B-Physics at DØ

Christos Leonidopoulos

April 8, 2003

- The *B*-Physics program in Run-II
- Triggers & data samples
- Current analyses - First results
- Outlook

"Making the world a better place, one particle at a time..."

Fermilab: the Tevatron $p-\bar{p}$ Accelerator

circumference: 6.2 km

- 1992-1996: Run-I (125 pb^{-1})
  DØ & CDF discover *t*-quark
- 1996-2000: detector upgrade
  E=1.8 TeV → 1.96 TeV
- 2001-2005: Run-IIa (2′000 pb^{-1})
  Luminosity: 1×10^{32} cm^{-2} s^{-1} (x5 increase)
  Bunch crossing time: 396 ns (x10 decrease)
- 2005-2008: Run-IIb (10−15′000 pb^{-1})
  Luminosity: 2×10^{32} cm^{-2} s^{-1} (x10 increase)

Higgs needs to be discovered!

As of last week: L_{max}: 4.1×10^{31} cm^{-2} s^{-1}

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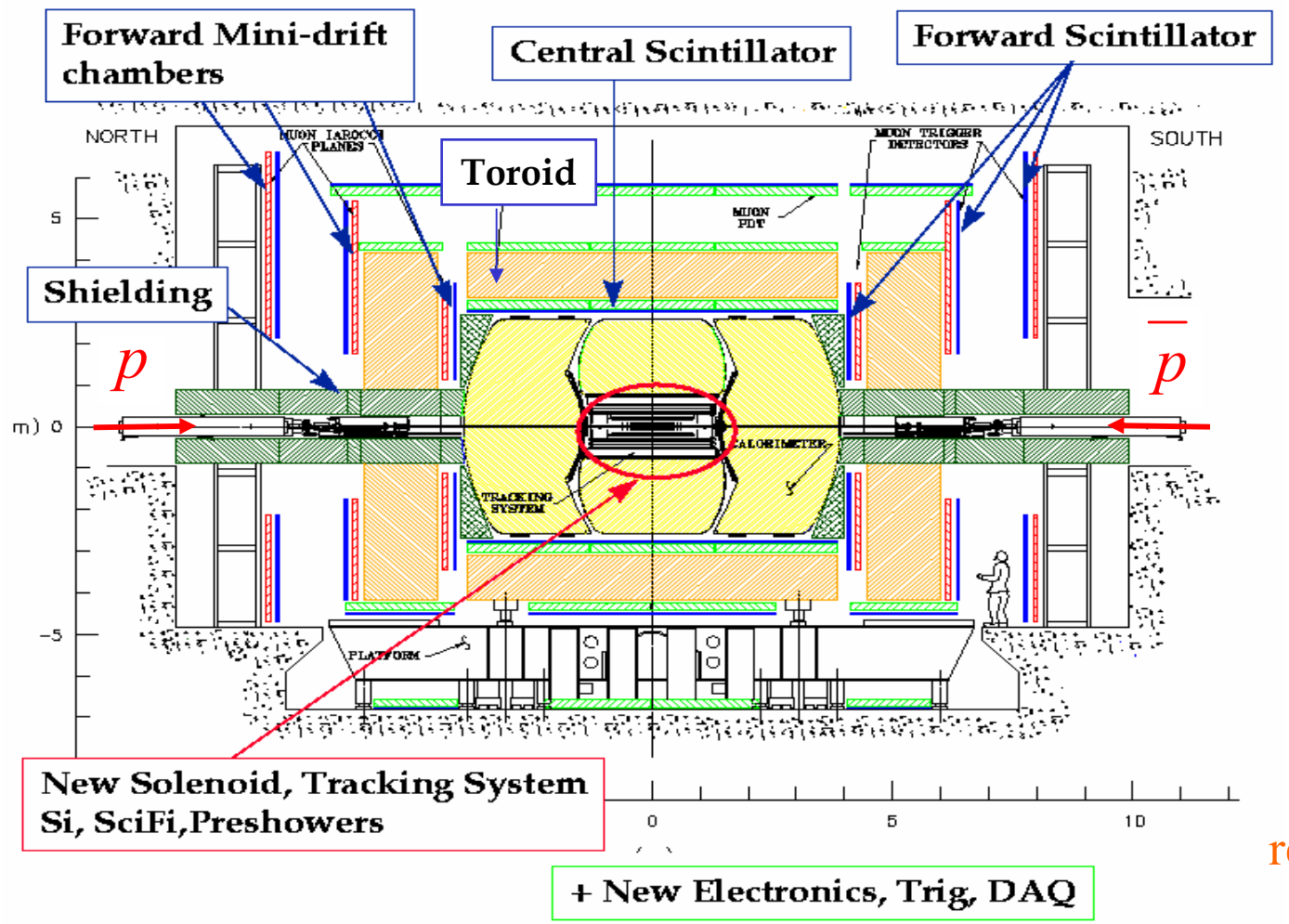
DØ: The Upgraded 5′000-ton Detector

5 years and $100 M later…



What's new at DØ:

- Solenoid!
- New subdetectors
  - silicon tracker
  - fiber tracker
  - preshowers
  - forward muon
- Enhanced trigger system, electronics
- Extra shielding around beamlines

DØ in Run-II is really a *new* detector!

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DØ: An International Collaboration

January 2001: just before detector roll-in…

- 646 people (312 non-US)
- 73 institutions (40 non-US)
- 18 countries

b Physics program in Run-II

Unique at Tevatron!

- Lots of B's: B_d, B_s, Λ_b, B_c,...

A $b\bar{b}$ pair can give any combination of mesons & baryons!

$$\sigma(p\bar{p} \to b\bar{b}) = 150\ \mu\text{b @2 TeV}$$
$$\sigma(e^+e^- \to Z^0 \to b\bar{b}) = 7\ \text{nb}$$
$$\sigma(e^+e^- \to \Upsilon(4S) \to b\bar{b}) = 1\ \text{nb}$$

- Rich physics program:
  - B_s studies: mixing, $\Delta\Gamma$ measurements
  - CP Violation: B_d ✓ & B_s systems
  - Rare decays, cross section measurements
  - Baryon studies: B_c, Λ_b, Ξ_β, η_b
  - Confront CKM matrix in complementary ways to e^+e^- B-factories

First goals:

- Putting the pieces together
  - Final state reconstruction
  - Proper time distributions
  - Flavor tagging studies
- Proving we understand the detector before we move on to important measurements

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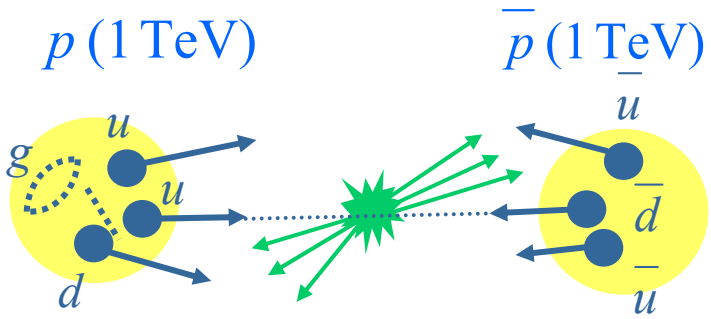
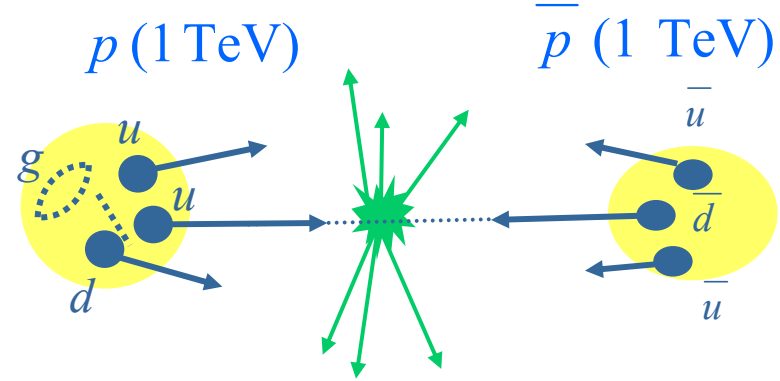
Fermilab as a hadron collider

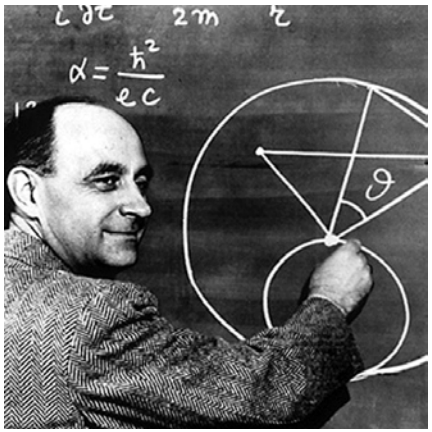


- Colliding quarks carrying small fraction of $p/\bar{p}$ momentum
- Products boosted mainly along beam line

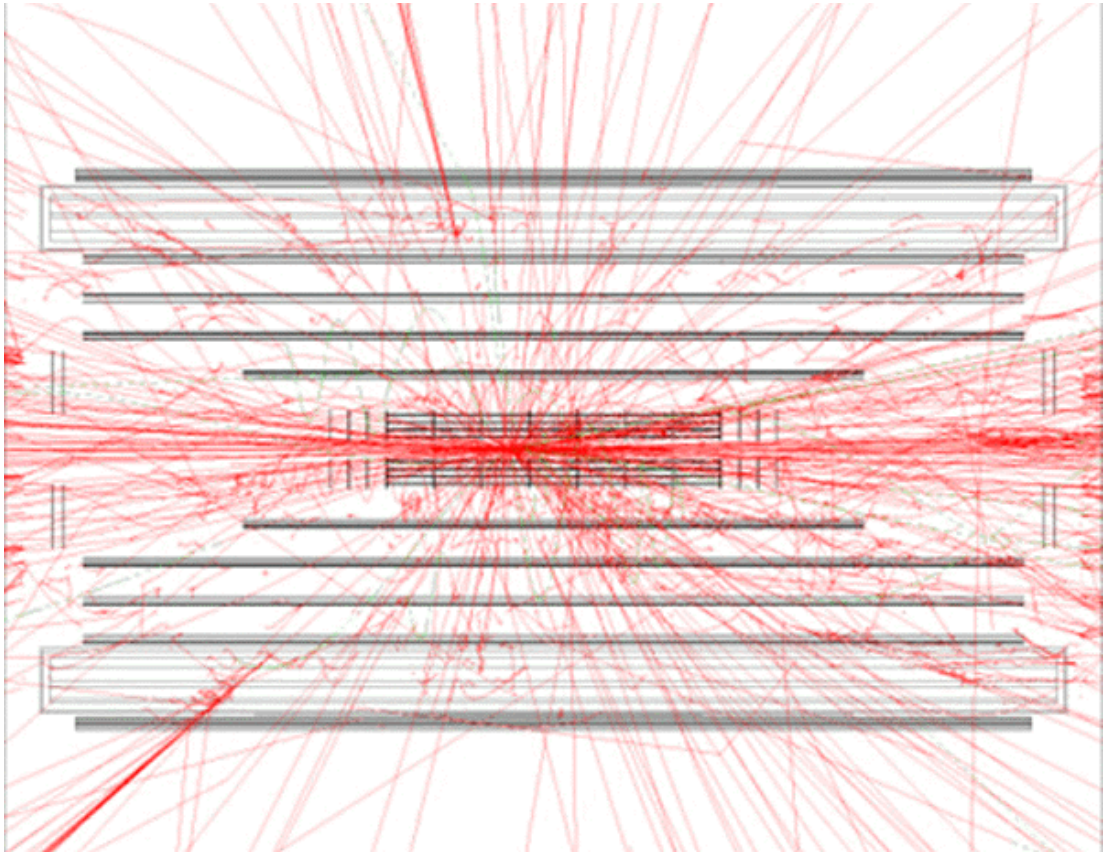


- Colliding quarks carrying large fraction of $p/\bar{p}$ momentum
- Massive products with large momentum component transverse to beam line: p_T

- Signature of hard scattering: this is an interesting event
- What do we know about event?
  - total energy of colliding quarks? unknown
  - total longitudinal momentum? unknown
  - total transverse momentum? zero!



