Measurements of beauty quark production at CMS

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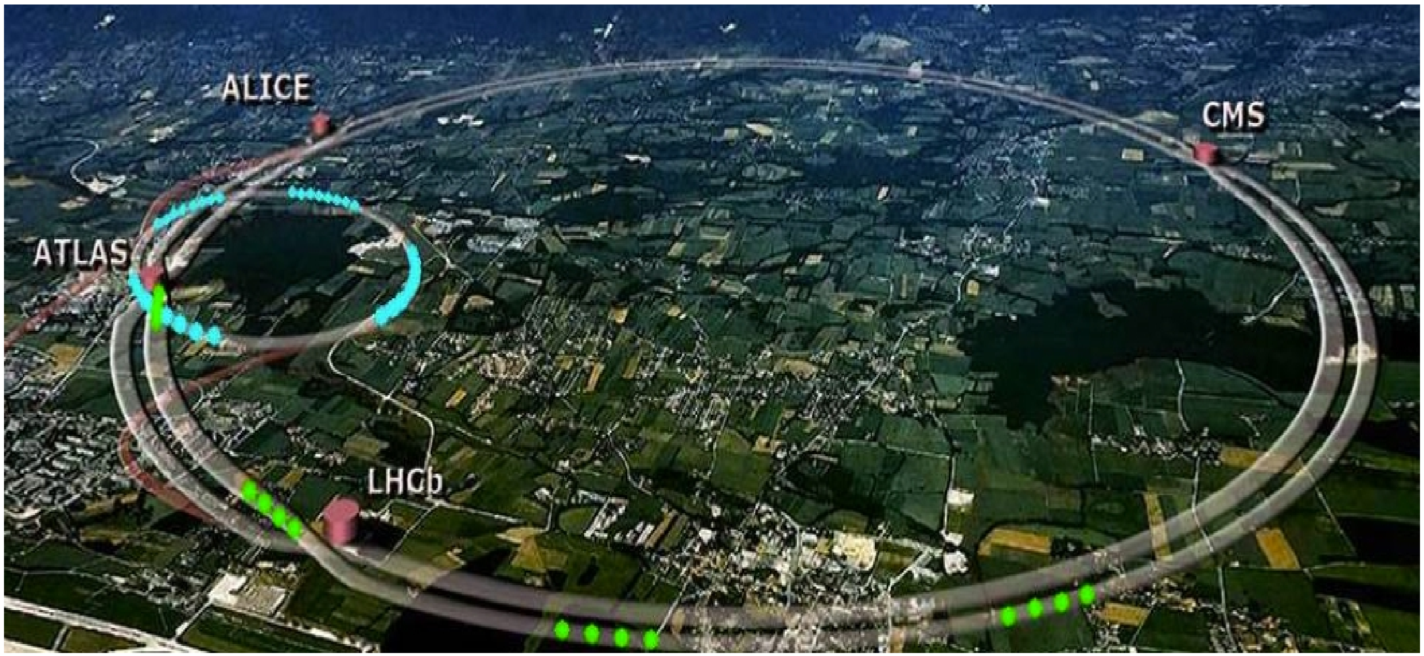
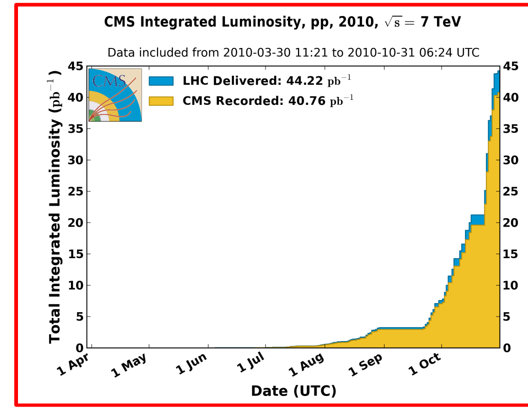
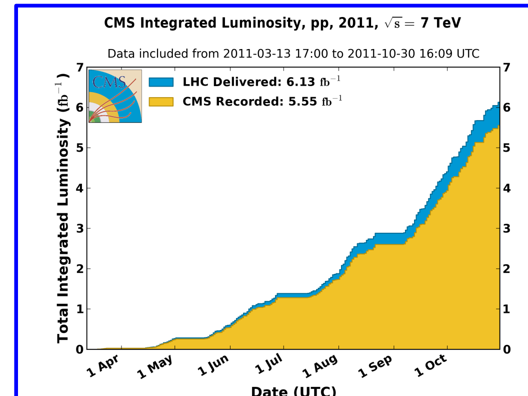
Summary

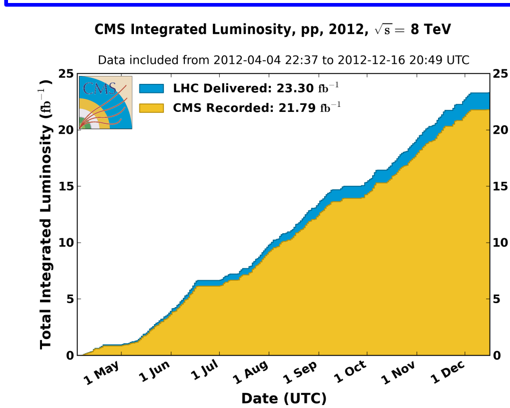
- Introduction: LHC run and CMS performance
- Measurement of $b\bar{b}$ angular correlations
- Λ_b^0 cross section and lifetime
- B_s^0 lifetime difference $\Delta\Gamma_s$
- Observation of B_c meson decays

