Elastic e-p scattering at ePIC for Early Physics

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Early science data

- for elastic scattering only e-p runs will be considered, years 2 and 3 will provide overall data amount of about 10 fb^{-1} for this study;
- year 4 will provide 8 fb^{-1} at higher energy, which are less interesting due to lower p' acceptance in FD:

$$\theta_p \underset{E\to\infty}{\to} \frac{\sqrt{Q^2}}{E_p}$$

per nucleon

	Species	Energy (GeV)	Luminosity/year (fb-1)	Electron polarization	p/A polarization
YEAR 1	e+Ru or e+Cu	10 x 115	0.9	NO (Commissioning)	N/A
YEAR 2	e+D e+p	10 x 130 ★	11.4 4.95 - 5.33	LONG	NO TRANS
YEAR 3	e+p	10 x 130 ★	4.95 - 5.33	LONG	TRANS and/or LONG
YEAR 4	e+Au e+p	10 x 100 10 x 250 ★	0.84 6.19 - 9.18	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au e+3He	10 x 100 10 x 166	0.84 8.65	LONG	N/A TRANS and/or LONG
Note: the eA luminosity is per nucleon					

- e+D and e+^{3}He runs could be used to access neutron form-factors, but require a different reconstruction procedure: LFHCAL + B0 EmCal (mixed with γ).

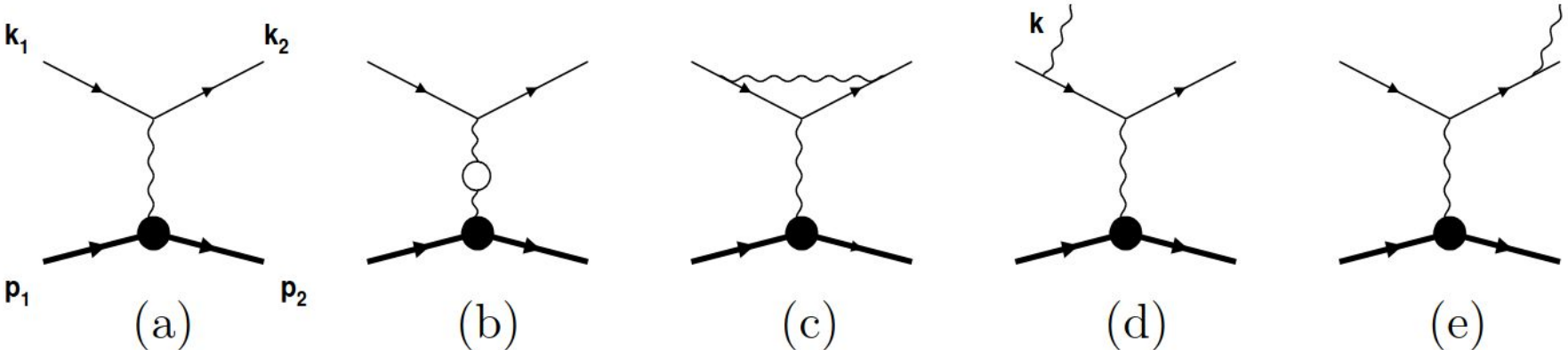
Elastic e-p scattering

- the process under study is 2→2 type:

$$e(k) + p(P) \rightarrow e'(k') + p'(P')$$

- QED Radiative Corrections to this process change the peak value and add the bremsstrahlung tail;
- cross section/polarization asymmetries give access to proton EM-form-factors $G_E(Q^2)$ and $G_M(Q^2)$:

$$\frac{d\sigma}{dQ^2} \approx \frac{4\pi\alpha^2}{Q^4}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau}\right] \quad \text{for } s >> Q^2, M^2$$



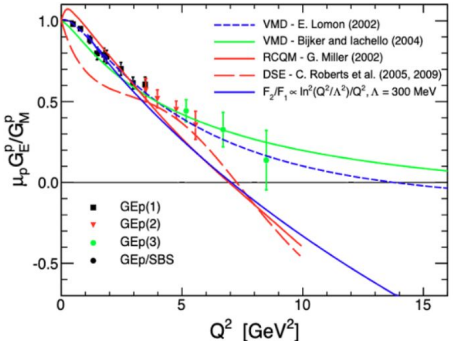
Target (proton) polarization asymmetry

- scattering off a polarized proton gives asymmetry [C.F. Perdrisat et al.,Prog. Part. Nucl. Phys. 59, (2007) 694] in TRF:

$$A = -\frac{2\sqrt{\tau(1+\tau)}\tan(\theta_e/2)}{G_E^2 + \frac{\tau}{\epsilon}G_M^2}\left[\sin\theta^*\cos\phi^* G_E G_M + \sqrt{\tau[1+(1+\tau)\tan^2(\theta_e/2)]}\cos\theta^* G_M^2\right]$$

- for target polarized transversely to q we obtain Target Spin Asymmetry:

$$< \cos\phi^* > \sim \frac{G_E G_M}{G_E^2 + \frac{\tau}{\varepsilon}G_M^2} \sim \frac{G_E}{G_M}$$



- in collider kinematics invariant form should be used [A. Afanasev et al., Phys. Rev. D 64 (2001) 113009]:

$$\frac{d\sigma_0}{dQ^2} = \frac{2\pi\alpha^2}{S^2Q^4}\sum_i \theta_B^i \mathcal{F}_i \qquad \mathcal{F}_3 = -2M^2 G_E G_M, \qquad \mathcal{F}_4 = -M^2 G_M \frac{G_E - G_M}{1+\tau_p}$$

$$\theta_3^B = \frac{2m}{M}(q\,\eta\,k_2\xi - \eta\xi Q^2), \qquad \theta_4^B = \frac{mQ^2 q\,\eta}{M^3}(2p_1\xi - k_2\xi),$$

$$\eta_L = \frac{1}{\sqrt{\lambda_s}}\left(k_1 - \frac{S}{M}p_1\right),$$

$$\eta_T = \frac{1}{\sqrt{\lambda_s\lambda}}[(-SX + 2M^2Q^2 + 4m^2M^2)k_1 + \lambda_s k_2 - (SQ^2 + 2m^2 S_x)p_1],$$

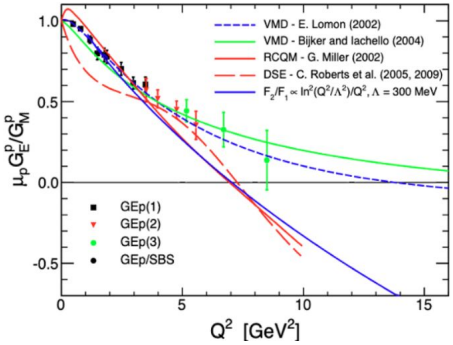
Double polarization asymmetry

- longitudinal polarization of electrons and protons in elastic scattering gives double spin asymmetry [M.J. Alguard et al., Phys.Rev.Lett.37, 1258 (1976)] in TRF:

$$A_{LL} = 2\tau \frac{G_M}{G_E} \frac{\frac{M}{E} + \frac{G_M}{G_E}[\tau \frac{M}{E} + (1+\tau)\tan^2\frac{\theta}{2}]}{1 + \frac{\tau}{\varepsilon}\left(\frac{G_M}{G_E}\right)^2} \underset{E\to\infty}{\to} \frac{2\tau}{\frac{\tau}{\epsilon} + \left(\frac{G_E}{G_M}\right)^2}(1+\tau)\tan^2\frac{\theta}{2}$$

- for not very large Q^2 the asymmetry may give access to the form-factor ratio (requires 1% precision);

$$\varepsilon = \frac{1-y}{1-y-\frac{1}{2}y^2} \to 1 \quad \tau = \frac{Q^2}{4M^2} \qquad A_{LL} \underset{Q^2\to\infty}{\to} 2\varepsilon\tau\left(\frac{M}{E} + \tan^2\frac{\theta}{2}\right)$$



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Parity-violating Single Spin Asymmetry

- scattering of polarized electrons of an unpolarized proton allows to observe γ-Z interference:

$$\varepsilon' \equiv \sqrt{\tau(1+\tau)(1-\varepsilon^2)},$$

$$A_{ep}^{\mathrm{PV}} \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx \frac{2\Re(\mathcal{M}_{\mathrm{EM}}\mathcal{M}_{\mathrm{weak}})}{|\mathcal{M}_{\mathrm{EM}}|^2 + \Re(\mathcal{M}_{\mathrm{EM}}\mathcal{M}_{\mathrm{weak}})}.$$

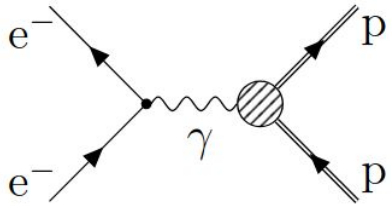
In the large energy limit we will get:

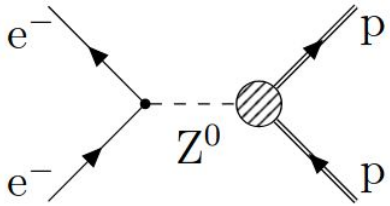
$$A_{ep}^{\mathrm{PV}} = \left(\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right)\left(\frac{\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z + g_V^e \varepsilon' G_M^\gamma G_A^e}{\varepsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}\right),$$

$$y = \frac{Q^2}{s} \to 0$$

$$\varepsilon = \frac{1-y}{1-y-\frac{1}{2}y^2} \to 1$$

$$A_{ep}^{PV} \underset{Q^2\to\infty}{\simeq} \left(-\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right)\left[\frac{G_M^Z}{G_M^\gamma} + g_V^e y \frac{G_A^e}{G_M^\gamma}\right] \simeq \left(-\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right)\frac{G_M^Z}{G_M^\gamma}$$

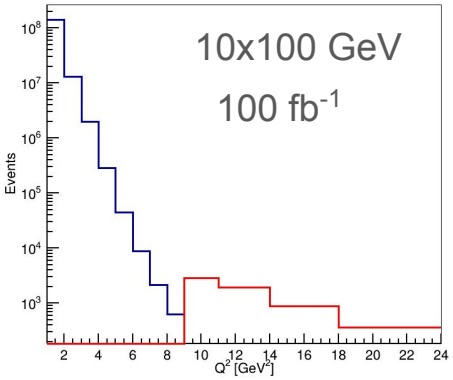




$$A_{ep}^{PV} \simeq 10^{-4} \times Q^2$$

$$N > \frac{10^8}{Q^4}$$

but $N_{ep}>10^6$ required at $Q^2=10$ GeV^2.



