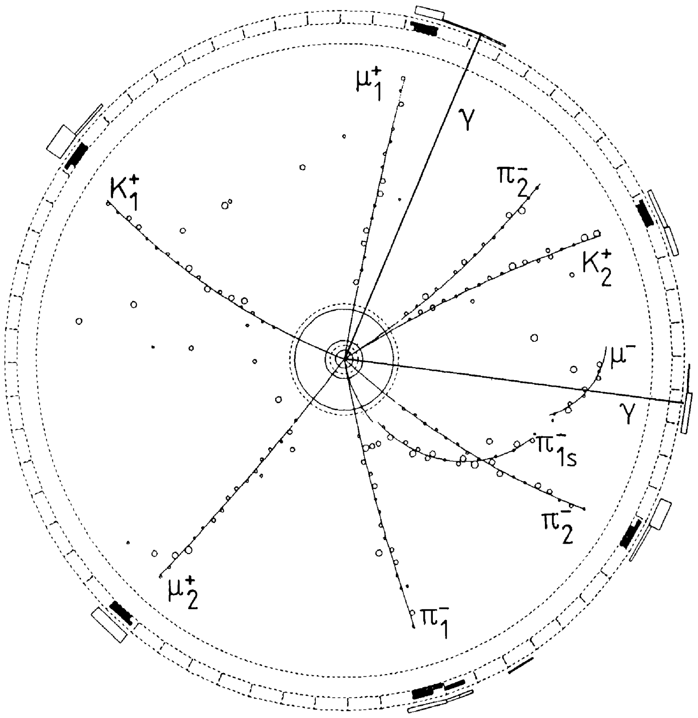
B Physics at CDF: Educating the Theorists

Manfred Paulini (LBNL)
23 September 1999
$\boldsymbol{B}$ physics workshop
Fermilab

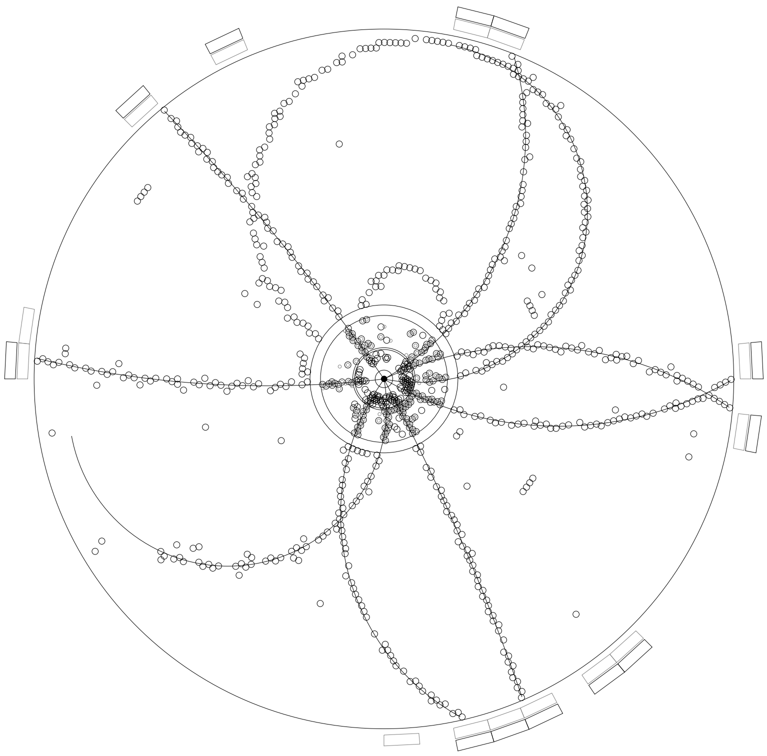
- B Physics at CDF
  - Features of B Physics at a hadron collider
  - Trigger issues
- The CDF II detector
- A case study: $B^0 \to \pi^+\pi^-$
- Conclusion

Typical B Events at the $\Upsilon(4S)$

ARGUS:

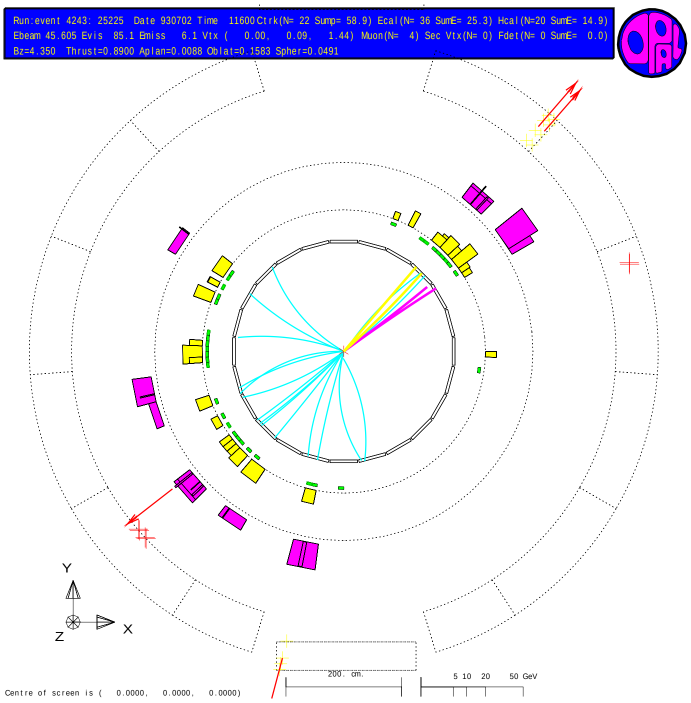


CLEO:

