

Studies of *beauty* and *charm* quark production and decays with the CMS experiment

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On behalf of the CMS collaboration

BEACH 2012, Wichita, July 23rd-28th

Introduction

- Measurements of heavy-flavor production provide a testing ground for QCD calculations in a new energy regime
 - NLO contributions dominate at LHC, large uncertainties remain due to factorization and renormalization scales
- b -flavor identification is crucial in many new physics studies: SM backgrounds must be understood
- Measurements of B -hadrons properties provide important tests of the SM: any deviation would be indirect indication of New Physics

Outline

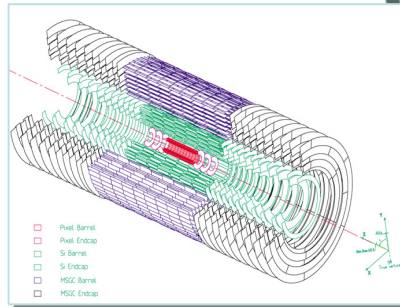
- CMS detector and performance
- B-hadrons
 - Observation of a new Ξ_b baryon
 - Observation of B_c^+ decays to $J/\psi\pi$ and $J/\psi 3\pi$
 - Measurement of the $\Lambda_b \rightarrow J/\psi \Lambda$ differential cross section
- Inclusive b measurements
 - $bb \rightarrow \mu\mu$ cross section
- Rare decays
 - Search for the decay $D^0 \rightarrow \mu^+ \mu^-$
- CMS topics covered by other speakers
 - Quarkonium production in pp and PbPb
 - Search for the decay $B_{(s)}^0 \rightarrow \mu^+ \mu^-$
 - Higgs searches

The CMS detector

weight: 12500 t
overall diameter: 15 m
overall length: 21.6 m

SOLENOID
B = 3.8 T

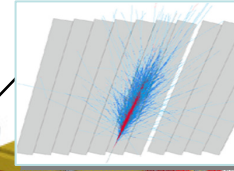
TRACKER



Pixels
Silicon Strips

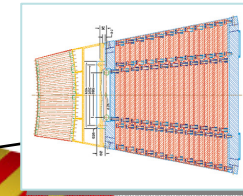
JINST 3, S08004 (2008)

ECAL Scintillating PbWO_4
Crystals

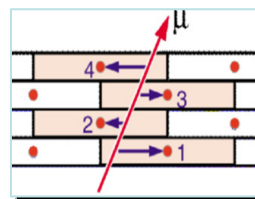


CALORIMETERS

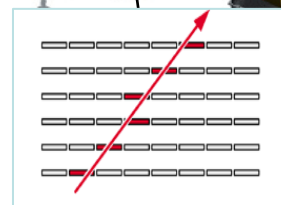
HCAL Plastic scintillator
Brass



MUON BARREL

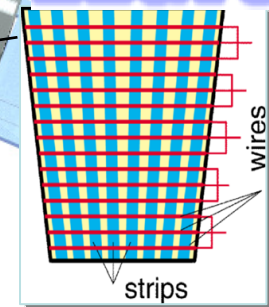


Drift Tubes (DT)



Resistive Plate
Chambers (RPC)

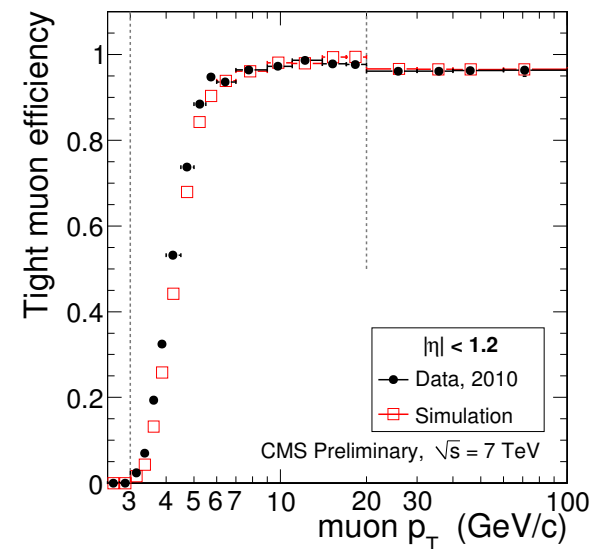
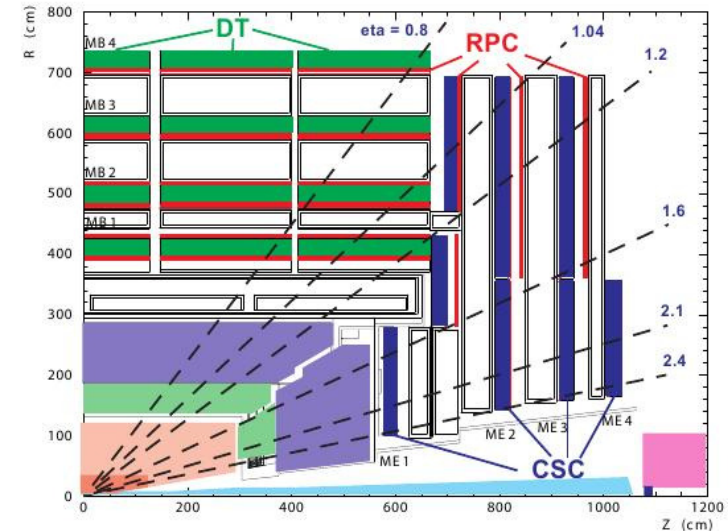
**MUON
ENDCAPS**



Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

Tracking and muon reconstruction

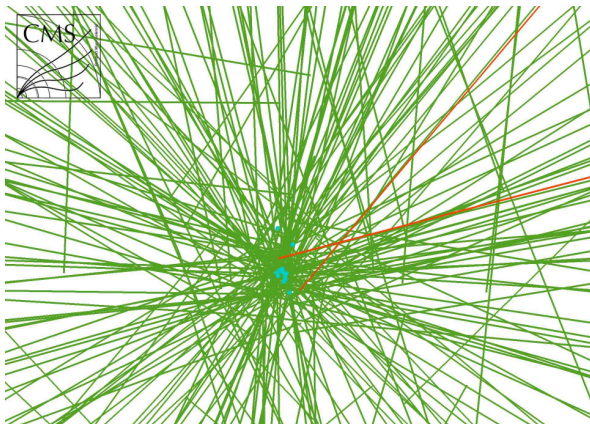
- Tracks: Excellent p_T resolution $\approx 1\%$
 - Tracking efficiency $> 99\%$ for central muons
 - Excellent vertex reconstruction and impact parameter resolution ($\approx 15 \mu\text{m}$)
 - Muon candidates: Match between muon segments and a silicon track
 - Large pseudorapidity coverage: $|\eta| < 2.4$
-
- Muon efficiencies evaluated with
 1. MC methods
 2. Data-driven methods: Tag & Probe



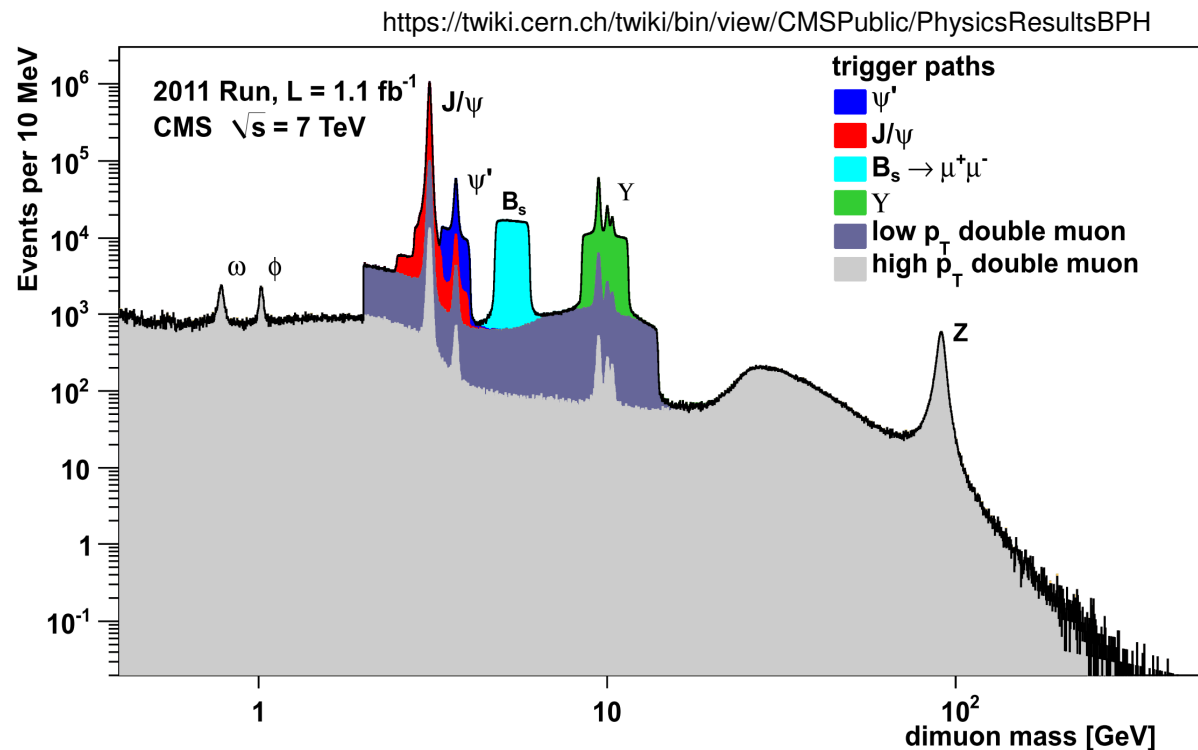
CMS-PAS-MUO-10-002

B-Physics Triggers

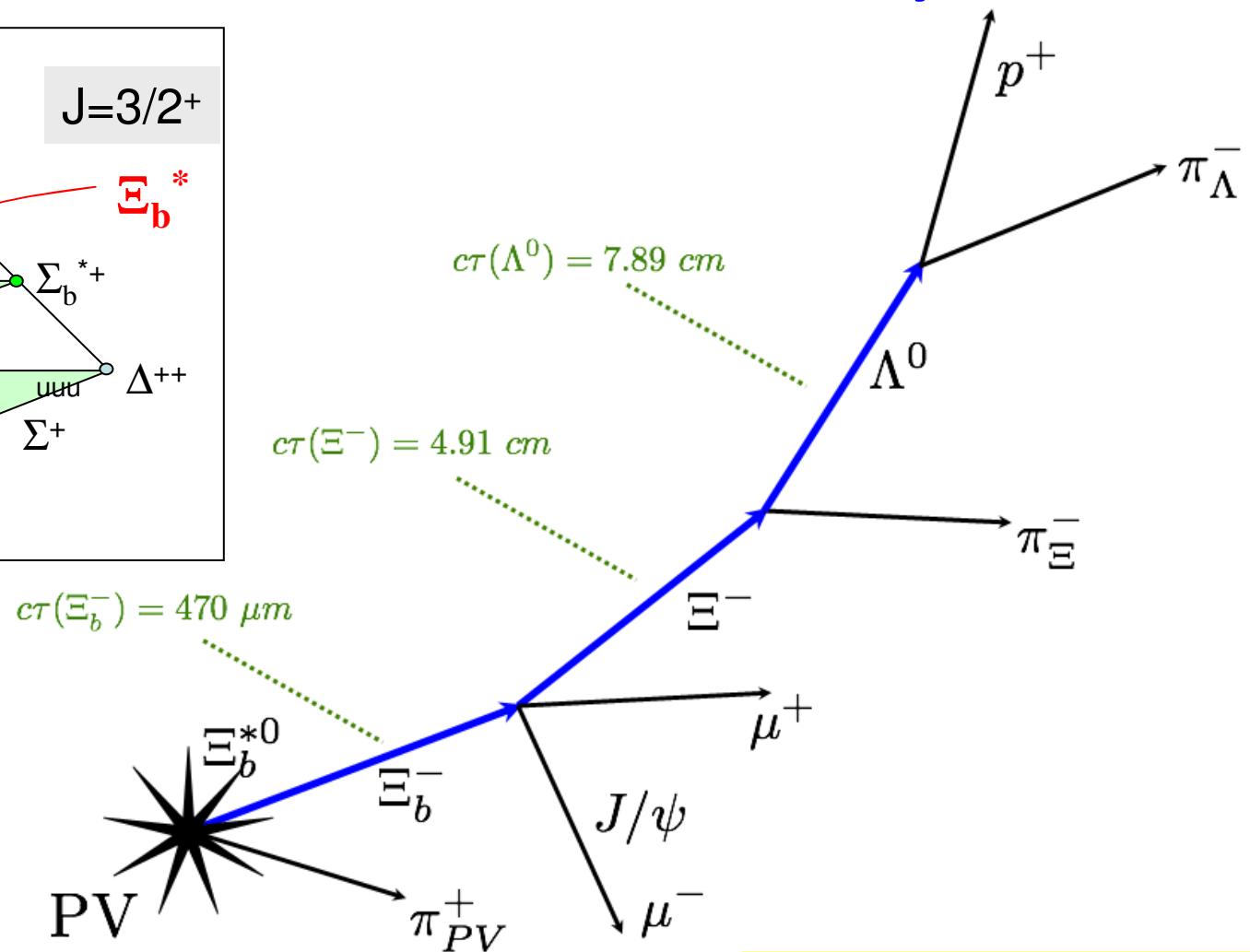
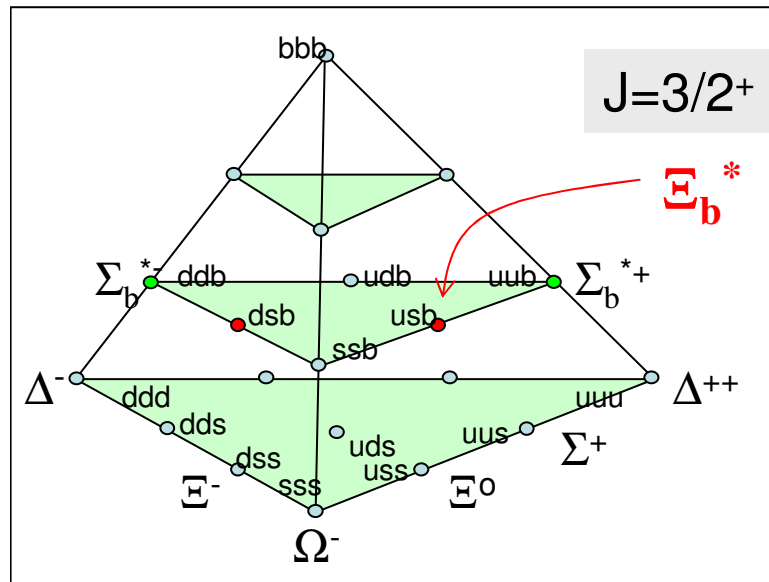
- Rates of a few Hertz (total CMS rate $\sim 300\text{Hz}$)
 - Mostly muon triggers
 - Requirements tightened following the increase in instantaneous luminosity
- Trigger selections based on:
 - p_T and $|\eta|$ of (di)muons
 - dimuon invariant mass
 - secondary vertex probability
 - impact parameters
 - flight length
 - pointing angle



