Heavy Flavor Results from CMS

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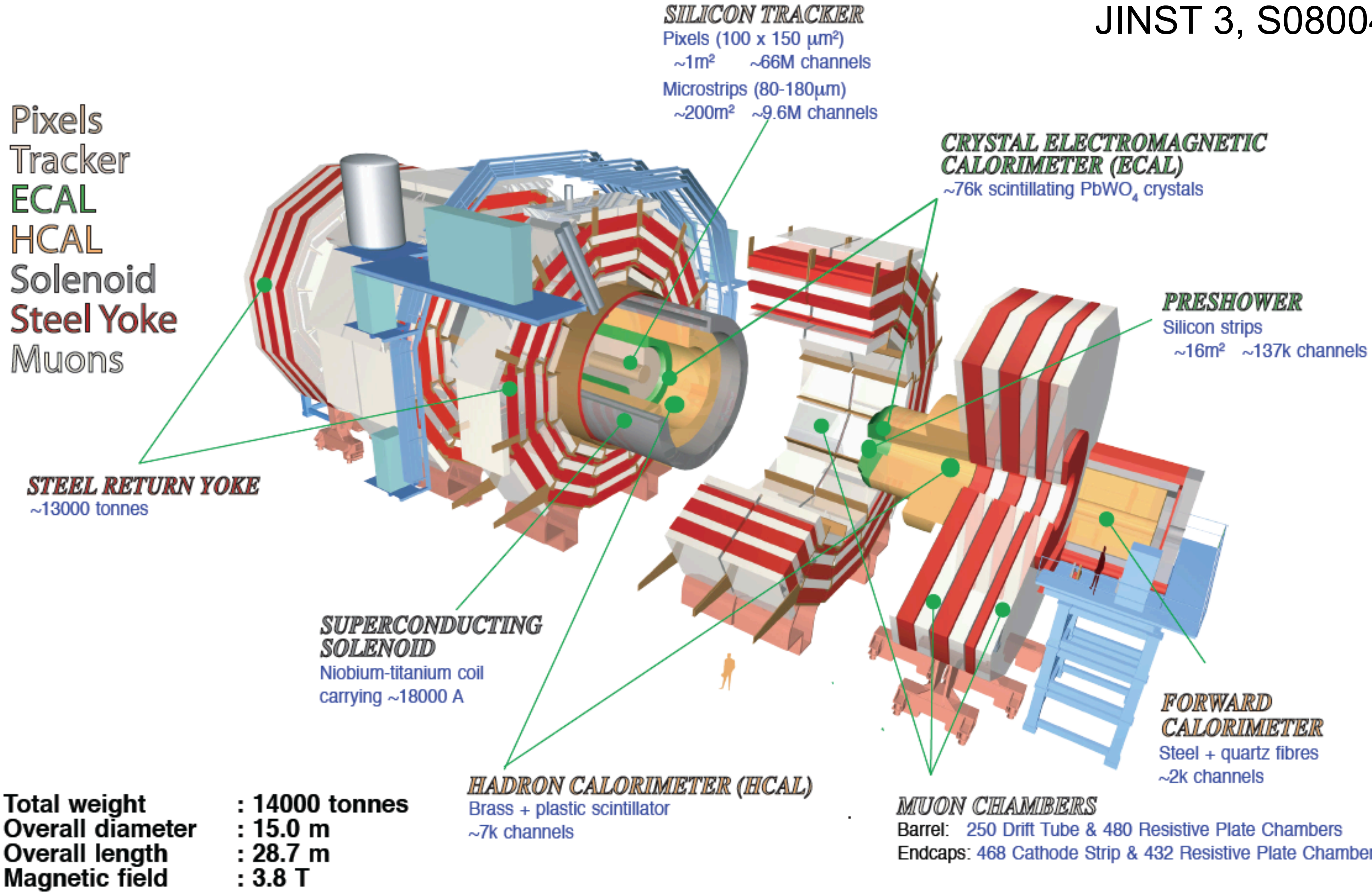
University of Colorado
on behalf of the CMS collaboration

ICHEP, Melbourne, Australia July 6th, 2012

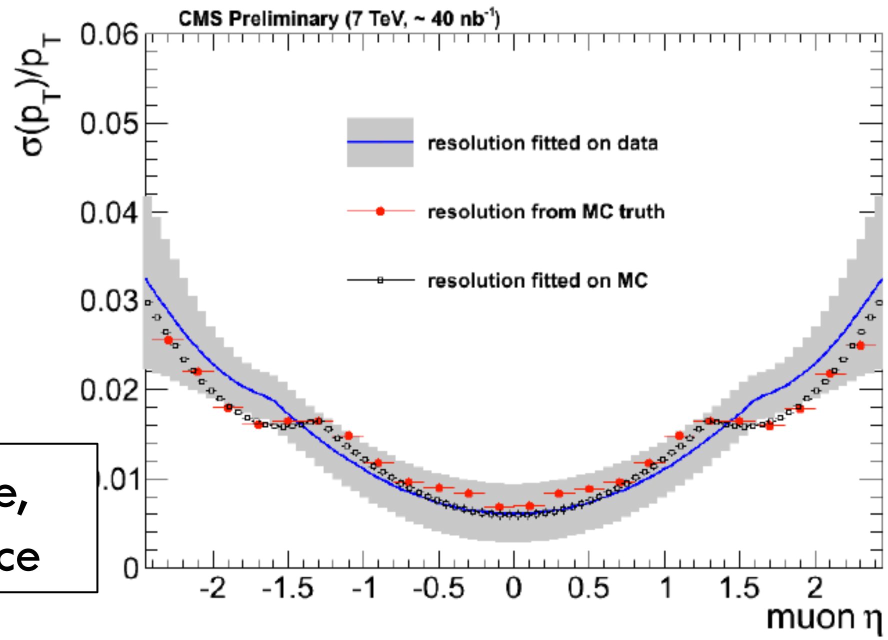
The CMS detector

JINST 3, S08004 (2008)

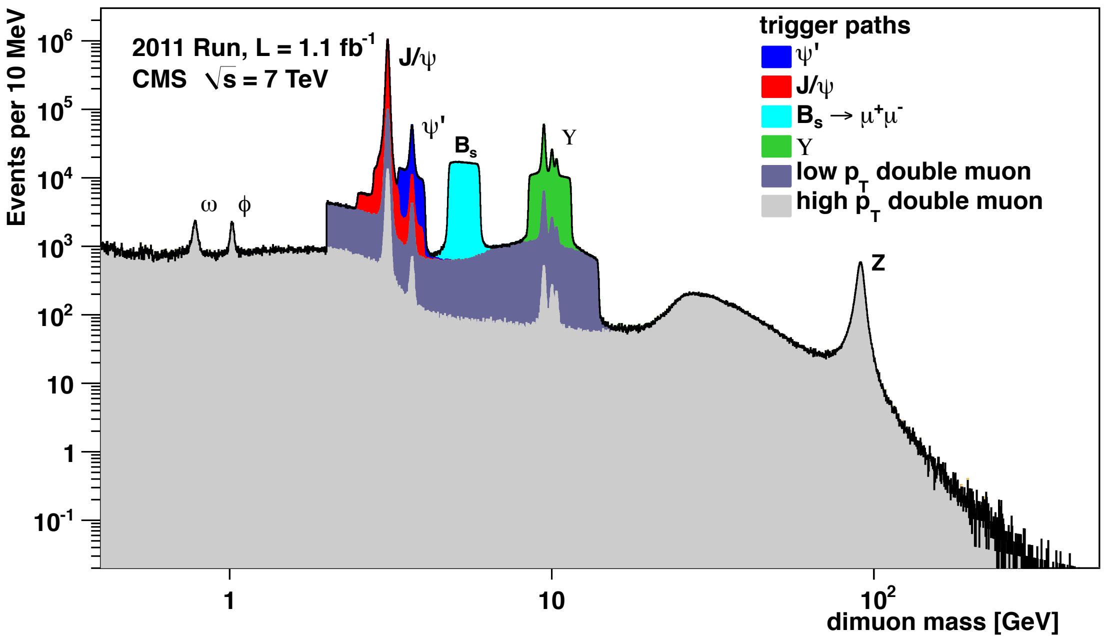


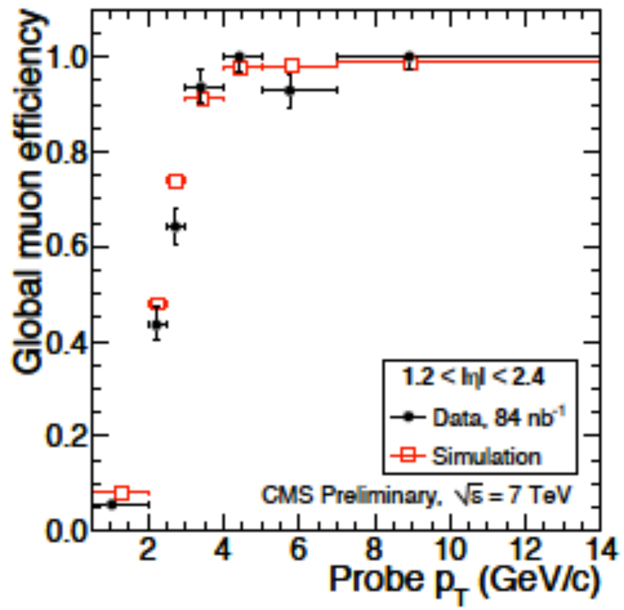
Tracker and Muon performance

- All silicon tracker
  - High tracking efficiency: ~100% for central muons
  - Great momentum and vertex resolution
- Efficient muon system for reconstruction and triggering

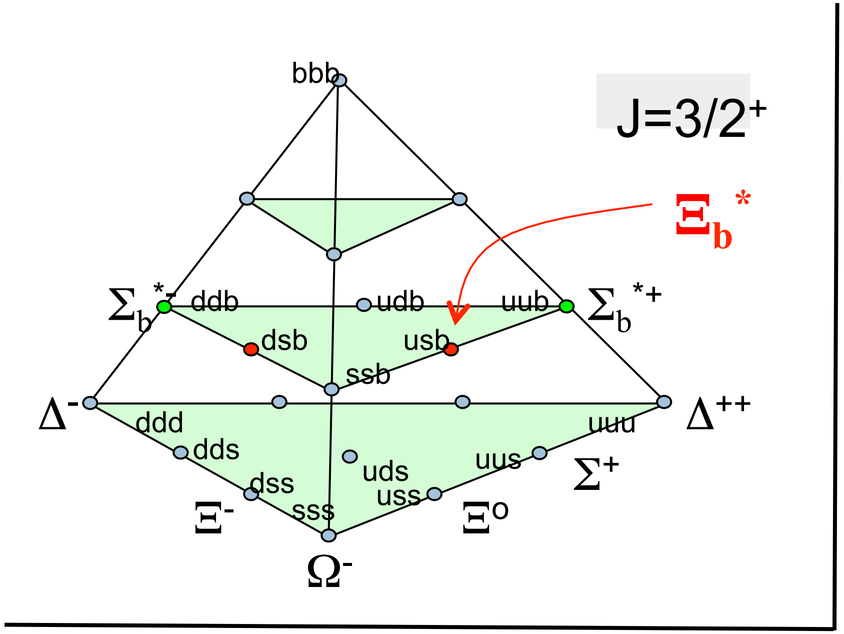


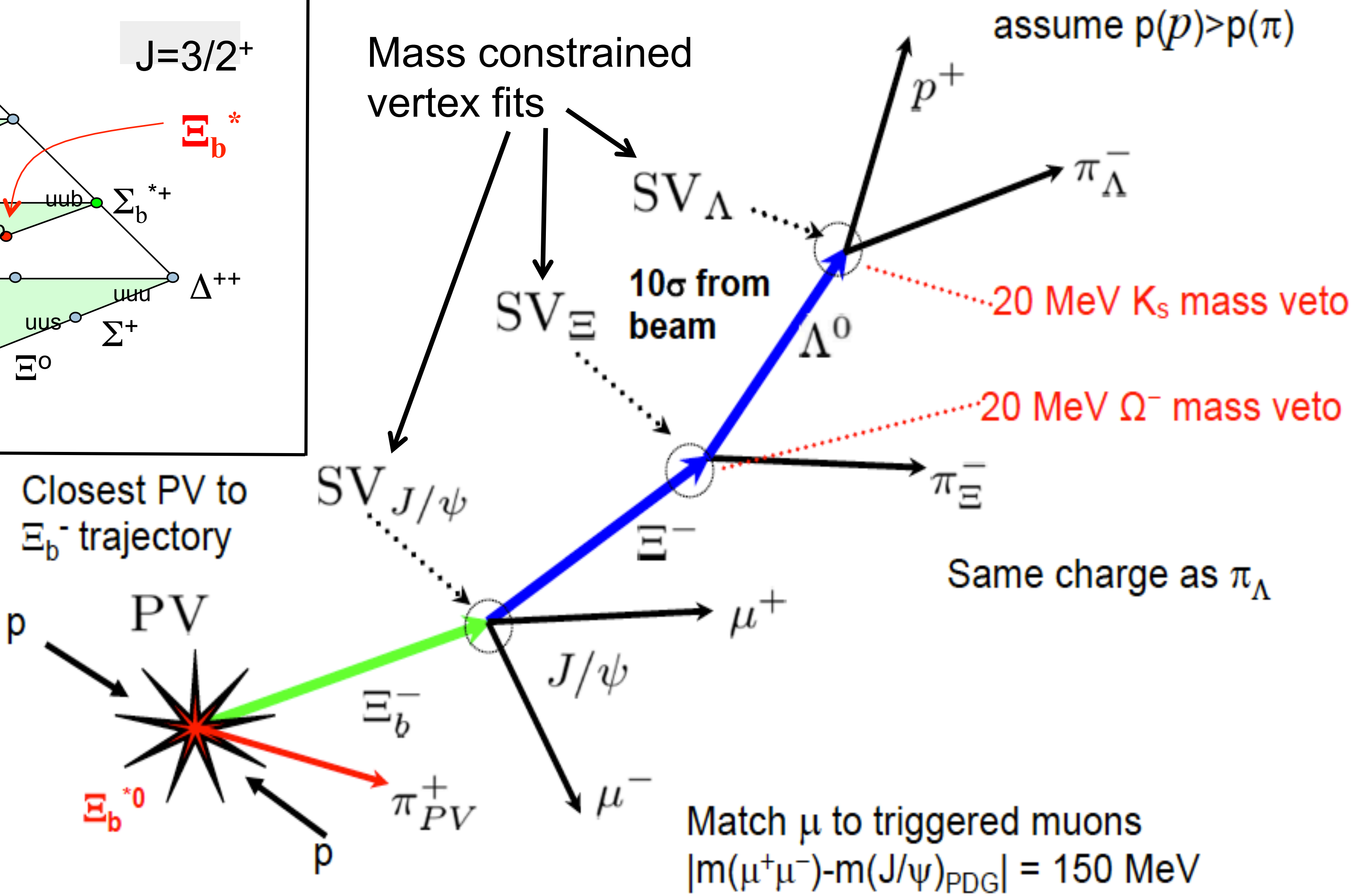
See dedicated talks yesterday: E. Butz Tracker performance, R. Castello Tracker alignment, G. Pugliese Muon performance





