Radiative Corrections in SIDIS

I. Akushevich[1],A. Ilyichev[2],M. Osipenko[3]

[1]Duke University, Durham, USA, [2]High Energy Phys. Ctr., Minsk, Belarus, [3]INFN Genova

Structure of Nucleons and Nuclei,
Como, Italy, June 13, 2013

Outline

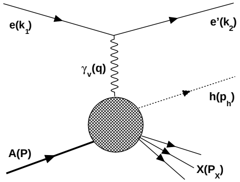
1. Introduction
2. HAPRAD 2
3. Nuclear Effects
4. Proton Production
5. Conclusions
6. Backup

Why do we need Radiative Corrections

$$e(k_1) + A(P) \rightarrow e'(k_2) + h(p_h) + X(p_X)$$

- Born cross section:

$$\sigma_B = \frac{2E_h d\sigma}{d^3 p_h dx dy} = \frac{2\pi\alpha^2 M y}{Q^4} L_{\mu\nu} W_{\mu\nu}$$

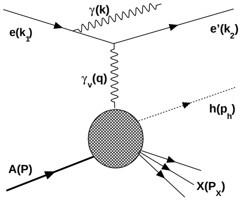


- Observed cross section:

$$\sigma_{obs} \sim \sigma_B + \alpha \int \sigma_\gamma \frac{dk}{k_0}$$

$$Q_r^2 \simeq Q^2 + 2k(k_1 - k_2) \sim Q^2 \left[1 - \frac{E_\gamma}{E_1}\right]$$

$$W_{\mu\nu} \sim F(Q_r^2) \sim 1/Q_r^6$$



- Radiative tail for open kinematics reactions

History of SIDIS RC

- First explicitly calculated for SIDIS in (code POLRAD 2, with SIRAD option):

  A.V. Soroko, N.M. Shumeiko, Sov.J.Nucl.Phys. 49, 838 (1989), Yad.Fiz. 49, 1348 (1989); Sov.J.Nucl.Phys. 53, 628 (1991), Yad.Fiz. 53, 1015 (1991); I. Akushevich, A. Ilyichev, N. Shumeiko, A. Soroko and A. Tolkachev, Comp.Phys.Com.104, 201 (1997)

  for polarized and unpolarized cross sections integrated in p_T and ϕ, including only diagonal SFs.
- Later extended in (HAPRAD):

  I. Akushevich, A. Soroko, N. Shumeiko, EPJ C10, 681 (1999)

  for fully differential unpolarized cross section.
- Further extended in (HAPRAD 2):

  I. Akushevich, A. Ilyichev and M. Osipenko, Phys.Lett. B672, 35 (2009)

  by adding the exclusive radiative tail and modeling explicitly $< cos\phi >$ and $< cos2\phi >$ terms.

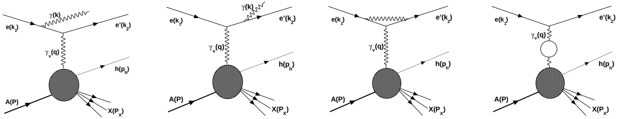
State of Art

- unpolarized cross section at order α^3:

$$\sigma_{RC} = \sigma_B e^{\delta_{soft,inf}}(1 + \delta_{VR,fin} + \delta_{vac}) + \sigma_{si.tail} + \sigma_{ex.tail}$$

- modeling of SIDIS and exclusive cross sections in a broader kinematic range:

$$\sigma_{si,ex.tail} \sim \alpha \int \sigma_{B,ex} \frac{dk}{k_0}$$

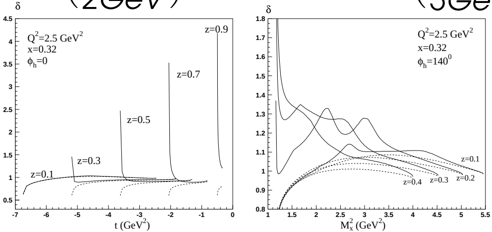


Exclusive tail

$$\frac{d\sigma_{ex}}{dxdydzdtd\phi} = \frac{1}{(4\pi)^7}\frac{sy^2}{(1-\frac{m_h^2}{E_1^1})(y^2+\frac{Q^2}{E_1^2})}\int\int_0^{2\pi}\frac{2(kP)|M|^2}{1+\tau-\frac{kp_h}{kP}}d\tau d\phi_k$$

where $\tau = \frac{kq}{kP}$ and σ^B_{ex} MAID modified at large W and large Q^2 by Cornell parametrization[1]

$$C_W = \left(\frac{W}{2GeV}\right)^{-0.002\theta^2_{CM}},\ C_{Q^2} = \left(\frac{Q^2}{5GeV^2}\right)^{-1.15} \qquad (1)$$



[1] A. Browman et al., Phys. Rev. Lett. 35 (1975) 1313.

