Chiral dynamics in hard processes

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- **Chiral symmetry breaking - the phenomenon shaping our World**

- **New soft pion theorems in hard processes– how ChSB works for quark-gluon clusters**

- **Data: present & future**

Chiral symmetry is broken spontaneosly

Nambu, Nobel Prize 2008

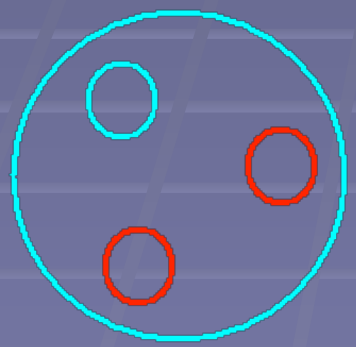
$$\Rightarrow Goldstone\ bosons \leftarrow pions$$

$$Order\ parameters \leftarrow \langle 0|\bar{\psi}\psi|0\rangle \simeq -(250\,MeV)^3$$

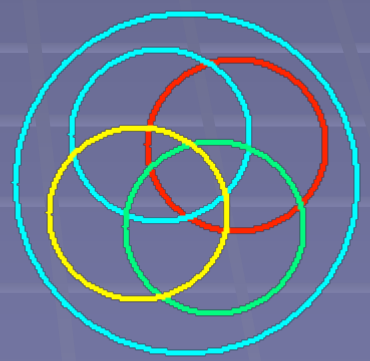
$$\leftarrow dynamical\ quark\ mass$$

$$M \simeq 350\,MeV$$

One of puzzles: Why nucleon looks like



not like



$$Why\quad MR_Q << 1? \qquad Hidden\ small\ parameter?$$

To solve this and other puzzles one has to understand mechanisms of ChSB in QCD.
As important as understanding of confinement!

Due to spontaneous chiral symmetry breakdown: 95% mass of the nucleon is generated→ 95 % mass of visible Universe!

Chiral symmetry is broken spontaneously that is why:

- Protons and neutrons exist and are massive
- Pions are light
- Nuclei exist
- ... We are here and can discuss strong interactions

Spontaneous breakdown of chiral symmetry really shapes our world!

Up to now ChSB phenomenon has been studied only in soft processes and it was never studied at the level of quark and gluon degrees of freedom.

Main idea of soft pion theorems is in the following equation:

$$|\pi\, state> = i\, Q\, |0>$$

generator of broken subgroup

$$\lim_{\kappa^\mu \to 0} \langle \pi^a(\kappa) B | \theta | A \rangle =$$

$$= \frac{i}{f_\pi} \langle B | \left[Q_5^a, \theta \right] | A \rangle + \ldots$$

Would be breakthrough if here we would have a well defined cluster of quarks and gluons! Would allow to connect ChSB with fundamendal d.o.f. of QCD! Big potential for discovery of new phenomena and understanding of mechanisms of “world shaping phenomenon” in QCD.

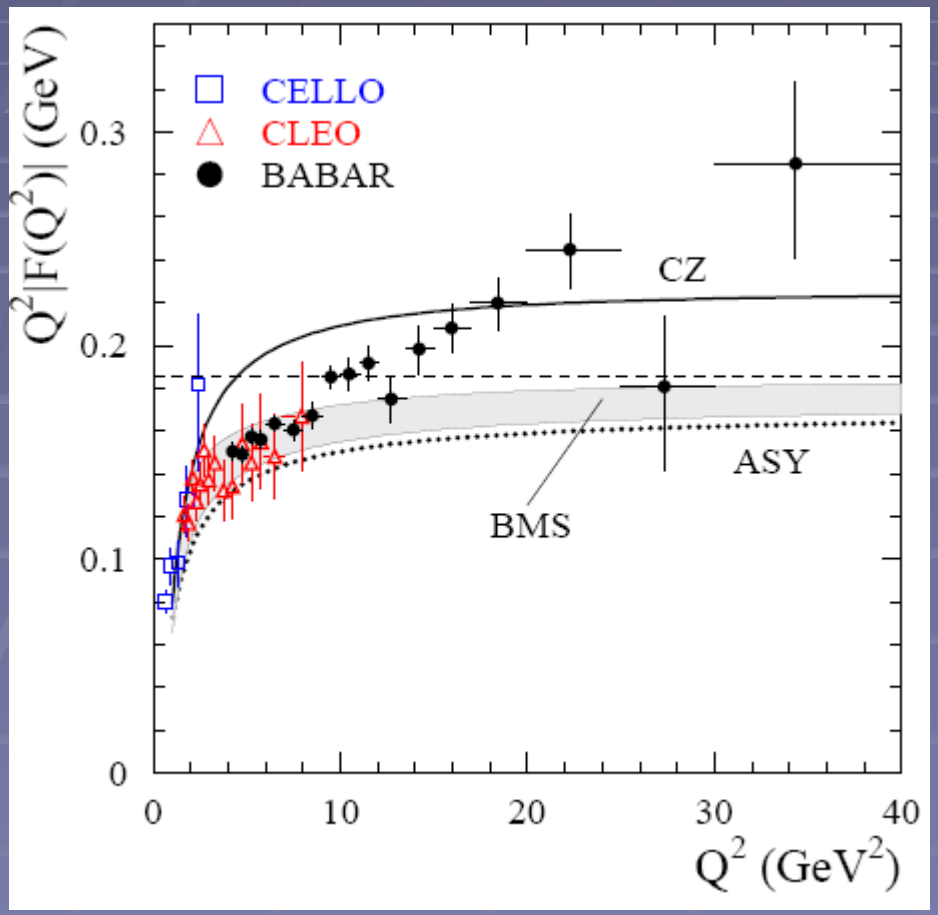
$e.g.$

$$\left[Q_5^a, \psi(\kappa) \right] = \gamma_5 \tau^a \psi(x)$$

Sensational result of the BaBar collaboration on $\gamma\gamma^* \to \pi^0$
[Phys.Rev.D80:052002,2009]

