Heavy Flavor Results from the LHC

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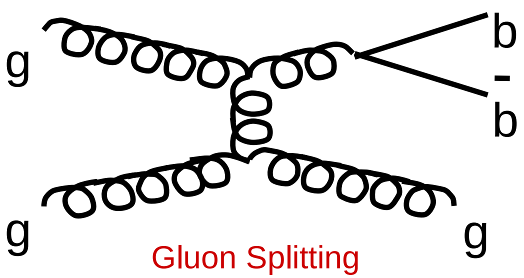
On behalf of the CMS and ATLAS collaborations

13 Feb 2012

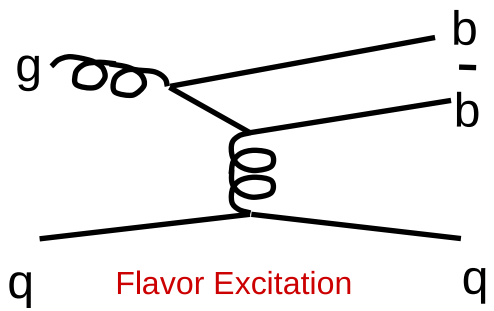
Aspen 2012 - The Hunt for New Particles

B production at the LHC

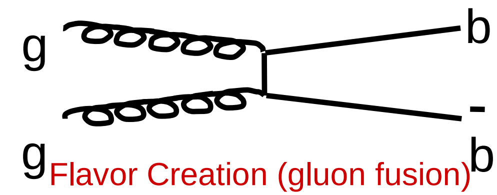
- Dominant b-quark production mode at LHC : $b\bar{b}$ pair production (QCD).



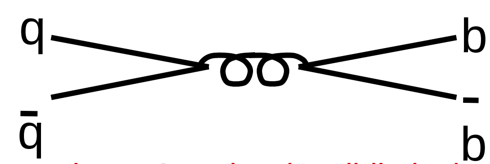
Gluon Splitting



Flavor Excitation



Flavor Creation (gluon fusion)



Flavor Creation (annihilation)

- Allows tests of the perturbative QCD and MC generators at new energies
- Different phase space than previous measurements (Tevatron, LEP, HERA...)
- Improves understanding of b background for many searches
- Improves understanding of the detector, specially tracking and μ reco.
- Expected $b\bar{b}$ production rate (from MC@NLO, 7 TeV) ≈ 238 μb

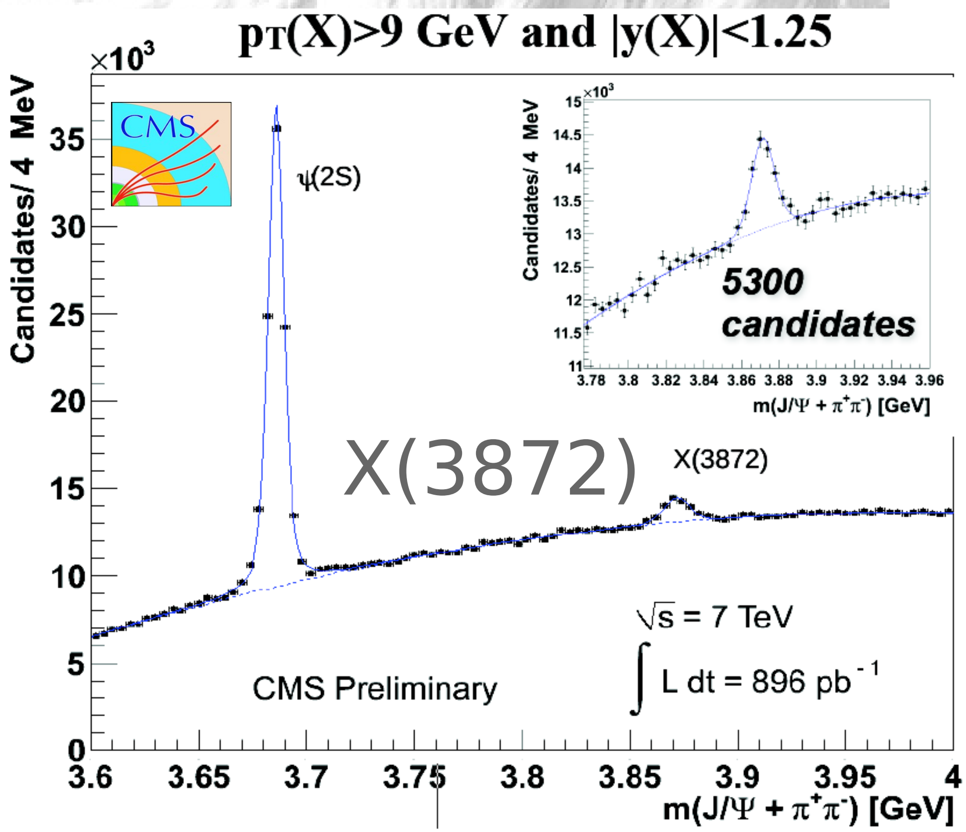
Detectors

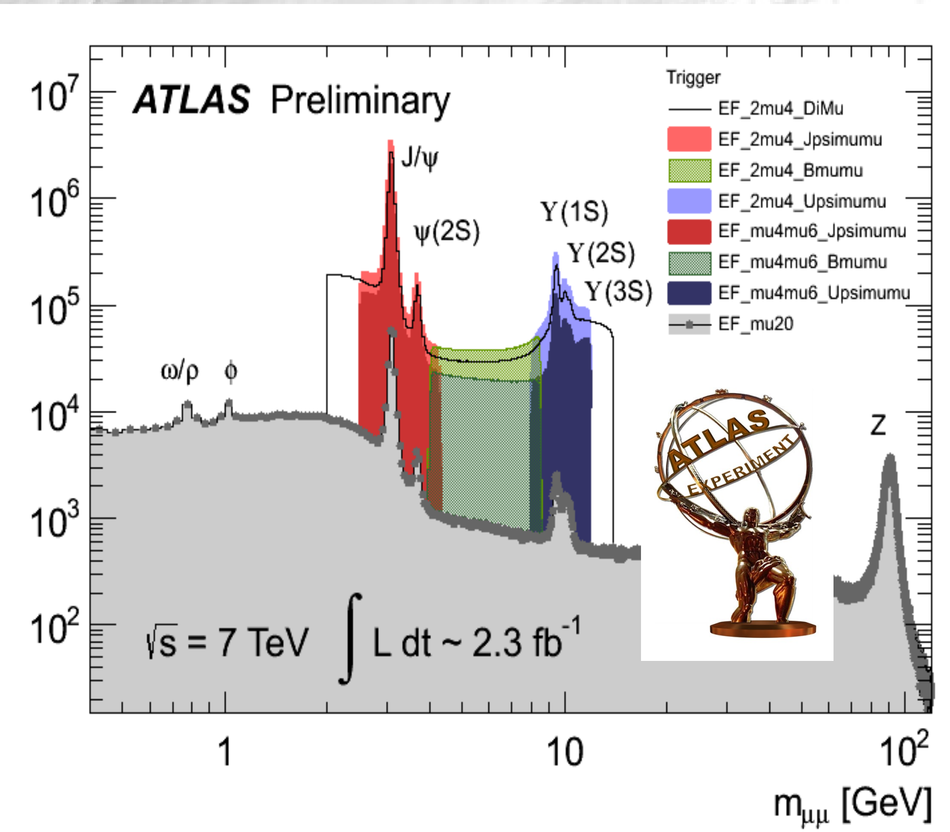
- Precise innermost tracking
- Hermetic calorimeter with excellent energy and rapidity resolution
- stand-alone muon trigger & tracking system

Relevant detector characteristics for the analyses presented

	CMS	**ATLAS**
Paper: 2008 JINST 3	S08004	S08003
• Tracker	Silicon	Silicon+TRT
• Solenoidal magnetic field of	3.8 T	2 T
• Coverage |η|	< 2.5	<2.5
• Impact parameter resolution	~10 μm (up to p_T 100 GeV/c)	~10 μm
• p_T resolution	~1.5% (up to p_T 100 GeV/c)	~2.5%
• Muon detector coverage |η|	< 2.4	< 2.7

Detectors' performance





- CMS X(3872)
- $p_T(X) > 9$ GeV && $|\eta(X)| < 1.25$
- CMS-DP-2011-009 ; CERN-CMS-DP-2011-009
- Cross section ratio

$$R = \frac{\sigma(pp \to X(3872) + \text{anything}) \times BR(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + \text{anything}) \times BR(\psi(2S) \to J/\psi\pi^+\pi^-)}$$

$$R = 0.087 \pm 0.017(stat.) \pm 0.009(syst.)$$

- ATLAS invariant mass of oppositely charged muon candidate pairs selected by a variety of triggers

Analyses presented here are:

- **CMS**
  - Inclusive $b\bar{b}$ cross section with dimuons
  - $b\bar{b}$ angular correlation based on secondary vertices
  - Search for $B_s \to \mu^+\mu^-$ and $B_0 \to \mu^+\mu^-$ decays
  - χ_c State in Radiative Transitions to J/ψ
- **ATLAS**
  - Observation of a New χ_b State in Radiative Transitions to ϒ(1S) and ϒ(2S)
  - Inclusive electron and muon cross-sections from HF decays
- **Both CMS and ATLAS**
  - J/ψ → μμ differential cross-section (inclusive, prompt and non-prompt) [CMS also includes ψ(2S)]
- Links to all physics results :

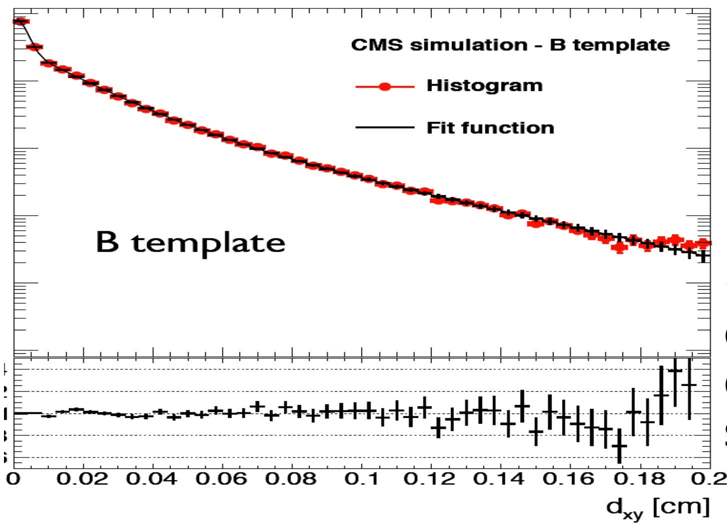
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH [CMS]

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults [ATLAS]

