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RADIATIVE CORRECTIONS IN SIDIS FROM COMPASS

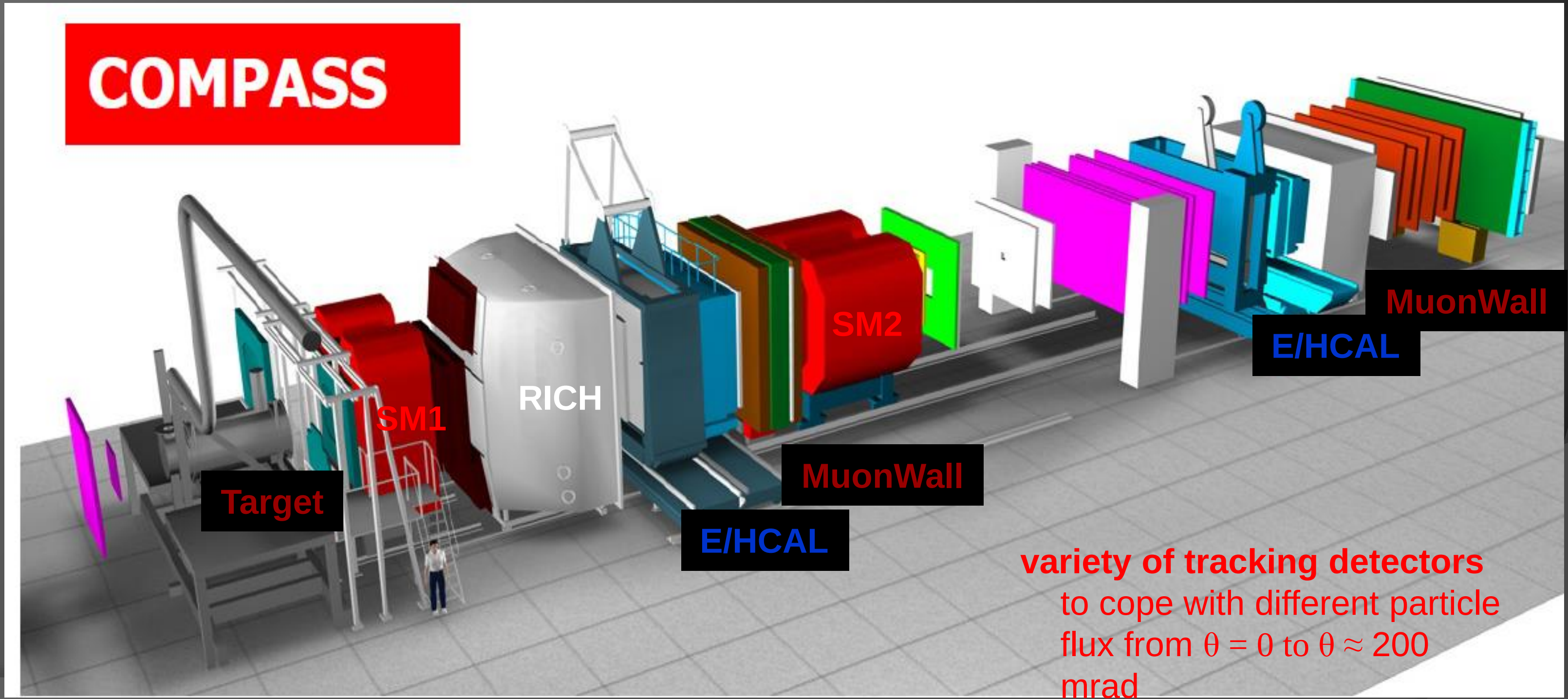
COMPASS-I

- high energy beam
- large angular acceptance
- broad kinematical range

two stages spectrometer

Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)



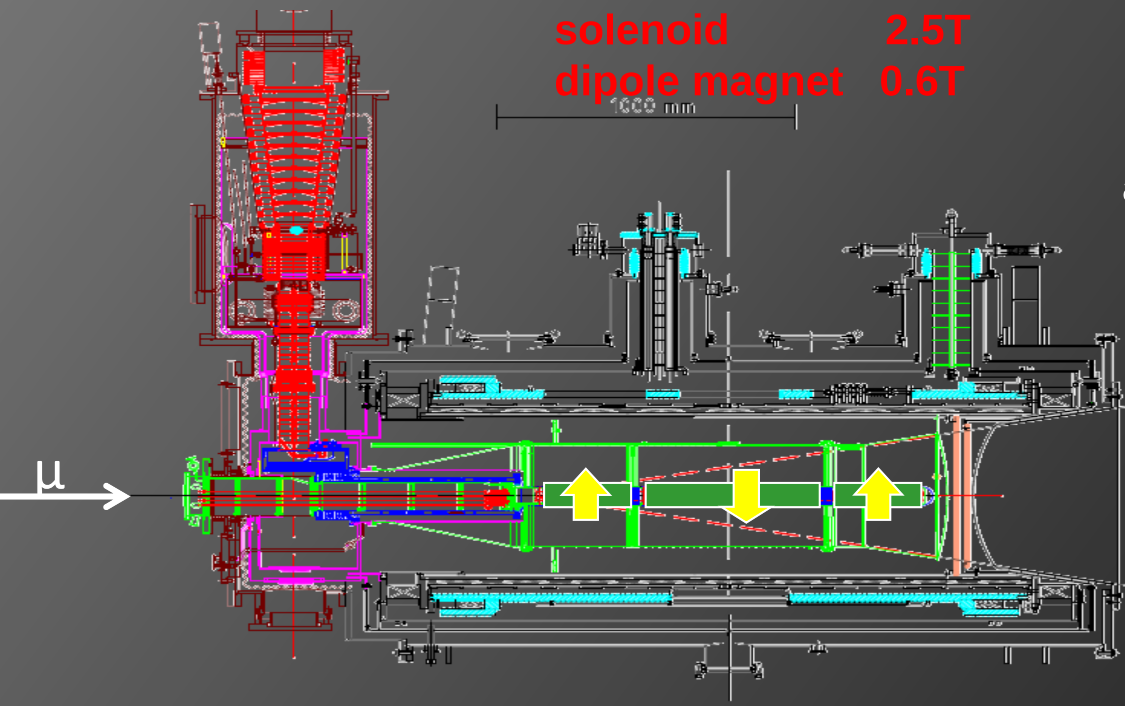
variety of tracking detectors

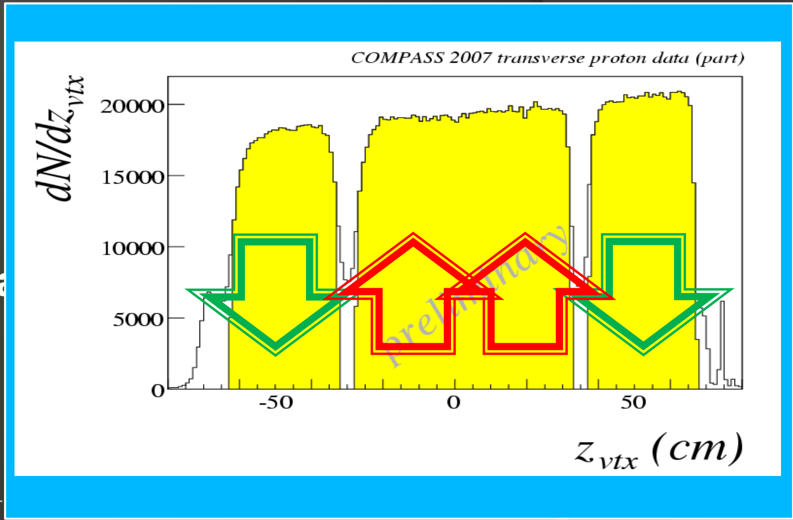
to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad

the polarized target system

^3He – ^4He dilution refrigerator (T~50mK)

solenoid 2.5T
dipole magnet 0.6T





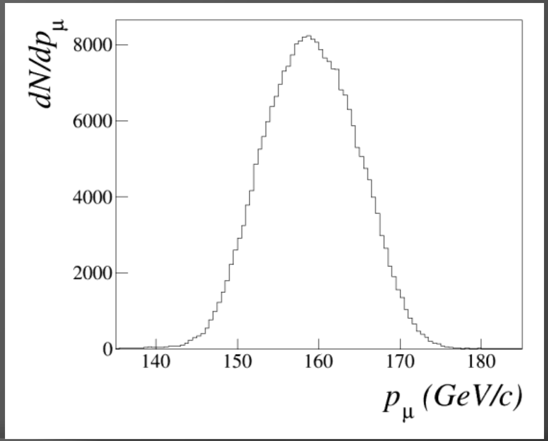
opposite polarisation

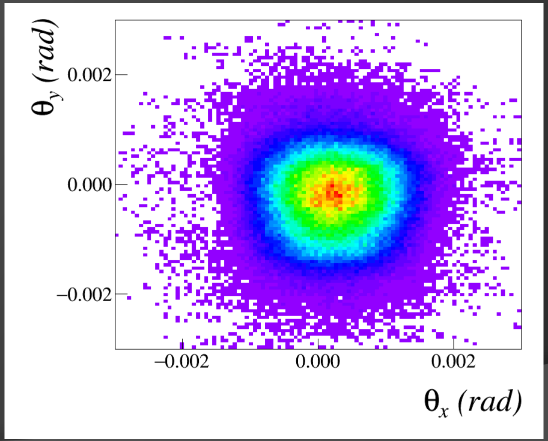
	d (^6LiD)	p (NH_3)
polarization	50%	90%
dilution factor	40%	16%

