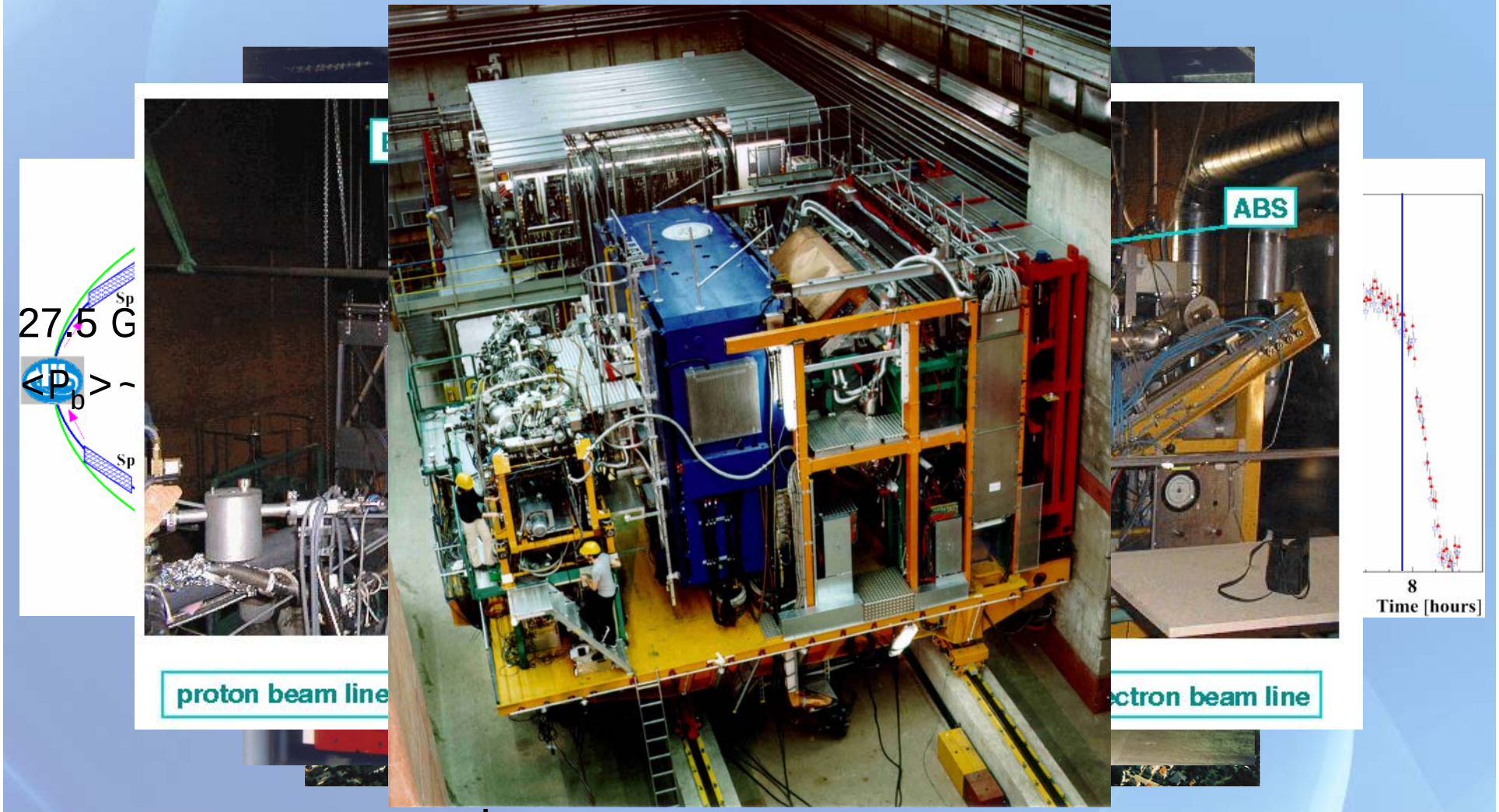
The challenge to extract $\Delta G/G$ from HERMES data

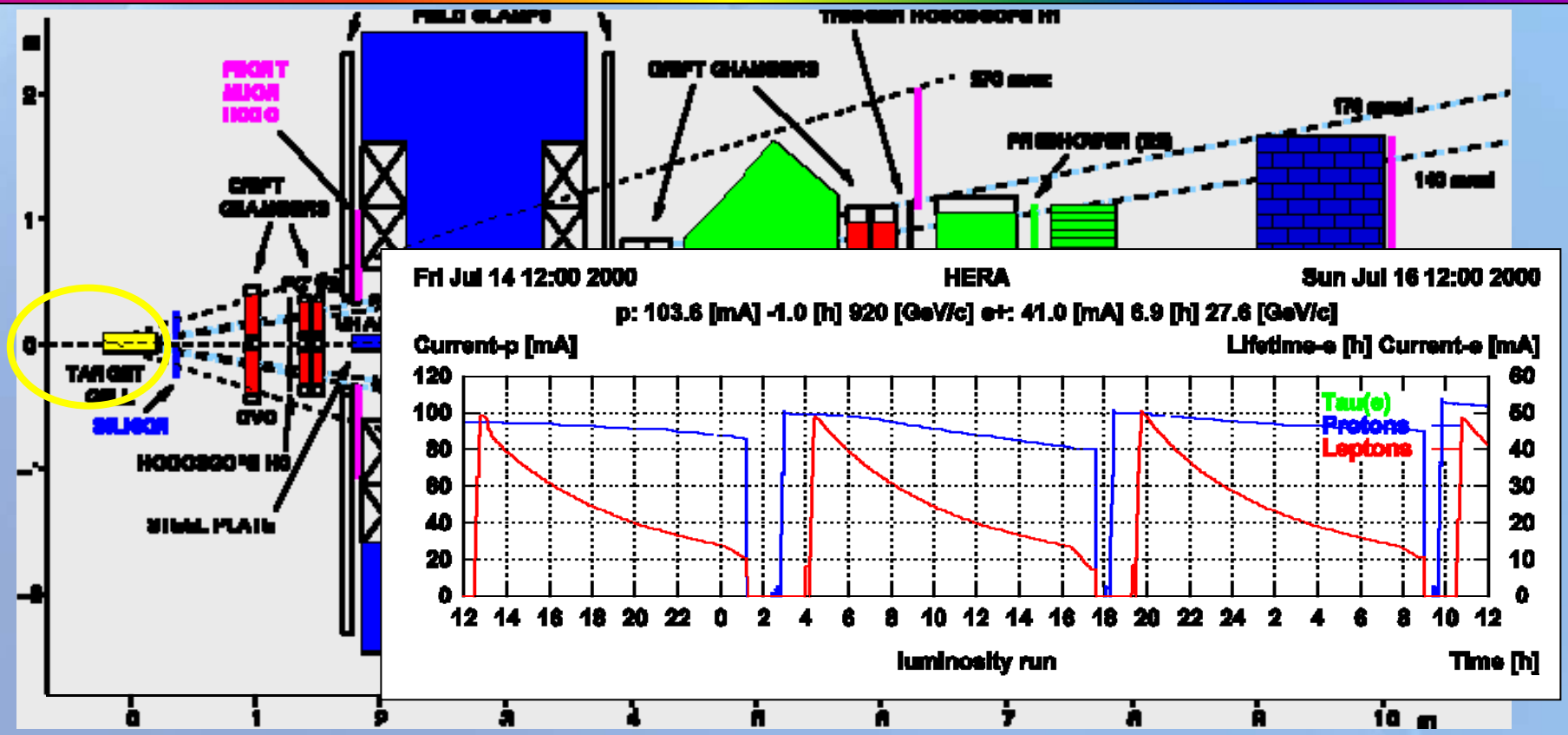
HERMES @ HERA



HERA: e^+/e^- (27GeV) - proton collider

pure nuclear-polarized atomic gas, flipped at 90s time intervals

The HERMES Spectrometer



Kinematic Range: $0.02 < x < 0.8$ at $Q^2 > 1$ GeV^2 and $W > 2$ GeV

Reconstruction: $\Delta p/p < 2\%$, $\Delta\theta < 1$ mrad

Internal Gas Target: unpol: H_2,D_2,He,N,Ne,Kr, Xe $\vec{He}$, $\vec{H}$, $\vec{D}$, $H\uparrow$

Particle ID: TRD, Preshower, Calorimeter

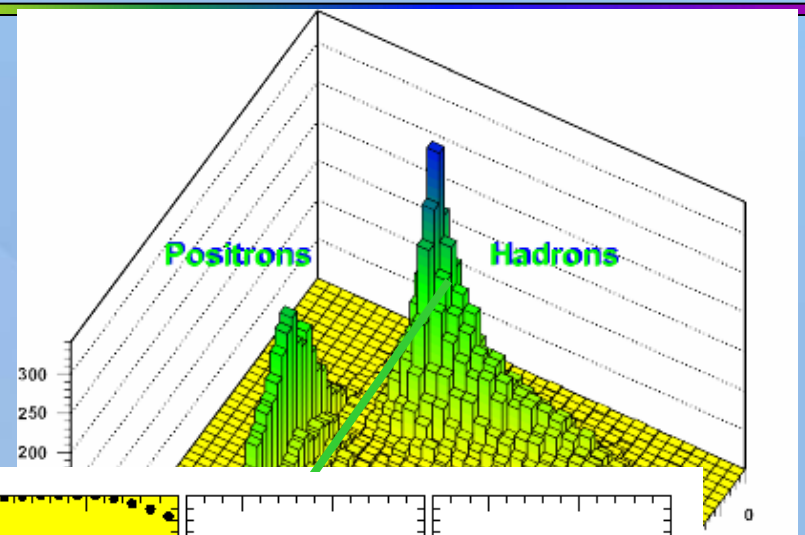
α1997: Cherenkov, 1998α: RICH + Muon-ID

Particle Identification

hadron/positron separation

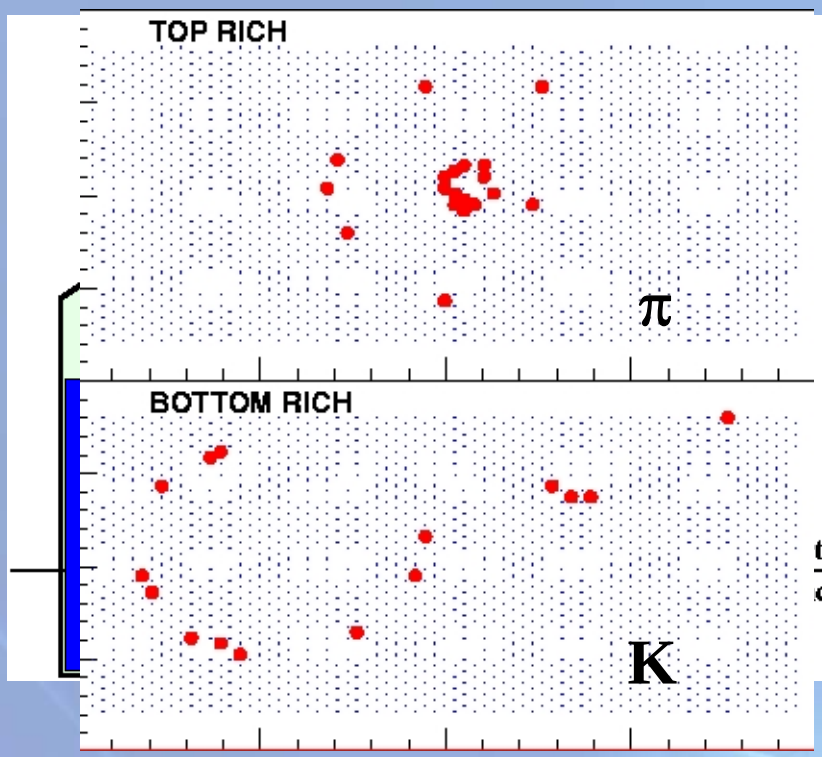
combining signals from:

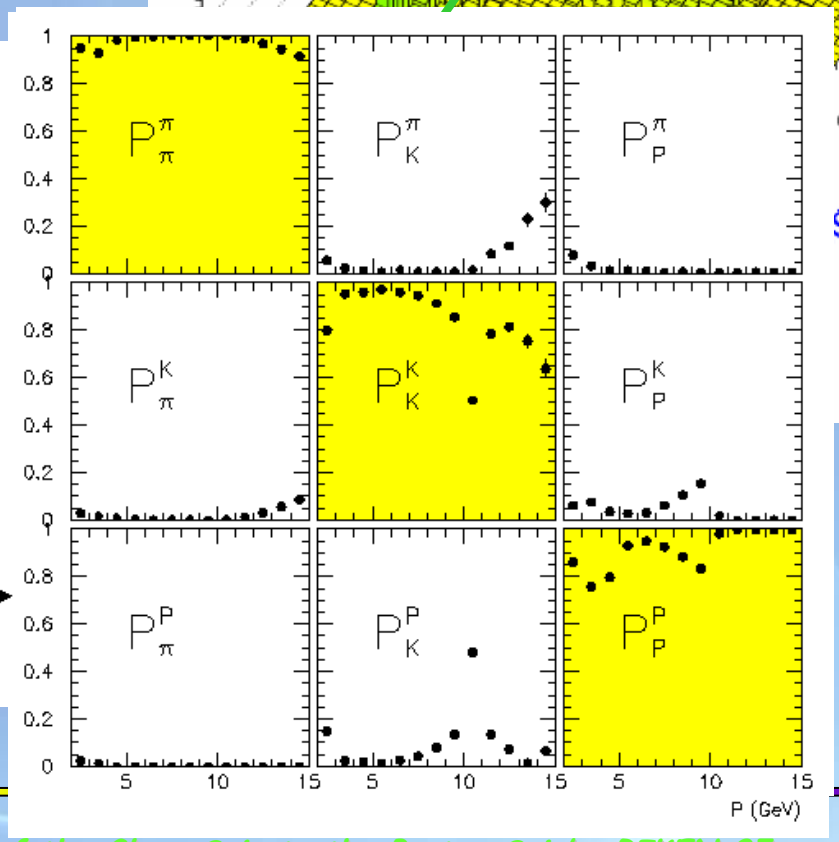
TRD, calorimeter, preshower, RICH



hadron separation

Dual radiator RICH for π, K, p

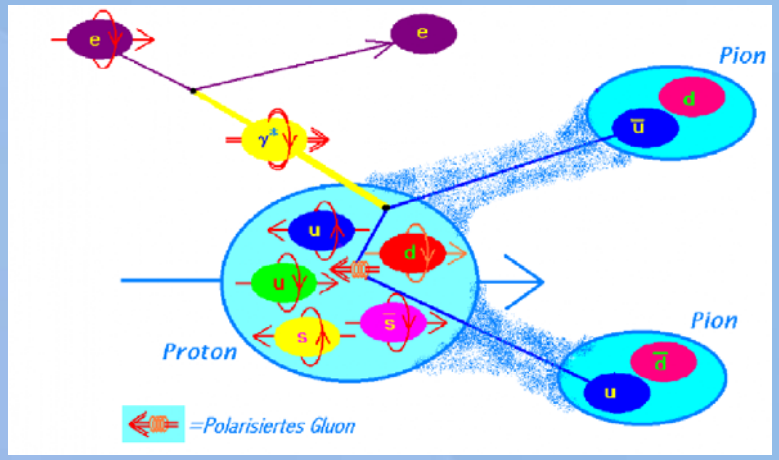




The golden channels

Idea: Direct measurement of ΔG

⟹ Isolate the photon gluon fusion process (PGF)



- Open Charm production
  - ⟹ HERMES $\sqrt{s}$ = 7.2GeV
    - ⟹ too low count rates
- high p_t hadrons or pairs of hadrons
  - ⟹ $e + p \rightarrow e' + h^{+/-} + X$
  - ⟹ $e + p \rightarrow h^{+/-} + X$
  - ⟹ $e + p \rightarrow h_1 h_2 + X$
  - ⟹ go to low Q^2 ⟹ increase statistics
  - ⟹ scale of hard sub-processes $\hat{p}_t^2$
- Data on tape:
  polarized proton data 50pb^{-1}
  polarized deuterium data 140pb^{-1}

What is needed to get $\Delta G/G$

- Double spin asymmetries for high p_t hadrons and pair of hadrons
- A theoretical model describing
  - all underlying sub-processes
  - fragmentation
  - two possibilities:
    - QCD calculation a la
      B. Jaeger, M. Stratmann, W. Vogelsang hep-ph/0505157
      Advantage: can be done to order α_s^2
      Disadvantage: to include detector effects (acceptance,..) difficult
    - Monte Carlo simulation (PYTHIA-6)
      Advantage: detector effects can easily be included
      Disadvantage: max. order α_s^1

The Asymmetries

- **Inclusive hadron double spin asymmetries:**

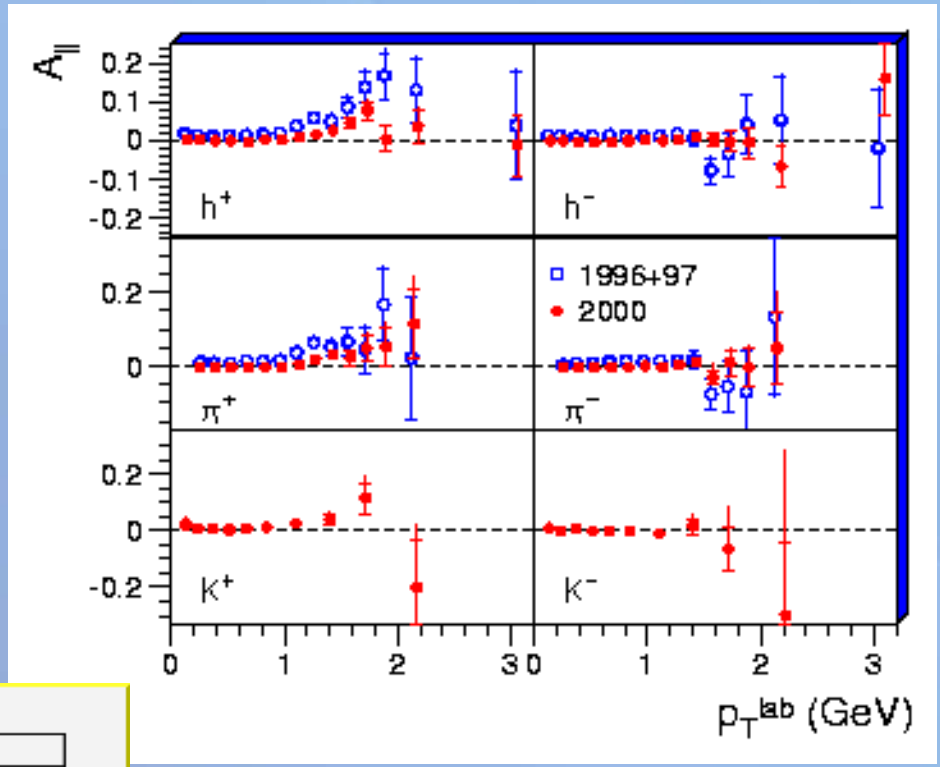
$$A_{\parallel} = \frac{1}{\langle P_B P_T \rangle} \frac{N_h^{\rightleftarrows} L^{\rightrightarrows} - N_h^{\rightrightarrows} L^{\rightleftarrows}}{N_h^{\rightleftarrows} L^{\rightrightarrows} + N_h^{\rightrightarrows} L^{\rightleftarrows}}$$

- **2 kinematical regions:**
  - **"Photo-production": anti-tagging of scattered lepton**
    - ***Event kinematics unknown***
    - ***p_t vs beam-axis***
  - **"Transition region": tagging of scattered lepton**
    - ***p_t defined relative to virtual photon direction***
    - ***$Q^2 > 0.1$ GeV^2***

- **high p_t pairs of hadrons**
  - **"Photo-production" + "Transition region":**
    - ***p_t vs beam-axis***
    - ***Event kinematics unknown; only 10% events have e'***

The Asymmetries („Photo-production")

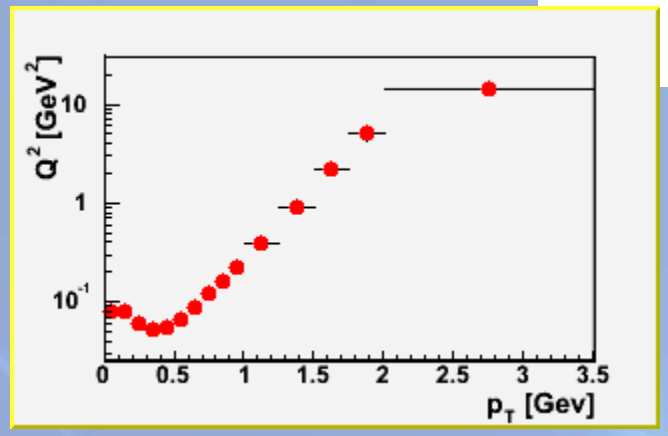
- Blue: Proton data
- Red: Deuteron data



← All hadrons

← Pions

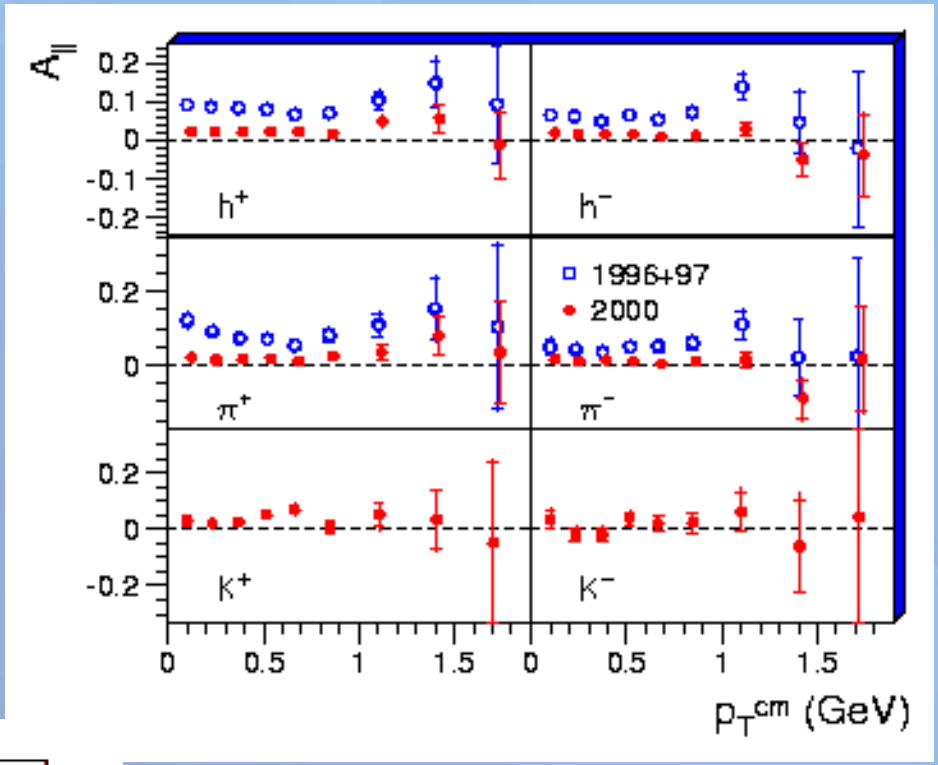
← Kaons



- P-asym.'s > 0
- D-asym.'s ~ 0 at small p_t
- Positive h have positive asym.
- negative h have 0 or negative asym. at large p_t

The Asymmetries („Transition")

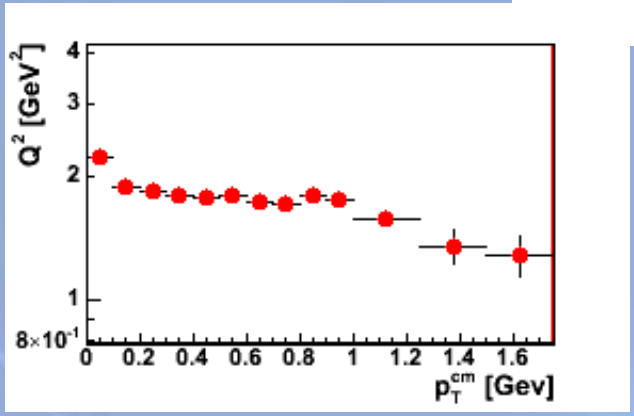
- ❑ Blue: Proton data
- • Red: Deuteron data



