CRIMEA-2011
New Trends in High-Energy Physics

Heavy-Flavour Physics with the CMS Experiment

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Introduction

- Perturbative and non-relativistic QCD do not succesfully reproduce measured production cross sections and polarization
- Discovery of new resonances opened up a new chapter in studies of QCD and spectroscopy as their J^{PC} sometimes do not fit in the SM
- Rare decays are sensitive to new physics and can therefore provide constraints on the models under evaluation
- Some of the presented measurements share technique and data sample: aim is to give the taste of the quality of the ongoing effort focussing on common points and strengths of CMS shared by the different analyses

Outline

1. Quarkonia Production at the LHC

2. *b*-Production at the LHC

3. Rare Decays and CP Violation with CMS

4. Concluding Remarks

The CMS Experiment

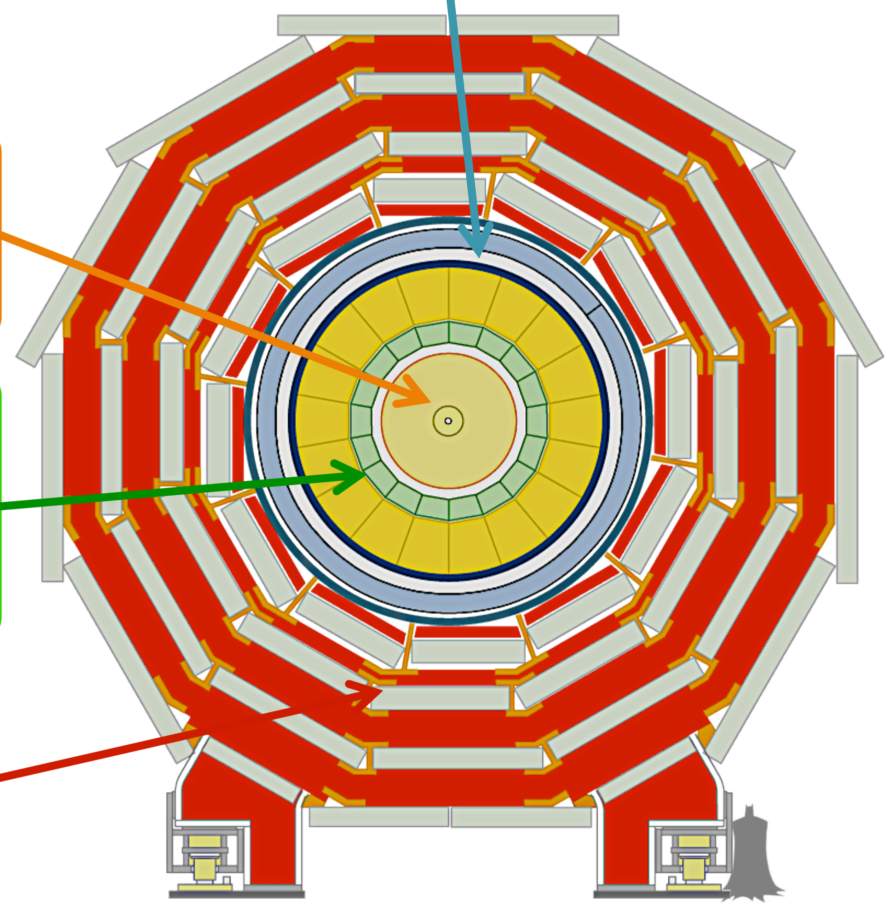
Housed at the CERN Large Hadron Collider, it is designed to collect data from proton-proton collisions at a center-of-mass energy up to 14 TeV, at luminosities of 10^{34} cm^{-2}s^{-1} (currently: $\sqrt{s}$ = 7 TeV, lumi: 2-3×10^{33} cm^{-2}s^{-1})

CMS is a general-purpose experiment designed around a large solenoid capable of a 4 T field (curr. 3.8 T)

high-precision tracking: transverse momentum and vertex position measurement with silicon pixels and strips

excellent electron and photon energy measurement in $PbWO_4$ crystals, identification and energy measurement of hadrons with brass absorber, missing E_T

good muon identification, charge and transverse momentum measurement within magnet return yoke



Part 1

Quarkonia Production at the LHC

J/ψ and ψ(2S) Production

36.7/pb of *pp* collision data at $\sqrt{s}$ = 7 TeV (2010) dimuon final state

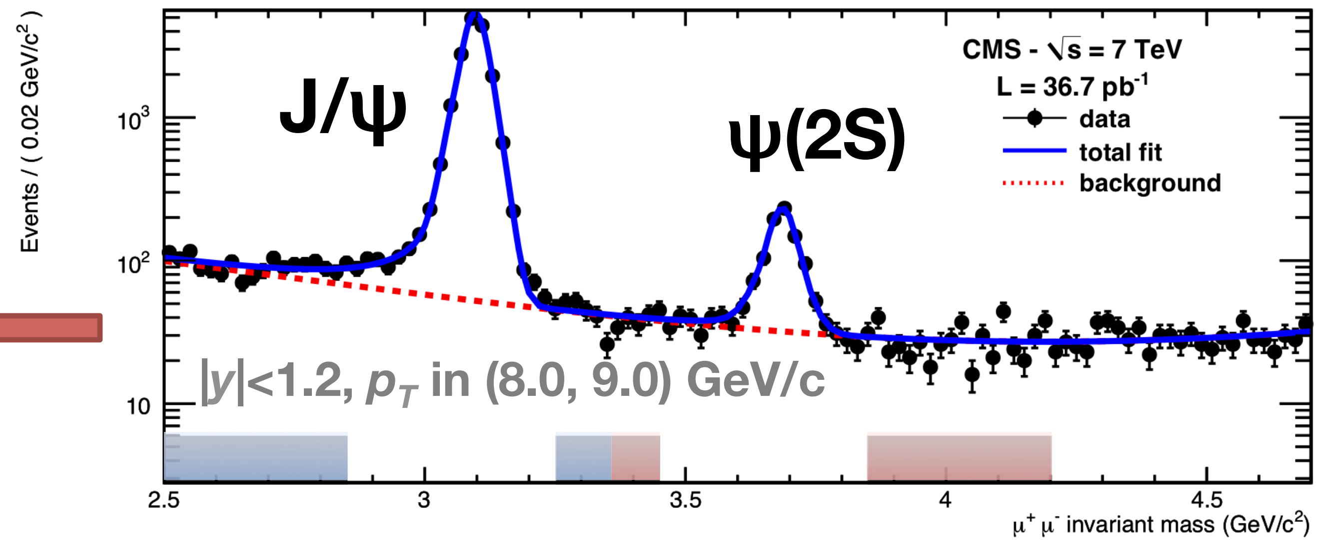
double muon trigger, opposite charge, common vertex, invariant mass in (2.5, 4.7) GeV/c^2

$$\frac{d^2\sigma \times BR}{dp_T d\eta} = \frac{N_{signal}}{Acc \times Eff \times Lumi \times \Delta p_T \Delta\eta}$$

Fit to dimuon invariant mass shape:

Resonance: Gaussians + CrystalBall *(Gaussian resolution + power law lower tail to handle FSR)*

Background: Exponentials



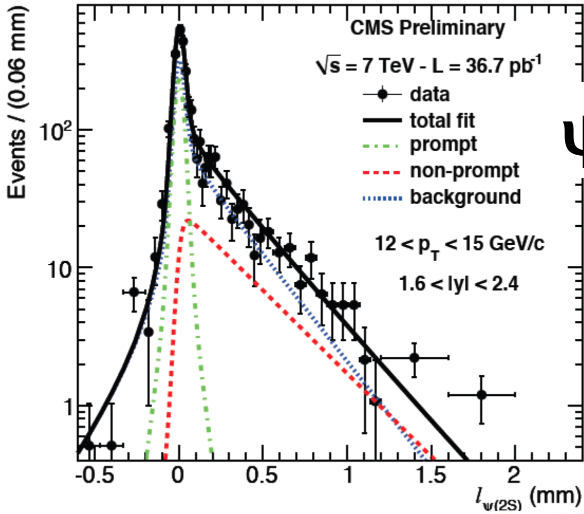
Prompt and non-prompt components (decays of *b*-hadrons):

2D fit: dimuon invariant mass and most probable distance $L_{J/\psi}$ in trasverse plane between primary vertex and dimuon vertex

PDF used in fit includes $\mathbf{PDF_{SIG}(L_{J/\psi})}$ =
= $\mathbf{f_{DEC} \times PDF_{DEC}(L_{J/\psi}) + (1\text{-}f_{DEC}) \times PDF_{prompt}(L_{J/\psi})}$

Background parameters from fit in mass sideband regions *(shaded in picture)*

J/ψ and ψ(2S) Production



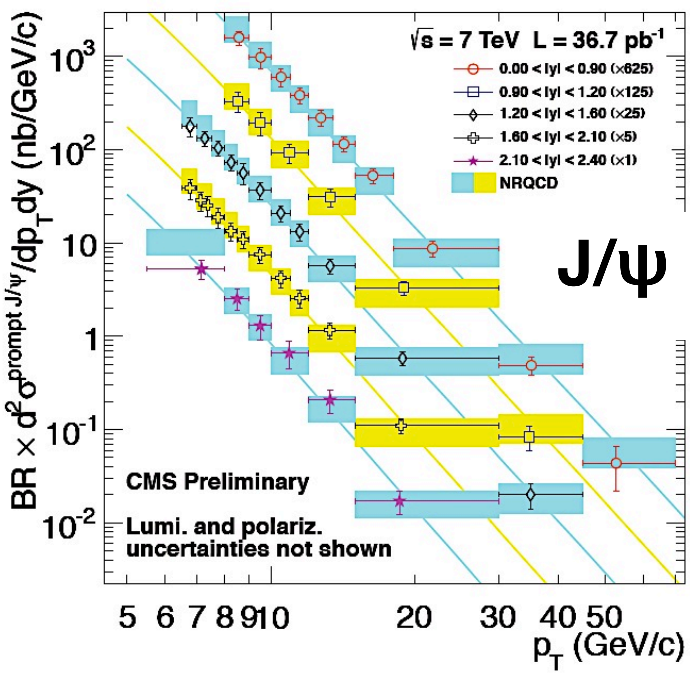
ψ(2S)

Fraction systematics:

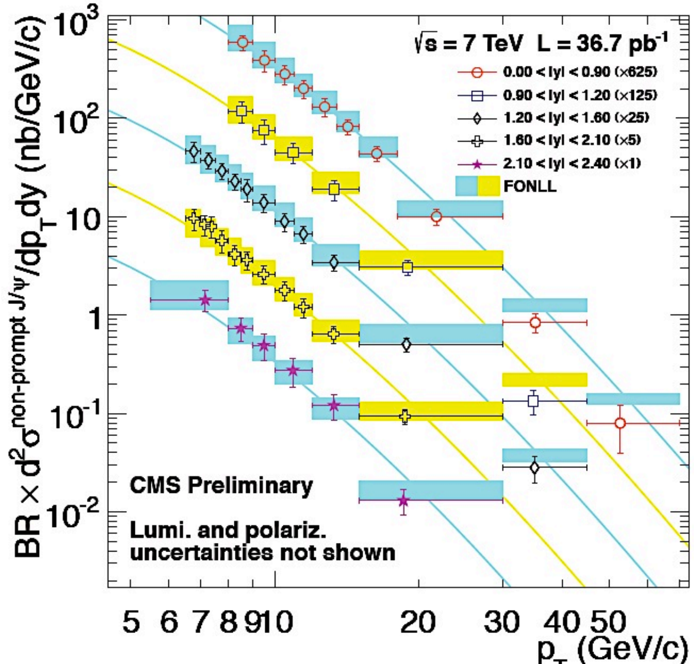
Tracker misalignment, *b*-lifetime model, primary vertex estimation, background fit in mass sidebands regions, resolution model, different efficiencies for prompt and non-prompt

Polarization assumed to be 0: no relevant hints from previous measurements

prompt



J/ψ



non-prompt

X(3872) and ψ(2S) Production

40/pb of *pp* collision data at $\sqrt{s}$ = 7 TeV (2010) dimuon+$\pi^+\pi^-$ final state

trigger and muon selection as described for J/ψ, pair of tracks (pion candidates) of opposite charge, 4-tracks common vertex

Strong suppression of combinatoric background:

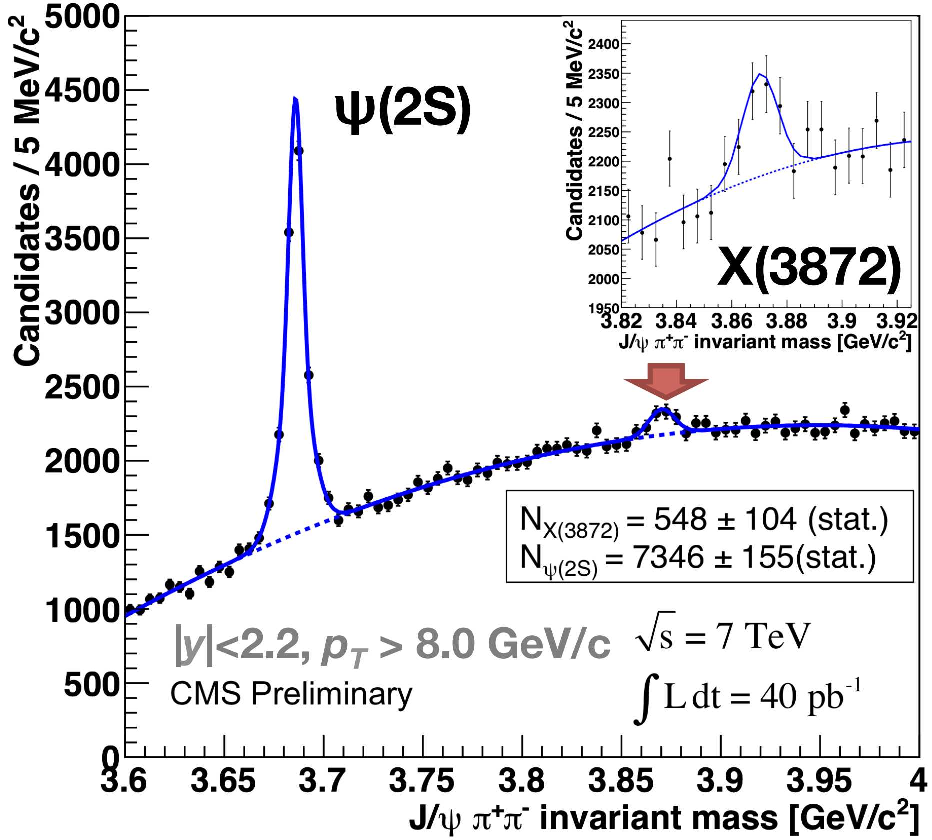
Pion pair with $p_T > 1.5$ GeV/c (0.4 GeV/c each), close to J/ψ in opening angle $\Delta R < 0.7$

Ratio of production cross section × BR(to J/ψ$\pi^+\pi^-$), X(3872)/ψ(2S):

= 0.087 ± 0.017 (stat) ± 0.009 (syst)

Signal extraction:

Unbinned likelihood fit to dimuon+ππ mass spectrum

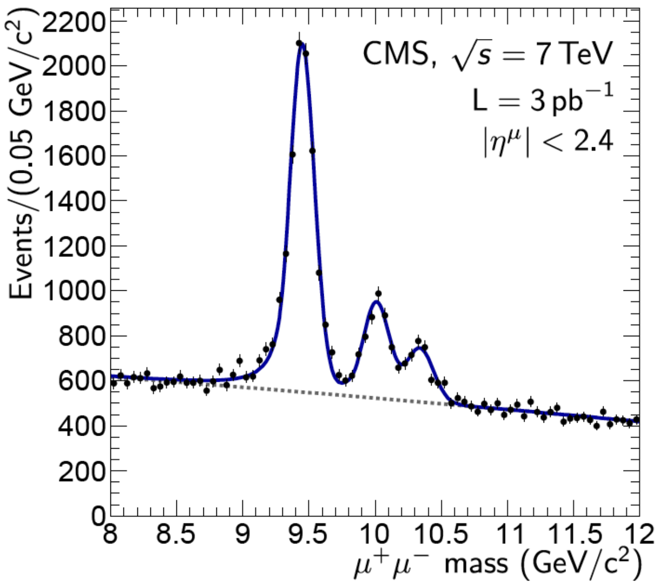


REF: PAS CMS BPH-10-018

Inclusive Υ Production

3.1/pb of *pp* collision data at $\sqrt{s}$ = 7 TeV (2010) dimuon final state

same approach as for J/ψ, dimuon invariant mass in (8.0, 14.0) GeV/c^2



Fit to dimuon invariant mass shape:

Each resonance: CrystalBall

Background: 2nd order Polynomial

Total and differential cross-section:

Fit either inclusive, or in 15 different p_T ranges *(not shown)*

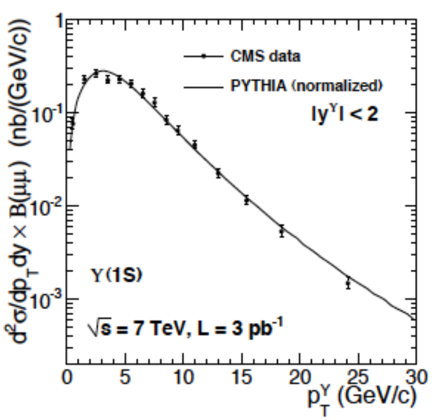
Cross-section × BR(dimuons):

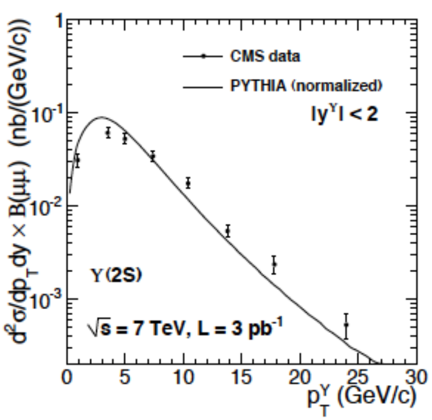
Υ(1S): 7.37 ± 0.13 (stat) $^{+0.61}_{-0.42}$ (syst) ± 0.81 (lumi) nb

Υ(2S): 1.90 ± 0.09 (stat) $^{+0.20}_{-0.14}$ (syst) ± 0.24 (lumi) nb

Υ(3S): 1.02 ± 0.07 (stat) $^{+0.11}_{-0.08}$ (syst) ± 0.11 (lumi) nb

Shapes agree w/ PYTHIA predictions





REF: Phys Rev D, 83 (2011) 112004

Quarkonia Production

- Measurement of J/ψ and ψ(2S) differential cross-section (p_T and η), determination of prompt and non-prompt cross-sections, with reasonable agreement with NRQCD predictions (exception: non-prompt at high p_T)
- Clear signal of X(3872) is observed, determination of the ratio between cross sections × BR to μμππ (ψ(2S))
- Measurement of ϒ(nS) integral and differential cross-section (p_T, in two η regions)

Quarkonia Production

- A larger amount of data will allow the measurement of polarization to better understand and constrain models of quarkonium production

Part 2

b-Production at the LHC

$B^{\pm} \rightarrow J/\psi\ K^{\pm}$

5.84/pb of *pp* collision data at $\sqrt{s}$ = 7 TeV (2010) dimuon+track final state

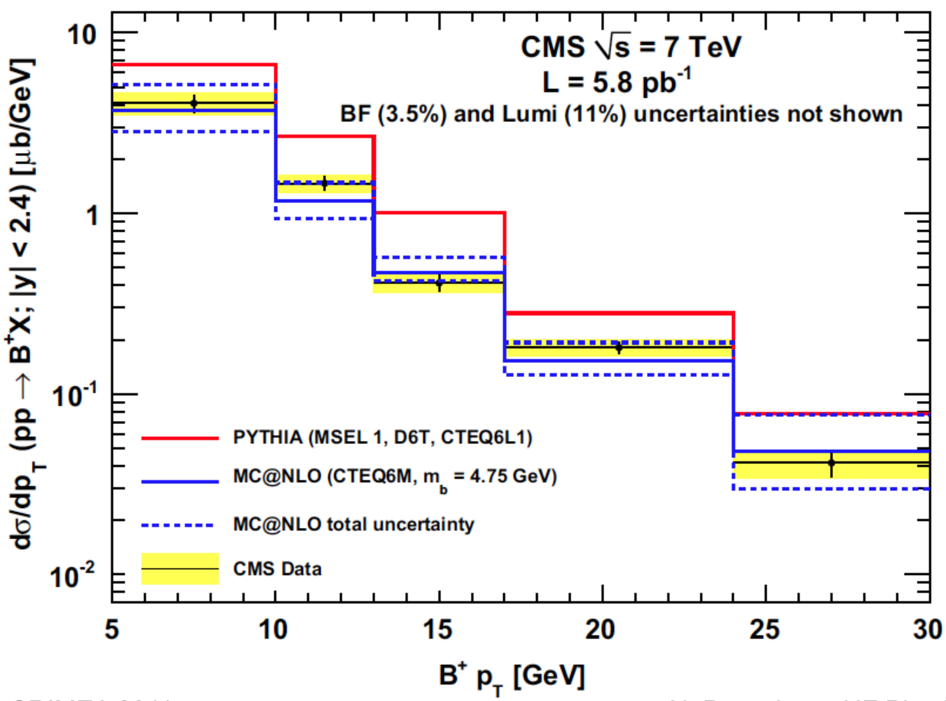
first measurement of $B^{\pm} \rightarrow J/\psi K^{\pm}$ at LHC, double muon trigger for J/ψ