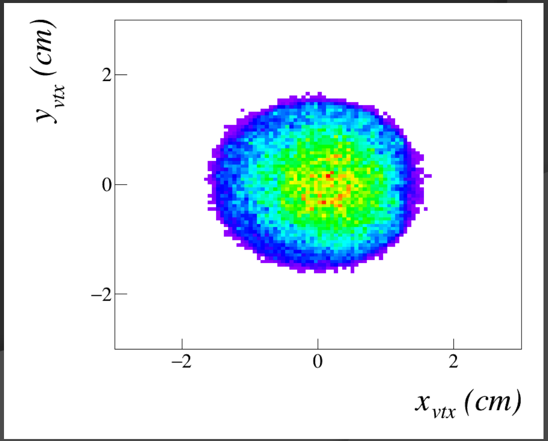
no evidence for relevant nuclear effects *(160 GeV)*

COMPASS Muon Beam

- We mainly used 160 GeV/c μ^+.
- The momentum and direction of each μ^+ is measured.







CORRECTIONS IN COMPASS SIDIS

- TERAD (A. Akhundov, D. Bardin, L. Kalinovskaya and T. Riemann, Fortschr. Phys. 44 (1996) 373). Used for the tables of radiative corrections and in the calculation of the dilution factors. Analitical calculation; not a generator.

- HAPRAD (I. Akushevich et al, Eur.Phys.J.**C**10:681-687) used by Andrei Afanasev to calcultate f.i. effects in the $\cos\phi$ and $\cos 2\phi$ modulation Analitical calculation; not a generator.

- RADGEN (I.Akushevich, H.Boettcher, D.Ryckbosch, arXiv:hep-ph/9906408) called from Lepto or Pythia. Generates hard photons and gives true virtual photon 4-momentum

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.
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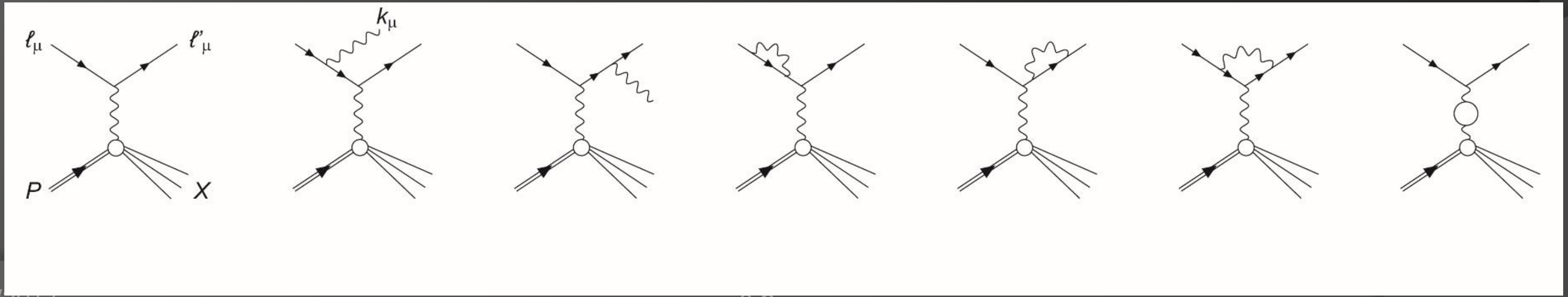
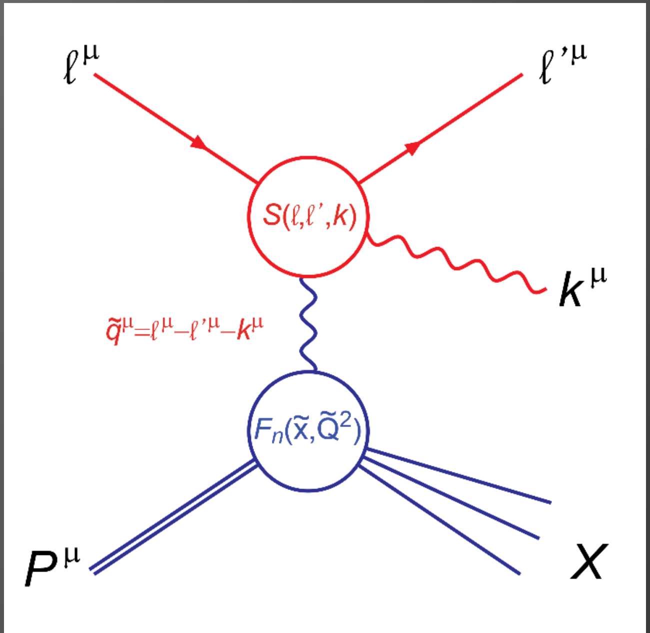


RADIATIVE CORRECTIONS



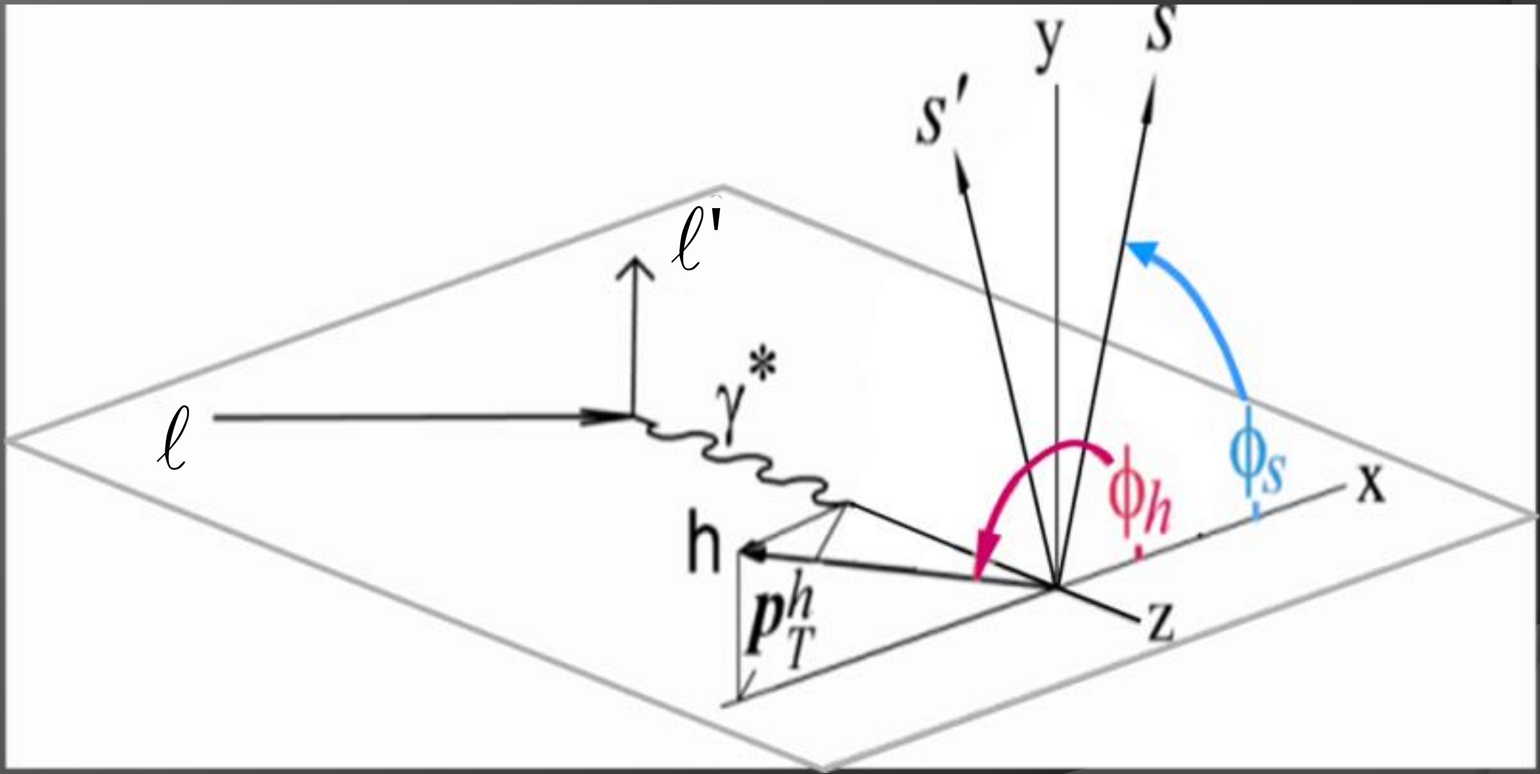
- The radiative leptonic tensor $S(\ell, \ell', k)$ is
  - Gauge invariant
  - Infrared finite
  - Universal (for 1γ exchange)
  - The kinematic is shifted

