Studies of π^0 multiplicities in SIDIS with CLAS12

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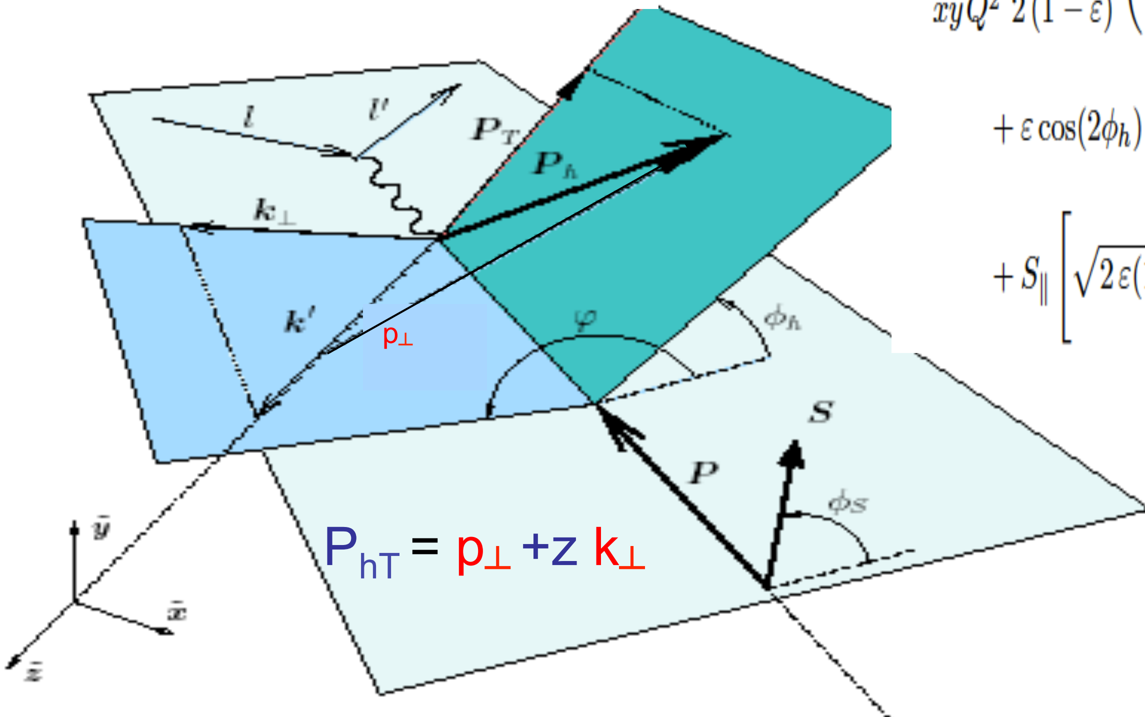
- Introduction
- MC-generators
- Advantages of π^0 SIDIS
- Comparing SIDIS generated (PEPSI) with data
- π^0 PID, Efficiencies and background
- Summary

SIDIS Kinematics

$$\ell(l) + N(P) \to \ell(l') + h(P_h) + X$$

$$x = \frac{Q^2}{2\,P\cdot q}, \quad y = \frac{P\cdot q}{P\cdot l}, \quad z = \frac{P\cdot P_h}{P\cdot q},$$



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$
$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\left\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}\right.$$
$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$
$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$

$$F_{UU,T}(x,z,P_{hT}^2,Q^2) = \sum_a \mathcal{H}^a_{UU,T}(Q^2;\mu^2)\int dk_\perp\,dP_\perp\,f_1^a(x,k_\perp^2;\mu^2)\,D_1^{a\to h}(z,P_\perp^2;\mu^2)\,\delta(zk_\perp - P_{hT} + P_\perp)$$

Multiplicities in SIDIS

$$m_N^h(x,z,P_{hT}^2,Q^2) = \frac{d\sigma_N^h/dx\,dz\,dP_{hT}^2\,dQ^2}{d\sigma_{\mathrm{DIS}}/dx\,dQ^2}$$

$$\frac{d\sigma}{dx\,dQ^2\,d\psi} = \boxed{\frac{2\alpha^2}{xQ^4}\,\frac{y^2}{2\,(1-\varepsilon)}}\left\{F_{UU,T}(x,Q^2) + \varepsilon F_{UU,L}(x,Q^2)\right\}.$$

DIS

$$F_{UU,T}(x,Q^2) = F_T(x,Q^2) = 2xF_1(x,Q^2) = \sum_h \int z\,dz F_{UU,T}(x,z,Q^2)$$

Kinamtical factors cancel leaving the ratio of structure functions:

$$\frac{d\sigma}{dx\,dQ^2\,d\psi\,dz\,d\phi_h\,d|\boldsymbol{P}_{h\perp}|^2} = \boxed{\frac{\alpha^2}{xQ^4}\,\frac{y^2}{2\,(1-\varepsilon)}}\left(1+\frac{\gamma^2}{2x}\right)\left\{F_{UU,T} + \varepsilon F_{UU,L}\right\}.$$

SIDIS

$$F_{UU,T}(x,z,Q^2) = \int d^2\vec{P}_{h,\perp} F_{UU,T}(x,z,P_{h,\perp}^2,Q^2)$$

$$\boxed{m_N^h(x,z,P_{hT}^2,Q^2) = \frac{\pi F_{UU,T}(x,z,P_{hT}^2,Q^2) + \pi\,\varepsilon F_{UU,L}(x,z,P_{hT}^2,Q^2)}{F_T(x,Q^2) + \varepsilon F_L(x,Q^2)}}$$

Multiplicities in SIDIS

For simple Gaussian distributions in k_T and p_T

$$m_N^h(x,z,\boldsymbol{P}_{hT}^2) = \frac{\pi}{\sum_a e_a^2\, f_1^a(x)} \times \sum_a e_a^2\, f_1^a(x)\, D_1^{a\to h}(z)\, \frac{e^{-\boldsymbol{P}_{hT}^2/\left(z^2\langle \boldsymbol{k}_{\perp,a}^2\rangle + \langle \boldsymbol{P}_{\perp,a\to h}^2\rangle\right)}}{\pi\left(z^2\langle \boldsymbol{k}_{\perp,a}^2\rangle + \langle \boldsymbol{P}_{\perp,a\to h}^2\rangle\right)}$$

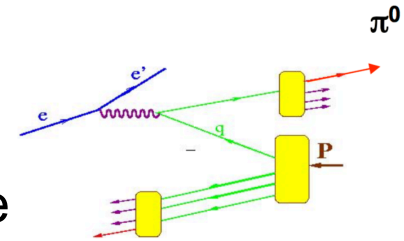
For p0 at large x, when sea contribution can be neglected the ratio e'π^0X/ e'X should follow z-dependence of the fragmentation function (after integration over P_T)

$$\sigma_p^{eX} \propto 4u + d + \ldots$$

$$\sigma_p^{\pi^0} \propto 4uD^{u\to\pi^0} + dD^{d\to\pi^0} + \ldots$$

$$D^{u\to\pi^0} \approx D^{d\to\pi^0}$$

$\pi0$ SIDIS: advantages-I



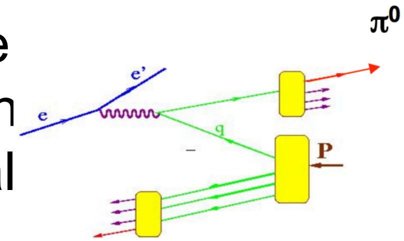
1) suppression of higher-twist contributions at large hadron energy fraction (particularly important at JLab energies where small z events are contaminated by target fragmentation)

2) the absence of $\rho0$ production which complicates the interpretation of the charged single-pion data

3) the fragmentation functions for u and d quarks to $\pi0$ are the same in first approximation

4) suppression of spin-dependent fragmentation for $\pi0$ s, due to the roughly equal magnitude and opposite sign of the Collins fragmentation functions for up and down

$\pi 0$ SIDIS: advantages-II



5) longitudinal photon contribution, is suppressed in exclusive neutral pions production with respect to the transverse photon contribution, which is higher twist, suggesting that longitudinal photon contribution to SIDIS $\pi 0$ will also be suppressed.

