D0 -> mu mu at hadron machines

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Theory

- The study of FCNC has been mainly dedicated to transitions as

$$s \to d\, \ell^+ \ell^- ,\ s \to d\, \nu\, \nu,\ b \to s\, \gamma,\ b \to s\, \ell^+ \ell^-$$

- The analogous FCNC processes in the charm sector have been investigated less
- In the SM, the FCNC in charm decays are highly suppressed by the GIM mechanism
- Charm decay provides a unique laboratory to search for new physics in the *up*-quark sector

Theory

- In the SM

$$\text{Br}\,(D^0 \to \mu^+\mu^-) \sim 10^{-19} - 10^{-13}$$

beyond the reach of the present experiments

- Several extensions of the SM (R-parity violating SUSY, multiple Higgs doublets, extra fermions, extra dimensions) predict an enhancement of the Br by several orders of magnitudes

- MSSM with R-parity violation

$$\text{Br}\,(D^0 \to \mu^+\mu^-) \sim 3.5 \times 10^{-7}$$

Burdman et al, Phys. Rev. D66 (2002) 014009

Theory

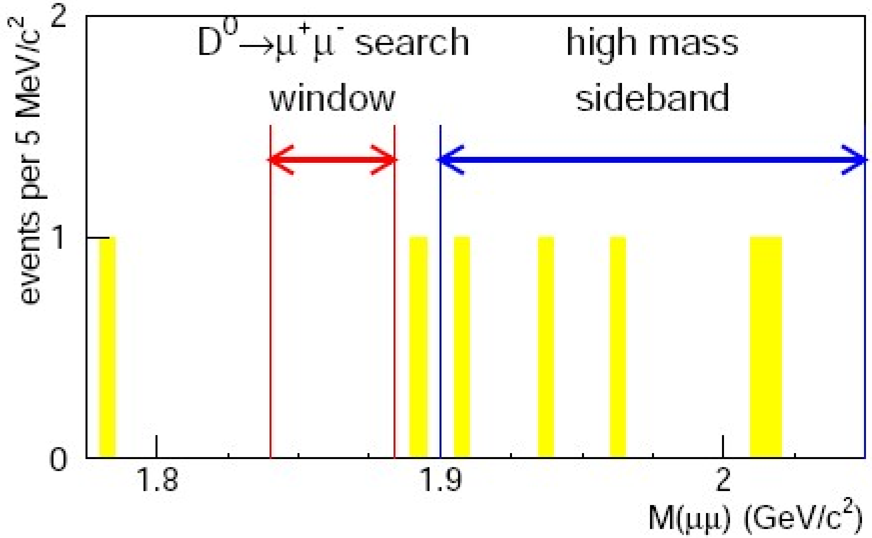
- Small predicted effects could leave open window to New Physics effects
- Observation of the decay

$$D^0 \to \mu^+ \mu^-$$

  at a rate significantly exceeding the SM expectation would indicate the present of non-SM particles or couplings
- Thus a large, unexplored region exists in which to search for New Physics

Experimental situation

- CDF Collaboration (65 pb^-1 data sample)

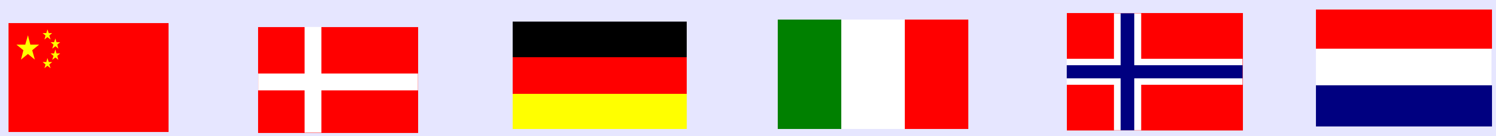


$$Br\,(D^0 \rightarrow \mu^+\mu^-) = \frac{N_{cl}}{N_{\pi\pi}} \frac{\alpha_{\mu\mu}}{\alpha_{\pi\pi}} \frac{\varepsilon_{\mu\mu}}{\varepsilon_{\pi\pi}} Br\,(D \rightarrow \pi^-\pi^+)$$

$$Br\,(D^0 \rightarrow \mu^+\mu^-) < 2.5 \times 10^{-6} \quad (90\% \text{ C.L.})$$

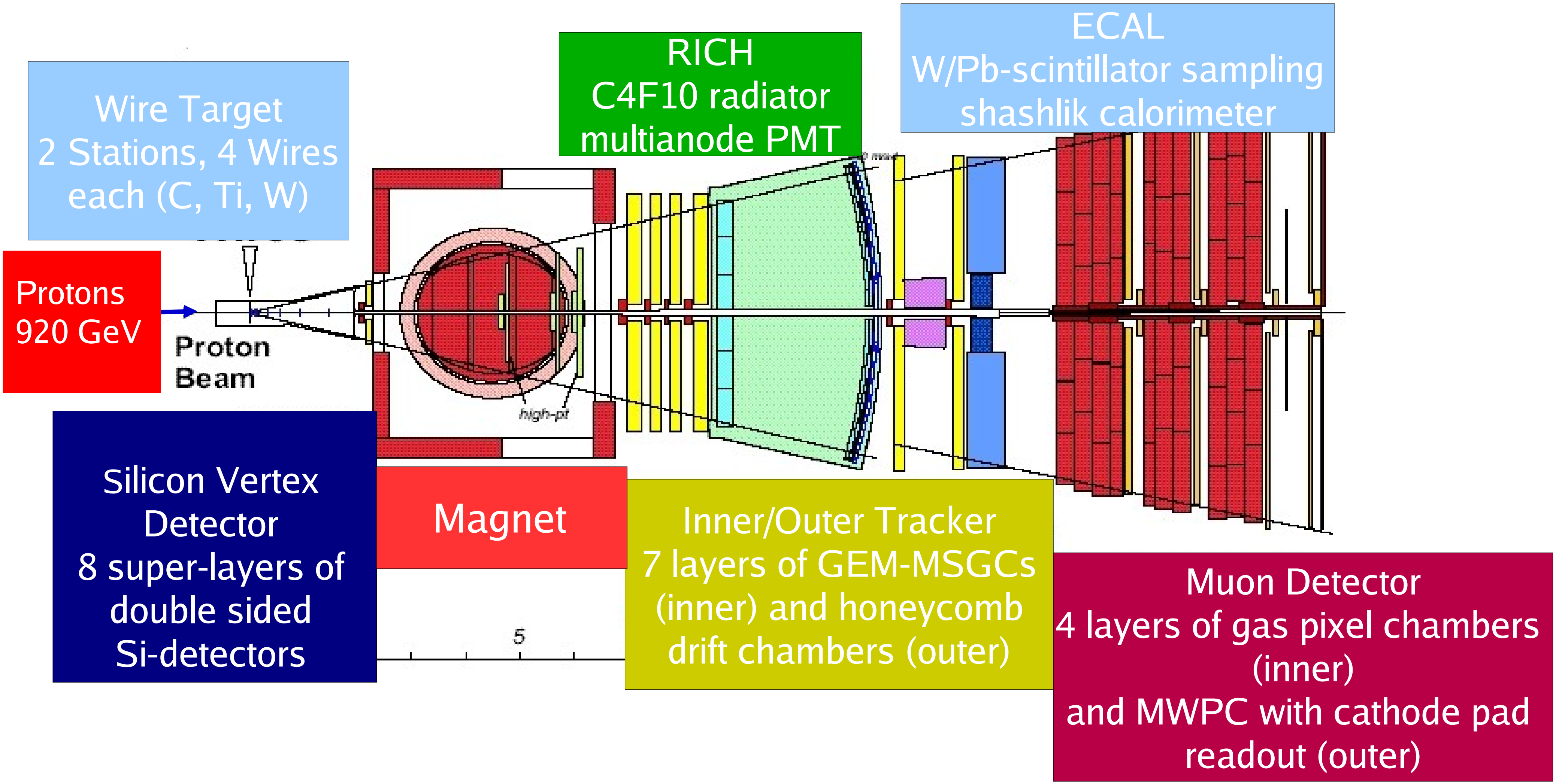
- Further searches are very desirable

HERA-B Collaboration



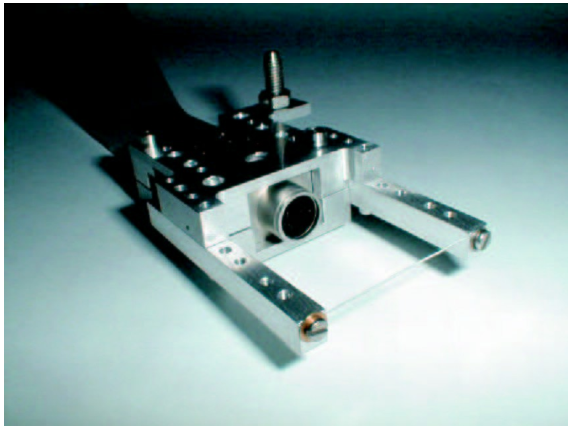
150 physicists from 13 nations

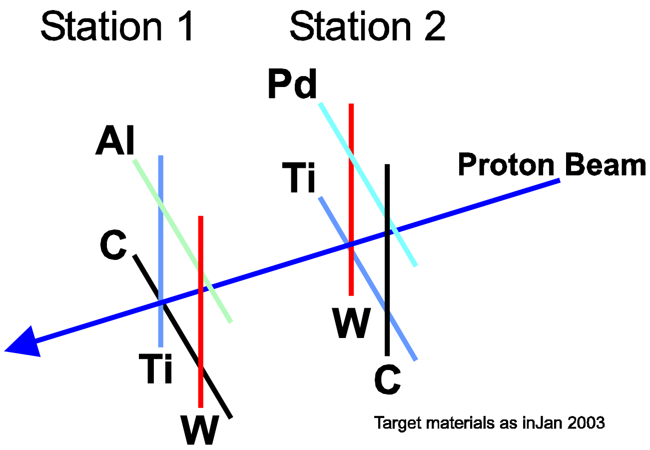
The HERA-B detector

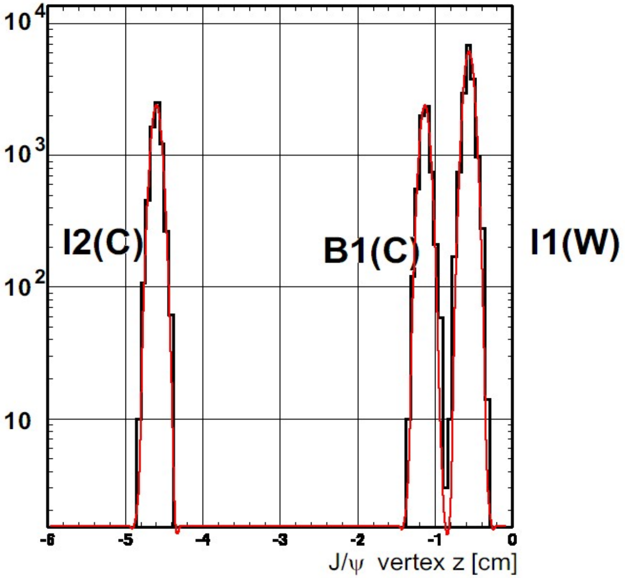


The HERA-B fixed-target spectrometer operated at the 920 GeV proton beam of the HERA storage ring at DESY and featured a vertex detector and extensive tracking and particle identification systems (RICH, MUON, ECAL)

