On the group velocity of virtual photons in DIS at HERA

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- Motivation and the problem statement
- Tools:

need to be developed based on

I — Uncertainty relations

$\mathbf{\Delta x} \cdot \mathbf{\Delta P_x} \geq \hbar/\mathbf{2}\,, etc$ $\qquad \mathbf{\Delta E} \cdot \mathbf{\Delta t} \geq \hbar$

II — Direct model calculations

III — The method of indirect measurements

- Preliminary results based on published data tables
- Discussion and interpretation

Motivations -I

«The effective quark radius limits» Phys. Lett. B757 (2016) 468, arXiv:1604.01280

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{\mathrm{SM}}}{dQ^2}\left(1 - \frac{R_e^2}{6}Q^2\right)^2 \left(1 - \frac{R_q^2}{6}Q^2\right)^2$$

$$\bar{r_q} = \sqrt{|\langle R_q^2 \rangle|} < 0.43 \cdot 10^{-3}\,\mathrm{fm}$$

Discussions with Filip and Iris
(A.F. Zarnecki, I. Abt, Jan-Feb, 2016)

Here is one of the outcomes of this highly useful discussions:

«With Rq and Q in hands, even possible to check how well works an estimation of Rq based on the Heisenberg's uncertainty relation,
Rq ~ h/Q.»

I started these calculations out of curiosity, but now everything is very serious!

Motivations -II

-Which variables should be tabulated in ZEUS publications so that it is possible to independently make a qualitative calculation without referring to the original "raw" data?

- For example, to estimate ΔR for a quark by $\sqrt{(\Delta R)^2(\Delta \vec{q})^2} \geq \hbar/2$

or by $\sqrt{(\Delta R)^2 Q^2} \geq \hbar/2$??

But $Q^2 = -[(q_0)^2 - c^2(\vec{q})^2]$ is a «mixed» photon variable.

Uncertainty relations must contain variables of the same object!

In addition, the estimation of ΔR is *"encumbered"* by the parton distribution model.

What can be evaluated only with the use of (x_{Bj}, Q^2) tables ?

Q2 and x_Bj HERA data from tables

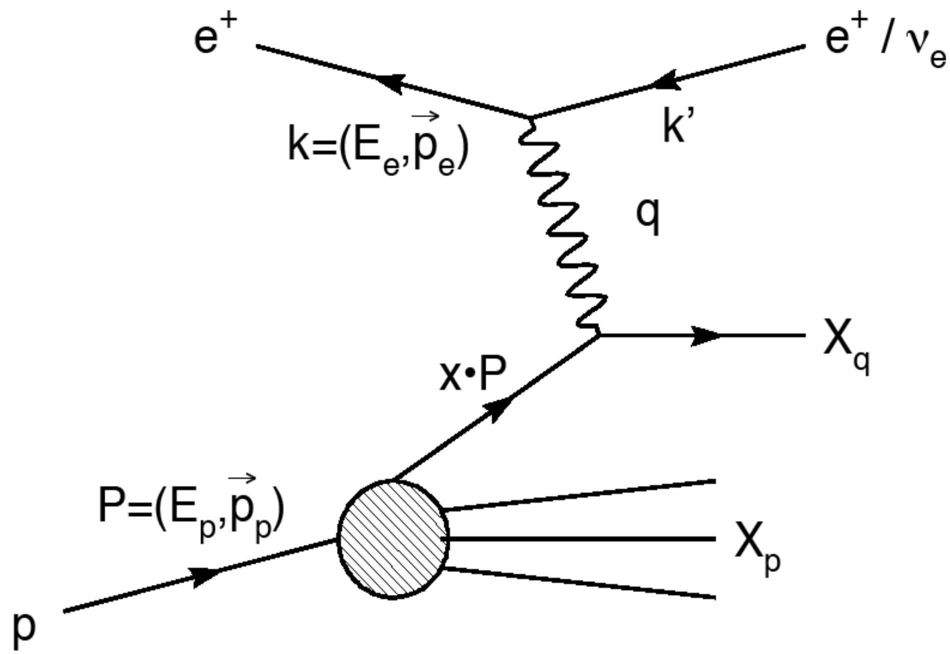
Combination of Measurements of Inclusive Deep Inelastic e+- p Scattering Cross Sections and QCD Analysis of HERA Data

Eur. Phys. J. C 75 (2015) 580

Q^2 GeV^2	x_{Bj}	$\sigma^{+}_{r,\mathrm{NC}}$	δ_{stat} %	δ_{uncor} %	δ_{cor} %	δ_{rel} %	
3.5	0.406×10^{-4}	0.806	6.14	4.17	1.18	1.09	-
3.5	0.432×10^{-4}	0.881	3.08	2.83	3.31	0.70	-
3.5	0.460×10^{-4}	0.965	3.05	2.99	1.10	0.35	-
3.5	0.512×10^{-4}	0.940	2.16	2.25	1.53	0.52	-
3.5	0.531×10^{-4}	0.880	3.10	2.64	0.91	0.48	-
3.5	0.800×10^{-4}	0.952	1.25	1.55	0.88	0.43	-
3.5	0.130×10^{-3}	0.918	0.66	0.86	0.80	0.45	-
3.5	0.200×10^{-3}	0.854	0.68	0.83	0.81	0.44	
3.5	0.320×10^{-3}	0.791	0.72	0.88	0.86	0.50	-
3.5	0.500×10^{-3}	0.749	0.76	1.17	0.89	0.37	-
3.5	0.800×10^{-3}	0.659	0.67	1.16	0.91	0.37	
3.5	0.130×10^{-2}	0.623	0.87	1.38	0.97	0.42	-
3.5	0.200×10^{-2}	0.568	0.51	0.87	0.85	0.44	-

Q2 and x_Bj are connected via kinematics and dynamics

e±p DIS Kinematics



$$Q^2 = -(k - k')^2$$

$$x_{Bj} = \frac{Q^2}{2P \cdot q}$$

$$y = \frac{P \cdot q}{P \cdot k}$$

HERA (1992-2007):
Energies
e± : 27.5 GeV
p : 820, 920, 575 and 460 GeV

$(x_{Bj} = x)$

Motivation and the problem statement: γ^* velocity estimation

My old result

BBL, DIS98, Brussels

«An alternative to the Breit frame», 1998

$$q_0 = \epsilon - \epsilon' = \frac{(k - xP)Q^2}{2x(kE + \epsilon P)} \simeq c(k - xP)y$$

$$|\vec{q}| = \frac{1}{c}\sqrt{q_0^2 + Q^2}$$

$q_0=0$ **at** $x = k/P$ **!**

And apply to virtual photons group velocity estimation U_γ

✔ $$\beta* = U_\gamma / c \sim (1/c)\sqrt{(\Delta R)^2/(\Delta t)^2}$$ As a first guess

Is it enough to know only (x, Q^2) ? It is not !

Is it possible technically?

Why U should be «the group velocity» ?

