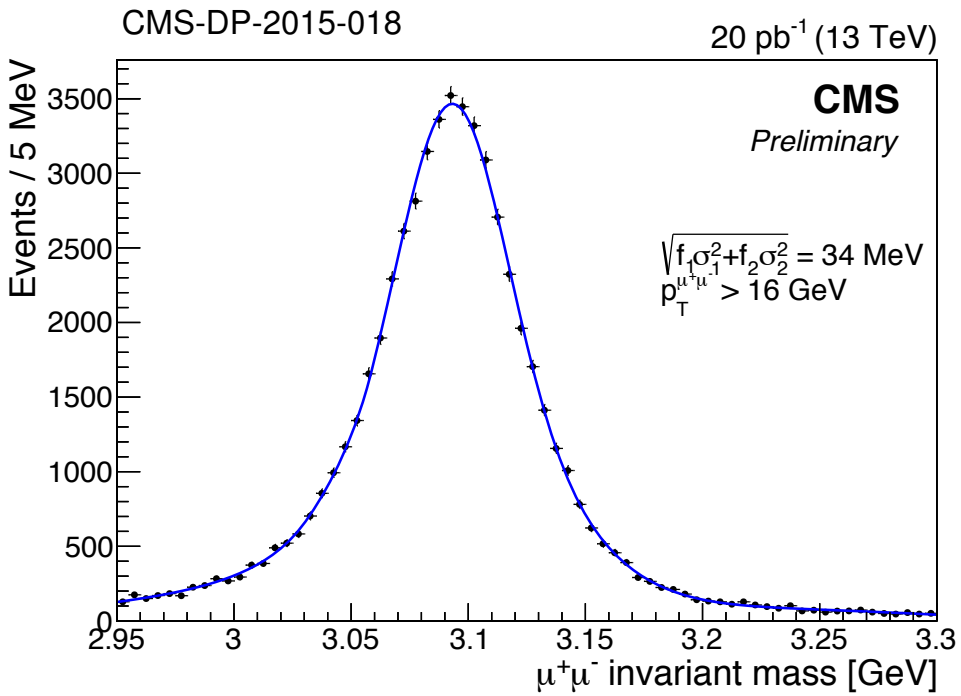




Preliminary results

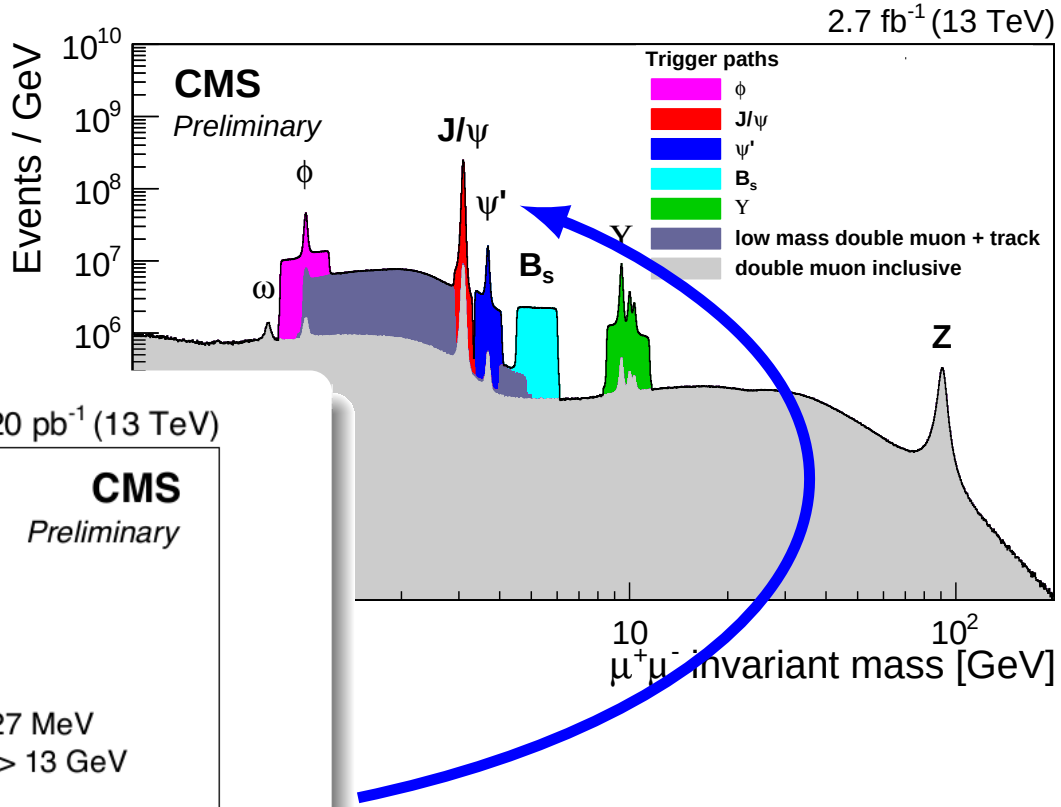
$$J/\psi \rightarrow \mu^+\mu^-$$

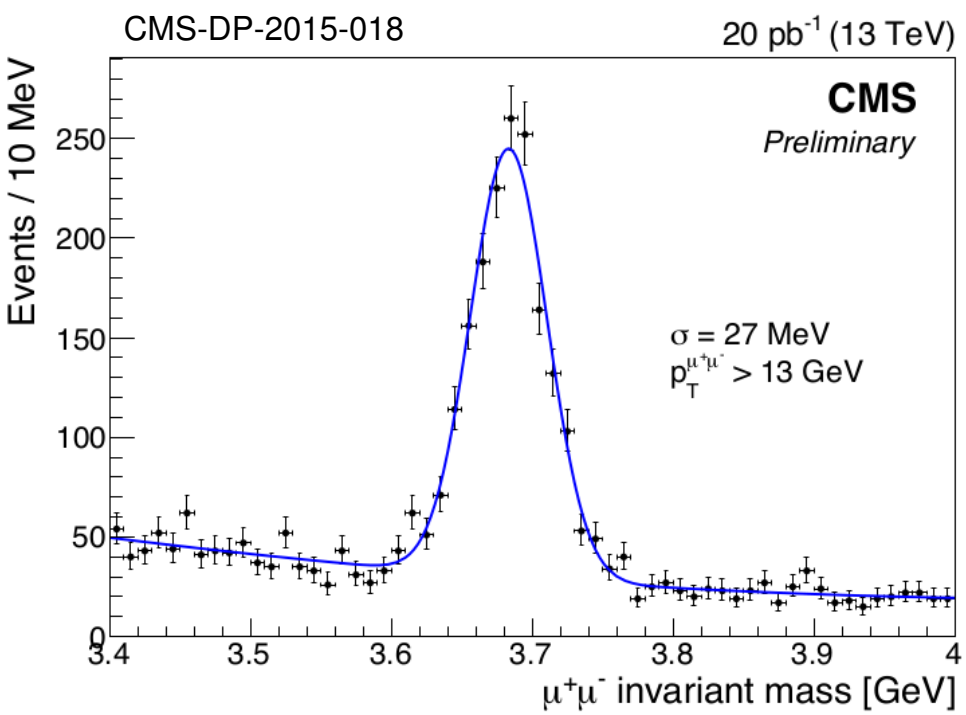




Preliminary results

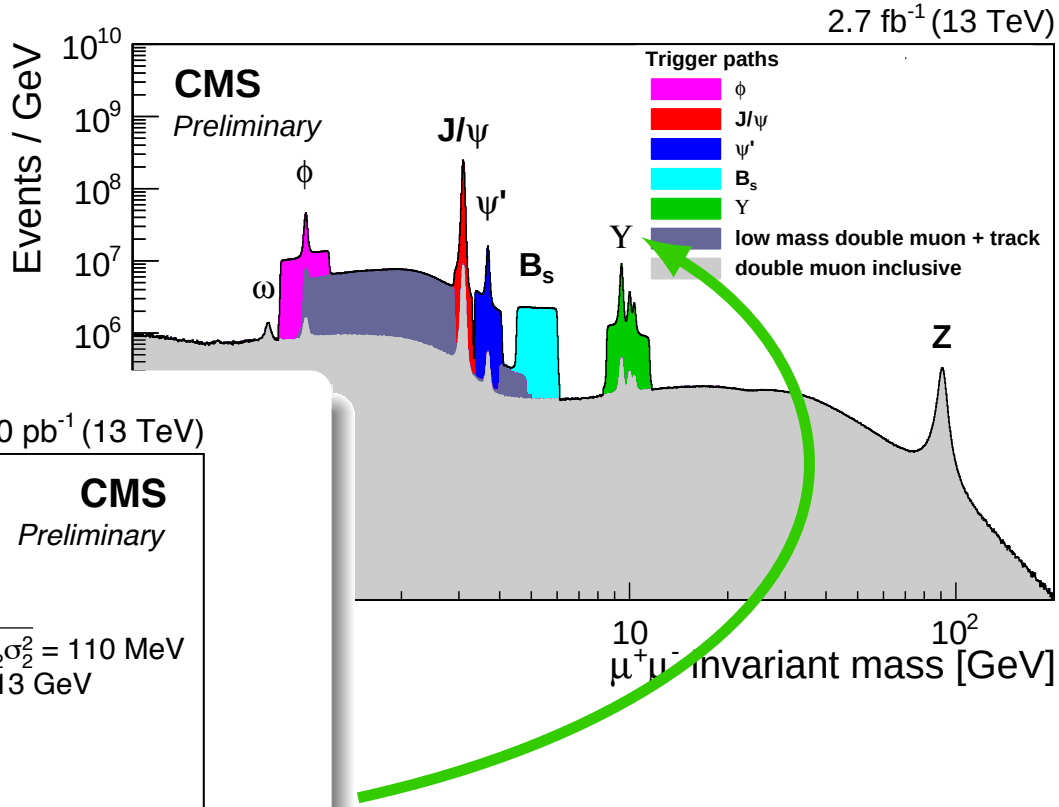
$$\psi' \rightarrow \mu^+\mu^-$$

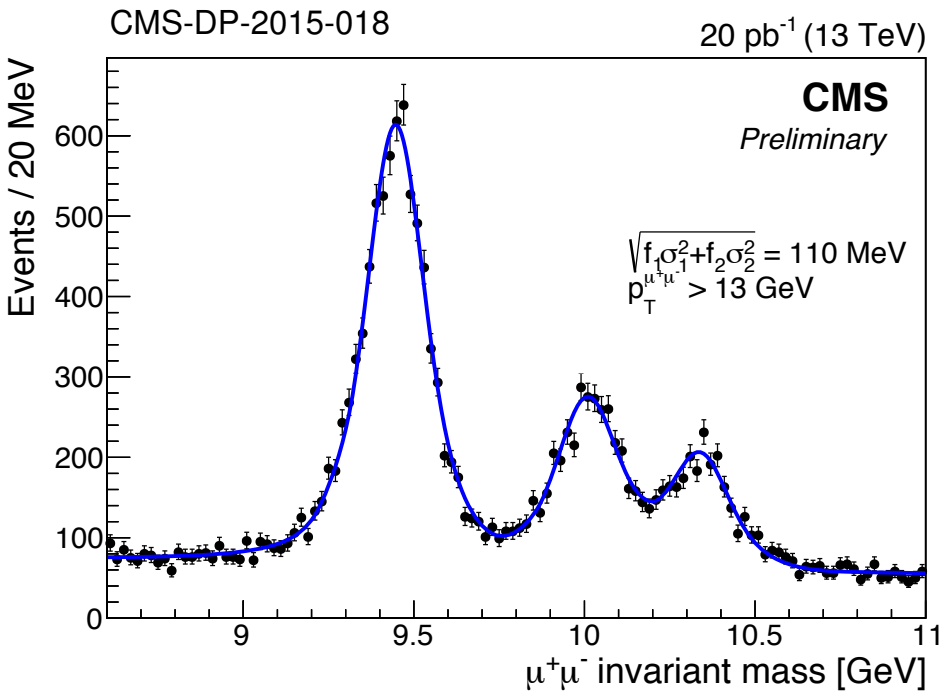




Preliminary results

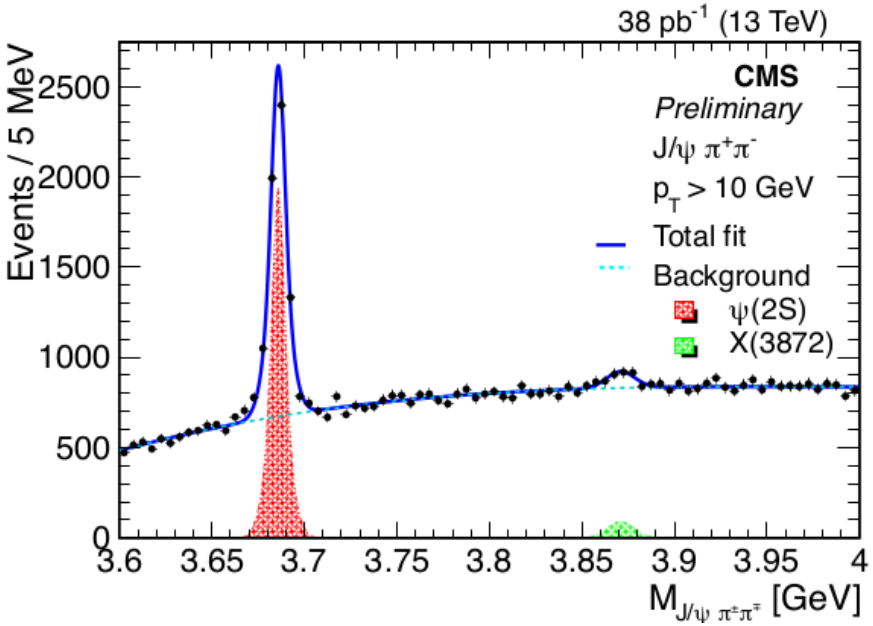