23/07/2012

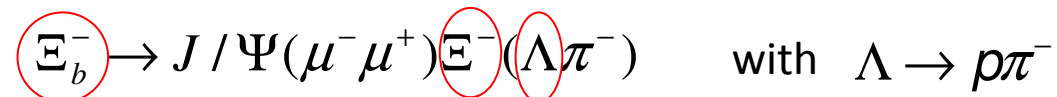


Observation of the Ξ_b^* baryon

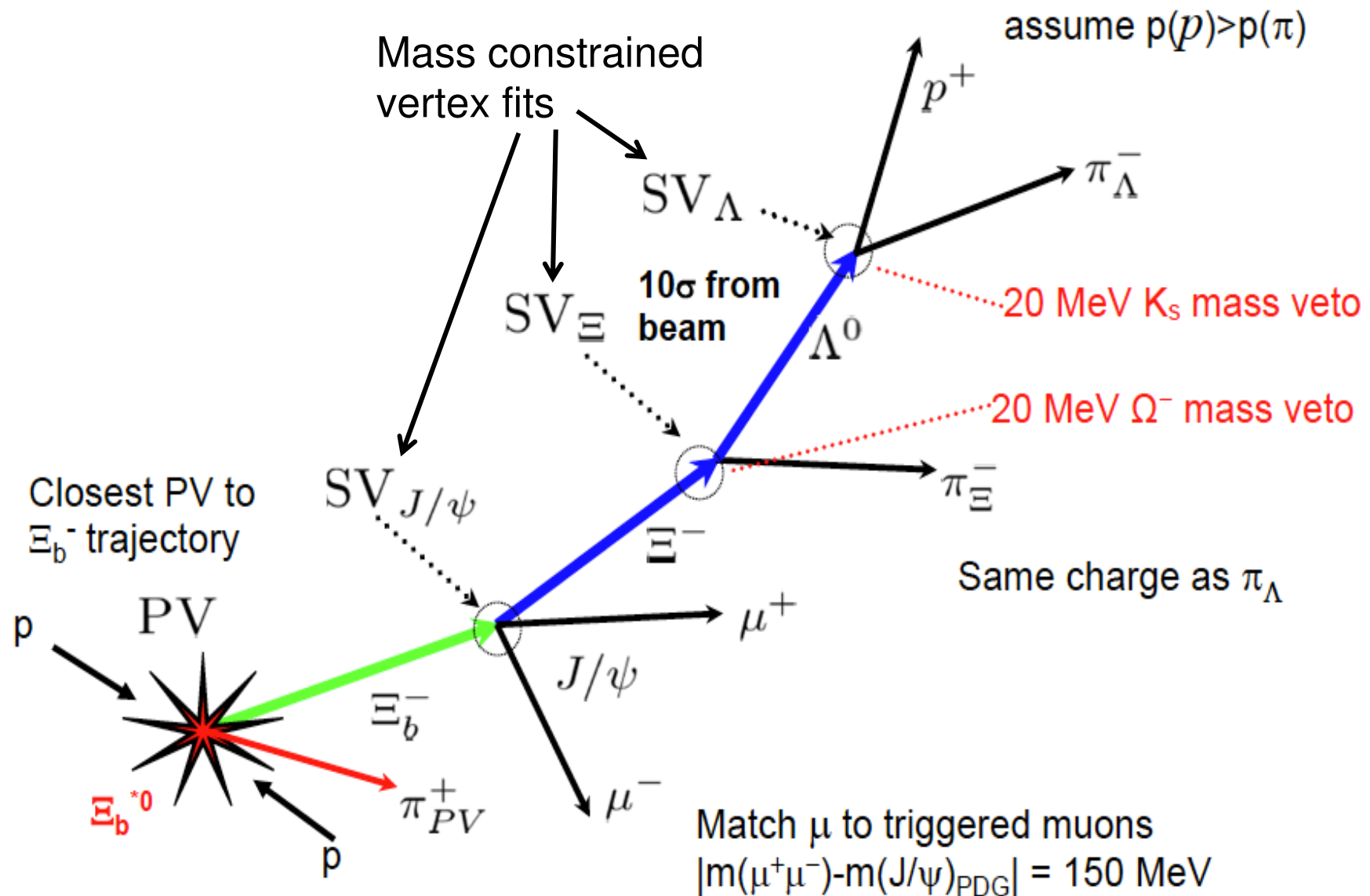


Phys.Rev.Lett. 108:252002 (2012)

Ξ_b^* decay chain contains 3 displaced secondary vertices:

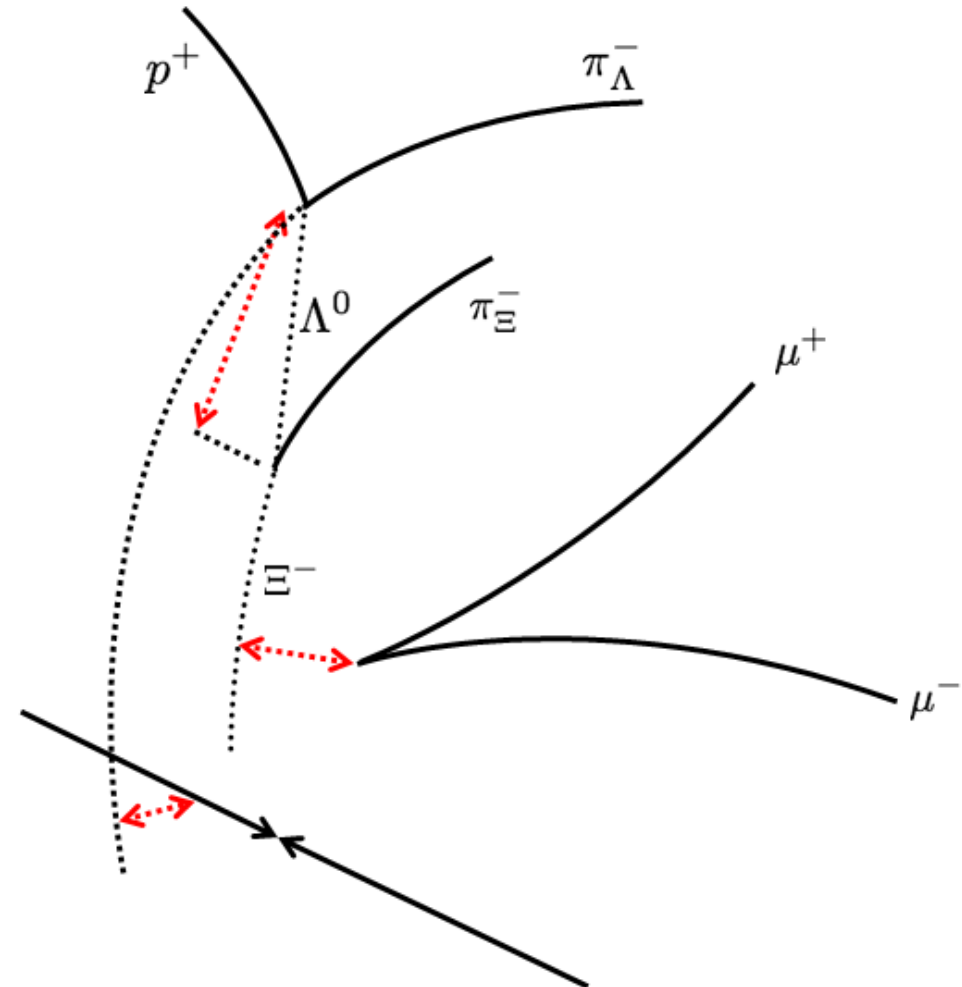


Ξ_b^* reconstruction



Ξ_b^- selection

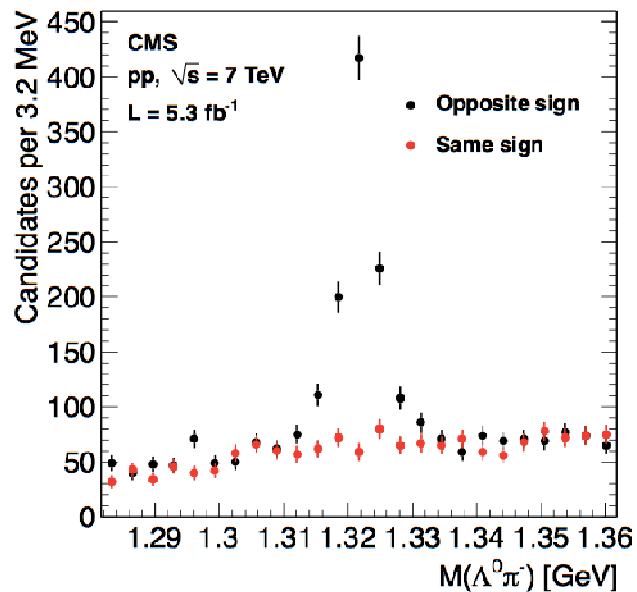
- Algorithm to optimize the selection.
- 30 discriminating variables:
 - transverse momentum of μ^\pm , p , π_Λ , π_Ξ , Ξ , J/ψ , Ξ_b
 - pseudo-rapidity of J/ψ
 - mass before fit of Λ , Ξ , J/ψ
 - I.P. significance w.r.t. the beam line for p , π_Λ , π_Ξ , Λ , Ξ
 - Vtx. Probability, ct and Lxy significance of Λ , Ξ , Ξ_b
 - 3D distance significance for (J/ψ vtx. - Ξ traj.) & (PV - Ξ_b traj.)



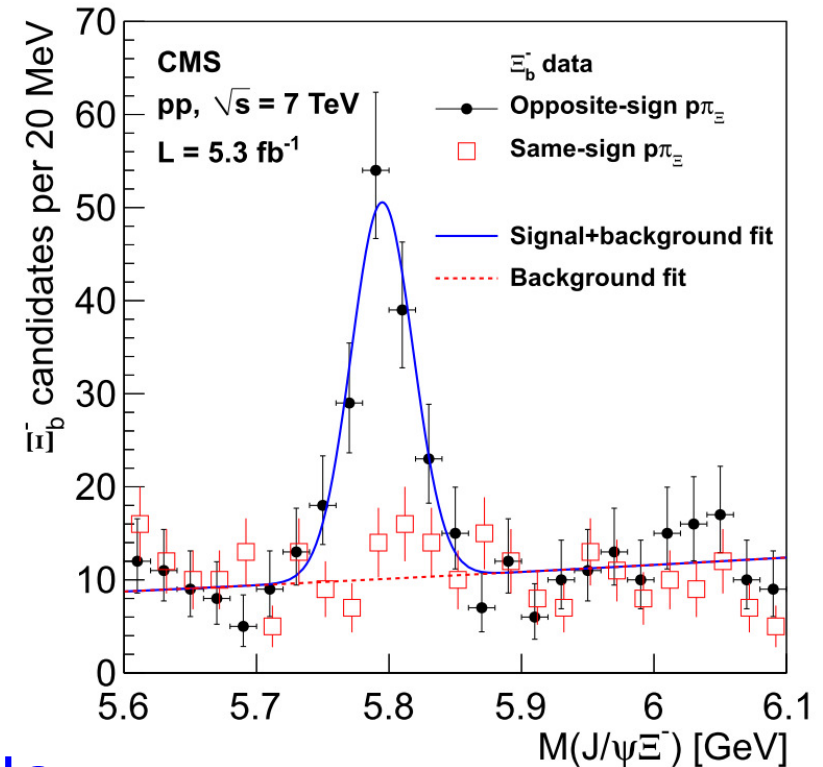
Iterative procedure maximizes the Ξ_b^- yield (S) and $S/\sqrt{S+B}$

Ξ_b^- selection (cont'd)

Ξ_b^- candidate mass distributions after selection cuts
+ $IP(tk)/\sigma_{IP} > 3$



Ξ_b^- candidates



Ξ_b^- fit results:

$$\mu = 5795.0 \pm 3.1 \text{ MeV}$$

$$\sigma = 23.7 \pm 3.2 \text{ MeV}$$

PDG mass: $5790.5 \pm 2.7 \text{ MeV}$

$$S = 108 \pm 14$$

$$B = 38 \pm 7$$

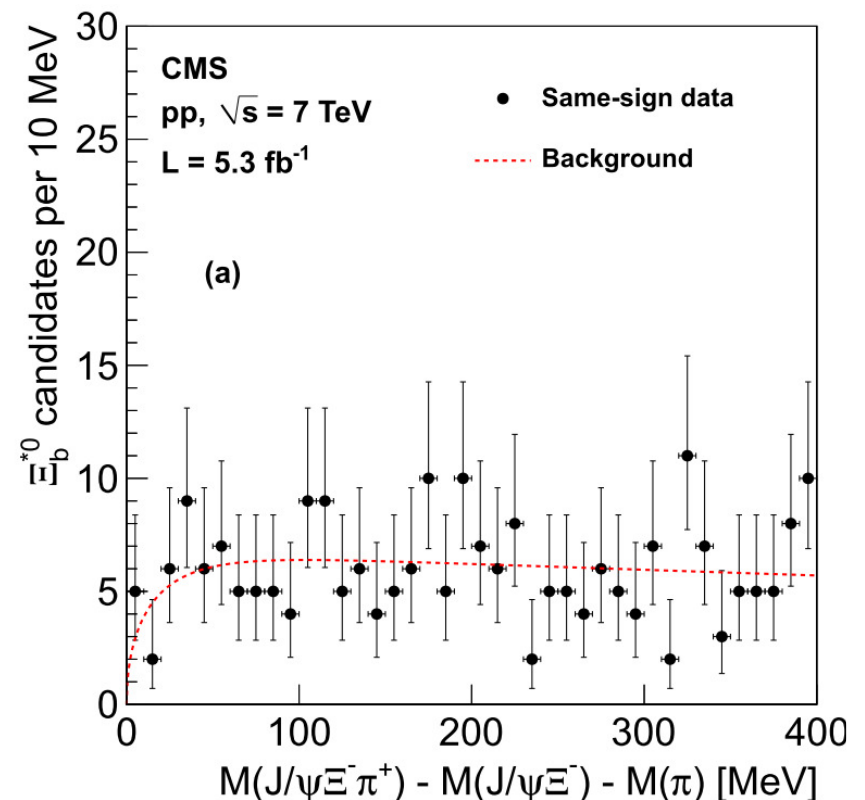
$$S/\sqrt{S+B} = 8.9$$

$$\sqrt{2 \ln \left(\frac{L_{s+b}}{L_b} \right)} = 11.4$$

Ξ_b^{*0} reconstruction

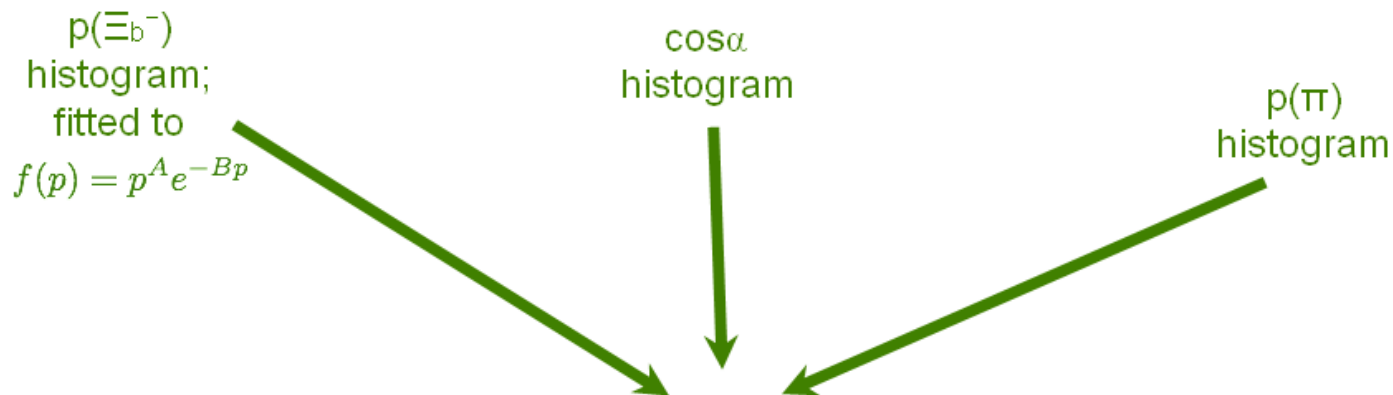
- Combine Ξ_b^- candidates (within 2.5σ of the mass peak) with tracks.
- Track requirements include:
 - Opposite sign w.r.t. Ξ_b^- . Same sign used to model the background.
 - $p_T > 0.25$ GeV

- $Q = M(\Xi_b^{*0}) - M(\Xi_b^-) - M(\pi^+)$ removes uncertainties from Ξ_b^- mass resolution.
- No peak seen in Same sign $\Xi_b^- \pi$ as expected



