The nucleon helicity as seen by HERMES

From g_1 to ΔG

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for the hermes collaboration

Annual RHIC and AGS Users Meeting, BNL, June 18-22 2007

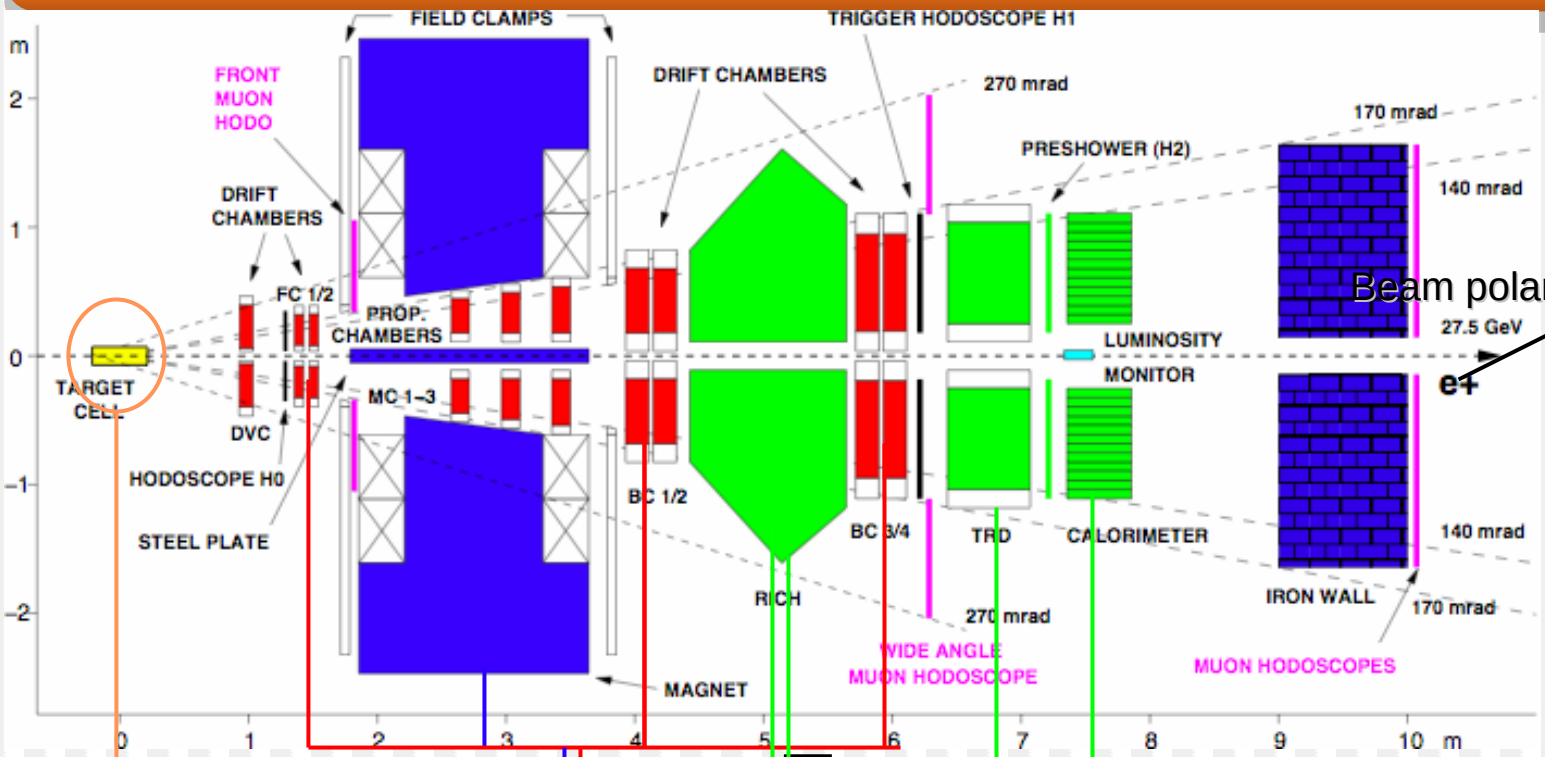
Outline

- Nucleon helicity structure has been studied by Hermes mainly in 3 ways
  - Inclusive DIS -> g_1
  - Semi-inclusive DIS -> purity analysis
  - High-p_T hadrons with sensitivity to Δg
- No data with longitudinally polarized data since 2000, but
  - Ongoing, refined and complementary analyses
  - Analysis of unpolarized data for F_2, d_v/u_v and FF

A Quick Reminder

HERA ep collider at DESY (Hamburg)
Polarized $e^{\pm}$ with 27.5 GeV
Hermes cms energy (fixed target) 7.2 GeV

Hermes



Beam polarization 50%

Internal longitudinally polarized H,D target
P≈0.□85
Flip every 60, 90s

Resolution:
$\Delta p/p \approx 1\text{-}2\%$
$\Delta\Theta \approx 1$mrad

e/h separation efficiency >98%, contamination<1%

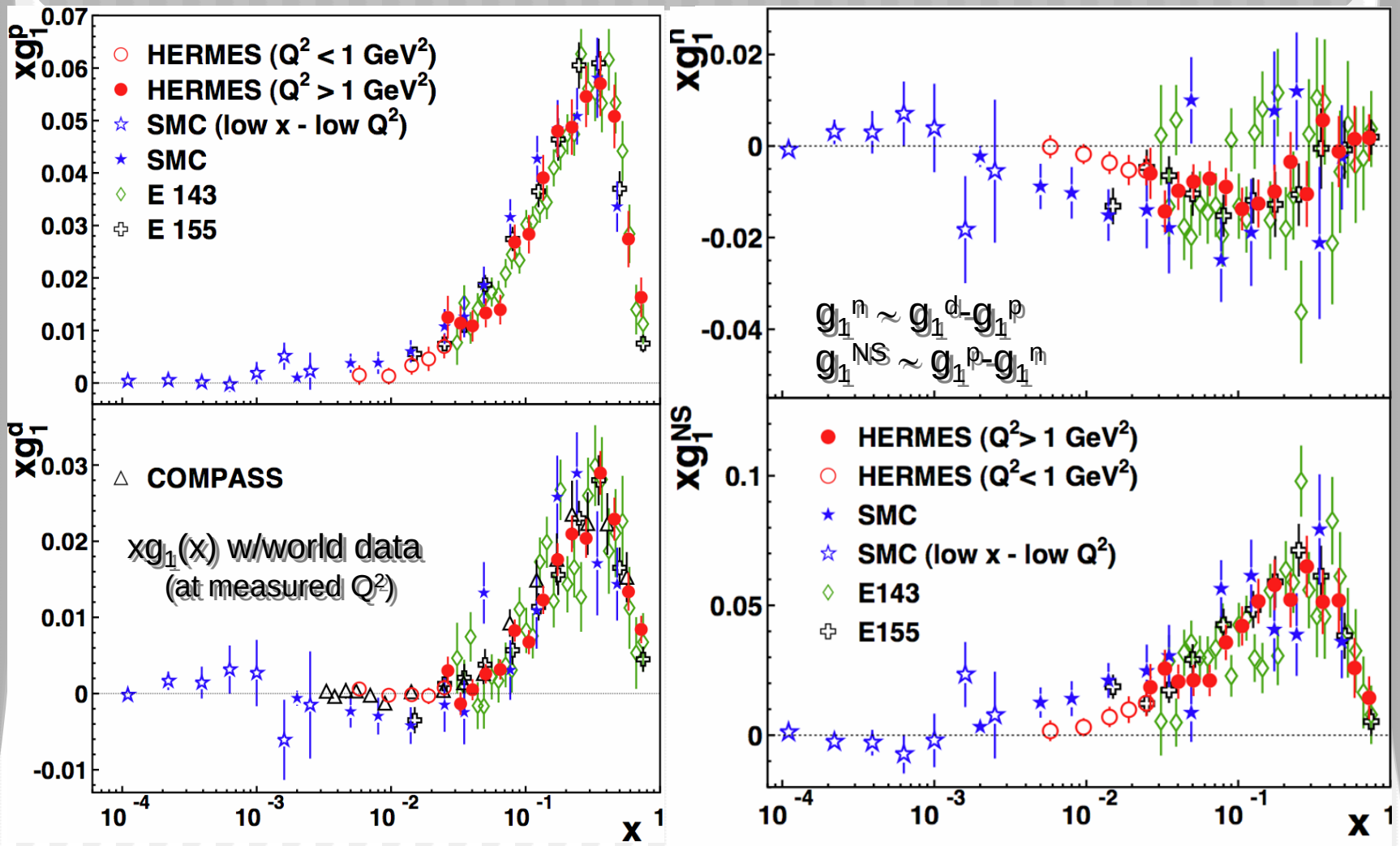
π/k/p separation w/dual radiator RICH
2<p<15 GeV
π ID 4<p<13 GeV w/threshold Cherenkov

g_1 Finally Published!

A. Airapetian et al, Phys. Rev. D 75 (2007) 012007

- $g_1^{p,d}$ corrected (unfolded) for instrumental smearing and QED radiative effects
  - Points *statistically* correlated
  - Only diagonal elements of covariance matrix shown in plots
- Error bars include systematics from F_2, R parametrization and Q^2 evolution (within x bin)

Final Results on g_1



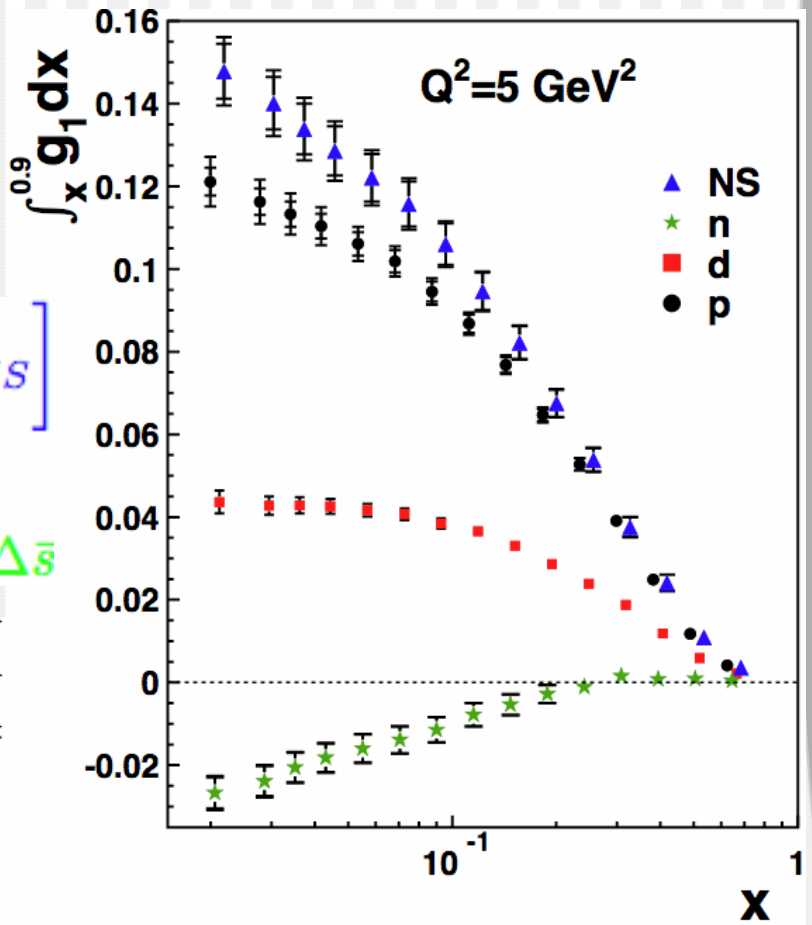
g_1 Integrated

- Integrals for 0.021<x<0.9
- Integral seems to saturate at x<0.04 for Deuteron
  - Use Γ_1^d to extract

$$a_0(Q^2) = \frac{1}{\Delta C_S}\left[\frac{9\Gamma_1^d}{1-\frac{3}{2}\omega_D} - \frac{1}{4}a_8\Delta C_{NS}\right] = \Delta\Sigma_{MS}$$

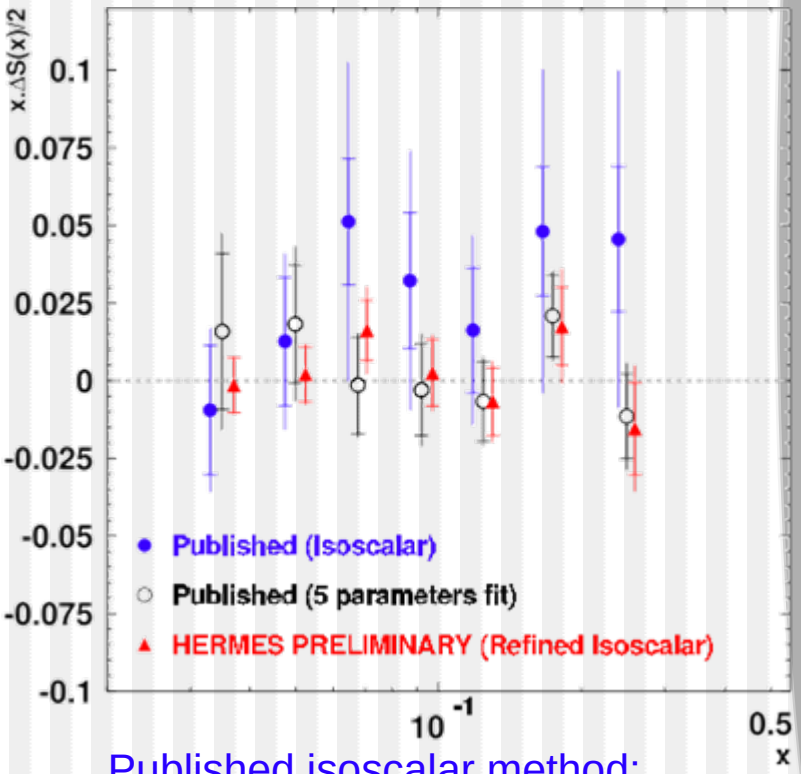
and $\Delta u + \Delta\bar{u},\ \Delta d + \Delta\bar{d},\ \Delta s + \Delta\bar{s}$

NNLO	central value	uncertainties		
		theor.	exp.	evol.
a_0	0.330	0.011	0.025	0.028
$\Delta u + \Delta\bar{u}$	0.842	0.004	0.008	0.009
$\Delta d + \Delta\bar{d}$	-0.427	0.004	0.008	0.009
$\Delta s + \Delta\bar{s}$	-0.085	0.013	0.008	0.009



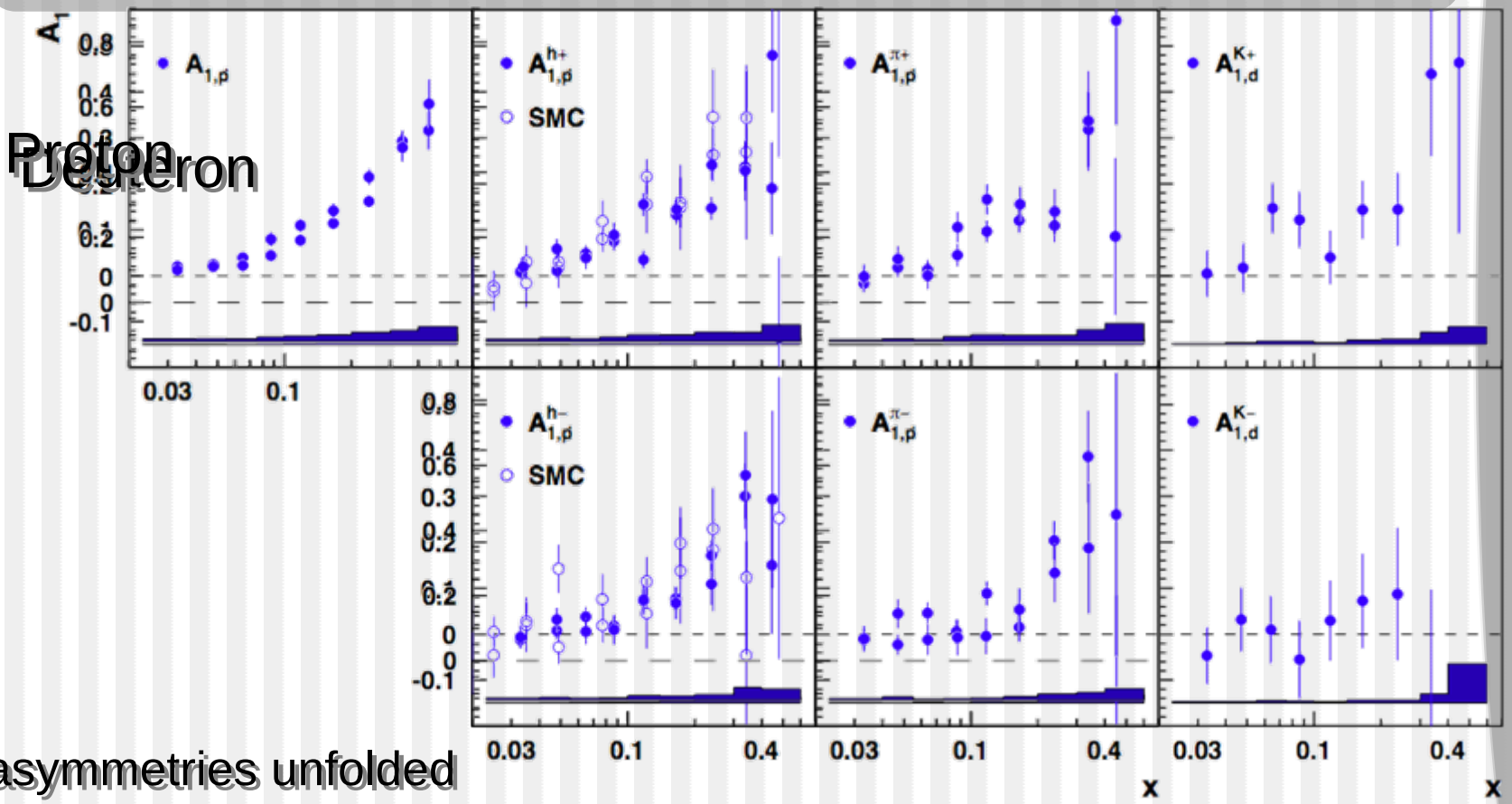
Δs vs. Δs?