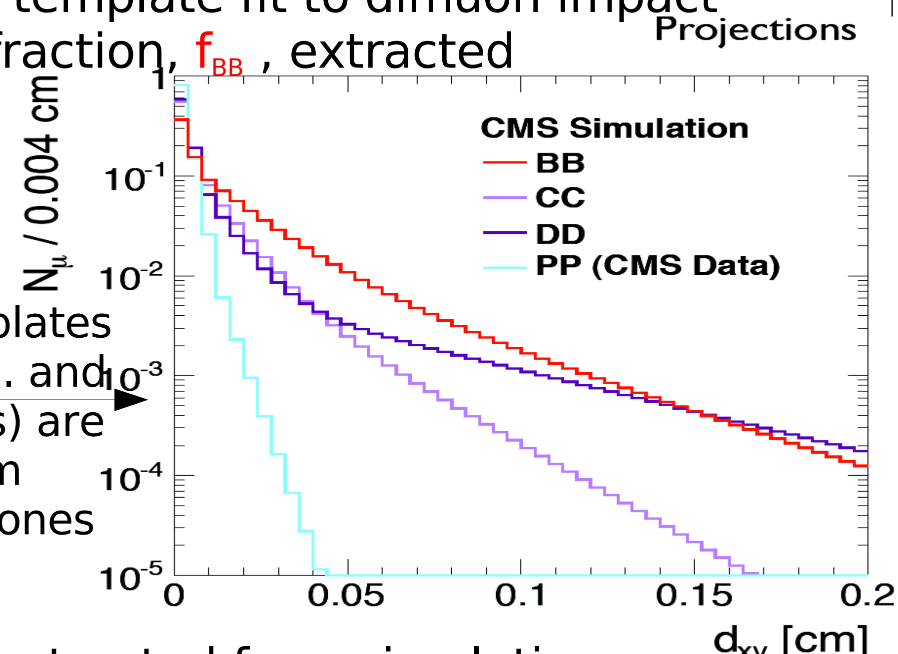
Inclusive $b\bar{b}$ cross section with dimuons

CMS-PAS-BPH-10-015

- Cross section for $b\bar{b}$ production with both b quarks decaying into muons
- Sources of muons in the final state in MC:
  - B: $b \rightarrow \mu$ (sequential $b \rightarrow c \rightarrow \mu$ are considered part of the signal) [79%]
  - C: $c \rightarrow \mu$ [14.3% of the sample composition]
  - P: prompt muons (from primary vertex or hadron punch–through) [0.1%]
  - D: decays in flight ($\pi \rightarrow \mu$, $K \rightarrow \mu$) [6.5%]
- Sample composition determined from template fit to dimuon impact parameter distribution (d_{xy}) and signal fraction, f_{BB} , extracted

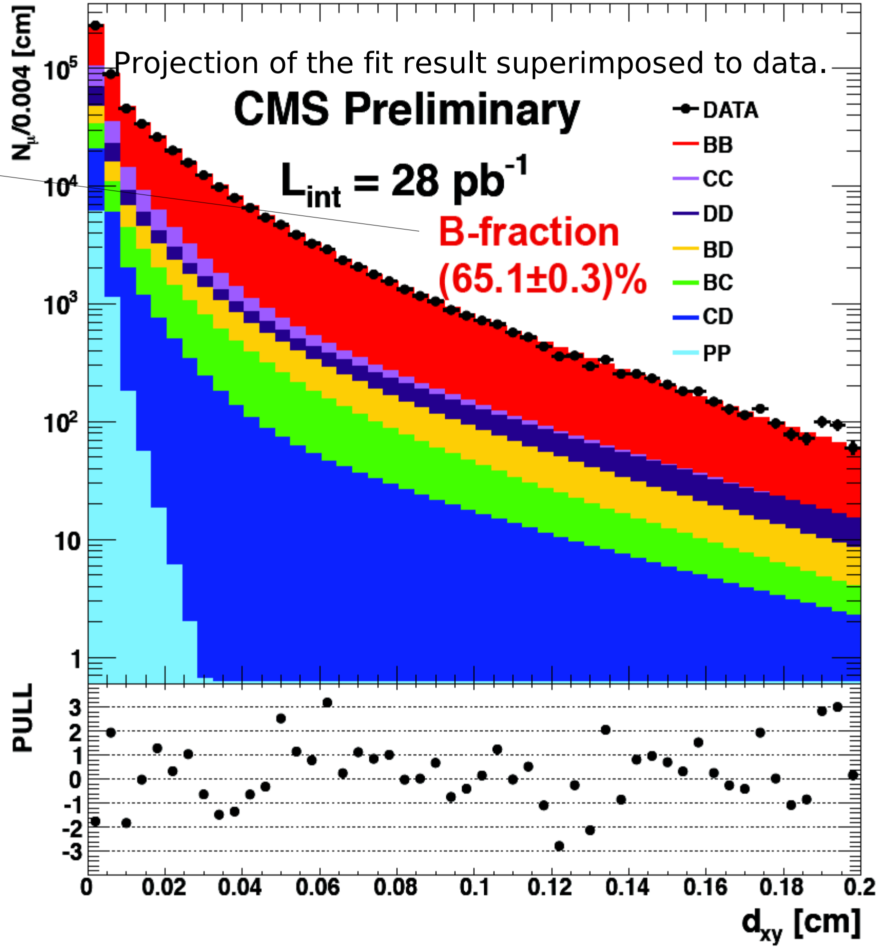


Dimuon templates (BB, CC, etc... and combinations) are obtained from single muon ones



  - d_{xy} distributions for B, C and D are extracted from simulation
  - d_{xy} distribution for P is extracted from data (from $\Upsilon(1S)$ decays)

$\sigma(pp \rightarrow b\bar{b}\, X \rightarrow \mu\mu\, Y) = N_{\mu\mu}\, f_{BB} / \varepsilon\, L$



L luminosity

f_{BB} signal fraction

$N_{\mu\mu}$ observed number of events

ε average efficiency for the trigger, muon identification and event selection:

- Kinematic cuts
- $z_\mu - z_{PV}$ cut
- mass cuts :
  - $5 < M_{\mu\mu} < 8.9$
  - $10.6 < M_{\mu\mu} < 70$

$\sigma(pp \rightarrow b\bar{b}\, X \rightarrow \mu\mu\, Y)$ [$p_T(\mu) > 4$ GeV/c and $|\eta(\mu)| < 2.1$] =

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

MC@NLO = 19.95 ± 0.46 nb

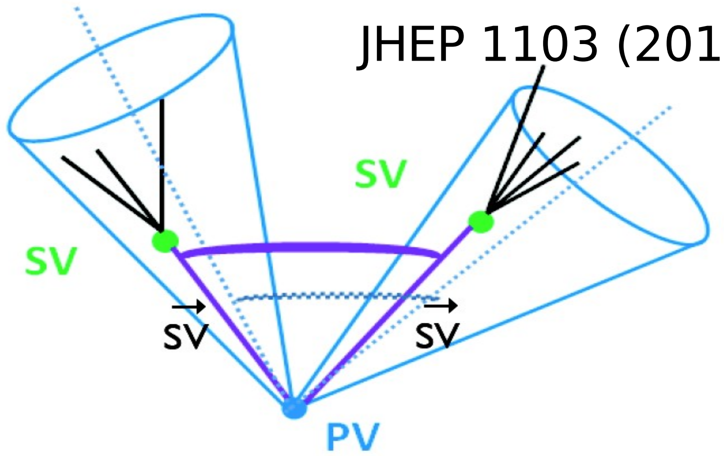
The result is consistent with the NLO QCD expectations

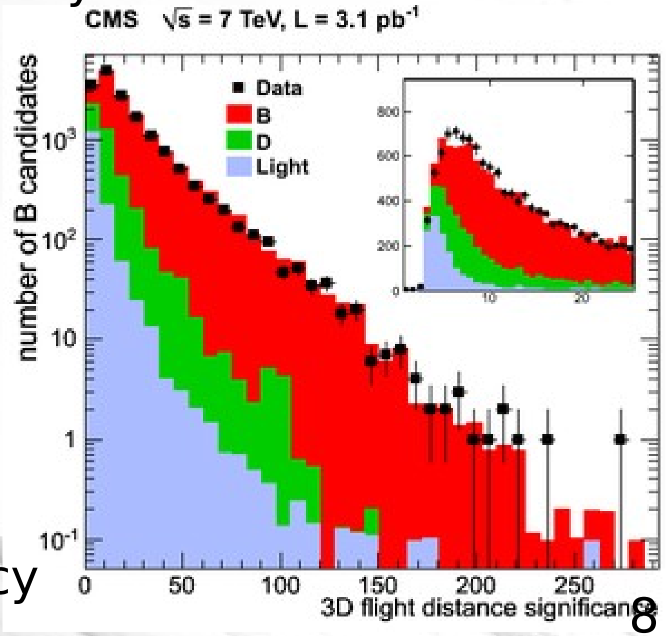
$b\bar{b}$ angular correlation based on secondary vertices

- Select events with at least one reconstructed jet with a minimum p_T, a reconstructed primary vertex and at least two reconstructed secondary vertices (SV) seeded by high IP tracks – jet independent
- b-hadron candidates are formed based on 3D flight distance significance, SV pseudorapidity, p_T, mass
- Events are retained if they have exactly two b-hadron candidates with mass sum > 4.5 GeV/c^2
- Vertices from chain decays (B→C) merged into a single B candidate
- Differential cross section computed as a function of the b-hadron's opening angles: azimuthal $\Delta\phi$,$\Delta\eta$ $\Delta R = \sqrt{(\Delta\eta^2+\Delta\phi^2)}$)

