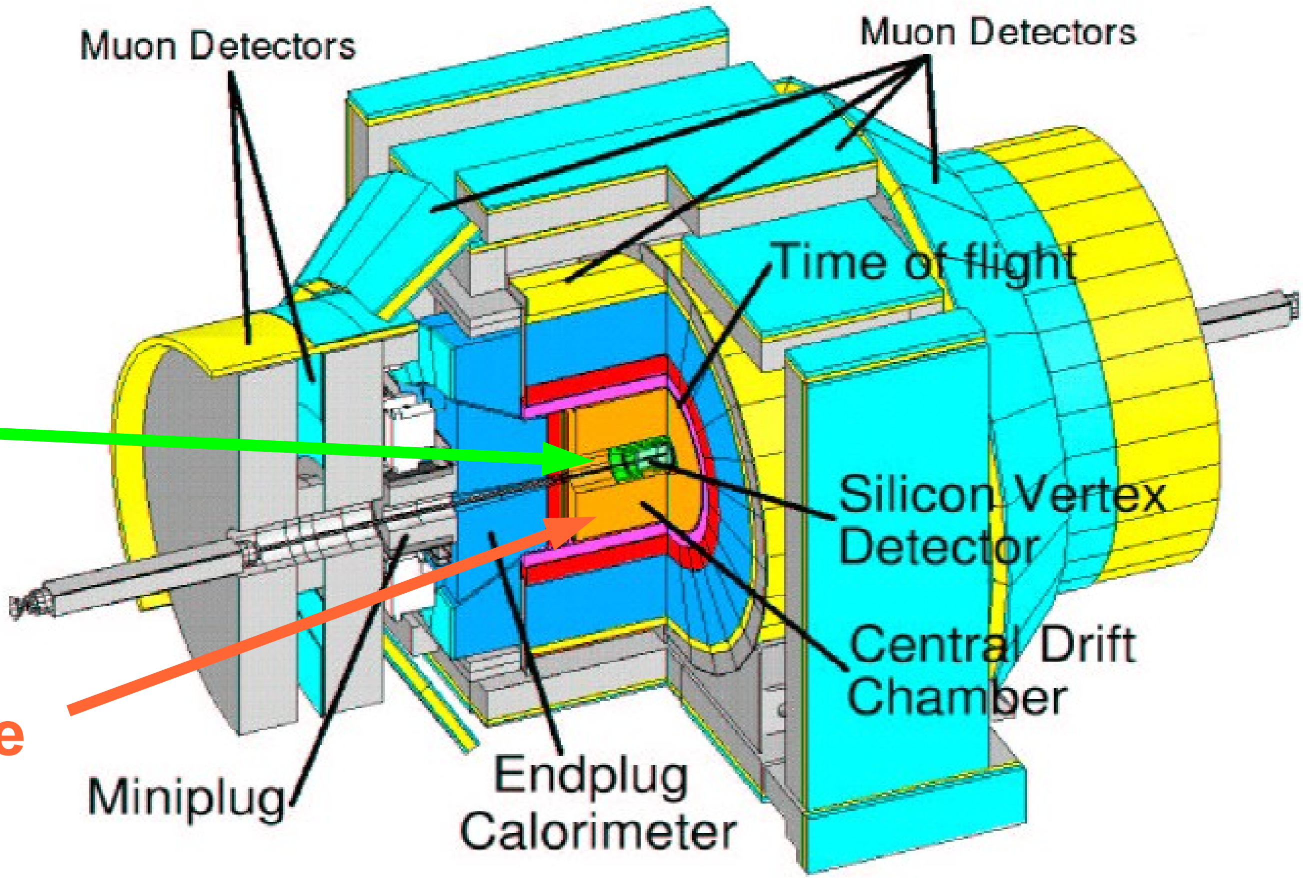
B Spectroscopy at CDF

Petar Maksimovic, for the CDF collaboration

- *Test: lattice calculations, potential models, HQET*
- *All already tested for heavy mesons (Qq) systems – interesting to check for baryons (Qqq)*
- Featured:
  - Refresher: best measurement of B_s, Λ_b and B_c masses
  - Discovery of B_{s1}! ... Measurement of masses of 2 narrow B_s**
  - Discovery of Σ_b! ... Measurement of 4 masses

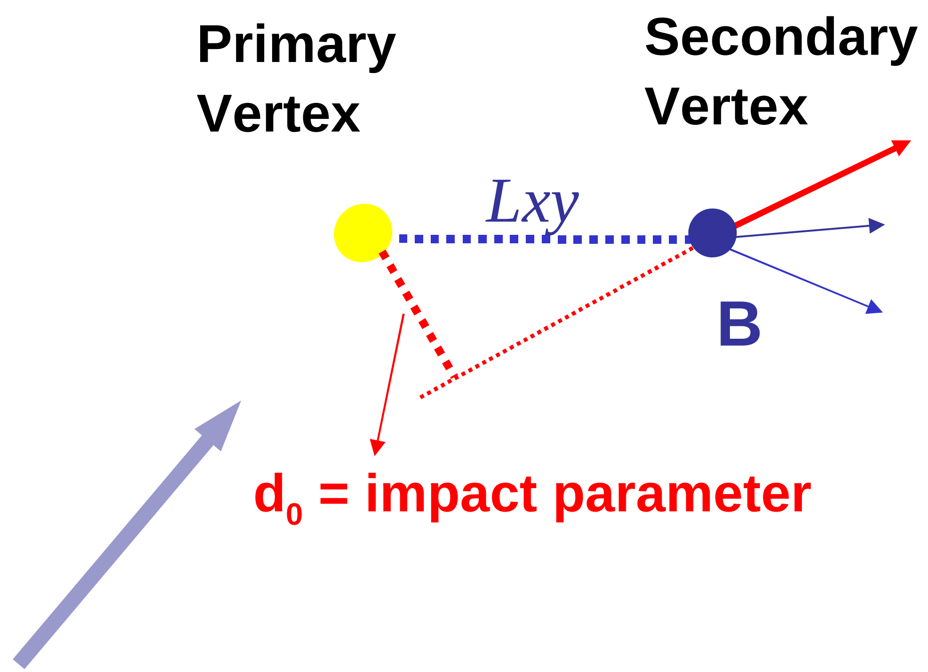
Tevatron + CDF = *b*-hadron factory

- *All species of b-hadrons produced!*
- Tevatron's has been performing really well: here using ~ 1.1 fb^{-1} of data
- CDF has excellent tracking:
  - **d_0 resolution (needed for B physics)**
  - **p_T resolution (needed to measure masses)**



Mining *b*-hadrons

- $\sigma_{b\bar{b}}$ is very large, but cross section of soft QCD is 1000x larger
- *b*-physics program lives and dies by the trigger!
- Trigger paths used by these analyses:
  - 2 muons (J/ψ)
  - 2 displaced tracks (full hadronic decays)

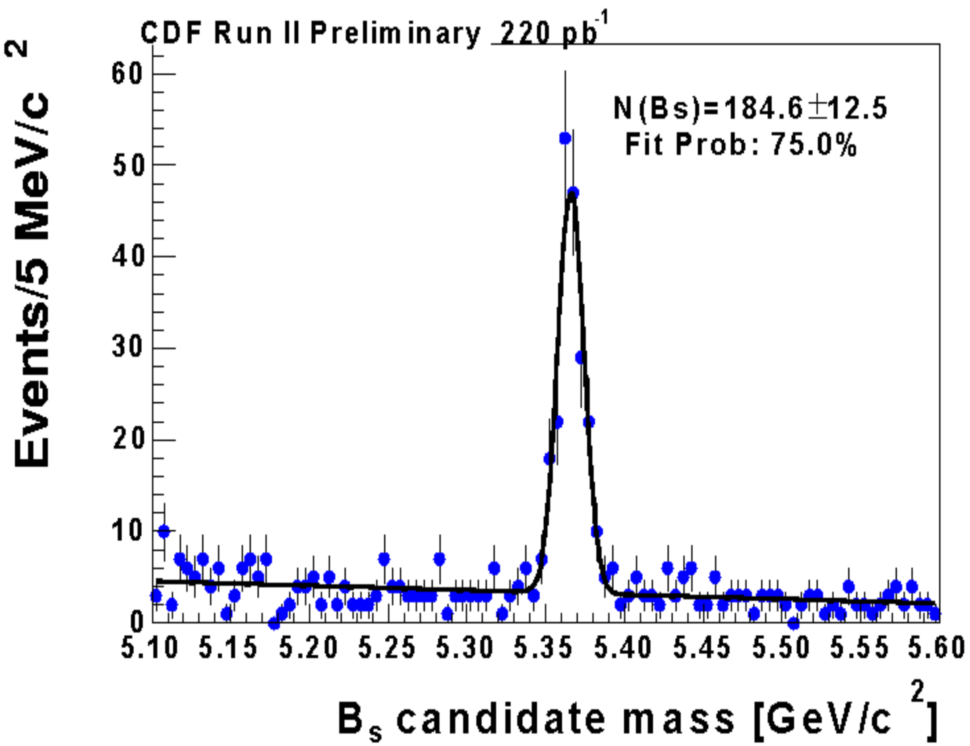


- *Silicon Vertex Trigger* (SVT) – part of trigger system that finds displaced tracks and triggers on heavy flavor

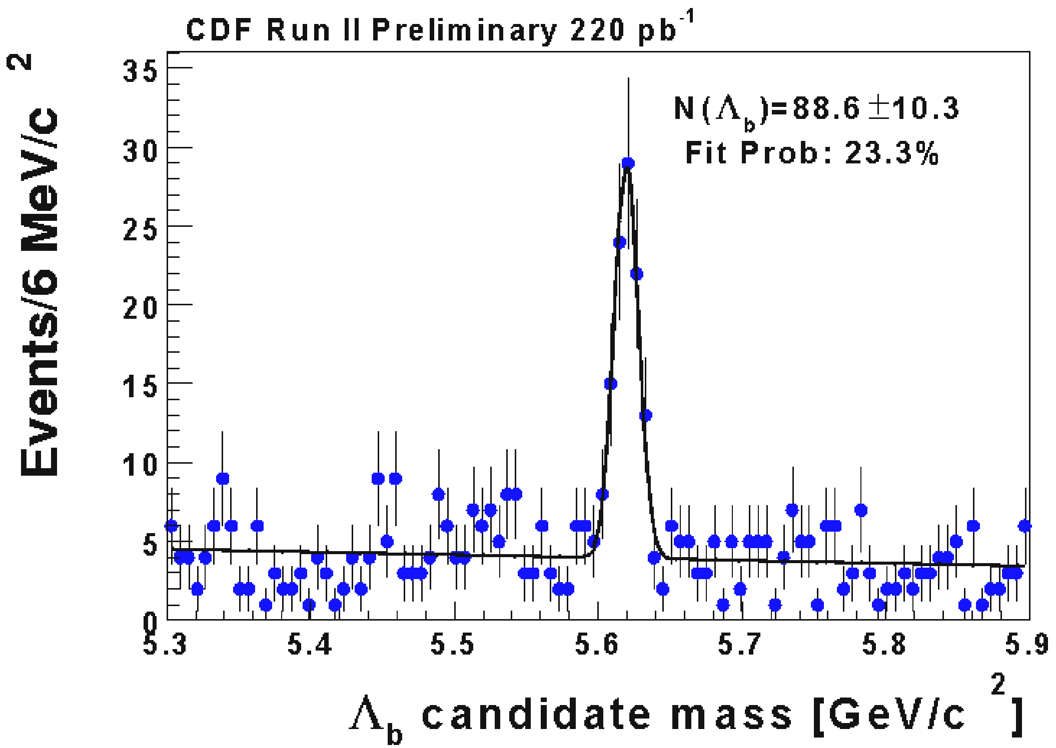
Refresher: B_s and Λ_b masses

- Both from di-muon trigger: $J/\psi \rightarrow \mu^+\mu^-$
- Cuts optimized to make background low and *flat*

$B_s \rightarrow J/\psi\phi, \phi \rightarrow K^+K^-$



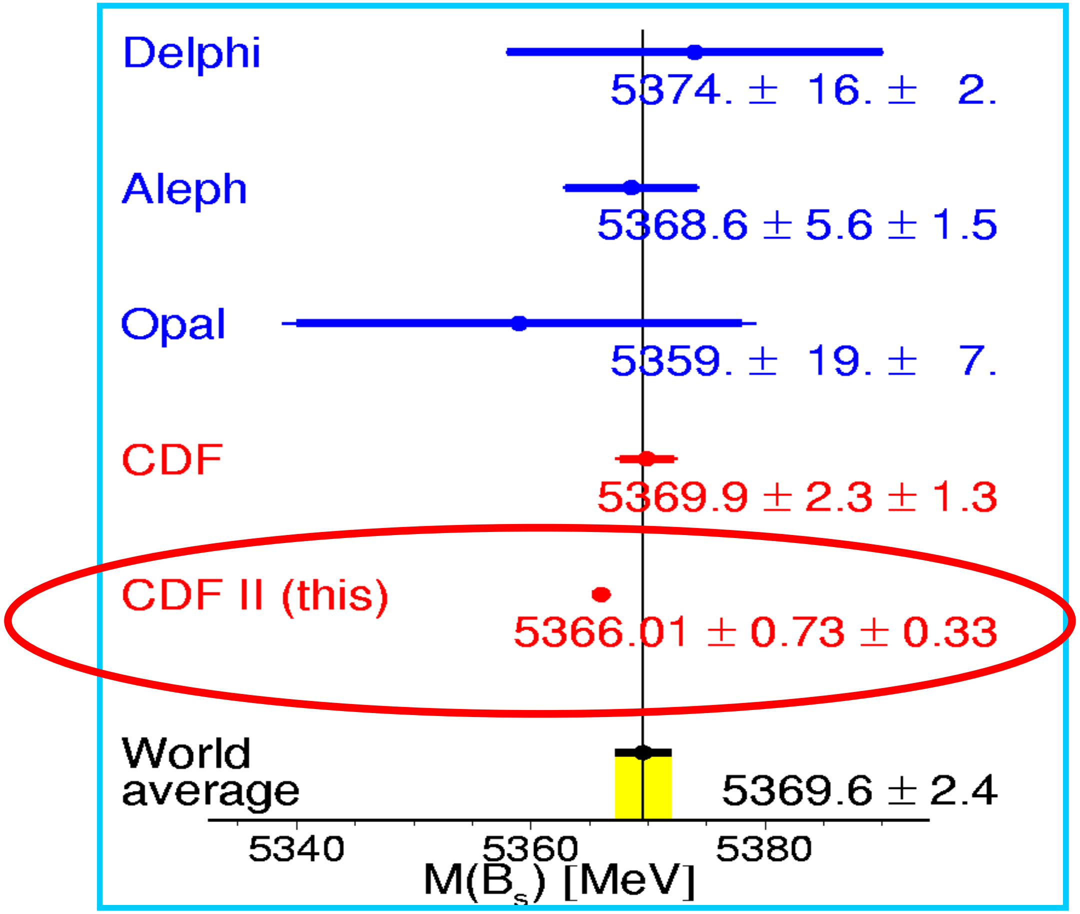
$\Lambda_b \rightarrow J/\psi\Lambda, \Lambda \rightarrow p\pi$

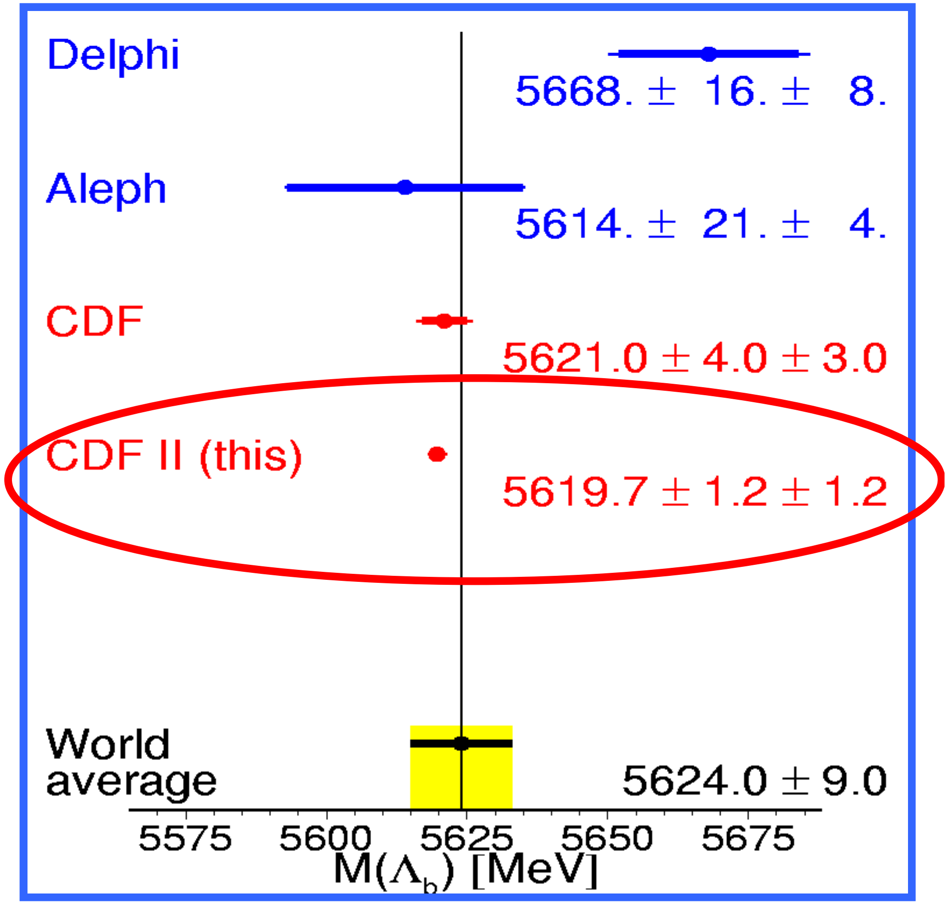


Refresher: B_s and Λ_b masses

- Both significantly better than the world average!

(Really in a league of their own!...)