Things are never quite as simple…



# of interactions/crossing

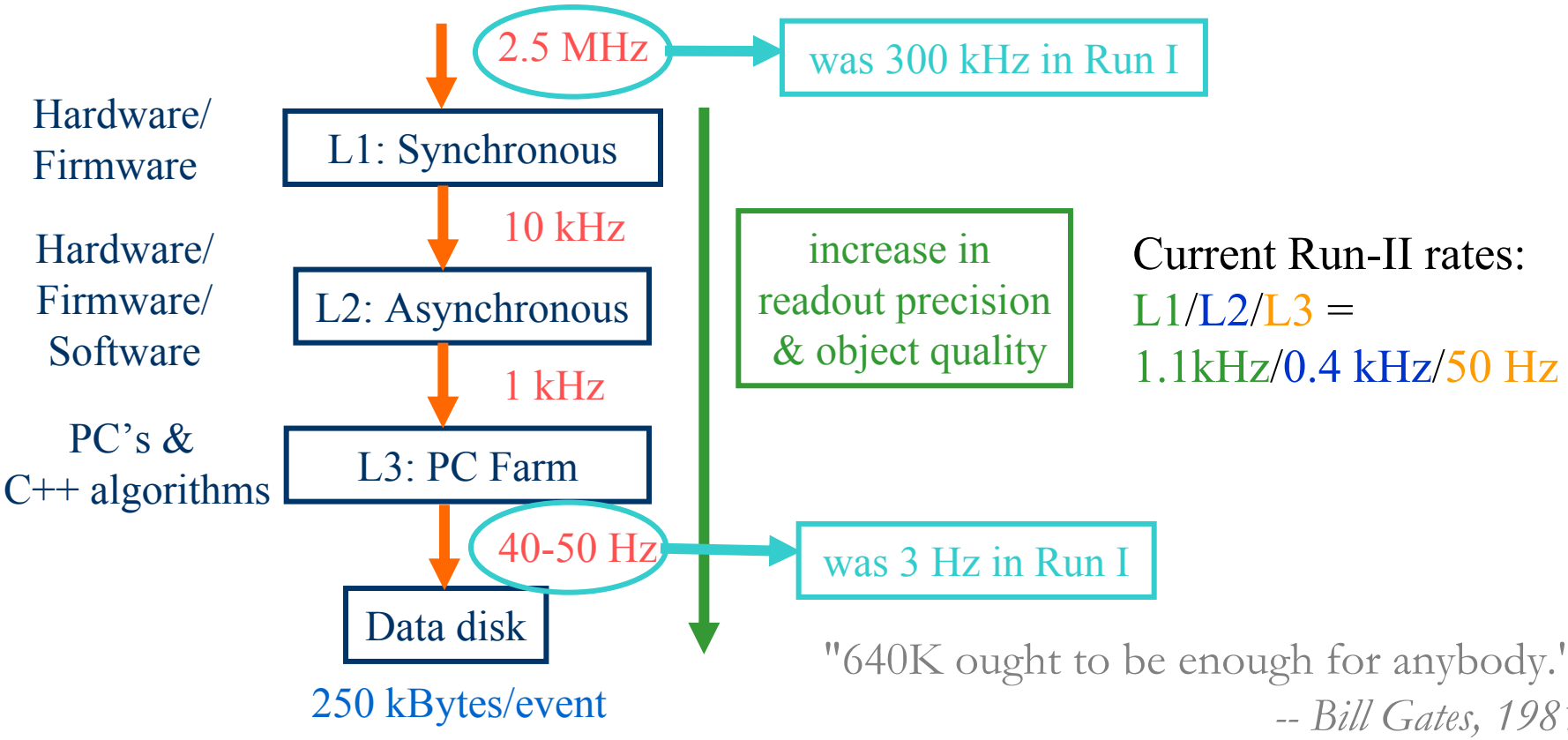
bunch Xing	$b\bar{b}$	Total
396 ns	0.008	6.0
132 ns	0.003	2.0

This is the highest-energy collider in the world!

- Great place for great discoveries: lots of data
- But: Tons of background, messy collisions, scarily high rates

DØ: Triggering on interesting events

- $p-\bar{p}$ collisions: we have to look at 2.5 M crossings every sec
- Huge data volume: 0.6 TB/s; impossible to save everything on disk
- Focus on "interesting" events: reduce data flow to ~ 10 MB/s
- Use modular system of three filtering levels: trigger system



"640K ought to be enough for anybody."
-- Bill Gates, 1981.

B Physics triggers

DØ does not exploit purely hadronic triggers, but benefits from

- large muon acceptance: $|\eta| < 2$
- forward tracking coverage: $|\eta| < 1.7$ (tracking), < 3.0 (silicon)
- and can use $J/\psi \to e^+e^-$ (excellent, hermetic calorimeter)

Remember:

pseudorapidity

$\eta \equiv -\log(\tan\vartheta/2)$

$\eta = -3 \Leftrightarrow \vartheta = 174°$

$\eta = -2 \Leftrightarrow \vartheta = 165°$

$\eta = -1 \Leftrightarrow \vartheta = 140°$

$\eta = 1 \Leftrightarrow \vartheta = 40°$

$\eta = 2 \Leftrightarrow \vartheta = 15°$

$\eta = 3 \Leftrightarrow \vartheta = 6°$

- <u>This talk:</u> mainly dimuon triggers $J/\psi \to \mu^+\mu^-$

$$|\eta| < 1: \; p_T > 3.5\,\text{GeV}/c \;\; (\text{"central"})$$
$$1 < |\eta| < 2: \; p_T > 2 - 2.5\,\text{GeV}/c \;\; (\text{"forward"})$$

about 18 Hz of *B*-physics to tape at 2×10^{31} cm^{-2} s^{-1}

- <u>Coming soon:</u>
  - L2−track trigger: *May*
    track matches with μ, e; add $J/\psi \to e^+e^-$
  - L2−silicon trigger *June*
    displaced vertices; trigger on impact parameter

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Tevatron Performance

- Not up to Run-II speed yet, slowly improving
- Finally exceeded Run-I performance
- Luminosity delivered:
  - Jun´01-Apr´02: 36 pb^{-1}
  - Apr´02-Mar´03: 144 pb^{-1} ← (tracker fully commissioned)

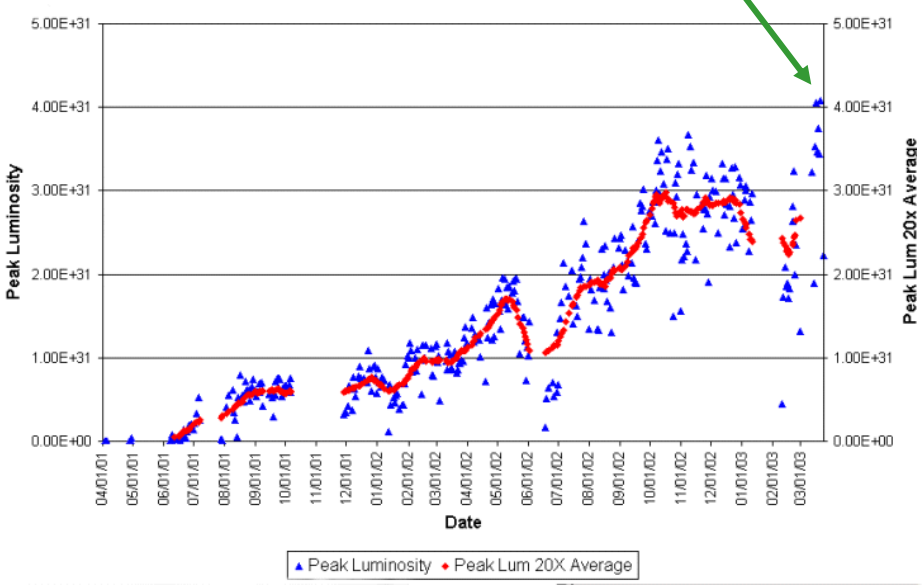
Physics data recorded at DØ since full tracker installation:

- Apr´02-Mar´03: 91 pb^{-1}
- Aug´02-Jan´03: ~ 50 pb^{-1}

(Spring conferences, this talk)

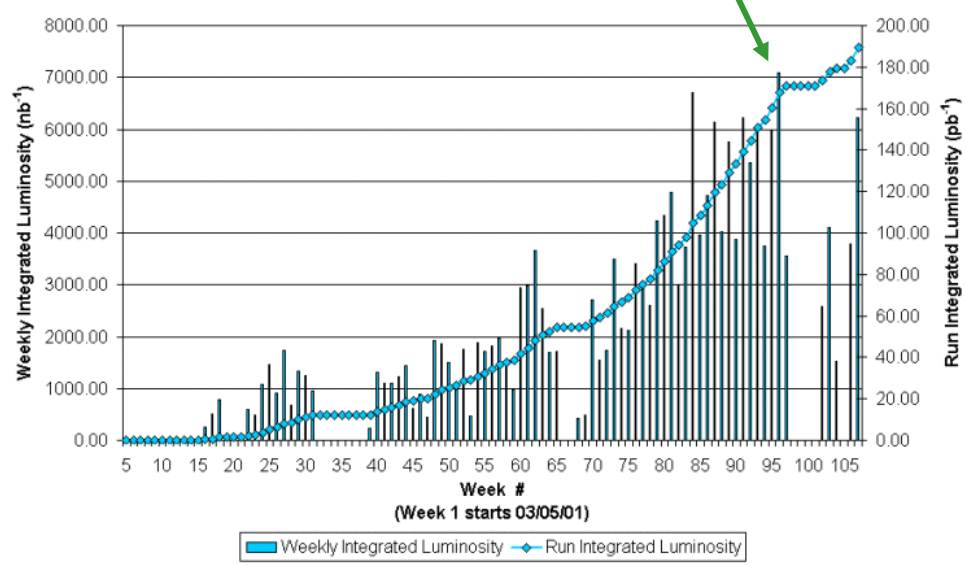
$L_{max} = 4.1\times10^{31}\ cm^{-2}\ s^{-1}$ – March 20, 2003