$$Q^2F(Q^2) = \frac{\sqrt{2}f_\pi}{3}\int_0^1 \frac{dx}{x}\phi_\pi(x,Q^2) + \mathcal{O}(\alpha_s) + \mathcal{O}(\Lambda^2_{\rm QCD}/Q^2)$$

$$\text{pQCD at } Q^2 \to \infty: \quad Q^2F(Q^2) = \sqrt{2}f_\pi \approx 0.185 \text{ GeV}$$



Surprising is not that the high Q^2 data points are above the asymptotic value, but that the Q^2 dependence is governed by a large mass parameter of order several GeV!

That phenomenon can be explained if the pion WF is flat [A. Radyushkin ´09, MVP´09]

The flat pion WF implies that the pion (Goldstone boson!) contains considerable point like q qbar component!

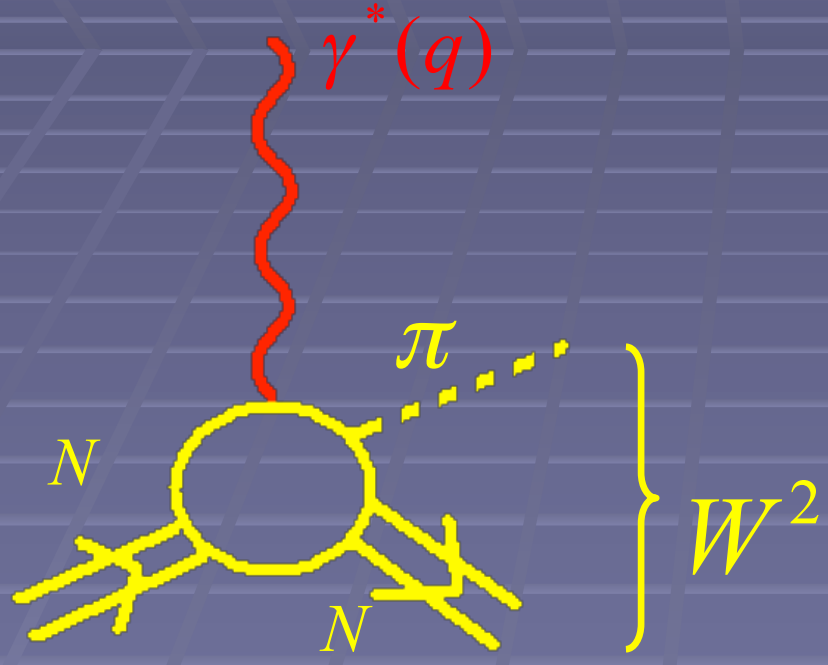
Presence of such component is natural for the instanton mechanism of ChSB [V. Petrov et al. ´99]. It is also neccessary in V.N. Gribov theory of confinement, that Intimately related to ChSB.

It can be that for the first time we see Goldstone nature of the pion in a hard process!

One can study the mechanisms of ChSB in number of hard processes!

Chiral perturbation theory for quark-gluon clusters – emerging field.

Pion production near threshold



$$-q^2 = Q^2$$

$$W - W_{th} \sim m_\pi$$

$$W_{th} = M_N + m_\pi$$

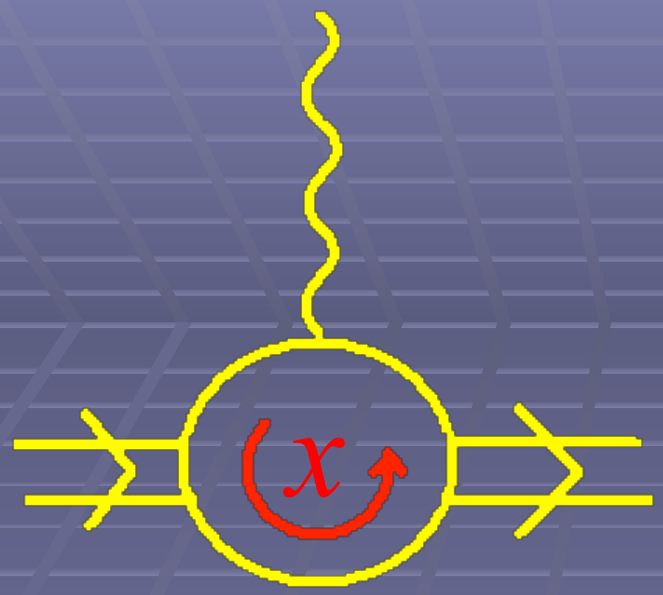
Pion is a (pseudo) Nambu-Goldstone Boson of SBChS => soft pion theorem

/Nambu, Lurie '62

Nambu, Shraumer '62/

These ideas created a new direction:

ChPT. Note however that the fundamental d.o.f. Of QCD are not involved!