6) at large x , where the sea contribution is negligible, $\pi 0$ multiplicities and double spin asymmetries will provide direct info on the fragmentation function of u and d -quarks to p$\pi 0$.

7) $\pi 0$ data has better uniformity and smaller variations of averages of $\mathbf{P}_T$ with $\mathbf{x}$ due to correlations between longitudinal and transverse momentum of quarks and hadrons

8) Particle ID (invariant mass of 2 photons) very different from charged pions

Generators for MC simulations

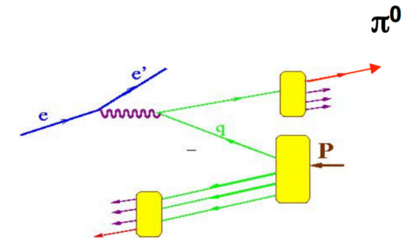
- Full event generators (PYTHIA, PEPSI, LEPTO)
- Dedicated event generators (e' hX,e' hhx,…)

Types of event generators:

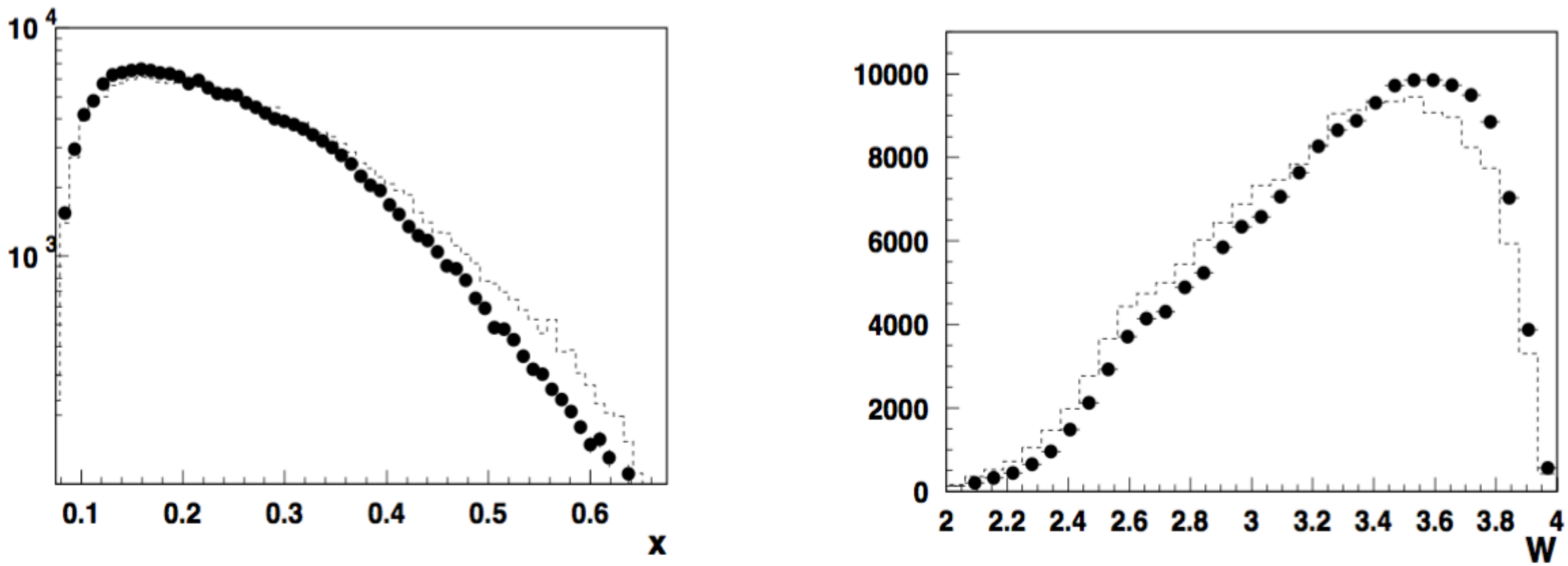
1) Providing events with cross section
    1) pros: easier defined systematics, can be directly compared with data
    2) cons: require huge statistics to provide acceptance functions for kinematic edges with reasonable error bars.
2) Phase space with realistic x-sections provided as weight factors.
    1) pros: acceptance for all acceptable kinematics can be provided with small error bars, much faster, easy to incorporate different models
    2) cons: more efforts to define systematics, need weighting

Candidate for first SIDIS publication: ep → e’ π^0X

e’π^0X/ e'X ratio (ratio of semi-inclusive π^0 to inclusive electron): need good control over acceptance for neutrals, radiative corrections

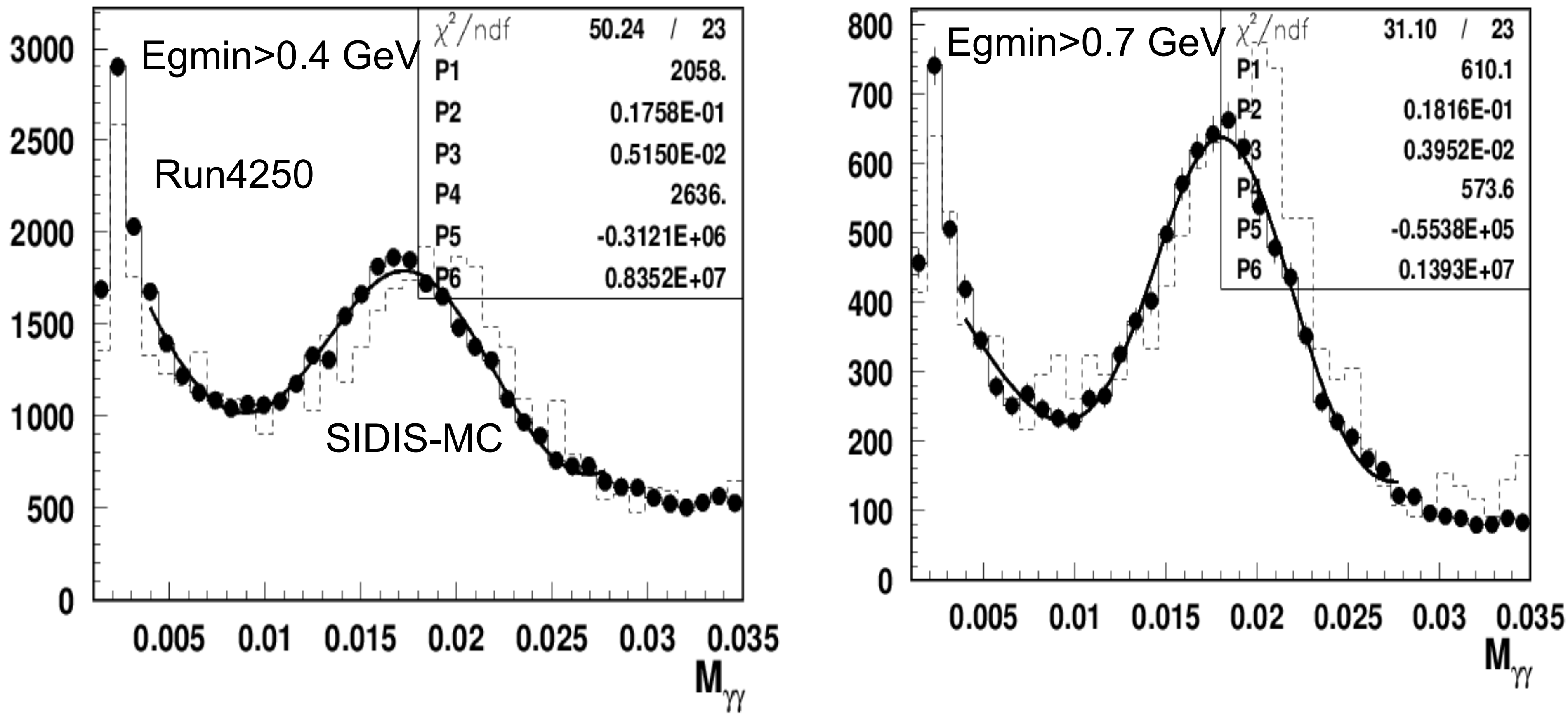


CLAS12: SIDIS-MC vs Data (200 files ~10% of 1 run)