Average CDF + DØ peak luminosity



7.1 pb^{-1}/week

Integrated luminosity



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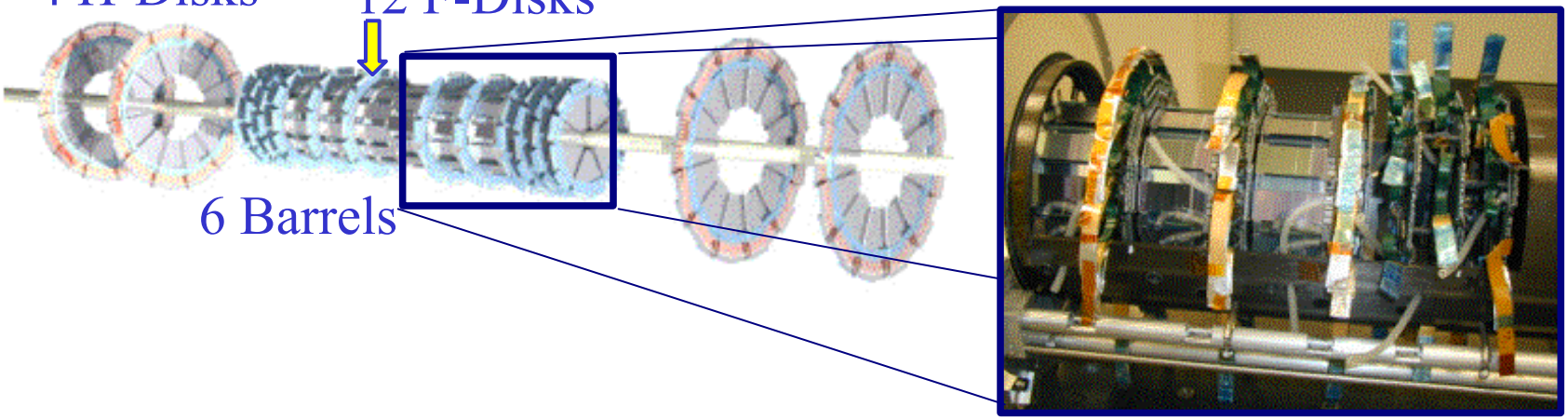
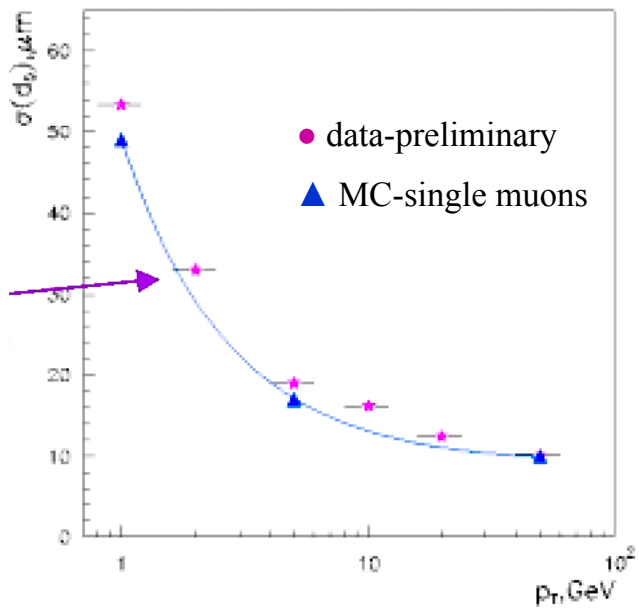
Detector performance: tracking



Silicon Microstrip Tracker: 793k channels

Impact parameter resolution

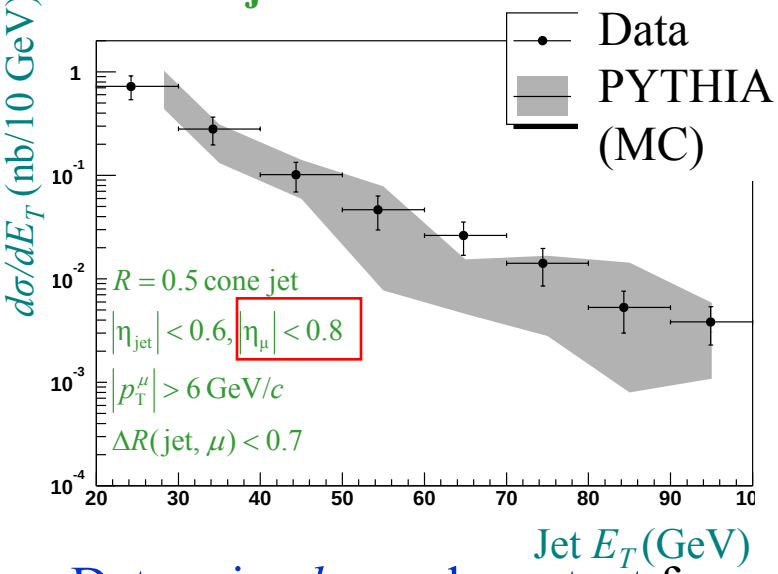


Getting close to expectations

Inclusive *b*-production cross section

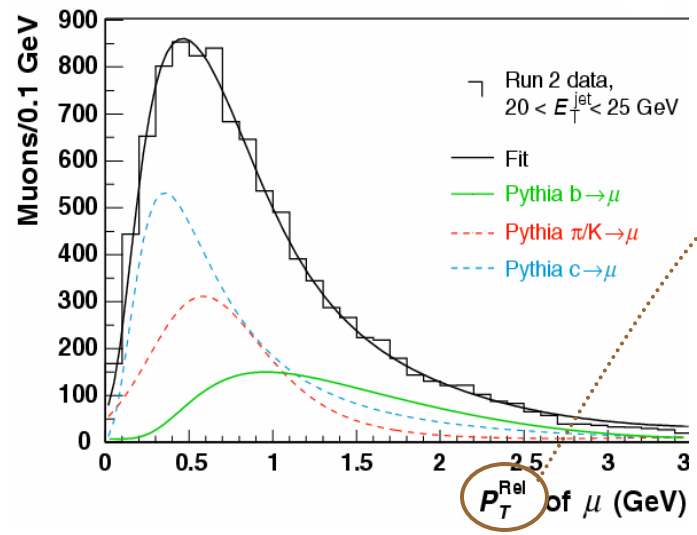
- Get cross section distribution for lepton included in jets (just muons for now)

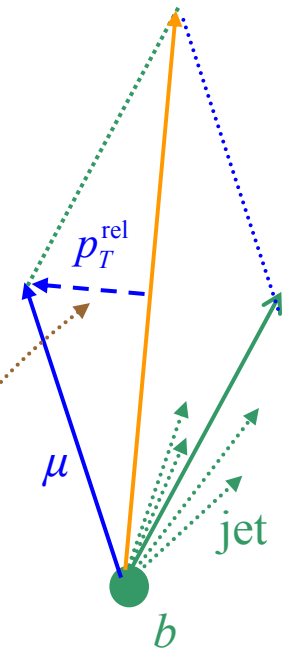
muon + jet cross section



- Determine *b*-quark content from lepton momentum distribution (fit for *b*- and non-*b*- content for each jet-E_T bin)

***b*-content from p_T^{rel} fits**





- Studies *with muon detector hits* only (i.e. no tracks)
- Jet trigger efficiency: 100% for $E_T > 20$ GeV
- Muon trigger efficiency: ~ 55 −70%
- Muon reconstruction efficiency: 43.7 ± 0.8 ± 2.2%

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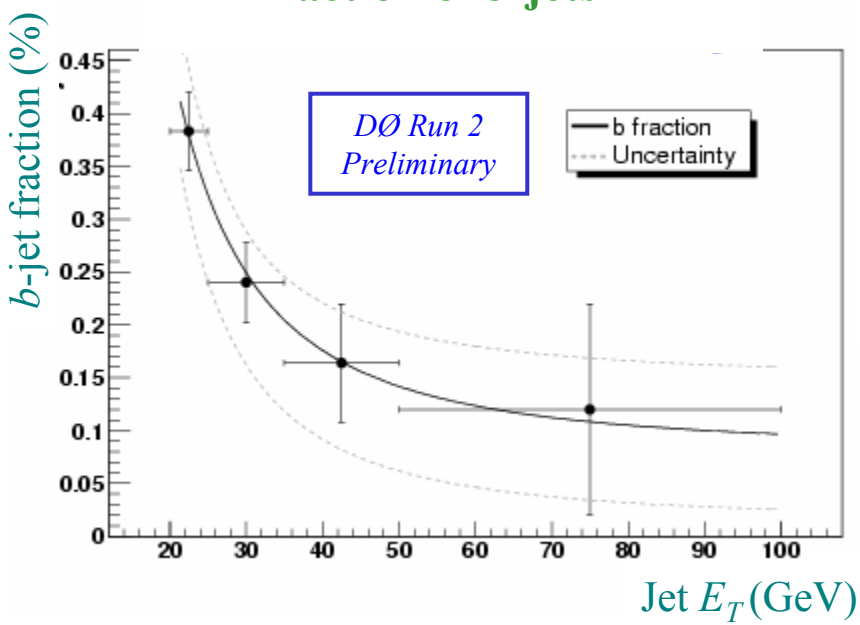
…Inclusive *b*-production cross section

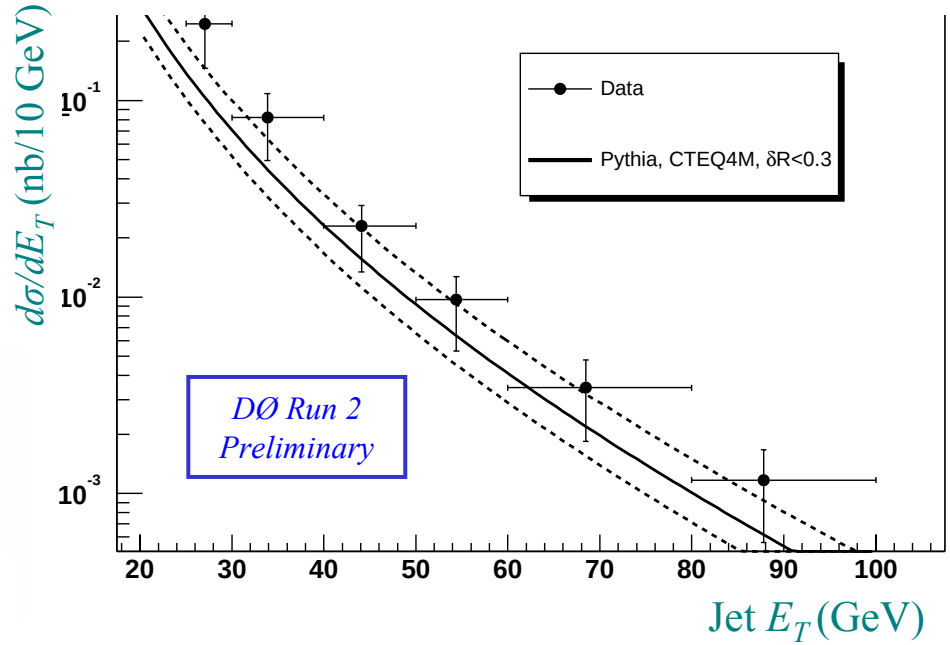
Using 3.4 pb^{-1} of data (Mar-May 2002)

fraction of *b*-jets



***b*-quark cross section**

(corrected E_T spectrum using "assantz" function)



- Energy resolution measured using event imbalance
- Main contribution to systematic error: jet energy scale uncertainty
- Run-I result was compared to NLO (+MRSA´) prediction Nucl. Phys. **B483** (1997) 321
  Different $\sqrt{s}$, not directly comparable - still 2-3 times higher than predictions