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

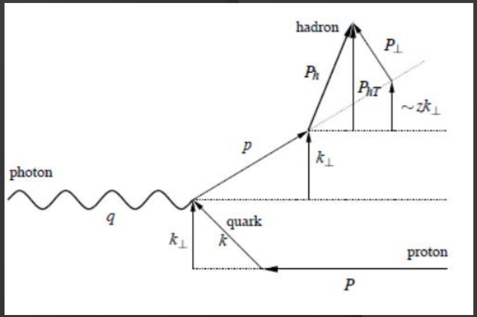
The problem for SIDIS

- 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



Importance of unpolarized SIDIS for TMDs

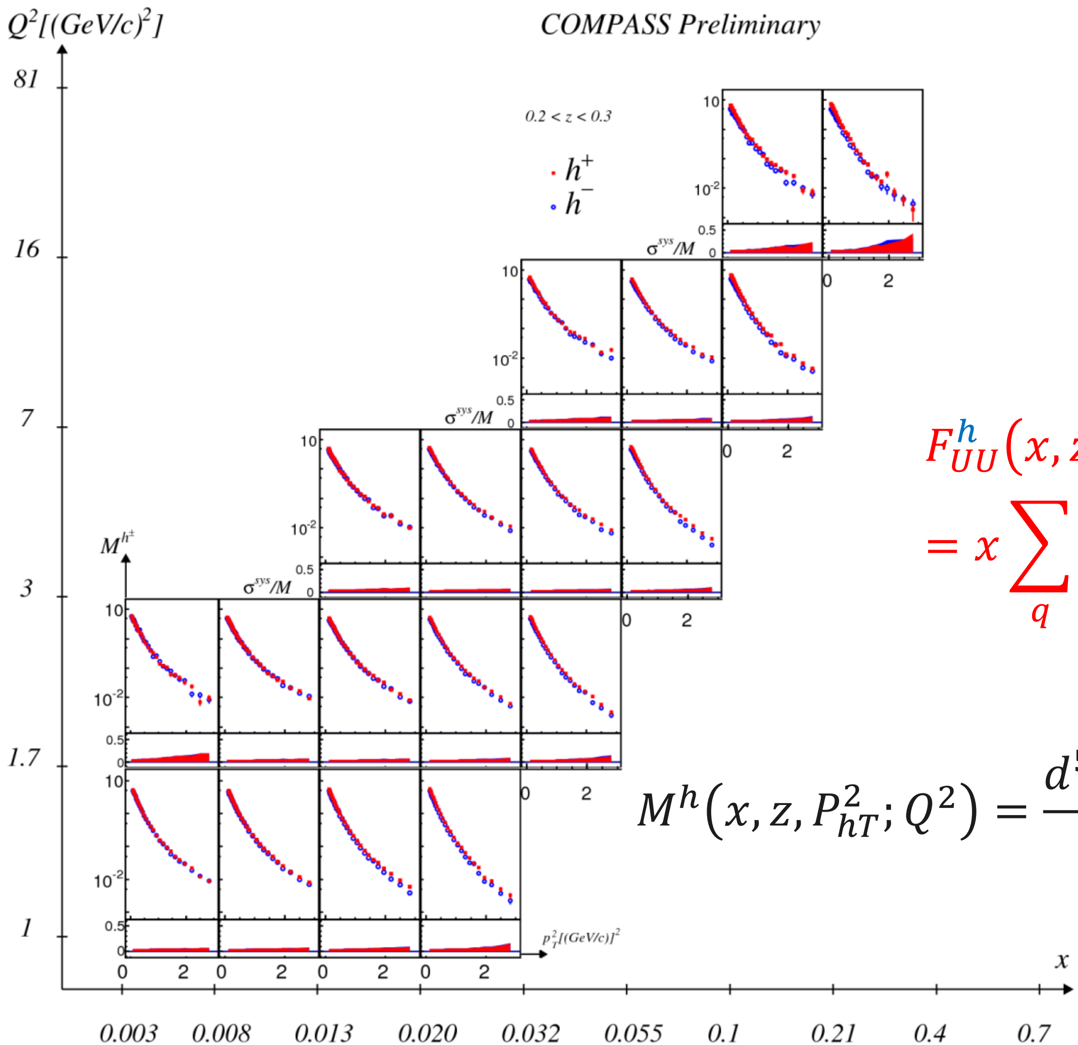


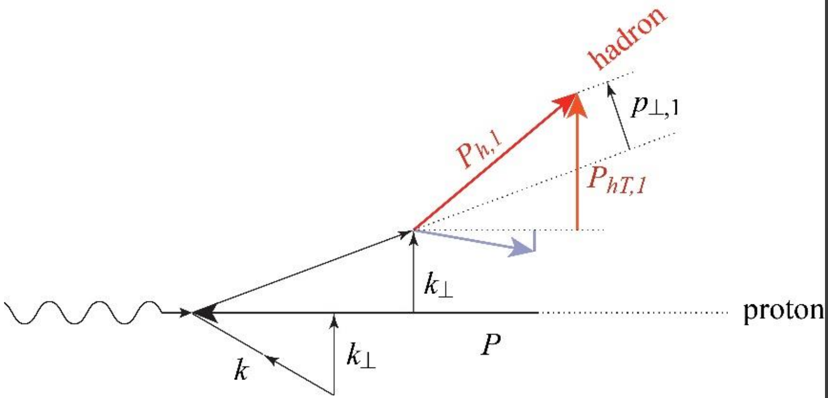
- The cross-section dependence from p_T^h results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation
  - A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to
  - $\langle p_{T,h}^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$

- The azimuthal modulations in the unpolarized cross-sections comes from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF

These are difficult measurements were one has to correct for the apparatus acceptance

