The Suppressed Charm of HERA-B

Forschungsseminar des Fachbereichs Physik

Universität Siegen, June 25, 2003

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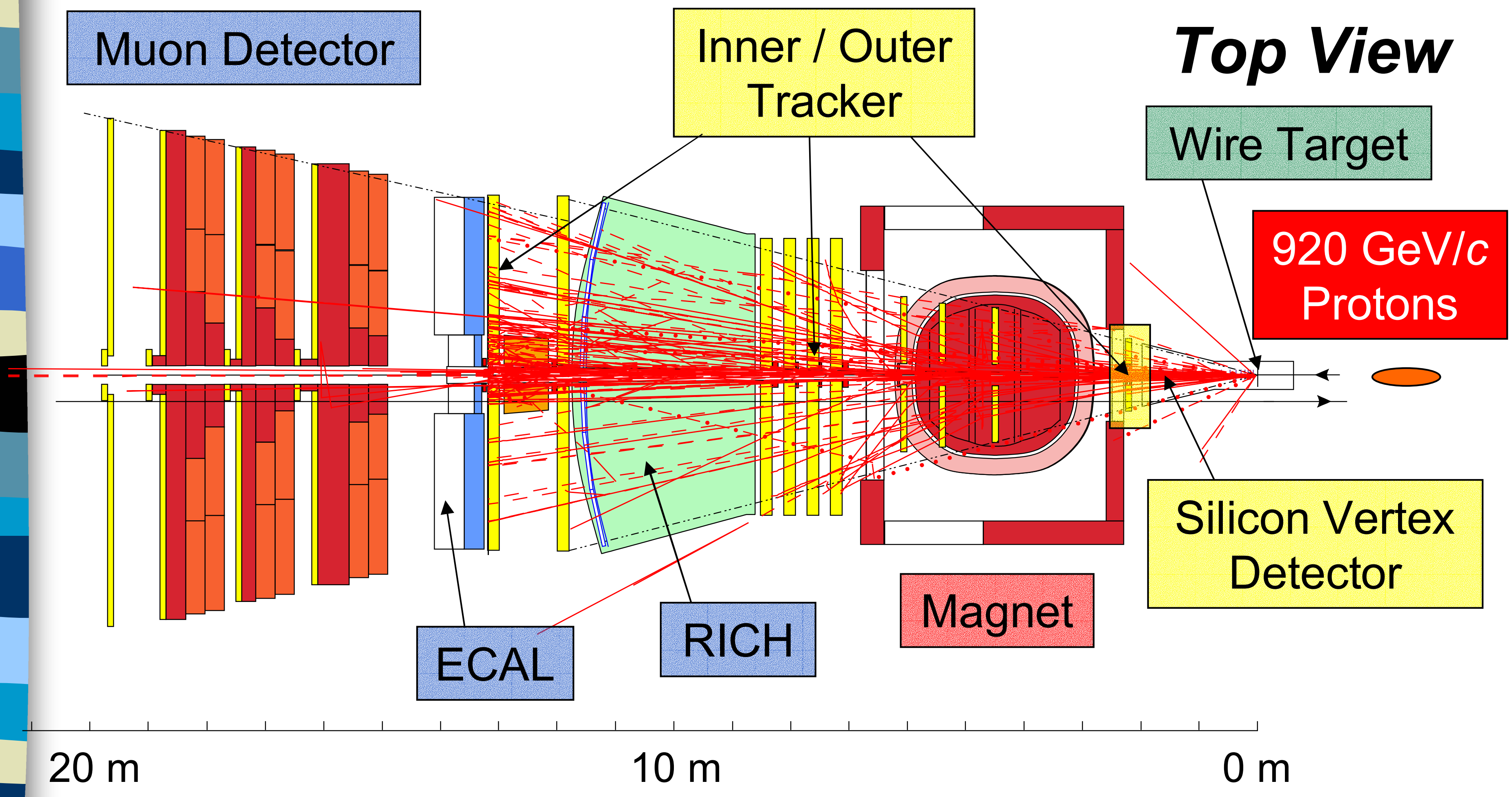
Outline of the Talk

- The HERA-B detector and trigger: Challenges, technologies, performance
- The HERA-B physics program for the data-taking period 2002/2003
- Charmonium physics at HERA-B: Strategy and status of the analysis
- Conclusions and outlook

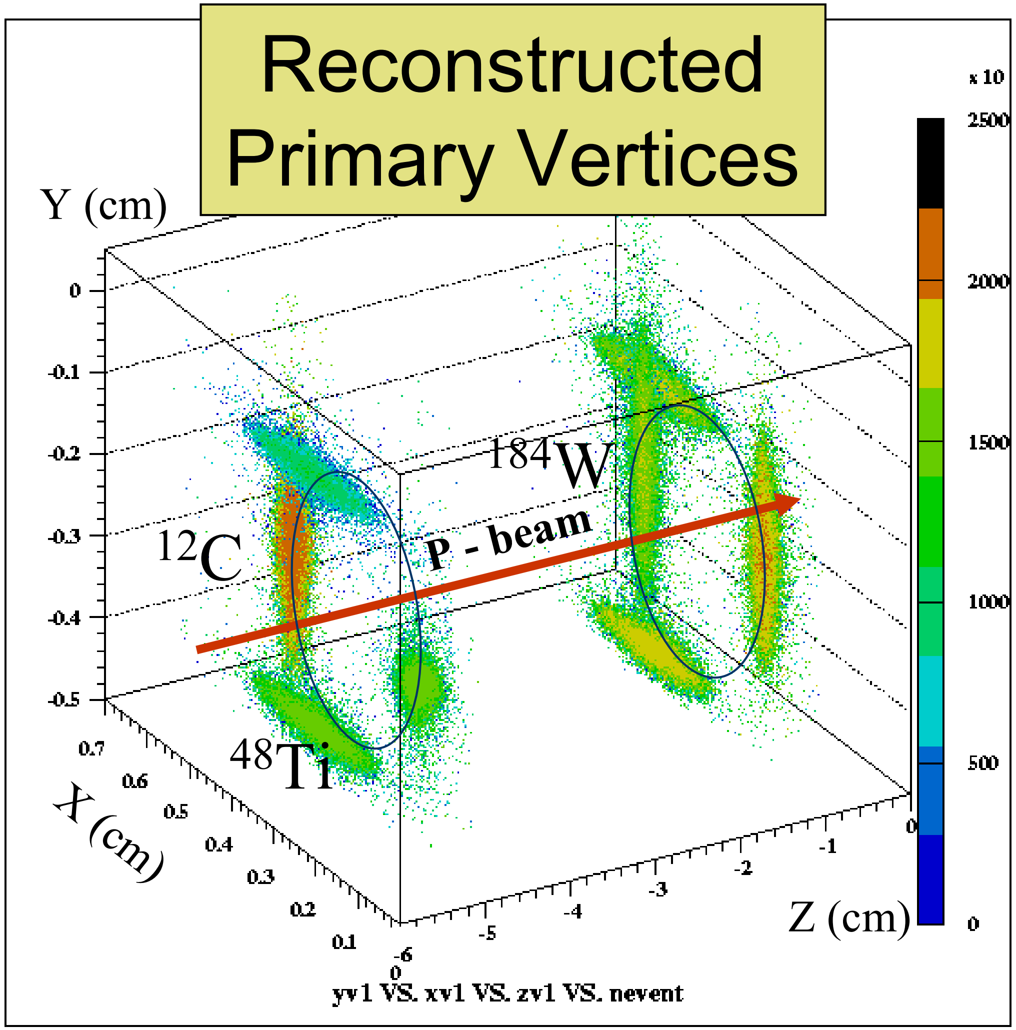
Detector

The HERA-B Detector

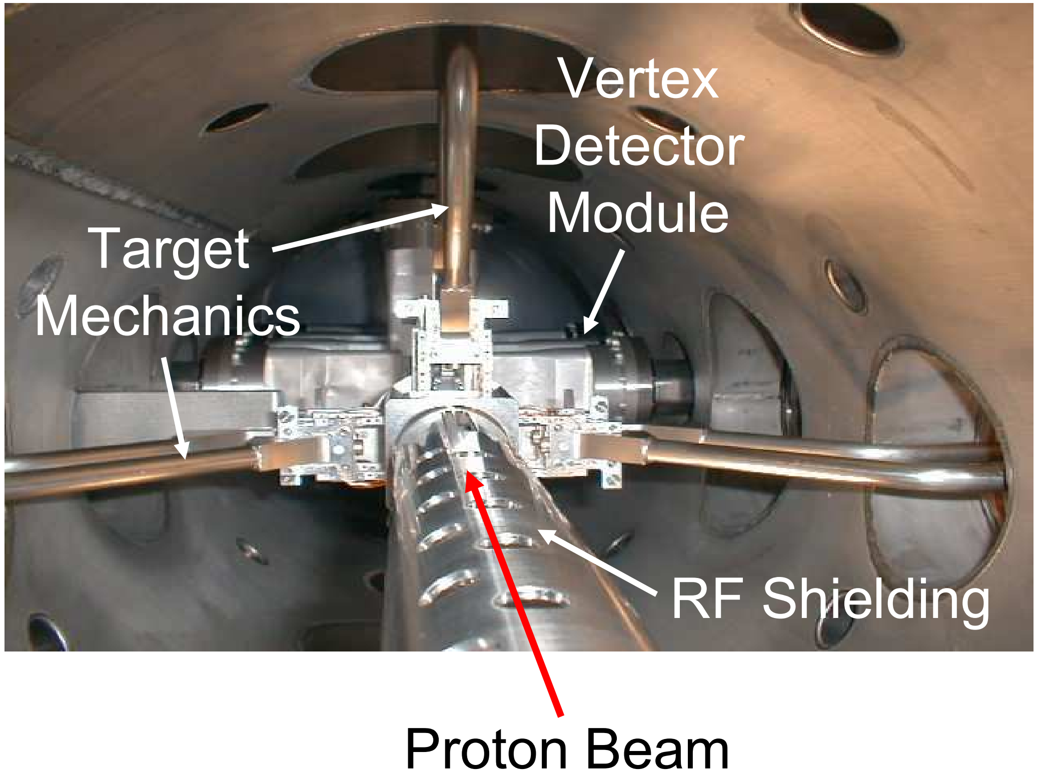


Wire Target

- Eight wires (50-500 μm) in halo of HERA proton beam
- Wire materials with atomic numbers *A* from 12 to 184
- Target steering (transverse to beam): constant interaction rates, rate sharing between wires

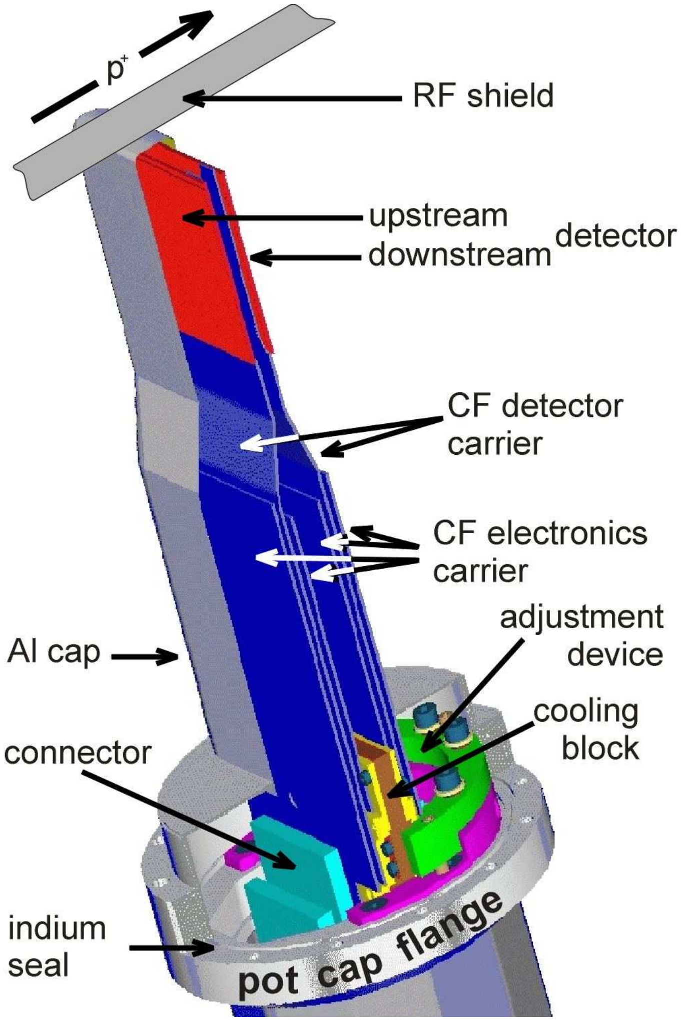


Wire Target



- Target mechanics mounted inside Vertex Detector vessel (HERA vacuum)
- Easy access to target mechanics: broken wire can be replace in one day

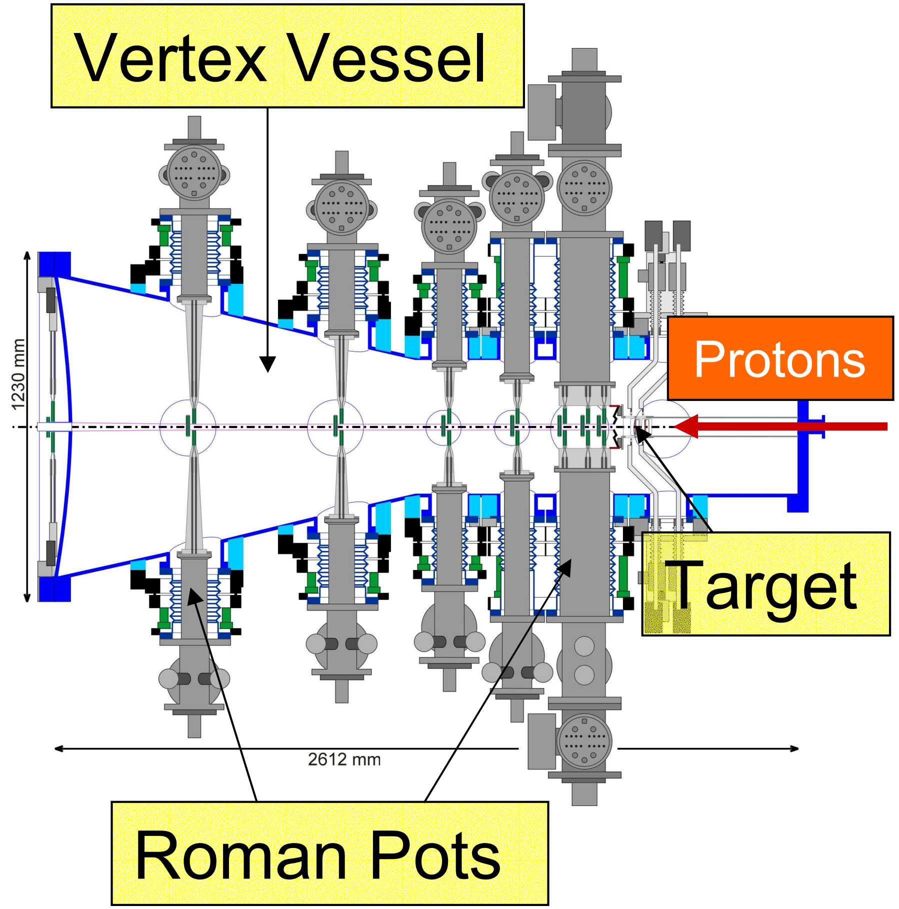
Vertex Detector



- Double-sided double layers of silicon-strip detectors (50 μm pitch)
- Vertex Detector mounted in “Roman Pots” inside vacuum
  → moved in safe position during HERA injection