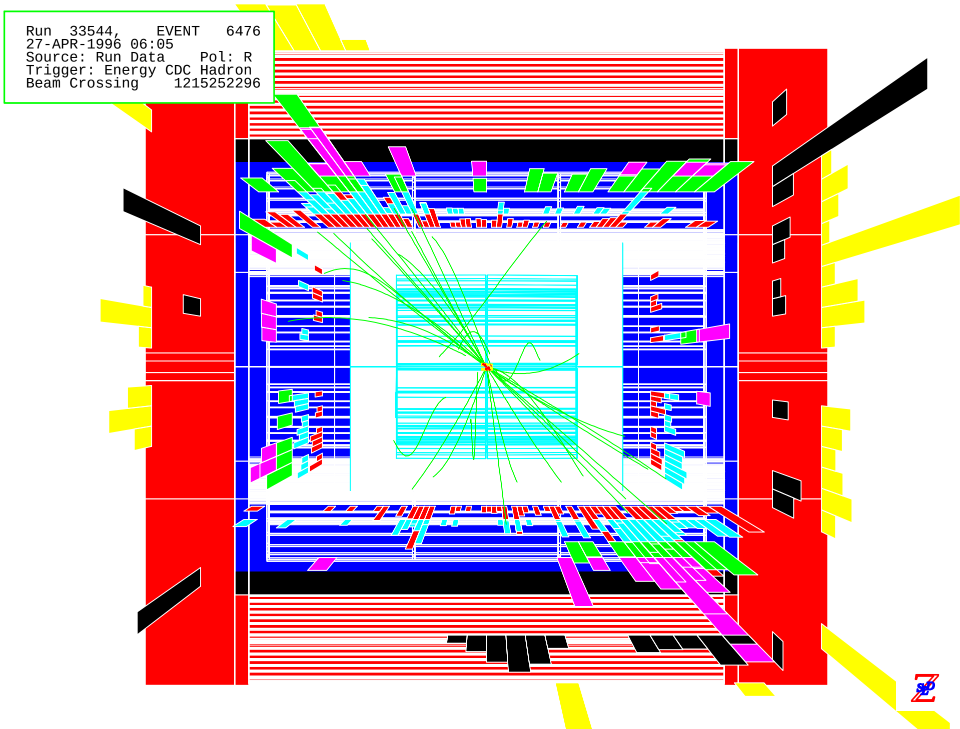


Typical B Events at the Z^0 Pole

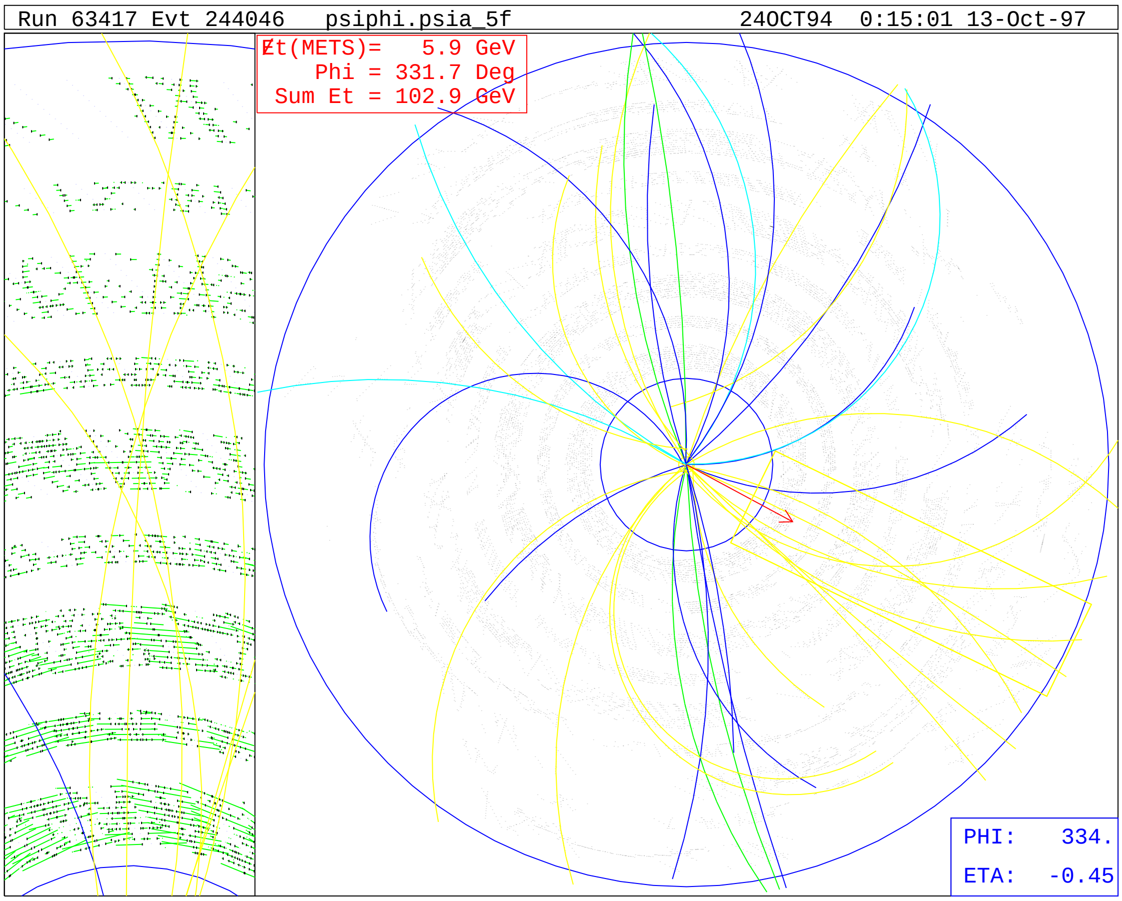
OPAL:



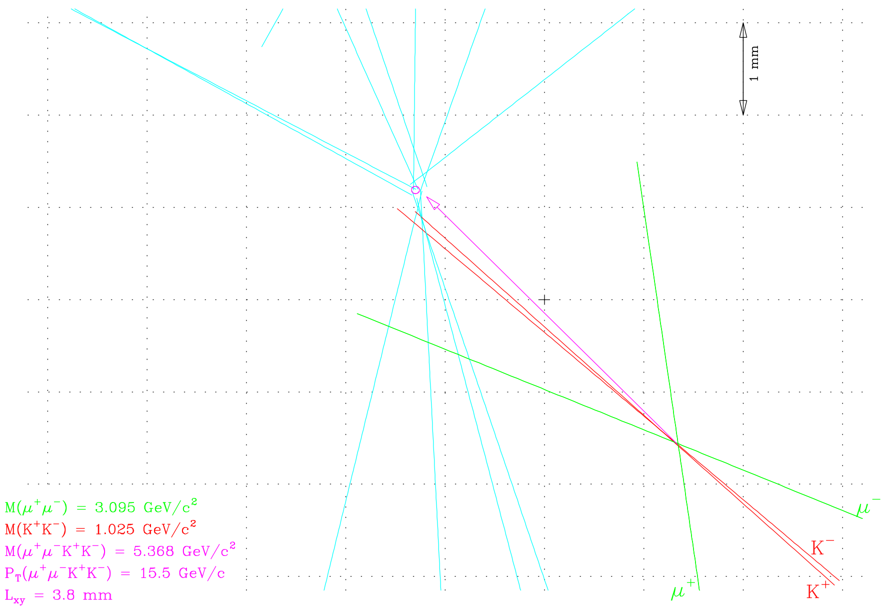
SLD:



Typical B Event at CDF



Example of $B_s \to J/\Psi\ \phi \to \mu^+\mu^-\ K^+\ K^-$

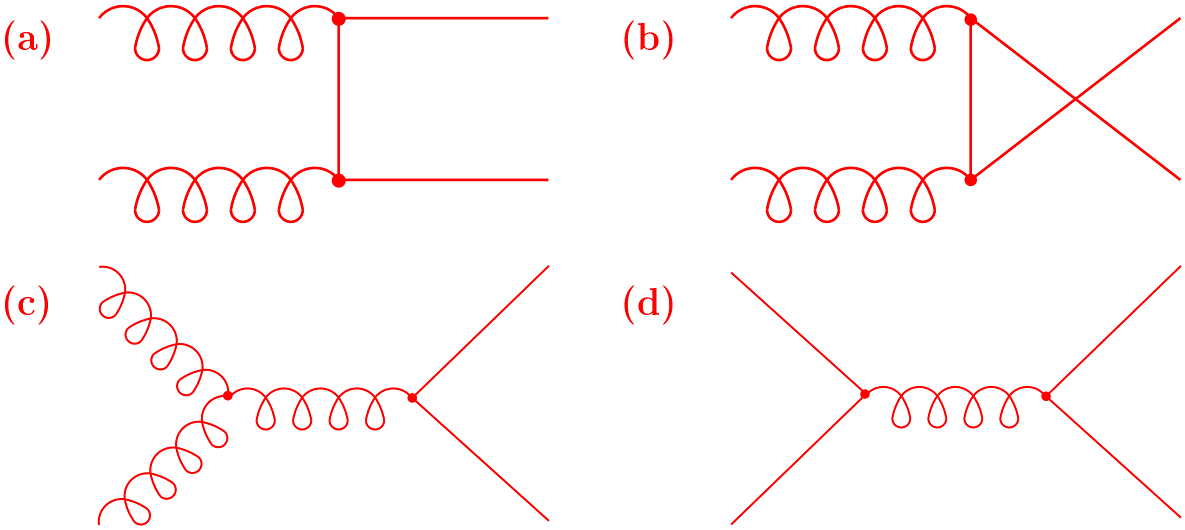


b Quark Production at the Tevatron

- Lowest order $\mathcal{O}(\alpha_s^2)$ diagrams for $b\bar{b}$ production

  (a)-(c) gluon-gluon fusion

  (d) quark-antiquark annihilation



- Characteristics of $b\bar{b}$ production in $p\bar{p}$:
  - average b quark momentum $\langle\, p_T(b)\, \rangle \sim m_b \sim$ 4-5 GeV
  - But: p_T spectrum for b harder than for light quarks
  - p_T distribution falls rapidly to zero for $p_T > m_B$
  - $b\bar{b}$ production larger in central region falling off at higher rapidities
  - b and $\bar{b}$ produced back-to-back transverse to beam
  - rapidity difference between b and $\bar{b}$ of order unity $\Rightarrow \eta(b) \sim \eta(\bar{b})$

b Quark Production at the Tevatron

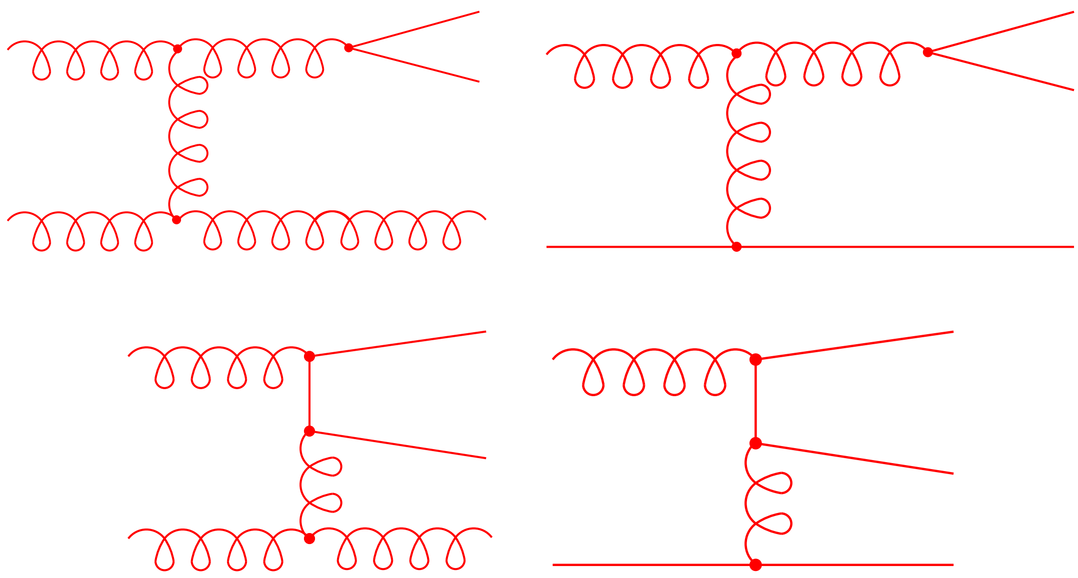
- Higher order mechanisms for $b\bar{b}$ production

  (a) gluon splitting

  (b) flavour excitation

(a)

(b)



- Gluon splitting
  - $b\bar{b}$ produced close together $\Rightarrow$ appear in same jet
- Flavour excitation
  - usually only one of the heavy quarks at high p_T

B Physics at a Hadron Collider

- Advantages of B Physics at the Tevatron:
  - All B hadrons are produced: B^0, B^+, B_S, B_c^+, Λ_b^0
  - Enormous cross section
    - at $\Upsilon(4S)$: $\sigma(B\bar{B}) \approx 1\ nb$
    - at Tevatron: $\sigma(p\bar{p} \to b\bar{b}) \approx 50\ \mu b$
  - $\approx 5 \cdot 10^9$ $b\bar{b}$ pairs produced in Run I during 1992-96

- Compare yield of B mesons:

CLEO: $\mathcal{L} = 3100$ pb^{-1}

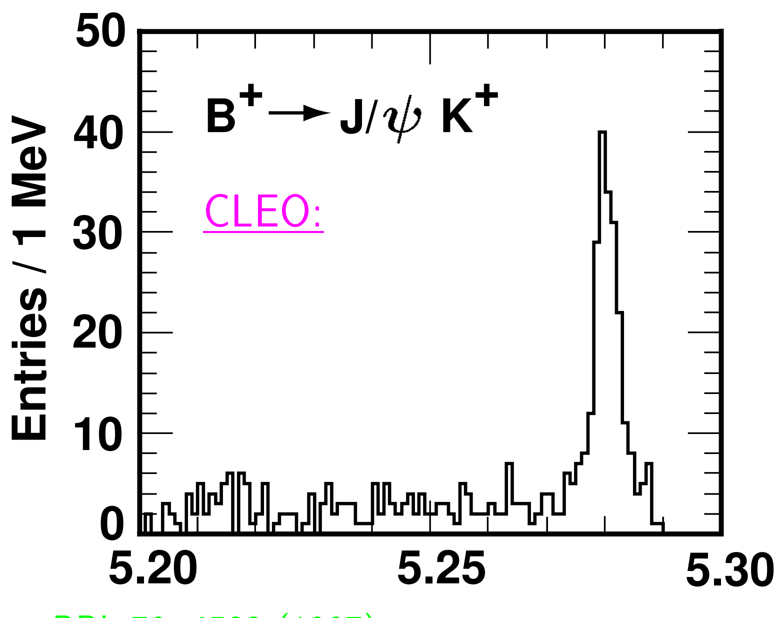
$N(B^+ \to J/\psi K^+) =$

198 ± 15

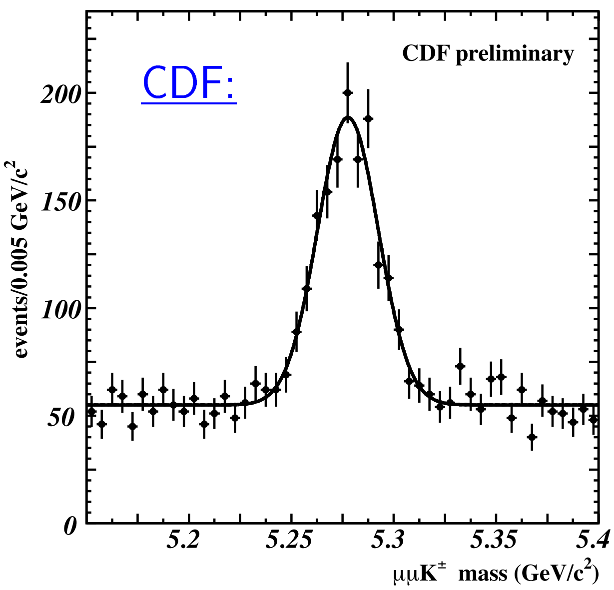
CDF: $\mathcal{L} = 110$ pb^{-1}

$N(B^+ \to J/\psi K^+) =$

998 ± 51

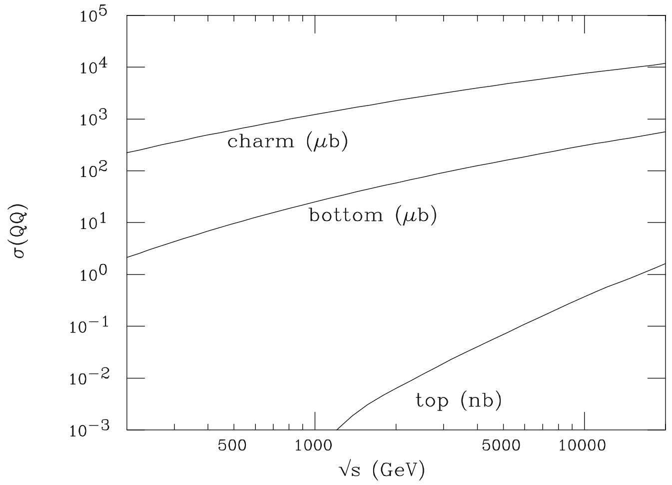


PRL 79, 4533 (1997)

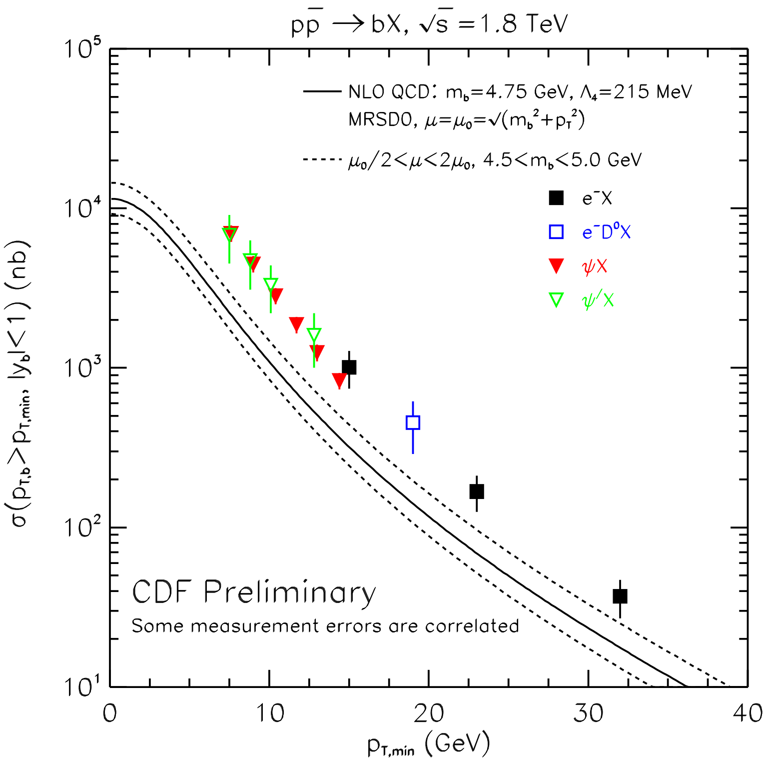


B Physics at a Hadron Collider

- Comparison with charm production:



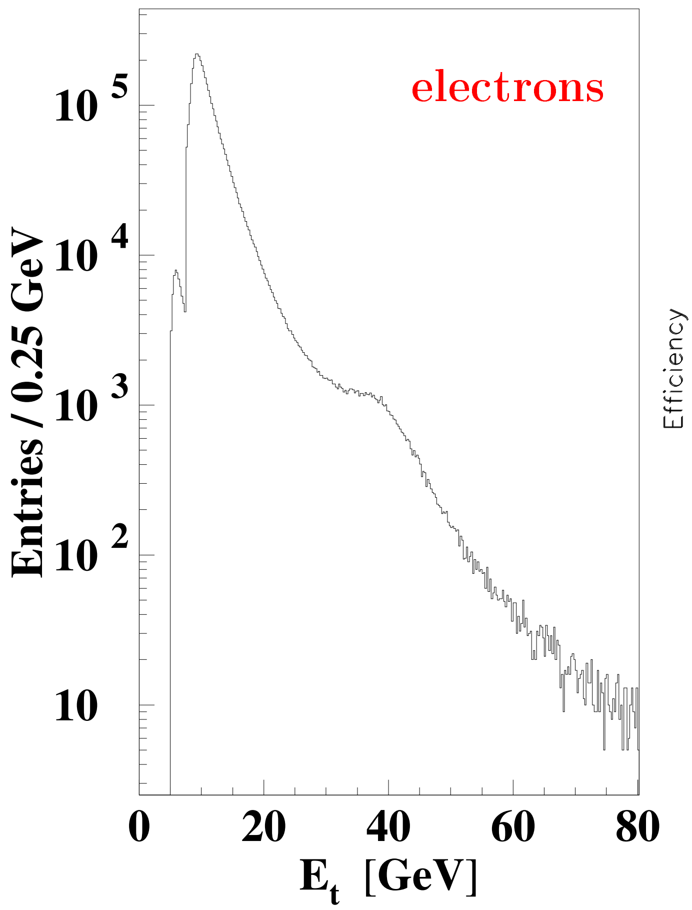
- Total inelastic cross section: $\sigma_{tot}/\sigma_b \sim 10^3$
- Require specialized triggers
- Rapidly falling cross section

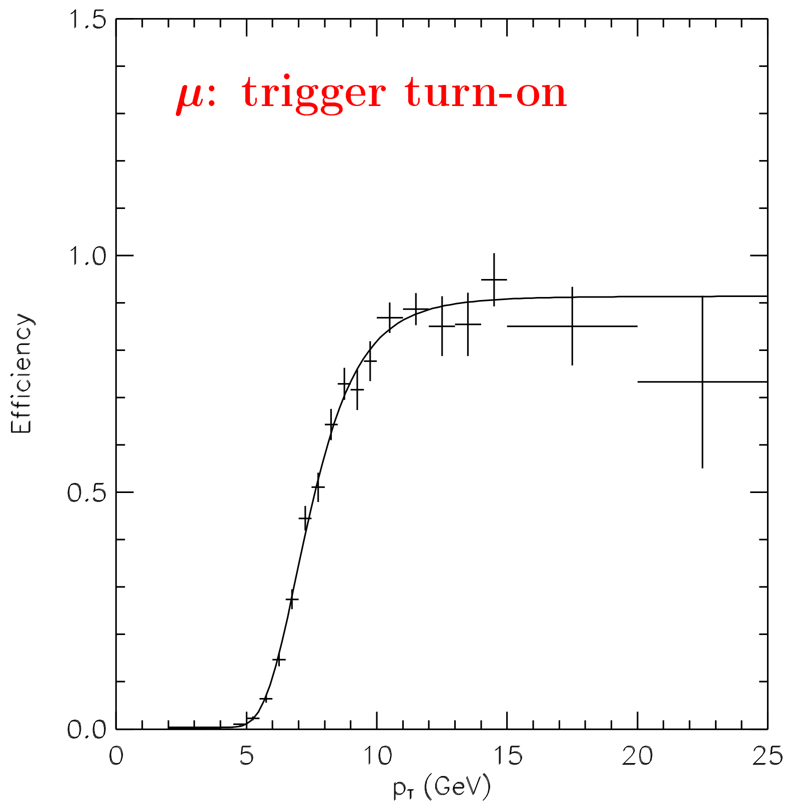


B Trigger at CDF

- Run I: B trigger based on leptons
- Dilepton trigger: (J/ψ, mixing)
  - dimuons: $p_t^\mu > 2.0$ GeV$/c$
- Single lepton trigger: (semileptonics)
  - e/μ: $E_t^e > 8.0$ GeV, $p_t^\mu > 7.5$ GeV$/c$
- Run II: hadronic track trigger