LHC proton-proton runs





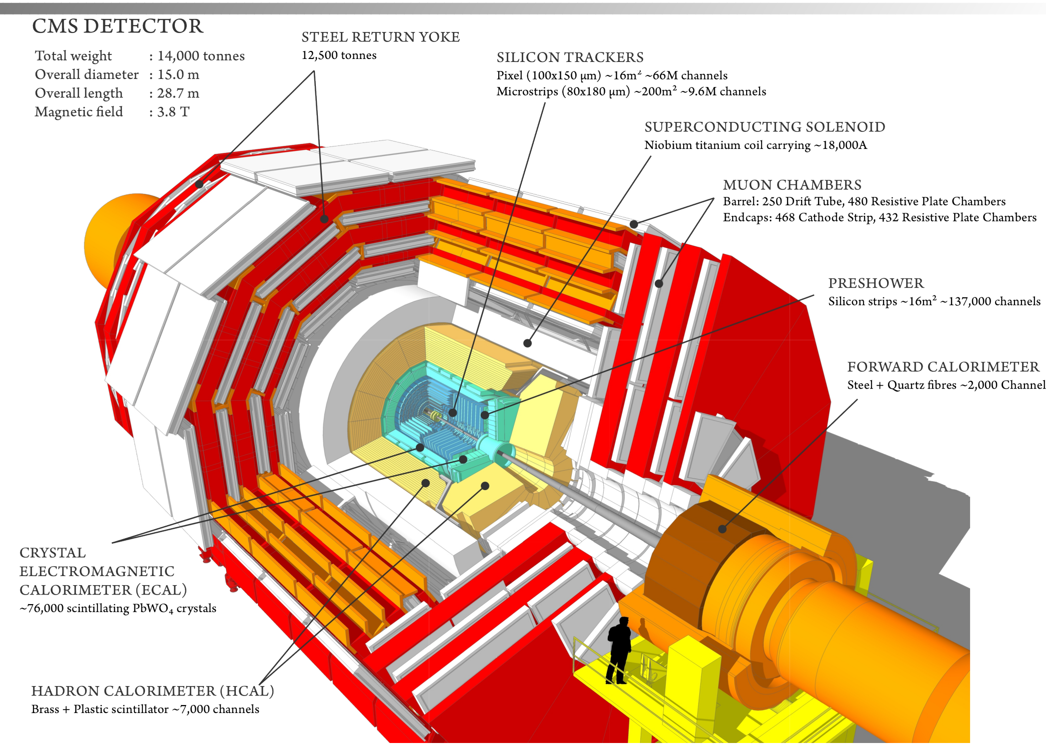


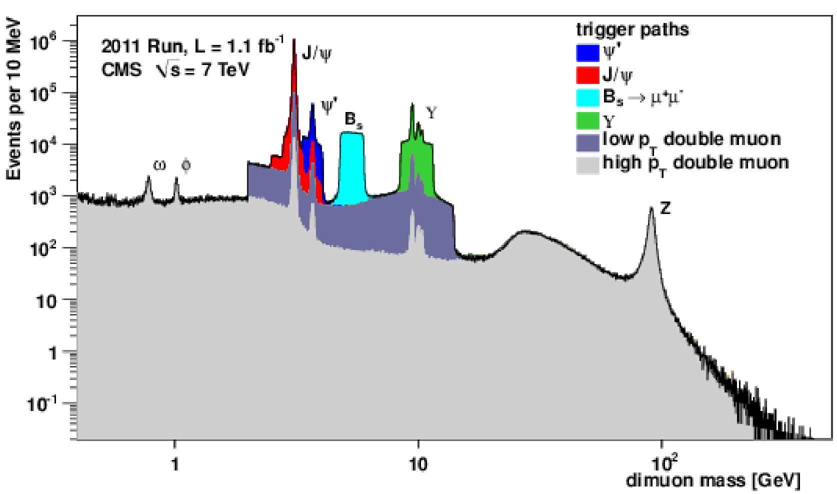


- In the past 3 years LHC has collided two proton beams at c.m. energies up to 7 TeV (2010-2011) and 8 TeV (2012)
- Total luminosity delivered to CMS raised from ~40 pb^{-1} in 2010 to ~5 fb^{-1} in 2011 and ~20 fb^{-1} in 2012
  - **For this talk, I will concentrate on 2010 and 2011 data, as most 2012 b-physics analyses are still being finalized**

Heavy-Flavor physics in CMS

- CMS Heavy-Flavor program taking great advantage from the excellent performance of the CMS detector
  - >93% data taking efficiency
  - Excellent vertex and p_t resolution (~15μm and ~1% for high-p_t central tracks)
- "Tight" muon selection possible with high efficiency for real μ and very low hadron⟶μ misidentification rate (~0.1% for π, K, and p)





- Flexible High Level Trigger which allows to have many specialized di-μ triggers with high efficiency and high purity
  - Dedicated triggers centered on the J/ψ, ψ(2S), B^0, Υ(nS) mass peaks
  - Generic low-p_t and high-p_t di-μ

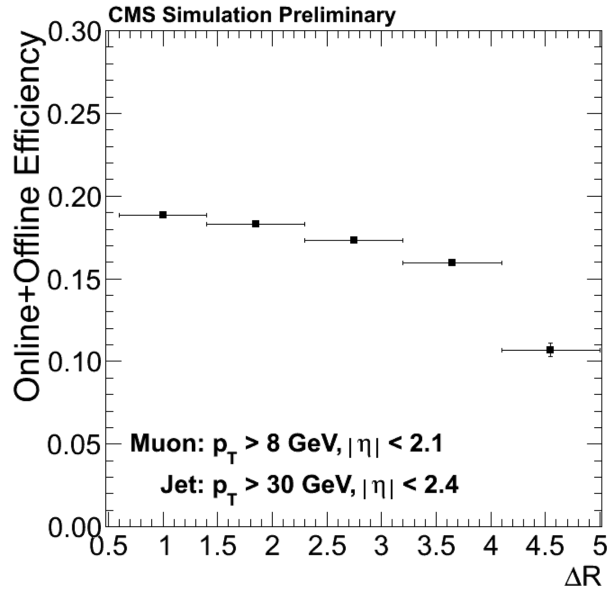
Measurement of $b\bar{b}$ angular correlations

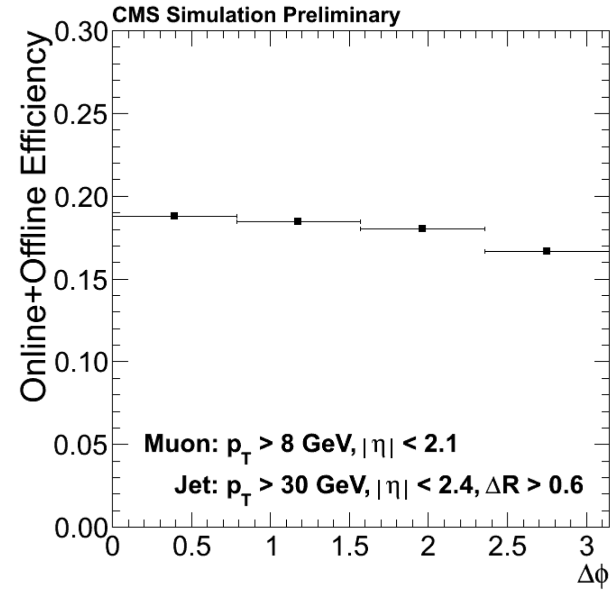
CMS-PAS-BPH-10-019

- Angular correlations of pairs of b quarks allow to test pQCD
  - At LO, only back-to-back processes are possible
  - At higher orders, additional particles in the final state allow for different topologies
- A new measurement complements a published CMS study JHEP03 136 (2011)
  - Different experimental technique: select events with **pairs of jets tagged as b** → previous analysis used secondary vertices
  - Improved results: measure **absolute cross section as a function of ΔA (i.e. Δϕ and ΔR)** → previous analysis did it with a quite large experimental uncertainty (~47%)
- Using 3 pb^{-1} of 7 TeV pp data collected in 2010 by a **low-p_t single-μ trigger**
- Selected events with at least **2 jets** with **p_t(jet) > 30 GeV and |η(jet)|<2.4**
  - ≥1 containing a **"tight" μ**, with **p_t(μ) > 8 GeV, |η(μ)|<2.1** and ≥1 **not** containing a muon
  - Jets **b-tagged** with the Track Counting algorithm, using a medium (tight) working point for the μ (non-μ) jet
  - **ΔR(jet-jet)>0.6** to avoid overlap

Measurement of $b\bar{b}$ angular correlations

- **Total selection efficiency** ε_{bb}^{total} found from MC corrected with scale factors derived from data
- **Purity** P_{bb} **of signal sample** in data found by applying the selection in 4 separate steps and solving the resulting system of 4 equations in 4 unknowns
  - $P_{bb} = 0.933 \pm 0.017(stat)$
  - Bin-by-bin purity corrections applied to data





- **Overall precision** dominated by systematic uncertainties
  - Mainly given by data/MC scale factors, jet energy scale, selection purity, trigger efficiency
  - Total uncertainty depending on the bin, **typically ~10-20%**

Measurement of $b\bar{b}$ angular correlations

- Cross section as a function of ΔA (ΔA=Δϕ, ΔR) found with: and compared with theoretical predictions

$$\left(\frac{d\sigma}{d\Delta A}\right)_i = \frac{N^{Data}\, P_{bb}}{\mathcal{L}\, \Delta A_{bin}\, \epsilon^{Total}_{b\bar{b}}}$$

- **Pythia** describes best the absolute normalization, disagrees at low Δϕ
- **Cascade** disagrees in both Δϕ and ΔR, underestimates σ
- **MadGraph** has best description of shape, overestimates σ

Total cross sections:

Data:

$\sigma = 12.2 \pm 0.2(\text{stat.})^{+1.6}_{-1.2}\ (\text{syst.})$ nb

Cascade:

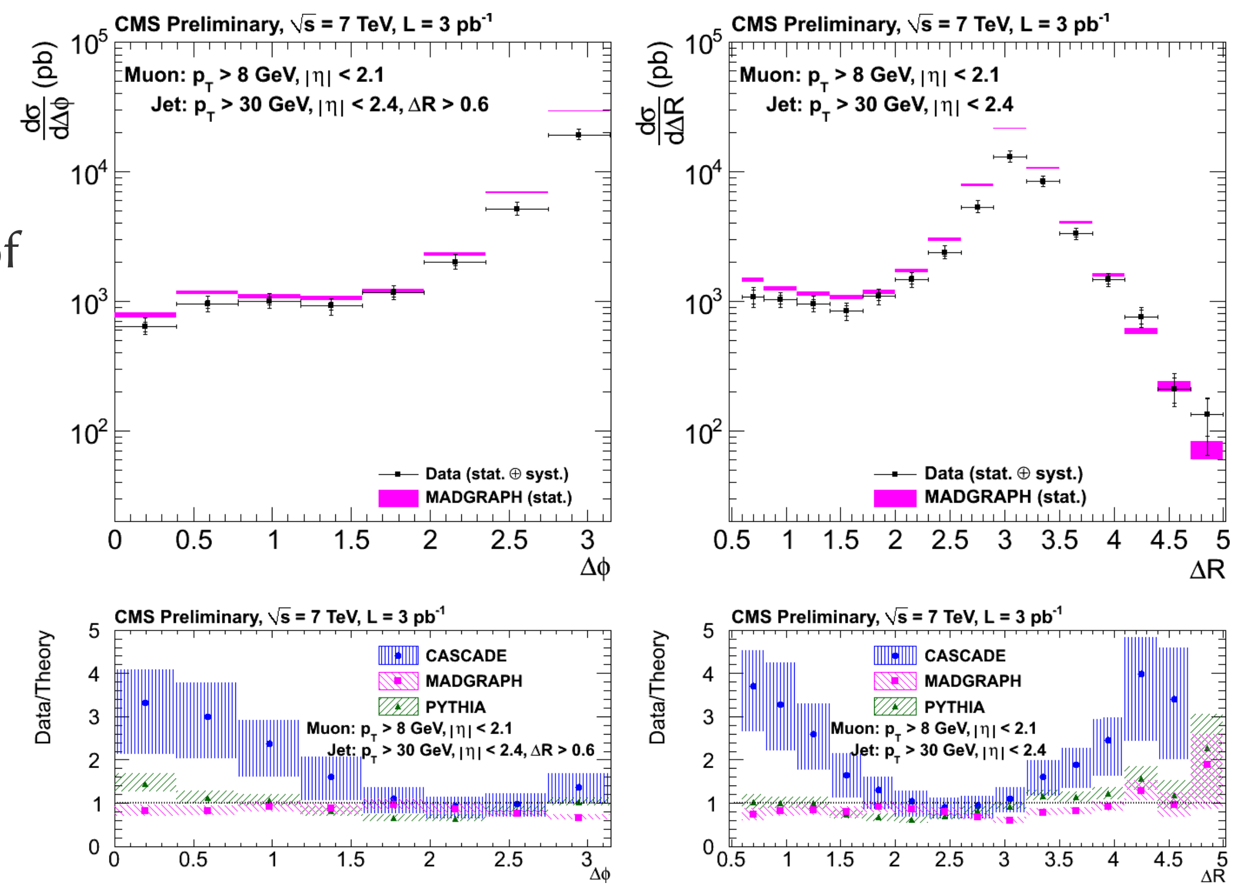
$\sigma = 9.48 \pm 0.04(\text{stat.})^{+1.93}_{-2.65}\ (\text{syst.})$ nb

MadGraph:

$\sigma = 17.1 \pm 0.1(\text{stat.})$ nb

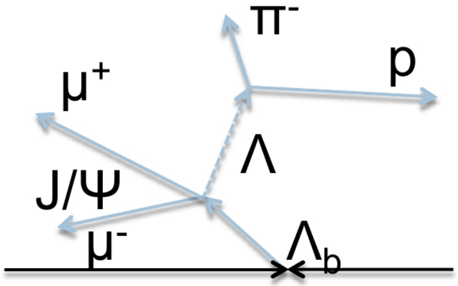
Pythia:

$\sigma = 13.18 \pm 0.02(\text{stat.})$ nb

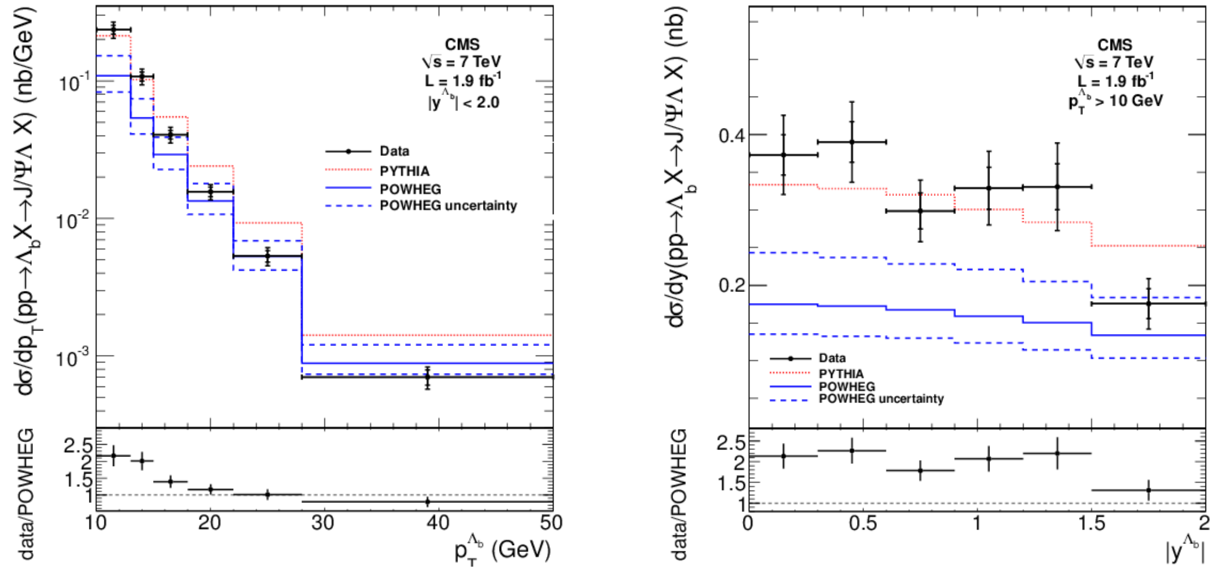


$\Lambda_b^0 \to J/\psi\Lambda$ cross section

PLB 714 (2012) 136-157



- Measurement done on $1.9\ \mathrm{fb}^{-1}$ of pp collisions at 7 TeV collected in 2011
- The decay $\Lambda_b^0 \to J/\psi\Lambda$ is reconstructed in the channels $J/\psi \to \mu^+\mu^-$, $\Lambda \to \pi^- p$
- Events triggered by μ pairs compatible with displaced $J/\psi \to \mu^+\mu^-$ decays
- $\Lambda \to \pi^- p$ reconstructed from displaced 2-track vertices



