Comments / Thoughts
Physics at Low Q^2

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U.S. DEPARTMENT OF ENERGY | Office of Science

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Outline

- Formulation of inclusive ep scattering: DIS to PHP

  Transition from high Q^2 to low Q^2 to photo production

- HERA data

- Kinematic variable resolution / precision (Angular and Energy scale precision)

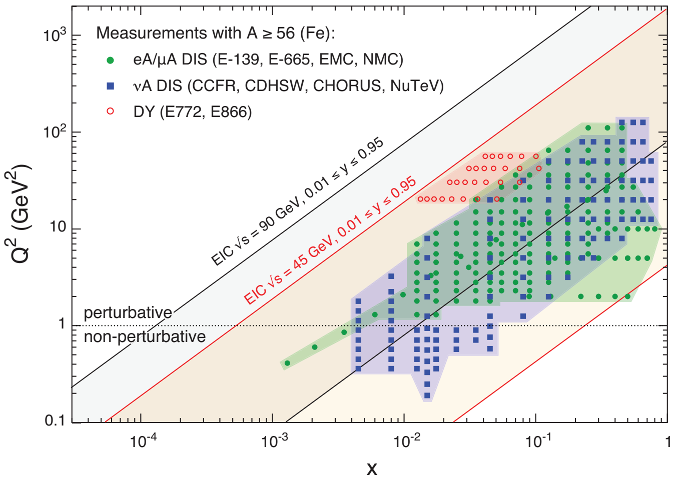
- Acceptance - ePIC

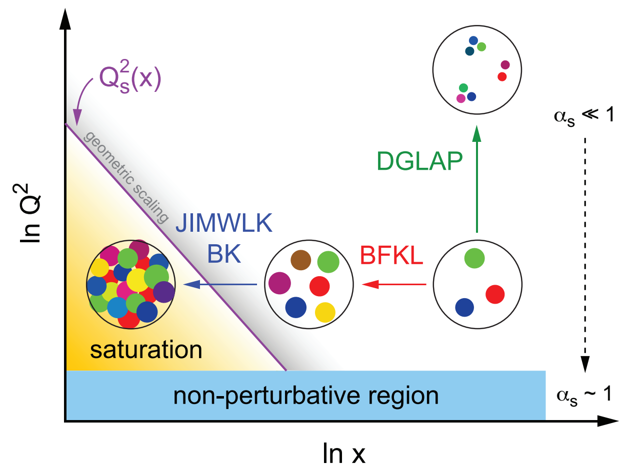
- Requirements

- Summary

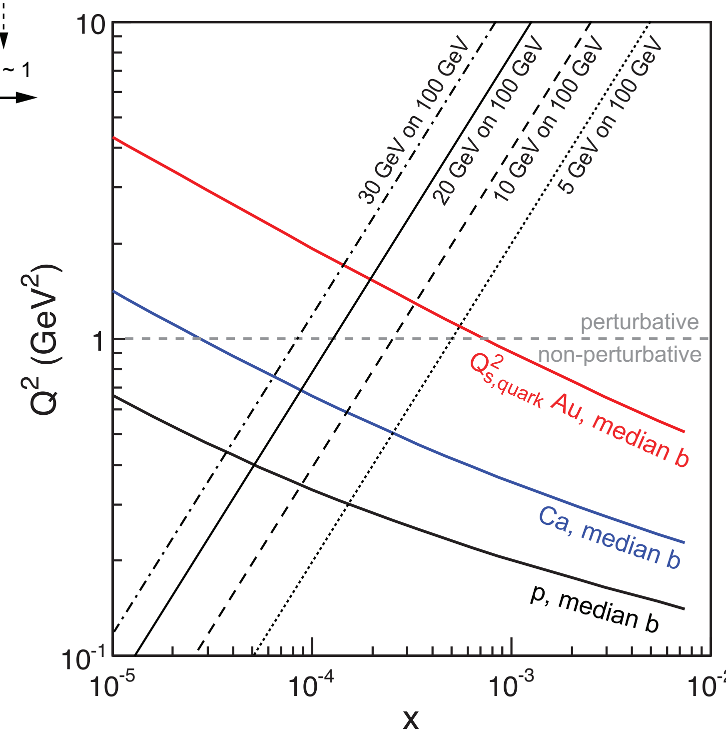
Motivation

- Exploring low-x physics / Onset of saturation phenomena at EIC





- Transition from pert. to non-pert. region around $Q^2 = 1\,\mathrm{GeV}^2$
- Partonic (Large Q²) to hadronic behavior (Low Q²), in particular in photoproduction limit, i.e. $Q^2 \to 1\,\mathrm{GeV}^2$
- Formulation of structure function $F_2(x, Q^2)$ to $\gamma^* p$ cross-section $\sigma_{\mathrm{tot}}^{\gamma^* p}(W^2, Q^2)$, in particular in photoproduction limit, i.e. $Q^2 \to 1\,\mathrm{GeV}^2$
- Probing transition region requires measurements around $Q^2 = 1\,\mathrm{GeV}^2$, above and below, down to at least $Q^2 = 0.1\,\mathrm{GeV}^2$



Formulation of inclusive ep scattering: DIS to PHP

- Process

$$s = (k+p)^2 \simeq 4E_e E_P$$

$$t = (p-p')^2$$

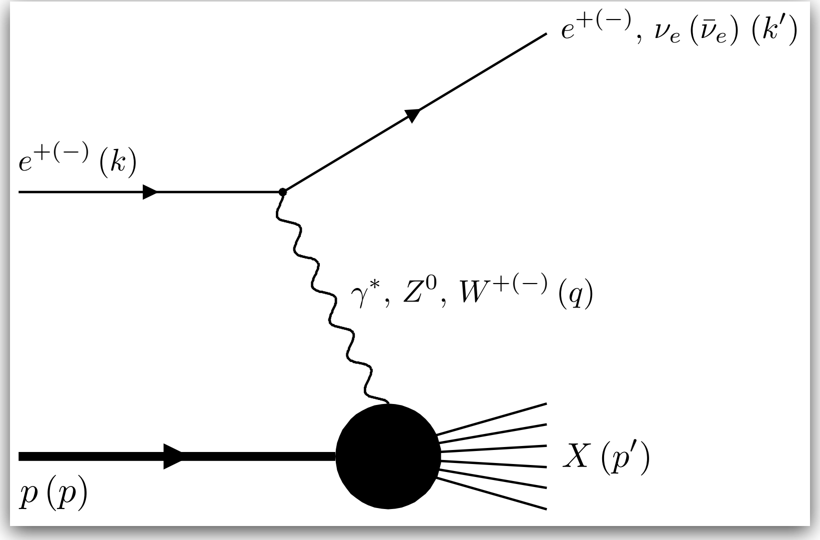
$$u = (k'-p)^2$$

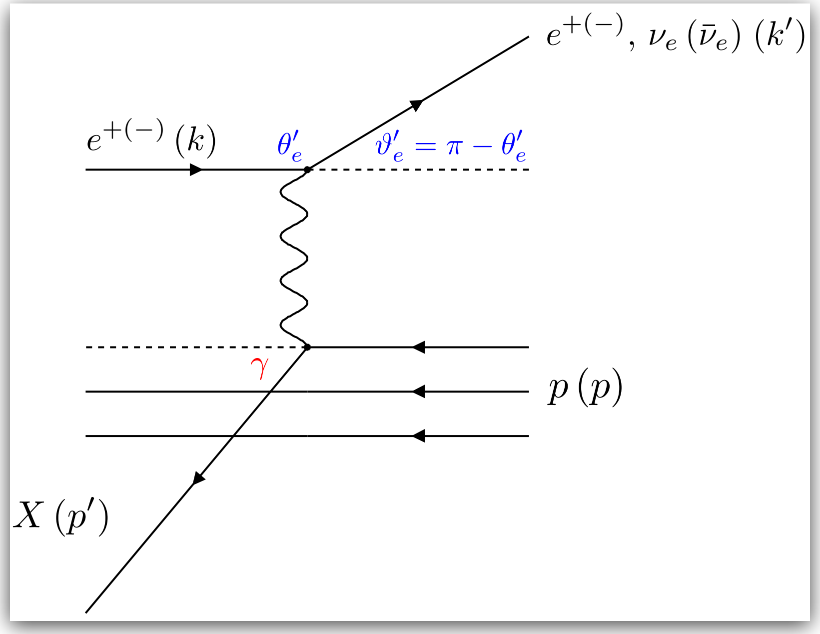
$$Q^2 = -(k-k')^2 = -(p-p')^2 = -t = -q^2$$

$$x = \frac{Q^2}{2(p\cdot q)} \simeq -\frac{t}{u+s} \qquad 0 \leq x \leq 1$$

$$y = \frac{p\cdot q}{p\cdot k} \simeq \frac{u+s}{s} \qquad 0 \leq y \leq 1$$

$$W^2 = (p+q)^2 = (p')^2 = m_p^2 + \frac{Q^2}{x}(1-x) \simeq s+t+u$$





- Large W^2 refers to small x / At very small x: $W^2 \approx Q^2/x$!
- Small x refers to high-energy region (Large W^2) in $\gamma^* p$ scattering!
- Coordinate system: Positive z-axis along proton direction / Sometimes angle $\vartheta'_e = \pi - \theta'_e$ is used instead of θ'_e !

