First look at DIS and SIDIS

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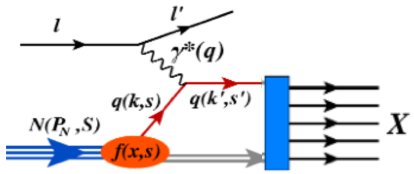
"CLAS collaboration meeting, 8 March 2018"

- DIS and SIDIS
- DIS as monitoring tool
- Compare DIS-MC with data
- SIDIS as monitoring tool
- Pion multiplicities
- Conclusions

DIS and SIDIS at high Q^2

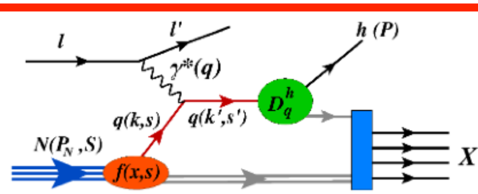
0h DIS



Testing stage:
pQCD predictions, observables in the kinematics where theory predictions are easier to get (higher energies, 1D picture, leading twist, current fragmentation, IMF)

$$\frac{d\sigma}{dx\, dQ^2\, d\psi} = \frac{2\alpha^2}{xQ^4} \frac{y^2}{2\,(1-\varepsilon)} \left\{ 2(1-\varepsilon)xF_1(x,Q^2) + \varepsilon(1+\gamma^2)F_2(x,Q^2) \right\}$$

1h SIDIS/DVMP



Understanding stage:
non-perturbative QCD, strong interactions, fragmentation functions, quark-gluon correlations, orbital motion)

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

Generating DIS and SIDIS

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
```

Dedicated DIS generator (Bosted)