Modeling SIDIS

$$\frac{d^5\sigma}{dxdydzdtd\phi} = \frac{2\pi\alpha^2 sz}{Q^4}\sqrt{\kappa}\zeta\left[(\epsilon\mathcal{H}_1+\mathcal{H}_2)(1+B\cos\phi+C\cos 2\phi)\right]$$

- LO pQCD-like parametrization for ϕ-independent part (PDFlib and Kretzer FFs), Gaussian p_T-model:

$$\mathcal{H}_2 = \sqrt{1-\frac{(M+m_h)^2}{M_X^2}}\,\frac{e^{-\frac{p_T^2 \vee p_T^2+2p_\parallel^2}{<p_T^2>}}}{\pi<p_T^2>}\sum_i e_i^2 x q_i(x) D_i^h(z)$$

- longitudinal to transverse ratio R is taken[1] $R = 0.12$:

$$\mathcal{H}_1 = (1+\gamma^2)\frac{\mathcal{H}_2}{2x(1+R)}$$

[1] C.J. Bebek *et al.*, *Phys. Rev. Lett.* **38**, 1051 (1977).

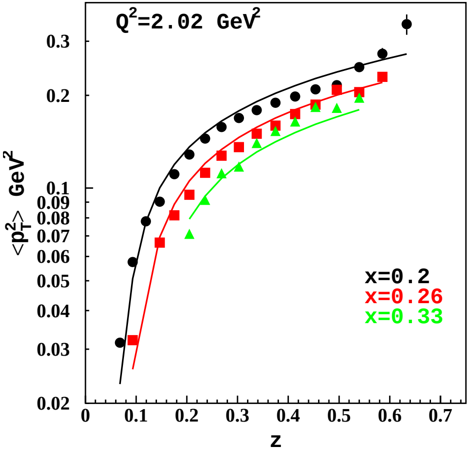
Modeling p_T-distribution

- mean p_T^2 linear in W, instead of linear in s as in[1] and $\sqrt{z}$ instead of $a+bz^2$ from[2]:

$$<p_T^2>_0 = \frac{0.12W\sqrt{z}}{1+(3.2\frac{m_h}{\nu z})^4}$$

- low-z phase space shrinkage:

$$<p_T^2> = \frac{<p_T^2>_0}{1+\frac{<p_T^2>_0}{p_h^2}}$$



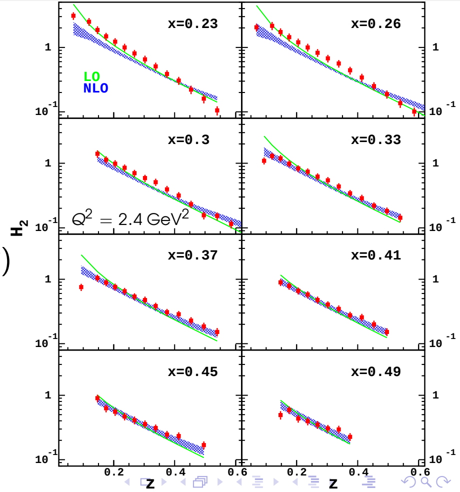
[1] P. Schweitzer et al., Phys.Rev. D81, 094019 (2010)
[2] M. Anselmino et al., Phys.Rev. D71, 074006 (2005)

Modeling *xyz*-distributions

- except for very low-z LO calculations reproduce data fairly well.

$$H_2 = \int \mathcal{H}_2 dp_T^2 = \sum_i e_i^2 x q_i(x) D_i^h(z)$$

- CTEQ5 PDF and Kretzer FF are shown.