← All hadrons

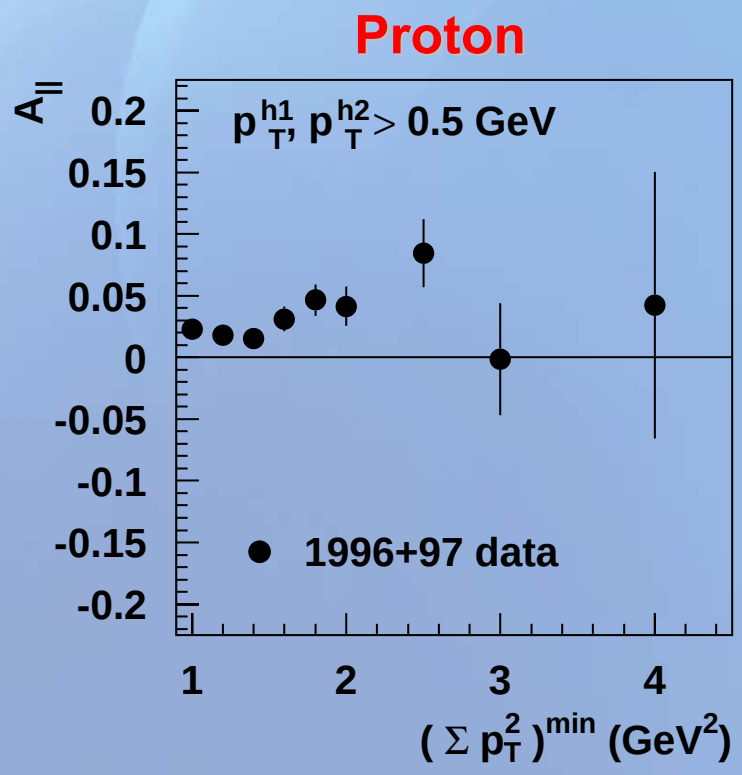
← Pions

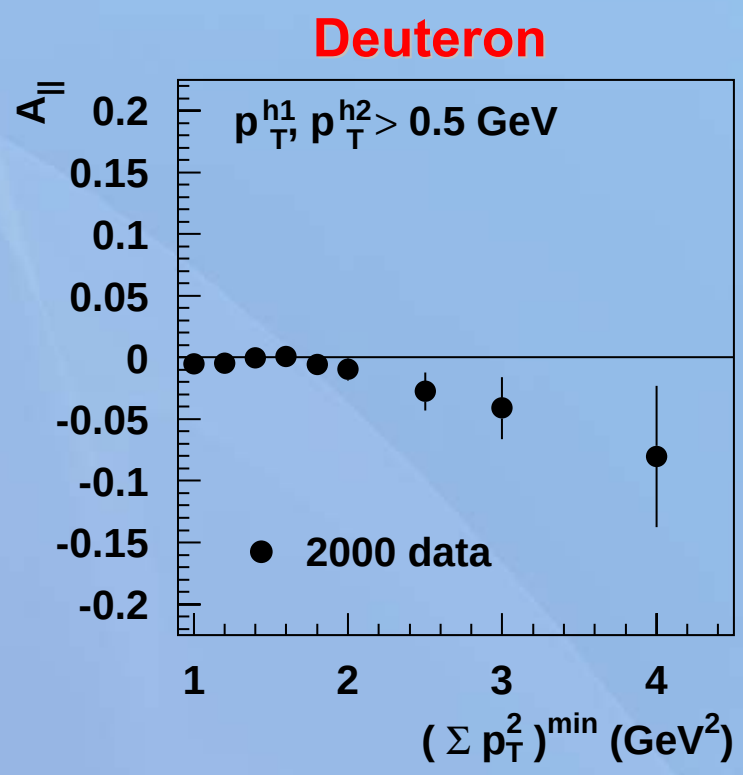
← Kaons



- At p_t>1 GeV: $Q^2 \approx 1.5$ GeV^2, $x \approx 0.05$
- $A_{||}$ relatively flat in p_t
  - Follows average behavior in SIDIS
  - Small difference of positive and negative h
- Statistics at p_t>1 GeV limited

The Asymmetries (pairs of hadrons)





Define:

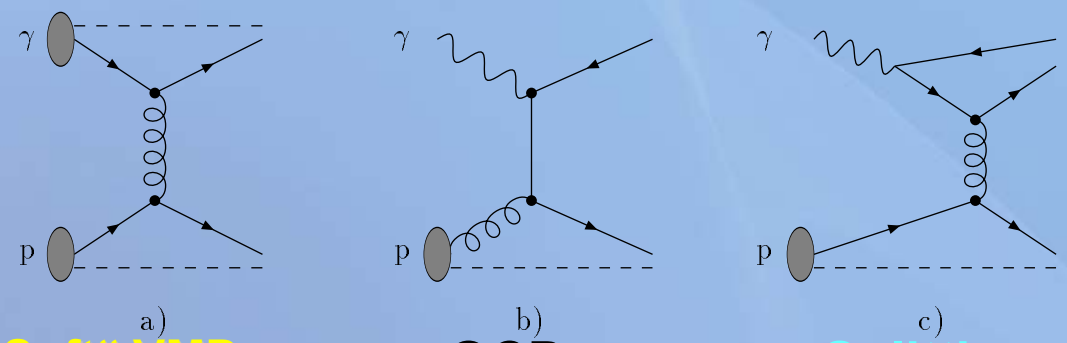
$$\sum p_t^2 = \left(p_t^{h_1}\right)^2 + \left(p_t^{h_2}\right)^2$$

- $A_{||}$ relatively flat in Σp_t^2
  - Proton asym. > 0 for all Σp_t^2
  - Deuteron asym. < 0 for Σp_t^2 > 2 GeV
- Statistics at Σp_t^2 > 2 GeV limited

The Model in PYTHIA-6

- **Model:** Mix processes with different photon characteristics

VMD | direct | anomalous photon



„Soft“ VMD: Elastic, diffractive, non-diffractive („minimum bias“, „low-p_T“) processes

Hard VMD: QCD 2→2 processes

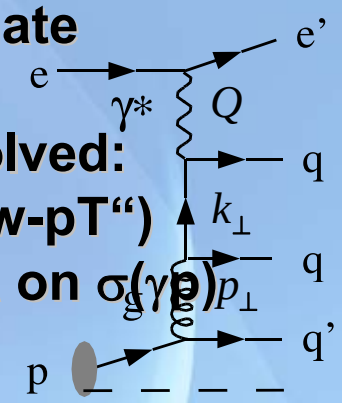
QCD-Compton

DGF: LO DIS (virtual photon)

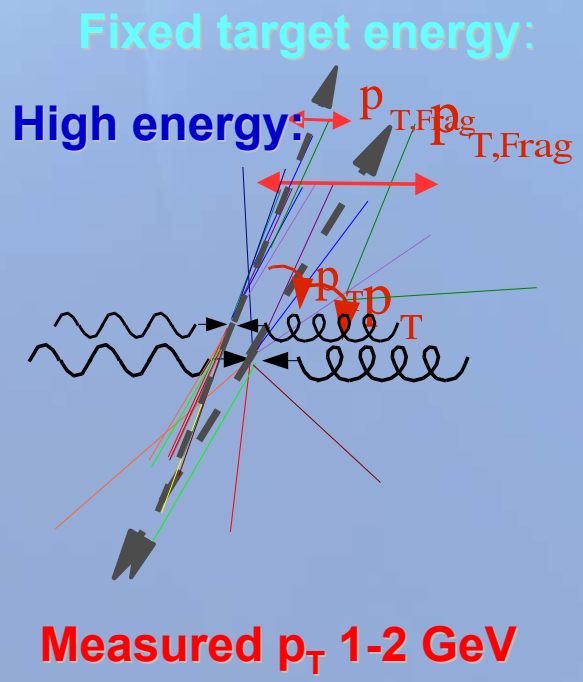
Splitting of γ→qq

“QCD 2→2 processes

- Small Q^2: VMD+anomalous (=„resolved“) photon dominate
- Large Q^2: LO DIS dominates
- Choice of hard process according to hardest scale involved:
- If all scales are too small, „soft“ VMD (diffractive or „low-pT“)
- The „resolved“ part is modeled to match the world data on $\sigma_g(\gamma p)$



The Challenges



Measured p_T 1-2 GeV

- Intrinsic $k_T \approx 0.4$ GeV
- p_T from fragmentation ≈ 0.35 GeV
- Q^2 small

  $\Rightarrow$ expect contribution from VMD processes
- Small scales (O(1 GeV^2))

  $\Rightarrow$ Important:

  non-perturbative contributions, NLO corrections
- Fraction of hard gluon initiated processes small

  $\Rightarrow$ large background
- All effects are folded with acceptance

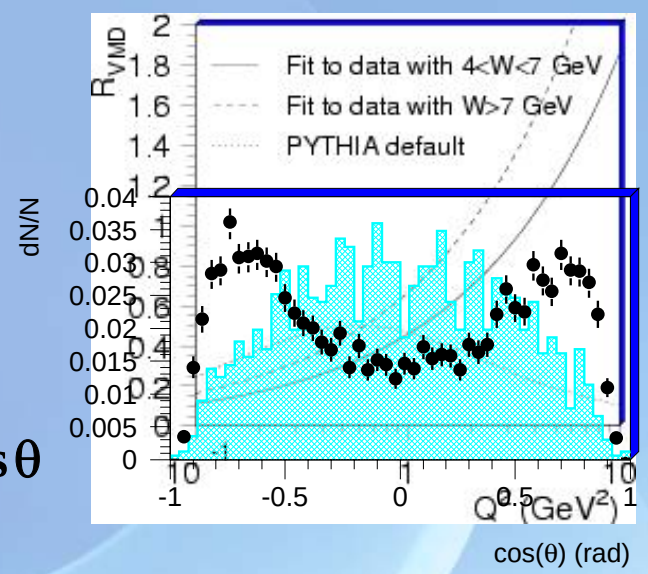
Adapting Pythia to Hermes Kinematics

- Check PYTHIA VMD model to exclusive ρ^0 production
  - ⟹ In "Transition" region as full kinematics known; $Q^2 > 0.1\,\mathrm{GeV}^2$
- Default PYTHIA: σ(PYTHIA) ~ 6*σ(HERMES)
- Changes:
  - The Q^2 slope of the total (resolved) γ^*p-cross section of world data

$$\frac{\sigma(Q^2)}{\sigma(Q^2=0)} = \left[\frac{M_\rho^2}{\left(M_\rho^2+Q^2\right)}\right]^m \qquad m = 2 \rightarrow 2.6$$

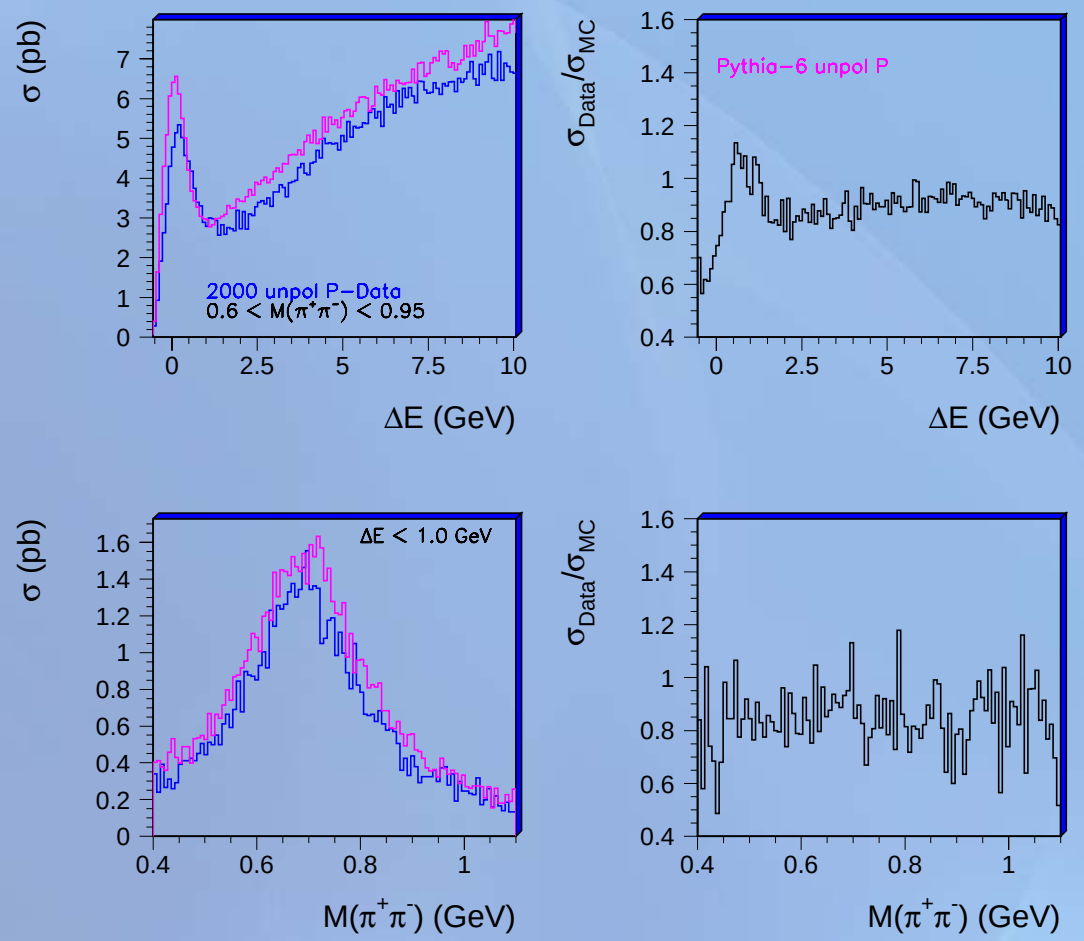
  - The parametrisation of $R_{VMD} = \frac{\sigma_L}{\sigma_T}$
  - The γ-VM couplings
  - The angular distribution of the ρ decay products

$$\frac{d\sigma}{d\theta^*}\left(Q^2=0\right) \sim \sin\theta \qquad \frac{d\sigma}{d\theta^*}\left(Q^2>0\right) \sim A\sin\theta + B\cos\theta$$