- Extraction of $\Delta u + \Delta\bar{u}$, $\Delta d + \Delta\bar{d}$ uses SU(2) flavor symmetry - Bjorken Sum Rule
- Extraction of $\Delta s + \Delta\bar{s}$ uses SU(3) flavor symmetry
- But: $\Delta s + \Delta\bar{s} < 0$, even with 20% SU(3) breaking while semi-inclusive Hermes data give $\Delta s + \Delta\bar{s} \approx 0$
- Consistent?
  - Negative contribution at lower x<0.02?



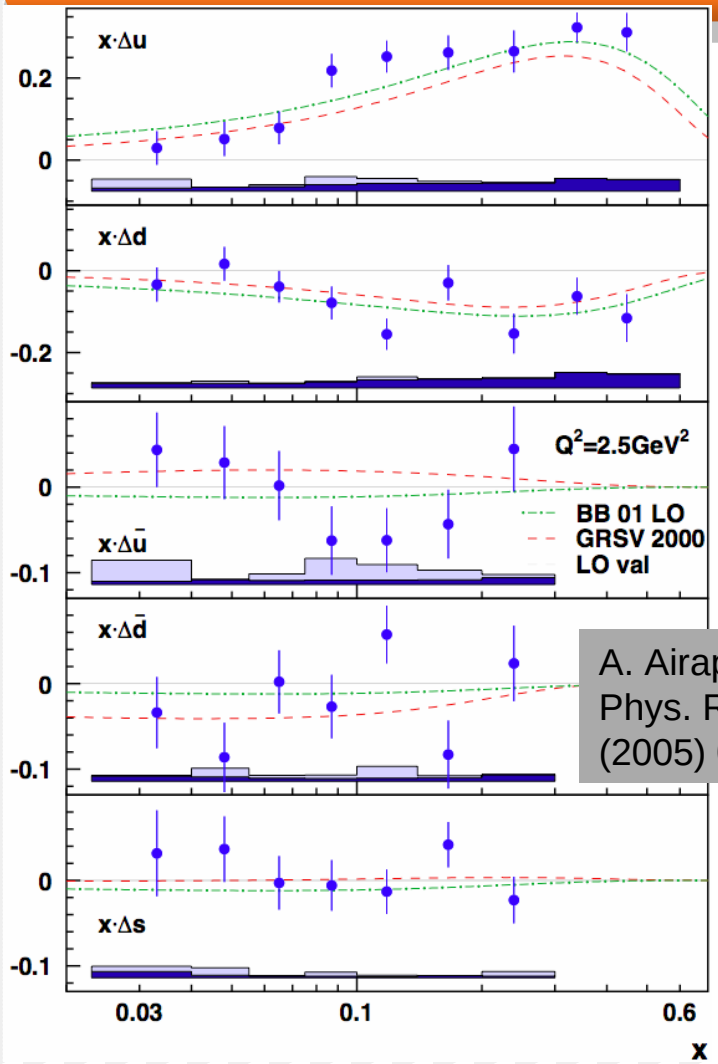
Published isoscalar method:
Assumed FF from BKK
(Phys. Rev. D 52, 4947 (1995))

SIDIS Asymmetries



All asymmetries unfolded
to correct for smearing
and QED radiative effects

Analysis of SIDIS Data



A. Airapetian et al, Phys. Rev D 71 (2005) 012003

- Quark polarizations obtained from DIS+SIDIS (identified pion, kaon) asymmetries on proton and deuteron, using purity formalism:

$$A_1^h = c\sum_q \frac{e_q^2 q(x)\int_z dz D_q^h}{\sum_{q'} e_{q'}^2 q'(x)\int_z dz D_q^h}\frac{\Delta q(x)}{q(x)}$$

Purity: $P_q^h(x)$

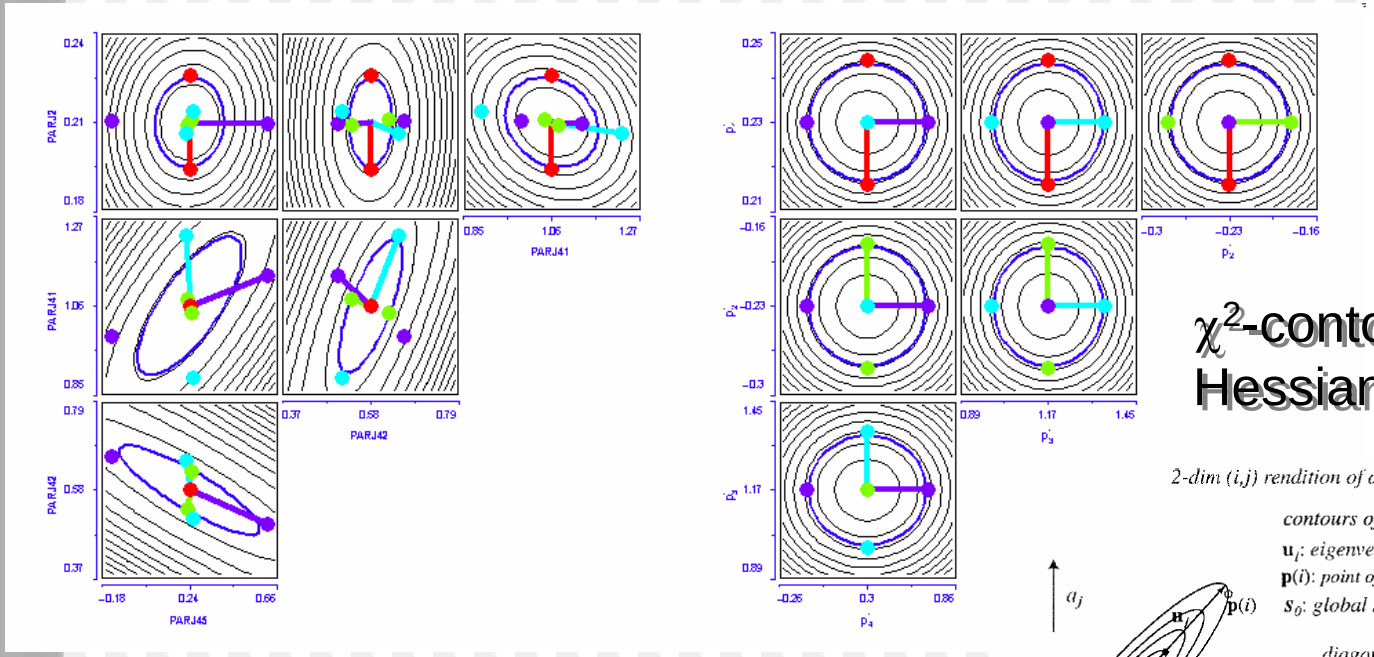
$$\vec{A}_1 = P\vec{Q}$$

- Purities determined by MC
- Caveat: LO analysis, dependent on MC fragmentation model

Study of Lund Fragmentation

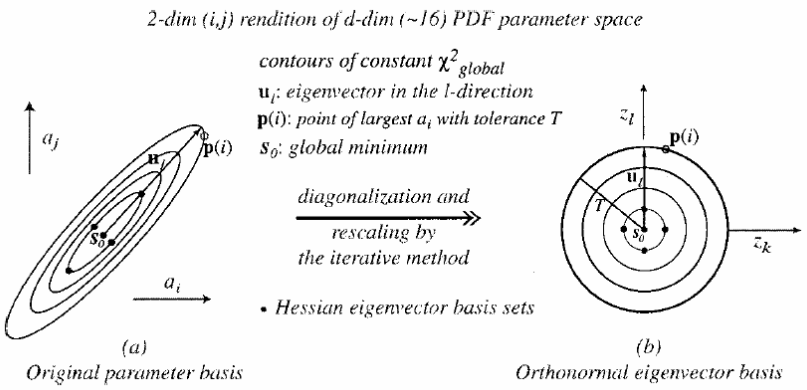
- LUND string fragmentation parameters are tuned by minimizing the difference of MC and data (identified) hadron multiplicities
  - Find agreement within ~10% (for pions)
- But: What are the errors?
  - Estimate systematic uncertainties of values extracted using LUND MC (e.g. on $\Delta q/q$ from purity method)
  - Usual method: Compare an old "historical" fit with the current one ➔normally gives large uncertainties
- Error scan using Hessian matrix (similar to CTEQ)

LUND Error Scan



χ^2-contours in correlated LUND parameter space

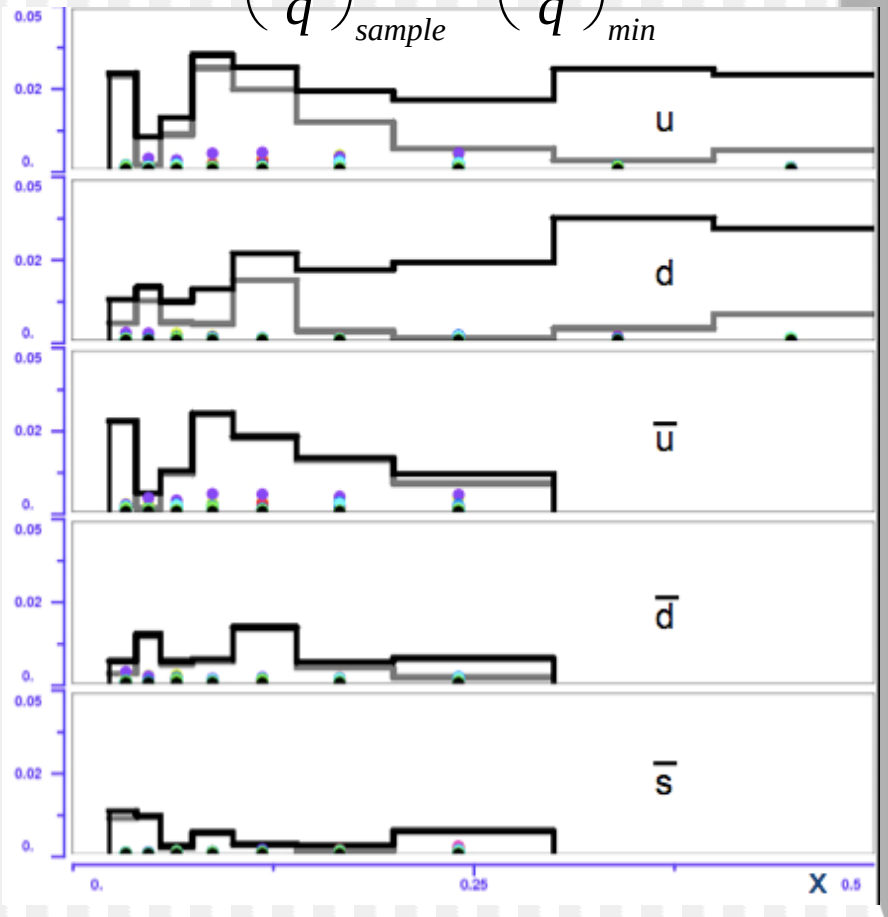
χ^2-contours in uncorrelated Hessian parameter space



Result of Error Scan

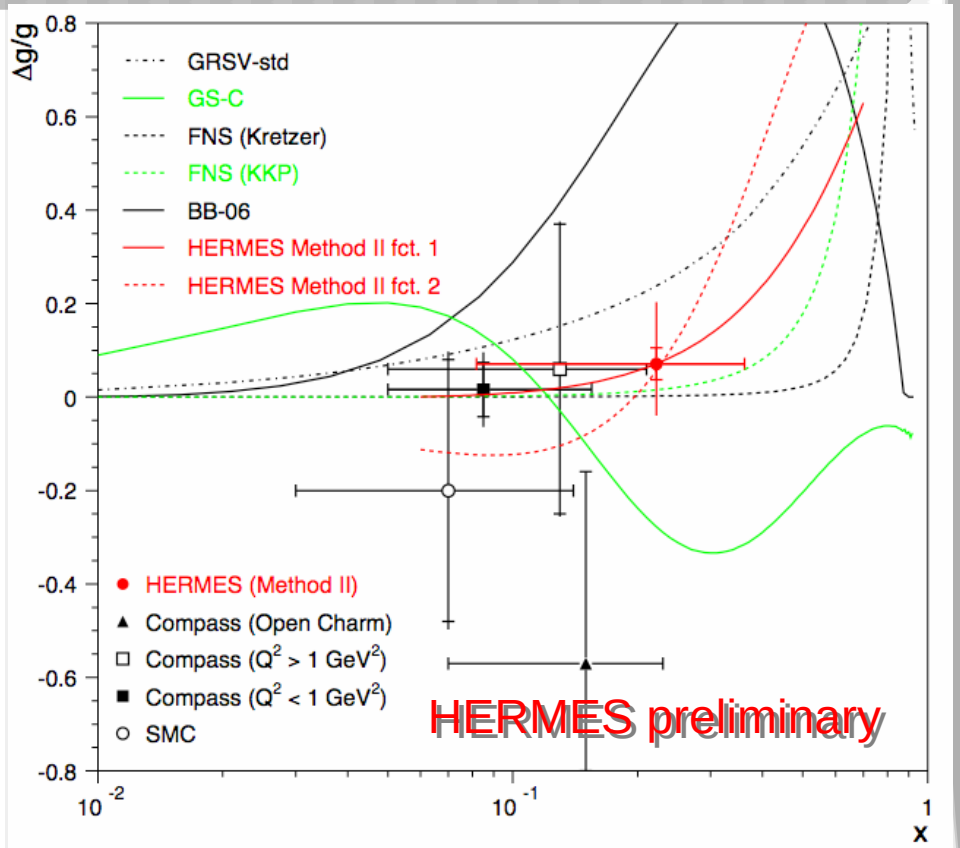
- Black line = total systematic error estimate on $\Delta q/q$
- Grey line = contribution from comparing old and new tunes
- Colored points = Sample $\Delta q/q$ with parameters along 68% Hessian contour
  - "True" error from LUND tune is much smaller than estimate
- But: The overall χ^2/ndf ≈20 for the best tune ➔ MC model itself is not perfect
  - Uncertainty due to "use of MC" unknown
  - Studies are ongoing

$$\left(\frac{\Delta q}{q}\right)_{sample} - \left(\frac{\Delta q}{q}\right)_{min}$$



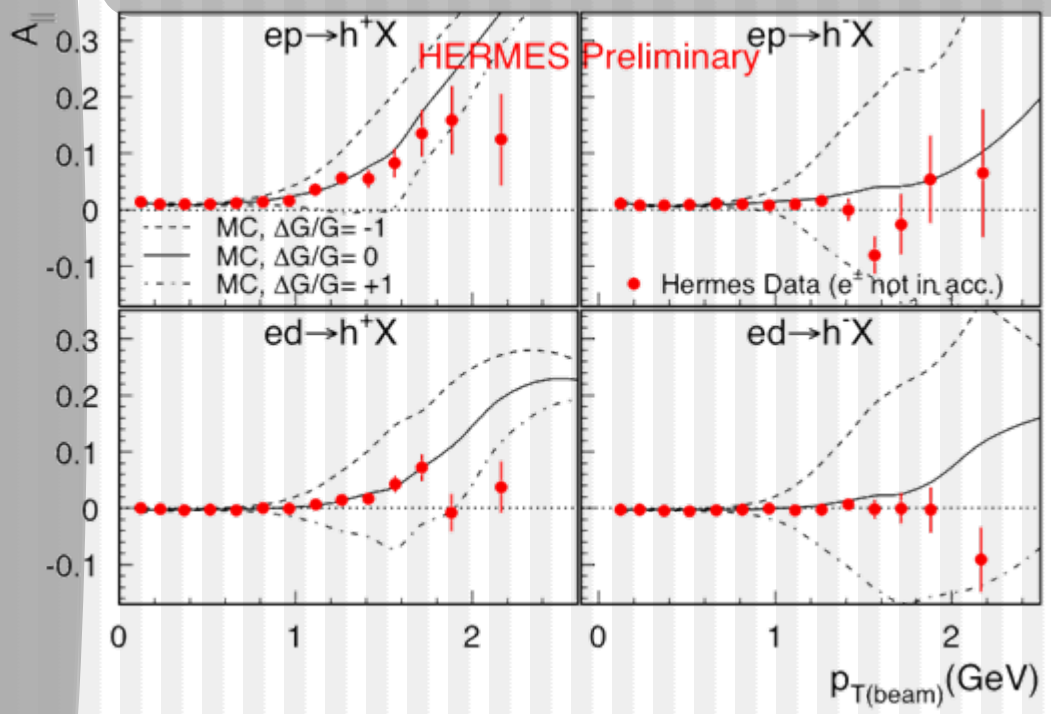
Model Dependent, Leading Order Result on Δg/g

- Black and green curves from pQCD fits to g_1
- Red curves: Fits to HERMES high-p_T hadron data using LO MC+pol. PDF model and 2 functional forms
- Red point: Average Δg/g from fits.