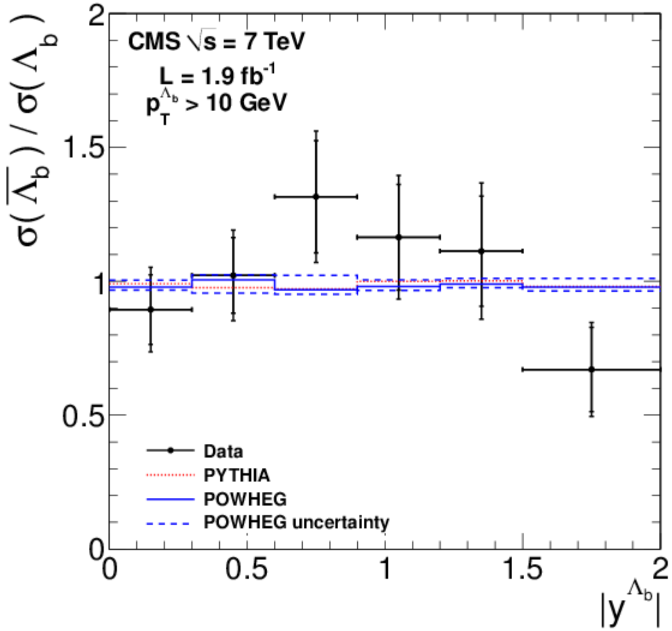
- $\sigma \times BF$ binned as a function of p_t and $|y|$ of the Λ_b^0
  - $BF(\Lambda_b^0 \to J/\psi\Lambda) = 5.7 \pm 3.1 \times 10^{-4} \to$ 54% theory uncertainty
  - **$d\sigma/dp_t$** falls faster in data than theory, **$d\sigma/dy$** shows no significant deviations in the shape
- **Total cross section** ($p_t(\Lambda_b^0) > 10\mathrm{GeV}$, $|y(\Lambda_b^0)| < 2.0$):

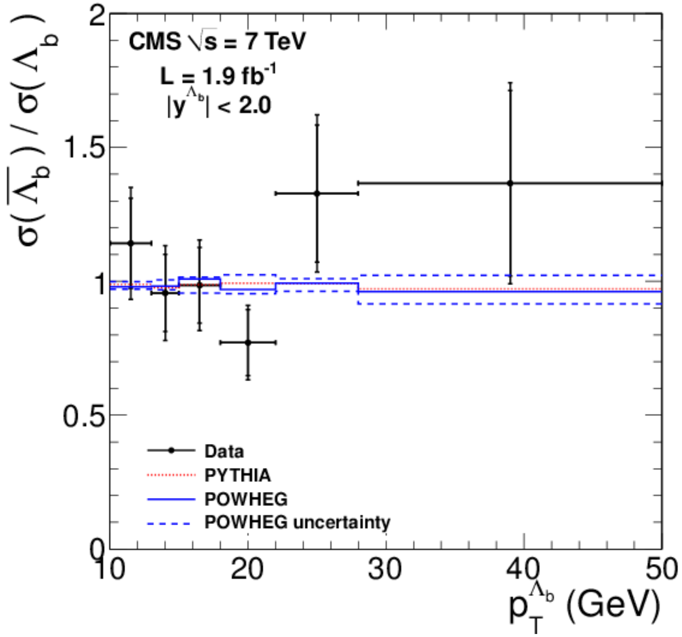
$\sigma(\Lambda_b^0) \times BF(\Lambda_b^0 \to J/\psi\Lambda) = 1.16 \pm 0.06(\mathrm{stat}) \pm 0.12(\mathrm{syst})$ nb

POWHEG: $\sigma \times BF = 0.63\ {-0.37}\ {+0.41}$ nb

PYTHIA: $\sigma \times BF = 1.19 \pm 0.64$ nb

$\overline{\Lambda}_b^0$ / Λ_b^0 asymmetry





- Ratio $\boldsymbol{\sigma(\overline{\Lambda}_b^0)/\sigma(\Lambda_b^0)}$ found as a function of p_t and |y| with:

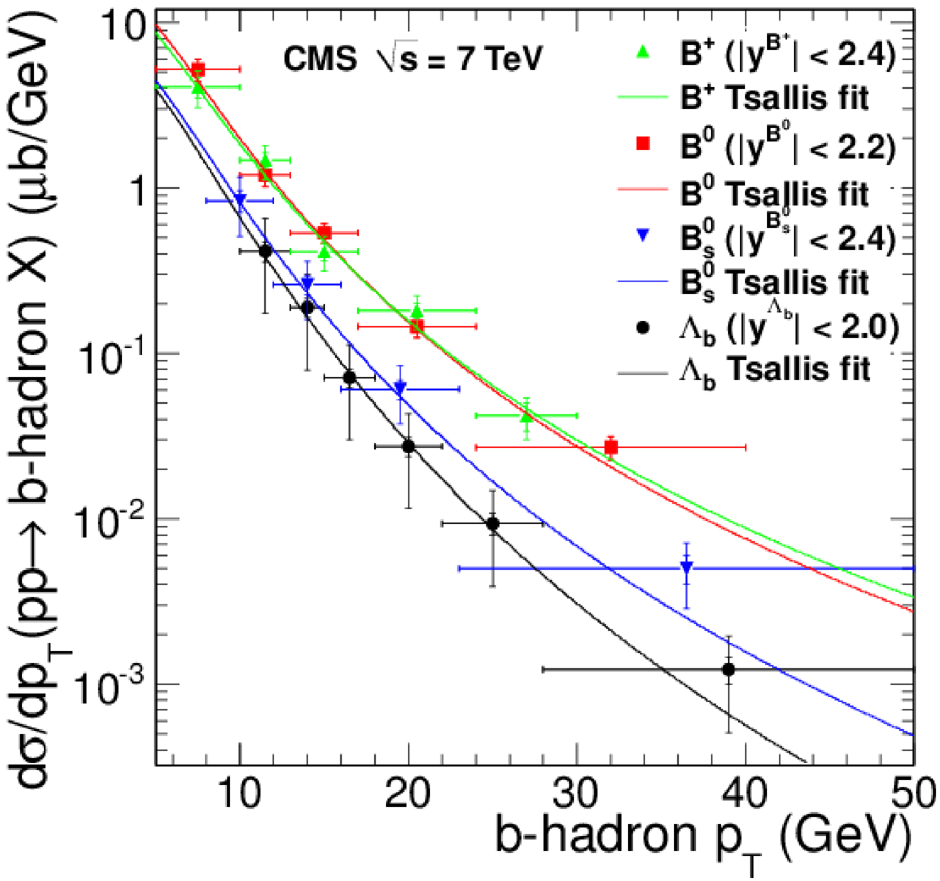
$$\boldsymbol{\sigma(\overline{\Lambda}_b^0) / \sigma(\Lambda_b^0) = [n_{sig}(\overline{\Lambda}_b^0) / n_{sig}(\Lambda_b^0)] \times [\varepsilon(\Lambda_b^0) / \varepsilon(\overline{\Lambda}_b^0)]}$$

- POWHEG and PYTHIA both predict ratio to be flat and ≈1
- Measurement consistent with predictions within experimental uncertainties:

$$\boldsymbol{\sigma(\overline{\Lambda}_b^0) / \sigma(\Lambda_b^0)\ [p_t(\Lambda_b^0)>10\,\mathrm{GeV},\ |y(\Lambda_b^0)|<2.0)] = 1.02\pm0.07(\mathrm{stat})\pm0.09(\mathrm{syst})}$$

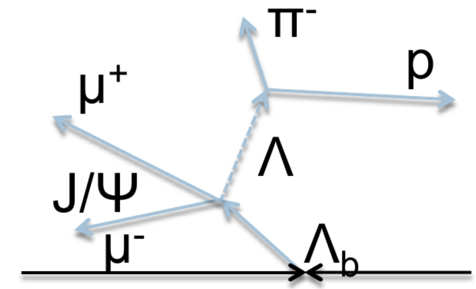
CMS B-hadron cross sections vs. p_t

- Summary of CMS measurements of B-hadron cross sections vs. p_t
  - **$B^+ \to J/\psi K^+$**
    PRL 106, 112001 (2011)
  - **$B^0 \to J/\psi K_s$**
    PRL 106, 252001 (2011)
  - **$B_s \to J/\psi \phi$**
    PRD 84, 052008 (2011)
  - **$\Lambda_b^0 \to J/\psi \Lambda$**
    PLB 714 (2012) 136-157
- Slope of cross section vs. p_t steeper for heavier hadrons (Λ_b and B_s) than for B^0 and B^+
  - Similar effect also observed by LHCb