- chirally rotated e.m. current
=> related to axial FF

Example:

$$A(\gamma^* p \to \pi^+ n)\Big|_{W=W_{th}} =$$

$$= \frac{1}{\sqrt{2} f_\pi}\left[G_A(Q^2) + g_A G_{Mn}(Q^2) \frac{Q^2}{Q^2 + 2M_N} \right] + O\left(\frac{m_\pi}{\Lambda}\right)$$

$$\lim_{\kappa^\mu \to 0} \langle \pi^a(\kappa) B | \theta | A \rangle =$$

$$= \frac{i}{f_\pi} \langle B | \left[Q_5^a, \theta \right] | A \rangle + \ldots$$

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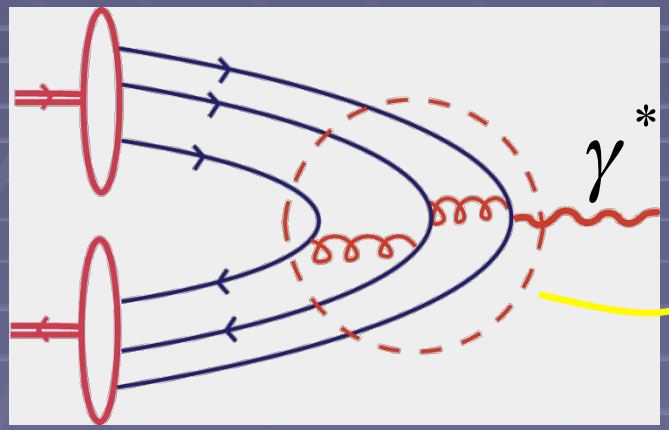
In the limit of $Q^2 \to \infty$ Nucleon FF's are described in terms of partons-clusters of quarks



hard interactions
=>pQCD

Nucleon

Light-cone WF

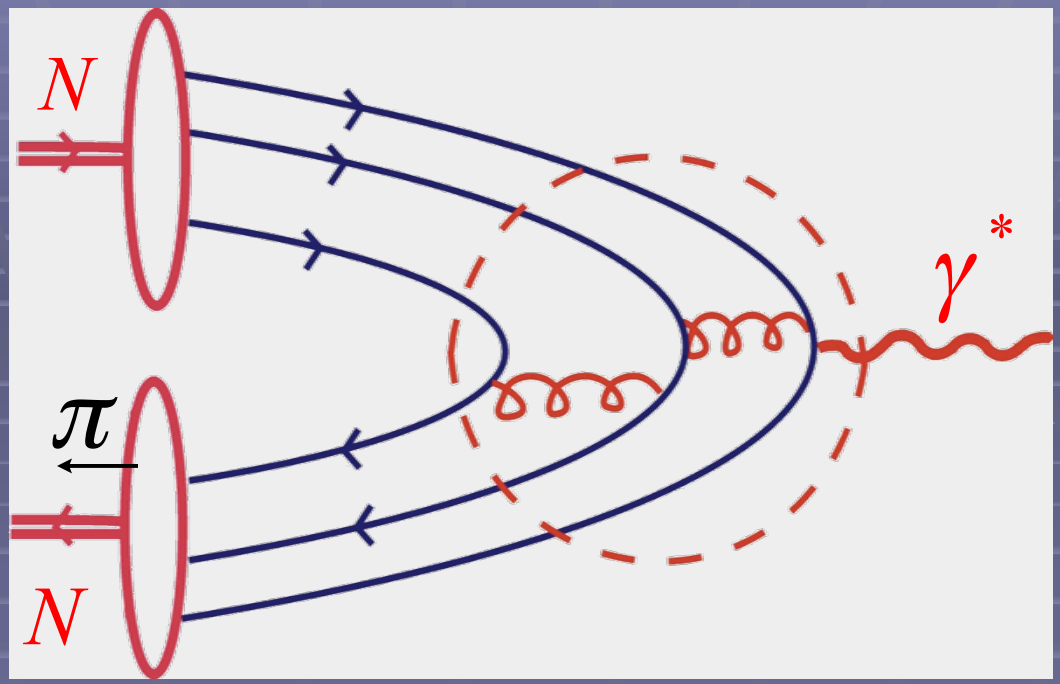
$$F(Q^2) \sim \frac{\alpha^2{}_S(Q)}{Q^4} \int [dx][dy] \phi_N(x)\, T_H(x,y)\, \phi_N(y)$$

Filtering out the lowest Fock component of the hadron's WF

$$\alpha_S = \frac{g^2}{4\pi}$$

/S. Brodsky, P. Lepage/

/Efremov, Radyushkin/



$$A\left(\gamma^* N \to \pi N\right)_{th} \sim \frac{\alpha_S^2}{Q^4} \int [dx][dy] \Phi_N(x)\, T_H(x,y)\, \Phi_{\pi N}(y)$$