The background model

- Background expected to be combinatorial. From the same sign sample:



Generate 100M sets of 3 values and use:

$$Q = \sqrt{M(\Xi_b^-)^2 + M(\pi)^2 + 2E(\Xi_b^-)E(\pi) - 2p(\Xi_b^-)p(\pi) \cos \alpha - M(\Xi_b^-) - M(\pi)}$$

Get high statistics Q histogram. Then fit it to:

$$f_{bkg}(Q) = Q^A (e^{-BQ} + e^{-CQ} + e^{-DQ})$$

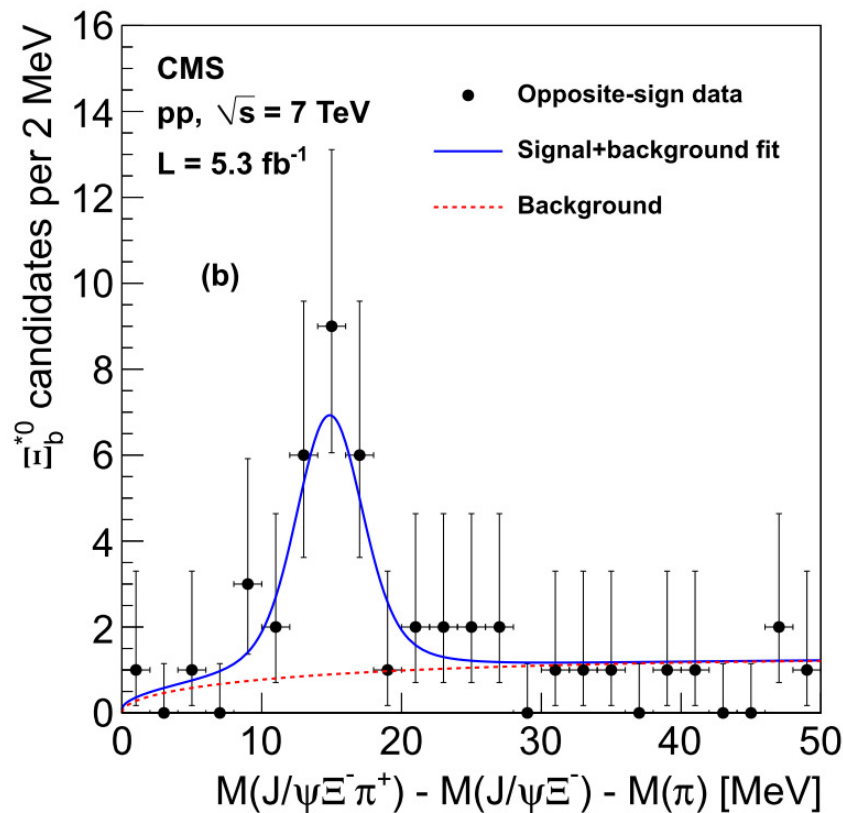
- To take systematic uncertainties into account:
- Use different functions for $f(p)$

Results

- Constrain Q peak resolution to value from signal MC generated with $\Gamma(\Xi_b^{*0}) = 0$.

$$\sigma_{MC} = 1.91 \pm 0.11 \text{ MeV}$$

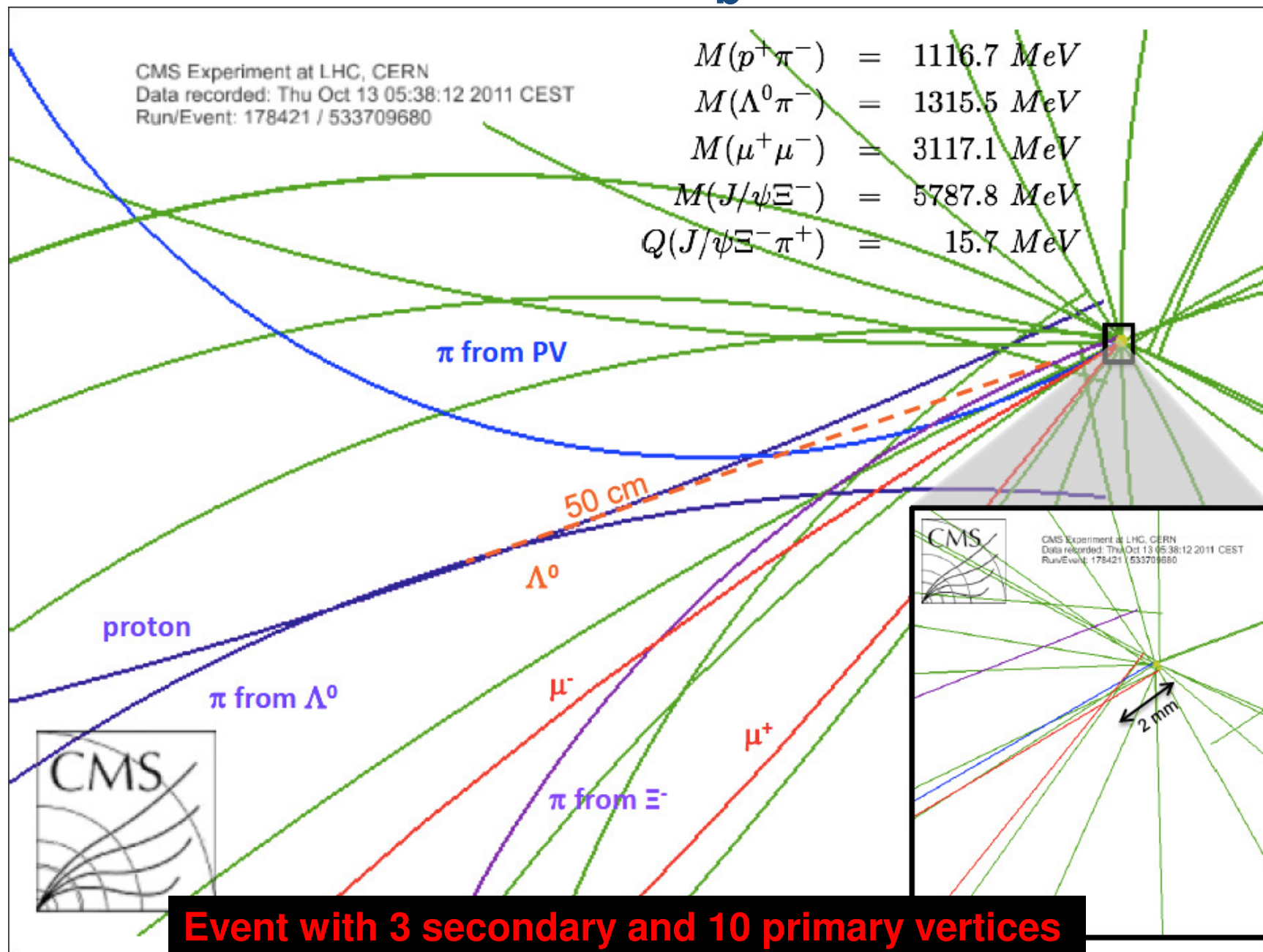
- Use un-binned likelihood fit



- Significance:
 - From the fit (likelihood ratio): 6.9σ
 - From pseudo-experiments: 5.7σ
- $\Gamma(\Xi_b^{*0}) = 2.1 \pm 1.7(\text{stat.}) \text{ MeV}$
- $Q(\Xi_b^{*0}) = 14.84 \pm 0.74(\text{stat.}) \pm 0.28(\text{syst.}) \text{ MeV}$
(Γ and Q compatible with expectations)
- $m(\Xi_b^{*0}) = 5945.0 \pm 0.7 \pm 0.3 \pm 2.7 \text{ (PDG) MeV}$
- Systematic uncertainties from:
 - Difference between measurement in the signal MC and the input to the generator.
 - Assuming a flat background Q distribution.

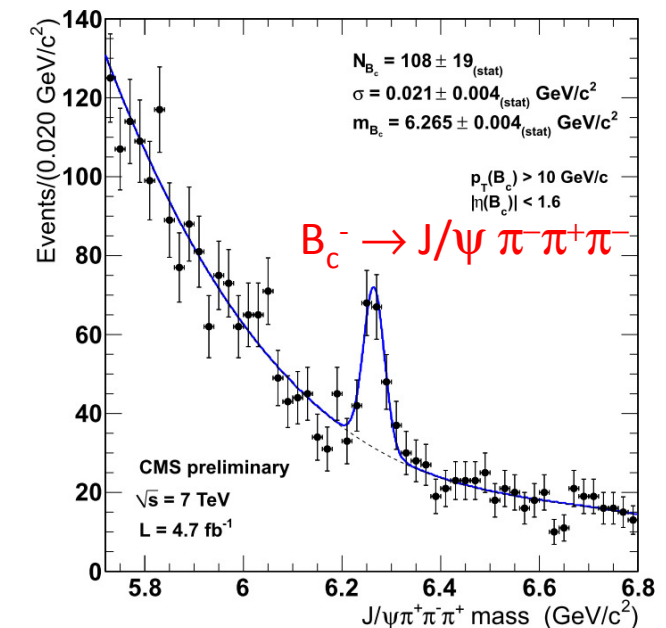
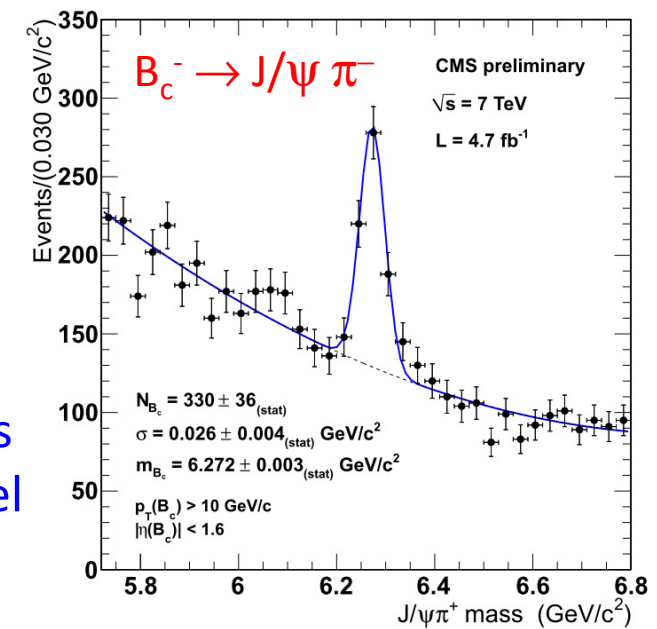
Candidate Ξ_b^{*0} event

14



B_c^+ meson studies

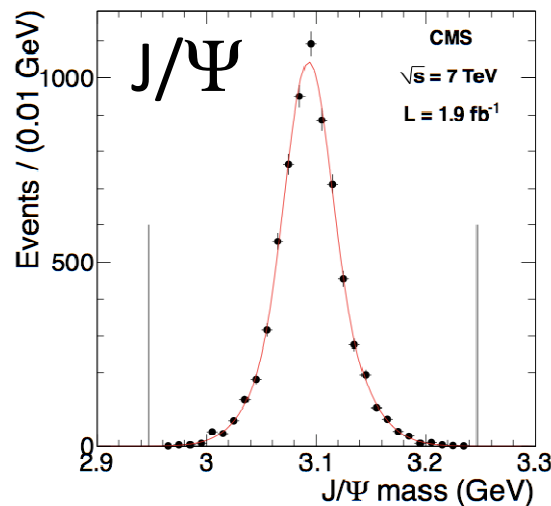
- B_c^+ is ground state of bound $b\bar{c}$ system
- Offers access to two different heavy quarks
 - Production requires $b\bar{b}$ and $c\bar{c}$ to be created
 - Branching ratio measurements help understand interplay between b and c decays
 - Lifetime measurement also tests decay model
- Large LHC dataset allows for 100's of reconstructed B_c 's at CMS
 - Very good resolution ~ 20 -25 MeV
 - Confirmation of two observed decay channels:
 - $B_c^+ \rightarrow J/\psi \pi$ by CDF in 1998
 - $B_c^+ \rightarrow J/\psi 3\pi$ by LHCb in April '12



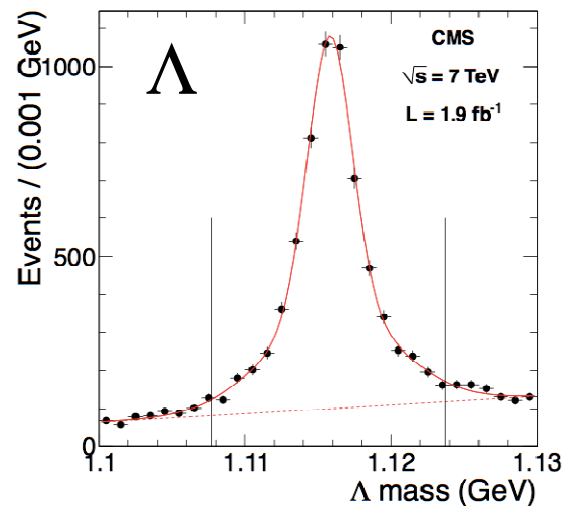
$\Lambda_b \rightarrow J/\psi \Lambda$ differential cross section

arXiv:1205.0594 accepted by PLB

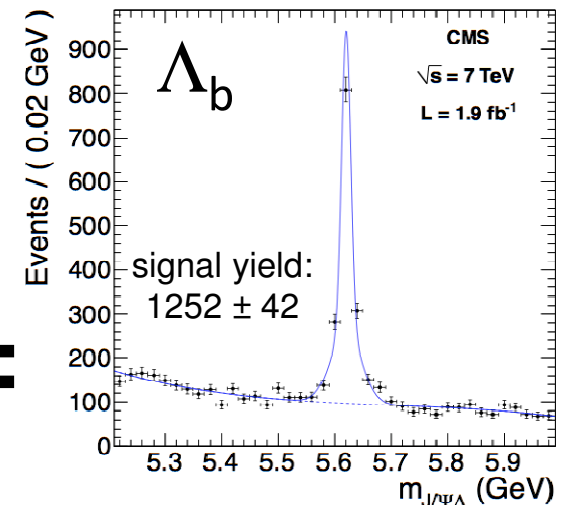
- B-hadron production cross sections provide a critical test of NLO calculations of perturbative QCD and fragmentation models
- Λ_b complements the B^+ , B^0 , B_s^0 measurements already performed by CMS
- Cross section from decay $\Lambda_b \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\Lambda^0(\rightarrow p^+\pi^-)$
- Λ_b reconstruction:
 - J/ψ : 2 opposite sign muons, matched to the trigger objects, with tighter cuts.
 - Λ reconstruction (77% purity): 2 tracks forming a very displaced vertex. Proton chosen as highest $|p|$ track.
 - Λ_b candidate obtained by a kinematic vertex fit, constraining the J/ψ and Λ masses.



