The proton spin puzzle / “crisis”

1988 European Muon Collaboration:
measured polarization of quarks adds to only ~1/3 of proton spin 1/2

Unpolarised:

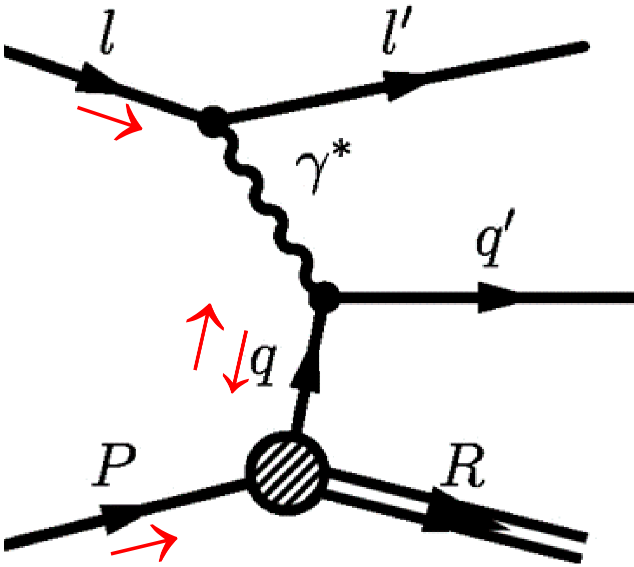
$$\frac{d^2\sigma}{dx\,dQ^2} \sim F_2(x,Q^2) = \sum_f e_f^2\, x[q_f(x,Q^2) + \bar{q}_f(x,Q^2)]$$

$$q(x) \equiv q^{\uparrow}(x) + q^{\downarrow}(x)$$

Polarised:

$$\frac{d^2\Delta\sigma}{dx\,dQ^2} \sim g_1(x,Q^2) = \sum_f e_f^2\, [\Delta q_f(x,Q^2) + \Delta\bar{q}_f(x,Q^2)]$$

$$\Delta q(x) \equiv q^{\uparrow}(x) - q^{\downarrow}(x)$$



$$\rightarrow \Delta\Sigma = \int_0^1 dx\, \sum_f \Delta q_f(x) \approx = 0.3 \;!?$$

proton spin $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g$

Towards solving the proton spin puzzle

arXiv:1808.06631 – A. Ekstedt, H. Ghaderi, G. Ingelman, S. Leupold

p-wave → L=1 not observed in DIS

$$|p\rangle = \alpha_0 |p_0\rangle + \alpha_{p\pi} |p\pi^0\rangle + \alpha_{n\pi} |n\pi^+\rangle + \ \dots$$

