Recent QCD Advances at the LHC
Les Houches, February 17th, 2011

Quarkonia and Heavy Quark Production in pp Collisions

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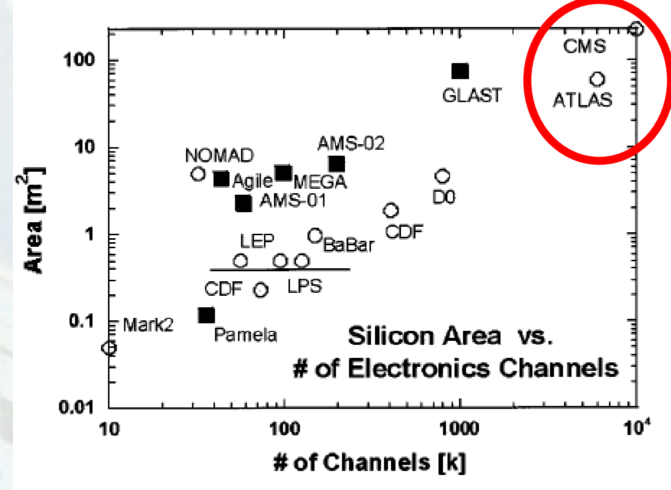
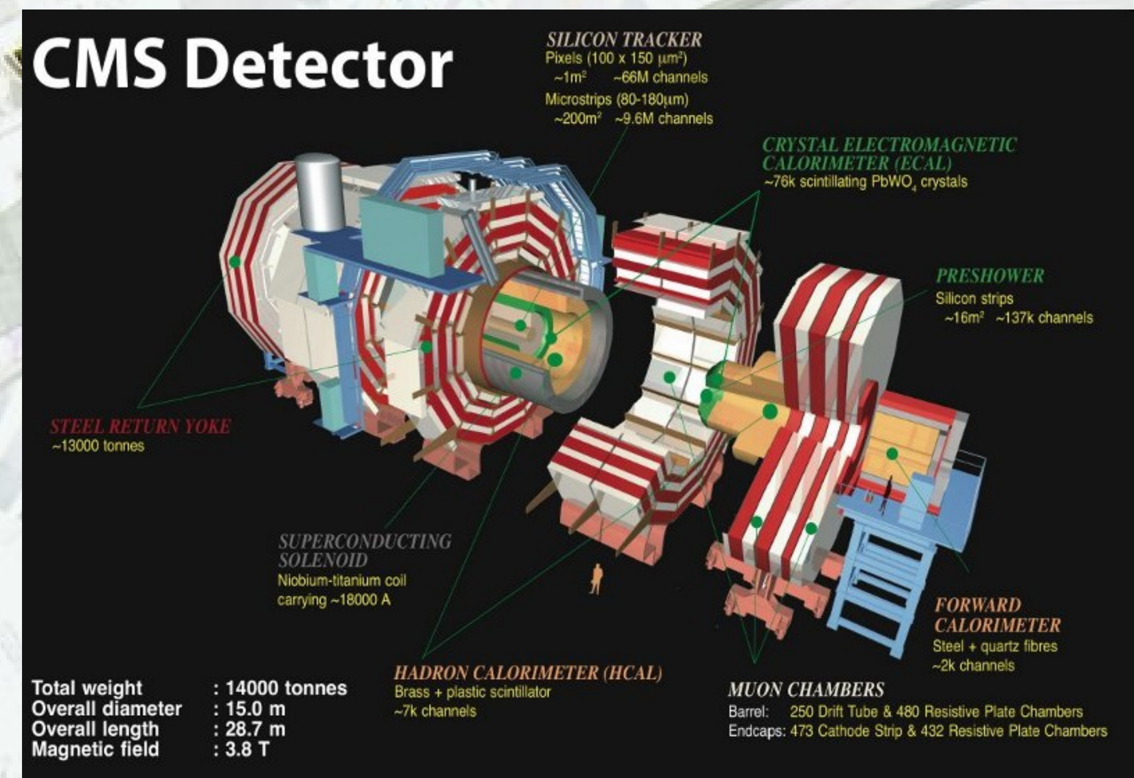
CMS Detector Specifications



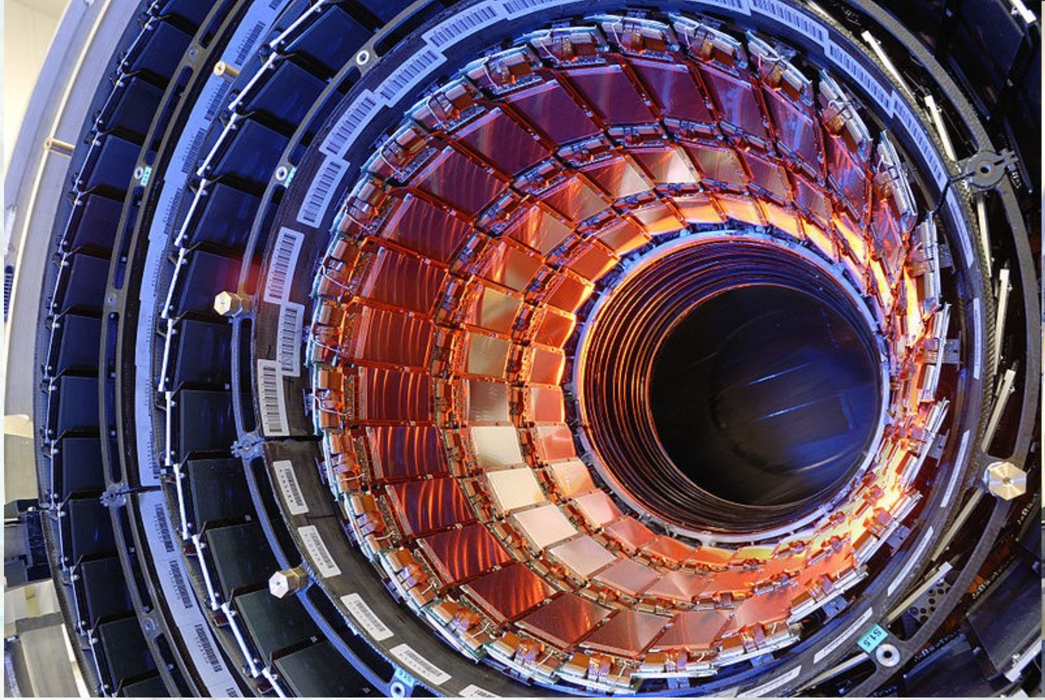
- Magnetic inner spectrometer (B=3.8T) endowed with
  - 3 barrel + 2 disk layers = 66M silicon pixels
  - 10 barrel +12 disk layers = 10M silicon strips
    - p_T resolution ~1% for muons used in analyses presented here
    - d_0 resolution ~20 μm
  - EM ($PbWO_4$ crystals) and HAD (brass/scint) calorimeters

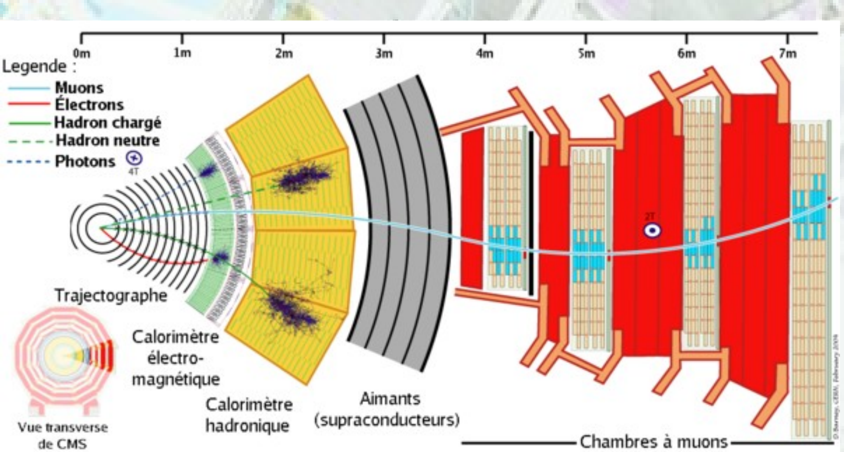
- Highly redundant muon system
  - 4 stations of self-triggering drift tubes, cathode strip chambers, resistive plate chambers embedded in magnet flux return steel
  - measures muons with p_T>2-4 GeV for pseudorapidity $|\eta|$<2.4

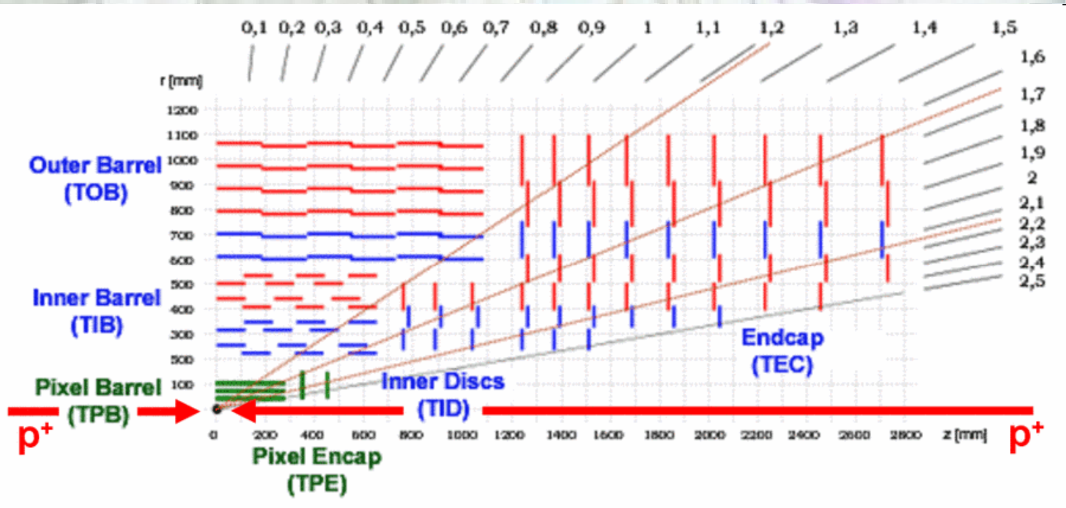


Particle Tracking in CMS

- Crucial for many B-physics results is the inner tracker
- Organized in barrels and disks of silicon pixels and strips
- Redundant system reduces fakes, allows precise vertexing
- Full coverage for $|\eta|<2.5$
  - matches acceptance of muon system
- Good tracks usually have 12 or more hits