Discovery of Ξ_b^* baryon



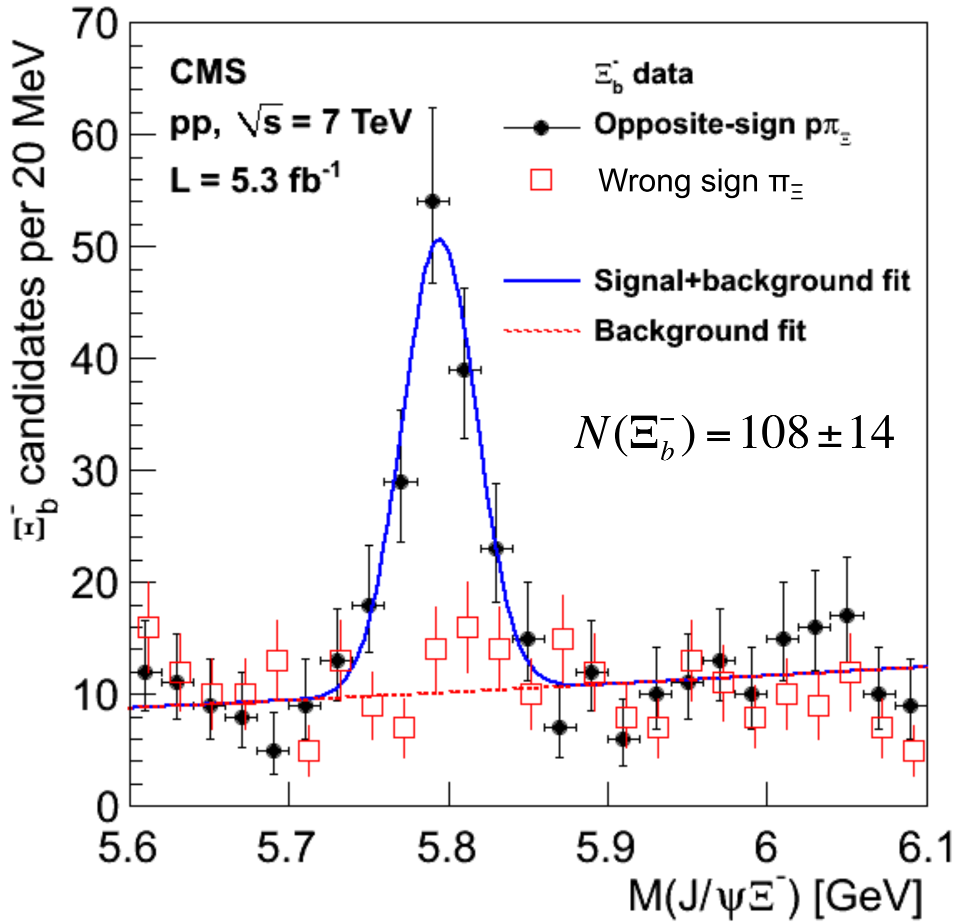


Ξ_b^- reconstruction

- Search strategy to maximize Ξ_b^- yield

$$\Xi_b^- \rightarrow J/\Psi(\mu^-\mu^+)\Xi^-(\Lambda\pi^-) \text{ with } \Lambda \rightarrow p\pi^-$$

- Selection cuts determined with optimization algorithm on data
  - Randomly vary selection and keep better combination
  - Select on track d_0/σ, vertex displacement significance, pointing angles, vertex confidences, and track and resonance p_T
  - 30 variables in total
- Last step to add prompt π consistent with Ξ_b^- direction, with p_T>250 MeV

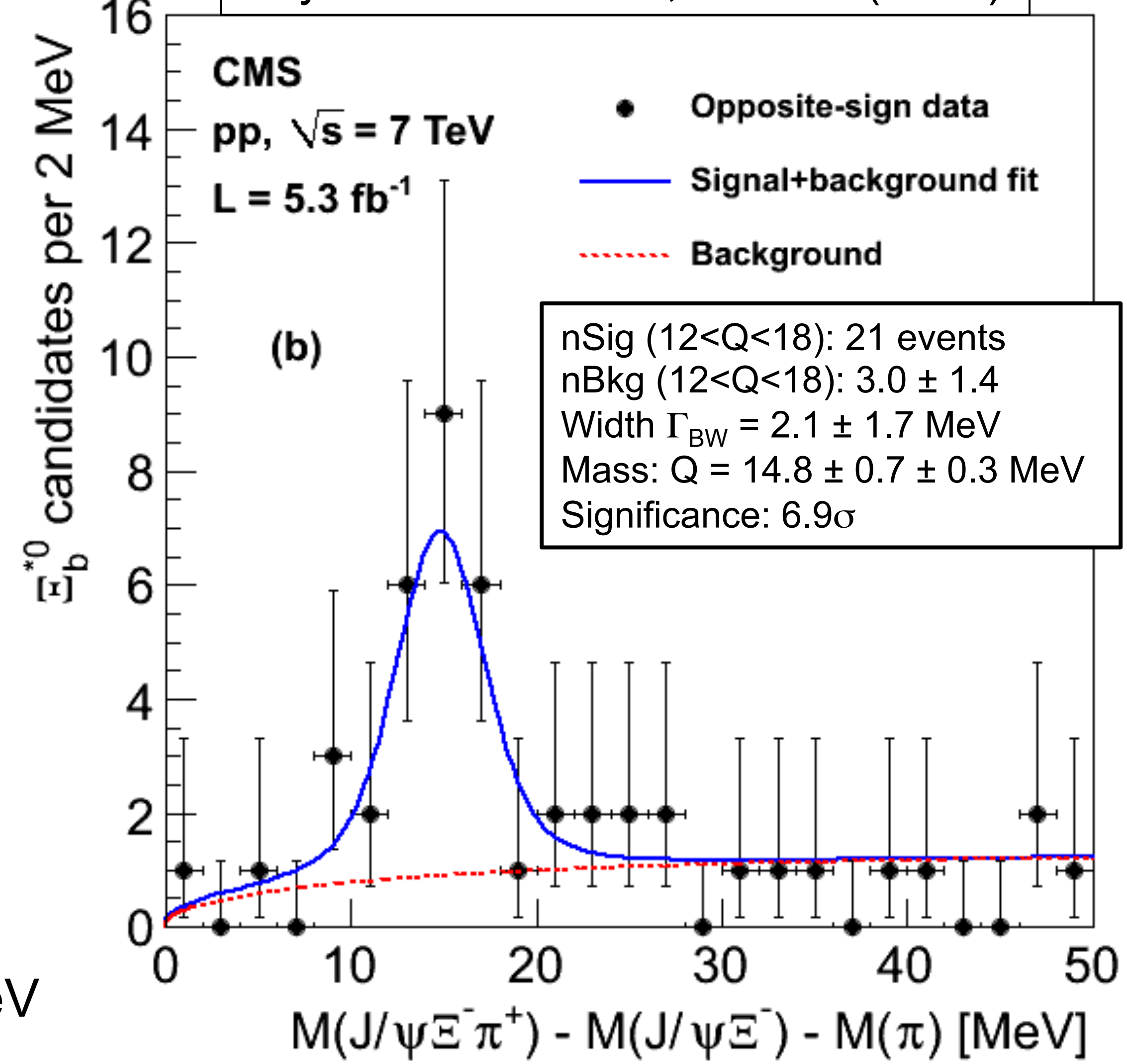


Ξ_b^* signal

- Background dominated by random $\Xi_b\pi^+$ combinations
  - Obtain with toy model from data shapes for $p(\Xi_b)$, $p(\pi)$ and opening angle
  - Consistent with wrong-sign Q value distribution
- Significance determination from $\ln(\mathcal{L}_{s+b}/\mathcal{L}_b) = 6.9\sigma$
- Confirmed with toys varying backgrounds within uncertainties including LEE = 5.7σ
- Measured mass =

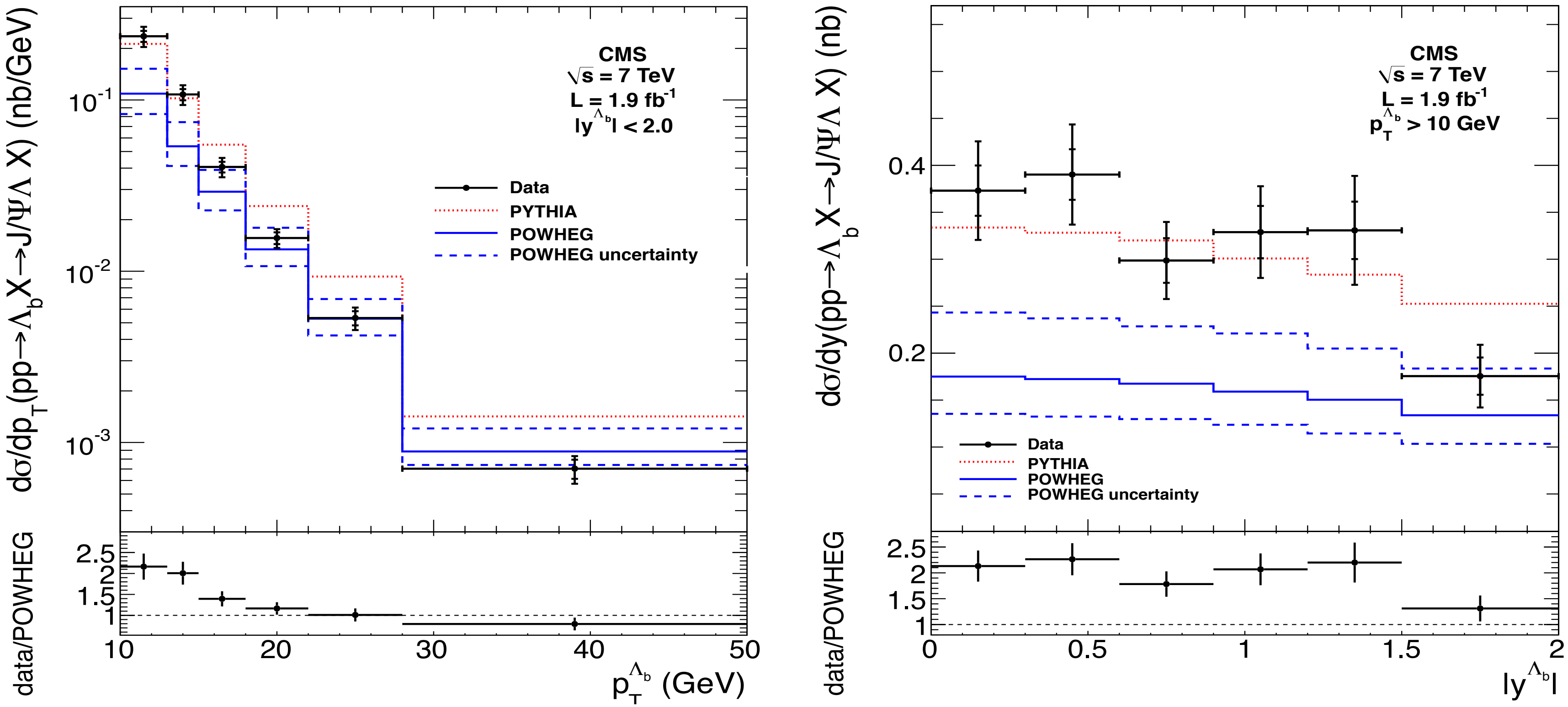
$m(\Xi_b^*) = 5945.0 \pm 0.7 \pm 0.3 \pm 2.7$ (PDG) MeV

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



Λ_b production measurement

- Λ_b production measured in decays to $J/\psi\,\Lambda$
- Yields and efficiencies computed in bins of $p_T(\Lambda_b)$ and $y(\Lambda_b)$ to obtain differential cross section

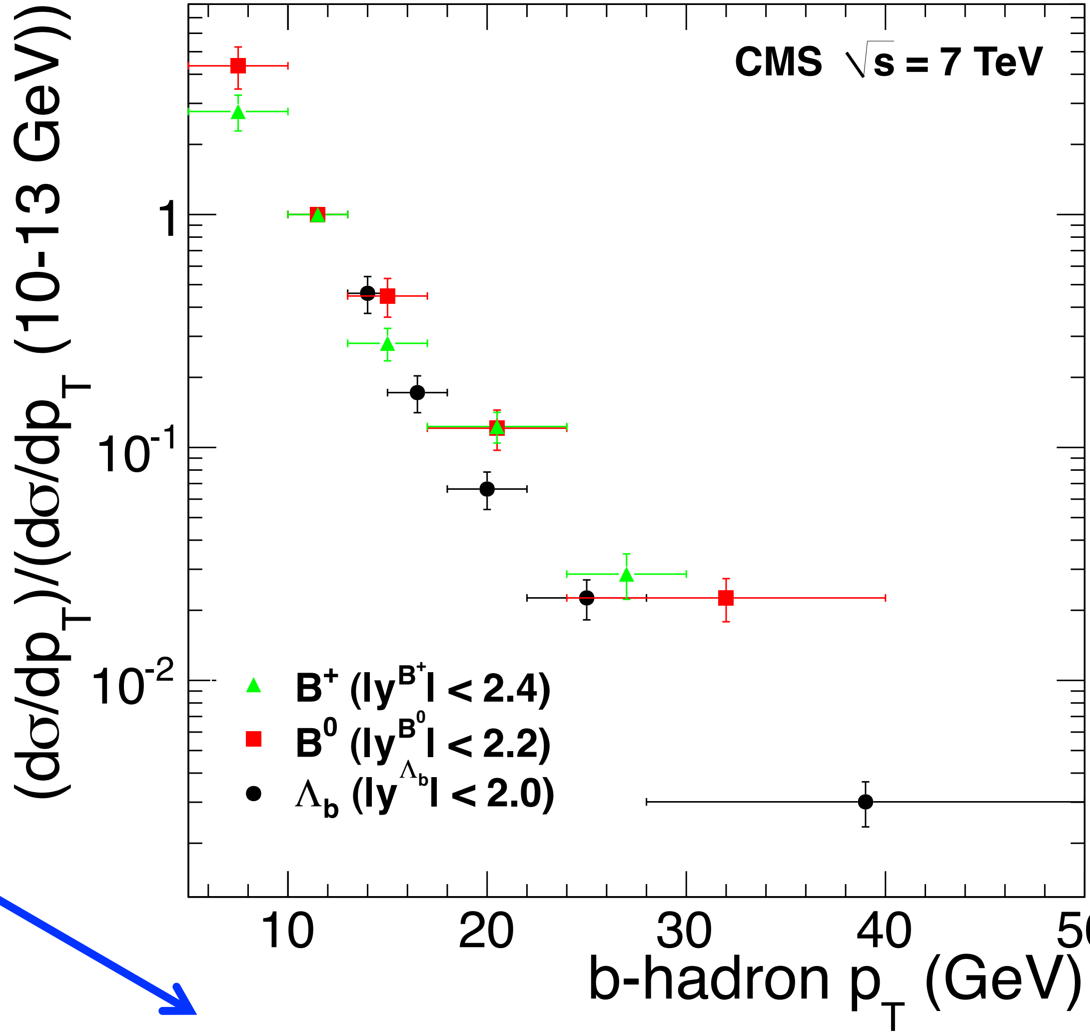


arXiv:1205.0594
accepted by PLB

Uncertainty on $BF(\Lambda_b \rightarrow J/\psi\Lambda) = 54\%$,
So report $\sigma(pp \rightarrow \Lambda_b X)$* $BR(\Lambda_b \rightarrow J/\psi\Lambda)$

