B-Physics at CMS

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(ETH Zurich)
On behalf of the CMS Collaboration

- Introduction
- Selected new results
  - Exclusive b-hadron production
  - Discovery of new Ξ_b -state
  - Inclusive b-production
  - Search for $B_s \rightarrow \mu\mu$
- Concluding remarks

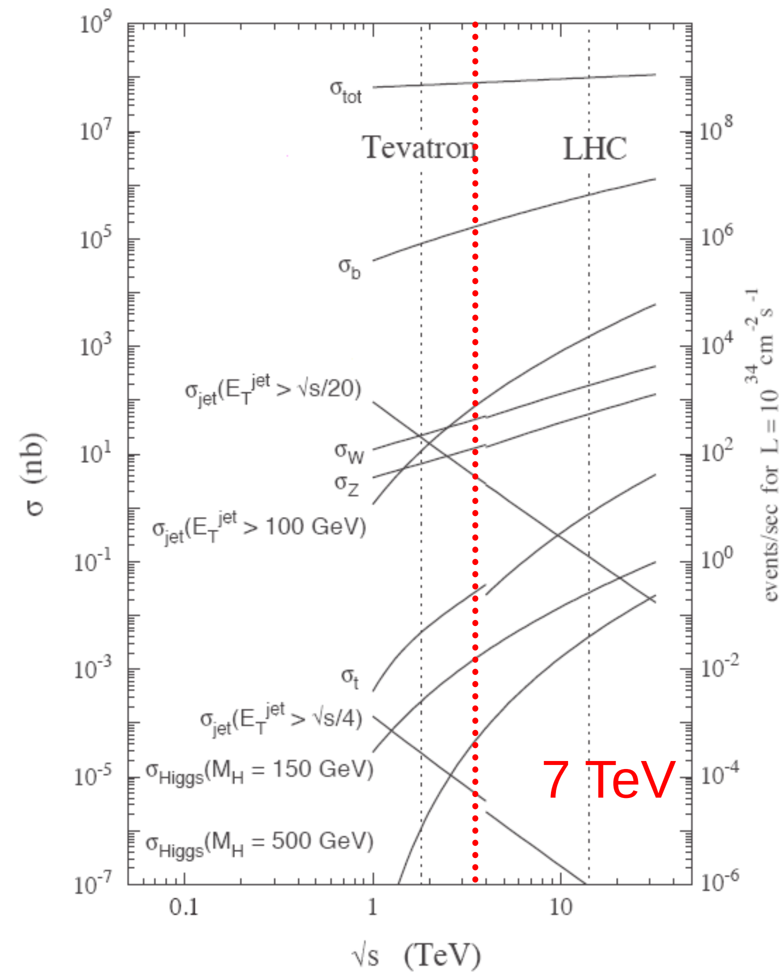
ICFP 2012

b-quark Production at LHC – WHY ?

- Open b-production is an excellent **test of perturbative QCD** & models in new phase space
  →**understand production dynamics**

- b-quark production is **a tool** for and constitutes a **major background in many searches for new physics**
  - Topology of final-state b quarks relevant to reject background for searches

- CMS detector is well suited :
  - **excellent tracking and vertexing**
  - **muon id, flexible trigger**

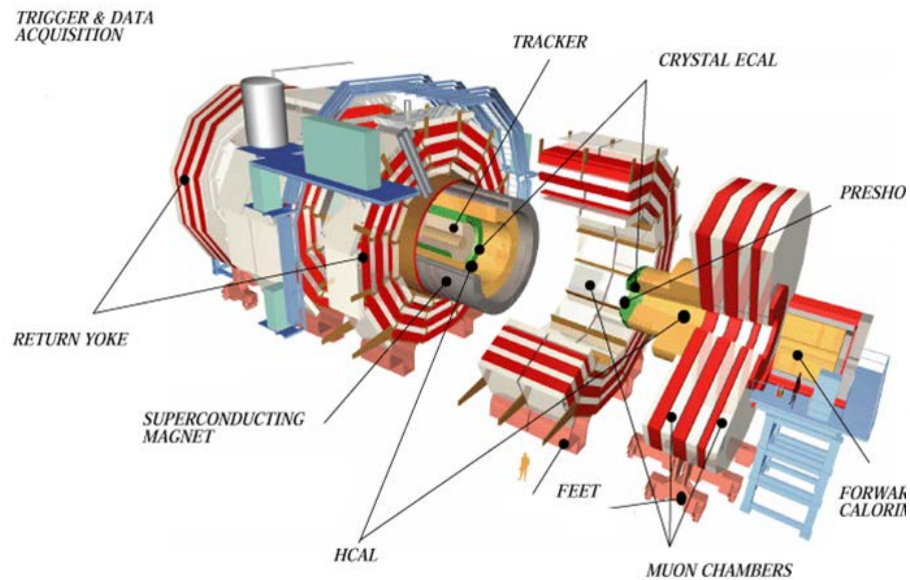


Beauty production cross section is large
$\sigma(pp \rightarrow bb) \sim 250$ [μb] @7 TeV [270 (8 TeV); 457 (14TeV) [μb], MC@NLO]

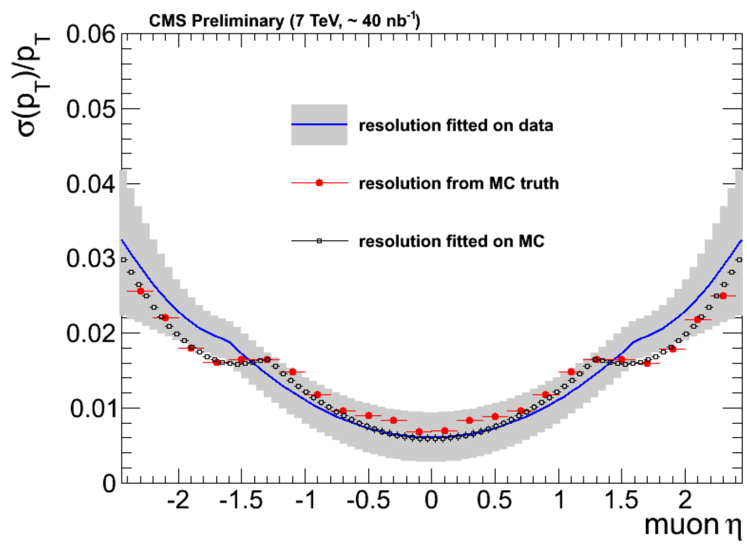
> 10^{12} bb pairs produced so far in CMS

Introduction

- b-production profits from excellent performance of CMS detector
- Main sub-detectors for B-physics: Si tracker and muon detectors
- Excellent tracking → momentum + vertex
- Sophisticated b-tagging algorithms
- Flexible HLT trigger: allows specialized (μ/ di-μ) triggers at high ε&P

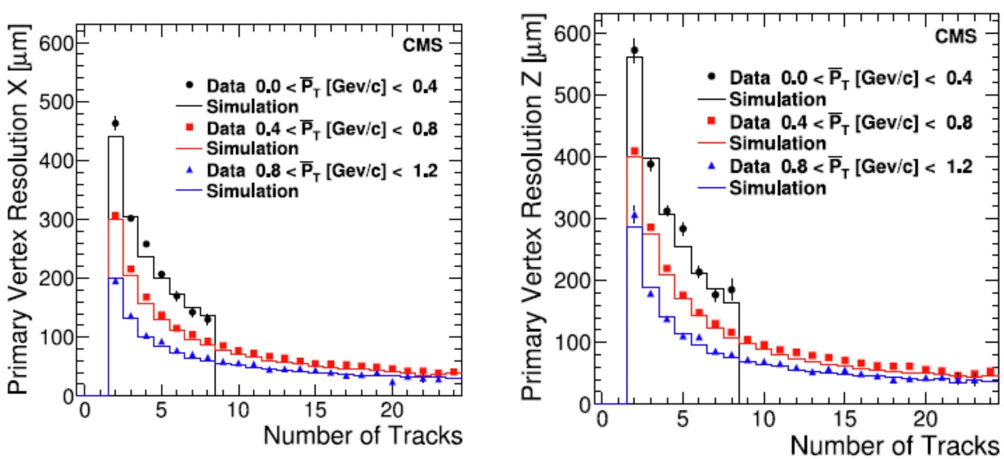


Muon momentum resolution



CMS-PAS-TRK-10-004/5

Vtx-resolution in x and z



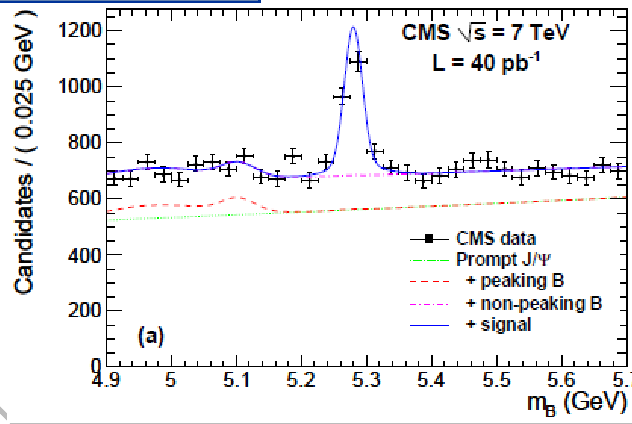
EPJ C70, 1165

Results on b-production

Exclusive b-Hadron Production

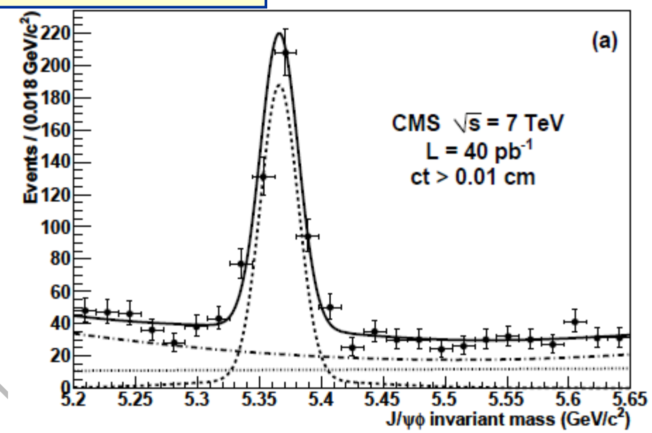
b-hadron Production : the “Harvest”

$B^0 \to J/\psi\ K_S$



Phys. Rev. Lett. **106** (2011) 252001

$B_S^0 \to J/\psi\ \phi$



Phys. Rev. **D84** (2011) 052008

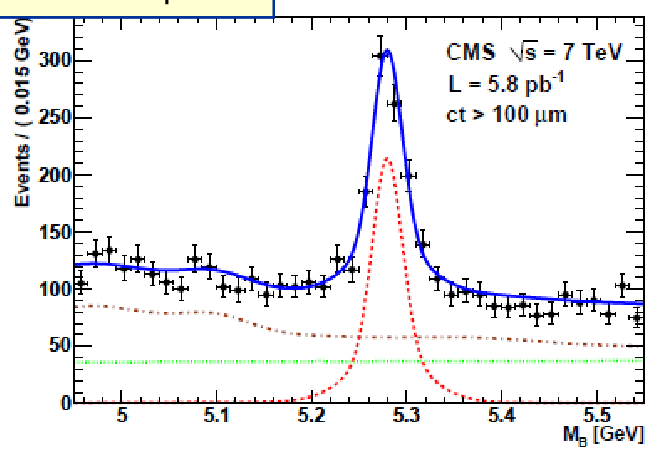
$J/\psi \to \mu^+\mu^-$

$\phi \to K^+K^-$

$K_S \to \pi^+\pi^-$

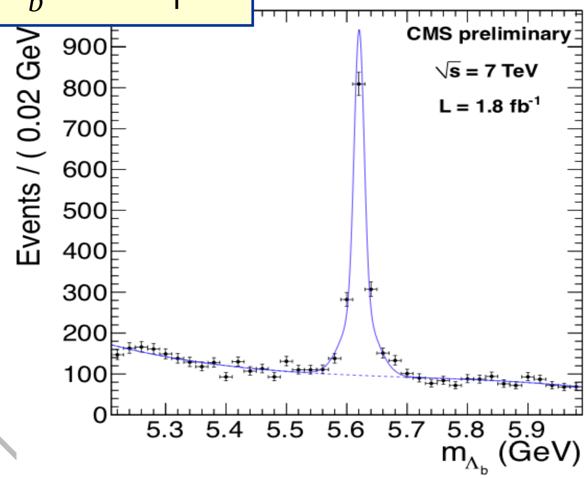
$\Lambda \to p^+\pi^-$

$B^+ \to J/\psi\ K^+$



Phys. Rev. Lett.**106** (2011) 112001

$\Lambda_b \to J/\psi\ \Lambda$



CMS-PAS-BPH-12-007; accepted by. PLB

B-hadrons – Analysis Strategy

PRL106(2011)252001

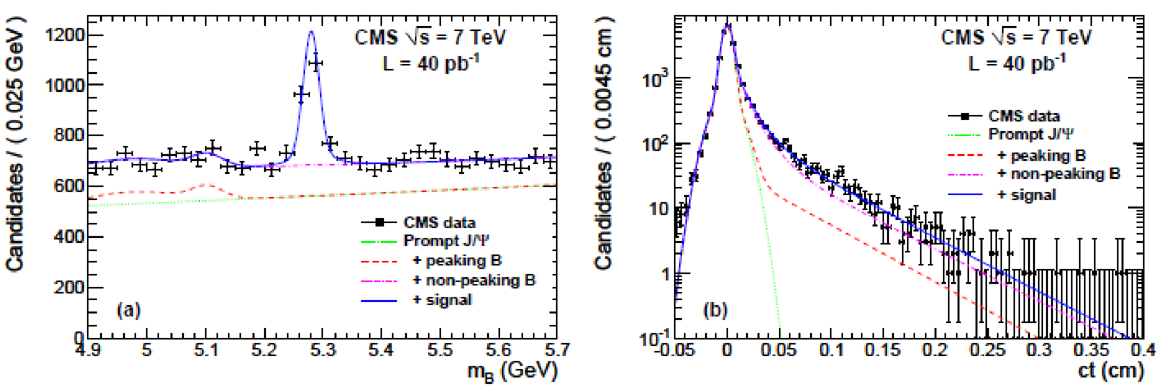
- Similar strategy for all b-hadron modes
- Signal extracted bin by bin by unbinned extended maximum likelihood fits to mass (m_B) and lifetime $c\tau=(m_B/p^B_T)\ L_{xy}$ distributions.

$$\mathcal{L} = \exp\left(-\sum_i n_i\right) \prod_j \left[\sum_i n_i \mathcal{P}_i(M_B; \vec{\alpha}_i)\mathcal{P}_i(ct; \vec{\beta}_i)\right]$$

- Fitting to (3(B_S), 4(B^0), or 5 (B^+)) components
  - Signal events, prompt J/ψ events, non-prompt J/ψ (peaking and non-peaking), bb-peaking
  - Shapes of PDFs (P) signal and background taken from data where possible, else MC
  - Mass resolution for B typically 20 MeV; core cτ resolution ~45-50 μm;

$B^0 \rightarrow J/\psi\ K_S$

(example)

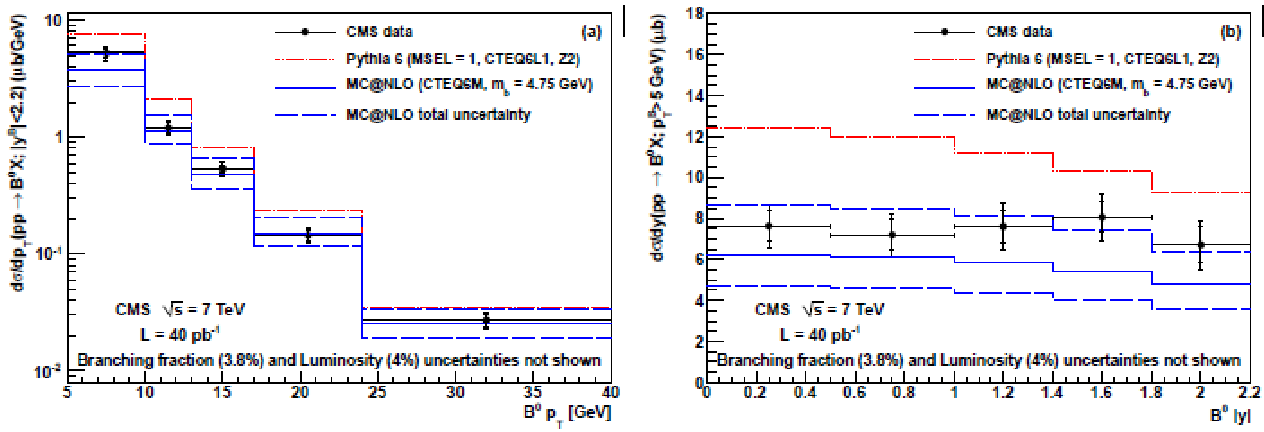


Systematics dominated by :
- PDF parameters
- K_S and B selection
- Correlations m to cτ small
- Some BR not well known

