Hadron Spin Physics

Spin Muon Collaboration (SMC)

Spin Crisis !!!

not as bad as the subprime market crisis…

many Spin Doctors… surviving …

Spin Physics: …a “niche market”…?

Aldo Penzo, INFN -Trieste

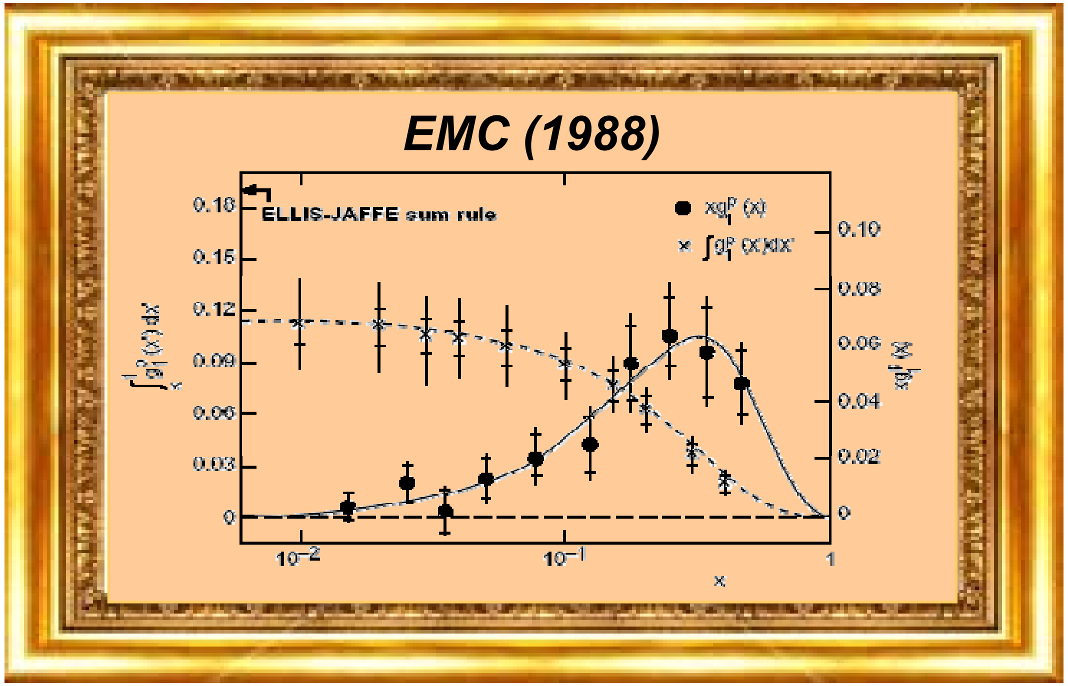
International Conference on Particle Physics
29 October 2008, Bogazici University, Istanbul

INFN Istituto Nazionale di Fisica Nucleare

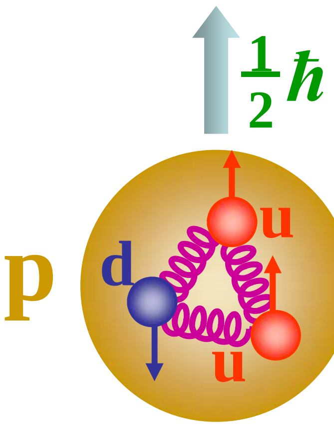
…to enjoy a mystic spin experience…???

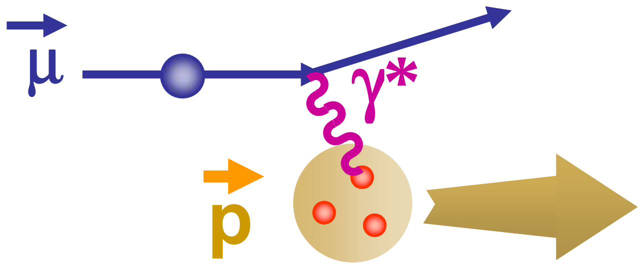
… and thrive …

“Spin Crisis” …since 20 years…



- Success of **“naive quark model”** predicting ratios of magnetic moments of octet baryons,
- assumption that spin of proton should be carried by its **3 valence quarks**.
- It was therefore a surprise when it was discovered that the proton spin is not fully carried by quarks.
- A large fraction of proton spin should be carried by gluons, or strange quarks, or orbital angular momenta.





$$\frac{1}{2} = \frac{1}{2}\Delta q + \Delta G + L_z$$

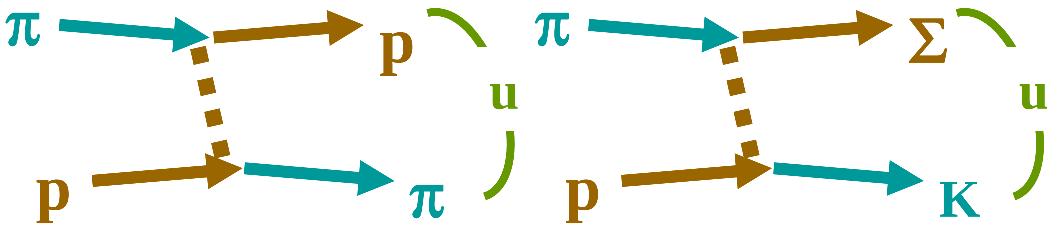
In the 70's… golden age of spin …

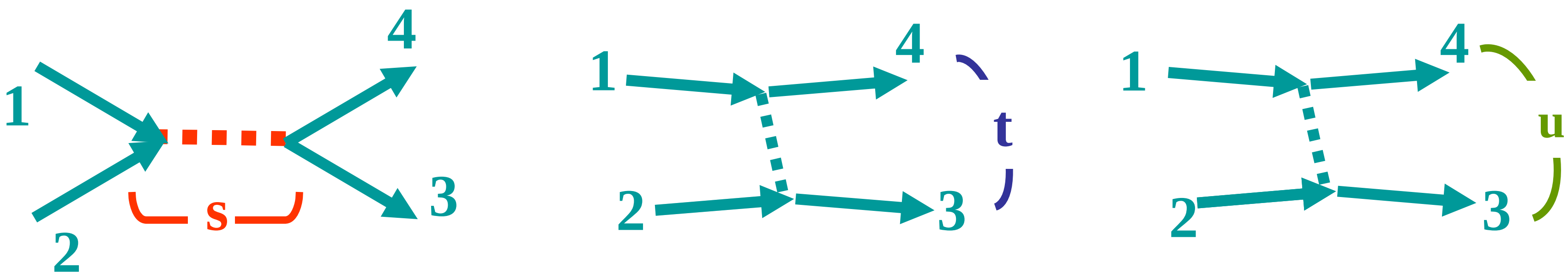
- 1969 - Butanol Polarized Targets (high $P_T \approx 0.7$; large H content) CERN team will build SMC giant target
- 1973 - First high energy polarized proton beam at the ZGS; achieve $2x10^{10}$ intensity with 70% P_B at 11.75 GeV/c; pioneering AGS and RHIC
- 1975 - GaAs Polarized Electron Sources: at SLAC currents up to 15 mA in 1.6-μsec pulses were accelerated at 180 pps. P_B at high energy was ~37%.
- For SLC sources were improved and P_B was regularly ~80%

Through the 70's…and 80's…

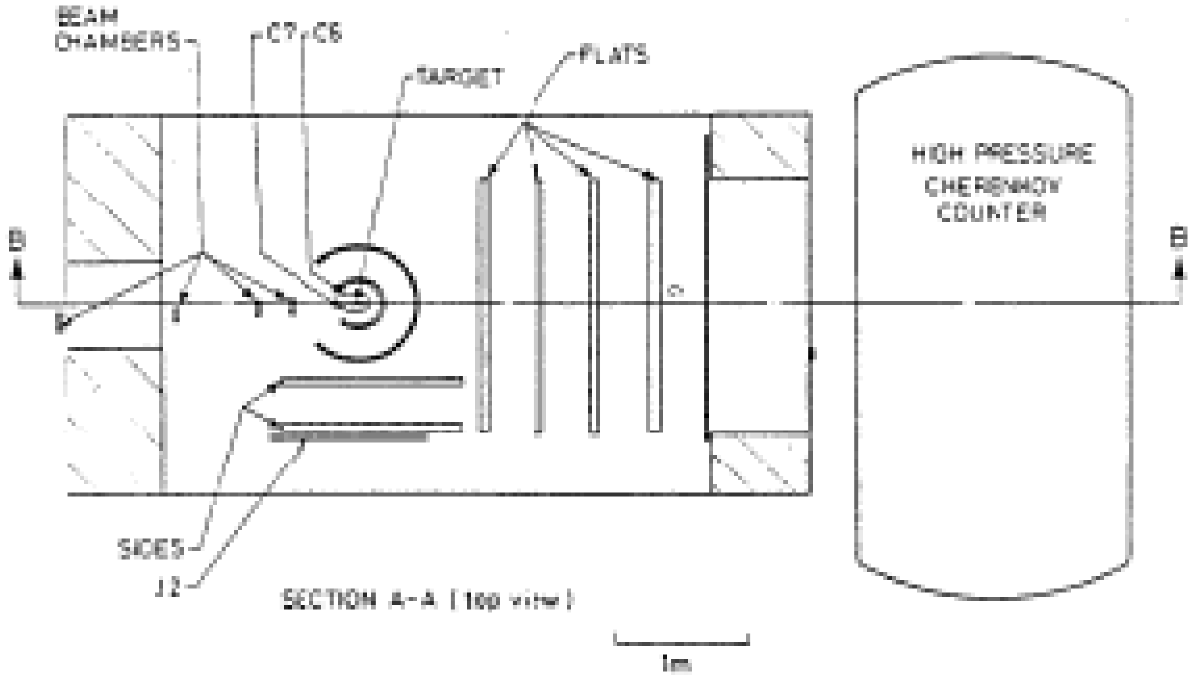
Engin Arik

- 1976 -1979: Westfield College London
- **Measurement of π+ p backward elastic differential cross-section using the RMS (Rutherford Multiparticle Spectrometer).**
- **Measurement of π+ p → K+ Σ+ differential cross-section and polarization between 1.27 GeV/c and 2.50 GeV/c.**
- (In Proceedings Baryon 1980, Toronto)





