Ξ_b observation at CDF

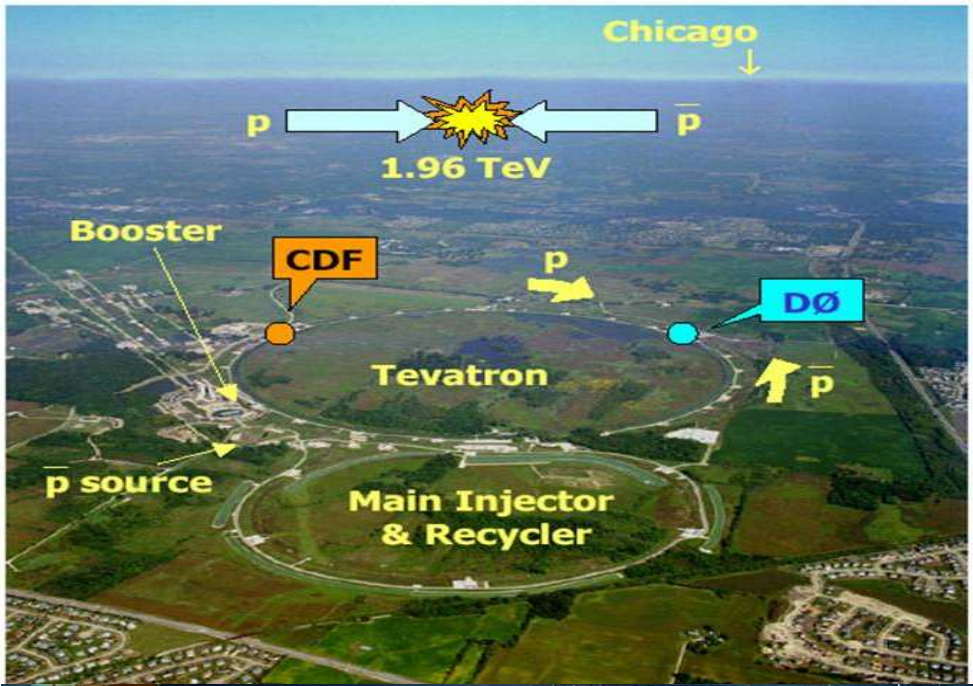
Dmitry Litvintsev (Fermilab)

for CDF Collaboration

December 6, 2007

BNL HEP Seminar

Source of da


Chicago
p
p̄
1.96 TeV
Booster
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p
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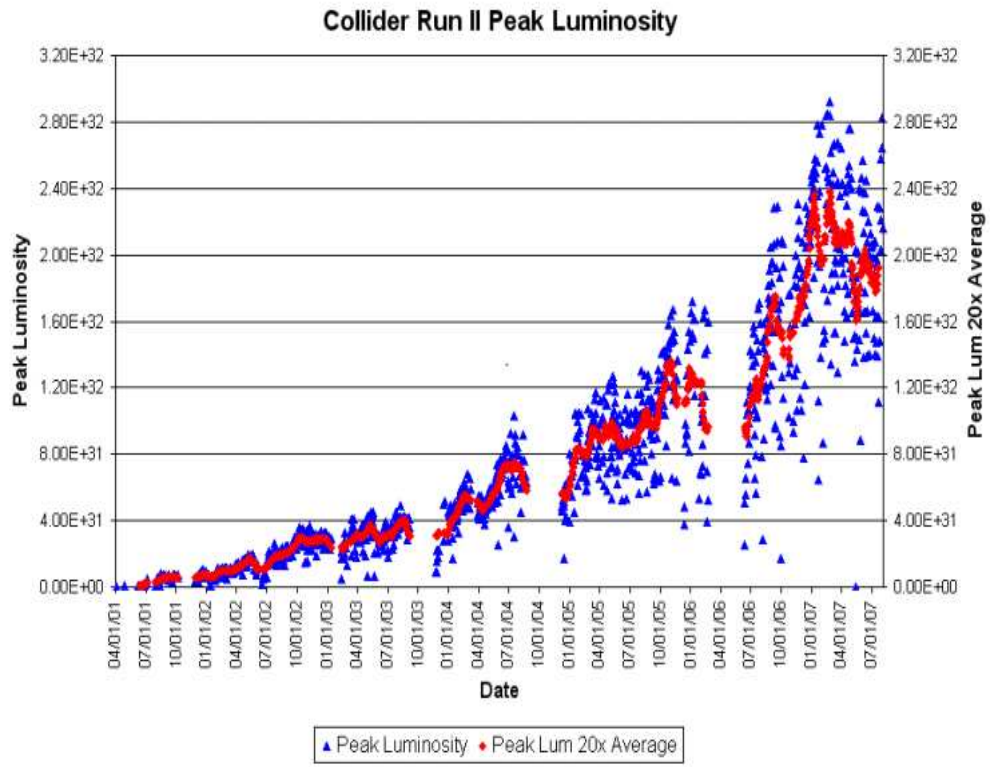
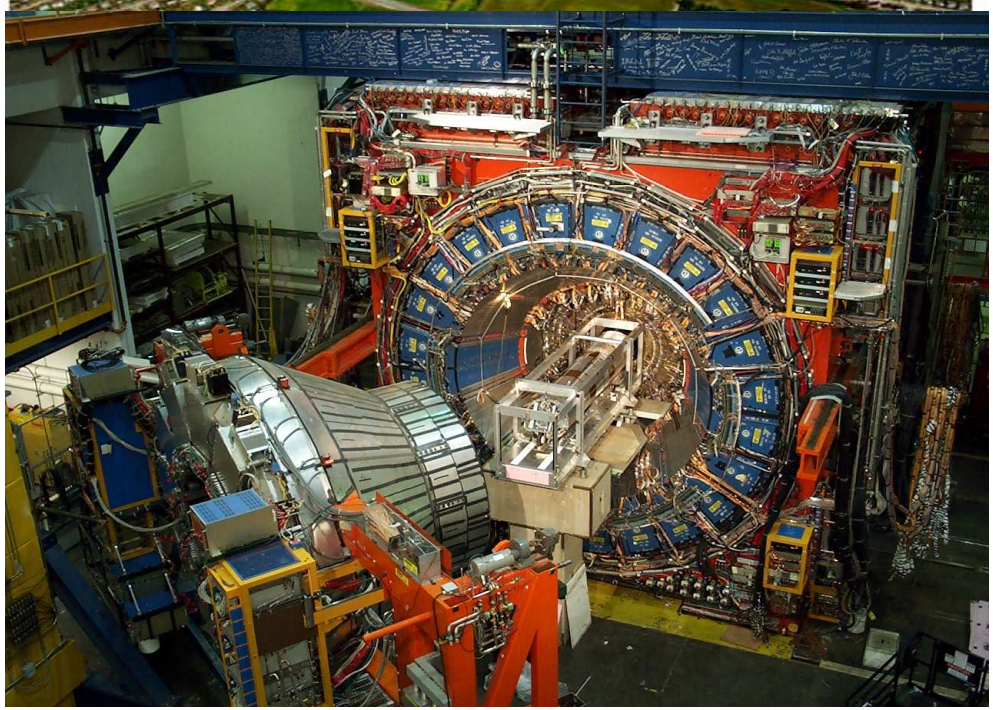
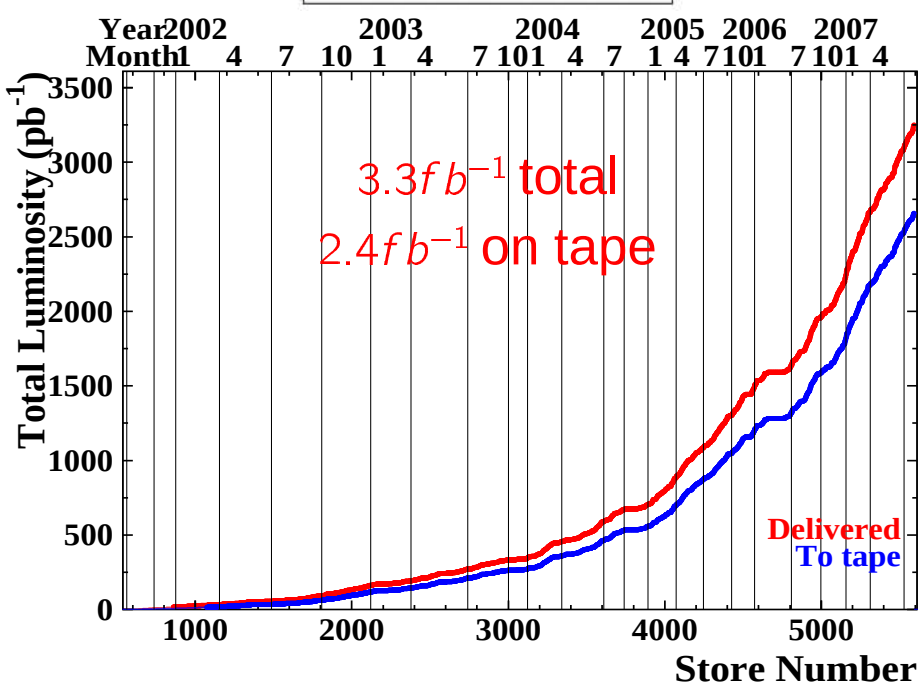
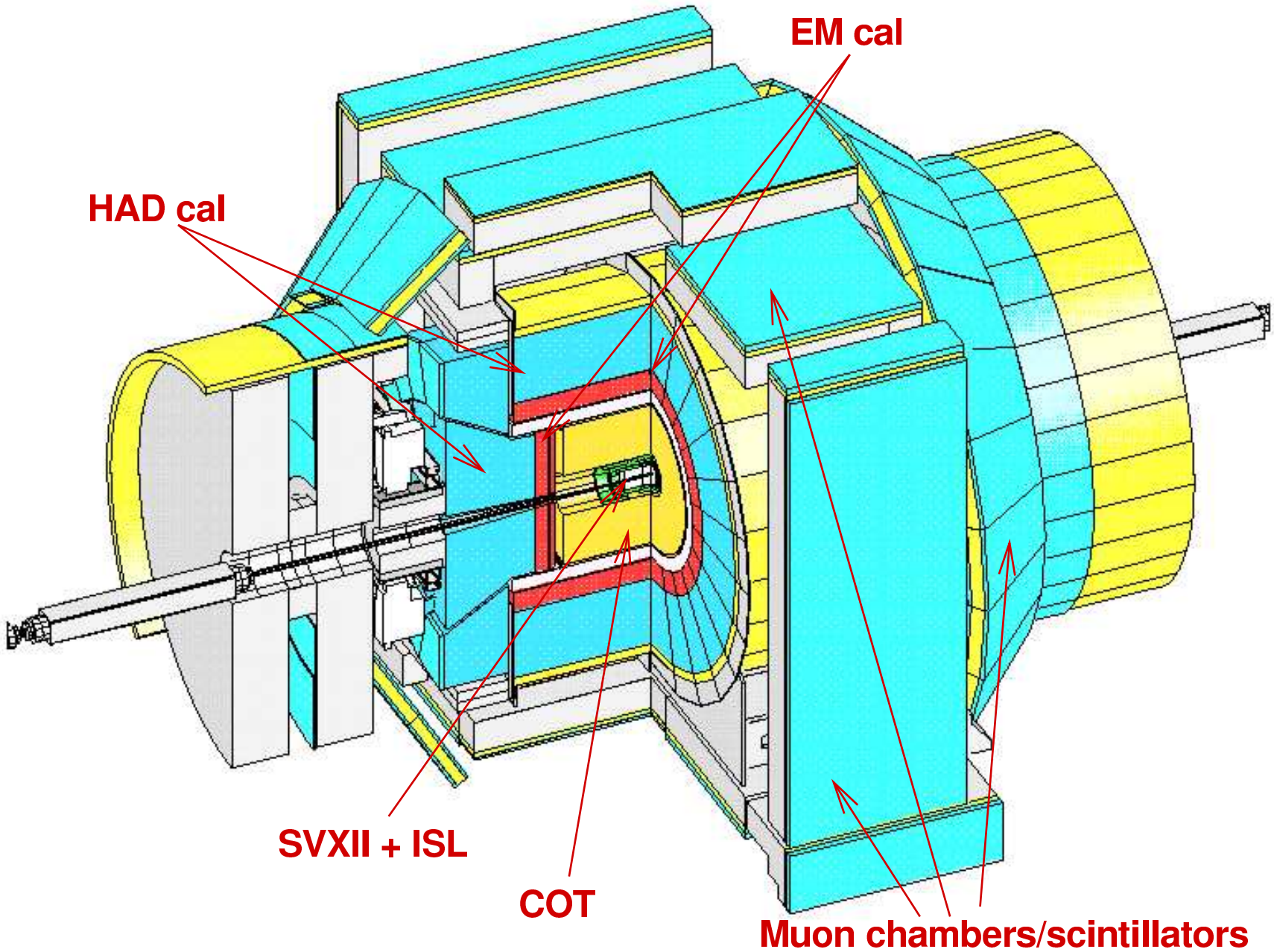
p̄ source
Main Injector
& Recycler


Collider Run II Peak Luminosity
Peak Luminosity
Peak Lum 20x Average
Date
Peak Luminosity
Peak Lum 20x Average




Year 2002 2003 2004 2005 2006 2007
Month 1 4 7 10 1 4 7 10 1 4 7 1 4 7 10 1 7 10 1 4
Total Luminosity (pb^{-1})
$3.3 fb^{-1}$ total
$2.4 fb^{-1}$ on tape
Delivered
To tape
Store Number