A photon is a tiny part of electromagnetic field. ***It is a particle and a wave train.***
The velocity of the wave train is the group velocity $U = \dfrac{\partial \omega}{\partial n}$

The phase velocity of the wave is $V = \dfrac{\omega}{n}$

In 1D, U and V are connected via L. Rayleigh relation $U = V - \lambda \dfrac{\partial V}{\partial \lambda}$ (♦)

For radio waves in the upper part of the atmosphere (ionosphere), V>c and U<c, but **$UV = c^2$.**

I've generalized 1D (♦) for 3D waves

$$\boxed{2\vec{V}^2 + n_j \frac{\partial \vec{V}^2}{\partial n_j} - 2(\vec{U}\cdot\vec{V}) = 0} \rightarrow \boxed{|\vec{U}| = \frac{1}{\cos\alpha}\left(|\vec{V}| + \frac{n_j}{2|\vec{V}|}\frac{\partial \vec{V}^2}{\partial n_j}\right)}$$

And calculate $|\vec{U}||\vec{V}|$ **too !**

BB L, 2021

Tools : I

Uncertainty relations: I coordinate - momentum

W. Heisenberg (1927, 23 March, Copenhagen), Zs. Phys., 1927, 43, 172

- $pq - qp = \frac{h}{2\pi i} \rightarrow p_1 q_1 \sim h$

(From the original.)
p1, q1 — errors

Proof :

- $\Delta p_x \cdot \Delta x \geq \hbar / 2$

H. Weyl, «Gruppentheorie und Quantenmechanik», 1928
«The Theory of Groups and Quantum Mechanics», 1930
p. 77, p. 408 (Transl. H.P. Robertson, Princeton)
gave the inequality a modern look

- $(\Delta A)^2 = \langle A^2 \rangle - \langle A \rangle^2,$ $\Delta A = \sqrt{\overline{(A - \bar{A})^2}}$

H. Weyl
shift origin

- $(\Delta x)^2 = \int_{-\infty}^{+\infty} x^2 \bar{\psi}(x) \psi(x) dx,$ $(\Delta p)^2 = -h^2 \int_{-\infty}^{+\infty} \bar{\psi}(x) \frac{d^2\psi}{dx^2} dx$

At this stage, I'm not going to analyze the original data, but will work with tables of $(\mathbf{x}_{Bj}, \mathbf{Q^2})$ **and**

$$q_0 = c(k_e - x_{Bj} \cdot P)y \qquad |\vec{q}| = \frac{1}{c}\sqrt{q_0^2 + Q^2}$$

Therefore , there is no way to restore the virtual photon momentum projections.

For this reason, I cannot lawfully apply HUR presented ***for projections*** **of conjugate quantities.**

What I have to do ?

Just to derive new uncertainty relations !

Tools : I

New!

Uncertainty relations coordinate -momentum II:
A «hidden» parameter

According to Weyl

BB Levchenko, 2020

$$(\Delta p_x)^2 \cdot (\Delta x)^2 \geq (\hbar/2)^2$$

$$(\Delta p_y)^2 \cdot (\Delta y)^2 \geq (\hbar/2)^2$$

$$(\Delta p_z)^2 \cdot (\Delta z)^2 \geq (\hbar/2)^2$$

add

$$\overrightarrow{(\Delta P)^2} \cdot \overrightarrow{(\Delta R)^2} \geq 3(\hbar/2)^2$$

The dot product of vectors in Hilbert space !!

These vectors are

$$\overrightarrow{(\Delta P)^2} = \left((\Delta p_x)^2, (\Delta p_y)^2, (\Delta p_z)^2\right)$$

$$\overrightarrow{(\Delta R)^2} = \left((\Delta x)^2, (\Delta y)^2, (\Delta z)^2\right)$$

Finally,

✔ $$\left|(\Delta P)^2\right| \left|(\Delta R)^2\right| \geq \frac{3\hbar^2}{4\cos\psi}$$

✔

A new variable

ψ

Old Slavonic symbol

			Образы
Щ ц		1	пространство, ограни
		2	ченное пределом
		3	плотность
		4	разнообразие
		5	неопределённое состояние
ЩА		6	
		7	
шта	-	8	
		9	
-шт-		10	

-Space limited by a boundary

-density
-diversity
- uncertain state

sounds as “sch’ta”

Domain of the function and the domain of the angle

$0 < \cos\psi \leq 1, \qquad \psi \in [0, \pm\pi/2)$

- **For 3D harmonic oscillator: $\cos\psi = 1/(2n+1)^2$, $n=0,1,2,3,\ldots$**

- **3D rectangular potential well with infinite walls: $\cos\psi = 3/(n^2\pi^2-6)$, $n=1,2,3,\ldots$**

♦**The angular variable appeared as a result of the reduction of six degrees of freedom to three degrees of freedom .**

Tools : I

Uncertainty relations time-energy I

W. Heisenberg (1927, 23 March, Copenhagen), Zs. Phys., 43, 172 (1927)

$$E t - t E = \frac{h}{2\pi i} \qquad E_1 t_1 \sim h.$$

(is in the original.)
E1, t1 — errors

N. Bohr (Sept., 1927, Como), **N. Bohr. Naturwiss., 16, 245 (1928)**

and presented own version of obtaining

$$\Delta E \cdot \Delta t \geq \delta \hbar$$

Heisenberg-Bohr relation

δ is a constant

The act of measurement is the interaction of two systems: a microobject described by quantum mechanically, and a device described classically.

Tools : I

Uncertainty relations time-energy II: a «hidden» parameter II

In the relativistic domain

Landau and Peierls. Zs. Phys., 69, 56, (1931)

Applying the relationship,

$$\Delta E = \frac{\partial E}{\partial P} \Delta P = U \Delta P$$

they found,

$$U_x \Delta p_x \Delta t \sim \hbar \qquad (*)$$

Here U is the particle group velocity.

Adding the squares of the relations (*) for (x, y, z), like above I get

✔ $$\vec{U}^2 (\Delta |\vec{q}|)^2 (\Delta t)^2 \sim 3 \hbar^2 / \cos \Psi_u$$

Tools I. Finally, an estimate of a virtual photon group velocity

- $\left|\vec{U}^2\right|\left|(\Delta \vec{q})^2\right|(\Delta t)^2 \sim 3\hbar^2/\cos\psi_u$ **(I)**
- $(\Delta R)^2\left|(\Delta \vec{q})^2\right| \geq 3\hbar^2/4\cos\psi$ **(II)**

$$(\Delta t)^2 \sim \delta^2\hbar^2/(\Delta q_0)^2$$

By taking the ration of the inequalities,

The velocity is not just $\Delta R/\Delta t$!

- $$\left|\vec{U}^2\right| \sim 4\frac{(\Delta R)^2}{(\Delta t)^2}\frac{\cos\psi}{\cos\psi_u} = \frac{(\Delta q_0)^2}{\left|(\Delta \vec{q})^2\right|}\frac{3}{\delta^2 \cdot \cos\psi_u}$$

$$\boxed{|U| \leq \sqrt{3\left|\vec{U}^2\right|}}$$

Due to Cauchy-Bunyakovsky-Schwarz inequality

From data with the condition U=c at $Q^2 \to 0$!

Tools II. U is the group velocity

A photon is *a particle and a wave train.*
The velocity of the wave train is the group velocity $$U = \frac{\partial \omega}{\partial n}$$

The phase velocity of the wave is $$V = \frac{\omega}{n}$$

In 1D, U and V are connected via L. Rayleigh relation $$U = V - \lambda \frac{\partial V}{\partial \lambda} \qquad (\blacklozenge)$$

For radio waves in the upper part of the atmosphere (ionosphere),
V>c and U<c, but $UV = c^2$.

I've generalized 1D (♦) to 3D waves

$$\boxed{2\vec{V}^2 + n_j \frac{\partial \vec{V}^2}{\partial n_j} - 2(\vec{U}\cdot\vec{V}) = 0} \rightarrow \boxed{|\vec{U}| = \frac{1}{\cos\alpha}\left(|\vec{V}| + \frac{n_j}{2|\vec{V}|}\frac{\partial \vec{V}^2}{\partial n_j}\right)}$$

And calculate $|\vec{U}||\vec{V}|$ too !

BB L, 2021

Tools II. What are the predictions ?

Group velocity: I Direct calculation

I apply the method developed by de Broglie (*a duality between waves and particles*)

W. Pauli, General Principles of Quantum Mechanics, (1980) p. 5

The wave vector $\vec{n}$ and the frequency ω of a photon γ^*

$$\vec{q} = \hbar \vec{n}, \; q_0^{\,2} = (\hbar \omega)^2$$ With the use $$E^2/c^2 = m^2 c^2 + \sum p_i^{\,2}$$

Then,

$$(\omega/c)^2 = (\omega_0/c)^2 + \sum n_i^{\,2}$$ where $(\omega_0)^2 = (m{*}c^2/\hbar)^2$ and $(m{*})^2 = -Q^2$

The group velocity is calculated via (dispersion formula)

$$U^2 = \left(\frac{\partial \omega}{\partial n_1}\right)^2 + \left(\frac{\partial \omega}{\partial n_2}\right)^2 + \left(\frac{\partial \omega}{\partial n_3}\right)^2 \rightarrow \boxed{\frac{U}{c} = \beta{*} = \sqrt{1 + \frac{Q^2}{q_0^2}}}$$

BB L, 2020

Tools II. What are the predictions ?

