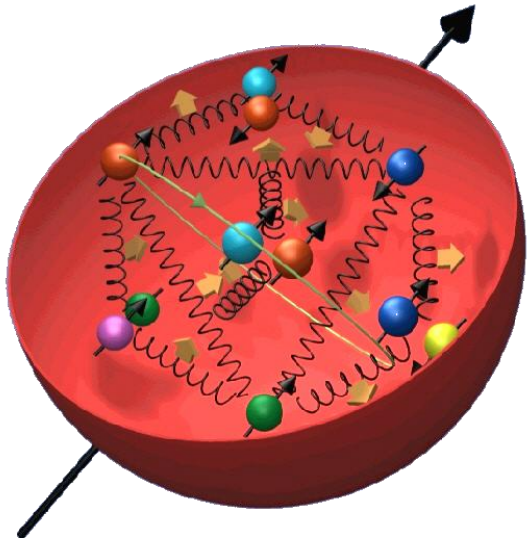
The Nucleon Spin Structure



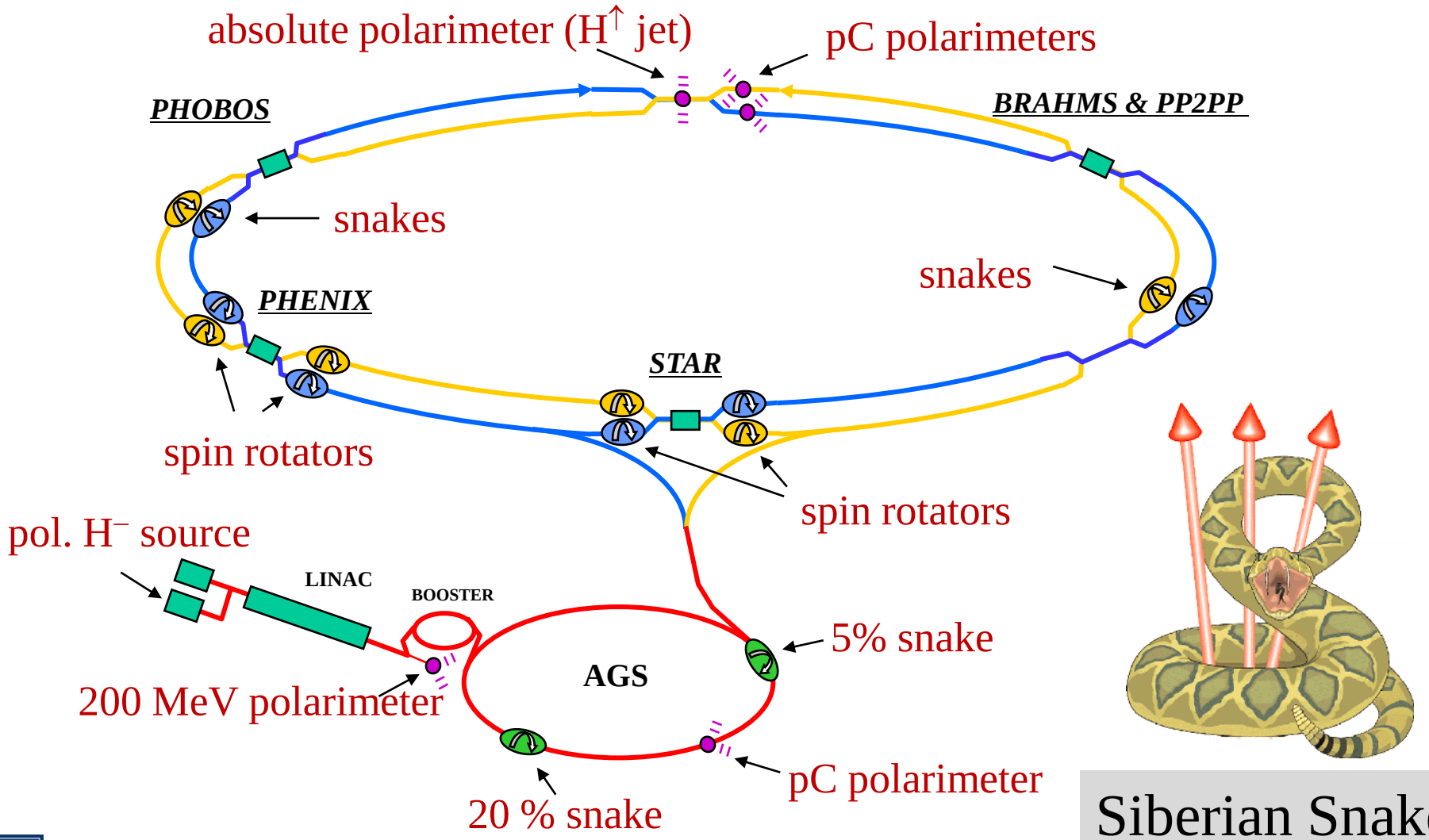
Gerhard Mallot

Lecture 3

- Experimental status
  - RHIC pp data
  - transverse asymmetries
- Excursion: pion polarisability

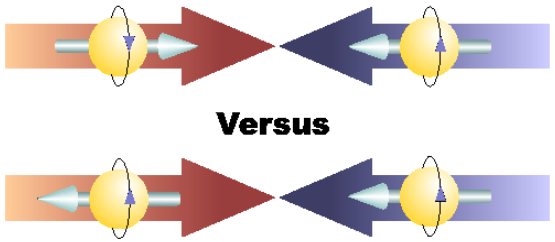
RHIC $\vec{p}\vec{p}$

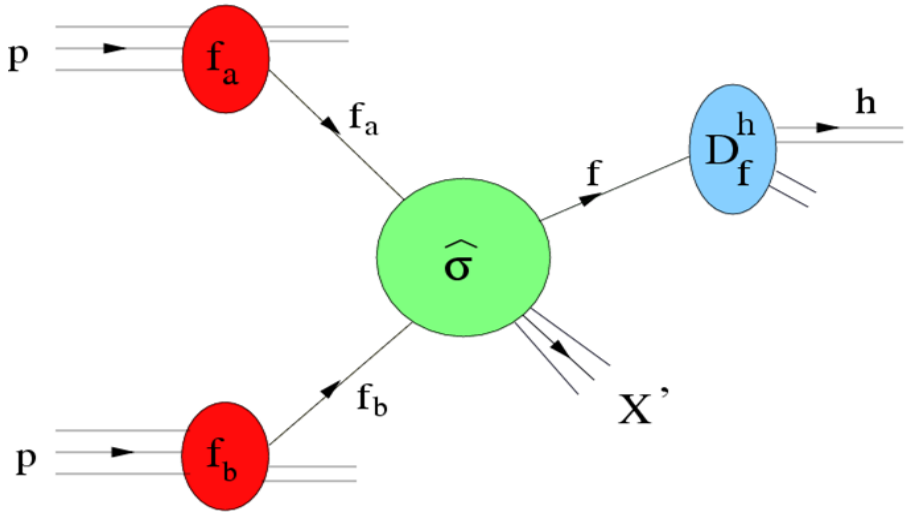
RHIC polarised $\vec{p}\vec{p}$ Collider



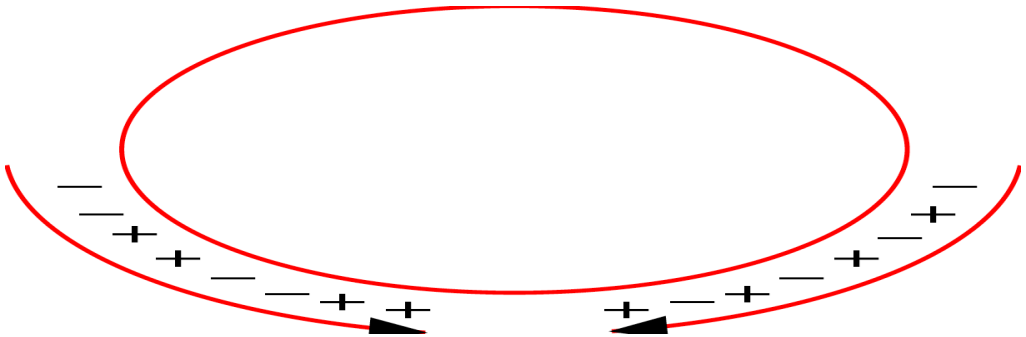
Siberian Snake

$\vec{p}\vec{p}$ collisions





polarisation ~ 45 % in 2005
~ 60 % in 2006

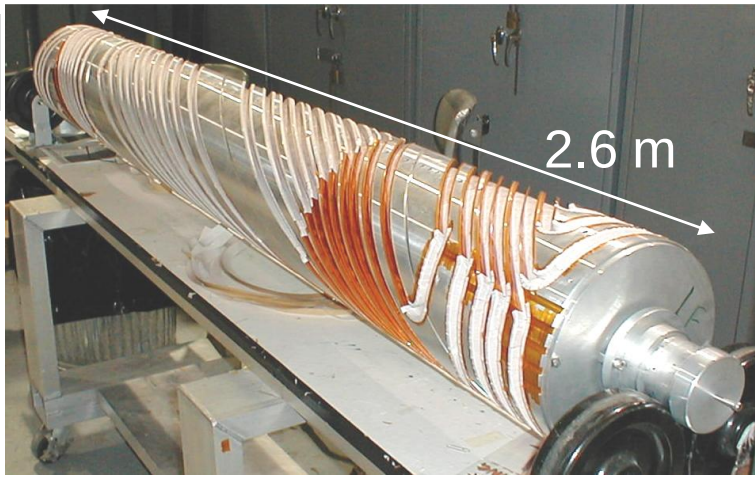


$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

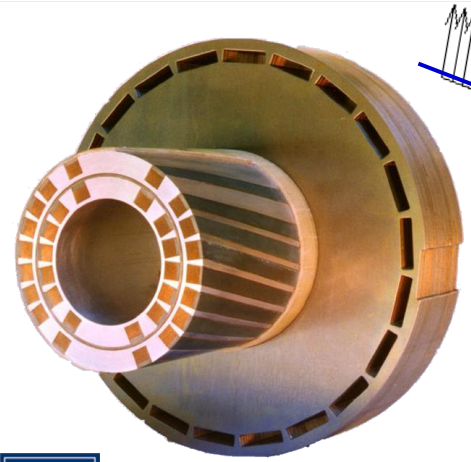
Siberian Snakes (helical dipoles)

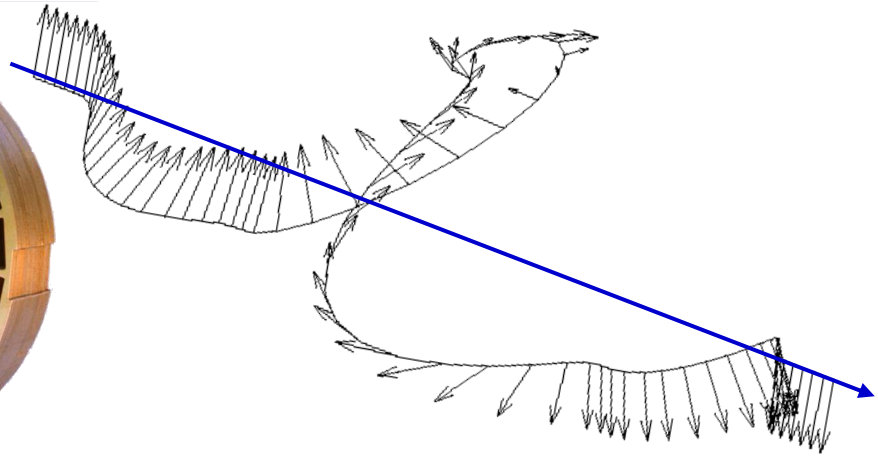
from Th. Roser

AGS partial snakes, 1.5T (RT) & 3T(SC)

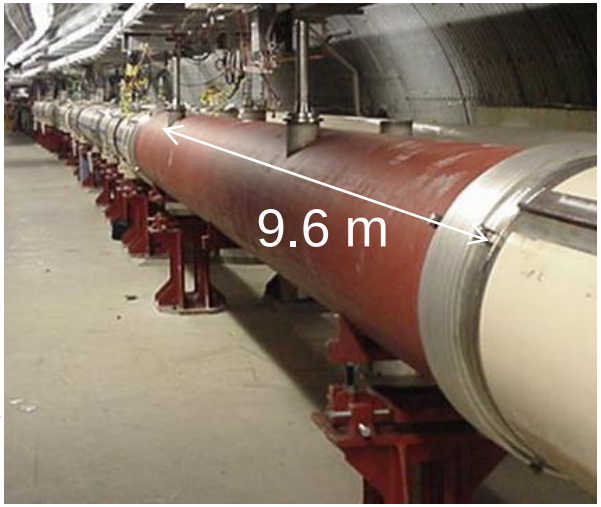


RHIC full Siberian Snakes: 4 x 4 T (SC), each 2.4





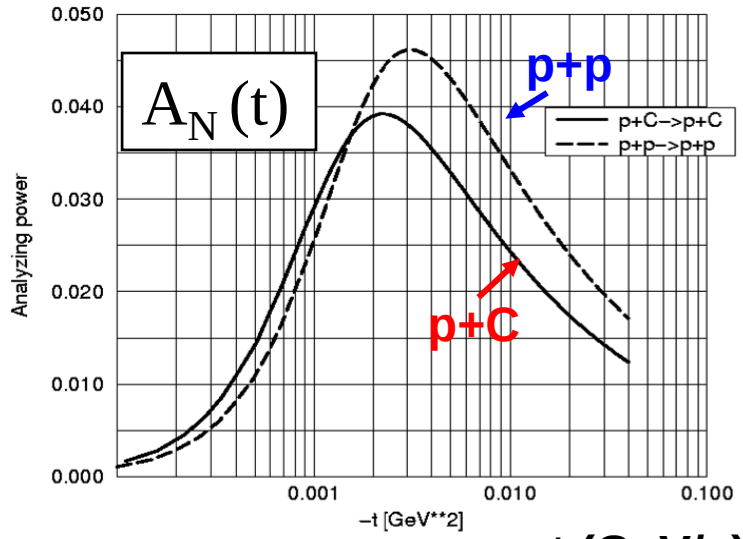
w/o: 1000 depolarising resonances



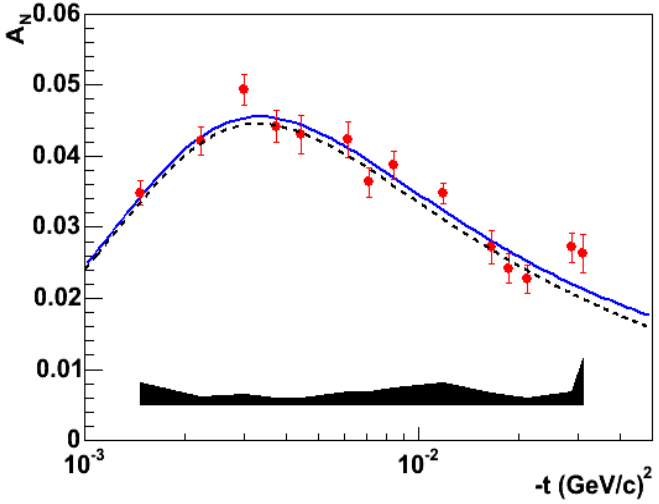
Polarimetry

- left-right asymmetry A_N in elastic $p^{\uparrow}p$ and $p^{\uparrow}C$ scattering
- interference of em and nuclear spin-flip amplitude, Coulomb−Nuclear Interference (CNI), up to 4.5 %
- self calibration with polarised H jet target

