# Beam Normal Spin Asymmetry: Theory

*Andrei Afanasev*
*Jefferson Lab*

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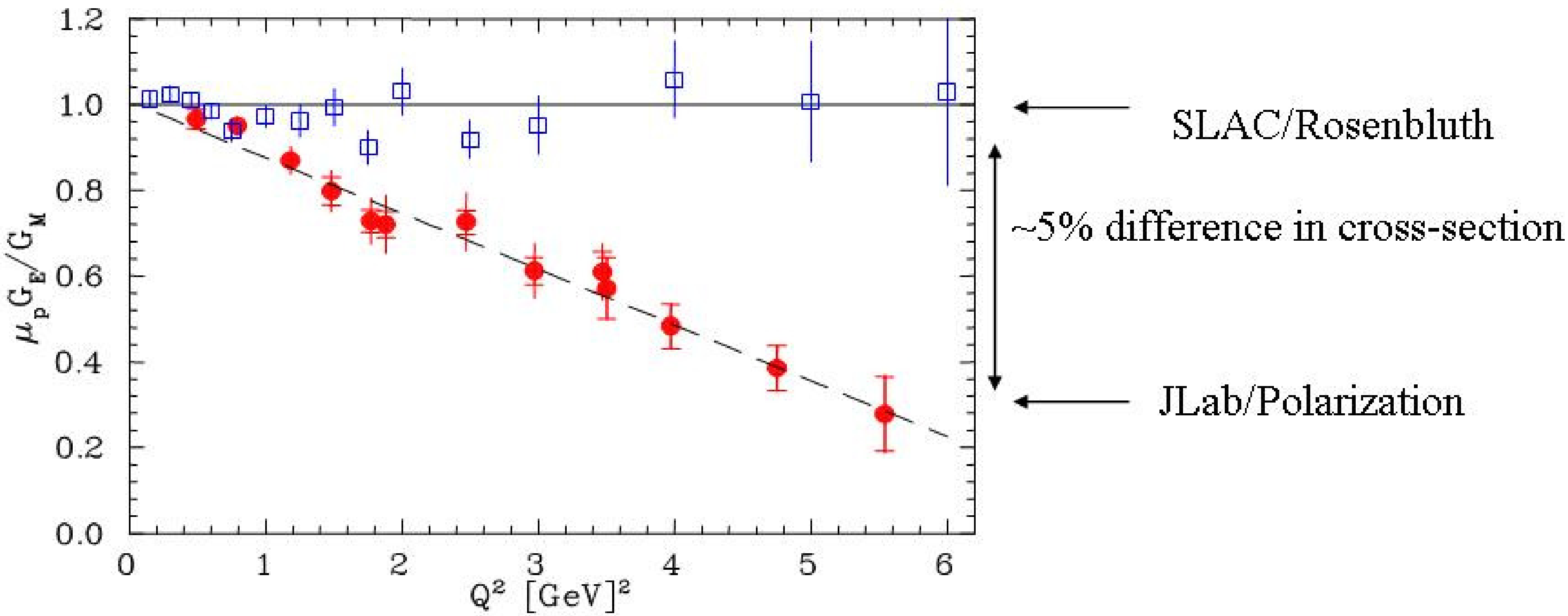
# Observables affected by Two-Photon Exchange in Elastic ep-scattering

**Two-photon exchange effects in the process** $e{+}p \rightarrow e{+}p$

- Cross sections
- Polarization transfer and double-polarization asymmetries
- Parity-violating asymmetry
- Parity-conserving single-spin asymmetries **are zero** in absence of two-photon (or multi-photon) exchange