Target system

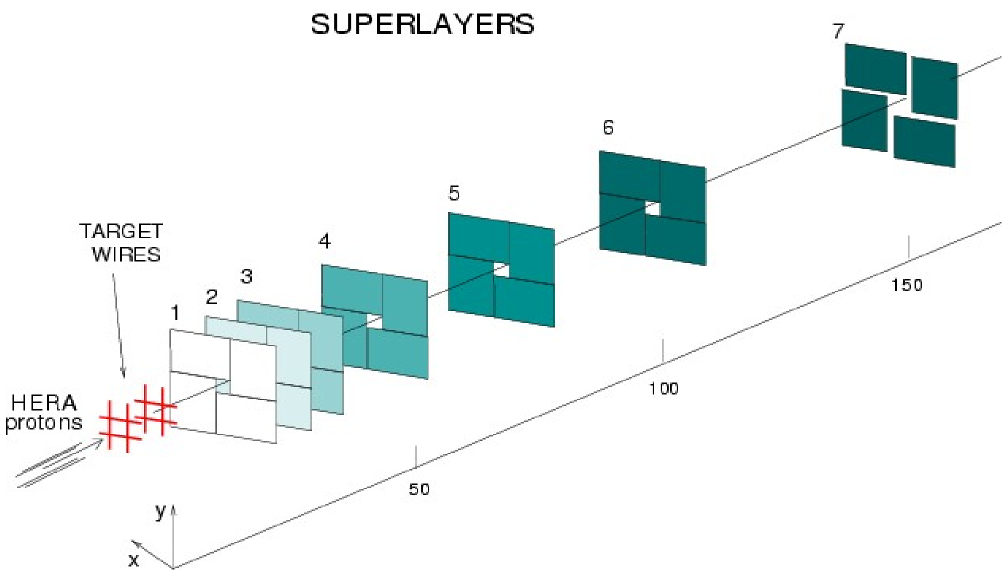


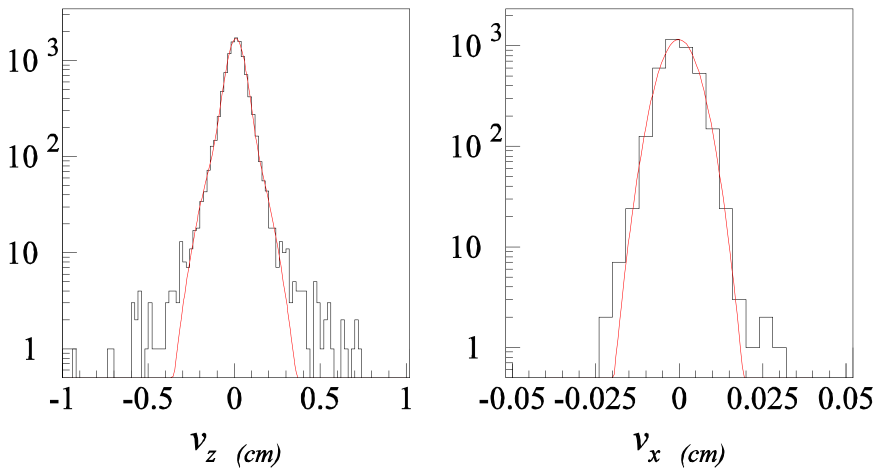




- The target system consists of two station of four wires each
- The wires are made from various materials (C, Ti, W)
- The stations are separated by 40 mm along the beam direction
- The wires can be individually moved into halo of the proton beam
- Events from different wires can be easily separated

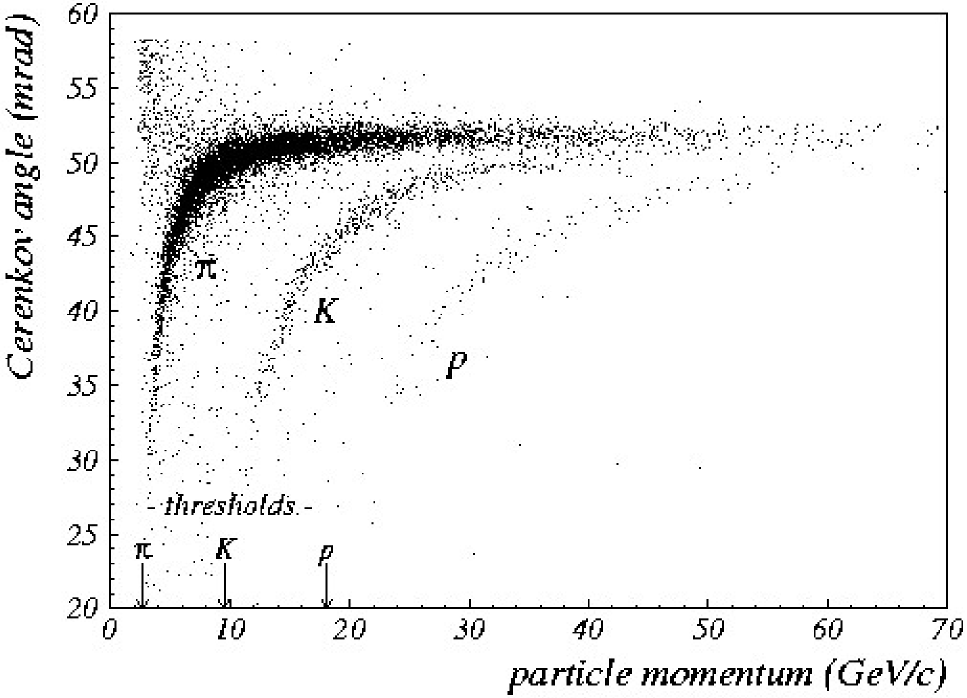
Vertex Detector System

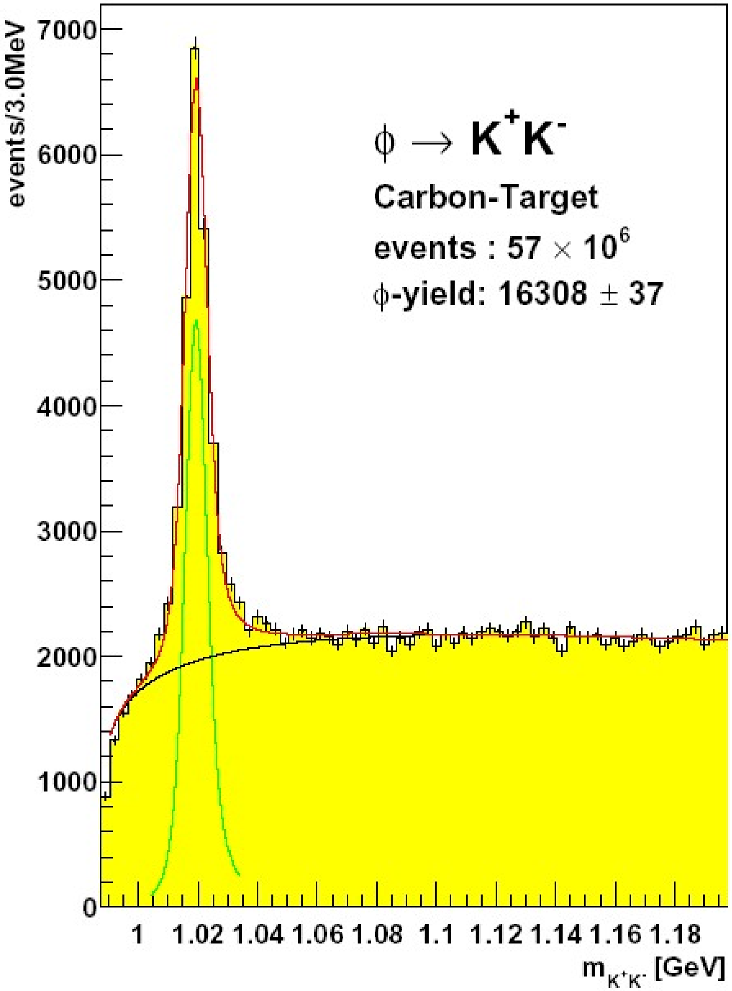




- forward microvertex detector
- consists of 7 stations of double-sided silicon strip detectors
- precise measurement of primary and secondary vertices
- primary vertex resolution $\sigma_z \sim 450\ \mu m$, $\sigma_{x,y} \sim 50\ \mu m$