Calculation



pp measurement

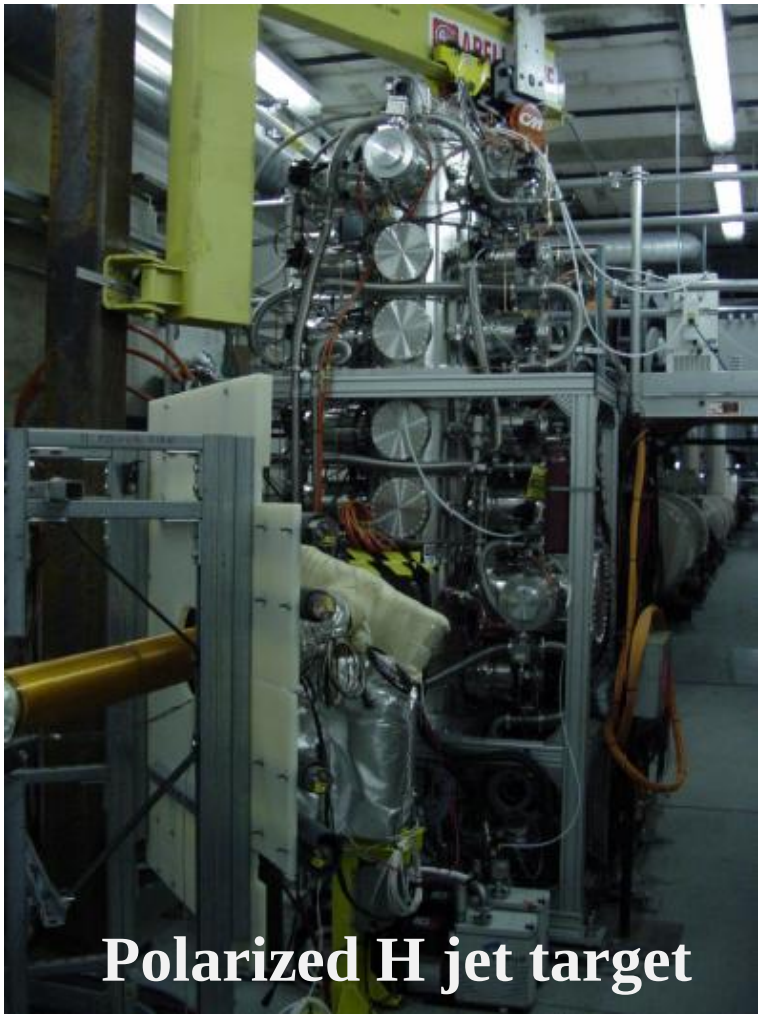


-t (GeV/c) ^{2}

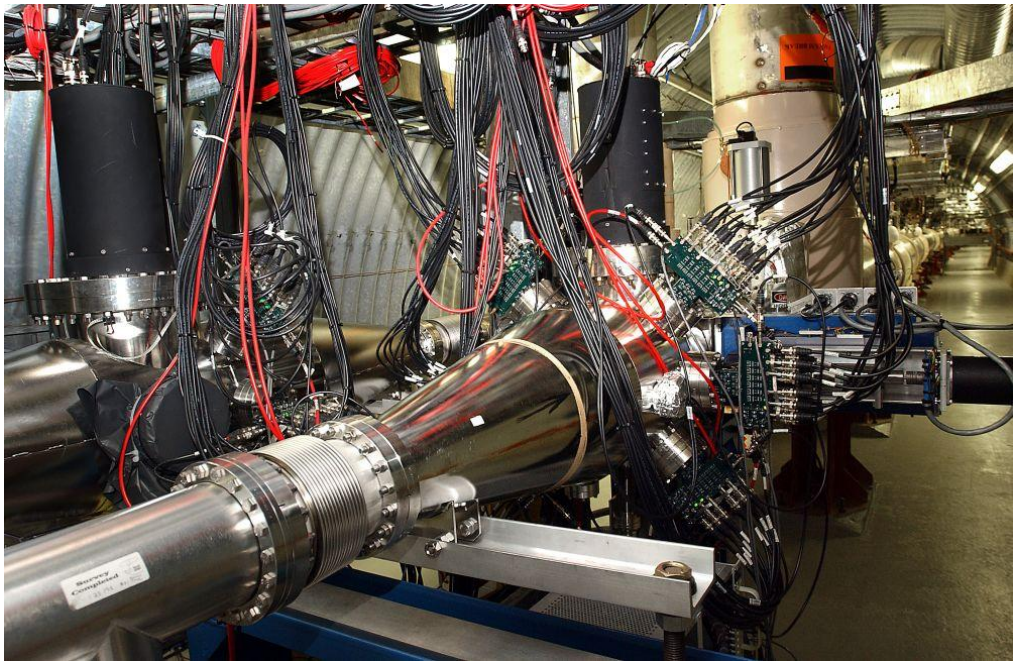
H. Okada et al., PLB 638 (2006), 450

RHIC polarimeters

from G. Bunce

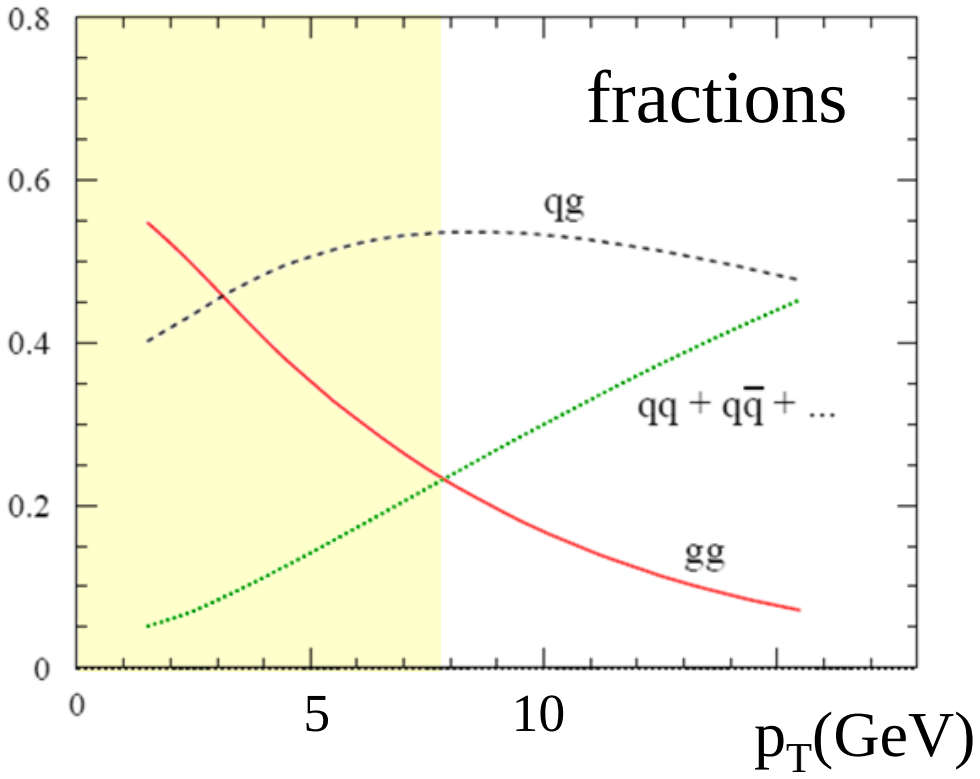


Carbon target polarimeters
3μm carbon ribbon
every 2h, Δp/p < 5%
calibration with H-jet target



qg - qq - gg processes

100+100 GeV ‖ 250+250 GeV upgrade



present energy:
100 on 100 GeV

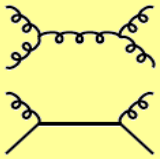
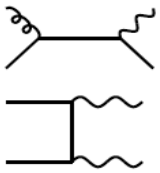
gg processes dominate

$\propto \Delta g^2$

sign ambiguity

pp: NLO Calculations

In better shape than semi-inclusive DIS:

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

Jäger,Schäfer, Stratmann, Vogelsang; de Florian

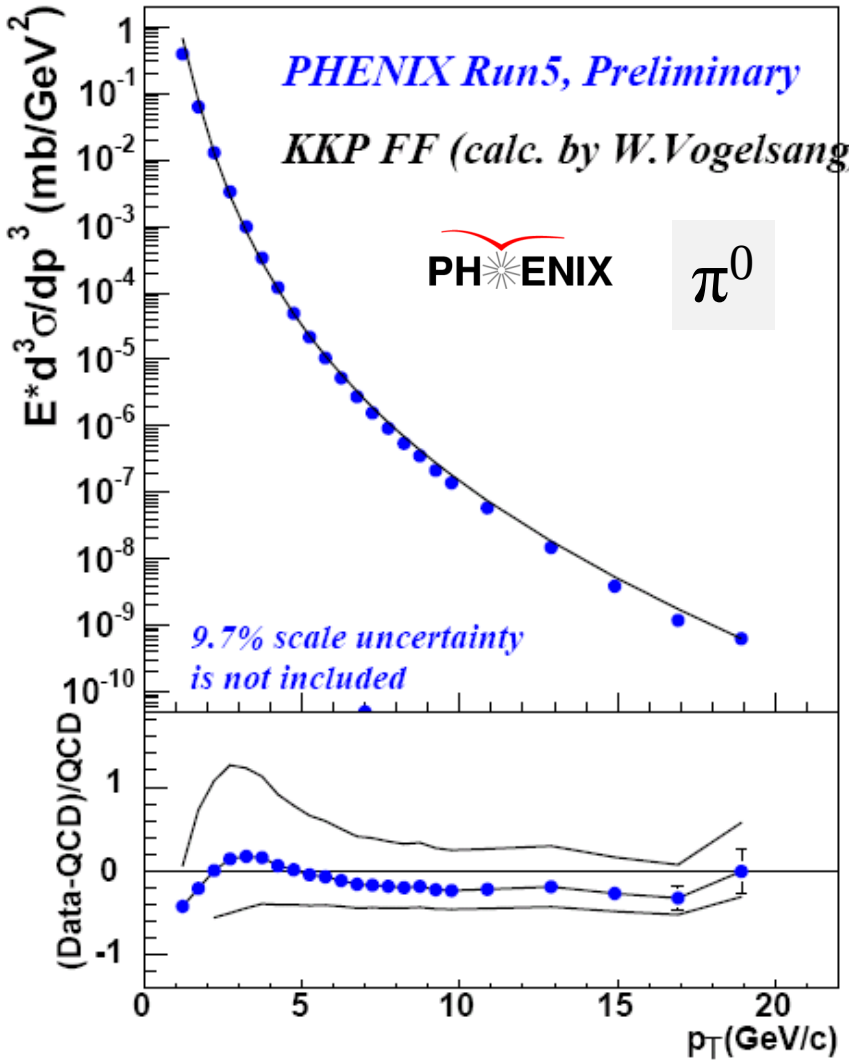
Jäger,Stratmann, Vogelsang; Signer et al.

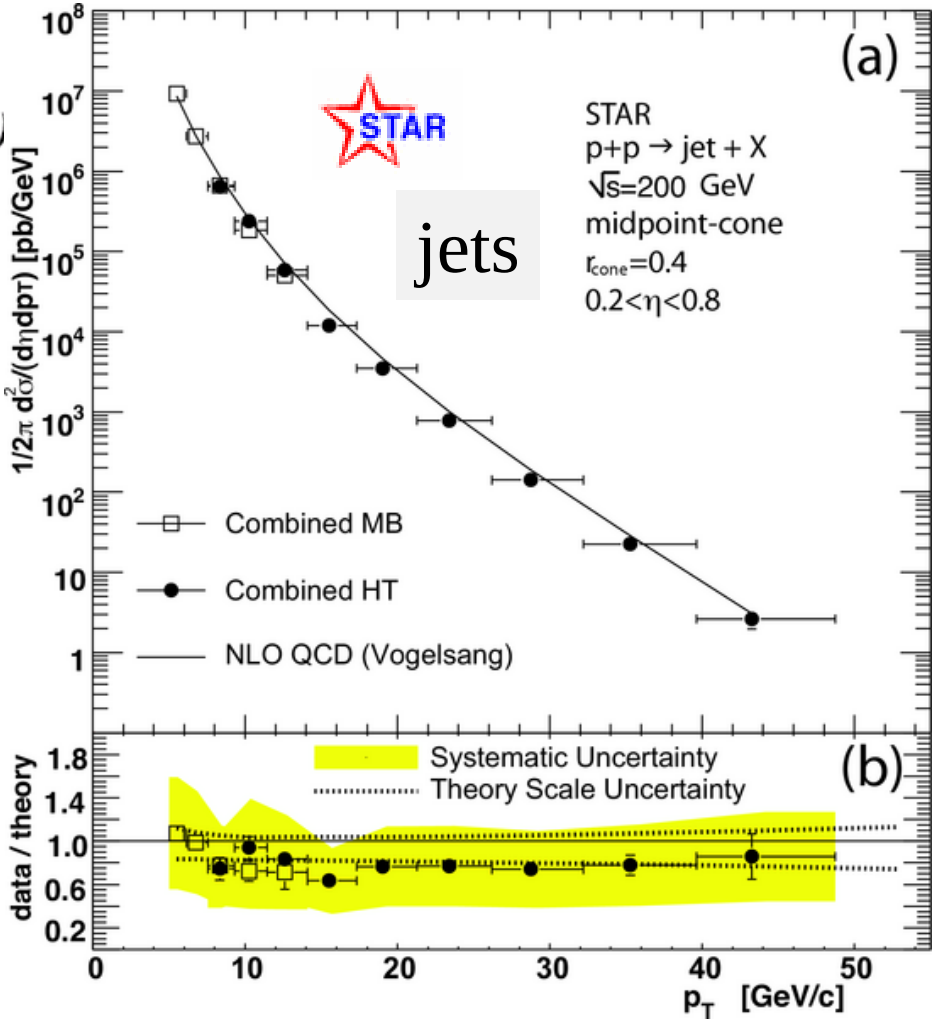
Gordon,Vogelsang; Contogouris et al.; Gordon, Coriano

Bojak, Stratmann

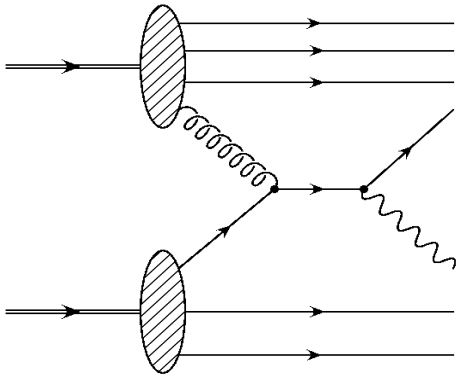
Summary by Stratmann, DIS2006

NLO vs data (unpol)

