HEAVY-FLAVOR RESULTS AT CMS

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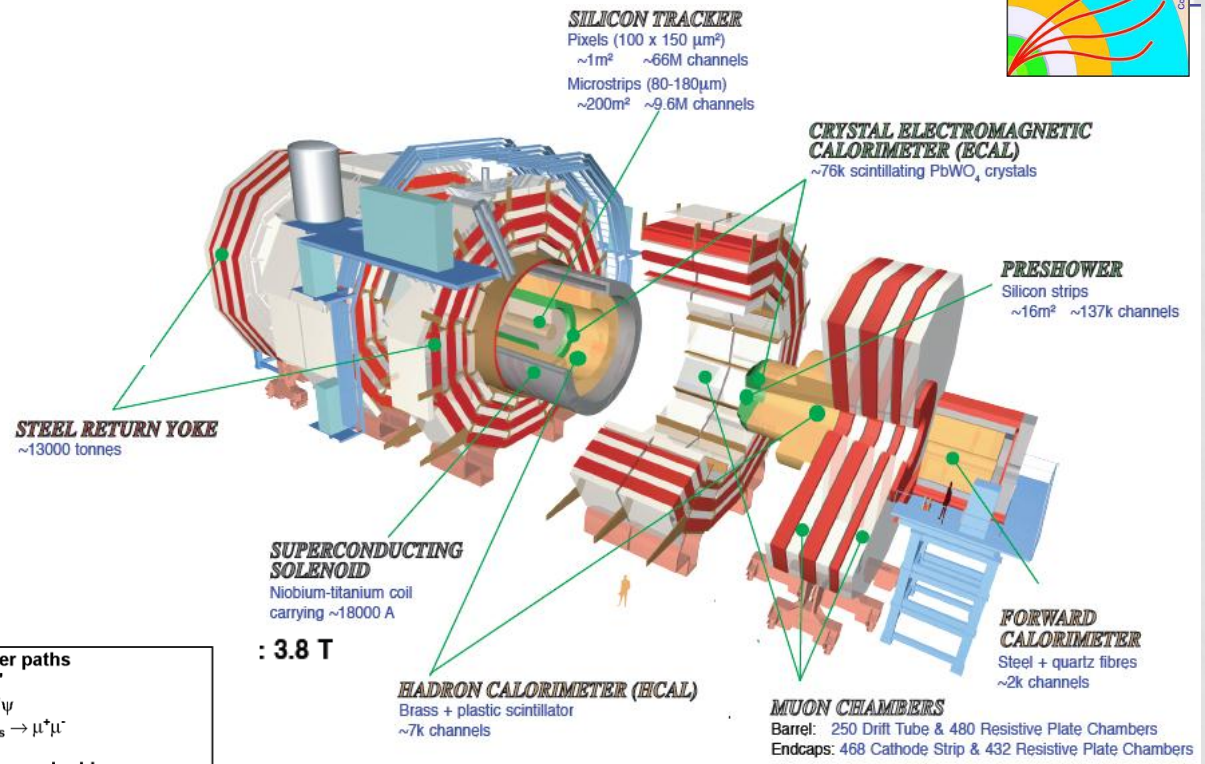
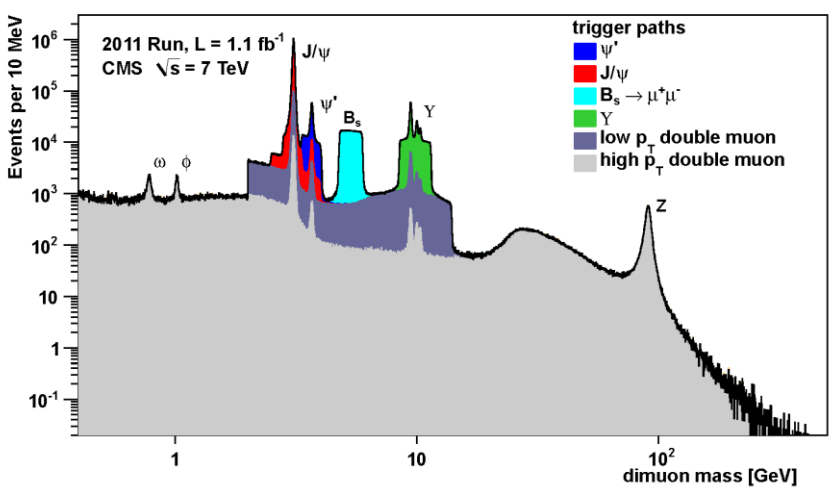
PHYSICS AT THE LHC
VANCOUVER, 4-9 JUNE 2012

THE CMS DETECTOR

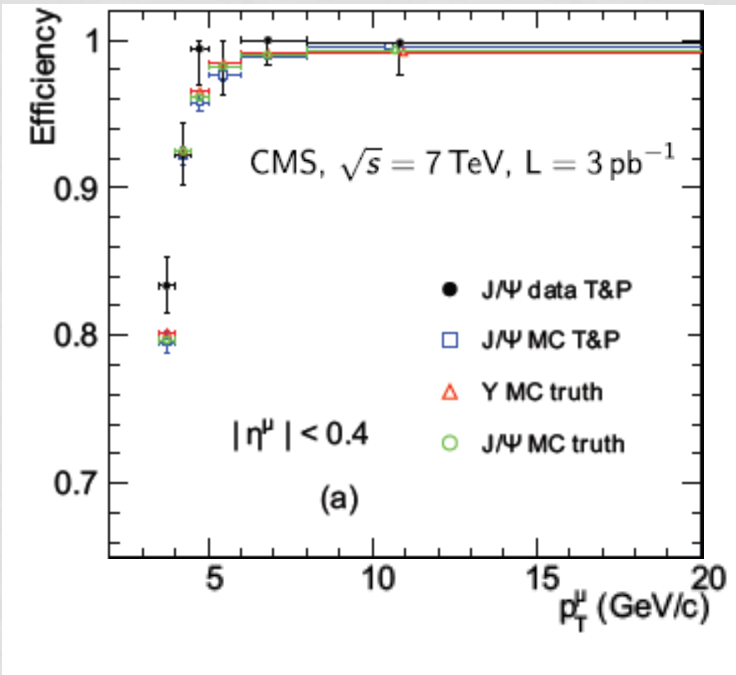
Muon reconstruction from combined information of silicon tracker and external detectors (DT, CSC, RPC)





- Di-muon triggers:
  - Level 1: segments in muon detectors
  - High-Level Trigger:
    - fast regional track reconstruction
    - "Special" requirements for B-physics (invariant mass, vertex displacement, etc.)

MUON EFFICIENCIES



- Use data-driven measurements of the muon efficiency ("tag-and-probe" method) on dedicated trigger streams
  - In events with a J/ψ candidate, ask for one well-identified muon ("tag")
  - The other muon ("probe") can pass or not pass the selection *S* under investigation
  - The fitted $N_{pass\text{-}S}/N_{all}$ yield gives an unbiased estimate of the efficiency ε_S

- Limitation of the method: assumes efficiency factorization, does not take into account correlations due e.g. to trigger requirements