Inclusive lepton trigger:

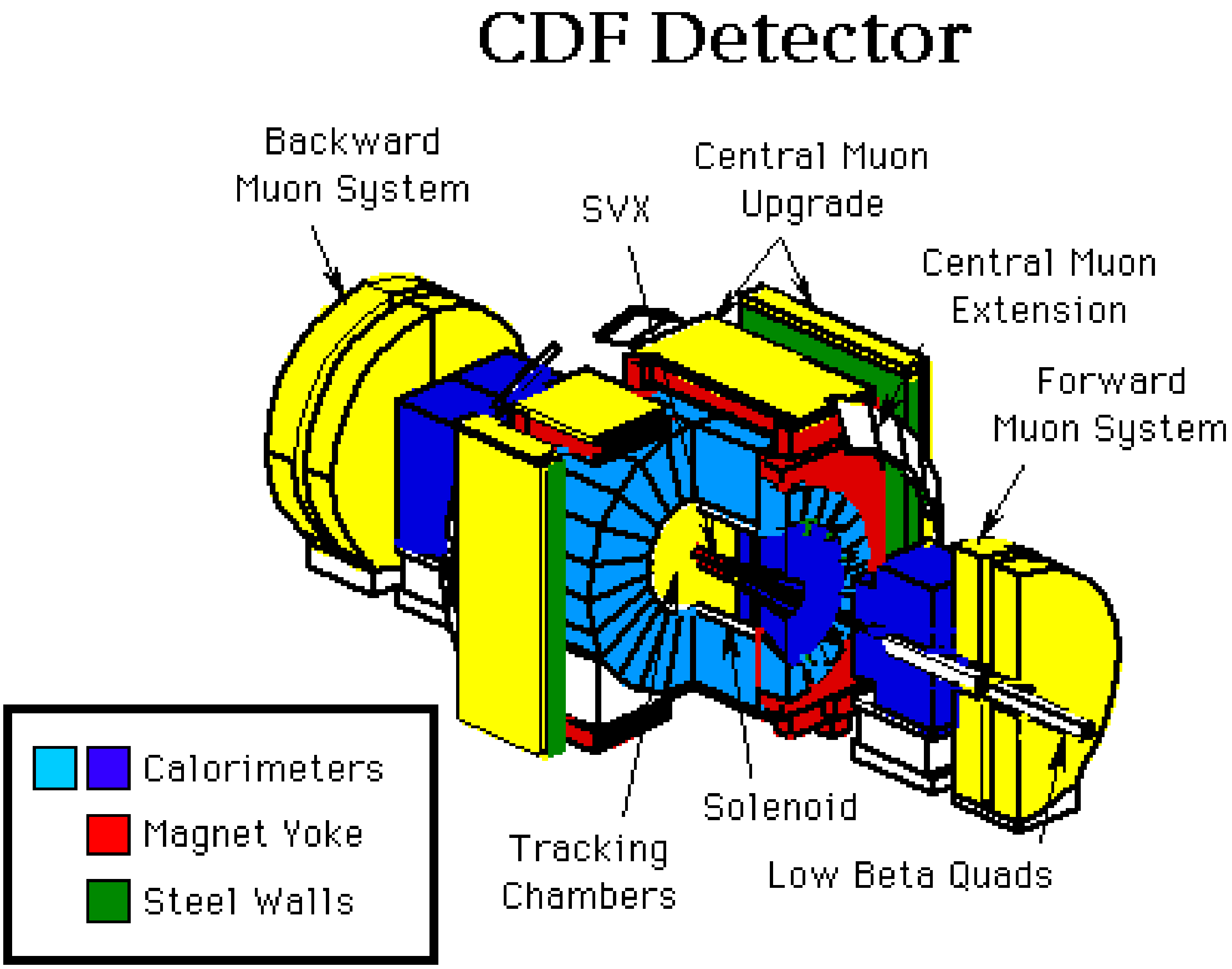




The CDF Detector

- μ system: CMU/P: $|\eta| < 0.6$, CMX: $0.6 < |\eta| < 1.1$
- calorimeter: HAD/EM: $|\eta| < 1.1$
- tracking and vertexing:

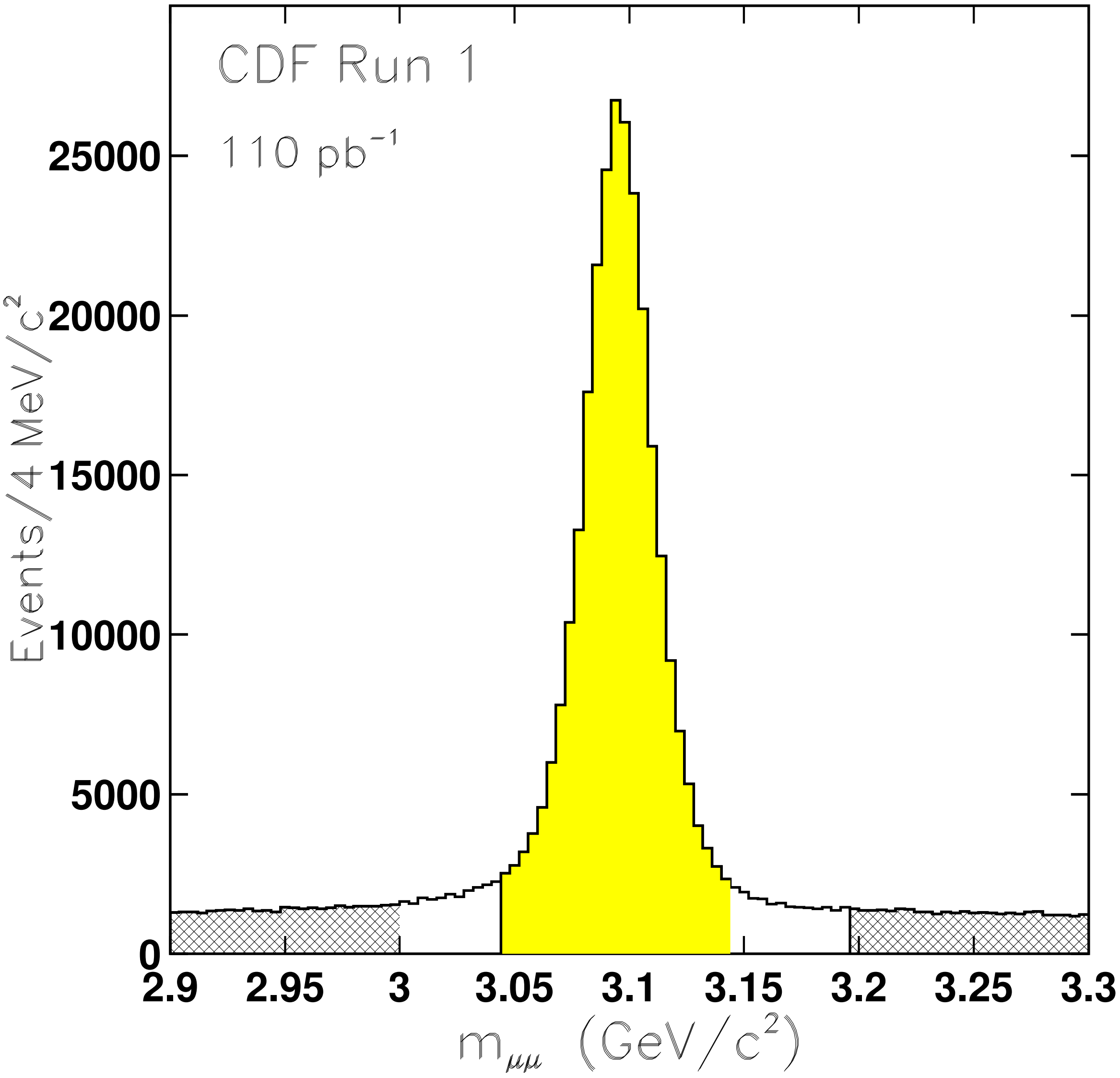
  - SVX: 2-dim. tracking in $r\varphi$
    4 layer (2.9 cm - 8.0 cm)
    $\sigma_d = 13\ \mu$m
  - CTC and SVX: $\Delta p_t/p_t = [(0.0009 p_t)^2 + (0.0066)^2]^{1/2}$



Features of B Physics at CDF

How to study B physics at a hadron collider?