$$\Upsilon(nS) \rightarrow \mu^+\mu^-$$

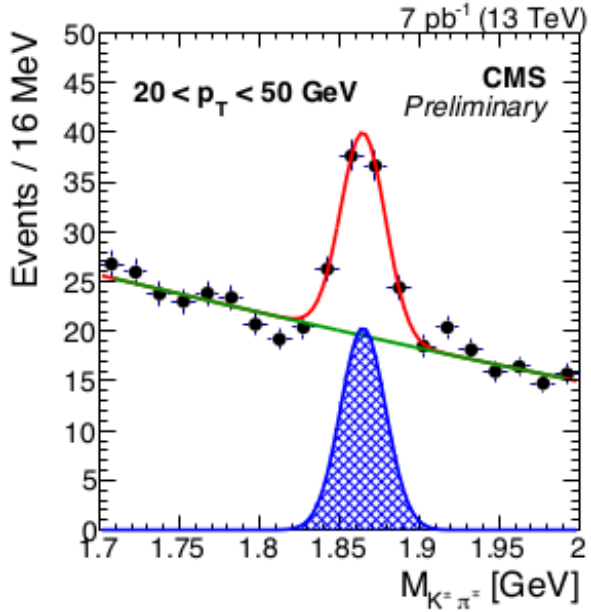


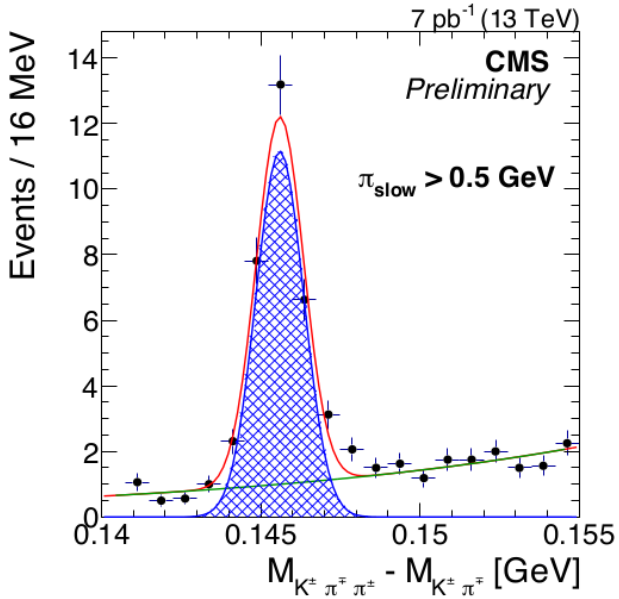


Preliminary results

Other... CMS-DP-2015-018







Run-2

LHC: 2015 run with $\sqrt{s} = 13$ TeV and 50/25ns bunch spacing

CMS improvements

Detector, trigger and software improvements during the shutdown

- Higher fraction of active channels in subdetectors
- Re-commissioning of physics objects