B-hadrons: Cross sections in p_T & y

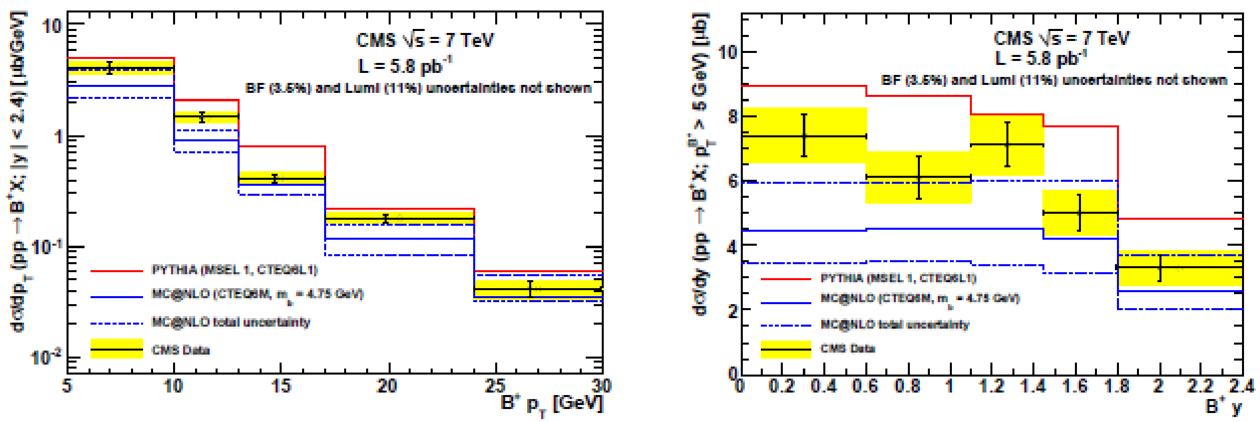
$B^0 \rightarrow J/\psi\, K_S$

PRL106(2011)252001



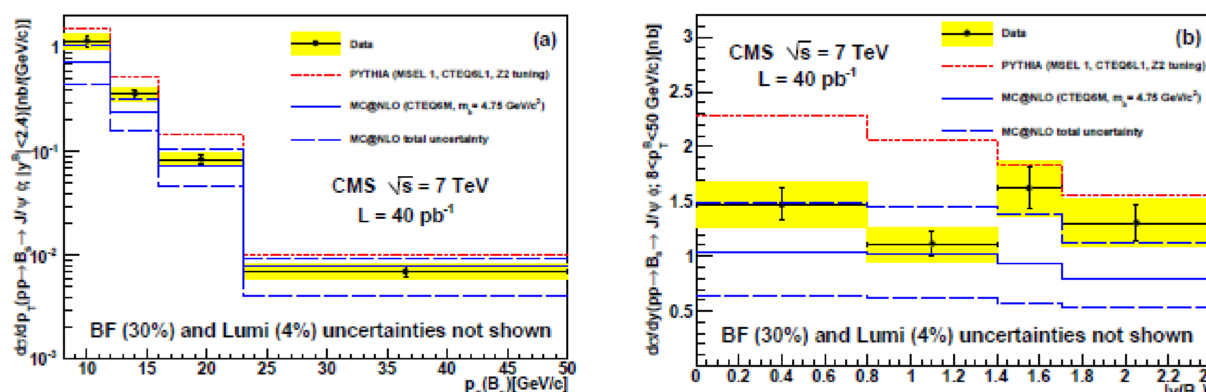
$B^+ \rightarrow J/\psi\, K^+$

PRL **106** (2011) 112001



$B^0_S \rightarrow J/\psi\, \phi$

Phys. Rev. **D84** (2011) 052008



Pythia: too high,
different y-shape;
MC@NLO: too low,
shape ok…

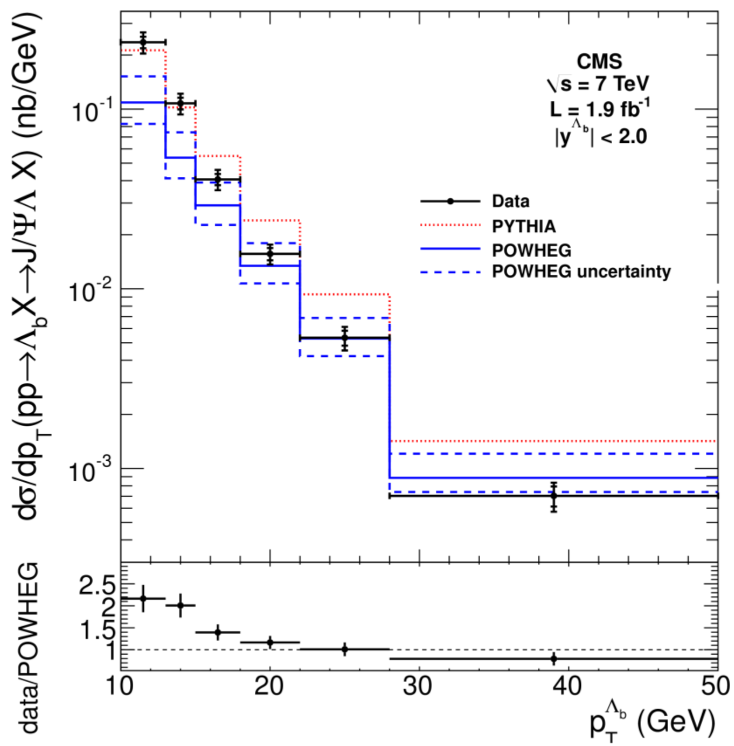
Λ_b : p_T & y differential cross section

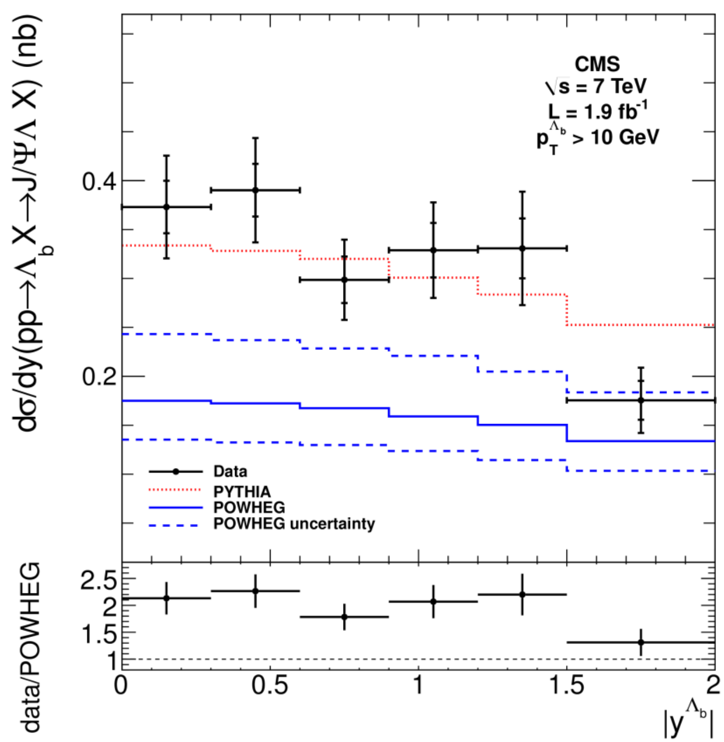
$\Lambda_b \rightarrow J/\psi\ \Lambda$

$\Lambda_b \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\Lambda^0(\rightarrow p^+\pi^-)$

arXiv:1205.0594; accepted by PLB

- Signal extracted bin-wise by unbinned 1D extended.ML fits to Λ mass .
- BR($\Lambda_b \rightarrow J/\psi\ \Lambda$) = $5.7\pm3.1\times10^{-4}$: correlated among bins, and not shown in plots





p_T > 10 GeV
$|y_B|$ < 2.0.

- Predictions: harder in p_T; Pythia overestimates at high pT; Powheg below data; y shape agrees well

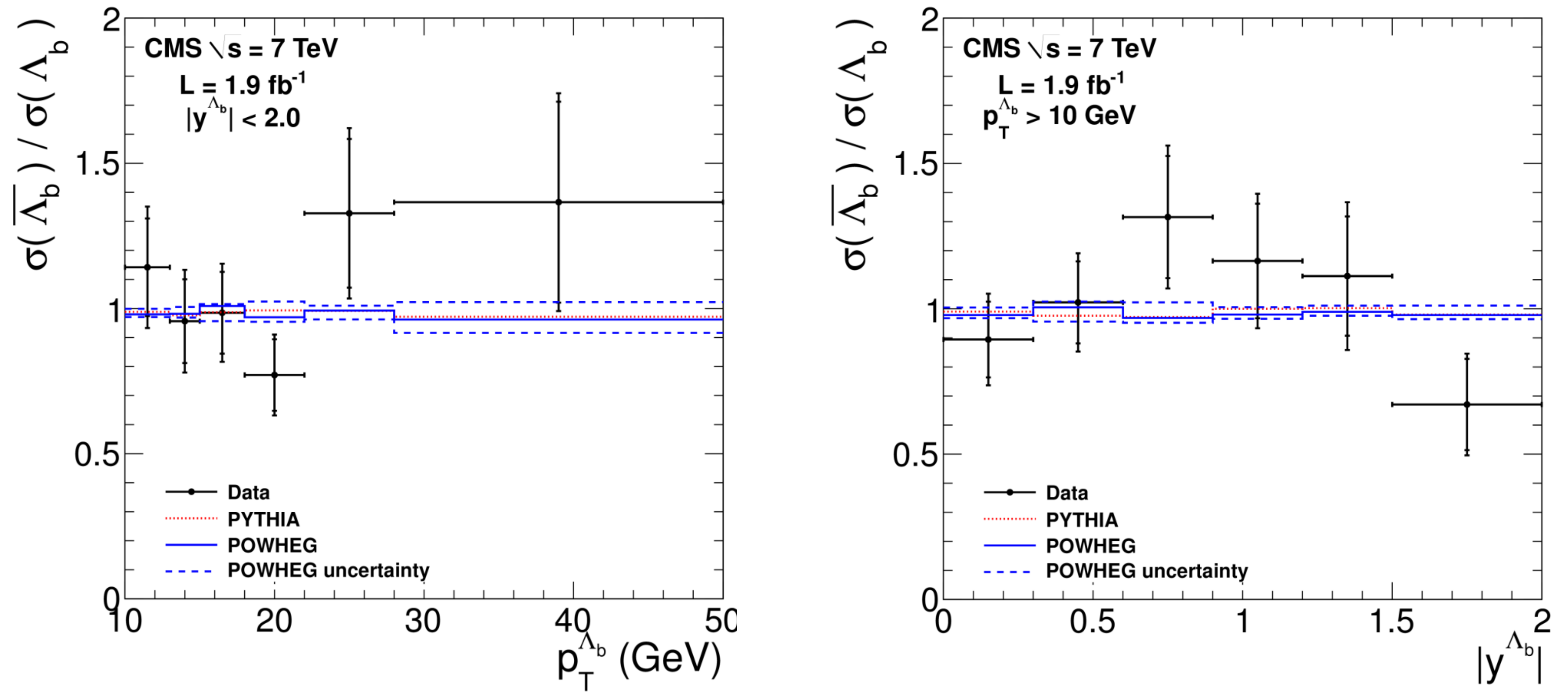
Λ_b : Particle to anti-particle ratio

$$\Lambda_b \to J/\psi\,\Lambda$$

arXiv:1205.0594; accepted by PLB

$$\frac{\sigma(\bar{\Lambda}_b)}{\sigma(\Lambda_b)} = \frac{N(\bar{\Lambda}_b)}{N(\Lambda_b)} \times \frac{\varepsilon(\Lambda_b)}{\varepsilon(\bar{\Lambda}_b)}$$

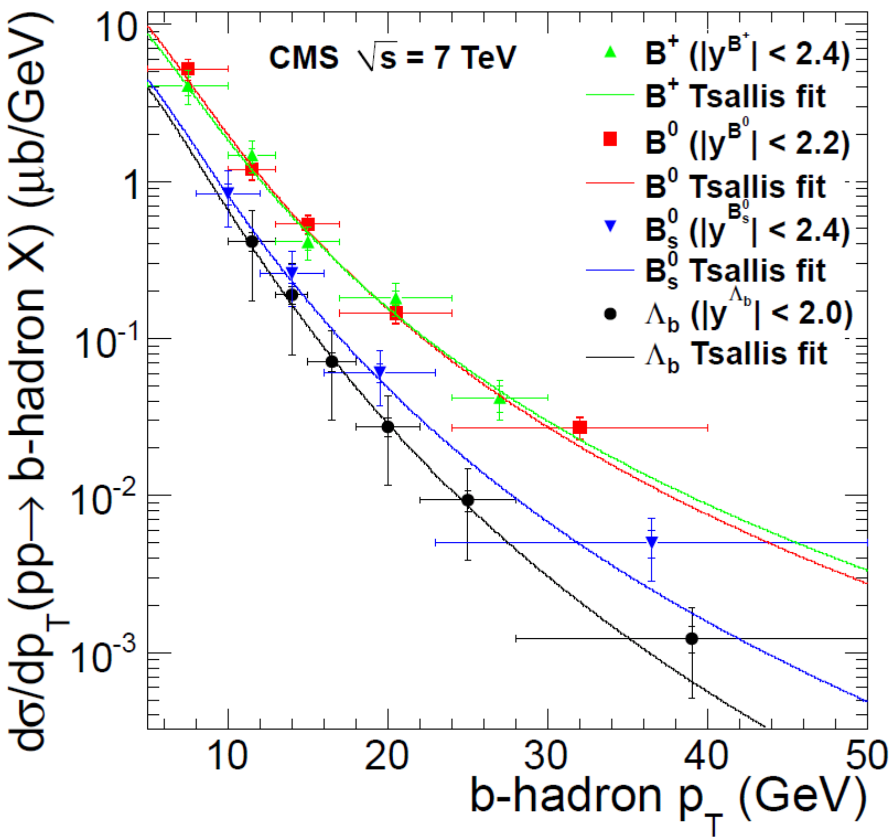
- Extract ratio in bins of pt and y from
- Efficiency (anti-Λ_b) is ~13 % lower than efficiency (Λ_b) (due to p NI)

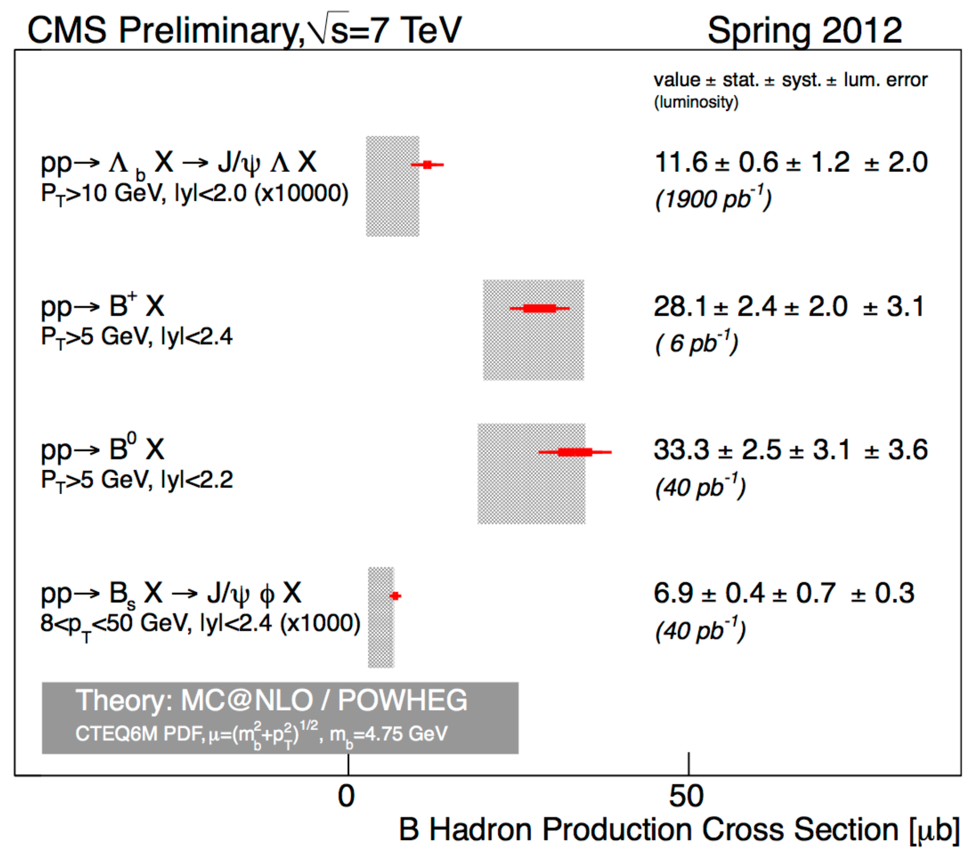


- Ratio appears flat in p_T and y

Summary exclusive b-hadron production

arXiv:1205.0594; accepted by PLB
Phys. Rev. Lett.**106** (2011) 112001
Phys. Rev. Lett. **106** (2011) 252001
Phys. Rev. **D84** (2011) 052008