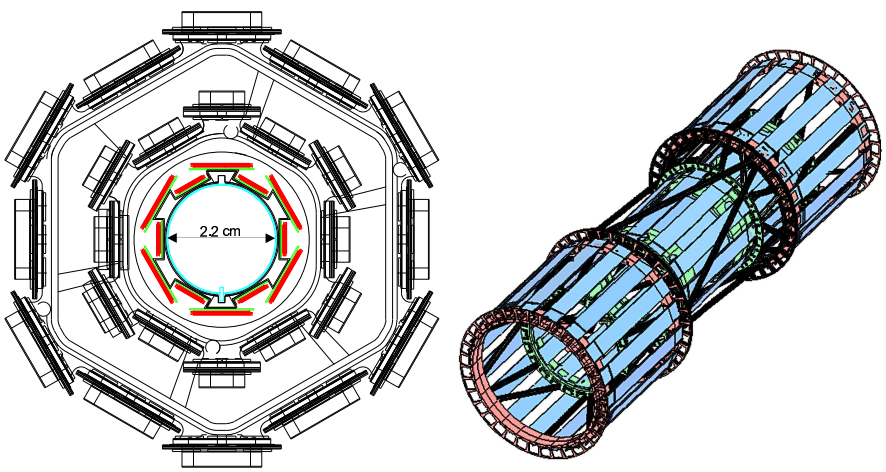
CDF II Detector

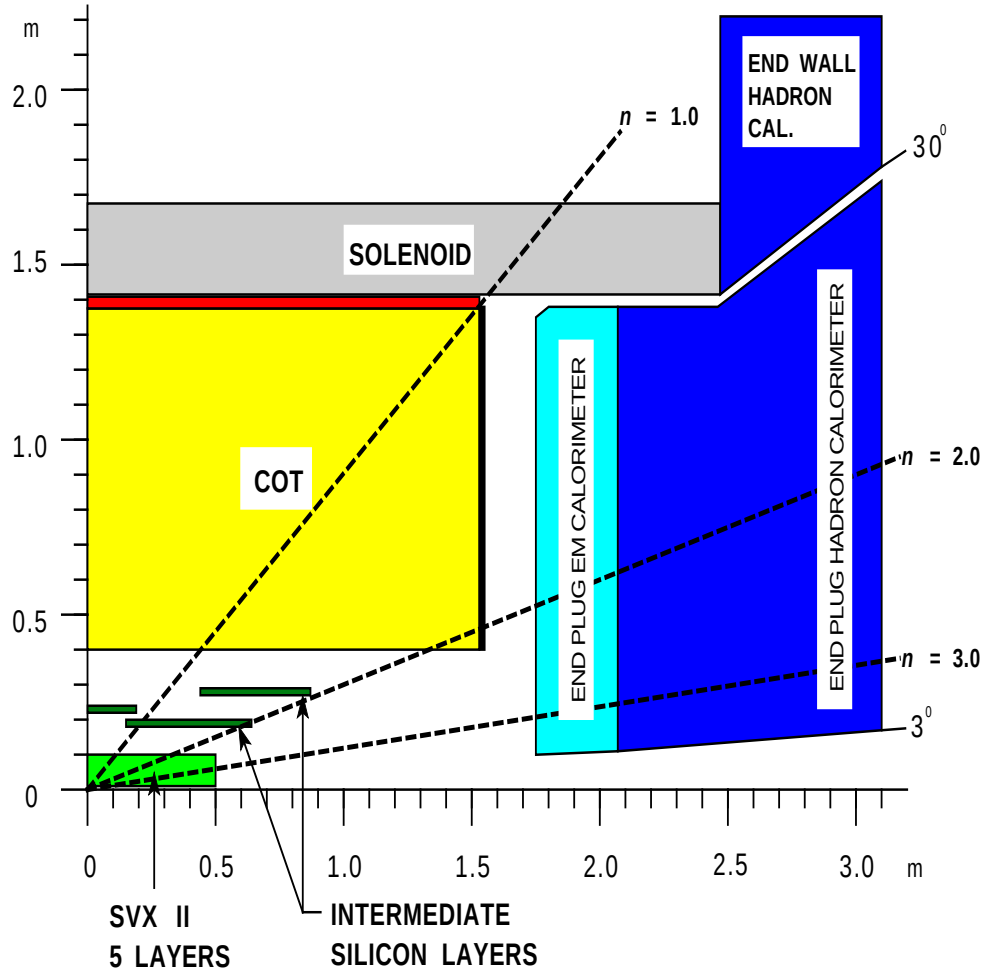


Tracking System

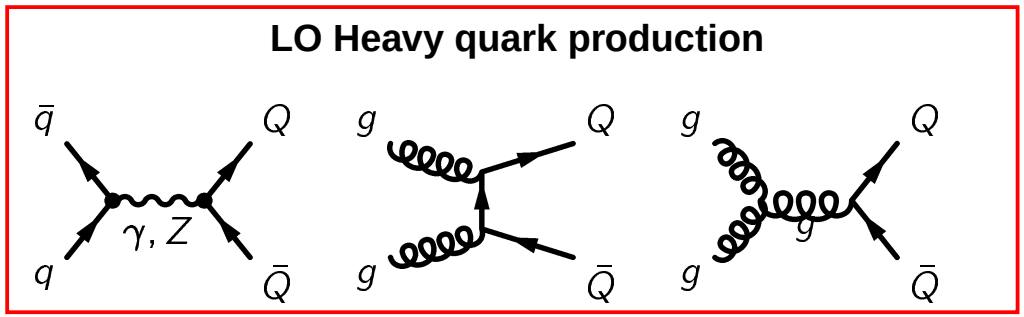
Central Outer Chamber (Run I CTC shown)

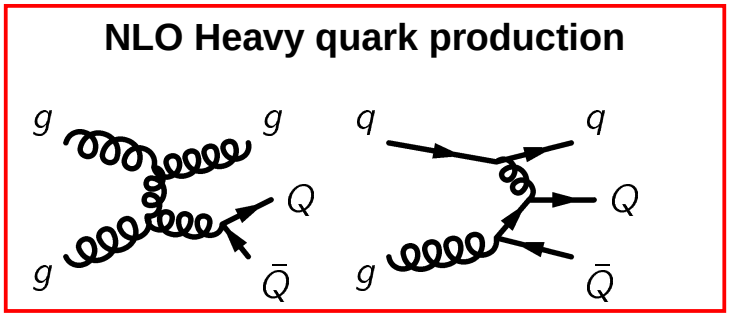
L00, SVXII, ISL





Tevatron as a B-factory

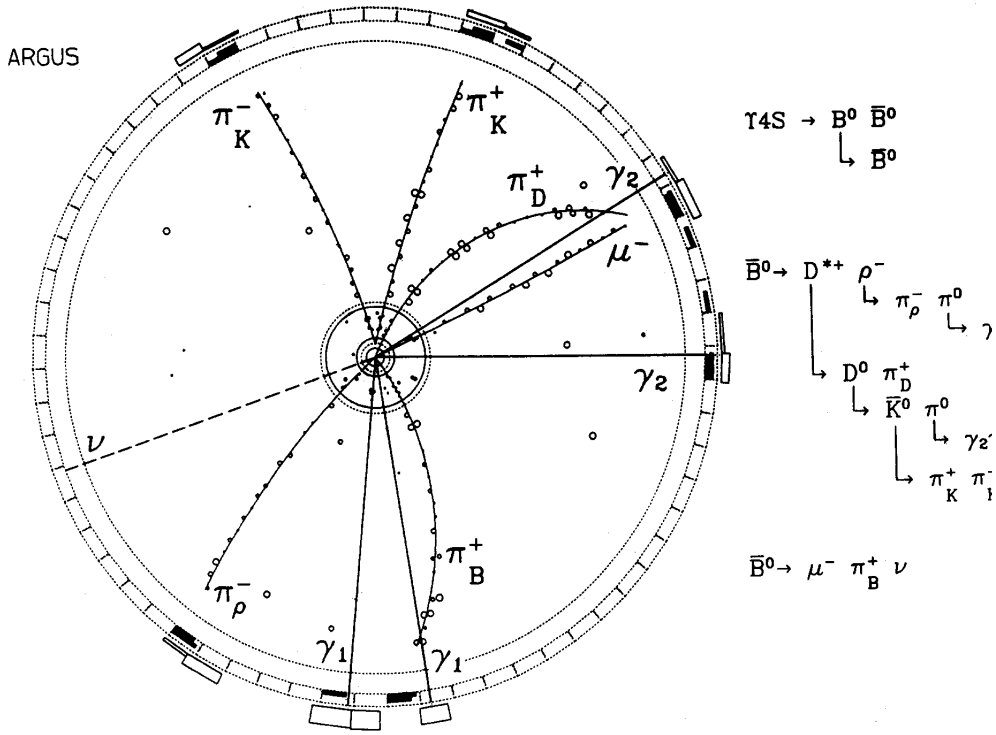




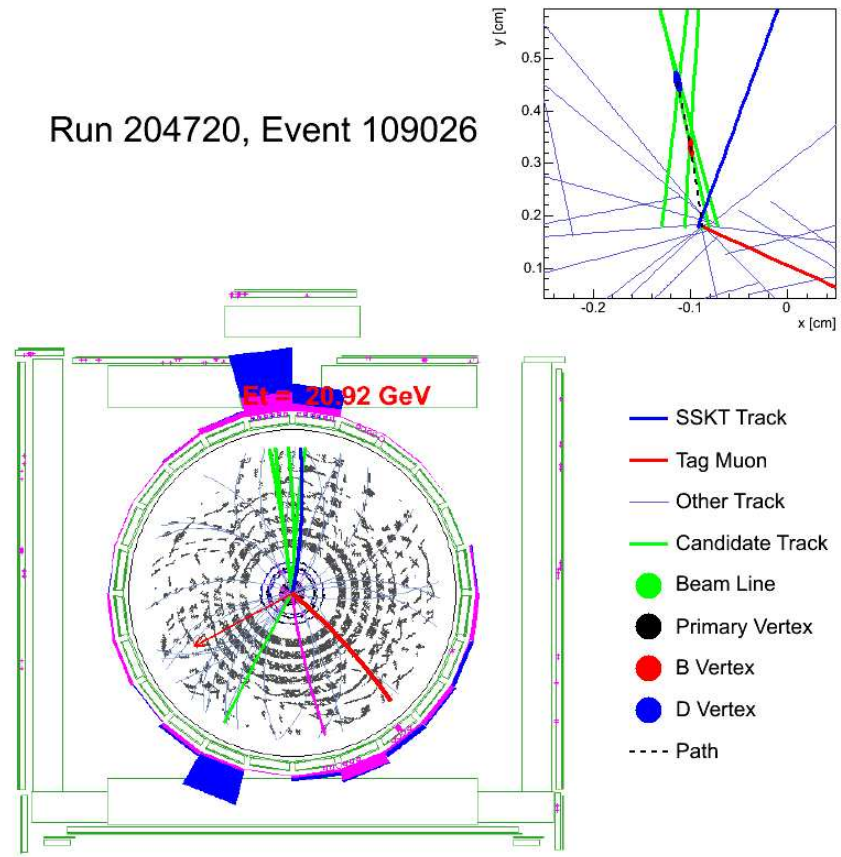
- High production x-section $\sigma(b\bar{b}) = 100\mu b$ ($10\mu b$ $|y| < 1$)
- All species of b-hadrons produced.
- $\beta\gamma = 2 - 4$ – good B-vertex separation.
- Huge background ($\sigma(b\bar{b}) : \sigma(had) = 0.001$).
- High track density in an event.
- Can't use beam energy constraint.

Dedicated triggers are needed to extract heavy flavor signals from the data.

Source of data: Event Environment

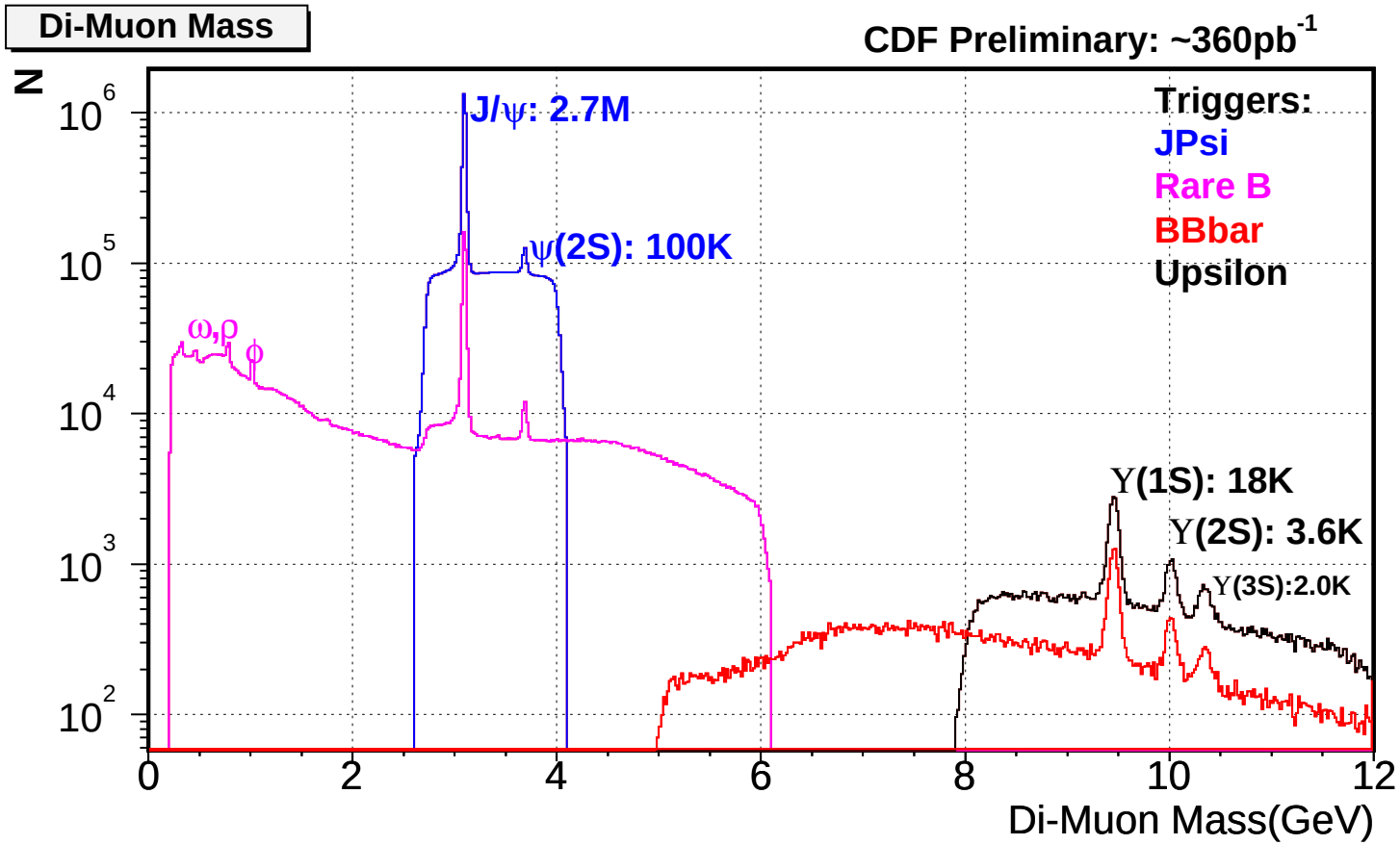


fully reconstructed $\Upsilon(4S) \to B^0\bar{B}^0$ event with $B^0 - \bar{B}^0$ mixing in ARGUS Detector (circa 1987)



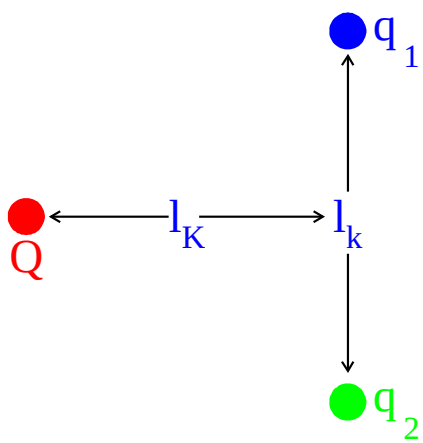
$B^0_s - \bar{B}^0_s$ mixing candidate, CDF II , 2006

The trigger



- Analysis presented today uses traditional J/ψ-trigger:
  - ✓ J/ψ trigger – di-muon events with masses around J/ψ, $\psi(2S)$ (two CMU muons or 1 CMU and 1 CMX muon). $p_T(\mu) > 1.35$ GeV/c

Heavy Baryons



- $q = u, d, s; Q = c, b; m_Q \gg \Lambda_{QCD}$
-

$$\vec{k} = \tfrac{1}{2}(\vec{p}_1 - \vec{p}_2)$$
$$\vec{K} = \tfrac{1}{2}(\vec{p}_1 + \vec{p}_2 - 2\vec{p}_3)$$

- 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 $l_k = 0, l_K = 0$:
  - $j_{qq} = s_{qq} = 0$

$$J = j_{qq} \otimes s_Q = \frac{1}{2}^+ \{\Lambda_c, \Xi_c, \Lambda_b, \Xi_b\}$$