Flight direction of the b-hadron is approximated by the vector $\vec{SV}$

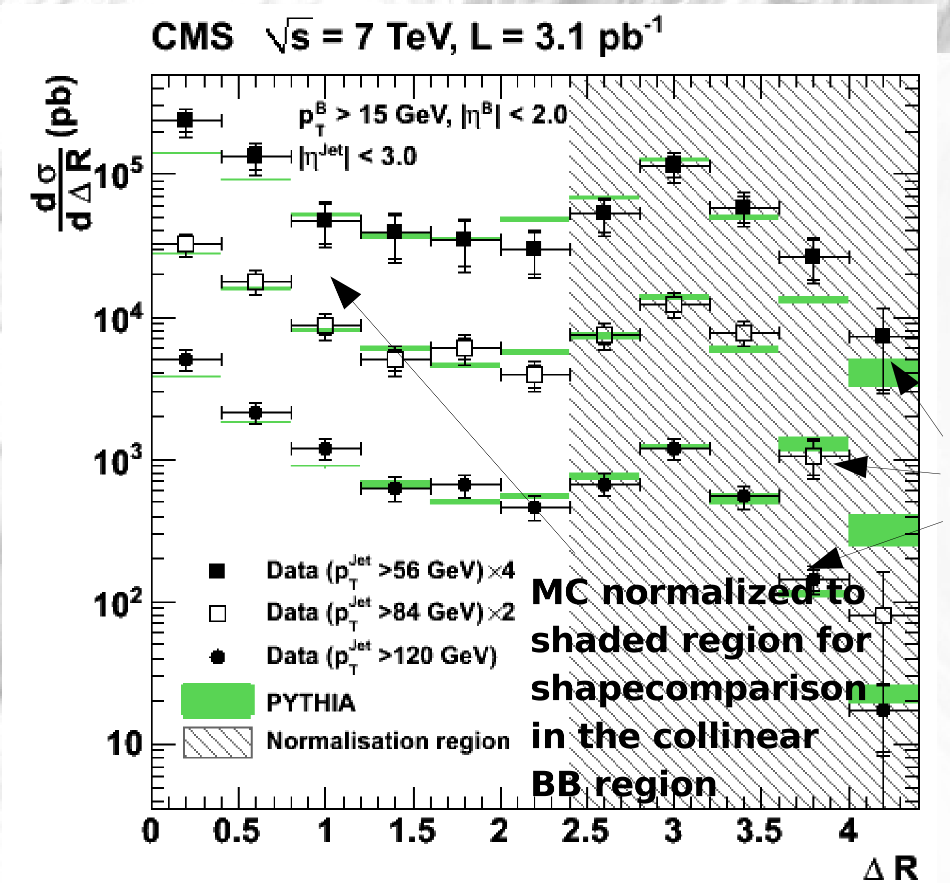
JHEP 1103 (2011) 136



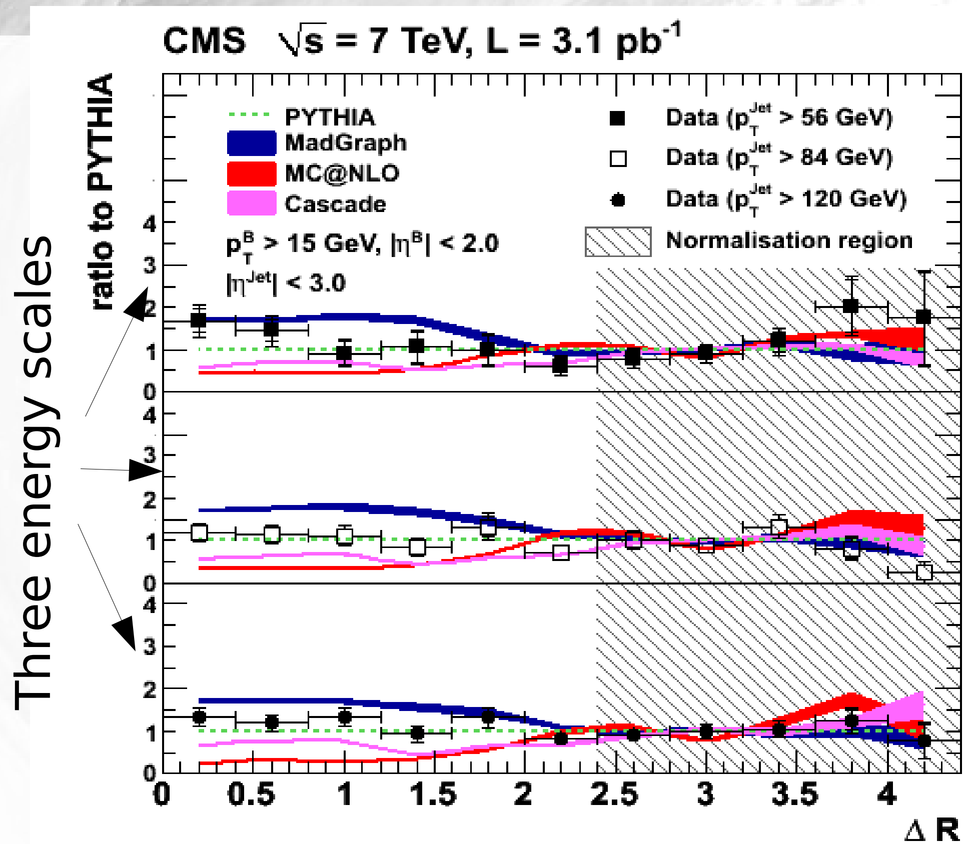


The quality of the B candidate reconstruction technique is illustrated: the simulation (used for efficiency and purity correction) describes the data

Results: Differential cross section vs ΔR



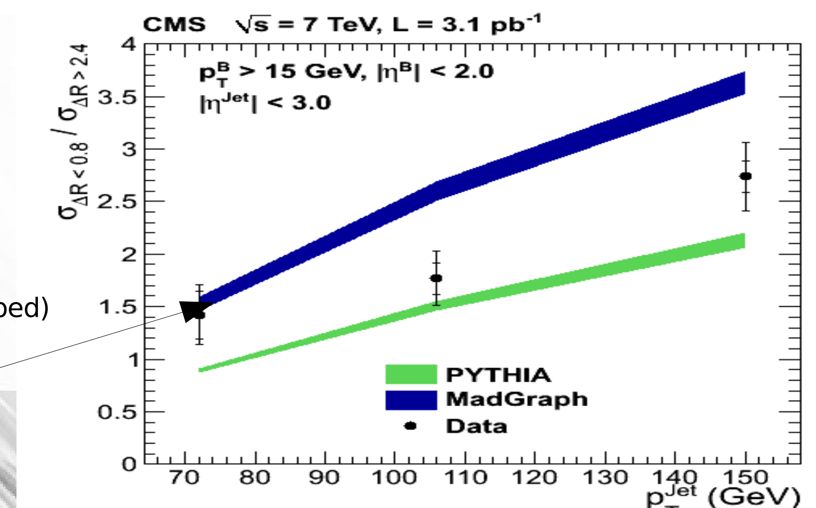
Comparison with MC/predictions



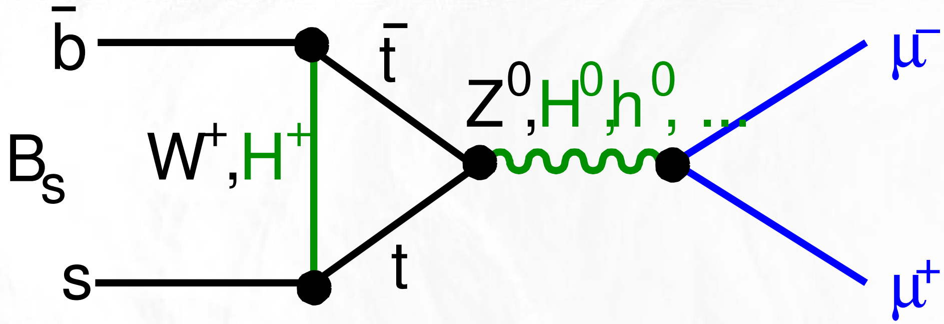
- Sizable fraction of σ_{tot} from collinear B-hadron pairs
- Data lie between MADGRAPH and PYTHIA MC;
- Neither MC@NLO nor CASCADE describe ΔR well

especially at small ΔR (gluon processes expected to dominate and not well described)

- Fraction of collinear pair production increases with scattering hardness



Search for $B_s \to \mu^+\mu^-$ and $B_0 \to \mu^+\mu^-$ decays in CMS



PRL 107, 191802 (2011)
CMS-PAS-BPH-10-019

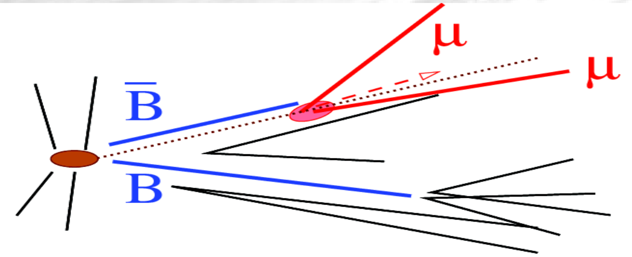
Penguin diagram

- b →s(d) FCNC transitions highly suppressed in SM
  - forbidden at tree level; can only proceed via Penguin/Box diagrams
  - are helicity suppressed by factors of $(m_\mu/m_B)^2$
  - require an internal quark annihilation within the B meson

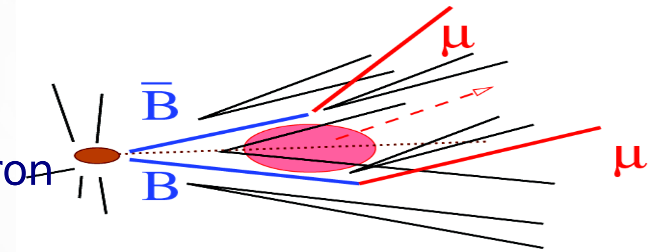
Standard Model predictions
$B(B_s \to \mu\mu) = (3.2 \pm 0.2) \times 10^{-9}$
$B(B_0 \to \mu\mu) = (1.0 \pm 0.1) \times 10^{-10}$

- Sensitivity to new physics: the SM predictions are significantly enhanced in several extensions of the SM, although in some cases the decay rates are lowered.

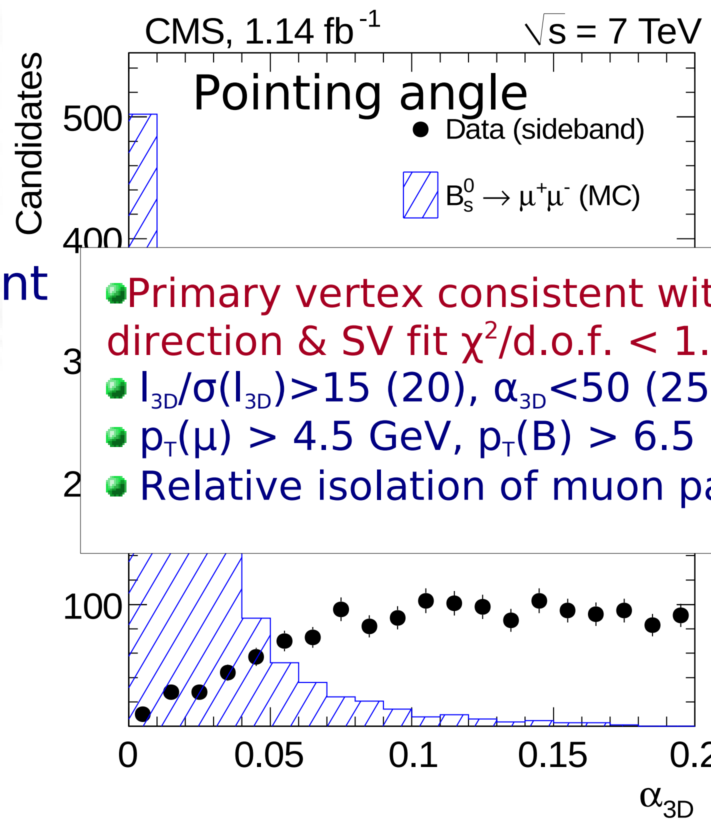
- Signal characteristics:
  - Two muons from a single decay vertex
  - Mass compatible with B_s (or B_0)
  - Well reconstructed secondary vertex
  - Dimuon ***p*** aligned with flight direction

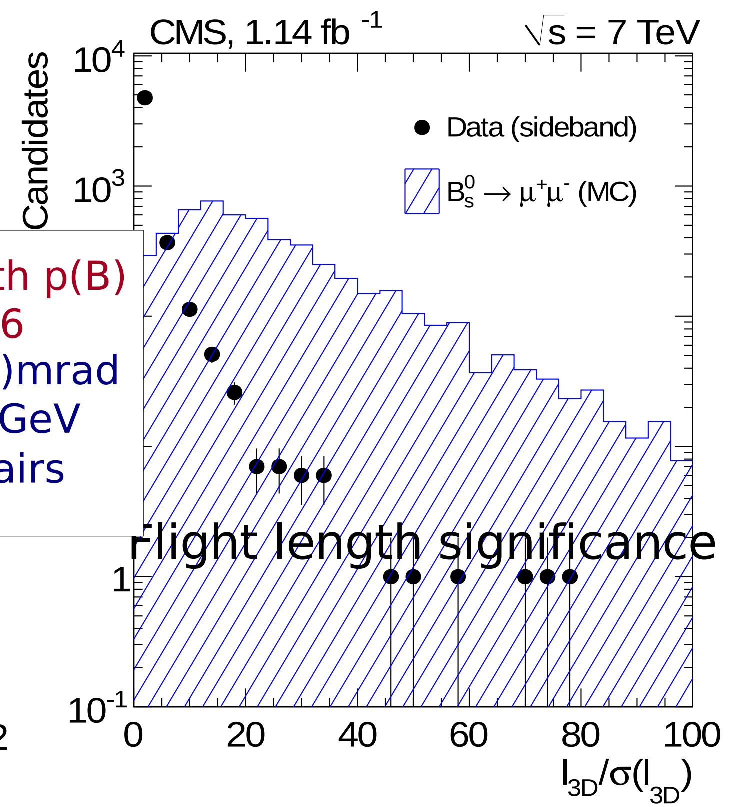


- Background sources:
  - Two semi-leptonic B decays (gluon splitting)
  - One semi-leptonic B decay + misidentified hadron
  - Rare B decays (e.g. $B_s \to KK$, $B_s \to K^- \mu^+ \nu$)