# Do the techniques agree?

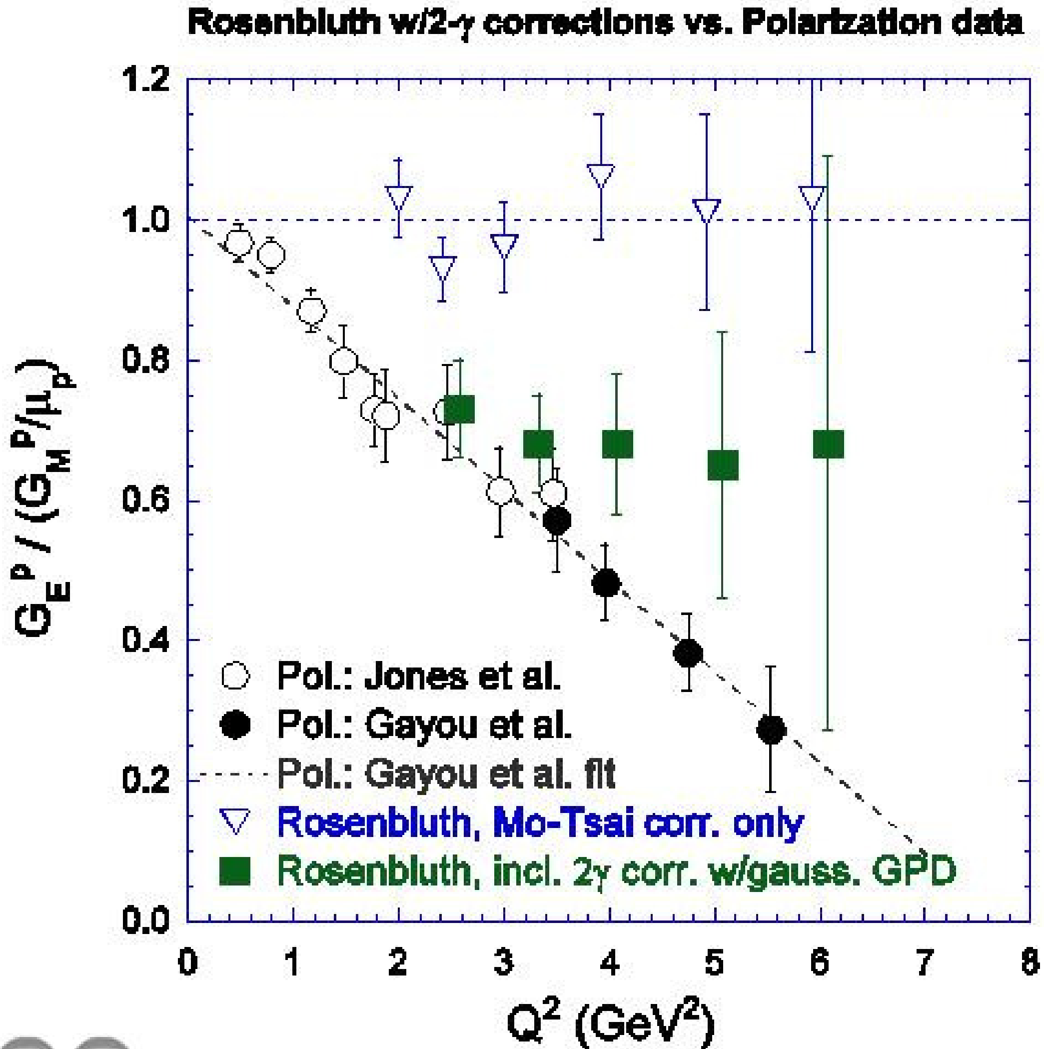



- Both early SLAC and Recent JLab experiments on (super)Rosenbluth separations followed Ge/Gm~const
- JLab measurements using polarization transfer technique give different results (Jones'00, Gayou'02)

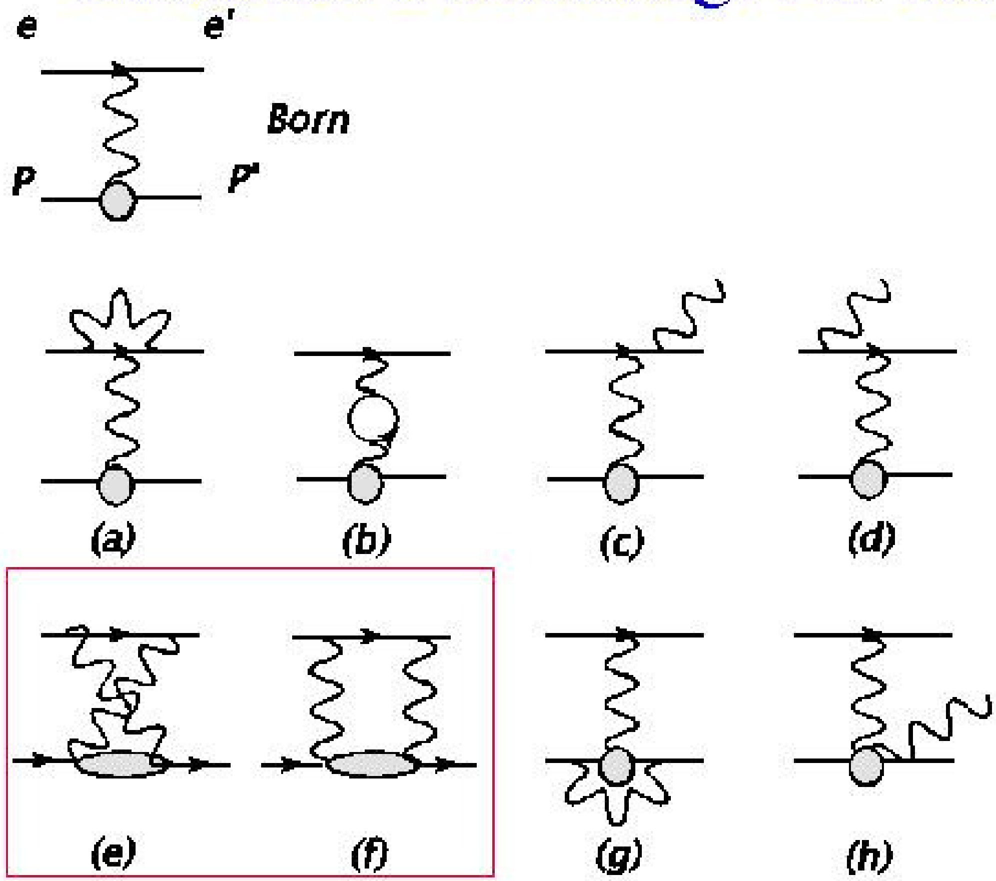
***Radiative corrections, in particular, a short-range part of 2-photon exchange is a likely origin of the discrepancy***

# Updated Ge/Gm plot

AA, Brodsky, Carlson, Chen, Vanderhaeghen,
Phys.Rev.Lett.93:122301,2004; **hep-ph/0502013**



# Electron Scattering: LO and NLO in $\alpha_{em}$




Radiative Corrections:

- Electron vertex correction (a)
- Vacuum polarization (b)
- Electron bremsstrahlung (c,d)
- Two-photon exchange (e,f)
- Proton vertex and VCS (g,h)
- Corrections (e-h) depend on the nucleon structure

•Guichon&Vanderhaeghen'03: *Can (e-f) account for the Rosenbluth vs. polarization experimental discrepancy? Look for ~3% …*

**Main issue: Corrections dependent on nucleon structure**

Model calculations:

•Blunden, Melnitchuk,Tjon, Phys.Rev.Lett.**91**:142304,2003

•Chen, AA, Brodsky, Carlson, Vanderhaeghen, Phys.Rev.Lett.**93**:122301,2004

# Normal Spin Asymmetries

- Observed spin-momentum correlation of the type:

$$\vec{s} \cdot \vec{k}_1 \times \vec{k}_2$$

where $k_{1,2}$ are initial and final electron momenta, $s$ is a polarization vector of a target OR beam

- For elastic scattering asymmetries are due to absorptive part of 2-photon exchange amplitude