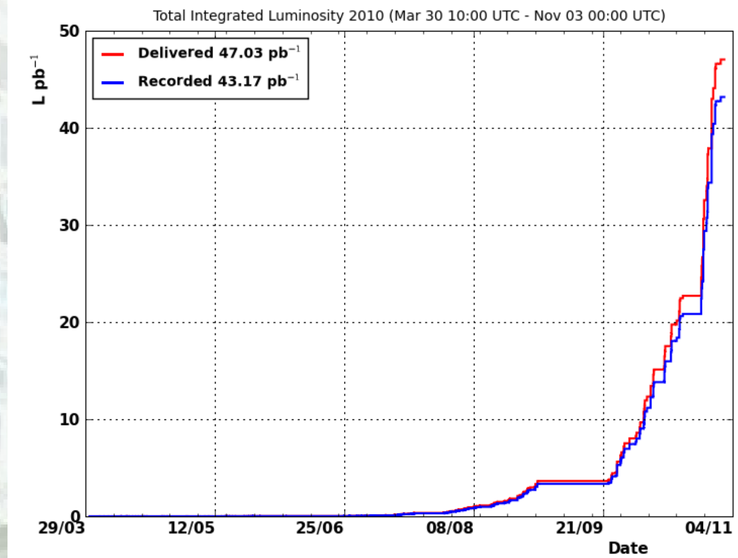


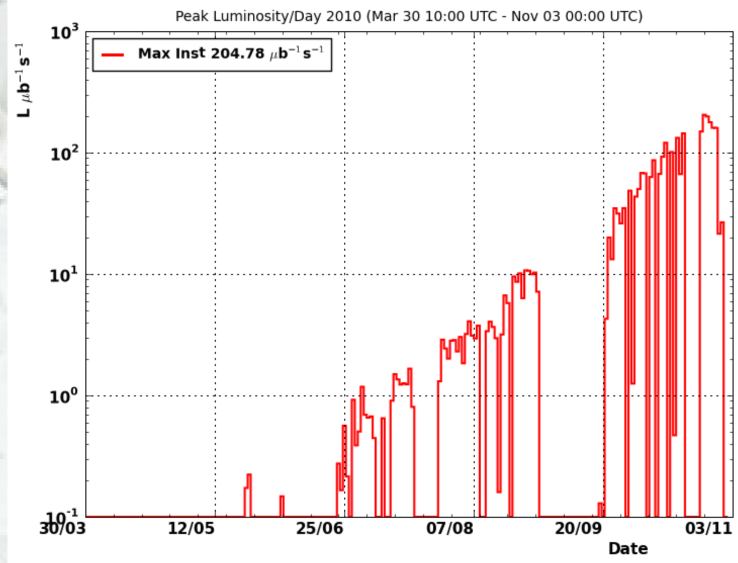


CMS in the 2010 LHC Run

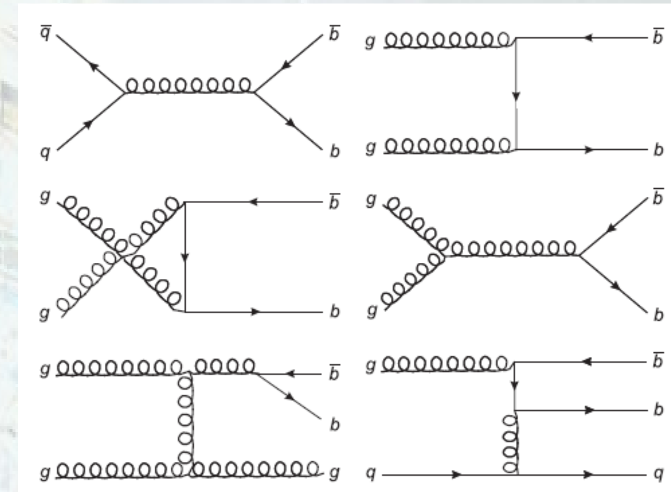
CMS collected 43.2/pb of 7 TeV pp collisions in 2010

- High overall efficiency for data collection (92%)
- Fully operational detector
- Large variation of instantaneous luminosity, 3 orders of magnitude up to $2*10^{32}$ cm^{-2} s^{-1}
- Trigger tables adapted to changing run conditions
  - Low thresholds enable measurements down to low values of transverse momenta

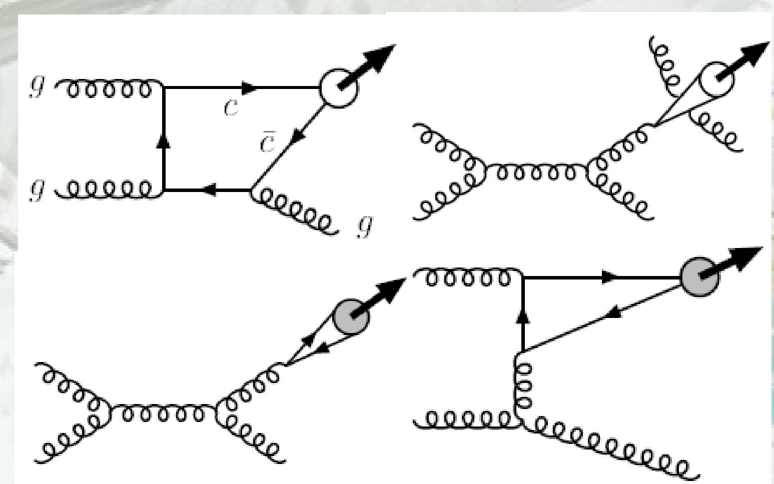




Heavy Flavour Production in Hadron Collisions



Bottom-quark production by energetic parton beams proceeds mostly via gluon collisions and can be classified at LO as direct production, gluon splitting, and flavour excitation
The latter two are $O(\alpha_s)^3$ but they still dominate the total rate
Charm production also receives a significant contribution from the c-quark PDF



Quarkonium production at hadron colliders receives large contribution from colour octet configurations

NRQCD approach evaluates the cross section as sum of terms for the states of given colour, spin, and angular momentum. Each term factorizes a short-distance coefficient and a long-distance matrix element

Issues in B Production

- Production cross sections have a history of disagreement with theory
  - Tevatron measurements off by one order of magnitude
  - but FONLL approaches have practically solved the riddle
  - Large theoretical uncertainties remain, due to dependence to factorization and renormalization scales
    - Generally a large μ_F and a small μ_R increase predictions, due to the growing of g(x) at small x and the decrease of α_s
    - The b quark pole mass yields typical uncertainties of the order of 10%
    - Important contributions from powers of $\ln(\mathrm{sqrt}(s)/m_b)$ at low p_T, and $\ln(p_T/m_b)$ at high p_T → LHC measurements become an important test

- The crucial impact of b-jet signatures in many new-physics searches is another strong motivation for extensive tests of NLO QCD in the production of b-quark jets

- For quarkonium, the most pressing question is on its non-understood polarization properties

Open Beauty Production Cross Section at CMS

One of the first b-physics measurements produced last year by CMS (85±9/nb) is that of open beauty production

Arxiv: 1101.3512

Trigger: low-p_T inclusive muons (p_T>3 GeV, d_0<2cm)
Offline: global muons, p_T>6 GeV, $|\eta|$<2.1, d_0<2mm, d_z<1cm, χ^2<10 for track fit

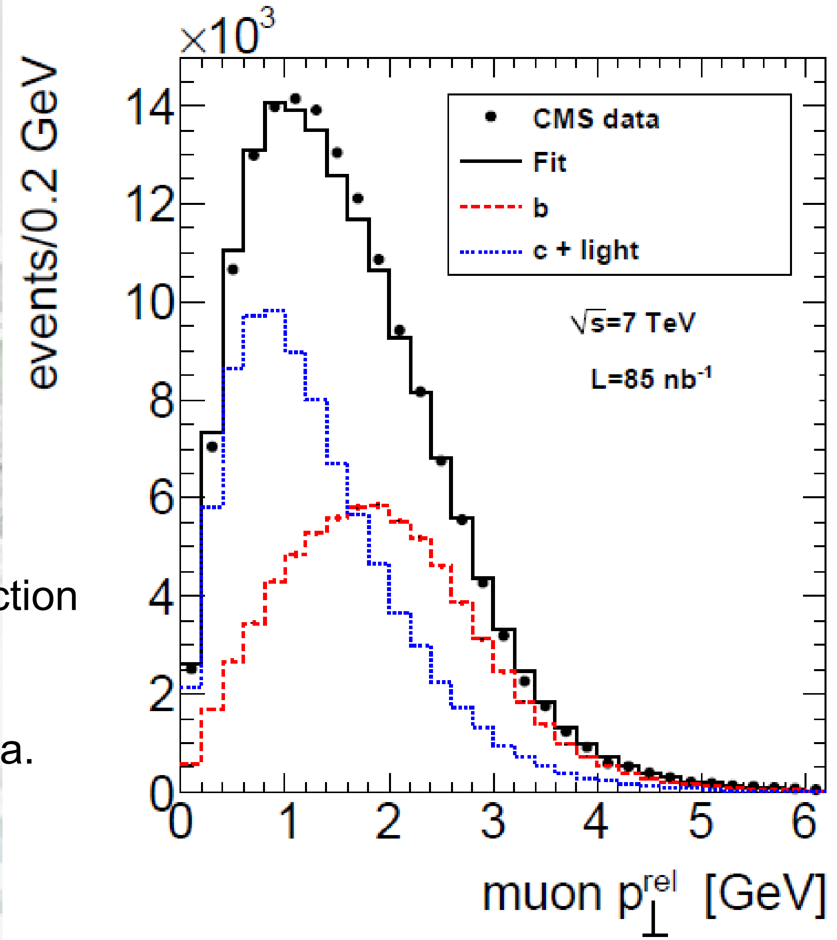
Track jets (p_T>1 GeV) are reconstructed with anti-k_T (ΔR=0.5, N(track)>=1, p_T(tracks)>0.3 GeV) and the closest jet is associated to the muon.

157,783 events pass the selection in 85±9 /nb of 7 TeV pp collision data. Only the highest-p_T muon is considered in the measurement.

The $p_T^{rel} = |p^\mu \times p^j| / |p^j|$ is used to determine the b fraction

b. c templates are derived from simulation;
udsg template from fake muon parametrization in data.

