The Discovery of $\Sigma_b^{(*)}$

Petar Maksimovic, for the CDF collaboration

- Introduction: what is Σ_b ?
- CDF detector, trigger, Λ_b sample
- Blind optimization, background estimates
- Fitting for the $\Sigma_b^{(*)}$ signals
- Systematics, significance

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

- Most b-mesons found and their decays studied *extensively*
- Comparatively little is known about heavy baryons (but several c-baryons recently observed by B factories)
- Finding and studying b-baryons completes and checks the Standard Model
- Measuring masses, decay rates tests theoretical approaches (*description different from B mesons!*)
- Discovering new particles is cool! (And good practice for LHC too)

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

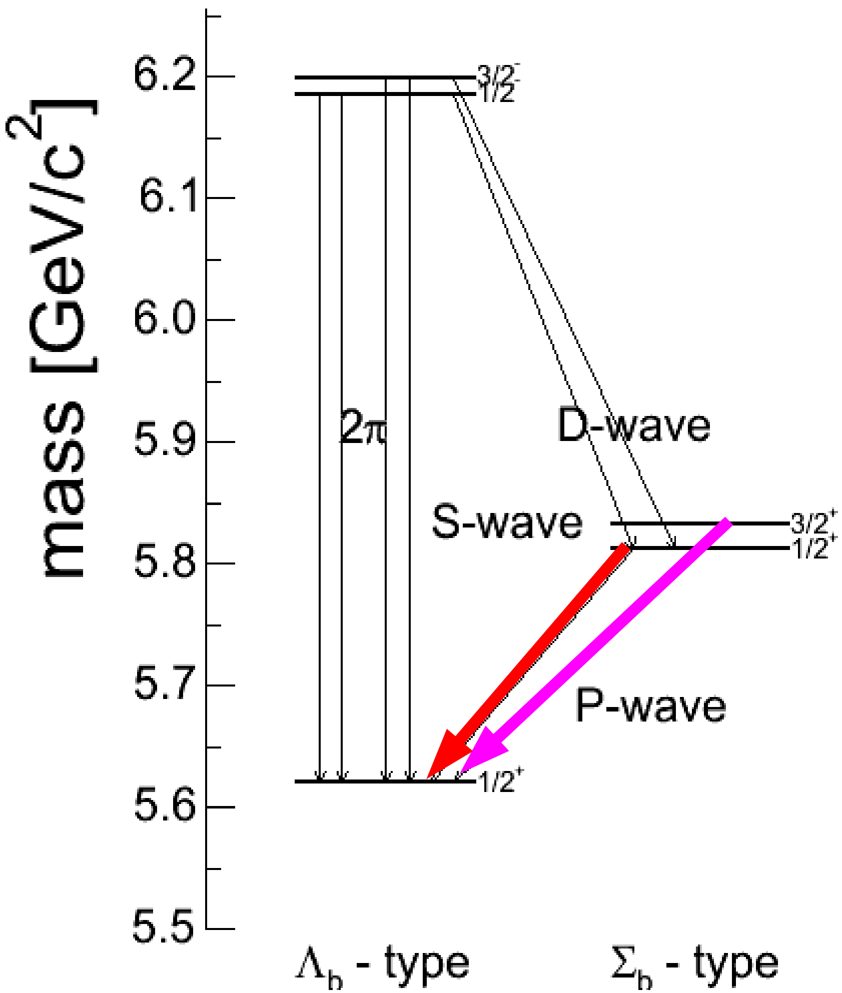
have

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

The four states of Σ_b



- In HQET picture: b-quark is a static source of color field
- Light diquark pair decoupled if $m_b \to \infty$

Σ_b $\quad b\{qq\}, q = u,d; \quad J^P = S_Q + s_{qq}$ = $3/2^+ (\Sigma_b^*)$ / = $1/2^+ (\Sigma_b)$

- For finite m_b, the $3/2^+(\Sigma_b^*)$ and $1/2^+$ (Σ_b) levels split due to spin-spin interaction with the b-quark

⟹ **Two states very close together**

Theoretical expectations

- Predictions from a combinations of potential models, HQET, $1/N_c$ expansion, and lattice

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

- Enough as a rough guide for a blind search
- Expect: $\Sigma_b^{(*)}$ is massive enough to decay strongly to $\Lambda_b \pi$, but just barely

Analysis strategy

- Reconstruct Λ_b as:

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

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

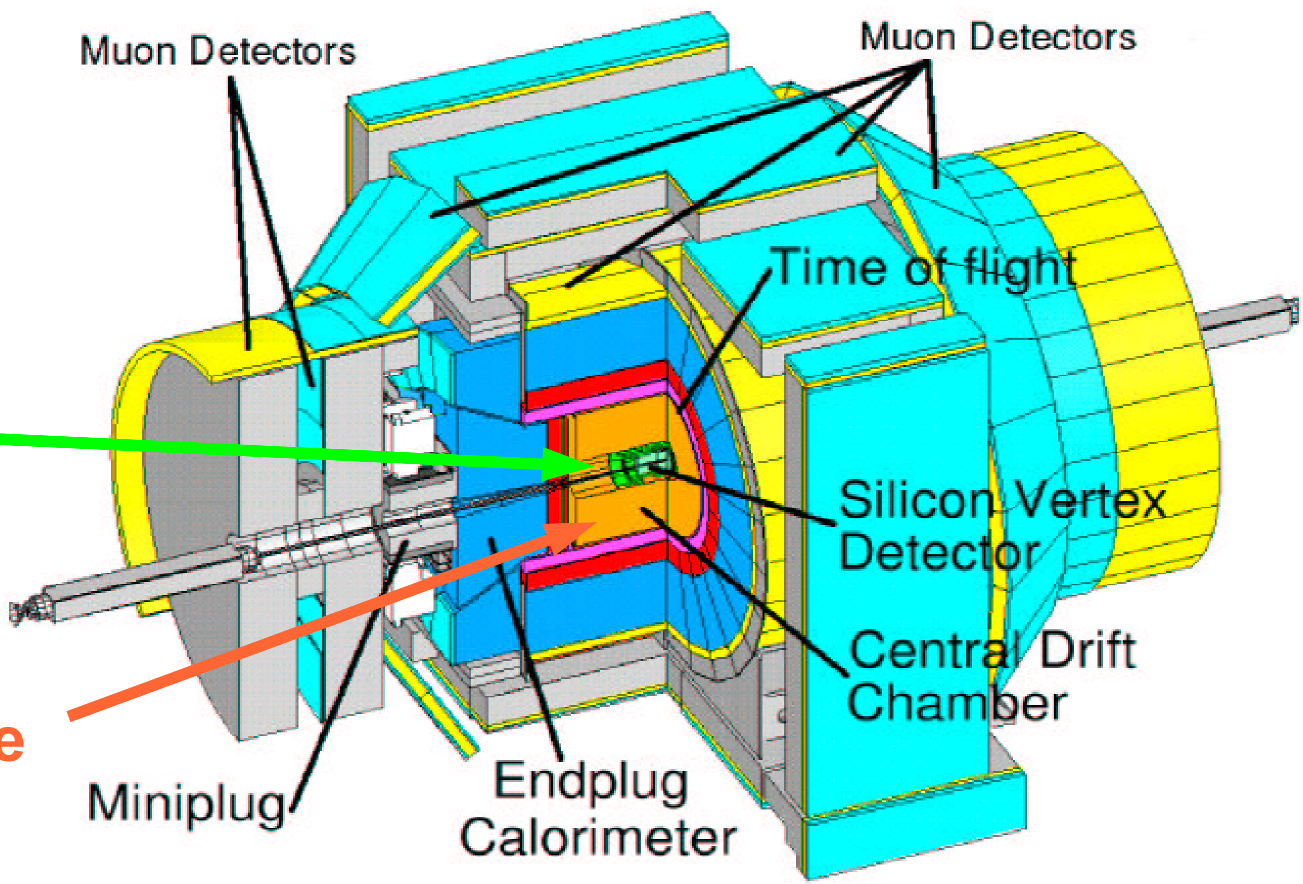
- Then combine Λ_b with pions around it to form Σ_b, but treat π^+ and π^- separately:

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

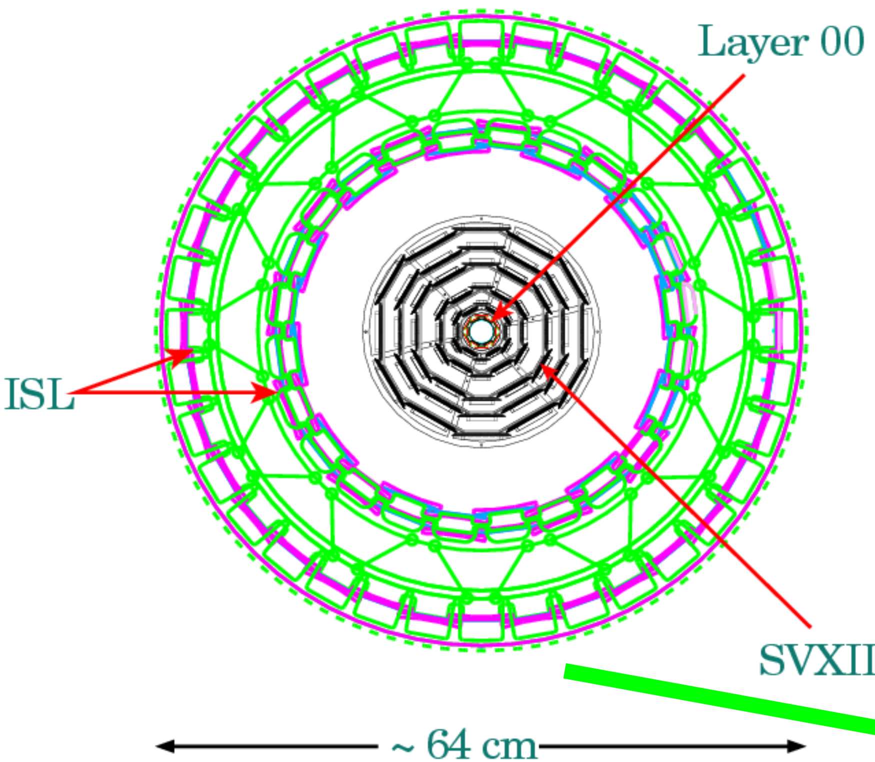
$$\Sigma_b^{(*)-} \rightarrow \Lambda_b^0 \pi^-$$

Tevatron + CDF = *b*-hadron factory

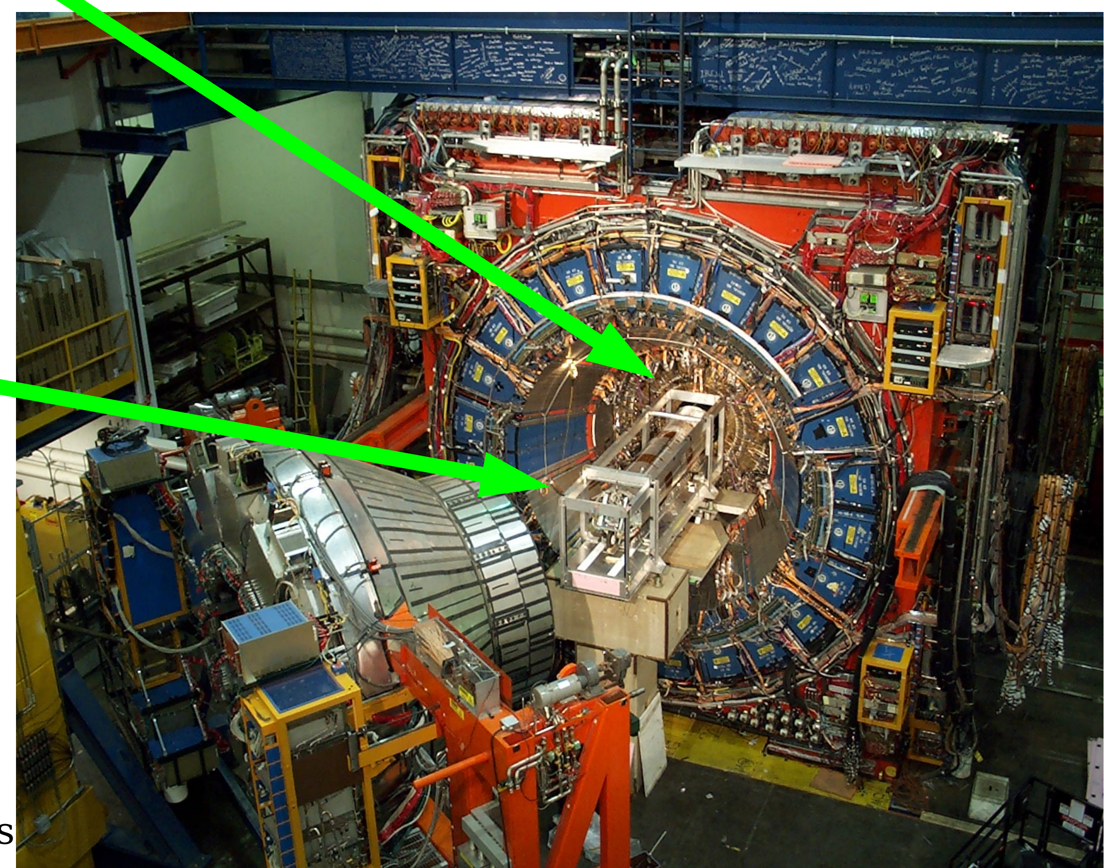
- *All species of b-hadrons produced!*
- Tevatron's has been performing really well: here using ~ 1.1 fb^{-1} of data
- CDF has excellent tracking:
  - d_0 resolution (needed for B physics)
  - p_T resolution (needed to measure masses)



Reconstructing heavy hadrons



- Those CDF can reconstruct are boosted sideways
- Use displacement in transverse plane

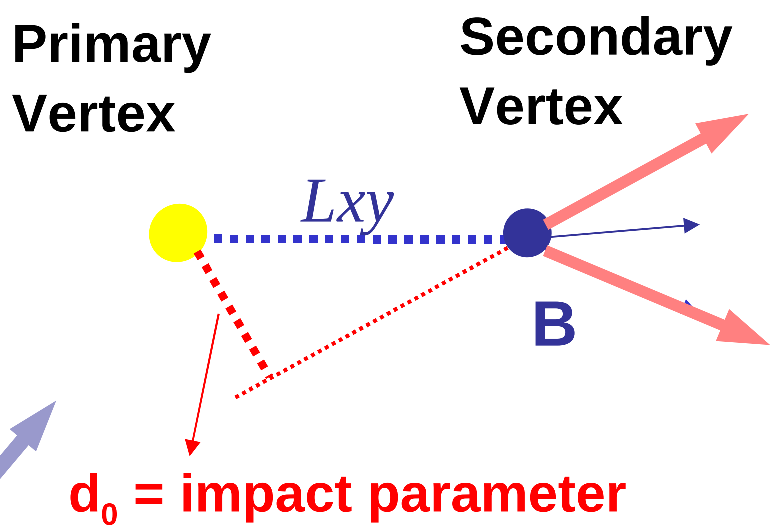


- Decays of hadrons with b and c quarks can be observed with a ***Silicon Detector***

Mining *b*'s from mountains of junk!