- Signal event selection: some key ingredients
  - Primary vertex consistent with p(B) direction & SV fit χ^2/d.o.f. < 1.6
  - $l_{3D}/\sigma(l_{3D})$>15 (20), α_{3D}<50 (25)mrad
  - $p_T(\mu)$ > 4.5 GeV, $p_T(B)$ > 6.5 GeV
  - Relative isolation of muon pairs



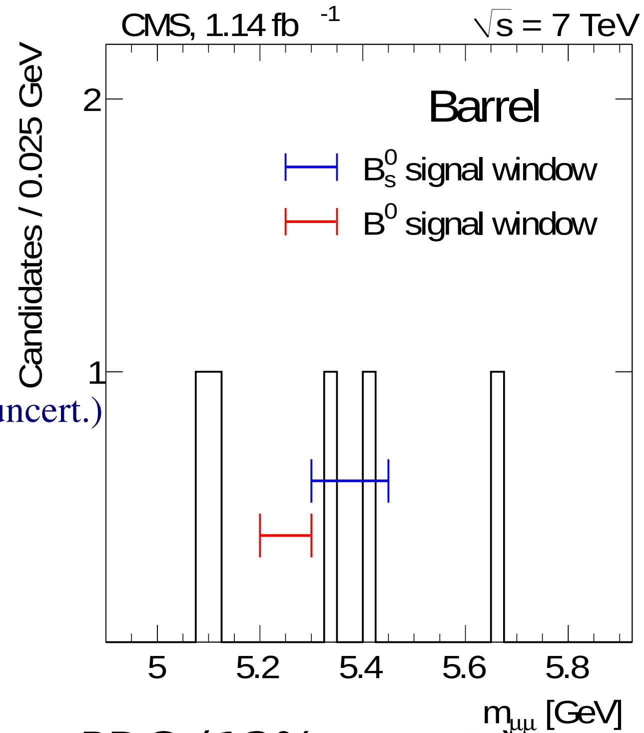


- Counting experiments in the μμ mass distribution
- The background estimated from sidebands and from MC simulation
- Normalization relative to $B^+ \to J/\psi(\mu\mu)K^+$

Many systematic uncertainties cancel in ratio

No need for absolute luminosity and b-quark cross section

Large B_+ yield and well known branching ratio to $J/\Psi K^+$ (3% uncert.)



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \frac{N_S}{N_{obs}^{B^+}} \frac{f_u}{f_s} \frac{\varepsilon_{tot}^{B^+}}{\varepsilon_{tot}} \mathcal{B}(B^+)$$

- Signal efficiency -> MC
- Ratio of fragmentation fractions, fu/fs, from PDG (13% uncert.)

Decay	Expected (95% CL)	Observed (95% CL)	Background-only p value
$B_s \to \mu^+\mu^-$	1.8×10^{-8}	**1.9×10^{-8}**	11% (1.2σ)
$B^0 \to \mu^+\mu^-$	4.8×10^{-9}	**4.6×10^{-9}**	40% (0.3σ)

The observed event yields are consistent with those expected adding background and SM signals. Set upper limit on $BR(B_s)<11\times10^{-9}$(95% CL) for combined with LHC_b

Within SM branching ratio by end of 2012

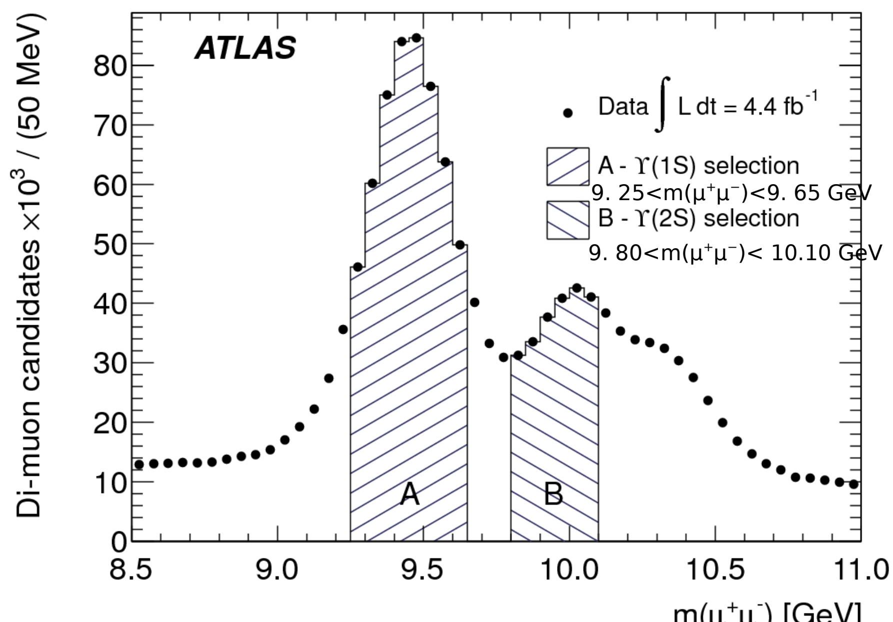
Observation of a New χ_b State in Radiative Transitions to Υ(1S) and Υ(2S) at ATLAS

Reconstructed through the radiative decay modes $\chi_b(nP) \rightarrow \Upsilon(1S)\gamma$ and $\chi_b(nP) \rightarrow \Upsilon(2S)\gamma$, in which $\Upsilon(1S, 2S) \rightarrow \mu^+\mu^-$

http://arxiv.org/abs/1112.5154

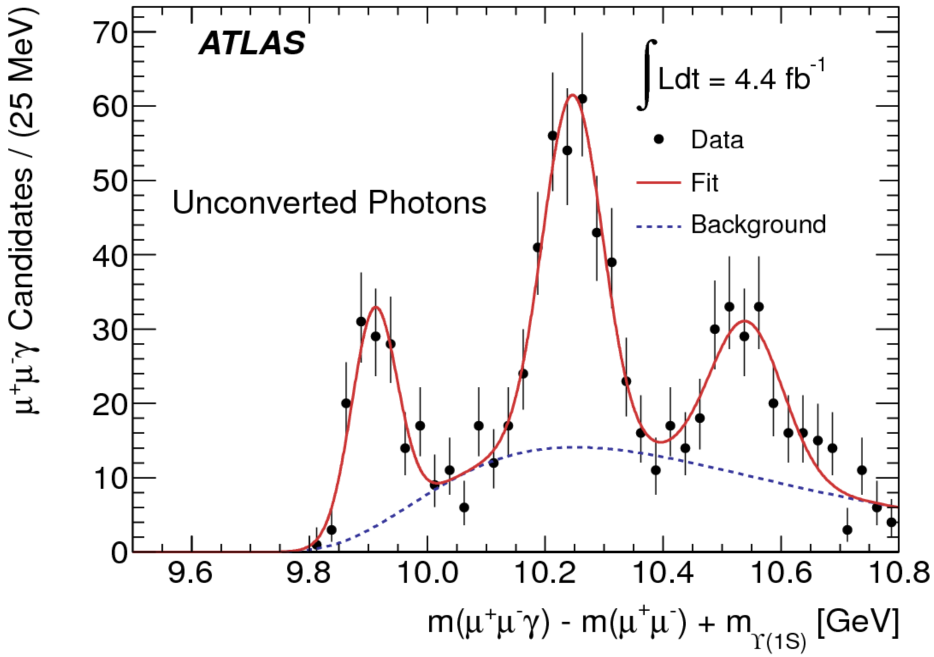
- Select $p_T(\mu) > 4$ GeV && $|\eta(\mu)| < 2.3$
- Fit $\mu^+\mu^-$-pair to a common vertex [Υ(1S, 2S)] ($\chi^2 < 20$; no **m** or **p** constraints)
- $p_T(\Upsilon) > 12$ GeV && $|\eta(\Upsilon)| < 2.0$
- Select candidates in A && B

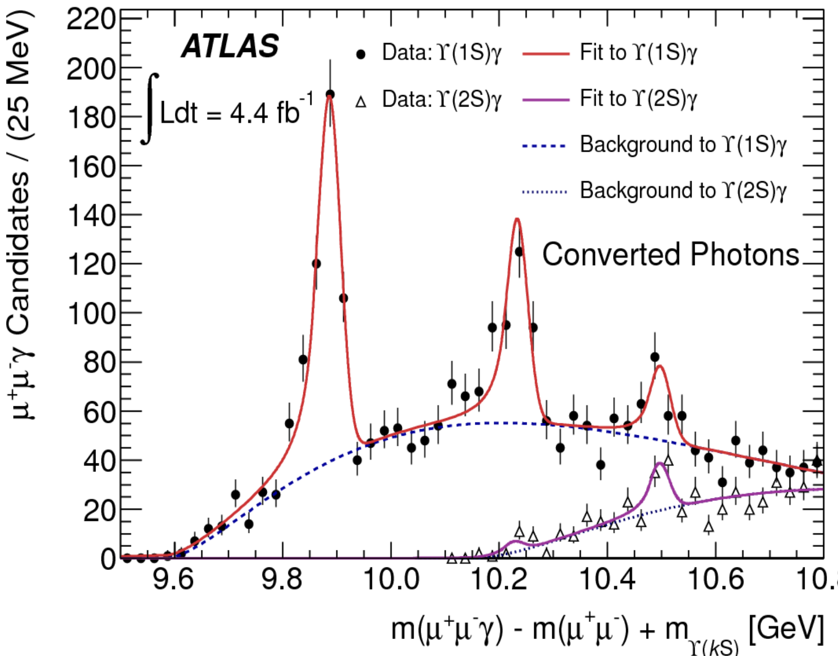
as Υ(1S) && Υ(2S) candidates



- The asymmetric mass window for Υ(2S) candidates chosen to reduce contamination from the Υ(3S) peak and continuum background contributions.
- photon reconstructed either through conversion to e^+e^- or by direct calorimetric measurement ; $|\eta(\gamma)| < 2.3$ (2.37) [avoid 1.37-1.52:transition barrel-endcap]
- With longitudinal segmentation of unconv. γ, check same vertex as Υ

- The χ_b candidates are formed by associating a $\Upsilon \rightarrow \mu^+\mu^-$ with a photon
- $\Delta m = m(\mu^+\mu^-\gamma) - m(\mu^+\mu^-)$ calculated to minimize the effect of Υ mass resolution.