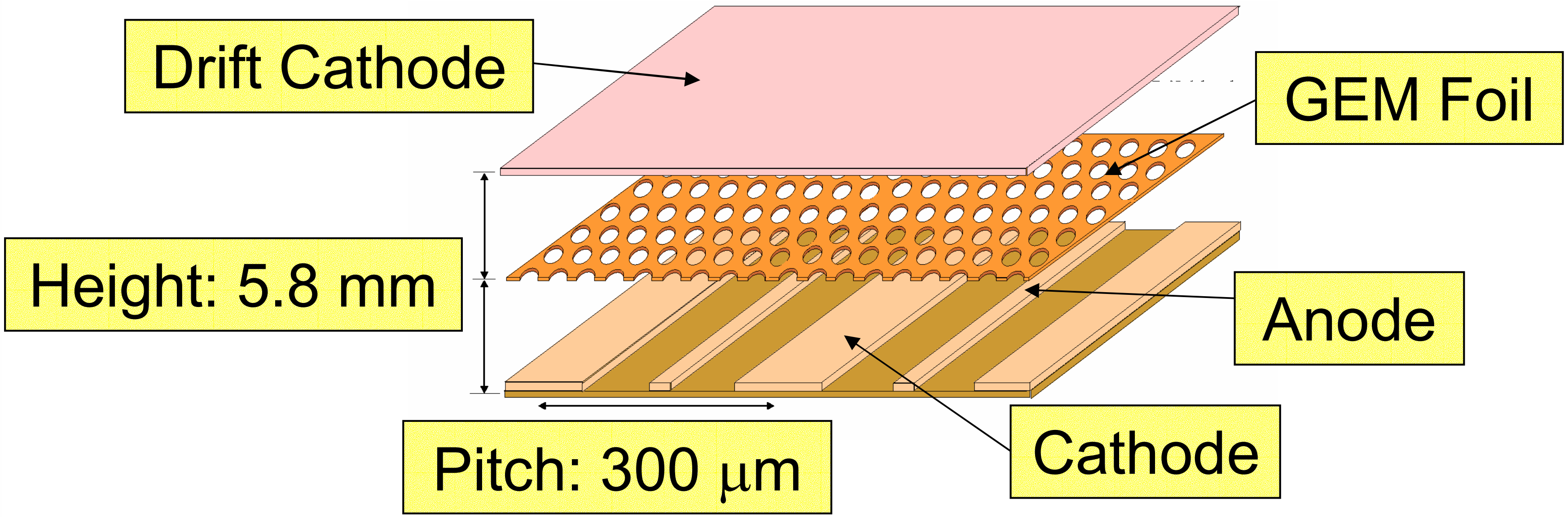
Vertex Detector

- Purpose: primary and secondary vertex reconstruction, tracking in front of magnet
- Large angular acceptance: 10-250 mrad
- Primary vertex resolution 2002/2003: 700 μm in proton flight direction (size of target wire ⊗ Vertex Detector resolution)

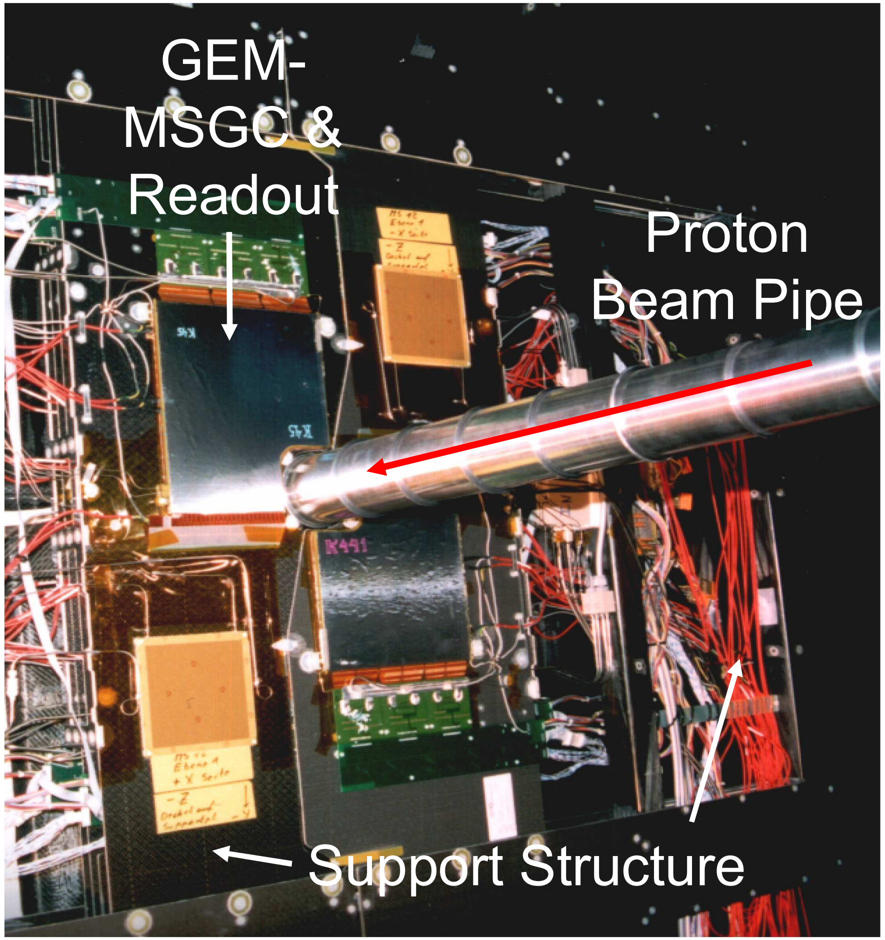


Inner Tracker

- Coverage of inner acceptance: 6-30 cm from beam
- Fast and radiation-hard detector technology needed: Micro-strip gaseous chambers (MSGC)
- Large chambers require high gas-gain: additional amplification by gas electron multiplier foil (GEM)



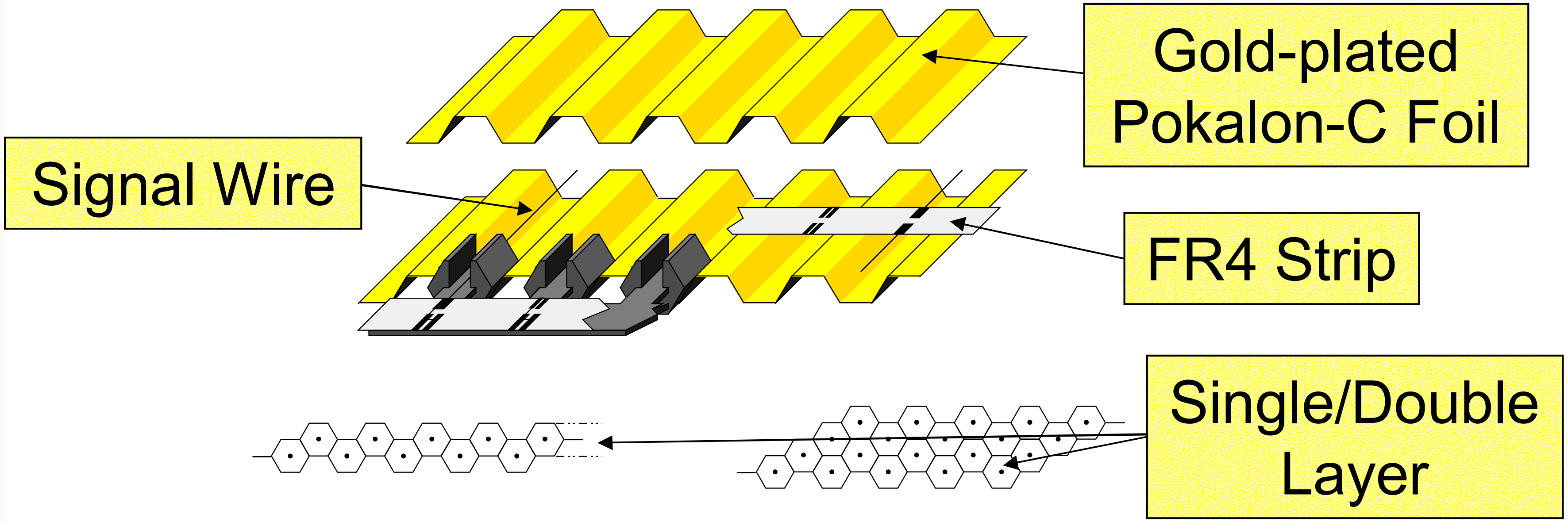
Inner Tracker



- GEM-MSGC difficult to construct and operate: careful assembly and testing, high-voltage “training” with beam
- Successful chamber operation in 2002/2003
- Single hit efficiency: 85-90% (95% for double layers)

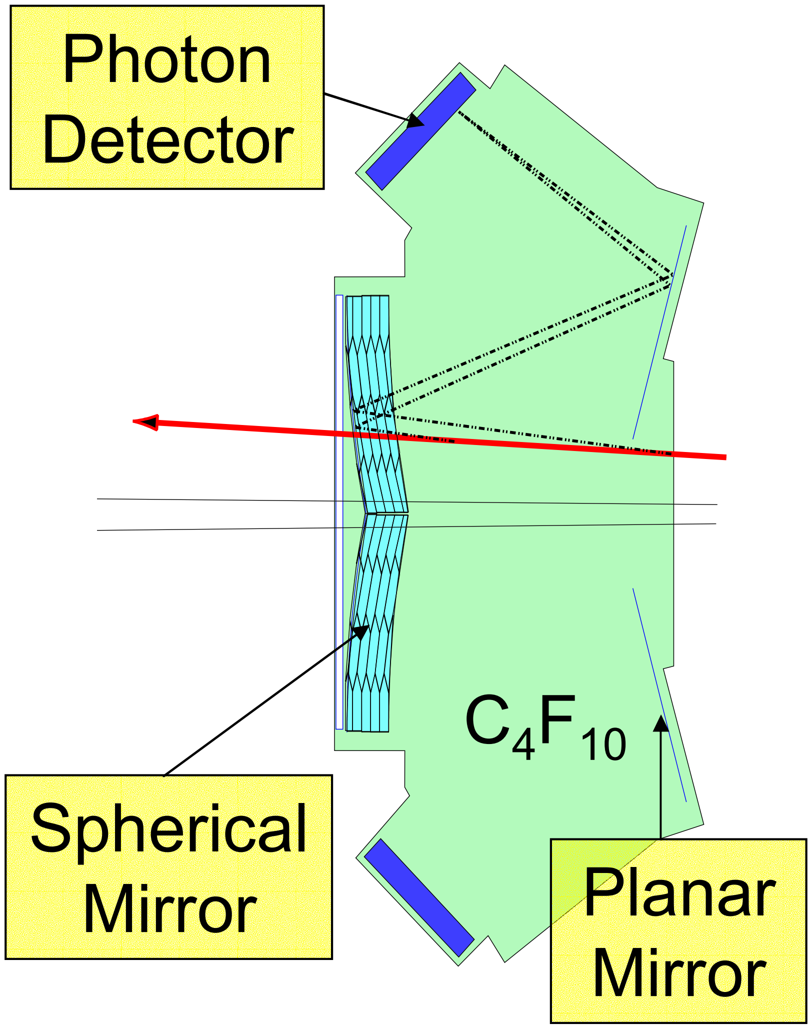
Outer Tracker

- Coverage of outer acceptance: 20-400 cm
  → Challenge for mechanical stability
- Technology: Drift-chambers with honeycomb profile, cell sizes: 5 mm (inner part), 10 mm (outer part)

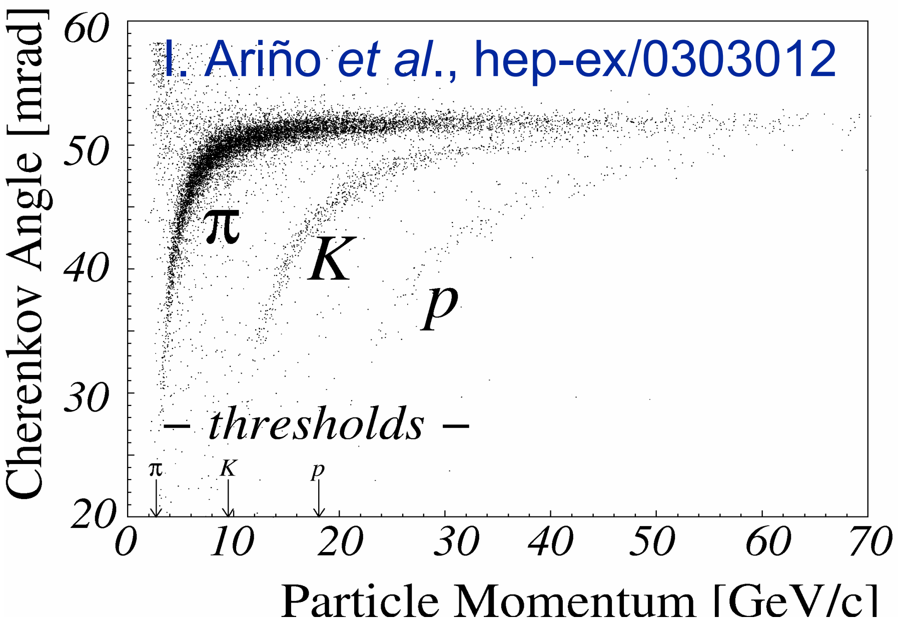


Ring-Imaging Cherenkov Counter

- Charged particles emit Cherenkov photons in C_4F_{10}
- Parallel photons are projected to rings by spherical mirrors
- Photon detection by photomultiplier tubes: measure Cherenkov angle