Data sample

- LHC-delivered luminosity: $\mathcal{L} \sim 4$ fb^{-1}
- CMS-recorded luminosity: $\mathcal{L} \sim 3.6$ fb^{-1}
  - 25% without magnetic field
  - $\mathcal{L} \sim 2.2$fb^{-1} with full-operational detector
  - $\mathcal{L} \sim 2.7$fb^{-1} for muon-based analyses

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"Legacy" results from Run-1: ($\sqrt{s} = 7, 8$ TeV)

B meson production

$\sigma(pp \to B^+ X)$	PRL 106 (2011) 112001
$\sigma(pp \to B_0 X)$	PRL 106 (2011) 252001
$\sigma(pp \to B_s \to J/\psi\phi)$	PRD 84 (2011) 052008
$B_c^{\pm} \to J/\psi\pi^{\pm}(\pi^+\pi^-)$	CMS-PAS-BPH-12-011

Quarkonia production & polarization

$\sigma(pp \to (J/\psi\ , \psi(2S))X)$ (integrated & differential)	JHEP 02 (2012) 011
$\sigma(pp \to (J/\psi\ , \psi(2S))X)$ (differential)	PRL 114 (2015) 191802
$\sigma(pp \to \Upsilon(n\mathrm{S})X)$	PLB 727 (2013) 101
$(J/\psi\ , \psi(n\mathrm{S}))$ polarization	PLB 727 (2013) 381
$\Upsilon(n\mathrm{S})$ polarization	PRL 110 (2013) 081802
$\Upsilon(n\mathrm{S})$ polarization vs. multiplicity	arXiv:1603.02913
$\sigma(\chi_{c2})/\sigma(\chi_{c1})$	EPJ C (2012) 72:2251
$\sigma(\chi_{b2})/\sigma(\chi_{b1})$	CMS-PAS-BPH-13-005

Double quarkonia & exotica

Double J/ψ production	CMS-PAS-BPH-11-021
$X(3872)$ production	JHEP 04 (2013) 154
Search for $X_b \to \Upsilon(1\mathrm{S})\pi^+\pi^-$	PLB 727 (2013) 57

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$\sigma(pp \to B^+X)$ cross-section

New results at $\sqrt{s} = 13$ TeV
extended p_T range

Quarkon

$\sigma(pp \to (J/\psi\ , \psi(2S))X)$ (integrate	
$\sigma(pp \to (J/\psi\ , \psi(2S))X)$ (different	
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Doub

Double J/ψ production	
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$\sigma(pp \to (J/\psi, \psi', \Upsilon(n\mathrm{S}))X)$ cross-section

New results at $\sqrt{s} = 13$ TeV

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$\sigma(pp \to (\Upsilon(1S)\Upsilon(1S))X)$ cross-section

New results

(still at $\sqrt{s} = 8$ TeV)

Double quarkonia & exotica

Double J/ψ production	CMS-PAS-BPH-11-021
$X(3872)$ production	JHEP 04 (2013) 154
Search for $X_b \to \Upsilon(1S)\pi^+\pi^-$	PLB 727 (2013) 57
Double Υ production	CMS-PAS-BPH-14-008

Double Υ production

High parton densities in *pp* collisions

- Single parton scattering (SPS):
  - assumed to dominate
  - strongly correlated pairs, small $|\Delta y|$
- Double parton scattering (DPS):
  - multiple heavy-flavour production,
  - large $|\Delta y|$ values

S. Baranov,*et al.*, PLB 705 (2011) 116-119 , C.H. Kom *et al.*, PRL 107 (2011) 082002

Quarkonium pair production mechanism

- Color singlet: dominant at low p_T
- Color octet: important at high p_T

P. Ko *et al.*, JHEP01(2011)070 , J. Campbell *et al.*, PRL 98 (2007) 252002

Possibly produced in decays of tetra-quarks

A.V. Berezhnoy, *et al.*, PRD 86 (2012) 034004

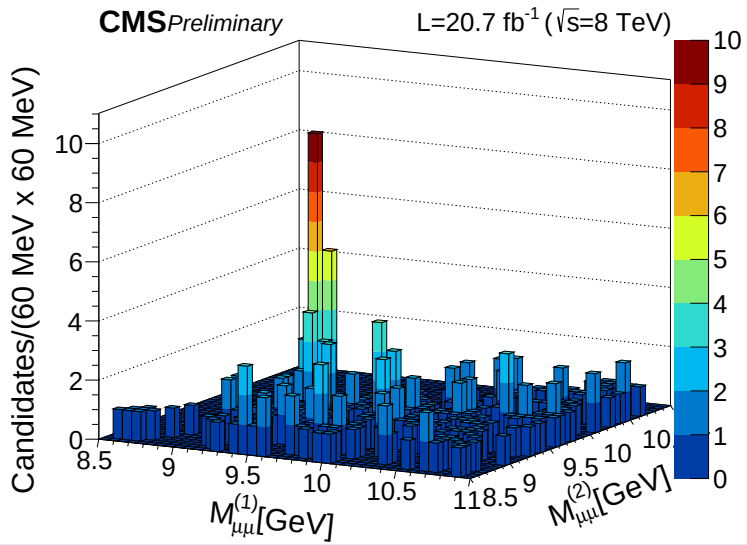
Double Υ selection & signal extraction

Event selection

- Muon quality:
  - hits in tracker and pixel detector
  - match chamber segment with extrapolated track
- $p_{T,\mu} > 3.5$ GeV , $|\eta_\mu| < 2.4$
- $p_{T,\Upsilon} < 50$ GeV , $|y_\Upsilon| < 2.0$

} uniform muon acceptance region

- Multiple Υ events discarded
- Non-prompt production negligible



Invariant mass distributions

- $\Upsilon(1S)\Upsilon(1S)$ and $\Upsilon(1S)\Upsilon(2S)$ yield estimated,
- no visible signal for $\Upsilon(3S)$
- $2D$ unbinned max likelihood fit, 5 components

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- CB function (signal)
- 1^{st} Chebyshev polynomial (bg)
- $\Upsilon(1S)\Upsilon(1S)$, $\Upsilon(1S)\Upsilon(2S)$
- $\Upsilon(1S)/\Upsilon(2S)$-combinatorial
- combinatorial-combinatorial