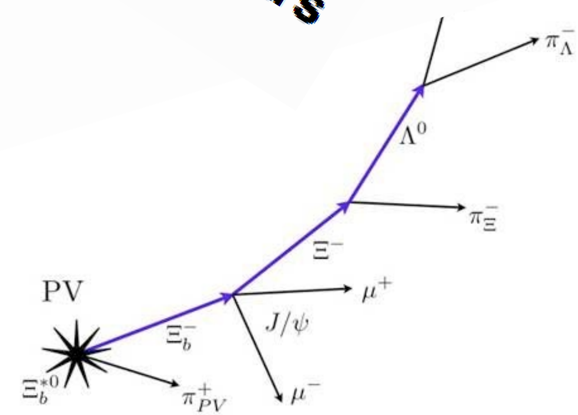


- Λ_b baryon steeper in p_T than B-mesons
- Outer errors: normalization added (dominated by branching ratio error)
- Integrated cross sections for b-hadrons
- NLO predictions compatible within errors tendency to be below data

Discovery of new Ξ_b -state

b-hadrons : Observation of NEW b-hadron …

Ξ_b^{*0}

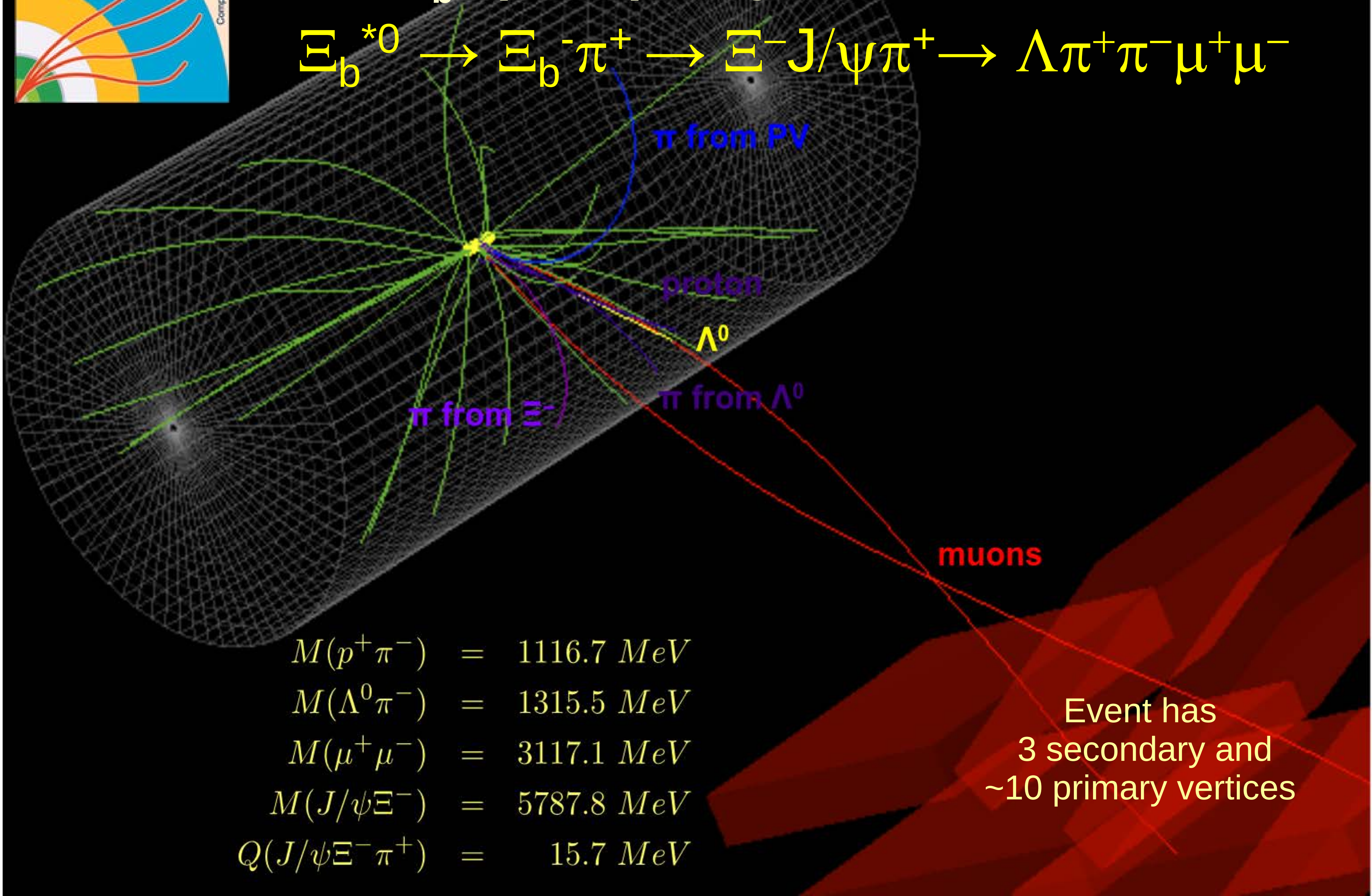


arXiv:1204.5955;
accepted by PRL

First observation of a new Ξ_b^0 (5945) baryon

CMS Experiment at LHC, CERN
Data recorded: Thu Oct 13 05:38:12 2011 CEST
Run/Event: 178421 / 533709680

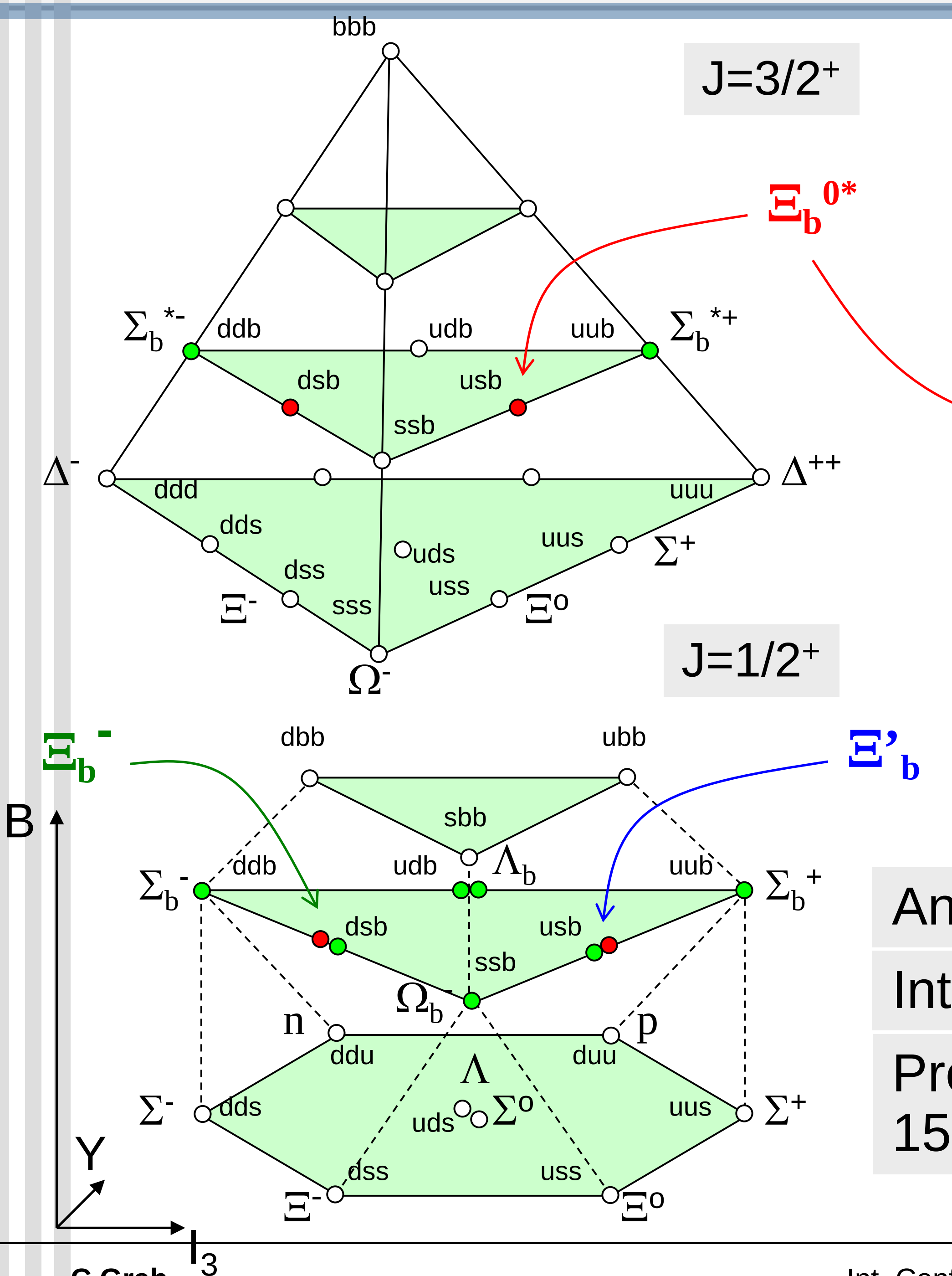
$$\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+ \rightarrow \Xi^- J/\psi \pi^+ \rightarrow \Lambda \pi^+ \pi^- \mu^+ \mu^-$$

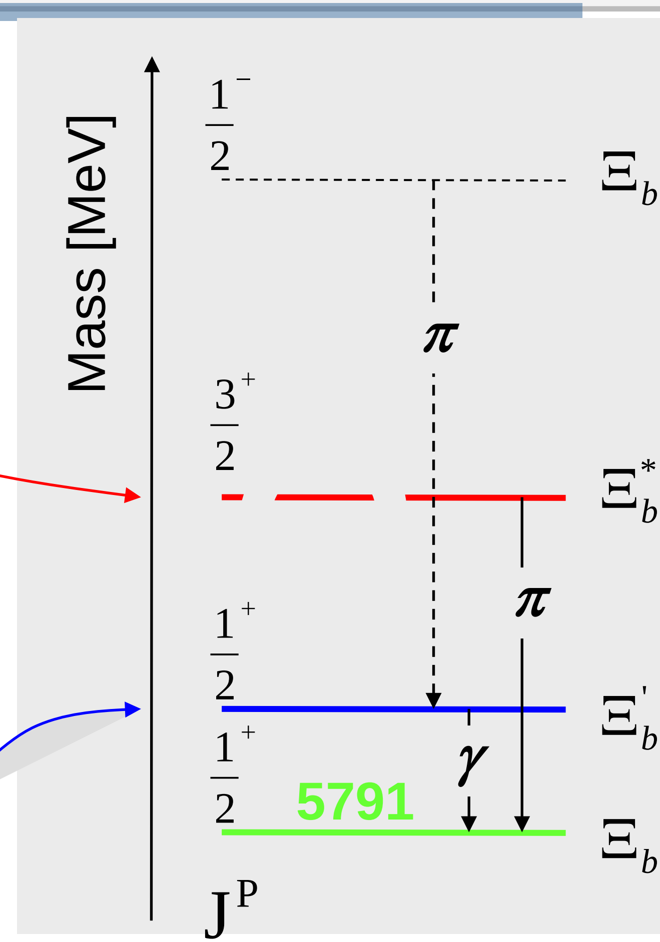


$$
\begin{aligned}
M(p^+\pi^-) &= 1116.7\ MeV \\
M(\Lambda^0\pi^-) &= 1315.5\ MeV \\
M(\mu^+\mu^-) &= 3117.1\ MeV \\
M(J/\psi\Xi^-) &= 5787.8\ MeV \\
Q(J/\psi\Xi^-\pi^+) &= 15.7\ MeV
\end{aligned}
$$

Event has
3 secondary and
~10 primary vertices

b Baryon States





?

Analog to charmed baryon spectrum

Inter-quark potential + color hyperfine

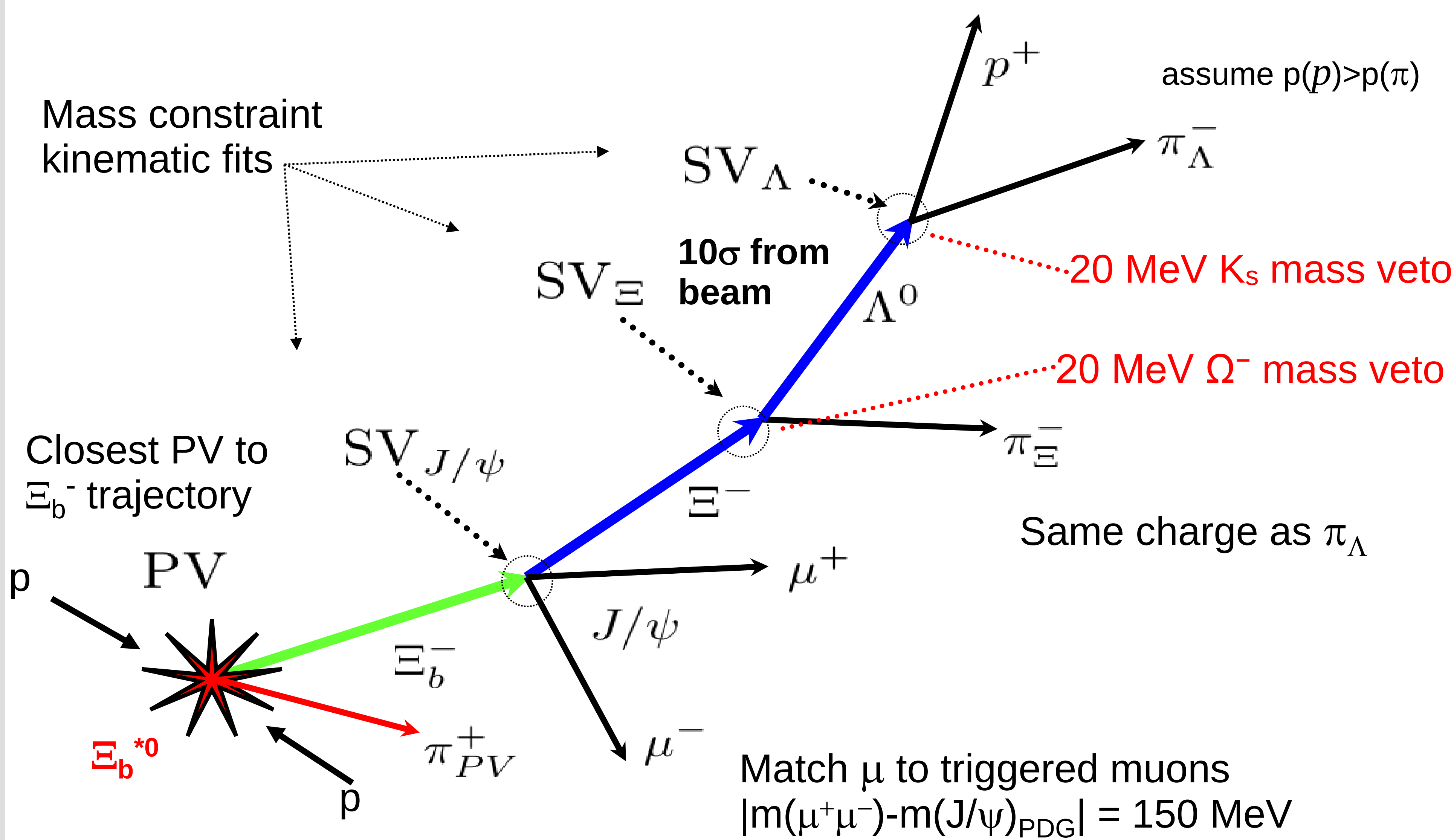
Predicted masses for higher states:
150 – 160 MeV higher; width ~ 1MeV

Korner 94, Karliner 09, Jenkins 97,08;

Ξ_b^{*0} Decay Chain Reconstruction

$\Xi_b^{*0} \rightarrow \Xi_b^{-}\pi^{+} \rightarrow \Xi^{-}J/\psi\pi^{+} \rightarrow \Lambda\pi^{+}\pi^{-}\mu^{+}\mu^{-}$

arXiv:1204.5955;
accepted by PRL

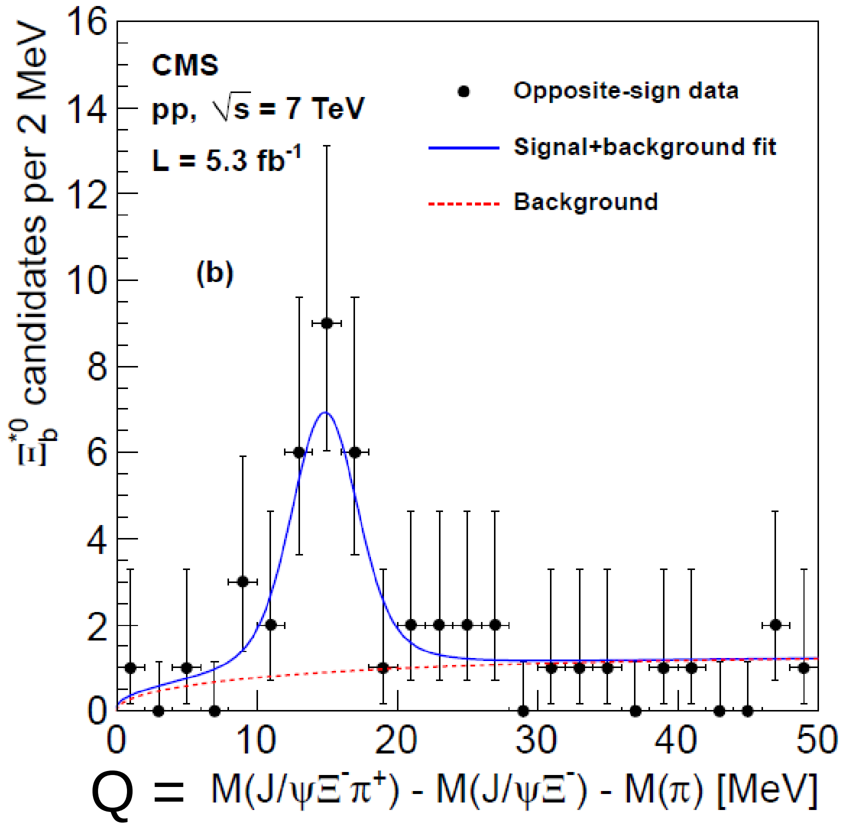


Ξ_b^{*0} - Results

arXiv:1204.5955; accepted by PRL

Signal from ML fit to RS combination using BW x Gauss (σ=1.9±0.1 MeV from MC)
BGND: WS combinatorial background