Formulation of inclusive ep scattering: DIS to PHP

- Structure function
  - At large Q², well above $Q^2 = 1\,\mathrm{GeV}^2$, partonic behavior dominates / Theoretical description of pQCD in terms of unpolarized PDFs and evolution using DGLAP evolution!
  - The formulation in terms of structure functions is appropriate at large Q² with kinematic variables of: x(y) / Q2
  - Double-differential cross-section:

$$\left(\frac{d^2\sigma}{dydQ^2}\right)_{\mathrm{Born}} = \frac{2\pi\alpha^2 Y_+}{yQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right)$$

with:

$$Y_+ = 1 + (1-y)^2 \qquad F_L = F_2 - 2xF_1$$

Formulation of inclusive ep scattering: DIS to PHP

- Cross-section $\gamma^* p$ scattering
  - Besides differential ep cross-section in terms of structure functions, one can interpret ep cross-section as the product of the flux of virtual photons and $\gamma^* p$ cross-section:

$$\sigma_{\mathrm{tot}}^{\gamma^* p}(W^2, Q^2) \equiv \sigma_{\mathrm{T}}^{\gamma^* p}(W^2, Q^2) + \sigma_{\mathrm{L}}^{\gamma^* p}(W^2, Q^2)$$

  - The total virtual-photon proton cross-section is given as follows:

$$\sigma_{\mathrm{tot}}^{\gamma^* p}(W^2, Q^2) = \frac{4\pi^2\alpha}{Q^2(1-x)} \frac{Q^2 + 4m_p^2 x^2}{Q^2} \cdot F_2(x, Q^2)$$

At small x:

$$\sigma_{\mathrm{tot}}^{\gamma^* p}(W^2, Q^2) \approx \frac{4\pi^2\alpha}{Q^2} \cdot F_2(x, Q^2)$$

  - The formulation in terms of cross-sections is appropriate at small Q^2 and small x (x < 0.01), requiring that the lifetime of the virtual photon is large compared to the interaction time. Appropriate kinematic variables are: W^2 and Q^2
  - This is in particular true in the photoproduction limit $Q^2 \rightarrow 0$ for which $F_2 \rightarrow 0$!

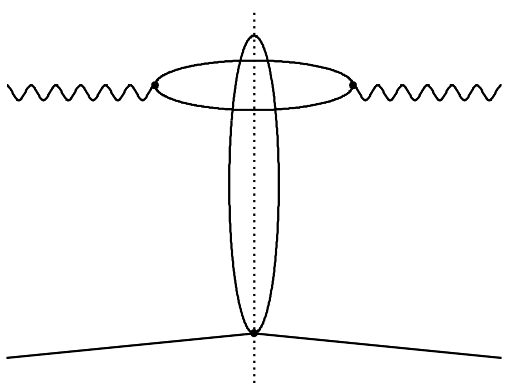
Formulation of inclusive ep scattering: DIS to PHP

- Comments on formulation DIS to PHP

  - At large Q², well above $Q^2 \approx 1\,\mathrm{GeV}^2$, slope ($\lambda(Q^2)$) in $F_2 \sim x^{-\lambda(Q^2)}$ rises with Q² / Partonic behavior dominates, successfully described by pQCD / DGLAP evolution!

  - Below $Q^2 \approx 1\,\mathrm{GeV}^2$, slope in $F_2 \sim x^{-\lambda(Q^2)}$ is flat in Q² / pQCD / DGLAP evolution breaks down / Hadronic behavior dominates with similar energy dependence (W²) for $\sigma_{\mathrm{tot}}^{\gamma^* p}(W^2, Q^2)$ as total photoproduction cross-section, $\sigma_{\mathrm{tot}}^{\gamma p}(W^2)$!

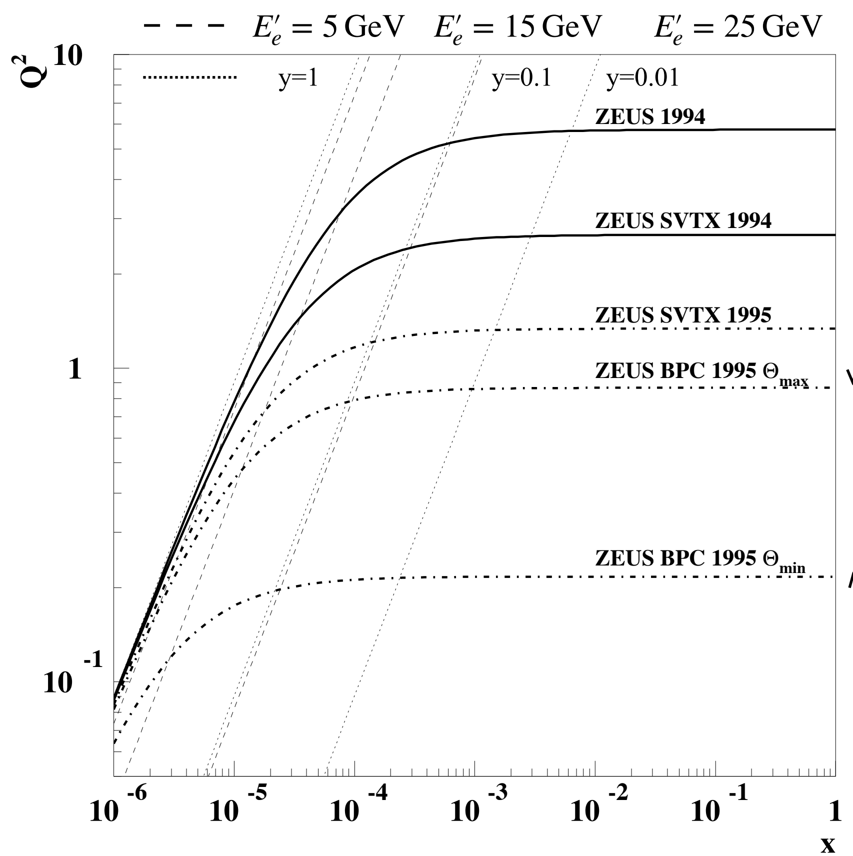
  - New formulation of ep scattering at low x born out of HERA program: Color-dipole picture at low x (x < 0.01) by several groups

