Introduction to eA physics
and
A new Monte Carlo for Small x Diffraction at an Electron-Ion Collider

Tobias Toll
BNL

Outline:

What is the Electron Ion Collider?

Small x in eA DIS

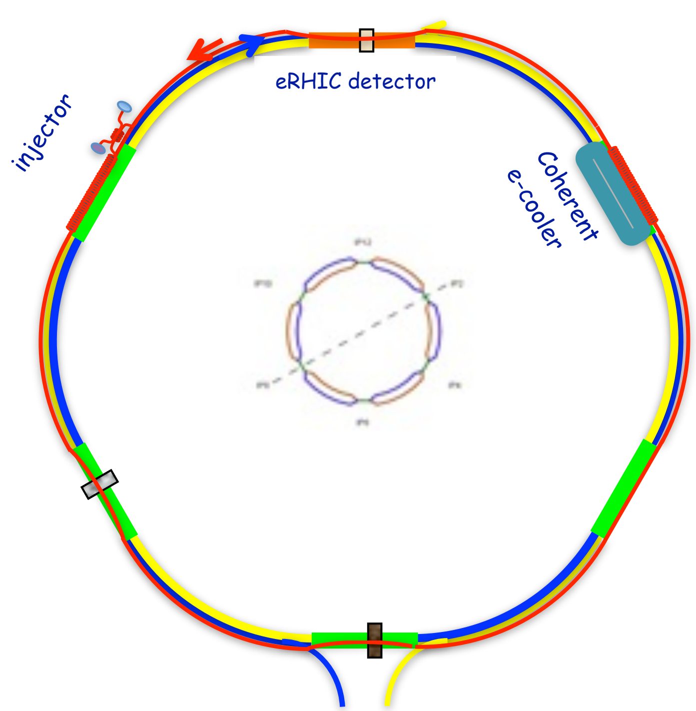
Diffractive Vector Mesons in ep

Diffractive Vector Mesons in eA

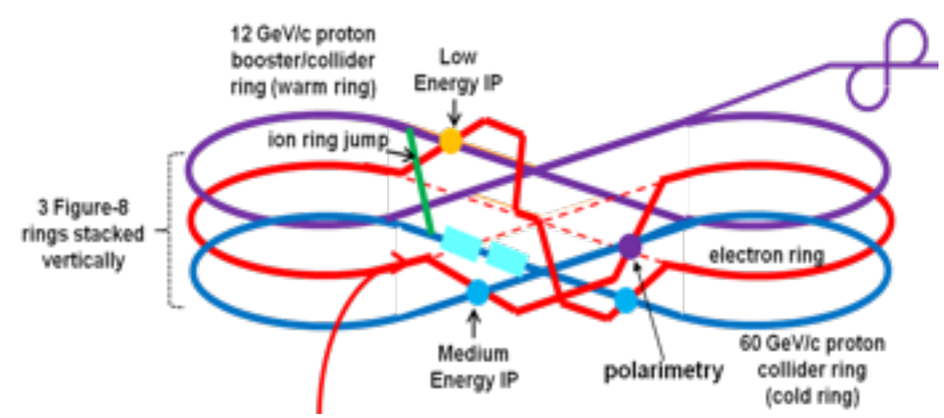
The EIC - 2 concepts

eRHIC = RHIC +

Energy-Recovery Linac



ELIC = CEBAF + Hadron Ring



eRHIC luminosity at top energy

Vladimir N. Litvinenko for eRHIC team

	e	p	$^{2}He^{3}$	$^{79}Au^{197}$	$^{92}U^{238}$
Energy, GeV	20 (30)	325	215	130	130
CM energy, GeV		161	131	102	102
		(197)	(161)	(125)	(125)
Number of bunches/distance between bunches	74 nsec	166	166	166	166
Bunch intensity (nucleons) ,10^{11}	0.24 (.05)	2	3	5	5
Bunch charge, nC	3.8 (0.4)	32	32	32	32
Beam current, mA	50 (10)	420	420	420	420
Normalized emittance of hadrons , 95% , mm mrad		1.2	1.2	1.2	1.2
Normalized emittance of electrons, rms, mm mrad		23 (34)	35 (52)	57 (85)	57 (85)
Polarization, %	80	70	70	none	none
rms bunch length, cm	0.2	4.9	4.9	4.9	4.9
β*, cm	5	5	5	5	5
Luminosity per nucleon, $cm^{-2}s^{-1}$			1.46×10^{34} (0.29×10^{34})		

Hourglass effect is included: $h\left(\sigma_s/\beta^*\right) = 0.851$

The EIC - Rough Time Line

Proceedings from the INT meeting fall 2010
to be final spring 2011

http://www.int.washington.edu/talks/WorkShops/int_10_3/

This is a launching pad for the white paper
1st draft white paper in fall 2011

Convince Nuclear Science Advisory Committee
to make the EIC the top priority in the next long range
plan by the end of 2012/early 2013.

Site selection?

First Beam 2020-2022

The EIC - Measurements

Small x/Saturation:

Momentum Gluon Distributions of Nuclei:

$$F_2^A \ \& \ F_L^A$$

Spacial Gluon Distribution of Nuclei

Exclusive diffractive $J/\Psi, \ \phi \ \rho, \ \mathrm{DVCS}$

Dijets, azimuthal decorrelation

Large x:

Internal Spin Landscape of Nuclei:

Exclusive and SIDIS measurements

Polarized Beams!

Electroweak Physics

Much more information on:

http://web.mit.edu/eicc/

The EIC - Measuremens

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Dijets

"Oomph" factor - increase in non-linear effects/ black body scattering

Expensive Oomph: High Energy, small x

Cheap Oomph: Large A:

$$Q_s^{A^2} \propto A^{1/3} Q_s^{p2}$$

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Slides from Markus Diehl
7/10 at the INT workshop

Can one expect nonlinear effects (saturation) in F_2 and F_L at an EIC

- as long as have no data, answer is necessarily model-dependent
- here: use dipole models checked against HERA data (ep), adapted to eA

$$F_{2,L}(x,Q^2) = \int d^2b\, d^2r\, dz\, \left[\psi^*(r,Q^2)\psi(r,Q^2)\right]_{2,L} \mathcal{N}(x,r,b)$$

$\mathcal{N}$ = dipole scattering amplitude, between 0 and 1

- larger $\mathcal{N}$ $\rightarrow$ expect stronger nonlinear effects
  to assess typical values of $\mathcal{N}$ calculate average:

$$\langle\mathcal{N}\rangle_{2,L} = \frac{\int d^2b\, d^2r\, dz\, [\psi^*\psi]_{2,L}\, \mathcal{N}^2}{\int d^2b\, d^2r\, dz\, [\psi^*\psi]_{2,L}\, \mathcal{N}}$$

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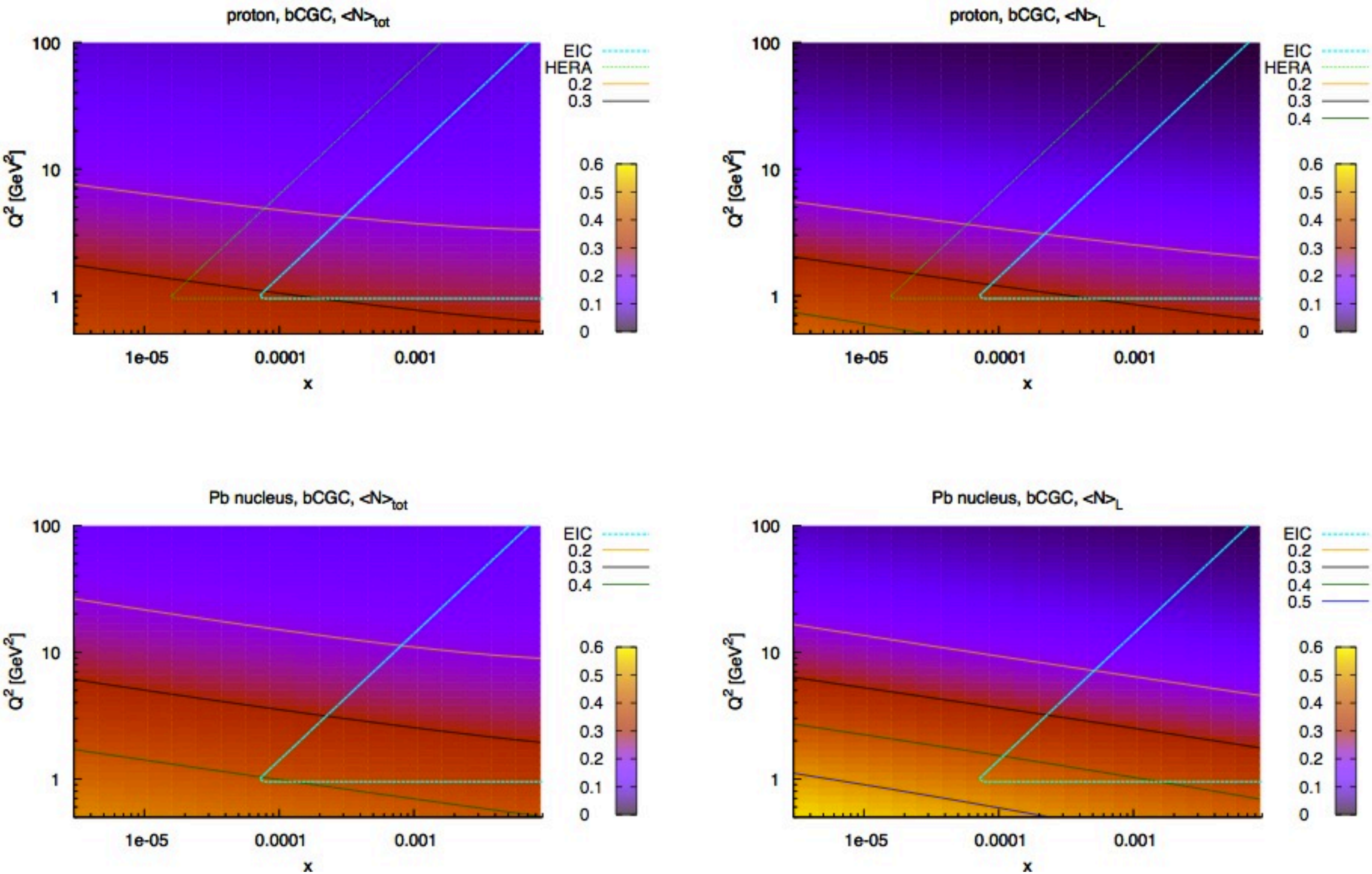
- note: F_2 and F_L average over all b
  including dilute region of target
  examples:
  - Gaussian density profile $T(b) = \exp(-b^2/R^2) \Rightarrow \langle \mathcal{N} \rangle \leq 1/2$
  - hard sphere $T(b) = \sqrt{1 - b^2/R^2} \Rightarrow \langle \mathcal{N} \rangle \leq 3/4$
- following plots show $\langle \mathcal{N} \rangle_{2,L}$
  with kinematic limits in x, Q^2 plane
  - for EIC with $E_e = 30\,\mathrm{GeV}$, $E_A = 130\,\mathrm{GeV}$, $y \leq 0.9$
  - for HERA (ep)

using bCGC dipole cross section:

Figures by T. Lappi



The EIC - Measuremens

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F_2^A & F_L^A

$\boxed{\text{Spacial Gluon Distribution of Nuclei}}$

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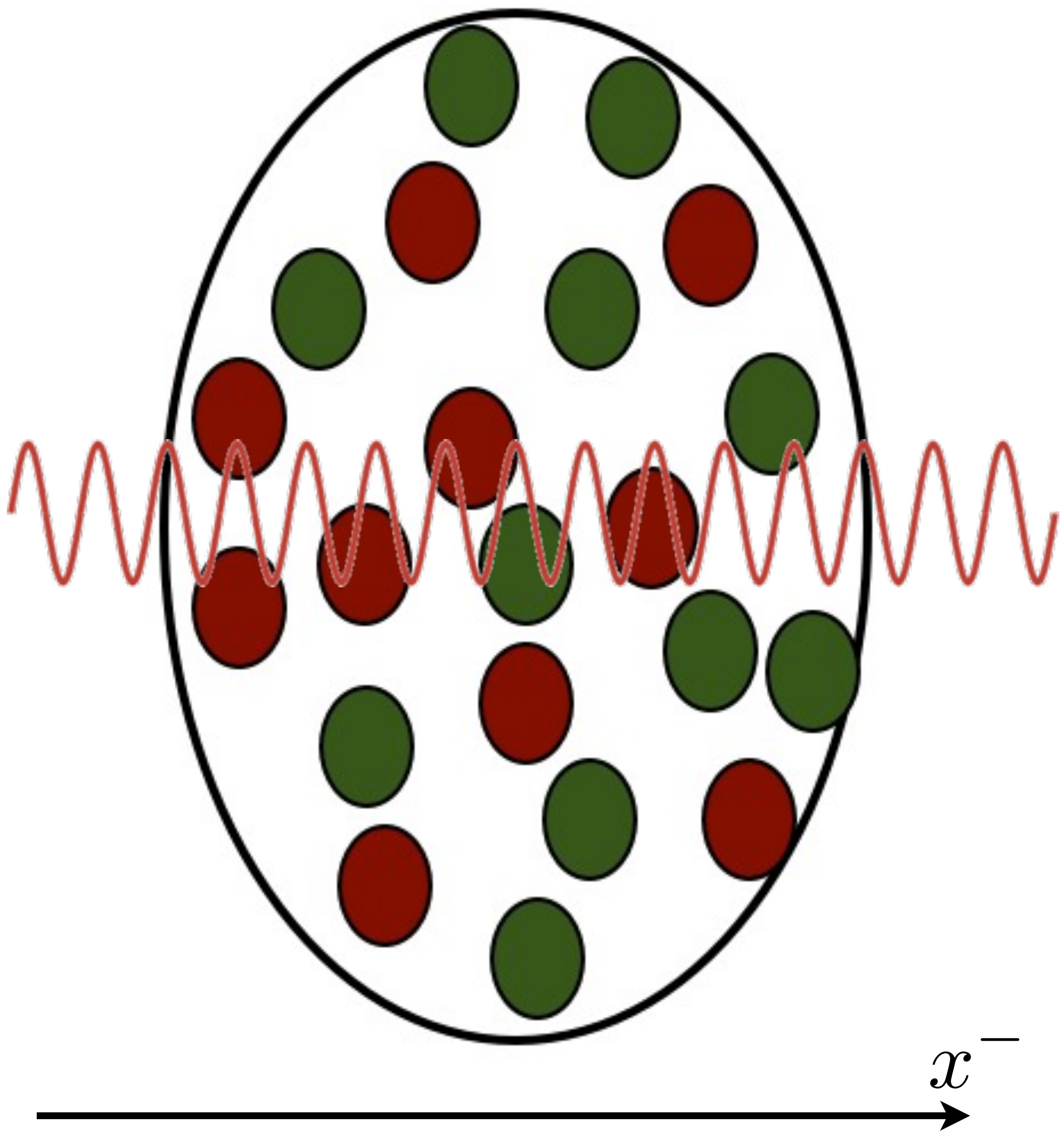
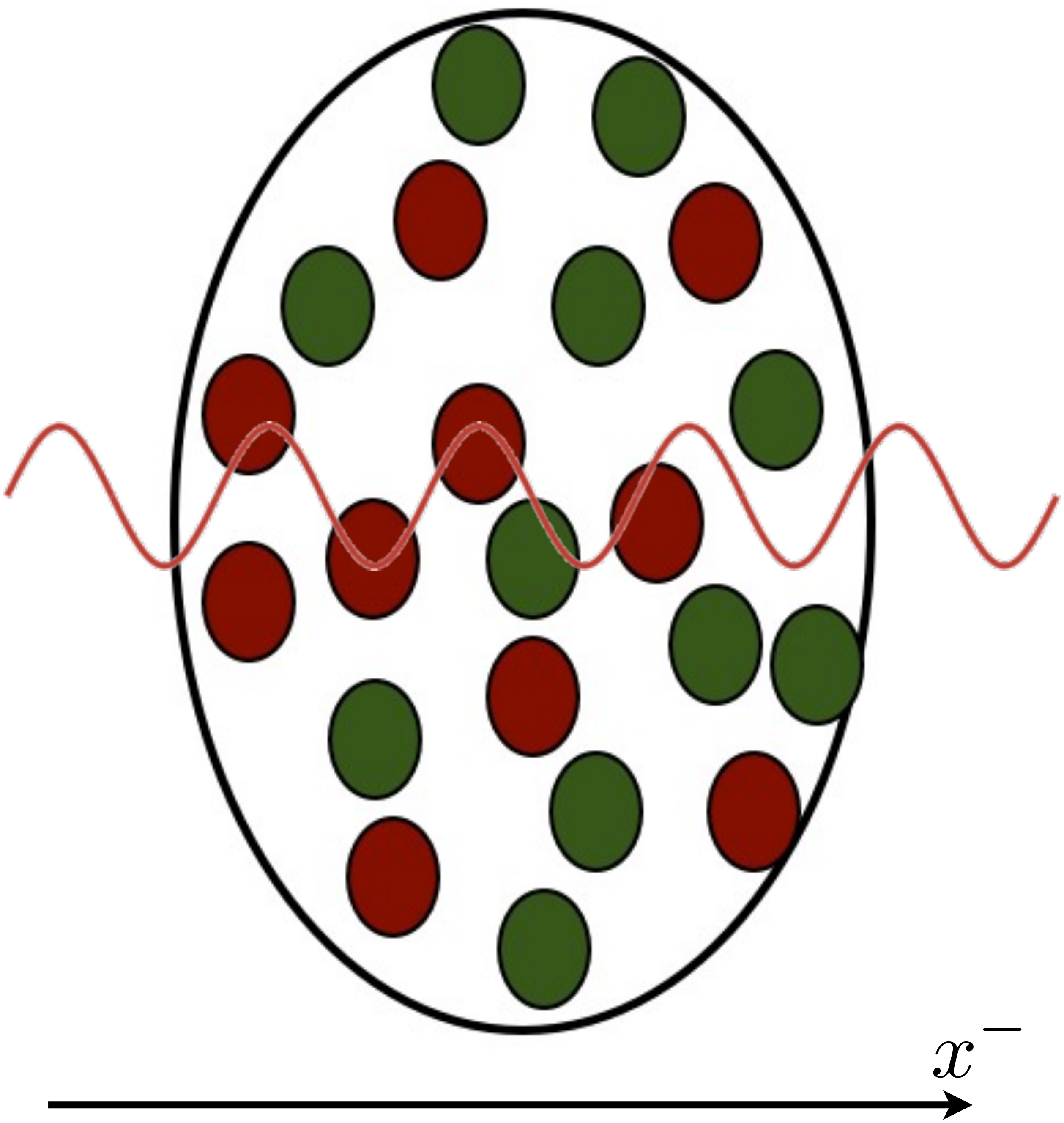
Probing the Nucleus at small x



At large x: large p^+, short wavelength in x^-, individual nucleons can be resolved.

Probing the Nucleus at small x



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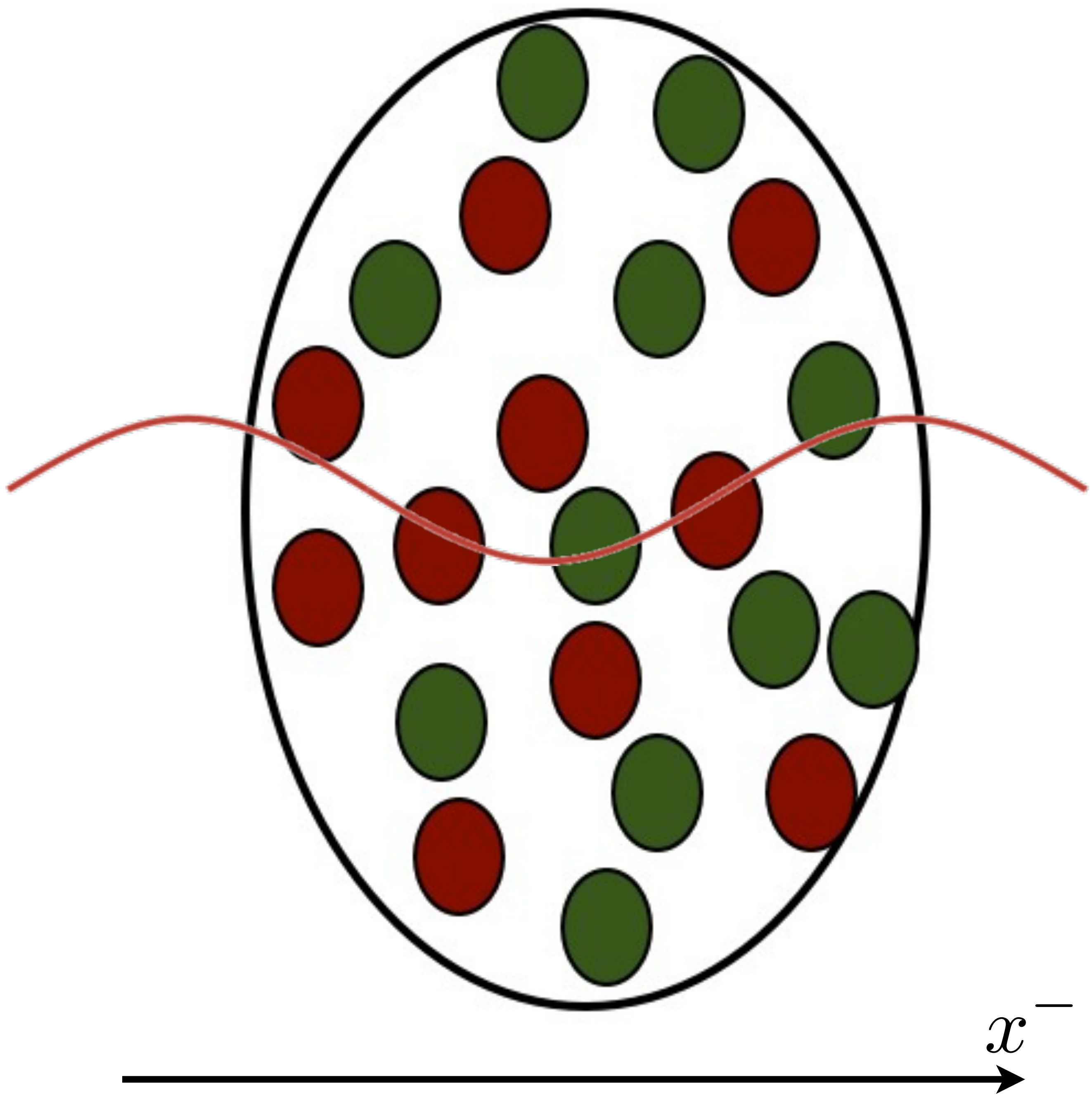
At smaller x, coherently probe larger area.

Probing the Nucleus at small x



At large x: large p^+, short wavelength in x^-, individual nucleons can be resolved.

At smaller x, coherently probe larger area.

At $x \ll \frac{A^{-1/3}}{M_N R_p}$ coherently probing the whole nucleus.

Challenge for MC, can not just use "A x Pythia"!!

Building An Event Generator For EIC

What we want

- A multi purpose generator
  - High and low Q2
  - High and low x
  - Exclusive final states
  - Diffraction
  - ...

Will probably need to be a collection of many programs collected in a package.

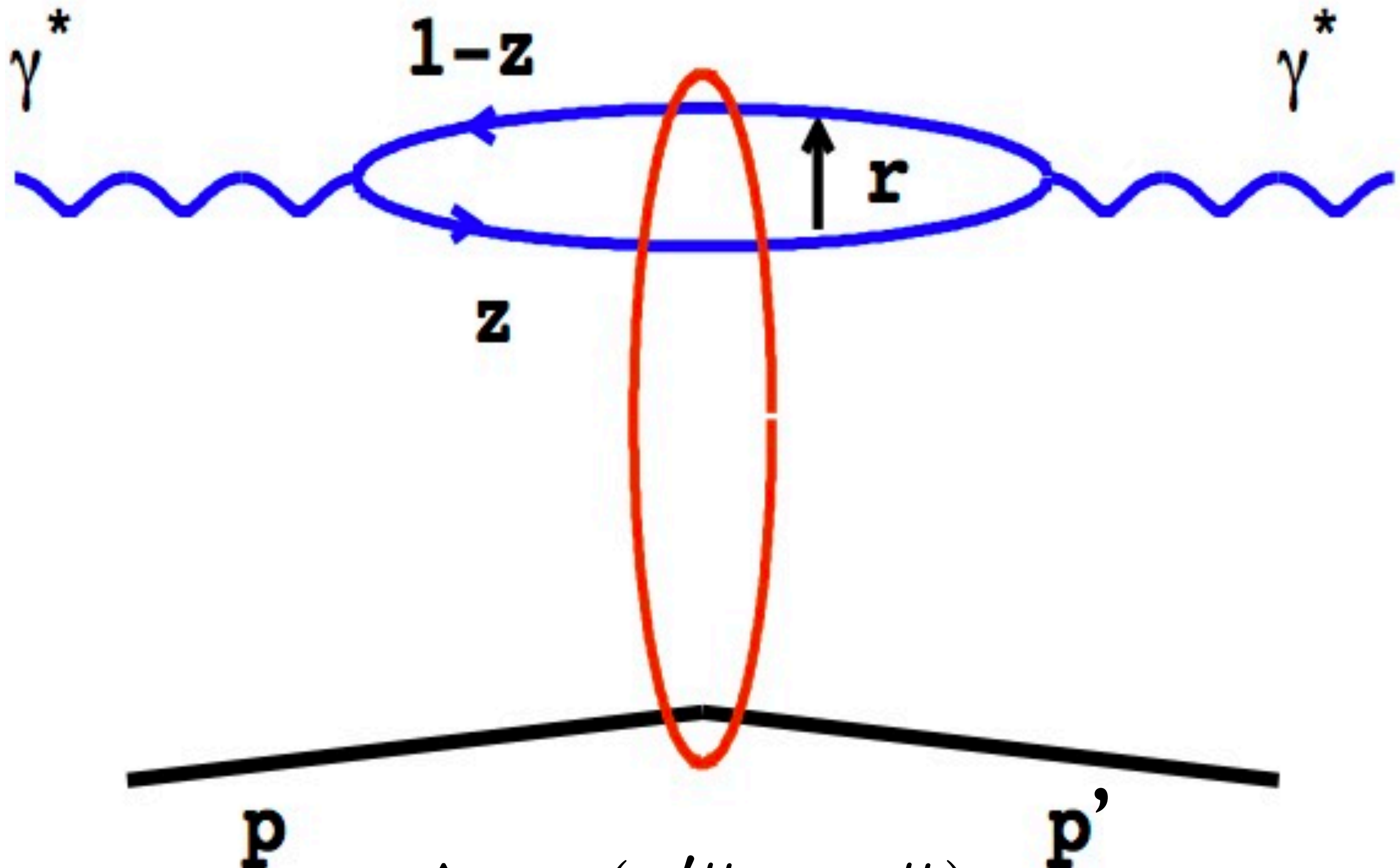
XDVMP

eXclusive Diffractive Vector Meson Production

http://rhig.physics.yale.edu/~ullrich/xdvmp/

The Dipole Model

Elastic photon-proton scattering



$$\Delta \equiv (p'^{\mu} - p^{\mu})_{\perp}$$

$$\mathcal{A}^{\gamma^* p}(x, Q, \Delta) = \sum_f \sum_{h,\bar{h}} \int \mathrm{d}^2\mathbf{r} \int_0^1 \frac{\mathrm{d}z}{4\pi} \Psi^*_{h\bar{h}}(r, z, Q) \mathcal{A}_{q\bar{q}}(x, r, \Delta) \Psi_{h\bar{h}}(r, z, Q)$$

Exclusive diffractive processes at HERA within the dipole picture, H. Kowalski, L. Motyka, G. Watt, Phys. Rev. D74, 074016, arXiv:hep-ph/0606272v2

The Dipole Model

$$\mathcal{A}^{\gamma^* p}(x, Q, \Delta) = \sum_f \sum_{h,\bar{h}} \int \mathrm{d}^2\mathbf{r} \int_0^1 \frac{\mathrm{d}z}{4\pi} \Psi^*_{h\bar{h}}(r, z, Q) \mathcal{A}_{q\bar{q}}(x, r, \Delta) \Psi_{h\bar{h}}(r, z, Q)$$

Use:

Optical theorem:

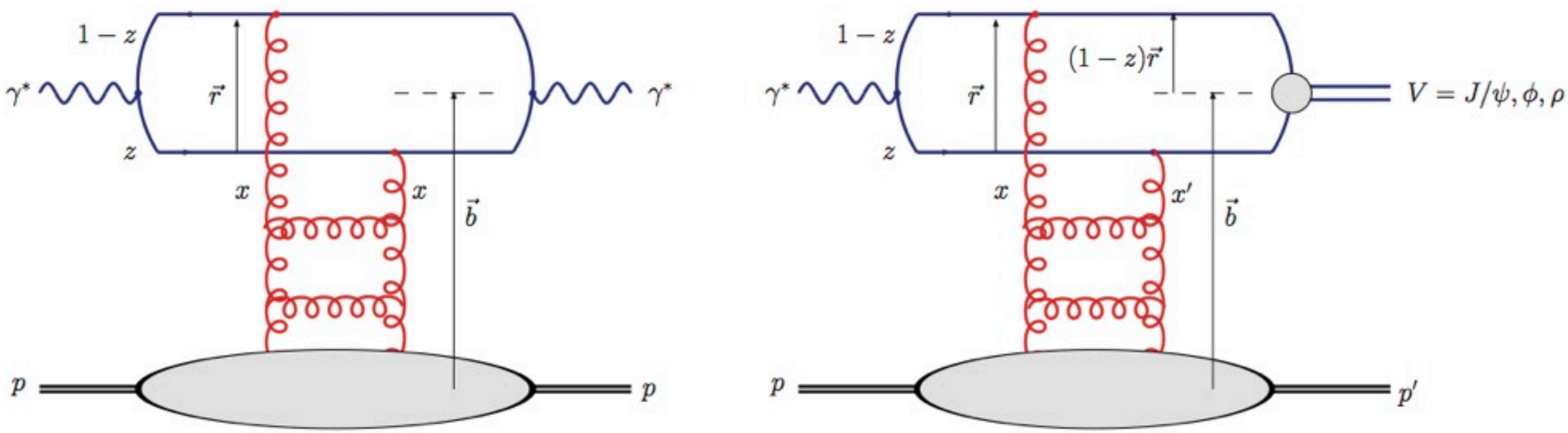
$$\mathcal{A}_{q\bar{q}}(x, r, \Delta) = \int \mathrm{d}^2\boldsymbol{b}\, \mathrm{e}^{-\mathrm{i}\boldsymbol{b}\cdot\boldsymbol{\Delta}} \mathcal{A}_{q\bar{q}}(x, r, b) = \mathrm{i} \int \mathrm{d}^2\boldsymbol{b}\, \mathrm{e}^{-\mathrm{i}\boldsymbol{b}\cdot\boldsymbol{\Delta}}\, 2\,[1 - S(x, r, b)]\,.$$

Real Part of S-matrix:

$$\sigma_{q\bar{q}}(x, r) = \mathrm{Im}\,\mathcal{A}_{q\bar{q}}(x, r, \Delta = 0) = \int \mathrm{d}^2\boldsymbol{b}\, 2\overbrace{[1 - \mathrm{Re}\, S(x, r, b)]}^{\mathcal{N}(x,r,b)}$$

Define dipole cross-section: $$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\boldsymbol{b}} = 2[1 - \mathrm{Re}\, S(x, r, b)]$$

Vector Meson Production



$$\Delta \equiv (p'^{\mu} - p^{\mu})_{\perp}$$

$$\mathcal{A}_{T,L}^{\gamma^* p \to Vp}(x, Q, \Delta) =$$

$$i \int \mathrm{d}^2\mathbf{r} \int_0^1 \frac{\mathrm{d}z}{4\pi} \int \mathrm{d}^2\mathbf{b} (\Psi_V^* \Psi)_{T,L} e^{-i([1-z]\mathbf{r}+\mathbf{b})\cdot\mathbf{\Delta}} \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}}$$

Known from QED

Needs to be modeled

The Dipole Models

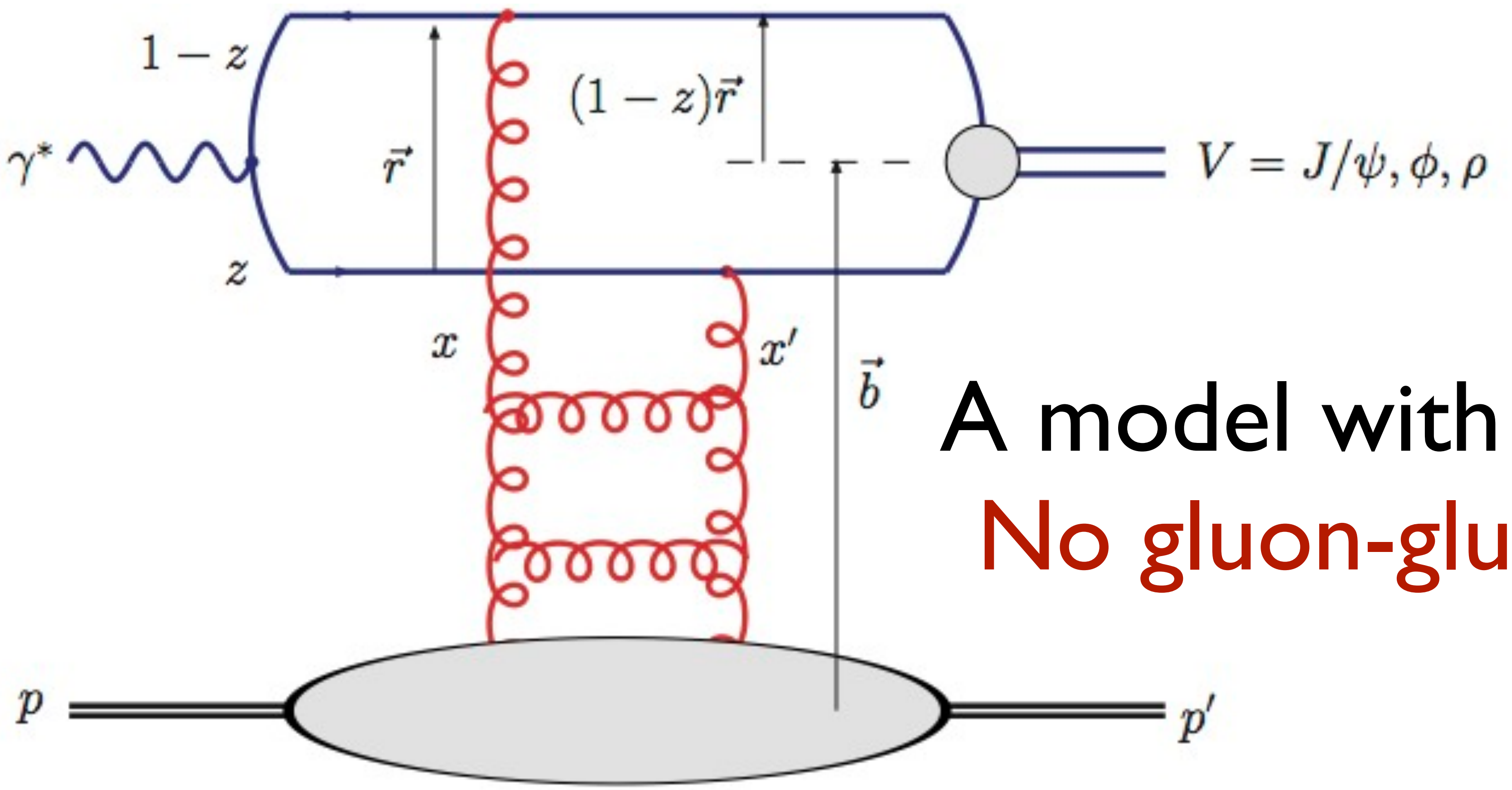
$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}}$$

Two models for the dipole cross-section implemented in XDVMP:

b-Sat

b-CGC

The b-Sat Model

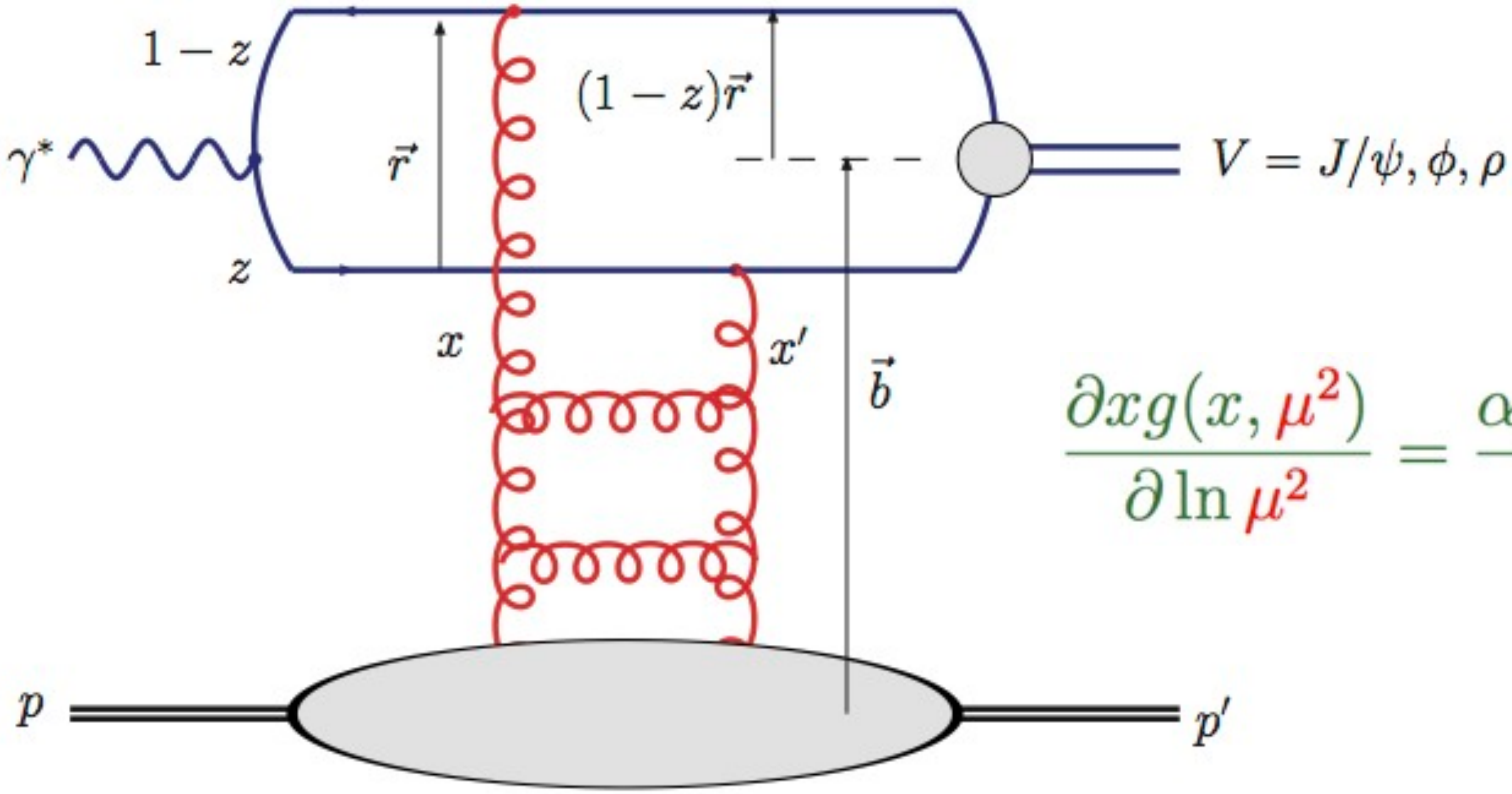


A model with multiple scatterings.

No gluon-gluon recombinations!

$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) x g(x, \mu^2) T(b)\right)\right]$$

The b-Sat Model

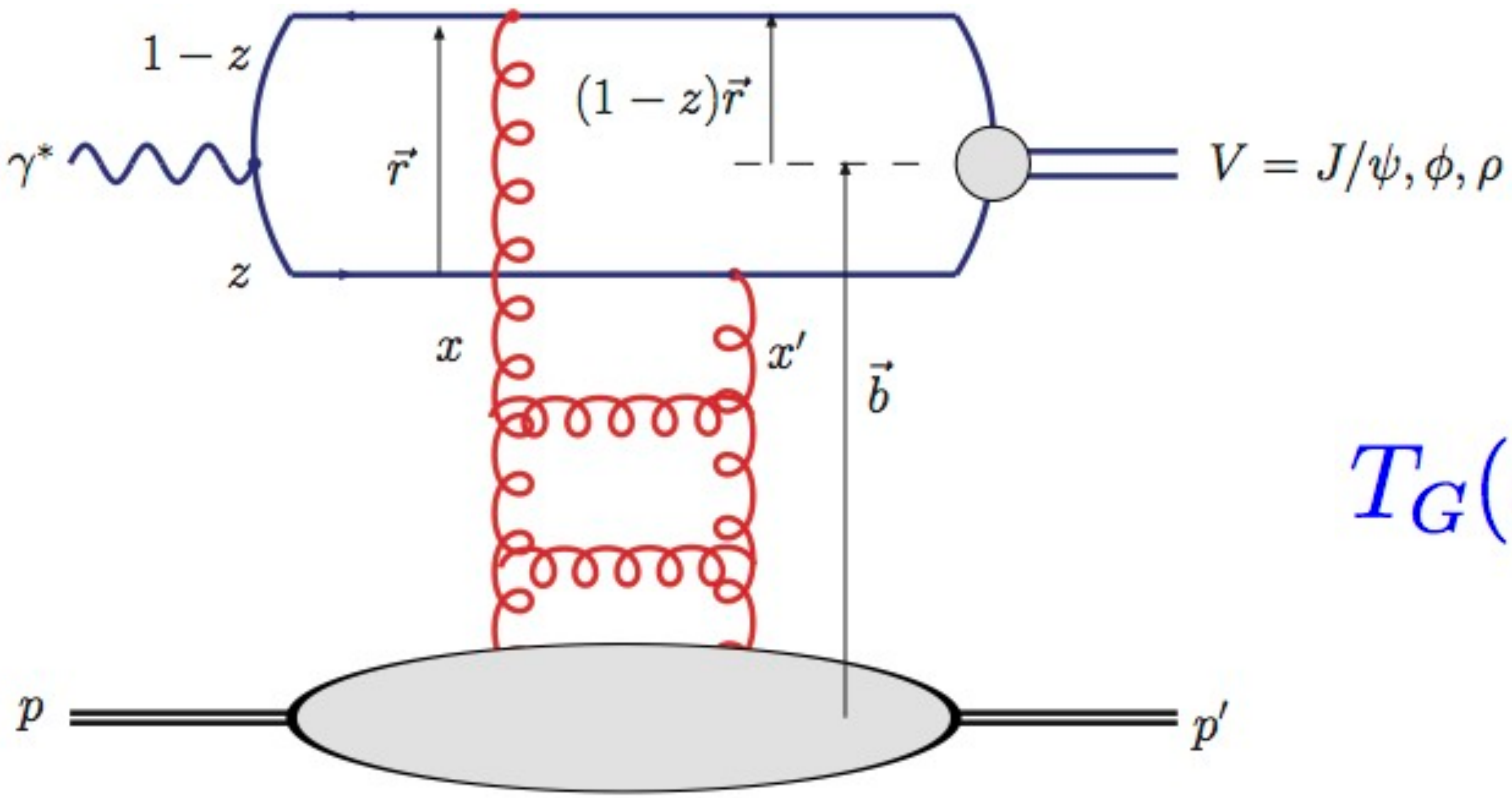


$$\frac{\partial xg(x,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} \int_x^1 \mathrm{d}z P_{gg}(z) \frac{x}{z} g\left(\frac{x}{z}, \mu^2\right)$$