Ring-Imaging Cherenkov Counter



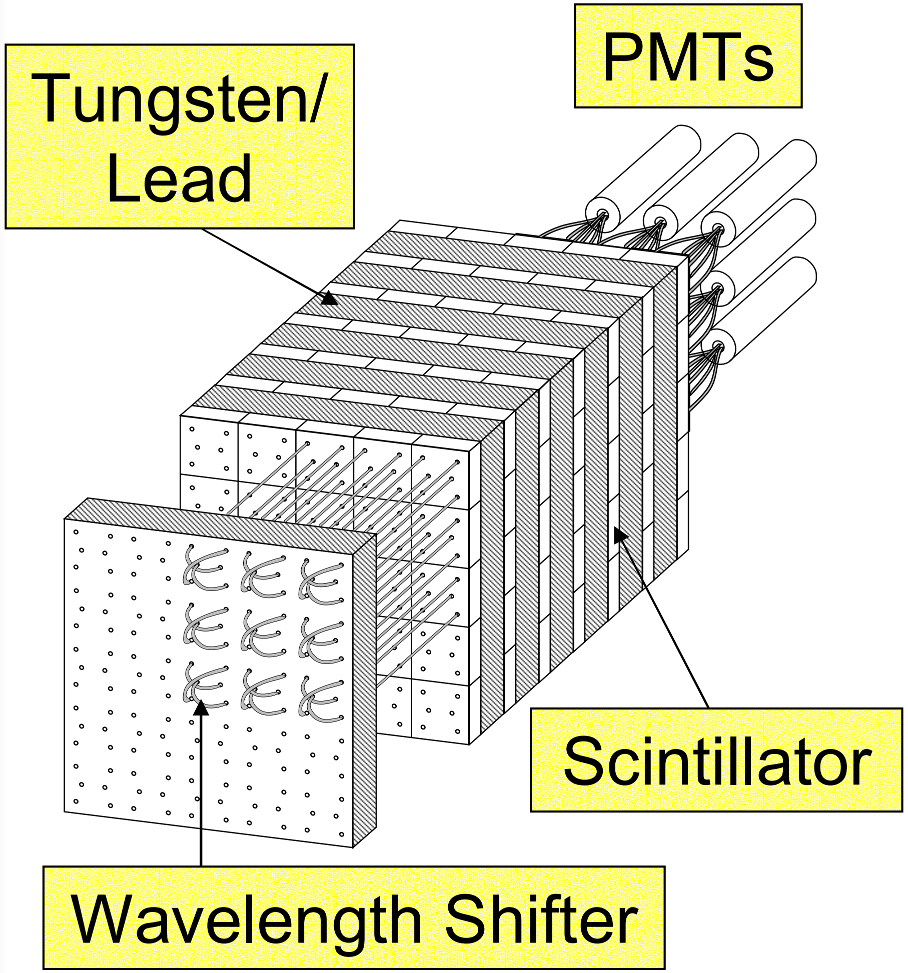
- Cherenkov angle:

$$\cos\theta_C = 1/\beta n$$

  Particle identification for pions, kaons, protons with known momenta
- Output: likelihoods for particle hypotheses

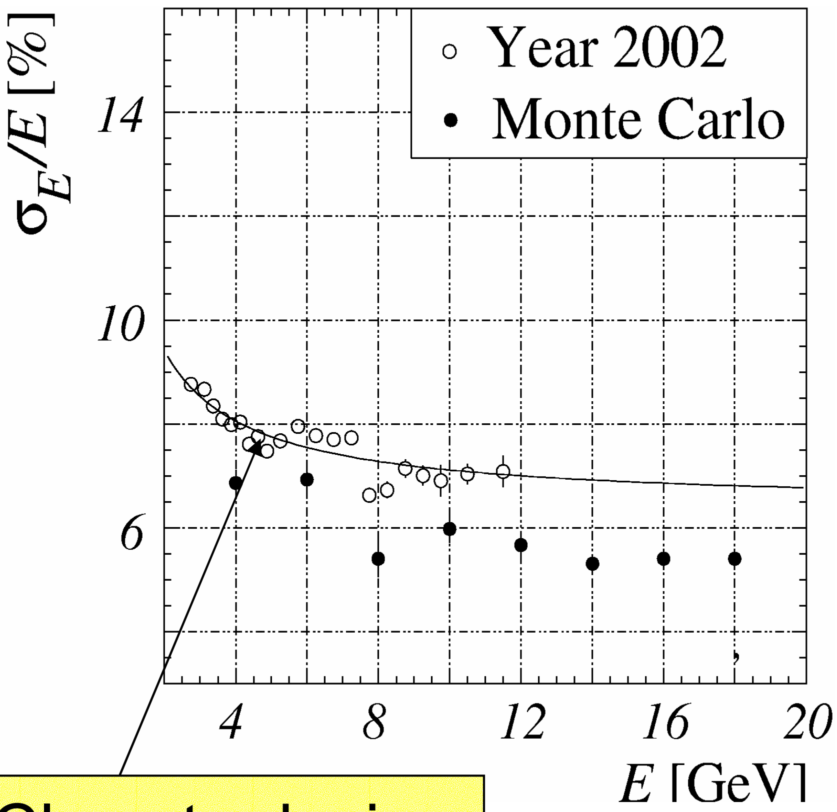
- Example: kaon identification ("medium" likelihood cut)
  - Efficiency (10 GeV/c < p < 60 GeV/c): 95-60%
  - Pion misidentification: 5%

Electromagnetic Calorimeter



- Shashlik calorimeter: wavelength shifter rods "spear" scintillator and absorber
- Inner/Middle/Outer ECAL: different cell sizes & materials (W/Pb/Pb)
- ECAL Pretrigger: starting point for di-electron trigger

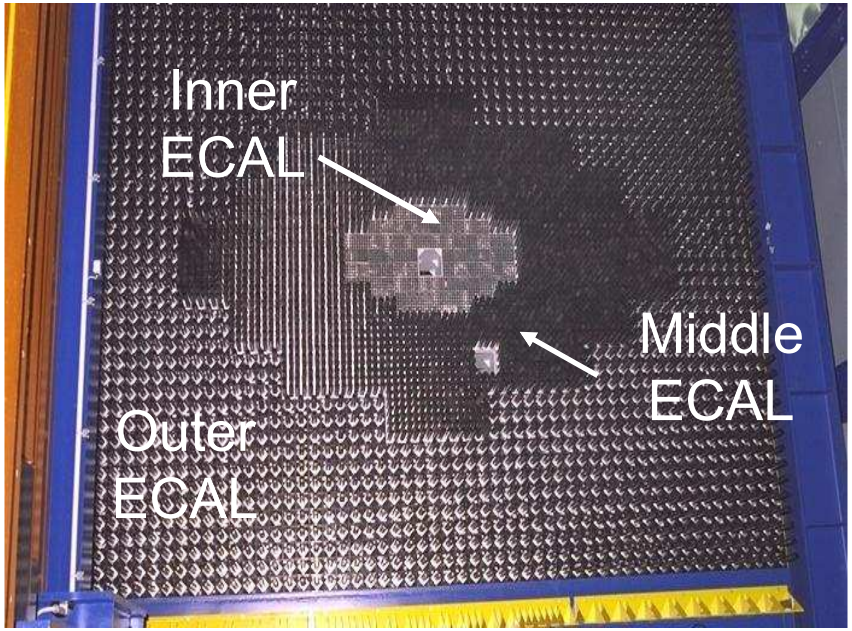
Electromagnetic Calorimeter



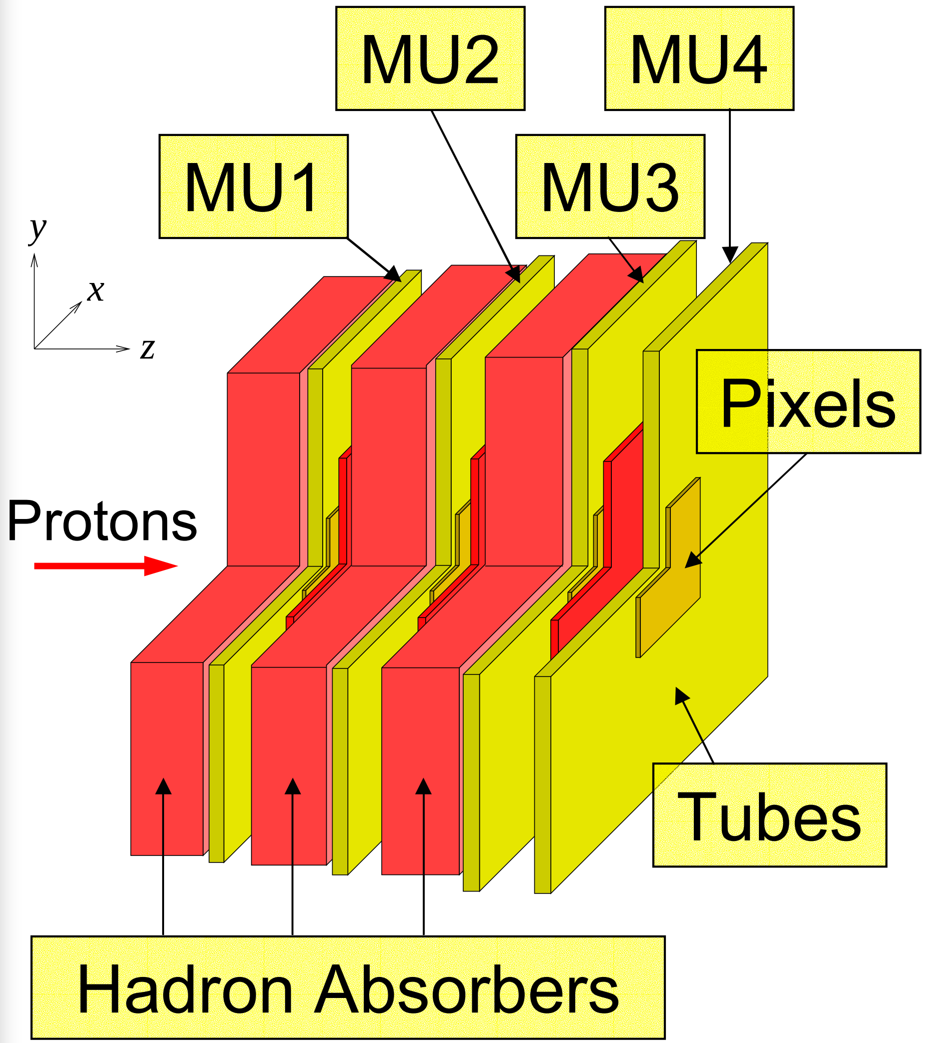
Close to design resolution

Energy Resolution (Middle ECAL):

$$\frac{\sigma_E}{E} = \frac{9.8\%}{\sqrt{E}} \oplus 6.4\%$$



The Muon Detector



- Three hadron absorbers (material: iron/concrete)
- Four layers of
  - Multi-wire proportional chambers ("Tubes", outer part)
  - Gas pixel chambers ("Pixels", inner part)
- MU3 and MU4: tube chambers with additional cathode pad readout, used in Muon Pretrigger (starting point for di-muon trigger)

Trigger

The Di-Lepton Trigger

HERA-B detector: data is read out and buffered for 10 μs (proton bunches cross every 96 ns, 0.5 interactions/BX)

5 MHz

Pretriggers: ECAL cluster or hit coincincence in Muon Detector as trigger seed (custom hardware)

3 MHz

First Level Trigger (FLT): Track trigger in hardware using tracking detectors behind magnet, seeding by pretriggers

20 kHz

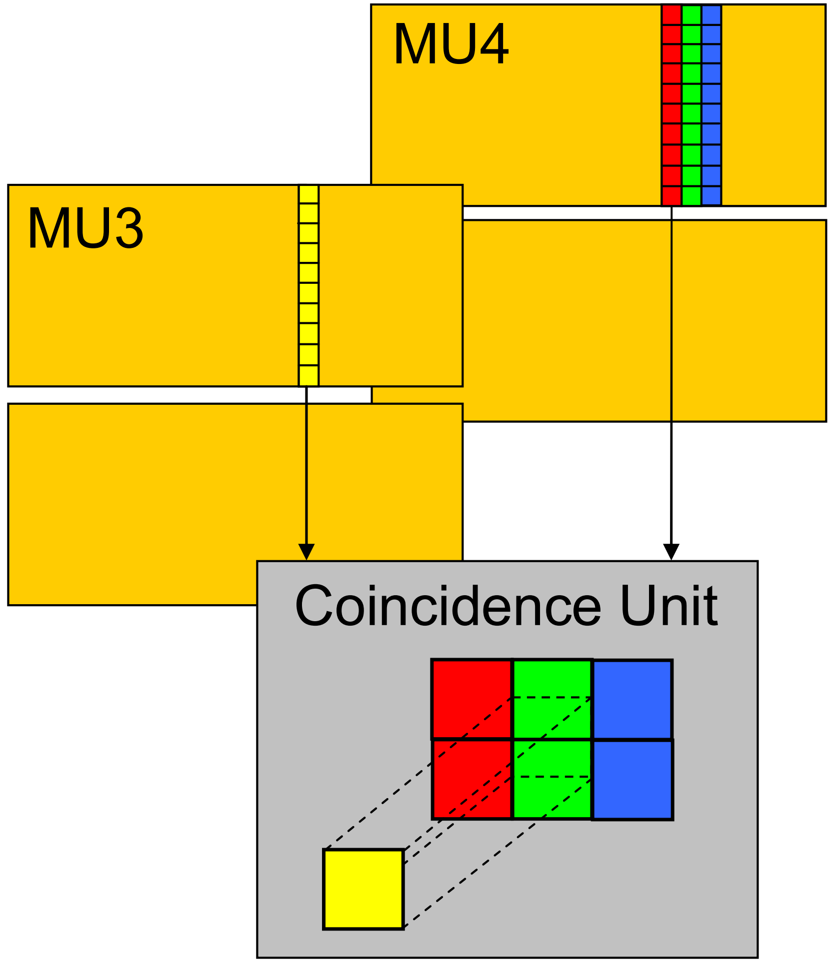
Second Level Trigger (SLT): FLT tracking confirmed, extrapolation to Vertex Detector, vertex fit (PC farm)

100 Hz

Muon Pretrigger

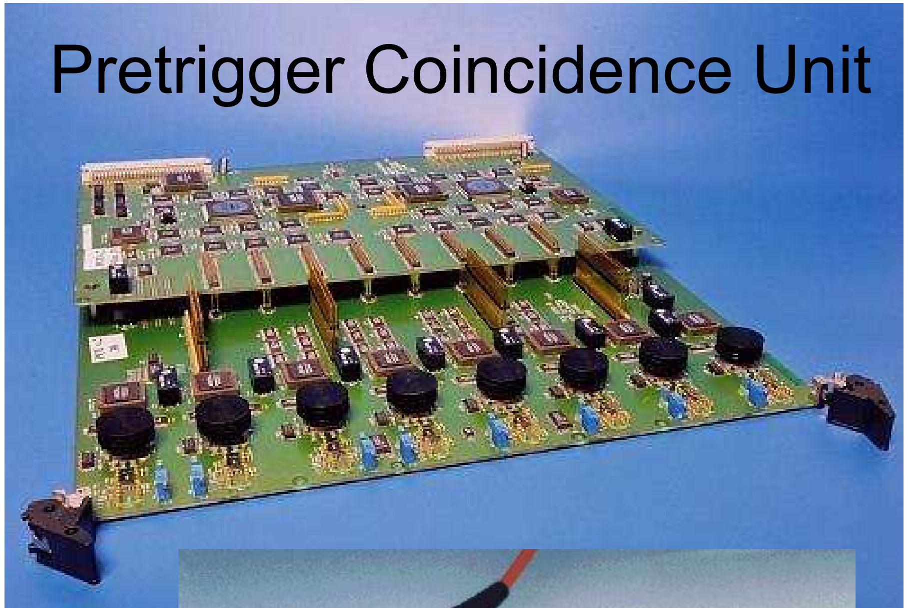
- Goal: deliver starting points of at least two muon tracks for FLT
- Trigger algorithm: "1-to-6" coincidence of cathode pad hits in last two layers of the Muon Detector
- Large data rates: 18 GB/s (4,000 channels)
- Max. Latency: 1.6 μs