CTC and SVX provide good tracking



- $\mathrm{N}(J/\psi) \approx 240{,}000$
- $\sigma \approx 16$ MeV$/c^2$

Features of B Physics at CDF

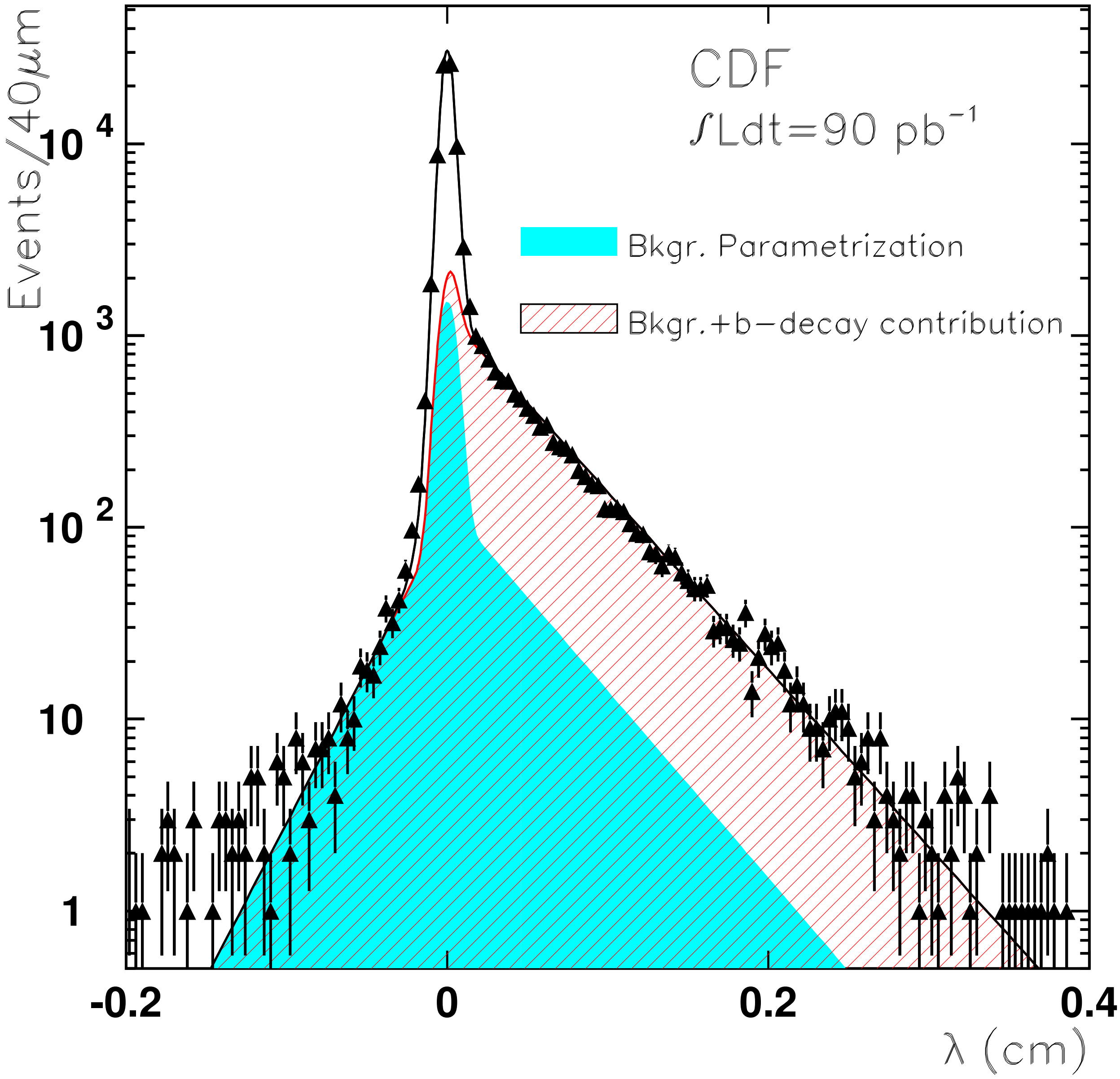
SVX provides excellent vertexing

Inclusive B Hadron Lifetime: $B \to J/\psi\, X$

$$\tau_B = (1.533 \pm 0.015 \pm^{+0.035}_{-0.031})\ \mathrm{ps}$$

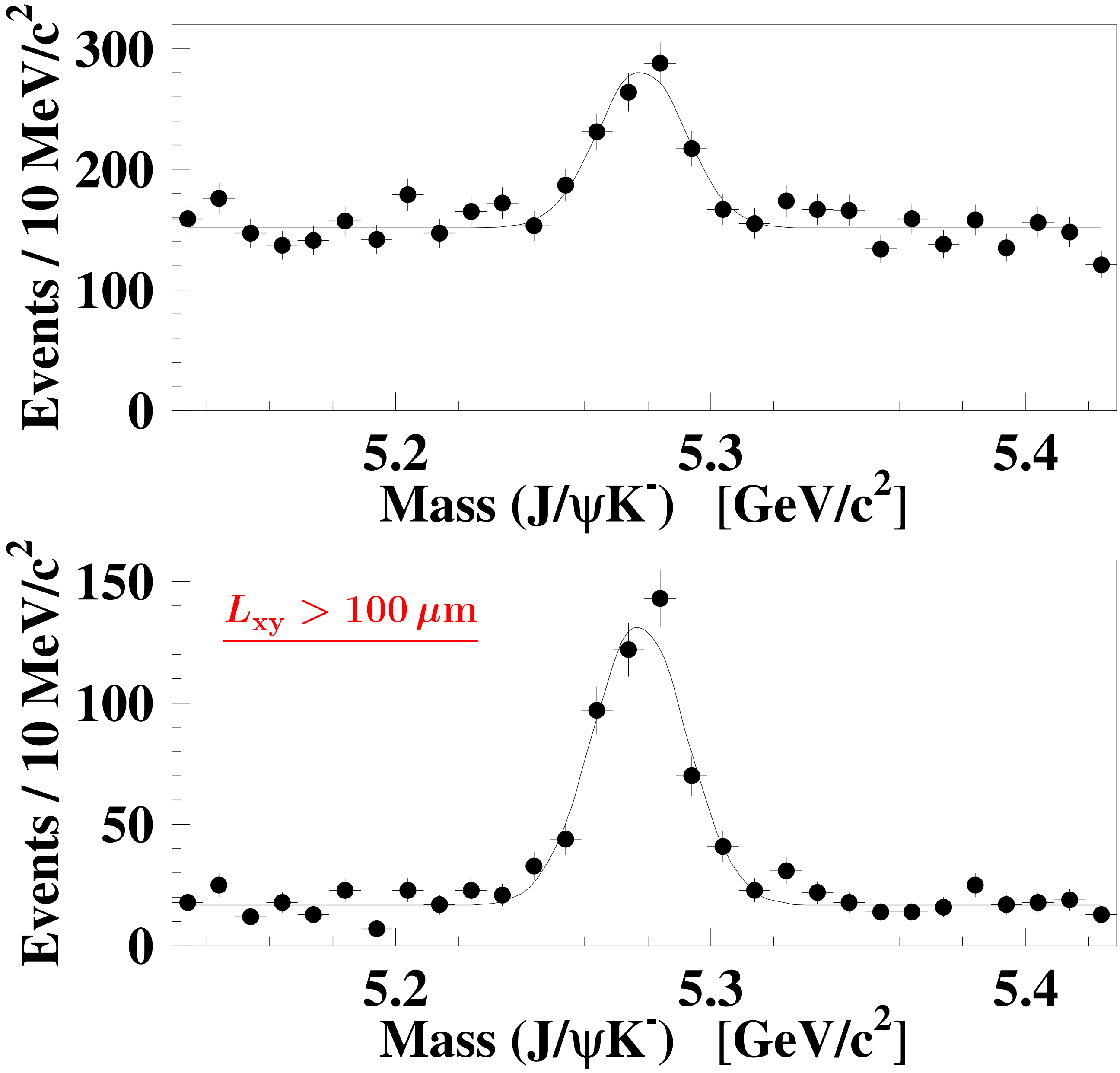
ALEPH: $(1.533 \pm 0.013 \pm 0.022)$ ps

DELPHI: $(1.582 \pm 0.011 \pm 0.027)$ ps



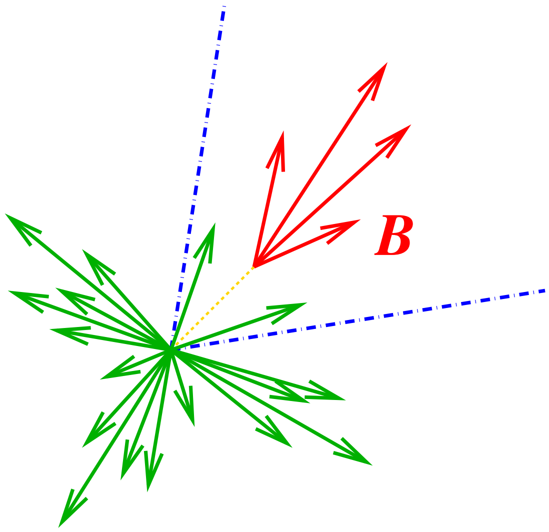
Features of B Physics at CDF

combine J/ψ with eg. K^+ candidates and
require displaced vertex: eg. $L_{xy} > 100\,\mu m$