Λ_b cross section compared to mesons

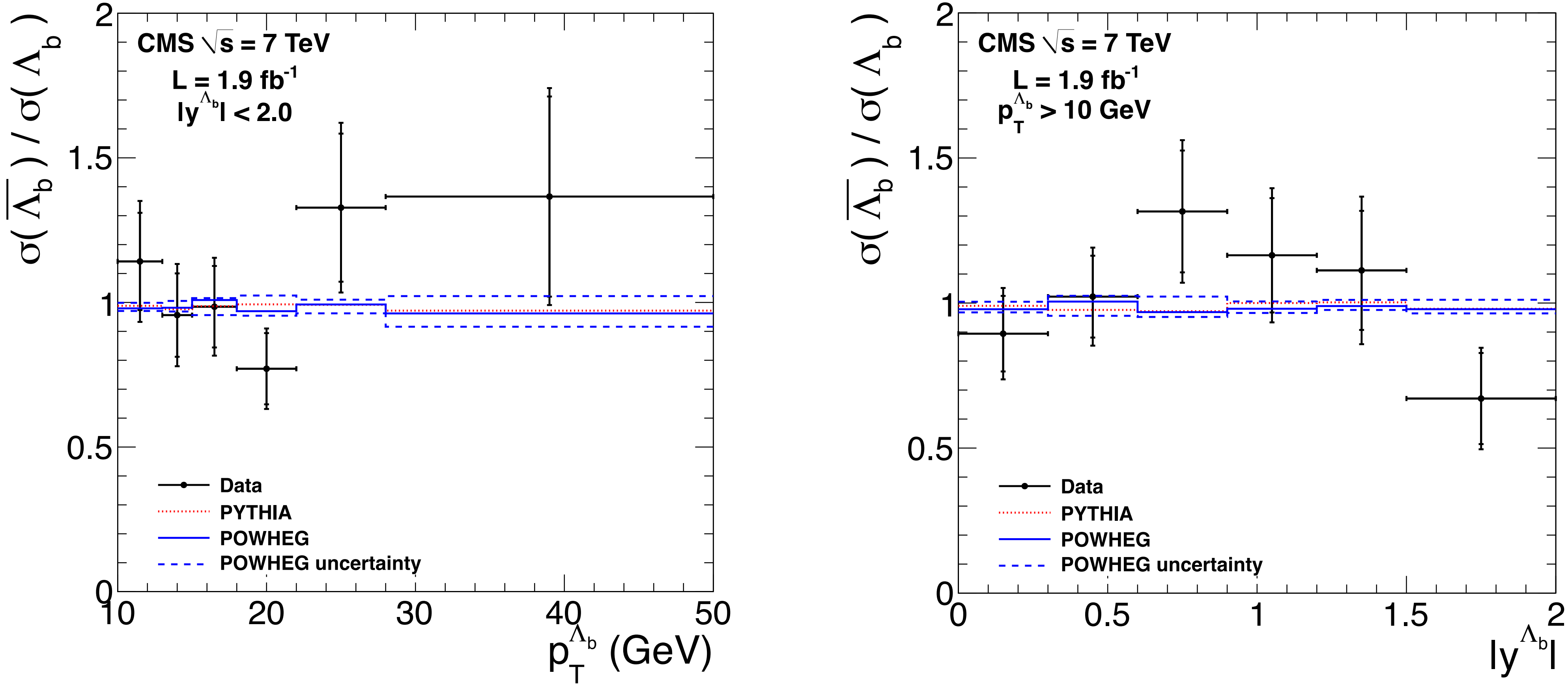
- New Λ_b measurement allows for comparison to B^+, B^0 and B_s mesons
- Shape vs B p_T shows interesting feature
  - Baryon spectrum falls faster than meson spectra
  - Effect in baryon vs meson hadronization
- Historically, hadronization fractions assumed to be constant, but LEP and Tevatron measurements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



HFAG 2012	<f(b-baryon)>	< p_T(B) >
LEP	0.212 ± 0.069	~40 GeV
Tevatron	0.090 ± 0.015	~10 GeV

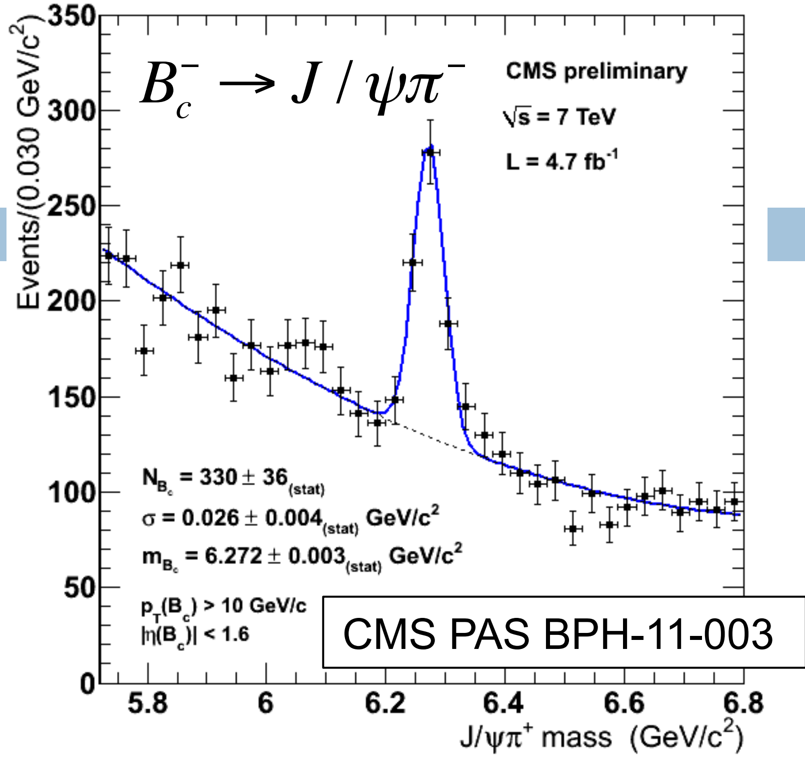
$\overline{\Lambda}_b / \Lambda_b$ asymmetry results

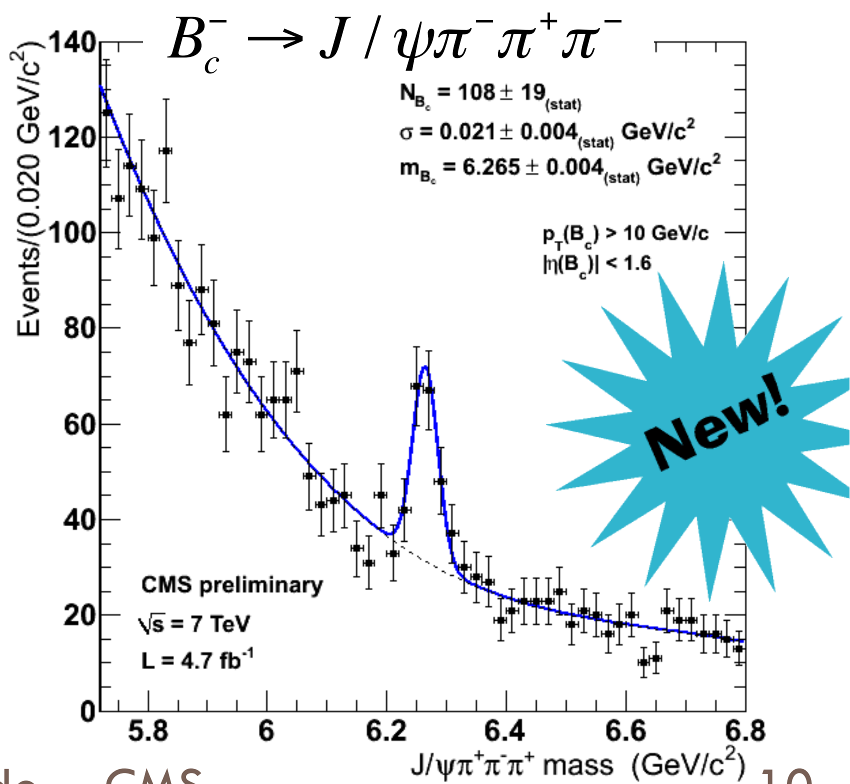
- Also measure yields and efficiencies as ratios between particles and antiparticles
  - Use charge of higher momentum Λ track to identify the (anti)proton
- Results consistent with no asymmetry, within large uncertainties
- Tests baryon transport models from initial pp state



B_c^+ meson studies

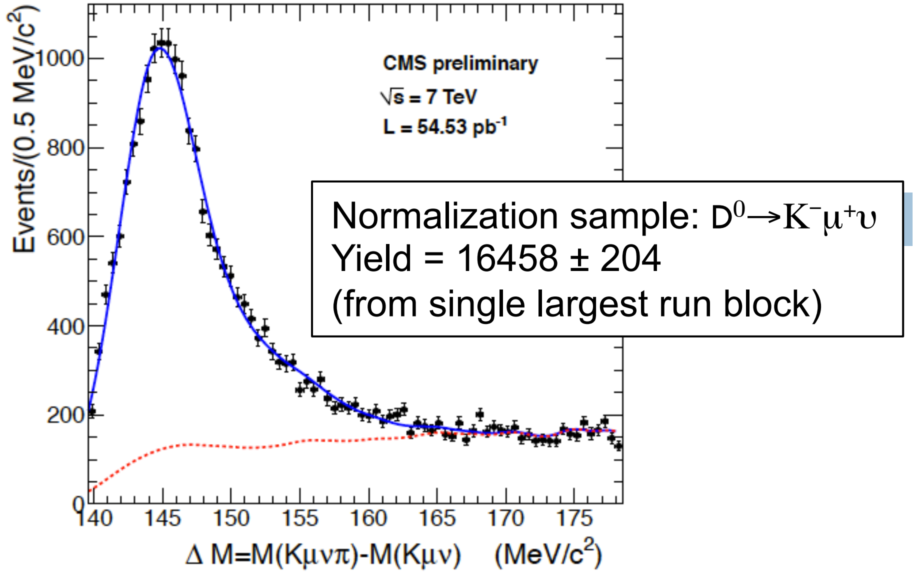
- B_c^+ is ground state of bound $\bar{b}c$ system
- Offers access to two different heavy quarks
  - Branching ratio measurements help understand interplay between b and c decays
  - Lifetime measurement also tests decay model
- Large LHC dataset allows for 100's of reconstructed B_c's at CMS
  - Very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



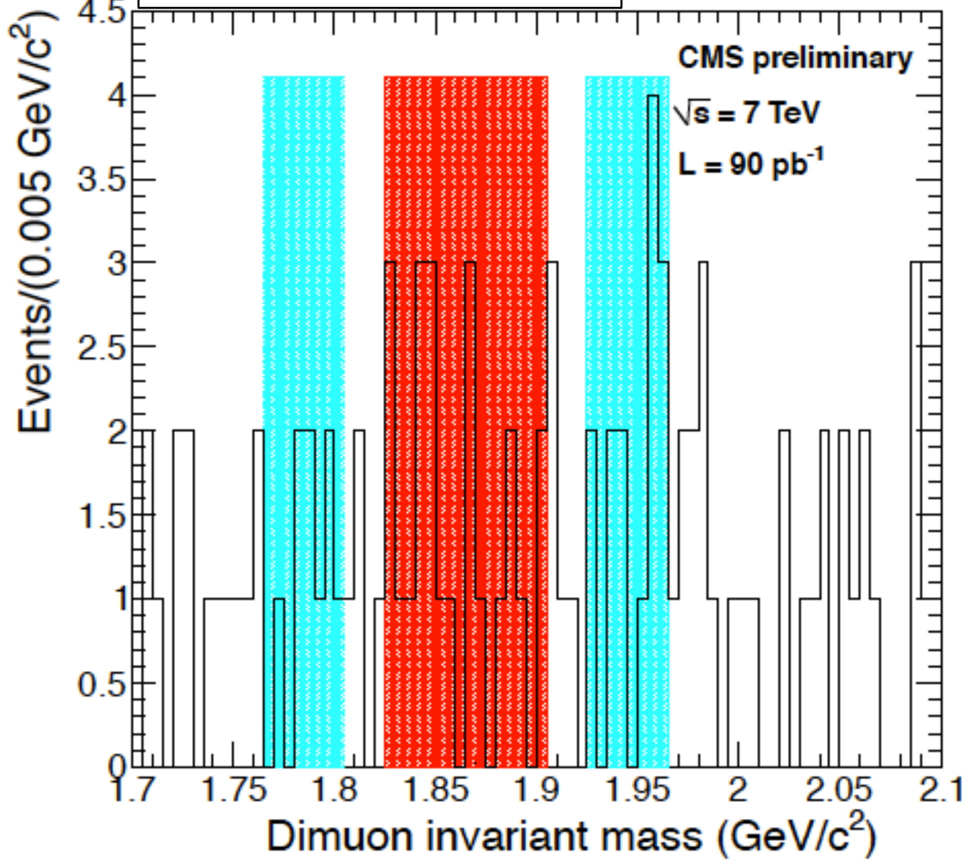


Search for $D^0 \to \mu^+\mu^-$

- $D^0 \to \mu^+\mu^-$ highly suppressed in SM ($\sim 10^{-13}$), but enhanced in many NP scenarios
- Analysis strategy
  - Use D^0 tagged by combination with prompt π to make D^*
  - Measure $\frac{D^{*+} \to D^0(\mu^-\mu^+)\pi^+}{D^{*+} \to D^0(K^-\mu^+\nu)\pi^+}$ to cancel many systematic uncertainties in the ratio
  - Limitation: must use low p_T single μ trigger (from 7 run periods with different thresholds in 2010/11 data)
- Estimate of background in signal region determined from sidebands