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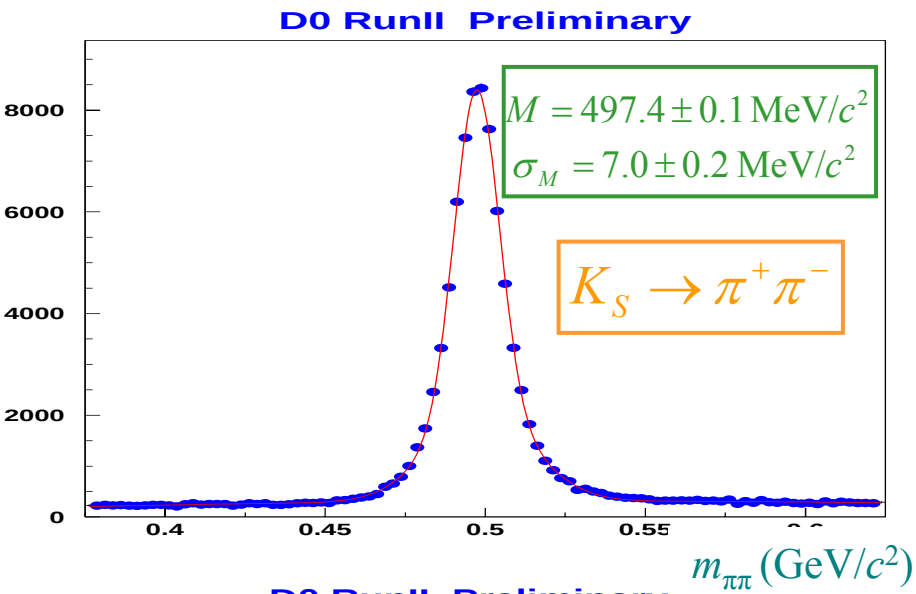
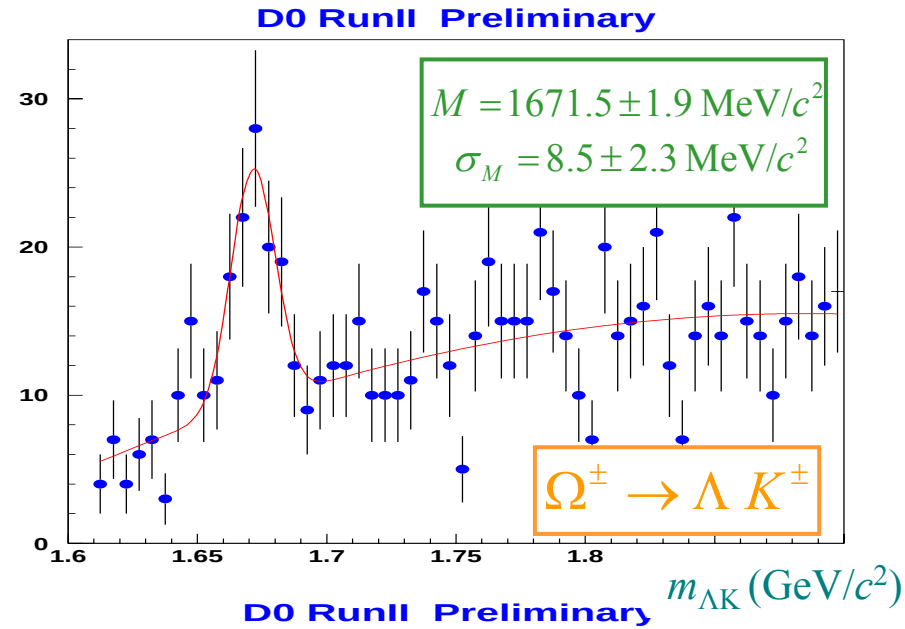
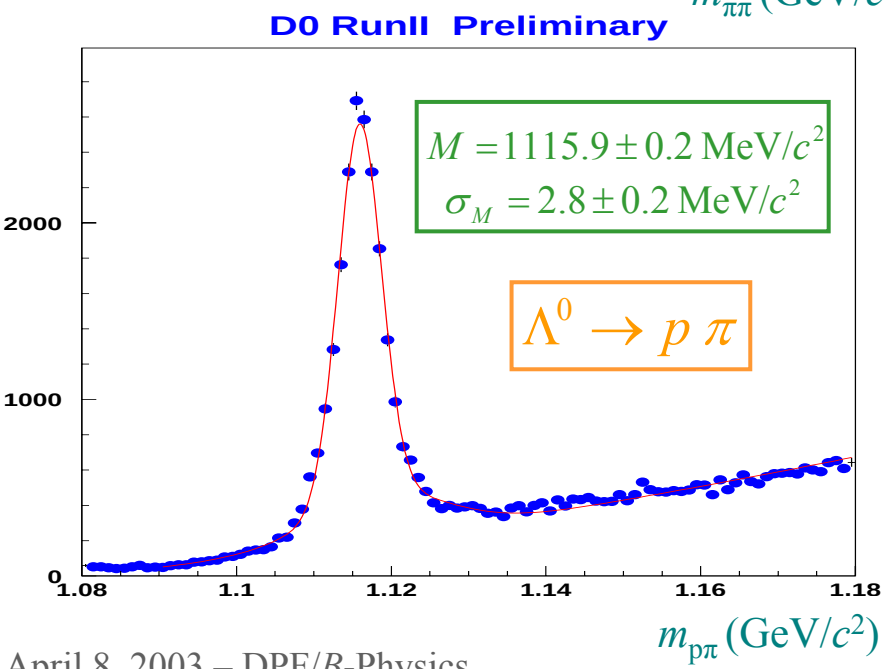
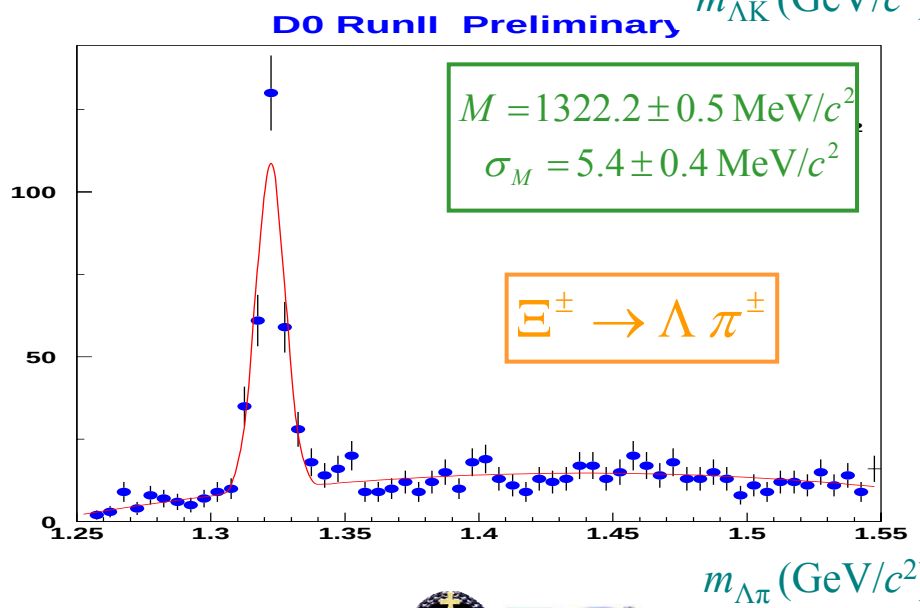
Tracking as an identification tool

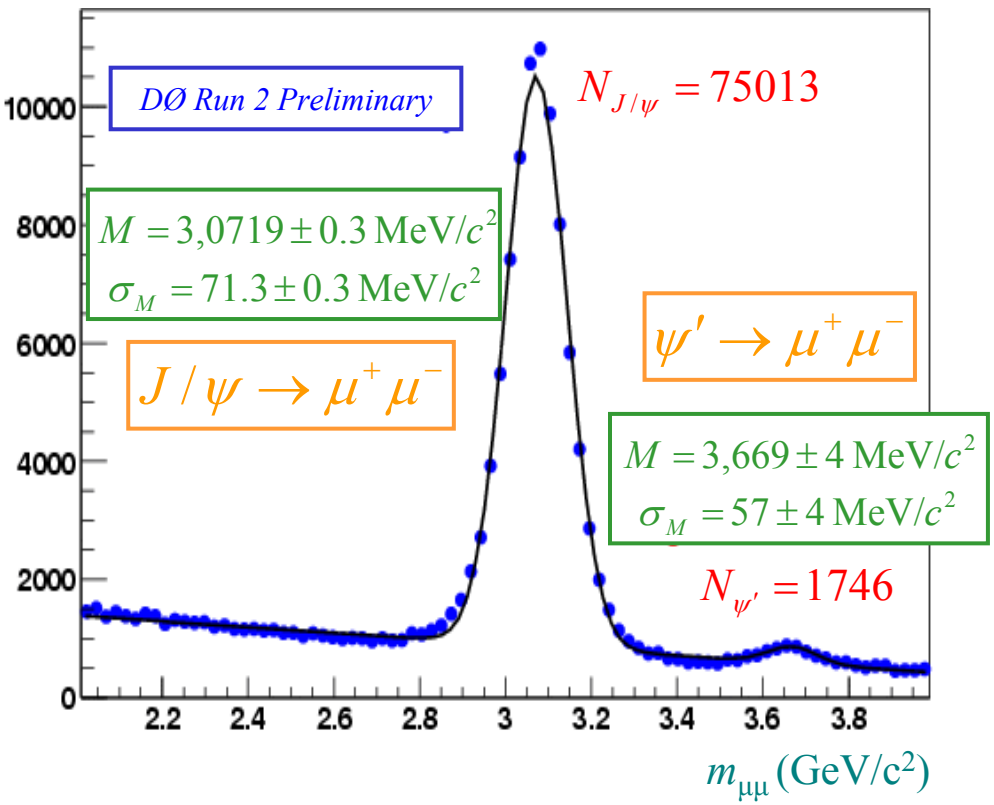








Charmonium decays

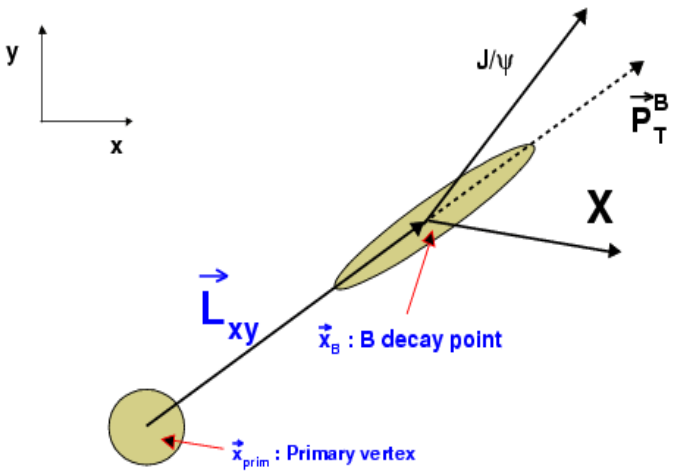


Today's results use only $J/\psi \to \mu^+\mu^-$ mode:

- Easy, unprescaled trigger
- Clean signal
- Lots of *B* mesons

- Calibration not finalized yet: ⅓ σ discrepancy from PDG value
- Muon cuts: $p_T > 1.5$ GeV/c, >3 silicon hits, >4 fiber track hits
- J/ψ cuts: $p_T > 3$ GeV/c

Inclusive *B* lifetime



- Using 75 k $B \rightarrow J/\psi\, X$ decays
- J/ψ transverse decay length determined from
  - interaction point (primary vertex)
  - J/ψ decay (secondary vertex)

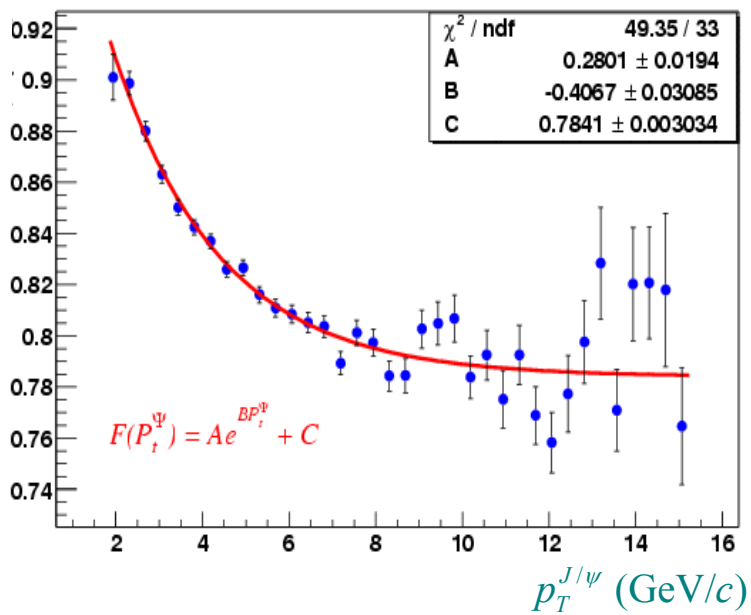
$$c\tau_{J/\psi} = L_{xy} \frac{M^{J/\psi}}{p_T^{J/\psi}}$$

- Inclusive measurement: p_T of B meson unknown

Infer $c\tau_B$ from $c\tau_{J/\psi}$

$$c\tau_B = \frac{\lambda_{J/\psi}}{\left\langle F(p_T^{J/\psi}) \right\rangle}$$

$\left\langle F(p_T^{J/\psi}) \right\rangle$



…by applying average MC correction

$$\left\langle F(p_T^{J/\psi}) \right\rangle = \frac{M_{J/\psi}}{M_B} \frac{p_T^B}{p_T^{J/\psi}}$$

PYTHIA + QQ (CDF Run-I tuned parameters)