→ 21 events observed
BGND expected 3.0 +- 1.4



Width: Γ_{BW} = 2.1±1.7 MeV
(Theory: 0.93 MeV)
Mean: Q = 14.84 + 0.74 MeV
Significance: 6.9 σ

Other b-hadrons (B^0, B^+, B_s, Λ_b) excluded as background by MC

Systematic Uncertainties
- different background models
- differences data – simulation

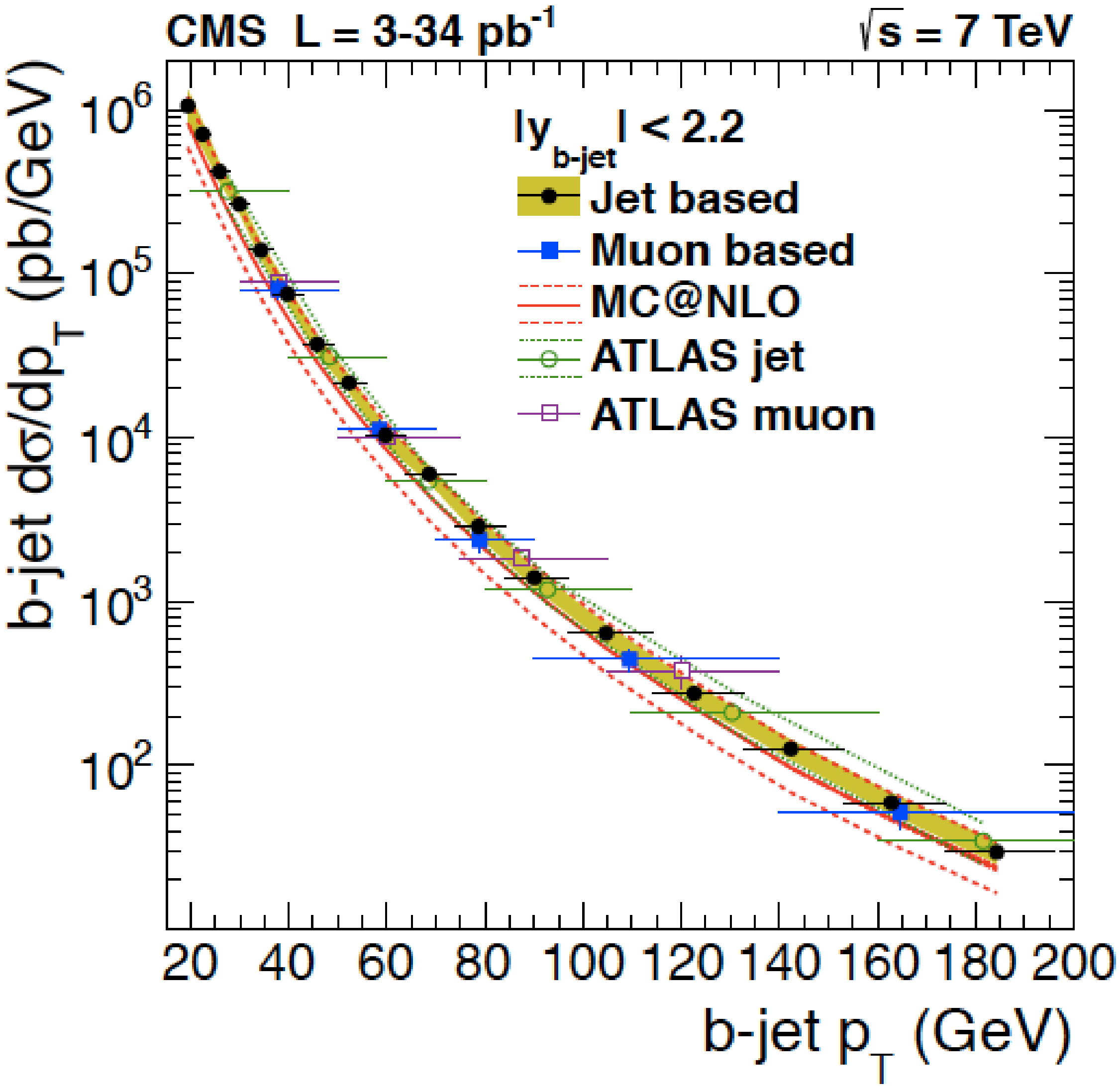
→ $m = 5945.0 \pm 0.7_{stat} \pm 0.3_{syst} \pm 2.7_{PDG[m(\Xi^b)]}$ MeV

.. the first particle discovered by CMS, and the first b-baryon @ LHC

Inclusive b-jet production

- Muon based analysis: with muon pT_rel
- Jet-based using 2nd vertex b-tagging

Inclusive b-jets - jets and muons

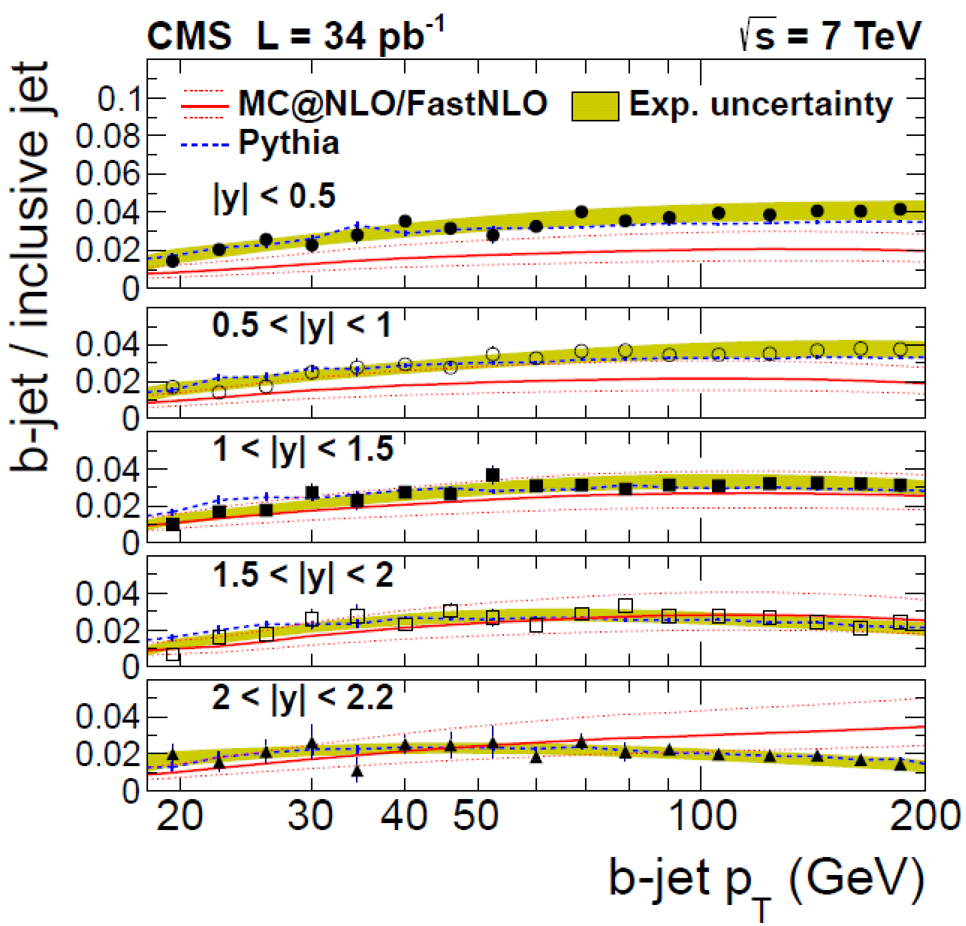


- Muon result extrapolated
- Agreement between jet based (2[nd] vtx b-tag) and muon based (pT-rel) analyses
- Good agreement between CMS and ATLAS
- NLO predictions agree within errors
- Some discrepancies in high p_T & $|\eta|$.

arXiv:1202.4617 accepted by JHEP

Ratio of b-jets to Inclusive Jets

- Reduces experimental uncertainty due to jet energy reconstruction and luminosity
- Dominant systematics are b-tag efficiency and sample purity
- Theory:
  use MC@NLO for b-jets and FastNLO for inclusive jets



- Fraction of b-jets increases by up to factor 2x for high p_T

- Pythia: agrees well within errors
- NLO tends to be below data in central region; but above in high p_T and high y

arXiv:1202.4617
accepted by JHEP

Measurement of ***bb pair*** production

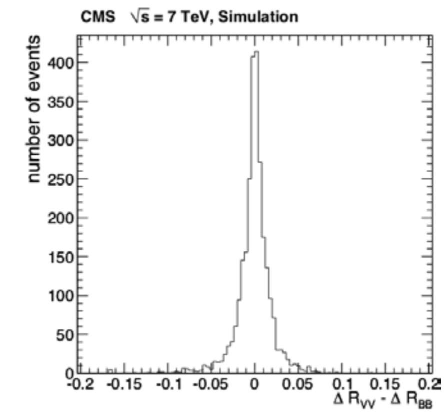
- two B hadrons via decay vertices
- two muons from b decays

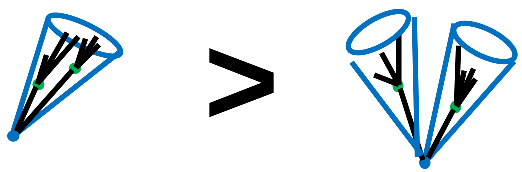
Angular Correlations in pp → BBbar X

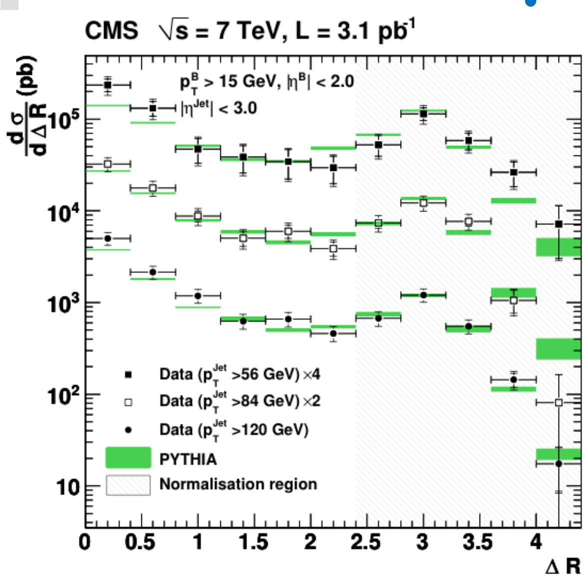
JHEP **1103** (2011) 136

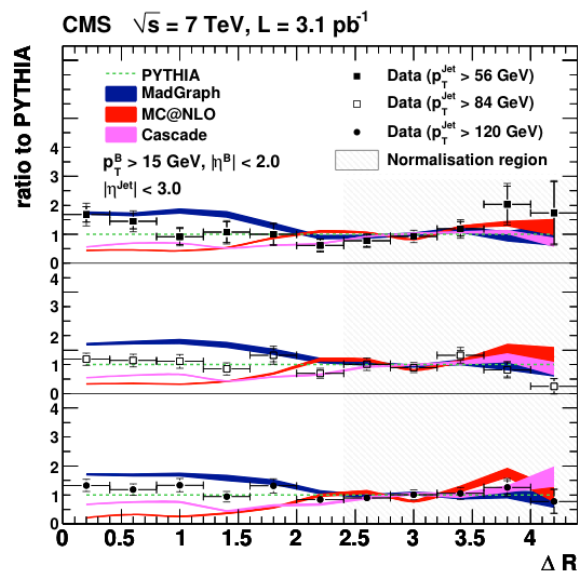
Dedicated Inclusive Vertex Finder:
reconstructs secondary vertices; **no jets**;

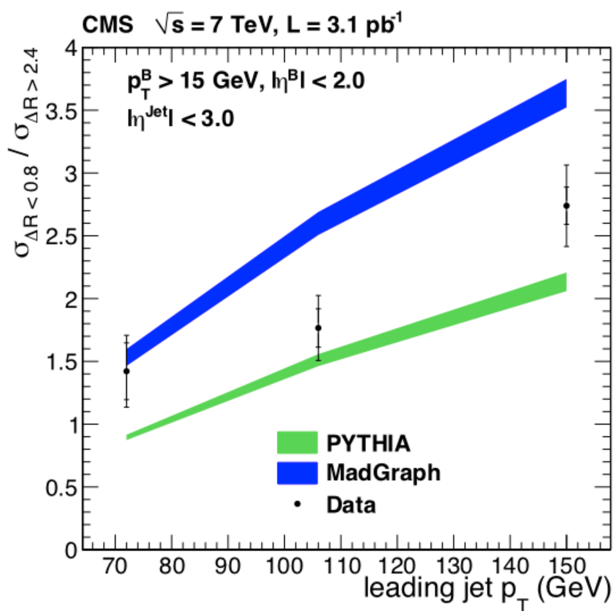
- Low efficiency (~10% total for BB) but **high angular precision (0.02 rad)** .
- **Allows to study smaller angular separations**.









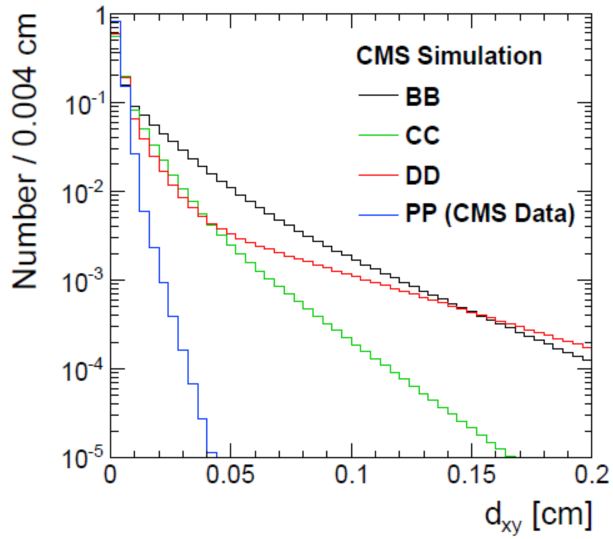


Small angular separation region dominant → collinear emission processes !

- **None of the predictions describe data accurately at small ΔR.**

bb-production in dimuons: pp→bb →μμX

→ *very precise cross section measurement*

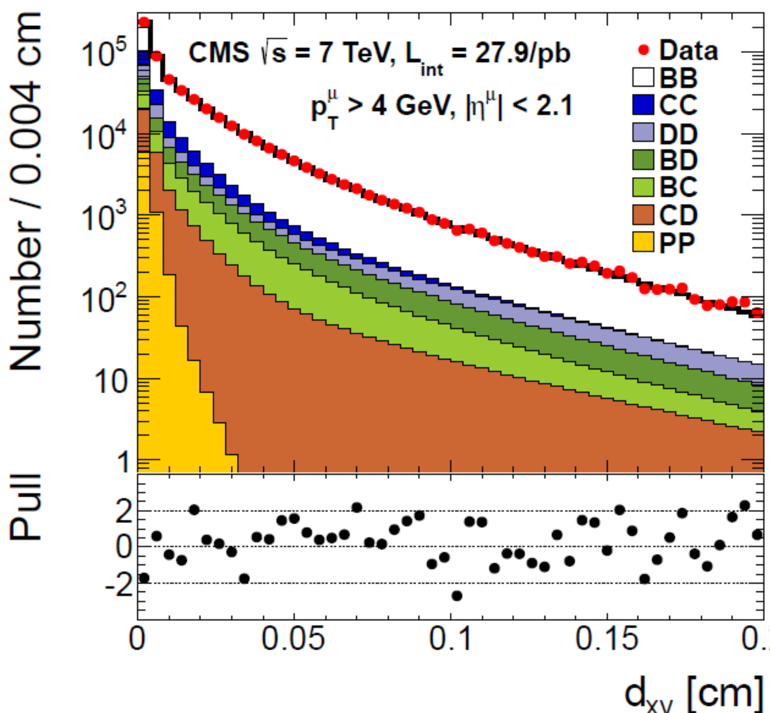


***Select* pairs of muons** with p_T> 4 GeV
Select 5 GeV < m(μμ) < 70 GeV,+ veto Upsilon
Separate four sources using **mu impact par. d_{xy}**

- (B) b → X
- (C) charm
- (P) prompt muons (DY, resonances)
- (D) light hadron decay-in-flight

Extract signal by binned ML-fit to data in 2D, using the 1D symmetrized d_{xy} templates:

- take B,C,D from simulation, P from data



Data: = 25.7±0.1 (stat) ± 2.2(syst) ± 1.0 (lumi) nb
MC@NLO=19.7±0.3(stat) $^{+6.5}_{-4.1}$(syst) nb
Pythia (LO) = 48.2 nb

- **systematics limited :** largest syst. uncertainty from muon efficiency and model dependency
- MC@NLO agrees within uncertainty, below data

arXiv:1203.3458 , sub. to JHEP

Search for $B_s \rightarrow \mu\mu$

B→ μμ : Why look for it ?

