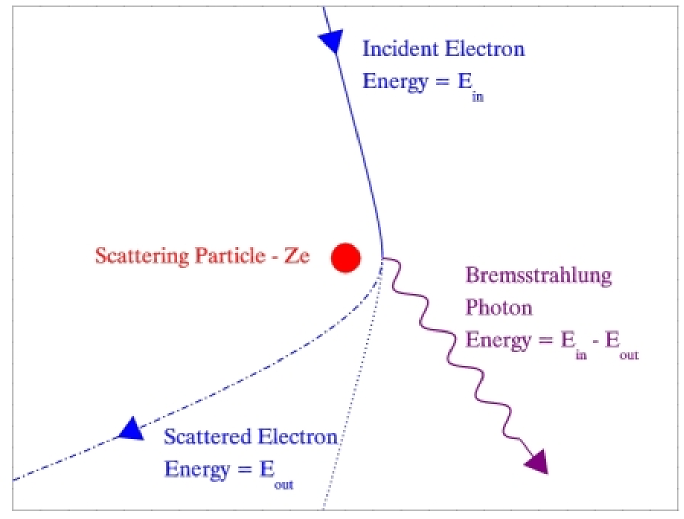
Andrea Bressan

RADIATIVE CORRECTIONS

Radiative Events

•In scattering experiments, a photon may be emitted by a charged particle due to Bremsstrahlung radiation.

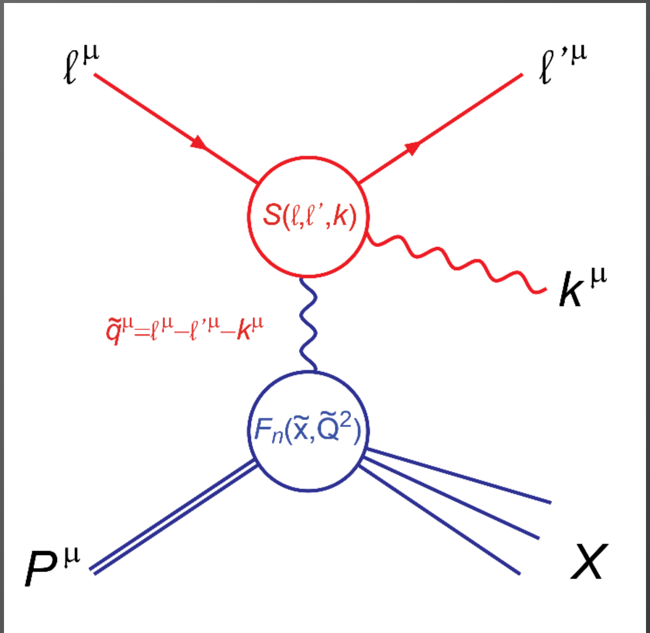
•This type of radiation is due to the deceleration of a charged particle as it approaches the culombic field of another.



Bremsstrahlung radiation

Only the scattered lepton is measured during the event, while the radiated photon usually evades detection. Therefore, there is a loss of energy in the system which is not accounted for.

RADIATIVE CORRECTIONS

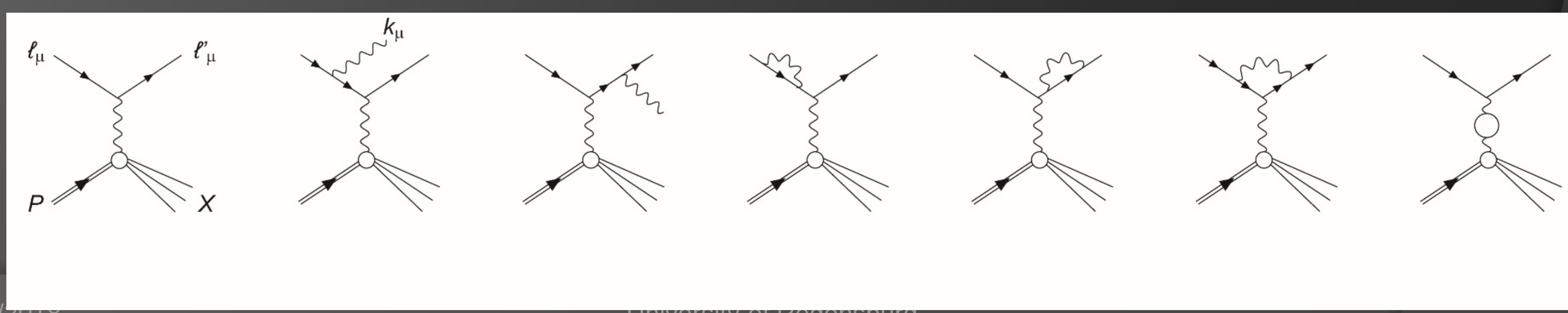


- The radiative leptonic tensor $S(\ell,\ell',k)$ is
  - Gauge invariant
  - Infrared finite
  - Universal (for 1γ exchange)
  - The kinematic is shifted

$$\tilde{q}^\mu = q^\mu - k^\mu$$

RADIATIVE CORRECTIONS

- Three basic channels contribute to lepton-nucleus ℓA scattering at different Q^2 and ν
- These are the
  - Elastic scattering $(\nu = Q^2/2M_A)$
  - Quasi elastic scattering $(\nu \sim Q^2/2M_N)$
  - Inelastic scattering$(\nu > Q^2/2M_N + m_\pi)$
- At Born level, Q^2 and ν are fixed by measuring energy and scattering angle of the lepton and the we can distinguish between the three processes.
- In case of an extra (radiated) photon the fixing of Q^2 and from θ and E' is removed and the photon has to be included in the kinematic calculation.
-



