Discovering New Particles with CDF Detector at Tevatron

Igor Gorelov

University of New Mexico

On behalf of

CDF Collaboration, F.N.A.L.

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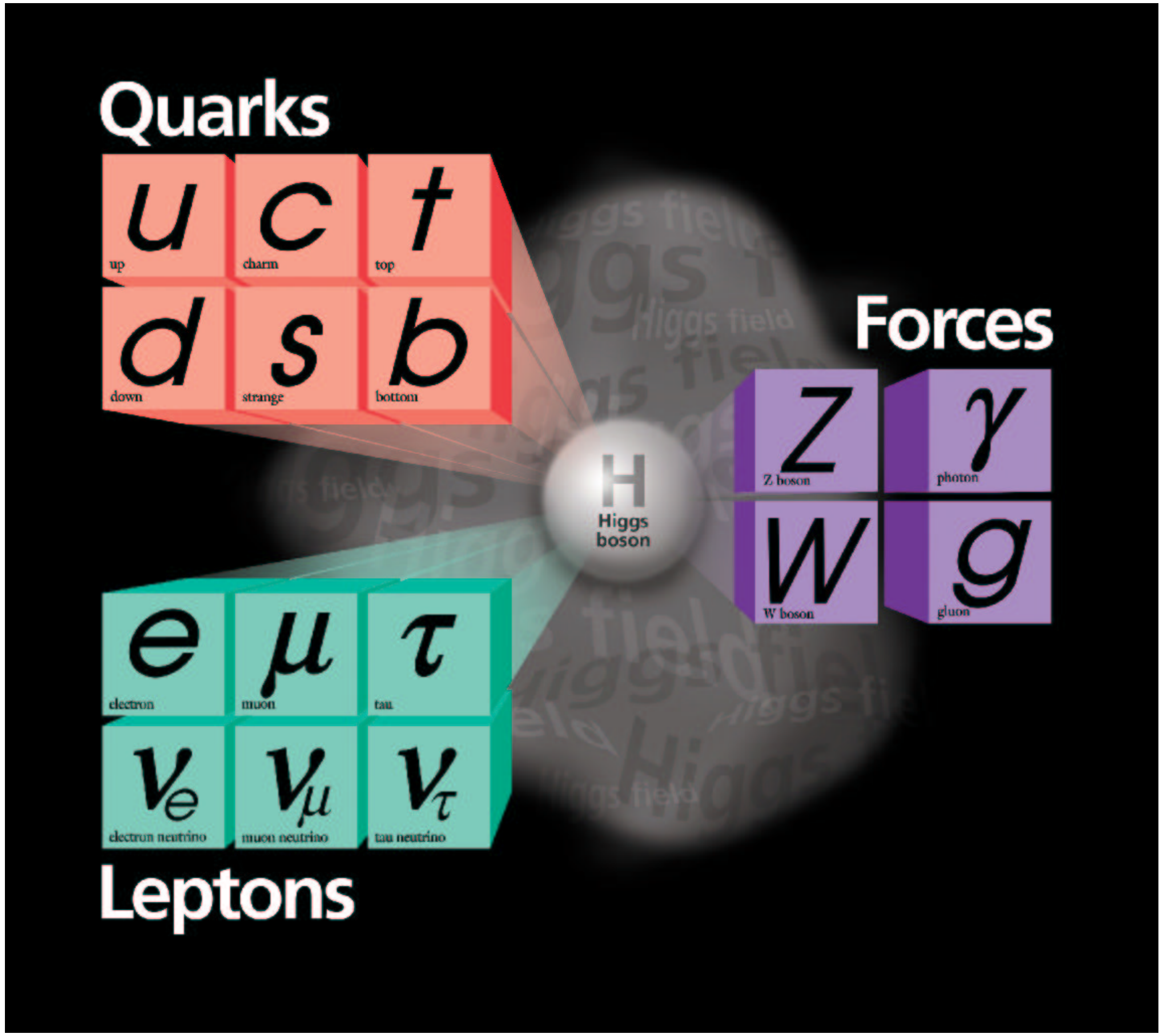
1 – Experiments in High Energy Physics

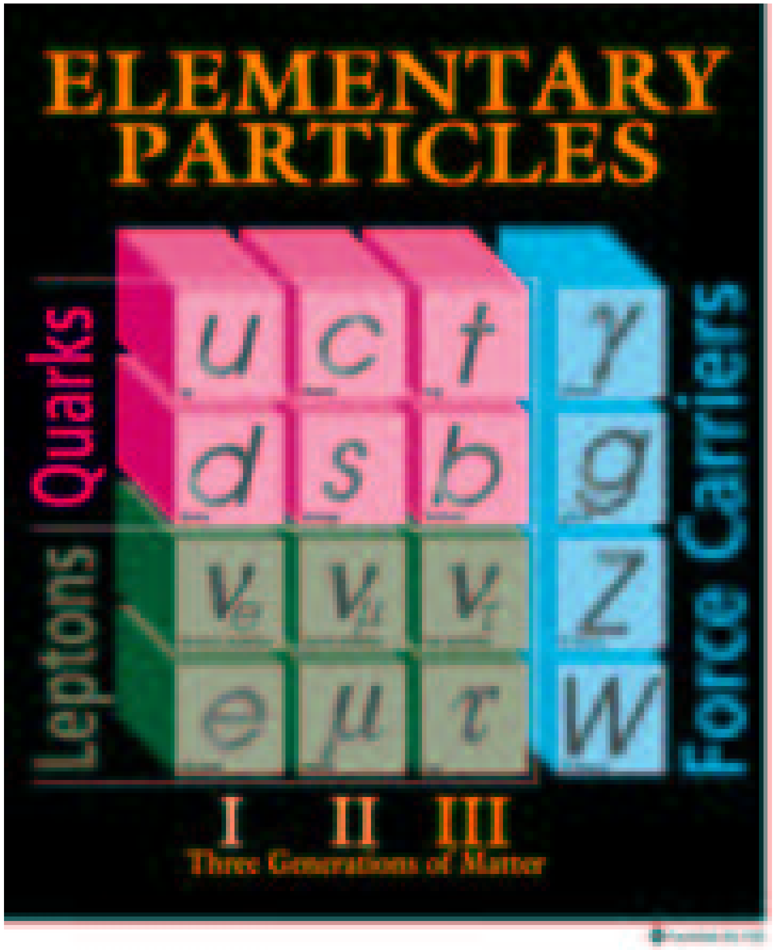
- People are programmed to want to understand how our world is put together.
- Driven by this desire HEP physicists conduct experiments to reveal the elementary structure of matter.
- The motivation: to learn about the Universe.
- But such experiments have many more general benefits for the society.

2 – Standard Model

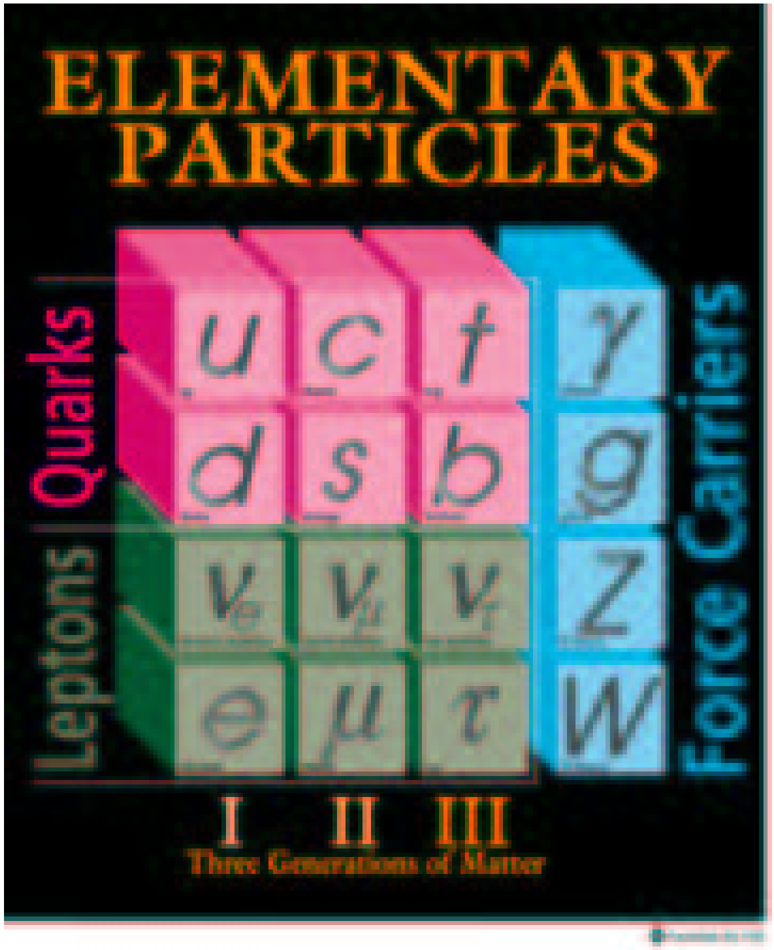
- **12 elementary "bricks" of matter**
- **6 Quarks**
- **6 Leptons**
- **4 Gauge Bosons mediating forces of Nature**
- **1 Higgs Boson as a source of a mass**