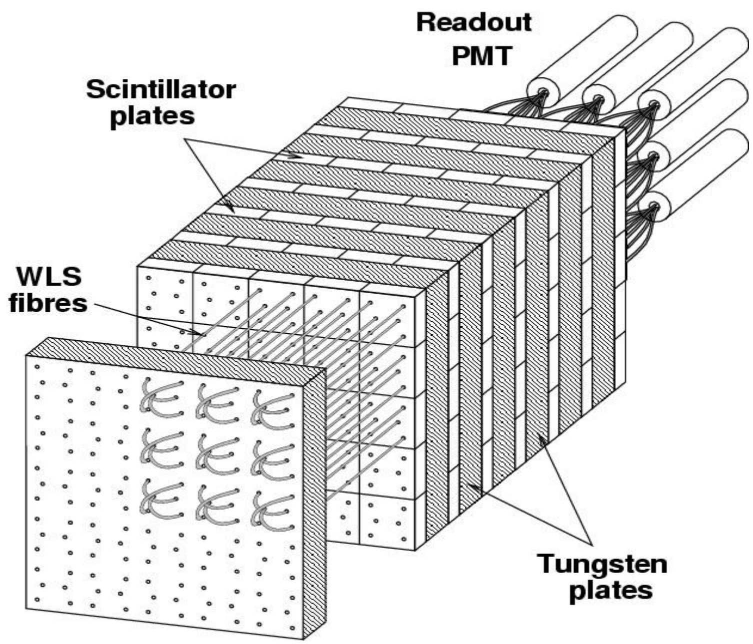
Particle ID (RICH)



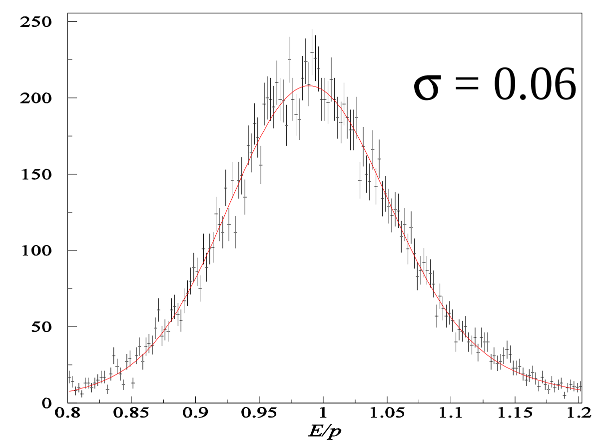


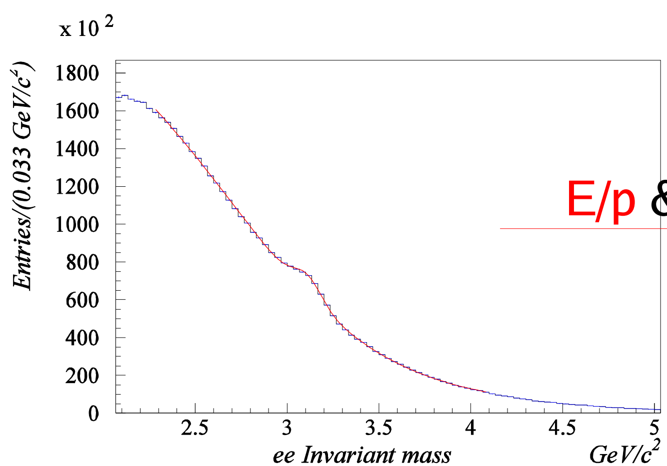
- π/K separation 10 < p < 60 GeV/c
- K/*p* separation 20 < p < 90 GeV/c

Particle ID (ECAL)

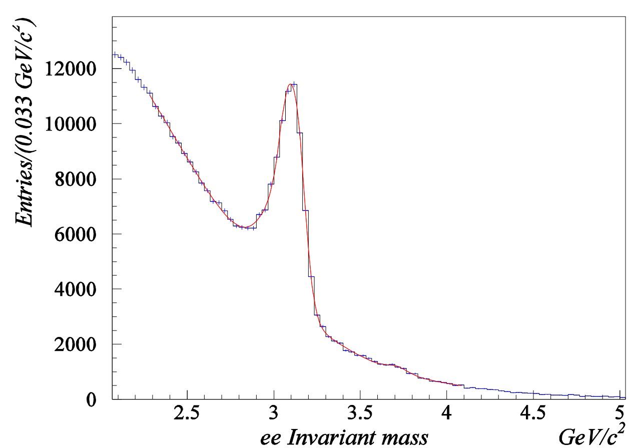


$$\frac{E}{p} = \frac{\text{Cluster energy on Ecal}}{\text{Momentum from tracker}}$$



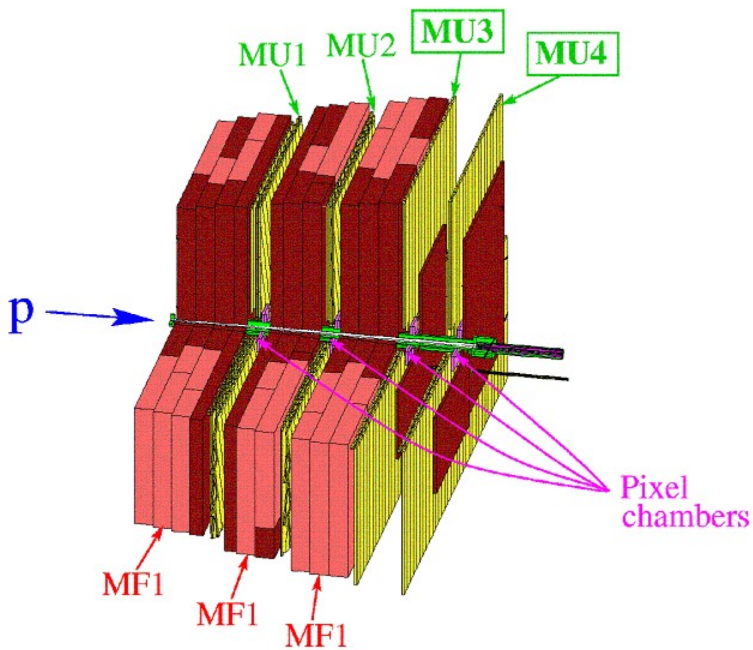


E/p & opt cut



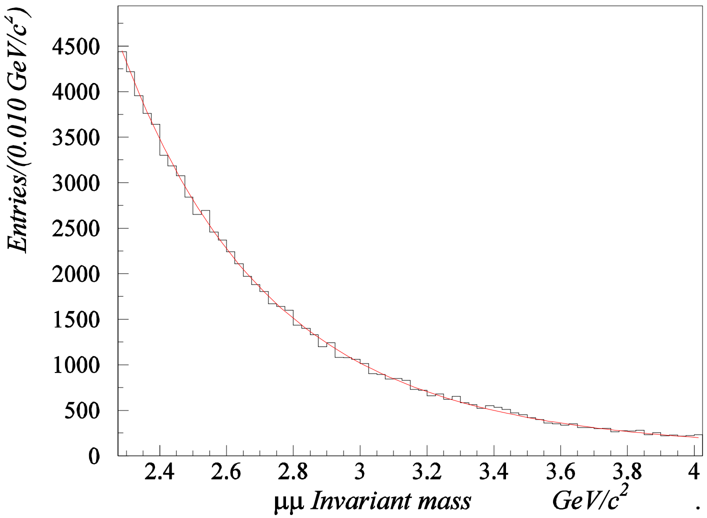
Particle ID (Muon)

Drift tubes + iron absorber



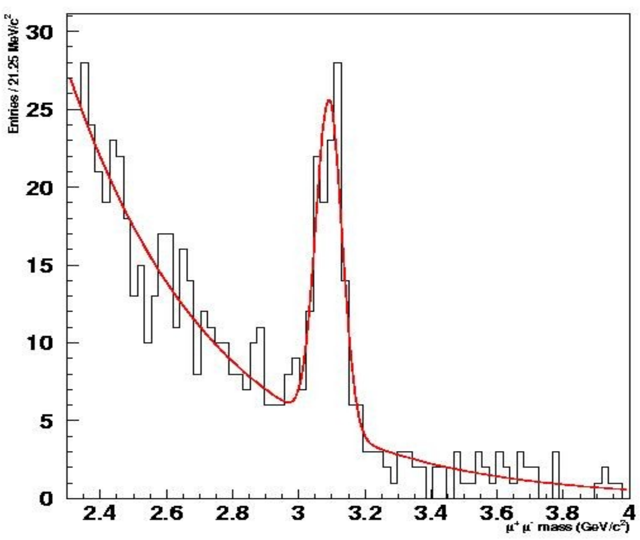
MB events

Without likelihood request



With likelihood request

=> J/ψ peak is visible



The first two superlayers consist of three layers of tube chambers with different stereo angles

The last two superlayers consist of one layer of pad chambers

Dilepton Trigger and DAQ system

HERA-B detector:
~0.5 interaction per bunch
(96 nsec cycle)

5 M Hz

Pre-Triggers:
ECAL-clusters or Muon hit coincidences

3 M Hz

First Level Trigger
(hardware based)
One track in OTR linked to pre-trigger information

20 k Hz

Second Level Trigger
(farm with 240 PC's)
Improved track finding, 2nd track,
VDS tracking and vertexing

100 Hz

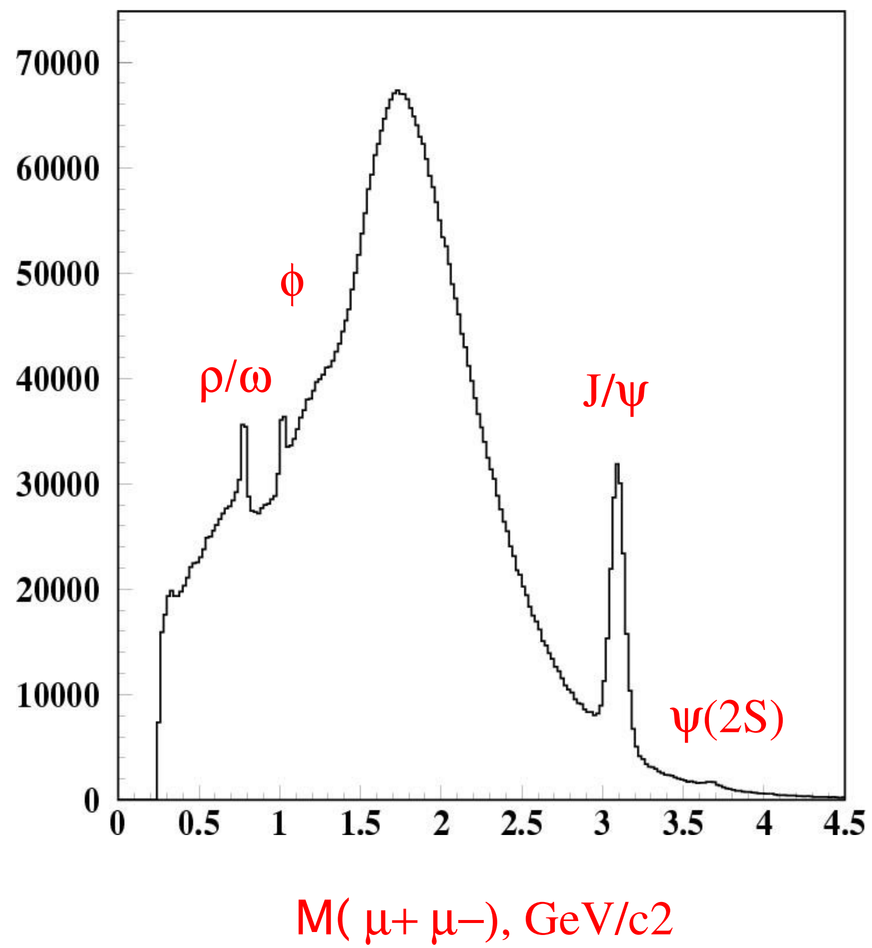
Fourth Level Trigger
(farm with 100 dual processor PC's)
Full online event reconstruction and classification