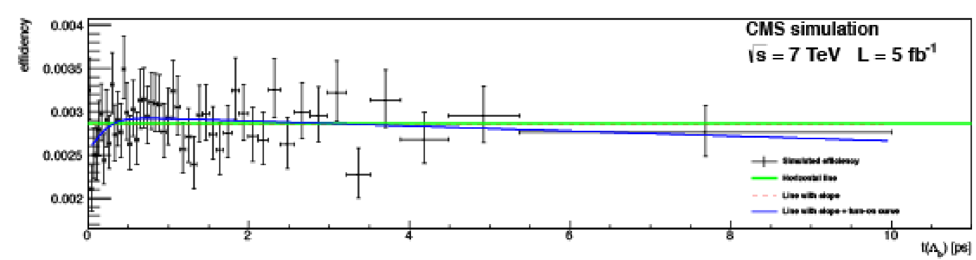


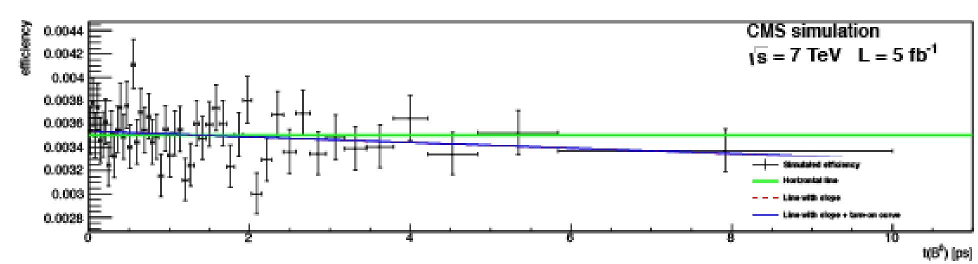
Measurement of Λ_b^0 lifetime

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11013



- Measurement of $\boldsymbol{\tau(\Lambda_b^0)}$ is complementary to cross section measurement, probe of non-perturbative QCD predictions
  - Looked at the same decay, $\Lambda_b^0 \rightarrow J/\psi \Lambda$, with $J/\psi \rightarrow \mu^+\mu^-$ and $\Lambda \rightarrow p\pi$
  - Similar selection criteria
- As cross-check, measured also $\boldsymbol{\tau(B^0)}$ with a procedure similar to the signal:
  - Use decay $B^0 \rightarrow J/\psi K_s^0$, with $J/\psi \rightarrow \mu^+\mu^-$ and $K_s^0 \rightarrow \pi^+\pi^-$
- **Main backgrounds** from prompt and non-prompt J/ψ associated with real or misidentified Λ candidates
- **Efficiency** found from simulation, treated as flat vs. lifetime
- **Main systematic uncertainty** related to efficiency determination. Other systematics from alignment, event selection and fit model





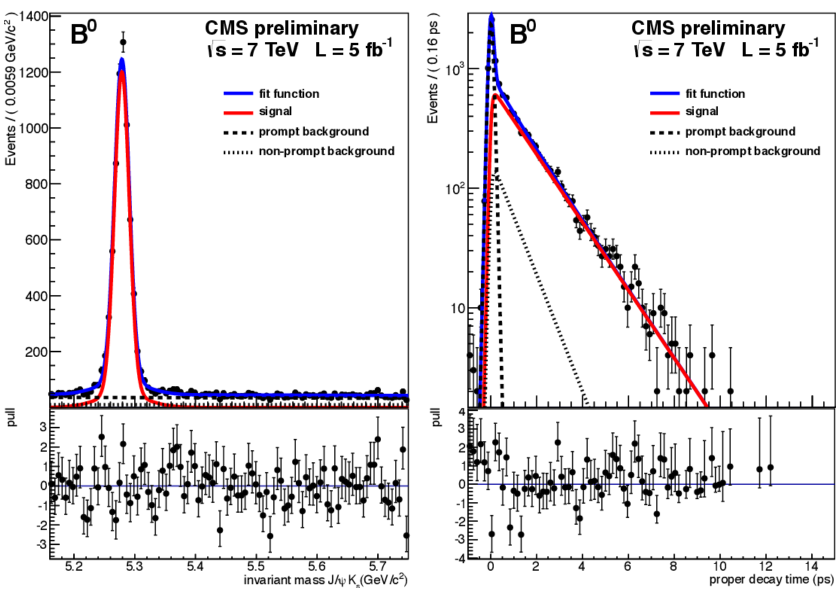
Measurement of Λ_b^0 lifetime

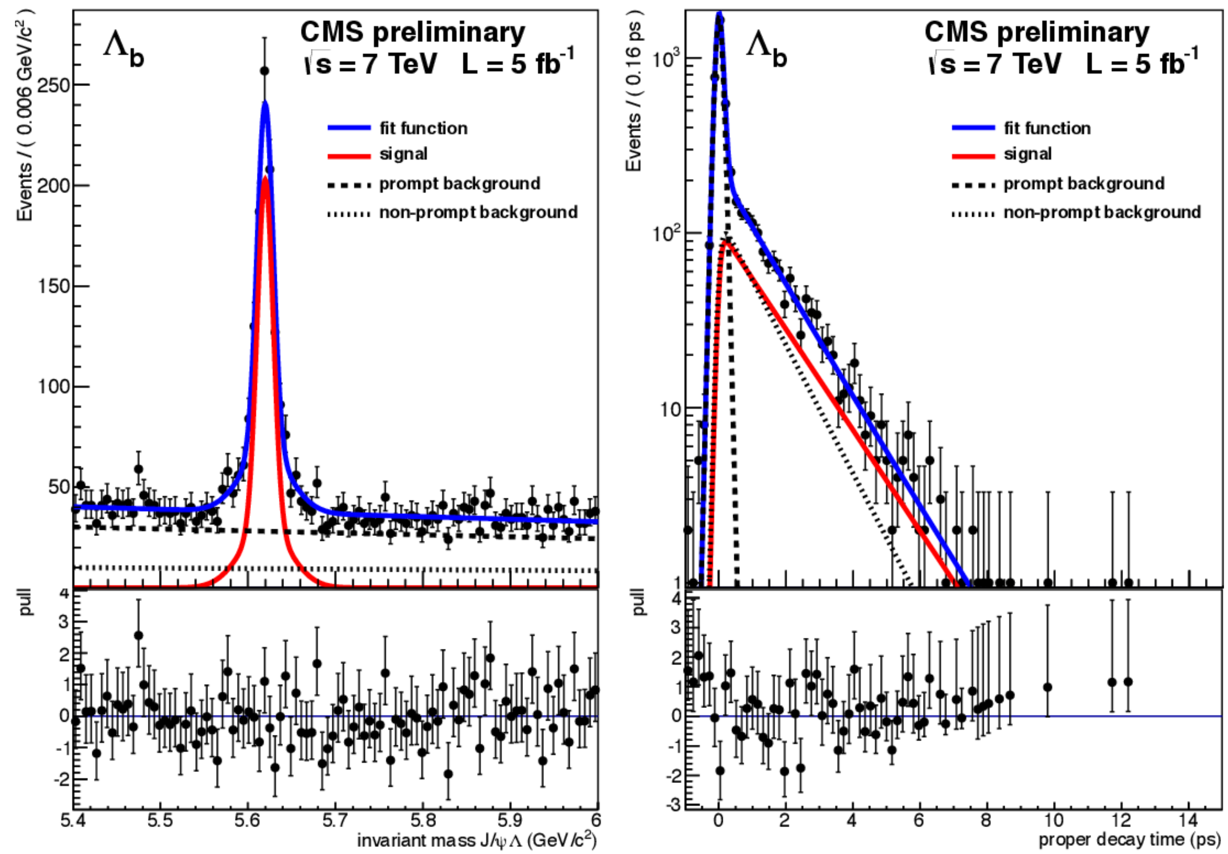
- $\tau(\Lambda_b^0)$ determined from an unbinned maximum-likelihood fit on:
  - **Λ_b^0 invariant mass m**
  - **Λ_b^0 proper decay time and uncertainty t and σ_t**
- **Result: $\tau(\Lambda_b^0)$ = 1.503±0.052(stat)±0.031(syst) ps**