Extensive checks of fitting procedure exclude significant biases in the estimate

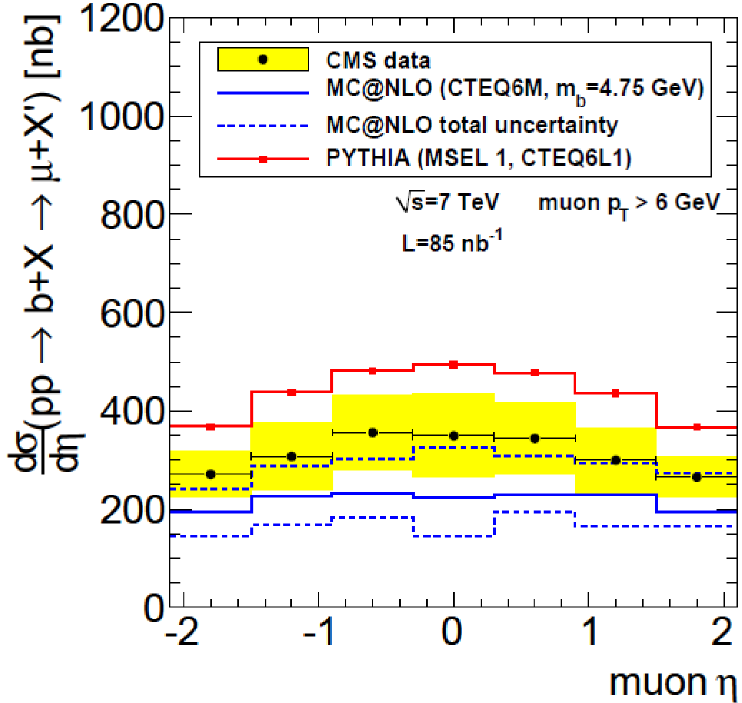


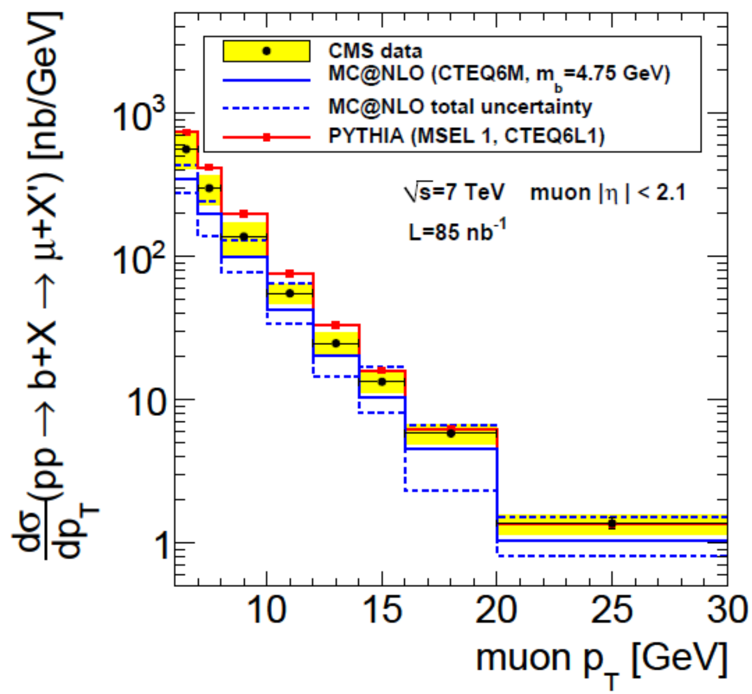
$b \rightarrow \mu$ Cross Section Results

- Shape systematics dominate the b fraction measurement (21% from b-template, 2-14% from bgr template);
- Efficiency uncertainties: largest is track-jet matching (77±8%)
- The cross section is inclusively measured as

$$\sigma(pp \rightarrow bX \rightarrow \mu X') = 1.32 \pm 0.01 \pm 0.30 \pm 0.15\ \mu b$$
$$(p_T^{\mu} > 6\ \text{GeV},\ |\eta^{\mu}| < 2.1)$$

- σ is also studied as a function of muon transverse momentum, for $|\eta^{\mu}|<2.1$, and rapidity, for $p_T^{\mu}>6$ GeV
- b production rates overshoot MC@NLO predictions (0.84 μb) by a factor 1.6, but are smaller than Pythia ones
- Shapes agree with MC@NLO





B^+ Production Cross Section

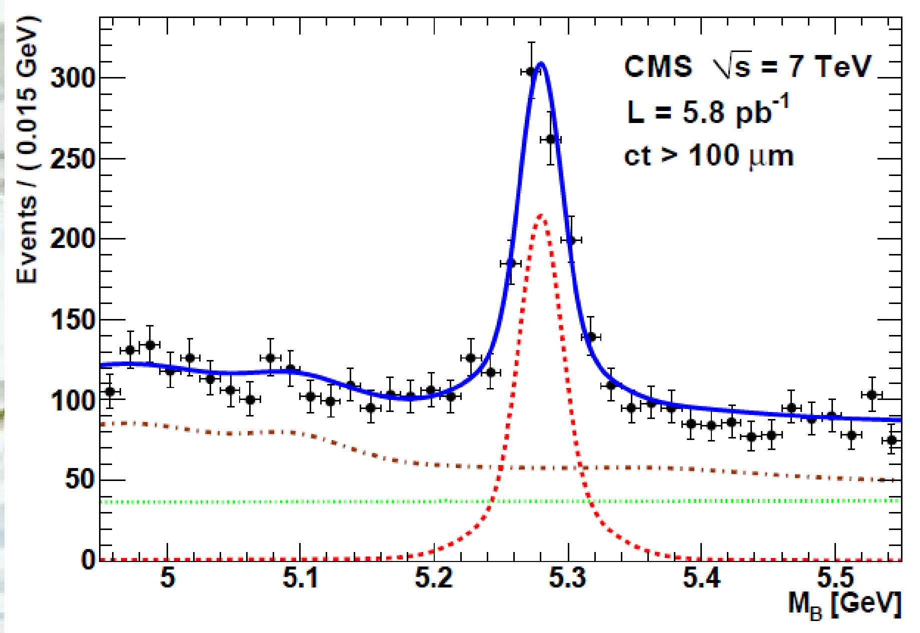
A measurement of total and (p_T- and y-) differential cross sections for B^+ production has been performed in 5.84±0.64 /pb of 7-TeV pp collisions using $B^+ \rightarrow J/\psi\ K^+$ decays

J/ψ decays are reconstructed in the $\mu^+\mu^-$ final state, providing the trigger primitives; muon p_T cuts are η-dependent to reflect the increasing low-p_T acceptance at high-η

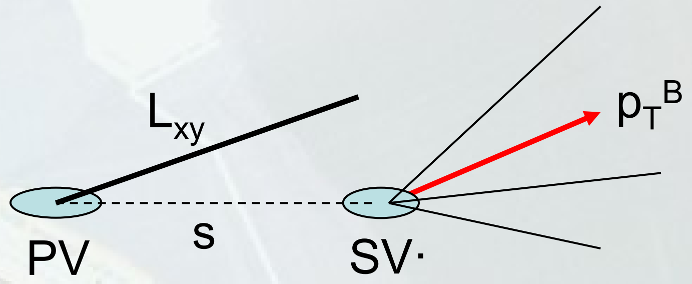
J/ψ candidates are paired with a track of p_T>0.9 GeV; the highest-p_T combination is retained (95% efficient).

Total reconstruction efficiencies range from few % to 40% for p_T^B between 5 and >24 GeV

A kinematic fit to the $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+\mu^- K^+$ hypothesis selects B^+ candidates if $4.95 < M_{\mu\mu K} < 5.55$ GeV and the fit probability exceeds 0.1%

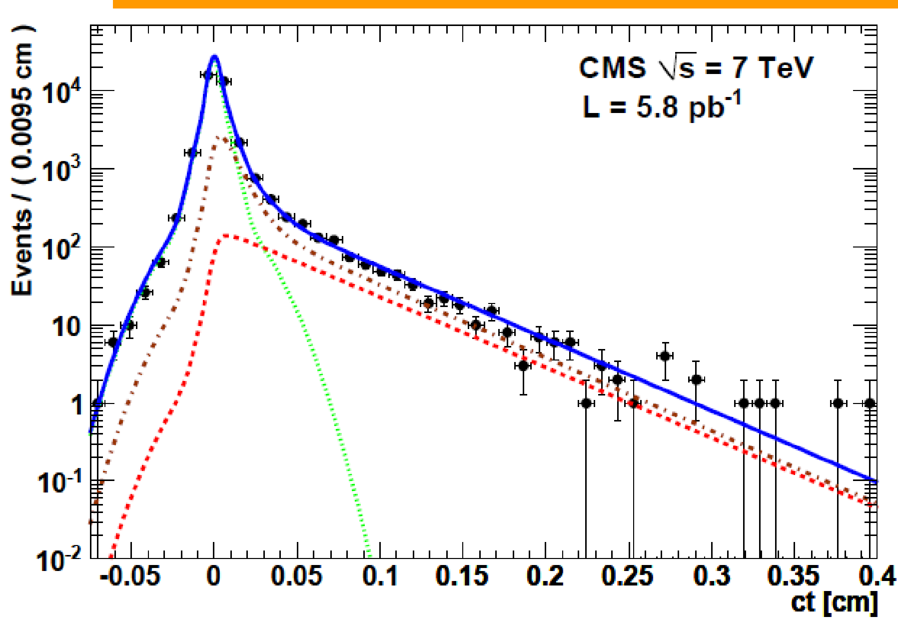


Mass and Lifetime Fit



- The proper decay length is determined as $ct=(m^B/p_T^B)L_{xy}$, where $L_{xy}=(s\cdot p_T^B)/|p_T^B|$ and s is the vector connecting primary vertex (PV) and $\mu\mu K$ vertex (SV)
  - Resolution σ_{ct}~30 μm
- Reconstructed mass $m_{\mu\mu K}$ and ct are used in a unbinned extended ML fit to five components: signal, $B^+ \rightarrow J/\psi\pi^+$ (rel. norm. fixed wrt signal by ratio of BRs), other bb, prompt and non-prompt J/ψ
- Shapes are derived from data when possible. Sidebands to mass-peaking components are used by the fit to determine the resolution function in ct, which is then applied to the signal

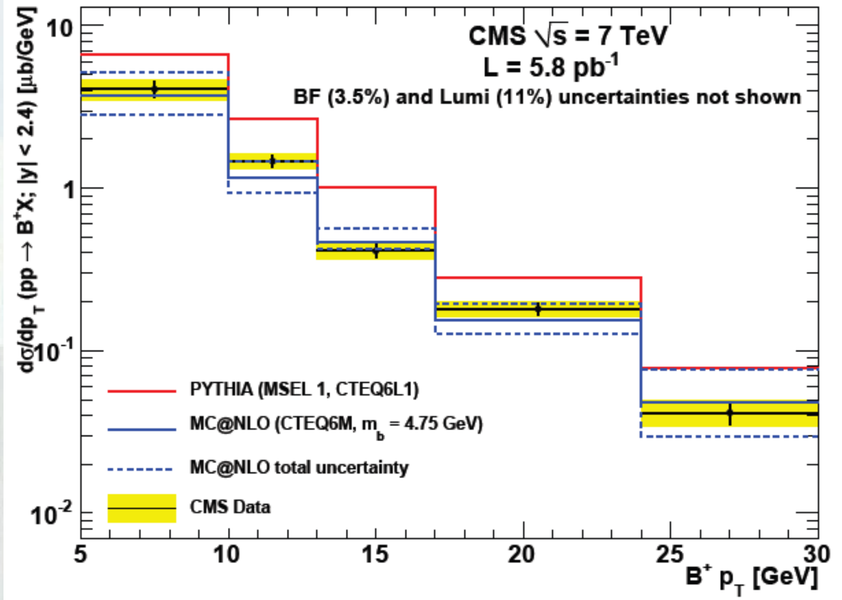
Signal in red; prompt J/ψ in green; other bgrs in brown; total fit in blue