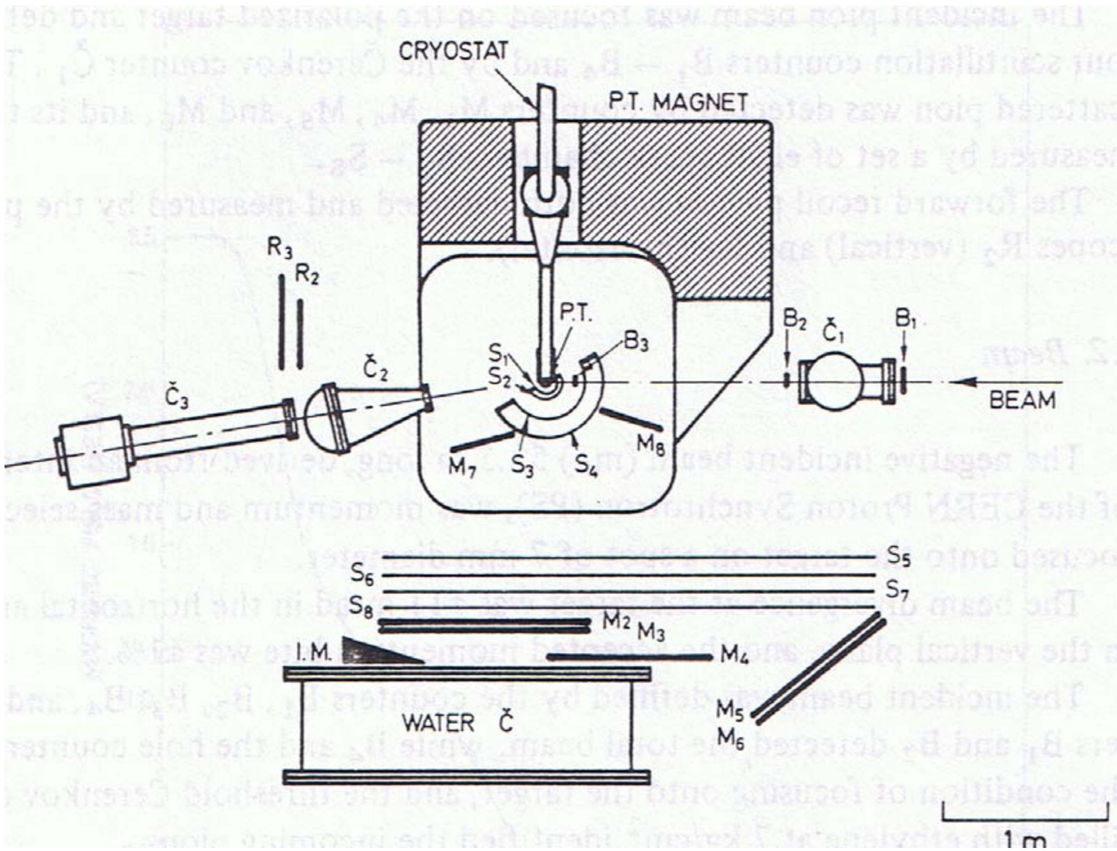
The RMS at Nimrod



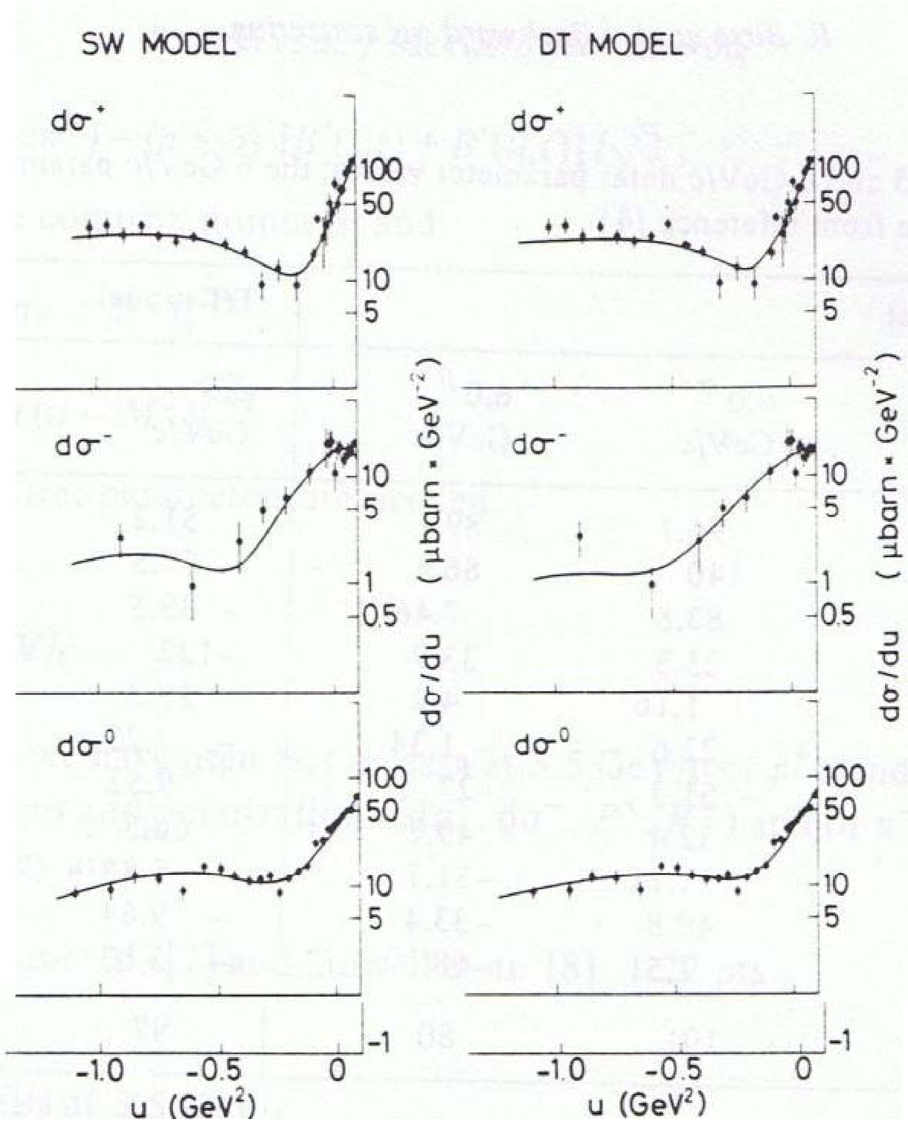
- The Rutherford Multiparticle Spectrometer at Nimrod was equipped with chambers to measure tracks in magnetic field and a large Cherenkov counter for particle discrimination

A Polarized target experiment at CERN

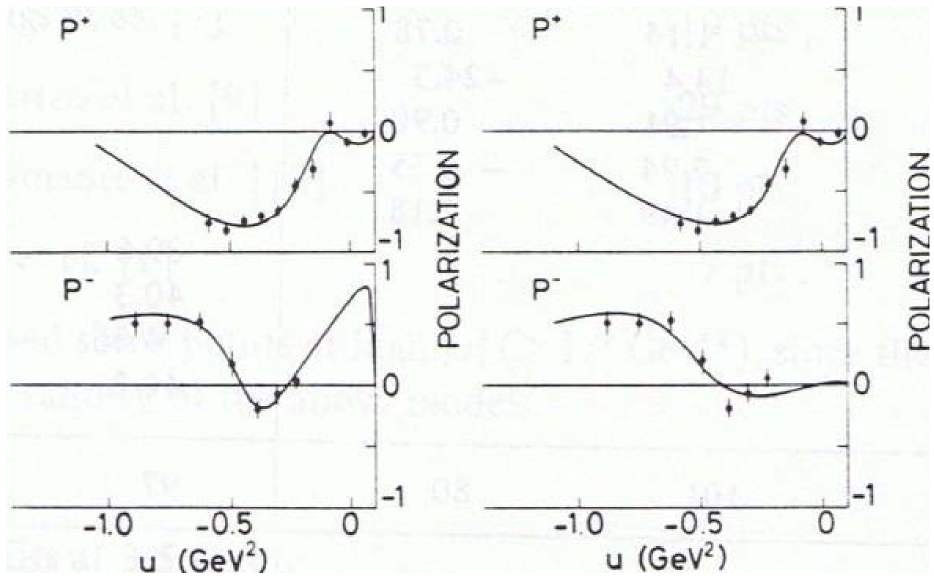
- A system of wire chambers (some also in the magnet gap for momentum reconstruction, trigger given by scintillators and Cherenkov counters.



πp elastic backward scattering



3.5 GeV/c

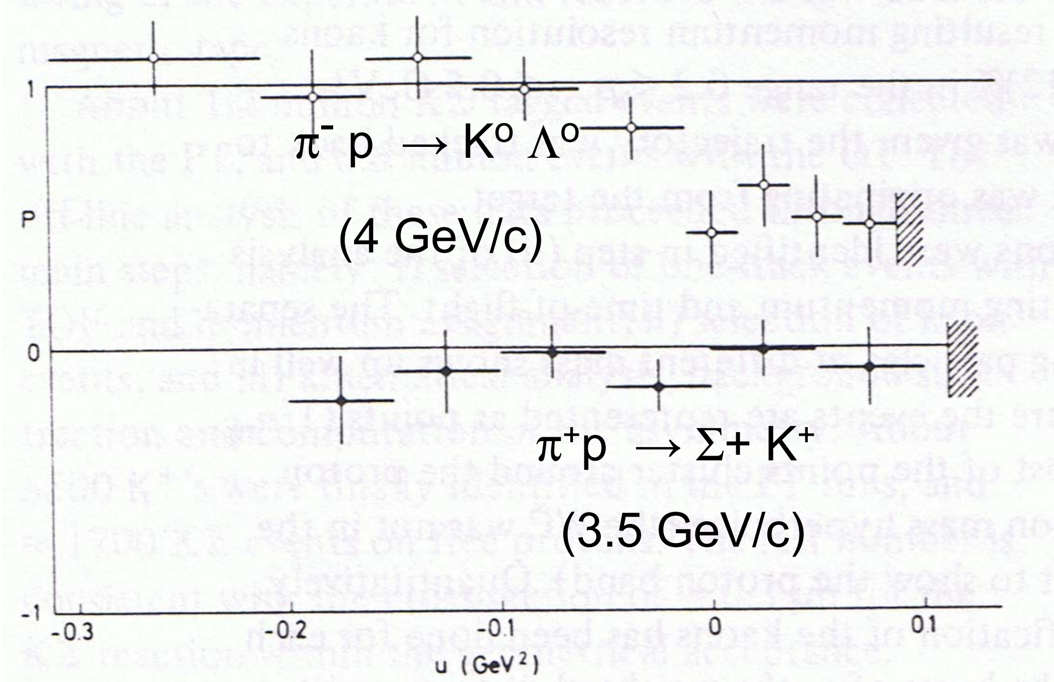


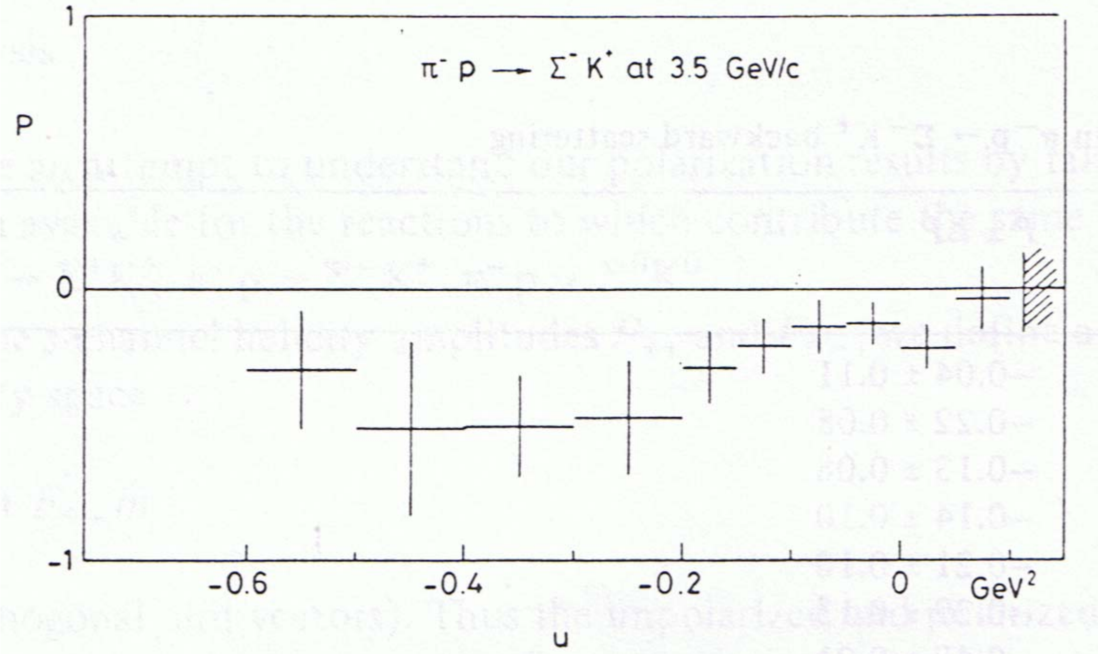
Results

- In backward πp the large polarization is contribution of at least 2 exchanges, having nucleon N, Δ quantum numbers, and as well in reactions

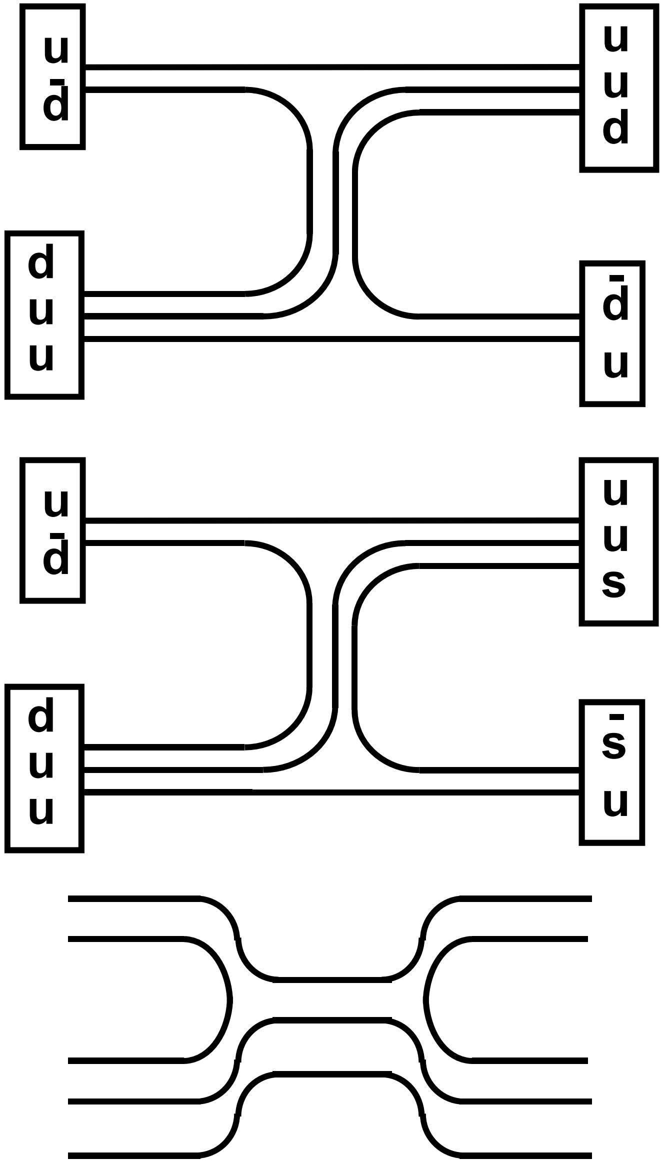
  $\pi^- p \rightarrow K^o \Lambda^o$

  $\pi^- p \rightarrow K^o \Sigma^+$
- but with strangeness exchange (Λ, Σ)



