Future High Precision Measurements on the Spin Structure g_1 at EIC

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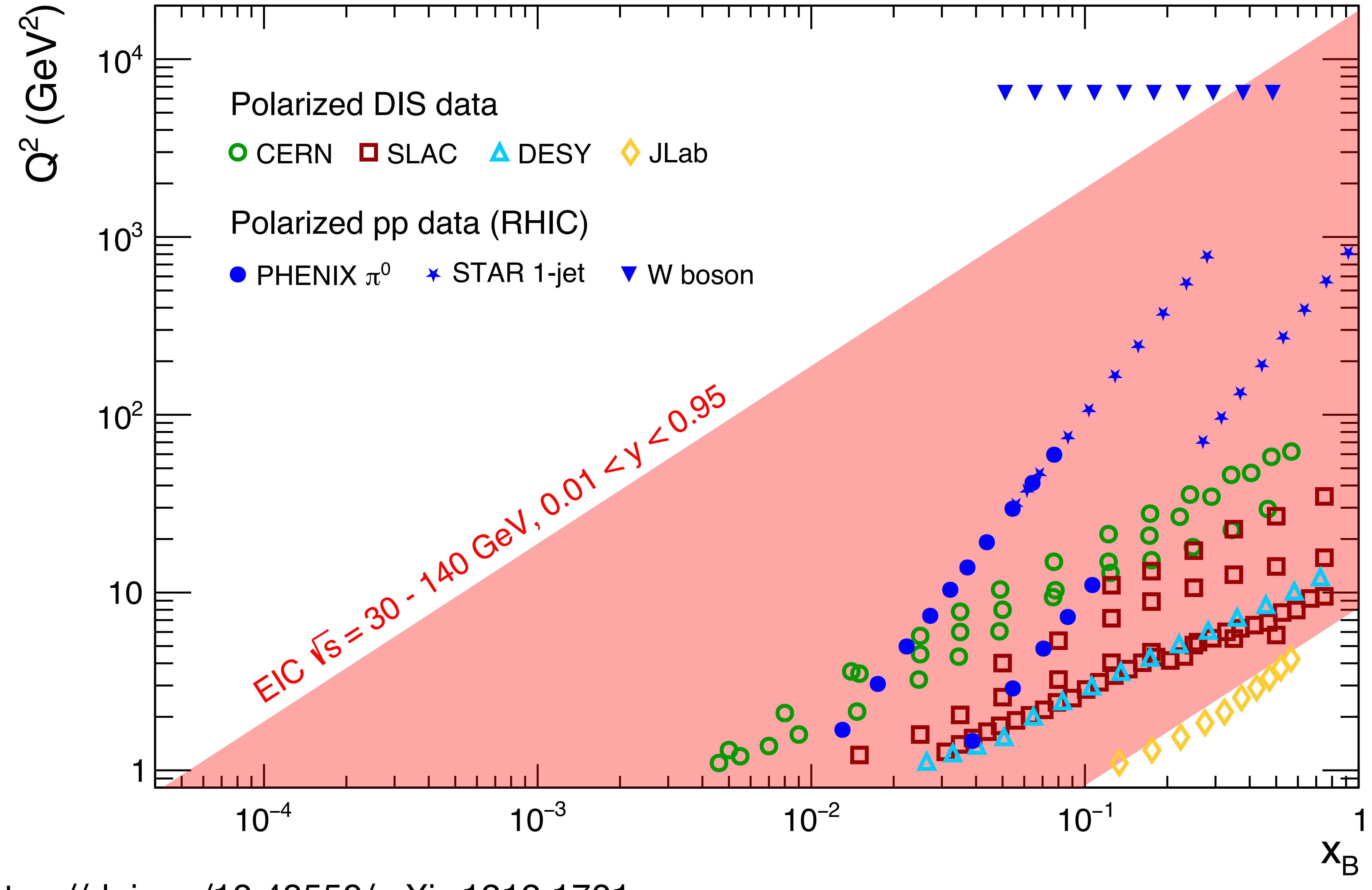
The Nucleon Spin Puzzle

https://doi.org/10.1103/PhysRevLett.113.012001



https://doi.org/10.48550/arXiv.1212.1701

Spin composition (Jaffe-Manohar sum):

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$

Quark-Parton Model:

$$\Gamma_1^{p(n)} = \int_0^1 \boxed{g_1^{p(n)}}\,dx = \frac{1}{12}\left[+(-)a_3 + \frac{1}{3}a_8\right] + \frac{1}{9}a_0$$

$$a_0 = \Delta u + \Delta d + \Delta s \equiv \boxed{\Delta\Sigma}$$

$$a_3 = \Delta u - \Delta d = \left|\frac{g_A}{g_V}\right|$$

$$a_8 = \Delta u + \Delta d - 2\Delta s$$

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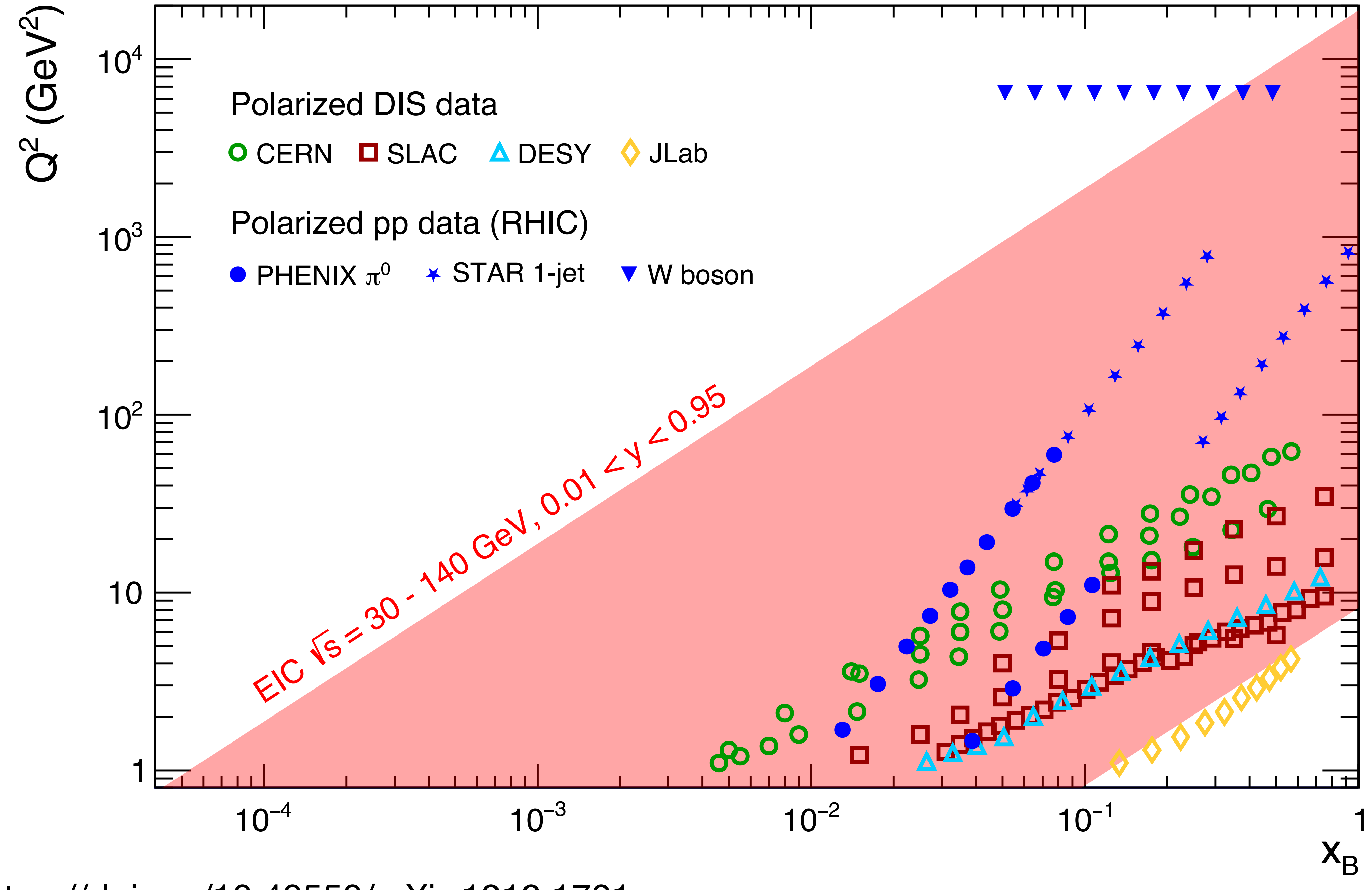

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Perturbative QCD:

$$g_1(x,t) = \frac{1}{2}\sum_{k=1}^{n_f}\frac{e_k^2}{n_f}\int_x^1 \frac{dy}{y}\left[C_q^S\left(\frac{x}{y},\alpha_s(t)\right)\boxed{\Delta\Sigma(y,t)} + 2n_f C_g\left(\frac{x}{y},\alpha_s(t)\right)\boxed{\Delta G(y,t)} + C_q^{\mathrm{NS}}\left(\frac{x}{y},\alpha_s(t)\right)\Delta q_{\mathrm{NS}}(y,t)\right]$$

Follow DGLAP evolution

g_1 constrains the contributions through Q^2 dependence

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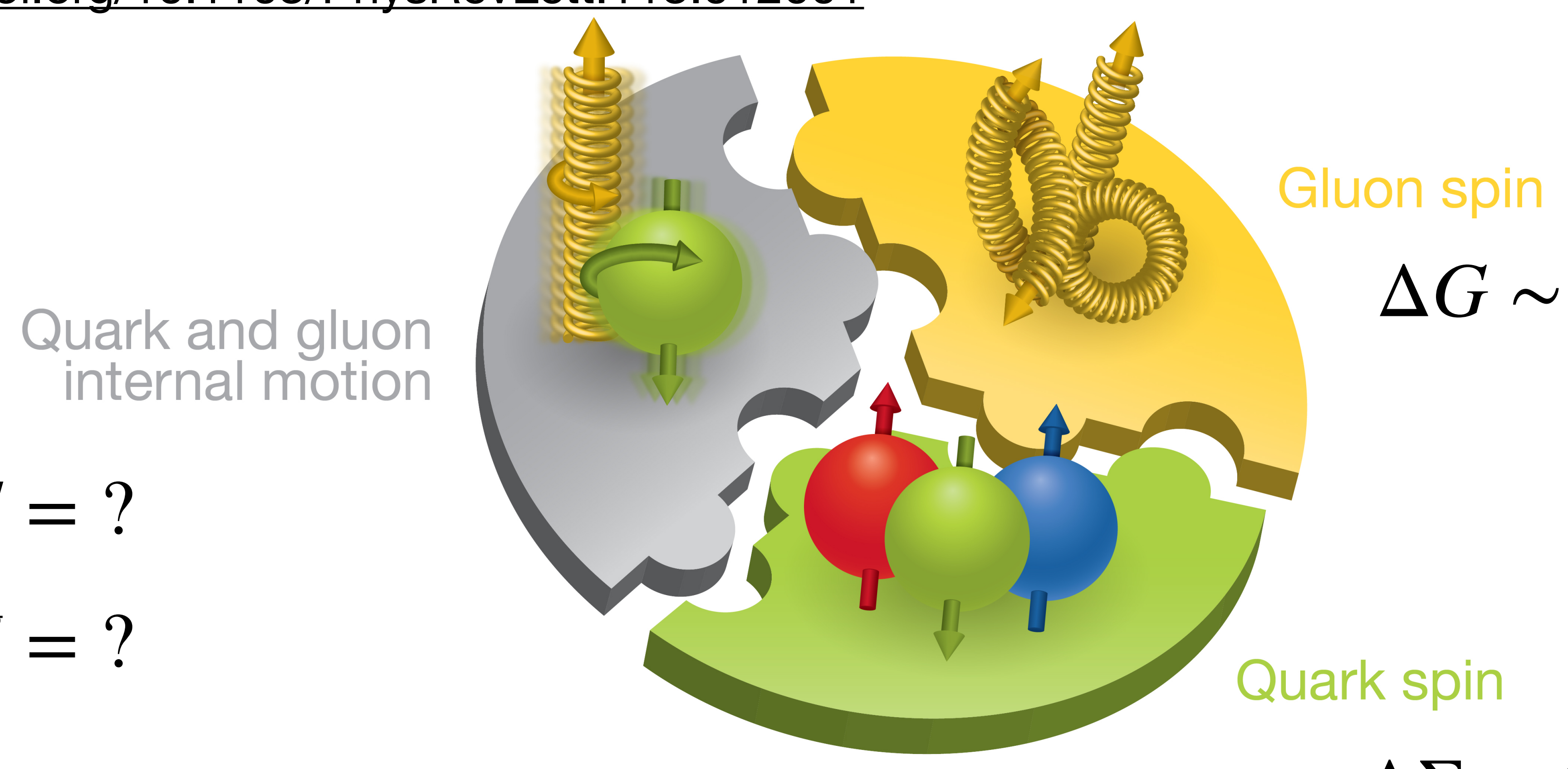
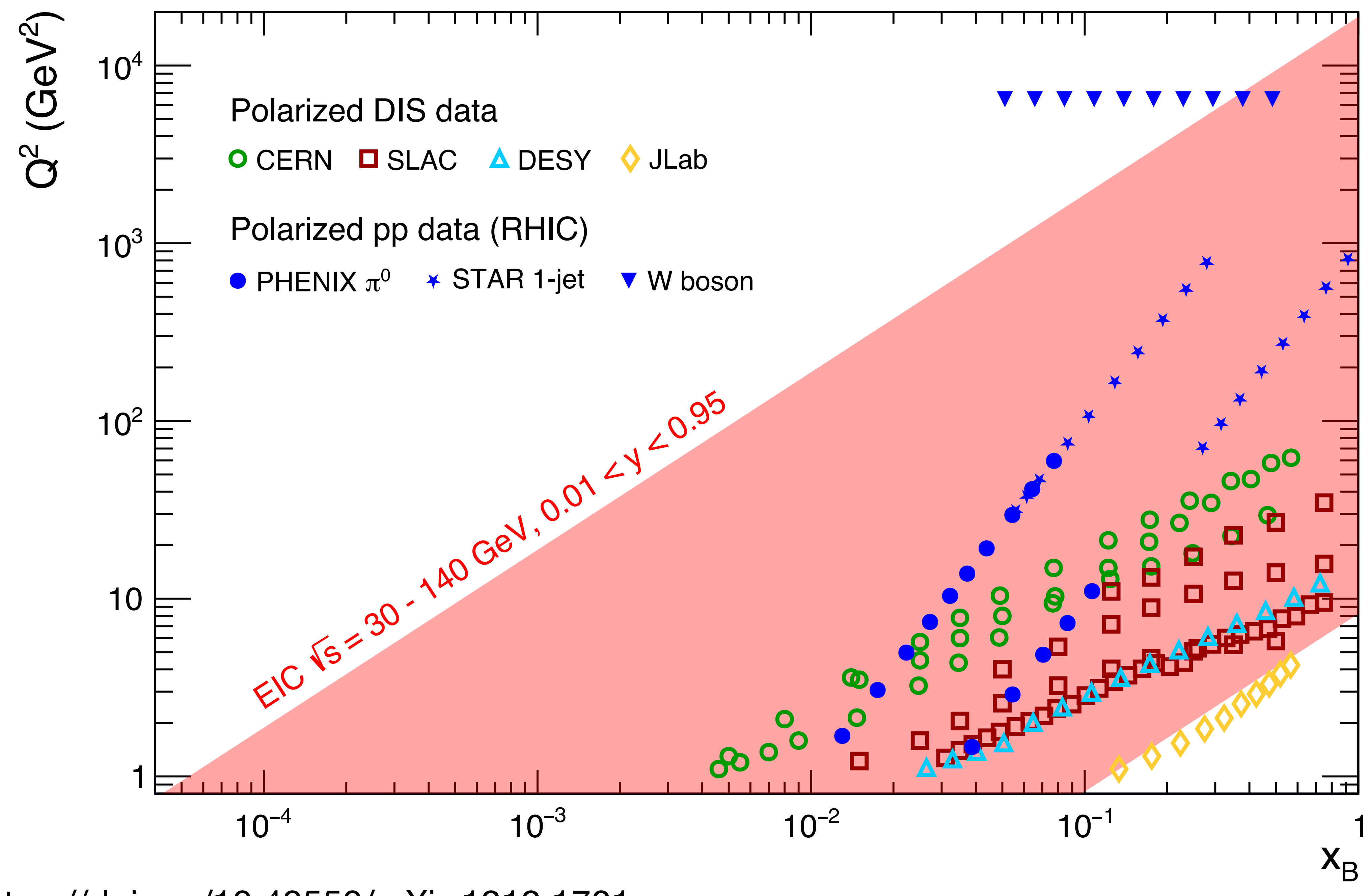


$\Delta G \sim 0.2?$

$L^q = ?$

$L^g = ?$

$\Delta\Sigma \sim 0.25?$



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Follow DGLAP evolution

g_1 constrains the contributions through Q^2 dependence

Need wide range data in x and Q^2 !

