New Bottom Baryons at CDF

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for CDF Collaboration

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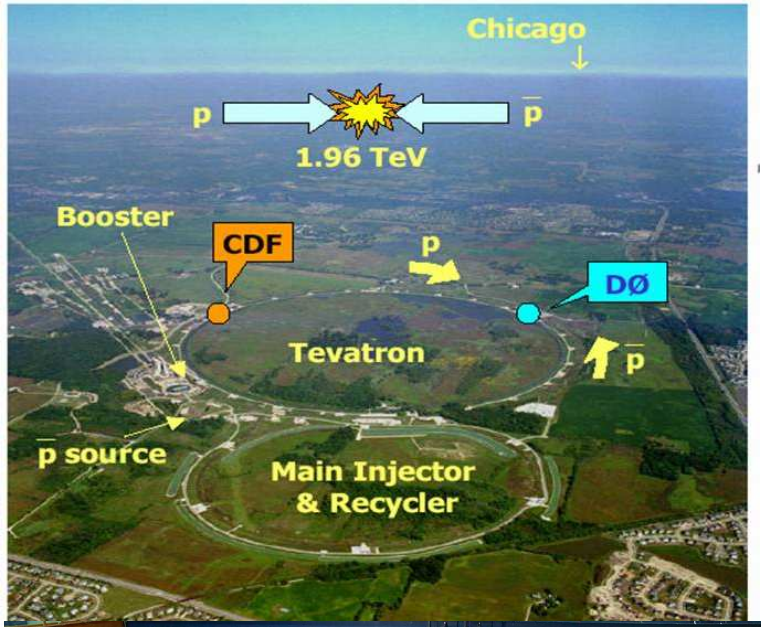
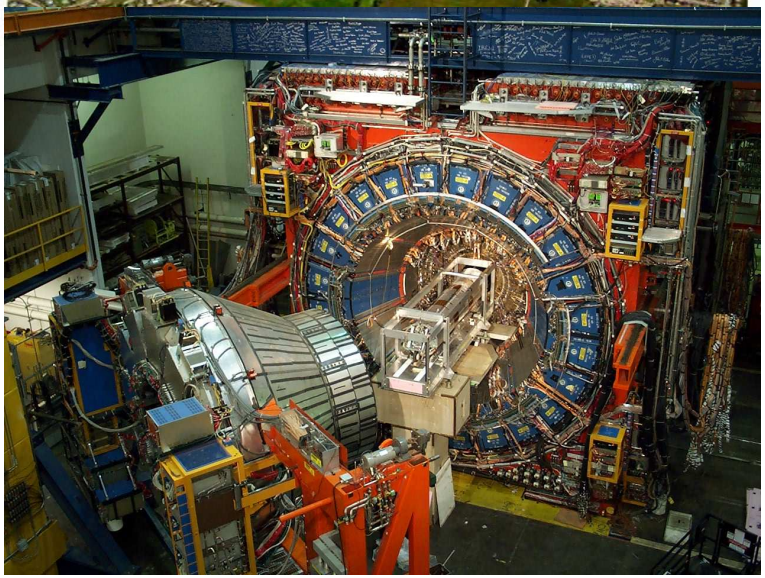
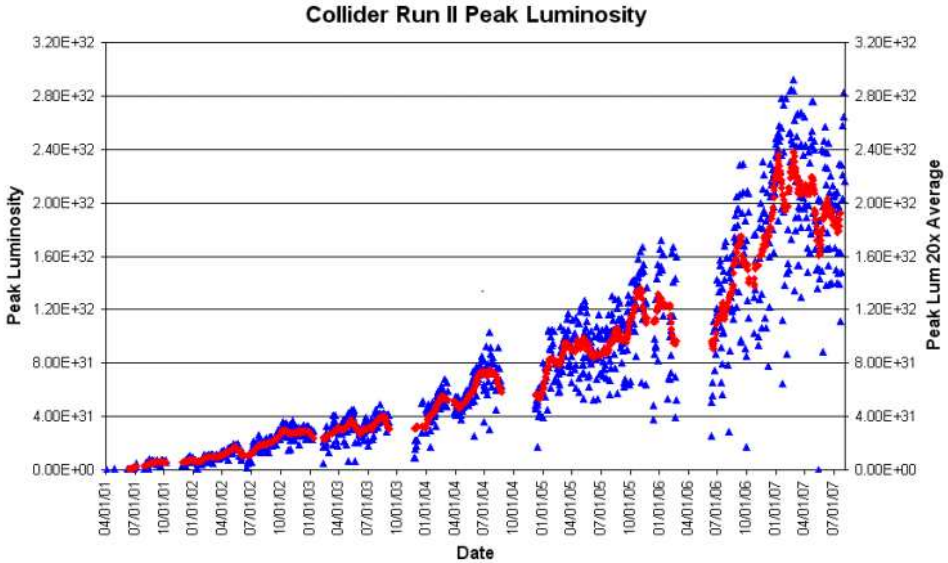
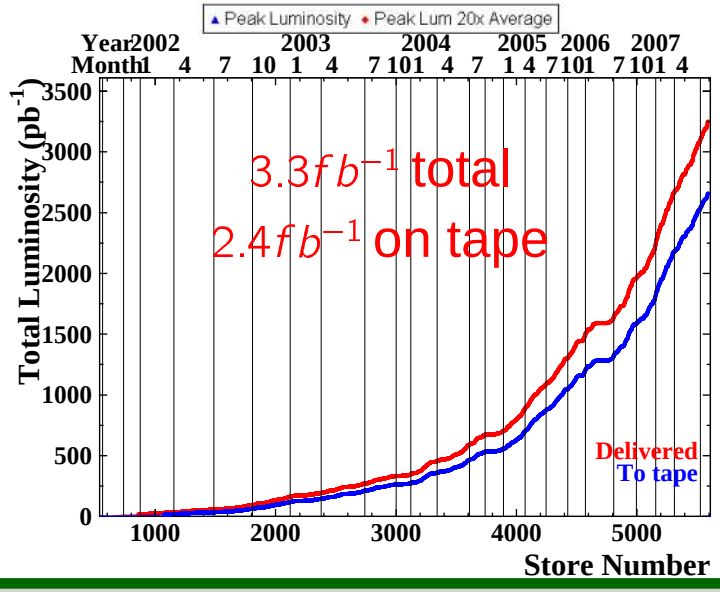
Source of data: Tevatron



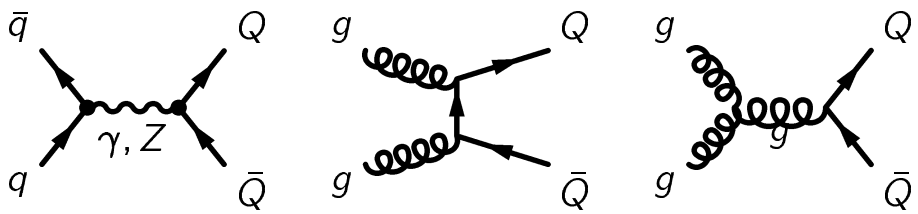




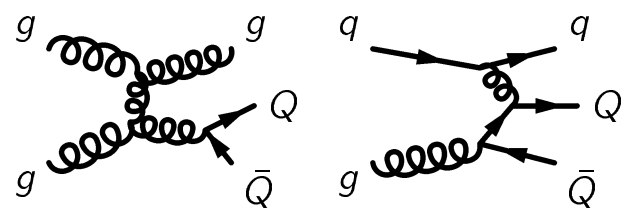


Heavy Flavor Production at Tevatron

LO Heavy quark production



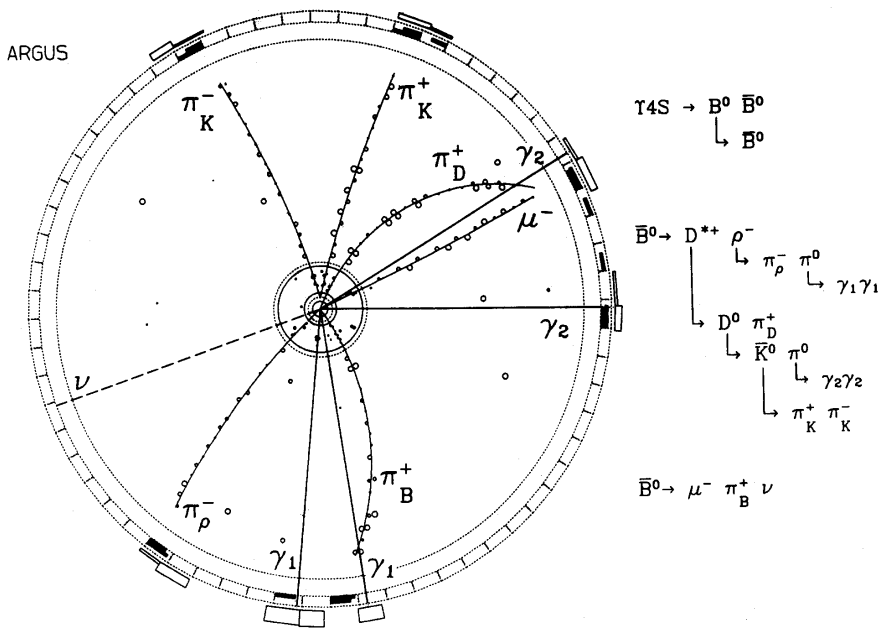
NLO Heavy quark production



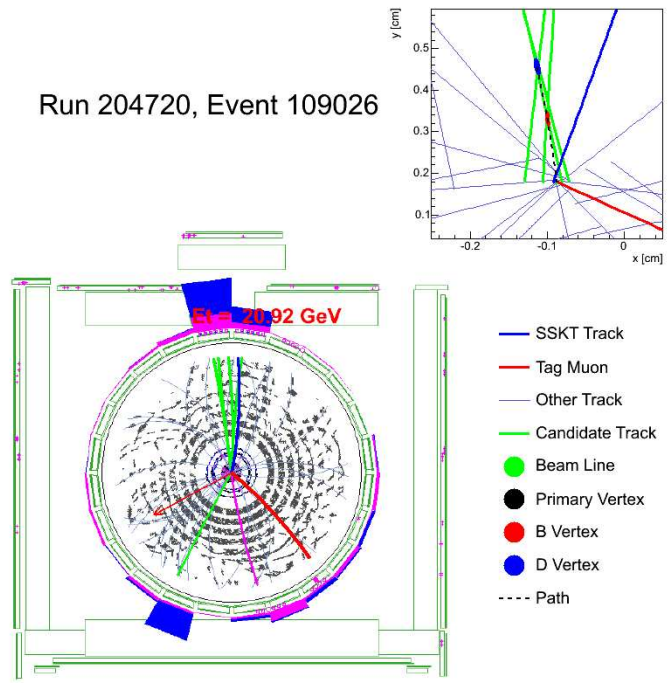
Accelerator	PEPII,KEK	Tevatron
$\sigma(b\bar{b})$	1 nb	100 μb (10 μb $\lvert y\rvert < 1$)
$\sigma(b\bar{b}) : \sigma(had)$	0.26	0.001
Production	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$	$p\bar{p} \to b\bar{b}X$
Environment	clean	messy
Hadrons produced	B^0, B^+	all
Boost	0.5	2-4
Kinematics	forward boost	$b\bar{b}$ not back-to-back, second b usually lost
pile-up	no	yes
Trigger	inclusive	selective
Beam energy constraint	yes	no

Dedicated triggers are pre-requisite to efficient extraction of heavy flavor signals from the data

Source of data: Event Environment



Completely reconstructed $\Upsilon(4S) \to B^0\bar{B}^0$ event with $B^0 - \bar{B}^0$ mixing in ARGUS Experiment (Phys. Lett. B55 (1991),297)



$B^0_s - \bar{B}^0_s$ mixing candidate event in CDF II, 2006

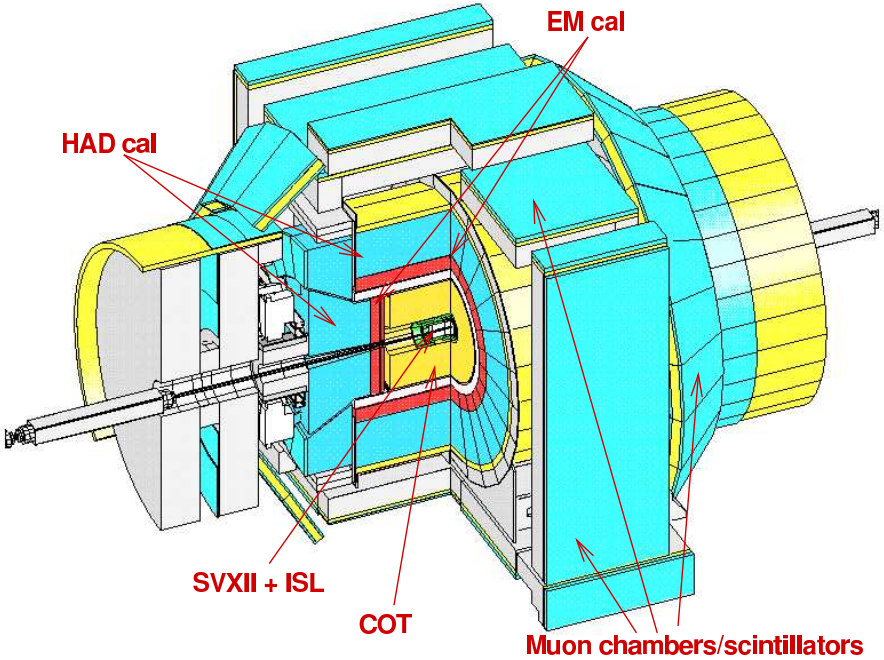
CDF II Detector

- **tracking**
  - Drift Chamber – Central Outer Chamber
  - Layer00 + SVXII + ISL
- **new plug calorimeter**
- **extended muon coverage, $|\eta| < 1.5$**
- **ToF system, (100 ps @ 150 cm)**
- **improved DAQ and trigger systems**
  - new frontend electronics
  - Level 1 all digital synch. h/w trigger. 132 ns pi
  - 40kHz/1kHz/100 Hz
  - COT Tracks @ Level 1
  - Si Tracks @ Level 2
  - Full analysis @ Level 3
  - First hadronic B-trigger

- Silicon vertex trigger (SVT)

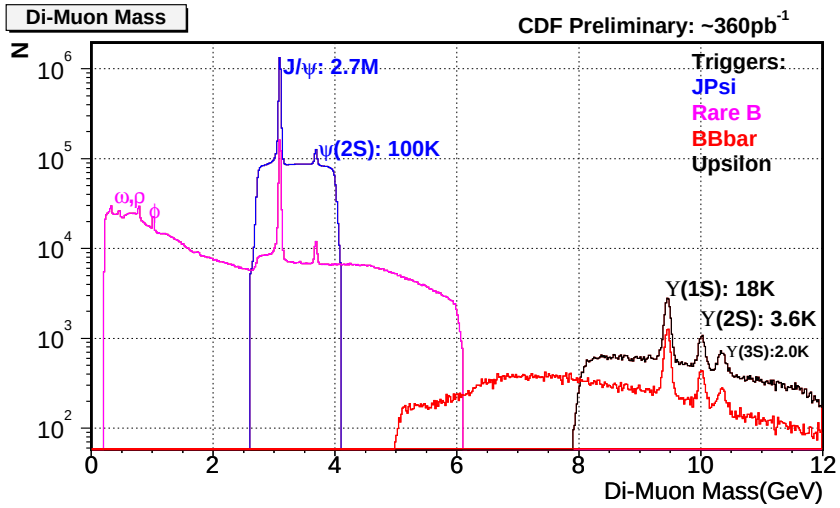
- PID with ToF and dE/dx

- Excellent mass resolution



CDF Run II di-muon triggers

- di-muon triggers ($B \to \mu\mu X$):
  - ✓ J/ψ trigger – di-muon events with masses around $J/\psi, \psi(2S)$ (two CMU muons or 1 CMU and 1 CMX muon)
  - ✓ Rare B trigger – di-muon events with masses in expanded mass range from 0 to 6 GeV with tighter cuts.
    - Either two CMU muons
    - or CMU muon and CMX muon plus lateral displacement of di-muon intersect w.r.t. primary vertex, and $\Sigma(p_T)$ cut
    - or alternatively as CMU or CMX muon and a CMUP(CMU and CMP) muon without requirements of displacement or $\Sigma(p_T)$
  - ✓ $b\bar{b}$ trigger – di-muon events with masses in expanded mass range from 5 to 12 GeV. Both muons must be CMUP muons.
  - ✓ Upsilon trigger: di-Muon events in a mass range around the Upsilon. Either a CMU or CMX muon and a CMUP muon.