  - $j_{qq} = s_{qq} = 1$

$$J = j_{qq} \otimes s_Q \begin{cases} \nearrow \frac{3}{2}^+ \\ \searrow \frac{1}{2}^+ \end{cases} \left\{ \begin{array}{l} \Sigma_c^*, \Xi_c^*, \Sigma_b^*, \Xi_b^*, \Omega_b^* \\ \\ \Sigma_c, \Xi_c', \Sigma_b, \Xi_b', \Omega_b \end{array} \right\}$$

- 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)

  - give 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 $J_Q \cdot J_{qq}$ Clebsch term:

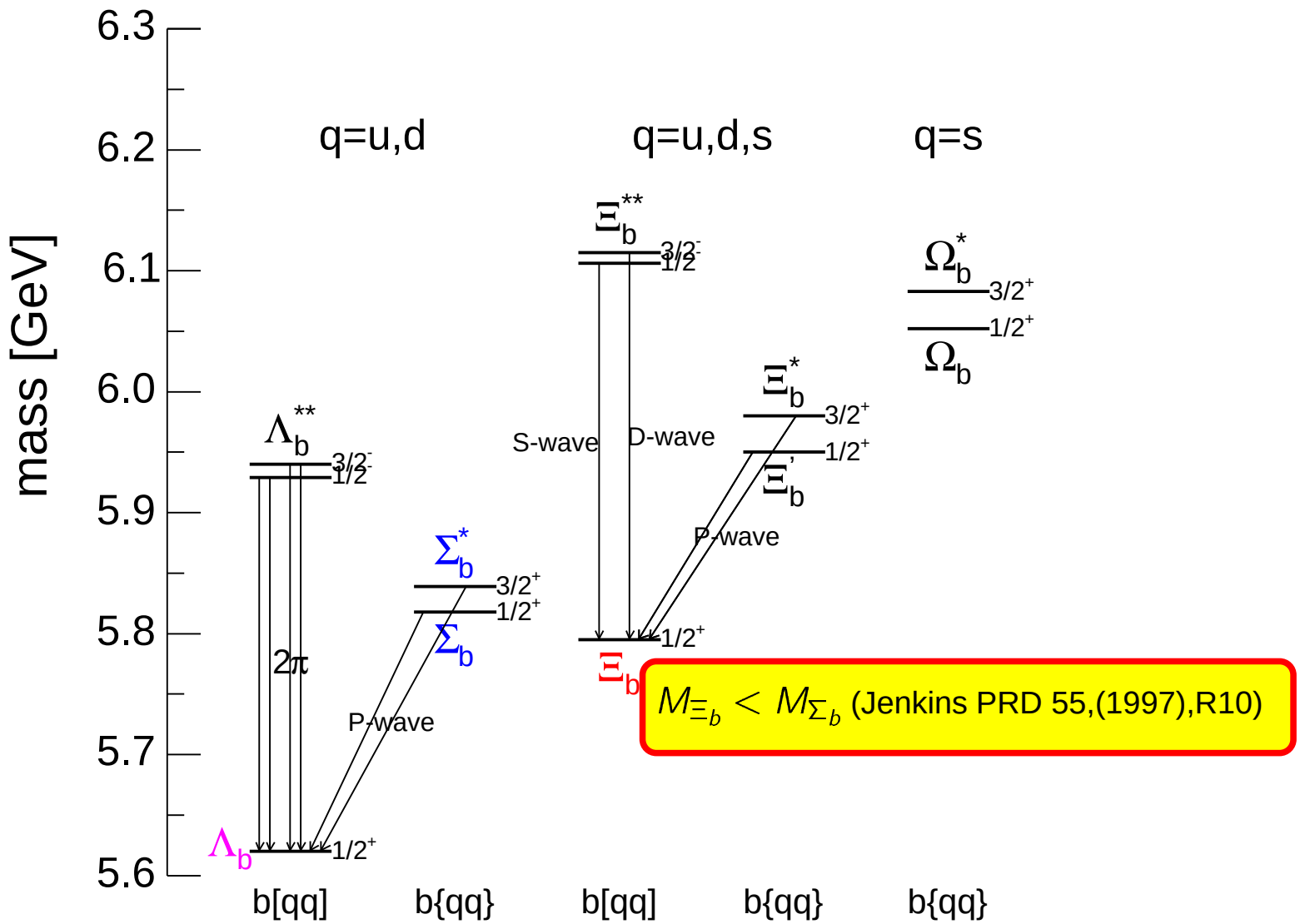
$$0 \text{ for } J^P = \tfrac{1}{2}^+, \bar{\mathbf{3}} \text{ states } (\Lambda_Q, \Xi_Q)$$

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

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

- 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

Weak Decays of Bottom Baryons

- J/ψ trigger:

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

- Displaced track trigger:

$$\Xi_b \to \Xi_c + n\boxed{\pi} \quad \hookrightarrow \Xi^- + n\boxed{\pi} \quad , \Omega_b \to \Omega_c + n\boxed{\pi} \quad \hookrightarrow \Omega^- + n\boxed{\pi}$$

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

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

- SVT+lepton trigger:

$$\Xi_b \to \Xi_c + \boxed{\ell^-}X \quad \hookrightarrow \Xi^- + n\boxed{\pi} \quad , \Omega_b \to \Omega_c + \boxed{\ell^-}X \quad \hookrightarrow \Omega^- + n\boxed{\pi}$$

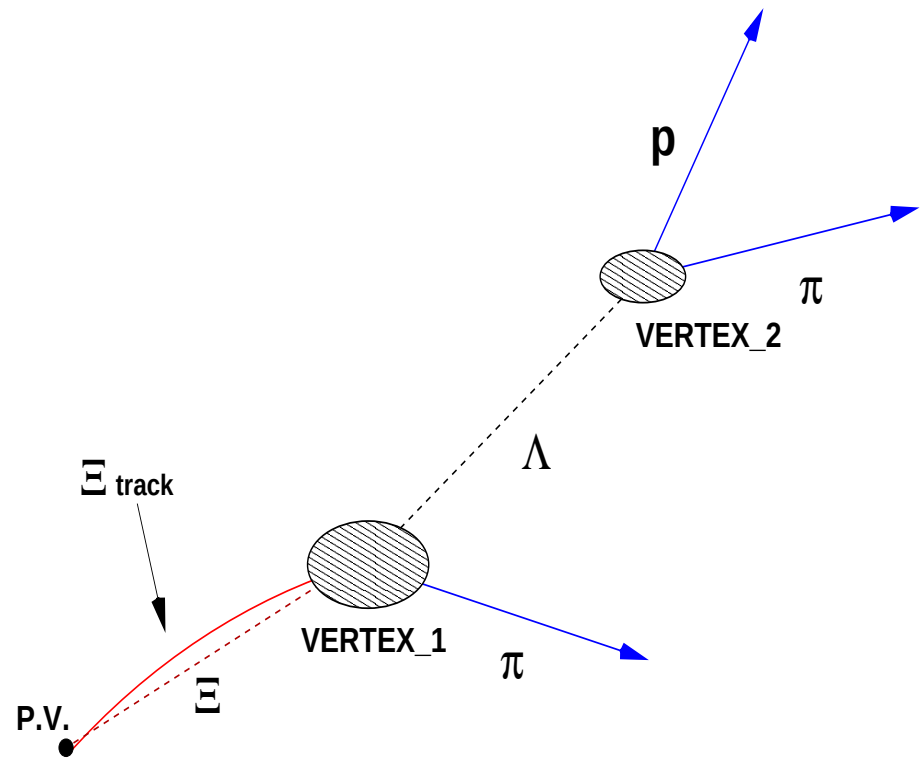
- Expected lifetime pattern:

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

- Can use high statistics B and Λ_b as control samples
- Decays of bottom-strange baryon involve long lived hyperons as decay products.
- => start with reconstruction of long lived hyperons

Cascades at CDF

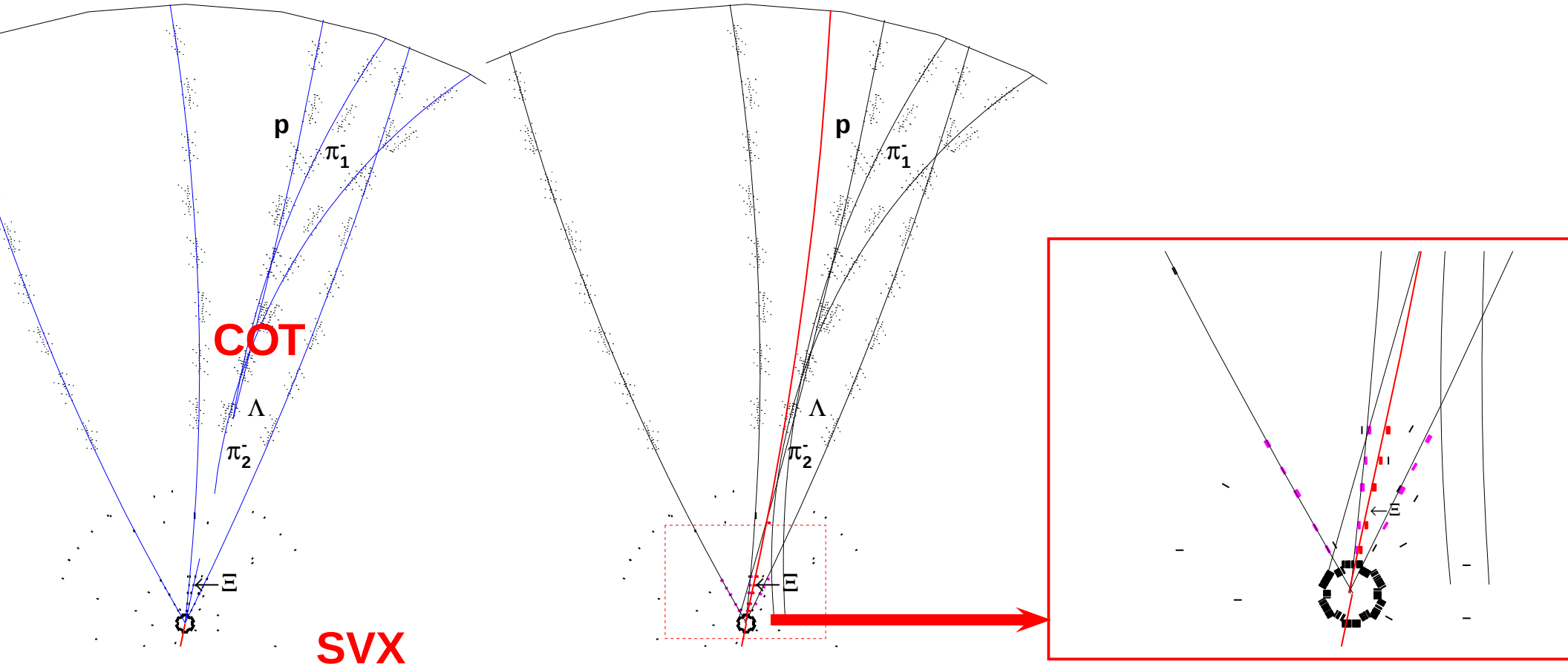
- Ξ^- long lived ($c\tau = 4.91 cm$) & charged.
- Can be tracked in SVX (previously done at LEP)
- CDF developed tracking of Ξ. 1st in hadron collider experiment.
  - Find and form V0 : $\Lambda \rightarrow p\pi^-$
  - Attach pion to Λ, form Ξ candidate, do vertex fi t.
  - Convert Ξ momentum and vertex position into helix in CDF track parameter $(cu, \phi_0, d_0, \lambda, z_0)$ basis and convert elements of Vertex fi t 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 fi le 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 fi ts and parent tracks)



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

Cascade Tracked!

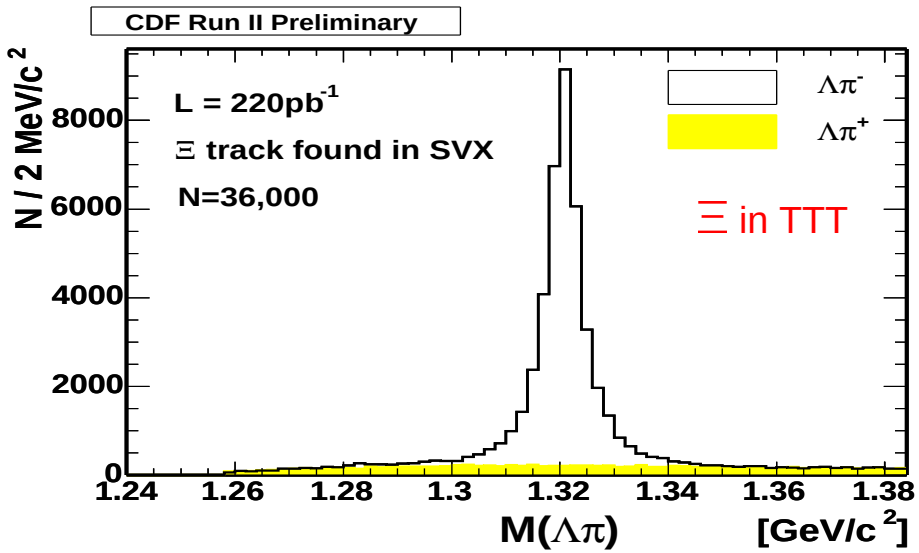
Event Display of generated Hyperons Tracked in Silicon



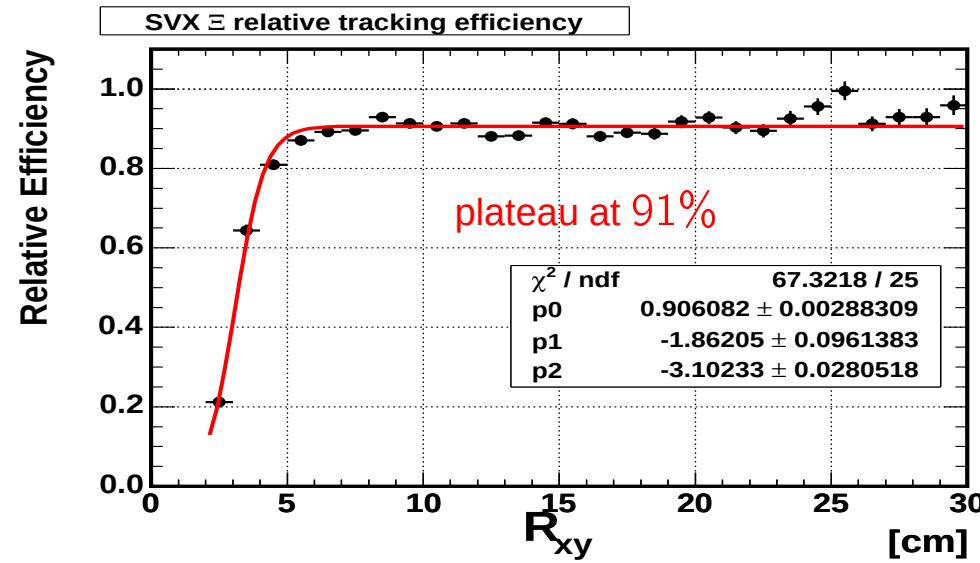
$$\Xi_b \to \Xi_c^+ \pi^- \quad \Xi_c^+ \to \Xi^- \pi^+ \pi^+ \quad \Xi^- \to \Lambda \pi_2^- \quad \Lambda \to p \pi_1^-$$