# Parity-Conserving Single-Spin Asymmetries in Scattering Processes (early history)

- N. F. Mott, *Proc. R. Soc. (London)*, **A124**, 425 (1929), noticed that polarization and/or asymmetry is due to spin-orbit coupling in the Coulomb scattering of electrons (Extended to high energy ep-scattering by AA et al., 2002).
- Julian Schwinger, *Phys. Rev.* **69**, 681 (1946); *ibid.*, **73**, 407 (1948), suggested a method to polarize fast neutrons via spin-orbit interaction in the scattering off nuclei
- Lincoln Wolfeinstein, *Phys. Rev.* **75**, 1664 (1949); A. Simon, T.A.Welton, *Phys. Rev.* 90, 1036 (1953), formalism of polarization effects in nuclear reactions

# Proton Mott Asymmetry at Higher Energies

*Spin-orbit interaction of electron moving in a Coulomb field*

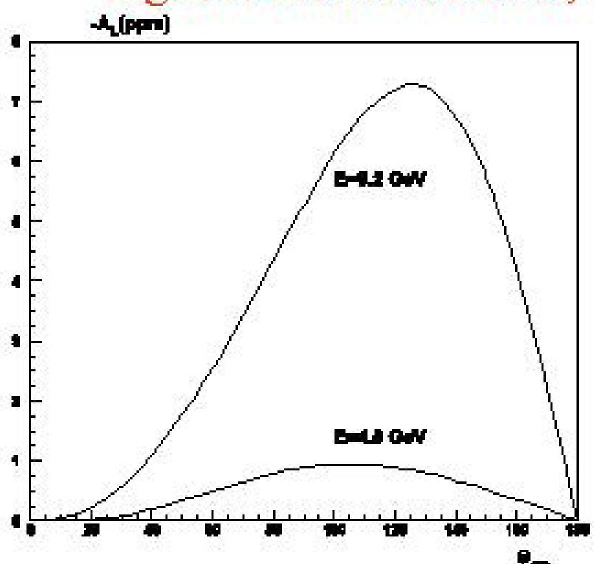
N.F. Mott, Proc. Roy. Soc. London, Set. A **135**, 429 (1932);

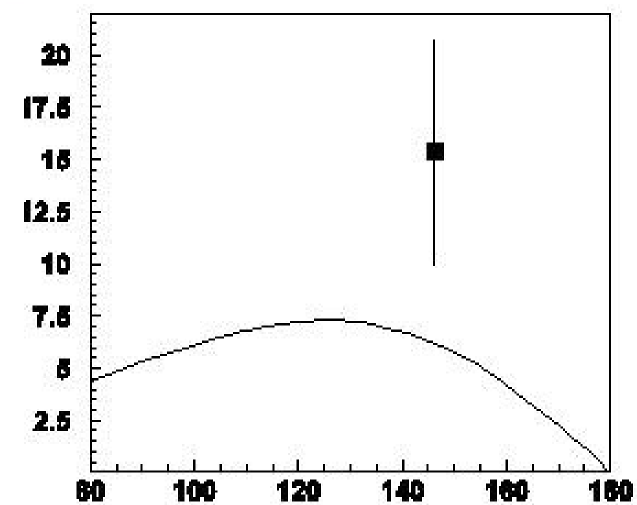
*BNSA for electron-muon scattering*: Barut, Fronsdal, Phys.Rev.120, 1871 (1960);

BNSA for electron-proton scattering: Afanasev, Akushevich, Merenkov, hep-ph/0208260

**Transverse beam SSA, units are parts per million**

Figures from AA et al, hep-ph/0208260



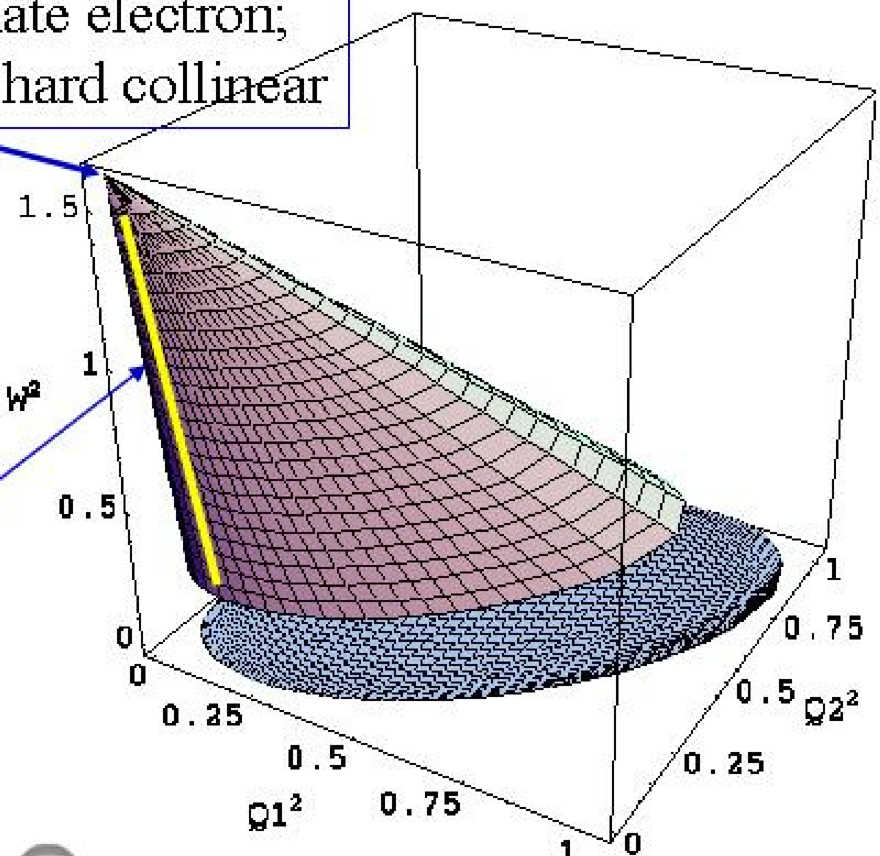

- **Due to absorptive part of two-photon exchange amplitude; shown is elastic contribution**
- **Nonzero effect observed by SAMPLE Collaboration (S.Wells et al., PRC63:064001,2001) for 200 MeV electrons**
- Calculations of Diaconescu, Ramsey-Musolf (2004): low-energy expansion version of hep-ph/0208260