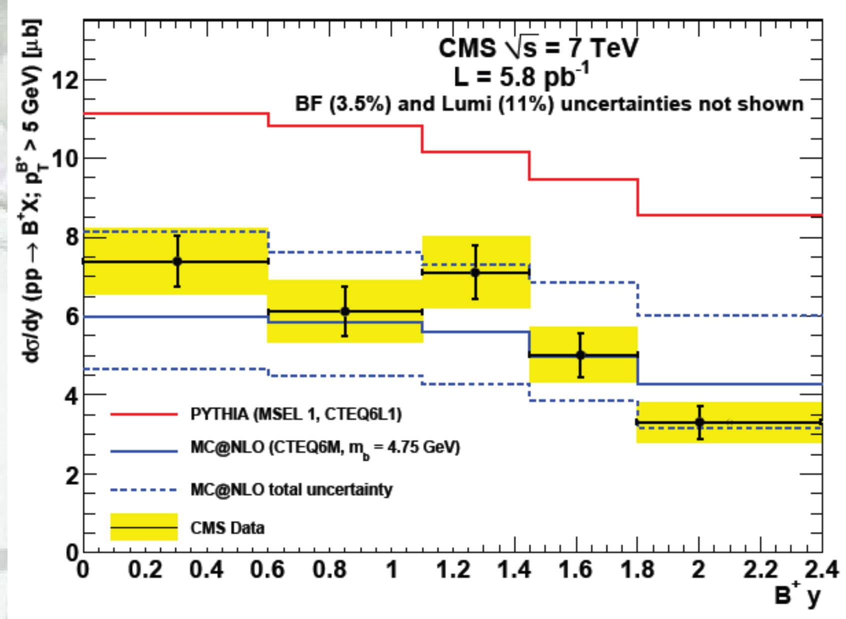
B^+ Results

- The total cross section is computed for p_T^B>5 GeV, $|y^B|$<2.4 as
  $\sigma = 28.1 \pm 2.4 \pm 2.0 \pm 3.1\ \mu b$
- results agree with MC@NLO predictions (25.5μb); PYTHIA higher by 50% (48 μb)
- Differential distributions not in disagreement with data considering uncertainties
  - MC@NLO: use m_b=4.75(±0.25) GeV, μ=(0.5,2) x sqrt(m_b^2+p_T^2), CTEQ6M (6.6) PDF
  - Pythia use m_b=4.8 GeV, CTEQ6L1 PDF, D6T tune for UE

Arxiv: 1101.0131



Warning: Theory predictions subject to modification (shown are preliminary updates of those in arxiv paper)



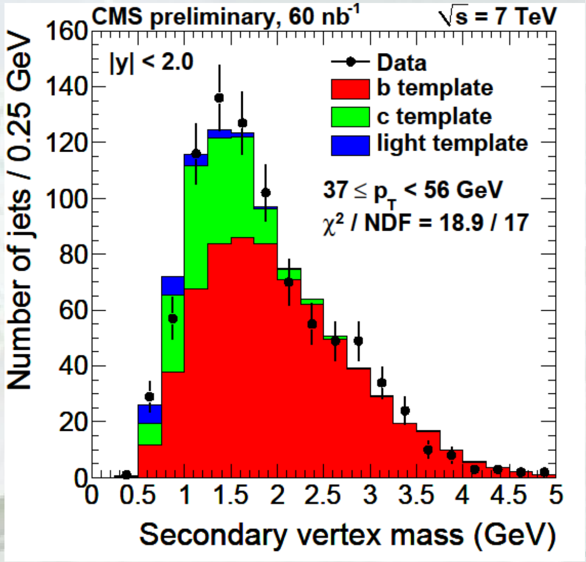
Inclusive B-jet Cross Section

60/nb of collision data at 7 TeV were used last summer to measure the cross section of b-jet production, for $18<p_T<300$ GeV

Events were triggered by a combination of a minimum bias trigger and single jet ones, used in the p_T range where they are fully efficient

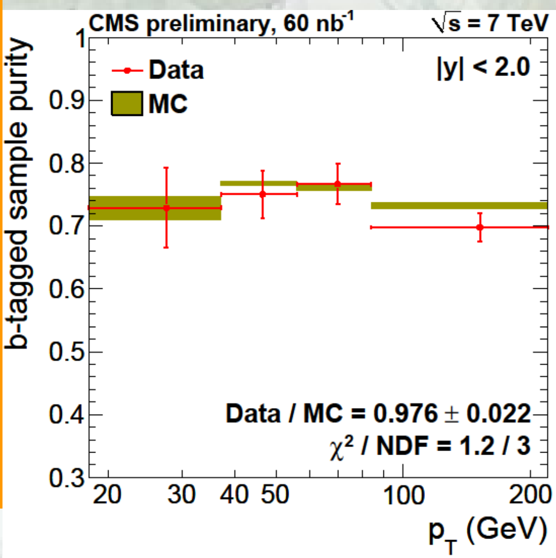
Jets found by anti-k_T with $\Delta R=0.5$, using PF objects as input

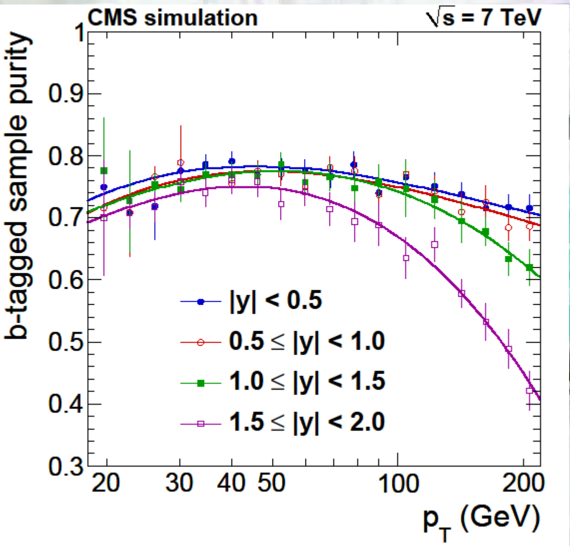
Energies are corrected with estimates based on MC for absolute scale and p_T dependence; data is used for the η dependence. Uncertainties are determined with γ-jet events and dijet balancing techniques.



B-jets are found by a high-purity secondary vertex tagger requesting >2 tracks. Efficiency ~60% at p_T=100 GeV, with mistag rates <1%.

Sample purity is estimated from fits of the SV mass, and checked with MC simulations of efficiencies and sample composition. Scale factors for data/MC are consistent with 1.





B-jet Cross Section Results

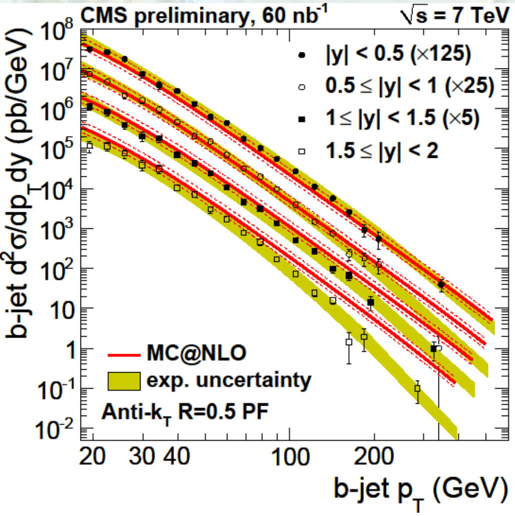
The differential p_T cross section is computed in four rapidity intervals

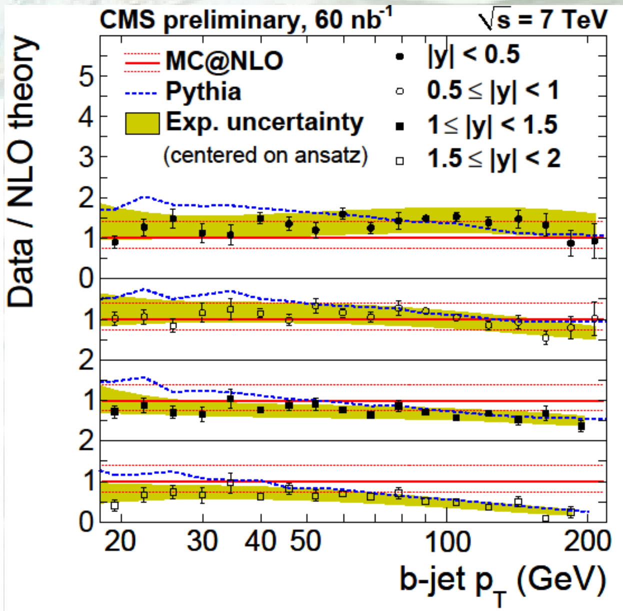
Experimental uncertainties from jet energy reconstruction and luminosity are reduced in the ratio of the b-jet production cross section to the inclusive jet production cross section.

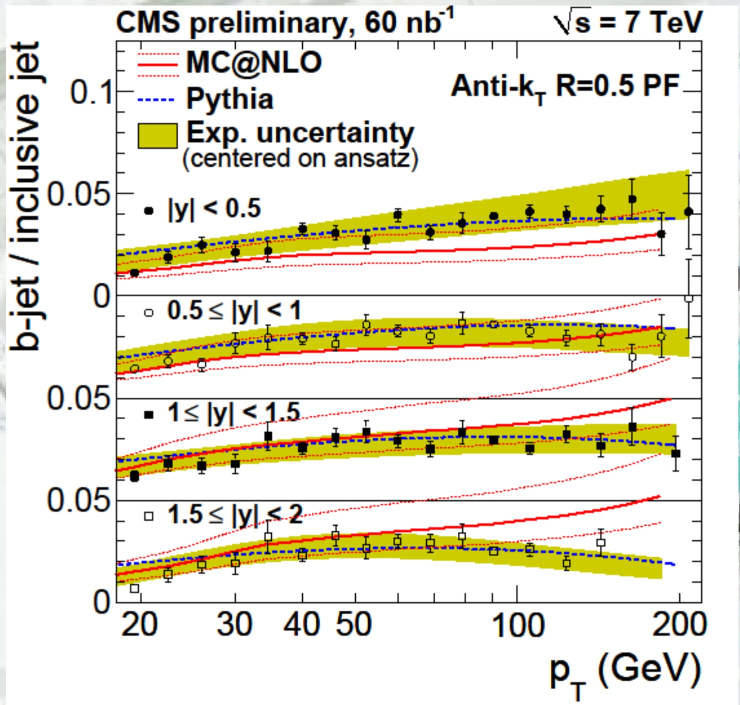
Overall, the ratio is found to be in good agreement with expectations based on calculations made with Pythia and with NLO QCD

- NLOjet++ for inclusive xs, MC@NLO for b-jet xs; CTEQ6M PDF used, scales set to jet p_T.
- A global data/Pythia scale factor of 0.99±0.02(stat)±0.21(syst) is found in the range 30-150 GeV

Significant shape differences with NLO predictions are observed in p_T and y.