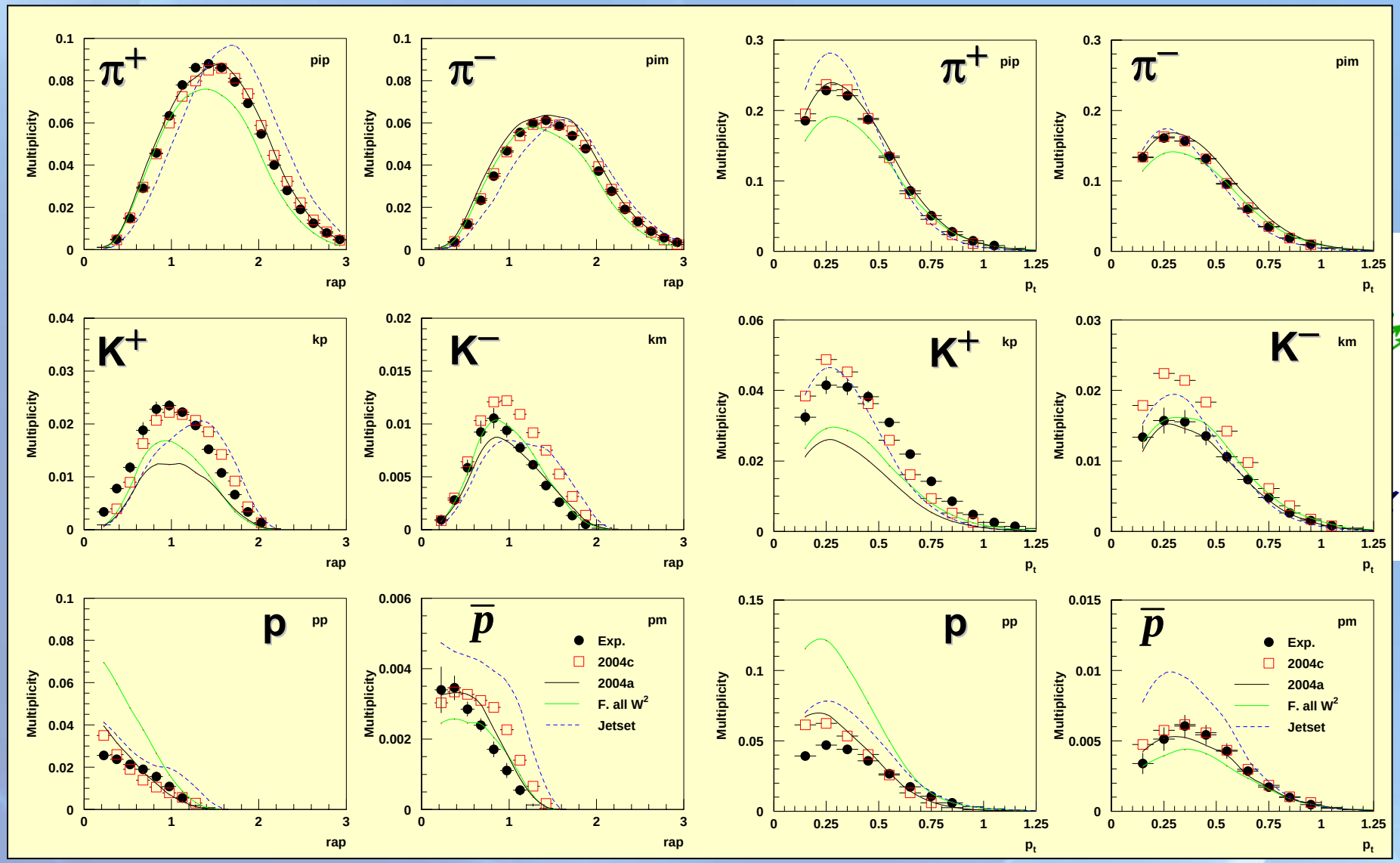
Adapting Pythia to Hermes Kinematics

- **The exclusive ρ^0 cross section data-MC agrees now within 10%**
  - ***Diffractive contribution ~10%***

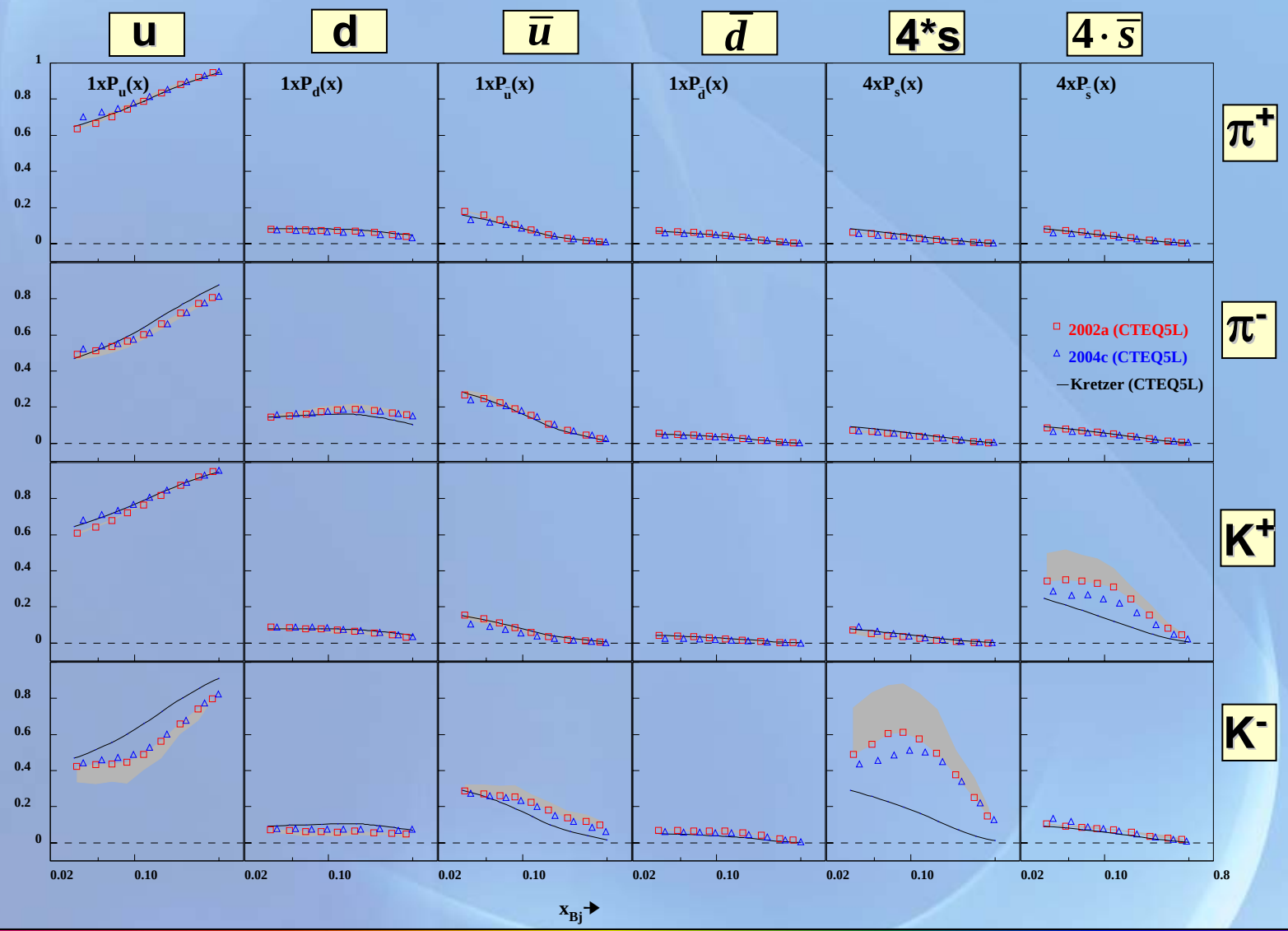


- **The PYTHIA ρ^0 cross section also matches the "photo-production" data well**

Fragmentation



Proton target purities

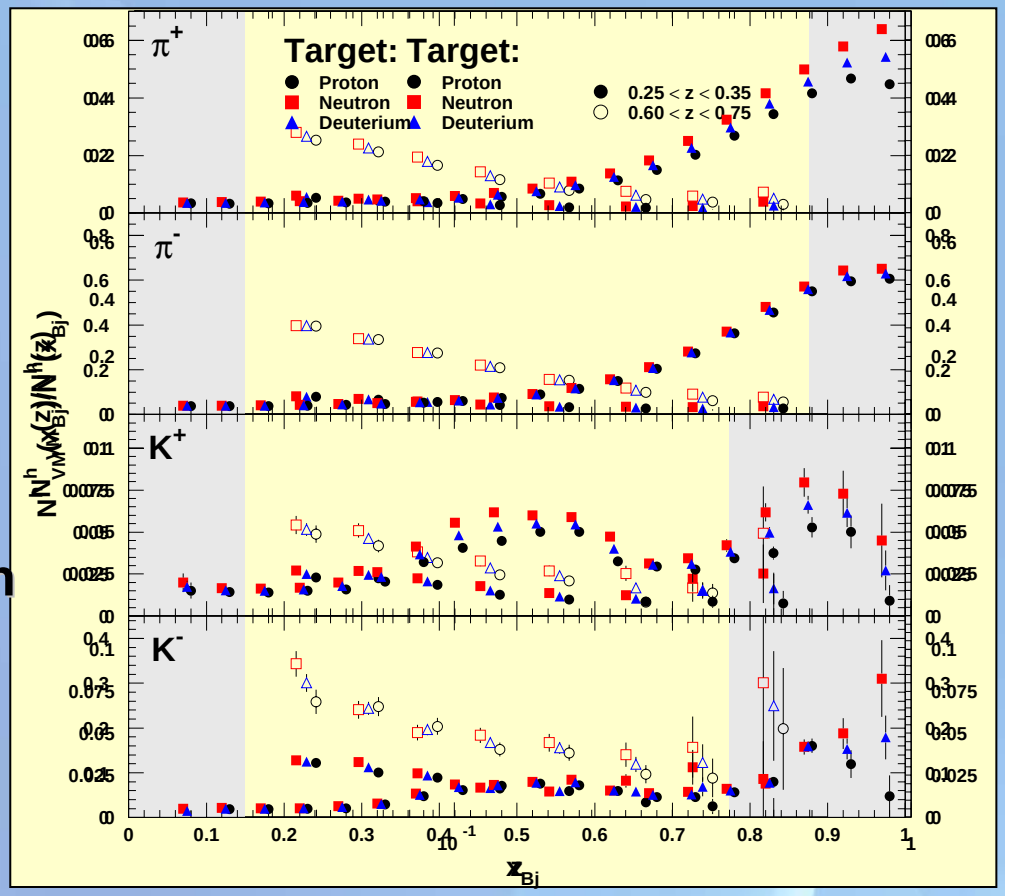


Contamination from excl. VM

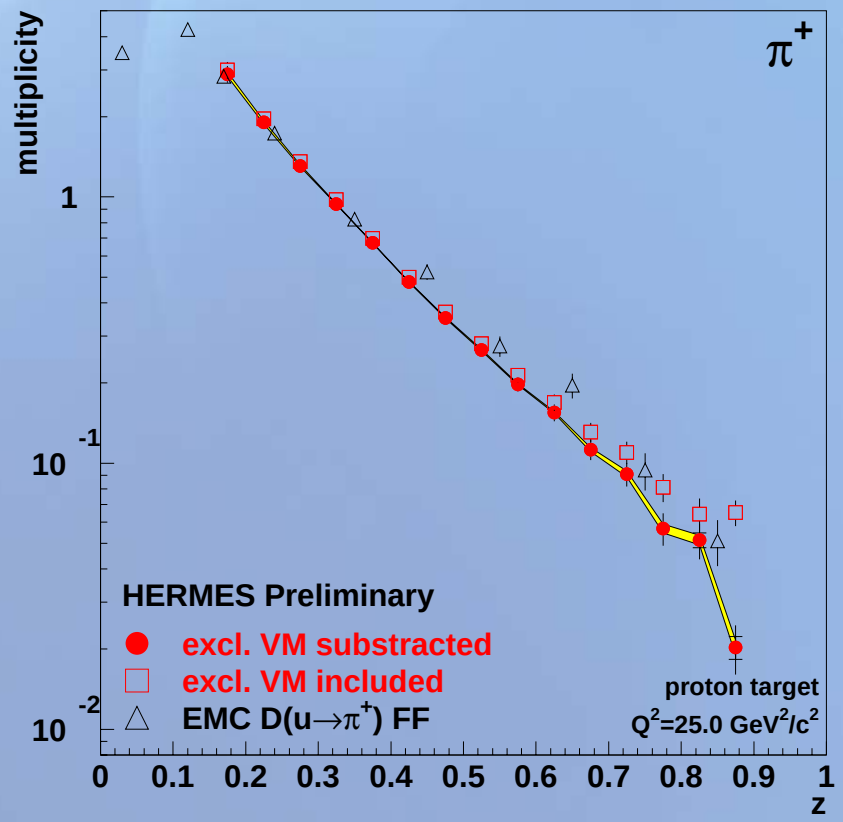
- Exclusive VM production different process than SIDIS
- estimate the contribution from **Pythia-6**