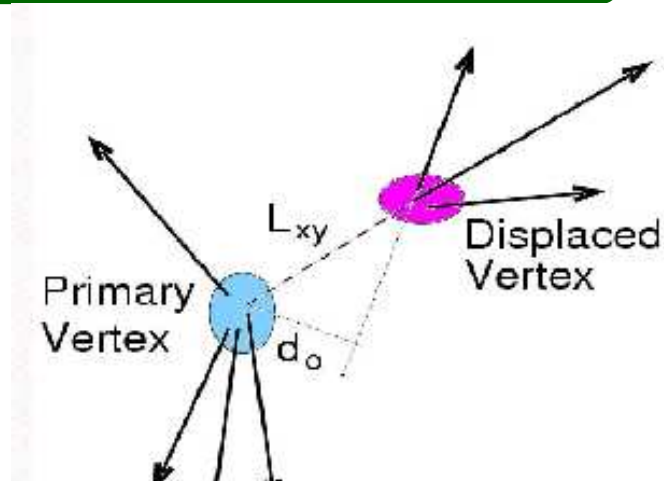


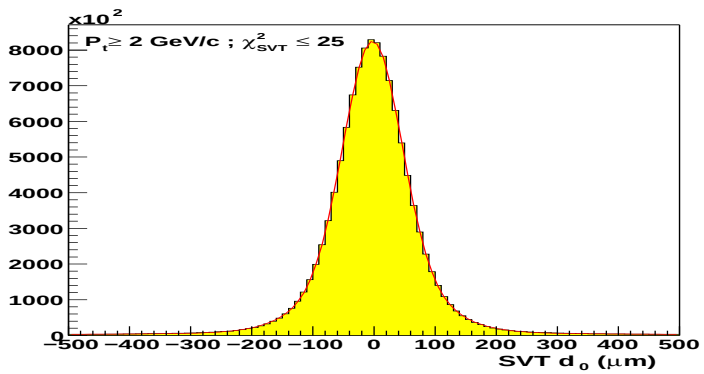
di-muon mass in CDF II di-muon triggers

Displaced track triggers

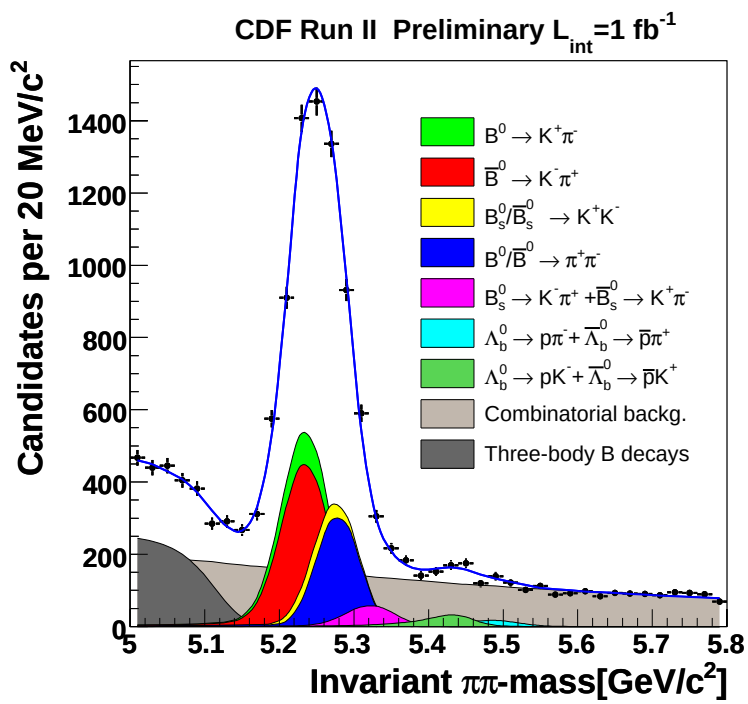
- New displaced track triggers (two track and ℓ+track) exploit b-quark lifetime.
  - Level 1
    - ✓ XFT tracking in COT ($r-\phi$)
    - ✓ opposite charged track pair with $p_T > 2$ GeV/c each
    - ✓ $\Sigma p_T > 5.5$ GeV/c
    - ✓ $\Delta\phi < 90°$
  - Level 2
    - ✓ XFT track seeds SVT boards, that perform fast ($r-\phi$) track fit
    - ✓ repeat Level 1 cuts
    - ✓ require tracks impact parameter to be $0.012 < |d_0| < 0.1$ cm
    - ✓ require $L_{xy} > 0.02$ cm

ℓ+track uses slightly different set of cuts

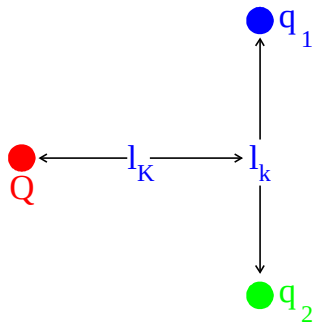




$\sigma(d_0)_{SVT} = 47\ \mu m$ (including $\sigma(beam) = 33\ \mu m$)



Heavy Baryons



- $q = u, d, s$; $Q = c, b$; $m_Q \gg \Lambda_{QCD}$
- $$\vec{k} = \tfrac{1}{2}(\vec{p}_1 - \vec{p}_2)$$
  $$\vec{K} = \tfrac{1}{2}(\vec{p}_1 + \vec{p}_2 - 2\vec{p}_3)$$
- Convenient to consider that q_1, q_2 form a diquark, in SU(3):
  $$\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}} \oplus \mathbf{6}.$$
- Λ-type $Q[q_1 q_2]$ Σ-type $Q\{q_1 q_2\}$,

- ground states $l_k = 0, l_K = 0$:
  - $j_{qq} = s_{qq} = 0$
    $$J = j_{qq} \otimes s_Q = \frac{1}{2}^+ \{\Lambda_c, \Xi_c, \Lambda_b, \Xi_b\}$$
  - $j_{qq} = s_{qq} = 1$
    $$J = j_{qq} \otimes s_Q \begin{array}{l} \nearrow \frac{3}{2}^+ \\ \searrow \frac{1}{2}^+ \end{array} \left\{ \begin{array}{l} \Sigma_c^*, \Xi_c^*, \Sigma_b^*, \Xi_b^*, \Omega_b^* \\ \\ \Sigma_c, \Xi_c', \Sigma_b, \Xi_b', \Omega_b \end{array} \right\}$$
- Λ-like P-wave excitations $l_k = 0, l_K = 1$:
  - $j_{qq} = 1, s_{qq} = 0$
    $$J = j_{qq} \pm s_Q \begin{array}{l} \nearrow \frac{3}{2}^- \\ \searrow \frac{1}{2}^- \end{array} \left\{ \begin{array}{l} \Lambda_c(2625), \Lambda_{b3/2}^{**} \\ \\ \Lambda_c(2593), \Lambda_{b1/2}^{**} \end{array} \right\}$$
- In HQS limit $m_Q \to \infty$ j_{qq} and s_Q are conserved separately allowing predictions for decay patterns.

Spectroscopy 1

- potential quark modes:
  - 3-quark Hamiltonian

$$H = H_0 + H_{hyp}$$

where

$$H_0 = \sum_i^3 \left(m_i + \frac{\vec{p}_i^{\,2}}{2m_i} \right) + \sum_{i<j} V_{conf}^{ij}(r_{ij})$$

is perturbed by spin-spin interactions induced by gluon exchange hyper-fine term:

$$\boxed{H_{hyp} = \sum_{i<j} \frac{16\pi\alpha_s}{9m_i m_j} \vec{s}_i \cdot \vec{s}_j \delta^3(\vec{r}_i - \vec{r}_j)}$$

(non-relativistic case, A.De Rujula, Howard Georgi, S.L.Glashow Phys.Rev., D12, (1975) 147)

- gives reasonable description of baryon masses

Spectroscopy 2

- HQET, $B_Q(Qqq)$:

$$M(B_Q) = M_Q + m_{qq} - \frac{1}{2m_Q}(\lambda_1 + d_M\lambda_2) + \mathcal{O}\left(\frac{1}{m_Q^2}\right)$$

λ_1 – kinetic energy of Q and λ_2 – chromomagnetic energy in HQS limit
d_M is spin-orbit interaction term:

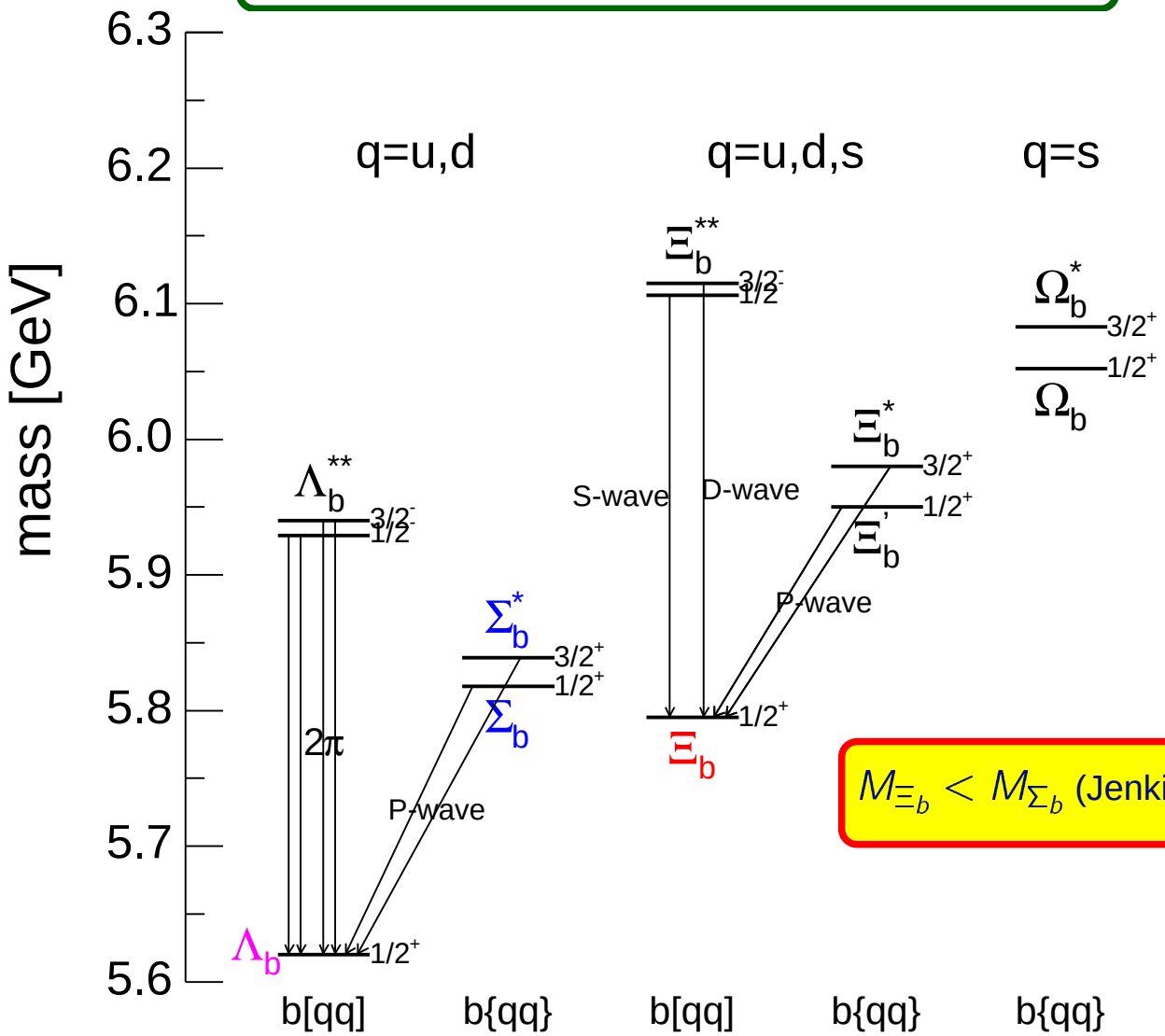
$$0 \text{ for } J^P = \tfrac{1}{2}^+, \bar{\mathbf{3}} \text{ states } (\Lambda_Q, \Xi_Q)$$

$$1 \text{ for } J^P = \tfrac{1}{2}^+, \mathbf{6} \text{ states } (\Sigma_Q, \Xi'_Q, \Omega_Q)$$

$$-\tfrac{1}{2} \text{ for } J^P = \tfrac{3}{2}^+, \mathbf{6} \text{ states } (\Sigma^*_Q, \Xi^*_Q, \Omega^*_Q)$$

- Lattice QCD
  - ☛ Calculate baryon masses from the first principles. Model independent results.

Bottom Baryon Masses



$M_{\Xi_b} < M_{\Sigma_b}$ (Jenkins PRD 55,(1997),R10)

masses taken from latest works my Karliner, Lipkin and Rosner

$\Sigma_b^{(*)}$

- Heavy quark spin doublet $\{\Sigma_b, \Sigma_b^*\}$ (degenerate if $m_b \to \infty$)

- Related to well established $\Sigma_c^{(*)}$:

$$\underbrace{\frac{M(\Sigma_b^*) - M(\Sigma_b)}{M(\Sigma_c^*) - M(\Sigma_c)}}_{70\ \text{MeV}} = \left(\frac{m_c}{m_b}\right) \sim 0.33,$$

$$M(\Sigma_b^*) - M(\Sigma_b) \sim 23\ \text{MeV}$$

$$M(\Sigma_b) - M(\Lambda_b) \sim 180 - 190\ \text{MeV}$$

- P-wave pion emission:

$$\Gamma_{\Sigma_b \to \Lambda_b \pi} = \frac{1}{6\pi} \frac{M_{\Lambda_b}}{M_{\Sigma_b}} \left|\frac{g_A}{f_\pi}\right|^2 |\vec{p}(\pi)_{CM}|^3$$

$$g_A = 0.75,\ f_\pi = 92\ \text{MeV}$$

$$\Gamma(\Sigma_b) \sim 8\ \text{MeV}, \Gamma(\Sigma_b^*) \sim 17\ \text{MeV}$$

- Two iso-spin triplets:

$$\Sigma_b^-(bdd), \Sigma_b^0(bdu), \Sigma_b^+(buu)$$

$$\Sigma_b^{*-}(bdd), \Sigma_b^{*0}(bdu), \Sigma_b^{*+}(buu)$$

$$M(\Sigma_b^-) - M(\Sigma_b^+) = 5 - 6\ \text{MeV}$$

- Charged states are detectable via pion transitions:

$$\Sigma_b^{\pm(*)} \to \Lambda_b^0 \pi^\pm_{soft}$$
$$\hookrightarrow \Lambda_c^+ \boxed{\pi^-}$$
$$\hookrightarrow \boxed{p} K^- \pi^+$$

with Λ_b^0 decay product satisfying displaced track trigger conditions.