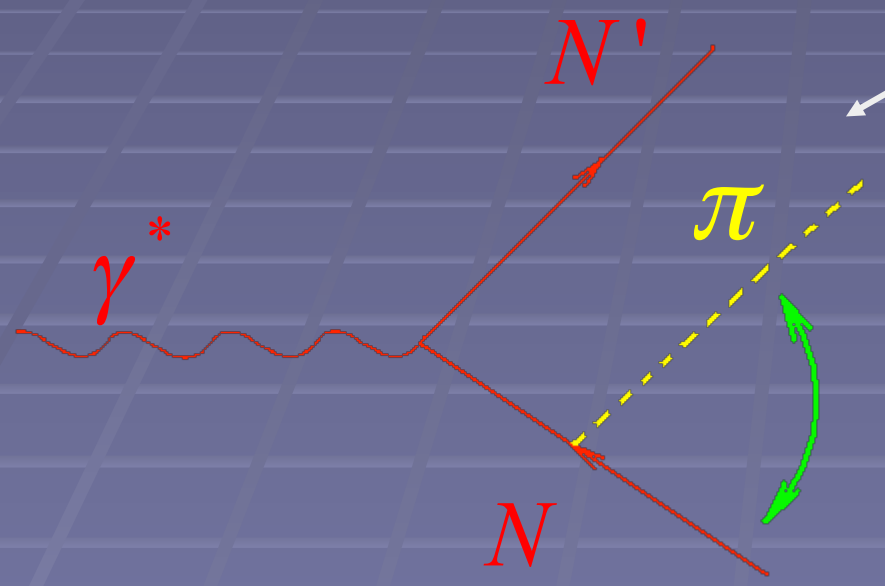
LC WF of nucleon

LC WF of πN system

For NS theorem to work the pion should soft relative to **all** hadrons!

$$Let\ us\ take\ first\ \hat{Q}^2 \to \infty \quad and\ then\ m_\pi \to 0$$

$$We\ need\ this\ for\ W - W_{th} \sim m_\pi$$

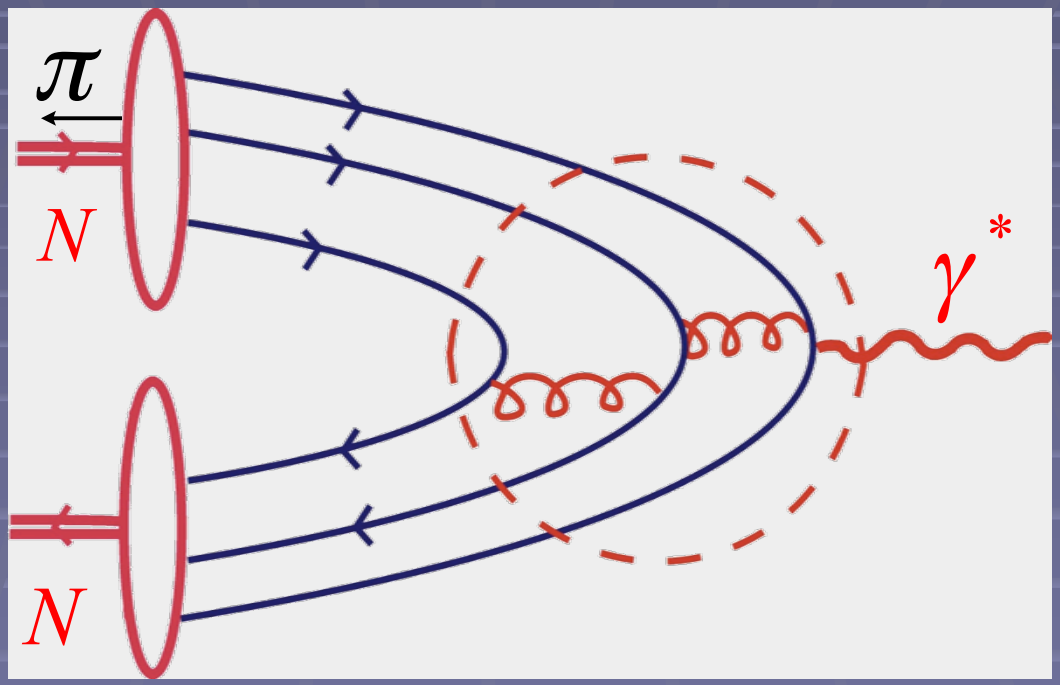


$$W_{N\pi} \sim \sqrt[3]{m_\pi Q^2}$$

$$\Rightarrow for\ \hat{Q}^2 >> \frac{\Lambda^3}{m_\pi}$$

the pion is not soft relative to initial nucleon

Higher twists ($1/Q^2$ supressed) –suppression of initial Nambu-Goldstone immision!

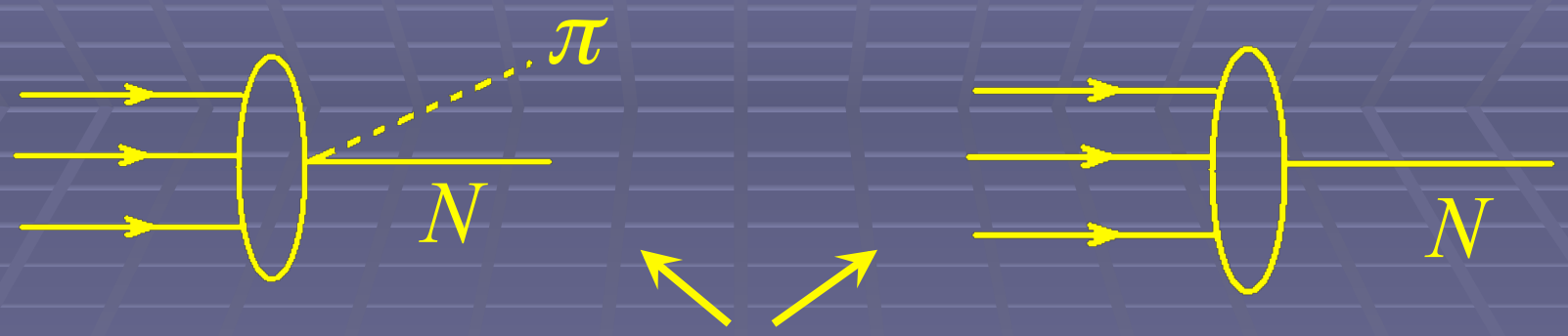


$$For\ \ Q^2 >> \frac{\Lambda^3}{m_\pi}\ \ one\ has\ prove\ SPTh$$

$$For\ LC\ \ WF\ of$$

$$\pi N\ Low\ mass\ system$$

What are πN WF's when π is near threshold?