CMS PAS BPH-11-017



$D^0 \to \mu^+\mu^-$ results

CMS PAS BPH-11-017

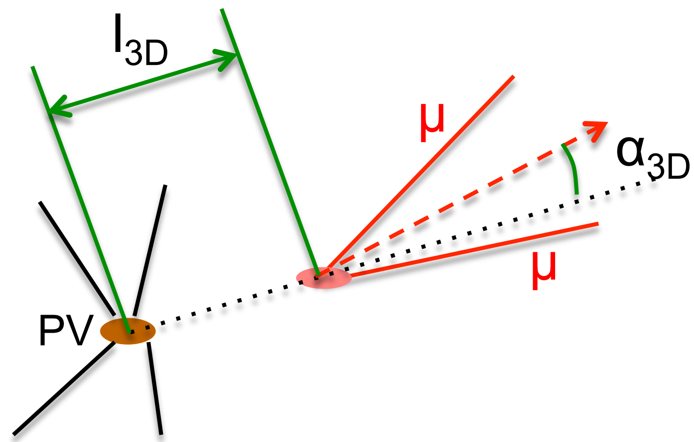
- No significant signal observed
  - Predicted background = 23 events
  - Signal region yield = 23 events
- Determine 90% confidence UL's with CLs to be

$$B(D^0 \to \mu^+\mu^-) \leq 5.4 \times 10^{-7} (90\% \, \mathrm{CL}).$$

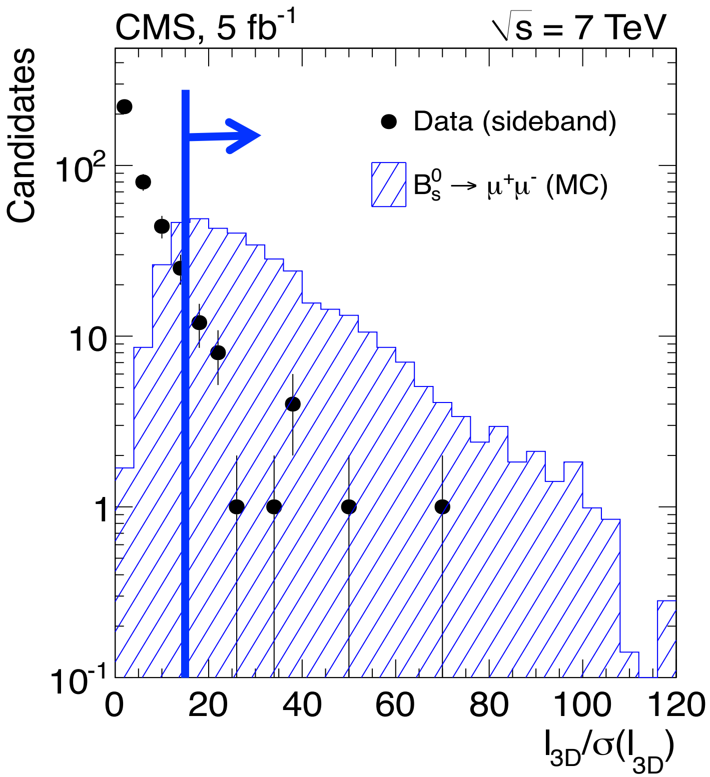
- Comparison to other experiments
  - Best published limit: Belle $< 1.4 \times 10^{-7}$ PRD, 81 091102
  - Best preliminary limit: LHCb $< 1.1 \times 10^{-8}$ LHCb-CONF-2012-005
  - BaBar 2 sided limit: $[0.6 - 8.1] \times 10^{-7}$ arXiv:1206.5419
- Prospects for CMS: lots more data available, but requires new analysis strategy with double μ trigger

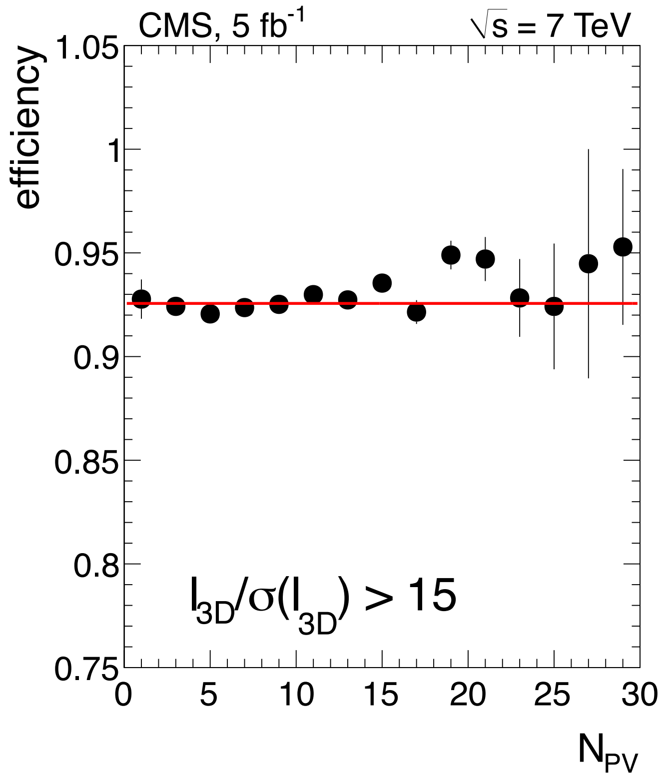
Search for $B^0_{(s)} \to \mu^+\mu^-$

- $B^0_{(s)} \to \mu^+\mu^-$ suppressed in SM, but highly sensitive to NP, such as high tan β SUSY or extended Higgs sectors
- Select pair of oppositely charged, displaced, isolated muons pointing to PV



- Reject background from
  - Combinatorial dimuons
  - Peaking B decays with decay-in-flight muons
- Signal efficiency observed to be independent of N_{PV}
- Normalize signal candidates to $B^+ \to J/\psi K^+$ yield





$B^0_{(s)} \to \mu^+\mu^-$ results

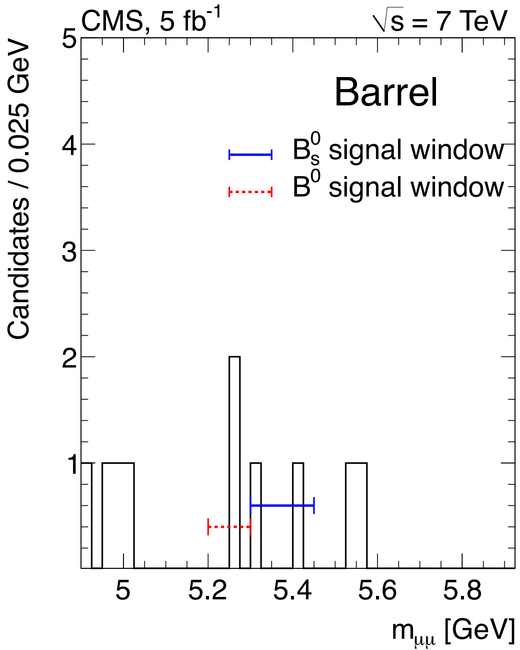
- Observation consistent with background + SM signal in all 4 channels

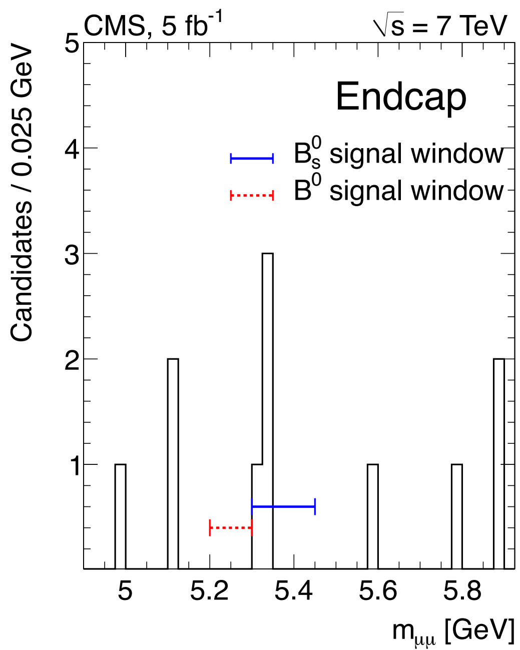
Variable	$B^0 \to \mu^+\mu^-$ Barrel	$B^0_s \to \mu^+\mu^-$ Barrel	$B^0 \to \mu^+\mu^-$ Endcap	$B^0_s \to \mu^+\mu^-$ Endcap
Signal (SM)	0.24 ± 0.02	2.70 ± 0.41	0.10 ± 0.01	1.23 ± 0.18
Combinatorial bg	0.40 ± 0.34	0.59 ± 0.50	0.76 ± 0.35	1.14 ± 0.53
Peaking bg	0.33 ± 0.07	0.18 ± 0.06	0.15 ± 0.03	0.08 ± 0.02
Sum	0.97 ± 0.35	3.47 ± 0.65	1.01 ± 0.35	2.45 ± 0.56
Observed	2	2	0	4

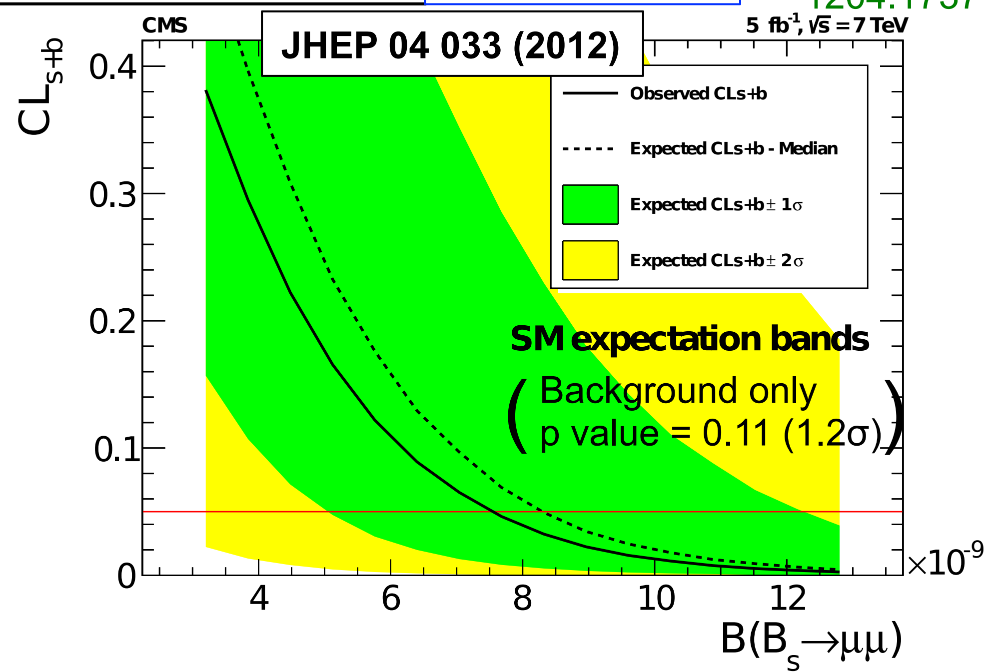
upper limit (95%CL)	observed	(median) expected	SM expectation
$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	7.7×10^{-9}	8.4×10^{-9}	$(3.2 \pm 0.2) \times 10^{-9}$
$\mathcal{B}(B^0 \to \mu^+\mu^-)$	1.8×10^{-9}	1.6×10^{-9}	$(1.0 \pm 0.1) \times 10^{-10}$

A. Buras 1012.1447

→ 3.5×10^{-9} Mixing correction 1204.1737







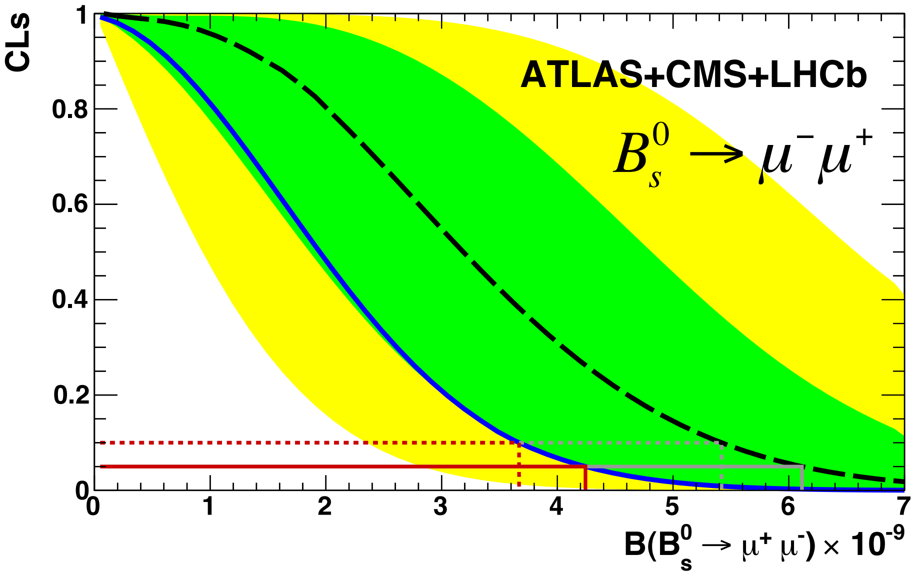
$B^0_{(s)} \to \mu^+\mu^-$ 2011 LHC combination

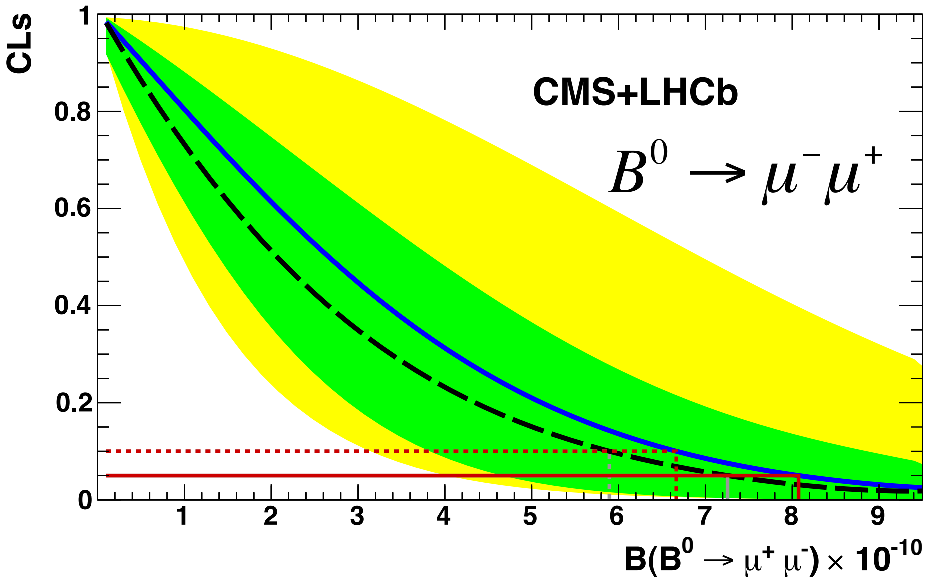
- CMS, LHCb and ATLAS combined for $B^0_s \to \mu^-\mu^+$
- CMS and LHCb combined for $B^0 \to \mu^-\mu^+$

CMS PAS BPH-12-009

$$UL(B^0_s\,@95\%CL) < 4.2\times10^{-9}$$
$$UL(B^0\,@95\%CL) < 8.1\times10^{-10}$$

- 95% upper limits:
  - Computed with CLs
  - All uncertainties treated as uncorrelated, except for f_s/f_d, which is taken to be 100% correlated between the measurements
- World's best limits
  - Increasing tension with CDF result: $BF(B^0_s \to \mu^-\mu^+) = 13^{+9}_{-7}\times10^{-9}$