we look for 2 pairs of close narrow states near threshold

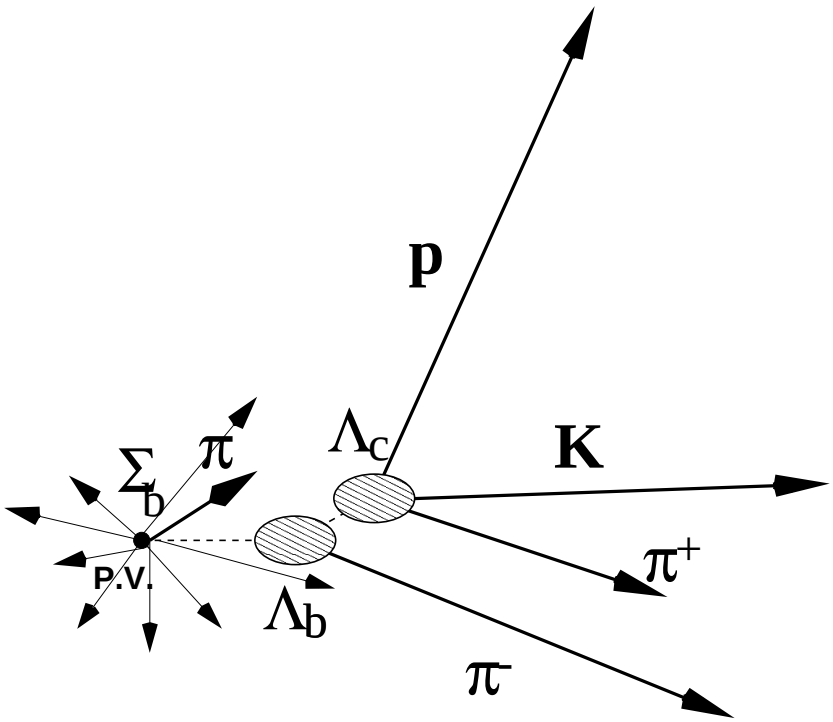
Analysis Strategy

- Λ_b candidates:
  - pre-select $\Lambda_b \to \Lambda_c \pi^-; \Lambda_c \to pK^-\pi^+$ requiring 2-tracks (out of 4) to match SVT-tracks and satisfy two-track trigger requirements
  - tighten the cuts to achieve the best $S/\sqrt{S+B}$ for Λ_b signal
- Σ_b candidates:
  - study Q-value spectrum:

$$Q = M(\Lambda_b \pi) - M(\Lambda_b) - m_\pi$$

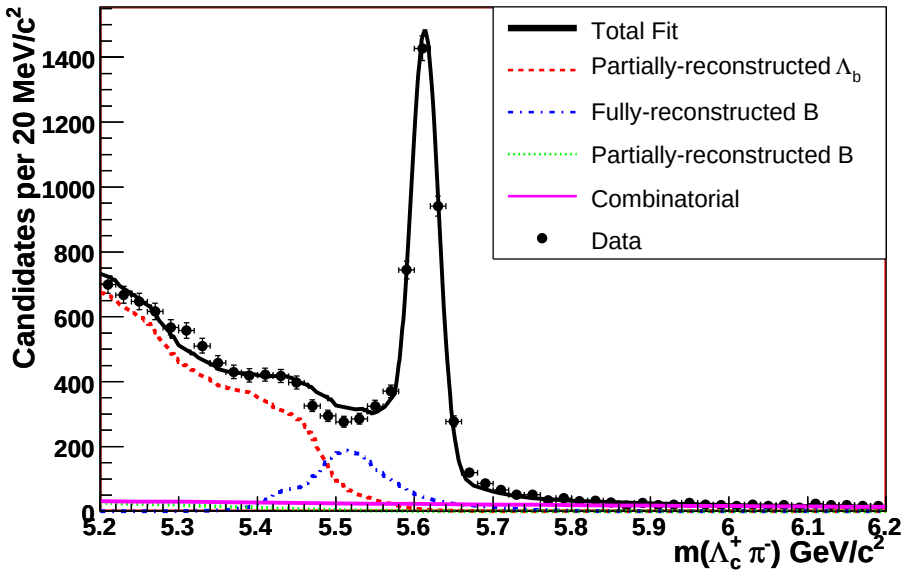
  - optimize cuts on Σ_b candidates by scoring $S/\sqrt{1.5+B}$ where "B" is background obtained from sidebands:
    left sideband : $0 < Q < 0.03$ GeV/c^2
    right sideband : $0.1 < Q < 0.5$ GeV/c^2
  - take "S" from PYTHIA Monte Carlo
  - keep Signal Region blind:

$$0.03 < Q < 0.1 \text{ GeV/c}^2$$



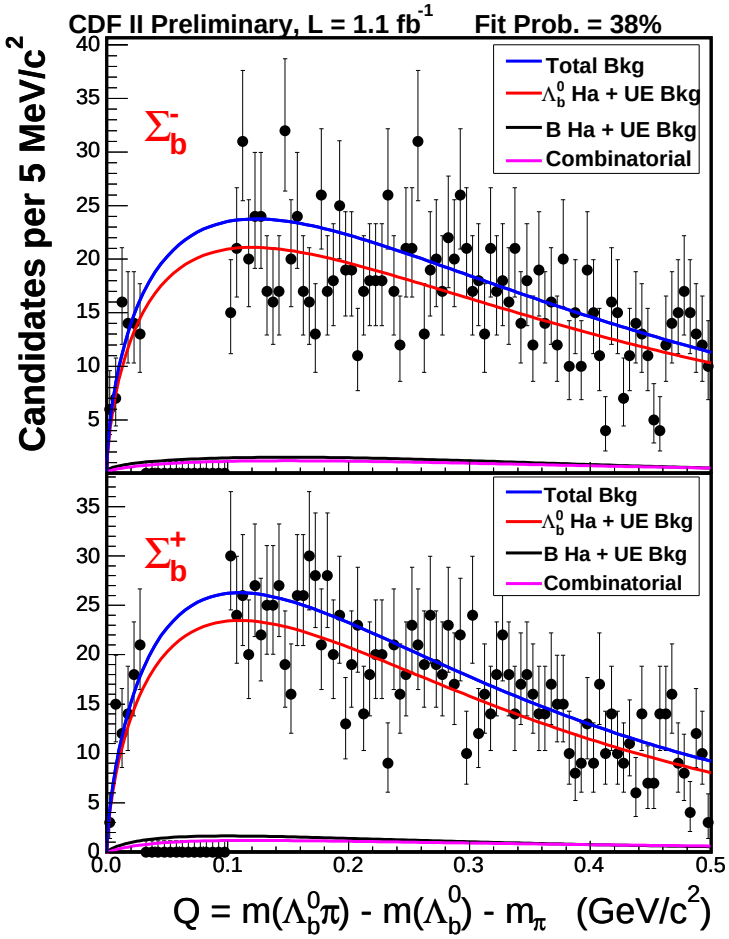
Λ_b Signal in $1fb^{-1}$

- 3180 ± 60 Λ_b candidates
- Backgrounds in signal window
  $5.565 < |m(\Lambda_c\pi) - M(\Lambda_b)_{PDG}| < 5.67$
  - 86.4% of Λ_b (all decays)
    - 9.3% of B-mesons (all decays)
    - 4.3% combinatorial
- Backgrounds under Σ_b will be normalized using these numbers.
- Shape of background – from PYTHIA



projection of unbinned max log-likelihood fit

Blinded Q-plots

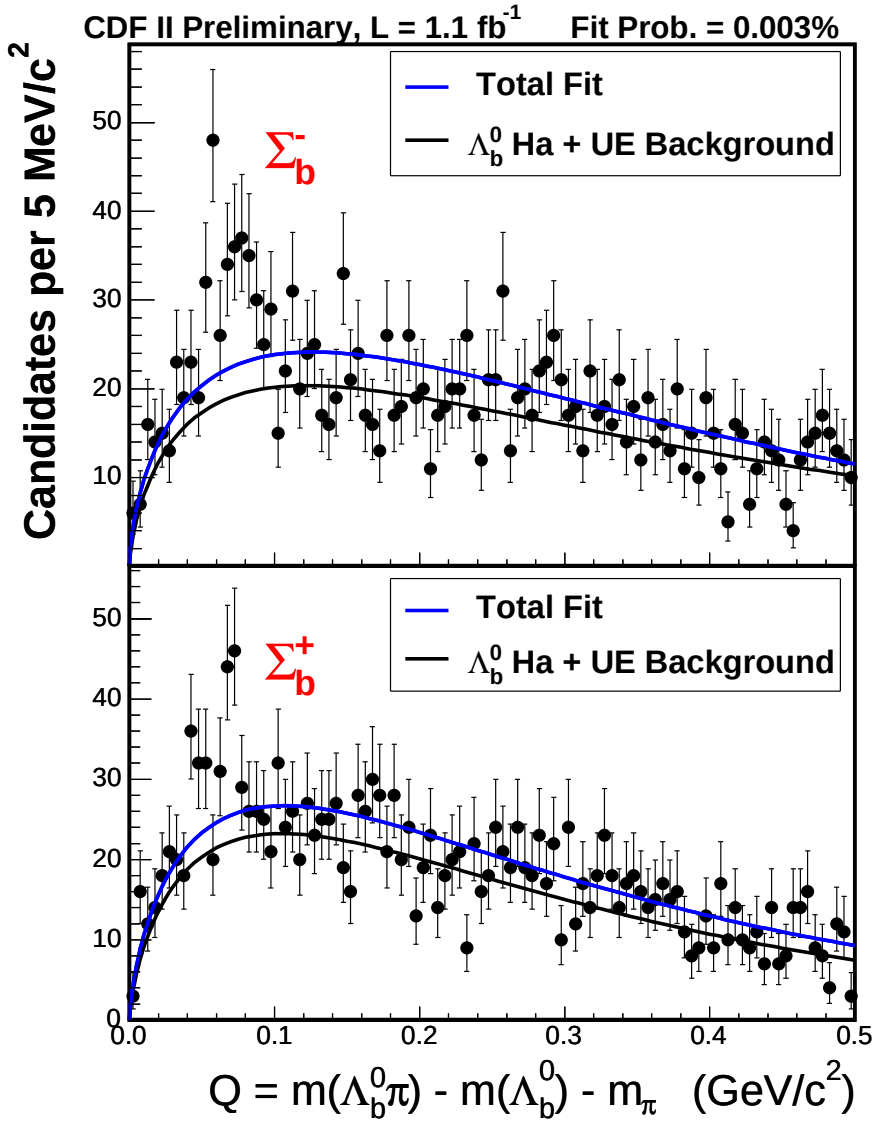


- Backgrounds
  - "real" Λ_b plus random soft track from b-quark hadronization of underlying event
    Λ_b HA+UE background, a major background (Monte Carlo simulation)
  - "real" B-meson faking Λ_b plus random soft track from b-quark hadronization or underlying event
    B HA+UE background (Monte Carlo simulation)
  - Combinatorial background (estimated using upper Λ_b sideband
    $5.8 < M(\Lambda_c\pi) < 6$ GeV/c^2
- Fit Function: Shapes and relative normalization of background contributions were determined prior to opening the box

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

- p_T spectrum of soft tracks in PYTHIA re-weighted to reproduce data

Open Box



- count observed candidates in the signal region
- compare with background extrapolation

sample	$S+B$	B	S	$S/\sqrt{S+B}$
$\Lambda_b^0\pi^-$	416	268	148	7.3
$\Lambda_b^0\pi^+$	306	298	108	5.4

- there is a significant excess in the signal region in both spectra!
- proceed to fit adding signal terms:

$$G \otimes BW(Q, Q_{\Sigma_b}, \sigma_{\Sigma_b}, \Gamma_{\Sigma_b}) +$$

$$G \otimes BW(Q, Q_{\Sigma_b^*}, \sigma_{\Sigma_b^*}, \Gamma_{\Sigma_b^*})$$

for all four $\Sigma_b^{(*)\pm}$ states

- simultaneous unbinned maximum log-likelihood:
  - background shapes frozen
  - 7 floating variables – $Q_{\Sigma_b^-}, Q_{\Sigma_b^+}, Q_{\Sigma_b^*}$ – $Q_{\Sigma_b}, N(\Sigma_b^-), N(\Sigma_b^{*-}), N(\Sigma_b^+), N(\Sigma_b^{*+})$
  - detector resolutions and natural widths fixed.

Fit Result

Yields:

$$N(\Sigma_b^-) = 59^{+15}_{-14}(stat)^{+9}_{-4}(syst)$$

$$N(\Sigma_b^+) = 32^{+13}_{-12}(stat)^{+5}_{-3}(syst)$$

$$N(\Sigma_b^{*-}) = 69^{+18}_{-17}(stat)^{+16}_{-5}(syst)$$

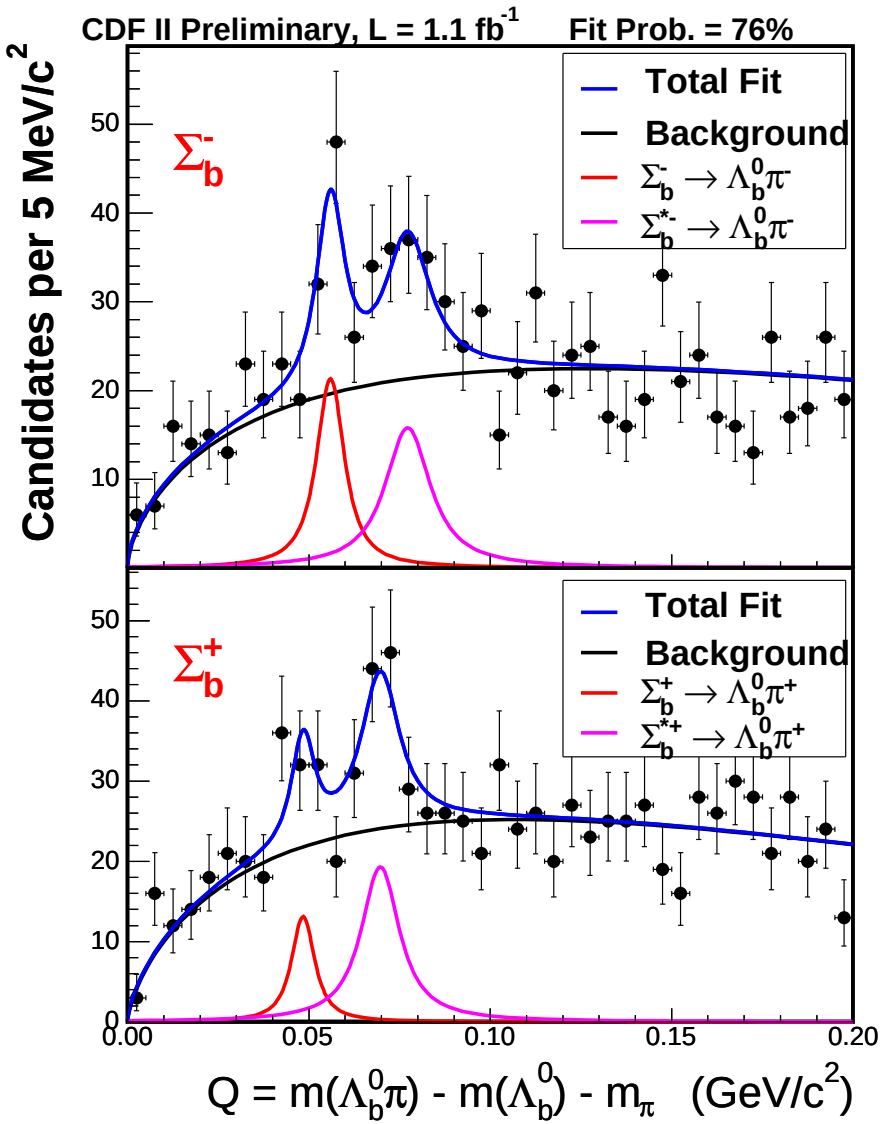
$$N(\Sigma_b^{*+}) = 77^{+17}_{-16}(stat)^{+10}_{-6}(syst)$$

Q-values:

$$Q(\Sigma_b^-) = (55.9 \pm 1.0 \pm 0.2)\ \mathrm{MeV}/c^2$$

$$Q(\Sigma_b^+) = (48.5^{+2.0+0.2}_{-2.2-0.3})\ \mathrm{MeV}/c^2$$

$$Q(\Sigma_b^*) - Q(\Sigma_b) = (21.2^{+2.0+0.4}_{-1.9-0.3})\ \mathrm{MeV}/c^2$$



Weak Decays of Bottom Baryons

- J/ψ trigger:

  $\Xi_b \to \boxed{J/\psi}\ \Xi^- + n\pi \quad , \Omega_b \to \boxed{J/\psi}\ \Omega^- + n\pi$

  $\hookrightarrow\ \Lambda\pi^- \qquad\qquad \hookrightarrow\ \Lambda K^-$

- Displaced track trigger:

  $\Xi_b \to\ \Xi_c + n\boxed{\pi} \qquad , \Omega_b \to\ \Omega_c + n\boxed{\pi}$

  $\hookrightarrow\ \Xi^- + n\boxed{\pi} \qquad \hookrightarrow\ \Omega^- + n\boxed{\pi}$

  $\Xi_b \to\ D^0\Lambda\ , \Omega_b \to\ D^0\Xi^-$

  $\Xi_b \to\ \Lambda_c K + n\pi\ , \Omega_b \to\ \Xi_c K + n\pi$

- SVT+lepton trigger:

  $\Xi_b \to\ \Xi_c + \boxed{\ell^-}X \qquad , \Omega_b \to\ \Omega_c + \boxed{\ell^-}X$

  $\hookrightarrow\ \Xi^- + n\boxed{\pi} \qquad \hookrightarrow\ \Omega^- + n\boxed{\pi}$