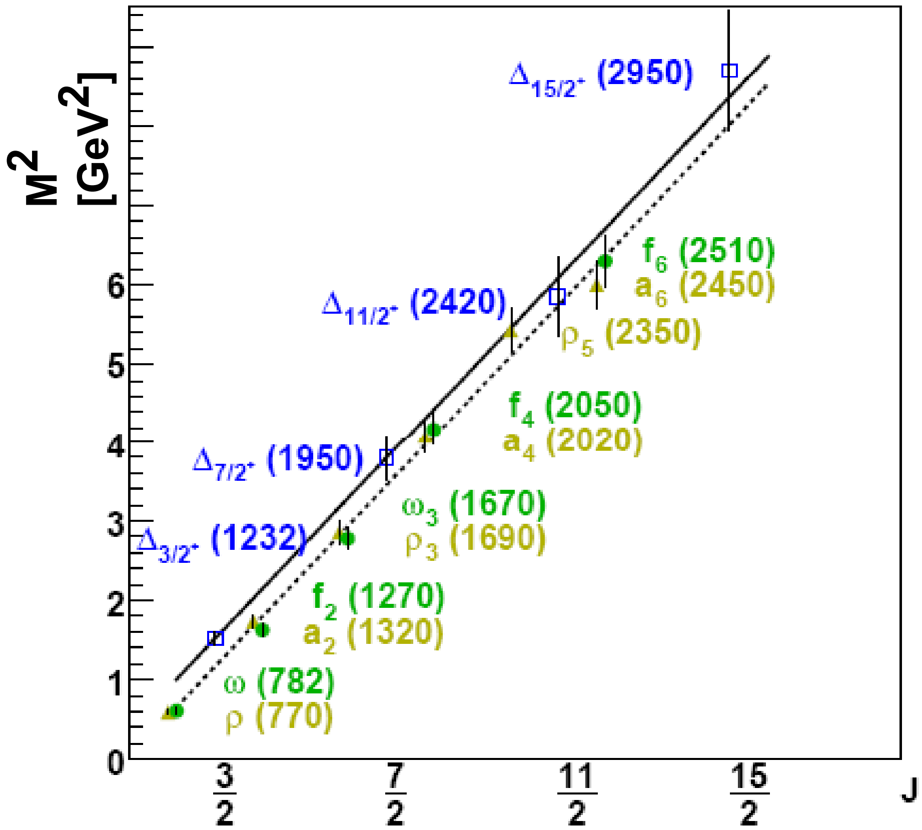


Baryon Exchanges



- The backward scattering cross section is very small and decreases rapidly with increasing energy and has a peak at 180°.
- Backward elastic scattering of pions by nucleons goes through **baryon exchange**.
- At low energies, families of resonances produced in the s-channel, have angular momentum J approximately linear in M^2 and belong to **Regge trajectories**.
- At larger energies Regge trajectories exchanged in the t-channel (u-channel) produce the forces that create s-channel particles. The general idea that *s*-channel resonances should be equivalent to, and not added to, the *t*-channel exchanges is referred to as **Duality**

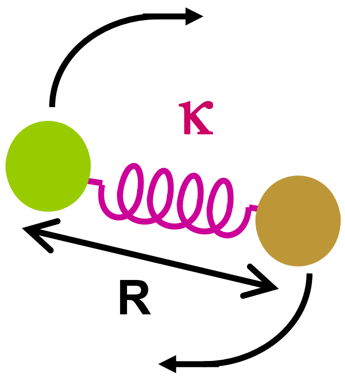
Baryon Regge trajectories



1. Same slope of Regge trajectories for mesons and Δ' s;
2. Δ resonances with S=1/2 and S=3/2 are on the same Regge trajectory.
3. N and Δ resonances with spin S=3/2 lie on a same Regge trajectory; S= 1/2 N's are shifted.

Degeneracy of (baryon) Trajectories (EXD) is characteristic property of dual models, with dynamic consequences

From duality to strings



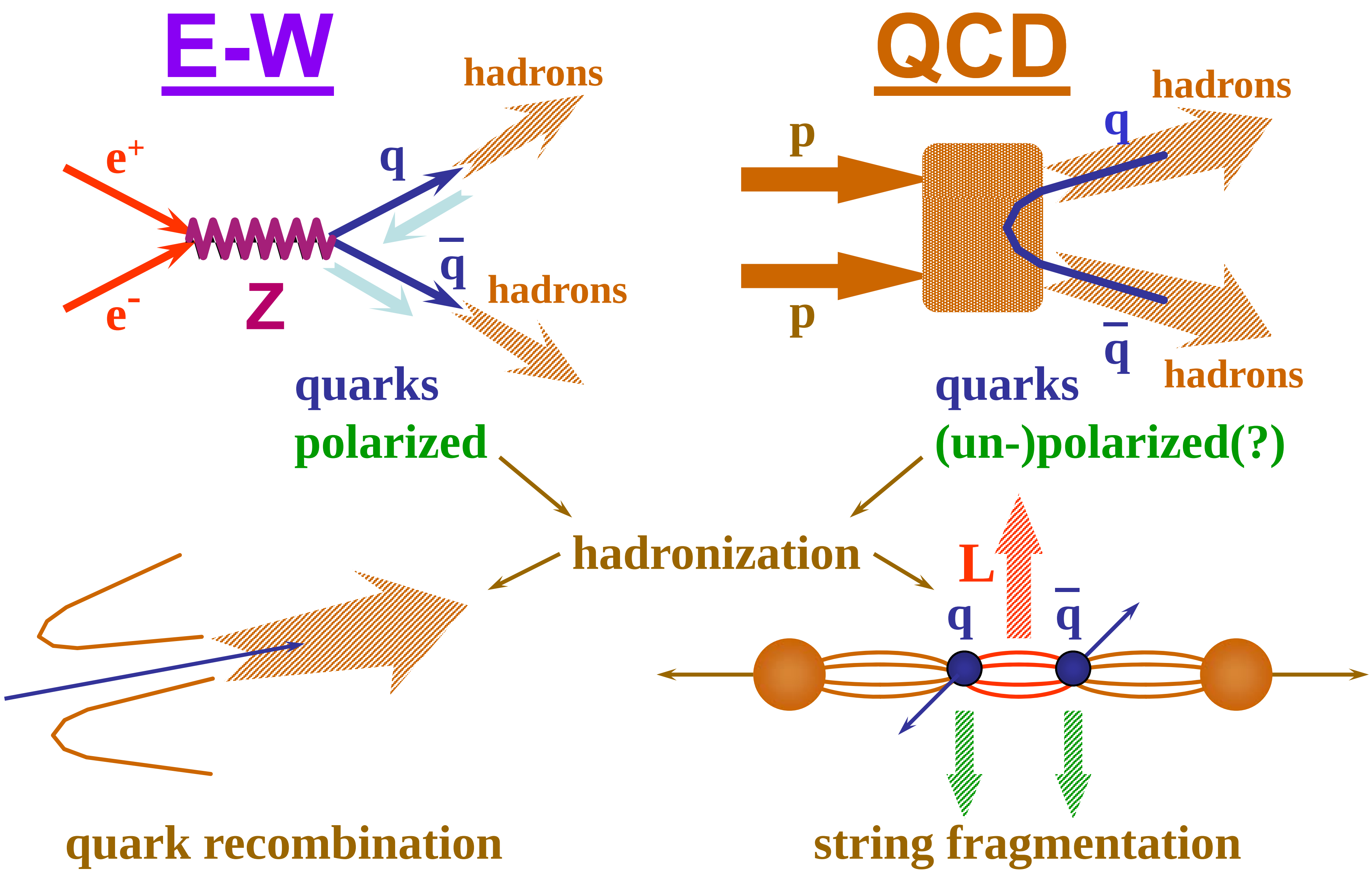
$M \approx E \approx \pi\kappa R$

$J \approx (1/2)\, \pi\, \kappa\, R^2$

$\alpha \approx (2\pi\kappa)^{-1} \sim 0.9\ GeV^{-2}$

- Veneziano established a mathematical frame for dual models (Euler Beta function)
- Nambu gave a physical representation of nuclear forces as vibrating strings (with quarks at the ends) in rotation
- The strings have a linear energy density of κ [GeV/fm]; the energy is $E \approx \pi\kappa R$ and the angular momentum is $J \approx (1/2)\, \pi\, \kappa\, R^2$; thus the Regge slope is $\alpha \approx J/M^2 \approx (2\pi\kappa)^{-1} \sim 0.9\ GeV^{-2}$

Production of Quarks with Polarization and its Measurement

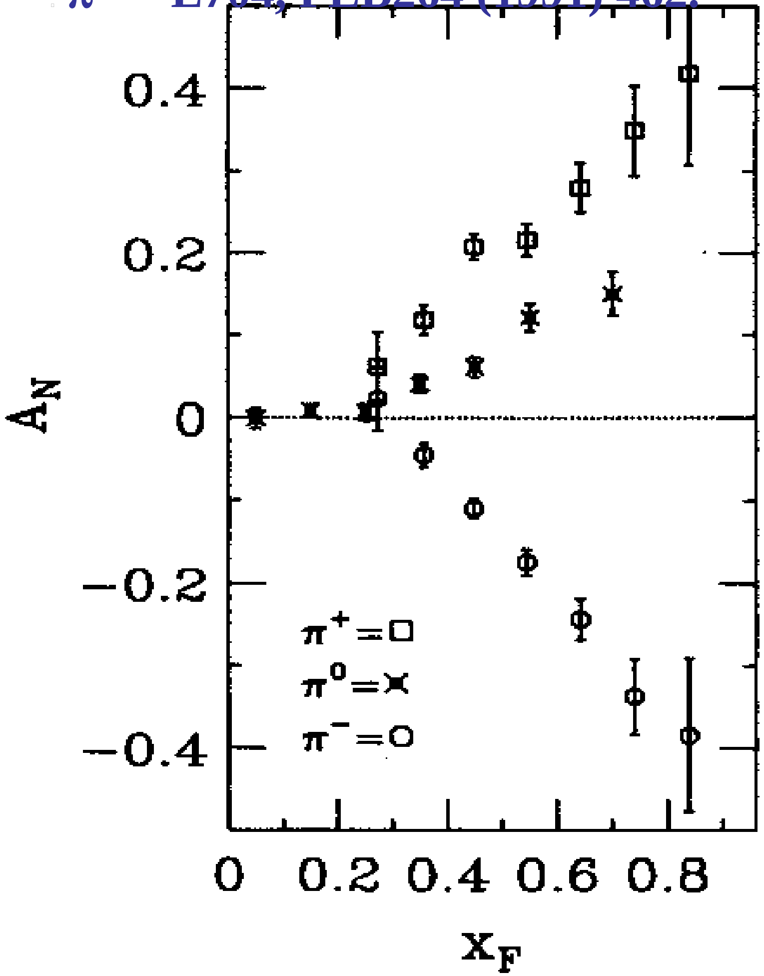


$$p_\uparrow + p \rightarrow \pi + X$$

FNAL E704

π^0 – E704, PLB261 (1991) 201.

