# Measuring diffractive processes at HERA

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[DESY]

Contents:

- Rapidity gap / Mx methods
- HERA-I: FPS detectors and results
- HERA-II VFPS status and prospects

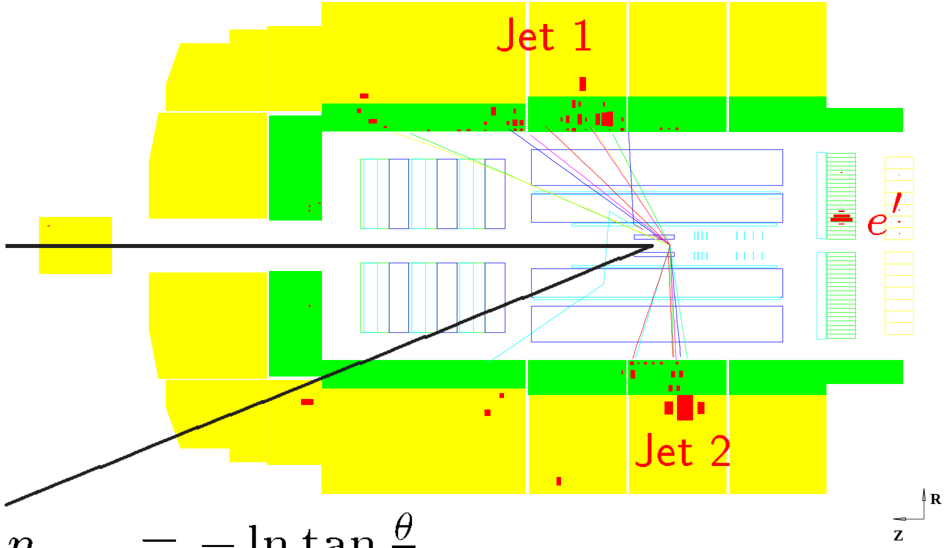
Diffraction at the LHC

Rio de Janeiro, April 2004

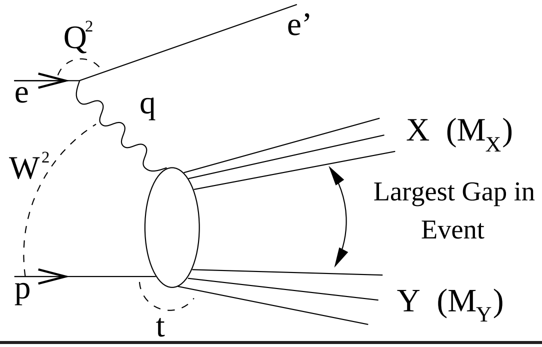
# The Rapidity Gap Method (H1,ZEUS)

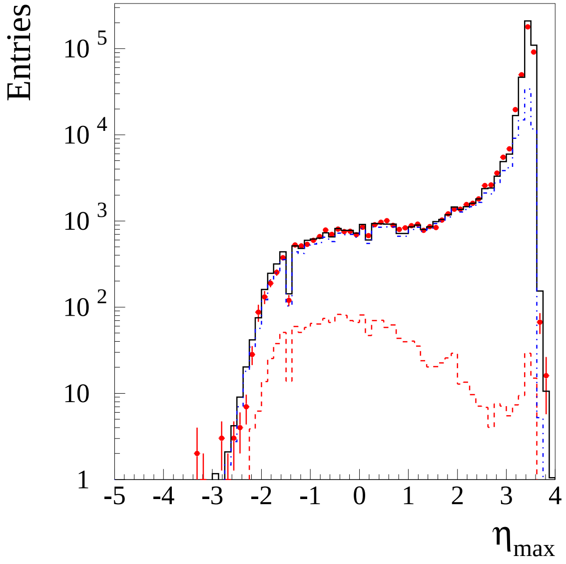
Select (offline!) diffractive events by demanding no activity above noise in fwd part of detector

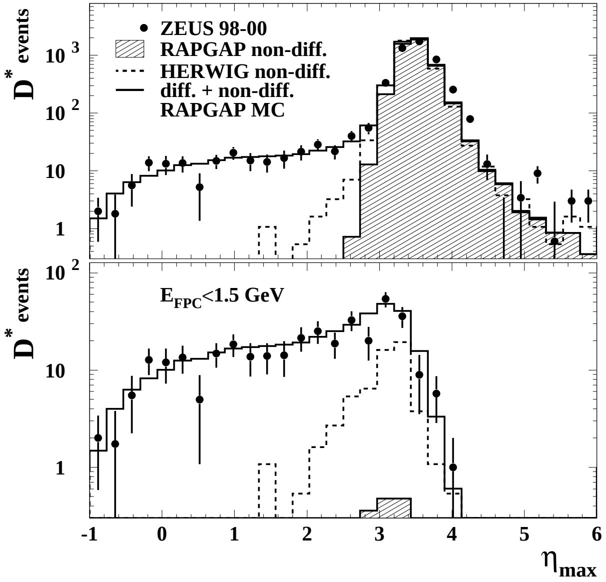
$\eta_{max}$: rapidity of most fwd. cluster with $E > E_{min}$



$$\eta_{max} = -\ln\tan\frac{\theta}{2}$$



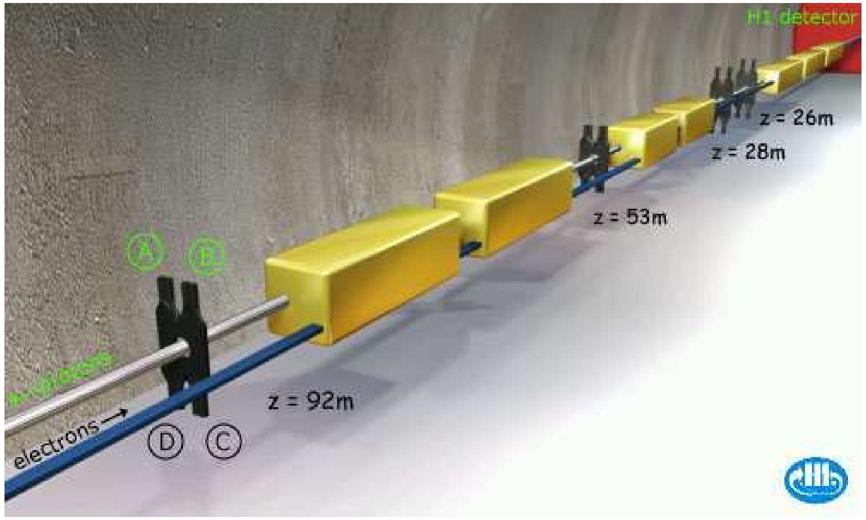




# The Rapidity Gap Method (cont.)

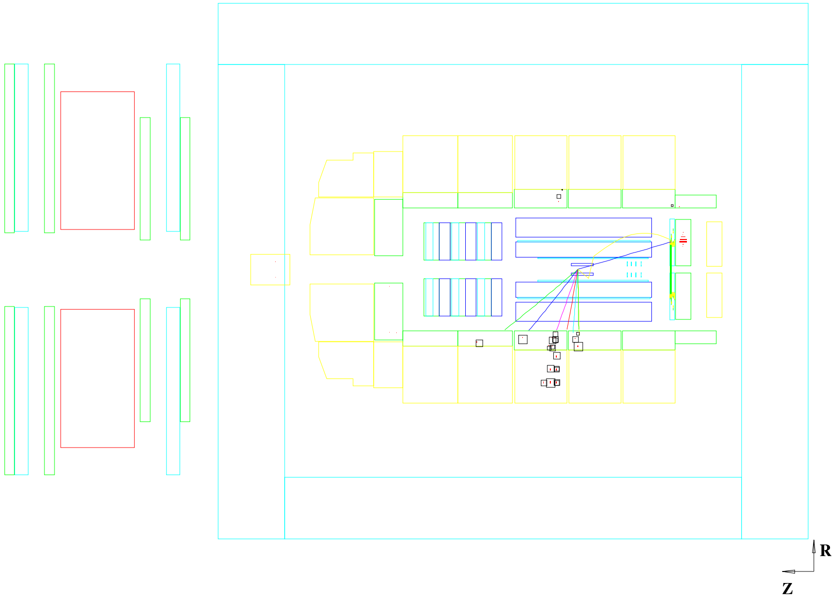
Complement $\eta_{max}$ with detectors sensitive to very fwd. particle production

## Forward Tagging System FTS



- – Scintillator pairs surrounding $p$ beam pipe
- – Veto on hits
- – Sensitive to $6.0 < \eta < 7.5$
- – Problem: aging

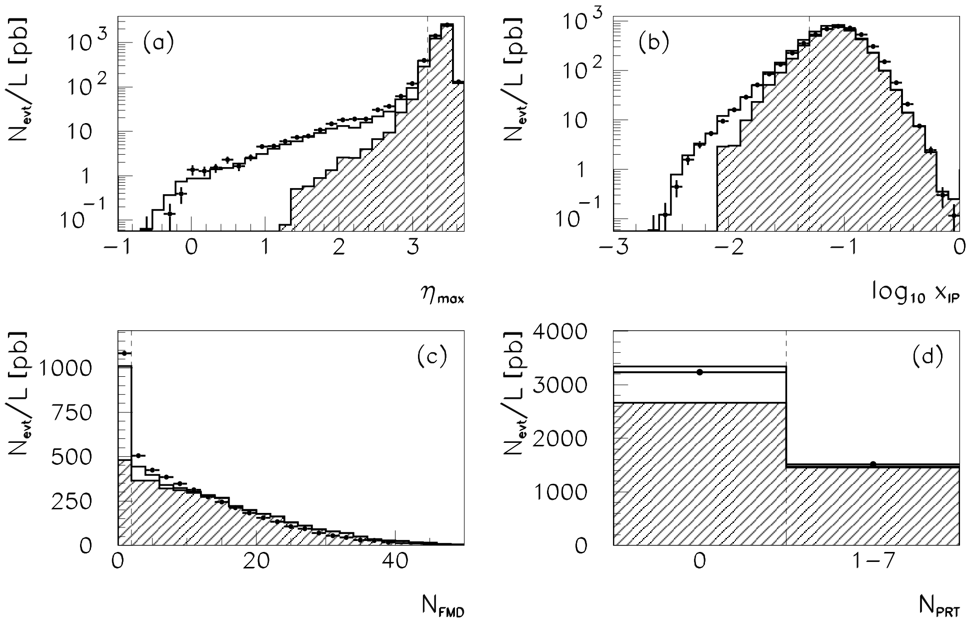
## Forward Muon Spectrometer FMD

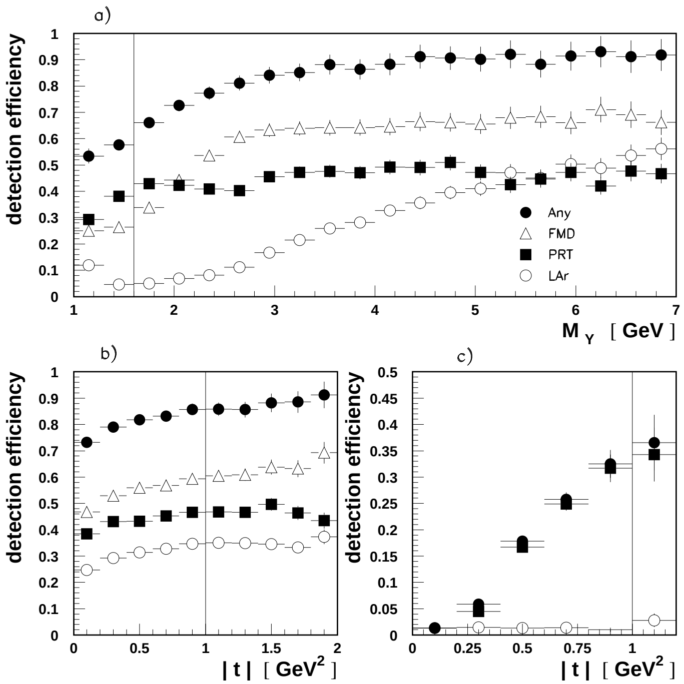


- – Veto on hit pairs in pre-toroid layers
- – Sensitive to $\eta < 3.7$
- – indirectly even to bigger $\eta$ due to secondary scattering)

