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 colour clusters**
- **Data: present & possibilities to discover new chiral phenomena @ PANDA**

QCD & chiral symmetry

$$S_{QCD} = \int d^4x \left\{ -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_f \bar{\Psi}_f (i\partial\!\!\!/ - g A\!\!\!/^a t^a - m_f)\psi_f \right\}$$

Contains all strong interaction phenomena

$$m_p = const\Lambda_{QCD}$$

$$m_{U^{235}} = const\Lambda_{QCD}$$

$$\sigma_{tot}(p + U^{235}) = \frac{1}{\Lambda^2_{QCD}} f\left(\frac{\Lambda_{QCD}}{E}\right)$$

Transmutation of dimension: scale is given not by quark masses but

$$\Lambda_{QCD} = M_{cut} e^{-\frac{8\pi^2}{bg^2(Mcut)}}$$

$$b = \frac{11}{3} N_c - \frac{2}{3} N_f$$

Symmetries:

$$m_d \approx m_d \approx 0 \qquad U_L(N_f) \otimes U_R(N_f)$$

But:

$$m_\rho = 770 MeV \qquad m_{A_1} \approx 1300 MeV$$

$$m_N = 940 MeV \qquad m_{N^-} \approx 1535 MeV$$

Chiral symmetry is broken spontaneosly

Nambu, Nobel Prize 2008

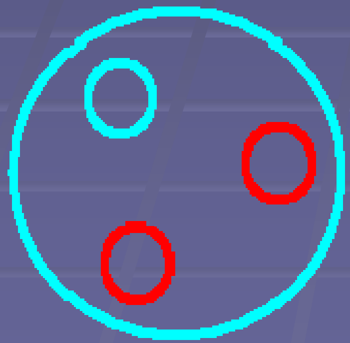
$$\Rightarrow Goldstone\ bosons \leftarrow\ pions$$

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

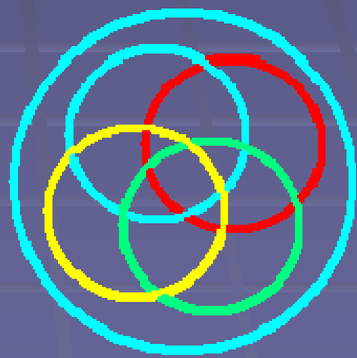
$$\leftarrow dynamical\ quark\ mass$$

$$M \approx 350 MeV$$

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 study strong interactions @ FAIR

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

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

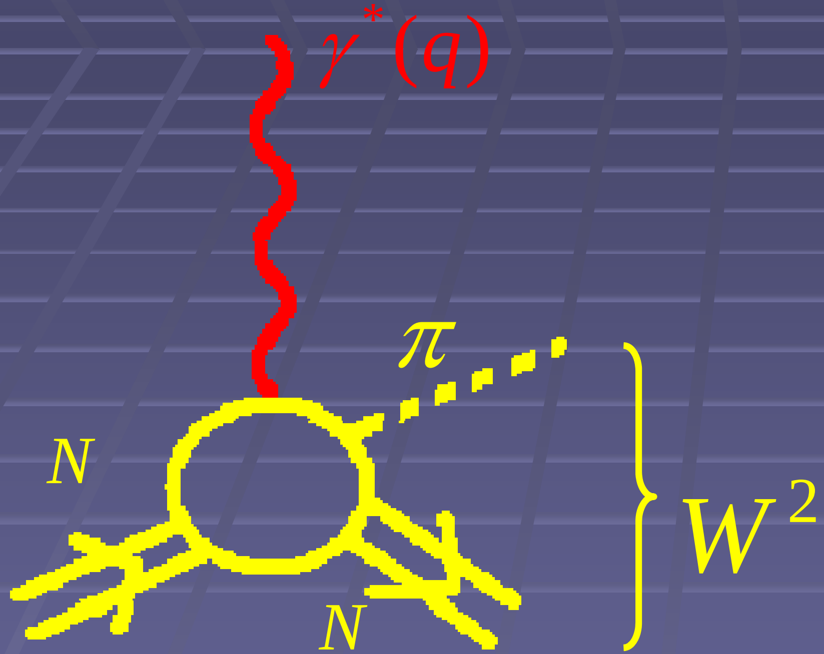
$$= \frac{i}{f_\pi} \langle B | \left[Q_5^a, \theta \right] | A \rangle + \ldots$$

computable by symmetry transformation

e.g.