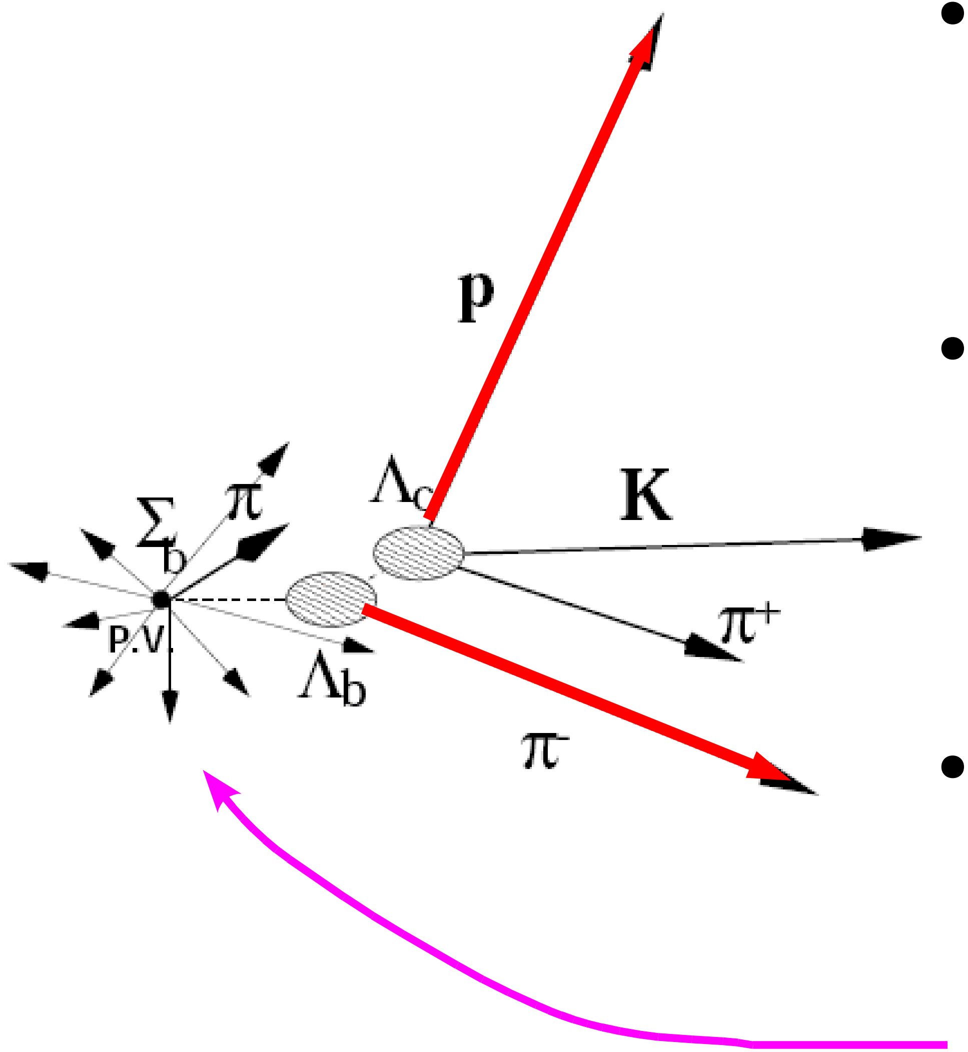
- Production rate of b-quarks is very large, but rate of (uninteresting) soft QCD is 1000x larger
- *b*-physics program lives and dies by the "trigger system"
  - very fast electronics
  - examines events in real time
  - decides to keep some events

    (e.g. those with two displaced tracks)



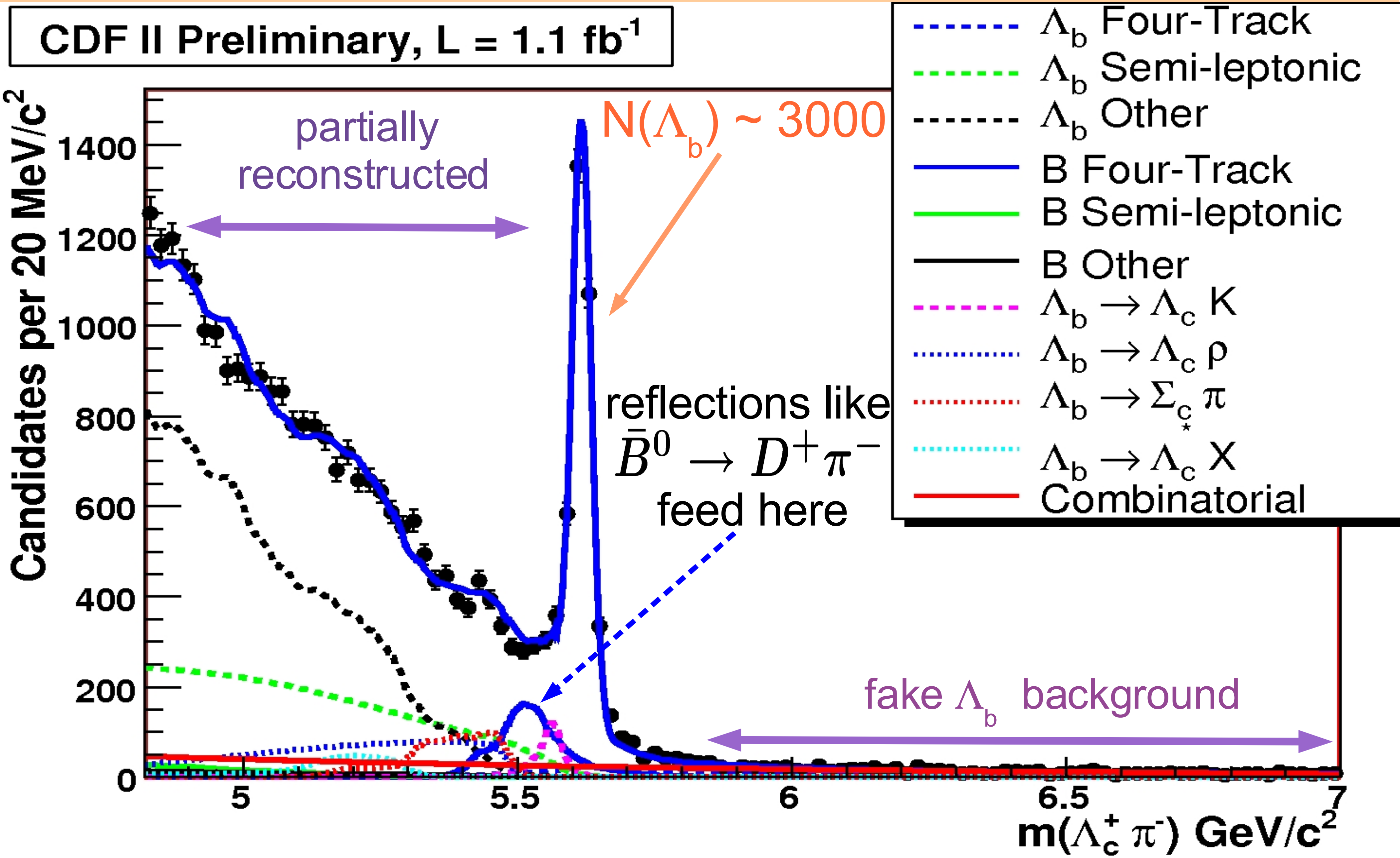
- *Silicon Vertex Trigger* (SVT) – part of trigger system that finds displaced tracks and triggers on heavy hadrons

Reconstructing Λ_b and Σ_b



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

The largest Λ_b sample in the world



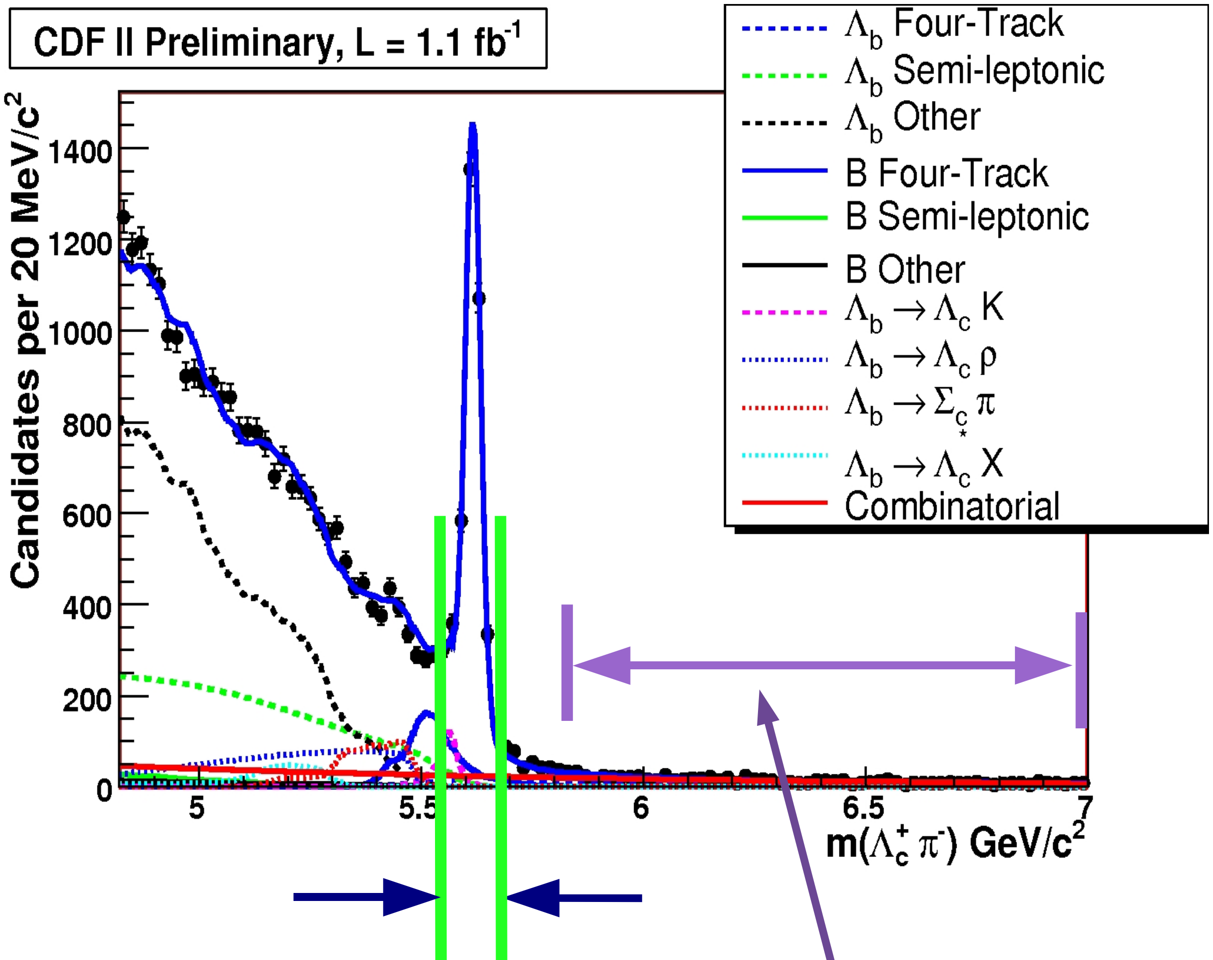
Composition of Λ_b signal window

- 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

Reconstructing Σ_b



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

"Λ_b signal region"

"Λ_b upper sideband"
(source of fake Λ_b background)

Reconstructing Σ_b

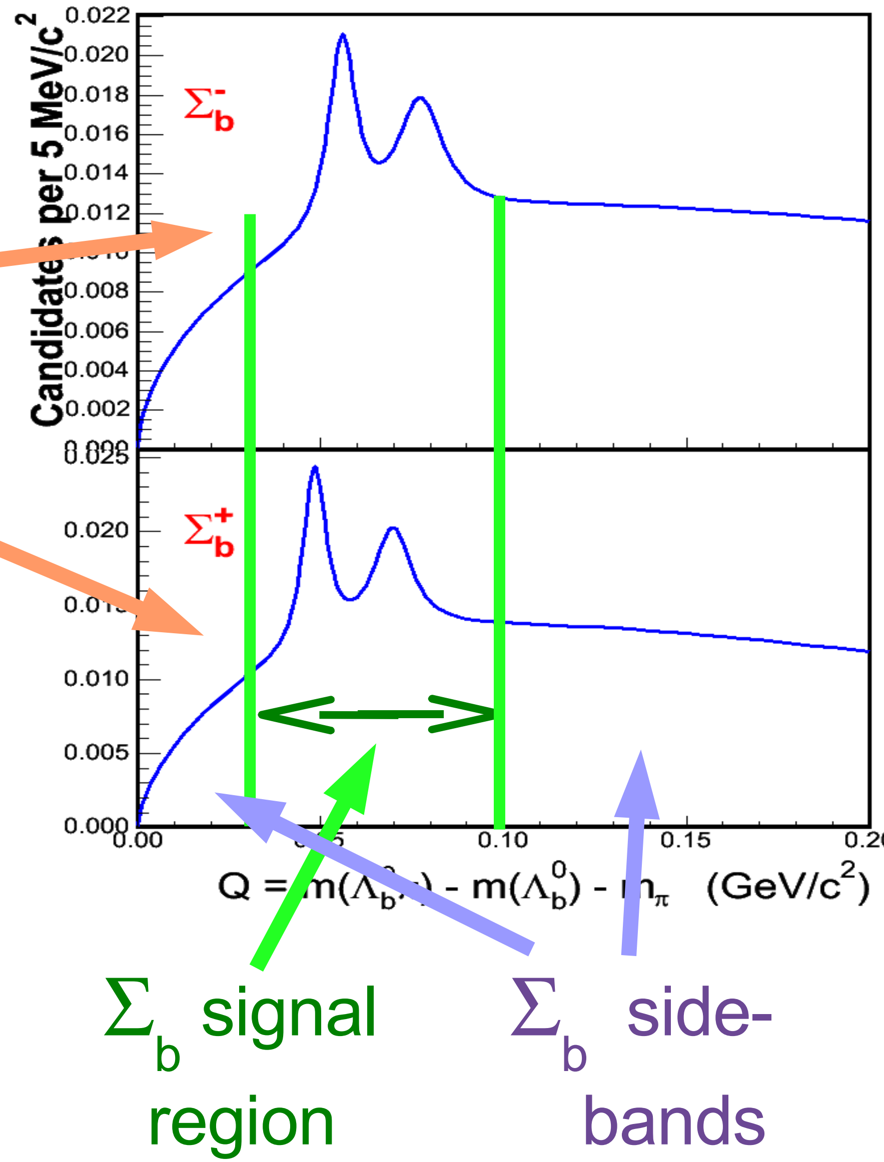
- Split into two sub-samples:

  $\Lambda_b\pi^-$: look for Σ_b^- and Σ_b^{*-}

  $\Lambda_b\pi^+$: look for Σ_b^+ and Σ_b^{*+}

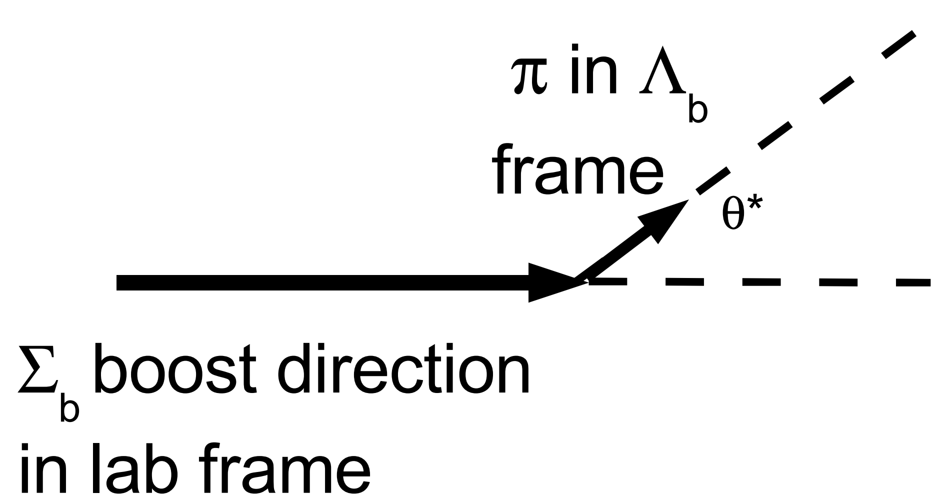
- Remove effect of Λ_b resolution by looking at

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



Σ_b optimization

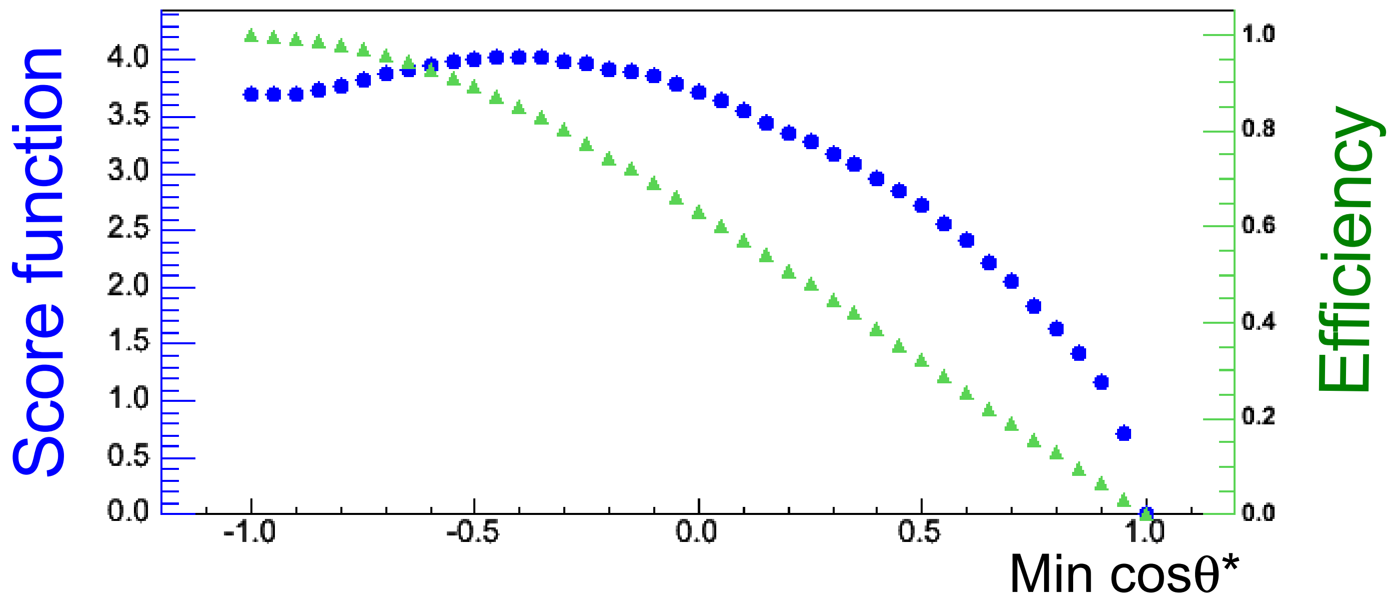
- Use Λ_b signal region (3σ around Λ_b peak)
- Note: no cut on $p_T(\pi \text{ from } \Sigma_b)$!
- Only cosθ* makes substantial difference
- Optimized cuts



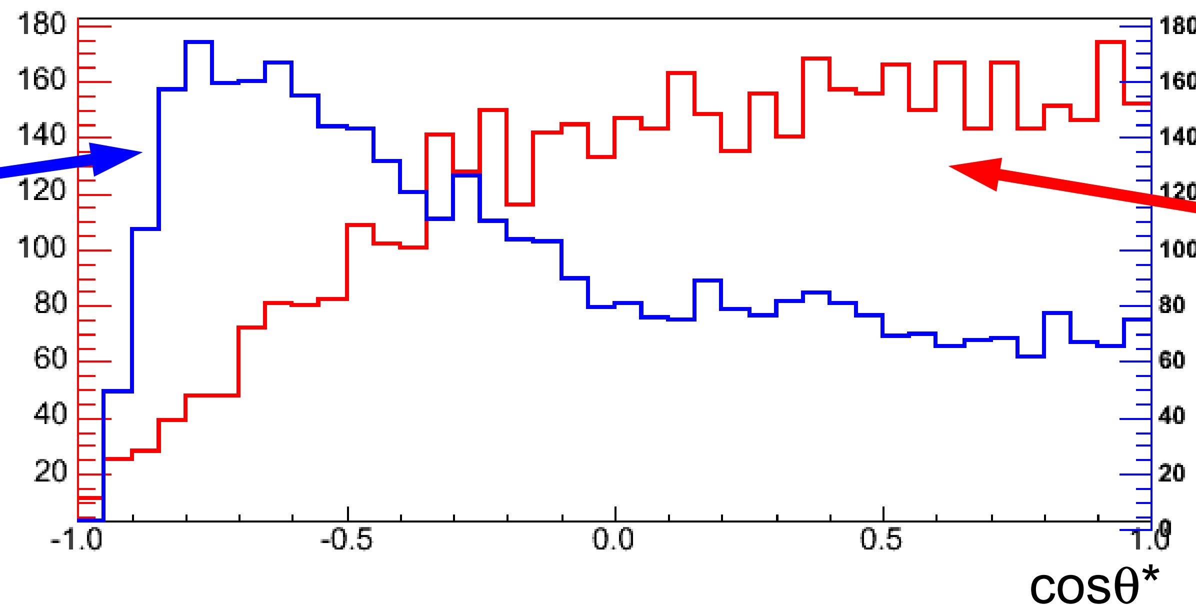
Variable	Cut value
$p_T(\Sigma_b)$	> 9.5 GeV/c
$\lvert d_0/\sigma_{d_0} \rvert$	< 3.0
$\cos\theta^*$	> -0.35

Σ_b optimization: N-1 scan for cosθ*

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

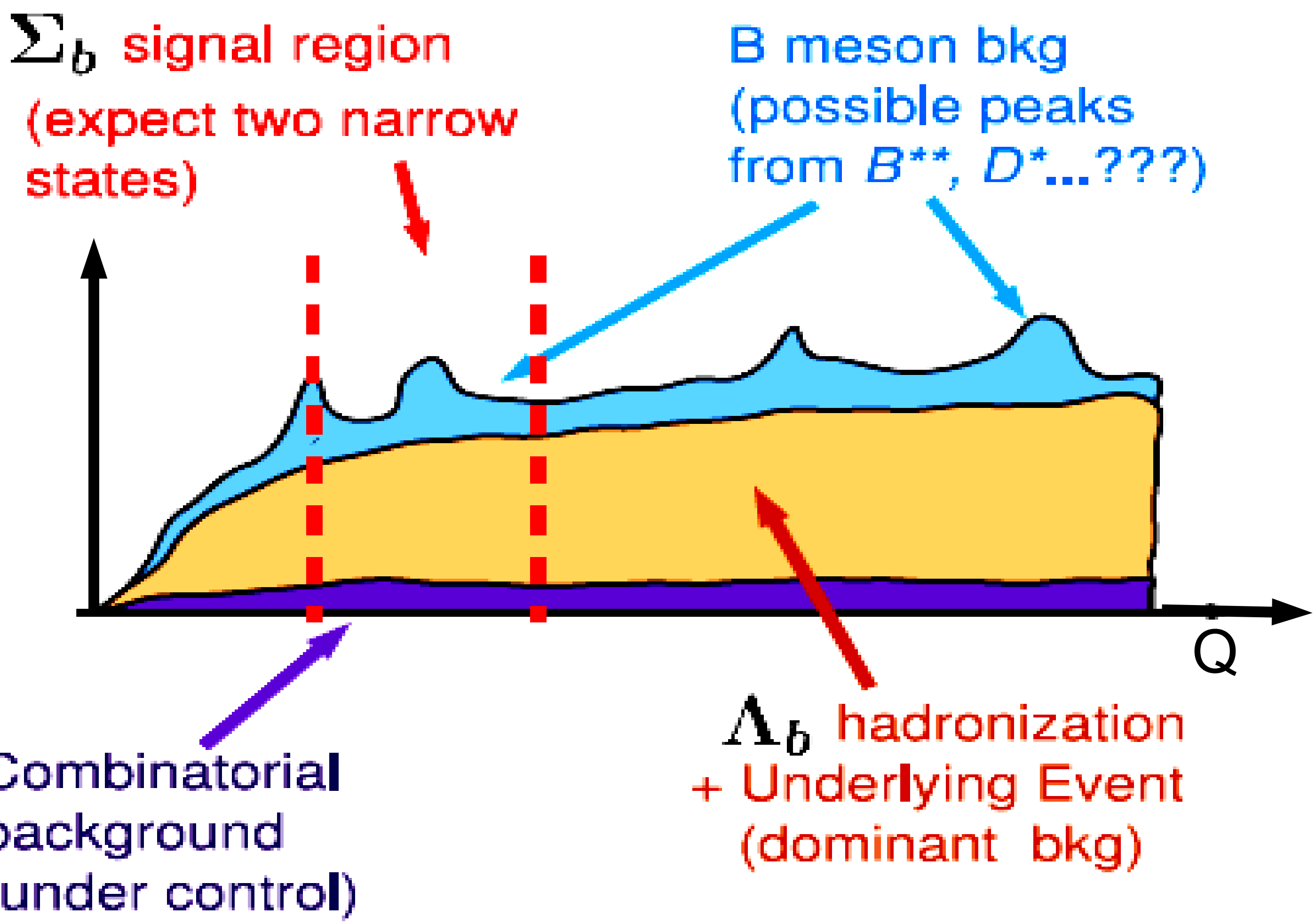


Σ_b sidebands (data)



Σ_b signal (PYTHIA)

Backgrounds to worry about



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

PDF form for background shapes

- All backgrounds modeled with a PDF of this form:

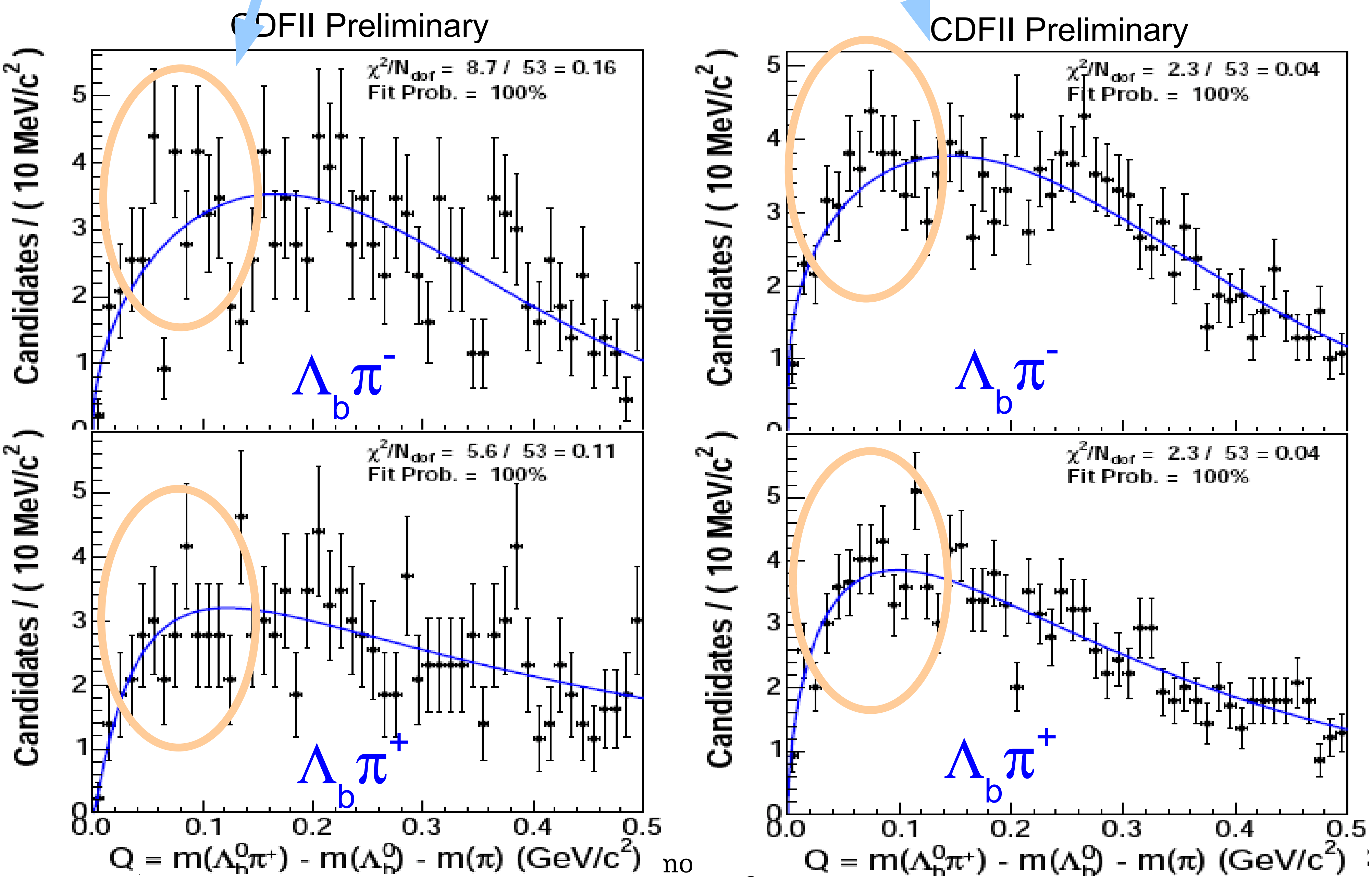
$$f(Q;\alpha,Q_{max},\gamma) = \left(\frac{Q}{Q_{max}}\right)^{\alpha} e^{-\frac{\alpha}{\gamma}\left(\left(\frac{Q}{Q_{max}}\right)^{\gamma}-1\right)}$$