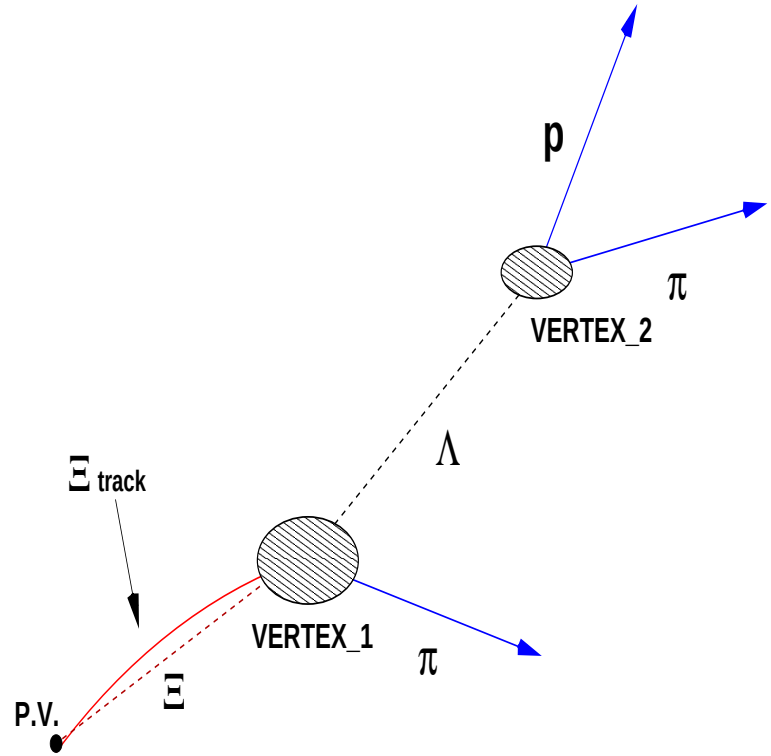
- Expected lifetime pattern:

$$\boxed{\tau(B^+) \simeq \tau(\Xi_b^-) \simeq \tau(\Omega_b^-) \geq \tau(\Lambda_b^0) \geq \tau(\Xi_b^0)}$$

- Decays of bottom-strange baryon involve long lived hyperons as decay products.
- => start with reconstruction of long lived hyperons

Cascades at CDF

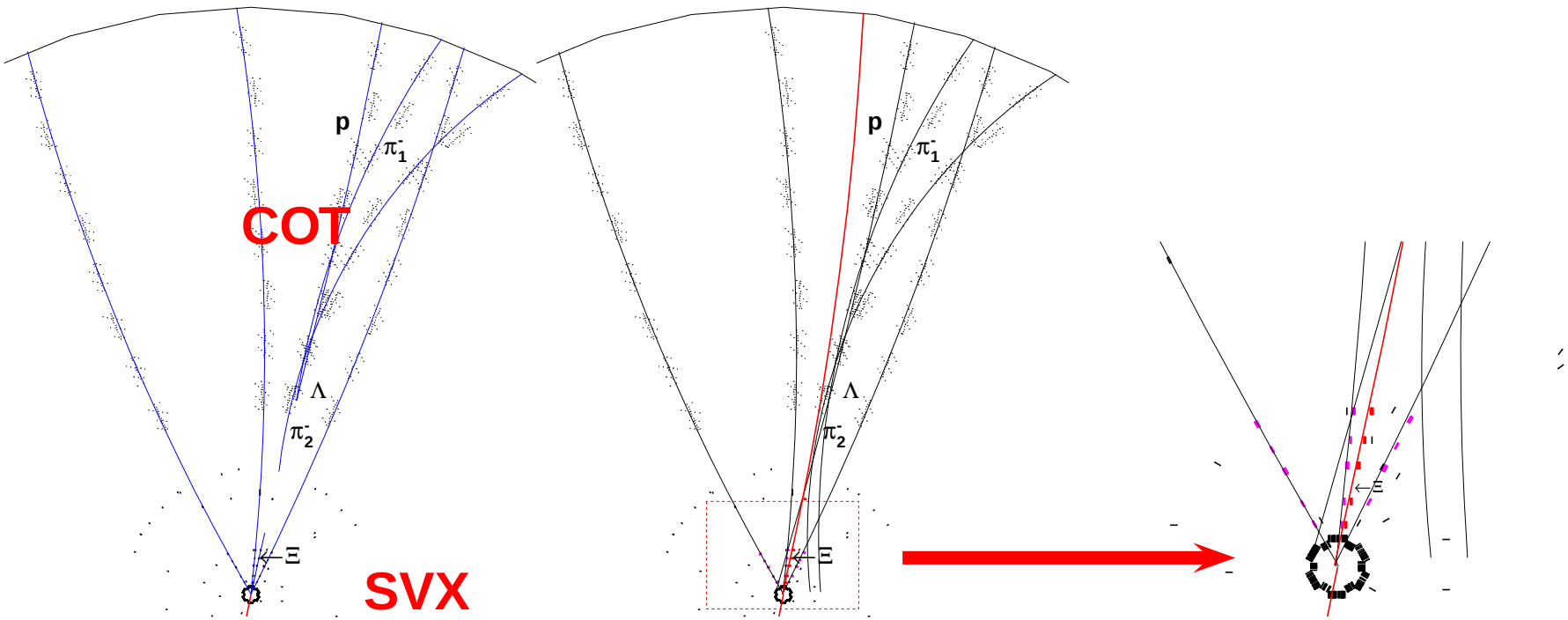
- Ξ^- long lived ($c\tau = 4.91cm$) & charged.
- Can be tracked in SVX (previously done at LEP)
- CDF developed tracking of Ξ. 1st in hadron collider experiment.
  - Find and form V0 : $\Lambda \rightarrow p\pi^-$
  - Attach pion to Λ, form Ξ candidate, do vertex fit.
  - Convert Ξ momentum and vertex position into helix in CDF track parameter $(cu, \phi_0, d_0, \lambda, z_0)$ basis and convert elements of Vertex fit error matrix into track 5×5 error matrix
  - Use this track to seed Outside In (OI)Z Silicon tracking.
  - Attach silicon hits starting from vertex point and going to PV.
  - Store SVX Ξ tracks in the event record on the file for subsequent analysis.
  - The Ξ -track is used in analysis as any "normal" track but it is also a "loaded" track as it "remembers" its history (has pointers to vertex fits and parent tracks)



- Φ pentaquarks search was based on this technique (Phys.Rev.D75:032003,2007)

Cascade Tracked!

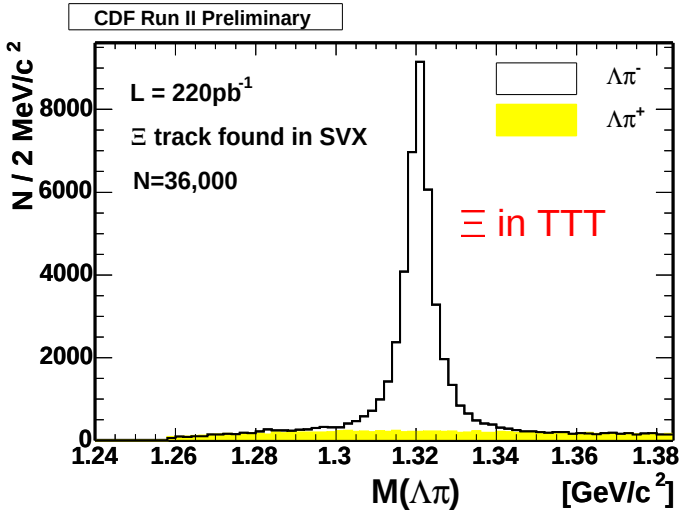
Event Display of generated Hyperons Tracked in Silicon



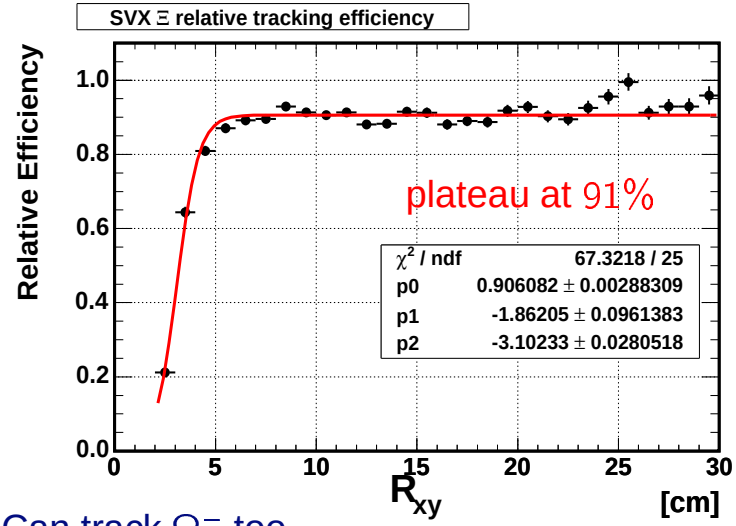
$$\Xi_b \to \Xi_c^+ \pi^- \quad \Xi_c^+ \to \Xi^- \pi^+ \pi^+ \quad \Xi^- \to \Lambda \pi_2^- \quad \Lambda \to p \pi_1^-$$

Benefits of Hyperon Tracking

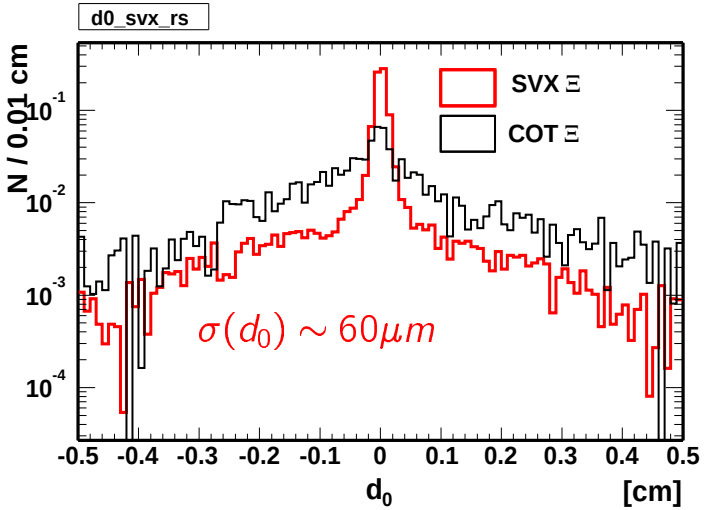
- Clean Ξ samples:



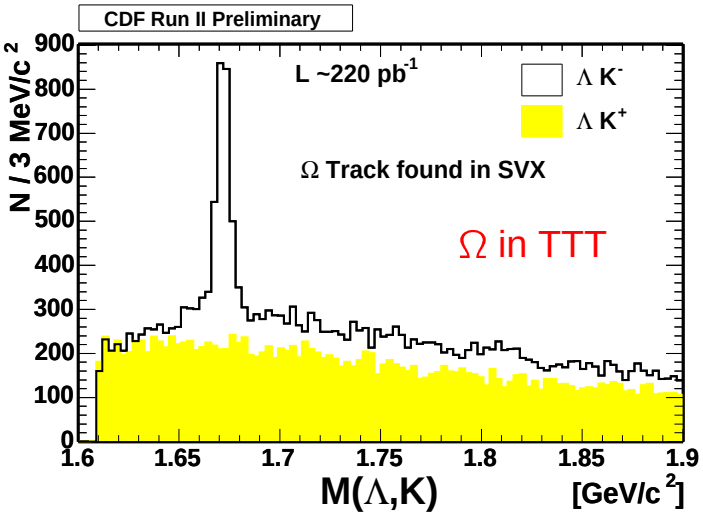
- Good efficiency (total ~ 40%)



- Improvement in Ξ impact parameter resolution:

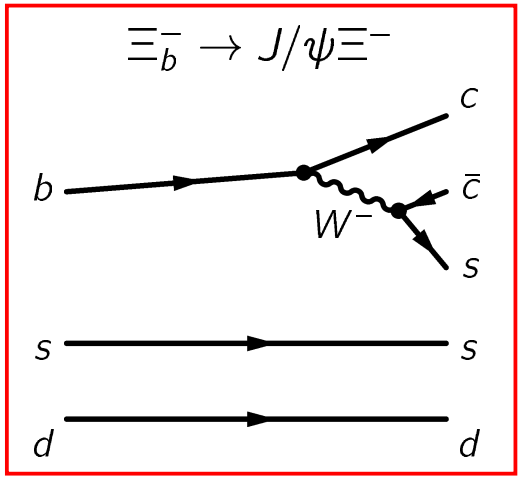


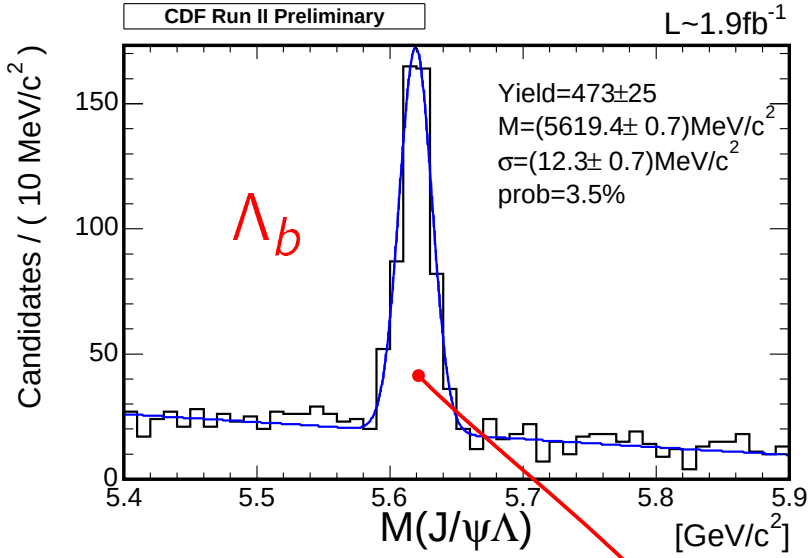
- Can track Ω⁻ too



$$\Xi_b^- \rightarrow J/\psi \Xi^-$$

Ξ_b Yield in JPSI trigger





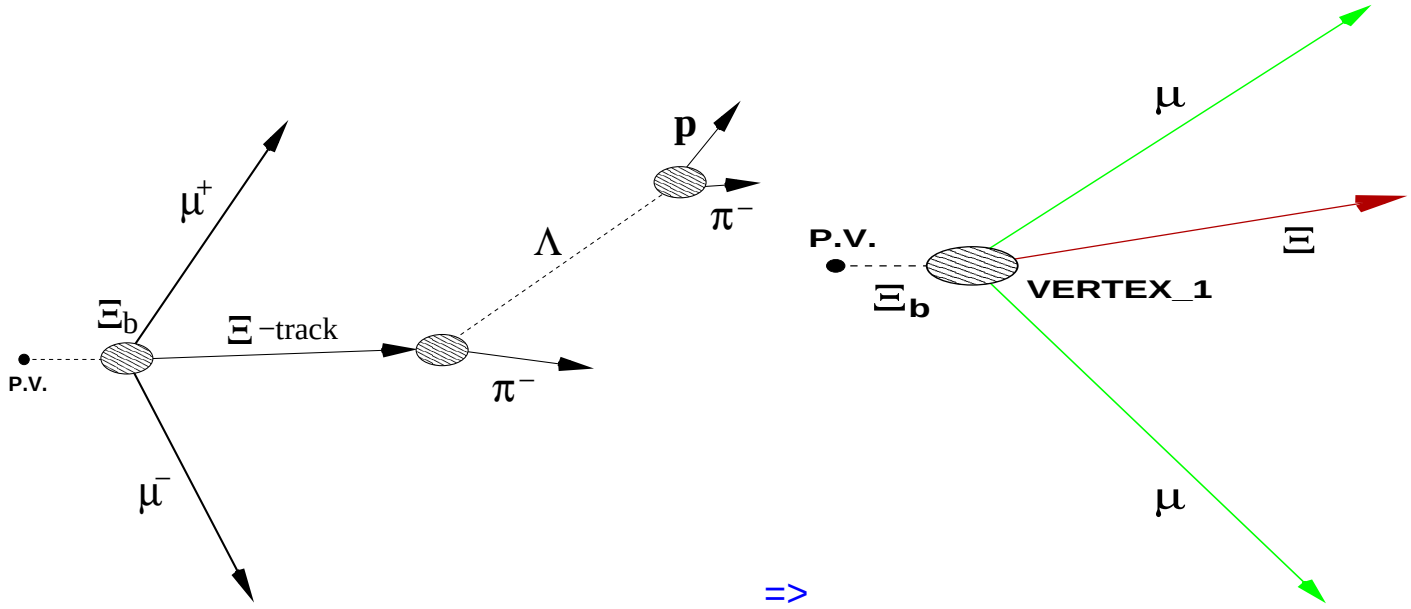
- Look for Ξ_b^- as $\Xi_b^0 \to \Xi^0\ J/\psi$ is lost (π^0 in the final state)
- Production rate w.r.t. Λ_b :
  - Assuming $\mathcal{B}(\Lambda_b \to J/\psi\Lambda) = \mathcal{B}(\Xi_b^- \to J/\psi\Xi)$:

$$N(\Xi_b^- \to J/\psi\Xi) \sim \frac{N(\Lambda_b \to J/\psi\Lambda)}{8} \cdot 0.9 \cdot \epsilon_{kink-\pi} \cdot \epsilon_{SVX} \sim \frac{N(\Lambda_b \to J/\psi\Lambda)}{30.} \sim 15-20$$