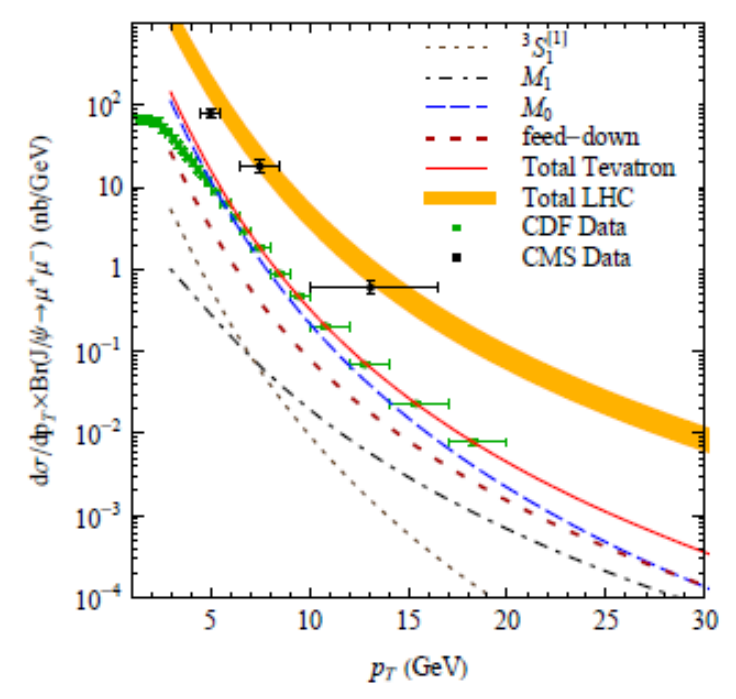
} (Small) MC corrections required

1. QUARKONIA

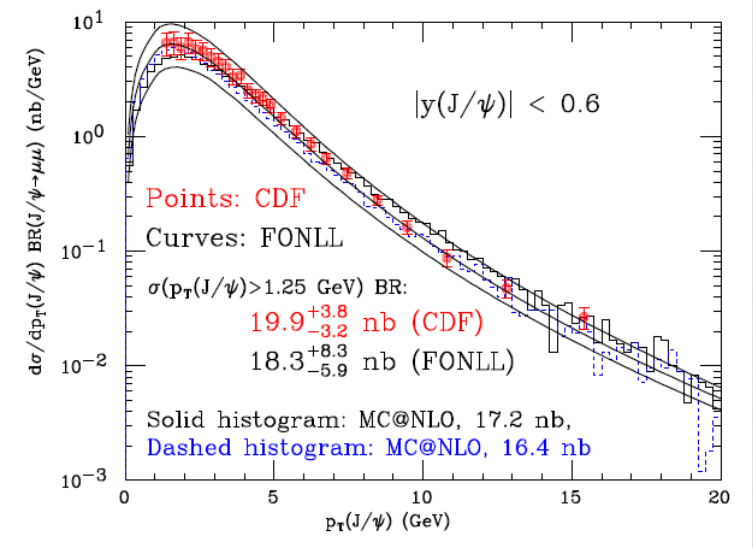
PHYSICS MOTIVATIONS (I)

- Quarkonium prompt production:
  - Includes feed-down for J/ψ (χ_{cJ}, ψ(2S) → J/ψ) and Υ (χ_{bJ} → Υ)
  - Direct only in the ψ(2S) case: theoretically cleaner
- Recent calculations at NLO in NRQCD ($O(\alpha_s^4 v^4)$), including both color-singlet and color-octet contributions, are available for charmonium
  - Good agreement with TeVatron and first (low-p_T) LHC measured cross-sections
  - Interesting to investigate:
    - $1/p_T^n$ dependence at high p_T
    - ψ(2S) vs. J/ψ with same LDMEs
    - Ratios to reduce experimental uncertainties

Y.-Q. Ma et al.
Phys. Rev. Lett. 106, 042002 (2011)



PHYSICS MOTIVATIONS (II)



- J/ψ non-prompt production:
  - Test FONLL approach at 7 TeV
  - Test improved b- fragmentation function (fitted from data of several experiments)

M. Cacciari et al., JHEP 0407, 033 (2004)

M. Cacciari et al., JHEP 0604, 006 (2006)

- χ_c studies
  - Measurement of $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ and the fraction of J/ψ coming from χ_c decays ($\chi_c \to J/\psi\ \gamma$) provide additional important "handles" for comparison to NRQCD predictions

J/Ψ AND Ψ(2S) CROSS-SECTIONS

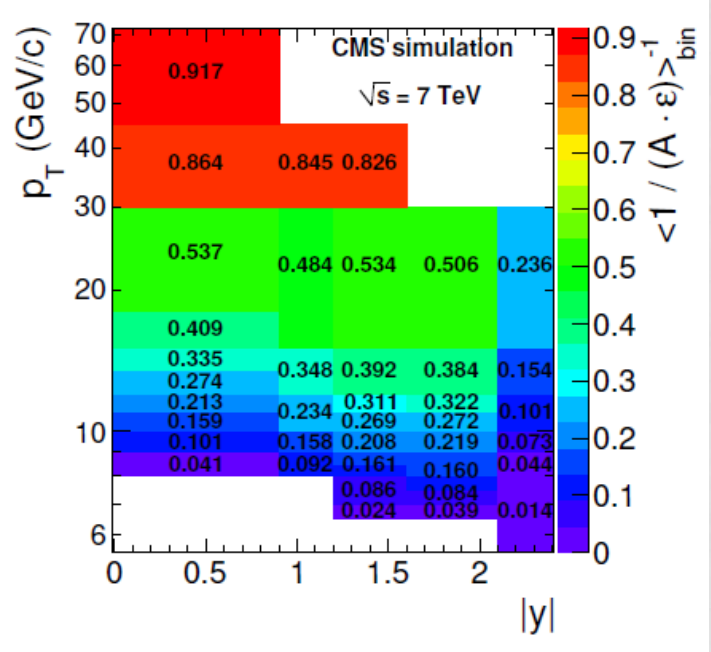
Eur. Phys. J. C71, 1575 (2011)
JHEP 1202, 011 (2012)

$$\frac{d^2\sigma}{dp_T dy}(Q\bar{Q})BR(Q\bar{Q} \rightarrow \mu^+\mu^-) = \frac{N_{fit}(Q\bar{Q})}{\int Ldt \cdot A \cdot \epsilon \cdot \Delta p_T \Delta y}$$

$$N_{fit}(\mathrm{J}/\psi, \psi(2\mathrm{S})) = \begin{cases} (1 - f_B)N_{tot} & \text{(prompt)} \\ f_B N_{tot} & \text{(non prompt)} \end{cases}$$

- A = acceptance → determined from simulation using unpolarized production as a default. Maximum variations are given based on "extreme" polarization scenarios
- ε = efficiency → tag-and-probe
- L = luminosity
- Δp_T, Δy = sizes of p_T, y bins