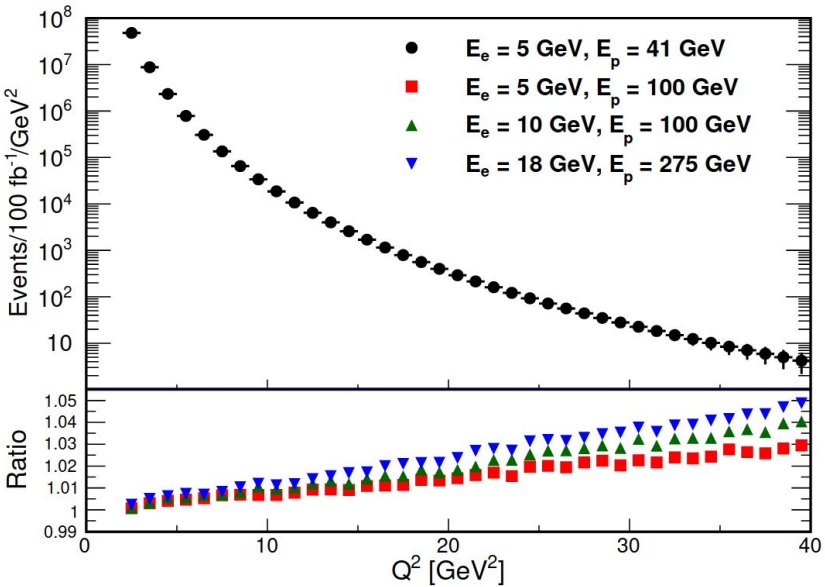
$$G_E^{\gamma,p} = \frac{2}{3}G_E^u - \frac{1}{3}G_E^d - \frac{1}{3}G_E^s$$

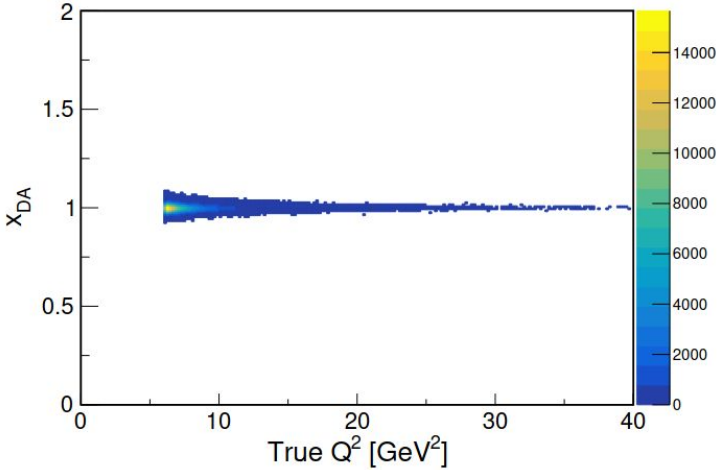
$$G_E^{Z,p} = \left(1 - \frac{8}{3}\sin^2\theta_W\right)G_E^u + \left(-1 + \frac{4}{3}\sin^2\theta_W\right)G_E^d + \left(-1 + \frac{4}{3}\sin^2\theta_W\right)G_E^s.$$

Previous study

B. Schmookler et al., arxiv:2207.04378 (2022) + github.com + presentations:

- elastic cross sections can be obtained in range of $6<Q^2<40$ GeV^2;
- DA method allows to reconstruct x;
- background can be removed by $\Delta\phi$, P_T, P_z and E cuts.





(d) DA method

Veto	Total Events (Scaled to 100 fb^{-1})
None	500×10^6 (8×10^{12})
1	148 (2.37×10^6)
1+2	1 (16000)
1+2+3	1 (16000)
1+2+3+4	0 (0)
1+2+3+4+5	0 (0)

This study

Generator:

- started with ELRADGEN 2.0 I. Akushevich et al., Comput.Phys.Commun. 183 (2012) 1448-1467
- adapted to high energy kinematics (few terms can still be improved);
- implemented of fully differential form in TFoam;
- calculation is completely Lorentz invariant - frame independent;
- include polarizations of both e^- and P beams;
- include both the elastic peak with radiative correction and hard bremsstrahlung tail;

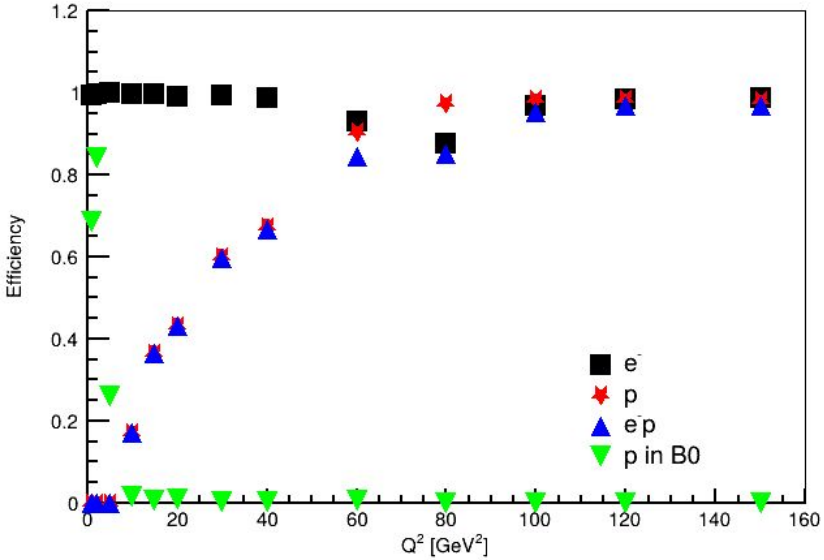
MC method:

- using beam effects through “abconv” v0.1.3 (approximate, changes energies);
- using “npsim” v1.4.6 simulations with the “epic_craterlake.xml” configuration;
- using “eicrecon” v2.4.3 reconstruction and root script to read results.

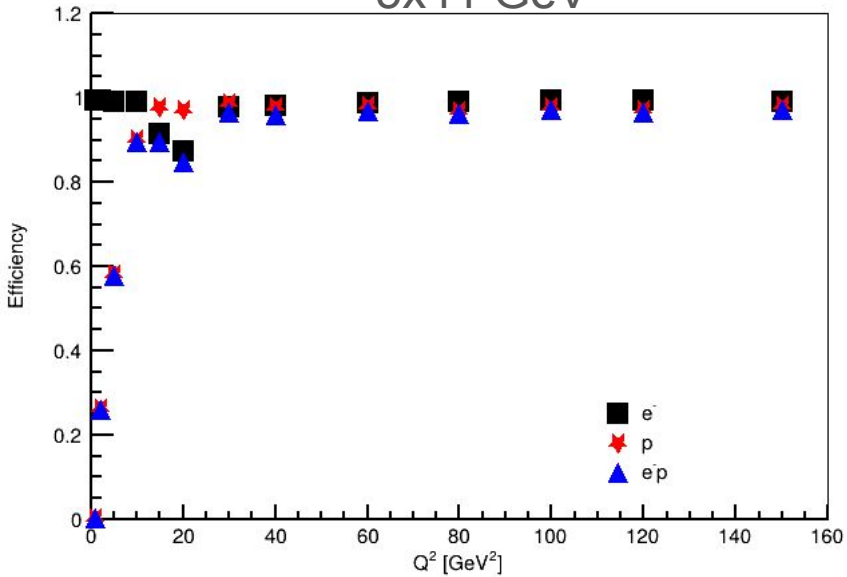
Elastic reaction efficiency

- efficiency is high for e^- everywhere, at least for $Q^2>1$ GeV^2;
- for 10x100 GeV config. p-efficiency drops to zero at $Q^2<10$ GeV^2 where p' goes into the gap between FD ($\eta<3.5$) and B0 ($\eta>4.6$) or in B0 (TruthSeeded tracking);
- for 5x41 GeV config. p-efficiency also falls at low Q^2, and at $Q^2=1$ GeV^2 it drops to 0.2%, while B0 efficiency is still negligible;

10x100 GeV



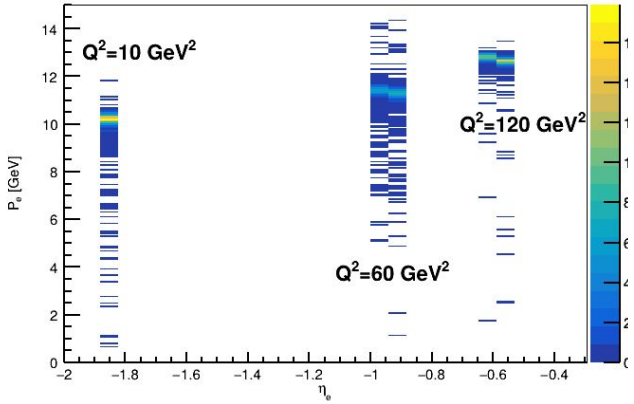
5x41 GeV



Elastic reaction kinematics

- e^- and p move with Q^2 into higher FD acceptance region, momenta remain almost fixed;
- at medium Q^2=10-15 GeV^2 the proton sometimes goes into the detector gap: 3.5<η<4.6;
- at low Q^2=1-10 GeV^2 the proton goes into B0 η>4.6;
- at Q^2<0.1 GeV^2 the proton goes into RomanPots (η>6);

10x100 GeV



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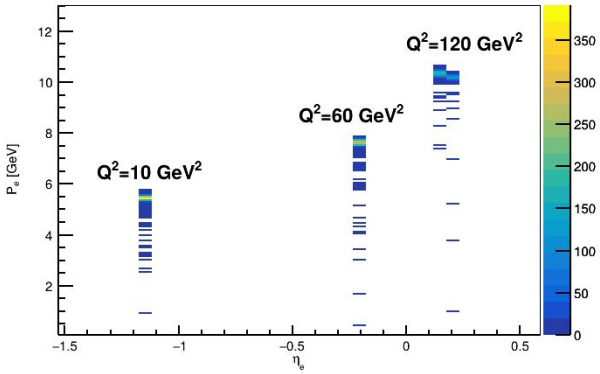
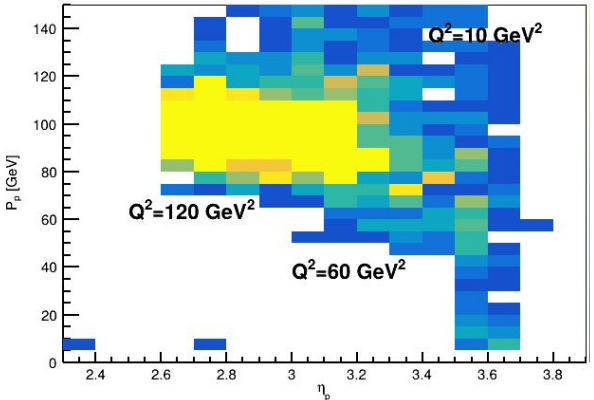
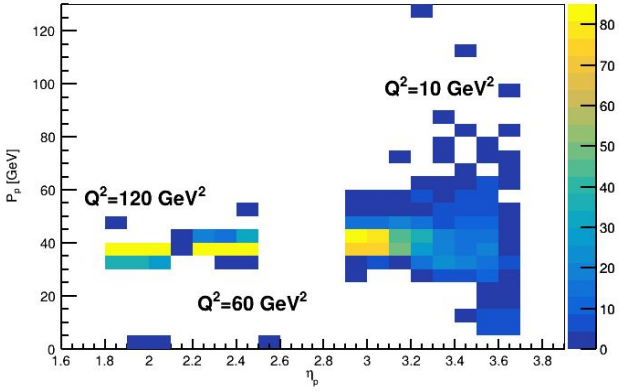
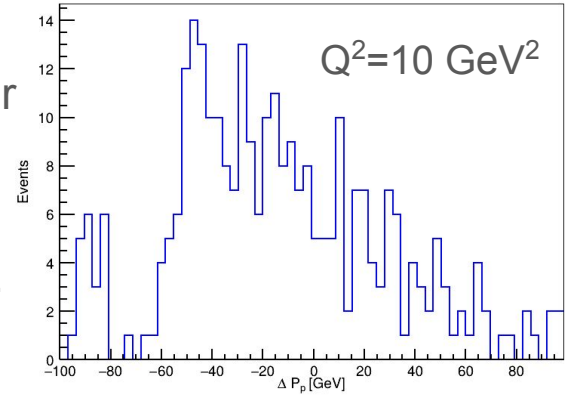