  - If $\epsilon_{kink-\pi} = 0.8$ and $\epsilon_{SVX} = 0.4$

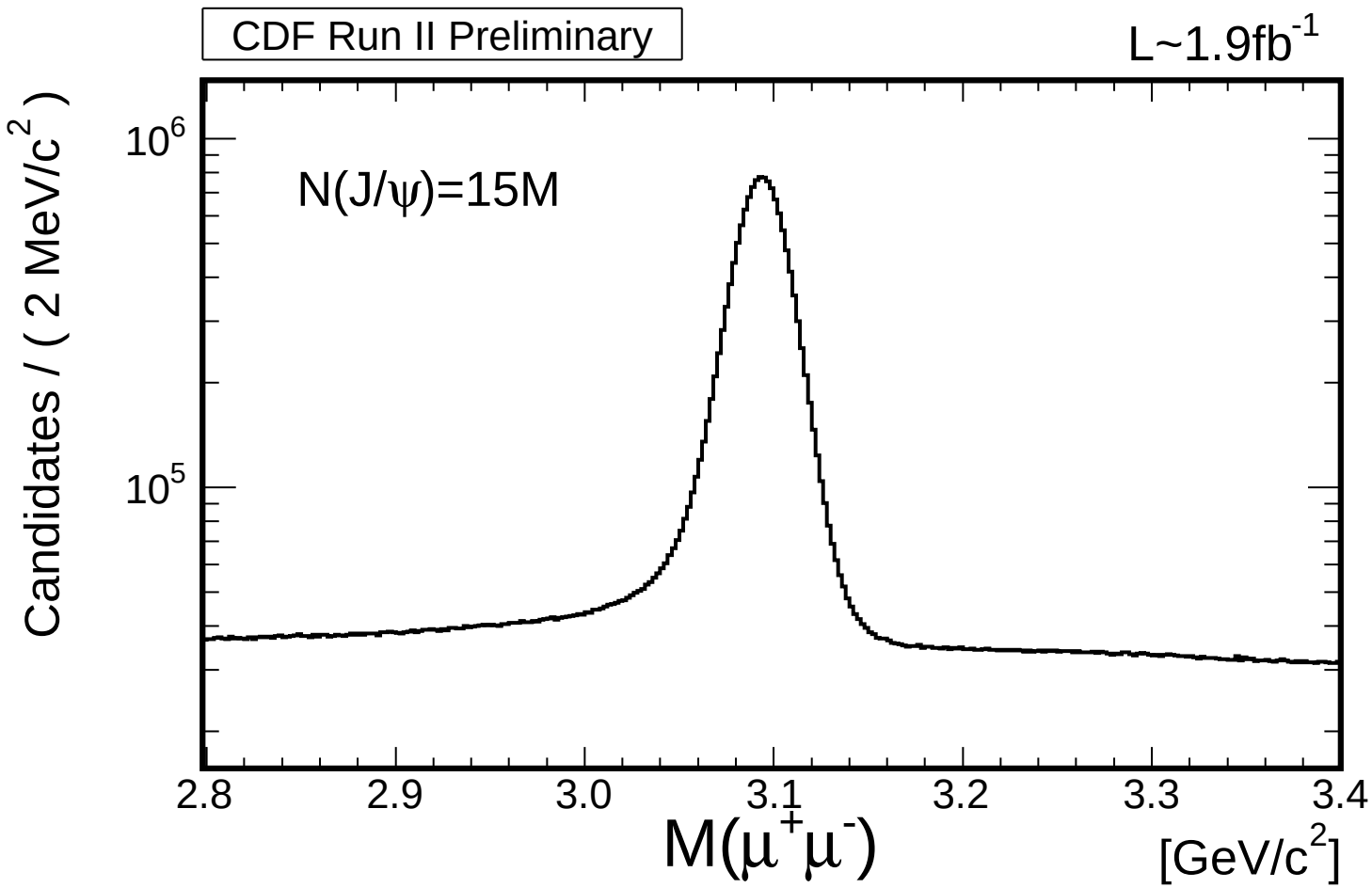
Analysis Strategy

- Use silicon Ξ tracks to look for $\Xi_b \to J/\psi\Xi$



- Collapse 3-track Ξ candidate to 1-track.
- $\Xi_b \to J/\psi\Xi^-$ becomes like $B^+ \to J/\psi K^+$. Use $B^+ \to J/\psi K^+$ as control sample.
- Selection is completely data driven & independent of signal under study.
- Optimize cuts for best $B^+ \to J/\psi K^+$ signal. Apply same cuts to $\Xi_b \to J/\psi\Xi$ candidates.
- Approach is based on assumption "$B^+ \to J/\psi K^+$ look similar to $\Xi_b \to J/\psi\Xi$". Validated assumption with Simulation.
- Same approach used to discover $B_c \to J/\psi\pi$. Should work even better for $\Xi_b \to J/\psi\Xi$.

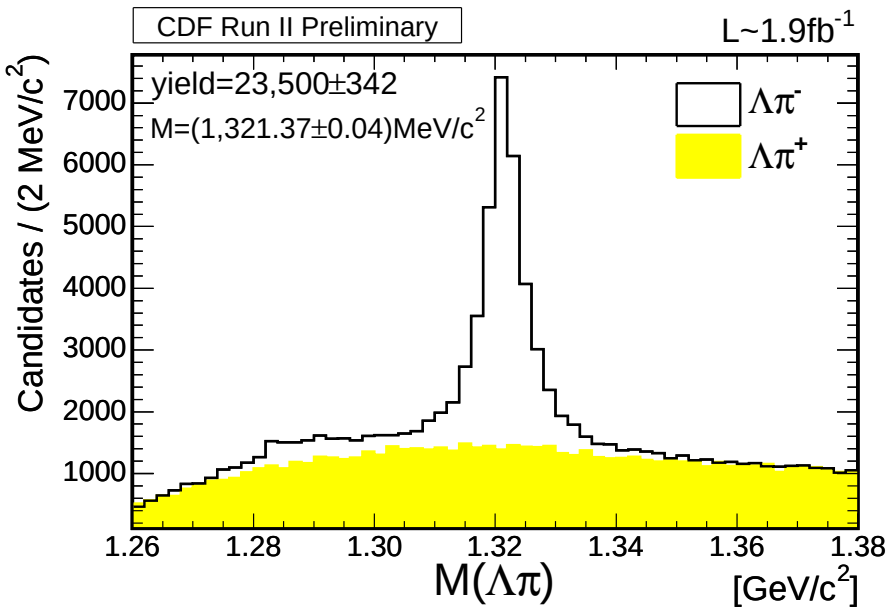
$J/\psi \to \mu\mu$



15M J/ψs using sideband subtraction counting

Cascade Yield in J/ψ trigger

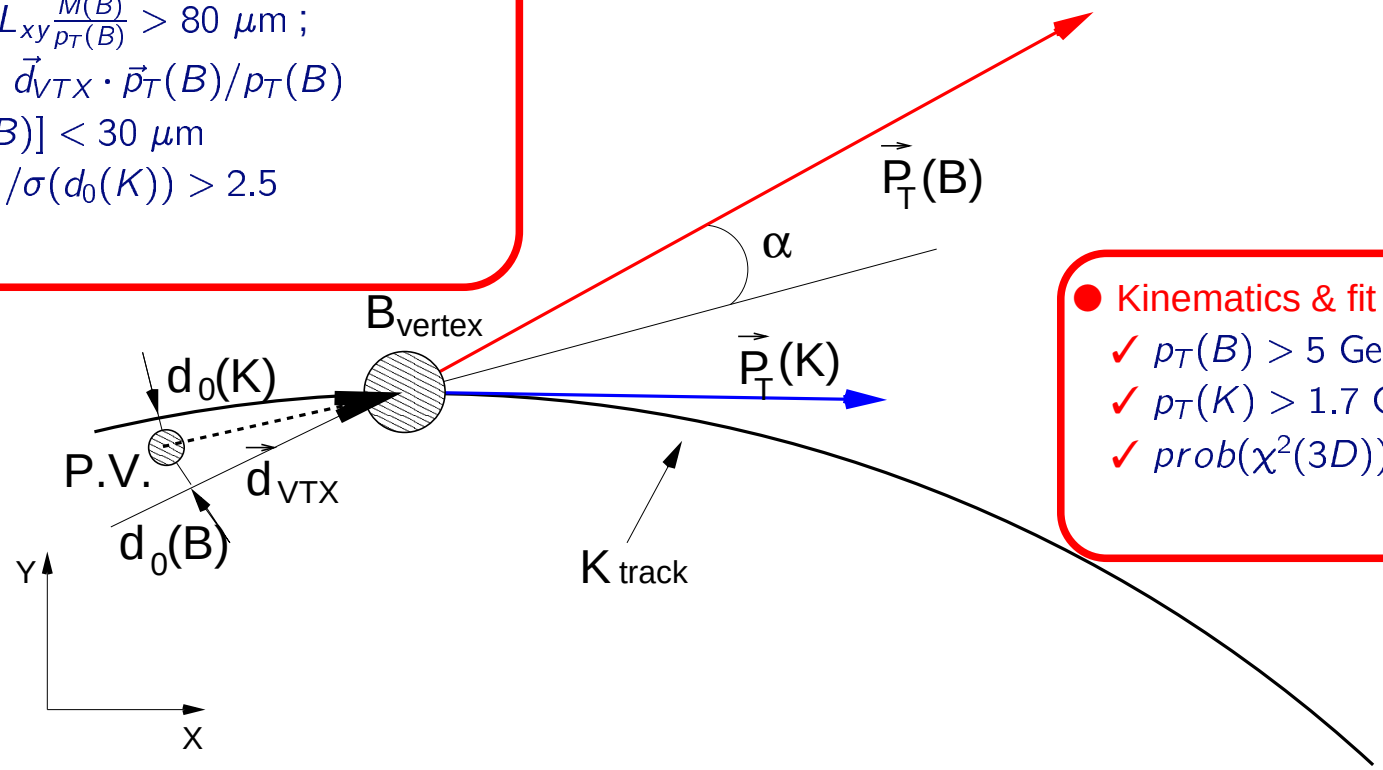
- Λ^0 candidates:
  - No p_T cuts on daughter tracks
  - $p_T(p) > p_T(\pi)$
  - $|d_0(p)| > 0.05\ cm$
  - $|d_0(\pi)| > 0.05\ cm$
  - $|\Delta z(p,\pi)| < 5$ cm (at the 2-track intersection point)
  - 2-track vertex fit, $\chi^2(2D) < 49$
  - $|m(p\pi) - M(\Lambda)| < 10\mathrm{MeV/c^2}$
  - $L_{xy} >= 1\ cm$
- Ξ candidates:
  - No p_T cuts on daughter tracks
  - Vertex and mass constrained fit (both Λ^0 and Ξ)
  - $|m(\Lambda\pi) - M(\Xi)| < 10\mathrm{MeV/c^2}$
  - $R(\Xi)_{vtx} < R(\Lambda)_{vtx} + 1$
- Ξ tracks:
  - $|d_0(\Xi)| < 0.1\ cm$
  - $N_{SVX}(r-\phi) \geq 2$



- 23.5K events
- Mass is consistent with PDG

$B^+ \to J/\psi K^+$ selection variables

- Displacement of B-vertex w.r.t P.V.:
  - ✓ $ct = L_{xy}\frac{M(B)}{p_T(B)} > 80\ \mu m$;
    $L_{xy} = \vec{d}_{VTX} \cdot \vec{p}_T(B)/p_T(B)$
  - ✓ $\delta[ct(B)] < 30\ \mu m$
  - ✓ $d_0(K)/\sigma(d_0(K)) > 2.5$



- Kinematics & fit quality:
  - ✓ $p_T(B) > 5$ GeV/c
  - ✓ $p_T(K) > 1.7$ GeV/c
  - ✓ $prob(\chi^2(3D)) > 10^{-3}$

- Pointing of B-candidate to P.V. :
  - ✓ $\alpha < 0.4$ radians
  - ✓ $|d_0(B)| < 75\ \mu m$; $\vec{d}_0(B) = \vec{d}_{VTX} \times \vec{p}_T(B)/p_T(B)$

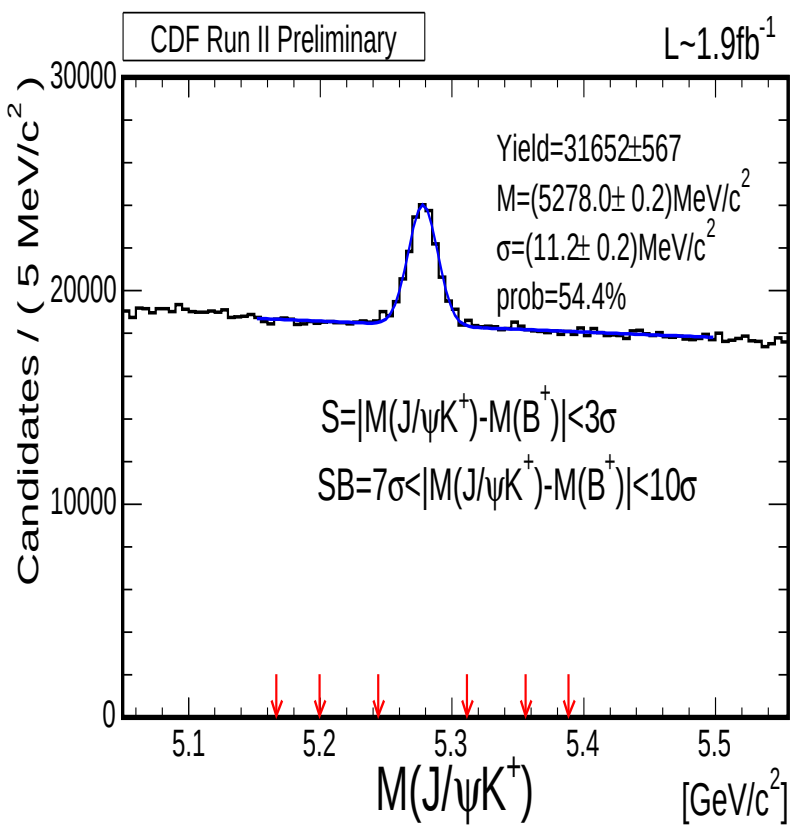
- Require Kaon IP w.r.t. B-vertex be small:
  - ✓ $|d_0(K)(w.r.t.\ \ B_{vertex})| < 100\ \mu m$