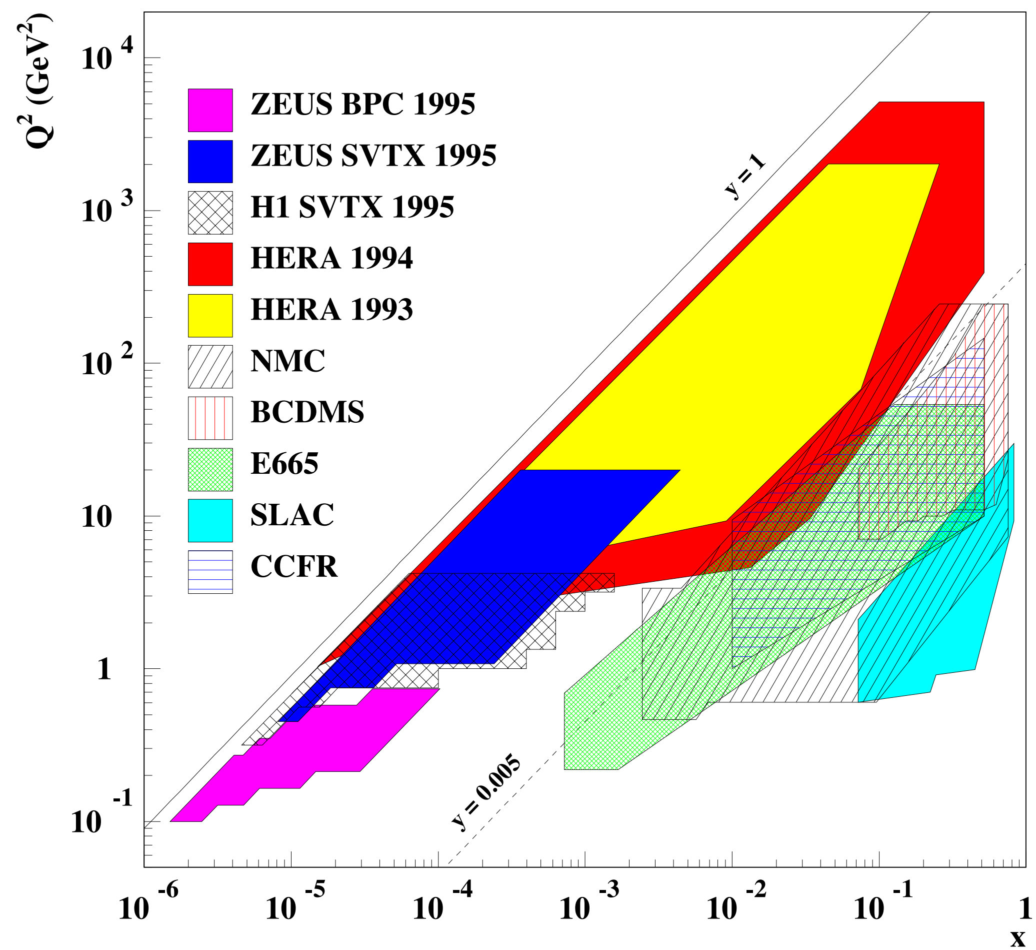


HERA data

- Kinematic coverage

~35mrad





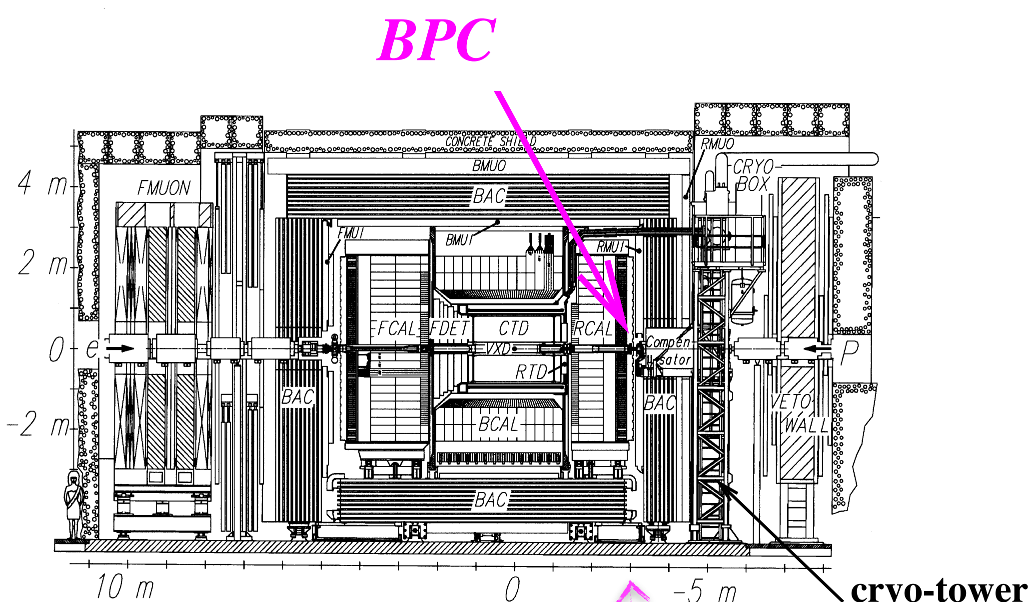
~17mrad

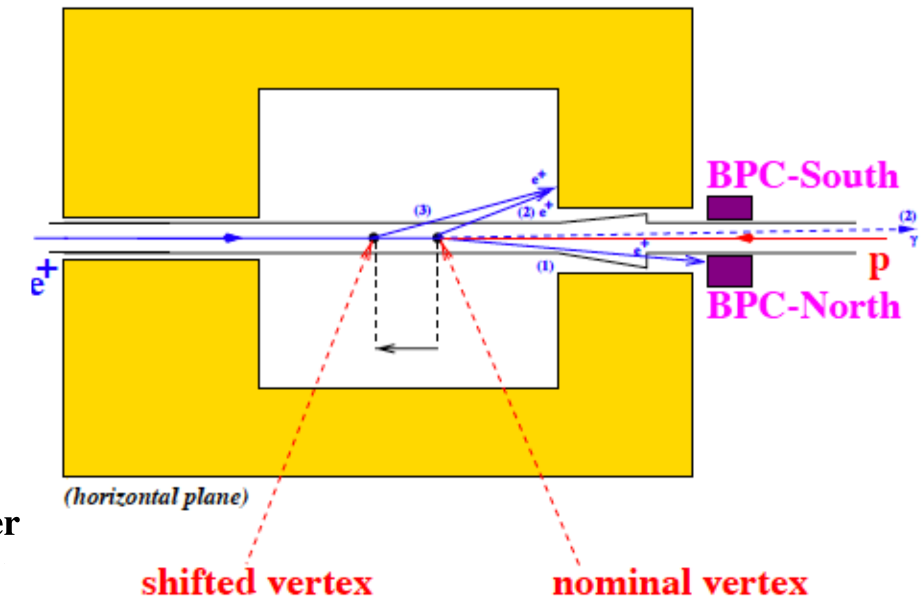
$$Q^2 = 4E_e E_e^{'} \sin^2\left(\frac{\vartheta_e^{'}}{2}\right) \simeq E_e E_e^{'} \vartheta_e^{'2}$$