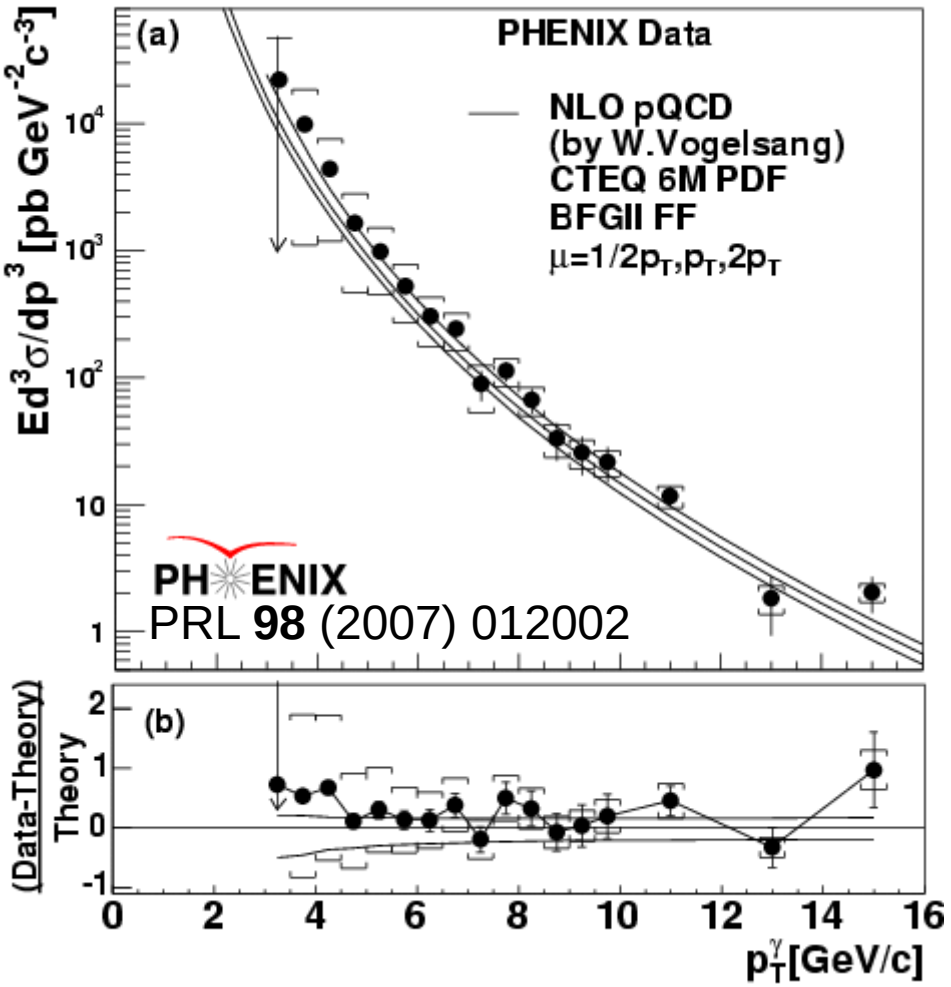




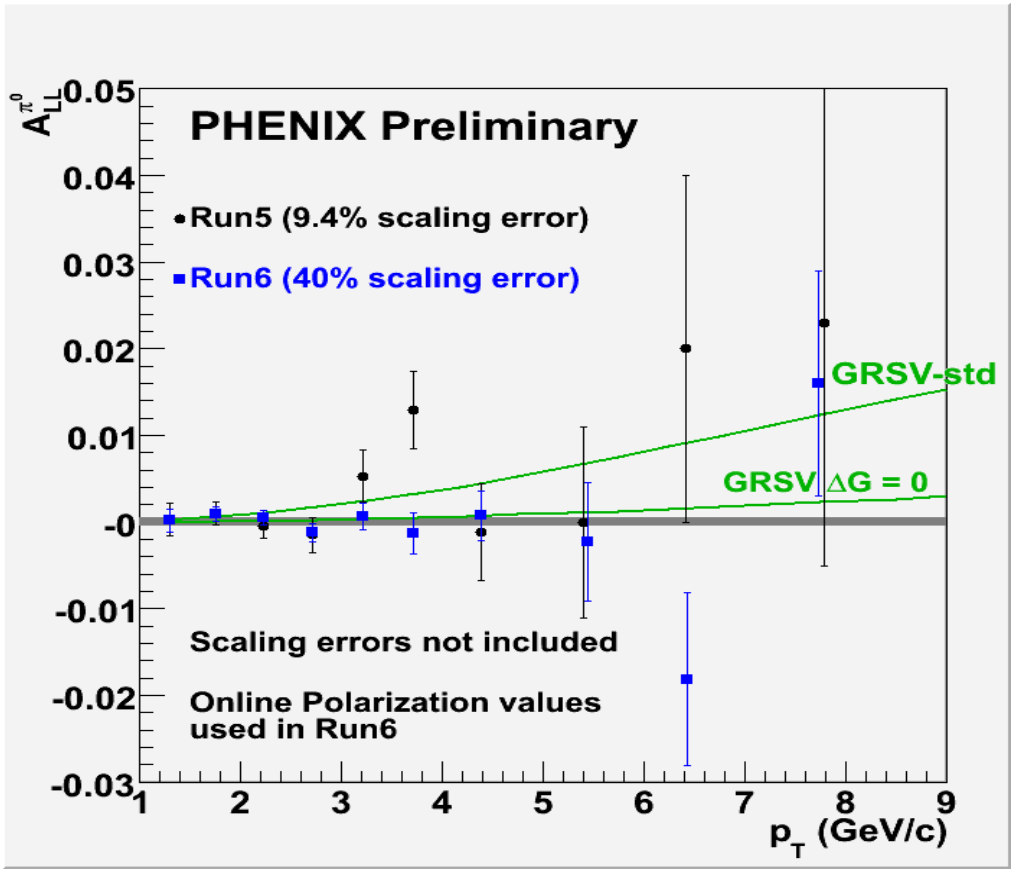
Direct photons

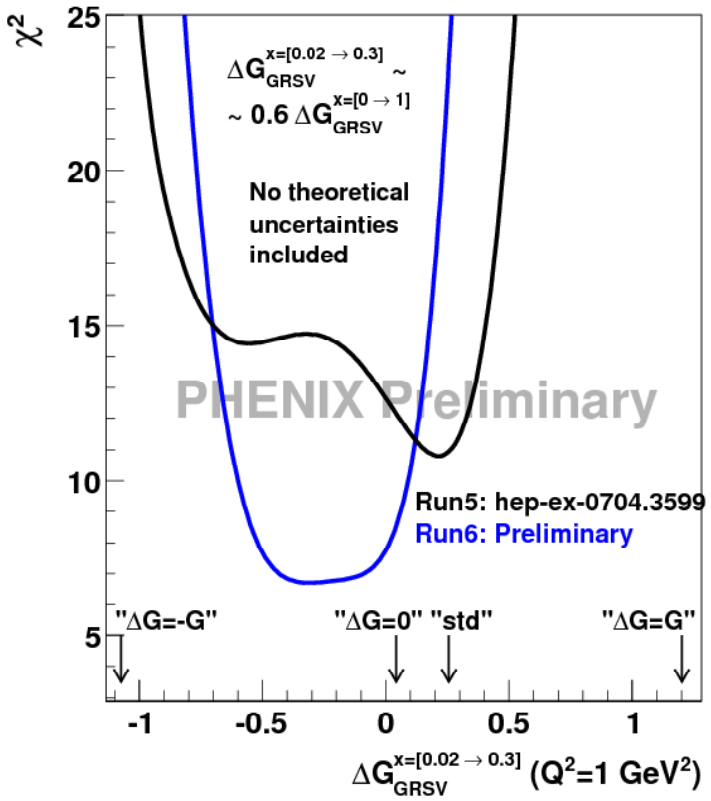


- good agreement of calc. and data at collider energies



Phenix π^0 asymmetries





STAR jet asymmetries

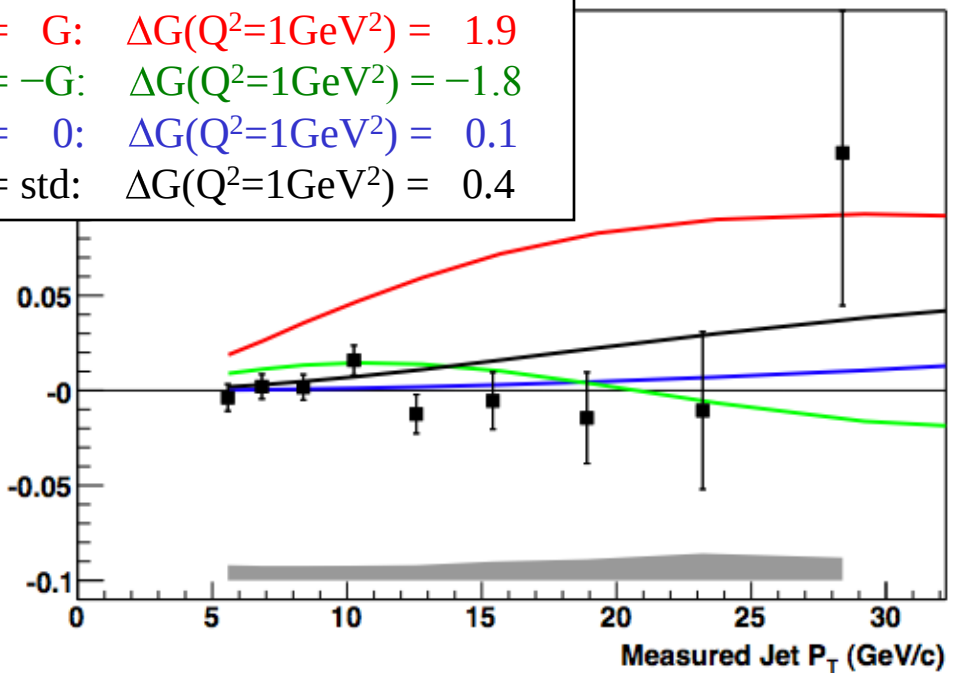
GRSV Models:

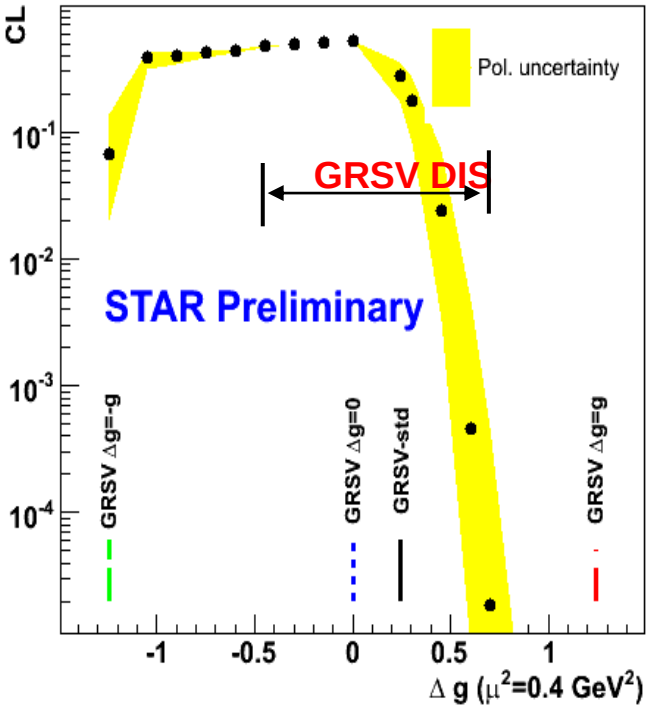
$\Delta G = G$: $\Delta G(Q^2=1\text{GeV}^2) = 1.9$

$\Delta G = -G$: $\Delta G(Q^2=1\text{GeV}^2) = -1.8$

$\Delta G = 0$: $\Delta G(Q^2=1\text{GeV}^2) = 0.1$

$\Delta G = \text{std}$: $\Delta G(Q^2=1\text{GeV}^2) = 0.4$

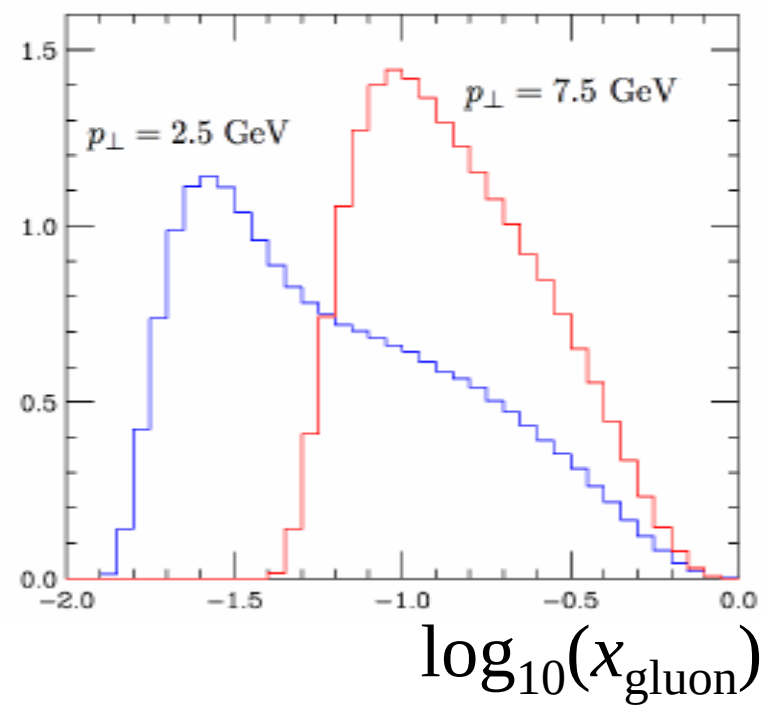




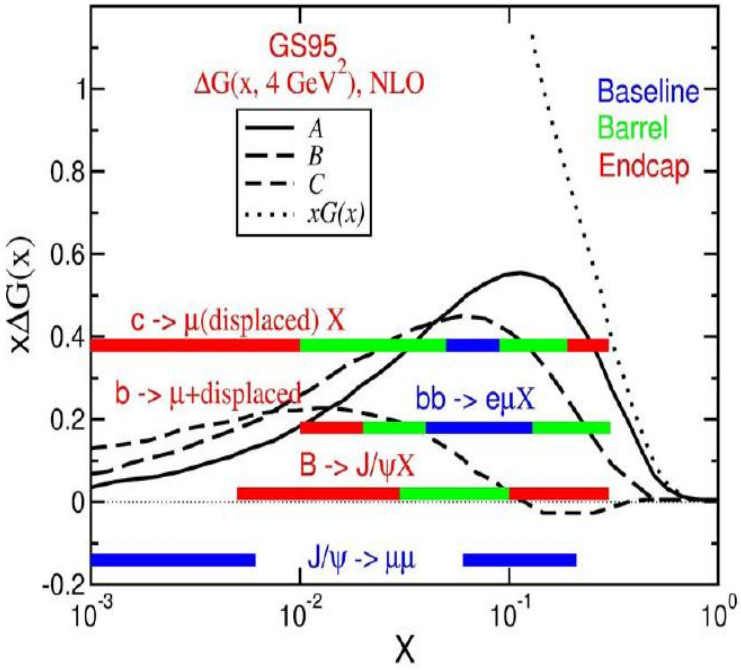
- Phenix/Star χ^2-tests for fixed GRSV shape, not (yet) conclusive for ΔG; no refit of the PDF parameters