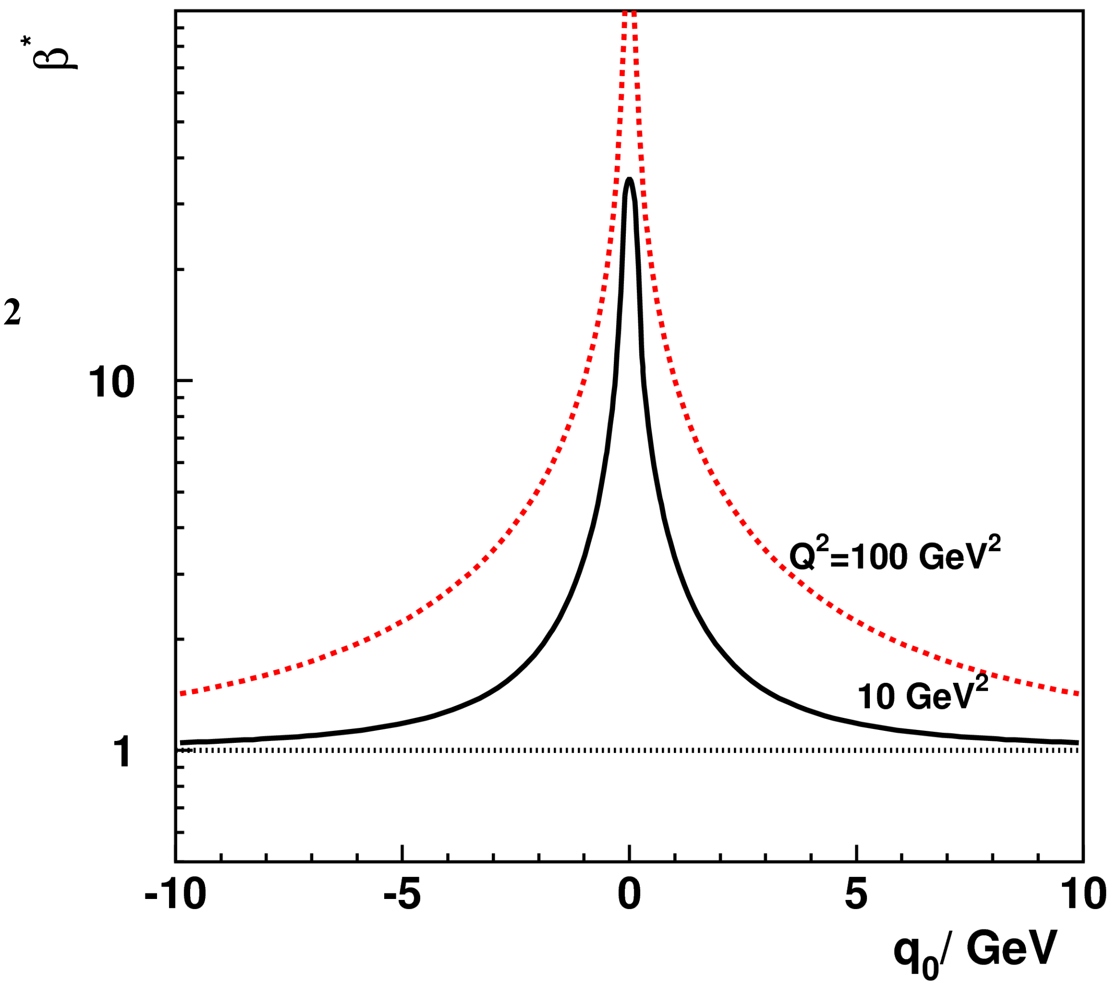
Group velocity: II Plots

$$\beta * = \sqrt{1 + \frac{Q^2}{q_0^2}}$$

- $\beta^* \geq 1$, U >c, V<c , $|\vec{U}||\vec{V}| = c^2$
- $\beta^* \rightarrow 1$, if $Q^2 \rightarrow 0$, $x \neq x_0$

- Singular behavior close to $x_0 = k_e / P$, $(q_0 \rightarrow 0)$!

$$q_0 = \frac{(k_e - xP)\, Q^2}{2x\,(k_{eE} + \epsilon\, P)}$$



NB

The act of measurement is the interaction of two systems: a microobject described by quantum mechanically, and a device described classically.

We need to account the apparatus effects!

Tools : III

The method of indirect measurements. General statements

Leonid Mandelstam (1879 -1944)
Lectures at Moscow State University on the basics of quantum mechanics
Theory of indirect measurements (1939)

The last stage of measurement in wave mechanics is necessarily macroscopic. We call direct measurements such measurements in which the first step is macroscopic. The principle of indirect measurement is that this system (I) in which we want to measure A, we force to interact with another microsystem (II) for which direct measurement is already possible, and then theoretically determine the value of A.

For our problem: $I=\gamma^*$, $II= p$, $A=U^*$,
+ ZEUS detector ->(x,Q2)

Tools : III

The method of inderect measurements . I Applications

Semyon G. Rabinovich, Measurement Errors and Uncertainties. Theory and Practice, 3-d ed., 2005

An indirect measurement is such a measurement when an unknown quantity is calculated from measurements of other quantities associated with the desired variable by a known function.

For our problem I need to calculate $(\Delta \vec{q})^2$ **and** $(\Delta q_0)^2$

And then insert them in

$$(\Delta R)^2 \sim 1/(\Delta \vec{q})^2 \qquad (\Delta t)^2 \sim 1/(\Delta q_0)^2$$

For example,

$$z = F(x, y), \quad (\Delta z)^2 = (\partial F/\partial x)^2 (\Delta x)^2 + (\partial F/\partial y)^2 (\Delta y)^2$$

Tools : III

The method of indirect measurements . II Applications

In this way, from $$|\vec{q}| = \frac{1}{c}\sqrt{q_0^2 + Q^2}, \;\; q_0 = c(k_e - x_{Bj} \cdot P)y$$

follows $$(\Delta q)^2 \;=\; \frac{1}{c^4}[(\frac{q_0}{|\vec{q}|})^2(\Delta q_0)^2 + \frac{(\Delta Q^2)^2}{4(\vec{q})^2},]$$

and $$(\Delta q_0)^2 \;=\; c^2P^2y^2 \cdot (\Delta x_{Bj})^2 + c^2(k_e - x_{Bj}P)^2 \cdot (\Delta y)$$

etc. A long chain of equations.

- But, without an additional "input," there is no way to get a closed solution!