- There are three pairs of quarks:
  - “up” = u and “down” = d, “light” quarks.
  - “charm” = c and “strange” = s, “heavy” quarks.
  - “top” = t and “bottom” = b, “heavy” quarks.
- Quarks make up particles:
- Baryons (three quarks):
  - Proton $\mathbf{p} \equiv (\mathbf{uud})$
  - Neutron $\mathbf{n} \equiv (\mathbf{udd})$
  - which make up the nucleus of the atom.
- Mesons (quark and anti-quark):
  - π -Mesons $\pi^{+,0,-} \equiv (\mathbf{u\bar{d}}, \mathbf{u\bar{u}}, \mathbf{d\bar{u}})$
  - Non-stable, one of the component of cosmic rays.



- There are three pairs of leptons:
  - Electron e^- is the prototype for leptons.
  - e^- is orbiting nucleus; responsible for chemistry etc.
  - Neutrino ν_e initiates the reactions on a Sun, source of energy.
  - $(\mathbf{e}^-, \nu_\mathbf{e}), (\mu^-, \nu_\mu), (\tau^-, \nu_\tau)$
- There are three findamental forces between quarks and leptons.
- They arise through the exchange of bosons:
  - Electromagnetic - Photon = γ, long range
  - Weak nuclear - Weak bosons = W, Z^0 , range $\sim 10^{-16}\mathrm{cm}$
  - Strong nuclear - gluons = g, range $\sim 10^{-13}\mathrm{cm}$; Domain of Quantum Chromo-Dynamics
  - Gravity - ???, long range



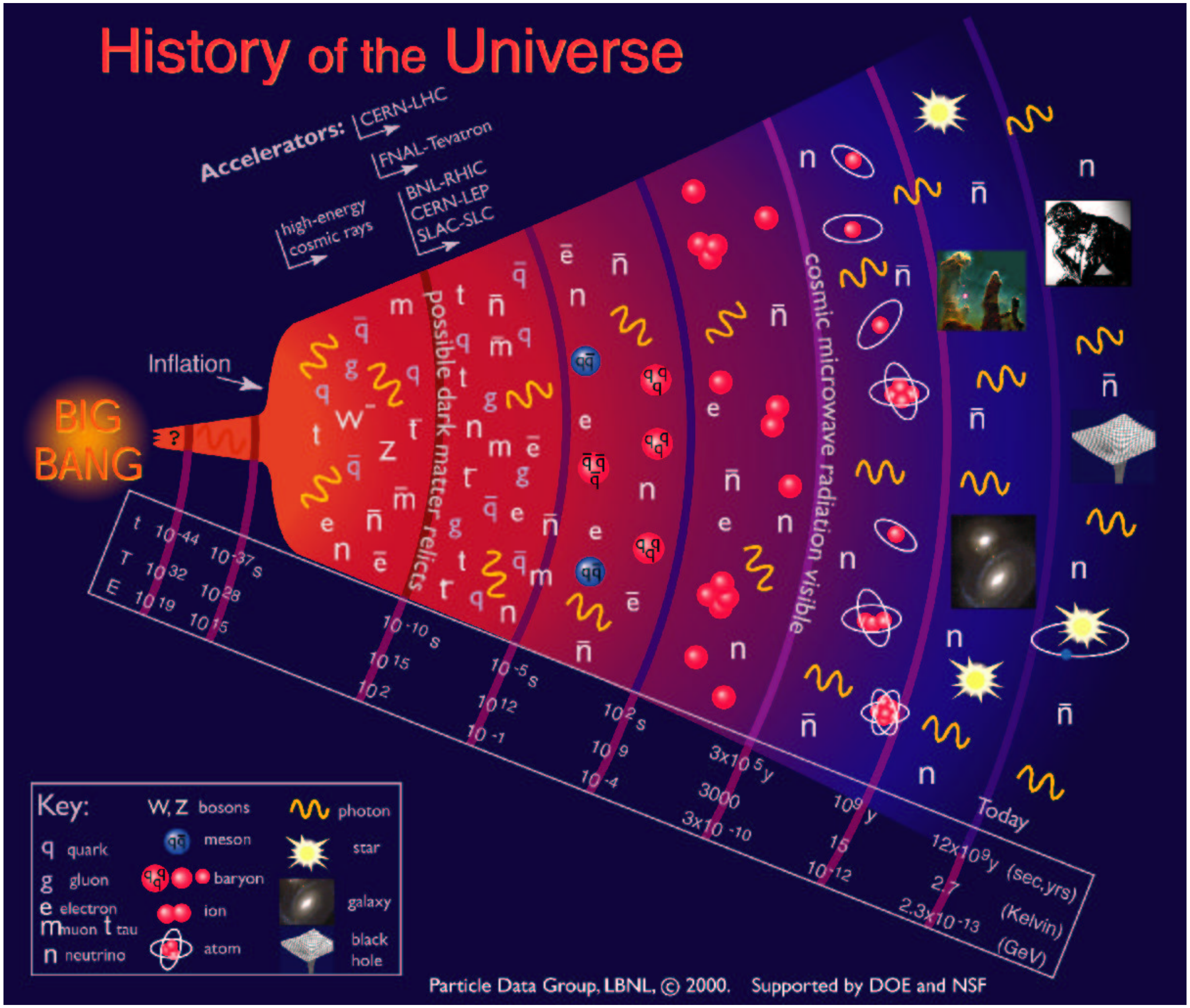
- **Quantum Chromodynamics (QCD) is believed to be the underlying theory of the strong interaction. It predicts gluons and confinement of quarks:**
  "The interaction is feeble at small separations, powerfull at large separations. (Confinement!)",
  Prof. Frank Wilczek (MIT), Nobel Lecture.
  - **In the high energy regime, QCD has been tested up to 1% level.**
  - **In the low energy sector, i.e. for bound quark states, QCD is highly nonperturbative due to its non-abelian nature. It is very difficult to calculate the whole hadron spectrum from first principles in QCD.**
  - **QCD-based quark model still has been up to now the most successful one. It is widely used to classify hadrons and calculate their masses, static properties and low-energy reactions, e.g. Heavy Quark Effective Theory approach developed by Isgur, Wise and Jonathan Rosner.**

$\Rightarrow$ **... and finally ...**

- **Baryons are the stuff of which our world is made. Thus the understanding of how QCD makes baryons must form the basis for an eventual understanding of the origin of the forces between nucleons and hence of the origin of the Mendeleev's Periodic Table.**

3 – Long Time Ago...

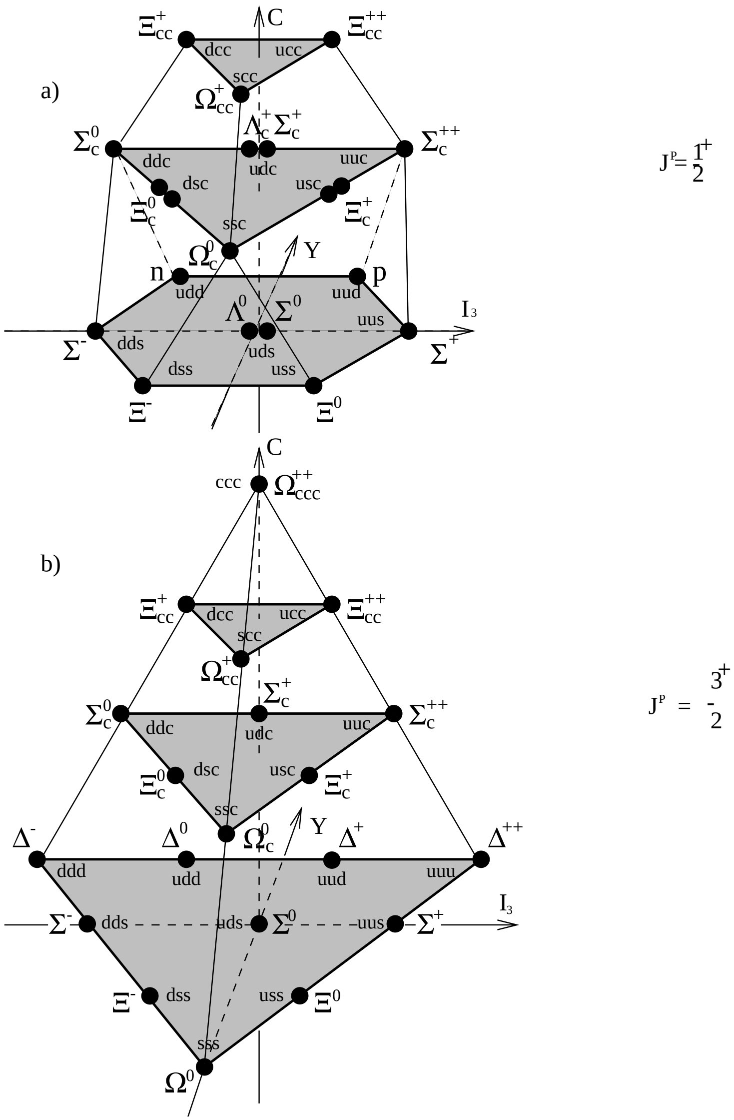
- $10\,\mu s$.
    - Quark flavours form variety of mesons and baryons, pions and protons etc.
- $300,000$ yrs.
    - Nuclei capture electrons: atoms.
- 13.7×10^9 yrs.
    - Today.



