Elastic e-p scattering at ePIC 10x100

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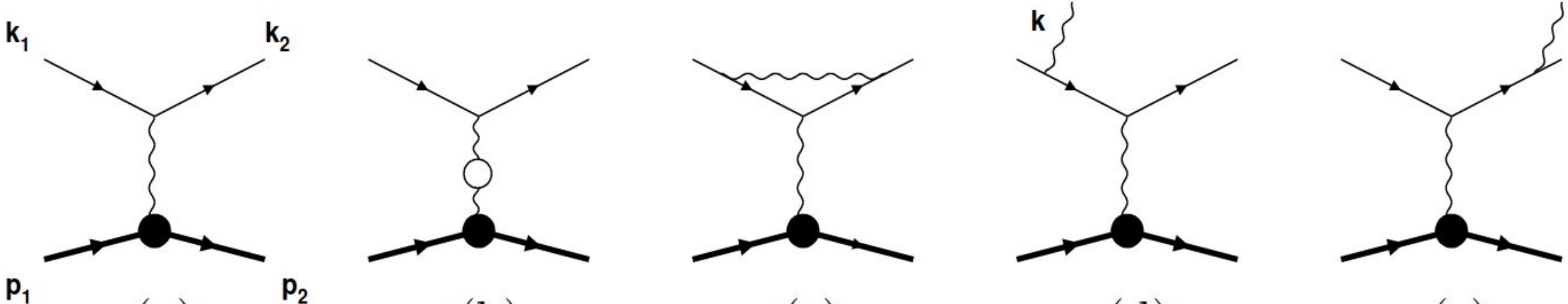
Elastic e-p scattering

- 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 bremsstrahlung tail;
- cross section/polarization asymmetries give access to proton EM-form-factors $G_E(Q^2)$ and $G_M(Q^2)$:

$$\frac{d\sigma_{Born}}{dQ^2} \simeq \frac{4\pi^2\alpha^2}{Q^4}\frac{G_E^2 + \tau G_M^2}{1+\tau}$$



(a) (b) (c) (d) (e)

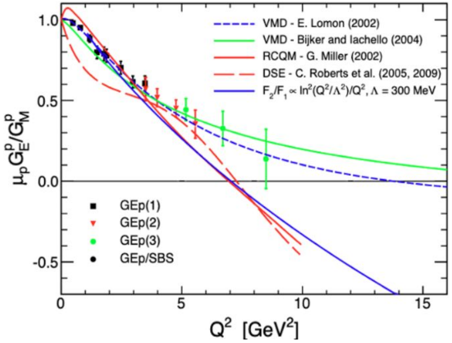
Target polarization

- scattering of 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]:

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

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

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

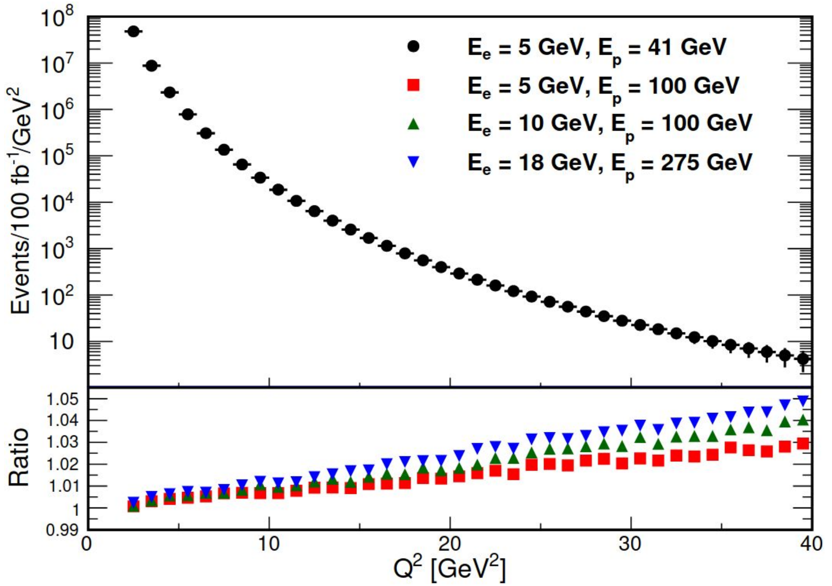
$$\eta_L = \frac{1}{\sqrt{\lambda_s}}\left(k_1 - \frac{S}{M}p_1\right),$$

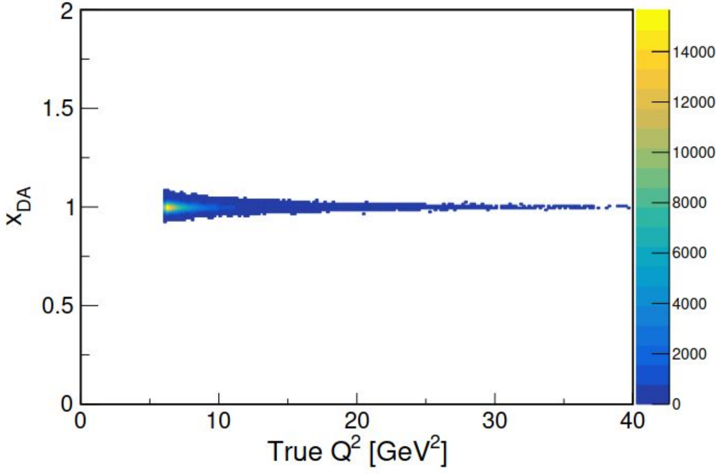
$$\eta_T = \frac{1}{\sqrt{\lambda_s\lambda}}[(-SX+2M^2Q^2+4m^2M^2)k_1 + \lambda_s k_2 - (SQ^2+2m^2S_x)p_1],$$