# The Rapidity Gap Method (cont.)

## Diffractive Selection:





– typically $\eta_{\max} < 3.2$
– additional $x_{I\!P} < 0.05$ cut to reduce non-diffr. and reggeon contributions
– good description by sum of diffr.+non-diffr. MC

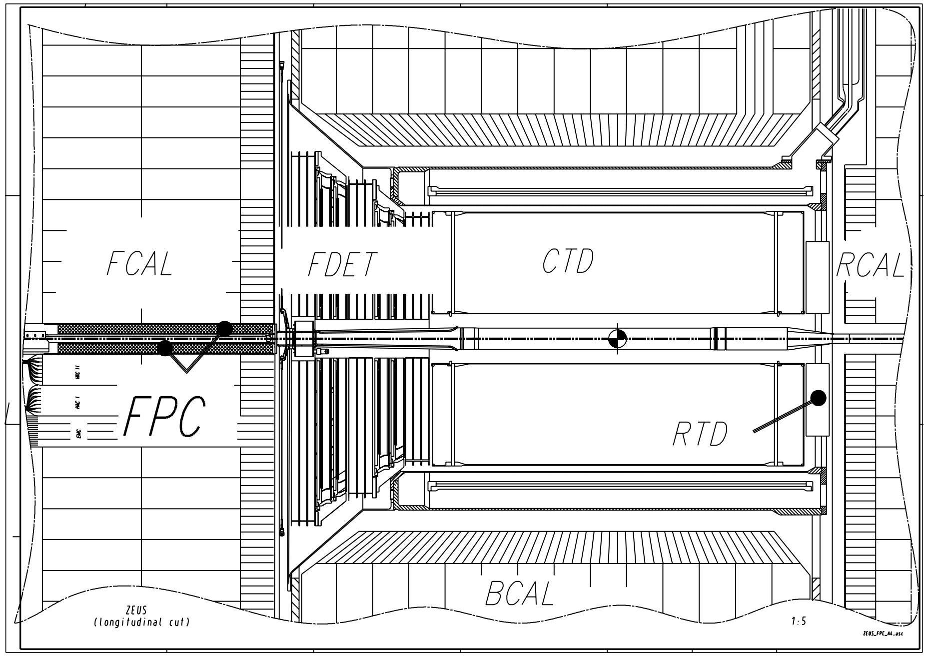
– Efficiency for dissociation (a,b) and elastic (c)

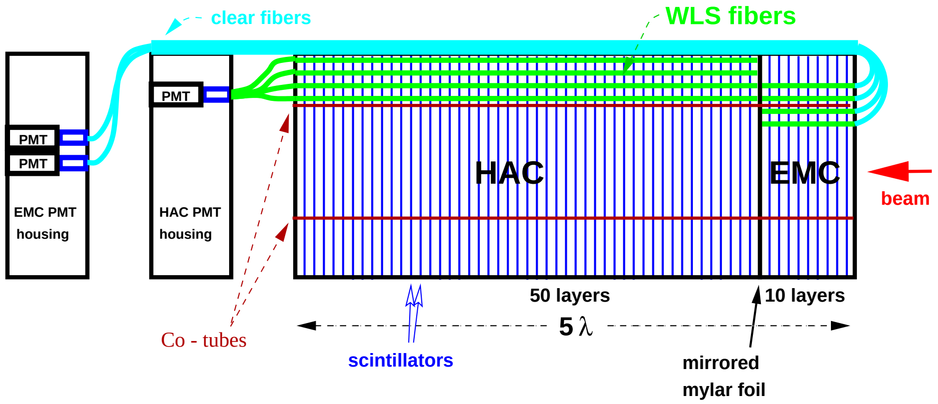
– Profit from combination of several detectors

Final cross sections corrected to well-defined region $M_Y < 1.6$ GeV, $|t| < 1.0$ GeV$^2$

Dominant systematic uncertainty due to this correction (modelling of $Y$ system)

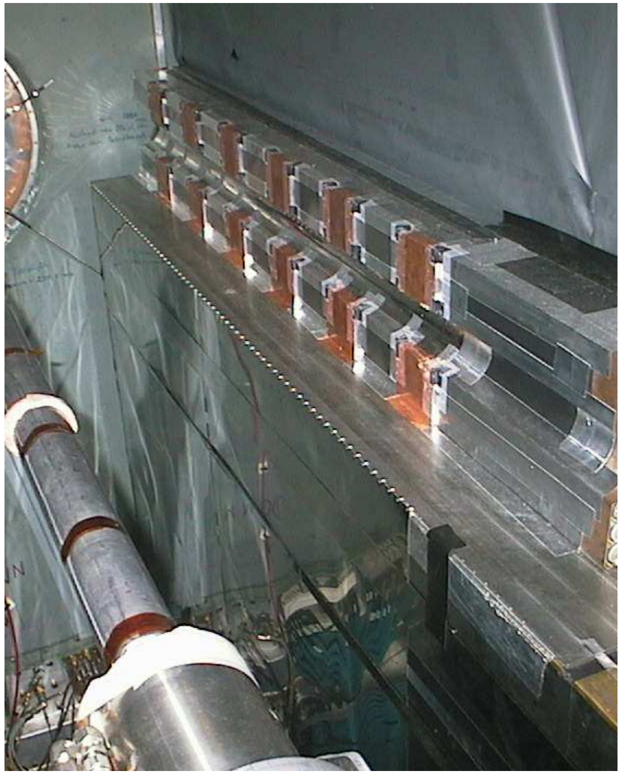
# The ZEUS Forward Plug Calorimeter (1998-2000)

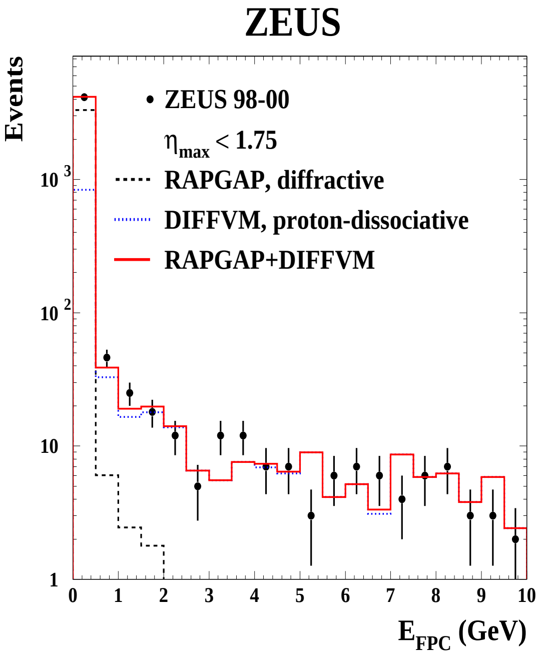




- Lead/scintillating fibre sandwich calorimeter
- Installed in 20x20 cm diameter beam hole of forward Calorimeter
- 3.2 cm radius hole for beampipe
- Length 110 cm, 5.4 $\lambda$ (nucl. absorption lengths), EM+HAD sections
- Increase acceptance from $\eta = 4$ to 5

# The ZEUS Forward Plug Calorimeter (cont.)

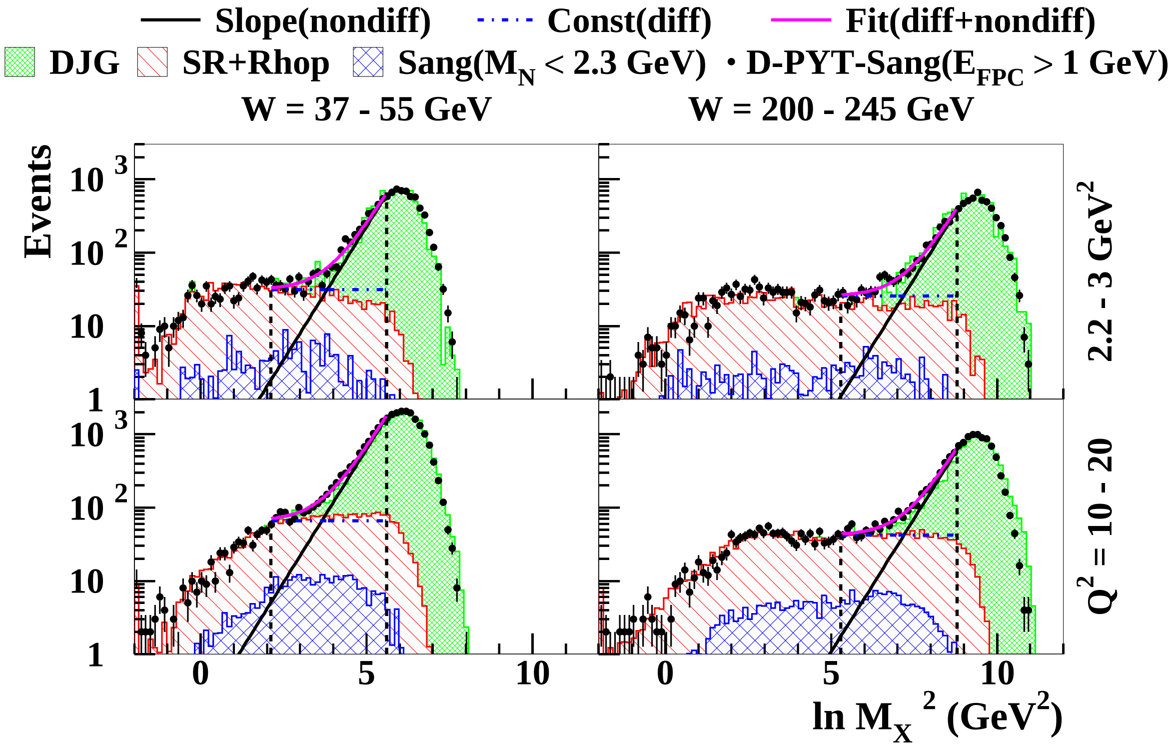




- hadronic(elmg.) energy resolution: $\sim 65(40)\%/\sqrt{E/GeV}$
- Absolute scale uncertainty: em: $4\%$ had: $3\%$
- Increased acceptance at high $M_X$ and low $W$

- Rejection of p dissociation for $M_Y > 2.3$ GeV
- Device removed for lumi upgrade (s.c. quad installation)

# The $M_X$ Method (ZEUS)



Properties of $M_X$ distribution:

- Exponentially falling for decreasing $M_X$ for non-diffractive events (random gap probability)
- flat vs $\ln M_X^2$ for diffractive events

$$\frac{dN}{d\ln M_X^2} = D + ce^{b\ln M_X^2}$$

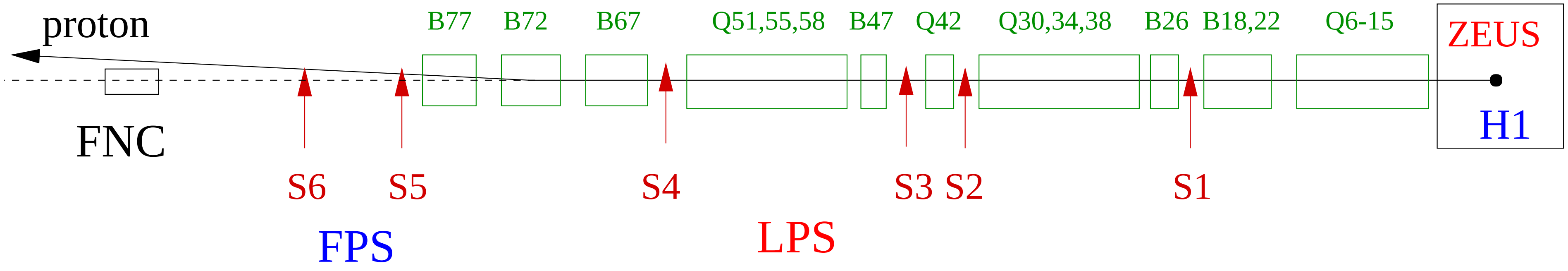
Determine $D$, $c$, $b$ from fit in each measured bin

Contamination from dissociation: $ep \rightarrow eXY$

Benefits from FPC calorimeter (larger $M_X$)

# The H1 Forward Proton Spectrometer FPS

- Roman Pot technology, scintillating fiber detectors
- readout by position sensitive photo-multipliers (PSPM)



proton

B77 B72 B67 Q51,55,58 B47 Q42 Q30,34,38 B26 B18,22 Q6-15

ZEUS

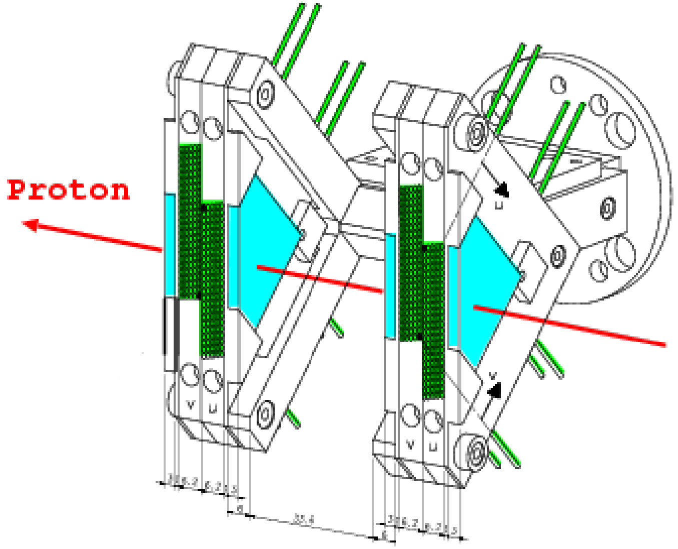
H1

FNC

S6 S5 S4 S3 S2 S1

FPS

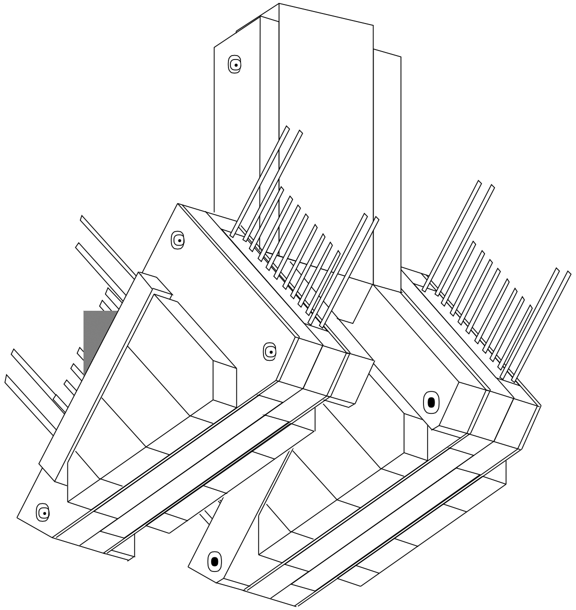
LPS



- $x_{I\!P}$ measurement: $x_{I\!P} = 1 - \frac{E'_p}{E_p}$
- $t$ measurement: $p_X, p_Y, x_{I\!P}$
- sensitive in the range $x_{I\!P} < 0.5$
  (but low acceptance in diffractive regime)
- low p dissociation background

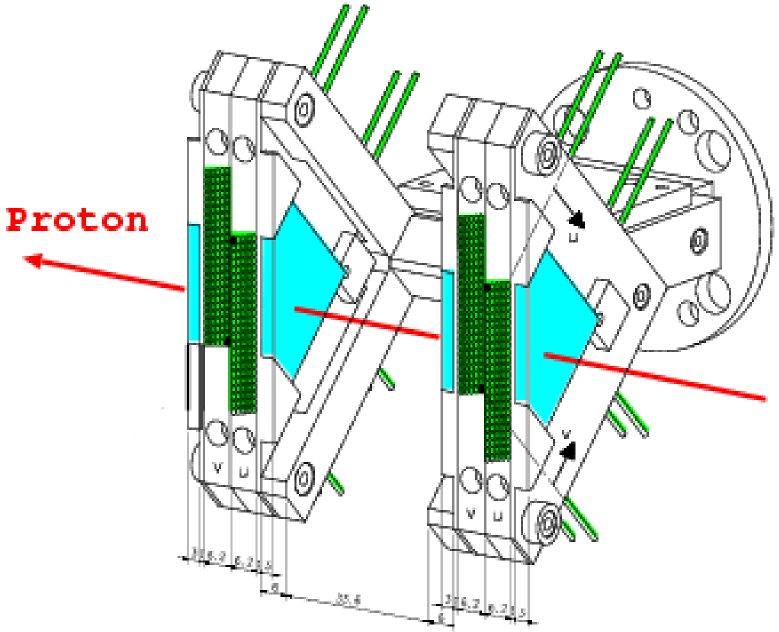
# FPS: Vertical and Horizontal Stations

## Vertical: 2 stations at 81 and 90m



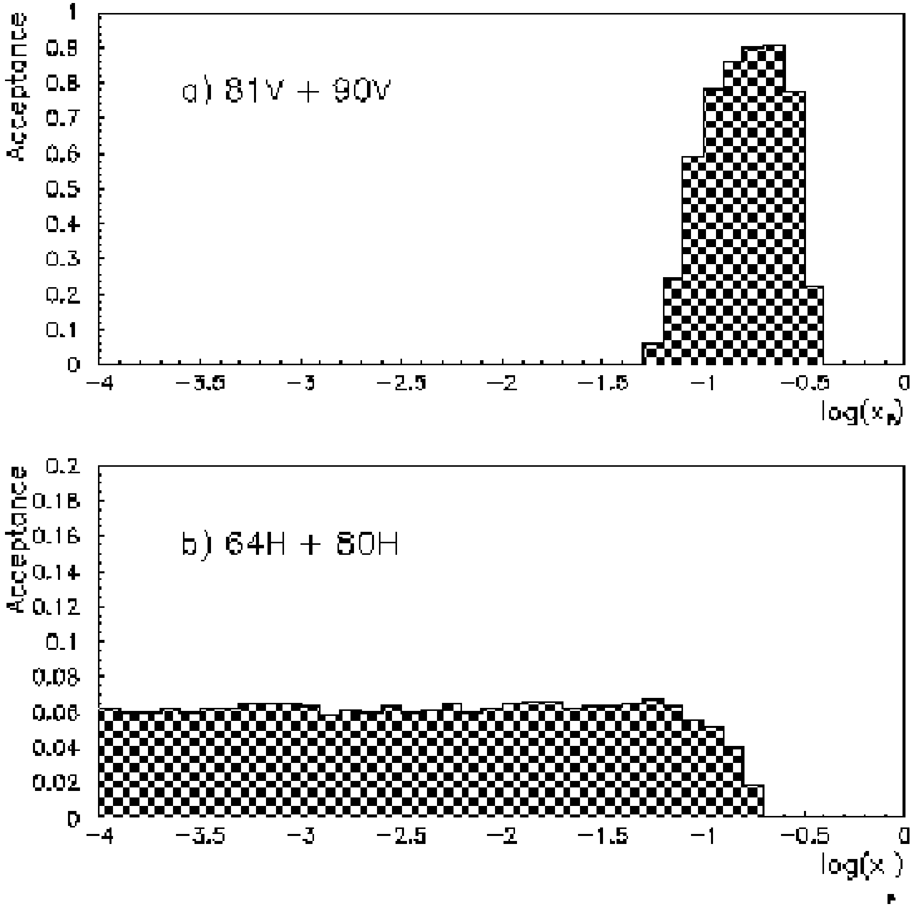
- 2 fiber detectors per pot (u/v)
- 5 fiber layers per coordinate (48/layer)
- 4 fibers / PSPM pixel (multiplexing)
- 4 64-pixel fine mesh Hamamatsu PSPM's per Pot

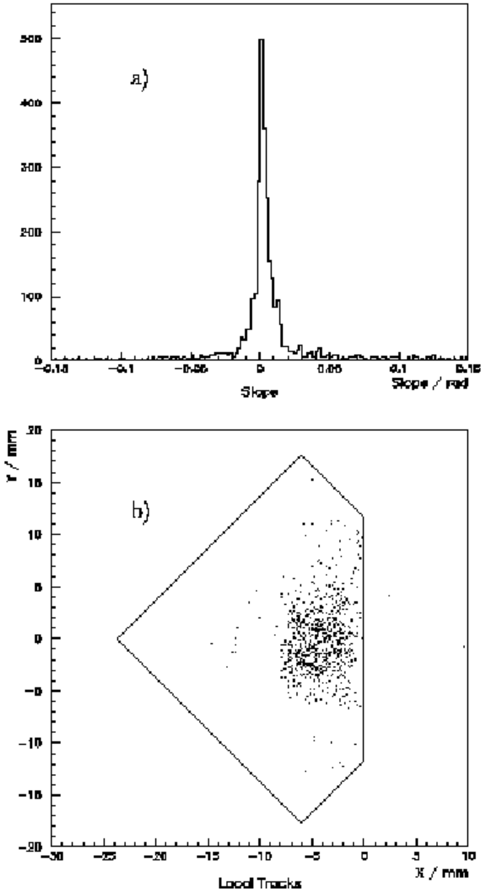
## Horizontal: 2 stations at 64 and 80m



- 2 fiber detectors per pot (u/v)
- 5 fiber layers per coordinate (24/layer)
- no multiplexing
- 4 124-pixel micro channel plate PSPM's per Pot