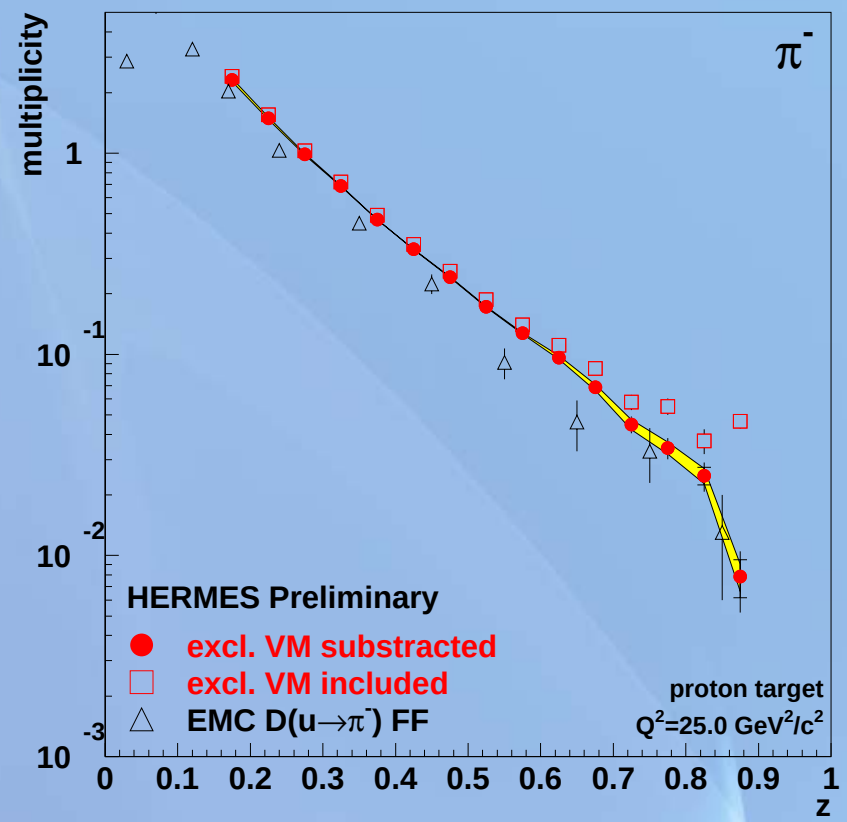
$$N^{h}_{excl.VM}(z) / N^{h}_{SIDIS}(z)$$

- π: large contribution at high z
  K: moderate contribution vs. z
- π/K: contribution growing with x_B decreasing



Experimental Multiplicities

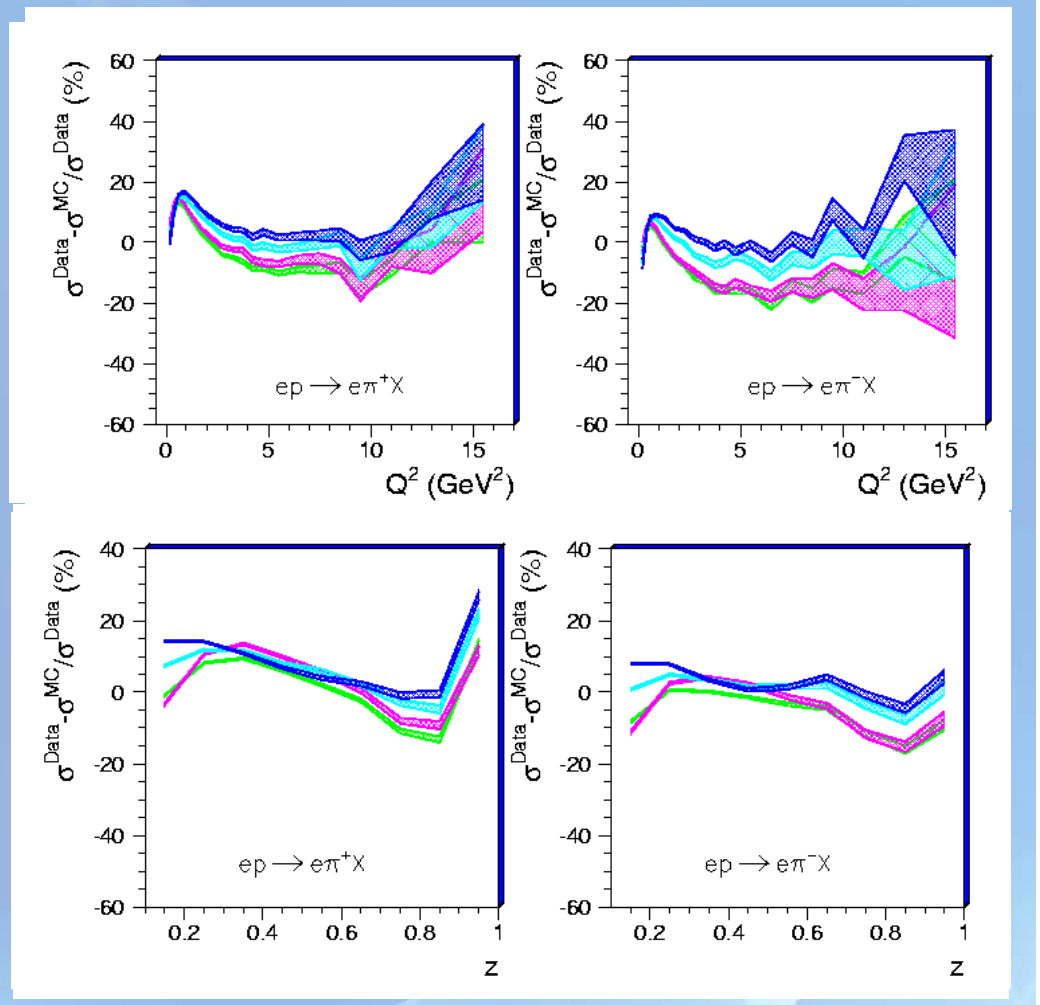




- systematic uncertainty mainly from hadron PID correction
- $Q^2 > 1\text{GeV}^2$, $W^2 > 10\text{GeV}^2$
- EMC: Fragmentation Function $D_u^{\pi^\pm}$ (Nucl. Phys. B321 (1989) 541)

Cross Section vs Q^2 and z

- Implement QED radiative corrections into PYTHIA using RADGEN
- Cross section for "Transition" region $Q^2 > 0.1 GeV^2$
  - green curve relevant one
  - Agreement in < 20%
- How are things looking vs p_t?
  - three critical variables
    - intrinsic k_t of parton in photon or nucleon (PARP 91 / 99)
    - p_t from fragmentation (PARJ 21)



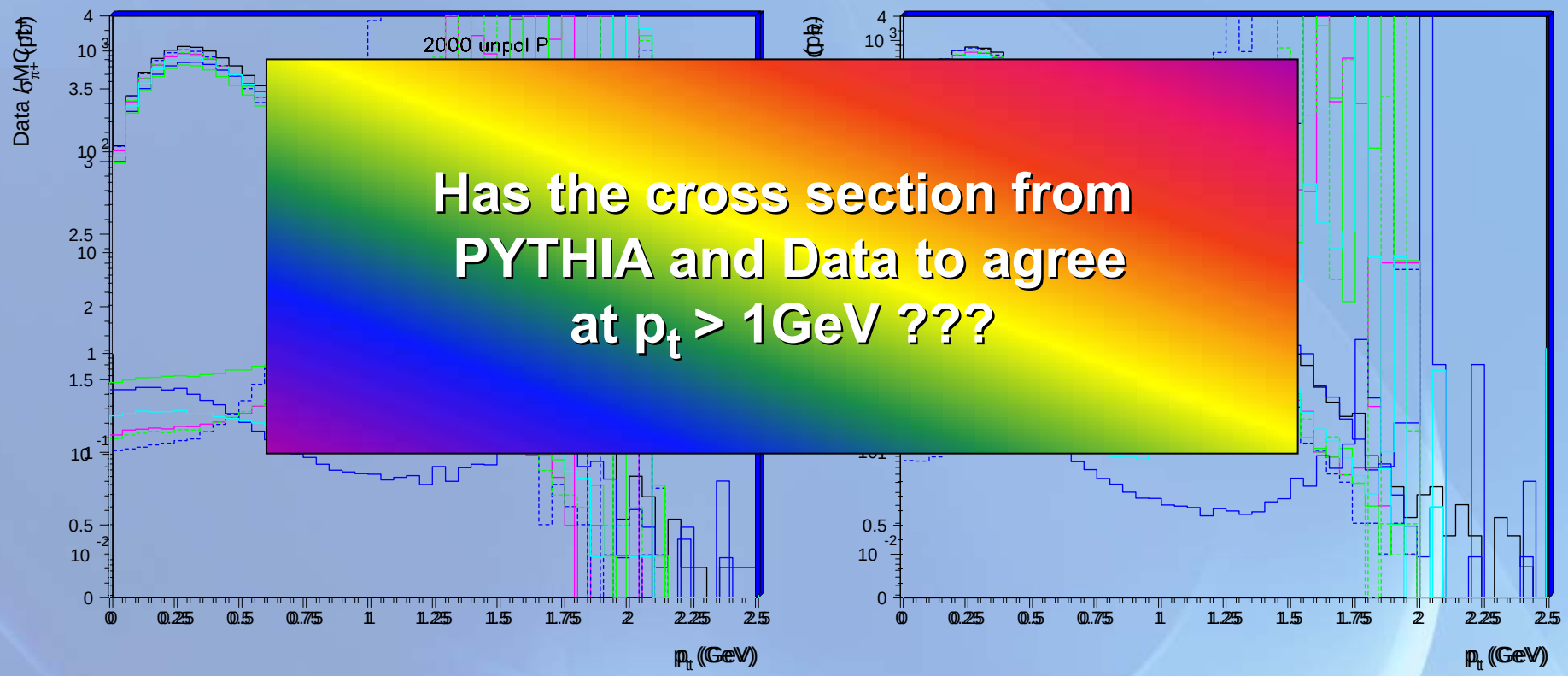
Cross Section vs p_t

- **HERMES standard values:** $k_t^{p/\gamma} = 0.44GeV$ $p_t = 0.38GeV$

  → **M. Anselmino et al. Phys. Rev. D71,074006**

  $\langle k_t^2 \rangle = 0.25GeV^2 \pm 20\%$ $\langle p_t^2 \rangle = 0.20GeV^2 \pm 20\%$

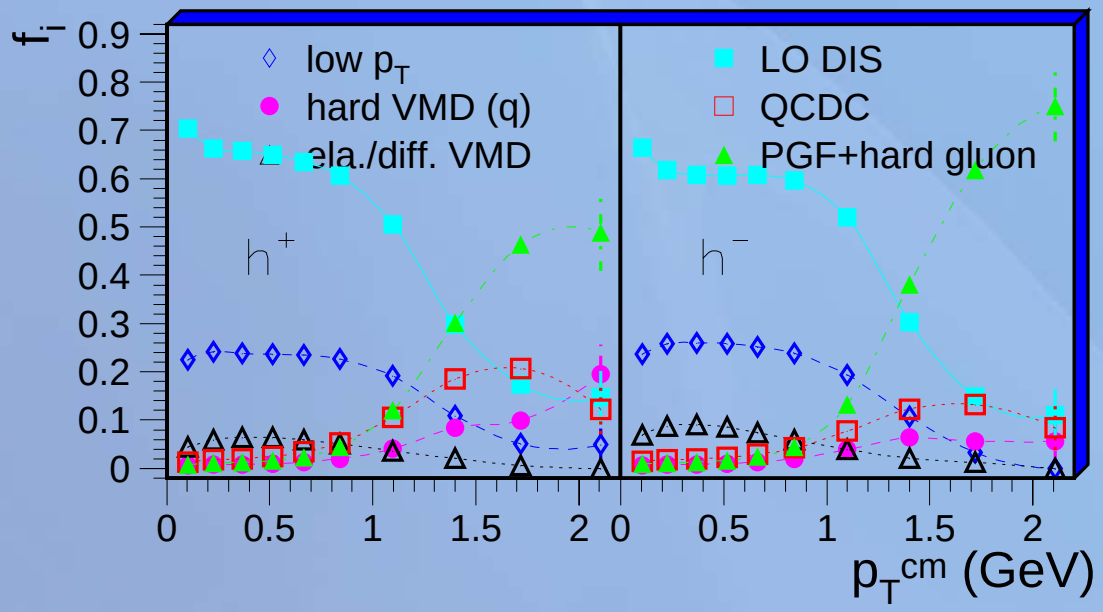
- **Cross section for "Transition" region $Q^2 > 0.1GeV^2$**



Has the cross section from PYTHIA and Data to agree at p_t > 1GeV ???