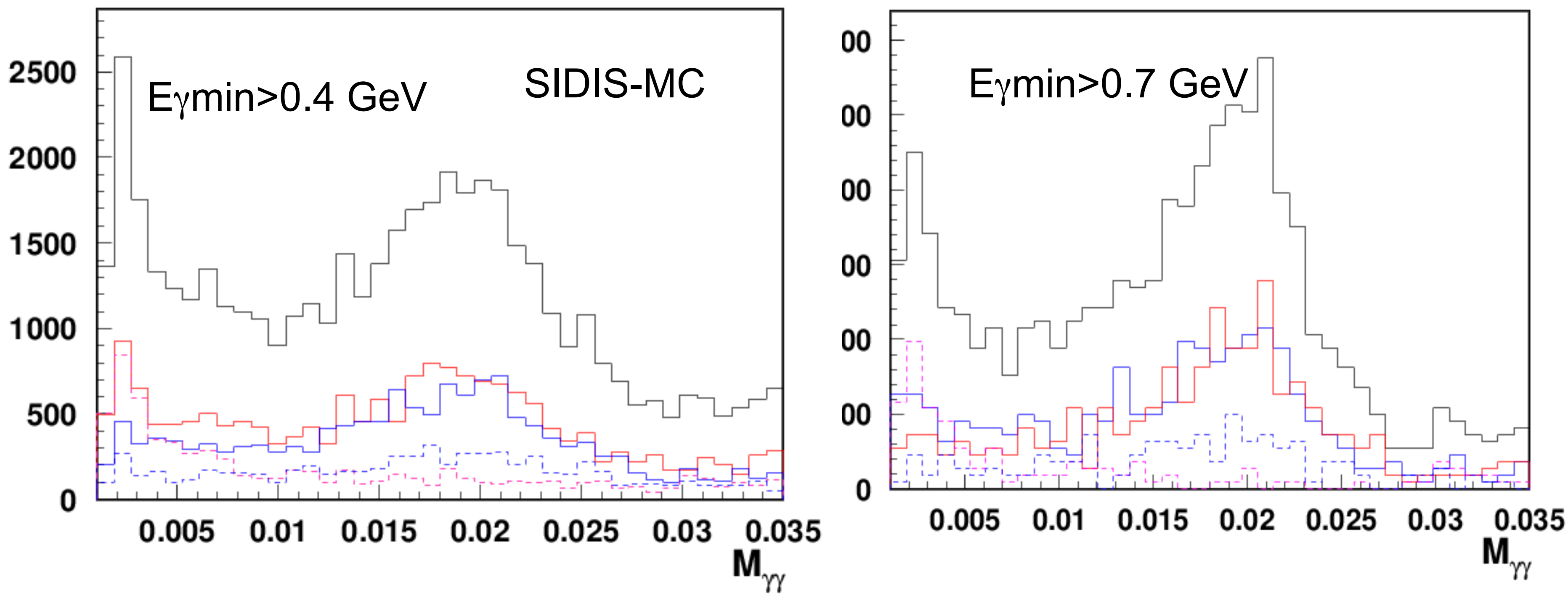
In a wide kinematical range (θ_e>12) scattered lepton distributions are consistent with SIDIS-MC (Lund)

Identification of pi0



- Higher the minimum energy cut, less background
- Background well described in the SIDIS MC

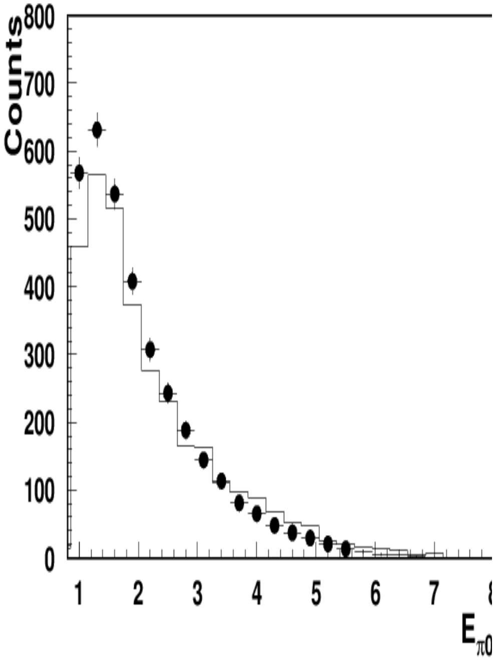
Understanding the background under π0 mass



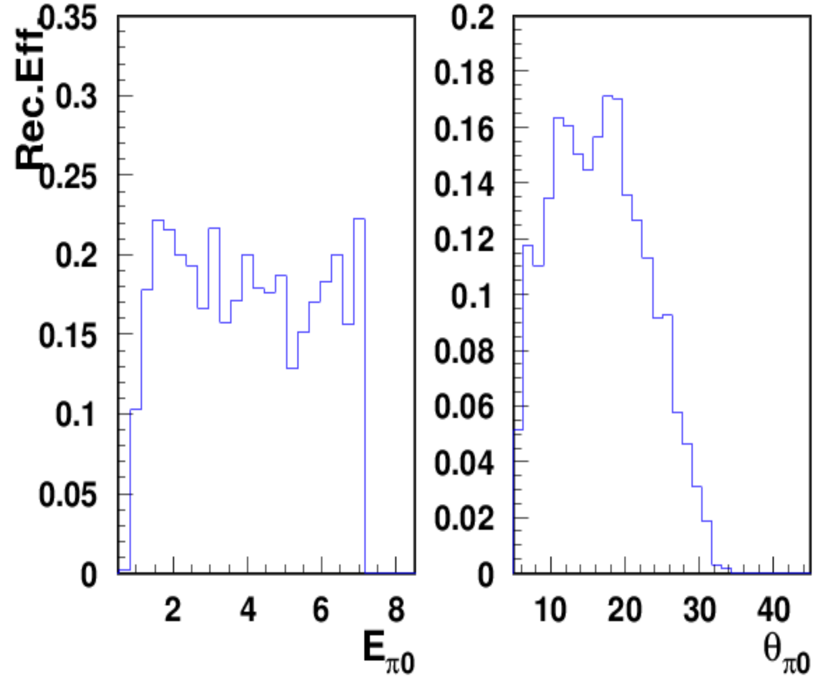
- The peak (and surrounding) are dominated by single and 2 pi0 events (red and blue) both for 0.4 GeV and 0.7 GeV min. energy cuts (may be more enhanced after better fid. cuts)
- Small fraction of events comes from radiative gammas (dashed red) and multi-photon events (dashed blue)

