$\boxed{\text{TUTORIAL}}$

E161

MEASUREMENT OF GLUON SPIN DISTRIBUTION IN NUCLEONS USING POLARIZED OPEN CHARM PHOTOPRODUCTION

- WHY MEASURE THIS
- SOME THEORY
- EXPERIMENTAL SETUP
- PROJECTED RESULTS
- OTHER EXPERIMENTS

WHY MEASURE THE GLUON POLARIZATION?

1. FUNDAMENTAL SUM RULE

$$\mathbf{1/2 = 1/2 \cdot \Delta\Sigma + \Delta G + L_z}$$

– $\mathbf{\Delta\Sigma \sim 0.23 \pm 0.07}$ (from quarks)

– $\mathbf{\Delta G}$ (from Gluons)

– $\mathbf{L_z}$ includes quarks and gluons. Possible to measure it.

2. pQCD CONSISTENCY FOR ALL REACTIONS

– $\mathbf{g_1}$ FROM DIS (SLAC,SMC,EMC,HERMES)

– PHOTOPRODUCTION (COMPASS, HERMES, SLAC?)

– P-P at RHIC

3. FUNDAMENTAL PROPERTY OF NUCLEON

– 30 YEARS ON UNPOLARIZED PARTON DISTRIBUTIONS

– 10 YEARS ON POLARIZED QUARKS

UNPOLARIZED PARTON DISTRIBUTIONS

DIS LEPTON SCATTERING

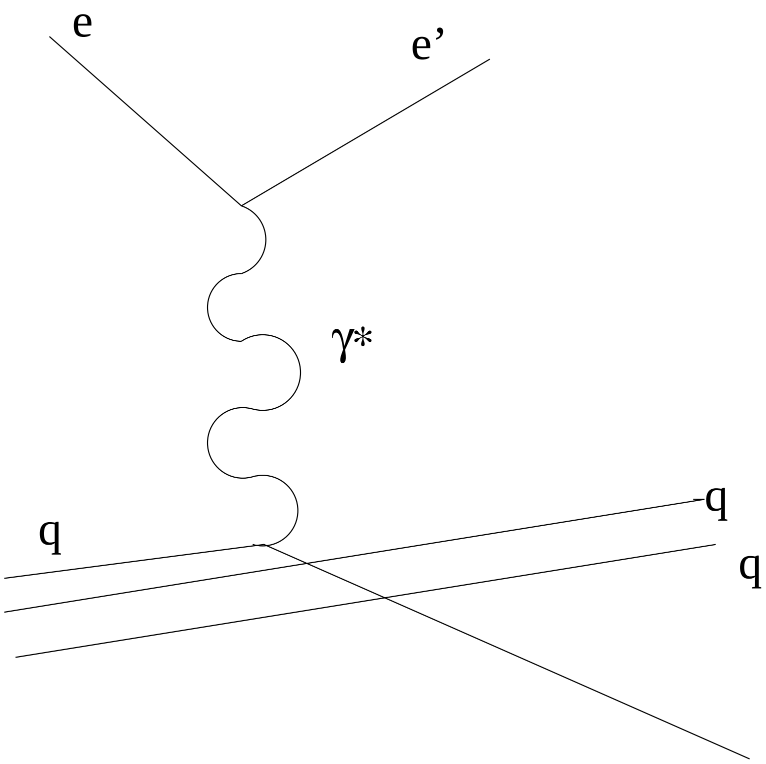
SLAC	**electrons**	**1968-1986**
HERA	**electrons**	**1992-**
EMC	**muons**	**1976-1980**
NMC	**muons**	**1981-1990**
BCDMS	**muon**	**1981-1985**
CCFR	**neutrino**	**1980's**
NuTeV	**neutrino**	**1995**

PROTON-PROTON

DIRECT PHOTON PRODUCTION
High P_T JETS
Drell-Yan
Z, W, top production

⇒ SEARCH FOR NEW PHYSICS

Inclusive Deep Inelastic Scattering



- θ : scattering angle of electron
- Q^2: 4-momentum transfer squared $(e - e')^2)$
- ν : energy transfer $(e - e')$
- $x = \frac{Q^2}{2M\nu}$: Bjorken scaling variable

Unpolarized Deep Inelastic Scattering

$$\mathbf{\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2(\theta/2)}{Q^4}\left[\frac{F_2(x,Q^2)}{\nu} + \frac{2F_1(x,Q^2)}{M}\tan^2(\theta/2)\right]}$$

F_1 and F_2 are the unpolarized structure functions.

In naive quark parton model F_1 is related to the spin averaged quark distribution functions:

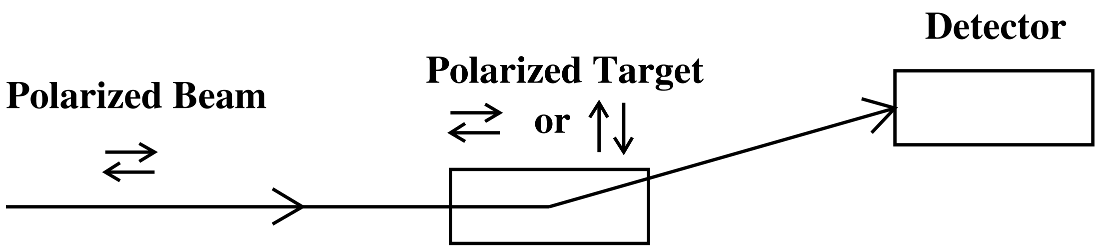
$$F_1(x,Q^2) = \frac{1}{2}\sum_i e_i^2[q_i^{\uparrow}(x,Q^2) + q_i^{\downarrow}(x,Q^2)]$$

$\longrightarrow$ Up (down) arrow denotes spin aligned (anti-aligned) with nucleon spin

$\longrightarrow$ i sums over the quark and antiquark flavors

$\longrightarrow$ e_i is the quark or antiquark charge

Polarized Deep Inelastic Scattering



$$A_{\parallel} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} = f_k \Big[g_1(x,Q^2)[E + E'\cos(\theta)] - \frac{Q^2}{\nu} g_2(x,Q^2) \Big]$$

$$A_{\perp} = \frac{\sigma^{\downarrow\leftarrow} - \sigma^{\uparrow\leftarrow}}{\sigma^{\downarrow\leftarrow} + \sigma^{\uparrow\leftarrow}} = f_k E' \sin(\theta) \Big[g_1(x,Q^2) + \frac{2E}{\nu} g_2(x,Q^2) \Big]$$

g_1 and g_2 are the polarized structure functions.

$\longrightarrow$ $\mathrm{A}_{\parallel}$ is primarily sensitive to g_1

$\longrightarrow$ $\mathrm{A}_{\perp}$ is more sensitive to g_2

$\longrightarrow$ f_k includes contribution from kinematics and unpolarized structure functions

g_1 Structure Function

In QPM g_1 is related to the spin distribution functions:

$$g_1(x, Q^2) = \frac{1}{2} \sum_i e_i^2 \Delta q_i$$

$$\Delta q_i = q_i^{\uparrow}(x, Q^2) - q_i^{\downarrow}(x, Q^2)$$

The index i runs over the quark and antiquark flavors and e_i is the corresponding charge

However, in pQCD g_1 is also sensitive to the polarized gluon distribution ΔG:

$$g_1(x, Q^2) \;=\; \frac{1}{2} \sum_q \; e_q^2 \; [\; C_q \otimes \Delta q \;+\; C_G \otimes \Delta G \;]$$

where $C_{q,G}$ are the perturbative coefficients

Global pQCD Fitting

- **Use pQCD expansion for g_1:**

$$\mathbf{g_1(x, Q^2) = \frac{1}{2}\sum_q e_q^2\,[\,C_q \otimes \Delta q + C_G \otimes \Delta G\,]}$$

$\rightarrow$ **C_q contribution starts at order 1, C_G at order α_S^1**

- **Evolve Δq and ΔG from initial Q_0^2 to Q^2 using NLO DGLAP equations.**

- **Parameterize non-perturbative inputs.**

$$e.g.: \quad \Delta f(x, Q_0^2) = A_f x^{\alpha_f} f(x, Q_0^2)$$

where f = valence Δu_v and Δd_v, sea, gluons

- **Factorization Scheme Dependence**
  - **Common schemes are $\overline{MS}$ and Adler-Bardeen**
  - **Ambiguity in definition of contributions**

$$\Delta\Sigma(AB) = \Delta\Sigma(\overline{MS}) + \frac{N_f}{2\pi}\alpha_S \Delta G$$

$\alpha_S(Q^2)\Delta G(Q^2)$ is independent of Q^2 to $O(\alpha_S^2)$

WHAT WE KNOW

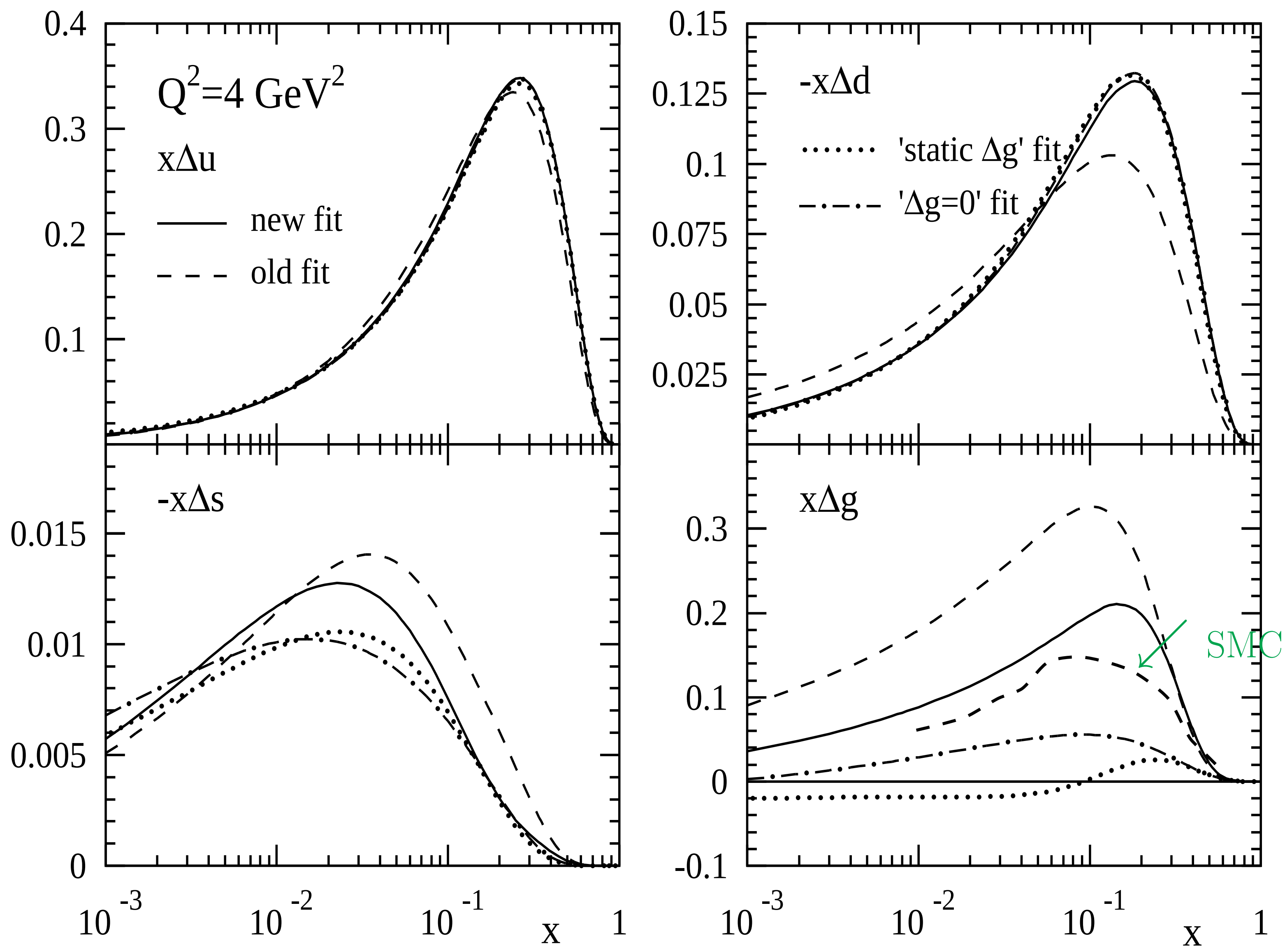
POLARIZED PARTON DISTRIBUTIONS FROM pQCD EVOLUTION EQUATIONS.

THE FIT OF

Gluck, Reya, Stratmann and Vogelsang (1999)

$$\Delta q(x, Q^2) = q_i^{\uparrow}(x, Q^2) - q_i^{\downarrow}(x, Q^2)$$

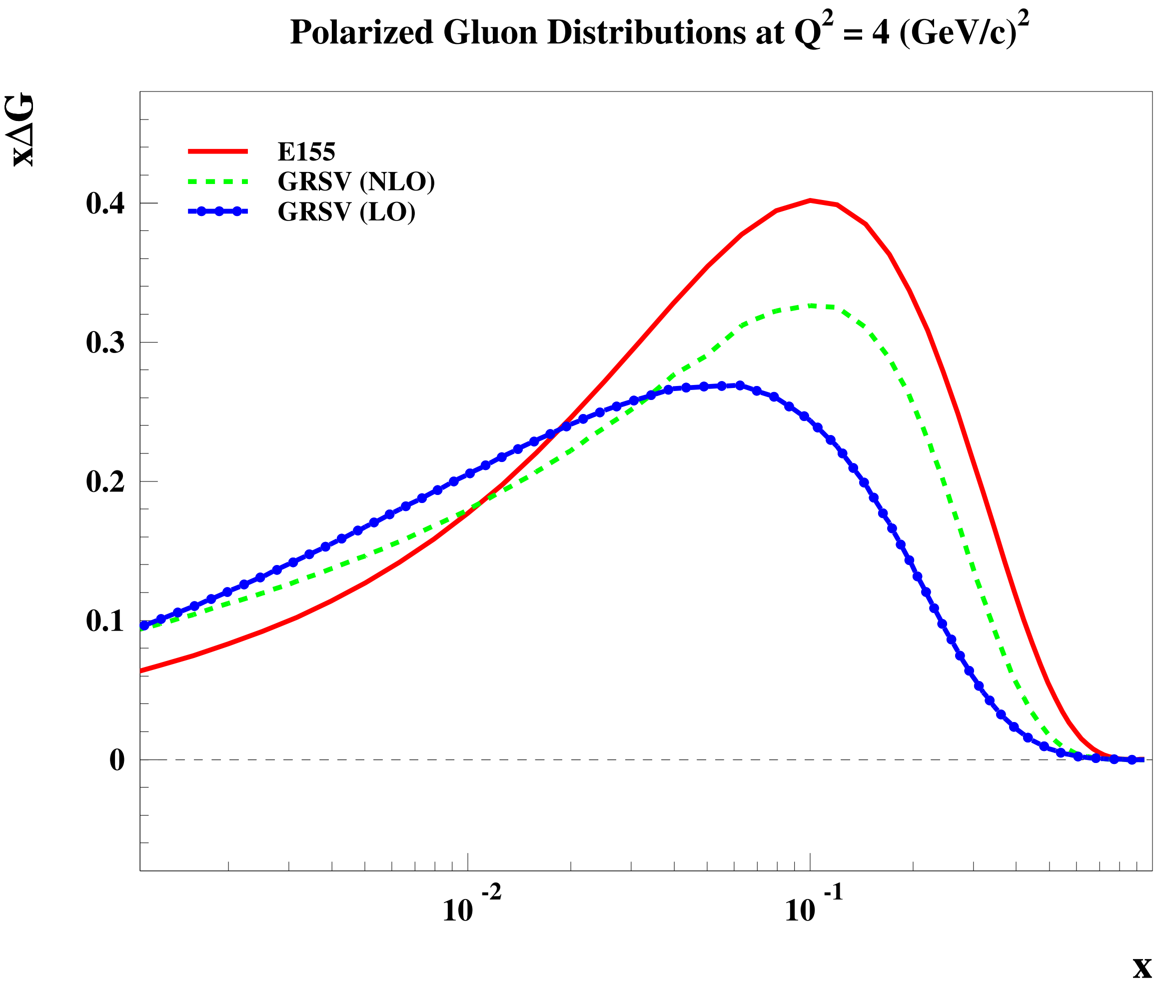
Δg ONLY APPEARS in NLO



POLARIZED PARTON DISTRIBUTIONS FROM pQCD EVOLUTION EQUATIONS.