Benefits of Hyperon Tracking

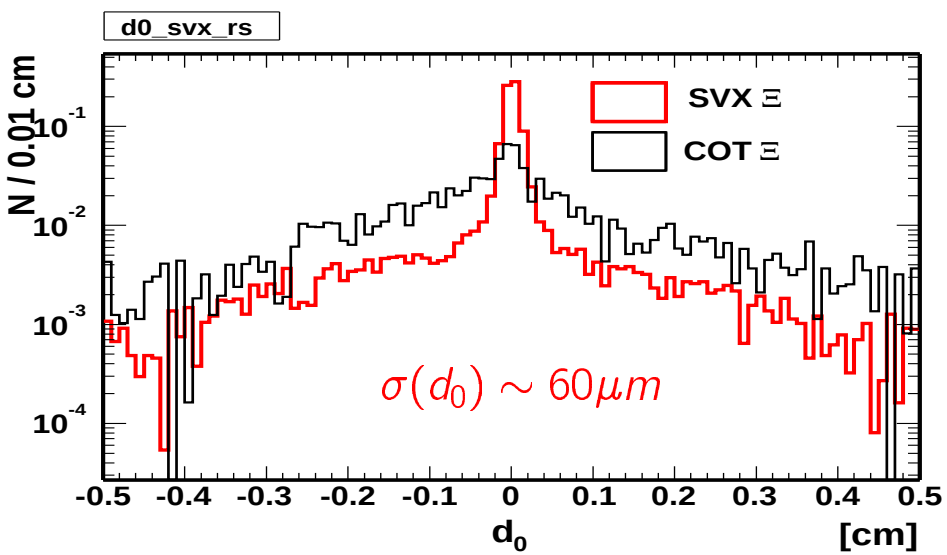
- Clean Ξ samples:



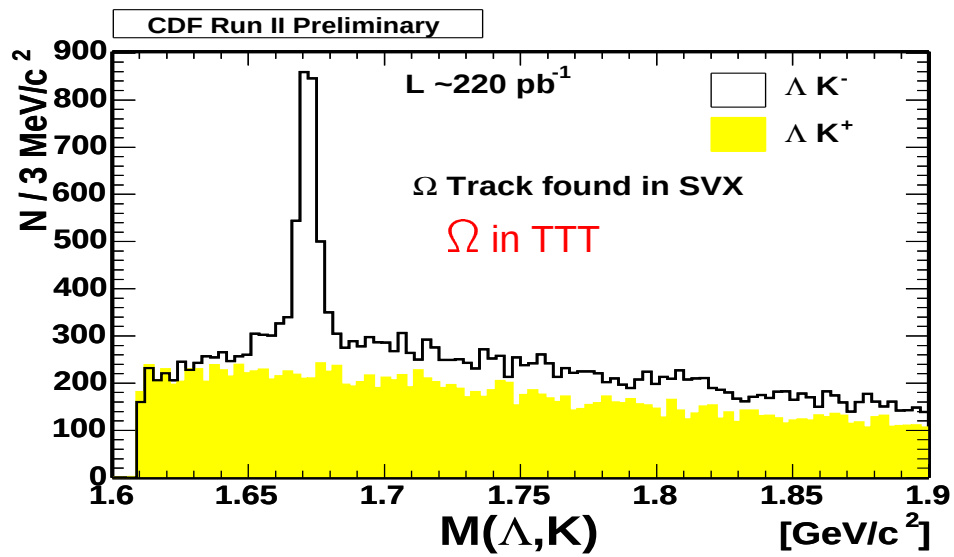
- Good effi ciency (absolute $\sim 40\%$)



- Improvement in Ξ i.p. resolution:

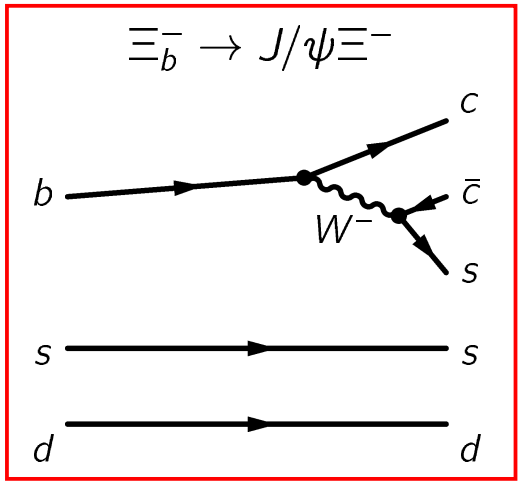


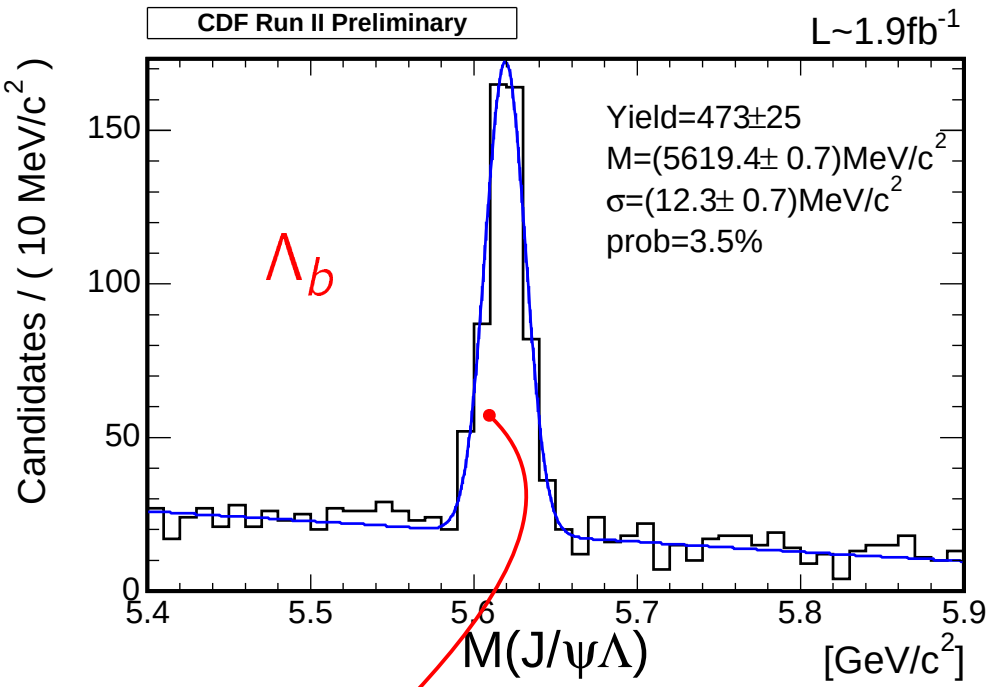
- Can track Ω^- too!



Expected Ξ_b yield in JPSI trigger

- Two states: $\Xi_b^0(bsu)$ and $\Xi_b^-(bsd)$
- Look for Ξ_b^- ($\Xi_b^0 \to \Xi^0\ J/\psi$ is lost due to π^0 in the fi nal state)





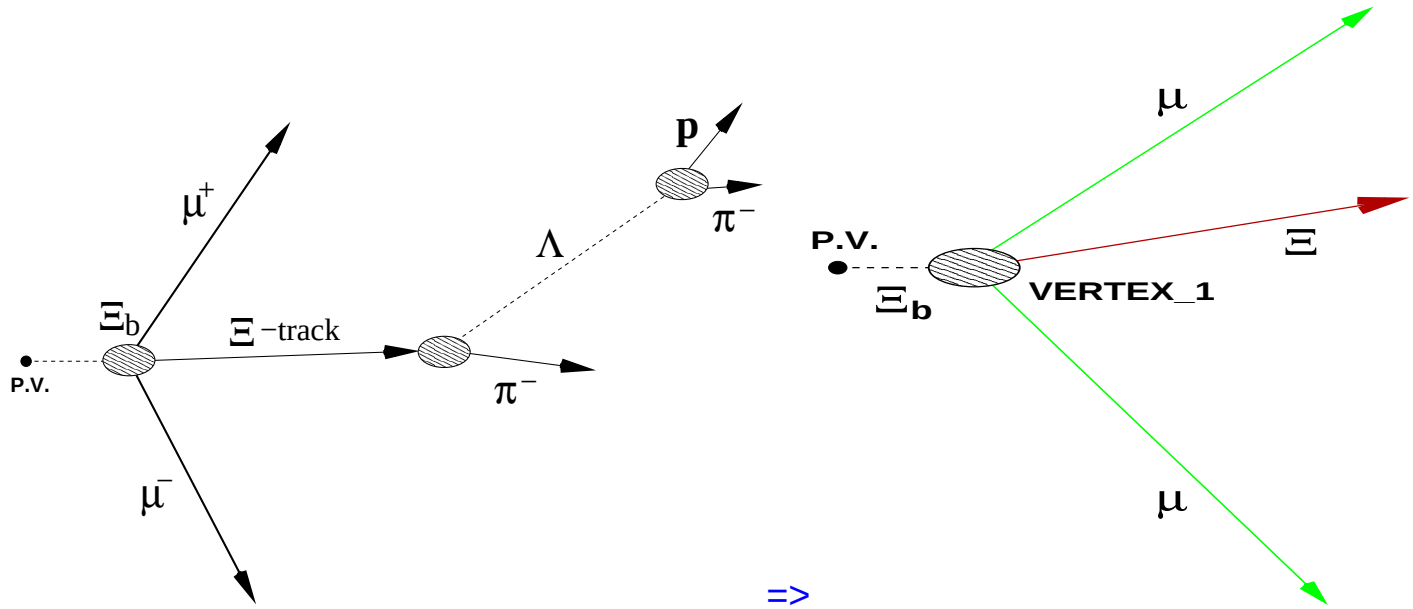
- Use Λ_b yield to estimate $N(\Xi_b)$
  - Assuming $\mathcal{B}(\Lambda_b \to J/\psi\Lambda) = \mathcal{B}(\Xi_b^- \to J/\psi\Xi)$:

$$N(\Xi_b^- \to J/\psi\Xi) \sim N(\Lambda_b \to J/\psi\Lambda) \cdot \frac{\sigma(\Xi_b)}{\sigma(\Lambda_b)} \cdot \epsilon_r \sim 15 - 20$$

  - ($\epsilon_r = r \cdot \epsilon(\pi)\epsilon_{SVX}(\Xi) \sim 1/4.$, $r = 0.9$ (relative acceptance), $\epsilon_\pi = 0.8$ and $\epsilon_{SVX} = 0.4$)

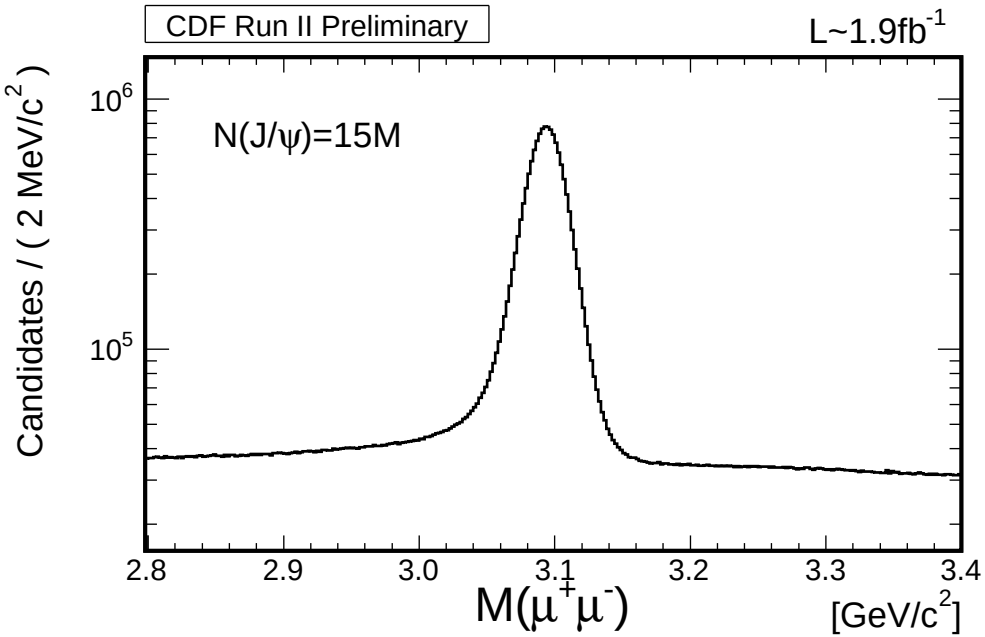
Analysis Strategy

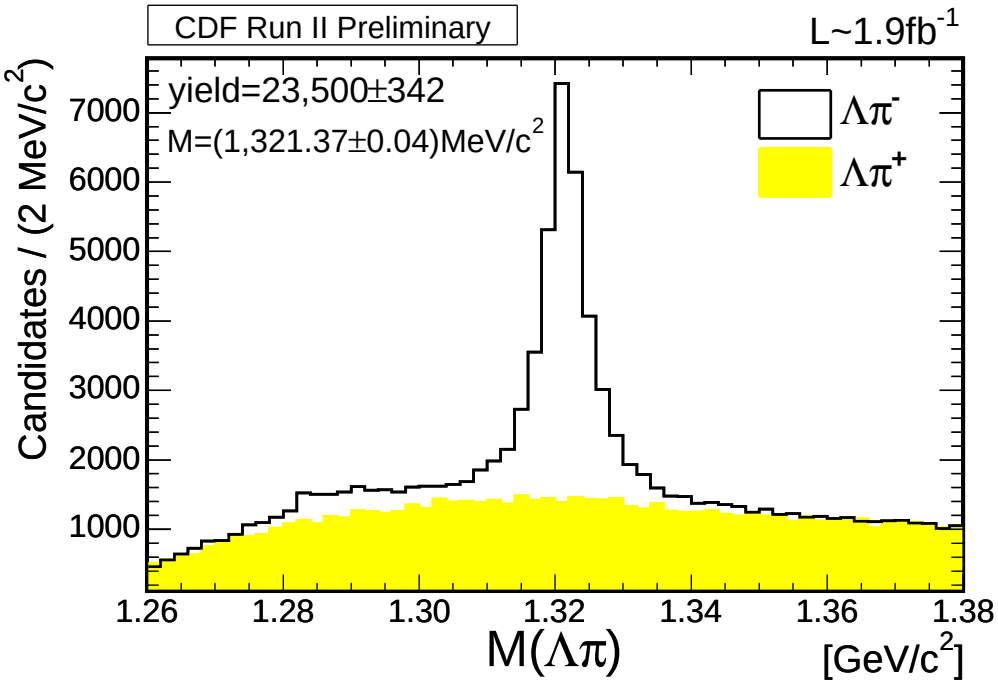
- Use silicon Ξ tracks to look for $\Xi_b \to J/\psi\Xi$