2002/3 run: > 1,000 J/psi per hour

Relevant data sample

- Data taking finished in March 2003
- 164 M di-lepton trigger events (ee/mu mu)
    - 300,000 J/ψ
    - 15,000 χ_c
    - 5,000 ψ (2S)
- 210 M minimum bias events -> 1,000 ev/s , > 1 TB/day

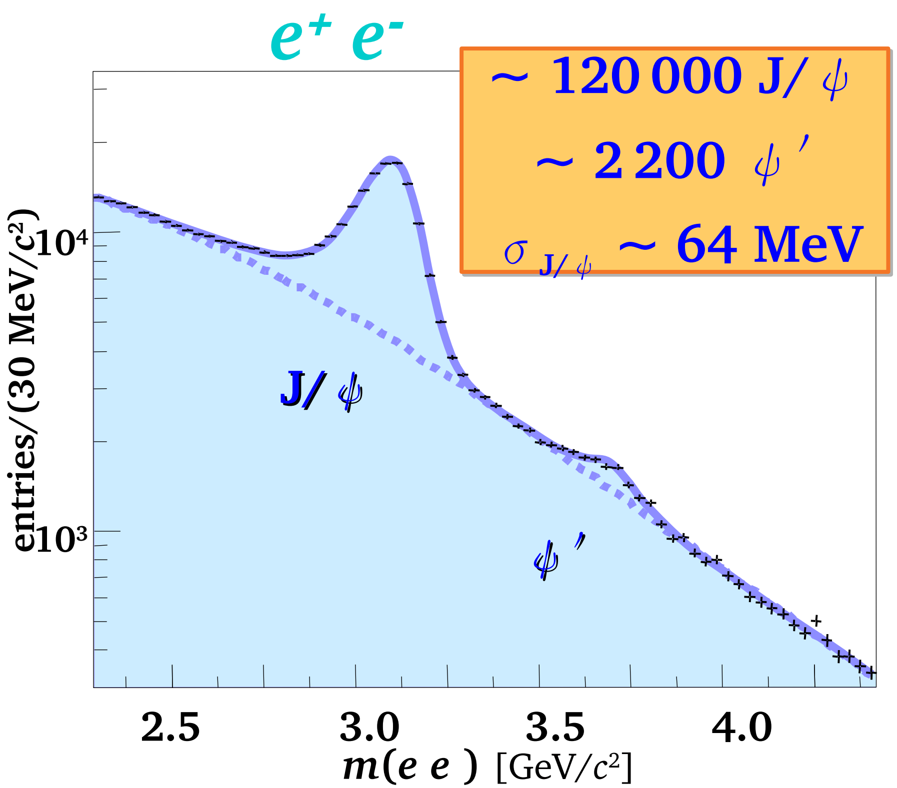
Only 4 months of physics data taking!

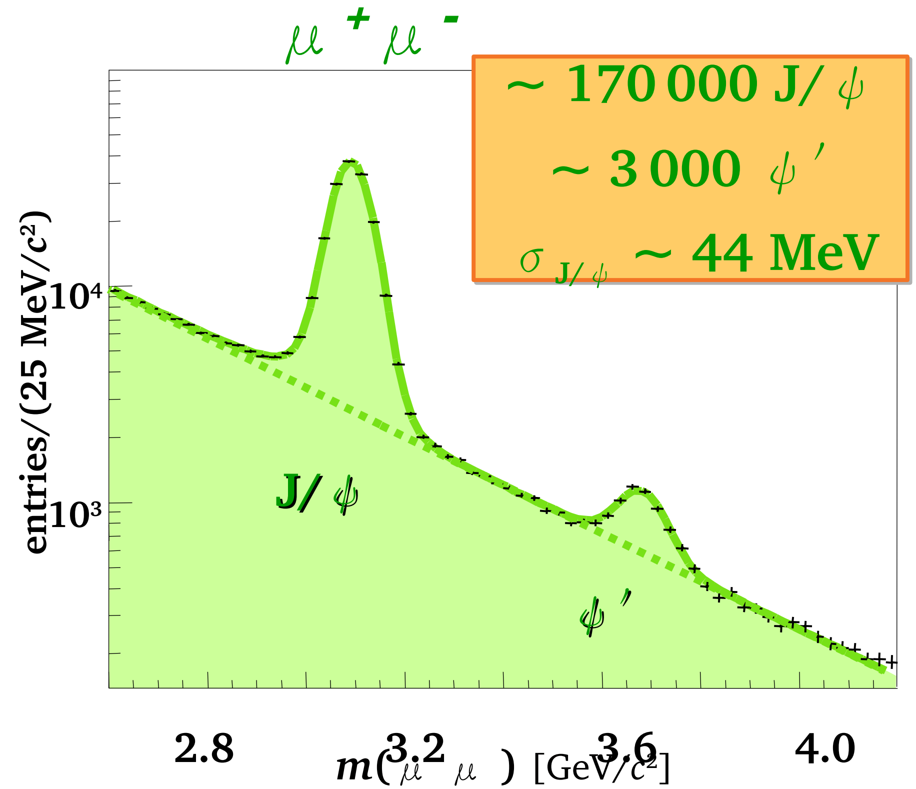


Physics with di-lepton trigger

- FCNC D0 -> mu mu
- Beauty production
  - bb production cross section
  - Υ production

- Charmonium studies:
  - J/ψ production
  - Ψ(2s) production
  - χc / J/ψ prod. ratio



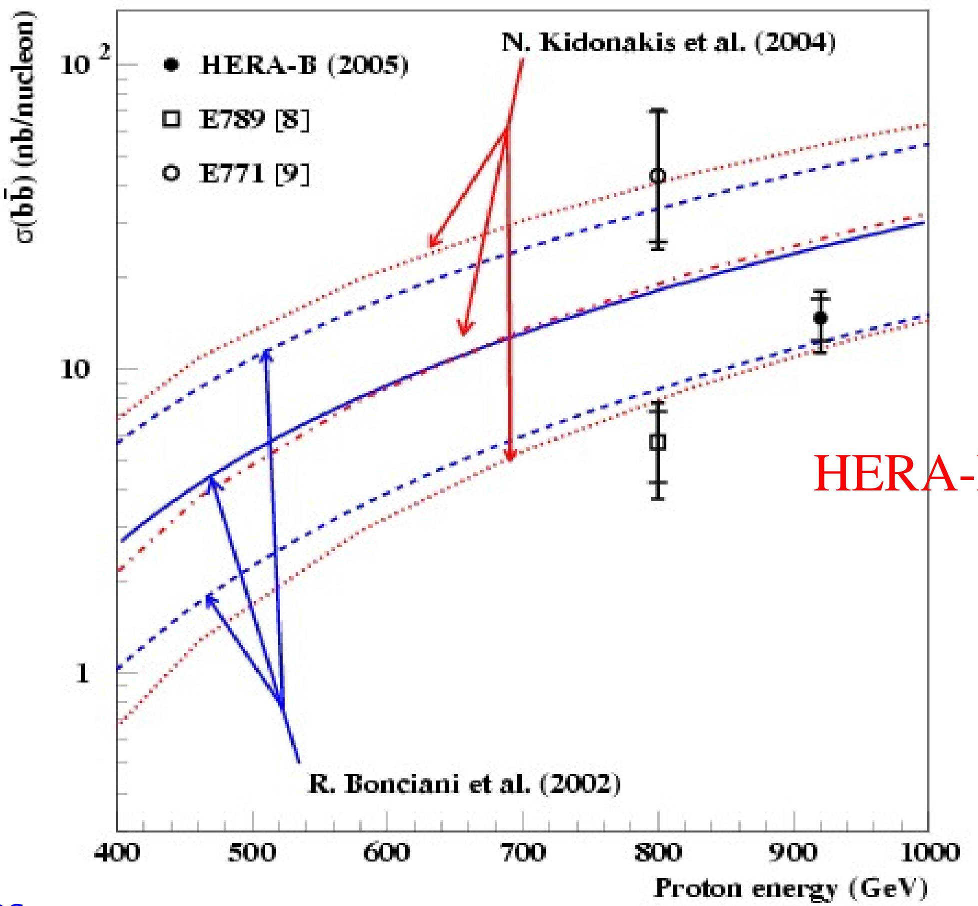


Open and Hidden

Beauty production at HERA-B

Open beauty production

- Previous measurements (E789, E771) do not agree with each other
- The present value is within 1.5 σ of the E789 experiment (after rescaling to the same √s)
- 1.8 σ below the rescaled E771 measurement
- theoretical uncertainty:
  - renormalization and factorization scales
  - *b*-quark mass