Codes for RC in *ep*-scattering

POLRAD 2.0 *FORTRAN code for the RC procedure of experimental data in polarized inclusive and semi-inclusive DIS. The iteration procedure based on MINUIT fitting the data is included. Estimation of higher order and electroweak corrections is done.*

DIFFRAD *FORTRAN code for RC calculation in the processes of electroproduction of vector mesons. Versions with Monte Carlo and numerical integrations are available. Monte Carlo code allows to estimate RC to the quasi-real photoproduction case (i.e., the final electron is not detected)*

HAPRAD *FORTRAN code for RC calculation in the processes of semi-inclusive hadron electroproduction. Versions with Monte Carlo and numerical integrations are available.*

ESFRAD *(Authors: A. Afanasev, I. Akushevich, N. Merenkov) FORTRAN code for RC calculation in the processes of elastic, inelastic and deep inelastic scattering using the method of electron structure functions.*

ELARADGEN *(Authors: A. Afanasev, I. Akushevich, A. Ilychev, B. Niczyporuk) Monte Carlo generator of radiative events in the kinematics of elastic ep-scattering measurements.*

MASCARAD *FORTRAN code for RC calculation in elastic electron-nucleon scattering with a polarized target and/or recoil polarization. The experimental acceptances are accounted for.*

EXCLURAD *(Authors: A. Afanasev, I. Akushevich, V. Burkert, K. Joo) FORTRAN code for RC calculation in the process of exclusive pi electroproduction on a nucleon.*

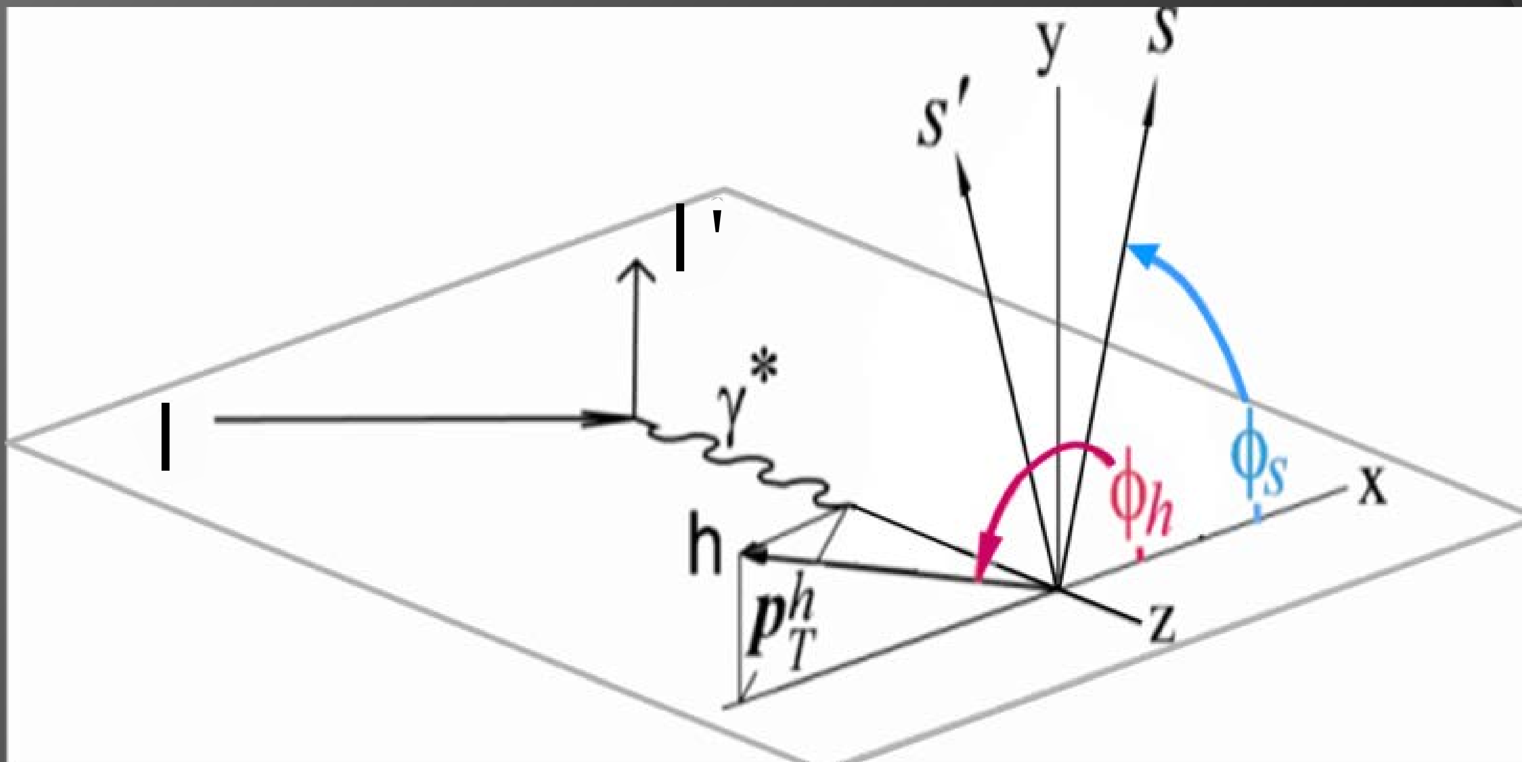
AVAILABLE Monte Carlo CODES

- RADGEN (I.Akushevich, H.Boettcher, D.Ryckbosch, arXiv:hep-ph/9906408) *Monte Carlo generator of radiative events in the DIS on polarized and unpolarized targets. Can be applied for RC generation in inclusive, semi-inclusive and exclusive DIS processes.*
- HERACLES and DJANGOH (Bohm, Hollik, Hubert Spiesberger): *Monte Carlo generator of radiative events in DIS* lepton-nucleon scattering including both QED and QCD radiative effects.