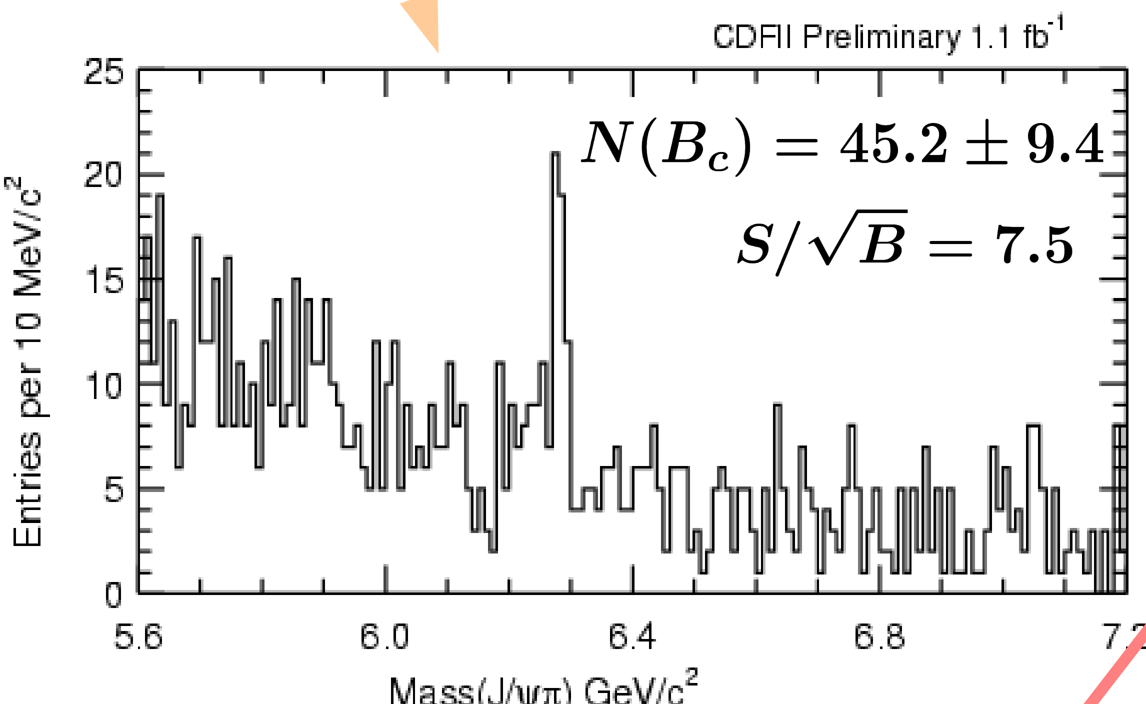




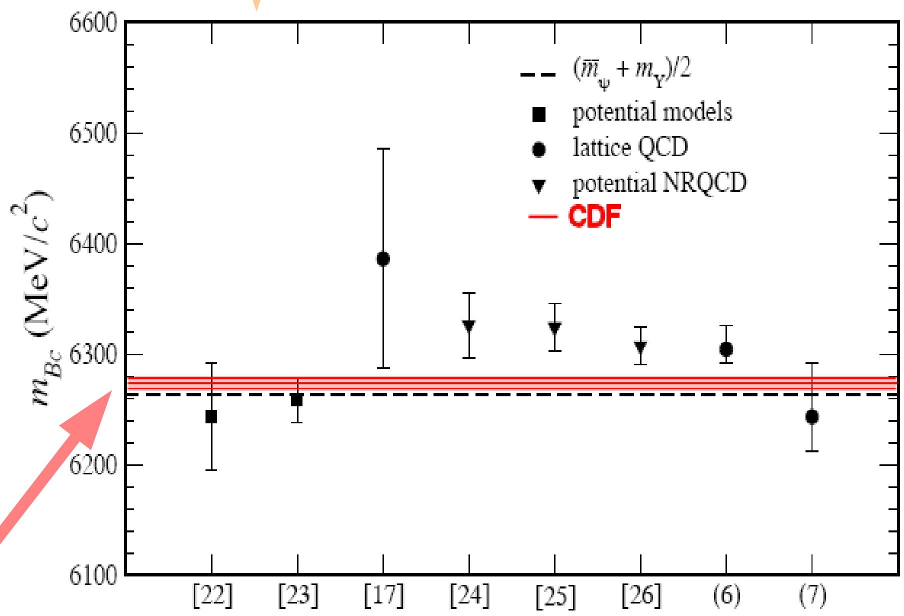
Mass of B_c

- Largest sample of fully reco. B_c decays

$$B_c^+ \to J/\psi\pi^+$$



- Already challenging theoretical predictions



$$m(B_c) = 6276.5 \pm 4.0(stat) \pm 2.7(syst)\ \mathrm{MeV}/c^2$$

Search for orbitally excited B_s^{**}

- L=1 states observed for D, D_s, B_d, B_u,

- For L=1, expect:

too broad

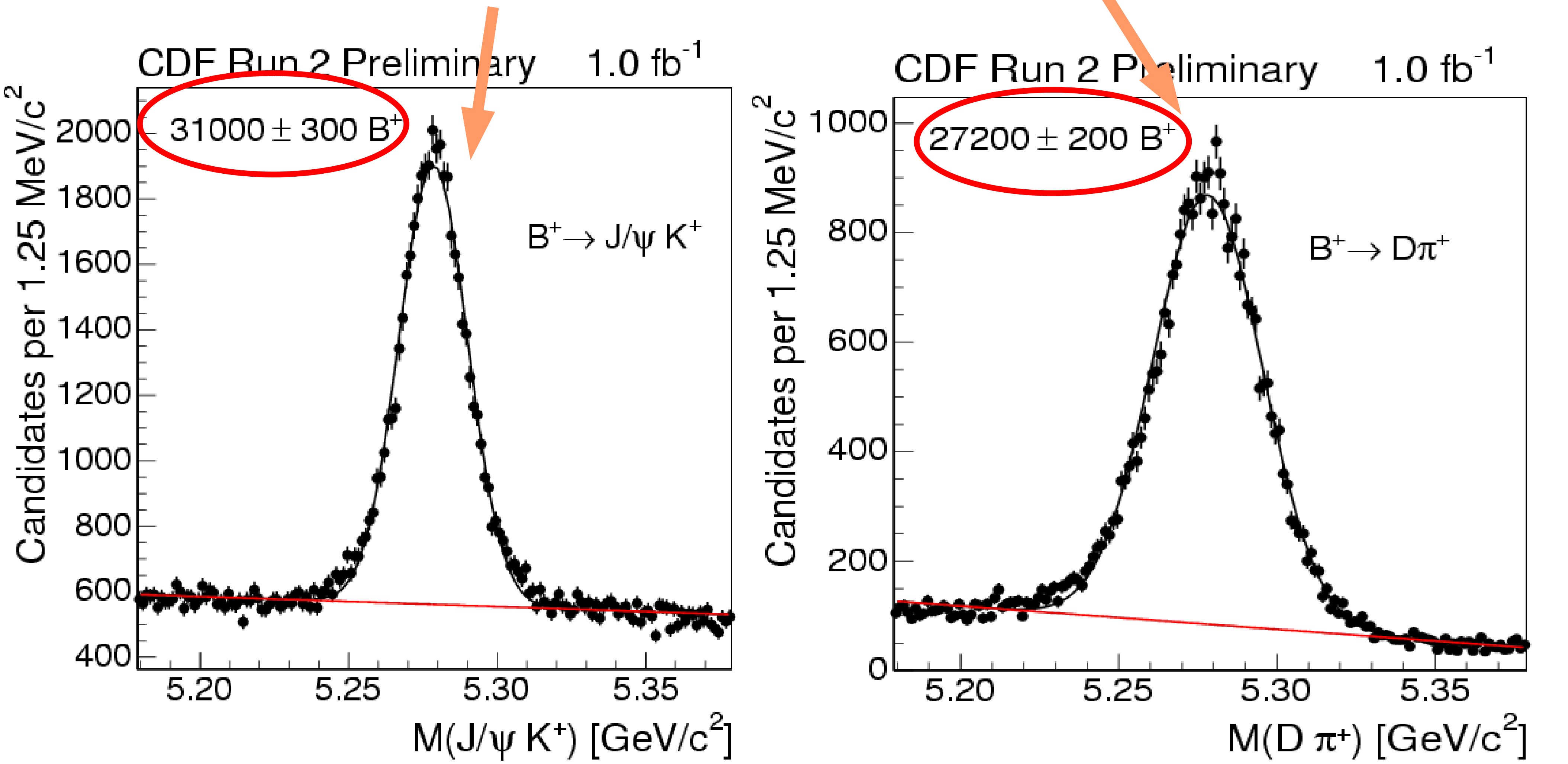
j_q	J^P	B_s^{**} state	decay mode	width
$1/2$	0^+	B_{s0}^*	BK	broad (S-wave)
$1/2$	1^+	B_{s1}	B^*K	broad (S-wave)
$3/2$	1^+	B_{s1}	B^*K	narrow (D-wave)
$3/2$	2^+	B_{s2}^*	BK, B^*K	narrow (D-wave)

few MeV wide, good S/B – doable

- One Bs** state observed by OPAL, DELPHI, D0
  ...but ... which one?

B_s^{**} Reco: Use ~ 60k B^+'s!

- Reconstruct as $B_s^{**} \to B^+ K^-$ *(kaon is prompt!)*
- Use $B^+ \to J/\psi K^+$ and $B^+ \to \bar{D}^0 \pi^+, \bar{D}^0 \to K^+ \pi^-$



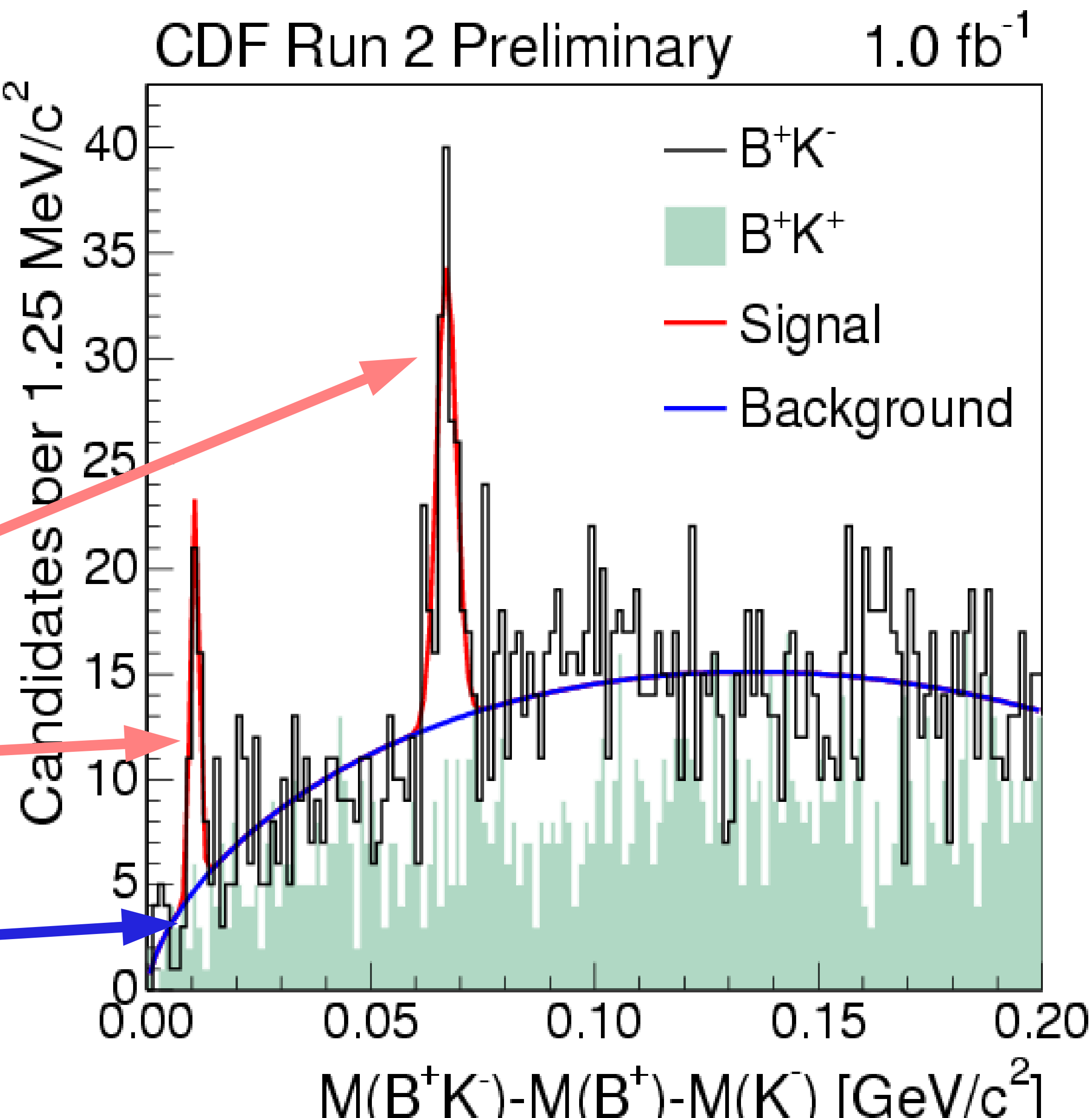
B_s^{**} Masses

- Use *Neural Network* to simultaneously optimize B^+ and B_s^{**} selection
- Observe both narrow states!

$N(B_{s2}^*) = 94.8 \pm 23.4$ (stat)

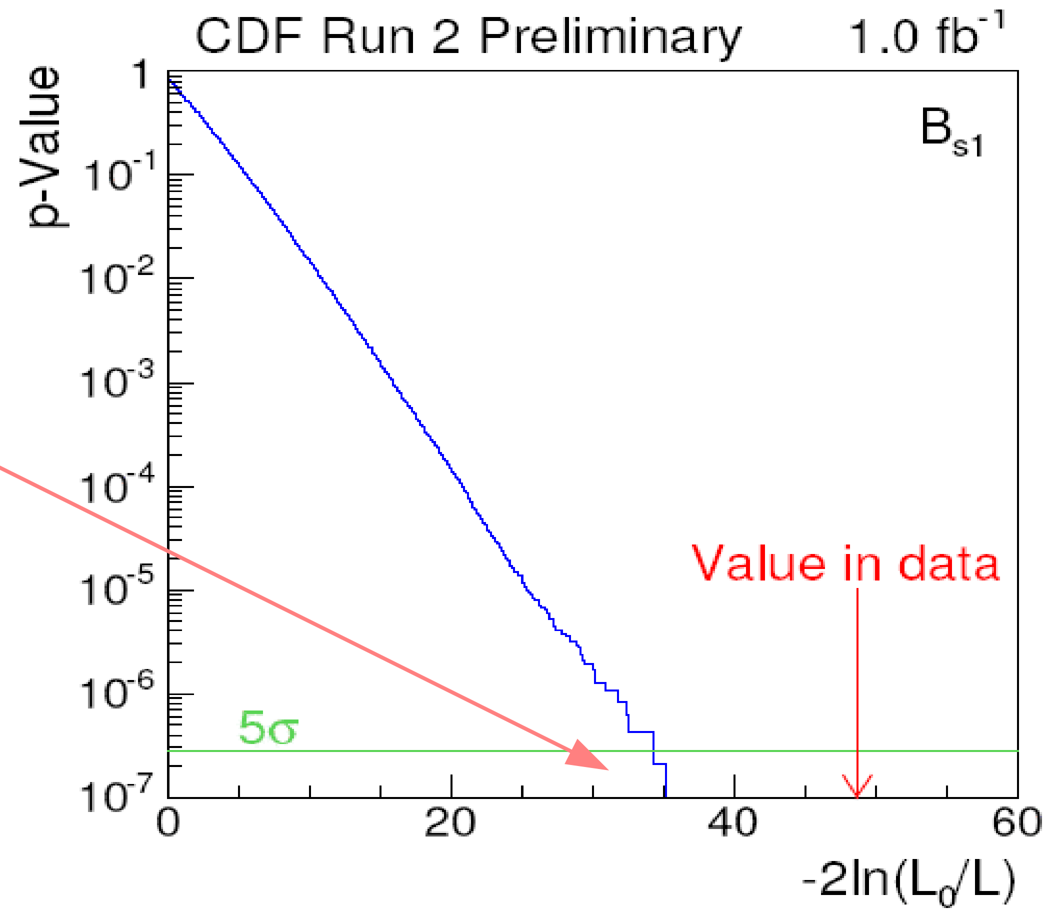
$N(B_{s1}) = 36.4 \pm 9.0$ (stat)

- Empirical bkg shape



Discovery of B_{s1}!

- Significance of B_{s1} peak evaluated by Toy MC
- p-value < $2 * 10^{-7}$
- *Significance is > 5σ !*

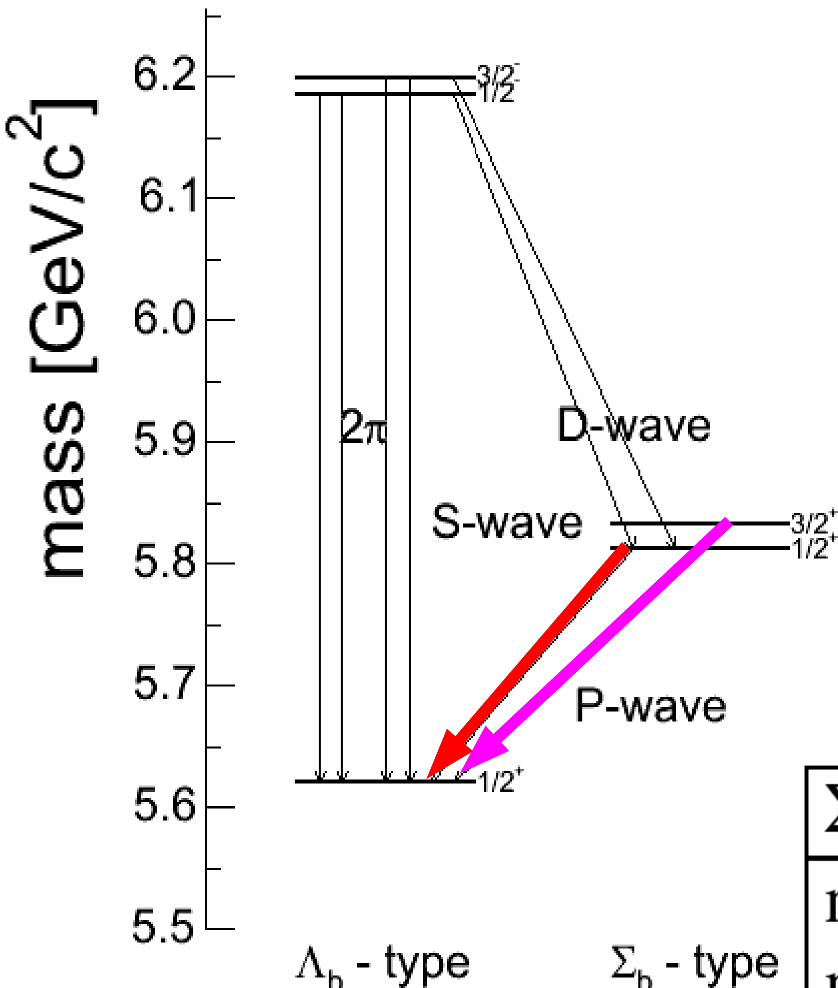


Measurement of masses:

$$m(B_{s1}) = 5829.41 \pm 0.21\,(\text{stat}) \pm 0.14\,(\text{syst}) \pm 0.6\,(\text{PDG})\ \text{MeV}/\text{c}^2$$
$$m(B_{s2}^{*}) = 5839.64 \pm 0.39\,(\text{stat}) \pm 0.14\,(\text{syst}) \pm 0.5\,(\text{PDG})\ \text{MeV}/\text{c}^2$$