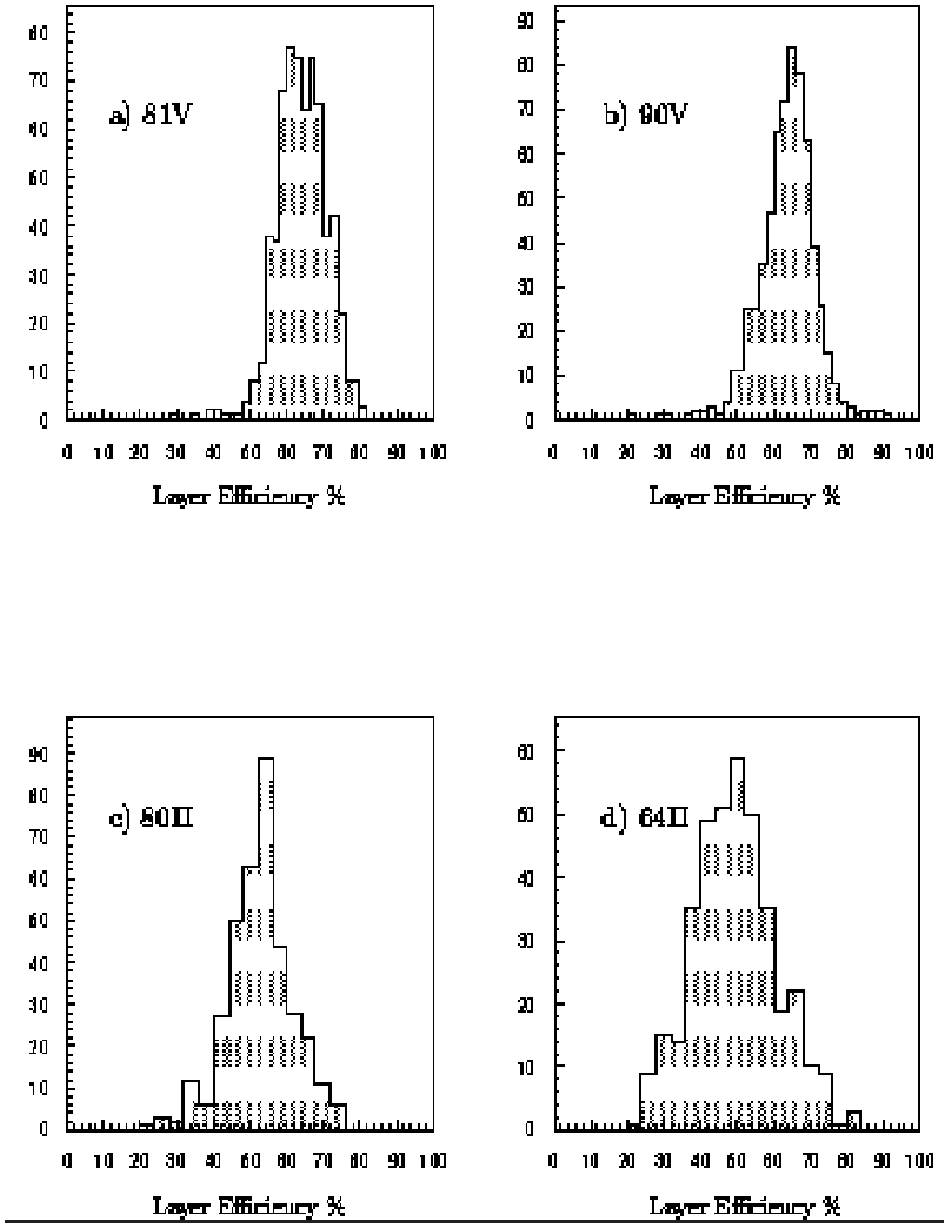
# FPS: Acceptance





- Vertical FPS acceptance: $0.1 < x_{I\!P} < 0.5, p_T < 0.4$ GeV
- Horizontal FPS acceptance: $x_{I\!P} < 0.15, 0.06 < |t| < 0.6$ GeV$^2$

# FPS: Fiber layer efficiency + upgrade



- Vertical FPS: Fiber layer eff. $60 - 70\%$
  Track eff in 2 pots $\sim 50\%$
  reduced to $30\%$ after 5 years

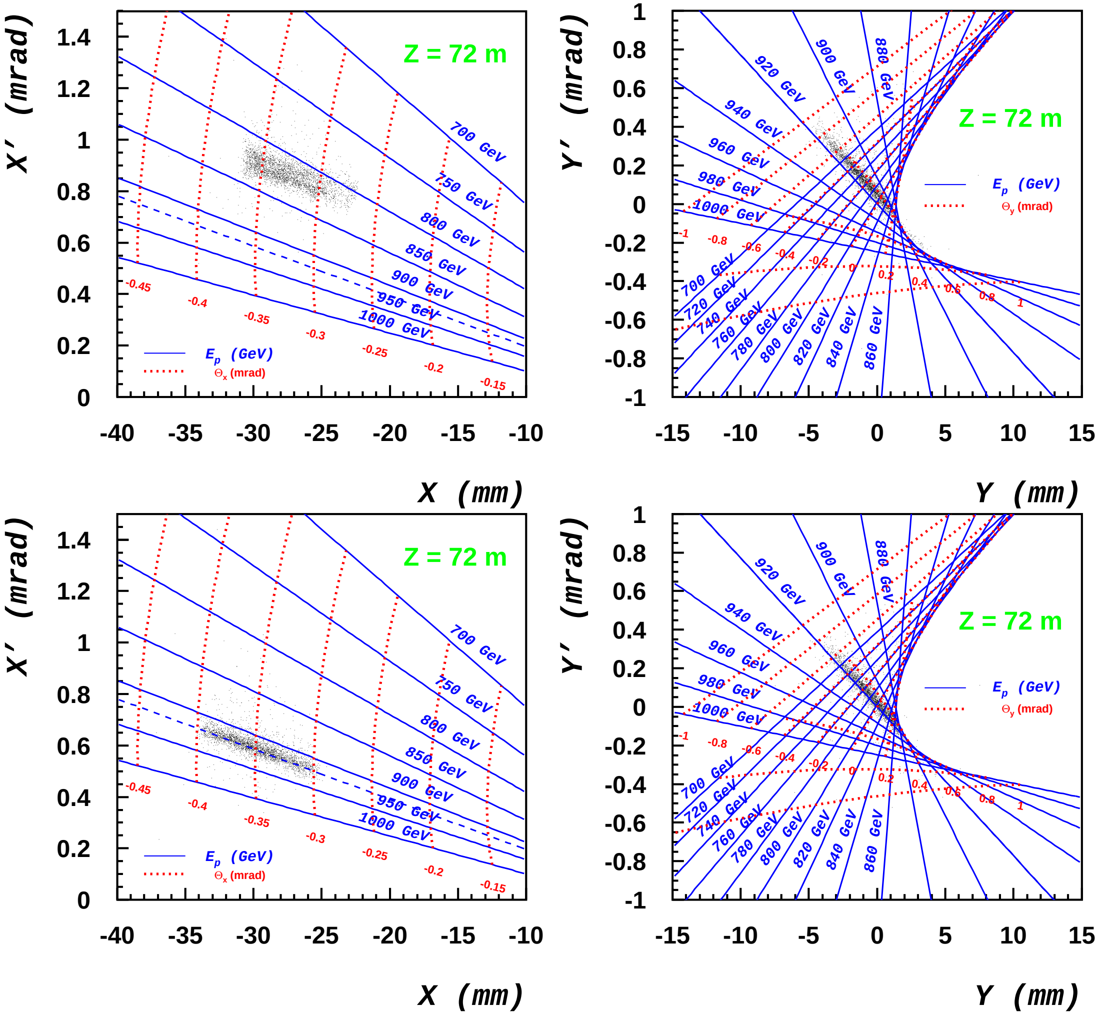
- Horizontal FPS: Fiber layer eff. $50\%$
  Track eff in 2 pots $\sim 30\%$
  reduced to $20\%$ after 2 years

- Radiation degradation of fibers;
  reduced PSPM efficiencies

HERA-II upgrade:

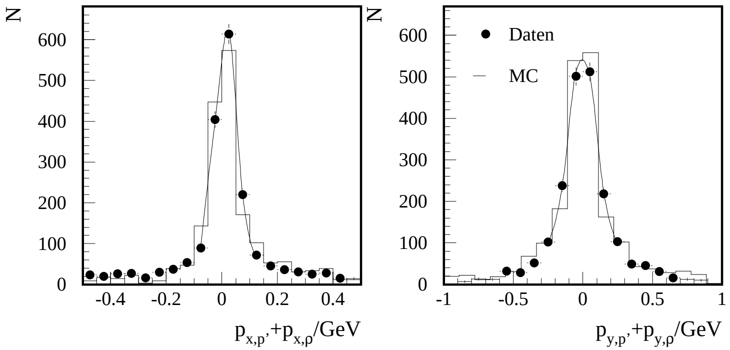
- New radiation resistent scintillating fibers
- 0.48 mm fibers: better resolution
- New PSPM's

# FPS: Calibration

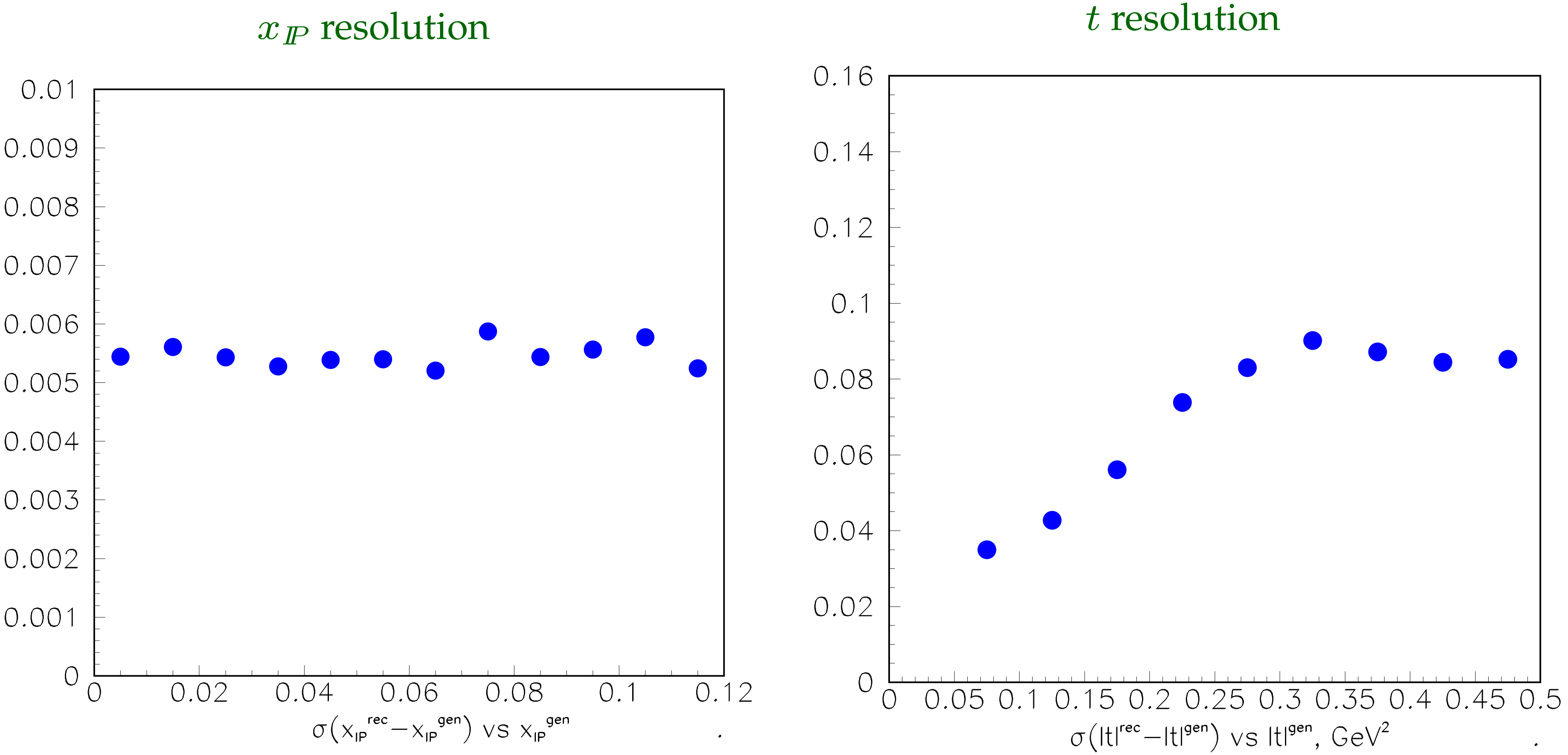


Calibration of horizontal stations:

- Use elastic $\rho$ meson photoproduction $\gamma p \rightarrow \rho p'$
- Momentum balance between $\rho$ and leading proton



# FPS: Resolution

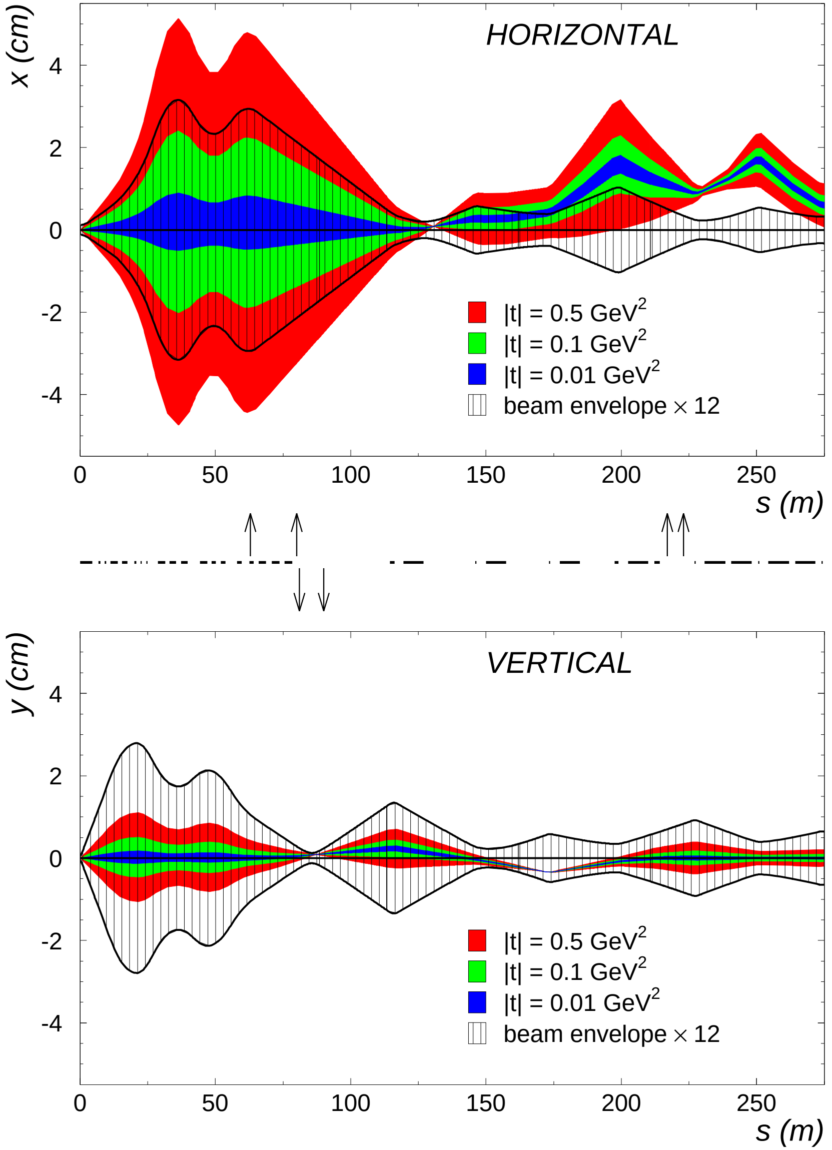


- Resolution dominated by beam optics, fiber detector resolution and Pot position calibration
- $x_{I\!P}$ resolution better than reconstruction from central detector for $x_{I\!P} > 0.02$
- 4 $|t|$ bins for $0.08 < |t| < 0.5$ GeV$^2$

# The H1 Very Forward Proton Spectrometer VFPS

- Tag and measure scattered proton at HERA II with large acceptance at low $x_{I\!P}$ and down to lowest $|t|$

- Precision studies of $ep \longrightarrow epX$



HERA II beam optics simulation:

- Best location is at 220m in horizontal plane (use HERA bend)

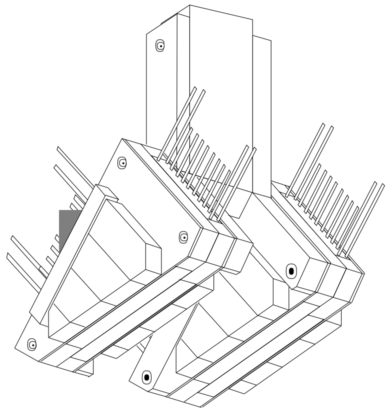
- Down to $t = 0$ for $x_{I\!P} \sim 0.01$

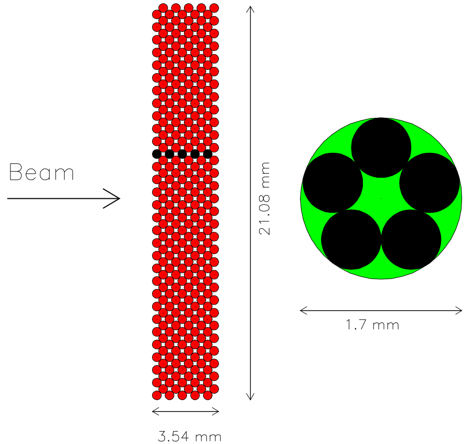
BUT: Cold magnet section!

# VFPS: Detector Design

## Detectors:

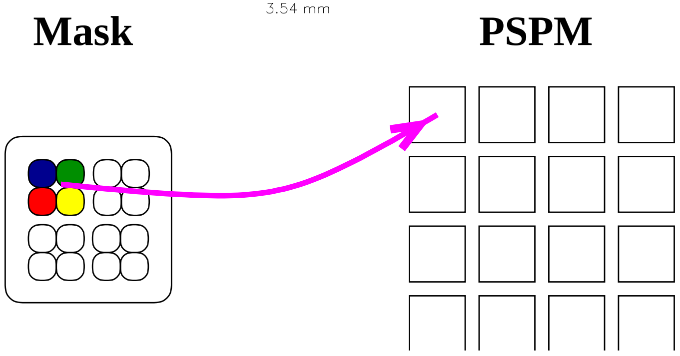
- Same design as vertical FPS
- 2 detectors at 218m and 222m
- 2 planes (u,v) per detector
- 5 fiber layers / plane
- 4 trigger tiles / plane
- Fibers for spatial reconstruction
  $\longrightarrow$ Resolution $100\mu$





## Optical Connection:

- Tiles: PM; Fibers: PSPM
- 1 light guide / plane of 5 fibers
- 4 light guides / PSPM pixel
  (multiplexing, decode with trigger tiles)



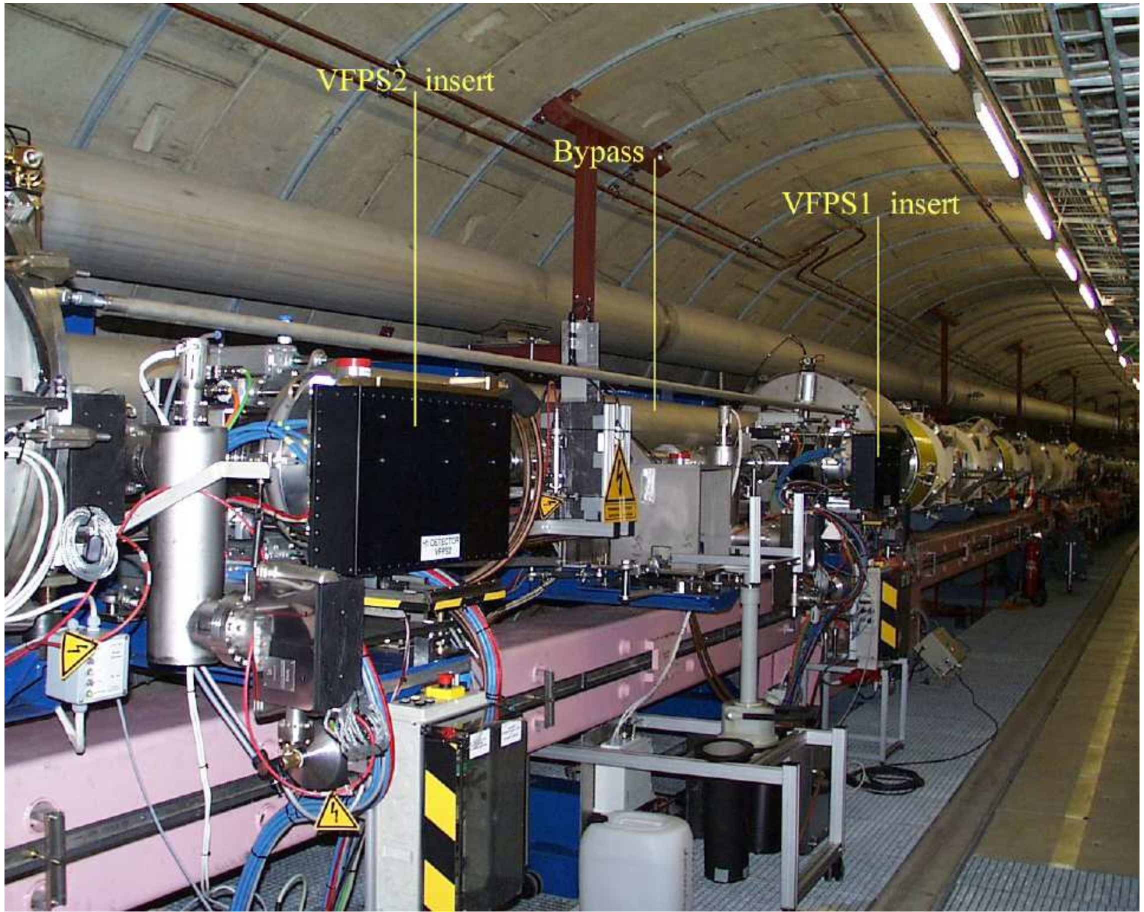
## Trigger:

- Provde L1 trigger (within $2.2\mu s$) using air-core cable
- Cruical for getting all VFPS events on tape