A lot of the analysis is in the determination of the systematic error and the mean x

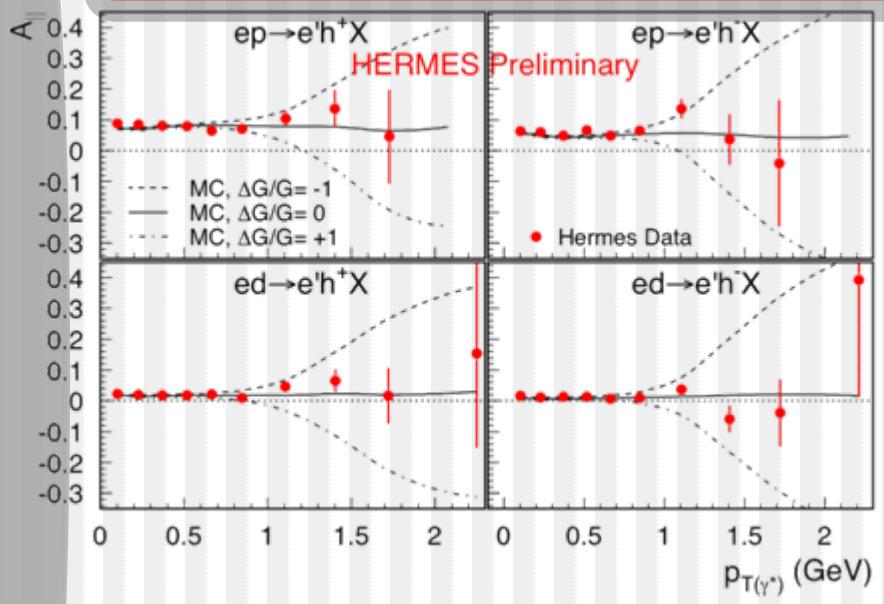
From Measurements …

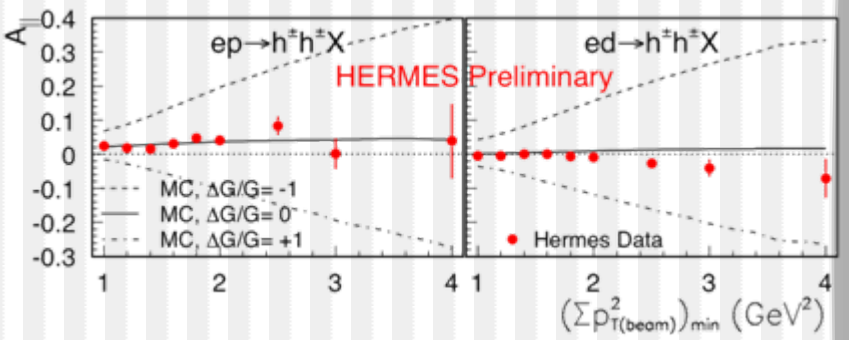


- "Antitagged" data:
  - Scattered lepton not in the acceptance
  - p_T measured w/respect to beam axis
- Curves from MC+asymmetry model using
  - $\Delta g/g(x)=0$: central
  - $\Delta g/g(x)=-1$: upper
  - $\Delta g/g(x)=+1$: lower

$\Delta g/g=0$: asymmetry is due to quarks only! Gluons become important for the cross section (asymmetry) above $p_T \approx 1$ GeV

(More Asymmetries)





- "Tagged" inclusive charged hadrons
  - Scattered lepton detected
  - $Q^2>0.1$ GeV^2, $W^2>4$ GeV^2
  - p_T w/respect to virtual photon

- Inclusive Pairs of charged hadrons
  - No regard to scattered lepton
  - All charge combinations
  - p_T w/respect to beam axis
  - $p_T(h1,h2)>0.5$ GeV
- Plotted vs. lower cut on:

$$\sum p^2_{T(beam)} = p^2_{T(beam)}(h_1) + p^2_{T(beam)}(h_2)$$

… via MC information …

- Fractions of contributing subprocesses
  - From PYTHIA 6.2 model
  - Tuned and adapted for HERMES data (see later)
- Their asymmetries
  - Initial state partons
  - Kinematics of the hard subprocess
    - Scale, x, p_T
  - Subprocess kinematics of hard processes with gluons in the nucleon in initial state -> Signal

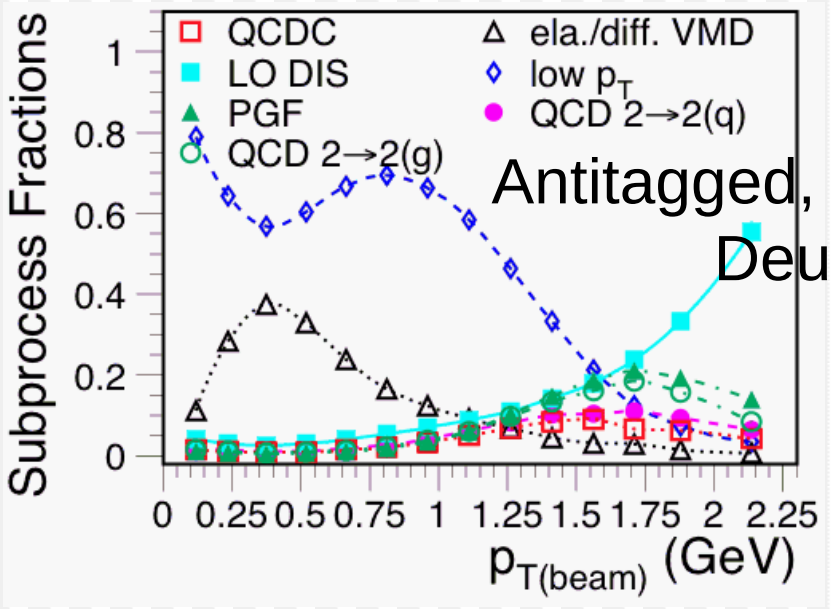
… and an Asymmetry Model

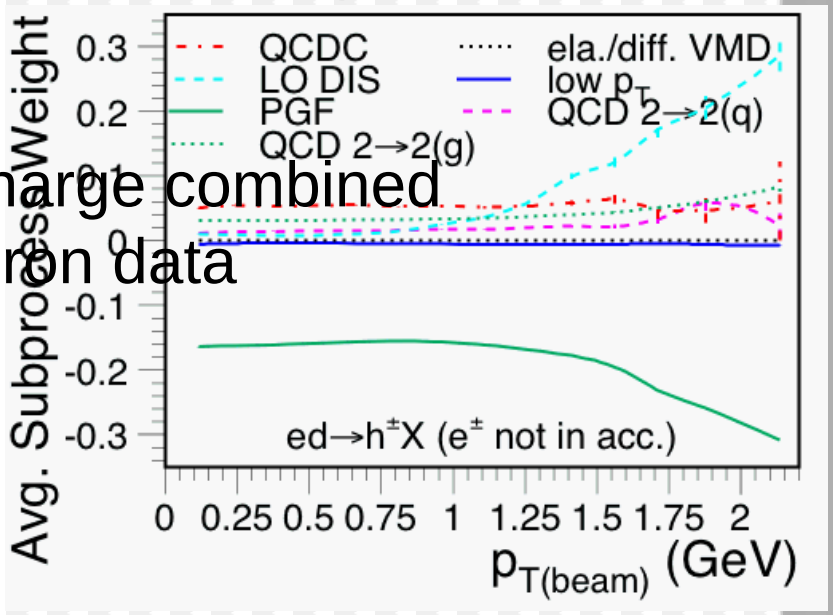
- Event-by-event calculation from MC kinematics, flavors, subprocess type
  - Hard processes: Use pol. LO PDF (GRSV 2000)
  - Hard resolved photon processes: Use 1/2(maximal+minimal) scenarios from GRS
  - Soft processes: Use assumptions
    - A=0 for exclusive/diffractive processes
    - $A \sim A_1$(low x) from world data for soft nondiffractive ("low-p_T")
- Vary PDFs/assumptions for syst. error

(Fractions and Asymmetries)

Subprocess Fraction

Subprocess Asymmetries (using GRSV std.)





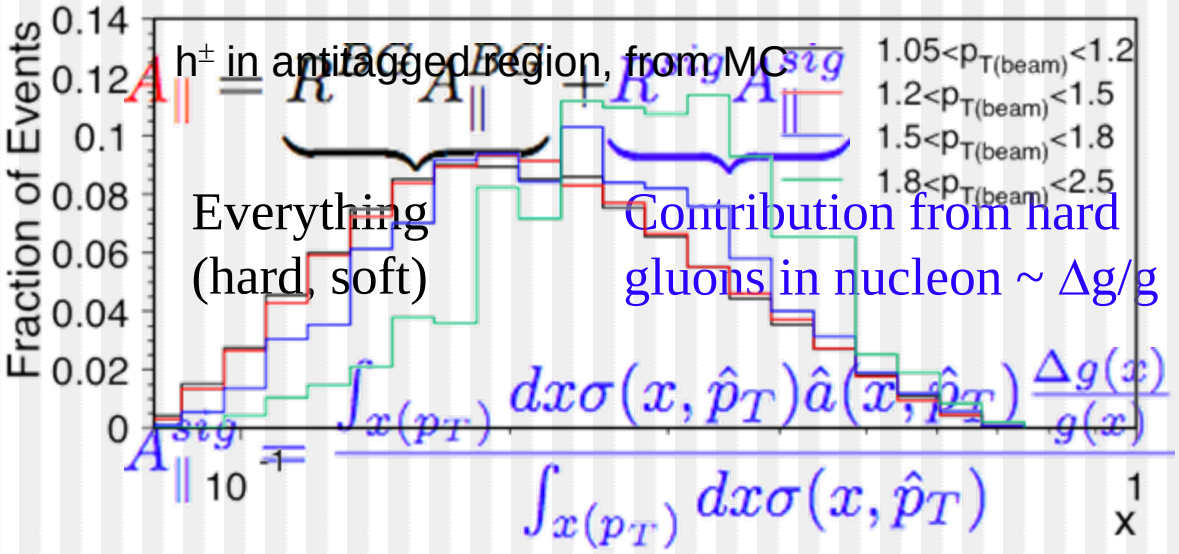
Antitagged, charge combined
Deuteron data

VMD (elast.+diffr., low-p_T) decreasing w/p_T
DIS increasing with p_T
QCDC/QCD2->2(q) increasing with p_T
Signal processes are PGF and QCD2>2(g) (resolved photon)

DIS increasing with p_T (x) - positive
QCDC/QCD2->2,VMD flat and small
Important for background asymmetry!
|PGF| increasing with p_T - negative
QCD2->2(g) opposite to PGF, small

… to Δg/g

- Once we know everything necessary: How do we get Δg/g out of this?



x-range covered by data (unpolarized): 0.07<x<0.7

Methods for Δg/g Extraction

- Method I:
  - Factorize

$$A_{\parallel}^{sig} \approx \langle \hat{a} \rangle (p_T) \left\langle \frac{\Delta g}{g} \right\rangle (p_T)$$

  - Assumes
    - No sign change in â(x)
    - "flat" Δg/g(x)
  - No information on <x> of measurement
  - Gives average Δg/g over covered x range (0.07<x<0.7)

- Method II:
  - Fit: find a Δg/g(x) such that

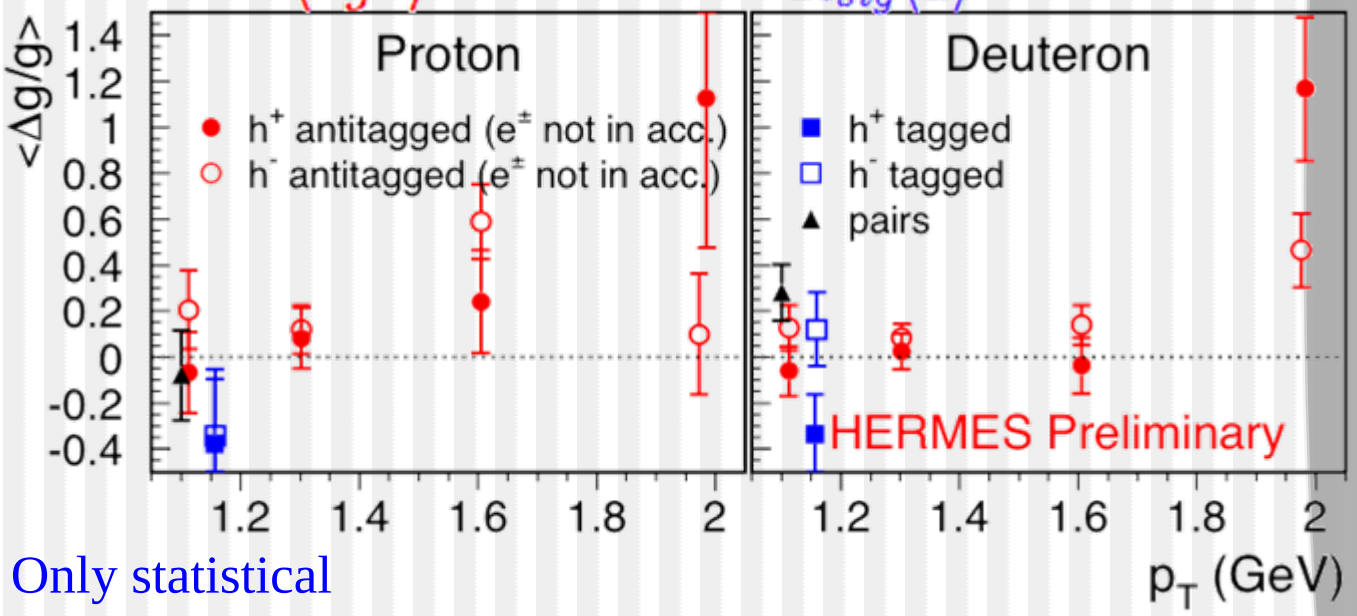
$$A_{\parallel}^{MC} = A_{\parallel}^{meas}$$

  - Assumes functional form for Δg/g(x)
  - Only small range in p_T
  - Gives Δg/g(x) and average x of measurement

Δg/g From Method I

$$\left\langle \frac{\Delta g}{g} \right\rangle (p_T) = \frac{A_{\parallel}^{meas} - R_{BG} A_{BG}}{R_{sig} \langle \hat{a} \rangle}$$

h⁺,h⁻ antitagged:
4 points between
$1.05 < p_T < 2.5$ GeV
h⁺,h⁻ tagged:
1 point for
$p_T > 1$ GeV
Pairs:
1 point for
$\sum p_T^2 > 2\text{GeV}^2$