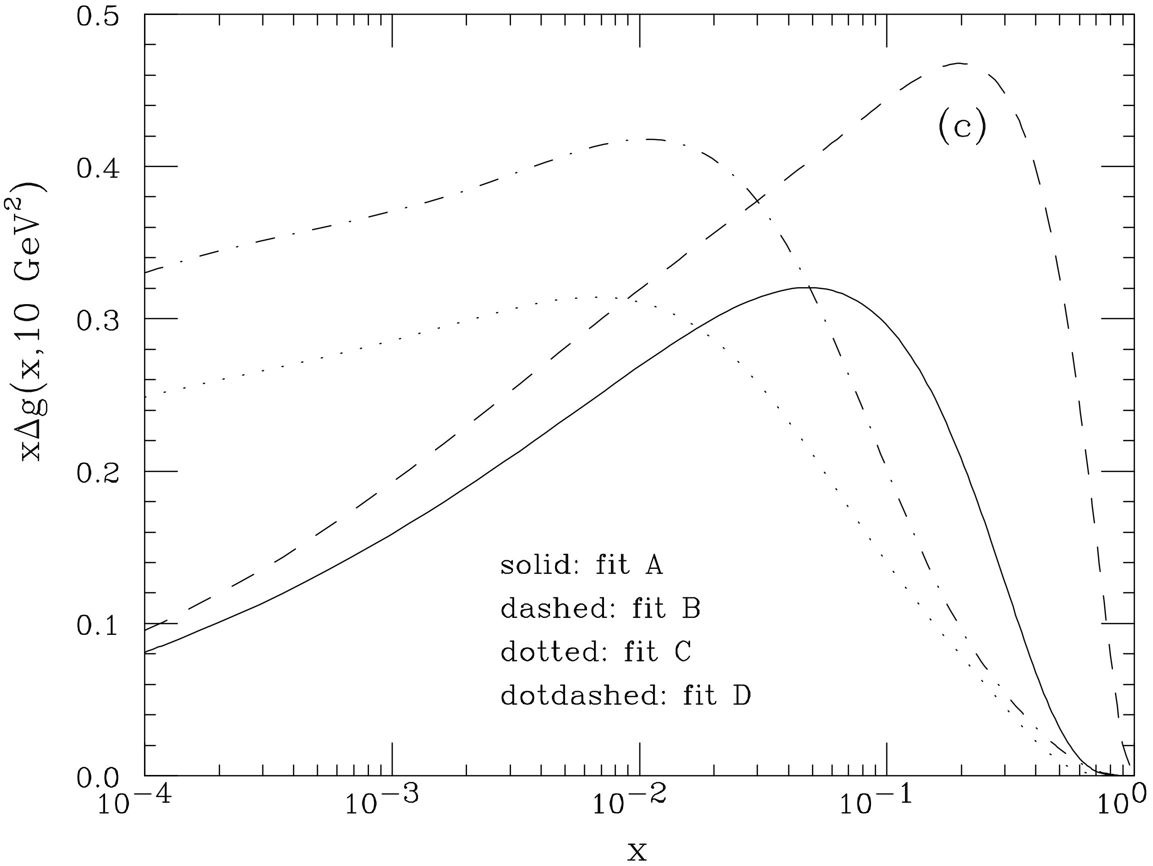
THE FIT OF E155 COLLABORATION (2000)

$$\Delta G = \int_0^1 g(x)dx = 1.6 \pm 0.8 \pm 1.1$$



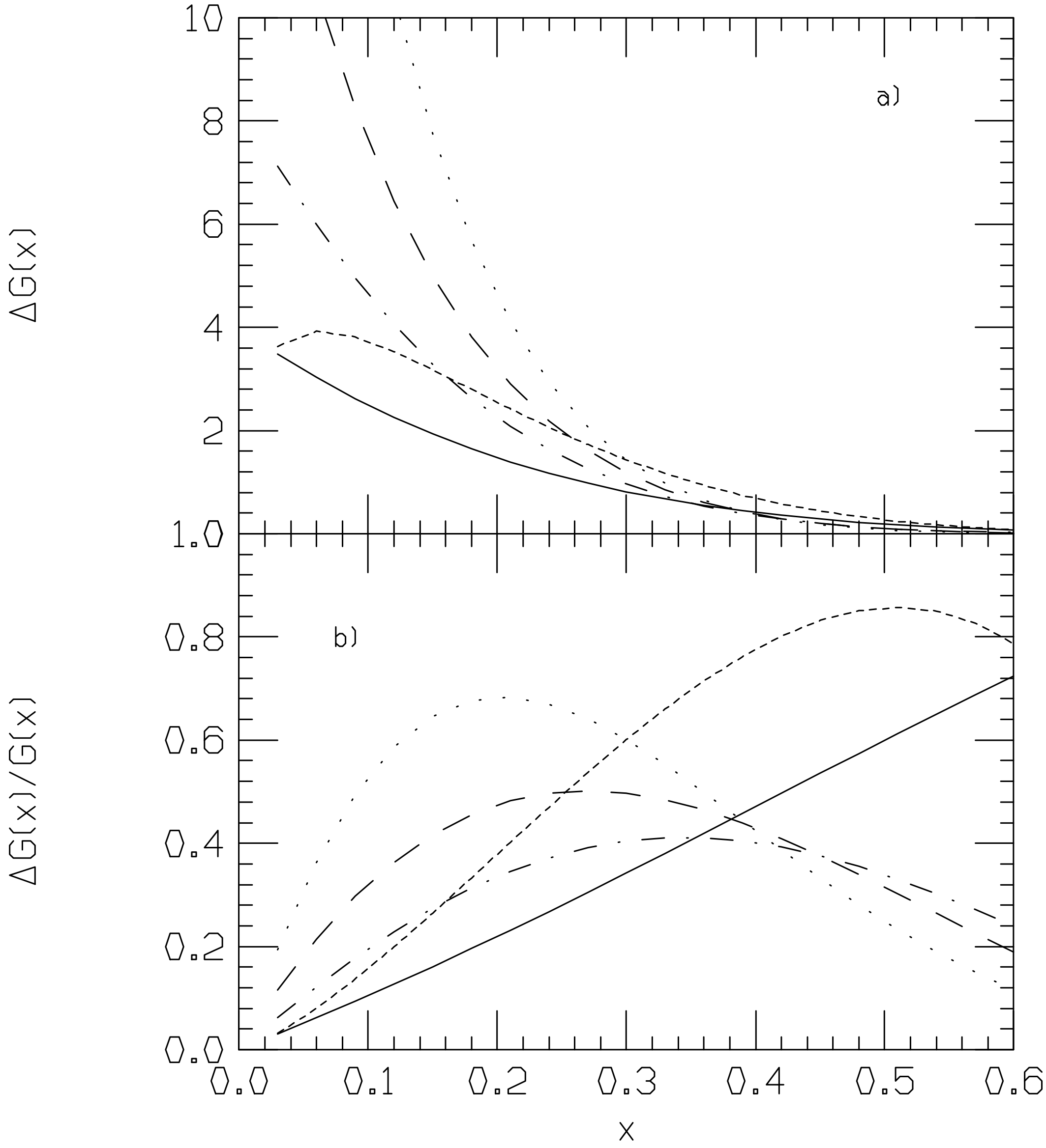
POLARIZED GLUON DISTRIBUTIONS FROM pQCD EVOLUTION EQUATIONS.

THE FITS OF Altarelli, Ball, Forte and Ridolfi (1998) $\Delta G = 1$ to 2.2



POLARIZED GLUON DISTRIBUTIONS FROM pQCD EVOLUTION EQUATIONS.
VARIOUS FITS

———	Brodsky (1995) $\Delta G = 0.7$
— — —	Sterling (1996) $\Delta G = 1.7$
· · · · · ··	GRSV (1996) $\Delta G = 2.3$
— · —	Ball AR Model (1996) $\Delta G = 1.1$
- - - -	Ball OS Model (1996) $\Delta G = 1.0$

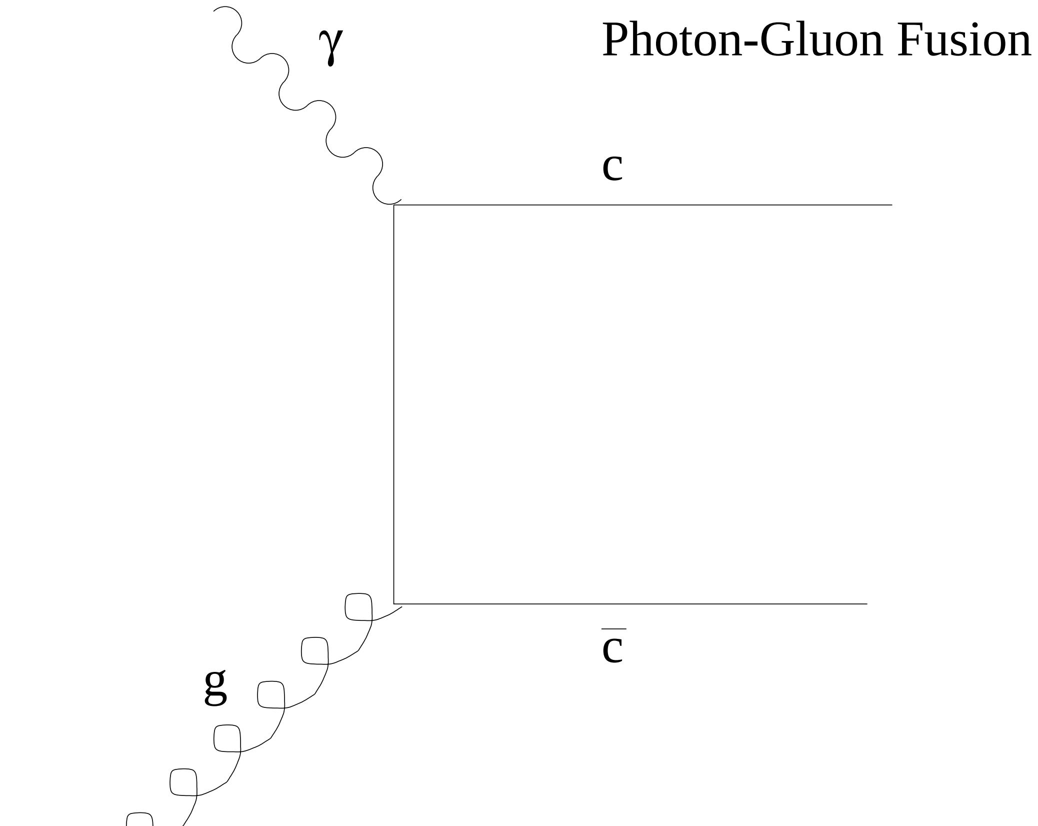


$\boxed{\textbf{HOW TO MEASURE } \Delta g(x, Q^2) \textbf{ DIRECTLY}}$

POLARIZED PHOTON BEAM

POLARIZED LiD TARGET

PHOTON-GLUON FUSION



TOTAL CHARM PHOTOPRODUCTION σ

$$\sigma_{\gamma p}(k) = \int_{x_{min}}^{1} g(x,Q^2)dx \int_{-1}^{1} \sigma(\hat{s},\cos(\theta^*))\,\beta\, d\cos(\theta^*)$$

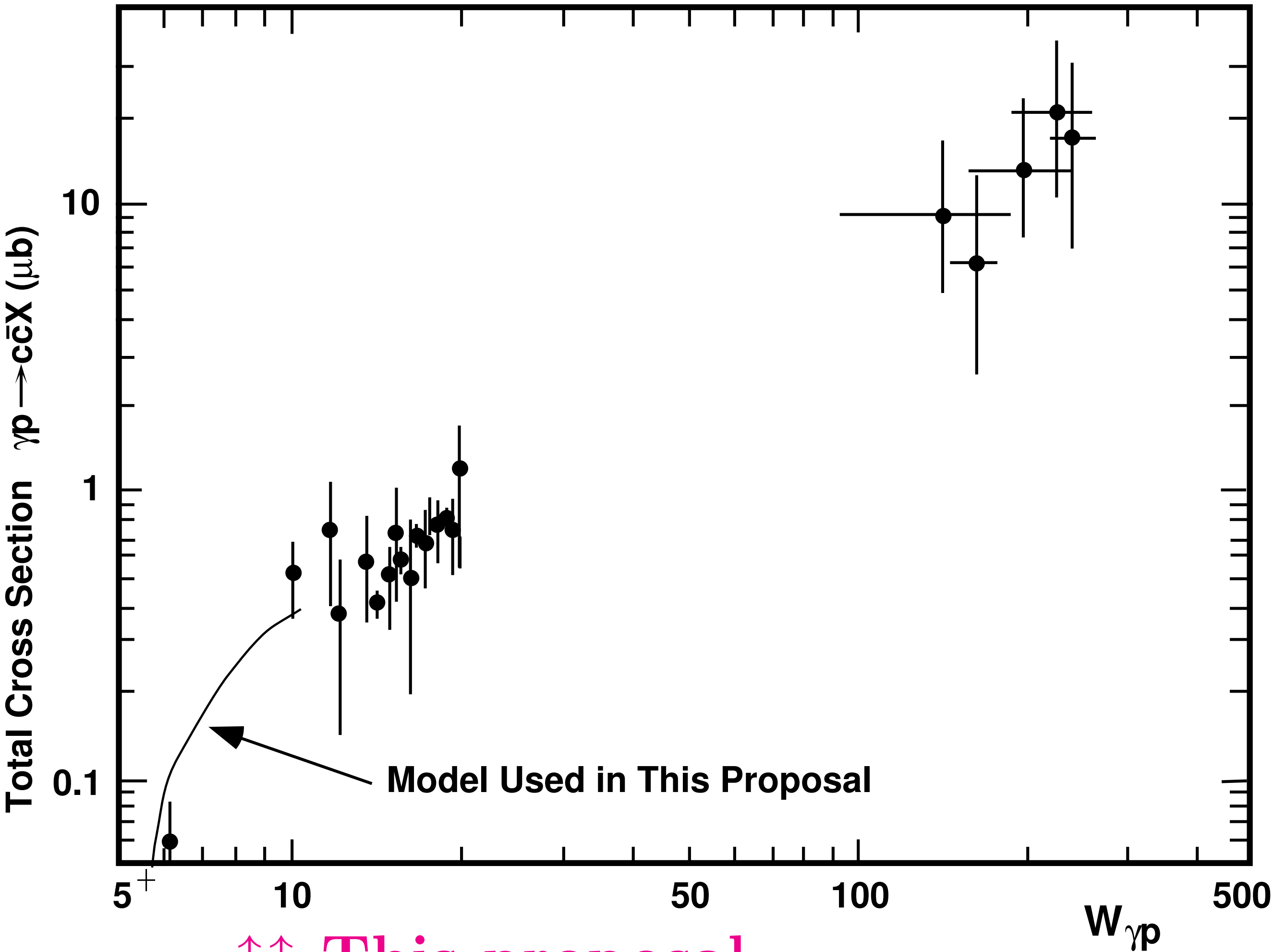
$\mathbf{x_{min} = 4m_c^2/2Mk}$

$s = 2Mk + M^2$

$\beta = \sqrt{1 - 4m_c^2/\hat{s}}$ **is the c.m. velocity of $\mathbf{c}, \bar{\mathbf{c}}$**

$\hat{\mathbf{s}} = \mathbf{xs}$ **is the energy of the photon-gluon system squared**

$\sigma(\hat{s},\cos(\theta^*))$ **is for the hard scattering**



↑↑ This proposal

POLARIZED $c\bar{c}$ CROSS SECTION

$$\boxed{\boldsymbol{\Delta\sigma = \sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}}$$

$$\Delta\sigma_{\gamma p}(k) = \int_{x_{min}}^{1} \Delta g(x, Q^2) dx \int_{-1}^{1} \Delta\sigma(\hat{s}, \cos(\theta^*))\, \beta\, d\cos(\theta^*)$$

where

$$\Delta\sigma(\hat{s}, \cos(\theta^*)) = \frac{4}{9}\frac{2\pi\alpha\alpha_s(\hat{s})}{\hat{s}}\left[\frac{4m_c^4(\hat{t}^3+\hat{u}^3)}{\hat{t}^2\hat{u}^2} + 2\frac{\hat{t}^2+\hat{u}^2-2m_c^2\hat{s}}{\hat{t}\hat{u}}\right].$$