Connected by chiral rotation

$$|p\uparrow\rangle = \frac{\varphi_S}{\sqrt{6}}|2U\uparrow d\downarrow U\uparrow - U\uparrow U\downarrow d\uparrow - d\uparrow U\downarrow U\downarrow\rangle + \frac{\varphi_a}{\sqrt{2}}|U\updownarrow U\downarrow d\uparrow - d\uparrow U\downarrow U\uparrow\rangle$$

$$|p\uparrow\pi^0\rangle = \frac{\varphi_S}{2\sqrt{6}f_\pi}|6U\uparrow d\downarrow U\uparrow + U\uparrow U\downarrow d\uparrow + d\uparrow U\downarrow U\uparrow\rangle + \frac{\varphi_a}{2\sqrt{2}f_\pi}|U\uparrow U\downarrow d\uparrow - d\uparrow U\downarrow U\uparrow\rangle$$

/Pobylitsa, Strikman,MVP , PRL 2001/

Simple algebra!

New theorem = “1/2”of NS theorem

For new SPTh important that QCD is a gauge theory!

Comparison

$$"Nambu-Shrauner\ window" \left(\Lambda^2 << Q^2 << \frac{\Lambda^3}{m_\pi} \right)$$

$$A\left(\gamma^* p \to \pi^+ n\right)_{th} = \frac{1}{\sqrt{2} f\pi}\left(G_A + g_A G_{Mn}\right)$$

$$"Our\ window" \left(Q^2 >> \frac{\Lambda^3}{m_\pi} >> \Lambda^2 \right)$$

/Pobylitsa, Strikman,MVP , PRL 2001/

$$A\left(\gamma^* p \to \pi^+ n\right)_{th} = \frac{1}{\sqrt{2} f\pi}\left(\frac{5}{3} G_{Mp} + \frac{4}{3} G_{Mn}\right)$$

What about data?

$\rightarrow E136\ SLAC\ experiment$

$F_2^P(w,Q^2)\ at\ W - W_{th} \sim m_\pi\ \&\ Q^2 \geq 9GeV^2$

/P.Bosted etal. '94/

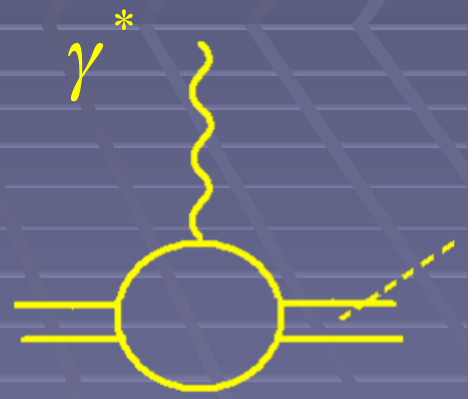
$$F_2^P(W,Q^2) \underset{Q^2\to\infty}{\sim} \frac{1}{Q^6}\ for\ both\ theorems$$