$$\vartheta_e^{'} = \pi - \theta_e^{'}$$

HERA data

- Extension towards small Q^2: Example from ZEUS



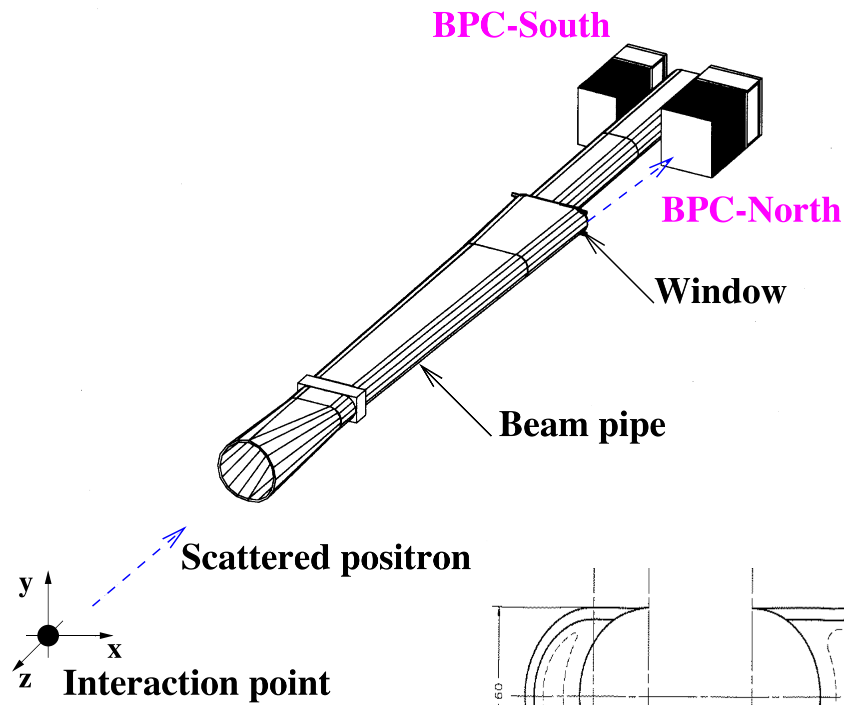


Distance of BPC to nominal IP: 3m

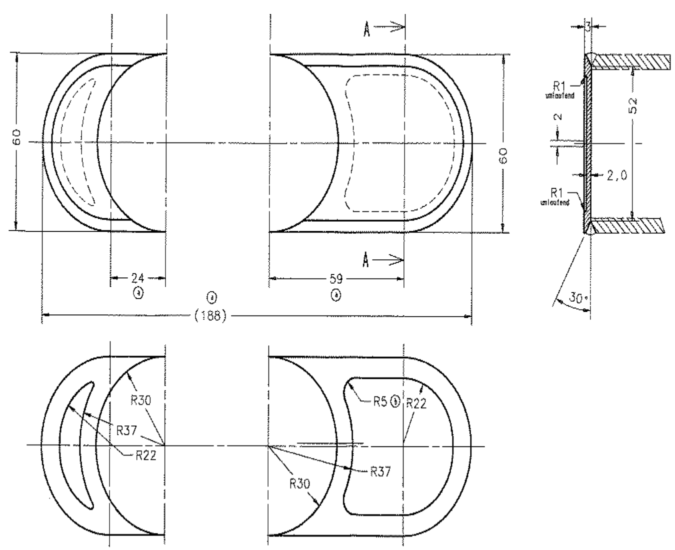
Angular coverage: ~17-35 mrad

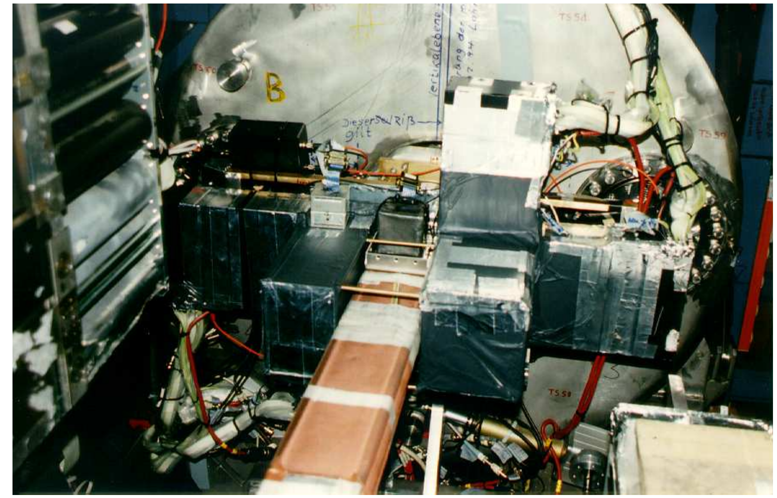
HERA data

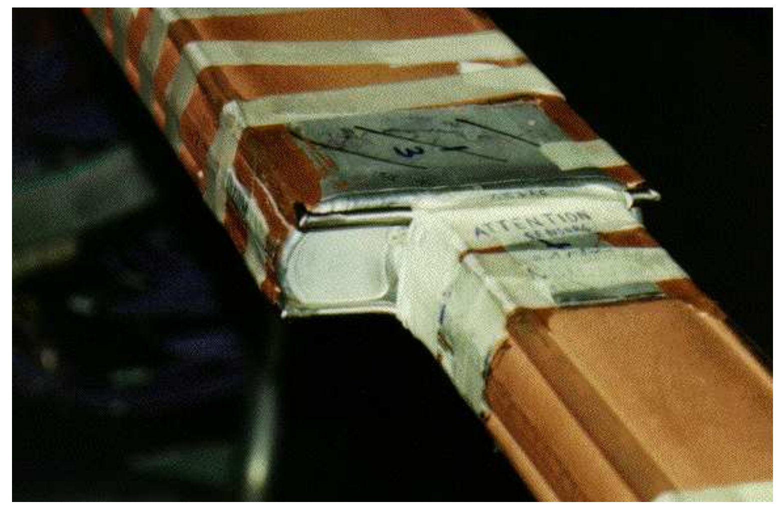
- Technical realization for ZEUS Beam-Pipe Calorimeter (BPC)



Beam pipe window (AL): 1.5mm at 2.5m







HERA data

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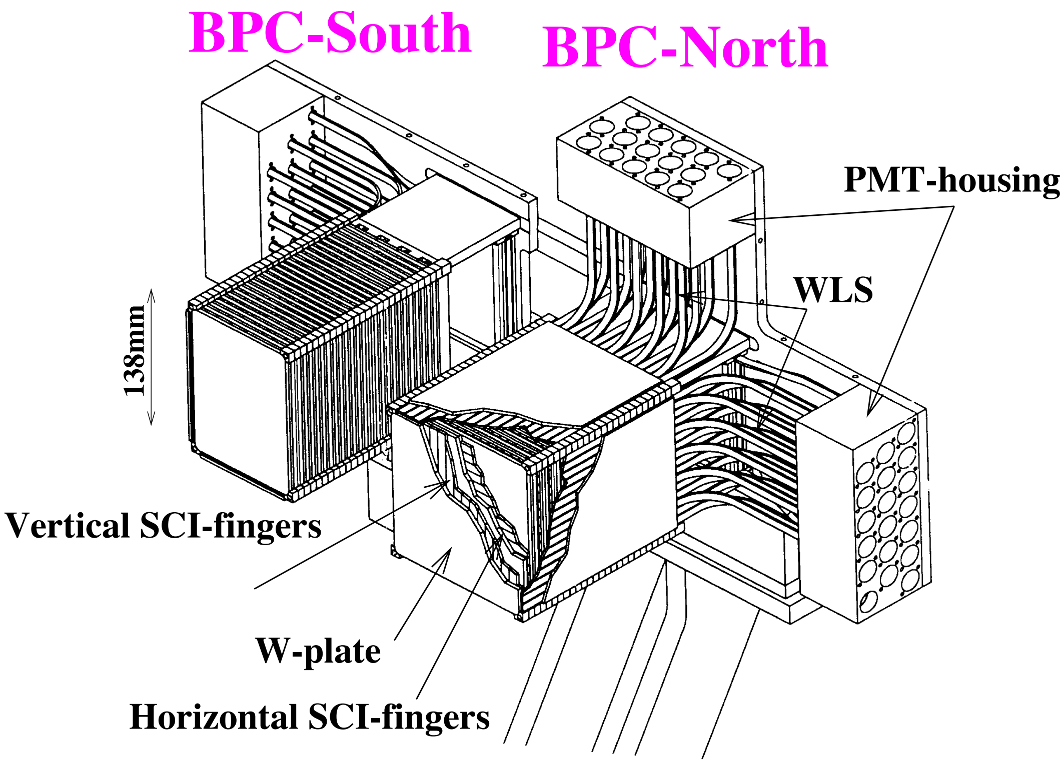
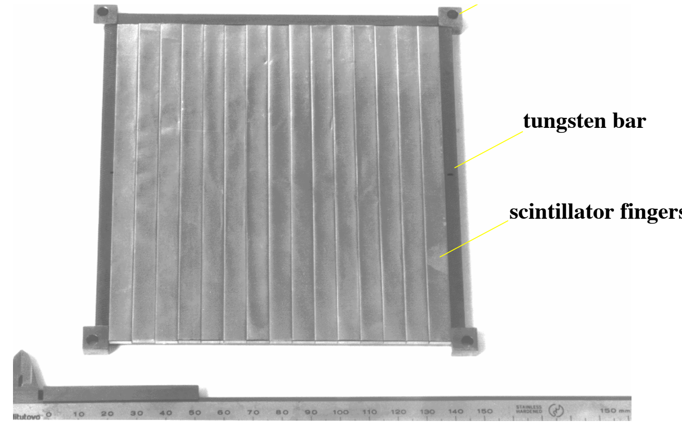
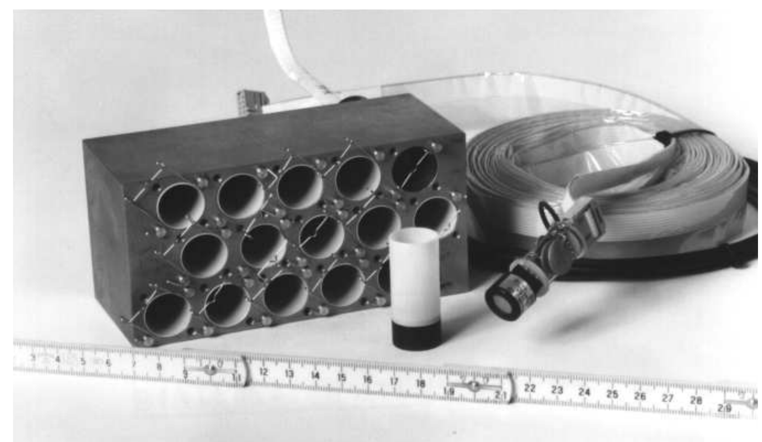
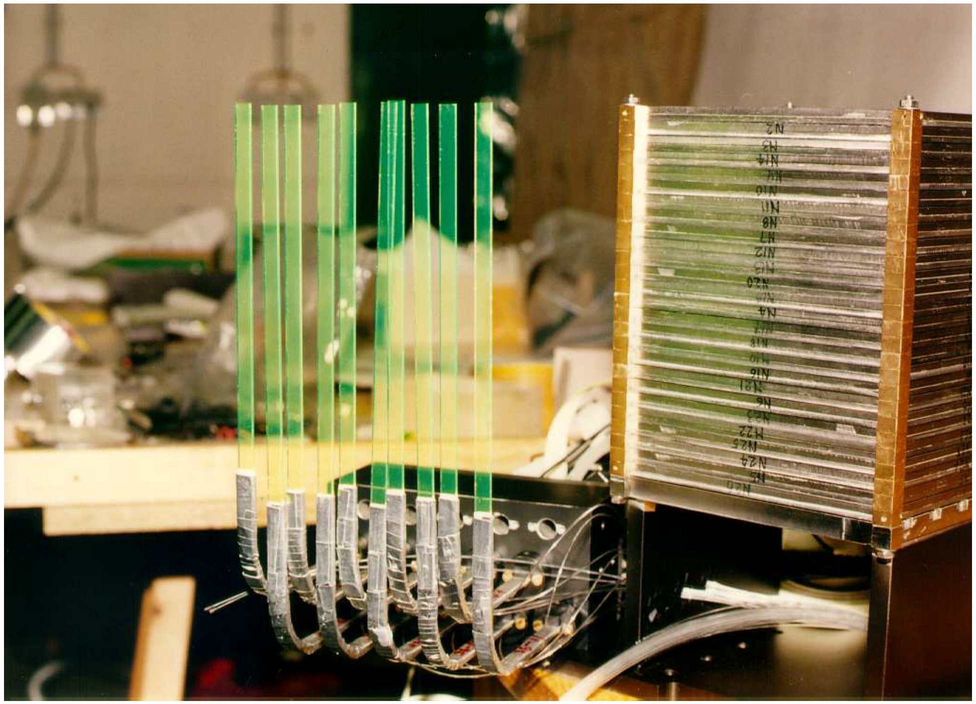