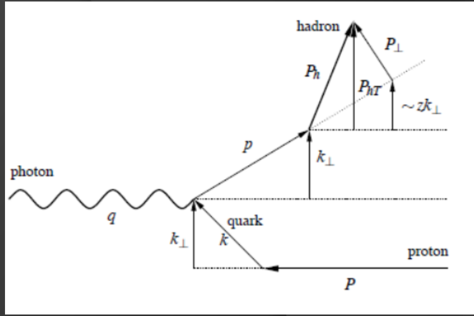
The problem for SIDIS

- Photon radiation from the muon lines changes the DIS kinematics on the event by event basis
- The direction of the virtual photon is changed with respect to the one reconstructed from the muons
  - This introduces false asymmetries in the azimuthal distribution of hadrons calculated with respect to the virtual photon direction
  - Smearing of the kinematic distributions (f.i. z and P_{hT})
- Due to the energy unbalance, in the lepton plane the true virtual photon direction is always at larger angles with respect to the reconstructed one
- In SIDIS, having an hadron in the final state, only the inelastic part of the radiative corrections plays a role

Azimuthal asymmetries in SIDIS



Unpolarized TMDs



- The cross-section dependence from P_{hT} (the hadron tranverse momentum with respect to the virtual photon) results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation
- The azimuthal modulations in the unpolarized cross-sections comes from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF

Measured cross-section

- The measured cross section σ_{obs} is not the Born, 1γ, cross section $\sigma_{1\gamma}$; typically:

$$\frac{d^2\sigma_{obs}}{dydQ^2} = \delta_R\left(E^{\gamma}_{min}\right)(1+\delta_{vertex}+\delta_{vacum}+\delta_{i.r})\frac{d^2\sigma_{1\gamma}}{dydQ^2}+$$

$$\frac{d^2\sigma_{add}}{dydQ^2}\left(E^{\gamma}_{min}\right)+\frac{d^2\sigma_{el}}{dydQ^2}+\frac{d^2\sigma_{q}}{dydQ^2}+\frac{d^2\sigma_{in}}{dydQ^2}\left(E^{\gamma}_{min}\right)$$

- where E^{γ}_{min} defines the minimum energy needed to detect the radiated photon by the experimental setup:

- Then a term $\sigma_{add}\left(E^{\gamma}_{min}\right)$ is used to take into account the approximation that the photon energy is considered to be small $\left(E_{\gamma} < E, E'\right)$ for $E_{\gamma} < E^{\gamma}_{min}$

RADGEN+LEPTO

Radgen changes the virtual photon, therefore the procedure is the following

- Use Lepto to generate x and y of the event (i.e. fix E' and θ of the lepton) but not the hadronisation
- Call Radgen with the incoming lepton energy and the virtual photon q^{*}_{μ}
- Obtain in output the true $q^{*}_{\mu,true}$ and the possible radiated photon k^{μ}
- Call Lepto to generate the hadronisation if $\left(q^{*}_{\mu,true} + P\right)^{2} > 4\ (\mathrm{GeV}/c)^{2}$

HERACLES + DJANGOH

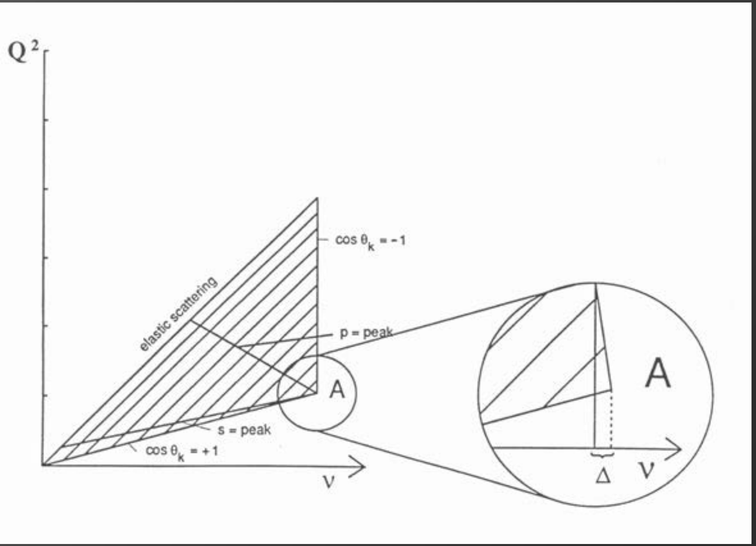
- DJANGOH is an interface to HERACLES and LEPTO 6.5.1:
  - The use of HERACLES allows to take into account the complete one-loop electroweak radiative corrections and radiative scattering.
  - The LUND string fragmentation as implemented in the event simulation program JETSET is used to obtain the complete hadronic final state.
  - At low hadronic mass, SOPHIA is used instead of LEPTO.
  - Several routines of LEPTO modified both for cross section calculations and to kinematic generation
  - No weights, events are generated accordingly to the full cross section (Born+RC)

Inputs to RC Calculations

$$\sigma_{\mathbf{meas}} = v\sigma_{1\gamma} + \sigma_{\mathbf{tails}} = v\sigma_{1\gamma} + \sigma_{\mathbf{inel}} + \sigma_{\mathbf{el}} + \sigma_{\mathbf{qel}}$$

υ – virtual corrections + soft photon emission.

Range of kinematical variables from which the radiative tails contribute to the cross section measured at the point $A(Q^2,\ \upsilon)$; parallel lines: W = const



Even if we measure at DIS, information on $F_1,\ F_2$ (or $R,\ F_2$) needed down to $Q^2 = 0$!