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

Pion production near threshold



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

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

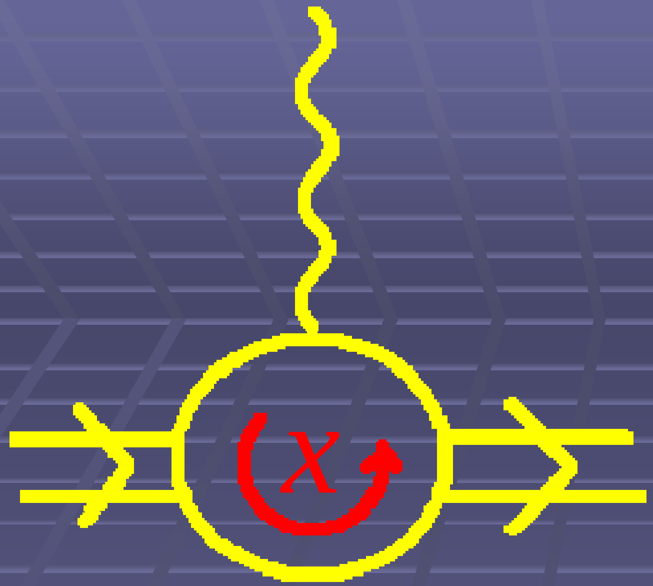
$$W_{th} = M_N + m_\pi$$

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:

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

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

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

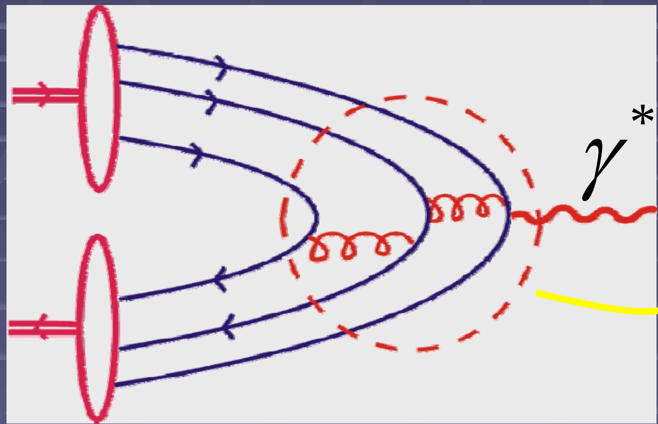
$$= \frac{i}{f_\pi} \langle B | \left[Q_5^a, \theta \right] | A \rangle + \ldots$$

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.