Σ_b: motivation

- Λ_b only established *B* baryon
- Enough statistics at Tevatron to probe other heavy baryons
- Next accessible baryons:



$\boldsymbol{\Sigma_b}$ $b\{qq\}$, $q = u,d$; $J^P = S_Q + s_{qq}$

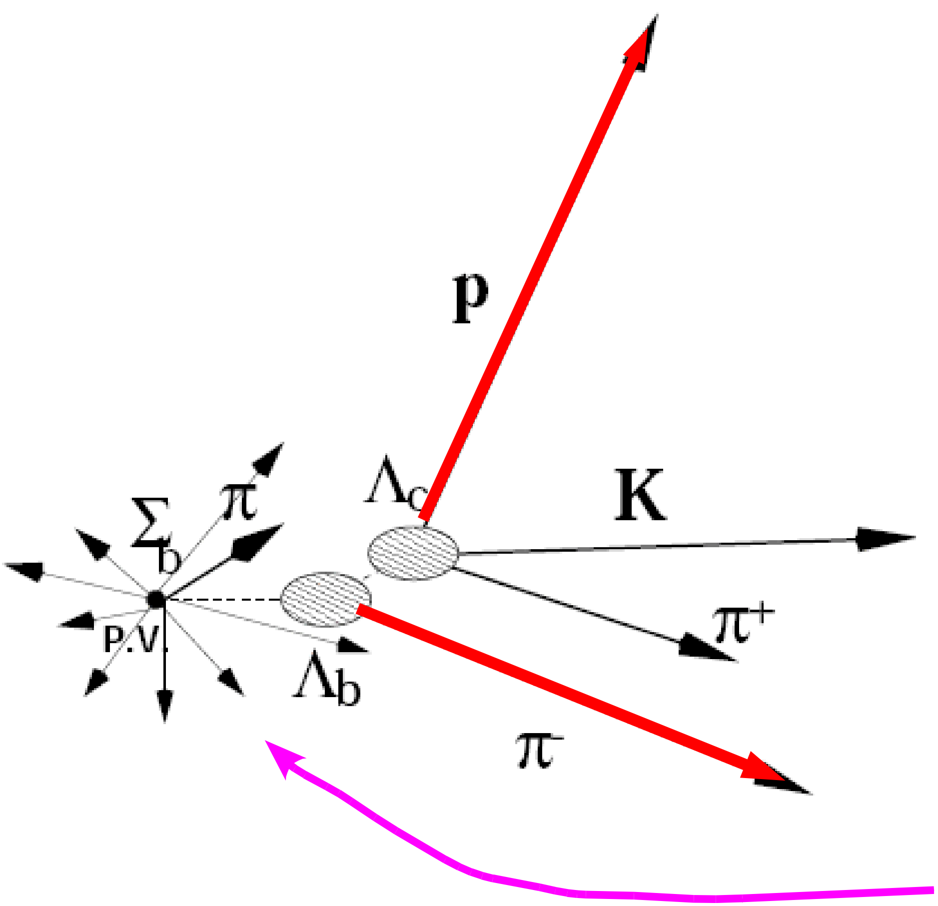
$= 3/2^+ (\Sigma_b^*)$

$= 1/2^+ (\Sigma_b)$

Σ_b property	Expected value (MeV/c^2)
$m(\Sigma_b) - m(\Lambda_b^0)$	180 - 210
$m(\Sigma_b^*) - m(\Sigma_b)$	10 - 40
$m(\Sigma_b^-) - m(\Sigma_b^+)$	5 - 7
$\Gamma(\Sigma_b), \Gamma(\Sigma_b^*)$	$\sim$8, $\sim$15

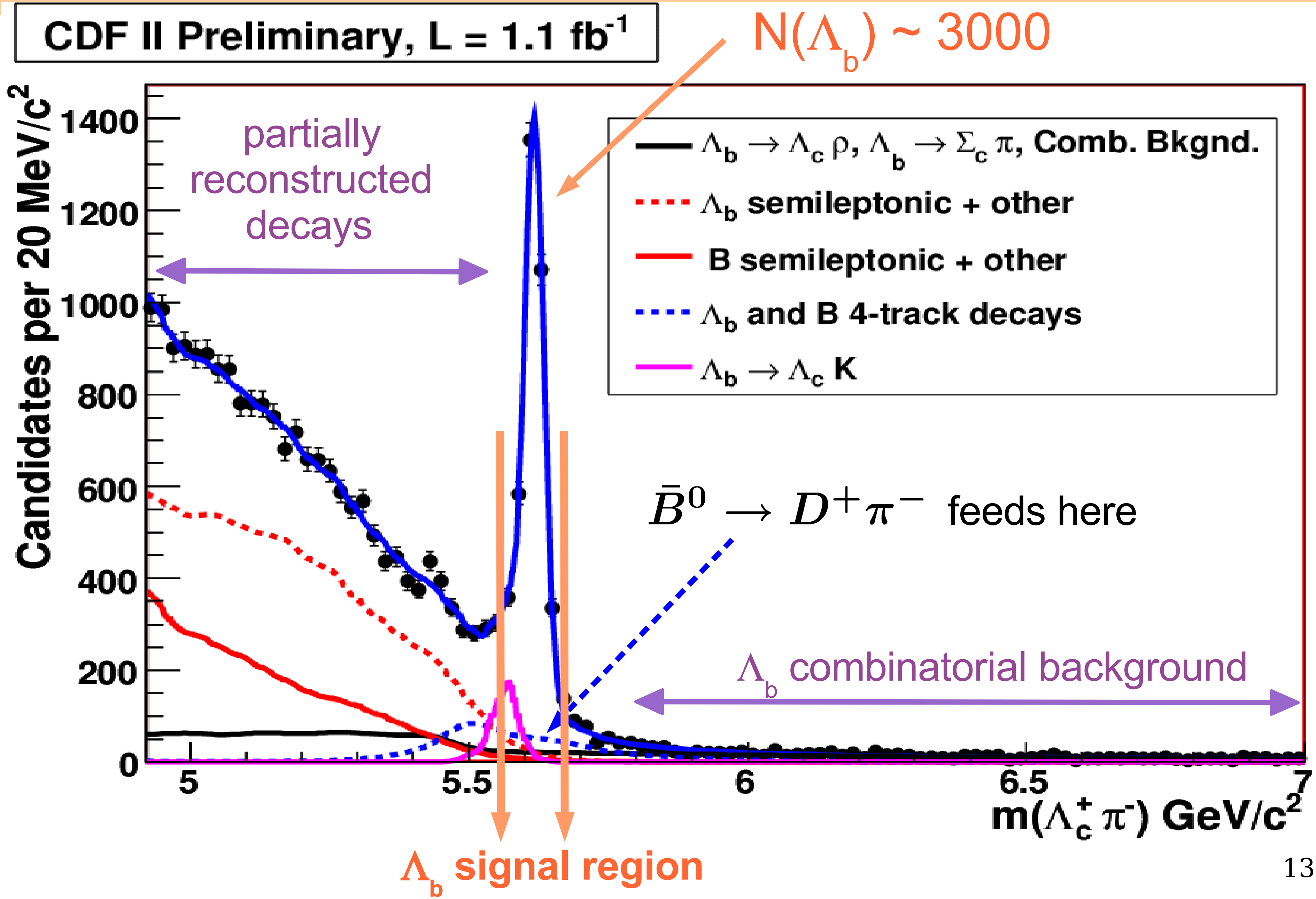
Reconstructing Λ_b and Σ_b

$$\Lambda_b^0 \to \Lambda_c^+ \pi^-$$
$$\hookrightarrow pK^-\pi^+$$



- Proton and π from Λ_b usually fire Two (displaced) Track Trigger (based on SVT)
- $\bar{B}^0 \to D^+\pi^-$ has similar topology, and can be mistaken for $\Lambda_b \to \Lambda_c^+\pi^-$ decay
- π from Σ_b comes from primary vertex, *along with tracks from hadronization and Underlying Event*

The largest (fully reconstructed) Λ_b sample in the world

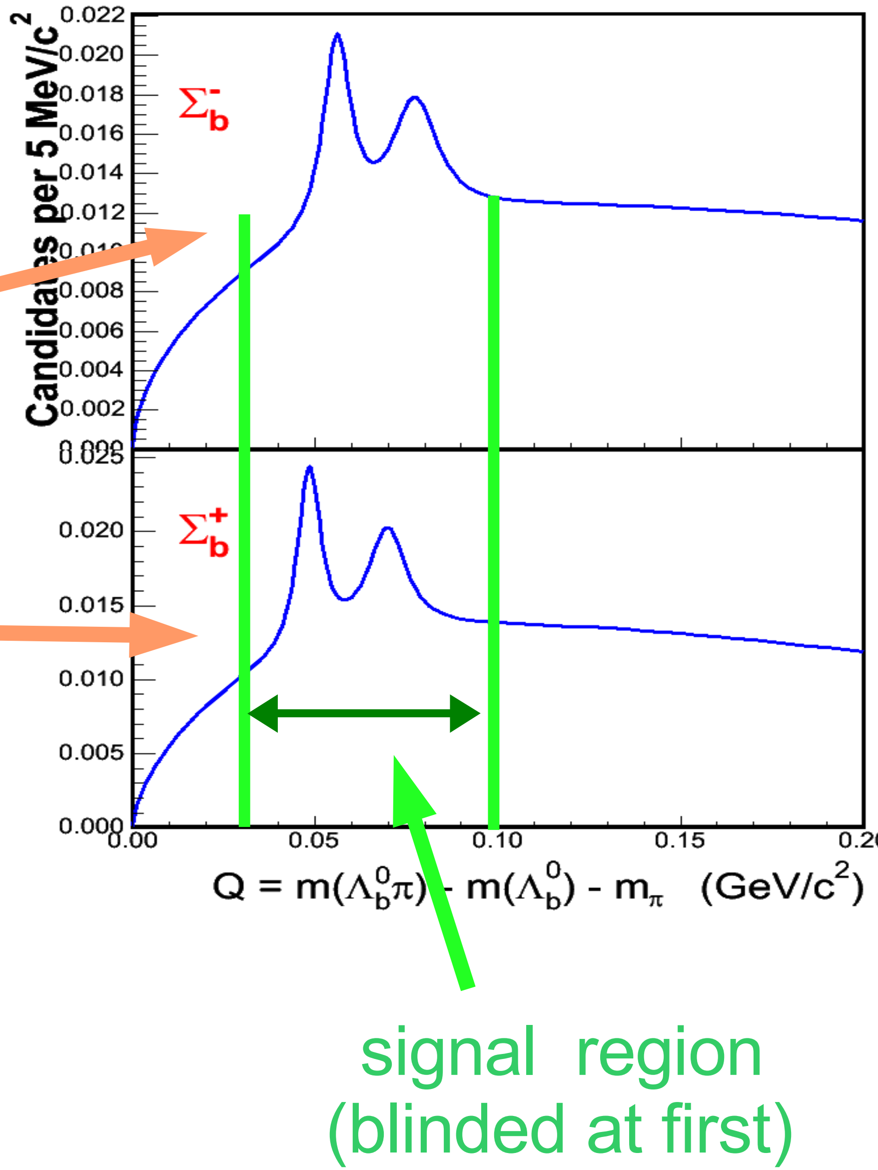


Reconstructing Σ_b

- Split into two sub-samples:

  Look for Σ_b^- and Σ_b^{*-} in $\Lambda_b^0\pi^-$ and $\overline{\Lambda}_b^0\pi^+$

  Look for Σ_b^+ and Σ_b^{*+} in $\Lambda_b^0\pi^+$ and $\overline{\Lambda}_b^0\pi^-$



- Remove effect of Λ_b resolution by looking at

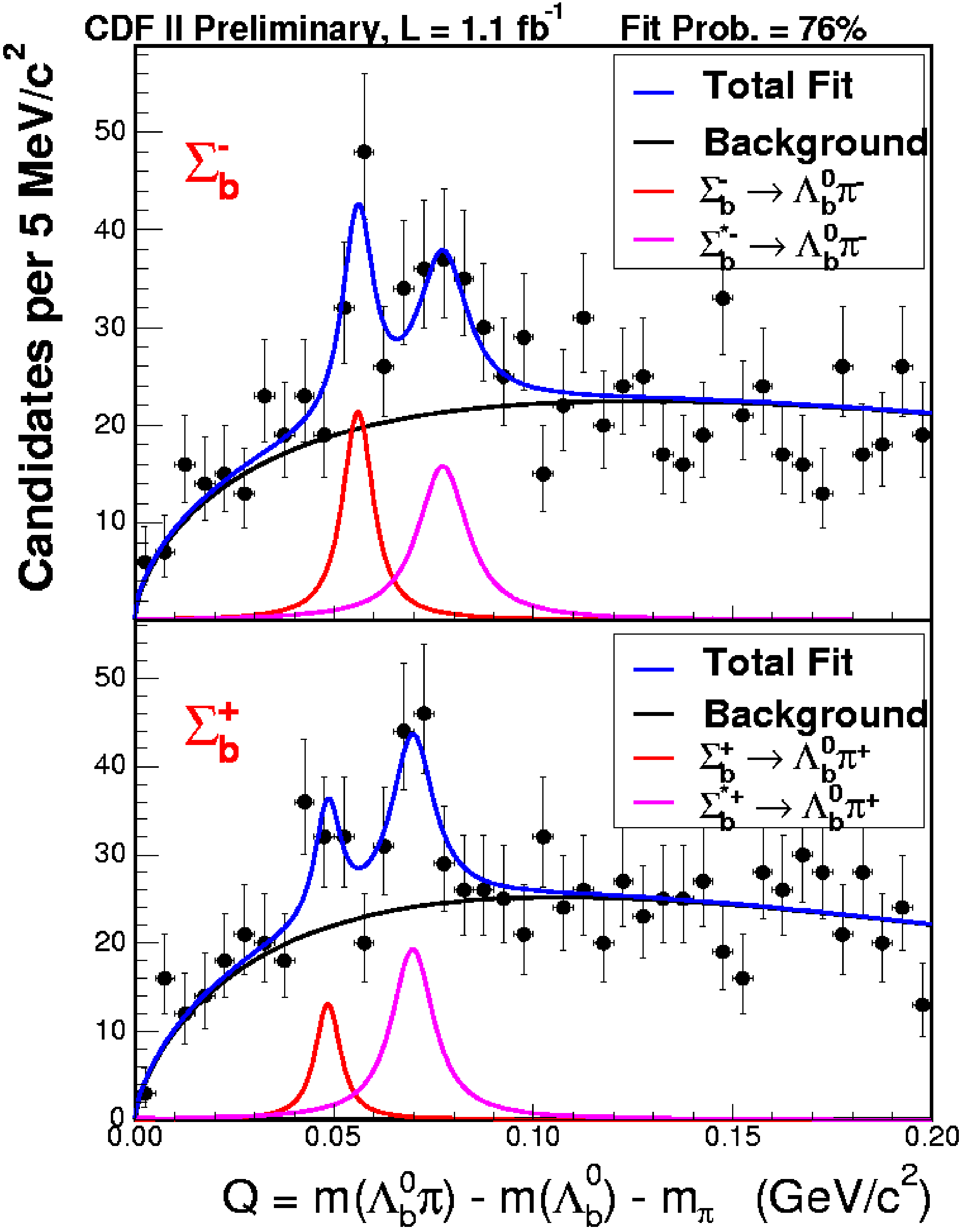
$$Q \equiv m(\Lambda_b\pi) - m(\Lambda_b) - m_\pi$$

Σ_b: Composition of backgrounds

Background type		Source	Contribution
Λ_b hadronization		PYTHIA	dominant
Combinatorial		Upper Λ_b sideband $m(\Lambda_b) \in [5.8, 7.0]$	small
B meson hadronization		B^0 data	small
All B meson reflections	*π_Σ from B hadronization*	B^0 PYTHIA	Dominant within B^0
	π_Σ from B decay (D, D**)*	Inclusive b-had MC	negligible
	*π_Σ from B***	B^0 PYTHIA	negligible

Will be ignored from now on

Σ_b Fit



- Backgrounds frozen
- Signal: 4 peaks, each
  - 2 Breit-Wigners (resolution has 2 Gaussians)
  - $\Gamma(\Sigma_b)$ as a function of center of each peak

    [hep-ph/9406359]
- $m(\Sigma_b^*)$-$m(\Sigma_b)$ common parameter

Σ_b Yields (including systematics)

- $N(\Sigma_b^-) = 60^{+14.8}_{-13.8}\ (\text{stat})\ ^{+8.4}_{-4.0}\ (\text{syst})$
- $N(\Sigma_b^+) = 29^{+12.4}_{-11.6}\ (\text{stat})\ ^{+5.0}_{-3.4}\ (\text{syst})$
- $N(\Sigma_b^{*-}) = 74^{+18.2}_{-17.4}\ (\text{stat})\ ^{+15.6}_{-5.0}\ (\text{syst})$
- $N(\Sigma_b^{*+}) = 74^{+17.2}_{-16.3}\ (\text{stat})\ ^{+10.3}_{-5.7}\ (\text{syst})$

In total, a very significant signal

- Naïve $S/\sqrt{S+B}$ gives **~ 9σ !**
- P-value calculation > 5σ: don't have enough Toy MC to probe the 9σ-level (extrapolation too imprecise)

Strenght of Σ_b hypothesis

- Evaluated by Likelihood Ratio:

$$LR \equiv \frac{L_{\text{no peak fit}}}{L_{\text{4 peak fit}}}$$

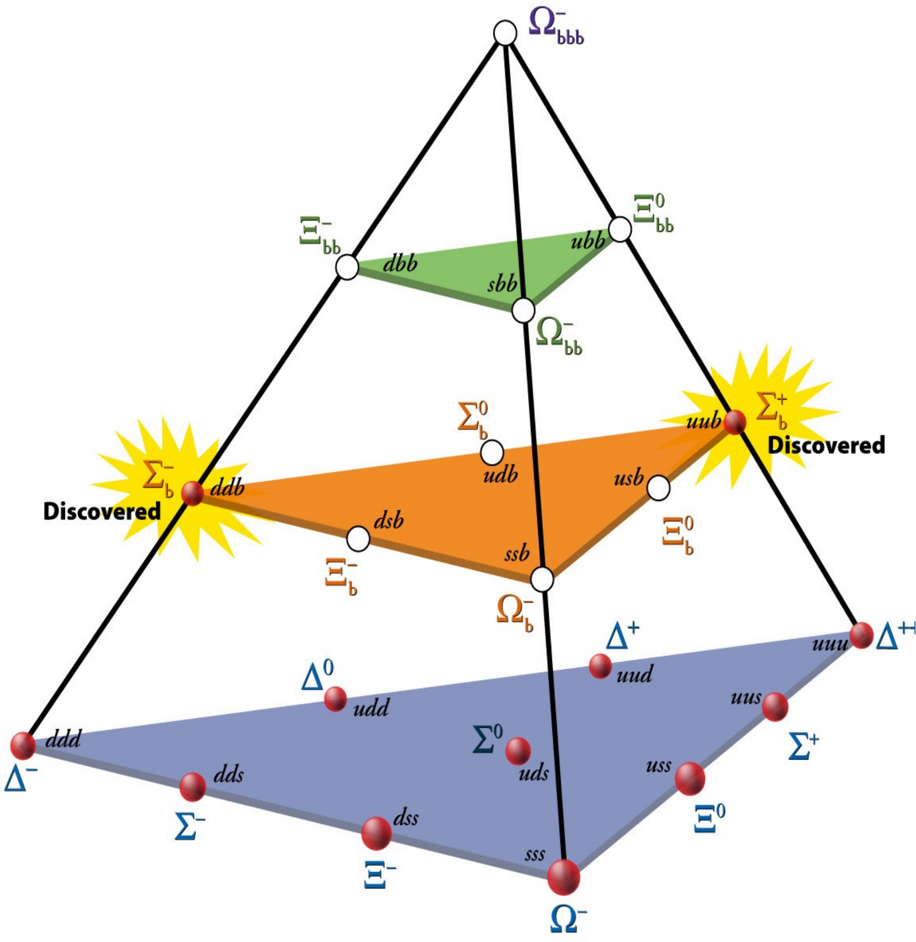
Evaluate LR for multiple fit models and pick the worst case scenario!