- Therefore it is necessary to take into account the resolution of the **ZEUS:**

$$\sigma_\Sigma/\Sigma_e = [0.18/\sqrt{\Sigma_e}] \quad \Delta y = 0.18\sqrt{(1-y)/2ck_e} \quad (cp_t)^2 = Q^2(1-y)$$

$$\Delta p_t \;=\; \left(\frac{\sigma(p_t)}{p_t}\right)p_t = p_t\sqrt{(0.0058p_t)^2 + (0.0065)^2 + (0.0014/p_t)^2}$$

Tools : III

The method of inderect measurements : III Applications

As a result, the formulas are closed by the **accuracy** of the measuring devices:

$$(\Delta x_{Bj})^2 = \frac{4x_{Bj}^2}{(1-y)Q^2}(c\Delta p_t)^2 + x_{Bj}^2\left[\frac{1}{(1-y)^2} + \frac{1}{y^2}\right](\Delta y)^2$$

All these parts have to be inserted in :

$$\boxed{U^2 \sim \frac{(\Delta R)^2}{(\Delta t)^2} = A\frac{(\Delta q_0)^2}{\left|(\Delta \vec{q})^2\right|}}$$

A — normalization factor

Q2 and X_Bj data from tables

Combination of Measurements of Inclusive Deep Inelastic e+- p Scattering Cross Sections and QCD Analysis of HERA Data

Eur. Phys. J. C 75 (2015) 580

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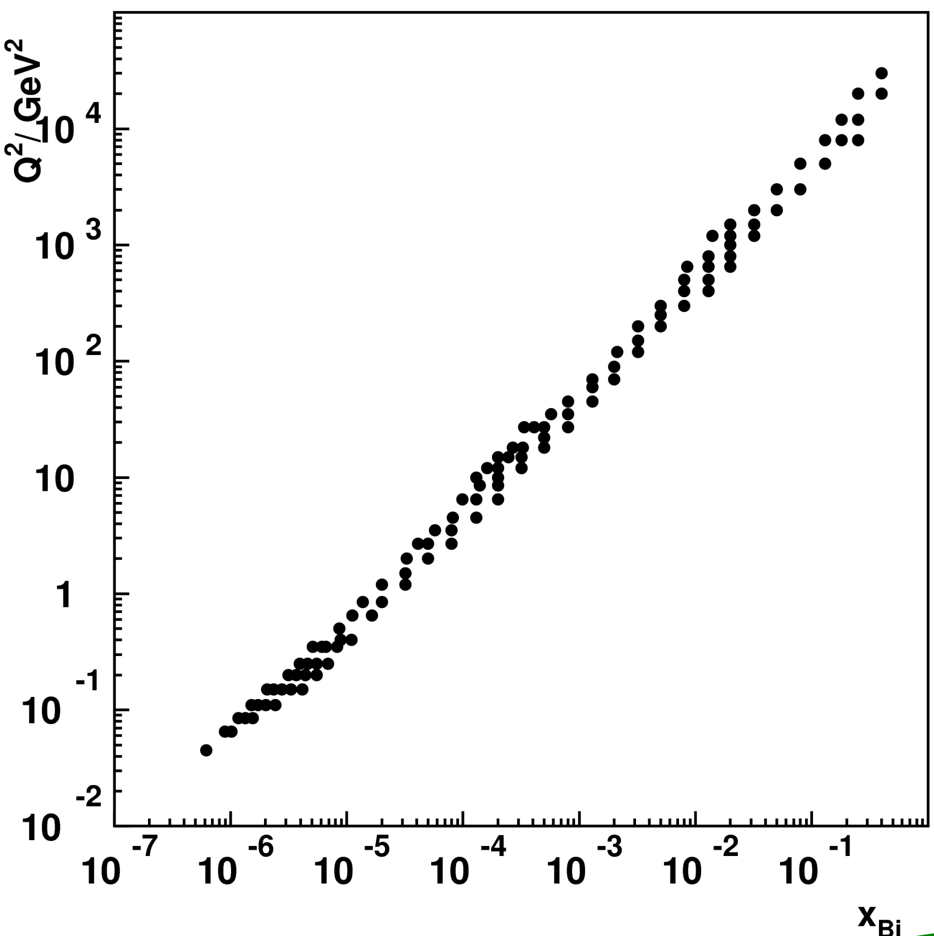
3.5	0.130×10^{-3}	0.918	0.66	0.86	0.80	0.45	-
3.5	0.200×10^{-3}	0.854	0.68	0.83	0.81	0.44	
3.5	0.320×10^{-3}	0.791	0.72	0.88	0.86	0.50	-
3.5	0.500×10^{-3}	0.749	0.76	1.17	0.89	0.37	-
3.5	0.800×10^{-3}	0.659	0.67	1.16	0.91	0.37	
3.5	0.130×10^{-2}	0.623	0.87	1.38	0.97	0.42	-
3.5	0.200×10^{-2}	0.568	0.51	0.87	0.85	0.44	-

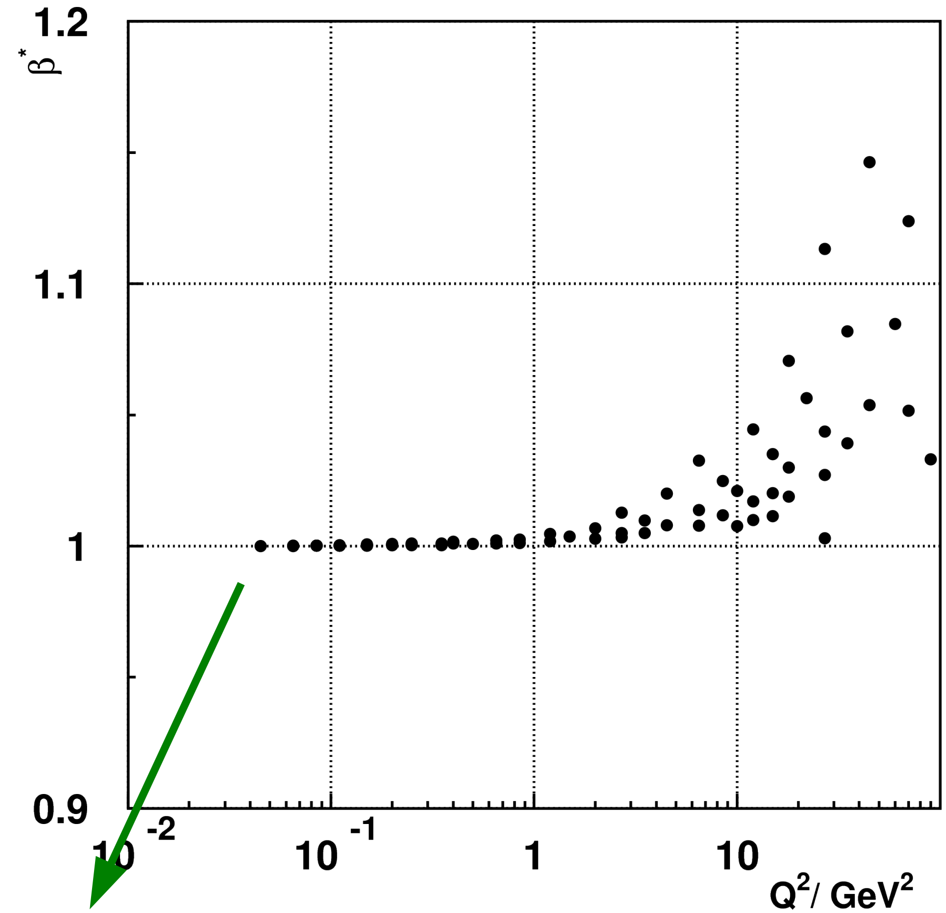
Compromise association of ZEUS and H1 data

HERA data

Each (x, Q ²) point is averaged values in bin on (x, Q ²) -plane.

