Study of the $B_s \to J/\psi\,\phi$ Decay in pp Collisions at √7 TeV

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Brown University (Providence, RI)

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on behalf of the CMS collaboration

b-quark Production at LHC

- Test of perturbative QCD and Monte Carlo models

- Understand Standard Model b-quark background for other processes (i.e. Higgs search)

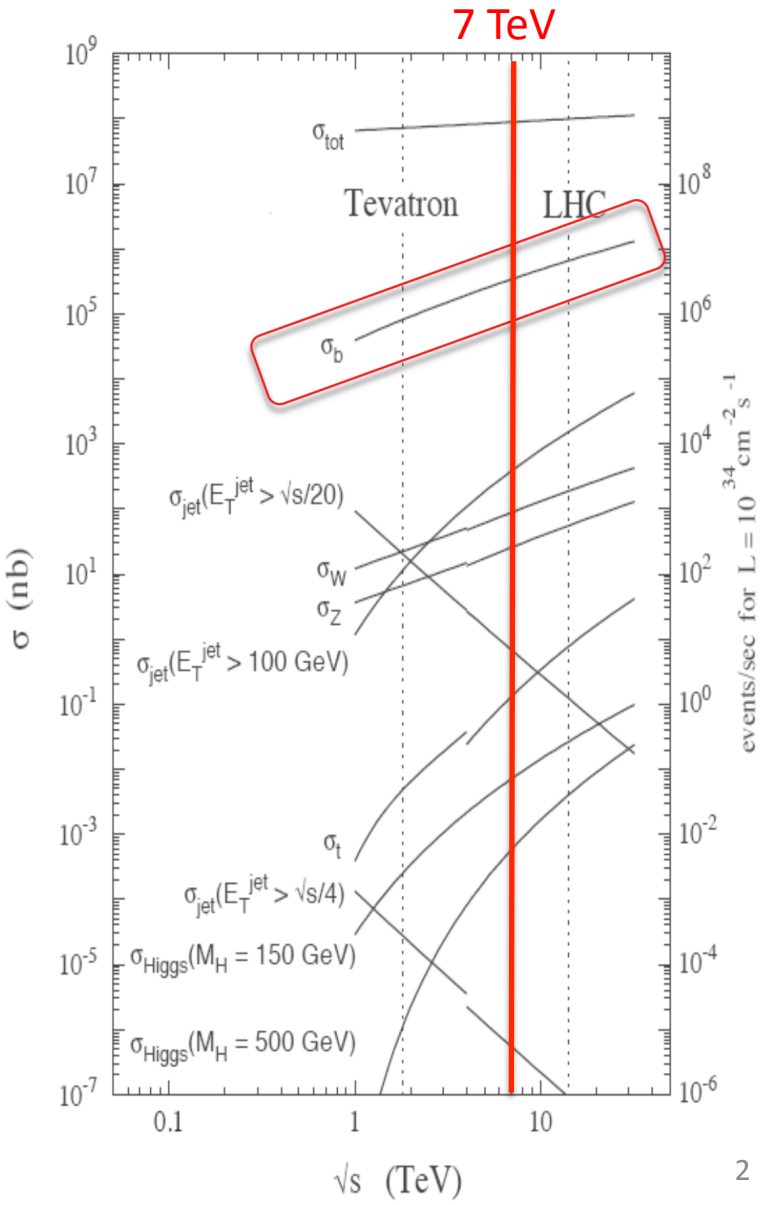
- Build confidence in the CMS experiment
- Excellent tracking and vertexing
- Muon identification
- Flexible trigger system

For the decay $B_s \rightarrow J/\psi\ \phi$:

- Measurement of $d\sigma(pp \rightarrow B_s X) \times BF(B_s \rightarrow J/\psi\ \phi)/dx$ ($x=p_T, y$) in the range $8 < p_T^{Bs} < 50$ GeV/c and $0 < |y^{Bs}| < 2.4$

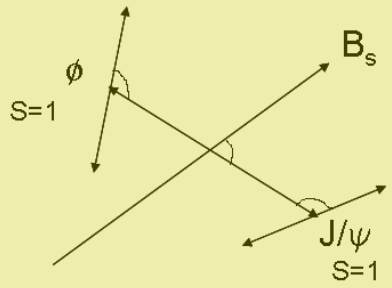
$$y^B = \frac{1}{2} \ln \left(\frac{E^B + p_z^B}{E^B - p_z^B} \right)$$

- Measurement of $\Delta\Gamma$ and CP-violating weak phase ϕ_s



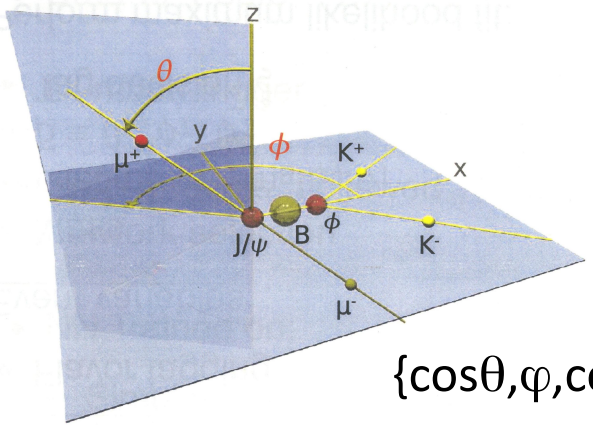
Angular analysis

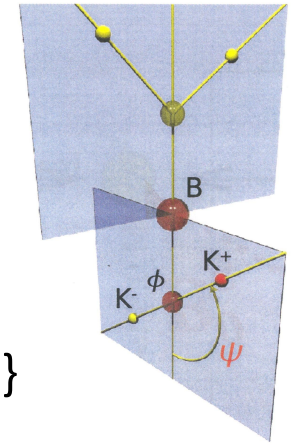
$B_s \to J/\psi\,\phi$ is not a CP eigenstate ⟶ Partial wave analysis is required to split CP-even and CP-odd components of the decay amplitude → transversity basis