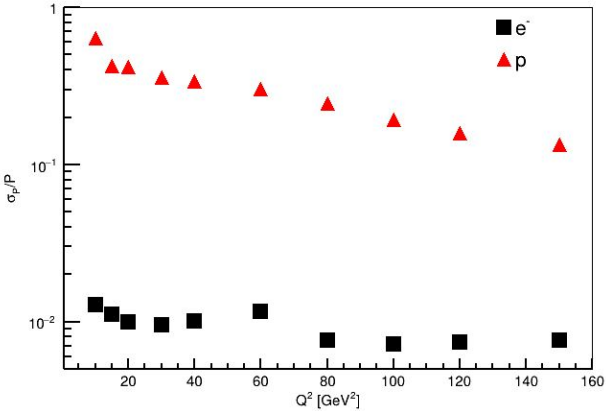


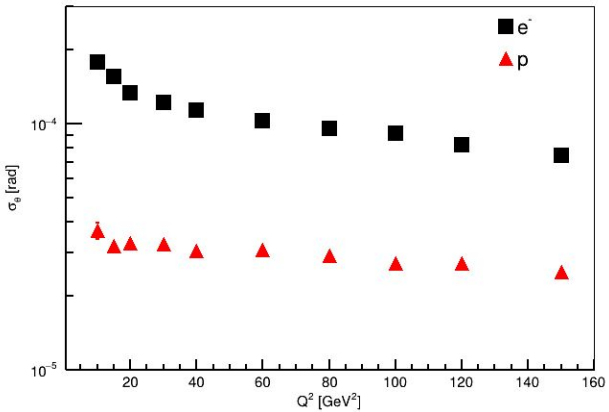


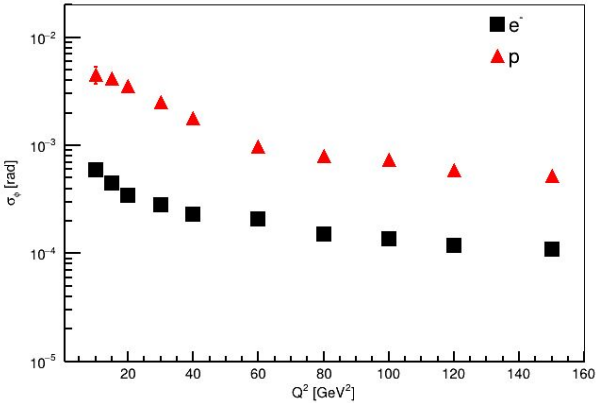
Elastic reaction: particle resolutions

- e^- momentum and angular resolutions improve slightly with Q^2;
- p momentum and angular resolutions also improve with Q^2;
- e^- momentum resolution is better than p, opposite for angular resolutions;
- overall angular resolutions are good, while momentum resolution of proton is much larger than nucleon mass scale.









Momentum resolution of dRICH

- dRICH is measuring Cherenkov angle, assuming PID we can obtain particle momentum:

$$p = \frac{M}{\sqrt{(n^2 - 1) - n^2 \sin^2 \theta_C}}$$

- momentum resolution is then:

$$\frac{\sigma_p}{p} = n^2 \frac{p^2}{2M^2} \sin 2\theta_C \sigma_{\theta_C}$$

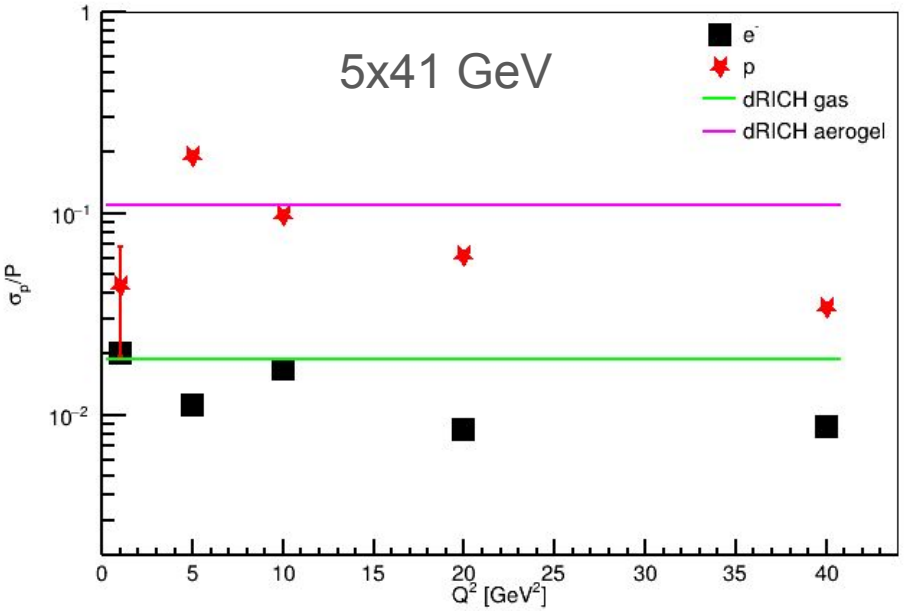
where:

$$\theta_C(gas) \sim 2^\circ \qquad \sigma_{\theta_C} \sim 3 \times 10^{-4}$$

$$\theta_C(aerogel) \sim 11^\circ$$

better than tracking

(will not work for higher energies)

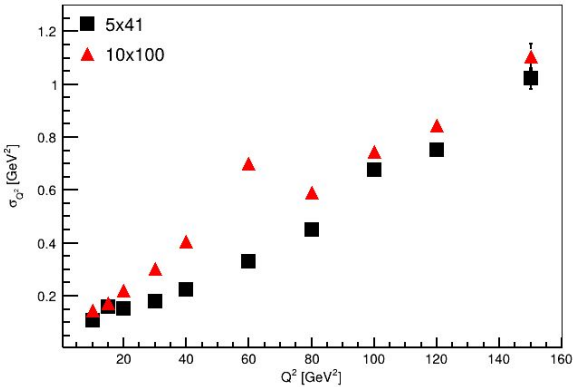


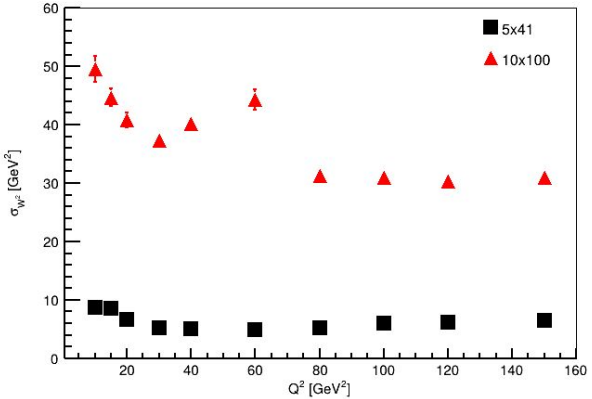
Elastic reaction: invariant resolutions

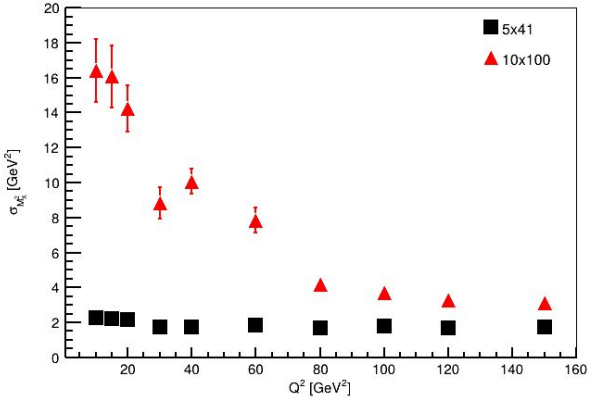
The measurement of elastic e'p' cross section requires:

1. separation from radiative processes (e'p'γ) - q+P invariant mass<m_π;
2. separation from inelastic processes (e'p'X) - e+P missing mass<m_π or momentum conservation veto;
3. reconstruction of the scale Q^2.

<u>Using directly reconstructed 4-momenta first two steps cannot be performed.</u>

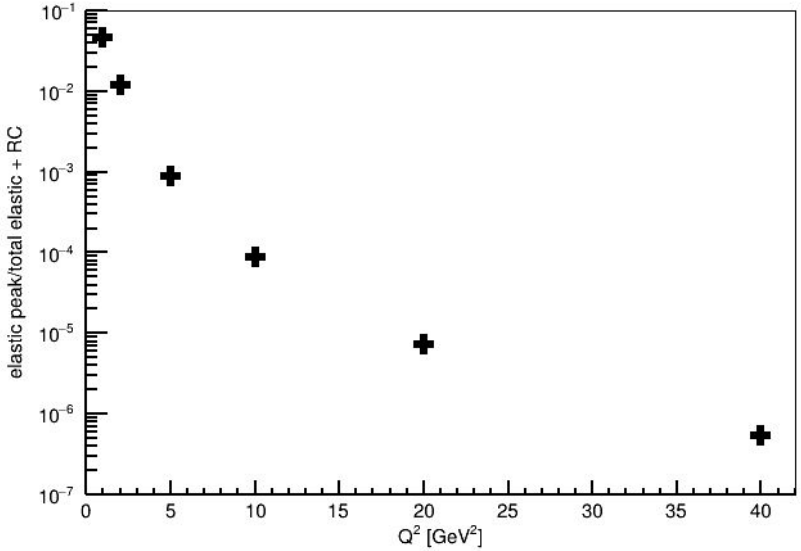


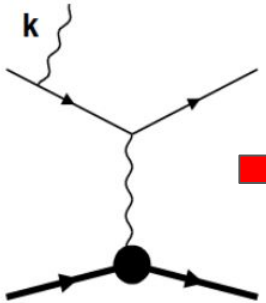


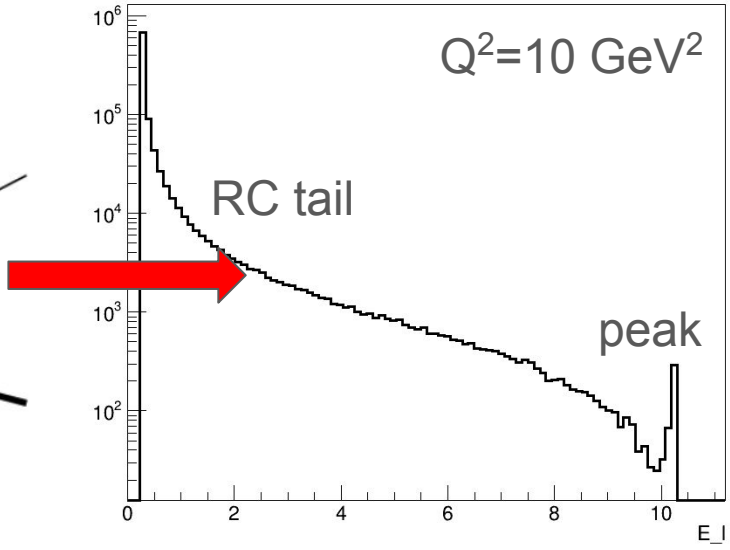


Elastic peak contribution

- NB at high Q^2 the contribution of the elastic peak into the total elastic cross section (including RC) becomes negligible;
- since bremsstrahlung gamma mass is zero the missing mass of this channel is also zero, the only separation can be done using electron W or x variables;
- to separate elastic peak ePIC must have W-resolution better than pion mass.