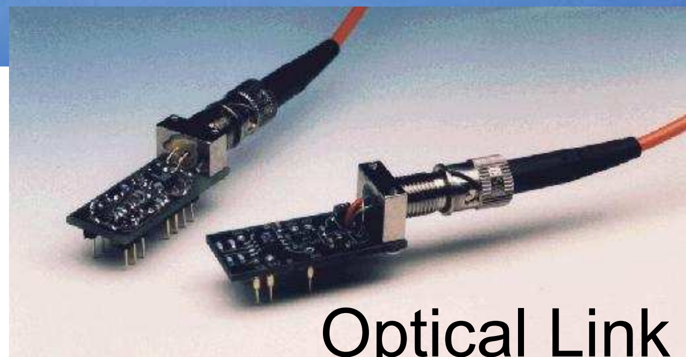
➔ Modular message-driven system



Muon Pretrigger

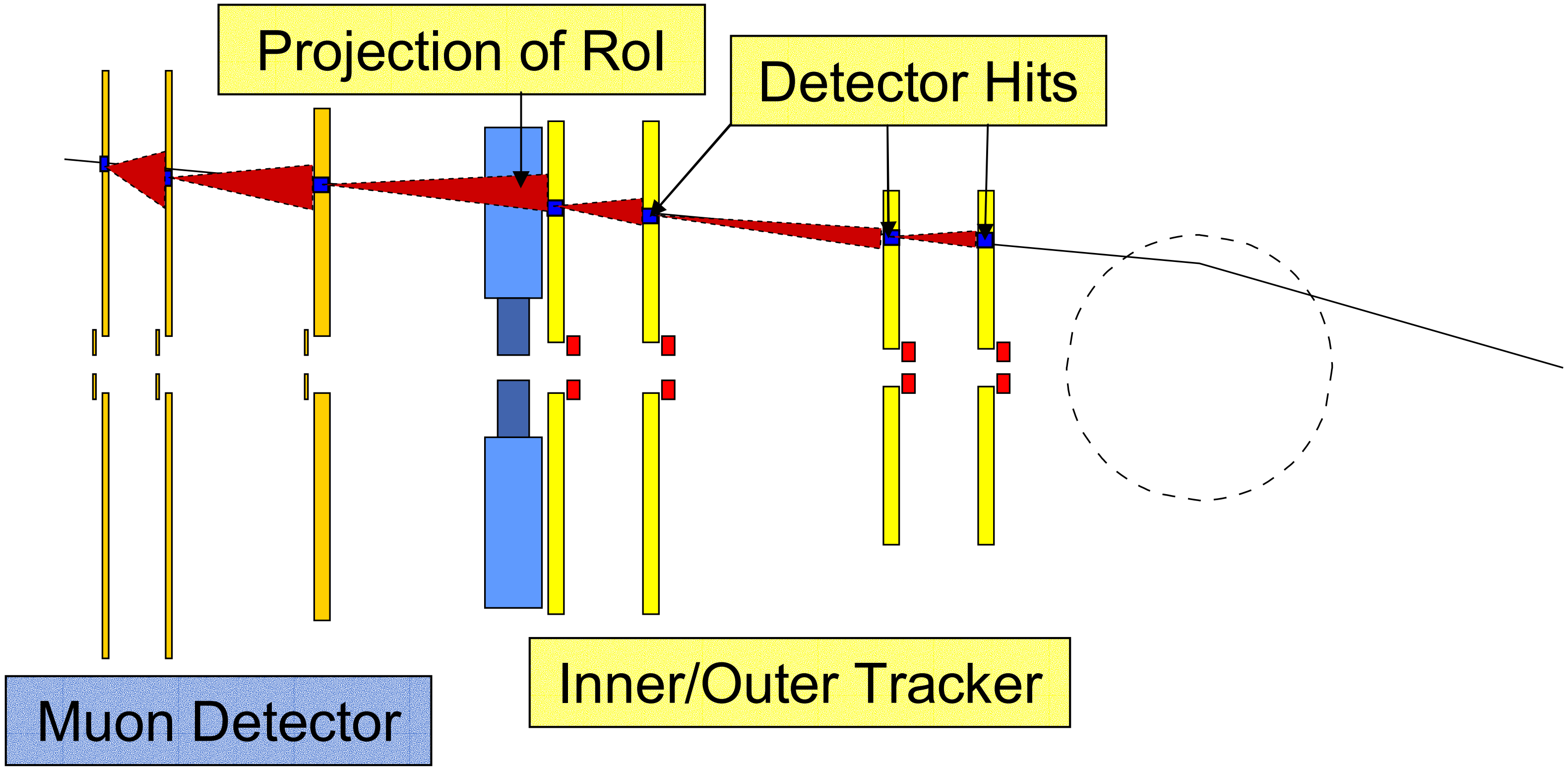
- Approx. 100 complex 9U electronic boards
- Pretrigger Link Board: digitized pad hits transmitted via optical links (60 m)
- Pretrigger Coincidence Unit: calculation of hit coincidences (FPGA)
- Pretrigger Message Generator: message with coincidence position to FLT





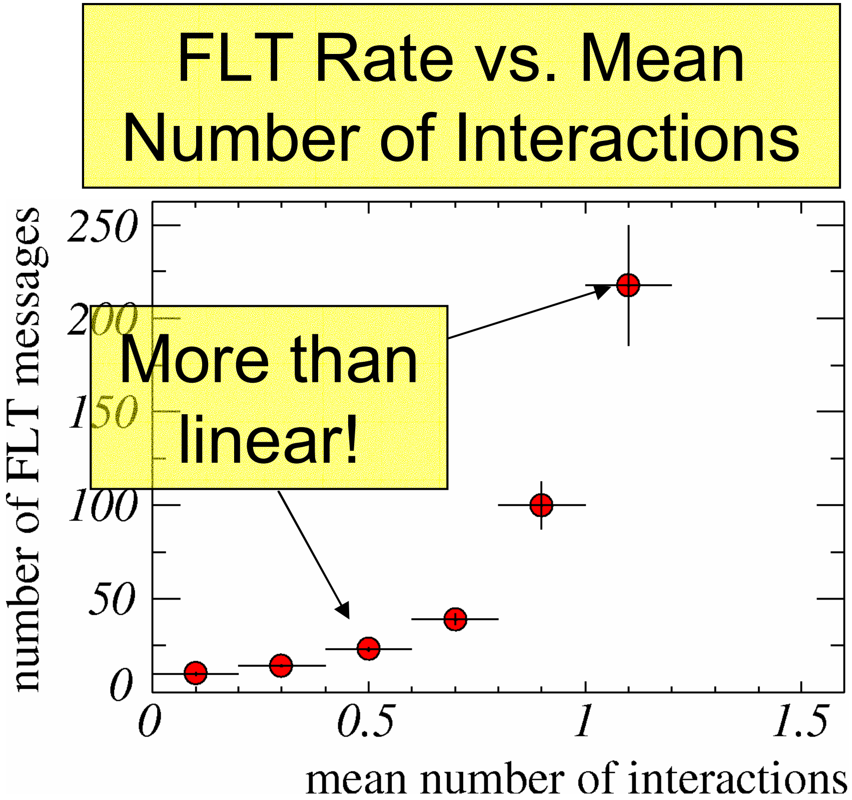
First Level Trigger

- Iterative tracking (Kalman filter) in hardware:
  - Search for hits in region of interest (first RoI from pretriggers)
  - Project weighted mean of RoI and found hits to next layer



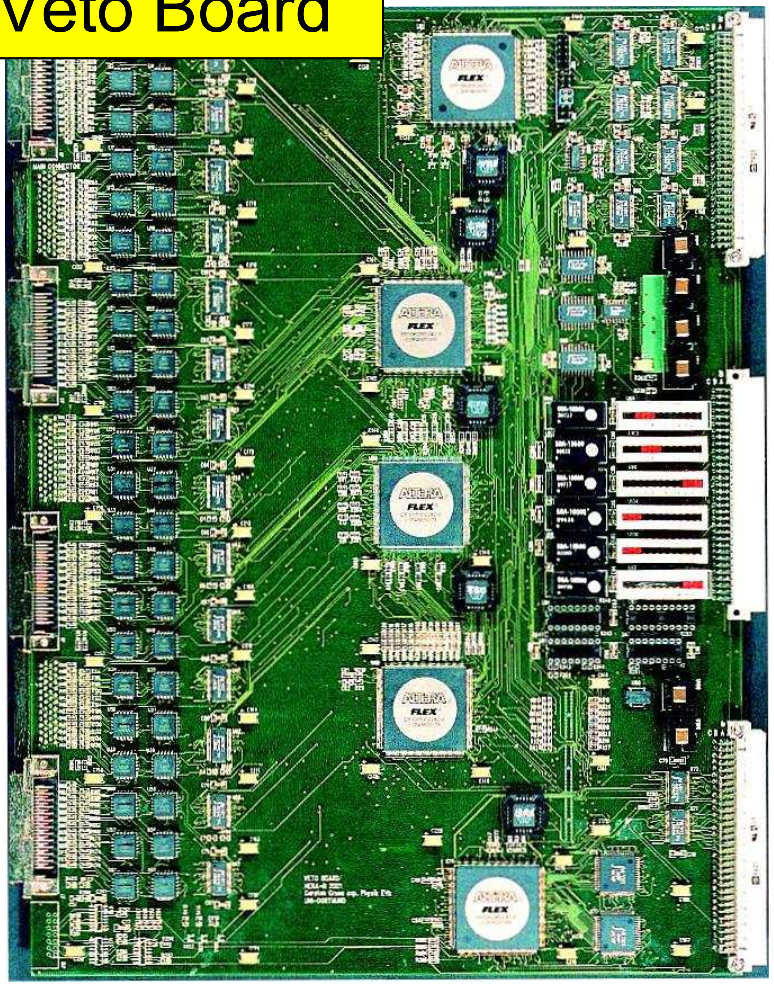
RICH Multiplicity Veto

- FLT: message-driven track-trigger, sensitive to large hit multiplicities, can be blocked by too many messages
- Large hit multiplicities caused by pile-up of events: very small fraction of interesting physics
- Idea: protect FLT by a veto system that stops pretriggers



RICH Multiplicity Veto

Veto Board



- Number of photons in RICH good measure of hit multiplicity in trigger
- Implementation:
  - Cascaded digital sum of RICH photons, separately in front-end readout crates,
  - Flat-cable transmission to Veto Board
  - Veto Board: comparison with two adjustable thresholds (FPGA)

→ Stop pretriggers

Second Level Trigger

- Software trigger: farm of 240 Linux PCs
- Improve FLT-decision using additional information from Vertex Detector:
  - Iterative track fit in Main Tracker
  - Extrapolation through magnet
  - Tracking in Vertex Detector
  - Di-lepton vertex fit, cut on vertex probability
- Starting point: FLT track or pretriggers
- Main trigger mode 2002/2003:
  Single track in FLT, two independent tracks in SLT

Fourth Level Trigger

- Approx. 100 dual-processor Linux PCs
- Full online reconstruction of (part of the) events
- Sophisticated data quality monitoring ("J/ψ peak online")
- 3 data streams to tape: logging with > 50 MB/s

Data Taking 2002/2003

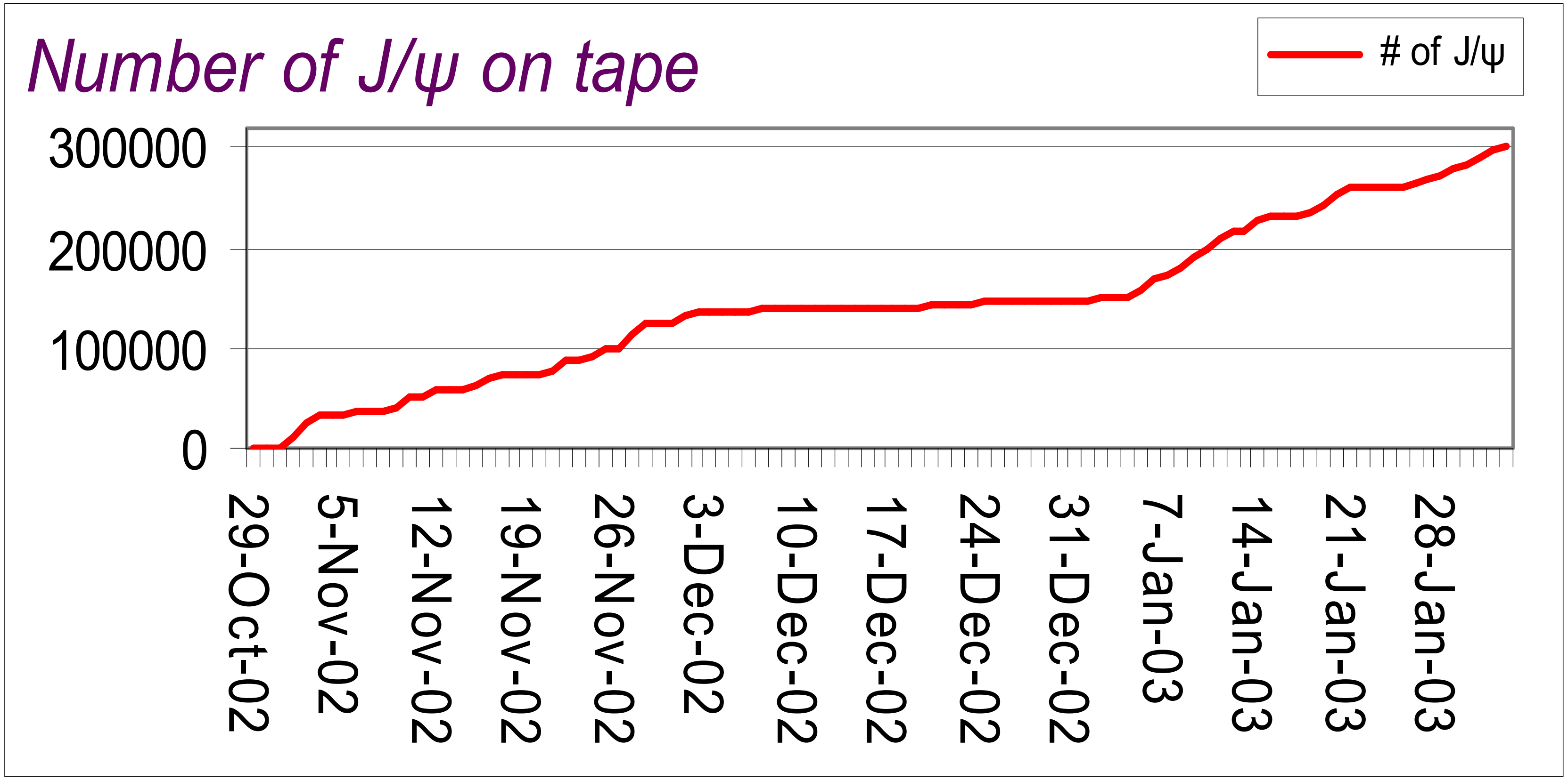
The Data Set 2002/2003

- Three months of data-taking in 2002/2003 (November 2002 – February 2003)
- Data-taking in parallel to commissioning of HERA-II collider program (H1, ZEUS)
  → low data-taking efficiency (30% target at beam)
- 150 million events with di-lepton trigger, main target materials: Carbon & Tungsten