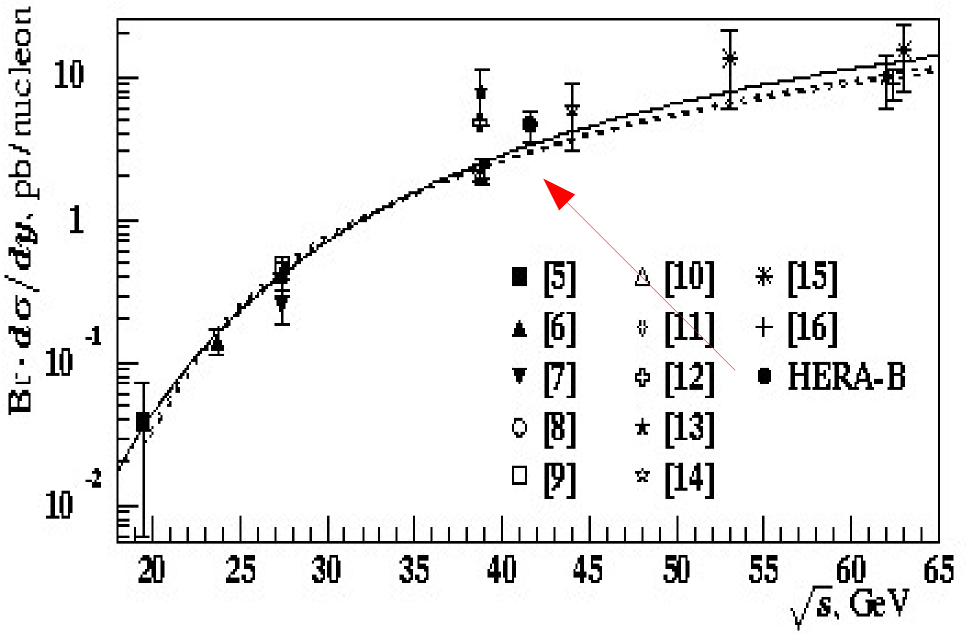


HERA-B

Phys. Rev. D73: 052005, 2006

Upsilon production

- Good agreement with CEM prediction
- The present value is half way between of E605 and E772 results



$$Br\,(\Upsilon \rightarrow l+\ l-) \bullet d\sigma\,(\Upsilon)\,dy\Big|_{y=0} = 4.5 \pm 1.1\ pb/N$$

Open and Hidden

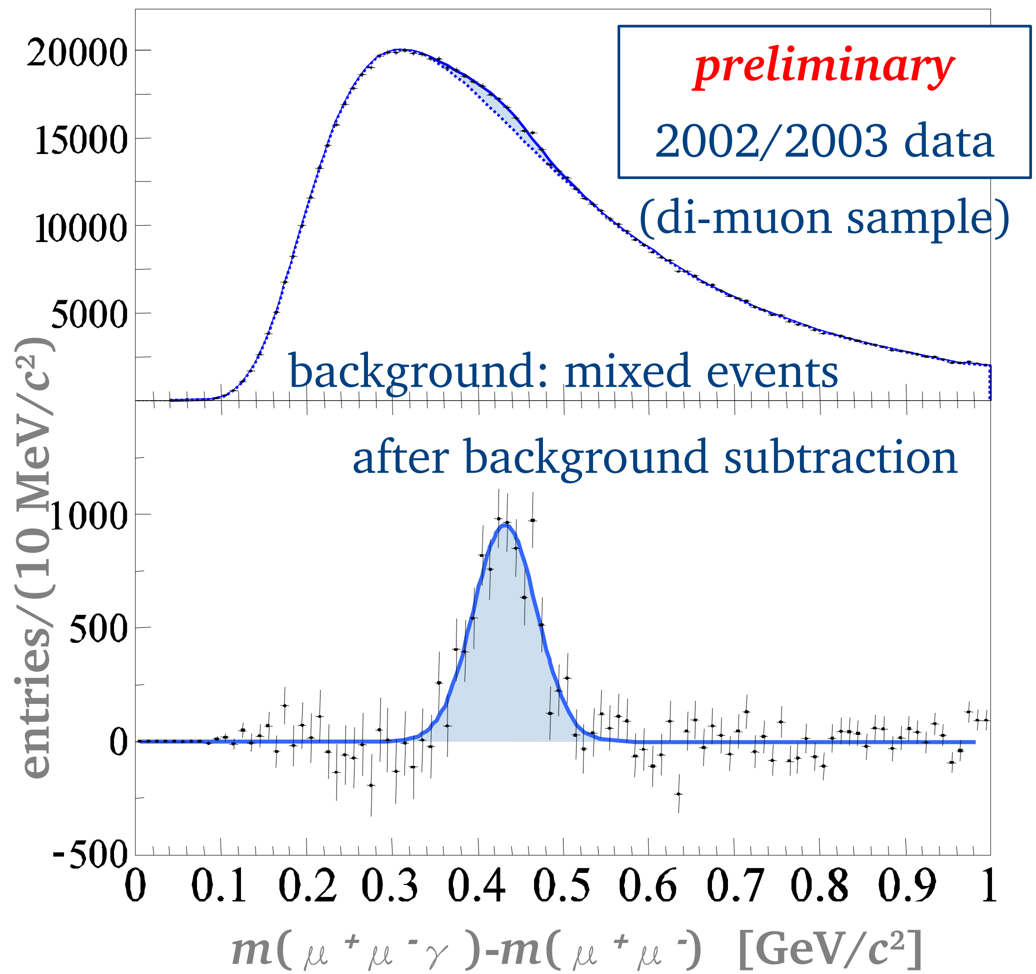
Charm production at HERA-B

χ_c Production

Selection:

$\chi \to J/\psi\, \gamma$, $J/\psi \to \ell\ell$

- Fraction of J/ψ's from χ
- kinematical distributions



from the 2000 data, with
370 ± 74 χ_c**'s** ($\mu^+\mu^-$ + e^+e^-):
$R(\chi_c)$ **= 0.32 ± 0.06 ± 0.04**
[Phys. Lett. B 561, 61 (2003)]

new data: 40 x bigger χ_c **statistics**
(the largest analyzed in a hadronic experiment)

Method

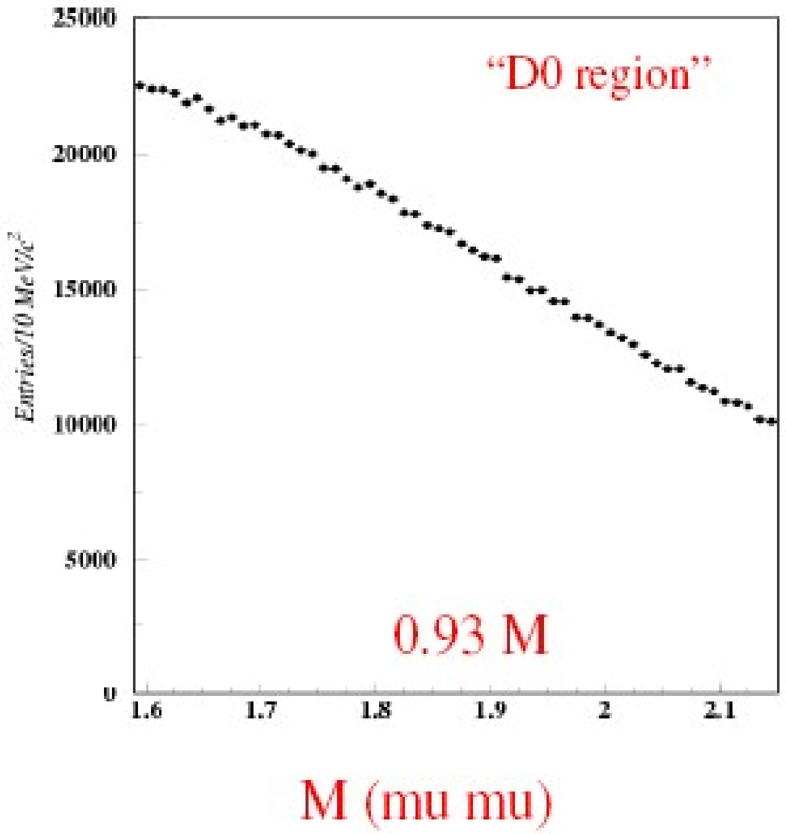
Br ratio computation relies on normalizing the number of events in the D0 signal region to the number of reconstructed $J/\psi \rightarrow \mu^+ \mu^-$ events

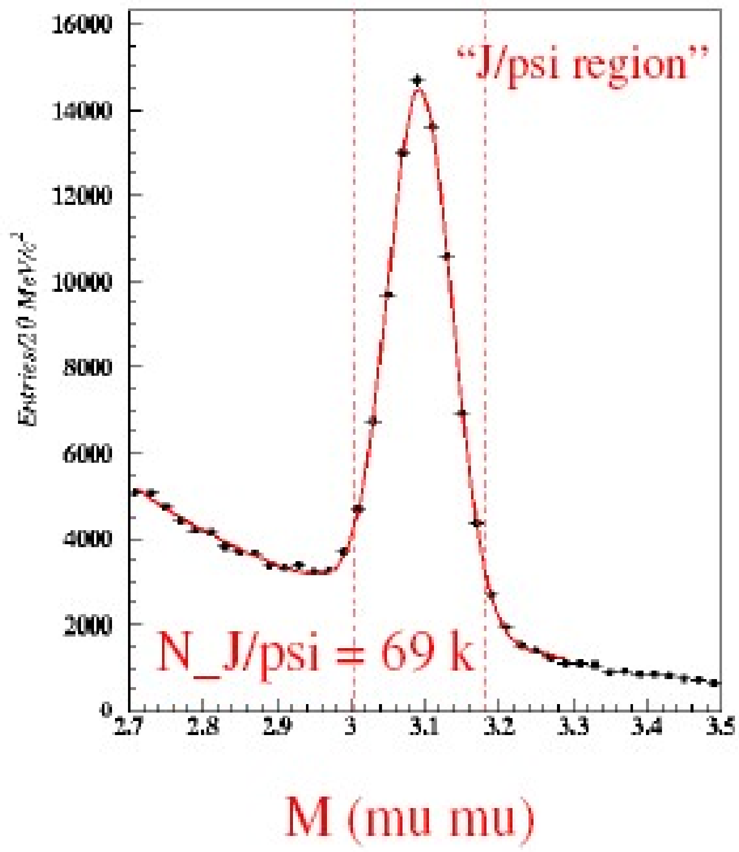
$$Br(D^0 \rightarrow \mu^+ \mu^-) = \frac{N_{cl}}{N_{J/\psi}} \frac{\alpha_{J/\psi}}{\alpha_D \varepsilon_D} \frac{\sigma_{J/\psi}}{\sigma_D} Br(J/\psi \rightarrow \mu^- \mu^+)$$