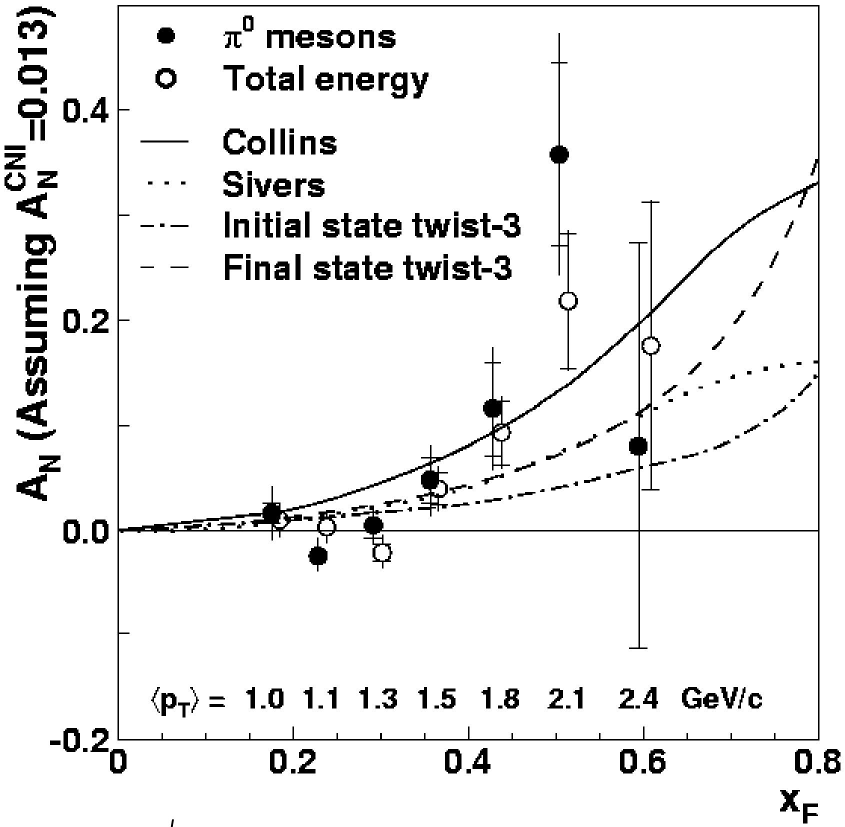
$\pi^{+/-}$ - E704, PLB264 (1991) 462.



√s=20 GeV, p_T=0.5-2.0 GeV/c

STAR collaboration

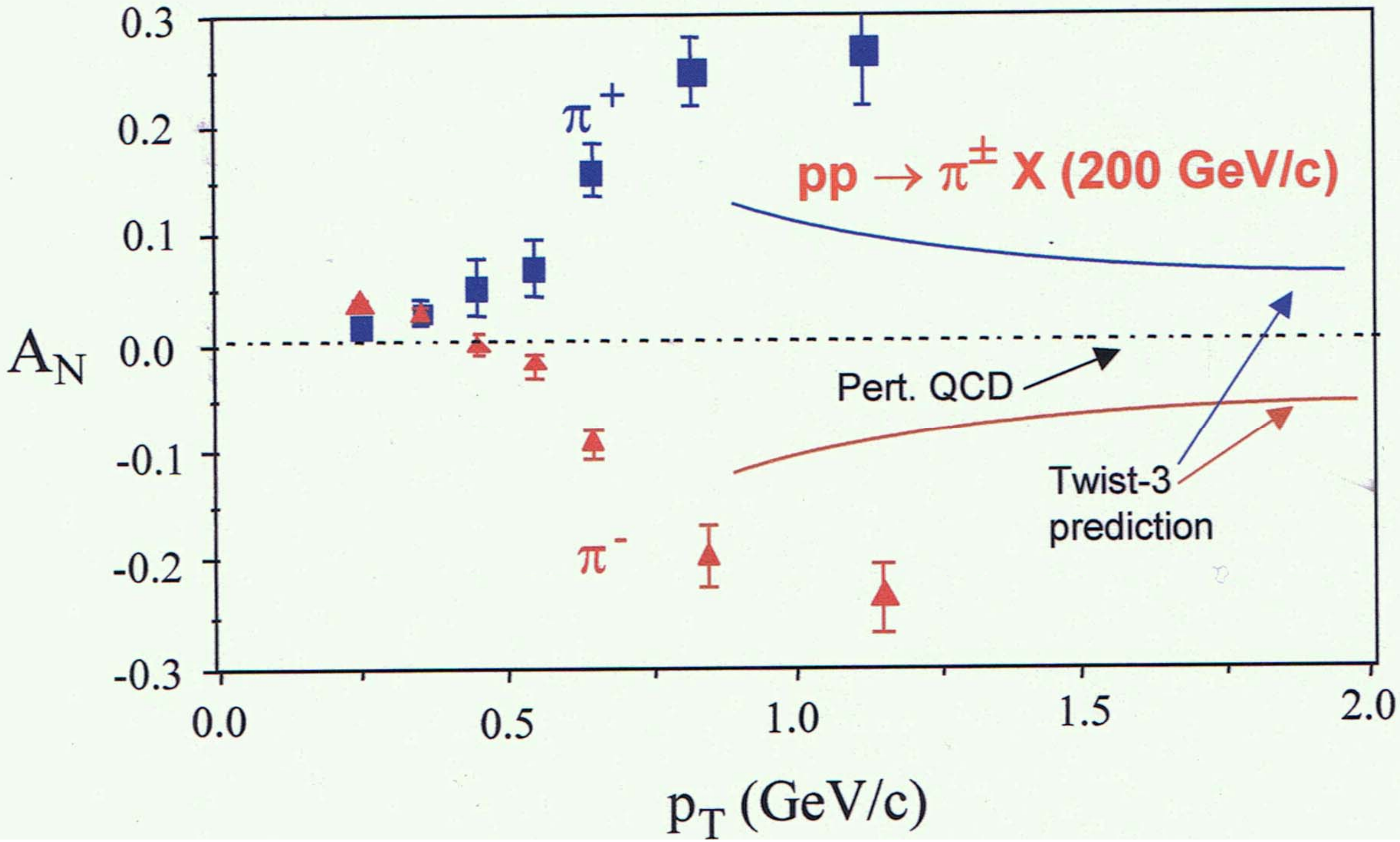
Phys. Rev. Lett. 92 (2004) 171801



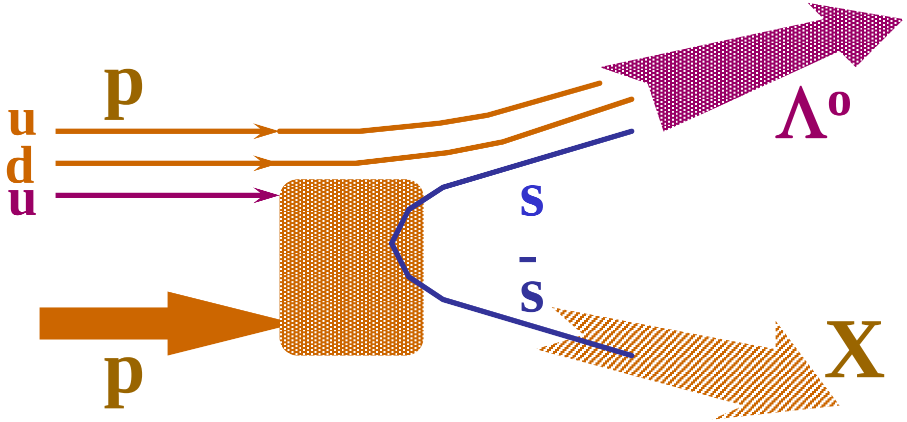
√s=200 GeV, <η> = 3.8

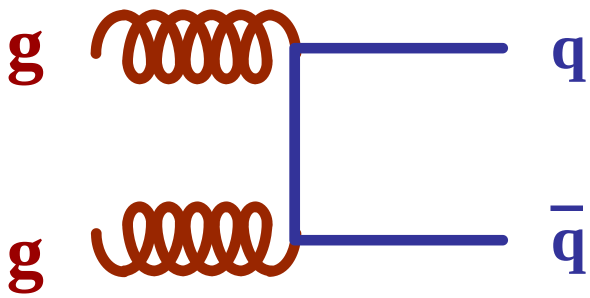
- Similar pattern…maybe different mechanisms

Spin Asymmetry for $pp \to \pi^{\pm} X$

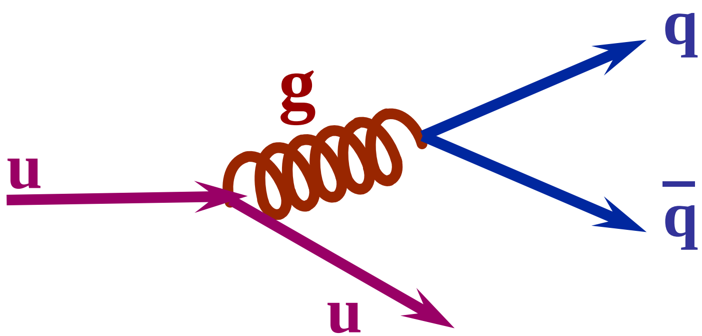


Hyperon Production and Polarization

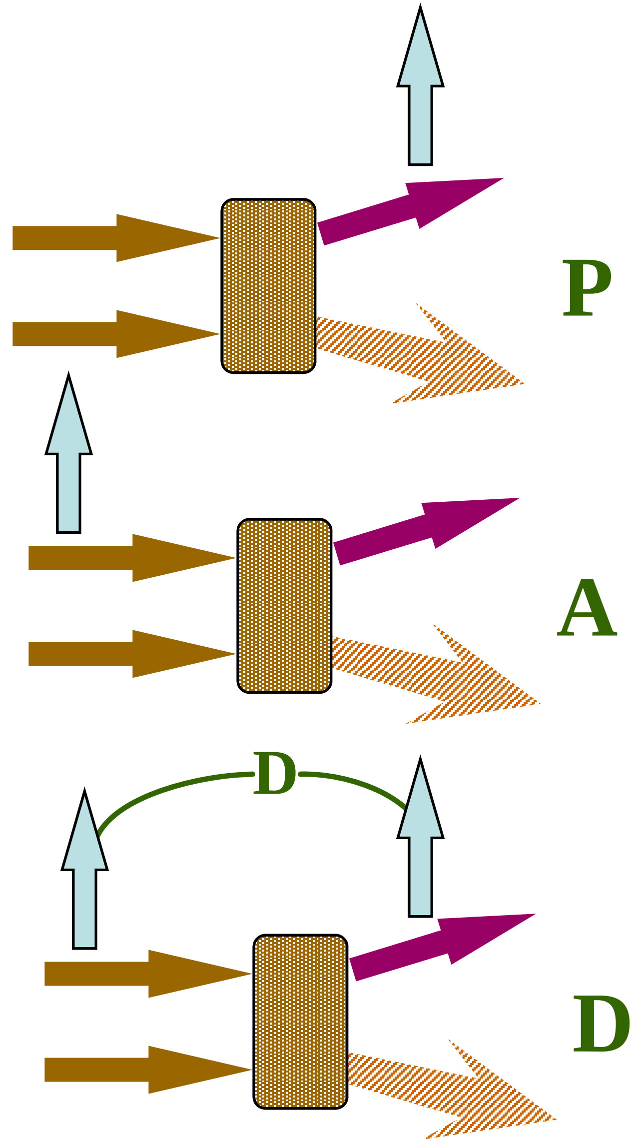




$$P_q \sim \frac{m_q}{\sqrt{s}}$$



Spin Observables



Λ^o Hyperon production and decay

- With its "self-analyzing" decay $\Lambda \to p\pi^+$ (Br~64%), the $\mathbf{\Lambda^o}$ polarization can be measured from the angular distribution of decay proton:

$$\frac{dN}{d\Omega} \propto 1 + \alpha\,(\vec{P}_\Lambda \cdot \hat{p}_p)$$

Unit vector along proton momentum in Λ rest frame.

decay parameter 0.642(PDG)

Λ polarization vector

- Λ polarization plays an important role in spin physics:

1. Well-known transverse polarization in unpolarized pp, pA (G. Bunce et al 1976).
2. Study pol. fragmentation function and spin content of hyperon.
3. A tool to study spin structure of nucleon .