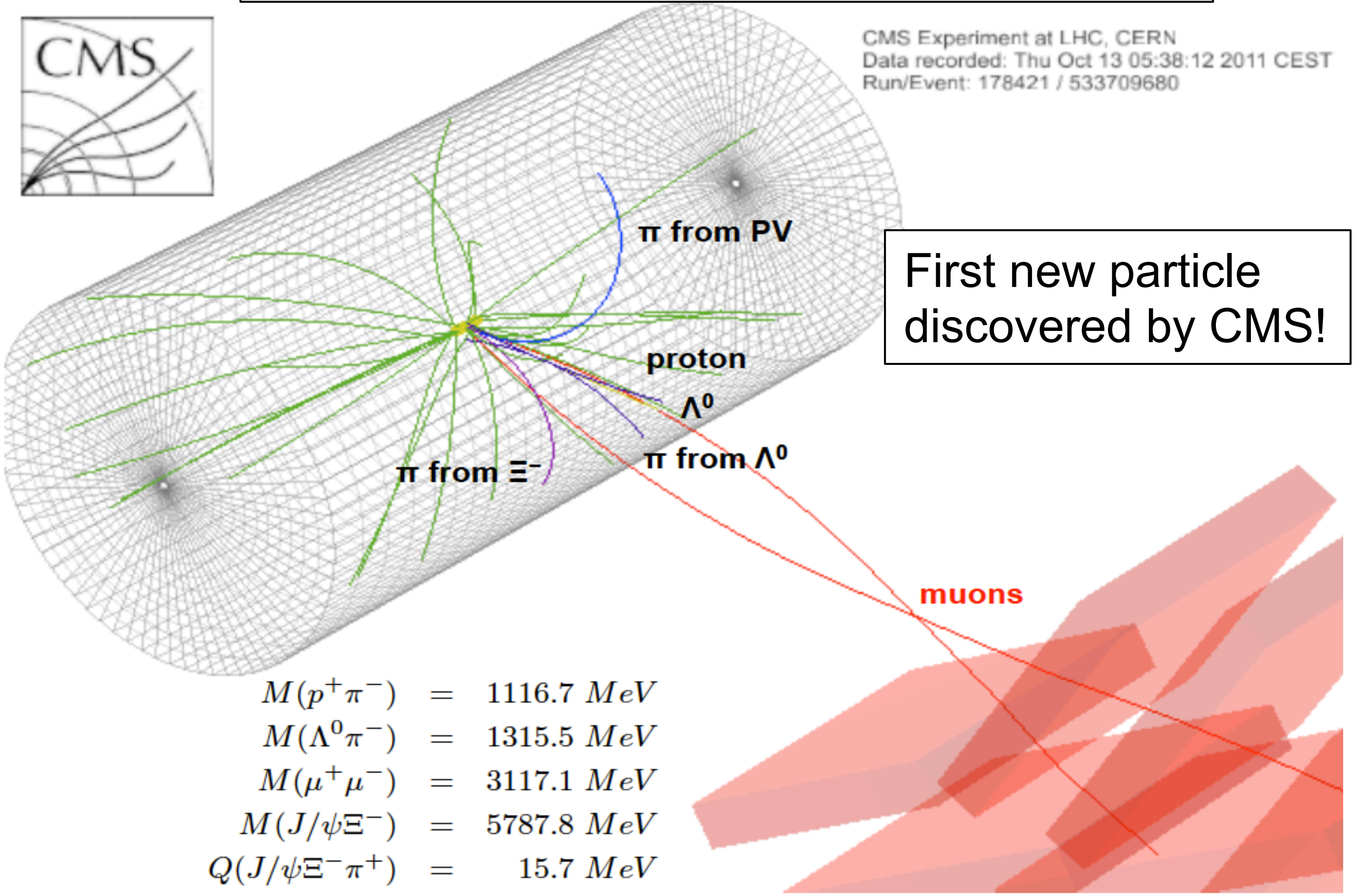




Conclusion: Active flavor program at CMS

- First observation of new b baryon state, Ξ_b^{*0}
- Λ_b production shows unexpected meson/baryon differences
- Search for $B_s \rightarrow \mu\mu$ closing in on SM sensitivity
- Many more measurements to come from CMS

See also dedicated talks on quarkonia:
K. Yi Quarkonia production (yesterday)
V. Knunz Υ polarization (tomorrow)



First new particle discovered by CMS!

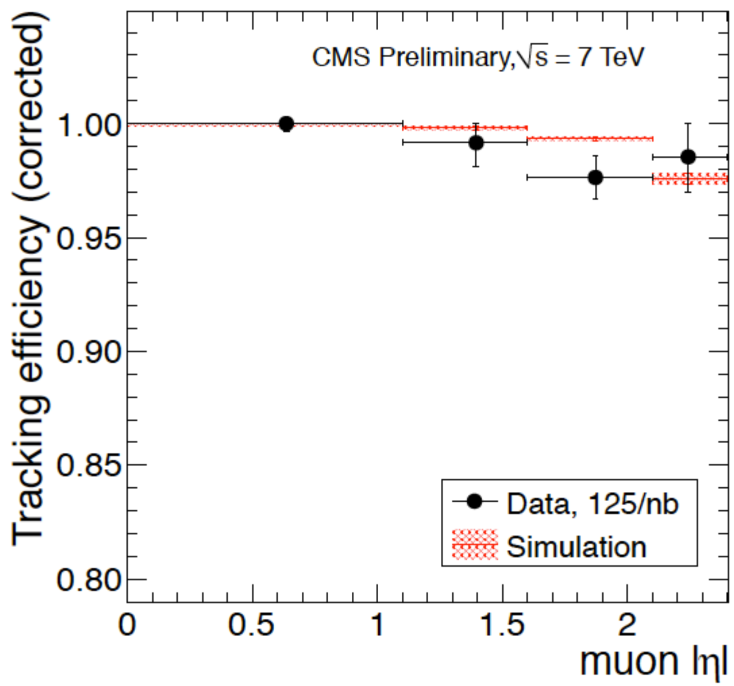
$$M(p^+\pi^-) = 1116.7\ MeV$$
$$M(\Lambda^0\pi^-) = 1315.5\ MeV$$
$$M(\mu^+\mu^-) = 3117.1\ MeV$$
$$M(J/\psi\Xi^-) = 5787.8\ MeV$$
$$Q(J/\psi\Xi^-\pi^+) = 15.7\ MeV$$

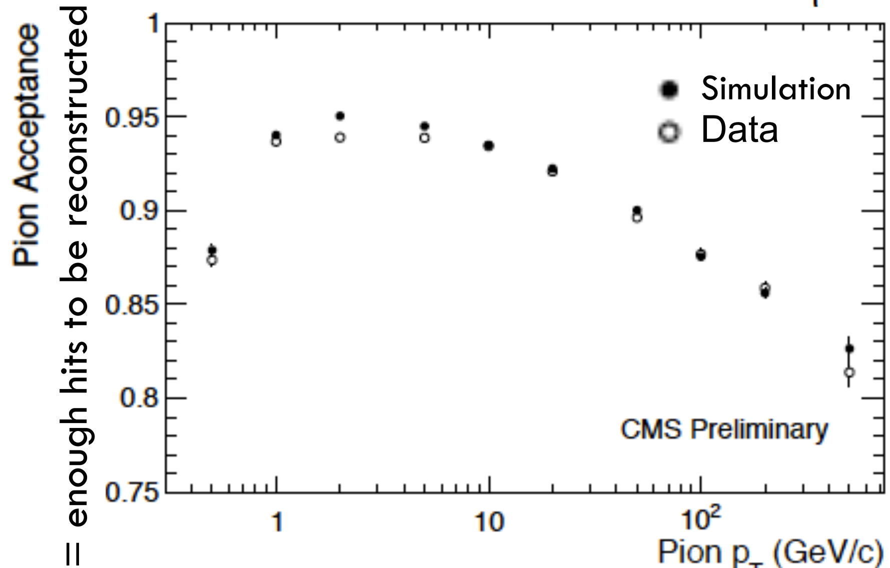
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

Extra slides

Tracking efficiency

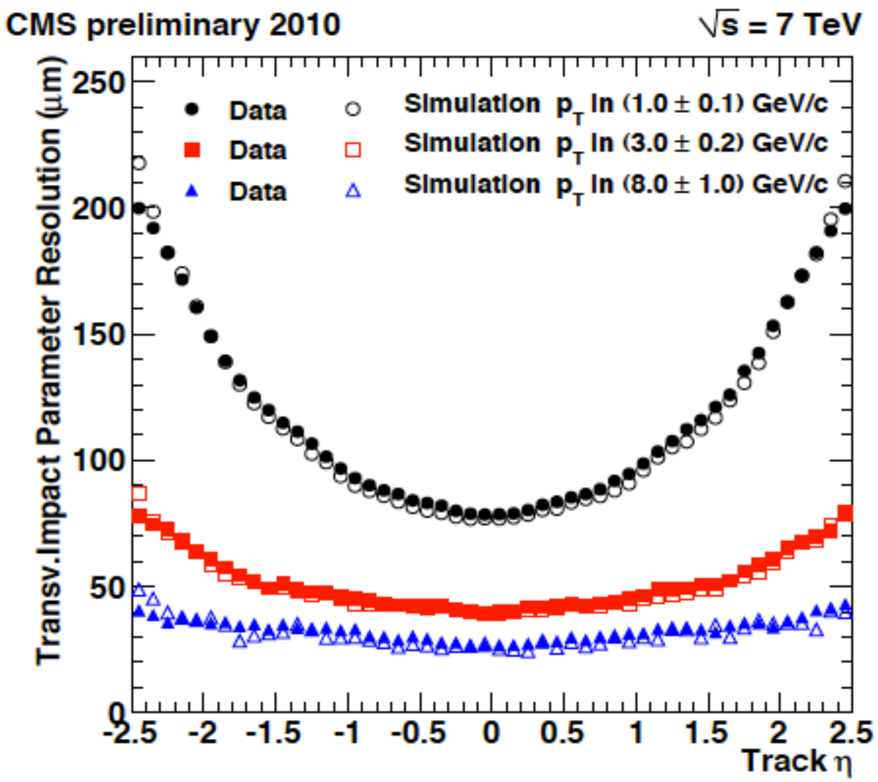
- Silicon tracker covers out to $|\eta|<2.4$ and down to track $p_T > 300$ MeV
- Great track reconstruction efficiency
  - Measured in data with good agreement with simulation
  - ~100% for central muons
  - Hadron efficiency 85-95% due to tracks lost in interactions
  - Excellent displaced track reconstruction out to 50 cm displacement from beamline