Physics Signal	Events
J/ψ (muon channel)	170,000
J/ψ (electron channel)	150,000

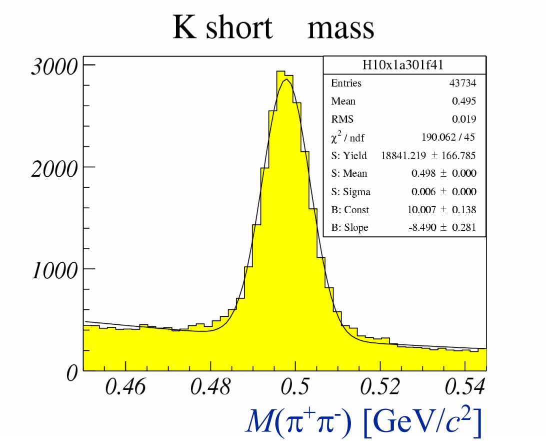
The Data Set 2002/2003

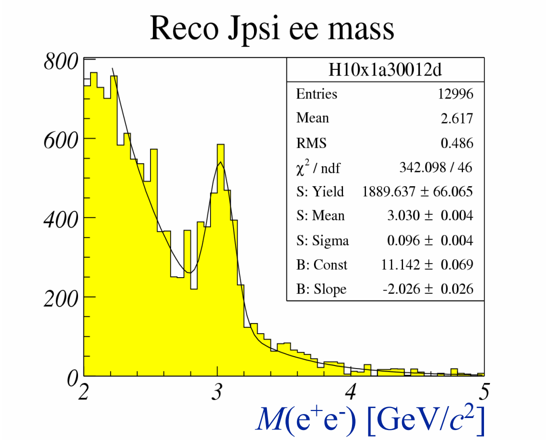
- HERA-B's „integrated luminosity“: number of J/ψ



Performance during the Data-taking 2002/2003

Online Data Quality





- Indicator for detector performance: quality of physics signals

K_S width: 5-6 MeV/c^2 (as expected from MC simulations)

Electron-J/ψ visible online (not possible in 2000)

Performance during the Data-taking 2002/2003

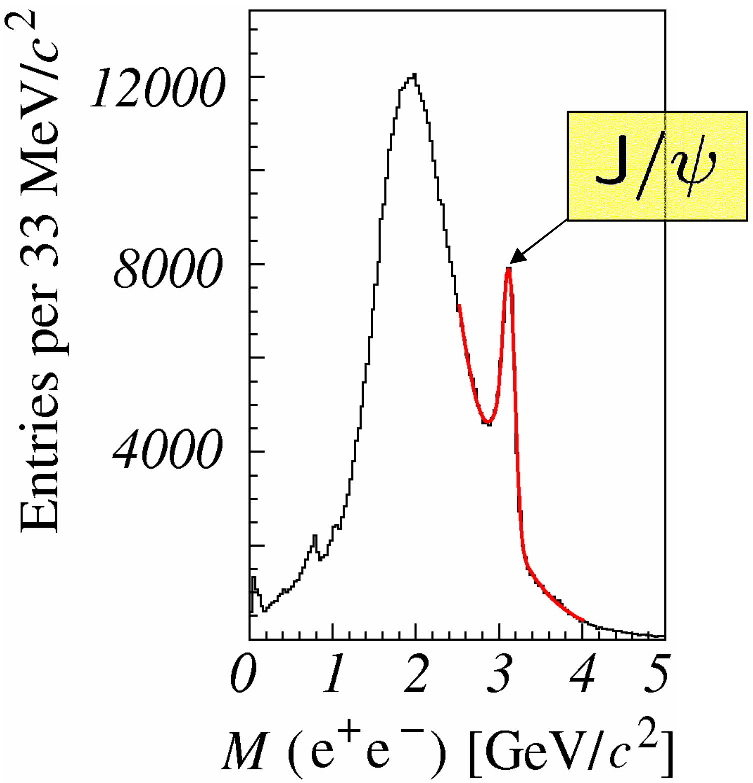
- Indicator for trigger performance: number of J/ψ per hour on tape

Period	$J/\psi\ h^{-1}$
2000	25–30
2002/3	1,000–1,500

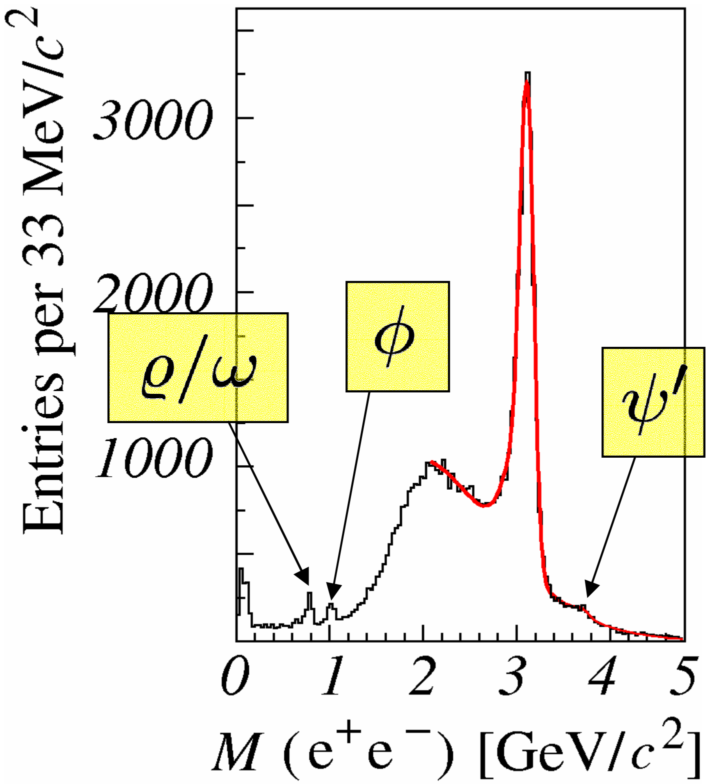
Picture Gallery

Invariant Mass of Electron-Positron Pairs

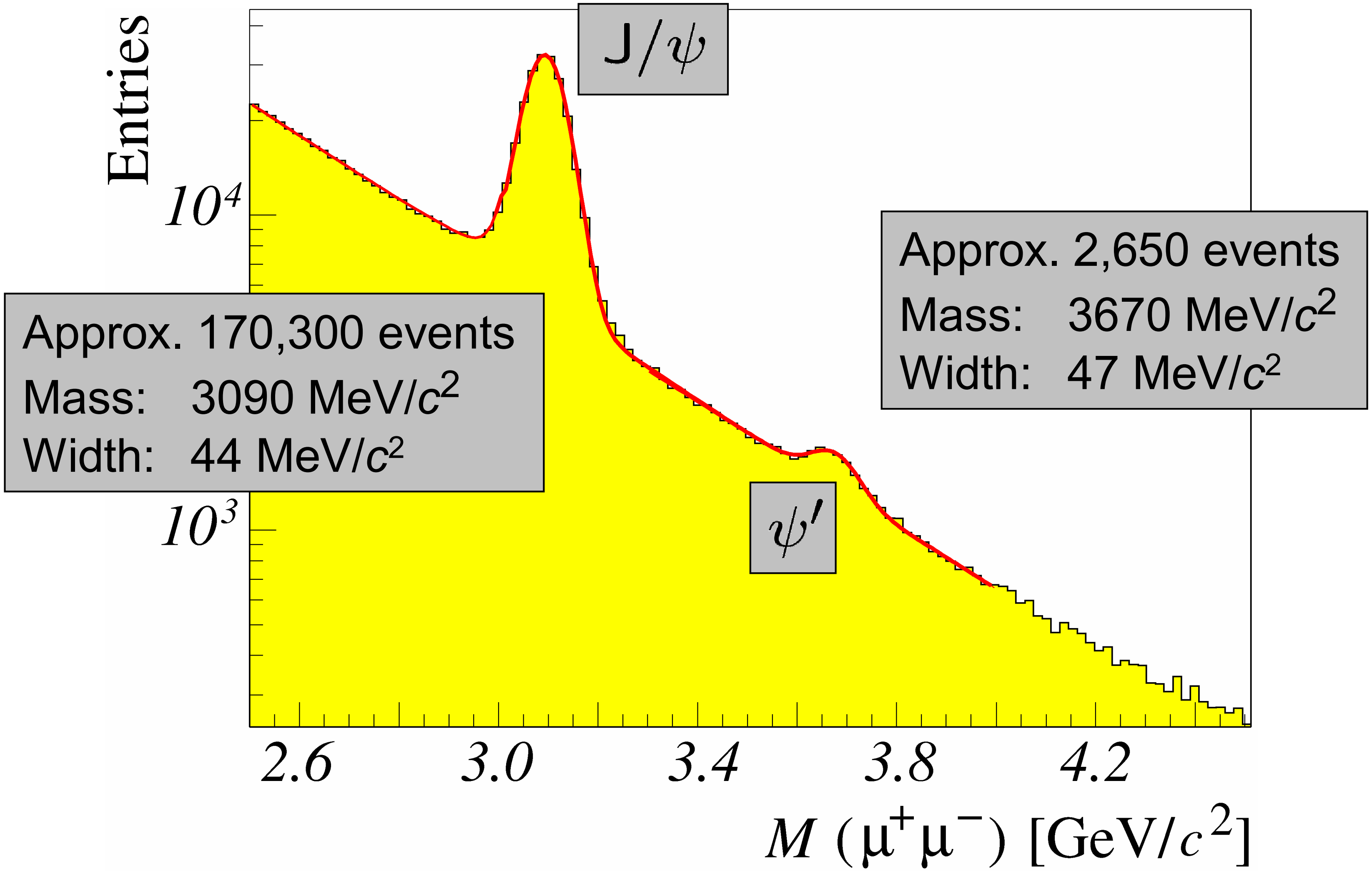
Without electron ID via bremsstrahlung



1 electron identified by bremsstrahlung

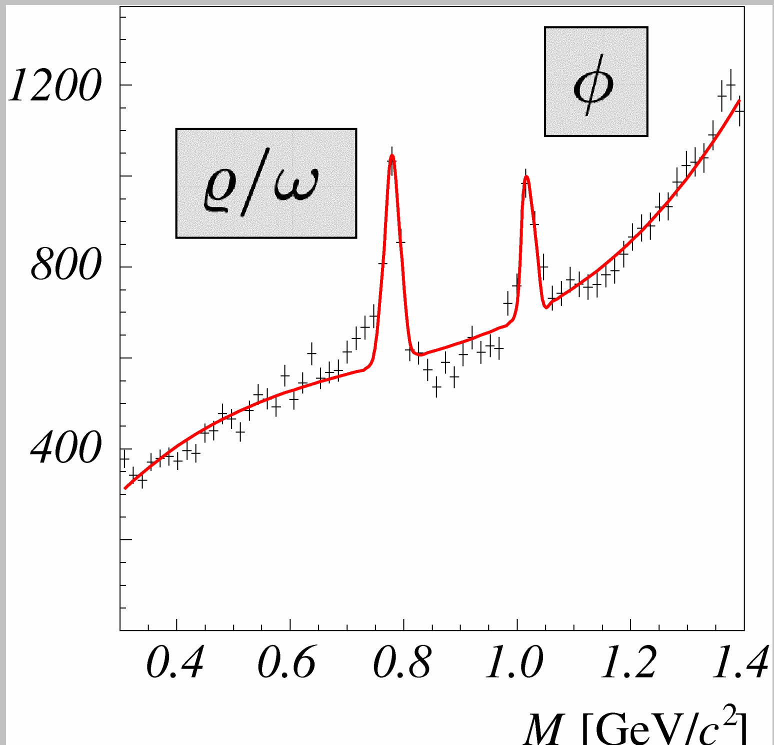


Invariant Mass of Muon Pairs (Full Statistics)

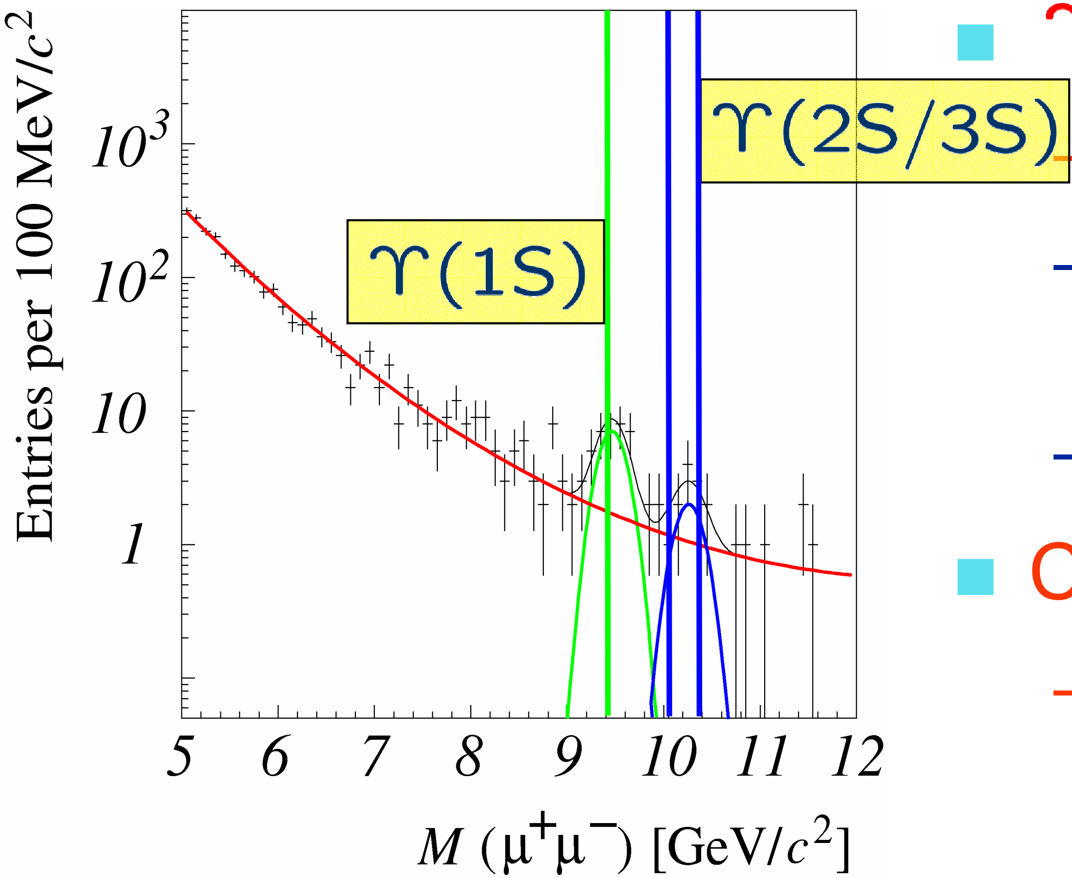


Invariant Mass of Muon Pairs

Low-mass region:

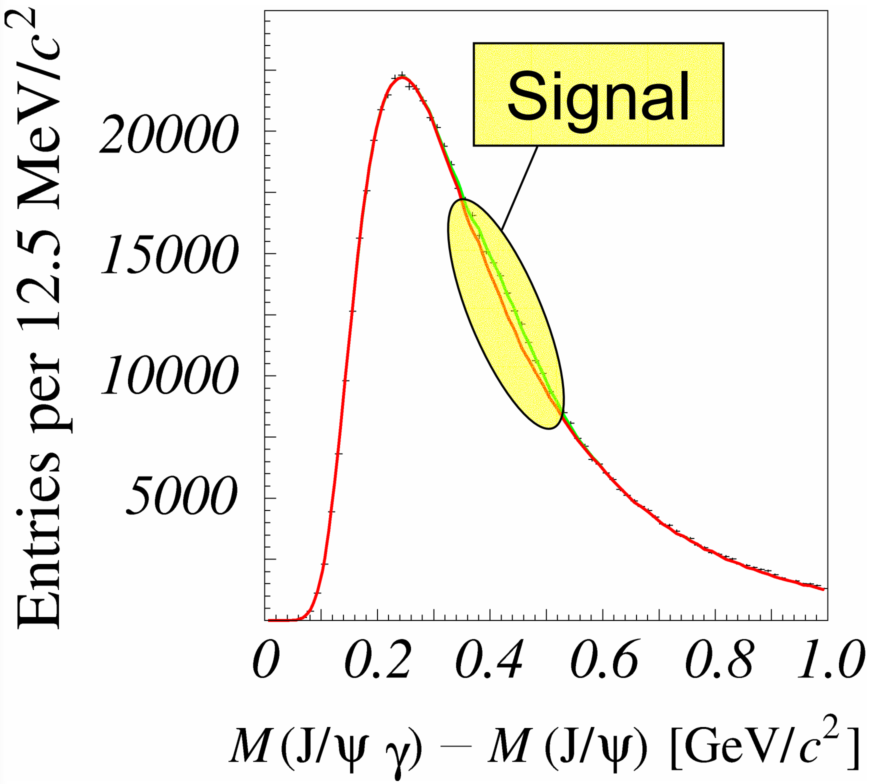


Muon Pairs with Large Invariant Masses



- Υ signals
  - Approx. 33 events
  - Masses agree with PDG values
  - Width: 150 MeV/c^2
- Continuum:
  - Drell-Yan events: study angular distributions

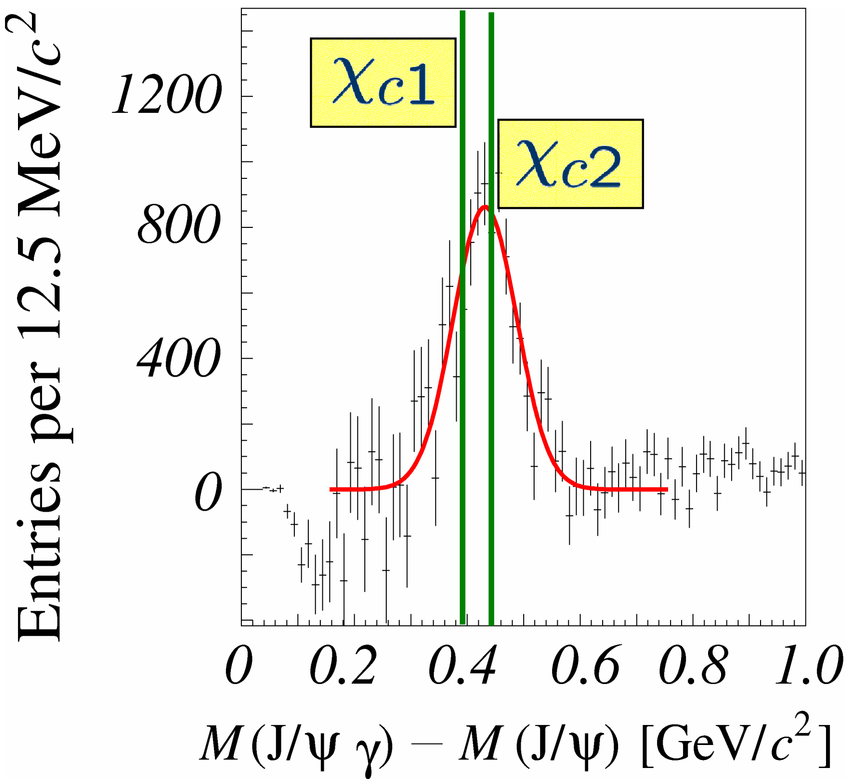
Decays of χ_c-Mesons



- Radiative decay: $\chi_c \to J/\psi\,\gamma \to \mu^+\mu^-\gamma$
- Signal in histogram of mass difference $M(J/\psi\,\gamma) - M(J/\psi)$
- Signal on top of combinatorial background from wrongly assigned photons

Decays of χ_c-Mesons

- Estimate of combinatorial background: “event mixing“, i.e. mix photons from other events → subtraction
- Approx. 9,000 events
  - Mass: 3525 MeV/c^2
  - Width: 56 MeV/c^2
- Signal: composed from χ_{c1} and χ_{c2}
- Separation of χ_{c1} and χ_{c2}: feasible with converted γ?



Physics

Physics Program 2002/2003

A. How does the production of Charmonium depend on the atomic number *A* of the target nucleus?

B. What is the $b\bar{b}$ production cross-section?

C. Charmonium spectroscopy: J/ψ, ψ', χ_c

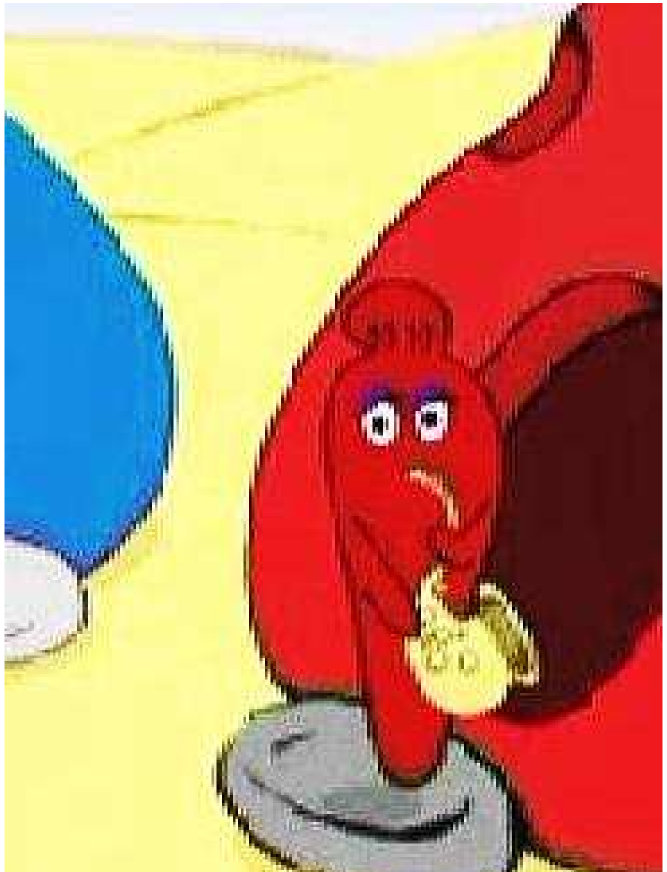
In this talk: concentrate on A. → "*A*-dependence"

Second group of topics: "Minimum Bias Program"

- 220 million events recorded with interaction trigger
- Analysis topics include strangeness production, Λ polarization, hyperons, open charm production etc.

Why is Charmonium *A*-dependence interesting?

- Learn more about mechanisms of Charmonium hadroproduction and suppression in proton-nucleus interactions
- Interesting input for heavy-ion physics (SPS, RHIC, LHC):
  - "Anomalous" Charmonium suppression: signature for quark-gluon plasma in nucleus-nucleus collisions
  - Understand Charmonium suppression in proton-nucleus collisions first
- Charm quarks play saxophone!



[Quarks & Co.]

Charmonium Production: Models (I)

Color Evaporation Model:

- Each $c\bar{c}$ pair below the open charm threshold (i.e. mass of 2 D-mesons) has probability to form Charmonium:

$$\sigma^H = A^H \int_{2m_c}^{2M_D} \mathrm{d}m \, \frac{\mathrm{d}\sigma}{\mathrm{d}m}$$

→A^H universal constant
Same cross-section for all Charmonia

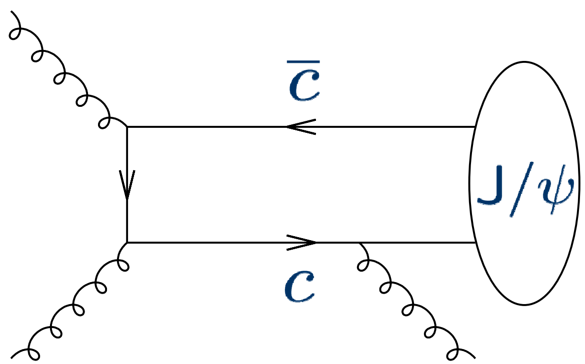
→No absolute cross-section prediction

Charmonium Production: Models (II)

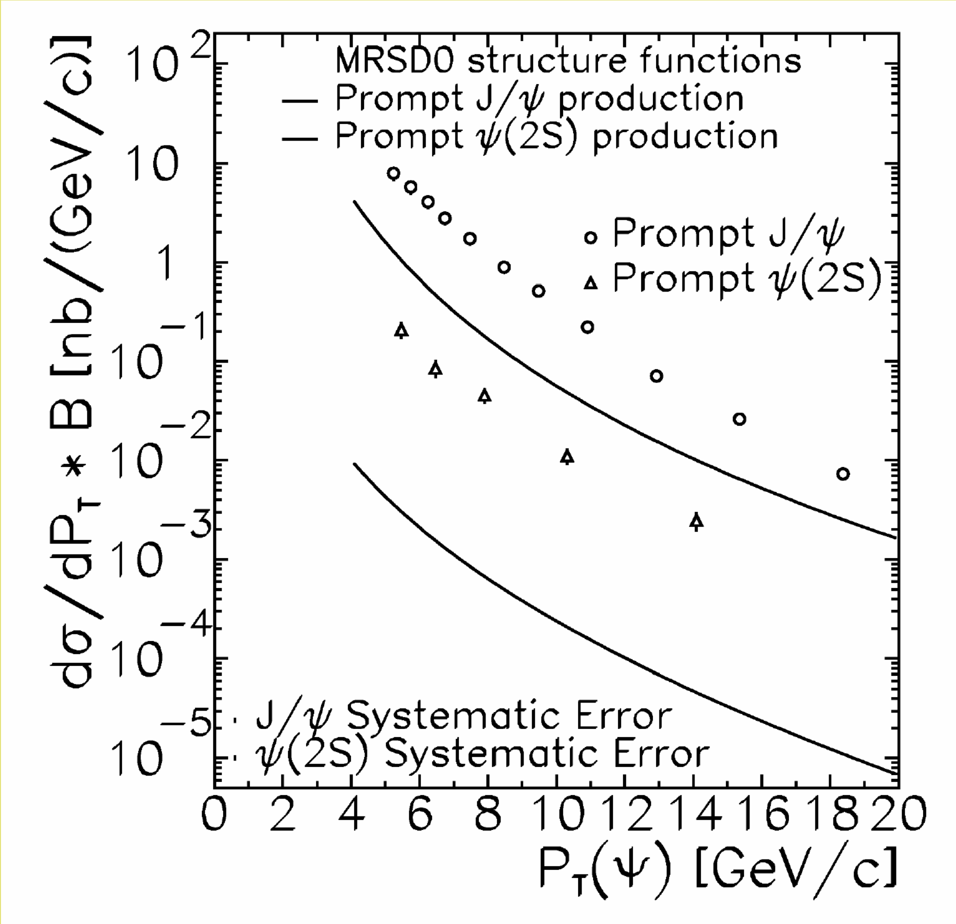
Color Singlet Model:

- Heavy-quark pair $c\bar{c}$ produced in color-neutral state, with same quantum numbers as J/ψ
- Consequence 1: no *s*-channel gluon (not color-neutral)
- Consequence 2: $C = (-1)^{L+S}$, $P = -(-1)^L$ gluon-gluon fusion yields wrong quantum numbers ($J^{PC} \neq 1^{--}$ as for J/ψ)

  → Radiate another gluon:



PROBLEM: Measured cross-section (CDF) much larger for large p_T



F.Abe *et al.*, Phys. Rev. Lett. **79** (1997) 572

Charmonium Production: Models (III)

Non-Relativistic QCD:

- Relative velocities of heavy quarks $v \ll c$:
  - Perturbative expansion in v and α_s
  - Charmonium formed from color singlet and color octet states

$$\sigma^H = \sum_n \sigma^{c\bar{c}}(n) \langle \mathcal{O}^{c\bar{c}}(n) \rangle$$

perturbative

non-perturbative

- J/ψ, ψ': sizable contribution from color octet states → CDF data can be described
- Problem: non-perturbative matrix elements from fits, not yet from lattice QCD → predictive power?

Nuclear Effects I

- Many models predict many different effects
  → Experimentally and theoretically inconclusive
- Initial state effects:
  - Shadowing:
    Nuclear parton distribution functions (PDF) are different from proton PDFs
    → HERA-B: enhancement of gluons
  - Energy loss:
    Partons lose energy while transversing nuclear matter
    → Depletion of gluons in HERA-B's kinematic range
  - Transverse momentum broadening:
    Multiple scattering with nuclear matter
    → Average p_T increases with nuclear path length

Nuclear Effects II

Final state effects:

- Absorption in nucleus:
  - "Pre-meson" (Charmonium not yet formed): lower probability of forming Charmonium due to small "p_T kicks" from other partons
  - Charmonium: σ^{abs} depending on binding energy → small effect for J/ψ, up to 4× larger for ψ', χ_c
- Absorption by "co-movers": Interaction with associated particles (close in phase space) after leaving the nucleus

→ Dissociation to open-charm mesons: D, D*, etc.