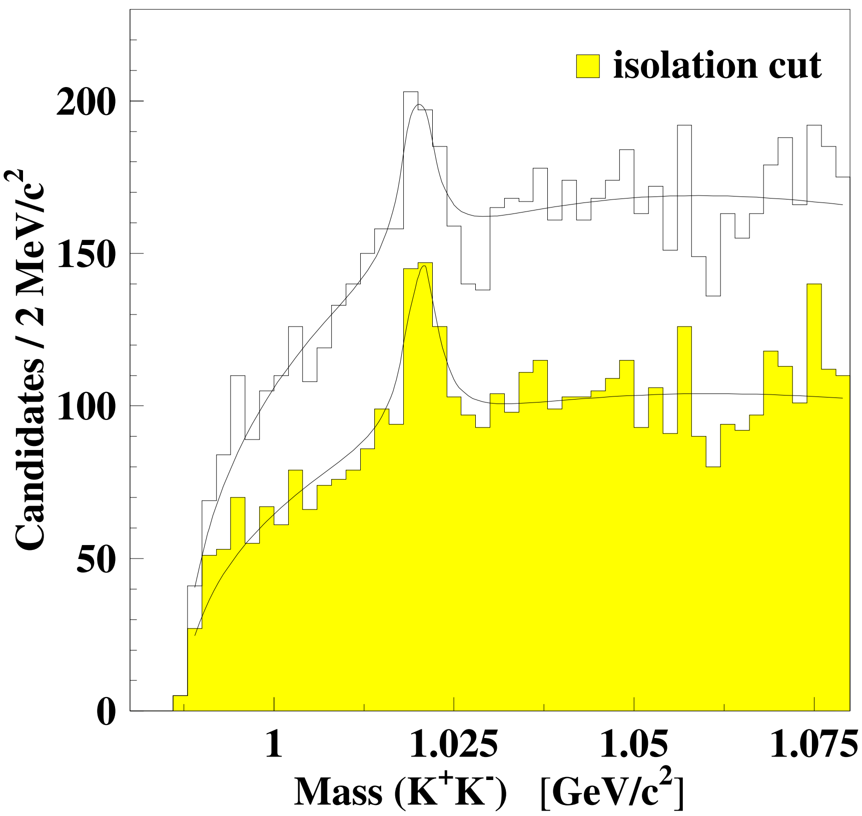
Features of B Physics at CDF

- B mesons are often isolated



$$R = \frac{p_t^B}{p_t^B + \sum_i p_t^{\rm cone}}$$

Exploit in search for $B_S^0 \to D_S^- \mu^+ \nu$ with $D_S^- \to \phi \mu^- \nu$:



Features of B Physics at CDF

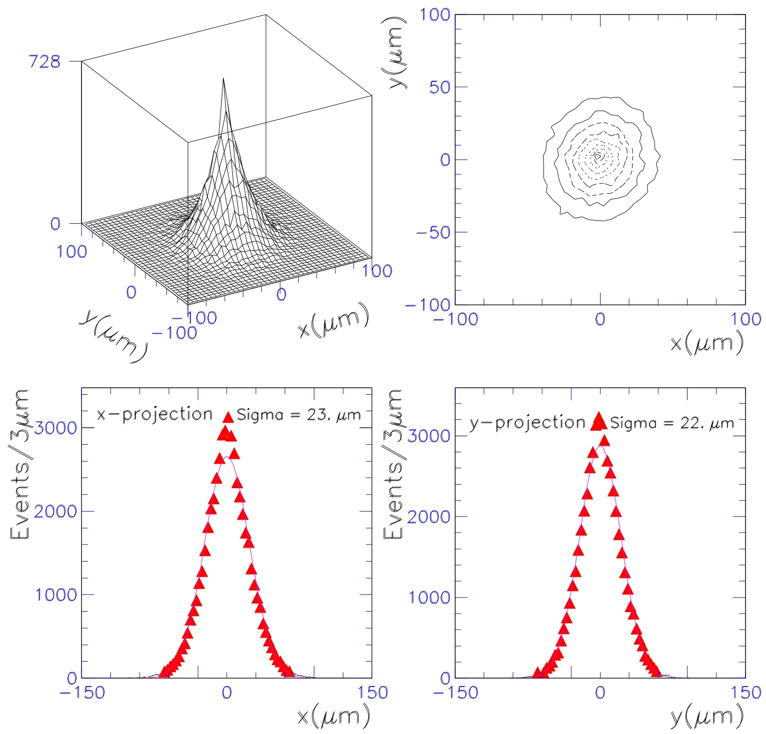
⋆ Elements for successful B physics at CDF:

- High rate B production in central region
- Excellent tracking in central tracker & silicon
  - Excellent $\sigma(p_T) \Rightarrow$ excellent $\sigma(m)$
  - Mean multiplicity of charged particles is same per unit of rapidity $\Rightarrow$ particles produced in central rapidity are physically spread out most
- Superb vertexing with silicon vertex detector
  - Proper time resolution for B decays roughly independent of Lorentz boost (except for multiple scattering effects) $\Rightarrow \sigma_{\mathrm{VX}}^{\mathrm{LEP}} \sim \sigma_{\mathrm{VX}}^{\mathrm{CDF}}$
- Efficient identification of electrons and muons
- Wishlist: Good calorimeter to detect low energy neutrals and real particle id (π/K separation)
- Hard p_T spectrum of particles from b hadrons

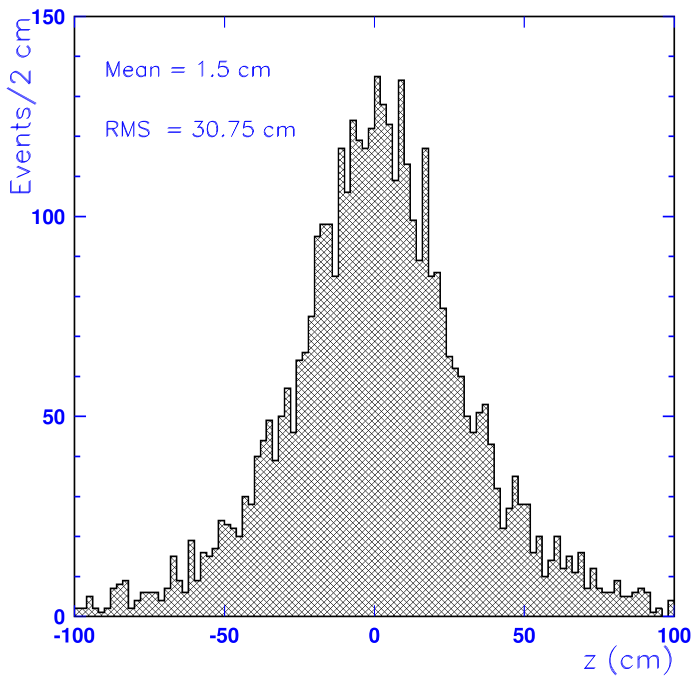
  $\Rightarrow p_T$ cuts enhance S/B substantially ($\sigma_b \sim 0.1\%\ \sigma_{\mathrm{tot}}$ but at high p_T $\sigma_b \sim 1 - 2\%\ \sigma_{\mathrm{tot}}$
- B hadrons are often isolated
- Tevatron beamspot is small in transverse plane but large along beam axis $\Rightarrow$ exploit at trigger level with impact parameter cuts

Tevatron $p\bar{p}$ Beam Profile

- Transverse profile of beam spot

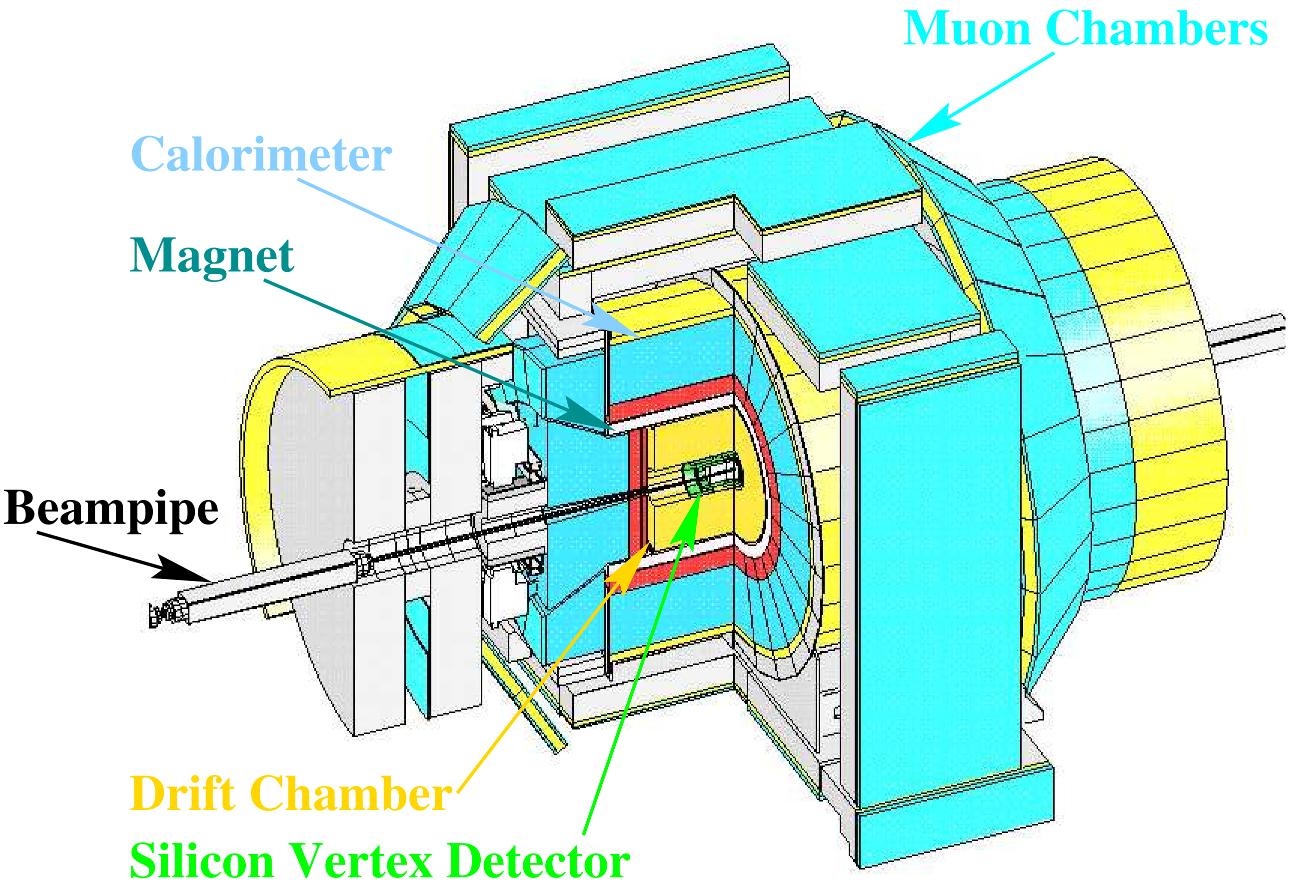


- Profile of $p\bar{p}$ interaction vertices along beam axis



CDF in Run II

- Cross section of CDF II detector:

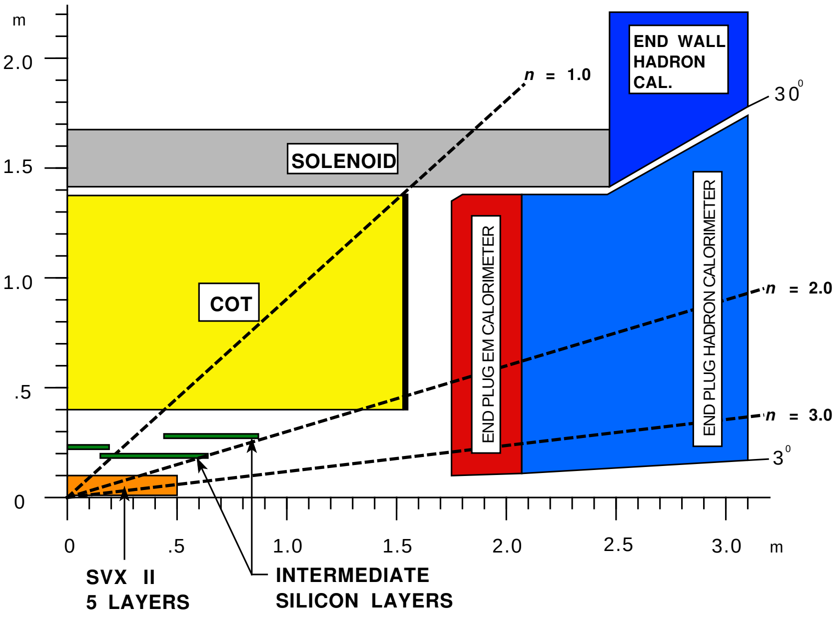


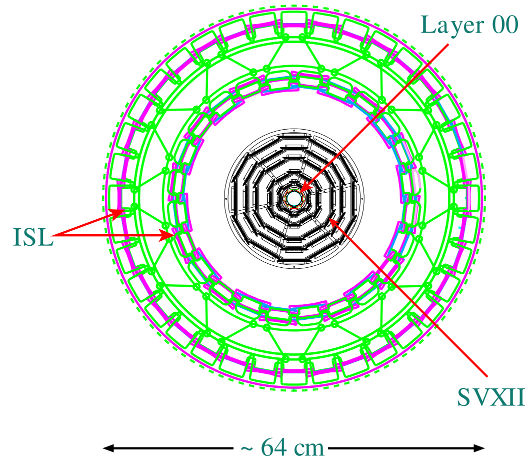
- Major upgrade of tracking system
- New endplug calorimeter
- Improved muon coverage
- Trigger/DAQ upgrade (pipelined)
- New front end electronics
- Time of flight system

CDF Tracking Upgrade

- Optimized integrated tracking system:

CDF Tracking Volume





- New silicon tracking system:
  - SVX II: 5 layers (2.5<R<10.6 cm), double sided Si $\Rightarrow$ 3-d tracking ($r\phi$ and rz), 96 cm long (double Run I acceptance)
  - ISL: 2 additional Si layers (R<28 cm); cover $|\eta| < 2$
  - L00: inner layer of Si at beam pipe (R=1.5 cm)

$\Rightarrow$ Standalone silicon tracking up to $|\eta| = 2$

- New central outer tracker (COT):
  - open cell drift chamber (30,240 sense wires)
  - maintain Run I tracking efficiencies and resolutions
  - dE/dx capability

A Case Study

* CP Asymmetry in $B \to \pi\pi$: $\sin 2\alpha$

  The issues: signal and background

* Signal: closely related to trigger

  Use displaced two-track hadronic trigger:

  Level 1: XFT: Fast track trigger finds oppositely charged track pairs in COT with $p_T > 1.5$ GeV/c ($\sigma(p_t)/p_t^2 < 0.015(\mathrm{GeV}/c)^{-1}$) (50 kHz max.)

  Level 2: SVT: Link tracks into Silicon and require track impact parameter $d > 100$ μm ($\sigma(d) \approx 19 + 40/p_T$ μm) (300 Hz max.)

  Level 3: Use full event information such as invariant $\pi\pi$ mass cut. (75 Hz max.)

* Expected trigger rates:

  L1: use min. bias data and XFT simulation

  L2: use 2-track trigger data and SVT simulation

Scenario	T_{bunch} [ns]	$\mathcal{L}$ [cm^{-2}s^{-1}]	$\langle N_{p\bar{p}} \rangle$	L1 rate [kHz]	L2 rate [Hz]
A	396	0.7×10^{32}	2	18	25
B	132	2.0×10^{32}	2	30	39
C	396	1.7×10^{32}	5	28	14

A Case Study: $B \to \pi\pi$

∗ Signal: Expected number of $B^0 \to \pi^+\pi^-$ events

- Use measured $\sigma(p\bar{p} \to B^0 X)$
- Use simulation:
  - generate $p\bar{p} \to bX$
  - fragment $b \to B^0$ (ϵ_b)
  - decay B^0 into $\pi^+\pi^-$
- Know BR($B^0 \to \pi^+\pi^-$)
  - use BR($B^0 \to \pi^+\pi^-$) $= 1 \cdot 10^{-5}$
  - CLEO: BR($B^0 \to \pi^+\pi^-$) $= (0.47 \pm 0.18) \cdot 10^{-5}$
- Trace tracks through detector; simulate trigger (XFT, SVT)

∗ Expected signal in 2 fb^{-1}:

$\sim$ 4000 - 7000 $B^0 \to \pi^+\pi^-$ (BR=$0.47{\cdot}10^{-5}$)

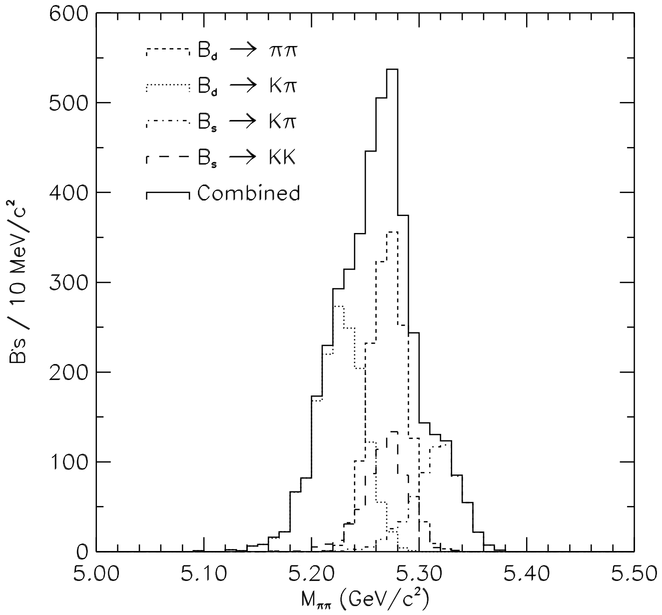
$\sim$ 16,000 - 28,000 $B^0 \to K^+\pi^-$ (BR=$1.88{\cdot}10^{-5}$)

∗ Backgrounds:

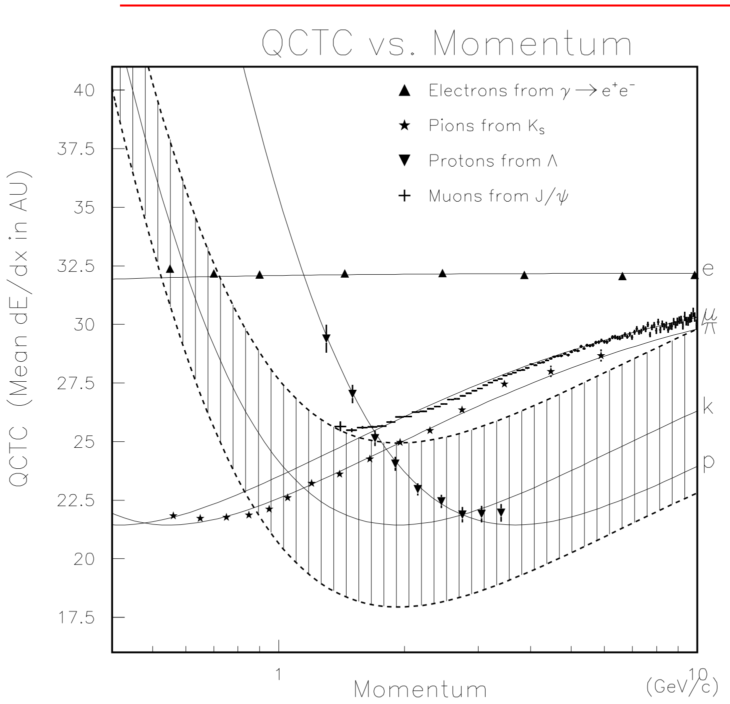
- Physics backgrounds
- Combinatorial background