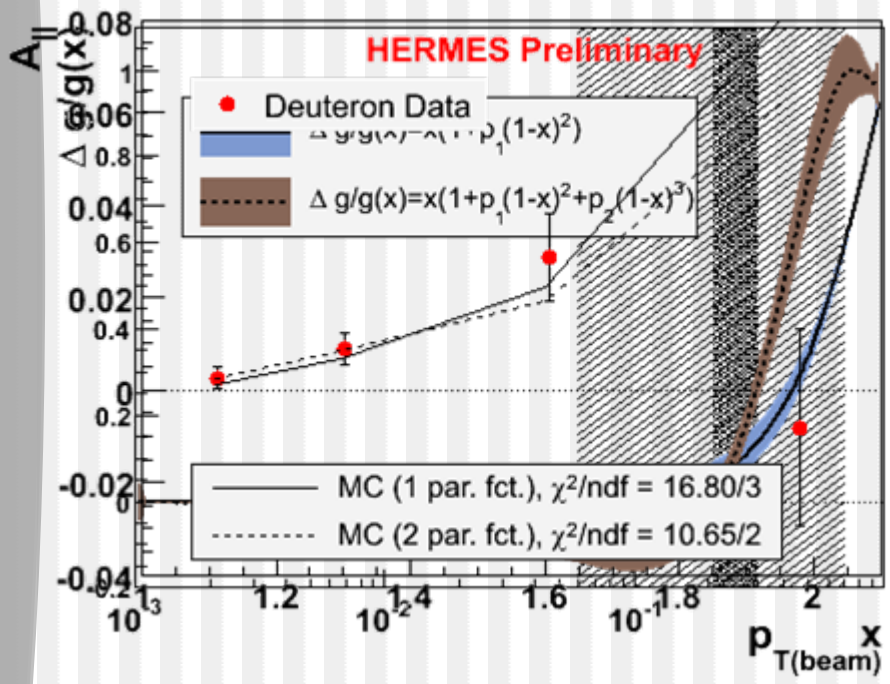


Only statistical

- Results for different data samples agree within statistics
- Dominating sample: Deuteron antitagged -> Used for Method II and syst. error analysis (charge combined)

Δg/g from method II

Fit results



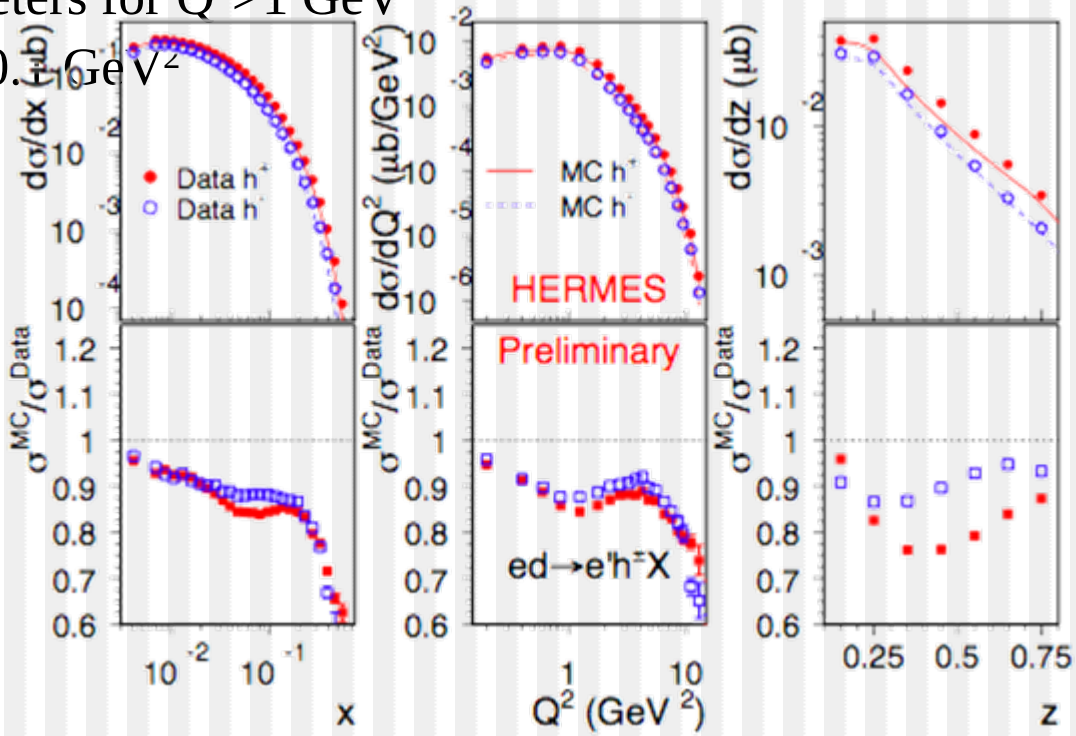
•Light shaded area: range of data
•Dark shaded area: fit center of gravity

- Final 2 functions used are polynomials with 1(2) free parameters
- Fix:
  - $\Delta g/g \rightarrow x$ for $x \rightarrow 0$ and
  - $\Delta g/g \rightarrow 1$ for $x \rightarrow 1$ (Brodsky et al.)
- $|\Delta g/g(x)|<1$ for all x
- Difference between functions is a systematic uncertainty
- $\chi^2/ndf \approx 5$ due to highest p_T point
  - Model syst. not included in fit
  - 1-2 parameter function is too smooth

How Good is the Model?

- PYTHIA 6.2 has been tuned
  - Fragmentation parameters for $Q^2>1$ GeV^2
  - VMD Model for $Q^2>0.1$ GeV^2

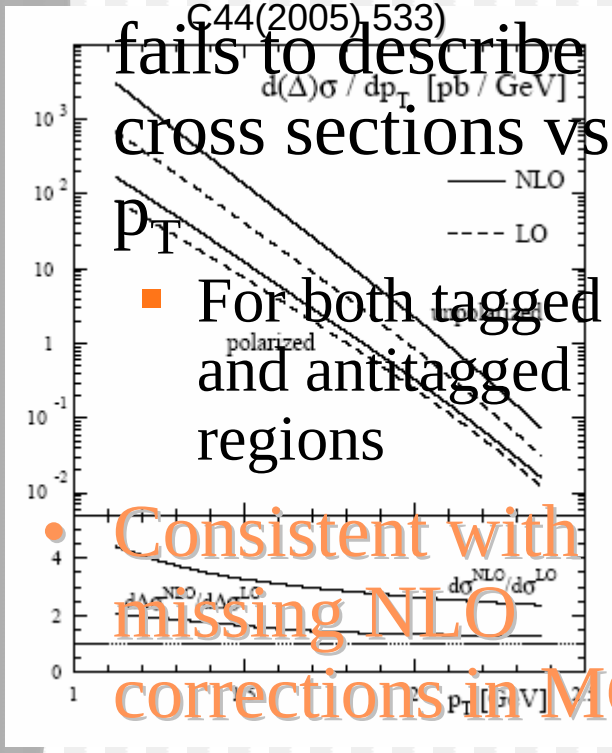
Tagged region:
Comparison of cross sections for charged hadrons (:in HERMES acceptance:)



- Get fair agreement in tagged region ($Q^2>0.1$ GeV^2) when integrating over p_T

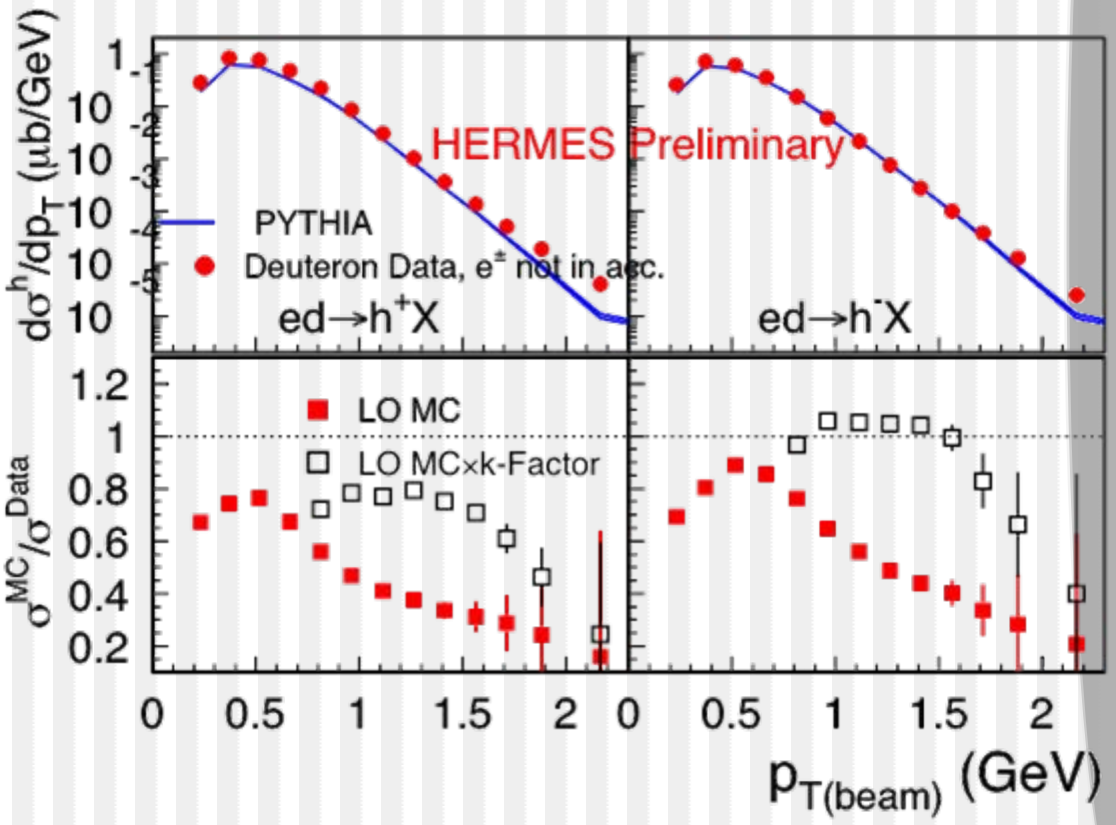
How Good is the Model Really?

- Polarized and unpol. cross sections and k factors (B. Jäger et al., Eur.Phys.J. C44(2005) 533)



- The very same tuned PYTHIA fails to describe cross sections vs. p_T
  - For both tagged and antitagged regions
- Consistent with missing NLO corrections in MC

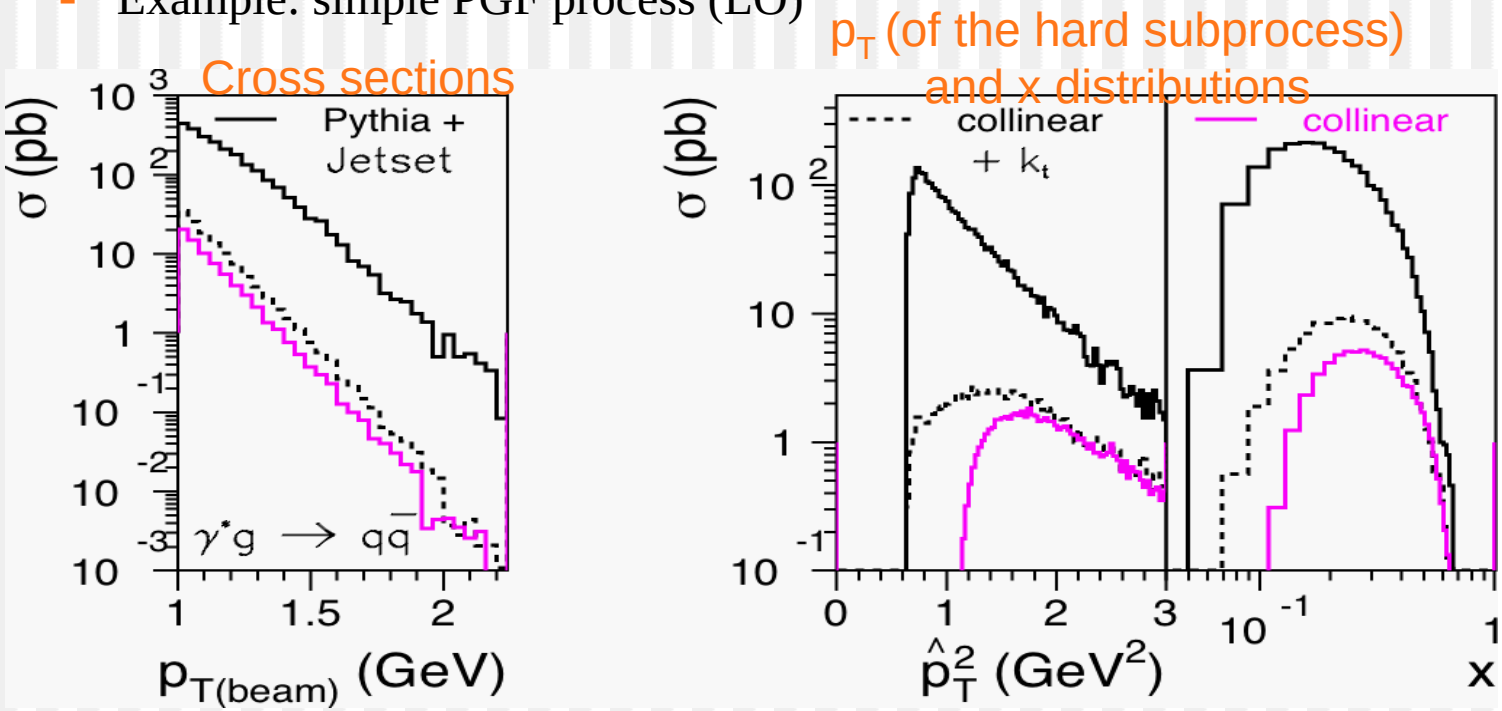
Antitagged region: Comparison of cross sections of charged hadrons (:in HERMES acceptance:)



Application of k-factor to relevant processes in MC gives better agreement with data

LO MC vs. NLO pQCD

- Why can we not (yet) use NLO pQCD calculations to extract $\Delta g/g$?
  - Example: simple PGF process (LO)



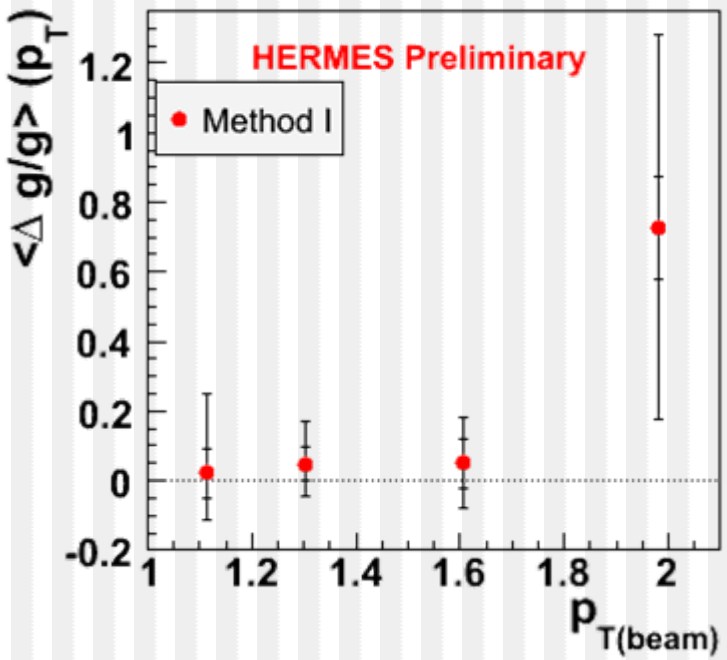
  - Magenta curves are what LO pQCD would give
  - Dashed curves are for intrinsic k_T is included (0.4 GeV)
  - Solid curves are intrinsic and fragmentation p_T (0.4 GeV) included

What Does This Result Tell Us?

- Despite the obvious shortfalls stick with LO MC
  - Includes effects of intrinsic transverse momentum (k_T) and transverse momentum acquired in fragmentation (p_T(frag))
    - Impact on cross section larger than NLO correction
    - p_T<->x relation changes
- Result is in LEADING ORDER, with model uncertainties
  - Scale variation 1/2*scale - 2*scale (NLO effects!)
  - Variation of k_T and p_T(frag) within range allowed by HERMES and world SIDIS (p_T<1 GeV) data
  - Variation of crucial PYTHIA parameters
  - Variation of (pol. and unpol.) PDFs and low-p_T asymmetry
  - Variation of functional form for $\Delta g/g(x)$ (for Method II)

What Does That Look Like?