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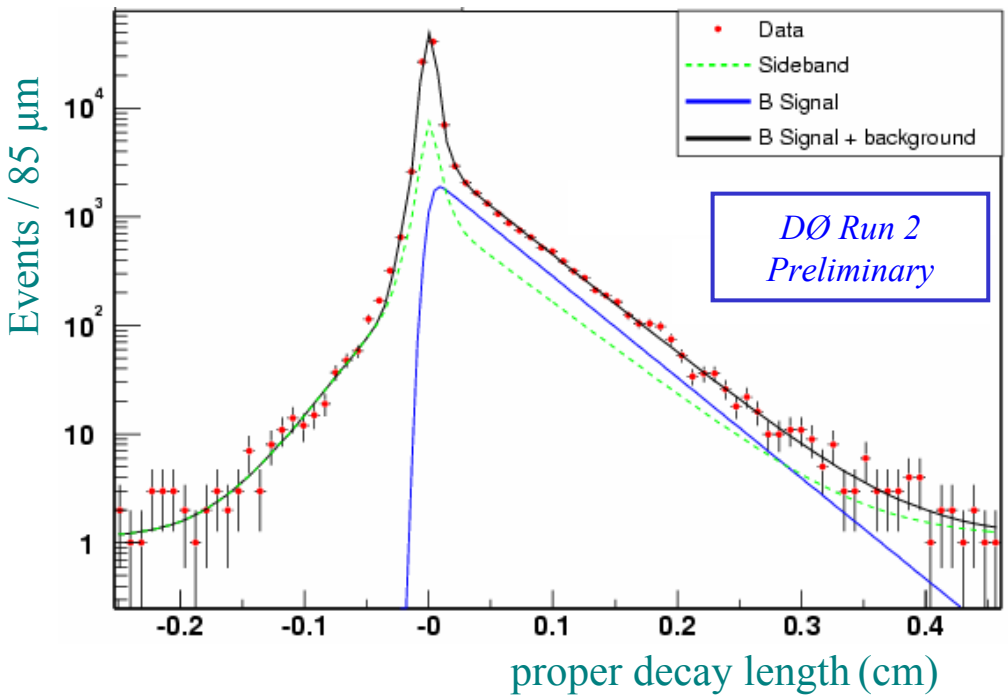
…Inclusive *B* lifetime

Proper B decay length ($B \to J/\psi + X$)



- "zero-lifetime" components (modeled as double Gaussians):
  - "prompt" J/ψ: $p\bar{p} \to c\bar{c}X$
  - combinatorial background
- exponential components:
  - B signal: $p\bar{p} \to b\bar{b} \to c\bar{c}X$
  - background from semileptonic b, c cascade decays
- Gaussian parameters, background normalization: from sidebands to J/ψ mass peak
- B signal fraction, resolution: free to float

$c\tau_B = 468 \pm 7 \pm 22$ μm

$\tau_B = 1.561 \pm 0.024 \pm 0.074$ ps

PDG $\tau_B = 1.564 \pm 0.014$ ps

- B signal fraction: 14.6% (~11k events)
- Prompt J/ψ fraction: 64.6%
- Background fraction: 21.3%

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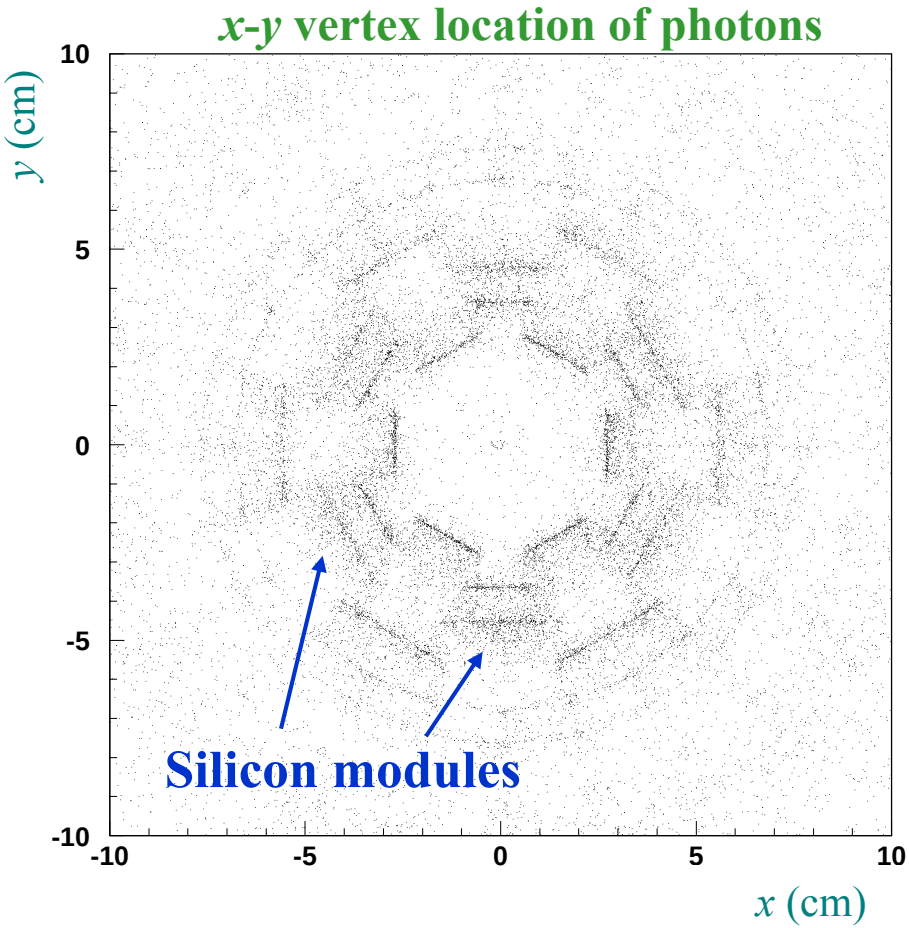
χ_c reconstruction



- "Photometry": tracking efficiency does not strongly depend on impact parameter
- Low p_T, large impact parameter tracking: critical for B Physics

- Targeting $BR(b \to \chi_C + X) \sim 1\text{–}2\%$
- Attempting $\chi_C \to J/\psi\, \gamma$ reconstruction
- Low energy photons visible through $\gamma \to e^+e^-$ conversion (require $p_T > 1$ GeV/c, expect $\varepsilon_\gamma \sim 0.4$ %)
- Fraction of J/ψ's from χ_C:

$$F_x^{J/\psi} = (27.4 \pm 1.6 \pm 5.2)\%$$

CDF Run-I, PRL **79**, 578 (1997)

- Expected # of χ_C events:

$$N_{J/\psi} \times F_x^{J/\psi} \times \varepsilon_\gamma \sim 80$$

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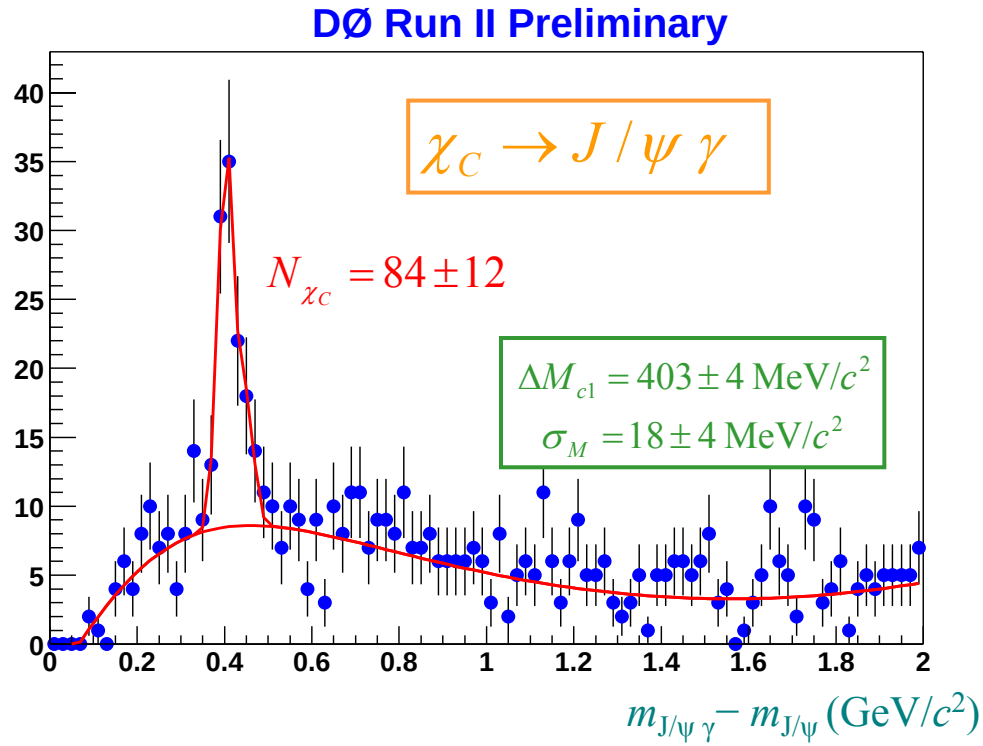
...χ_c reconstruction



- Mass resolution not sufficient for χ_{C1}, χ_{C2} separation; Fit with fixed $\Delta M_{C1} - \Delta M_{C2} = 46\ \mathrm{MeV}/c^2$, let relative contributions float

- Neglecting χ_{C0} contribution

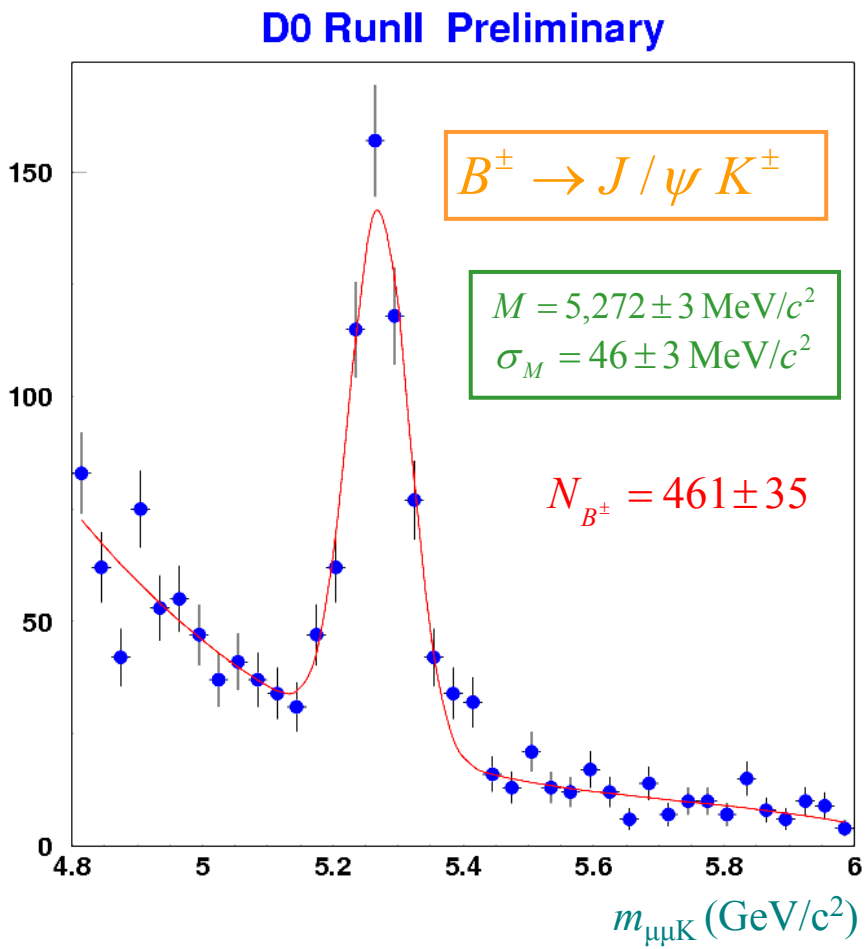
  Compare:

  $BR(\chi_{C0} \to J/\psi\,\gamma) \sim 1\%$
  $BR(\chi_{C1} \to J/\psi\,\gamma) \sim 32\%$
  $BR(\chi_{C2} \to J/\psi\,\gamma) \sim 19\%$