Parametrization of *A*-dependence

- Typical parametrization of *A*-dependence:

$$\sigma_{\mathrm{pA}} = \sigma_{\mathrm{pN}} \cdot A^{\alpha}$$

  Nuclear effects: $\alpha \neq 1$

- J/ψ, ψ', χ_c have different binding energies of $c\bar{c}$

  → Nuclear effects depend on Charmonium type

- Finite formation time of Charmonium state $\sim 1/m_c v^2$ could be formed inside or outside nucleus

  → Nuclear effects depend on kinematics:

$$\alpha = \alpha(x_F, p_T)$$

Parametrization of *A*-dependence

Fixed Target Kinematics:

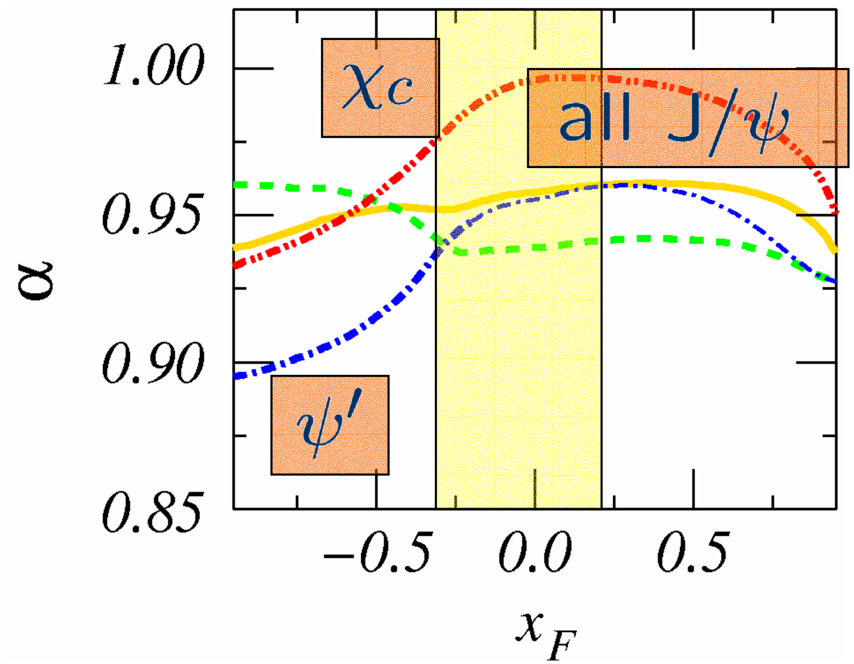
- Longitudinal momentum: Feynman's scaling variable

$$x_F \equiv \frac{p_L}{p_{L,\mathrm{max}}} = x_1 - x_2$$

- Transverse momentum: p_T

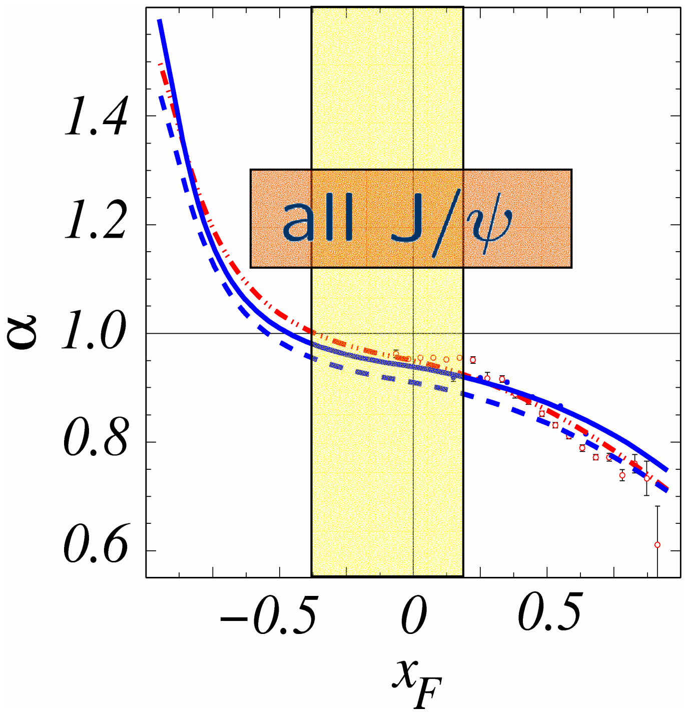
Theory: Predictions

- Prediction 1: NRQCD + nuclear effects



R. Vogt,
Nucl. Phys. **A700** (2002) 539

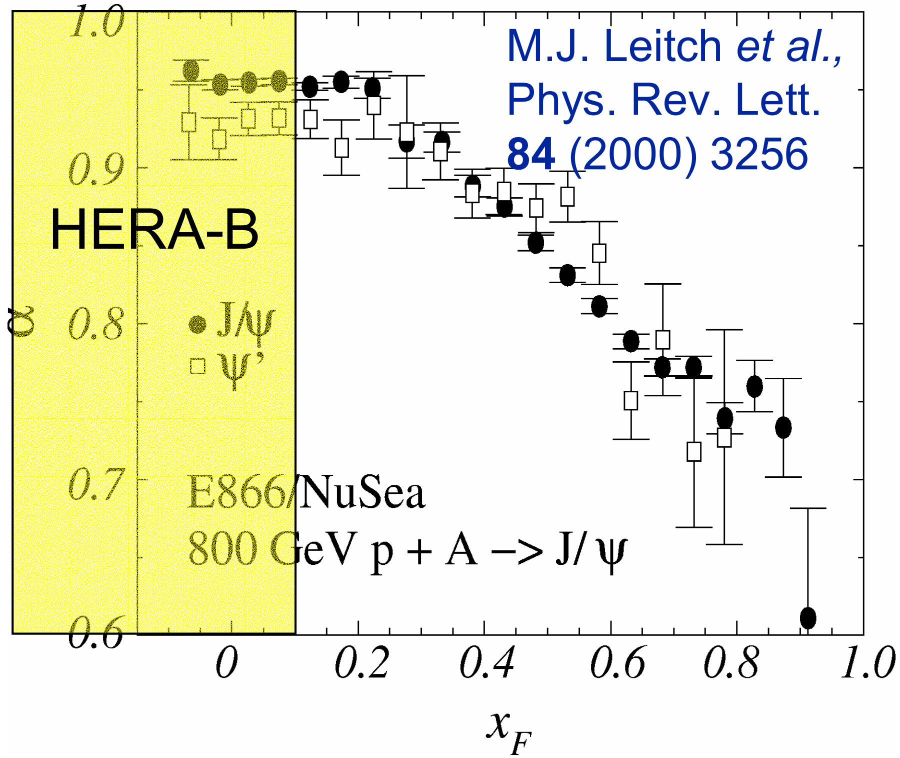
- Prediction 2: Regge theory



K.G. Boreskov, A.B. Kaidalov,
hep-ph/0303033

A-Dependence: The E866 Data

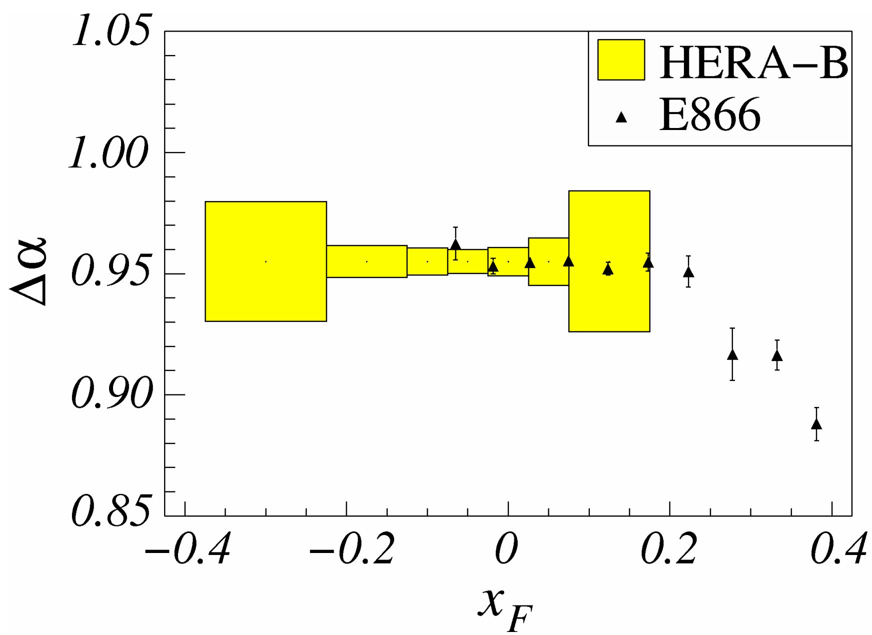
- Available measurements in proton-nucleus scattering (beam-dump experiment Fermilab E866/NuSea) as a function of x_F



HERA-B's Contribution

- Extend measurement to $x_F < -0.3$
- new: A-dependence of χ_c
- Simultaneous data-taking with C- and W-targets
  → better handle on systematic effects
- Full di-muon statistics: 3-5% uncertainty on $\alpha(x_F)$
- Further improvement by combination with di-electron channel

HERA-B: Expected uncertainty of α



Analysis

Analysis Chain

- Remember: $\sigma_{\text{pA}} = \sigma_{\text{pN}} A^{\alpha}, \qquad \sigma = N/\varepsilon\mathcal{L}$

  → α can be determined from measurement with two materials, in HERA-B: two-wire running

$$\alpha = \frac{1}{\log(A_1/A_2)} \log\left(\frac{N_1}{N_2} \frac{\mathcal{L}_2}{\mathcal{L}_1} \frac{\varepsilon_2}{\varepsilon_1}\right)$$

- 3 ingredients of *A*-dependence measurement:

  1: Ratio of J/ψ yields

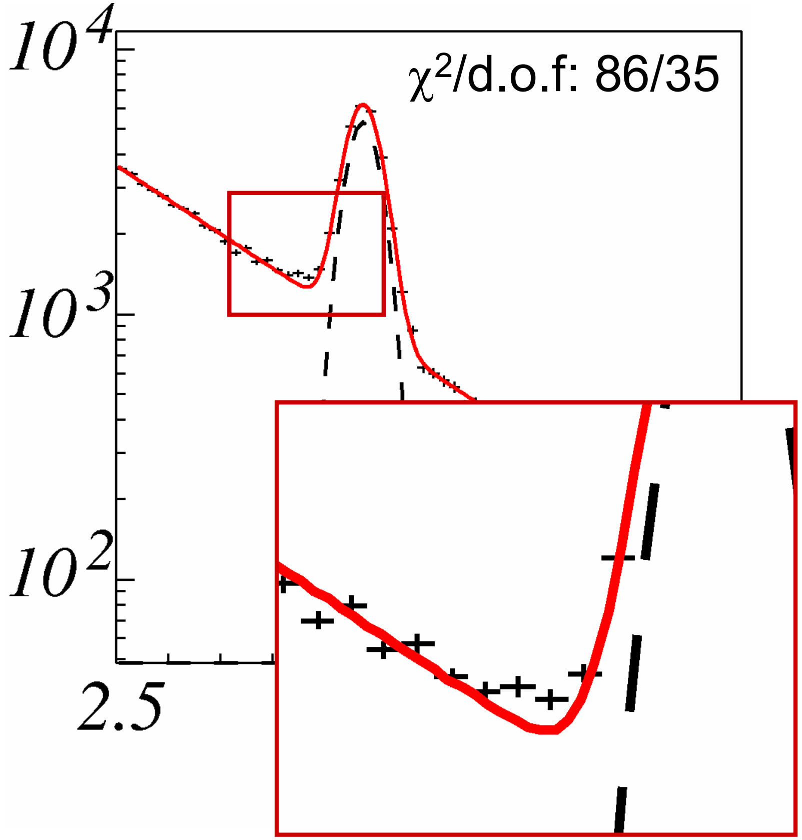
  2: Ratio of luminosities

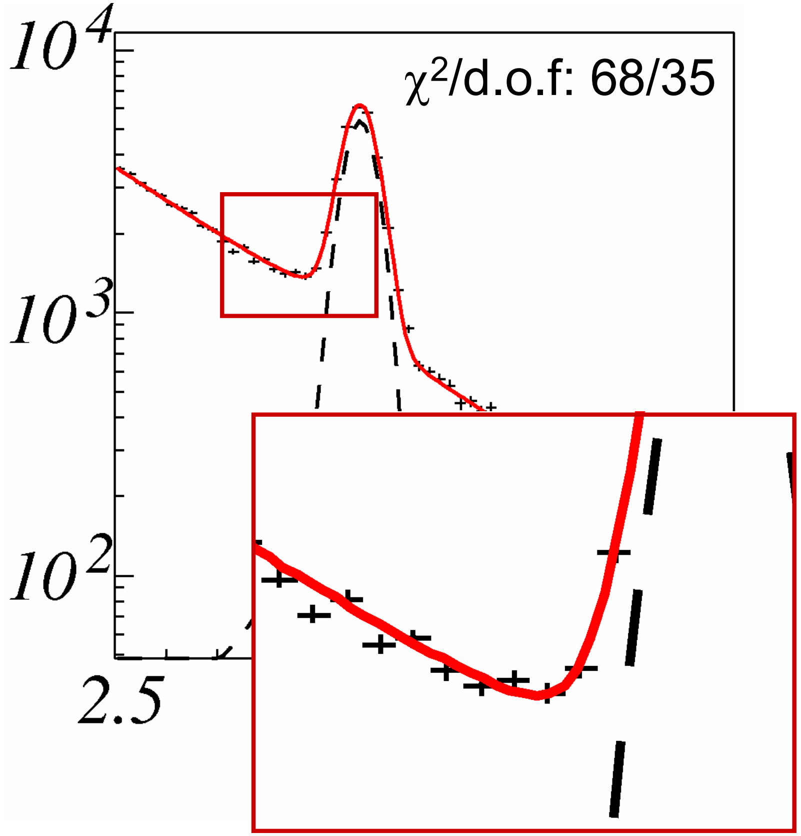
  3: Ratio of efficiencies

Ingredient 1: J/ψ Yield

- Selection of muon pairs:
  - "Long" tracks crossing Vertex Detector and Main Tracker, confirmed by Muon Detector
  - Vertex fit of opposite-charge track pairs, cut on minimum χ^2-probability of vertex
- Number of J/ψ from fit to invariant mass spectrum:
  - Signal width dominated by detector resolution: Gaussian signal model
  - Combinatorial background, mainly decays in flight of pions and kaons, $\pi/K \to \mu\nu$: Exponential background model