- Overall significance
- Four or only two peaks?
- What if one peak is fake?

Hypothesis	$\Delta(-\ln(L))$	$1/LR$
Null	44.7	2.6e19
2 peaks	14.3	1.6e6
No Σ_b^- Peak	10.4	3.3e4
No Σ_b^+ Peak	1.1	3
No Σ_b^{*-} Peak	10.1	2.4e4
No Σ_b^{*+} Peak	9.8	1.8e4

Discovered Σ_b!

- "It is ~ 2.6×10^{19} more likely that this is a 4 peak Σ_b signal than that it's a background fluctuation!"



Their masses:

- $m(\Sigma_b^-) - m(\Lambda_b^0) - m(\pi) = 55.9^{+1.0}_{-1.0}$ (stat) ± 0.1 (syst) MeV/c^2
- $m(\Sigma_b^+) - m(\Lambda_b^0) - m(\pi) = 48.4^{+2.0}_{-2.3}$ (stat) ± 0.1 (syst) MeV/c^2
- $m(\Sigma_b^{*-}) - m(\Sigma_b^-) = m(\Sigma_b^{*+}) - m(\Sigma_b^+) = 21.3^{+2.0}_{-1.9}$ (stat) $^{+0.4}_{-0.2}$ (syst) MeV/c^2

Summary

- Best measurement of B_s, Λ_b and B_c masses
- First observation of B_{s1} state!
  - Precision measurements of both B_s^{**} states
- First observation of lowest lying charged Σ_b states!
  - With m(Λ_b) = 5619.7 ± 1.2 (stat) ± 1.2 (syst) MeV/c^2,

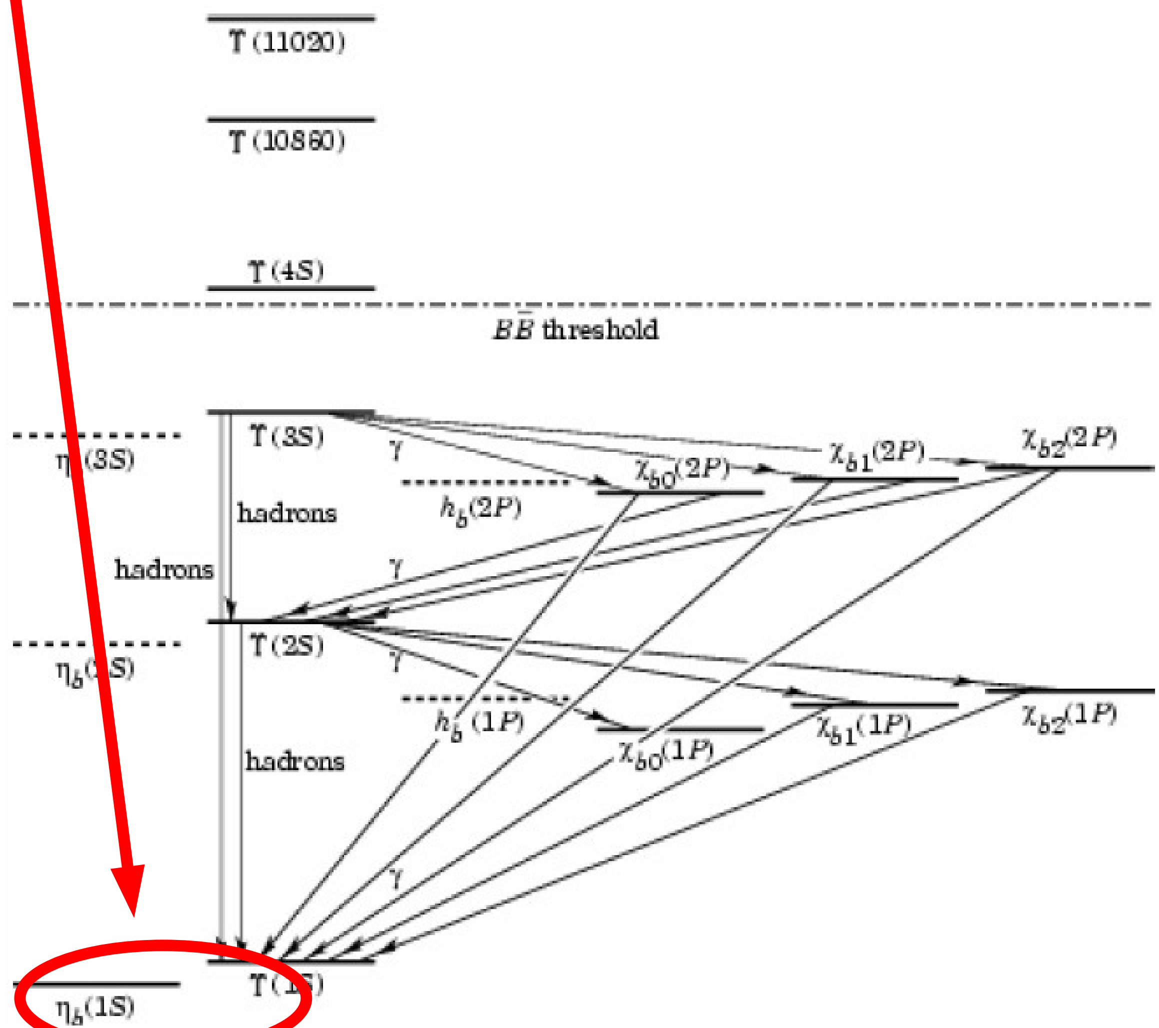
$$m(\Sigma_b^-) = 5816^{+1.0}_{-1.0}\ \text{(stat)}\ \pm 1.7\ \text{(syst)}\ \text{MeV}/c^2$$
$$m(\Sigma_b^+) = 5808^{+2.0}_{-2.3}\ \text{(stat)}\ \pm 1.7\ \text{(syst)}\ \text{MeV}/c^2$$
$$m(\Sigma_b^{*-}) = 5837^{+2.1}_{-1.9}\ \text{(stat)}\ \pm 1.7\ \text{(syst)}\ \text{MeV}/c^2$$
$$m(\Sigma_b^{*+}) = 5829^{+1.6}_{-1.8}\ \text{(stat)}\ \pm 1.7\ \text{(syst)}\ \text{MeV}/c^2$$

...and this is only from the first inverse femtobarn...

BACKUP SLIDES

Search for $\eta_b \to J/\psi\ J/\psi$

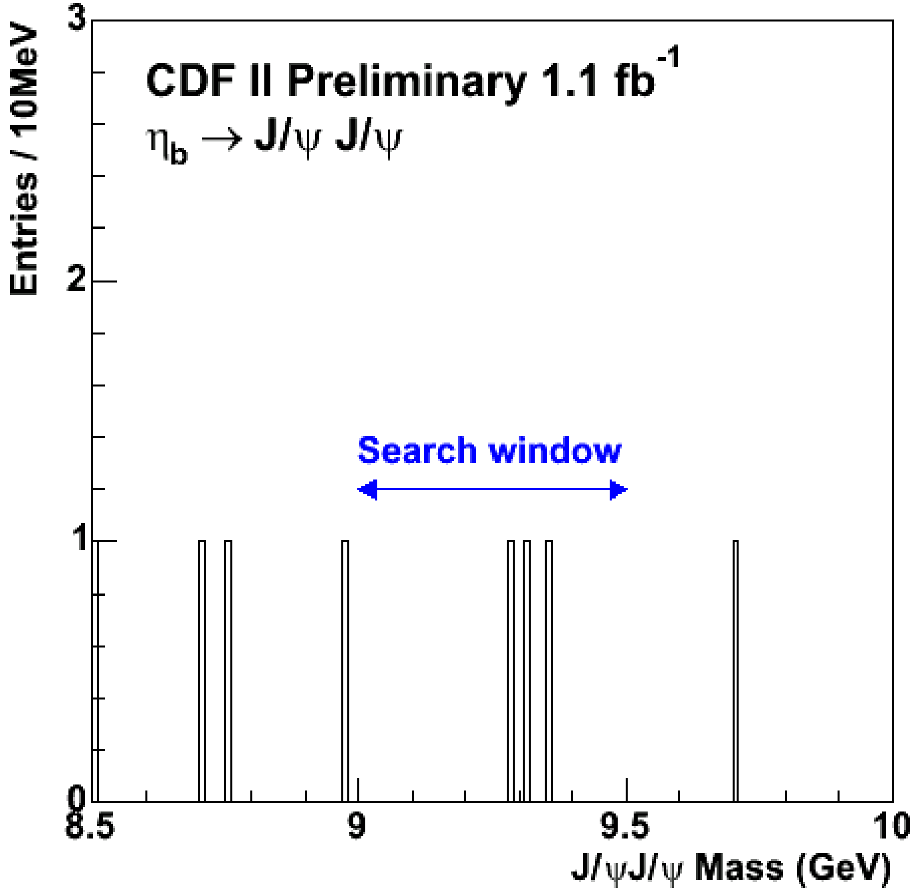
- Spin-singlet $b\bar{b}$ bound state η_b yet to be observed
- $\sigma(p\bar{p} \to \eta_b X) \sim \mu\mathrm{b}$
- Look for $\eta_b \to J/\psi\ J/\psi$ in 1.1 fb^{-1}
  - Large uncertainty in expected BR
  - *Expect between 0.2 and 20 events* with both $J/\psi \to \mu^+\mu^-$
  - ***Reconstruct as 3μ + track***

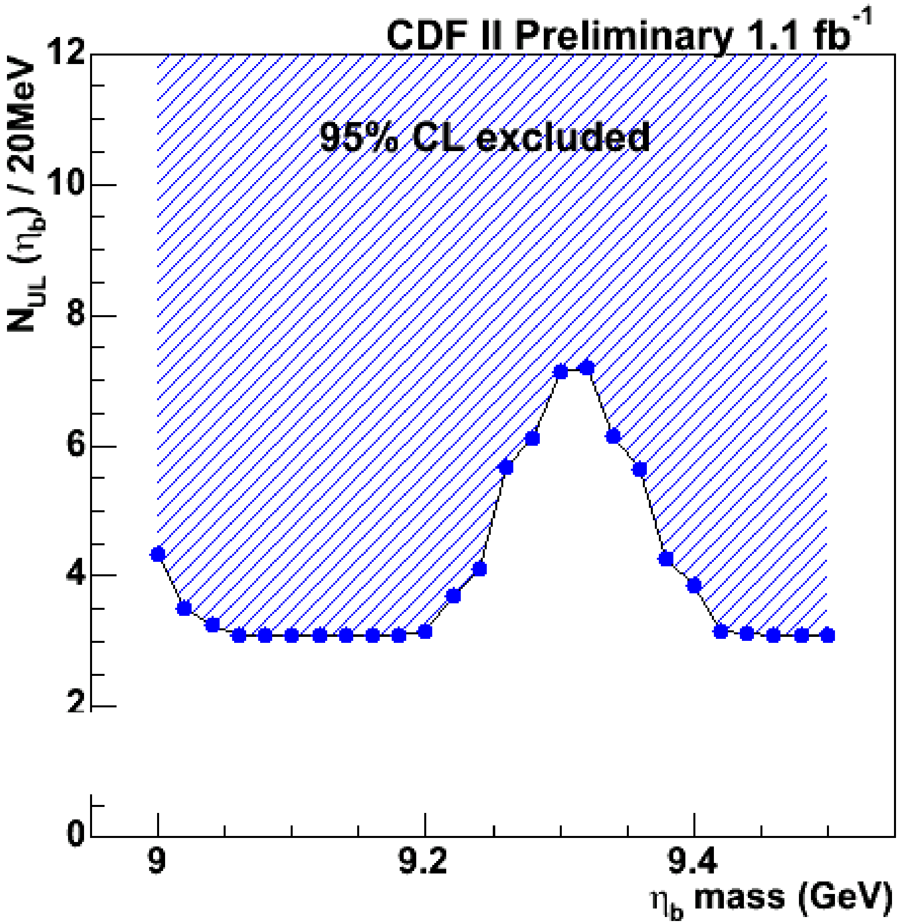


Search for $\eta_b \to J/\psi\ J/\psi$

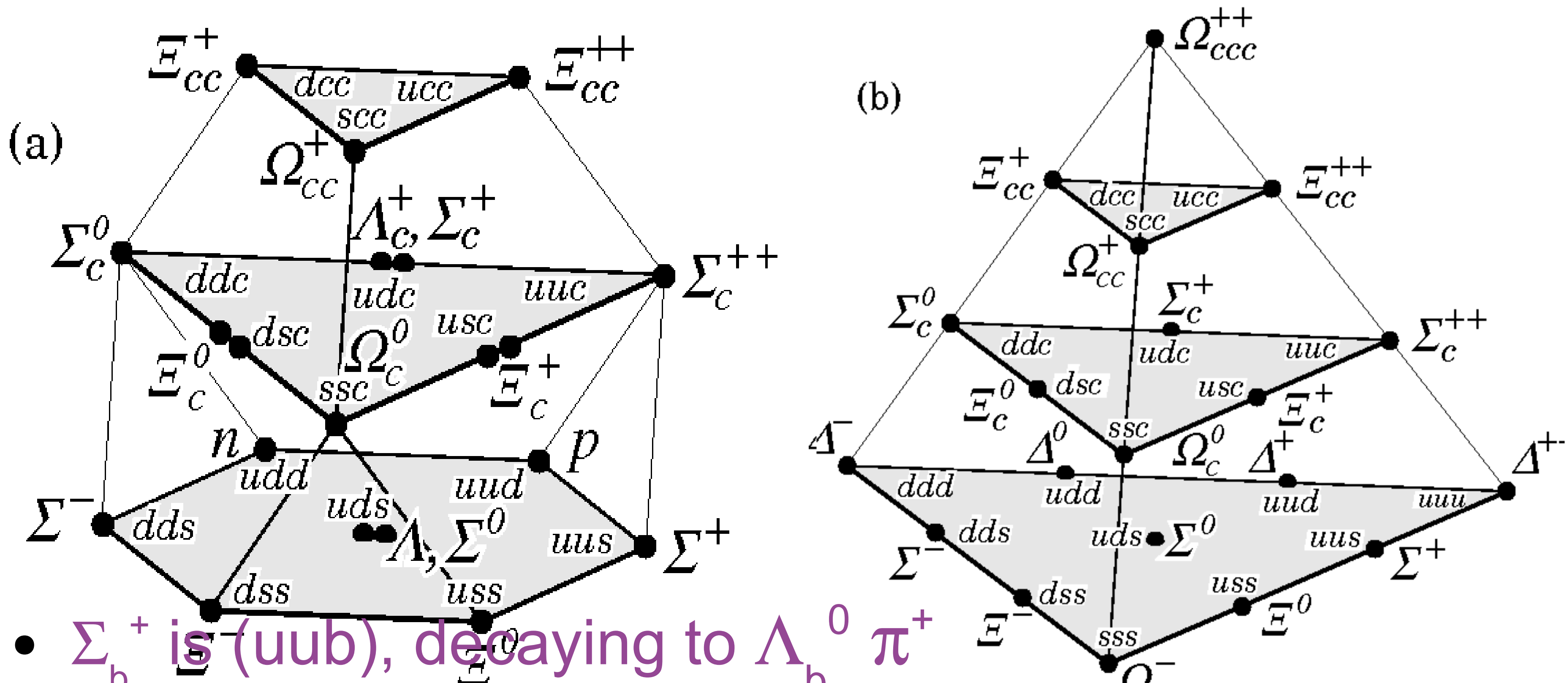
- Expected 3.6 bkg events; observe 3 events
- Upper limit for production cross section:

$$\sigma(p\bar{p} \to \eta_b X, |y(\eta_b)| < 0.6, p_T(\eta_b) > 3GeV) \cdot Br(\eta_b \to J/\psi J/\psi) \cdot [Br(J/\psi \to \mu\mu)]^2 < 2.6\ \mathrm{pb}$$