Badelek, Bardin, Kurek, Scholz, Z. Phys. C66 (1995) 591

Inputs for RC calculations

The following inputs for the full cross section calculation have to be known for

$$x_{meas} < x < 1$$
$$0 < Q^2 < Q^2_{MAX}$$

- Spin independent structure function $F_2(x, Q^2)$ (nucleon, nuclei)
- Spin independent structure function $R(x, Q^2)$
- Spin dependent structure function $g_1(x, Q^2)$
- Quasielastic suppression factors (Q^2) (nuclei)
- Elastic form factors (Q^2) (nucleon, nuclei)
- TMDs…GPDs?

X SECTIONS of RADGEN

$$\sigma_{el} = -\frac{\alpha^3 y}{A^2} \int_{\tau_{Amin}}^{\tau_{Amax}} d\tau \sum_{i=1}^{4} \sum_{j=1}^{k_i} \theta_{ij}(\tau_A) \frac{2M_A^2 R_{el\,A}^{j-2}}{(1+\tau_A)(Q^2 + R_{el\,A}\tau_A)^2} \mathfrak{I}_i^{el}(R_{el\,A}, \tau_A)$$

$$\sigma_q = -\frac{\alpha^3 y}{A} \int_{\tau_{min}}^{\tau_{max}} d\tau \sum_{i=1}^{4} \sum_{j=1}^{k_i} \theta_{ij}(\tau) \frac{2M^2 R_{el}^{j-2}}{(1+\tau)(Q^2 + R_{el}\,\tau)^2} \mathfrak{I}_i^{el}(R_{el}, \tau)$$

With $\tau_{min,max} = \frac{Q^2}{2M^2 x}\left(1 \pm \sqrt{1 + \frac{4M^2x^2}{Q^2}}\right)$

$R_{el\,(A)} = \frac{2M_{(A)}\nu - Q^2}{1+\tau}$ and θ_{ij} are kinematic factors, while $\mathfrak{I}$ are combinations of DIS structure functions, elastic FF and quasi-elastic response functions

X SECTIONS of RADGEN

$$\sigma_{in}\left(E^{\gamma}_{min}\right) = -\alpha^3 y \int_{\tau_{min}}^{\tau_{max}} d\tau \sum_{i=1}^{4} \sum_{j=1}^{k_i} \theta_{ij}(\tau) \int_{R_{min}}^{R_{max}} dR \frac{R^{j-2}}{(Q^2 + R\tau)^2} \mathfrak{I}_i(R,\tau)$$

$$\sigma_{add}\left(E^{\gamma}_{min}\right) = -\alpha^3 y \int_{\tau_{min}}^{\tau_{max}} d\tau \sum_{i=1}^{4} \left\{ \theta_{i1}(\tau) \int_{0}^{R_{min}} \frac{dR}{R} \left[\frac{\mathfrak{I}_i(R,\tau)}{(Q^2 + R\tau)^2} - \frac{\mathfrak{I}_i(0,0)}{Q^4} \right] \right.$$

Corrections for azimuthal asym.s:

- For each multidimensional bin in x, Q^2, z, P_{hT} and ϕ used for the analysis one has to look at the ratio

$$\frac{N(x, Q^2, z, P_{hT}, \phi)_{\mathrm{MCEG+RC}}}{N(x, Q^2, z, P_{hT}, \phi)_{\mathrm{MCEG}}}$$

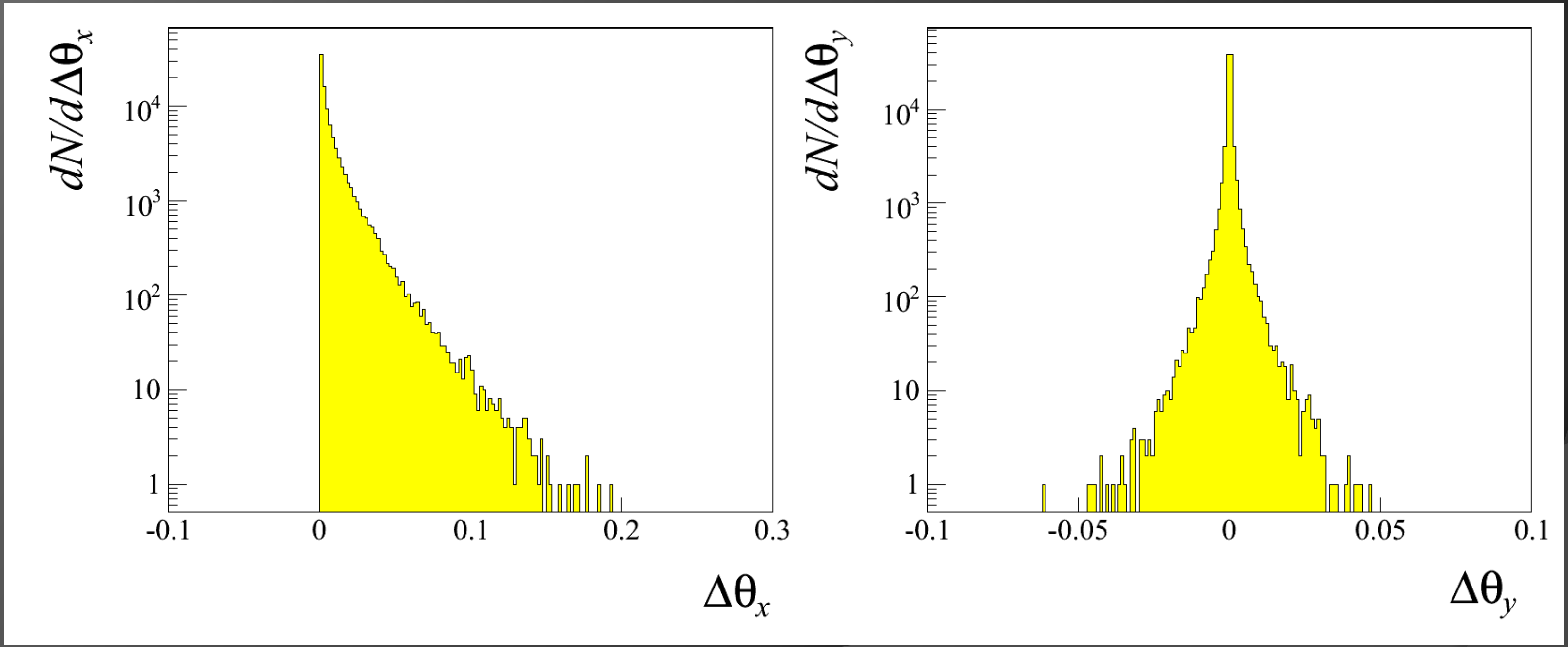
Some kinematic distribution for events with radiation