Fitting the J/ψ Signal

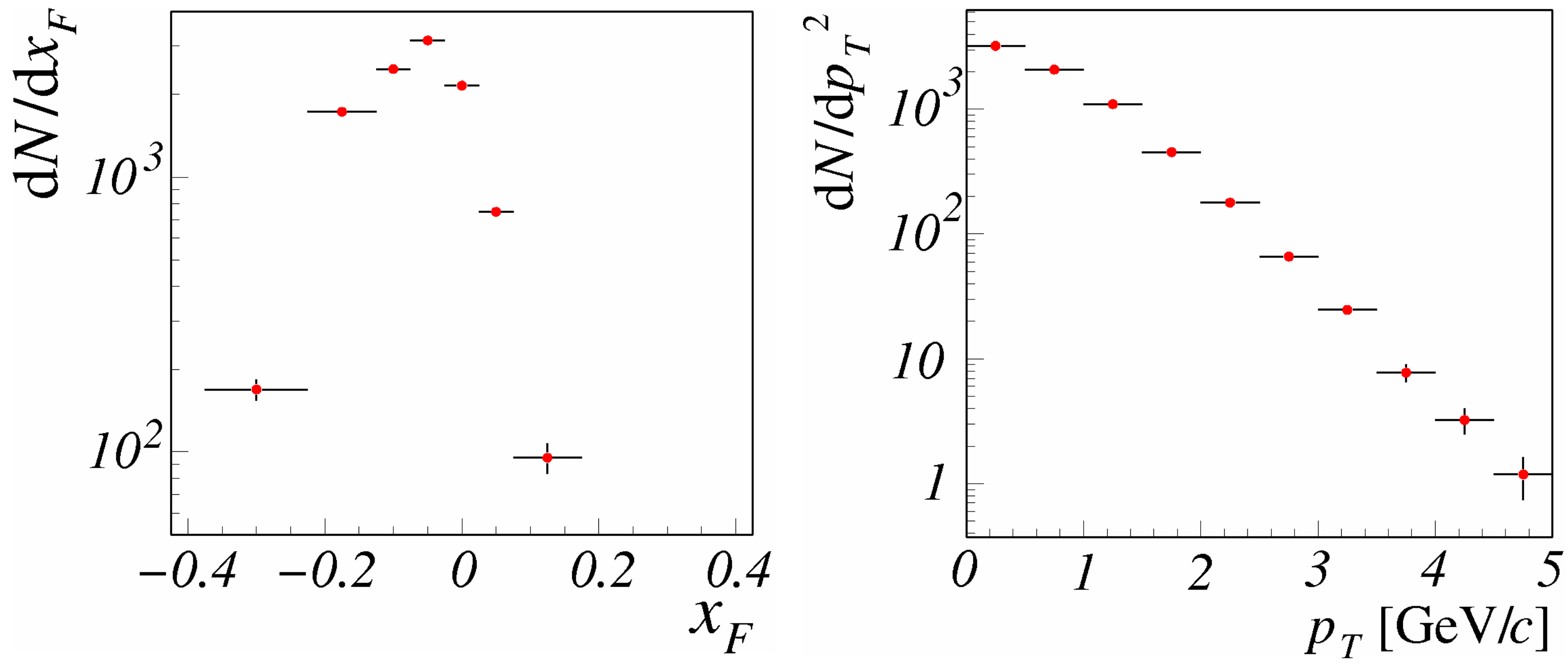




- QED predicts final state radiation: J/ψ signal contains 5% contribution of radiative decay $J/\psi \rightarrow \mu^+\mu^-\gamma$

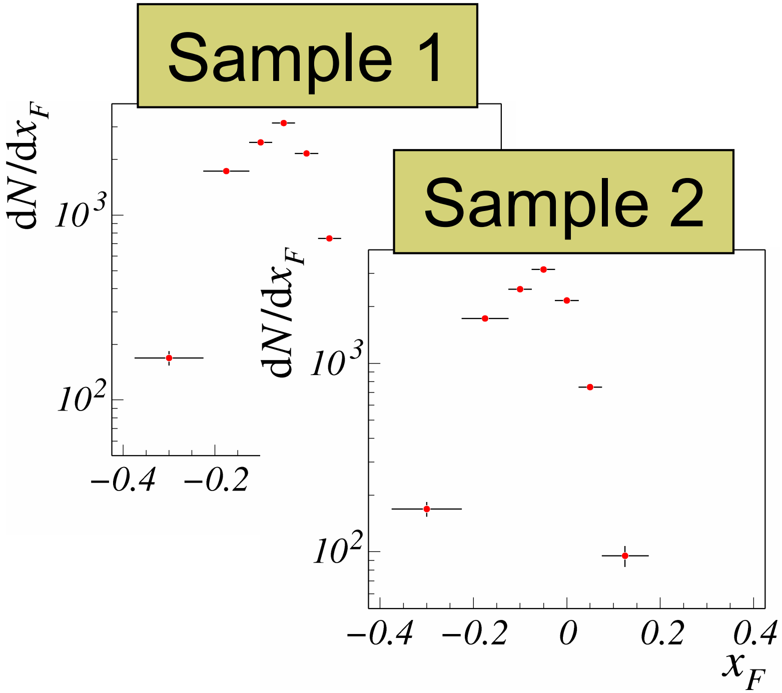
Raw Spectra: x_F and p_T

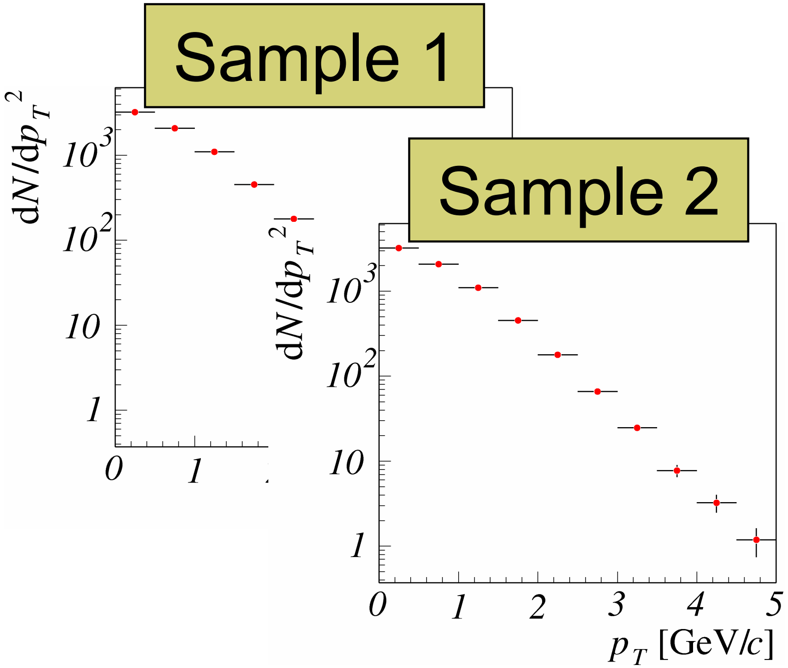
- Step 1: Split up data-sets in two samples: wire 1/2
- Step 2: Fit invariant mass spectrum in bins of x_F / p_T:



Raw Spectra: x_F and p_T

- Step 1: Split up data-sets in two samples: wire 1/2
- Step 2: Fit invariant mass spectrum in bins of x_F / p_T:
- Two samples: apply corrections and calculate ratios





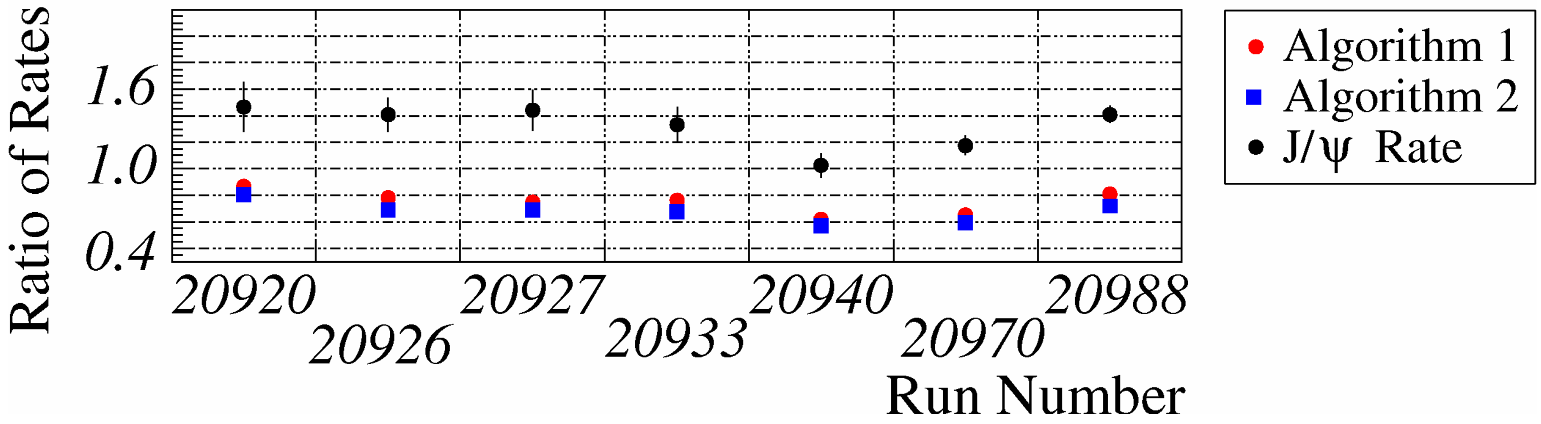
Ingredient 2: Luminosity

- Ratio of luminosities obtained from ratio of interaction rates (same dead-time!)
  → Measure interaction rate ratio for inelastic events
- Target provides automatic rate-sharing mechanism: Current of δ-electrons emitted from wire proportional to interaction rate
- Rate-sharing depends on quality of target calibration
  → Cross-check rate sharing from data
- Control sample in J/ψ data: inelastic events recorded with random trigger (rate: 4 Hz)

Rate Sharing

Two ways of measuring rate sharing:

- Algorithm 1: count primary vertices per wire
  → Need vertexing efficiency from MC
- Algorithm 2: count tracks from primary vertices
  → Need average track multiplicity per wire material



→Agreement within 5-10% (still expected to improve)

Ingredient 3: Efficiency

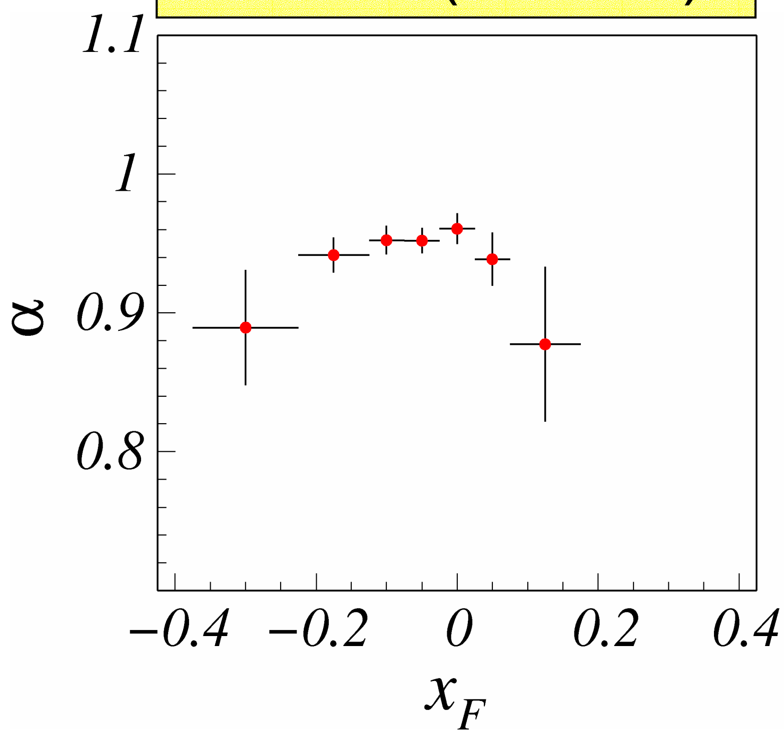
- Efficiency to detect J/ψ is composed of
  - Geometrical acceptance of detector and trigger: wires separated by approx. 4 cm in proton flight direction
  - Detector and trigger efficiency (varying in space & time)
  - Reconstruction efficiency
  - → All efficiencies are functions of the kinematic variables
- Relative measurement: need only efficiency ratios
  - Efficiencies expected to cancel to first order in ratios
  - Correct only for geometrical acceptance? → to be checked!
- Monte-Carlo-based acceptance correction methods:
  - Correct every x_F/p_T-bin by $N(J/\psi)_{generated} / N(J/\psi)_{reconstructed}$
  - Unfolding techniques

Reference Measurement I

Measure “α” in data-set without *A*-dependence:

- Events in single-wire runs (same acceptance): split up into two random samples:
  - Data set equivalent to ¼ of full two-wire statistics
  - α compatible with flat distribution (46% prob.)
  - Uncertainties cross-checked with non-parametric method (“Bootstrap MC”)

Single Wire: Inner 2 (Carbon)



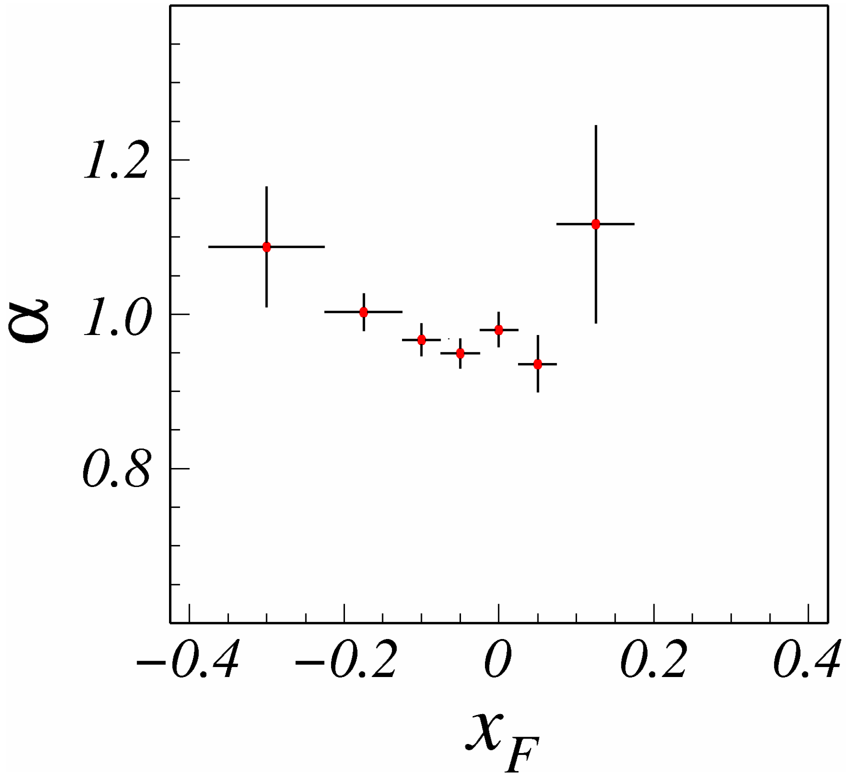
Reference Measurement II

- Measure "α" in runs with two wires of the same material: understand acceptance effects
- Bin-by-bin acceptance correction from MC with (simplified) trigger simulation: "α" is "less flat" (27% probability)

→ More detailed MC

→ Acceptance from data

Two Carbon Wires: Below 1 – Inner 2



Analysis: Current Status

Analysis of Charmonium *A*-dependence:

- Extraction of Charmonium signals ☑
- Correction for luminosity ratio ongoing
- Correction for efficiency ratio ongoing

Summary & Conclusions

- HERA-B has successfully finished the data-taking period 2002/2003
  → approx. 300,000 J/ψ on tape
- One of the main physics goals:
  A-dependence of Charmonium production
- *A*-dependence analysis ongoing:
  first results expected end of this year