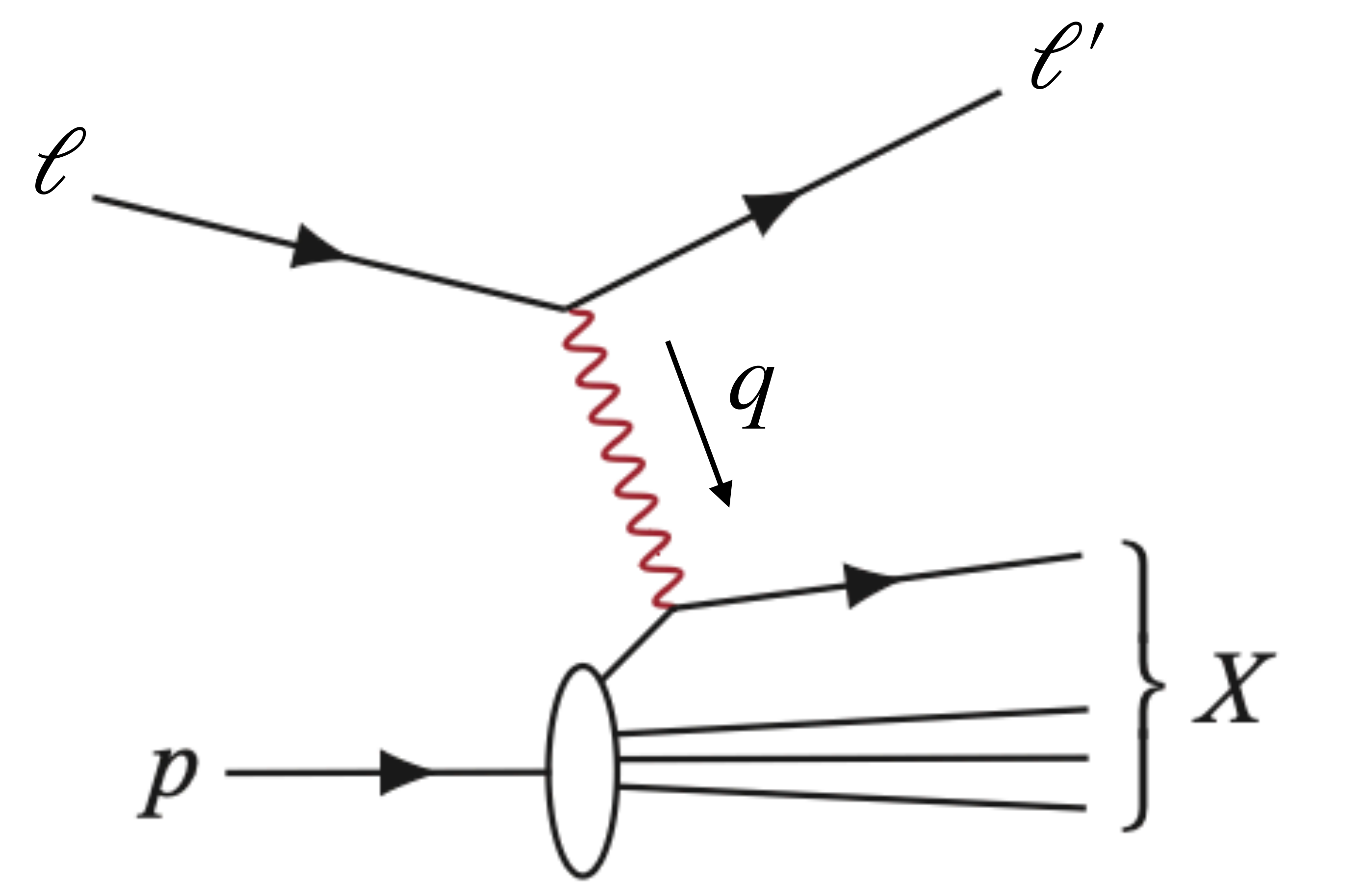
Probing Spin Structure with DIS

Deep Inelastic Scattering is a strong tool for probing nucleons and nuclei structure!

$$\frac{d^3\sigma(\beta)}{dQ^2dxd\phi} = \frac{d^3\sigma_0}{dQ^2dxd\phi} - \frac{d^3\Delta\sigma(\beta)}{dQ^2dxd\phi}$$

$$\frac{d^2\sigma}{dQ^2dx} = \frac{4\pi\alpha^2}{Q^4}\frac{1}{x}\left[xy^2F_1(x,Q^2) + \left(1 - y - \frac{Mxy}{2E}F_2(x,Q^2)\right)\right]$$

$$\frac{d^3\Delta\sigma(\beta)}{dQ^2dxd\phi} = \frac{4\alpha^2}{Q^2}y\left\{\cos\beta\left[\left(1 - \frac{y}{2} - \frac{\gamma^2y^2}{4}\right)g_1(x,Q^2) - \frac{\gamma^2y}{4}g_2(x,Q^2)\right]\right.$$
$$\left. - \cos\phi\sin\beta\frac{\sqrt{Q^2}}{\nu}\left(1 - y - \frac{\gamma^2y^2}{4}\right)^{\frac{1}{2}}\left[\frac{y}{2}g_1(x,Q^2) + g_2(x,Q^2)\right]\right\}$$



NC Inclusive DIS: $e + p \rightarrow e' + X$

https://arxiv.org/abs/2103.05419

Double Spin Asymmetry

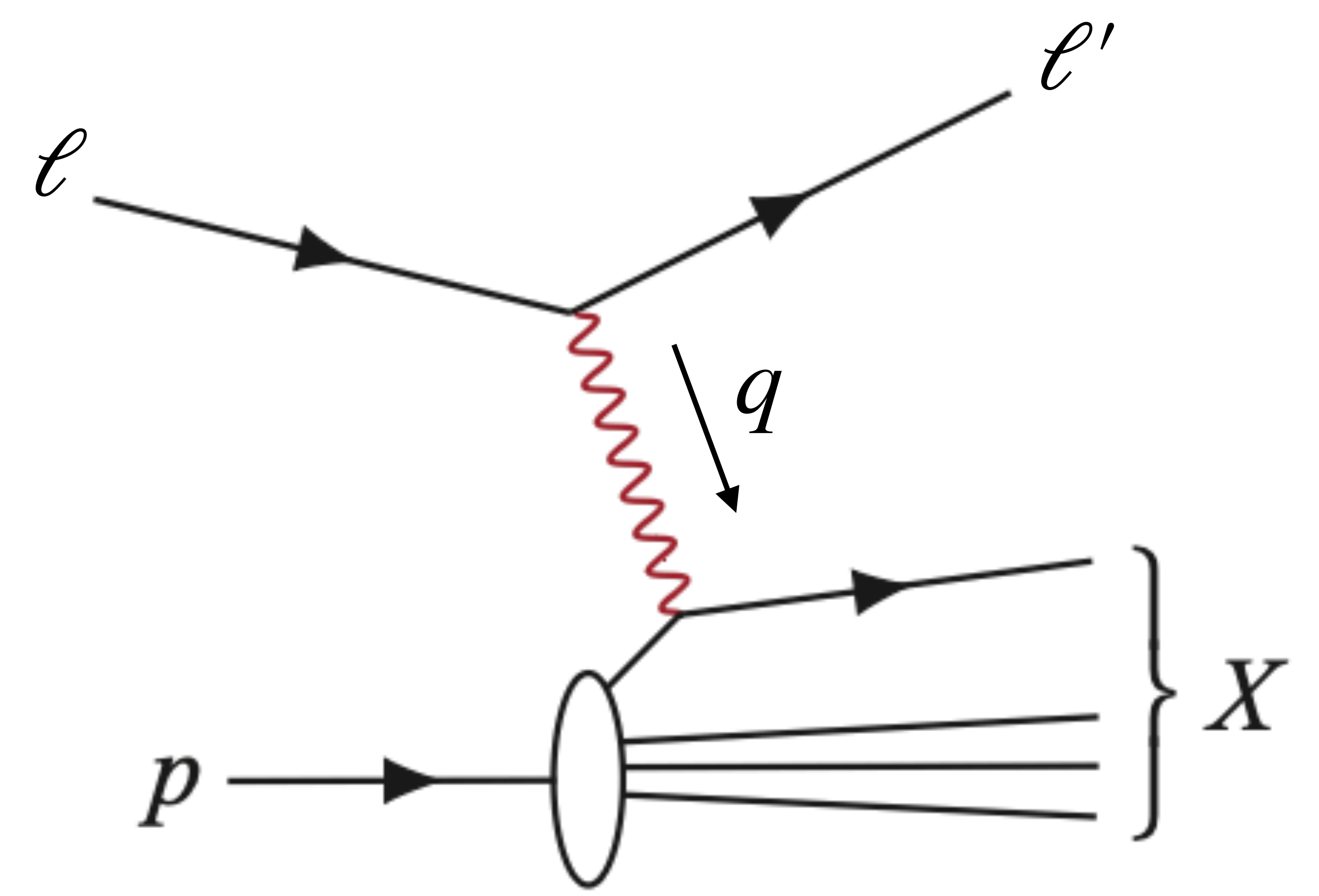
$$\frac{d^3\Delta\sigma(\beta)}{dQ^2dxd\phi} = \frac{4\alpha^2}{Q^2}y\left\{\cos\beta\left[\left(1-\frac{y}{2}-\frac{\gamma^2y^2}{4}\right)g_1(x,Q^2)-\frac{\gamma^2y}{4}g_2(x,Q^2)\right]\right.$$
$$\left.-\cos\phi\sin\beta\frac{\sqrt{Q^2}}{\nu}\left(1-y-\frac{\gamma^2y^2}{4}\right)^{\frac{1}{2}}\left[\frac{y}{2}g_1(x,Q^2)+g_2(x,Q^2)\right]\right\}$$

- Direct measurement is more challenging
- Easier to measure via cross section ratio
- Systematic is largely canceled out

$$g_1 = \frac{F_2}{2x(1+R)}(A_1+\gamma A_2)$$

$$A_1(x,Q^2) \equiv \frac{\sigma_{1/2}-\sigma_{3/2}}{\sigma_{1/2}+\sigma_{3/2}} = \frac{A_\parallel}{D(1+\eta\xi)} - \frac{\eta A_\perp}{d(1+\eta\xi)}$$

$$A_\parallel = \frac{\sigma_{\downarrow\Uparrow}-\sigma_{\uparrow\Uparrow}}{\sigma_{\downarrow\Uparrow}+\sigma_{\uparrow\Uparrow}} \qquad A_\perp = \frac{\sigma_{\downarrow\Rightarrow}-\sigma_{\uparrow\Rightarrow}}{\sigma_{\downarrow\Rightarrow}+\sigma_{\uparrow\Rightarrow}}$$



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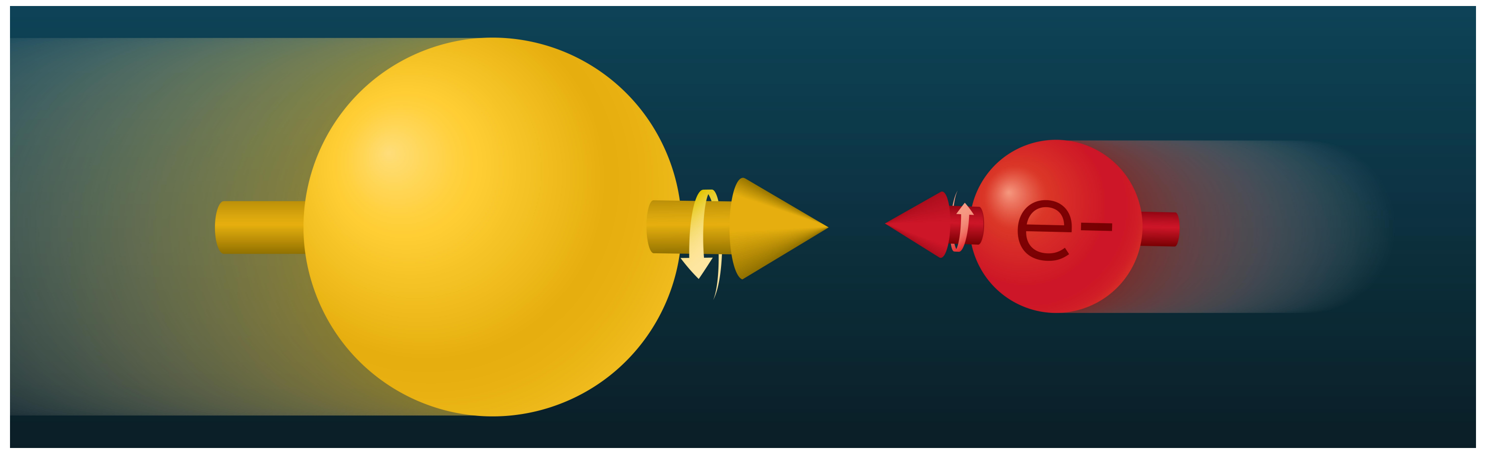

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$\sigma_{1/2}$: p & γ^* spins anti-aligned

$\sigma_{3/2}$: p & γ^* spins aligned

$$A_{\parallel} = \frac{\sigma_{\downarrow\Uparrow} - \sigma_{\uparrow\Uparrow}}{\sigma_{\downarrow\Uparrow} + \sigma_{\uparrow\Uparrow}}$$

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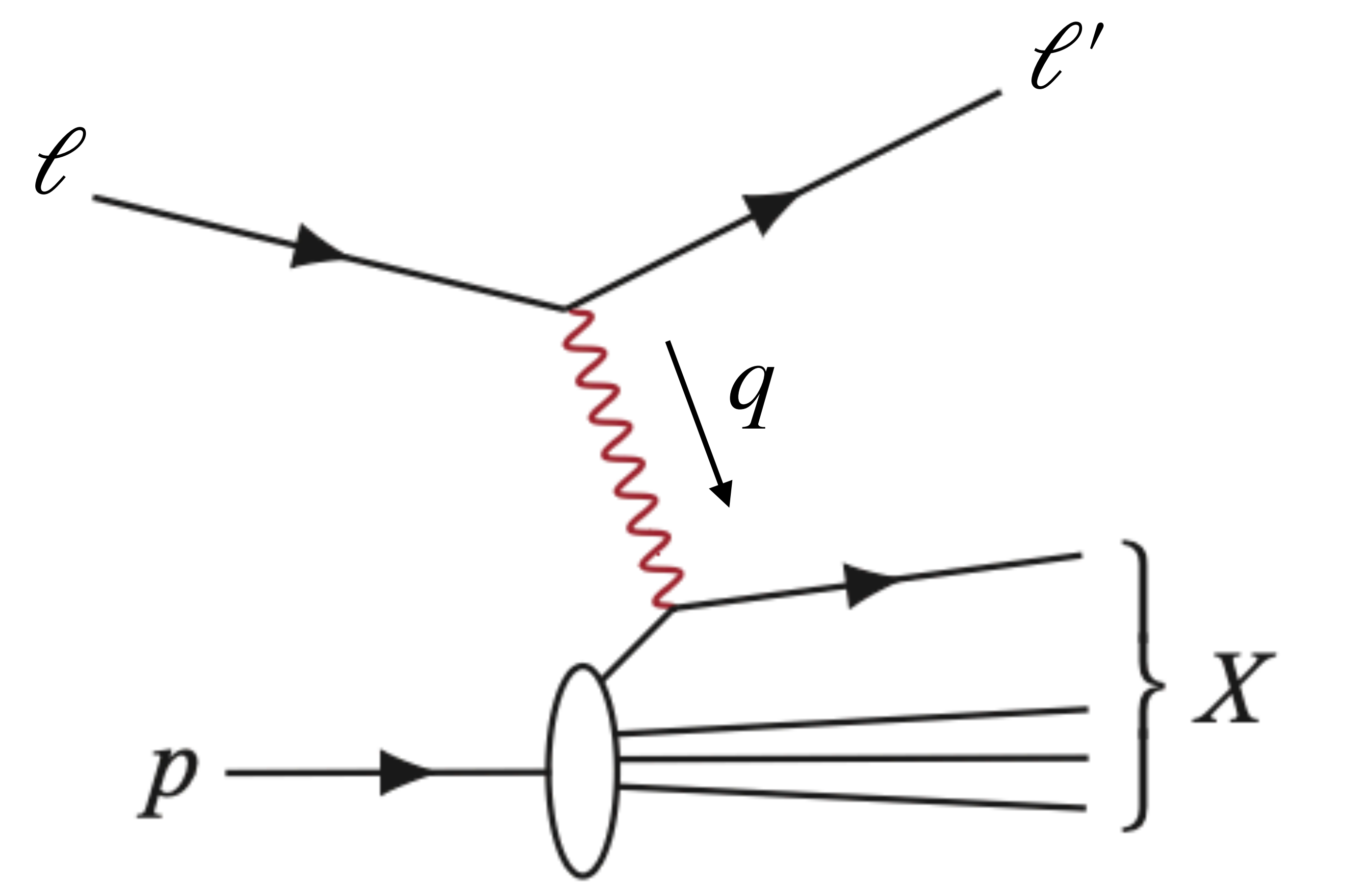
$\sigma_{\uparrow\Rightarrow}$: p & e spins perpendicular



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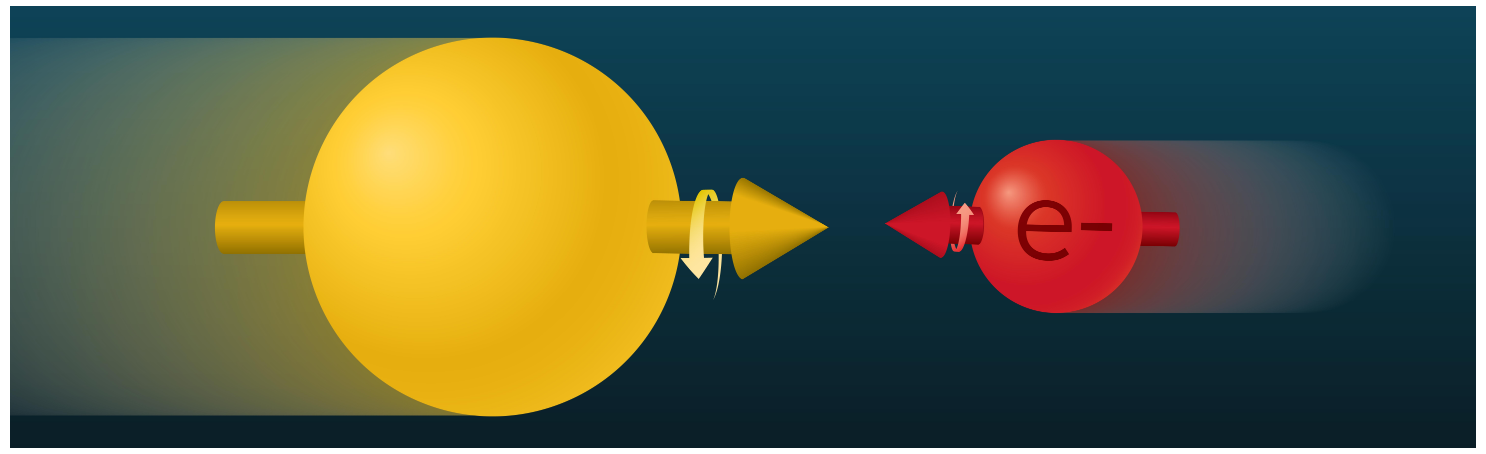

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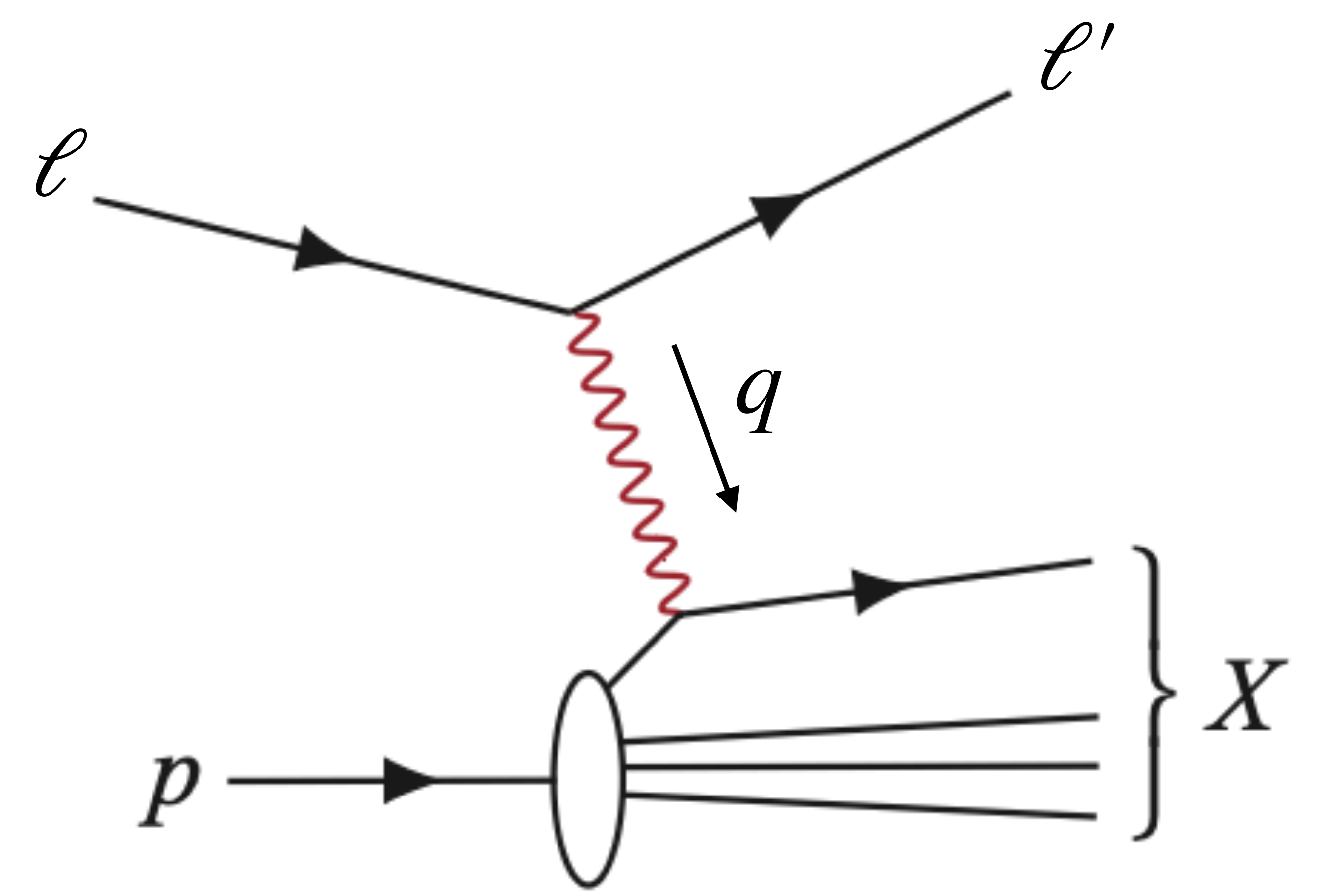
$$D = \frac{y(2-y)(2+\gamma^2 y)}{2(1+\gamma^2)y^2 + (4(1-y) - \gamma^2 y^2)(1+R)} \qquad d = \frac{D\sqrt{4(1-y) - \gamma^2 y^2}}{2-y}$$

$$R \equiv \frac{\sigma_L}{\sigma_T} = \frac{F_L}{F_2 - F_L} \qquad \gamma^2 = \frac{4M^2x^2}{Q^2} \qquad \eta = \frac{4(1-y) - \gamma^2 y^2}{(2-y)(2+\gamma^2 y)} \qquad \xi = \frac{\gamma(2-y)}{2+\gamma^2 y}$$