W^2 reconstruction

- q+P invariant mass is defined as following:

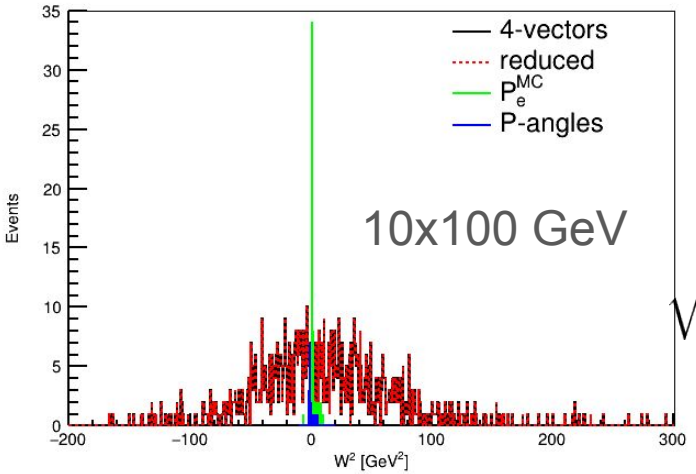
$$W^2 = (k + P - k')^2 = M^2 - Q^2 + y(s - M^2) \qquad y = 1 - \frac{Pk'}{Pk}$$

- as noticed in previous study y~10^{-2} but its resolution is compromised by e' momentum resolution, however assuming that 2→2 process is already identified (X=0) it can be improved using p' angles:

not working for collinear γ

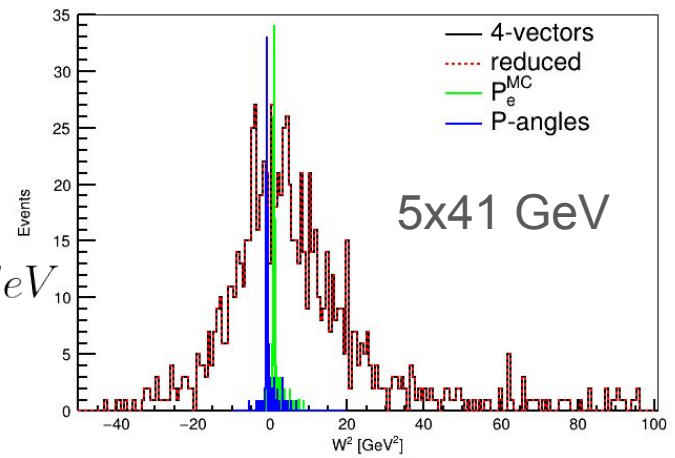
$$y = \frac{PP' - M^2}{Pk}$$

$$|\vec{P'}| = \frac{|\vec{P}|\cos\gamma - E_0}{\cos\theta_p - \sin\theta_p \frac{\sin\phi_p}{\tan\theta_e \sin\phi_e}}$$



$$\sigma_{W^2} \sim 0.2\,GeV^2$$

$$\sqrt{M^2 + 1.5\sigma_{W^2}} \simeq 1.086\,GeV$$

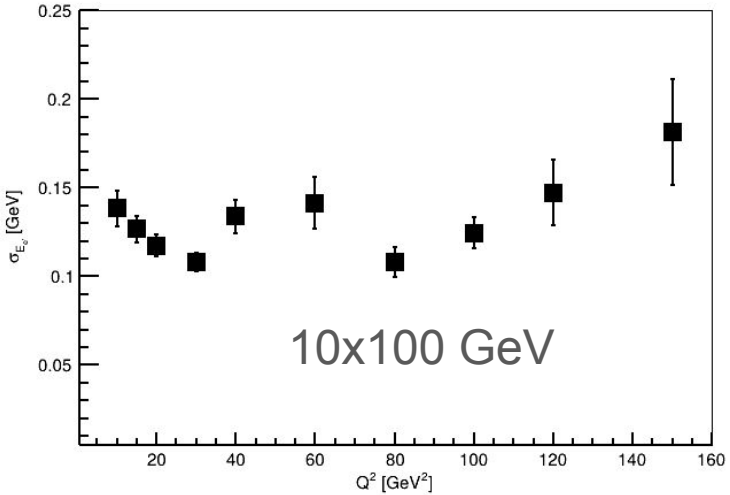


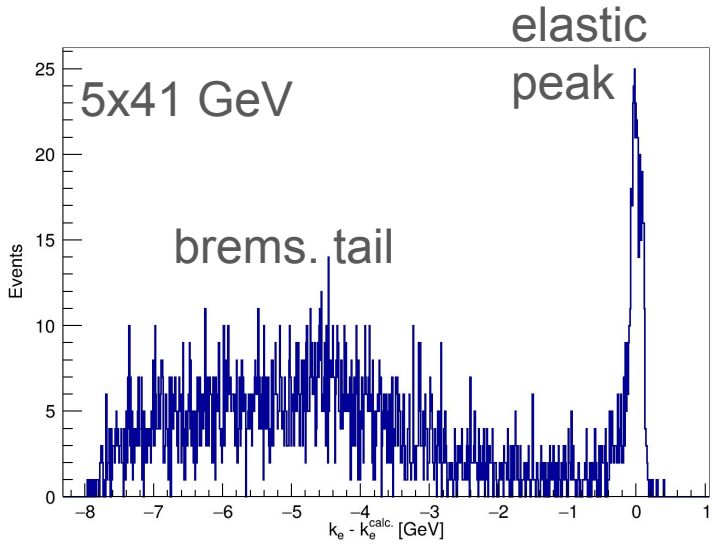
E’ reconstruction

- to cut off bremsstrahlung gammas we can use LAB equations [C. Sofiatti and T.W. Donnelly, Phys.Rev.C84, 014606 (2011)]:

$$k' = \frac{1}{a}\left[b + E_{tot}\sqrt{\xi^2 - m_e^2(M^2 + p_{tot}^2 \sin^2\theta_e)}\right]$$

- comparing the measured electron momentum with calculated from the electron scattering angle allows to separate bremsstrahlung tail very clearly:





M_X^2 reconstruction

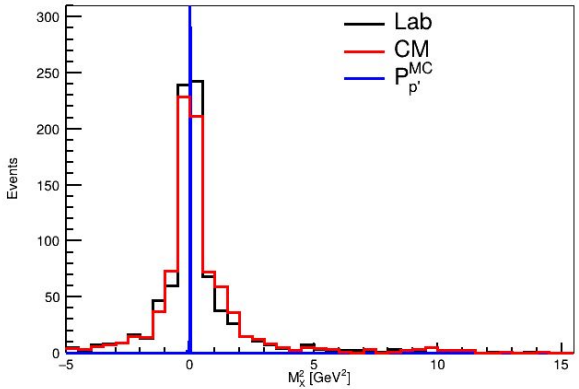
- identification of the elastic e+p->e'+p' process requires:

$$M_X^2 = \left[(k - k') + (P - P')\right]^2 < m_\pi^2$$

- no simplification is possible (until final state remains unknown);
- e-p CM can be used to cancel some spatial vectors:

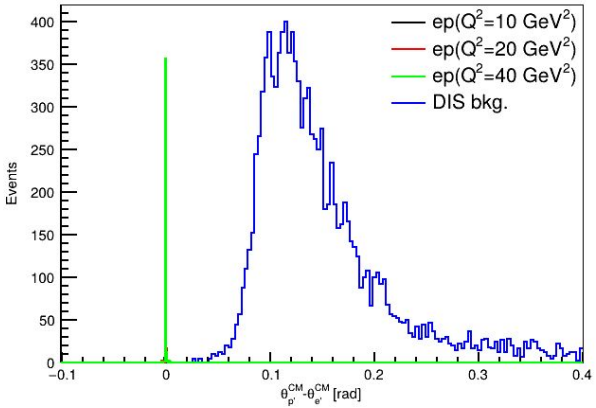
$$M_X^2 = s + M^2 + 2E_{e'}^{CM} E_{p'}^{CM} (1 - \cos\theta_{e'p'}^{CM}) - 2\sqrt{s}(E_{e'}^{CM} + E_{p'}^{CM}) < m_\pi$$

- no significant difference between CM and LAB;
- best resolution at 5x41 GeV and Q^2>4 GeV^2 reaches 0.9 GeV^2; **NB - using generated P_p get 0.006 GeV^2;**
- cannot separate (3σ) channels with: ≤21π, ≤6 K, ≤3 p;
- without AfterBurner the resolution is slightly better;
- must use 4-momentum conservation vetoes.

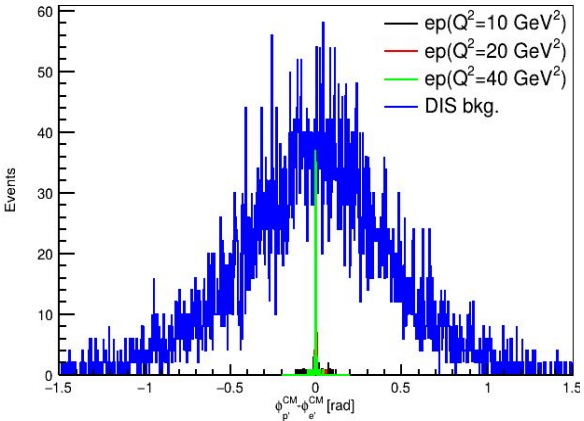


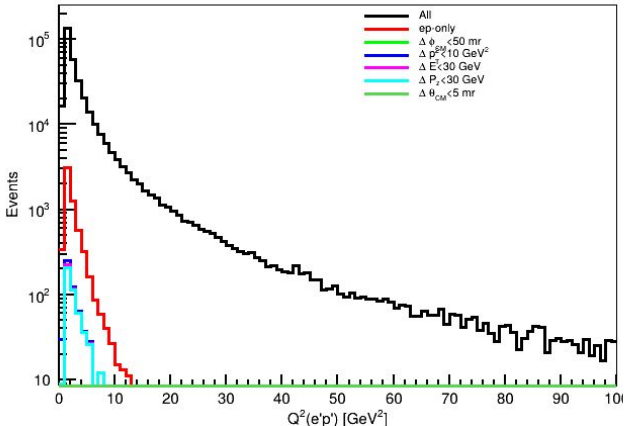
DIS backgrounds from Pythia8

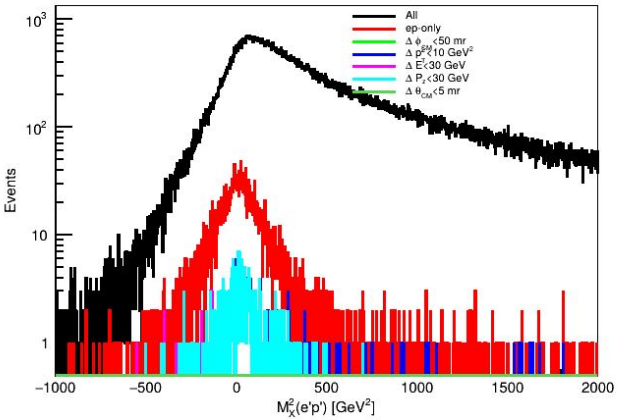
1. veto on additional (to e'p') reconstructed particles reduces yield by 2 orders of mag.;
2. coplanarity ($\Delta\varphi$) in CM indeed provides a good elastic channel selection power;
3. P_T, E and P_Z cuts have no separation power due to poor resolution;
4. the total suppression of all cuts is $0.75*10^{-4}$, sufficient to compensate cross section ratio elastic(Q^2>1 GeV^2)/DIS(Q^2>1 GeV^2)=2.2 nb/0.6 μb=$4*10^{-3}$;
5. Q^2 dependence of the DIS background is similar to the elastic one, background residuals are mostly present at low Q^2 and can be completely removed by $\Delta\theta$ CM cut.