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 phi, PT, Pz 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:

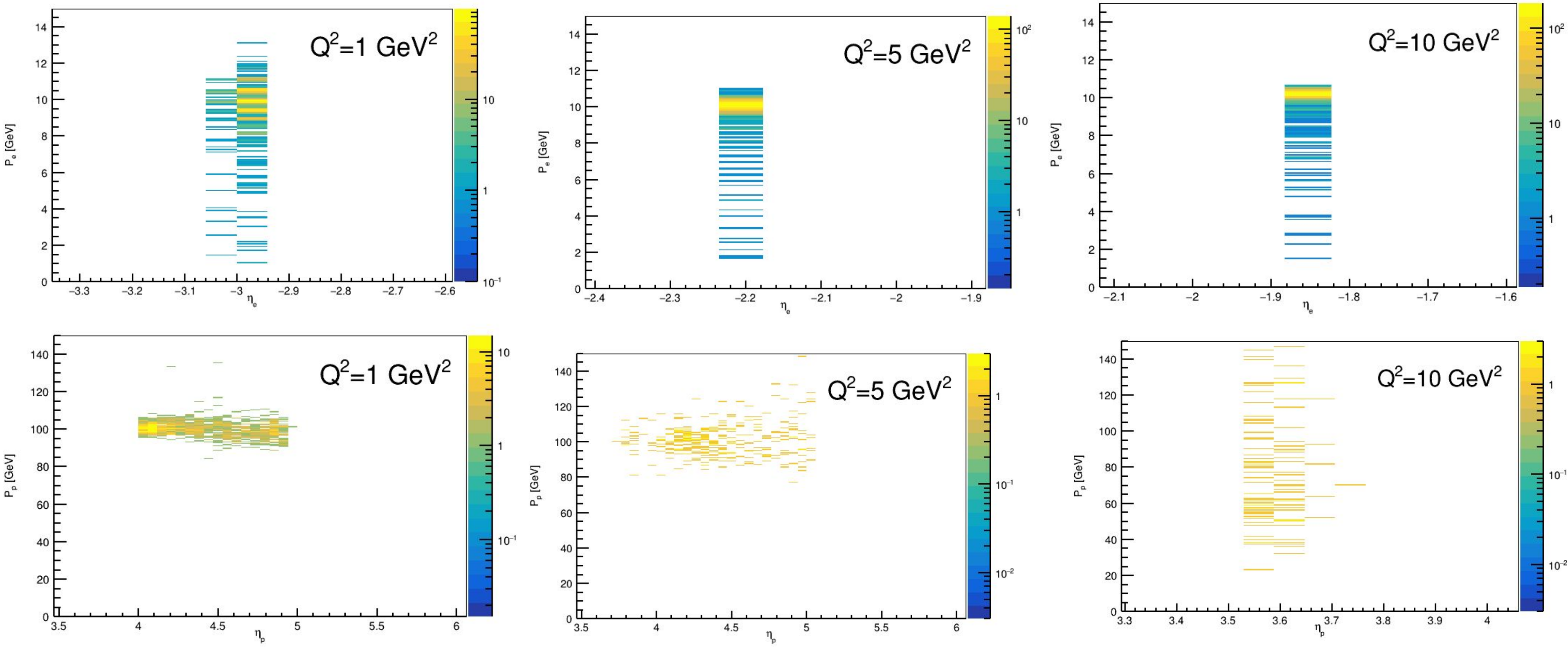
- started with ELRADGEN 2.0 I. Akushevich et al., Comput.Phys.Commun. 183 (2012) 1448-1467
- adapted to high energy kinematics (few terms can still be improved);
- implemented of fully differential form in TFoam;
- calculation is completely Lorentz invariant - frame independent;
- include polarizations 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” (approximate, changes energies);
- using “npsim” simulations with the “epic_craterlake.xml” configuration;
- using “eicrecon” construction and root script to read results.

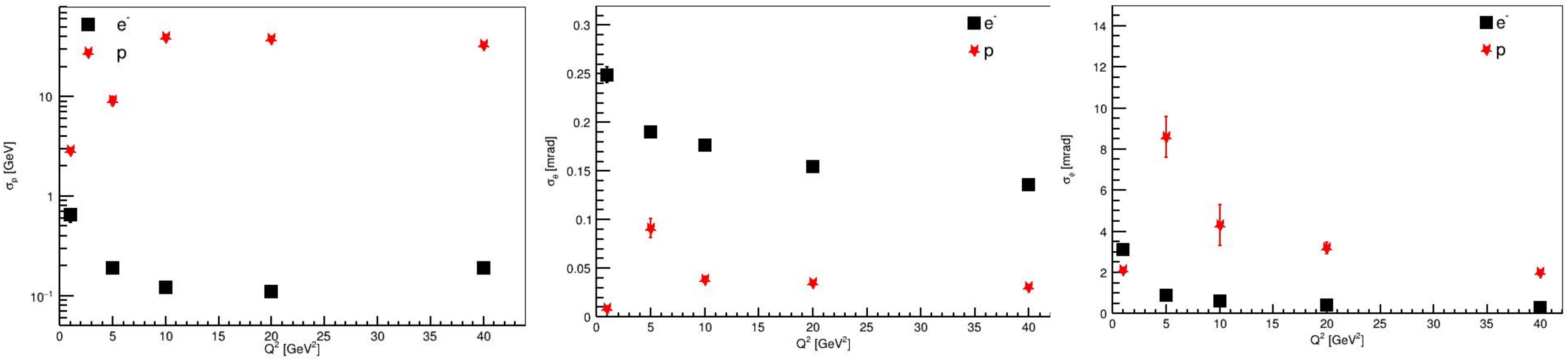
Elastic peak kinematics

- e^- and p move into higher acceptance region, momenta almost fixed;
- η-distribution of p is due to beam effects.