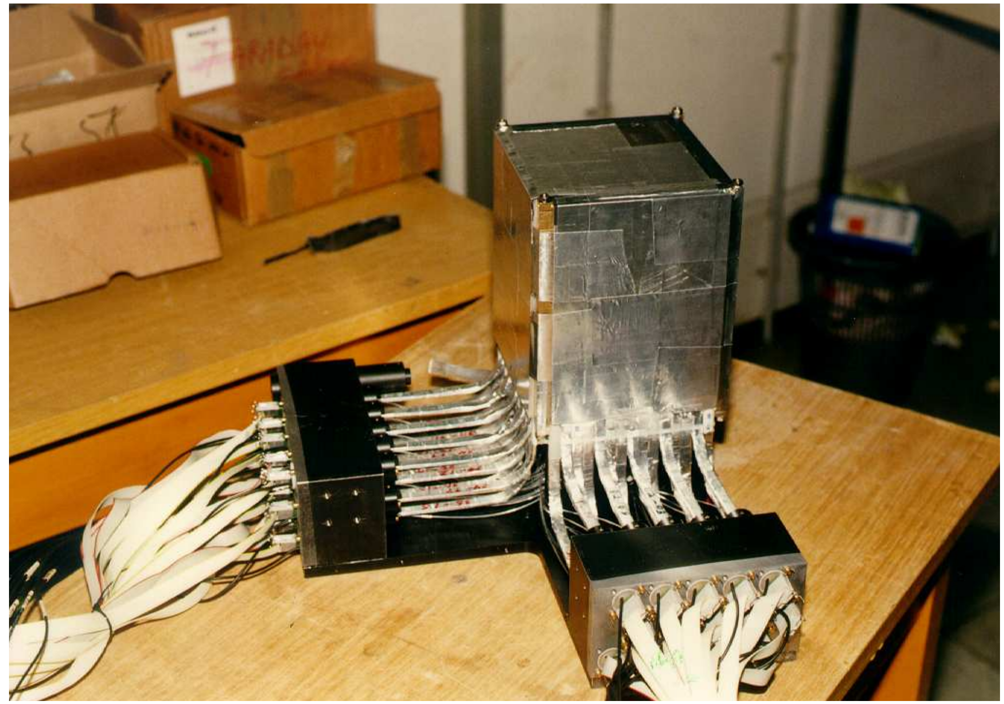




HERA data

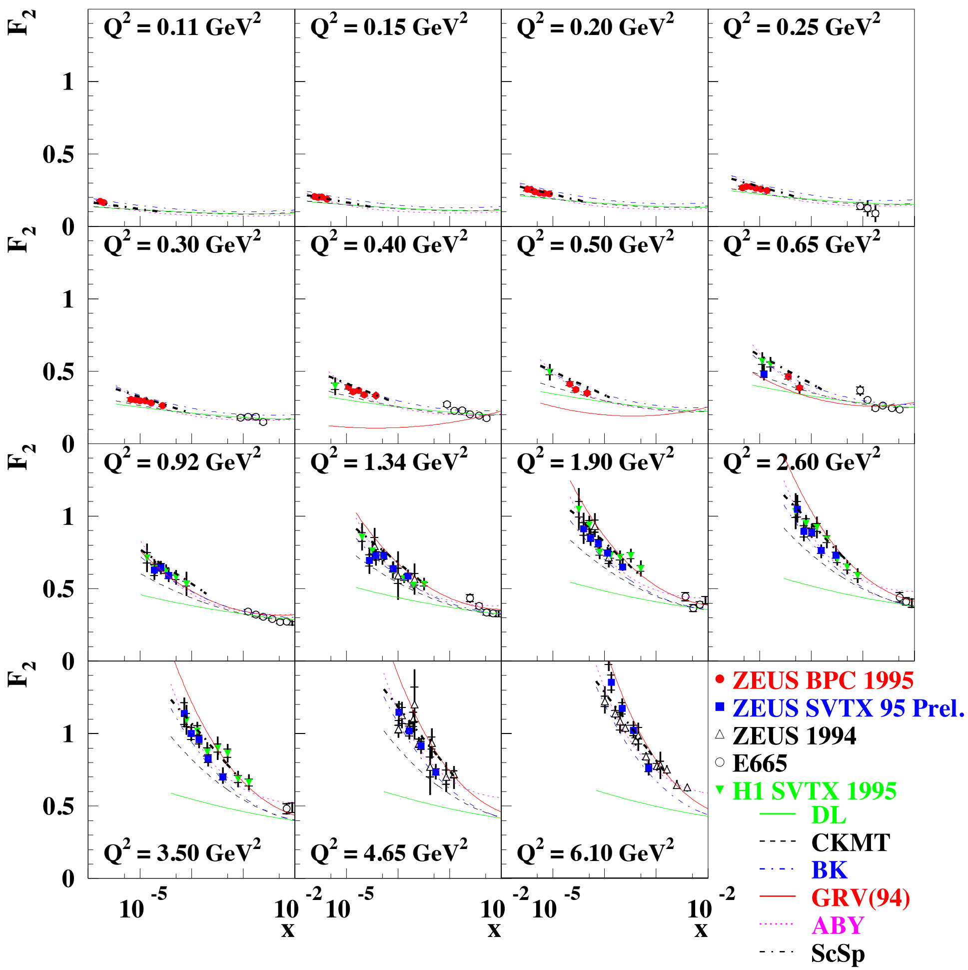
- Technical realization for ZEUS Beam-Pipe Calorimeter (BPC)