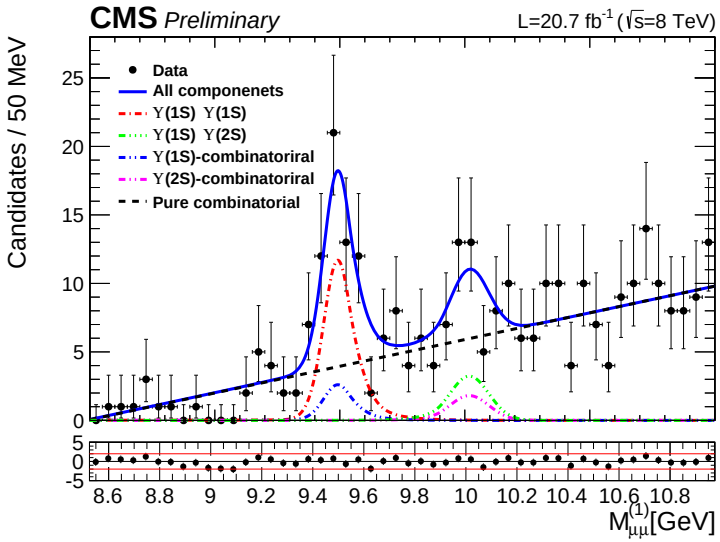
Double Υ production cross-section

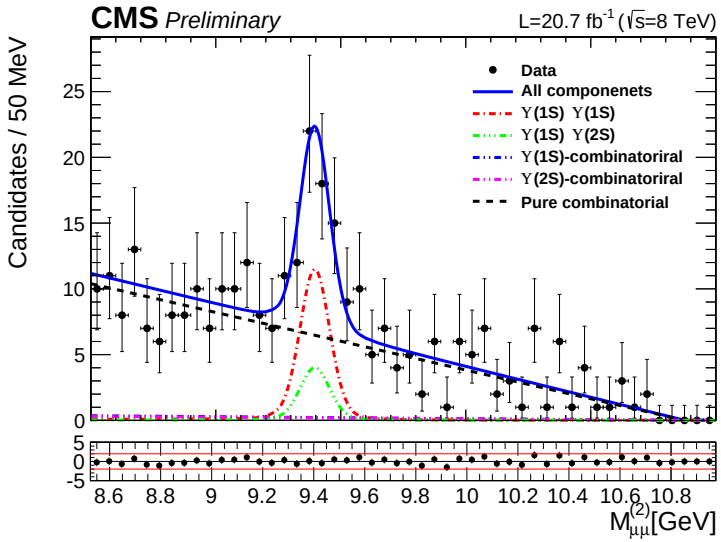
$$\sigma_{\Upsilon} = \frac{n_{sig} \cdot \bar{\omega}}{\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)^2 \cdot \mathcal{L}}$$

n_{sig} = $\Upsilon(1S)\Upsilon(1S)$ signal yield $\mathcal{L}$ = integrated luminosity

$\bar{\omega}$ = acceptance & efficiency factor

- Acceptance and efficiency computed event-by-event on a MC sample
- Υ mesons assumed to decay isotropically





Double Υ production: results

$\sqrt{s} = 8$ TeV , $\mathcal{L} = 20.7$ fb^{-1} CMS-PAS-BPH-14-008

$$\sigma_T = (68.8 \pm 12.7(\text{stat}) \pm 7.4(\text{syst}) \pm 2.8(\text{BR}))\text{pb}$$

Systematic uncertainties

- Signal/background shapes
- Acceptance and efficiency
- Integrated luminosity

Υ polarization

- Acceptance computed assuming unpolarized production compared with full longitudinal/transverse polarization hypotheses
- -38%/+36% variation found

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$B^{\pm}$ production cross-section

$$B^{\pm} \to J/\psi K^{\pm} \, , J/\psi \to \mu^{+}\mu^{-}$$

- Studies of b-hadron production at the higher energies
  $\Rightarrow$ new important test of theoretical calculations
- First $B^{\pm}$ production cross-section measurement at $\sqrt{s} = 13$ TeV

$\mathcal{L} = 50.8\ \text{pb}^{-1}$, $|y_B| < 2.4$, $10\ \text{GeV} < p_{T,B} < 100\ \text{GeV}$ CMS-PAS-BPH-15-004

Differential cross-section, vs. transverse momentum and rapidity

$$\frac{d\sigma(pp \to B^{+}X)}{dz} = \frac{n_{\text{sig}}(z)}{2 \cdot \mathcal{B} \cdot A \cdot \epsilon(z) \cdot \mathcal{L} \cdot \Delta z}$$

z	=	$p_{T,B}$, $\lvert y_B \rvert$	$n_{\text{sig}}(z)$	=	signal yield
2	=	account for B charge symmetry	A	=	acceptance
			$\epsilon(z)$	=	efficiency
$\mathcal{B}$	=	$\mathcal{B}(B^{\pm} \to J/\psi K^{\pm})$ $\cdot\mathcal{B}(J/\psi \to \mu^{+}\mu^{-})$	$\mathcal{L}$	=	integrated luminosity
			Δz	=	bin width

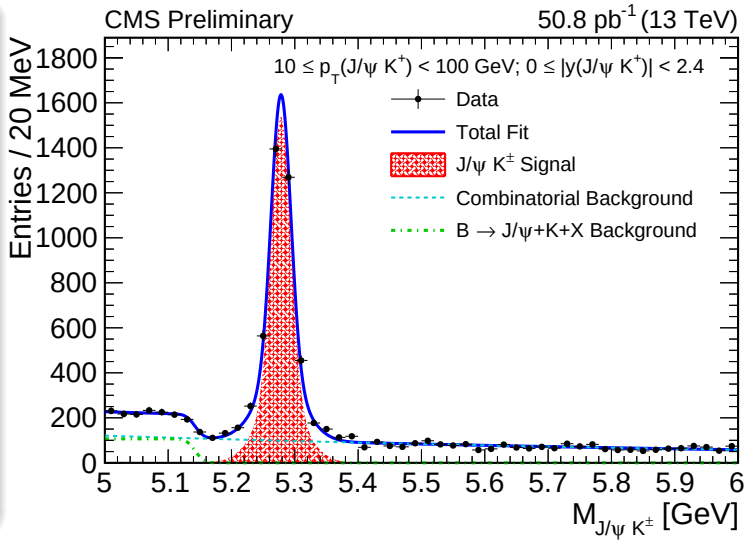
$B^{\pm}$ signal extraction

Event selection

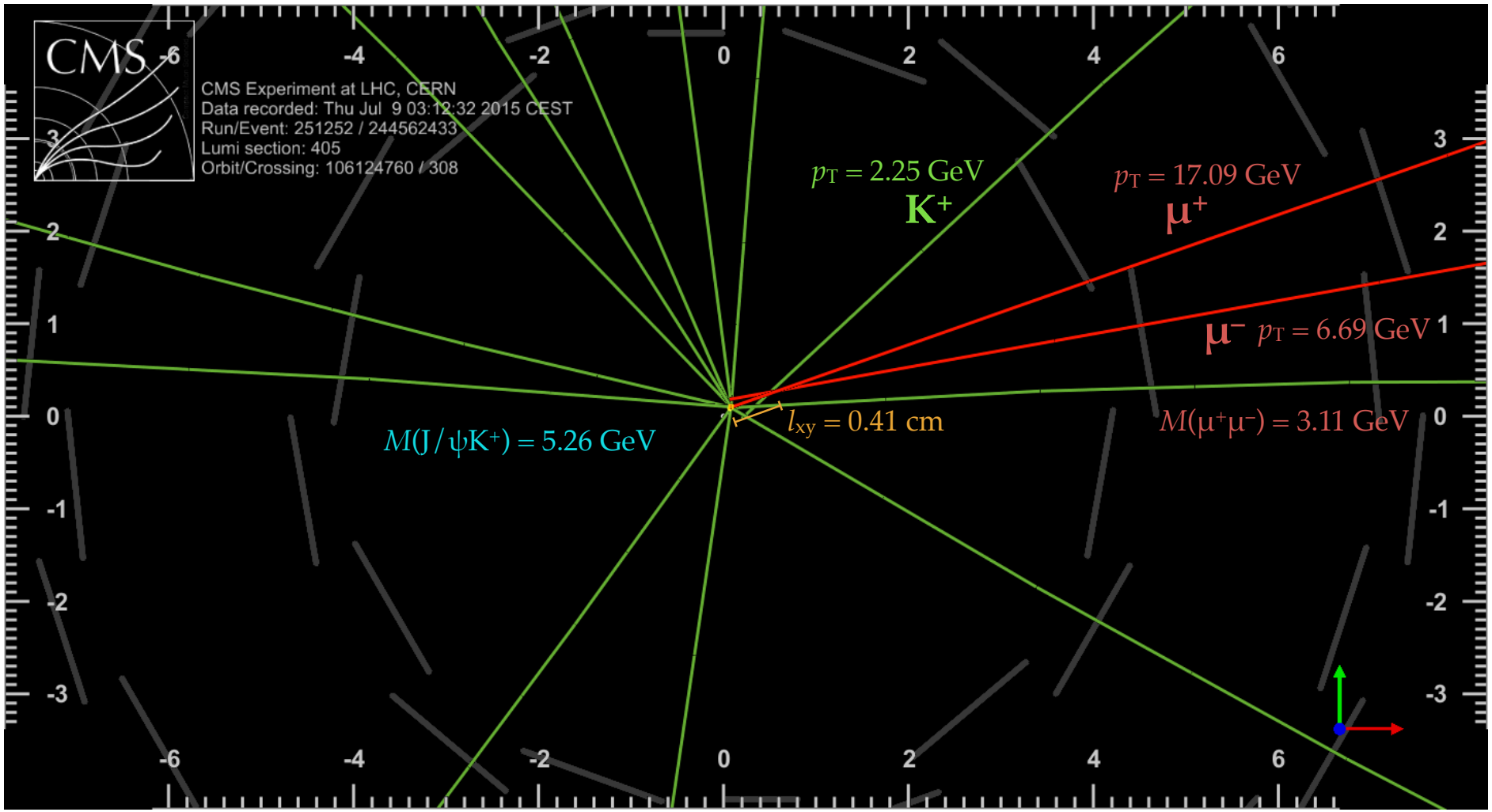
- Muon quality: match chamber segment with extrapolated track
- J/ψ candidate quality: invariant mass and vertex fit χ^2
- $B^{\pm}$ candidate quality: common vertex, flight distance and direction