$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) xg(x,\mu^2) T(b)\right)\right]$$

$$\mu^2 = \frac{4}{r^2} + \mu_0^2$$

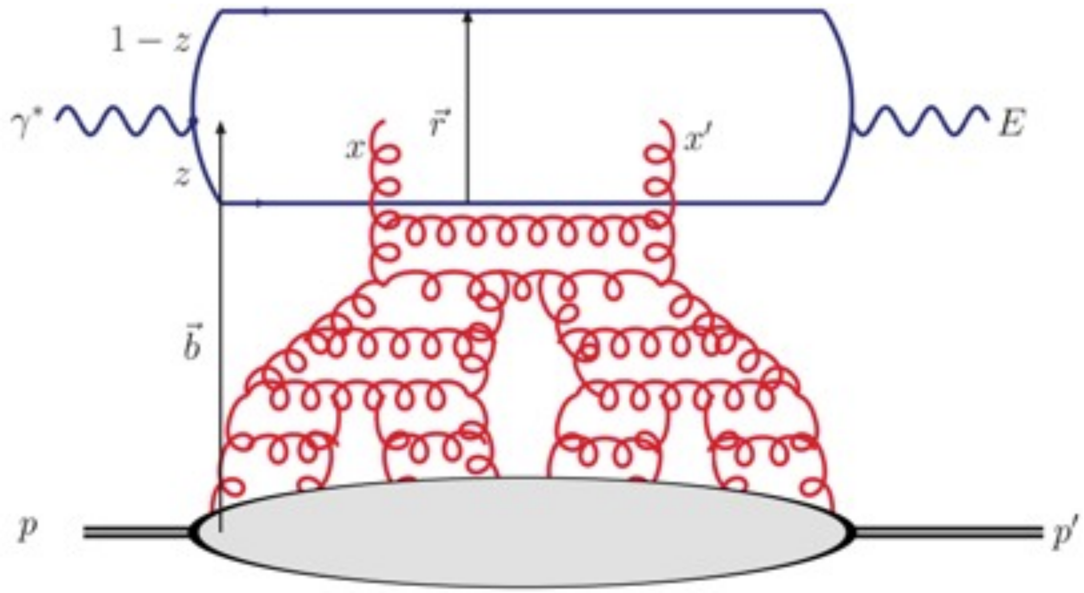
The b-Sat Model



$$T_G(b) = \frac{1}{2\pi B_G} e^{-\frac{b^2}{2B_G}}$$

$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s(\mu^2) x g(x, \mu^2) T(b)\right)\right]$$

The b-CGC Model



Includes gluon recombinations

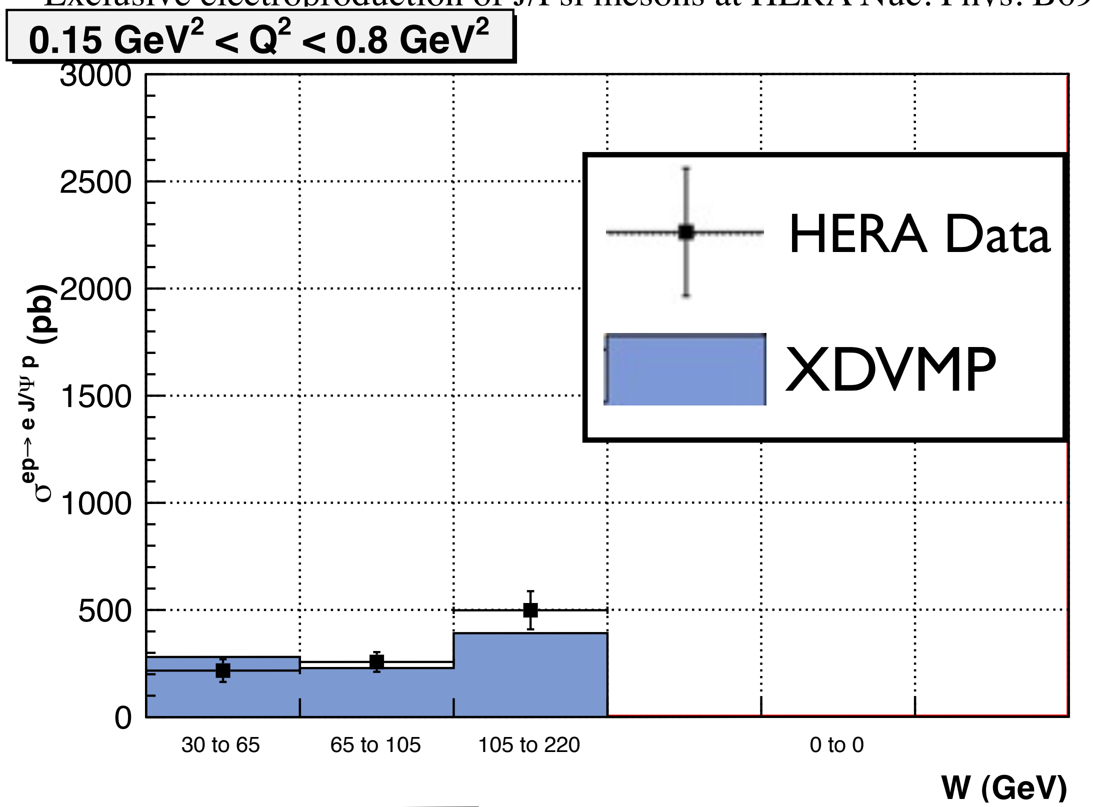
$$Y = \ln(1/x),\ \gamma_s = 0.63,\ \kappa = 9.9$$

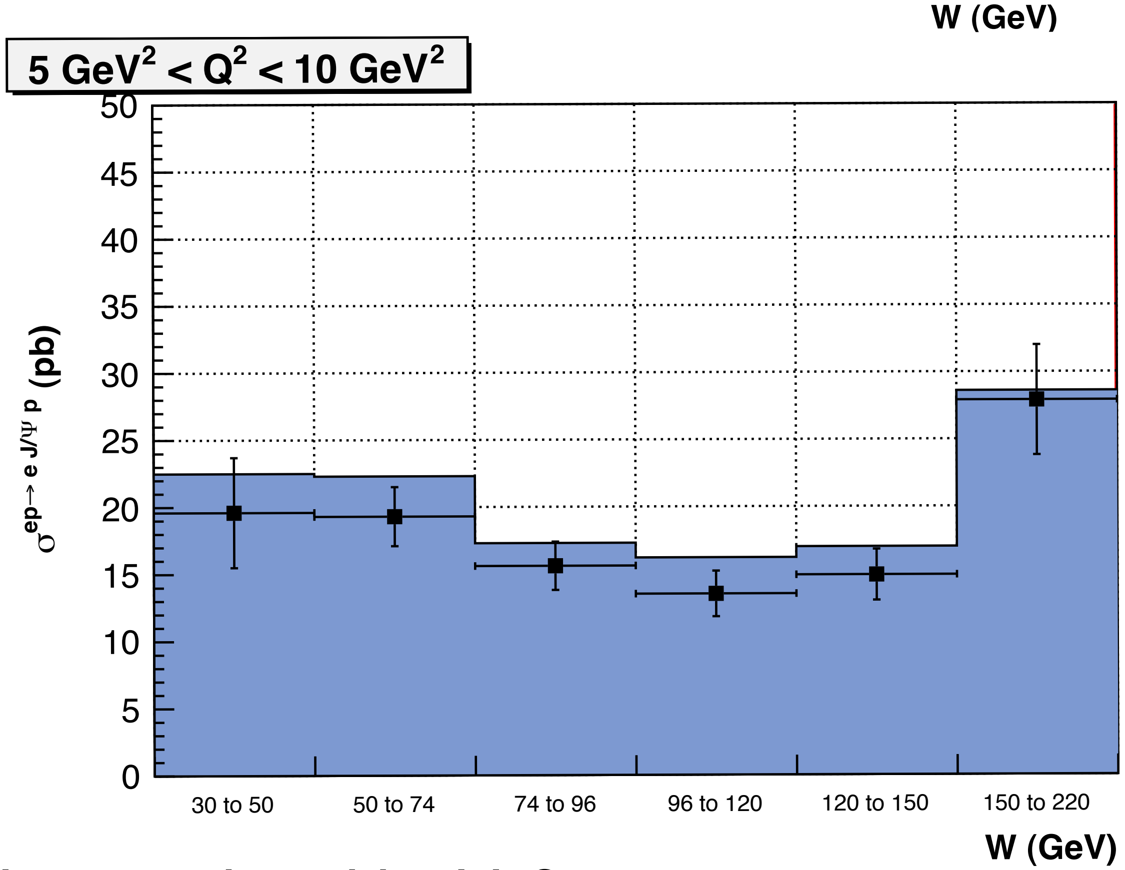
$$\frac{d\sigma_{q\bar{q}}}{d^2\mathbf{b}} = 2 \times \begin{cases} \mathcal{N}_0 \left(\frac{rQ_s}{2}\right)^{2\left(\gamma_s + \frac{1}{\kappa\lambda Y}\ln\frac{2}{rQ_s}\right)} & rQ_s \le 2 \\ 1 - e^{-A\ln^2(BrQ_s)} & rQ_s > 2 \end{cases}$$

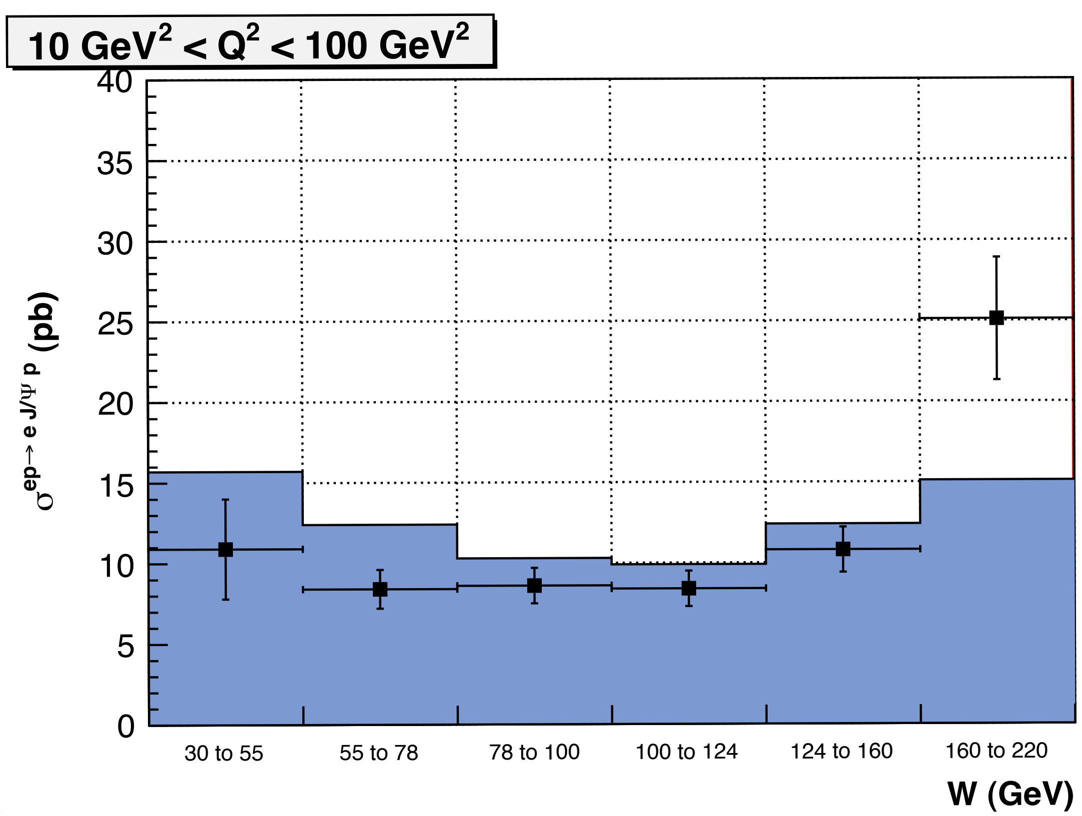
$$Q_s \equiv Q_s(x,b) = \left(\frac{x_0}{x}\right)^{\lambda/2}\left[\exp\left(-\frac{b^2}{2B_{\mathrm{CGC}}}\right)\right]^{\frac{1}{2\gamma_s}}$$