(acceptance x efficiency) unpolarized J/ψ

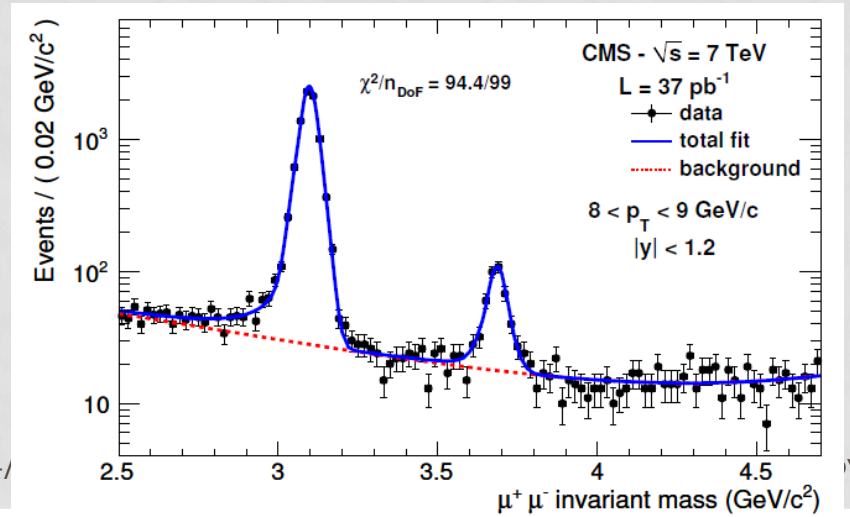


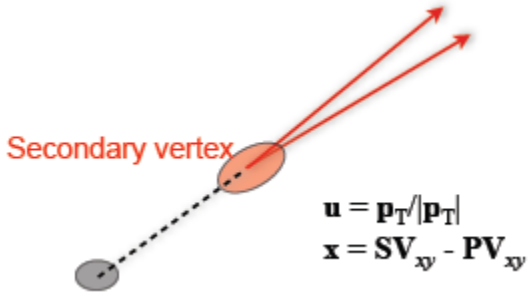
MASS AND DECAY LENGTH FITS

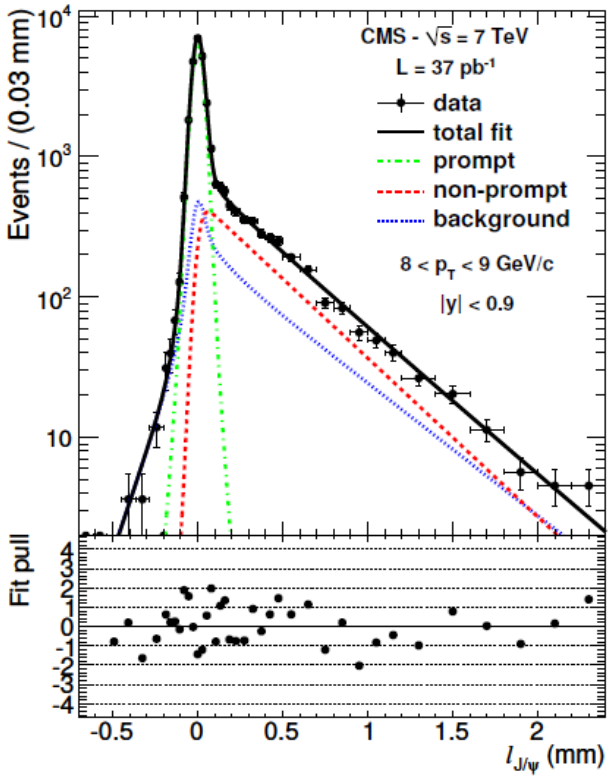
- Use unbinned maximum likelihood fits to mass distributions extract yields (N_{tot})
  - Typical mass resolution: 20-60 MeV/c^2 depending on rapidity
- To determine non-prompt fraction (f_B):
  - Fit simultaneously invariant mass and

$$\ell_{J/\psi} = L_{xy} \cdot m_{J/\psi} / p_T$$

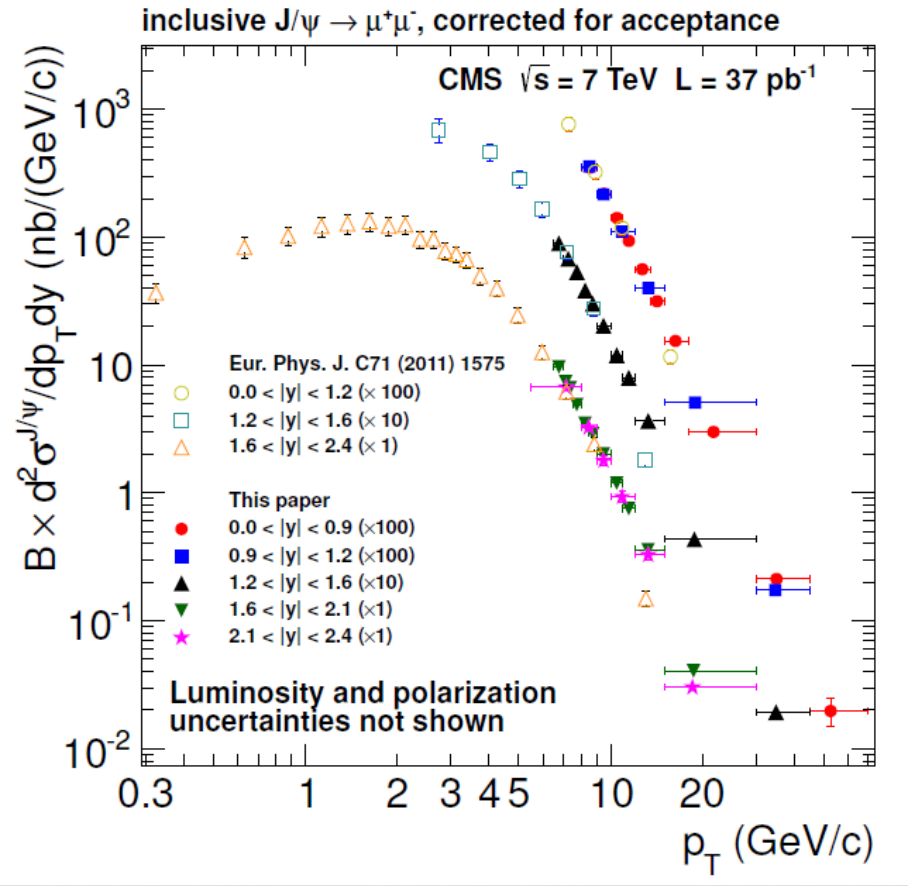
$$L_{xy} = \frac{\mathbf{u}^T \sigma^{-1} \mathbf{x}}{\mathbf{u}^T \sigma^{-1} \mathbf{u}}$$







CROSS-SECTION RESULTS

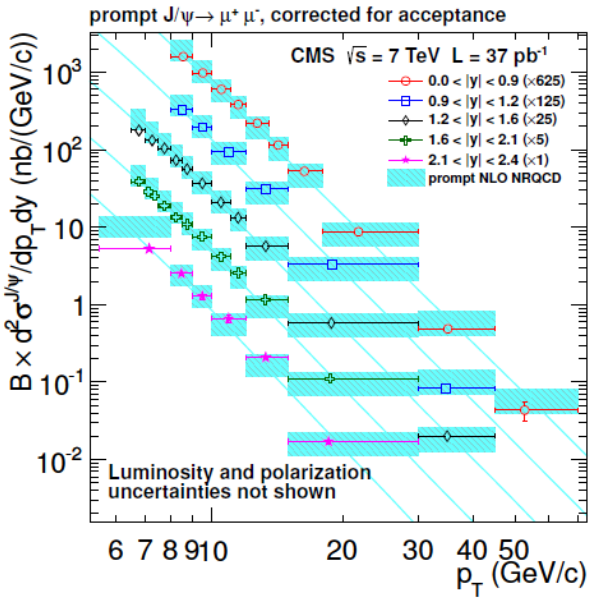


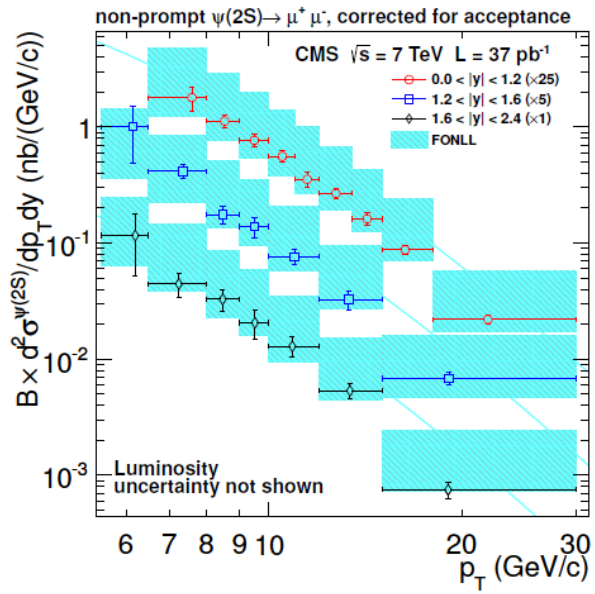
- Main systematic uncertainties:
  - Total cross sections
    - Efficiency correlations
    - Acceptance edge effects
    - Luminosity uncertainty
  - Non-prompt fractions
    - Tracker alignment
    - B-lifetime model
    - Resolution model

Shown here: J/ψ inclusive cross-section by merging CMS results with 0.3 pb^{-1} (low p_T) and 37 pb^{-1} (high p_T)

PROMPT/NON-PROMPT J/Ψ, Ψ(2S)

Prompt J/ψ





Non-prompt ψ(2S)