4 – Multiplets of Heavy Baryons

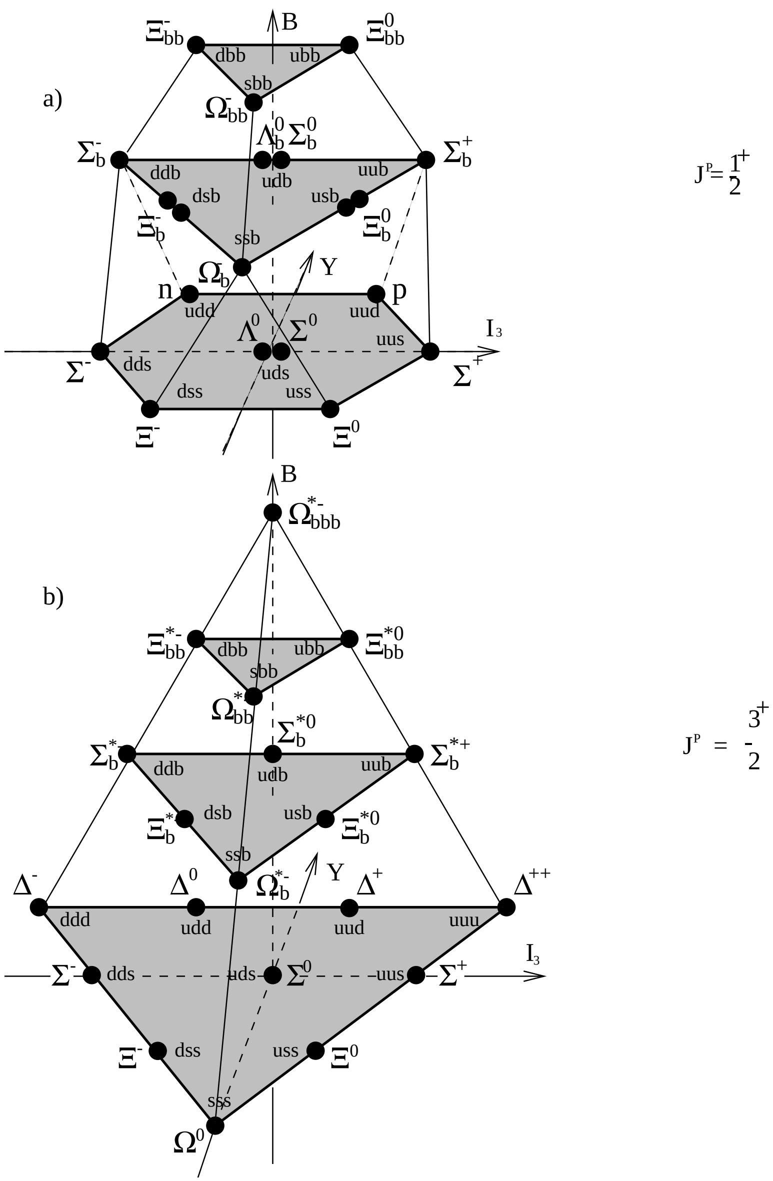
⇒ Baryons: Charm Sector

- **Baryon:** $\mathbf{q_{f_1}, q_{f_2}, q_{f_3}}$
- $\mathbf{I_3} \equiv$ **isospin (or electric charge) state.**
- $\mathbf{Y} \equiv \mathcal{B} + \mathbf{S} - \frac{\mathbf{C}}{\mathbf{3}}$**, hypercharge.**
- $\mathbf{C = +1}$**, charm of** c**- quark.**
  - **Ordinary SU$_f$(3) with** $\mathbf{f_i \in\ u,\ d,\ s}$
  - **Charmed SU$_f$(4) with** $\mathbf{f_i \in\ u,\ d,\ s,\ c}$
  - **SU$_f$(3) "ground-state" (no orbital excitations!)**
  - **SU$_f$(4) adds to "ground-states" additional floors along** $C-$**axis.**
- Presently established charmed ones:
  - $\mathbf{\Lambda_c^+, \Sigma_c, \Sigma_c^*, \Xi_c, \Xi_c^*, \Omega_c}$



$\Rightarrow$ Baryons: Bottom Sector

- **Baryon: $q_{f_1}, q_{f_2}, q_{f_3}$**
- **Ordinary SU$_f$(3) with $f_i \in$ u, d, s**
- **Bottom SU$_f$(5) with $f_i \in$ u, d, s, c, b**
- $\mathbf{Y \equiv \mathcal{B} + S - \frac{B}{3}}$**, hypercharge.**
- $\mathbf{B = -1}$**, bottomness of b- quark.**
  - **SU$_f$(3) "ground-state" (no orbital excitations!)**
  - **SU$_f$(5) adds to "ground-states" additional floors along $B-$axis**
- Established: $\mathbf{\Lambda_b^0 \equiv b\,[u\,d]}$
- **Recently discovered: $\mathbf{\Sigma_b^{(*)\pm} \equiv b\,q\,q}$**
- **Recently discovered: $\mathbf{\Xi_b^- \equiv b\,s\,d}$**

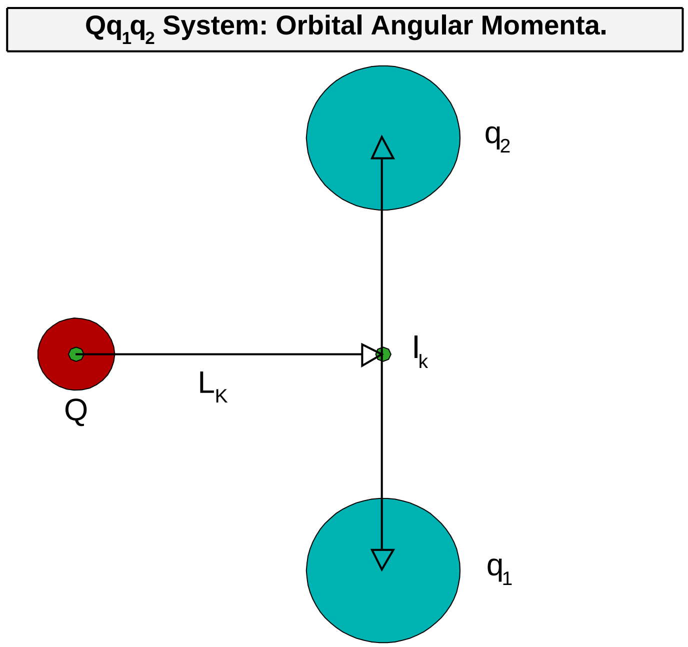


5 – QCD Phenomenology: Heavy Quark Effective Theory

$\Rightarrow$ **Quark "Helium"**

- QCD simplifies substantially in a presence of a heavy quark $\mathbf{Q}$, i.e.
- $\mathbf{m_Q \gg \Lambda_{QCD} \gg m_q}$, where
- $\mathbf{\Lambda_{QCD} \simeq 400\,MeV}$, typical scale of strong interaction's.
- $\mathbf{m_Q \simeq 4.8\,GeV,\ Q \equiv b}$.
- heavy quark spin **decouples** from light quark degrees of freedoms.
- $\mathbf{L_K}$ is orbital momentum of light $q_1 q_2$ w.r.t. heavy Q.
- $\mathbf{l_k}$ is internal, relative orbital momentum of light $\mathbf{q_1\ q_2}$ system.