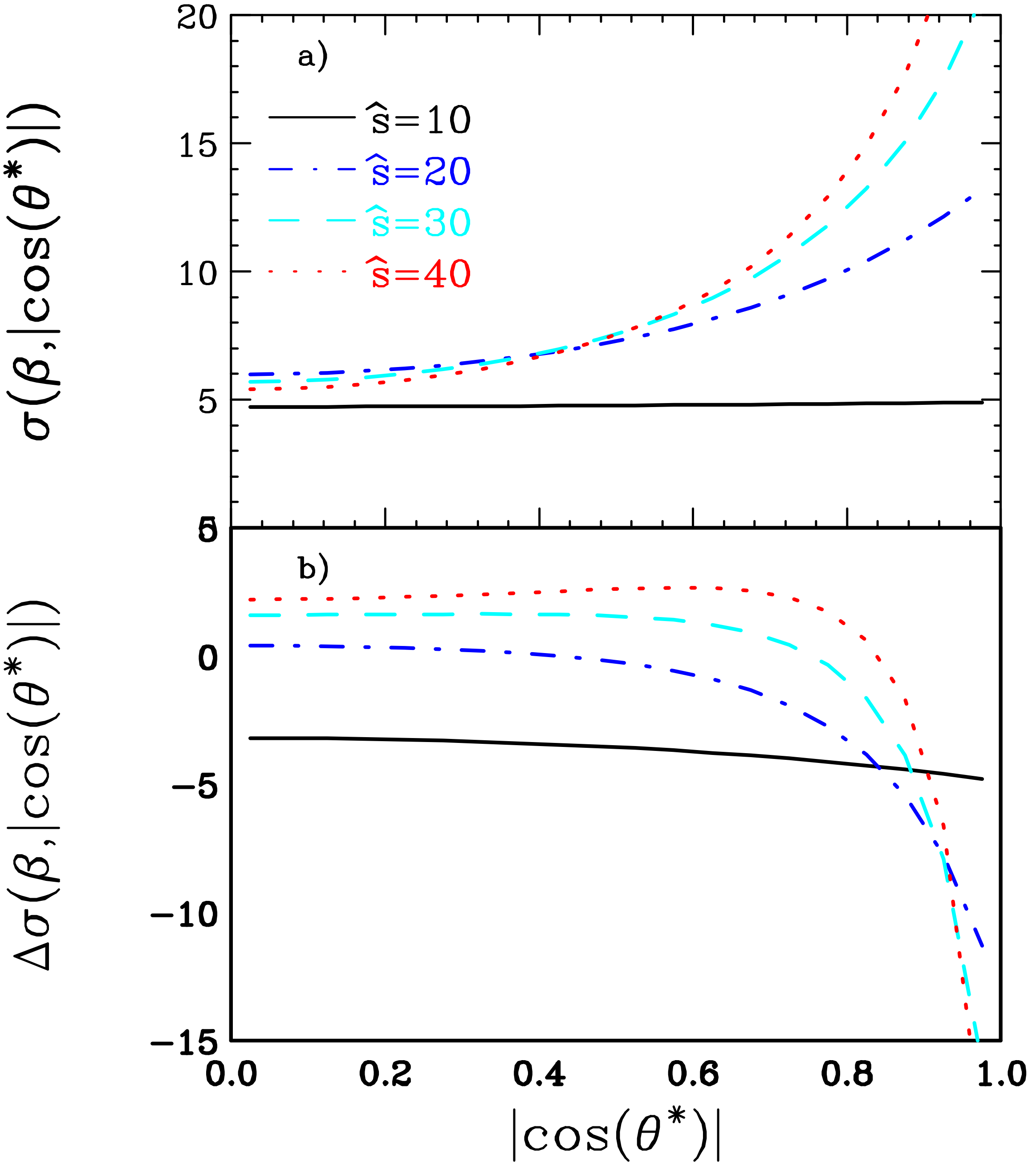
Integrated over $\cos(\theta^*)$**, this becomes**

$$\Delta\sigma(\hat{s}) = \frac{4}{9}\frac{2\pi\alpha\alpha_s(\hat{s})}{\hat{s}}\left[-3\beta + \ln\frac{1+\beta}{1-\beta}\right].$$

$$\boxed{\mathbf{A_{cc}(k) = \Delta\boldsymbol{\sigma}_{\gamma p}(k)/\boldsymbol{\sigma}_{\gamma p}(k) = \frac{1}{P_t P_b f}\frac{N^{\uparrow\uparrow}-N^{\downarrow\uparrow}}{N^{\uparrow\uparrow}+N^{\downarrow\uparrow}}}}$$

CROSS SECTION and $\Delta\sigma$

DEPENDENCY ON CENTER OF MASS ANGLE

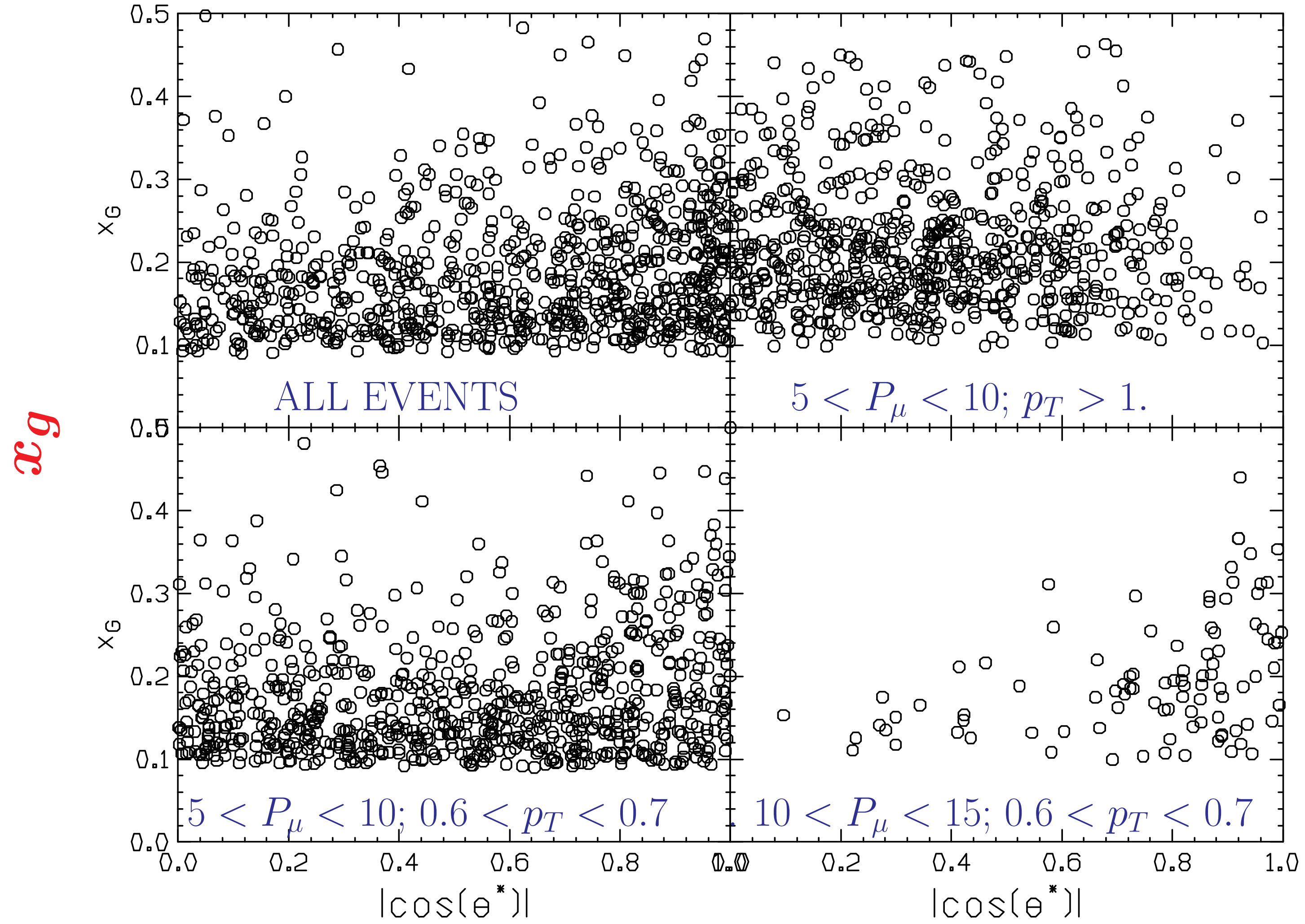


EXPERIMENT

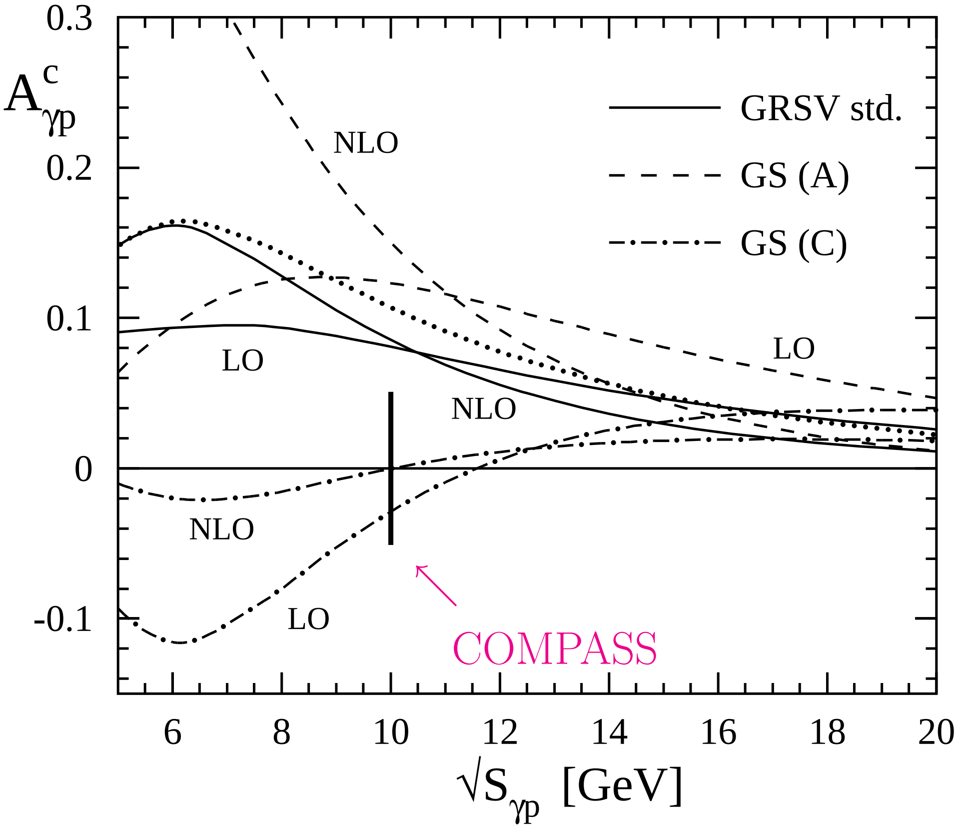
$\boxed{\mu \text{ and c KINEMATICS}}$

$$x_{min} = 4m_c^2/(2Mk)$$

Photon Energy	x_{min}
35.	0.14
40.	0.12
45.	0.10 $\Leftarrow$



NLO pQCD



↑↑↑ This proposal

(I. Bojak and M. Stratmann)
also calculated by Z. Merebashvili et al.

EXPERIMENTAL STRATEGY

TAG CHARM WITH SINGLE DECAY μ

VERY SHORT LIFETIME

	D^+	D^0	D_s^+	Λ_c^+
produced(%)	19	63	8	8
Branching Ratio(%)	17	7	8	4
decay to μ^+(%)	37	47	8	4
	D^-	$\bar{D}^0$	D_s^-	Λ_c^-
produced(%)	21	71	6	2
decay to μ^-(%)	40	53	5	1

Fraction of different charmed particles produced with k=40 GeV photons and a deuterium target with $p_T > 0.5$ GeV generated using PYTHIA 5.7. Also shown is the percent of muons of each charge which ORIGINATED from the parent charmed particle.

BEAM PARAMETERS

Electron Energy (GeV)	45.1	48.3	48.3
Electron Current (10^{10}/spill)	2.0	2.0	2.0
Peak Photon Energy (GeV)	35.0	40.0	43.0
Photons (10^7/spill) ♡	2	1.5	1.1
Circular Polarization	0.75	0.80	0.84
x_{min}	.10	.12	.14
High p_t Muons/day	160,000	140,000	120,000
days (at 120 Hz, 100% efficiency)	9	10	11

♡ **E155 had** 3×10^9 e^- **into ESA**

BACKGROUNDS

OTHER SOURCES OF μ

- μ **FROM K and** π **DECAY (Long Lifetime)**
- **Bethe-Heitler** μ **PAIRS**
- **J/**ψ **DECAY (Small)**
- **VECTOR MESON DECAYS (Small)**

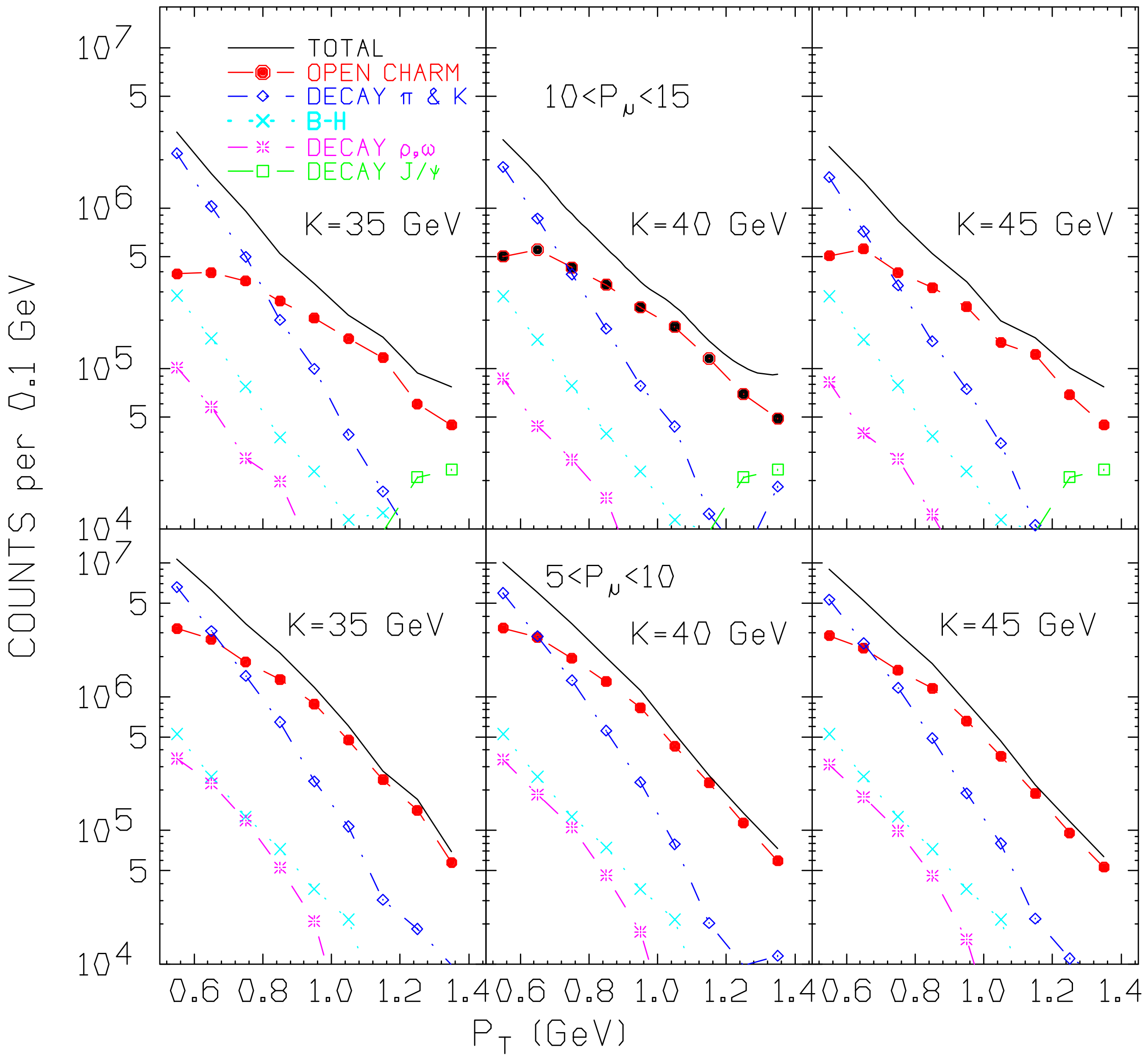
PHYSICS BACKGROUND

- **ASSOCIATED PRODUCTION (Small)**
- **FINAL STATE INTERACTIONS (Small)**
- **DIFFRACTIVE PRODUCTION (Small)**

NUMBER OF EXPECTED SINGLE μ

SIGNAL and BACKGROUNDS

BEFORE BACKGROUND SUBTRACTION



EXPERIMENTAL STRATEGY

- HIGH POLARIZATION TARGET
- HIGH POLARIZATION BEAM
- MEASURE MOMENTUM of μ
  - High Field Magnet
  - Fine Grain Hodoscopes
  - Good Time Resolution
- ABSORB K and π BEFORE DECAY
  - $\sim$ 10 Interaction Lengths (38 R.L.)
  - Monte Carlo Predicts Rates
  - Asymmetry Very Small (E155)
  - Two Absorber Setups
    75% and 25% of Time
  - Multiple Scattering of μ Almost the Same
- VETO $\mu^+\mu^-$ PAIRS
  (B-H, J/ψ, VECTOR MESONS)
  - Some Singles Remain (Acceptance)
  - Calculate Based on Pairs and Known σ