but the coefficient is given by different combinations of FF's of nucleon

E136 experiment /Bosted et al '94/

$$F_2(W,Q^2) \;\; at \;\; W - W_{th} - m_\pi$$

$$Q^2 \geq 9\, GeV^2$$

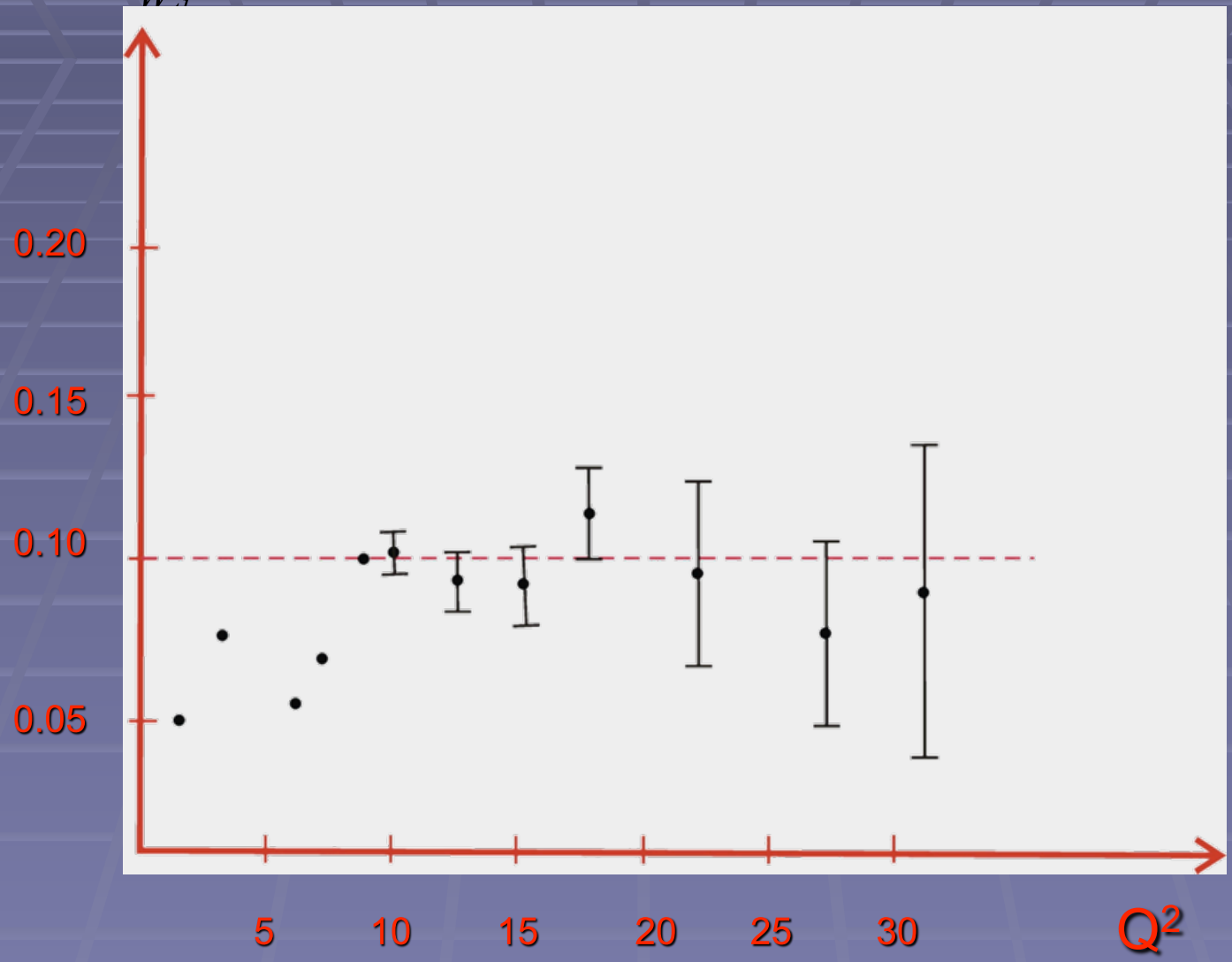


$$F_2^P(W,Q^2) = \frac{Q^2 \beta(w)}{16\pi^2} *$$

$$* \left[\sum_{\substack{x = p\pi^0 \\ n\pi^+}} \left| A(\gamma^* p \to x) \right|^2 + \frac{3 g_A^2 G_{Mp}^2(Q^2) \beta^2(w) w^4}{4(w^2 - M_N^2 + m_\pi^2)^2} + O\left(\frac{m_\pi}{\Lambda}\right) \right]$$

$$\beta(w) = \sqrt{1 - \frac{(M_N + m_\pi)^2}{W^2}} \sqrt{1 - \frac{(M_N - m_\pi)^2}{W^2}}$$

$$\int_{W_i^2}^{1,4GeV^2} dw^2 Q^6 F_2^P(W,Q)$$



$$For\ Q^2 \geq 9\,GeV^2$$

$$E136\ \ gives$$

$$\int_{W_{th}^2}^{1,4GeV^2} dw^2 Q^6 F_2(W,Q^2) = \left[0,1 \pm 0,02\right] GeV^8$$