Kinematical distributions

Egmin>0.4 GeV



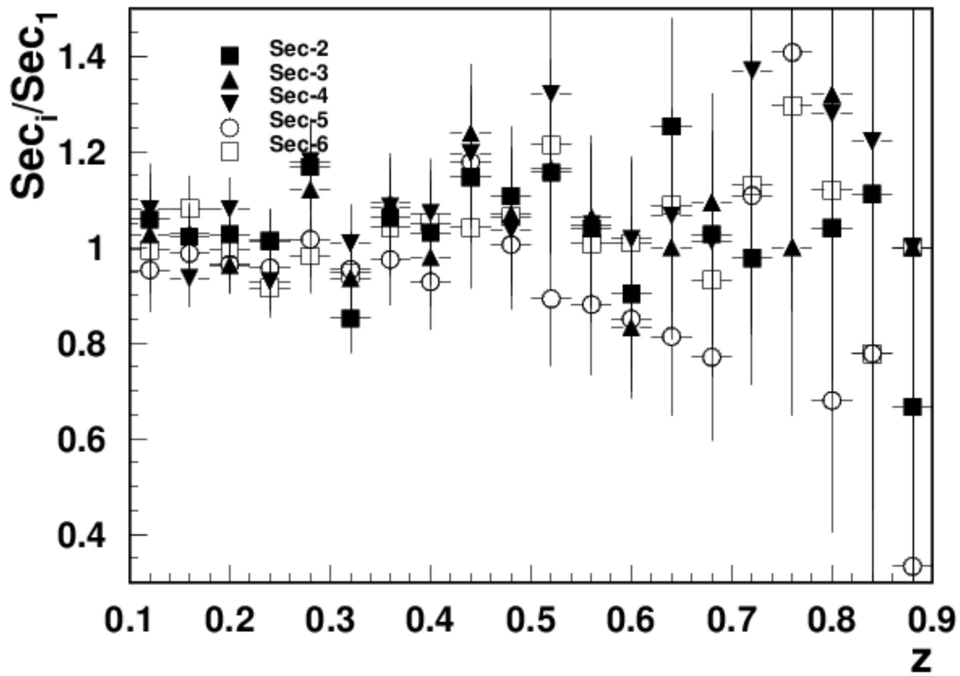
Reconstruction Efficiency fro clasDIS MC



- Kinemtical distributions well described in the SIDIS MC
- Rec efficiency of pi0s with Eg>0.4 is ~15% at small angles

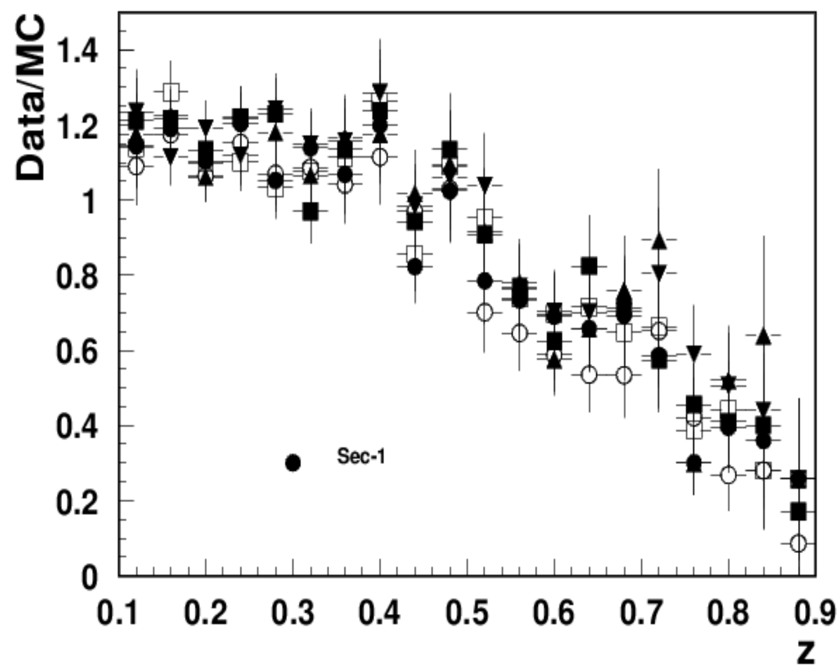
Understanding the background under π0 mass