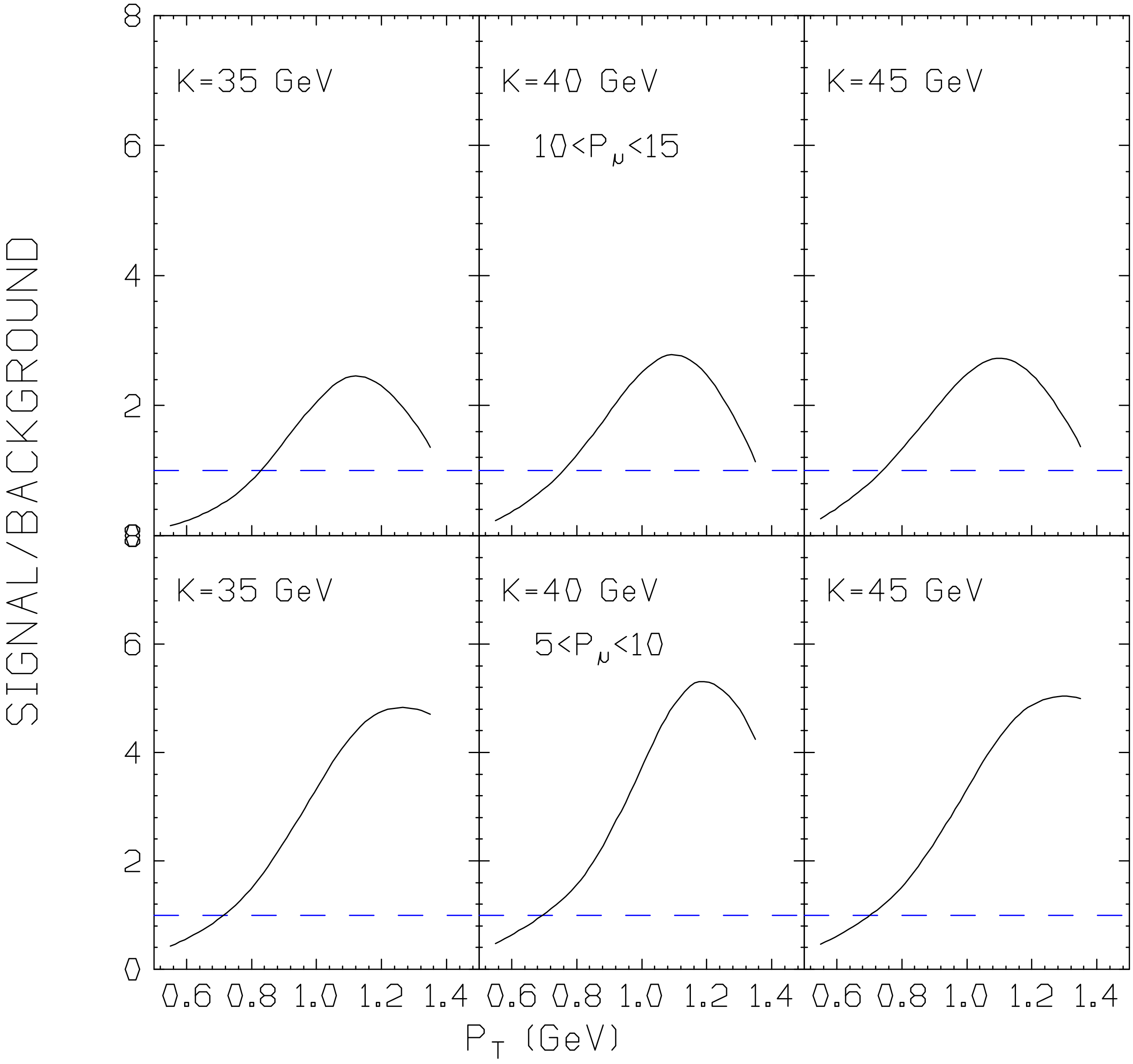
π AND KAON DECAY

μ Range Out at About 2 GeV

	π	KAON
Lifetime($10^{-8}sec$)	2.6	1.2
Branching Ratio to μ	1.00	.69
$c\tau$	7.8 m	3.7m
Distance - 10 GeV	560 m	74 m
Distance - 5 GeV	280 m	37 m