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

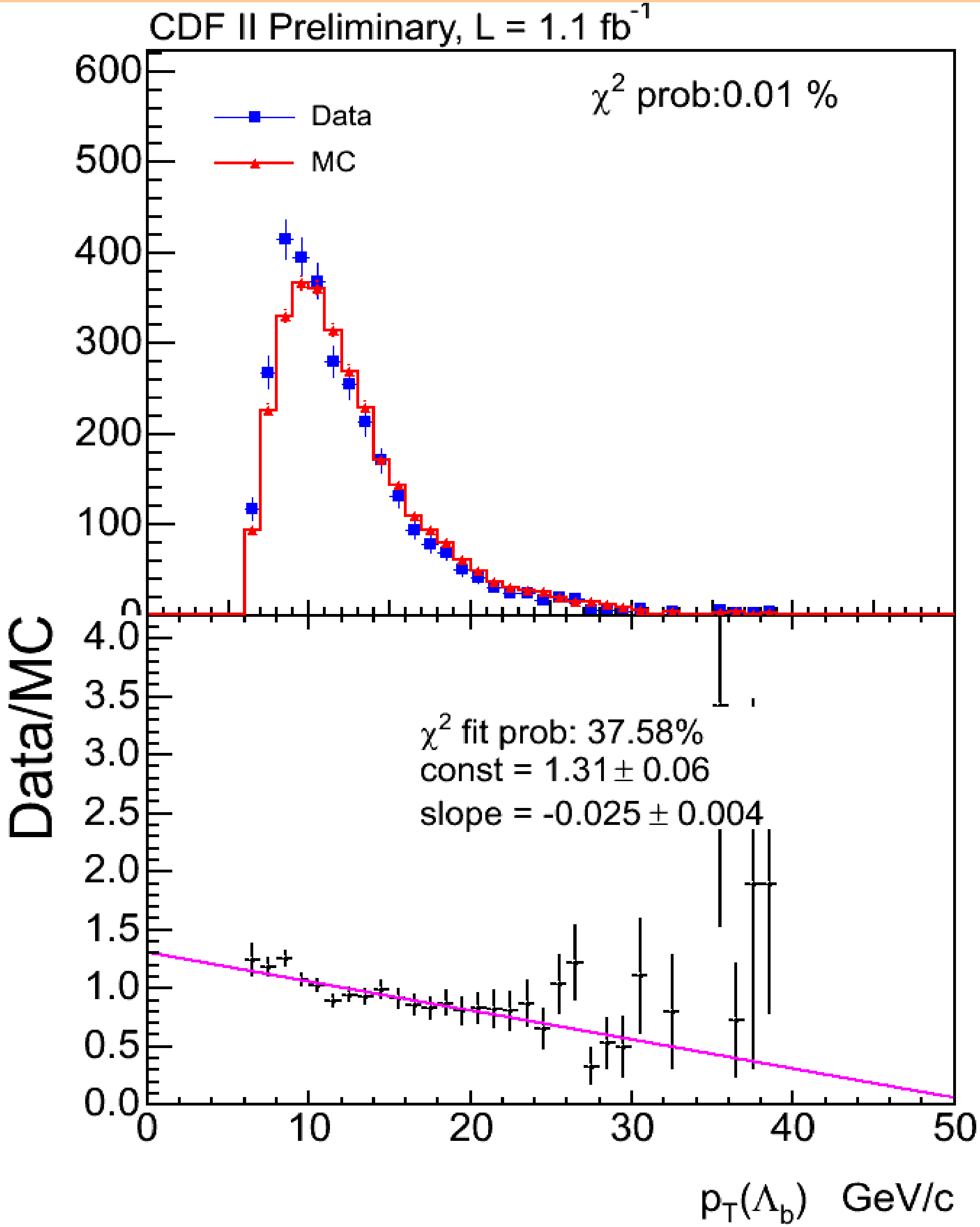
- Fit separately every background component

(Systematics: try alternative shapes)

Λ_b combinatorial and *B* hadroniz. bkgs

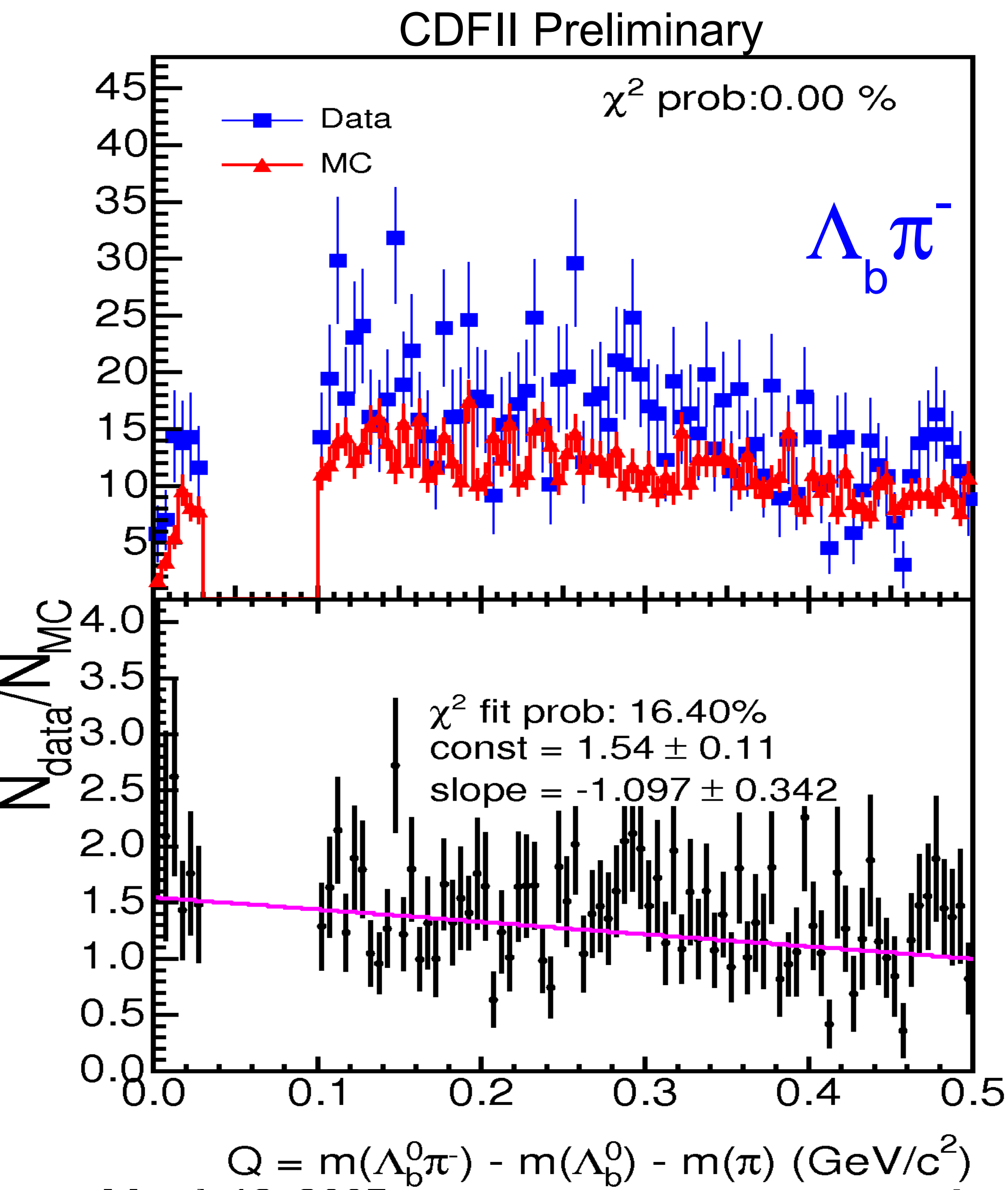


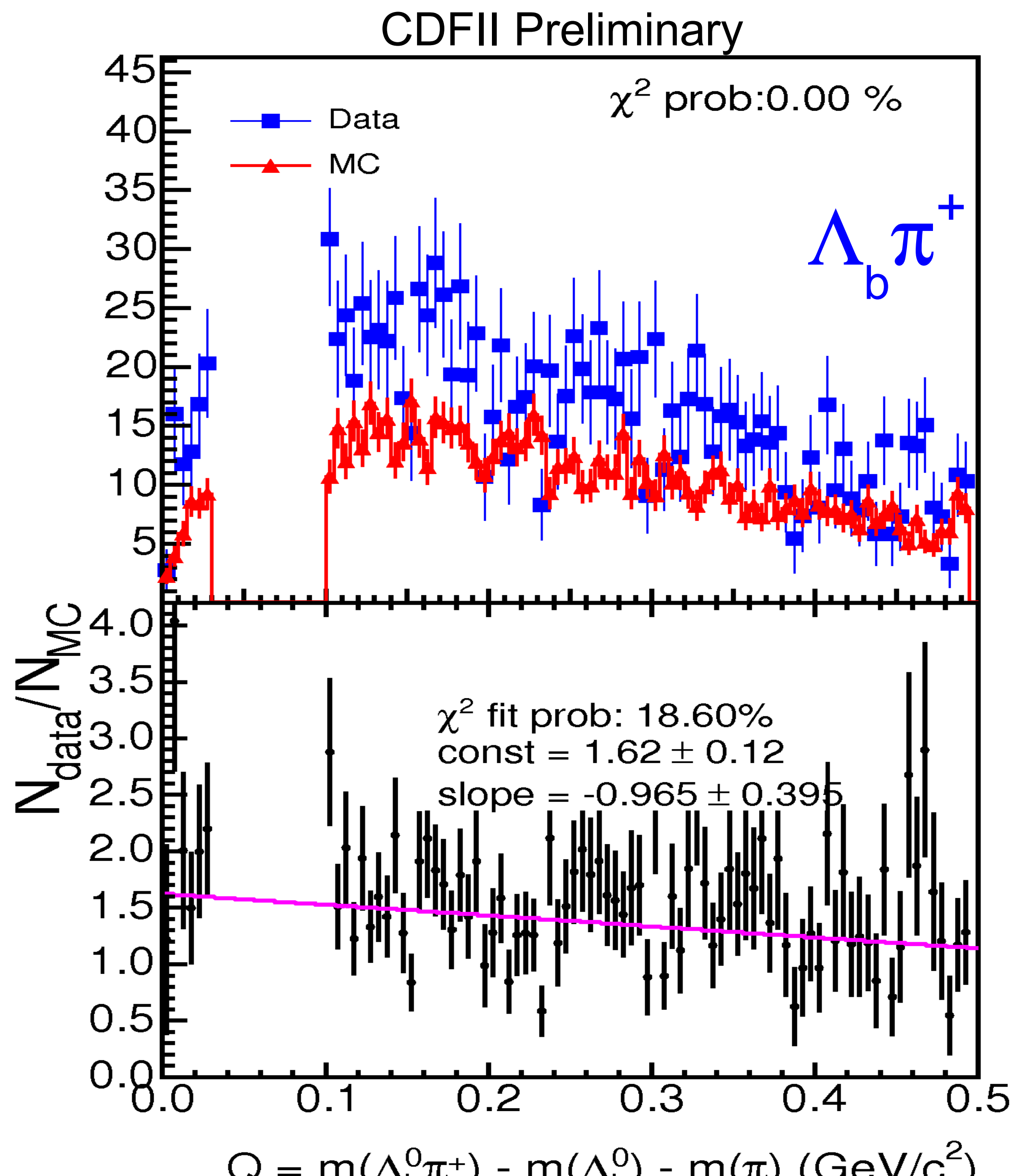
Λ_b hadronization in PYTHIA



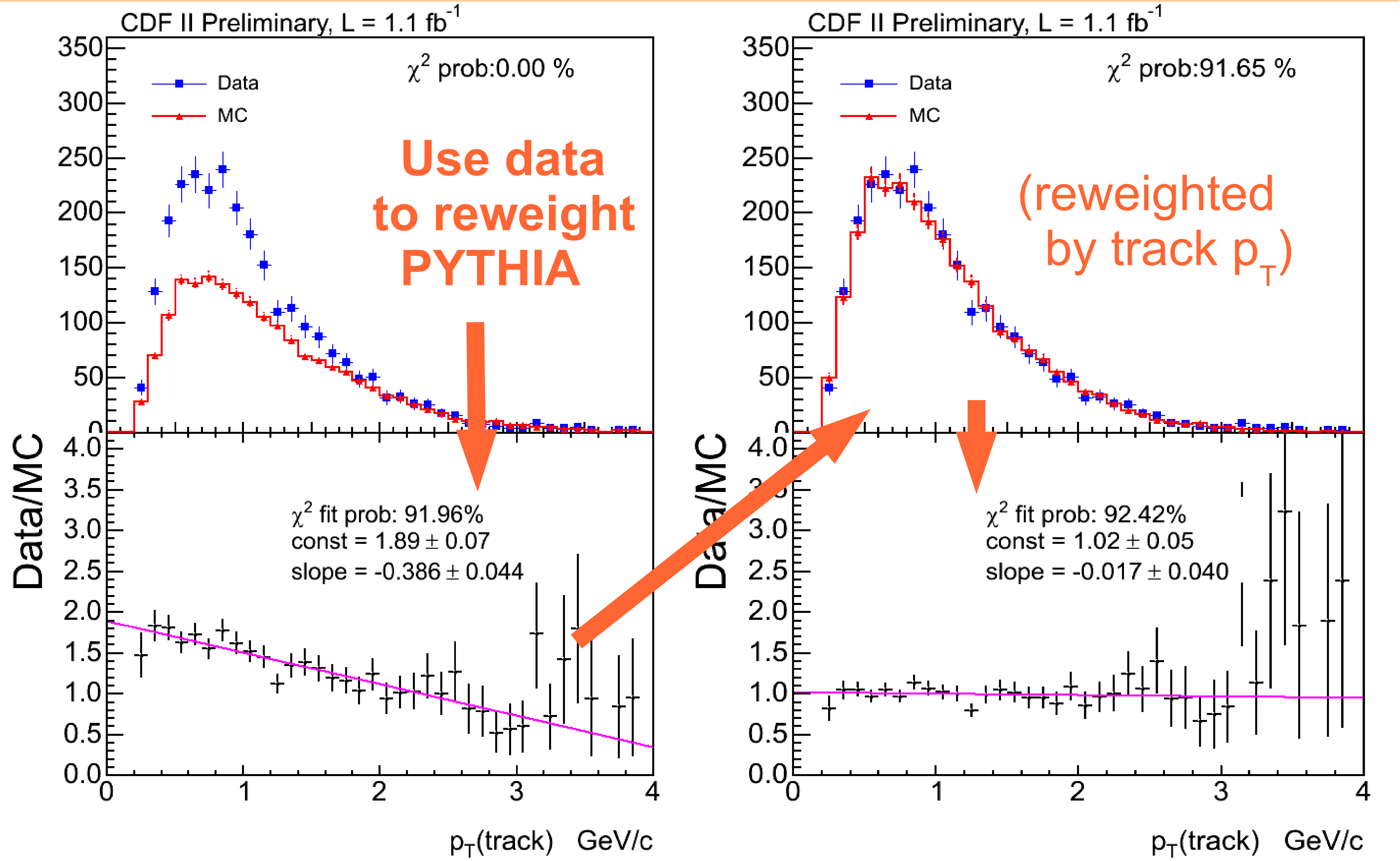
- Need hadronization and Underlying Event background (shape, norm)
- For *B* mesons, PYTHIA works like a charm
  - cf. SSKT for Bs mixing
- No guarantees for baryons!
- Same as for B mesons, $p_T(\Lambda_b)$ spectrum ***must be reweighted***