$\Rightarrow$ **Heavy Q - Light $(\mathbf{q_1\ q_2})$**



$\Rightarrow \mathbf{j_{qq} = s_{qq} + L_{qq}}$

$\Rightarrow \mathbf{J_{Qqq} = s_Q + j_{qq}}$

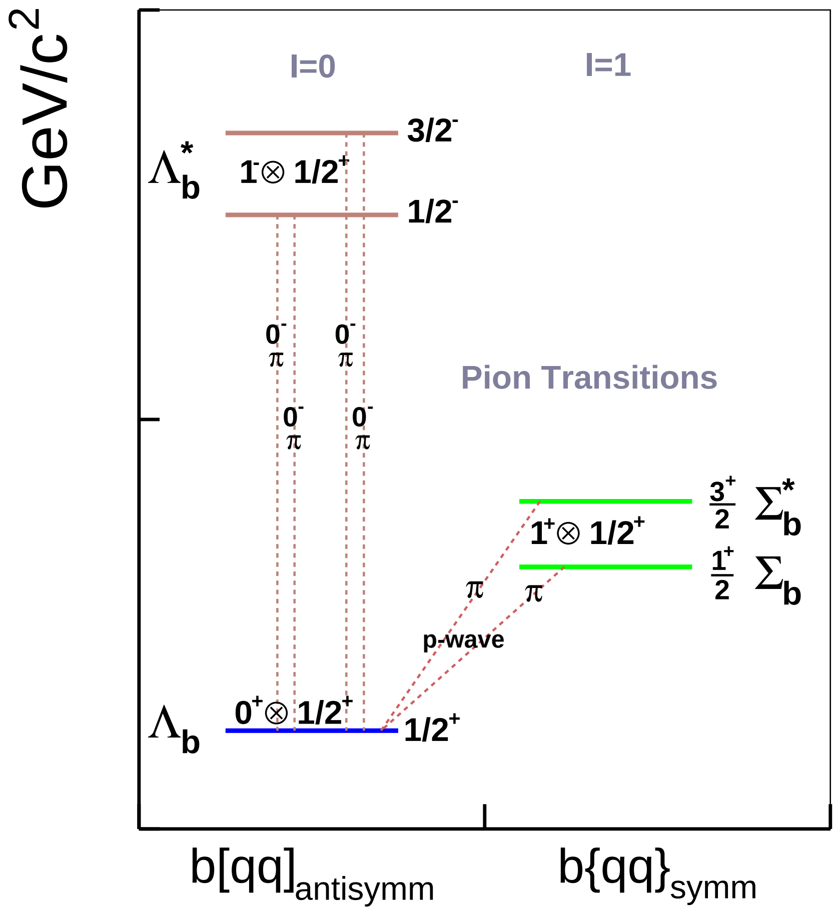
⇒ **Low Lying $\Sigma_b^{(*)\pm}$**

⇒ **Bottom Baryons**

⇒ **Theoretical Expectations:**

Σ_b property	MeV/c^2
$\mathbf{m(\Sigma_b) - m(\Lambda_b^0)}$	$\mathbf{180 - 210}$
$\mathbf{m(\Sigma_b^*) - m(\Sigma_b)}$	$\mathbf{10 - 40}$
$\mathbf{m(\Sigma_b^-) - m(\Sigma_b^+)}$	$\mathbf{5 - 7}$
$\mathbf{m(\Lambda_b^0)}$, fixed	$\mathbf{5619.7}$
from CDF II	$\pm 1.2 \pm 1.2$
$\mathbf{\Gamma(\Sigma_b), \Gamma(\Sigma_b^*)}$	$\sim 8, \sim 15$

⇒ HQET etc. models



⇒ $\mathbf{\Lambda_b^0} \rightarrow \mathbf{\Lambda_c^+}\pi^-$, weak decay.

⇒ $\mathbf{\Sigma_b^{(*)\pm}} \rightarrow \mathbf{\Lambda_b^0}\pi^\pm$, strong decay.

⇒ $\mathbf{\Lambda_b^{*0}} \rightarrow \mathbf{\Lambda_b^0}\pi^+\pi^-$, strong decay.

⇒ phase space allowing...

- **Cascade Bottom Baryon Ξ_b discovery channel:**
- **weak decay** $\Xi_b \rightarrow J/\psi\,\Xi^-$
- **with** $\Xi^- \rightarrow \Lambda^0 \pi^-$, $\Lambda^0 \rightarrow p\pi^-$
- **and** $J/\psi \rightarrow \mu^+\mu^-$
- **Theoretical Expectations:**
  - $m(\Xi_b) \sim (5788 - 5812)\,\mathrm{MeV}/c^2$

6 – Motivation for an Experimental Search on Σ_b

$\Rightarrow$ **It is fun to discover new particles!**

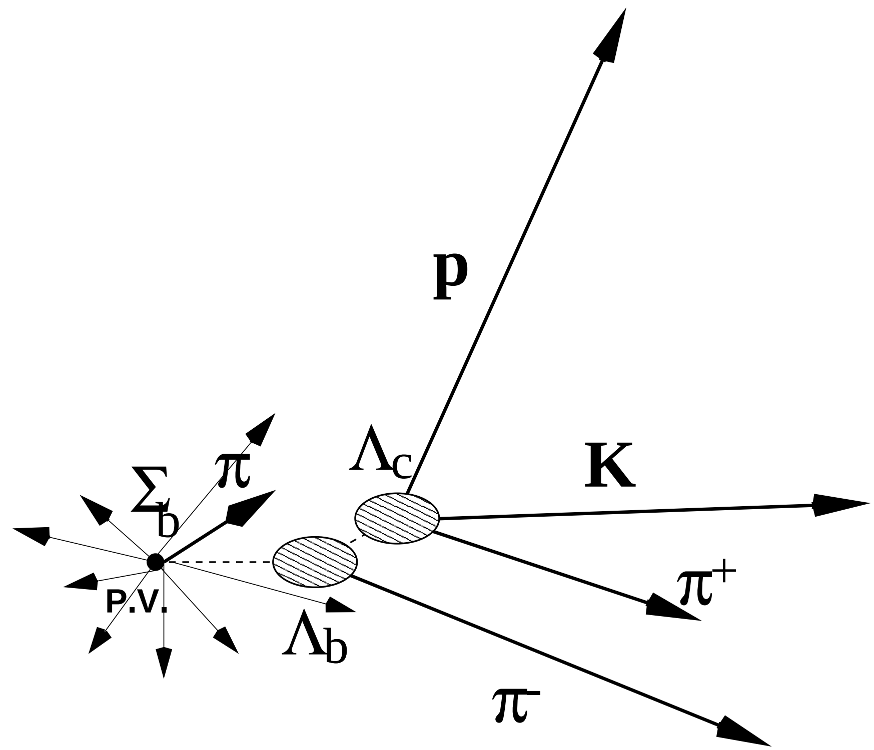
- Wealth of experimental data on bottom B-mesons from e^+e^- and hadron beams.
- Established **only one bottom baryon, the Λ_b^0,**
  - $\mathbf{\Lambda_b^0 \to J/\psi\, \Lambda^0}$
  - $\mathbf{\Lambda_b^0 \to \Lambda_c^+ \pi^-}$
  - $\mathbf{\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu}$

- **None of Σ_b states have been established so far.**
- Excellent track resolution of CDF tracker ...
- ...precise vertex reconstruction by Si-Detector SVX II ...
- both provide fine mass resolution.
  - Make possible to observe $\mathbf{\Sigma_b^{(*)\pm} \to \Lambda_b^0 \pi^\pm}$
  - Make possible to observe $\mathbf{\Xi_b^- \to J/\psi\, \Xi^-}$

7 – Principle of the Analysis

- Reconstruct Λ_b^0 baryon candidates:
  - $\mathbf{\Lambda_b^0 \to \Lambda_c^+ \pi^-}$
  - $\mathbf{\Lambda_c^+ \to pK^- \pi^+}$
- Candidates: $\mathbf{\Sigma_b \to \Lambda_b^0 \pi^\pm_{\Sigma_b}}$
- $\pi^\pm_{\Sigma_b}$, **soft track from Prim. Vtx.**
- **To remove the mass resolution of each Λ_b^0 candidate search for narrow signatures in**
- $\mathbf{Q = M(\Lambda_b^0 \pi^\pm_{\Sigma_b}) - M(\Lambda_b^0) - M_{PDG}(\pi^\pm)}$
- **Blind signal region.**
- **The S.B. represent Σ_b bgr.**