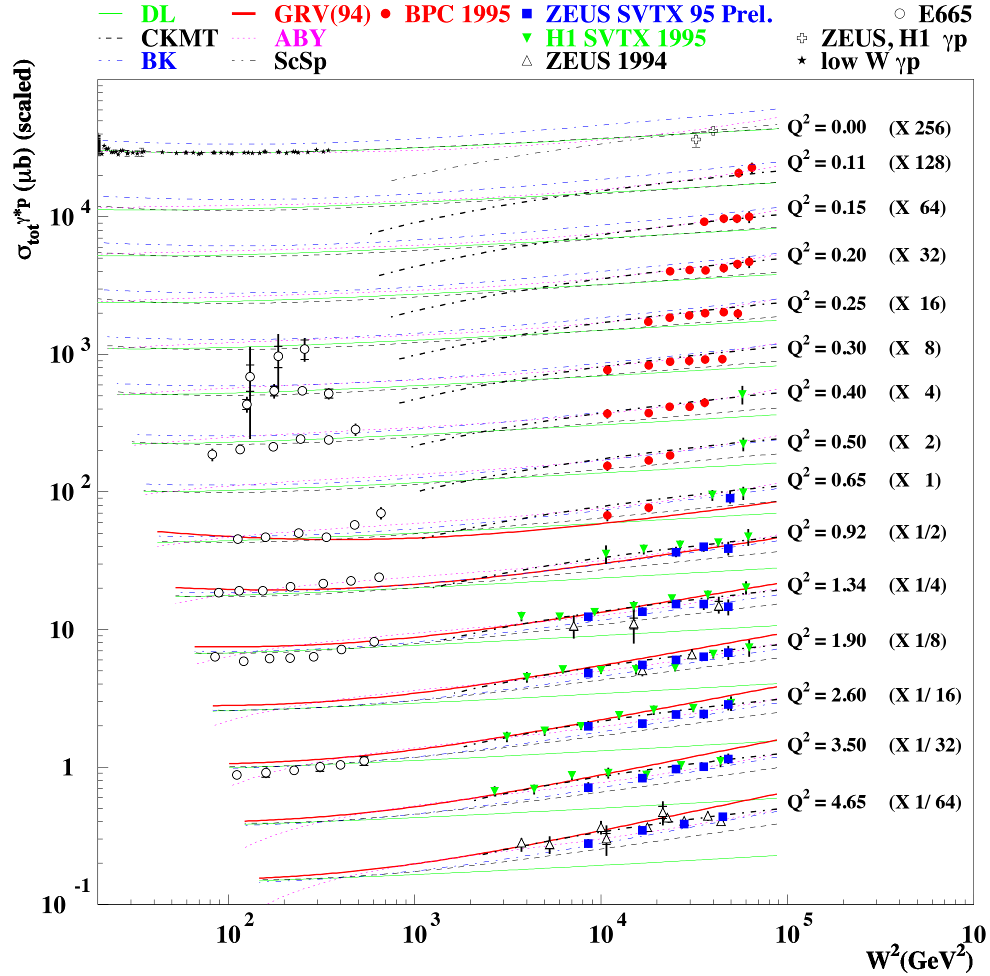




HERA data

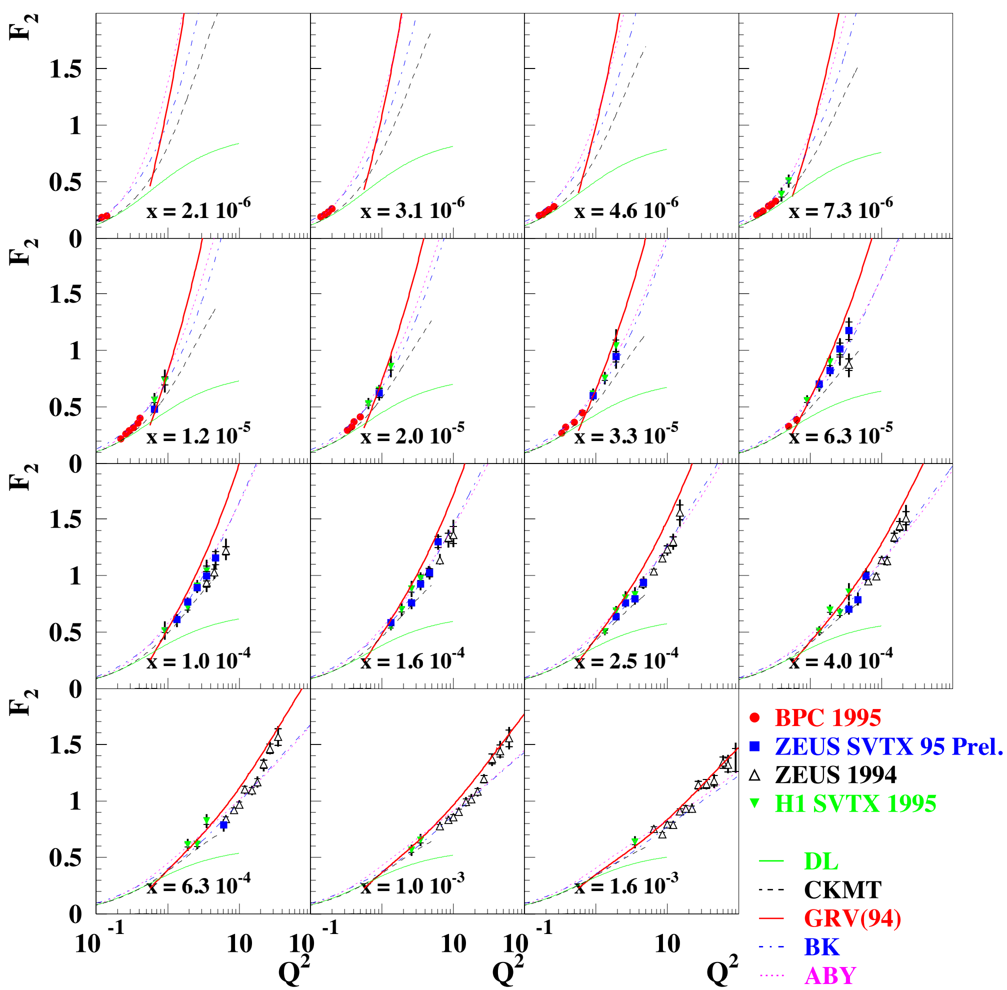
- F_2 vs. x / Cross-section vs. W^2

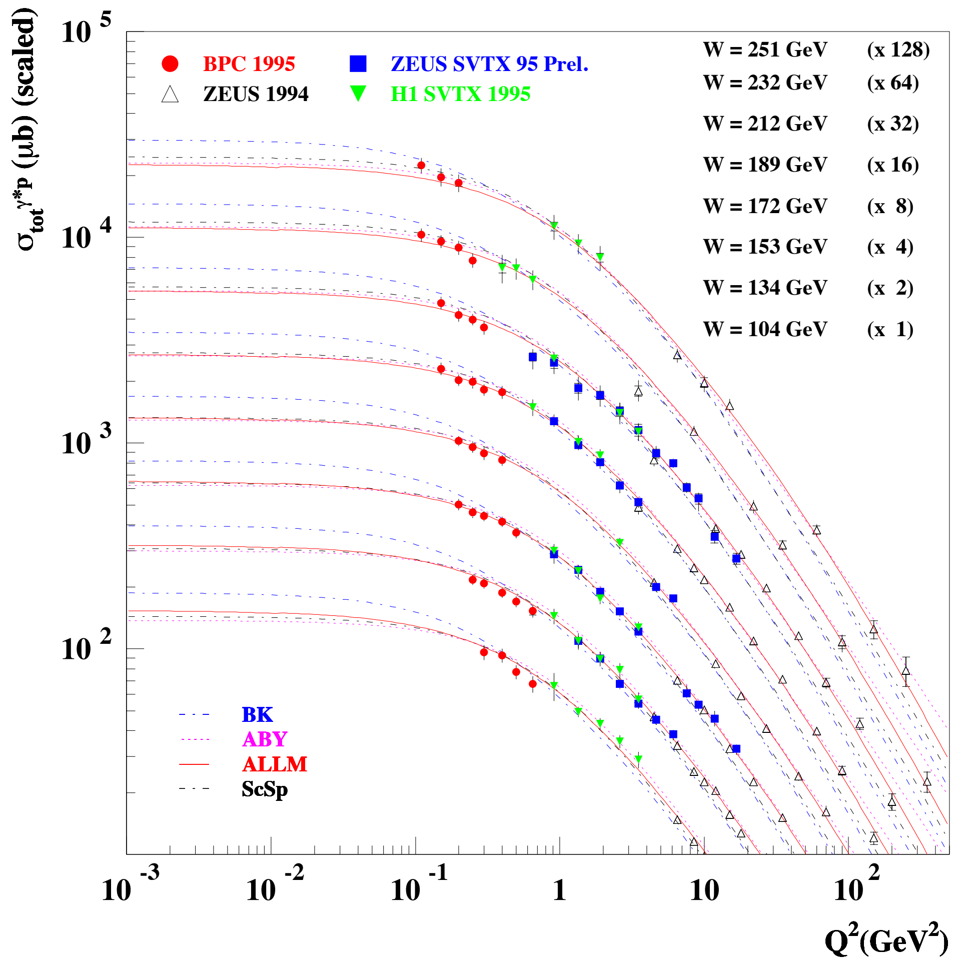




HERA data

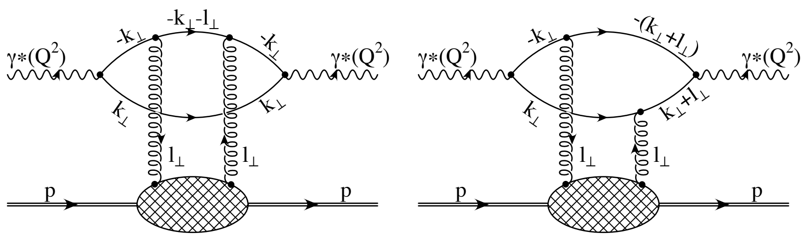
- F_2 vs. Q^2 / Cross-section vs. Q^2





HERA data

- Color-dipole model formulation



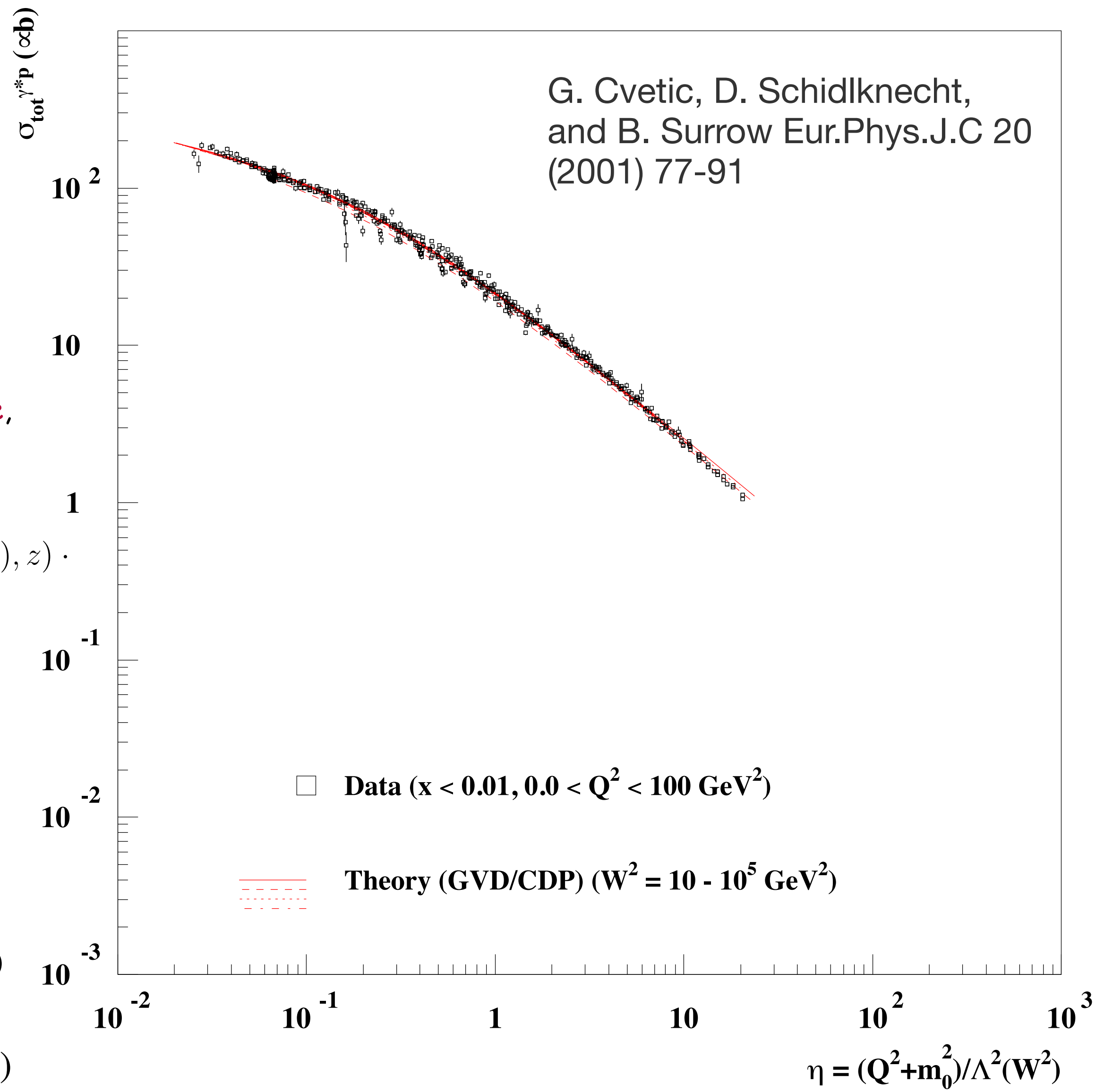
- Formulation of $\sigma_{\rm tot}^{\gamma^* p}(W^2, Q^2)$ in color-dipole picture, including photoproduction limit:

$$\sigma_{\gamma^* p}(W^2, Q^2) = \int dz \int d^2 r_\perp |\psi|^2 (r_\perp^2 Q^2 z(1-z), Q^2 z(1-z), z) \cdot \cdot \; \sigma_{(q\bar{q})p}(r_\perp^2, z(1-z), W^2).$$

- η-variable:

$$\eta(W^2, Q^2) = \frac{Q^2 + m_0^2}{\Lambda^2(W^2)}$$

- HERA data for x < 0.01 exhibit scaling behavior!
- Two limits:
  - Q^2: PHP limit $\lim_{Q^2 \to 0} \sigma_{\rm tot}^{\gamma^* p}(W^2, Q^2) = \sigma_{\rm tot}^{\gamma p}(W^2)$
  - W^2: HE limit $\lim_{W^2 \to \infty} \sigma_{\rm tot}^{\gamma^* p}(W^2, Q^2) = \sigma_{\rm tot}^{\gamma p}(W^2)$



Kinematic variable resolution and precision

- Mathematical formulation: At low x / high y consider only e-method!

$$Q^2[E'_e,\theta'_e] = 2E_eE'_e(1+\cos\theta'_e)$$