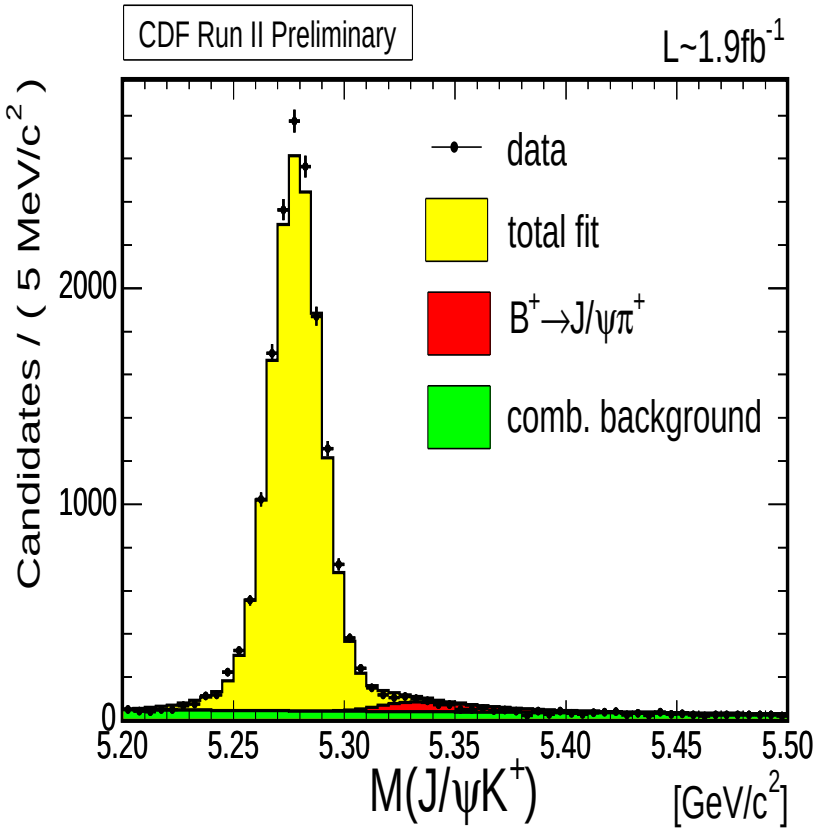
Two step procedure

Selection variable	Optimization A	Optimization B
$p_T(K/\Xi)$ [GeV/c]	> 1.7	> 2.5
$p_T(J/\psi K/\Xi)$ [GeV/c]	$> 5.$	$> 6.$
$ct(J/\psi K/\Xi)$ [cm]	> 0.008	> 0.01
$\delta[ct(J/\psi K/\Xi)]$ [cm]	< 0.003	< 0.0025
Pointing angle	< 0.4 radians	< 0.3 radians
$prob(\chi^2(3D))$	$> 10^{-3}$	$> 10^{-2}$
$\lvert d_0(J/\psi K/\Xi)\rvert$ [cm] (w.r.t p.v.)	< 0.0075	< 0.006
$\lvert d_0(K/\Xi)_{sig}\rvert$ (w.r.t p. v.)	> 2.5	> 3.0
$\lvert d_0(K/\Xi)\rvert$ [cm] (w.r.t sec. vtx.)	< 0.01	< 0.008

- Apply Optimization A. If candidate fails just one cut, apply Optimization B. Accept if it does not fail any other cuts in Optimization B.
- Any single cut of Optimization A has almost 90% signal efficiency

$B^+ \to J/\psi K^+$





- Loose cuts – 31K B^+
- Optimized cuts 16K B^+.
- Signal effi ciency 52%, background reduced by factor of 500

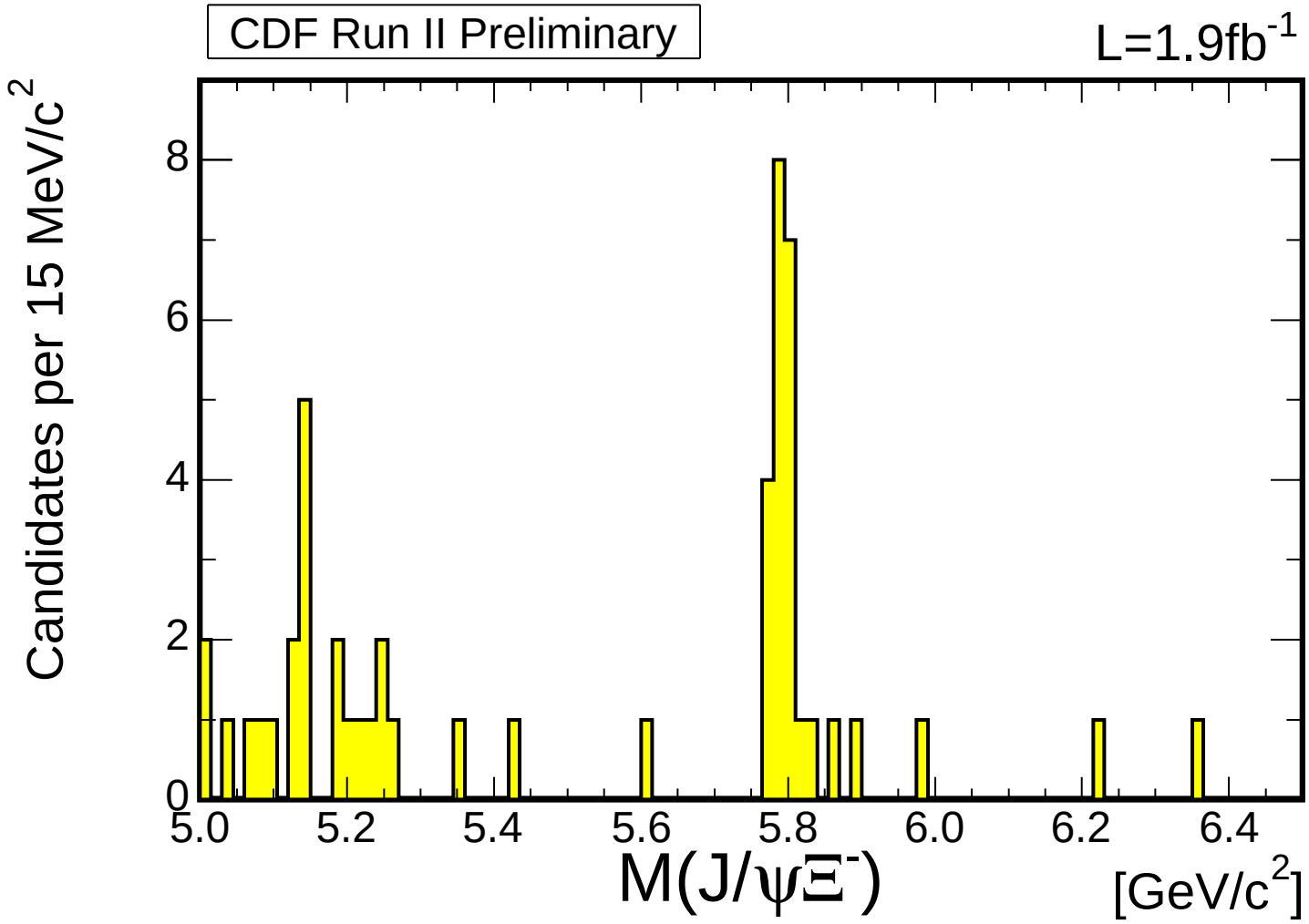
The yields

parameter	Optimization A	Optimization B	Optimization A+B
$N(J/\psi K^+)$	$12,185 \pm 115$	$3,837 \pm 67$	$16,044 \pm 134$
$N(J/\psi \pi^+)$	447 ± 29	134 ± 18	572 ± 34
$M(B^+)$ [MeV/c^2]	$5,278.3 \pm 0.1$	$5,278.3 \pm 0.2$	$5,278.3 \pm 0.1$
σ_1 [MeV/c^2]	28.6 ± 1.4	26.5 ± 2.2	27.8 ± 1.2
σ_2 [MeV/c^2]	11.0 ± 0.1	10.3 ± 0.1	10.8 ± 0.1
R (fraction of wide Gaussian)	0.17 ± 0.02	0.24 ± 0.05	0.19 ± 0.02

Optimization B "recovers" 24% of signal events

Apply the same procedure to $J/\psi\Xi$ candidates (replace K^+ with Ξ^-)

Behold the Peak

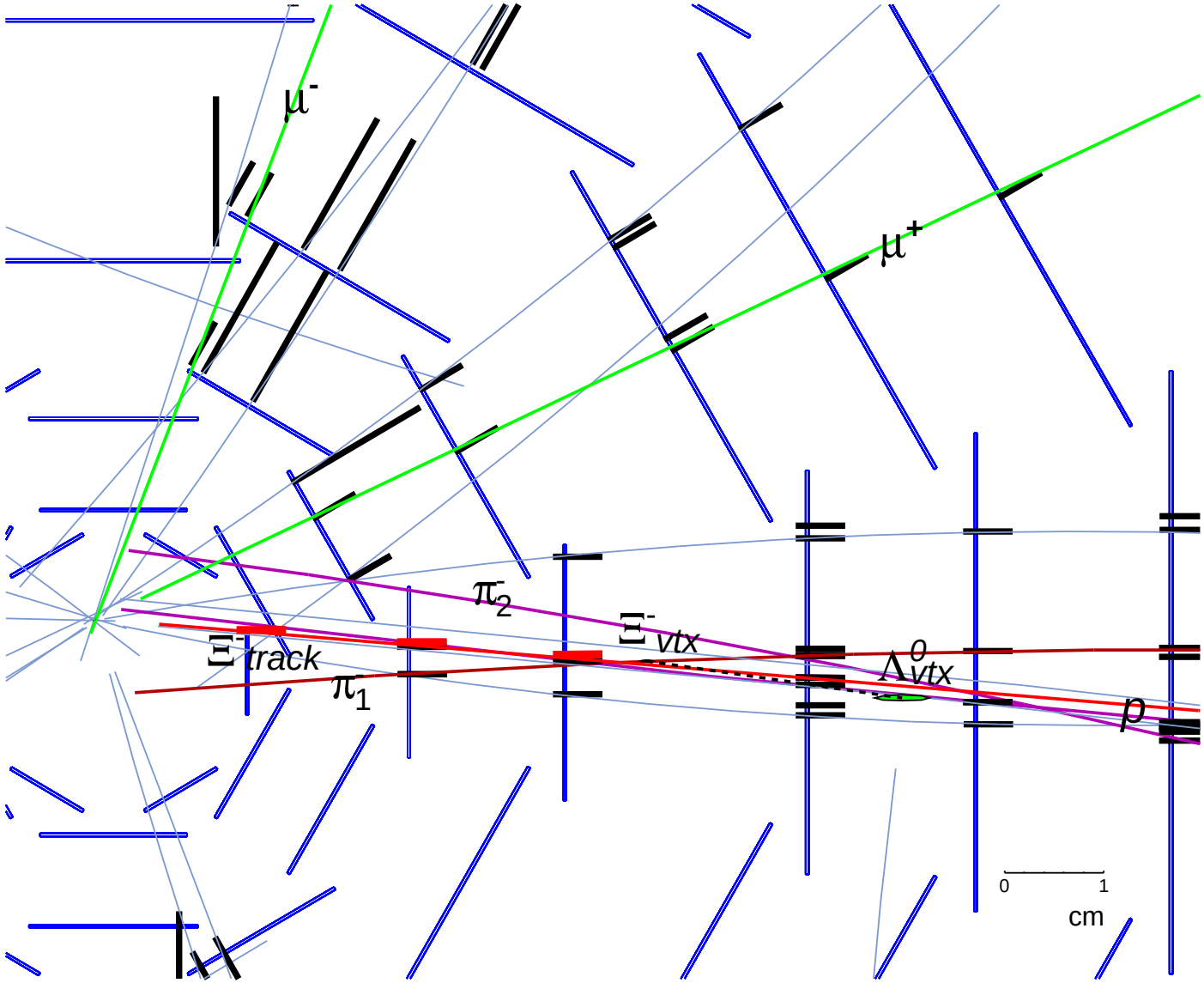


Cross-checks

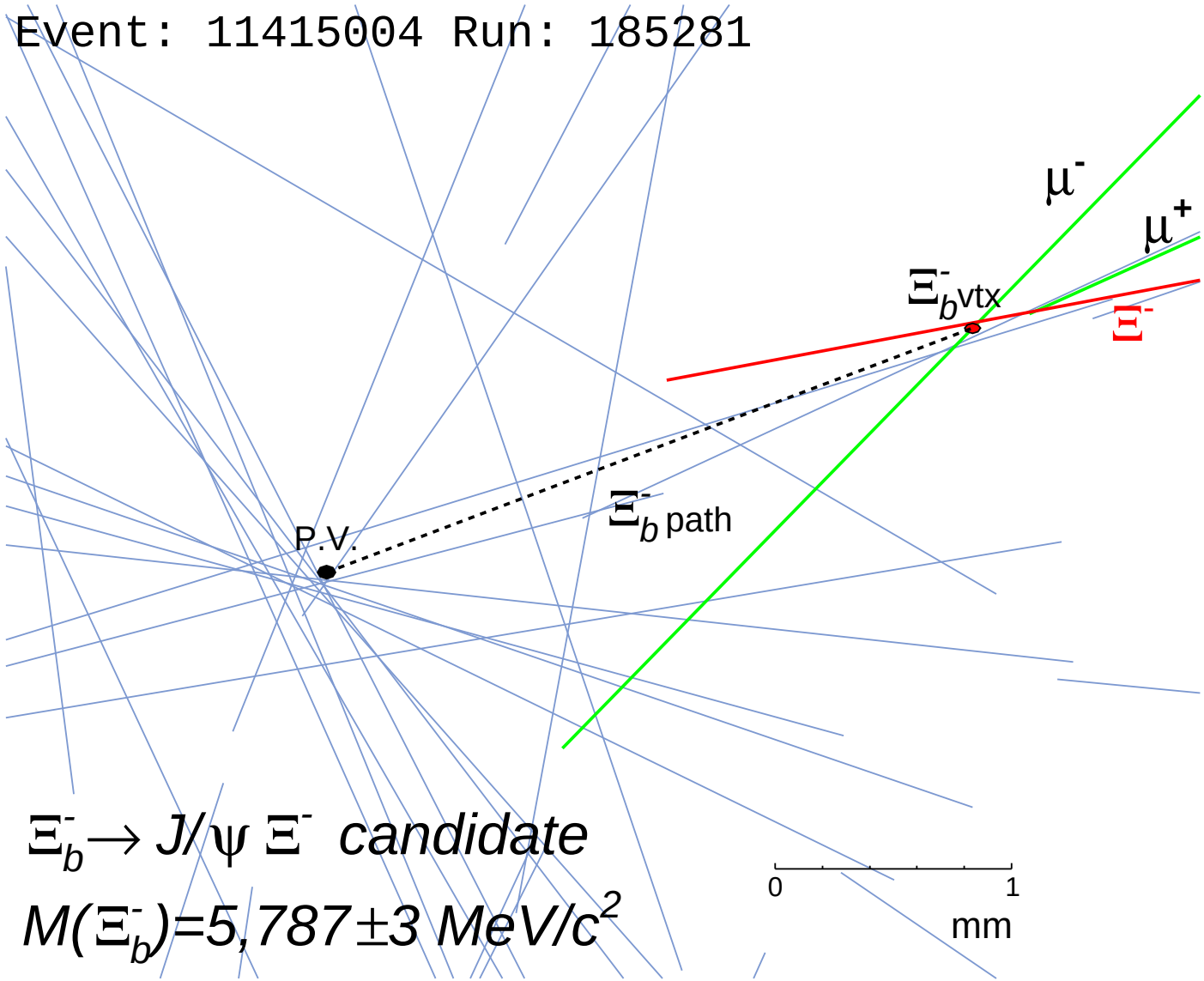
- ✓ J/ψ and Ξ sidebands
- ✓ Wrong charge $J/\psi\Xi^+$ where "$\Xi^+ \to \Lambda\pi^+$"
- ✓ Checked number of Ξ_b and $\bar{\Xi}_b$ candidates – 50/50
- ✓ Signal is robust against cut variations
- ✓ No existing B-hadron can produce a signal in $M(J/\psi\Xi^-)$ spectrum at $M \sim 5.8\ \mathrm{GeV}/c^2$

Signal is consistent with Ξ_b

Event Display 1



Event Display 2



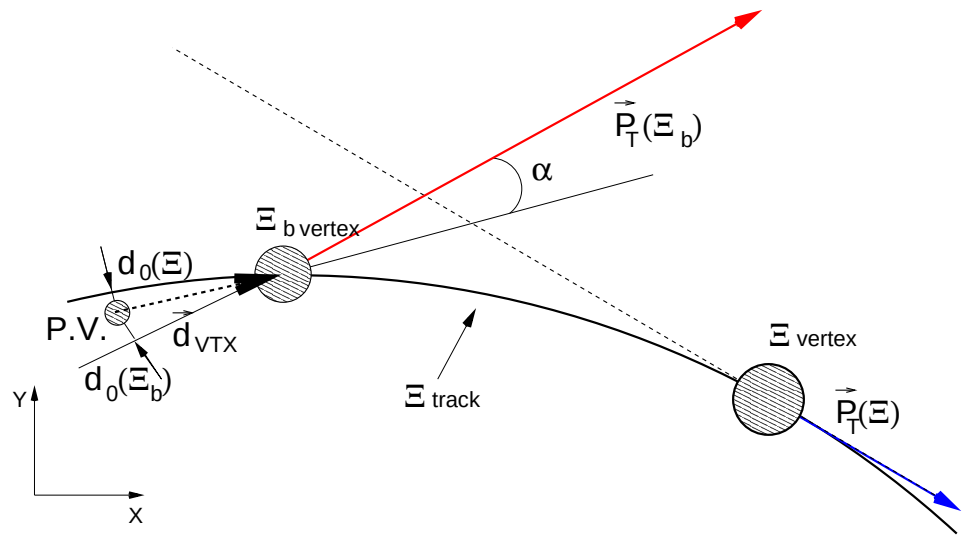
$\Xi_b^- \rightarrow J/\psi\ \Xi^-$ *candidate*