Probed x-Bjorken range

π^0 production

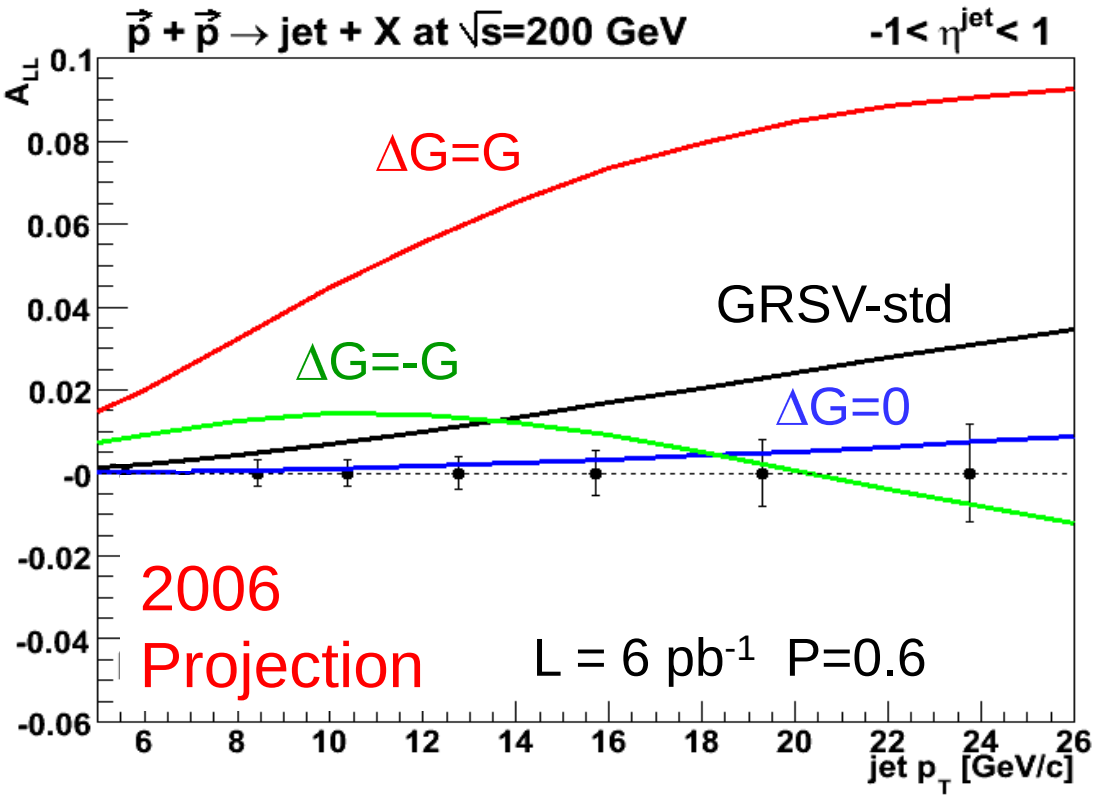


detector upgrades (Phenix)



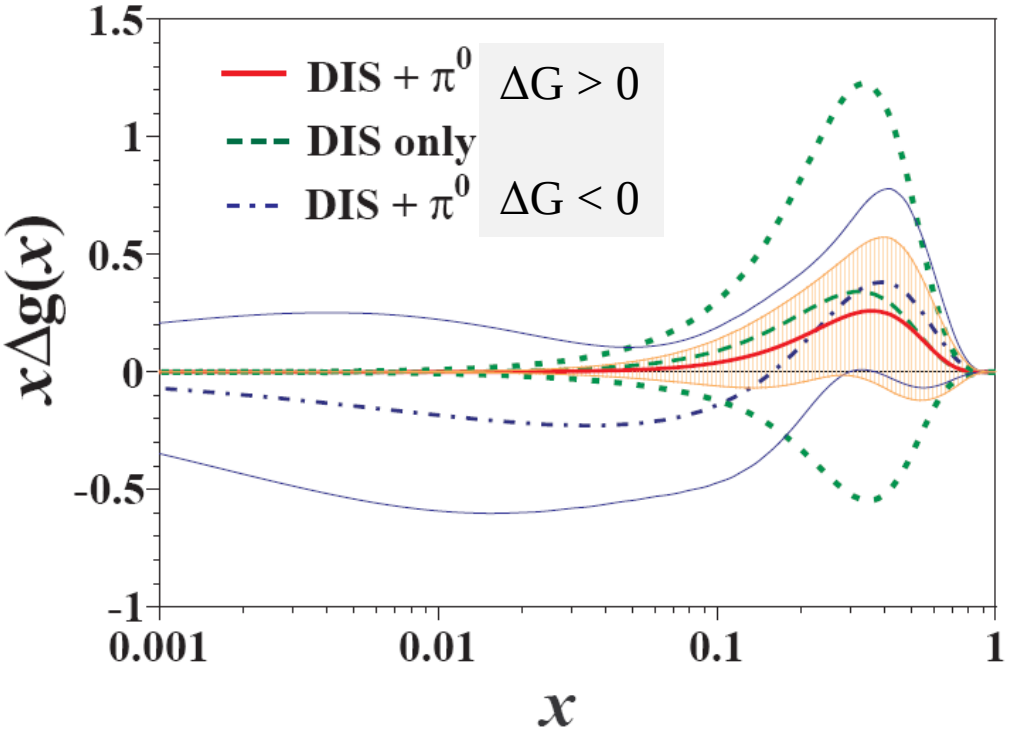
STAR jet asymmetries 2006

projected precision!



Global analysis

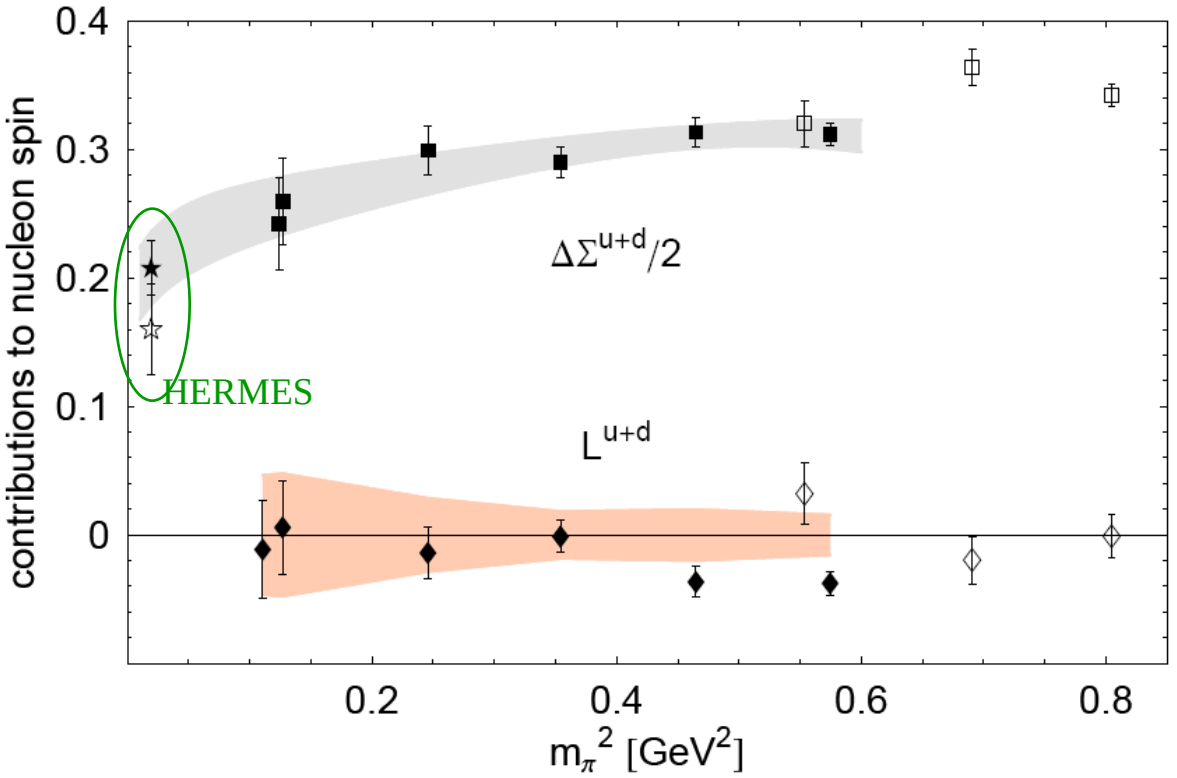
- need global analysis of all data relevant for Δg:
  DIS, hadron pairs, charm, pp π and jets (direct γ, …)
- first attempt AAC2006



Lattice results

$\Delta\Sigma^{\text{lat}}_{u+d} = 0.50(5)$ @ $m_\pi \approx 350$ MeV; $L_u + L_d \approx 0$

chiral extrapolation to physical pion mass m_π

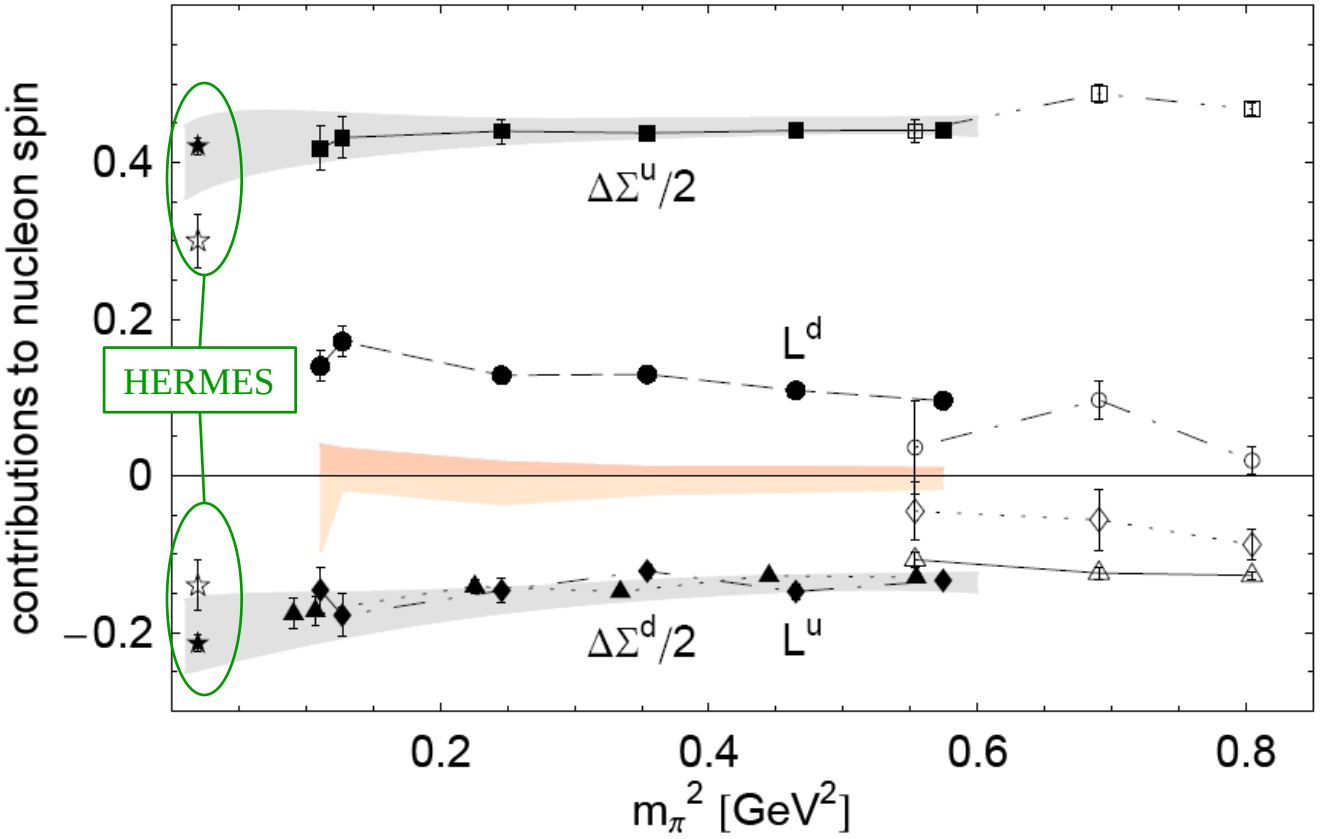


Ph. Hägler et al., LHPC/MILC **arXiv:0705.4295** [hep-lat]

Lattice results

extrapolated to phys. m_π :

$$J_q^u \approx 0.22 \pm 0.02, \quad J_q^d \approx 0 \pm 0.02$$
$$L^u \approx 0.2, \quad L^d \approx -0.2$$

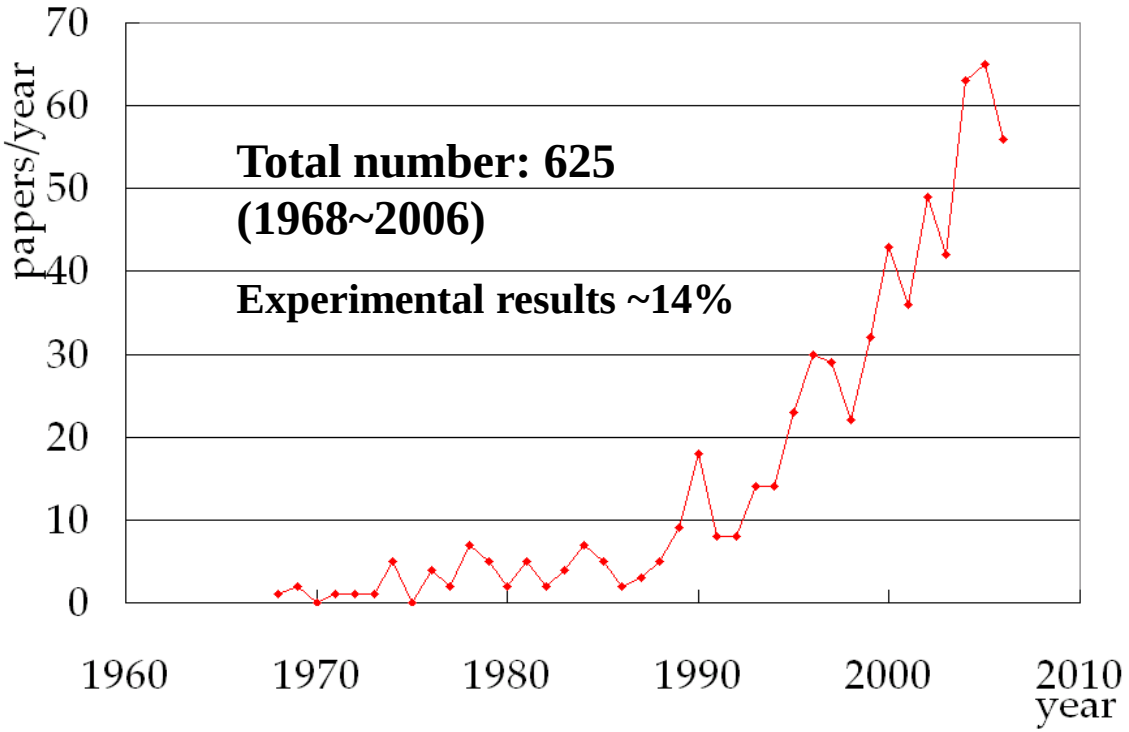


Ph. Hägler et al., LHPC/MILC **arXiv:0705.4295** [hep-lat]

Transverse spin effects

SPIRES-HEP: search title including:
"Transverse spin, Transversity, single spin"