Elastic peak: particle resolutions

- e^- momentum and angular resolutions improves with Q^2;
- p momentum and angular resolutions become worse at large Q^2;
- e^- momentum resolution is better than p, opposite for angular resolution;
- overall angular resolutions are good, while momentum resolutions are much larger than pion mass scale.



Momentum resolution of dRICH

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

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

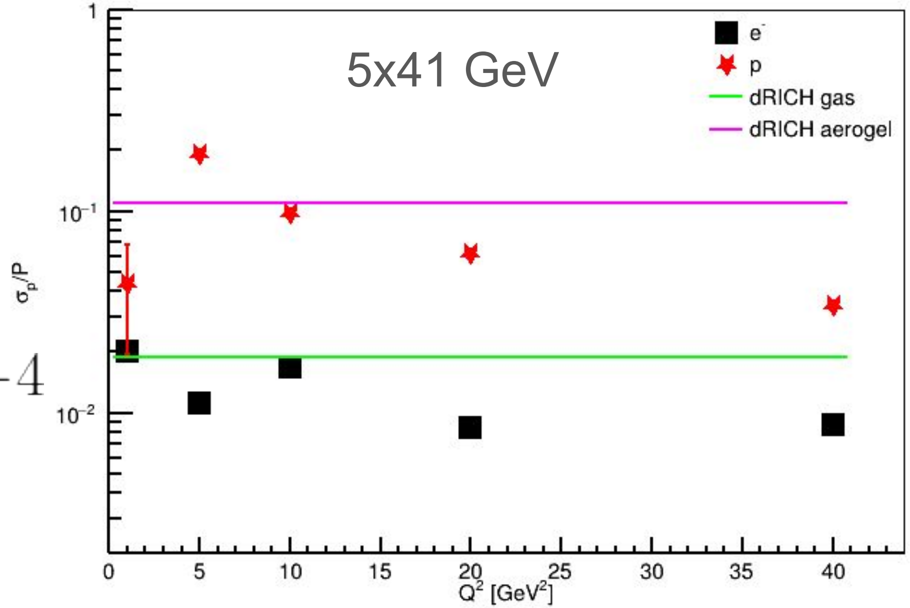
- momentum resolution is then:

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

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

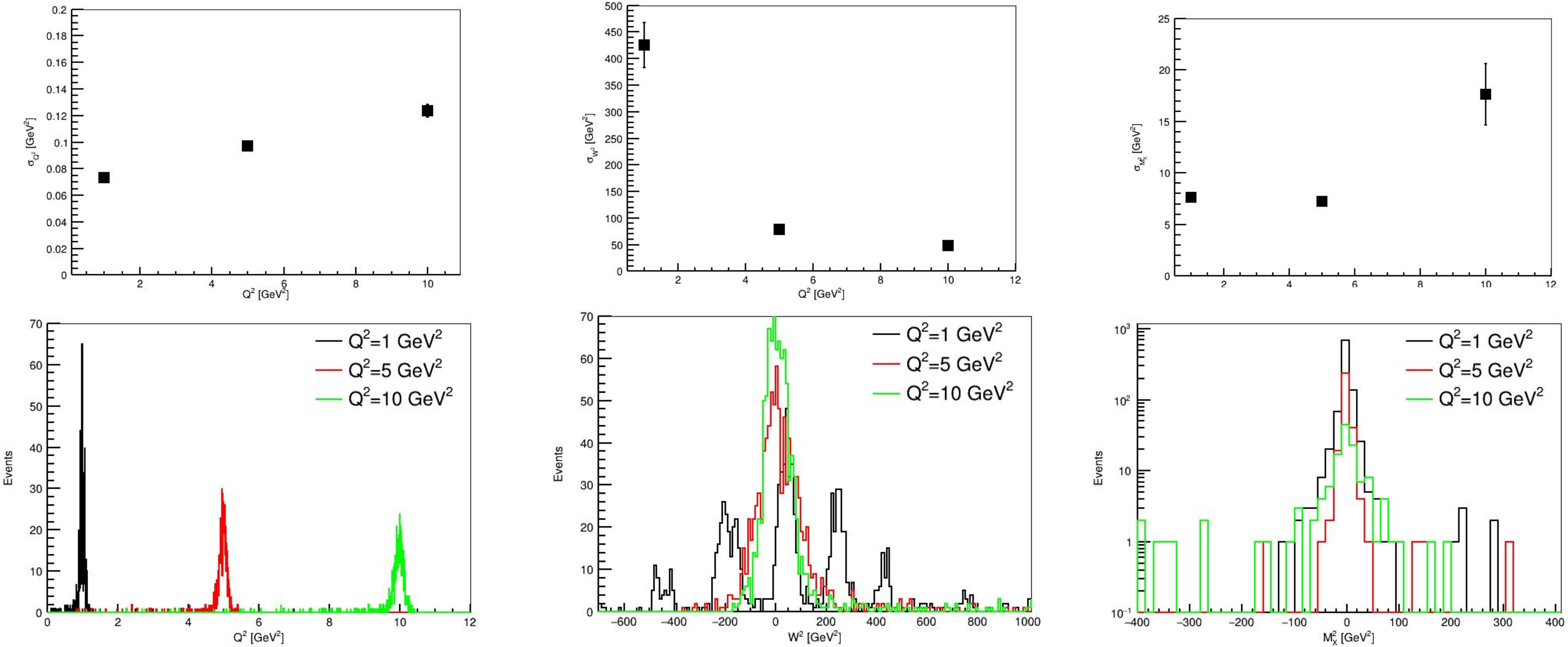
$$\theta_C(aerogel) \sim 11^\circ$$

better than tracking



Elastic peak: invariant resolutions

- reconstructed kinematic variables must allow to isolate elastic e-p process from inelastic channels (missing mass); Q^2 gives reference point;