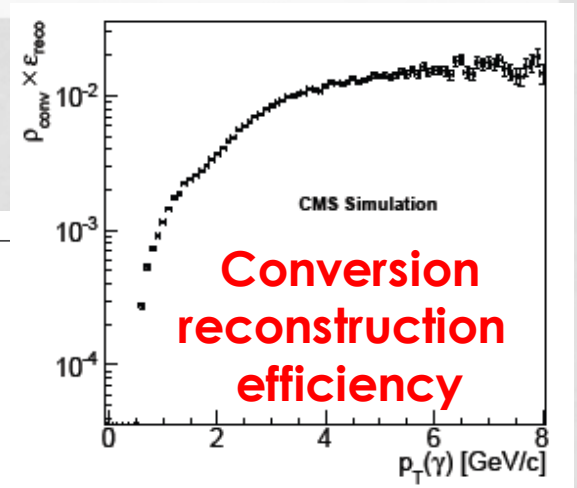
- Excellent agreement with NRQCD predictions
- Good agreement with FONLL predictions
  - Overall shift in the ψ(2S) case (uncertainty on B → ψ(2S) rate) → improved determination of B → ψ(2S) BR from non-prompt ratio:

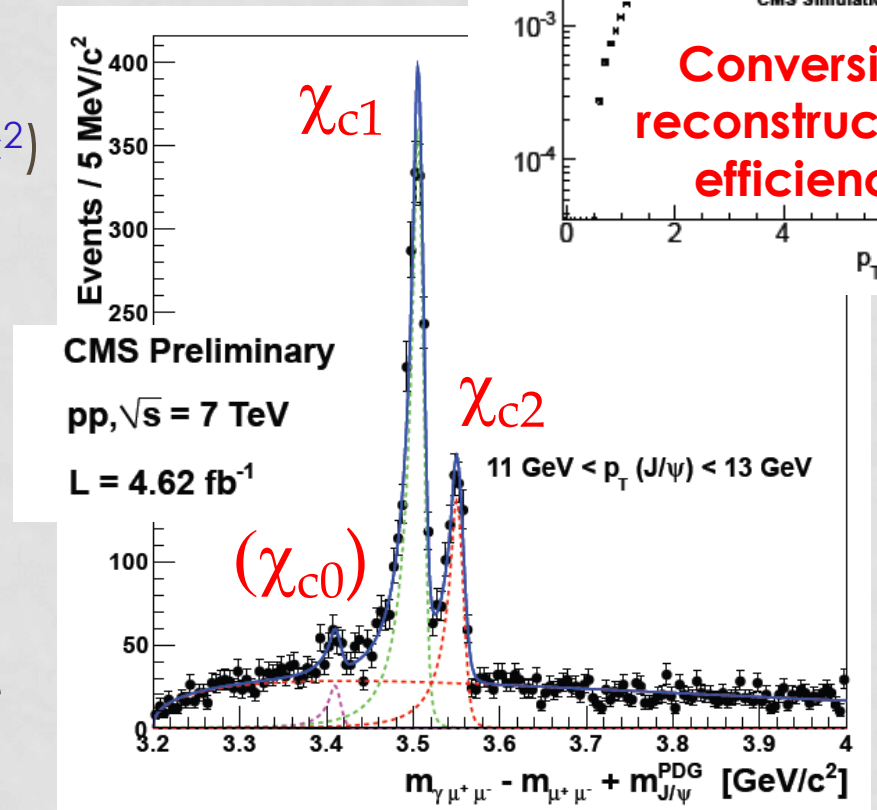
$$\mathcal{B}(\mathrm{B} \to \psi(2\mathrm{S})X) = (3.08 \pm 0.12\,(\mathrm{stat.+syst.}) \pm 0.13\,(\mathrm{theor.}) \pm 0.42\,(\mathcal{B}_{\mathrm{PDG}})) \times 10^{-3}$$

χ_{c2} / χ_{c1} CROSS-SECTION RATIO (I)

- Full 2011 sample (4.6 fb^{-1})
- Combine a prompt J/ψ candidate with a photon converted to e^+e^- in the silicon tracker ($\sigma \sim 6$ MeV/c^2)
- Conversion selection:
  - Vertex compatibilities
  - Conversion radius
  - p_T
  - π^0 veto combining candidates with photons in the EM calorimeter
- UML simultaneous fits to the two states give yield ratios

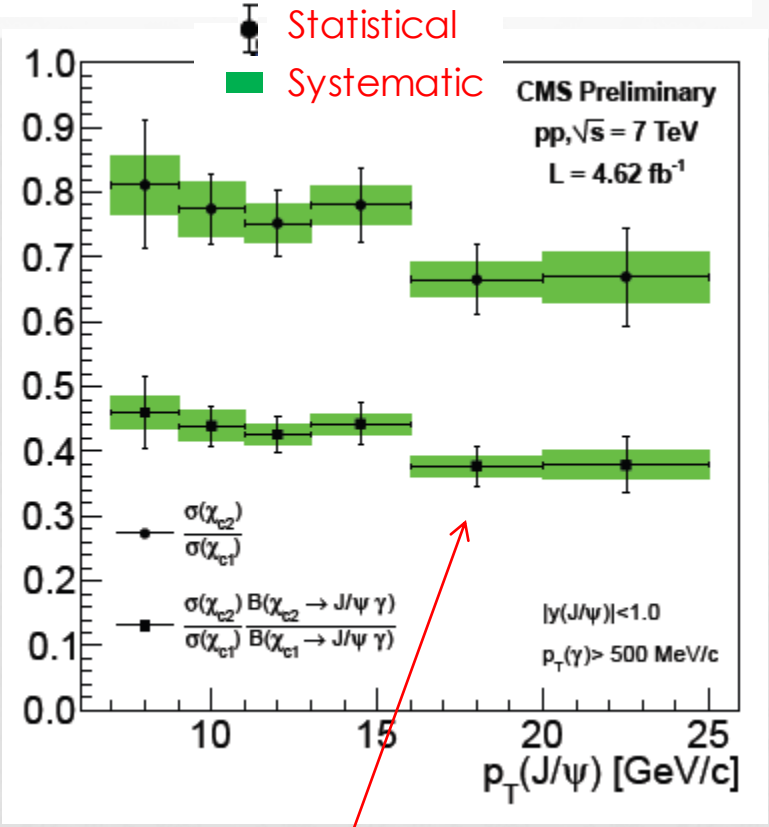
CMS-PAS-BPH-11-010 (2012)





χ_{c2} / χ_{c1} CROSS-SECTION RATIO (II)

- Yield ratio corrected with MC-derived efficiency ratio
  - Departures from 1 mostly due to slightly different $p_T(\gamma)$ spectra in the laboratory frame
- Main systematic uncertainties:
  - Signal-MC statistics
  - Signal and background mass-difference parameterization
  - Unknown production p_T spectrum and polarization (not shown) of the χ_c states

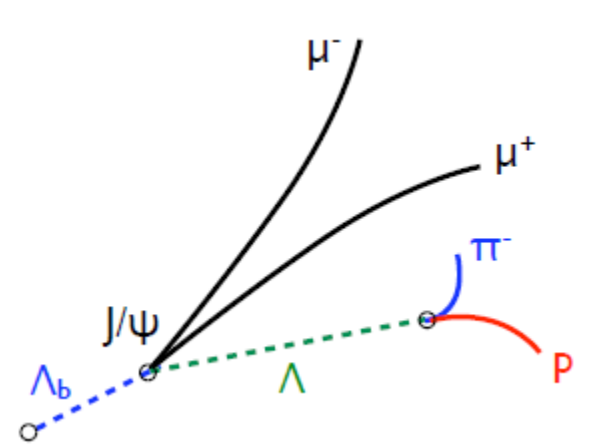


Y.-Q. Ma et al.
Phys. Rev. D83, 111503 (2011)

- NLO NRQCD: $\sigma \cdot BR(\chi_{c2})/\sigma \cdot BR(\chi_{c1}) \sim 0.3 - 0.5$
  - Waiting for exact calculation in CMS acceptance