$B^{\pm} \to J/\psi K^{\pm}$ invariant mass distributions

- $p_{T,B}$ and $|y_B|$ bins
- Unbinned max likelihood fit:
  - Sum of 2 gaussians (signal)
  - exponential (background)
  - error function (mis-reconstructed $B^{\pm} \to J/\psi KX$)



$B^{\pm} \to J/\psi K^{\pm}$ event



$B^{\pm} \to J/\psi K^{\pm}$ acceptance and efficiency

Overall $A \cdot \epsilon$ estimation

- Simulated events with $|y_B| < 2.4$, 10 GeV $< p_{T,B} <$ 100 GeV
- Selected event fraction:
  - 0.5% ($p_{T,B} \sim$ 10 GeV) ; 19% (70 GeV $< p_{T,B} <$ 100 GeV)
  - 4% ($|y_B| \sim 0$) ; 0.4% ($1.8 < |y_B| < 2.4$)

Trigger and muon-reconstruction efficiency

- Inclusive $J/\psi \to \mu^+\mu^-$ data sample
- Tag-and-probe method
  - one muon satisfying stringent quality requirements
  - second muon identified only with tracker or muon system
- Efficiency compared with simulation,
  difference included in systematic uncertainties

$B^{\pm}$ production: systematic uncertainties

Signal yield

- Different mass modeling functions:
  - signal: 3 gaussians
  - background: 2nd order polynomial
  - $B^{\pm} \to J/\psi KX$ events: gaussian, mass shift
- Include the rare decay $B^{\pm} \to J/\psi\pi^{\pm}$
- p_T , $|y|$ bin to bin migration due to finite resolution

Other sources

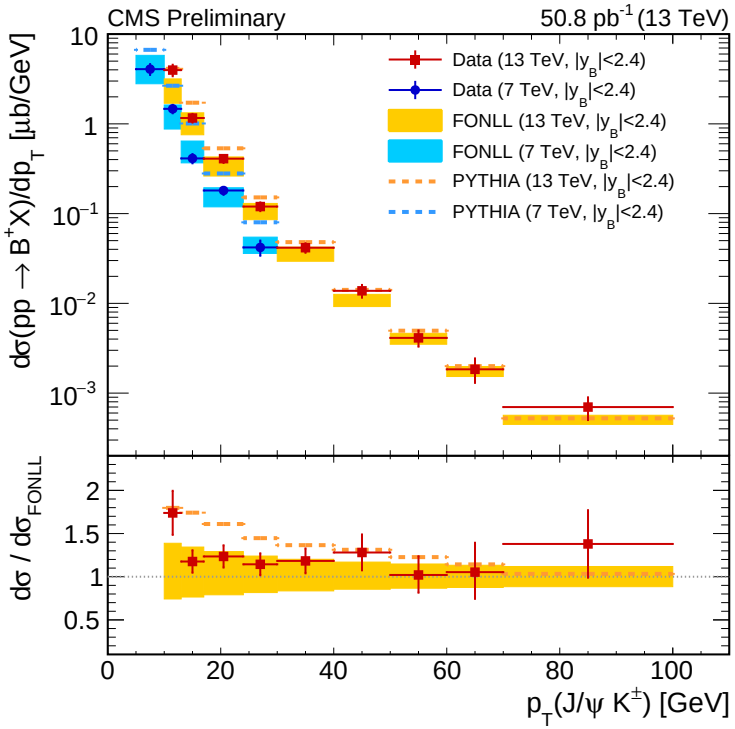
- Luminosity: 4.8%
- $\mathcal{B}(B^{\pm} \to J/\psi K^{\pm} \to \mu^{+}\mu^{-}K^{\pm})$: 3.1%

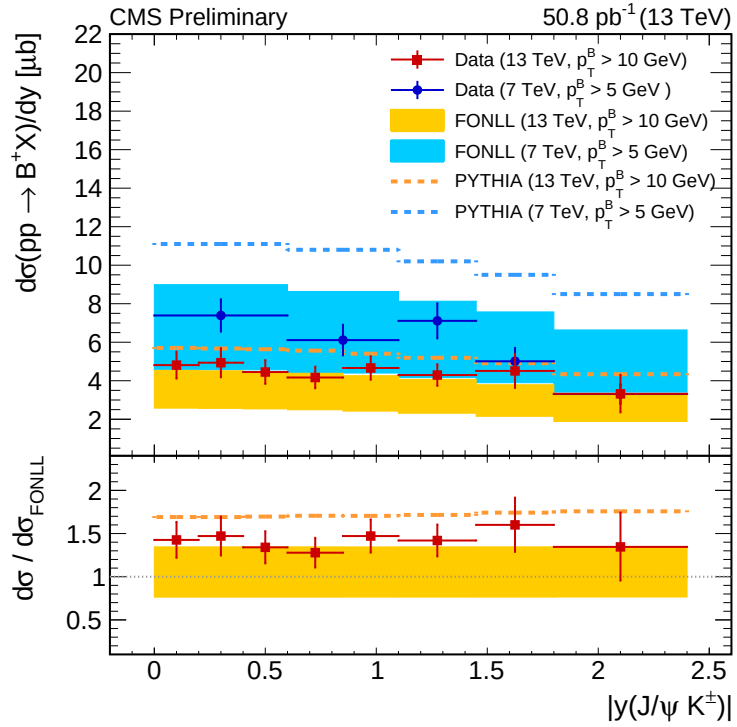
$B^{\pm}$ production: results

Differential cross-section vs. $p_{T,B}$, $|y_B|$

- Left: $d\sigma/dp_{T,B}$ (integrated over $|y_B| < 2.4$)
- Right: $d\sigma/d\,|y_B|$ (integrated over 10 GeV $< |y_B| <$ 100 GeV)
- Comparison with FONLL and PYTHIA

M. Cacciari *et al.*, JHEP 05 (1998) 007 , JHEP 03 (2001) 006 , JHEP 10 (2012) 137 , arXiv:1507.06197





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Quarkonia production cross-section

J/ψ , $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

- Test factorization and NRQCD
- 2 phases:
  - perturbative generation of $Q\bar{Q}$ pair (singlet/octet)
  - hadronization producing bound state (LDME)
- Different center of mass energies:
  - perturbative calculations appropriate for energy
  - same LDME
- Higher energy and higher cross-section: extended p_T reach

G.T. Bodwin *et al.*, PRD 51 (1995) 1125
G.T. Bodwin *et al.*, PRD 55 (1997) 5853
P. Cho and A.K. Leibovich, PRD 53 (1996) 150
P. Cho and A.K. Leibovich, PRD 53 (1996) 6203