Elastic peak: invariant resolutions 5x41 GeV

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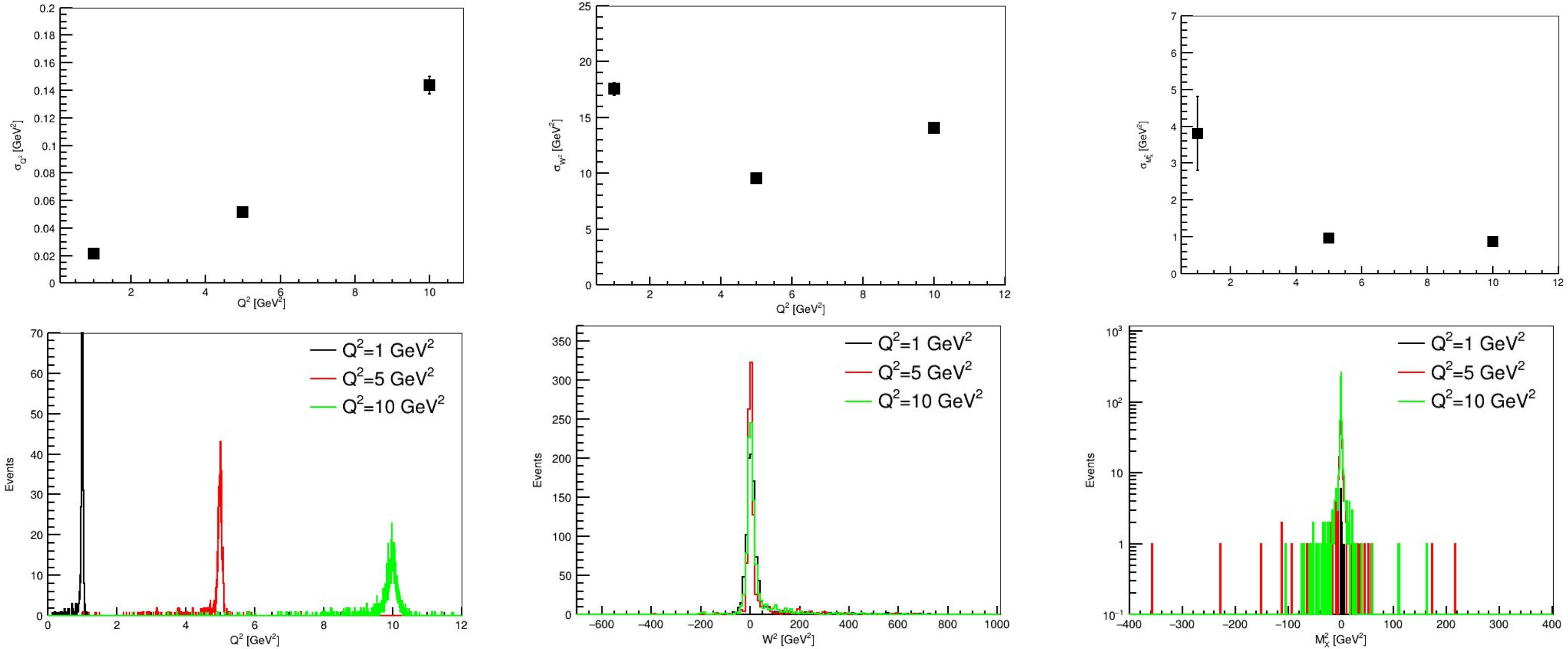
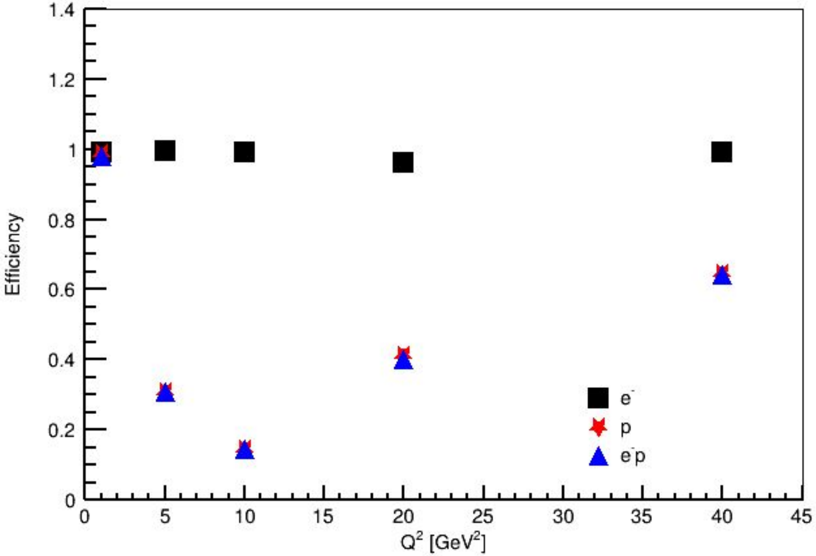