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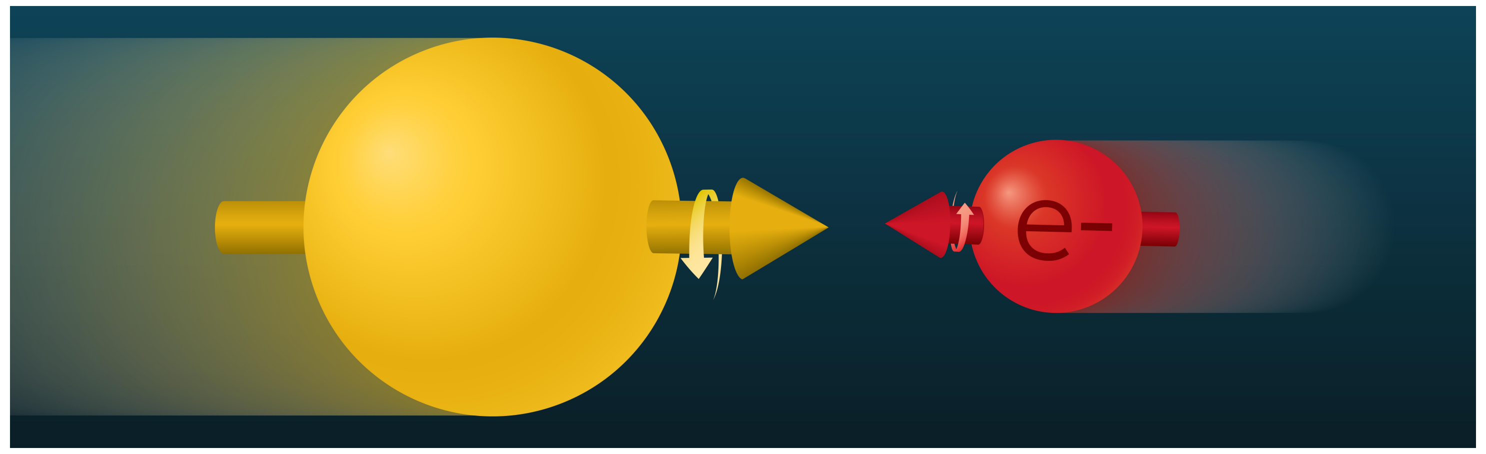
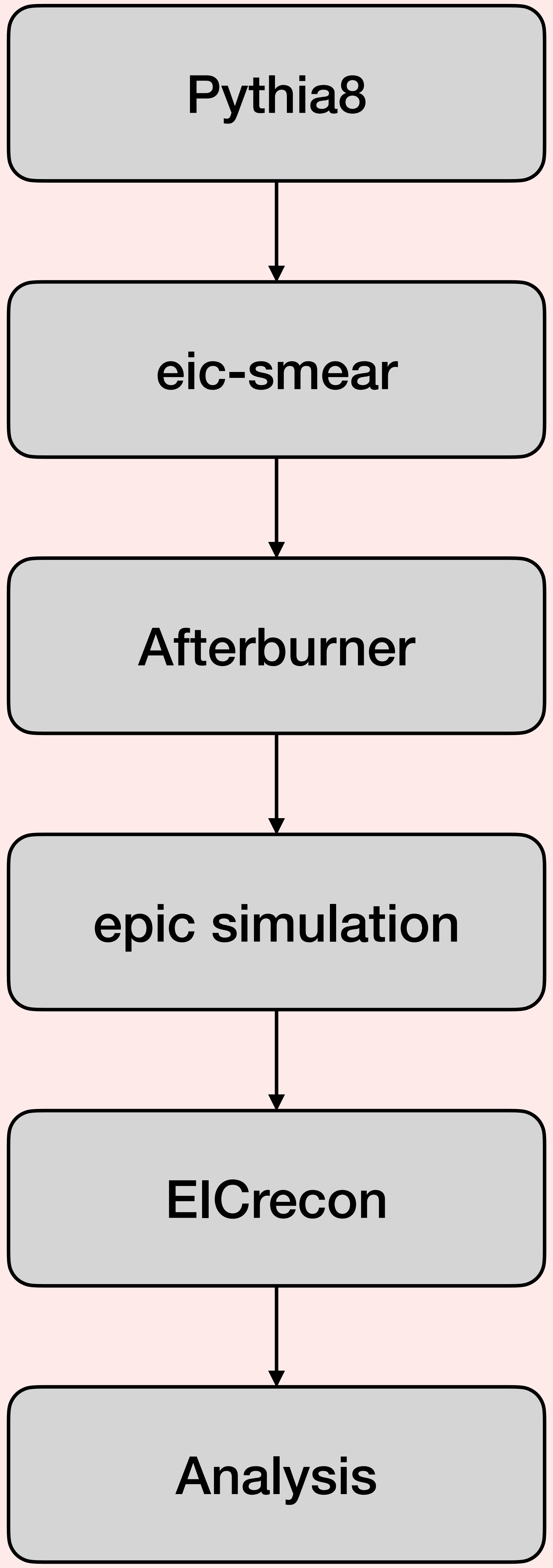
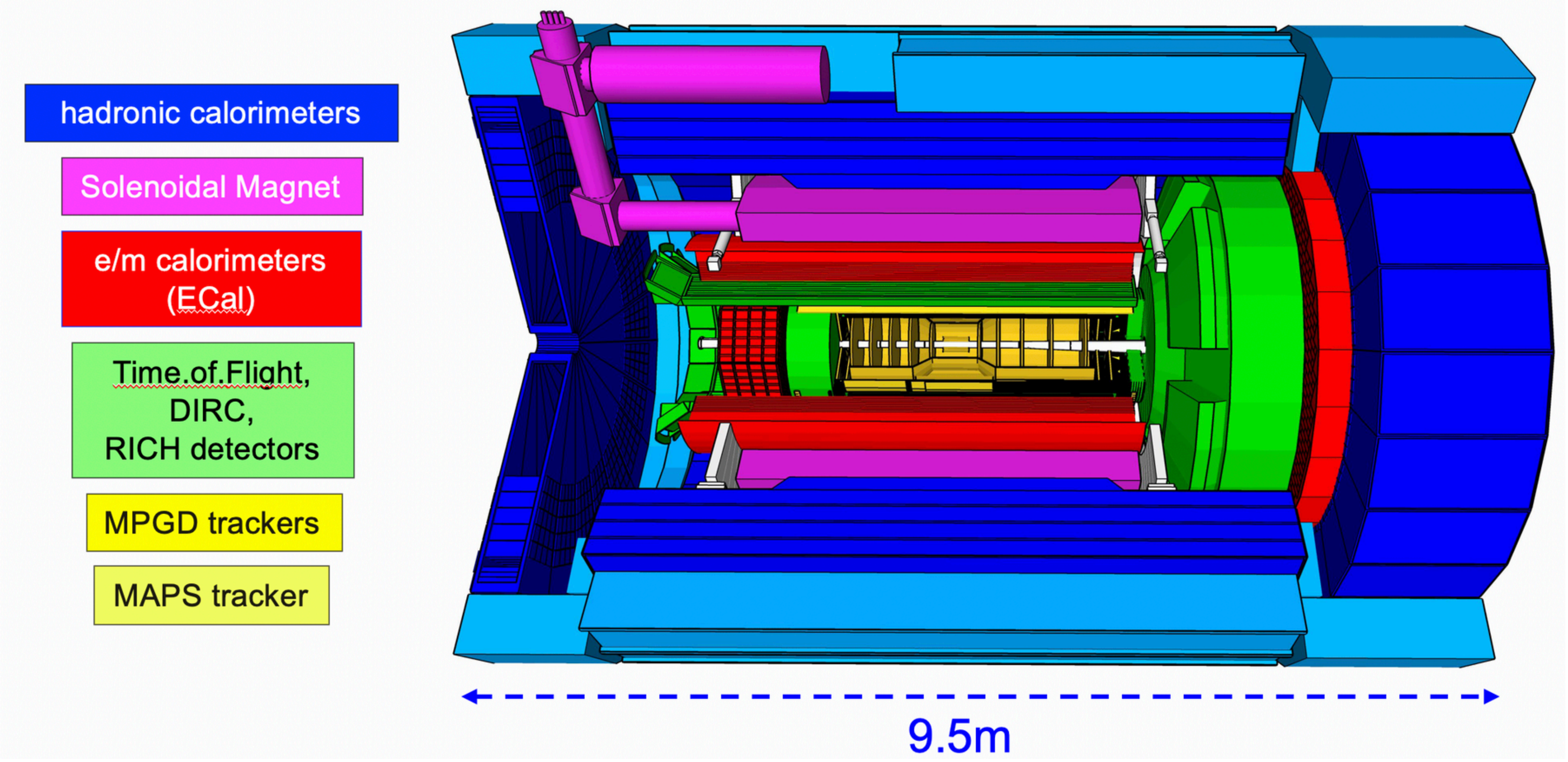


Projection study analysis chain for g_1^p



- Simulation with full ePIC detector setup
- Beam crossing angle and smearing included

ePic central detectors



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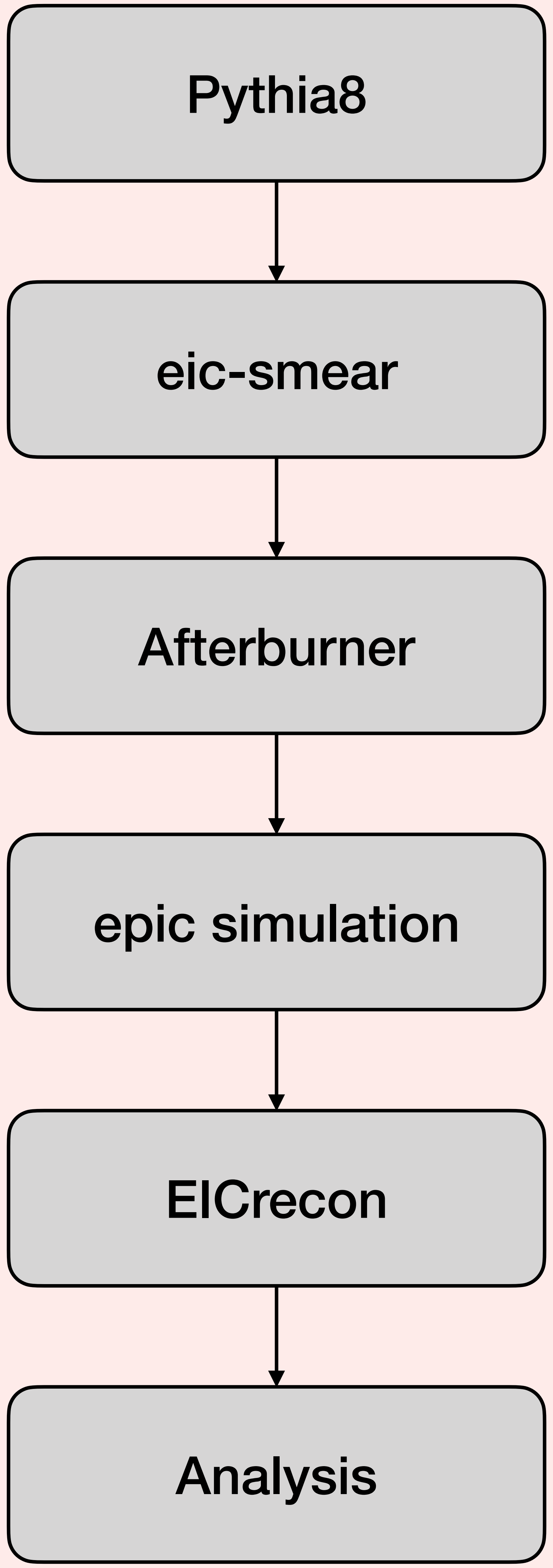
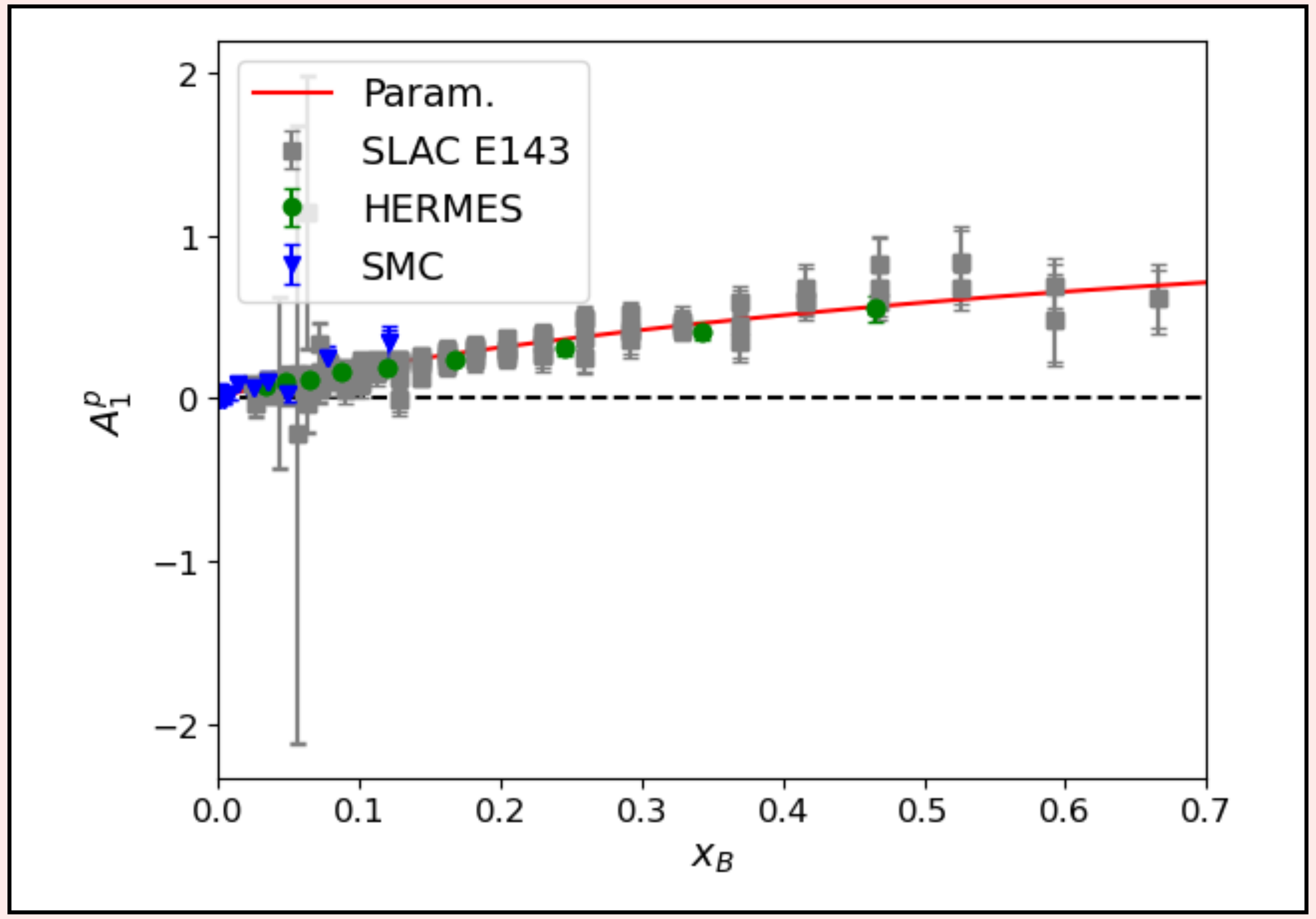


- Simulation with full ePIC detector setup
- Beam crossing angle and smearing included

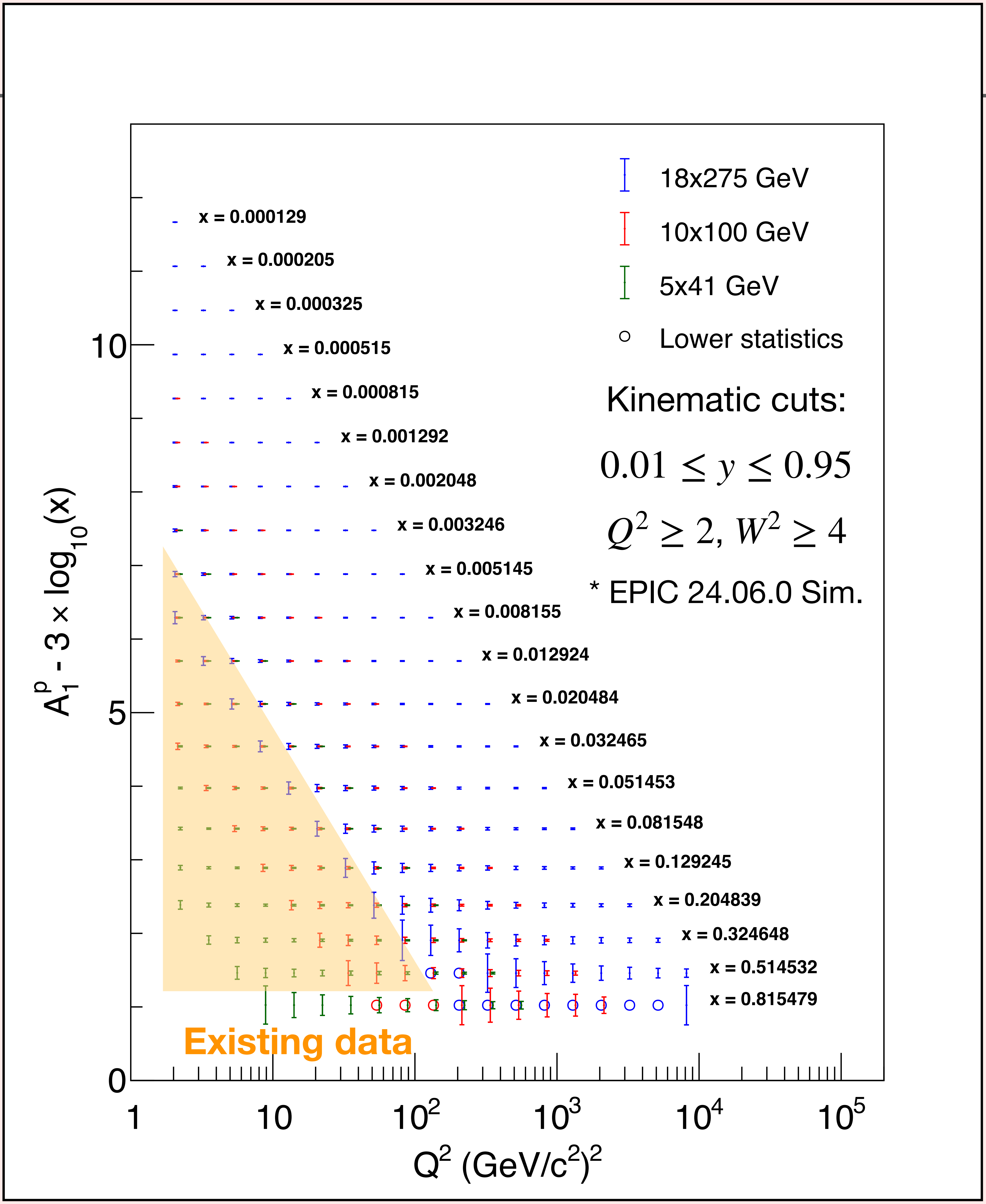
- Generated events are non-polarized
- Central A_1^p is calculated from JLab global fit (Doi: 10.1103/PhysRevC.70.065207)
- Statistical uncertainty is estimated by $\delta A_{\parallel,\perp} \approx \frac{1}{\sqrt{N} P_e P_N}$