- 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/ψ and Ξ



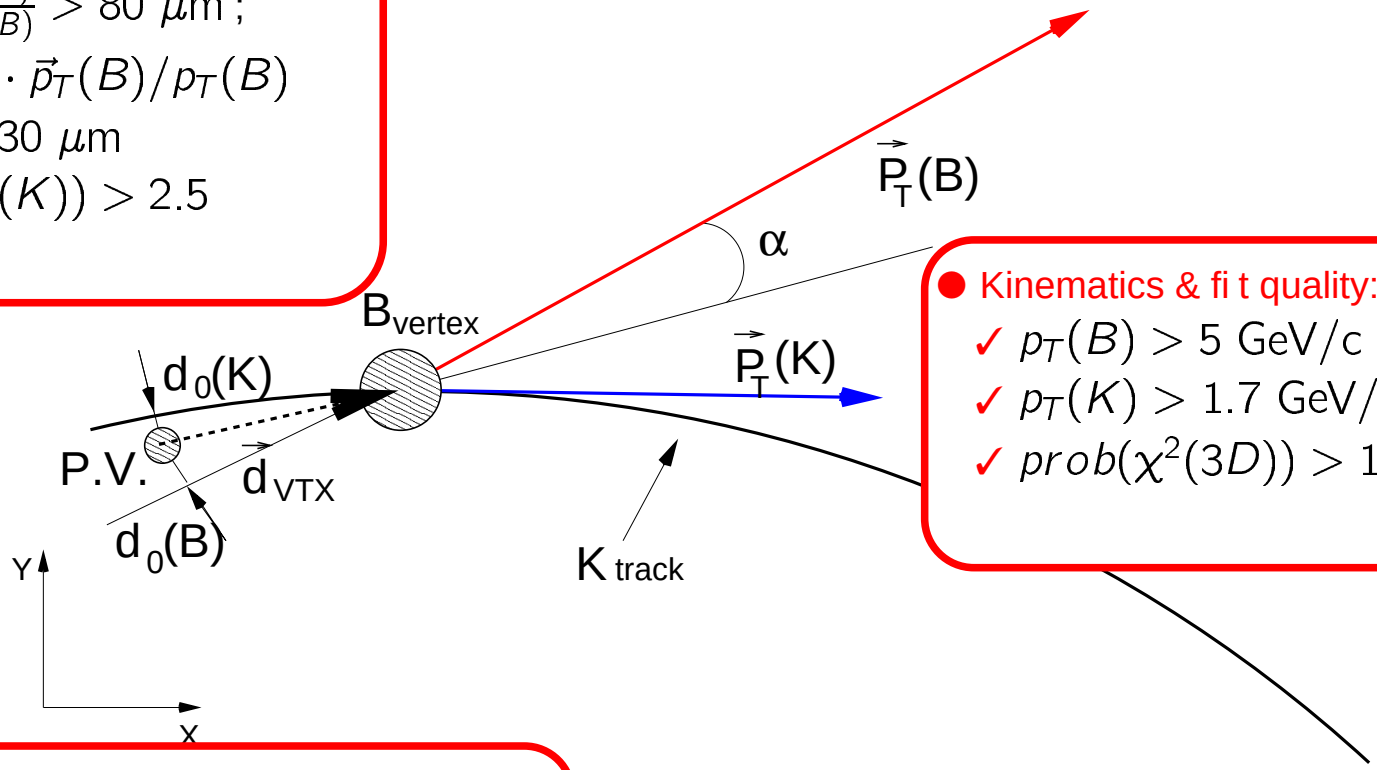


- Two central muons, $p_T > 1.5$ GeV/c fit to the same vertex
- 15M J/ψs

- Ξ candidates:
  - No p_T cuts on daughter tracks
  - Vertex and mass constrained fit (both Λ^0 and Ξ)
- 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 & fi t 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
  - ✓ $|d_0(B)| < 75\ \mu m$;
    $\vec{d}_0(B) = \vec{d}_{VTX} \times \vec{p}_T(B)/p_T(B)$

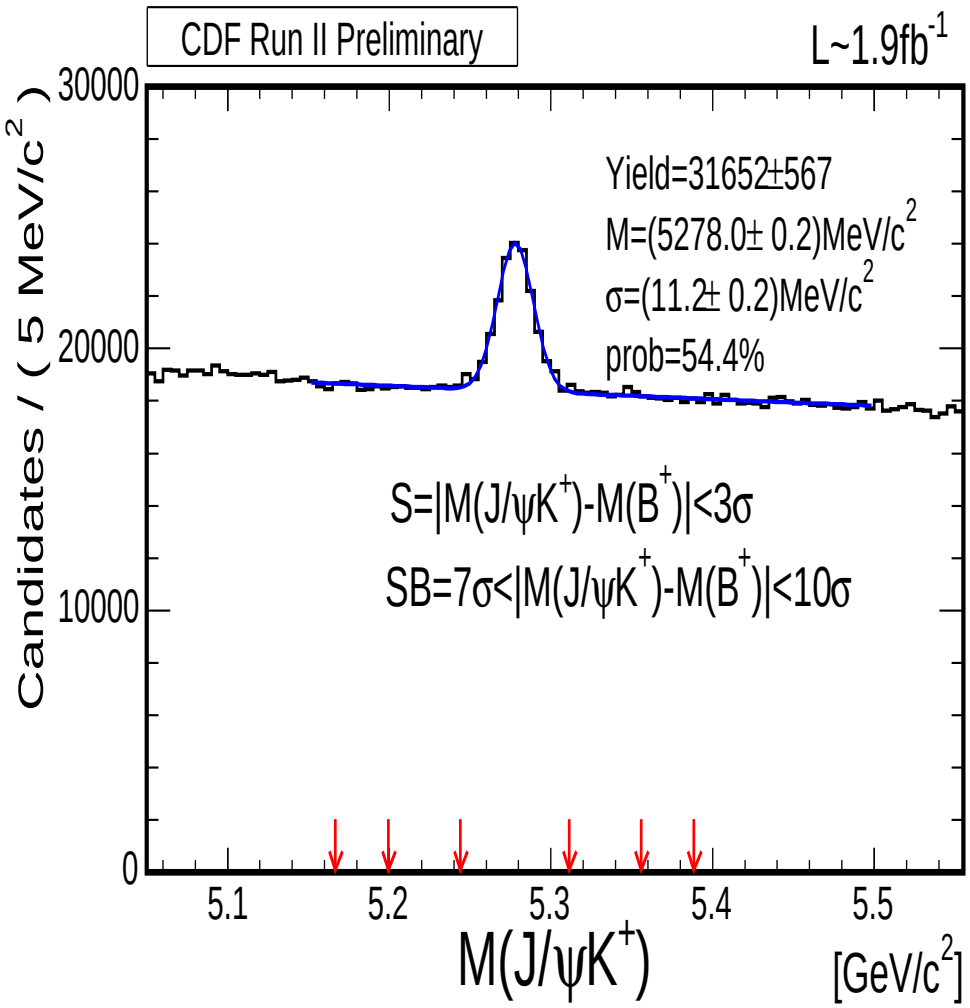
- Require Kaon IP w.r.t. B-vertex be small:
  - ✓ $|d_0(K)(w.r.t.\ \ B_{vertex})| < 100\ \mu m$

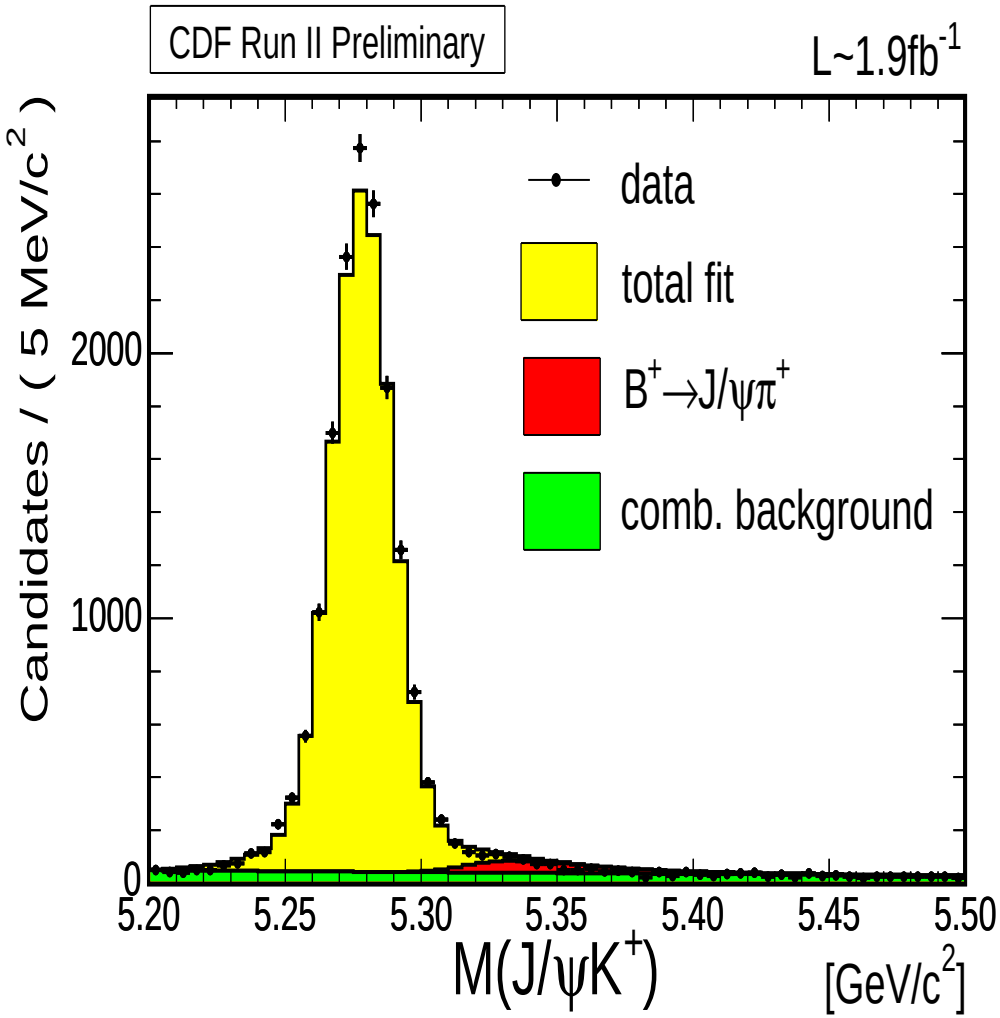
Two step optimization procedure

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 efficiency 52%, background reduced by factor of 500

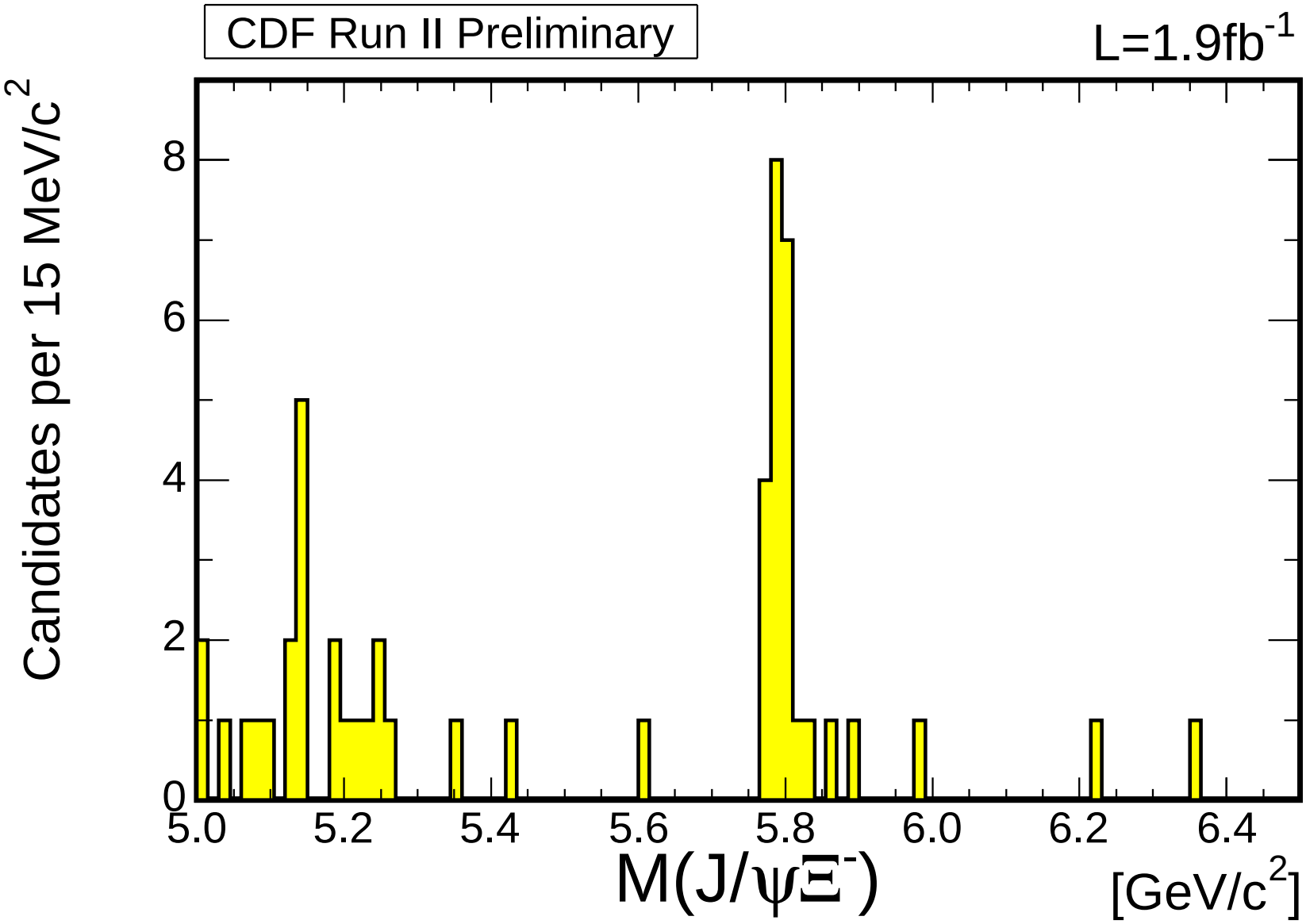
B^+ yields

parameter	Optimization A	Optimization B	Optimization A+B
$N(J/\psi K^+)$	$12,185 \pm 115$	$3,837 \pm 67$	$16,044 \pm 134$
$S/\sqrt{S+B}$	106	57	120
$N(J/\psi \pi^+)$	447 ± 29	134 ± 18	572 ± 34
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. Improves significance.