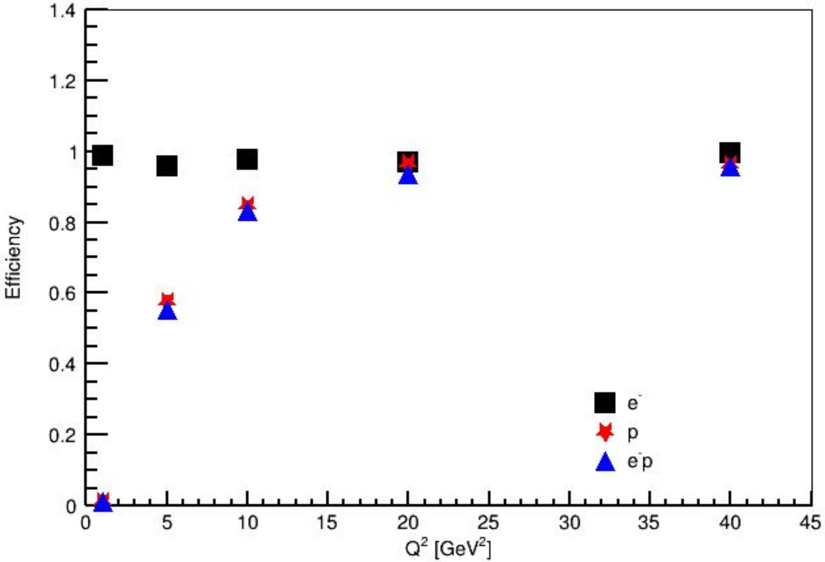
Elastic peak: efficiency

- efficiency is high for e^- everywhere;
- for 10x100 GeV config. p-efficiency has a minimum at Q^2=10 GeV^2 where it drops to 11%;
- for 5x41 GeV config. p-efficiency falls at low Q^2, and already at Q^2=1 GeV^2 it drops to 1.4%;

10x100 GeV

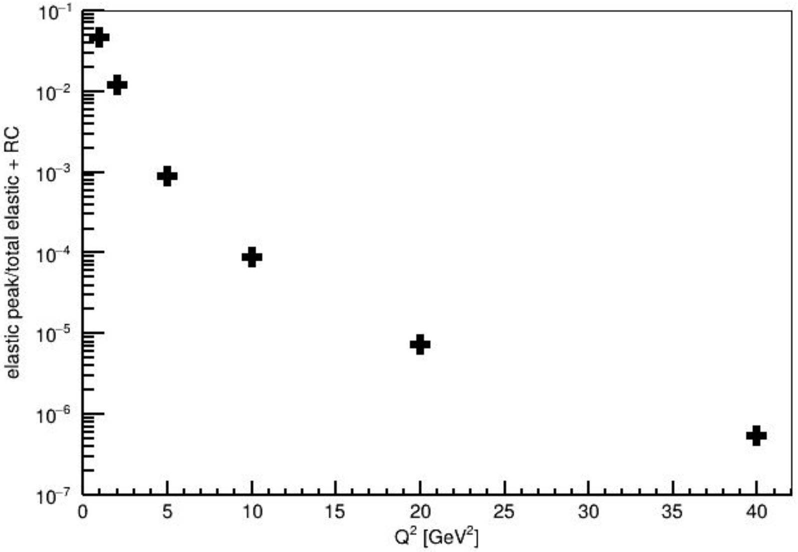


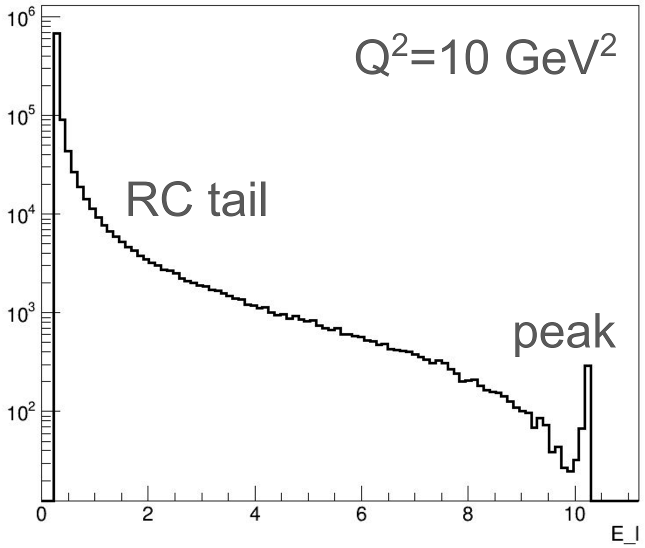
5x41 GeV



Elastic peak: contribution

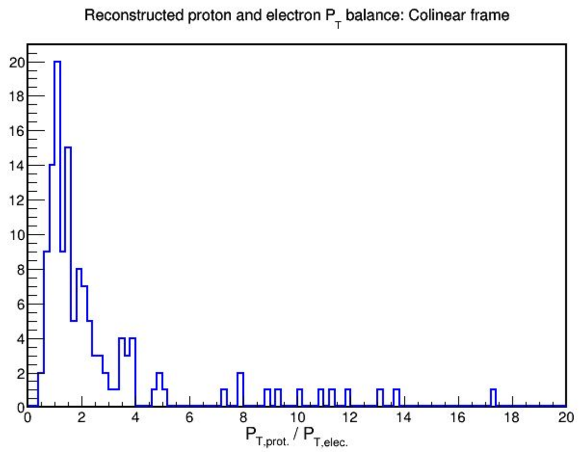
- NB at high Q^2 the contribution of the elastic peak into the total elastic cross section (including RC) becomes negligible;
- since bremsstrahlung gamma mass is zero the missing mass of this channel is also zero, the only separation can be done using electron W or x variables;
- to separate elastic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