- Parameterization at $Q^2 = 2.88\ \mathrm{GeV}^2$
- Data points are at various Q^2 with majority $< 5\ \mathrm{GeV}^2$

Projected A_1^p at EIC

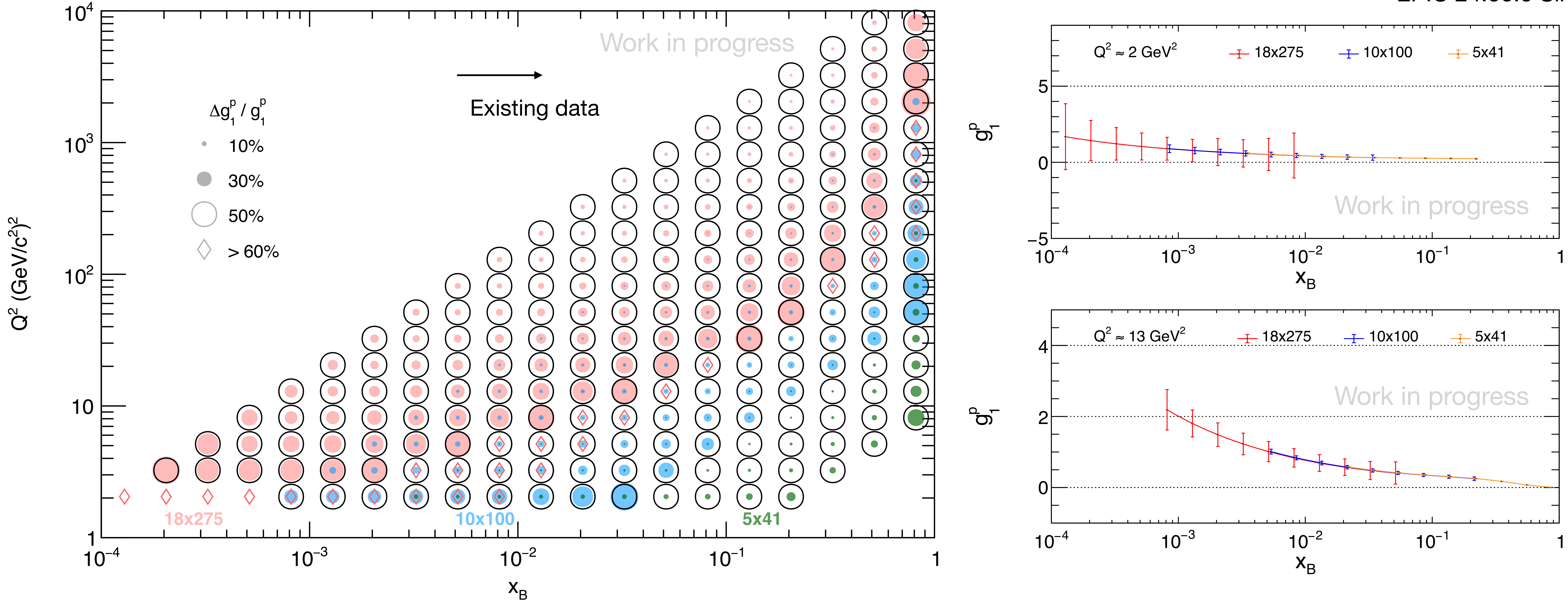
- $A_1(x, Q^2) \equiv \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{A_{\parallel}}{D(1+\eta\xi)} - \frac{\eta A_{\perp}}{d(1+\eta\xi)}$
- $\delta A_{\parallel,\perp} = \frac{1}{\sqrt{N} P_e P_N}$
- $\mathcal{L} = 10\ \text{fb}^{-1}$, $P_e = P_p = 70\,\%$
- Data split evenly between $A_{\parallel}$ and $A_{\perp}$
- R calculated from https://doi.org/10.1016/S0370-2693(99)00244-0
- Statistical uncertainty only, correction not yet applied



Projected g_1^p at EIC

- $A_1 \approx g_1/F_1$ with F_1 calculated from JAM22
- Statistical uncertainties only

* EPIC 24.06.0 Sim.



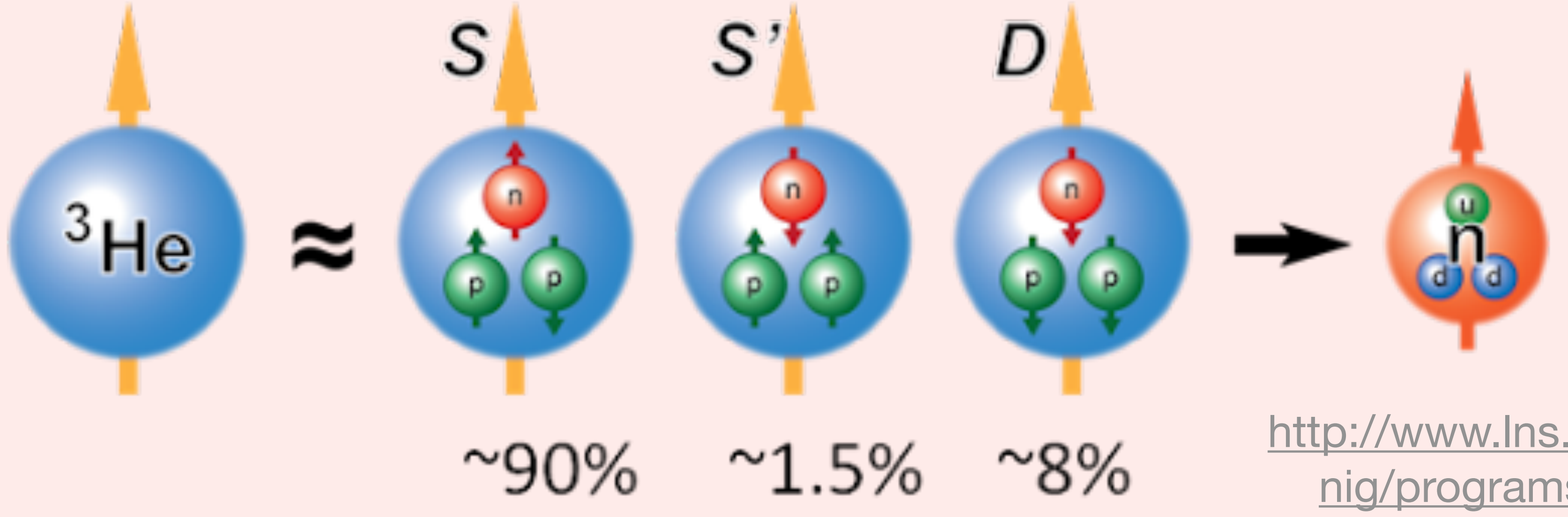
A_1^n from $e^3\text{He}$ DIS:

What about A_1^n ?

- Can be extracted from $A_1^{^3\text{He}} = P_n \frac{F_2^n}{F_2^{^3\text{He}}} A_1^n + 2P_p \frac{F_2^p}{F_2^{^3\text{He}}} A_1^p$

$$P_n = 0.86 \pm 0.02 \qquad P_p = -0.028 \pm 0.004$$

https://doi.org/10.1103/PhysRevC.64.024004



http://www.lns.mit.edu/nig/programs.html

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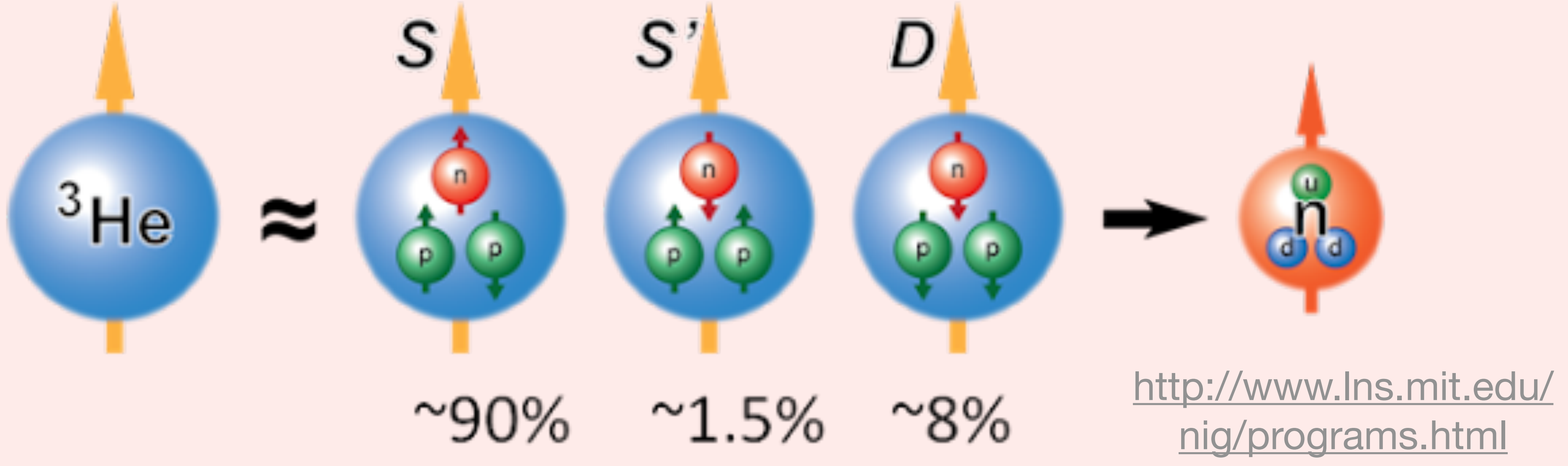
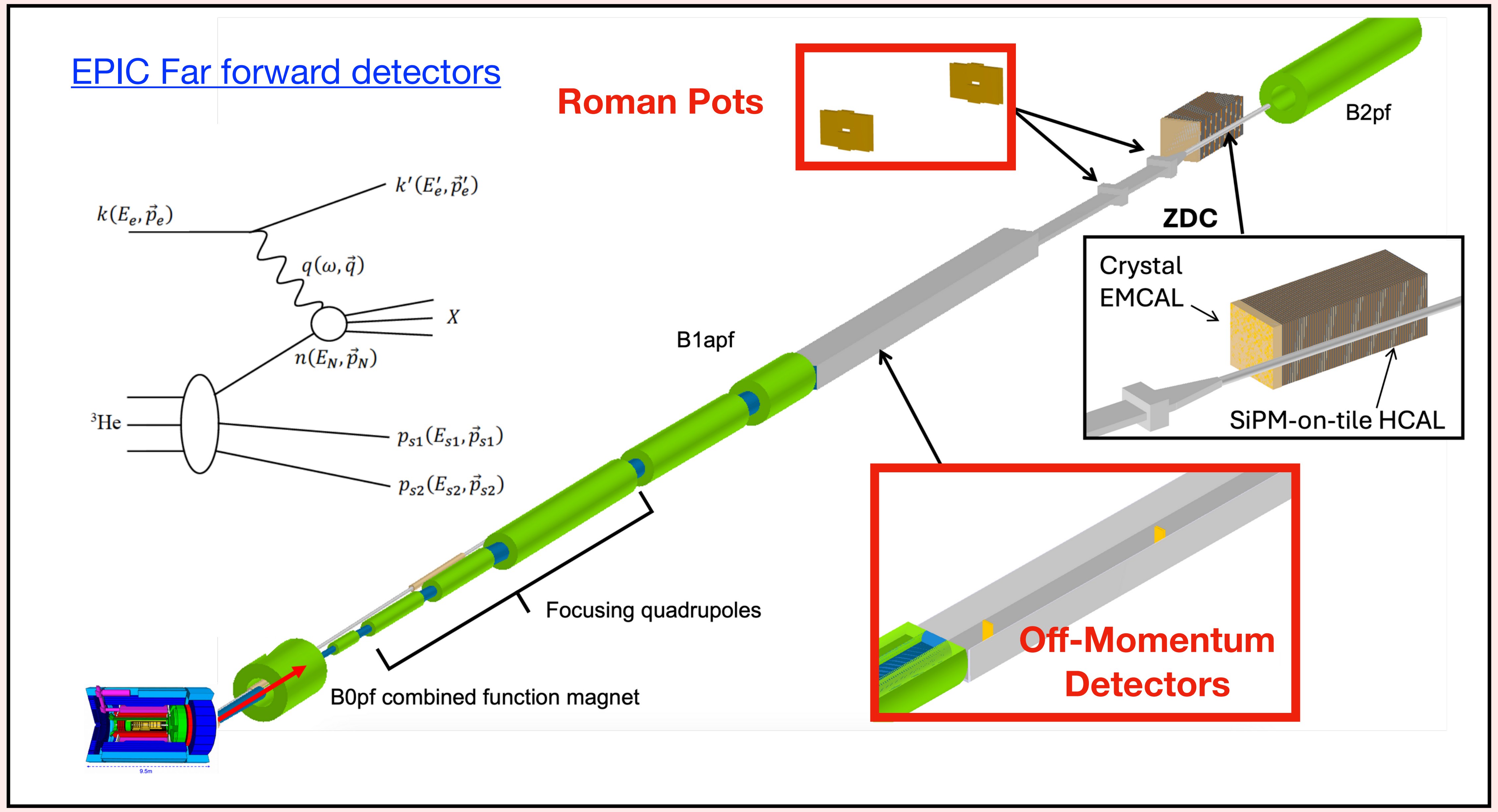


- Or **directly** measured double spectator tagging:



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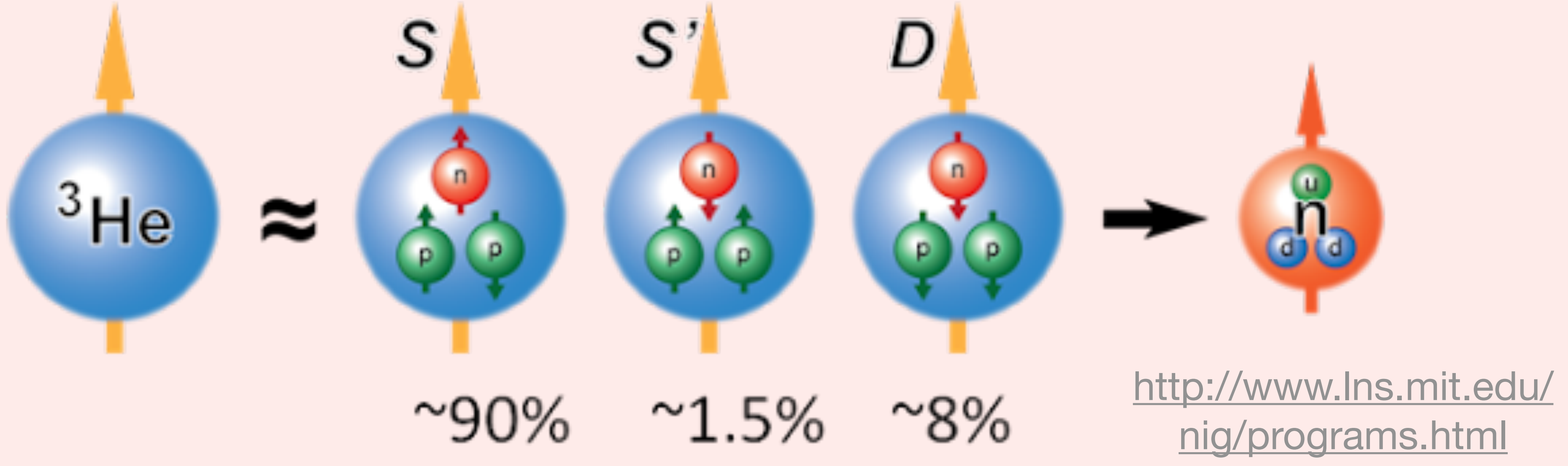

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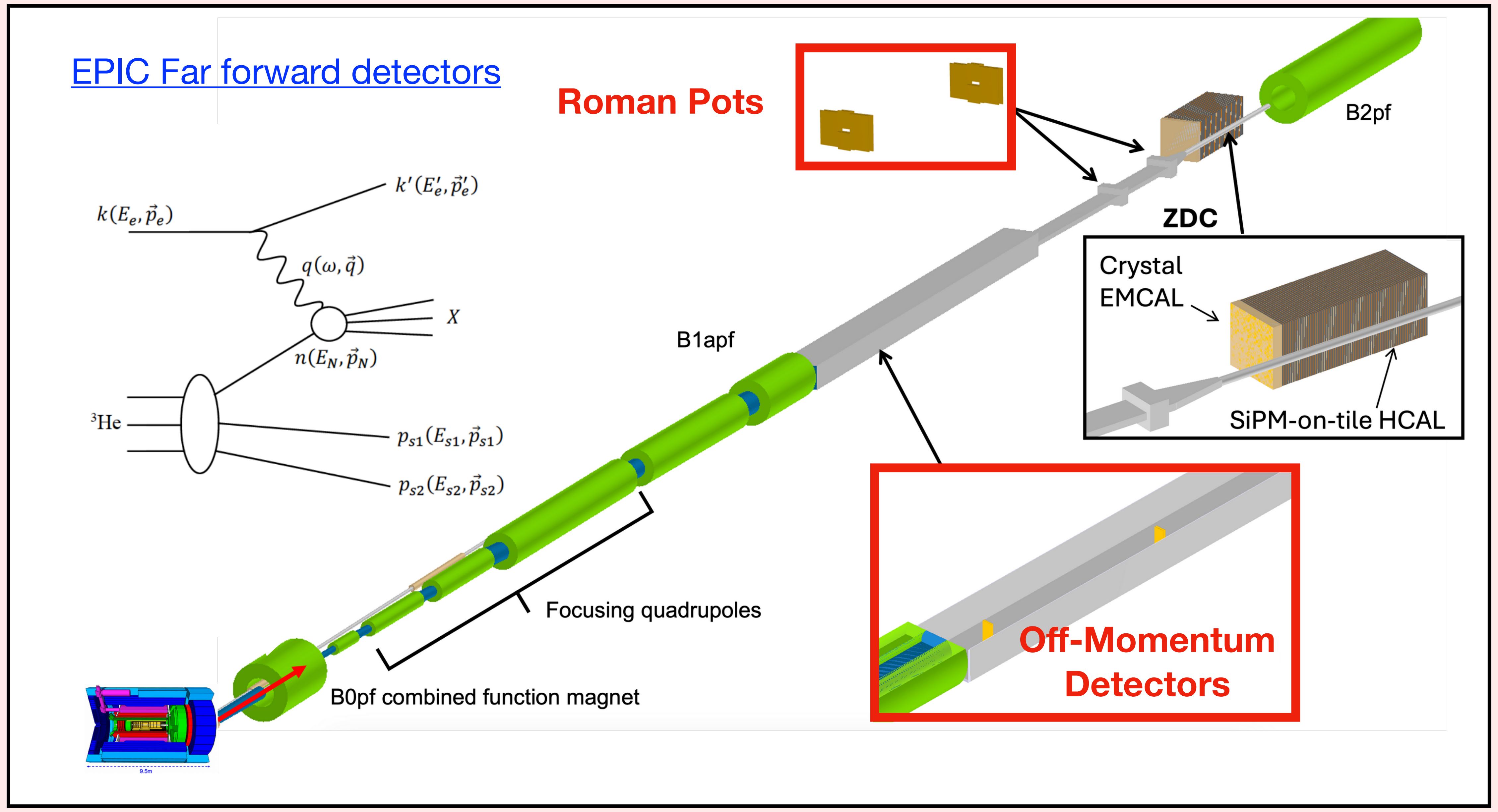