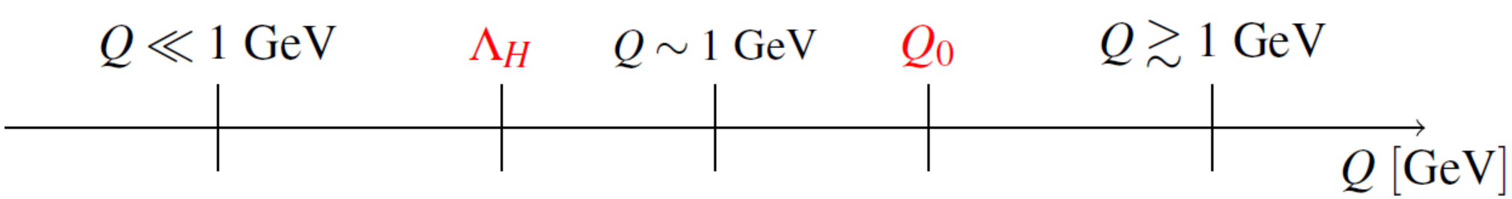
hadronic fluctuations

partonic fluctuations $|uud\ q\bar{q}\rangle$

ChPT

phenomenological
form factor + starting PDFs

pQCD

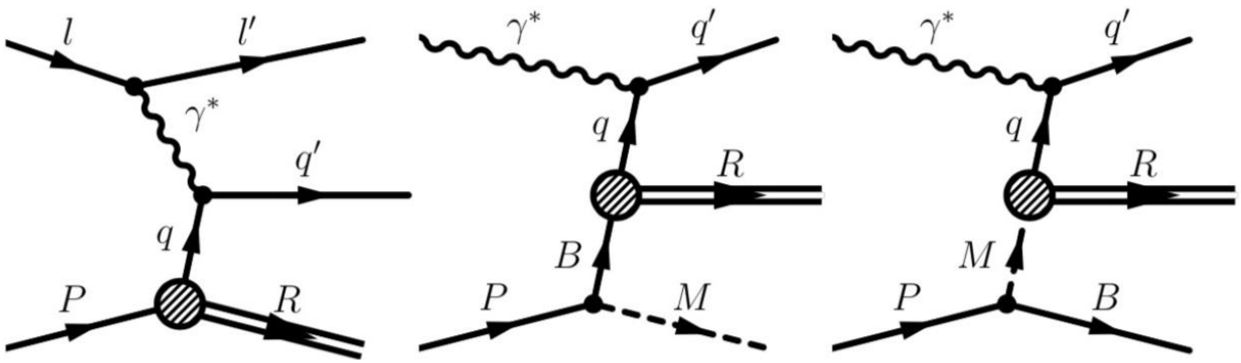


Goldstone bosons
+ non-relativistic baryons

partons

Fock expansion of proton state $|P\rangle = \sqrt{Z}\,|P\rangle_{\text{bare}} + \alpha_{n\pi^+}\,|n\pi^+\rangle + \alpha_{P\pi^0}\,|P\pi^0\rangle$

$$+ \alpha_{\Delta^{++}\pi^-}\,|\Delta^{++}\pi^-\rangle + \alpha_{\Delta^+\pi^0}\,|\Delta^+\pi^0\rangle + \alpha_{\Delta^0\pi^+}\,|\Delta^0\pi^+\rangle$$
$$+ \alpha_{\Lambda K^+}\,|\Lambda K^+\rangle + \cdots$$



$$f_{i/P}(x) = f^{\text{bare}}_{i/P}(x) + \sum_{\lambda, H\in\{B,M\}} \int \mathrm{d}y\,\mathrm{d}z\,\delta(x-yz)\,f^{\text{bare}}_{i/H}(z)\,f^{\lambda}_{H/P}(y)$$

- LO ChPT Lagrangian $\rightsquigarrow f^{\lambda}_{H/P}(y) = \frac{|g_{BM}|^2}{(2\pi)^3 2y(1-y)} \int \mathrm{d}^2 k_\perp \left| \phi \frac{S^\lambda(y, \boldsymbol{k}_\perp)}{m_P^2 - m^2(y, k_\perp^2)} \right|^2$