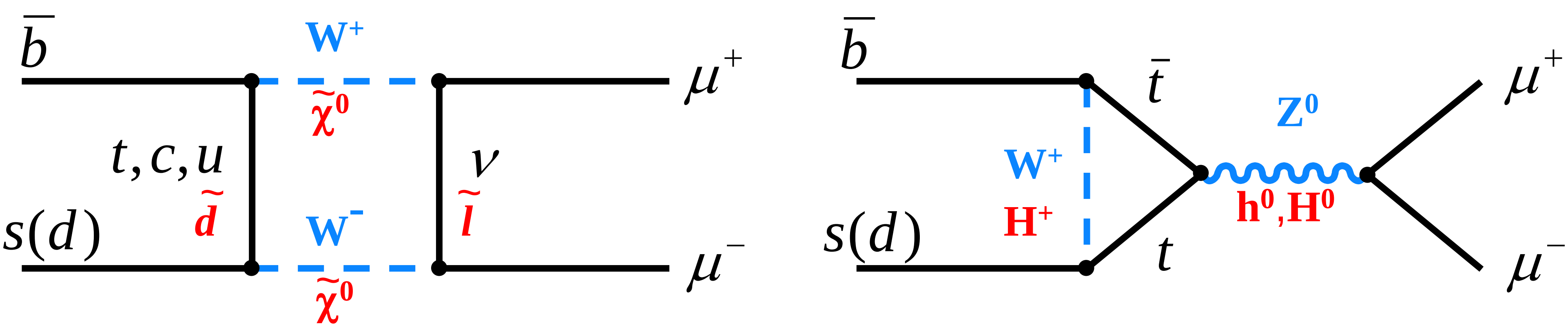
$B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ are strongly suppressed in the **SM**

- Strictly forbidden at tree level
- effective FCNC, helicity suppressed
- require an internal quark annihilation

Buras arXiv:1009.1303.

Decay	BF SM
$B_s^0 \rightarrow \mu^+\mu^-$	$(3.2 \pm 0.2) \times 10^{-9}$
$B^0 \rightarrow \mu^+\mu^-$	$(1.1 \pm 0.1) \times 10^{-10}$

- Sensitivity to *New Physics* comparable to $\mu \rightarrow e\gamma$, etc
  e.g. sensitive to extended Higgs boson sector (MSSM, 2HDM)
- Complementary to direct searches at LHC
- Limits have implications on model parameters space



B→ μμ : Strategy

Region	Mass (GeV)
$B^0 \to \mu^+\mu^-$	5.20 - 5.30
$B_s^0 \to \mu^+\mu^-$	5.30 - 5.45

$$M_{B_s^0} - M_{B^0} = 90 \pm 3\,\mathrm{MeV}$$

- Search in $\mu^+\mu^-$ invariant mass region *simultaneously* for B_s and B^0 signals
- **Blind Analysis** – optimized cut-&-count
  - Barrel: ($|\eta_\mu|<1.4$) → higher sensitivity, resolution $\sigma(m_{\mu\mu})$ ~ 40MeV
  - Endcap ($|\eta_\mu|>1.4$) → add statistics, $\sigma(m_{\mu\mu}) \approx 60$ MeV
- **Measure with respect to $B^+ \to J/\psi(\mu^+\mu^-) K^+$ *(similar selection)***

$$BR\left(B_s^0 \to \mu^+\mu^-\right) = \frac{(N_{obs} - N_{BGND})}{N_{obs}^{B^+}} \frac{\varepsilon_{tot}^{B^+}}{\varepsilon_{tot}} \frac{f_u}{f_s} BR\left(B^+ \to J/\psi(\mu^+\mu^-)K^+\right)$$

  - reduce efficiency uncertainties
  - luminosity and production cross sections cancel

$BR(B^+)=6.0 \pm 0.2$ [PDG]

$f_s/f_u = 0.267 \pm 0.021$ [LHCb]

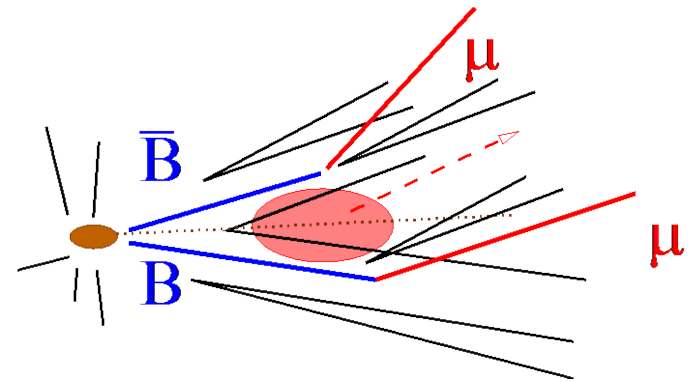
✓ Use $B_s \to J/\psi(\mu^+\mu^-)\,\phi(K^+K^-)$ as control channel for B_s meson reconstruction

B→ μμ : Background Processes

Combinatorial Background

- Two semi-leptonic B decays
- One semi-leptonic B decay and one mis-identified hadron

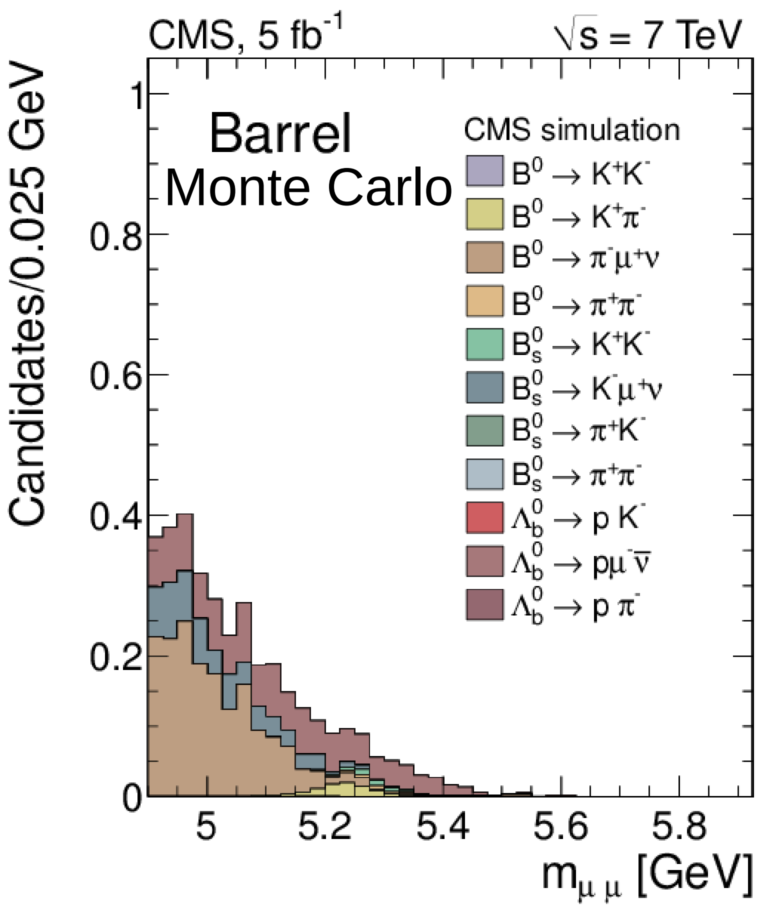
→ Flat / estimated from sidebands



Single B Decays

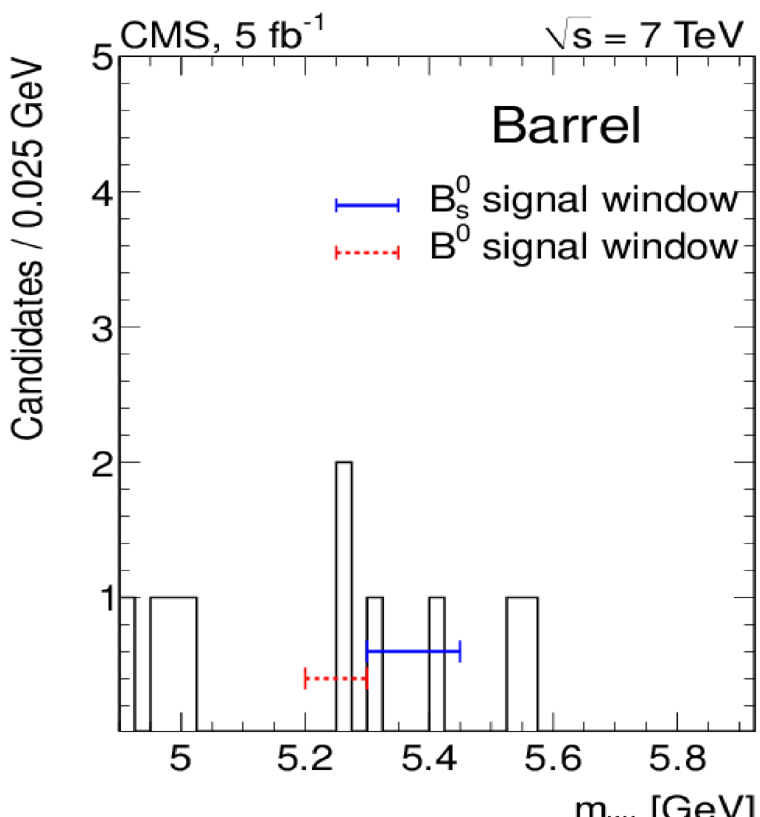
- peaking (B_s^0 → K^+K^-)
  shifted to lower mass $m_{\mu\mu}$
- non-peaking (B_s^0 → K^- μ+ ν_μ)
  one fake μ, lower mass $m_{\mu\mu}$

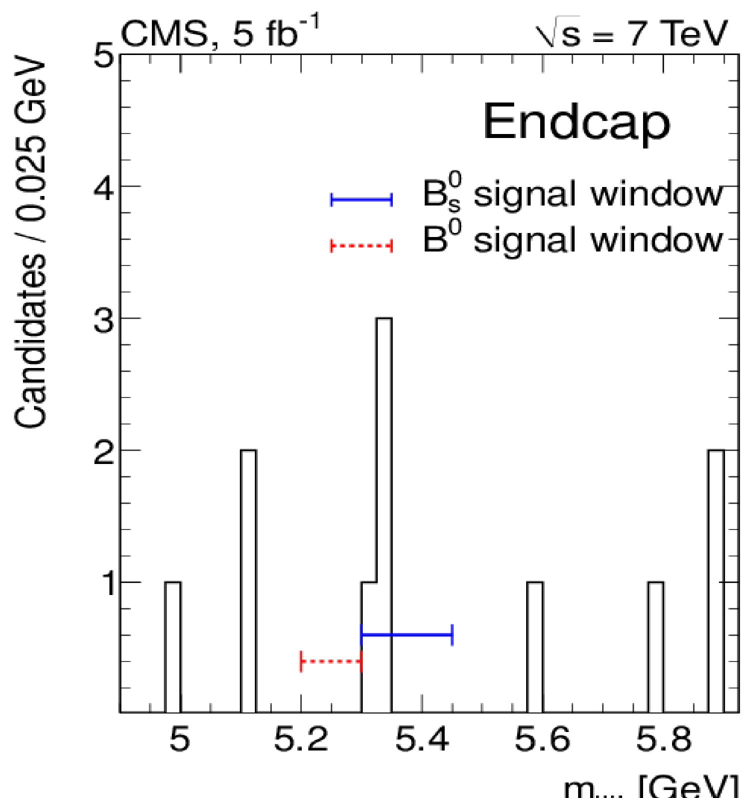
→Shape from MC
→Rate from normalization to B^+



$B \to \mu\mu$ Decay : Results

	$B^0 \to \mu\mu$ 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_{signal}^{exp}	0.24 ± 0.02	2.70 ± 0.41	0.10 ± 0.01	1.23 ± 0.18
N_{total}^{exp}	**0.97 ± 0.35**	**3.47 ± 0.65**	**1.01 ± 0.35**	**2.45 ± 0.56**
N_{obs}	**2**	**2**	**0**	**4**





$B \rightarrow \mu\mu$ Decay : Results

Calculate 95%CL for 5/fb using the CLs method
(including systematic uncertaint.):

Statistics limited !

UPPER Limit	observed	median expected
$BR(B_s^0 \rightarrow \mu\mu)$	7.7×10^{-9}	8.4×10^{-9}
$BR(B^0 \rightarrow \mu\mu)$	1.8×10^{-9}	1.6×10^{-9}

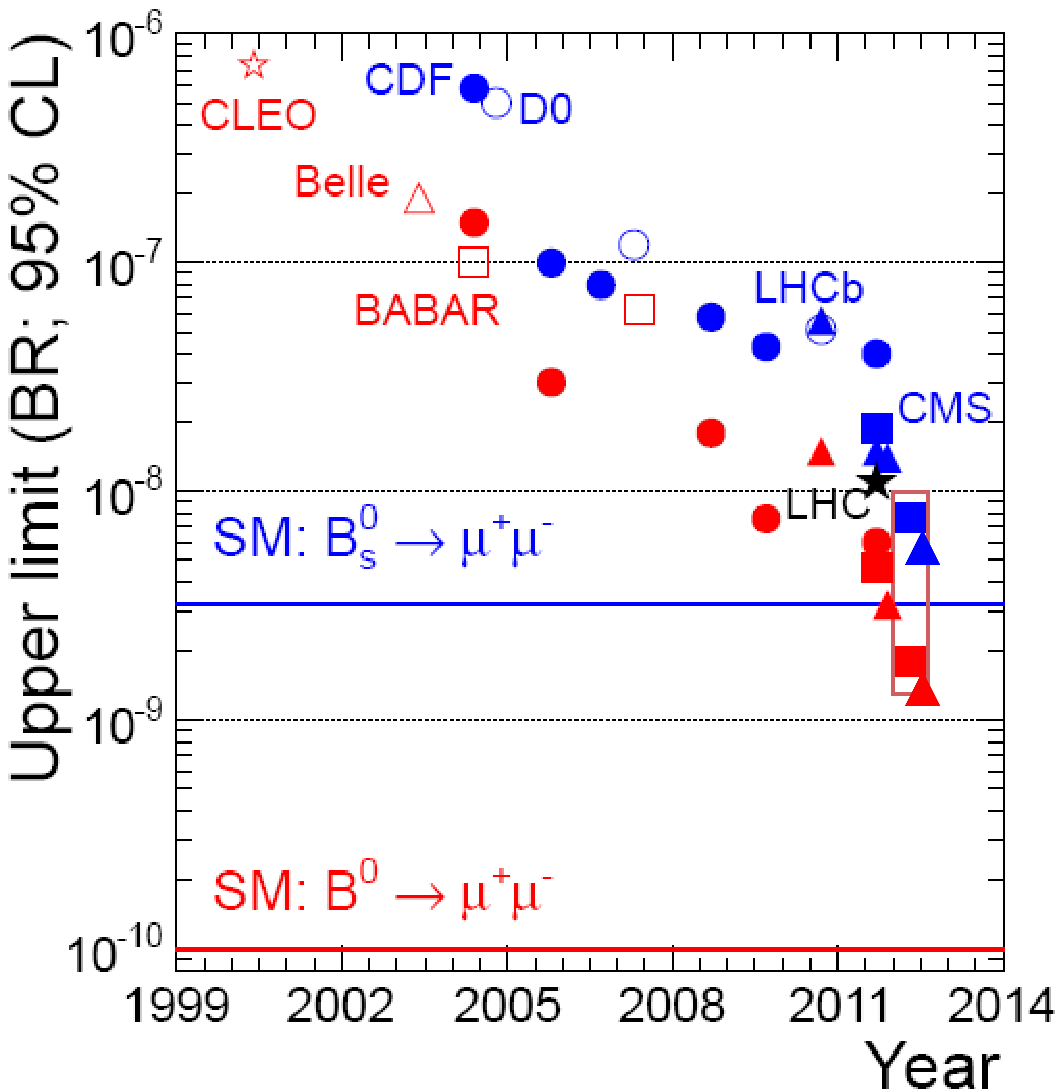
The observed number of events is consistent with background plus Standard Model signals.