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

Behold the Peak

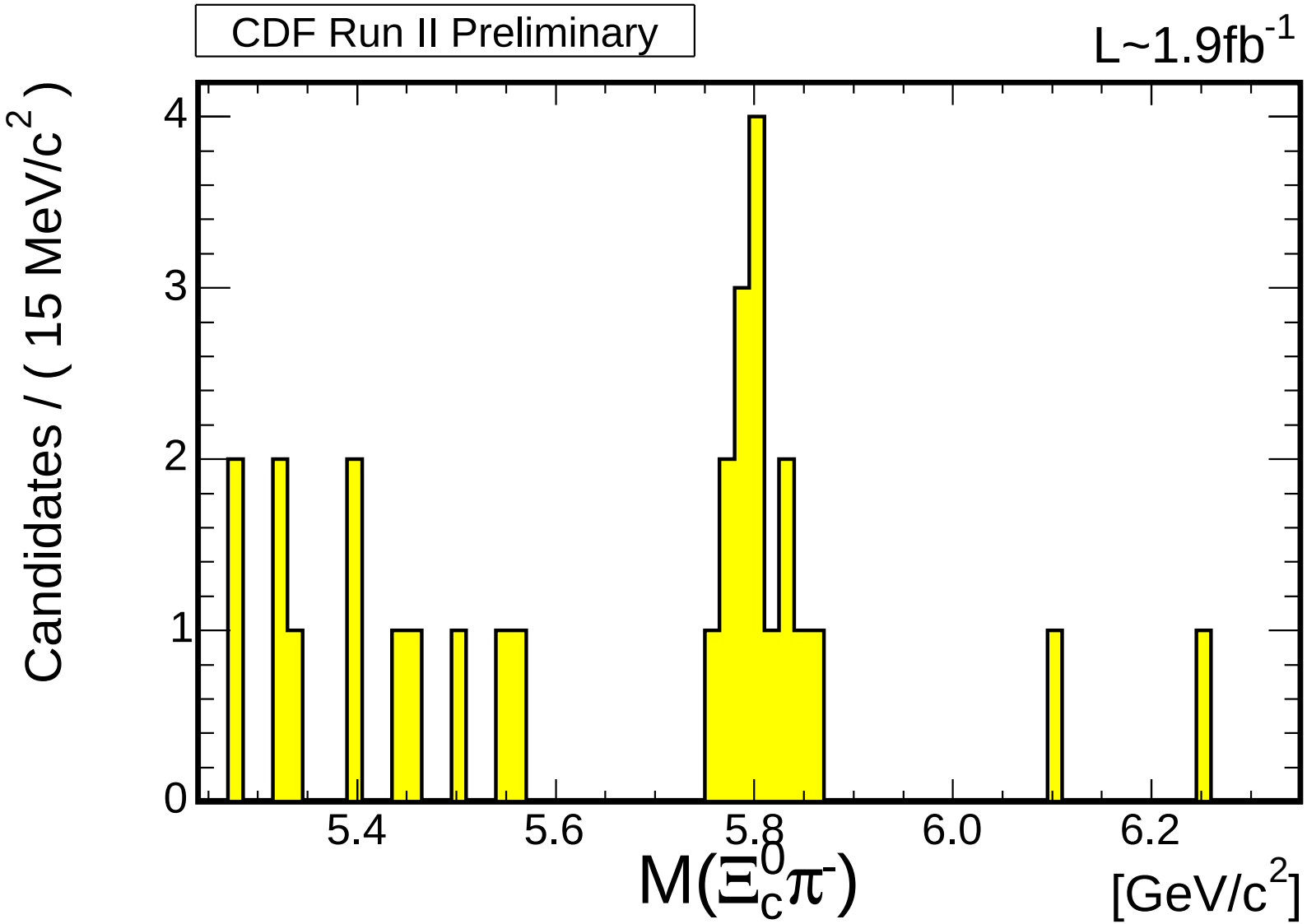


Cross-checks

- ✓ Check J/ψ and Ξ sidebands
- ✓ Check wrong charge $J/\psi\Xi^+$ where "$\Xi^+ \to \Lambda\pi^+$"
- ✓ Signal is robust against cut variations
- ✓ No existing B-hadron produces a signal in $M(J/\psi\Xi^-)$ spectrum at $M \sim 5.8\ \mathrm{GeV/c^2}$
- ✓ Check if we see a signal at the same mass in $\Xi_b^- \to \Xi_c^0\pi^-$ channel.

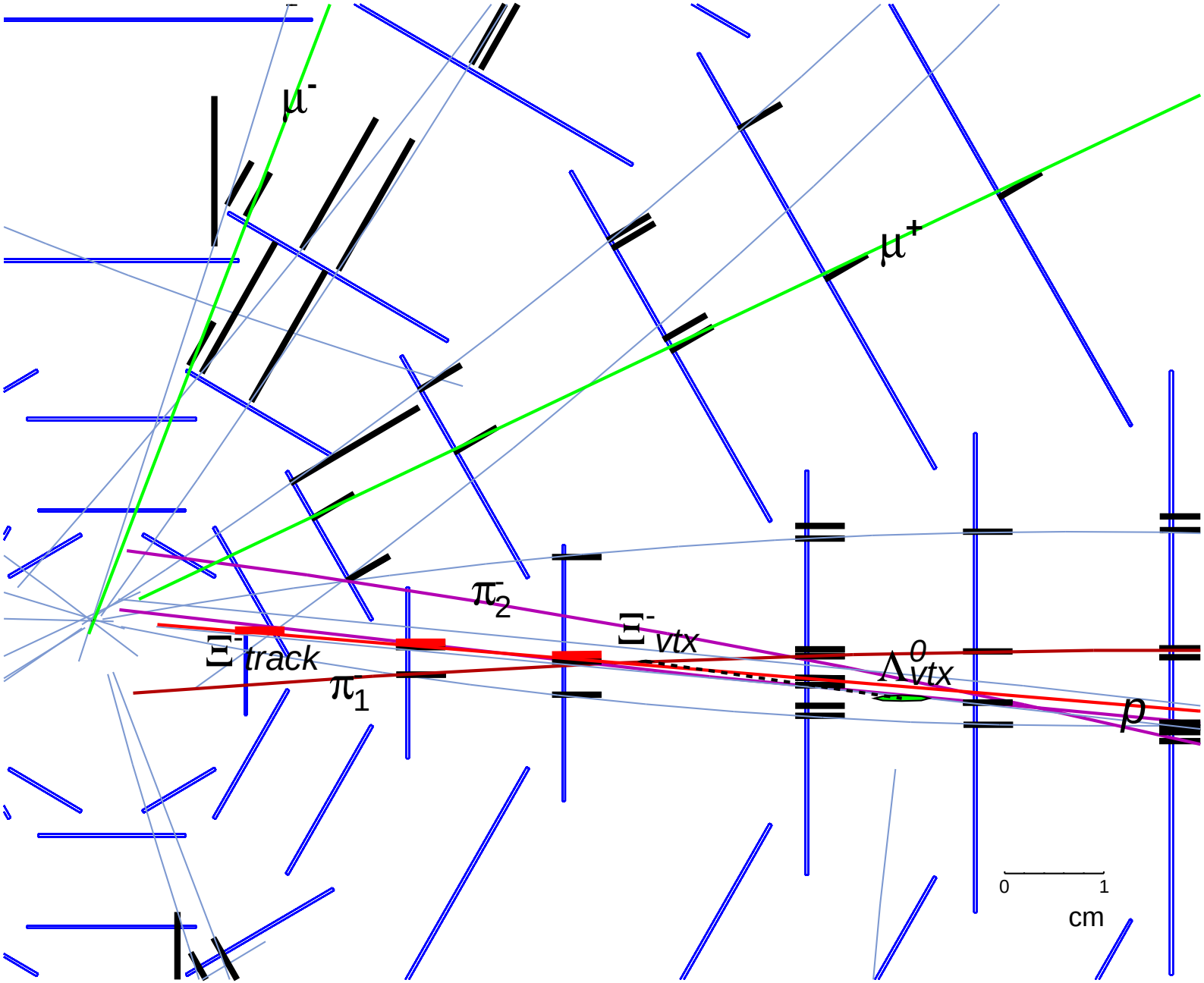
Cross-check $\Xi_b^- \to \Xi_c^0 \pi^-$

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

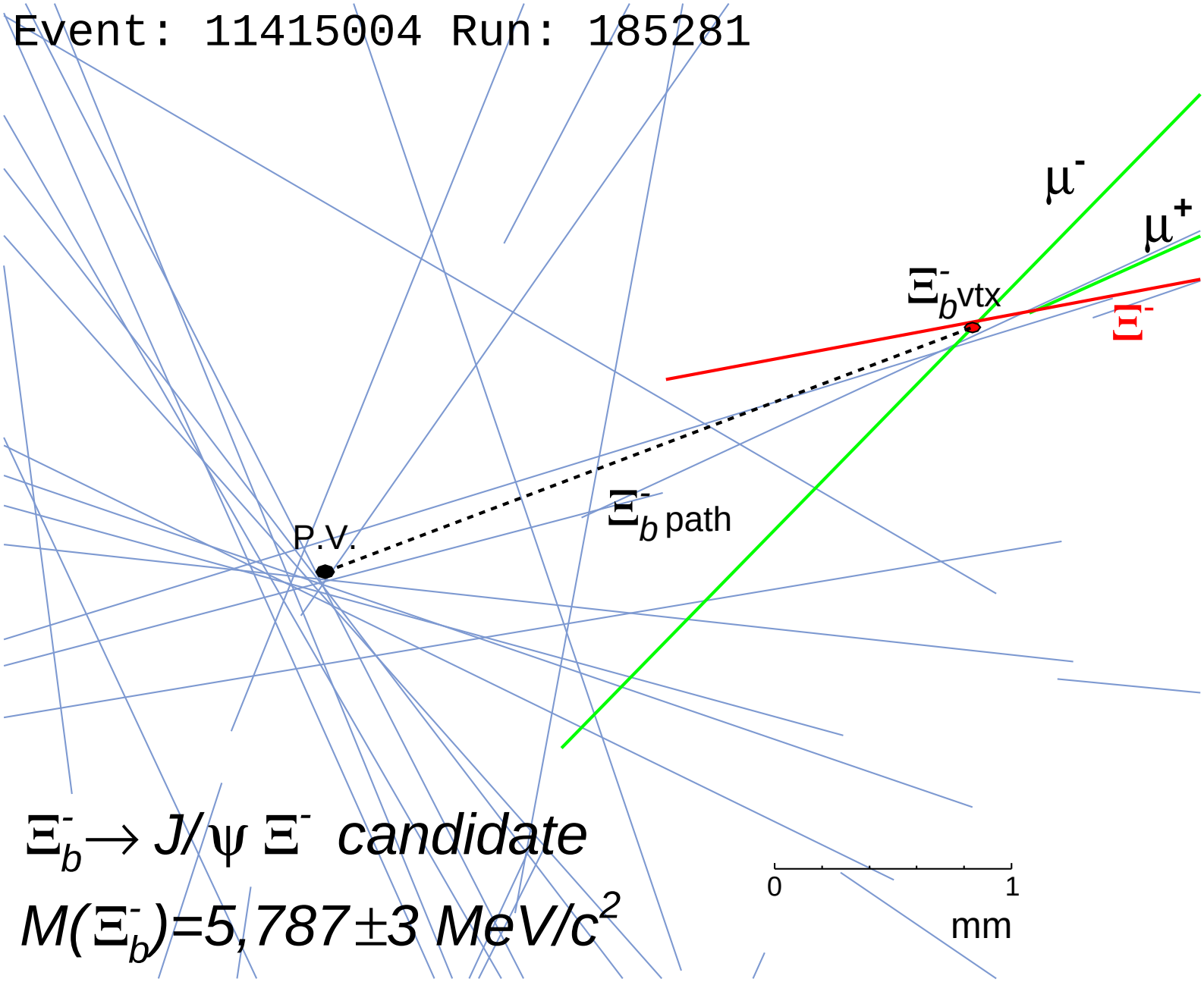


See signal at the same mass. Work in progress. Processing the full $2.5 fb^{-1}$ sample to have a shot at $\Xi_b^0 \to \Xi_c^+ \pi^-$

Event Display 1



Event Display 2



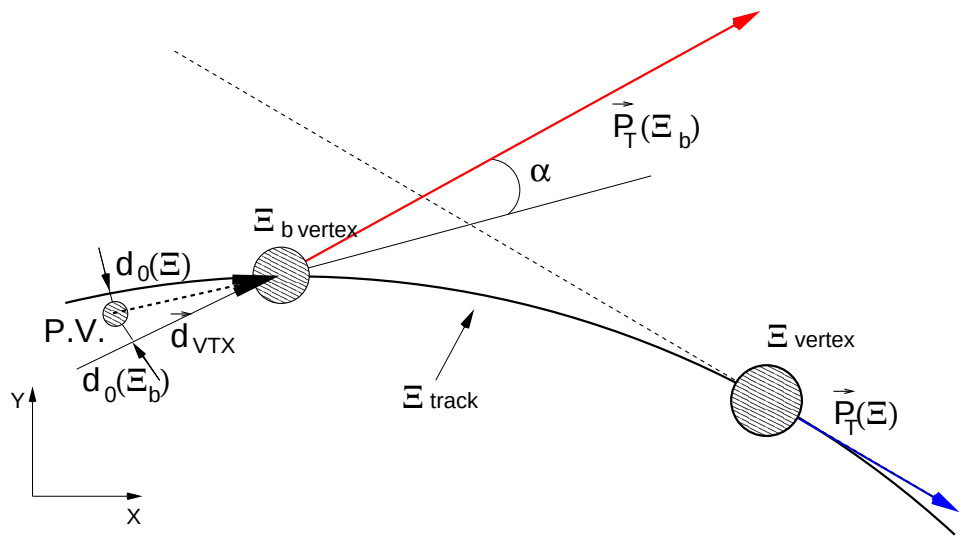
$\Xi_b^- \rightarrow J/\psi\ \Xi^-$ *candidate*

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

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

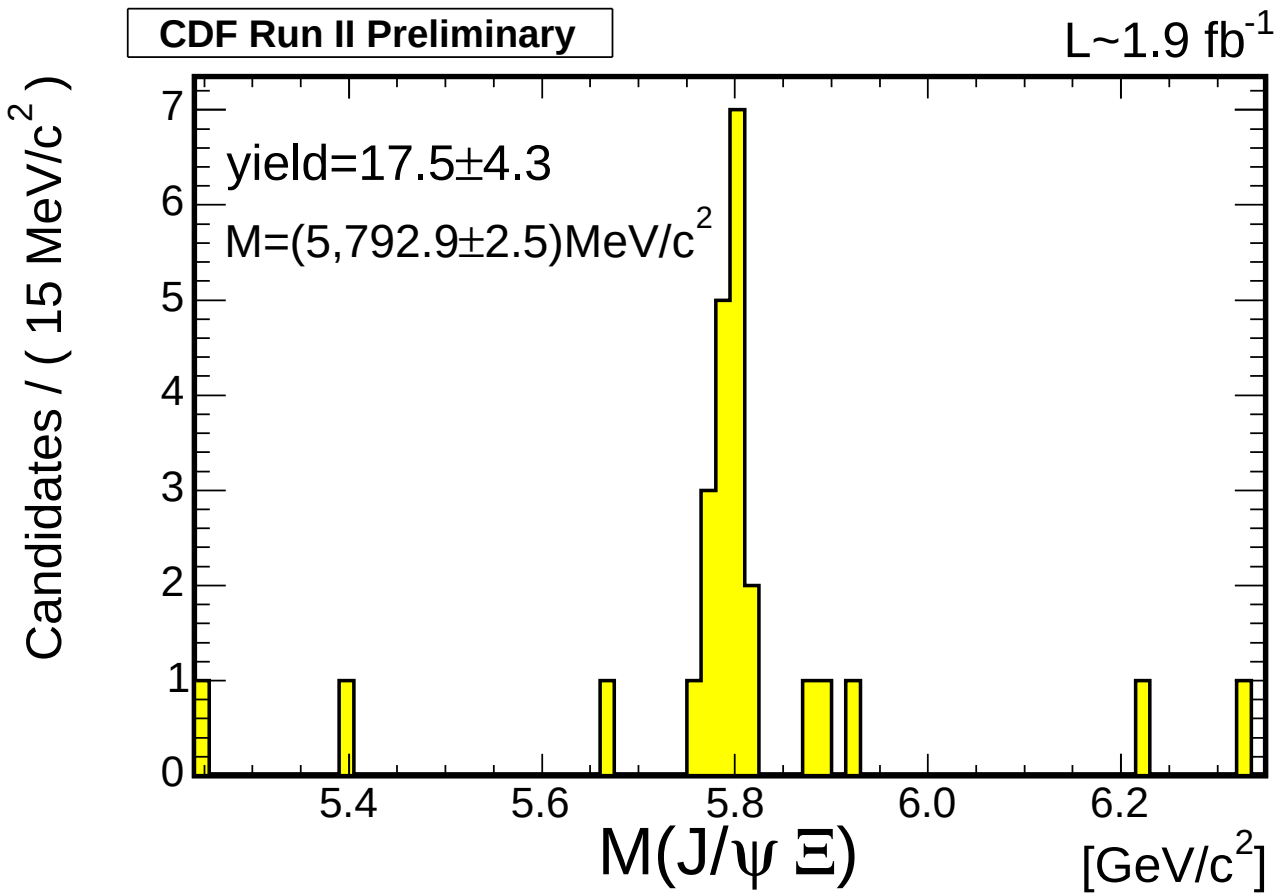
- Full 5-track vertex fit gives 15% better mass resolution compared to 3-track vertex fit.
- But in order for it to work we had to fix our Vertex Fit software to handle charged vertices.