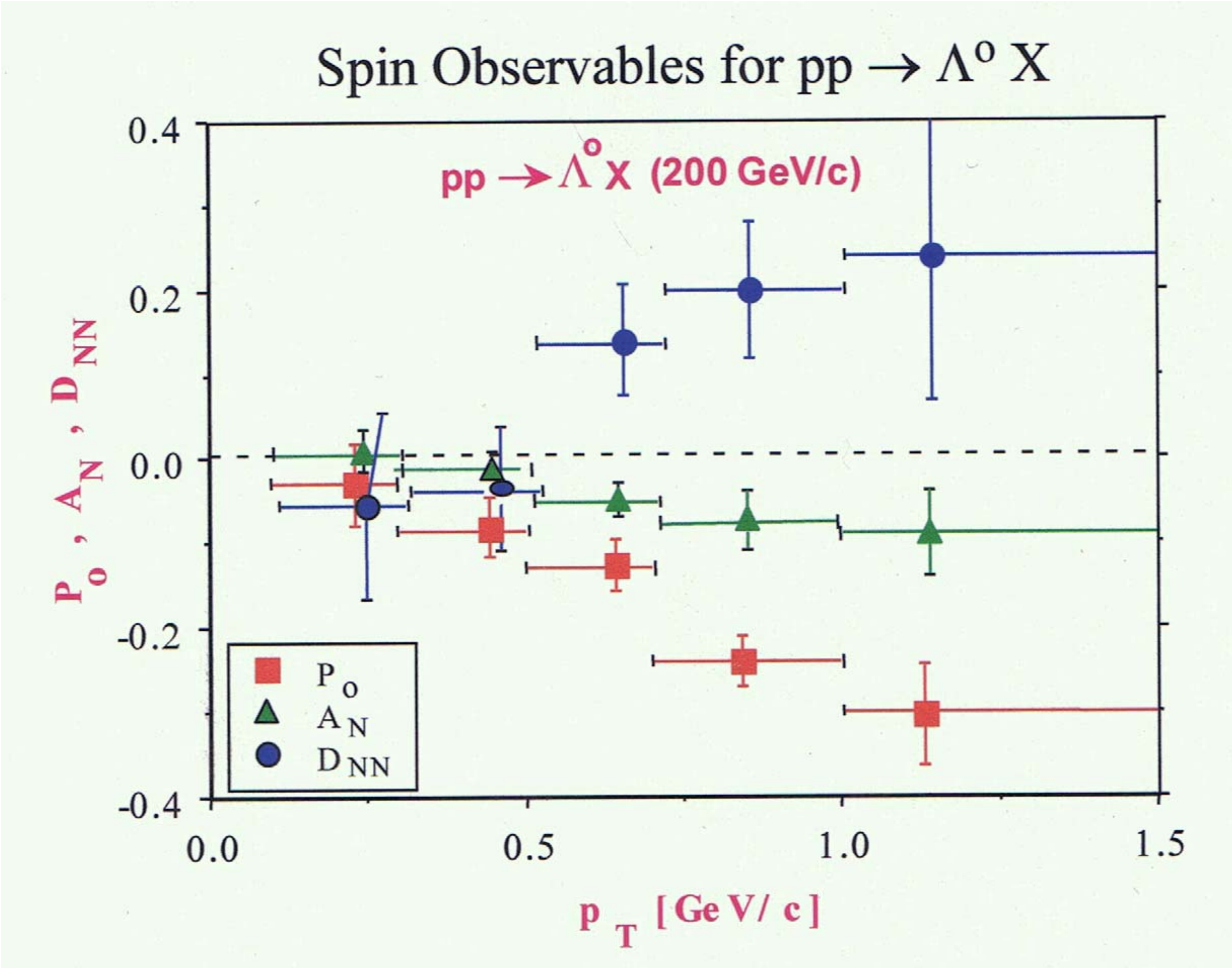
- Transverse $\mathbf{\Lambda}$ polarization with pol. beam:

✓ fixed Target pp: E704 (PRL'97), DISTO(PRL'99)...

✓ lepton-nucleon : COMPASS

✓ pp collider : RHIC

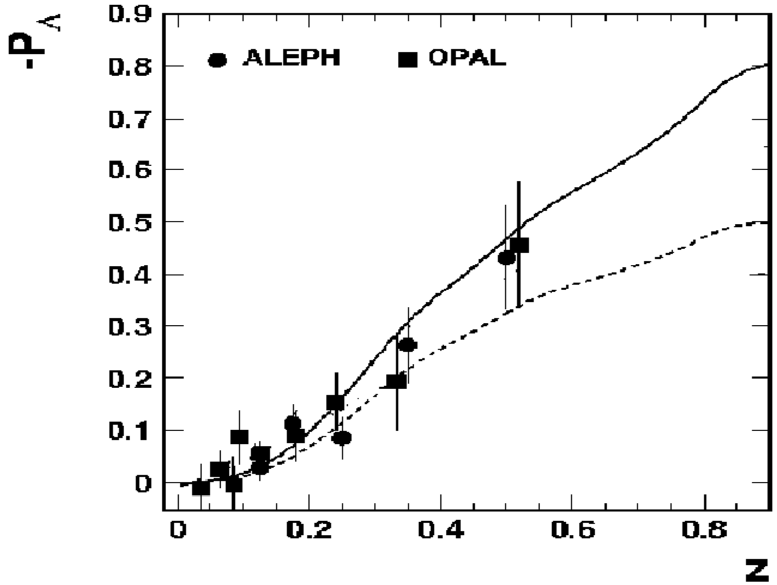
FNAL E704

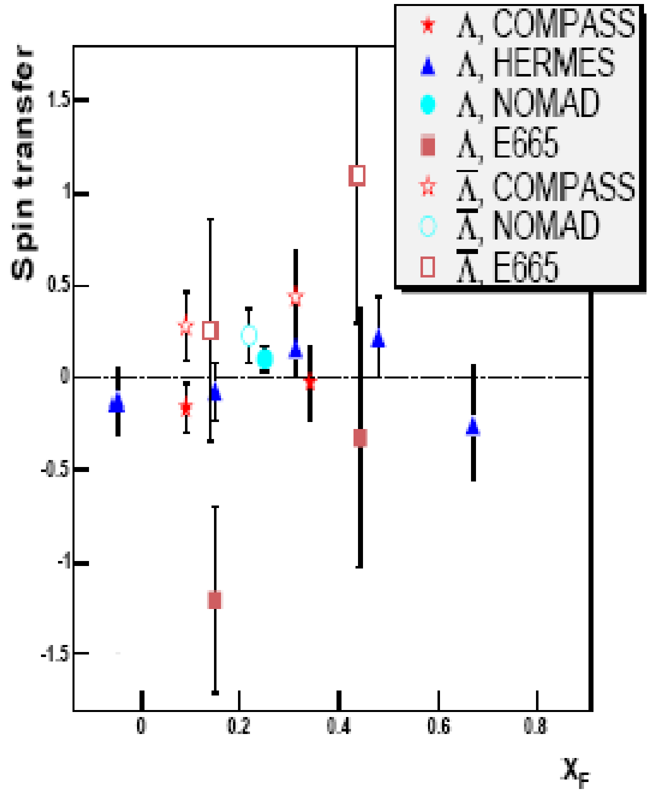

Spin Observables for pp → Λ° X
pp → Λ° X (200 GeV/c)
0.4
0.2
0.0
-0.2
-0.4
0.0
0.5
1.0
1.5
P_o , A_N , D_NN
p_T [GeV/c]
P_o
A_N
D_NN

Longitudinal Λ^o polarization

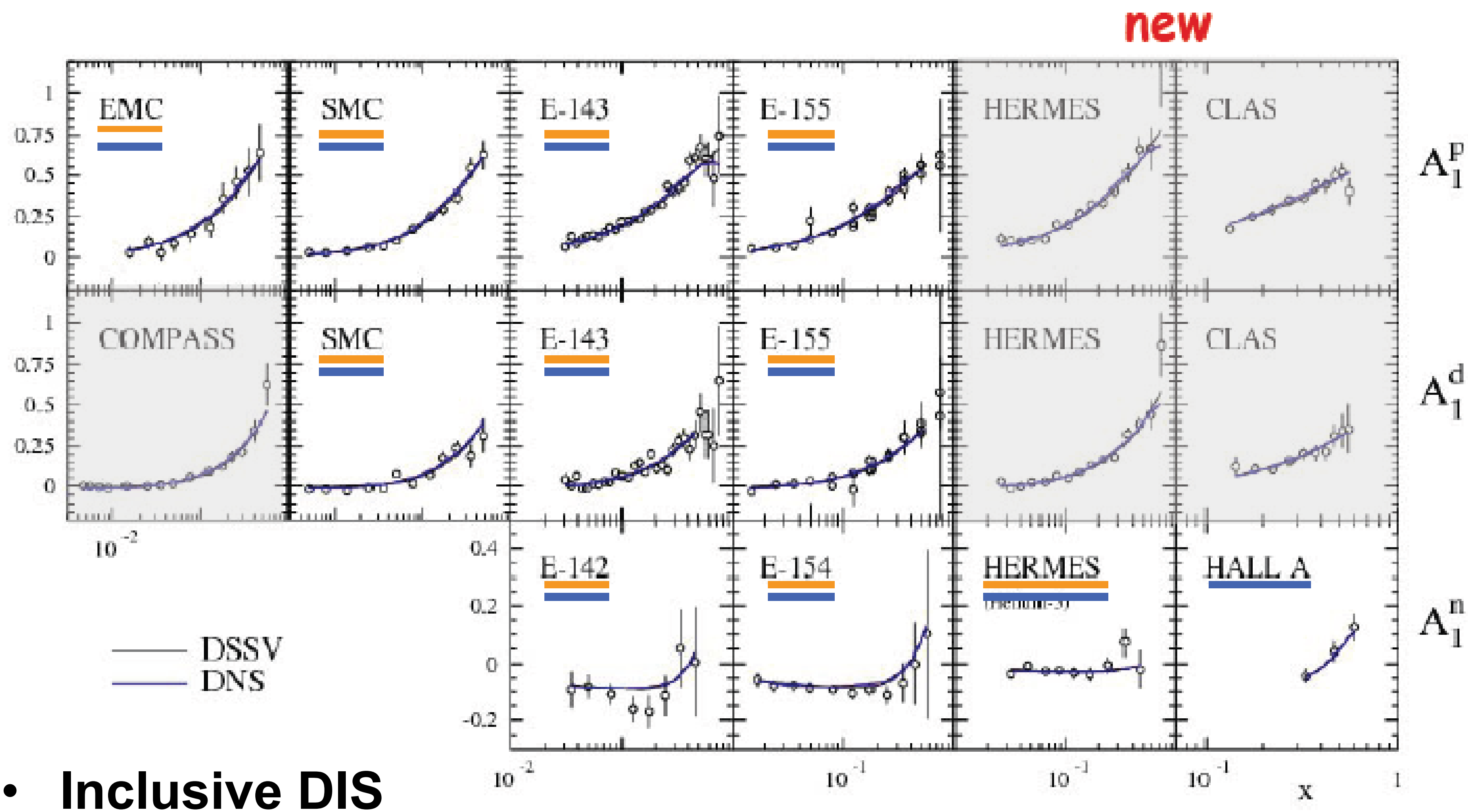
- ✓ e+e-: ALEPH(PLB'96), OPAL(EPJC'98)
- ✓ Polarized lepton-nucleon DIS:
  E665(EPJC'00), HERMES(PRD'01),
  NOMAD(NPB'01), COMPASS
- ✓ Polarized pp collider: RHIC