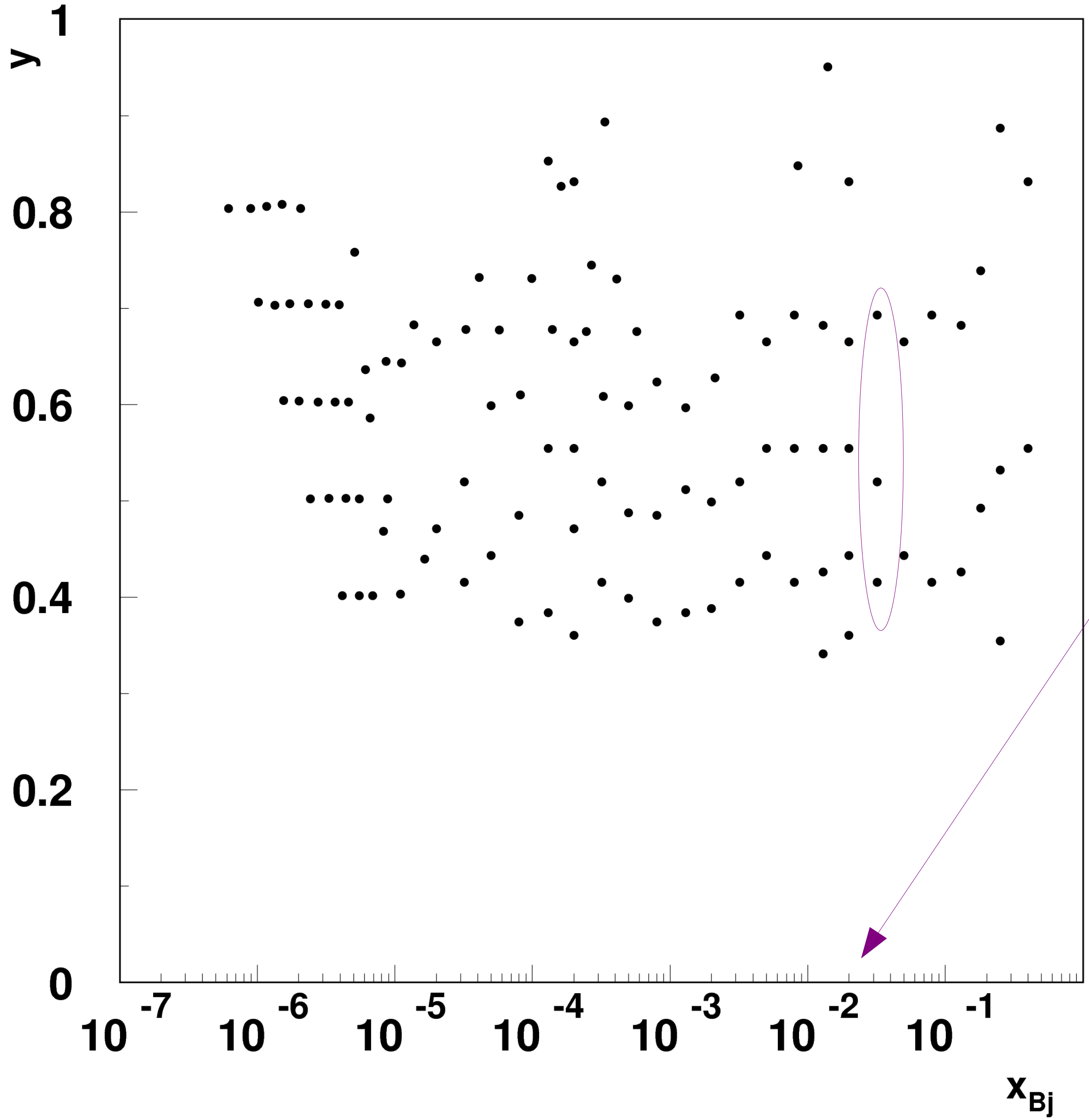
Ep = 820 GeV, NC, table 11 (limited range in y)





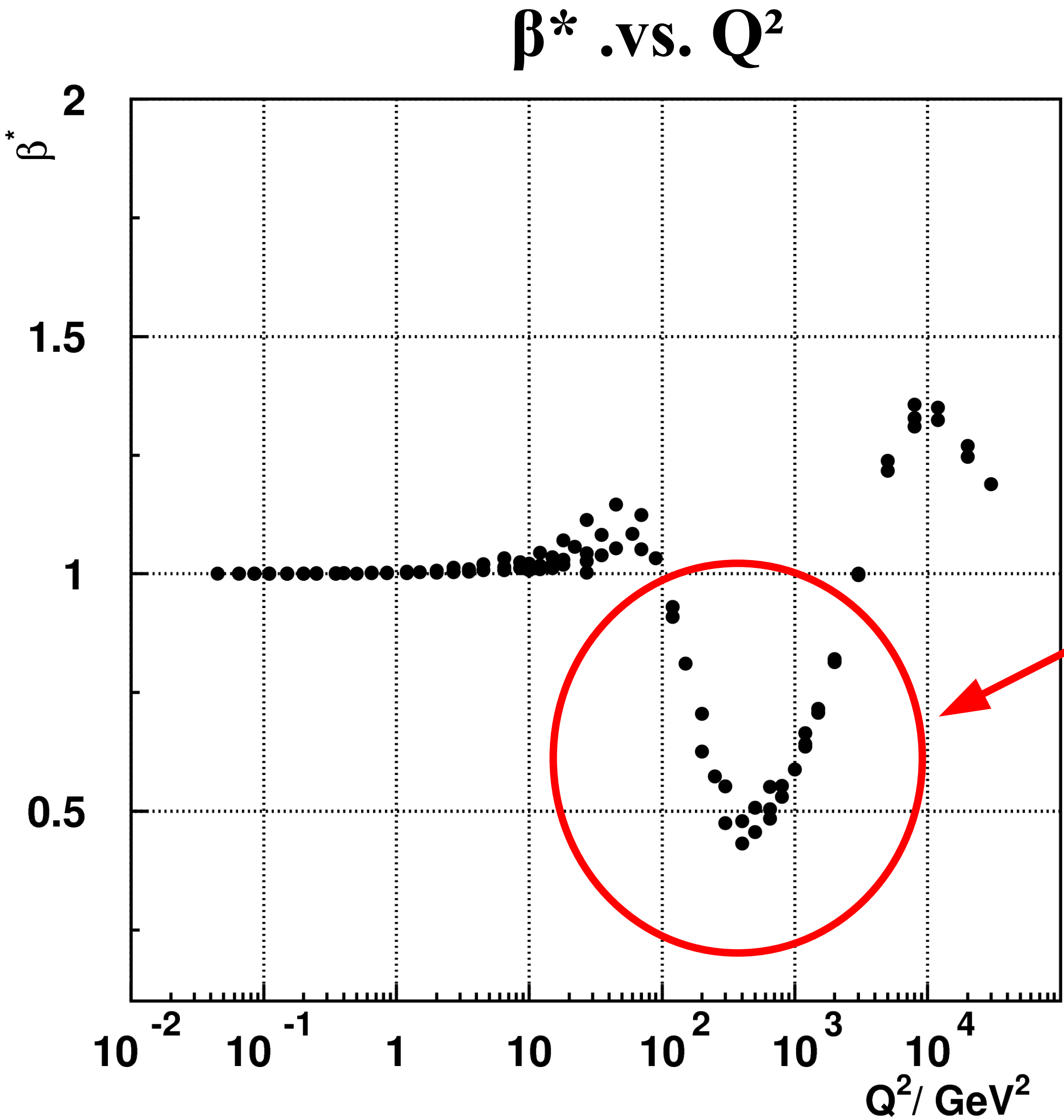
$Q^2 \rightarrow 0$ $\rightarrow$ $A = \dfrac{3}{\delta^2 \cdot \cos\psi u} = 1/3$ $\rightarrow$ $\beta * = \sqrt{\dfrac{(\Delta q_0)^2}{(c \Delta q)^2}}$