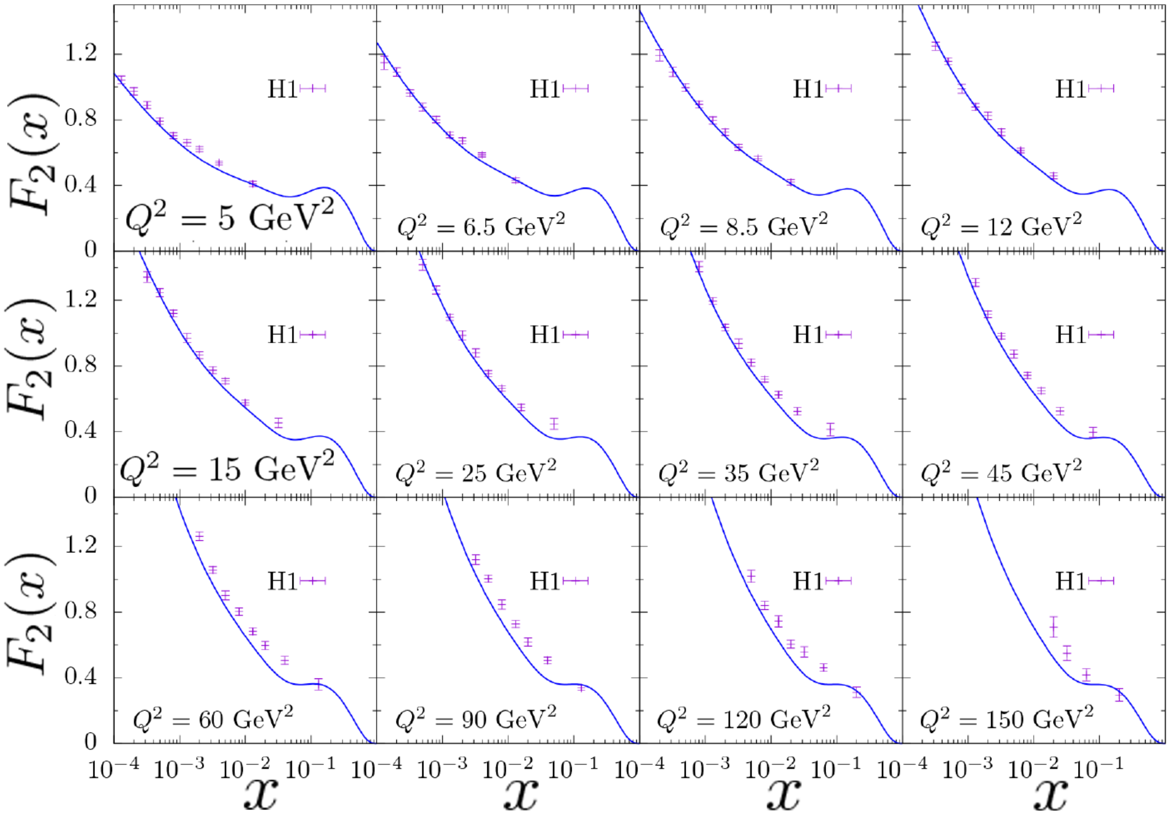
  $y = p_B^+/p_P^+ \qquad \phi(y, k_\perp^2, \Lambda_H^2) = \exp[-(\boldsymbol{p}_M^2 + \boldsymbol{p}_B^2)/(2\Lambda_H^2)]$

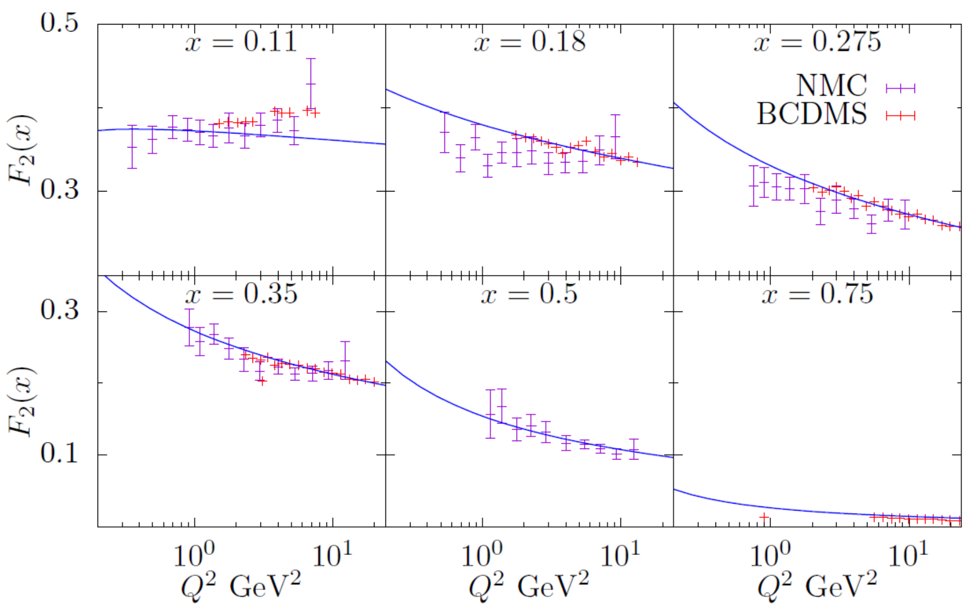
- $f^{\text{bare}}_{i/H}(x) = \int \frac{\mathrm{d}^4 k}{(2\pi)^4}\,\delta\left(k^+/p_H^+ - x\right) \exp\left[-\frac{(k_0-m_i)^2 + k_x^2 + k_y^2 + k_z^2}{2\sigma_i^2}\right]$ at $Q = Q_0$