0→1 1 so L=0,1,2

$P=(-1)^L$ → CP=±1





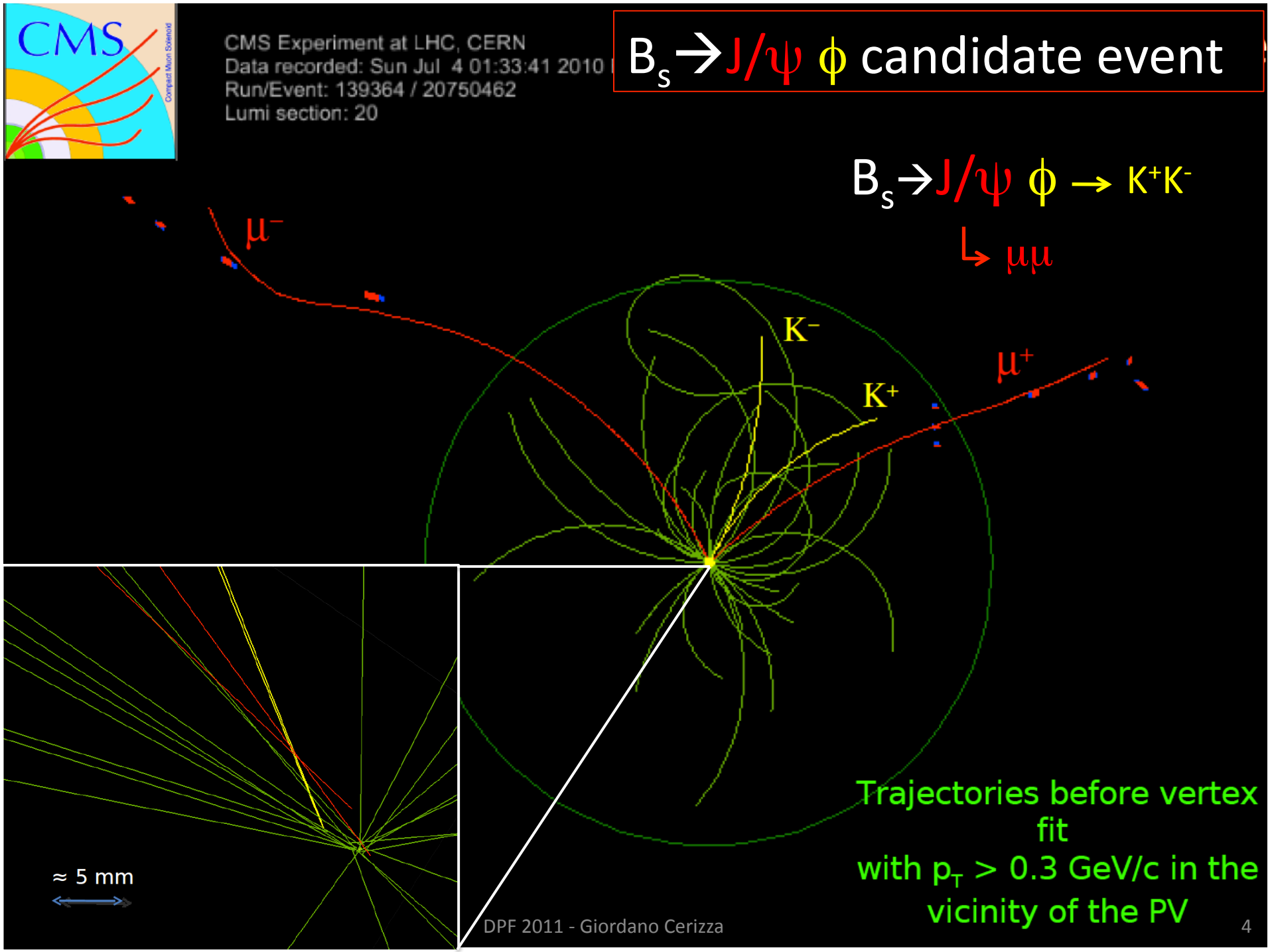
{cosθ,φ,cosψ}

Differential decay rate described by:

$$\frac{d^4\Gamma}{d(\cos\theta)d\varphi\; d(\cos\psi)dt} = f(A_0, A_{\|}, A_{\perp}, \Gamma_L, \Gamma_H, \varphi_s, \delta_1, \delta_2)$$

Amplitude strengths — Decay widths — Weak phase — Strong phases

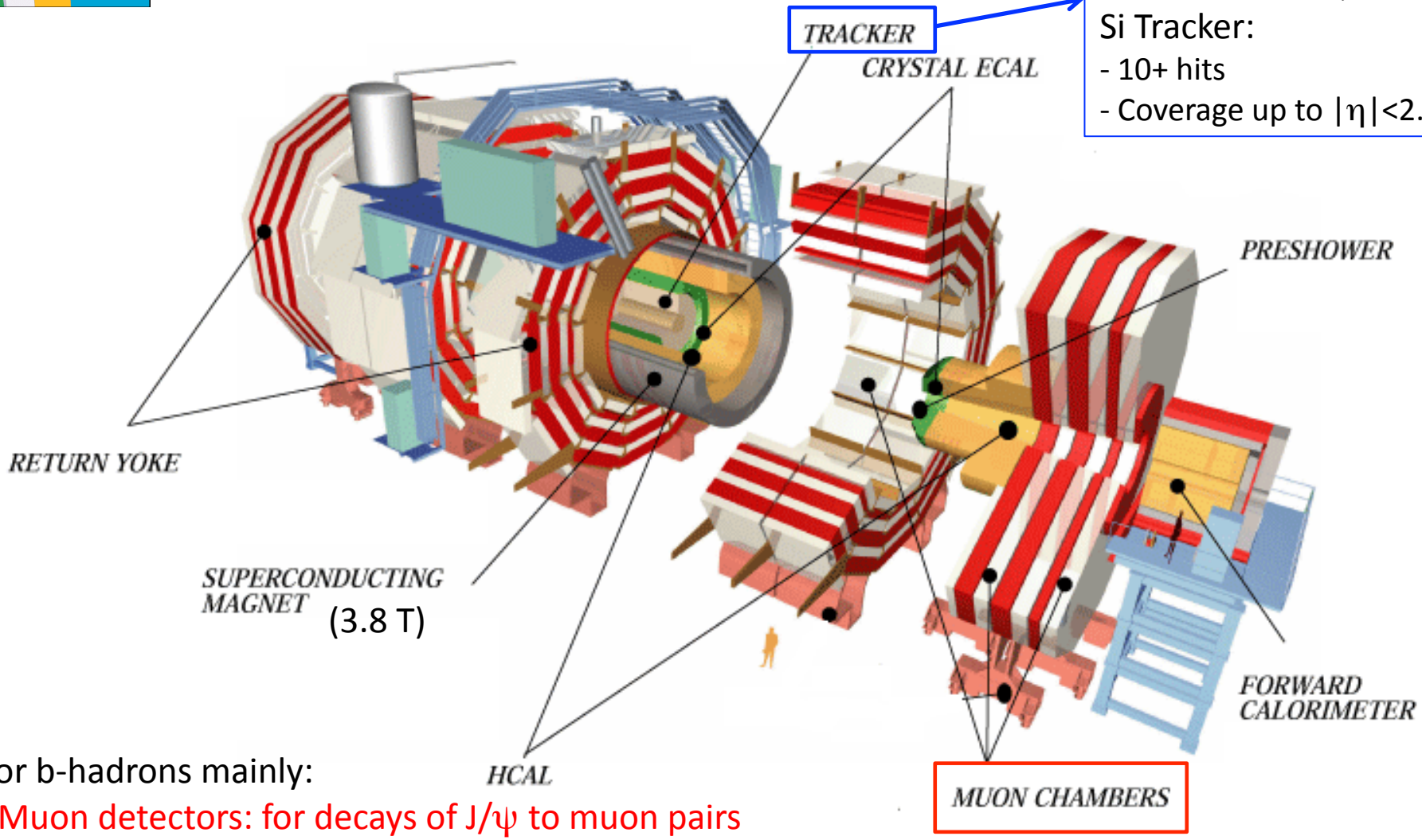
The analysis for the extraction of $\Delta\Gamma$ is ongoing!


CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Jul 4 01:33:41 2010
Run/Event: 139364 / 20750462
Lumi section: 20
$B_s \rightarrow J/\psi\ \phi$ candidate event
$B_s \rightarrow J/\psi\ \phi \rightarrow K^+K^-$
$\hookrightarrow \mu\mu$
μ^-
K^-
K^+
μ^+
≈ 5 mm
Trajectories before vertex fit
with $p_T > 0.3$ GeV/c in the vicinity of the PV

CMS Detector

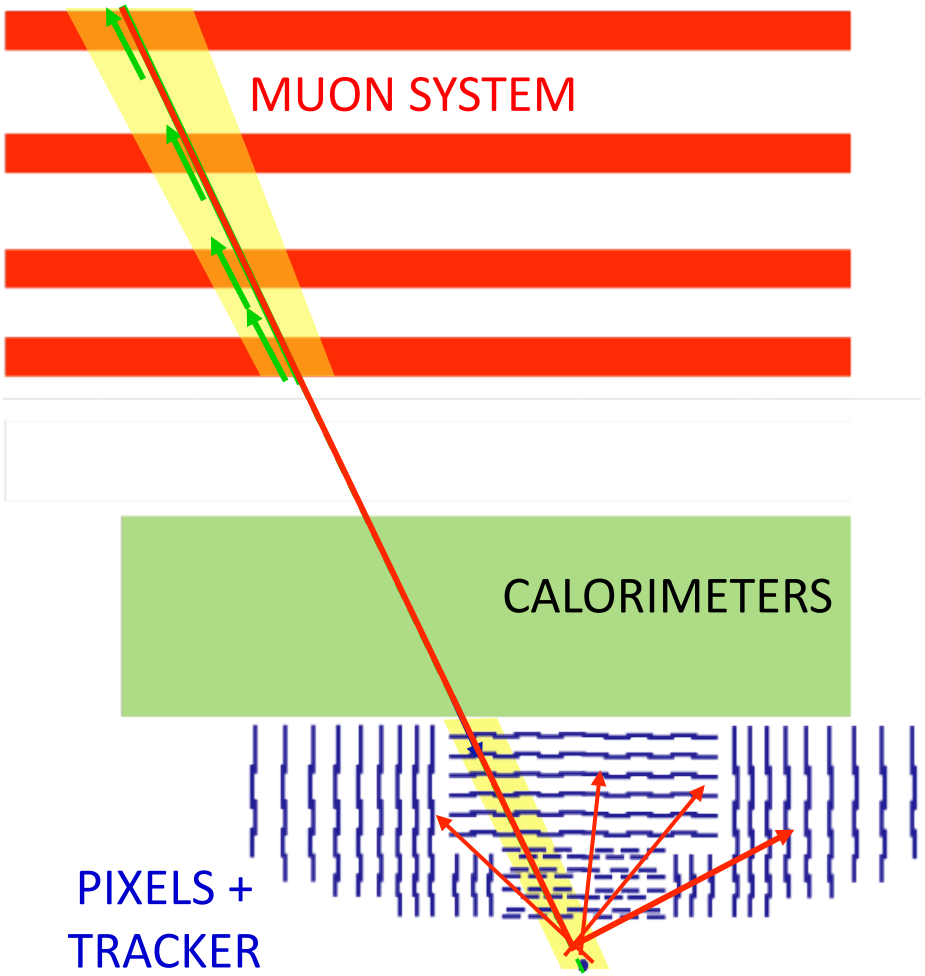
Pixel (forward + barrel):
- 3 layers + (2+2) disks
- Resolution 9-25 μm

Si Tracker:
- 10+ hits
- Coverage up to $|\eta|<2.4$

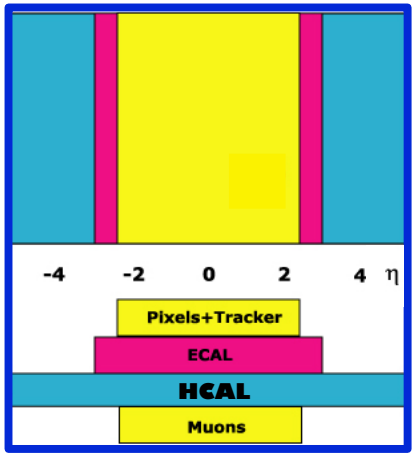


For b-hadrons mainly:
- Muon detectors: for decays of J/ψ to muon pairs
- Silicon Tracker detector: charged tracks as well as precise reconstruction of primary and secondary vertices

Muon Reconstruction



- Four "stations" for both barrel and endcaps
- Large rapidity coverage:
  - $|\eta| < 2.4$
  - CMS covers unique p_T-η range complementary w.r.t. LHCb