Ep = 820 GeV, NC



HERA data

$$x_0 = k_e / P = 0.033$$



Ep = 820 GeV, NC

HERA data

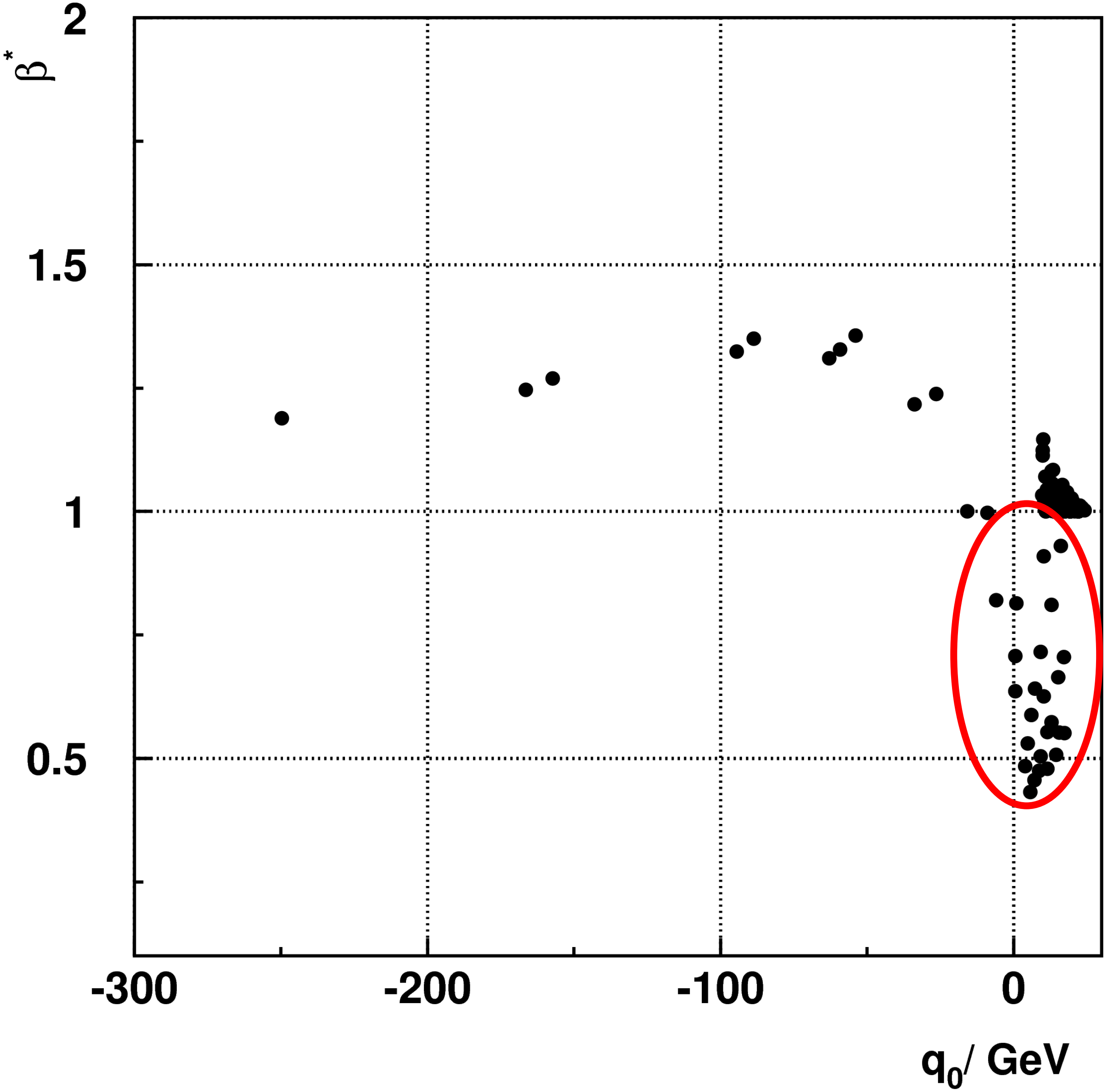
"The Hardware Effect":
a degradation of transverse momentum measurement accuracy.
- limited in y data

Close to q**0**~0,

$$\beta^2 \sim y + \frac{(1-y)^2}{y + 0.033 \cdot y^2 (1-y)^2 \cdot E_e^3 + 0.0001 / E_e}$$

Hardware part

β^* .vs. q_0



Ep = 820 GeV, NC

HERA data

There is no peak at q_0 =0 !

Close q_0~0, y~0.5

$$\beta^2 \sim y + \frac{(1-y)^2}{y + 0.033\cdot y^2(1-y)^2\cdot E_e{}^3 + 0.0001/E_e}$$