  DGLAP $Q > Q_0$

- 'Free' parameters: σ_1, σ_2, σ_g and Λ_H, Q_0

  A priori expected value: $\sigma_i \sim 1/D_H \sim 0.1$ GeV and $\Lambda_H \sim Q_0 \sim 0.5$ GeV





Unpolarised structure functions
↓
parameter values

F_2 *at small* x

$\rightarrow \sigma_g\,, Q_0$

F_2, F_3 *at larger* x

$\rightarrow \sigma_1, \sigma_2\,, \Lambda_H$

$\sigma_g = 0.028$ GeV,

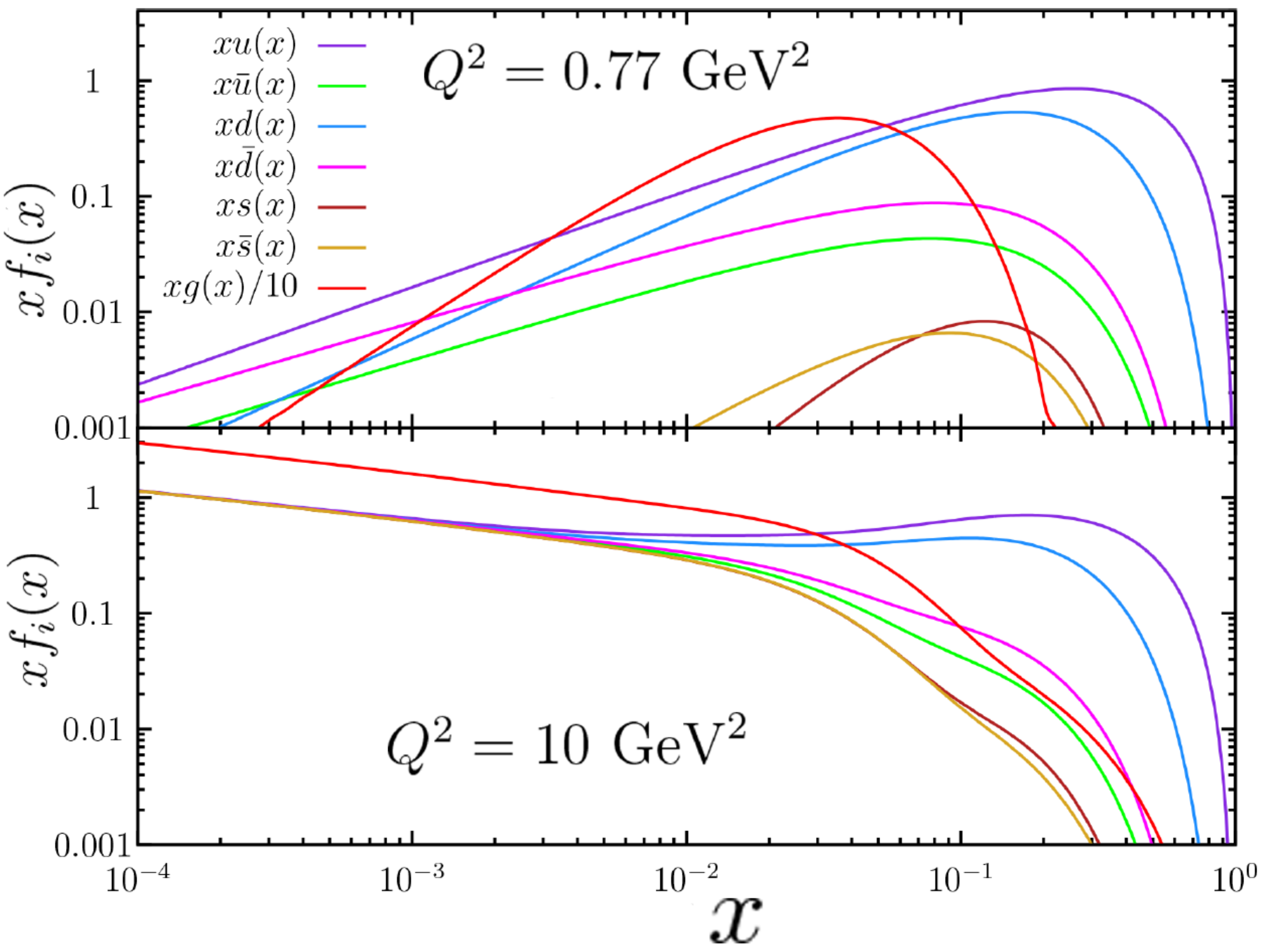
$\sigma_1 = 0.11$ GeV,

$\sigma_2 = 0.22$ GeV,

$\Lambda_H = 0.87$ GeV,