$\Rightarrow$ Topology of Σ_b event



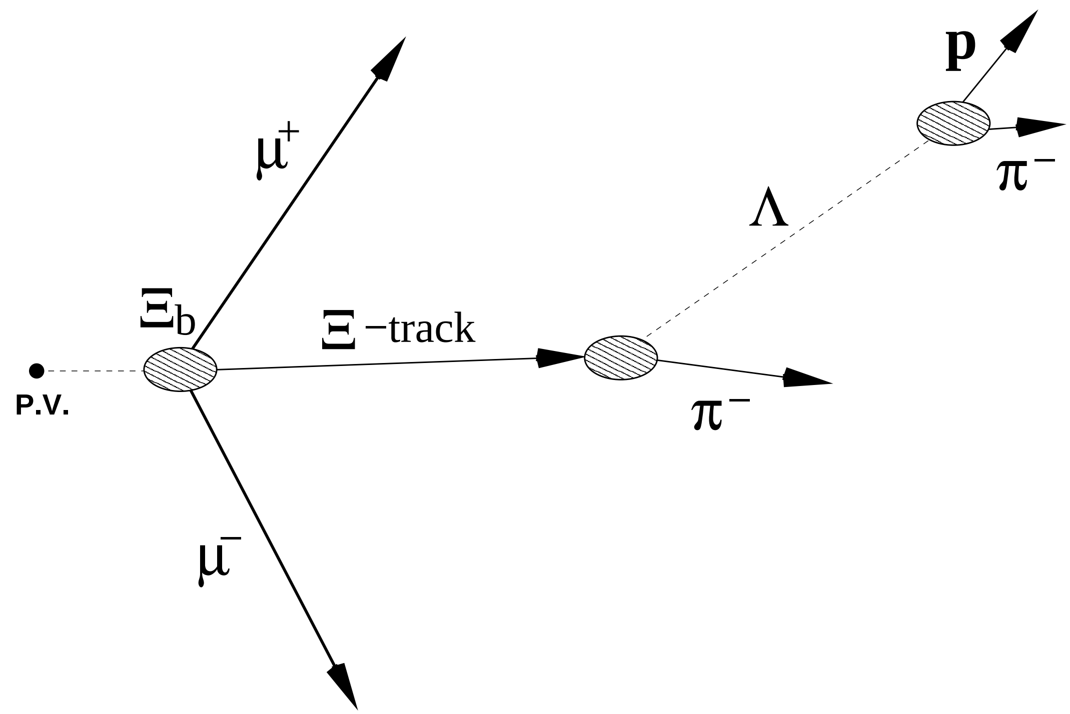
$\Rightarrow$ **Use bgr. from S.B. for cut optim.**

$\Rightarrow$ **Use signal from Monte-Carlo events for cut optim.**

$\Rightarrow$ **Fix cuts and unblind ...**

- Reconstruct J/ψ and Ξ^- candidates:
  - $\mathbf{J/\psi \rightarrow \mu^+\mu^-}$
  - $\mathbf{\Xi^- \rightarrow \Lambda^0\pi^-}$,
    $\mathbf{\Lambda^0 \rightarrow p\pi^-}$
  - **Two Secondary Vertexes**
- **Candidates:** $\mathbf{\Xi_b \rightarrow J/\psi\,\Xi^-}$
- **Search for a signal: spectrum of** $\mathbf{M(J/\psi\,\Xi^-)}$

$\Rightarrow$ **Topology of Ξ_b event**



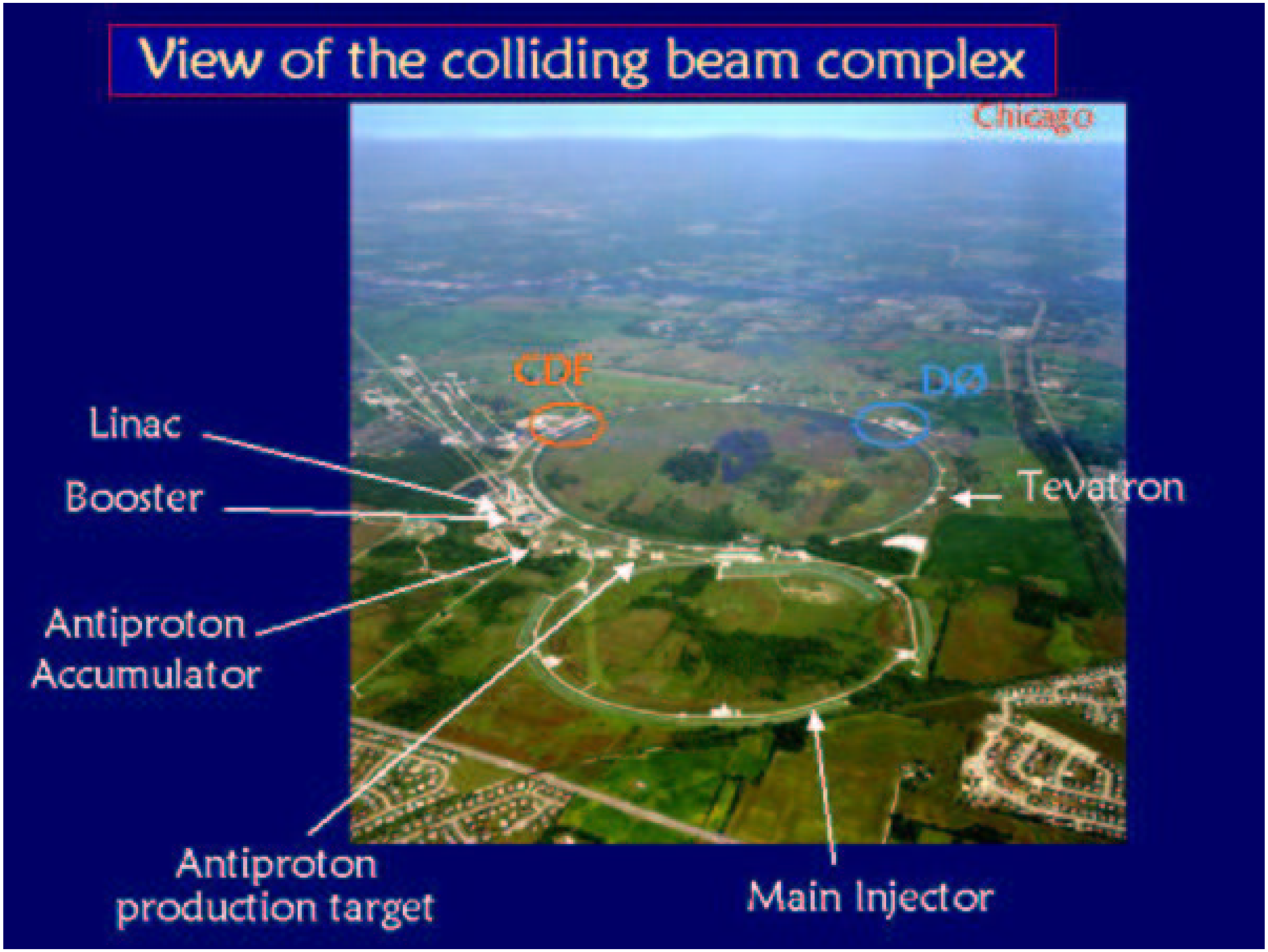
8 – Tevatron at FERMILAB

We need right tools and innovative ideas...