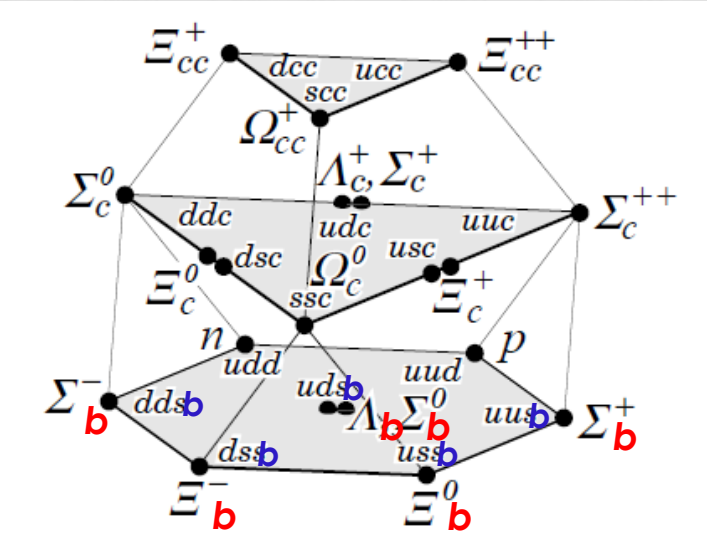
2. B-BARYONS

INTEREST IN B-BARYONS



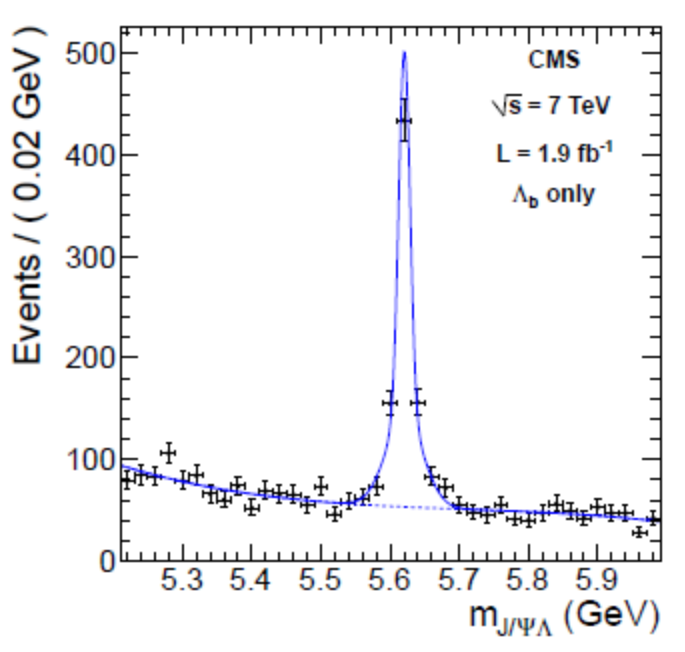
- Properties of the lightest B-baryon (Λ_b^0) still unknown or not precisely measured:
  - Production cross-section in hadron collisions ($f_{\Lambda b}$)
  - Polarization in hadron collisions
  - Lifetime (known with ~5-6% uncertainty)

- Vast "zoology" of B-baryon multiplets expected by the quark model
  - Detectable even in high-multiplicity pp collisions thanks to cascade weak decays → detached vertices



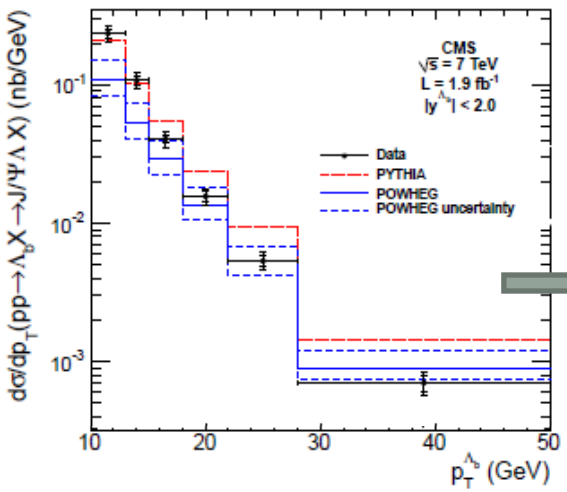
Λ_B , $\overline{\Lambda}_B$ CROSS-SECTIONS (I)

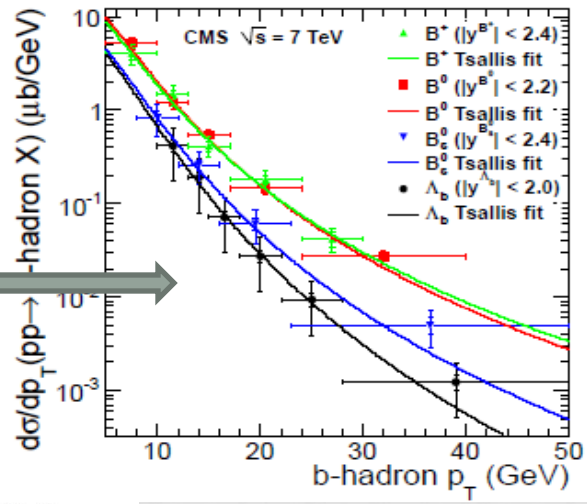
- Differential cross-sections in $p_T > 10$ GeV/c, $|y| < 2$
  - analysis performed on 1.9 fb-1
- Select $\Lambda_b^0 \rightarrow J/\psi\ \Lambda^0 \rightarrow \mu^+\mu^-\ p\pi^-$
  - Track and muon quality
  - Pointing angle of J/ψ
  - Significance of J/ψ and Λ^0 transverse vertex displacement
- UML fit to Λ_b candidates from mass-constrained vertex fit
- Efficiencies from tag-and-probe (muons, trigger) and MC simulation (selection criteria)



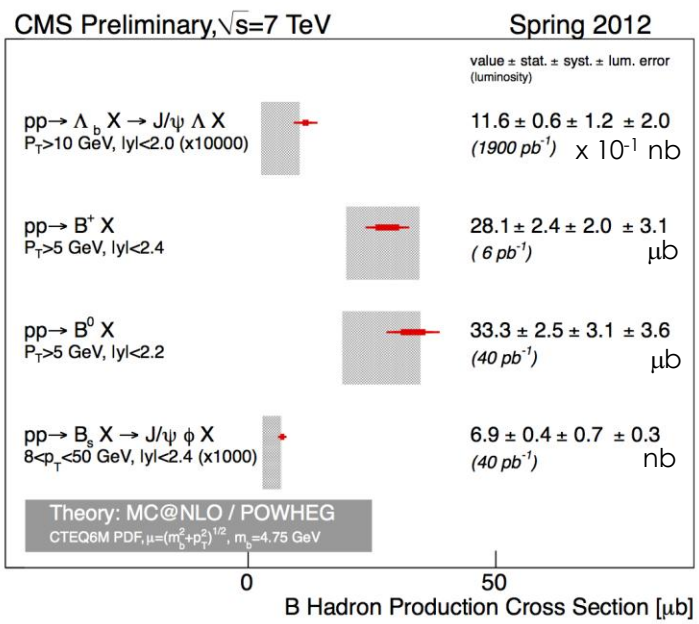
arXiv:1205.0594 [hep-ex]
to appear in Phys.Lett.B

Λ_B , $\overline{\Lambda}_B$ CROSS-SECTIONS (II)

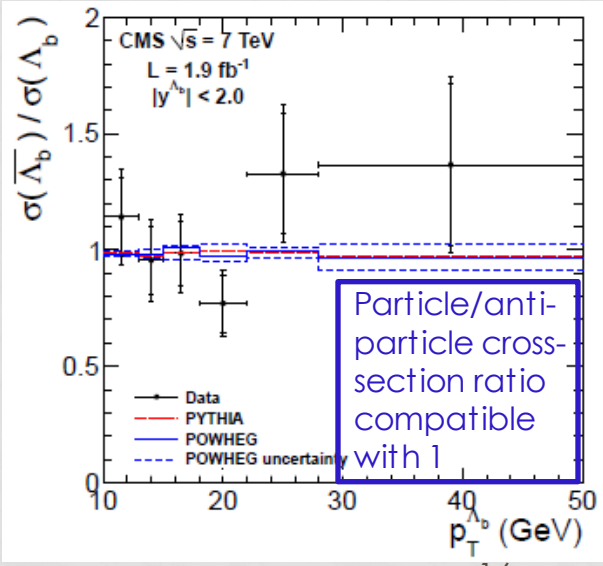




- Spectrum shape falling more steeply than NLO QCD predictions (and B-meson spectra)
  - attributed to hadronization effects



- Slight excess in total cross-section
  - also observed in other B species production



Particle/anti-particle cross-section ratio compatible with 1

OBSERVATION OF Ξ_B^{*0} (I)

arXiv:1204.5955 [hep-ex]
to appear in Phys.Rev.Lett.