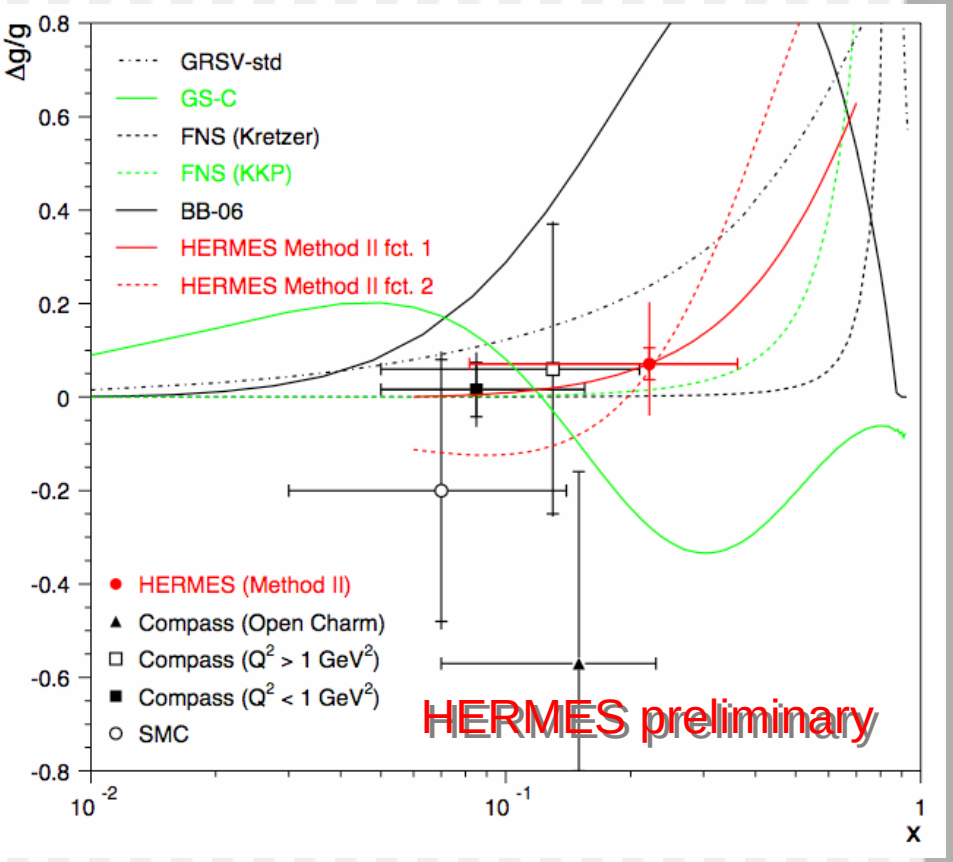
Method I



- Uncertainties from each group
  - PYTHIA params.
  - PDFs
  - low-p_T asym.
- summed linearly to "Models" uncertainty
  - Conservative approach
- Experimental (stat.+syst.) added in quadrature
  - syst. uncertainty from 4% scaling uncertainty 14% on $\Delta g/g$

Back To The Final Result

- For an accurate Δg/g extraction:
  - Need NLO MC and/or NLO pQCD with initial/ final state radiation effects (resummation?)
- From our results:
  - Δg/g is (likely) mostly small
- Need to combine all available data to get a better picture



Summary

- Hermes has collected a wealth of unpolarized and longitudinally polarized data on H and ^{2}D targets
- Analyses are being refined, including more and more understanding of the data (experimentally) and the physics (theoretically)
  - E.g.,LUND parameter tuning and error scan
  - “Overload” purity method for Δq, including π^0, k^0, Λ asymmetries
  - More multiplicities to come (maybe Fragmentation functions)

- ΔG results soon to be published

BACKUP

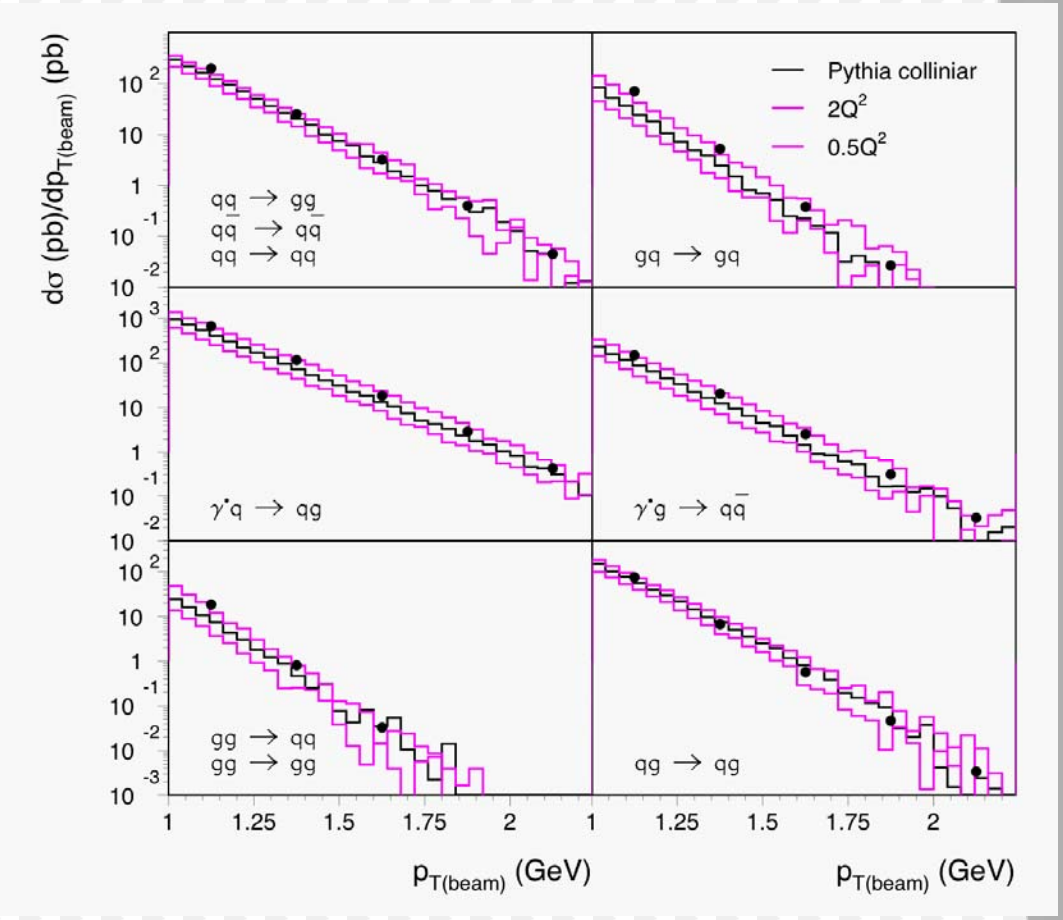
Pythia: Reminder

- Pythia simulates the total ep (γ*p) cross section using a mixture of different subprocesses
  - VMD (exclusive, diffractive, soft nondiffractive, hard nondiffractive)
  - Anomalous ($\gamma^* \to q\bar{q}$) processes
  - Direct photon processes (QCDC, PGF)
  - LO DIS $\gamma^* q \to q$

QCD 2→2

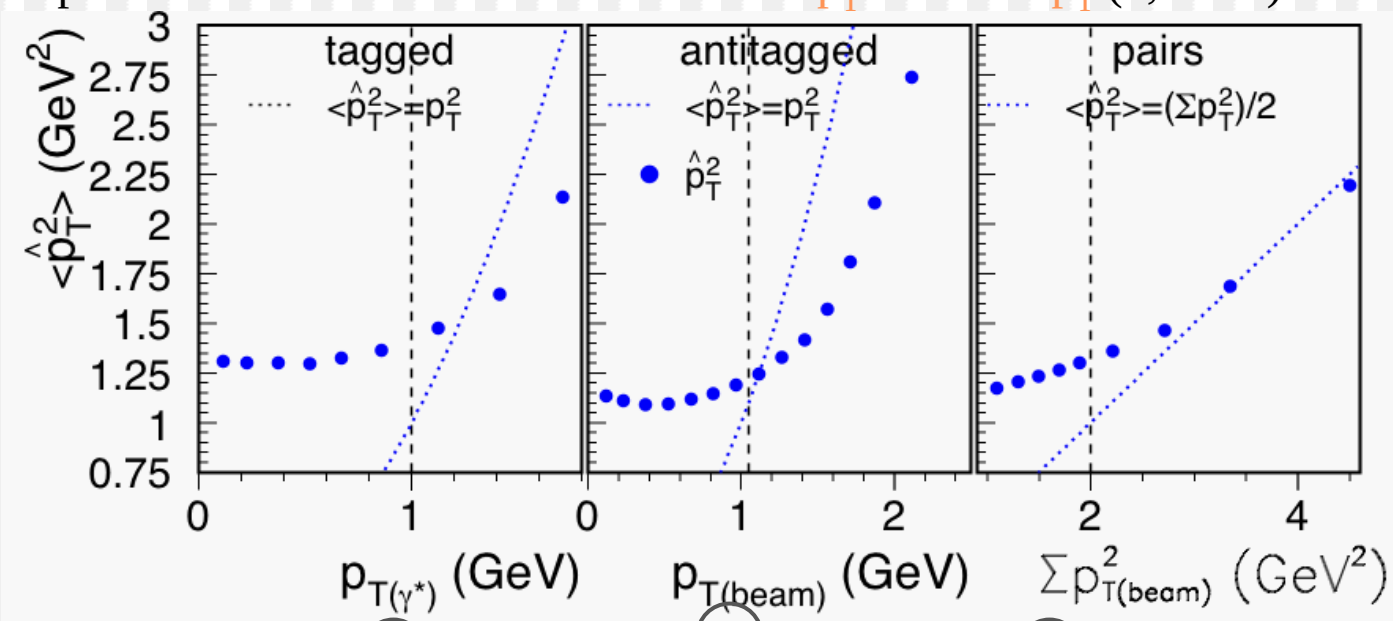
MC vs. LO QCD

- Comparison of LO cross section for hard subprocesses from pQCD (M. Stratmann) and MC (no JETSET, Kretzer FF instead)
- Magenta lines: Results from varying scale
  - Scale definition different for MC and calculation



Δg/g Extraction: Cuts

- Cuts are defined to balance statistics with sensitivity (S/B ratio)
- Also possible systematics under consideration
- Important: Correlation between measured p_T and hard p_T (x, scale)



1.0 1.05 2.0

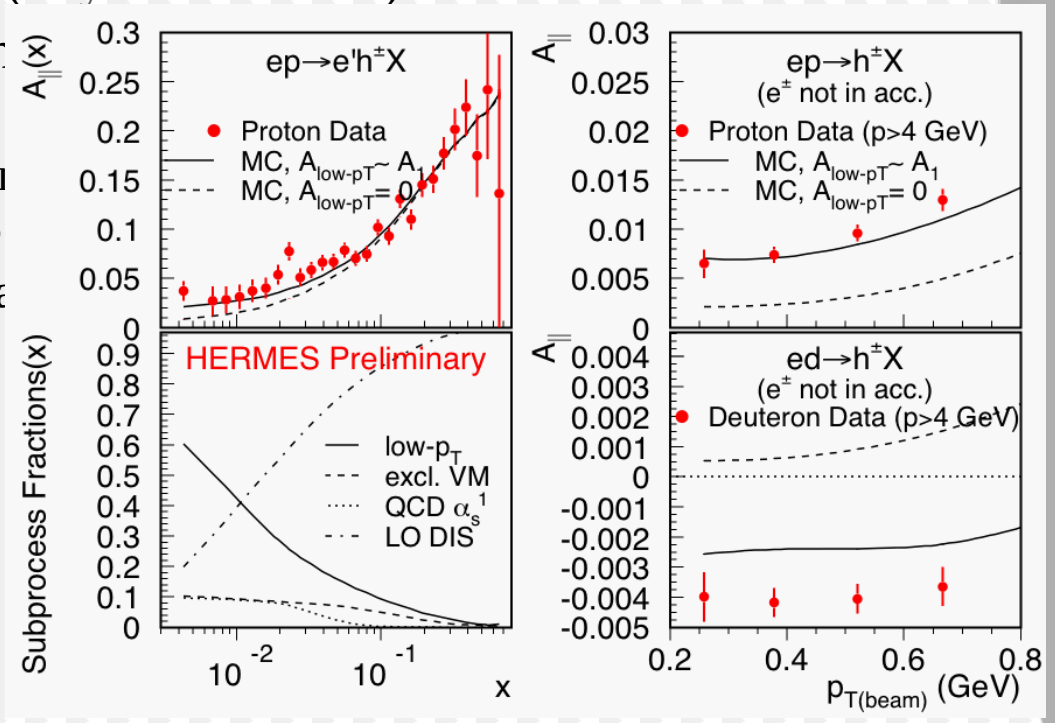
Lower cuts on p_T

Systematics: PDFs

- Standard PDFs used:
  - CTEQ5L(SaS2) for Pythia (unpol., Nucleon(Photon))
  - GRSV std./GRV98 for $\Delta q/q$ going into asymmetries
- Variation:
  - GRV98(GRS) for Pythia (unpol, Nucleon(Photon))
  - GS-B/GRV94, BB2006/CTEQ5L for $\Delta q/q$(nucleon) going into asymmetries
- Error:
  - For Pythia (unpol) the difference is taken as a 1σ error
  - For $\Delta q/q$I(nucleon) the maximum difference is taken as a 1σ error

Systematics: Asymmetries

- Besides PDFs, there are 2 more sources of uncertainties
  - Asymmetry of "low-p_T" VMD process
    - Std: $A^{low\text{-}pT}=A^{inclusive}$ (from fit to g_1/F_1)
    - Variation: $A^{low\text{-}pT}=0$ (!asymmetric error!)
  - Unknown polarized ph processes
    - Std: Arithmetic mea al., Phys. Lett. B503
    - Variation: maximal a



Systematics: pT smearing

- Initial state (intrinsic kT of partons in nucleon and photon) and final state (fragmentation) radiation generate additional pT with respect to the collinear "hadron pT" , .

$$p_T^h = z\hat{p}_T$$

  - Huge effects on measured cross sections, and the correlation between measured pT and hard subprocess pT , and x
  - Also large effects on subprocess fractions
  - See Elke's study in the paper draft
- Std.: kT (0.4 GeV) and pTFragm. (0.4 GeV) from $\chi 2$ minimization
- Variation: 1σ error from $\chi 2$ minimization ($\pm 0.04/0.02$ GeV)

Systematics: Scale Dependence

- Scale in Pythia was varied by factors 1/2 and 2
- Same variation for asymmetry calculation
- Error: Maximum difference to std. is taken as 1σ uncertainty

Systematics: Cutoffs

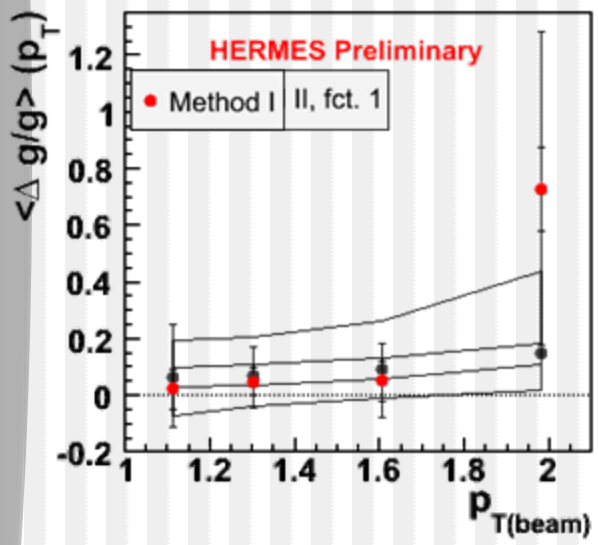
- A number of cutoffs in Pythia (to avoid double counting) can influence subprocess fractions
- Most important one: PARP(90) sets the dividing line between
  - PGF/QCDC and hard resolved QCD
  - Hard and soft (low-p_T) VMD
- Std: Default Pythia (0.16)
- Variation: 0.14-0.18 (from comparing Pythia LO cross section with theory LO cross section)

Systematics: Method 2

- An additional uncertainty is assigned for Method 2 due to the choice of functional shape
- Std: Function 1 (1 free parameter)
- Variation: Function 2 (2 free parameters)
- Error = difference (!asymmetric!)

What Does That Look Like?