# Phase Space Contributing to the absorptive part of 2γ-exchange amplitude

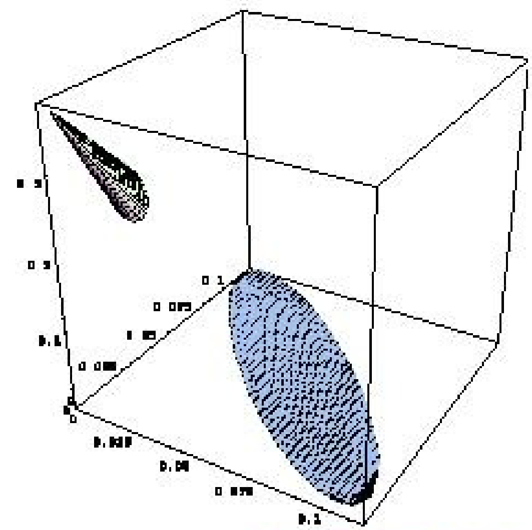
- 2-dimensional integration ($Q_1^2$, $Q_2^2$) for the elastic intermediate state
- 3-dimensional integration ($Q_1^2$, $Q_2^2$, $W^2$) for inelastic excitations

`Soft' intermediate electron;
Both photons are hard collinear

One photon is
Hard collinear



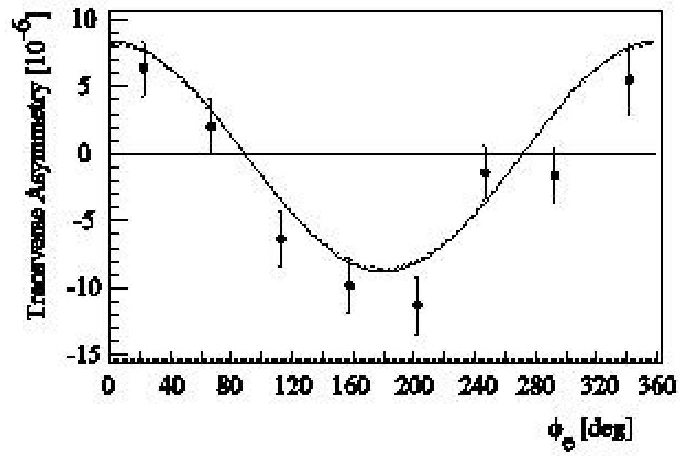

Examples: MAMI A4
E= 855 MeV
Θcm= 57 deg;
SAMPLE, E=200 MeV



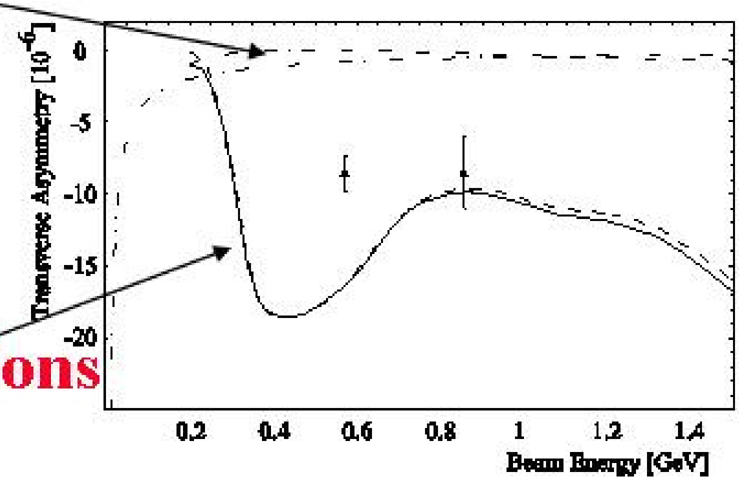
# MAMI data on Mott Asymmetry

- F. Maas et al., Phys.Rev.Lett.94:082001, 2005
- Pasquini, Vanderhaeghen:

  Surprising result: Dominance of inelastic intermediate excitations

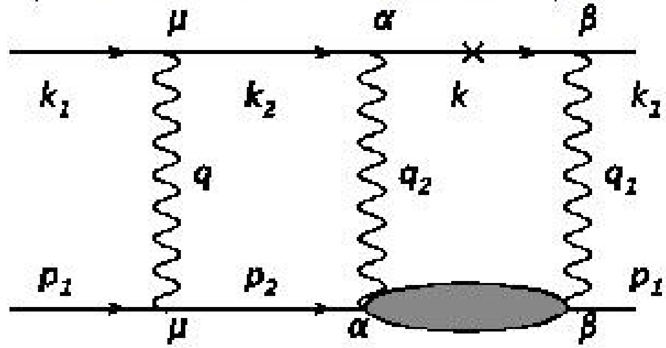



Elastic intermediate state




**Inelastic excitations dominate**

# Beam Normal Asymmetry (AA, Merenkov)




$$A_n^{e,P} = -\frac{\alpha Q^2}{\pi^2 D(s,Q^2)} \mathrm{Im} \int \frac{d^3 k}{2k_0} \cdot \frac{L_{\mu\alpha\beta} H_{\mu\alpha\beta}}{Q_1^2 Q_2^2}$$

$$L_{\mu\alpha\beta} = \frac{1}{4} Tr(\hat{k}_2 + m_e)\gamma_\mu(\hat{k}_1 + m_e)(1-\gamma_5\hat{\xi}_e)\gamma_\beta(\hat{k}+m_e)\gamma_\alpha$$

$$H_{\mu\alpha\beta} = \frac{1}{4} Tr(\hat{p}_2 + M)\Gamma_\mu(\hat{p}_1 + M)(1-\gamma_5\hat{\xi}_p)T_{\beta\alpha}$$

$$\hat{a} \equiv a_\mu \gamma_\mu$$

$$L_{\mu\alpha\beta} q_\mu = L_{\mu\alpha\beta} q_{2\alpha} = L_{\mu\alpha\beta} q_{1\beta} = H_{\mu\alpha\beta} q_\mu = H_{\mu\alpha\beta} q_{2\alpha} = H_{\mu\alpha\beta} q_{1\beta} = 0$$