$$y[E'_e,\theta'_e] = 1 - \frac{E'_e}{2E_e}(1-\cos\theta'_e)$$

$$\frac{\partial Q^2}{\partial E'_e} = 2E_e(\cos\theta'_e + 1) \qquad \frac{\partial y}{\partial E'_e} = \frac{\cos\theta'_e - 1}{2E_e}$$

$$\frac{\partial Q^2}{\partial \theta'_e} = -2E_eE'_e\sin\theta'_e \qquad \frac{\partial y}{\partial \theta'_e} = -\frac{E'_e\sin\theta'_e}{2E_e}$$

$$(\delta Q^2)^2 = \left(\frac{\partial Q^2}{\partial E'_e}\right)^2(\delta E'_e)^2 + \left(\frac{\partial Q^2}{\partial \theta'_e}\right)^2(\delta\theta'_e)^2$$

$$(\delta y)^2 = \left(\frac{\partial y}{\partial E'_e}\right)^2(\delta E'_e)^2 + \left(\frac{\partial y}{\partial \theta'_e}\right)^2(\delta\theta'_e)^2$$

$$\theta'_e = 176.5407^\circ / \eta = 3.5 \rightarrow \tan\left(\frac{\theta'_e}{2}\right) \approx 33$$

$$\left(\frac{\delta Q^2}{Q^2}\right) = \frac{\delta E'_e}{E'_e} \oplus \tan\left(\frac{\theta'_e}{2}\right)\delta\theta'_e$$

Q^2 resolution worsens for large θ', need excellent θ' resolution!

$$\left(\frac{\delta y}{y}\right) = \left(1-\frac{1}{y}\right)\frac{\delta E'_e}{E'_e} \oplus \left(\frac{1}{y}-1\right)\cot\left(\frac{\theta'_e}{2}\right)\delta\theta'_e$$

y resolution worsens for small y, need excellent E' resolution!