1. Accelerators... (Collider)

to produce very energetic particle beams for head-on collisions at the energy

$E_{CMS} = 1.96\,\mathrm{GeV}$

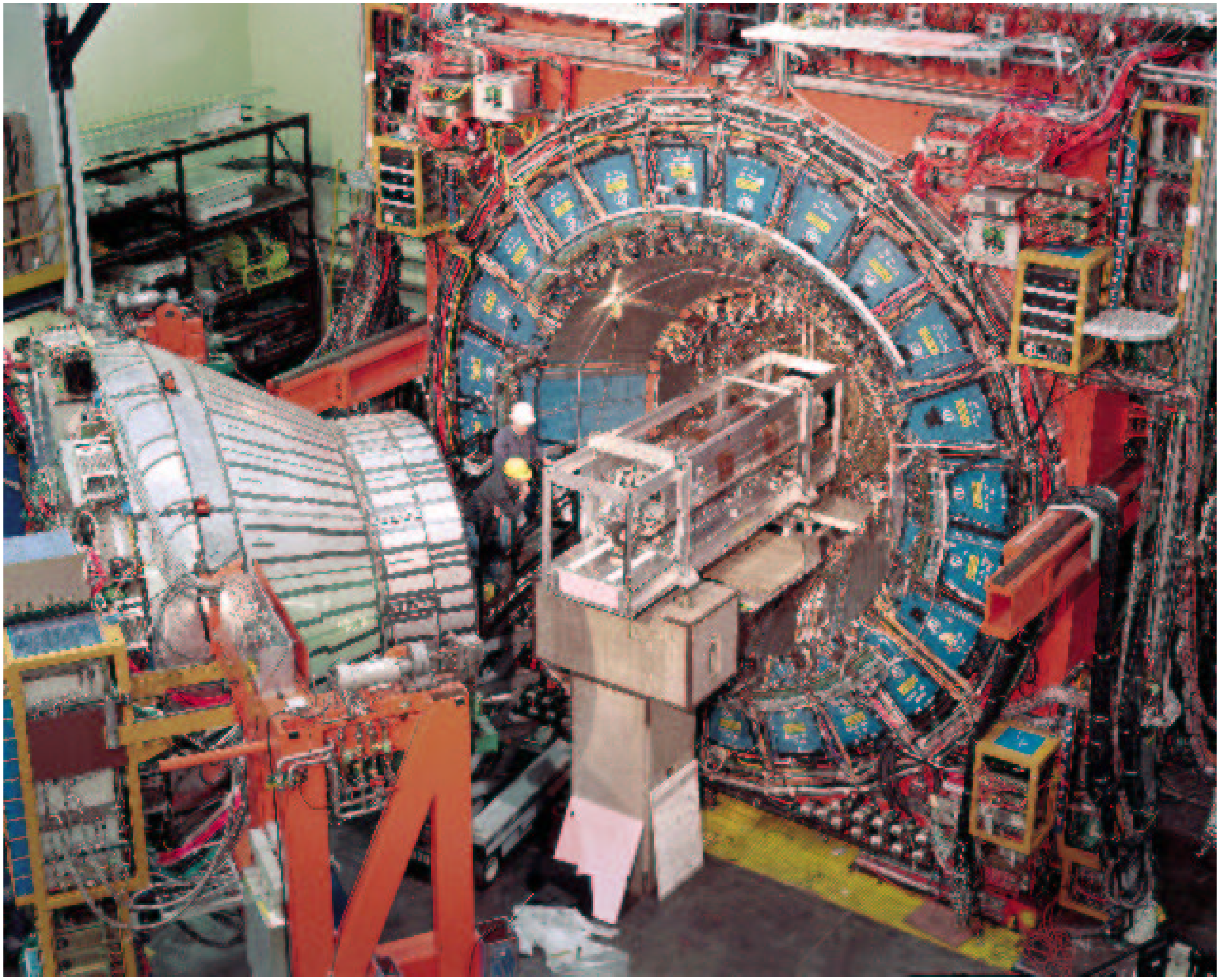


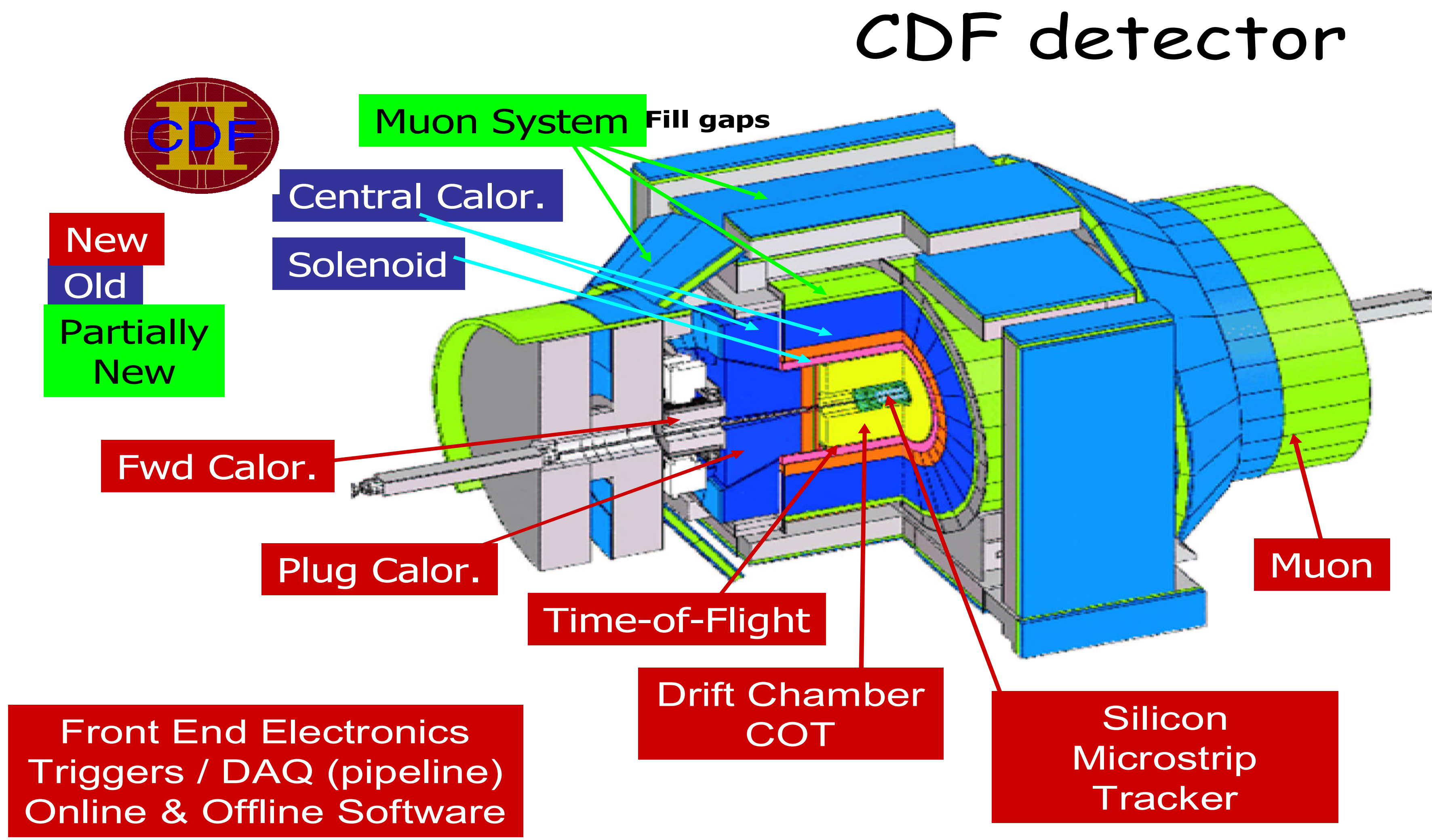
9 – CDF Detector at FERMILAB

We need right tools and innovative ideas...

2. Detectors...

to record particle directions, energy/momenta, and identity in violent $1.96\ \mathrm{TeV}\ p\bar{p}$-collisions.




CDF detector
CDF
New
Old
Partially New
Muon System
Fill gaps
Central Calor.
Solenoid
Fwd Calor.
Plug Calor.
Time-of-Flight
Drift Chamber COT
Silicon Microstrip Tracker
Muon
Front End Electronics
Triggers / DAQ (pipeline)
Online & Offline Software

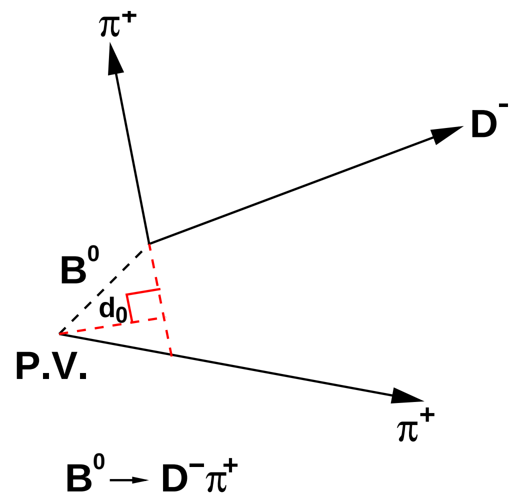
10 – b-Physics: Triggers and Data with CDF Detector

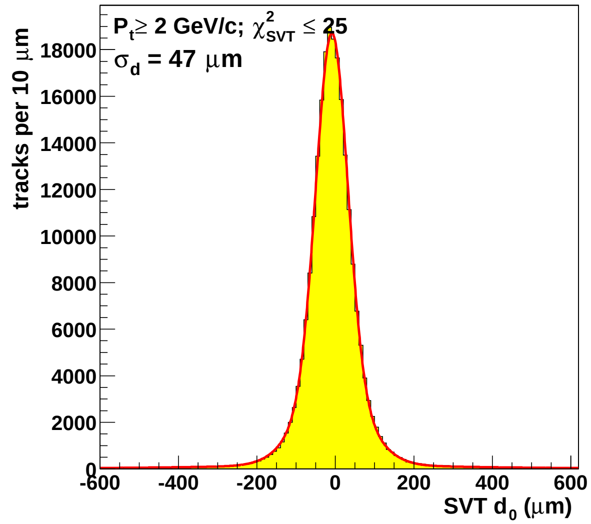
$\Rightarrow$ **Triggers and Events.**

- **The Trigger is a collection of devices, including electronics and detector components, that provide a fast signal (or decision) causing the entire detector information to be processed or finally recorded.**
- **Tevatron provides the $p\bar{p}$ collisions with the rate of ~ 1.7 MHz**
- **Trigger must reject $(1.7 \cdot 10^6 - 80)/1.7 \cdot 10^6 \approx$99.995% of collisions**
- **Need a trigger with the high efficiency to events of interest and high rejection power to the unwanted ones.**