Gauge invariance essential in cancellation of infra-red singularity for target asymmetry

$$L_{\mu\alpha\beta} H_{\mu\alpha\beta} \to 0 \quad if \quad Q_1^2 \ and/or \ Q_2^2 \to 0$$

Feature of the normal beam asymmetry: After $m_e$ is factored out, the remaining expression is singular when virtuality of the photons reach zero in the loop integral!
But why are the expressions regular for the target SSA?!

$$L_{\mu\alpha\beta} H_{\mu\alpha\beta} \to m_e \cdot const \quad if \quad Q_1^2 \ and/or \ Q_2^2 \to 0 \Rightarrow A \sim m_e \log^2 \frac{Q^2}{m_e^2},\ m_e \log \frac{Q^2}{m_e^2}$$

Also calculations by Vanderhaeghen, Pasquini (2004); Gorschtein, hep-ph/0505022
Confirm quasi-real photon exchange enhancement

# Peaking Approximation

- Dominance of collinear-photon exchange =>
- Can replace 3-dimensional integral over $(Q_1^2, Q_2^2, W)$ with one-dimensional integral along the line $(Q_1^2 \approx 0;\ Q_2^2 = Q^2(s-W^2)/(s-M^2))$
  - Save computing time
  - Avoid uncertainties associated with (unknown) double-virtual Compton amplitude
  - Provides more direct connection to VCS and RCS observables

# Special property of normal beam asymmetry

**AA, Merenkov, Phys.Lett.B599:48,2004, Phys.Rev.D70:073002,2004; +Erratum (2005)**

- Reason for the unexpected behavior: hard collinear quasi-real photons
  - Intermediate photon is collinear to the parent electron
  - It generates a dynamical pole and logarithmic enhancement of inelastic excitations of the intermediate hadronic state
  - For s>>-t and above the resonance region, the asymmetry is given by:

$$A_n^e = \sigma_{\gamma p} \frac{(-m_e)\sqrt{Q^2}}{8\pi^2} \cdot \frac{F_1 - \tau F_2}{F_1^2 + \tau F_2^2} (\log(\frac{Q^2}{m_e^2}) - 2)$$

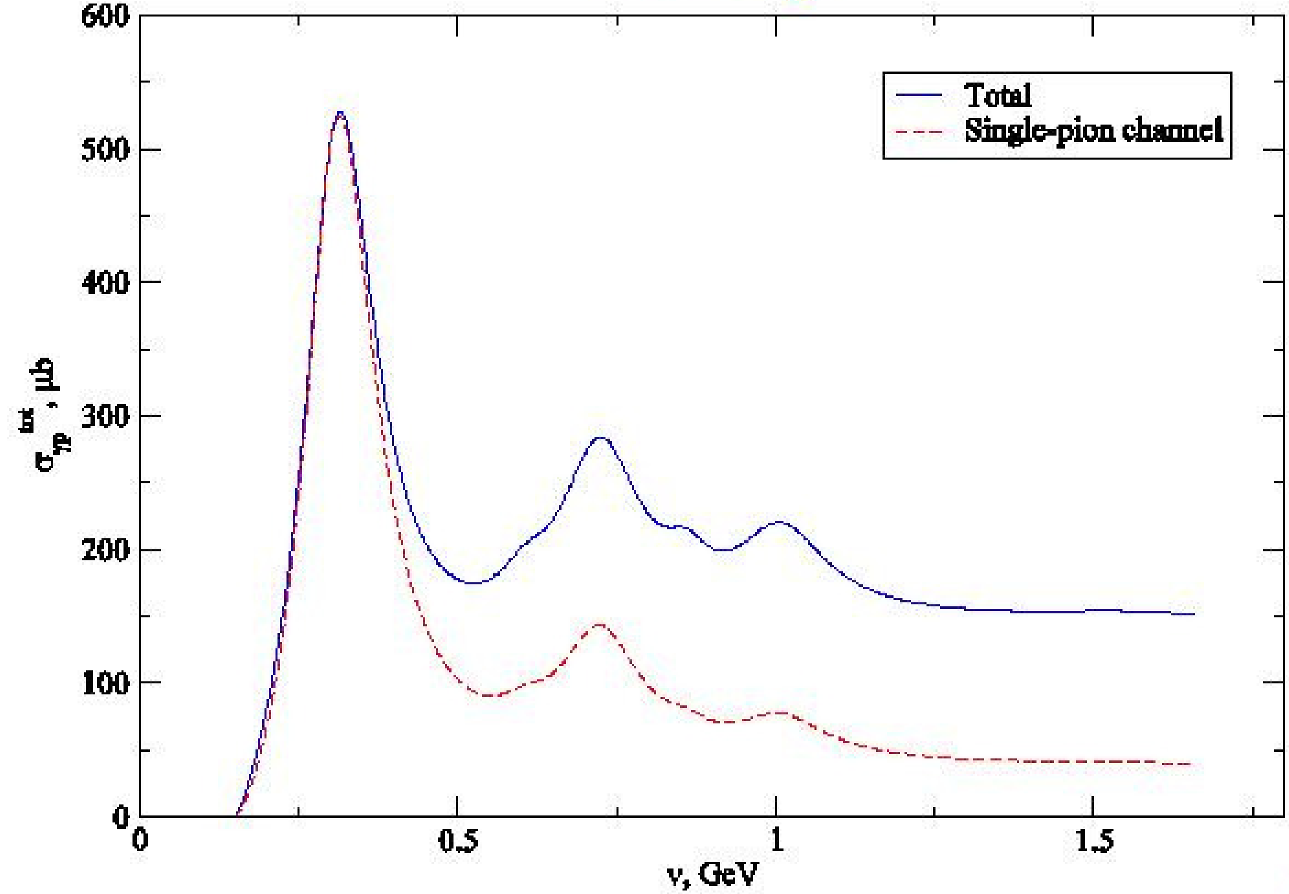
Also suppressed by a standard diffractive factor $\exp(-BQ^2)$, where $B=3.5\text{-}4\ GeV^{-2}$