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

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

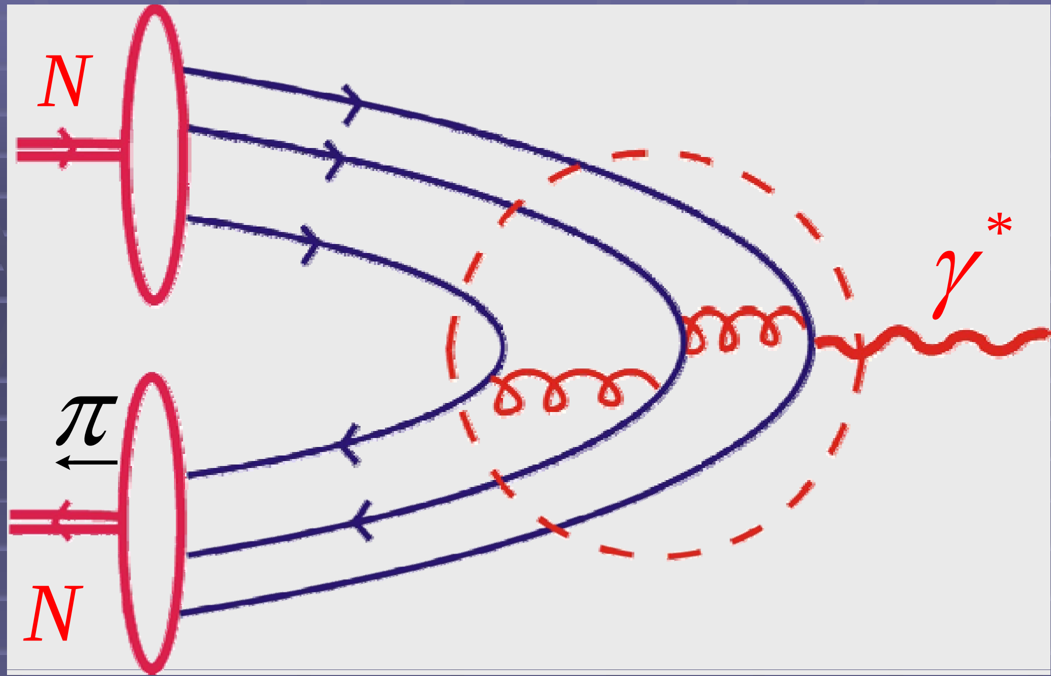
$$F\left(Q^2\right) \sim \frac{\alpha^2{}_s(Q)}{Q^4}\int [dx][dy]\,\phi_N(x)\,T_H(x,y)\,\phi_N(y)$$