- N – number of observed D or J/ψ events
- α - efficiency for observing D (J/ψ) $\rightarrow \mu\,\mu$ after applying all cuts (including trigger cuts) except for those applied only for D signal
- ε – reduction factor for D $\rightarrow \mu\,\mu$ due to cuts applied to extract the D0 signal
- σ - production cross-section per target nucleus

Data Analysis

One reconstructed primary vertex per active target wire





LHK_muon > 0.01, chi2/dof < 20, Prob(chi2_pr)>0.01

Common cuts

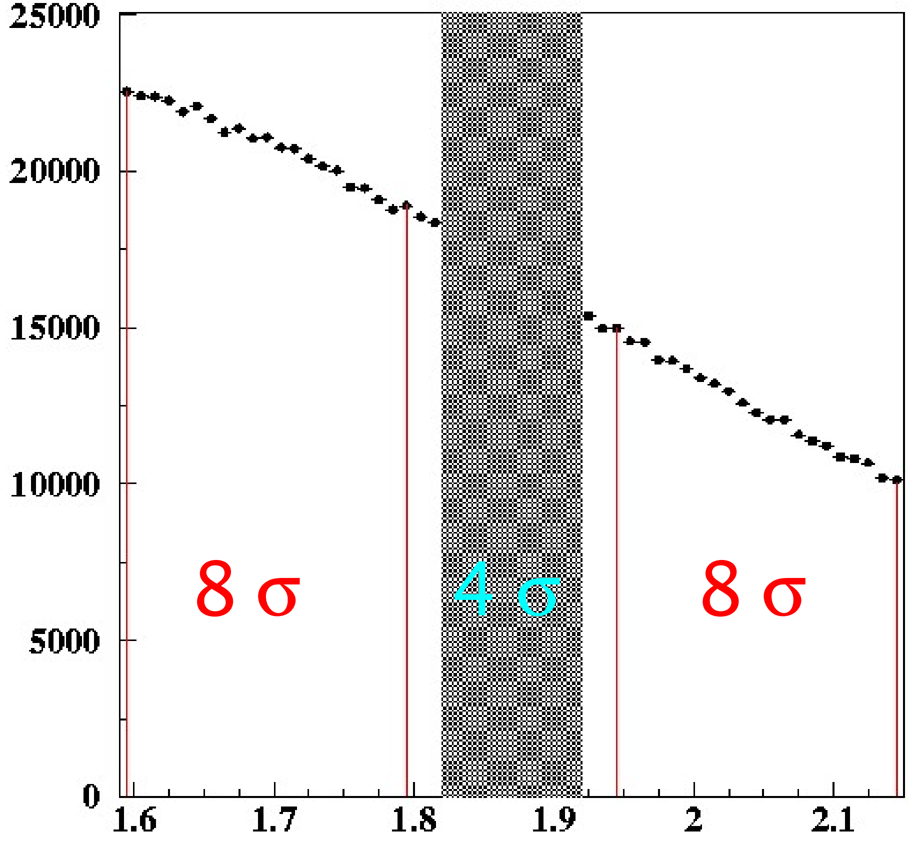
Common cuts applied both for "D0 region" and "J/ψ region"

- chi2/dof
- LHK_muon
- track-multiplicity cut
- transverse momentum

- to suppress ghost and pi/K decays in flight
- to reduce fake di-muon events
- to suppress multi-events pile-up
- Majority of pions and kaons produced in pA interactions have small pT

Common cuts

Cuts optimized without knowledge of their impact on the result

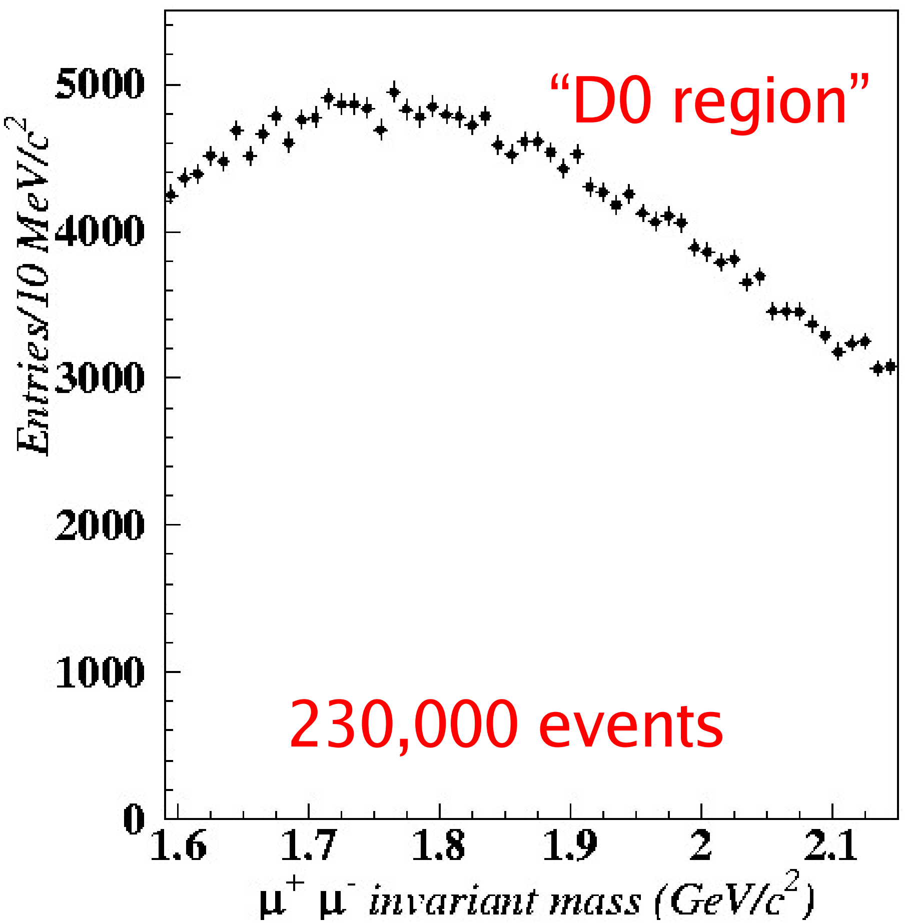


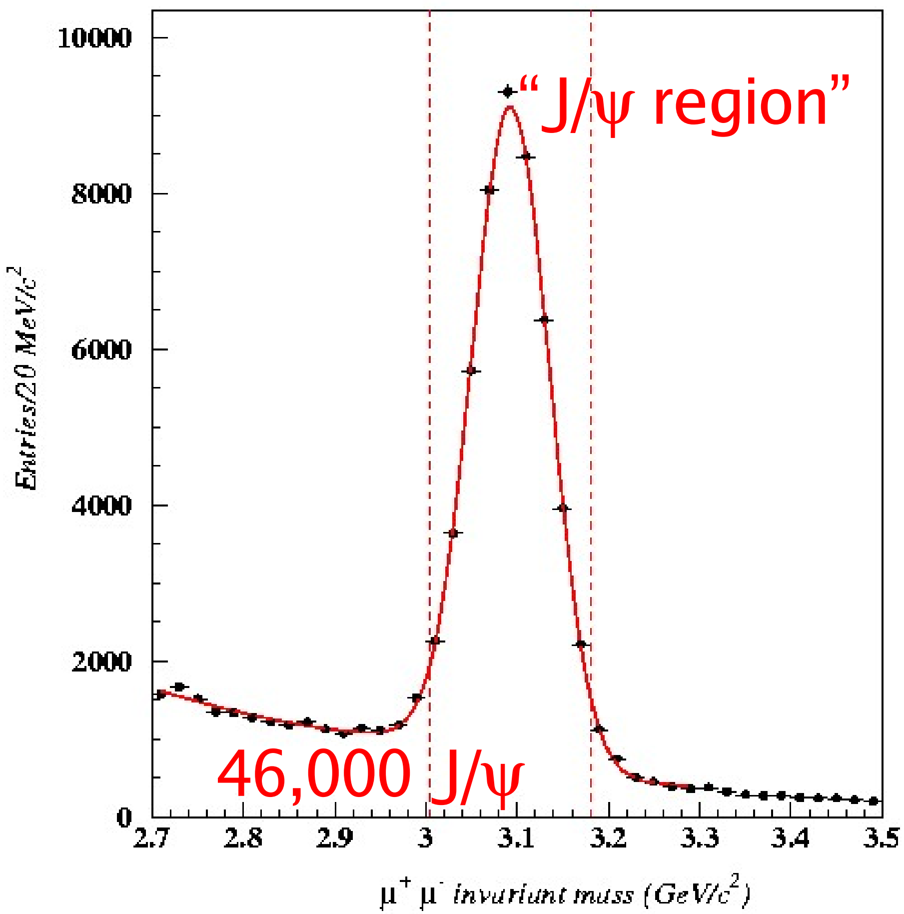
M (mu mu), GeV/c2

$N_{J/\psi} / \mathrm{sqrt}(B_D)$

- $N_{J/\psi}$ - number of J/ψ candidates
- B_D – expected background
- D0 signal region: 1.815 – 1.915 GeV/c2
- Sidebands:
  - 1.59 – 1.79 GeV/c2
  - 1.94 – 2.14 GeV/c2

Common cuts





After all common cuts have been applied

Lifetime cuts

- Impact parameter of the di-muon to the primary vertex

The distance between the primary vertex and the point of intersection of the di-muon pseudo-particle flight direction with the *xy* plane at the *z* position of the primary vertex

- Separation between primary and secondary vertices

(Z_sec – Z_pr) / sqrt ($\sigma^2_{pr} + \sigma^2_{sc}$), Z_sec and Z_pr ate the Z-coordinate along beam direction of primary and secondary vertices and σ's are their errors

- Proper decay length

Fraction of D0 arising from B decays is negligible (<0.1 %)