All shown at generator level

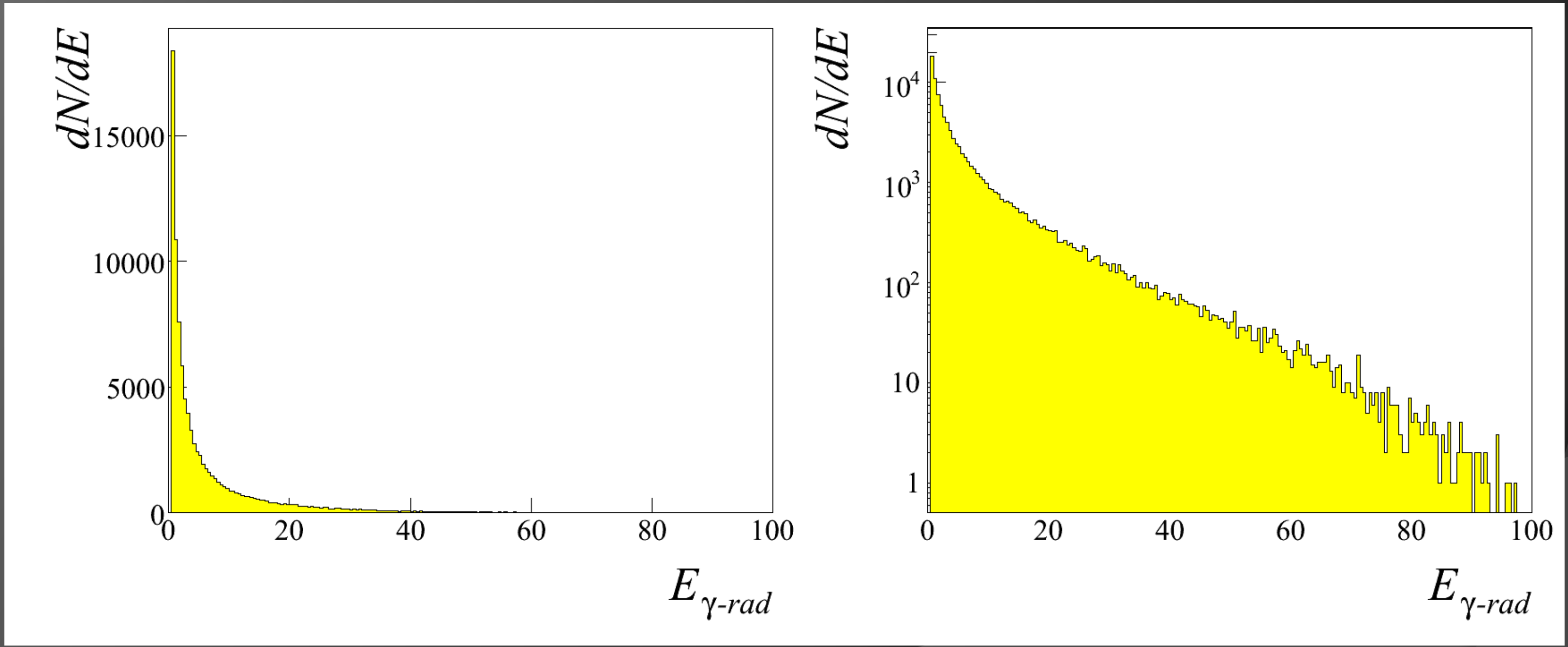
Virtual photon Δ's (Θ_{true}-Θ_m)