```
        1      1      1  1.0  1.0    11     10.600 2212     1 0.6224668E+00
   1 -1.    1      11  0  0  -0.6109   1.3411    8.1241   8.2567   0.0005     -0.1465   0.0724   -0.0298
```

COATJAVA   4a.8.4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"group": 41,
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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]**

Mapping θ vs E': json file for online monitoring

$$\frac{d\sigma}{d\Omega dE'} = \frac{d\sigma}{d\Omega}^{Mott}\left[\frac{F_2}{\nu} + \frac{F_1}{M}\tan^2(\theta/2)\right] \quad (4.50)$$

Using the Jakobian connecting (dx, dQ^2) with $(d\cos\theta, dE')$ with $J = 2xEE'/\nu$, we get

$$\frac{d\sigma}{dx dQ^2 d\psi} = \frac{d\sigma}{d\Omega}^{Mott}\frac{\nu}{2xEE'}\left[\frac{F_2}{\nu} + \frac{F_1}{M}\tan^2(\theta/2)\right] \quad (4.51)$$

{
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"reference": "N. Sato et al"
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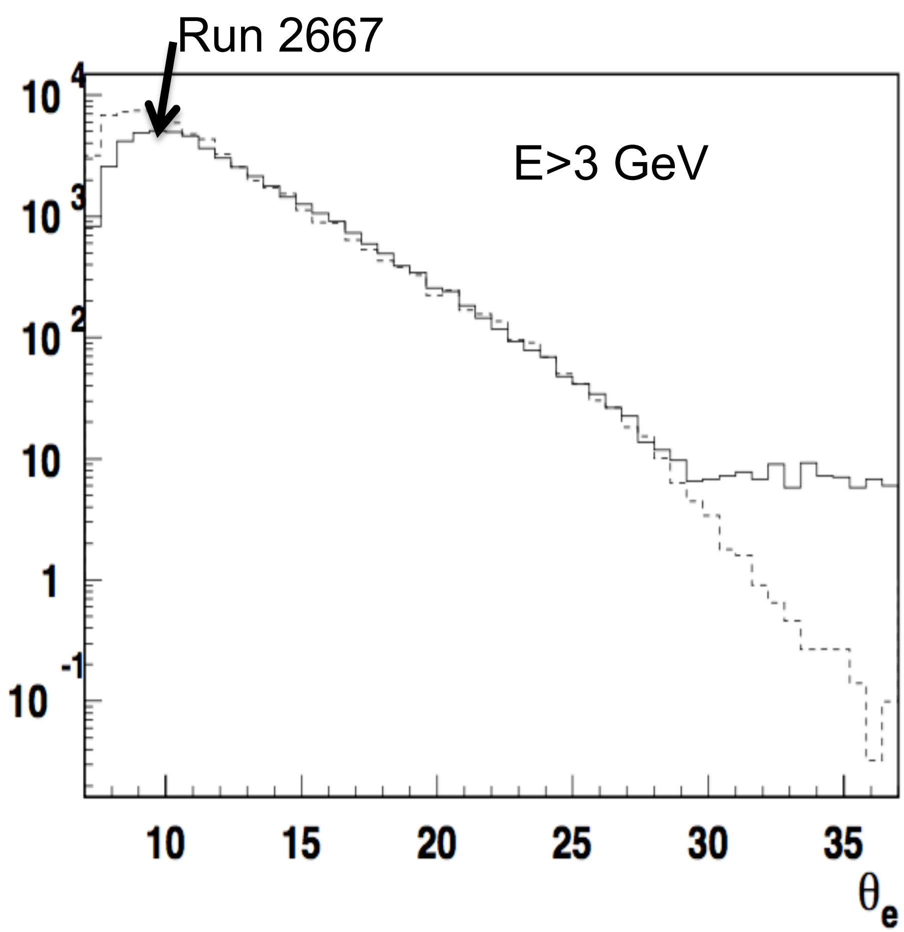
{"bins": 120,"min": 0.0,"max": 360.0,"scale":"lin","description":"$\phi_{e'}$"}
}

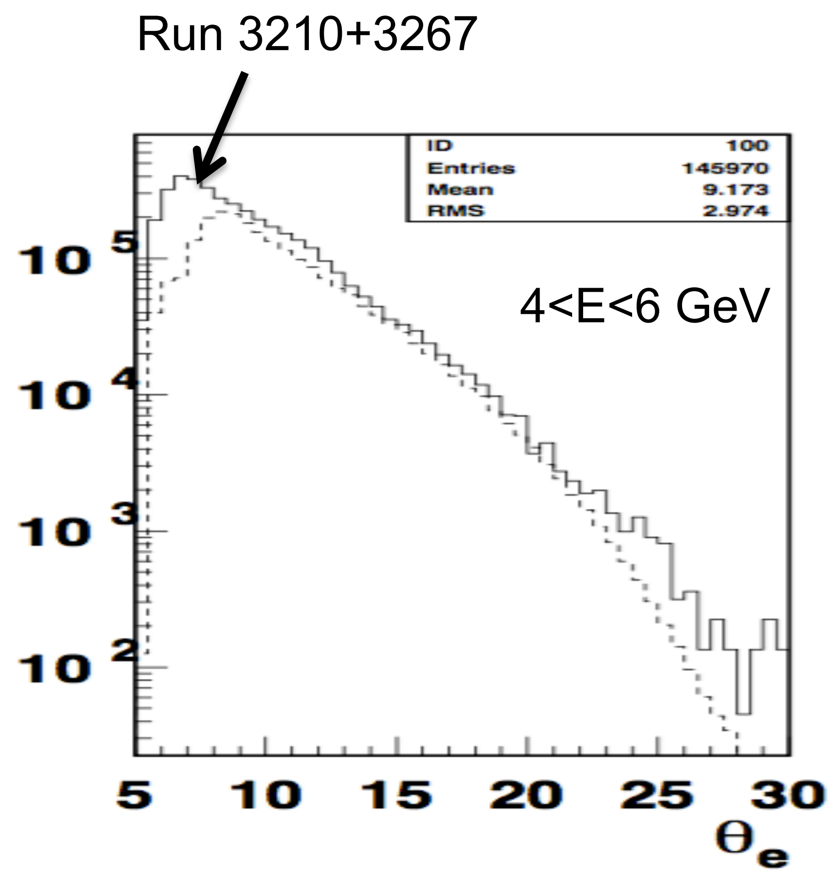
~0.2 GeV bins
~1-degree bins
~3-degree bins

32	1	1	0.13700E+03	0.67000E+02	0.81854E+01	0.4891
32	1	2	0.14000E+03	0.46000E+02	0.67823E+01	0.3286
32	1	21	0.12400E+03	0.58000E+02	0.76158E+01	0.4677
32	1	22	0.10600E+03	0.23000E+02	0.47958E+01	0.2170
32	1	41	0.98000E+02	0.64000E+02	0.80000E+01	0.6531
32	1	42	0.11000E+03	0.45000E+02	0.67082E+01	0.4091
32	1	61	0.11200E+03	0.67000E+02	0.81854E+01	0.5982
32	1	62	0.12300E+03	0.23000E+02	0.47958E+01	0.1870
32	1	81	0.14300E+03	0.69000E+02	0.83066E+01	0.4825
32	1	82	0.12800E+03	0.37000E+02	0.60828E+01	0.2891
32	1	101	0.10600E+03	0.51000E+02	0.71414E+01	0.4811
32	1	102	0.11900E+03	0.26000E+02	0.50990E+01	0.2185
33	1	0	0.47800E+03	0.50000E+01	0.22361E+01	0.0105
33	1	1	0.54700E+03	0.24100E+03	0.15524E+02	0.4406
33	1	2	0.48300E+03	0.12400E+03	0.11136E+02	0.2567

Monitor:
Experimental σ=Exp_counts/acceptance/Gen_counts

Electron distributions: inbending vs outbending



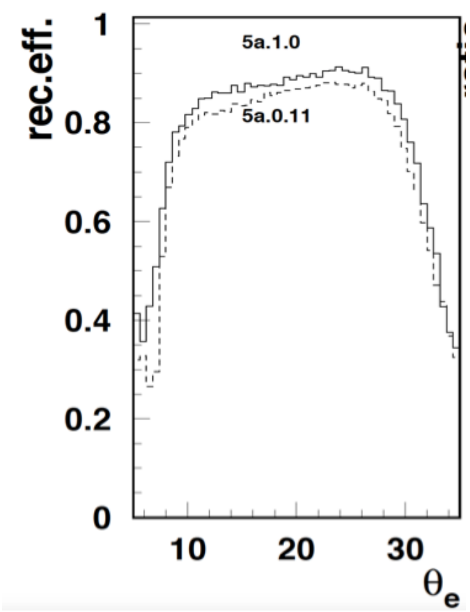


Significantly more electrons at small angles in MC

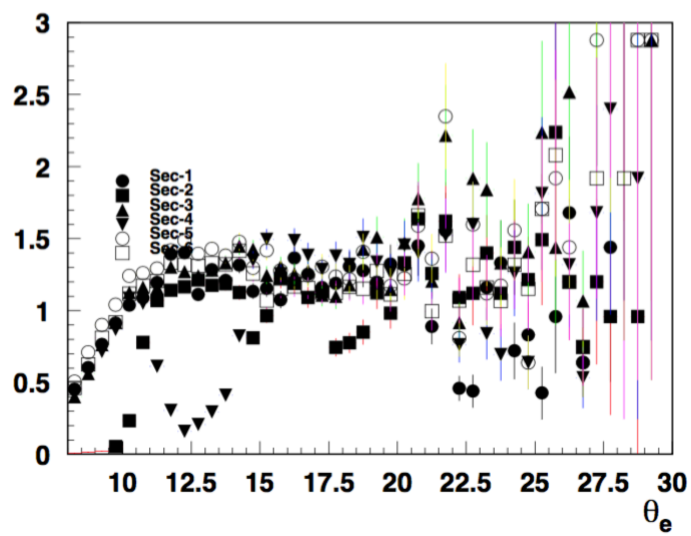
Significantly less electrons at small angles in MC

Comparing old and new runs vs MC

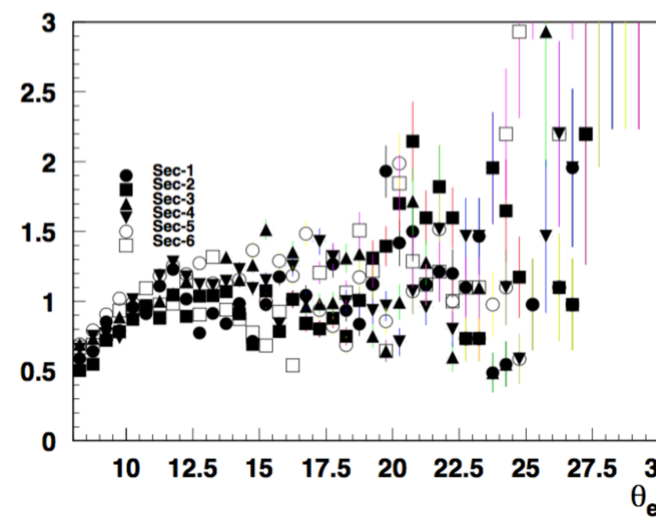
DIS-MC



run 2997 v 5a.0.11



run 3480 v 5a.1.0



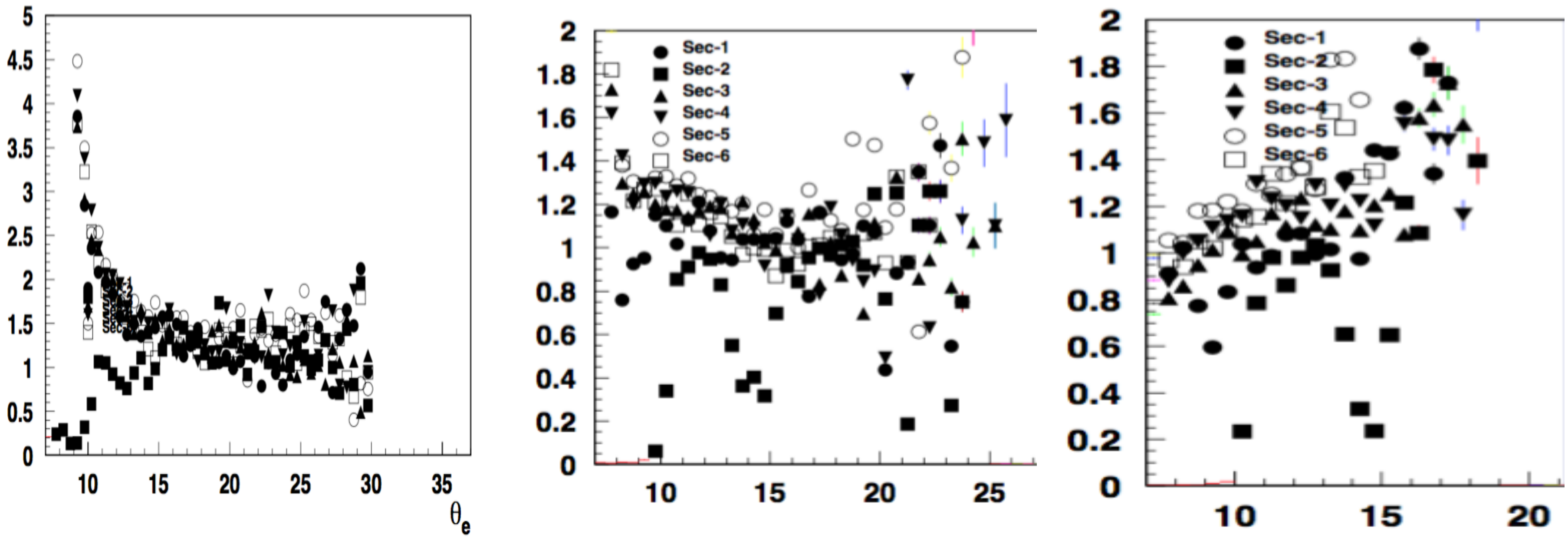