Are single pion production channels included in Pythia8?



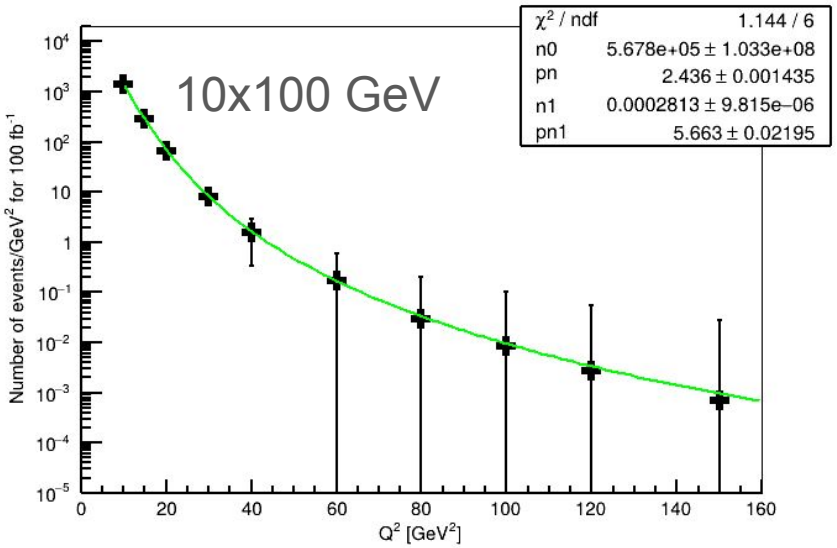


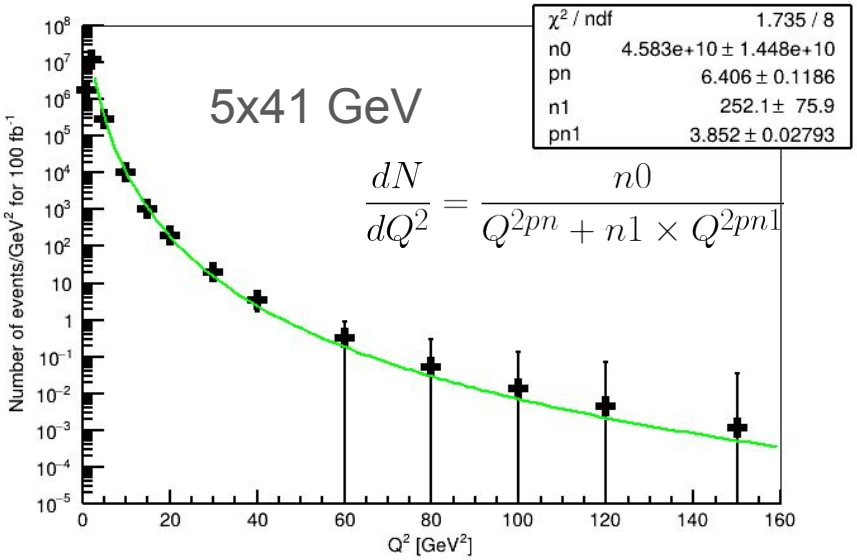


Projected statistics

- number of events are similar to the previous study, except the low Q^2 region;
- statistical precision of 1% reached at Q^2=10-20 GeV^2, for higher Q^2 elastic peak does not provide a precise reference.

$$L_{MC} = \frac{N_{gen}}{\int \sigma_{MC}(Q^2) dQ^2} \qquad N_{proj} = N_{rec}\frac{L_{ePIC}}{L_{MC}} = \frac{N_{rec}}{N_{gen}} L_{ePIC} \int \sigma_{MC}(Q^2) dQ^2$$



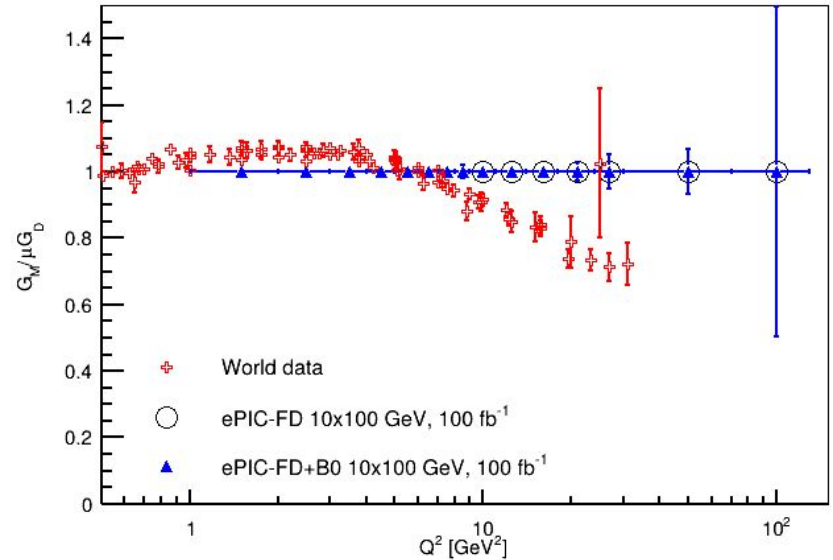


Final Runs projections

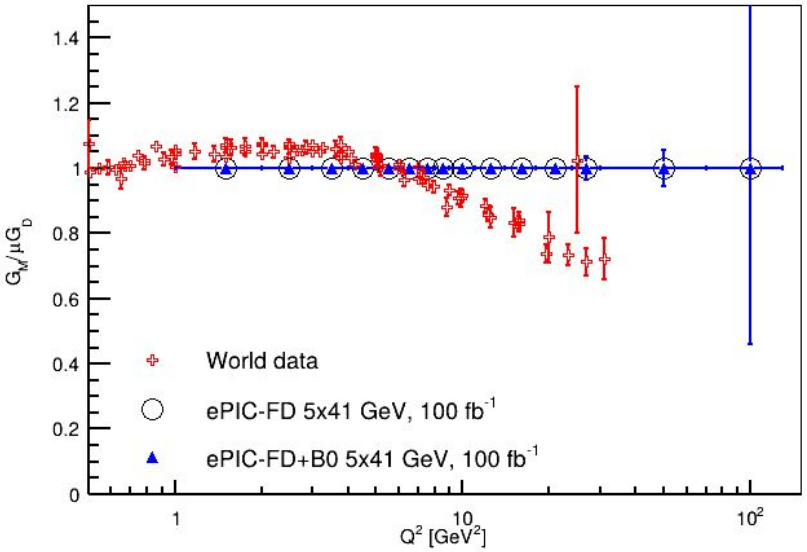
- at 100 GeV FD(η<3.5) acceptance limits Q^2>10 GeV^2, high stat. up to 50 GeV^2;
- at 41 GeV FD(η<3.5) acceptance limits Q^2>2 GeV^2, high stat. up to 50 GeV^2;
- at 100 GeV most of low Q^2 events are measured by B0 (η>4.6).

$$\theta_p \underset{E\to\infty}{\to} \frac{\sqrt{Q^2}}{E_p}$$

$\theta_p(E_p = 100GeV, Q^2 = 10GeV^2) \sim 1.8°$



$\theta_p(E_p = 41GeV, Q^2 = 1GeV^2) \sim 1.4°$

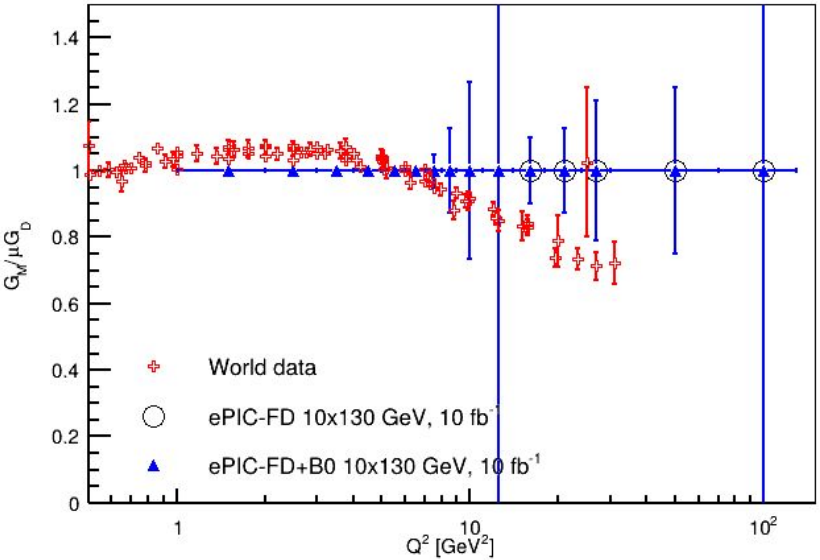


Early Physics projections

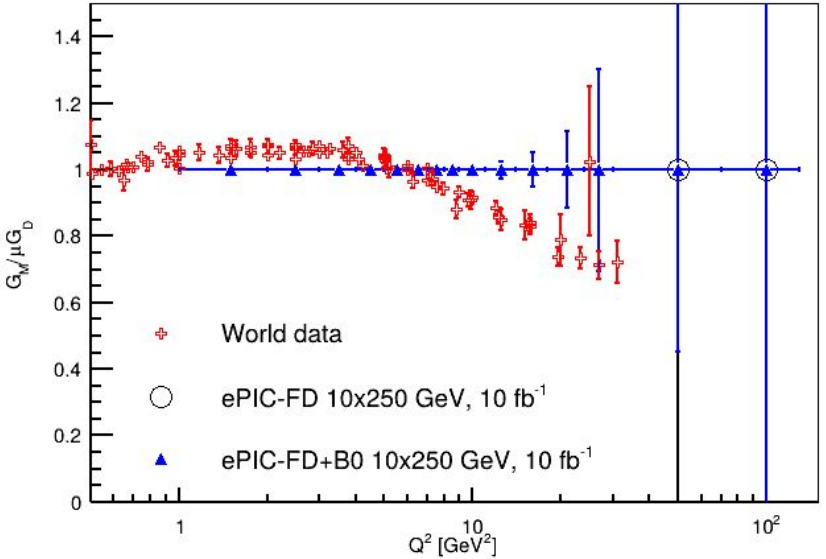
- at 130 GeV FD(η<3.5) acceptance limits Q^2>15 GeV^2, allowing to measure 50 events;
- at 250 GeV FD(η<3.5) acceptance limits Q^2>40 GeV^2, allowing to measure 0.2 events;
- most of low Q^2 events are measured by B0 (η>4.6). Some lost in the gap between FD and B0.