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

The Fit Result

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



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

Signal Significance

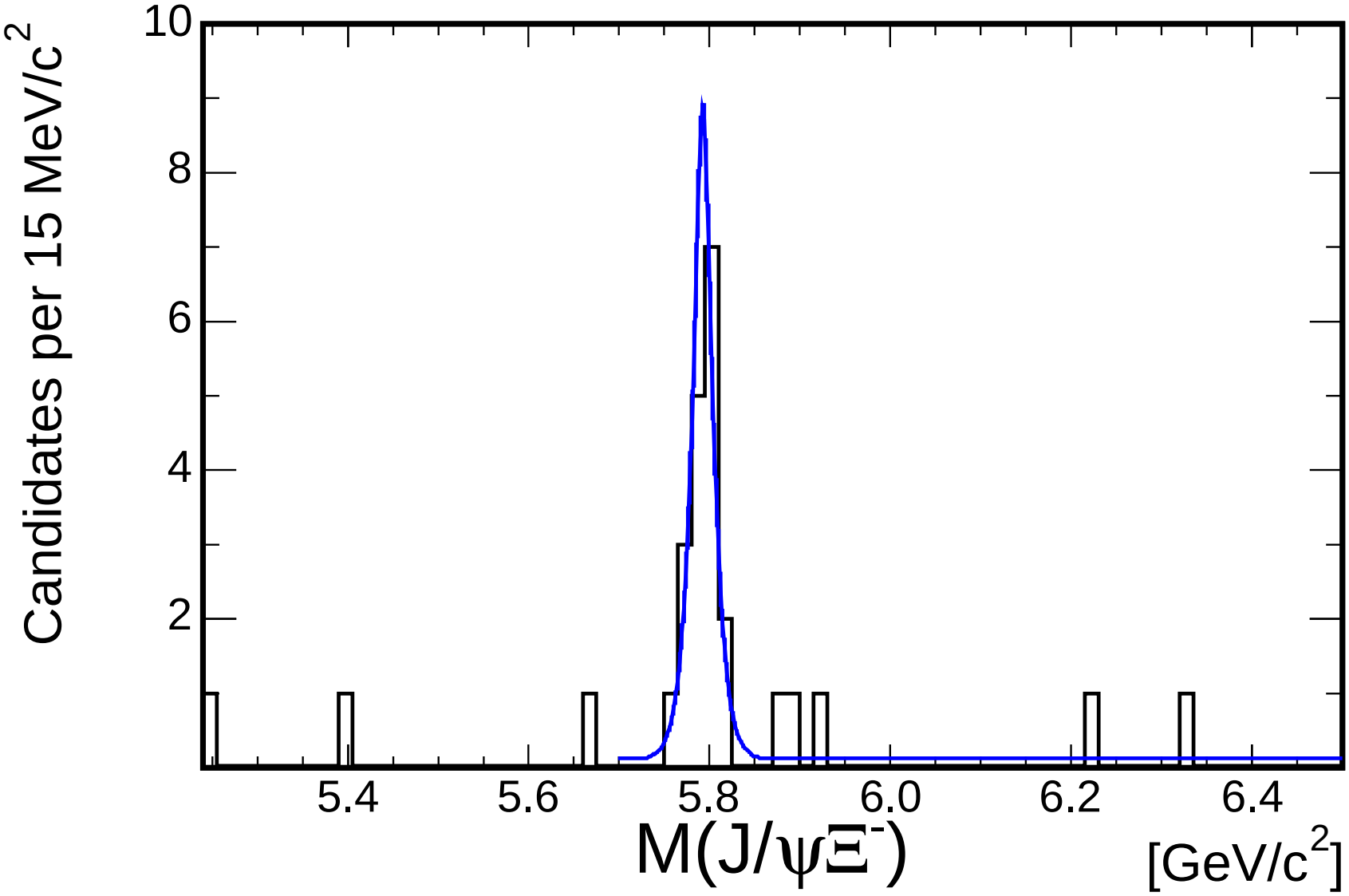
- Assume flat distribution of events in the mass region $[5.7 - 6.5]$ GeV/c^2
- The p-value is defined as probability to toss $N_{total} = 23$ events contained in this interval, so that there are $N_{signal} = 17$ observed events in 60 MeV/c^2 signal range ($\pm 2\sigma$).

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

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

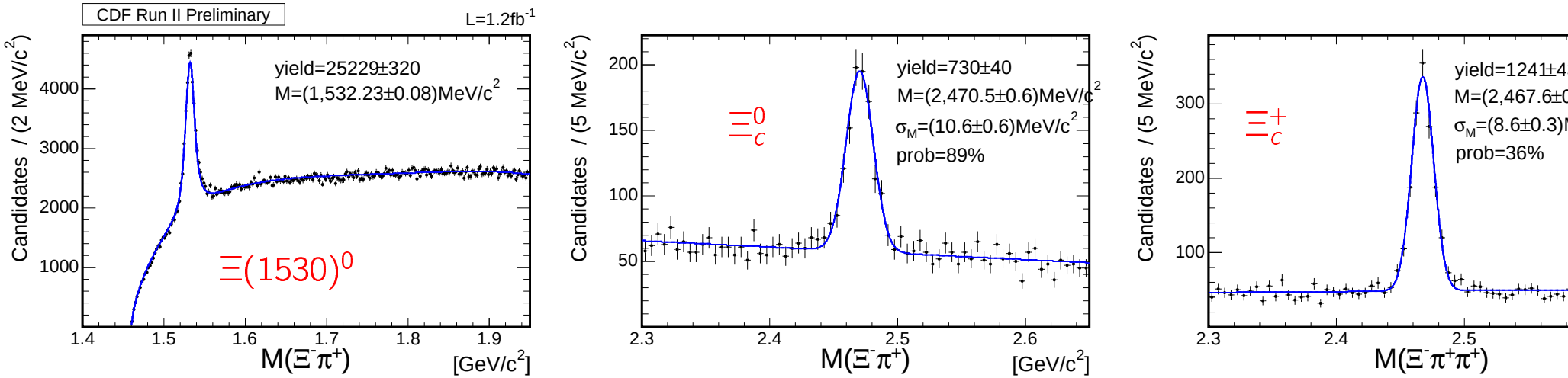
Plot for PRL

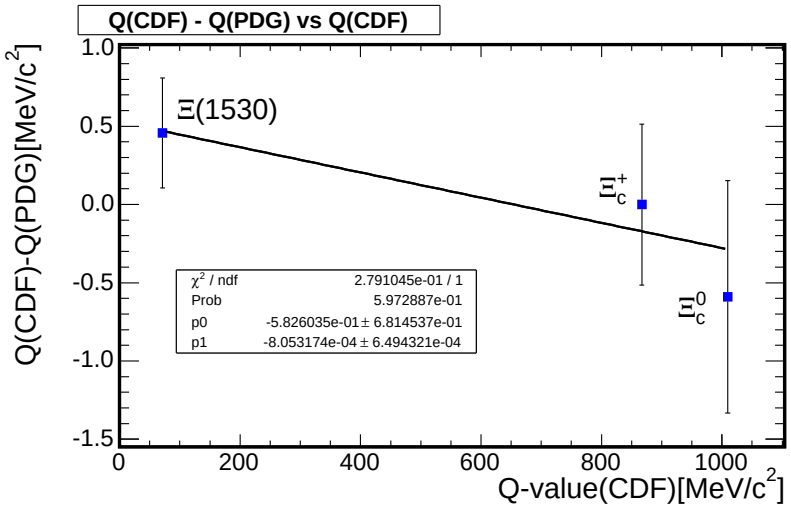
Projection of the unbinned fit



Mass Systematics

- check on large samples in TTT that Ξ tracking does not introduce a mass bias

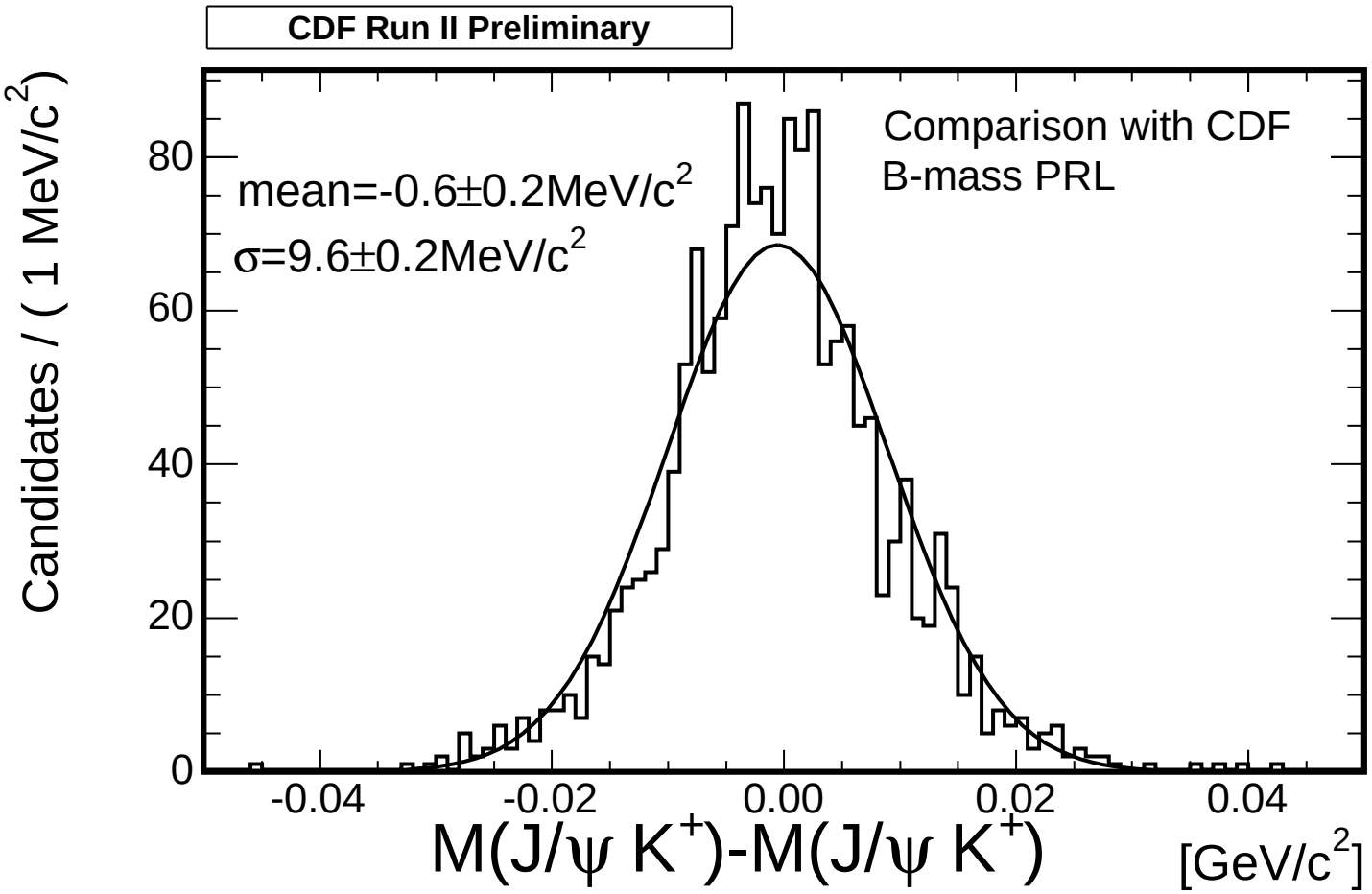




- projected shift at Ξ_b mass is $\delta m = (-1.69 \pm 1.54)\ \mathrm{MeV}/c^2$. Not significant.

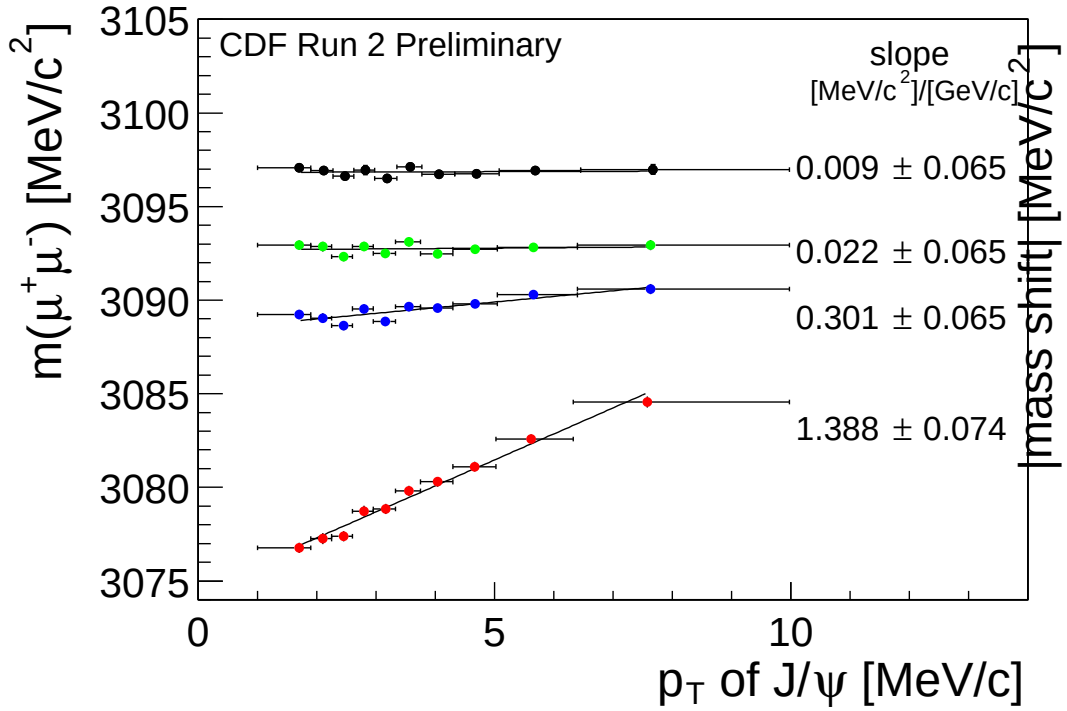
Mass Calibration

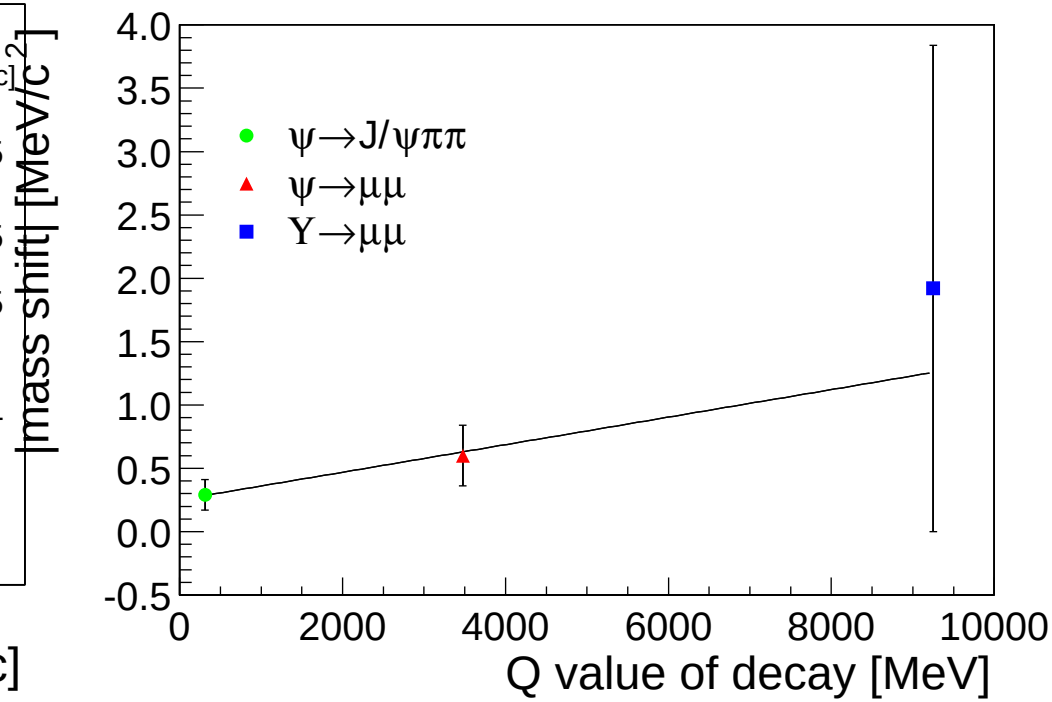
Mass calibration offset



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.)