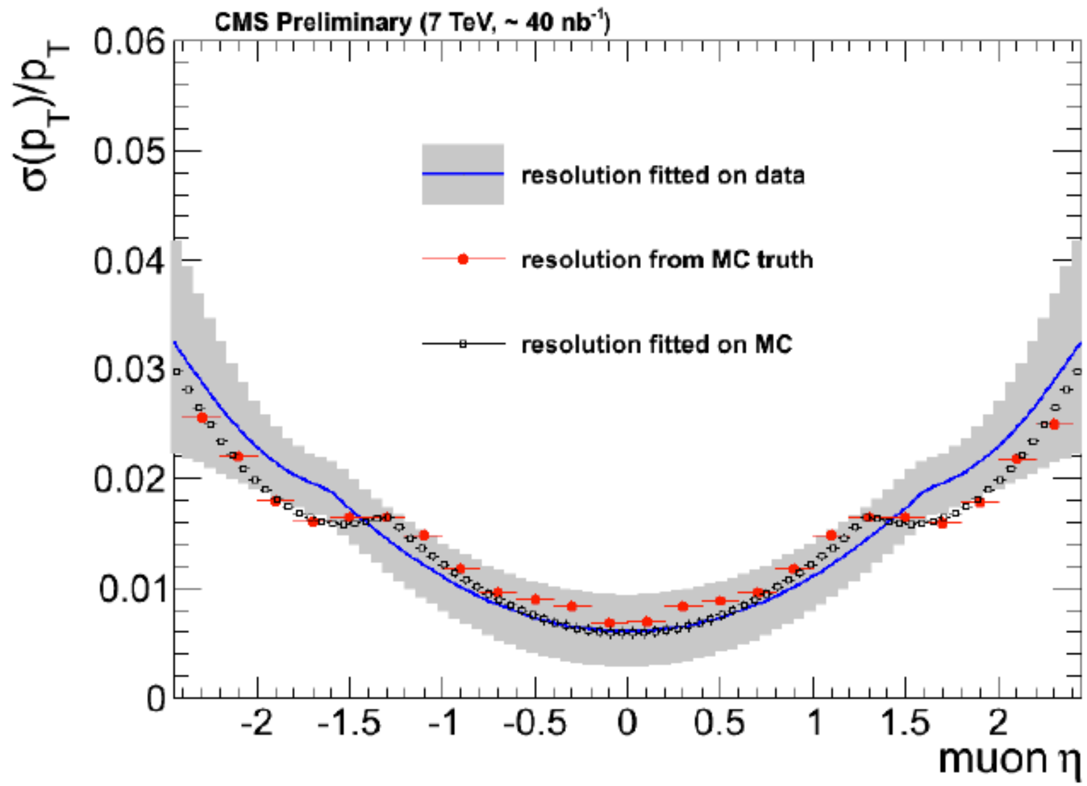




Tracking performance

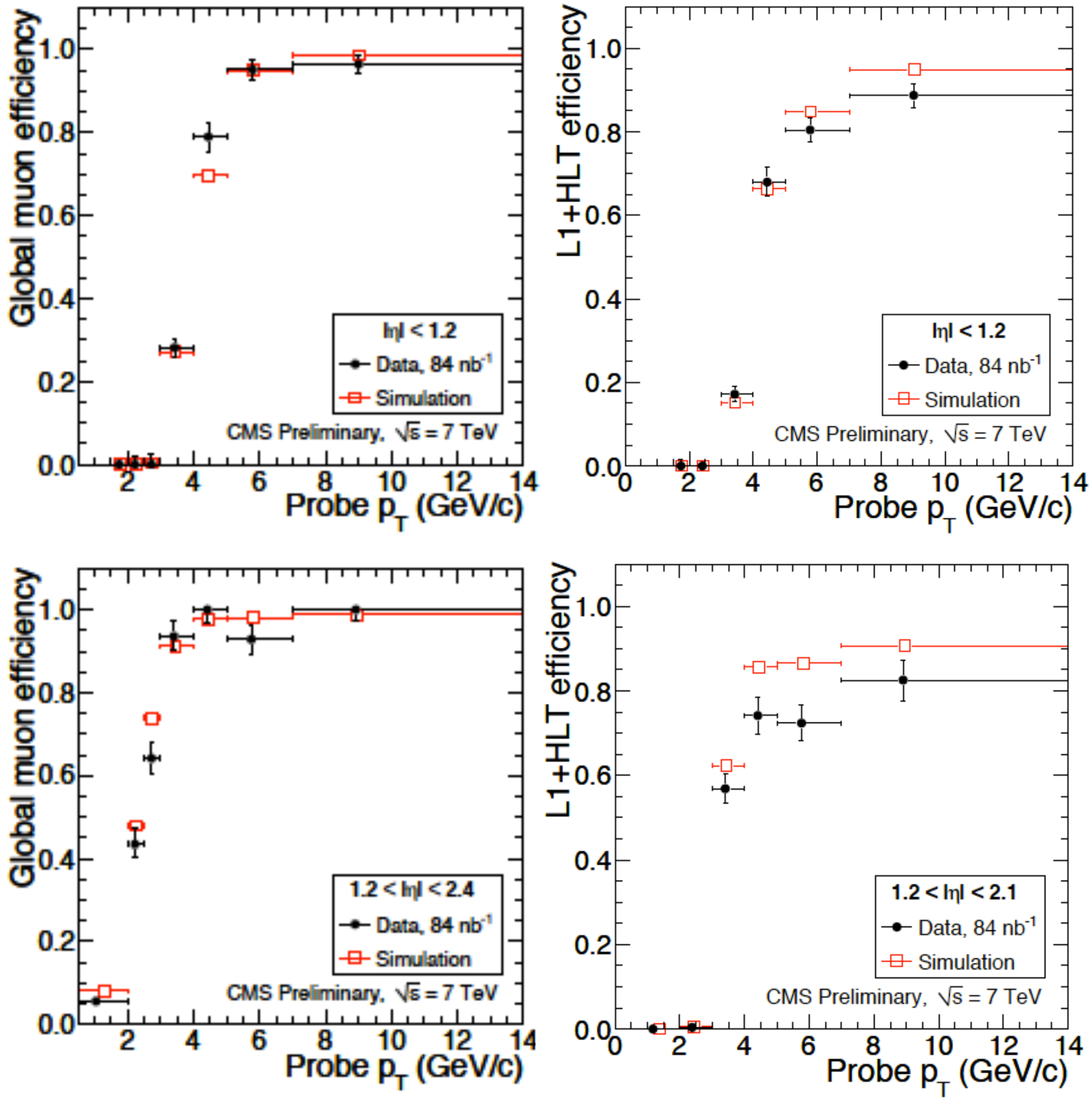
- Track impact parameter resolution 25-200 μm
  - Improves with higher p_T and smaller η
- Track momentum resolution 0.6-3.0%
  - Improves with smaller η
- Provides good mass and lifetime resolution
  - For $B^+ \rightarrow J/\psi K^+$ decays mass resolution ~30 MeV and core $c\tau$ resolution ~30 μm



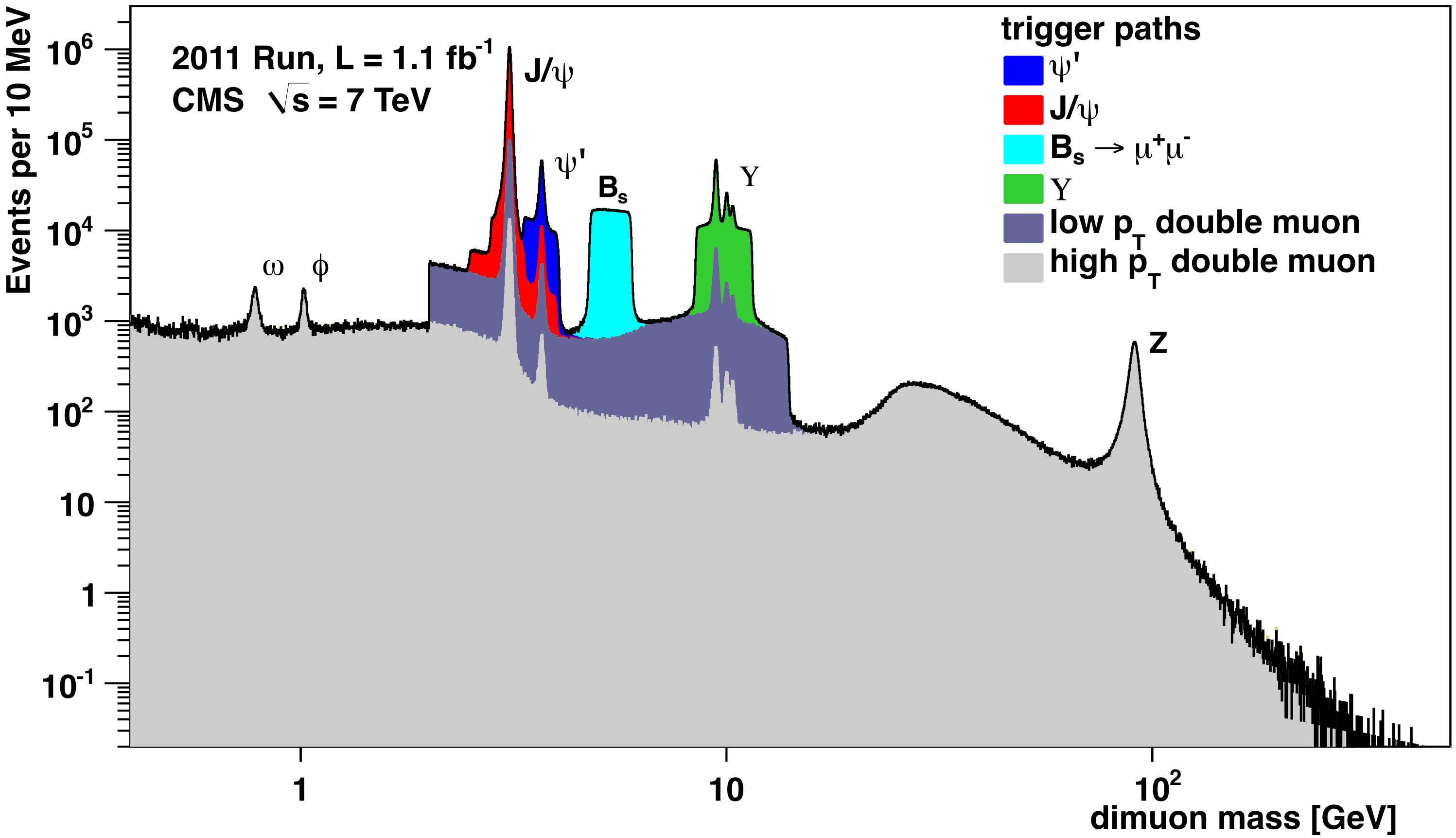


Muon reconstruction efficiency

- Muons reconstructed out to $|\eta|<2.4$ and down to $p_T > 3$ GeV
- Muon identification efficiency plateaus to nearly 100% with turn on at low p_T
- Trigger efficiency plateaus ~85%
- Low muon mis-ID rates measured in data
  - ≈0.1% for π and K
  - ≈0.05% for protons

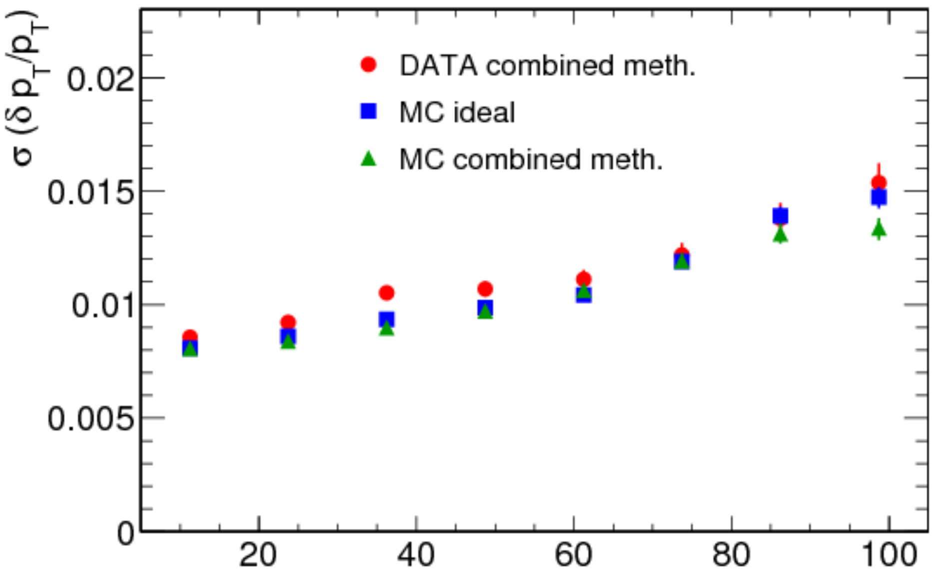


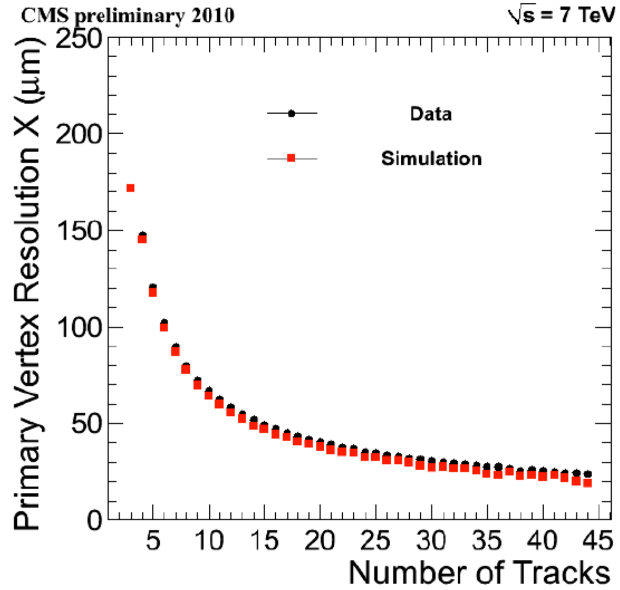
Heavy flavor triggers

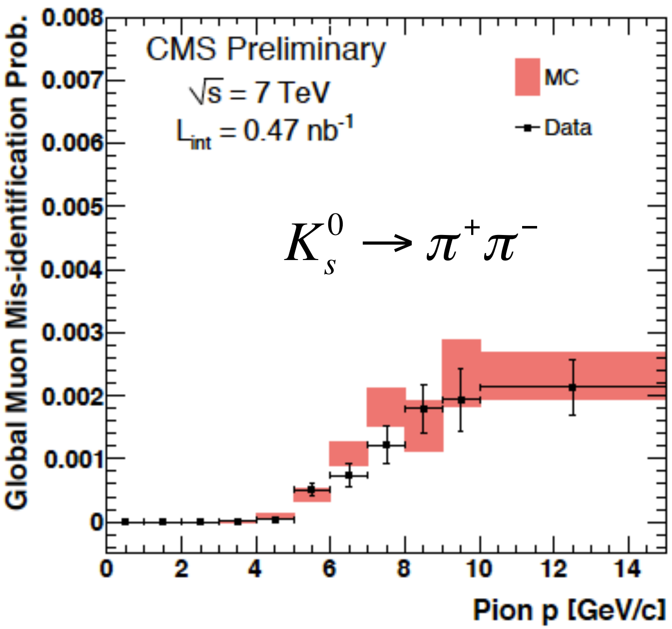


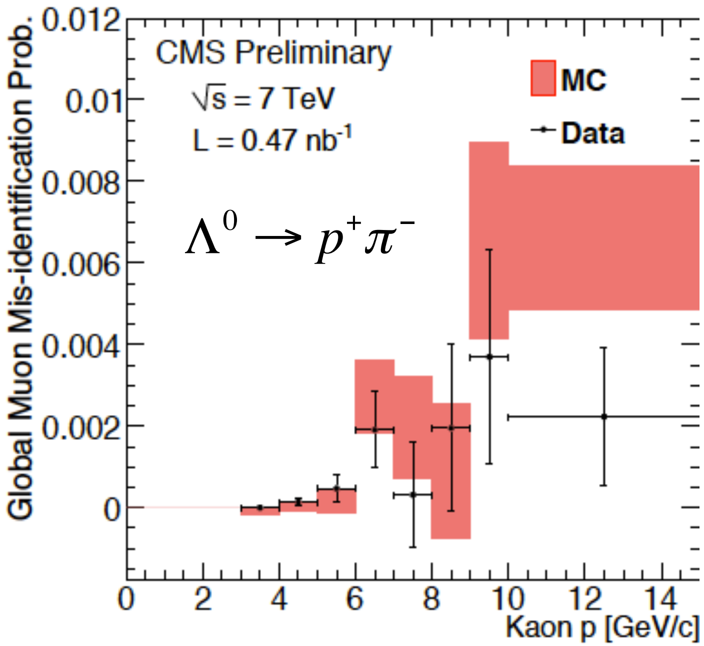
- Use dedicated dimuon trigger paths for heavy flavor studies
- Exploit good momentum, impact parameter, mass and vertex resolution at trigger level to select interesting topologies
- Bandwidth restrictions are the main limitation for most measurements

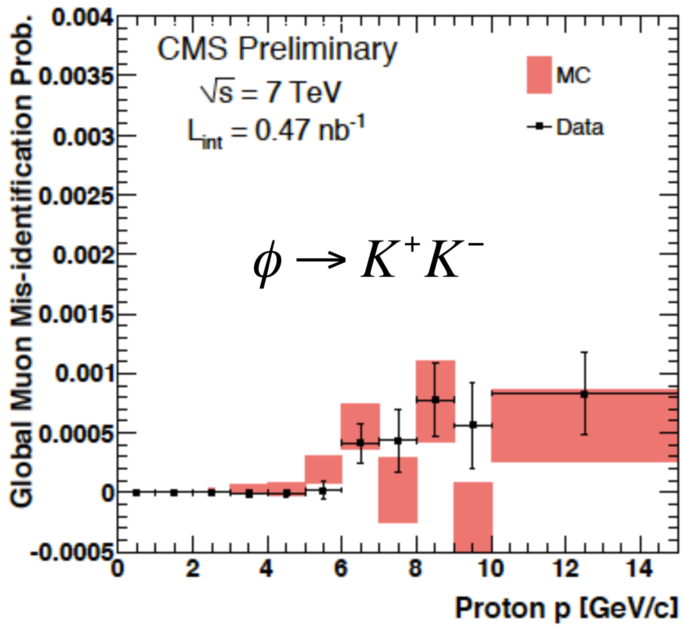
More tracking performance plots











Ξ_b^* event selection algorithm

- Ξ_b^- selection algorithm:
  - At every iteration:
    - Choose randomly 2 variables.
    - Randomly: tighten one, loosen the other.
    - Look at Ξ_b^- mass distribution:
      - Signal region: $5.75 < M < 5.83$ GeV
      - Side-bands: $5.69 < M < 5.75$ or $5.83 < M < 5.89$ GeV
    - Calculate: $B = 2N_{side\text{-}bands}/3$; $S = N_{signal} - B$
  - Accept iteration if S does not decrease and:
    - S/sqrt(S+B) increases (then save the iteration) or
    - S/sqrt(S+B) decreases by at most r*10% (r = uniform random number). In this case proceed but do not save the iteration.