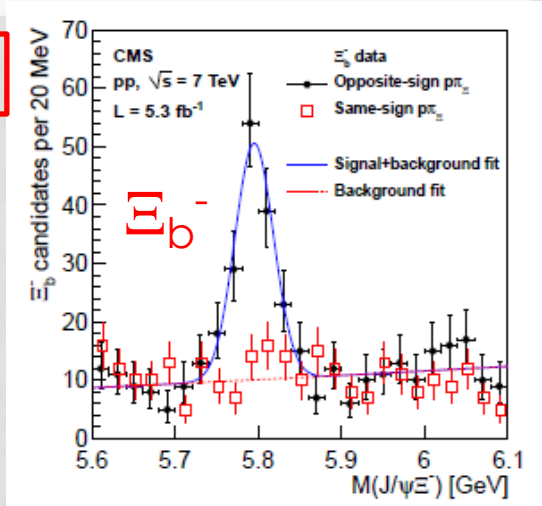
- "Cascade" B-baryons (valence quark content = *usb* or *dsb*) so far only observed in the $J^P = 1/2^+$ state
- Color hyperfine-splitting models predict the mass of the $J^P = 3/2^+$ state Ξ_b^* to be large enough for a $\Xi_b^* \rightarrow \Xi_b\pi$ transition
- Reconstruct Ξ_b^{*0} in the decay chain:
  - $\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+ \rightarrow \Xi^- J/\psi\, \pi^+ \rightarrow \Lambda^0\pi^-\mu^+\mu^-\pi^+ \rightarrow p\pi^-\pi^-\mu^+\mu^-\pi^+$
  - Three weakly-decaying particles: Ξ_b^-, Ξ^-, Λ^0 → reconstruction of one primary and three secondary vertices allow to separate signal from huge prompt background

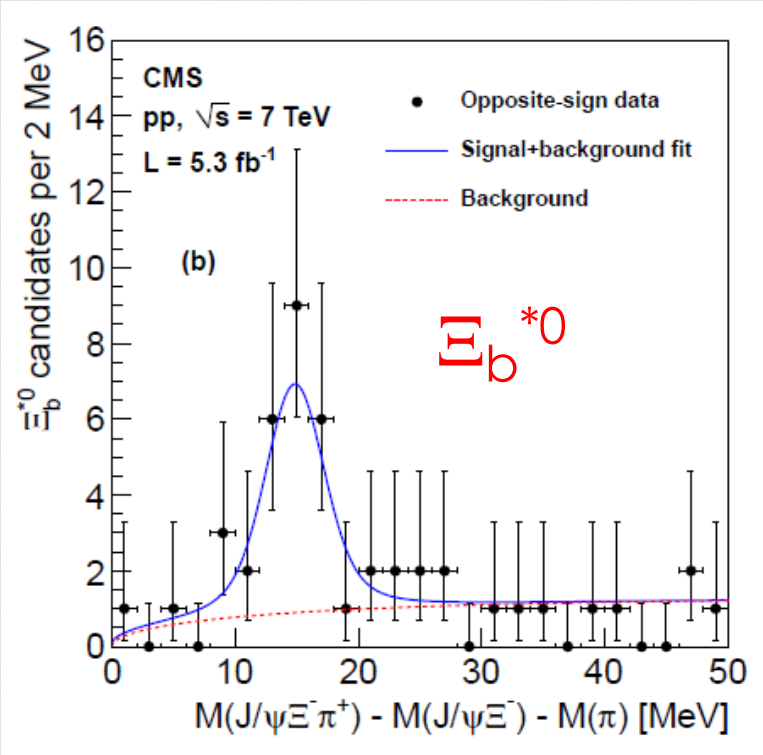
OBSERVATION OF Ξ_B^{*0} (II)

$M(\Xi_b^{*0}) = (5945.0 \pm 0.7(\text{stat}) \pm 0.3(\text{syst}) \pm 2.7(\Xi_b^-))$ MeV/c^2

- Theory: 5.94 GeV/c^2
- 6.9σ significance

J. G. Korner et al.
Prog. Part. Nucl. Phys. 33, 787 (1994)

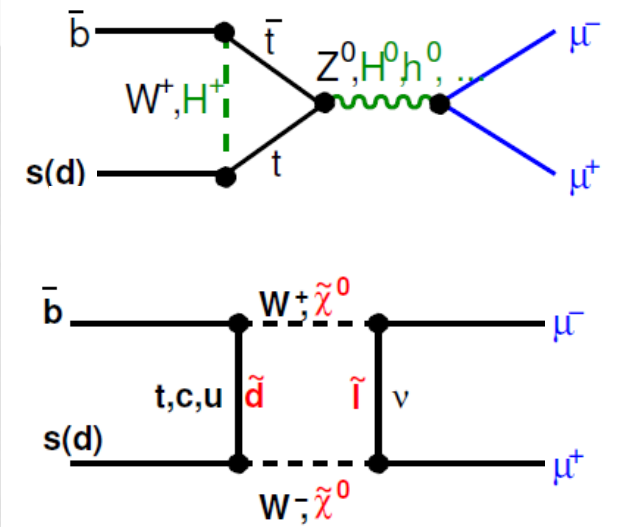




- Wrong-sign data used to check absence of excess
- Systematics:
  - Track/muon momentum scale
  - Fitting model

3. RARE DECAYS

$B_{s,d} \to \mu^+\mu^-$: THEORY



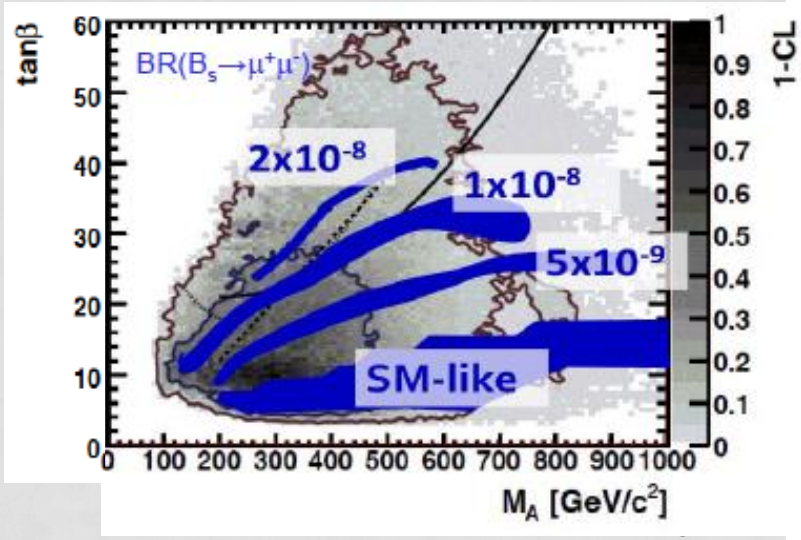
- Decays highly suppressed in SM
  - Effective FCNC decay
  - Helicity suppression
  - Overall Cabibbo suppression

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$$

Buras, Isidori & Paradisi Phys.Lett. B694 402 (2010)