Cross Section vs p_t (II)

- **Process fractions for "Transition" region $Q^2 > 0.1 GeV^2$:**
  - **p_t > 1GeV: (α_s^1) process start dominating**

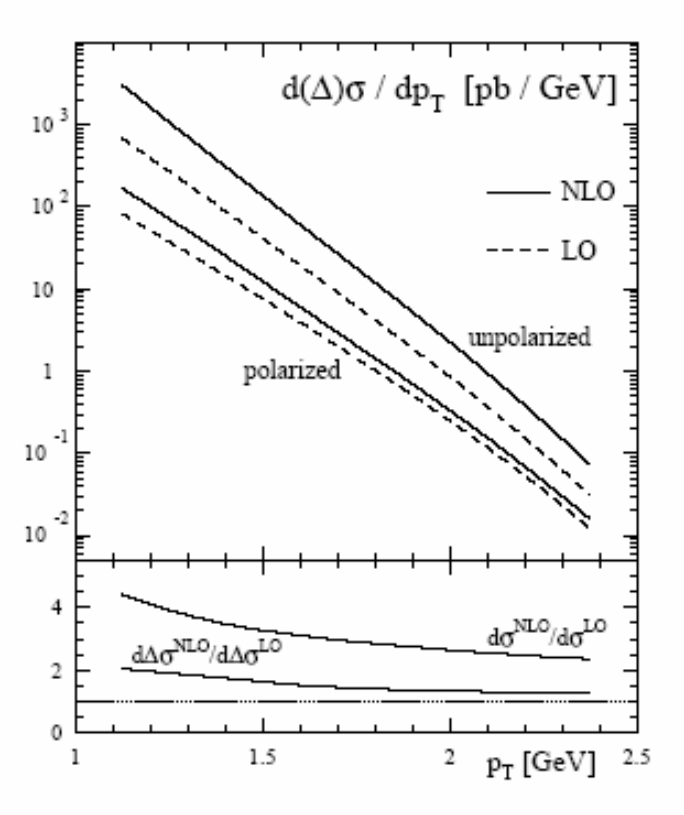


- **what about (α_s^2) corrections ???**

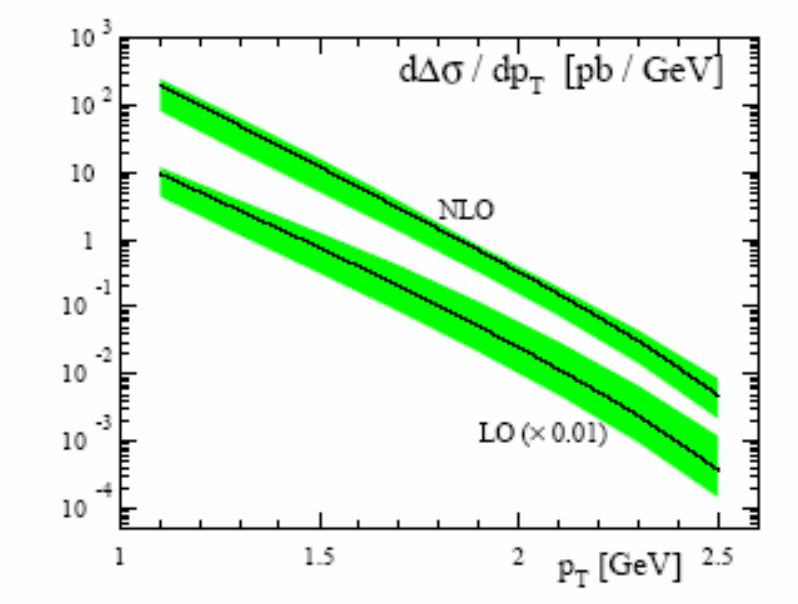
NLO Corrections

- Calculations from B. Jaeger et al. hep-ph/0505157 for HERMES:
  → "Photo-production" kinematics

Polarized and unpolarized cross sections and k factors

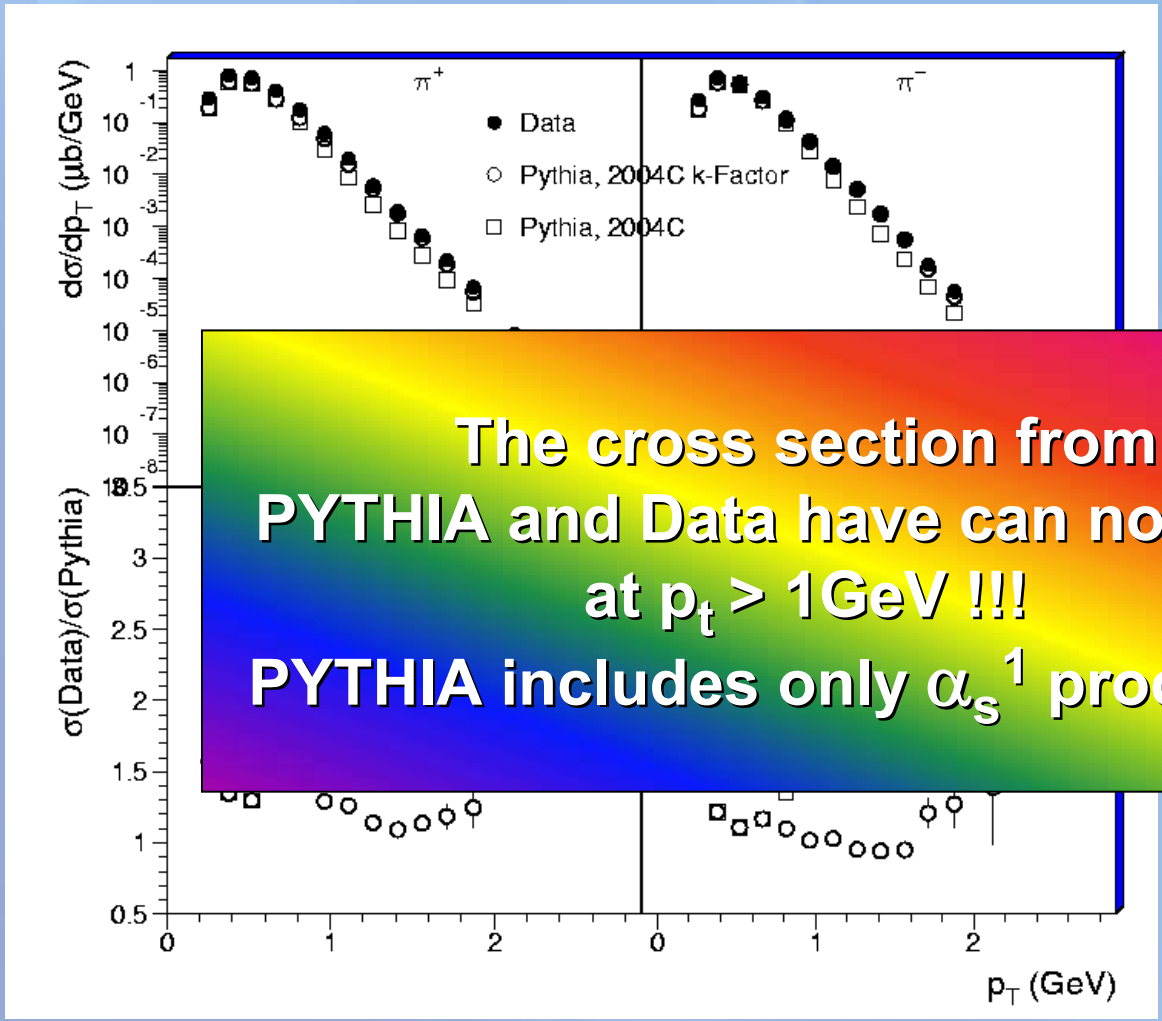


Scale dependence of polarized cross section at LO and NLO



→ **big NLO corrections**

- **Cross section vs pt in "Photo-production":**



The cross section from PYTHIA and Data have can not agree at p_t > 1GeV !!!

PYTHIA includes only α_s^1 processes

The Method

- **Measured asymmetry is an incoherent superposition of different sub-process asymmetries:**

$$A_{\parallel}^{meas}(p_t) = \sum_i f_i A_{\parallel}^{i} = f_{Bg} A_{\parallel}^{Bg} + f_{Sig} A_{\parallel}^{Sig}; \qquad f_i = \frac{\sigma_i}{\sigma_{tot}}$$

  - **Signal: Gluon of the nucleon in the initial state**

$$A_{\parallel}^{Sig}(p_t) = \langle \hat{a}_{Sig} \rangle \left\langle \frac{\Delta G}{G} \right\rangle; \qquad \hat{a}_{Sig}:$$

Asymmetry of the hard sub-process

  - **Background: all other sub-processes**

- **The gluon polarization is then:**

$$\left\langle \frac{\Delta G}{G} \right\rangle = \frac{1}{f_{Sig} \langle \hat{a} \rangle} [A_{\parallel}^{meas} - f_{Bg} A_{\parallel}^{Bg}]$$

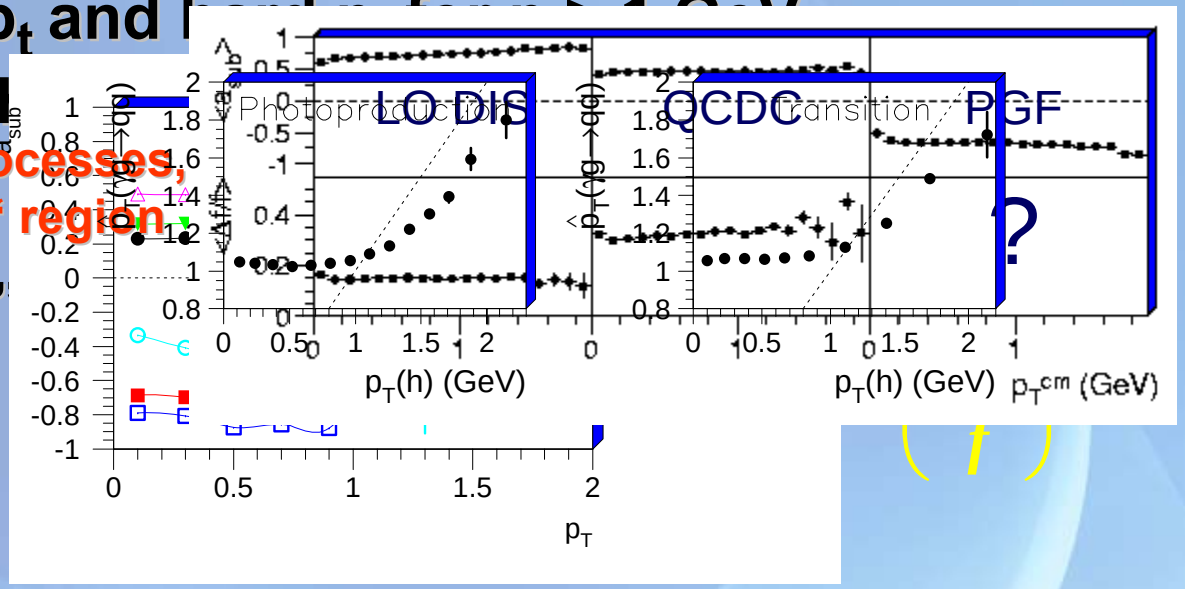
Results – MC Asymmetries

- PYTHIA itself gives only unpolarized xsec
  - Calculate asymmetry weight for each event