Signal channel ⇒

Control channel

⇓

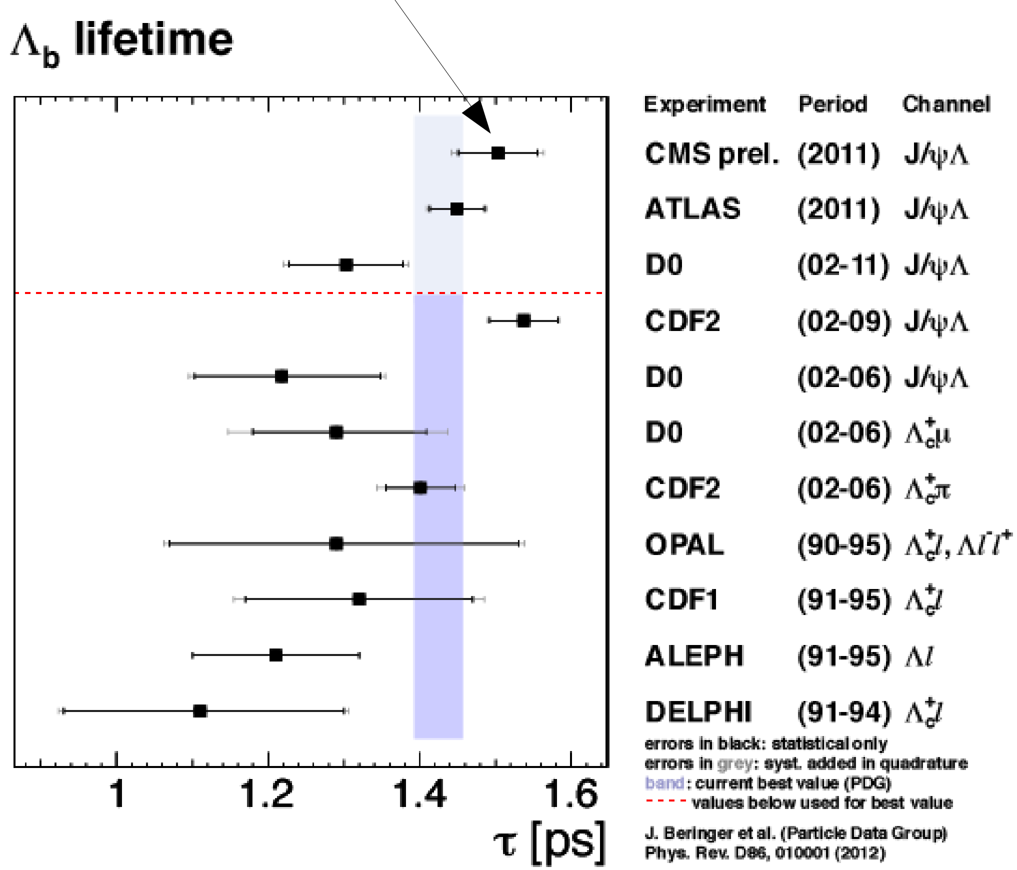




Summary of $\tau(\Lambda_b^0)$ measurements

- CMS preliminary result on Λ_b^0 lifetime is compared with **world average from PDG** (shaded blue band)
- Measurements contributing to PDG average shown below red dashed line
- Also shown **two other recent measurements** from ATLAS arXiv:1207.2284 and D0 arXiv:1204.2340
- **CMS result consistent with PDG average and confirming tendency of more recent measurements towards a larger Λ_b^0 lifetime**

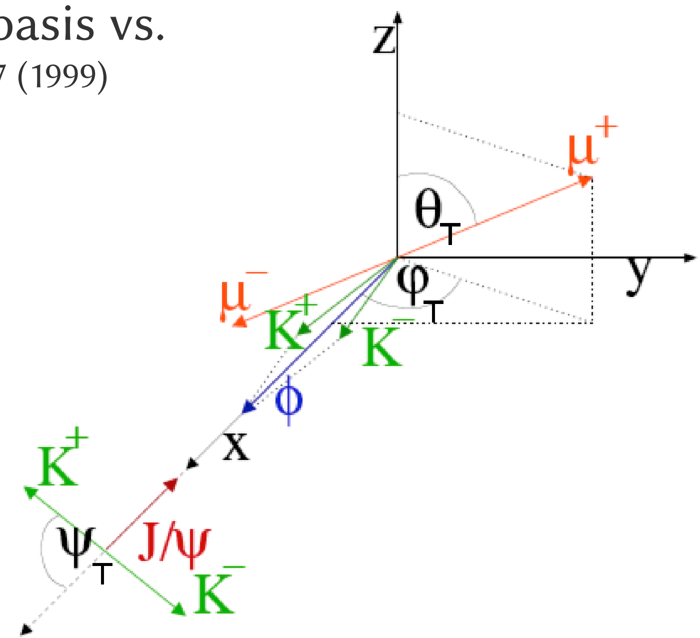
CMS preliminary:
$\tau(\Lambda_b^0)$ = 1.503±0.052(stat)±0.031(syst) ps