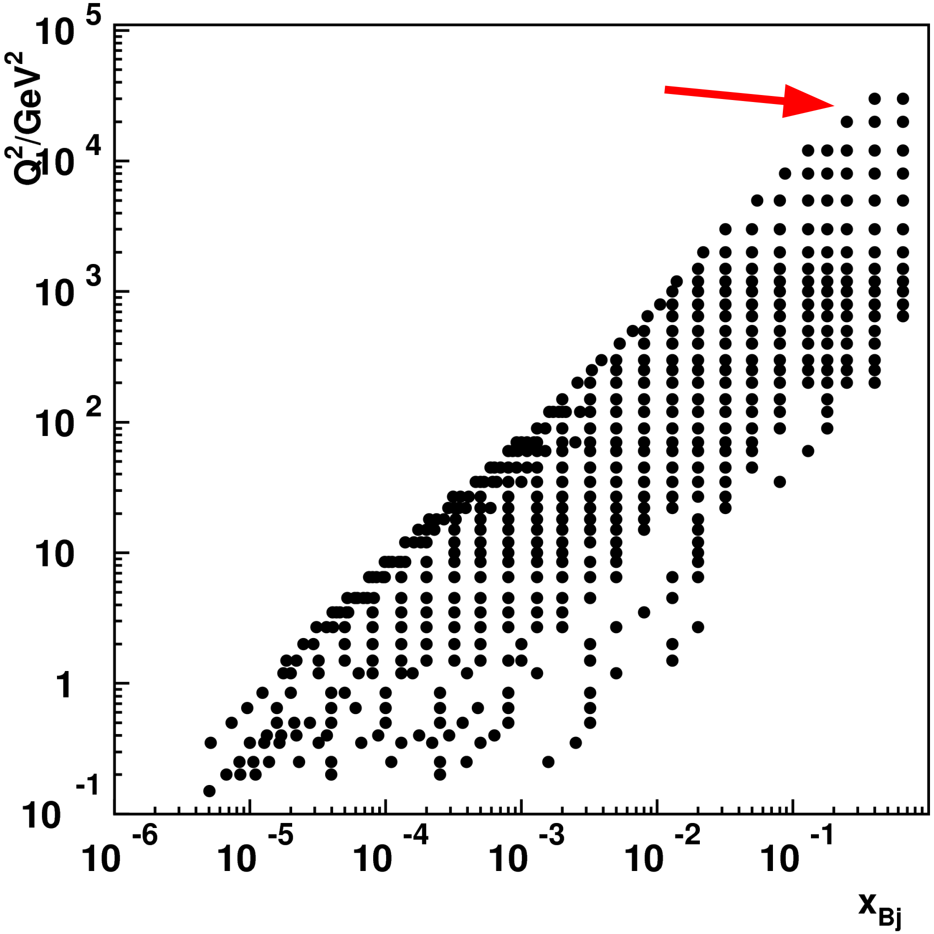
Hardware part

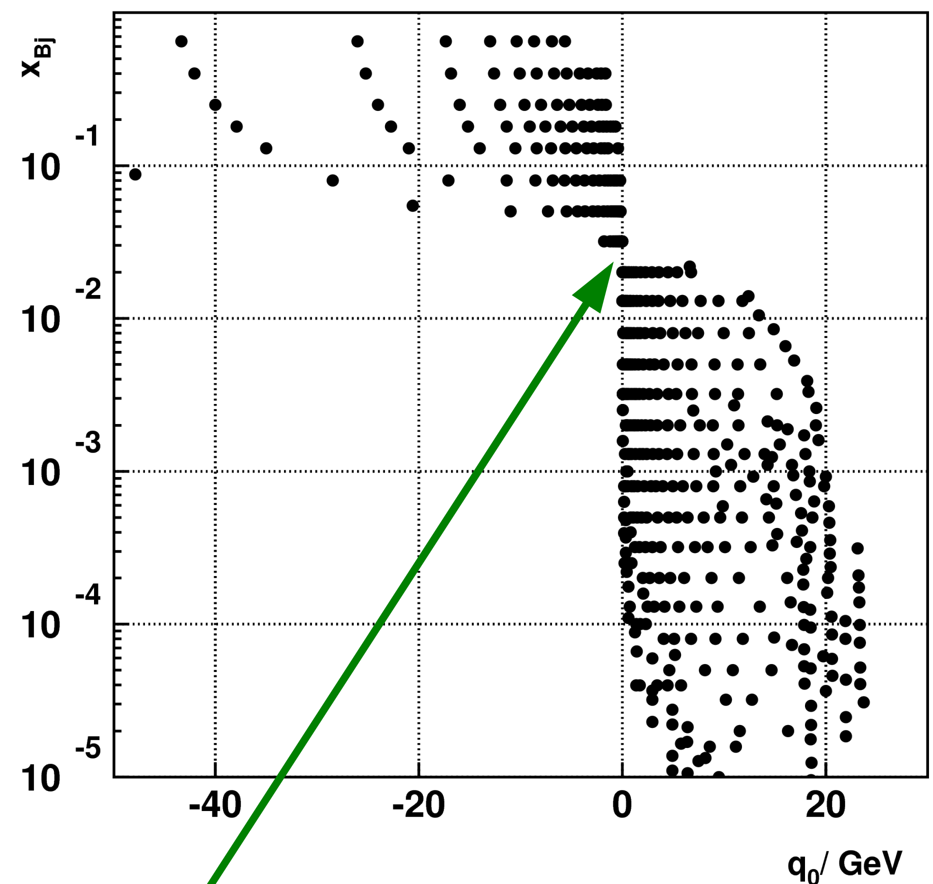
At $y \to 0$, $\beta^2 \to E_e/0.0001$ >>1

Results: Ep = 920 GeV, NC, Table 10

Kinematic domain

HERA data

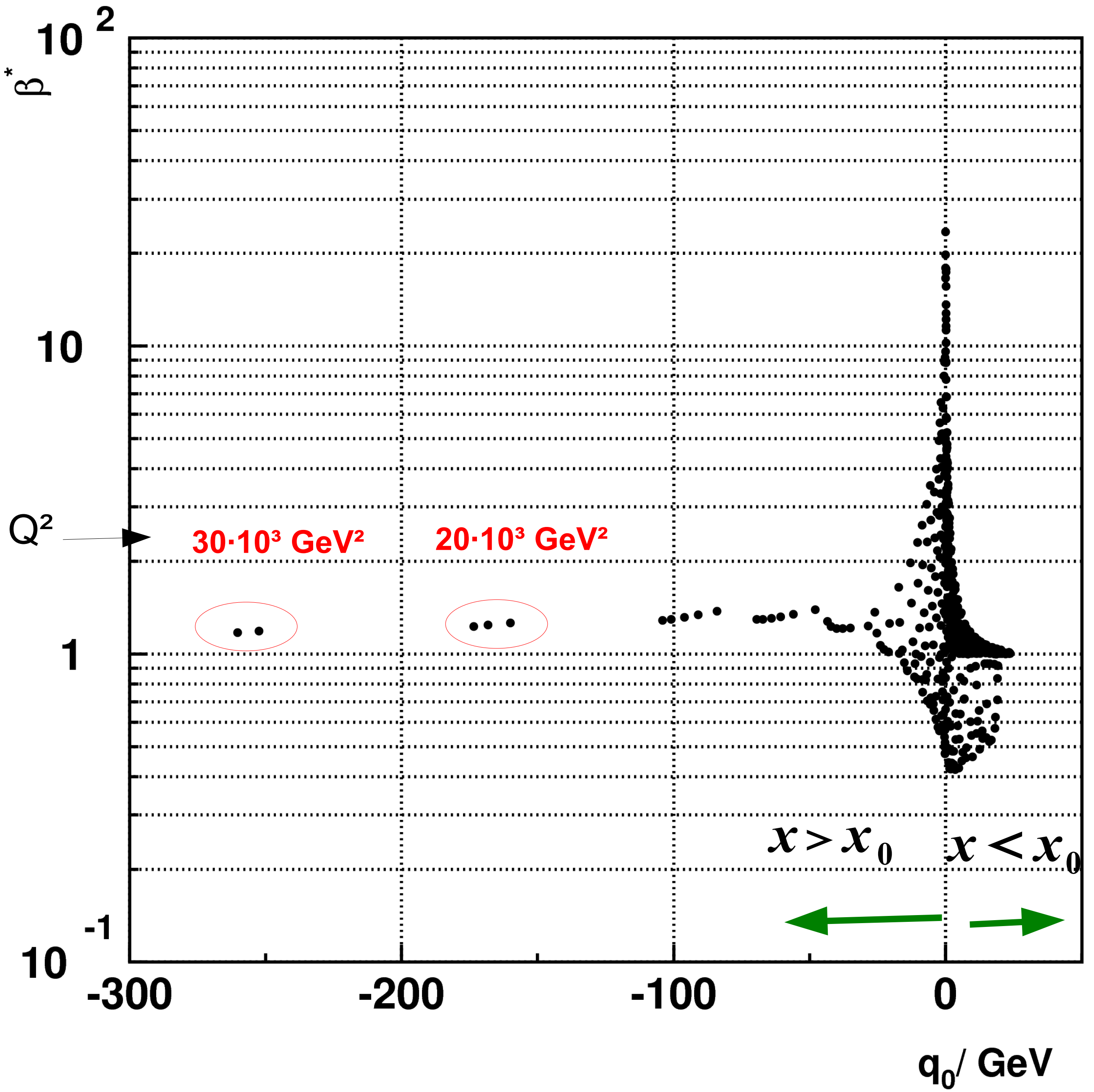




$$x_0 = k_e / P = 0.0299$$

Results: Ep = 920 GeV, NC, table 10

Virtual photon velocities I.