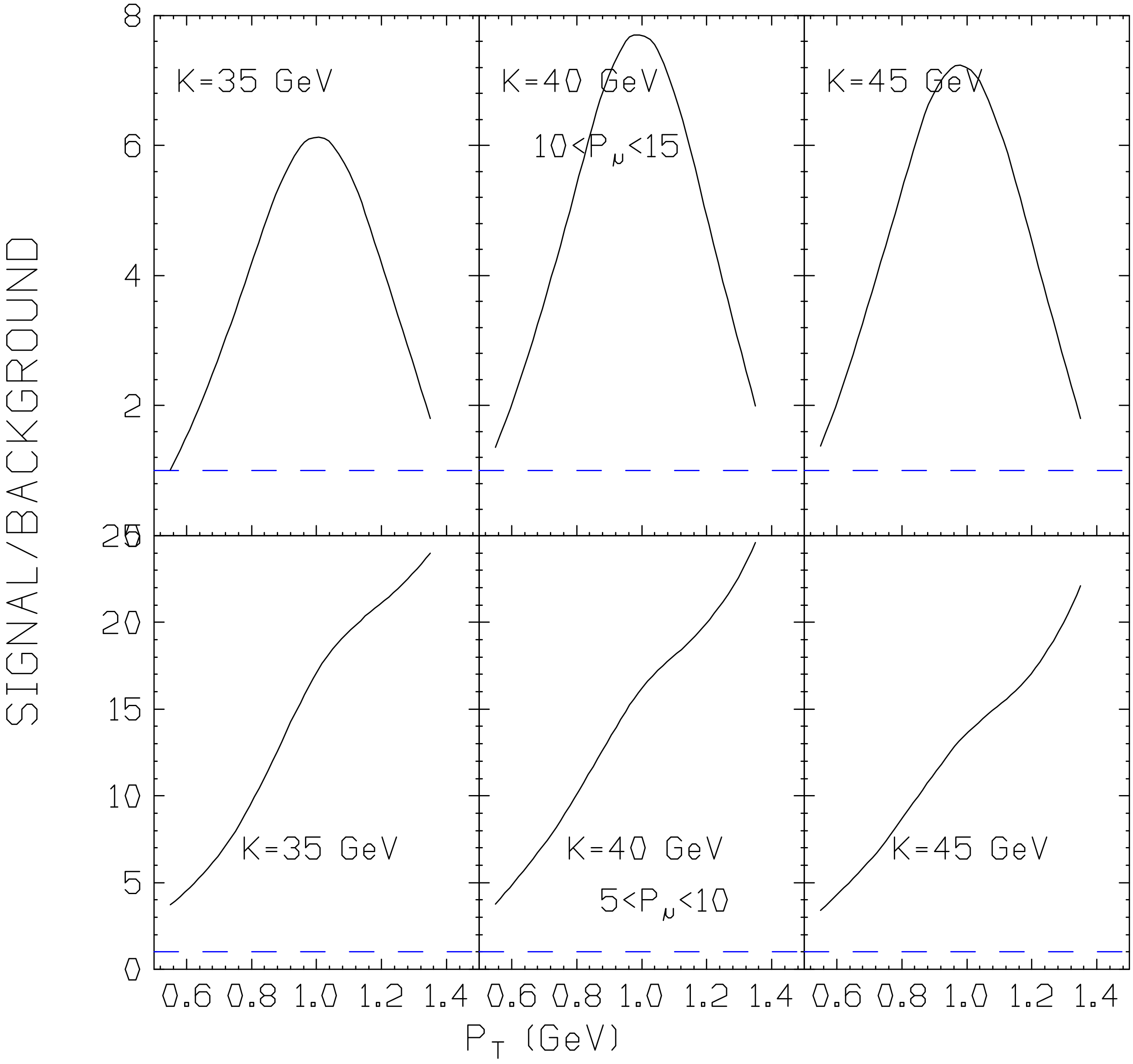
SIGNAL/BACKGROUNDS

BEFORE DECAY SUBTRACTION



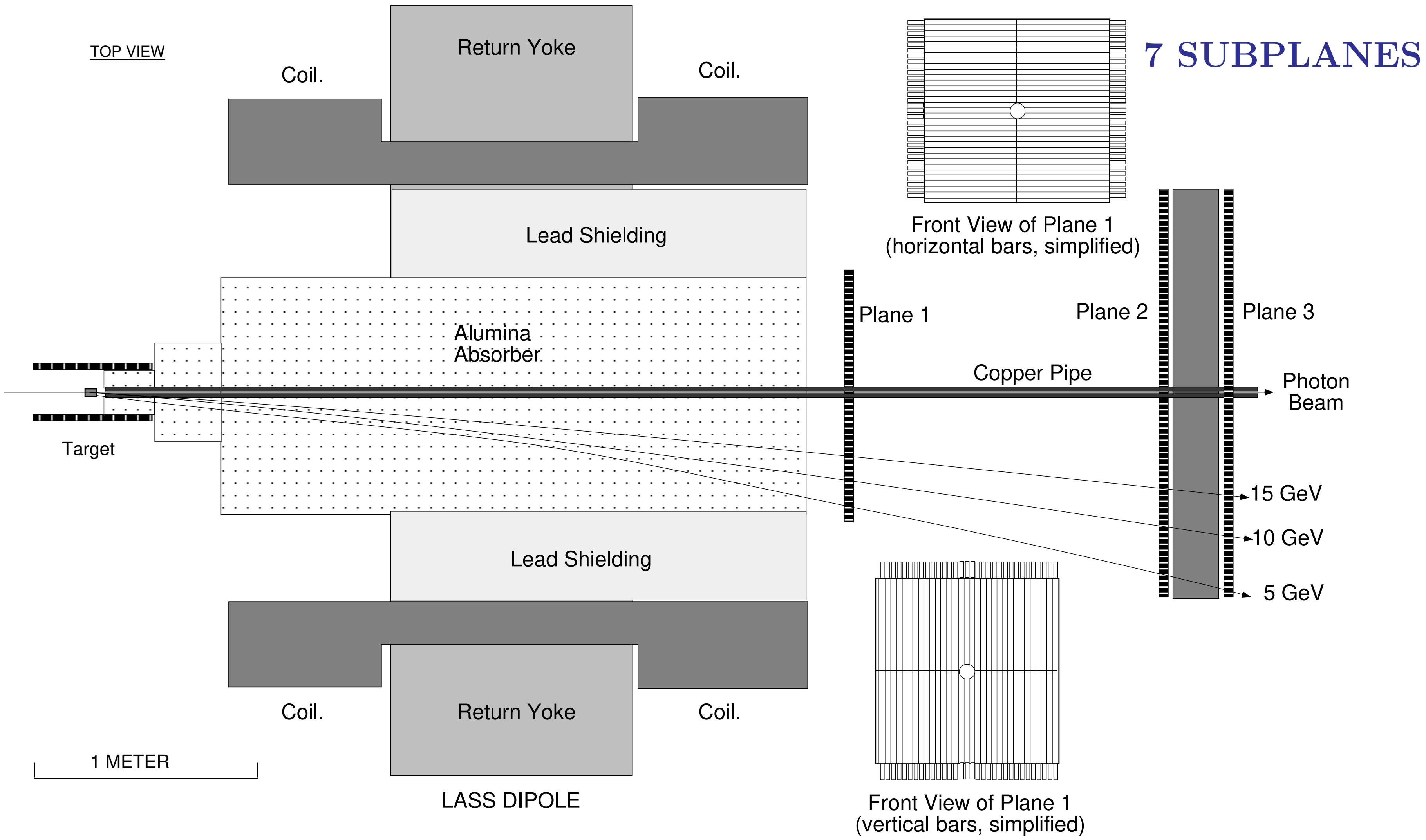
SIGNAL/BACKGROUNDS

DECAY SUBTRACTED



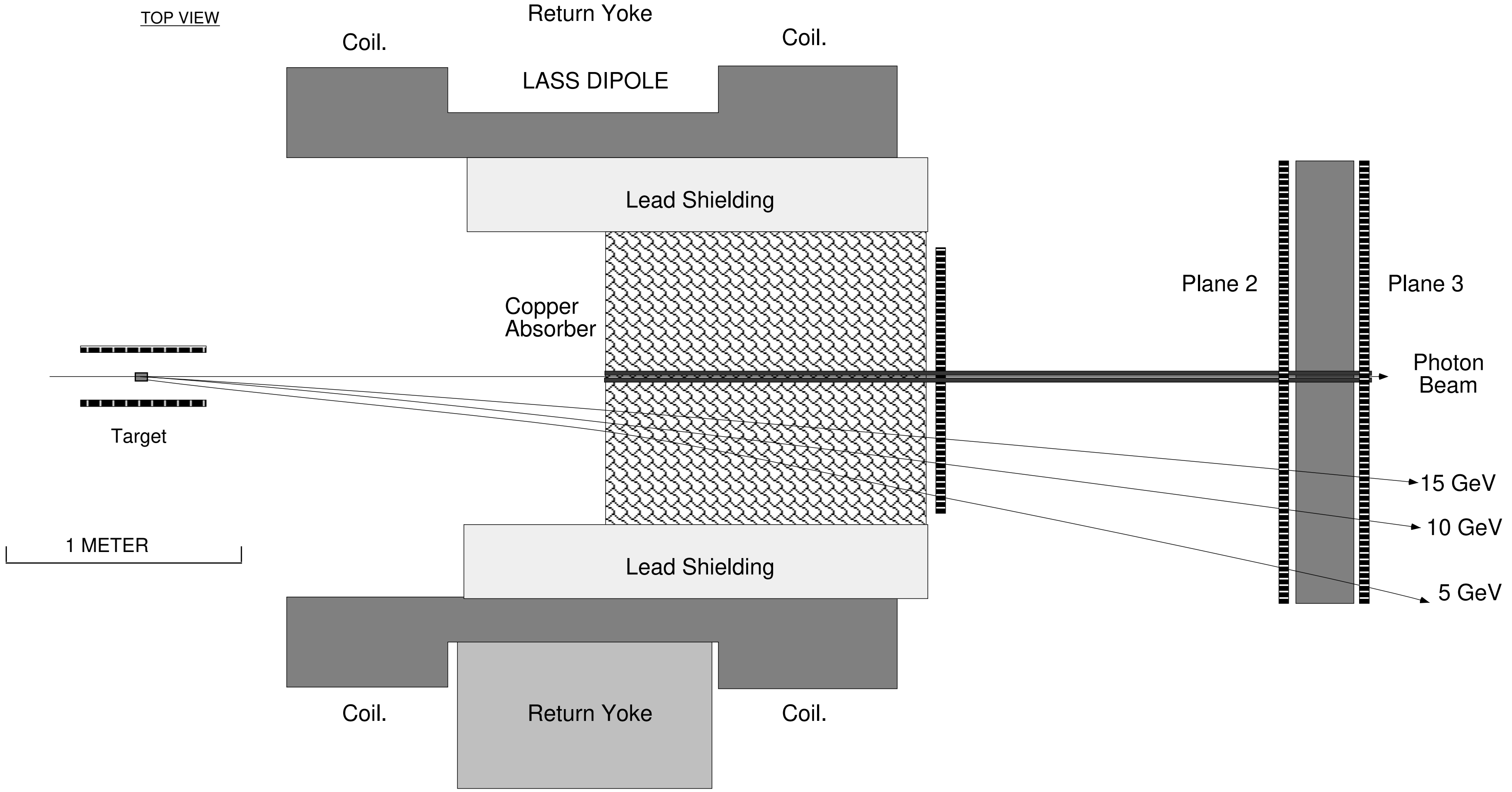
μ SPECTROMETER

NORMAL MODE



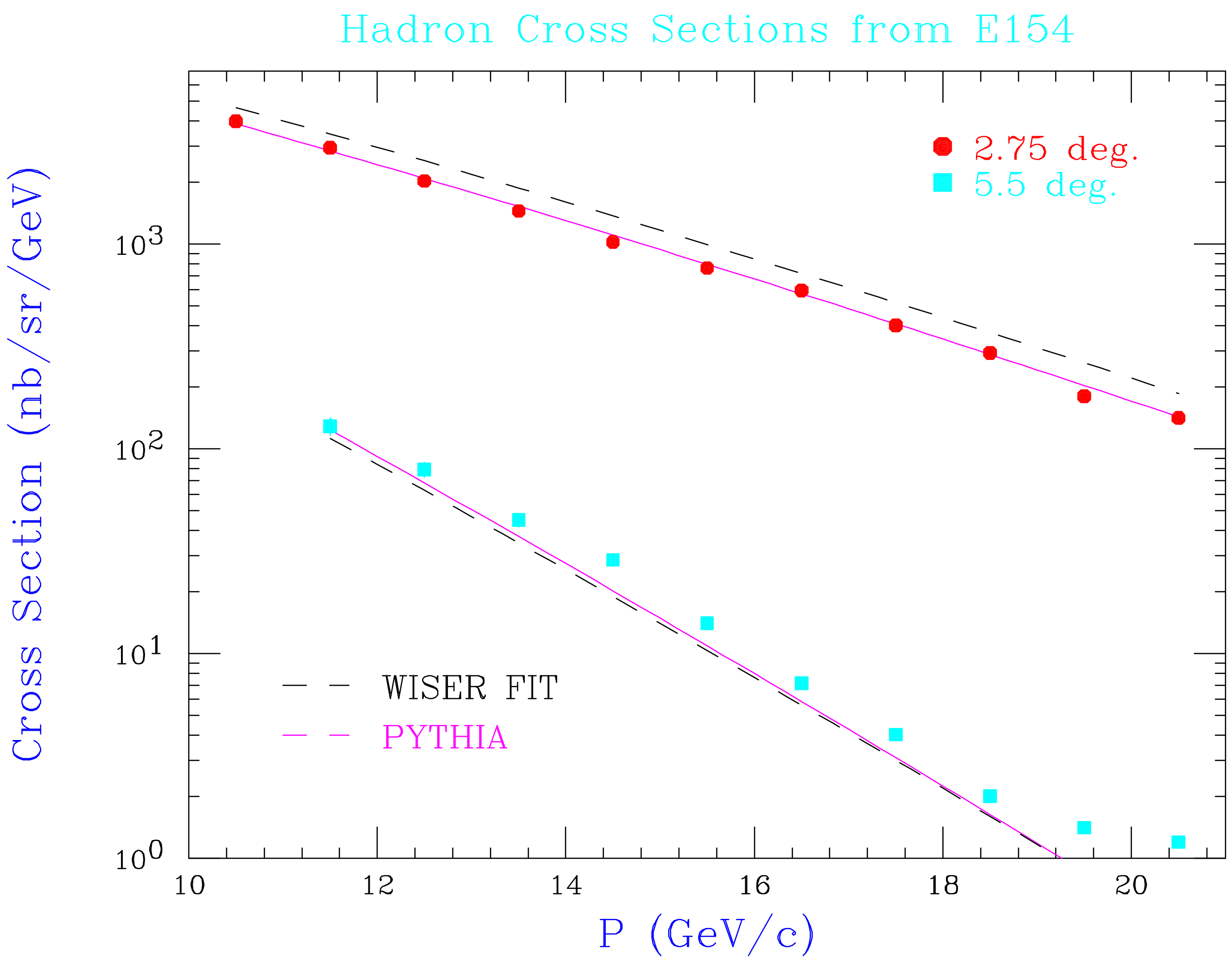
μ SPECTROMETER

BACKGROUND MODE



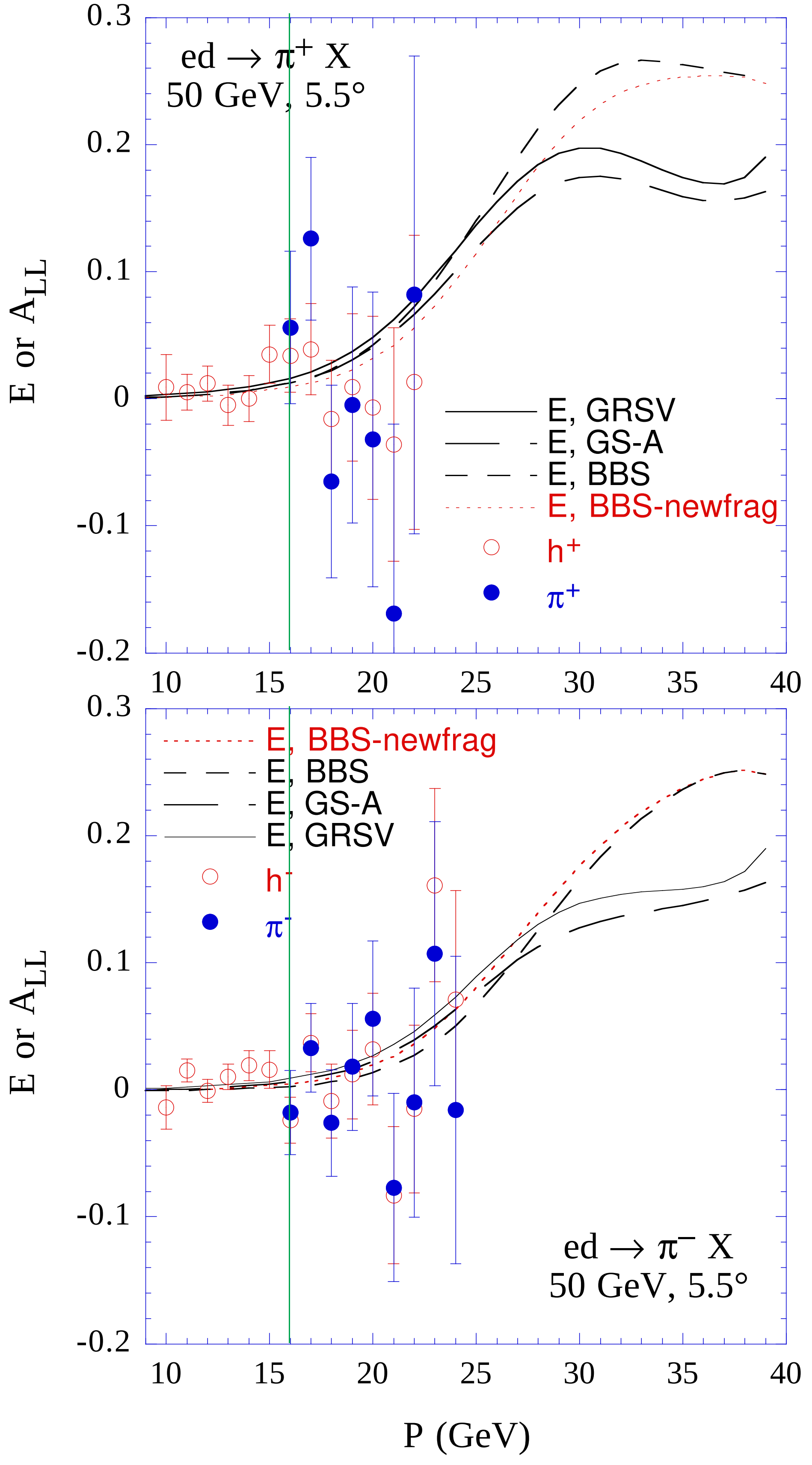
BACKGROUND: π, K DECAY

HOW WELL DO WE KNOW CROSS SECTION



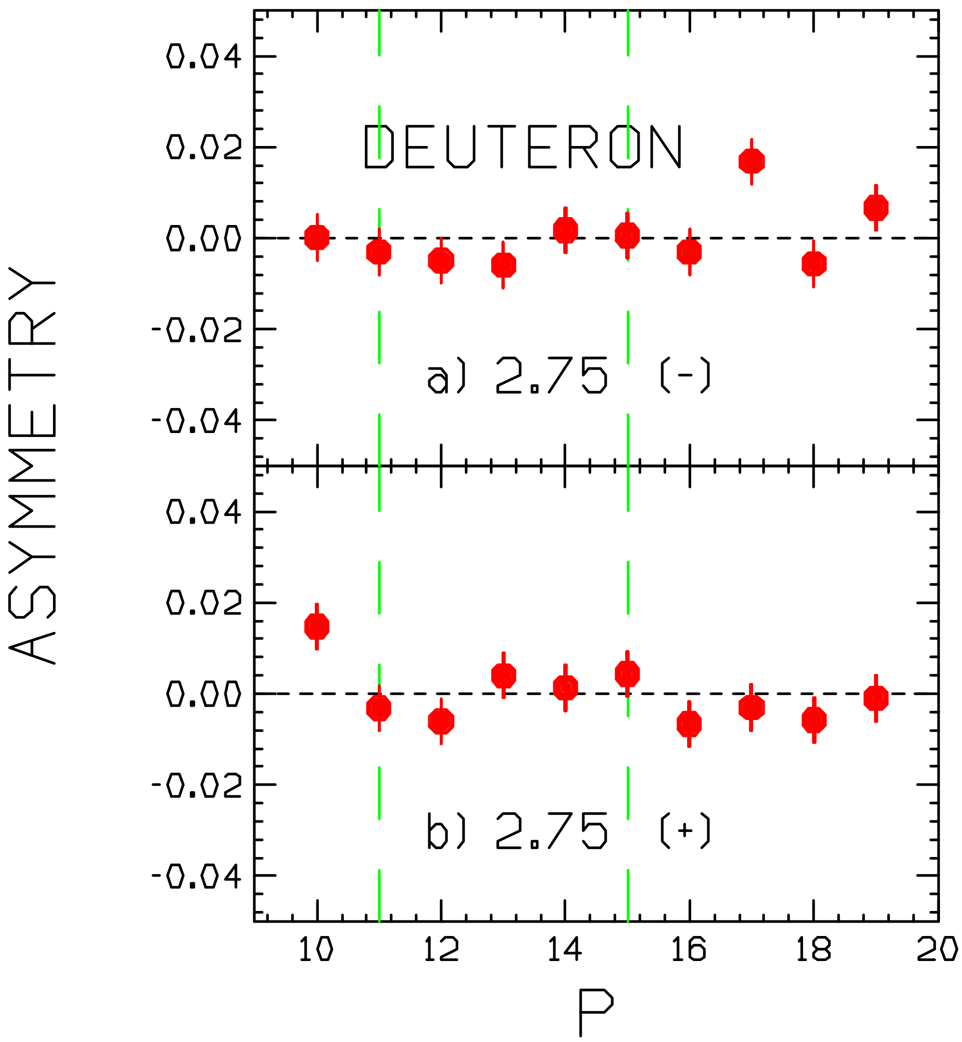
BACKGROUND: π, K DECAY

E155 HADRON ASYMMETRY 5.5°

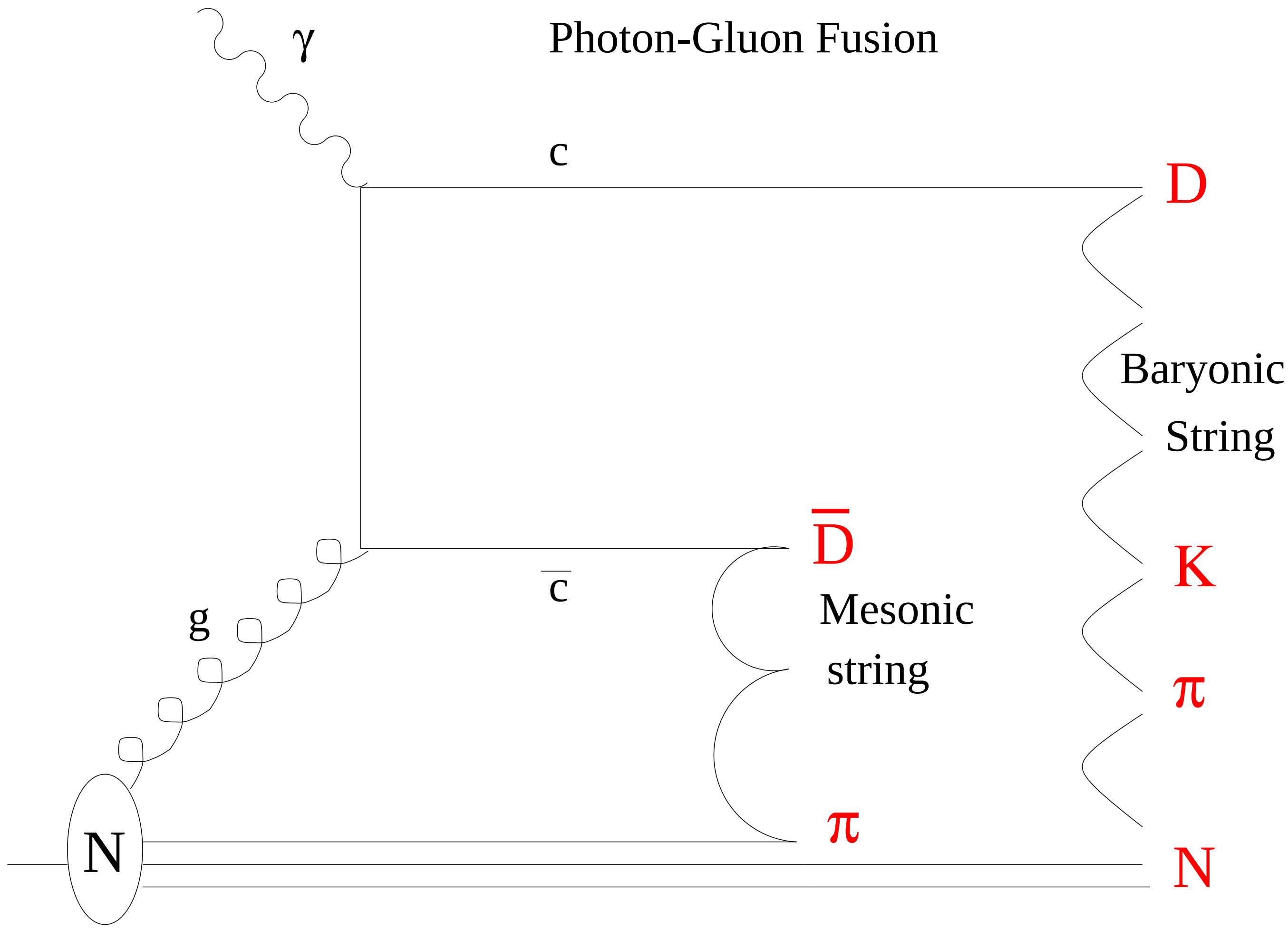


BACKGROUND: π, K DECAY

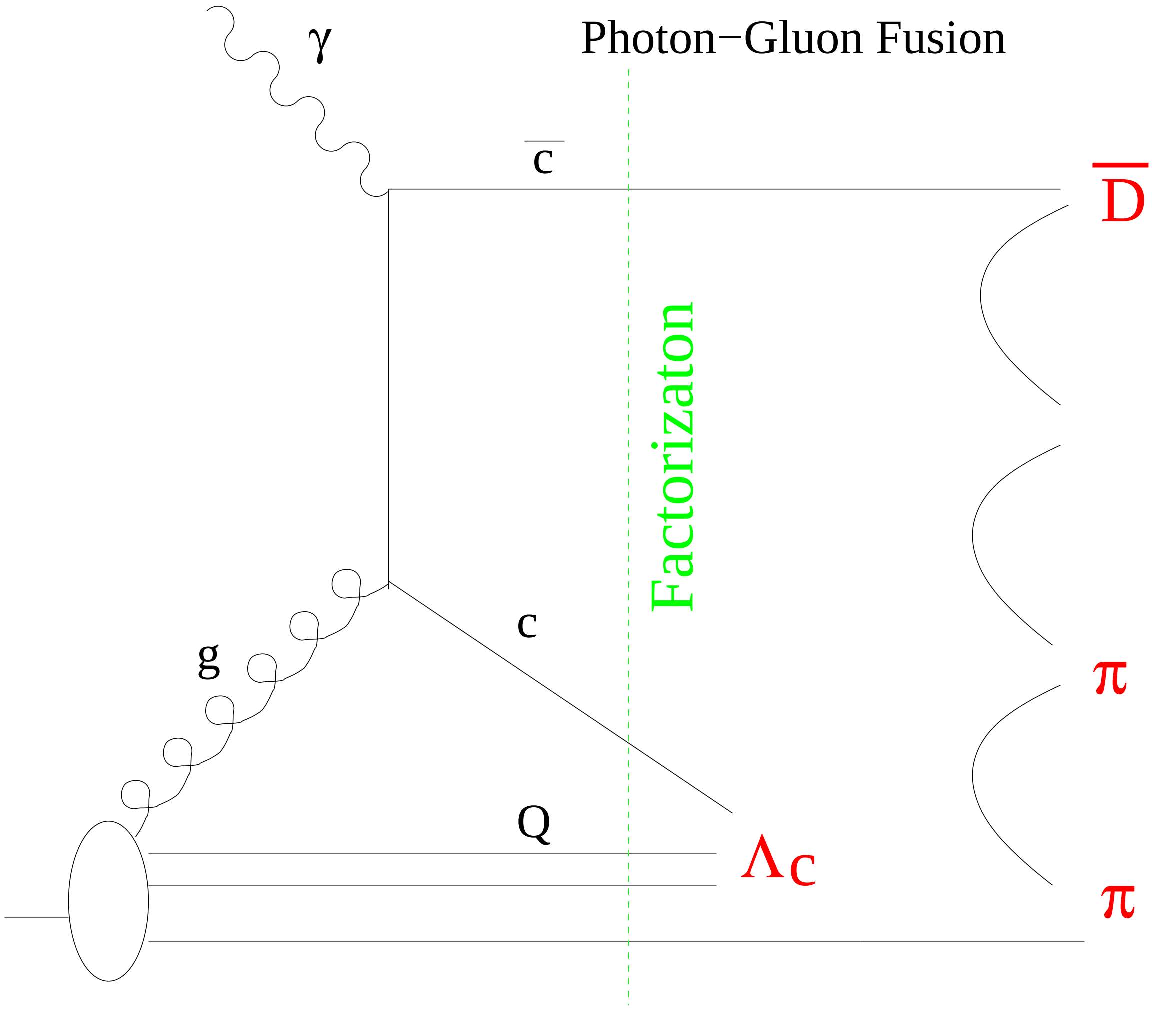
E155 HADRON ASYMMETRY 2.75°



PHYSICS BACKGROUND
NORMAL HADRONIZATION

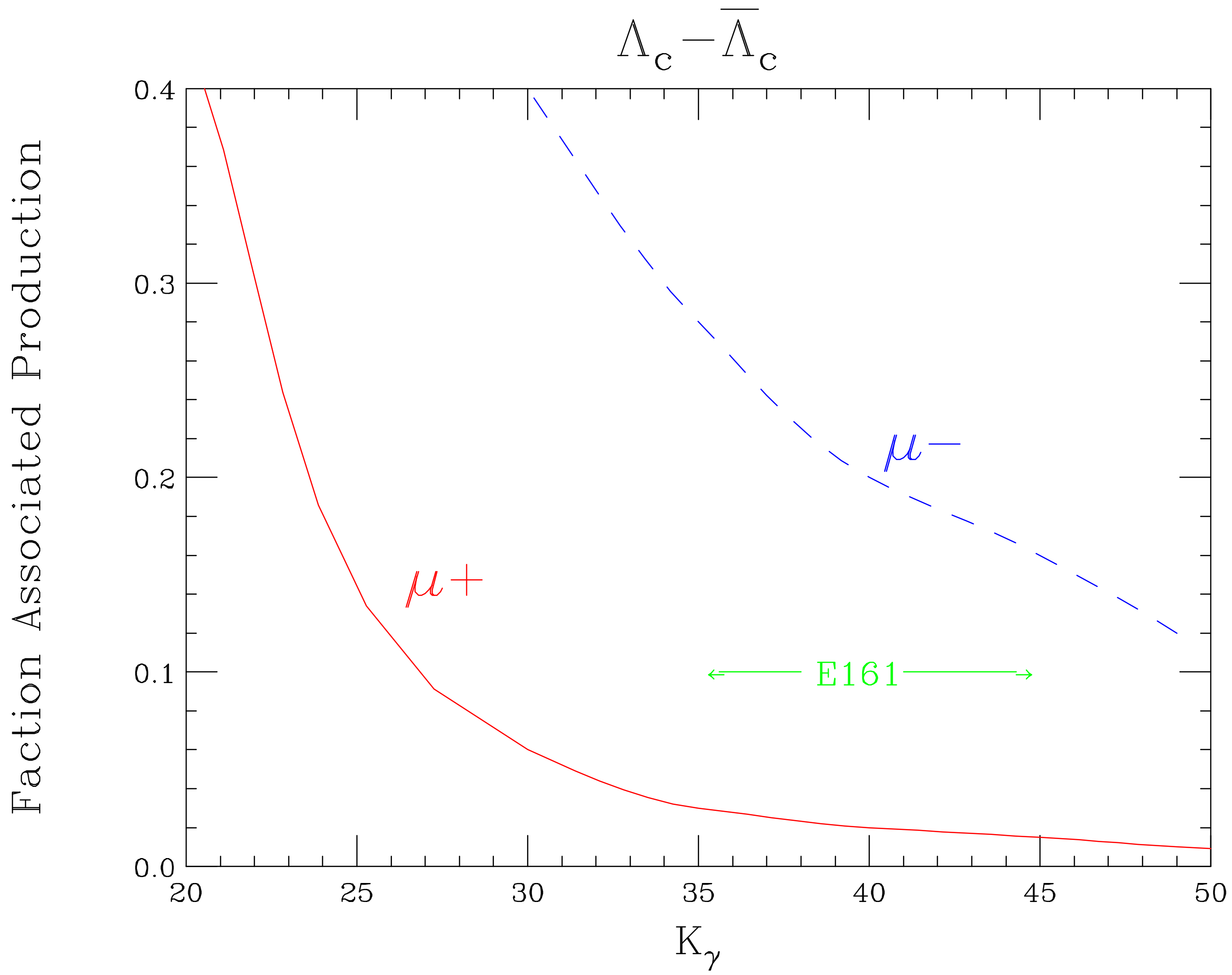


PHYSICS BACKGROUND
ASSOCIATED PRODUCTION
POLARIZED FRAGMENTATION?



- **FACTORIZATION**
- **RELATIVE DETECTED CROSS SECTION (Few Percent)**
- **HOW DOES c INTERACT WITH POLARIZED TARGET FRAGMENTS?**

PHYSICS BACKGROUND
ASSOCIATED PRODUCTION
PRODUCTION RATE LOW



μ^+ Mostly from D (c quark) $\Rightarrow$ No Λ_c^+

μ^- Mostly from $\bar{D}$ ($\bar{c}$ quark) $\Rightarrow$
c quark can form Λ_c^+

PHYSICS BACKGROUND
ASSOCIATED PRODUCTION
INTERACTION MECHANISM

Λ_c^+ PRODUCTION INDEPENDENT OF TARGET FRAGMENT POLARIZATION

- $\mathbf{\Lambda_c^+}$ = **cud with ud in Spin=0 State**
- **Production does NOT Depend on Polarization of c Quark.**