J/Ψ at HERA vs. b-CGC

Exclusive electroproduction of J/Psi mesons at HERA Nuc. Phys. B695







Plots produced by M. Savastio

J/Ψ at HERA vs. b-Sat

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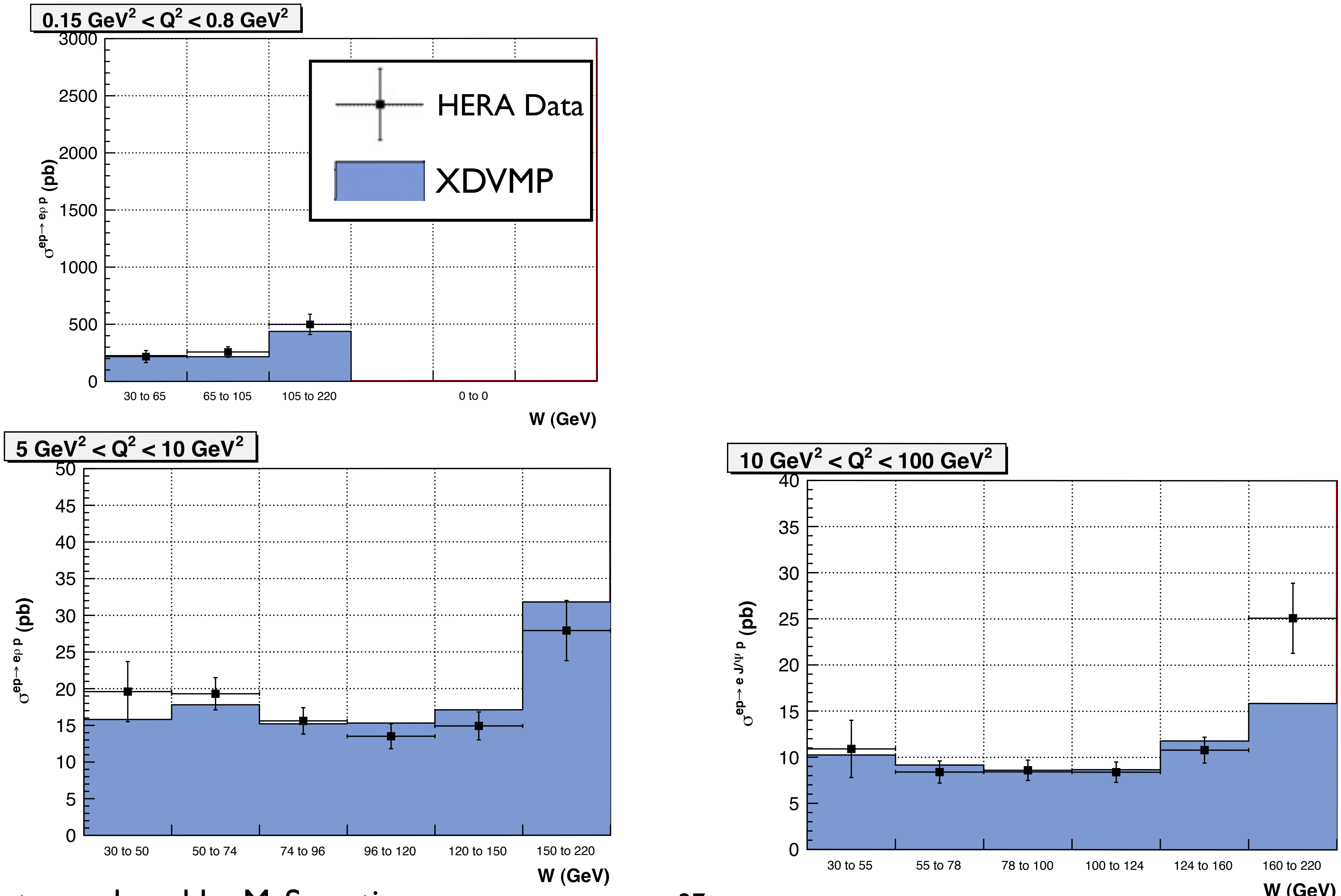


Plots produced by M. Savastio

Going from ep to eA

ep:

$$\mathrm{Re}(S) = 1 - \mathcal{N}^{(p)}(x, r, \mathbf{b}) = 1 - \frac{1}{2}\frac{\mathrm{d}\sigma^{(p)}_{q\bar{q}}(x, r, \mathbf{b})}{\mathrm{d}^2\mathbf{b}}$$

eA:

$$1 - \mathcal{N}^{(A)} = \prod_{i=1}^{A}\left(1 - \mathcal{N}^{(p)}(x, r, |\mathbf{b} - \mathbf{b}_i|)\right)$$

Should follow the Wood-Saxon distribution

Generating a Nucleus

Generate radii according to the Wood-Saxon distribution

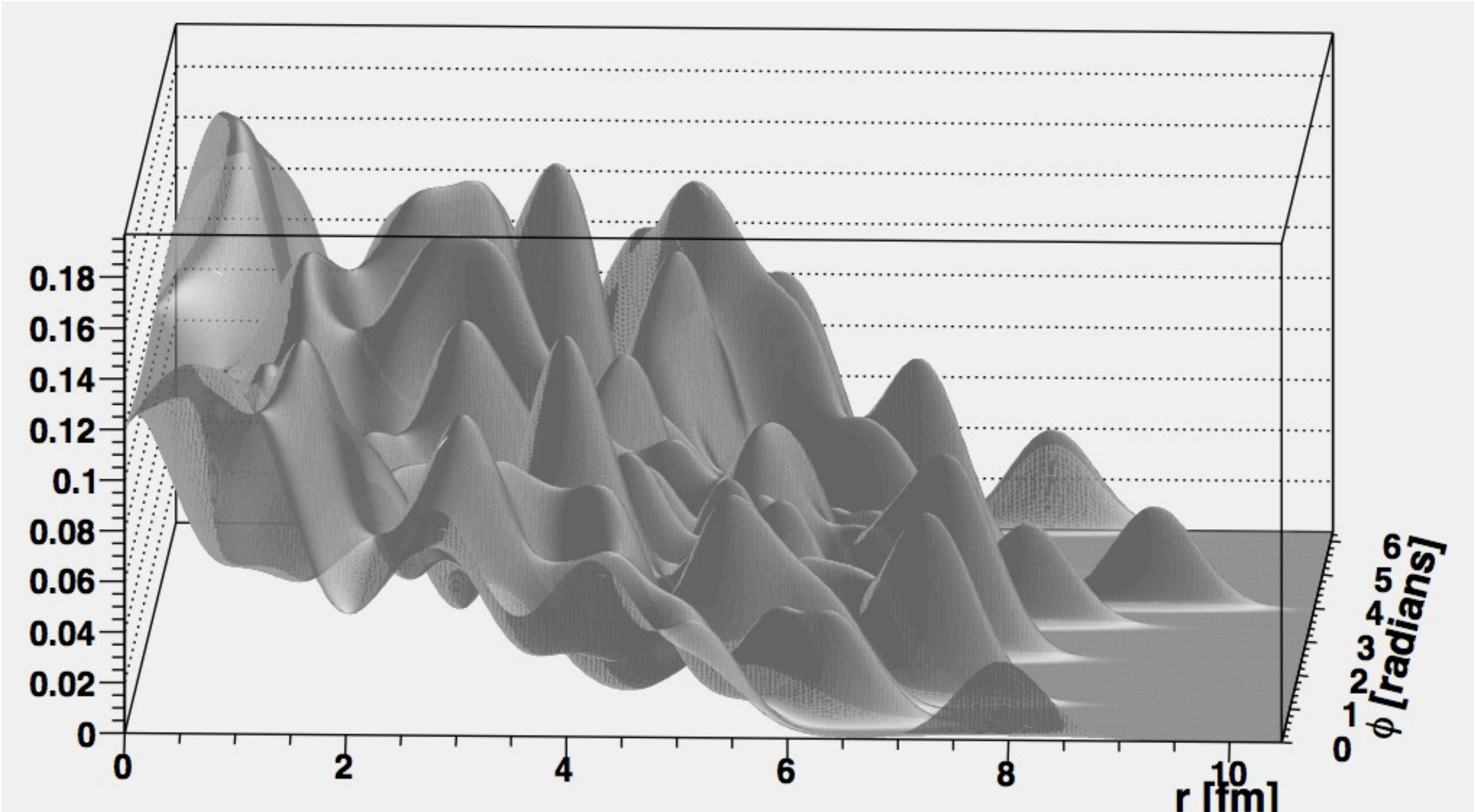
$$\rho(r) = \frac{\rho_0}{1 + e^{\frac{r - R_0}{d}}} \qquad \rho(r) = \frac{\mathrm{d}^3 N}{\mathrm{d}^3 \mathbf{r}}$$

First generate according to r: $\frac{\mathrm{d}N}{\mathrm{d}r} = 4\pi r^2 \rho(r)$

Then generate angular distributions uniform in ϕ and $\cos(\theta)$

This is done with a condition that two nucleons can not be within a core distance of ~0.8fm.
If they are: regenerate angles (not radius!)

Generating a Nucleus



Lead 208 in the r-phi plane, each nucleon is supplemented with a Gaussan width.

Technical Problem

$$\frac{\mathrm{d}\sigma^{(A)}{}_{q\bar{q}}(r,x,\mathbf{b})}{\mathrm{d}^2\mathbf{b}} = 2\left[1-\prod_{i=1}^{A}\left(1-\frac{1}{2}\frac{\mathrm{d}\sigma^{(p)}{}_{q\bar{q}}(r,x,|\mathbf{b}-\mathbf{b}_i|)}{\mathrm{d}^2\mathbf{b}}\right)\right]$$

Extremely slow!!!!

bSat:

$$\frac{\mathrm{d}\sigma^{A}_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}} = 2\left[1-\exp\left(-\frac{\pi^2}{2N_c}r^2\alpha_s(\mu^2)xg(x,\mu^2)\sum_{i=1}^{A}T_p(\mathbf{b}-\mathbf{b}_i)\right)\right]$$

Product becomes a sum over a function only dependent on b.

Not possible for bCGC!! Is abandoned for now.

Going from ep to eA

Another difference in eA:
The Nucleus can break up
into its colour neutral fragments!

When the nucleus breaks up, the scattering is called
incoherent

When the nucleus stays intact, the scattering is called
coherent

Total cross-section = incoherent + coherent

Incoherent Scattering

Nucleus dissociates ($f \neq i$):

Good, Walker

complete set

$$\sigma_{\text{incoherent}} \propto \sum_{f \neq i} \langle i|\mathcal{A}|f\rangle^{\dagger} \langle f|\mathcal{A}|i\rangle$$

$$= \sum_{f} \langle i|\mathcal{A}\underbrace{|f\rangle^{\dagger} \langle f|}\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^{\dagger} \langle i|\mathcal{A}|i\rangle$$

$$= \left\langle i \left| |\mathcal{A}|^2 \right| i \right\rangle - \left|\langle i|\mathcal{A}|i\rangle\right|^2 = \left\langle |\mathcal{A}|^2 \right\rangle - \left|\langle \mathcal{A}\rangle\right|^2$$

The incoherent CS is the variance of the amplitude!!

$$\frac{\mathrm{d}\sigma_{\text{total}}}{\mathrm{d}t} = \frac{1}{16\pi} \left\langle |\mathcal{A}|^2 \right\rangle \qquad \frac{\mathrm{d}\sigma_{\text{coherent}}}{\mathrm{d}t} = \frac{1}{16\pi} \left|\langle \mathcal{A}\rangle\right|^2$$

Averaging over initial state

$$\frac{d\sigma_{\text{coherent}}}{dt} = \frac{1}{16\pi} \left|\langle\mathcal{A}\rangle\right|^2$$

The average should be taken over initial nucleon configurations Ω within the nucleus (the nucleon configurations are not a QM observable).

$$\langle\mathcal{A}(\Delta)\rangle_\Omega = \int d\Omega P(\Omega)\mathcal{A}(\Omega,\Delta) \approx \frac{1}{C_{\max}} \sum_{j=1}^{C_{\max}} \mathcal{A}(\Omega_j,\Delta)$$

Coherent

$$\frac{\mathrm{d}\sigma_{\mathrm{coherent}}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\frac{1}{C_{\max}}\sum_{j=1}^{C_{\max}} \mathcal{A}(\Omega_j)\right|^2$$

$$\langle\mathcal{A}\rangle_\Omega = \left\langle \int \mathrm{d}r \int \frac{\mathrm{d}z}{4\pi} \int \mathrm{d}^2\mathbf{b} (\Psi_V^*\Psi)(r,z) 2\pi r b J_0([1-z]r\Delta) \right.$$

$$\left. e^{-i\mathbf{b}\cdot\boldsymbol{\Delta}} \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}}(x,r,\mathbf{b},\Omega) \right\rangle_\Omega$$

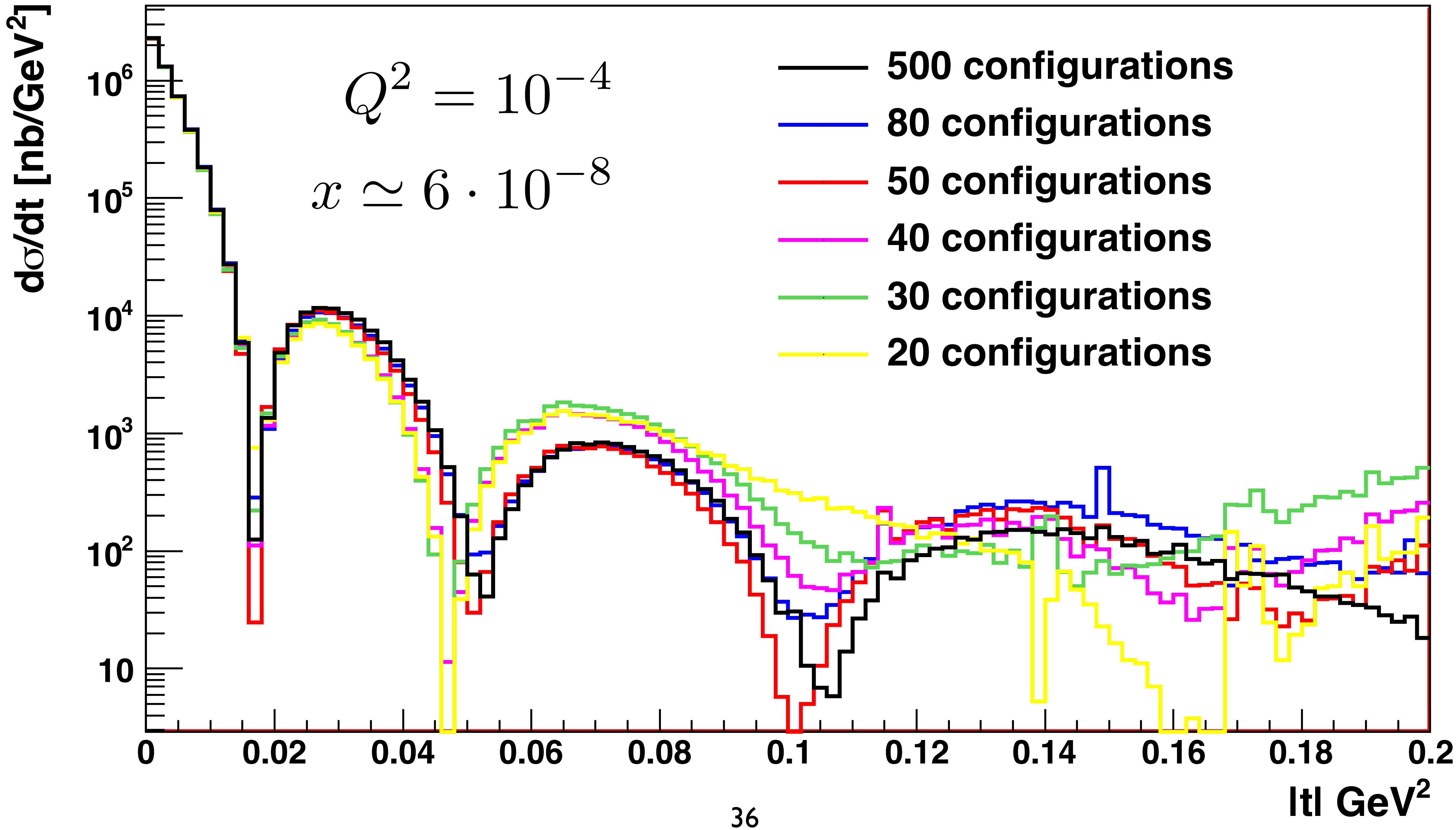
$$t \equiv -\Delta^2$$

$\mathcal{A}$ is a Fourier transform of b. This means that small variations in b will be seen at large t and vice versa

The question is how many configuration is needed to be averaged over for the cross-section to converge.