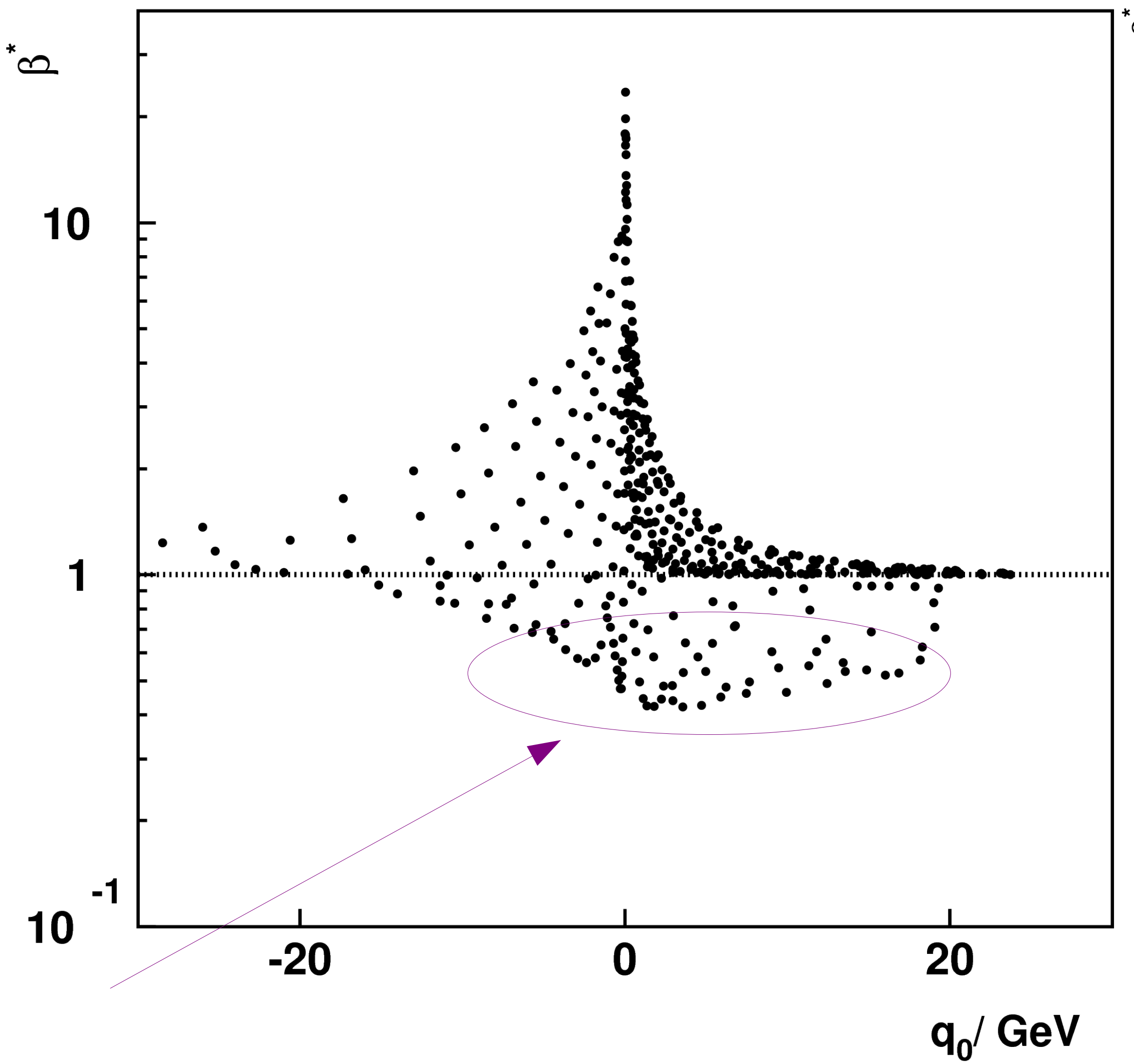
HERA data

β^* .vs. q_0

x_0=0.0299

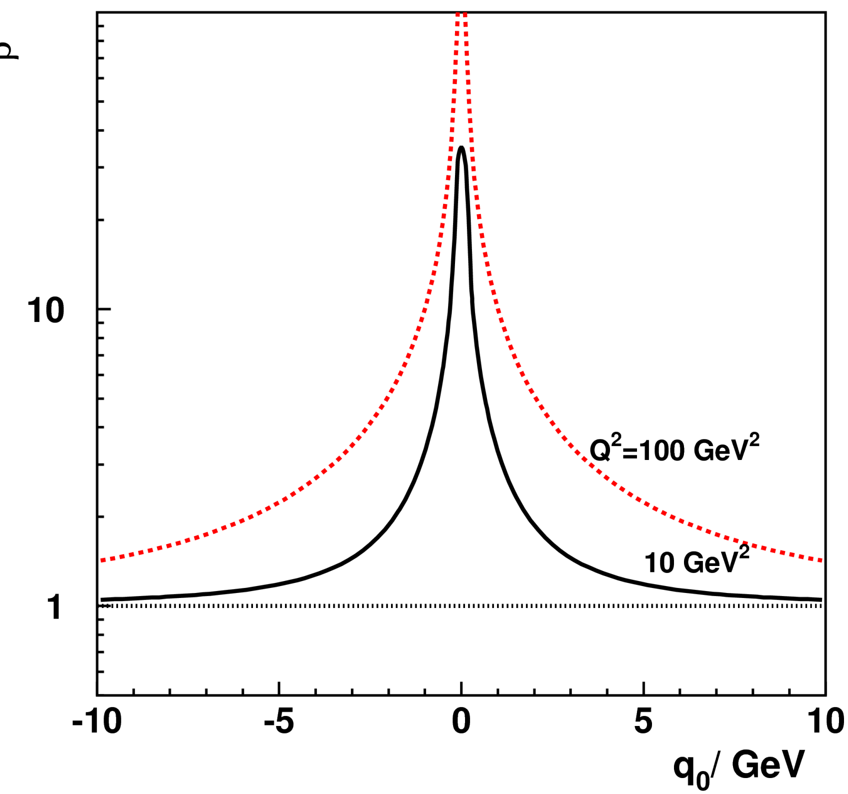
Results: Ep = 920 GeV, NC, table 10
Virtual photon velocities II

HERA data,



Data quality, «the hardware effect», photon properties!?

Dispersion formula



β^* .vs. q_0

At maximum, $\beta^* > 20$!

(effect of averaging)

Interpretation

Virtual photons

- mass, $(m^*)^2 = - Q^2$, <0
- energy, q_0 <,> 0 (in given RF)
- velocity, $\beta^* > 1$, $\beta^* < 1$
- $q_0 \to 0$, $\beta^* \to \infty$

On HERA :
Particle beams are asymmetric, x_0=0.0299

This explains the asymmetry of the velocity distribution, if compared with the dispersion formula (x_0 = 0.5).

Interpretation

Virtual photons

- **mass, $(m^*)^2 = - Q^2$, <0**
- **energy, q_0 <,> 0 (**in give RF)
- **velocity, β^* >1, β^*<1**
- **$q_0 \rightarrow 0$, $\beta^* \rightarrow \infty$**

Tachyons

- **mass, $(m^*)^2$ <0**
- **energy, ε <0, > 0**
- **velocity, $\beta^* \geq 1$**
- **$\varepsilon \rightarrow 0$, $\beta^* \rightarrow \infty$**

- The Virtual Photon behaves like a Tachyon !! -

Or ???

I have to point out:

For many decades we study unobservable objects:

- Quarks -

Some references

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- V.F.Perepelitsa, Looking for a Theory of Faster-Than-Light Particles, ArXiv:1407.3245v4 (2015)

E. Recami, a lot of papers

✚ Search the word **«superluminal» ....** in **ArXiv**

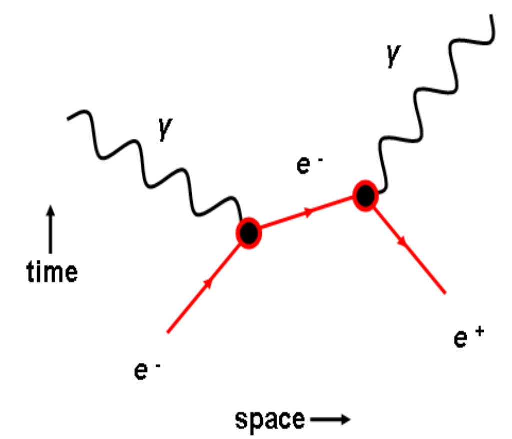
III. Systems with an imaginary proper mass, i.e., $M^2 < 0$.

Systems of the third kind include the virtual particles of quantum theory of field.

Hence, the virtual particles appearing in the quantum theory of elementary particles can be considered as physically real particles with imaginary proper masses exchanged by ordinary elementary particles. **The introduction of such particles does not violate the second law of thermodynamics** and, consequently, we cannot violate the macroscopic Principle of Causality with their help. (**Y.P. Terletskii, 1966)**

Stiickelberg-Feynman

Reinterpretation principle—interpretation of negative-energy tachyons propagating backward in time as positive-energy tachyons propagating forward in time. This reinterpretation invalidates causality objections to the possibility of existence of faster-than-light signals and permits construction of a consistent theory of tachyons.(**O. Belaniuk, E. Sudarshan)**



Conclusions I

► A general mathematical method based on the theory of indirect measurements and quantum relations of uncertainty is developed and made it possible to evaluate the group velocity of virtual photons based on DIS HERA data.

► The most general result is obtained without initial assumptions about the mass of virtual photons.

► The HERA data indicate that the group velocity of virtual photons can exceed the speed of light in free space, and at maximum exceeds $U^* > 20c$.

► The profile of the normalized velocity β^* as a function of the photon energy at different values of the photon virtuality Q^2 is well consistent with the dispersion formula for the group velocity of virtual photons.

Conclusions II

► The properties of virtual photons and a hypothetical tachyon particle are almost identical.

► I believe that the first particle from the tachyon family is identified.

It's a virtual photon!

► A direct analysis of the HERA data will help clarify our conclusions about the speed of virtual photons.