Method I/Method II



- Mean values, syst. and stat. errors in Method I are independent between p_T points

Meth. II

$$\left\langle \frac{\Delta g}{g} \right\rangle (p_T) = \frac{\int_{x(p_T)} dx \sigma(x, \hat{p}_T) \hat{a}(x, \hat{p}_T) \frac{\Delta g(x)}{g(x)}}{\int_{x(p_T)} dx \sigma(x, \hat{p}_T) \hat{a}(x, \hat{p}_T)}$$

- They are correlated in Method II (band)

- Error bars/bands: stat. and total errors (including exp. systematics from polarization measurements (4%))
- For Method 2 the errors are dominated by high statistics points

Modifying/Tuning PYTHIA

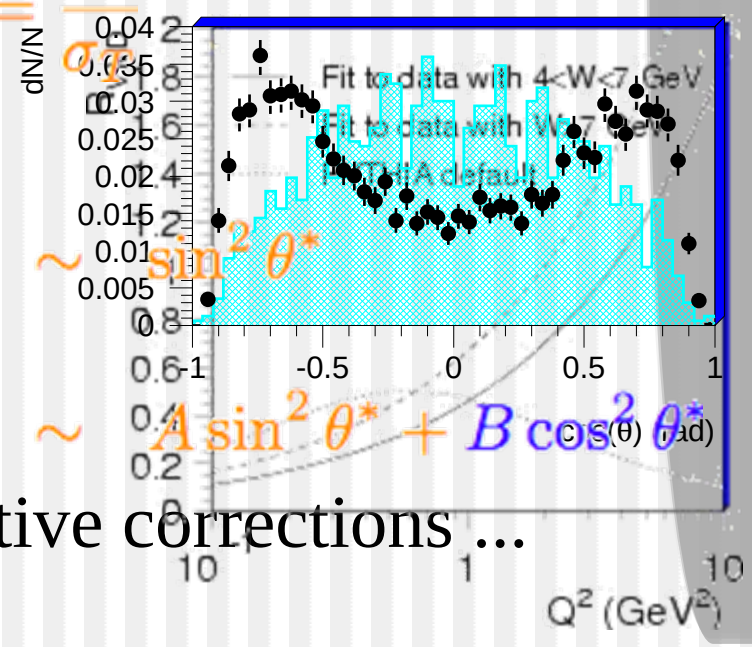
- Changes to the VMD model in PYTHIA
  - The Q^2 slope of the total (resolved) γ*p cross section: $\frac{\sigma(Q^2)}{\sigma(Q^2=0)} = \left(\frac{M_\rho^2}{M_\rho^2+Q^2}\right)^m$

$$m = 2 \rightarrow 2.6$$

  - The parametrization of $R_{VMD} = \frac{\sigma_L}{\sigma_T}$
  - The γ–VM couplings
  - The angular distribution of the ρ^0 decay products

$$\frac{d\sigma}{dQ^2}(Q^2=0) \sim \sin^2\theta^*$$

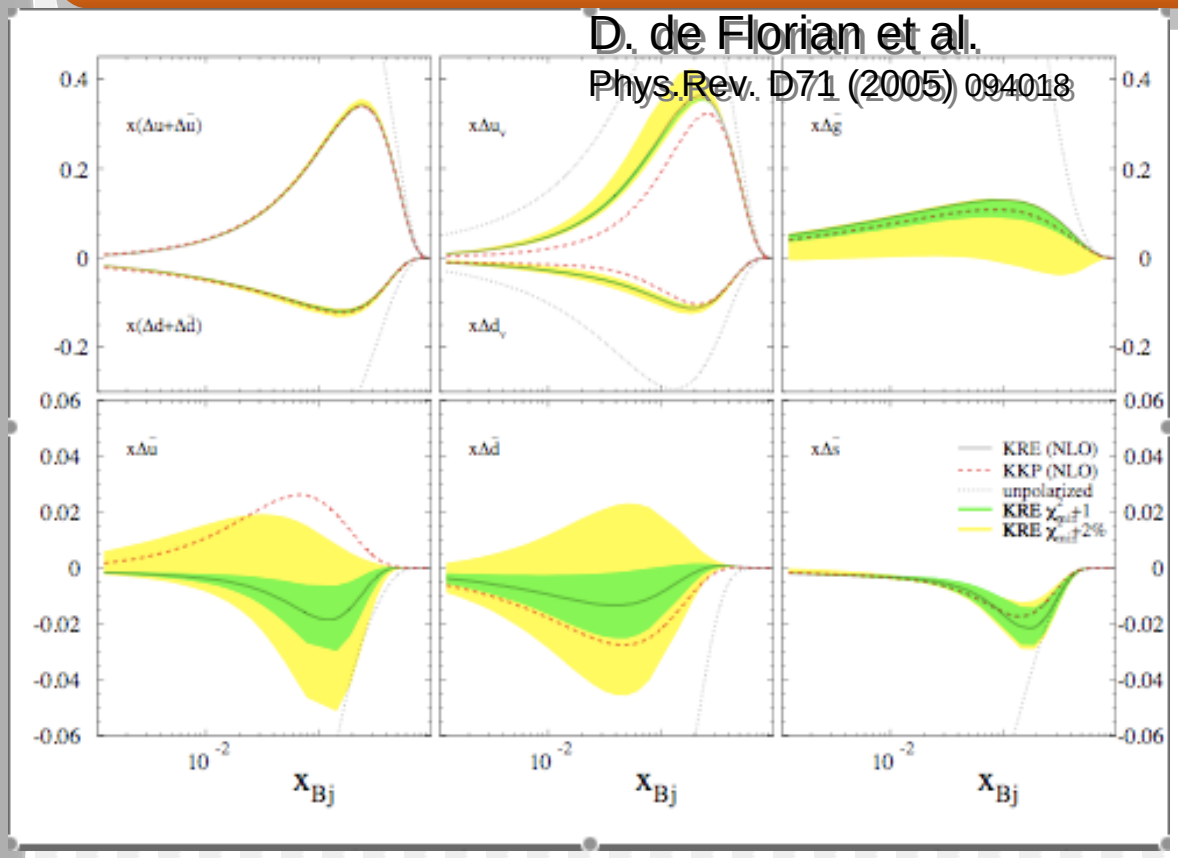
$$\frac{d\sigma}{dQ^2}(Q^2>0) \sim A\sin^2\theta^* + B\cos^2\theta^*$$



- And implementing QED radiative corrections …

BACK UP

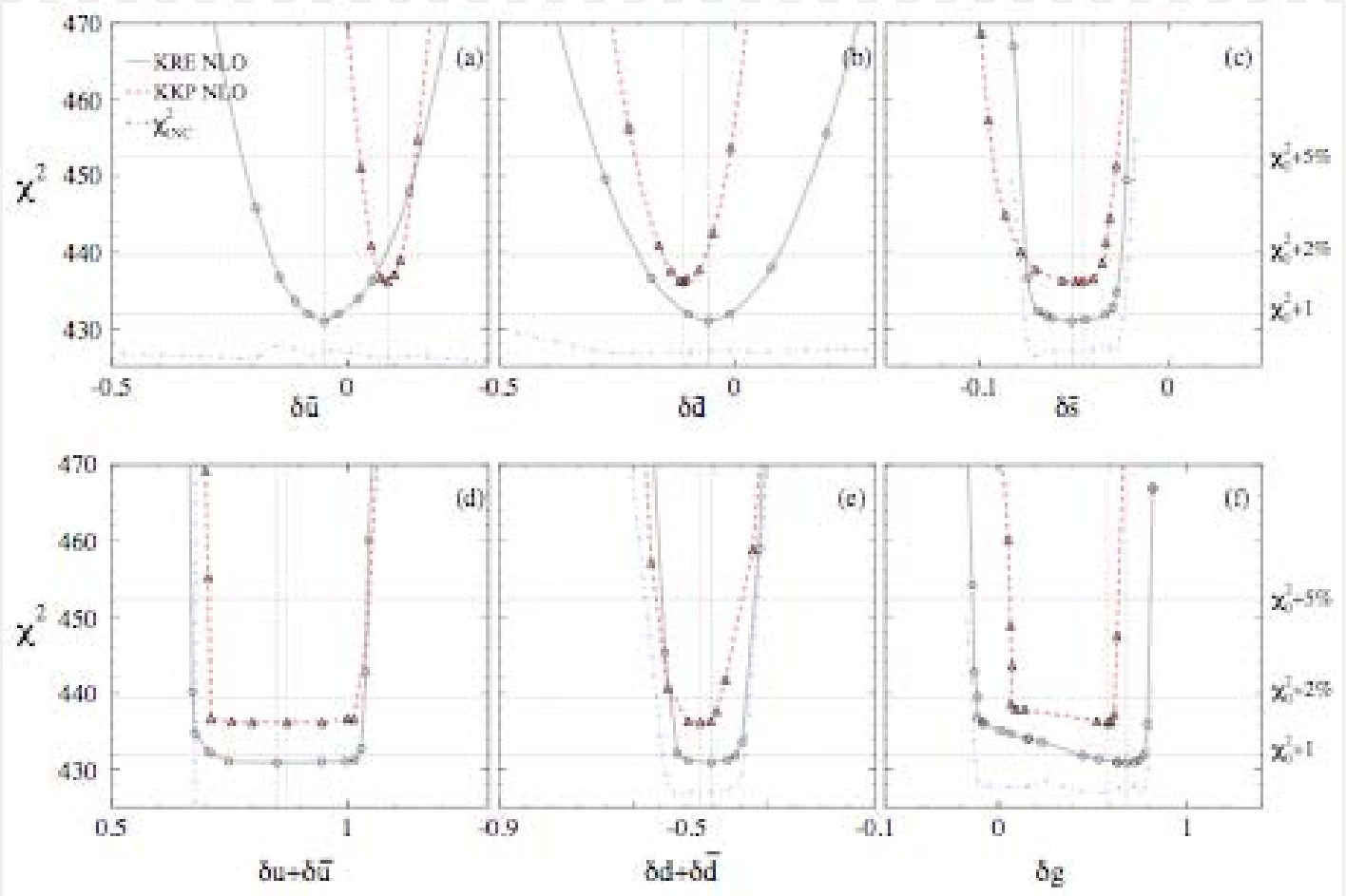
NLO QCD Analysis of SIDIS Data



- Fit to inclusive and Hermes/SMC SIDIS asymmetries
  - With error analysis
- Additional input: Fragmentation functions
- SIDIS data constrain sea quark densities better
  - Uncertainties still very large

- Results very sensitive to choice of fragmentation function
  - Need more precise FF from data

NLO SIDIS Fit Errors



Unpolarized Data

- Knowledge of unpolarized input to PDF fits very important
  - SIDIS multiplicities of identified hadrons (together with e^+e^--data from BELLE+LEP) provide valuable information for new, more precise Fragmentation functions
  - Understanding the unpolarized cross section (e.g., F_2) helps evaluating the validity of pQCD assumptions

Sorry, later …

Extraction of multiplicities at HERMES

Unpolarized H and D data

Charge symmetric background correction

Correction for RICH efficiency and misidentification

Multiplicities in acceptance

$$\frac{1}{N_{DIS}}\frac{dN^{\pi^\pm,k^\pm}}{dz}$$

Correction for exclusive VM production

MC input

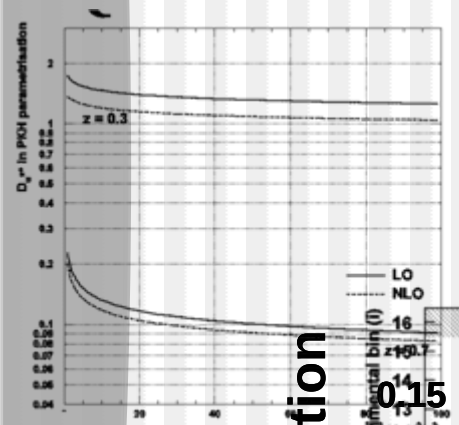
Unfolding of smearing and QED radiative effects

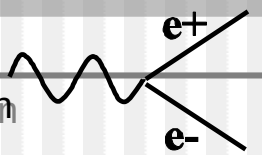
Acceptance correction

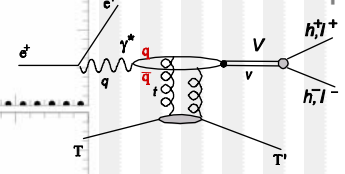
Multiplicities at Q^2=2.5, 25 GeV^2

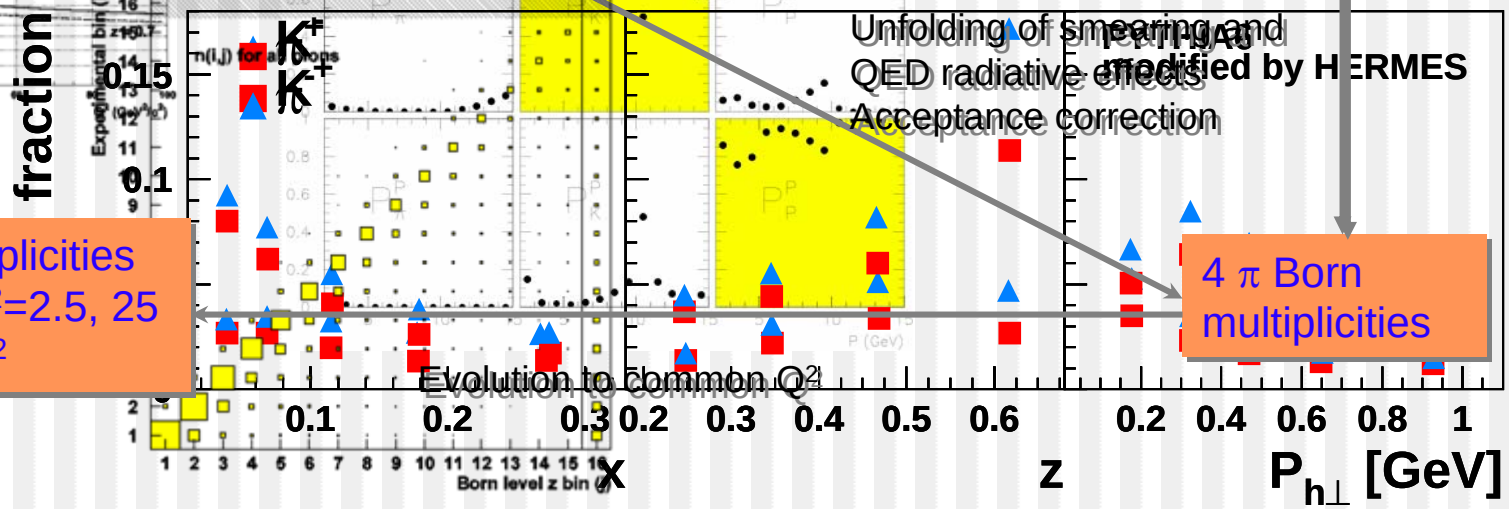
4 π Born multiplicities

Evolution to common Q^2



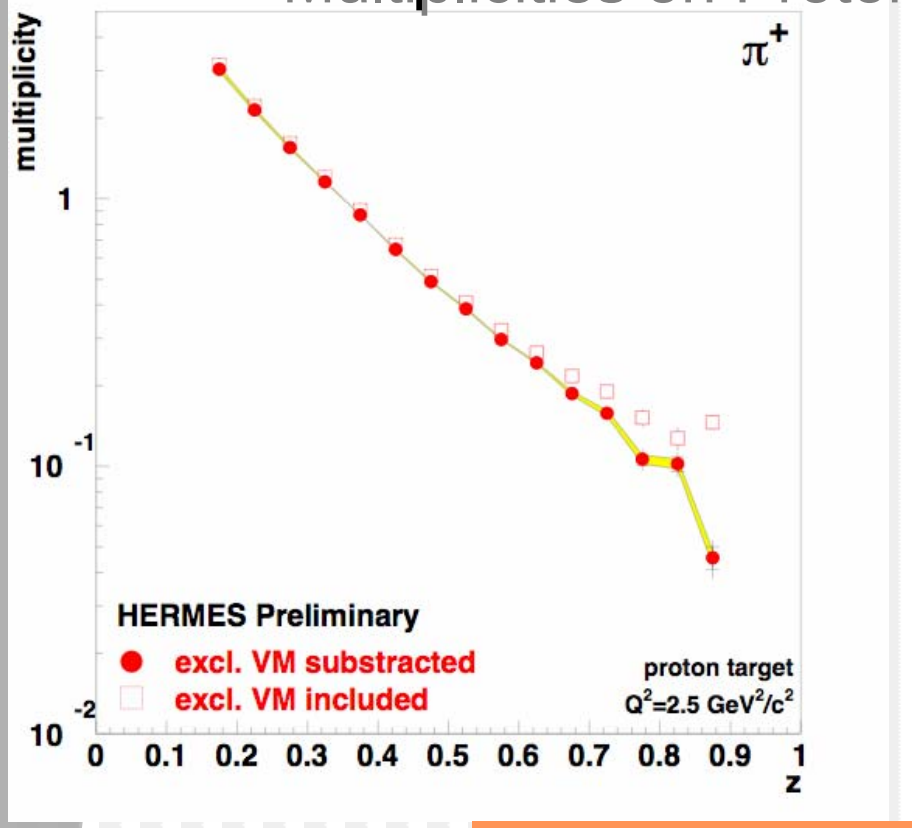


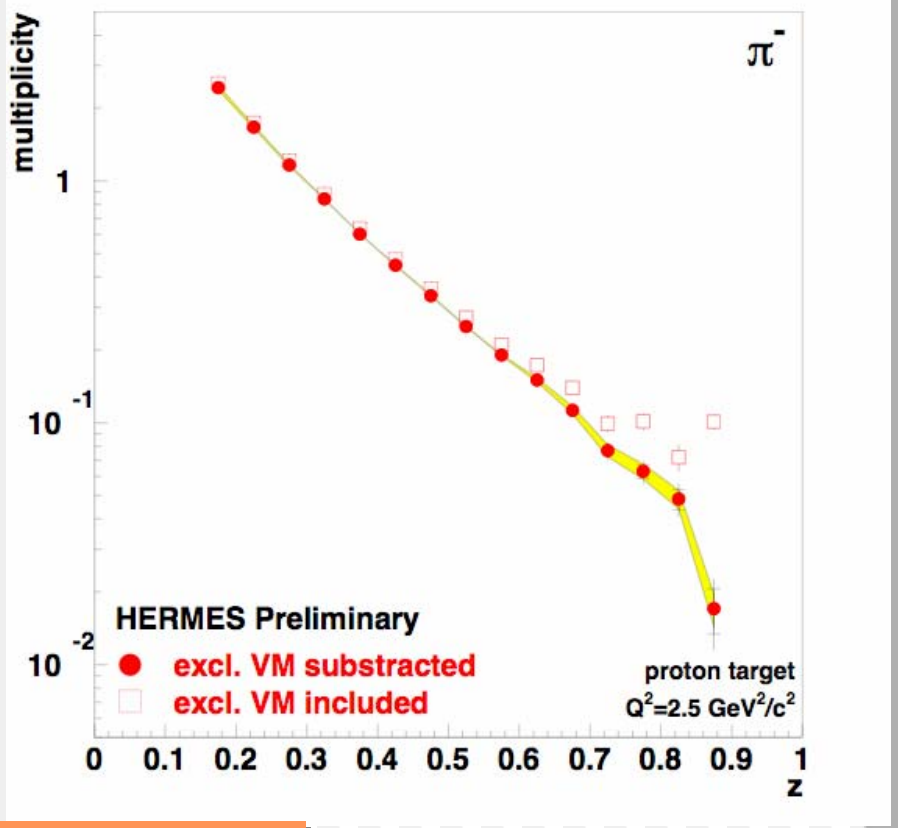




SIDIS Multiplicities (Pions)