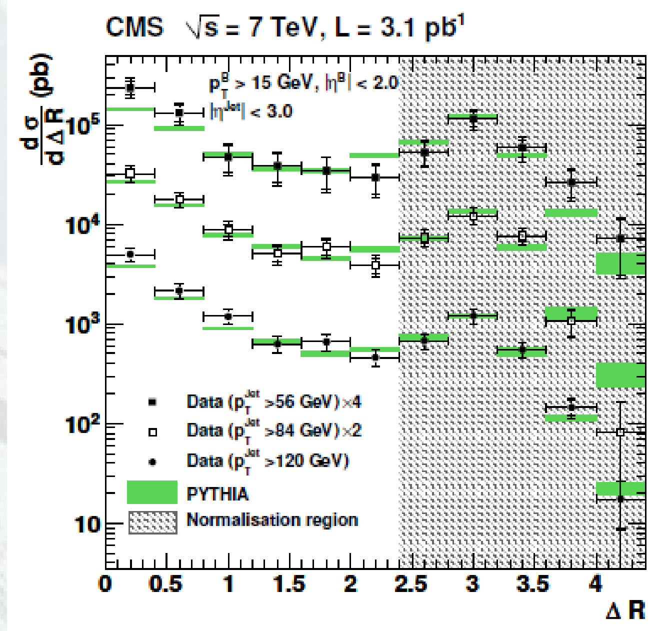


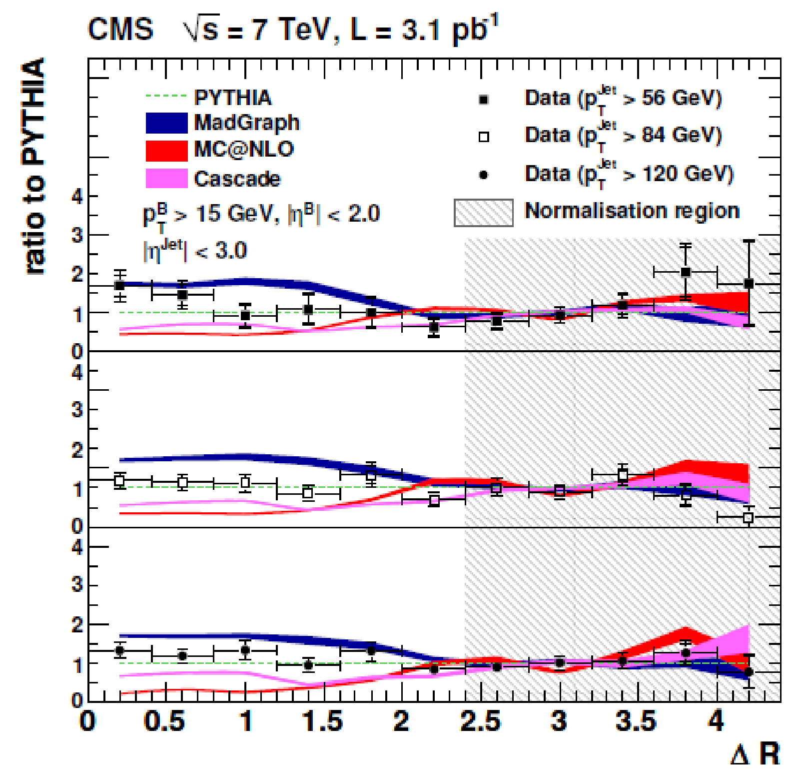
Hot Off The Press: BB Angular Correlations

- A first measurement of angular correlations of b-antib pairs has been recently produced from 3.1/pb of 7 TeV data

- b-jets are considered in a wide range of momenta. B identification is performed via secondary vertex tagging independent of jet direction
- The sample purity is studied with the vertex mass and displacement

- Cross sections differential in ΔR and ΔΦ are calculated and compared to various calculations
- At low angular separations the cross section is enhanced and is not described well by MC@NLO or CASCADE.





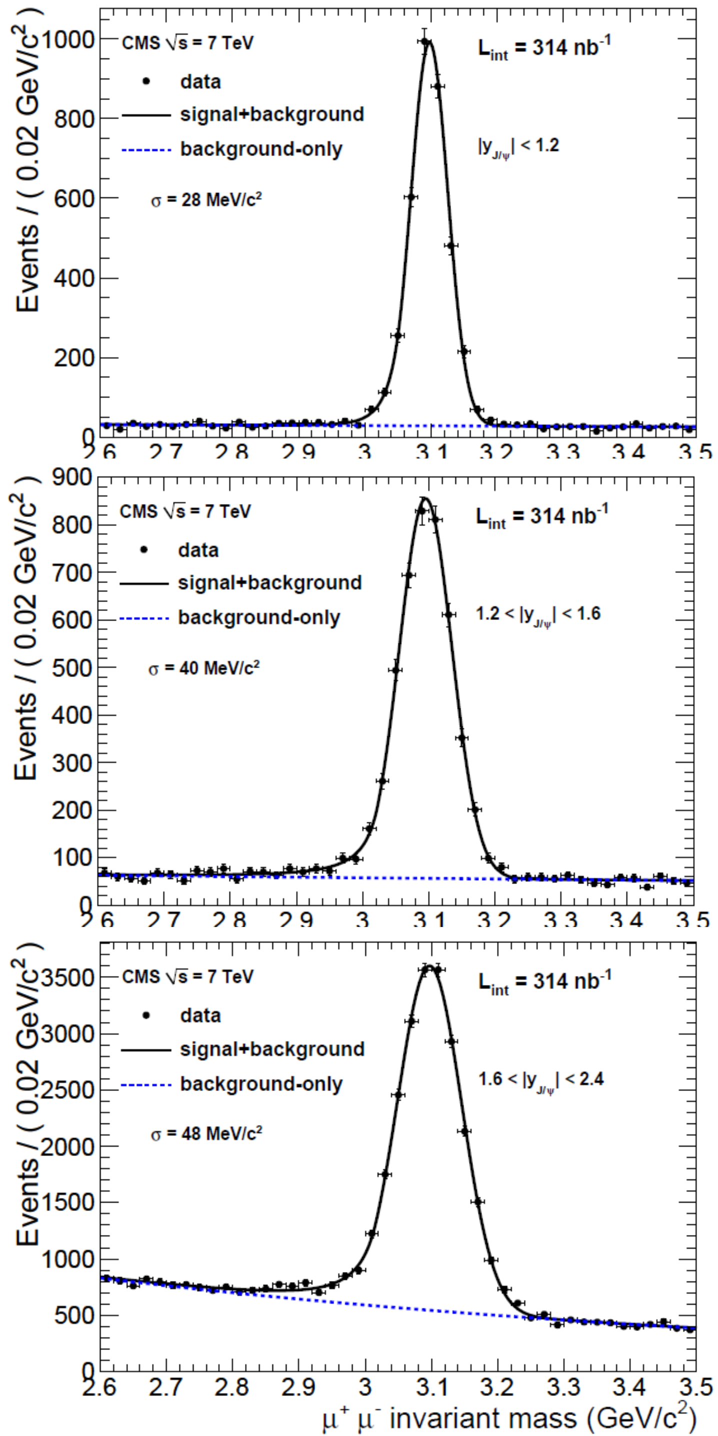
J/ψ Production at CMS

- J/ψ mesons are produced in three main ways at the LHC
  - Promptly, by direct ccbar production
  - Promptly, indirectly by decay of heavier charmonium states such as χ_c
  - non-promptly, from the decay of long-lived B hadrons
- Even after the “solution” of the quarkonium cross-section puzzles of the 90’s, charmonium production remains highly interesting in hadron collisions – none of the existing models correctly predicts the (high) p_T-differential cross section and the polarization
  - Experimentally, cross sections are heavily dependent on polarization:
    - We measure J/ψ essentially from their decay to muon pairs
    - Polarization affects the J/ψ p_T distribution heavily
    - This reflects on muon momenta
    - The detector is only sensitive to muons above a minimum p_T

For prompt J/ψ, CMS chooses to quote the cross section for different polarization scenarios: unpolarized, transverse, and longitudinally polarized. Differences are sizable (20% and above).

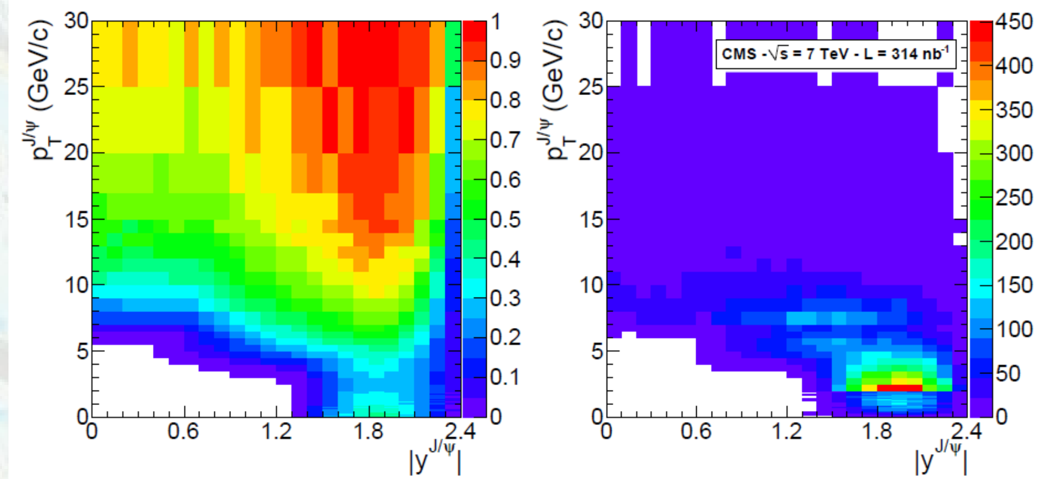
J/ψ Selection

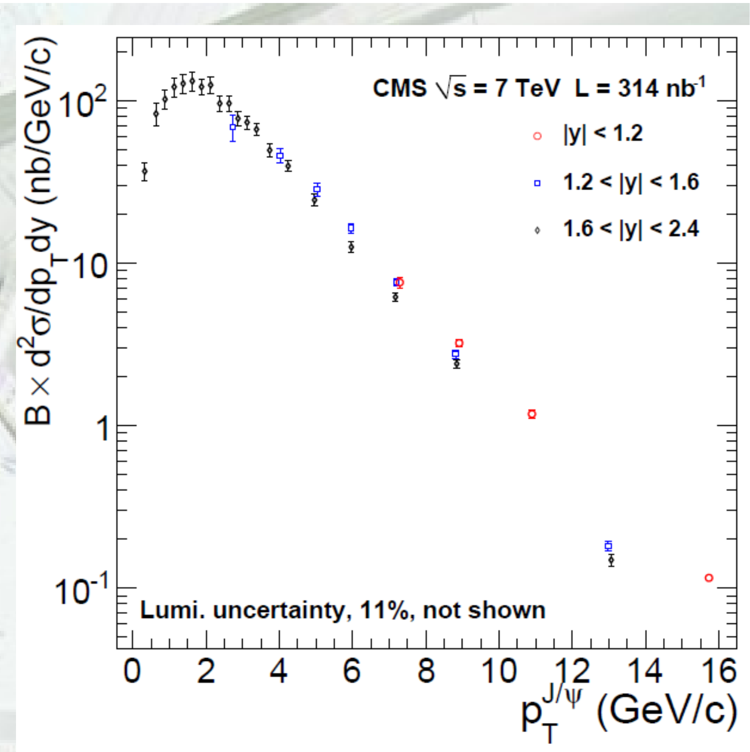
- Early 7 TeV data (314/nb) triggered by presence of two muons
  - low instantaneous luminosity →no threshold required on muon p_T
- MC simulation used for acceptance studies
  - Pythia 6.412 with LO singlet and octet production mechanisms, NRQCD matrix elements tuned to CDF data
  - For non-prompt component, bb production is followed by EvtGen
  - PHOTOS for FSR; GEANT4 detector simulation
- Muons identified as tracks in silicon tracker, with associated hits in muon system
  - global muons: p_T>~4 GeV in central region (|η|<1.3), or p_T> ~1 GeV in forward region, combined with silicon tracks
  - tracker muons: silicon tracks with calorimeter compatibility
  - momenta always measured in tracker
  - tight requirements on track fit (N_{hits}>12, χ^2<4) →reduce DIF background
- opposite-sign muons with a good vertex fit (p>0.001) → 27,000 candidates