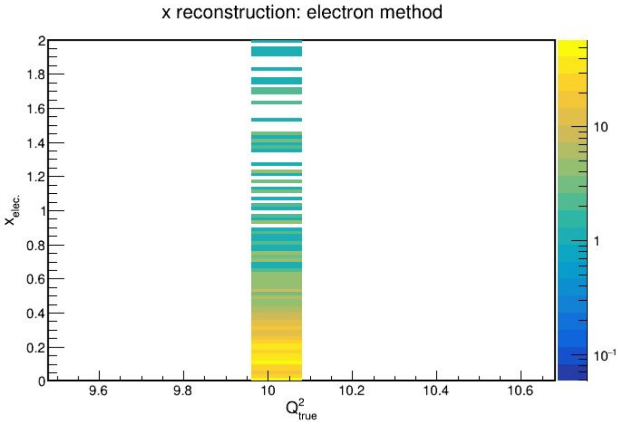


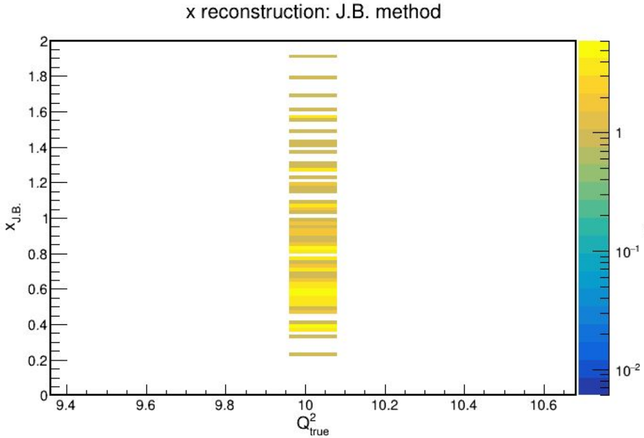


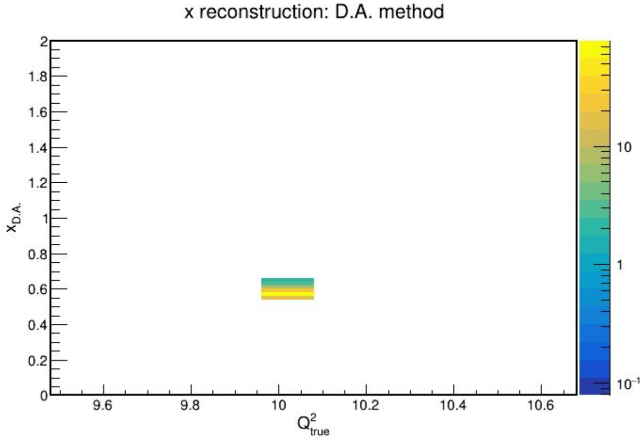
Collider kinematic methods

- 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).









M_X^2 reconstruction

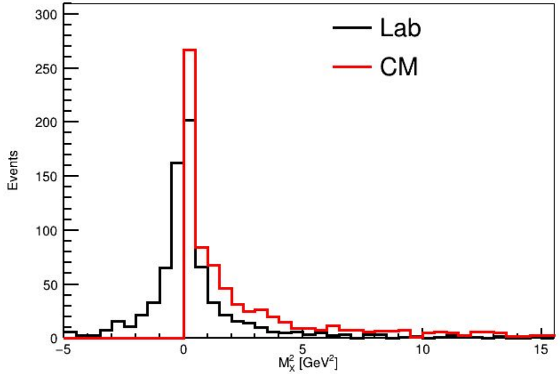
- identification of the elastic process requires:

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

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

$$M_X^2 = \left[(E_e^{CM} - E_{e'}^{CM}) + (E_p^{CM} - E_{p'}^{CM})\right]^2 < m_\pi^2$$

- no significant difference between CM and LAB evaluations;
- 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.



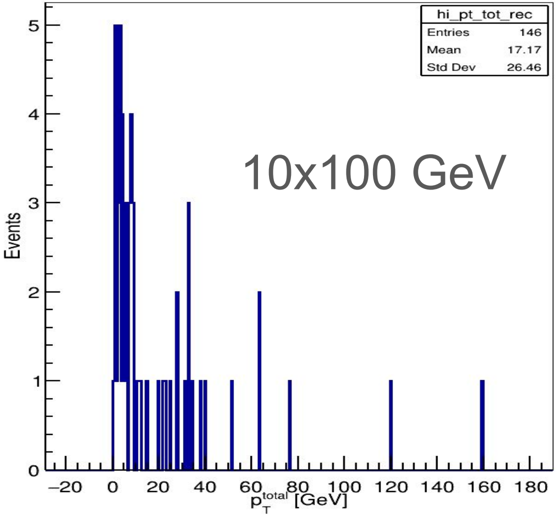
4-momentum conservation

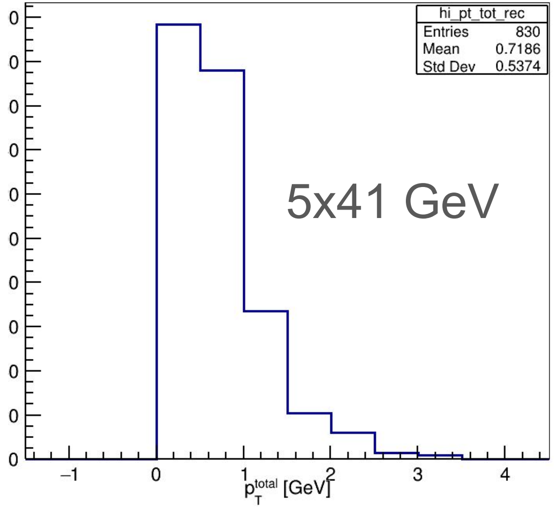
- p beam is off-axis, p_T and φ balance should include crossing angle correction, or evaluated in CM:

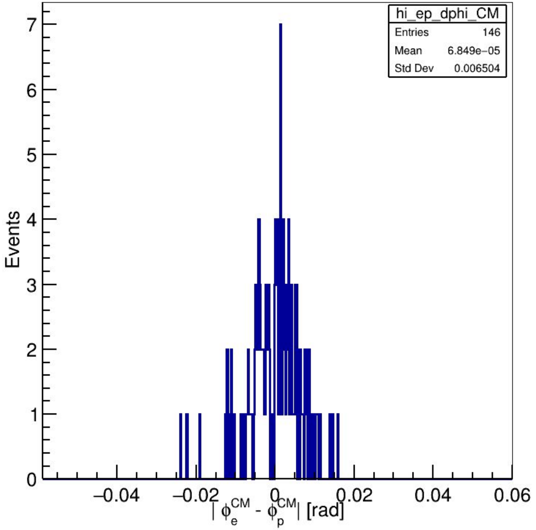
$$\sqrt{\vec{p}^{\,2}_{T,e-p} - \vec{p}^{\,2}_{T,beam}} = 0$$

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

Q^2=10 GeV^2







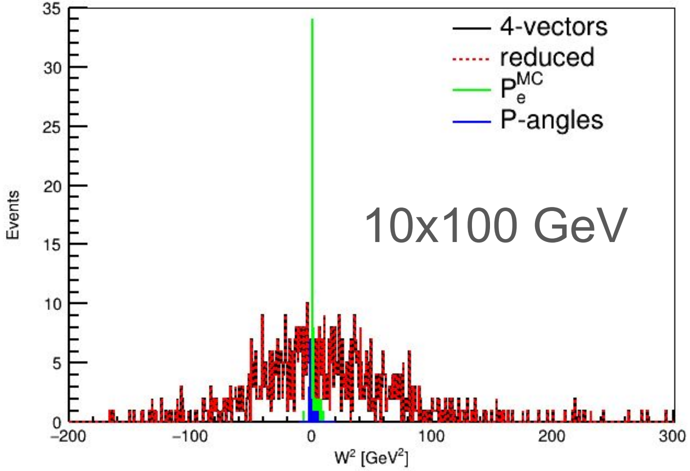
W^2 reconstruction

- invariant is defined as following:

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

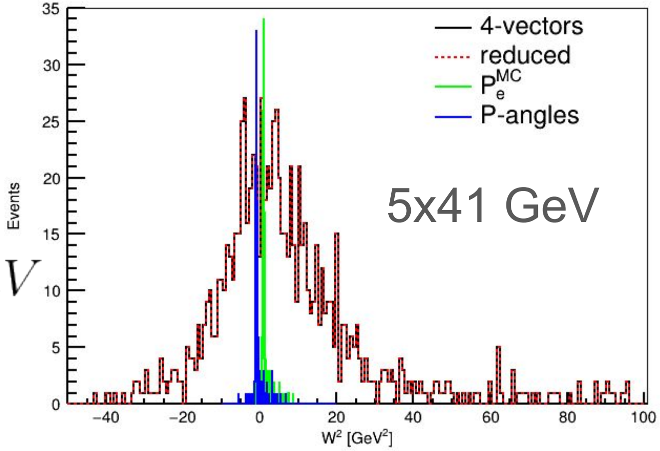
- as noticed in previous study $y \sim 10^{-2}$ but its resolution is compromised by e' momentum resolution, but assuming that 2→2 process is already identified ($M_X=0$) it can be improved using p' angles:

$$y = \frac{PP' - M^2}{Pk} \qquad |\vec{P}'| = \frac{|\vec{P}|\cos\gamma - E_0}{\cos\theta_p - \sin\theta_p \frac{\sin\phi_p}{\tan\theta_e \sin\phi_e}}$$



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

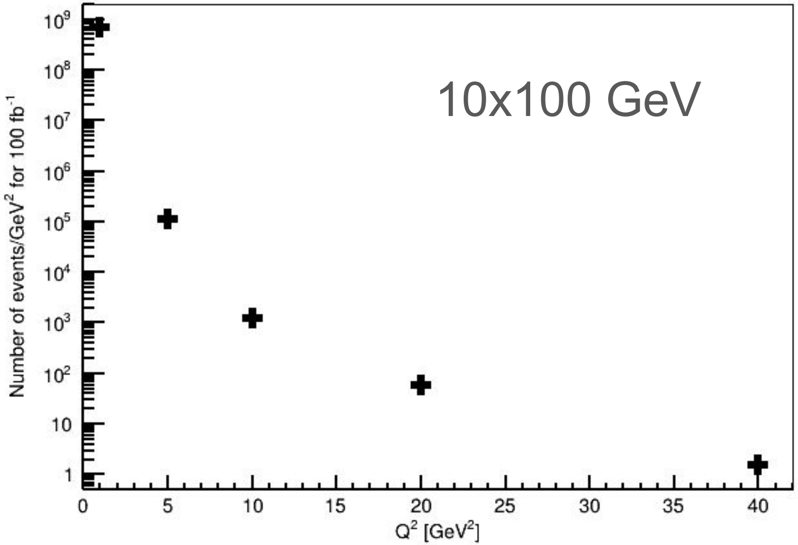
$$\sqrt{M^2 + 3\sigma_{W^2}} \sim 1.2\, GeV$$