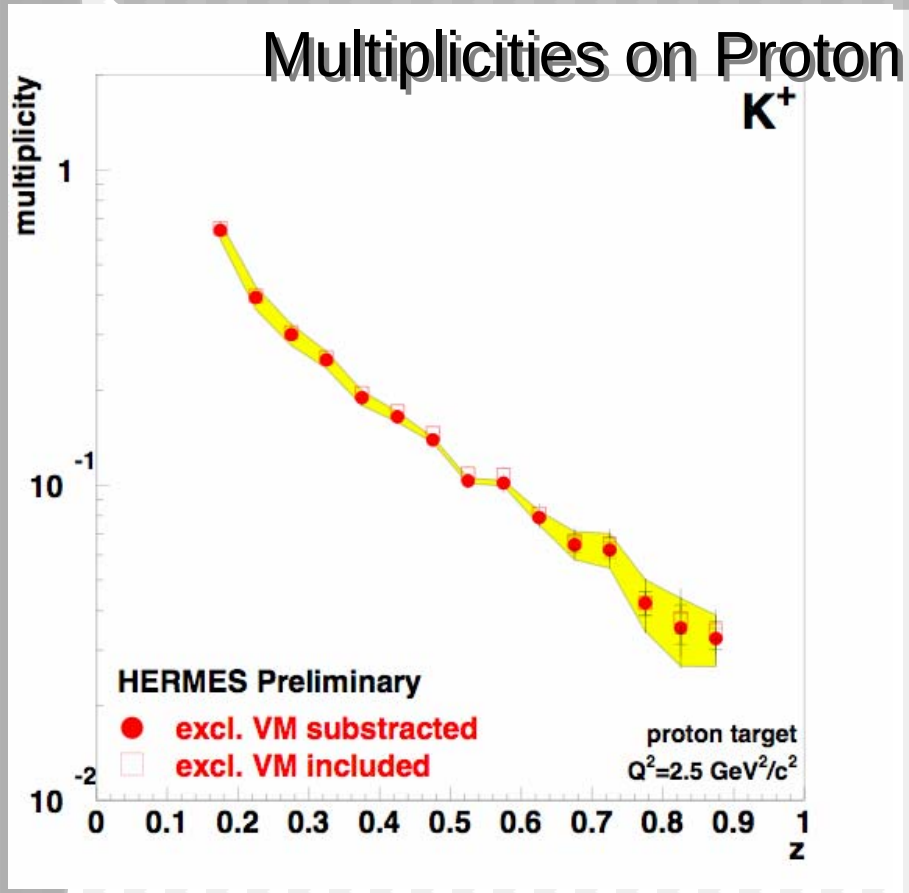
Multiplicities on Proton

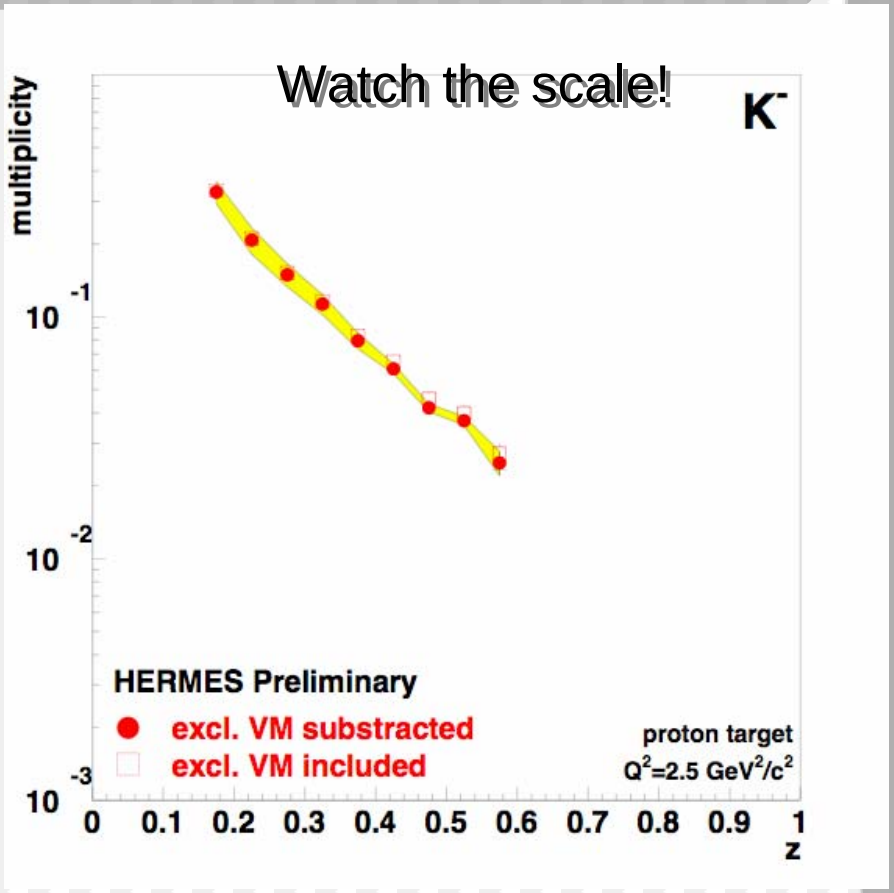




- VMD correction large at z>0.7
- π^+/π^- ratio ≈1.2

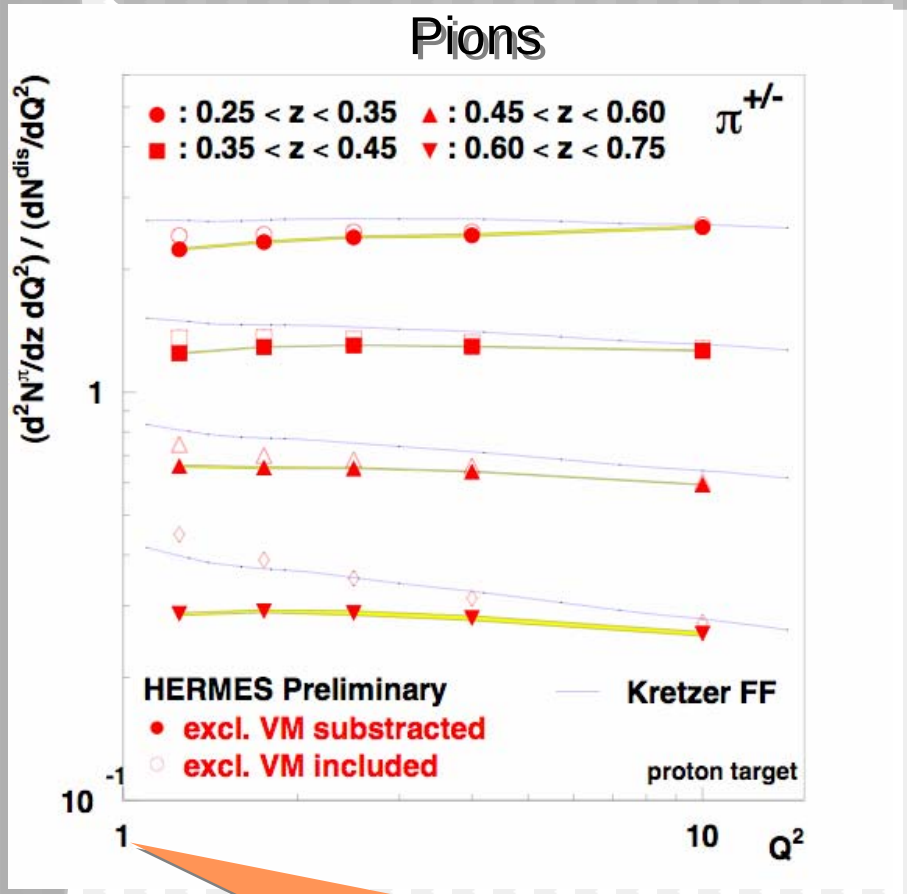
SIDIS Multiplicities (Kaons)

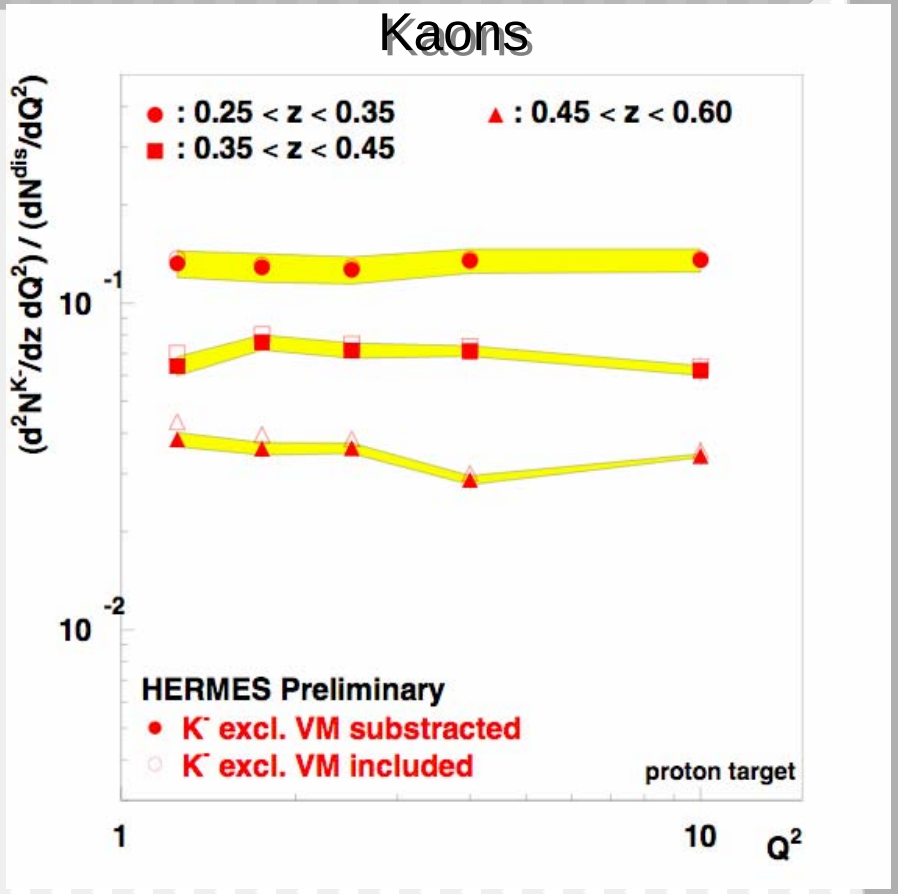




- VMD correction small
- k^+ / k^- ratio ≈ 2

SIDIS Multiplicities vs. Q^2





Including excl. VMD contribution may get Q^2 evolution (gluon FF) wrong!

Model Independent Extraction of Δs

- The deuteron inclusive and charged kaon asymmetries are isoscalars:□

$$A_1^d = C\frac{1}{5Q(x)+2S(x)}\left[5Q(x)\frac{\Delta Q(x)}{Q(x)}+2S(x)\frac{\Delta S(x)}{S(x)}\right]$$

$$A_1^{k=k^++k^-} = C\frac{1}{Q(x)D_Q^k+S(x)D_S^k}\left[Q(x)D_Q^k\frac{\Delta Q(x)}{Q(x)}+S(x)D_S^k\frac{\Delta S(x)}{S(x)}\right]$$

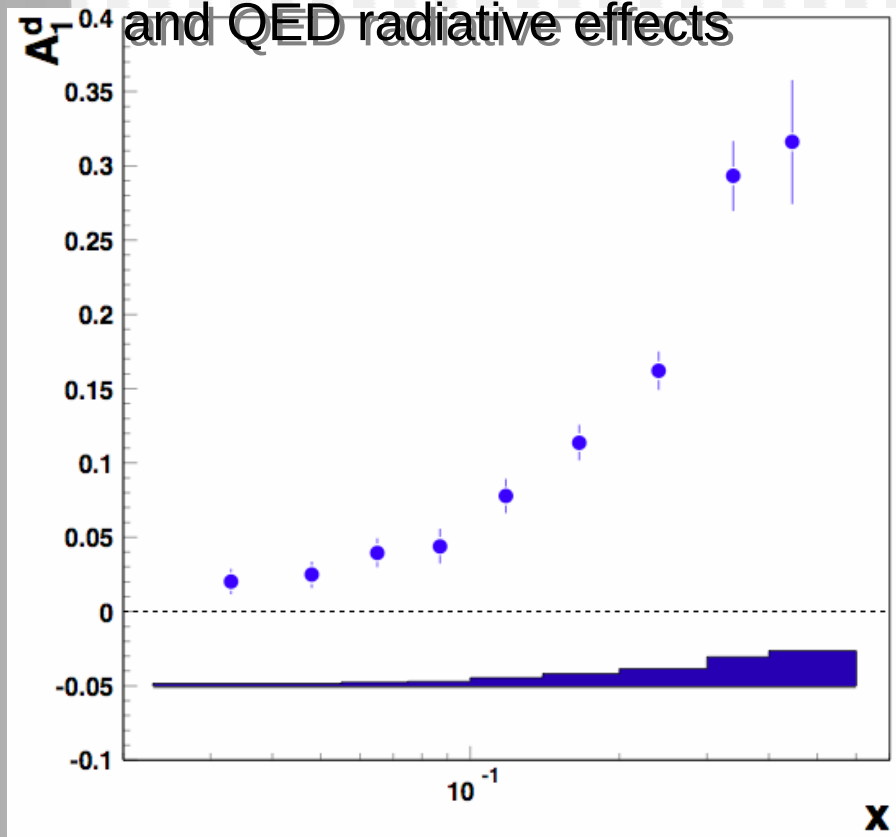
with:
$$(\Delta)Q(x) = (\Delta)[u(x)+\bar{u}(x)+d(x)+\bar{d}(x)]$$
$$(\Delta)S(x) = (\Delta)[s(x)+\bar{s}(x)]$$