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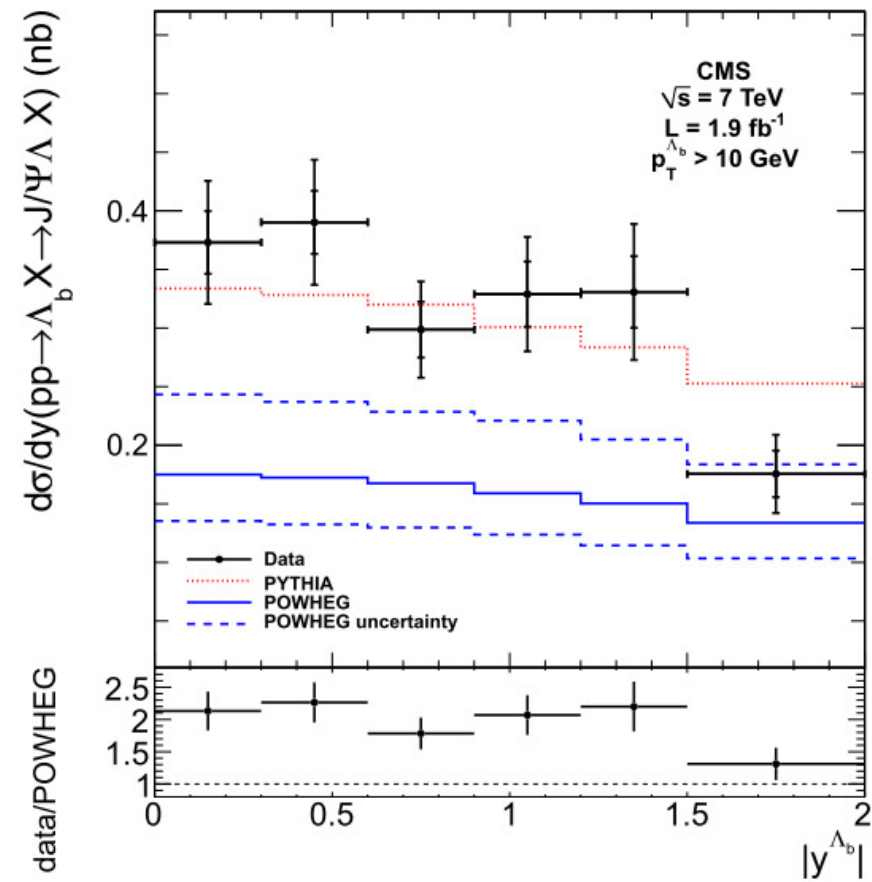
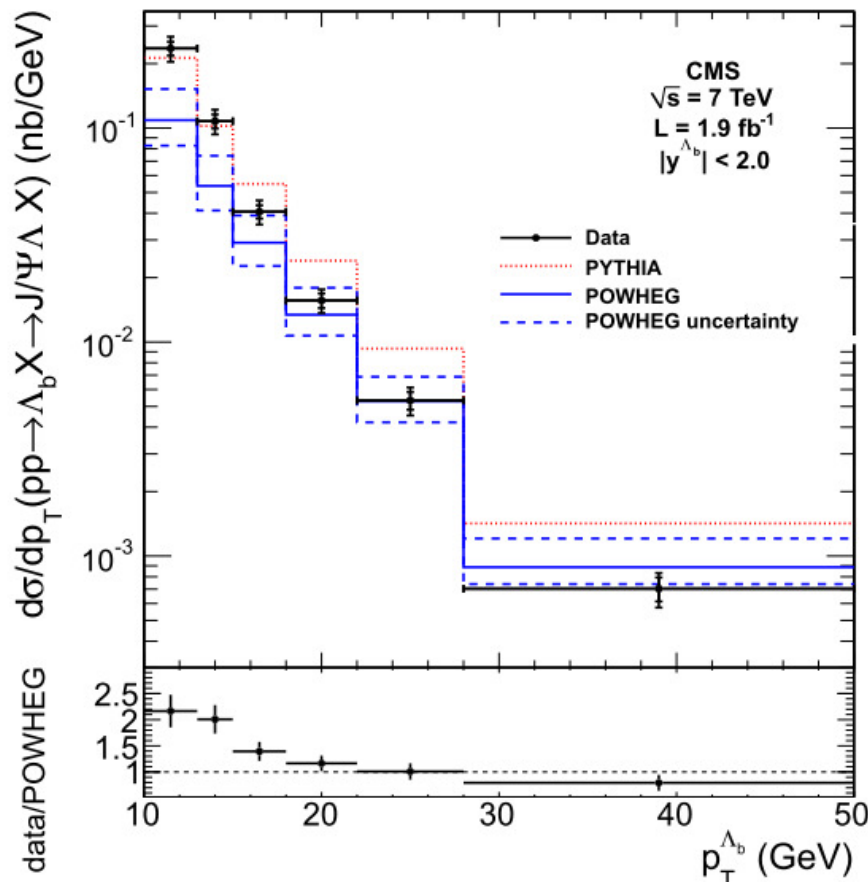


$\Lambda_b \rightarrow J/\psi \Lambda$ differential cross section

- Extract signal yield form mass fit. Then calculate average cross section:

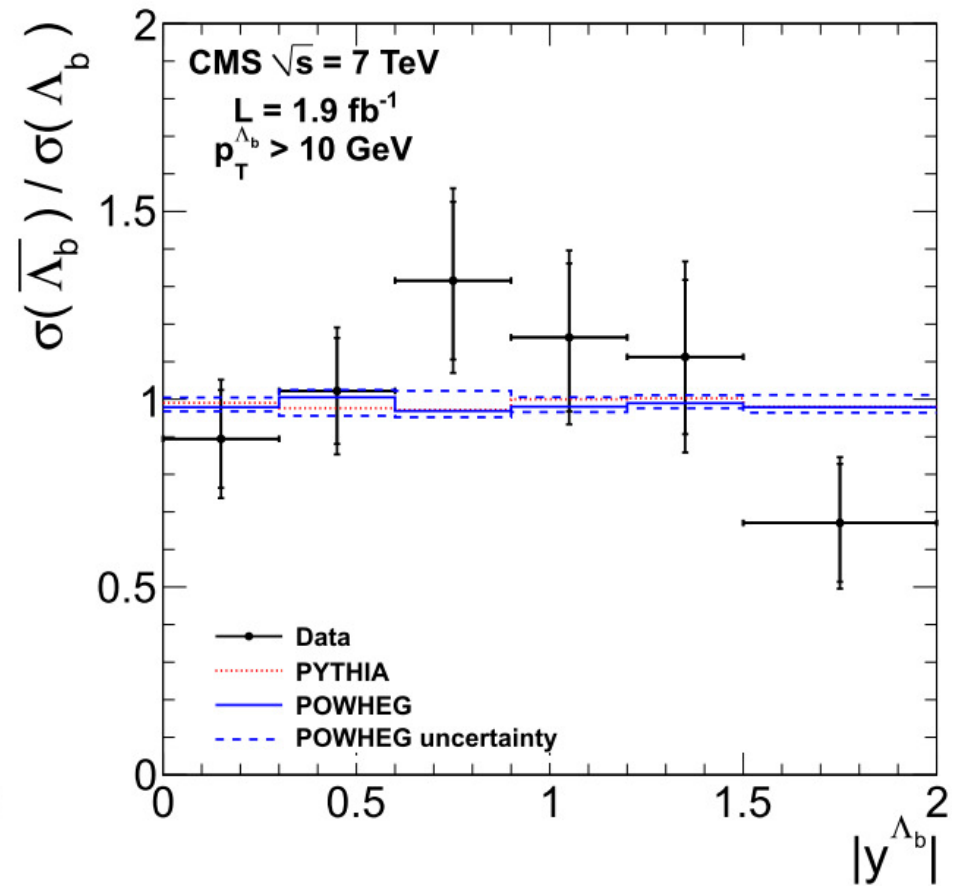
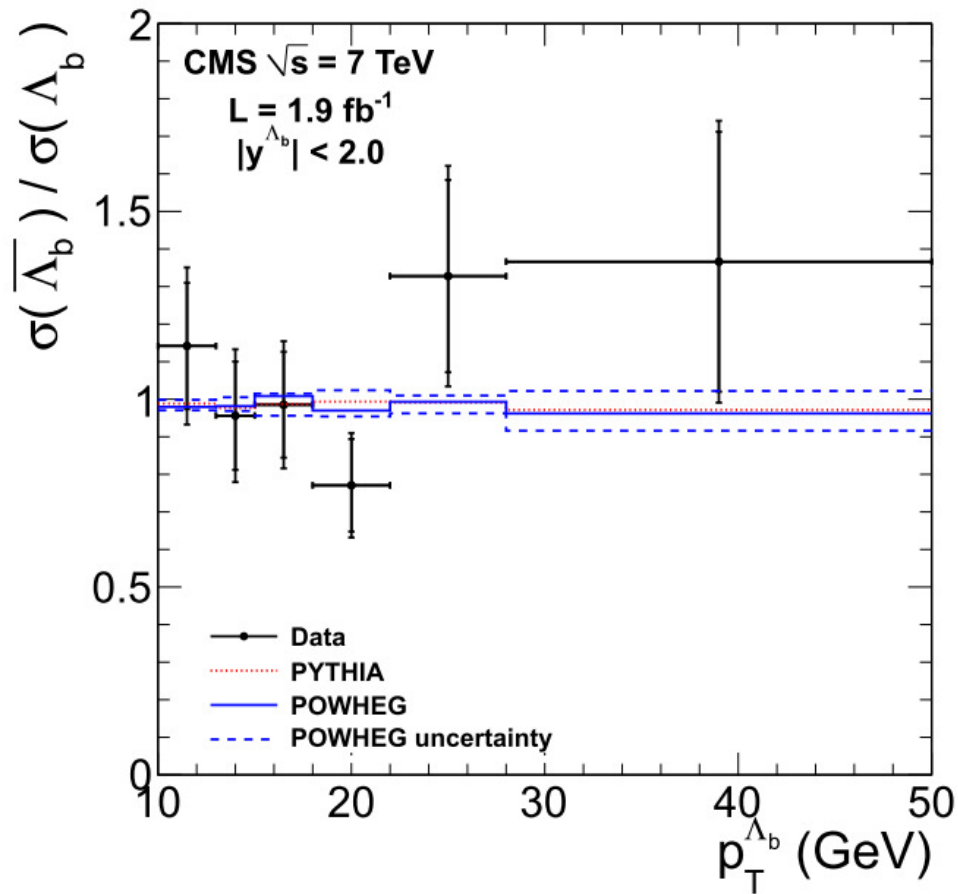
$$\frac{d\sigma(pp \rightarrow \Lambda_b X)}{dp_T^{\Lambda_b}} \times \mathcal{B}(\Lambda_b \rightarrow J/\psi \Lambda) = \frac{n_{\text{sig}}}{2 \cdot \epsilon \cdot \mathcal{B} \cdot \mathcal{L} \cdot \Delta p_T^{\Lambda_b}}$$

Data falls steeper
than Simulation



$\Lambda_b \rightarrow J/\psi \Lambda$ differential cross section

- Compare particle to anti-particle production
 - Tests baryon transport models from initial pp state
 - Results compatible with flat line as a function of p_T and y .

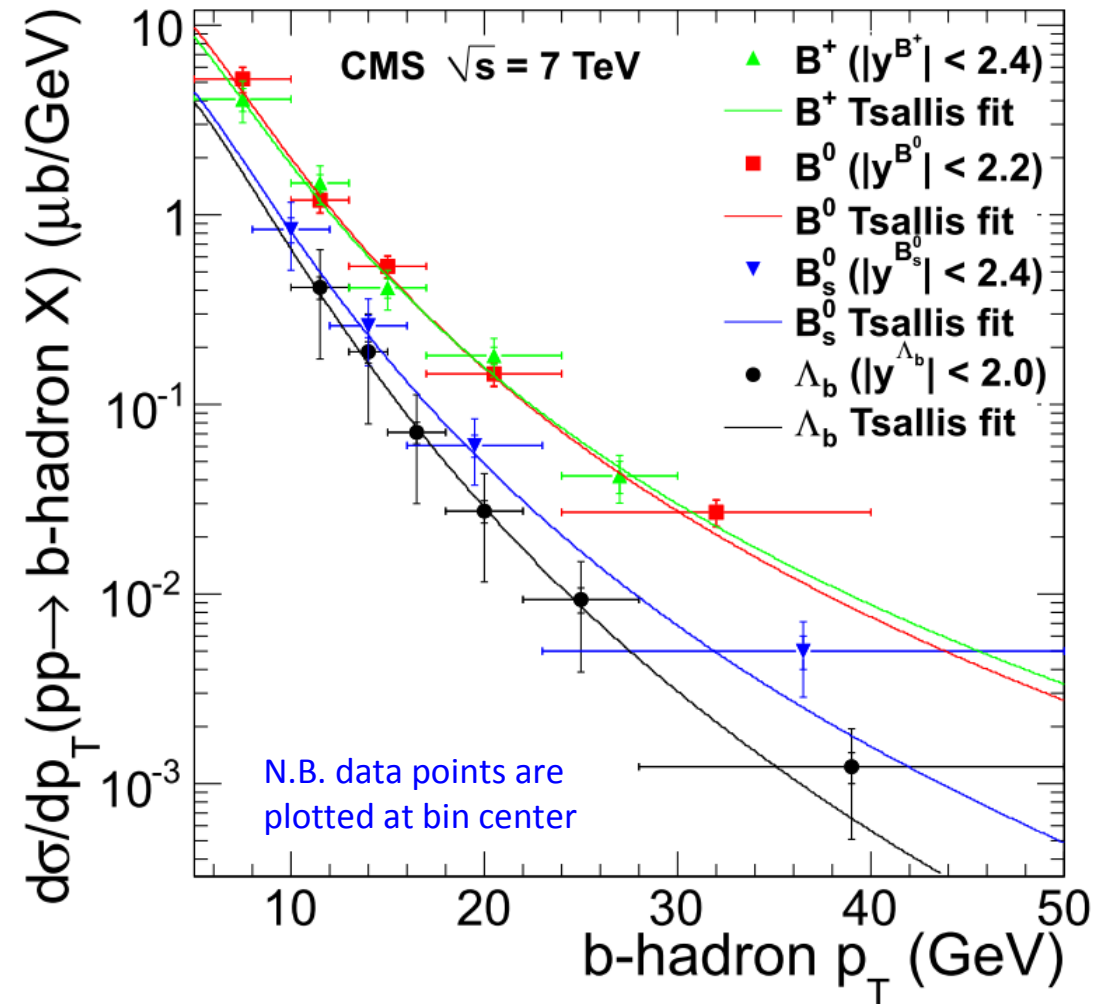


Summary of CMS exclusive B measurements

- Unexpectedly Λ_b baryon shows a steeper p_T dependence compared to the B-mesons
- Fit to Tsallis function:

$$\frac{1}{N} \frac{dN}{dp_T} = C p_T \left[1 + \frac{\sqrt{p_T^2 + m^2} - m}{nT} \right]^{-n}$$

hadron	n (T=1.1 GeV)
B^+	5.5 ± 0.3
B^0	5.8 ± 0.3
B_s	6.6 ± 0.4
Λ_b	7.6 ± 0.4

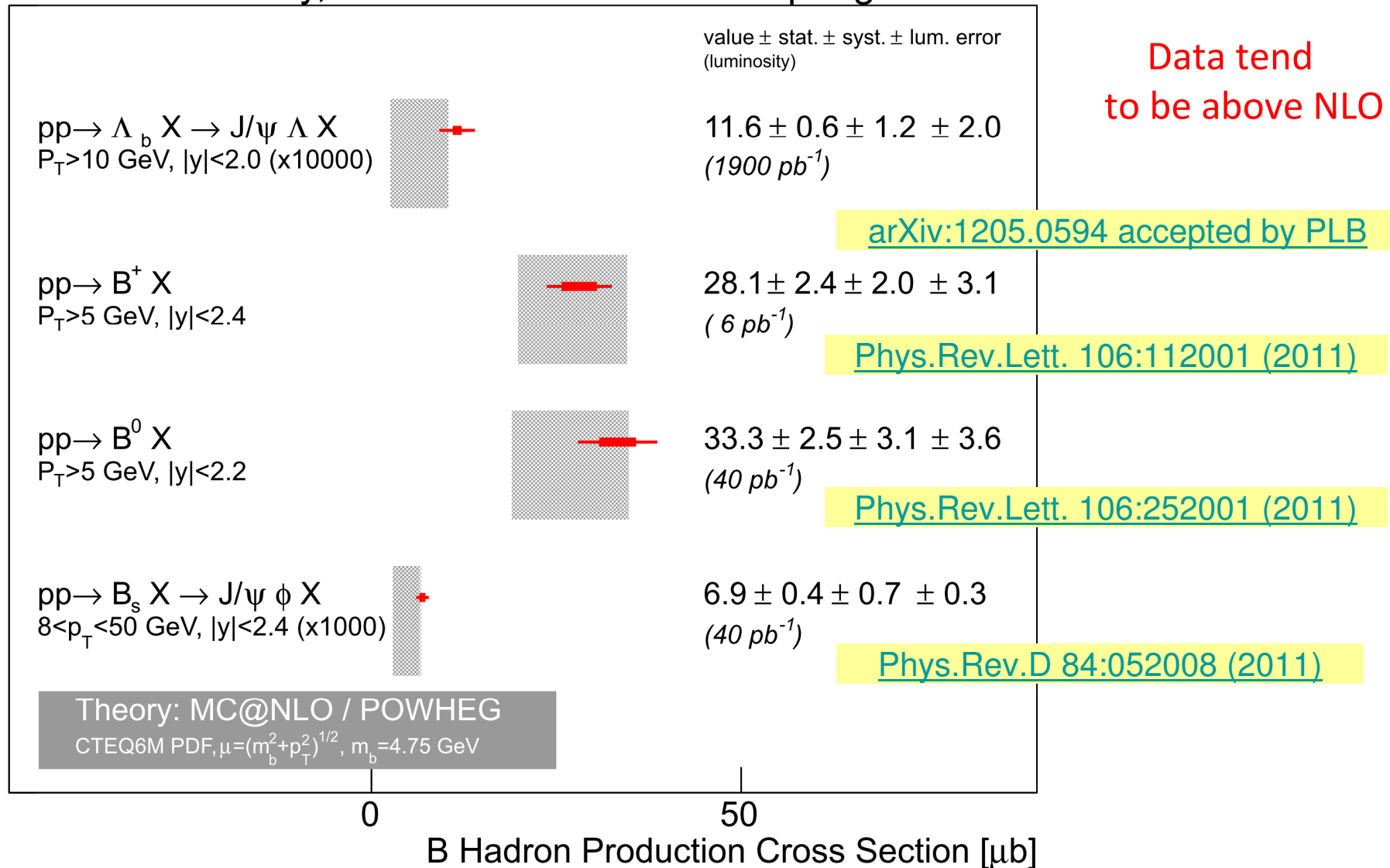


- Similar feature observed by LHCb in measurement of $f_{\Lambda_b}/(f_u + f_d)$ vs p_T