- **Production Does NOT Depend on Polarization of Target Fragments.**
- **Decay of Polarized Λ_c^+: small correction**

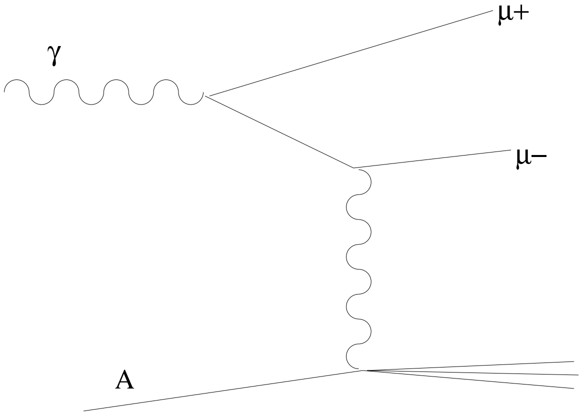
DIFFERENCE BETWEEN μ^+ and μ^-

- **Checks These Ideas**
- **Can Extrapolate to Zero Associated Production**

BEAM POLARIZATION MEASUREMENT

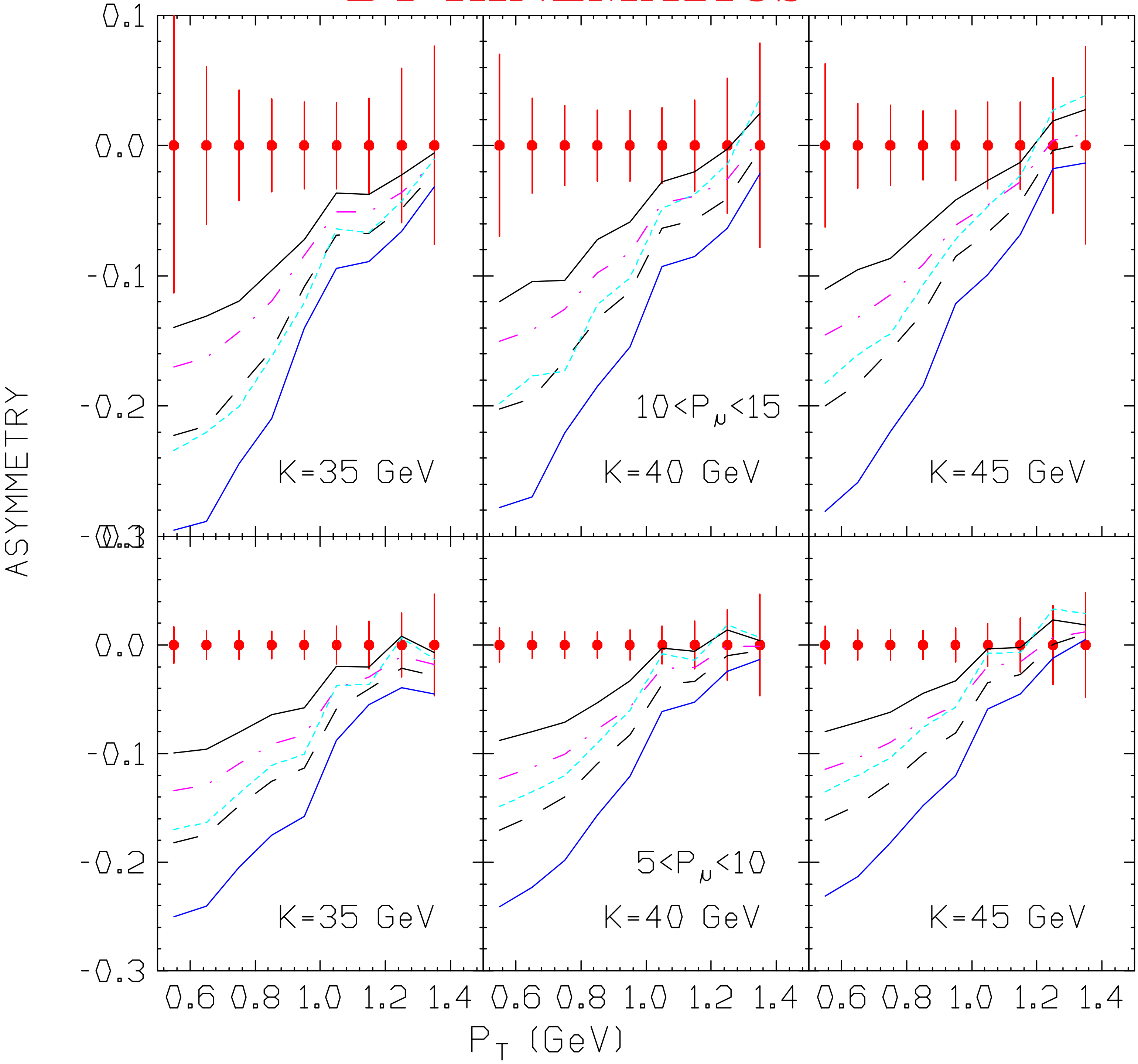
Use Bethe-Heitler Muon Pairs

Calculated by Gehrmann and Stratmann



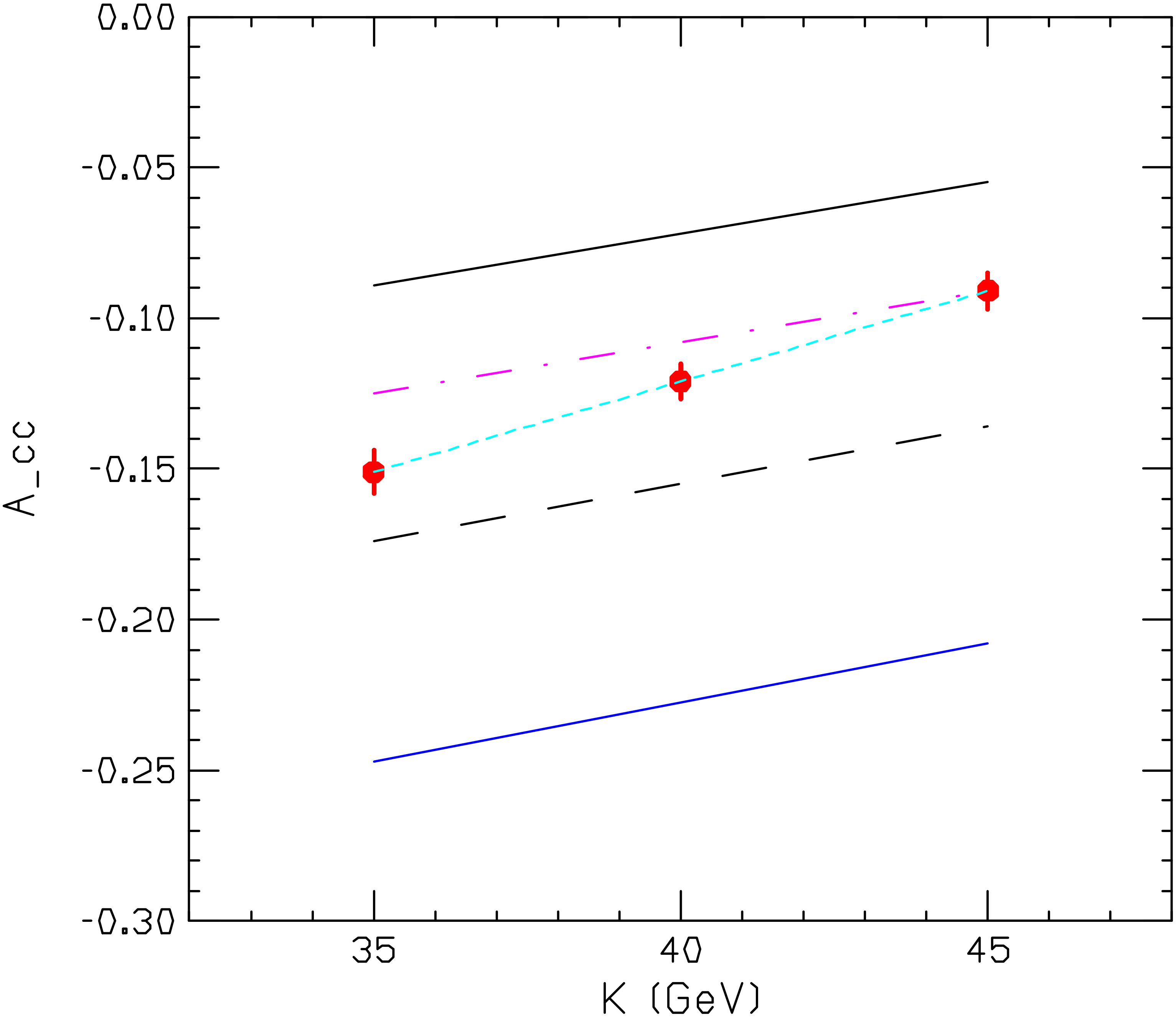
- Polarization Data taken Simultaneously with PGF
- Pairs with $1.2 < M_{\mu\mu} < 2.8$ GeV.
- Pair Rate Greater Than the PGF rate.
- Elastic (from ^{6}Li), Quasi Elastic and Inelastic Contributions.
- Relative importance depends on kinematics.
- Depends on Nuclear and Nucleon Form Factors and Polarized Structure Functions.
- Asymmetry about 3% depending on Kinematics.

EXPECTED RESULTS
BY KINEMATICS



EXPECTED RESULTS

AVERAGE



SYSTEMATIC ERRORS $\sim 8\%$

$\boxed{\text{OTHER EXPERIMENTS}}$
COMPASS

- NEXT GENERATION SMC
  5 TIMES SMC LUMINOSITY
- $\mu + d \longrightarrow c\bar{c}$ (LiD TARGET)
- DETECT D, $\bar{D}$
- BEAM ENERGY = 160 GeV
- MOST OF DATA AT VERY LOW Q^2
- ALSO USE HIGH P_T JETS
- START UP JUNE 2001
- PROBABLY SLOW STARTUP

$\boxed{\text{OTHER EXPERIMENTS}}$

HERMES

- LOW ELECTRON ENERGY (27 GeV)
- LOW LUMINOSITY
- RUNNING NOW
- TWO "HIGH P_T JETS"
- $0.06 < x < 0.28$
- FIRST RESULTS: $\Delta G/G = 0.41 \pm 0.18$