Unpolarized SIDIS

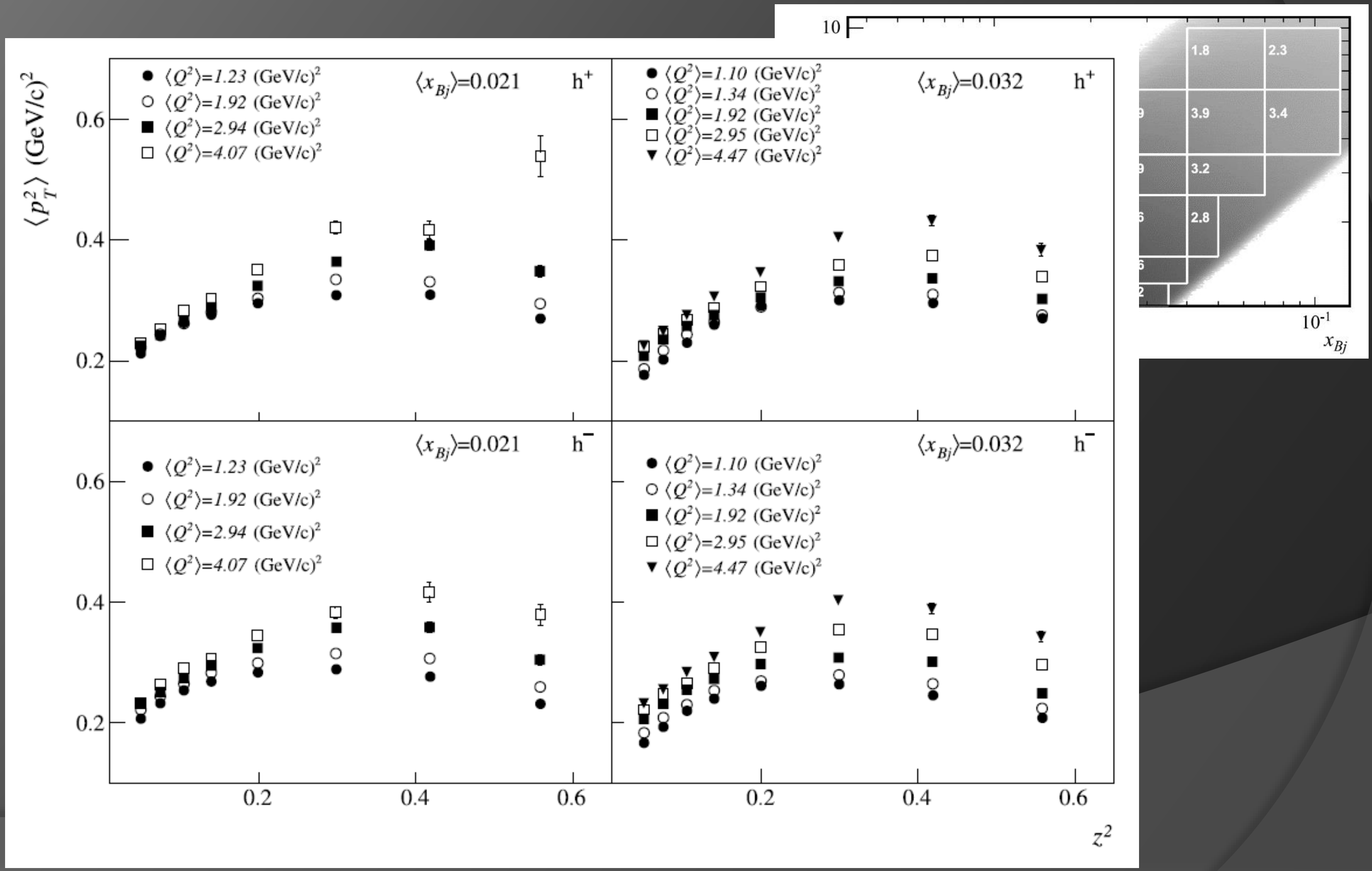




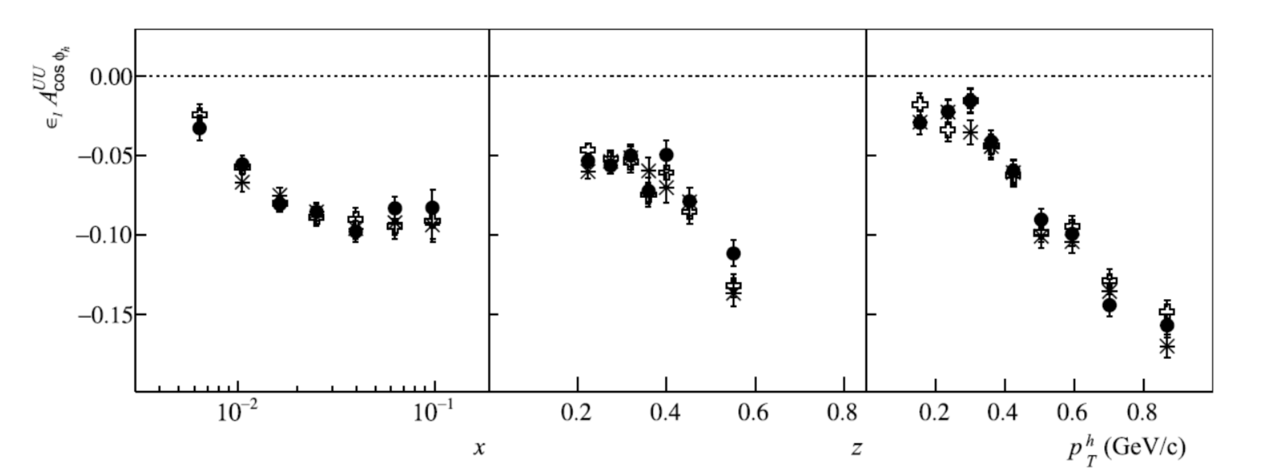
$$F_{UU}^{h}\left(x,z,P_{hT}^2;\ Q^2\right)$$
$$= x\sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \delta\left(\vec{p}_\perp - z\vec{k}_\perp\right)$$

$$M^h\left(x,z,P_{hT}^2;Q^2\right) = \frac{d^5\sigma^h/dxdQ^2dzd^2\vec{p}_T}{d^2\sigma^{DIS}/dxdQ^2} \sim \frac{F_{UU}^{h}\left(x,z,P_{hT}^2;\ Q^2\right)}{F_{UU,T}+\varepsilon F_{UU,L}}$$

X-section dep. from p_T^h

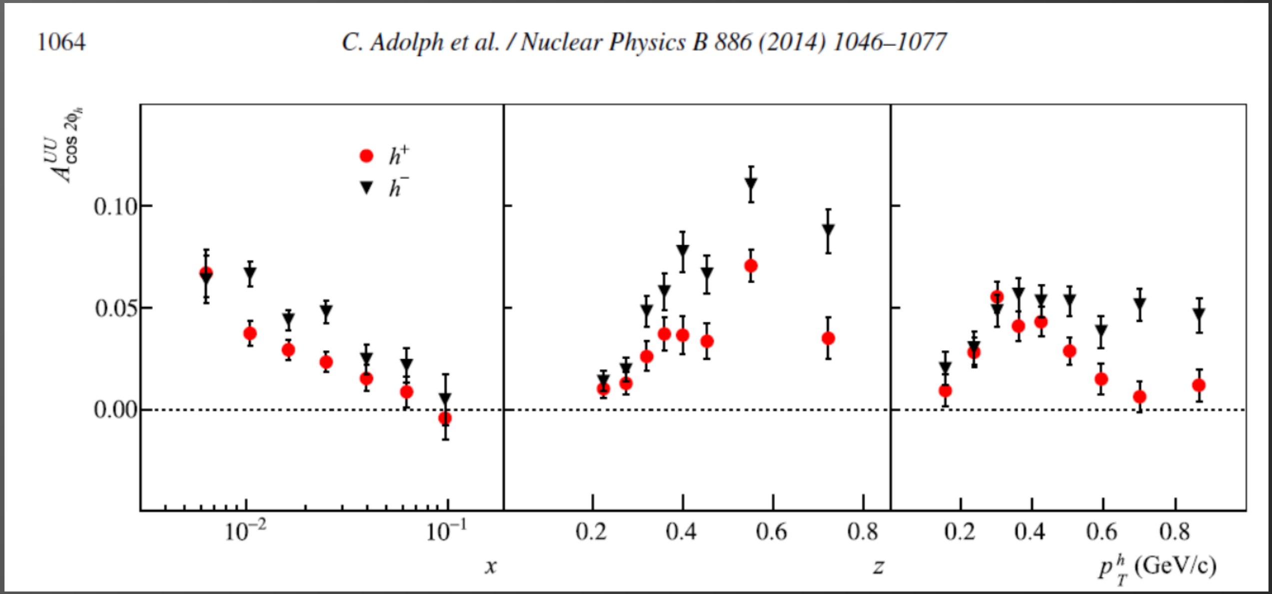


cos ϕ modulation



$$A_{UU}^{\cos\phi}(x, z, P_{hT}^2; Q^2) \propto \frac{1}{Q}\sum_q e_q^2\left[f_1^q \otimes D_1^{q\to h} - h_1^{\perp,q} \otimes H_1^{\perp,q\to h}\right]$$