PDG: $m_{J/\psi\,\gamma} - m_{J/\psi} = 414\ \mathrm{MeV}/c^2$

Exclusive $B^{\pm}$ decays: control samples #1

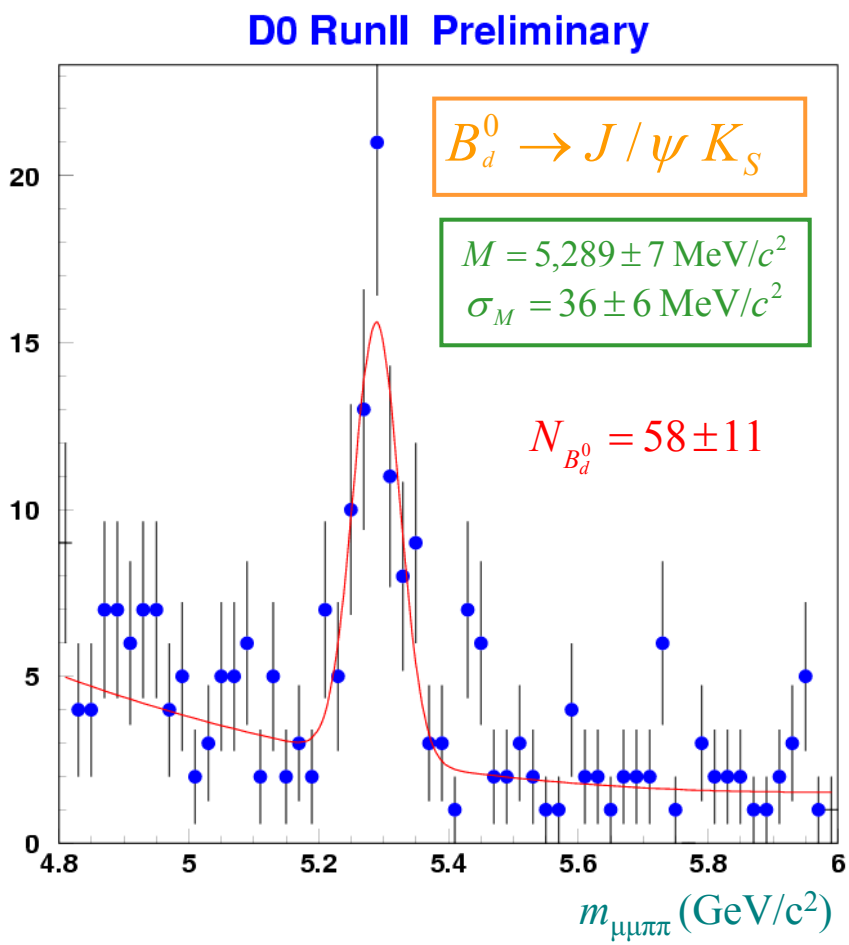
- Combine J/ψ with $K^{\pm}$
- Apply cut on decay length : $L/\sigma_L > 3$

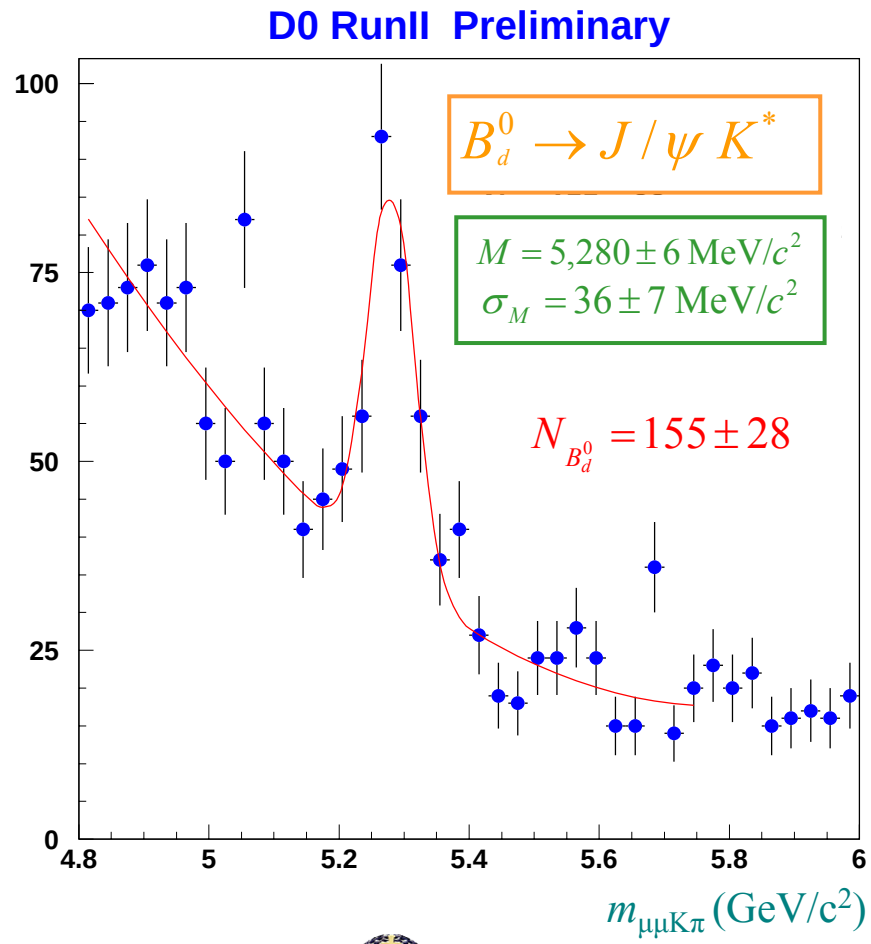


- Mass plots without any π/K ID/separation attempted
- Fully reconstructed B mesons seen at DØ for the first time!

Exclusive B_d decays: control samples #2

- Combine J/ψ with $\pi^+\pi^-, K^\pm\pi^\mp$
- Apply cut on decay length : $L/\sigma_L > 3$





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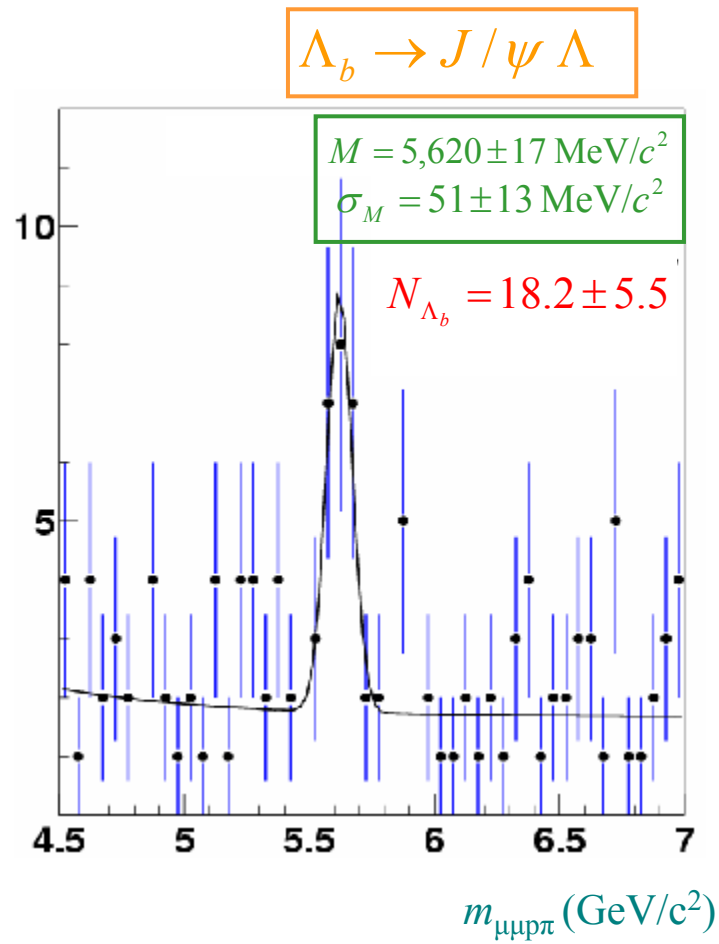
Exclusive Λ_b decays

Combine J/ψ with Λ

- Λ_b lifetime, $\tau_{\Lambda_b} / \tau_{B^0}$ ratio: probably the most confusing measurements in B physics today

- "The Λ_b lifetime…unexpectedly short…quite difficult to accommodate theoretically"



Exclusive B_s decays

- Combine J/ψ with K^+K^-
- Apply cut on decay length : $L/\sigma_L > 3$

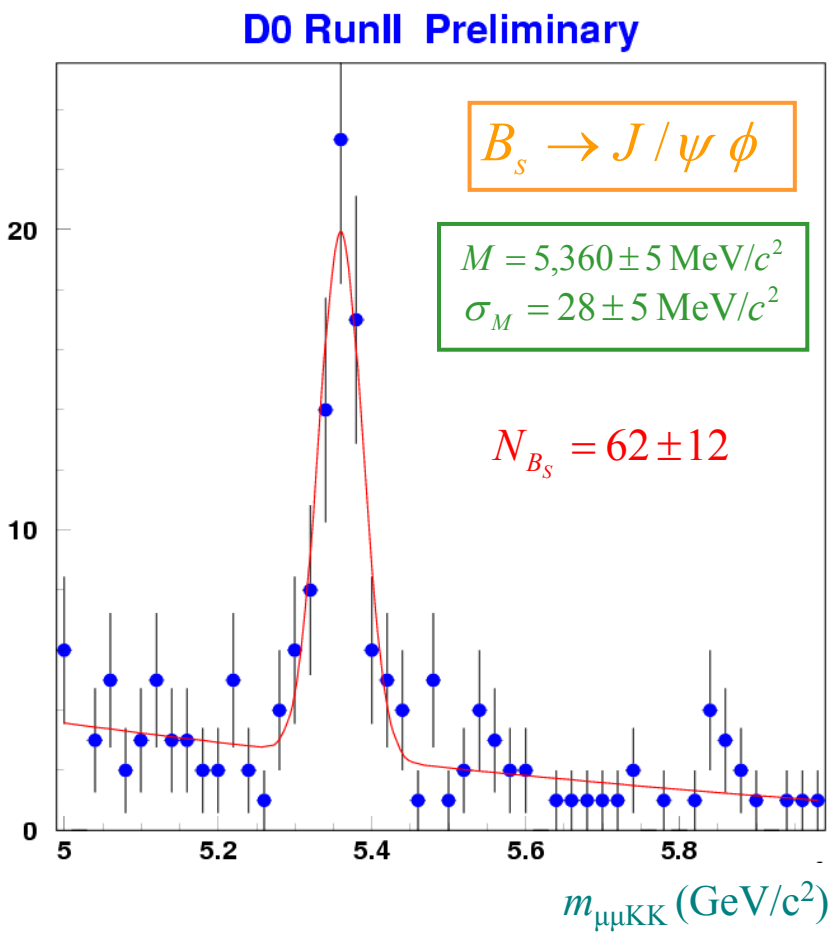
The "gold-plated" mode for B_s

- CP violation in B_s system

$$a(B_s \to J/\psi\,\phi) \sim \sin\beta_s$$

Is it large enough to see?