XZ is the lepton scattering plane

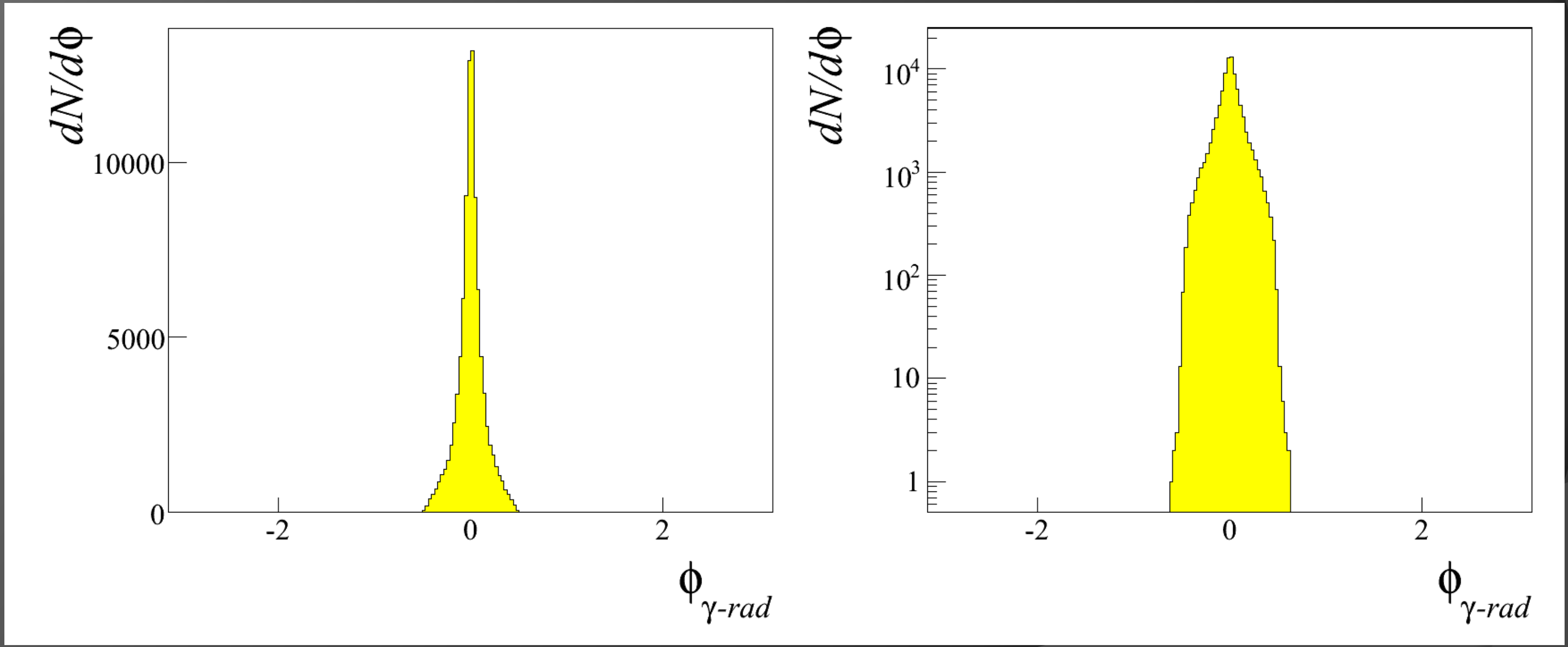
YZ is the off-lepton scattering plane



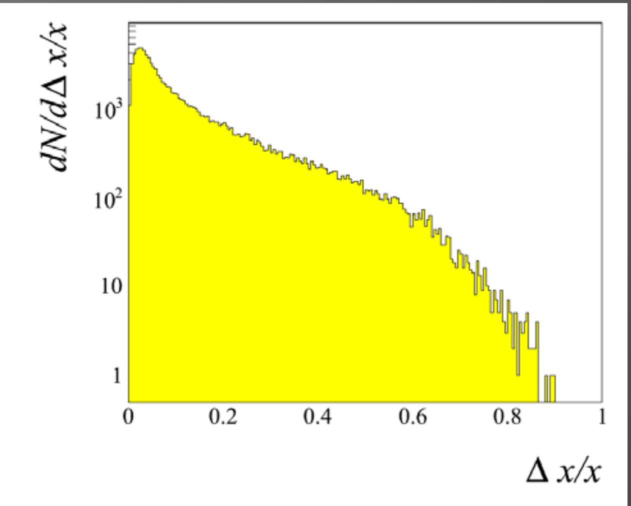
Radiated Photon: Energy

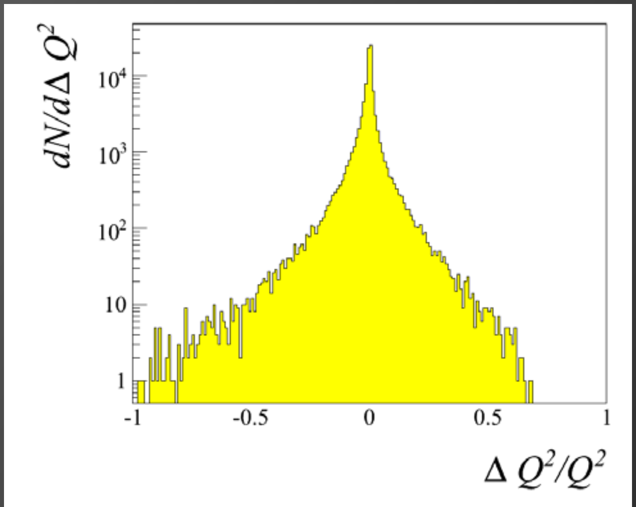


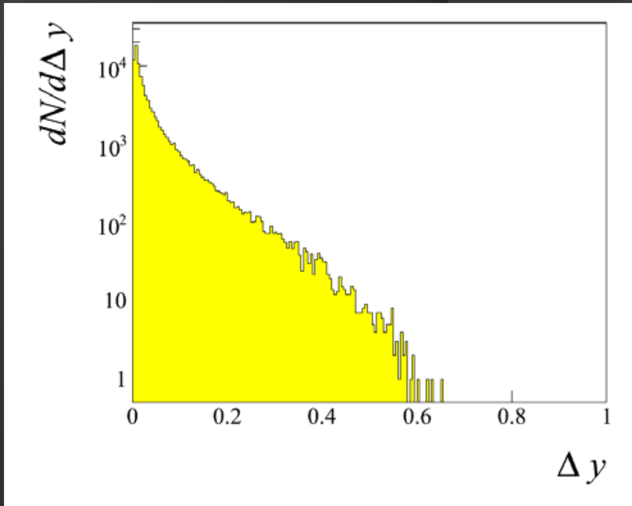
Radiated Photon: Azimuthal angle in GNS