Inclusive Cross Section Determination

- Critical to the measurement is the determination of muon acceptance
  - Studied with large MC samples, as a function of polarization
  - Systematic effects studied: FSR, production spectra, b-fraction and polarization, p_T scale and resolution
- Muon detection efficiency determined with tag-and-probe method
  - separately determined tracking efficiency, ID efficiency, and trigger efficiency





Cross section is determined in p_T and y intervals from the yield corrected for acceptance and efficiency:

σ ($6.5<p_T<30$ GeV, $|\eta|<2.4$) $B(\mu\mu)$ = $97.5 \pm 1.5 \pm 3.4 \pm 10.7$ nb

Non-Prompt J/ψ Measurement

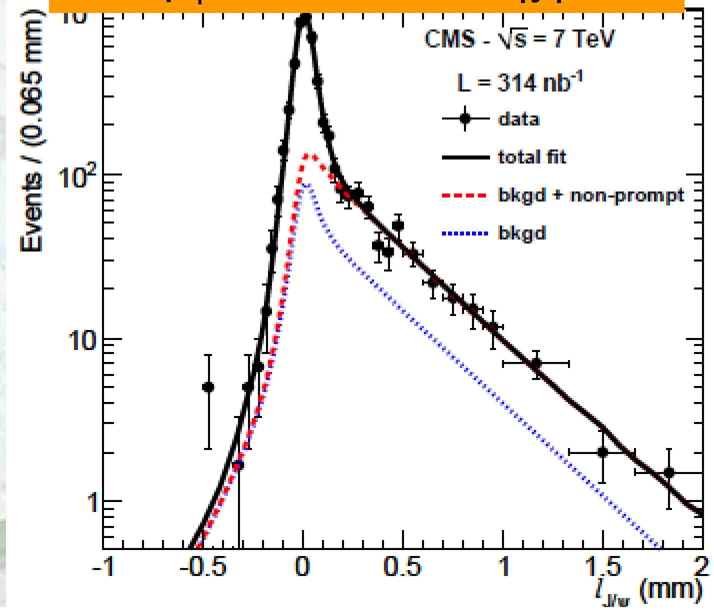
- The signal of J/ψ from displaced muon pairs can be turned into a measurement of b-production cross sections
- The fraction of B-produced J/ψ mesons is determined by a combined likelihood fit the transverse decay length $\ell_{xy}=L_{xy} m_{J/\psi}/p_T$ of dimuons together with the dimuon mass, in each p_T and y bin
- The non-prompt fraction rises with p_T much like observed at the Tevatron; almost no rapidity dependence of the fraction is observed

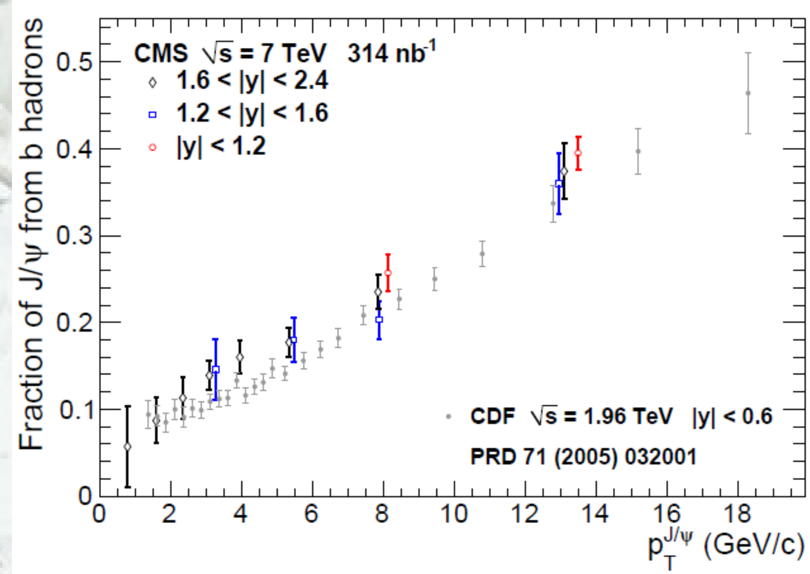
Non-prompt cross section:

$\sigma(pp \rightarrow bX \rightarrow J/\psi X')B(J/\psi \rightarrow \mu\mu) =$

$26.0 \pm 1.4 \pm 1.6 \pm 2.9$ nb

$6.5<p_T<10$ GeV, $1.6<|y|<2.4$





Comparisons with Models

- The cross section of the prompt component can be compared with models which include the feed-down from heavier charmonium states (as high as 30%): Pythia, Cascade, CEM
  - Predictions undershoot the data at low p_T in the high-y region; better agreement elsewhere

- The non-prompt cross section is compared also to FONLL calculations. B polarizations as measured by BaBar are assumed in the calculation
  - good agreement with predictions is observed

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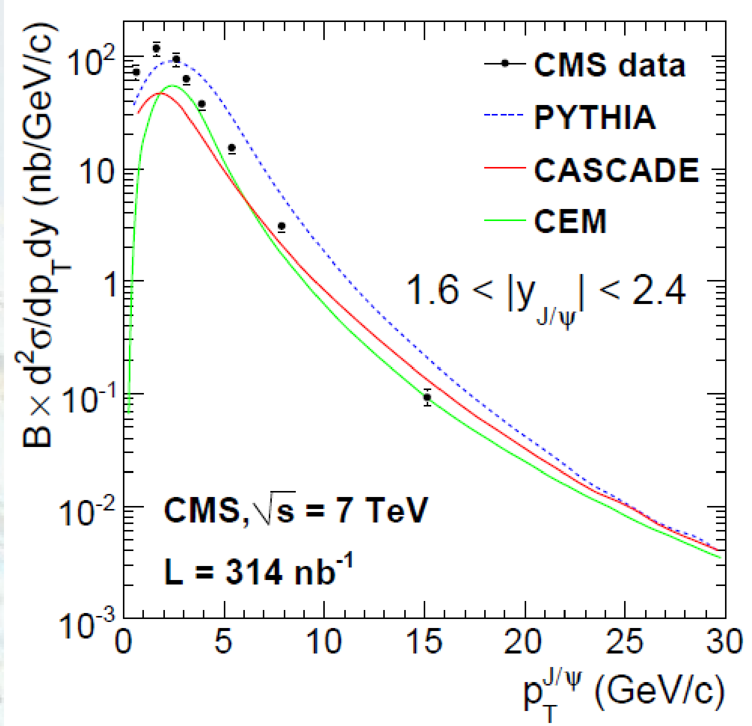
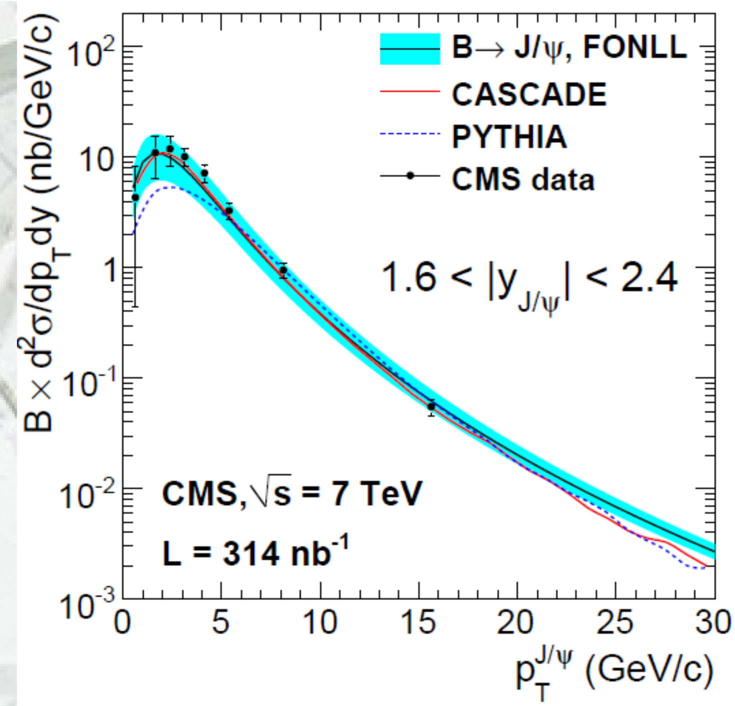


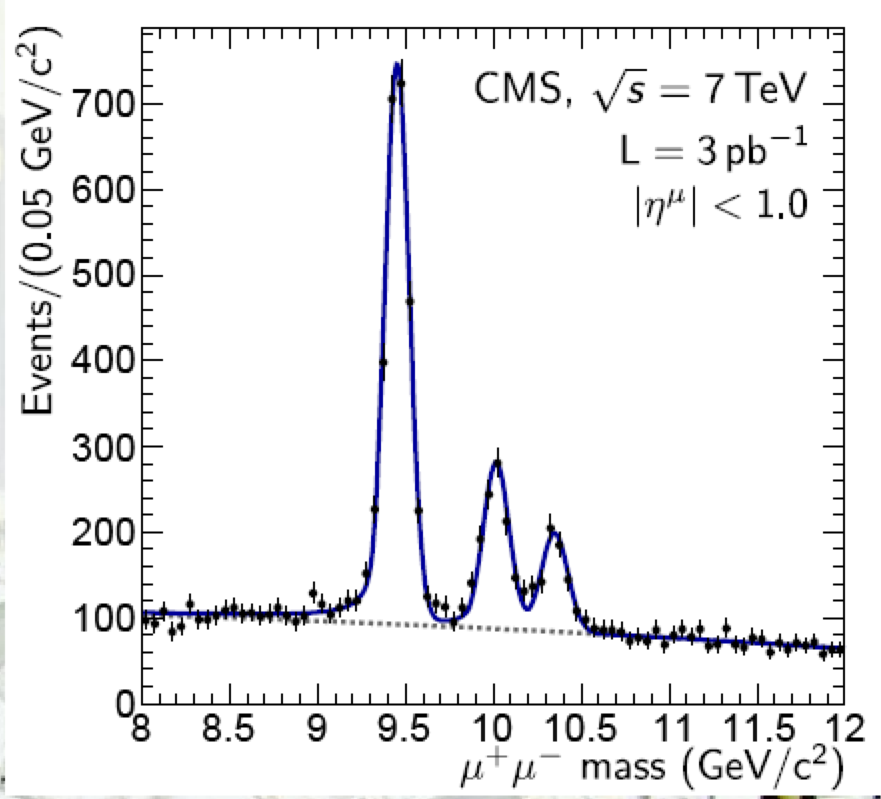


Upsilon Production at CMS

- No feed-down → Υ production an even better probe of quarkonium production mechanisms than that of charmonia. Furthermore, the higher b-quark mass makes calculations more reliable.
- Theoretical models that can be tested are the NRQCD approach and the CSM with NLO corrections, which yields good agreement with Tevatron data despite the absence of colour-octet contributions