Coherent

$$\frac{\mathrm{d}\sigma_{\text{coherent}}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\frac{1}{C_{\max}}\sum_{j=1}^{C_{\max}}\mathcal{A}(\Omega_j)\right|^2$$



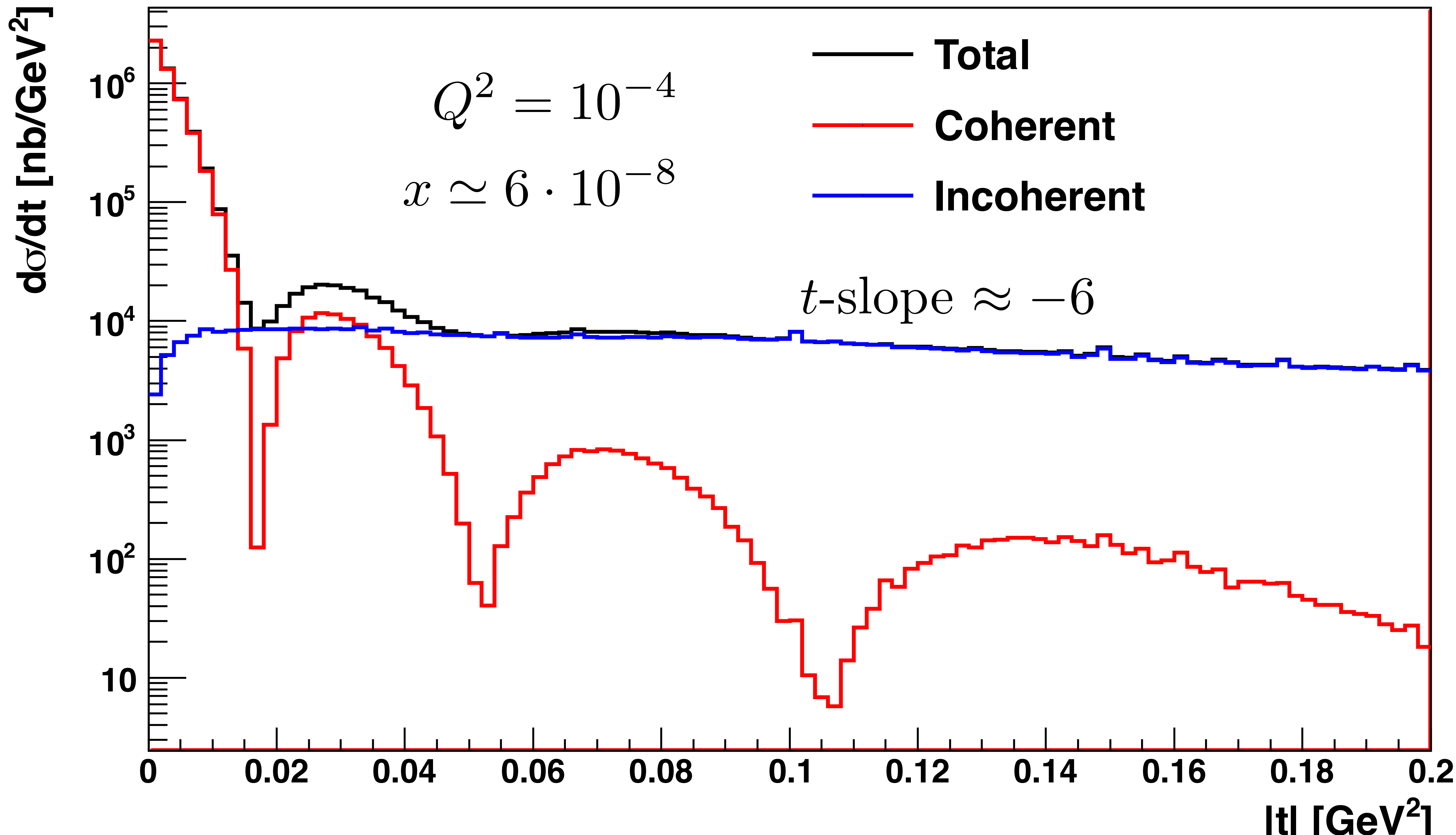
Incoherent/Total

$$\frac{\mathrm{d}\sigma_{\mathrm{total}}}{\mathrm{d}t} = \frac{1}{16\pi}\frac{1}{C_{\mathrm{max}}}\sum_{j=1}^{C_{\mathrm{max}}}\left|\mathcal{A}(\Omega_j)\right|^2$$

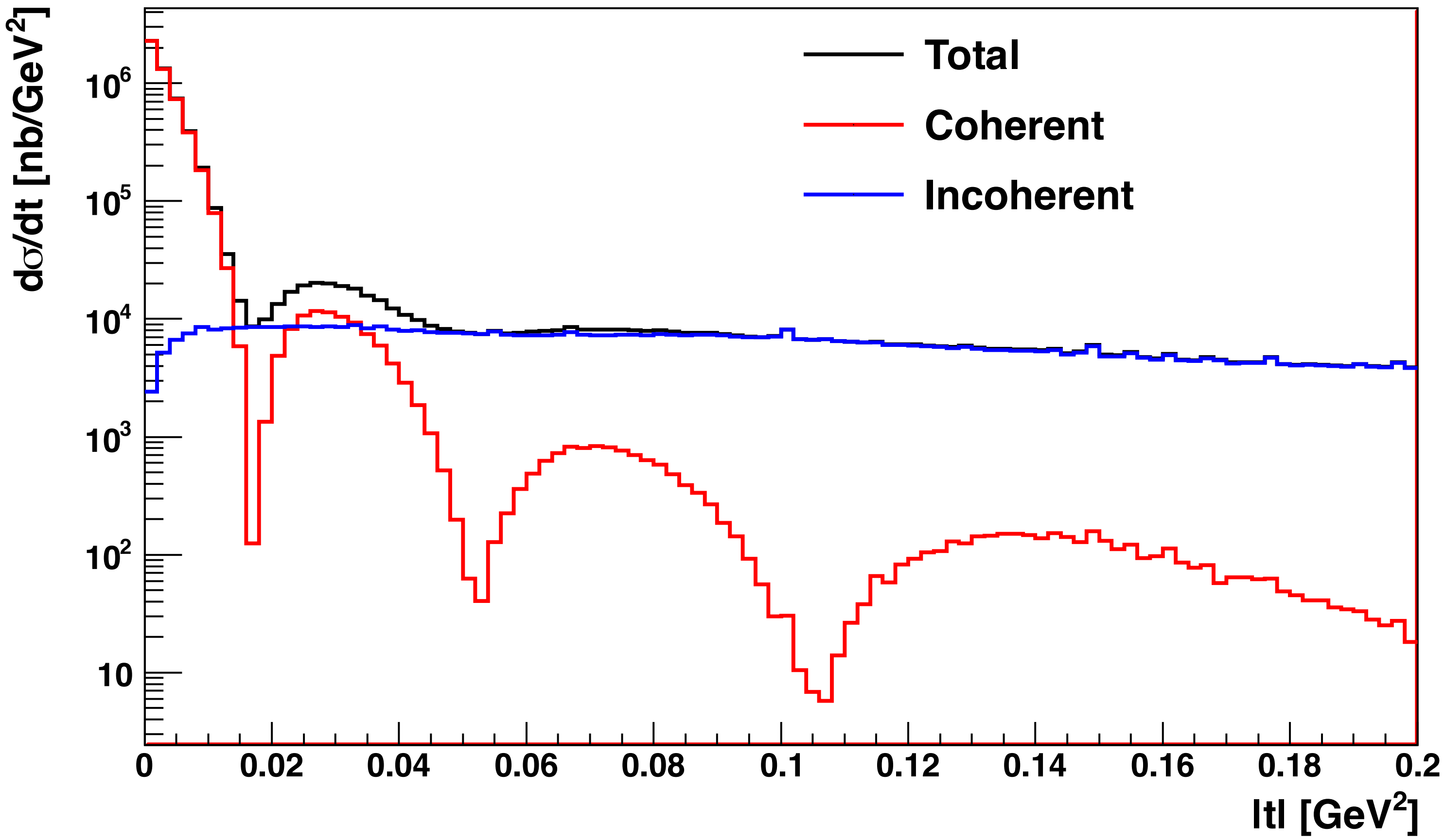
$$\frac{\mathrm{d}\sigma_{\mathrm{coherent}}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\frac{1}{C_{\mathrm{max}}}\sum_{j=1}^{C_{\mathrm{max}}}\mathcal{A}(\Omega_j)\right|^2$$

$$\frac{\mathrm{d}\sigma_{\mathrm{incoherent}}}{\mathrm{d}t} = \frac{\mathrm{d}\sigma_{\mathrm{total}}}{\mathrm{d}t} - \frac{\mathrm{d}\sigma_{\mathrm{coherent}}}{\mathrm{d}t}$$

Incoherent/Total



Incoherent/Total

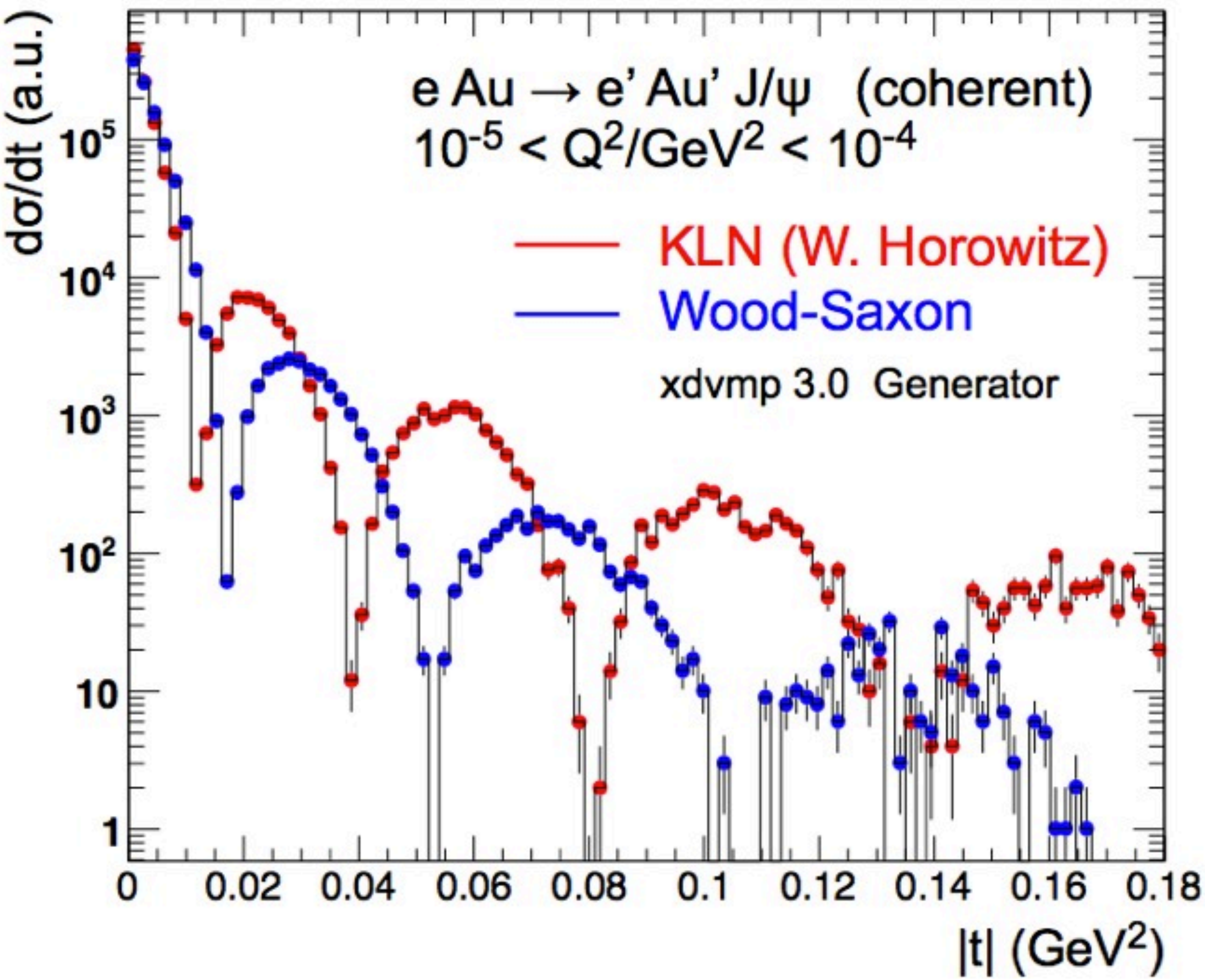


We can suppress the the incoherent background by 90-99%

This result means that it will be possible to measure the first 2-3 coherent bumps and access the spatial gluon distribution at an EIC!!