$M(\Xi_b^-)=5{,}787\pm3\ MeV/c^2$

Expected Mass resolution

Channel	yield	mass resolution(s) MeV/c^2
$B^+ \to J/\psi K^+$	$27,108 \pm 166$	11.01 ± 0.09
$\Lambda_b^0 \to J/\psi \Lambda^0$	$5,033 \pm 71$	12.5 ± 0.2
$\Xi_b^- \to J/\psi \Xi^-$ 3-track fit	$1,955 \pm 43$	14.3 ± 0.2
$\Xi_b^- \to J/\psi \Xi^-$ 5-track fit	$1,996 \pm 45$	12.3 ± 0.2

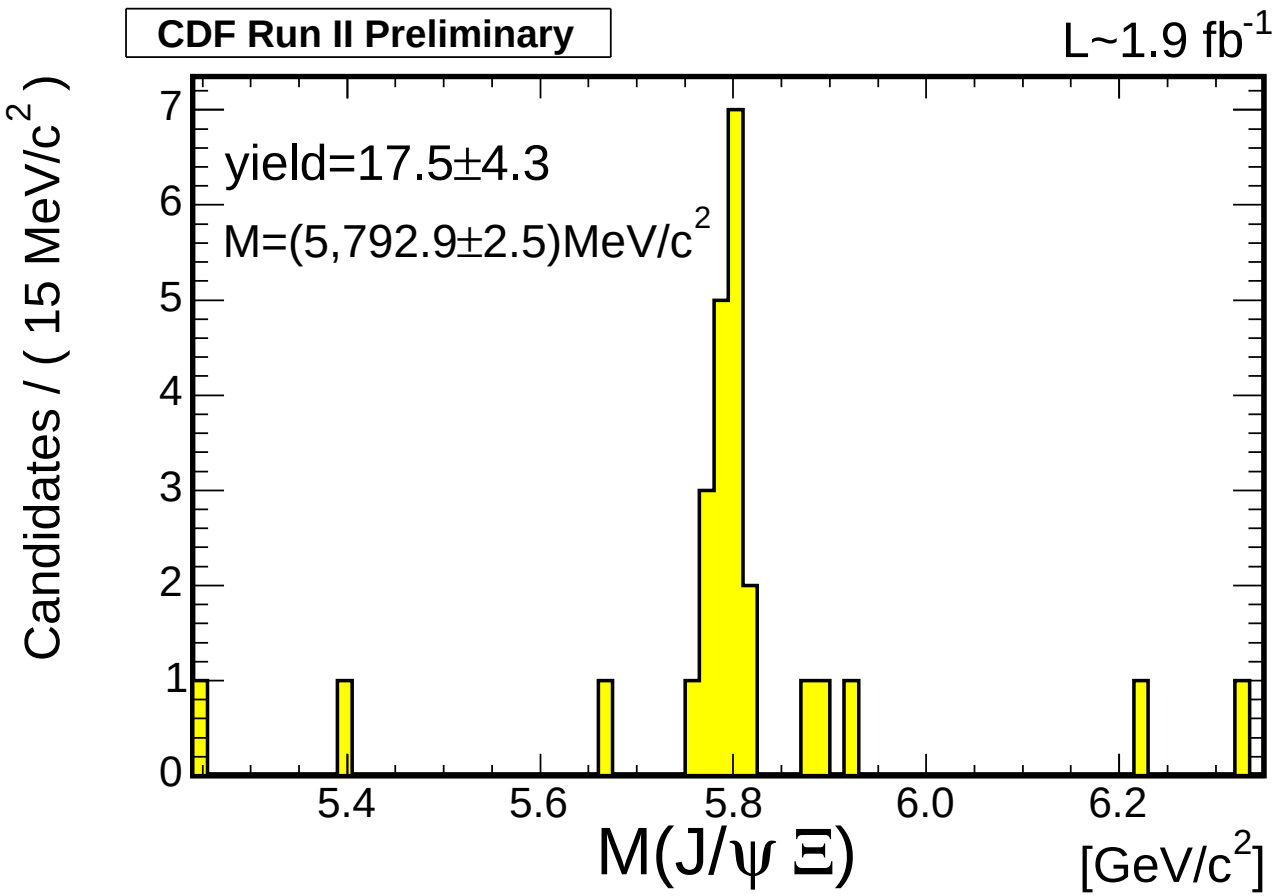
- Full 5-track vertex fit gives 15% better mass resolution compared to 3-track vertex fit.
- But in order for it to work we had to fix our Vertex Fit software to handle charged vertices.



- Full 5-track vertex fit is applied to previously selected 3-track candidates by utilizing properties of "loaded" Ξ-track

The Fit Result

Unbinned fit uses estimate of mass uncertainty of each candidate to improve mass resolution. Constant background. Gaussian Signal



Yield	Mass
17.5 ± 4.3	$(5,792.9 \pm 2.5)$ MeV/c^2

Signal Significance

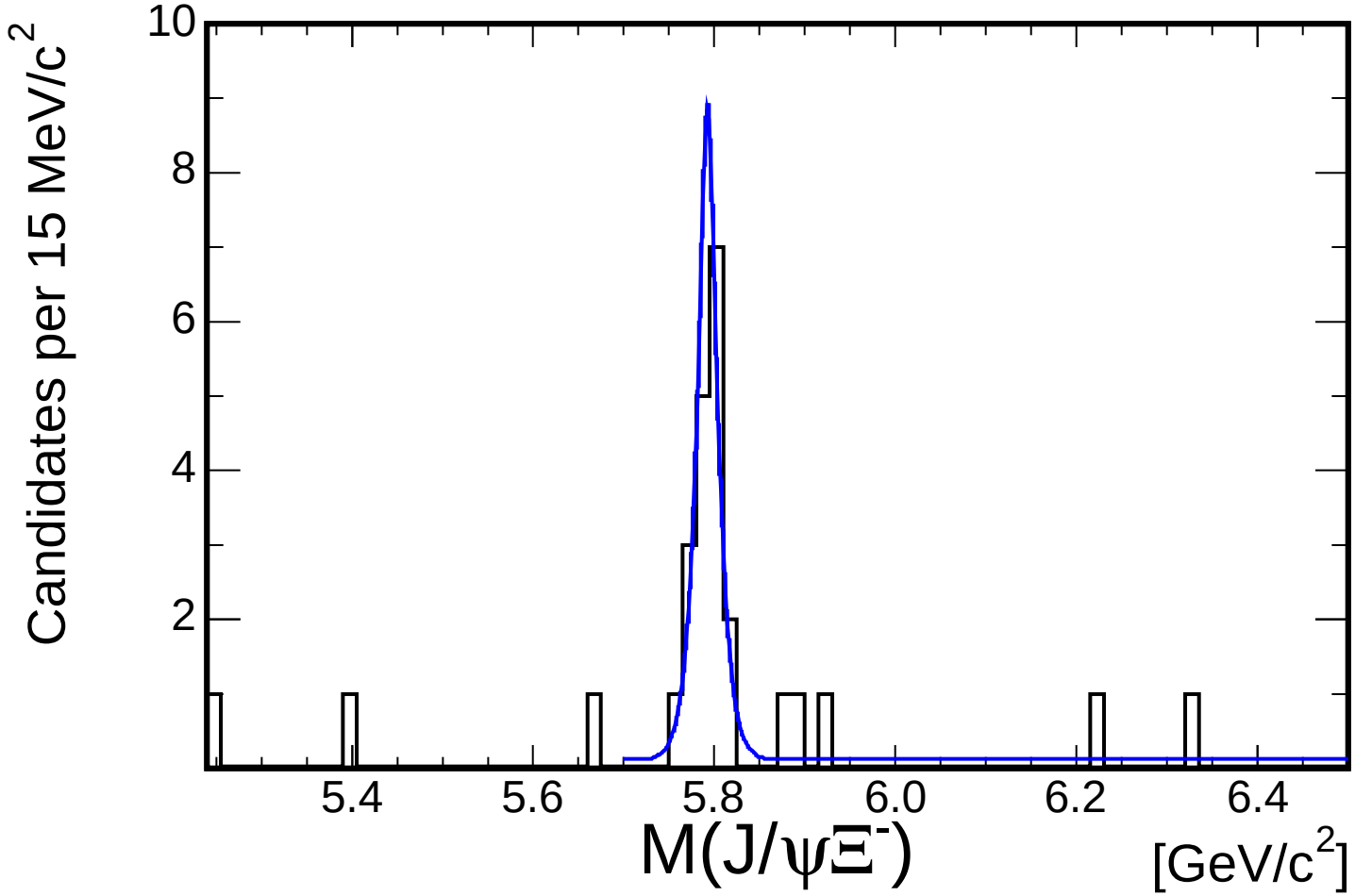
- Assume flat distribution of events in the mass region $[5.7-6.5]$ GeV/c^2
- The p-value is defi ned as probability to toss $N_{total} = 23$ events contained in this interval, so that there are $N_{signal} = 17$ observed events in 60 MeV/c^2 signal range ($\pm 2\sigma$).

$$p = 1 - \sum_{i=0}^{N_{signal}-1} \mathcal{B}(i, N_{total}, \frac{60}{800})$$

- putting in the numbers we get $4.1 \cdot 10^{-15}$ which corresponds to 7.8σ Gaussian signifi cance.

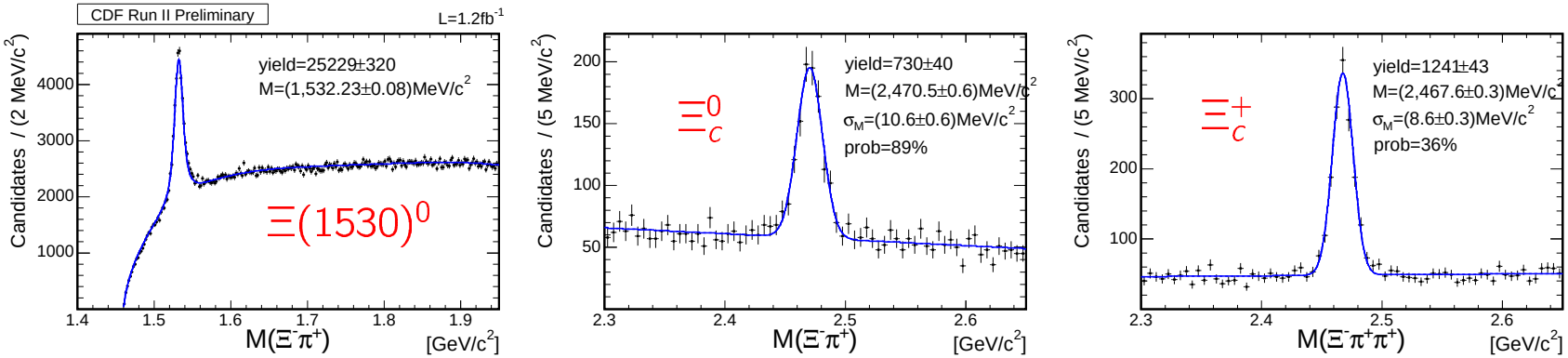
Plot for PRL

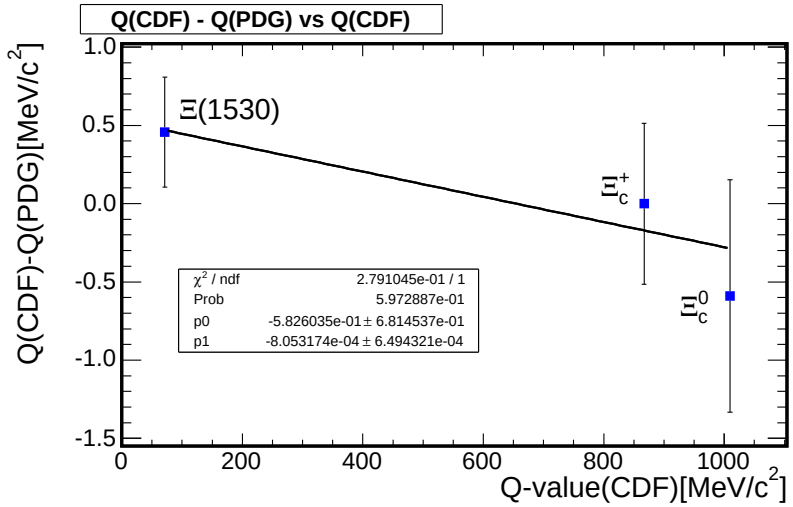
Projection of the unbinned fi t



Mass Systematics

- check on large samples in TTT that Ξ tracking does not introduce any additional tracking systematics

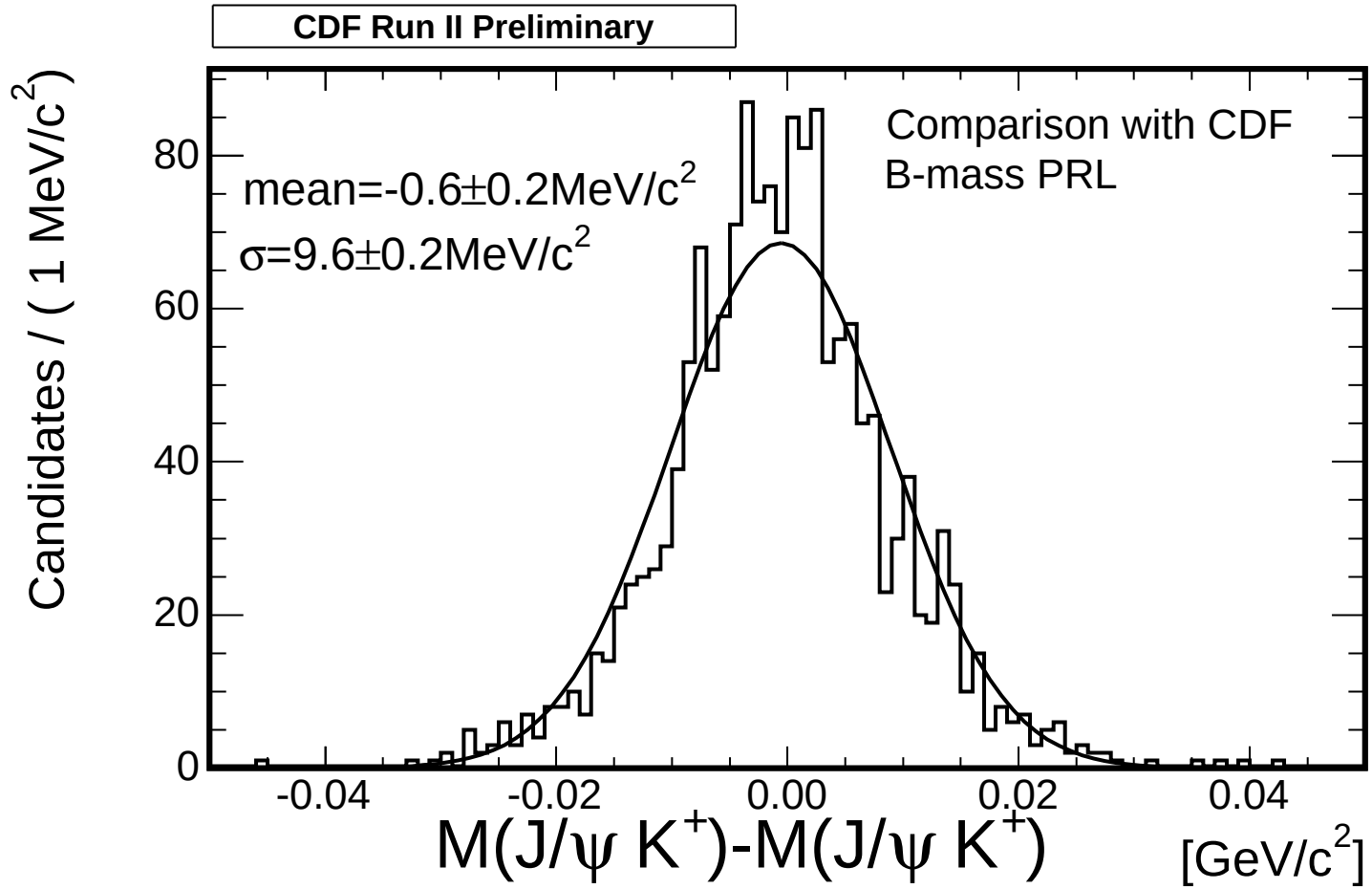




- projected shift at Ξ_b mass is $\delta m = (-1.69 \pm 1.54)\ \mathrm{MeV}/c^2$. Not significant.