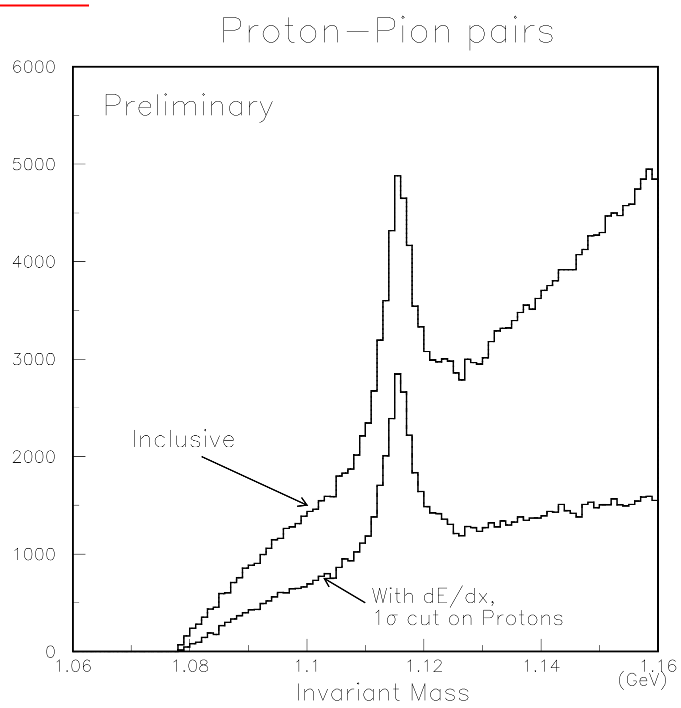
A Case Study: $B \to \pi\pi$

- Physics Backgrounds: $B \to K\pi$ and $B \to KK$
- Use inv. mass and dE/dx distributions



- Run I dE/dx performance:

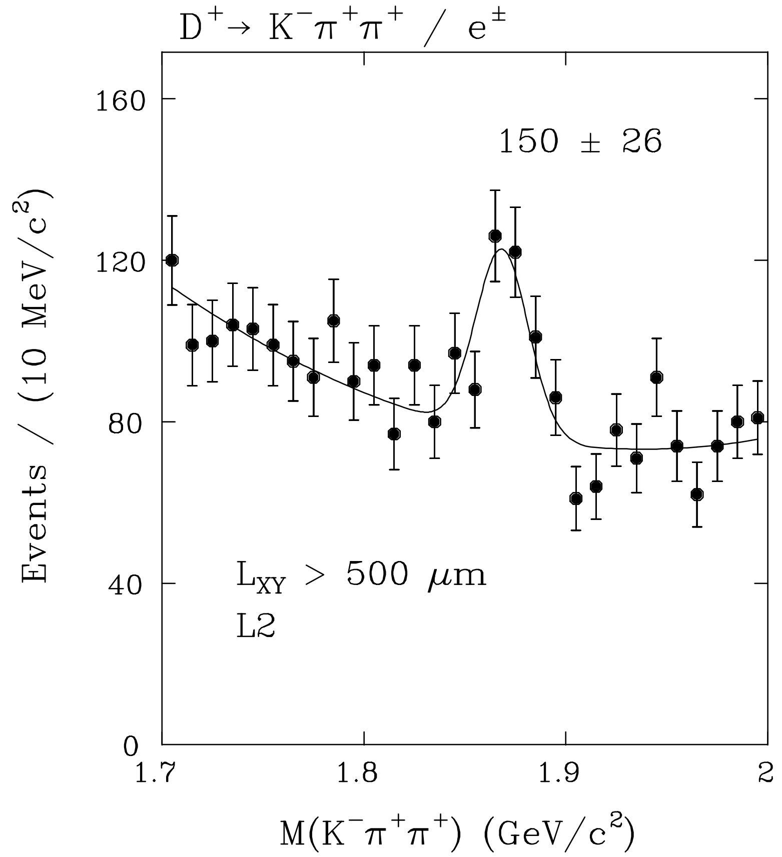




A Case Study: $B \to \pi\pi$

⋆ Combinatorial Background:

- Heavy flavour ($b\bar{b}$ and $c\bar{c}$):
  - have real lifetime; give displaced tracks
  - can be studied with Monte Carlo
  - better to use data
- Light quark production (generic QCD) plus mismeasured tracks or K_S^0, Λ, ...
  - cannot be predict by MC, must use data
- Example: D^+ opposite to lepton



CP Violation: $\sin(2\beta)$

* **Measurement of $\sin 2\beta$ with 2 fb^{-1}:**

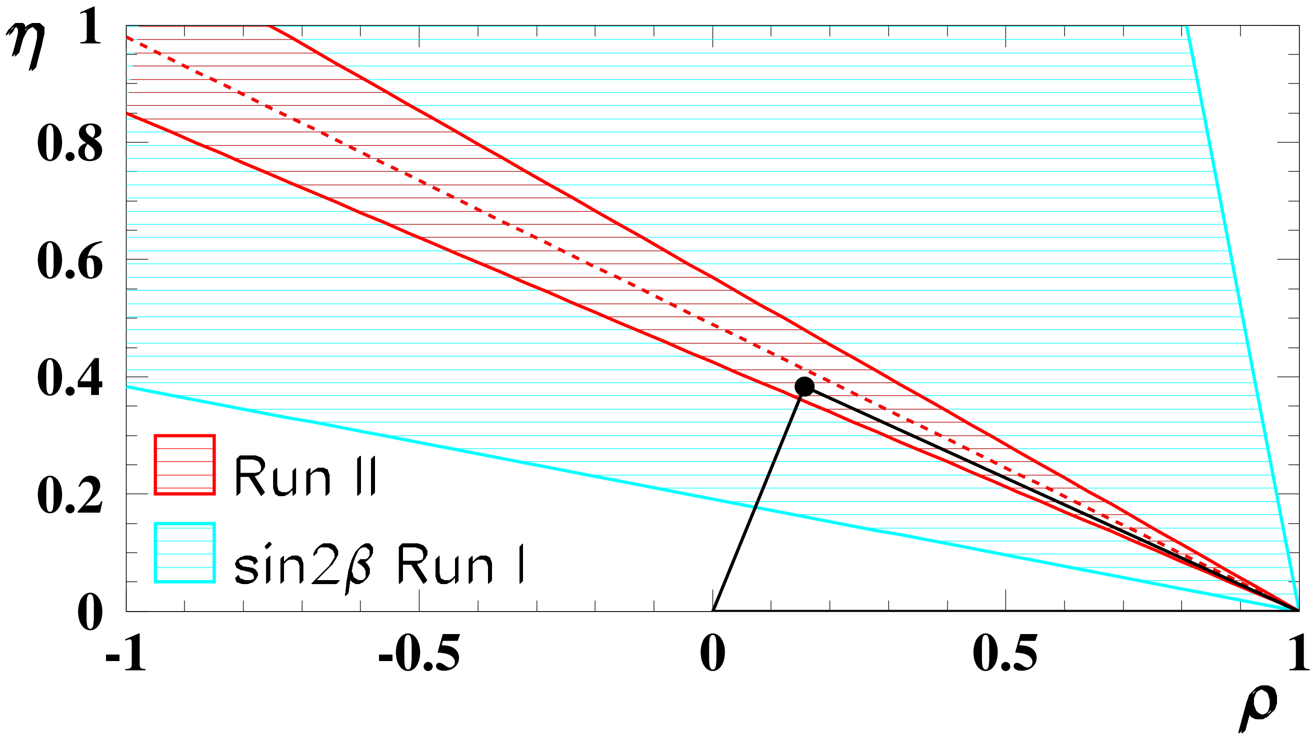
  $\sim 10\,000\ J/\psi K^0_S$ events with $J/\psi \rightarrow \mu^+\mu^-$

* **Improved B flavour tagging:**

Flavour tag	$\varepsilon\mathcal{D}^2$ Run I	$\varepsilon\mathcal{D}^2$ Run II
Same side tag	$(1.8 \pm 0.4 \pm 0.3)\%$	2.0%
Jet charge tag	$(0.78 \pm 0.12 \pm 0.08)\%$	3.0%
Lepton tag	$(0.91 \pm 0.10 \pm 0.11)\%$	1.7%
Kaon tag	–	2.4%

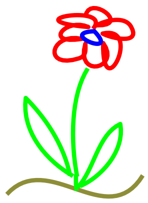
- Total $\varepsilon\mathcal{D}^2 \approx 9.1\%$

* Expect $\Delta \sin 2\beta \sim 0.07$ (2 fb^{-1})



CONCLUSION

- CDF: broad and competitive B physics program
- Excellent prospects for B physics in Run II
  - CP violation: $\underline{\Delta \sin 2\beta \sim 0.07}$
  - B_S mixing: Δm_S reach up to 40 ps^{-1}
- Waiting for theorists to educate experimentalists



"Anyone who keeps the ability
to see beauty never grows old."

(Franz Kafka)