Egmin>0.4 GeV



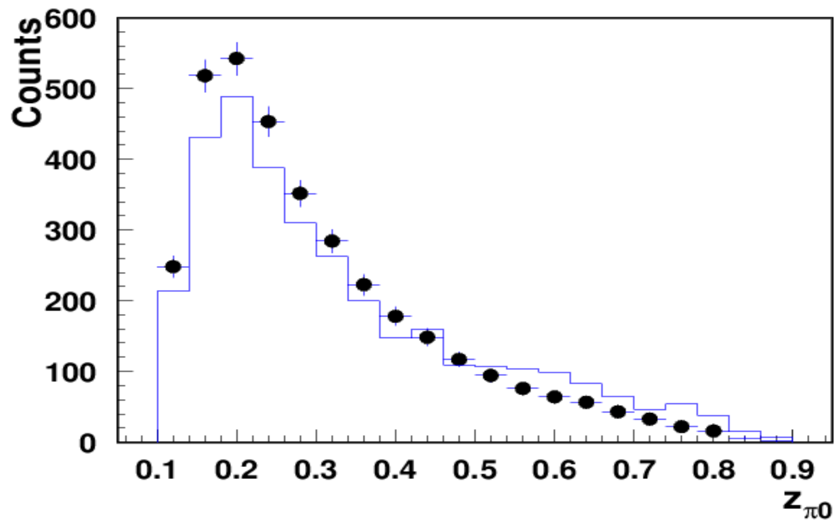
Sector dependence from Run 4205

Ratio of data to clasDIS MC

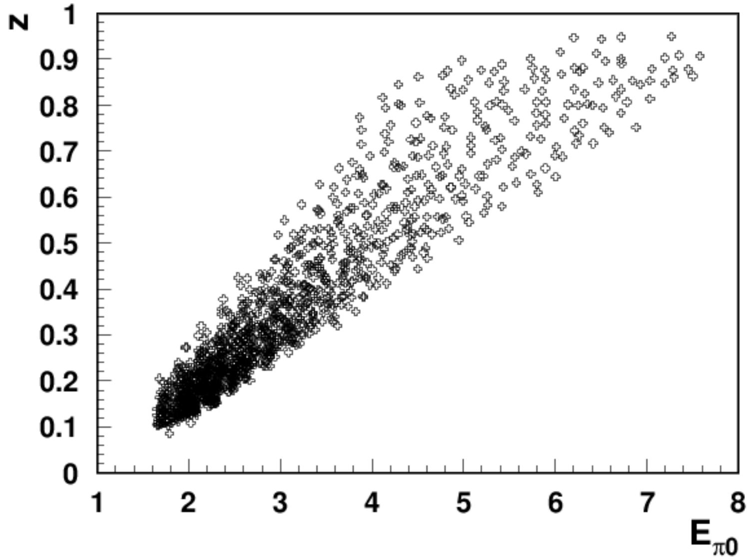


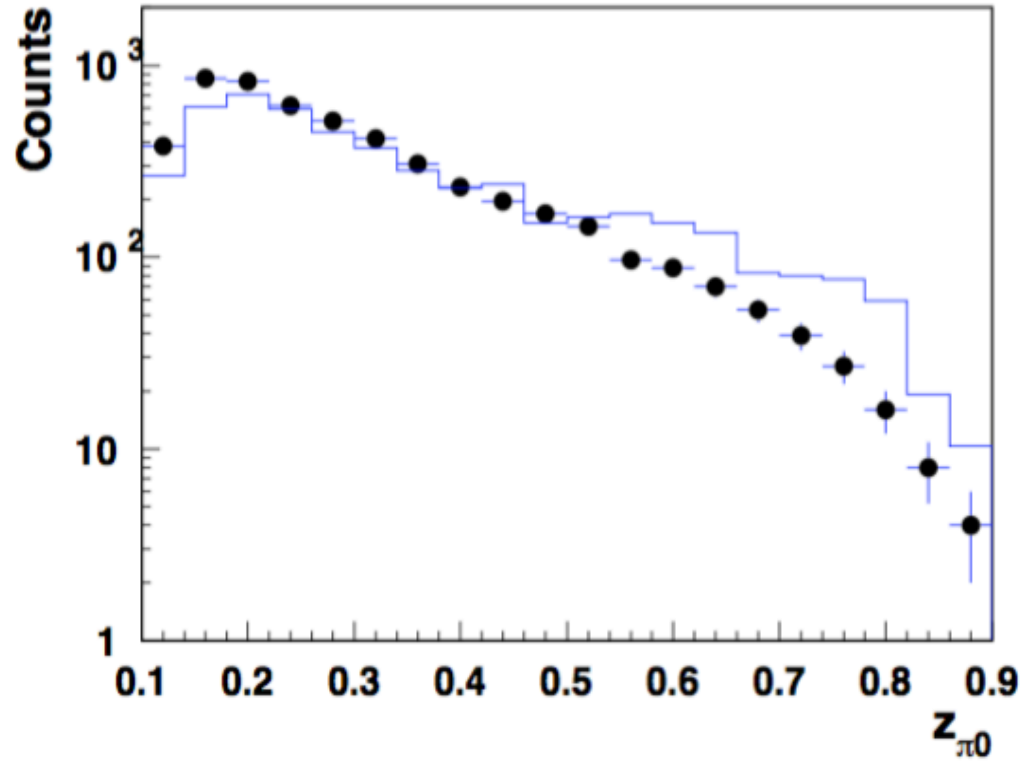
- Sectors agree within error bars
- More π^0s in MC at higher energy due to excess of exclusive events in MC

e’ π^0X: clas12 vs SIDIS-MC



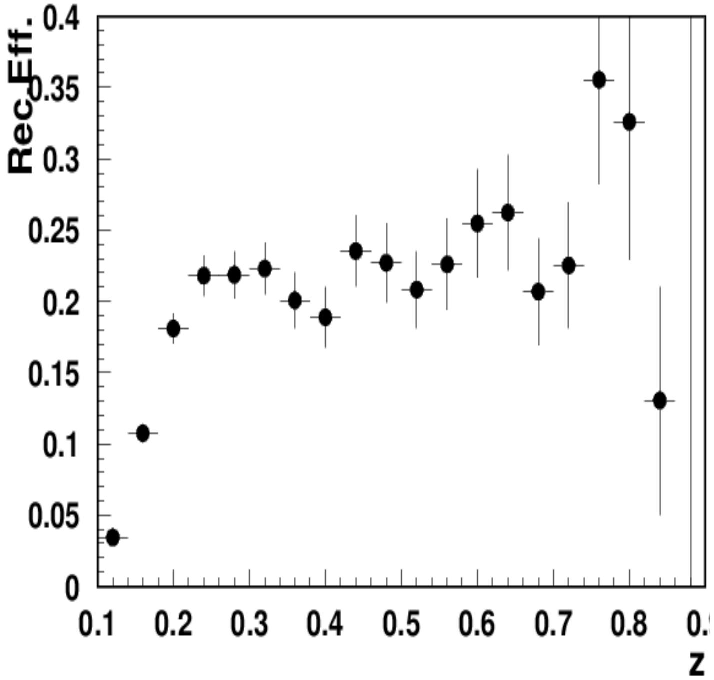
2<E_e<6 GeV



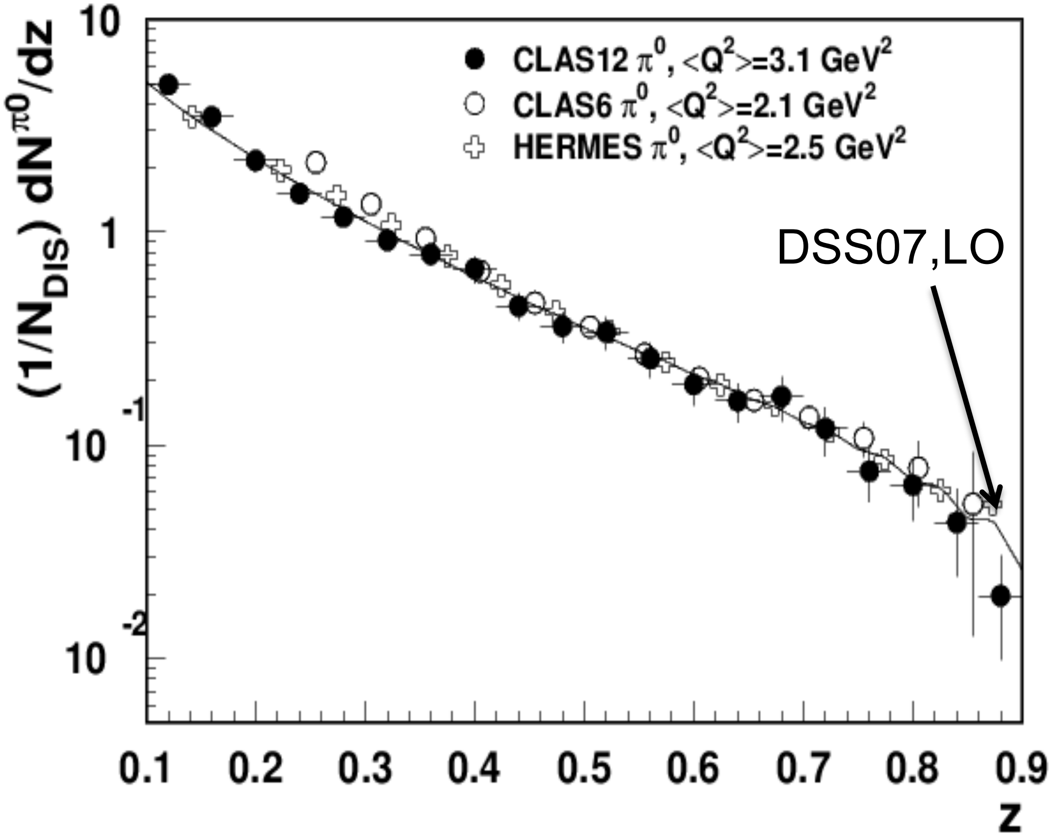


clas12 vs clasDIS LUND generator
1) Distributions of SIDIS pi0s are reasonable
2) Need to improve fiducial cuts and correct for radiative effects.

clas12: e’ π^0X multiplicity



Efficiency fairly constant at z>0.25



- Ratio <u>e’π^0X/ e'X</u> follows z-dependence of the fragmentation function
- Multiplicity consistent with HERMES,clas6,LO FFs
- Improve the fiducial cuts and estimate systematics due to various cuts

Summary

- Ratio $e'\pi^0X/ e'X$ provides direct info on the z,P_T-dependence of the fragmentation function
- Two different version of MC developed for comparison with data
- There is a good agreement of MC with π^0-distributions from data in certain kinematics for electrons (theta>12 degree)
- First preliminary π^0 multiplicity extracted from 0.5% data is consistent with LO FF calculations
- Development of the analysis procedure in progress

- Collaboration with theorists in Jlab (A. Signori, N. Sato) aiming at extraction of underlying multidimensional (z,P_T) fragmentation functions from measured multiplicities for pions