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

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

/S. Brodsky, P. Lepage/

/Efremov, Radyushkin/



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

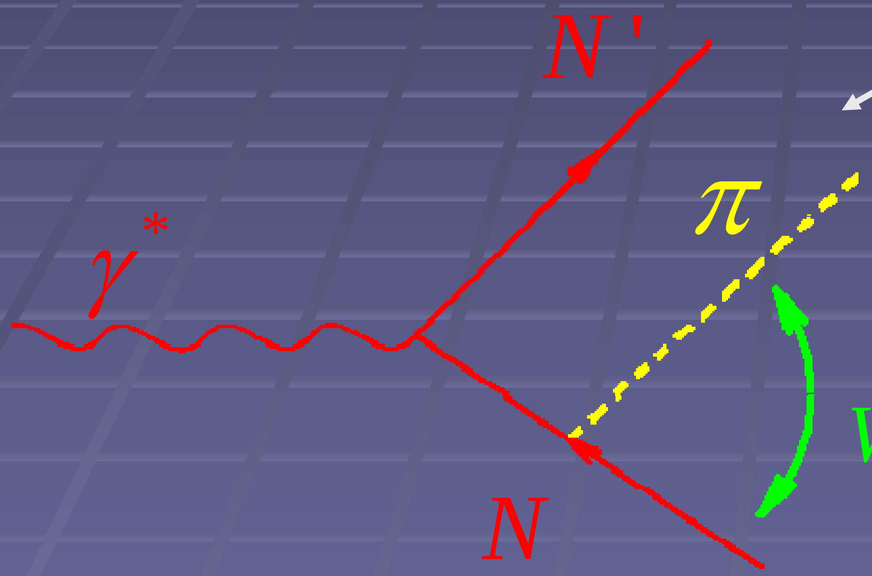
LC WF of nucleon

LC WF of πN system

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

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

$\textit{We need this for } W - W_{th} \,\square\, m_\pi$

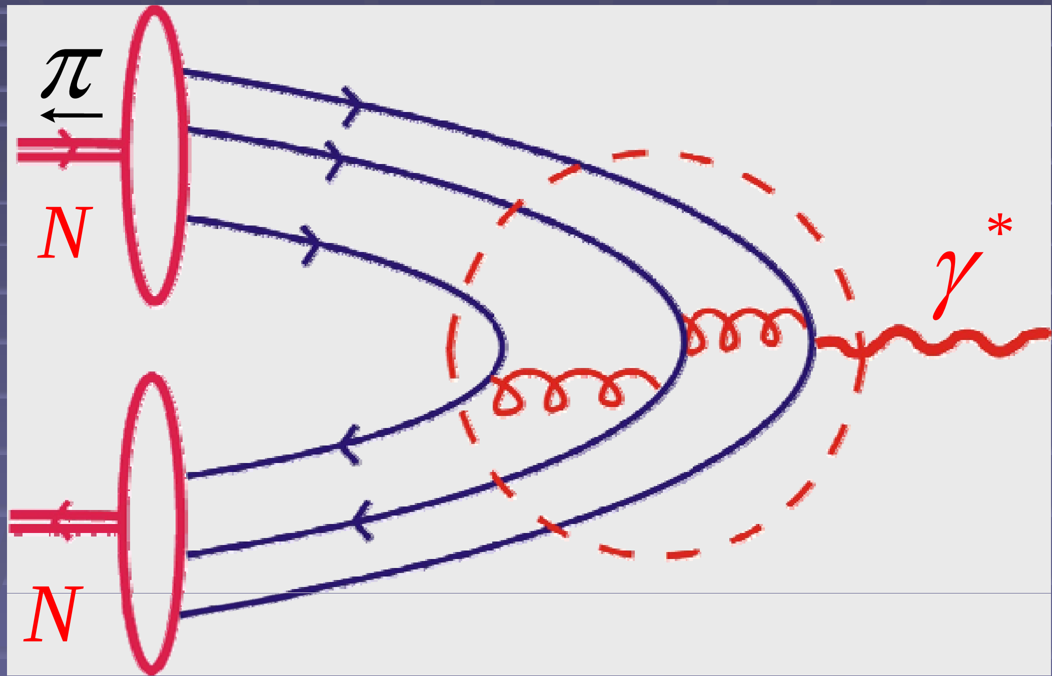


$W_{N\pi} \,\square\, \sqrt[3]{m_\pi Q^2}$ */ show this!/*

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

the pion is not soft relative to initial nucleon

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

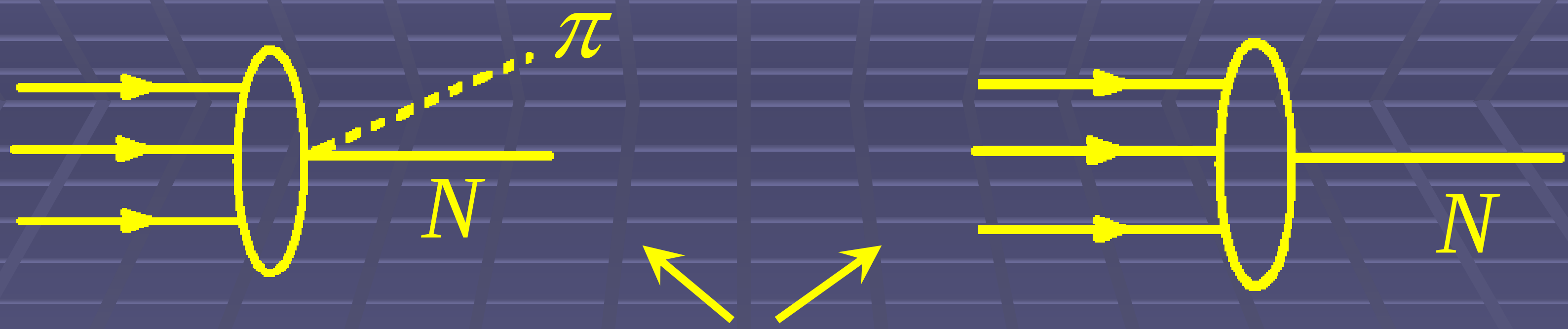


$$For\ \ Q^2 >> \frac{\Lambda^3}{m_\pi}\ \ one\ has\ prove\ SPTh$$

For LC WF of

πN *Low mass system*

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



Connected by chiral rotation

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

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

/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

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

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

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

/Pobylitsa, Strikman,MVP , PRL 2001/

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

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/

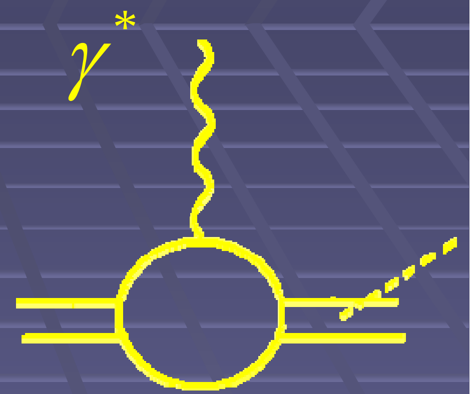
$$F_2^P(W,Q^2)\ \ \underset{Q^2\rightarrow\infty}{\sim}\ \ \frac{1}{Q^6}\ \ for\ both\ theorems$$