Lifetime cuts

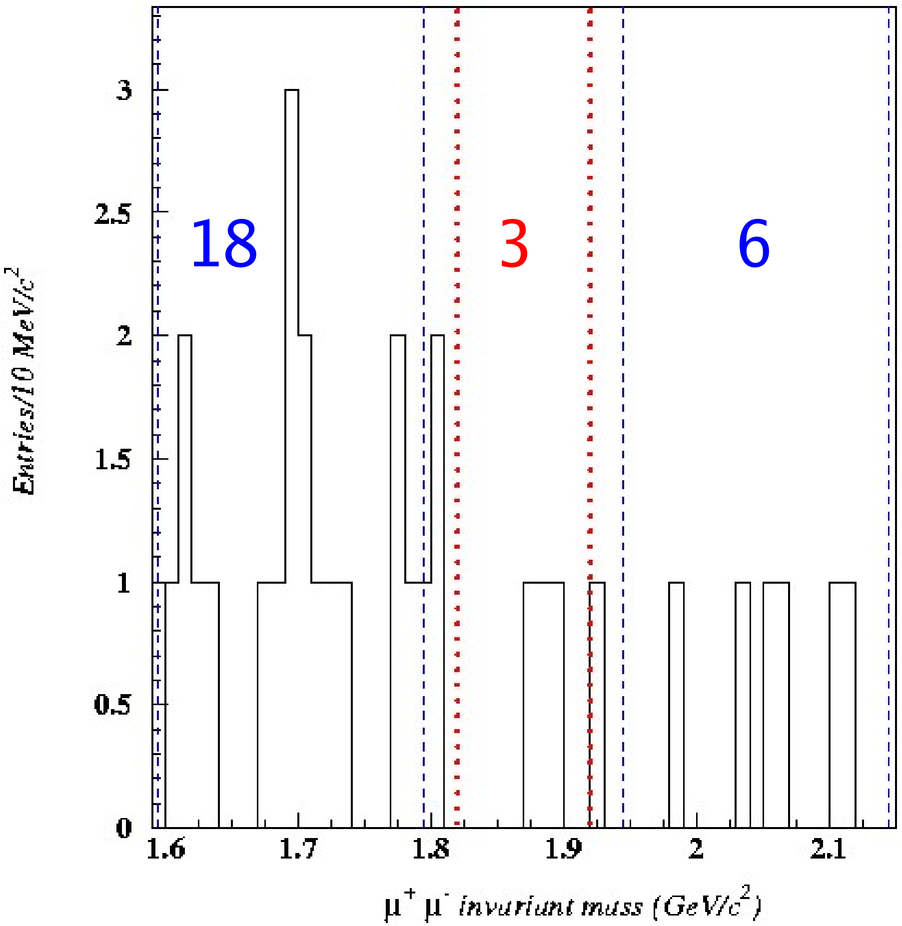
Three-dimensional optimization: N^{MC} / *sensitivity*

N – number of reconstructed D0 MC events
sensitivity – the average upper limit obtained with the expected background estimated from the D0 sidebands, assuming no signal from D0 -> μ μ is presented

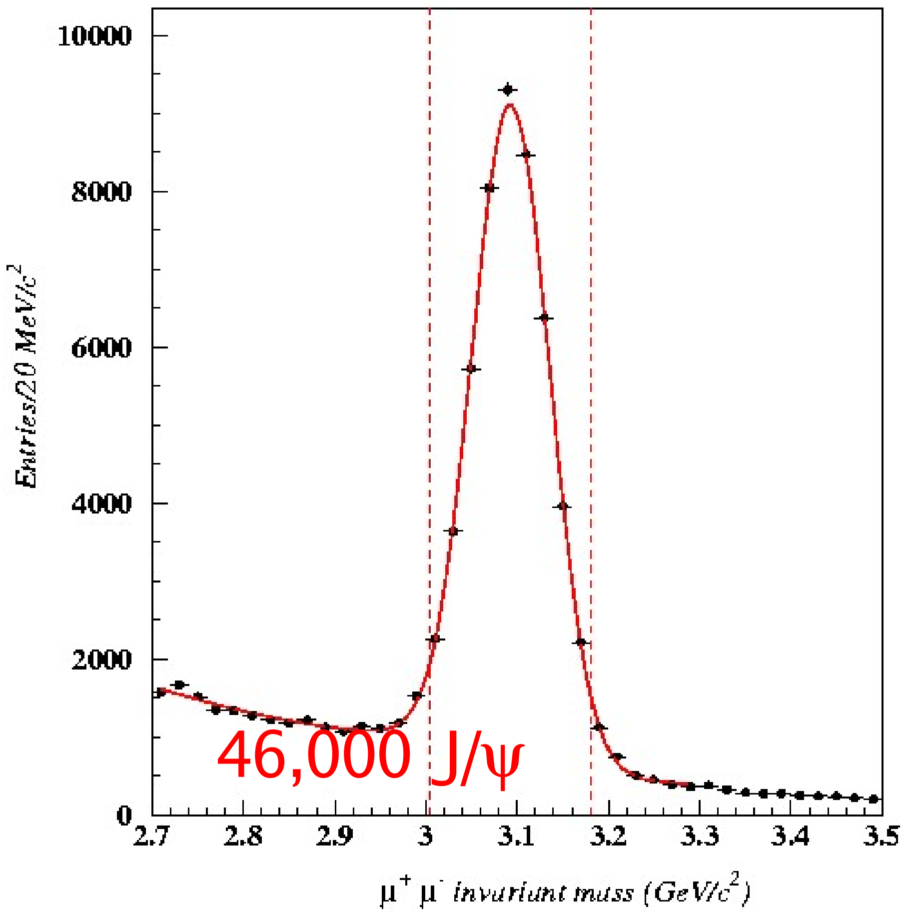
- 110 mkm for impact parameter cut
- 7.0 for the separation between primary and secondary vertices
- 0.25 mm for proper decay length

Result

after ALL cuts



after common cuts only



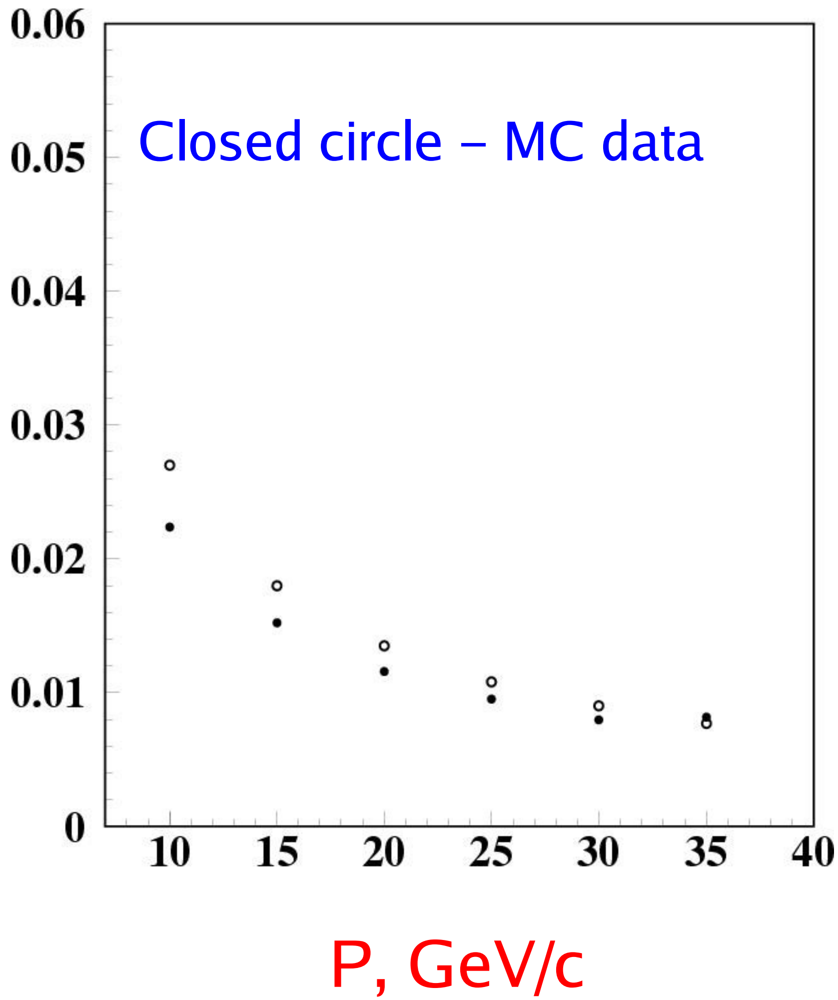
Result

- The number of background events in the “D0 region” from charm decays in which both decay products are identified as muons is estimated from MC
  - D0 -> K pi – two events (which survive all cuts) are in the low-mass sideband
  - all other modes (KK, pi pi pi0, pi pi) give a negligible contribution
- shape is NOT significantly influenced by charm decay
- The expected number of background events was estimated by using the shape of the mass plot before lifetime cuts are applied

N_exp = 6.0 +- 1.2

Simple linear interpolation also predicts 6.0 +- 1.2

Misidentification



- punch through probability is on a per mil level
- Misidentification – real data and MC
  - In RD we used pi from Ks, p from Lambda, K from Phi decays to check the muon misidentification probability
  - Good agreement between RD and MC

Result

- assume that the ratio of D0 and J/ψ production cross section does not change significantly between 800 and 920 GeV
- from two measurements (E653, E743 at 800 GeV) we obtained the D0 production cross section – 27.3 ± 7.7 μb/nucleon
- prompt J/ψ production cross section - $333 \pm 6 \pm 26$ nb/nucleon

Result

Factor	Value	%
$\alpha_{D0} / \alpha_{J/\psi}$	0.287 +– 0.028	9.8
ε_{D0}	$(6.83 +- 1.08)*10^{-2}$	15.8
J/ψ cross section	333 +- 6 +- 26	8.0
D0 cross section	27.3 +- 7.7	28.2
Br (J/ψ –> μμ)	$(5.88 +- 0.10)*10^{-2}$	1.7
Num_J/ψ_C	31010 +- 200	0.7
Num_J/ψ_W	12660 +- 140	1.1
Num_J/ψ_Ti	2430 +- 60	2.5

Total systematic error from all contributing terms – 37 %

Results

- Number of signal events – 3
- Expected background rate – 6.0 +- 1.2
- Systematic uncertainty - 37%

To incorporate systematic uncertainties and background fluctuation into the upper limit, we adopt the method of Cousins and Hihgland as implemented by G.Hill

$$Br\,(D^0 \rightarrow \mu^+\mu^-) < 2.0 \text{ x } 10^{-6} \quad (90\% \text{ C.L.})$$