Support slides…

Generating SIDIS

Full event generator (PEPSI)

N_{tracks} A N l-pol N-pol l-ID E_{beam} T T-ID process-ID x-section

13	1	1	0.0	1.0	11	10.600	2212	1	0.8052759E+05				
1	-1.	21	11	0	0	0.0000	0.0000	10.6000	10.6000	0.0005	0.0000	0.0000	0.0000
2	1.	21	2212	0	0	0.0000	0.0000	0.0000	0.9383	0.9383	0.0000	0.0000	0.0000
3	0.	21	22	1	0	-0.9974	-0.7292	3.5178	3.4109	-1.5059	0.0000	0.0000	0.0000
4	-1.	1	11	1	0	0.9974	0.7292	7.0822	7.1891	0.0005	0.0000	0.0000	0.0000
5	1.	13	2	0	6	-1.0092	-0.9040	3.2382	3.5102	0.0056	0.0000	0.0000	0.0000
6	0.	13	2103	2	0	0.0117	0.1747	0.2796	0.8389	0.7713	0.0000	0.0000	0.0000
7	1.	12	2	5	9	-1.0092	-0.9040	3.2382	3.5102	0.0056	0.0000	0.0000	0.0000
8	0.	11	2103	6	9	0.0117	0.1747	0.2796	0.8389	0.7713	0.0000	0.0000	0.0000
9	0.	11	92	7	10	-0.9974	-0.7292	3.5178	4.3492	2.2391	0.0000	0.0000	0.0000
10	2.	11	2224	9	12	-0.7729	-1.0806	3.4710	3.9069	1.2047	0.0000	0.0000	0.0000
11	-1.	1	-211	9	0	-0.2245	0.3514	0.0468	0.4422	0.1396	0.0000	0.0000	0.0000
12	1.	1	2212	10	0	-0.5843	-0.9049	2.3668	2.7645	0.9383	0.0000	0.0000	0.0000
13	1.	1	211	10	0	-0.1886	-0.1757	1.1042	1.1425	0.1396	0.0000	0.0000	0.0000

0 (twist-4)

$$\boxed{\frac{d\sigma}{dx\,dQ^2\,d\psi\,dz\,d\phi_h\,d|\boldsymbol{P}_{h\perp}|^2} = \frac{\alpha^2}{xQ^4}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\left\{F_{UU,T} + \varepsilon\,\cancel{F_{UU,L}}\right\}.}$$

Generating SIDIS with dedicated e'piX-generator

Dedicated SIDIS generator

```
         2     1     1  1.0  1.0   11    10.600 2212     1 0.1108596E-01
   1 -1.   1    11  0  0  -0.7583  -0.7440   3.9571   4.0972   0.0005    -0.0174   0.0305   1.3425
   2  1.   1   211  0  0   0.8698  -0.6332   3.2529   3.4291   0.1396    -0.0174   0.0305   1.3425
         2     1     1  1.0  1.0   11    10.600 2212     1 0.4220764E-02
   1 -1.   1    11  0  0  -1.1716   0.9665   3.2259   3.5656   0.0005     0.0016  -0.0436  -1.5889
   2  1.   1   211  0  0   0.1630  -0.4267   3.5986   3.6302   0.1396     0.0016  -0.0436  -1.5889
```