Λ_b hadronization: PYTHIA vs data

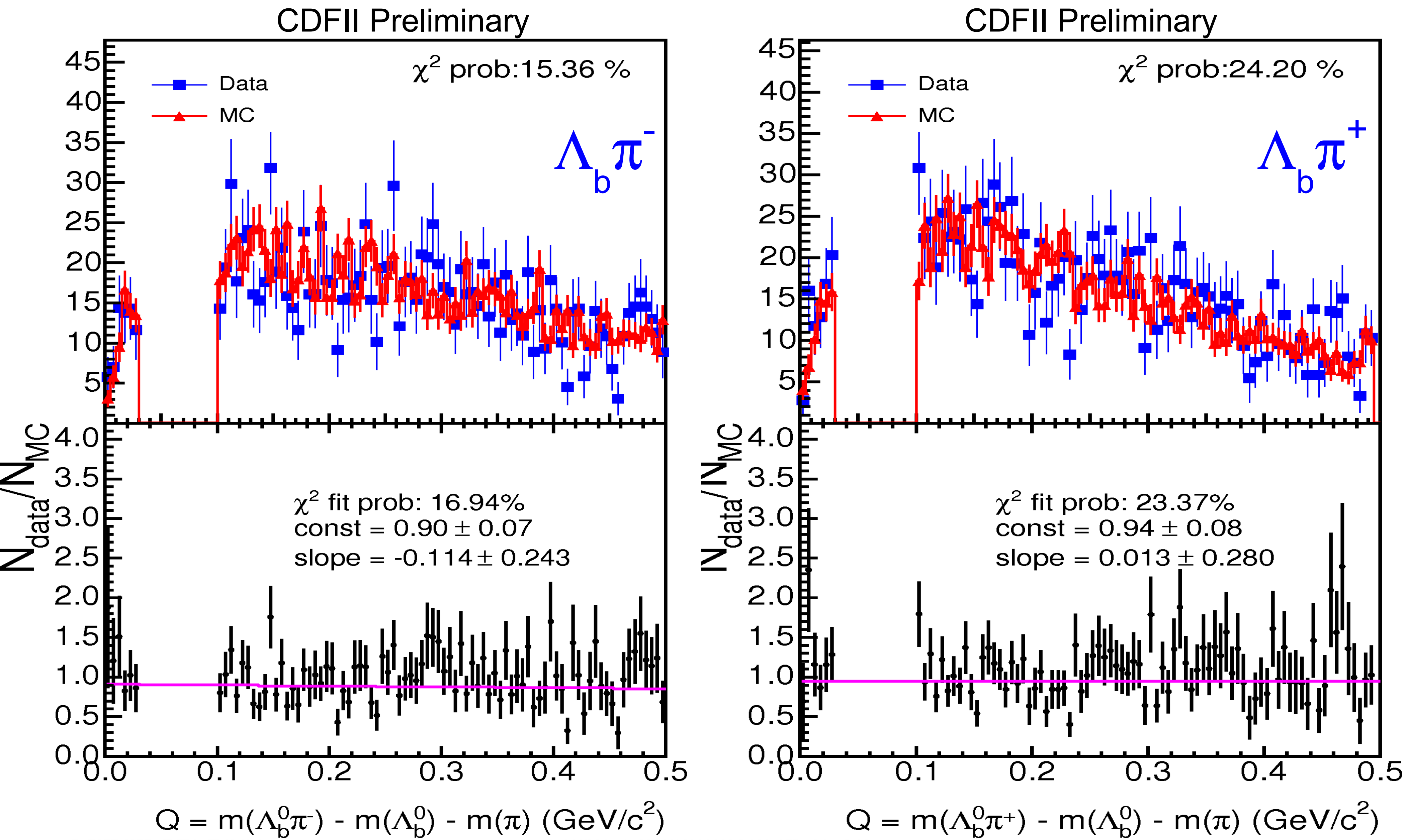




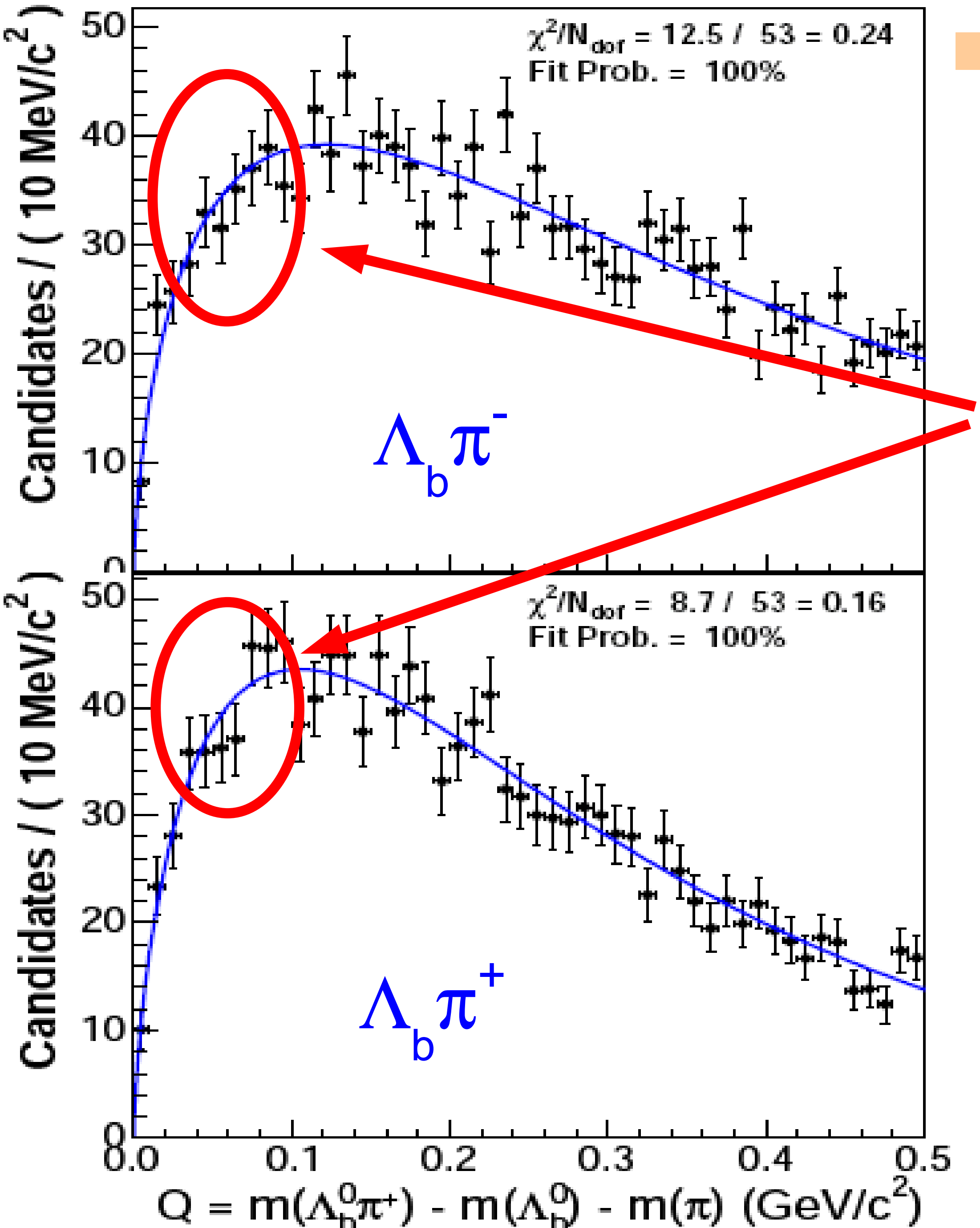
Reweighting Λ_b hadronization



Λ_b hadronization, after reweighting



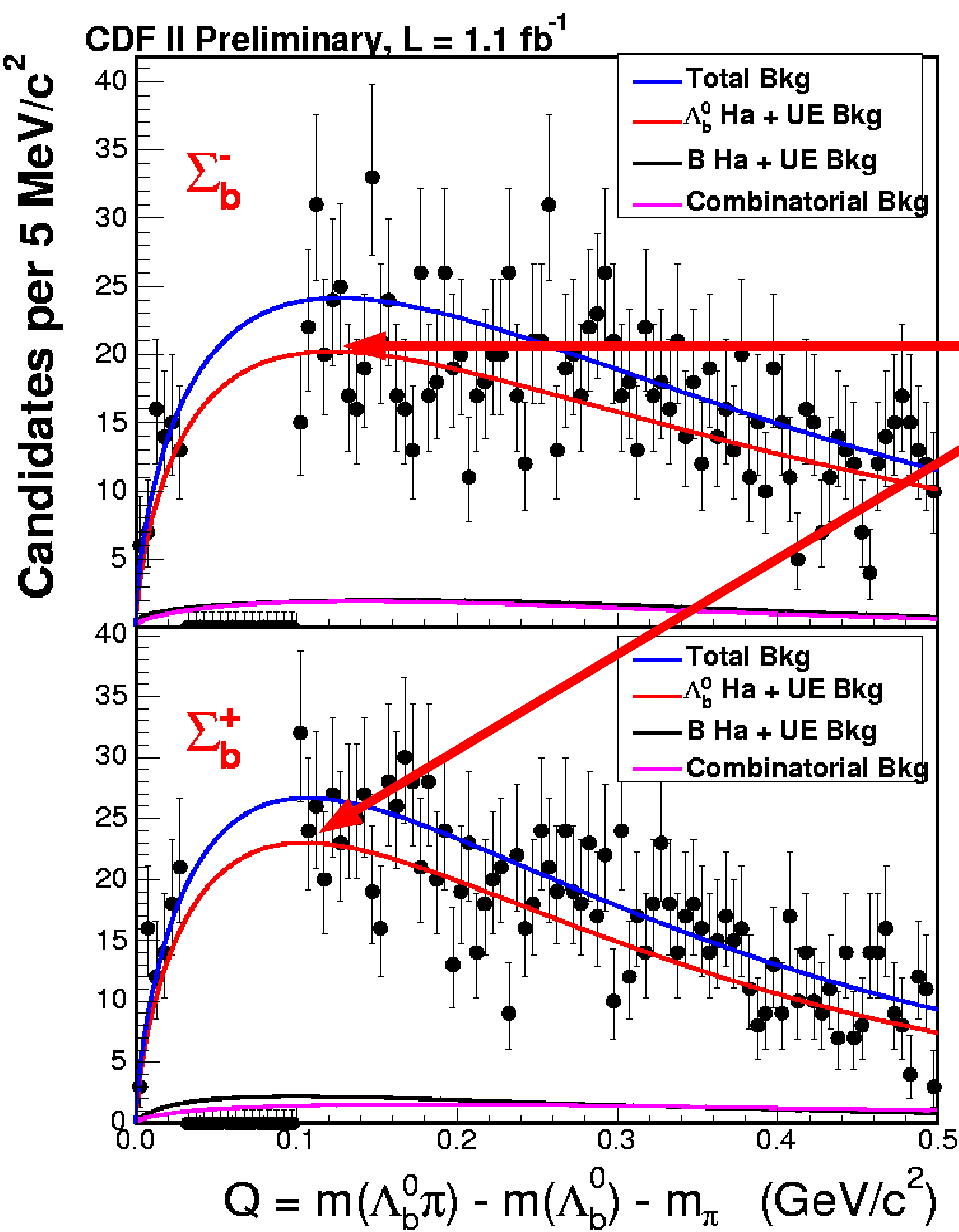
Λ_b hadronization background



- Effectively, used PYTHIA to interpolate
- Shape is ***smooth*** in Σ_b signal region!