- Upsilon production is measured by CMS with 3.1/pb of 7 TeV collision data in the range |y|<2.0 by studying the dimuon final state
- Data is collected by the same dimuon trigger discussed for J/y candidates; MC also similar (Pythia 6.412 using LO NRQCD matrix elemens, PHOTOS for FSR, GEANT4 for detector simulation)

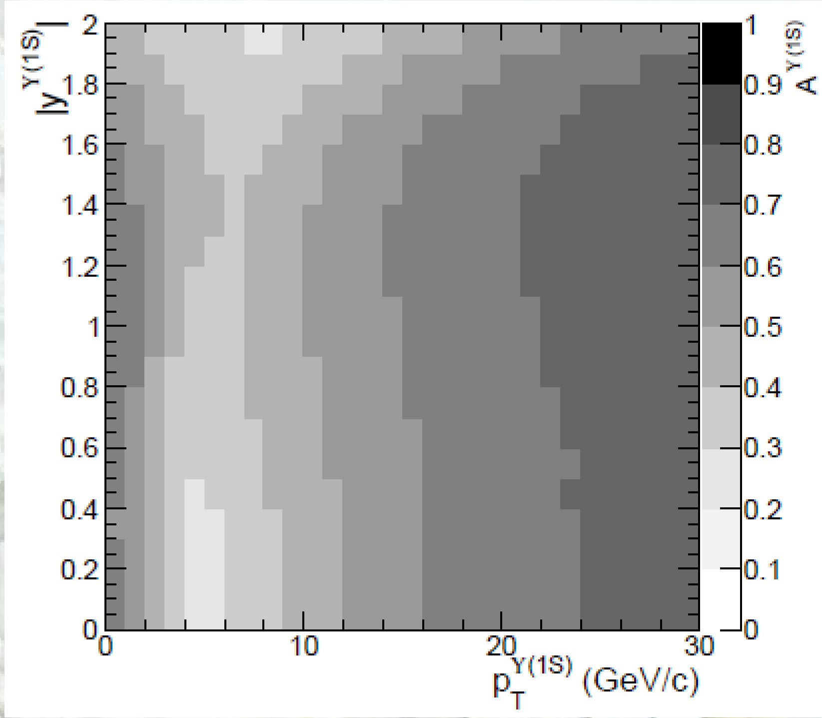
- Muon candidates must have >11 silicon hits, χ^2<5, p_T>3.5 GeV (|η|<1.6) or p_T>2.5 (1.6<|η|<2.4), Υ candidates are formed from opposite charge pairs with a common vertex fit of p>0.1%



The resolution of Υ candidates with muons with p_T<30 GeV and within |η|<1.0 is σ_m=69± MeV (96±2 MeV in the full rapidity range |η|<2.4)

Analysis Details

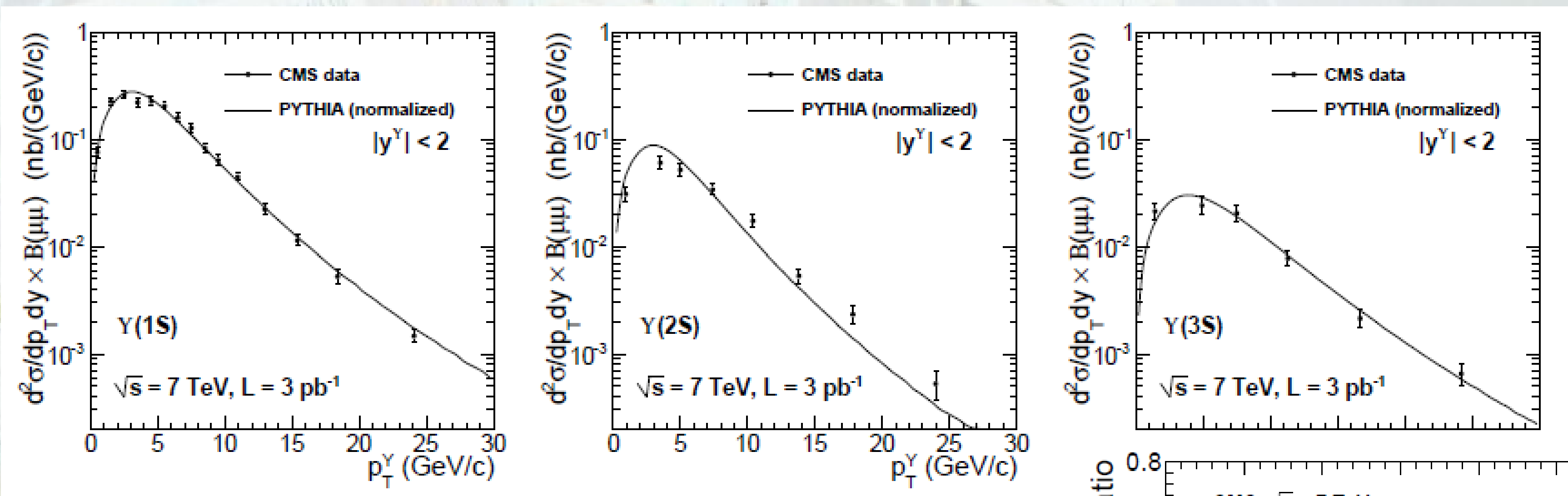
- Acceptance varies with Υ momentum and depends strongly on the assumed polarization
- Efficiency is determined with the tag and probe method using the J/ψ signal
- Yields are extracted from a fit to a Crystal-Ball function of the dimuon mass distribution in each p_T and y bin
- Cross sections are derived for five different polarization scenarios
- Integrated results (|y|<2.0):



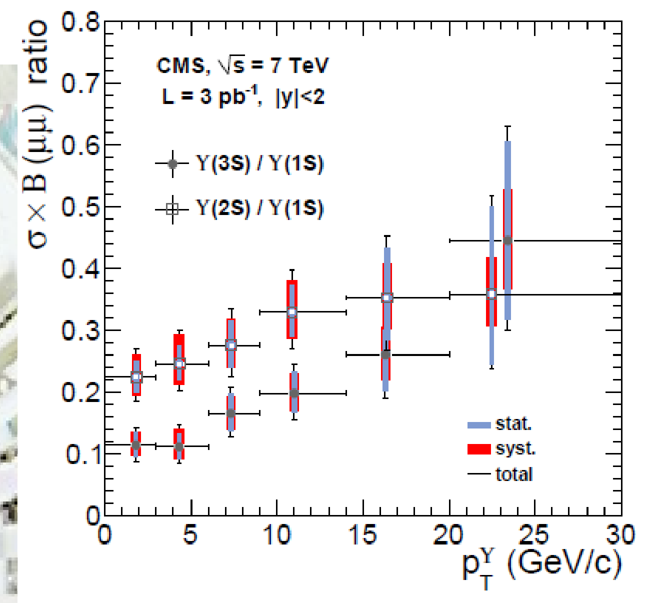
$$\sigma(pp \to \Upsilon(1S)X) \cdot \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = 7.37 \pm 0.13(\text{stat.})^{+0.61}_{-0.42}(\text{syst.}) \pm 0.81(\text{lumi.})\ \text{nb},$$
$$\sigma(pp \to \Upsilon(2S)X) \cdot \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = 1.90 \pm 0.09(\text{stat.})^{+0.20}_{-0.14}(\text{syst.}) \pm 0.24(\text{lumi.})\ \text{nb},$$
$$\sigma(pp \to \Upsilon(3S)X) \cdot \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = 1.02 \pm 0.07(\text{stat.})^{+0.11}_{-0.08}(\text{syst.}) \pm 0.11(\text{lumi.})\ \text{nb}.$$

Differential Cross Sections

- The p_T-differential cross section compares well in shape to Pythia predictions (normalized!) for the three Υ states in the range $0<p_T<30$ GeV



- The production ratio Υ(2,3S)/Υ(1S) is observed to grow with p_T as expected



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Conclusions

- CMS used the 2010 pp collision data to investigate heavy flavour production at 7 TeV in a number of ways

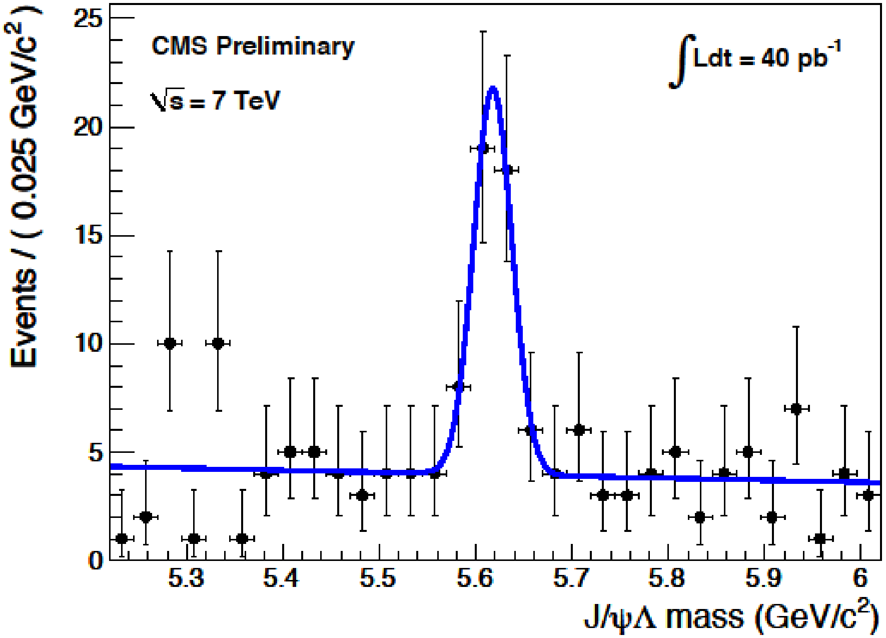
- Results for B production show that the data overshoots NLO predictions
- Differential shapes are generally in good agreement for b production at low and intermediate p_T
- The performances of secondary vertex b-tagging in CMS are excellent and very well understood already with modest amounts of experimental data

- The relative rate of b-jet production evidences interesting deviations from NLO QCD for high values of transverse momentum
- Angular distributions of bb pairs show large enhancements at low ΔR, above NLO predictions