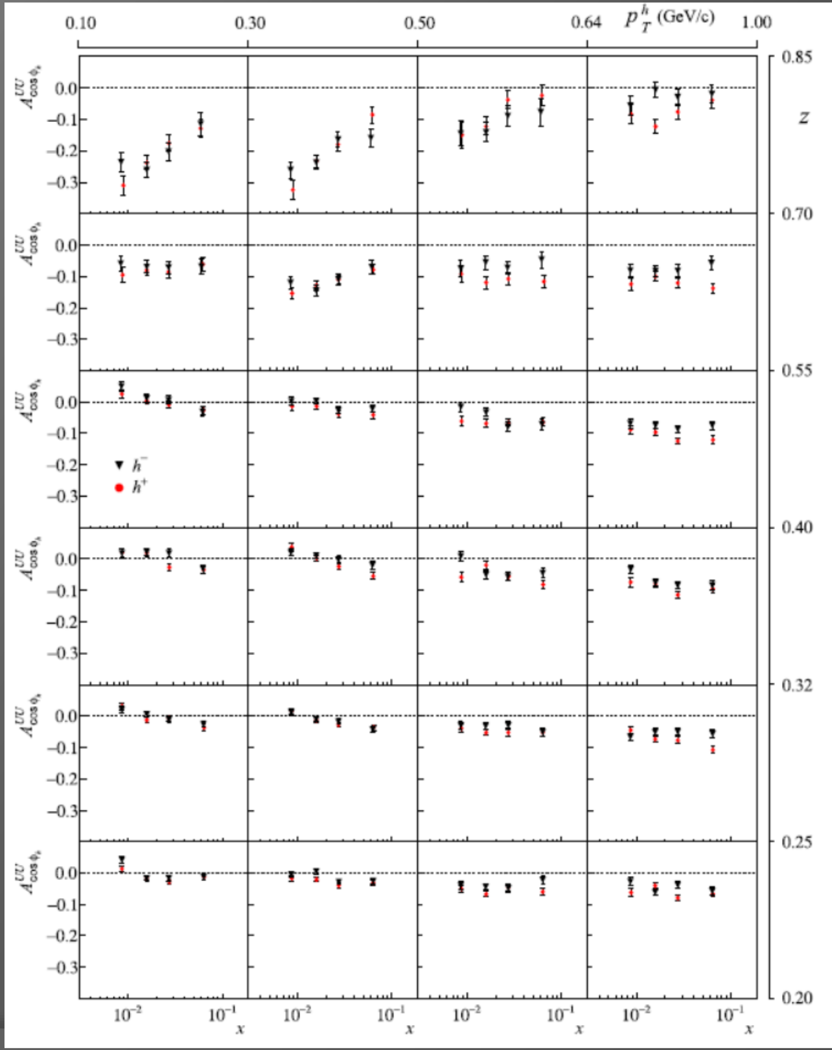
Boer-Mulders in $\cos 2\phi$

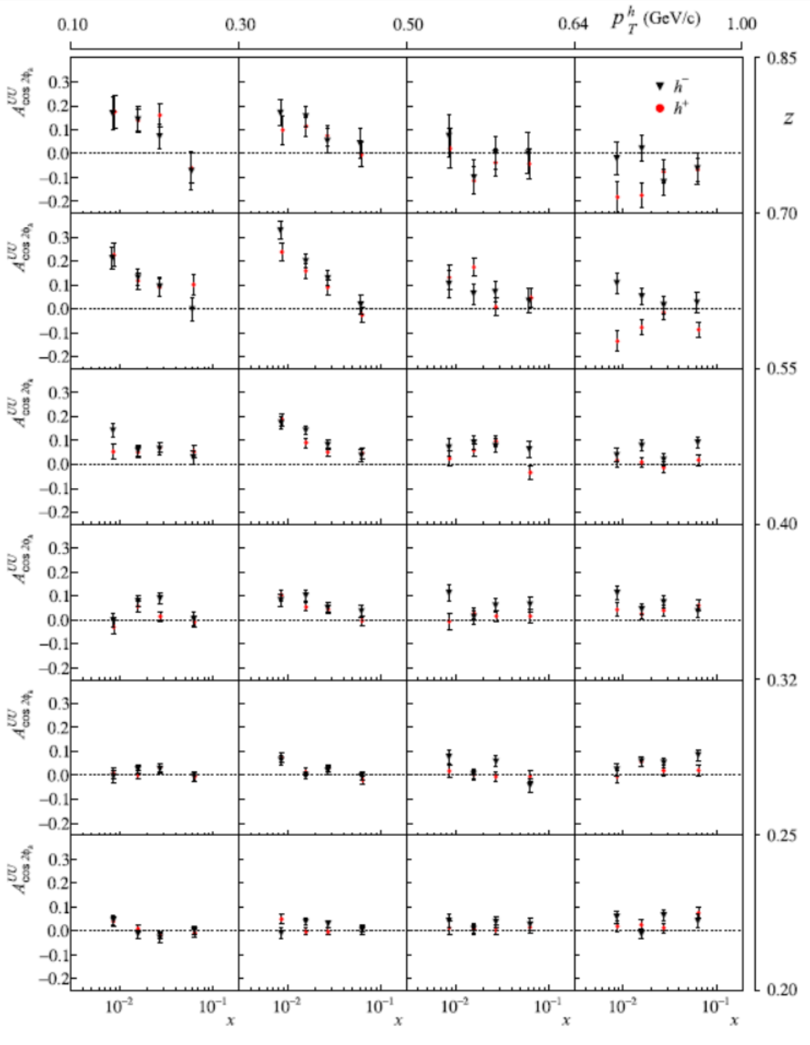


$$F_{UU}^{\cos 2\phi}(x, z, P_{hT}^2;\ Q^2)$$

$$= -x \sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \frac{2(\hat{h}\cdot\vec{k}_\perp)(\hat{h}\cdot\vec{k}_\perp) - \vec{k}_\perp\cdot\vec{p}_\perp}{M m_h}\ h_1^{\perp,q}(x, k_\perp^2; Q^2) H_1^{\perp,q\to h}(z, p_\perp^2; Q^2)$$

Boer-Mulders and Cahn effects





RADGEN

- In RADGEN E_{min}^{γ} defines the minimum energy needed to reconstruct the radiated photon by the experimental setup:

$$\sigma_{obs} = \delta_R\left(E_{min}^{\gamma}\right)(1 + \delta_{vertex} + \delta_{vacum} + \delta_{i.r})\sigma_{1\gamma} + \sigma_{add}\left(E_{min}^{\gamma}\right) + \sigma_{el} + \sigma_q + \sigma_{in}\left(E_{min}^{\gamma}\right)$$

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

RADGEN+LEPTO

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

- First 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 $\left(q_{\mu,true}^{*} + P\right)^{2} > 4\ (\mathrm{GeV}/c)^{2}$
- A toy MC for hadron and muon propagation trough the experimental setup is used to check acceptance effects already at generator level

How RADGEN+LEPTO works

Few things:

- We generate the event starting from a measured beam muon in the laboratory system and rotate and boost to the different systems.
- Of course $m_e \rightarrow m_\mu$ in RADGEN
- Due to the energy spread of our beam we do not use look up tables for RADGEN but the integrations are performed every event at the correct beam energy.
- RADGEN was further modified to have the possibility to choose between:
  - Original F_2, $R = \sigma_L^\gamma / \sigma_T^\gamma$, elastic FF and and quasi-elastic response functions
  - Same inputs as for the TERAD version used in COMPASS
  - Same F_2 as from the PDFs used in LEPTO (taken from LHAPDF)
- Lepto (6.5.1) works with PYTHIA 5.7 and Jetset 7.4. Following pythiaeRICH, we introduced recently the possibility to have the

$$\gamma^* N \rightarrow X$$

  performed by PYTHIA 6.4.28
- $\gamma^* N \rightarrow X$ by Lepto sometimes fails in the fragmentation

X SECTIONS of RADGEN

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

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

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

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

X SECTIONS of RADGEN

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

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

A problem with σ_{in}

$$\sigma_{in} = \int_{M_p+m_p}^{W} dm_h \, \sigma_{in}(m_h, \theta_{max})$$

If we have detected/generated in the setup $\sqrt{(\sum p_{hi})^2}$, should not start from there the integral?

Corrections for azimuthal asym.s:

- For each bin in x, z or P_{hT} used for the analysis we fitted the azimuthal distribution of the ratio

$$\frac{N(\phi)_{\mathrm{Lepto+RADGEN}}}{N(\phi)_{\mathrm{Lepto}}}$$

with the following function

$$f(\phi) = a(1 + p_1 \cos\phi + p_2 \cos 2\phi + \cdots)$$

Corrections for Multiplicities:

$$M^h(x,Q^2,z,p_T^2) = \frac{N^h(x,Q^2,z,p_T^2)}{N^\mu(x,Q^2)} \cdot \frac{a^\mu(x,Q^2)}{a^h(x,Q^2,z,p_T^2)} \cdot \frac{\eta^\mu(x,Q^2)}{\eta^h(x,Q^2)} \cdot \frac{N_{x,Q^2}^{h,MC}(z^t,p_T^t)}{N_{x,Q^2}^{h,MC}(z^r,p_T^r)}$$

$\frac{a^\mu(x,Q^2)}{a^h(x,Q^2,z,p_T^2)}$ acceptance correction

$\frac{\eta^\mu(x,Q^2)}{\eta^h(x,Q^2)}$ radiative corrections from TERAD tables

$\frac{N_{x,Q^2}^{h,MC}(z^t,p_T^t)}{N_{x,Q^2}^{h,MC}(z^r,p_T^r)}$ smearing due to radiative events in z and p_T