- Admixture of *CP*-even and *CP*-odd states; angular analysis is needed
- $\Delta\Gamma_s$ measurement: error depends on the admixture



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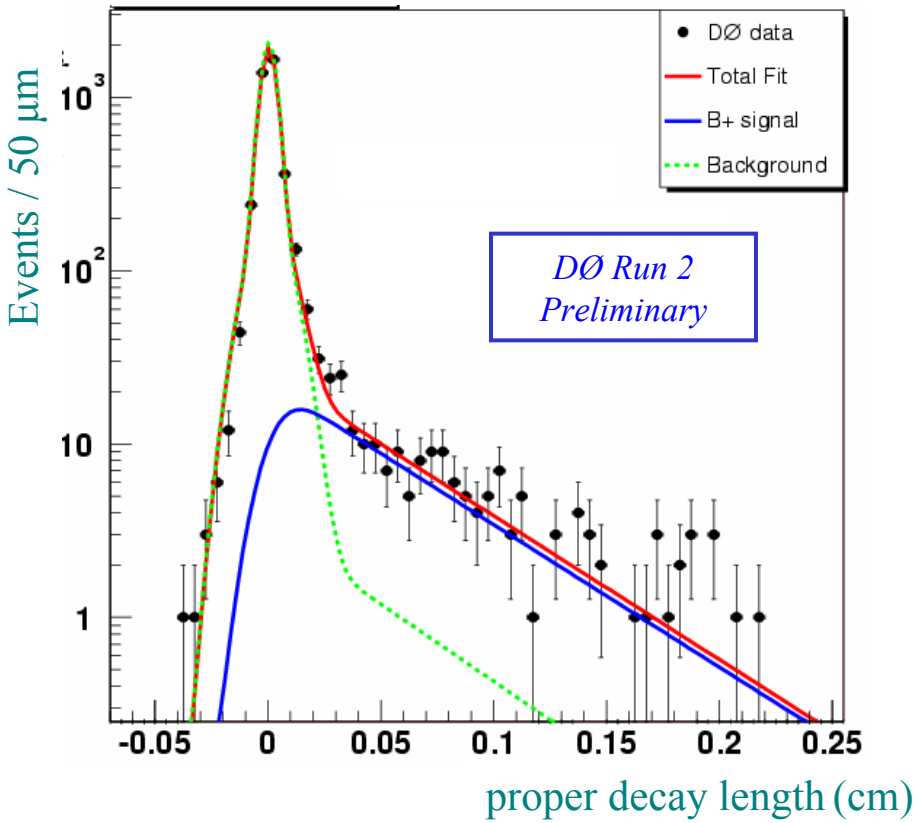
Charged *B* lifetime

Proper B decay length ($B^{\pm} \rightarrow J/\psi + K^{\pm}$)



- Full reconstruction: no hadronization or momentum uncertainties

$$c\tau_B = L_{xy} \frac{M^B}{p_T^B}$$

- Event selection w/o lifetime significance cut
- Using only right-hand sideband to model background
- *B* background contribution: 12% (MC)
- Prompt component described by double Gaussian
- *B* signal described by exponential (convoluted with resolution function)

$c\tau_B = 528 \pm 72$ (stat) μm

$\tau_B = 1.76 \pm 0.24$ (stat) ps

PDG $\tau_B = 1.674 \pm 0.018$ ps

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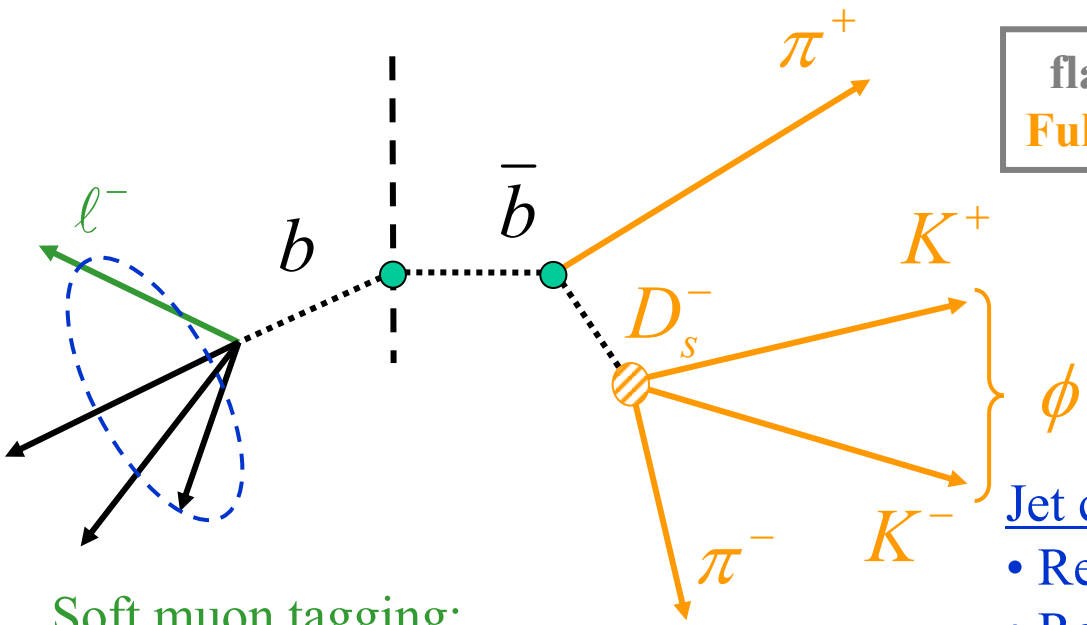
B-flavor tagging



flavor at "final state":
Full/Partial reconstruction

flavor at "$t = 0$":
- **Soft muon tagging**
- **Jet charge tagging**

Soft muon tagging:
- Remove muons from reconstructed B or within $\Delta\eta^2+\Delta\varphi^2 < 4$
- Must have $p_T > 1.9$ GeV/c
- Charge of highest-p_T muon in event gives B-tag

Jet charge tagging:
- Remove tracks from reconstructed B
- Remove tracks with impact parameter $d_{xy} > 2$ mm or $|\Delta z_{\mathrm{PV}}| > 2$ cm
- Use "p_T-weighted" sum of tracks' charges

$$Q_j = \frac{\sum q_i \, \vec{p}_i \cdot \hat{a}}{\sum \vec{p}_i \cdot \hat{a}}$$

- Events with $|Q|>0.2$ give B-tag

Different tagging methods → Different systematic errors

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…*B*-flavor tagging

- Using charged *B* mesons for study of tagging algorithms' performance (no mixing)
- "Other-side" *b* can decay to either of:
  - $B^{\pm}$ (~38.8%, no mixing)
  - B_d (~38.8%, mixing fraction ~17%)
  - B_s (~10.6%, mixing fraction ~50%)
  - baryons (~11.8%, no mixing)

$$\text{Efficiency } \varepsilon = \frac{N_{\text{correct}} + N_{\text{wrong}}}{N_{\text{correct}} + N_{\text{wrong}} + N_{\text{no tag}}}$$

$$\text{Dilution } D = \frac{N_{\text{correct}} - N_{\text{wrong}}}{N_{\text{correct}} + N_{\text{wrong}}}$$

Relevant for significance of mixing measurement

$$\text{Tagging power}: \varepsilon \times D^2$$

- Errors only statistical
- Errors in fractions of signal, bgd events in mass window (from fit) are ignored

DØ Run-II preliminary tagging results

	Jet Charge	Soft Muons
# of events	181	218
# of events with correct tag	66	13
# of events with wrong tag	48	5
Raw efficiency (%)	63.0±3.6	8.3±1.9
Raw dilution (%)	15.8±8.3	44.4±21.1
Purity	63.0	71.1
Estimated efficiency of signal events (%)	55.1±4.1	8.2±2.2
Estimated dilution of signal events (%)	21.0±10.6	63.9±30.1
Estimated $\varepsilon \times D^2$ of signal events (%)	2.4±1.7	3.3±1.8
Run-II B Physics Workshop 2000 predictions hep-ph 0201071	4.7%	3.1% (e+μ)

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Summary

- The *B*-Physics program at DØ has started!
  First Run-II results presented:
  - *b*-jet cross section
  - Exclusive *B* decays, first mass measurements
  - Lifetimes: Inclusive, reconstructed $B^{\pm}$
  - Preliminary studies on flavor tagging

- Short-term improvements:
  - Track, silicon triggers coming on-line soon
  - More calibration, data understanding underway
- Near future:
  - B_s, Λ_b lifetimes; $B_s \to D_s\, \ell\, \nu\, X$, more decay channels
  - More tagging studies; B_d mixing
  - Rare decays; precise cross-section, *BR* measurements
  - Estimations of B_s–mixing reach; studies on $\Delta\Gamma_s$
- Awaiting for large sets of data; lots of Physics ahead!
  This is the *best* place for HEP for the next 6 years!

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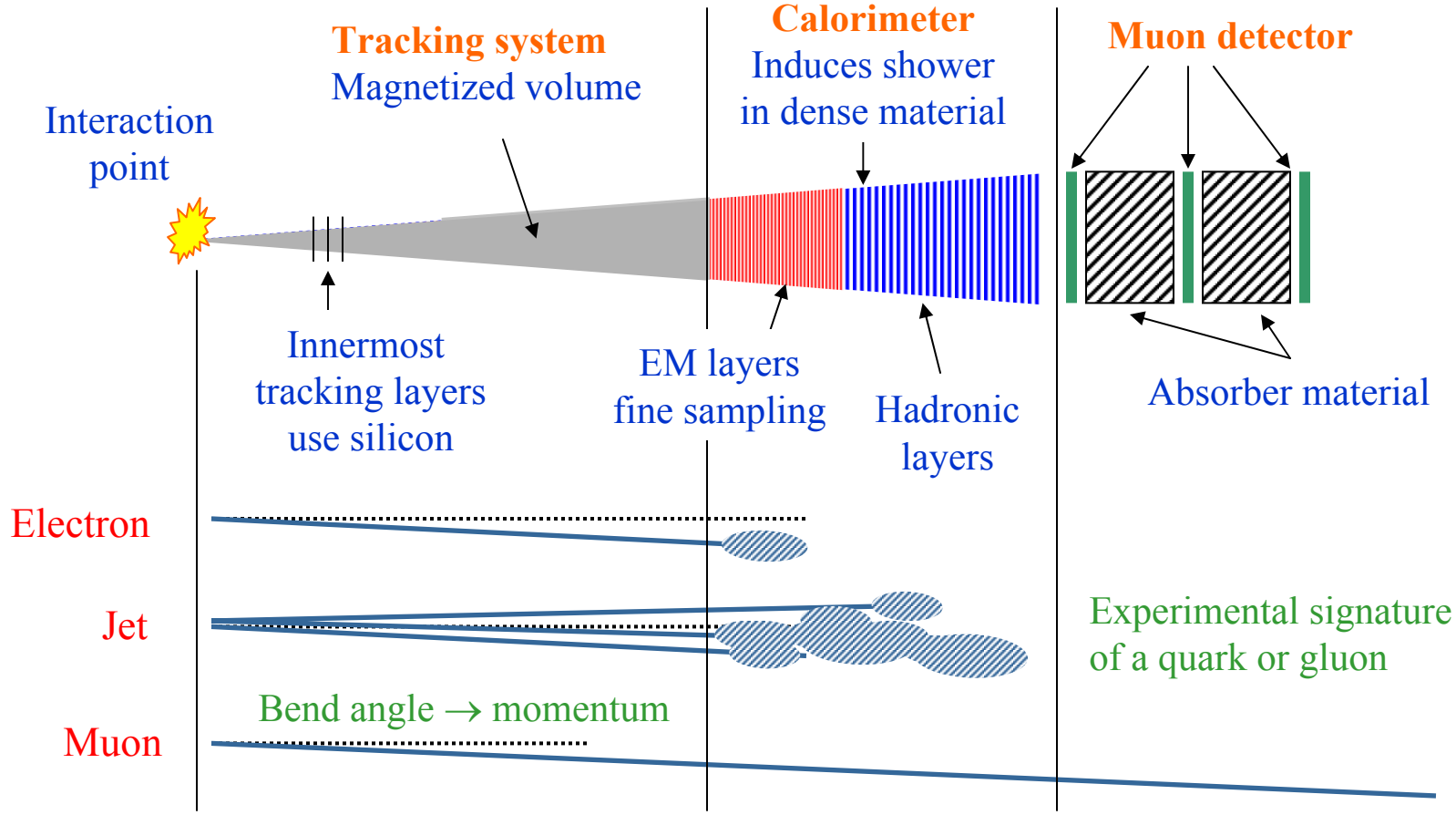
A typical HEP detector