- **The Event is a collective measurement or signals from all the Detector components (or subdetectors) in one time interval.**
- **The CDF event size $\sim \mathbf{0.25}\,\mathrm{Mbytes}$**
- **The actual output data flow to the tape is $\mathbf{20}\,\mathrm{Mbyte/s}$**

- **Enormous inelastic total cross- section of $\sigma_{\mathbf{tot}}^{\mathbf{inel}} \sim \mathbf{60}\,\mathrm{mb}$ at Tevatron.**
- $\sigma_{\mathbf{b}} \approx \mathbf{20}\,\mu\mathrm{b}\,(|\eta| < \mathbf{1.0}),\,@\mathbf{1.96\,TeV}$
- **Selective three-level trigger.**
- **Trigger on Hadron Modes .**
- **Exploit "long" $\mathrm{c}\tau$(b-hadrons)**
  - **Trigger on ≥ 2 tracks with large d_0.**
- **Present Σ_{b} analysis, base mode: $\mathbf{\Lambda_b^0} \rightarrow \mathbf{\Lambda_c^+}\pi_{\mathbf{b}}^-, \mathbf{\Lambda_c^+} \rightarrow \mathbf{pK}^-\pi^+, (\mathbf{p}, \pi_{\mathbf{b}}^-)$ are in trigger.**





Σ_b Candidates

11 – Σ_b Candidates

$\Rightarrow$ In $\mathbf{Q} \in (\mathbf{30}, \mathbf{100})\,\mathrm{MeV}/c^2$

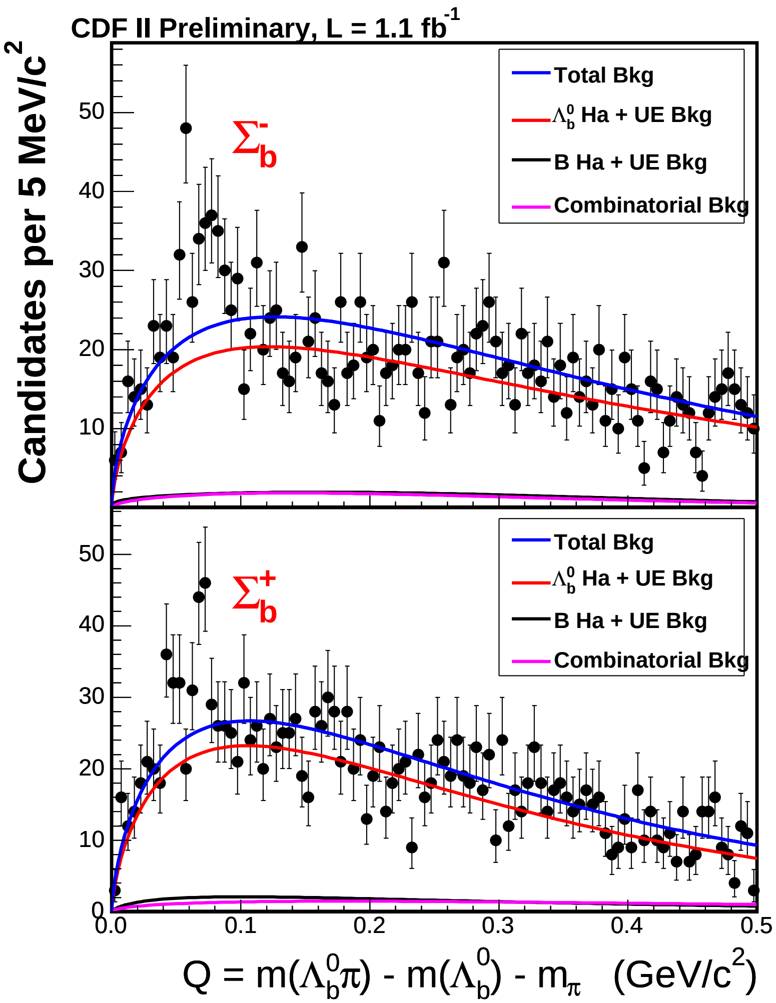
$\Rightarrow$ count number of evts:

Statistics	$\Lambda_b^0\pi^-$	$\Lambda_b^0\pi^+$
$S+B$	416	406
B	268	298
S	148	108
$S/\sqrt{S+B}$	7.3	5.4

$\Rightarrow$ The fit of the background

$\Rightarrow$ predicts B at signal area.

$\Rightarrow$ There is an excess in both spectra...



12 – Fit of $\boldsymbol{\Sigma_b}$ Spectra

$\Rightarrow$ **Fit Description:**

- Signals: 2 peaks Σ_b^-, Σ_b^{*-} and 2 peaks Σ_b^+, Σ_b^{*+}.
- Signal terms:

$$\mathbf{G_{1,2}} \otimes \mathbf{BW}(\mathbf{Q}; \mathbf{Q}_{\boldsymbol{\Sigma}_\mathbf{b}}, \sigma^{\mathbf{1,2}}_{\boldsymbol{\Sigma}_\mathbf{b}}, \boldsymbol{\Gamma}_{\boldsymbol{\Sigma}_\mathbf{b}}) +$$
$$\mathbf{G_{1,2}} \otimes \mathbf{BW}(\mathbf{Q}; \mathbf{Q}_{\boldsymbol{\Sigma}^*_\mathbf{b}}, \sigma^{\mathbf{1,2}}_{\boldsymbol{\Sigma}^*_\mathbf{b}}, \boldsymbol{\Gamma}_{\boldsymbol{\Sigma}^*_\mathbf{b}})$$

- **The shape and normalization of a background is frozen.**
- **Resolutions (narrow and wide components) $\sigma^{\mathbf{1,2}}_{\boldsymbol{\Sigma}^{(*)}_\mathbf{b}}$ (from CDF MC sim.)**

- **Natural widths are constrained by HQET formula $\boldsymbol{\Gamma}(\mathbf{Q}^{\text{being fit}}_{\boldsymbol{\Sigma}^{(*)\pm}_\mathbf{b}})$.**
- **Seven parameters floating:**
  - $\mathbf{Q}(\boldsymbol{\Sigma}^-_\mathbf{b})$, $\mathbf{Q}(\boldsymbol{\Sigma}^+_\mathbf{b})$
  - $\mathbf{Q}(\boldsymbol{\Sigma}^*_\mathbf{b}) - \mathbf{Q}(\boldsymbol{\Sigma}_\mathbf{b})$, constrained to be **the same** for both charged cands.
  - Number of events: $\mathbf{N}(\boldsymbol{\Sigma}^{(*)\pm}_\mathbf{b})$
- **Perform a simultaneous unbinned negative likelihood fit using full statistics of both spectra.**