$m_{\Upsilon(kS)}$ are the world average $\Upsilon(kS)$ masses

Fit
- Signal * from unc. photons : sum of 3 gaussians
  * from conv. photons : doublet of Crystal Ball functions (with radiative tail parameters common to all peaks & $\chi_{b1,2}$ mass values and hyperfine splittings fixed to WA)
- Background parametrization: $N_B \cdot \exp(A \cdot \Delta m + B \cdot \Delta m^{-2})$

- $\chi_b(3P)$ hyperfine mass splitting fixed to theory: 12 MeV Eur. Phys. J.C 4 (1998) 107

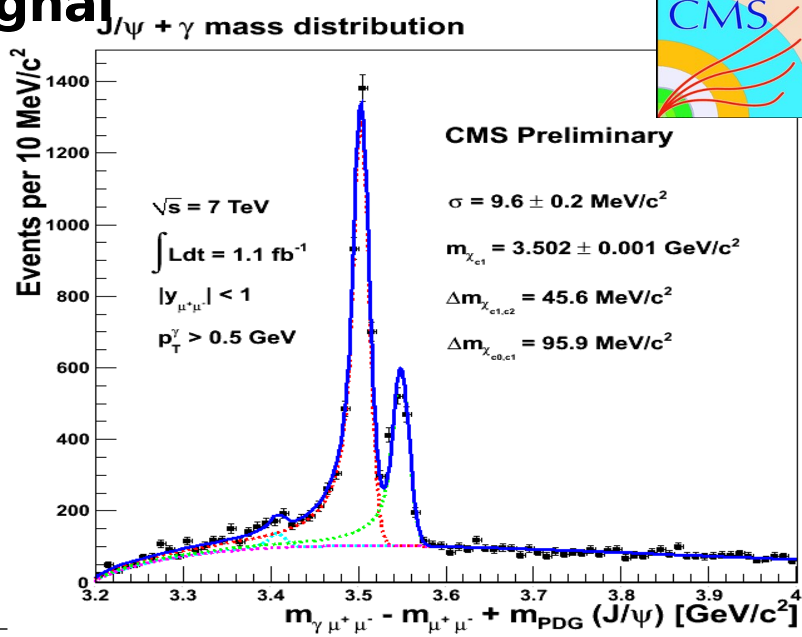
State	Predictions	Fitted masses Unc. Photons	Converted Photons [MeV]
$\chi_b(1P)$	9900	9910 ± 6 (stat.) ± 11 (syst.)	Fixed to χ_{b1}=9892.78 & χ_{b2}=9912.21
$\chi_b(2P)$	10260	10246 ± 5 (stat.) ± 18 (syst.)	Fixed to χ_{b1}=10255.46 & χ_{b2}=10268.65
$\chi_b(3P)$	10525	10541 ± 11 (stat.) ± 30 (syst.	10539 ± 4 (stat.) ± 8 (syst.)

Mass barycenter $m_k = \Delta m + m(kS)$

- The $\chi_b(3P)$ signal significance assessed from $\log(L_{max}/L_0)$,
  - L_{max} : likelihood value from nominal fit
  - L_0 : " " from a fit with no $\chi_b(3P)$ signal included
- Each of the unconverted and converted photon selections finds
  > 6σ significance of the $\chi_b(3P)$ signal

$\chi_b(3P)$ not previously observed

- **CMS** also searches for this type of final states (e.g. J/ψ+γ) :
  $\chi_c \rightarrow J/\psi\ \gamma$ (γ from photon conversion)
  Measure $m(\chi_{c1})$, $\Delta m_{\chi c1,c2}$ and $\Delta m_{\chi c0,c1}$ in $1.1\ fb^{-1}$.

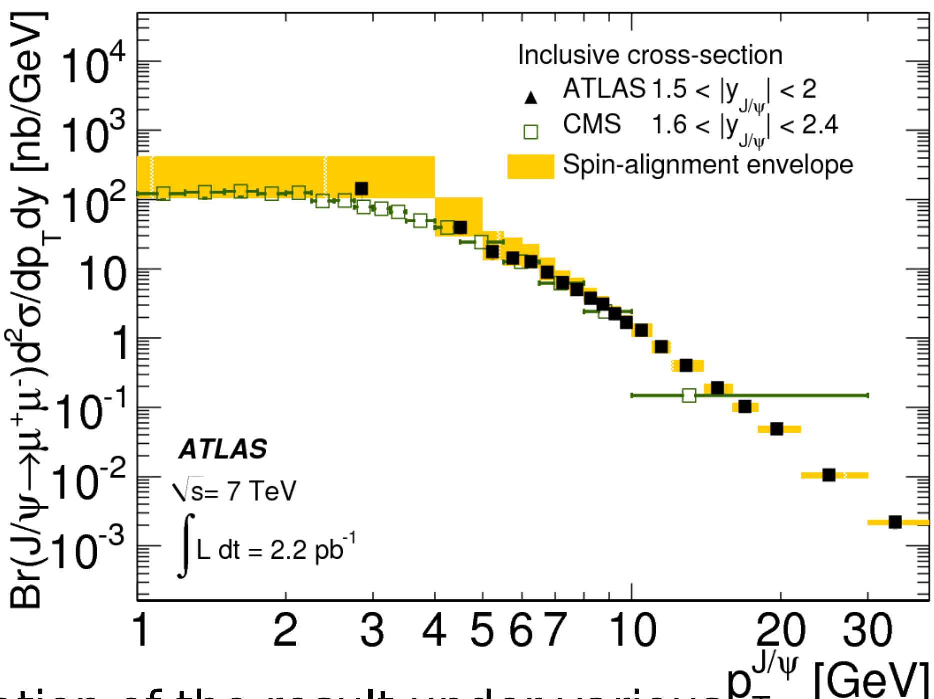


Differential cross-sections of inclusive, prompt and non-prompt J/ψ production 2.3 pb^{-1} [ATLAS]

Nuclear Physics B 850 (2011) 387–444

- Test theoretical models at higher p_T and wider rapidity than previously studied (J/ψ with p_T = 1-70 GeV and within |y| < 2.4)
- J/ψ candidates from $\mu^+\mu^-$ track-pairs fitted to common vertex, yield determined from fit to $\mu^+\mu^-$ invariant mass in p_T-y bins
- From reconstructed J/ψ candidates in p_T-y bin, true number obtained by applying weight: $w^{-1} = A \cdot M \cdot \varepsilon^2_{trk} \cdot \varepsilon^+_\mu (p^+_T, y^+) \cdot \varepsilon^-_\mu (p^-_T, y^-) \cdot \varepsilon_{trig}$

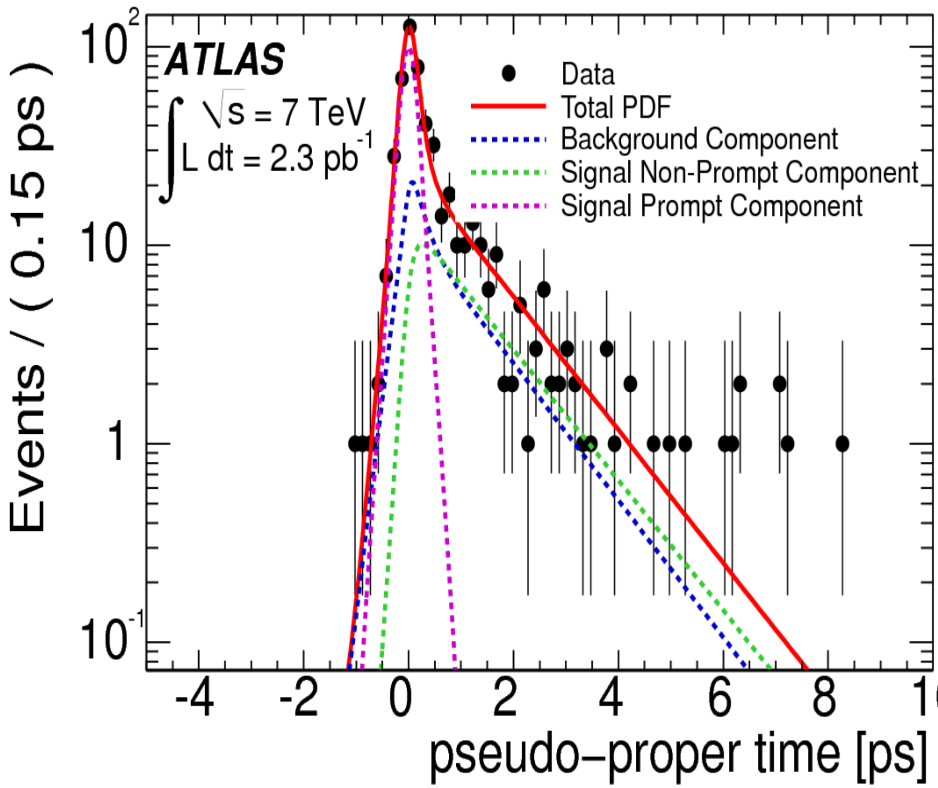
A = detector acceptance
NB: depends on unknown spin alignment of J/ψ
=>take envelope of max variation
M = bin migration correction
ε_{trk} = ID tracking efficiency
ε_μ = muon reconstruction efficiency w.r.t. ε_{trk} (tag & probe, also Z→μμ)
ε_{trig} = trigger efficiency

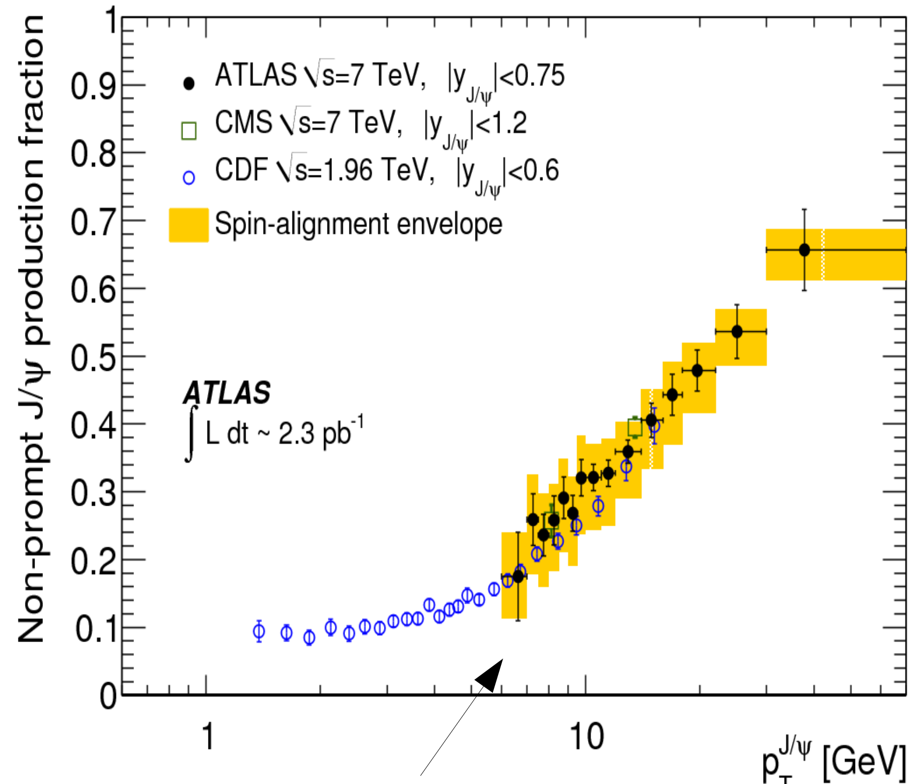


Overlaid is a band representing the variation of the result under various spin-alignment scenarios representing a theoretical uncertainty