MC with “ideal” geometry can be a primary check for software validation

Electron distributions:ratio /DIS-MC

DIS-MC (with RC)

run3210 (outbending)

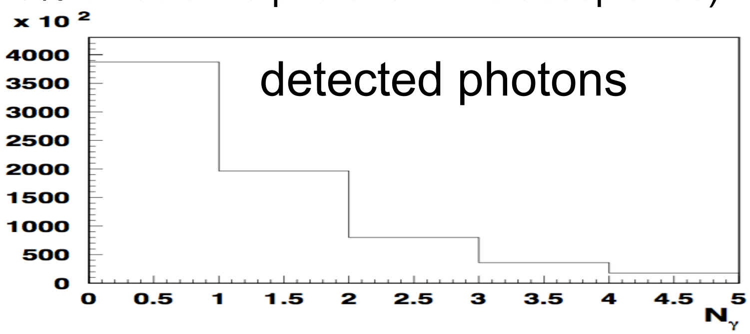
2<E<4 GeV　　4<E<6 GeV　　6<E<8 GeV

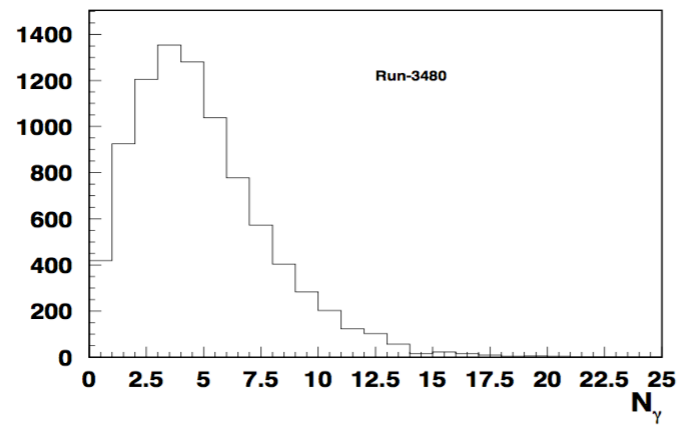


- Enhancement at large angles of high energy particles
- More electrons at small angles for outbending (except sec-2)!!

Missing electrons: outbending

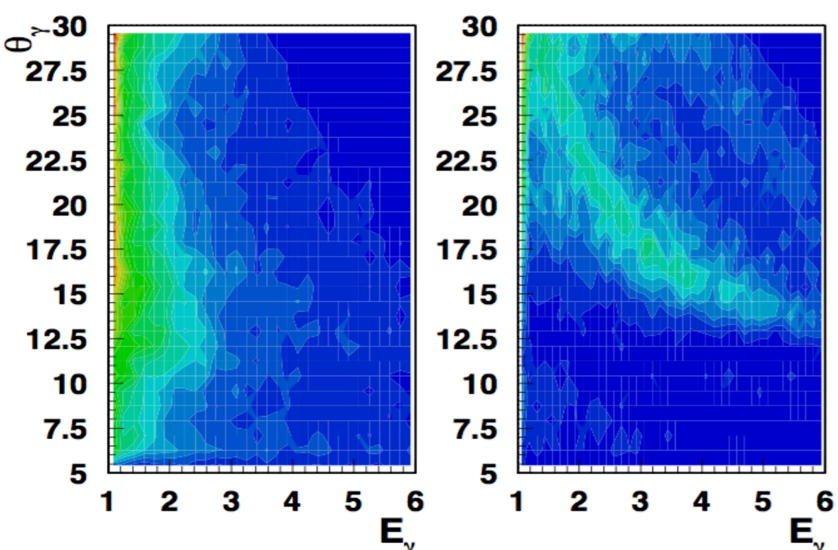
With a single electron in the generator (excluding ~20% of radiative photons in the acceptance)



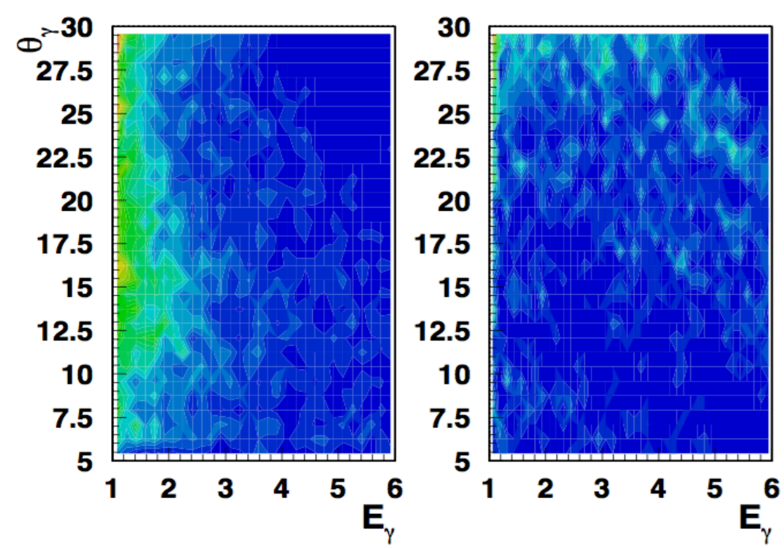


outbending-5a.0.11

n_{ele}=1 n_{ele}=0

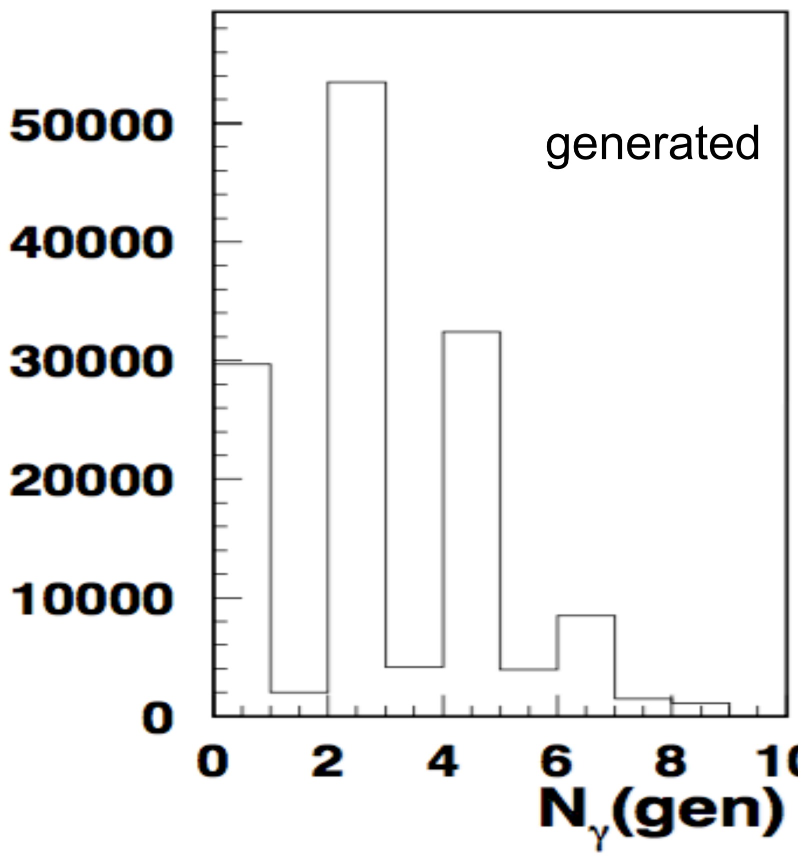


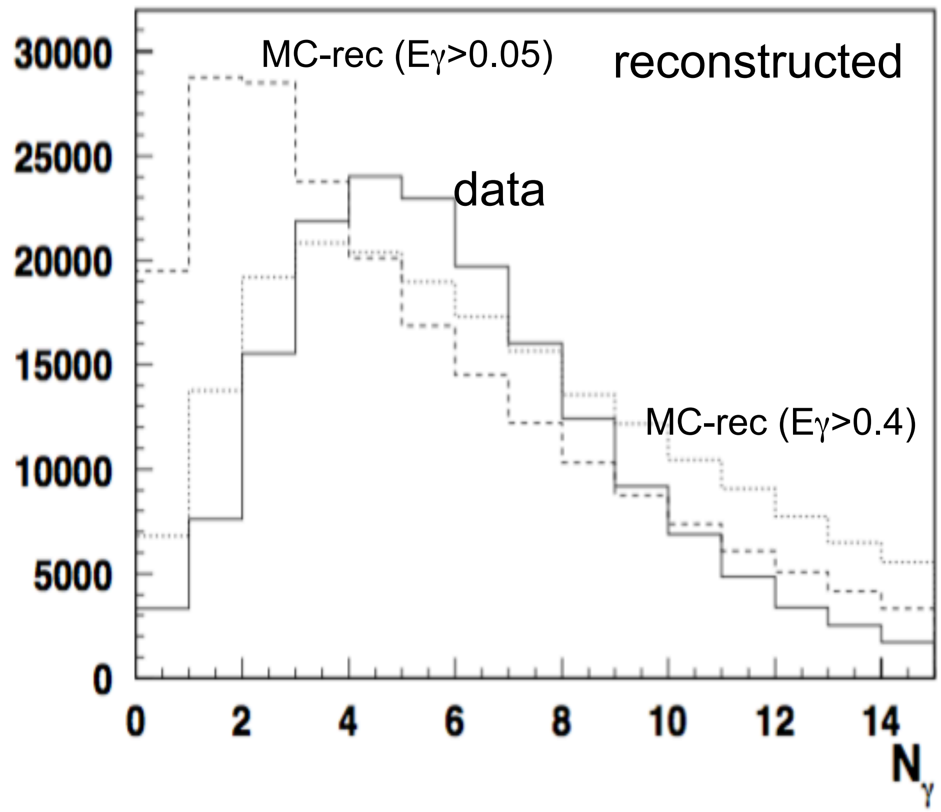
outbending-5a.1.0



pattern for photons disappeared in new version

Photons on clas12: SIDIS LUND-MC vs data

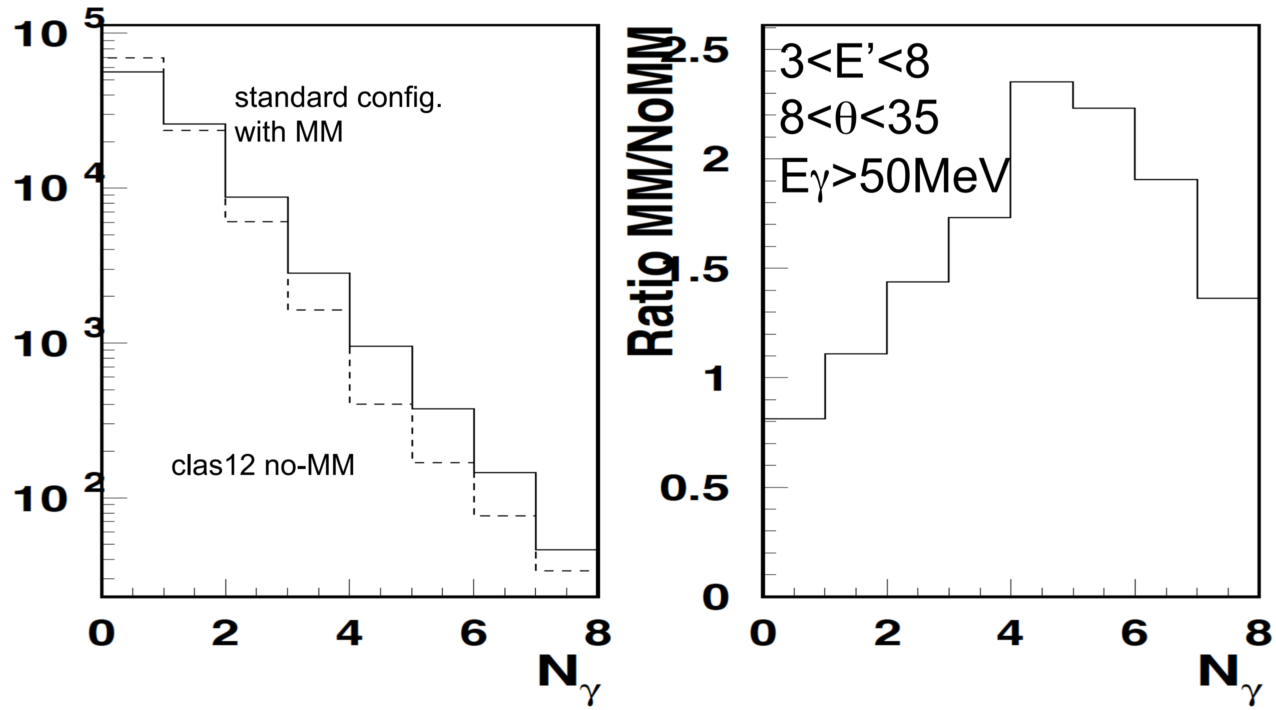




What are all those photons?

Photons from MM?

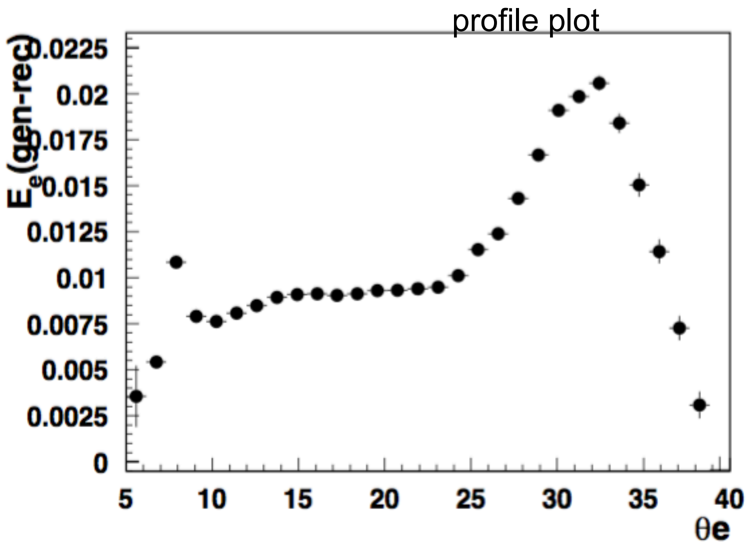
Use DIS-MC (a single e' in the final state) to test the MM vs NoMM clas12 configurations

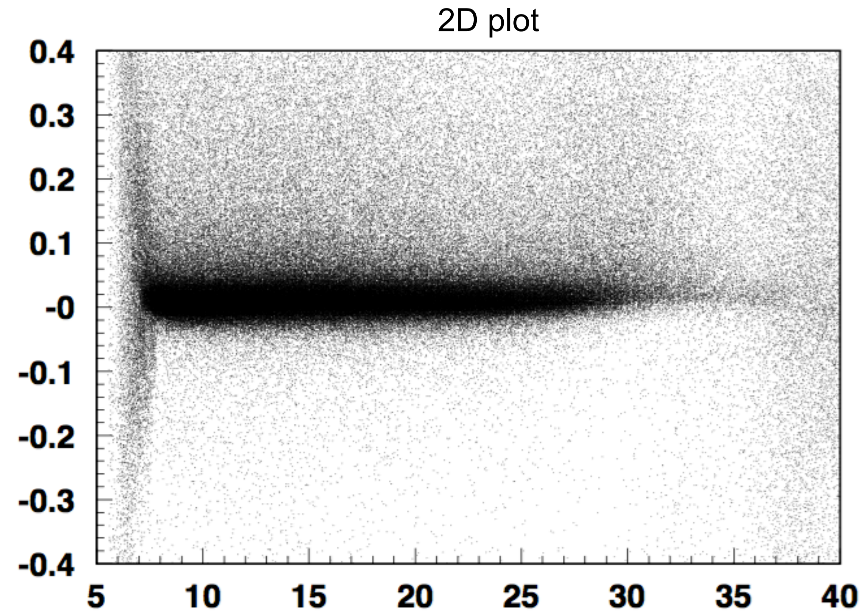


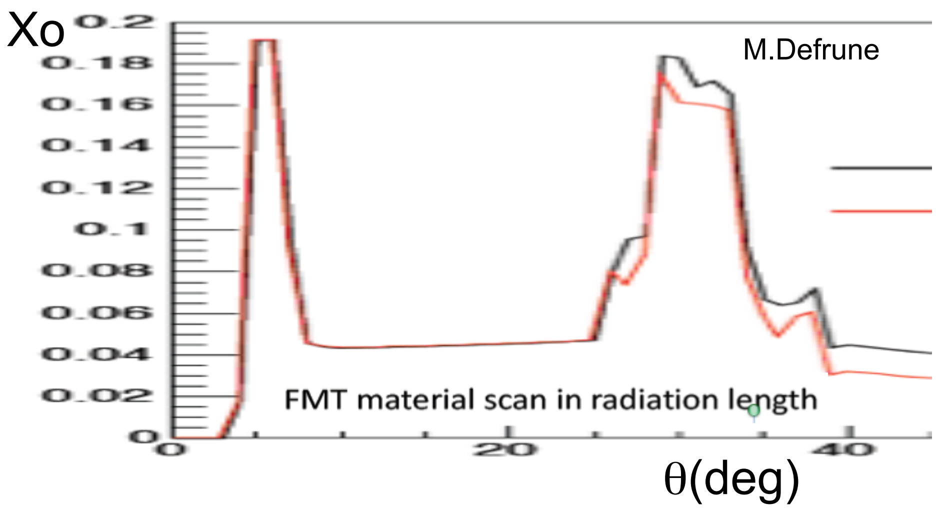
The number of reconstructed charge 0 events increases significantly with MM in.

Reconstructed electrons

Energy loss of electrons vs their angle in the CLAS12 outbending-gemc+coatjava 5.0.11



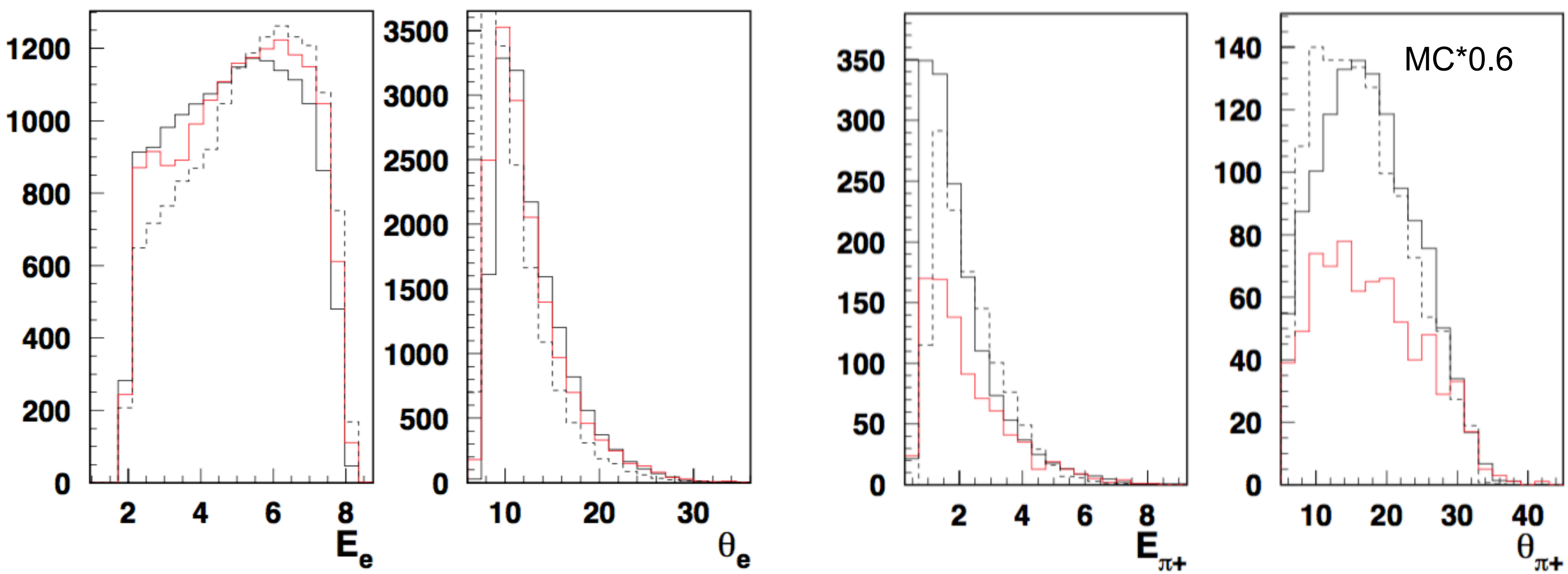




The energy loss shape consistent with MM angular coverage

Pi+ efficiency in inbending: new vs old release

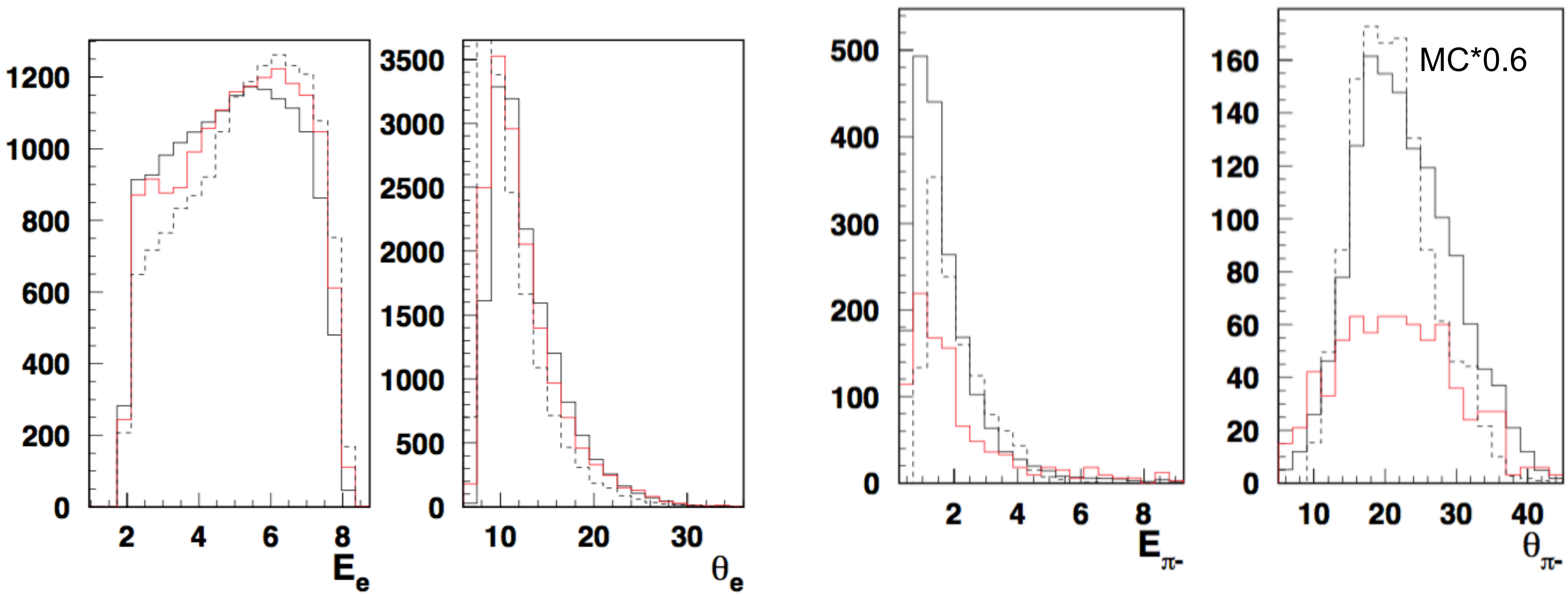
Comparing normalize by number of identified electrons from SIDIS-MC (dashed)
Run 3480 (solid red lines-v.5a.1.0) and Run 2997 (solid black v.5a.0.11?)



SIDIS-MC: new version improves small angle reconstruction for negatives, but the number of identified pions is ~x2 less than in v 5a.0.11

Pi- efficiency in inbending: new vs old release

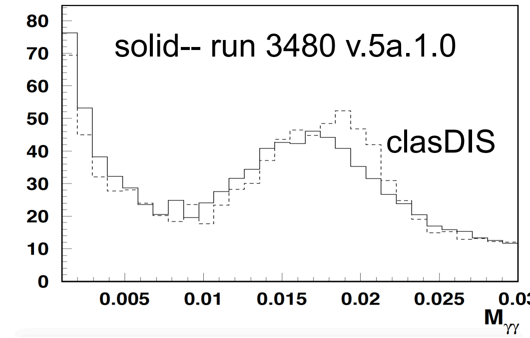
Comparing normalize by number of identified electrons from SIDIS-MC (dashed)
Run 3480 (solid red lines-v.5a.1.0)   and Run 2997 (solid black v.5a.0.11?)



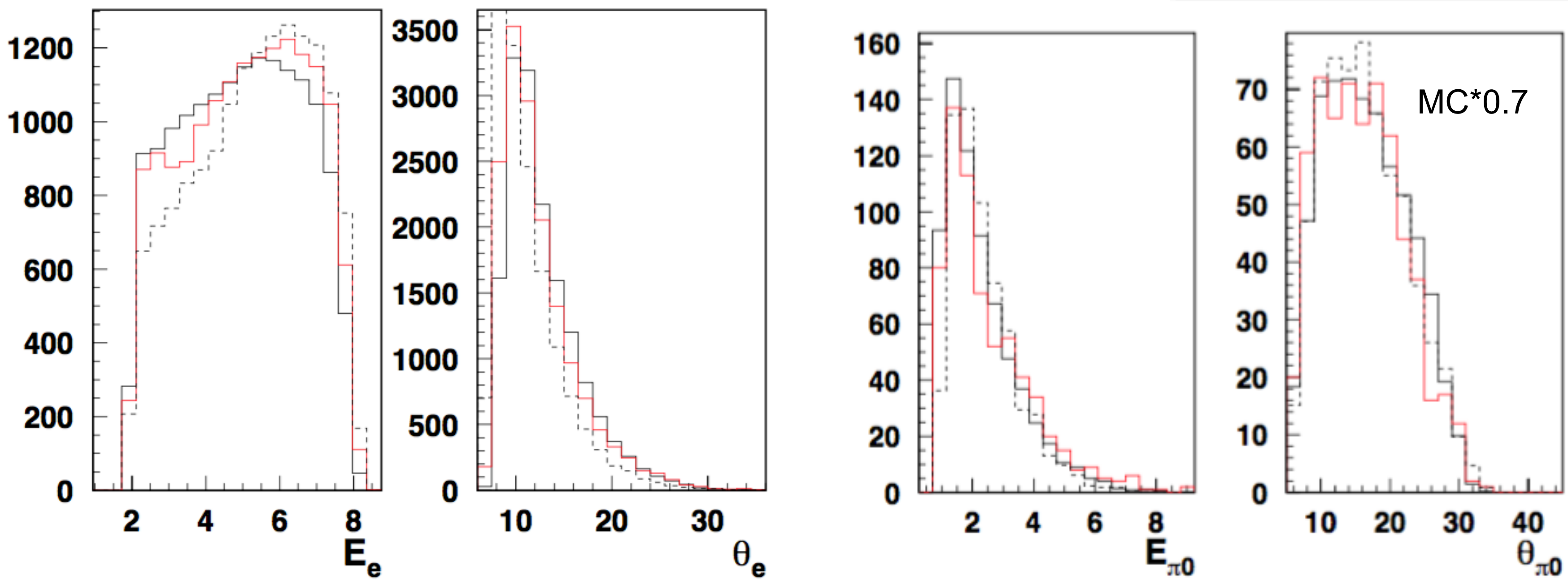
SIDIS-MC: new version improves small angle reconstruction, but the number of identified pi- is ~x2 less than in v 5a.0.11

Pi0 efficiency in inbending: new vs old release

Comparing normalize by number of identified electrons from SIDIS-MC (dashed)
Run 3480 (solid red lines-v.5a.1.0) and
Run 2997 (solid black v.5a.0.11?)