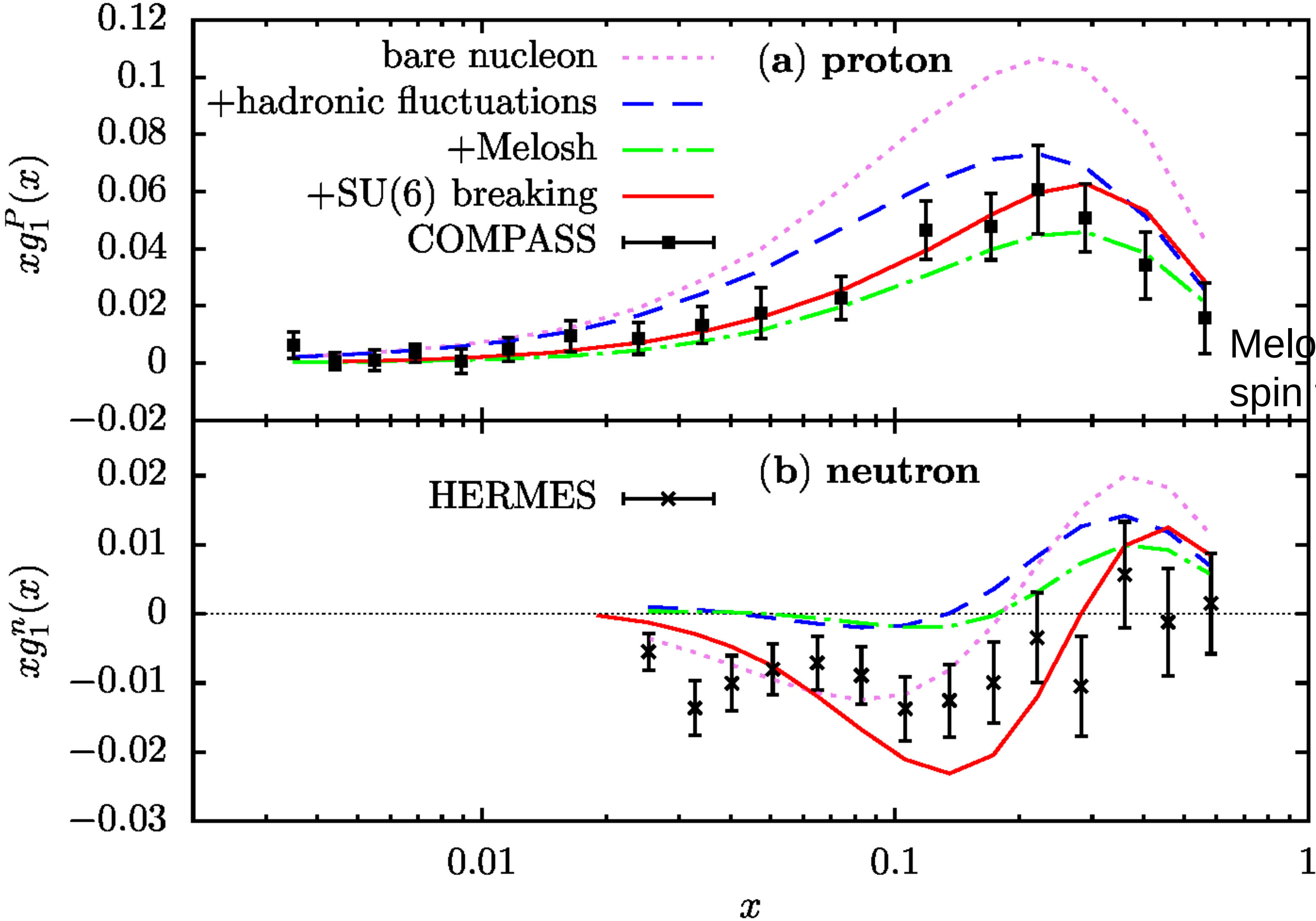
$Q_0 = 0.88$ GeV

Resulting unpolarised PDFs – based on 5 physical parameters



cf. conventional PDF parametrisations with ~30 parameters

Polarised PDFs: $\Delta f_{q/H}^{\text{bare}}(x) = \Delta f_{q/H}^{SU(6)} f_{q/H}^{\text{bare}}(x)$



Melosh = relativistic spin transformation

→ *p* spin OK ! But not *n* spin ?

More info in spin sum rules: $\Gamma^{P\pm n}(x_{\min}) = \int_{x_{\min}}^{1} \mathrm{d}x \left(g_1^P(x) \pm g_1^n(x) \right)$