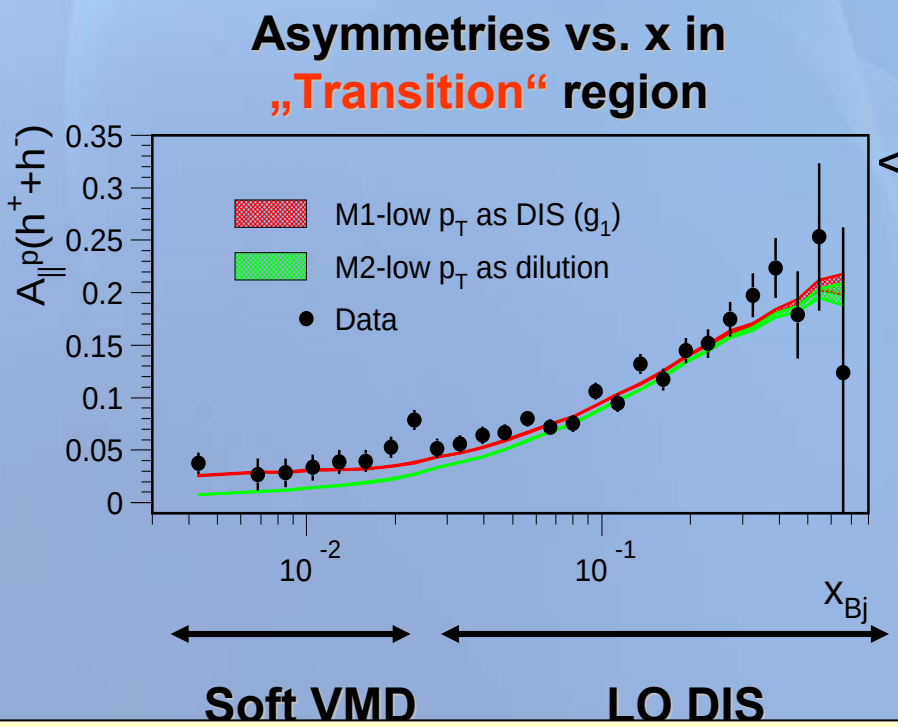
$$A_{\parallel}^{i}(p_t^h) = \frac{1}{N_h} \sum_{i=1}^{N_h(p_t^h)} \underbrace{\hat{a}_i(x, Q^2, \hat{p}_t, \hat{s}) \frac{\Delta f(x, Q^2)}{f(x, Q^2)}}$$

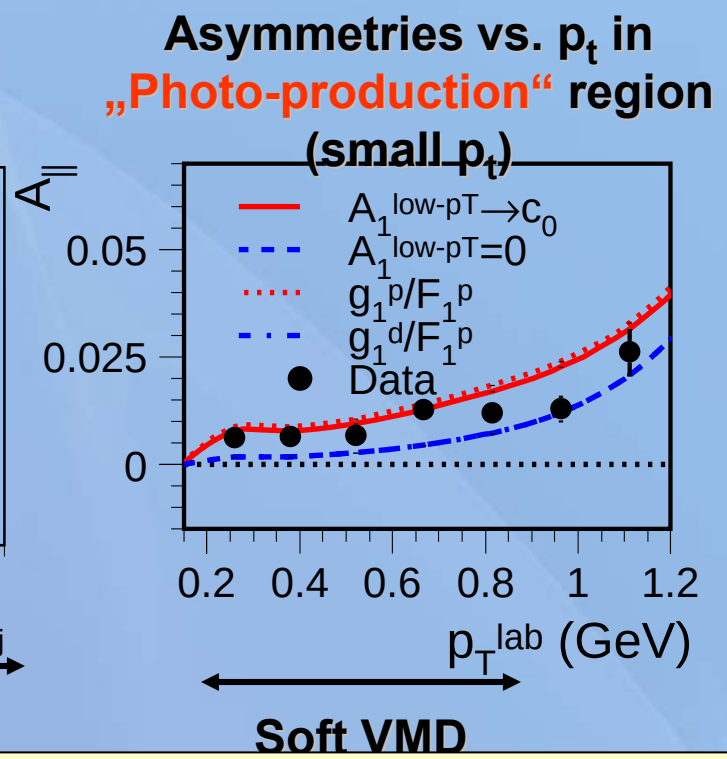
  - Takes kinematical distribution into account
- Asymmetries of hard processes known $A_{\parallel}^{i}(\langle x \rangle) \neq \langle A_{\parallel}^{i}(x) \rangle$
- Correlation of p_t and
- Assume someth
  - Polarization of
  - Asymmetry of „

LO/NLO DIS processes, in „Transition“ region, Average asymmetries for QCD 2→2 processes (hard VMD- und anomalous photon processes)



Results – MC Asymmetries

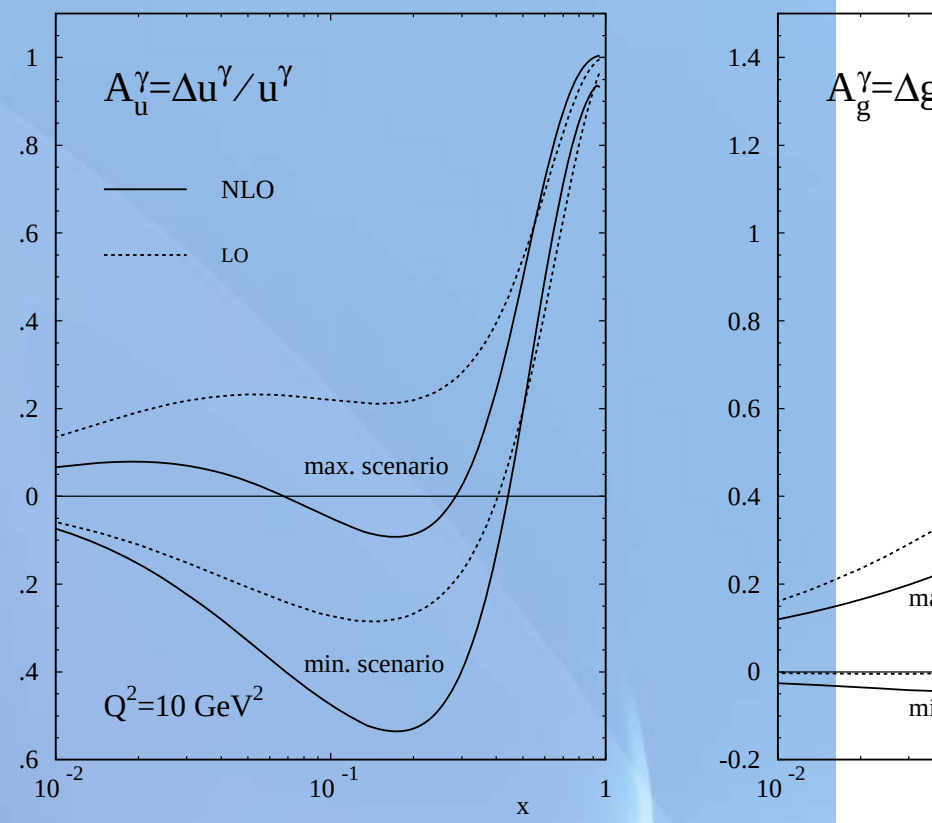




- **Large uncertainty in assigning asymmetry to low-p_t process**
  - **If it is VMD, it should not have an asymmetry**
  - **If it has an asymmetry, it should not be VMD**

Photon PDFs

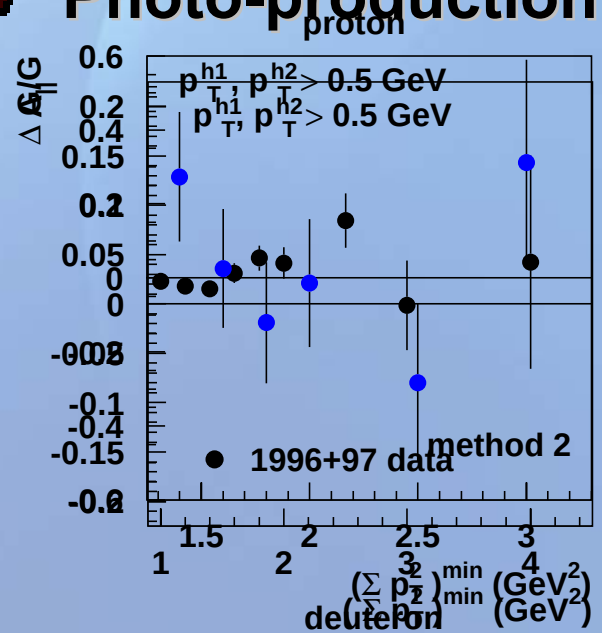
- Anomalous and hard VMD processes enter in background
  - q(photon)+q(nucleon)→2 „jets“
- and in signal
  - q(photon)+g(nucleon)→2 „jets“
- g(photon) negligible
- Only maximal and minimal scenarios for Δq/q (photon) available
  - using Δq/qmax=1 and Δq/qmin=-0.6
- Large part of total uncertainty, scales with central value



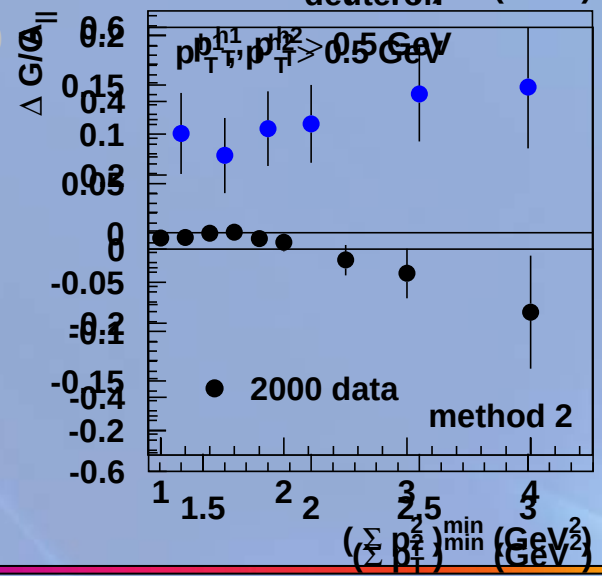
M. Glück et al., Phys. Lett. B503

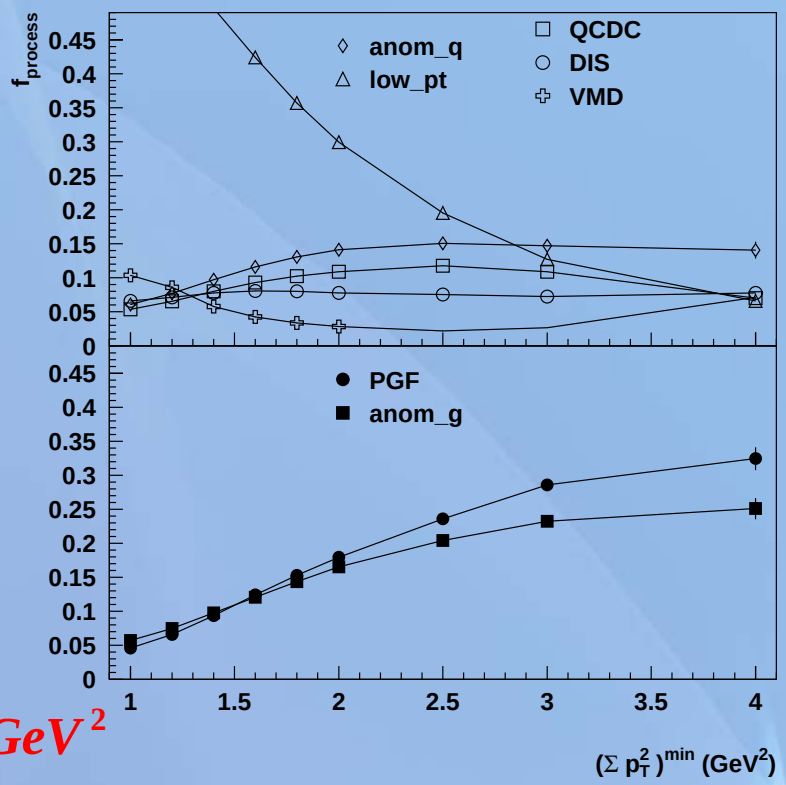
"Photo-production" high p_t hadron pairs

Proton



Deuteron





$\langle \hat{Q}^2 \rangle \sim 1.4 GeV^2$

$\langle x_g \rangle \sim 0.2$

DIS suppressed at high Σp_t^2, <10%

PGF+hard g ~ 3-4*QCDC (~10%)