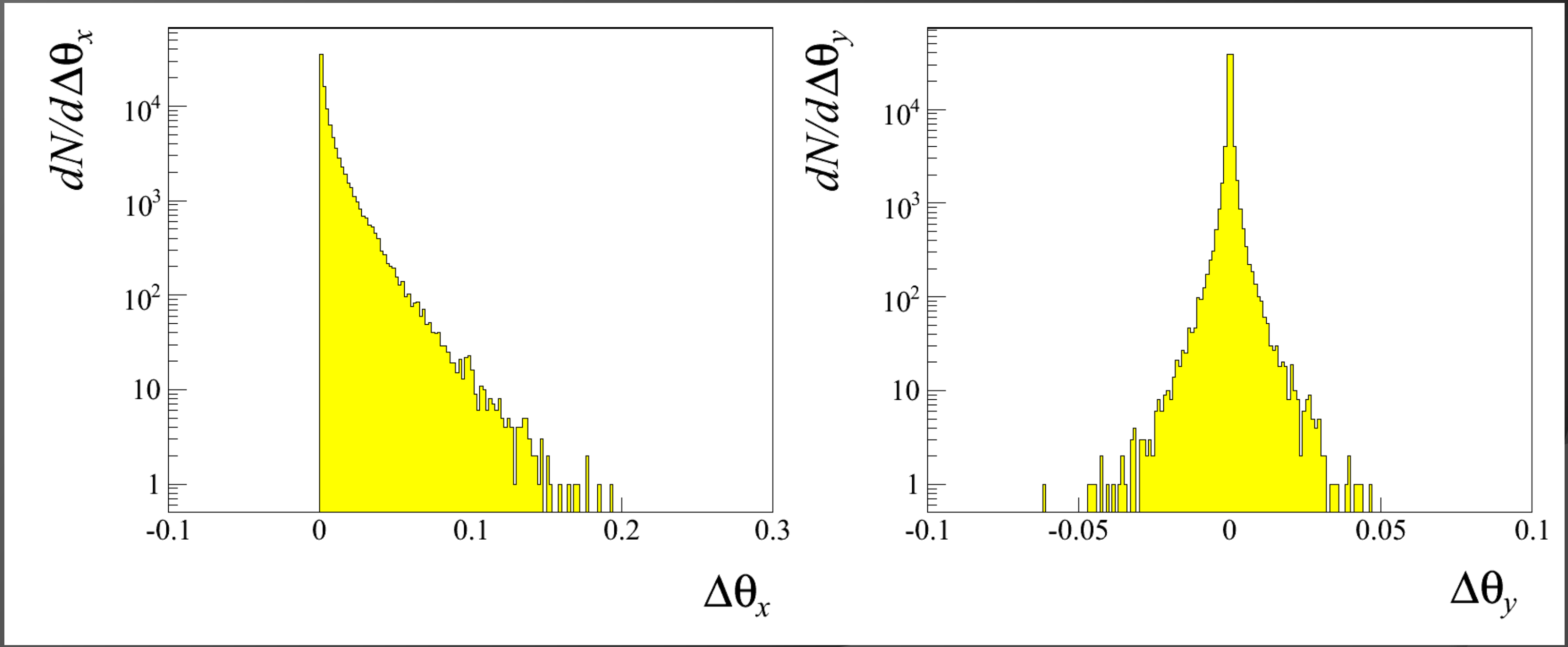
Some kinematic distribution for events with radiation

All shown at generator level

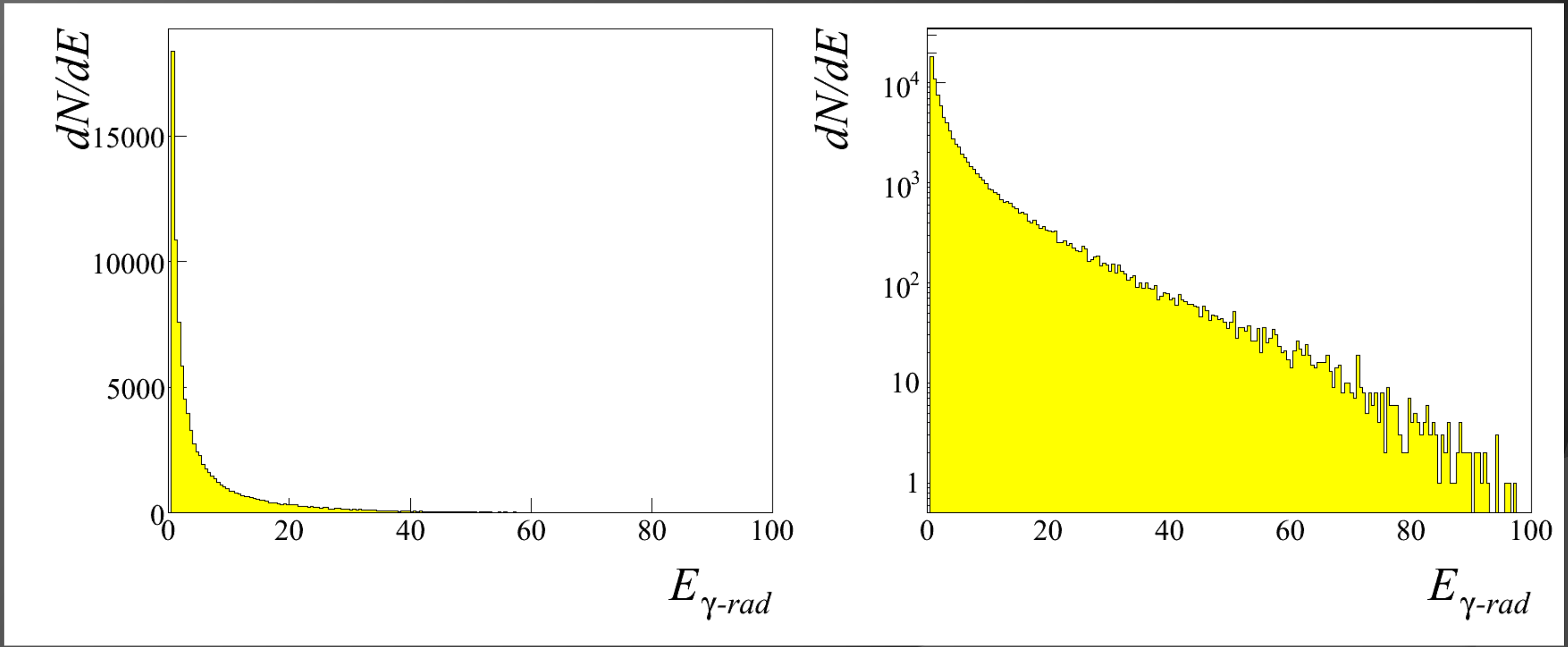
Virtual photon Δ's (Θ_{true}-Θ_m)