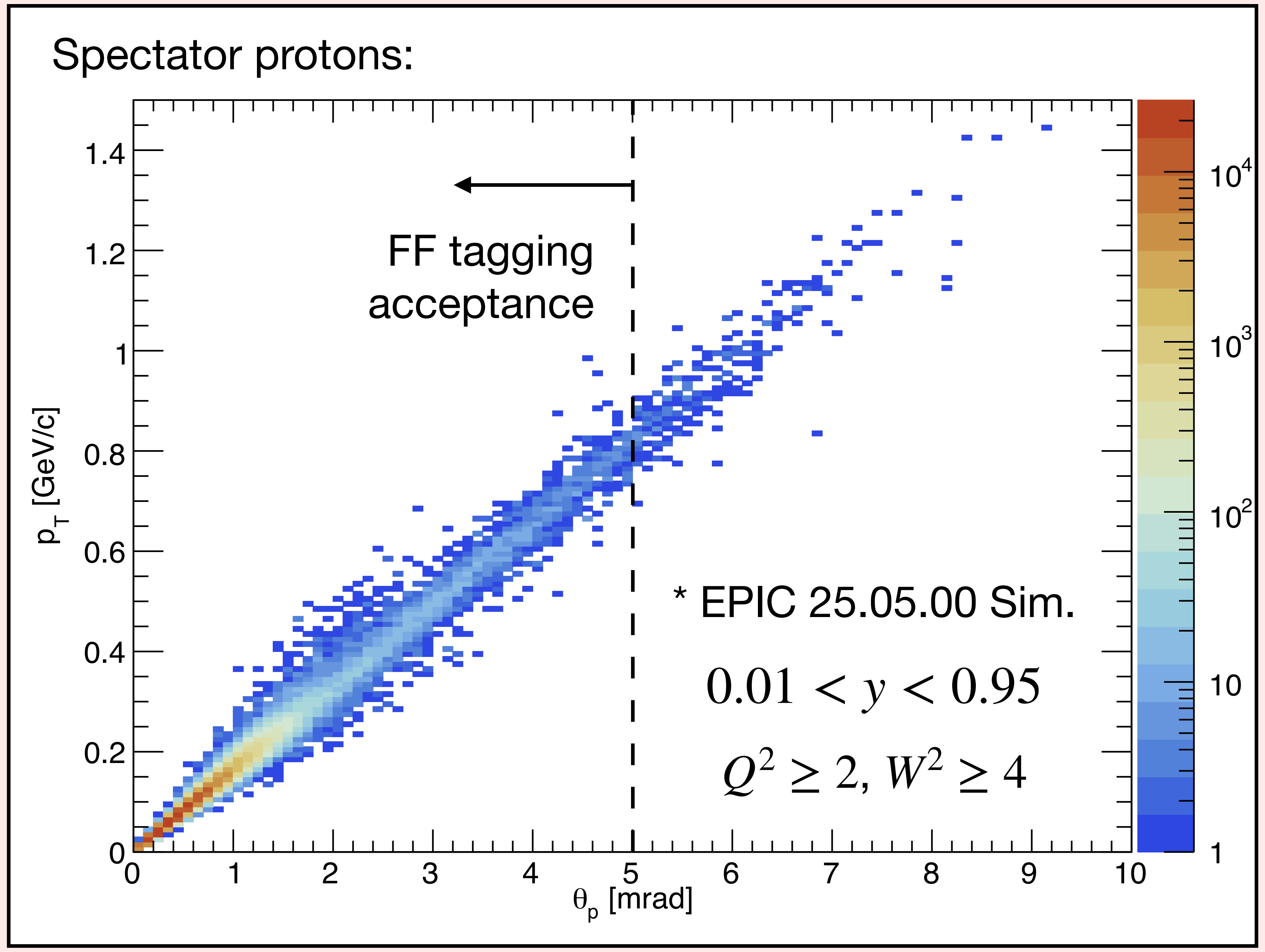

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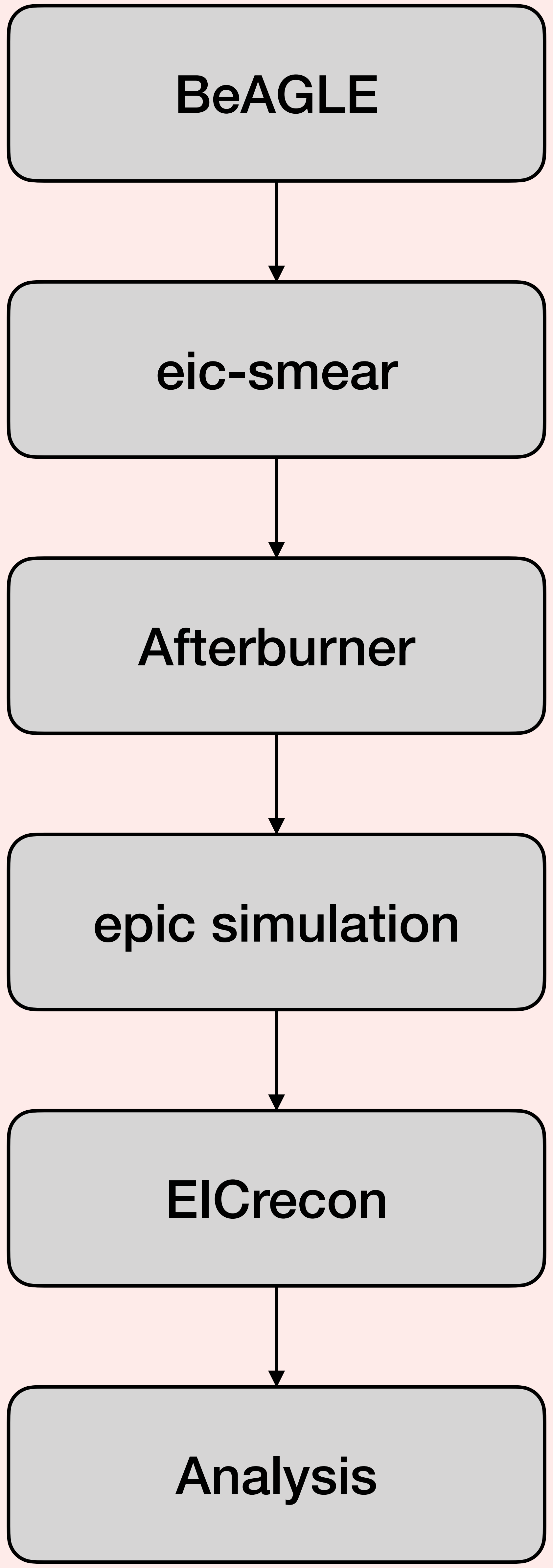
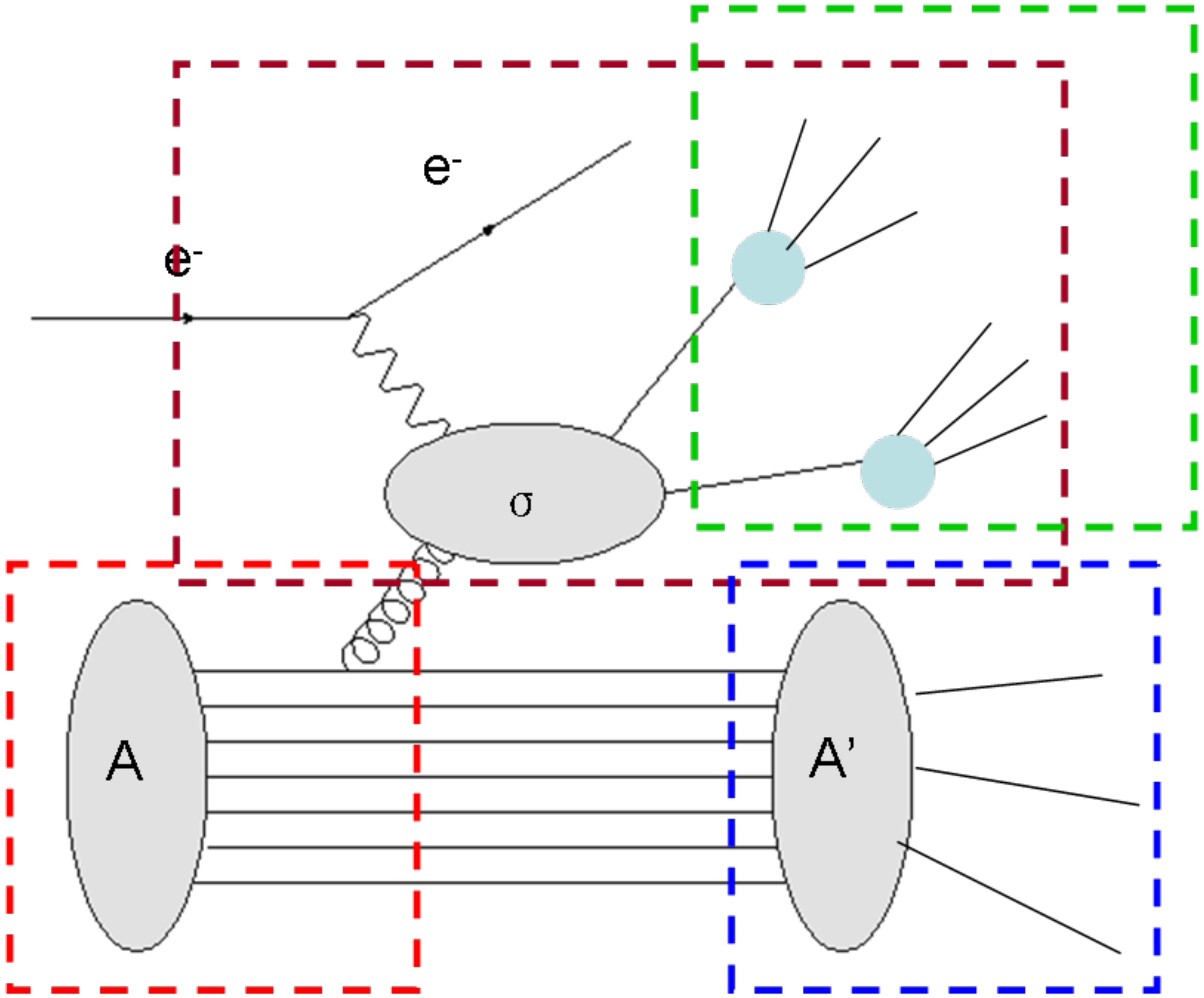


BeAGLE: eA event generator



A hybrid model consisting of DPMJet and PYTHIA with nPDF EPS09.

Nuclear geometry by DPMJet and nPDF provided by EPS09.

Parton level interaction and jet fragmentation completed in PYTHIA.

Nuclear evaporation (gamma dexcitation/nuclear fission/fermi break up) treated by DPMJet

Energy loss effect from routine by Salgado&Wiedemann to simulate the nuclear fragmentation effect in cold nuclear matter

- ☑ Parton distribution functions
- ☑ Short-range correlations
- ☑ Fermi motion
- ☑ Partonic (or "dipole") MS
- ☑ Partonic gluon radiation
- ☑ Formation times
- ☑ Hadronic Cascade
- ☑ Nuclear evaporation, break up
- ☑ Photonic de-excitation of A*

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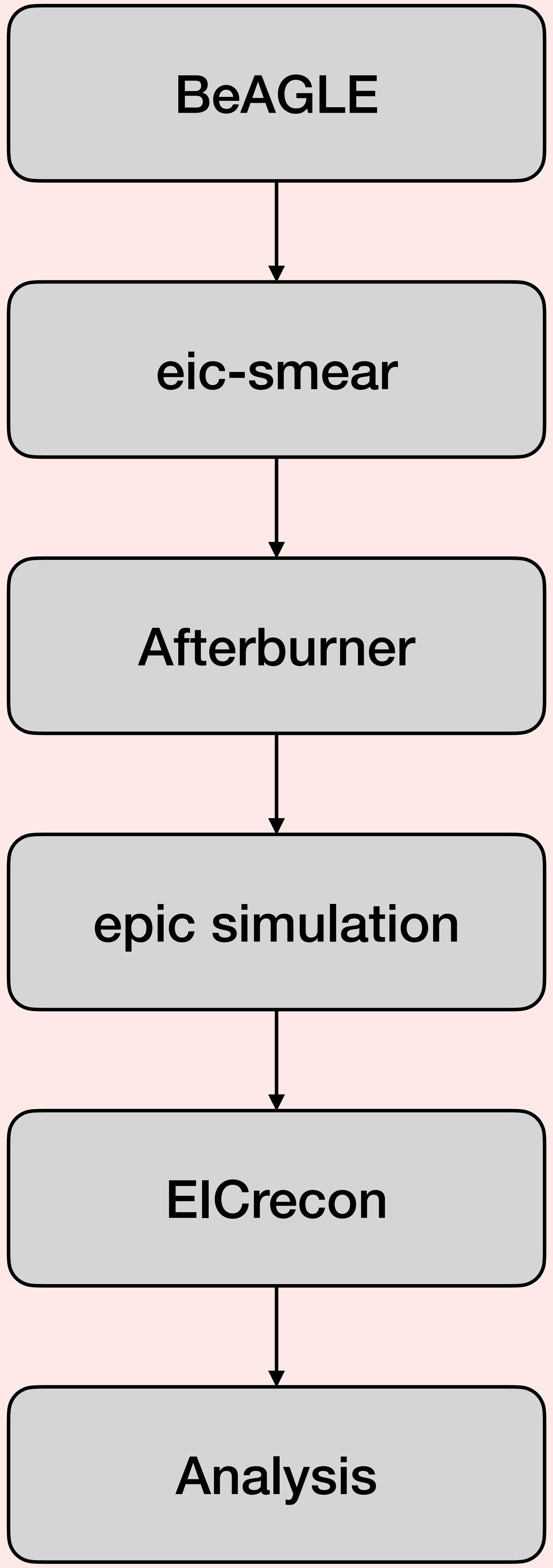

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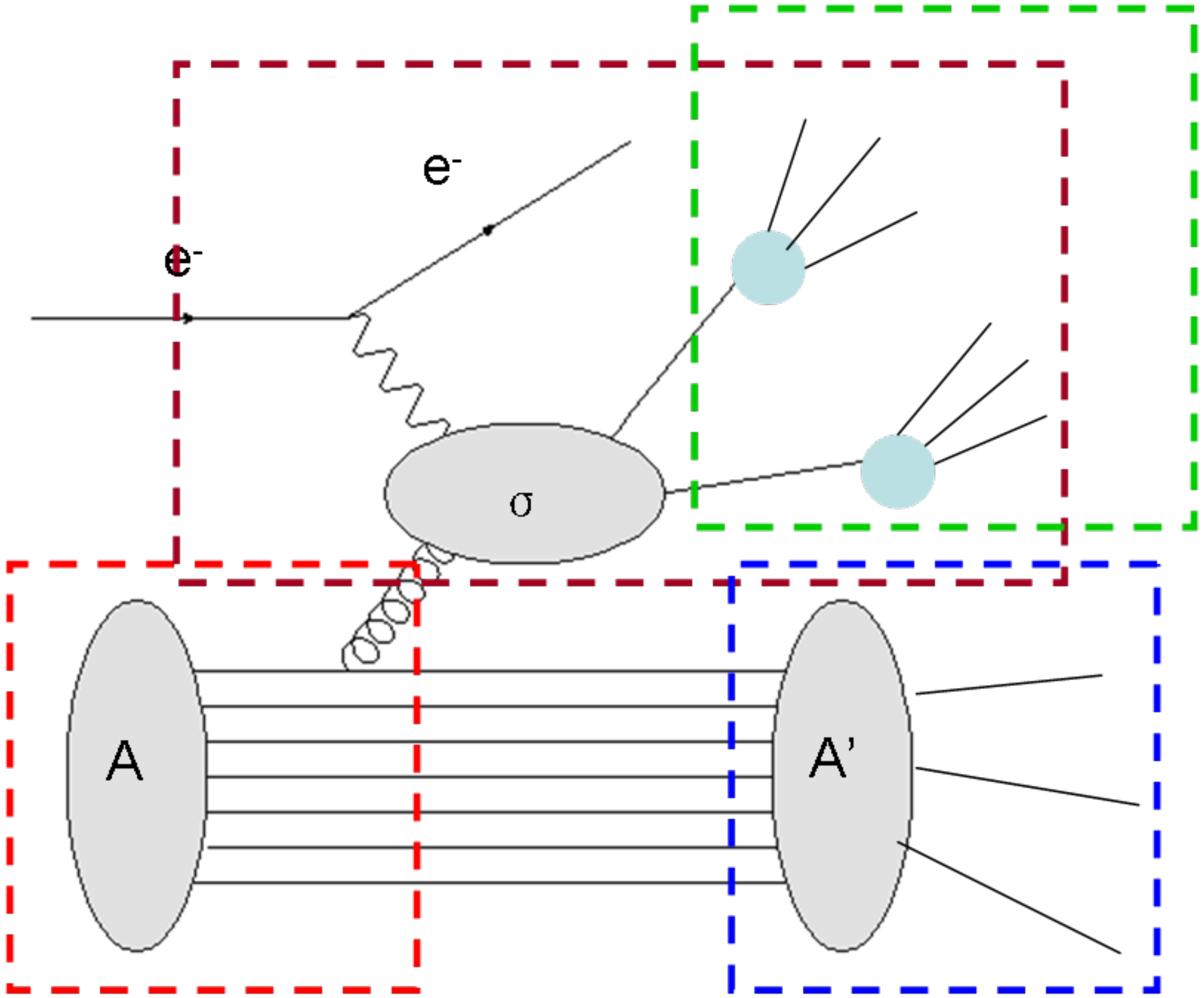