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

E136 experiment /Bosted et al ‘94/

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

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

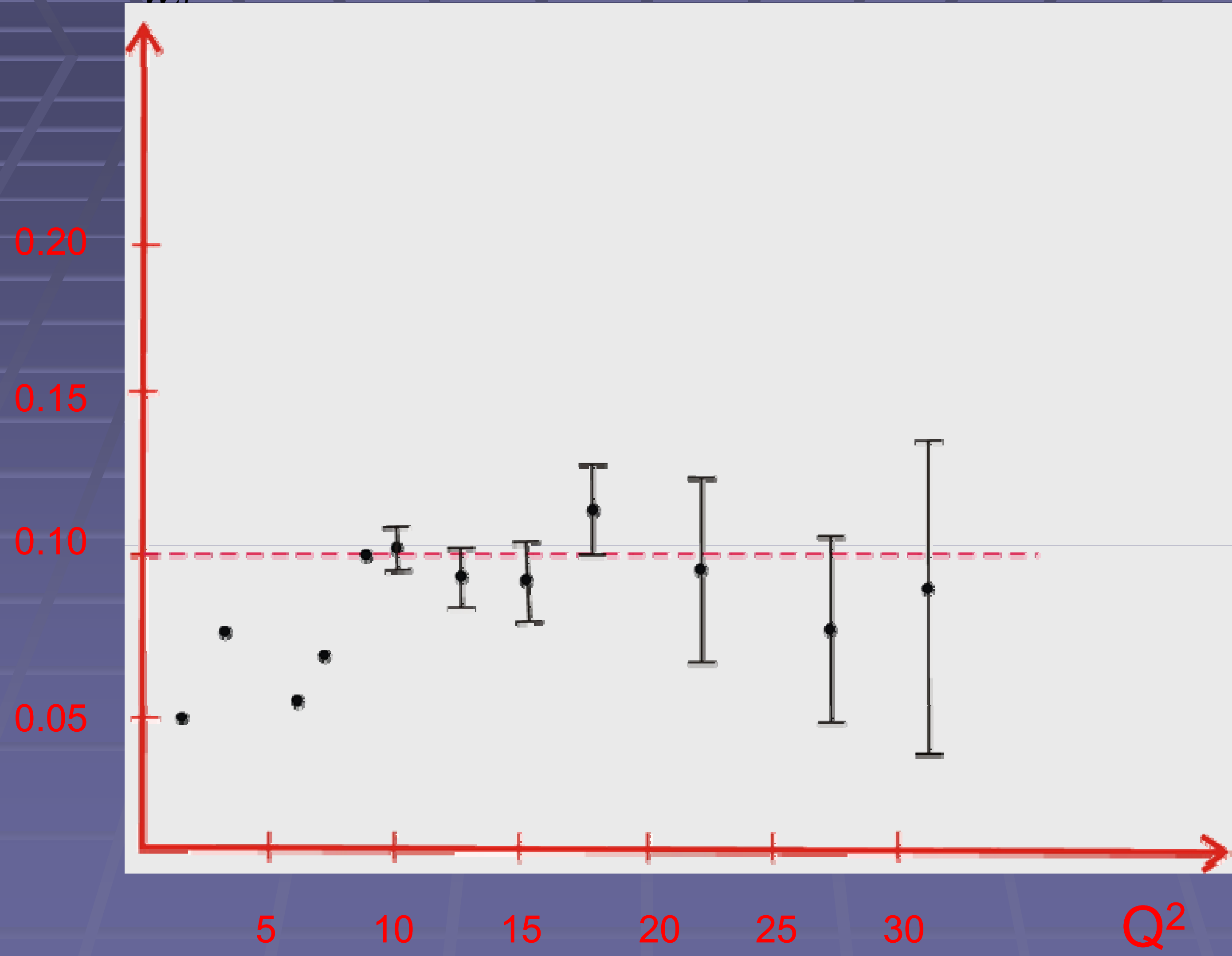


$$F_2^P(W,Q^2) = \frac{Q^2\beta(w)}{16\pi^2} *$$

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

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

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



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

$$E136\ \ gives$$

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