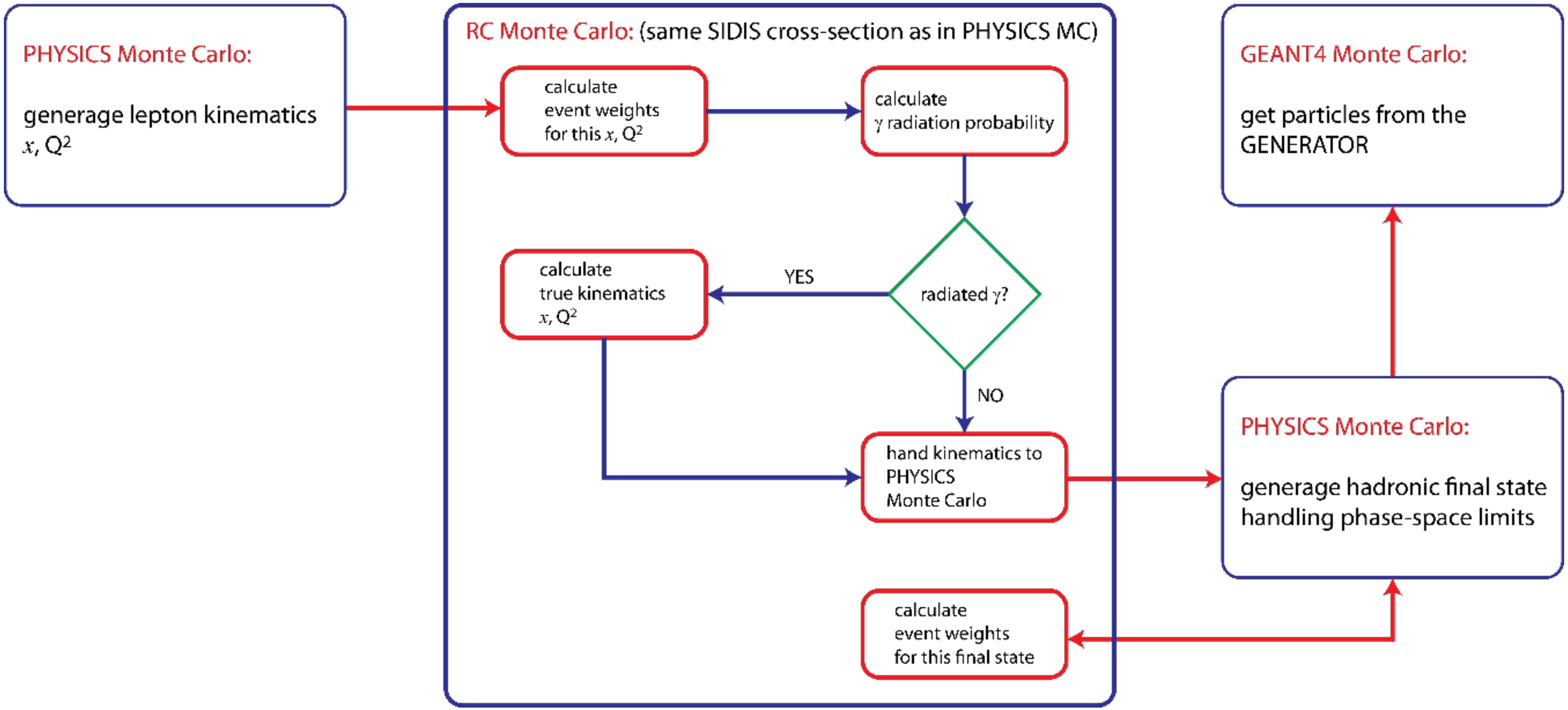
Projections:







Interfacing with modern MCEG



PYTHIA 6

- Steps:
  - Cross section calculation (LO, NLO)
  - Full cross section including radiative corrections (NNLO in QED)
  - Generate according to cross section
  - Final steps in Pythia using $\gamma^* N$ interactions