		SU(6)	DIS
ΔU	*(Σ-D)/3*	0	-0.17
ΔD	*(Σ-D)/3*	0	-0.17
ΔS	*(Σ+2D)/3*	1	0.62





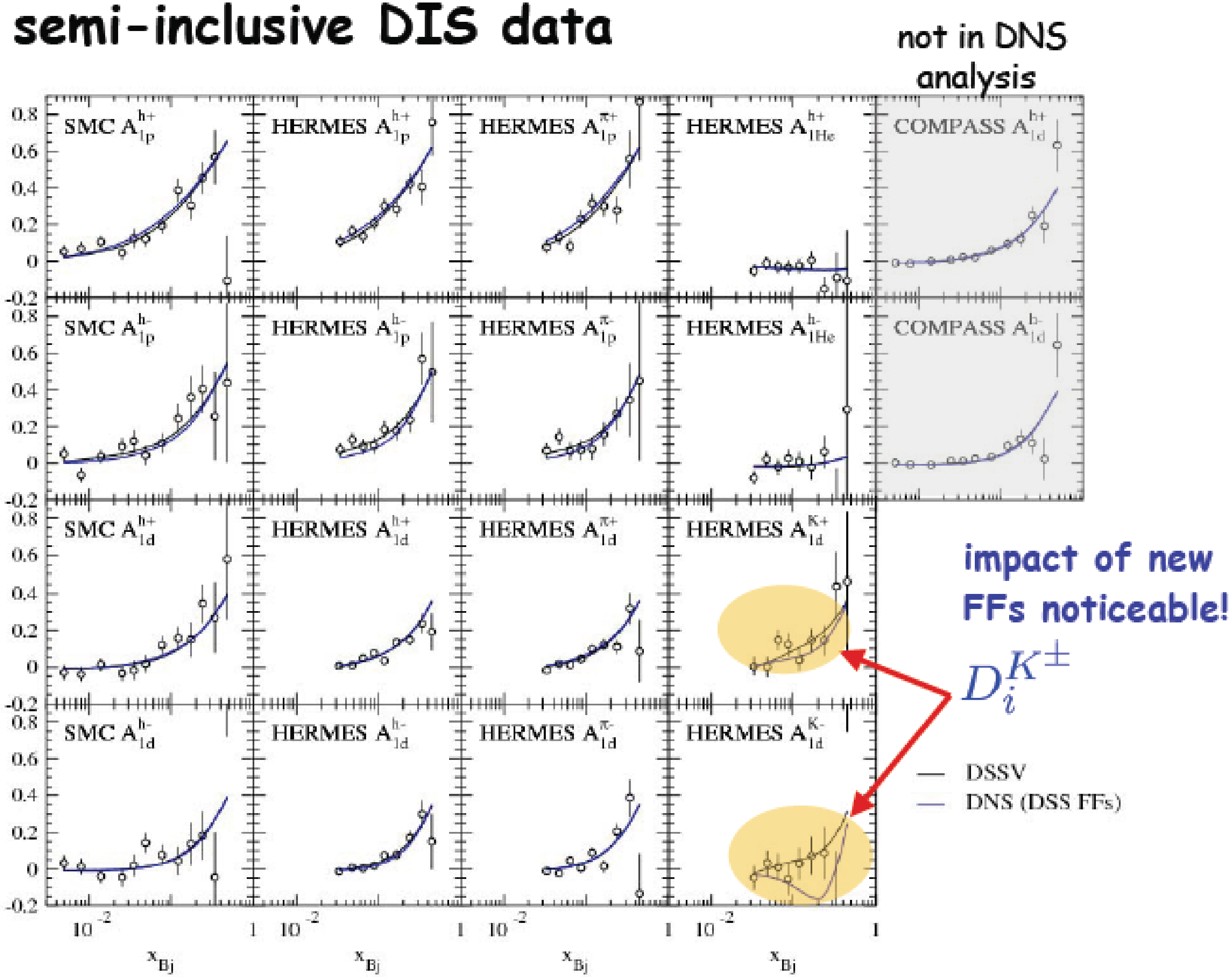
Spin crisis revisited



- **Inclusive DIS**
- **data** sets used in: the **GRSV** analysis
- the combined DIS/SIDIS fit of **DNSnew**

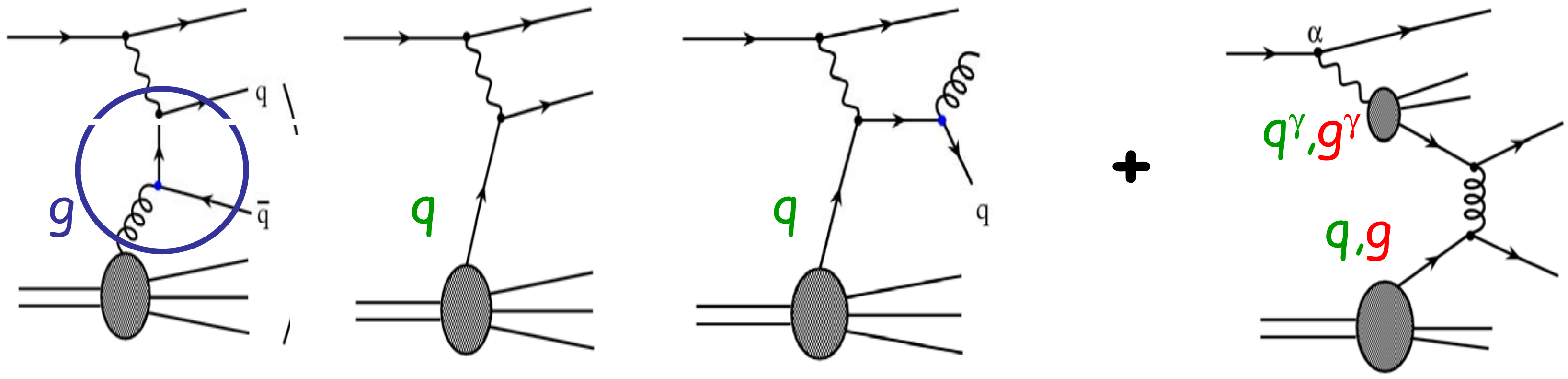
continued

semi-inclusive DIS data



DIS, SI-DIS

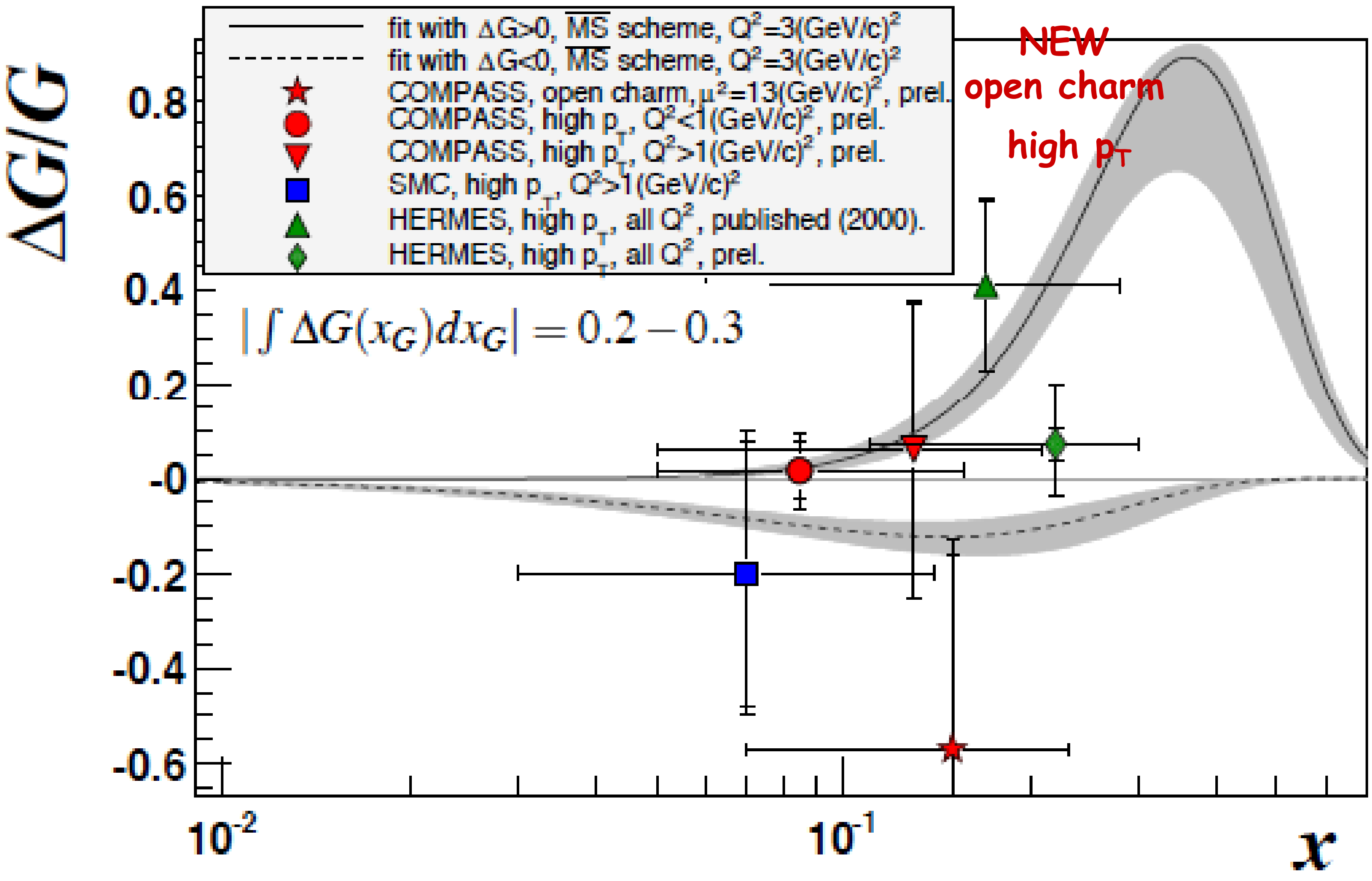
$Q^2 > 1\ (GeV/c)^2$ | $Q^2 < 1\ (GeV/c)^2$



Photon Gluon Fusion ~ 30% | Leading Order | QCD Compton | Resolved γ ~50%

- Processes that contribute to the DIS, SIDIS

State of the art in lepto-production



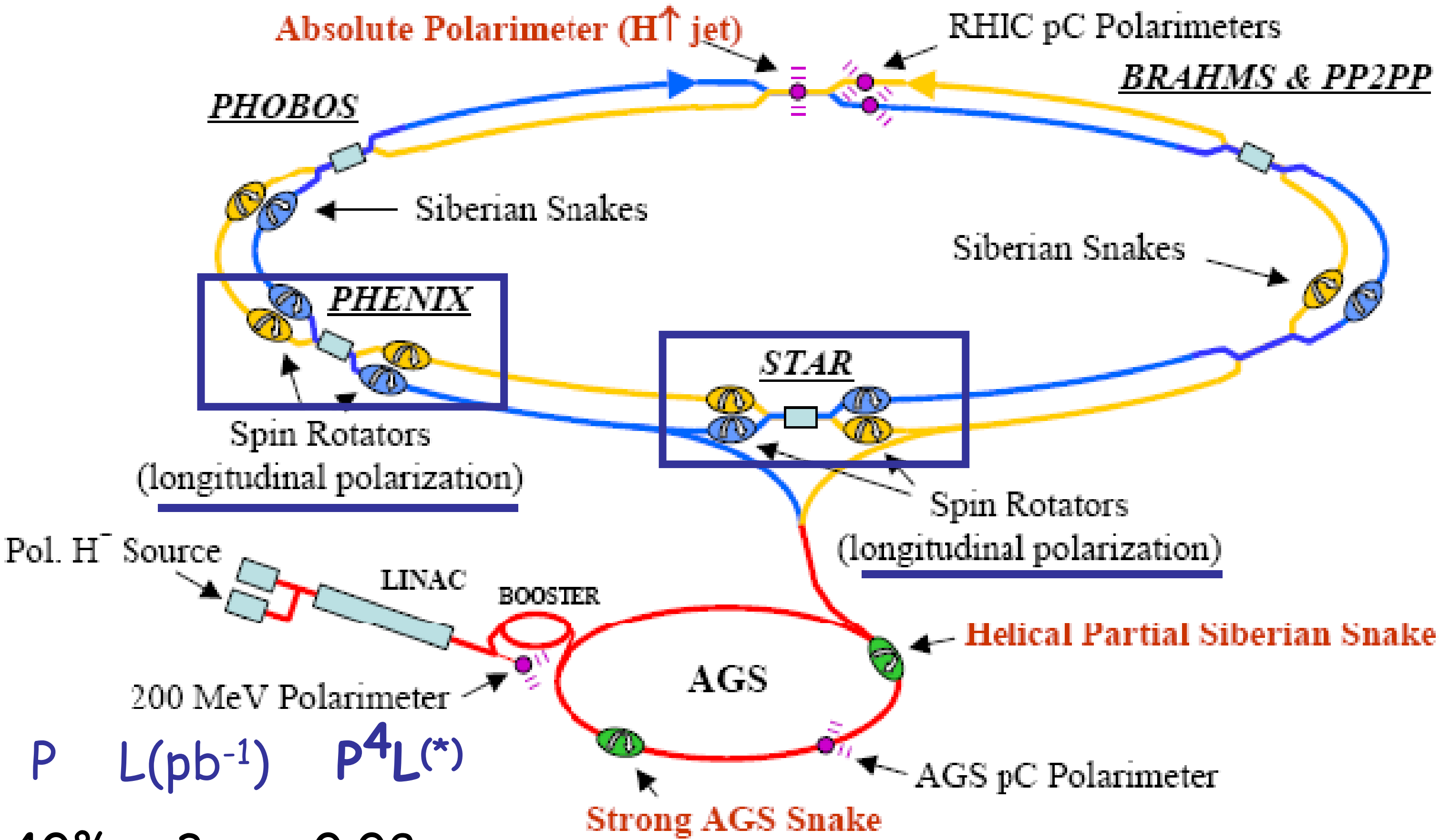
De Florian
Stratmann
Sasset
Vogelsong

DSSV global analysis 08

- **overall quality of the global fit:**
- **fitχ2/d.o.f. = 0.88**

experiment	data type	data points fitted	χ^2
EMC, SMC	DIS	34	25.7
COMPASS	DIS	15	8.1
E142, E143, E154, E155	DIS	123	109.9
HERMES	DIS	39	33.6
HALL-A	DIS	3	0.2
CLAS	DIS	20	8.5
SMC	SIDIS, $h^\pm$	48	50.7
HERMES	SIDIS, $h^\pm$	54	38.8
	SIDIS, $\pi^\pm$	36	43.4
	SIDIS, $K^\pm$	27	15.4
COMPASS	SIDIS, $h^\pm$	24	18.2
PHENIX (in part prel.)	200 GeV pp, π^0	20	21.3
PHENIX (prel.)	62 GeV pp, π^0	5	3.1
STAR (in part prel.)	200 GeV pp, jet	19	15.7
TOTAL:		467	392.6