XZ is the lepton scattering plane

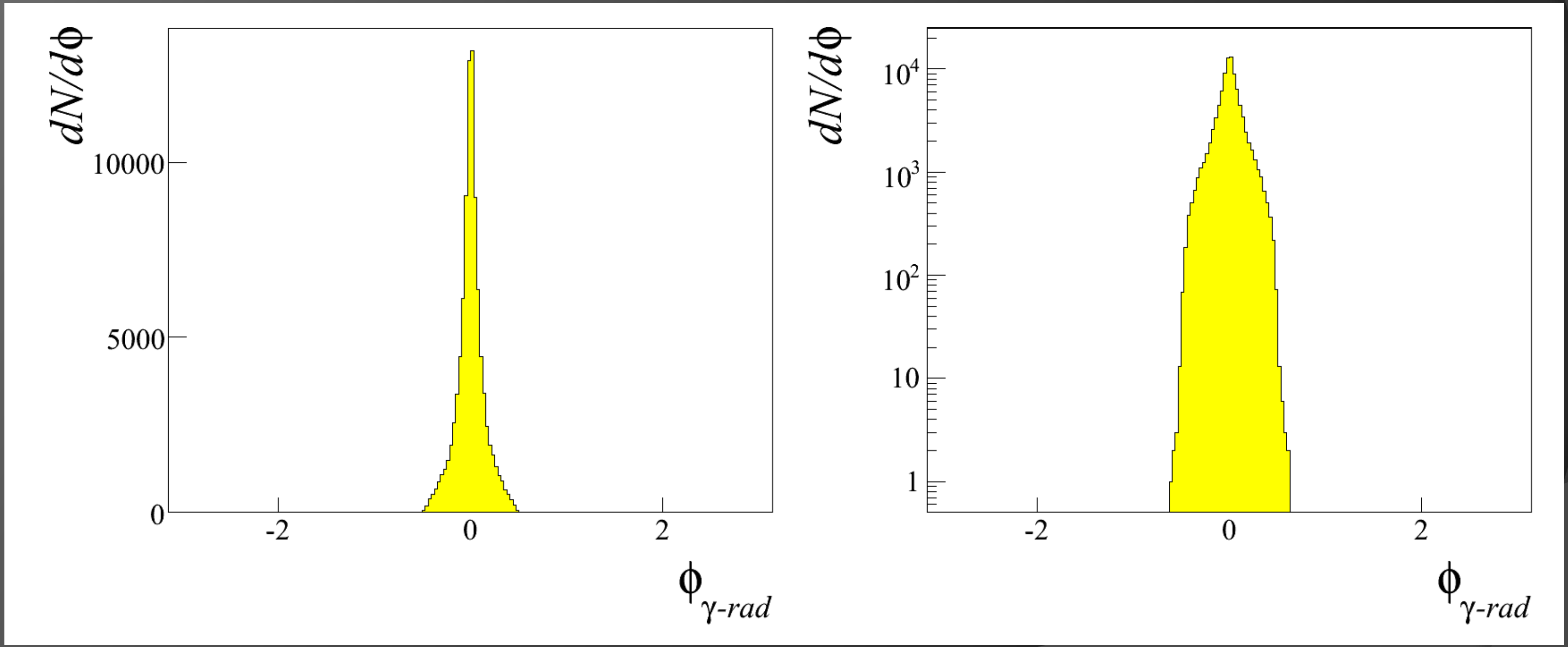
YZ is the off-lepton scattering plane



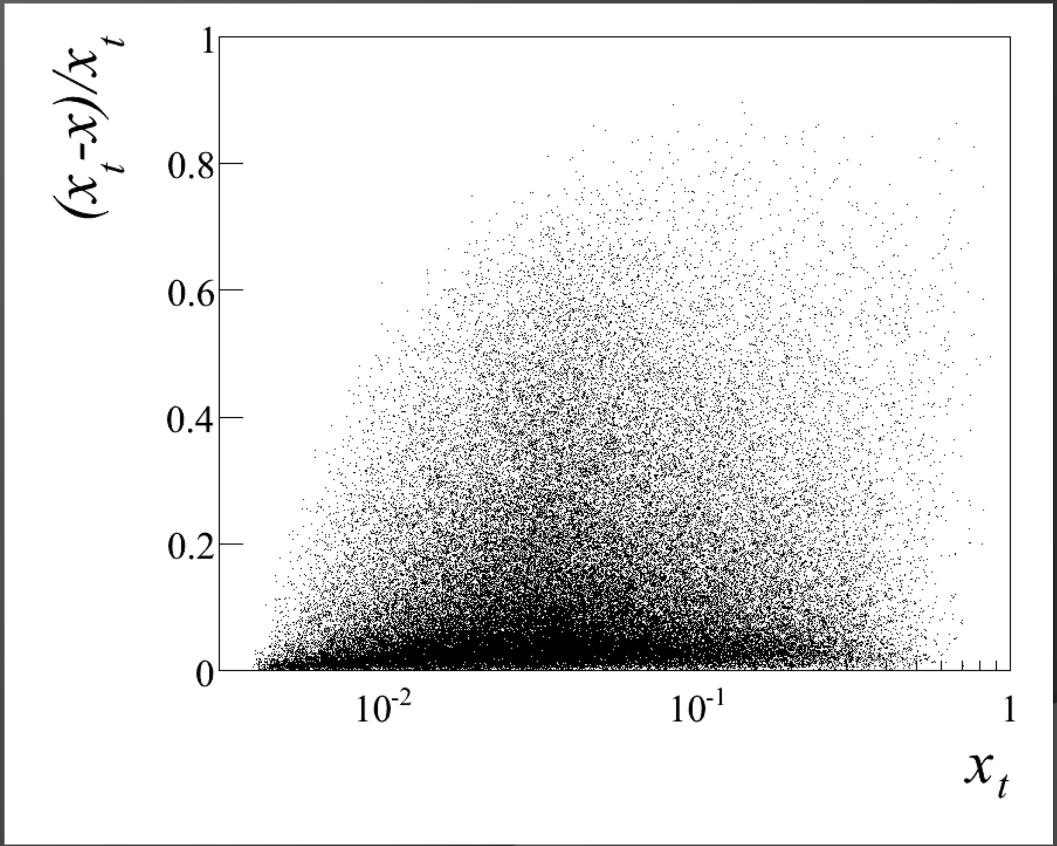
Radiated Photon: Energy



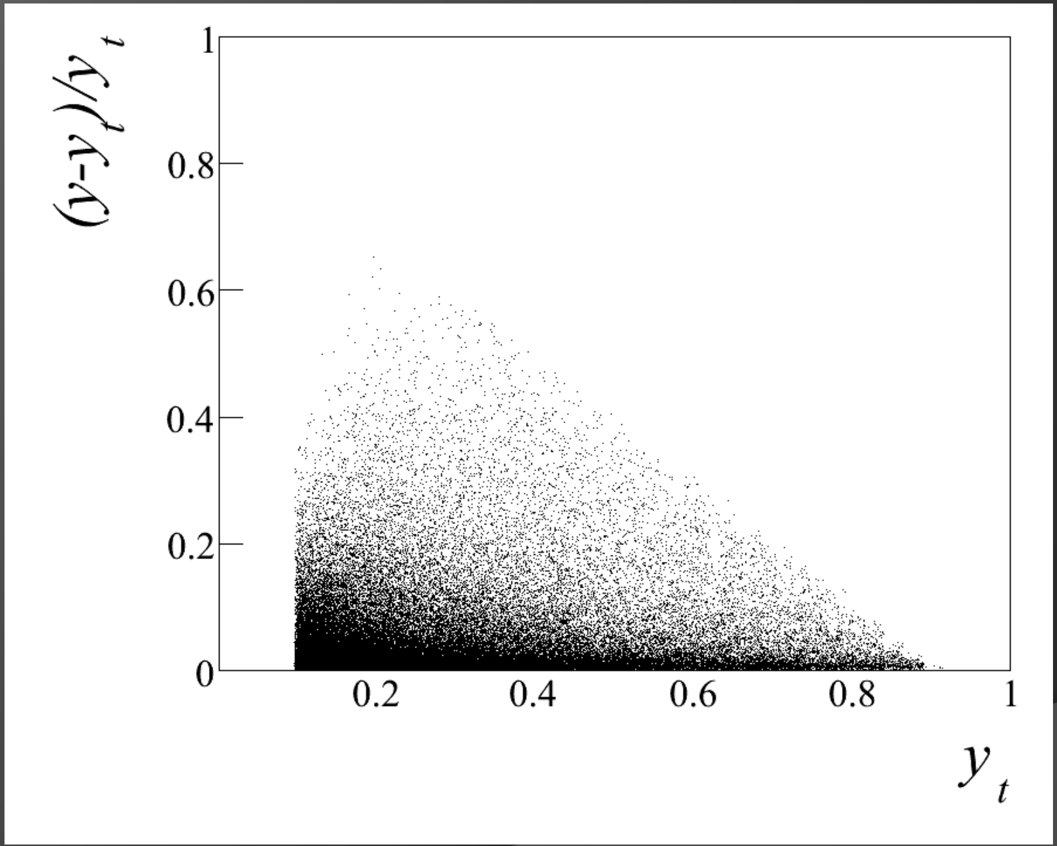
Radiated Photon: Azimuthal angle in GNS



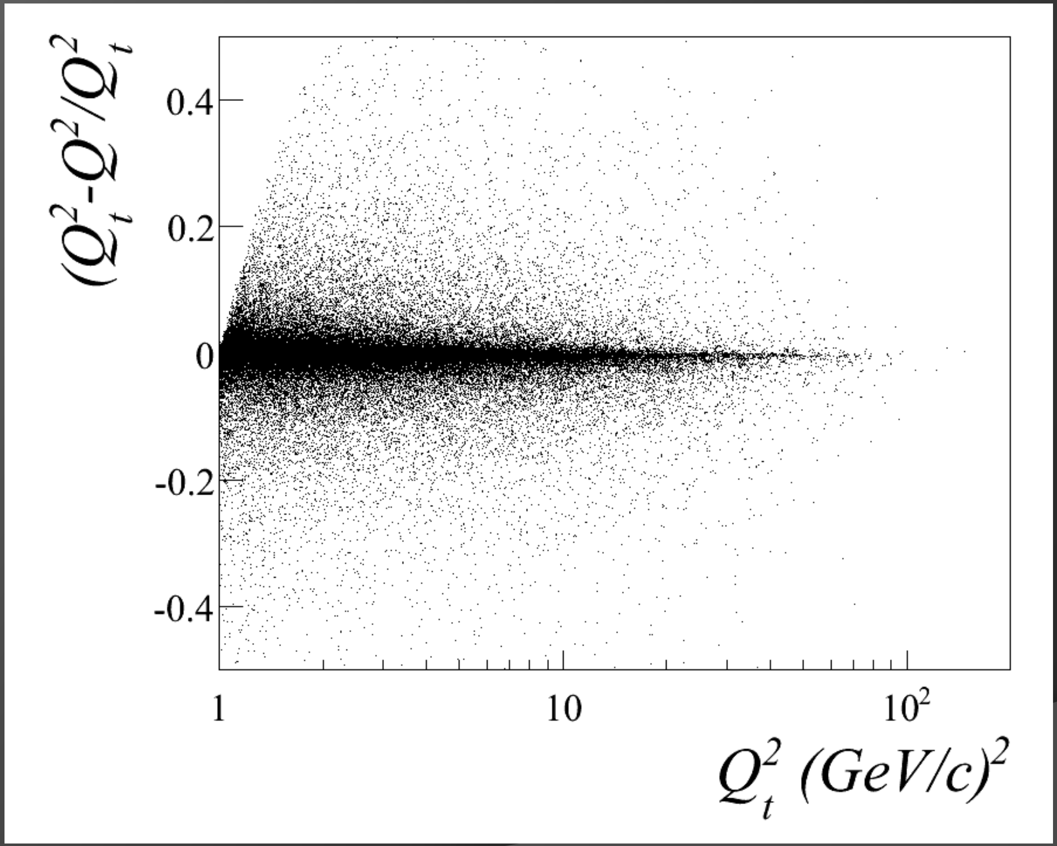
Bjorken-x



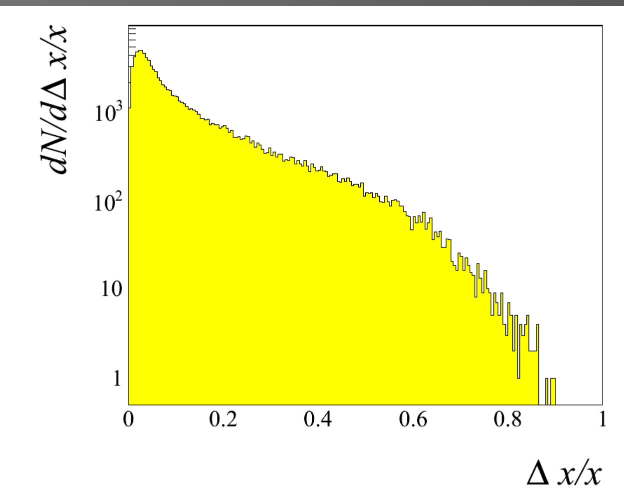
y

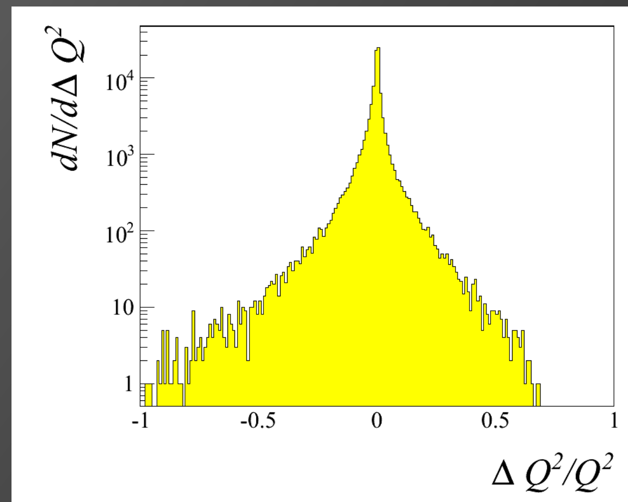


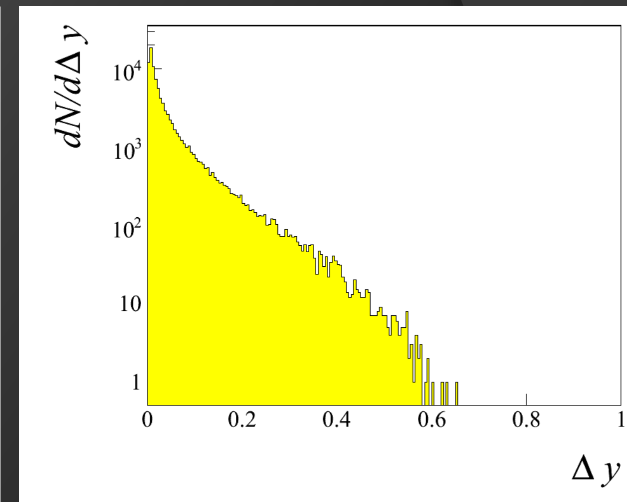
Q^2



Projections:







HAPRAD for COMPASS:
Muons at 160 GeV, sample kinematics

$\sigma_{exp}/\sigma_{Born}$ for E=160GeV, x_{Bj}=0.01 GeV, y=0.2, z=0.4

$p_{T,}$ GeV/c	1.0	1.5	2.0
$\sigma_{exp}/\sigma_{Born}$	+0.4%(muons) -8%(electrons)	+0.7%(muons) -6.8%(electrons)	+0.8%(muons) -6.8%(electrons)

Use power-like p_T-dependence. Choice of p_T-dependence may affect the calculated value of rad.correction

Rad Corrections for COMPASS (HAPRAD)

Xbj bins:	<Xbj>	<Q2>	<Y>	<Z>	<PT>	RC=exp/Born
0.003 – 0.008	0.006375	1.262	0.6718	0.3511	0.4647	1.020
0.008 – 0.013	0.01052	1.529	0.492	0.3506	0.4647	1.014
0.013 – 0.02	0.01628	1.822	0.3774	0.3509	0.4611	1.007
0.02 – 0.032	0.02509	2.614	0.3493	0.3485	0.4598	1.005
0.032 – 0.05	0.03974	4.195	0.3536	0.3449	0.4613	1.005
0.05 – 0.08	0.06284	6.528	0.3485	0.3426	0.461	1.004
0.08 – 0.13	0.09782	11.23	0.3804	0.3387	0.4667	1.007

Z bins:	<Xbj>	<Q2>	<Y>	<Z>	<PT>	
0.2 – 0.25	0.02644	3.032	0.4247	0.2234	0.4334	1.013