Systematics: use extremes of the track p_T spectrum to reweight

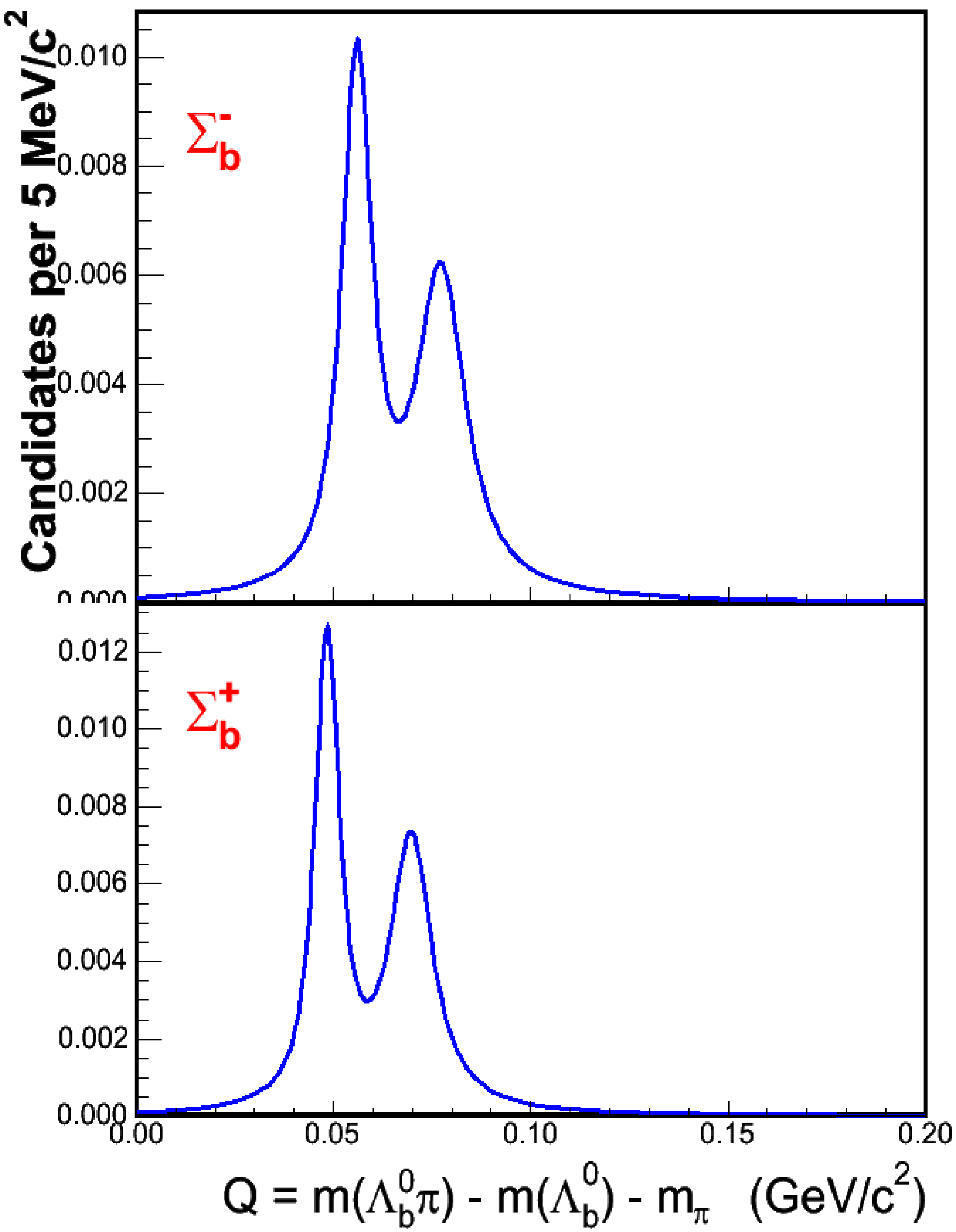
Bkgs before unblinding



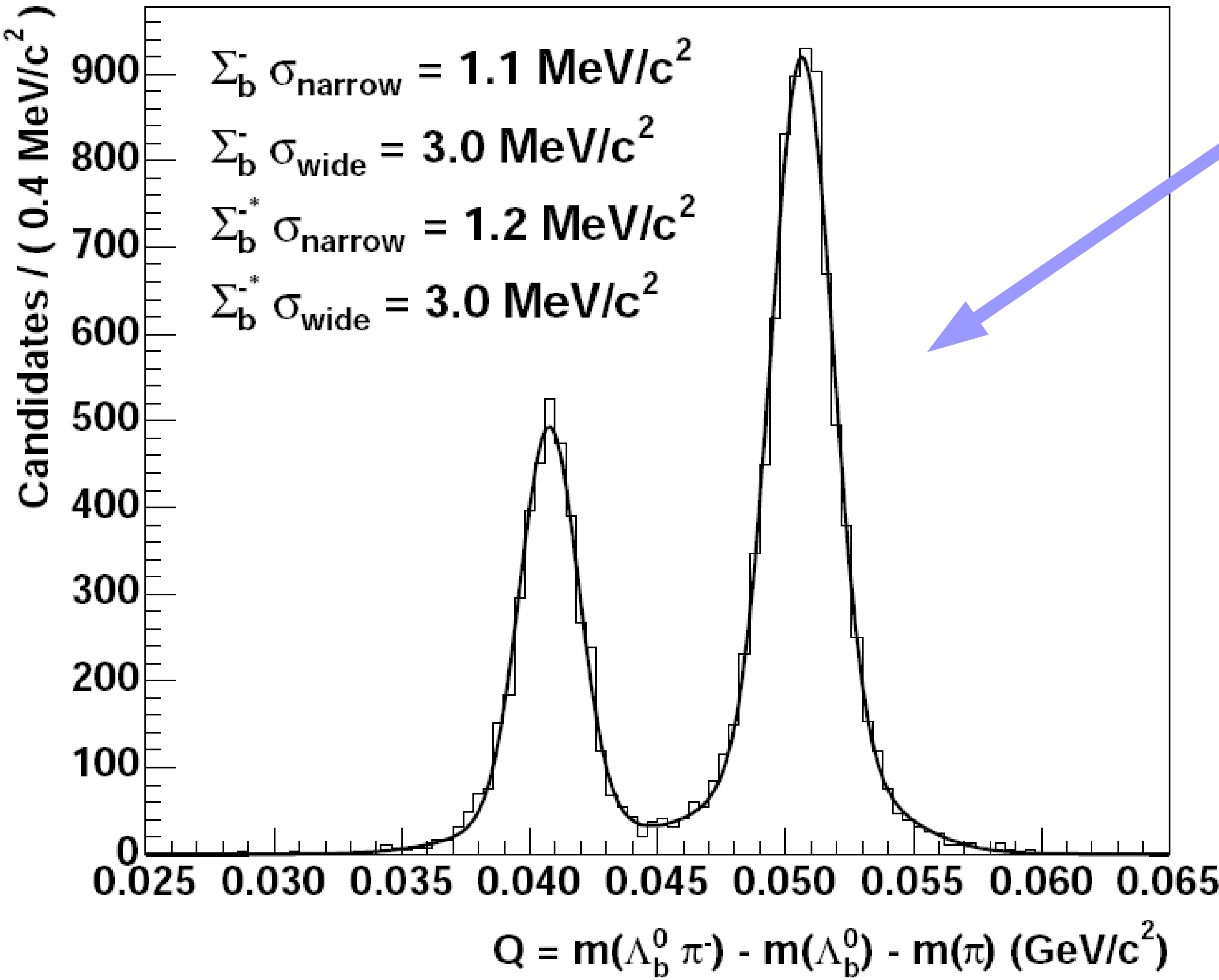
- **Λ_b hadronization dominates**
- Small contribution from
  - ***B* meson bkg**
  - **Combinatorial**
- *These backgrounds are **fixed** when we fit for Σ_b signals*

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
- Checked MC in Σ_c and D^*

Disagreement of 15-20% seen in some cases, use as syst.

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

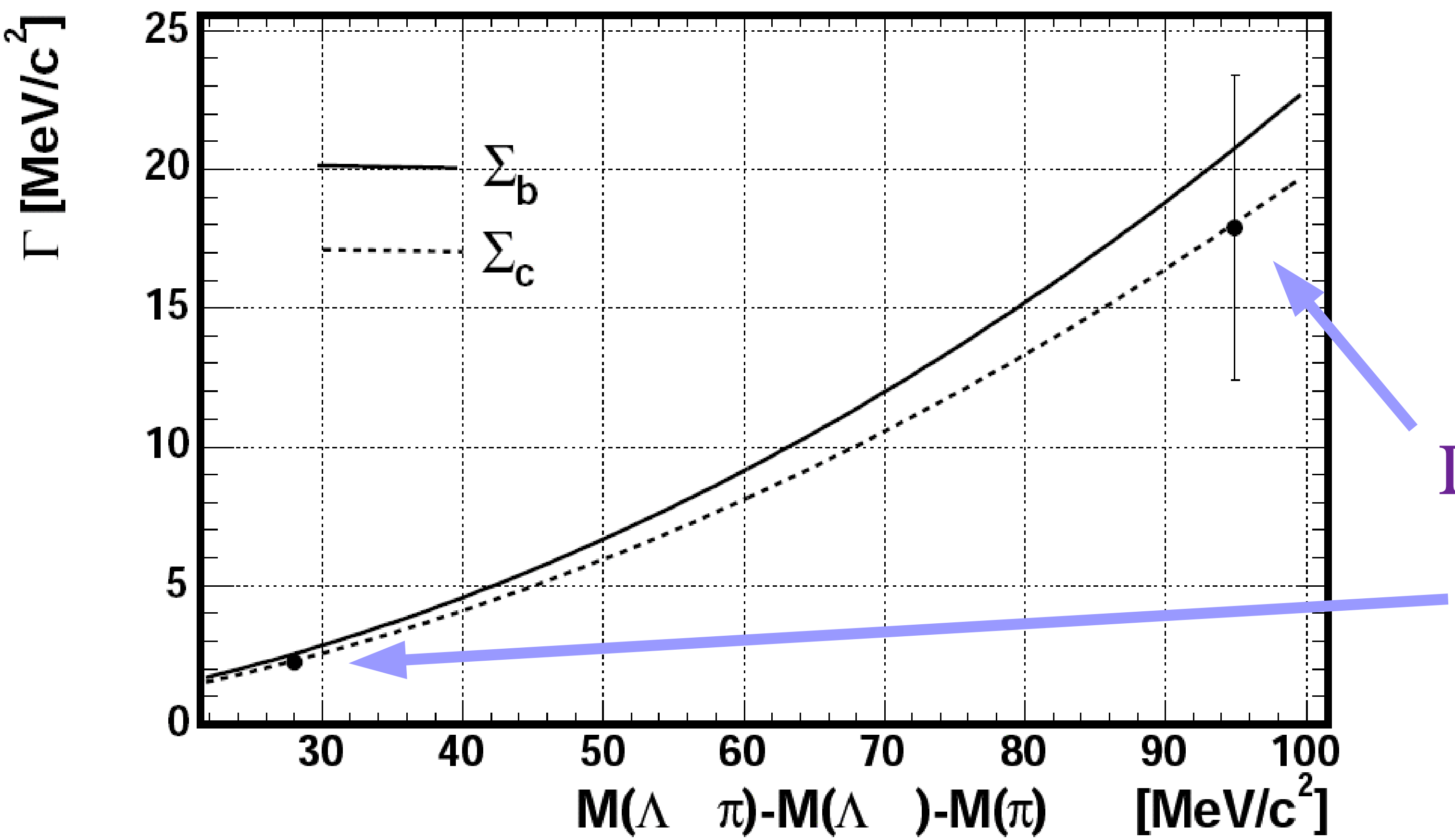
- $\Gamma(\Sigma_b)$ predicted by HQET:

  [hep-ph/9406359]

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

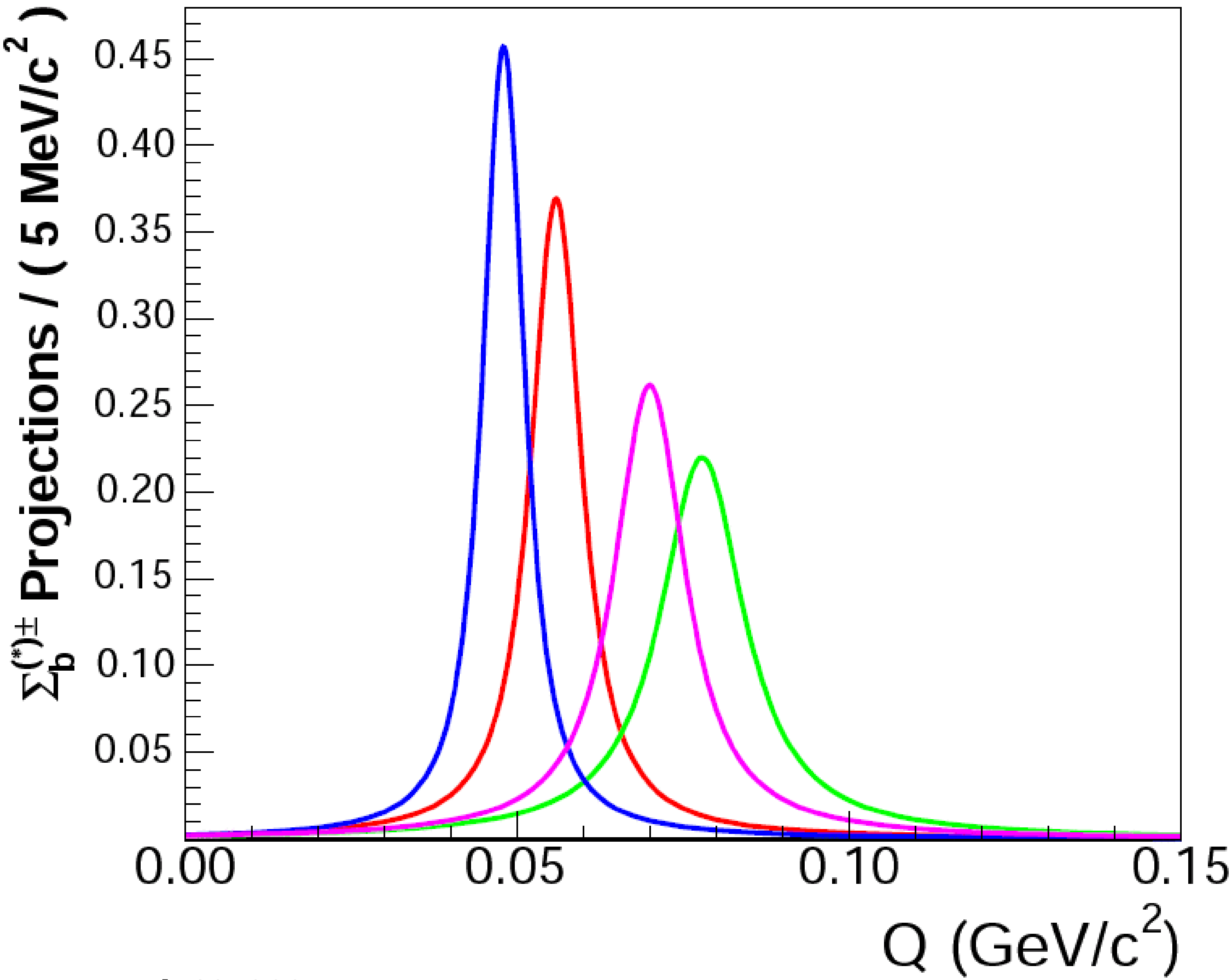
$$f_p \equiv g_A / \, f_\pi; \; g_A = 0.75 \pm 0.05$$