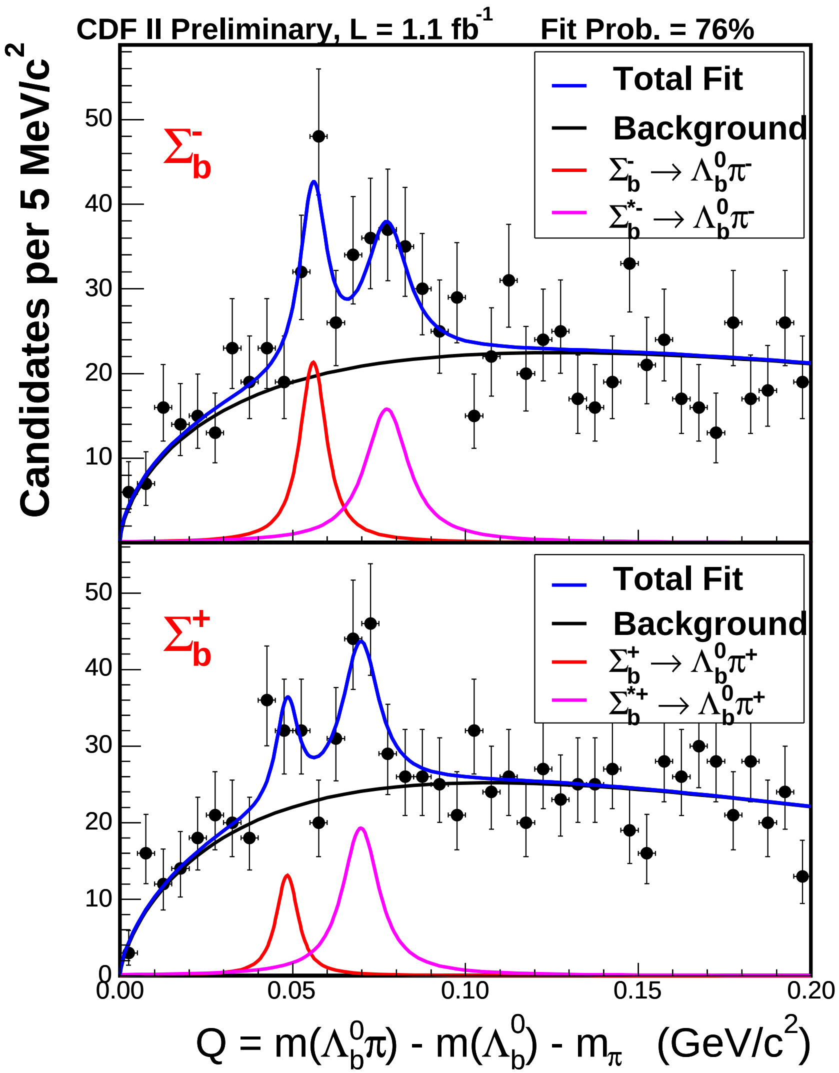
$\Rightarrow -\ln(\mathbf{Lh})$ **Fit Results:**

Parameter	Value$\pm\delta(\mathrm{stat})$
$Q(\Sigma_b^+)$ MeV$/c^2$	$48.4^{+2.02}_{-2.29}$
$Q(\Sigma_b^-)$ MeV$/c^2$	$55.9^{+0.99}_{-0.959}$
$[Q(\Sigma_b^*) - Q(\Sigma_b)]$ MeV$/c^2$	$21.3^{+2.03}_{-1.94}$
Σ_b^+ events	$29^{+12.4}_{-11.6}$
Σ_b^- events	$60^{+14.8}_{-13.8}$
Σ_b^{*+} events	$74^{+17.2}_{-16.3}$
Σ_b^{*-} events	$74^{+18.2}_{-17.4}$

$\Rightarrow$ **Errors come from MINOS.**

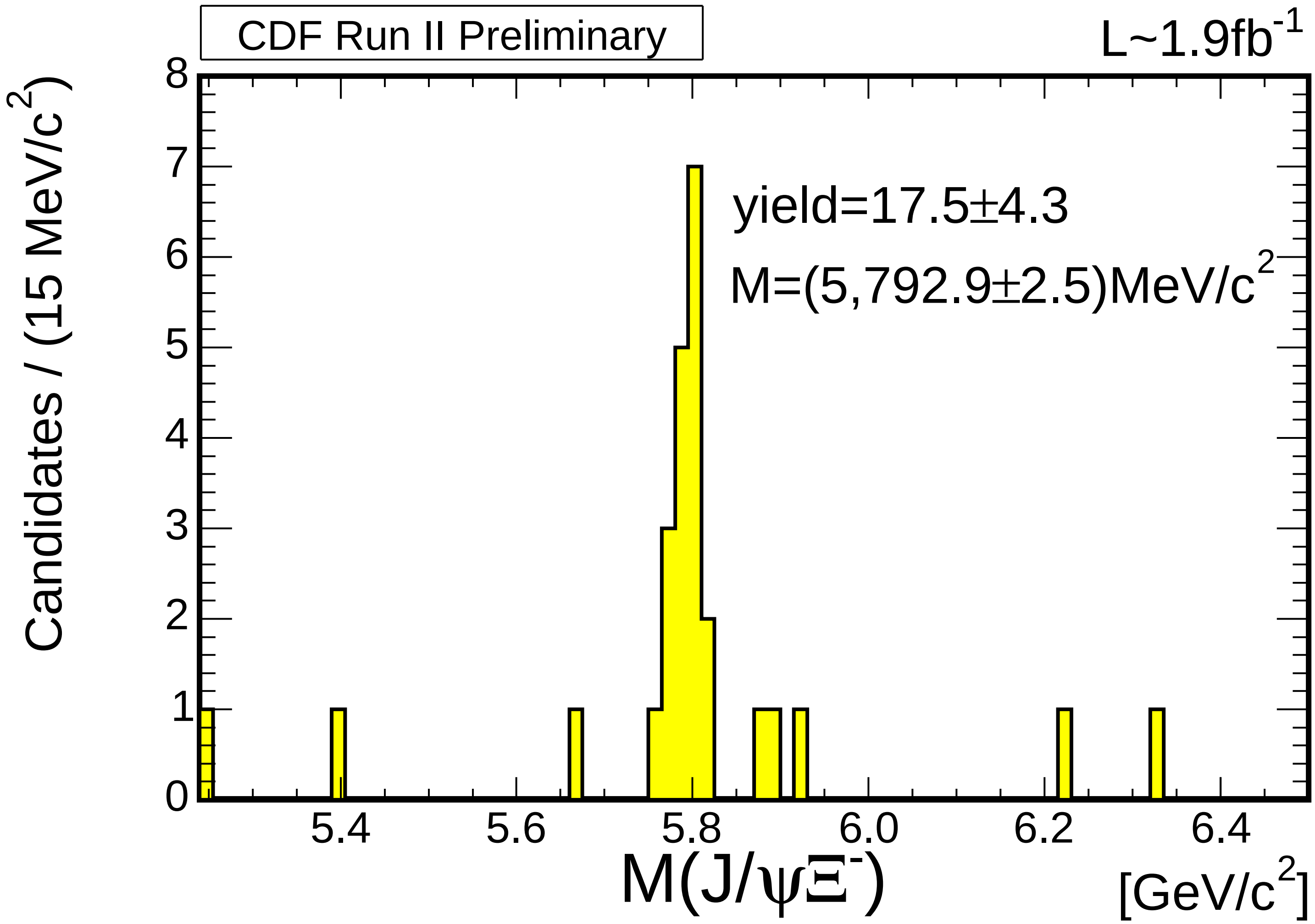
$\Rightarrow$ Σ_b^+ **yield is weak** $\Rightarrow$

$\Rightarrow$ $Q(\Sigma_b^+)$ **has large correlation with** ΔQ



Ξ_b Candidates

13 – Ξ_b Candidates

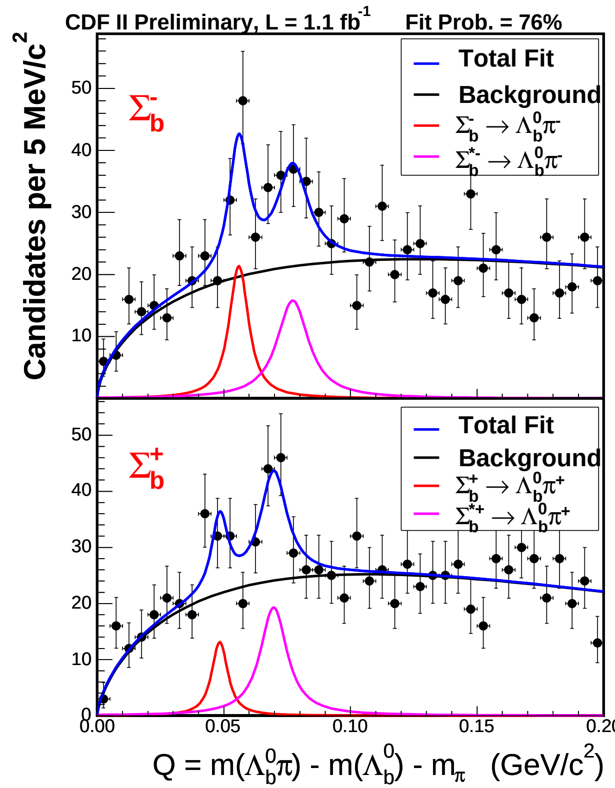


14 – Summary

$\Rightarrow$ **CDF (UNM, JHU, FNAL) Discovery of Σ_b**

$\Rightarrow$ **CDF (and D0) (FNAL) Discovery of Ξ_b**

Fermilab Today



http://www.fnal.gov/pub/today/archive_2006/today06-10-23.html

http://www.fnal.gov/pub/presspass/press_releases/sigma-b-baryon.html

THE END OF THE TALK.