P. Faccioli *et al.*, PLB 736 (2014) 98
G.T. Bodwin *et al.*, PRL 113 (2014) 022001

$\mathcal{L} = 2.4\ \text{fb}^{-1}$, $|y_{\mu^+\mu^-}| < 1.2$, $p_{T,\mu^+\mu^-}$ up to 120 GeV

CMS-PAS-BPH-15-005

Double-differential cross-section,
vs. transverse momentum and rapidity

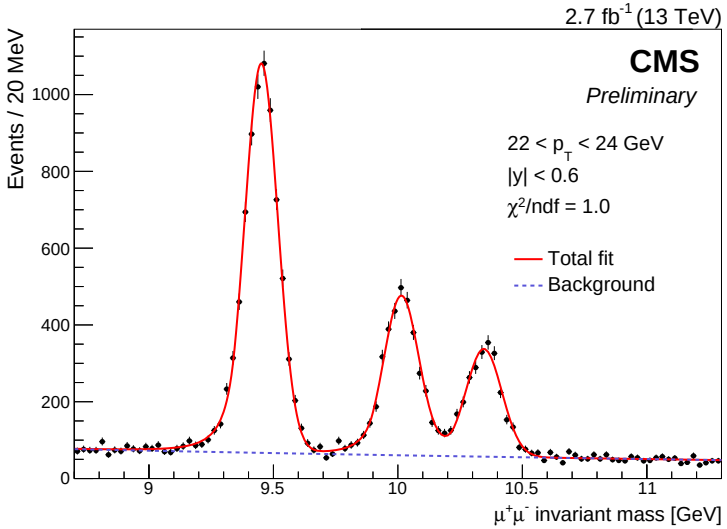
$$\mathcal{B}(Q\bar{Q} \to \mu^+\mu^-) \cdot \frac{d^2\sigma(pp \to Q\bar{Q}X)}{dp_T dy} = \frac{N_{Q\bar{Q}}(z)}{\mathcal{L} \cdot \Delta p_T \Delta y} \cdot \left\langle \frac{1}{A(p_T, y) \cdot \epsilon(p_T, y)} \right\rangle$$

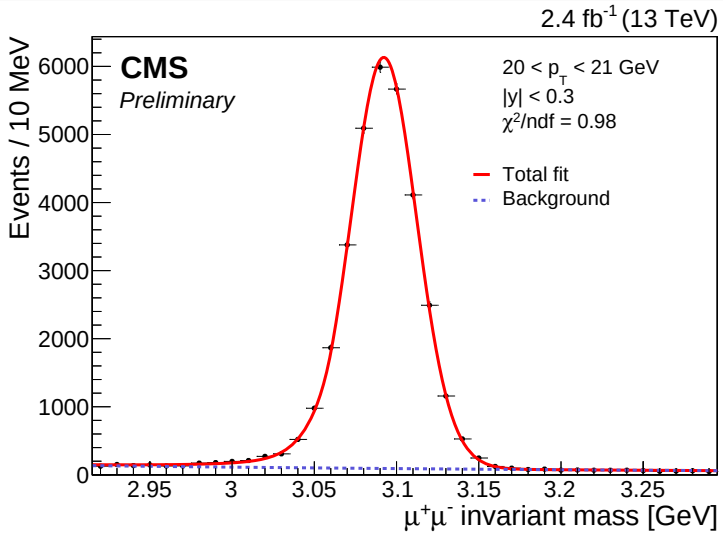
Quarkonia signal extraction

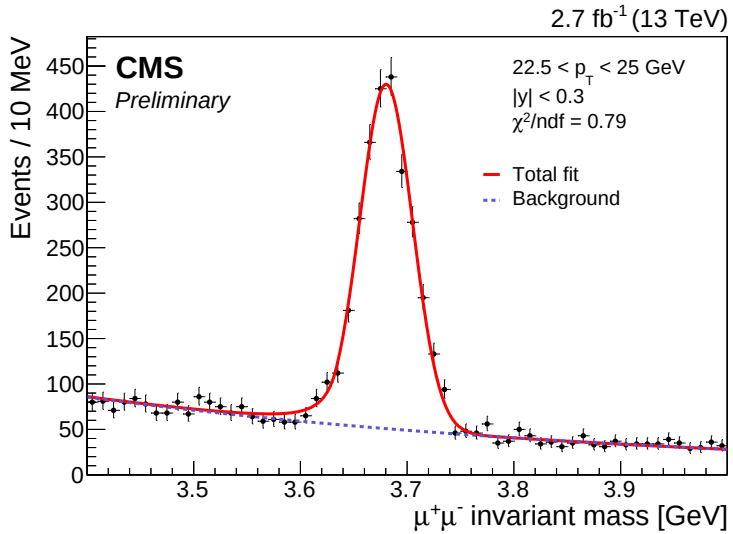
$Q\bar{Q}$ invariant mass distributions

- Muon & vertex quality selection
- Unbinned max likelihood fit in $p_{T,Q\bar{Q}}$ and $|y_{Q\bar{Q}}|$ bins
  - Crystal Ball function (signal)
  - exponential (background)

Parameters constrained to p_T-integrated fit result



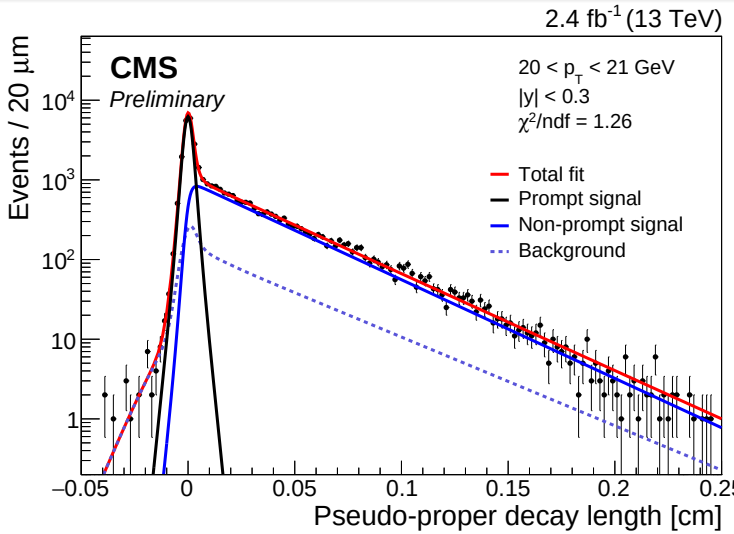


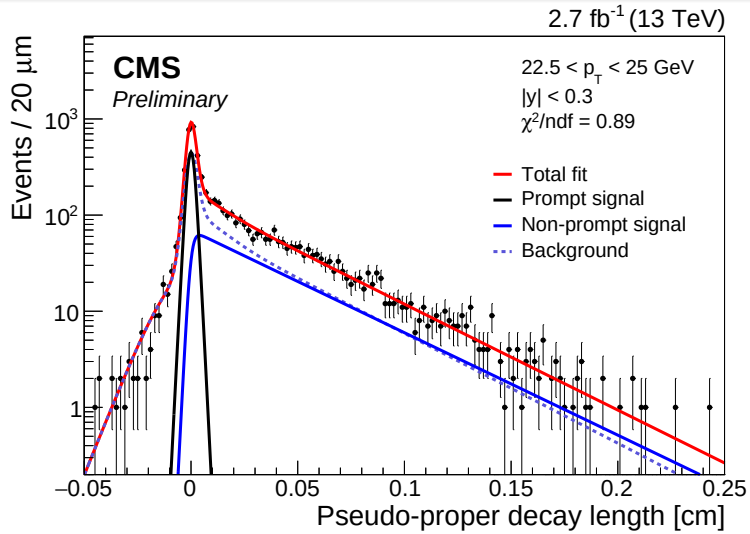


Prompt/non-prompt components

Chamonium sources

- Production in primary *pp* interaction: prompt
- Production in *b*-hadron decay: non-prompt





Simultaneous fit to mass and “pseudo proper decay length”:

- prompt: resolution function
- non-prompt: exponential convoluted with resolution function
- background: gaussian plus exponential