RHIC

Gluon Compton Scattering

$$g + q \rightarrow \gamma + X$$

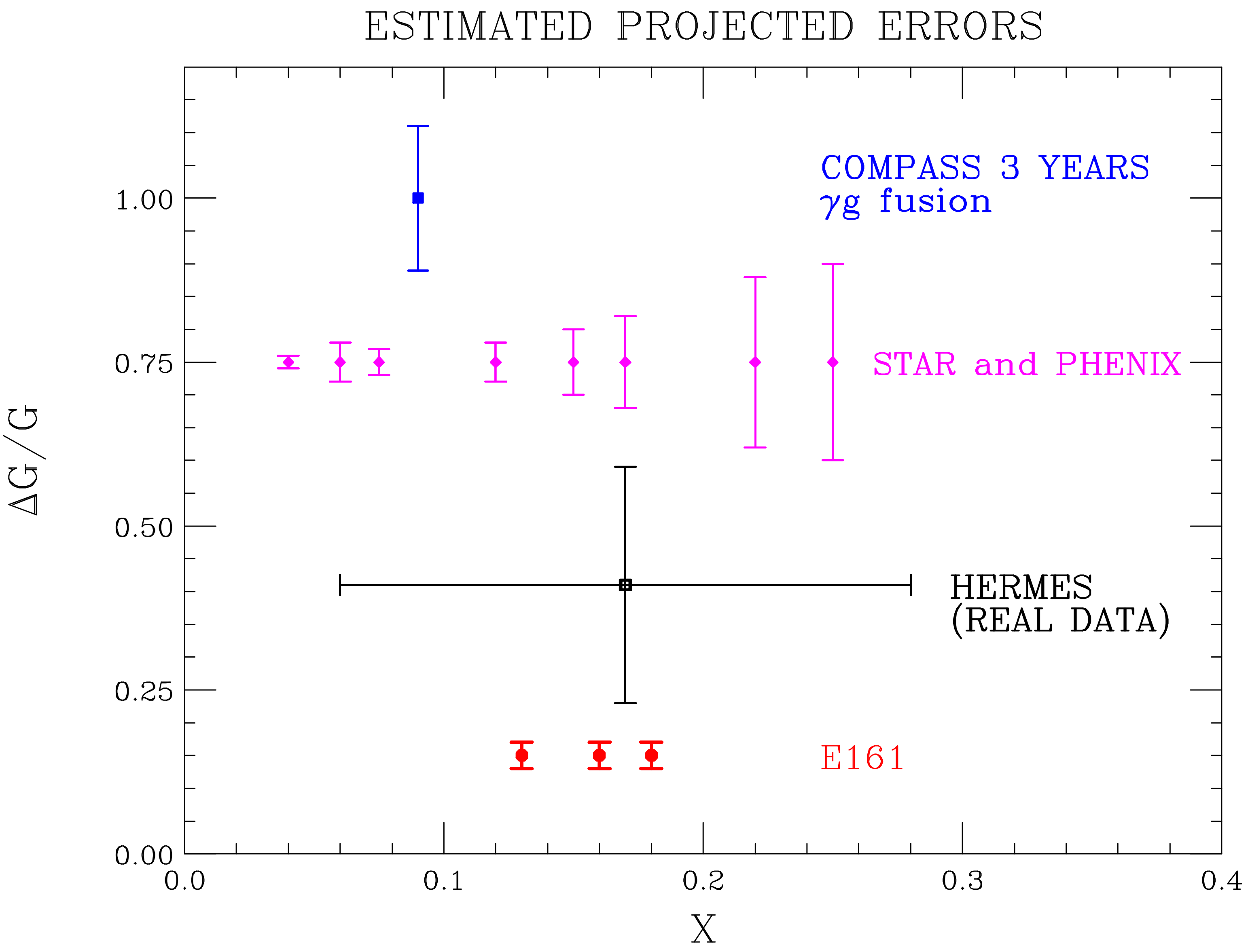
$$A_{LL} \cdot d\sigma \sim \sum_a \int \Delta q_a \cdot \Delta g \cdot d\Delta\sigma(q_a + g \rightarrow \gamma + X)$$

Gluon Fusion

$$g + g \rightarrow jet + jet$$

$$A_{LL} \cdot d\sigma \sim \int \Delta g \cdot \Delta g \cdot d\Delta\sigma(g + g \rightarrow X + X)$$

COMPARISON OF EXPERIMENTS



REQUEST TO SLAC

- RESOURCES TO BUILD BEAM
- RESOURCES TO BUILD DETECTOR
- RESOURCES FOR TARGET MAGNET and μWAVE HARDWARE
- 3 WEEKS CHECKOUT AT LOW REPETITION RATE
- 2 MONTHS OF DATA TAKING
  - 120 Hz Parasite on PEP-II
  - 50% Data Collection Efficiency

OTHER EXPERIMENTAL POSSIBILITIES

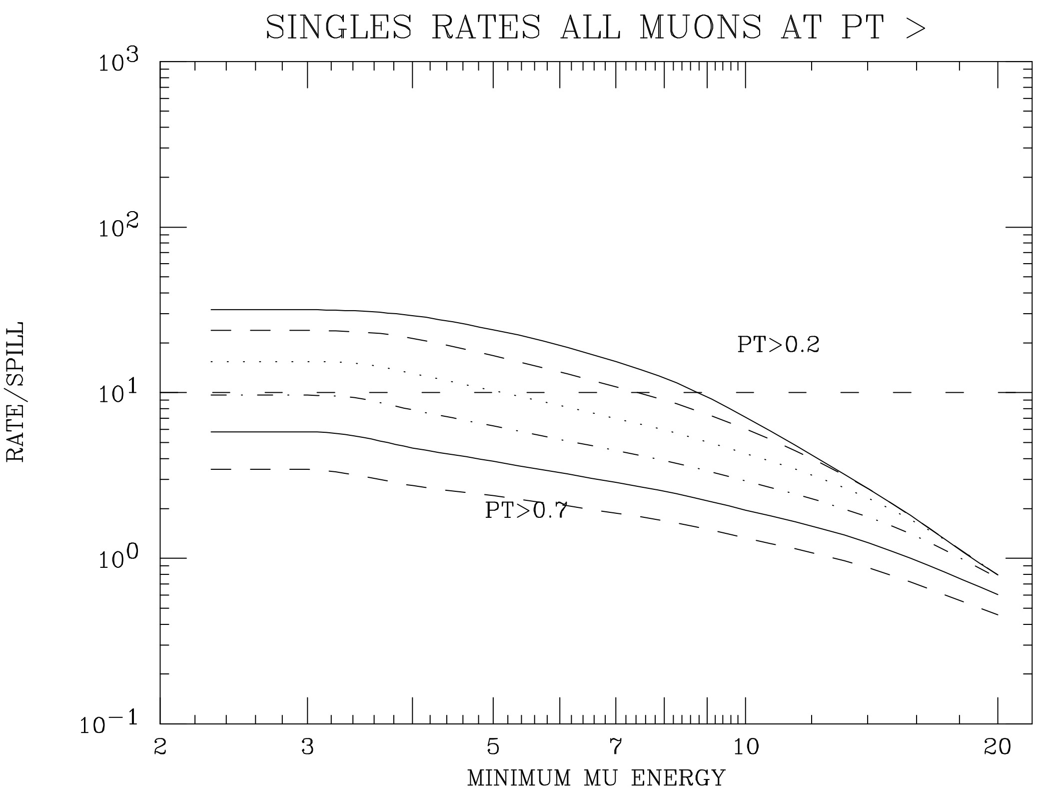
- MOTIVATION
  - REDUCE BACKGROUNDS
  - DECREASE ERROR
- DETECT BOTH MUONS
  - OPEN CHARM
  - J/ψ DECAY TO 2 MUONS

DETECTING TWO MUONS

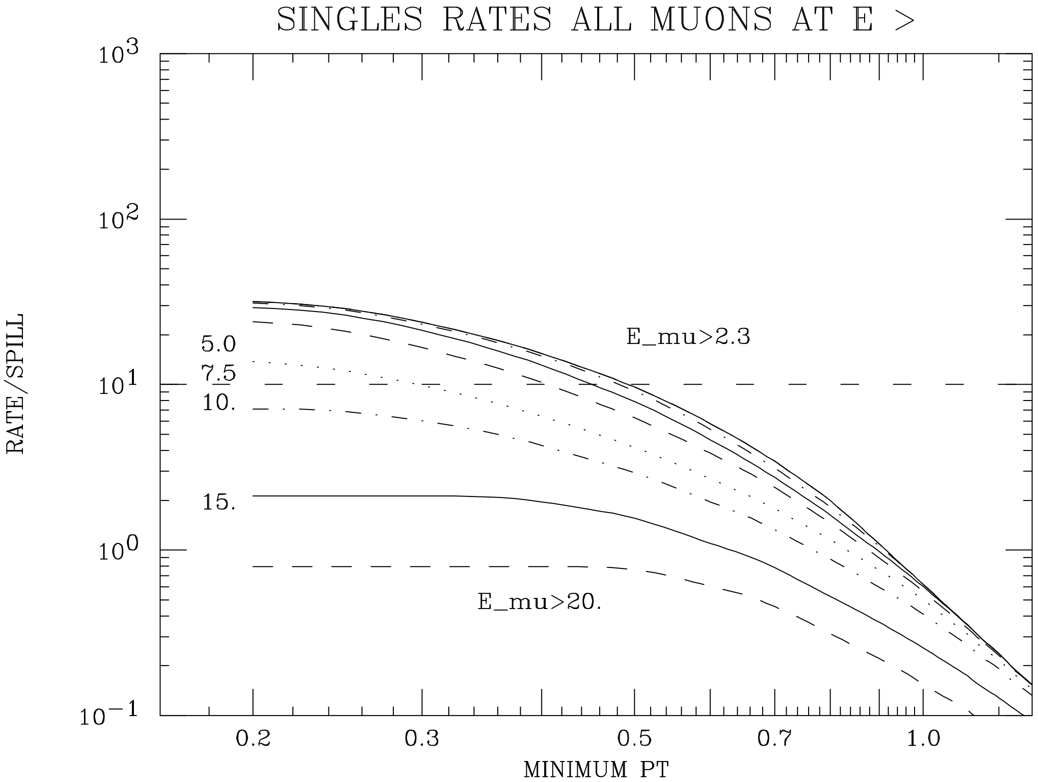
- RATES ARE LOWER
  - BRANCHING RATIO OF CHARMED PARTICLES $\sim$ 10%
  - PROBABILITY OF 1 MUON IN EVENT $\sim$ 20%
  - PROBABILITY OF 2 MUONS IN EVENTS $\sim$ 1%
  - $\Rightarrow$ INCREASE LUMINOSITY by factor of 50
  - INCREASE ELECTRON CURRENT by factor of 2.5
  - INCREASE THICKNESS OF DIAMOND $\times$ 20
- BACKGROUNDS CHANGE
  - FOR 1 MU, SINGLES FROM K,π DECAY, Bethe-Heitler
  - FOR 2 MU, RANDOM COINCIDENCS BETWEEN SINGLE MUONS
  - B-H COINCIDENCES
  - DECAY OF VECTOR MESONS e.g. $\rho^o \rightarrow \mu\mu$

SINGLES RATES

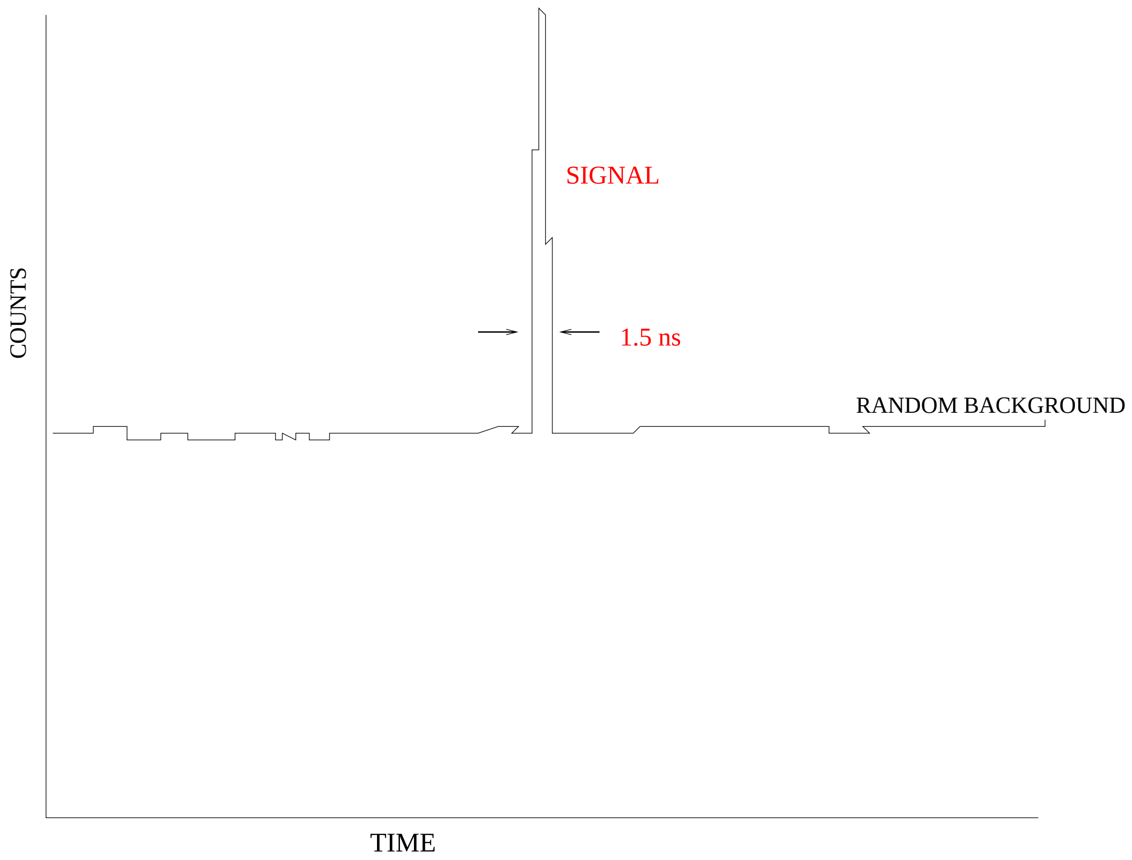
- K and π DECAY
  - BEFORE BEING ABSORBED BY SHIELDING
  - ESTIMATE ABOUT 2 INTERACTIN LENGTHS
- B-H elastic, quasielastic, inelastic
- CHARM DECAY
- RANDOMS WILL HAVE AN ASYMMETRY



SINGLES RATES ALL MUONS AT PT >
RATE/SPILL
PT>0.2
PT>0.7
MINIMUM MU ENERGY



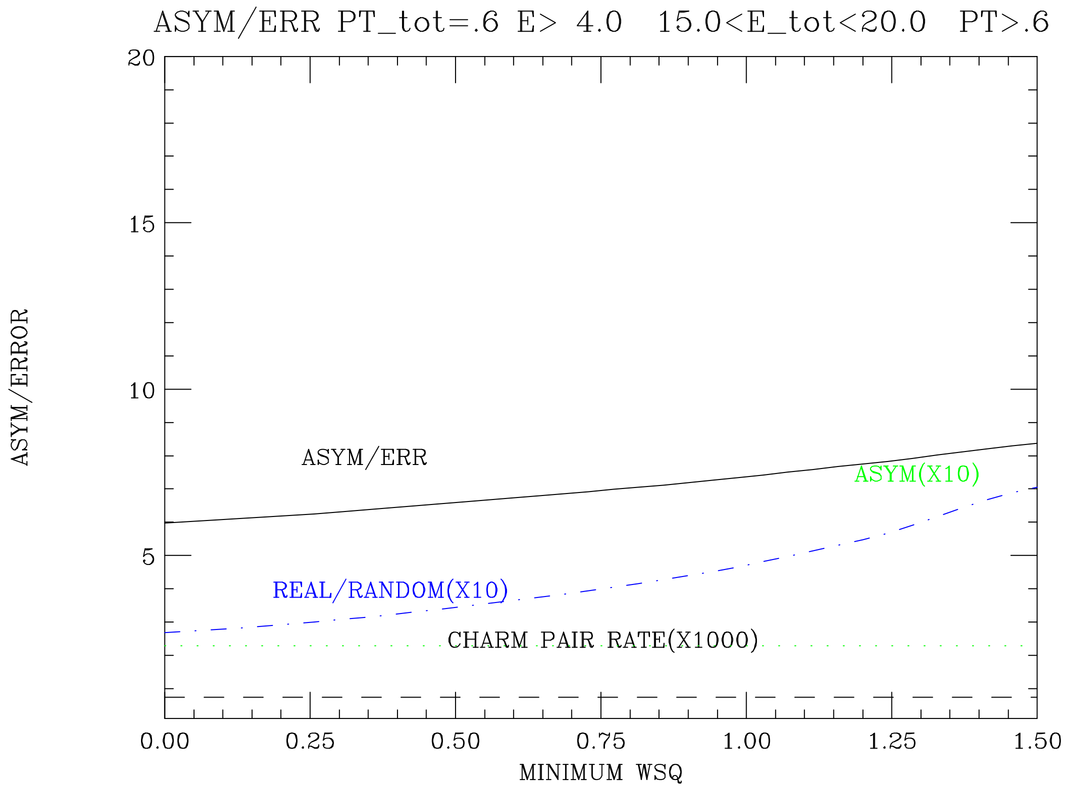
SINGLES RATES ALL MUONS AT E >
RATE/SPILL
E_mu>2.3
5.0
7.5
10.
15.
E_mu>20.
MINIMUM PT