Heavy baryon classification



- Σ_b^+ is (uub), decaying to $\Lambda_b^0\ \pi^+$
- Σ_b^- is (ddb), decaying to $\Lambda_b^0\ \pi^-$

b-baryons with $B=1, C=0, J^P = 1/2^+, 3/2^+$

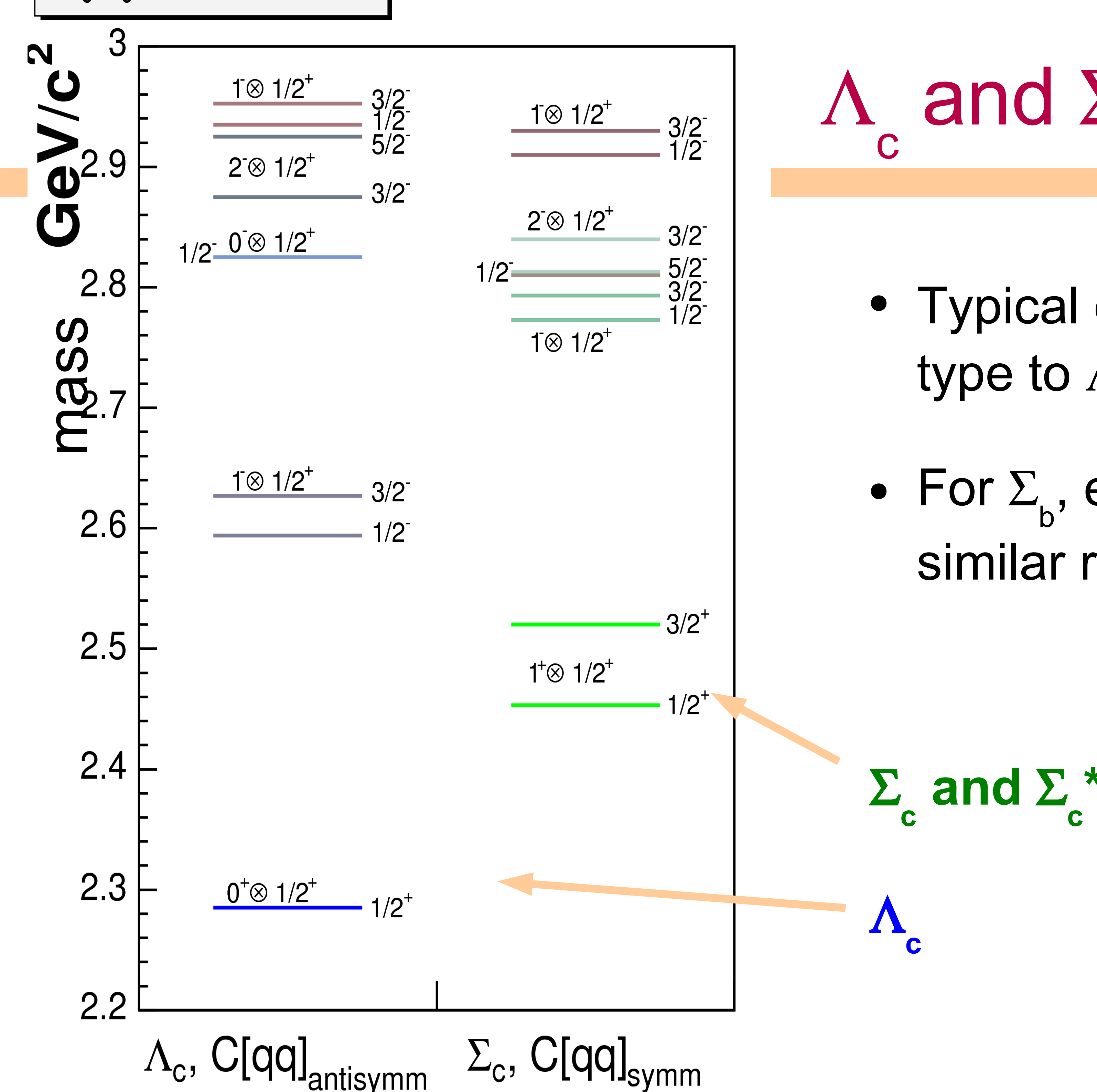
have

search for

Notation	Quark content	J^P	SU(3)	(I,I_3)	S	B	Mass
Λ_b^0	b[ud]	$1/2^+$	3*	(0,0)	0	1	5619.7±1.2±1.2 MeV
Ξ_b^0	b[su]	$1/2^+$	3*	(1/2,1/2)	-1	1	5.80 GeV
Ξ_b^-	b[sd]	$1/2^+$	3*	(1/2,-1/2)	-1	1	5.80 GeV
Σ_b^+	buu	$1/2^+$	6	(1,1)	0	1	5.82 GeV
Σ_b^0	b{ud}	$1/2^+$	6	(1,0)	0	1	5.82 GeV
Σ_b^-	bdd	$1/2^+$	6	(1,-1)	0	1	5.82 GeV
$\Xi_b^{0'}$	b{su}	$1/2^+$	6	(1/2,1/2)	-1	1	5.94 GeV
$\Xi_b^{0'}$	b{sd}	$1/2^+$	6	(1/2,-1/2)	-1	1	5.94 GeV
Ω_b^0	bss	$1/2^+$	6	(0,0)	-2	1	6.04 GeV
Σ_b^{*+}	buu	$3/2^+$	6	(1,1)	0	1	5.84 GeV
Σ_b^{*0}	bud	$3/2^+$	6	(1,0)	0	1	5.84 GeV
Σ_b^{*-}	bdd	$3/2^+$	6	(1,-1)	0	1	5.84 GeV
Ξ_b^{*0}	bus	$3/2^+$	6	(1/2,1/2)	-1	1	5.94 GeV
Ξ_b^{*-}	bds	$3/2^+$	6	(1/2,-1/2)	-1	1	5.94 GeV
Ω_b^{*-}	bss	$3/2^+$	6	(0,0)	-2	1	6.06 GeV

from hep-ph/9406359

Λ_c and Σ_c states



- Typical decay of Σ-type to Λ-type + π
- For Σ_b, expect similar relationship

Why $\Sigma_b^{(*)}$?

- Most b-mesons found and studied (Measurement of Δm_s a testament to this program)
- Comparatively little is known about heavy baryons -- and there are more of them
- Finding and studying b-baryons completes and checks the Standard Model
- Measuring masses, decay rates tests Heavy Quark Effective Theory (*description different from B mesons!*)
- Discovering new particles is cool! (And good practice for LHC too)

Theoretical expectations

- Predictions from a combinations of potential models, HQET and lattice

Σ_b property	Expected value (MeV/c^2)
m(Σ_b) - m(Λ_b^0)	180 - 210
m(Σ_b^*) - m(Σ_b)	10 - 40
m(Σ_b^-) - m(Σ_b^+)	5 - 7
$\Gamma(\Sigma_b)$, $\Gamma(\Sigma_b^*)$	$\sim$8, $\sim$15

- Enough to use as a rough guide

- Expect: $\Sigma_b^{(*)}$ is massive enough to decay strongly to $\Lambda_b \pi$, but just barely

Analysis strategy

- Reconstruct Λ_b as:

$$\Lambda_b^0 \to \Lambda_c^+ \pi^-$$

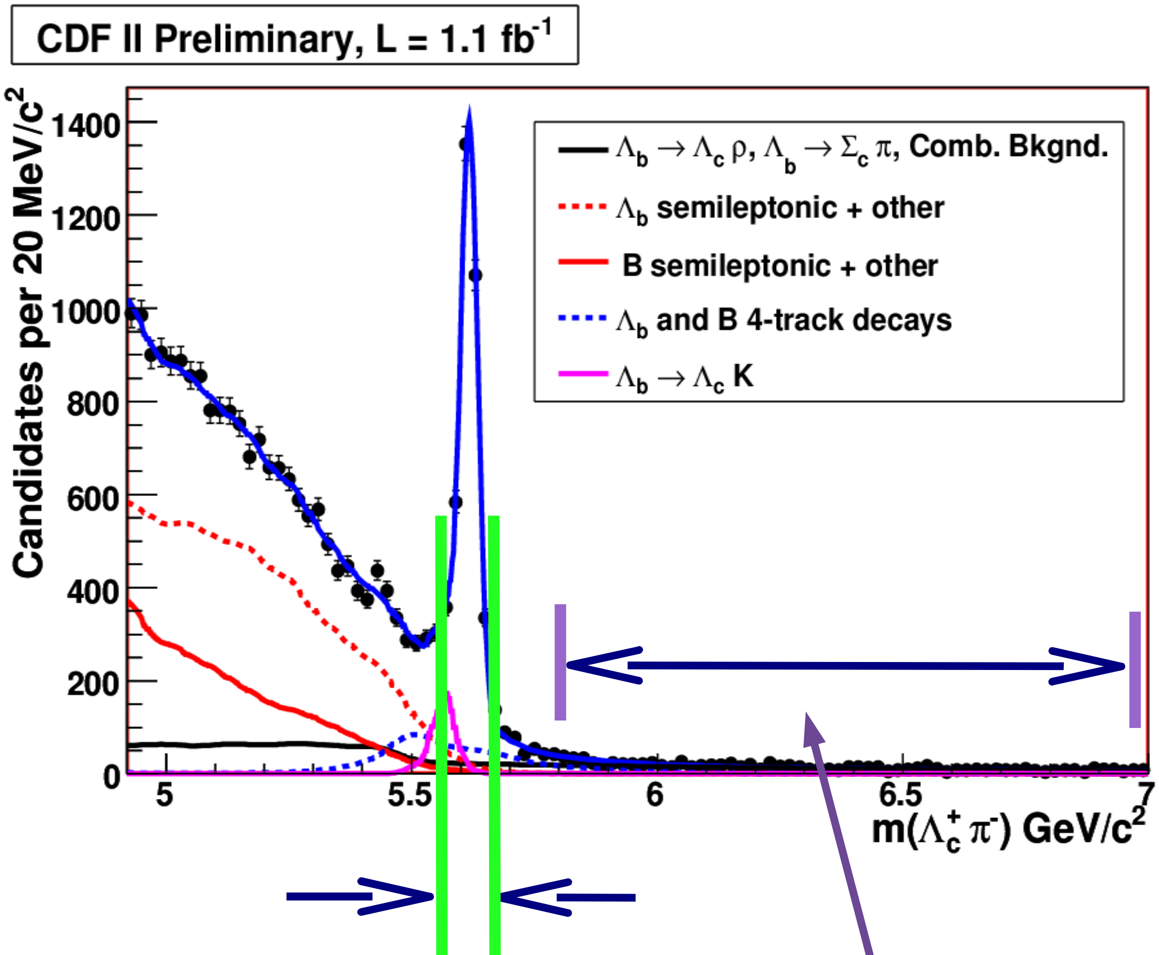
$$\Lambda_c^+ \to p K^- \pi^+$$

- Then combine Λ_b with pions around it to form Σ_b, but treat π^+ and π^- separately:

$$\Sigma_b^{(*)+} \to \Lambda_b^0 \pi^+$$

$$\Sigma_b^{(*)-} \to \Lambda_b^0 \pi^-$$

Reconstructing Σ_b



"Λ_b signal region"

"Λ_b upper sideband"

(source of fake Λ_b background)

- Use Λ_b candidates from "Λ_b signal region"
- Combine those with prompt tracks to form

$$\Sigma_b^{(*)+} \to \Lambda_b^0 \pi^+$$
$$\Sigma_b^{(*)-} \to \Lambda_b^0 \pi^-$$

Composition of Λ_b signal window

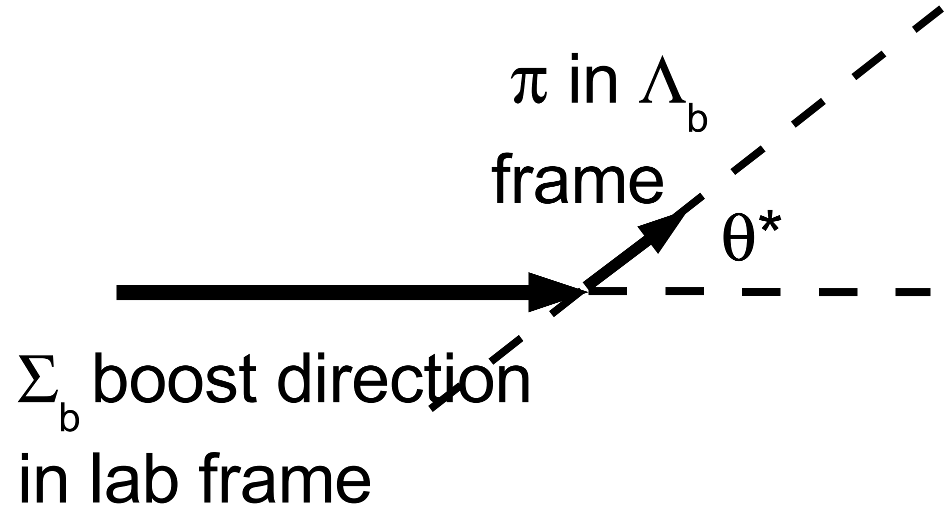
- 86.4% of Λ_b (all decays)
- 9.3% of B mesons (all decays)
- 4.2% of fake Λ_b (combinatorial)

For Σ_b search, use these numbers to normalize backgrounds on Q distribution

Systematics: shuffle up to 200 events from Λ_b component to two backgrounds

Σ_b optimization

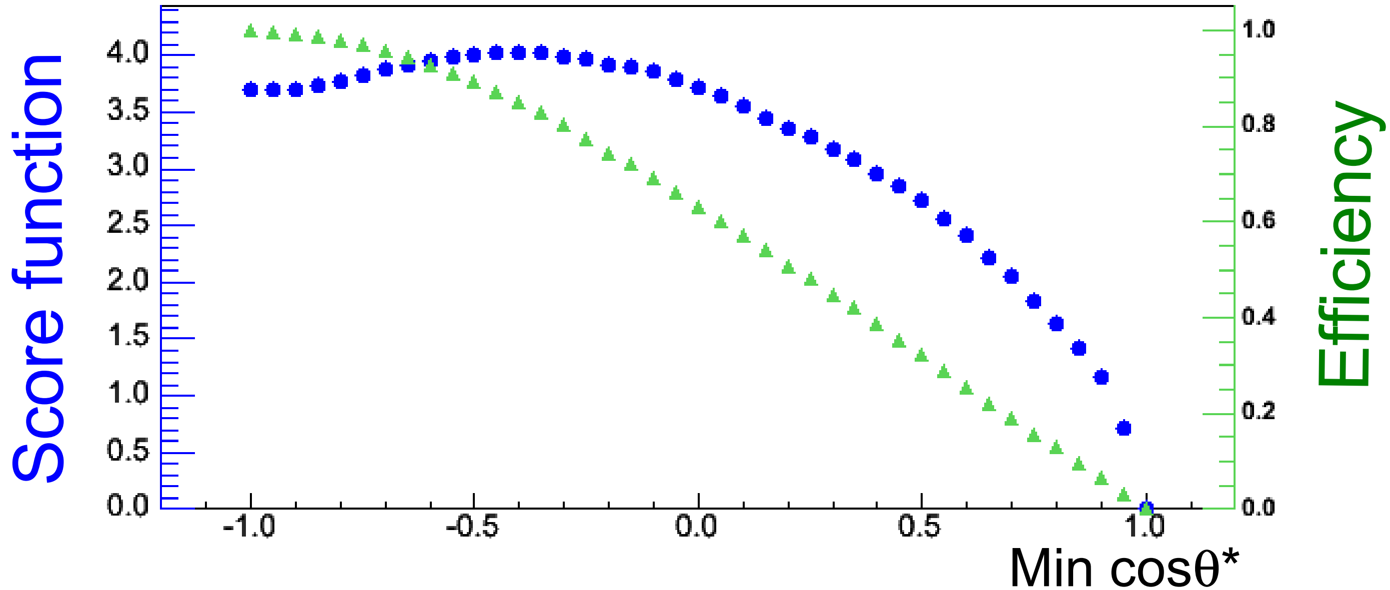
- Only Λ_b candidates from Λ_b signal region
  (3σ around Λ_b peak)
- Note: no cut on p_T(π from Σ_b) !
- Only cosθ* makes substantial difference
- Optimized cuts

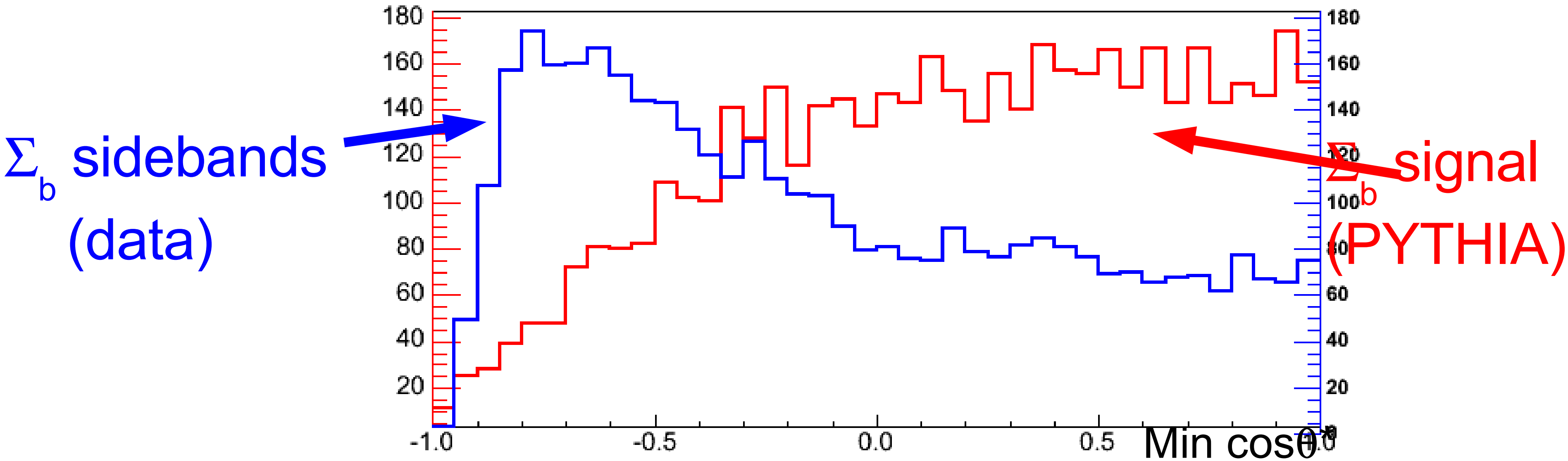


Variable	Cut value
$p_T(\Sigma_b)$	> 9.5 GeV/c
$\lvert d_0/\sigma_{d_0} \rvert$	< 3.0
$\cos\theta^*$	> -0.35

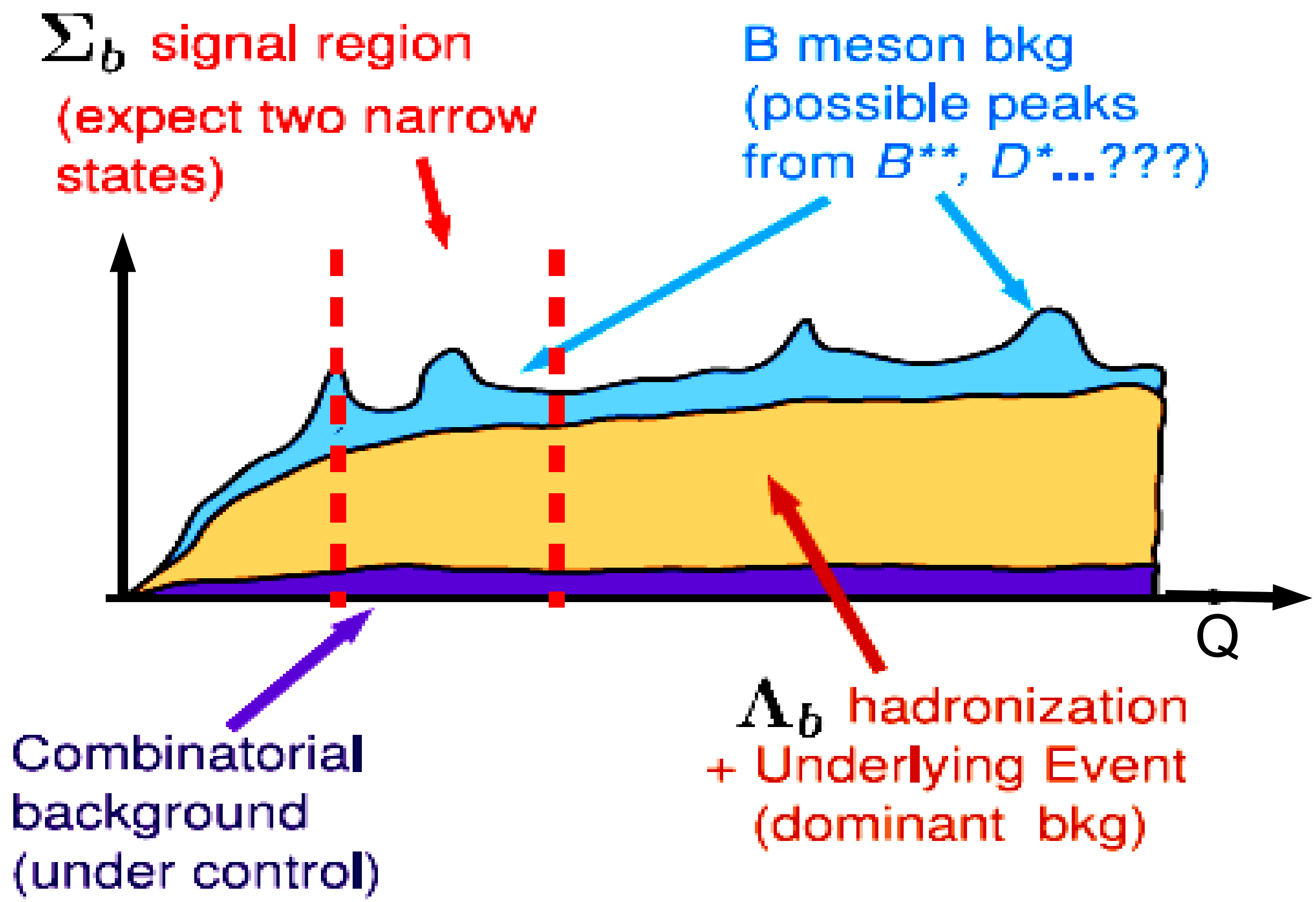
Σ_b optimization: N-1 scan for cosθ*

$$\frac{\epsilon(S)}{B} \equiv$$





Backgrounds to worry about



PDF form for background shapes

- All backgrounds modeled with a PDF of this form:

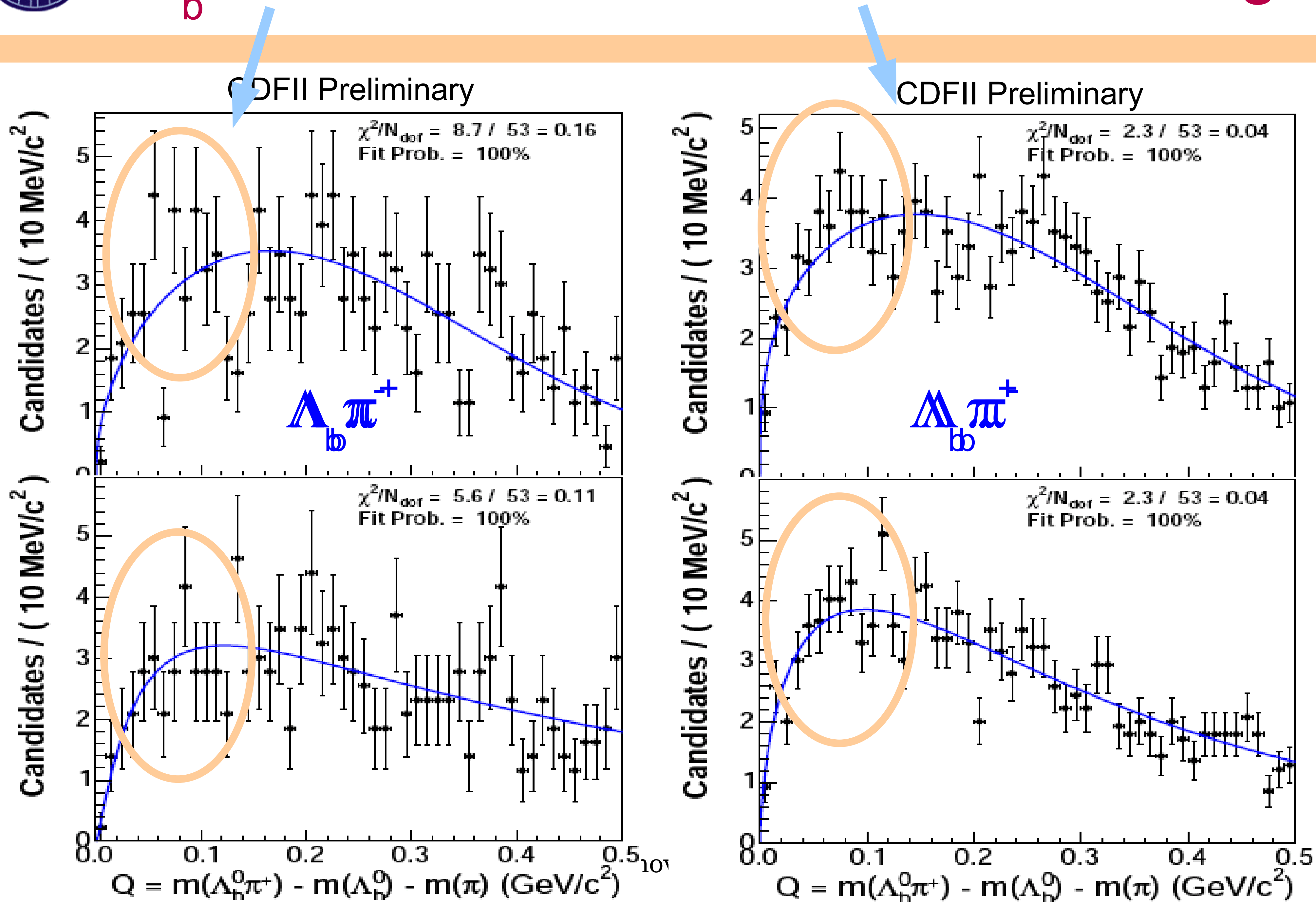
$$f(Q;\alpha,Q_{max},\gamma) = \left(\frac{Q}{Q_{max}}\right)^{\alpha} e^{-\frac{\alpha}{\gamma}\left(\left(\frac{Q}{Q_{max}}\right)^{\gamma}-1\right)}$$

(fits well a whole range of B meson fragmentation shapes)

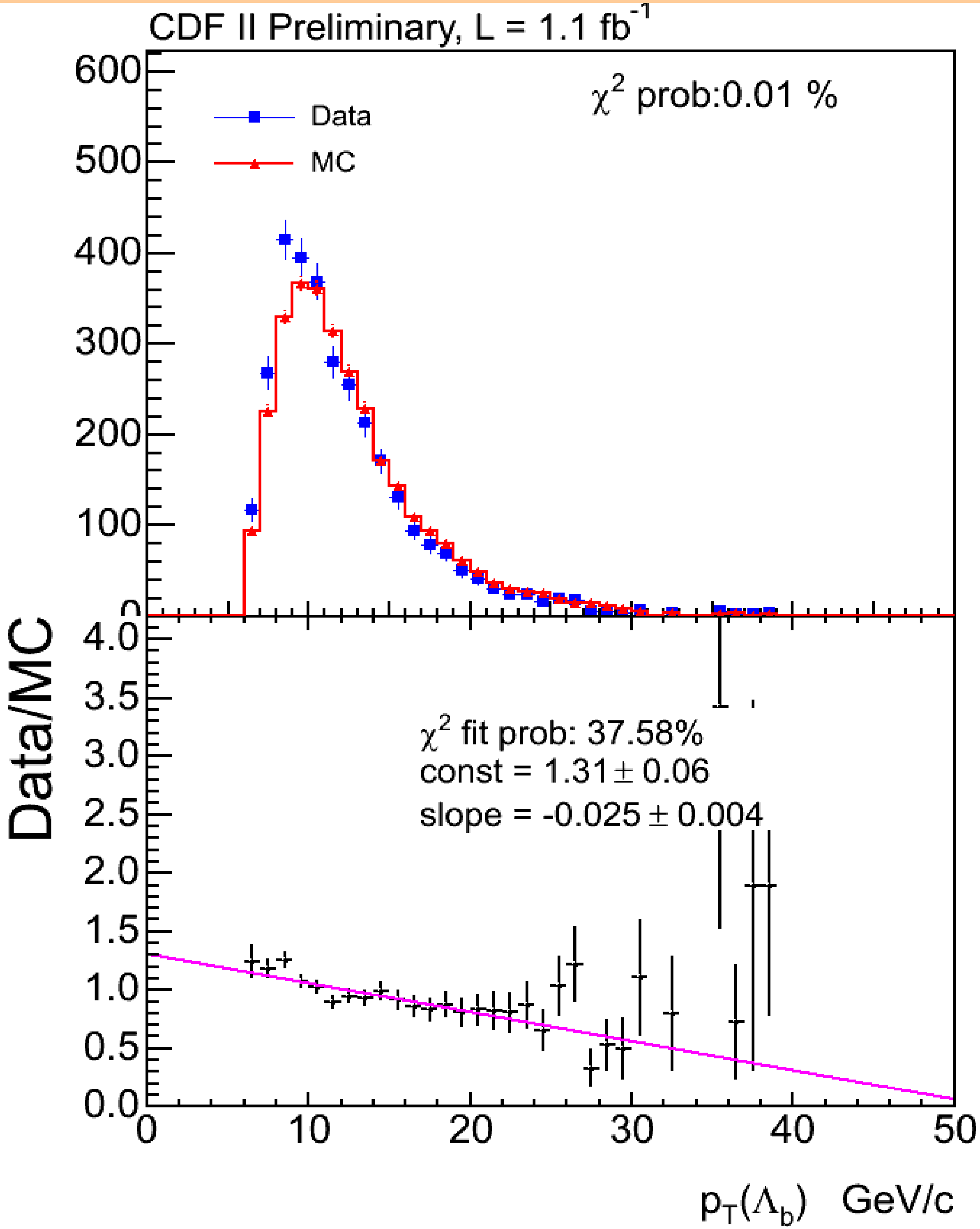
- For every component, fit separately its source

Systematics: try alternative shapes

Λ_b combinatorial and *B* hadroniz. bkgs

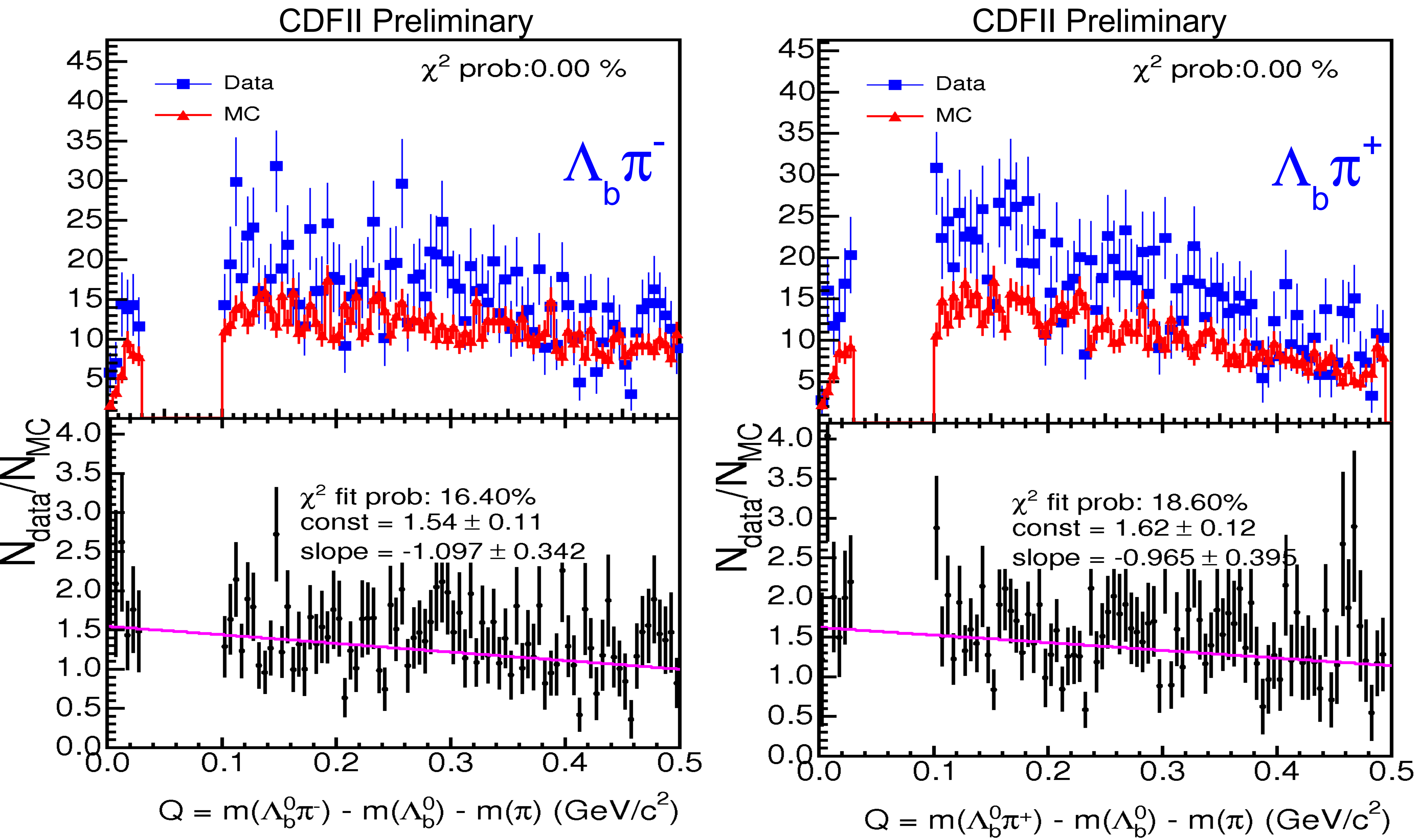


Λ_b hadronization in PYTHIA

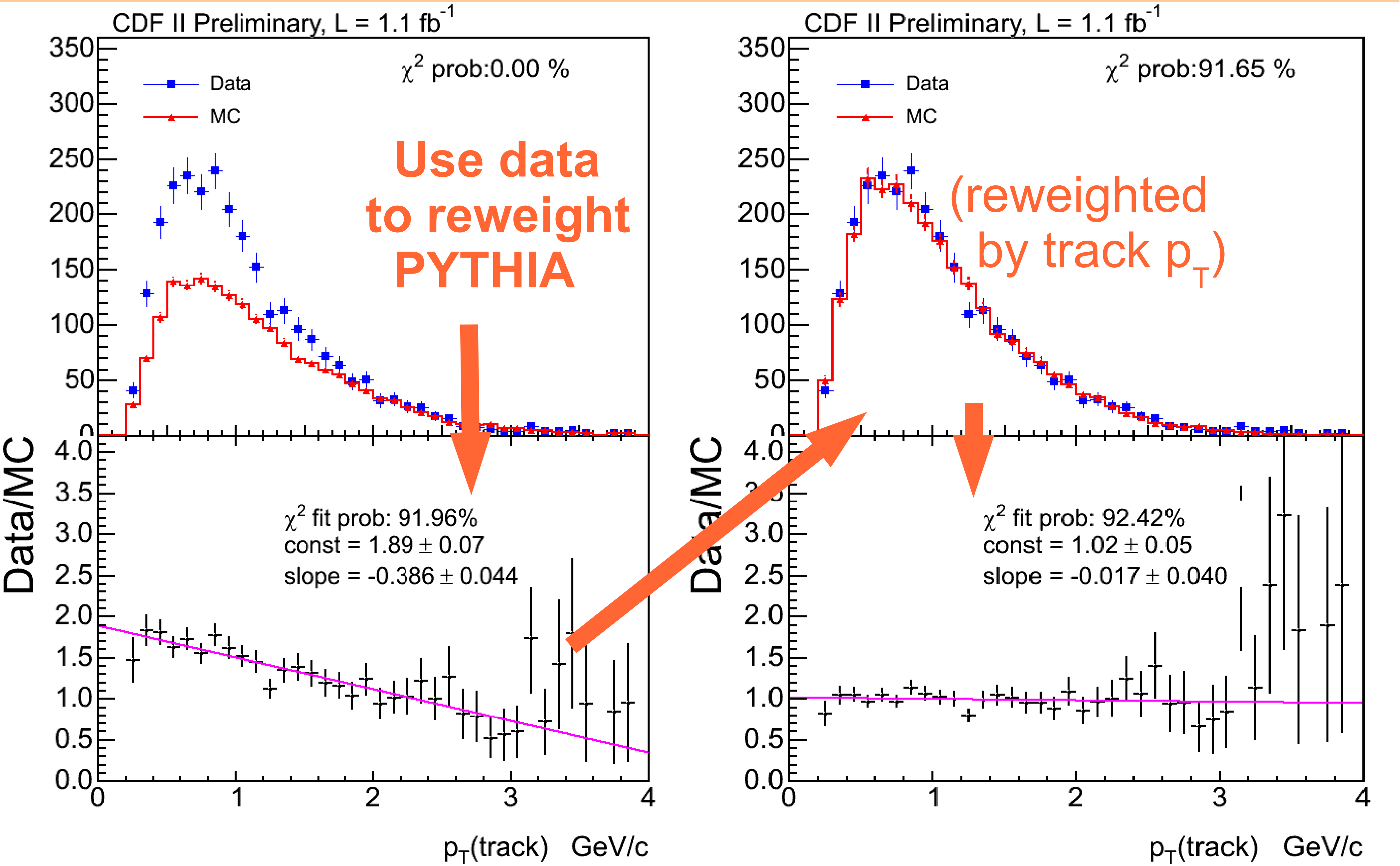


- Need hadronization and Underlying Event background (shape, norm)
- For *B* mesons, PYTHIA works like a charm
  - cf. SSKT for Bs mixing
- No guarantees for baryons!
- Same as for B mesons, $p_T(\Lambda_b)$ spectrum ***must be reweighted***