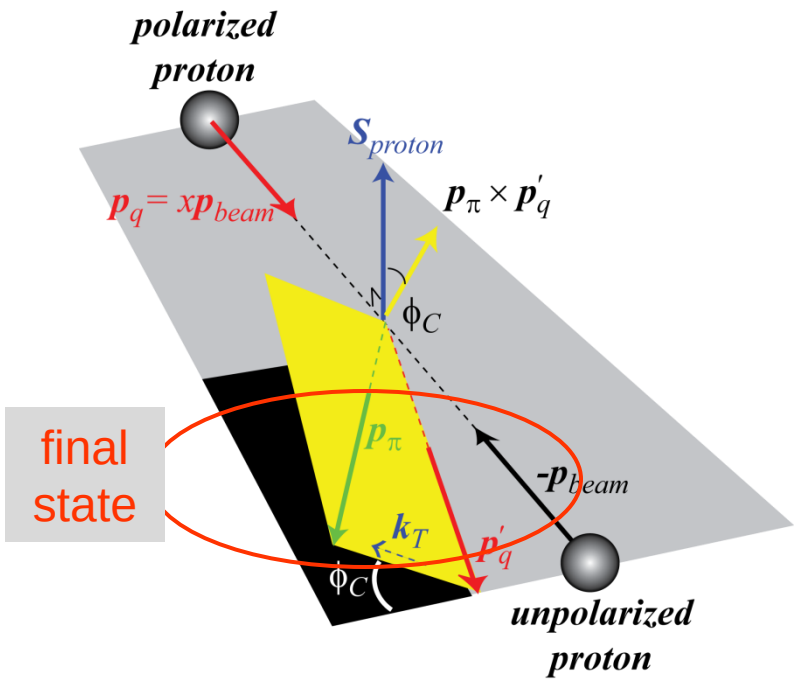
from L. Bland



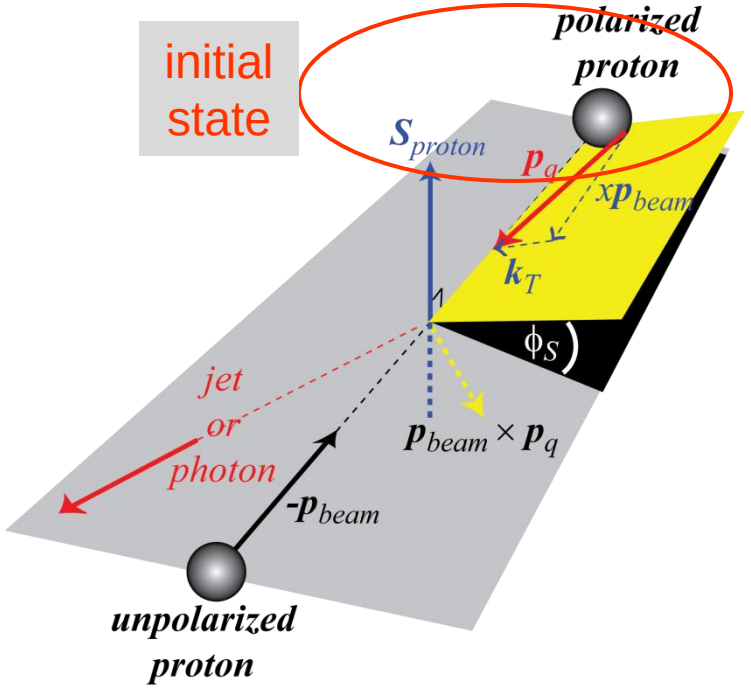
Origin of single-spin asymmetries

from L. Bland

Collins/Heppelmann mechanism requires *transverse quark polarization* and *spin-dependent fragmentation*



Sivers mechanism requires *spin-correlated transverse momentum* k_T in the proton (orbital motion).

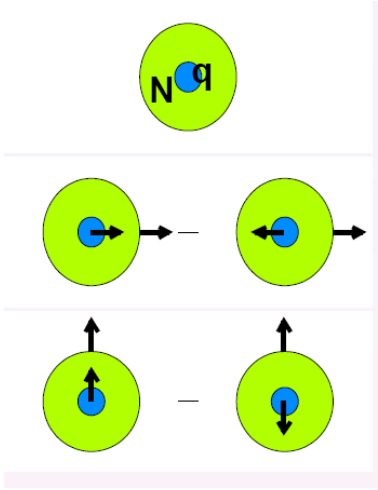


Transversity

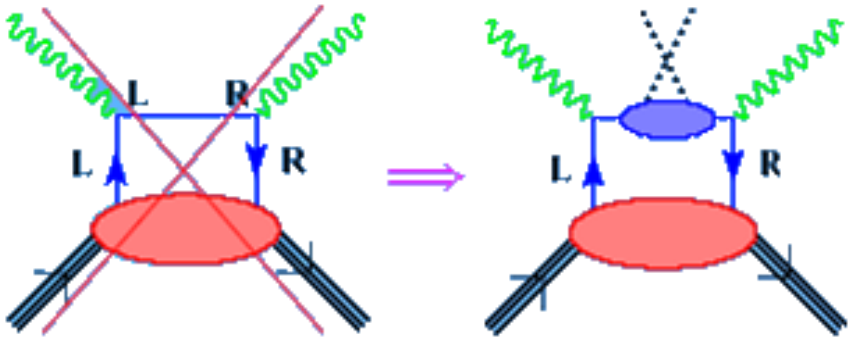
q, g momentum

$\Delta q, \Delta g$ helicity

$\Delta_T q$ transversity (alias h_1)



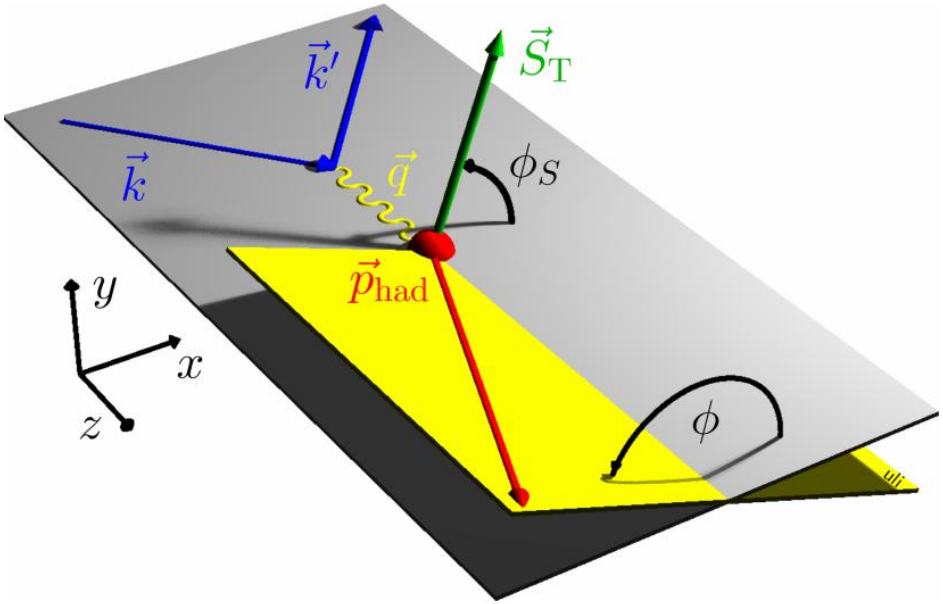
- 3 fundamental twist-2 PDFs, new transversity $\Delta_T q(x)$
- non-relativisic $\Delta_T q = g_1$
- chiral-odd PDF → not seen in DIS
- semi-inclusive DIS allowed if coupled to a chiral-odd FF
- Soffer bound: $2|\Delta_T q| \leq q + \Delta q$



Transversity

single-spin asymmetry:

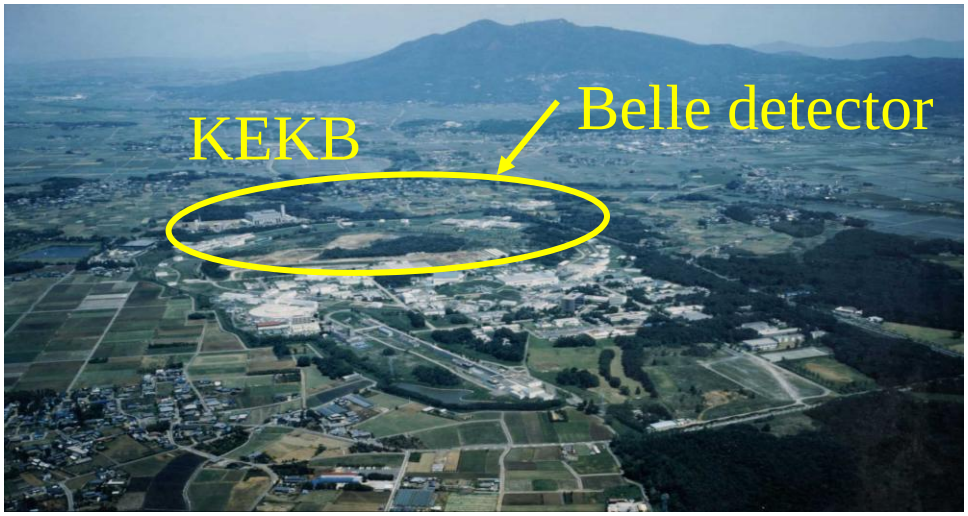
$$A_T^h = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \propto \frac{\Sigma_q e_q^2 \Delta_T q(x) \Delta_T^0 D_q^h(z)}{\Sigma_q e_q^2 q(x) D_q^h(z)} \sin(\Phi_S + \Phi)$$



Chiral-odd Collins FF:

$$\Delta_T^0 D_q^h(z) \neq 0?$$

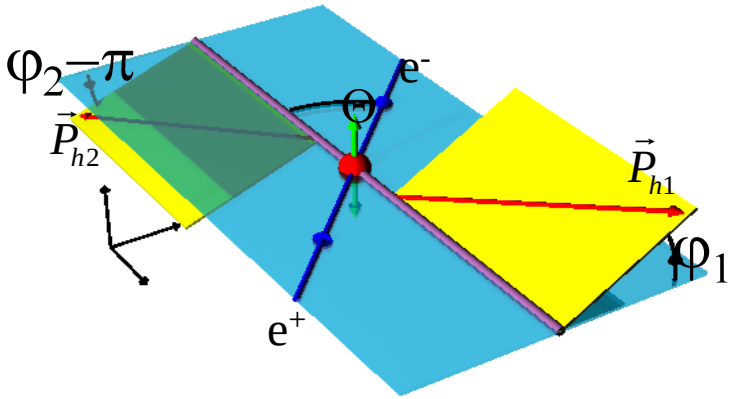
Fragmentation functions from

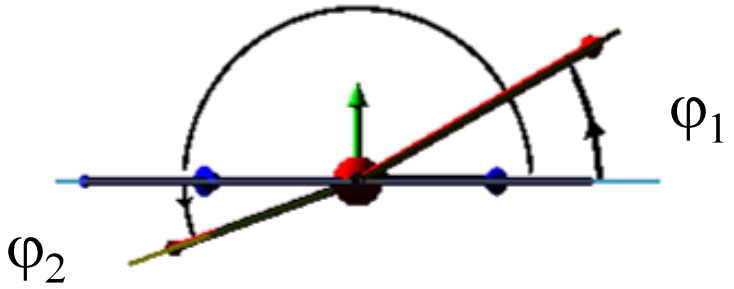


KEKB e^+e^- coll. 3.5+8 GeV

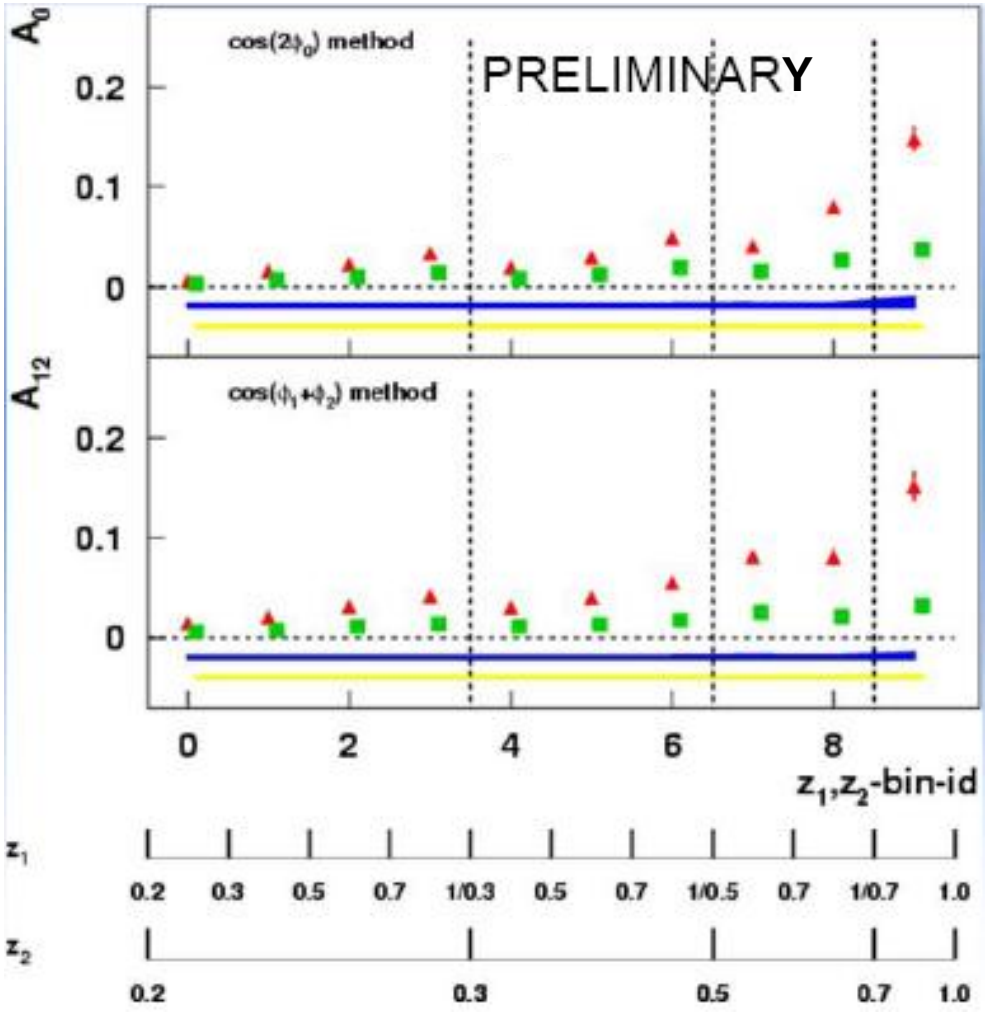
$L > 1.6 \times 10^{34} cm^{-2} s^{-1}$!