Summary of CMS exclusive B measurements

CMS Preliminary, $\sqrt{s}=7$ TeV

Spring 2012



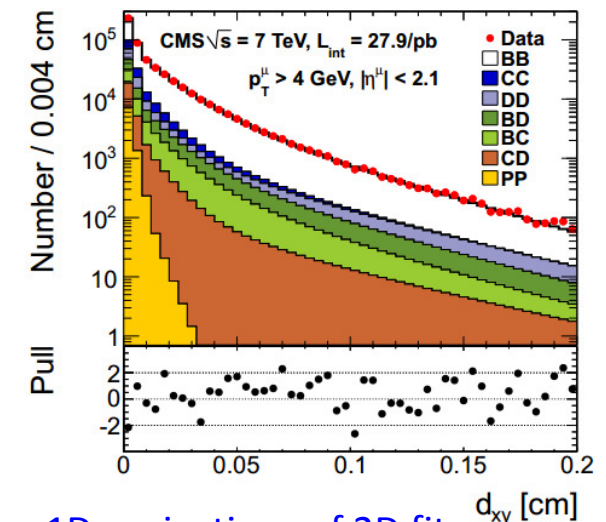
Inclusive $b\bar{b}$ cross section with muon pairs

- Complementary to measurements with jets
- Fraction of $b\bar{b} \rightarrow \mu\mu$ events in data extracted with a 2D template fit to the di- μ impact parameter
 - Distributions for B (bottom), C (charm) and D (decays in flight) taken from simulation
 - Distribution for P (prompt) from $Y(1s) \rightarrow \mu^+\mu^-$ decays in data
- High purity ($\sim 70\%$), small total systematic uncertainties both in data and NLO predictions

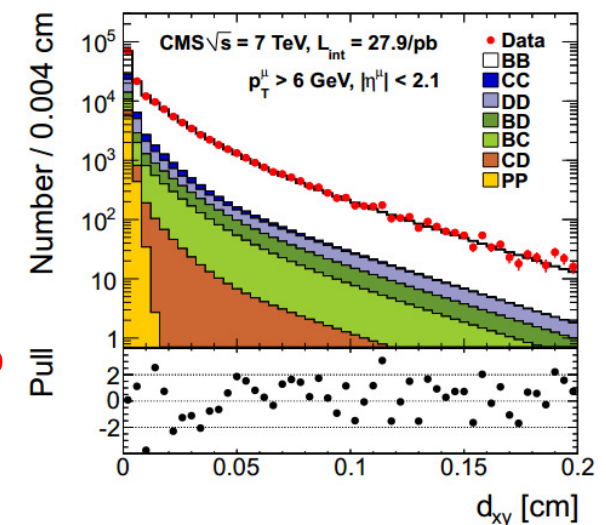
Source	Uncertainty	
	$p_T > 4 \text{ GeV}$	$p_T > 6 \text{ GeV}$
Model dependency	5.5	5.1
Impact parameter resolution	2.7	4.0
Monte Carlo precision and fit method	2.2	2.7
Efficiencies and acceptance	6.1	6.2
Total	8.9	9.4

- $\sigma(pp \rightarrow b\bar{b} \rightarrow \mu\mu X)$
 - $(p_T > 4 \text{ GeV}, |\eta| < 2.1) = 26.4 \pm 0.1(\text{stat}) \pm 2.4(\text{syst}) \pm 1.1(\text{lumi}) \text{ nb}$
 - $\sigma_{\text{MC@NLO}}(p_T > 4 \text{ GeV}, |\eta| < 2.1) = 19.7 \pm 0.3(\text{stat}) + 6.5 - 4.1(\text{syst}) \text{ nb}$
 - $(p_T > 6 \text{ GeV}, |\eta| < 2.1) = 5.12 \pm 0.03(\text{stat}) \pm 0.48(\text{syst}) \pm 0.20(\text{lumi}) \text{ nb}$
 - $\sigma_{\text{MC@NLO}}(p_T > 6 \text{ GeV}, |\eta| < 2.1) = 4.40 \pm 0.14(\text{stat}) + 1.10 - 0.84(\text{syst}) \text{ nb}$

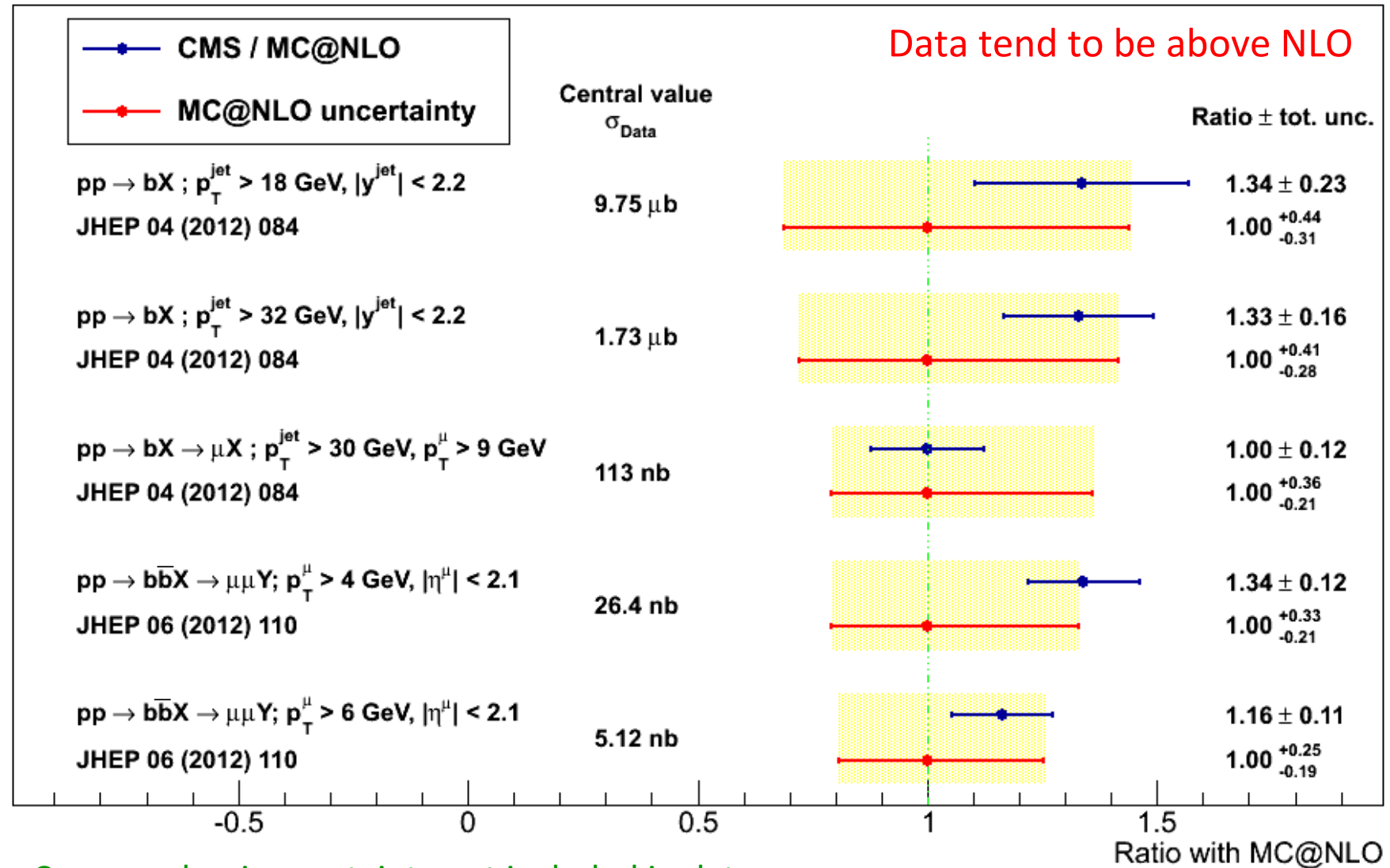
JHEP 06 (2012) 110



1D projections of 2D fits



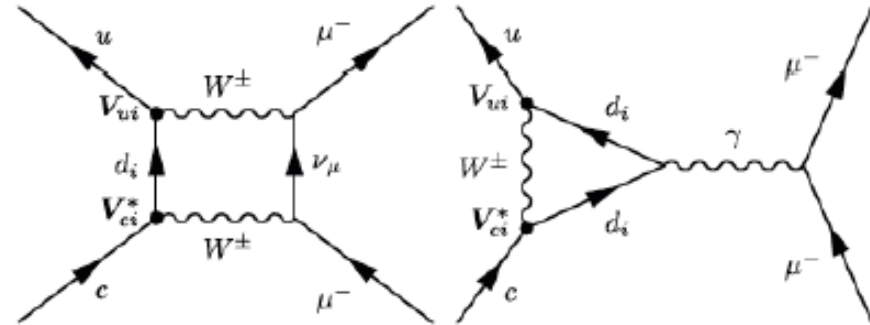
Summary of CMS inclusive B measurements



Common lumi uncertainty not included in data

Search for the rare decay $D^0 \rightarrow \mu^+ \mu^-$

[CMS-PAS-BPH-11-017](#)



- **Motivation:**

- FCNC forbidden at tree level.
- Standard Model predicts $BR \sim 10^{-13}$
- A difference would indicate New Physics.
- Current best limit from LHCb ($BR < 1.3 \times 10^{-8}$ @ 95% C.L.)
- Best limit from B factories: Belle ($BR < 1.4 \times 10^{-7}$ @ 90% C.L.).

[LHCb-CONF-2012-005](#)

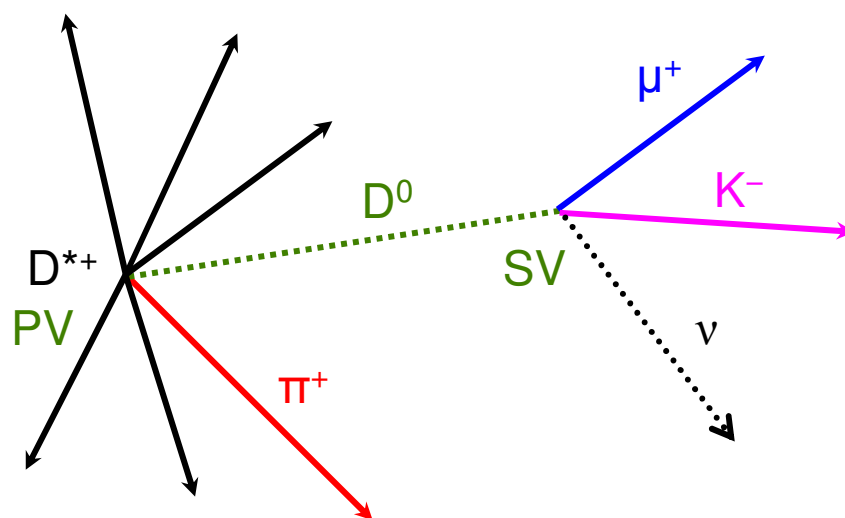
- **Strategy:**

- Calculate the $D^0 \rightarrow \mu^+ \mu^-$ branching ratio through $D^{*+} \rightarrow D^0 \pi^+$ (clean sample) using as normalization channel $D^0 \rightarrow K^- \mu^+ \nu$; $BR = (3.30 \pm 0.13)\%$.
- Normalization channel chosen to cancel out systematic uncertainties and minimize the differences at trigger level. First time that a semi-leptonic channel is chosen.
- Challenge: need a single muon trigger to reveal the normalization channel.

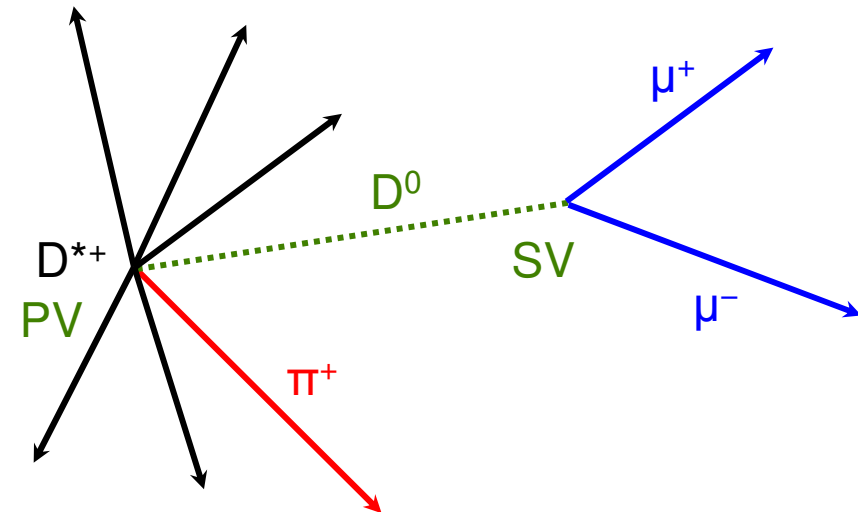
[Phys. Rev. D 81 \(2010\) 091102](#)

Selection

- Total sample: $\sim 90 \text{ pb}^{-1}$ (7 data taking periods with increasing muon p_T thresholds (3-15 GeV))
- Signatures:
- Muons: tight quality, $|\eta| < 2.1$, $p_T > 3 \text{ GeV}$, muon firing the trigger has same p_T cut.
- Kaon: tight quality, $|\eta| < 2.1$, $p_T > 0.8 \text{ GeV}$. p_ν reconstructed with kinematical considerations
- PV & SV: vertex probability $> 1\%$. 3D distance significance > 3 . [Phys. Rev. Lett. 62, 1587–1590 \(1989\)](#)
- Signal only: $\cos\alpha > 0.99$; α = angle between the D^0 momentum and the PV-SV direction.
- Prompt pion: track from the PV, $p_T > 0.6 \text{ GeV}$.