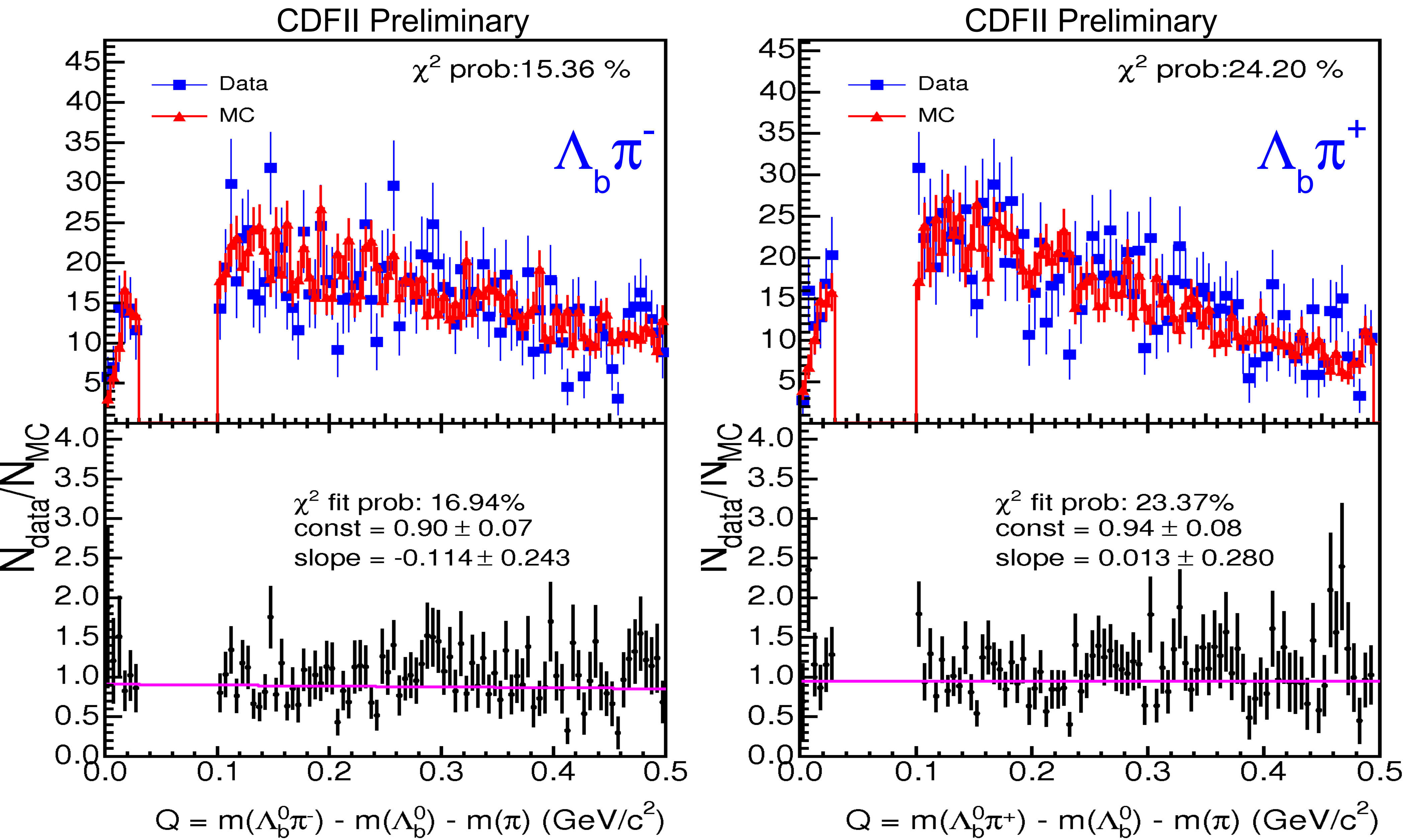
Λ_b hadronization: PYTHIA vs data



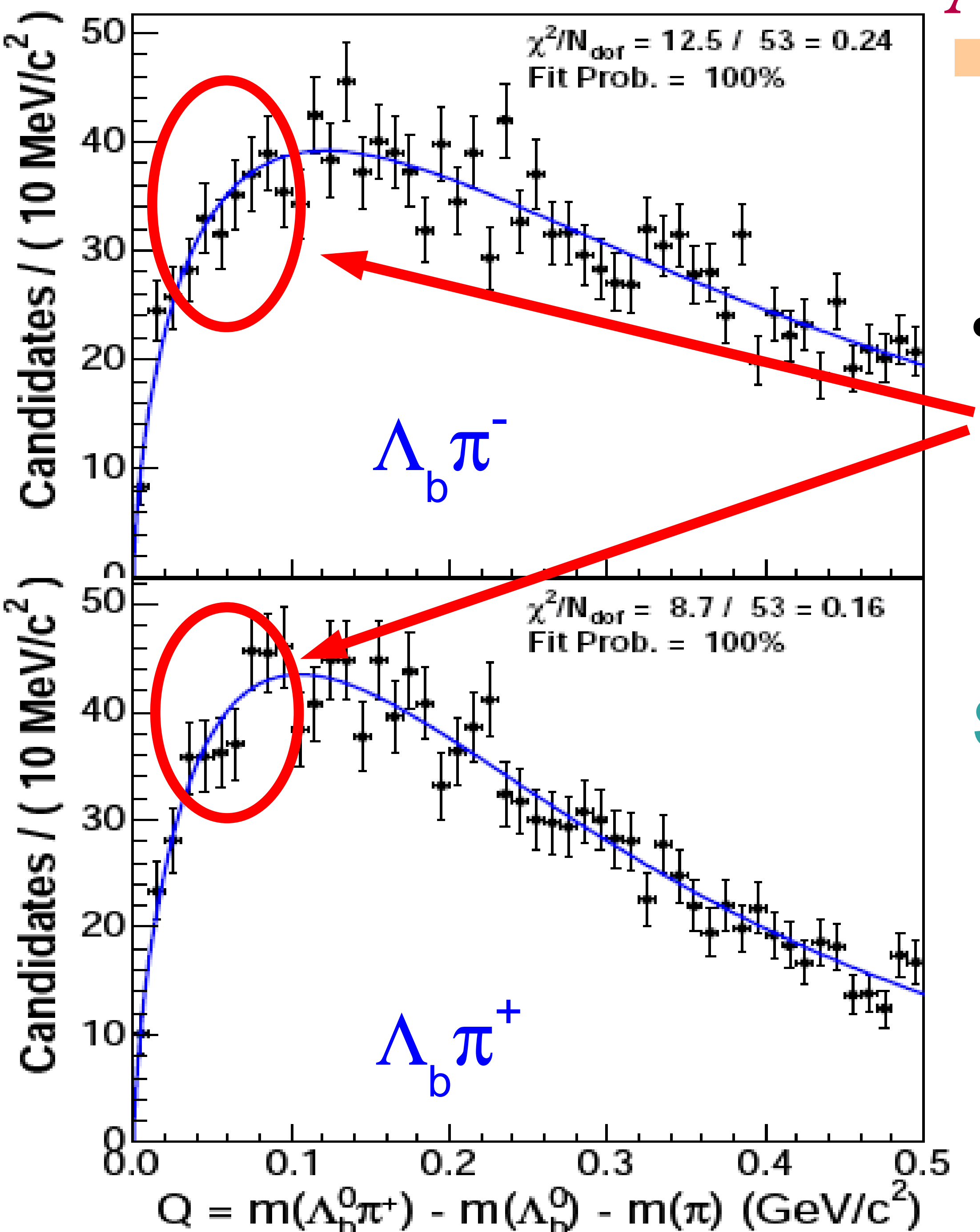
Reweighting Λ_b hadronization



Λ_b hadronization, after reweighting



Λ_b hadronization background

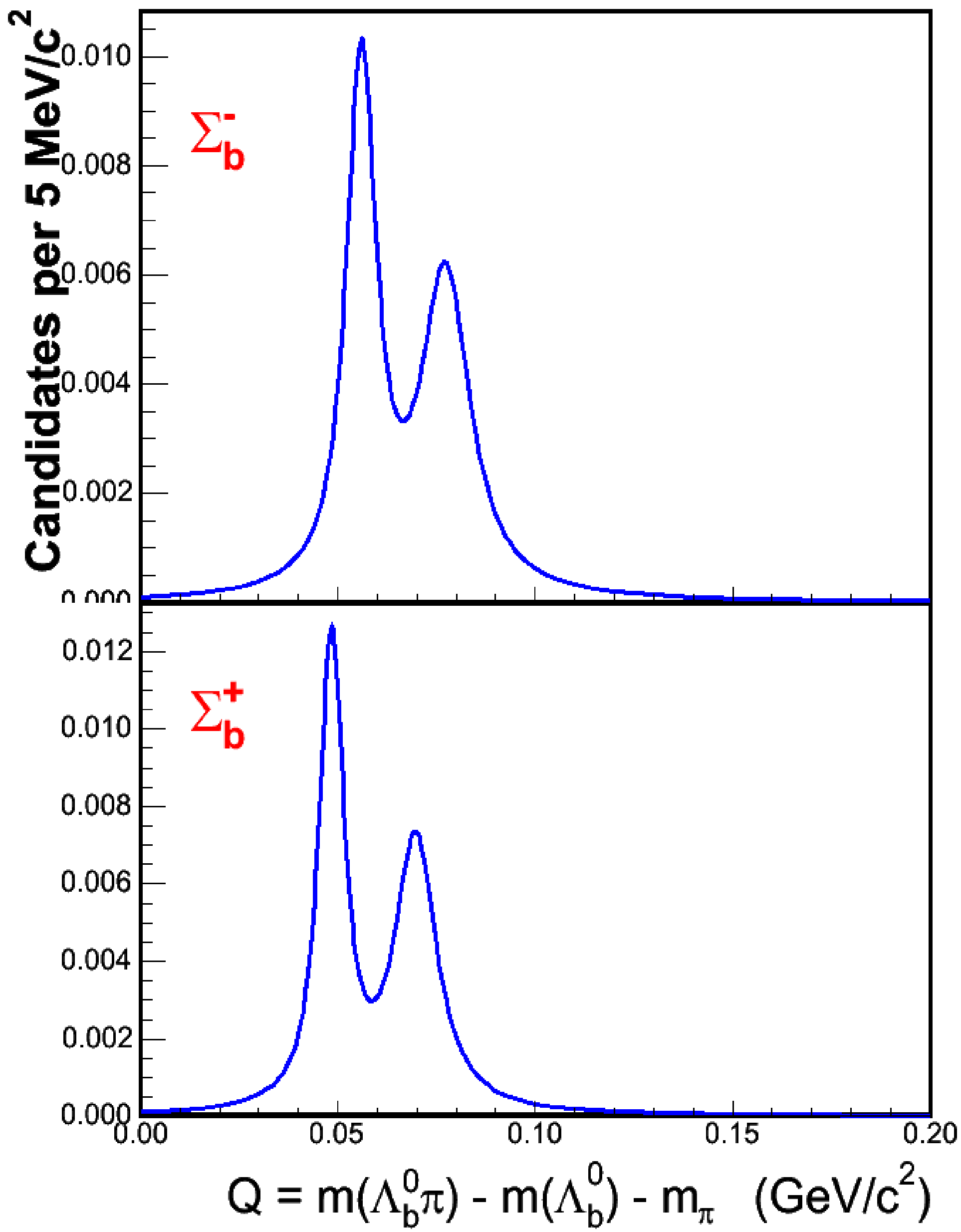


- Shape is ***smooth*** in Σ_b signal region!

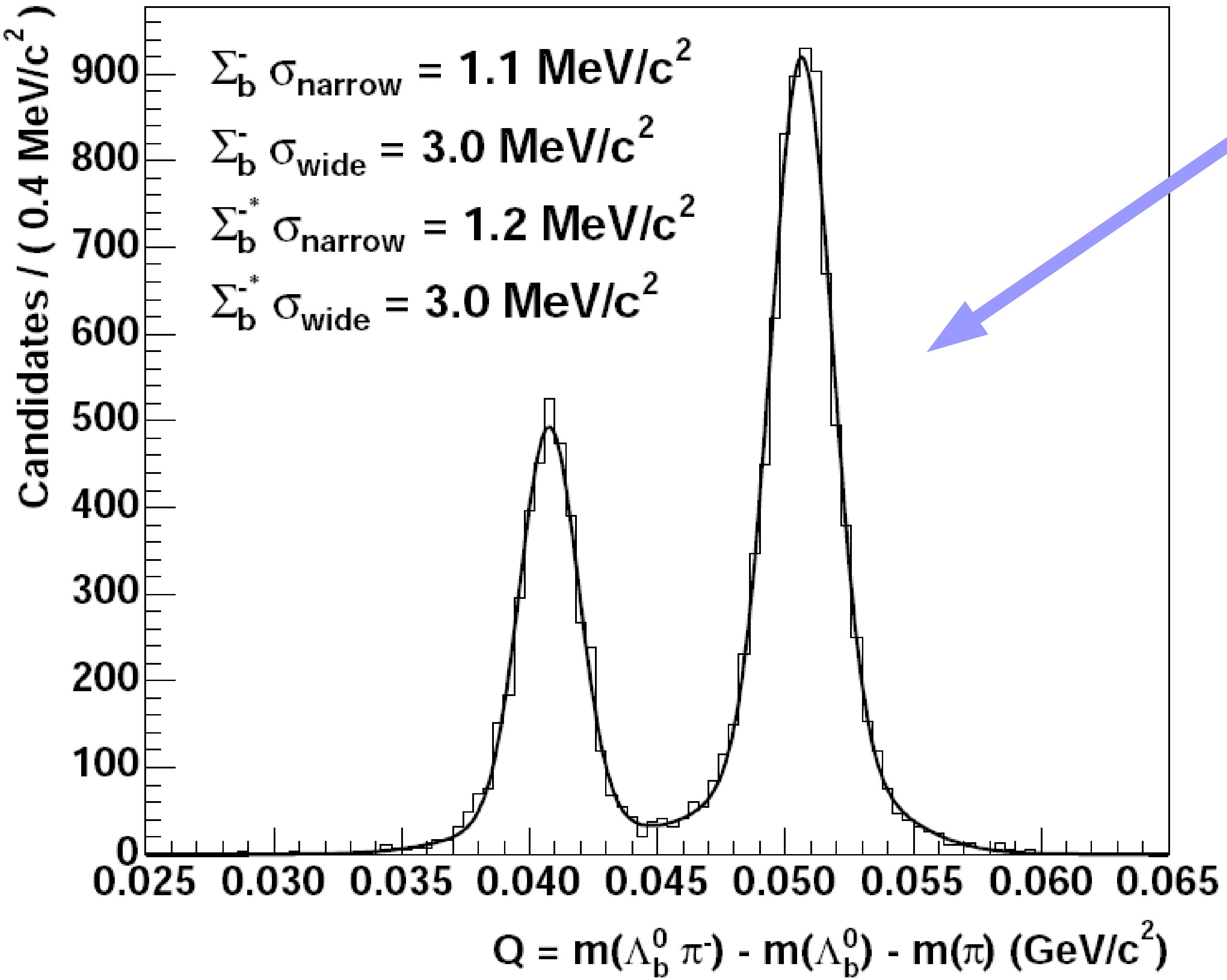
Systematics: use extremes of the track p_T spectrum to reweight

Expected signal (before unblinding)

- Expect 4 peaks:
  - Σ_b^- and Σ_b^{*-} in $\Lambda_b\pi^-$
  - Σ_b^+ and Σ_b^{*+} in $\Lambda_b\pi^+$
- Each peak:
  - Breit-Wigner (x) Resolution fun.
  - $\Gamma(\Sigma_b)$ predicted by HQET



Detector resolution of measuring Q



- Generated Σ_b PYTHIA MC
- Σ_b states with no natural width
- Resolution in MC checked on D*

Disagreement of 15-20% possible, taken as systematics!

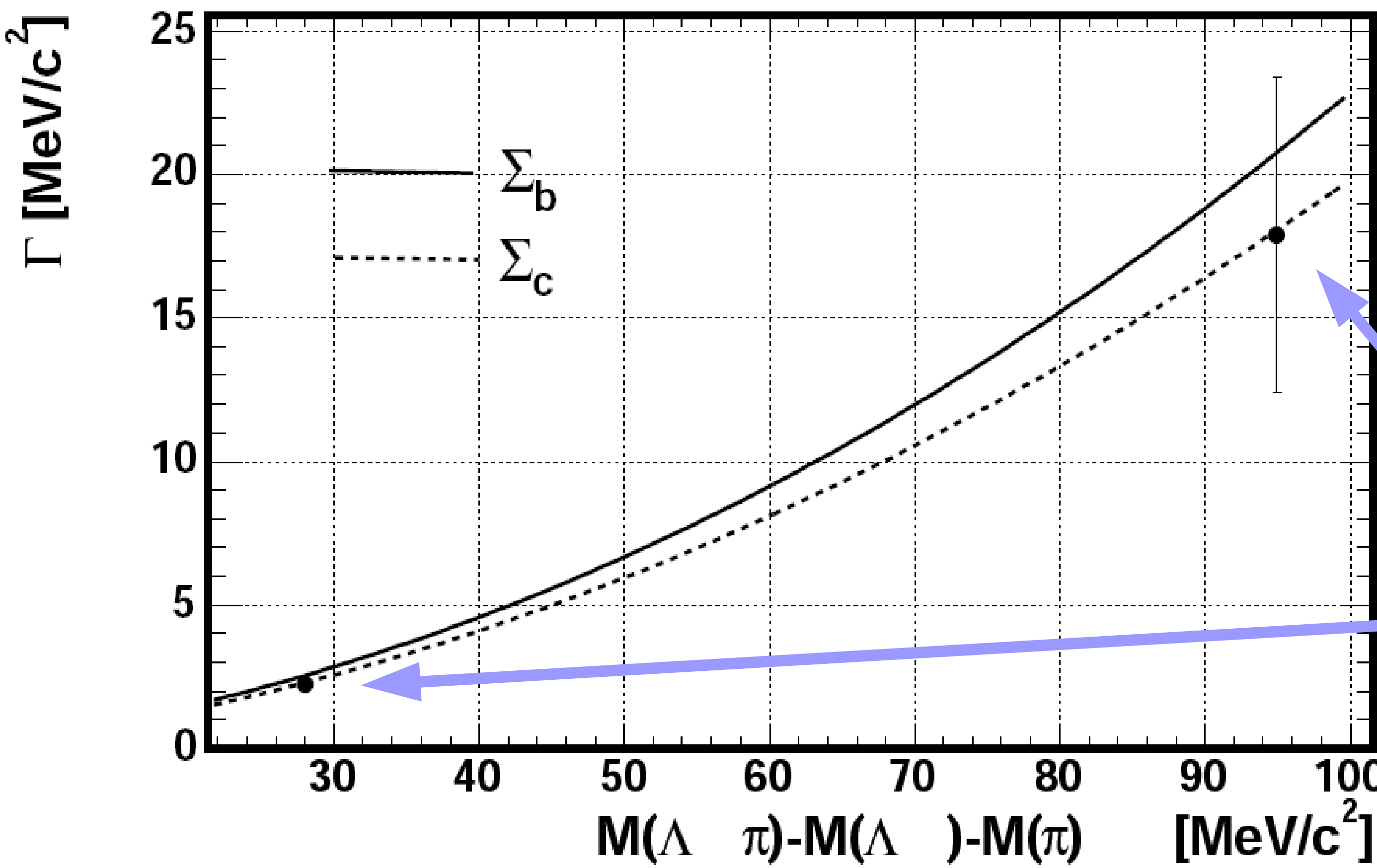
$\Gamma(\Sigma_b)$ as a function of $M_{\Sigma b}$

- $\Gamma(\Sigma_b)$ predicted by HQET:

$$\Gamma_{\Sigma_q \to \Lambda_q \pi} = \frac{1}{6\pi} \frac{M_{\Lambda_q}}{M_{\Sigma_q}} |f_p|^2 |\vec{p}_\pi|^3$$