correlation of hadron azimuthal angles





Collins asymmetries from e^+e^-



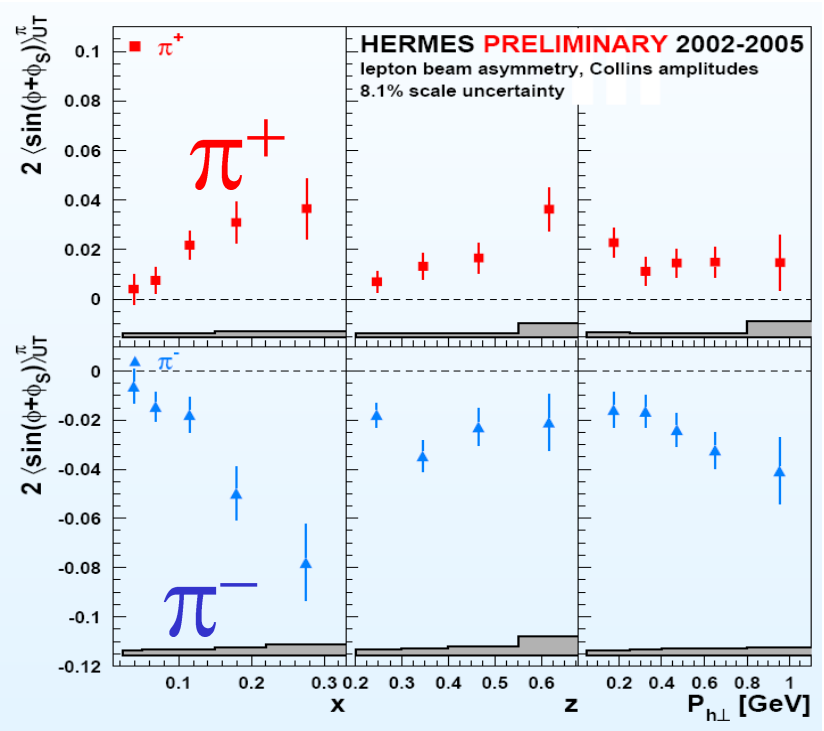
$e^+ e^- \rightarrow \pi\pi$ X (547 fb^{-1})

- first direct measurement of the Collins function
- rising with *z*
- UC unlike sign/all
- UL unlike sign/like sign
- different mix of favoured and unfavoured FF
- UC asymmetries about 40−50% of UL asymmetries

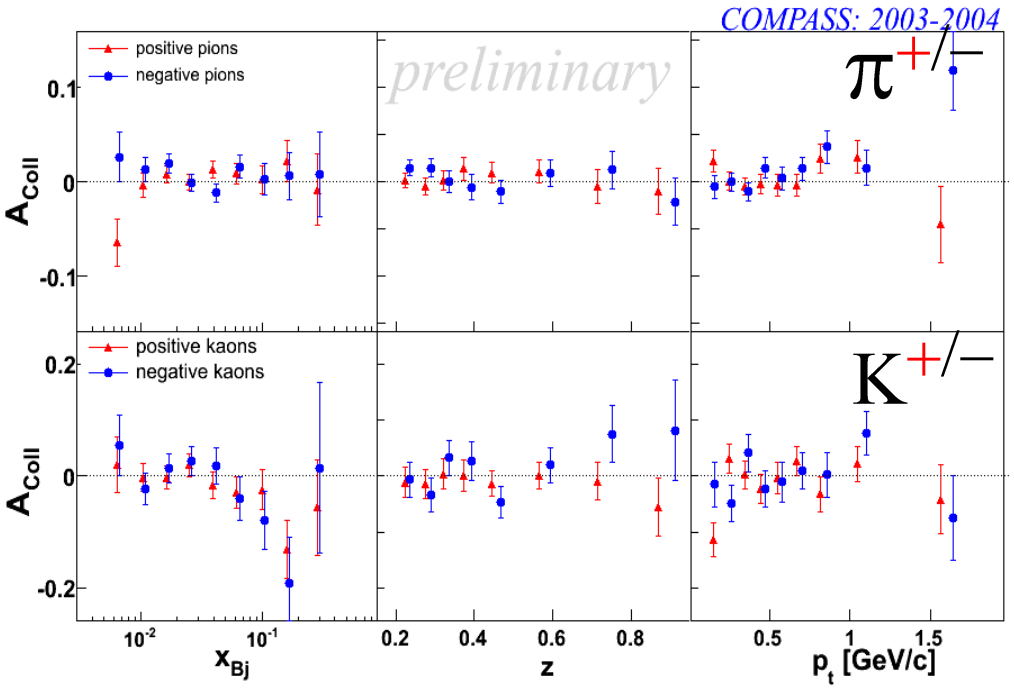
M. Grosse Perdekamp et al.