Compare with no-structure asymmetry at small θ:

$$A_n^e \propto \alpha \frac{m_e}{\sqrt{s}} \theta^3$$

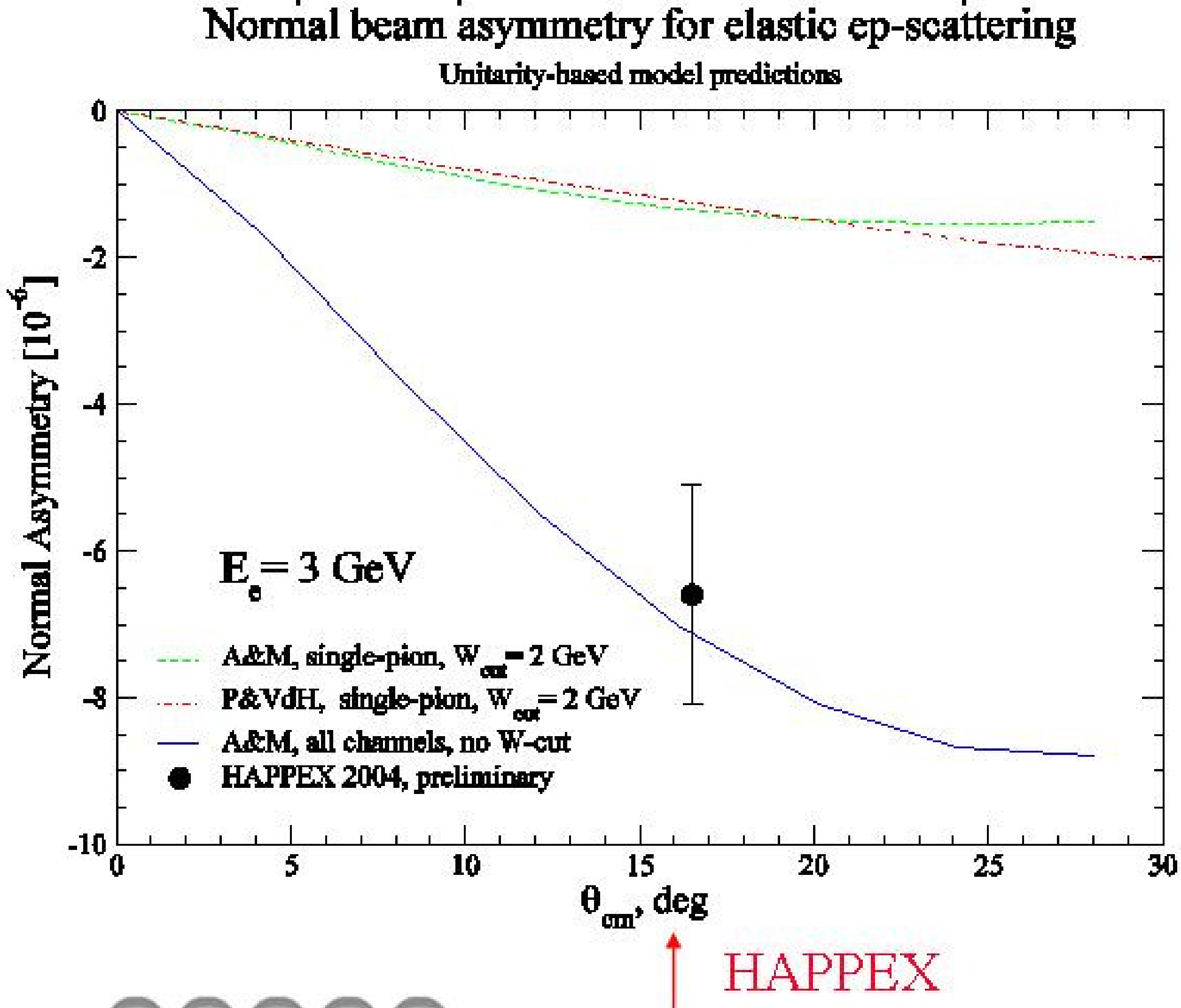
# Input parameters

- Used $\sigma_{\gamma p}$ from parameterization by N. Bianchi at al., Phys.Rev.**C54** (1996)1688 (resonance region) and Block&Halzen, Phys.Rev. **D70** (2004) 091901