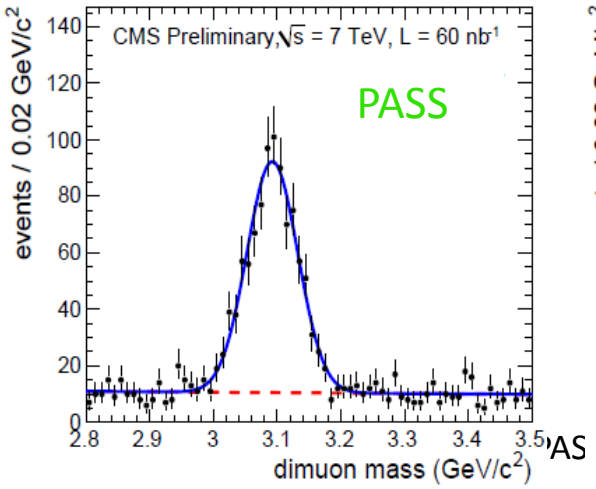


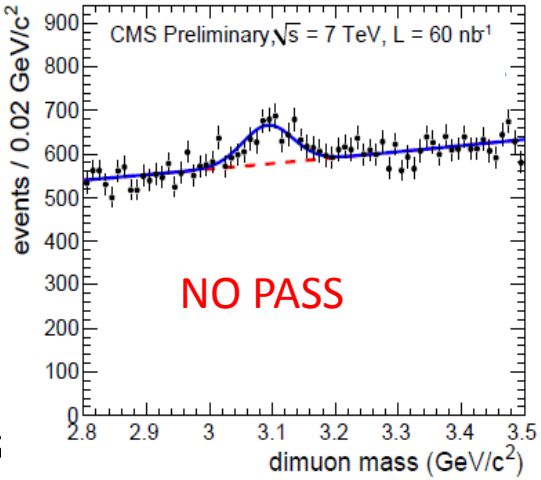
- Excellent muon momentum resolution:
  - Matching between muon chambers and the silicon tracker
  - Resolution as function of η because of the increasing material traversed

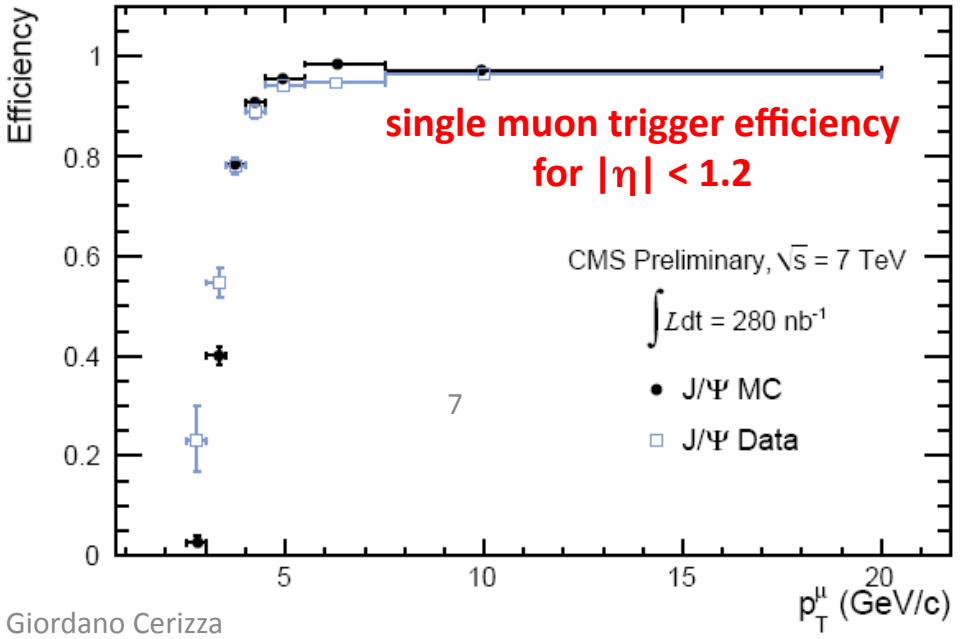
Muon Efficiency

Muon efficiency from data → the "Tag-and-Probe" method

- Require one well-identified muon in the event ("tag")
- Another candidate muon, with looser criteria L, is paired to it ("probe")
- Compare resonance yields for all tag-probe pairs and for pairs where the probes pass a given selection S → determine ε(S | L)







Strategy Outline

Measurement of the differential cross section in bins of Δx (with $\Delta x = p_T, y$)

$$\frac{d\sigma\,(pp \rightarrow B_s^0 X) \times BF(B_s^0 \rightarrow J/\psi\phi)}{dx} = \frac{n_{sig}}{2 \cdot \varepsilon \cdot B \cdot L \cdot \Delta x}$$

with $\sigma_{BF}/BF \sim 30\%$

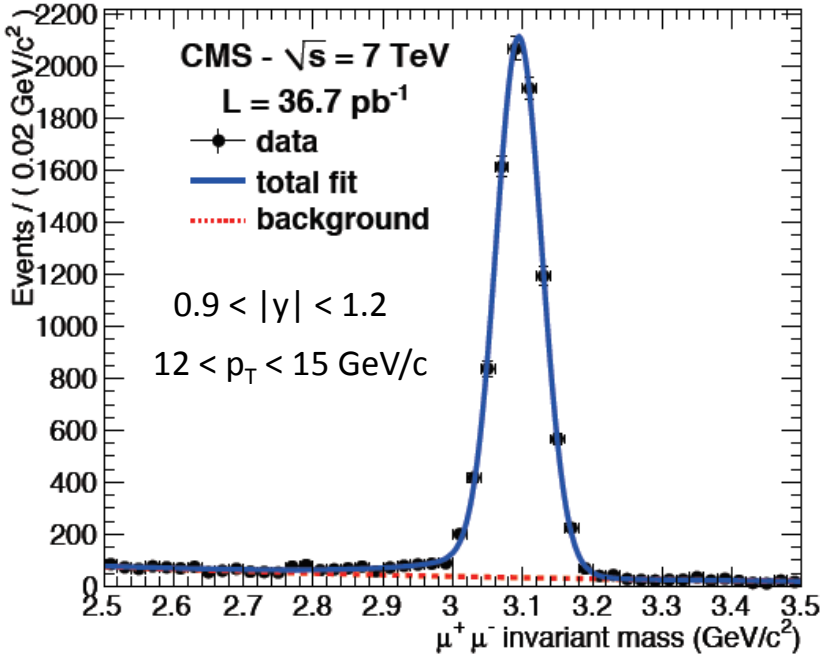
- Reconstruction and extraction of the signal yield (n_{sig}):
  - Optimized selection criteria requirements for event variables
  - Study of potential B background sources from MC
  - Expected sources of background: prompt J/ψ and non-prompt B background
  - 2D Maximum Likelihood fit to J/ψ ϕ invariant mass and proper decay length