→ **CMS** JHEP 1204.(2012) 033. **[7.7 (1.8) 10^{-9} 95%CL]**

→ **LHCb** arXiv:1203.4493 (acc. PRL) **[4.5 (1.0) 10^{-9} 95%CL]**

→ **ATLAS** arXiv:1204.0735 **[22 10^{-9} 95%CL]**

Searches for B→ μμ Decay



CMS significantly improved wrt. previous EPS2011 result (was $< 1.9 \times 10^{-8}$)

Expect further improvements with 2012 data.

Achieved
- higher purity
- pile- up robustness
- Improved sensitivity

Conclusions

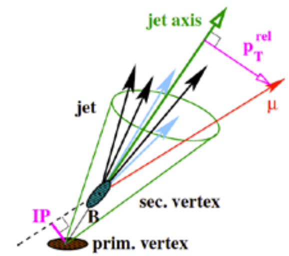
Conclusions

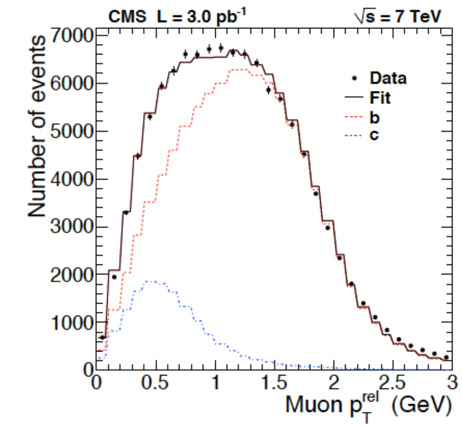
- Firsts:
  - CMS measured first b baryon cross section at LHC: Λ_b
  - CMS discovered first b-baryon at LHC : Ξ_b^{0*} state
- Production cross section measurements:
  - CMS did a complete set of B-hadron production cross section measurements: B^0, B^+, B_S, Λ_b
  - Comparisons with theory: overall reasonable description, but deviations visible in various details in p_T and y
  - Measured b- and b-bbar production: high precision cross sections and b-bbar angular correlations
- Search for $B_{(S)} \rightarrow \mu\mu$:
  - No signal (yet), closing in on the SM (and close to LHCb …)
  - Progress with 2012 data

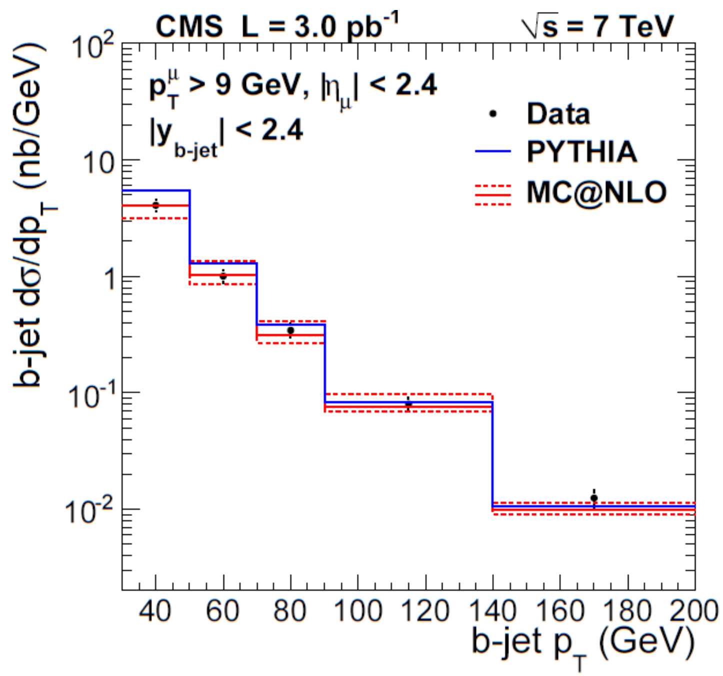
Backup…

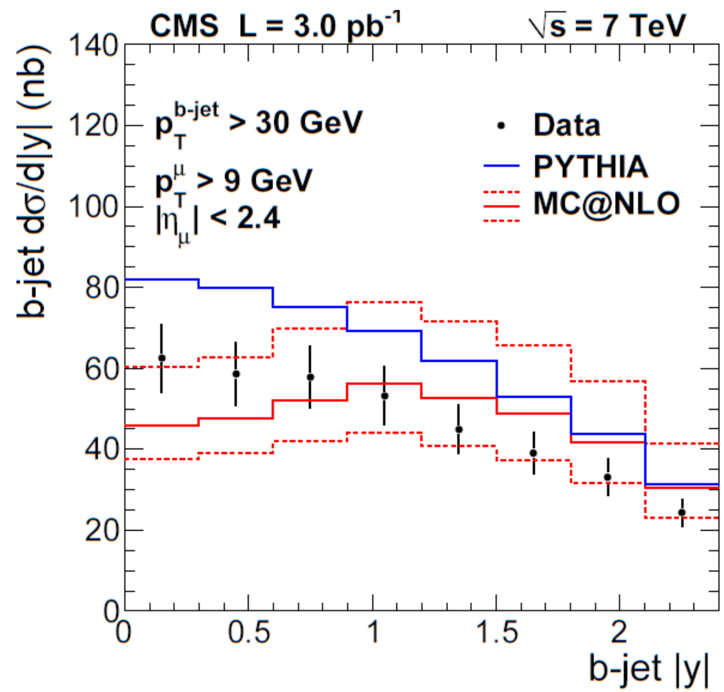
b-jet : Cross Sections – muon based

- ***b-tagged jets with a muon***
  - single muon trigger, L = 3:0 pb-1(2010)
  - high efficiency b-tagging (2-track vertex):
  - ε(btag) = 50%(@30) ---- 75%(@100 GeV)
  - b-fraction from fit to muon p_T-rel distribution







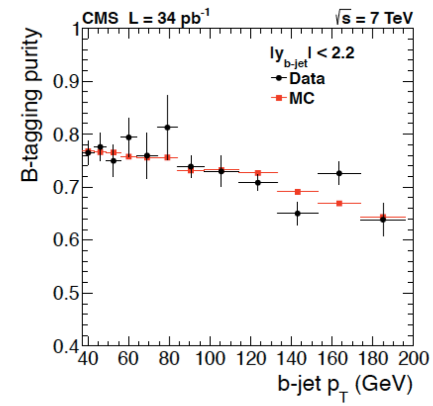


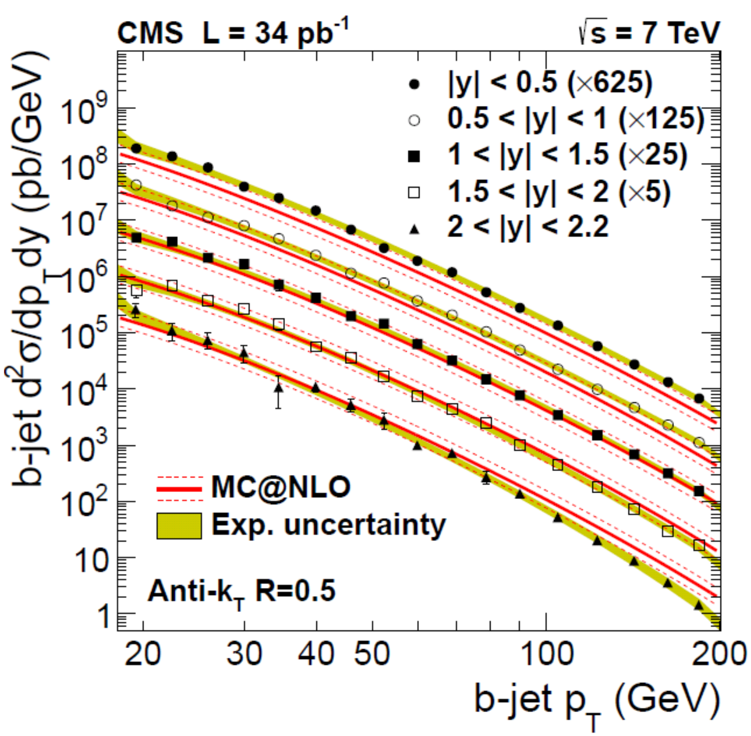
- Overall good agreement with PYTHIA;
- Reasonable agreement with MC@NLO for norm, but shape differs in p_T and y

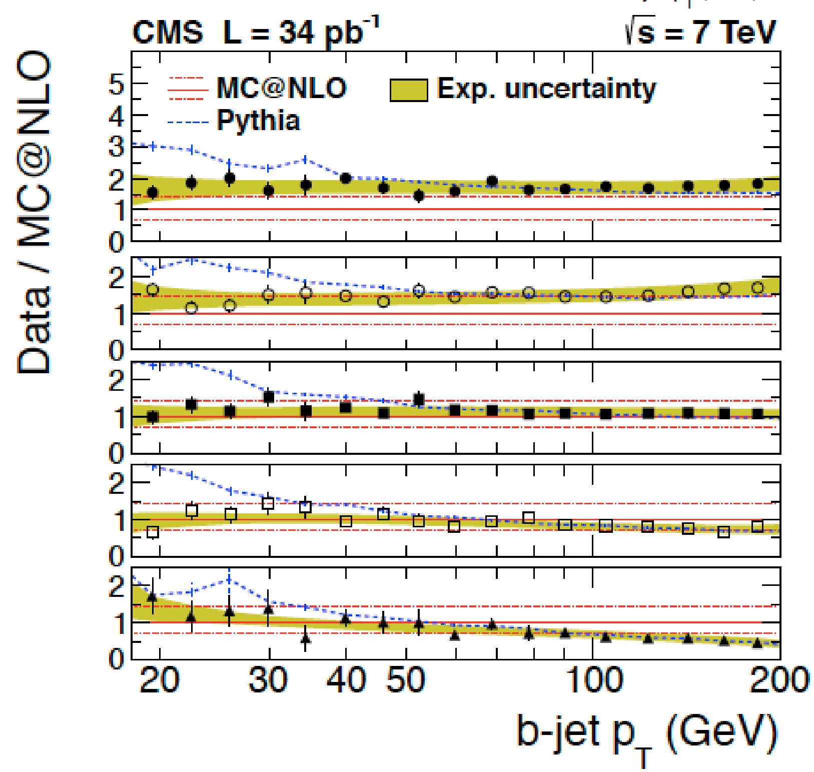
arXiv:1202.4617
accepted by JHEP

b-jet : Cross Sections – jet based

- ***b-tagged jets with high-purity tag using 2nd vertex***
  - ε(btag) : from 5% @18GeV to 56% @100GeV
  - b-fraction from fit to the vertex mass







- PYTHIA: agreement at high pt; overestimates at low pT
- MC@NLO: p_T-slope differs at high y; below data in central region

arXiv:1202.4617
accepted by JHEP

Additional
Exclusive b-Hadron Production

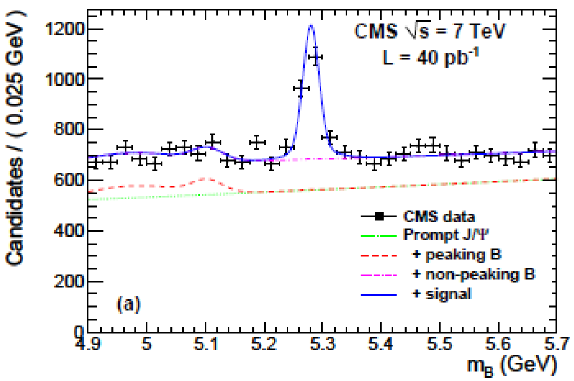
B^0 : p_T & y differential cross section

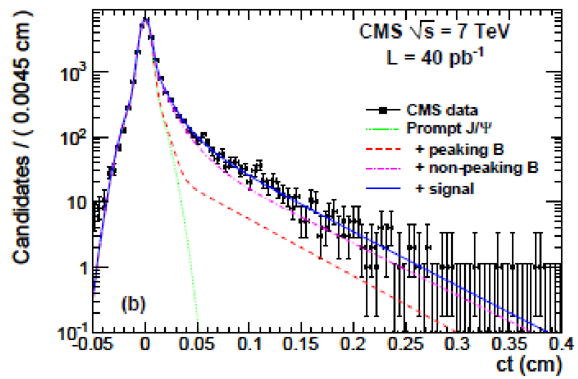
$B^0 \to J/\psi\, K_S$

Signal extracted bin by bin by unbinned extended.max.Likelihood fits to mB and cτ.

PRL106(2011)252001

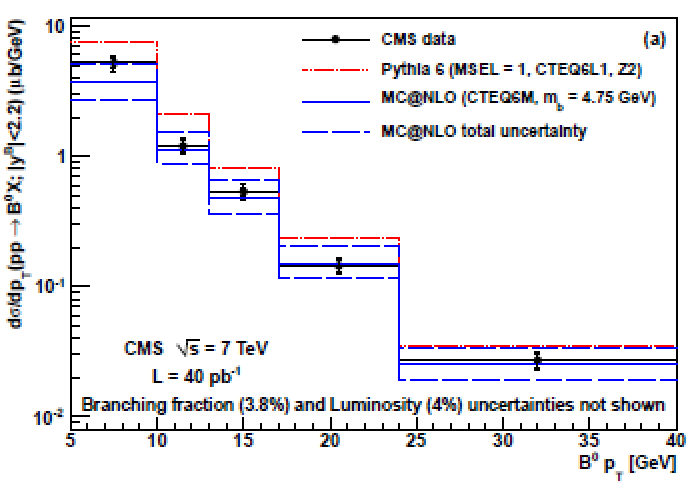
$$\mathcal{L} = \exp\left(-\sum_i n_i\right) \prod_j \left[\sum_i n_i \mathcal{P}_i(M_B; \vec{\alpha}_i)\mathcal{P}_i(ct; \vec{\beta}_i)\right]$$

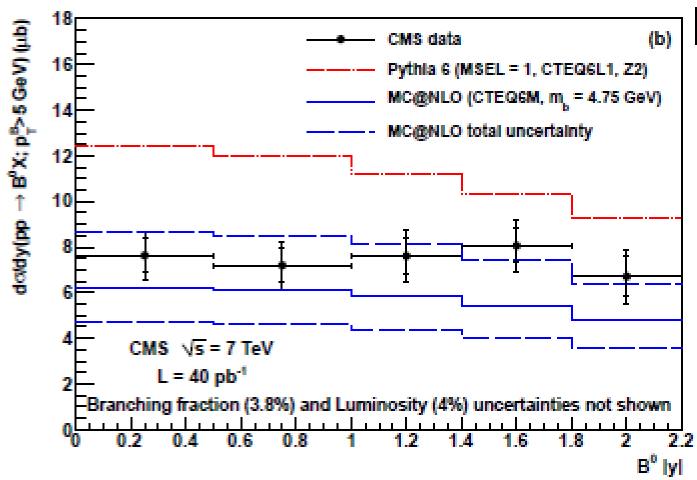




Similar method used for other b-hadrons.