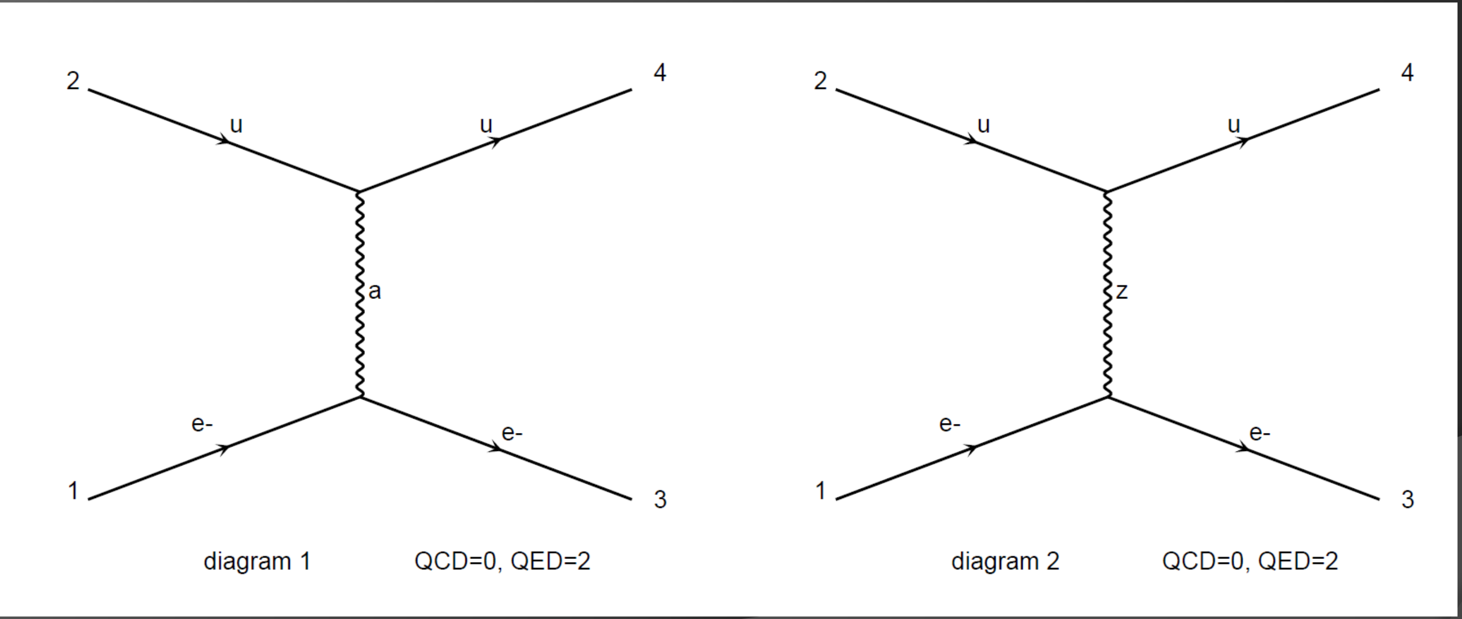
PYTHIA 8

- $\gamma^* N$ not available in PYTHIA 8
- Use of PDF:lepton? Can be used for initial/final state radiations from lepton lines (not for loops, Compton peak)
- Modification of the cross-section calculation for the multiplicative parts?

- Use of MadGraph5?
  - Adv: MadGraph output the results of a matrix-element calculation as a set of PYTHIA 8 C++ classes, that can then be linked and used within Pythia.

Use of MadGraph5?

- Can generate hard processes, including higher order QED



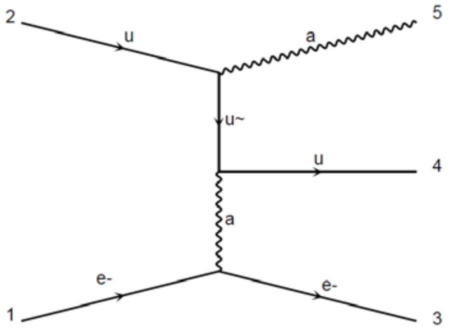


diagram 1 QCD=0, QED=3

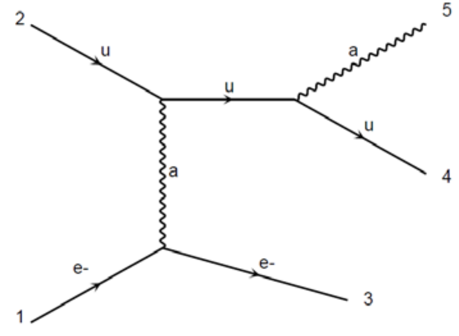


diagram 3 QCD=0, QED=3

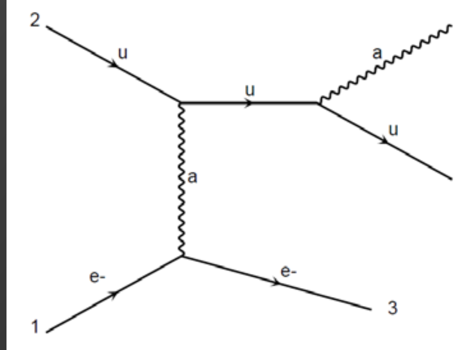


diagram 3 QCD=0, QED=3

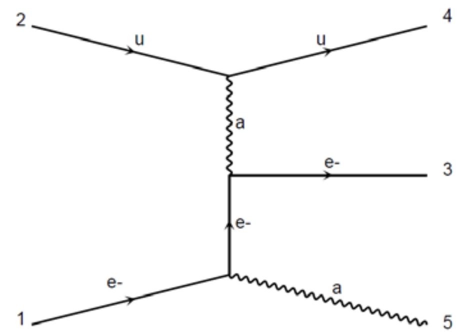


diagram 5 QCD=0, QED=3

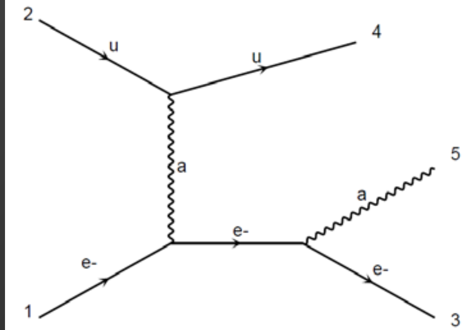
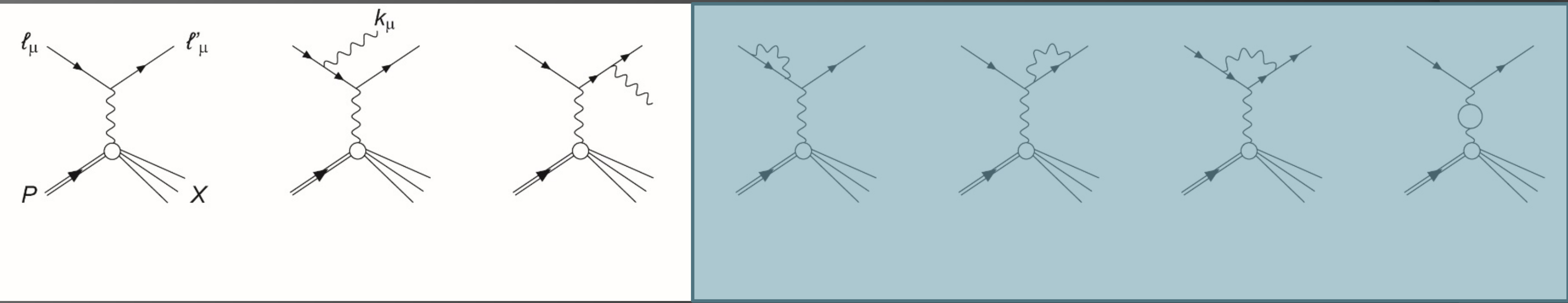


diagram 7 QCD=0, QED=3

QED=4 is missing



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