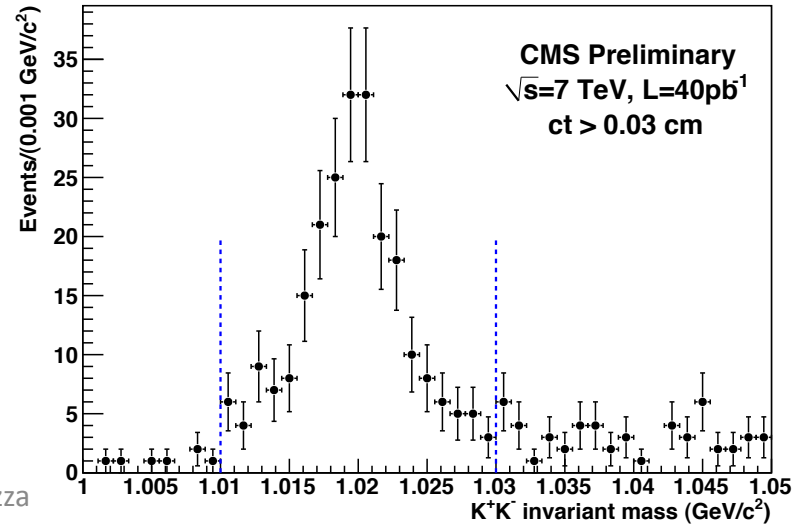
- Efficiency determination (ε):
  - Muon reconstruction efficiency – data driven
  - B_s/ϕ reconstruction efficiency – based on signal MC sample
  - Acceptance – based on signal MC sample

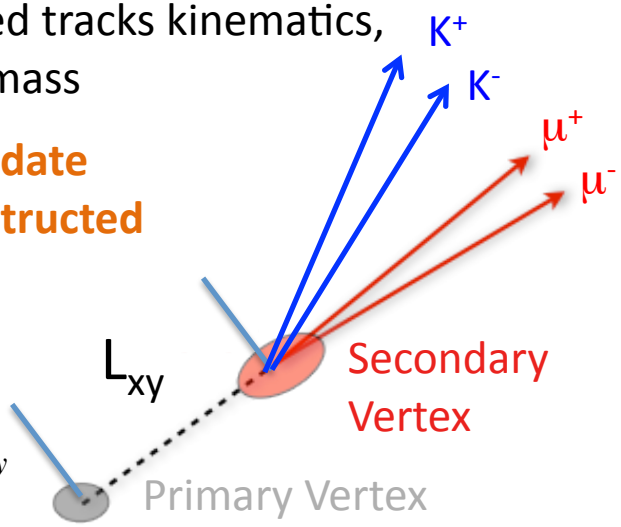
Reconstruction and B_s Selection

- Dimuon trigger with no threshold on p_T
- High quality muons combined to form J/ψ resonance
- Tight requirements on charged tracks (# hits, χ^2) with kaon mass hypothesis
- Kinematic fit to di-muon pairs and two charged tracks (di-muon pairs constrained to J/ψ mass value)
- Further requirements on vertex fit probability, charged tracks kinematics, di-kaon invariant mass

→ 6200 candidate events reconstructed







$$ct = c\frac{M_B}{p_T^B}L_{xy}$$

Fit Technique

- Extract the signal yield with a 2D unbinned maximum likelihood fit to B_s mass and proper decay length

$$L = \exp\left(-\sum_{1}^{3} n_i\right)\prod_{j}\left[\sum_{1}^{3} n_i P_i(M_B;\vec{\alpha}_i)\, P_i(ct;\vec{\beta}_i)\right]$$

- Three components in the fit: signal, non-prompt J/ψ, and prompt J/ψ
- PDFs extracted with data-driven method (except for signal B_s mass PDF – from MC)
- In the final fit all the parameters (except for the B_s mass) are free to float

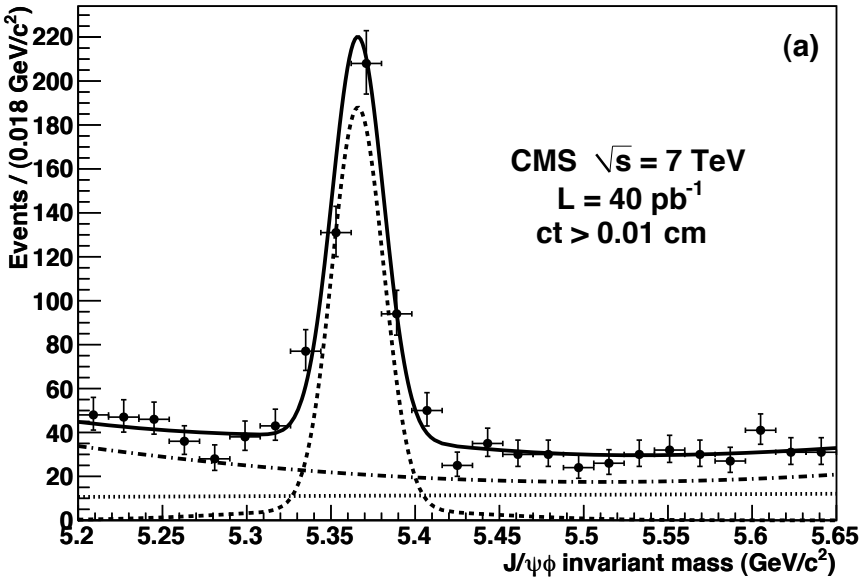
G = Gaussian

Category	J/ψ ϕ Inv. Mass	ct
Signal	$G_{core} + G_{tail}$	$R \otimes e^{-ct/\lambda}$
B background	2st Poly	$R \otimes (f e^{-ct/\lambda 1} - (1-f) e^{-ct/\lambda 2})$
Prompt J/ψ bkg	1st Poly	R

- We choose four p_T and four |y| bins to have equal samples in each, keeping a statistical uncertainty ~10 %

Fit Results

Performing 2D Maximum Likelihood fit:



$c\tau = 478 \pm 26\ \mu m$

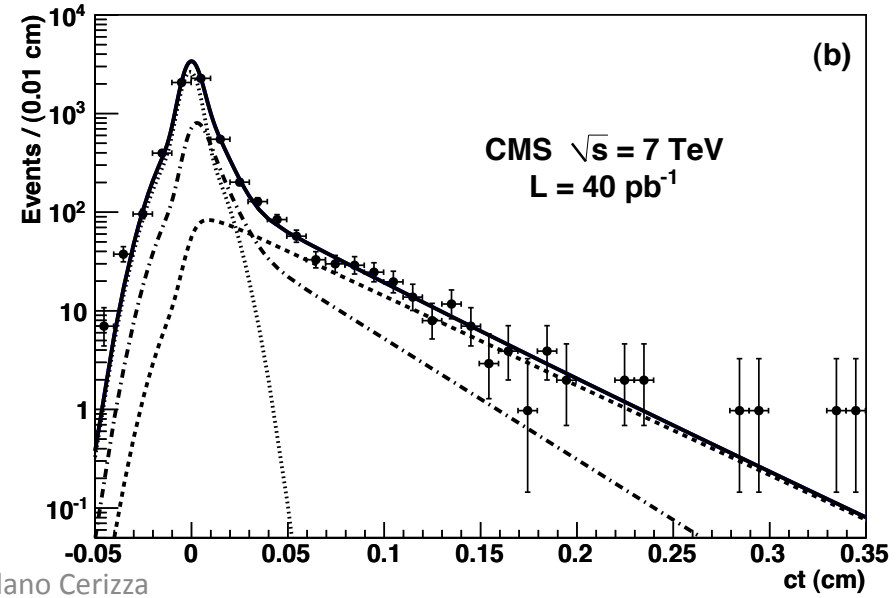
(fit with single exponential)

Accepted by
PRD-RC http://arxiv.org/abs/1106.4048

Signal yield extracted in the range
- $8 < p_T < 50$ GeV/c
- $|y| < 2.4$

$N_{sig} = 549 \pm 32$

Legend:
- ***Signal*** ------
- ***B background*** – · – ·
- ***Prompt J/ψ*** ·····

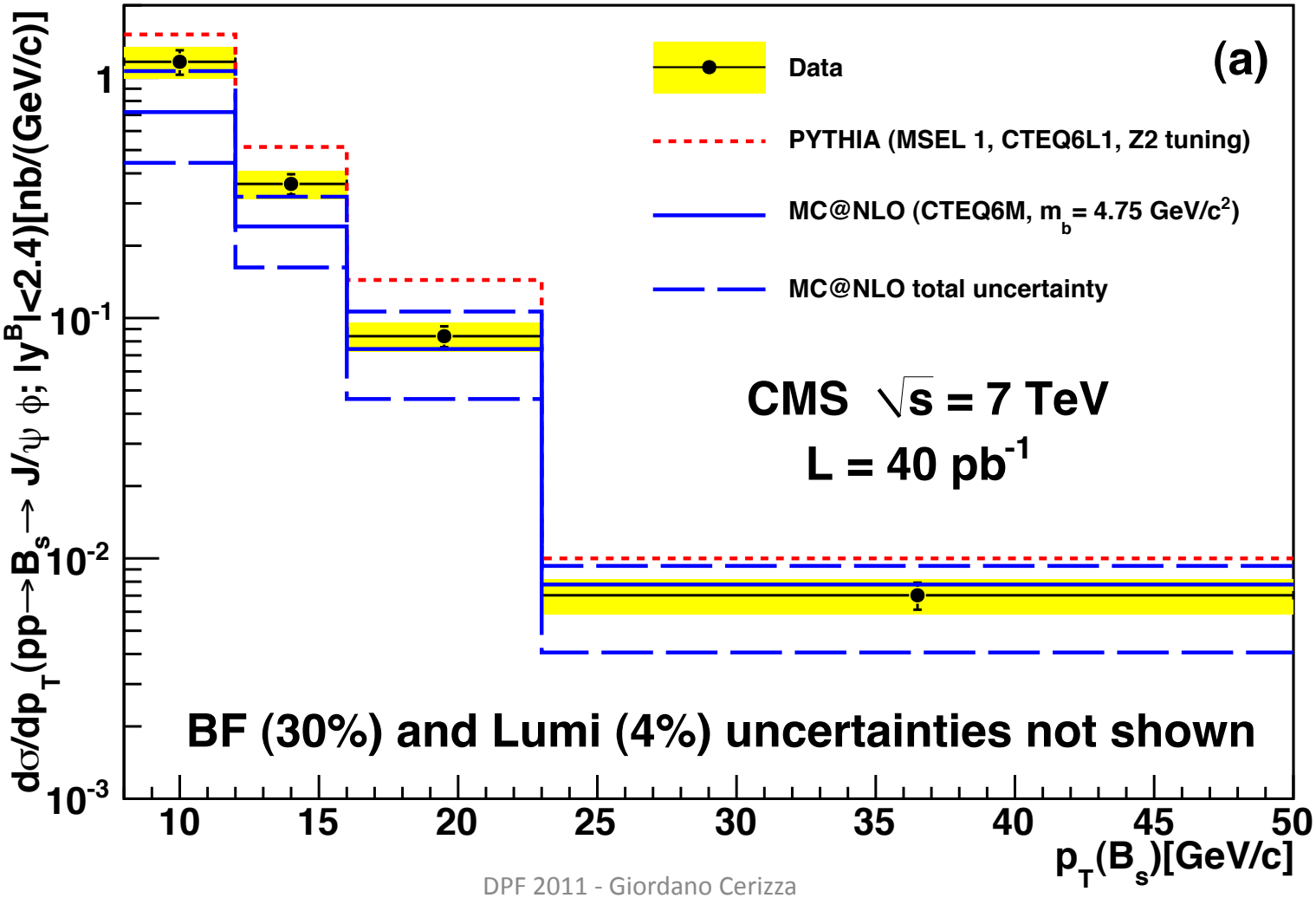


Systematics

Source	%
Muon Reconstruction Efficiency	3-5
Hadron Tracking Efficiency	7.8
Reconstruction Efficiency	2-3
Misalignment	2-4
p_T/y Spectrum	1-3
Probability Density Function	2-4
Uncorrelated Systematic Errors	**10-11**
Branching Fractions	1.4
Luminosity	4
Correlated Systematic Errors	**4.2**
Total Systematic Error	**11-12**