NORMALIZATION

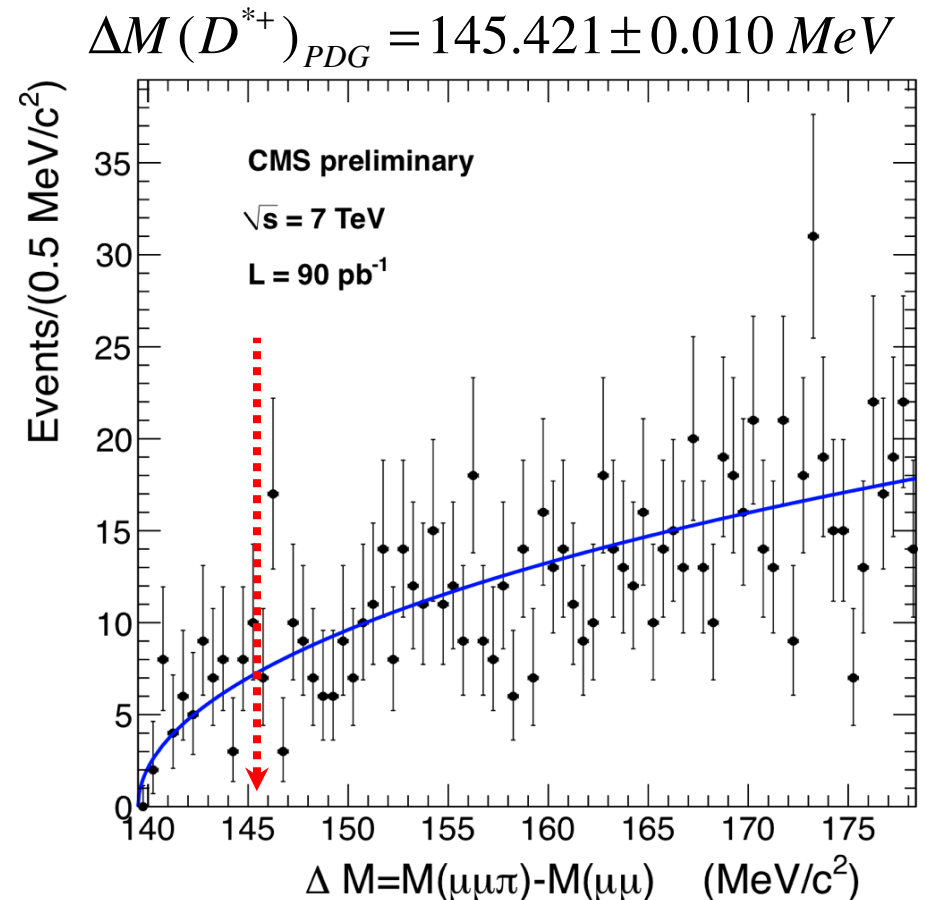
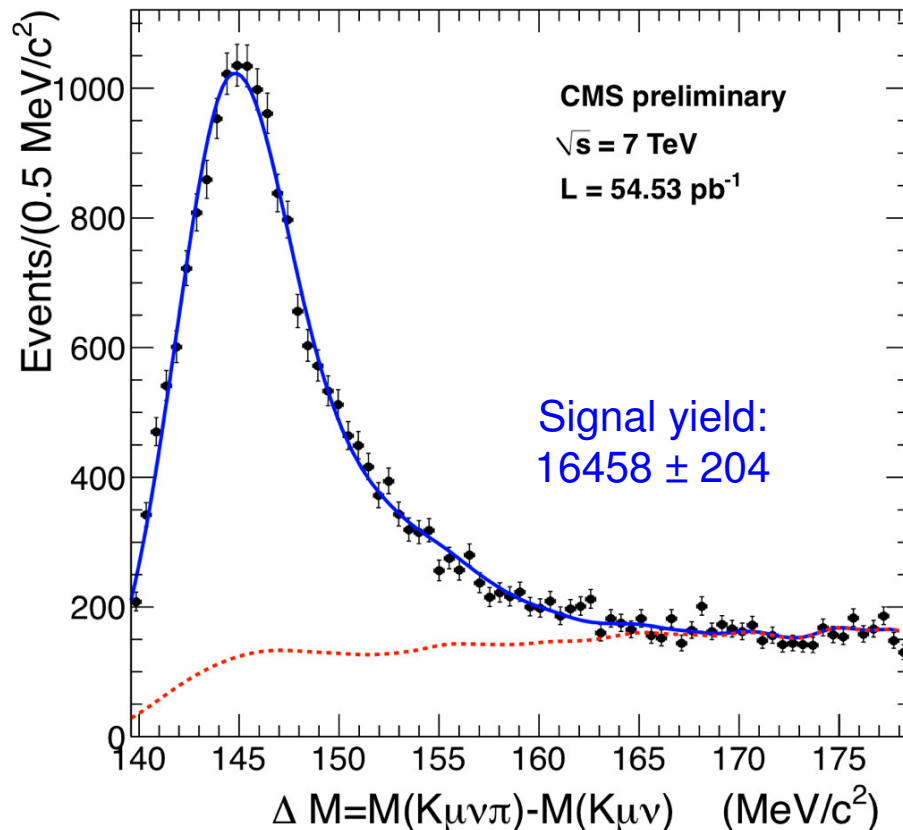


SIGNAL

D^{*+} mass difference

- **NORMALIZATION:** fit to extract $N(K\mu\nu)$
- **Signal:** two gaussians.
- **Background:** from same sign K- π sample.
- **SIGNAL:** no evidence of $D^0 \rightarrow \mu\mu$ from D^{*+}
- **Fit background to empirical function:**

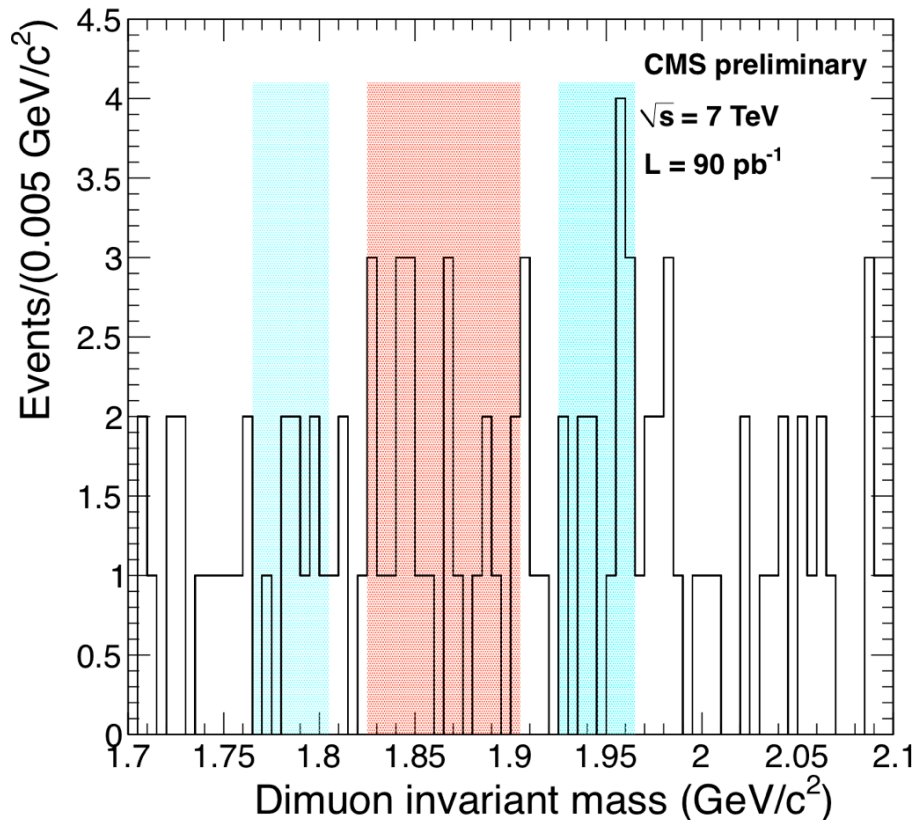
$$f(\Delta M) = p_1 \times [(\Delta M - M_\pi)^{1/2} + p_2 \times (\Delta M - M_\pi)^{3/2}]$$



Results

$$B(D^0 \rightarrow \mu^+ \mu^-) \leq B(D^0 \rightarrow K^- \mu^+ \nu) \times \frac{N(\mu\mu)}{N(K\mu\nu)} \times \frac{a(K\mu\nu)}{a(\mu\mu)} \times \frac{\epsilon_{\text{trig}}(K\mu\nu)}{\epsilon_{\text{trig}}(\mu\mu)} \times \frac{\epsilon_{\text{rec}}(K\mu\nu)}{\epsilon_{\text{rec}}(\mu\mu)}$$

$$|\Delta M - \Delta M_{\text{PDG}}| < 3 \text{ MeV}$$



- Separately for the 7 data-taking periods.
- $N(\mu\mu)$ is the 90% CL upper limit on the signal yield, obtained from the number of events in the **D0 mass region** and in the sidebands, assuming they obey Poisson statistics.
- Acceptance & efficiency ratios from MC.
- Systematic uncertainties:
 - Acceptance & efficiencies: MC & data-driven method.
 - Underestimated trigger efficiencies.
 - Contamination from $D^0 \rightarrow K^{*-}(K^- \pi^0) \mu^+ \nu$
 - PDG uncertainty for $B(D^0 \rightarrow K \mu \nu)$

$$B(D^0 \rightarrow \mu^+ \mu^-) \leq 5.4 \times 10^{-7} (90\% \text{ CL})$$

$$\text{LHCb: } 1.3 \times 10^{-8}$$

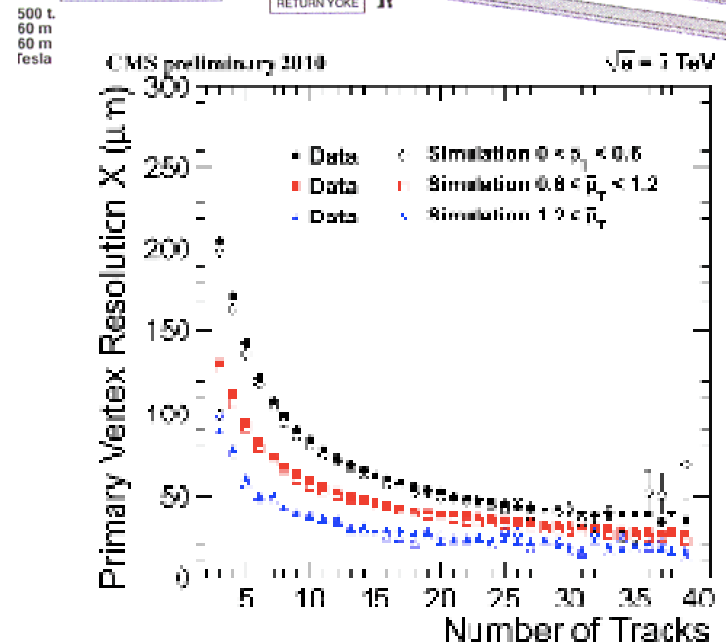
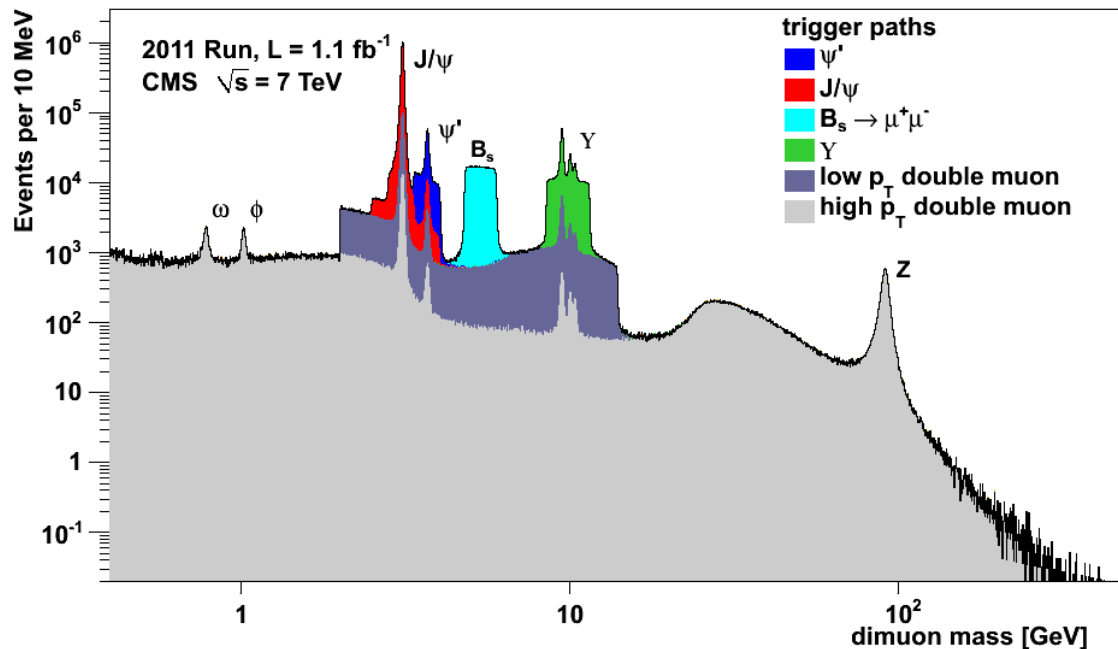
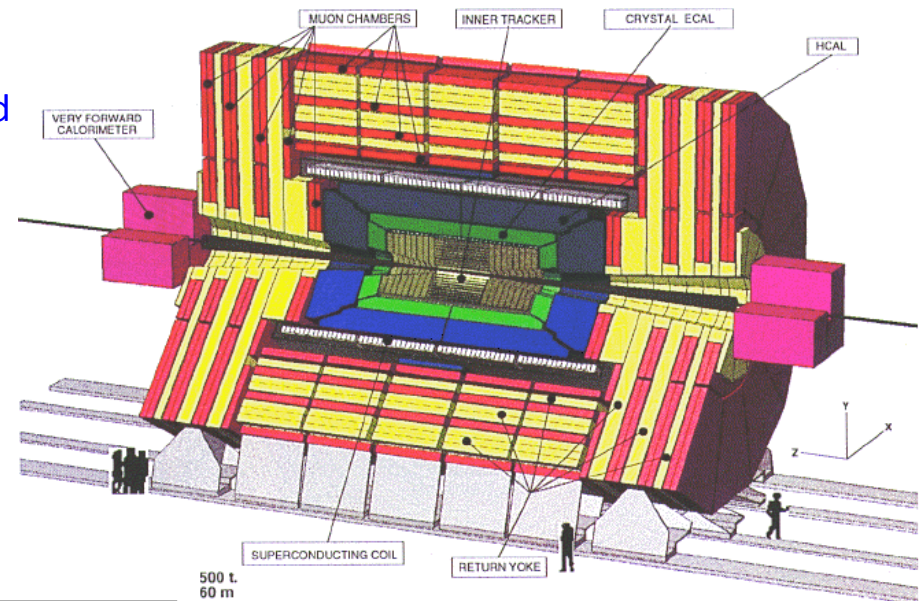
Conclusions

- CMS is producing high quality results on heavy flavor physics.
- Presented results:
 - Observation of a new strange b baryon, the Ξ_b^{*0}
 - Confirmation of $B_c \rightarrow J/\psi \pi$ $B_c \rightarrow J/\psi 3\pi$ decay channel observations
 - First measurement of a b baryon cross section in the LHC. p_T distribution for Λ_b falls steeper in data than in MC predictions as well as w.r.t. to B-meson cross sections.
 - Inclusive $b\bar{b} \rightarrow \mu\mu$ cross section measurement with reduced uncertainty on data and NLO prediction
 - Search for the rare decay $D^0 \rightarrow \mu^+ \mu^-$ with limit 5.4×10^{-7} @90% C.L.
- More results to come from 2011 data. Analysis of 2012 data in progress.
- Only the most recent results have been presented. Many more results here:
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH>