$\Gamma_{Bj}^{p-n}(x_{min} = 0) = 0.187 \rightarrow$

i.e. Bjorken sum rule

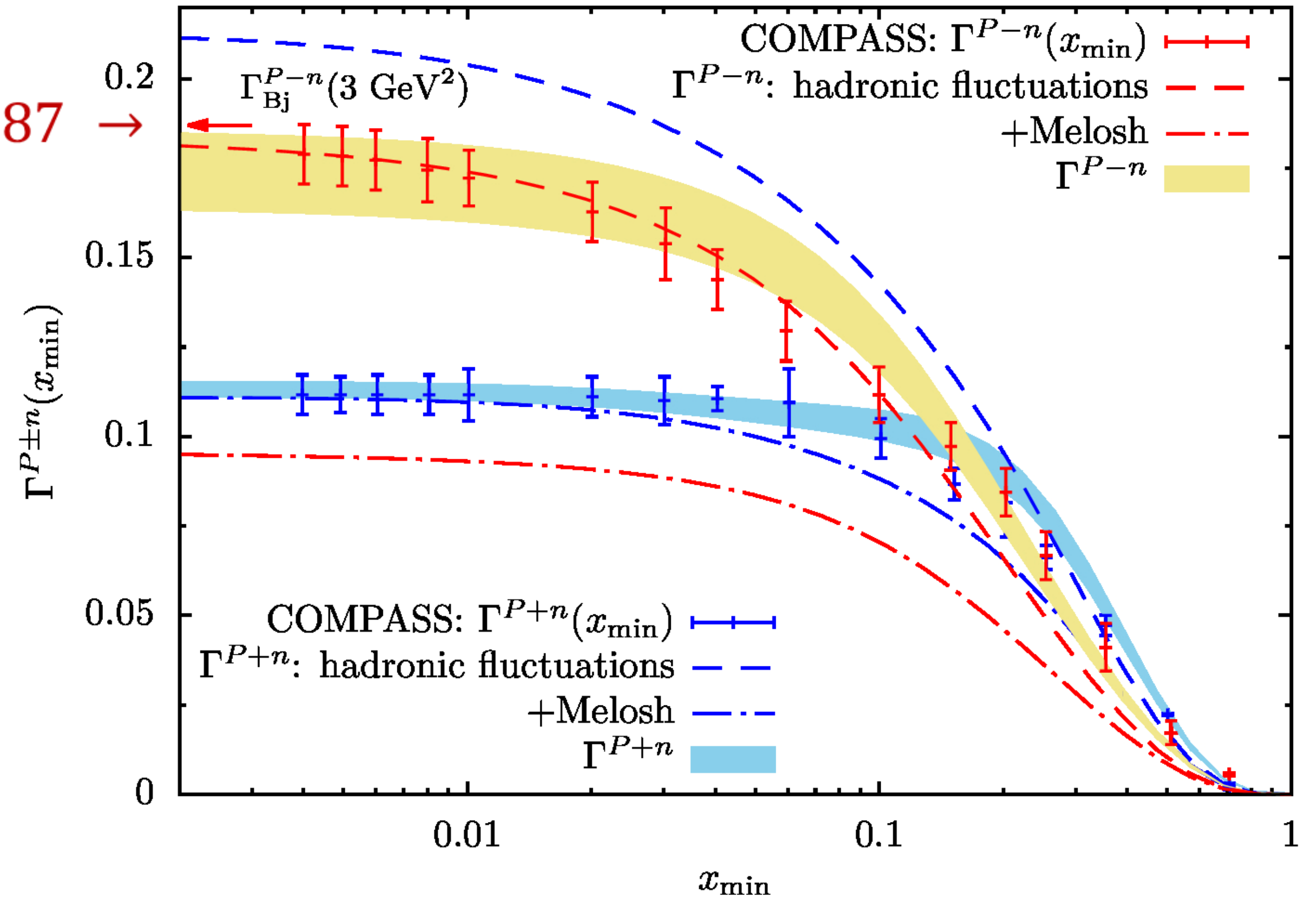
& $g_1^n(x)$ forces

SU(6) breaking,

available range:

$-2 \leq \Delta f_{u/p} \leq 2$

$-1 \leq \Delta f_{d/p} \leq 1$



Data $\rightarrow$ $\Gamma^{P-n}(0) \Rightarrow \Delta f_{u/P} = 2,\ \Delta f_{d/P} = -1$

$\rightarrow |p\rangle \approx |u^{\uparrow}u^{\uparrow}d^{\downarrow}\rangle$ in contrast to non-relativistic quark model

Conclusion

Hadron fluctuations (ChPT) + non-pQCD parton fluctuations
+ pQCD DGLAP evolution + SU(6) quark flavor-spin symmetry
$\rightarrow$ repoduce data on