Modeling ϕ-distribution

- Cahn effect[1]:

$$< \cos\phi >= -\sqrt{\frac{p_T^2}{Q^2}}\frac{2\times 0.25z}{0.2+0.25z^2}\frac{\sqrt{1-y}(2-y)}{1+(1-y)^2}$$

$$< \cos 2\phi >= \frac{p_T^2}{Q^2}\frac{2\times 0.25^2 z^2}{(0.2+0.25z^2)^2}\frac{1-y}{1+(1-y)^2}$$

- Berger effect[1]:

$$< \cos\phi >= \sqrt{\frac{p_T^2}{Q^2}}\frac{z l_1(l_2-\frac{p_T^2}{Q^2}l_1)}{l_2^2+4\frac{p_T^2}{Q^2}z^2 l_1^2+\frac{p_T^4}{Q^4}l_1^2+\epsilon\frac{l_2^2+\frac{p_T^4}{Q^4}l_1^2}{2x}}\frac{2-y}{\sqrt{1-y}}$$

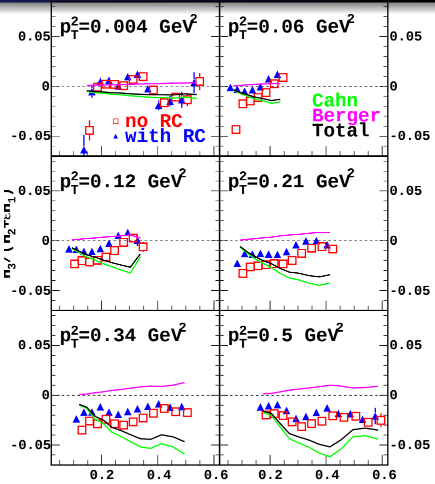
$$< \cos 2\phi >= \frac{p_T^2}{Q^2}\frac{-l_1 l_2}{l_2^2+4\frac{p_T^2}{Q^2}z^2 l_1^2+\frac{p_T^4}{Q^4}l_1^2+\epsilon\frac{l_2^2+\frac{p_T^4}{Q^4}l_1^2}{2x}}$$

[1] R.N. Cahn, Phys.Rev. D40, 3107 (1989)
[2] E. Berger, Z.Phys. C4, 289 (1980)

Effect on $< cos\phi >$

In JLab kinematics[1]:

- positive RC,
- decreasing with z,
- increasing with p_T^2,
- ranges from 0.003 up to 0.015 with average of 0.01.

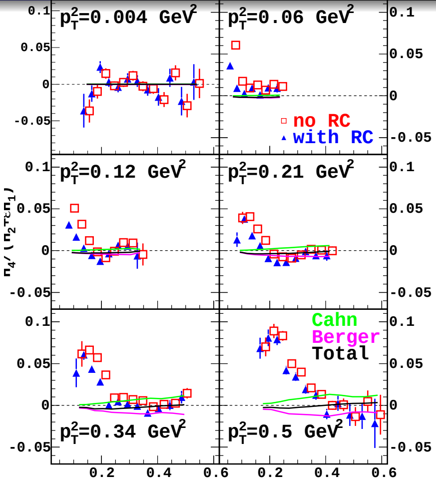


[1] M. Osipenko et al., Phys.Rev. D80 (2009) 032004

Effect on $< cos2\phi >$

In JLab kinematics[1]:

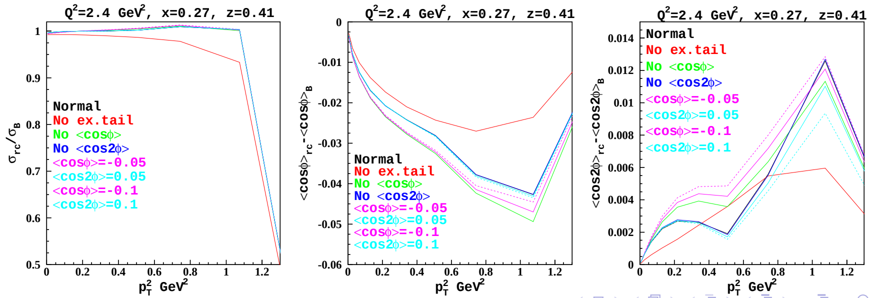
- negative RC,
- decreasing with z,
- increasing with p_T^2,
- ranges from -0.002 up to -0.02 with average of -0.007.