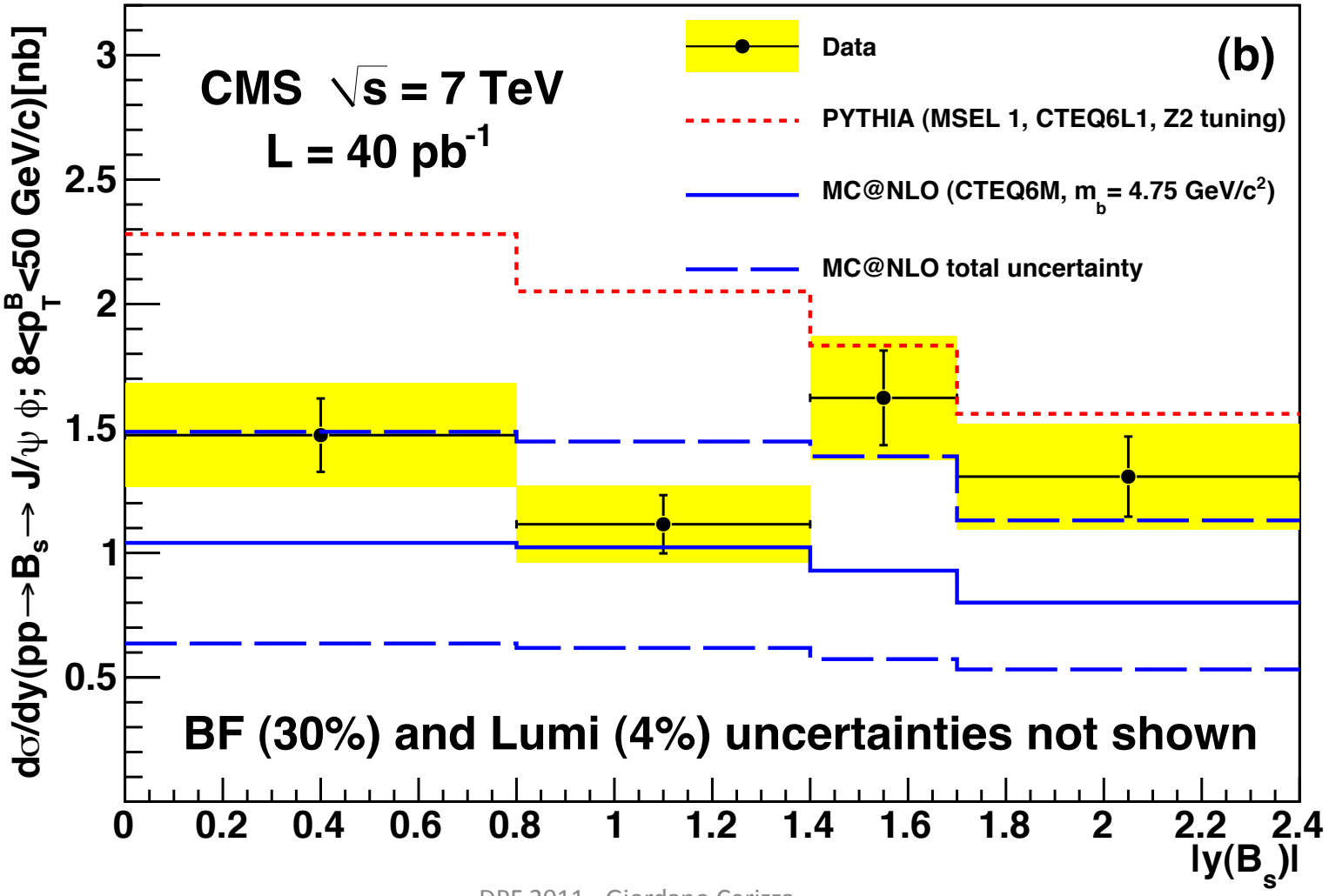
Differential Cross Section $d\sigma/dp_T$

(Accepted by PRD-RC http://arxiv.org/abs/1106.4048)



Differential Cross Section dσ/dy

(Accepted by PRD-RC http://arxiv.org/abs/1106.4048)



Differential Cross Section Results

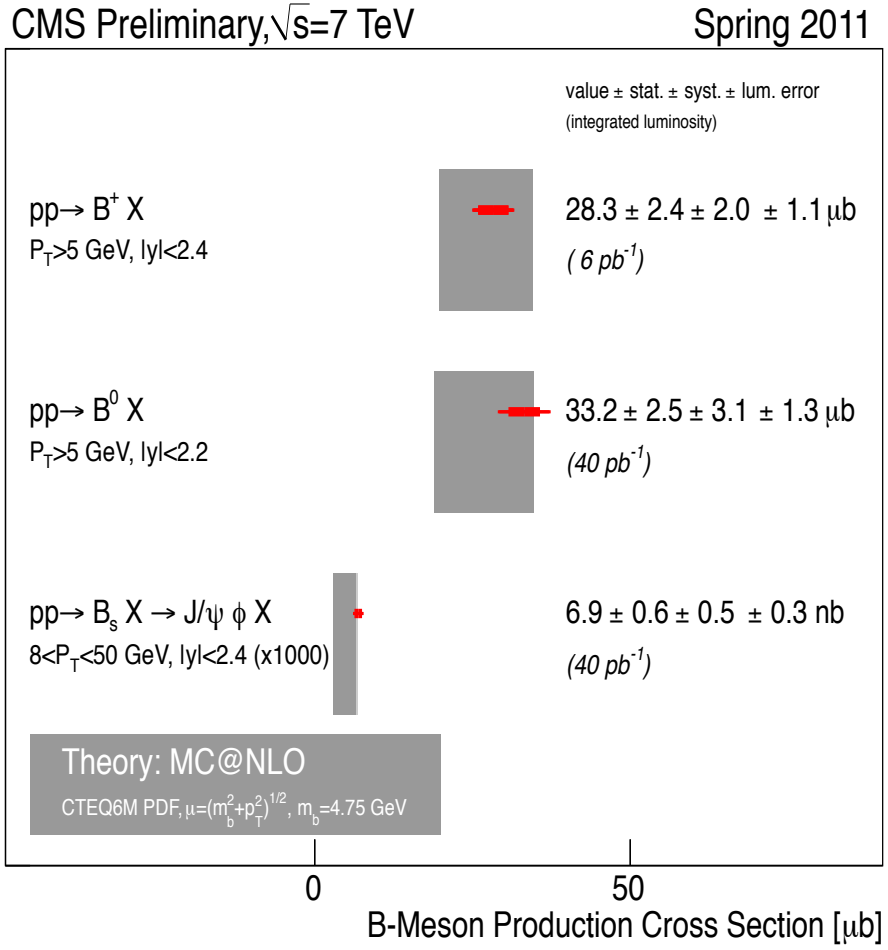
- Integrating the differential cross section over p_T bins:

$\sigma(pp \rightarrow B_s X) \times BF(B_s \rightarrow J/\psi\phi) =$
$(6.9 \pm 0.6_{(stat)} \pm 0.5_{(syst)} \pm 0.3_{(lumi)})$ nb

which is in agreement with the MC@NLO predictions:

MC@NLO:
$(4.57^{+1.93}_{-1.71(scale)} \pm 1.37_{(BF)})$ nb

- Results consistent with the other measured B-meson production cross sections



Measurement of the B+ Production Cross Section in pp Collisions at sqrt(s) = 7 TeV (PRL 106, 112001 (2011))

Measurement of the B0 Production Cross Section in pp Collisions at sqrt(s) = 7 TeV (PRL 106, 252001 (2011))

My Evaluation of BF($B_s \to J/\psi\,\phi$)

- For comparison we use HFAG/PDG2011 values for the fragmentation fractions and the BF measured by CDF [*PRD 54, 6596 (1996)*] published in PDF2011

- The BF is calculated from $B^+ \to J/\psi\, K^+$ and $B^0 \to J/\psi\, K^0_s$ cross sections:

$$BF(B_s^0 \to J/\psi\phi) = \frac{\sigma(pp \to B_S^0 \to J/\psi\phi)}{\sigma(pp \to B^{+,0}X)} \cdot \frac{f_{u,d}}{f_s} \cdot \frac{f_{kin}^{B^{+,0}}}{f_{kin}^{B_s}}$$

CMS cross-section measurements (PRL 106, 112001 & 252001, http://arxiv.org/abs/1106.4048)

Fragmentation fractions from HFAG/PDG2011

Kinematic correction ratio to extrapolate the full kinematic range from the limited p_T/η range (NLO generated events)

Fragmentation fractions from LEP+Tevatron

- $\Gamma(\bar{b} \to B_s) = (11.0 \pm 1.2)\%$
- $\Gamma(\bar{b} \to B^+) = (40.3 \pm 1.1)\%$
- $\Gamma(\bar{b} \to B^0) = (40.3 \pm 1.1)\%$

$$\frac{f_s}{f_{u,d}} = \frac{\Gamma(B_s)}{\Gamma(B^{+,0})} = (27.2 \pm 3.1)\ \%$$

Fragmentation fractions from Tevatron

- $\Gamma(\bar{b} \to B_s) = (11.1 \pm 1.4)\%$
- $\Gamma(\bar{b} \to B^+) = (33.9 \pm 3.1)\%$
- $\Gamma(\bar{b} \to B^0) = (33.9 \pm 3.1)\%$

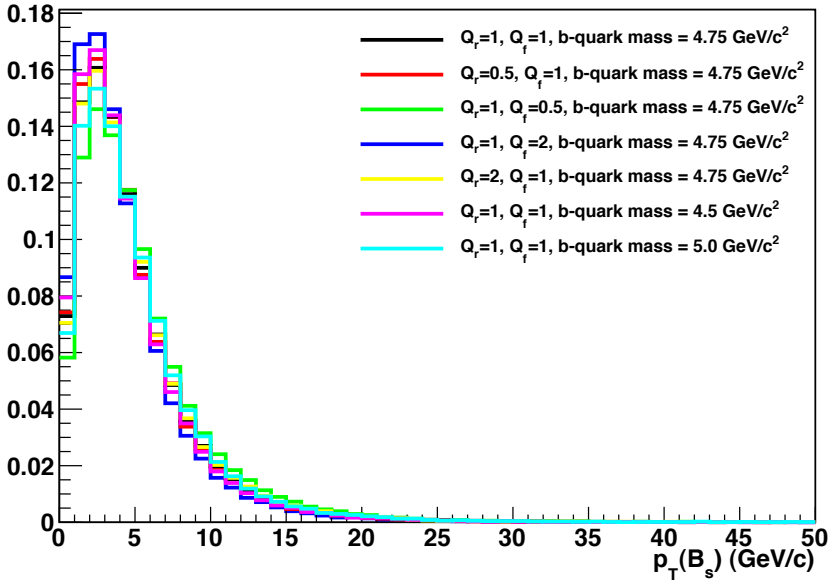
$$\frac{f_s}{f_{u,d}} = \frac{\Gamma(B_s)}{\Gamma(B^{+,0})} = (32.7 \pm 5.1)\ \%$$

Kinematic Correction Ratio

- Good agreement between NLO theoretical predictions and data for all the three B-meson cross sections

  → We use the central model (CTEQ6M, $Q_R=Q_F=1$, and m_b = 4.75 GeV/c^2) to predict the full kinematic range in p_T and y

- Varying the renormalization and factorization by factors of two and m_b from 4.5-5.0 GeV/c^2, ratios change less than 5%



Calculation

Source	$BF^{Bs\to J/\psi\,\phi}_{B+\to J/\psi\,K+}$	$BF^{Bs\to J/\psi\phi}_{B0\to J/\psi\,Ks}$
	Experimental Uncertainties	
Cross section	15.8%	16.5%
NLO spectrum	4.6%	4.3%
	PDG Uncertainties	
Branching fractions	3.5%	3.8%
Fragmentation fractions	11.2%	11.2%

The results obtained independently from the B^+ and B^0 analysis agree within one standard deviation. The error-weighted average is:

$$BF(B_s\to J/\psi\,\phi)= (1.8 \pm 0.2_{(exp)} \pm 0.2_{(PDG)}) \times 10^{-3}$$

$$BF(B_s\to J/\psi\,\phi)= (1.4 \pm 0.4_{(exp)} \pm 0.2_{(PDG)}) \times 10^{-3} \quad \text{(PDG2011)}$$

Using the fragmentation fractions from Tevatron, only:

$$BF = (1.5 \pm 0.2_{(exp)}) \times 10^{-3}$$

$$BF= (1.2 \pm 0.3_{(exp)}) \times 10^{-3} \quad \text{(PDG2011)}$$

Summary

- We presented the first measurement of $\sigma(pp \rightarrow B_s X) \times BF(B_s \rightarrow J/\psi\phi)$ at 7 TeV using the 2010 data in bins of p_T and rapidity y

- We find a value of $(6.9 \pm 0.6 \pm 0.5 \pm 0.3)$ nb that is in agreement with MC@NLO within the uncertainties
(accepted by PRD-RC http://arxiv.org/abs/1106.4048)

- The $BF(B_s \rightarrow J/\psi\ \phi)$ calculated via the CMS exclusive-B cross section measurements is in agreement with the PDG value

- We are working towards a lifetime difference measurement of the B_s mesons in 2011