5 GeV < pT
$|y_B|$ < 2.2.





Systematics dominated by :

- PDF parameters
- K_S and B selection

3.8% BR($B^0 \to J/\psi\, K_s$)

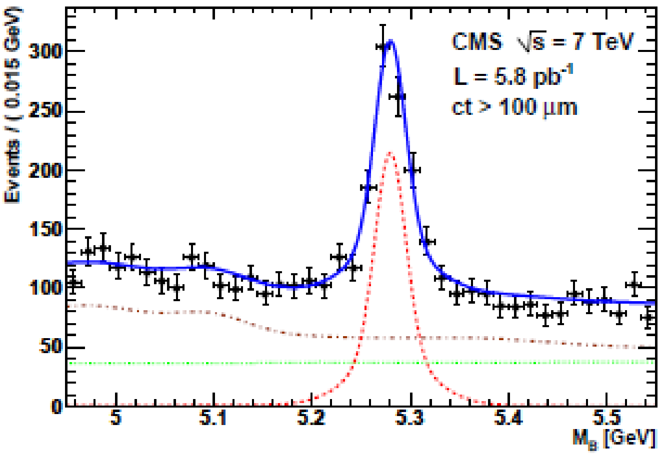
σ_{vis}= 33.2 ± 2.5 ± 3.5 ± 1.3 μb

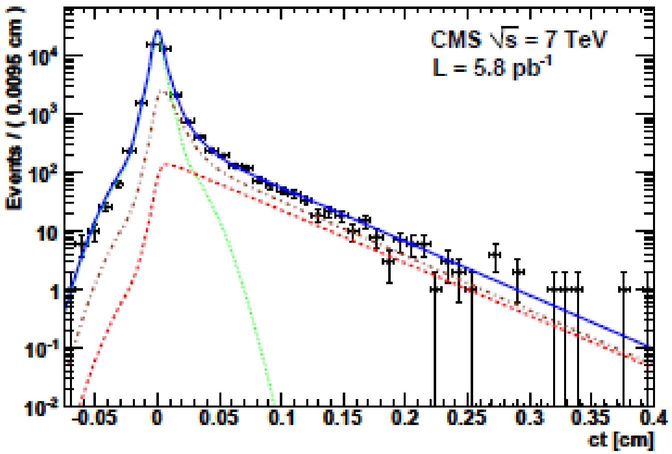
Pythia too high, different y-shape;
MC@NLO too low, shape ok…

B^+ : p_T & y differential cross section

$B^+ \to J/\psi\, K^+$

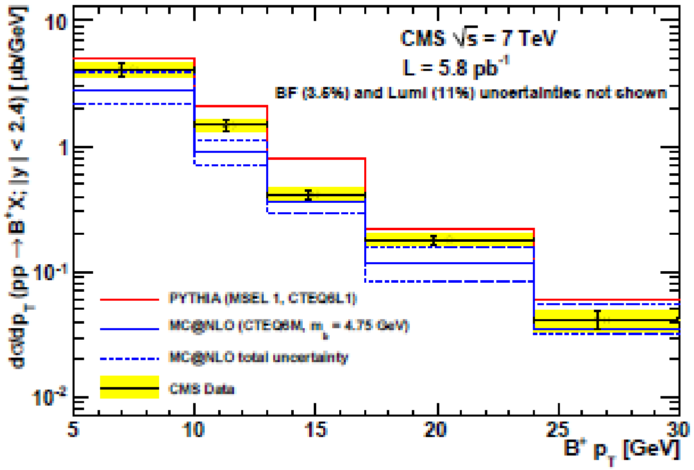
PRL106(2011)112001

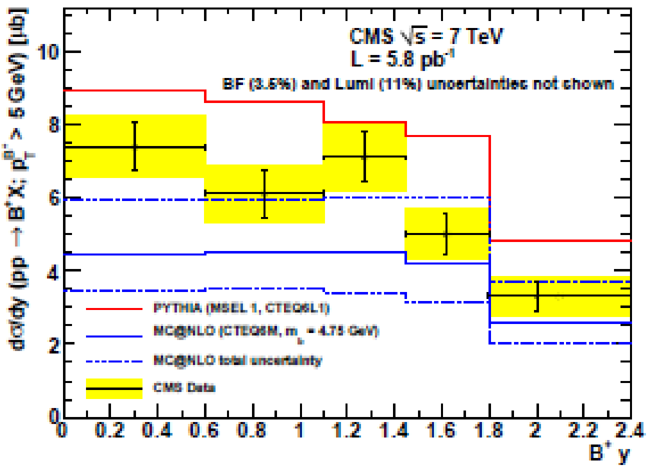




signal yields (per bin) by unbinned ext.ML fit to mB and $c\tau$.

5 GeV < pT
$|y_B| < 2.4$.





Systematics dominated by :

- PDF parameters
- mu efficiencies

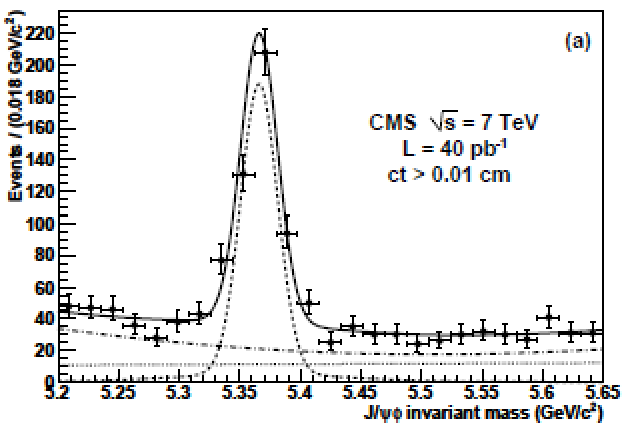
$\sigma_{vis} = 28.1 \pm 2.4 \pm 2.0 \pm 3.1\ \mu b$

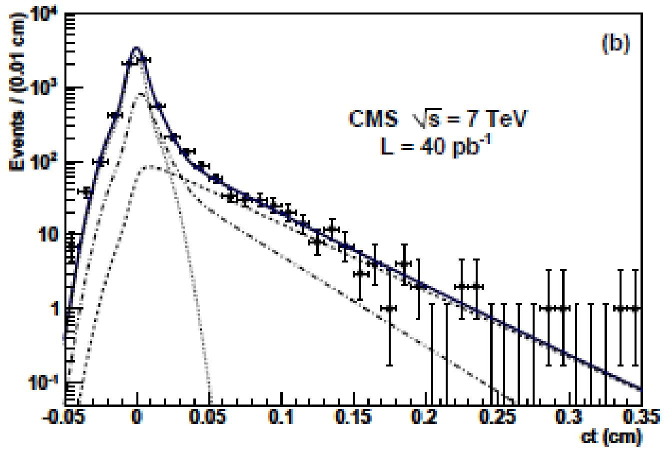
Pythia too high, different y-shape;
MC@NLO too low, shape ok…

B^0_s : p_T & y differential cross section

$B^0_S \to J/\psi\ \phi$

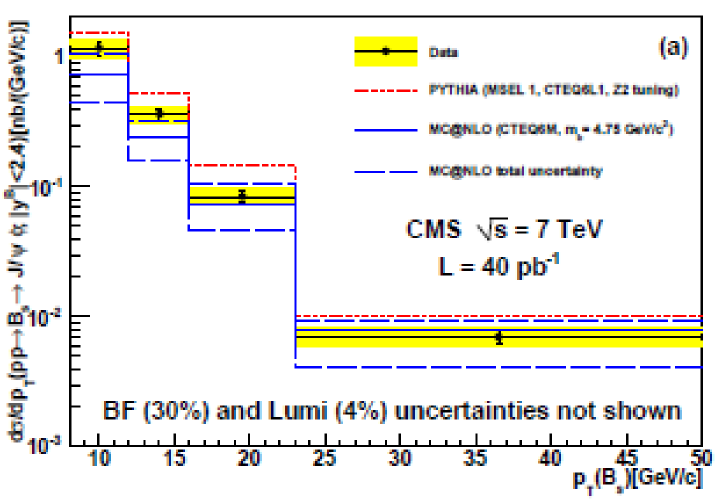
Phys. Rev. **D84** (2011) 052008

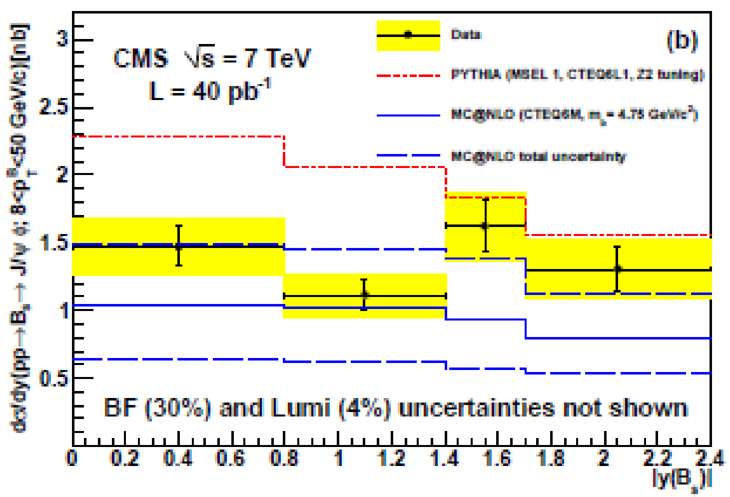




signal yields (per bin) by unbinned ext.ML fit to mB and cτ.

8 GeV < pT < 50 GeV
$|y_B| < 2.4$.





Systematics dominated by :

- PDF parameters
- mu efficiencies

30% BR(**$B^0_s \to J/\psi\ \phi$**)

$\sigma_{vis} = 6.9 \pm 0.6 \pm 0.6 \pm 0.3$ nb

Pythia too high, different y-shape;
MC@NLO too low, shape ok…

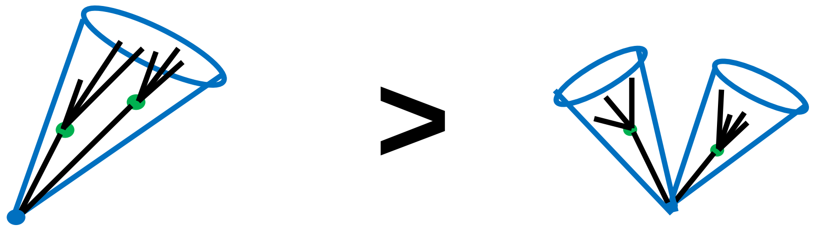
Backup on bb-production

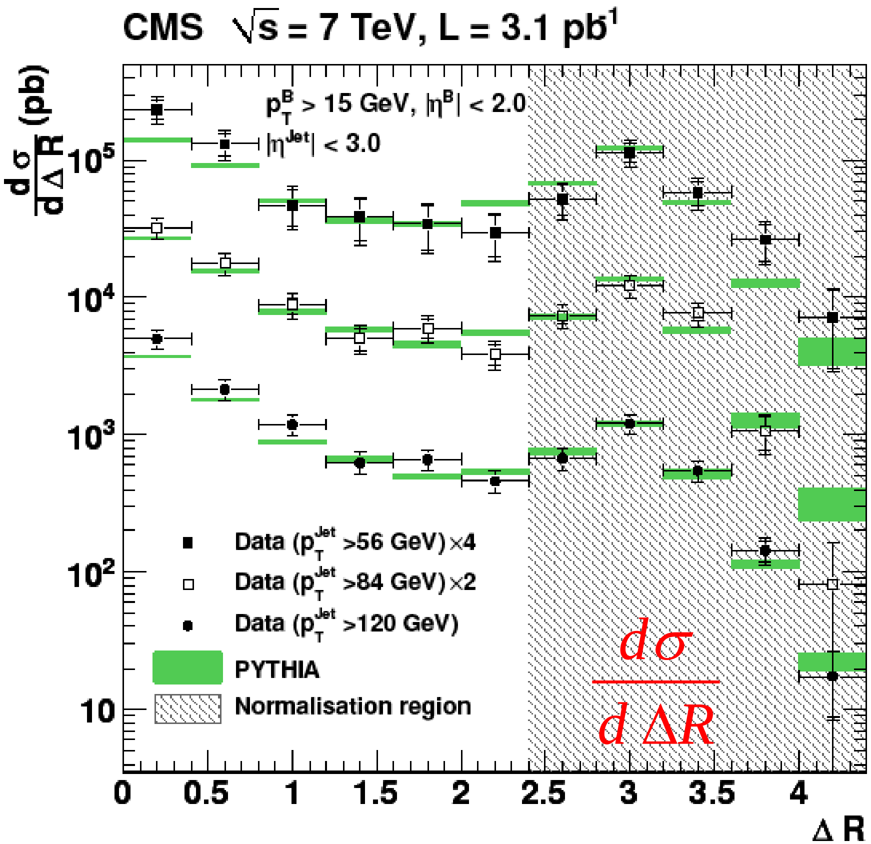
ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

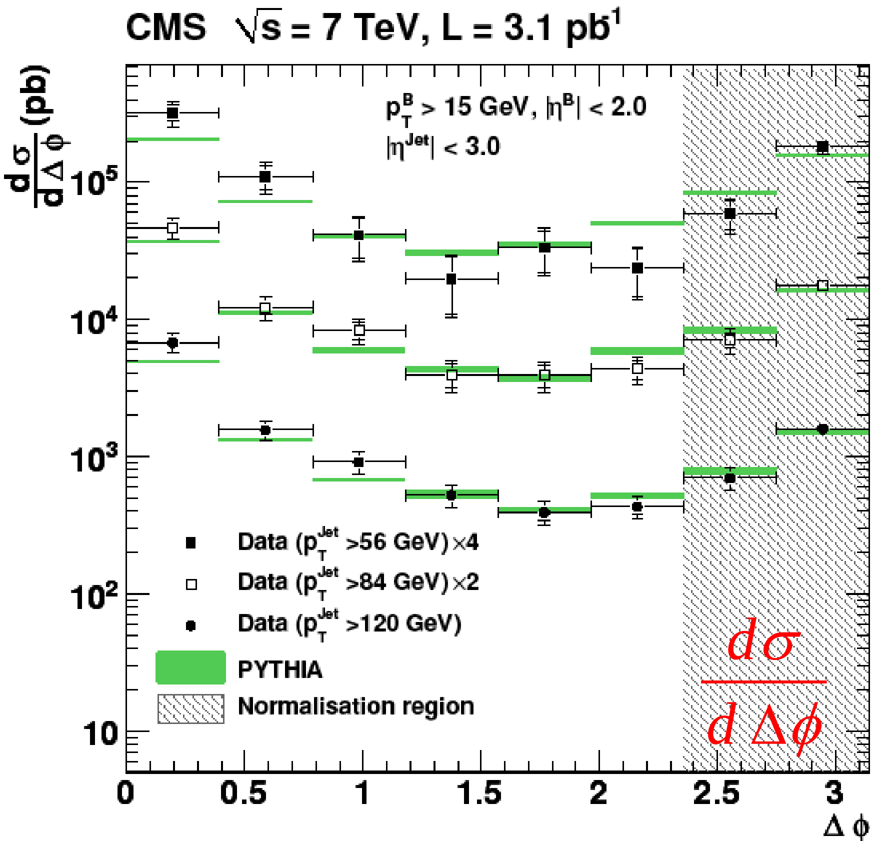
B-B Angular Correlations - Xsec

for visible region in B-hadrons

|η(B)|<2.0 ;   pT(B) > 15 GeV ;
for leading jet p_T^{jet} > 56, 84, 120 GeV







Small angular separation region dominant → collinear emission processes !
Pythia describes roughly shape, but normalization is off.

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B-B Angular Correlations vs Theory

Ratio of Cross sections shown relative to Pythia:

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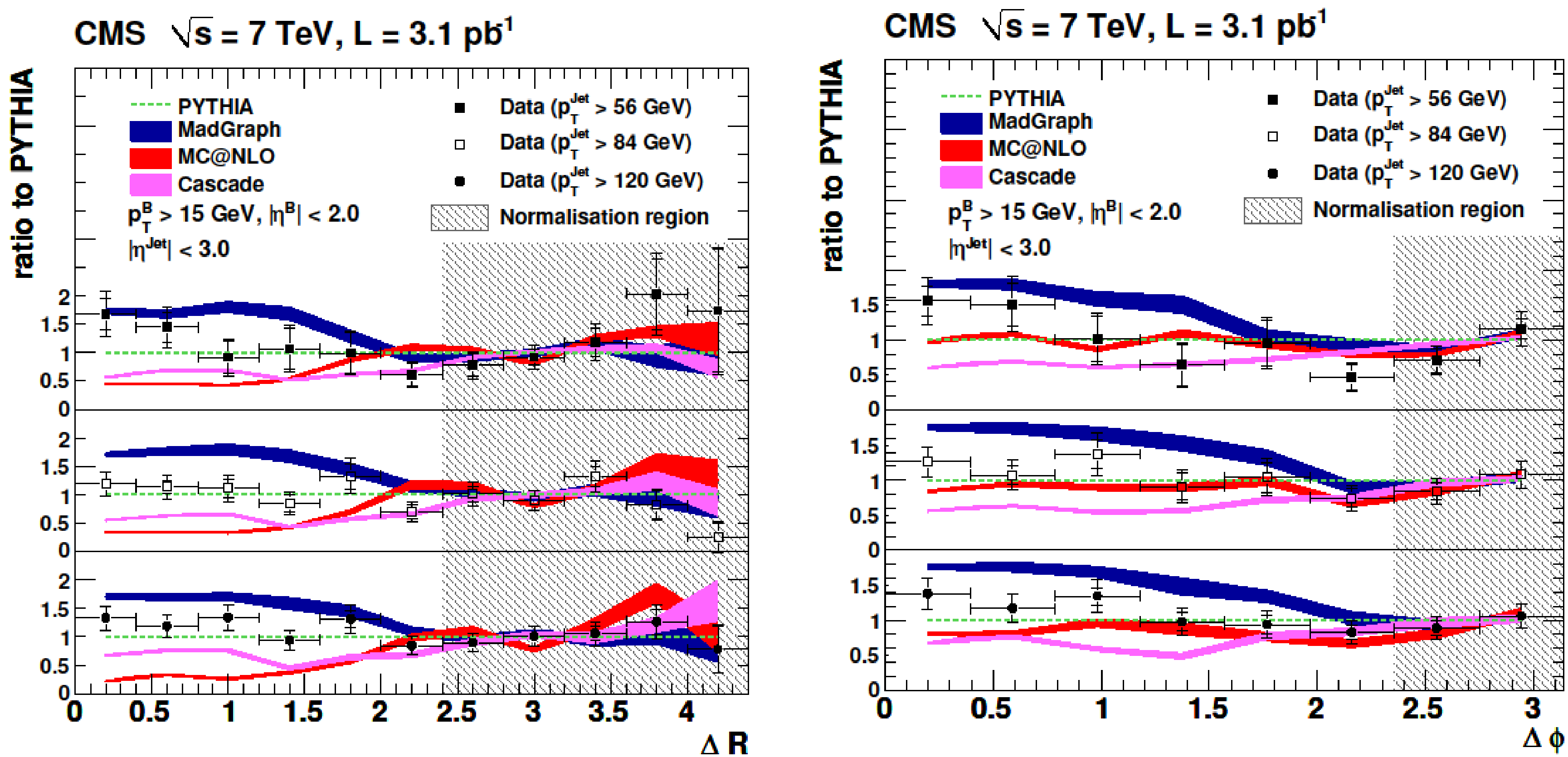