Collins asymmetries

Hermes: proton

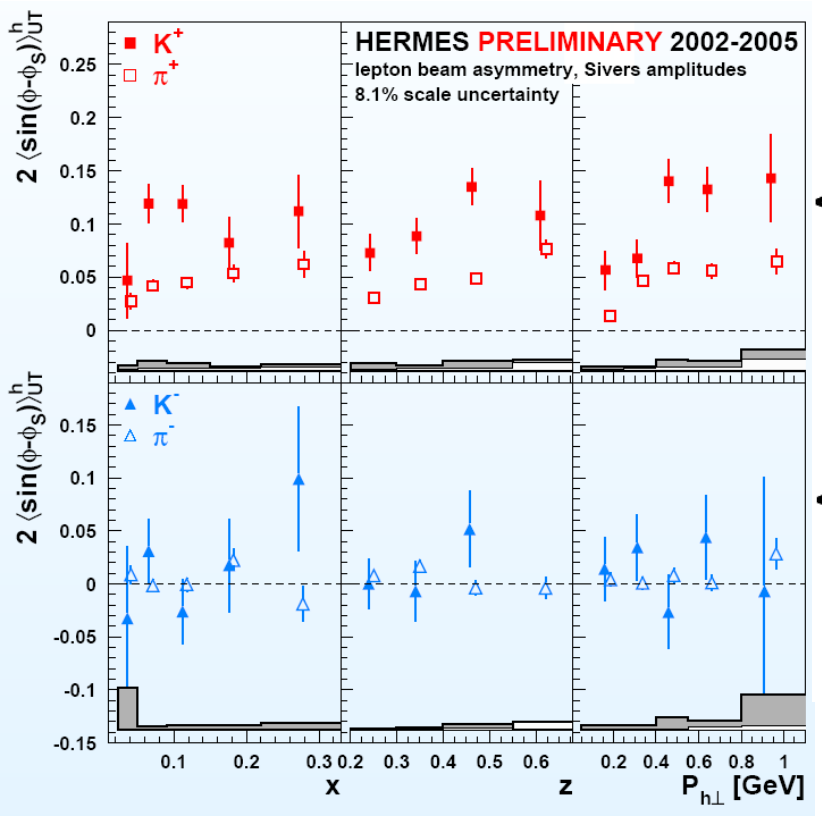


COMPASS: deuteron

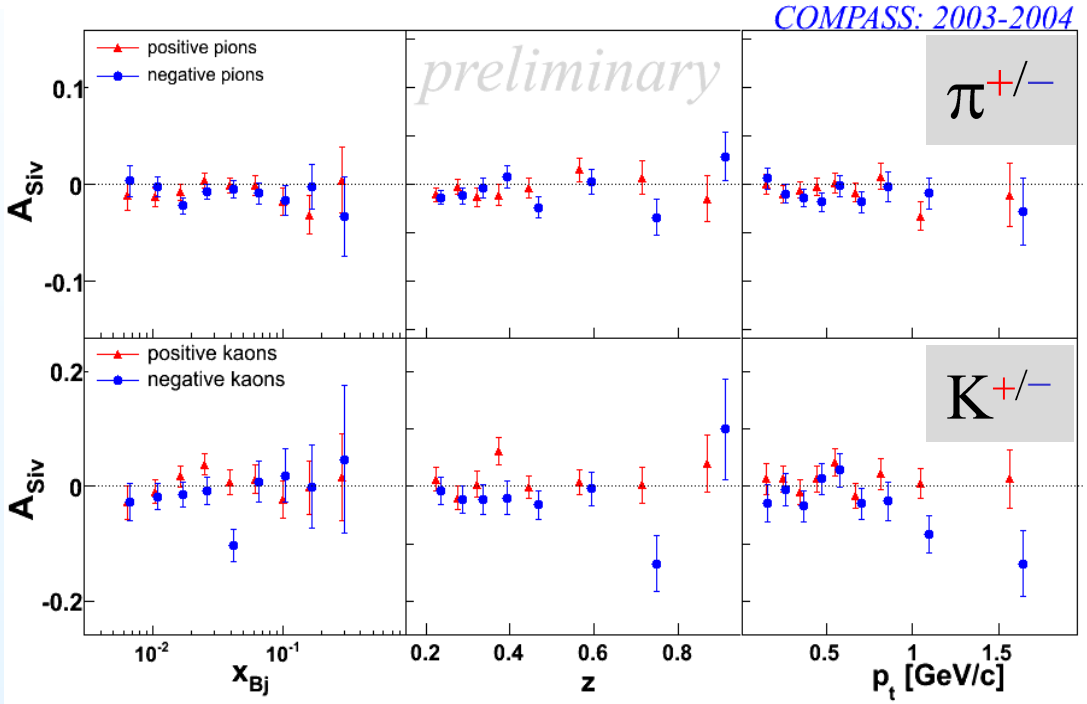


Sivers asymmetries

Hermes: proton

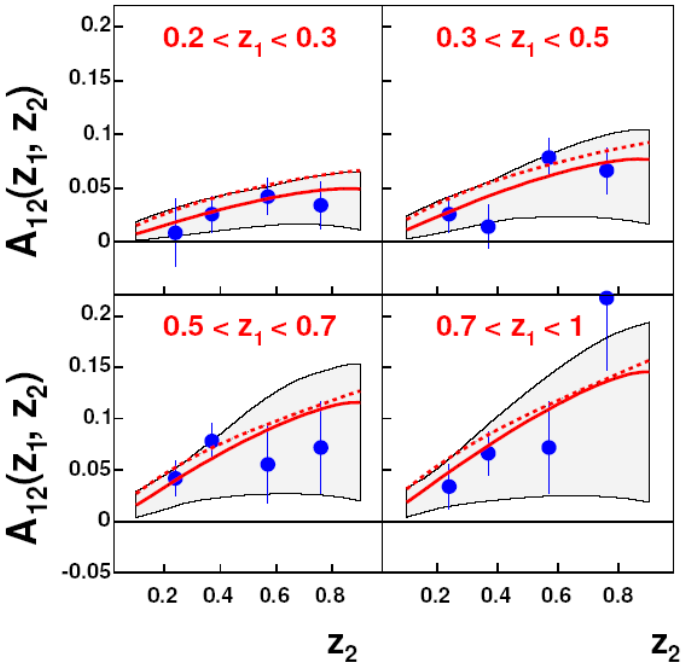


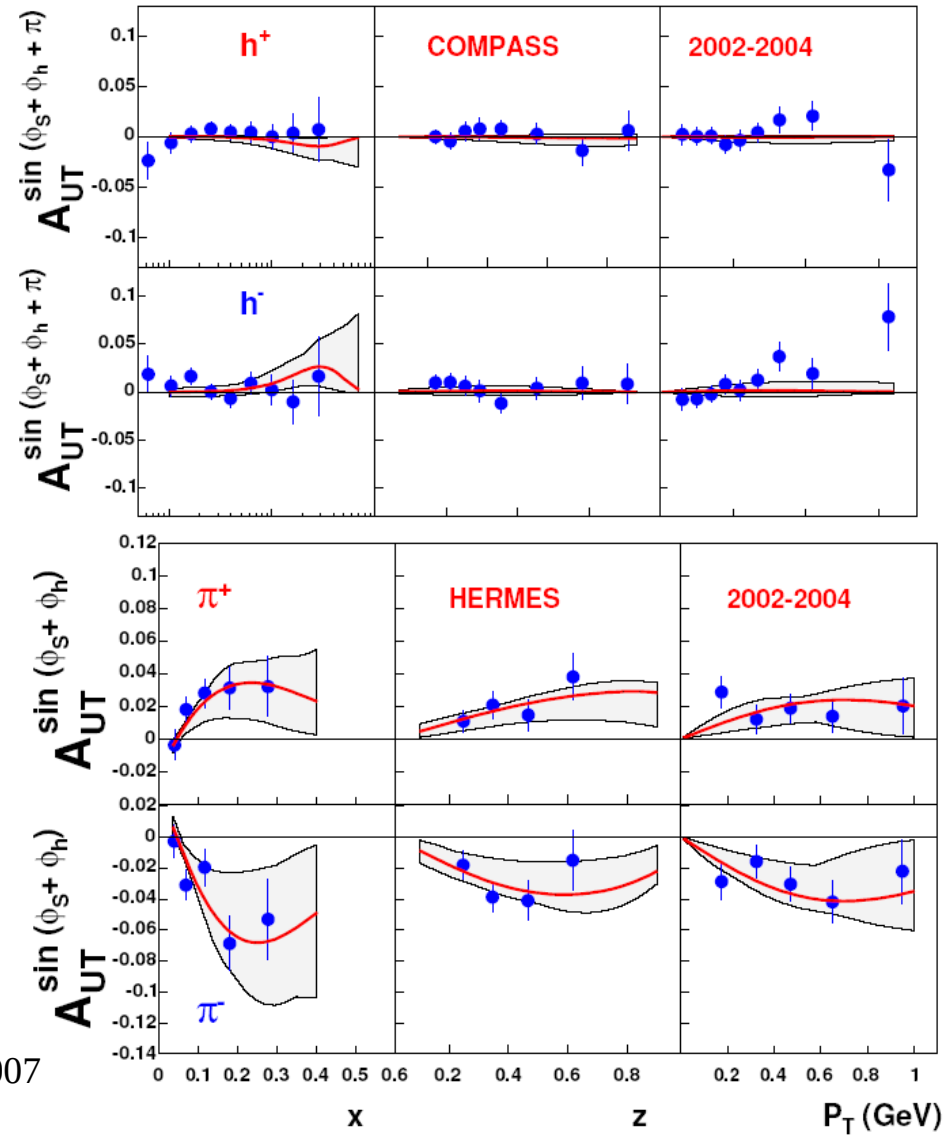
COMPASS: deuteron



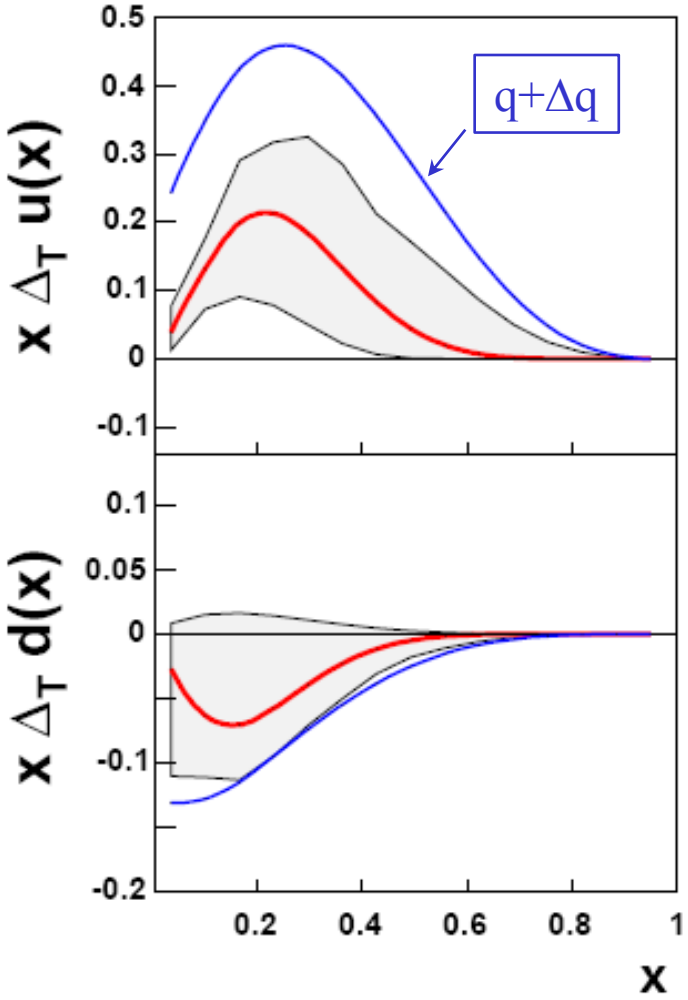
towards transversity

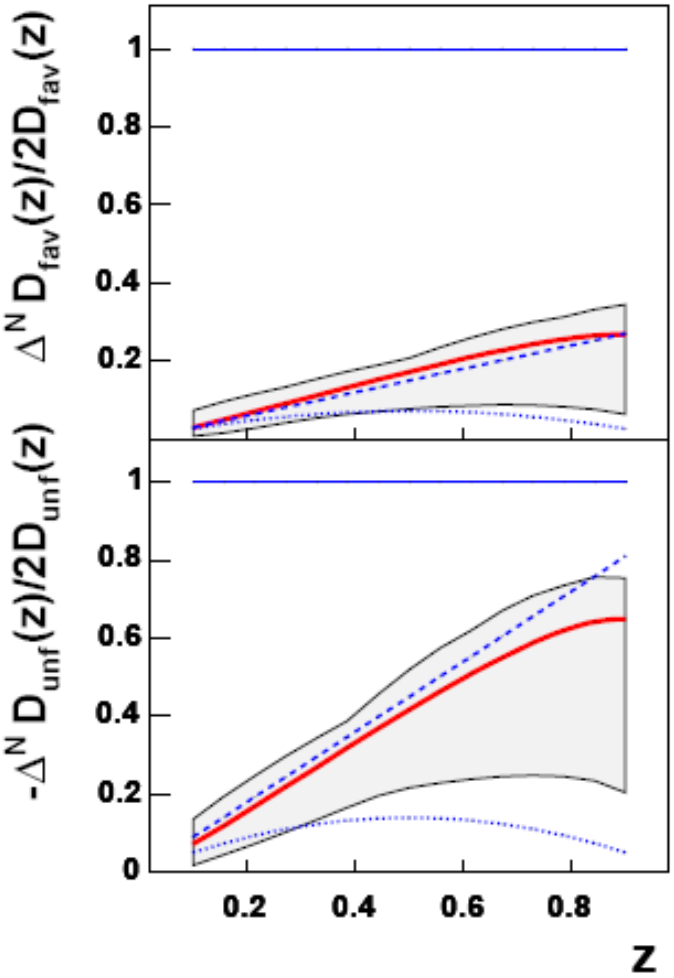
global fit of data to BELLE (*FF*), HERMES, COMPASS (*DFxFF*)





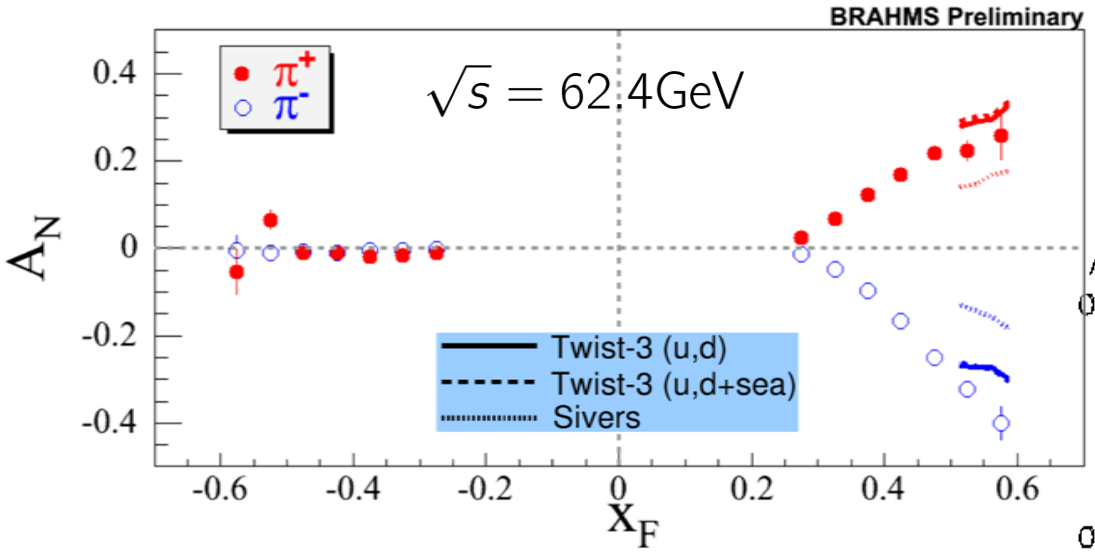
A first glimpse of transversity

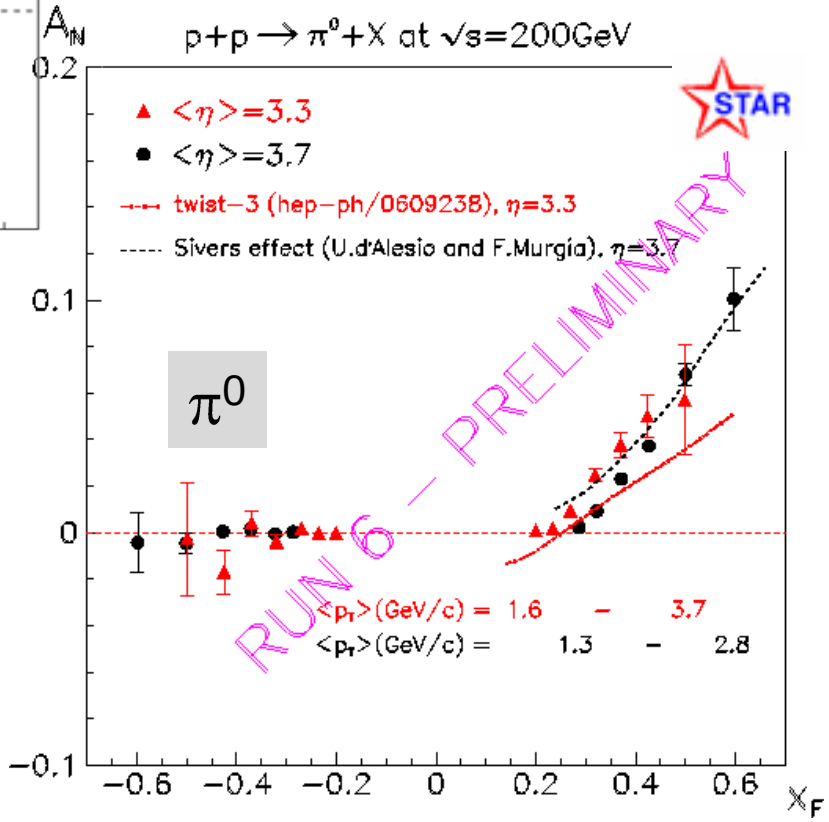




Anselmino *et al.*, Phys. Rev. D75 (2007) 054032

Transverse spin effects @ RHIC



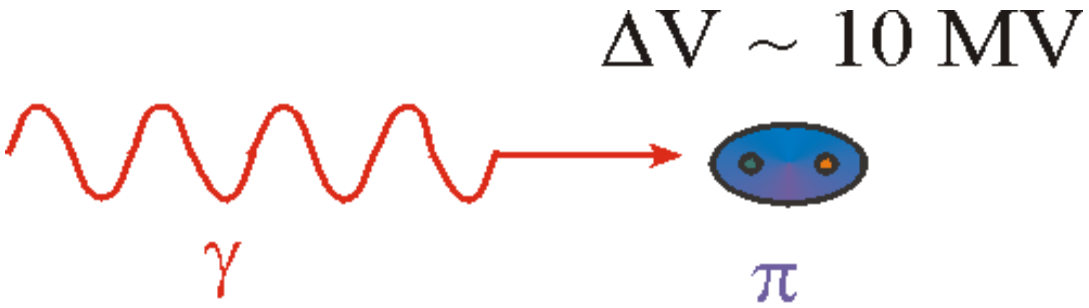


huge effects up to 40%

Pion Polarisability

Polarizabilities

- electric polarisability : $\vec{d} = \alpha \vec{E}$
- magnetic polarisability : $\vec{\mu} = \beta \vec{H}$



Charges oscillate ~ 0.1% π radius

From S. Paul

Polarisability: a test of χPT

- $\overline{\alpha}_\pi$ electrical , $\overline{\beta}_\pi$ magnetic polarisability
- χPT: $$\overline{\alpha}_\pi \pm \overline{\beta}_\pi = \frac{\alpha}{16\pi^2 m_\pi f_\pi^2}\left\{a_\pm + b_\pm + \mathcal{O}(\frac{m_\pi^2}{f_\pi^2})\right\}$$

1 loop

2 loop

- $a_+ = 0, \quad a_- \sim$ Low Energy Constant (LEC)
- χPT:

$$\overline{\alpha}_\pi + \overline{\beta}_\pi = (0.16 \pm 0.1) \cdot 10^{-4} \text{ fm}^3$$
$$\overline{\alpha}_\pi - \overline{\beta}_\pi = (5.7 \pm 1.0) \cdot 10^{-4} \text{ fm}^3$$

= 0 at 1 loop

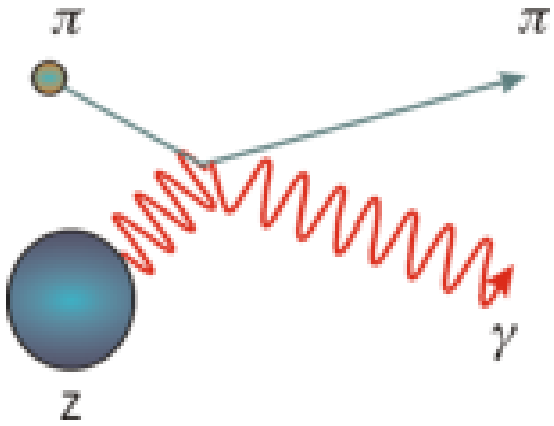
Polarisability: Primakoff

- measurable in Compton scatt.

$$\gamma\pi \rightarrow \gamma\pi$$

- Primakoff: inverse kinematics
- with $\omega = E_\gamma / E_{\text{beam}}$ and

$$\overline{\alpha}_\pi + \overline{\beta}_\pi = 0$$



$$\frac{d\sigma_{\gamma\pi}^{\text{Prim}}}{d\omega} = \frac{d\sigma_{\gamma\pi}^{\text{Thomson}}}{d\omega} + \omega\, 4Z^2\alpha^2 m_\pi \overline{\beta}_\pi \left\{ \ln\frac{Q^2_{\text{max}}}{Q^2_{\text{min}}} - 3 + 4\sqrt{\frac{Q^2_{\text{max}}}{Q^2_{\text{min}}}} \right\}$$

where $Q^2_{\text{min}} = \frac{m_\pi^2}{2E_{\text{beam}}} \frac{\omega}{1-\omega}$, Q^2_{max} depends on analysis cuts

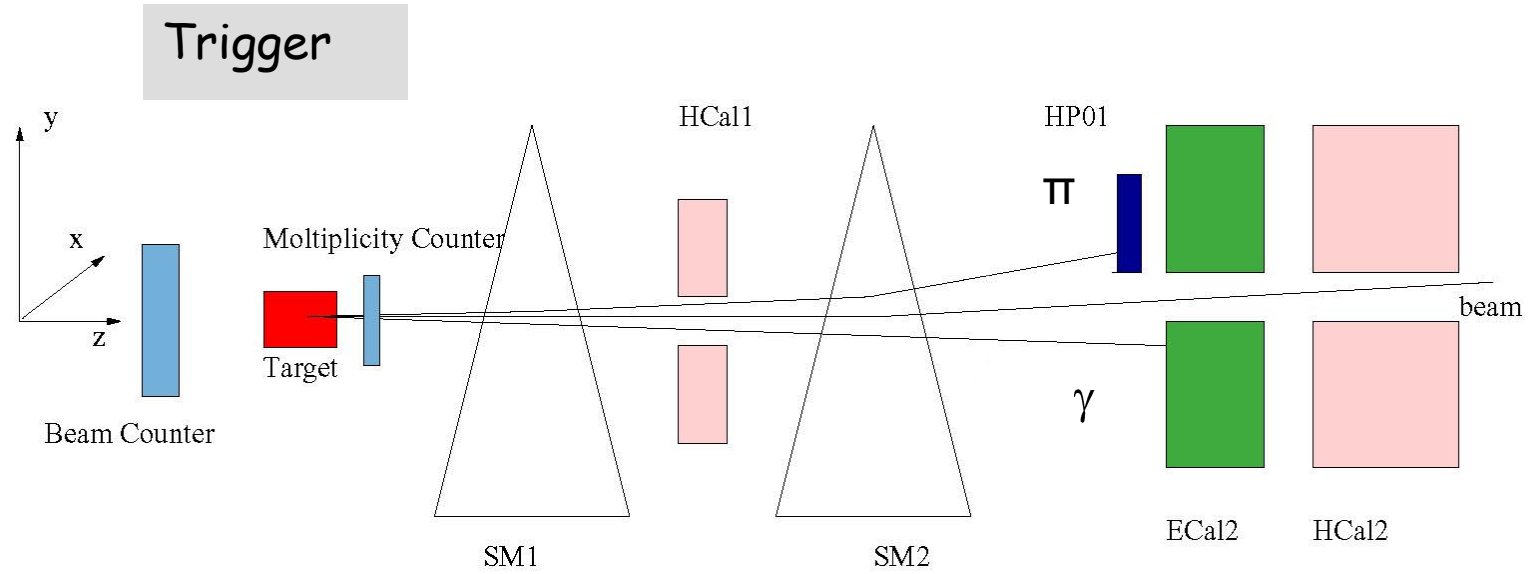
Polarisability: Primakoff

- Finally compare the shape of the measured Primakoff cross-section to a Monte Carlo simulation for the point-like case.

$$R(\omega) = \frac{\mathrm{d}\sigma_{\gamma\pi}^{\mathrm{Prim}}}{\mathrm{d}\sigma_{\gamma\pi}^{\mathrm{Thomson}}} \simeq 1 + \frac{3}{2}\frac{m_\pi^3}{\alpha}\frac{\omega^2}{1-\omega}\overline{\beta}_\pi$$