$$Nambu - Shrauner\ theorem$$

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

/Nambu, Shrauner PR `62/

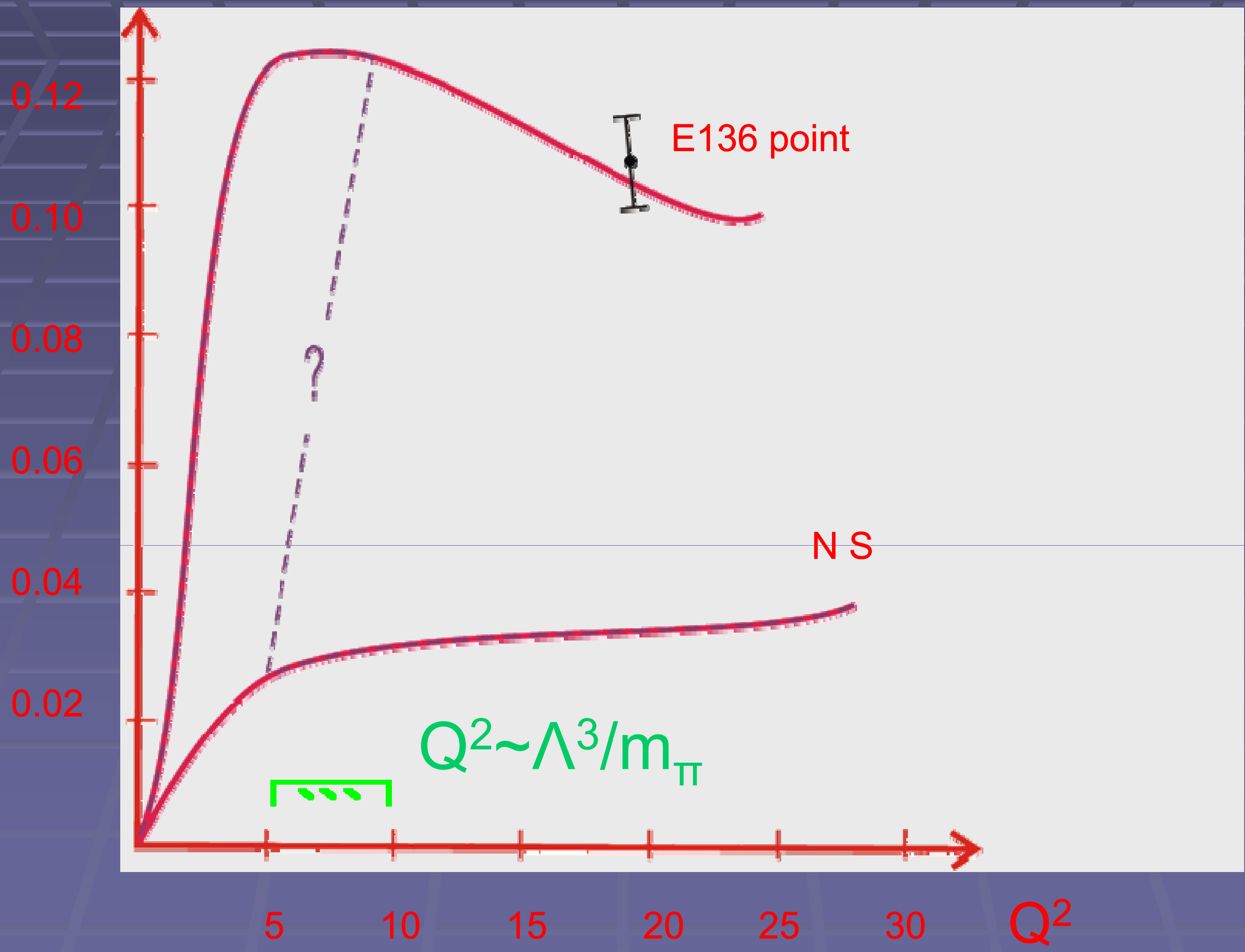
$$New\ soft\ \ pion\ theorem$$

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

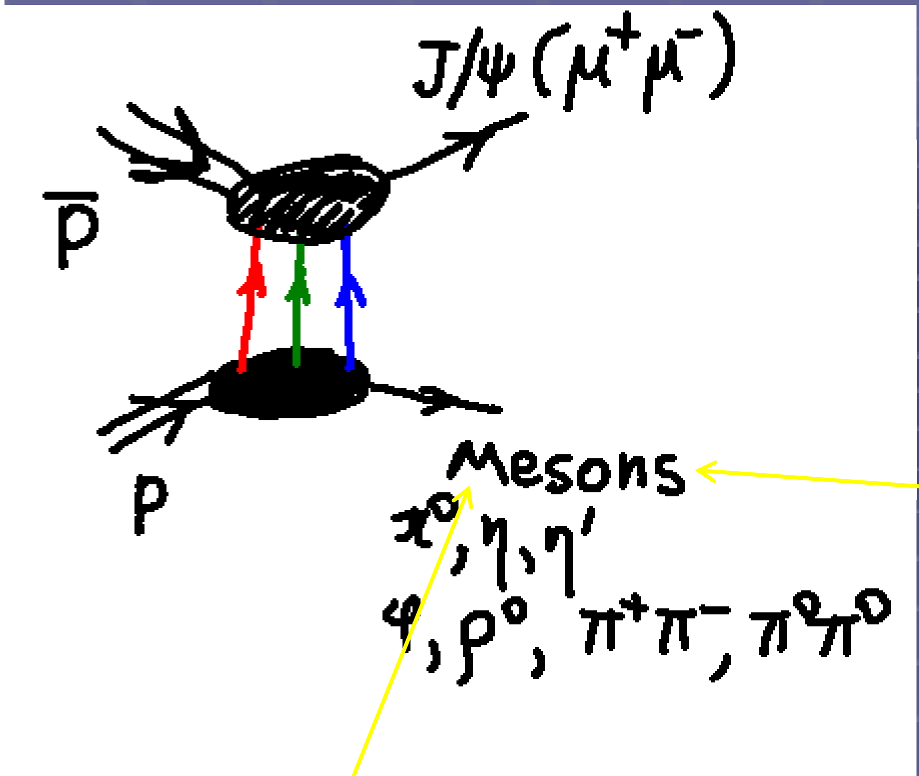
/Pobylitsa, Strikman,MVP , PRL `01/

:·) Nucleon FF's from experiment

… ? … very interesting domain Transition from one type of SPTh to another one



Opportunities for PANDA



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

Possibility to figure out how the chiral symmetry is restored