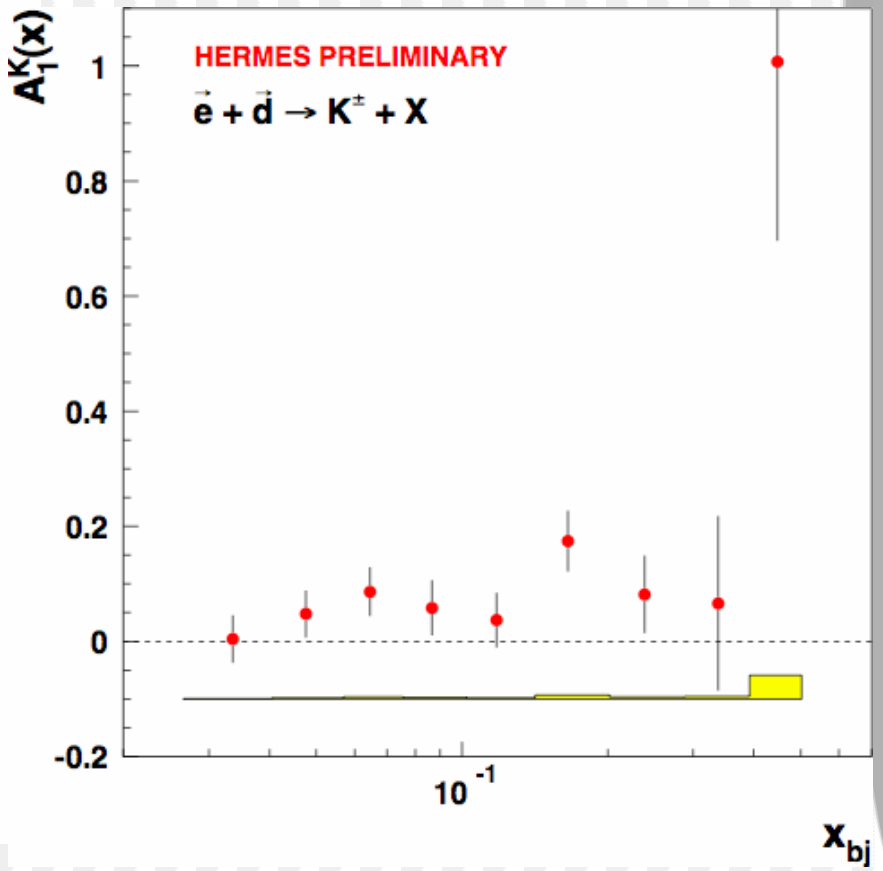
and:
$$D_Q^k = 4\int_{z_{min}}^{z_{max}} dz D_u^k(z) + \int_{z_{min}}^{z_{max}} dz D_d^k(z) \Big\} \quad D_u^k = D_{\bar{u}}^k,\ D_d^k = D_{\bar{d}}^k$$

$$D_S^k = \int_{z_{min}}^{z_{max}} dz D_s^k(z) \Big\} \quad D_s^k = D_{\bar{s}}^k$$

Inclusive and Charged Kaon Asymmetries

Asymmetries measured on deuteron,
unfolded to correct for smearing, PID efficiency (RICH)
and QED radiative effects





Model Independent Extraction of Δs

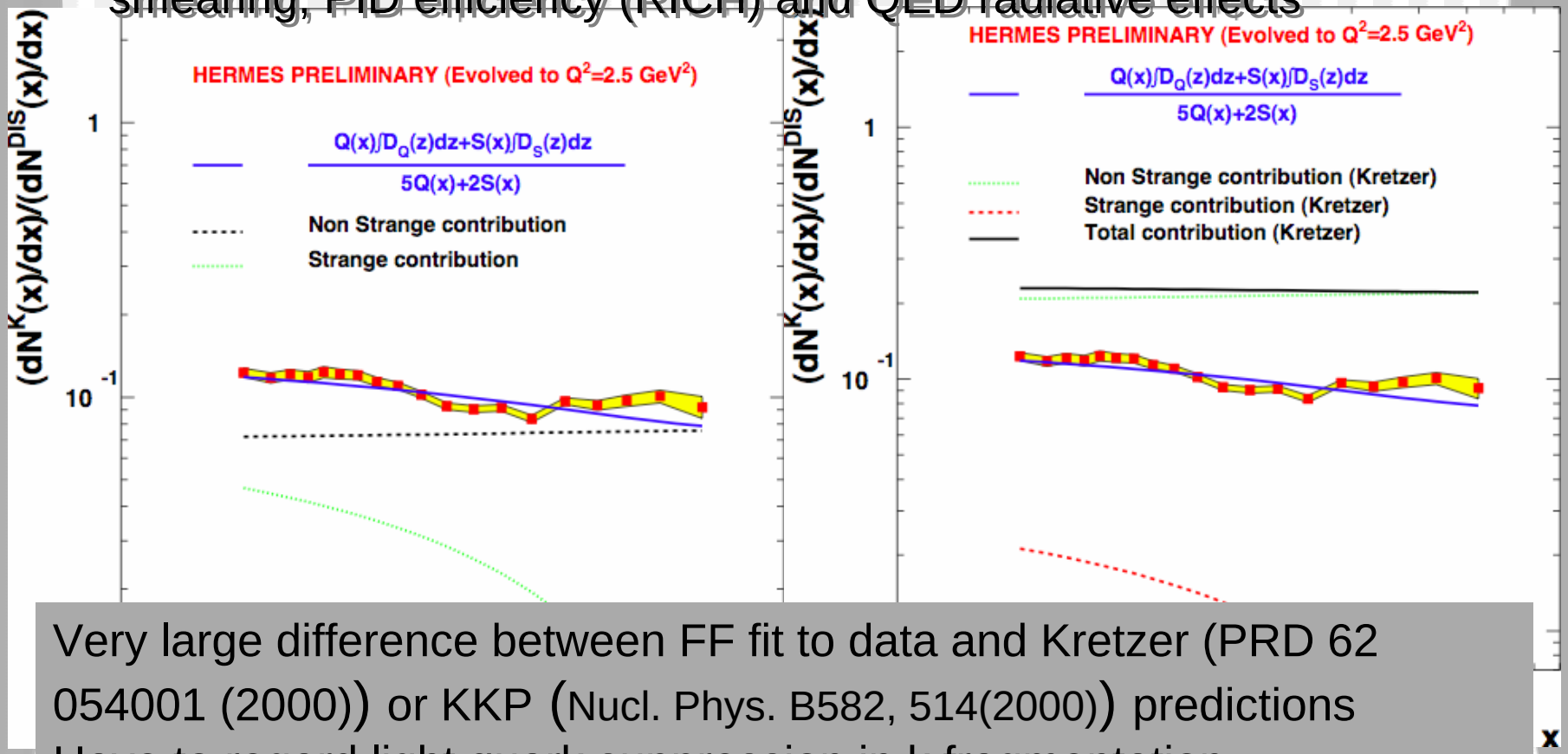
- From A_1^{incl} and A_1^{k} we can extract ΔQ and ΔS assuming only
  - Isospin invariance
  - Charge conjugation symmetry of FF
- Use charged kaon multiplicities to get D_Q^{k} and D_S^{k}

$$\frac{dN^k/dx}{dN^{DIS}/dx} = \frac{Q(x)D_Q^k + S(x)D_S^k}{5Q(x) + 2S(x)}$$

- Use CTEQ6LO for unpolarized PDFs

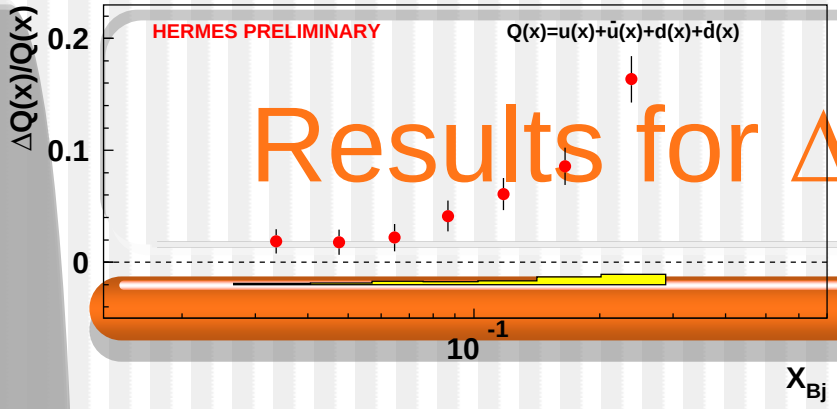
Charged Kaon Multiplicities

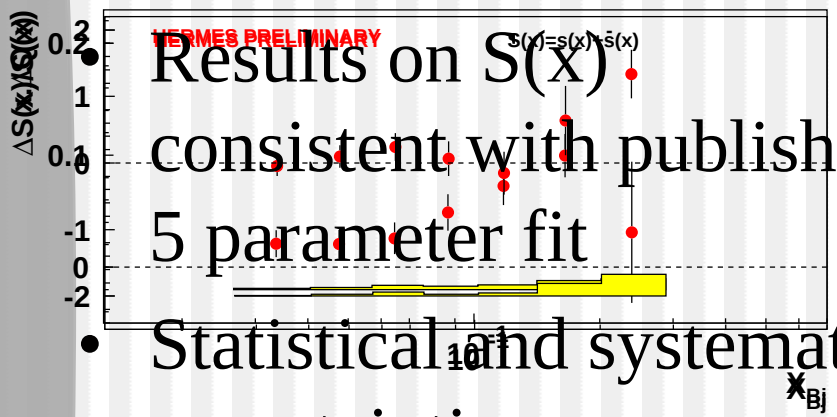
Multiplicities measured on deuteron, unfolded to correct for smearing, PID efficiency (RICH) and QED radiative effects

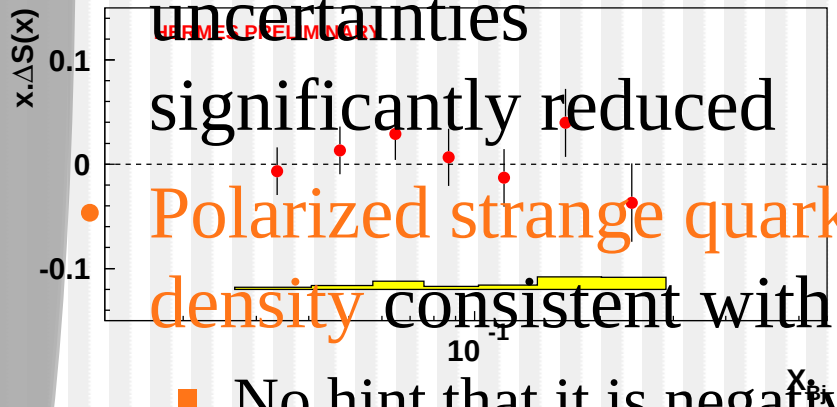


Very large difference between FF fit to data and Kretzer (PRD 62 054001 (2000)) or KKP (Nucl. Phys. B582, 514(2000)) predictions
Have to regard light quark suppression in k fragmentation

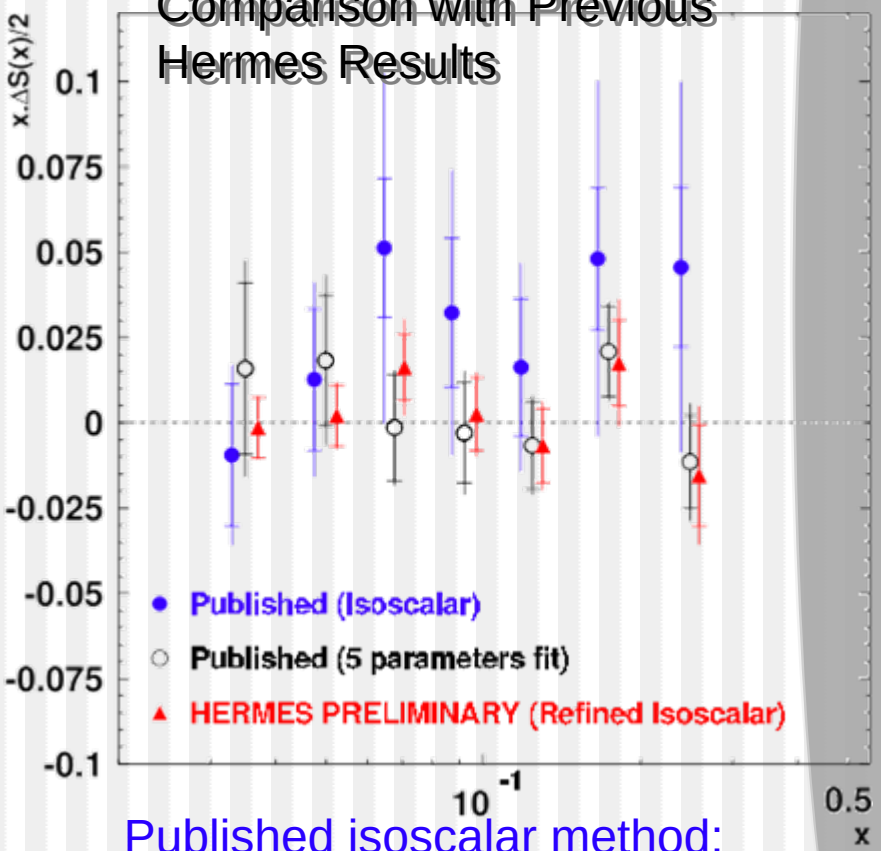
Results for ΔQ(x) and ΔS(x)



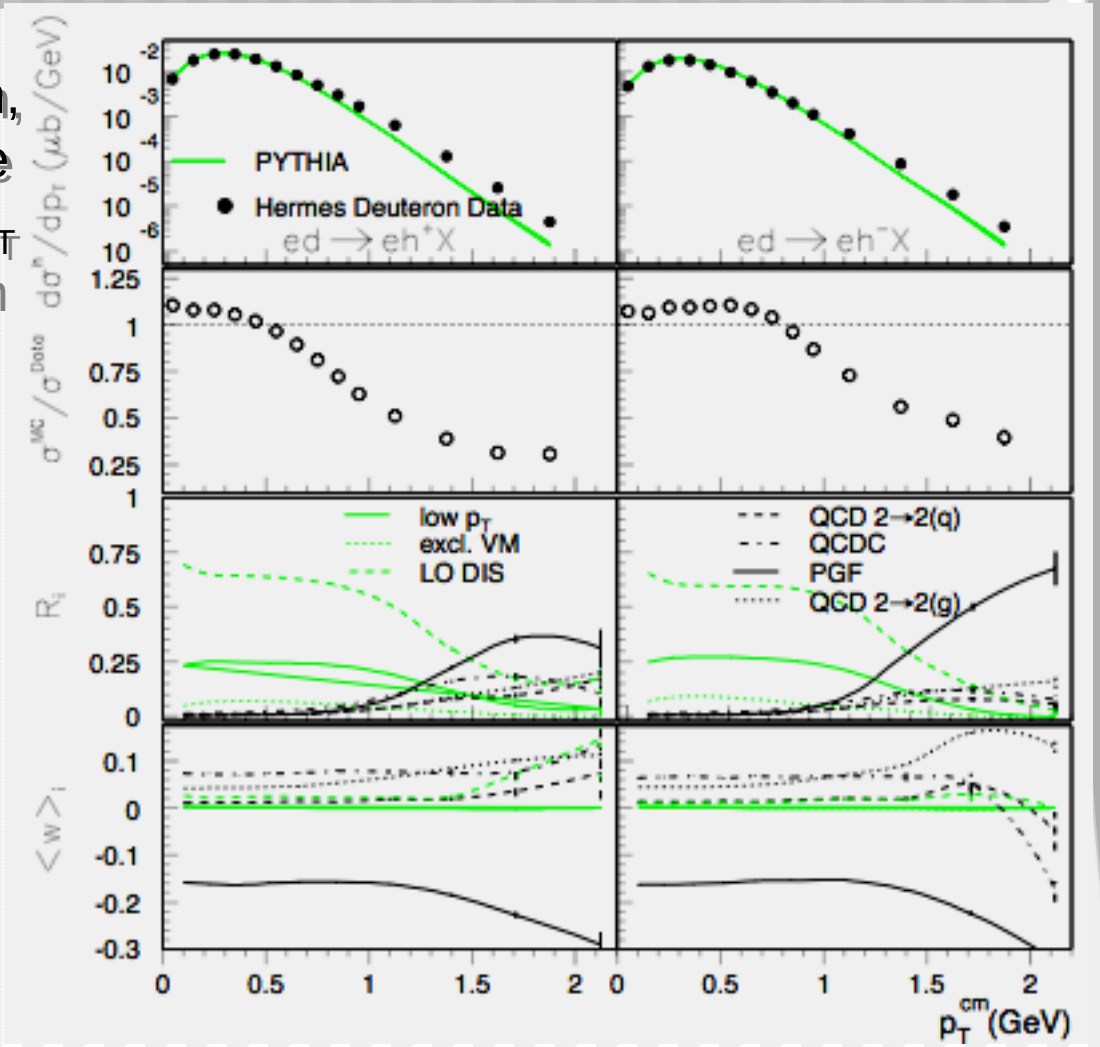




- Results on S(x) consistent with published 5 parameter fit
- Statistical and systematic uncertainties significantly reduced
- Polarized strange quark density consistent with 0
  - No hint that it is negative



Published isoscalar method:
Assumed FF from BKK
(Phys. Rev. D 52, 4947 (1995))

MC and data vs. pT $Q^2>0.1$

Cross section on deuteron, within Hermes acceptance
Semi-inclusive hadrons, p_T measured w.r.t. γ direction