[1] M. Osipenko et al., Phys.Rev. D80 (2009) 032004

Importance of different terms

- exclusive tail is important for large p_T^2 or small M_X,
- exclusive tail is important for azimuthal moments extraction,
- models of $< cos\phi >$ and $< cos2\phi >$ terms are important only for $< cos2\phi >$ evaluation.

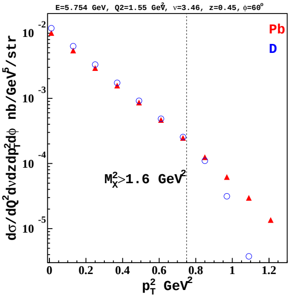


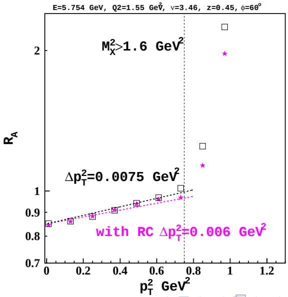
Fermi Motion

- Non-relativistic Fermi gas for few nuclei (D, C, Fe, Pb):

$$\sigma^{nucl} = \int f(|\vec{P_N}|)\sigma^N(\vec{P_N})d\vec{P_N}$$

- Restricting missing mass $M_X^2 < 2$ GeV^2 allows to avoid significant effects.

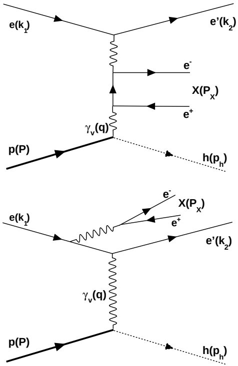




α^4 Contribution

$$e(k_1) + p(P) \rightarrow e'(k_2) + p'(p_h) + X(p_X)$$

- α^2 suppression is compensated by the nucleon elastic form-factor growth $\sim 1/Q_r^6$,
- appears as a peak in ϕ distribution at 180 degrees,

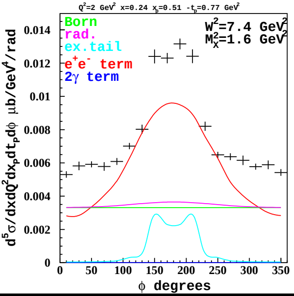


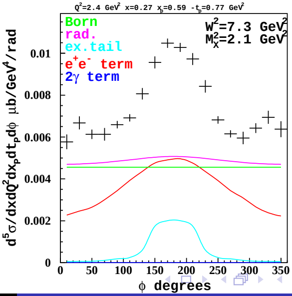
α^4 Contribution cont.

- comparison with CLAS preliminary data:

$$x_P = \frac{q(P - p_h)}{qP}, \; t_P = (P - p_h)^2$$

- Contribution decreases with missing mass M_X, but even at 1-3 GeV^2 it is significant.





Summary

Unpolarized SIDIS:

- RC for fully differential cross section, including exclusive tail (HAPRAD 2),
- α^4 terms for proton SIDIS,
- no radiation from the detected hadron,
- no external RC.

Polarized SIDIS:

- RC for double spin asymmetry integrated in ϕ and p_T^2 (POLRAD 2),
- only diagonal SFs.

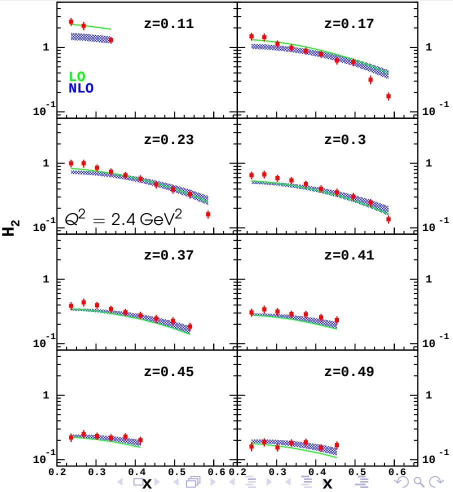
Reasonably achievable:

- RC for SSAs,
- soft photon terms for radiation from the detected hadron.

Backup Slides

Modeling *xyz*-distributions

- except for very low-z LO calculations reproduce data fairly well.



Modeling *xyz*-distributions

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