Measurement of B_s^0 lifetime difference

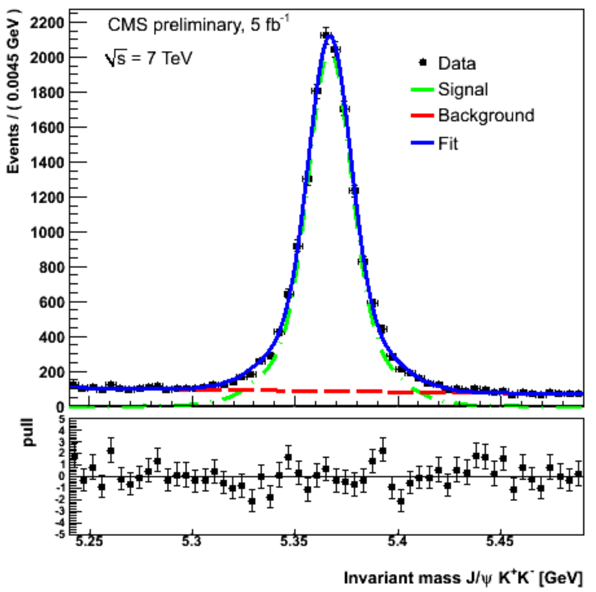
CMS PAS BPH-11-006

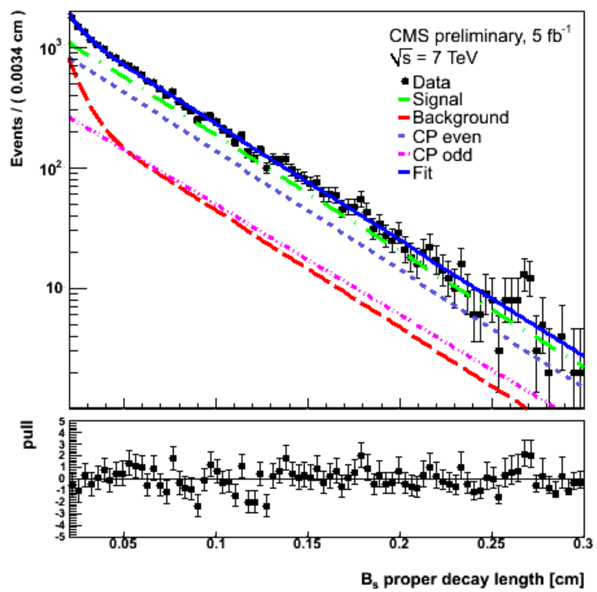
- The lifetime difference of the two B_s^0 mass eigenstates $\Delta\Gamma_s$ is studied using the decay channel $B_s^0 \to J/\psi\phi$, followed by $J/\psi \to \mu\mu$ and $\phi \to KK$
  - Small mixing phase in the SM → **assuming $\phi_s = 0$**
- Analysis done on 5 fb^{-1} of 7 TeV pp data collected in 2011
- Look at the differential decay rate in the transversity basis vs. EUR.PHYS.J. C 6 647 (1999)
  - The **mass M**
  - The **proper decay time t**
  - The **angular distributions $\Theta = \{\theta_T, \psi_T, \varphi_T\}$** of the final decay products (to disentangle the two CP states)
- Use a 5D unbinned maximum likelihood fit to extract:
  - B_s mean lifetime and lifetime difference: **τ, $\Delta\Gamma_s$**
  - Transversity amplitudes: **$|A_\perp|^2$, $|A_0|^2$**
  - Strong phase: **$\delta_\parallel$**



Measurement of B_s^0 lifetime difference

- Events triggered by two μ with $p_t(\mu)>4$ GeV
- **~14.5K B_s** candidates reconstructed from 2 μ + 2 tracks forming non-prompt J/ψ and ϕ candidates
  - **Main backgrounds** from non-prompt J/ψ from the decay of other B hadrons (B^0, B^+, Λ_b)
- Efficiency corrections coming from a simulated $B_s \rightarrow J/\psi\phi$ sample, found independently for each variable (negligible correlations)
- Main systematics from signal and background models, resolution, and efficiency
- **Results:** **$\Delta\Gamma_s$ = 0.048±0.024(stat)±0.003(syst) ps^{-1}**
  τ = 0.04580±0.00059(stat)±0.00022(syst) cm
  $|A0|^2$ = 0.528±0.010(stat)±0.015(syst)
  $|A\perp|^2$ = 0.251±0.013(stat)±0.014(syst)
  δ∥ = 2.79±0.14(stat)±0.19(syst) rad



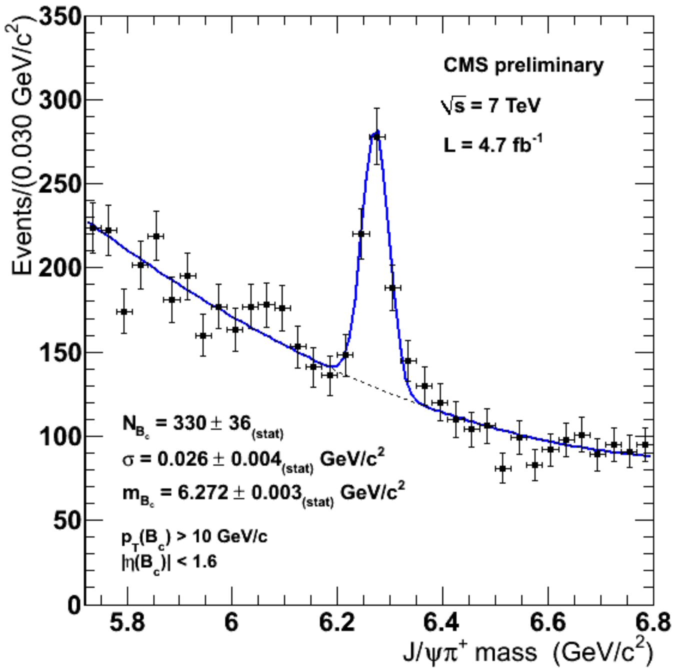


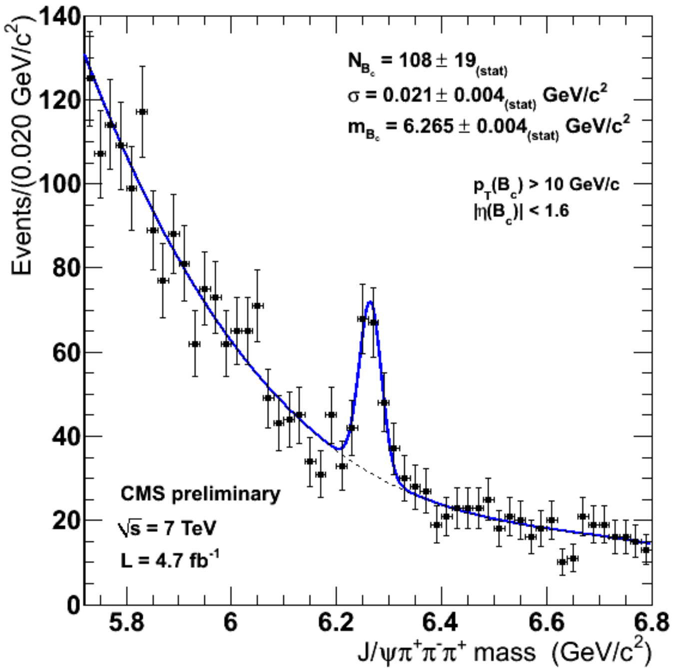
Observation of $B_c \to J/\psi\pi$ and $B_c \to J/\psi\pi\pi\pi$ https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11003

- Since B_c carries two different heavy flavors, it is a unique probe of heavy-quark dynamics
- Very few experimental measurements so far (produced only at hadron colliders)
- Preliminary CMS results based on 4.7 fb^{-1} of pp collisions collected in 2011
- Selection:
  - **Displaced J/ψ di-muon trigger** with $p_t(J/\psi) > 7$ GeV
  - **Kinematic vertex fit** using the di-μ candidate with mass constrained to the J/ψ world average + 1(3) tracks
  - Selected only B_c candidates with **$p_t(B_c) > 10$ GeV and $|\eta(B_c)| < 1.6$**

Observation of $B_c \to J/\psi\pi$ and $B_c \to J/\psi\pi\pi\pi$

- CMS able to cleanly observe B_c in both decay channels
- $\mathbf{B_c \to J/\psi\pi^+}$ (**10.5σ** significance)
- $\mathbf{B_c \to J/\psi\pi^+\pi^-\pi^+}$ (**6.1σ** significance)
    - First seen by LHCb, only experimental confirmation so far
- **Next steps:** measure cross sections, BF ratios, etc.