$$Nambu-Shrauner\ theorem$$

$$= \left[0,03 \pm 0,01\right] GeV^8$$

/Nambu, Shrauner PR `62/

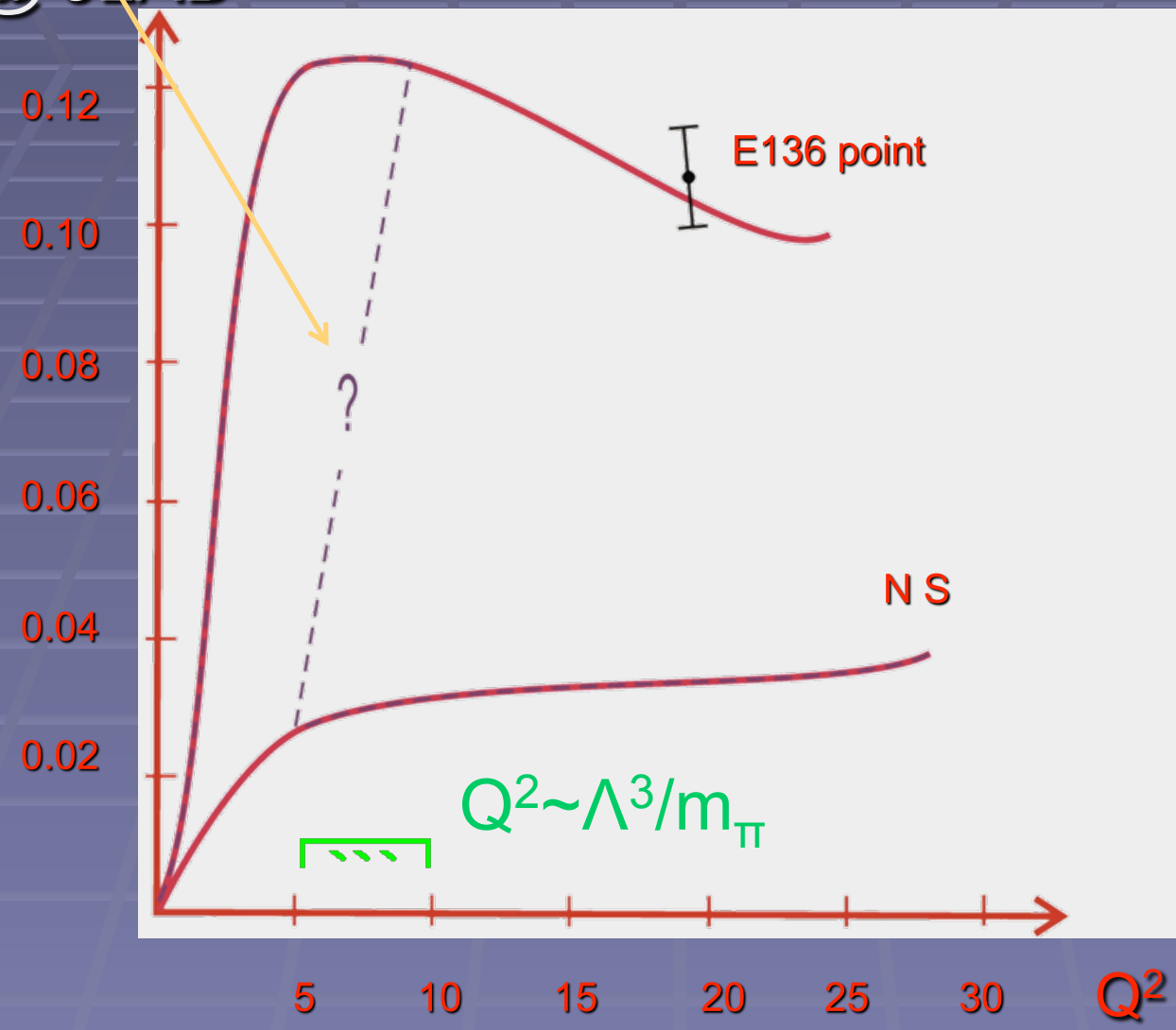
$$New\ sof\ t\ pion\ theorem$$

$$= \left[0,11 \pm 0,02\right] GeV^8$$

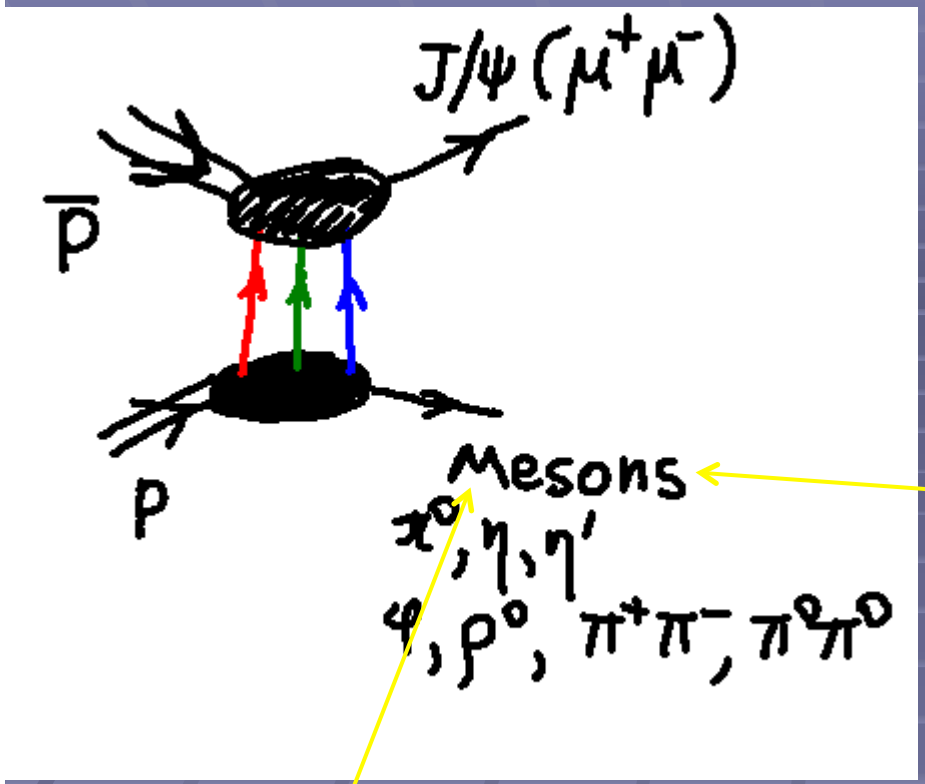
/Pobylitsa, Strikman,MVP , PRL `01/

∵) Nucleon FF's from experiment

very interesting domain of transition from one type of SPTh to another one: will be studied @ JLAB