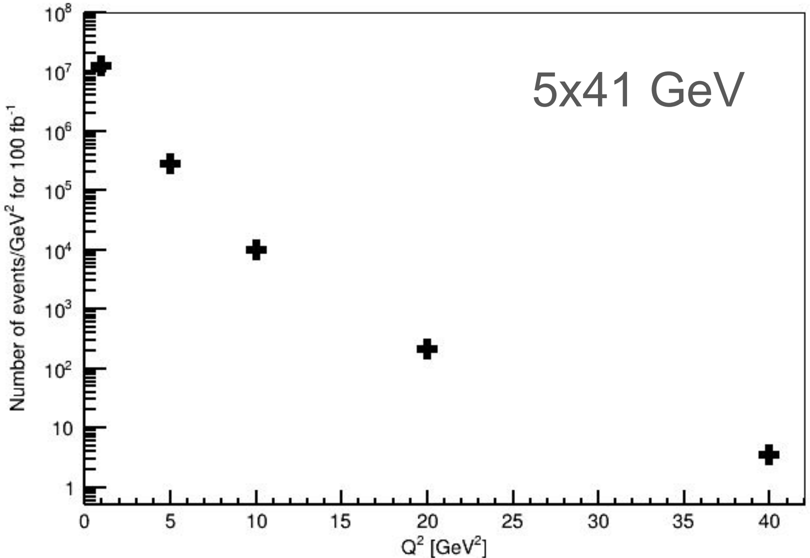


Projected statistics

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

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



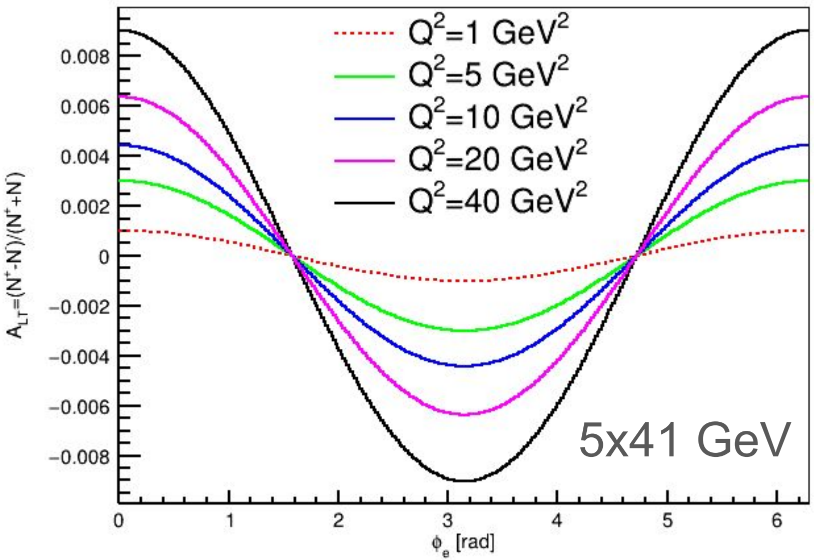


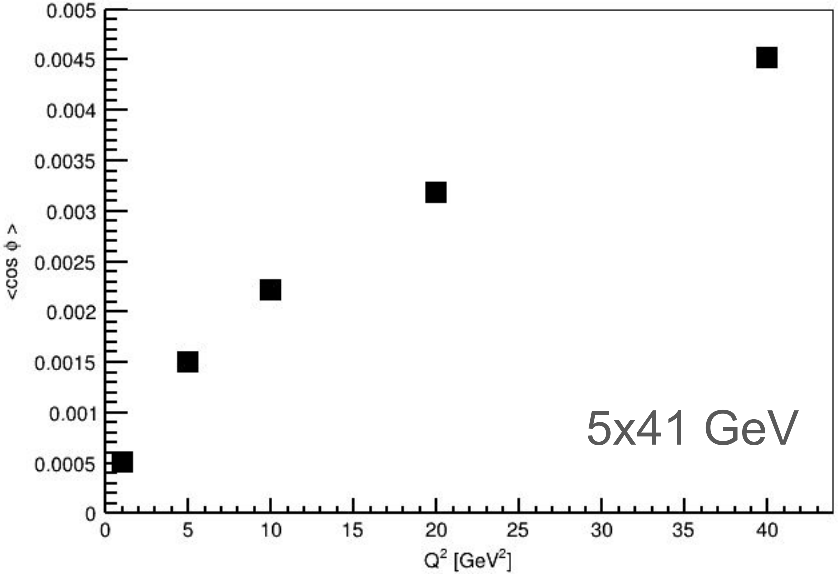
Projected polarization asymmetries

- 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%





Conclusions

- elastic scattering is the most precisely (1%) known cross section in e-p scattering, which can be used at EIC as a reference;
- overall angular resolutions are good, while momentum resolutions are much larger than pion mass scale; dRICH could provide good momentum resolution for protons;
- e^- efficiency is high, but p efficiency depends on beam energies and Q^2, reaching 11% at Q^2=10 GeV^2 for 10x100 GeV and 1.4% at Q^2=1 GeV^2 for 5x41 GeV;
- peak contribution falls exponentially with Q^2, reaching 10^{-4} at Q^2=10 GeV^2, requiring a high resolution on W to remove RC tail;
- missing mass resolution is insufficient to isolate the elastic channel, proton momentum resolution is dominant contribution to this uncertainty;
- assuming 2→2 kinematics W-resolution is barely sufficient to isolate the elastic peak, a cut just below Δ^{++} can be applied;
- projected statistics allow to reach 1% stat. precision at Q^2<10 GeV^2;
- transverse polarization of proton may allow to measure G_E/G_M ratio, but asymmetry is small at ePIC and statistical precision is order of magnitude higher.