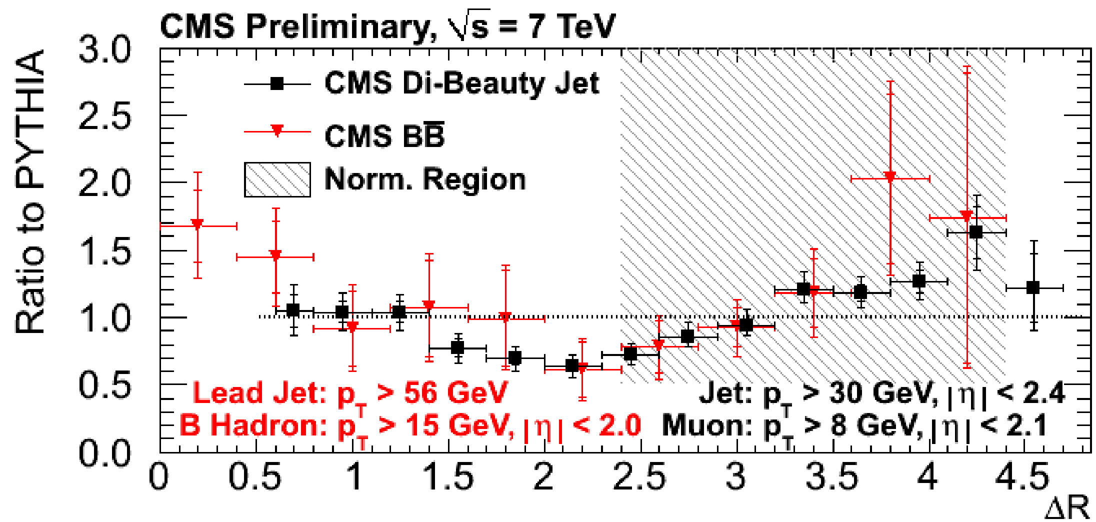
Conclusions

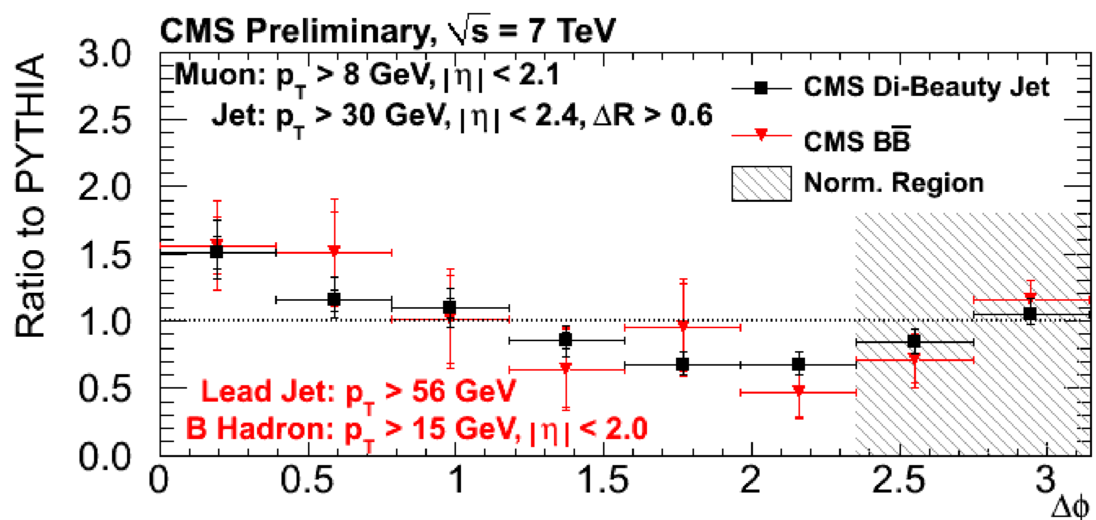
- In the last 3 years CMS has collected very high quality pp data at 7 and 8 TeV
- A rich Heavy-Flavor physics program is being carried on and has already delivered many results
- Among the latest:
  - A new measurement of **$b\bar{b}$ angular correlations** complementing previous CMS results
  - Several results in the **Λ_b^0 sector:**
    - Differential $\Lambda_b^0 \to J/\psi\Lambda$ cross section
    - Particle/antiparticle asymmetry
    - Mean lifetime
  - Measurement of the **B_s lifetime difference $\Delta\Gamma_s$**
  - Observation of **$B_c \to J/\psi\pi$ and $B_c \to J/\psi\pi\pi\pi$ decays**
- **As new data gets analyzed, more results are in the pipeline and will be published in the next months**
- **Last remark: follow also the talks by J. Seixas, E. A. Yetkin, X. Shi (today), and A. York (tomorrow) for a more comprehensive review of the CMS HF physics activities!**

Backup

Comparison between new and old $b\bar{b}$ correlation measurements

- Comparison between the two measurements done by CMS on $b\bar{b}$ angular correlation
- **Caveats:**
  - different phase space
  - different experimental techniques: jets with μ vs. secondary vertices
- Ratio to PYTHIA shown here for both, normalized in the back-to-back region
- Overall good agreement within experimental uncertainties





B_s^0 lifetime – signal model

$$\frac{d^4\Gamma(B_s(t))}{d\Theta\, dt} = f(\Theta, t; \alpha) = \sum_{i=1}^{6} O_i(\alpha, t).g_i(\Theta)$$

Differential decay rate as a function of Θ and t

$$\begin{aligned}
O_1 &= |A_0(t)|^2 = |A_0(0)|^2 e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) - \cos\phi_s \sinh(\Delta\Gamma_s t/2)] \\
O_2 &= |A_{||}(t)|^2 = |A_{||}(0)|^2 e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) - \cos\phi_s \sinh(\Delta\Gamma_s t/2)] \\
O_3 &= |A_\perp(t)|^2 = |A_\perp(0)|^2 e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) + \cos\phi_s \sinh(\Delta\Gamma_s t/2)] \qquad (2) \\
O_4 &= Im(A_{||}^*(t)A_\perp(t)) = |A_{||}(0)||A_\perp(0)|e^{-\Gamma_s t}[-\cos(\delta_\perp - \delta_{||})\sin\phi_s \sinh(\Delta\Gamma_s t/2)] \\
O_5 &= Re(A_0^*(t)A_{||}(t)) = |A_0(0)||A_{||}(0)|\cos\delta_{||} e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) - \cos\phi_s \sinh(\Delta\Gamma_s t/2)] \\
O_6 &= Im(A_0^*(t)A_\perp(t)) = |A_0(0)||A_\perp(0)|e^{-\Gamma_s t}[-\cos\delta_\perp \sin\phi_s \sinh(\Delta\Gamma_s t/2)]\,,
\end{aligned}$$

$\phi_s=0 \Rightarrow$ **$O_4=0$**

$\phi_s=0 \Rightarrow$ **$O_6=0$**

$$\begin{aligned}
g_1 &= 2\cos^2(\psi_T)(1 - \sin^2(\theta_T)\cos^2(\varphi_T)), \\
g_2 &= \sin^2(\psi_T)(1 - \sin^2(\theta_T)\sin^2(\varphi_T)), \\
g_3 &= \sin^2(\psi_T)\sin^2(\theta_T), \\
g_4 &= -\sin^2(\psi_T)\sin^2(2\theta_T)\sin(\varphi_T), \\
g_5 &= \frac{1}{\sqrt{2}}\sin(2\psi_T)\sin^2(\theta_T)\sin(2\varphi_T), \\
g_6 &= \frac{1}{\sqrt{2}}\sin(2\psi_T)\sin(2\theta_T)\sin(\varphi_T)\,.
\end{aligned}$$

B_s lifetime – likelihood function

$$\mathcal{L} = L_{\text{signal}} + L_{\text{background}} \,,$$
$$L_{\text{signal}} = (f(\Theta, t; \alpha) \otimes G(t, \kappa, \sigma(t))]) \cdot M(m) \cdot \epsilon(t)\epsilon(\Theta) \,,$$
$$L_{\text{background}} = b(\Theta, t, m) \,,$$

- $G(t,\kappa,\sigma(t))$ = Gaussian resolution function
  - $\sigma(t)$ = event proper decay time uncertainty
  - κ = uncertainty scaling factor
- $M(m)$ = signal mass PDF (sum of two gaussians)
- $\epsilon(t)$ = proper decay time efficiency function
- $\epsilon(\Theta)$ = angular efficiency function
- $b(\Theta, t, m)$ = background model

B_s lifetime – fits to angular distributions