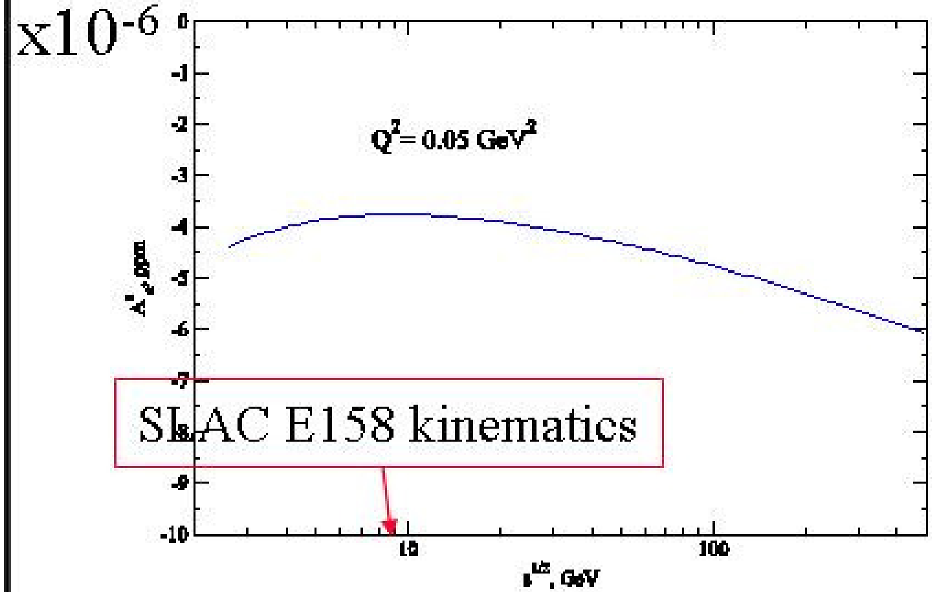
# Predictions for normal beam asymmetry

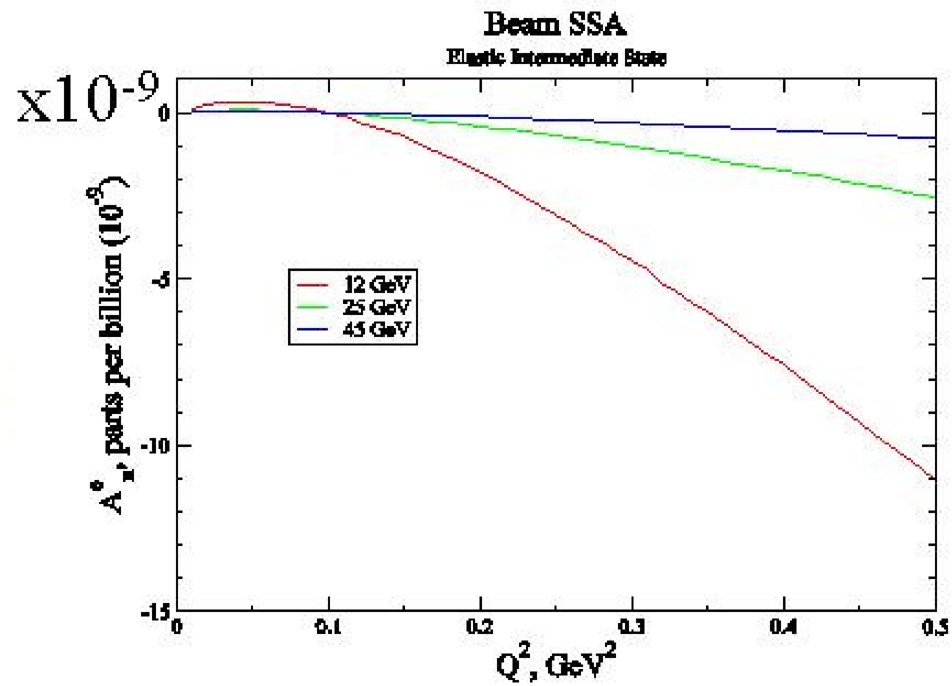
Use fit to experimental data on $\sigma_{\gamma p}$ and exact 3-dimensional integration over phase space of intermediate 2 photons