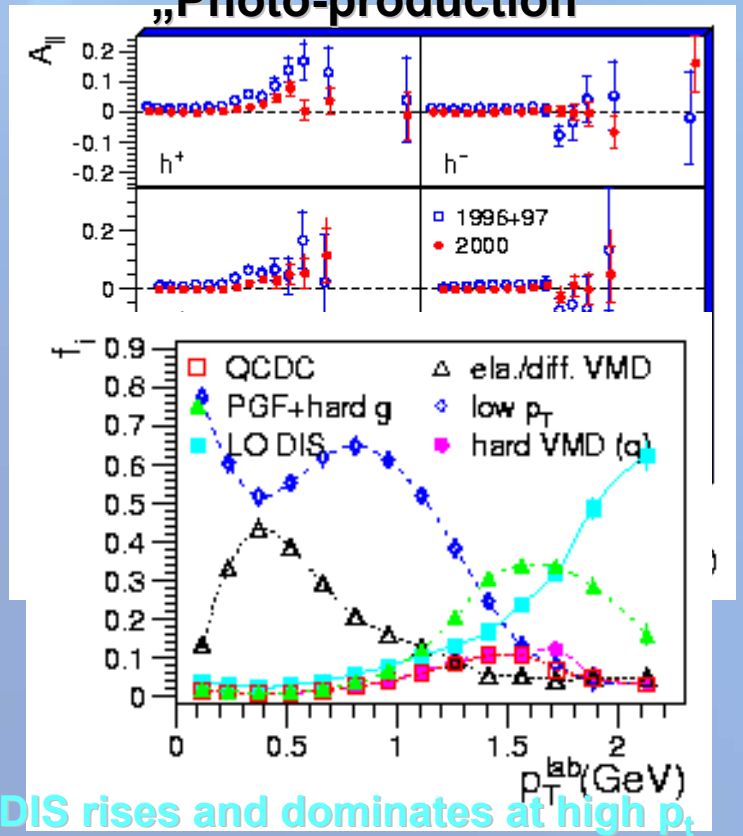
Σp_t^2 >2.5 GeV

„soft" VMD dominates at low Σp_t^2

Hard VMD processes ~15%, Σp_t^2 >2 GeV

Results - Sub-process Fractions

„Photo-production“



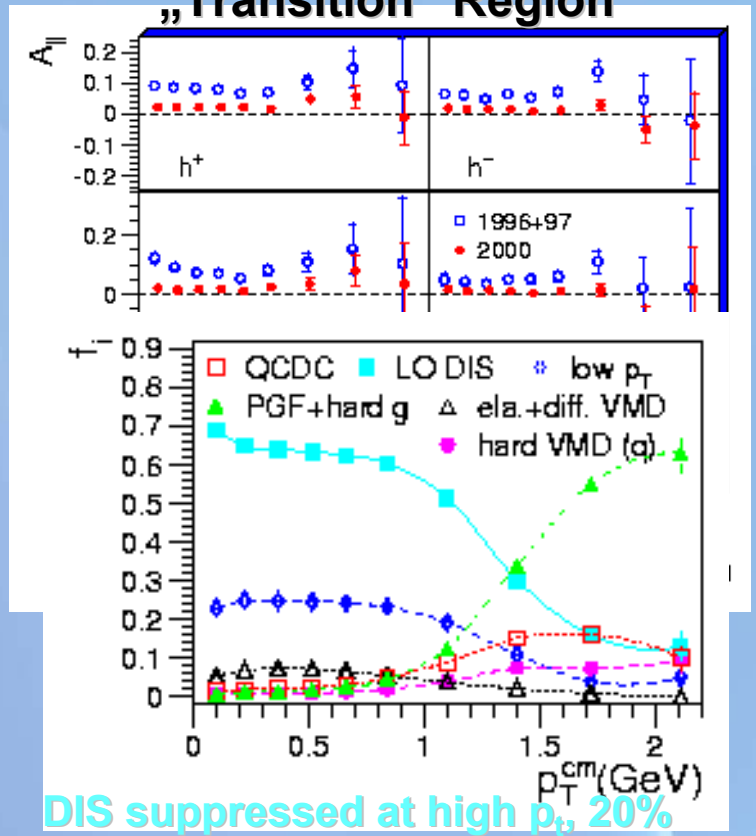
DIS rises and dominates at high p_t

PGF+hard g ~ 2-3*QCDC, ~25%, p_t >1 GeV, Hard g ~ 40% of signal

„soft“ VMD dominates at small p_T, ~40%, $p_T \geq 1$ GeV

Hard VMD processes 10%, p_T >1 GeV

„Transition“ Region



DIS suppressed at high p_t, 20%

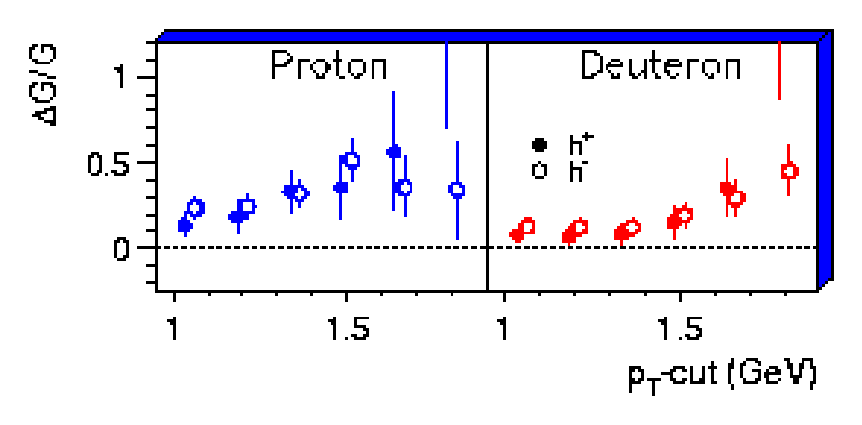
PGF+hard g ~ 2-3*QCDC, ~10-25% p_t >1 GeV

„soft“ VMD ~15%, $p_T \geq 1$ GeV

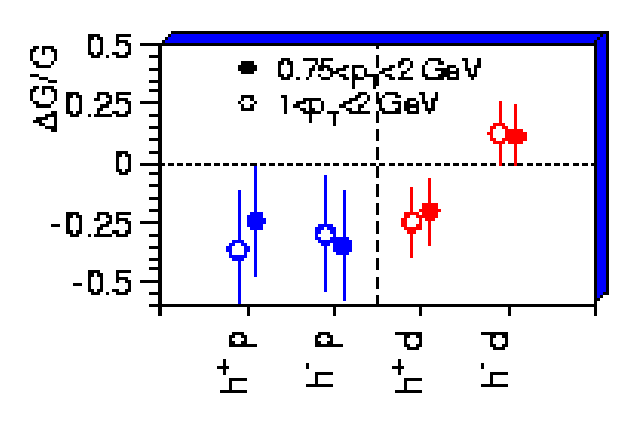
Hard VMD processes ~10%, p_T >1 GeV

Results – ΔG/G

- 4 independent data sets (p, d, $h^{\pm}$)
- „Photo-production“ reg.
  - Scale $Q^2 \approx 1.25$ GeV^2, $x \approx 0.15$
  - At p_T<1.5 GeV results for
    - Proton > Deuteron

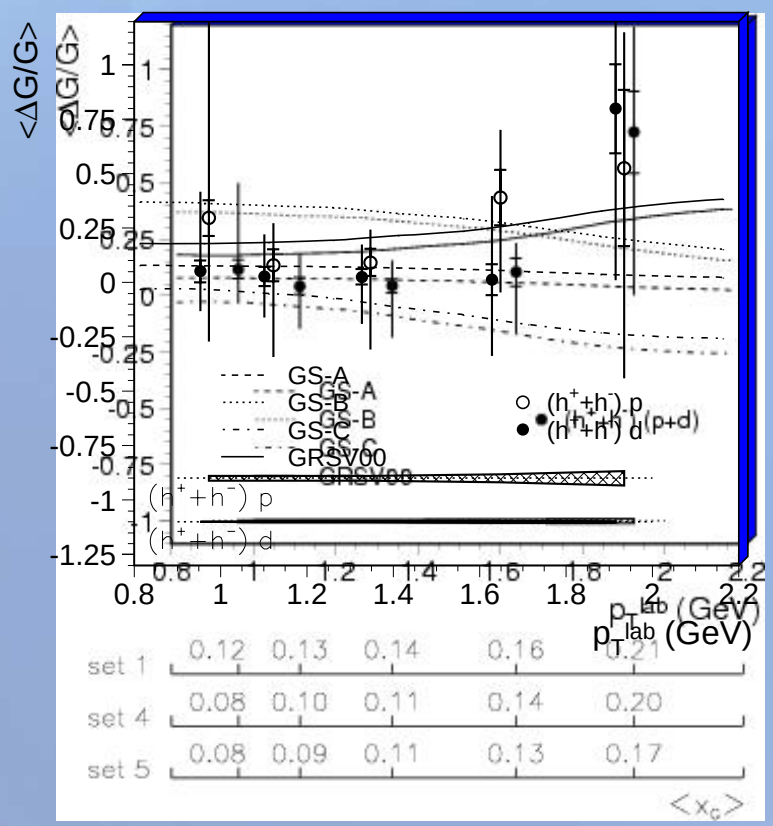


- „Transition“ region
  - Scale $Q^2 \approx 1.77$ GeV^2, $x \approx 0.16$
  - 2.8 σ difference between
    - h^+ and h^- Deuteron

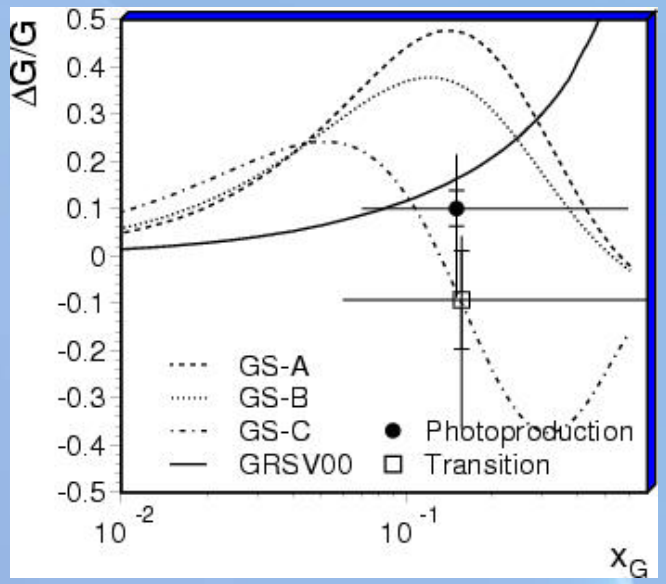


Results - ΔG/G

- "Photo-production"
  - combined data sets

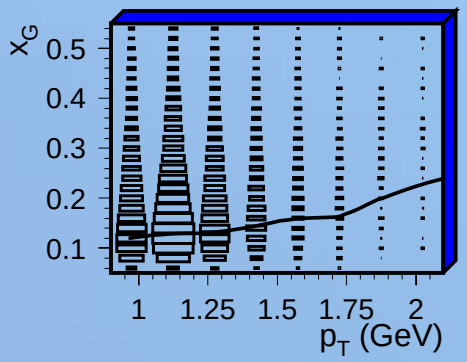


- Combined data in both regions
  - "Transition"
    only Deuteron data; p_t > 1 GeV
  - "Photo-production"; p_t > 1.35 GeV



Open Points

- Very wide correlation between p_t and x_g



- Can the mean value theorem be used to calculate $\Delta G/G$

$$A_{\parallel}^{Sig}(p_t) \sim \frac{\sigma_{pol}}{\sigma_{unpol}} = \frac{\Delta G \otimes \Delta\hat{\sigma}}{G \otimes \hat{\sigma}}; \quad \hat{a} = \frac{\Delta\hat{\sigma}}{\hat{\sigma}} \Longrightarrow A_{\parallel}^{Sig}(p_t) = \left\langle \hat{a}_{Sig} \right\rangle \left\langle \frac{\Delta G}{G} \right\rangle$$

depends strongly on shape of $\hat{a}(x_1)$ and $\Delta G(x_1)$

$\Longrightarrow$ if not, redo last step of analysis with different formalism

- Pythia calculates only unpolarised kinematics
  unpol. kinematics = / ≠ polarized kinematics
  only solution polarized MC

Conclusion

- Hermes can extract ΔG/G from tagged and anti-tagged high-p_t hadron asymmetries with good statistics and
  - Big model (MC) dependence
  - not so small estimated systematic uncertainties within one model
  - Not yet accounted for:
    - Large NLO corrections to pol. and unpol. cross sections
    - Statistical uncertainties of pol. and unpol. PDF used (including g(x))
- Analysis of high-p_t hadron pairs consistent
- Find solution to open points
- For less model dependent measurements:
  - Higher energy (collider) – need high luminosity
  - For ep or γp: Measure pol. photon PDFs
  - Clean process (prompt photon at RHIC?) and/or heavy quarks (open charm?)