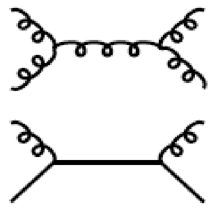
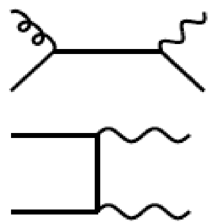
RHIC Polarized Collider



Year	P	L(pb^{-1})	P^4L(*)
2004	40%	3	0.08
2005	50%	13	0.8
2006	60%	46	6

(*) G.Bunce Dubna Spin07

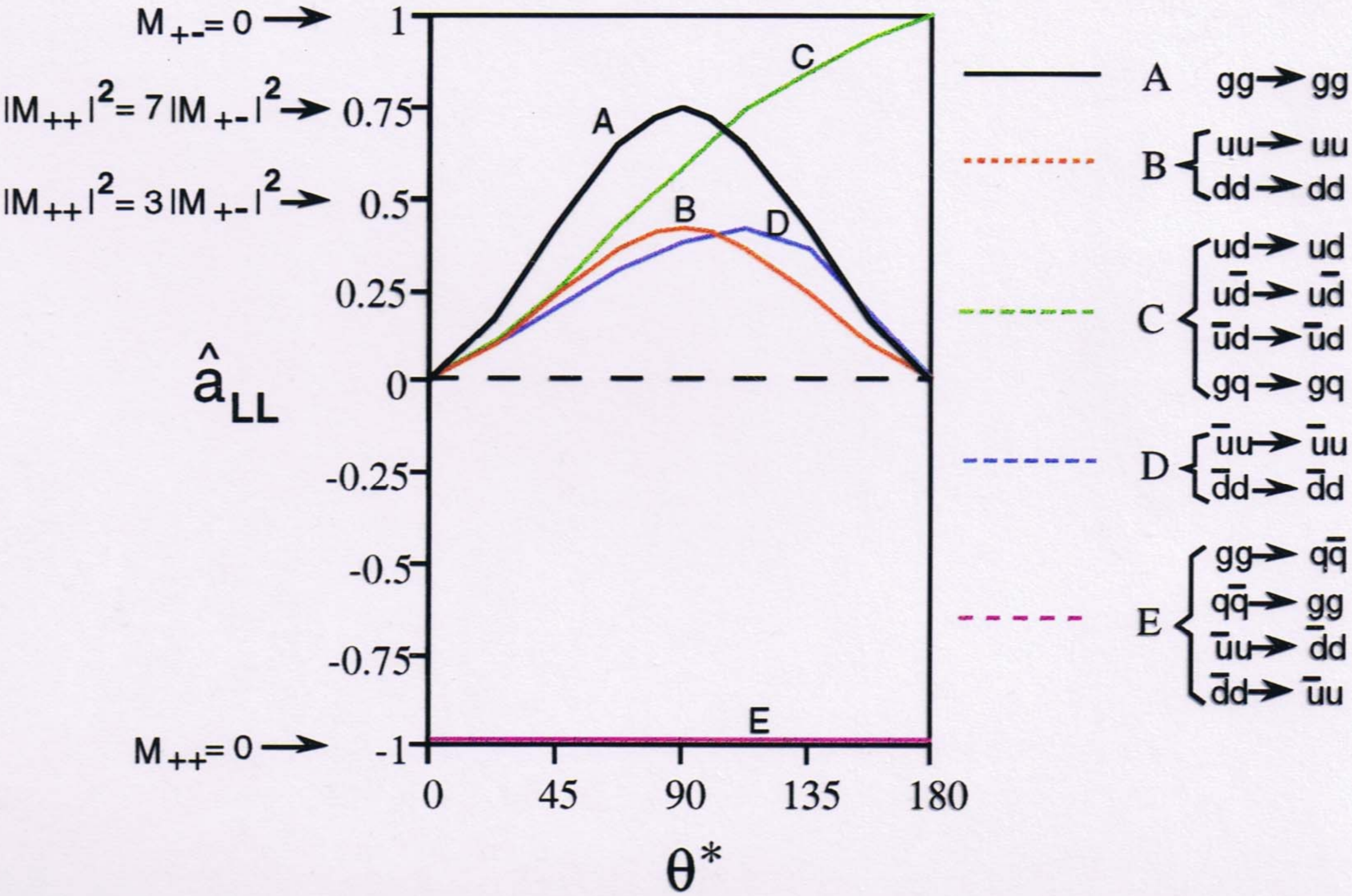
Hadron probes

Reaction	Dom. partonic process	probes	LO Feynman diagram	
$\vec{p}\vec{p} \to \pi + X$ [61, 62]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg		$\frac{\Delta G}{G} \times \frac{\Delta G}{G}$
$\vec{p}\vec{p} \to \text{jet(s)} + X$ [71, 72]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)	
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$ [67, 73, 74, 75, 76]	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$		$\frac{\Delta G}{G} \times \frac{\Delta q}{q}$
$\vec{p}\vec{p} \to DX, BX$ [77]	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg		$\frac{\Delta q}{q} \times \frac{\Delta \bar{q}}{\bar{q}}$

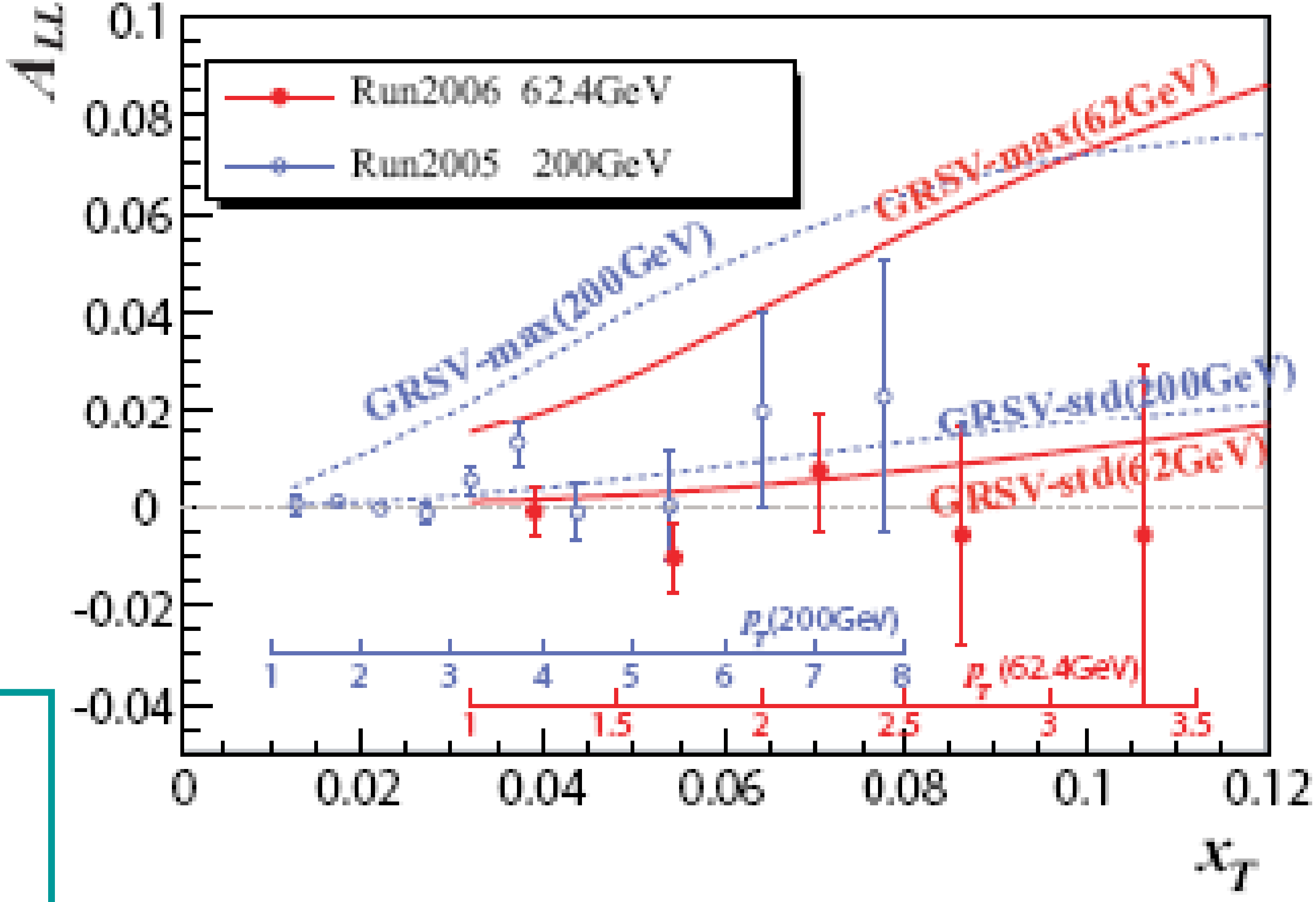
- Reactions pp -> pX, jet X, gX, $c\bar{c}$ X, probe gluon
- Measure product of 2 observables

Parton scattering : ab→cd

$$\hat{a}_{LL} = \frac{|M_{++}|^2 - |M_{+-}|^2}{|M_{++}|^2 + |M_{+-}|^2}$$



RHIC: PHENIX A_{LL} ($pp \rightarrow \pi^o X$)