- Prompt charmonium production shows excesses with respect to theoretical models at low p_T and high rapidity; bottomonium agrees well with calculations and has similar trends to Tevatron data

The presented results are based on integrated luminosities ranging from a few /nb to a few /pb of 7-TeV data
→ already 10x-500x datasets being studied; expect important increases in the precision in the near future

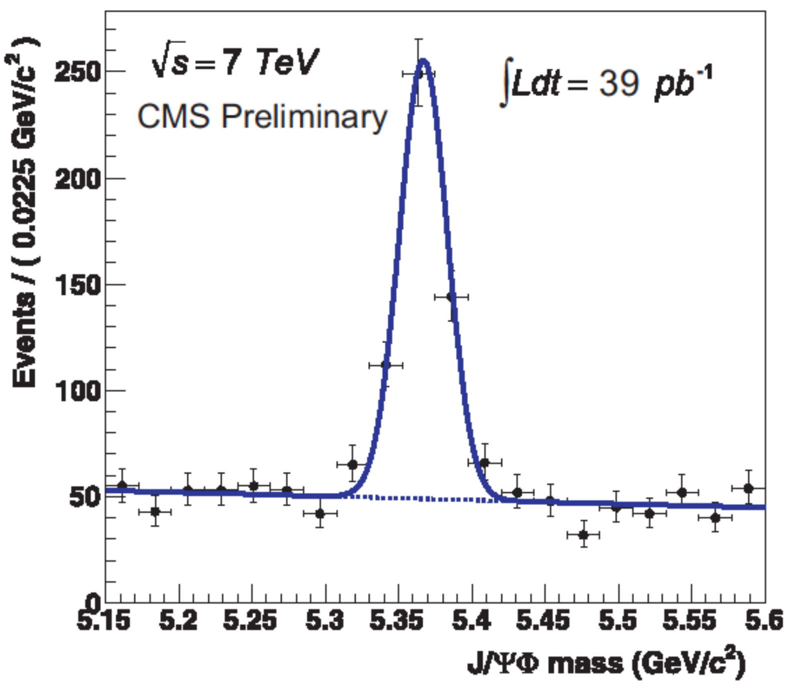
Bonus Track: Recent Signals



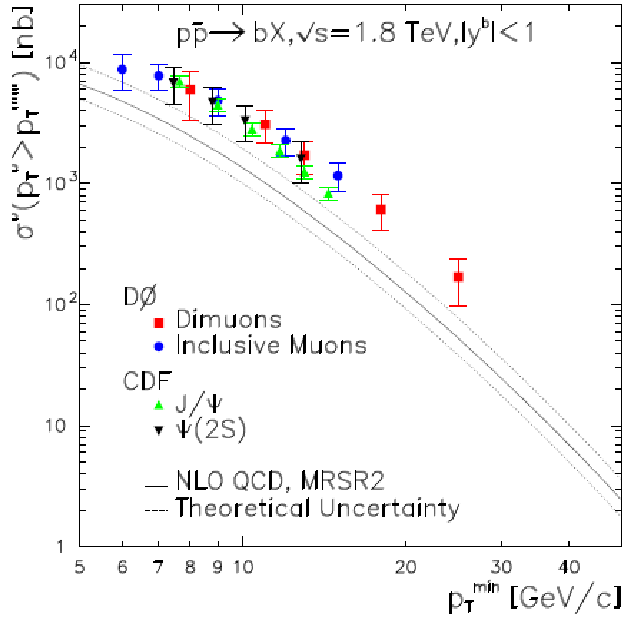
A couple of fully-reconstructed resonances extracted in the full 2010 data sample:

$\Lambda_b \rightarrow J/\psi\ \Lambda$ decays (top),

$B_s \rightarrow J/\psi\ \phi$ decays (bottom)



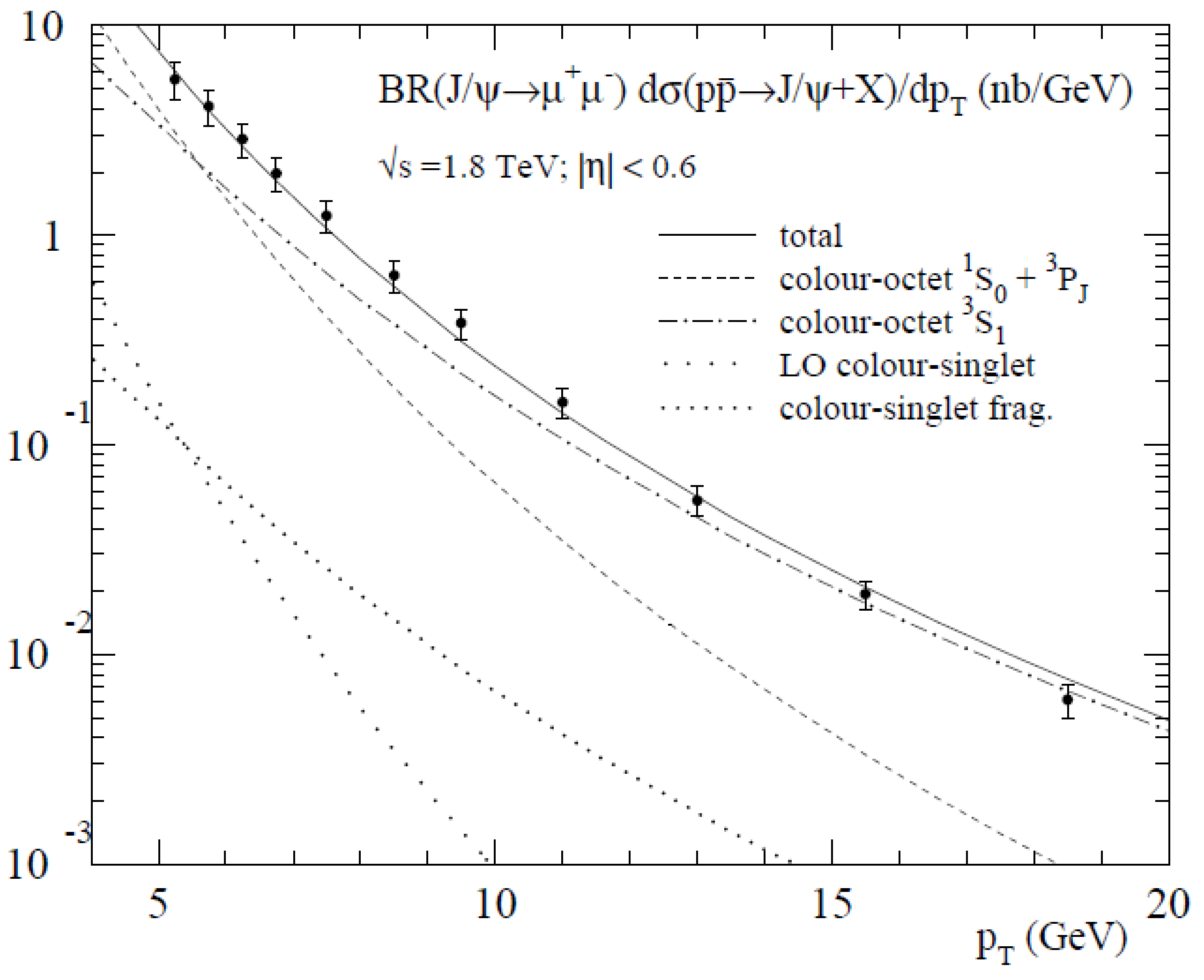
Notes on FONLL for HF production



- NLO QCD calculations are possible for heavy-quark production, where h.q. mass M acts as a infrared cutoff for collinear singularities
  - scale fixed to M for power expansions in α_s
- This works only when M is the only relevant parameter → problems arise at high p_T (M not the right scale)
  - large logarithms of p_T/M arise when μ_F, μ_R fixed to either, spoiling convergence
  - attempts to fix scale at p_T, perform NLO calculation and assign errors by size of $\alpha_s^3 \log(p_T/M)^2$ corrections work only in limited p_T range
  - also attempted to compute logs in "fragmentation function" formalism –essentially a m→0 limit for the resummed logs
- FONLL combine the two by adding to exact NLO all the NLL resummed logarithms
  - Showed to work well and fits well the data in wide p_T range

Quarkonium Production Details

- The comparison of predicted differential cross section makes evident the importance of colour-octet production mechanisms and the different behaviour on the transverse momentum of the produced bound state
- LO colour singlet scales with p_T^{-8}
- CS fragmentation has softer p_T^{-4} scaling and takes over at high p_T
- CO fragmentation depends on the velocity of the system, v^4
- CO t-channel gluon exchange important at low p_T (p_T^6 v^4 behaviour)



Systematics on J/ψ yields

Table 2: Relative systematic uncertainties on the corrected yield for different J/ψ rapidity bins. The variation range over the different p_T bins is given. In general, uncertainties depend only weakly on the p_T values, except for the fit function systematic uncertainty, which decreases with increasing p_T due to the better purity of the signal. The large excursion of the muon efficiency systematic uncertainty reflects changes in the event yield and in the signal purity among the p_T bins.

Affected quantity	Source	Relative error (%)		
		$\|y\| < 1.2$	$1.2 < \|y\| < 1.6$	$1.6 < \|y\| < 2.4$
Acceptance	FSR	0.8 – 2.5	0.3 – 1.6	0.0 – 0.9
	p_T calibration and resolution	1.0 – 2.5	0.8 – 1.2	0.1 – 1.0
	Kinematical distributions	0.3 – 0.8	0.6 – 2.6	0.9 – 3.1
	b-hadron fraction and polarization	1.9 – 3.1	0.5 – 1.2	0.2 – 3.0
Efficiency	Muon efficiency	1.9 – 5.1	2.3 – 12.2	2.7 – 9.2
	ρ factor	0.5 – 0.9	0.6 – 8.1	0.2 – 7.1
Yields	Fit function	0.6 – 1.1	0.4 – 5.3	0.3 – 8.8

Systematics on B fraction in J/ψ fits

Table 5: Summary of relative systematic uncertainties in the b-fraction yield (in %). The variation range over the different p_T bins is given in the three rapidity regions. In general, uncertainties are p_T-dependent and decrease with increasing p_T.

	$\|y\| < 1.2$	$1.2 < \|y\| < 1.6$	$1.6 < \|y\| < 2.4$
Tracker misalignment	0.5 – 0.7	0.9 – 4.6	0.7 – 9.1
b-lifetime model	0.0 – 0.1	0.5 – 4.8	0.5 – 11.2
Vertex estimation	0.3	1.0 – 12.3	0.9 – 65.8
Background fit	0.1 – 4.7	0.5 – 9.5	0.2 – 14.8
Resolution model	0.8 – 2.8	1.3 – 13.0	0.4 – 30.2
Efficiency	0.1 – 1.1	0.3 – 1.3	0.2 – 2.4

More on bb Angular Correlations

- Events are collected from single-jet triggers (thresholds at 15, 30, 50 GeV)
- Secondary vertices are found by algorithm decoupled from jet finding →sensitive to vertex pairs close in angle
  - B→D sequentials are merged using track mass and angle requirements