Event selection:

$J/\psi \rightarrow \mu\mu$: opposite charge, mass in (2.95, 3.25) GeV/c², one additional track with quality cuts(*K* candidate) → 35k *B* candidates

Backgrounds:

J/ψ (prompt, non-prompt), misreconstructed $B \rightarrow J/\psi\ K^*(892)$



Signal extraction:

Max likelihood fit to m_B (Gauss+Exp, 30 MeV/c² res.) in (4.95, 5.55) GeV/c² and proper decay length $L_{xy} \times m_B / p_T^B$ (Exp conv. resolution function; 30 μm res.), 912 ± 47 signal events

Proper decay length as consistency check:

measured: 481 ± 22 μm (stat)
world-average value: 491 ± 9 μm

REF: Phys Rev Lett, 106 (2011) 112001

$B^0 \to J/\psi\ K_S$

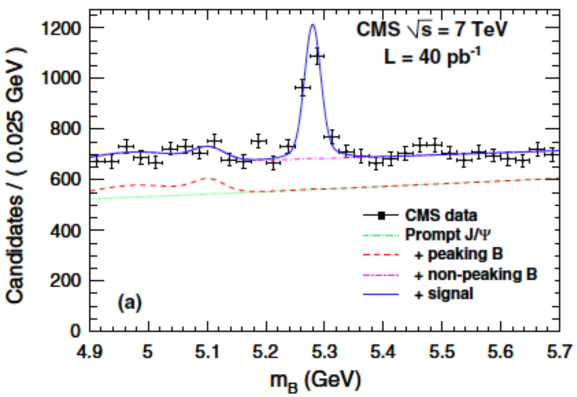
39.6/pb of *pp* collision data at $\sqrt{s}$ = 7 TeV (2010) dimuon+$\pi^+\pi^-$ final state

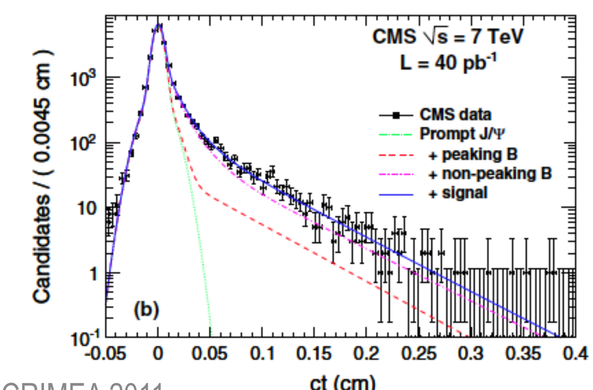
complementary to previous analysis, sharing selection criteria and backgrounds

Event selection:

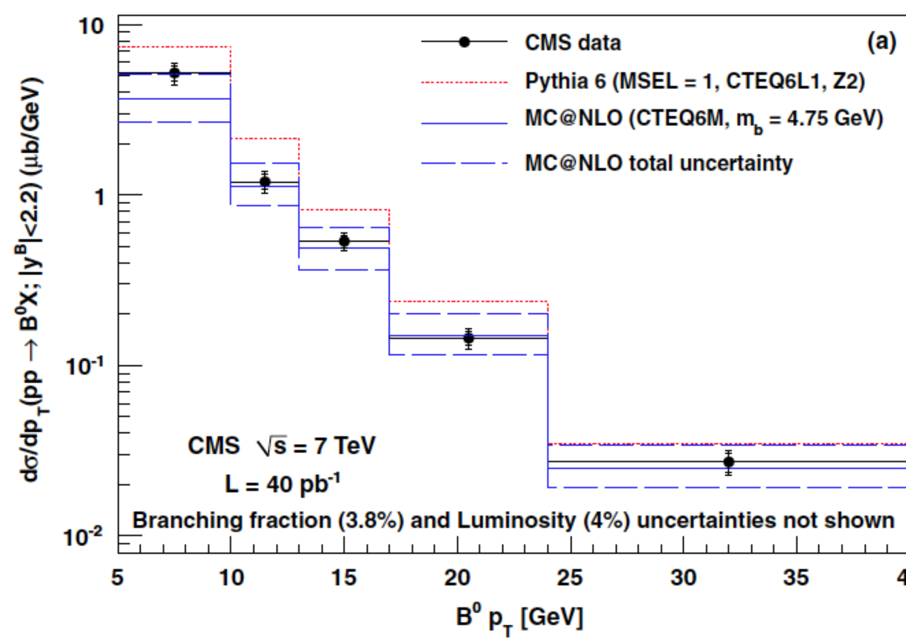
$J/\psi \to \mu\mu$: opposite charge, invariant mass in (2.95, 3.25) GeV/c², two additional opposite charge tracks, K_S mass in (478, 518) MeV/c²: → 23k *B* candidates

Signal extraction: Max likelihood fit to m_B and proper decay length: 809 ± 39 signal events





$|y^B|<2.2$
$p_T^B > 5.0$ GeV/c



REF: Phys Rev Lett, 106 (2011) 252001

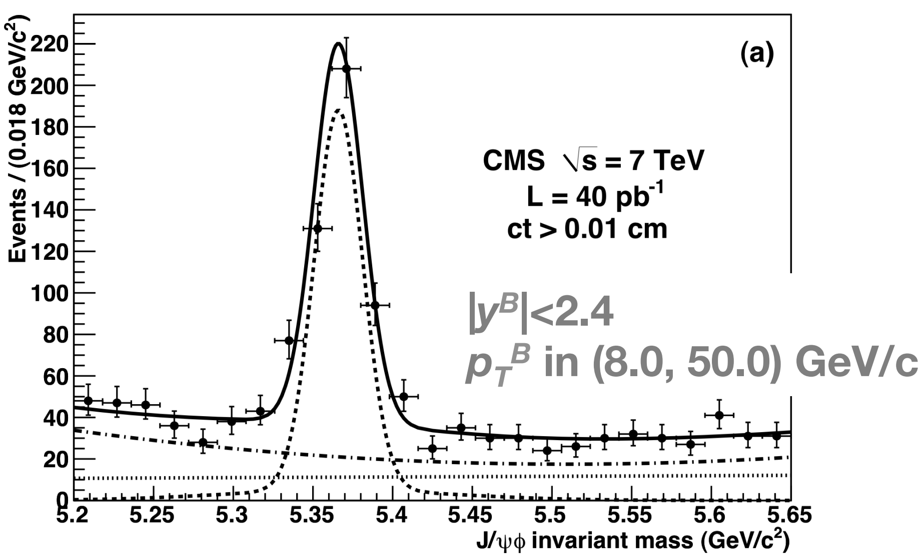
$B^0_s \to J/\psi\ \phi$

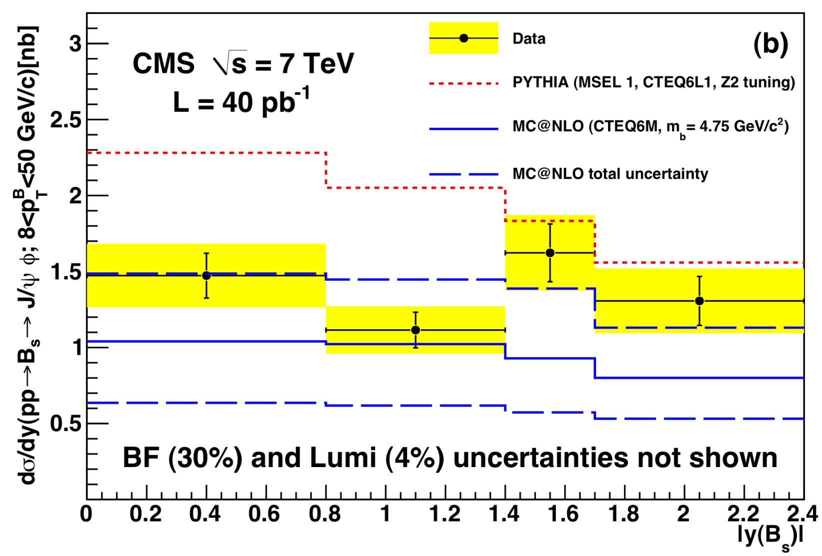
39.6/pb of *pp* collision data at $\sqrt{s}$ = 7 TeV (2010) dimuon+K^+K^- final state

complementary to previous analysis, sharing selection criteria and backgrounds

Event selection:
$J/\psi \to \mu\mu$: opposite charge, mass in (2.95, 3.25) GeV/c^2, two additional opposite charge tracks, ϕ mass in (1009, 1029) MeV/c^2:
→ 6200 *B* candidates

Signal extraction: Max likelihood fit to m_B and proper decay length: 549 ± 32 signal events