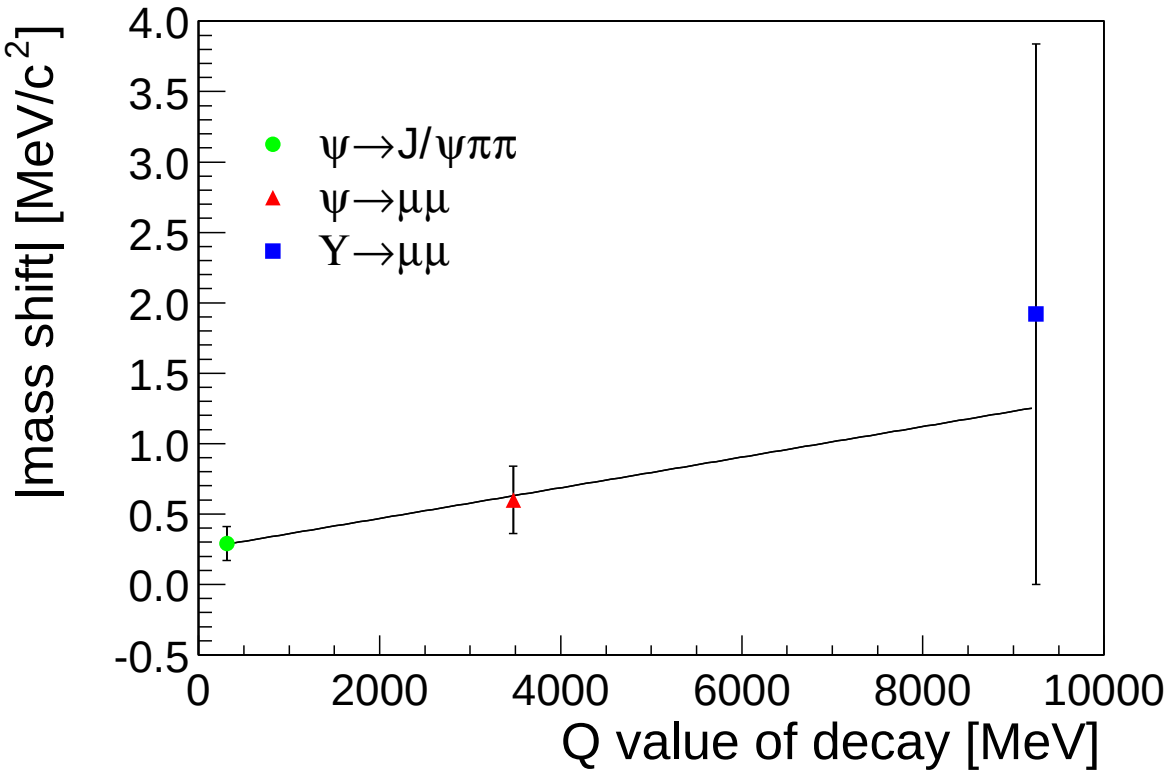
Mass Calibration

Mass calibration offset



Event by event difference between B-mass in $B^+ \to J/\psi K^+$ channel and CDF B-mass PRL events.

Tracking Momentum Scale



$$\delta m = 1.09 \cdot 10^{-4} \cdot Q + 0.25[MeV]$$

Phys.Rev.Lett.96:202001,2006.

Fit model variation

Fit	yield	mass
base	17.5	$(5,792.9)$ MeV$/c^2$
free sigma	17.4	$(5,791.8)$ MeV$/c^2$
double Gaussian	18.1	$(5,794.4)$ MeV$/c^2$

- Reasonable variation of background function and fit range does not change parameters of the peak appreciably
- Take maximum deviation as ± 1.5 MeV$/c^2$

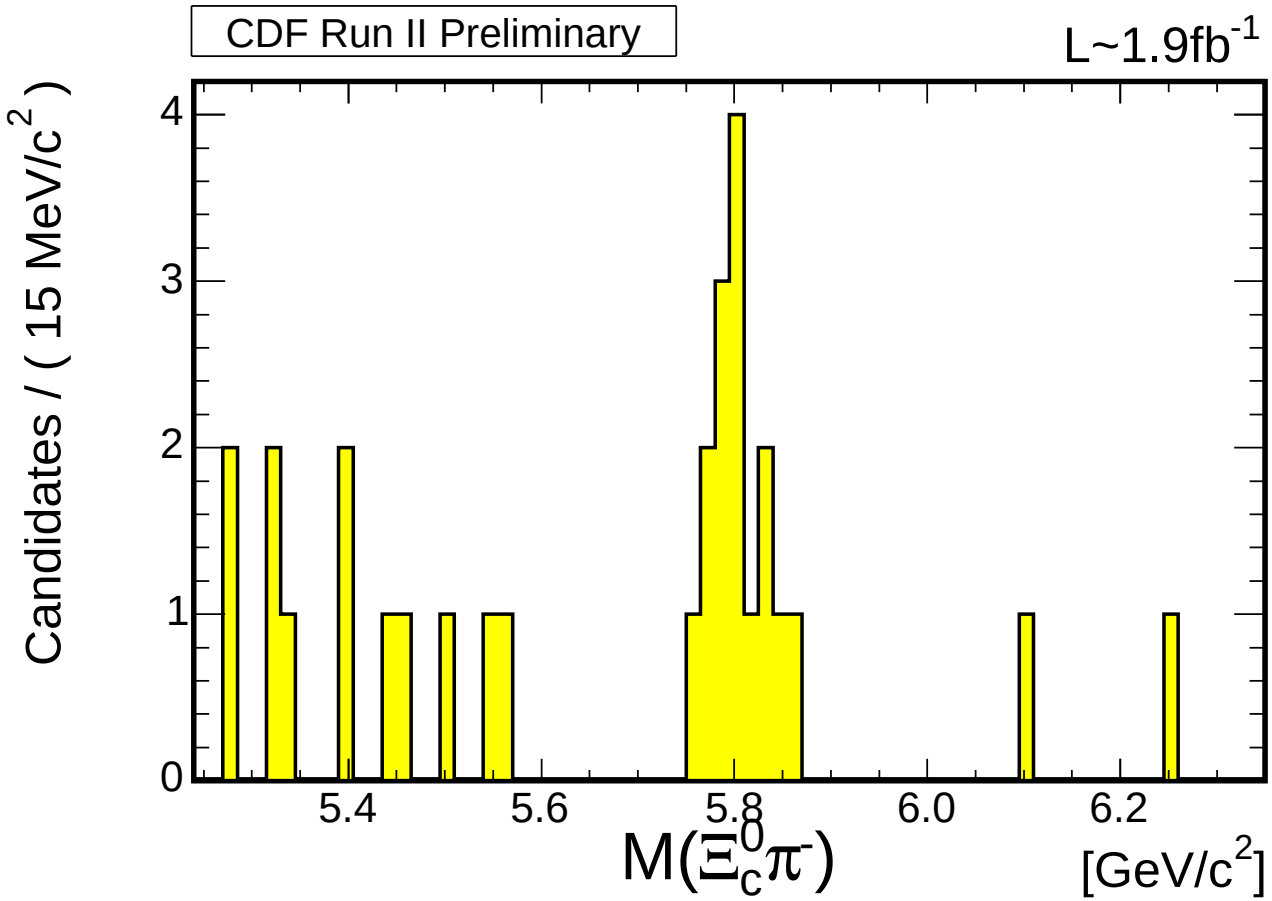
Summary Systematics

Error source	value
Tracking Momentum scale	$\delta m = \pm 0.4$ MeV/c^2
PDG Masses($J/\psi, \Xi$)	$\delta m = \pm 0.14$ MeV/c^2
Mass scale calibration	$\delta m = \pm 0.6$ MeV/c^2
Fit model/resolution	$\delta m = \pm 1.5$ MeV/c^2
Total	$\delta m = \pm 1.7$ MeV/c^2

$$M(\Xi_b^-) = (5,792.9 \pm 2.5(stat.) \pm 1.7(syst.))\ \text{MeV/c}^2$$

$\Xi_b^- \to \Xi_c^0 \pi^-$

Displaced track trigger (a.k.a. TTT)

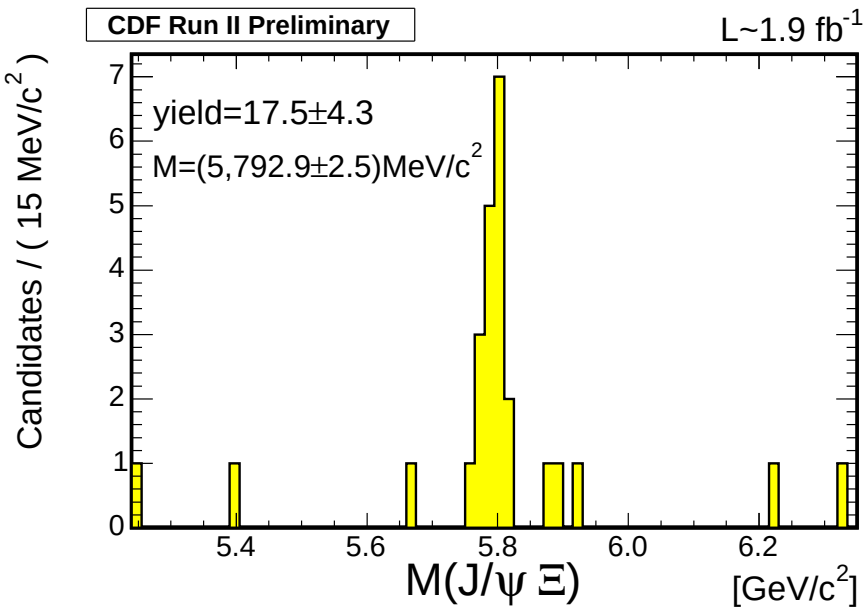


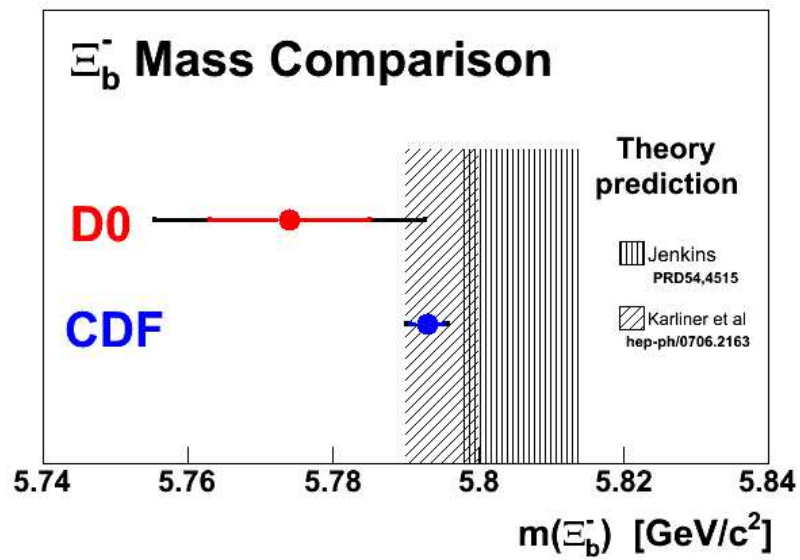
See signal at the same mass. Processing the full $2.5 fb^{-1}$ sample to have a shot at $\Xi_b^0 \to \Xi_c^+ \pi^-$

Conclusion 1

- CDF observes Ξ_b. Significance is 7.8σ
- The Ξ_b mass is measured to be

$$M(\Xi_b^-) = (5,792.9 \pm 2.5(stat.) \pm 1.7(syst.))\ \mathrm{MeV}/c^2$$





- DØ paper: Phys. Rev. Lett. 99, 052001 (2007)
- CDF paper: Phys. Rev. Lett. 99, 052002 (2007) significant improvement over DØ result
- Weighted mean mass $5792 \pm 3\ \mathrm{MeV}/c^2$.

Conclusion 2

- CDF observes $\Sigma_b^{\pm *}$ - 4 new particles!: Q-values:

$$Q(\Sigma_b^-) = (55.9 \pm 1.0 \pm 0.2)\ \mathrm{MeV}/c^2$$

$$Q(\Sigma_b^+) = (48.5^{+2.0+0.2}_{-2.2-0.3})\ \mathrm{MeV}/c^2$$

$$Q(\Sigma_b^*) - Q(\Sigma_b) = (21.2^{+2.0+0.4}_{-1.9-0.3})\ \mathrm{MeV}/c^2$$

Masses:

$$M(\Sigma_b^-) = (5815.2 \pm 1.0 \pm 1.7)\ \mathrm{MeV}/c^2$$

$$M(\Sigma_b^+) = (5807.8^{+2.0}_{-2.2} \pm 1.7)\ \mathrm{MeV}/c^2$$

$$M(\Sigma_b^{*-}) = (5836.4 \pm 2.0^{+1.8}_{-1.7})\ \mathrm{MeV}/c^2$$

$$M(\Sigma_b^{*+}) = (5829.0^{+1.6+1.7}_{-1.8-1.8})\ \mathrm{MeV}/c^2$$

Paper submitted to PRL (arXiv:0706.3868 [hep-exp])

- Measured masses of $\Sigma_b^{(*)}$, and Ξ_b^- are in agreement with theory.

Conclusion 3(final)

- Precision mass measurement of Ξ_b^- mass by CDF provides constraints on model parameters (c.f. arXiv:0708.4027 [hep-ph])
- The progress has happened within last 1.5 years. Basically we just started with broad B-physics program (recall Δm_s measurement in 2006)
- CDF can do wonders with its tracking system. The Ξ-tracking enables us to broaden our reach in B-physics. Expect more to come very soon:
  - Completion of $\Xi_b^0 \to \Xi_c^+ \pi^-$ and $\Xi_b^- \to \Xi_c^0 \pi^-$ analyses in TTT data
  - Measurement of Ξ_b^- lifetime
  - Measurement of $\sigma(p\bar{p} \to \Xi_b^- X)/\sigma(p\bar{p} \to \Lambda_b X)$
  - A shot at $\Omega_b \to D^0 \Xi^-$
  - Search for Ξ_{cc}
- Fermilab makes case for running Tevatron till 2010. The results presented today, and the planned analyses will contribute to making the decision in a positive way.

Backup Slides

Σ_b Significance

Hypothesis	LR	p-value	Significance (σ)
No Signal	2.6×10^{18}	$< 8.3 \times 10^{-8}$	> 5.2
Two Σ_b States	4.4×10^{6}	9.2×10^{-5}	3.7
No Σ_b^- Signal	1.2×10^{5}	3.2×10^{-4}	3.4
No Σ_b^+ Signal	49	9.0×10^{-3}	2.4
No Σ_b^{*-} Signal	4.9×10^{4}	6.4×10^{-4}	3.2
No Σ_b^{*+} Signal	8.1×10^{4}	6.0×10^{-4}	3.2

Σ_b Systematics

Parameter	Mass Scale	Λ_b Comp	Λ_b Norm	Λ_b Shape	Reweight	Reso	Σ_b Width	Δ_*	Total
$\Sigma_b^- \; Q$	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
$\Sigma_b^+ \; Q$	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
$\Sigma_b^* - \Sigma_b \; Q$	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
$\Sigma_b^{*-} \; Q$	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
$\Sigma_b^{*+} \; Q$	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
$\Sigma_b^- - \Sigma_b^+ \; Q$	0.03 -0.03	0.0 -0.07	0.01 -0.005	0.0 -0.03	0.14 0.0	0.003 -0.003	0.04 -0.02	0.19 0.0	0.24 -0.09