- Inclusive measurement = prompt + non-prompt
  - Prompt = direct prod'n from hard interaction+feed-down from heavier states
  - Non-prompt = via decay of B-hadron (non-prompt fraction = f_B)
- Non-prompt component identified by transverse displacement of decay vtx., L_{xy}
- L_{xy} related to decay time of B hadron by $t = L_{xy}\, m_B / p_T^B$
- As B hadron not reconstructed, construct pseudo proper time $\tau = L_{xy}\, m_{PDG}^{J/\Psi} / p_T^{J/\Psi}$
- Simultaneously fit mass & τ in(p_T,y) bins to find signal, J/ψ mass & f_B

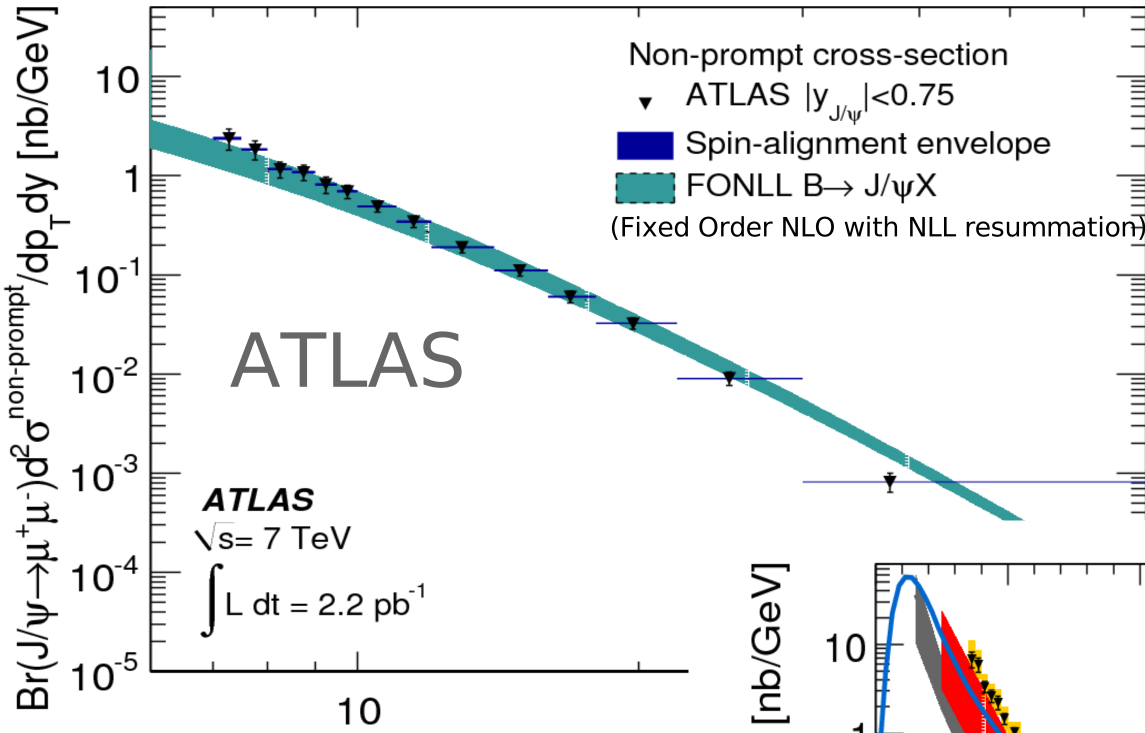
(mass sidebands constrain background in the lifetime)





Non-prompt fraction compared to CMS and CDF:

- f_B rises rapidly for J/ψ p_T > 7GeV;little y dependence
- no strong dependence on collision energy



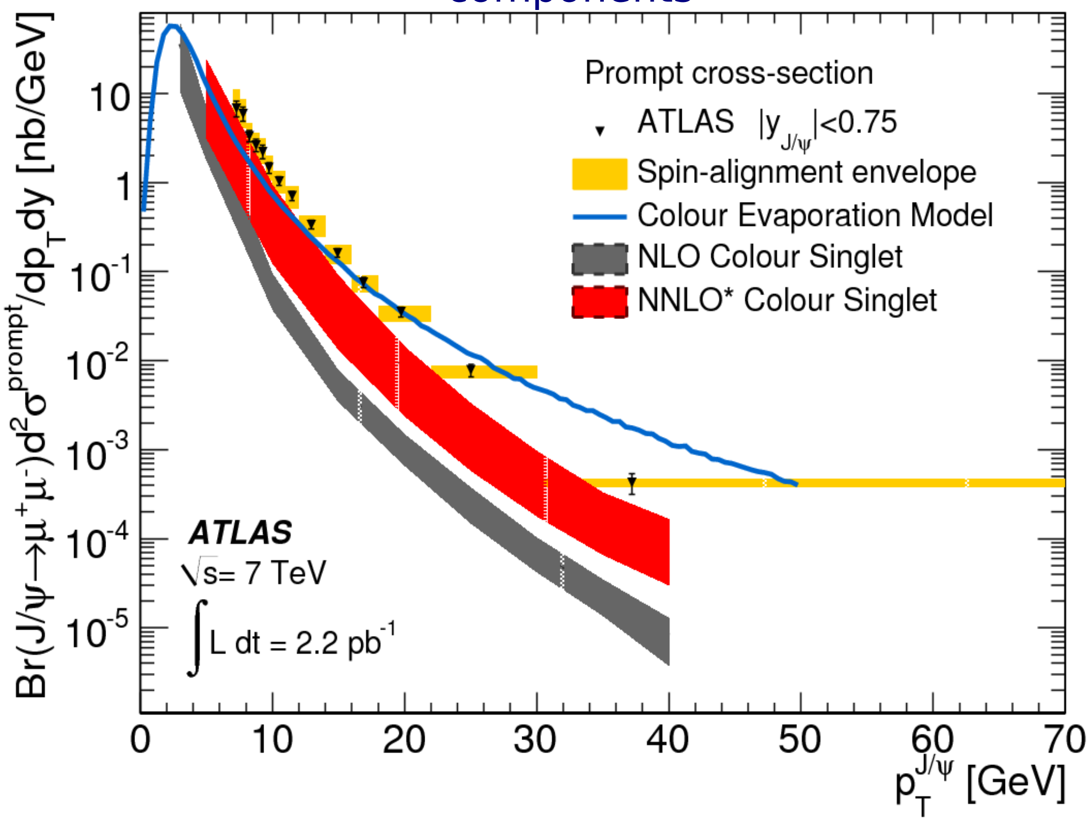
Non-prompt cross-section agrees with FONLL bellow 30 GeV, below theory at larger p_t

Band = variation under spin-alignment variations on the non-prompt J/ψ component

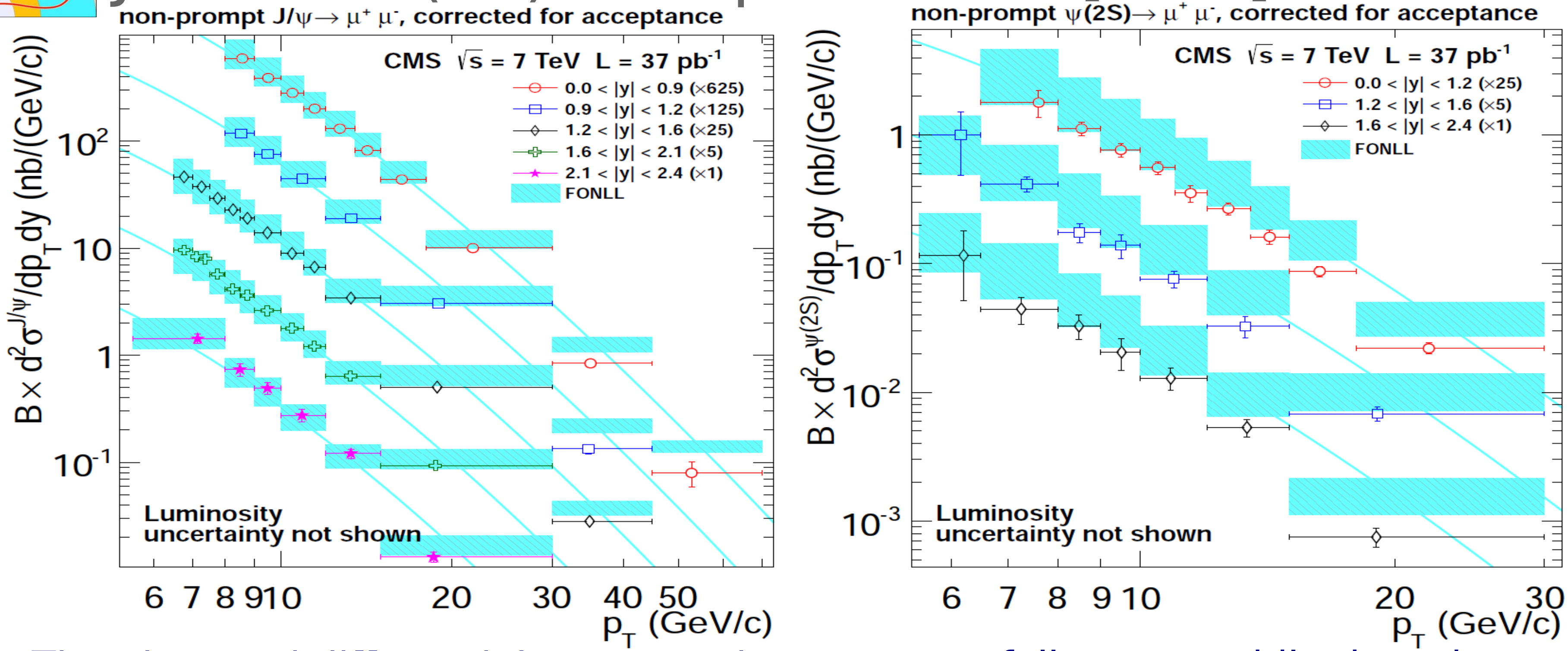
Central value assumes an isotropic polarisation for both prompt and non-prompt components

For the prompt cross-section

- CEM prediction too low & diverges at high p_T
- NNLO* calculations in Colour Singlet Model much better than NLO, still some discrepancy remains