Ξ_b^* event selection

- A sampling of some cut values determined from the algorithm
  - After trigger and Λ reconstruction

$$p_T(p) > 1.0\,\text{GeV},\ p_T(\pi_\Xi) > 0.18\,\text{GeV},\ p_T(\Xi^-) > 1.3\,\text{GeV},$$

$$p_T(\Xi_b^-) > 9.8 \text{ or } 10.6\,\text{GeV depending on whether } |\eta(\Xi_b^-)| < 1.2 \text{ or not},$$

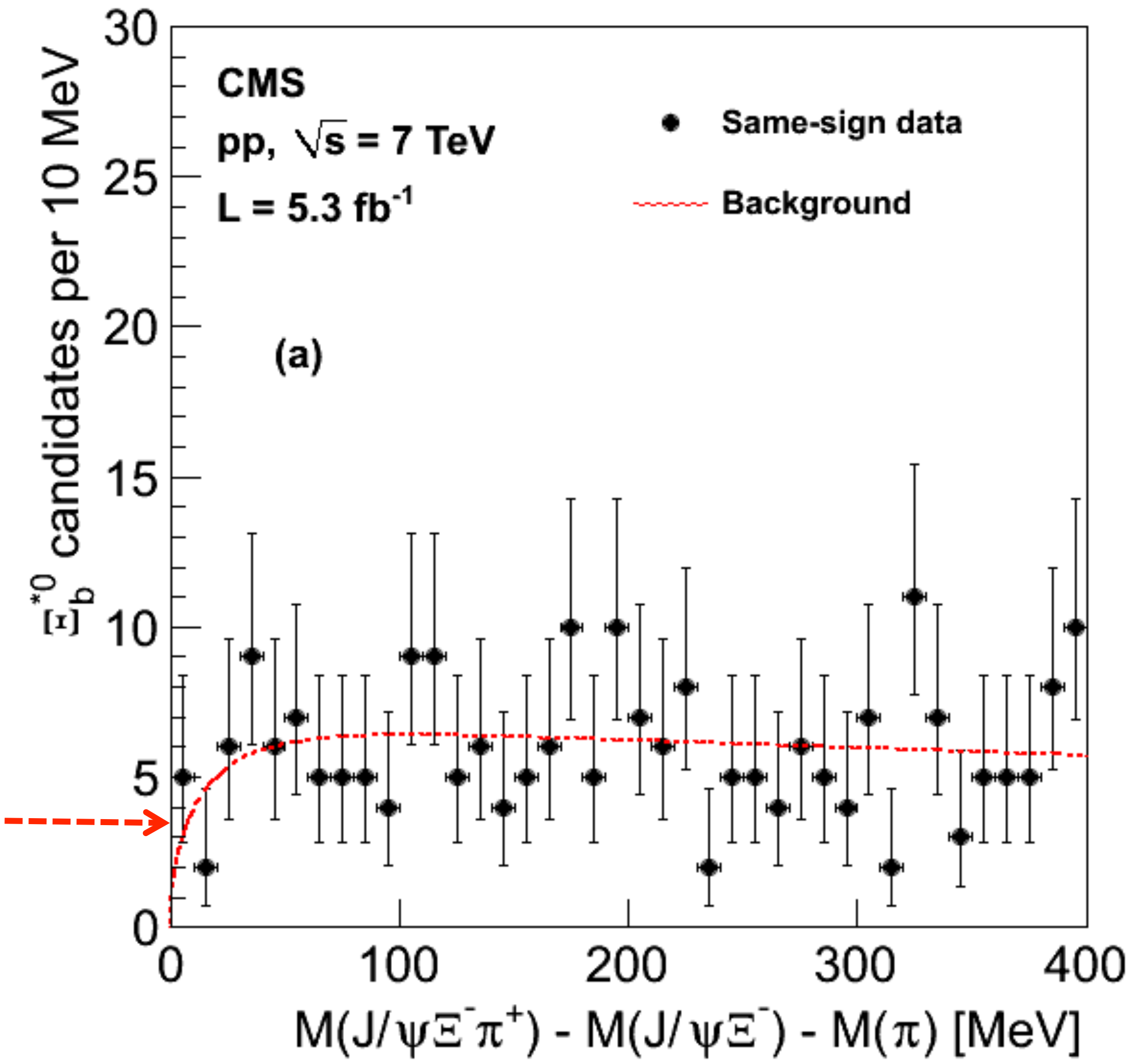
$$|\eta(J/\psi)| < 2.15,\ D_{ip}/\sigma_{Dip}(p) > 1.0,\ D_{ip}/\sigma_{Dip}(\pi_\Lambda) > 0.66,$$

$$L_{xy}/\sigma_{Lxy}(\Xi^-) > 2.8,\ CL(\Lambda^0) > 2.5\%,\ CL(\Xi_b^-) > 0.72\%,$$

$$D_{3d}/\sigma_{D3d}(\Xi^- - J/\psi) < 3.1 \quad D_{3d}/\sigma_{D3d}(\Xi_b^- - PV) < 3.5$$

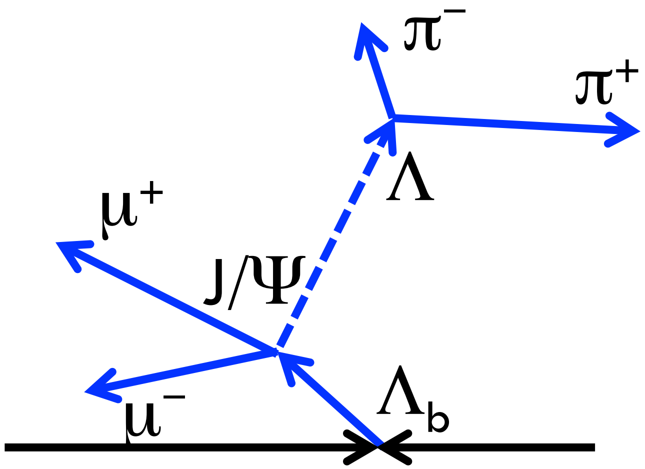
Ξ_b^* background shape

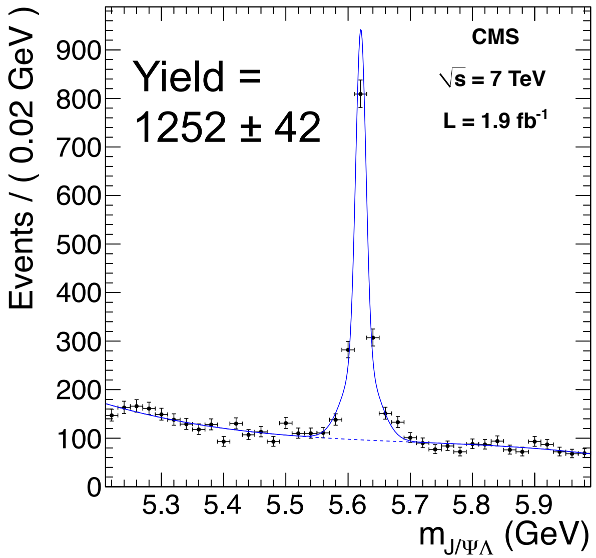
- Background dominated by random $\Xi_b^- \pi^+$
- Background shape from wrong sign pions
  - Toy model from data shapes for p(Ξ_b), p(π) and angle between Ξ_b and π, assumed to be uncorrelated
  - Fit toy results for shape
  - Compares well with nominal wrong sign distribution



(Q value)

Λ_b cross section measurement



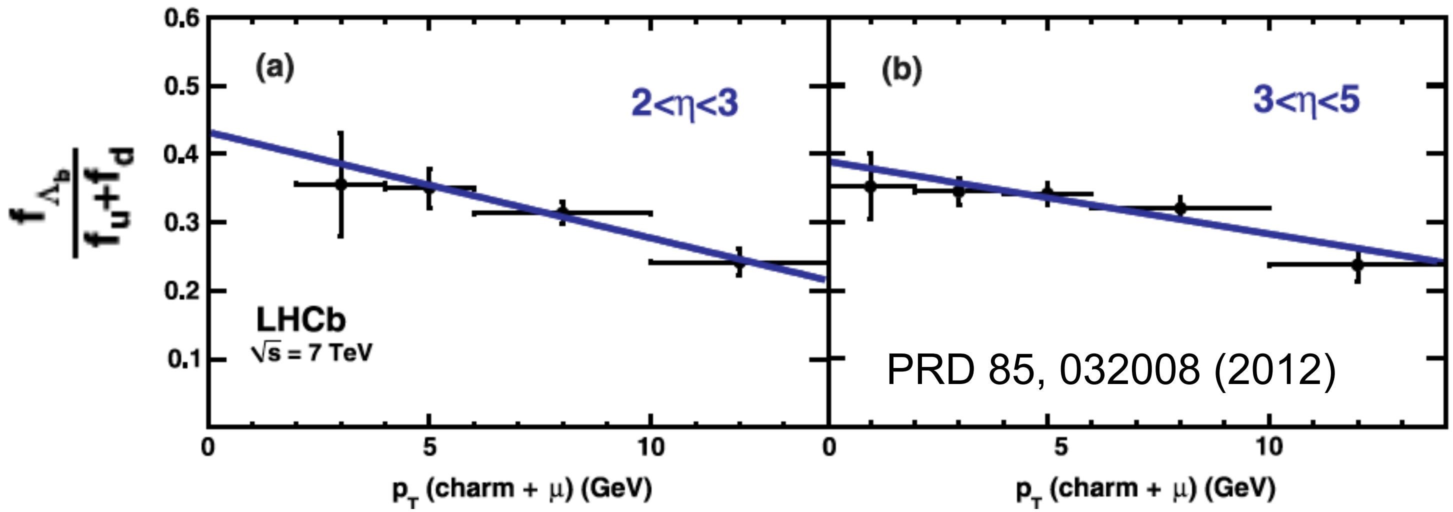


$p_T^{\Lambda_b}$ (GeV)	n_{sig} events	ϵ (%)
10 – 13	293 ± 22	0.29 ± 0.03
13 – 15	240 ± 18	0.79 ± 0.08
15 – 18	265 ± 19	1.54 ± 0.16
18 – 22	207 ± 16	2.34 ± 0.23
22 – 28	145 ± 14	3.21 ± 0.34
28 – 50	87 ± 11	3.96 ± 0.50
$\|y^{\Lambda_b}\|$	n_{sig} events	ϵ (%)
0.0 – 0.3	233 ± 17	0.74 ± 0.09
0.3 – 0.6	256 ± 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 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

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) ~10 GeV): f(b-baryon) = 0.212 ± 0.069
  - HFAG 2012: LEP (p_T(b) ~40 GeV): f(b-baryon) = 0.090 ± 0.015
- Discrepancy in baryon/meson production measurements between Tevatron and LEP could be explained by different p_T spectra

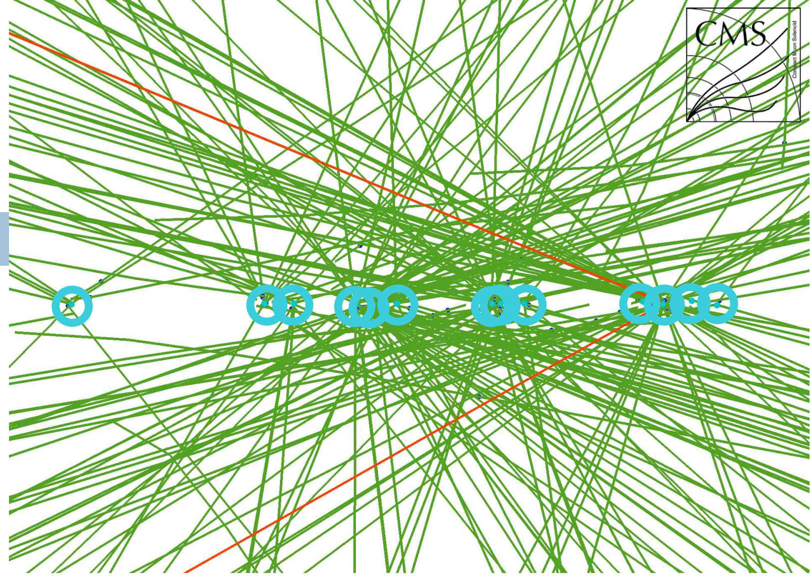
$D^0 \to K^- \mu^+ \nu$ and $D^0 \to \mu^- \mu^+$ analyses

- very tight cuts on muons (excellent p_T resolution and efficiency, large pseudorapidity coverage)
- tight cuts on kaon
- soft cuts on pion
- CL of primary vertex > 1%
- CL of secondary vertex > 1%
- for $D^0 \to \mu\mu$ analysis: D^0 pointing back to the primary
- L/S cut, that is the 3D-detachment between the primary and secondary vertices divided by its error (L/S > 3)
- D^0 candidate is combined with one track originating from the primary vertex to form D^{*+}

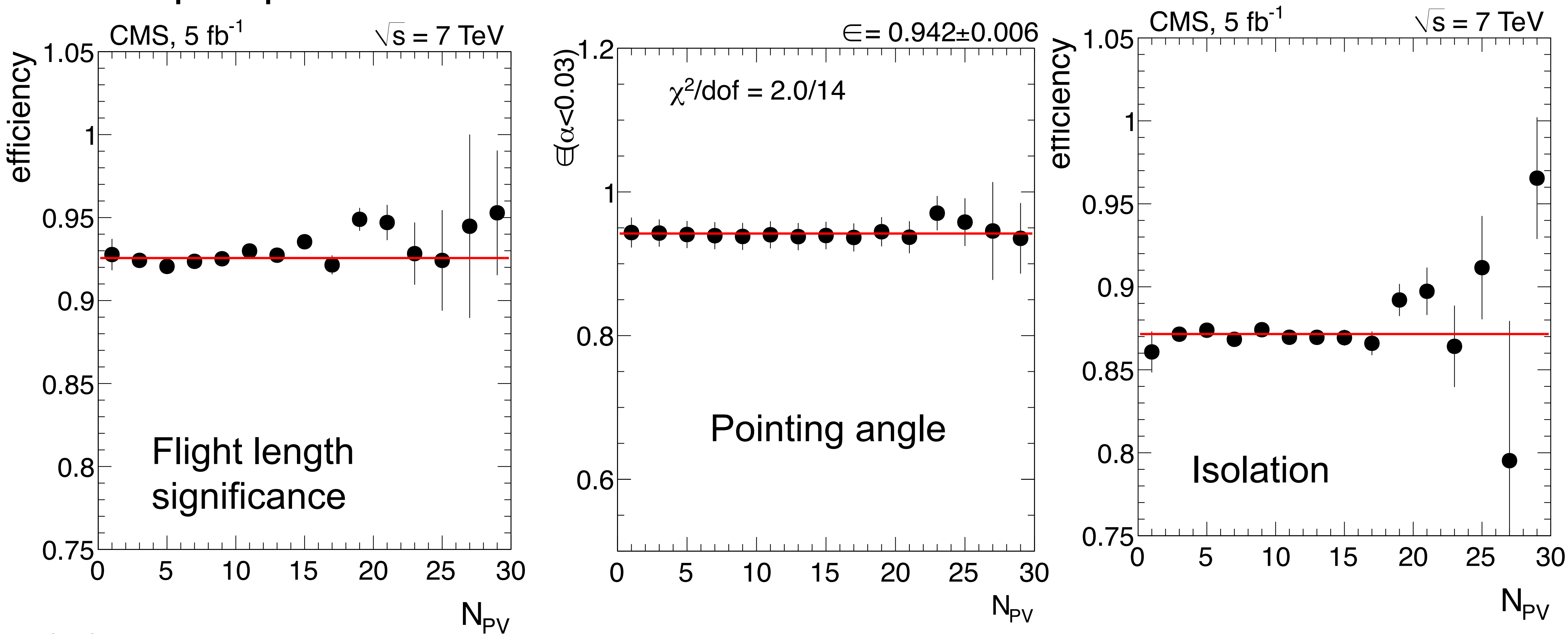
All $B^0_{(s)} \rightarrow \mu^+\mu^-$ selection cuts