Acceptance EIC

- Kinematic plane by observables

$$Q^2[x,E'_e] = \frac{xs\left(1-\frac{E'_e}{E_e}\right)}{1-\frac{xs}{4E_e^2}}$$

Fixed E'_e

2GeV steps:
2GeV-100GeV

$E_e = 10\,\mathrm{GeV}$

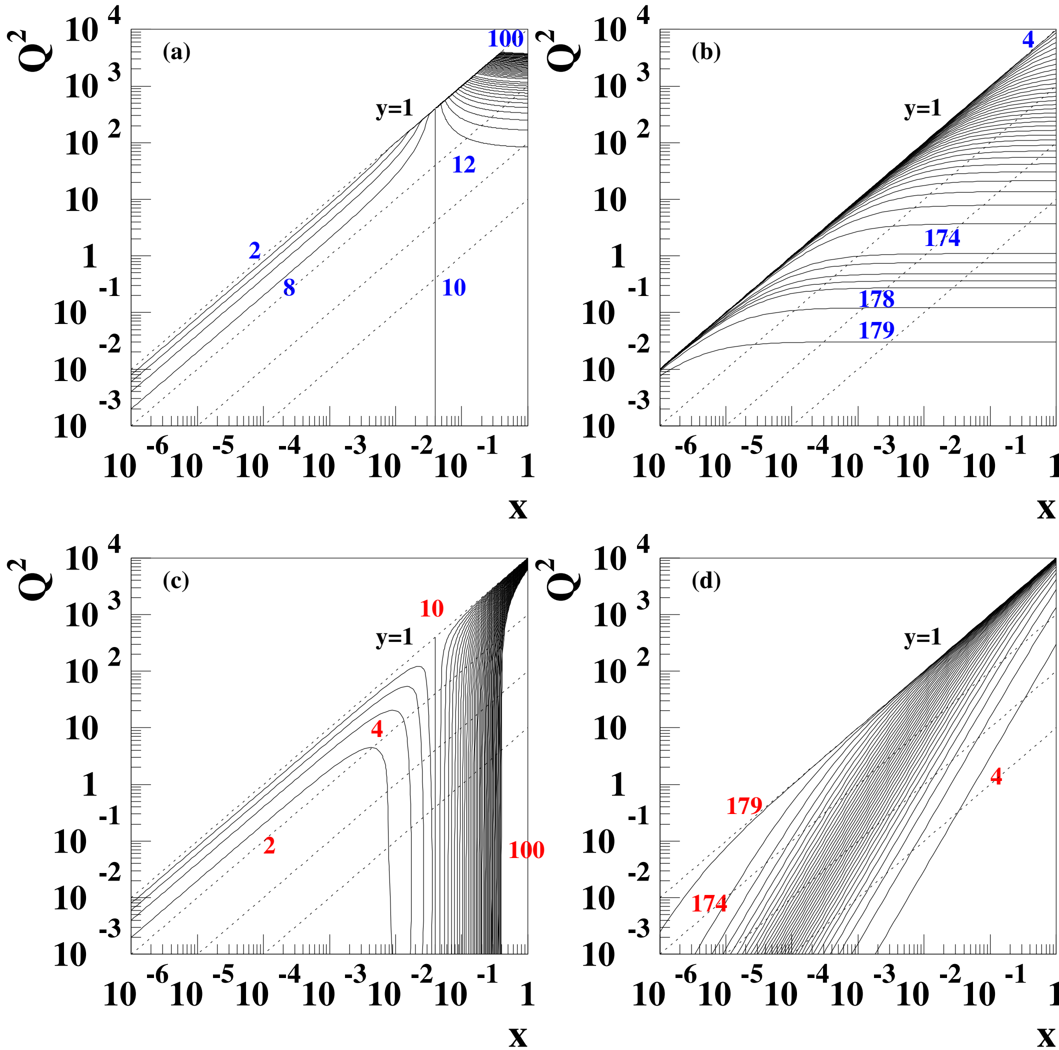
$E_p = 250\,\mathrm{GeV}$

Fixed F

2GeV steps:
2GeV-100GeV

$$Q^2[x,F] = \frac{4E_eF - sx}{\frac{4E_e^2}{sx} - 1}$$

EIC kinematics (E_e=10 GeV, E_p=250 GeV)



$$Q^2[x,\theta'_e] = \frac{xs}{\frac{xs}{4E_e^2}\tan^2\frac{\theta'_e}{2}+1}$$

Fixed θ'_e

5° steps: 4°-174°
1° steps to 179°

plus

θ'_e =176.5407° / η = 3.5

Fixed γ

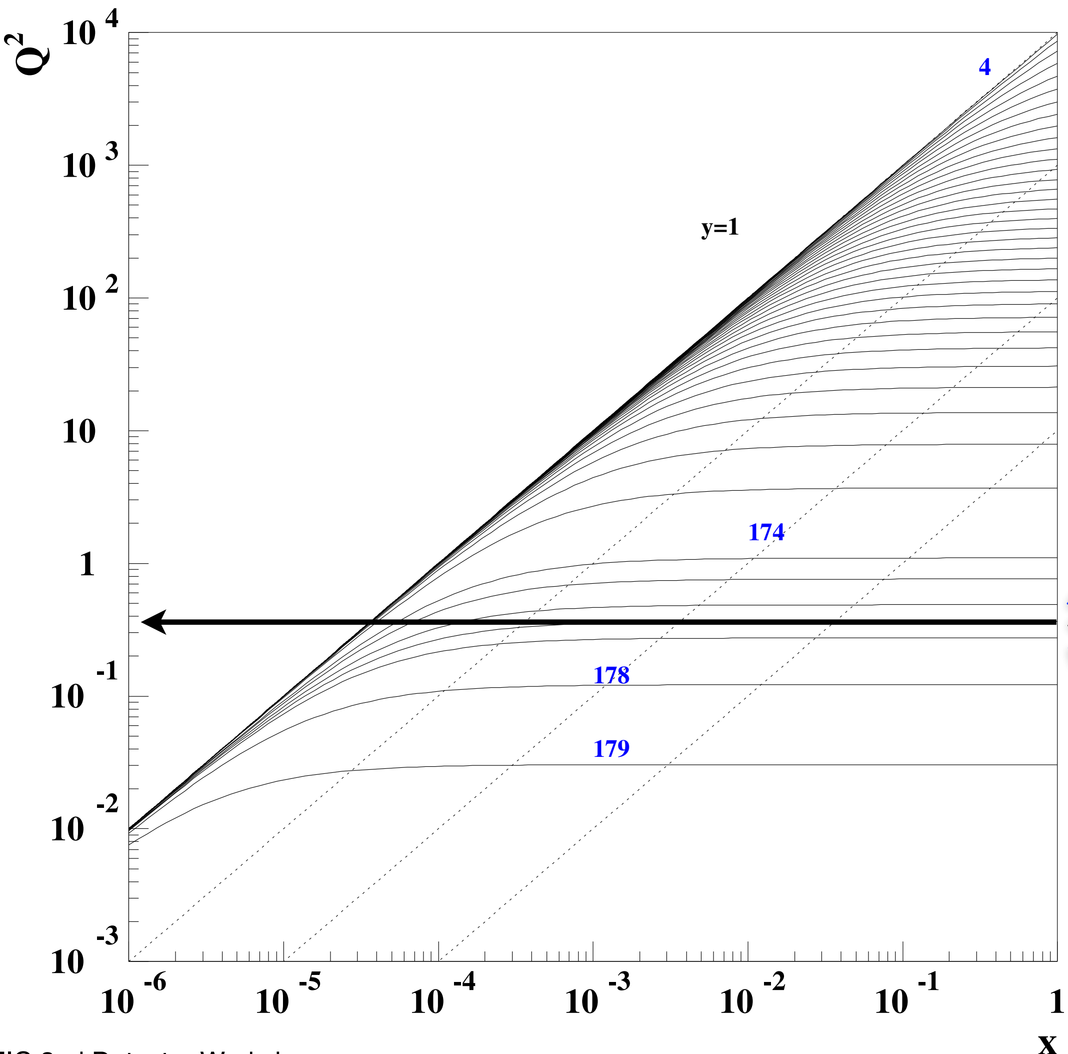
5° steps:
4°-179°

$$Q^2[x,\gamma] = \frac{sx}{\frac{4E_e^2}{sx}\cot^2\frac{\gamma}{2}+1}$$

Acceptance ePIC

- ePIC Central detector vs. low Q^2 tagger: Focus on angular acceptance

EIC kinematics (E_e=10 GeV, E_p=250 GeV)



$$Q^2[x,\theta'_e] = \frac{xs}{\frac{xs}{4E_e^2}\tan^2\frac{\theta'_e}{2}+1}$$

Fixed θ'_e

5° steps:
4°-174°
1° steps to
179° plus
176.5407°

θ'_e =176°

θ'_e =177°

θ'_e =176.5407° / η = 3.5

- Q^2 acceptance of Low-Q^2 tagger from collaboration meeting: Extremely small values in Q^2 —> PHP tagger!
- At η = 3.5 we get: θ'_e =176.5407°
- Concern: No continuous coverage down to at least Q^2=0.1GeV2
- Can we extend calorimetry/tracking/PID coverage down to Q^2=0.1GeV^2?
- No continuous coverage between Q^2=0.1GeV^2 and Low-Q^2 tagger!

Concluding remarks

- HERA program focused on various efforts to study the transition region:
  - Shifted vertex
  - Installation of flat beam pipe allowing to move top/bottom U-SCI calorimeter modules closer to beam (ZEUS)
  - Dedicated scintillating tracker to improve hit resolution (ZEUS)
  - Dedicated small-angle tagger: beam pipe calorimeter (ZEUS/H1)
- The physics program of exploring saturation phenomena requires continuous coverage below Q^2=1GeV^2, at least an order of magnitude below Q^2=1GeV^2, where pQCD description fails, i.e. to at least Q^2=0.1GeV^2
- ePIC low Q^2 tagger is a photoproduction tagger - critical for photoproduction physics and Q^2 acceptance well below Q^2=0.1GeV^2!
- Opportunity for 2nd detector: Maximize Q^2 tagger down to at least Q^2=0.1GeV^2 / Integrate detector design with appropriate IR layout concerning small electron-angle (θ'_e) acceptance!