$Q\bar{Q} \to \mu^+\mu^-$ acceptance and efficiency

Acceptance

Generated $Q\bar{Q}$ events, decay to $\mu^+\mu^-$ simulated with PYTHIA8

$$\mathcal{A} = \frac{N^{\text{gen}}_{\text{kin}}(p_T, y)}{N^{\text{gen}}(p_T, y)}$$

- $N^{\text{gen}}(p_T, y)$: generated events
  $N^{\text{gen}}_{\text{kin}}(p_T, y)$: events passing selection
- Acceptance stored in finely binned histograms
- Unpolarized production assumed

Efficiency

- Tag-and-probe method
- dimuon efficiency: product of two efficiencies multiplied by a correction factor accounting for correlation

Acceptance and efficiency calculated event-by-event

Quarkonia production: systematic uncertainties

Signal yield

Different mass fits:

- changes in CB function parameters
- fixed/free mean masses
- exponential/linear function for background

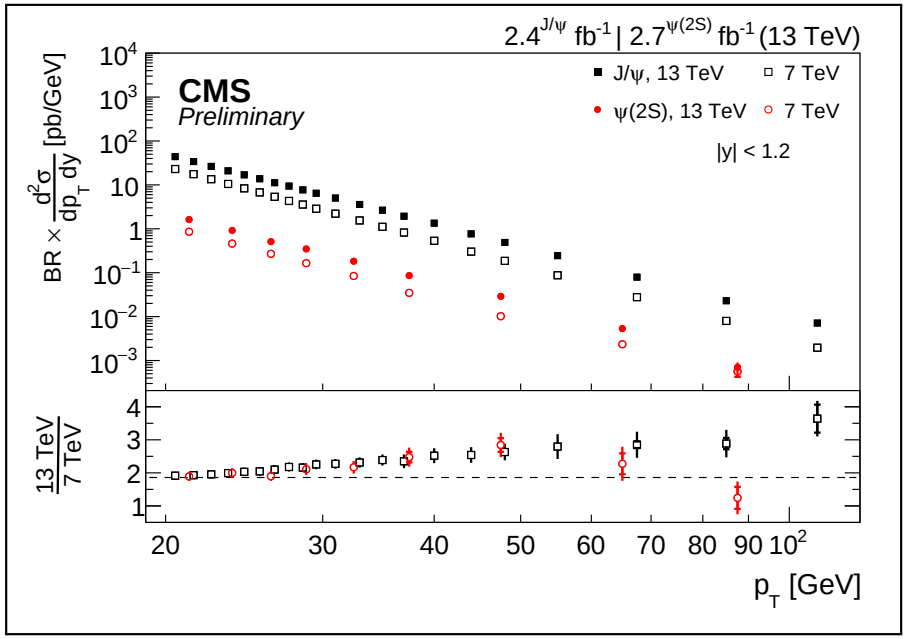
Non-prompt fraction

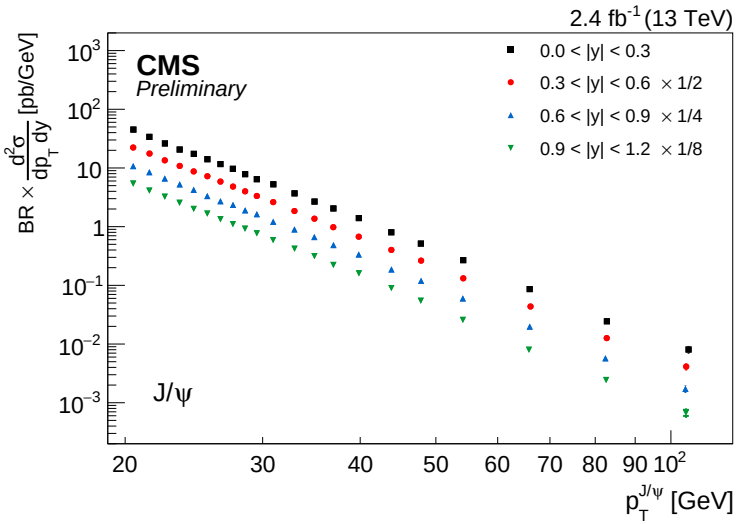
- Decay length from:
  - average interaction point
  - nearest primary vertex along beam direction
- Different functions for background modeling: right, left or double-sided exponential
- Changes in parameter constraints

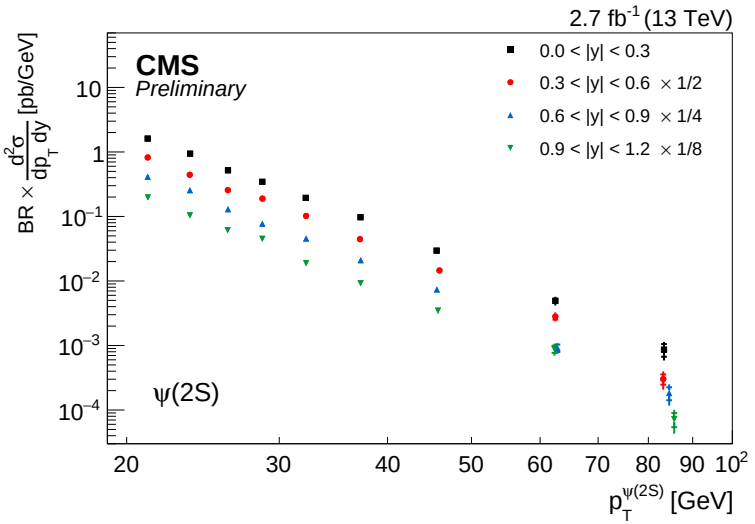
J/ψ , $\psi(2S)$: results

Double-differential cross-section

- Plot vs. p_T in 4 $|y|$ bins
- p_T up to:
  - 120 GeV(J/ψ)
  - 100 GeV($\psi(2S)$)
- weighted average for the integrated range $|y| < 1.2$