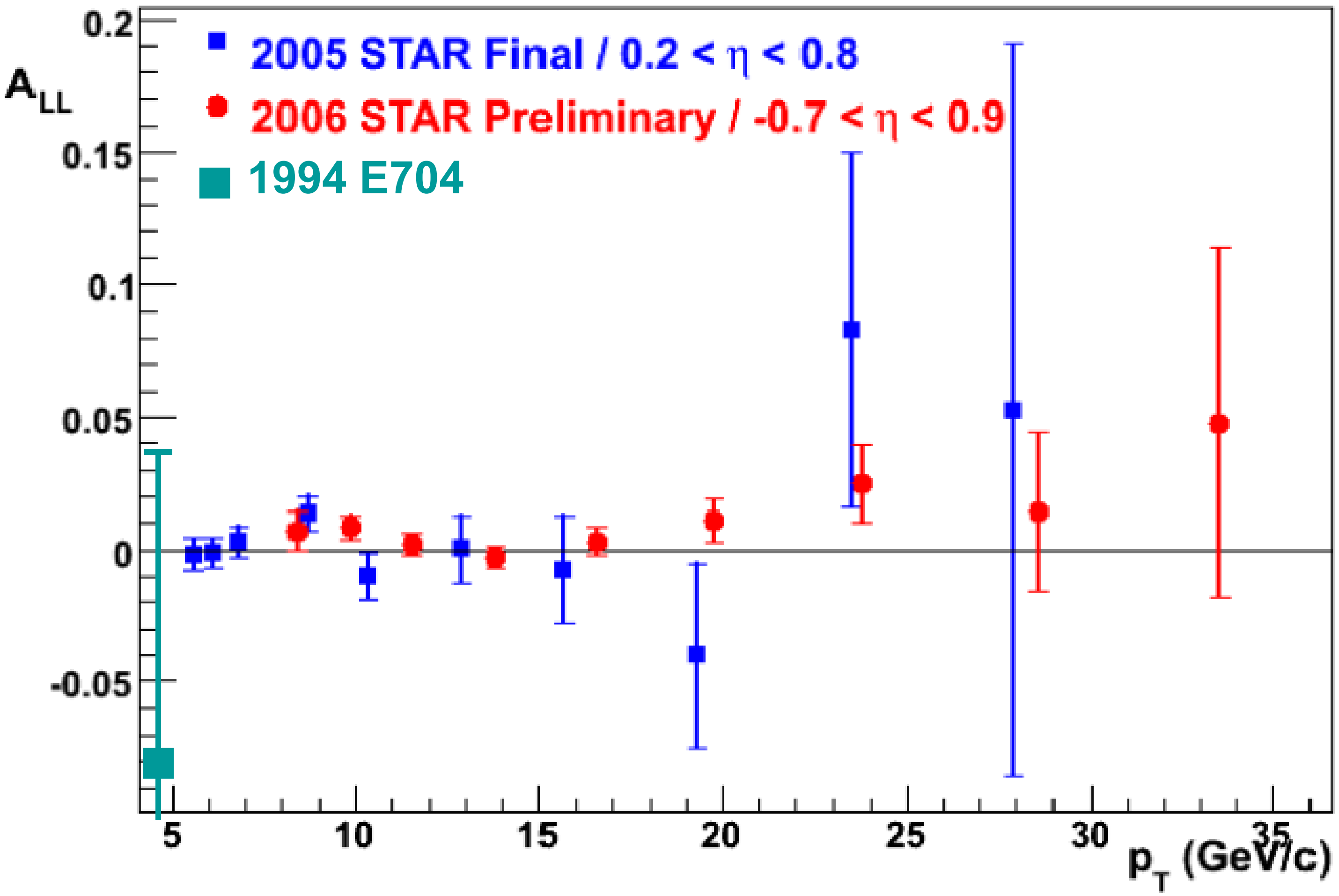
Gluck

Reja

Stratmann

Vogelsong

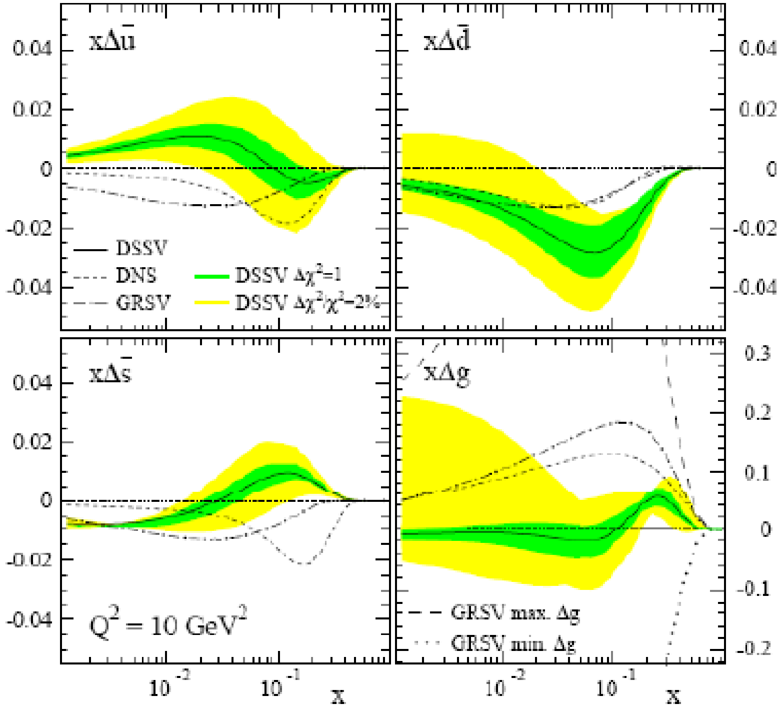
RHIC: STAR A_{LL} ($pp \to$ jet X)



(■ this point represents earlier data from E704 on ***" multiphoton"*** events)

Results DSSV global analysis

- pattern of flavor - **asymmetric** light quark-sea (even within uncertainties)
- small Δg, perhaps changing sign
- Δs positive at large x
- Δu + Δū and Δd + Δd̄ very similar to GRSV/DNS results

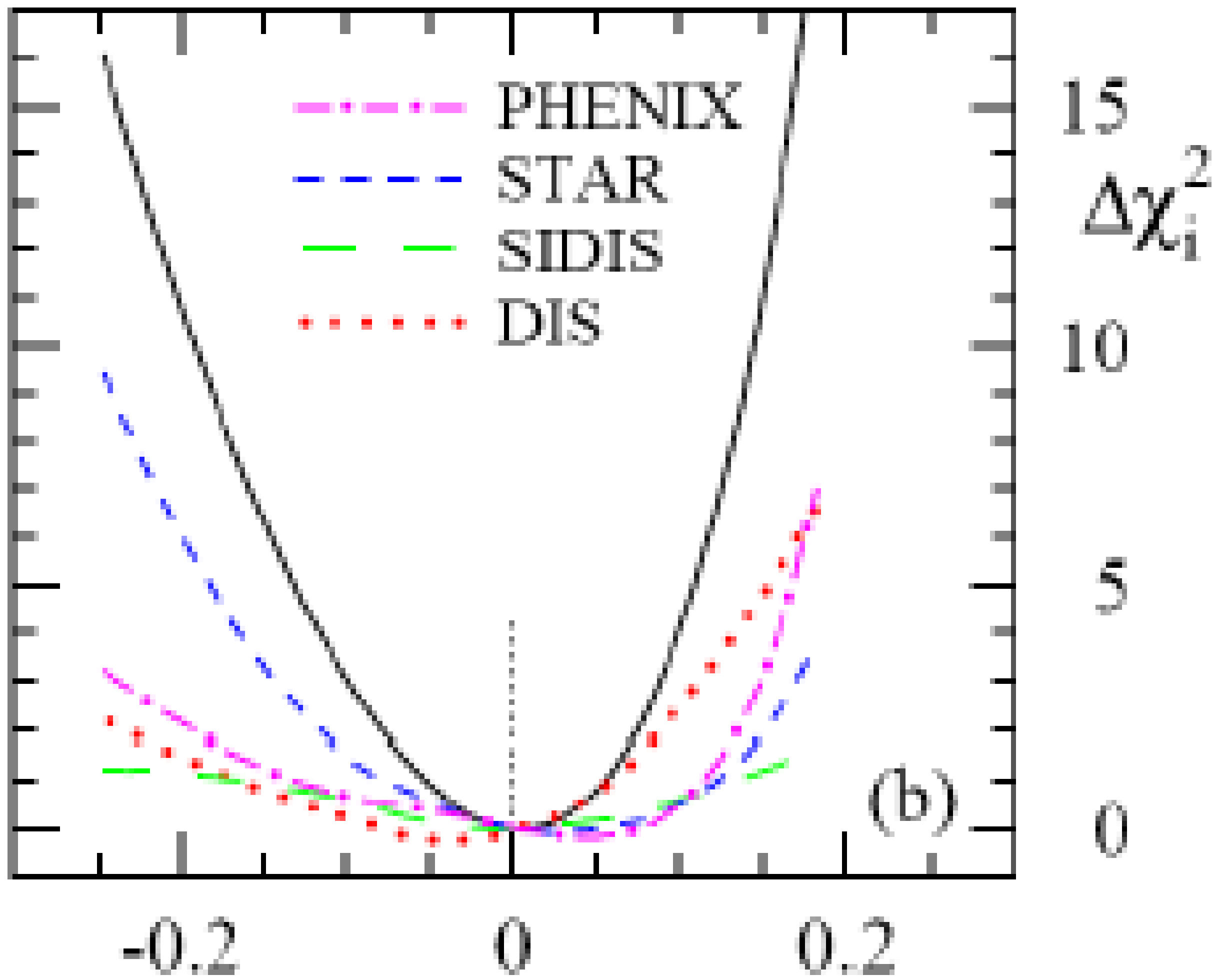


Δs: receives a large negative contribution at small x

Δg: huge uncertainty below 0.01; 1stmoment not well determined

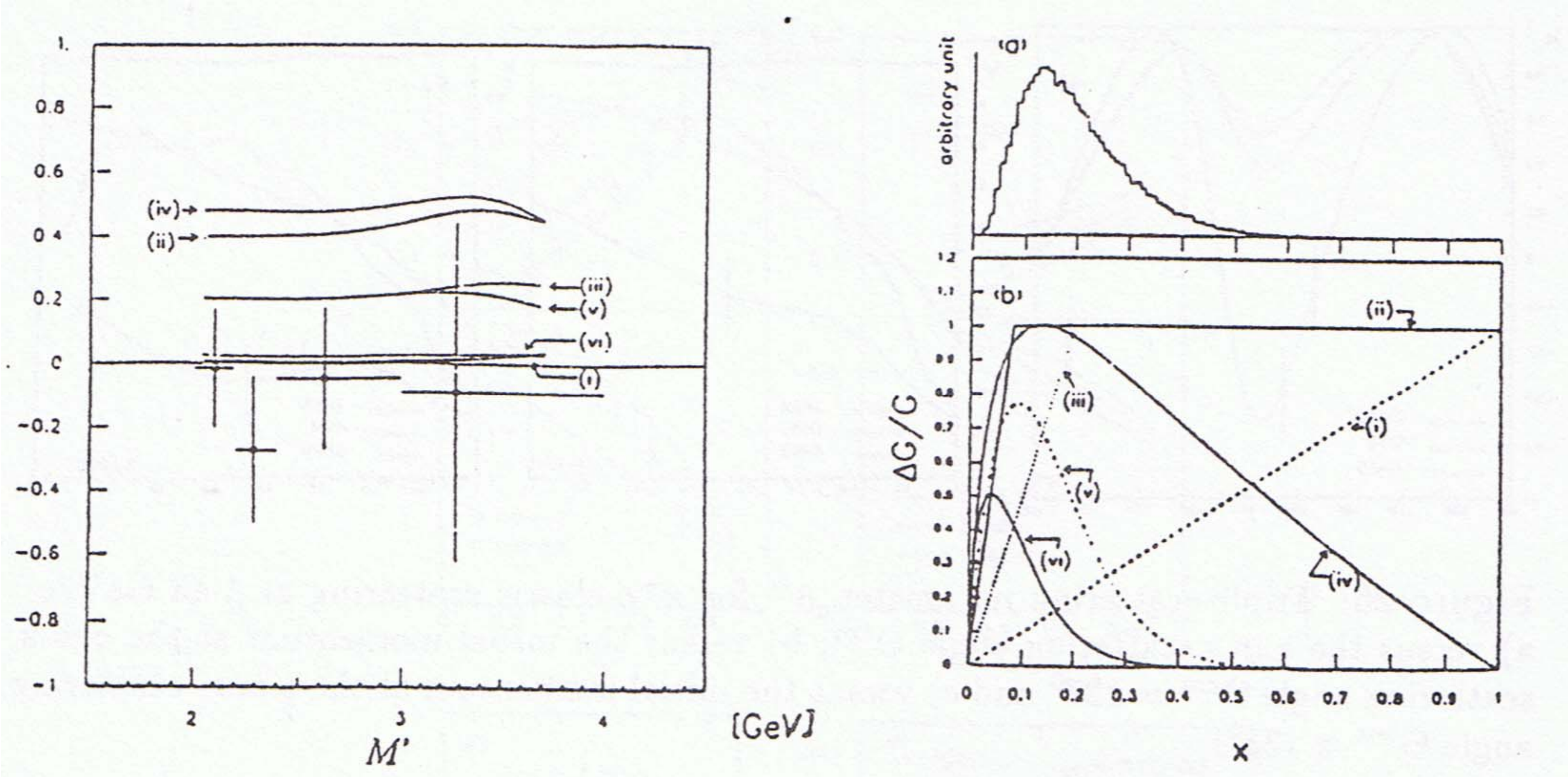
	$x_{min} = 0$ best fit	$x_{min} = 0.001$ $\Delta\chi^2 = 1$	$x_{min} = 0.001$ $\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793\ ^{+0.011}_{-0.012}$	$0.793\ ^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	-0.458	$-0.416\ ^{+0.011}_{-0.009}$	$-0.416\ ^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028\ ^{+0.021}_{-0.020}$	$0.028\ ^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-0.115	$-0.089\ ^{+0.029}_{-0.029}$	$-0.089\ ^{+0.090}_{-0.080}$
$\Delta\bar{s}$	-0.057	$-0.006\ ^{+0.010}_{-0.012}$	$-0.006\ ^{+0.028}_{-0.031}$
Δg	-0.084	$0.013\ ^{+0.106}_{0.120}$	$0.013\ ^{+0.702}_{0.314}$
$\Delta\Sigma$	0.242	$0.366\ ^{+0.015}_{-0.018}$	$0.366\ ^{+0.042}_{-0.062}$

χ^2 comparison of different methods



$$\delta g \equiv \int_{0.05}^{0.2} \Delta g(x, 10\,\mathrm{GeV}^2)\,dx$$

FNAL-E704: early hint of ΔG/G → 0



- Adams et al (1991) PL 261B, 197 (pp → π°X)
- Adams et al (1994) PL 336B, 269 (pp → multi-γ X)