Backup slides

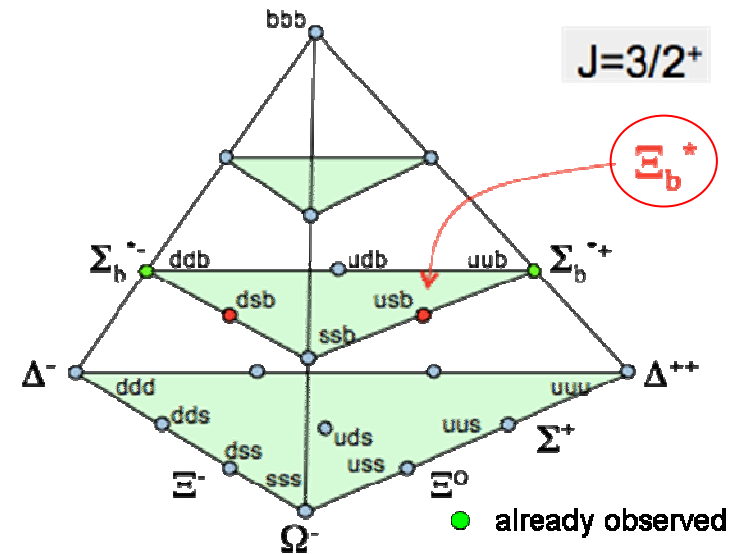
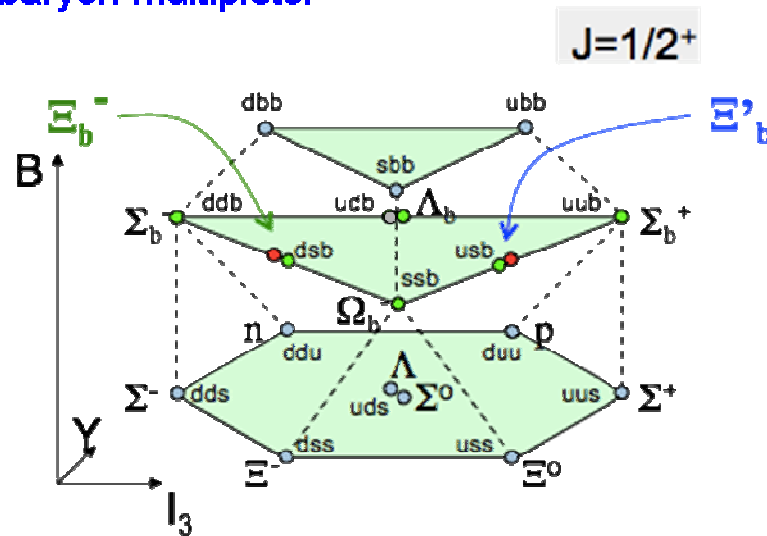
CMS Detector Performance

- All-silicon tracker (pixels and strips) give excellent p_T and vertex position resolutions.
- Trigger:
 - di-muon based (opposite sign),
 - uses DCA & vertex probability cuts (against PU).
 - For B hadrons: 3σ cut in the separation of the di-muon vertex and the beam line.



Observation of the Ξ_b^* baryon

- B-baryon multiplets:



- Charm sector cousin: $\Xi_c(2645)^0 \rightarrow \Xi_c^+ \pi^-$

Phys. Rev. Lett. 75, 4364 (1995)

- Expected $Q(\Xi_b^{*0}) = M(\Xi_b^{*0}) - M(\Xi_b^-) - M(\pi^+) \sim 11\text{-}29 \text{ MeV}$

Phys. Rev. D 66, 014502 (2002)

Phys. Rev. D 77, 034012 (2008)

Phys. Rev. D 79, 014502 (2009)

Phys. Rev. D 84, 014025 (2011)

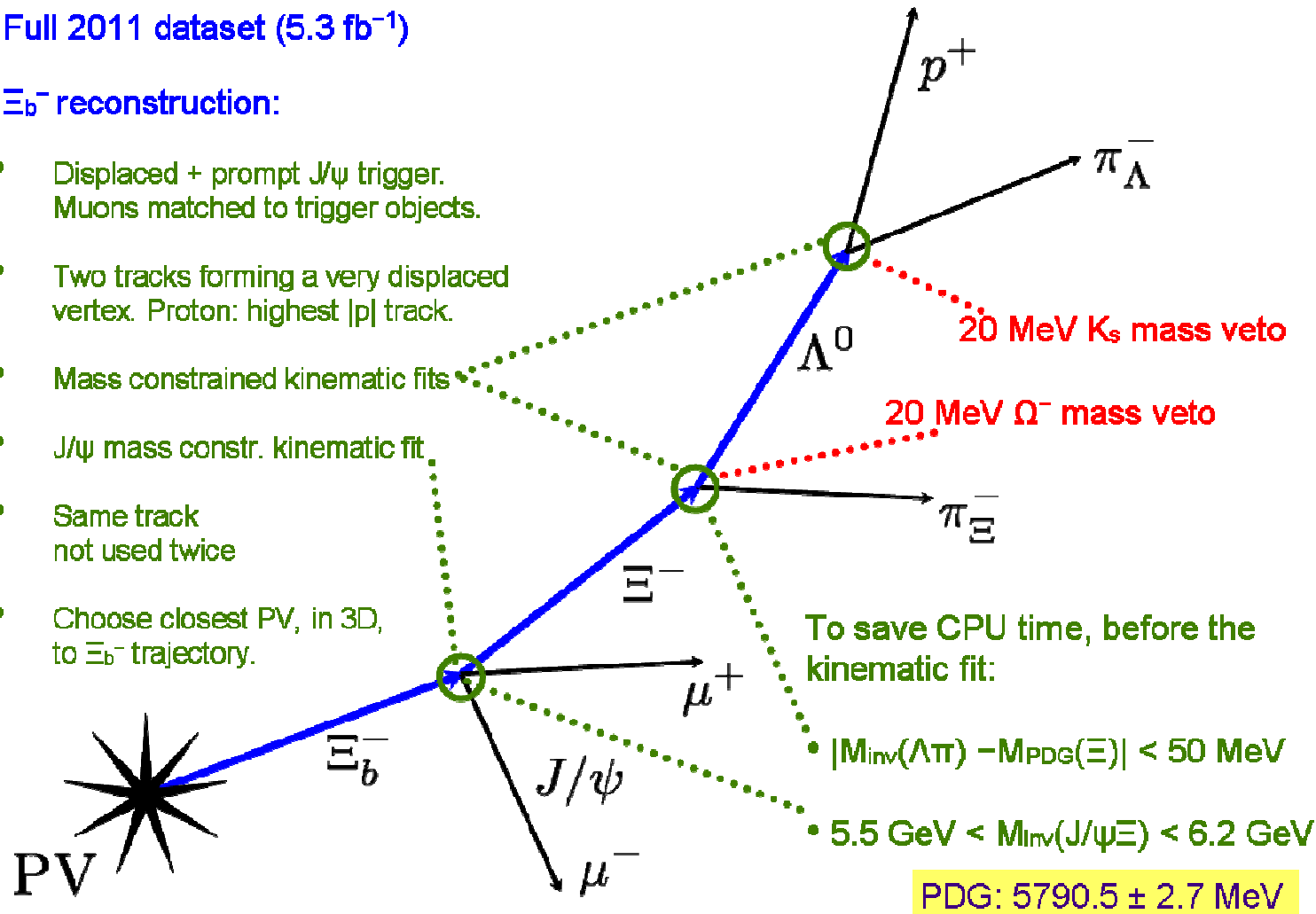
- Given the predicted Q , $\Gamma(\Xi_b^{*0}) < 1 \text{ MeV}$. [arXiv:1203.3378v1 \[hep-lat\]](https://arxiv.org/abs/1203.3378v1)

Ξ_b^- selection

- Full 2011 dataset (5.3 fb^{-1})

- Ξ_b^- reconstruction:

- Displaced + prompt J/ψ trigger.
Muons matched to trigger objects.
- Two tracks forming a very displaced vertex. Proton: highest $|p|$ track.
- Mass constrained kinematic fits
- J/ψ mass constr. kinematic fit
- Same track not used twice
- Choose closest PV, in 3D, to Ξ_b^- trajectory.

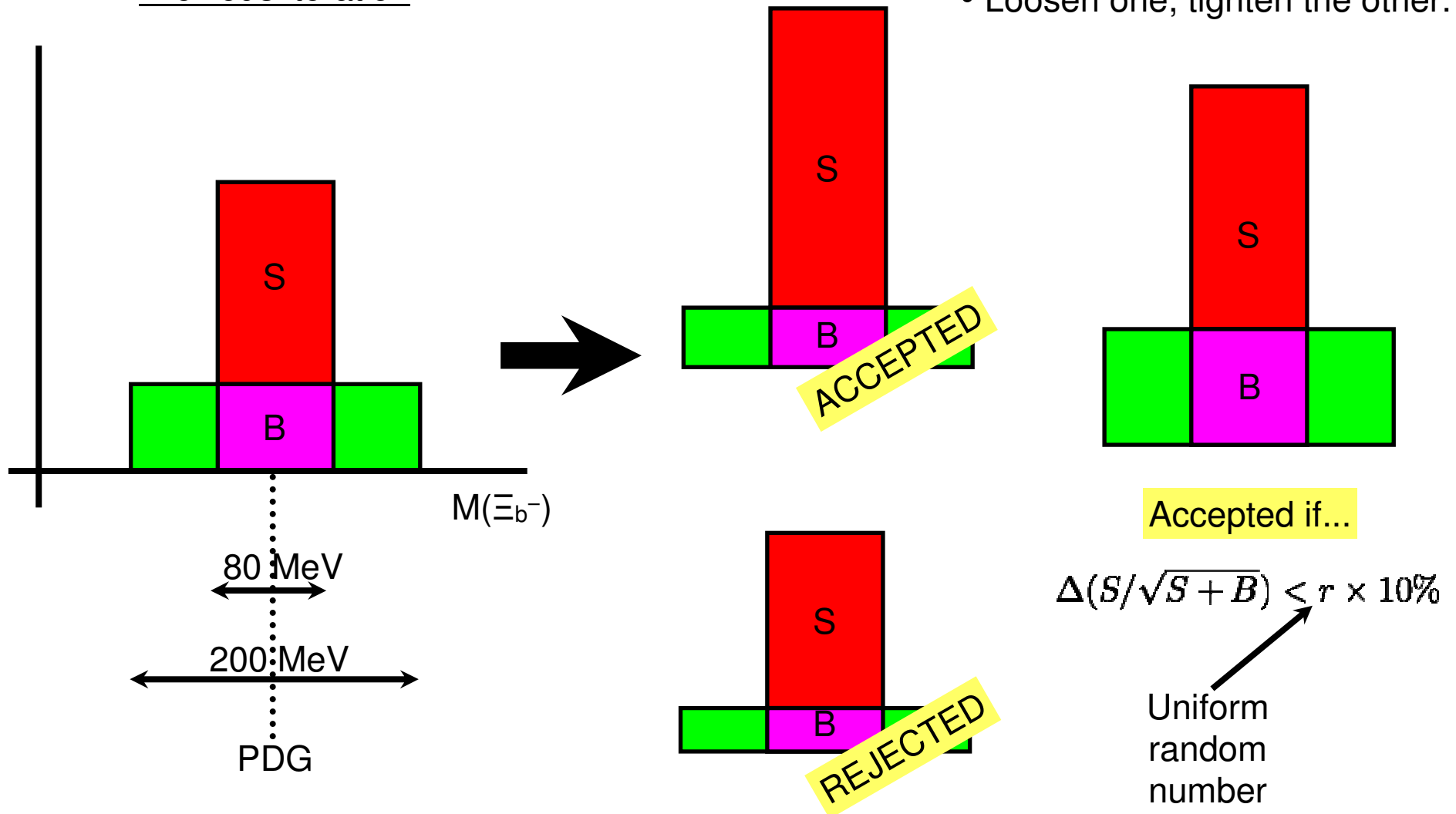


Ξ_b^- selection algorithm

Next iteration: randomly...

- Choose 2 variables,
- Loosen one, tighten the other.

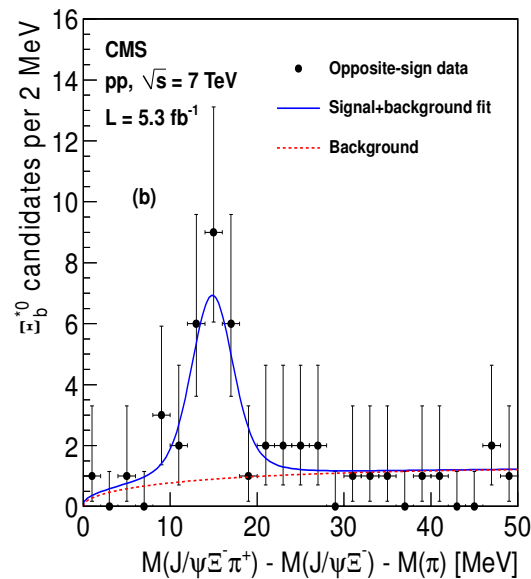
Previous iteration



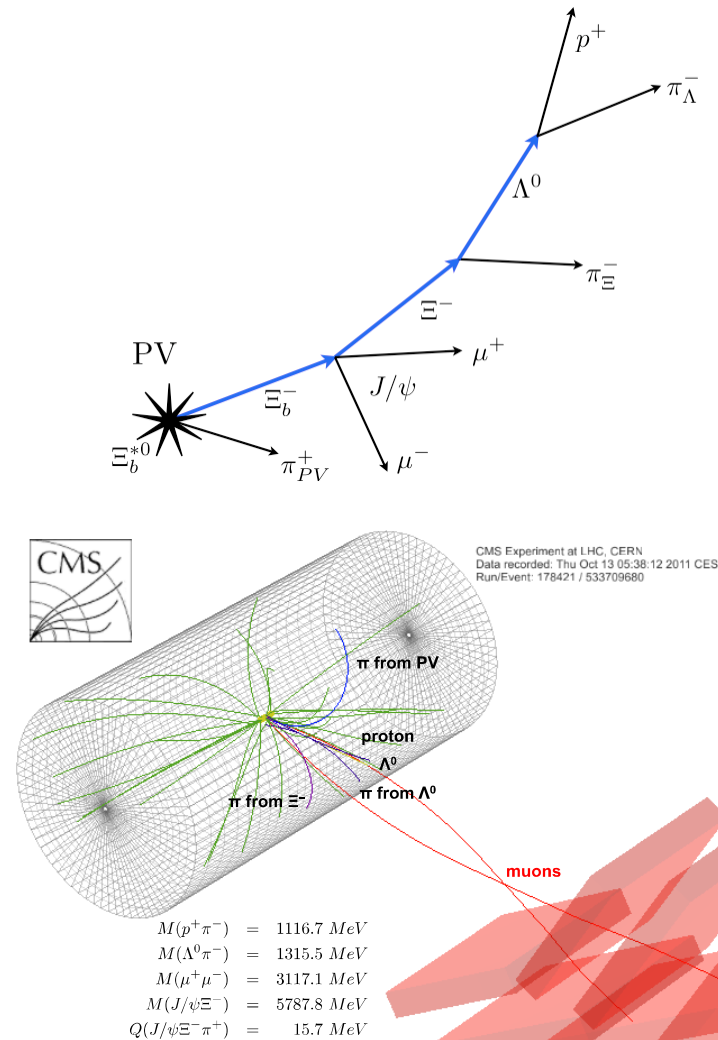
First observation of the Ξ_b^{*0} hadron

- Through the decay chain:

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



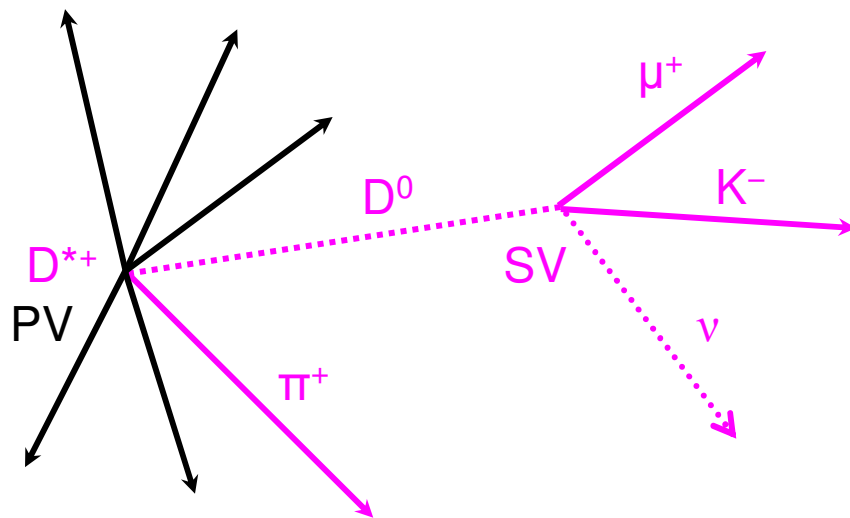
- Mass: $5945.0 \pm 2.8 \text{ MeV}$.
- Significance = 6.9σ



arXiv:1204.5955

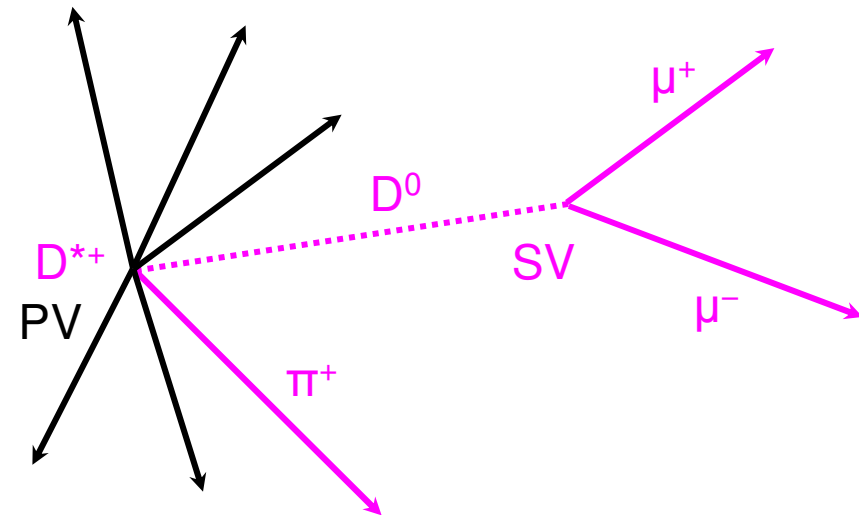
Sample & reconstruction

- Total sample: $\sim 90 \text{ pb}^{-1}$:
 - From 2010 ($\sim 36 \text{ pb}^{-1}$): 6 data taking periods with increasing muon p_T thresholds (3-15 GeV)
 - From 2011: single muon trigger not pre-scaled only for $\sim 54 \text{ pb}^{-1}$ with one threshold (15 GeV).
- Signatures:



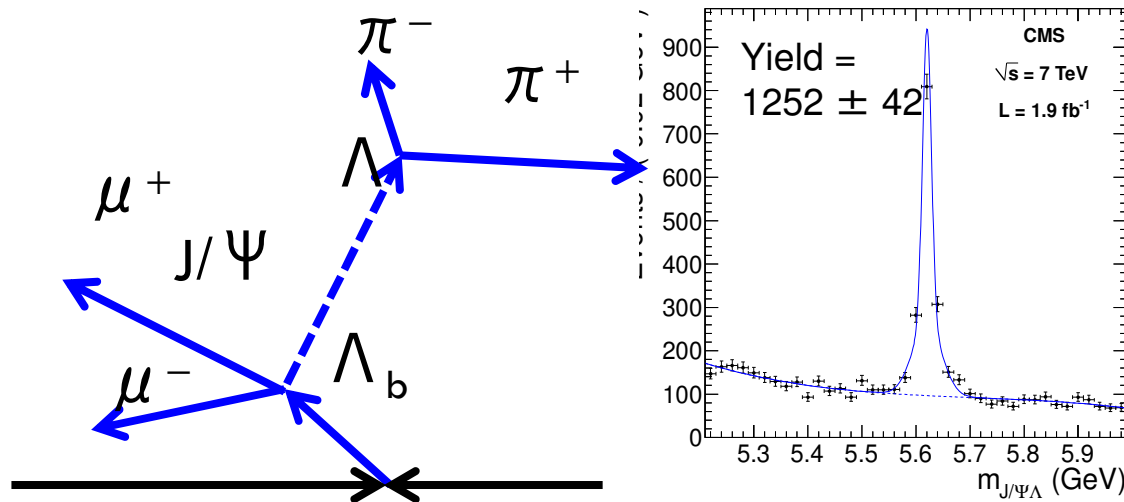
NORMALIZATION

Reconstructed using the PV-SV direction



SIGNAL

Λ_b cross section measurement



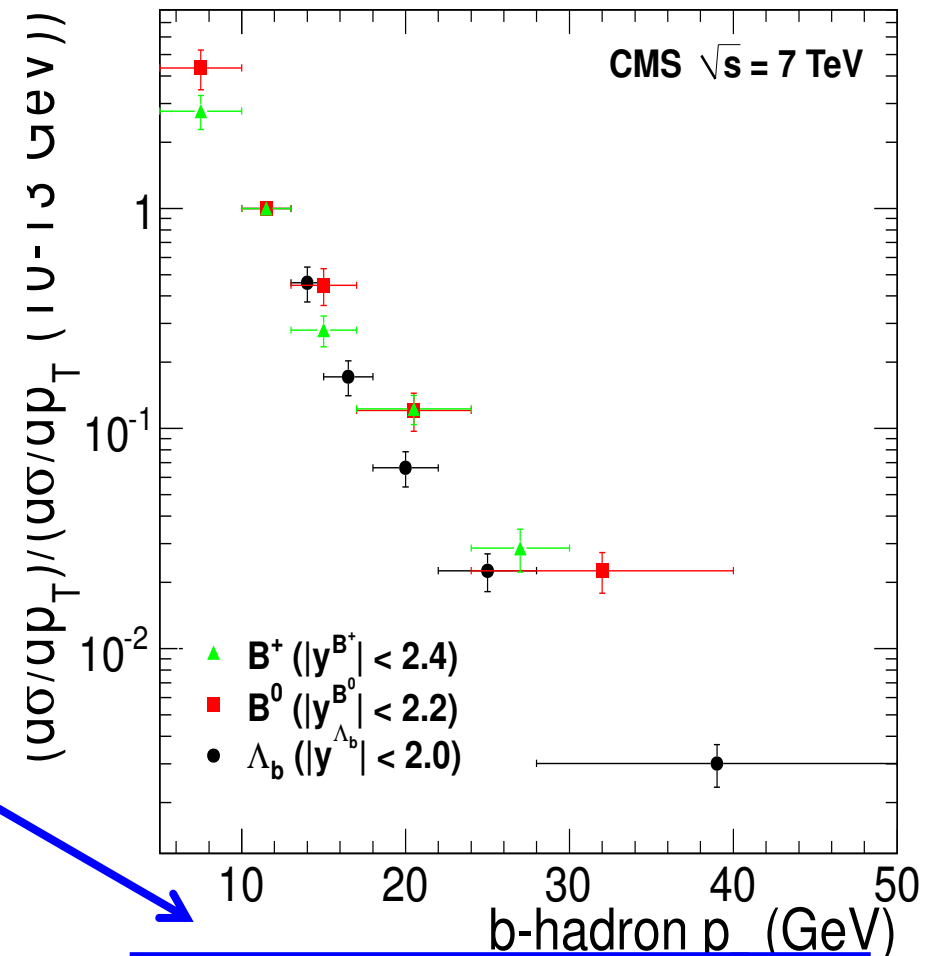
- Λ_b reconstructed in decays to $J/\psi(\mu^+\mu^-)\Lambda(p\pi)$
- Measure yield and efficiency in bins of p_T and rapidity to determine differential cross section
- Particle-antiparticle differences studied, too

$p_T^{\Lambda_b}$ (GeV)	n_{sig} events	ϵ (%)
10 – 13	293 ± 22	0.29 ± 0.03
13 – 15	240 ± 18	0.79 ± 0.08
15 – 18	265 ± 19	1.54 ± 0.16
18 – 22	207 ± 16	2.34 ± 0.23
22 – 28	145 ± 14	3.21 ± 0.34
28 – 50	87 ± 11	3.96 ± 0.50

$ y^{\Lambda_b} $	n_{sig} events	ϵ (%)
0.0 – 0.3	233 ± 17	0.74 ± 0.09
0.3 – 0.6	256 ± 18	0.77 ± 0.09
0.6 – 0.9	206 ± 16	0.81 ± 0.09
0.9 – 1.2	196 ± 17	0.70 ± 0.08
1.2 – 1.5	189 ± 17	0.67 ± 0.09
1.5 – 2.0	162 ± 18	0.65 ± 0.09

Λ_b cross section compared to mesons

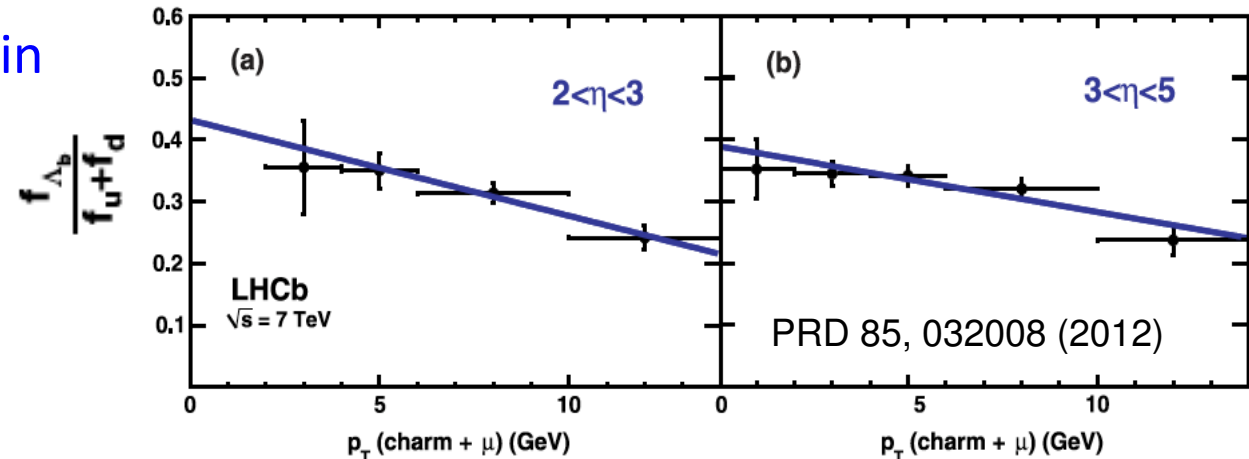
- New Λ_b measurement allows for comparison to B^+ , B^0 and B_s mesons
- Shape vs B p_T shows interesting feature
 - Baryon spectrum falls faster than meson spectra
 - Effect in baryon vs meson hadronization
- Historically, hadronization fractions assumed to be constant, but LEP and Tevatron measurements disagree
- Discrepancy in baryon/meson production could be explained by different p_T spectra



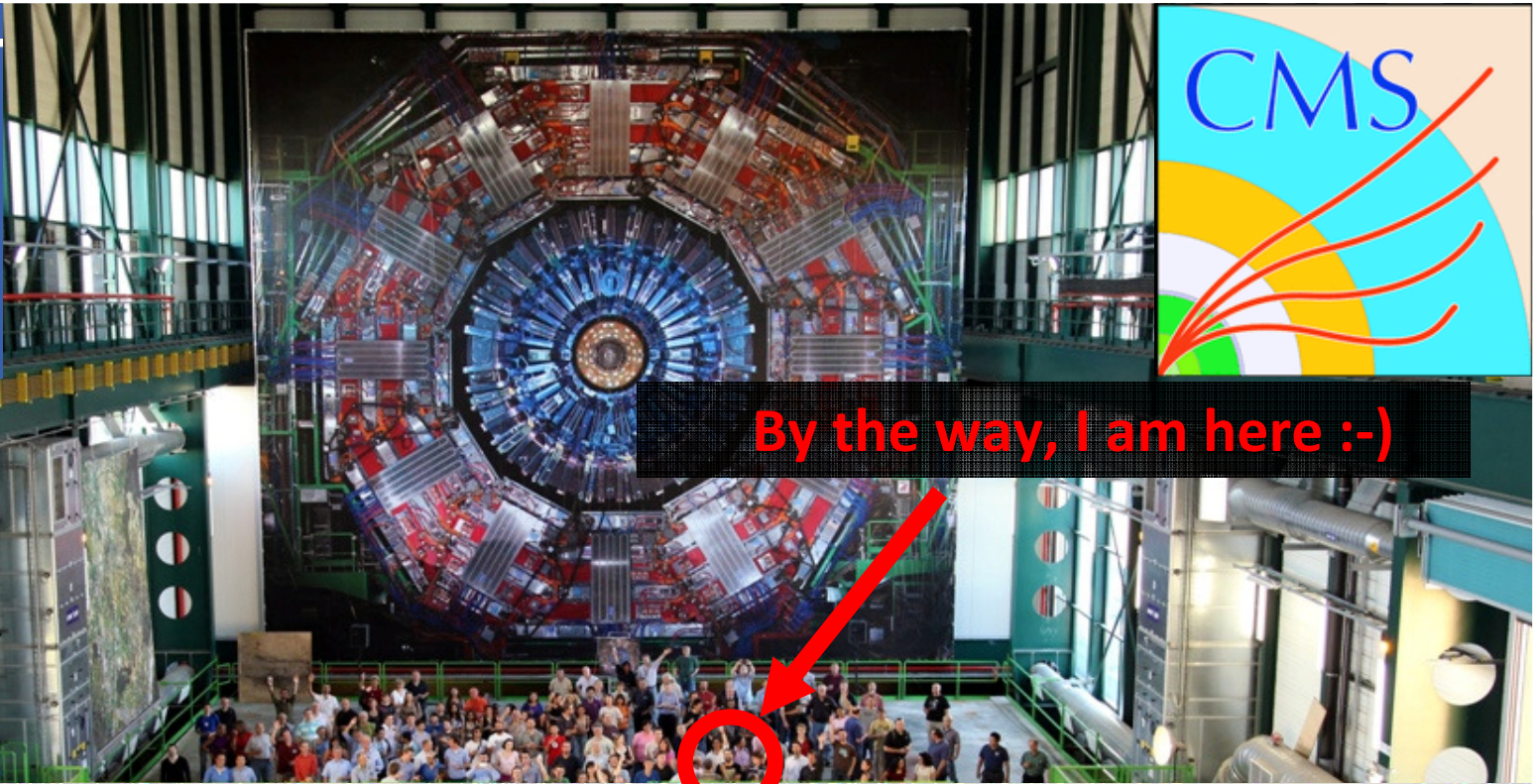
HFAG 2012	$\langle f(b\text{-baryon}) \rangle$	$\langle p_T(B) \rangle$
LEP	0.212 ± 0.069	~ 40 GeV
Tevatron	0.090 ± 0.015	~ 10 GeV

Λ_b cross section compared to mesons

- Similar feature observed by LHCb in measurement of $f_{\Lambda_b}/(f_u+f_d)$ vs momentum



- Historically, hadronization fractions assumed to be constant
- However, measurements between LEP and Tevatron not consistent
 - HFAG 2012: Tevatron ($p_T(b) \sim 10$ GeV): $f(b\text{-baryon}) = 0.212 \pm 0.069$
 - HFAG 2012: LEP ($p_T(b) \sim 40$ GeV): $f(b\text{-baryon}) = 0.090 \pm 0.015$
- Discrepancy in baryon/meson production measurements between Tevatron and LEP could be explained by different p_T spectra



By the way, I am here :-)

Studies of *beauty* and *charm* quark production and decays with the CMS experiment

Luca Perrozzi (CERN)

On behalf of the CMS collaboration

BEACH 2012, Wichita, July 23rd-28th