$E\gamma>0.4GeV$

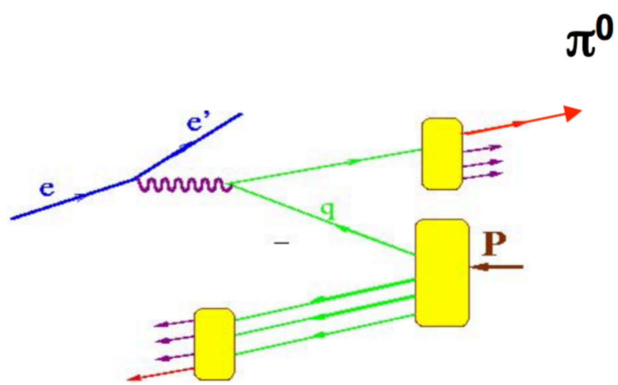


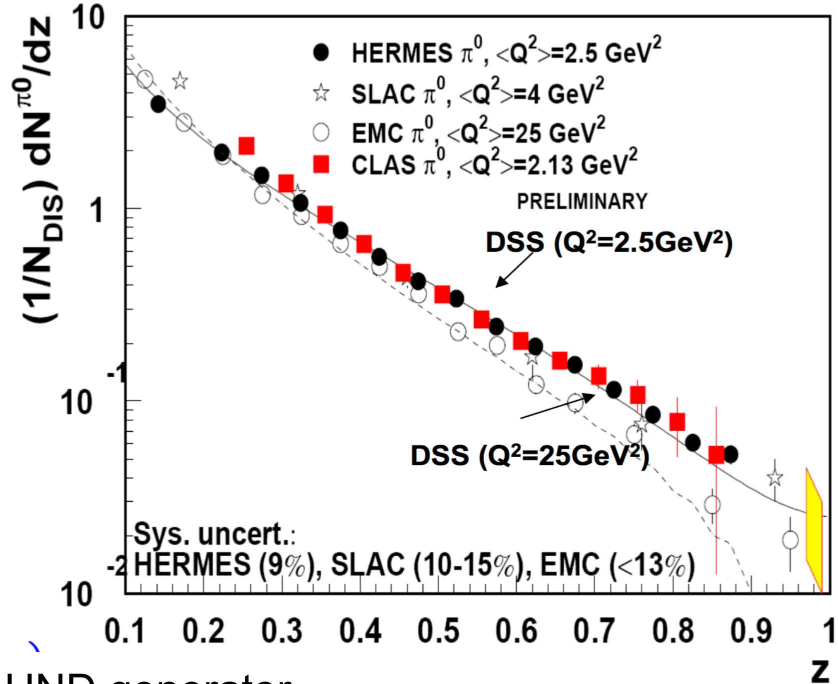
- Studies of SIDIS with pi-0 require reconstruction of electrons and photons (relatively stable in recent releases)
- Will require development of fiducial cuts for e- and photons for extraction of multiplicities

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

JLab Oct 5

1) e'X -cross section: electron acceptance is relevant for all other measurements cons: we need the acceptance and the luminosity as well as contamination from pions under control.
2) e’ π^0X/ e'X ratio (ratio of semi-inclusive pi0 to inclusive electron)
For the ratio we just need the gamma acceptance, which could be defined using the KPP
Need: good control for neutral acceptance





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

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

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

clasDIS LUND generator
1) ratio should have weak dependence on x
2) Ratio should follow z-dependence of the fragmentation function

Conclusions

- Realistic MC is crucial for understanding of detector performance and physics analysis
- Inclusive electron cross sections is well known and can provide possibility to look (monitor) for electron efficiency in the accessible kinematics
- Semi-inclusive cross sections are relatively well known and multiplicities (number of pions per DIS electron) can be used for monitoring
- Validation of software is crucial
  - include the set of constants used in the reconstruction
  - include in the release of the chain reconstruction (with plots) of

    a) single tracks

    b) simple lund file

    c) a data file with some good events (exclusive multiparticle,…)

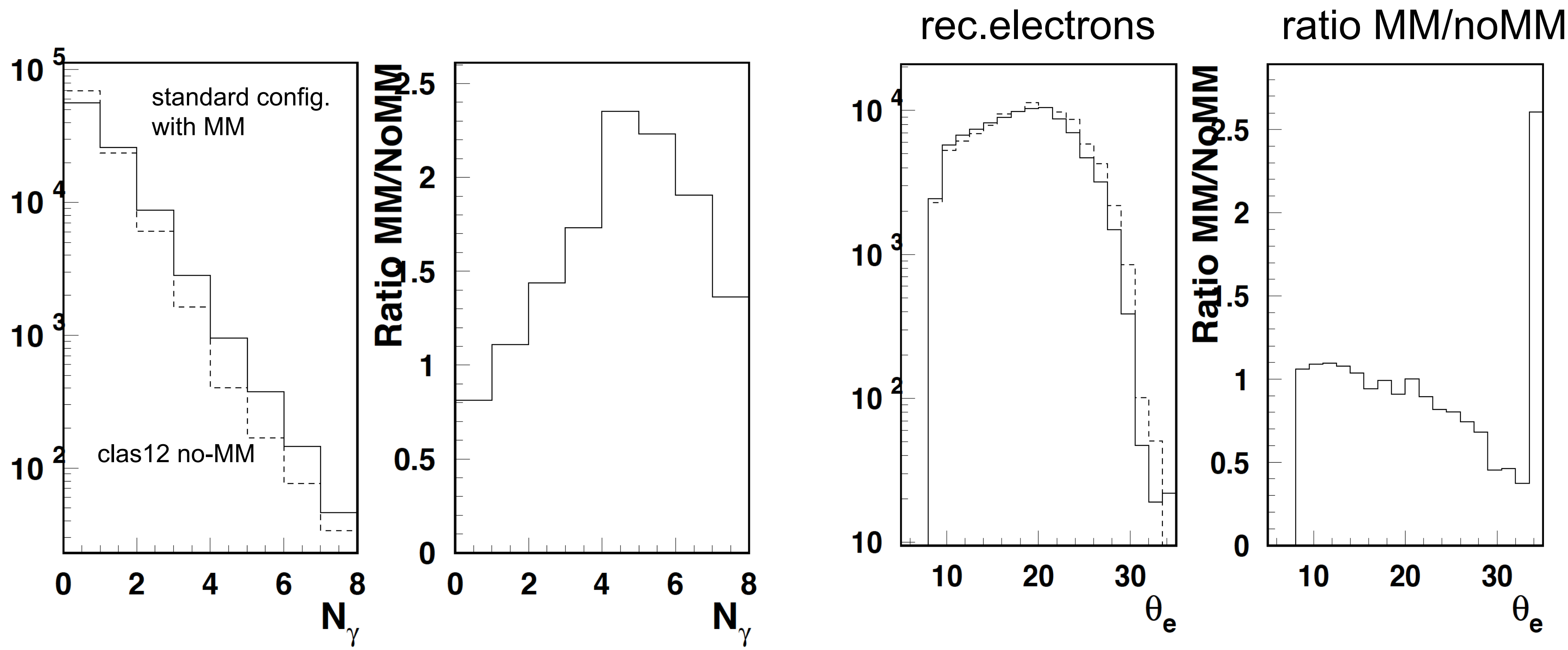
    d) keep also the gemc and hipo files (1-2K events)

    ………
- Use DIS sample to compare old and new releases to evaluate changes

Support slides…

Photons from MM?

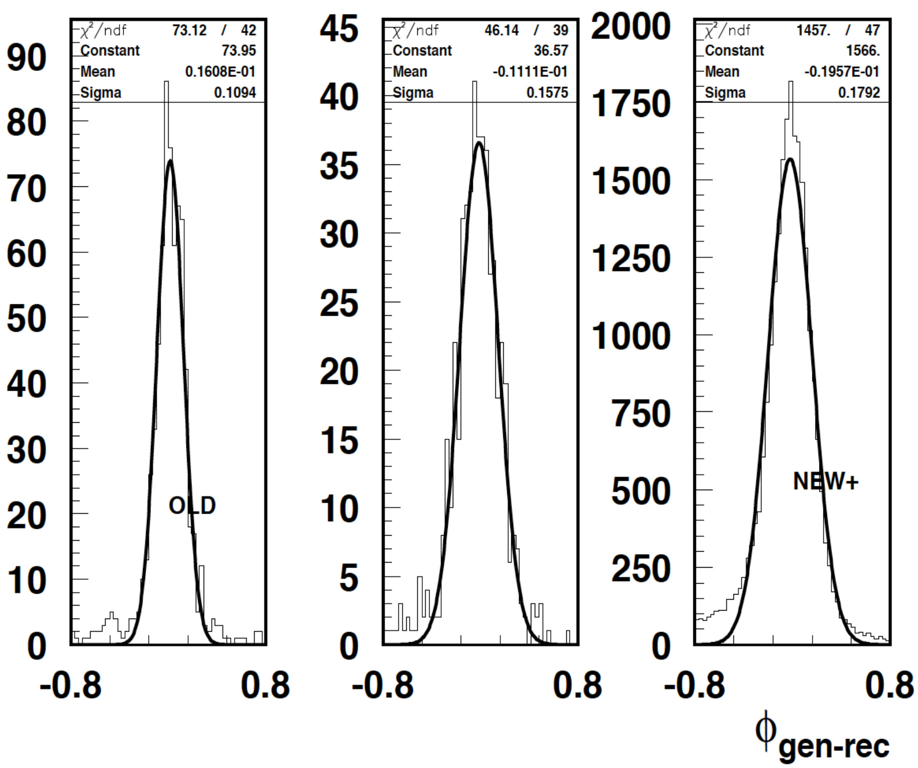
Use DIS-MC (a single e' in the final state) to test
the MM vs NoMM clas12 configurations



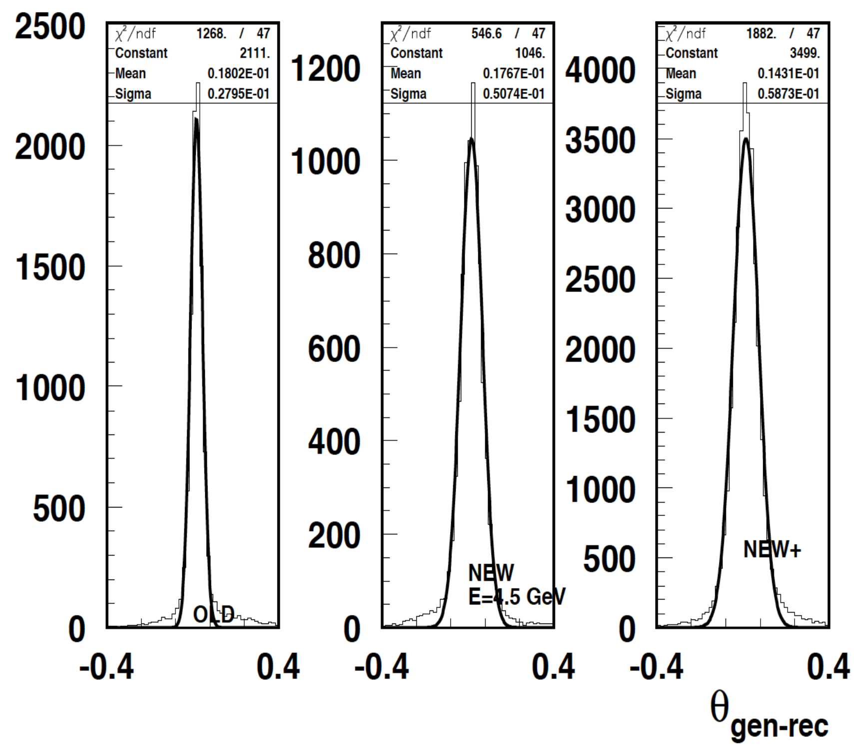
The number of reconstructed charge 0 events increases significantly with MM in.

MC reconstruction of DIS

release-4a.8.4 | release-5a.0.11 (Dec gemc) | release-5a.0.11 Jan gemc



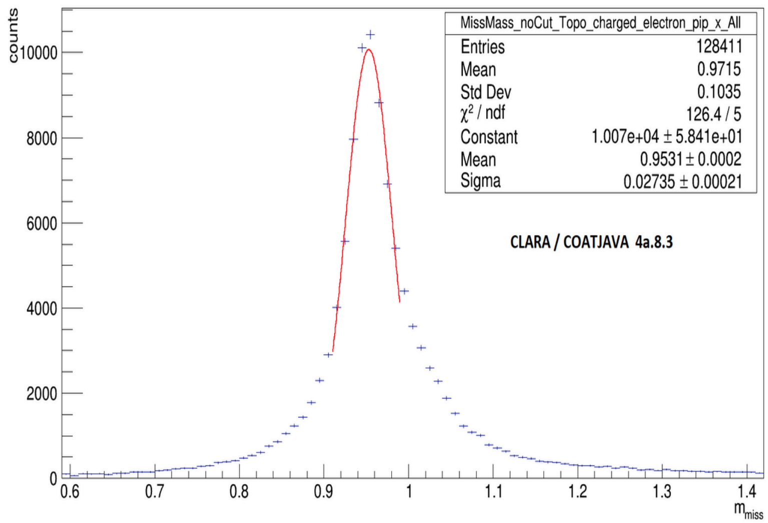
release-4a.8.4 | release-5a.0.11 (Dec gemc) | release-5a.0.11 Jan gemc