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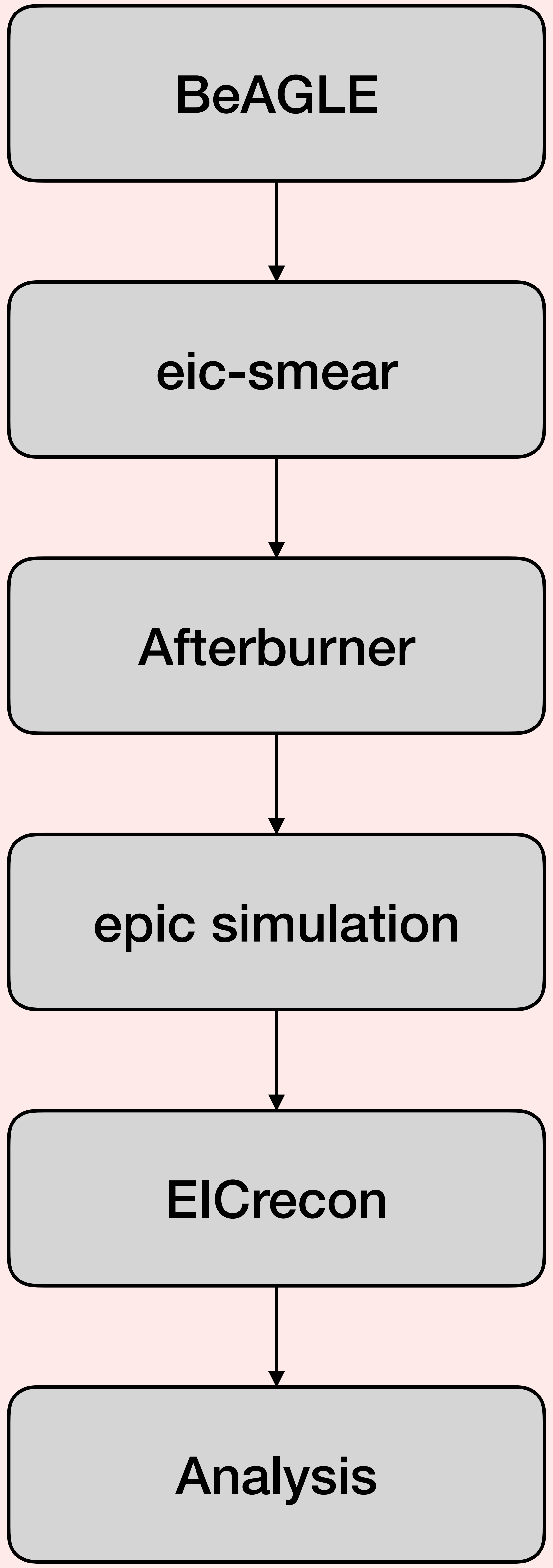

- A_1^n calculated from: Doi: 10.1103/PhysRevC.70.065207
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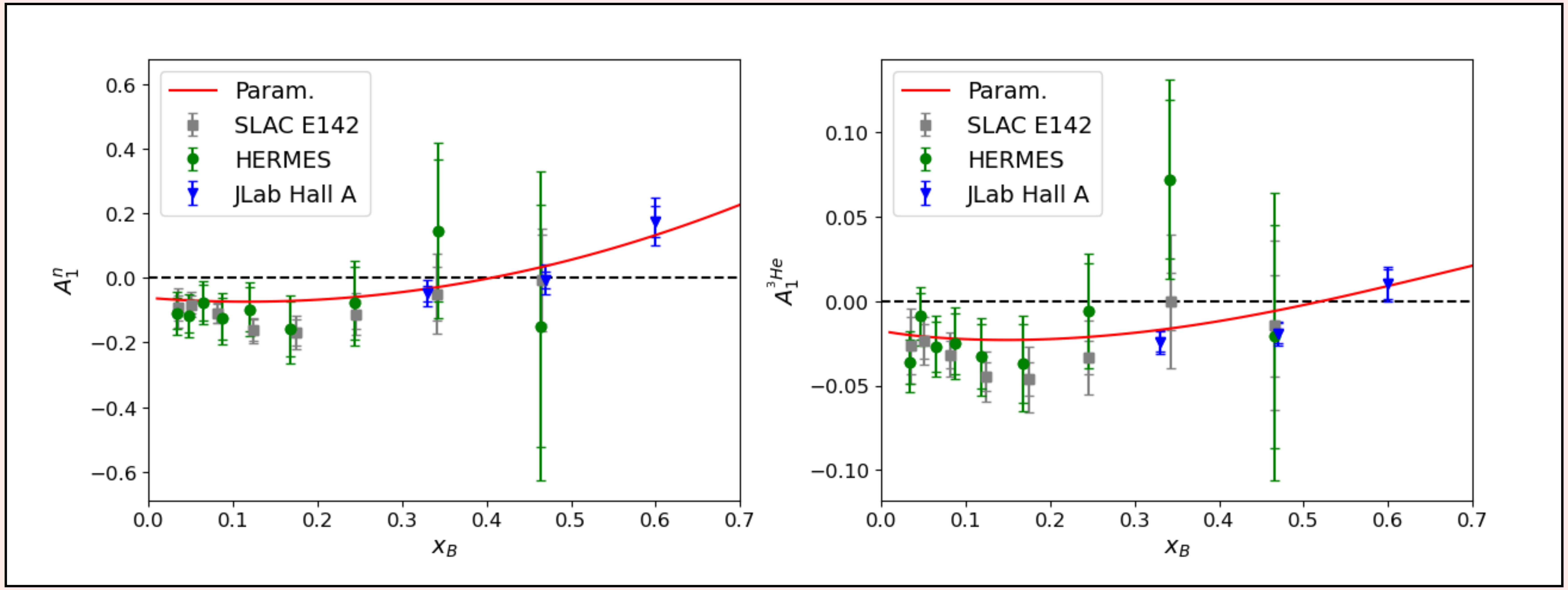
- all F_2's are taken from JAM22



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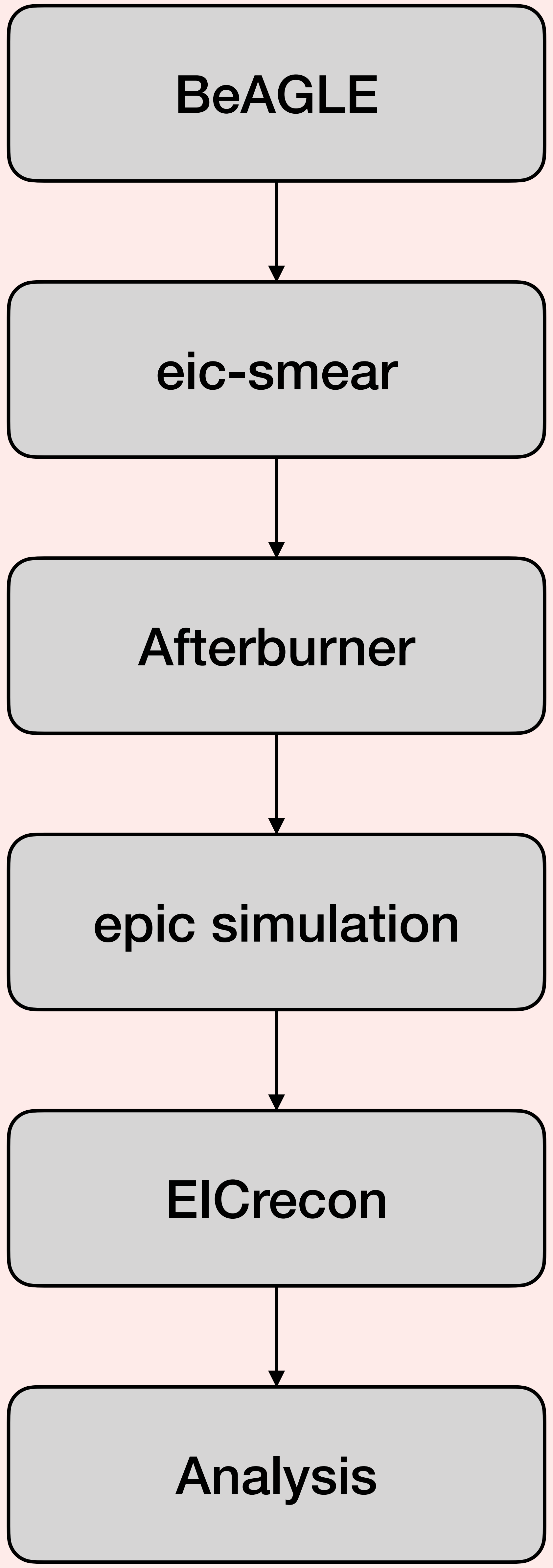
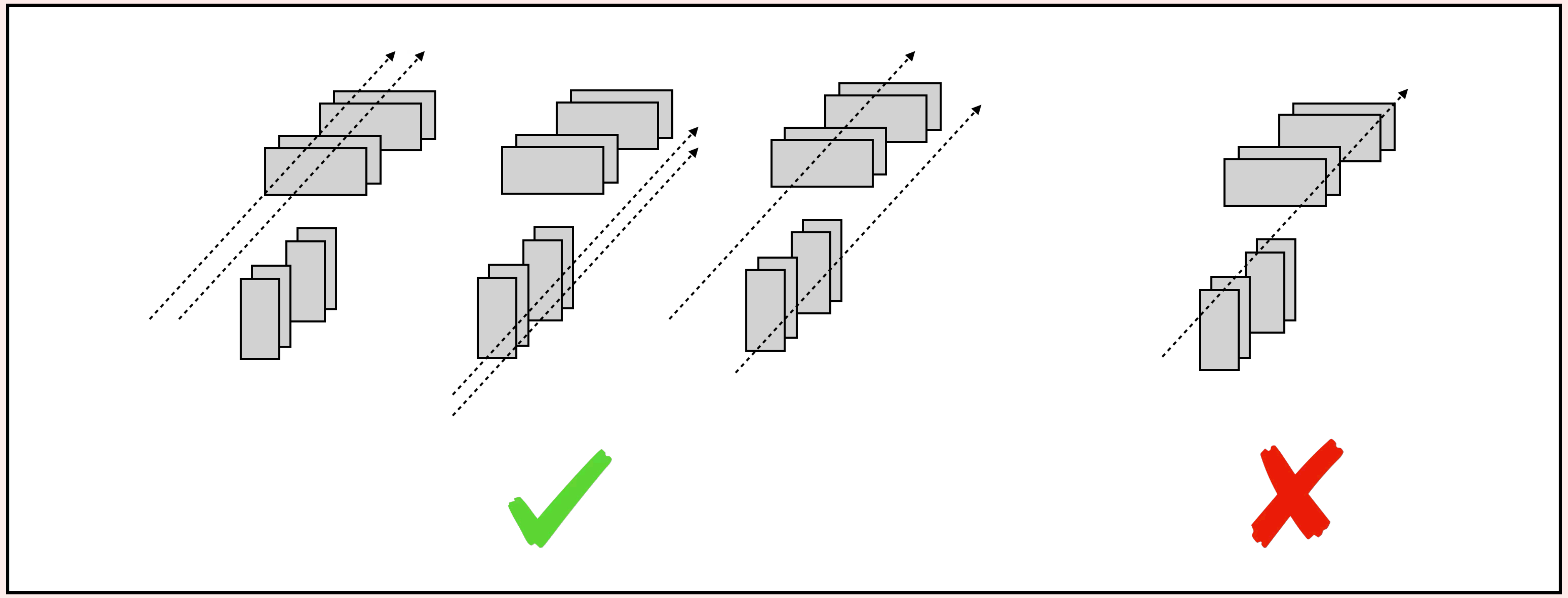
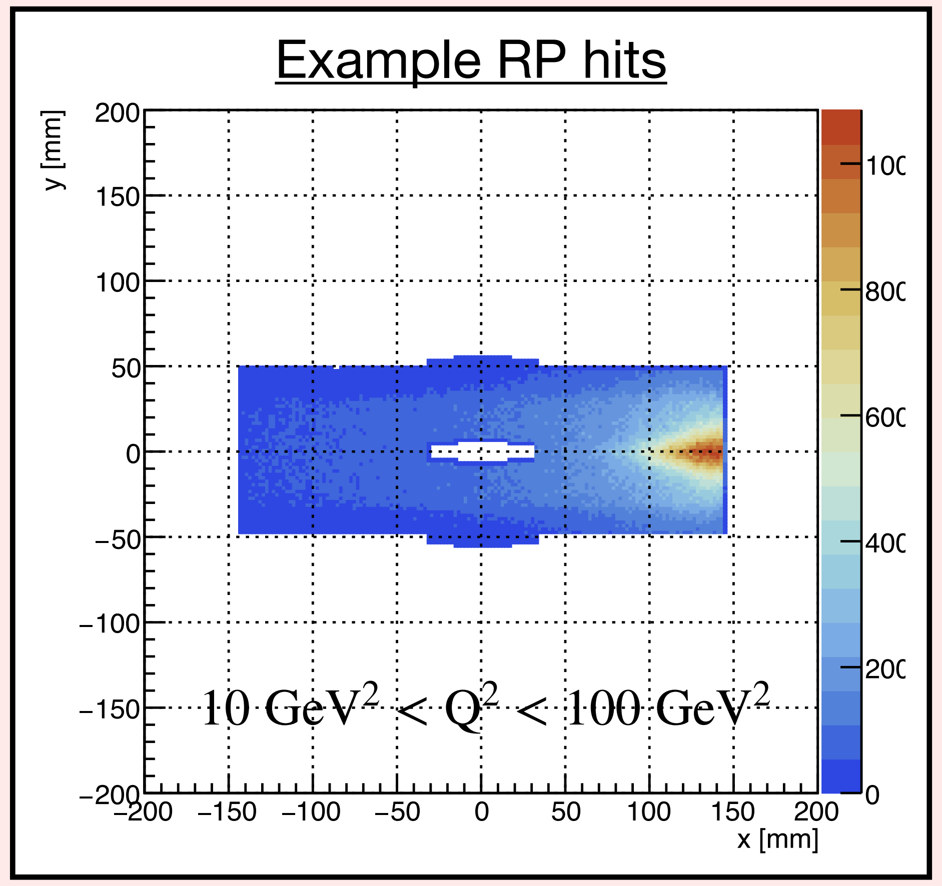
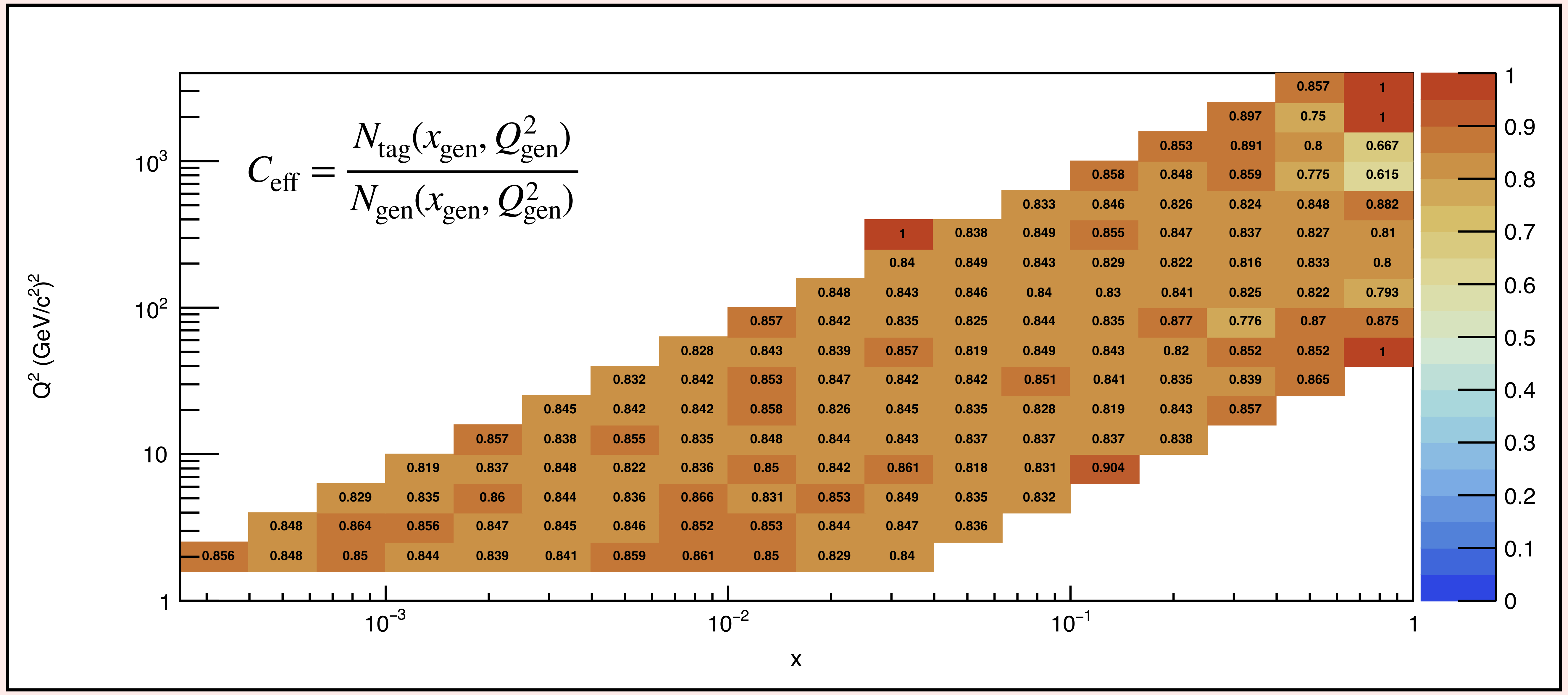
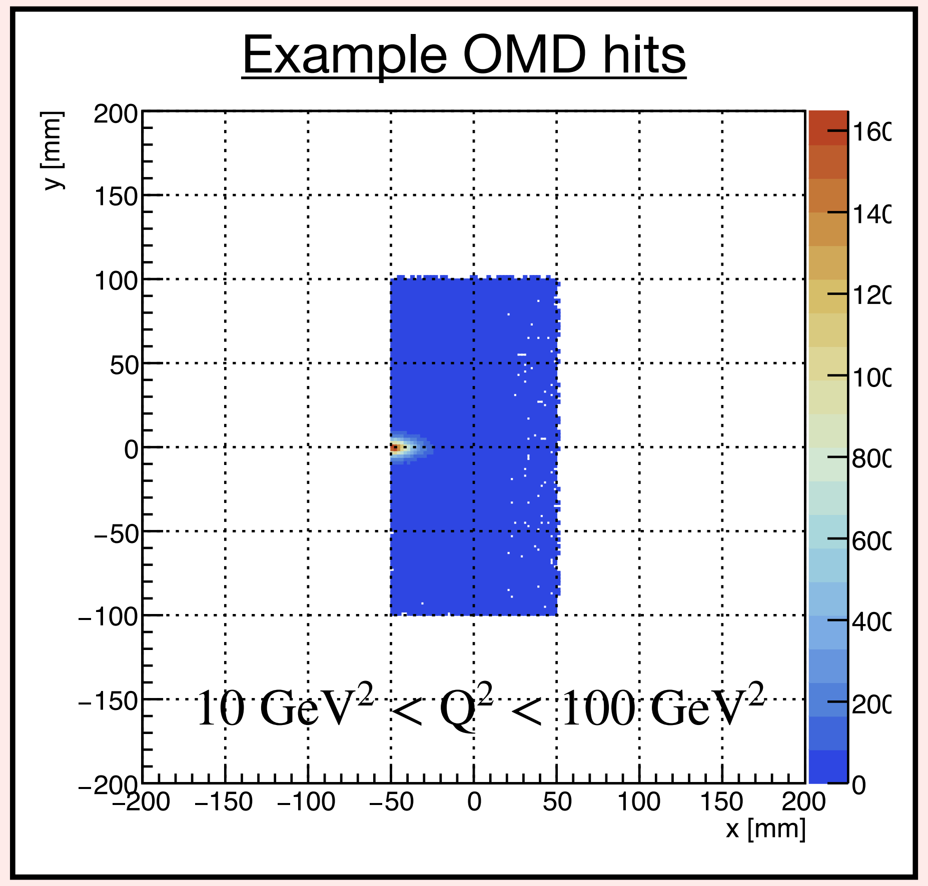