$$\theta_p \underset{E\to\infty}{\to} \frac{\sqrt{Q^2}}{E_p}$$

$$\theta_p(E_p = 130GeV, Q^2 = 20GeV^2) \sim 2^\circ$$



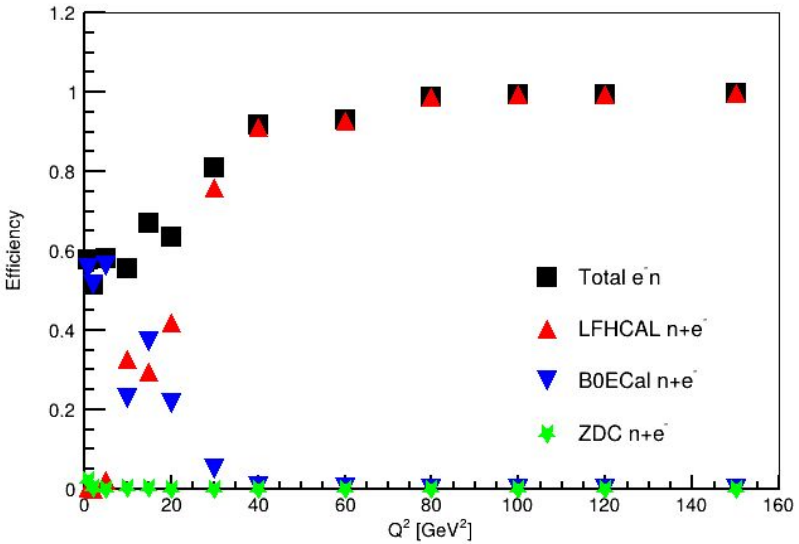
$$\theta_p(E_p = 250GeV, Q^2 = 40GeV^2) \sim 1.5^\circ$$

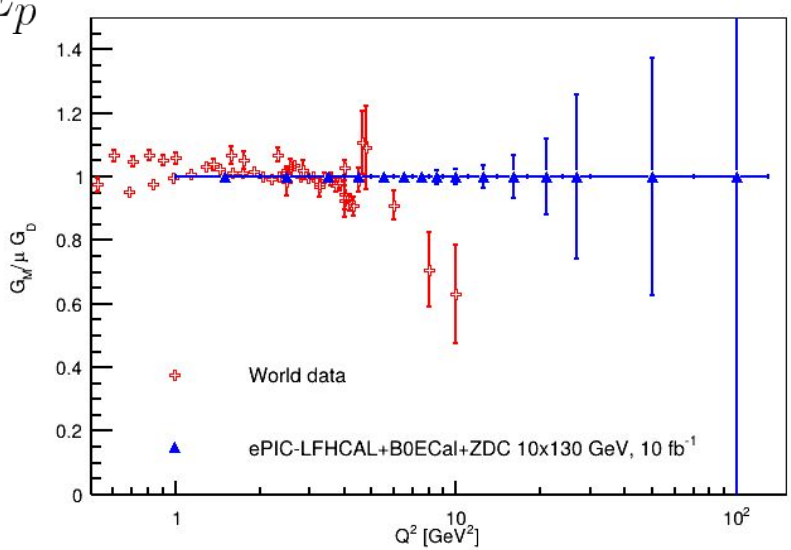


Early Physics projections for e-n

- e-D data at 130 GeV may allow to access less known neutron G_m;
- selected clusters in LFHCAL, B0ECal and ZDC with deposited energy >1 MeV;
- like for the proton, at Q^2<15 GeV^2 B0ECal is most efficient, above - LFHCAL;
- no background or neutron PID is considered here (every cluster = n).

$$\theta_p(E_p = 130GeV, Q^2 = 20GeV^2) \sim 2^\circ \quad \theta_p \underset{E\to\infty}{\to} \frac{\sqrt{Q^2}}{E_p}$$



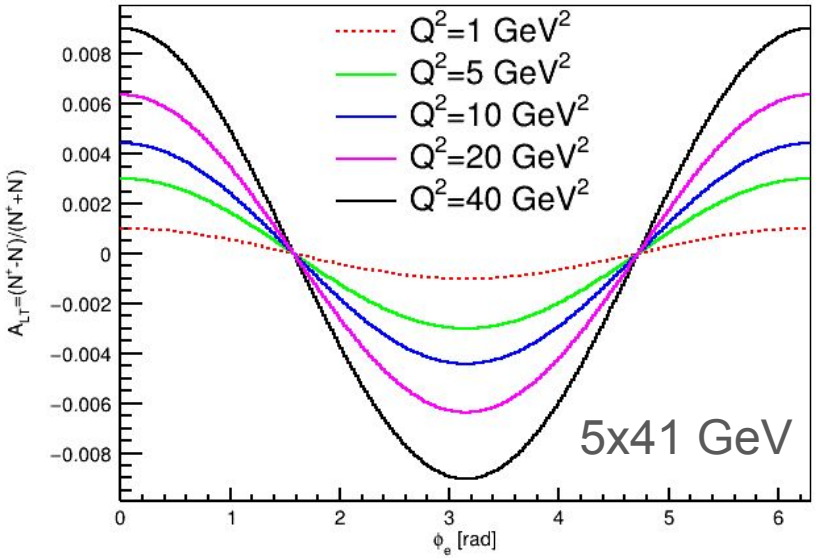


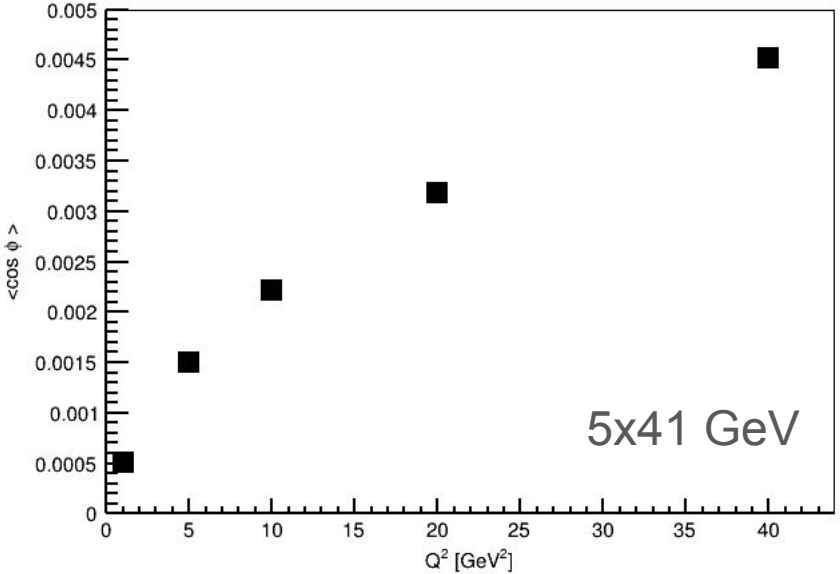
Projected proton spin asymmetries

- polarization asymmetry for transversely polarized protons indeed has cos(φ) shape;
- asymmetry increases with Q^2, but the absolute value is small <0.5%;
- at Q^2=10 GeV^2 we expected 10^4 events/100 fb^{-1}, thus the error on asymmetry >1%.

$$\lim_{A_{LT}\to 0} \sigma_{A_{LT}} \simeq \frac{1}{\sqrt{N_{tot}}}$$

at JLab 11 GeV Q^2=10 GeV^2
A_{LT} will be 11%

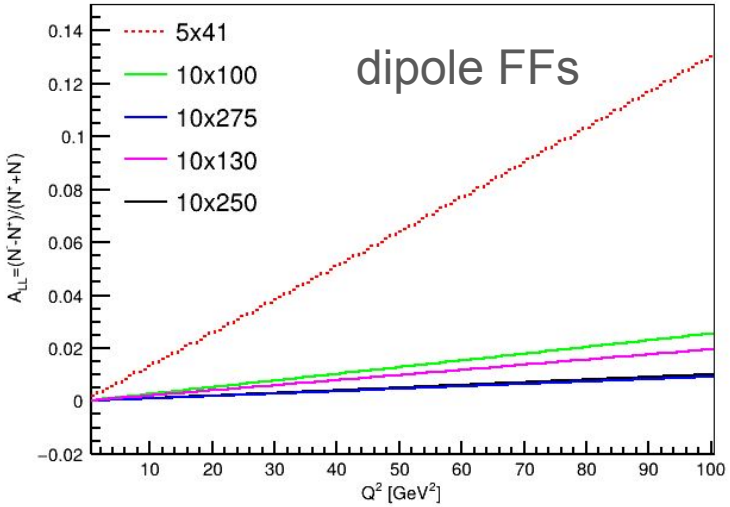


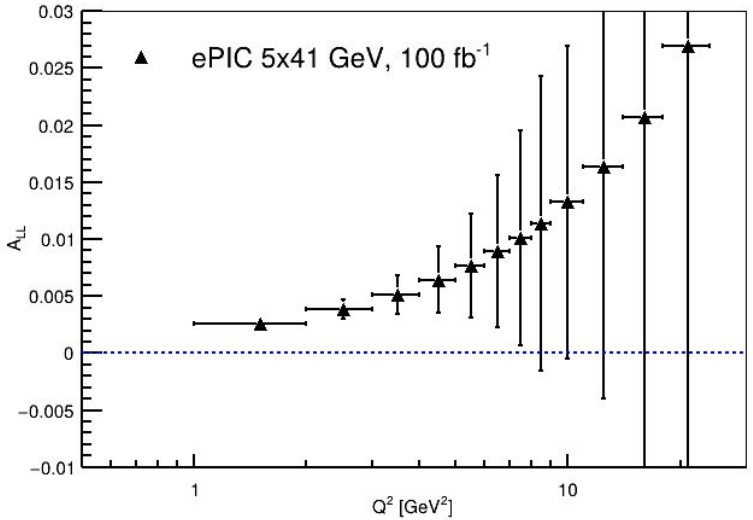


Projected double spin asymmetries

- double spin asymmetry for longitudinally polarized electrons and protons increases linearly with Q^2;
- asymmetry is largest at lowest ePIC energy - 5x41 GeV;
- with 100 fb^{-1} the asymmetry can be measured up to Q^2=5-7 GeV^2, however the precision could be insufficient to obtain G_E/G_M (maybe combining many runs it will be feasible).

$$\sigma_{A_{LL}} \underset{A_{LL}\to 0}{\to} \frac{1}{P_e P_p} \frac{1}{\sqrt{N}}$$