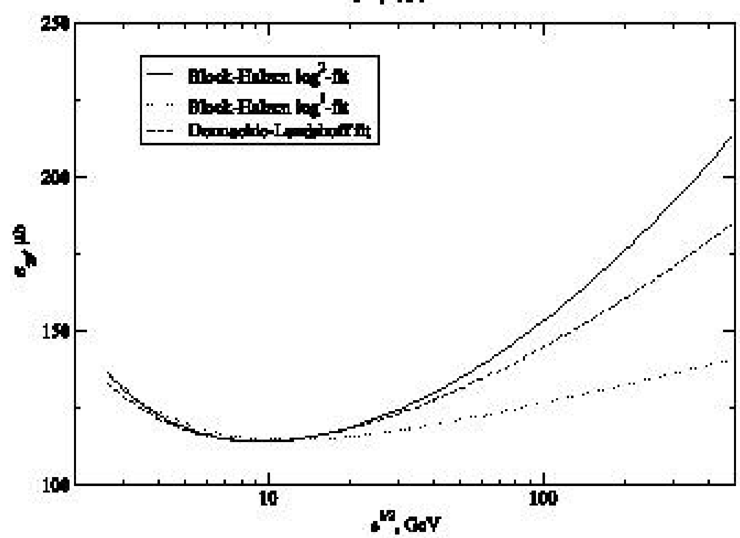



Data expected from HAPPEX, G0

# No suppression for beam asymmetry with energy at fixed $Q^2$

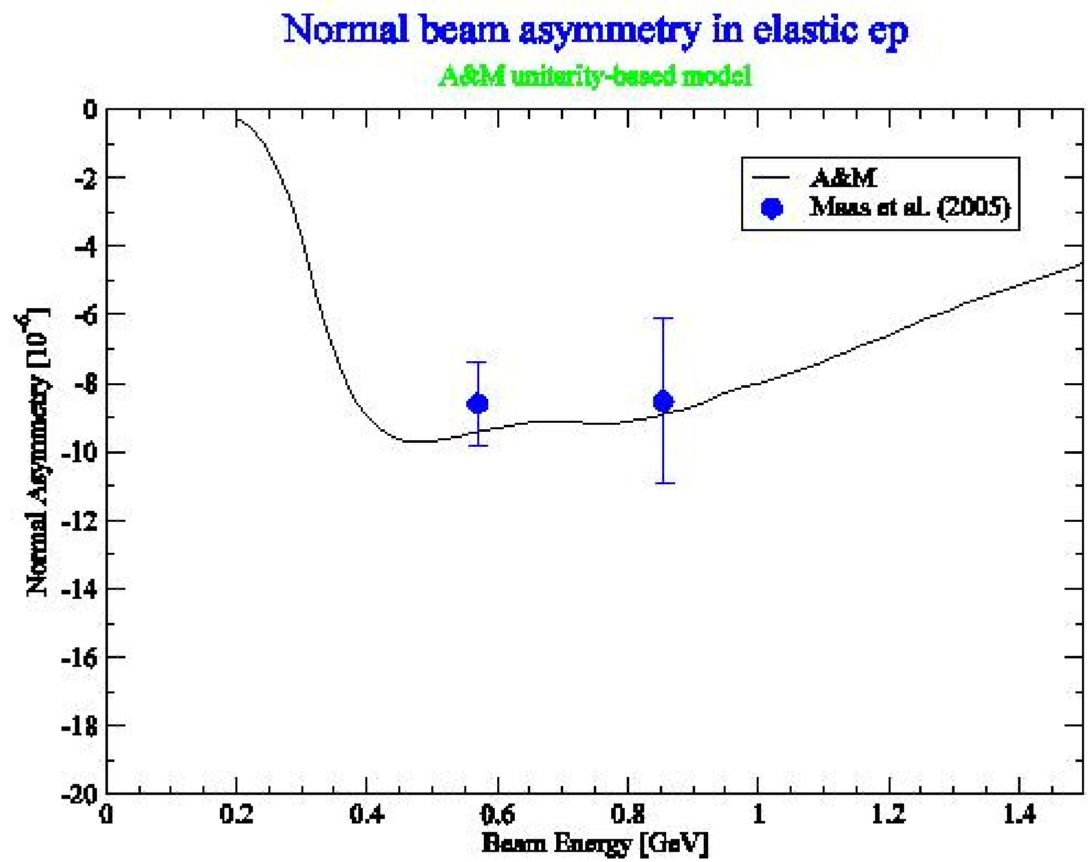


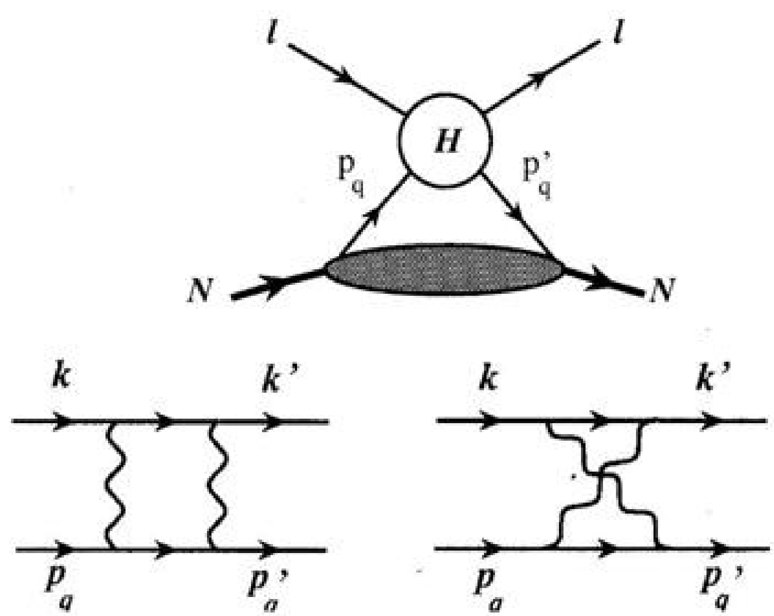

Parts-per-million vs. parts-per billion scales: a consequence of soft Pomeron exchange, and hard collinear photon exchange

# Beam SSA in the resonance region




For $\theta_{cm}$= 57 deg, small-angle approximation and Exp[Bt/2] should not be working…

# Trouble with `Handbag' for beam normal asymmetry




*Model schematics*:

- Hard eq-interaction
- GPDs describe quark emission/absorption
- Soft/hard photon separation
  - Use Grammer-Yennie prescription
- Hard interaction with a quark
- Applied for BSSA by ***Gorshtein, Guichon, Vanderhaeghen, NP A741, 234 (2004)***

- Exchange of hard collinear photons is kinematically forbidden if one assumes a handbag approximation (placing quarks on mass shell) , BUT…
- Collinear-photon-exchange enhancement (up to two orders of magnitude) is allowed for off-mass-shell quarks (higher twists) and Regge-like contributions

=> If the handbag approximation is violated at ≈ 0.5% level,

It would result in $(0.5\%)\log^2(Q^2/m_e^2) \approx 100\%$ level correction to beam asymmetry

⇒But target asymmetry, TPE corrections to Rosenbluth and polarization transfer predictions will be violated at the same 0.5% level

# Lessons from SSA in Elastic ep-Scattering

- Collinear photon exchange present in (light particle) beam SSA
- (Electromagnetic) gauge invariance of is essential for cancellation of collinear-photon exchange contribution for a (heavy) target SSA
- Unitarity is very helpful in reducing model dependence of calculations at small scattering angles, in particular for beam asymmetry
- Strong-interaction dynamics for BNSA small-angle ep-scattering above the resonance region is ***soft diffraction***

# Mott Asymmetry Promoted to High Energies

- Excitation of inelastic hadronic intermediate states by the consecutive exchange of two photons leads to logarithmic and double-logarithmic enhancement due to contributions of hard collinear quasi-real photons for the beam normal asymmetry
- The strongest enhancement has a form: $\log^2(Q^2/m_e^2)$ => two orders of magnitude+unsuppressed angular dependence
  - Can be generalized to transverse asymmetries in light spin-1/2 particle scattering via massless gauge boson exchange
  - Beam asymmetry at high energies is strongly affected by effects beyond pure Coulomb distortion
  - Supports Qiu-Sterman twist-3 picture of SSA in QCD
- What else can we learn from elastic beam SSA?
  - Check implications of elastic hadron scattering in QCD

    (Can large $A_{n,t}$ in pp elastic be due to onset of collinear multi-gluon exchange + inelastic excitations?)
  - Large SSA in deep-inelastic collisions due to hard collinear gluon exchange; in pQCD need NNLO to obtain unsupressed collinear gluons