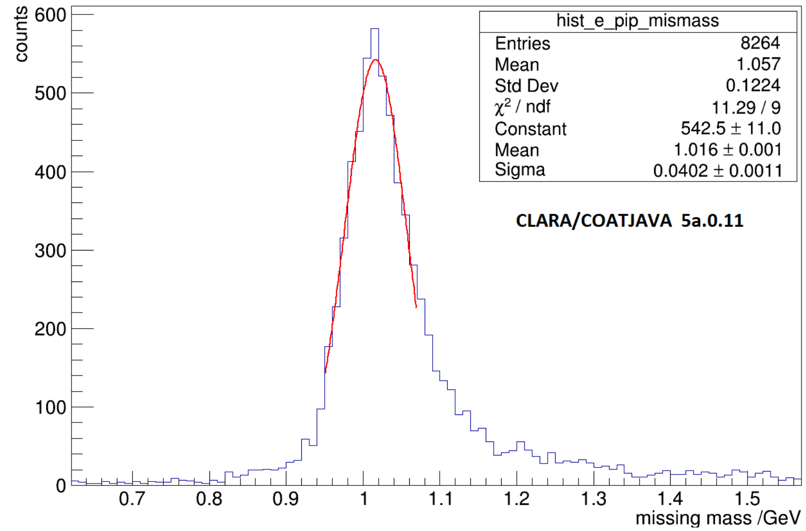


Worse resolutions for polar and azimuthal angles in new releases

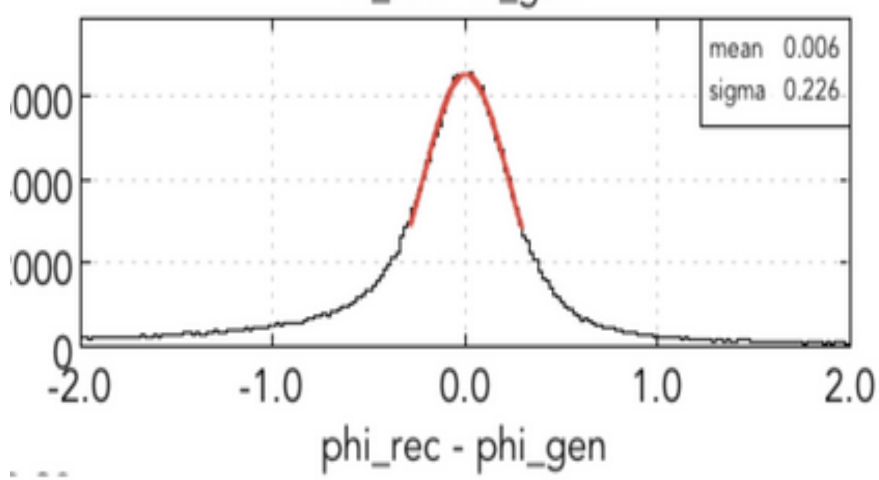
Resolutions from old and new reconstruction

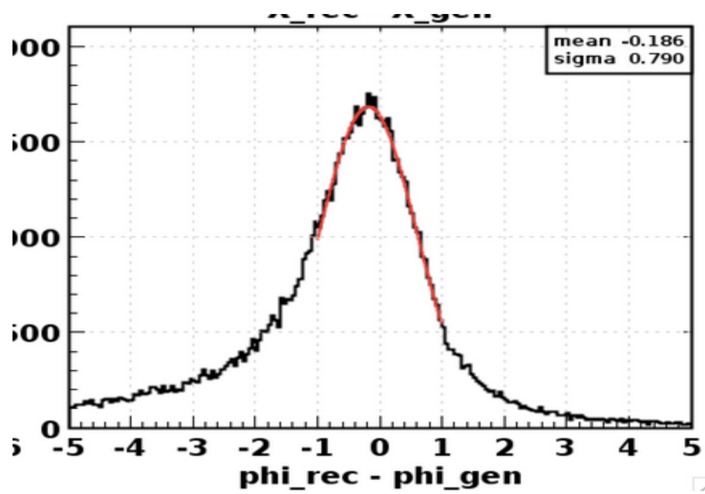
Diehl: e p --> e π^+ X missing mass





Markov: elastic

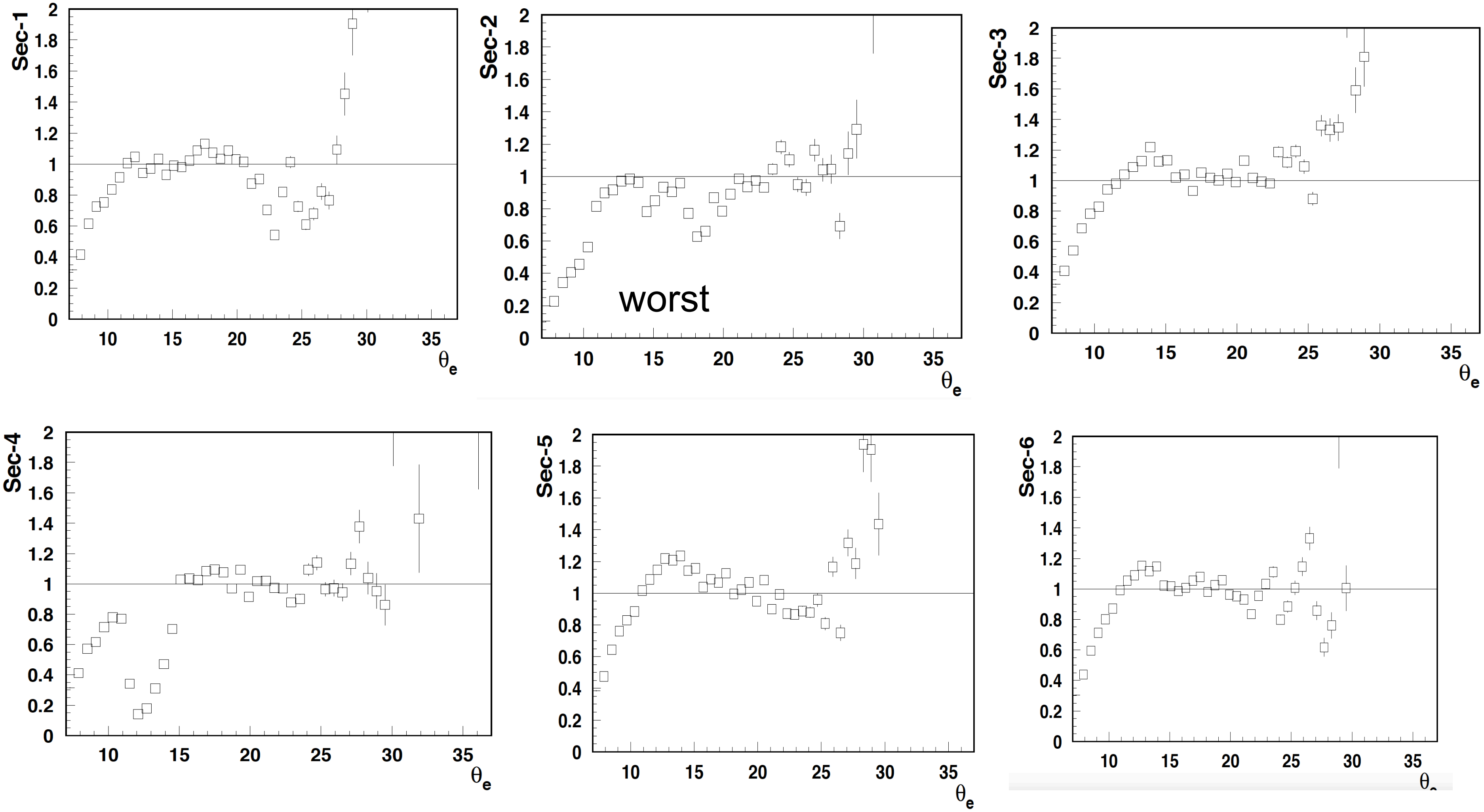




Change of resolutions from 4.8.3 to 5.0.11 may be due to new code/tables/constants

Electron distributions:ratio run2667/DIS-MC

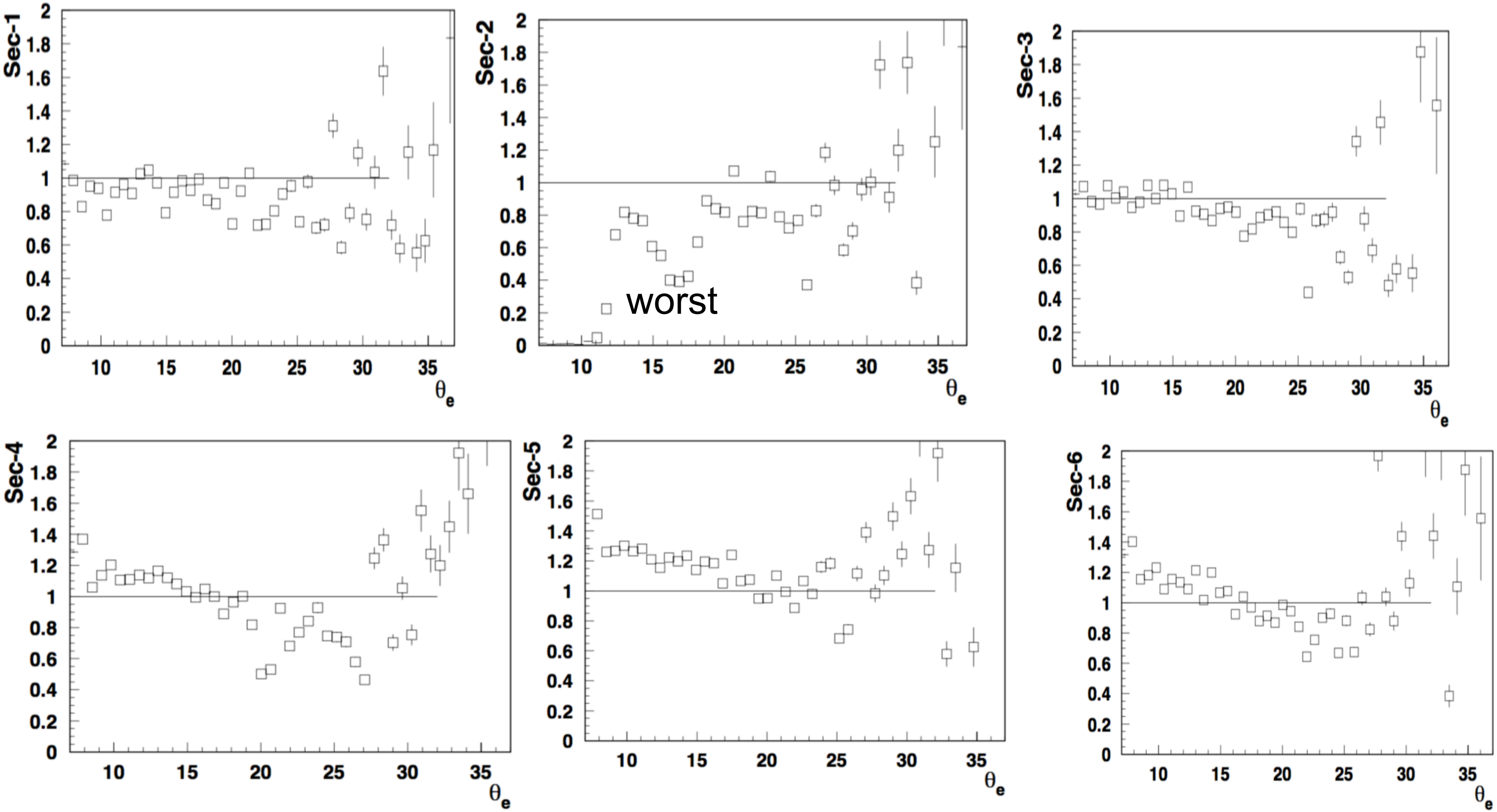
DIS-MC (with RC)



Significantly less electrons at small angles!!

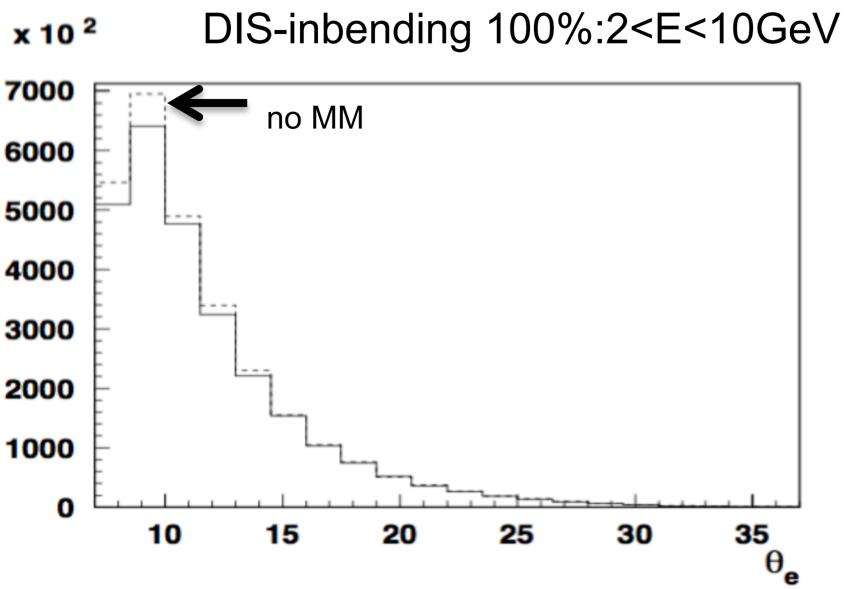
Electron distributions:ratio run3210/DIS-MC

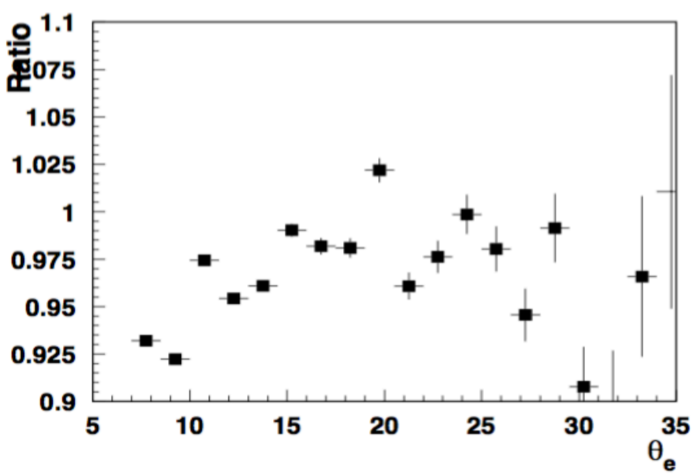
DIS-MC (with RC)

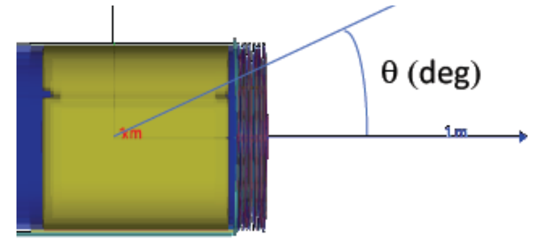


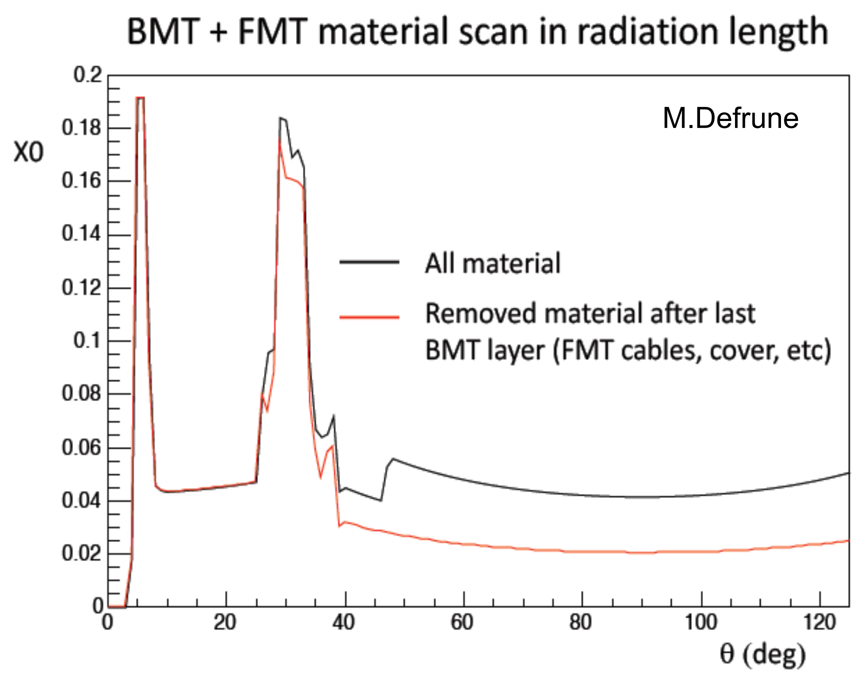
More electrons at small angles for outbending!!

MM effects in MC:noMM vs MM





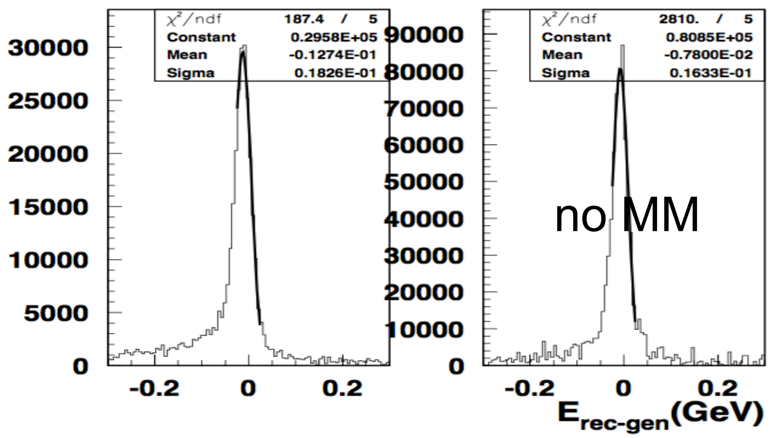




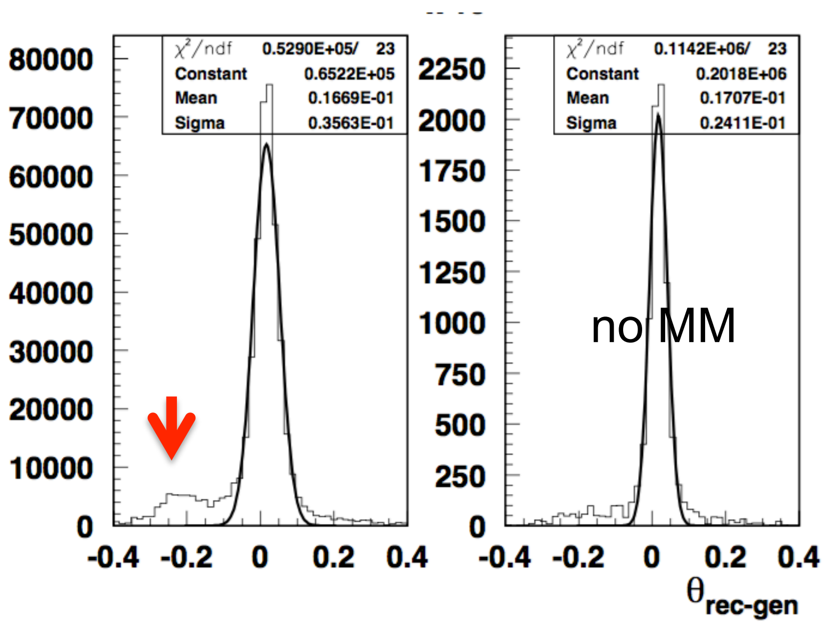
- Significant amount of material in the acceptance in forward angles.

MM effects in MC

$7<E<8GeV, 5<\theta<15$



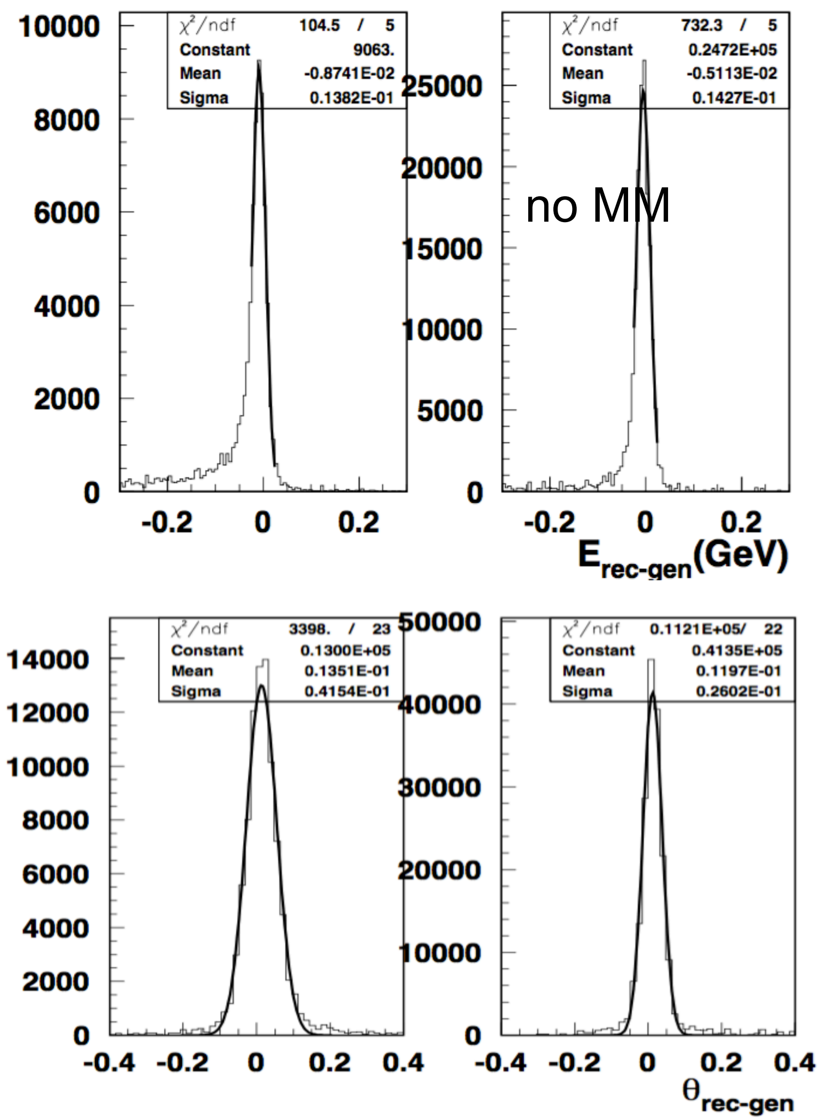
Significant energy loss >10 MeV



- Much worse angular resolutions
- Wrong angles (radiation?)

More plots for angular and energy ranges in https://userweb.jlab.org/~avakian/tmp/mm-effect.tar.gz

MM effects in MC:angular bins

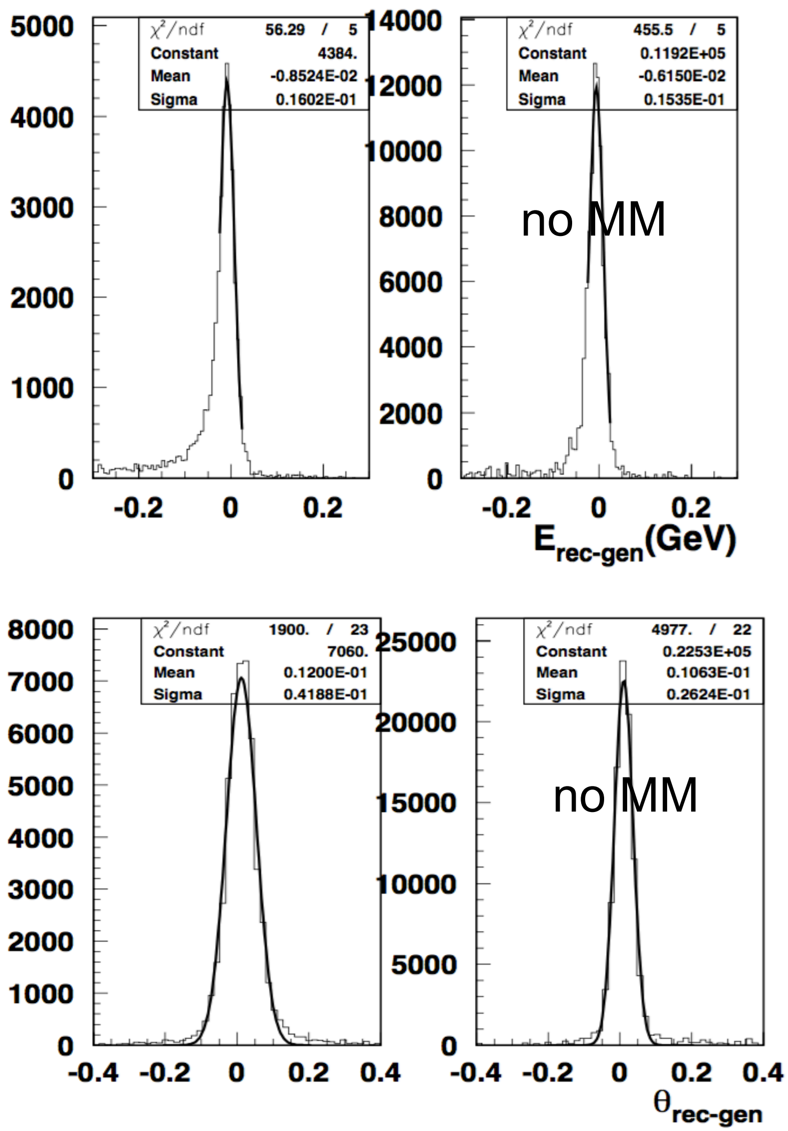


$5<E<6\,\text{GeV}, 12<\theta<15$

Significant energy loss from MM ~4 MeV

- Much worse angular resolutions in all angular bin

MM effects in MC:angular bins

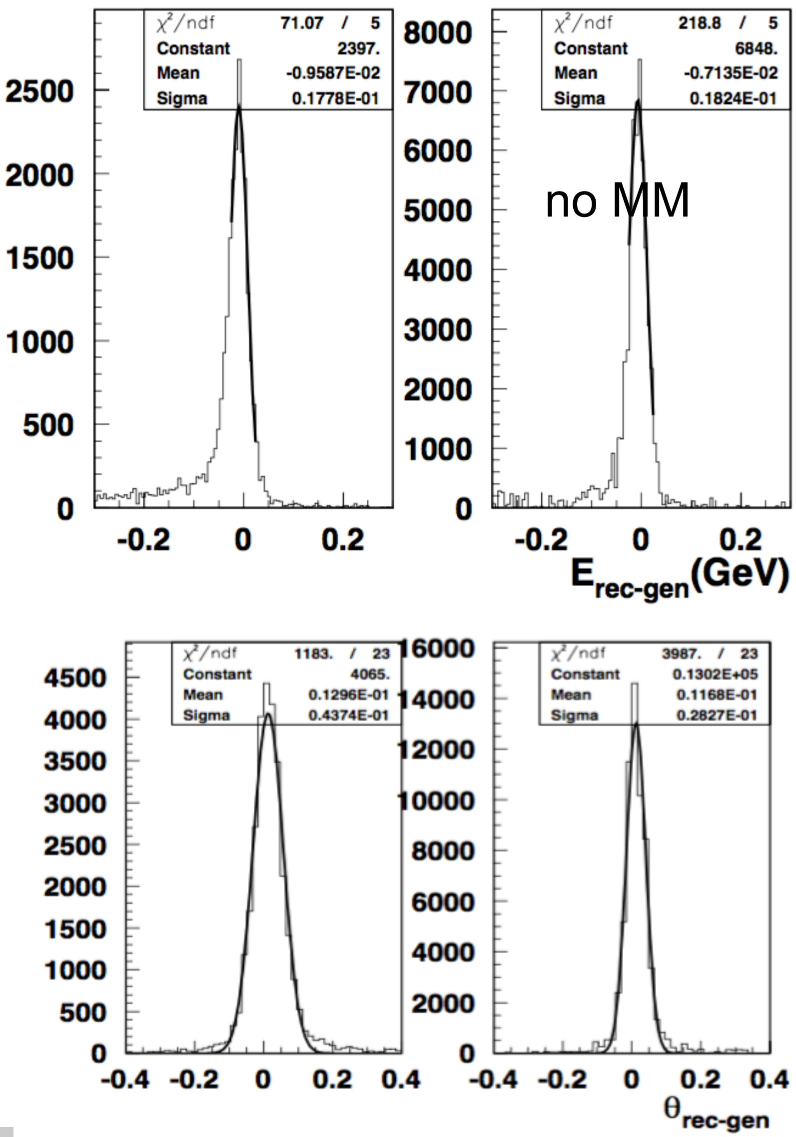


5<E<6GeV,15<θ<17

Significant energy loss from MM ~2-3 MeV

- Much worse angular resolutions in all angular bin

MM effects in MC:angular bins

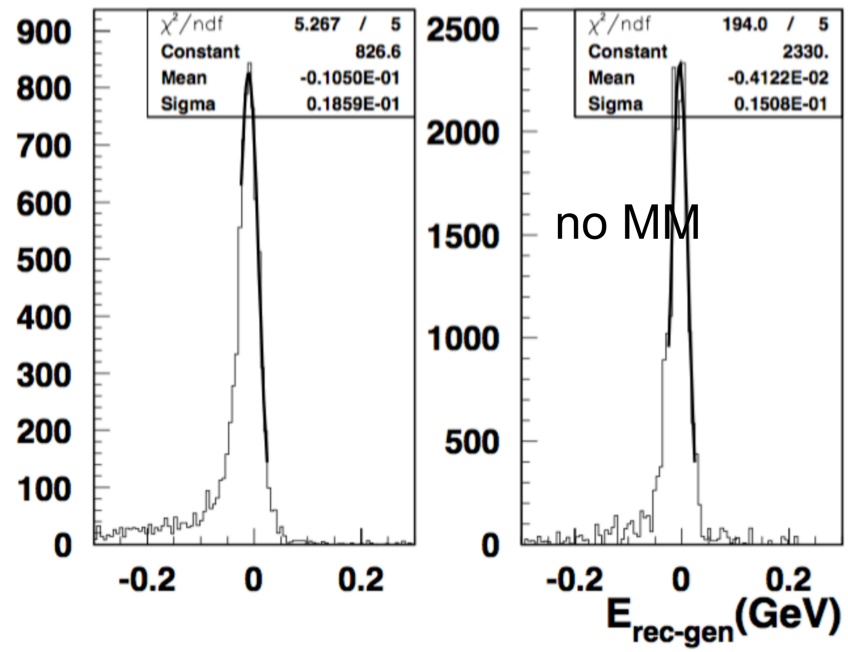


5<E<6GeV,17<θ<19

Significant energy loss from MM ~2-3 MeV

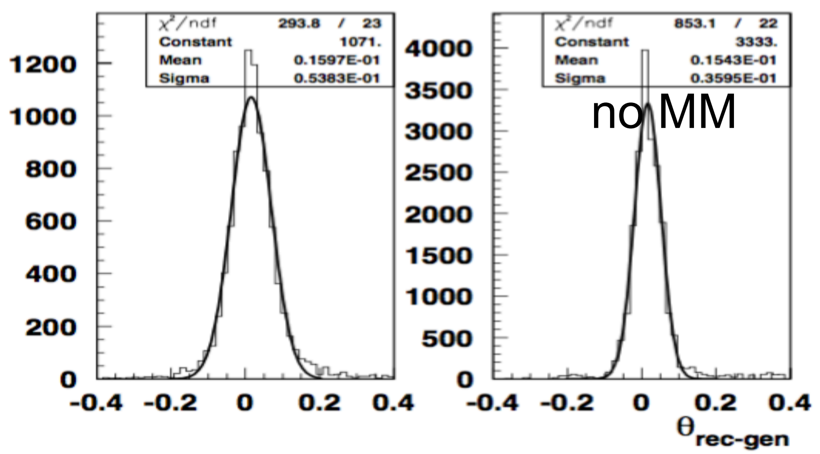
- Much worse angular resolutions in all angular bin

MM effects in MC:angular bins



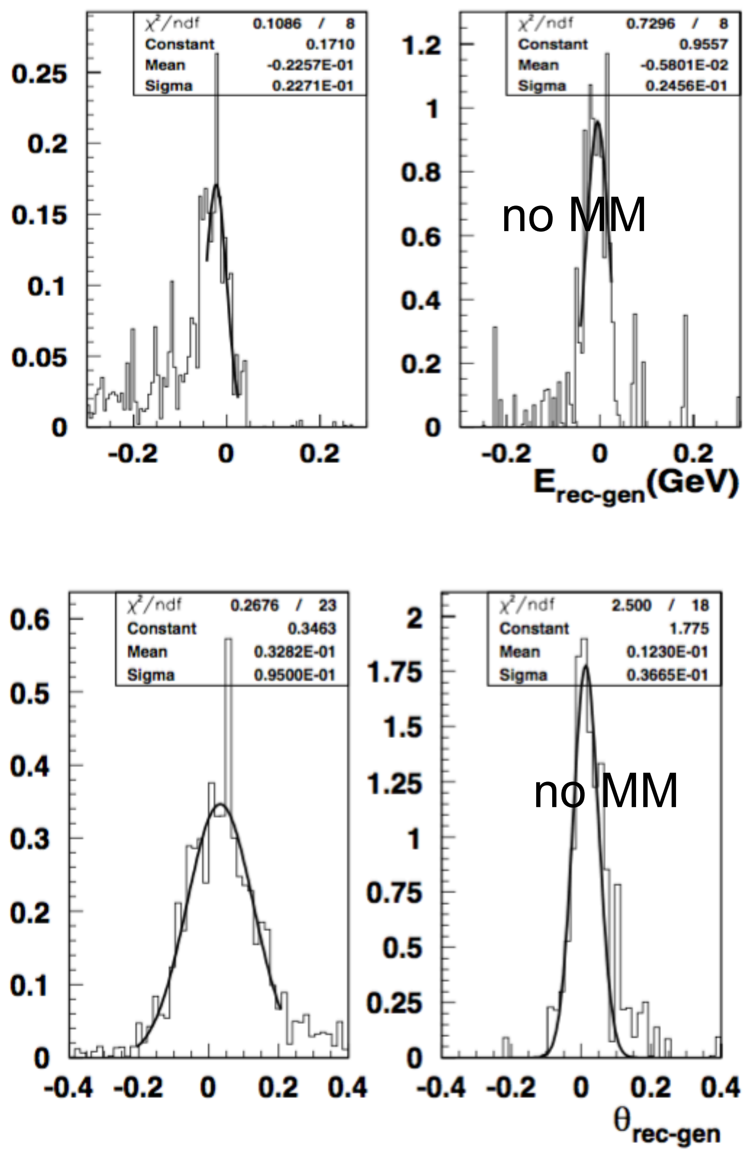
4<E<5GeV,21<θ<23

Significant energy loss from MM ~6 MeV



- Much worse angular resolutions in all angular bin

MM effects in MC:angular bins

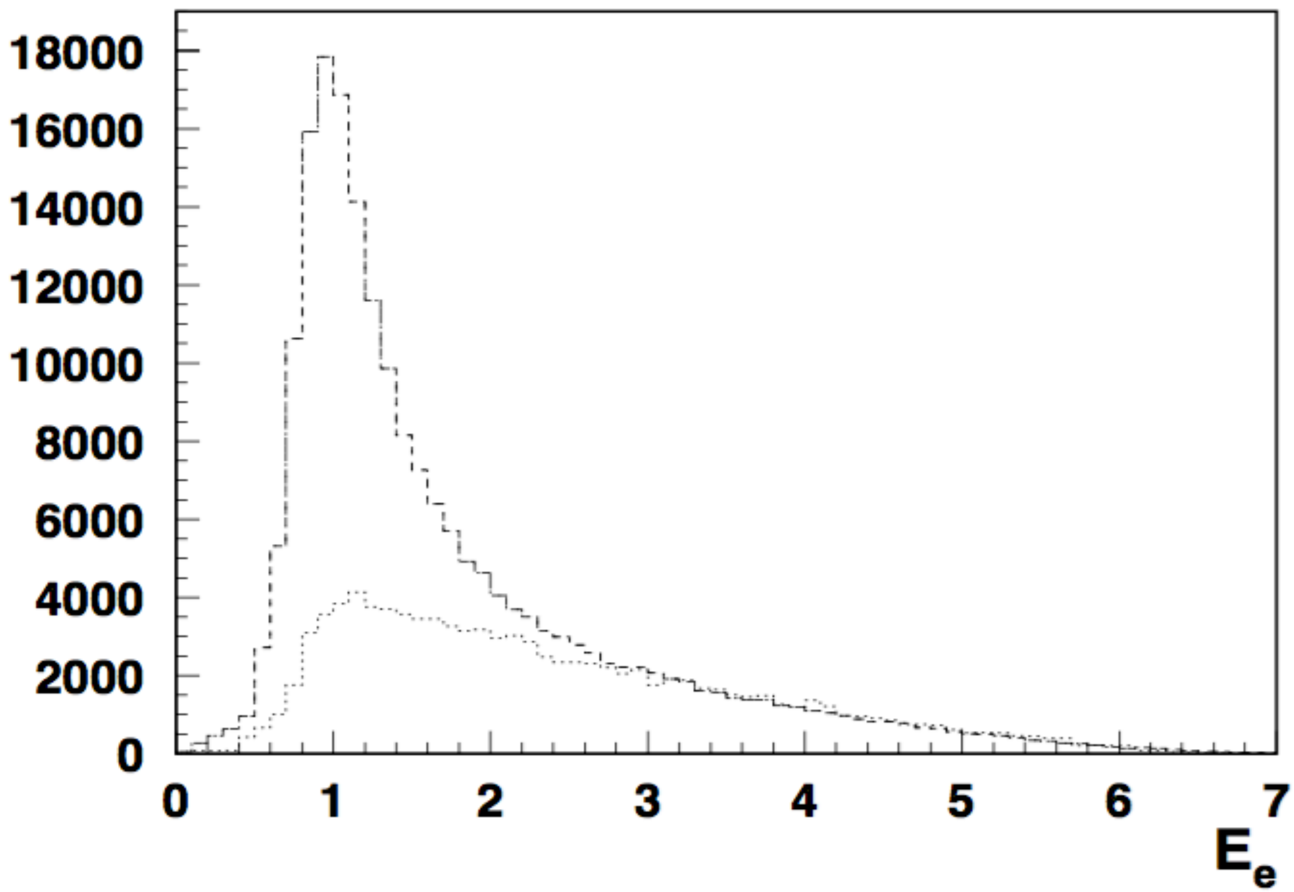


4<E<5GeV,29<θ<31

Significant energy loss from MM >15 MeV

- Much worse angular resolutions in all angular bin

Electron energies



Significantly more electrons at low energies

Extraction of DIS x-section and acceptance