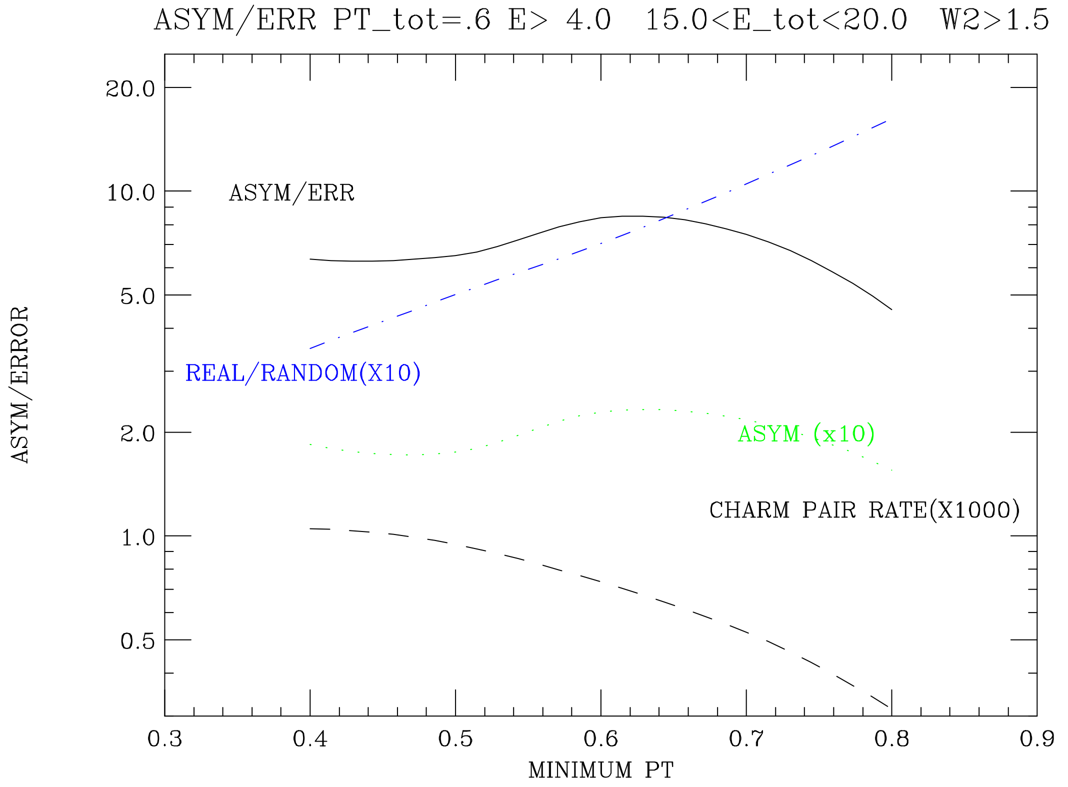
- **WANT BIG SIGNAL/BACKGROUND**
- **RANDOMS ARE A DILUTION FACTOR**
  - **NEED EXCELLENT TIME RESOLUTION (RMS = .25 ns)**
- **RANDOMS ARE MEASURED VERY WELL BECAUSE MANY BINS.**
- **CHOOSE KINEMATICS SO SIGNAL IS LARGE, BACKGROUND SMALL**

BEST KINEMATICS

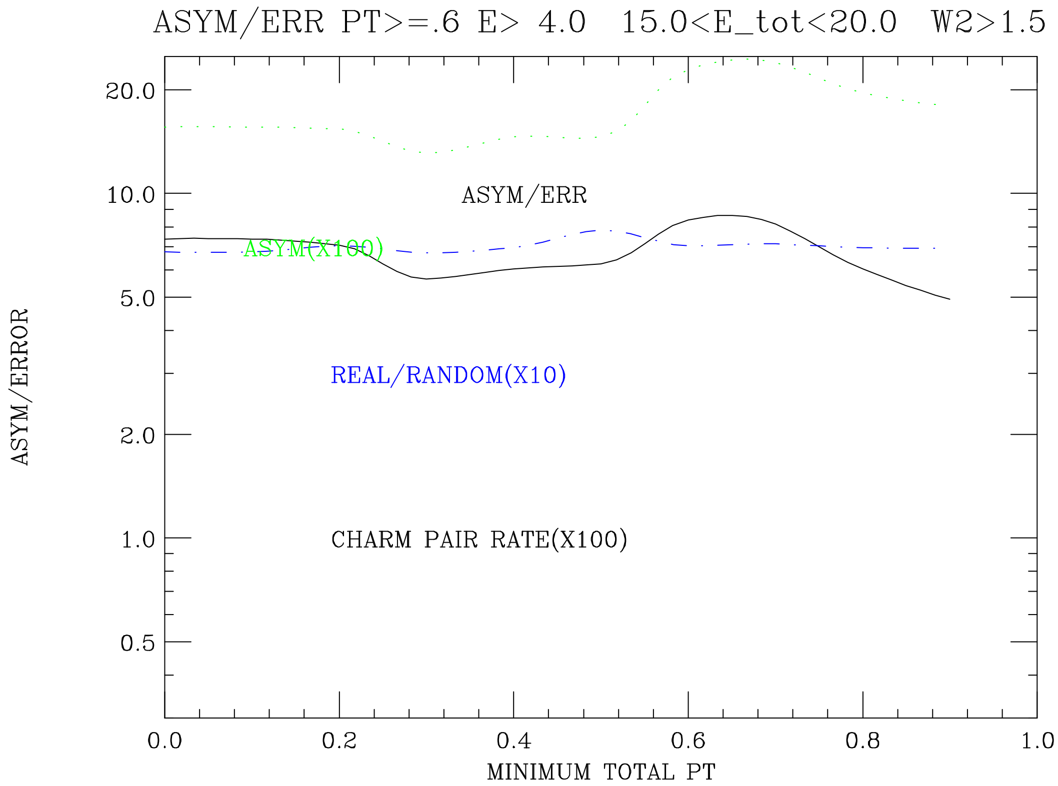
- **SIGNAL IS LARGE, BACKGROUND SMALL**
- **ANALYZING POWER IS LARGEST**
  - **EXPECTED ASYMMETRY FROM DIFFERENT MODELS LARGE**
  - **DIFFERENCE BETWEEN MODELS LARGE**
  - **MAXIMIZE ASYMMETRY/ERROR**



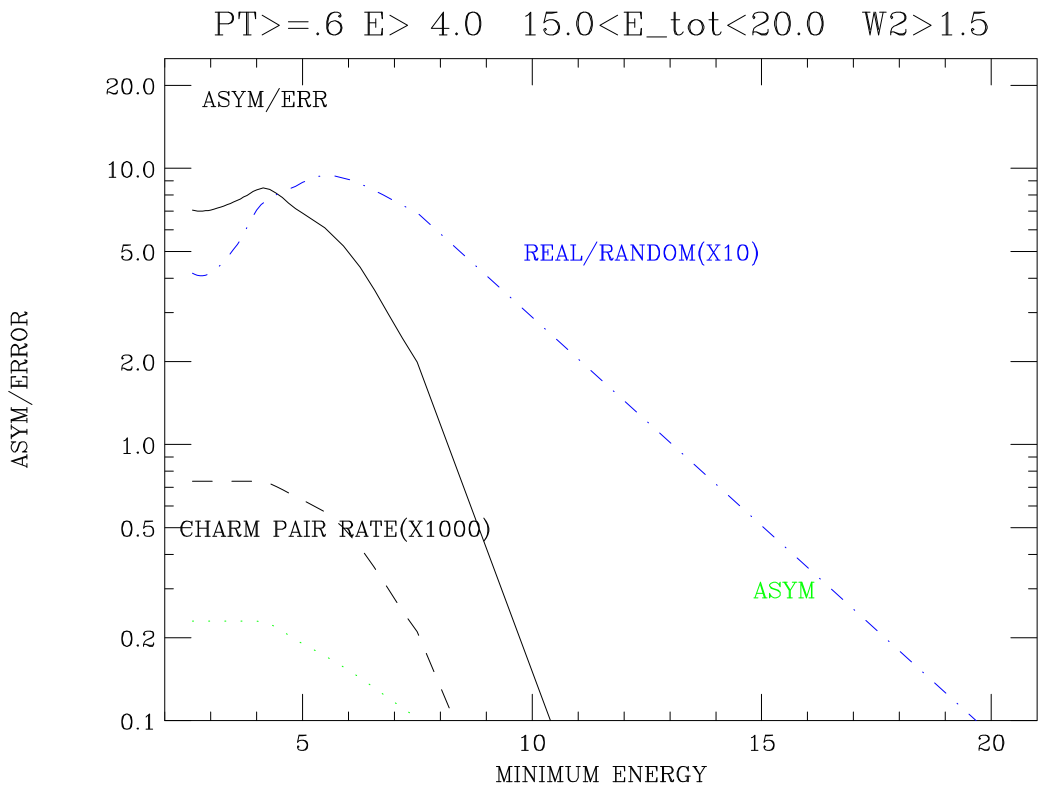
ASYM/ERR PT_tot=.6 E> 4.0 15.0<E_tot<20.0 PT>.6
ASYM/ERROR
ASYM/ERR
ASYM(X10)
REAL/RANDOM(X10)
CHARM PAIR RATE(X1000)
MINIMUM WSQ



ASYM/ERR PT_tot=.6 E> 4.0 15.0<E_tot<20.0 W2>1.5
ASYM/ERROR
ASYM/ERR
REAL/RANDOM(X10)
ASYM (x10)
CHARM PAIR RATE(X1000)
MINIMUM PT



ASYM/ERR PT>=.6 E> 4.0 15.0<E_tot<20.0 W2>1.5
ASYM/ERROR
ASYM/ERR
ASYM(X100)
REAL/RANDOM(X10)
CHARM PAIR RATE(X100)
MINIMUM TOTAL PT



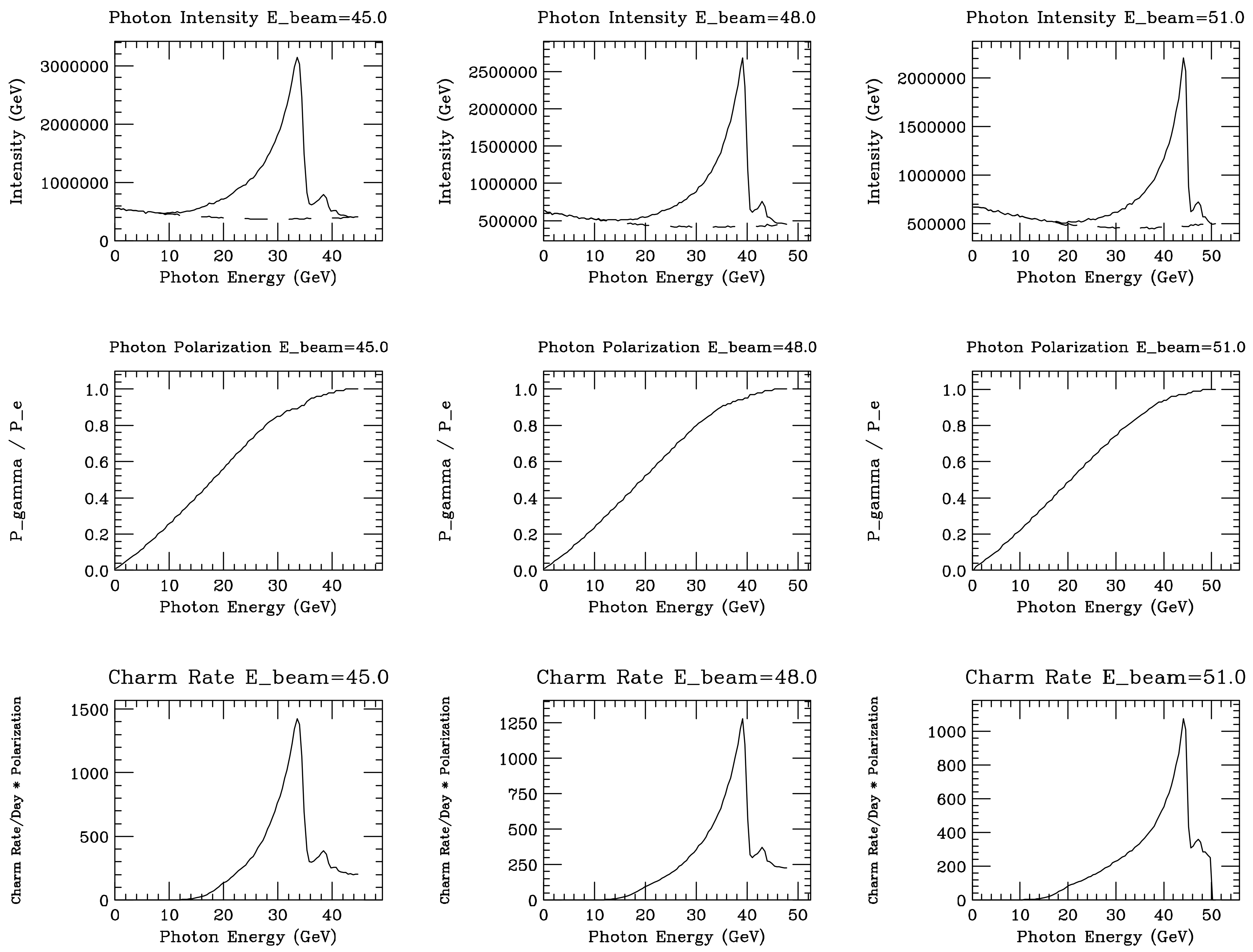
PT>=.6 E> 4.0 15.0<E_tot<20.0 W2>1.5
ASYM/ERROR
ASYM/ERR
REAL/RANDOM(X10)
CHARM PAIR RATE(X1000)
ASYM
MINIMUM ENERGY

PROBLEMS?

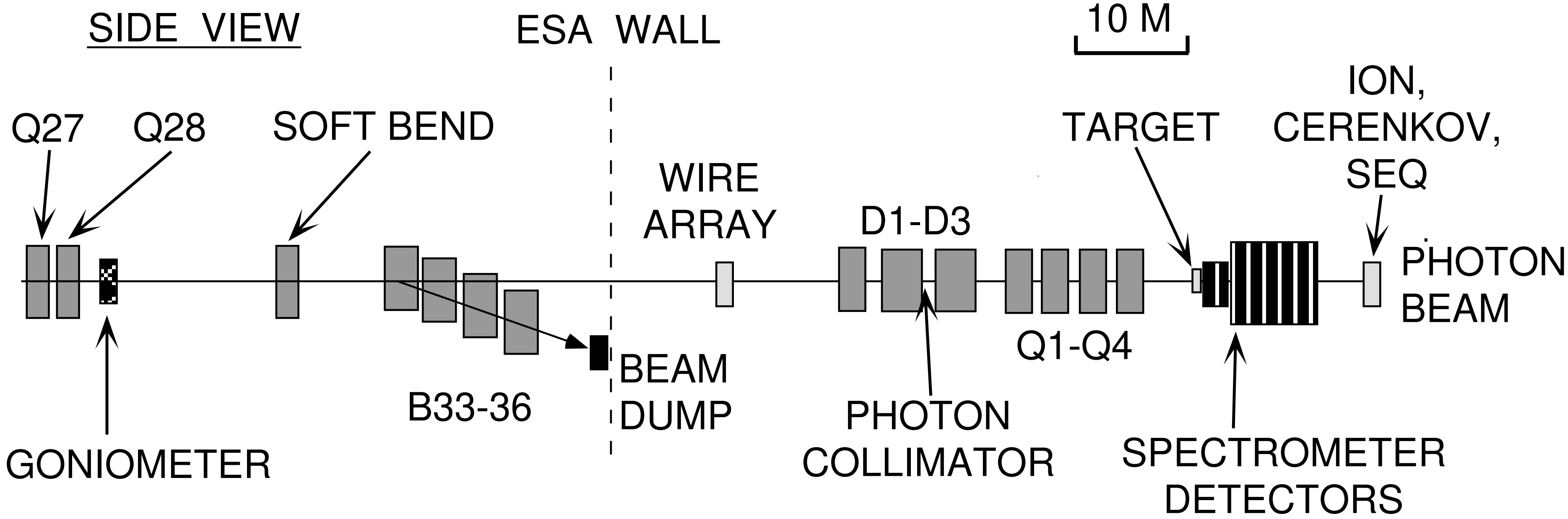
- Peter and I disagree by a factor of 10 inc, $\bar{c}$
  - HERWIG vs PYTHIA?
  - Some bug?
- Large B-H pair rate at some kinematics
- WORK IN PROGRESS

CONCLUSIONS

- **IMPORTANT TO MEASURE $\Delta g/g$**
- **E161 CAN MEASURE $\Delta g/g$ DIRECTLY**
- **PRECISION $\geq$ OTHER EXPERIMENTS**
- **COMPLEMENTARY TO OTHER EXPERIMENTS USING DIFFERENT HARD SCATTERING PROCESSES**



Photon Intensity E_beam=45.0
Intensity (GeV)
Photon Energy (GeV)
Photon Intensity E_beam=48.0
Intensity (GeV)
Photon Energy (GeV)
Photon Intensity E_beam=51.0
Intensity (GeV)
Photon Energy (GeV)
Photon Polarization E_beam=45.0
P_gamma / P_e
Photon Energy (GeV)
Photon Polarization E_beam=48.0
P_gamma / P_e
Photon Energy (GeV)
Photon Polarization E_beam=51.0
P_gamma / P_e
Photon Energy (GeV)
Charm Rate E_beam=45.0
Charm Rate/Day * Polarization
Photon Energy (GeV)
Charm Rate E_beam=48.0
Charm Rate/Day * Polarization
Photon Energy (GeV)
Charm Rate E_beam=51.0
Charm Rate/Day * Polarization
Photon Energy (GeV)


SIDE VIEW
ESA WALL
10 M
Q27
Q28
SOFT BEND
TARGET
ION, CERENKOV, SEQ
WIRE ARRAY
D1-D3
PHOTON BEAM
Q1-Q4
BEAM DUMP
B33-36
PHOTON COLLIMATOR
GONIOMETER
SPECTROMETER DETECTORS