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



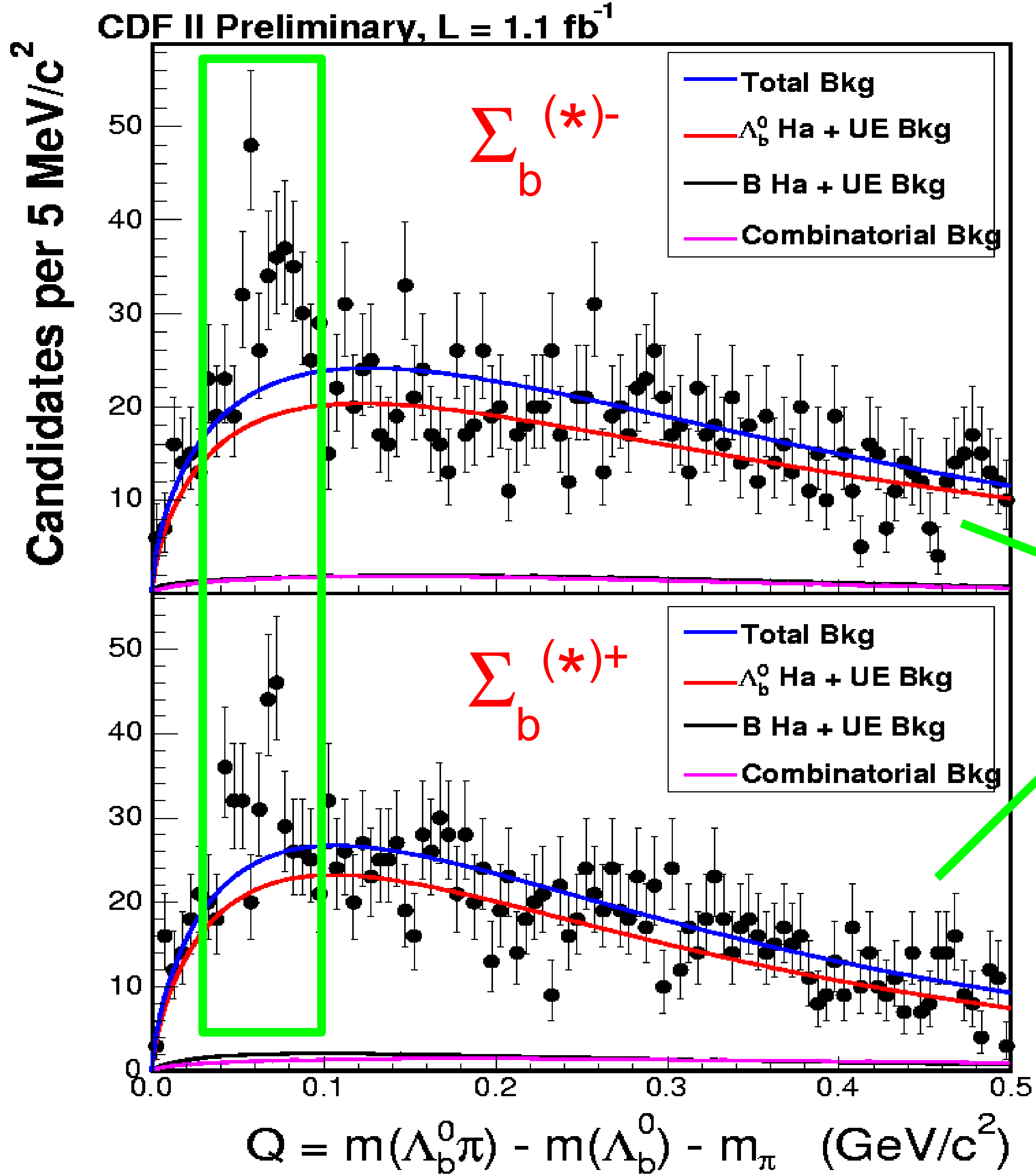
$\Gamma(\Sigma_c^{(*)++})$ in an excellent agreement with PDG

Modeling Σ_b signal peaks

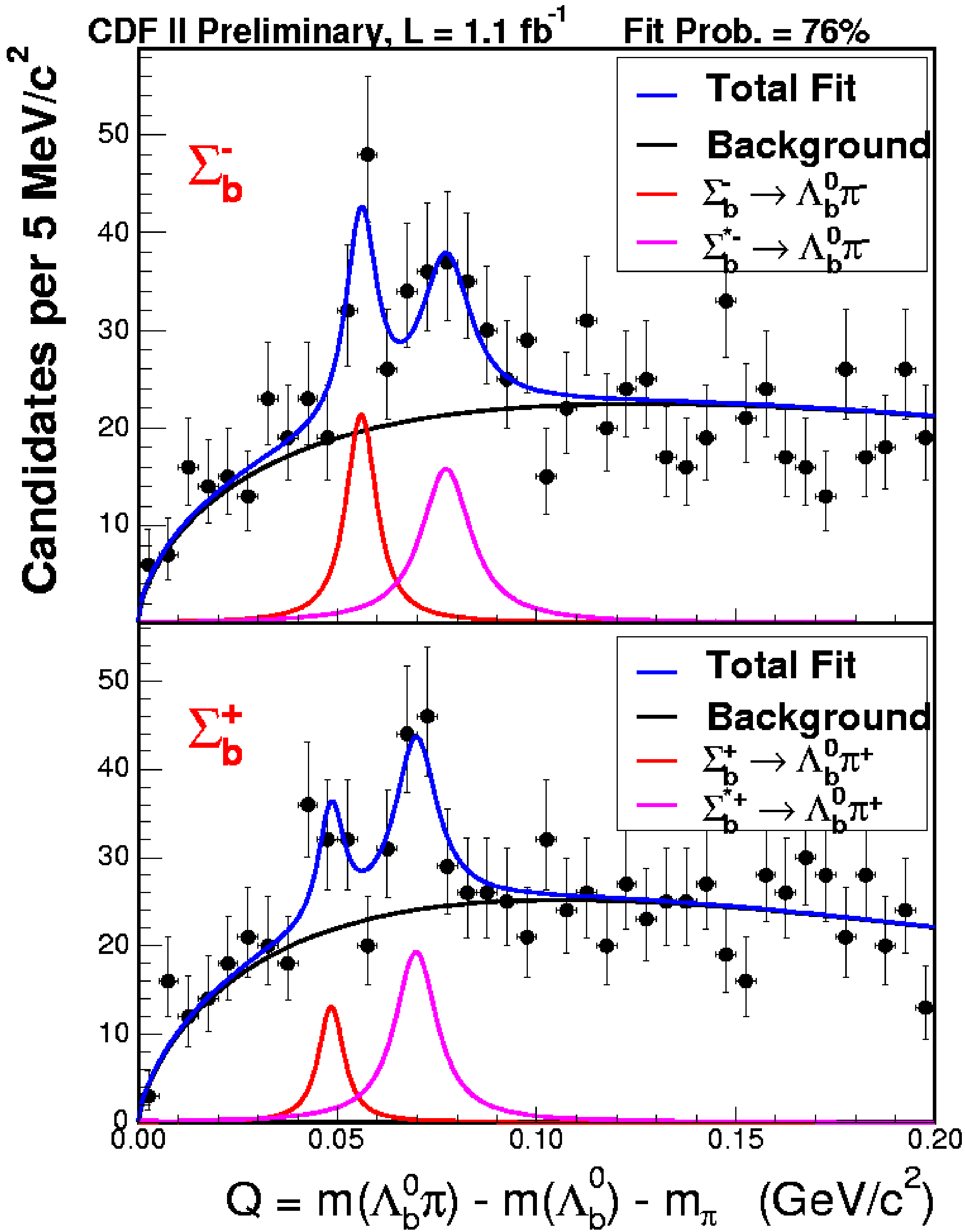


- Natural width from HQET formula
- Dominates over detector resolution!
- Breit-Wigner peaks get wider as $m(\Sigma_b)$ goes up

Box open!



Data	Bkg	excess
416	268	148
406	298	108



The fit

- Backgrounds frozen in the fit
- Signal: 4 peaks, each
  - 2 Breit-Wigners (resolution has 2 Gaussians)
  - $\Gamma(\Sigma_b)$ as a function of center of each peak
- $m(\Sigma_b{}^*)$-$m(\Sigma_b)$ common parameter

Fit results

Parameter	Value	Parabolic Error	MINOS Errors
Σ_b^- Q (MeV/c^2)	55.9	0.951	(+0.973, -0.950)
Σ_b^- events	59	14.2	(+14.6, -13.7)
Σ_b^+ Q (MeV/c^2)	48.5	1.97	(+1.98, -2.17)
Σ_b^+ events	32	12.1	(+12.5, -11.7)
Σ_b^{*-} events	69	17.6	(+18.0, -17.1)
Σ_b^{*+} events	77	16.8	(+17.3, -16.3)
Σ_b^* - Σ_b Q (MeV/c^2)	21.2	1.92	(+2.00, -1.94)
NLL	-24160.4	–	–

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

Systematics: procedure

- Already listed an array of "variations":
  - change: 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	Mass Scale	Λ_b^0 Comp.	Λ_b^0 Norm.	Λ_b^0 Shape	Reweight	Reso.	Σ_b Width	Δ_*	Total
Σ_b^- Q	0.22 -0.22	0.0 -0.03	0.009 -0.002	0.0 -0.011	0.04 -0.0004	0.0 -0.011	0.009 -0.005	0.06 0.0	0.23 -0.22
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	0.0 -0.08	8.5 -4.1
Σ_b^+ Q	0.19 -0.19	0.03 0.0	0.013 -0.013	0.013 0.0	0.0 -0.11	0.0 -0.014	0.01 -0.02	0.0 -0.11	0.19 -0.25
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	0.0 -0.004	5.0 -3.4
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	0.0 -0.16	15.6 -5.0
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	0.16 0.0	10.3 -5.7
Σ_b^* - Σ_b Q	0.10 -0.10	0.05 0.0	0.14 -0.13	0.04 0.0	0.32 0.0	0.02 0.0	0.07 -0.07	0.0 -0.26	0.38 -0.32
Σ_b^{*-} Q	0.28 -0.28	0.02 0.0	0.13 -0.13	0.03 0.0	0.32 0.0	0.003 0.0	0.08 -0.07	0.0 -0.184	0.45 -0.37
Σ_b^{*+} Q	0.32 -0.32	0.09 0.0	0.12 -0.13	0.05 0.0	0.17 0.0	0.001 0.0	0.05 -0.06	0.0 -0.39	0.40 -0.52

- Track p_T reweighting largest for yields

Yields (including systematics)

Number of events for each state:

- $N(\Sigma_b^-) = 59^{+15}_{-14}\ \text{(stat)}\ ^{+9}_{-4}\ \text{(syst)}$
- $N(\Sigma_b^+) = 32^{+13}_{-12}\ \text{(stat)}\ ^{+5}_{-3}\ \text{(syst)}$
- $N(\Sigma_b^{*-}) = 69^{+18}_{-17}\ \text{(stat)}\ ^{+16}_{-5}\ \text{(syst)}$
- $N(\Sigma_b^{*+}) = 77^{+17}_{-16}\ \text{(stat)}\ ^{+10}_{-6}\ \text{(syst)}$

Significance

- 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)
- Strength of signal hypothesis (4 Σ_b peaks) best expressed by Likelihood Ratio (LR):

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

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

Likelihood Ratios

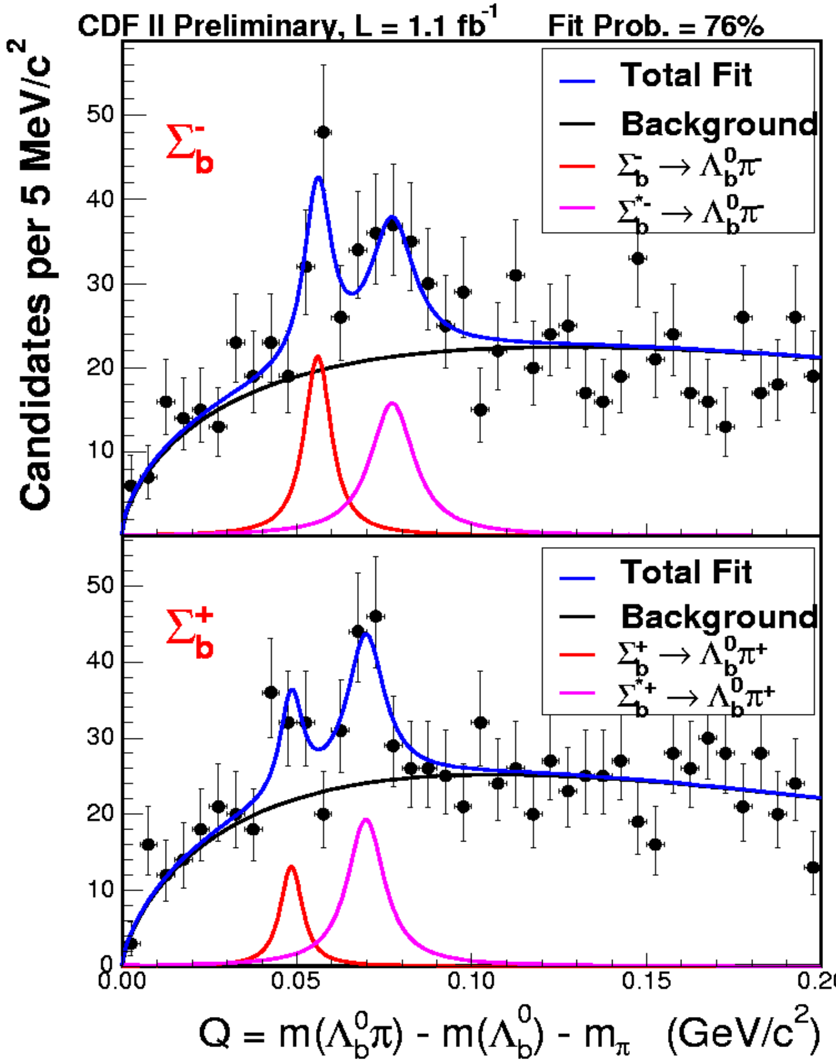
- Overall significance
- Four or only two peaks?
- What if one peak is fake?

Hypothesis	LR	$\sqrt{2 \cdot \ln(LR)}$
Null	4.3×10^{18}	9.3
Two Σ_b States	1.3×10^{6}	5.3
No Σ_b^- Signal	1.8×10^{4}	4.4
No Σ_b^+ Signal	6.0	1.9
No Σ_b^{*-} Signal	9.0×10^{3}	4.3
No Σ_b^{*+} Signal	4.4×10^{4}	4.6

- "It is ~ $4.3\text{x}10^{18}$ more likely that this is a 4 peak Σ_b signal than that it's a background fluctuation!"