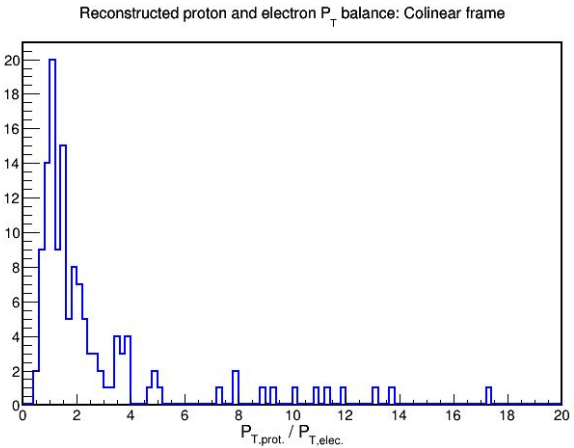


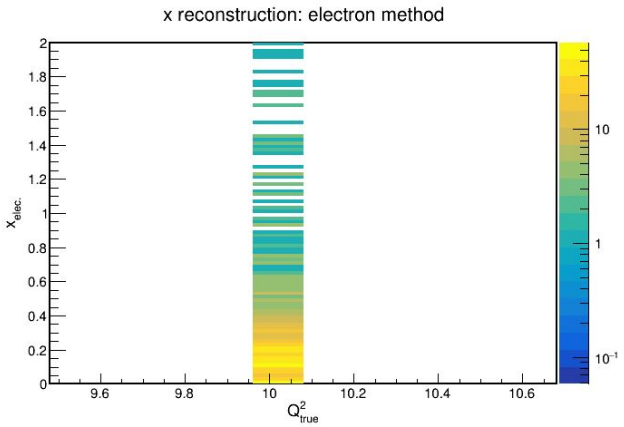
Conclusions

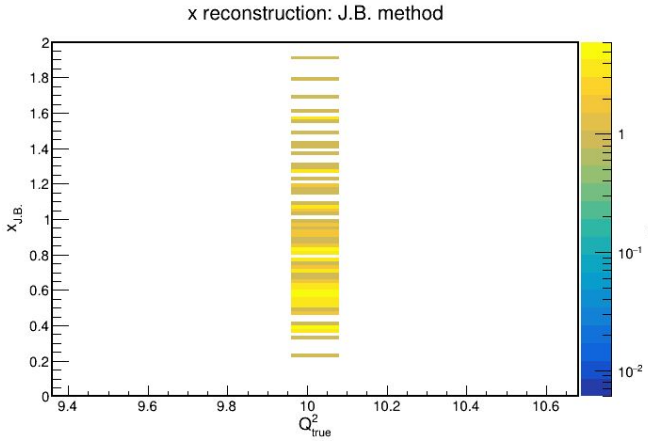
- elastic scattering is the most precisely (1%) known cross section in e-p scattering, which can be used at EIC as a reference for the absolute efficiency benchmark;
- overall angular resolutions are good, while momentum resolutions are much larger than pion mass scale; dRICH could improve momentum resolution for protons at lowest energy;
- e^- efficiency is high everywhere (except $Q^2<1$ GeV^2), but p-efficiency of FD is suppressed at low Q^2, where proton goes into the the gap between FD($\eta<3.5$) and B0($\eta>4.6$) or in B0;
- peak contribution falls exponentially with Q^2, reaching 10^{-4} at $Q^2=10$ GeV^2, requiring a high resolution on W to remove the bremsstrahlung tail;
- missing mass resolution is insufficient to isolate the elastic channel, proton momentum resolution is dominant contribution to this uncertainty, but angular correlation in CM seems to solve this problem;
- projected statistics allow to reach 1% stat. precision at $Q^2<10$ GeV^2, mostly covered by B0-detector;
- polarization asymmetries may allow to measure G_E/G_M ratio, but asymmetries are small at ePIC and statistical precision might be insufficient.

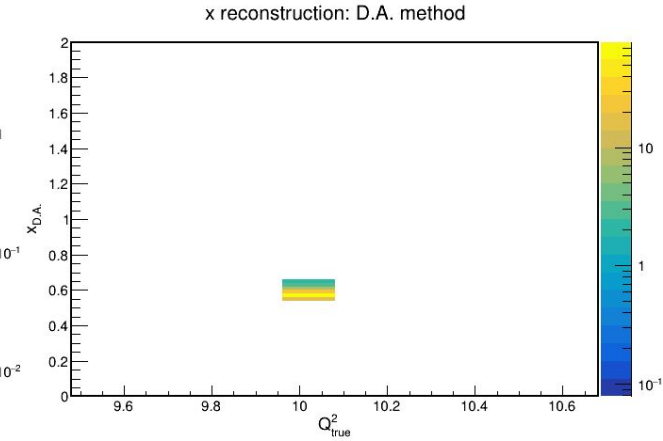
Collider kinematic methods

- using “Elastic_reco.C” macro from previous study we found that none of methods able to reconstruct x;
- only Q^2 reconstructed by DA method is very precise, but x is offset;
- ϕ and p_T widths in LAB are 10÷100 times larger than in previous study (50 mrad → 500 mrad, 0.05 GeV →5 GeV).









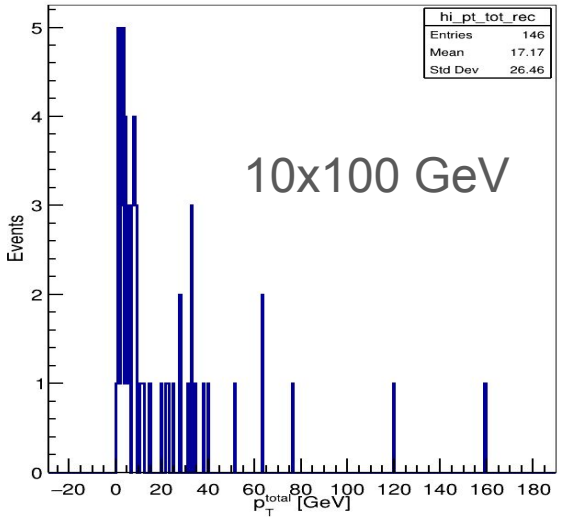
4-momentum conservation veto

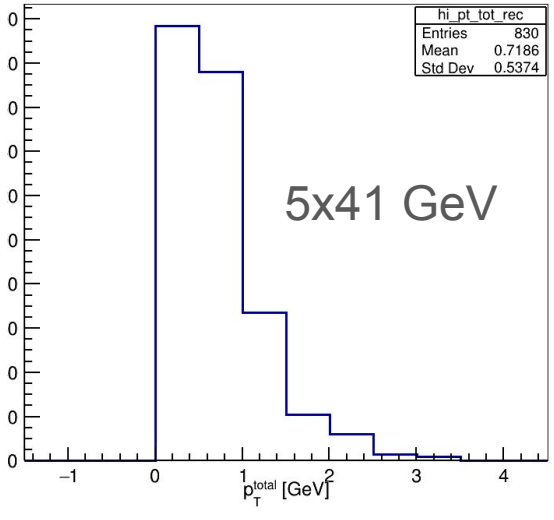
- p beam is off-axis, p_T and φ balance should include crossing angle correction, or evaluated in CM:

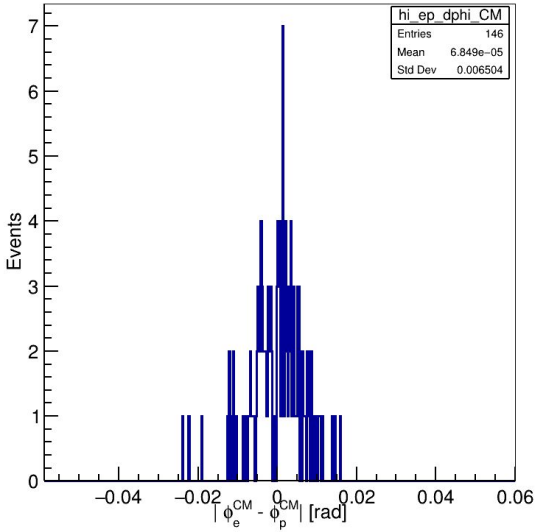
$$\sqrt{\vec{p}^{\,2}_{T,e-p} - \vec{p}^{\,2}_{T,beam}} = 0$$

- coplanarity ($\Delta\varphi$) in CM indeed provides a good channel selection power.

Q^2=10 GeV^2

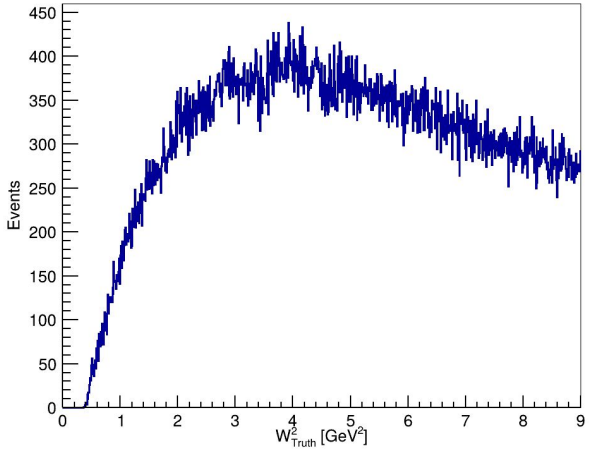


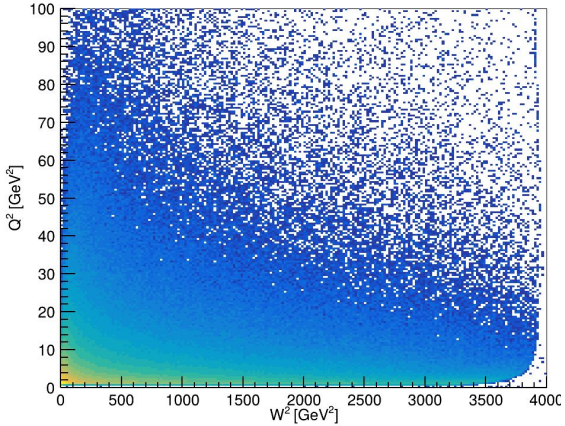


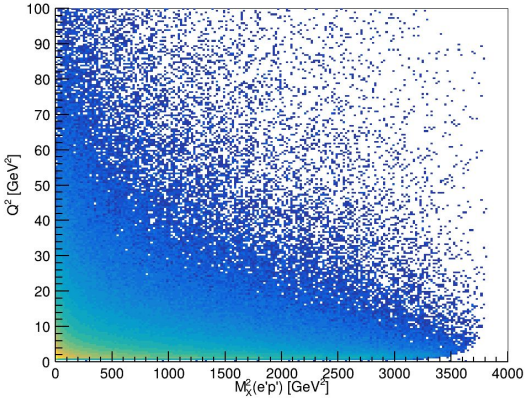


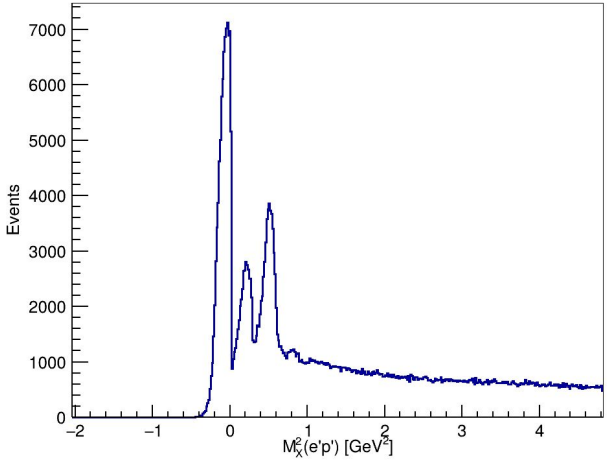
DIS backgrounds from Pythia8

1. Pythia8 simulation extends below elastic peak W=M, but shows no peaks of elastic and nucleon resonances;
2. it extends to zero missing mass, and exhibits 3 peaks, at -0.03, 0.22 and 0.5 GeV^2, presumably π^0, η and ϱ^0;
3. this region perhaps can be used as an estimate of elastic e'p' channel background.