0.25 – 0.3	0.0266	3.016	0.4212	0.2735	0.4509	1.010
0.3 – 0.34	0.0266	2.999	0.4194	0.319	0.4642	1.009
0.34 – 0.38	0.02659	2.982	0.4182	0.3591	0.4739	1.007
0.38 – 0.42	0.02653	2.967	0.4169	0.3992	0.4817	1.005
0.42 – 0.49	0.02624	2.921	0.416	0.4525	0.4924	1.003
0.49 – 0.63	0.02557	2.834	0.4152	0.5511	0.502	0.999
0.63 – 0.85	0.0242	2.638	0.4111	0.7223	0.4912	0.988

PT bins:	<Xbj>	<Q2>	<Y>	<Z>	<PT>	
0.1 – 0.2	0.02654	2.94	0.415	0.3344	0.1547	0.999
0.2 – 0.27	0.02629	2.912	0.4147	0.3363	0.2362	1.002
0.27 – 0.33	0.02602	2.891	0.4156	0.3387	0.3004	1.003
0.33 – 0.39	0.026	2.897	0.4163	0.3409	0.3599	1.004
0.39 – 0.46	0.02623	2.931	0.4166	0.3428	0.4245	1.006
0.46 – 0.55	0.02637	2.966	0.4182	0.3459	0.5036	1.008
0.55 – 0.64	0.02644	3.005	0.421	0.3522	0.5931	1.011
0.64 – 0.77	0.02637	3.038	0.4259	0.3633	0.7003	1.014
0.77 – 1	0.0262	3.104	0.4361	0.3818	0.868	1.018

NB: rad-correction depends on z and p_T

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Conclusions

- We are studying smearing effects from RC events in COMPASS by using RADGEN.
- Presently effects are small (i.e. smaller than the systematic errors our present measurements).
- Something is nevertheless missing: only the inclusive cross-sections are integrated in RADGEN. Not SIDIS
- We would also need to take into account the experimentally detected final state, i.e. the detected invariant mass of the $\gamma^* N$ system, in or we will overestimate σ_{in}.

END