```
{
      "model": "Nobuo_F2,FL"
      "reference": "N. Sato et al"
      "multiplicity":"Counts"
      "Beam Energy": 10.600
      "lepton-polarization": "0"
      "nucleon-polarization": "0"
      "particle": "pi+"
      "variables":["N","Counts","Err.Counts","acc","RadCor","xav","yav","q2av"
      "axis":[
              {"name":"a","bins": 99,"min": 0.05, "max": 0.95, "scale":"lin","description":"x_bj"}
              {"name":"b","bins": 99,"min": 0.95, "max": 13.1, "scale":"lin","description":"Q^2"}
   ],
      "parameters":[
   ]
}
```


0	0	0.81900E+03	0.33103E+07	0.11567E+06	0.18094E+00	2.5475	0.0566	0.9099	1.0248
0	1	0.17300E+03	0.79404E+06	0.60369E+05	0.83559E-01	3.1196	0.0583	0.9392	1.0883
1	0	0.14940E+04	0.45989E+07	0.11898E+06	0.43024E+00	1.7770	0.0631	0.8246	1.0334
1	1	0.24200E+04	0.78833E+07	0.16025E+06	0.38679E+00	2.2943	0.0637	0.8924	1.1298
1	2	0.74100E+03	0.25279E+07	0.92865E+05	0.18311E+00	2.7515	0.0664	0.9300	1.2276
2	0	0.10610E+04	0.29902E+07	0.91799E+05	0.34089E+00	1.4475	0.0725	0.7176	1.0332
2	1	0.21560E+04	0.54615E+07	0.11762E+06	0.44019E+00	1.5917	0.0723	0.7891	1.1339
2	2	0.26110E+04	0.66272E+07	0.12970E+06	0.51925E+00	2.0516	0.0722	0.8767	1.2579
2	3	0.15350E+04	0.41679E+07	0.10638E+06	0.29366E+00	2.5589	0.0744	0.9235	1.3654
2	4	0.48000E+02	0.14361E+06	0.20728E+05	0.41388E-01	3.0801	0.0768	0.9478	1.4485
3	0	0.82900E+03	0.23725E+07	0.82399E+05	0.30402E+00	1.3423	0.0816	0.6379	1.0341
3	1	0.15660E+04	0.38319E+07	0.96832E+05	0.35124E+00	1.4013	0.0816	0.6993	1.1334
3	2	0.20270E+04	0.42636E+07	0.94699E+05	0.44952E+00	1.5274	0.0814	0.7773	1.2578
3	3	0.24600E+04	0.49319E+07	0.99437E+05	0.54600E+00	1.8039	0.0814	0.8531	1.3798
3	4	0.22240E+04	0.48486E+07	0.10281E+06	0.43699E+00	2.3514	0.0822	0.9135	1.4934

Radiative corrections may be significant

- Acceptance can be used to correct distributions for monitoring
- DIS output can be generated using input F_1,F_2 or F_2,F_L or directly x-sections

Generating DIS and 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

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

0 (twist-4)

Dedicated (inclusive pion 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

$$\frac{d\sigma}{dx\,dQ^2\,d\psi} = \frac{2\alpha^2}{xQ^4}\frac{y^2}{2(1-\varepsilon)}\left\{2(1-\varepsilon)xF_1(x,Q^2)+\varepsilon(1+\gamma^2)F_2(x,Q^2)\right\}$$

Dedicated DIS generator

	2	1	1	0.12	1.04	11	10.600	2212	1	0.6882683E-05	0.1235496E+00	11.55	8.13	
1	-1.	1	11	0	0	-1.2610	-0.0968	1.5722	2.0177	0.0005	-0.0185	0.0768	-0.4312
2	0.	1	22	1	0	0.2821	-0.0185	0.3528	0.4521	0.0000	-0.0185	0.0768	-0.4312

Generating DIS and SIDIS

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
```