COATJAVA   4a.8.4

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    {"name":"atarget",  "id":2,  "type":"int16", "info":"Mass number of the target"},
    {"name":"ztarget",  "id":3,  "type":"int16", "info":"Atomic number oif the target"},
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    {"name":"pbeam",    "id":5,  "type":"float", "info":"Beam polarization"},
    {"name":"btype",    "id":6,  "type":"int16", "info":"Beam type, electron=11, photon=22"},
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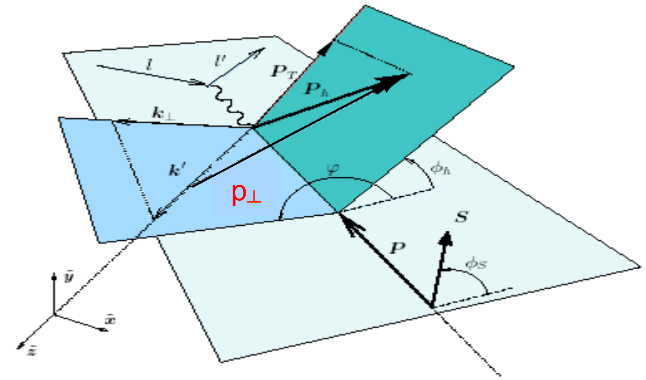
    {"name":"weight",   "id":10, "type":"float", "info":"Event weight"}
]
```

GEMC

LUND Header	
column	quantity
1	**Number of particles**
2	Number of target nucleons
3	Number of target protons
4	Target Polarization
5	**Beam Polarization**
6	beam PID (electron=11, photon=22)
7	beam energy
8	target nucleon ID
9	process ID
10	event weight/cross section

LUND Particles	
column	quantity
1	index
2	lifetime
3	**type (1 is active)**
4	**particle ID**
5	parent index
6	index of the first daughter
7	**momentum x [GeV]**
8	**momentum y [GeV]**
9	**momentum z [GeV]**
10	E
11	mass
12	**vertex x [cm]**
13	**vertex y [cm]**
14	**vertex z [cm]**

Reproduce SIDIS output with MC



SIDIS MC in 7D (10D)

$$\frac{d\sigma_{\lambda\Lambda}^{eN\rightarrow e'hX}}{dx\,dQ^2\,dz\,dP_{hT}^2\,d\phi_h\,d\phi_l\,d\phi_s} = \sum_{l=1}^{L} SF_l$$

Theory

Provide an input set of SF_l

For a given model/theory based on underlying non-perturbative input calculate SF_l

step-1 $x_i, Q_i^2 z_i P_{hT}^{i2} \phi_h^i \phi_l^i \phi_s^i$

step-2 (for a given E_{beam},λ,Λ) P_i^{el}, P_i^h

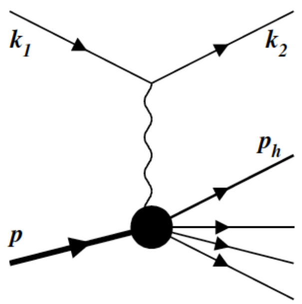
step-3 (detected for a given Detector configuration)

$$x_j, Q_j^2 z_j P_{hT,j}^2 \phi_h^j \phi_l^j \phi_s^j$$

Output counts for a given energy and detector setup

Radiative SIDIS

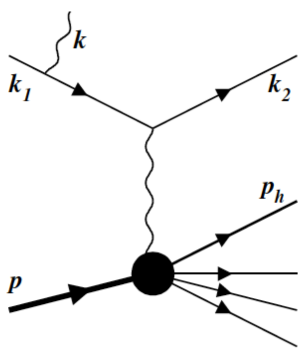
Akushevich&Ilyichev in progress



$$e(k_1,\xi)+n(p,\eta)\longrightarrow e(k_2)+h(p_h)+x(p_x)$$

$$\frac{d\sigma^B}{dx\,dy\,dz\,dp_t^2\,d\phi_h\,d\phi}$$

$$\boxed{d\sigma^B=\frac{\alpha^2}{\sqrt{\lambda_S}Q^4}W_{\mu\nu}L^{\mu\nu}\frac{d^3k_2}{k_{20}}\frac{d^3p_h}{p_{h0}}}$$



$$e(k_1,\xi)+n(p,\eta)\to e(k_2)+h(p_h)+x(\tilde{p}_x)+\gamma(k)$$