# VFPS: Cold Beampipe Bypass

Horizontal bypass for helium and s.c. lines
⇒ Access to proton beampipe for 10m


before installation

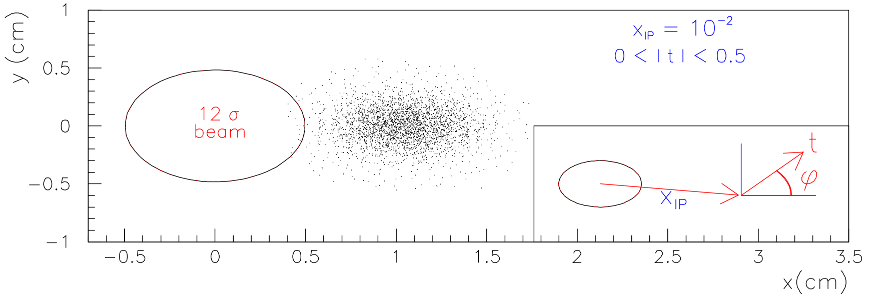


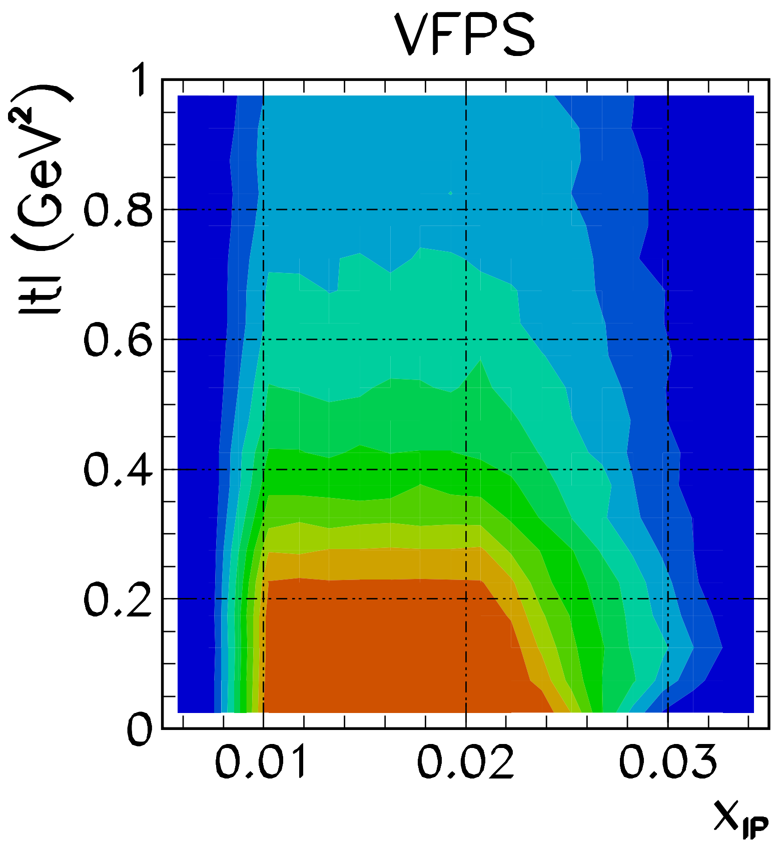
after installation

Installed successfully during summer 2003 shutdown

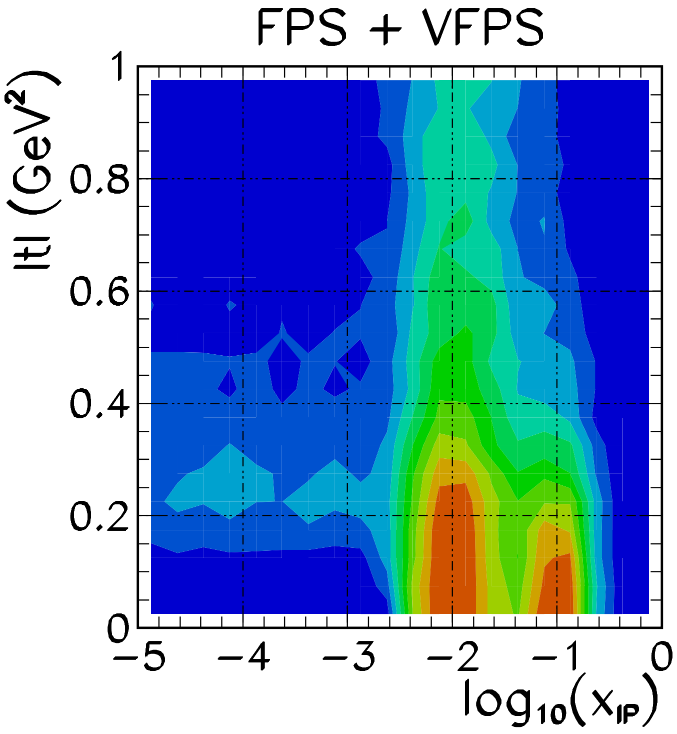
# VFPS: Acceptance

Acceptance defined by beam optics and envelope ($12\sigma$ detector approach limit)



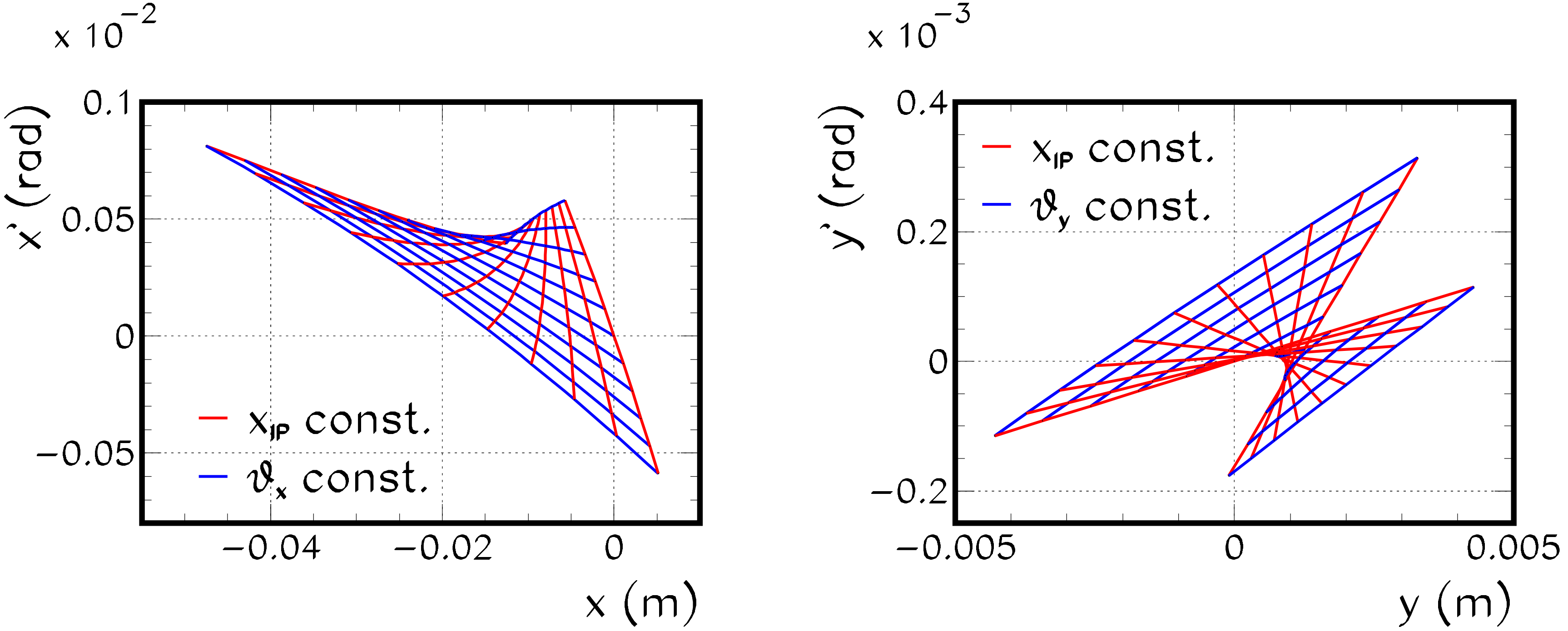


Complementary to FPS



⇒ 100% acceptance for $|t| < 0.2\ \mathrm{GeV}^2$ and $0.01 < x_{I\!P} < 0.02$!

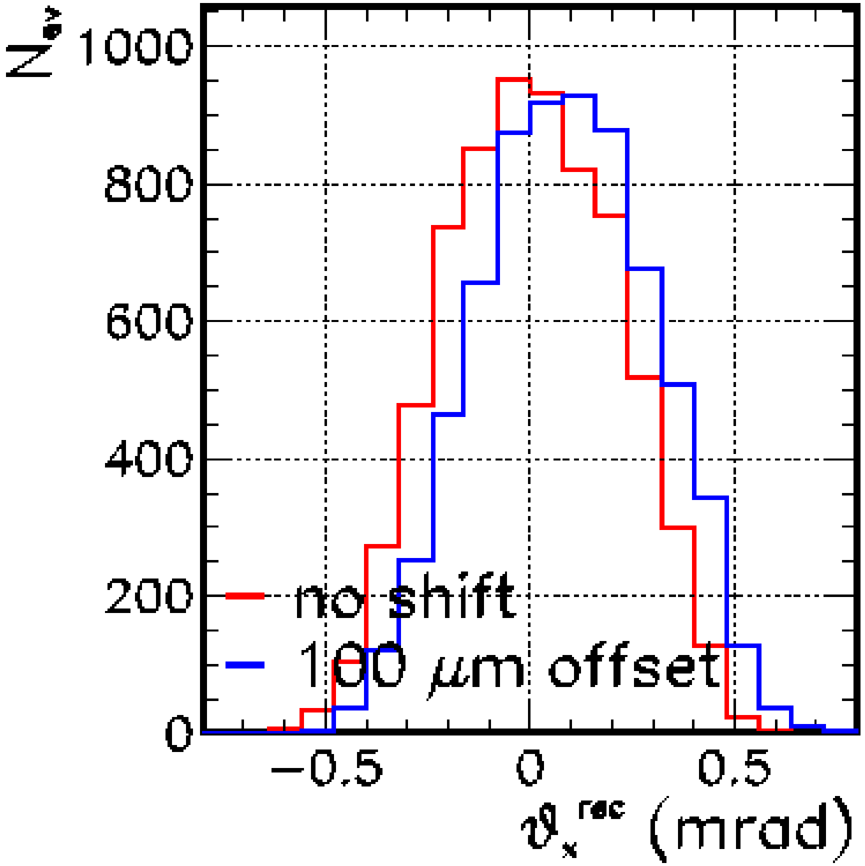
# VFPS: Reconstruction



$$(x, x', y, y') \rightarrow \text{beam optics} \rightarrow (t, x_{I\!P}, \phi)$$

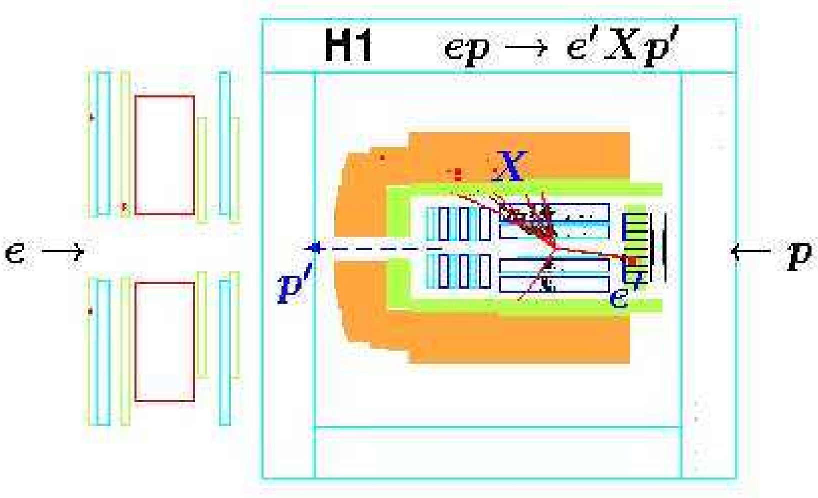
- Beam optics, tilt, smearing
- non-linear effects in $x_{I\!P}$: HERA sextupole magnets
- fiber detector resolution ($\sim 100\mu$), pot position calibration