Dedicated DIS generator (Bosted)

```
       1      1      1  1.0  1.0    11     10.600 2212    1 0.6224668E+00
 1 -1.    1     11  0  0   -0.6109    1.3411    8.1241    8.2567    0.0005     -0.1465    0.0724   -0.0298
```

COATJAVA   4a.8.4

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"group": 41,
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"items": [
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]
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GEMC

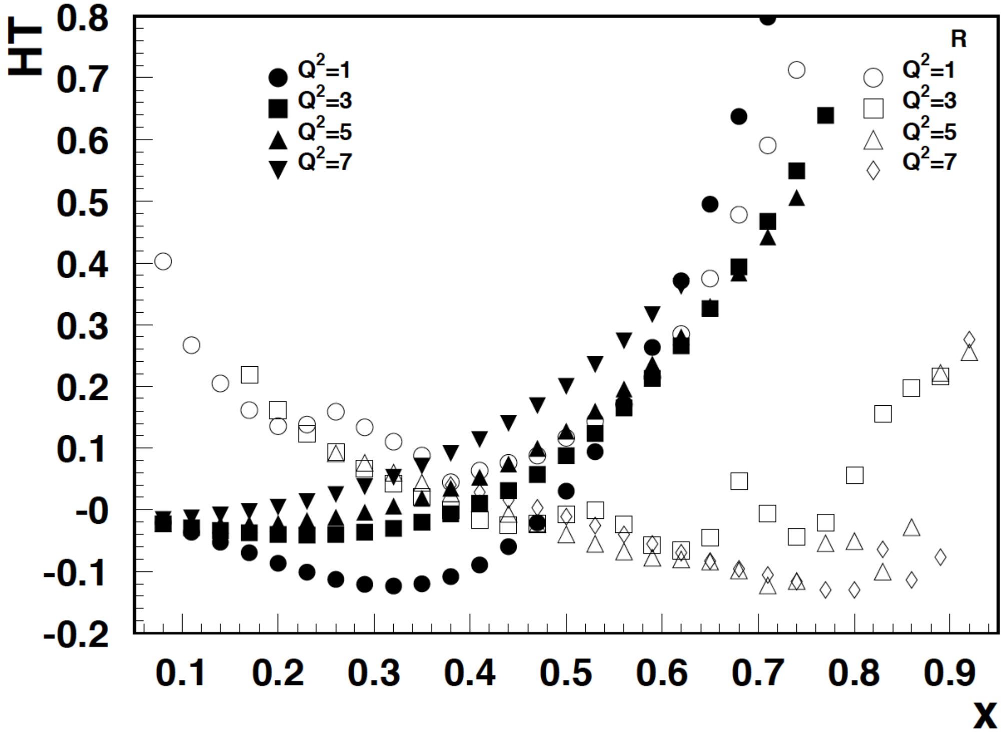
LUND Header	
column	quantity
1	**Number of particles**
2	Number of target nucleons
3	Number of target protons
4	Target Polarization
5	**Beam Polarization**
6	beam PID (electron=11, photon=22)
7	beam energy
8	target nucleon ID
9	process ID
10	event weight/cross section

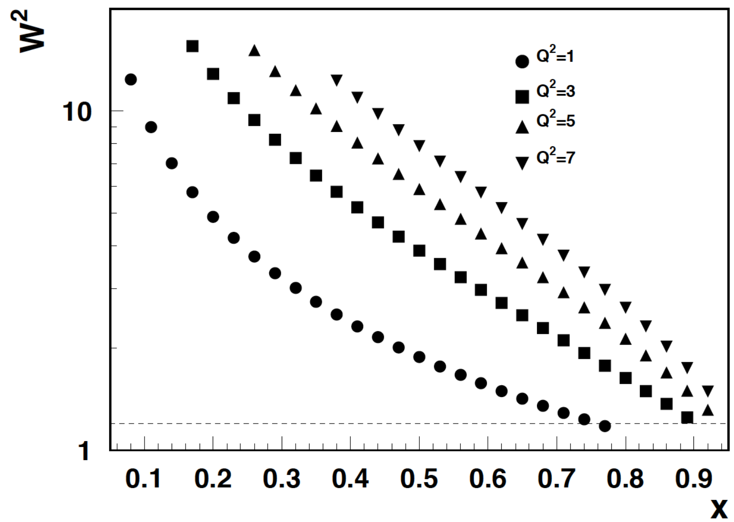
LUND Particles	
column	quantity
1	index
2	lifetime
3	**type (1 is active)**
4	**particle ID**
5	parent index
6	index of the first daughter
7	**momentum x [GeV]**
8	**momentum y [GeV]**
9	**momentum z [GeV]**
10	E
11	mass
12	**vertex x [cm]**
13	**vertex y [cm]**
14	**vertex z [cm]**

DIS input from theory and phenomenology

Study the effect of F_UU,L (accounted in DIS and ignored in SIDIS)

$$F_2(x,Q^2) = F_2^{\mathrm{LT}}(x,Q^2)\left(1+\frac{C_{\mathrm{HT}}(x)}{Q^2}\right) \qquad 1+R=\frac{(1+\gamma^2)F_2}{2xF_1}$$

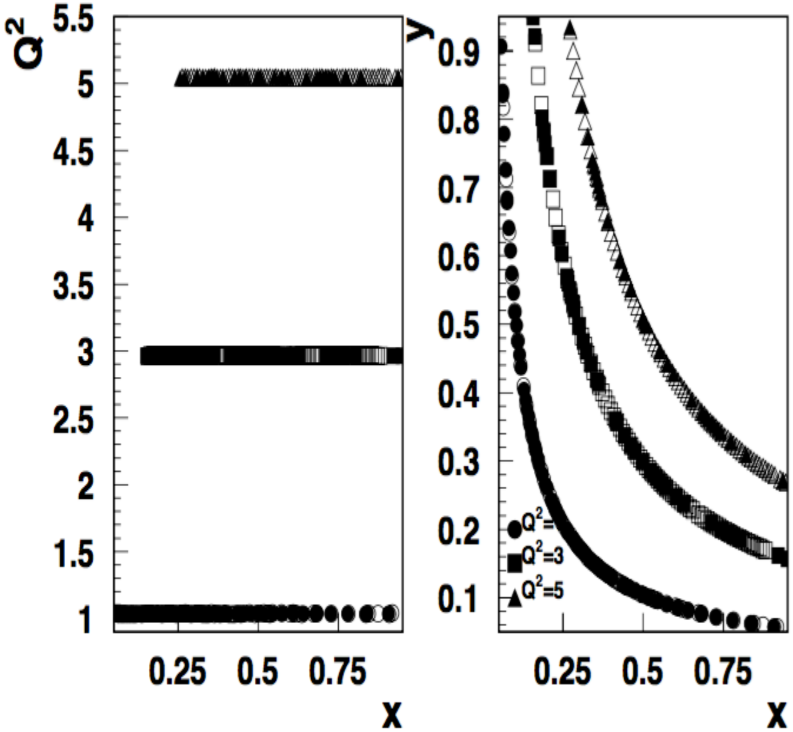




Consistent in kinematics, where HT are not significant

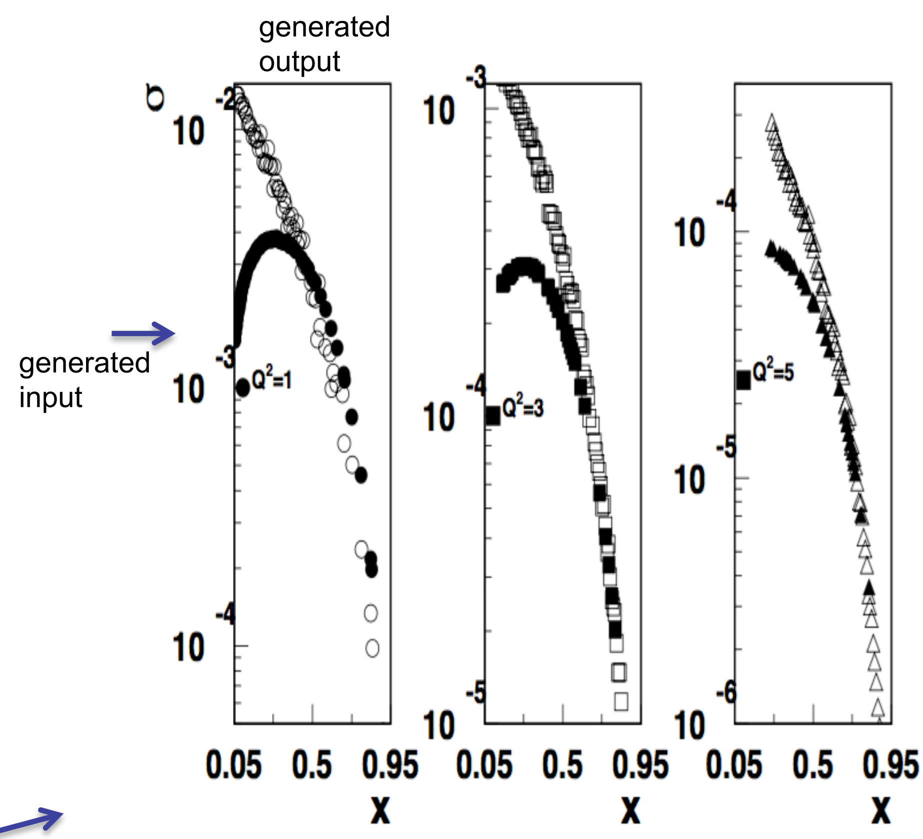
- Different Q^2-dependent factors contribute.
- Separation is important for DIS, but will be critical for SIDIS