- Currently using a simple tracking algorithm based on hit per plane, C_{eff} ~ 83%









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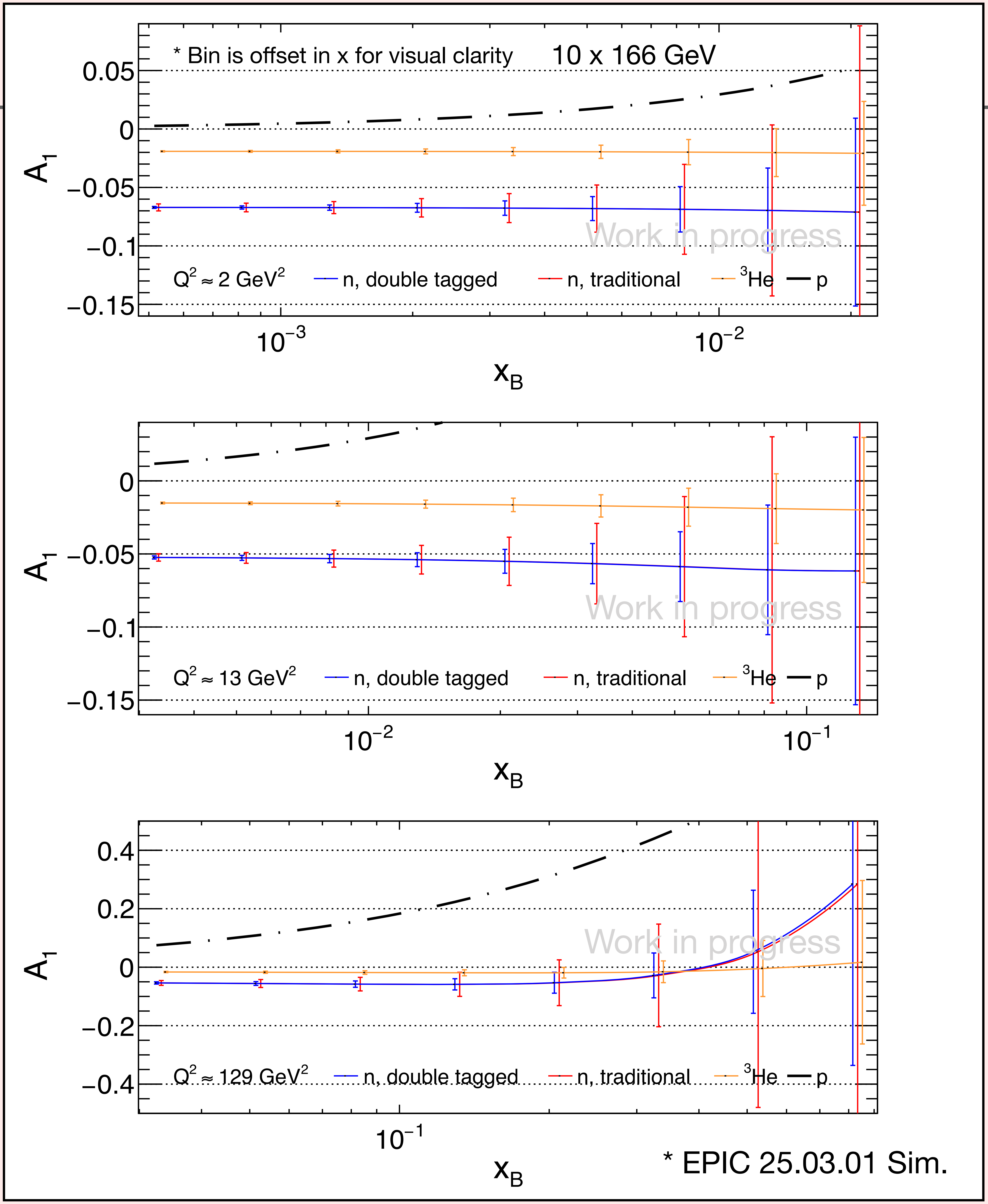
- $\mathscr{L} = 8.65\ \text{fb}^{-1}$, $P_e = P_n = 70\,\%$
- R calculated from https://doi.org/10.1016/S0370-2693(99)00244-0
- Statistical uncertainty and model uncertainties only



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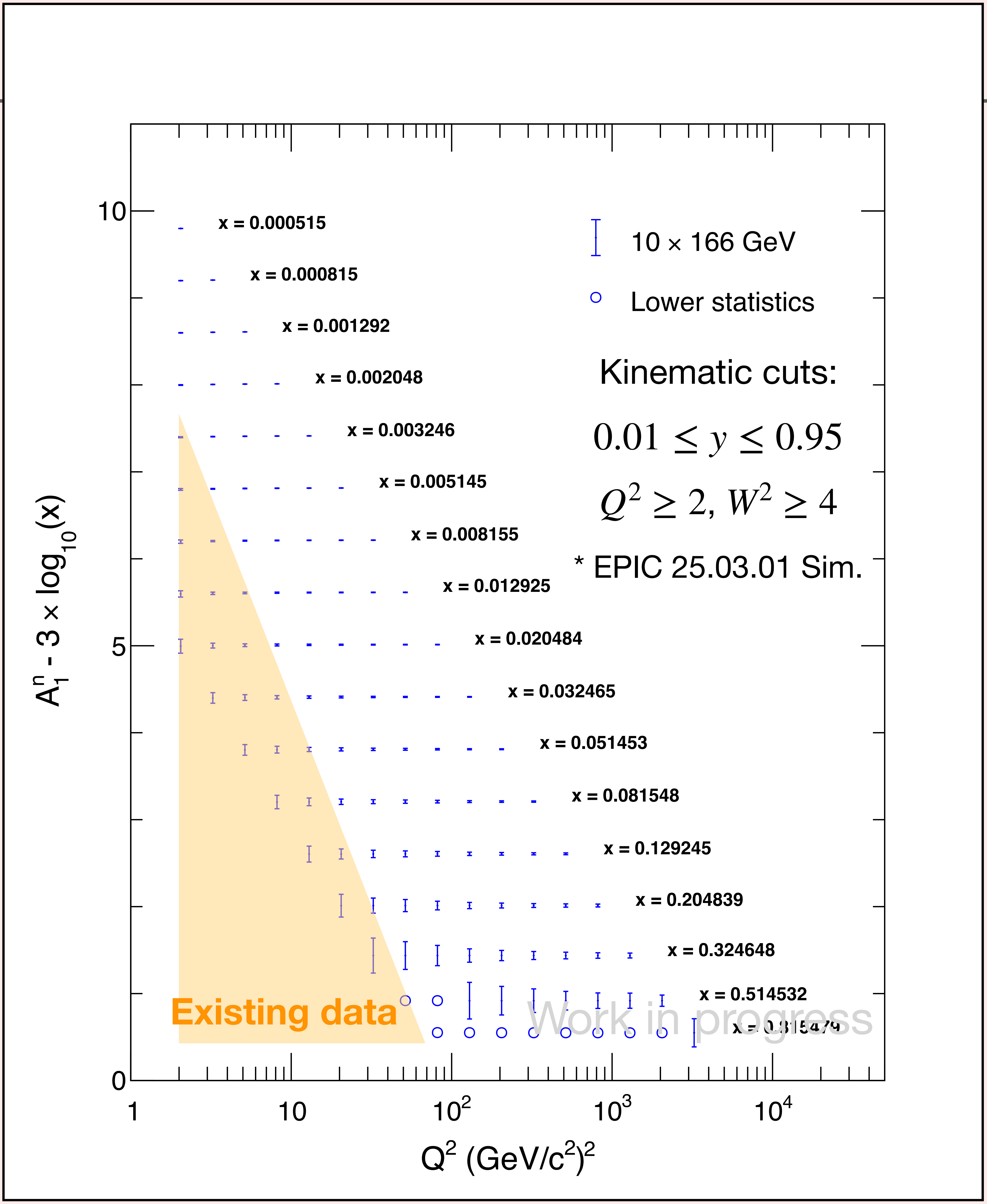
- R calculated from https://doi.org/10.1016/S0370-2693(99)00244-0
- Statistical uncertainty and model uncertainties only



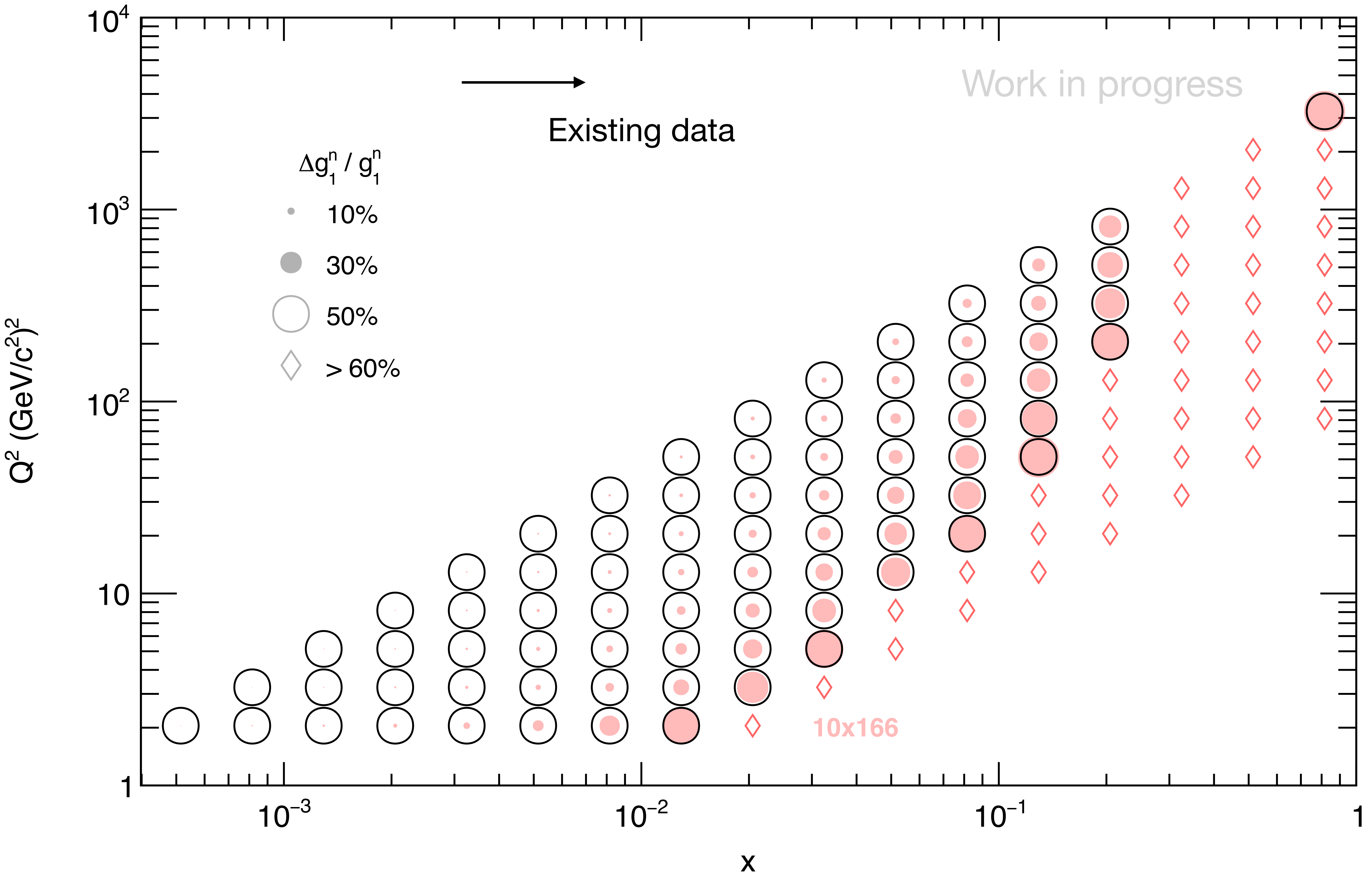
EIC Early Science

	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

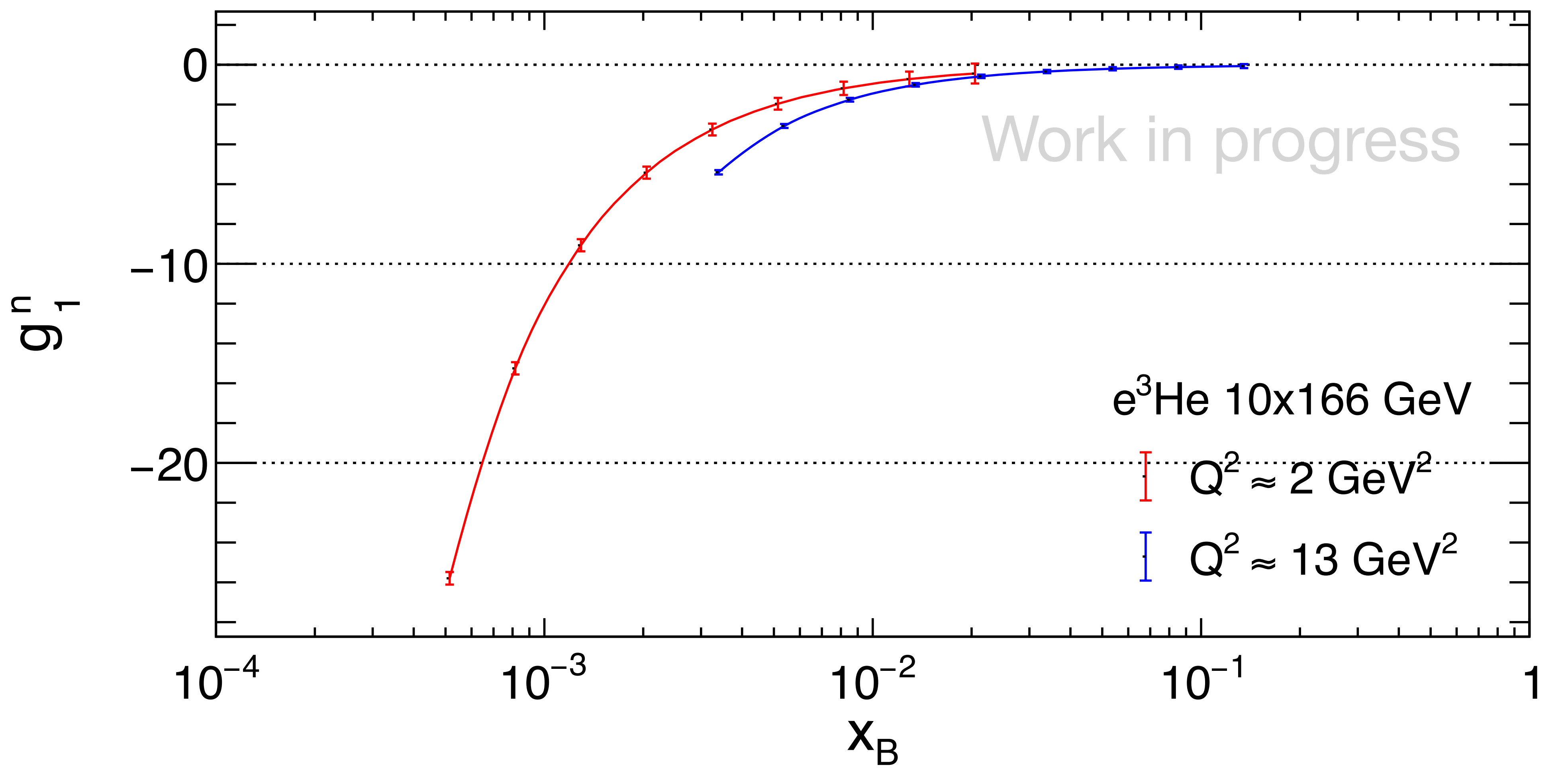
Note: the eA luminosity is per nucleon

Projected g_1^n at EIC Early Science

- $A_1 \approx g_1/F_1$ with F_1 calculated from JAM22
- Statistical uncertainties only



* EPIC 24.06.0 Sim.