Variable	Barrel	Endcap	units	comparison to old analysis
$p_{\perp\mu,1} >$	4.5	4.5	GeV	same
$p_{\perp\mu,2} >$	4.0	4.2	GeV	tighter in endcap
$p_{\perp B} >$	6.5	8.5	GeV	tighter in endcap
$\ell_{3d} <$	1.5	1.5	cm	tighter
$\alpha <$	0.050	0.030	rad	looser
$\chi^2/dof <$	2.2	1.8		looser
$\ell_{3d}/\sigma(\ell_{3d}) >$	13.0	15.0		looser
$I >$	0.80	0.80		redefined
$d^0_{ca} >$	0.015	0.015	cm	redefined
$\delta_{3D} <$	0.008	0.008	cm	new
$\delta_{3D}/\sigma(\delta_{3D}) <$	2.000	2.000		new
$N_{trk} <$	2	2	tracks	new

Pileup independence

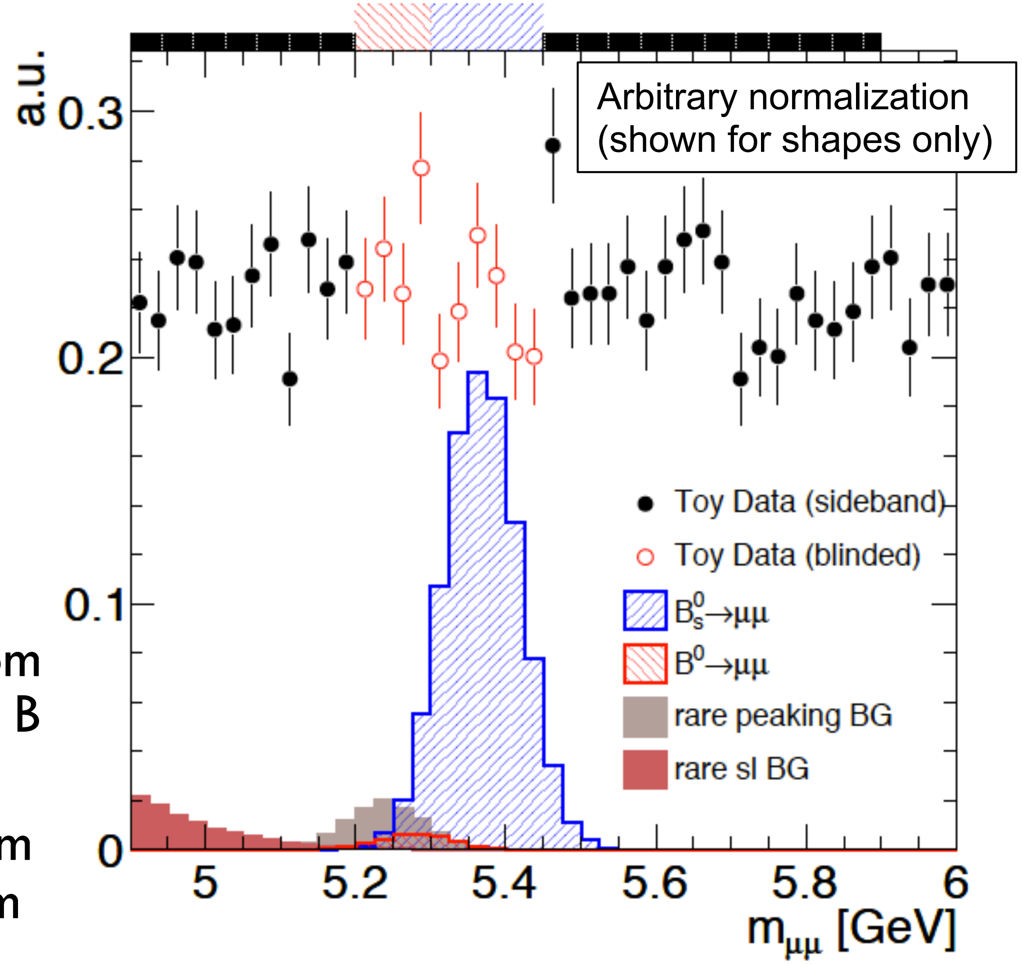


- Check influence of pileup on selection cuts with $B^{+} \rightarrow J/\Psi(\mu^{-}\mu^{+})K^{+}$ events in data
- Confirm with MC studies
- No significant dependence in efficiency vs pileup out to ~30 PV's



Background estimation

- Non-peaking background measured in data
  - Count events in B mass sidebands 4.80-5.20 GeV and 5.45-6.00 GeV
  - Interpolate to signal region with assumption of flat shape
- Peaking background obtained from MC with inputs from data
  - B→hh backgrounds with two muons from misidentified charged hadrons peak in B mass
  - Measure muon mis-ID rates in data from identified K and π from $D^{(*)}$ and p from Λ samples

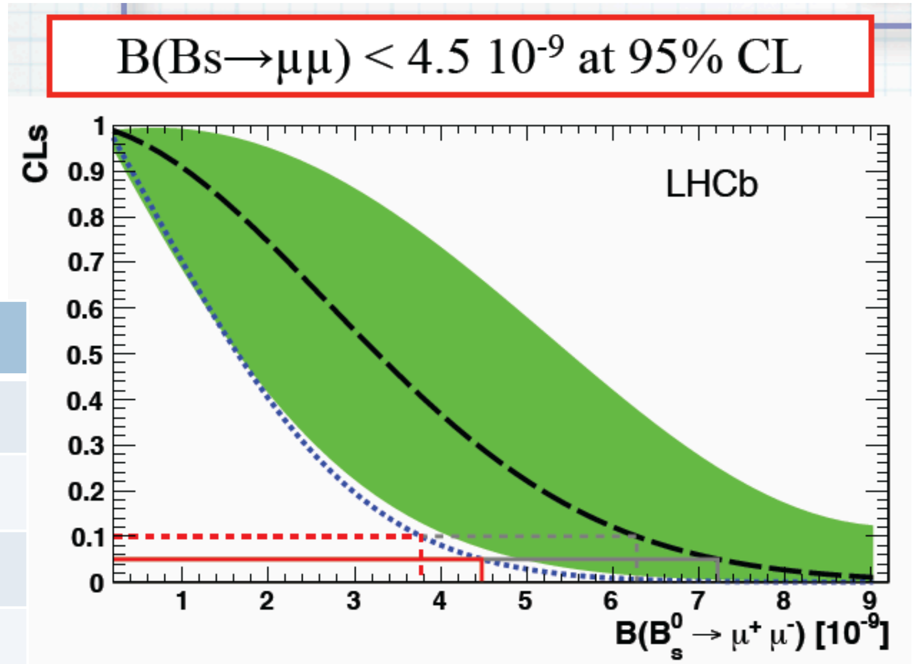


  - Use MC without muon selection cuts to simulate backgrounds and apply fake rate measurements from data
  - Affects B^0 more than B_s^0 because backgrounds peak low

$B_s \to \mu^+\mu^-$ comparison with LHCb

95% UL's ($\times 10^{-9}$)	CMS 5 fb-1	Atlas 2 fb-1	LHCb 1 fb-1	CDF 10 fb-1	D0 6 fb-1
$B_s \to \mu\mu$	7.7	22	4.5	31	51
$B^0 \to \mu\mu$	1.8	---	1.0	4.6	---

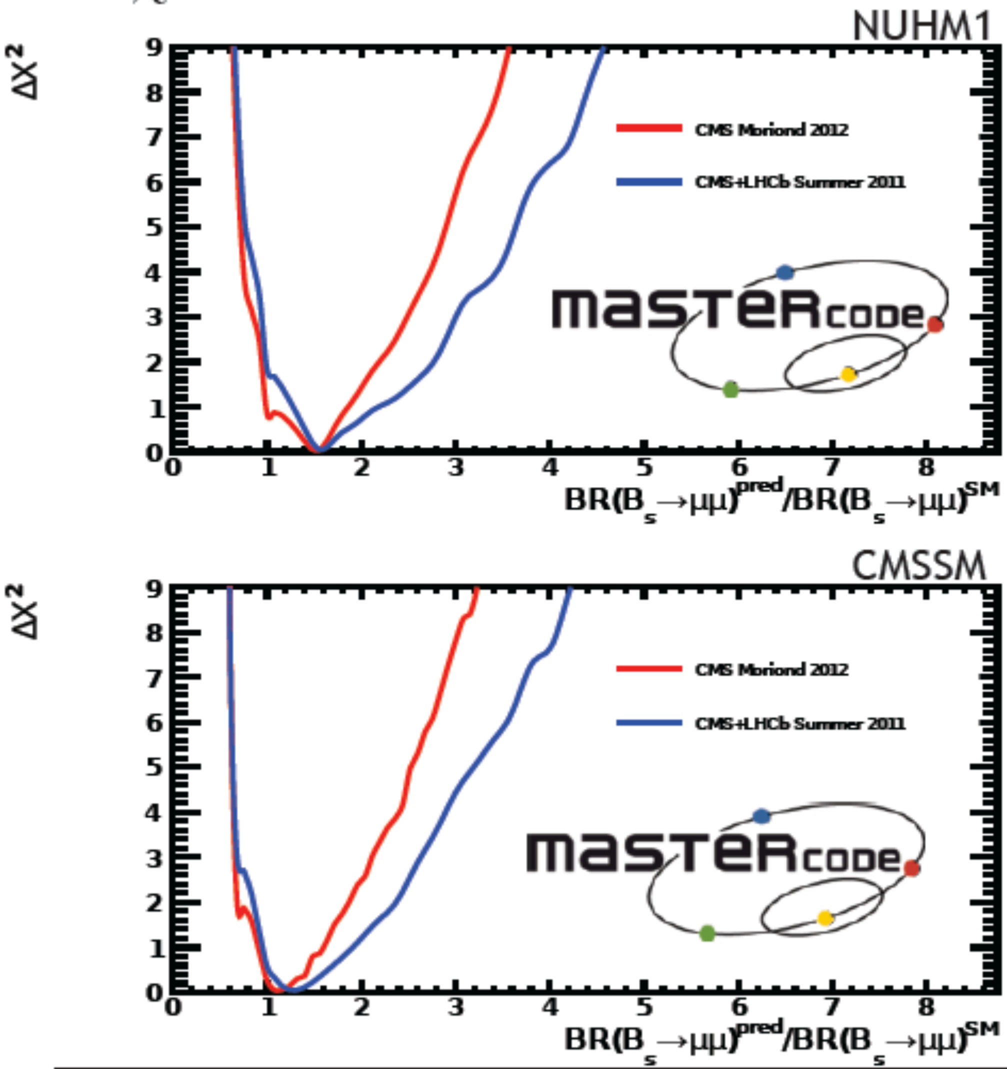
Full 2011 datasets, 95% UL's	CMS ($\times 10^{-9}$)	LHCb ($\times 10^{-9}$)
$Bs \to \mu\mu$ expected	8.8	7.2
$Bs \to \mu\mu$ observed	7.7	4.5
$B^0 \to \mu\mu$ expected	1.6	1.1
$B^0 \to \mu\mu$ observed	1.8	1.0



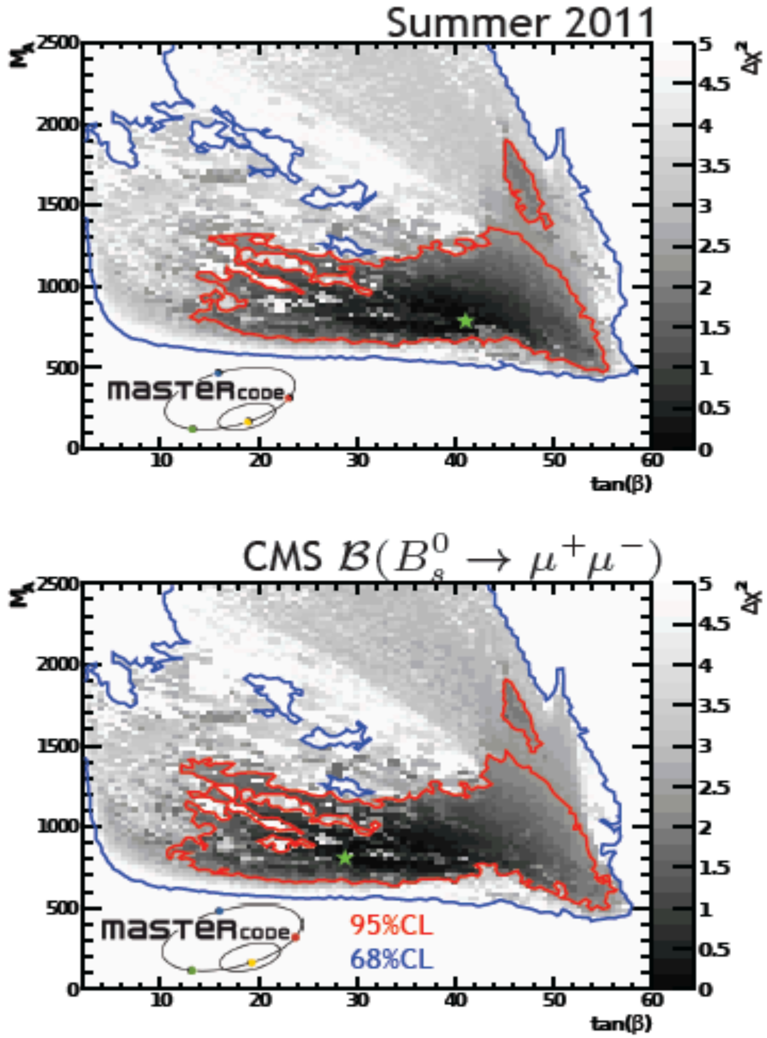
- LHCb advantages
  - Better mass resolution: ~25 MeV vs ~35-70 MeV
  - Higher trigger efficiency
  - More sophisticated analysis: BDT selection, combine different S/B bins vs cut and count in 2 bins
- CMS advantages
  - Higher luminosity: Factor of ~5 in 2011, currently factor of >10 in 2012
  - (More room for improvement in analysis technique)

More $B^0_{(s)} \to \mu^+\mu^-$ interpretation

- χ^2 difference



- 'best' fit for CMSSM



MasterCode collaboration arXiv:1112.3564