$$\boxed{d\sigma_R=\frac{\alpha^3}{4\pi^2\tilde{Q}^4\sqrt{\lambda_S}}W^{\mu\nu}(q-k,p,p_h)L^R_{\mu\nu}\frac{d^3k}{k_0}\frac{d^3k_2}{k_{20}}\frac{d^3p_h}{p_{h0}}}$$

+.....

additional photon can be described by three additional variables:

$$R=2kp,\quad \tau=\frac{kq}{kp},\quad \phi_k$$

$$S_x=2p(k_1-k_2)$$

$$\lambda_Y=S_x^2-4M^2Q^2$$

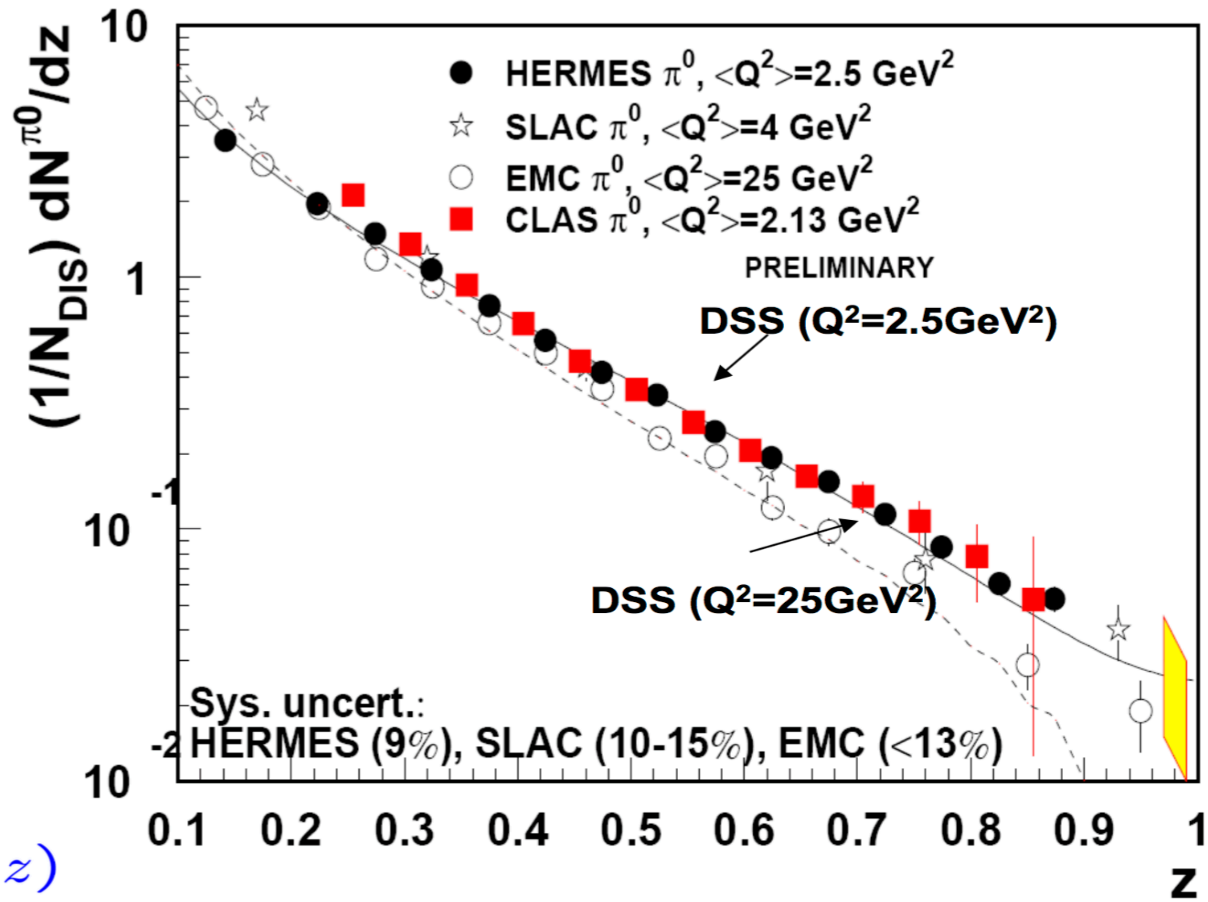
The phase space of the real photon: $$\frac{d^3k}{k_0}=\frac{R\,dR\,d\tau\,d\phi_k}{2\sqrt{\lambda_Y}}.$$

ϕ_k is an angle between $(\mathbf{k}_1,\mathbf{k}_2)$ and $(\mathbf{k},\mathbf{q})$ planes.

$$e(k_1,\xi)+n(p,\eta)\to e(k_2)+h(p_h)+u(p_u)+\gamma(k),$$

$$\delta^4(k_1+p-k_2-p_h-p_u-k)$$

π^0-Multiplicities in SIDIS: clas6



pi0-multiplicities consistent in a wide range of beam energies, indicating pi0 production is not sensitive to higher twist effects

CLAS12-MC vs theory: defining variables

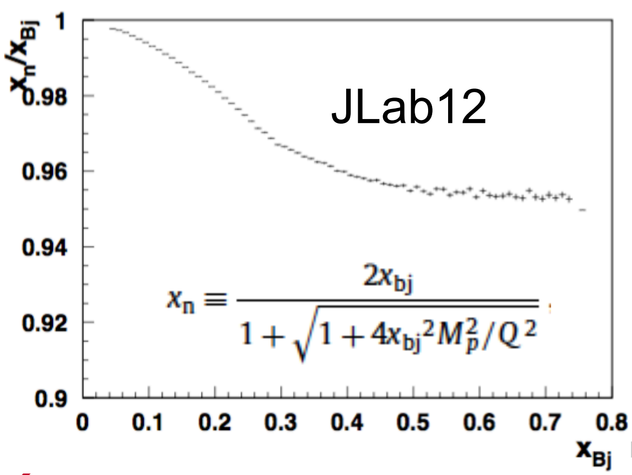
Boglione et al. $M_{hT} \equiv \sqrt{P_{hT}^2 + M_h^2}$

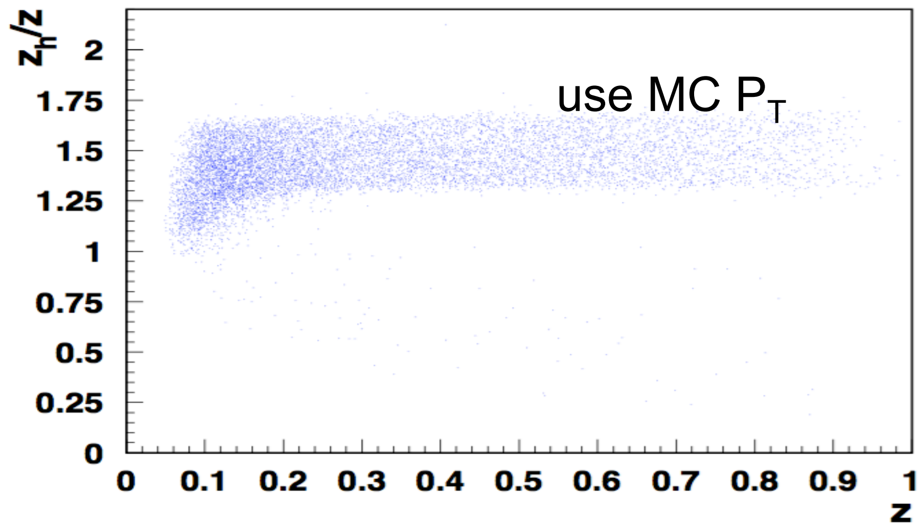
$$z_h = \frac{M_{hT}}{Q}\left(1 - x_n{}^2\frac{M_p^2}{Q^2}\right)^{-1}\left(e^{-y_h} + x_n{}^2\frac{M_p^2}{Q^2}e^{y_h}\right)$$

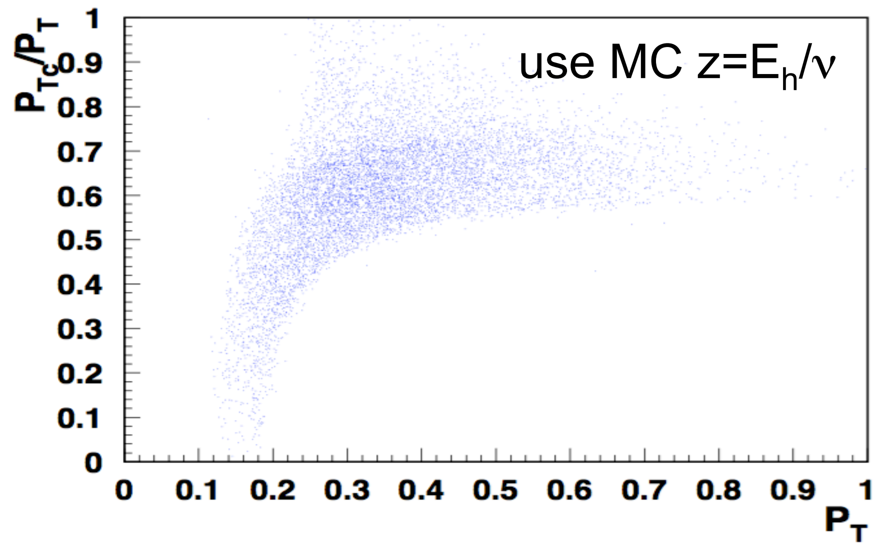
$$P_{Tc} = Q\sqrt{\frac{z_h{}^2 e^{2y_h}\left(1 - x_n{}^2 M_p^2/Q^2\right)^2}{\left(1 + e^{2y_h} x_n{}^2 M_p^2/Q^2\right)^2} - \frac{M_h^2}{Q^2}}$$

$$z = (P_h P)/(qP) = E_h/\nu$$

$$x = Q^2/2(qP)$$







Consistency check for z and P_T

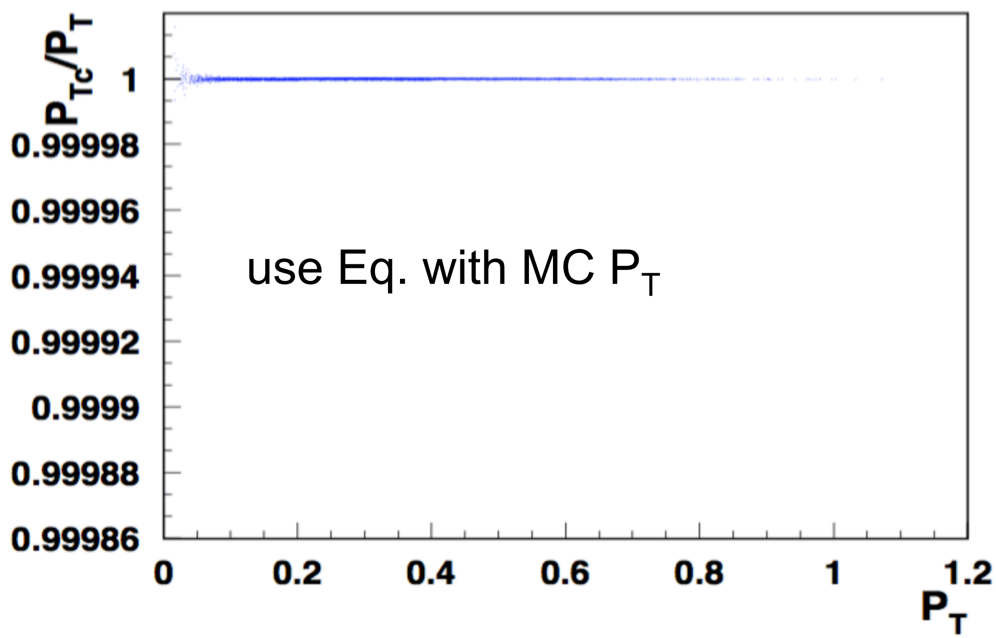
Boglione et al. $M_{hT} \equiv \sqrt{P_{hT}^2 + M_h^2}$

$$z_h = \frac{M_{hT}}{Q}\left(1 - x_n{}^2\frac{M_p^2}{Q^2}\right)^{-1}\left(e^{-y_h} + x_n{}^2\frac{M_p^2}{Q^2}e^{y_h}\right)$$

$$P_T = Q\sqrt{\frac{z_h{}^2 e^{2y_h}\left(1 - x_n{}^2 M_p^2/Q^2\right)^2}{\left(1 + e^{2y_h} x_n{}^2 M_p^2/Q^2\right)^2} - \frac{M_h^2}{Q^2}}$$

$$x = Q^2/2(qP)$$

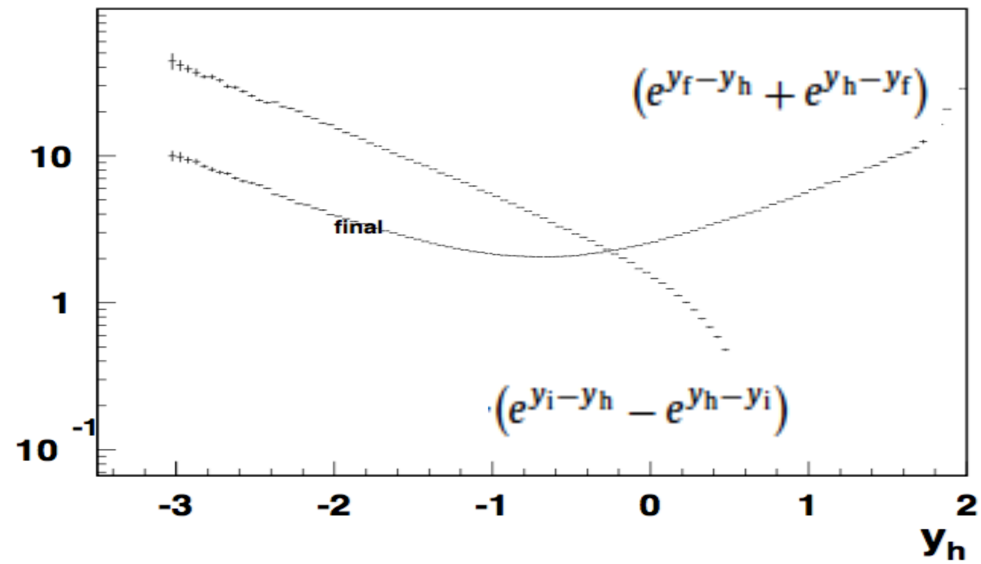
$$z = (P_h P)/(qP) = E_h/\nu$$



$$P_h \cdot k_f = \frac{1}{2} M_{hT} M_{fT} \left(e^{y_f - y_h} + e^{y_h - y_f}\right)$$

and

$$P_h \cdot k_i = \frac{1}{2} M_{hT} M_{iT} \left(e^{y_i - y_h} - e^{y_h - y_i}\right).$$



$$R(y_h, z_h, x_{bj}, Q) \equiv \frac{P_h \cdot k_f}{P_h \cdot k_i},$$

for which we identify

$$R(y_h, z_h, x_{bj}, Q) \ll 1 : \text{ collinear to outgoing quark},$$
$$R(y_h, z_h, x_{bj}, Q)^{-1} \ll 1 : \text{ collinear to incoming quark}.$$