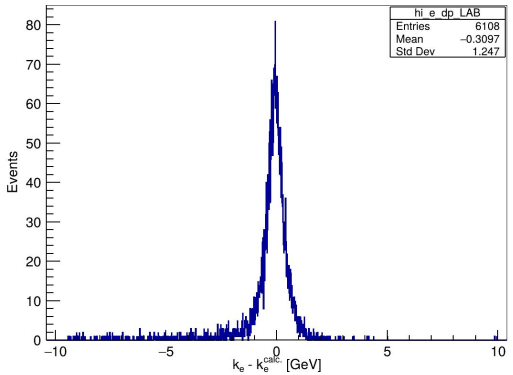


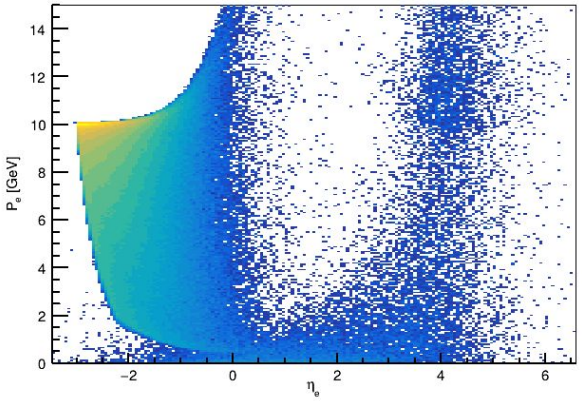


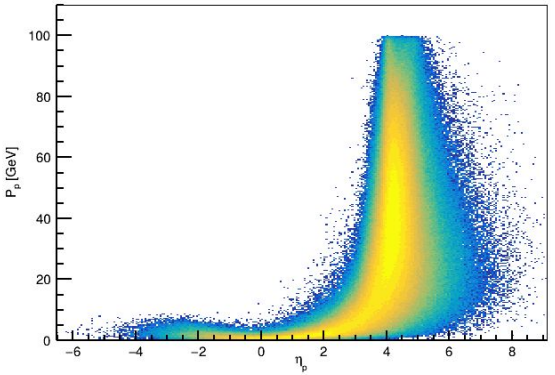


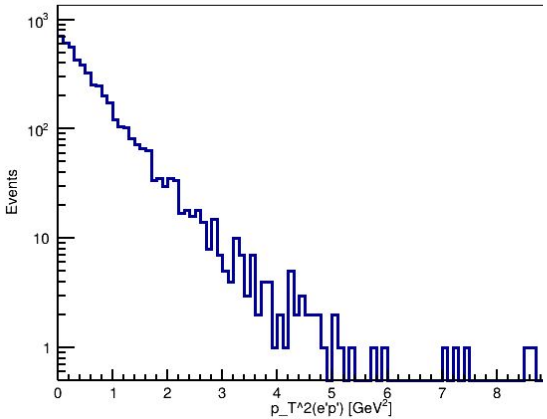


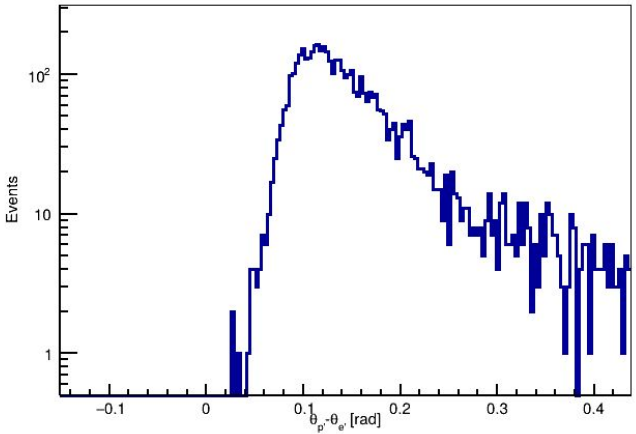
DIS backgrounds from Pythia8

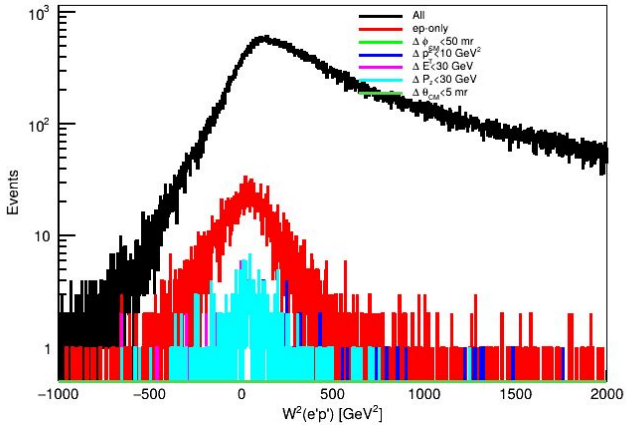












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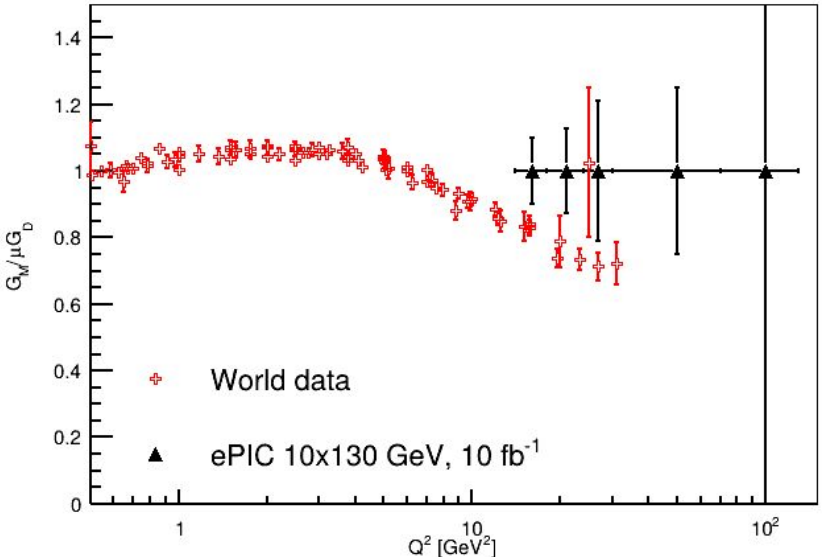
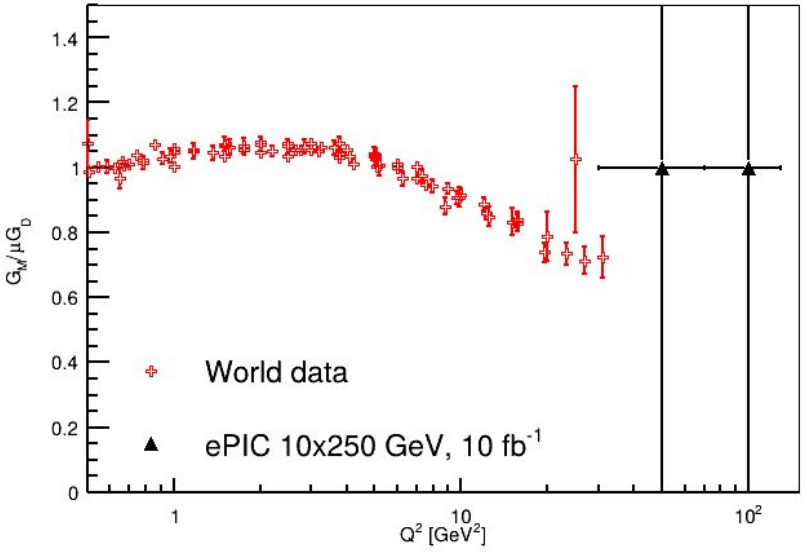
$$\theta_p(E_p = 130GeV, Q^2 = 20GeV^2) \sim 2^\circ \qquad \theta_p \underset{E\to\infty}{\to} \frac{\sqrt{Q^2}}{E_p} \qquad \theta_p(E_p = 250GeV, Q^2 = 40GeV^2) \sim 1.5^\circ$$





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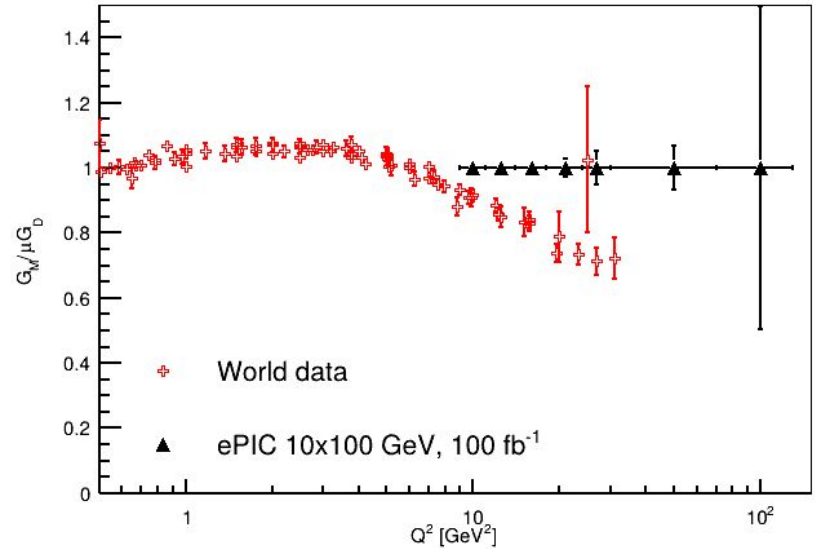

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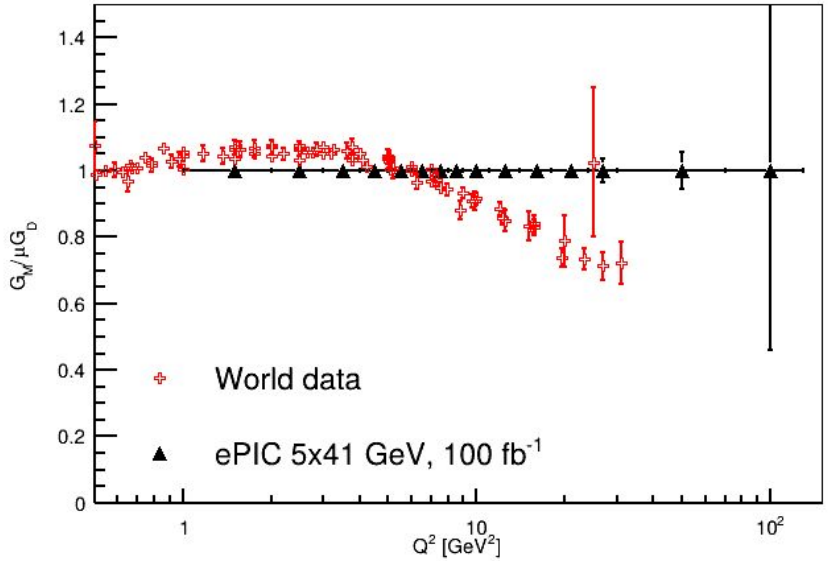

130 GeV neutron in calorimeters