REF: Phys Rev D (sub) hep-ex/1106.4048

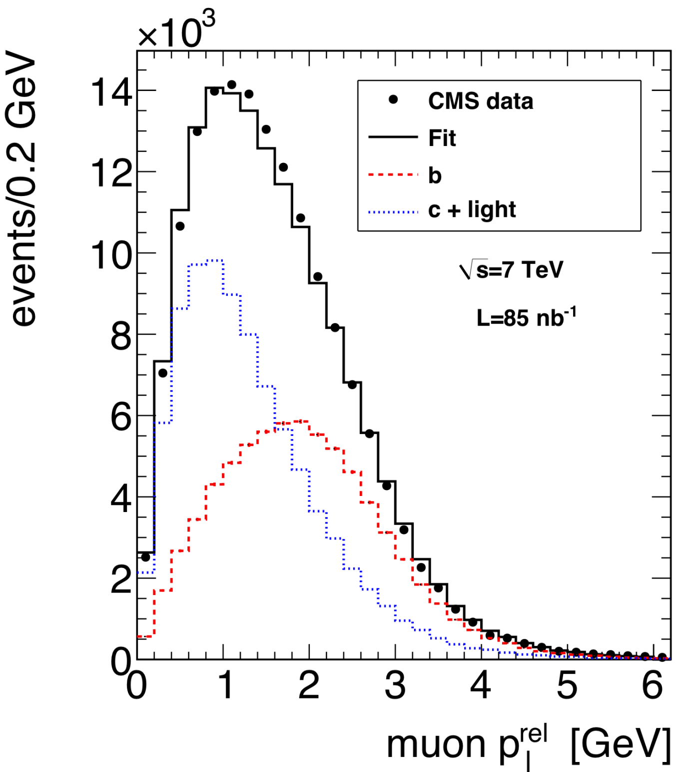
Exclusive *B* Production

- **Measurement of charged and neutral *B* mesons cross section, both integral and differential in p_T and η**
- **The result is in reasonable agreement with the predictions of MC@NLO in terms of shape and absolute normalization**

Open-beauty Production

85/nb of *pp* collision data at $\sqrt{s}$ = 7 TeV (2010) muons+jets final state

inclusive production of *b*-hadrons, single muon trigger, one central muon $p_T > 6$ GeV/c



b-jet:

all tracks are clustered in jets (anti-k_T), *b*-jet requires a clustered muon; energy and direction w/o muon!

Relative p_T:

$$p_T^{rel} = \frac{|\mathbf{p}_\mu \times \mathbf{p}_{jet}|}{|\mathbf{p}_{jet}|}$$

Signal extraction:

b-fraction from binned-likelihood fit to relative p_T templates from MC (*b*, *c*) and data (background), starting from ~158k candidate events

templates for c and light flavour backgrounds are too similar to each other: backgrounds merged

fit stability: pseudoexperiments and re-binning

Open-beauty Production

_b_-fraction:

overall fraction in acceptance after fit: 46%

Systematic uncertainties:

dominated by shape of relative p_T templates: signal template is validated with a *b*-enriched sample (muons with large impact parameter, *b*-fraction up to 85%)

Other non-trivial systematics:

data-driven LF-gluon template (2-14% difference wrt PYTHIA, according to different kinematic regions), MC generation and fragmentation models

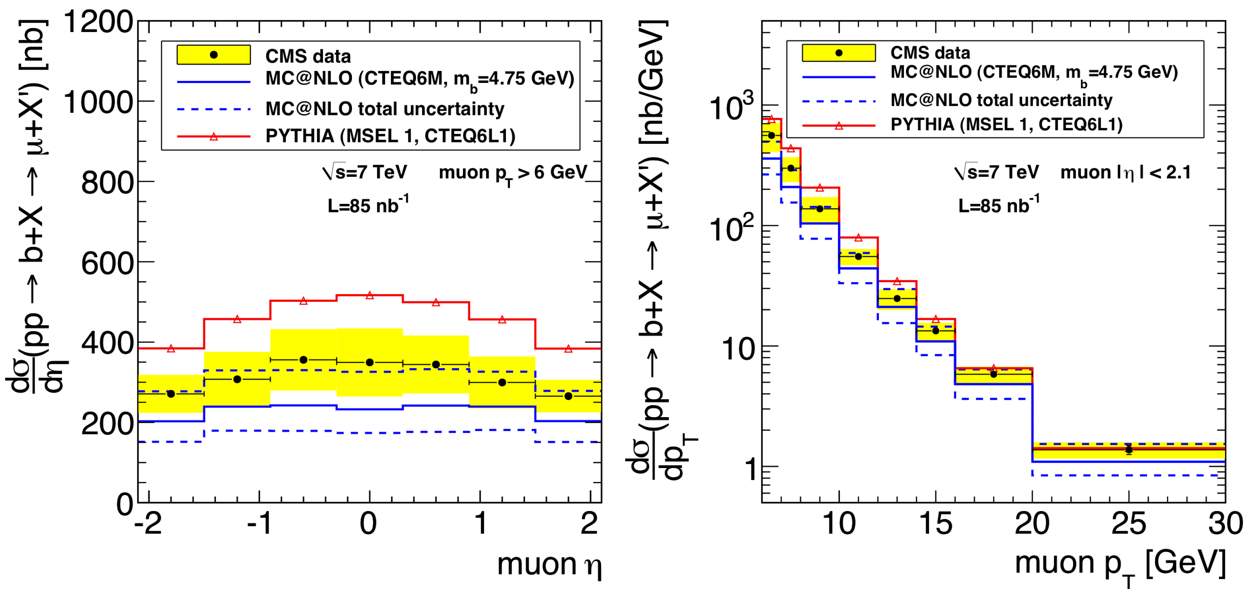
Cross section:

measured for muons in acceptance region $p_T > 6$ GeV/c and $|\eta| < 2.1$:

1.32 ± 0.01 (stat) ± 0.30 (syst) ± 0.15 (lumi) μb

MC@NLO:

$0.95^{+0.41}_{-0.21}$ (scale) ± 0.09 (m_b) ± 0.05 (pdf) μb



REF: JHEP (sub) hep-ex/1101.3512

Open-beauty Production

3/pb of *pp* collision data at $\sqrt{s}$ = 7 TeV (2010)
jets+muon+sec.vtx final state

inclusive production of *b*-hadrons, muon inside jet + secondary vertex: HF longer lifetime → higher impact parameter significance; muon trigger

Tagging of a *b*-quark inside a jet: ~independent of the details of the fragmentation: rate of jets is a direct measurement of the *b*-quark production rate

Secondary Vertex *b*-tagging: at least 3 tracks with Pixel hits to get clean signal, *(more details in next study described)*

Event selection: ~114k events selected

jets (anti-k_T), p_T > 30 GeV/c, $|y|$<2.4

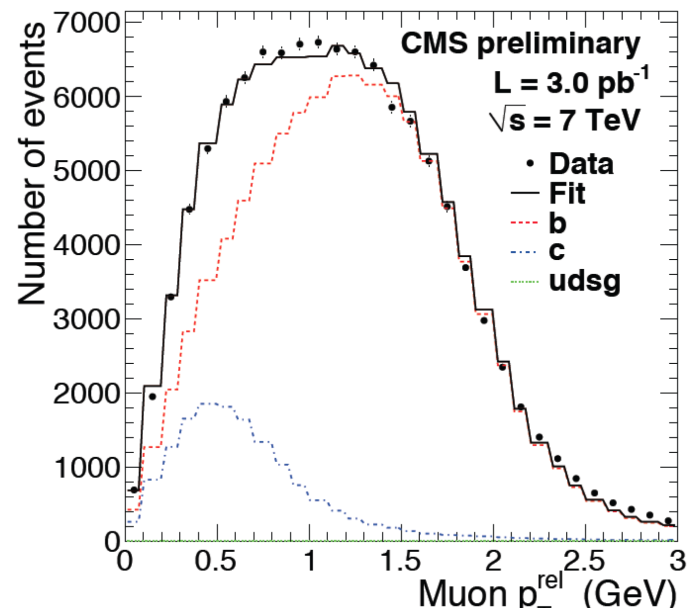
***b*-jet:** b-tag + muon (p_T > 9.0 GeV/c) within ΔR<0.3

***b*-fraction:** fit to relative p_T templates (meas. 86%)

Major systematics on cross section: *b* relative p_T template, *b*-tagging efficiency, jet energy scale, each ~10-15%

measured: 108 ± 1 (stat) ± 17 (syst) ± 4 (lumi) nb

MC@NLO: 113^{+40}_{-23} (scale) ± 3 (m_b) ± 5 (pdf) nb



REF: PAS CMS BPH-10-008

Inclusive *b*-Jet Production

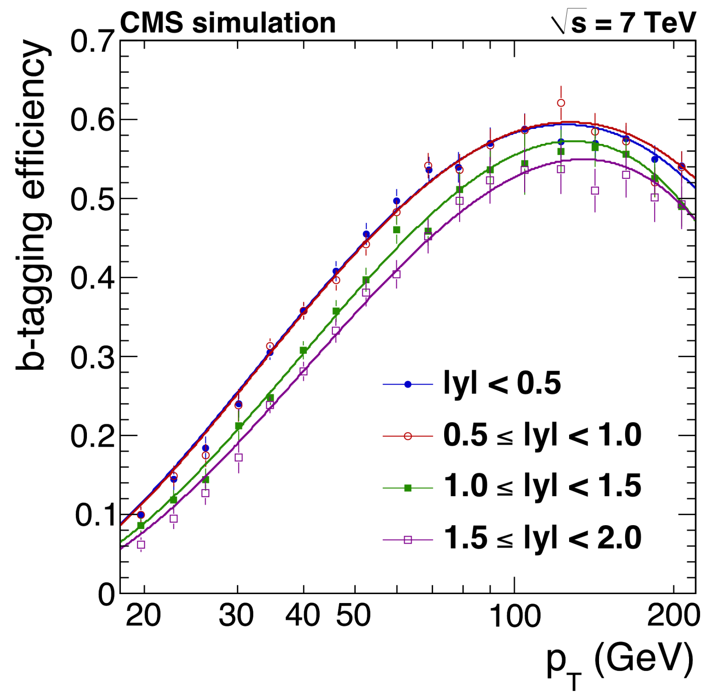
60/nb of *pp* collision data at $\sqrt{s}$ = 7 TeV (2010) jets+sec.vtx final state

inclusive production of *b*-hadrons, first search using only secondary vertex; min-bias and single jet trigger

Secondary Vertex *b*-tagging (3-tracks+Pixel) efficiency:

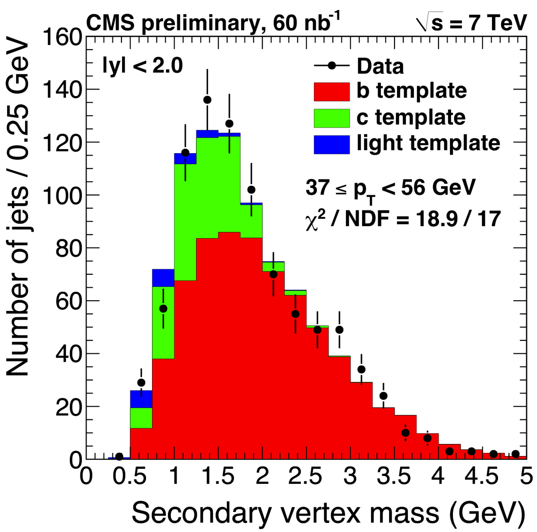
with muon jets, or directly from MC (pict. below)

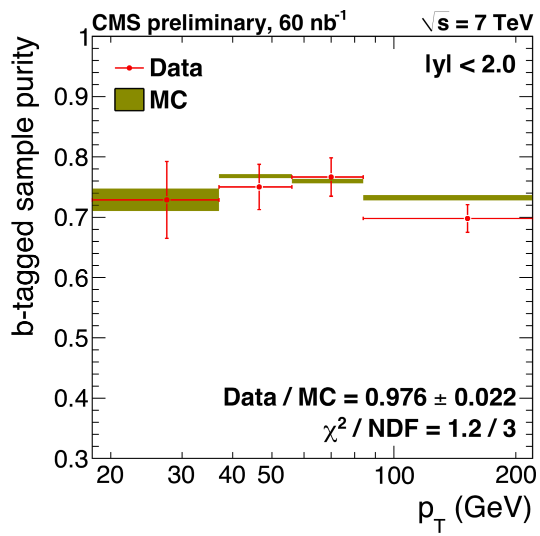
~60% on *b*-jets at p_T = 100 GeV/c; ~1% mistag (hadron lifetime larger at higher p_T → higher eff.)



Secondary Vertex *b*-tagging purity (1):

fit to vertex invariant mass templates from MC

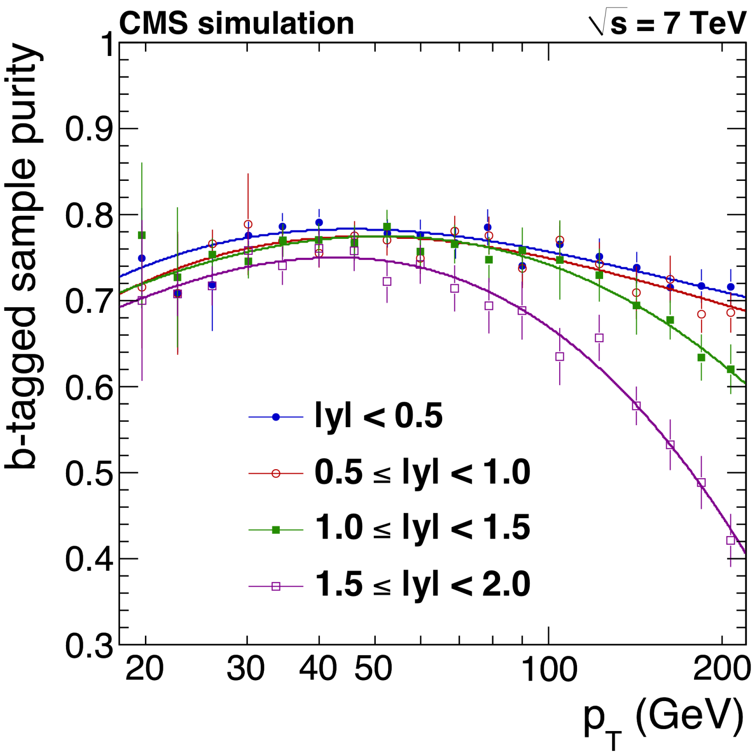




Inclusive *b*-Jet Production

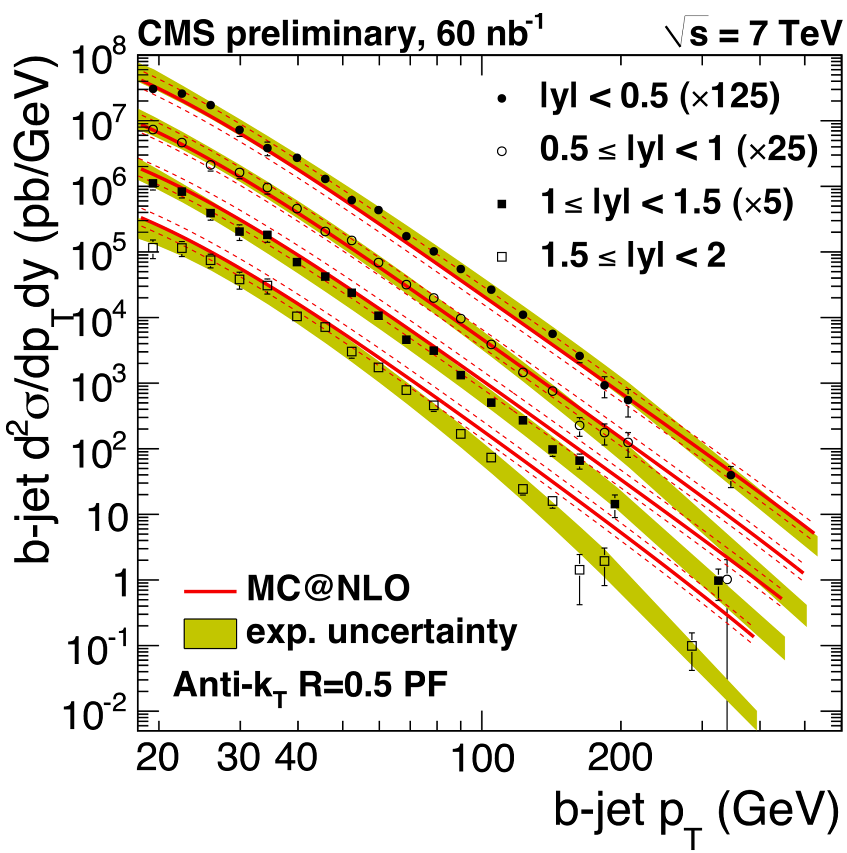
Secondary Vertex *b*-tagging purity (2): **REF: PAS CMS BPH-10-009**

MC-only, from flavour fractions and tagging efficiencies:



$$\text{purity} = \frac{\text{fraction}_b \text{efficiency}_b}{f_b e_b + f_c e_c + f_{LF} e_{LF}}$$

Differential Cross Section:



$b\bar{b}$ Production with Muon Pairs

27.9/pb of *pp* collision data at $\sqrt{s}$ = 7 TeV (2010) dimuon final state

dimuon trigger, $p_T > 4$ GeV/c in tracking volume

Z, ϒ, ψ's resonances: rejected using invariant mass

Technique:

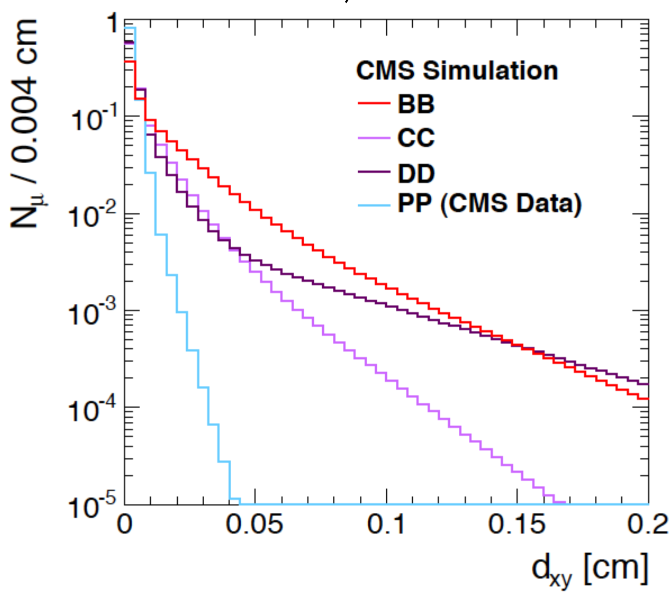
fit to transverse muon impact parameters templates from PYTHIA: beauty, charm, decay-in-flight; prompt muon templates from ϒ in data

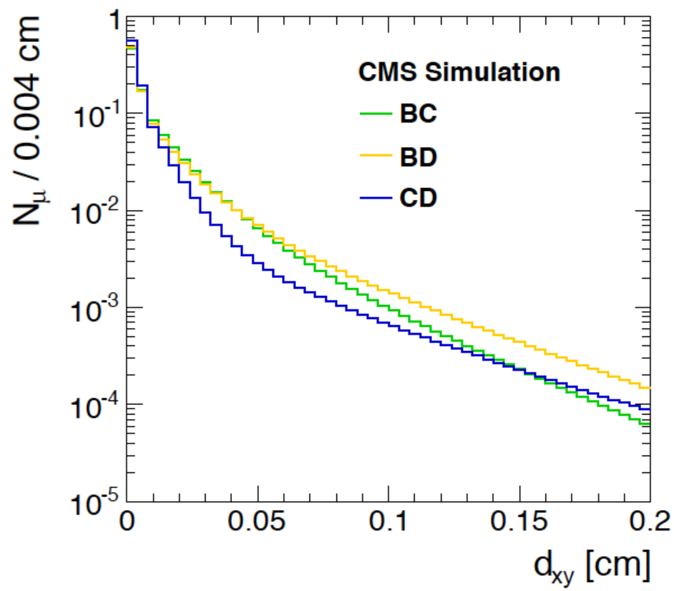
Symmetric templates:

$$T(i,j,x,y) = \frac{1}{2}\left(T(i,x)\cdot T(j,y) + T(i,y)\cdot T(j,x)\right)$$

i,j: muon classes
x,y: muon IP's

1D projections →





$b\bar{b}$ Production with Muon Pairs

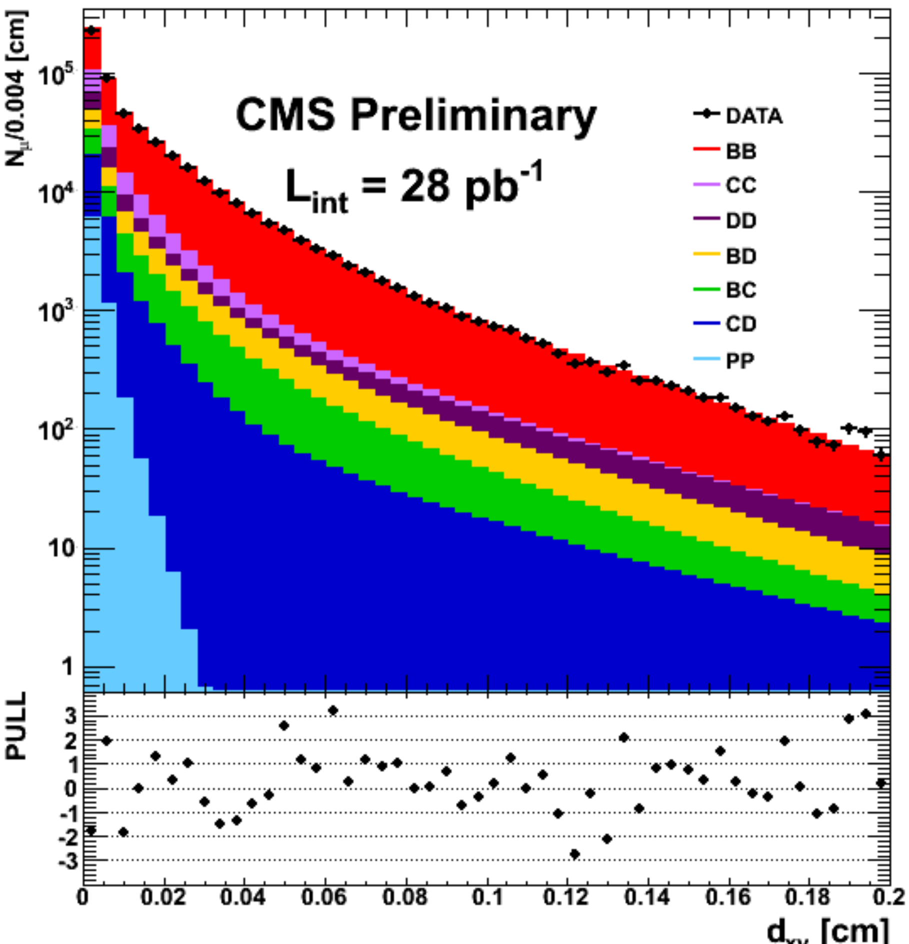
Likelihood fit results:

BB fraction: 65.10% ± 0.30%

Cross section × BR in acceptance:

26.18 ± 0.14 (stat) ± 2.82 (syst) ± 1.05 (lumi) nb

MC@NLO: 19.95 ± 0.46 (stat) $^{+4.68}_{-4.33}$ (syst) nb



Sources of systematic error:

detector IP resolution: 3.4%

relative fractions and lifetime: 3.8%

fit method: 4.7%

selection efficiency: 8.3%

REF: PAS CMS BPH-10-015

$B\bar{B}$ Angular Correlation

3.1/pb of *pp* collision data at $\sqrt{s}$ = 7 TeV (2010)

single jet trigger, $E_T > 15/30/50$ GeV, sample divided in 3 ranges: 99% efficiency of triggers, jet $|\eta| < 3$, *B* hadrons: $|\eta| < 2$, $p_T > 15$ GeV/c, valid primary vertex

Secondary vertex and angular correlation:

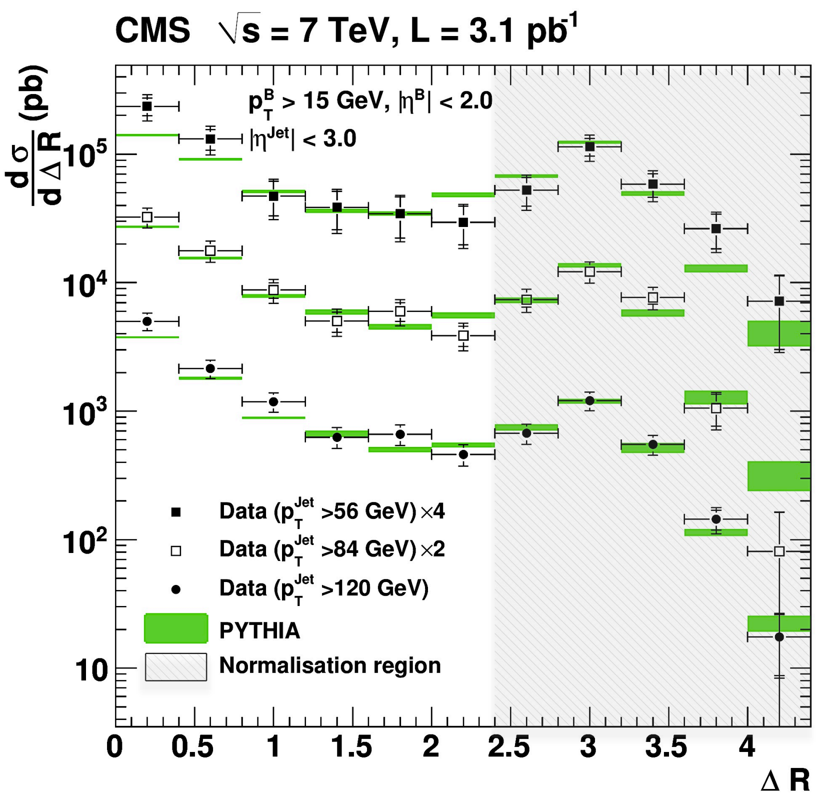
two secondary vertices (>3 tracks each) from a *BB* pair, angular correlation from flight directions (SV wrt PV), *B* momentum: sum of SV tracks momenta

Backgrounds:

signal events with misreconstructed SV, LF QCD, *cc* with *D*-hadrons, sequential *B*→*D*→… with both *B* and *D* SV

Flight direction comparison:

directions from SV ≈ directions from MC
ΔR difference in [-0.05, 0.05]



REF: JHEP (sub) hep-ex/1102.3194

Inclusive *B* Production

- Complementary analysis techniques: measurement of inclusive *b*-jet production and correlated $b\bar{b}$ production
- The results are in reasonable agreement with the predictions of MC@NLO in terms of absolute normalization, there are still discrepancies in p_T and η

Part 3

Rare Decays and CP Violation with CMS

Decay of B_s in Muon Pairs

1.14/fb of *pp* collision data at $\sqrt{s}$ = 7 TeV (2011) dimuon final state

dimuon trigger, $p_T > 3$ GeV/c in tracking volume, same vertex, opposite charge, mass in (4.9, 5.9) GeV/c^2, blind in (5.2, 5.45) GeV/c^2

Searching for: both $B_s \to \mu\mu$ and $B^0 \to \mu\mu$

Normalization: $B^+ \to J/\psi\, K^+ \to \mu\mu\, K^+$

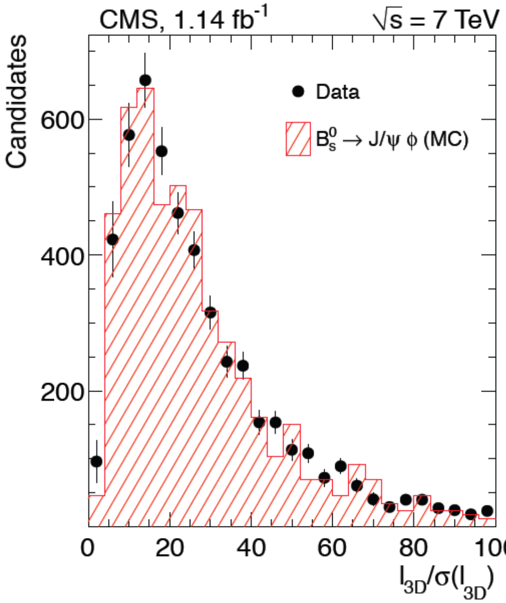
$$\frac{BR(B_s \to \mu\mu)}{N(B_s)} Acc(B_s) \times Eff(B_s \to \mu\mu) \times f_s =$$

$$= \frac{BR(B^+ \to J\psi[\mu\mu]K)}{N(B^+ \to J\psi K)} Acc(B^+) \times Eff(B^+ \to J\psi[\mu\mu]K) \times f_u$$

Optimisation of selection:

muon $p_T > 4.5$ (4.0) GeV/c, B $p_T > 6.5$ GeV/c, Isolation I_{3D}: 75% of p_T (tracks) within $\Delta R < 1$ from B candidate, additional requirements on flight direction and distance

Validation: $B^0 \to J/\psi\, \phi \to \mu\mu\, KK$



Backgrounds:

semileptonic B decays (+misidentified hadron), other rare decays ($B_s \to KK$, $B_s \to K\mu\nu$), misreconstructed SV…

Decay of B_s in Muon Pairs

	Barrel		Endcap	
	$B^0 \to \mu\mu$	$B^0_s \to \mu\mu$	$B^0 \to \mu\mu$	$B^0_s \to \mu\mu$
SM expected	0.065 ± 0.011	0.80 ± 0.16	0.025 ± 0.004	0.36 ± 0.07
combin. bg	0.40 ± 0.23	0.60 ± 0.35	0.53 ± 0.27	0.80 ± 0.40
peak bg.	0.25 ± 0.06	0.07 ± 0.02	0.16 ± 0.04	0.04 ± 0.01

Branching fractions upper limits:

$B^0_s \to \mu\mu$: < 1.9 E-8 @ 95% CL

$B^0 \to \mu\mu$: < 4.6 E-9 @ 95% CL

LHCb results:

0.037/fb (2010) +

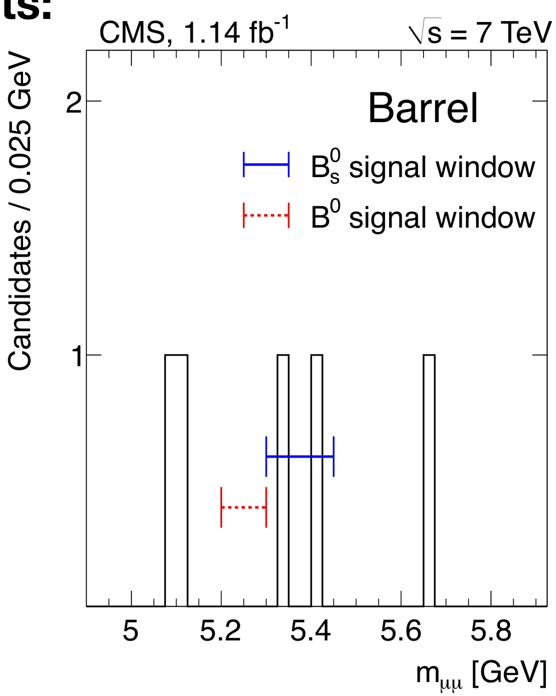
0.3/fb (2011)