Thanks to John Womersley

- *b*-quark's large lifetime allows it to travel a few mm's before it decays
- A set of displaced tracks is a *b*-quark signature ("displaced" or "secondary" vertex)

Status of DØ detector

Silicon detector

- Running smoothly: ~ 91% of channels are in readout
- A few noisy HDIs are causing infrequent HV trips
- Working on optimizing monitoring and L1 accept data speed transfer

Fiber tracker and preshowers

- More than 99% of channels are operating well
- Concentrating on commissioning the new tracking trigger

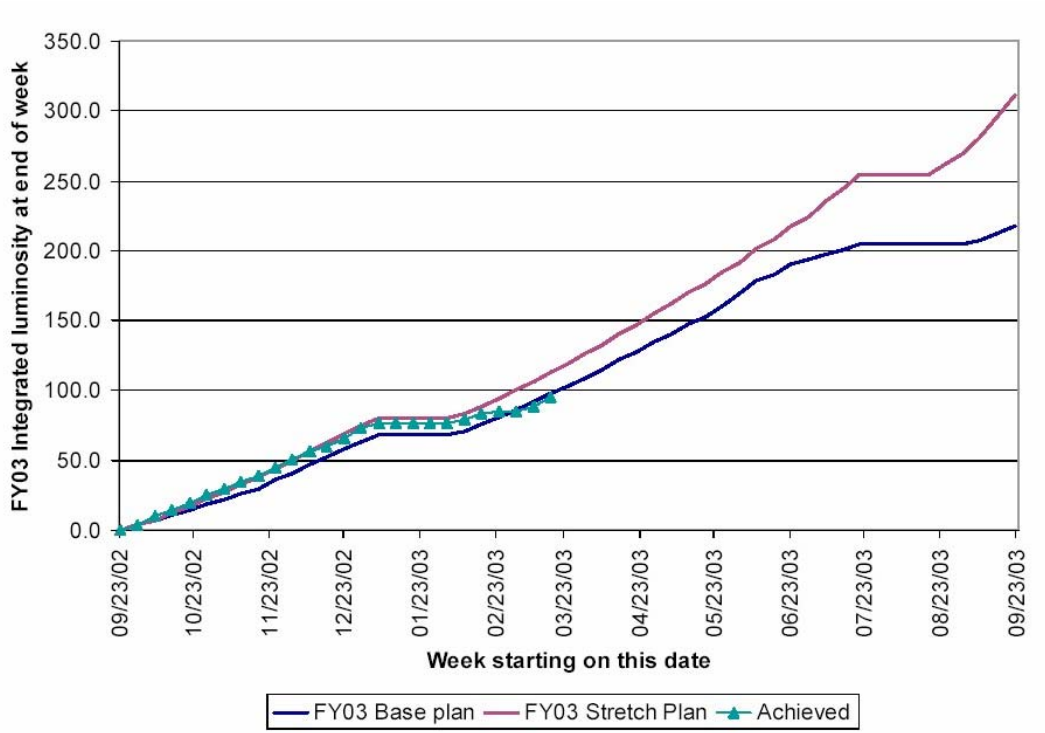
Calorimeter

- More than 99.9% of channels in operation
- Precision readout is working stably and reliably
- Concentrating on commissioning Level 1 calorimeter trigger in the (2.4, 3.3) $|\eta|$ region
- Triggering on jets and electrons in physics runs

Muon system

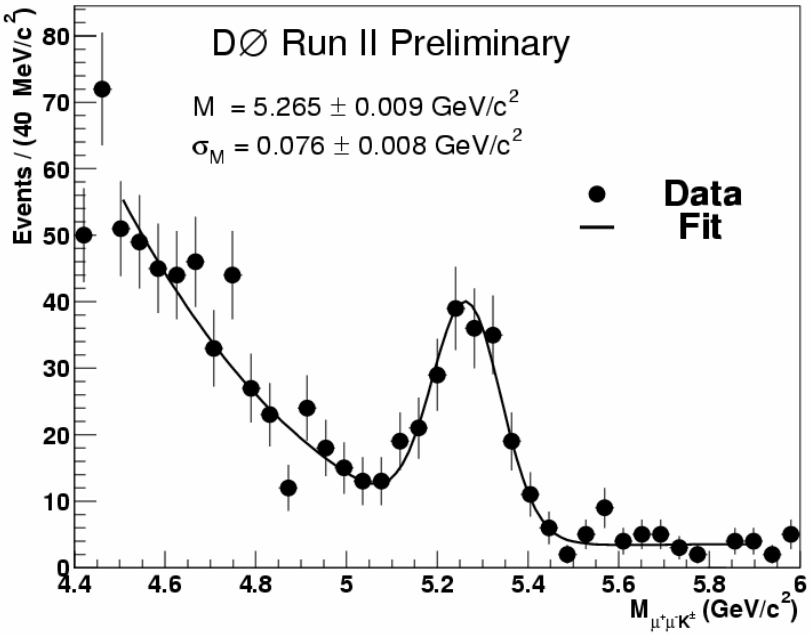
- Total number of dead channels is < 0.5% for tracking detectors and ~ 0.1% for trigger detectors
- Detectors are operating stably
- Triggering on muons (single, di-muon, muon+jets, etc.) during physics data taking

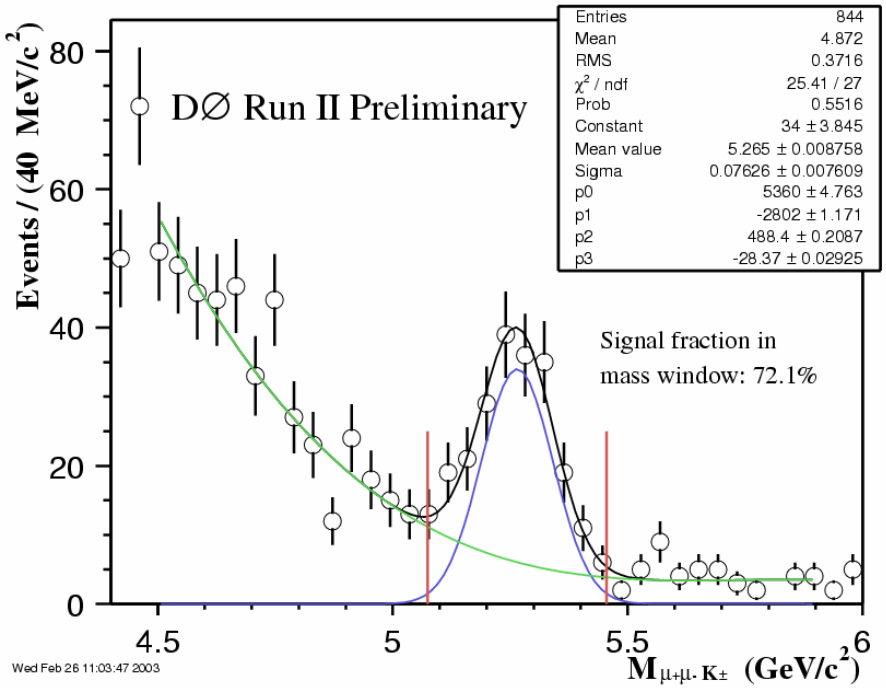
Tevatron: prospects for 2003



- Small, but steady improvements over last year
- No "silver bullets"
- Major issues:
  - Tevatron transfer & acceleration efficiencies
  - Emittance dilution
  - Beam lifetime at 150 GeV
  - Role of long range beam-beam effects

B-flavor tagging: $B^{\pm}$ mass peak





- ***J/ψ* :**

$\chi^2 < 10$, $p_T > 2$ GeV/c (both tracks), # of SMT hits ≥ 1 (both tracks), $2.8 < m_{\mu\mu} < 3.3$ GeV/c^2

- ***K*$^{\pm}$:**

$\chi^2_{vtx} < 10$, # of hits ≥ 3, $p_T > 2$ GeV/c

- ***B*$^{\pm}$:**

$\chi^2 < 20$, collinearity>0.9, B decay length >0.3 mm

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Δm_s measurements

Mode	Trigger	Initial Tag	Final Tag	# of reco. events	Δm_s reach
$B_S^0 \to D_S^- \ell^+ \nu X$ $D_S^- \to \phi \pi^- \to K^+K^-\pi^-$	$\ell\ell$	Soft lepton (OS)	lepton from B_s	~ 40k	< 20 ps^{-1}
Large statistics, missed ν carries momentum: affects t^*_B resolution					
$B_S^0 \to D_S^- \pi^+, D_S^- \pi^+\pi^-\pi^+$ $D_S^- \to \phi \pi^- \to K^+K^-\pi^-$	ℓ	Soft lepton (OS)	Sign of D_s	500-1200	< 22 ps^{-1}
Small statistics, good vertex resolution					
$B_S^0 \to J/\psi K^*, K^* \to K^+\pi^-$ $J/\psi \to e^+e^-, \mu^+\mu^-$	$\ell\ell$	All	Sign of K^+	400-1000	< 22 ps^{-1}
Small statistics, good vertex resolution, compare fitted mass of $K^+\pi^-$, $K^-\pi^+$					

Notes:

- **Additional modes $D_s \to K^{*0} K^-$, $J/\psi \to e^+e^-$ not explored yet**
- **Branching rations for B_s decays: poorly measured**
- **Studies with new tracking & vertexing underway**

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B lifetime: Systematic errors

Source	Error (μm)
Boost correction	15.9
Background modeling	3.0
Flight length dependence	1.1
Background normalization	0.7
Alignment bias	4.1
Fitting bias	13.0
Total	**22.0**

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Tevatron reference numbers

Parameter	Run-I	Run-IIa	Run-IIb
# of $\bar{p}$ ($\times 10^{12}$)	0.3	1.1	11.0
Bunches	6×6	36×36	140×103
Spacing (ns)	3500	396	132
E_{CM} (TeV)	1.8	1.96	1.96
Luminosity ($\times 10^{32}$ cm^{-2} s^{-1})	0.016	1-2	5.2
Luminosity/week (pb^{-1})	3.2	17.3	105.0
Total Luminosity (fb^{-1})	0.125	2.0	10.0-15.0
Interactions/crossing	2.5	2.3	4.8

Two ways to increase statistics:

- Integrated luminosity: ×10-20 (Run-IIa), ×150 (Run-IIb)
- Cross sections when E_{CM}=1.8 TeV → 1.96 TeV:
  - *W/Z*: ×1.1
  - *t*-quark: ×1.35
  - jets with $p_T > 400$ GeV/c: ×2

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Physics rates in Run-IIa

Process	Rate
Beam crossing	2.3 MHz (396 ns)
Inelastic $p\bar{p}$	10 MHz
$p\bar{p} \to b\bar{b}$ $(y<1)$	10 kHz
$p\bar{p} \to W + X$	4.4 Hz
$p\bar{p} \to t\bar{t}$	5 / hour
$p\bar{p} \to W/Z + H(*)$	7 / day

(*) If $m_H = 100$ GeV/c^2

Compare with ~50 events in Run-I

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The *B* Physics program

Measurement	Current	DØ (2 fb^{-1})	BTeV (2 fb^{-1})	Notes
$\#$ of $b\bar{b}$ / yr	5×10^{7}	6×10^{10}	1.5×10^{11}	
$\sin 2\beta$	Belle 0.72±0.074±0.035 Babar 0.74±0.067±0.034	±0.03	±0.02	$B_d^0 \to J/\psi\, K_S$
$N(B_d^0 \to \pi^+\pi^-)$	~200	~600	2.4×10^{4}	$\sin 2a$
$N(B_d^0 \to K^+K^-)$	0	~1100	3.3×10^{4}	
x_S	> 22	~30	> 75	$B_S \to D_S / X$
$N(B_c)$	20	600		$B_c \to J/\psi / \nu$
$\tau(\Lambda_b)$ (ps)	1.23±0.08	± 0.11	± 0.017	$\Lambda_b \to J/\psi\, \Lambda$
$N(B \to K^*\mu^+\mu^-)$	0	700	2200	FB asymmetry

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