- Enhancements in several BSM physics scenarios:
  - CMSSM $\frac{\mathcal{B}_{MSSM}}{\mathcal{B}_{SM}} \alpha \frac{(\tan\beta)^6}{M_A{}^4}$

    Isidori & Paradisi Phys.Lett. B639 499 (2006)
  - NUHM1



ANALYSIS TECHNIQUE

arXiv:1203.3976 [hep-ex]
to appear in JHEP

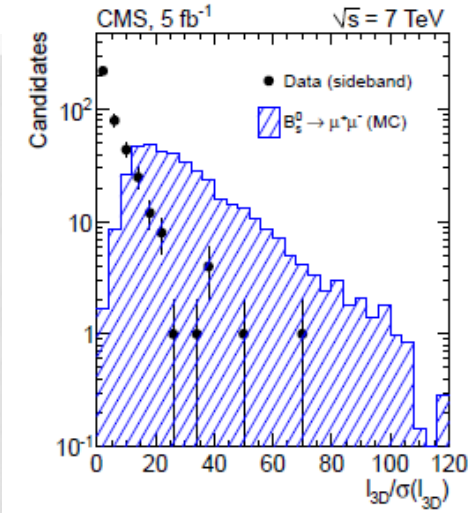
- Blind analysis
- Use of "normalization channel" $B^+ \rightarrow J/\psi\ K^+$ to
  - remove large uncertainties on luminosity and σ_{bb}
  - reduce efficiency systematic uncertainties in the ratio

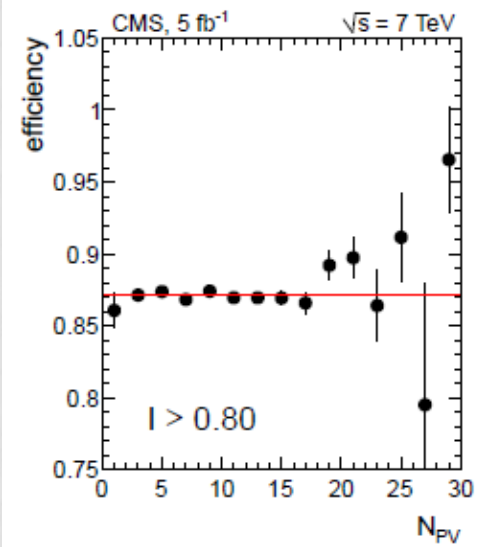
$$\mathcal{B}(B_q^0 \rightarrow \mu^+\mu^-) = \mathcal{B}_{\text{norm}} \times \frac{\epsilon_{\text{norm}}^{\text{REC}}\epsilon_{\text{norm}}^{\text{SEL|REC}}\epsilon_{\text{norm}}^{\text{TRIG|SEL}}}{\epsilon_{\text{sig}}^{\text{REC}}\epsilon_{\text{sig}}^{\text{SEL|REC}}\epsilon_{\text{sig}}^{\text{TRIG|SEL}}} \times \frac{f_{\text{norm}}}{f_{B_q^0}} \times \frac{N_{B_q^0\rightarrow\mu^+\mu^-}}{N_{\text{norm}}} = \alpha_{B_q^0\rightarrow\mu^+\mu^-} \times N_{B_q^0\rightarrow\mu^+\mu^-}$$

- Separated analysis in barrel/endcap: signal resolution: 36/77 MeV/c^2
- Main backgrounds:
  - Collimated muons from two semileptonic B decays (→ gluon splitting)
  - One muon from semileptonic B decay plus one misidentified hadron
  - Rare decays
    - Peaking (e.g. $B_s \rightarrow K^+ K^-$)
    - Non-peaking (e.g. $B_s \rightarrow K^+ \mu^- \nu$)

SIGNAL SELECTION

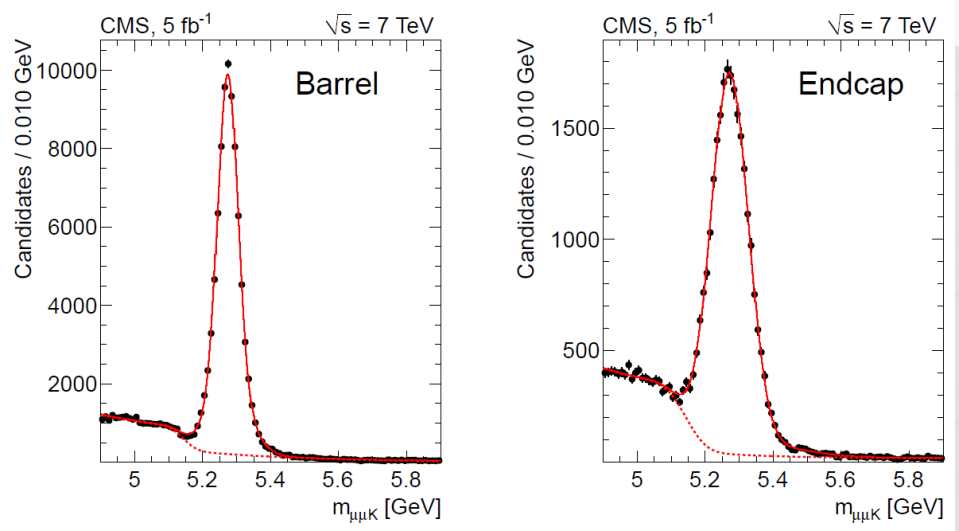
- Selection variables:
  1) Muon and dimuon p_T
  2) vertex χ^2 probability
  3) Pointing angle
  4) Impact parameter and flight length significance
  5) Di-muon isolation in a cone around the B direction
     - Σp_T + # of close tracks + DCA of the closest track
- Cut optimization and count in B^0 and B_s mass windows
  - check robustness against large pile-up variations
  - mass sidebands for expected background estimation
- Efficiency ratios from MC and checked in data
  - Muon efficiencies: using the "tag-and-probe" method
  - Selection efficiency: using the $B_s \rightarrow J/\psi\ \phi$ control sample

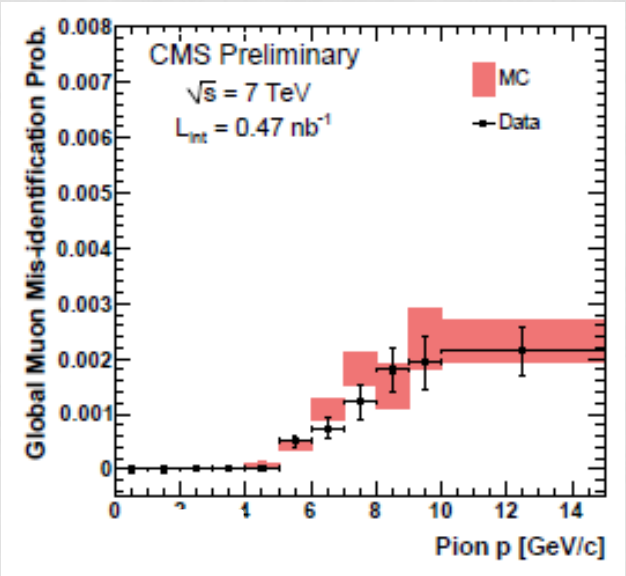




NORMALIZATION AND BACKGROUND

- N_{norm} from invariant mass fit to the $B^+ \rightarrow J/\psi\ K^+$ sample
  - Uncertainties include statistics and systematics (mainly from background shape)