R.D.Cousins, NIM A320 (1992) 331   G.J.Feldman, R.D.Cousins PR D57 (1998(3873
J.Conrad et al., PR D67 (2003) 012002   G.C.Hill, PR D67 (2003) 118101

Result

Using the values of D0 and J/ψ production cross sections published in the literature we have set an upper limit

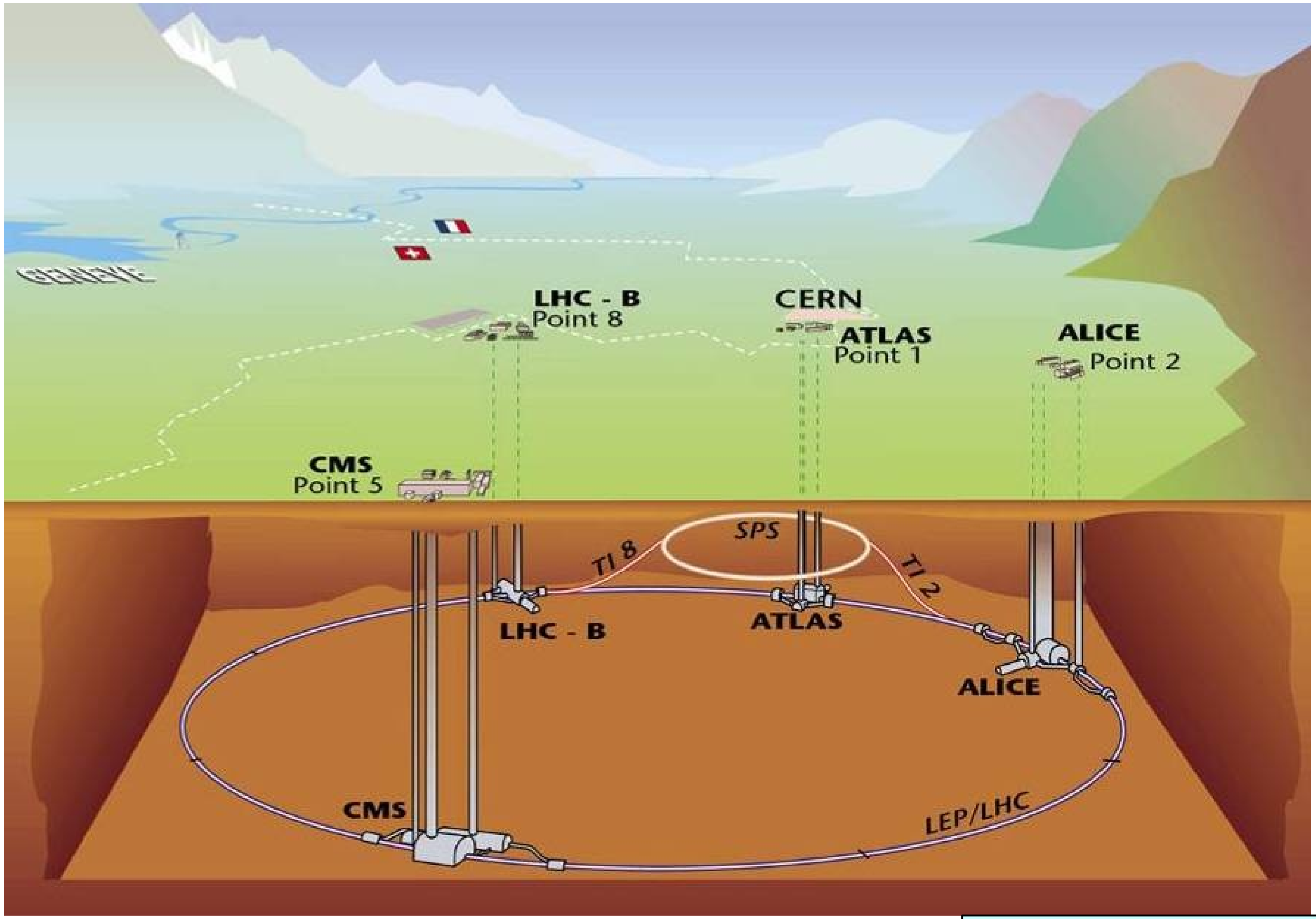
$$Br\ (D^0 \rightarrow \mu^+ \mu^-) < 2.0 \times 10^{-6} \quad (90\%\ C.L.)$$

Our limit D0 -> μ μ was the best (before BaBar result)

$$Br\ (D^0 \rightarrow \mu^+ \mu^-) < 1.3 \times 10^{-6} \quad (90\%\ C.L.)$$

BaBar Collaboration

From HERA-B to LHCb



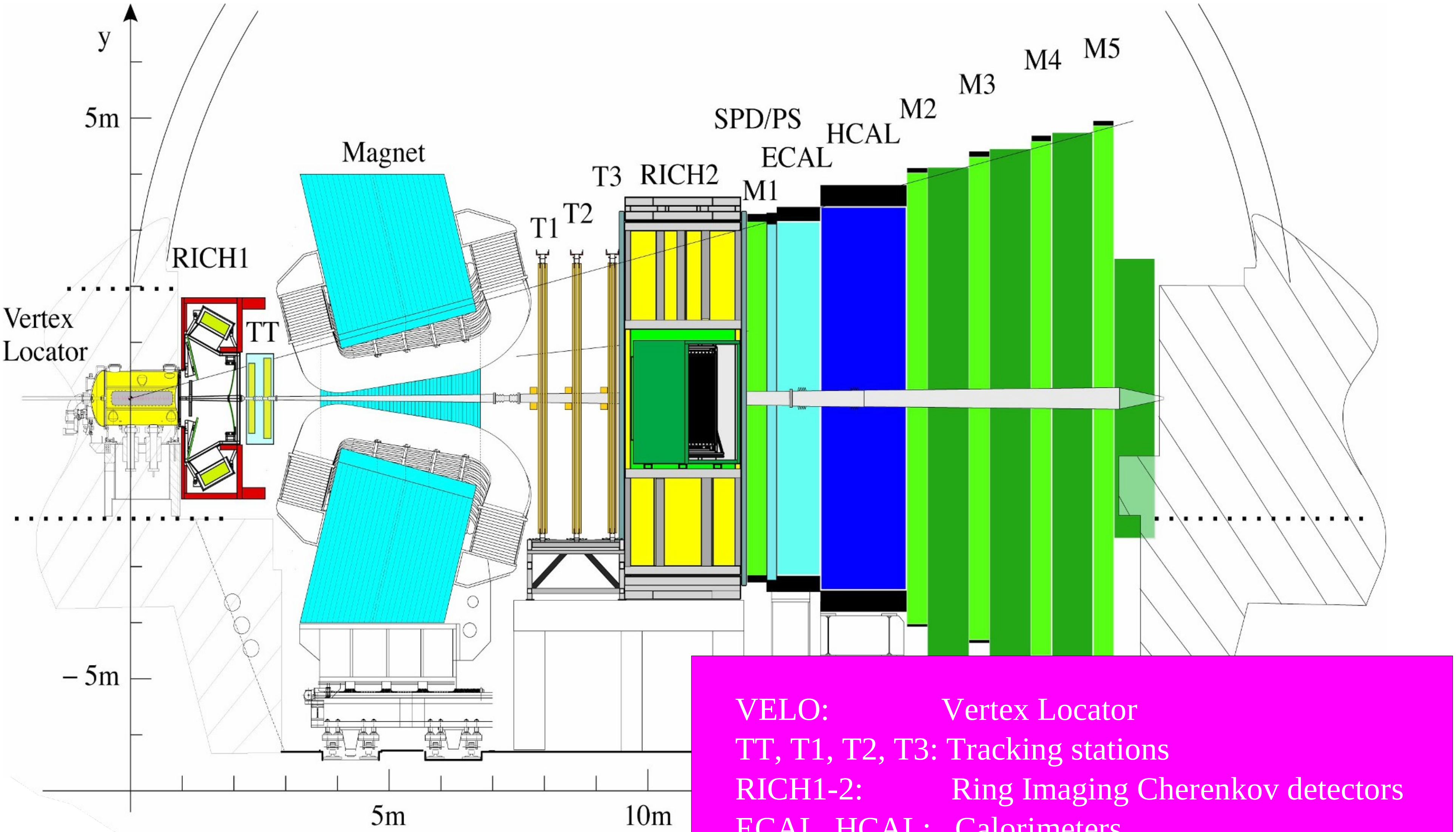
LHCb

47 institutes in 16 countries are participating in the LHCb project

> 600 collaborators

- pp with $\sqrt{s}$ =14 TeV
- $\mathcal{L}$ = 2.10^{32} cm^{-2}s^{-1}
- 10^{12} b-hadrons per year

The LHCb detector



VELO: Vertex Locator
TT, T1, T2, T3: Tracking stations
RICH1-2: Ring Imaging Cherenkov detectors
ECAL, HCAL: Calorimeters
M1–M5: Muon stations
Leptons + Hadrons trigger

Charm physics at LHCb

- Initial focus on D -> h h decays
- Lifetime difference of *CP* eigenstates
  - CP-even Singly-Cabibbo Suppressed (SCS): D^0-> $K^- K^+$ or $\pi^- \pi^+$
  - Non-CP eigenstate Right Sign: D^0-> $K^- \pi^+$
- Time-dependent mixing
  - Wrong Sign decay: D^0 -> $K^+ \pi^-$
- Direct *CP* violation
  - SCS decays: D^0 -> $K^+ K^-$ or $\pi^+ \pi^-$
- Other interesting topics
  - FCNC decay: D^0 -> $\mu^+ \mu^-$

Br $(D^0 \rightarrow \mu^+ \mu^-)$ < 5.0×10^{-8}

Summary

- Charm represents a good candidate for evidence of New Physics
- Compared to rare decay searches in the K and B sector, rare D sensitive to new physics involving the up-quark sector such as R-parity violating supersymmetric models
- Progress in charm physics has been prodigious over the last 20 years; it comes both fixed-target and collider experiments, and can guide us toward future investigations
- The LHCb physics programme includes search for FCNC decay D0 $\rightarrow \mu\,\mu$ (sensitive to exotic supersymmetric scenario as R-parity violation)