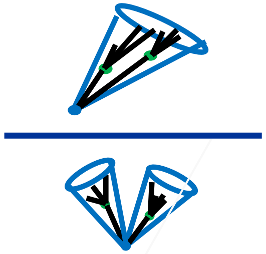
- **None of the predictions describe data accurately.**
- **Pythia itself describes roughly shape, but normalization is off.**
- **MC@NLO underestimates at low ΔR values. Δϕ better described.**

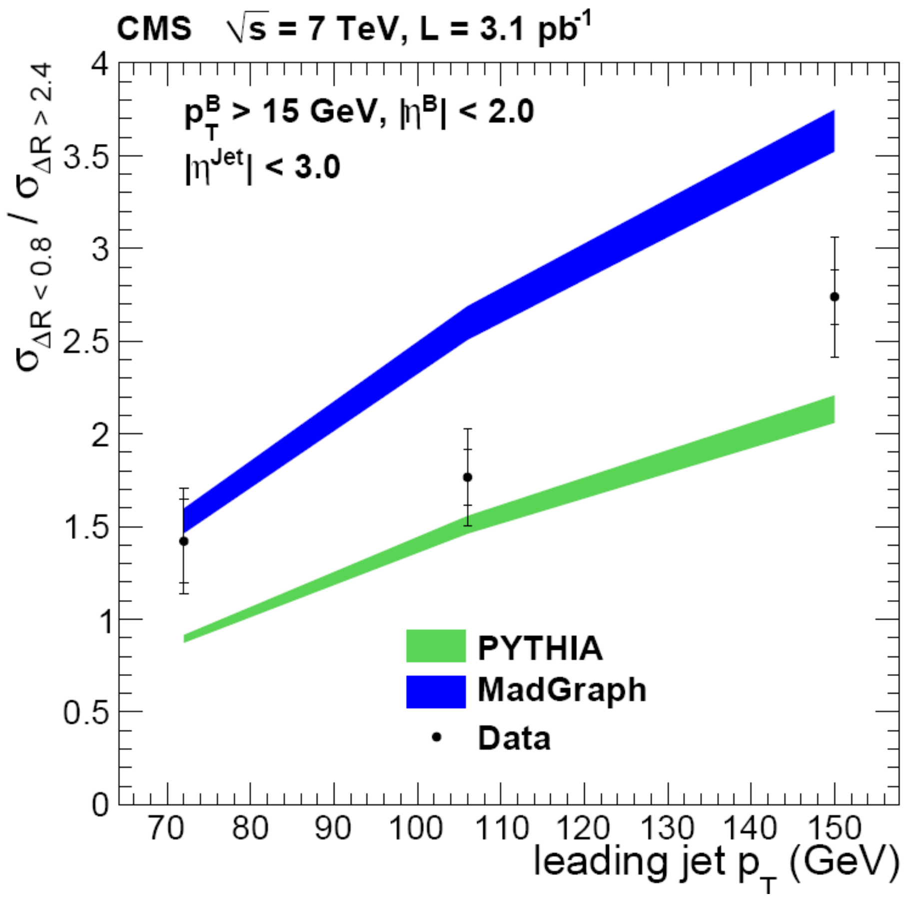
B-B : Collinearity Trend - Scale

- Ratio of cross section (small vs large ΔR) → "GSP vs FCR"

$$\rho_{\Delta R} = \frac{\sigma(\Delta R < 0.8)}{\sigma(\Delta R > 2.4)}$$

=





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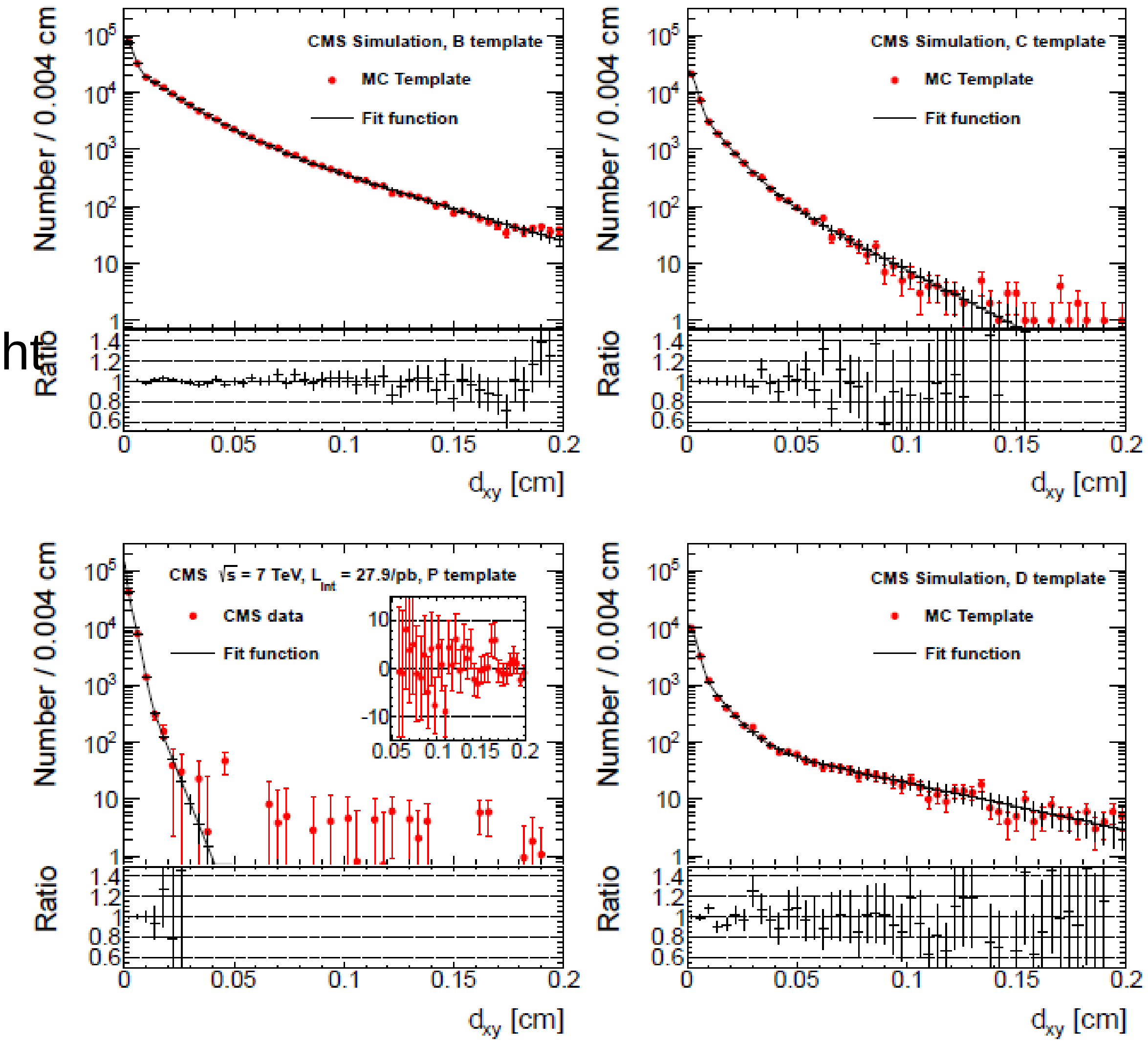
- $\rho_{\Delta R}$ **increases with larger p_T^{jet} values → more gluon radiation**
- **Trend of leading jet p_T dependence reproduced correctly by both MC.**
- **But normalization is off**

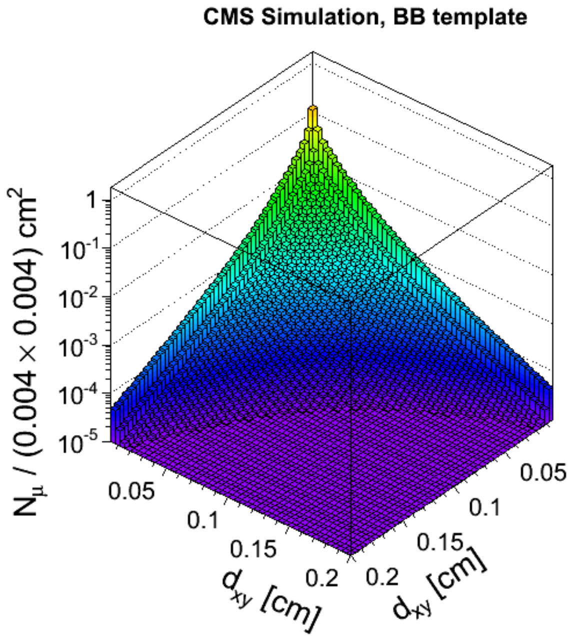
- Also used in Zbb CMS-PAS-EWK-11-015

bb-production in dimuons: pp→bb →μμX (opt)

Mu impact par. D_{xy} templates
- (B) b → X
- (C) charm
- (P) prompt muons
  (DY, resonances)
- (D) light hadron decay-in-flight



Example of 2D
D_{xy} templates

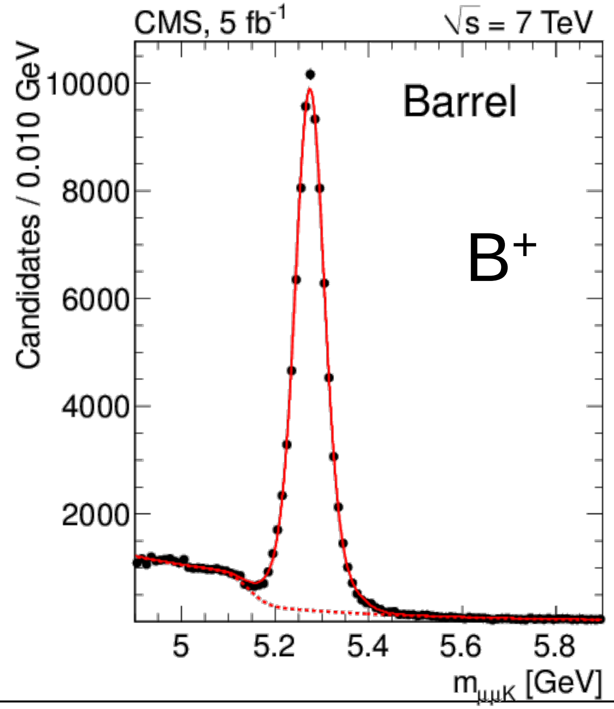


Previous results see JHEP **03** (2011) 090

Backup on $B_s \rightarrow \mu\mu$

B→ μμ : Systematic Uncertainties (opt)

	Barrel	Endcap
• Acceptance with mixture of hadronic production gluon fusion/flavor excitation/gluon splitting	~ 3.5%	5%
• Selection criteria (data % Monte Carlo) efficiency signal, normalization, kaon tracking	~ 7%	7%
• Muon trigger and identification efficiency	~ 4%	8%
• Fit yield in control channel ($B^+ \rightarrow J/\psi\ K^+$) #82700 + #23800 observed	~ 5%	5%

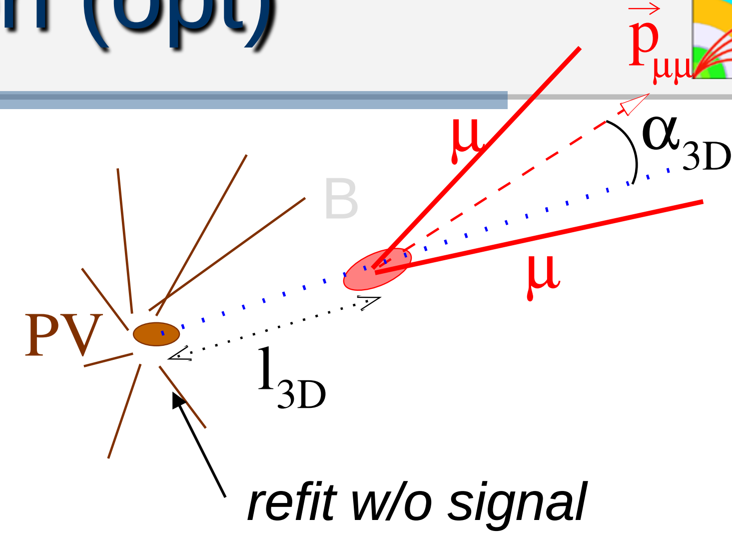


Cross Checks

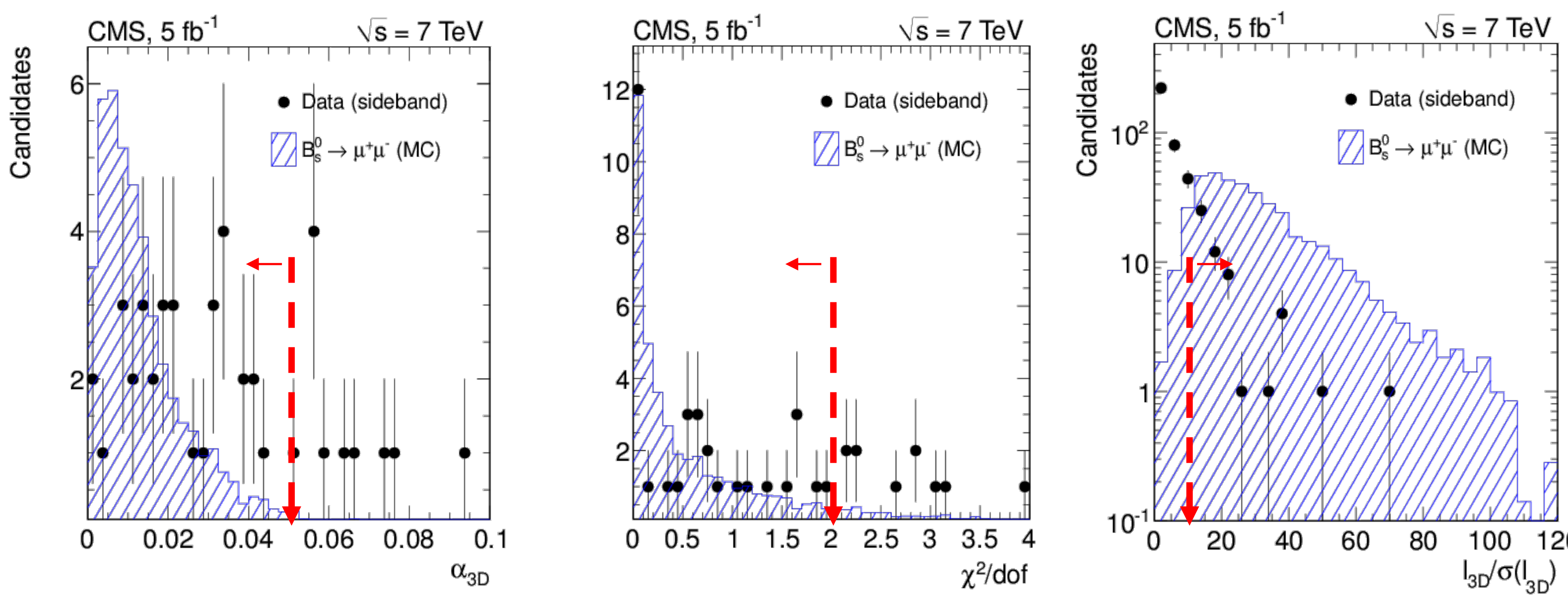
- Estimate background for anti-isolation cut
- Evaluate $BF(B_s \rightarrow J/\psi\ \phi)/BF(B^+ \rightarrow J/\psi\ K^+)$
- Signal in samples for different periods

B→ μμ : Signal Selection (opt)

- Pointing angle α_{3D}
- Vertex fit χ^2/dof
- Flight length significance $l_{3D}/\sigma(l_{3D})$
- Impact parameter 3D significance



Data Sideband % Signal MC

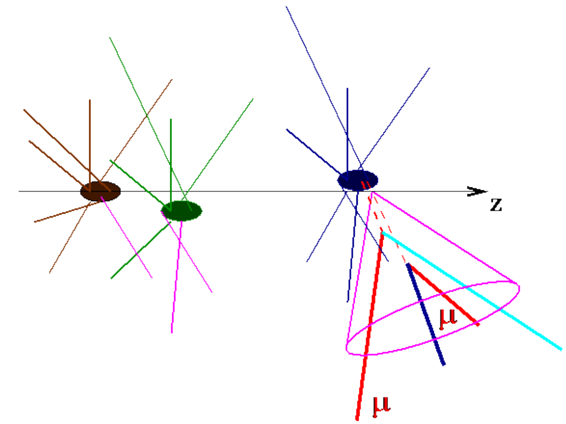


B→ μμ : Isolation of B candidates (opt)

- Isolation cone around primary vertex

for ΔR < 0.7 along B, $p_\perp$ > 0.9 GeV

$$I = \frac{p_\perp(B)}{p_\perp(B) + \sum_{trk} |p_\perp|}$$



- Number of close tracks (d_{ca}<300um, $p_\perp$>0.5 GeV)
- Distance of closest track to B vertex d^0_{ca}