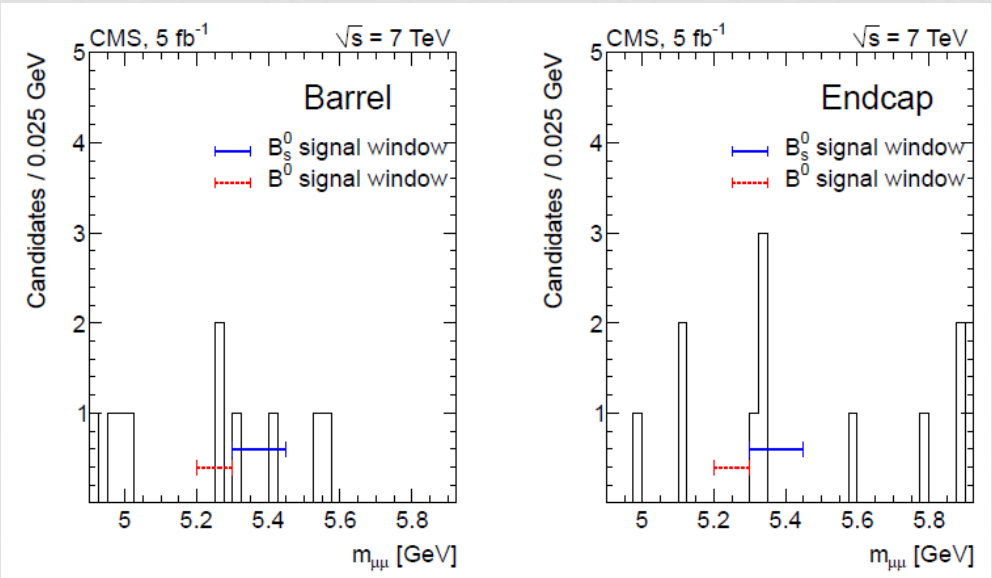




- Combinatorial background from dimuon mass sideband interpolation assuming flat distribution
- Peaking background shapes from MC → sum of many exclusive decays
  - Contribution in the signal region estimated by weighting with measured K, π and p muon mistag probabilities in data (from $K_s \rightarrow \pi^+ \pi^-$, $\phi \rightarrow K^+ K^-$ and $\Lambda \rightarrow p\ \pi^-$)

RESULTS

Variable	$B^0 \to \mu^+\mu^-$ Barrel	$B_s^0 \to \mu^+\mu^-$ Barrel	$B^0 \to \mu^+\mu^-$ Endcap	$B_s^0 \to \mu^+\mu^-$ Endcap
ε_{tot}	0.0029 ± 0.0002	0.0029 ± 0.0002	0.0016 ± 0.0002	0.0016 ± 0.0002
N^{exp}_{signal}	0.24 ± 0.02	2.70 ± 0.41	0.10 ± 0.01	1.23 ± 0.18
N^{exp}_{total}	0.97 ± 0.35	3.47 ± 0.65	1.01 ± 0.35	2.45 ± 0.56
N_{obs}	2	2	0	4



- Expected ULs:

$BR(B_s \to \mu\mu) < 8.4 \times 10^{-9}$ @ 95% CL

$BR(B_d \to \mu\mu) < 1.6 \times 10^{-9}$ @ 95% CL

- Observed ULs:

$BR(B_s \to \mu\mu) < 7.7 \times 10^{-9}$ @ 95% CL

(~2.5x SM value)

$BR(B_d \to \mu\mu) < 1.8 \times 10^{-9}$ @ 95% CL

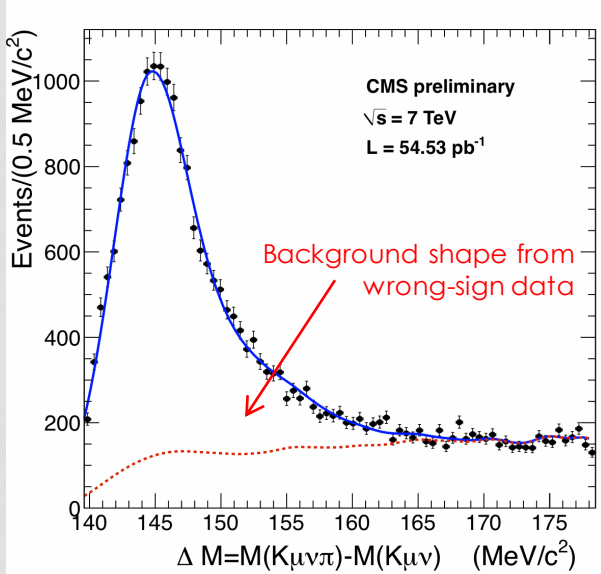
$D^0 \to \mu^+\mu^-$: STRATEGY

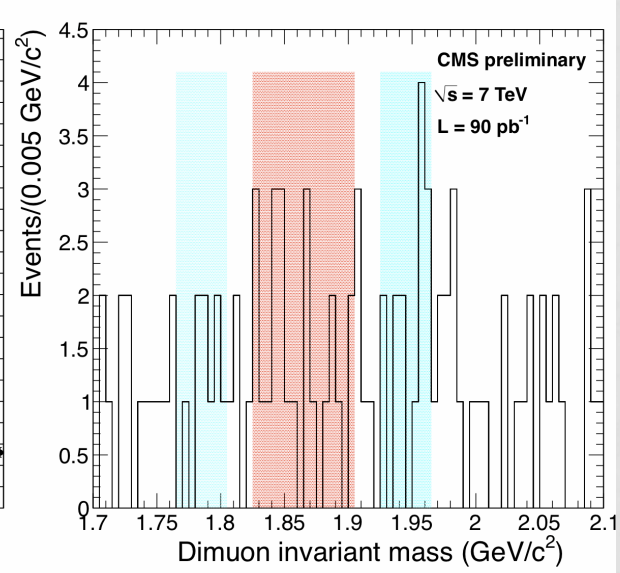
- (Not so) similar to $B_{s,d} \to \mu^+\mu^-$ → long-distance processes play and important role in the decay
  - SM branching ratio ~ 10^{-13} , analogous enhancements from NP models
- Consider BF ratio of $\frac{D^{*+} \to D^0(\mu^-\mu^+)\pi^+}{D^{*+} \to D^0(K^-\mu^+\nu)\pi^+}$
  - $D^0 \to K\mu\nu$ used as a normalization mode, not triggered throughout the full CMS dataset → use 90 pb^{-1} total statistics
  - $D^* \to D^0\pi$ decay used to:
    - produce a clean signal sample (use of Δm variable)
    - estimate approximately the z-component of the neutrino momentum (use of decay kinematics) in the normalization mode

CMS-PAS-BPH-11-017 (2012)

$D^0 \rightarrow \mu^+\mu^-$: RESULTS

Normalization channel





Signal channel

- Acceptance/efficiency ratio from MC
  - Main systematics on single-muon trigger and kaon tracking efficiencies
- Observed limit:

$BR(D^0 \rightarrow \mu\mu) < 5.4 \times 10^{-7}$ @ 90% CL

Trigger	$\Upsilon(D^0 \rightarrow K^-\mu^+\nu)$	N_{obs}, N_{bkg}
HLT_Mu3	2361 ± 131	0, 0
HLT_Mu5	2259 ± 180	1, 0
HLT_Mu7	11690 ± 209	6, 4
HLT_Mu9	9912 ± 170	6, 6

CONCLUSIONS

- CMS is pursuing a wide program of heavy flavor physics of which I have selected a few topics:
  - Heavy-flavor production
    - S- and P-wave quarkonium production in good agreement with (Tevatron-tuned) NLO NRQCD → test universality of long-distance matrix elements
    - Inclusive and exclusive $B \rightarrow J/\psi$ production measurements show excellent shape agreement with NLO QCD, normalization overshooting predictions
  - Baryon spectroscopy → new Ξ_b excited state observed
  - Rare decays:
    - BR limits on B_s, B_d, $(D^0) \rightarrow \mu^+\mu^-$ competitive with those of HF-dedicated experiments
    - Stringent constraints on new physics models (CMSSM, NUHM…)

BACKUP SLIDES

POLARIZATION UNCERTAINTIES

- Polarization uncertainties not shown in the plots: quoted as typical variations using the 4 extreme acceptance scenarios

- fully longitudinal polarization (Collins-Soper frame): $\pm 15\%$, $\pm 15\%$;
- fully transverse polarization (Collins-Soper frame): -6%, -6%;
- fully longitudinal polarization (helicity frame): -20%, -28%;
- fully transverse polarization (helicity frame): $+18\%$, $+25\%$.