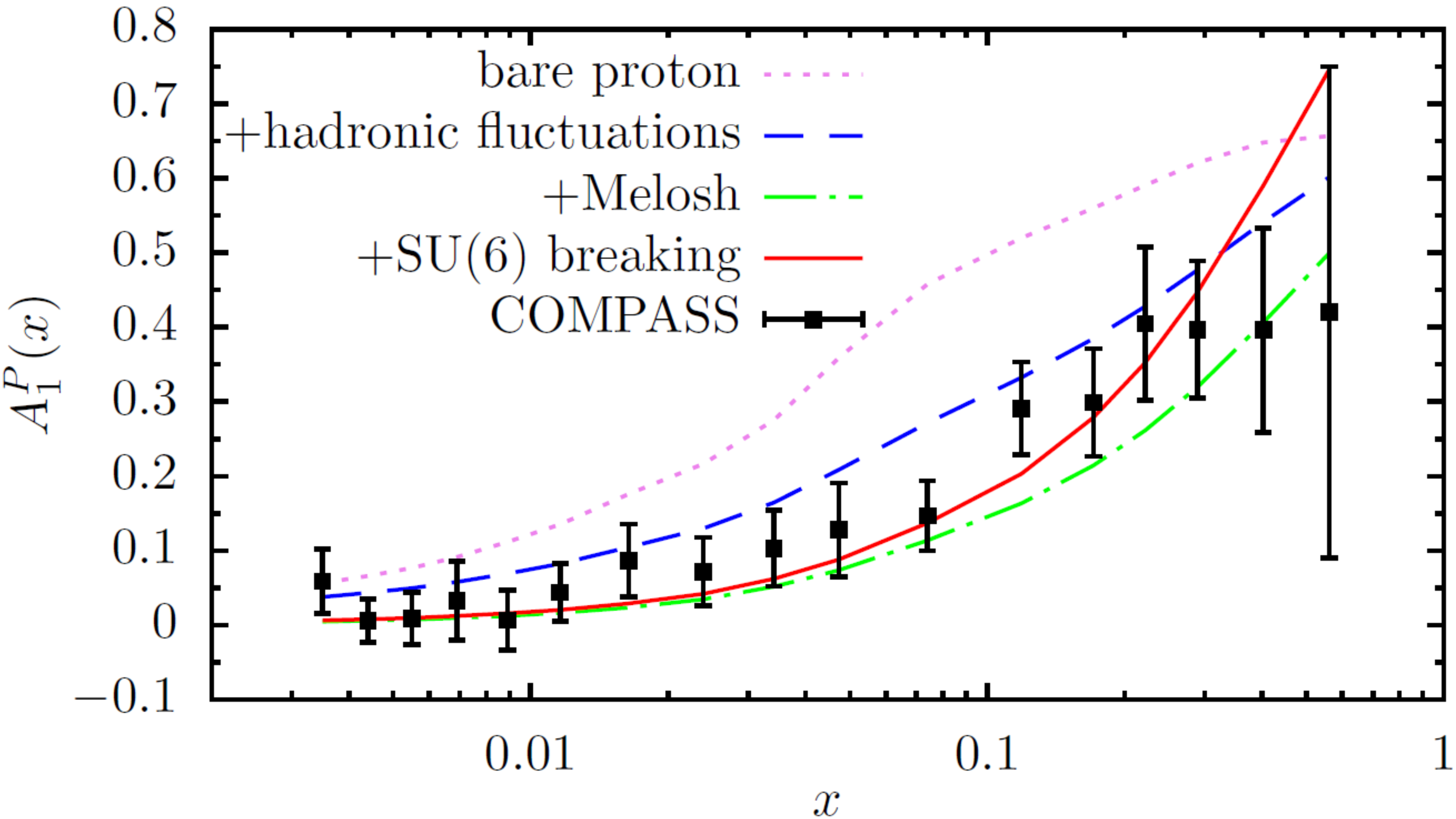
- proton spin structure function
- Ellis-Jaffe sum rule
- proton quark spin sum $\Delta\Sigma$

	bare	hadronic fluct.	Melosh	SU(6) break.	$\Delta\Sigma^{\rm exp}$
$\Delta\Sigma$	0.95	0.75	0.39	0.39	0.26–0.36

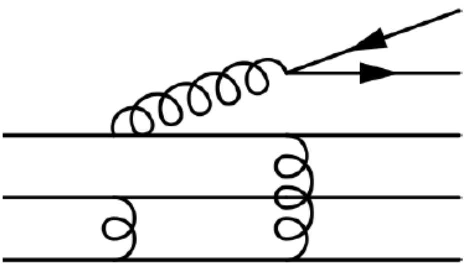
+ SU(6) breaking $\rightarrow$ reproduce data on

- neutron spin structure function
- Bjorken sum rule

- Also in agreement with virtual-photon–absorption asymmetry $A_1 \simeq g_1/F_1$



Sea quark asymmetry in proton



- From pQCD point of view: since $m_u, m_d \ll \Lambda_{\rm QCD}, Q_0 \rightsquigarrow$ the momentum distribution of the $\bar{d}$ and $\bar{u}$ sea in the proton should be similar
- $\rightsquigarrow$ pQCD $\Rightarrow x\bar{d} - x\bar{u} = 0$
- Hadronic fluctuations: (cheapest) $|n\pi^+\rangle$
- $\pi^+ \sim u\bar{d} \Rightarrow |n\pi^+\rangle \rightsquigarrow$ asymmetry
- Including $|\Delta\pi\rangle \rightsquigarrow$ even better agreement