# VFPS: Calibration



Pot position relative to p beam:

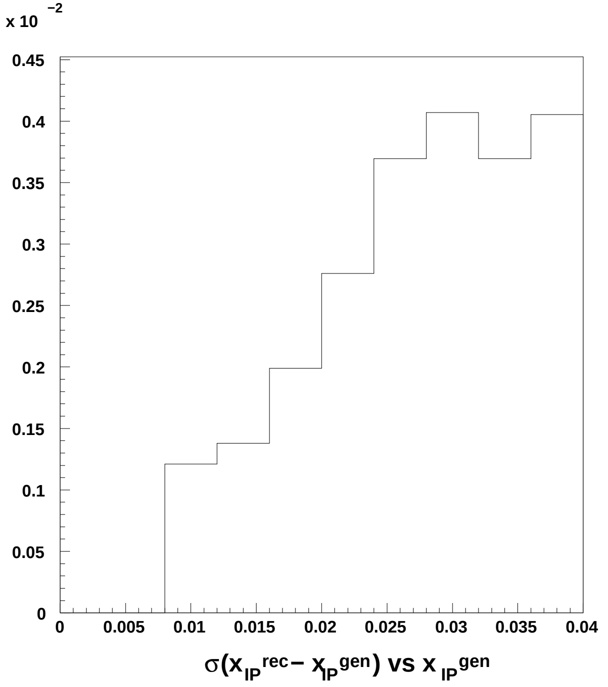
- Forward kinematic peak in $\theta_x$, $\theta_y$
  $x_{I\!P}$ measurement from central detector
  ($\sim$ 200 events for stable calibration)
- Cross-calibration with elastic $\rho$ meson photoproduction events (as for hor. FPS)



Pot position calibration with accuracy $\sim 100\mu m$

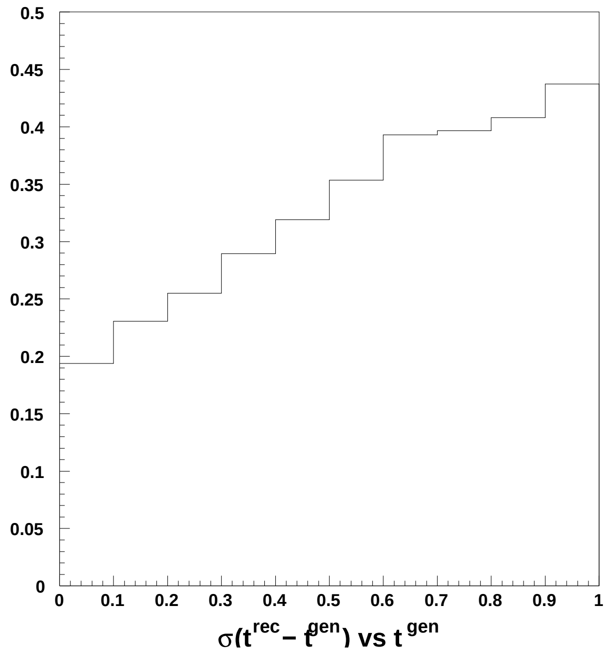
# VFPS: Resolution

$x_{I\!P}$ resolution:



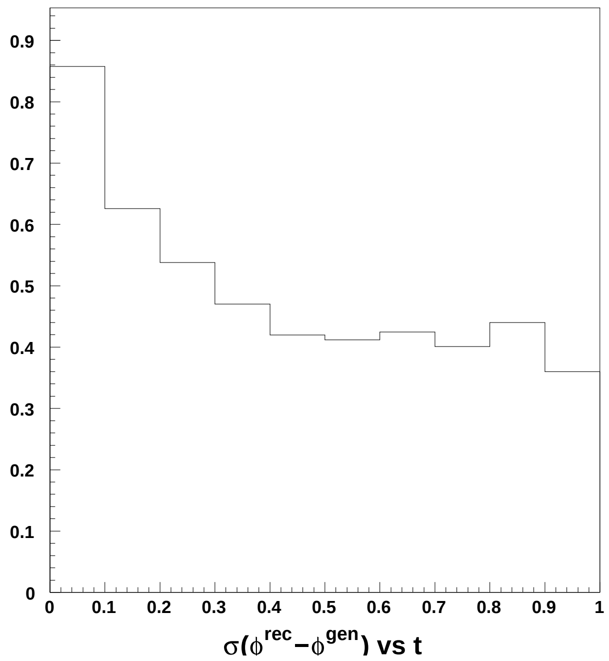
$x_{I\!P} = 0.0$ 0.04

$t$ resolution:



$|t| = 0.0$ 1.0

$\phi$ resolution:



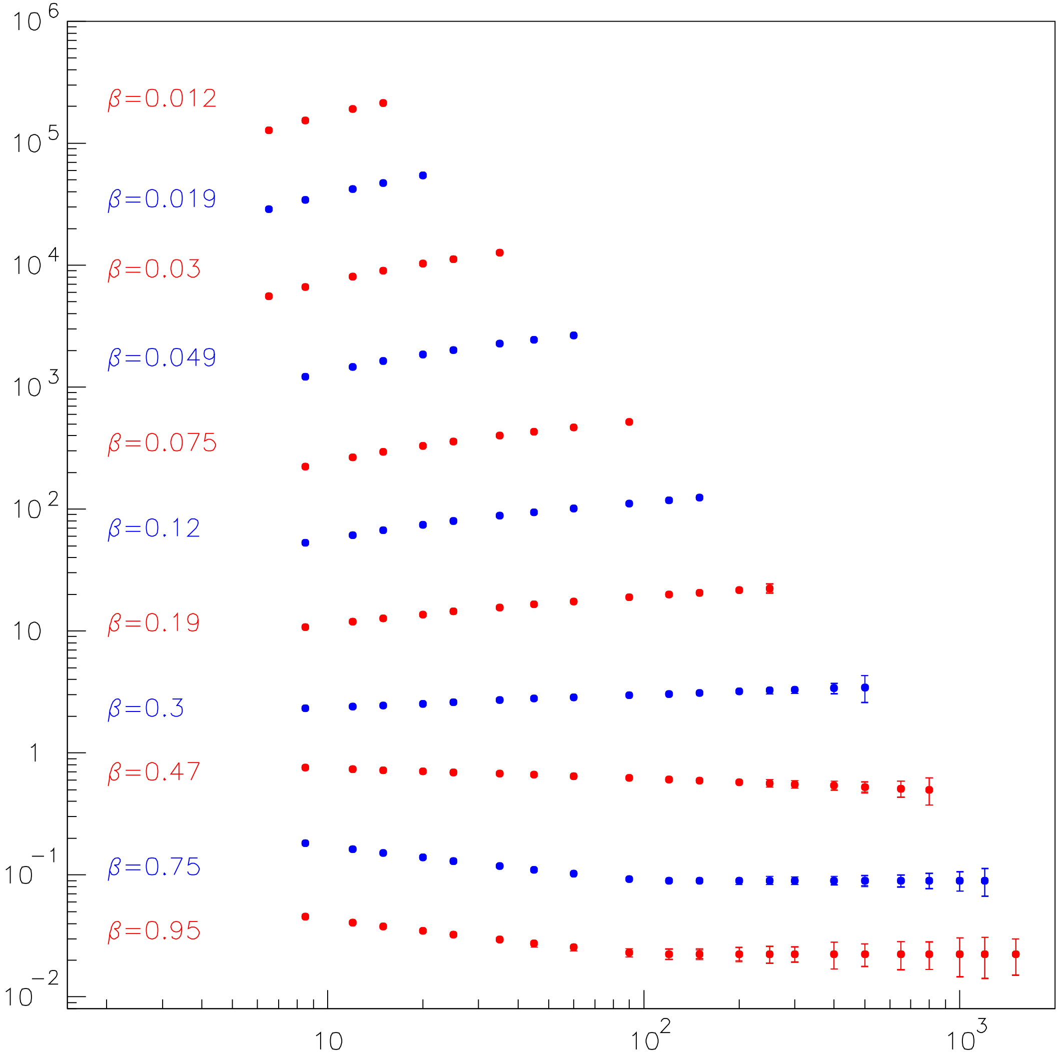
$|t| = 0.0$ 1.0

Resolution dominated by beam characteristics

- $x_{I\!P}$ resolution competetive with main detector reconstruction
- $\sim$ 4 bins in $|t|$
- $\sim$ 15 bins in $\phi$ for $|t| > 0.2\ \mathrm{GeV}^2$

# VFPS Physics: Inclusive Diffraction

Predicted $F_2^{D(3)}$ for 350 $\mathrm{nb}^{-1}$ (50% VFPS operation eff. for 3 years)



- $10^6$ events for $Q^2 > 5\ \mathrm{GeV}^2$
  $\rightarrow$ study $t$ dependence
  $\rightarrow F_2^{D(4)}(Q^2, \beta, x_{I\!P}, t)$
- Uncorrelated systematics $2 - 3\%$ (similar to $F_2$)
- Extract diffractive pdf's at fixed $x_{I\!P}, t$ and predict final states at same $x_{I\!P}, t$ to test QCD factorization

# VFPS Physics: $F_L^D$ Measurements

$$\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{2(1-y+y^2/2)} F_L^{D(4)} \qquad \text{(where } y = Q^2/s_{ep}x\text{)}$$

Sensitivity to $F_L$ through $\Phi$ asymmetry:

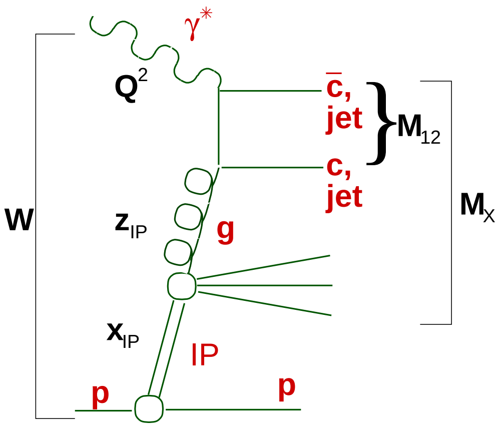
$$\frac{d\sigma^D}{d\Phi} \sim \sigma_T^D + \epsilon\sigma_L^D - 2\sqrt{\epsilon(1+\epsilon)}\sigma_{LT}^D \cos\Phi - \epsilon\sigma_{TT}^D \cos 2\Phi$$