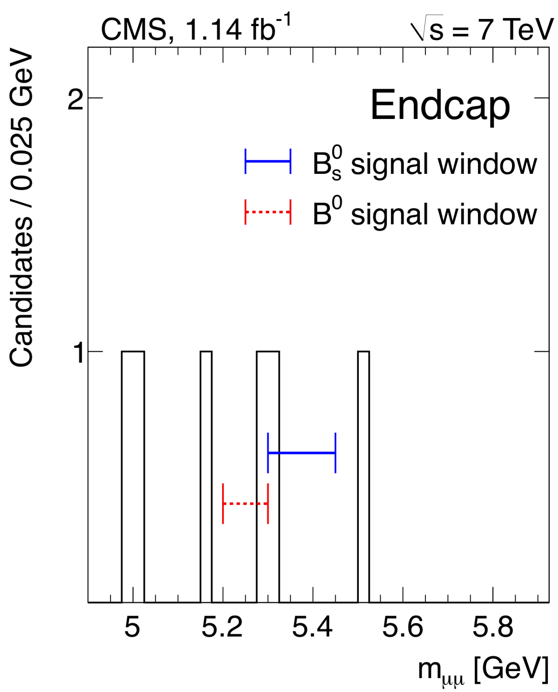
$B^0_s \to \mu\mu$: < 1.5 E-8 @ 95% CL

Combination CMS+LHCb:

$B^0_s \to \mu\mu$: < 1.1 E-8 @ 95% CL

REF: CMS PAS BPH-11-019





REF: Phys Rev Lett (sub) hep-ex/1107.5834

Rare Decays and CP Violation

- $B_s \rightarrow \mu\mu$: observed events are consistent with SM signal and background expectations, no evidence for this rare decay yet
- Other searches for rare decays and CPV started in 2010 but data analysis is still in progress

In Progress ...

Some other remarkable Heavy Flavour Physics ongoing analyses at CMS:

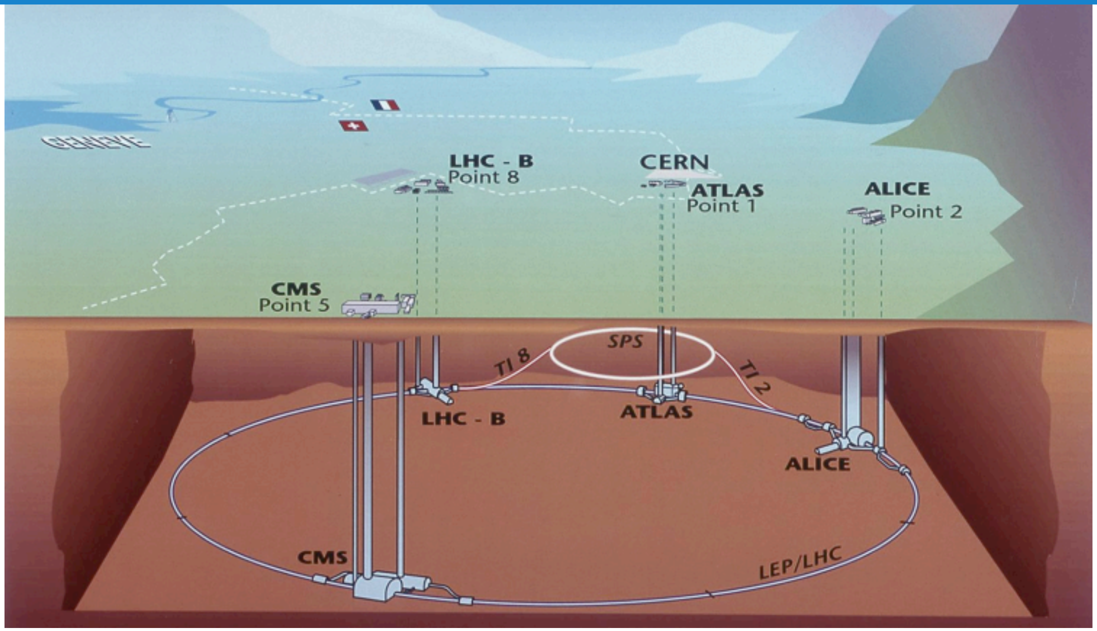
- **Observation of the $B_s \rightarrow J/\psi\ f_0(980)$ decay and CP violation in $B_s \rightarrow J/\psi\ \phi$ and $B_s \rightarrow J/\psi\ f_0(980)$ decays**
- **Forward/backward asymmetry in $B^0 \rightarrow K^{*0}\mu\mu$**
- **Observation of Λ_b and measurement of lifetime**

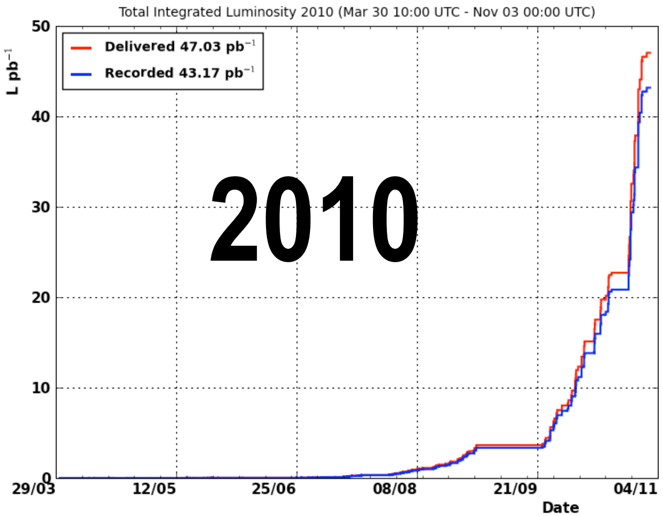
Concluding Remarks

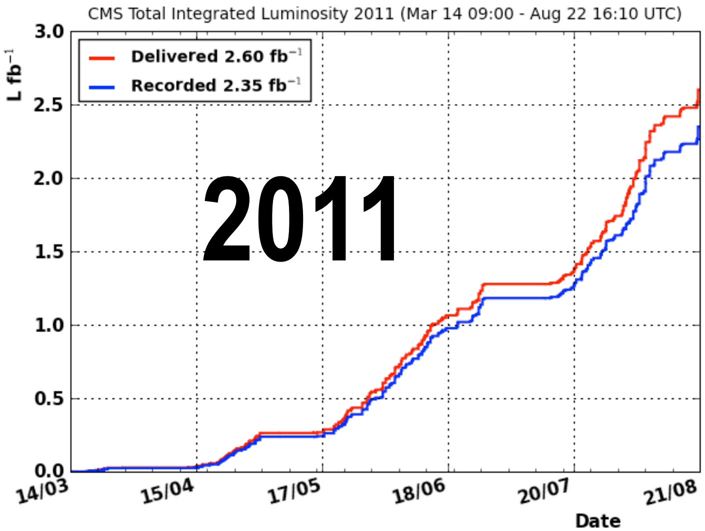
- The CMS experiment confirmed to be competitive in HF physics measurements with *pp* collisions, finding its strength in the Silicon Tracker and in the Muon System, which can provide precise identification and measurements of muons, tracks and vertices
- The event selection and data analysis techniques proved to be sound and effective and some of them are successfully shared among different search channels
- The CMS experiment could perform interesting HF physics measurements also with heavy ion collisions, which were not included in this presentation but are widely documented elsewhere, such as the suppression of excited Υ(nS) states

Backup

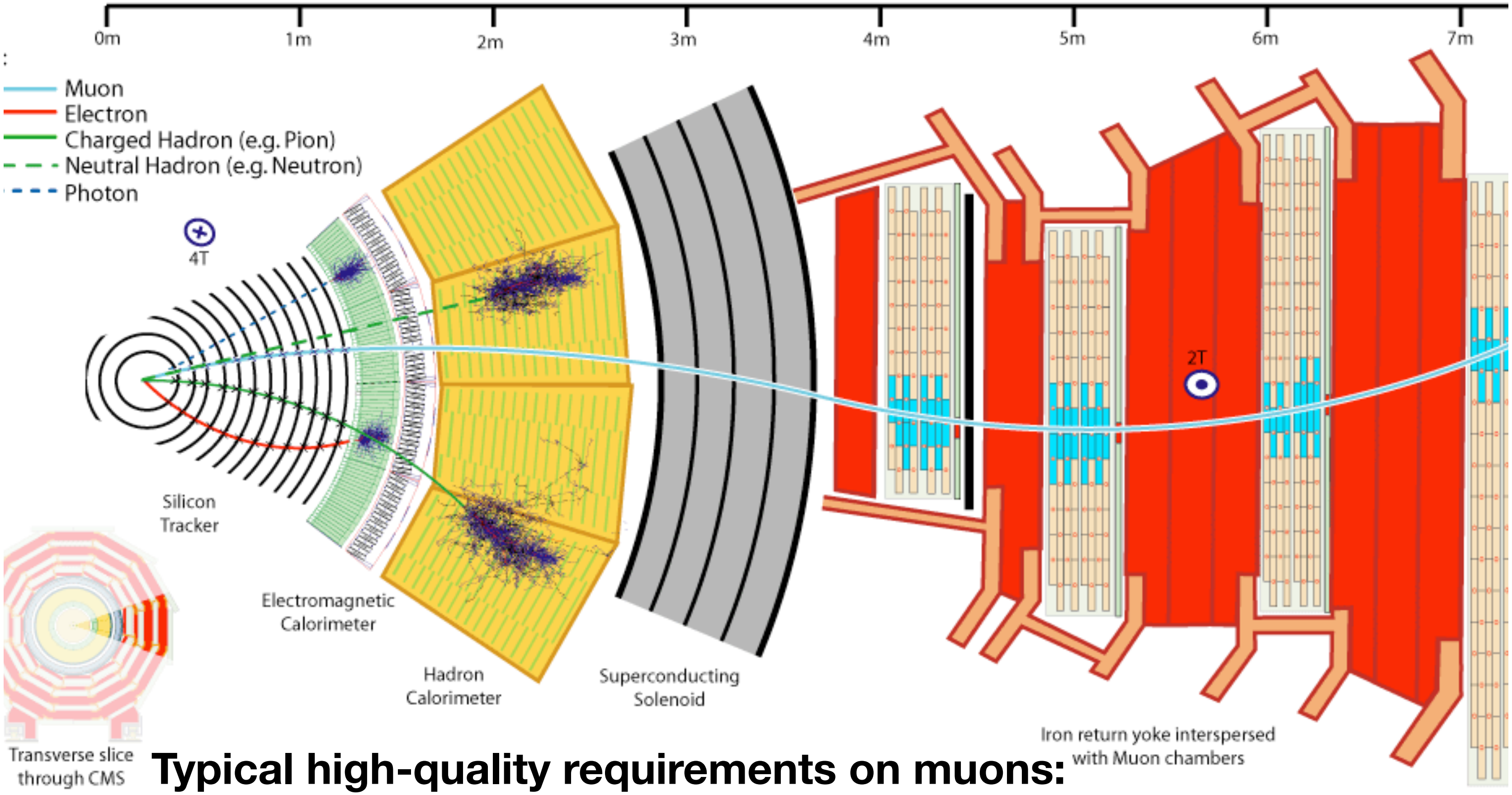
The Large Hadron Collider







Particle ID in CMS



Typical high-quality requirements on muons:

- **asociation Muon System + Silicon Tracker**
- **4-10 tracker hits (>1-2 in Pixels)**
- **reduced track χ^2<2-5**
- **constraints on vertex transverse IP wrt beamline and vertex |z|**

Smooth efficiency transition barrel/endcap:
p_T > 3.5-5 GeV/c if $|\eta| < 1.6$
p_T > 2.5 GeV/c if $1.6\,|\eta| < 2.4$

Particle Flow

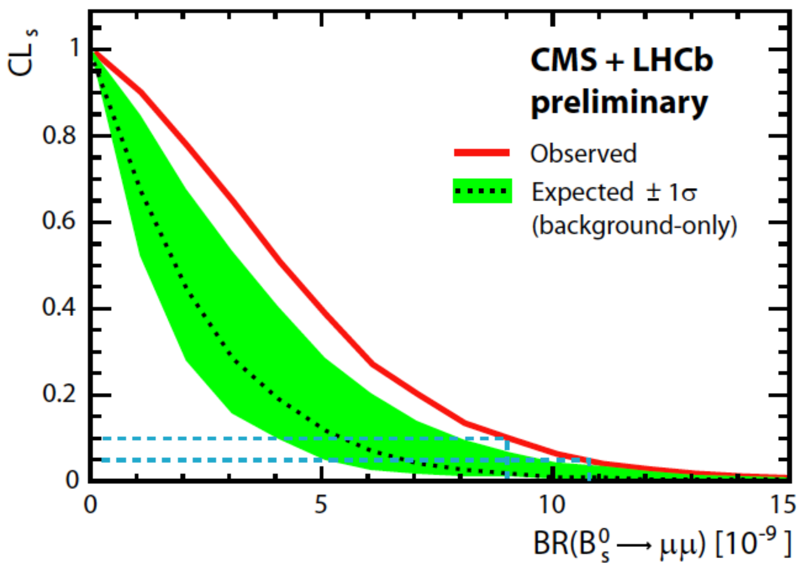
- reconstruction and identification of all stable particles: electrons, muons, photons, charged hadrons and neutral hadrons
- thorough combination of all CMS sub-detectors towards an optimal determination of particle direction, energy and type

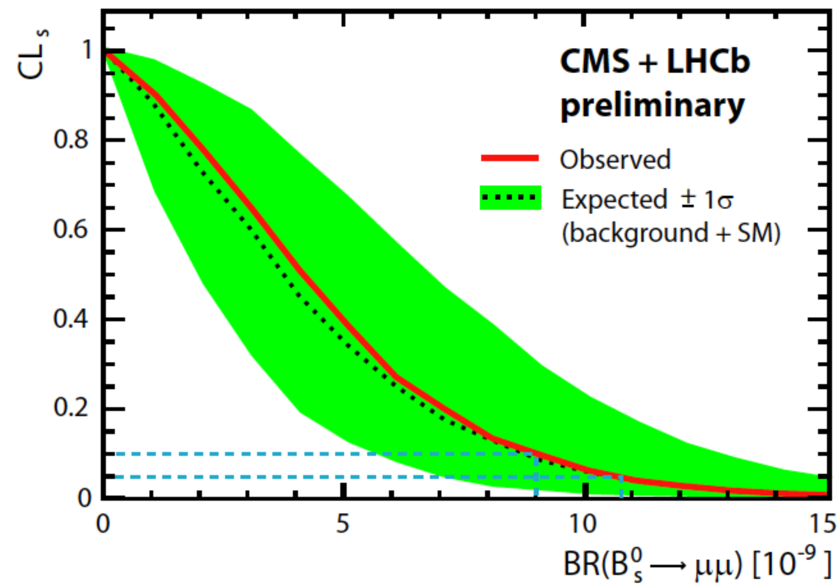
1. muons reconstructed first, track removed from list, calorimeter energy correction
2. electrons reconstructed after muons, track and ECAL deposit removed from list
3. charged hadrons from HCAL matching to tracks, until no tracks are left unmatched
4. photons and neutral hadrons from unmatched ECAL/HCAL
5. redundant cross checks for further muons/electrons

Anti-k_T Jets

- hard particles with transverse momenta k_{T1}, k_{T2}, . . . and many soft particles, R typical angular jet aperture
- $d_{1i} = \min(1/k_{T1}^2, 1/k_{Ti}^2)\Delta R^2_{1i}/R^2$ between hard particle *1* and soft particle *i* is exclusively determined by the transverse momentum of the hard particle and the *1i* separation d_{ij} between similarly separated soft particles will instead be much larger: soft particles will tend to cluster with hard ones long before they cluster among themselves
- if a hard particle has no hard neighbours within a distance 2R, then it will simply accumulate all the soft particles within a circle of radius R, resulting in a perfectly conical jet
- if another hard particle *2* is present such that $R < \Delta R_{12} < 2R$ then there will be two hard jets: it is not possible for both to be perfectly conical, if $k_{T1} \gg k_{T2}$ then jet *1* will be conical and jet *2* will be partly conical, instead if $k_{T1} = k_{T2}$ neither jet will be conical and the overlapping part will simply be divided by a straight line equally betweencthe two
- what happens with $\Delta R_{12} < R$: particles *1* and *2* will cluster to form a single jet: if $k_{T1} \gg k_{T2}$ then it will be a conical jet centered on *1*; for if $k_{T1} \approx k_{T2}$ the shape will be more complex, being the union of cones (radius < R) around each hard particle plus a cone (of radius R) centred on the final jet

B_s in Muon Pairs: CMS + LHCb



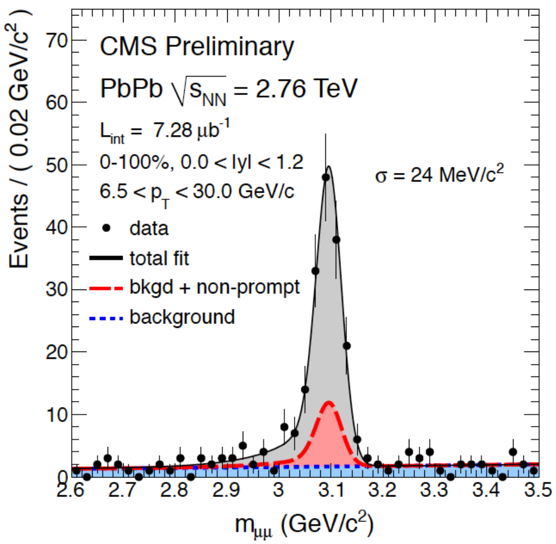


REF: PAS CMS BPH-11-019

HF with Heavy Ions at CMS

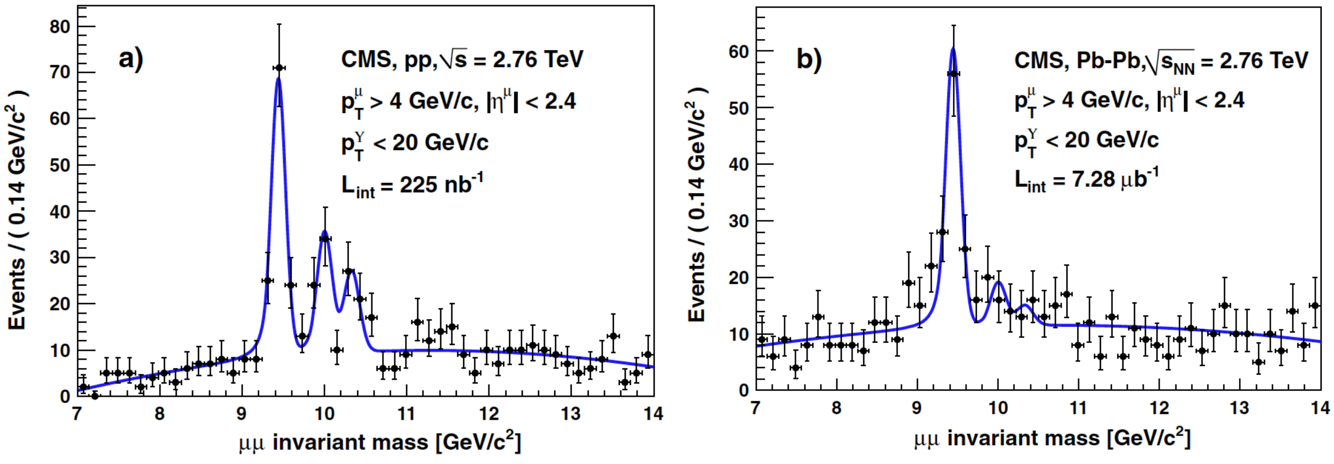
Observation of inclusive J/ψ and Υ(nS) production, prompt and non-prompt fractions, same technique as for *pp* collisions

REF: PAS CMS HIN-10-006



Hints of excited Υ(nS) states suppression confirmed by further measurements of Υ(2S+3S)/Υ(1S):

- **$0.78^{+0.16}_{-0.14}$ (stat) ± 0.02 (syst), pp @ 2.76 TeV**
- **$0.24^{+0.13}_{-0.12}$ (stat) ± 0.02 (syst) , PbPb @ 2.76 TeV/N**



REF: Phys Rev Lett 107 (2011) 052302