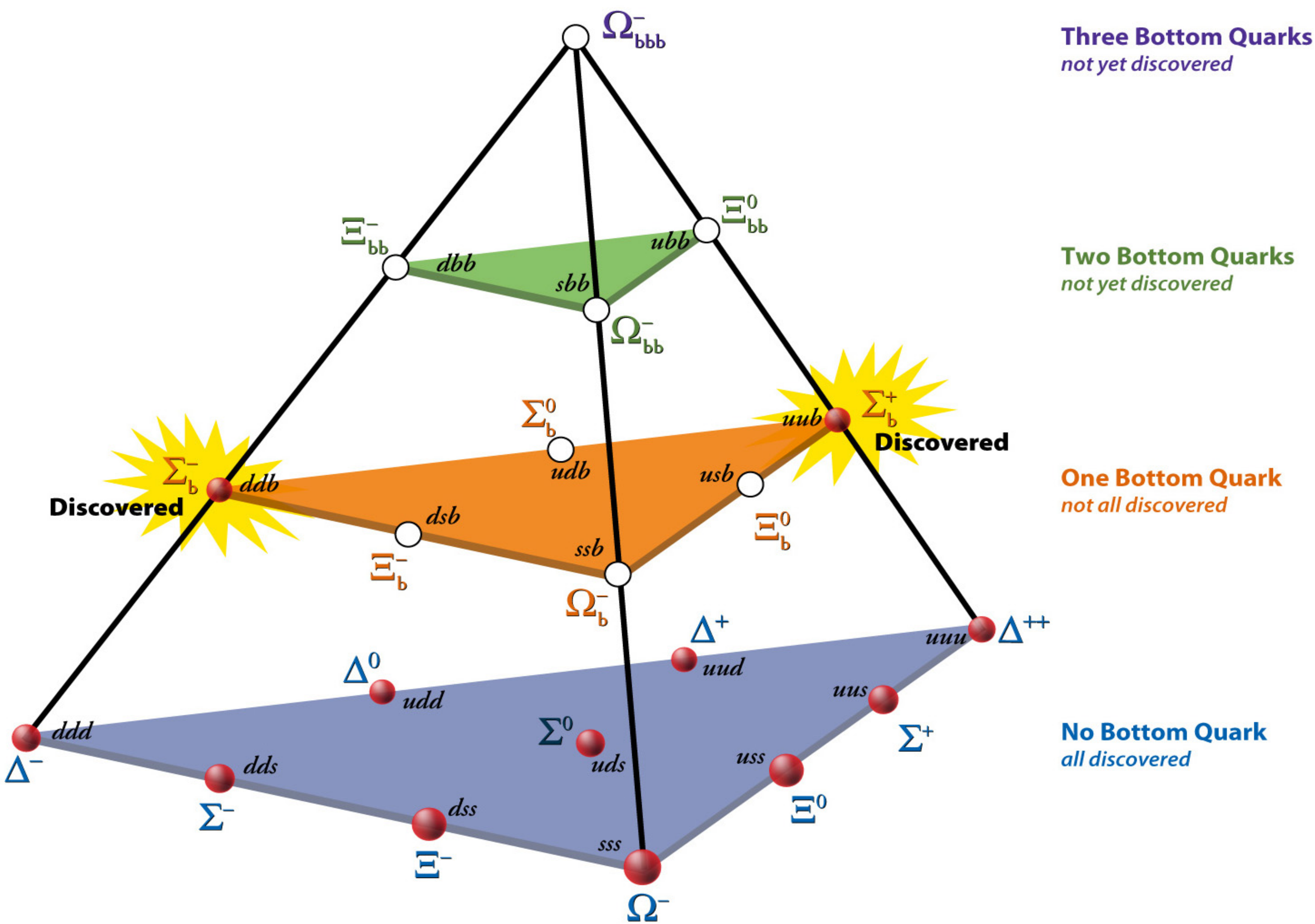
Summary

- *Discovered four new particles!*
- ~ 240 events in total



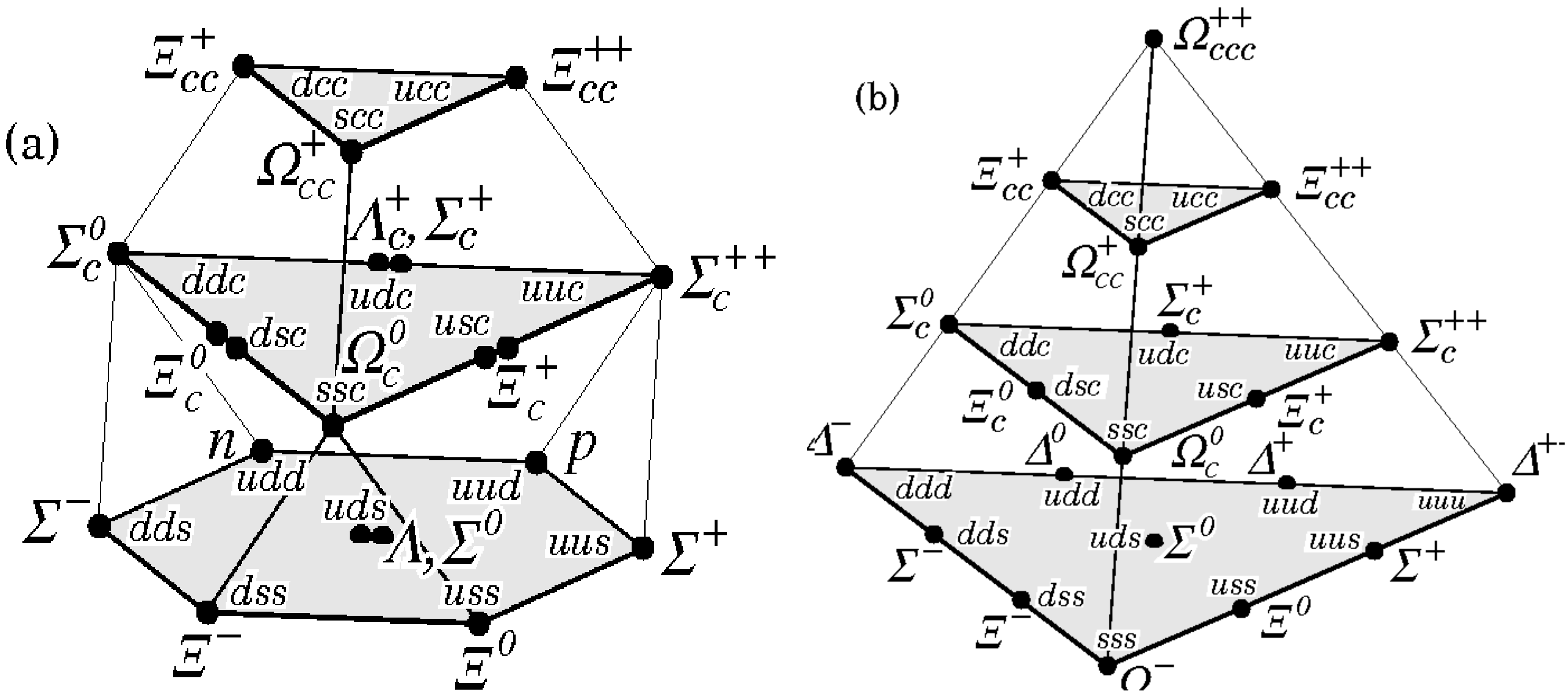
- And measured their masses:
  - $m(\Sigma_b^-) - m(\Lambda_b^0) - m(\pi) = 55.9 \pm 1.0 \text{ (stat) } \pm 0.2 \text{ (syst) MeV}/c^2$
  - $m(\Sigma_b^+) - m(\Lambda_b^0) - m(\pi) = 48.5^{+2.0}_{-2.2} \text{ (stat) } ^{+0.2}_{-0.3} \text{ (syst) MeV}/c^2$
  - $m(\Sigma_b^{*-}) - m(\Sigma_b^-) = m(\Sigma_b^{*+}) - m(\Sigma_b^+) = 21.2^{+2.0}_{-1.9} \text{ (stat) } ^{+0.4}_{-0.3} \text{ (syst) MeV}/c^2$

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



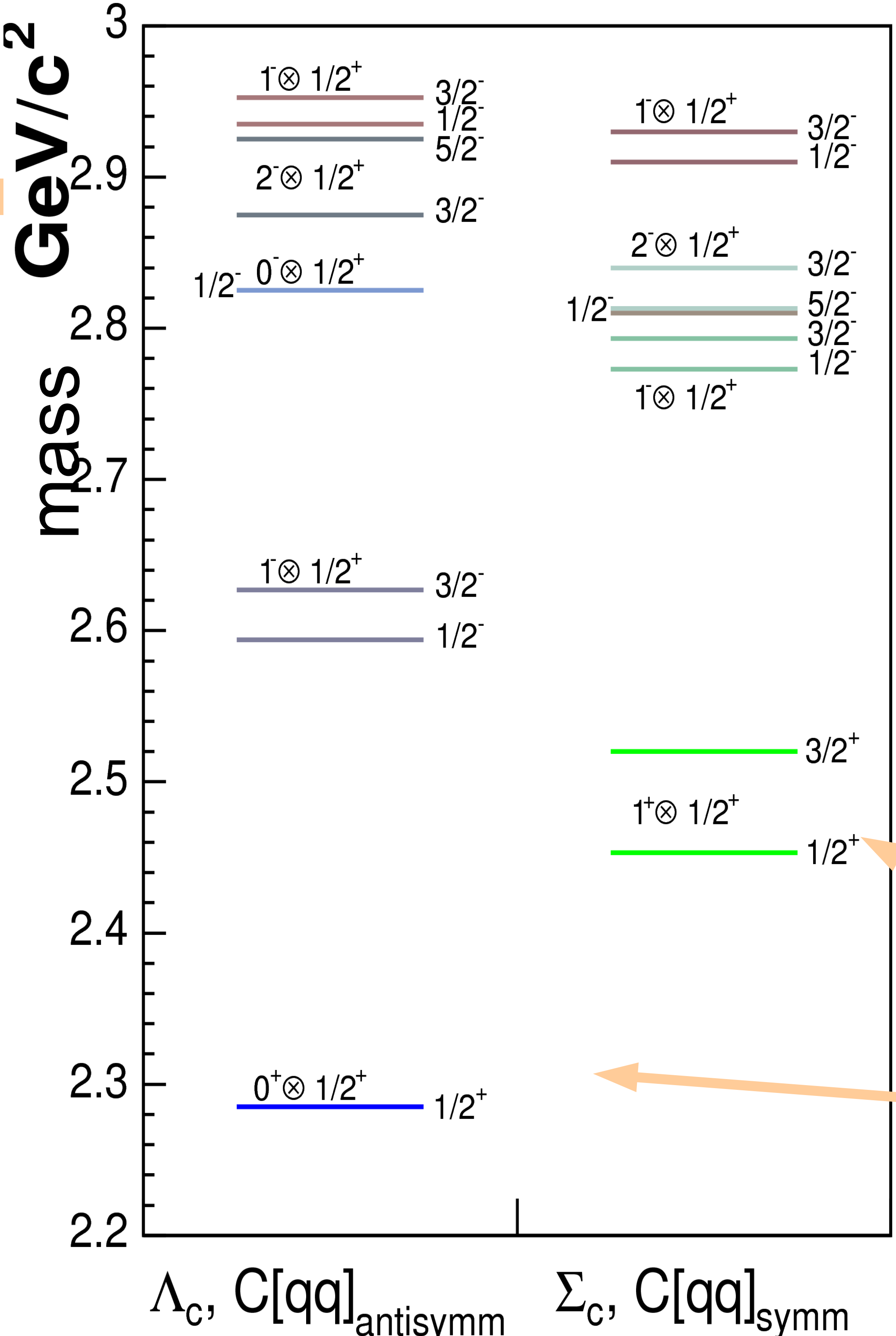
BACKUP SLIDES

Heavy baryon classification



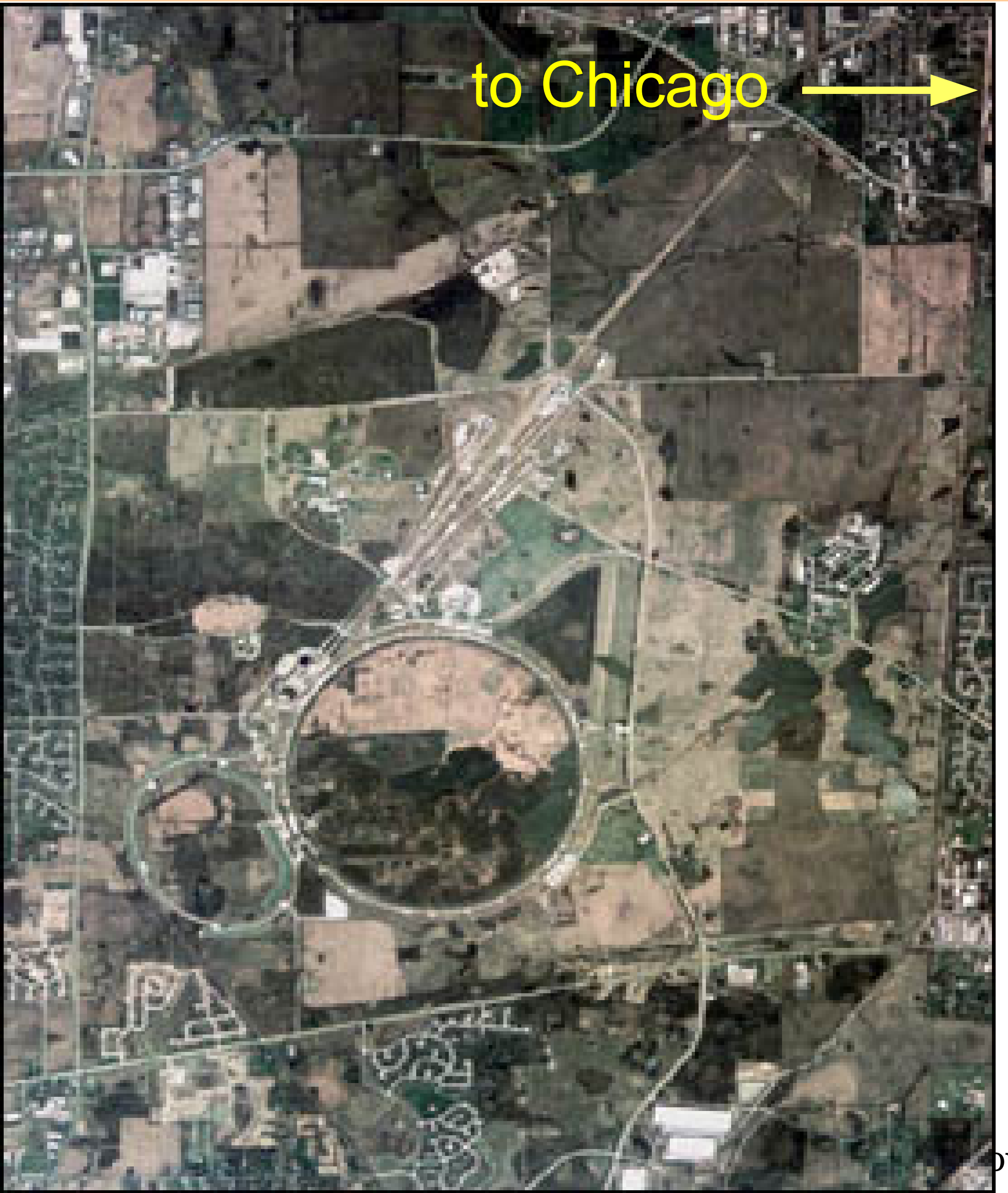
- Σ_b^+ is (uub), decaying to $\Lambda_b^0 \pi^+$
- Σ_b^- is (ddb), decaying to $\Lambda_b^0 \pi^-$

Λ_c and Σ_c states



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

Tools: Tevatron



- Recently, Tevatron has performed wonderfully
- By now over 2 fb^{-1} delivered to CDF and D0
- This analysis uses 1.1 fb^{-1} delivered to CDF by March 2006

Hopes for the future

- Have about 500 events in $\Lambda_b \to J/\psi\Lambda$
- Additional 1000 in $\Lambda_b \to \Lambda_c^+\pi^-$, but in different triggers
- Potentially another 1k in other channels like $\Lambda_b \to \Lambda_c 3\pi$

On the shopping list:

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