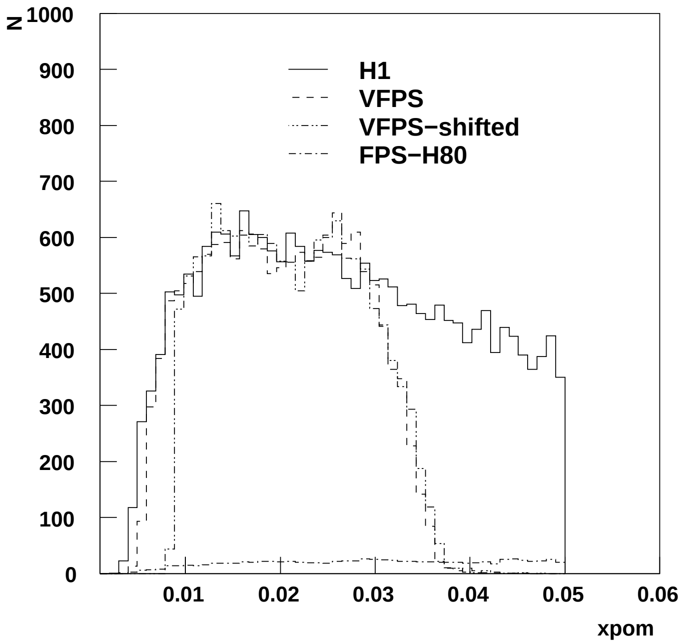
- Higher twist $F_L^D$ contribution expected dominant at high $\beta$ calculable in pQCD
  Measure $\Phi$ asymmetries vs $\beta$, $Q^2$
  VFPS: 15 $\Phi$ bins with 10k events each for $|t| > 0.2\ \mathrm{GeV}^2$

- Leading twist $F_L^D$ (at low $\beta$)
  Indirect extraction through NLO QCD fits (from gluon) to $\sigma_r^{D(4)}$

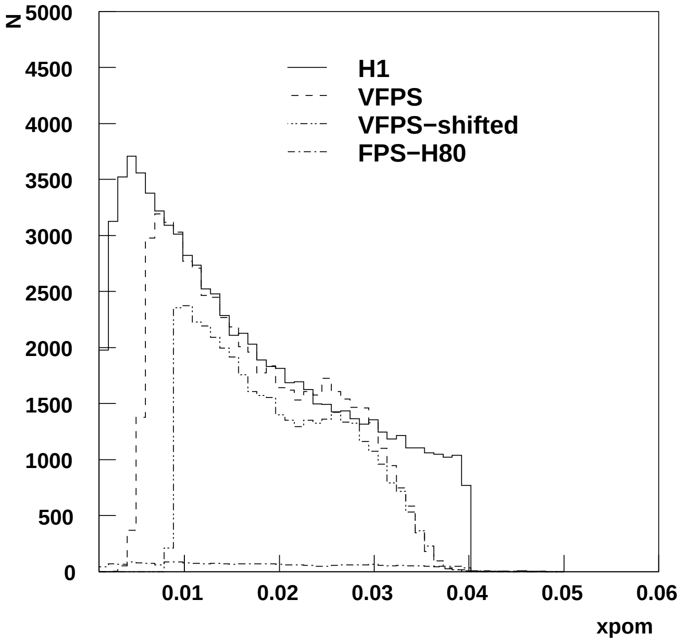
- Direct $F_L$ measurement:
  Reduced $p$ beam energy running
  40% precision on $\sigma_L^D/\sigma_T^D$ expected with 50 $\mathrm{pb}^{-1}$ at $E_p = 500$ GeV

# VFPS Physics: Diffractive final states





Dijets



Open Charm

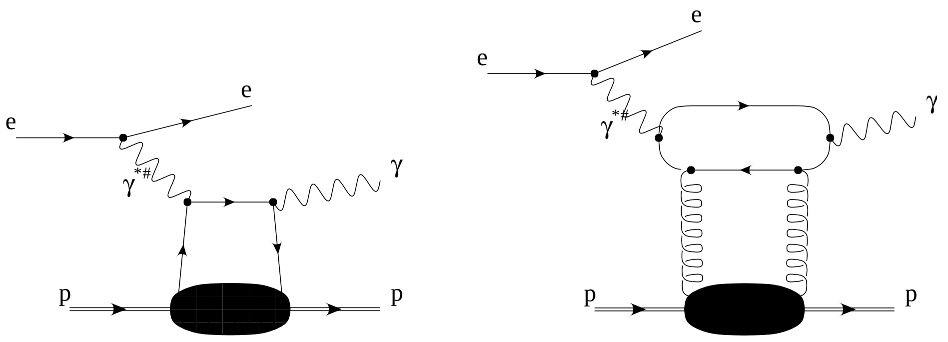
- Dijets: expect 20k events;
  Open charm ($D^*$): expect 400 events
  (factor 10 more than presently analyzed HERA I data)

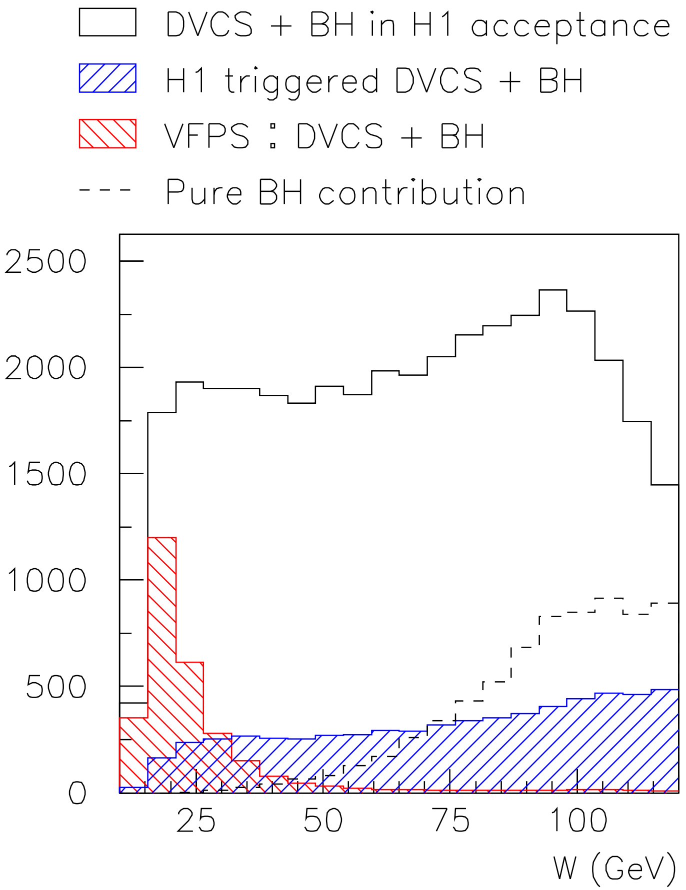
- More differential studies (in particular $D^*$)

- Tests of QCD factorization theorem at fixed $x_{I\!P}$, $t$

# VFPS Physics: Exclusive channels

## Deeply Virtual Compton Scattering (DVCS):





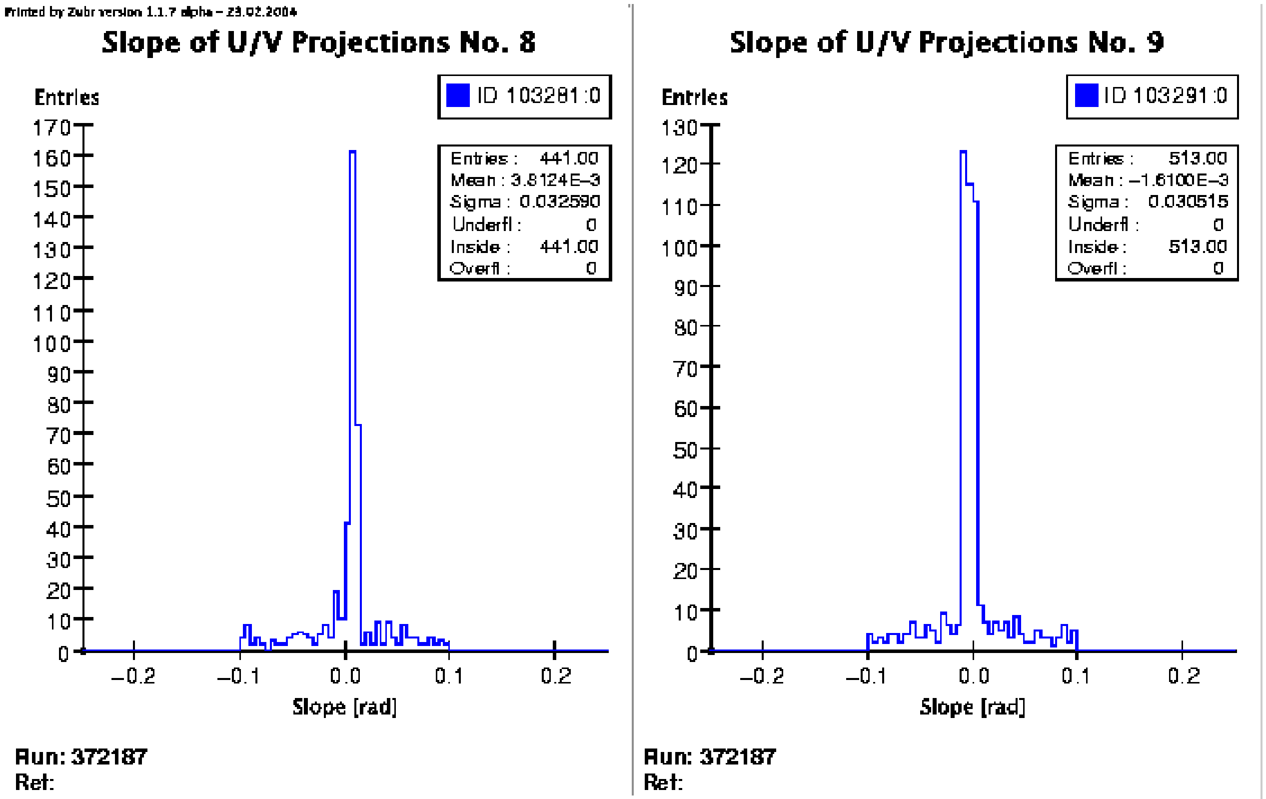
- Sensitive to GPD's via interference with Bethe-Heitler
- Measure
  - – charge asymmetry ($\sim$ Re $A_{\mathrm{DVCS}}$)
  - – helicity asymmetry ($\sim$ Im $A_{\mathrm{DVCS}}$)

## Vector Meson Production:

$$e + p \rightarrow e + p + VM \;\; ; \; VM = \rho, J/\Psi, \ldots$$

Clean elastic channel but only low $W$ accessible

# VFPS: Present Status (as of March 2004)



- VFPS was installed in HERA shutdown summer 2003
- Presently whole system is commissioned:
  trigger, readout, slow control, track and momentum reconstruction
- Clear forward proton tracks already visible!

# Detector Design Aspects

- Radiation hard detectors
- Low sensitivity to stray magnetic fields
- Clear process for calibration;
  possibility for cross-calibration
- Reliable mechanics and electronics for long running without access to detectors
- Monitoring system to control detector position relative to beam, rates, magnet currents
- Many measured points per coordinate to suppress detector noise and fake tracks

# Conclusions

## Rapidity Gap and $M_X$ methods:

- Large statistics diffractive samples at HERA-I
- Efficient suppression of non-diffractive events by combination of several large-$\eta$ sensitive detectors
- Dominating syst. uncertainty due to $p$ dissociation

## H1 Forward Proton Spectrometer:

- Roman Pot technology, scintillating fibers, PSPM's
- allowed measurements of $F_2^{D(3)}$, $t$-dependence, photoproduction with a leading proton
- upgrade for HERA-II to increase detection efficiency and radiation resistance

## H1 Very Forward Proton Spectrometer:

- 2 new Roman Pots at $z = 220$ m; based on FPS technology
- Fully efficient; big potential for diffractive physics ($F_2^{D(4)}$, jets, charm, DVCS)
- Status: Installed and being commissioned now