J/Ψ and Ψ(2S) and production[CMS] arXiV:1111.1557



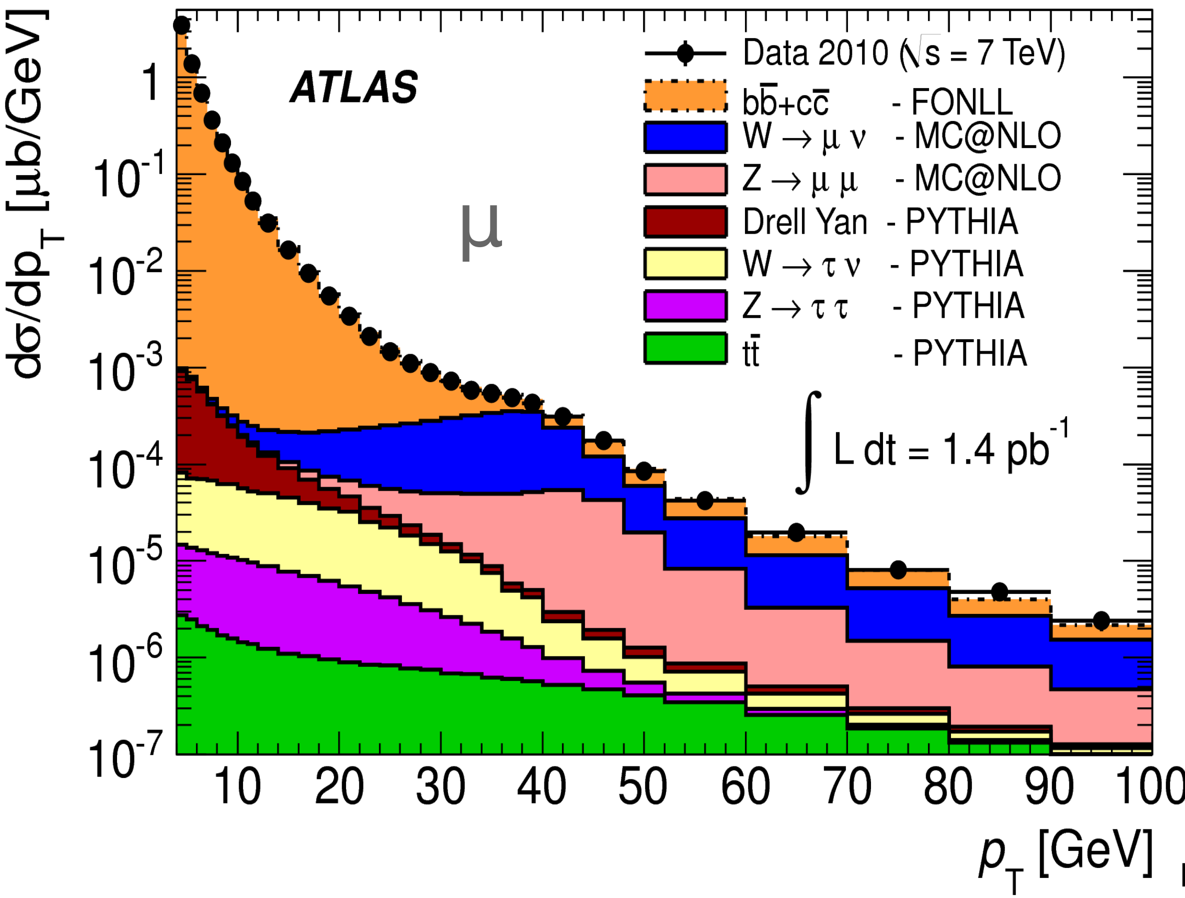
- The observed differential cross sections seem to fall more rapidly than the FONLL (as ATLAS, in agreement with FONLL below 30 GeV)
- Scale discrepancy observed for the Ψ(2S) possibly because of the assumption on the inclusive branching fraction Br[B →Ψ(2S)X]
- For plausible hypotheses on the polarizations of the two charmonium states the ratio of their differential cross sections is obtained. In this ratio systematic errors largely cancel

$$BR(B\to\psi(2S)X) = (3.08 \pm 0.12(\text{stat.+syst.}) \pm 0.13(\text{theor.}) \pm 0.42(\text{BR[PDG]}))\times 10^{-3}$$

- New estimate of Br[B →Ψ(2S)X] from cross section ratio has 3 times better accuracy than previous world average

Inclusive e and μ cross-sections from HF decays

Inclusive lepton spectra for $p_T < 30$ GeV dominated by decays of HF hadrons (above 30GeV isolated electrons from W/Z/γ* with high identification efficiency dominate that channel)



http://arxiv.org/abs/1109.0525v1

- Extract electron signal from background of QCD fakes and conversions
- Extract muon signal from background of QCD fakes and pion & kaon decays in flight
- Subtract theoretical contribution from W/Z production
=> Obtain heavy flavour component

$$\frac{\Delta\sigma_i}{\Delta p_{T_i}} = \frac{N_{\mathrm{sig}\,i}}{\Gamma_{\mathrm{bin}\,i} \cdot \int \mathcal{L}dt} \cdot \frac{C_{\mathrm{migration}_i}}{\epsilon_{(\mathrm{reco+PID})_i} \cdot \epsilon_{\mathrm{trigger}_i}}$$

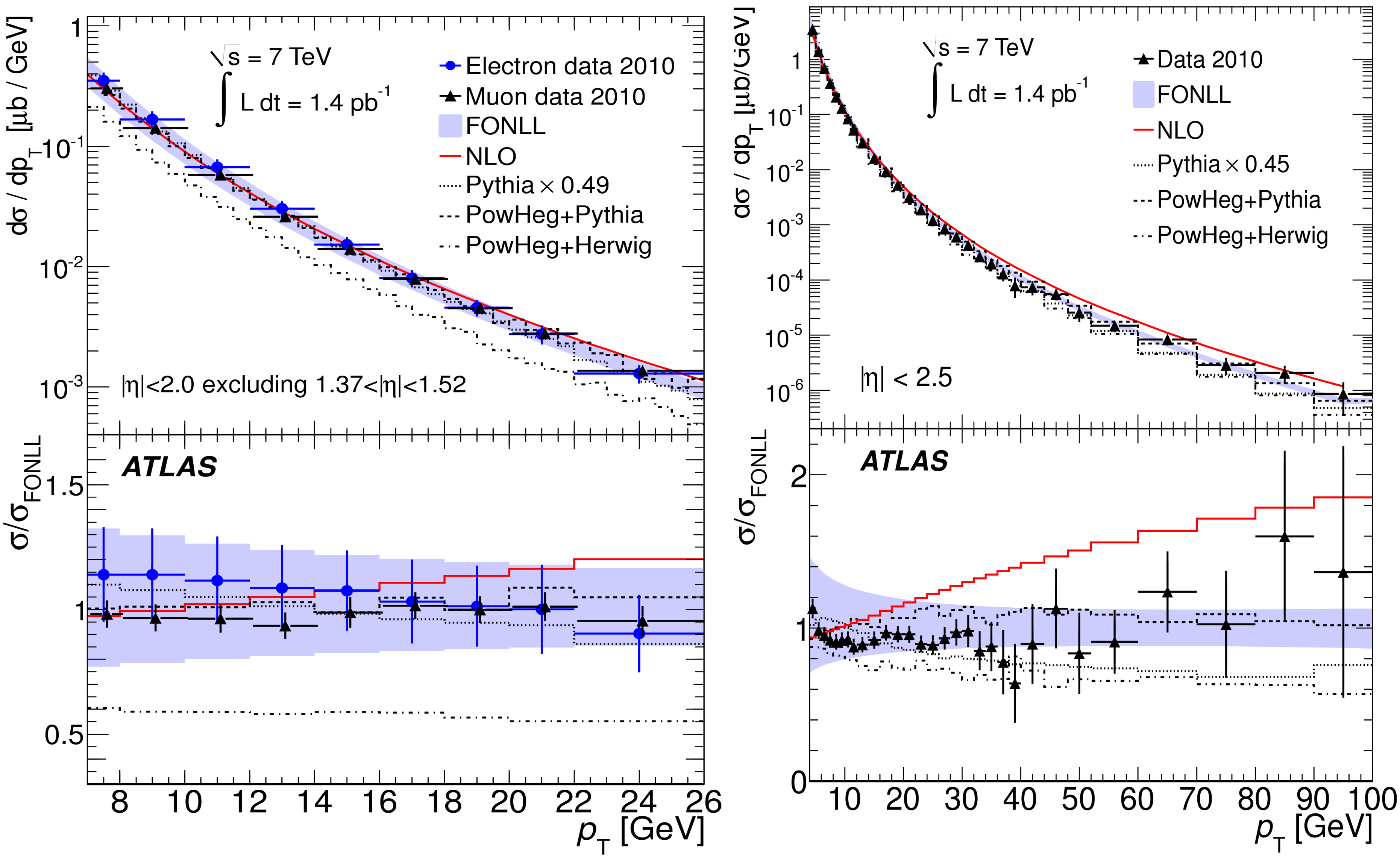
N_{sig} = no. of signal e or μ with p_T in bin i

$\varepsilon_{(reco+PID)}$ = reco.+ identification efficiency

ε_{trig} = trigger efficiency; Γ = bin width

$C_{migration}$ = bin migration correction factor

- Good agreement with FONLL (Fixed Order NLO calculations with NLL resummation)
- In particular, high-p_T region of muon analysis shows sensitivity to NLL terms