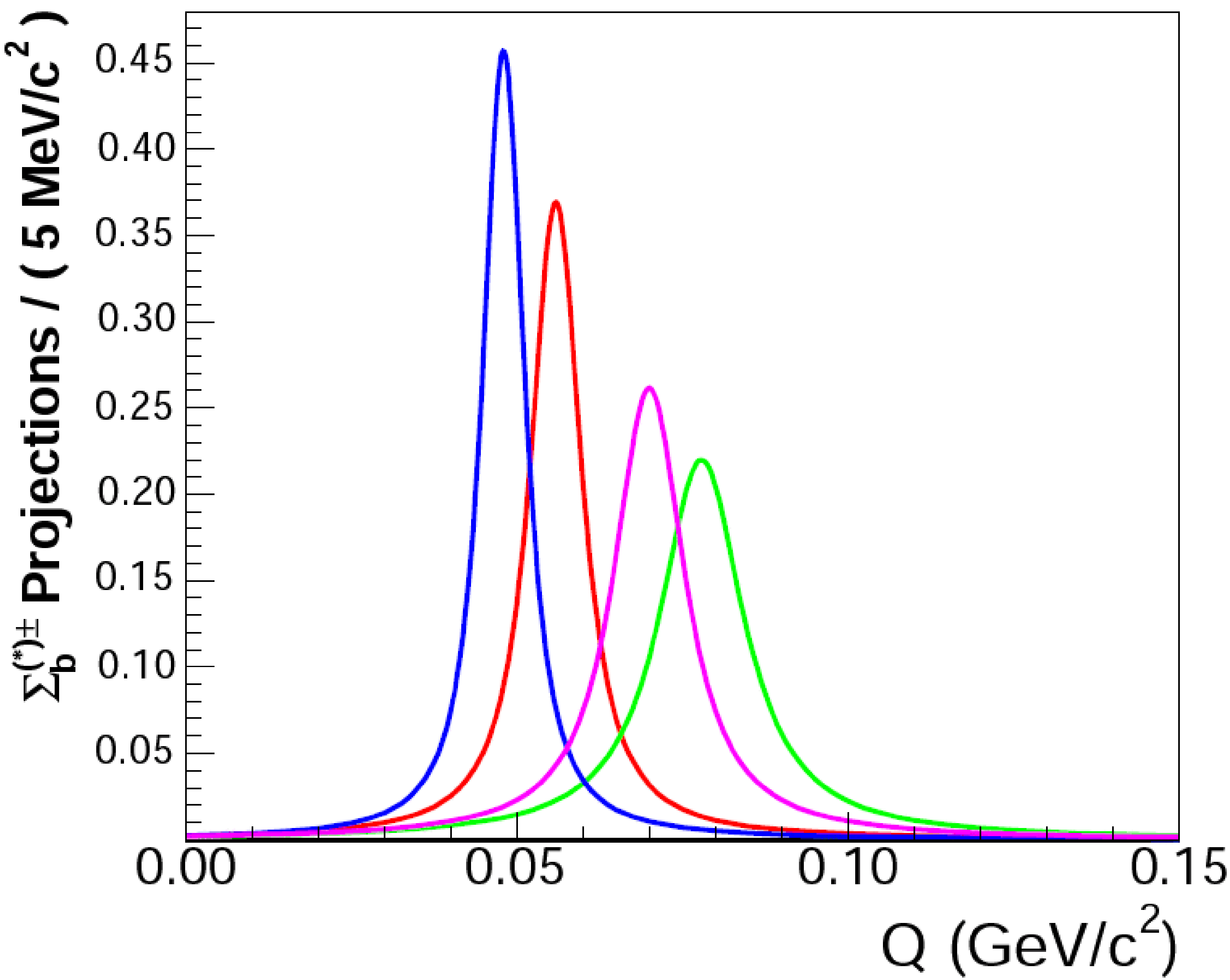
$$f_p \equiv g_A / f_\pi; \; g_A = 0.75 \pm 0.05$$

From fit to $\Sigma_c^{(*)++}$ states (use as systematics)

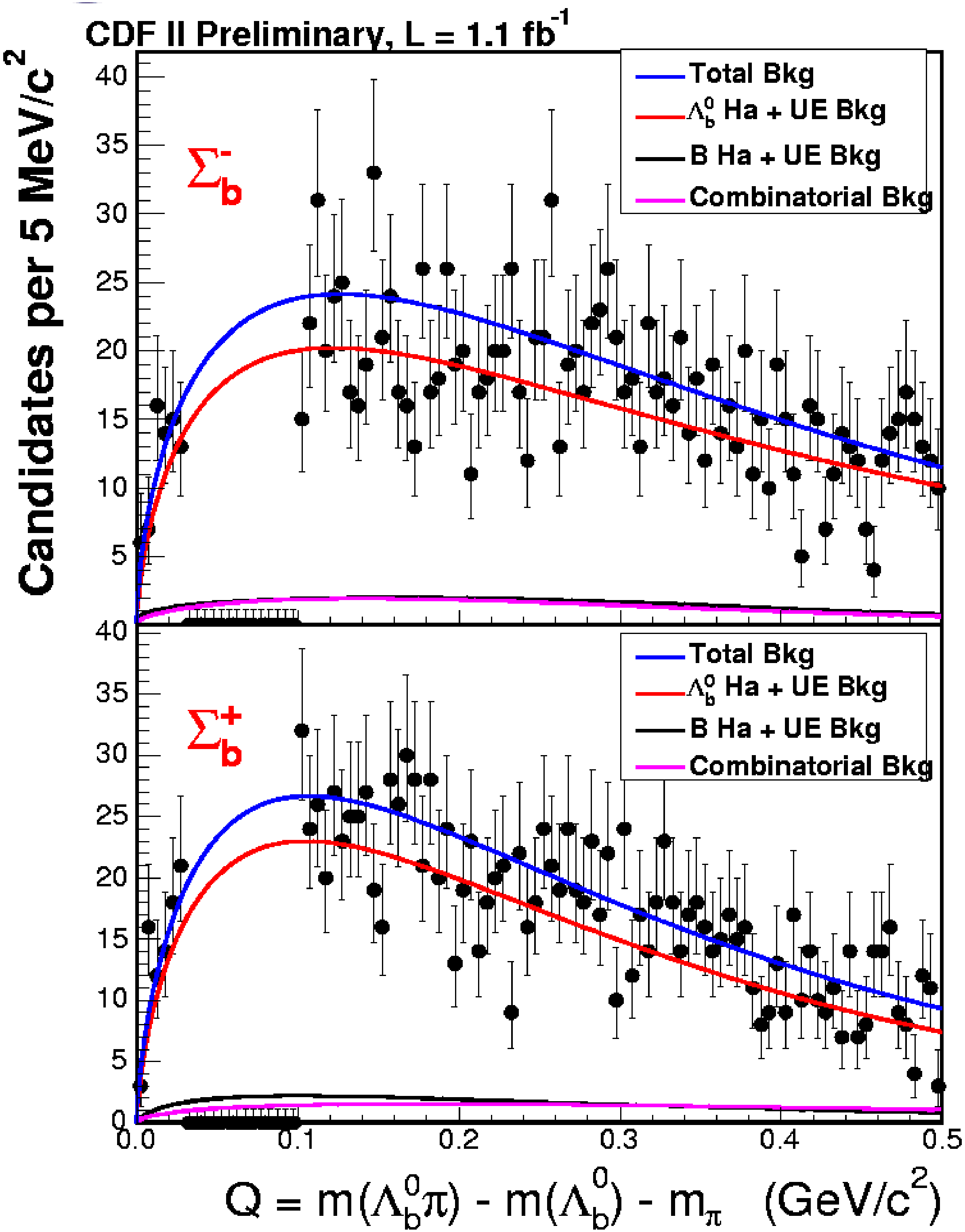


$\Gamma(\Sigma_c^{(*)++})$ in an excellent agreement with PDG

Modeling Σ_b signal peaks



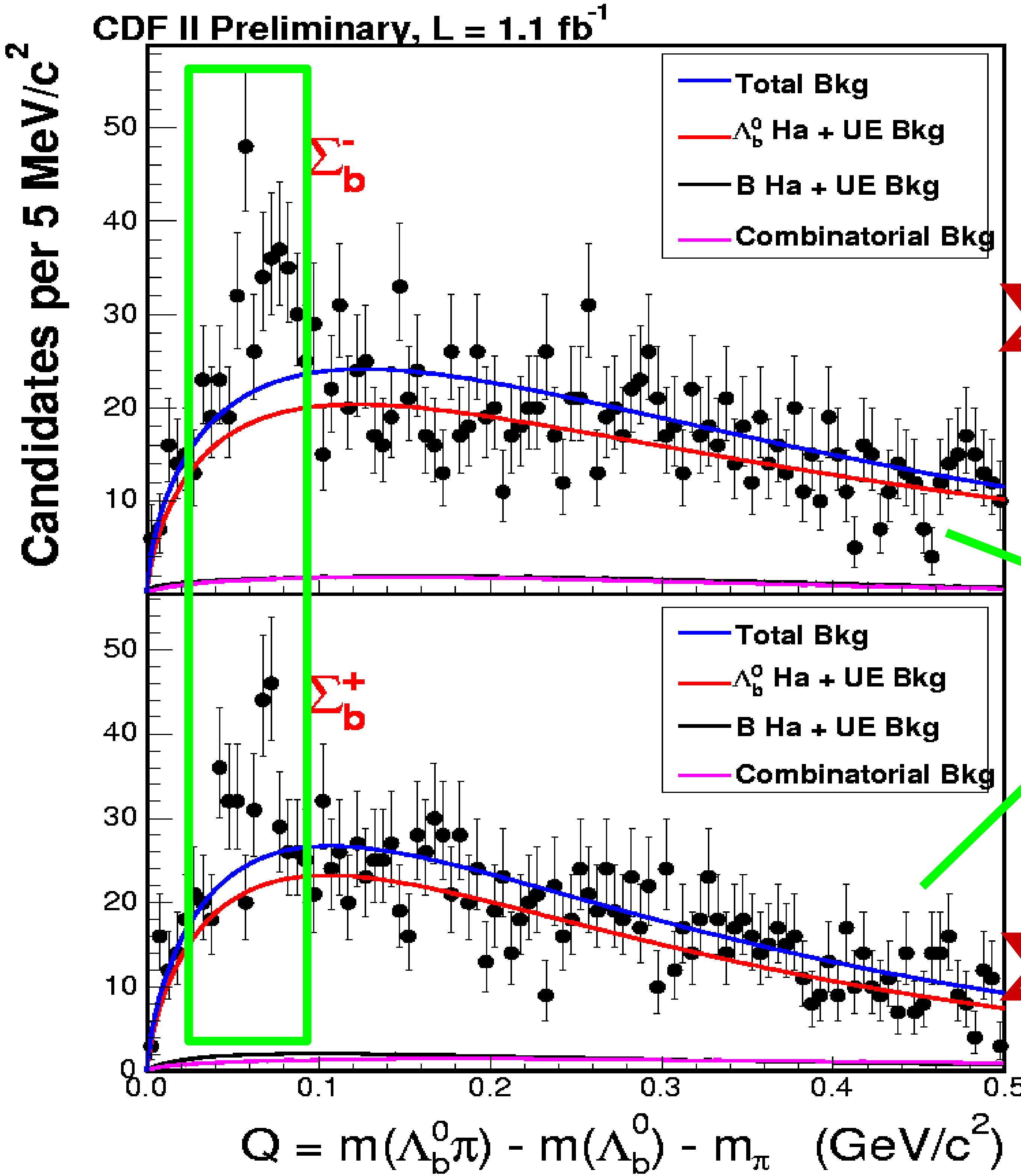
- Natural width from HQET formula
- Dominates over detector resolution!
- Breit-Wigner peaks get wider as $m(\Sigma_b)$ goes up



Bkgs before unblinding

- Λ_b HA+UE dominates
- Small contribution from
  - ***B*** **meson bkg**
  - **Combinatorial**
- These backgrounds are fixed when we fit for Σ_b signals

Box open!



$\Sigma_b^{-(*)}$

Data	Bkg	excess
416	268	148
406	298	108

$\Sigma_b^{+(*)}$

Fit results

Parameter	Value	MINOS Errors
Σ_b^- Q (MeV/c^2)	55.9	(+0.990, -0.959)
Σ_b^- events	60	(+14.8, -13.8)
Σ_b^+ Q (MeV/c^2)	48.4	(+2.02, -2.29)
Σ_b^+ events	29	(+12.4, -11.6)
Σ_b^{*-} events	74	(+18.2, -17.4)
Σ_b^{*+} events	74	(+17.2, -16.3)
Σ_b^* - Σ_b Q (MeV/c^2)	21.3	(+2.03, -1.94)

- Only significant correlation between Q(Σ_b^+) and Q(Σ_b^*) - Q(Σ_b) (because Σ_b^+ peak is weak...)

Systematics: procedure

- Already listed an array of "variations":
  - <u>change:</u> Λ_b signal region sample composition, det. resolution, natural width, functional form of background PDFs, extreme reweighting track p_T distribution, etc.
- For each variation:
  - generate 1000 Toy MC experiments with "changed" PDF
  - fit with "baseline" PDF
  - average differences between fit results is the systematic error

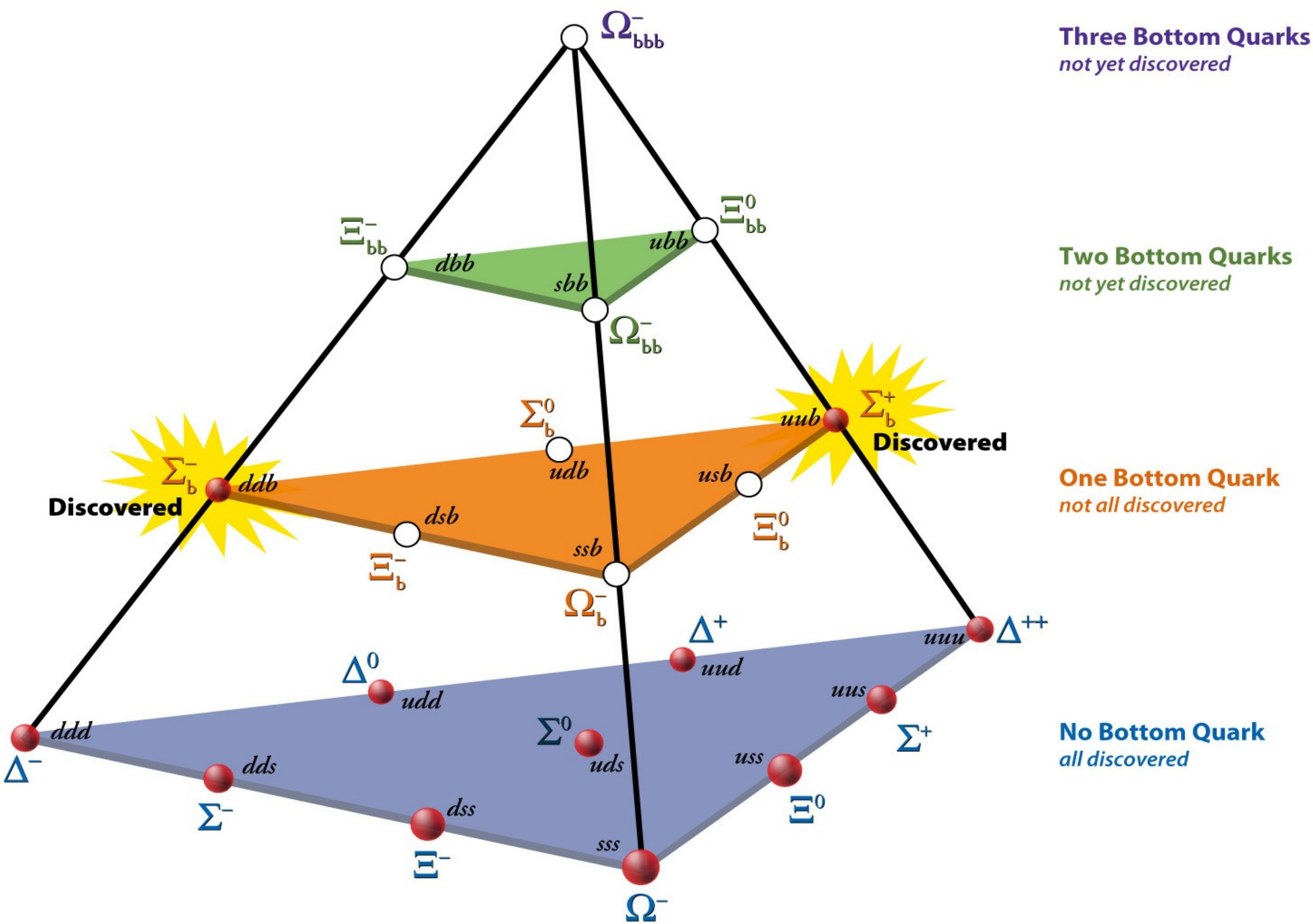
Systematics: results

- All small for mass measurements

Parameter	Tracking	Λ_b^0 Comp.	Λ_b^0 Norm.	Λ_b^0 Shape	Reweight	Reso.	Σ_b Width	Total
$Q(\Sigma_b^+)$ (MeV/c^2)	0.06 -0.06	0.03 0.0	0.013 -0.013	0.013 0.0	0.0 -0.11	0.0 -0.014	0.01 -0.02	0.07 -0.13
$Q(\Sigma_b^-)$ (MeV/c^2)	0.06 -0.06	0.0 -0.03	0.009 -0.002	0.0 -0.011	0.04 -0.0004	0.0 -0.011	0.009 -0.005	0.07 -0.07
$Q(\Sigma_b^*)$ - $Q(\Sigma_b)$ (MeV/c^2)	0.06 -0.06	0.05 0.0	0.14 -0.13	0.04 0.0	0.32 0.0	0.02 0.0	0.07 -0.07	0.37 -0.16
Σ_b^+ events	0.0 0.0	3.3 0.0	2.1 -2.1	1.2 0.0	2.3 -1.8	0.3 0.0	1.8 -2.0	5.0 -3.4
Σ_b^- events	0.0 0.0	0.7 0.0	2.2 -2.2	0.3 0.0	7.4 0.0	0.3 0.0	3.4 -3.4	8.5 -4.0
Σ_b^{*+} events	0.0 0.0	7.3 0.0	4.8 -4.8	2.8 0.0	4.6 -2.9	0.2 0.0	0.8 -0.8	10.3 -5.7
Σ_b^{*-} events	0.0 0.0	0.4 0.0	4.8 -4.7	0.3 0.0	14.7 0.0	0.1 0.0	1.7 -1.7	15.6 -5.0

- Track p_T reweighting largest for yields

Baryons with Up, Down, Strange and Bottom Quarks and Highest Spin ($J = 3/2$)



Hopes for the future

On the shopping list:

- Measure $\Delta m(\Sigma_b)$ in + and – data separately
- Measure production rate relative to Λ_b

$$\Lambda_b \longrightarrow J/\psi \Lambda$$

$$\Lambda_b \longrightarrow \Lambda_c^+ \pi^-$$

$$\Lambda_b \longrightarrow \Lambda_c 3\pi$$