- Note COMPASS also measured the point-like muon

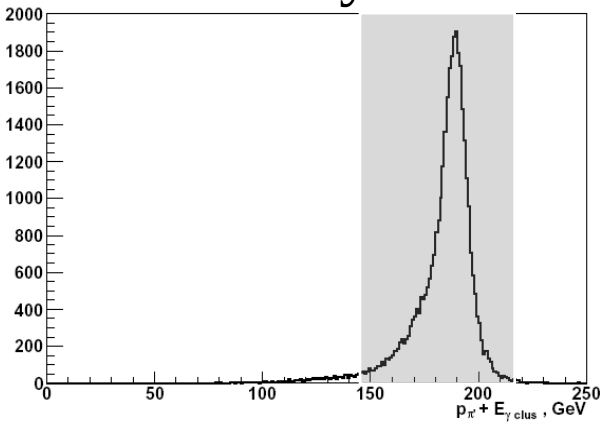
Pilot hadron-beam run 2004



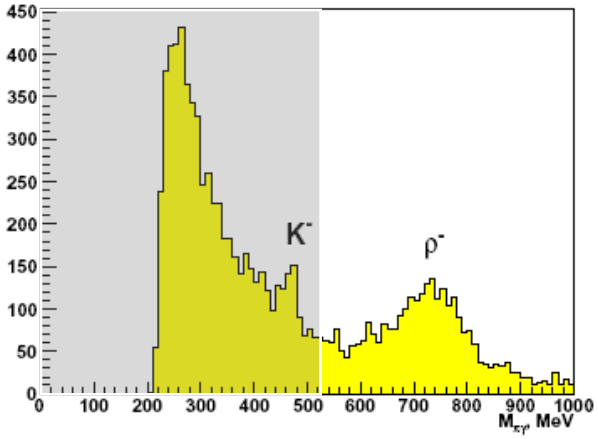
- 190 GeV π beam, low intensity: $2 \cdot 10^6$/spill
- Beam time: 7 days
- Trigger: beam, pion in hodoscope, and $E_\gamma > 90$ GeV
- Trigger rate (40−50k/spill)
- Different targets (Pb, C, Cu)

Event selection

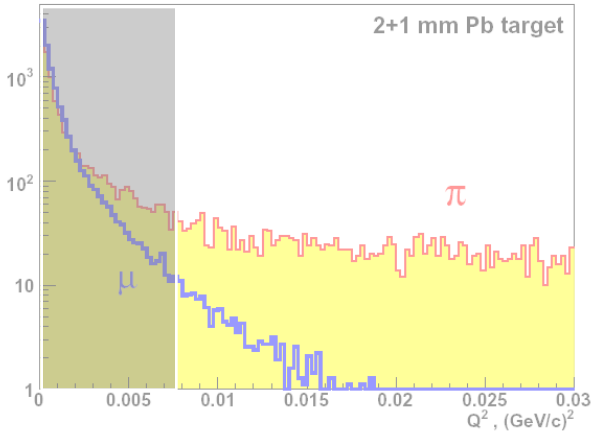
- Exclusivity



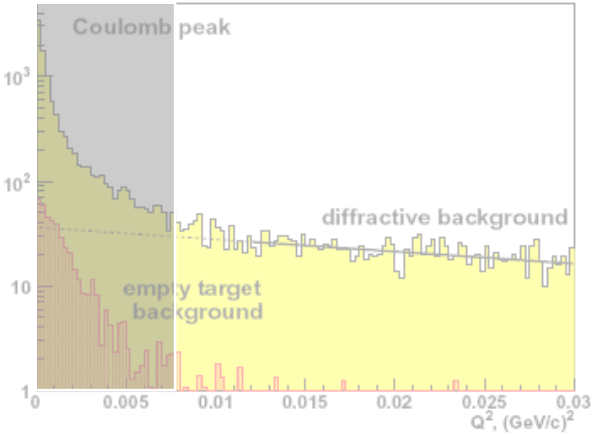
- Interference



- Diffractive background



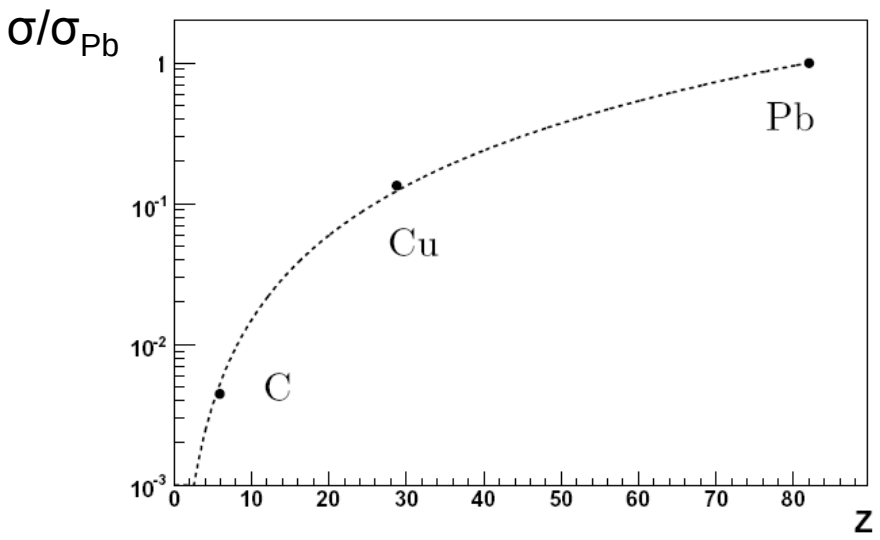
Coulomb peaks of π and μ agree



Extrapolate diffr.active background

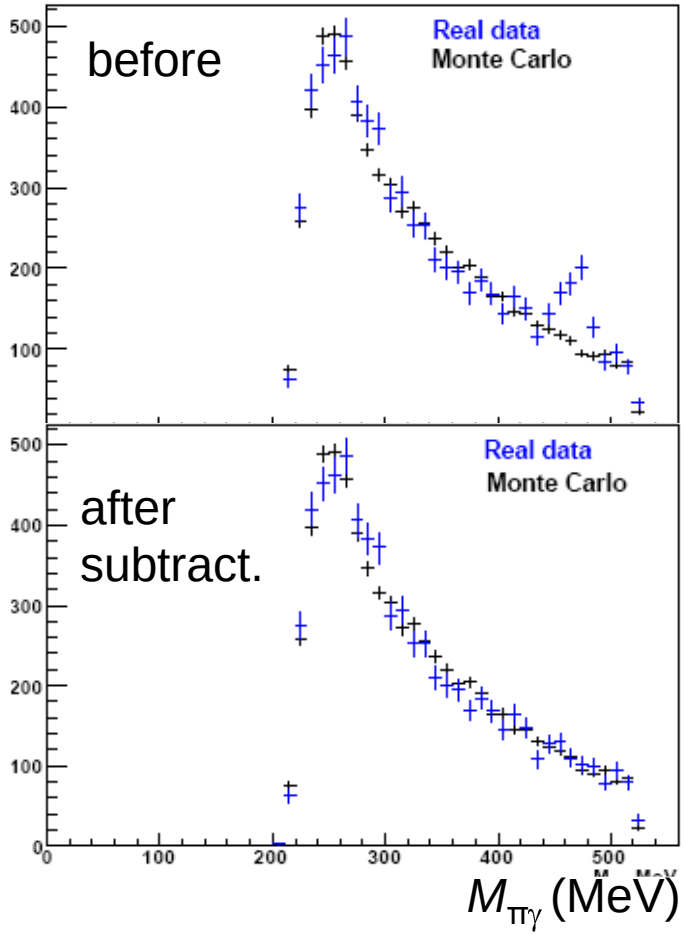
Cross checks

- Cross section ratios



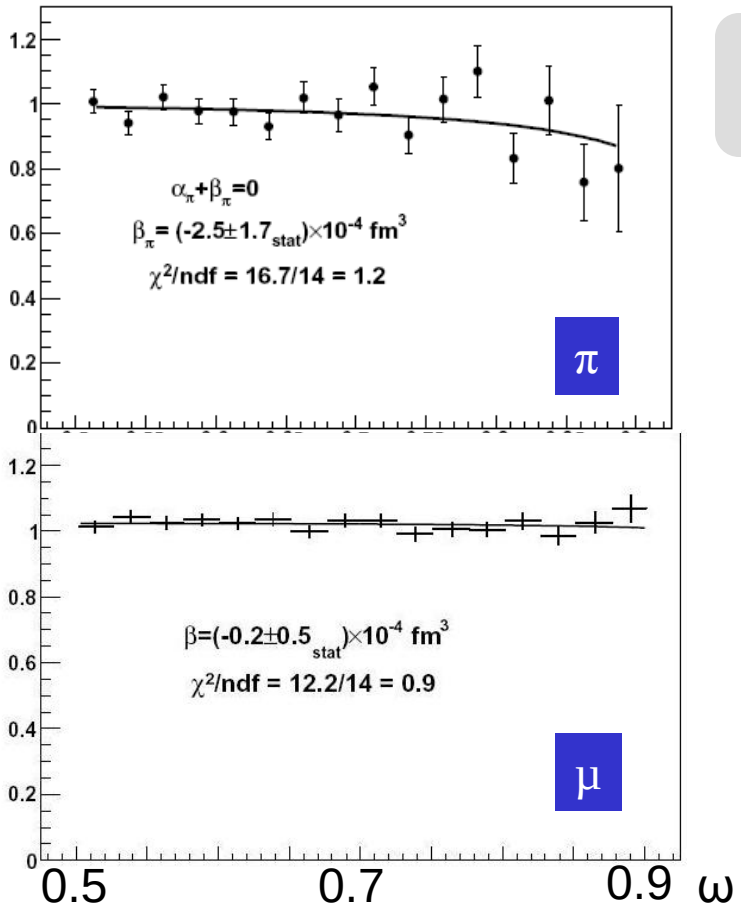
- Abs. Pb cross-section:
  estimate ~ 100 μb
  theory ~ 140 μb
- Not needed in analysis

- Empty target background



Result for $\bar{\beta}_\pi$

Ratio data/MC

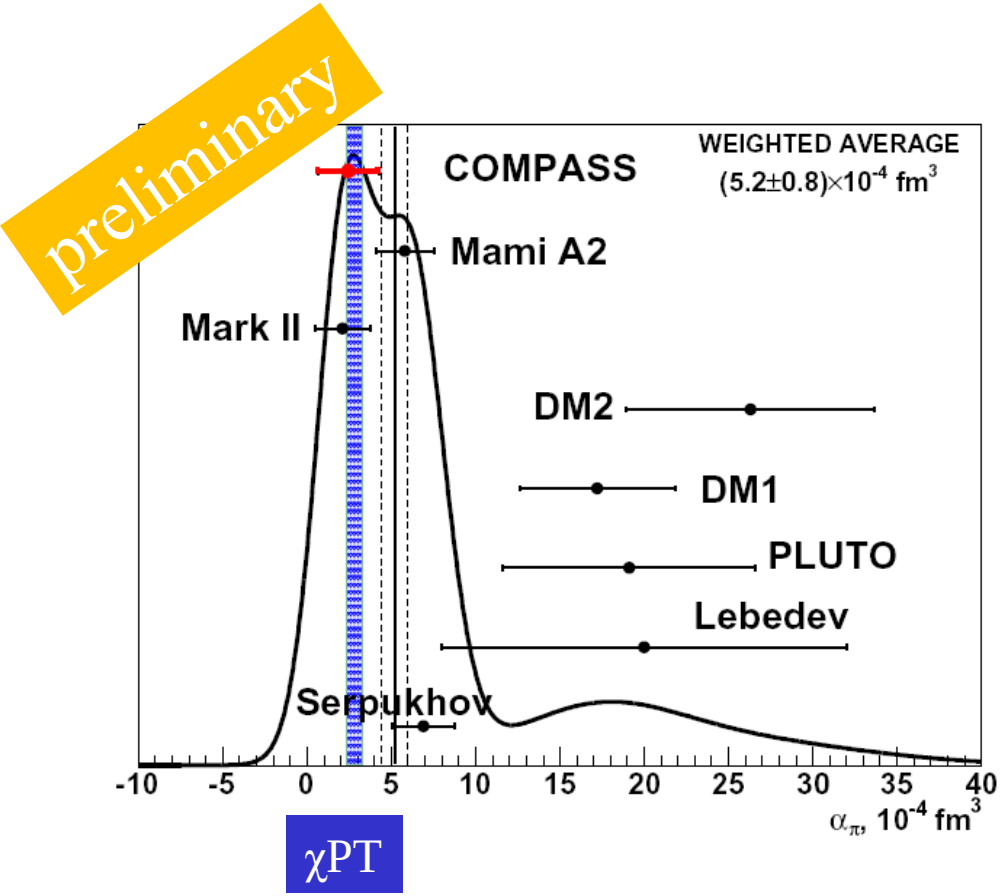


$$\bar{\beta}_\pi = (-2.5 \pm 1.7 \pm 0.6) \times 10^{-4}\ \mathrm{fm}^3$$

- Radiative corrections included
- zero result for muon
- Systematic error:

Origin	Syst. Error 10^{-4} fm^3
Setup description in MC	± 0.5
Background subtraction	± 0.3
Beam muons	< 0.2
Beam electrons	< 0.1
Total	± 0.6

World data on $\bar{\alpha}_\pi$



- Precise preliminary result
- Good agreement with χPT
- Smaller than Serpukhov and Mainz result

Summary

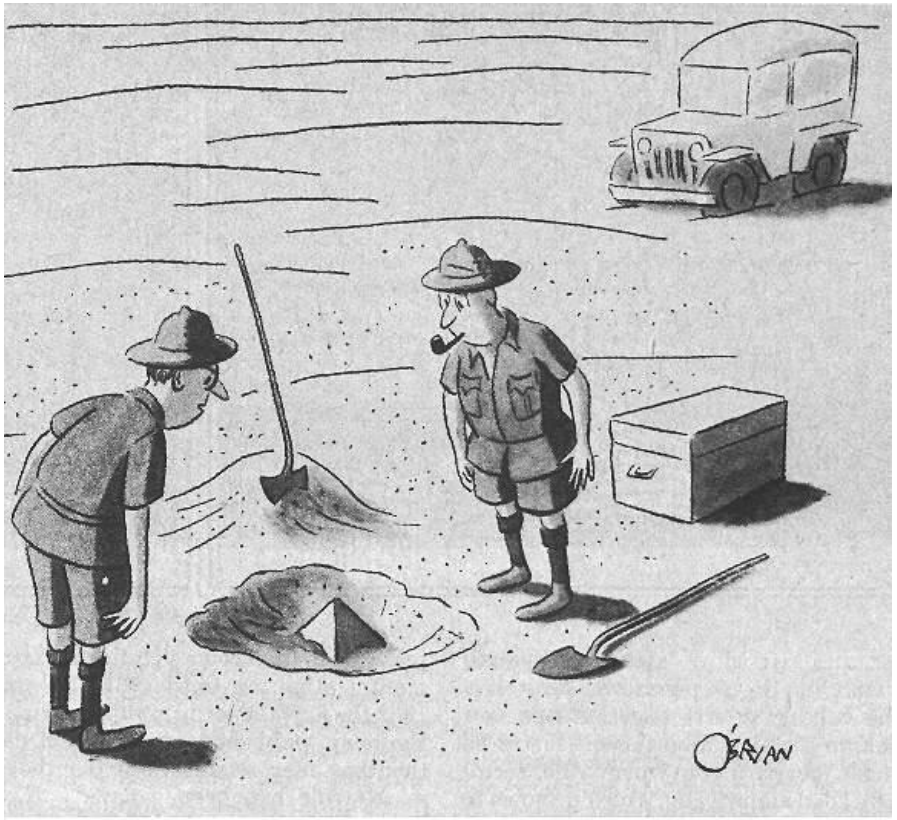
- We are starting to assess the gluon polarisation
- The large ΔG scenario is basically excluded
- Still the gluon can have a significant contribution to the nucleon spin.
- Need now precise measurements to actually determine the various contributions exactly.

- Transverse spin effects still puzzling

- Work for a polarised ep collider!

- "You think you understand something…, now add spin"

R. Jaffe



"This could be the discovery of the century. Depending, of course, on how far down it goes."

It seems spin goes pretty far down…


Thanks to the organisers
...
and the audience