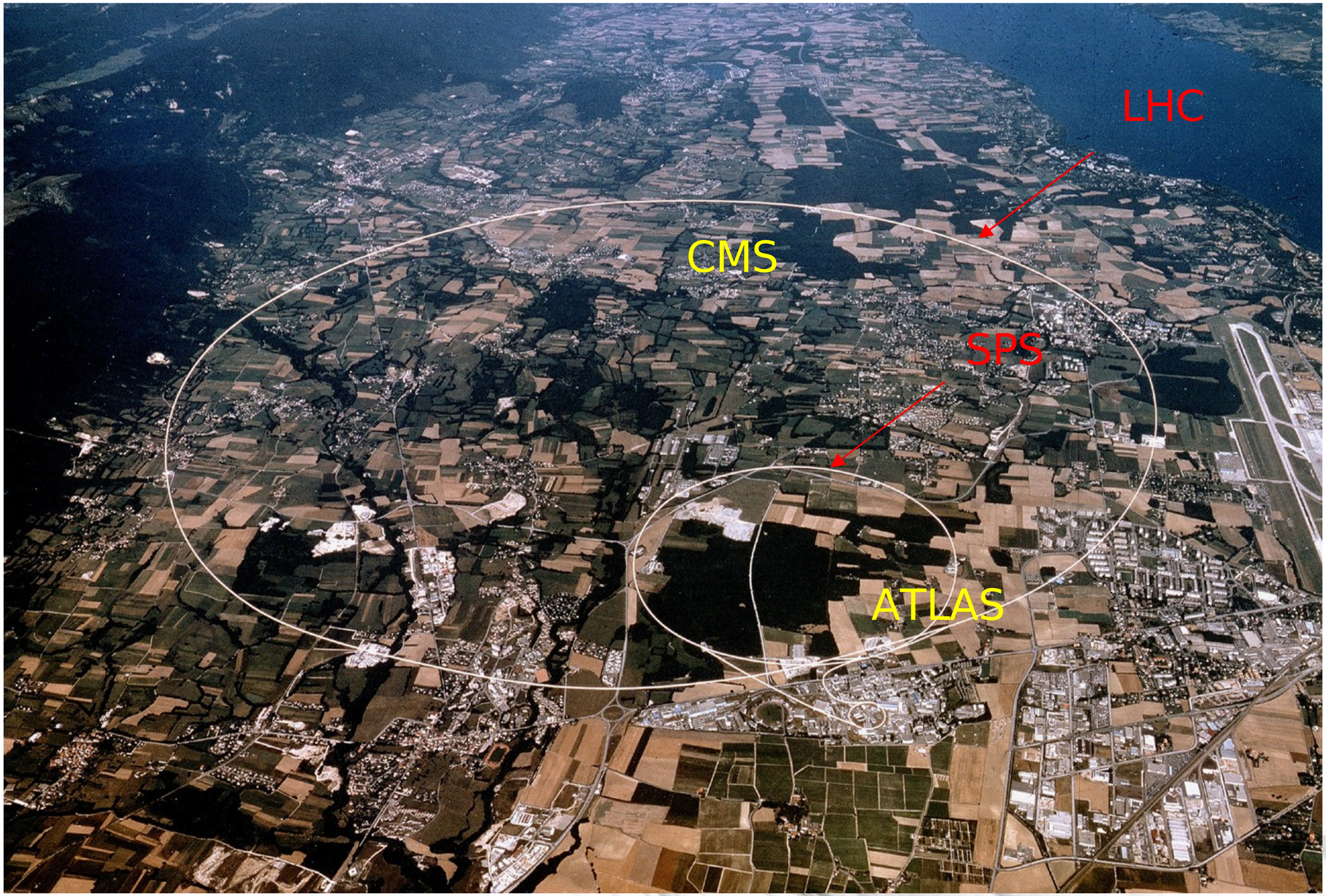
Conclusions

- Precise measurements of the b-quark production cross section are mandatory steps to control the background due to ordinary SM processes
- Thanks to excellent performance of CMS/ATLAS trigger, muon and tracking systems
- Confirming SM results and constraining theoretical models at LHC energies
  - Competitive (best) upper limit on B_s (B_d) branching ratio to dimuons
  - J/ψ and ψ(2S) non-prompt cross-section agree with FONLL bellow 30 GeV
  - Angular correlation measurements help disentangle underlying production processes
  - Extending beyond reach of Tevatron in e.g. sensitivity to NLL terms in inclusive lepton spectra
- Demonstration of methods and capabilities for future measurements with larger data samples to come (rare decays, CP violation etc)
- Challenges ahead:
  - Trigger bandwidth optimization at 5-7 x 10^{33} $cm^{-2}s^{-1}$
  - Robust event selection against pileup
- Rich programme to come afterwards

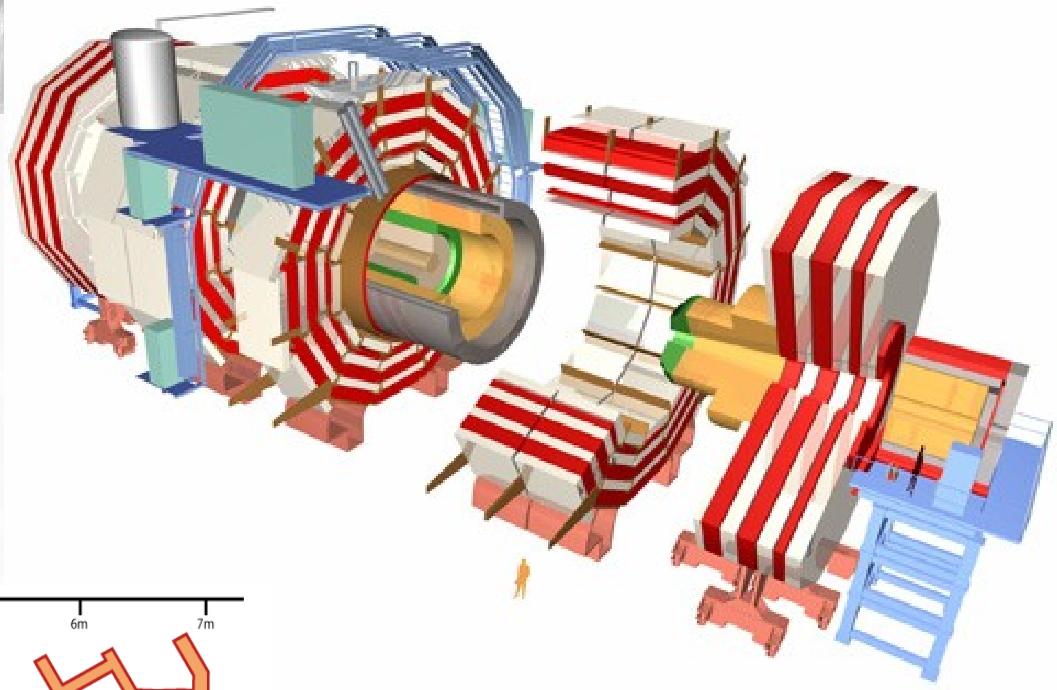
Back up

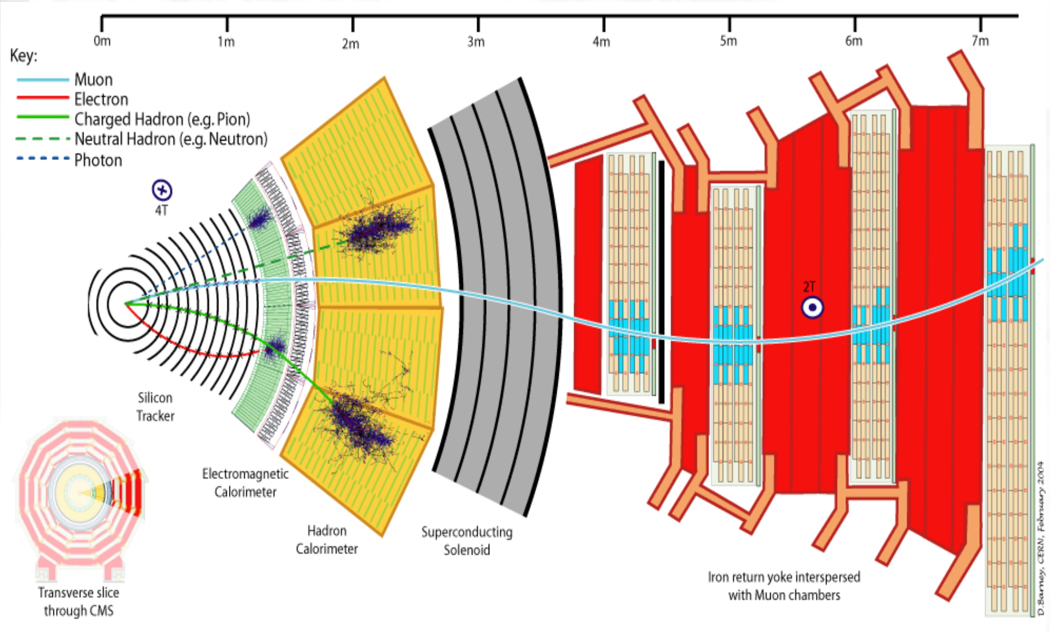
The Large Hadron Collider

9300 Superconducting Magnets; 1232 Dipoles (15m), 448 Main Quads, 6618 Correctors. Operating temperature: 1.9º K; 26.7 km tunnel



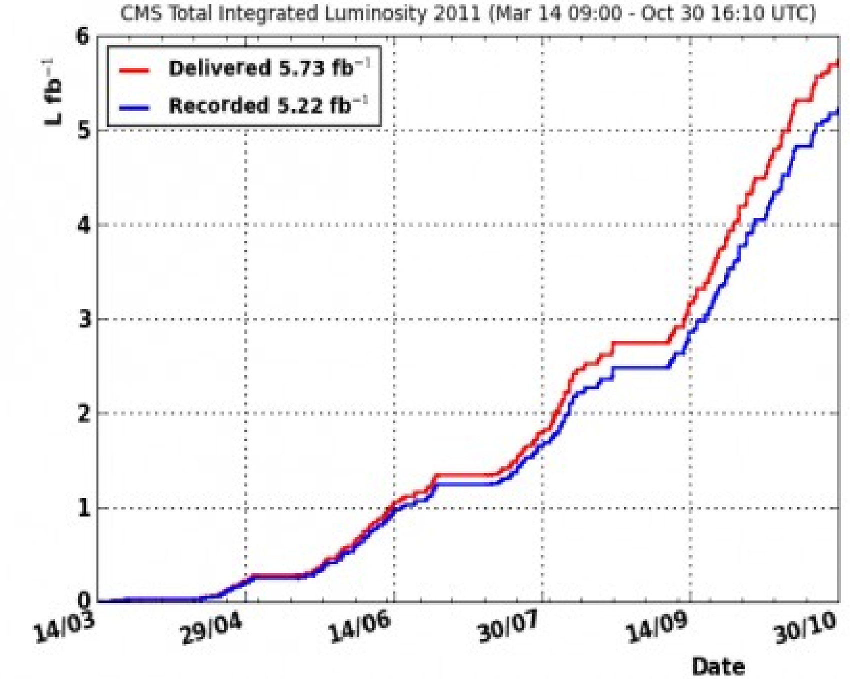
Introducing CMS

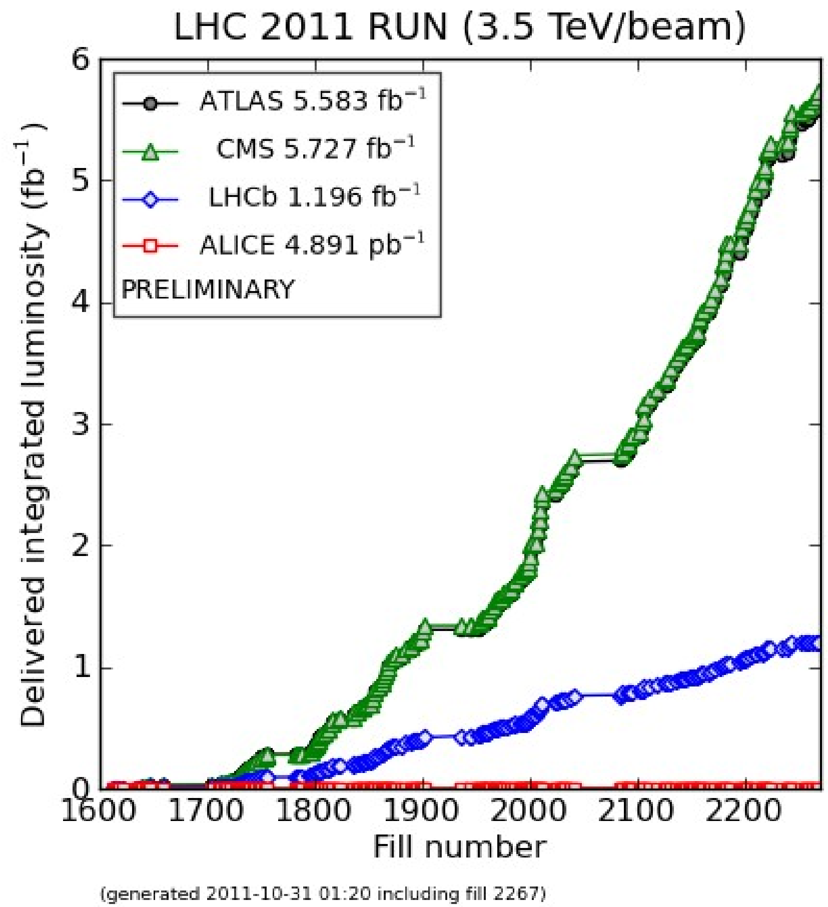




Size: 21 m long, 15 m wide and 15 m high.
Weight: 14000 tonnes
Design: barrel plus end caps
Project cost: 600+ M Euros

$p\bar{p}$ collisions at 7 TeV
Excellent performance of the machine





Good detector performance to give a high detector data taking efficiency

$b\bar{b}$ angular correlation based on secondary vertices