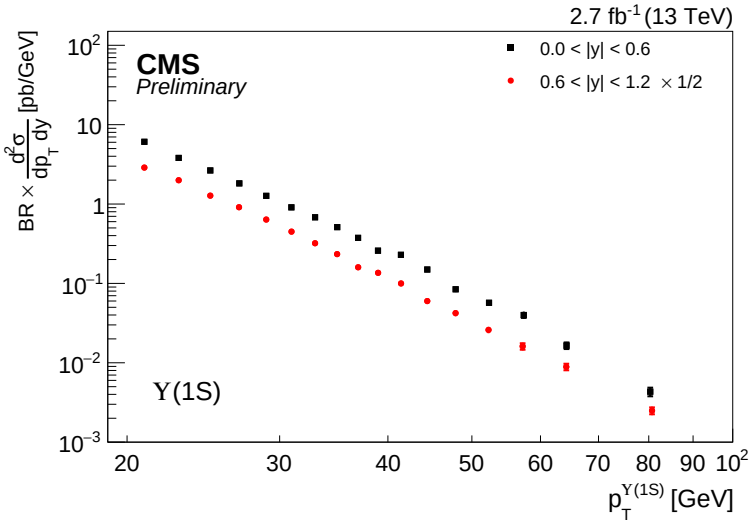


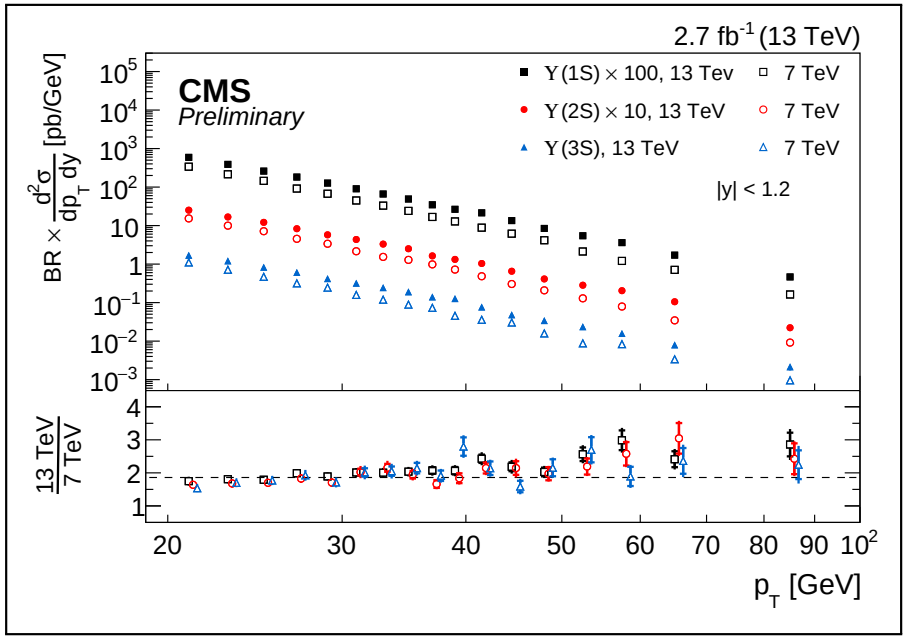


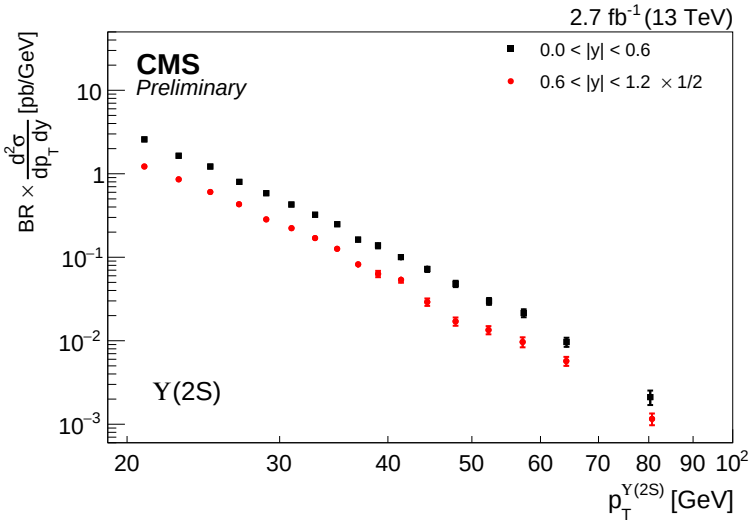


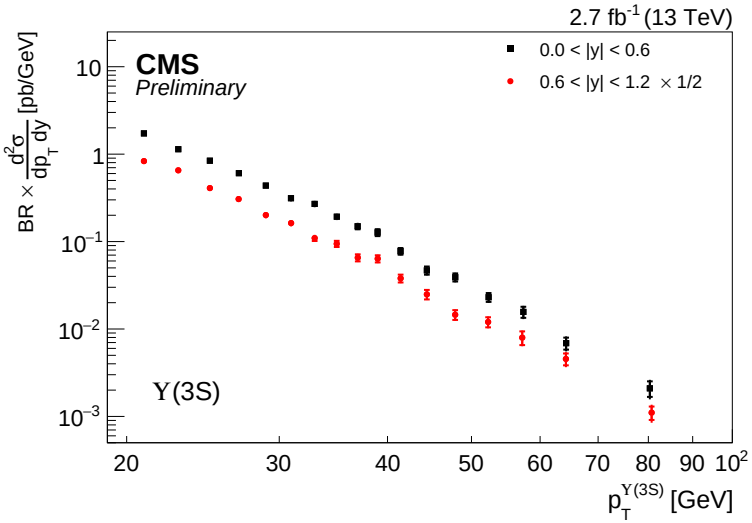
Υ(1S) ,Υ(2S) ,Υ(3S) : **results**

Plot vs. p_T in 2 $|y|$ bins



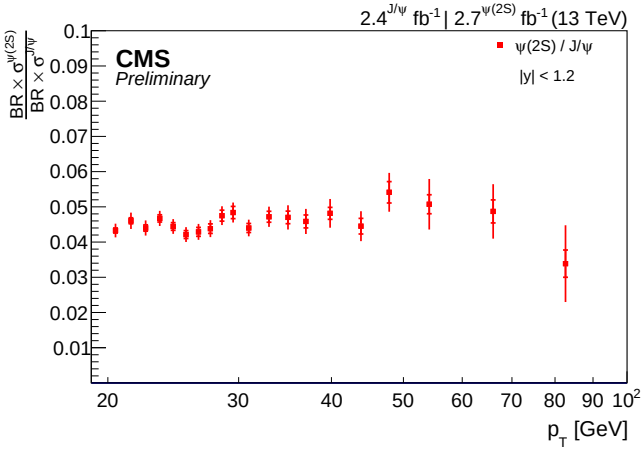


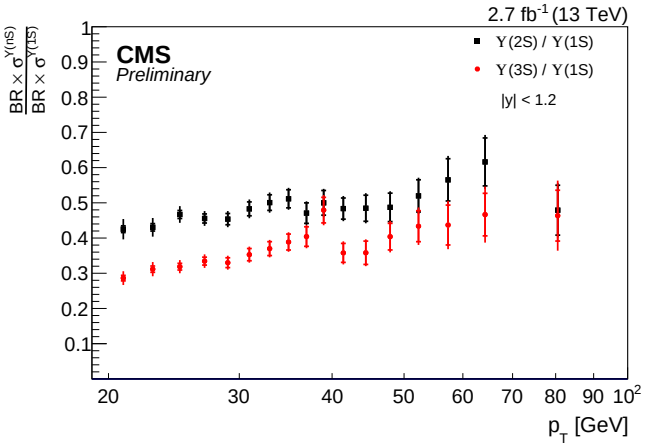




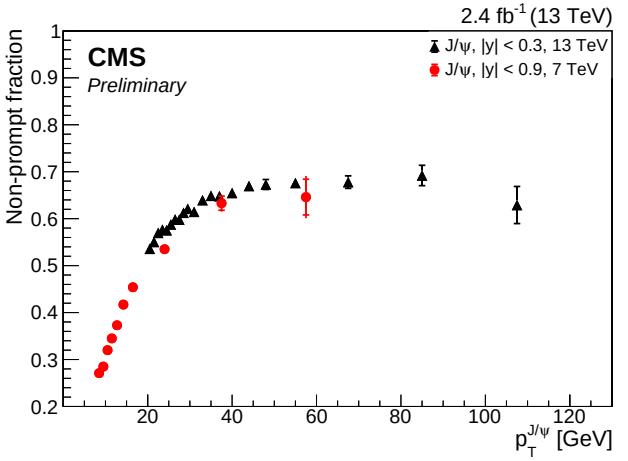
Quarkonia production : production ratios

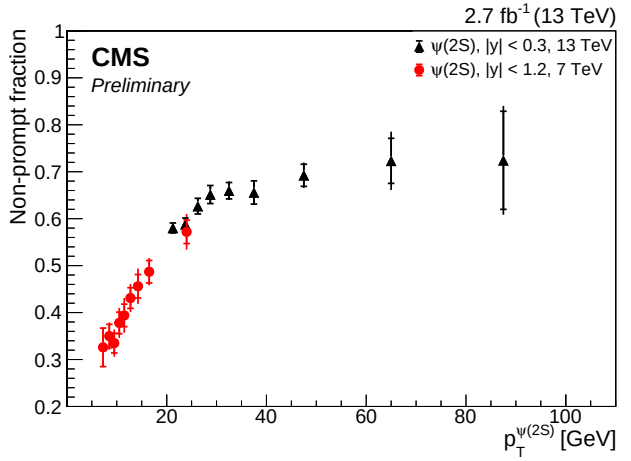
Cross section ratios





Non-prompt fractions





Conclusions

- Differential cross section for B^{+} production at $\sqrt{s} = 13$ TeV has been measured up to 100 GeV in p_T. A reasonable agreement with FONLL calculations and with PYTHIA has been found.
- The double differential production cross sections at $\sqrt{s} = 13$ TeV for J/ψ , $\psi(2S)$, $\Upsilon(n S)$ has been measured. These results shall contribute to consolidate the underlying hypotheses of NRQCD and provide further input to constrain the theory parameters.
- The simultaneous production of two $\Upsilon(1S)$ at $\sqrt{s} = 8$ TeV has been observed and the total cross-section has been measured.