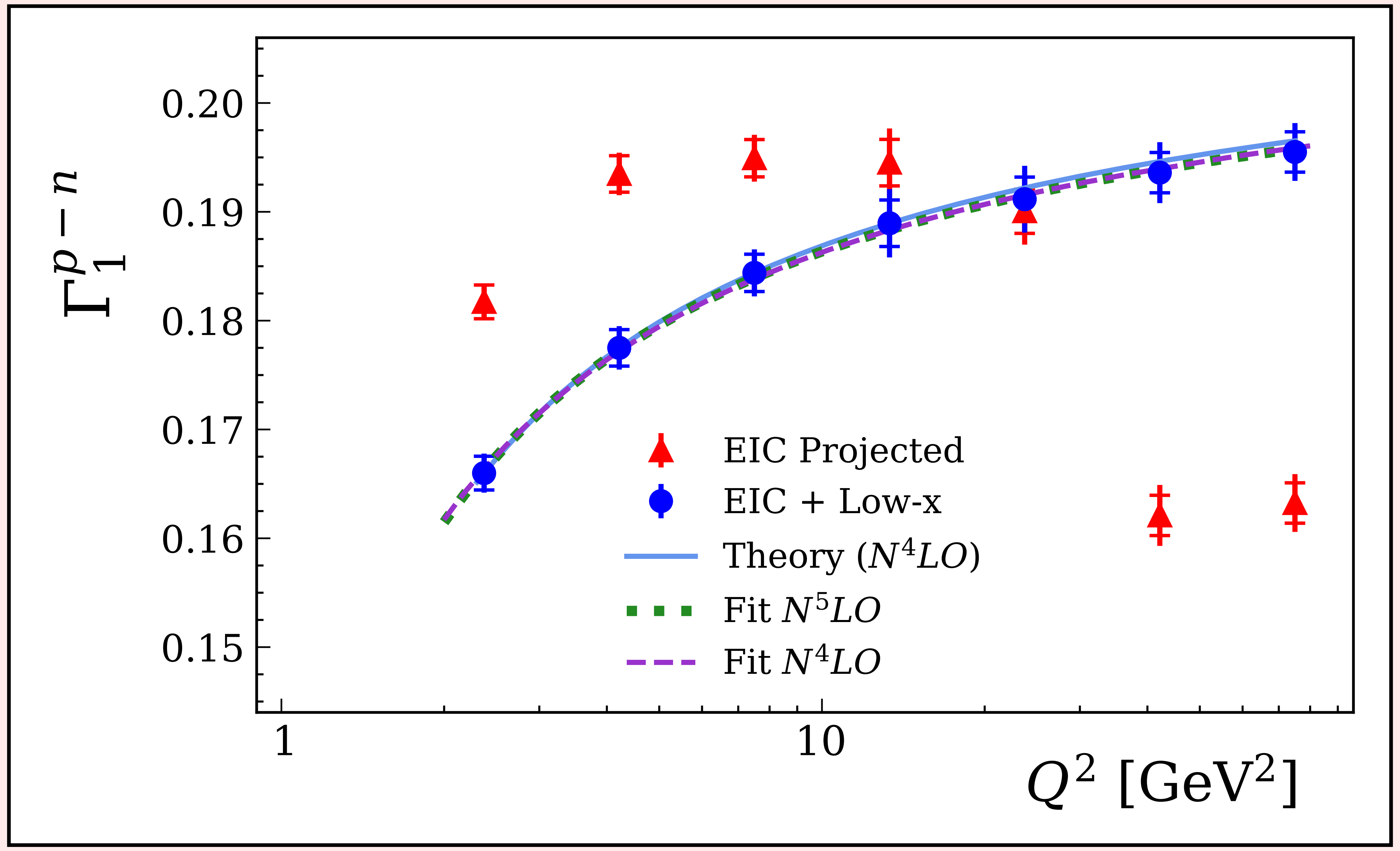


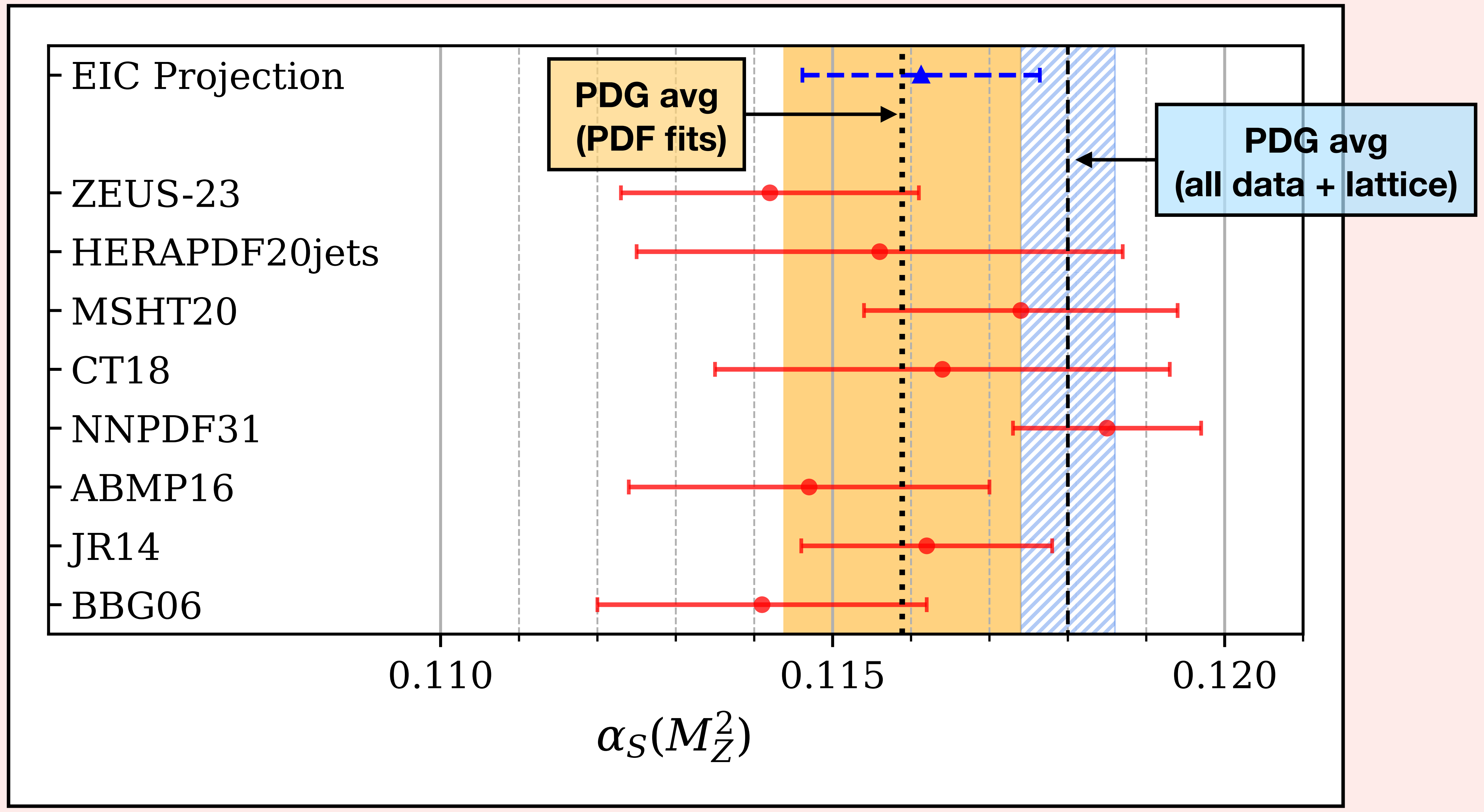
More energies for e and ^{3}He are available after year 5 of EIC running

α_s and Bjorken Sum

$$\Gamma_1^{\mathrm{p-n}}(\alpha_s) = \Gamma_1^{\mathrm{p-n}}(Q^2) = \int_0^{1^-} (g_1^p(Q^2) - g_1^n(Q^2))\, dx = \sum_{n>0} \frac{\mu_{2n}^{p-n}(\alpha_s)}{Q^{2n-2}}$$

$$= \frac{g_A}{6}\left[1 - \frac{\alpha_S(Q^2)}{\pi} - 3.58\left(\frac{\alpha_S(Q^2)}{\pi}\right)^2 - 20.21\left(\frac{\alpha_S(Q^2)}{\pi}\right)^3 - 175.7\left(\frac{\alpha_S(Q^2)}{\pi}\right)^4 - \mathcal{O}((\alpha_S)^5)\right] \quad \text{at finite } Q^2$$





Assume $\mathscr{L} = 10\ \mathrm{fb}^{-1}$ for each setting:

5x41, 10x100, 18x275 ep DIS

5x41, 10x100, 18x166 en DIS

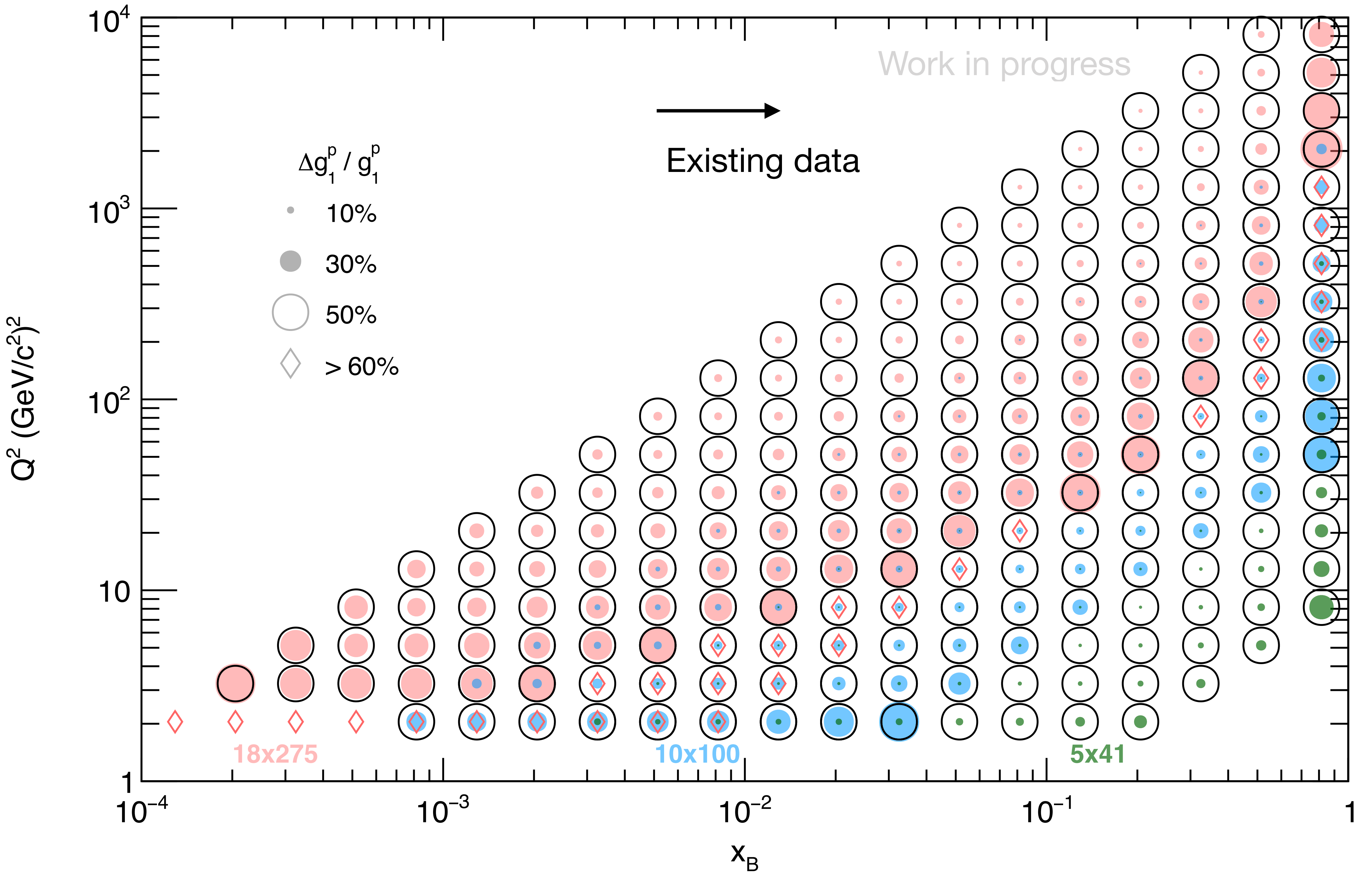
https://doi.org/10.1103/PhysRevD.110.074004

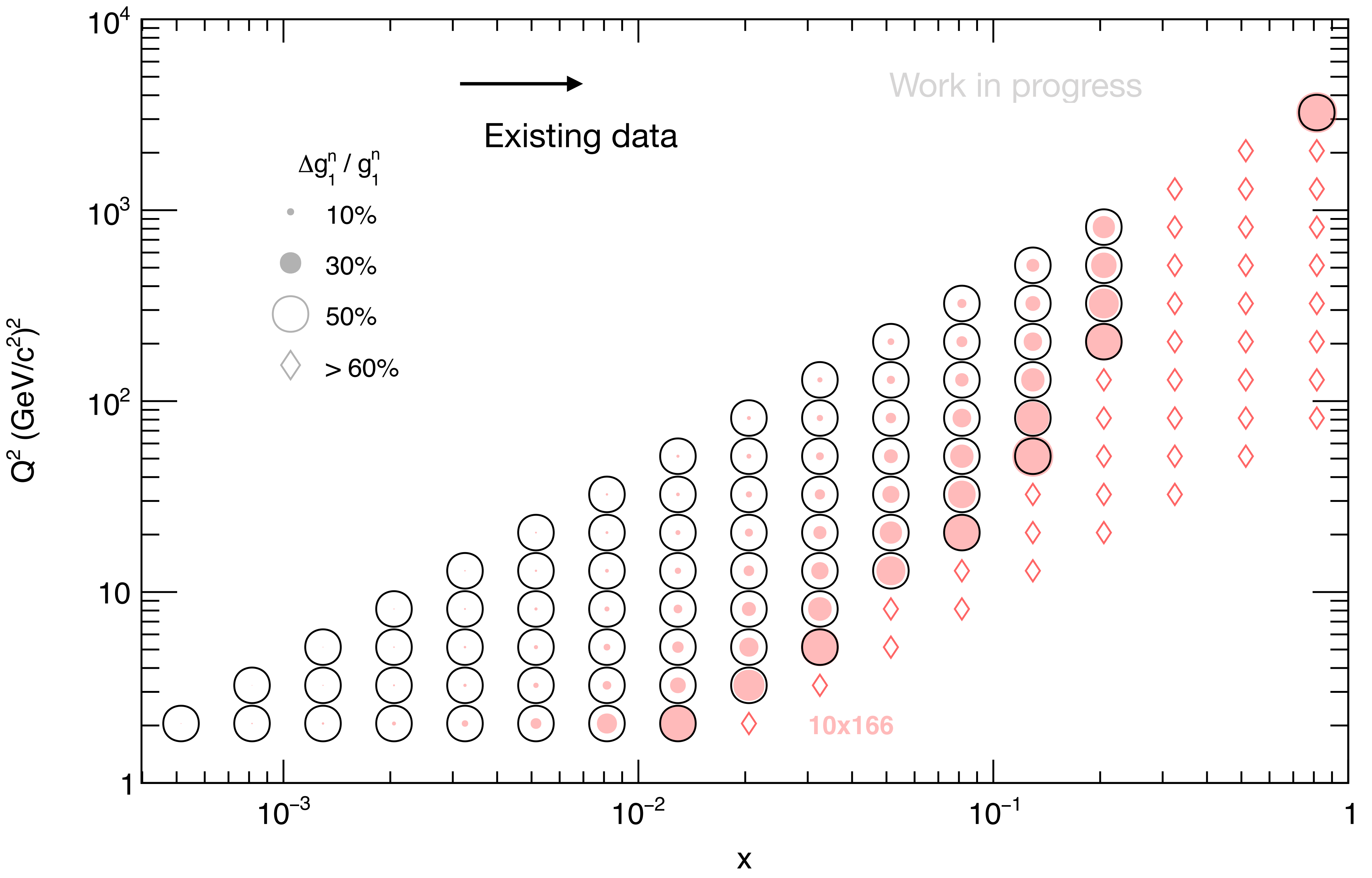
$$\Delta\alpha_s(M_Z)/\alpha_s(M_Z) = 1.3\ \%$$

Summary

- New g_1 measurement at EIC will help investigate the quark and gluon spin contributions to the nucleon spin
- Both g_1^p and g_1^n will be measured; double tagging method will help constrain model uncertainty and test light nuclei model
- EIC will be able to measure g_1 at low x region which has not been explored
- g_1^p and g_1^n lead to Bjorken sum which will provide a new high precision measurement on the α_s

Thank you!





Slides++ : Double Spin Asymmetry

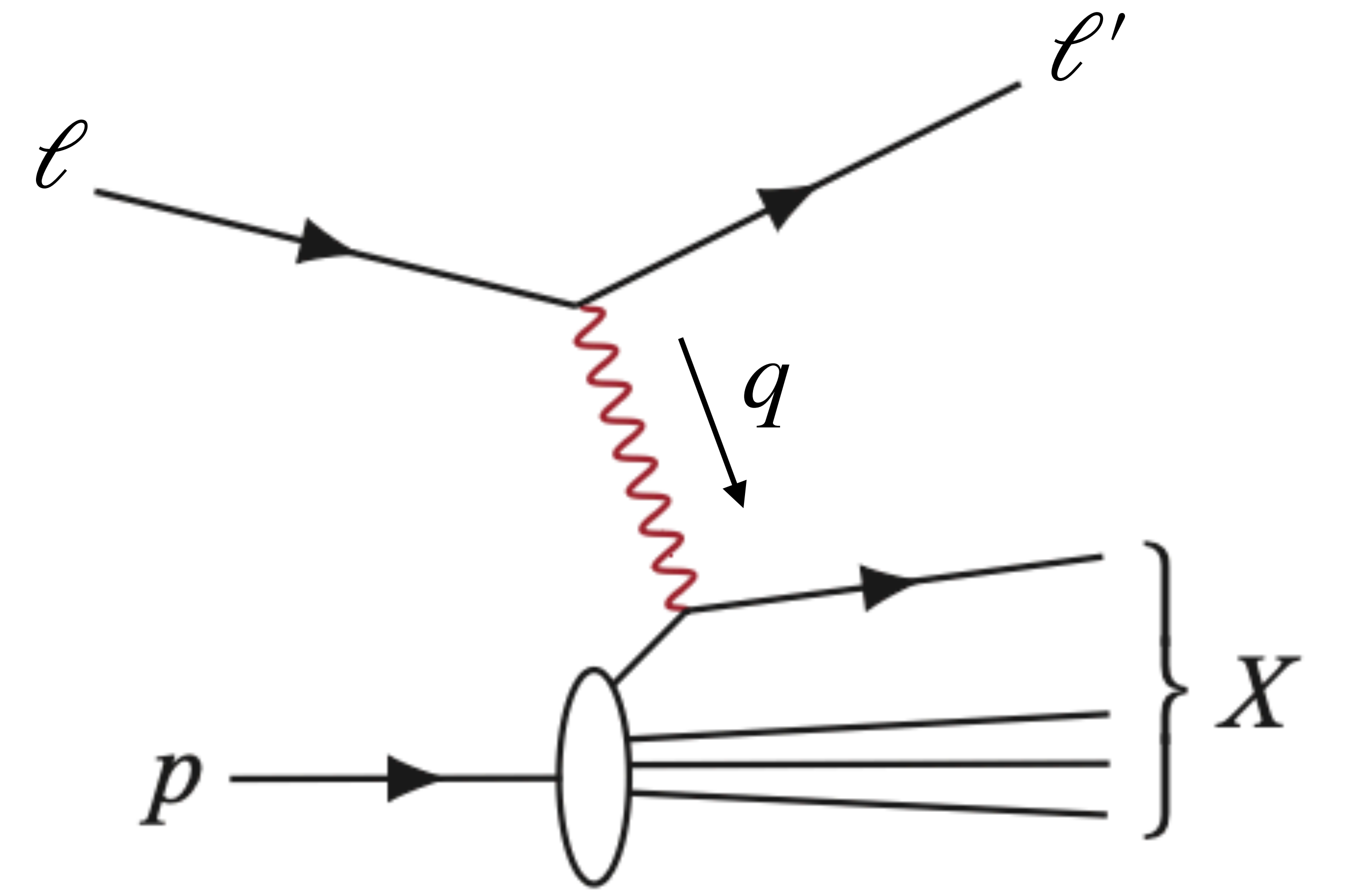
$$\frac{d^3\Delta\sigma(\beta)}{dQ^2dxd\phi} = \frac{4\alpha^2}{Q^2}y\left\{\cos\beta\left[\left(1-\frac{y}{2}-\frac{\gamma^2y^2}{4}\right)g_1(x,Q^2) - \frac{\gamma^2 y}{4}g_2(x,Q^2)\right] - \cos\phi\sin\beta\frac{\sqrt{Q^2}}{\nu}\left(1-y-\frac{\gamma^2y^2}{4}\right)^{\frac{1}{2}}\left[\frac{y}{2}g_1(x,Q^2)+g_2(x,Q^2)\right]\right\}$$

- Direct measurement is more challenging
- Easier to measure via cross section ratio
- Systematic is largely canceled out

$$g_1 = \frac{F_2}{2x(1+R)}(A_1+\gamma A_2)$$

$$A_1(x,Q^2) \equiv \frac{\sigma_{1/2}-\sigma_{3/2}}{\sigma_{1/2}+\sigma_{3/2}} = \frac{A_\parallel}{D(1+\eta\xi)} - \frac{\eta A_\perp}{d(1+\eta\xi)}$$

$$A_2(x,Q^2) \equiv \frac{2\sigma_{LT}}{\sigma_{1/2}+\sigma_{3/2}} = \frac{\xi A_\parallel}{D(1+\eta\xi)} - \frac{A_\perp}{d(1+\eta\xi)}$$



NC Inclusive DIS: $e+p\rightarrow e'+X$

https://arxiv.org/abs/2103.05419