Comparing generated ouput with input



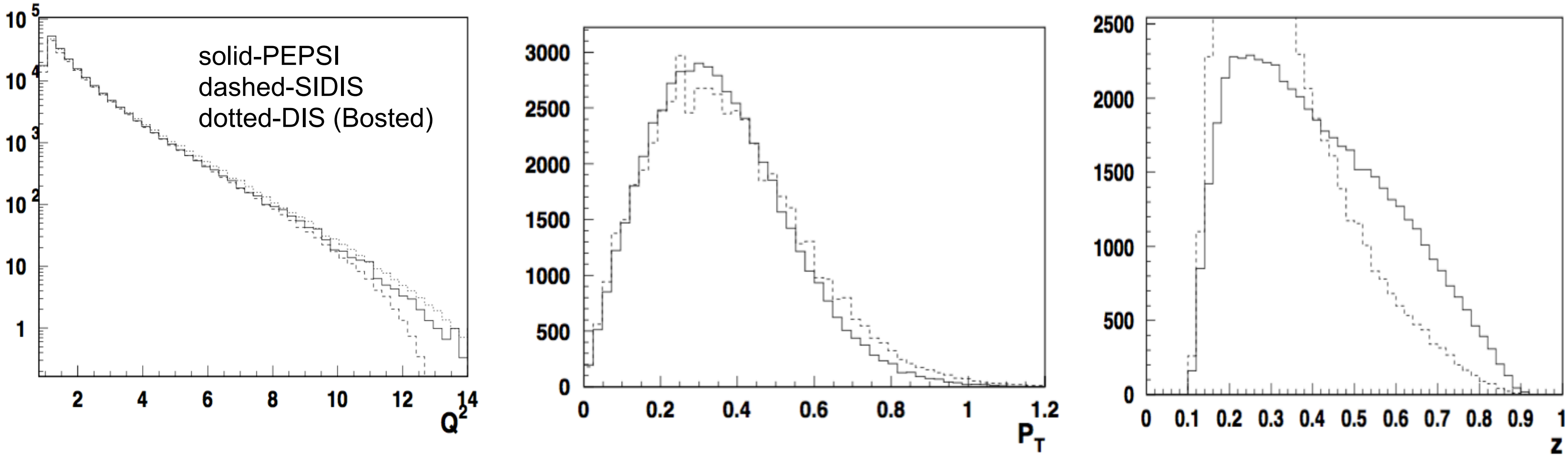
compare 3 bins in Q^2
average values agree

using x-section generator in x/y



Even with uniform distribution in x, the generated distribution is not uniform and depends on initial cuts on electron angle and energy

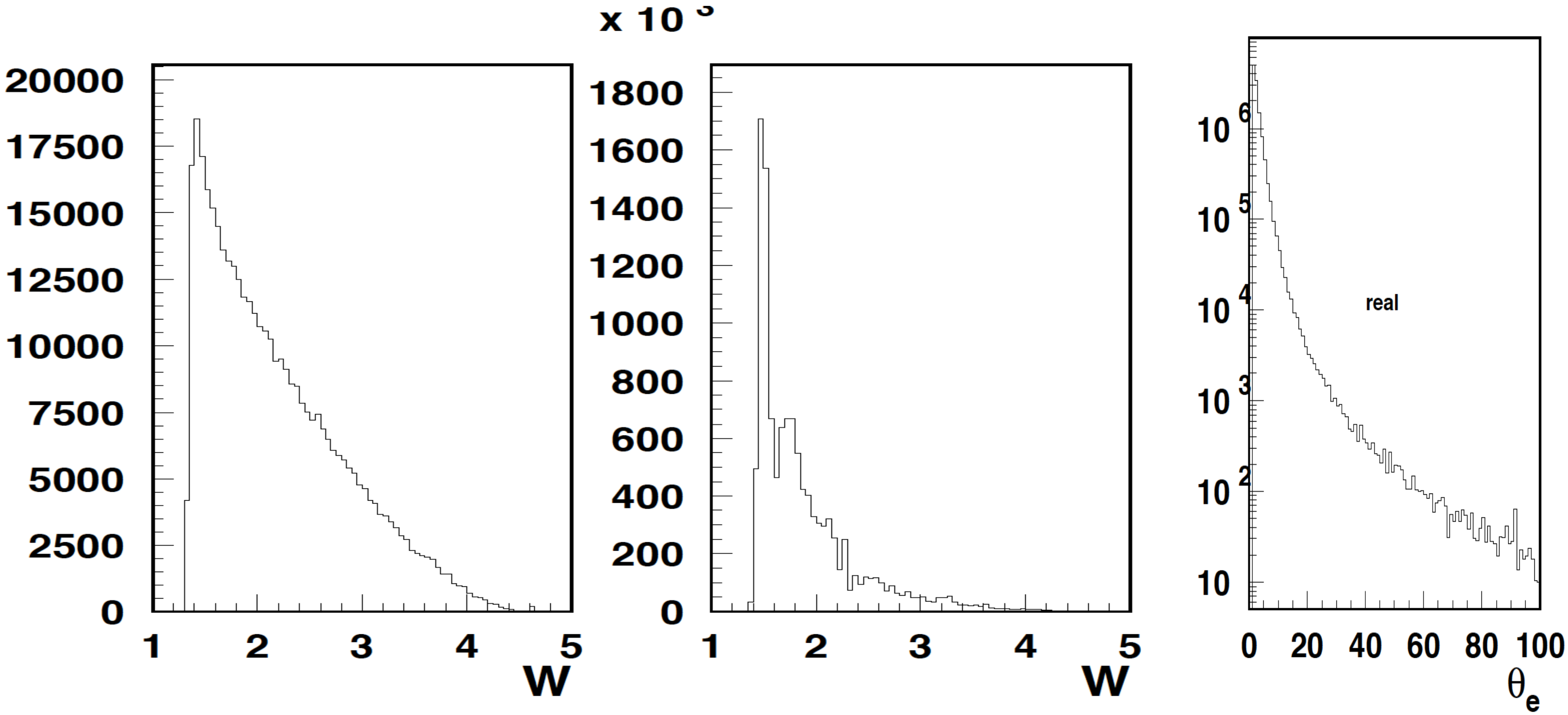
Kinematic distributions



eπX evnts compared with eπX events from PYTHIA tuned to data

Simple event generator should be “reasonable”

DIS generator



CLAS12-MC vs theory: defining variables

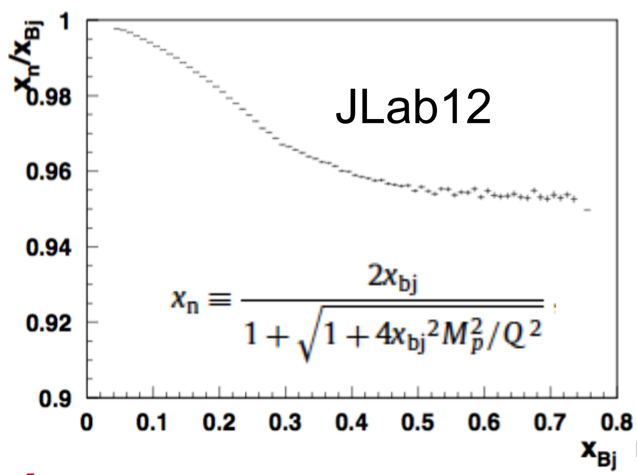
Boglione et al. $M_{h\mathrm{T}} \equiv \sqrt{P_{h\mathrm{T}}^2 + M_h^2}$

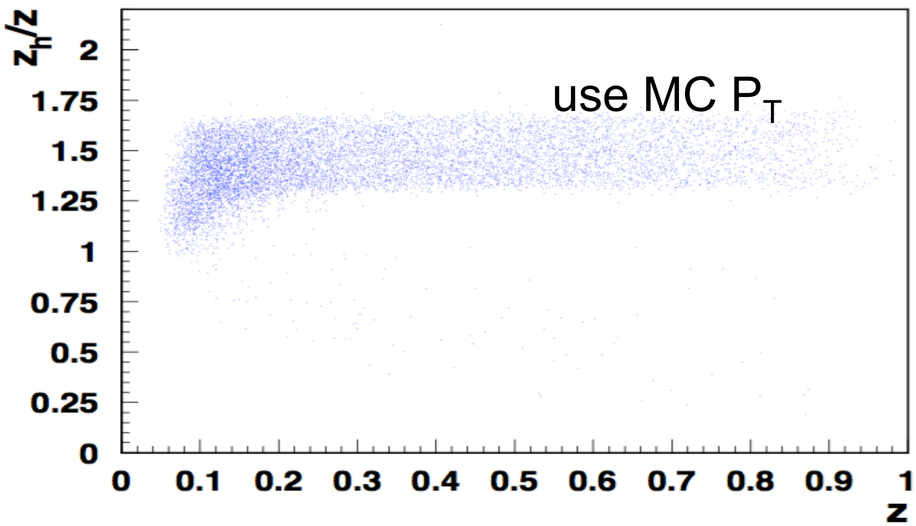
$$z_h = \frac{M_{h\mathrm{T}}}{Q}\left(1 - x_{\mathrm{n}}{}^2 \frac{M_p^2}{Q^2}\right)^{-1}\left(e^{-y_h} + x_{\mathrm{n}}{}^2 \frac{M_p^2}{Q^2} e^{y_h}\right)$$

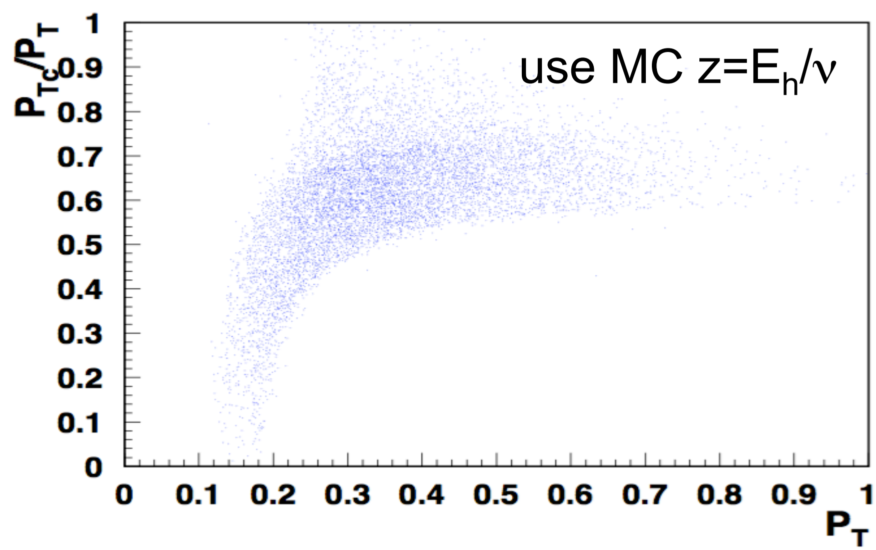
$$P_{Tc} = Q\sqrt{\frac{z_h{}^2 e^{2y_h}\left(1 - x_{\mathrm{n}}{}^2 M_p^2/Q^2\right)^2}{\left(1 + e^{2y_h} x_{\mathrm{n}}{}^2 M_p^2/Q^2\right)^2} - \frac{M_h^2}{Q^2}}$$

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

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







Consistency check for z and P_T

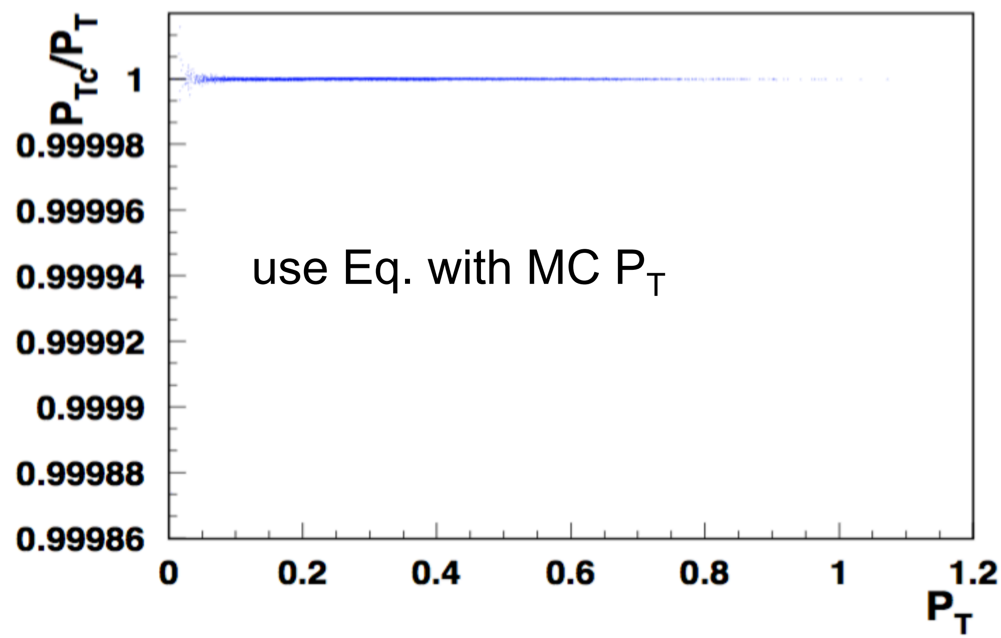
Boglione et al. $M_{hT} \equiv \sqrt{P_{hT}^2 + M_h^2}$

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

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

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

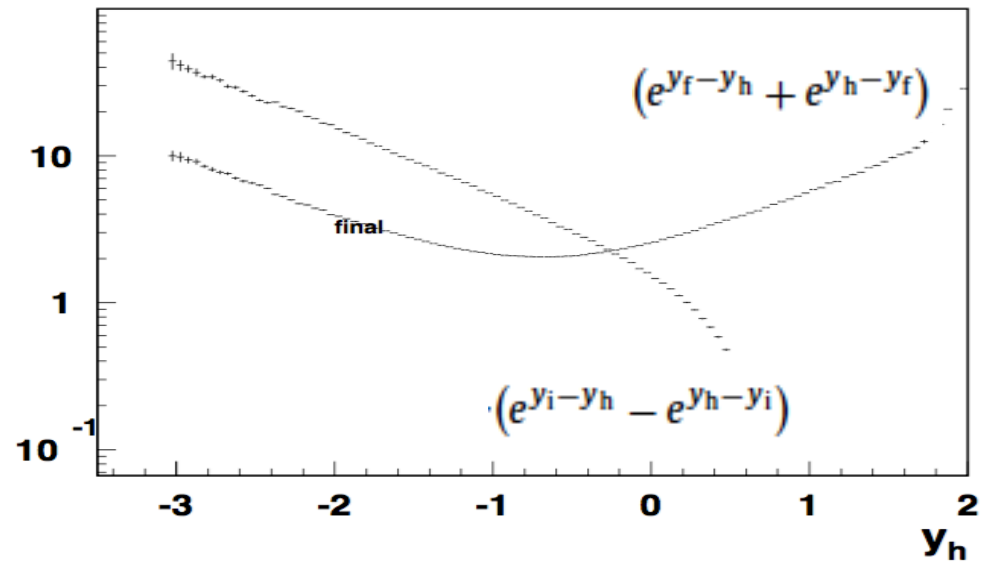
$$z = (P_h P)/(qP) = E_h/\nu$$



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

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

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