$$\delta m(Q = 1375) = 0.4 \text{ MeV/c}^2$$

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$/c^2$

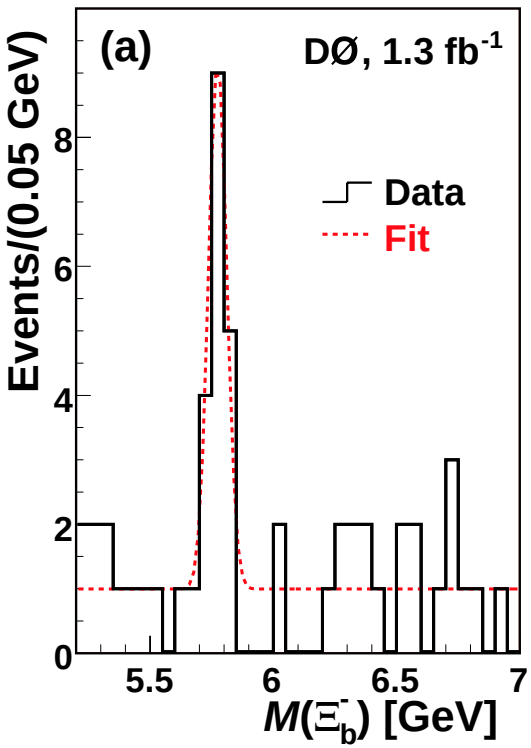
Summary Systematics

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

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

Meanwhile at D0...

- Fermilab Press Release on June 13th – "Fermilab physicists discover triple-scoop baryon".



$$N(\Xi_b) = 15.2 \pm 4.4(stat)^{+1.9}_{-0.4}(syst)$$

Significance 5.5σ

$$\frac{\sigma(\Xi_b)}{\sigma(\Lambda_b)} = 0.28 \pm 0.09(stat)^{+0.09}_{-0.08}(sy$$

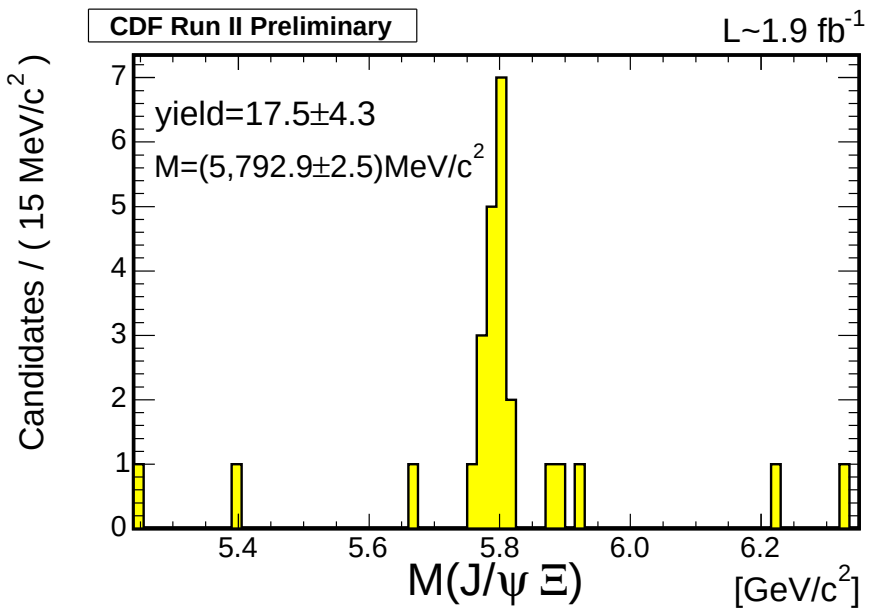
$$M(\Xi_b^-) = (5,774 \pm 11(stat.) \pm 15(syst.))\ \mathrm{MeV/c^2}$$

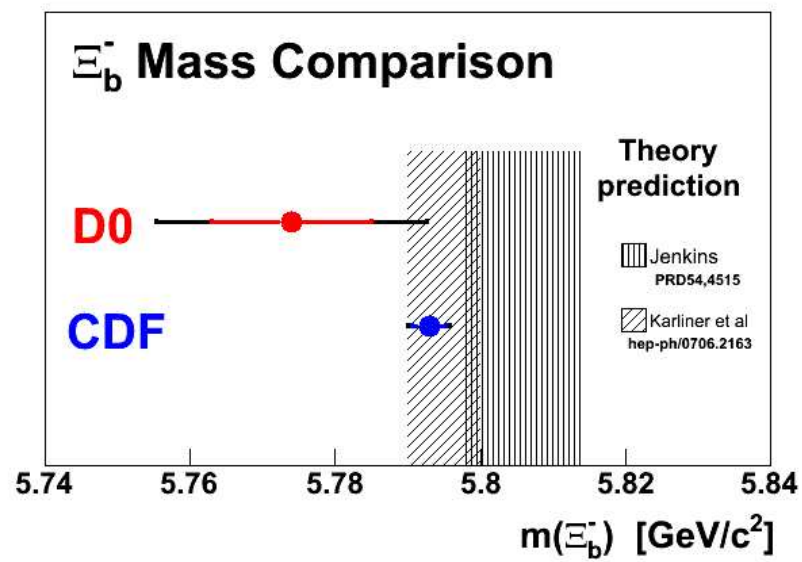
- CDF goes public on June 15th on joint D0 CDF Wine and Cheeze
- Press release "Back-to-Back Baryons in Batavia".

Conclusion 1

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

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





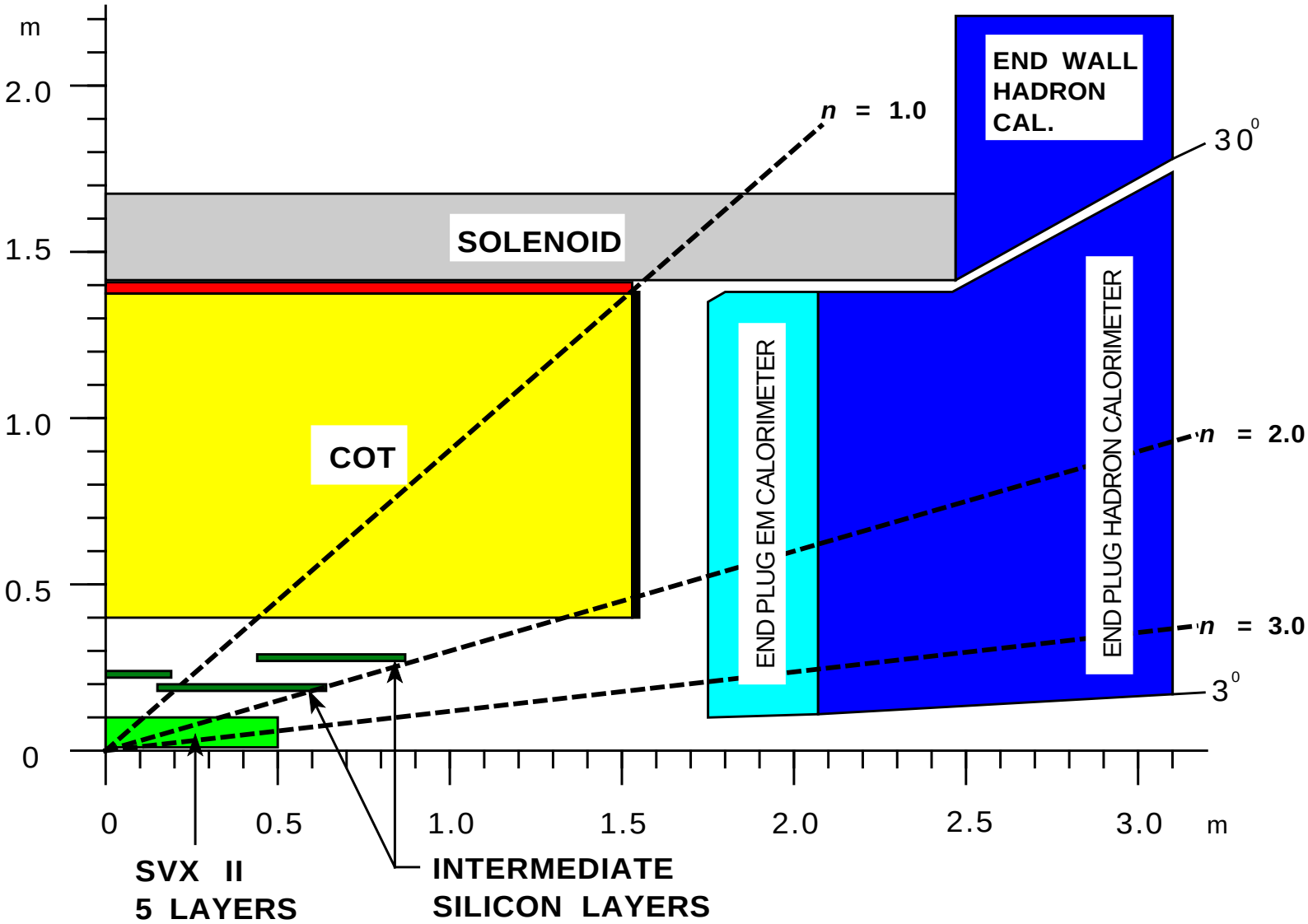
- DØ paper: Phys. Rev. Lett. 99, 052001 (2007)
- CDF paper: Phys. Rev. Lett. 99, 052002 (2007) signifi cant improvement over DØ result
- Weighted mean mass $5792 \pm 3\ \mathrm{MeV}/c^2$.

Conclusion 2(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.

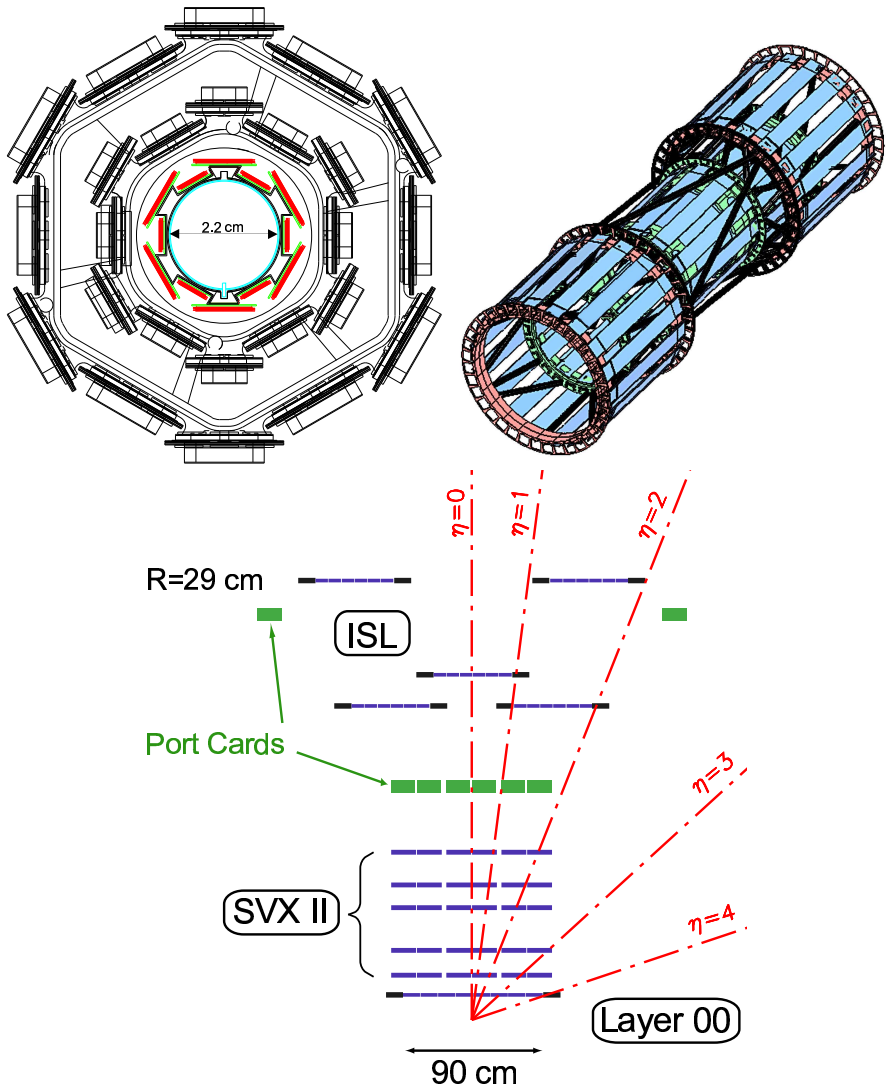
Backup Slides

Tracking System



COT

- The largest drift wire chamber
  - 8 superlayers: 4 axial, 4 stereo
  - 96 measurements between 44 and 132 cm
  - Tracking up to $|\eta| < 1$
- Resolution
  - Hit resolution $140\mu m$
  - $\delta p_T/p_T^2 \sim 0.15\%(\mathrm{GeV/c})^{-1}$
  - Impact parameter resolution $250\mu m$
  - Z0 resolution 5 mm
- 2D tracks in level 1

Silicon

- Silicon Detectors
  - 8 layers (Layer00, 5 SVXII, 2/1 ISL). 7 double sided
  - 3 90^0 and 4 small angle => 3D tracking
  - Standalone tracking up to $|\eta| < 2$
  - Layer00 provides precision measurement at 1.3-1.6 cm in high density environment
- Resolution
  - Impact parameter resolution $\sim 25\mu m$
  - Z0 resolution $50\mu m$
- Used in level 2 trigger