Opportunities for future



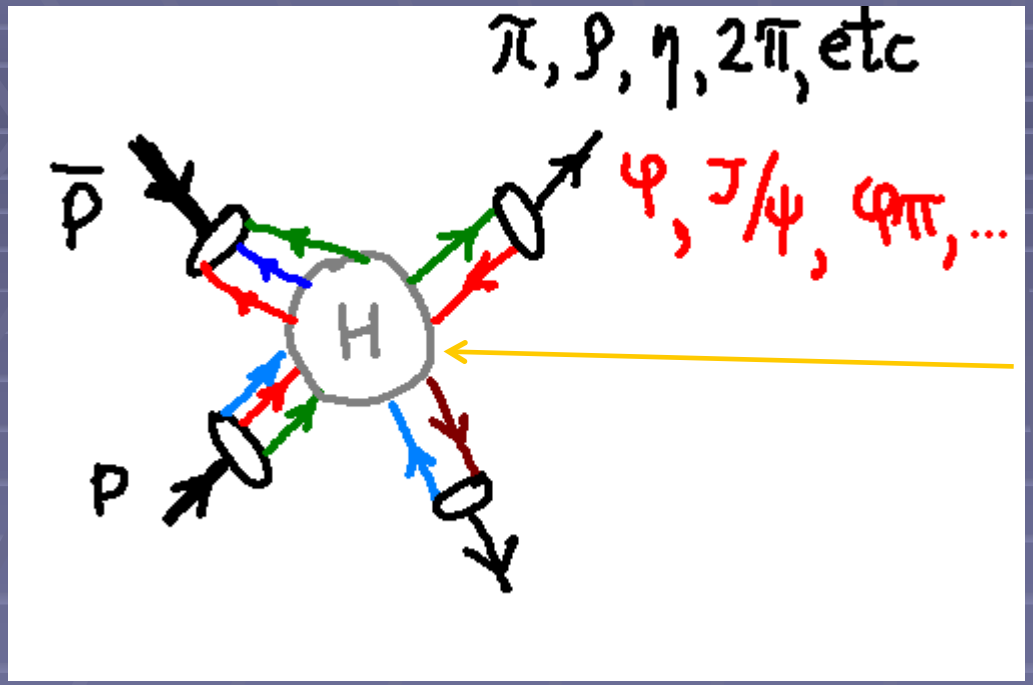
Frankfurt, Strikman, MVP `98

Lansberg, Pire, Szymanowski `07

Soft relative to the proton

- Direct mesurement of 5+ quark component of nucleon WF
- Measuring different mesons we probe different components of nucleon WF
- If here is a pion, eta (gluon rich) → chiral dynamics and anomaly for 5 quark cluster This is a „second half“ of Nambu soft pion theorem for production of pions near threshold
- Possibility to study of chiral symmetry restoration at high energies

Scattering with large P_T



Hard interaction – controlled by pQCD

- Possibility to figure out the mechanisms of hard scattering (e.g. the role of higher twists, or hard versus Landshof) comparing processes with and w/o soft pion
- Producing mesons made of sea quarks (+soft pion)→ chiral dynamics for gluons
- Production of strange mesons→ SU(3) chiral dynamics for strange quark clusters

CONCLUSIONS

New theoretical method is developed which paves the way to study spontaneous breakdown of chiral symmetry at the level of fundamental d.o.f. in QCD

There is wide class of hard (chiral) processes which can be studied in future which allow :

- -to study mechanisms of ChSB in QCD in detail
- -to study in details various components of nucleon WF
- -to learn about mechanisms of hard hadronic processes

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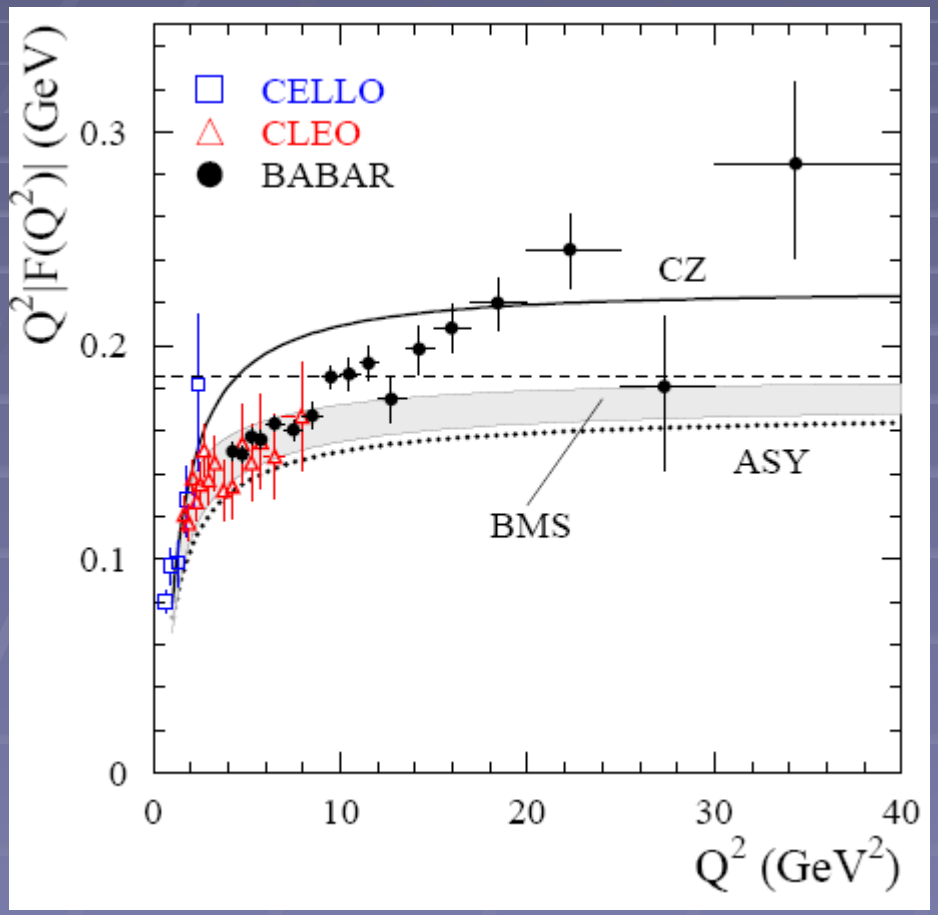

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