Incoherent/Total

This could be one of the main measurements of the EIC



Outlook

Will implement DVCS asap

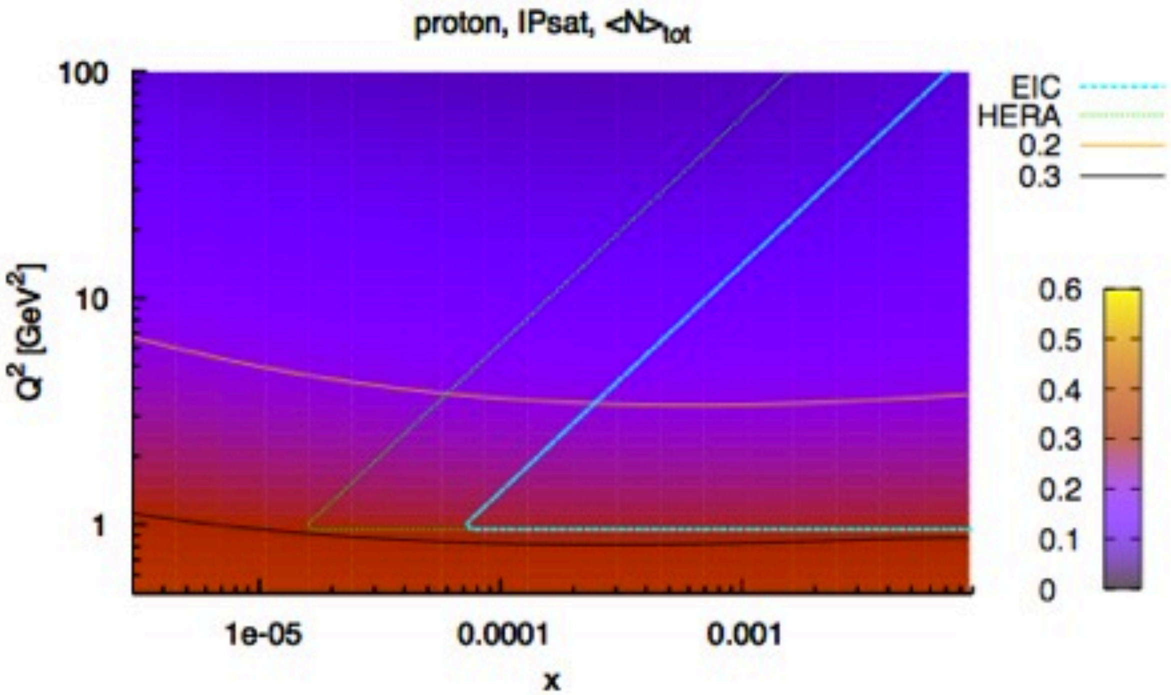
Semi inclusive DIS

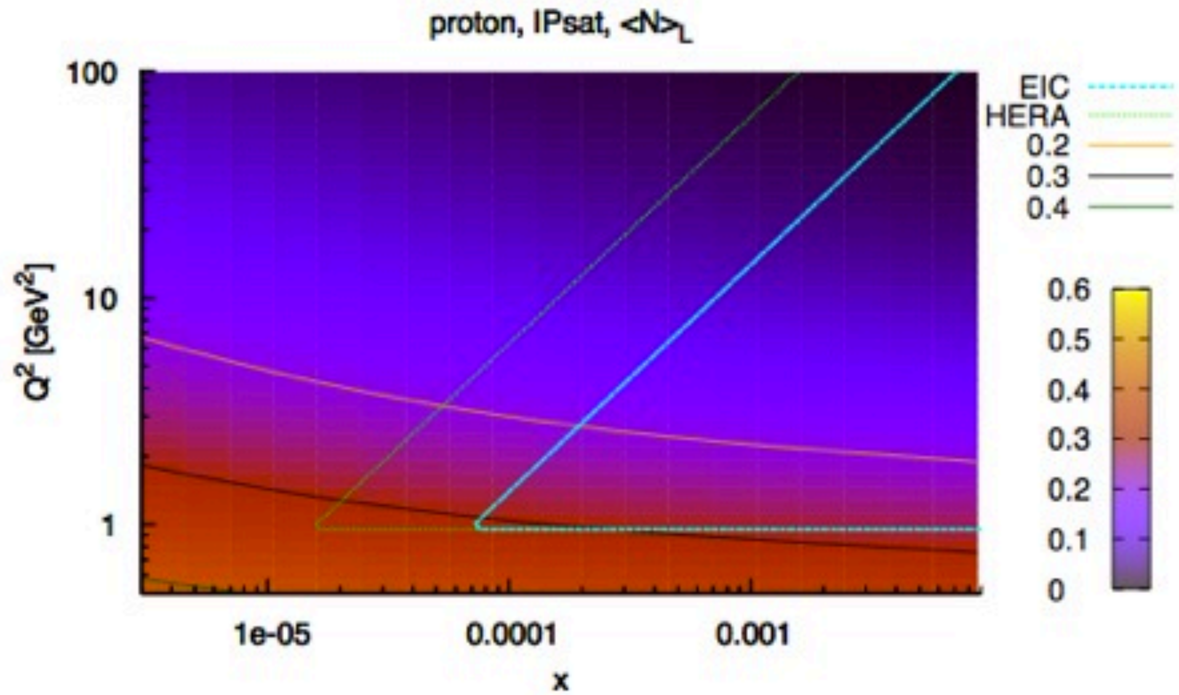
$$eA \to e' A' X$$

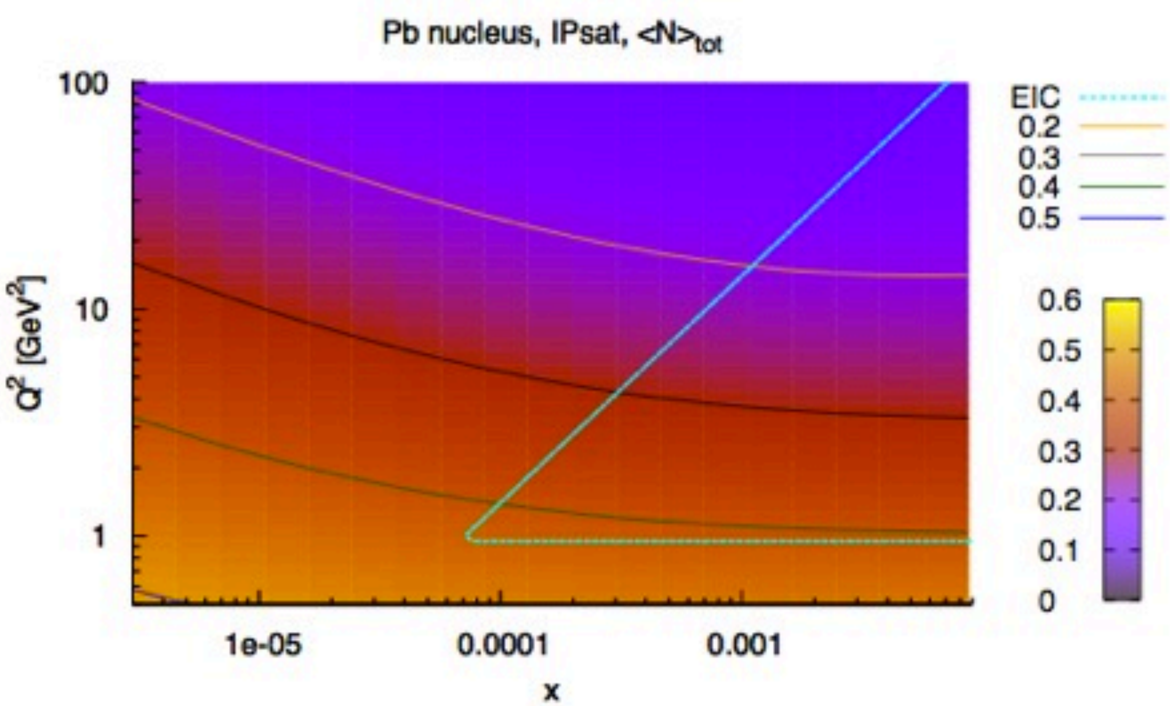
Back up

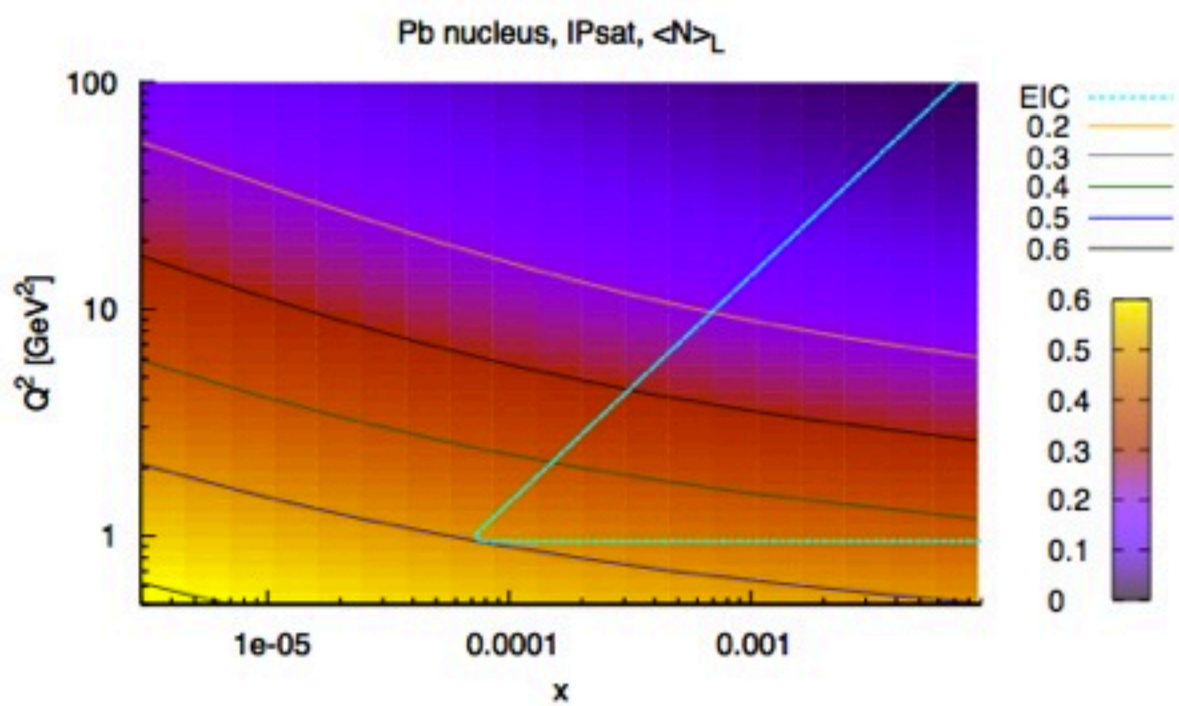
using IPSat dipole cross section:

Figures by T. Lappi



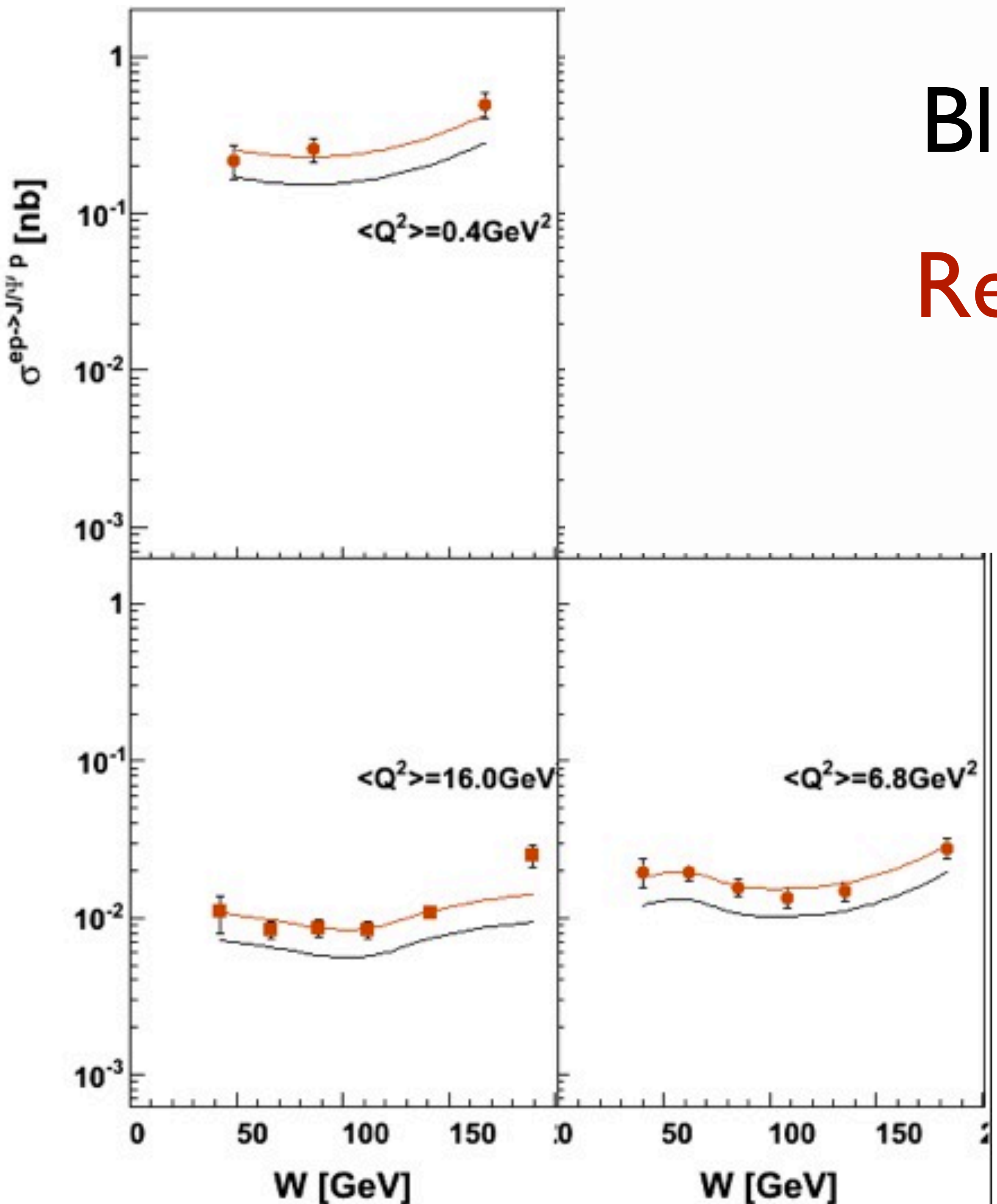






First comparison with data

Exclusive electroproduction of J/Psi mesons at HERA Nuc. Phys. B695



Black Curve: XDVMP b-CGC

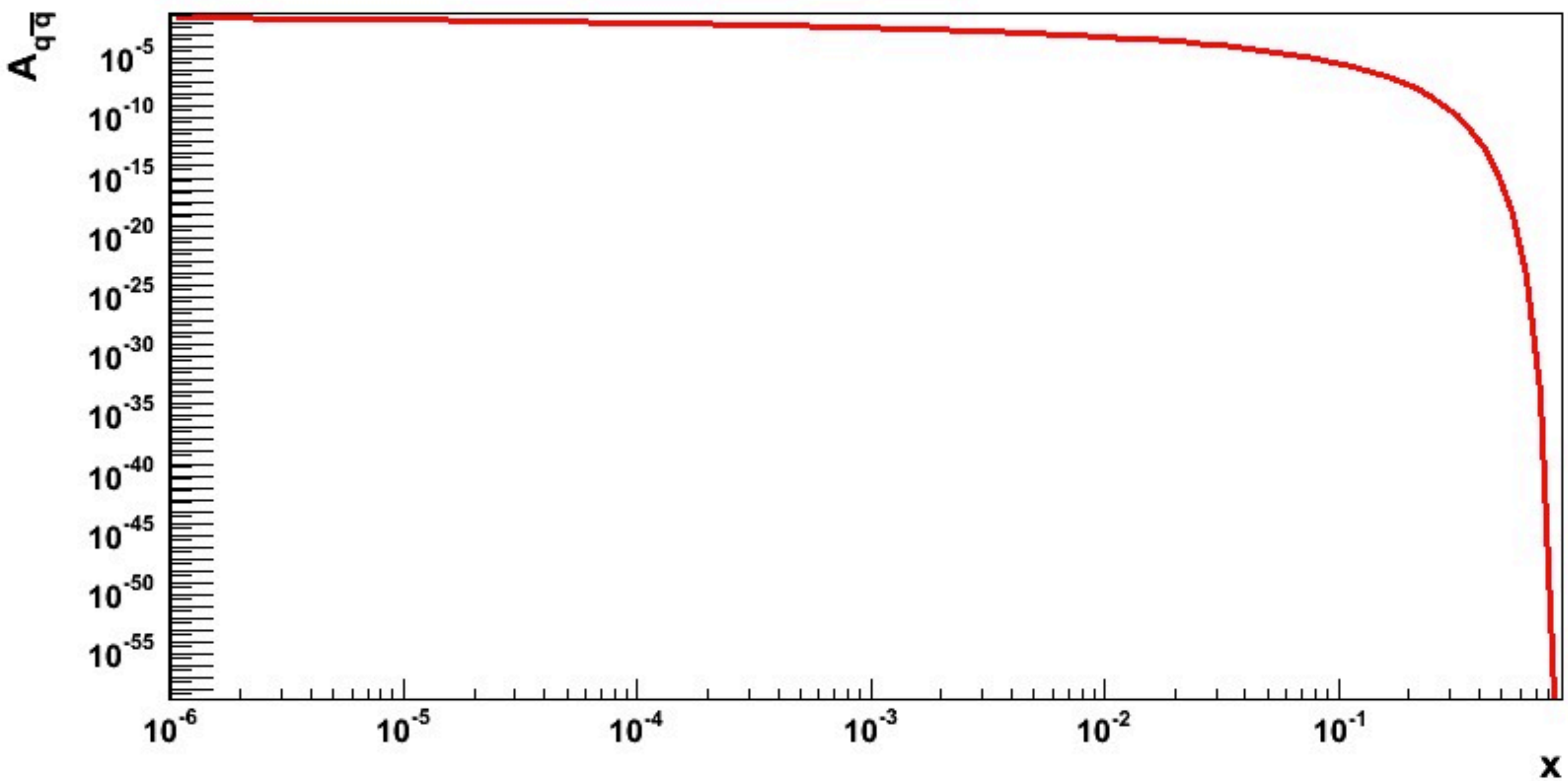
Red Curve: Black Curve x 1.5

Something is missing!!

Plots produced by Ramiro Debbe

Real Amplitude Corrections

$$\beta = \tan(\pi\lambda/2) \qquad \lambda \equiv \frac{\partial \ln\left(\mathcal{A}_{T,L}^{\gamma^* p \to E p}\right)}{\partial \ln(1/x)}$$



Real Amplitude Corrections

So far the amplitude has been assumed to be purely imaginary.

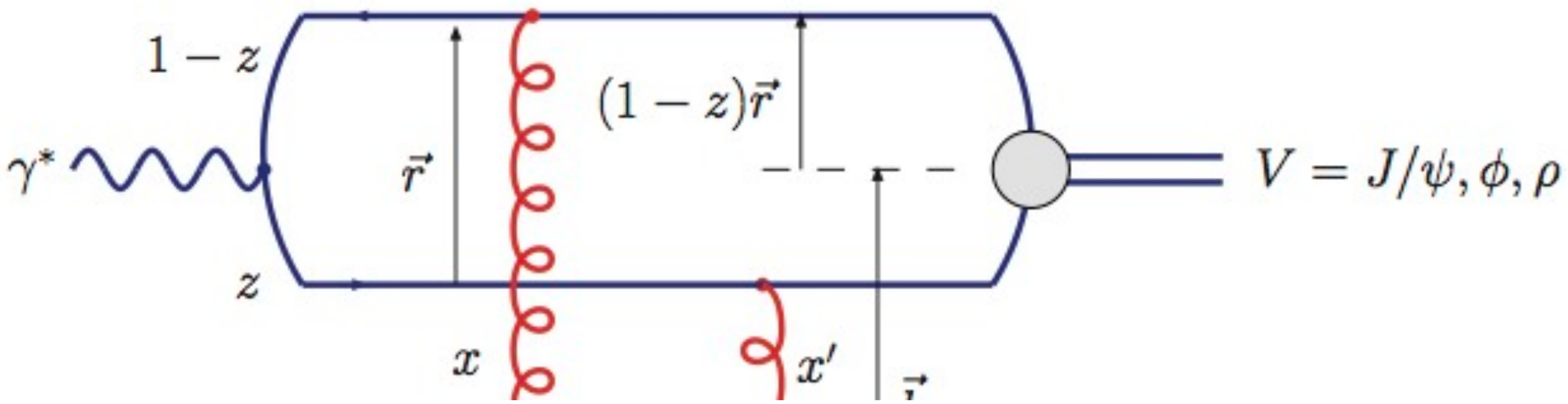
To take the Real part of the amplitude into account it can be multiplied by a factor $(1+\beta^2)$

β is the ratio Real/Imaginary parts of the Amplitude:

$$\beta = \tan(\pi\lambda/2) \qquad \lambda \equiv \frac{\partial \ln\left(\mathcal{A}_{T,L}^{\gamma^* p \rightarrow Ep}\right)}{\partial \ln(1/x)}$$

This goes bad for large $x \sim 10^{-2}$

Skewedness Corrections



The two gluons carry different momentum fractions

This is the Skewed effect

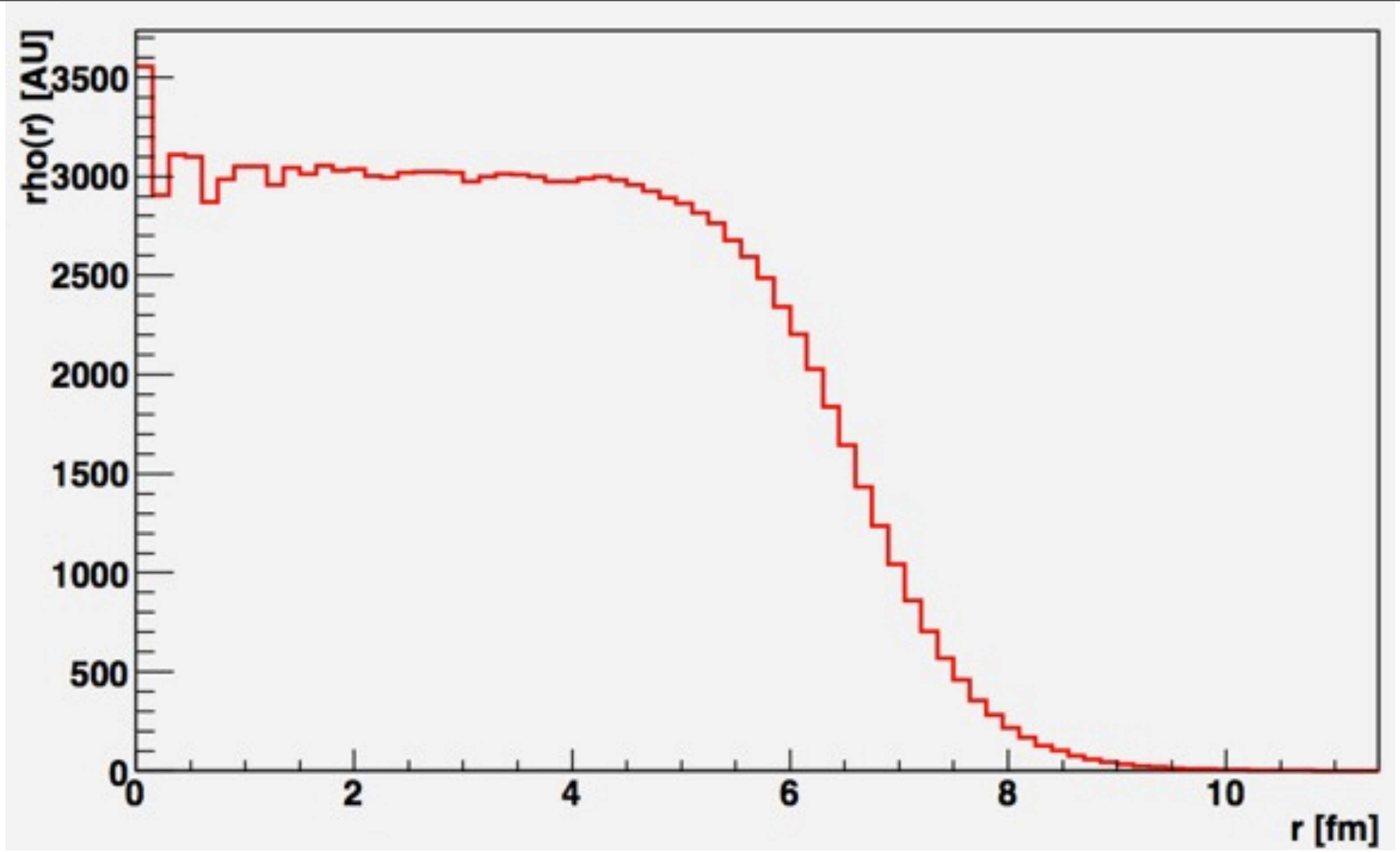
In leading ln(1/x) this effect disappears

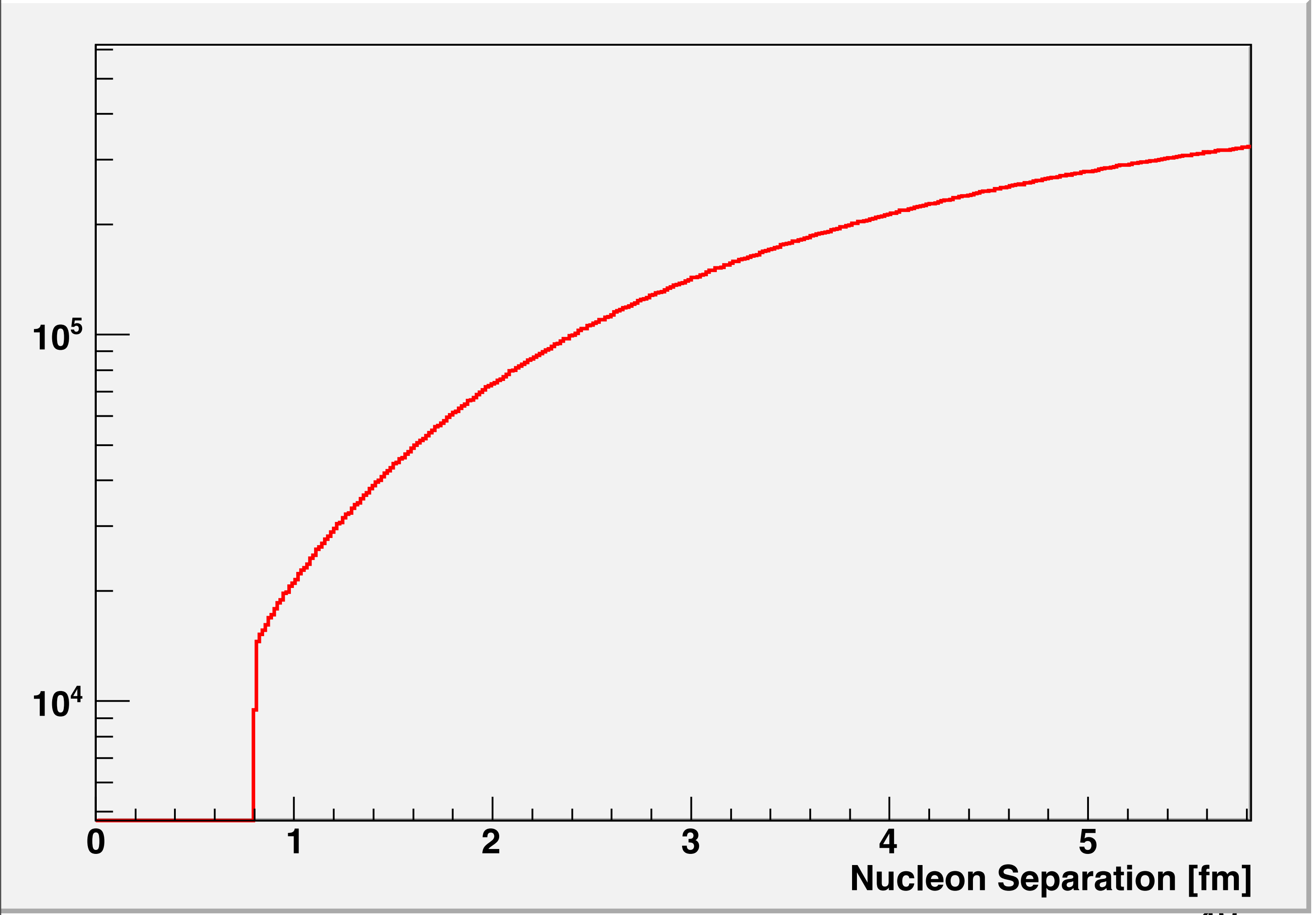
It can be accounted for by a factor R_g

$$R_g(\lambda) = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda + 5/2)}{\Gamma(\lambda + 4)} \qquad \lambda \equiv \begin{cases} \dfrac{\partial[xg(x,\mu^2)]}{\partial \ln(1/x)} & \text{bSat} \\[2ex] \dfrac{\partial \ln(\mathcal{A}_{T,L}^{\gamma^* p \to Ep})}{\partial \ln(1/x)} & \text{bCGC} \end{cases}$$

Again, this goes bad for large $x \sim 10^{-2}$!

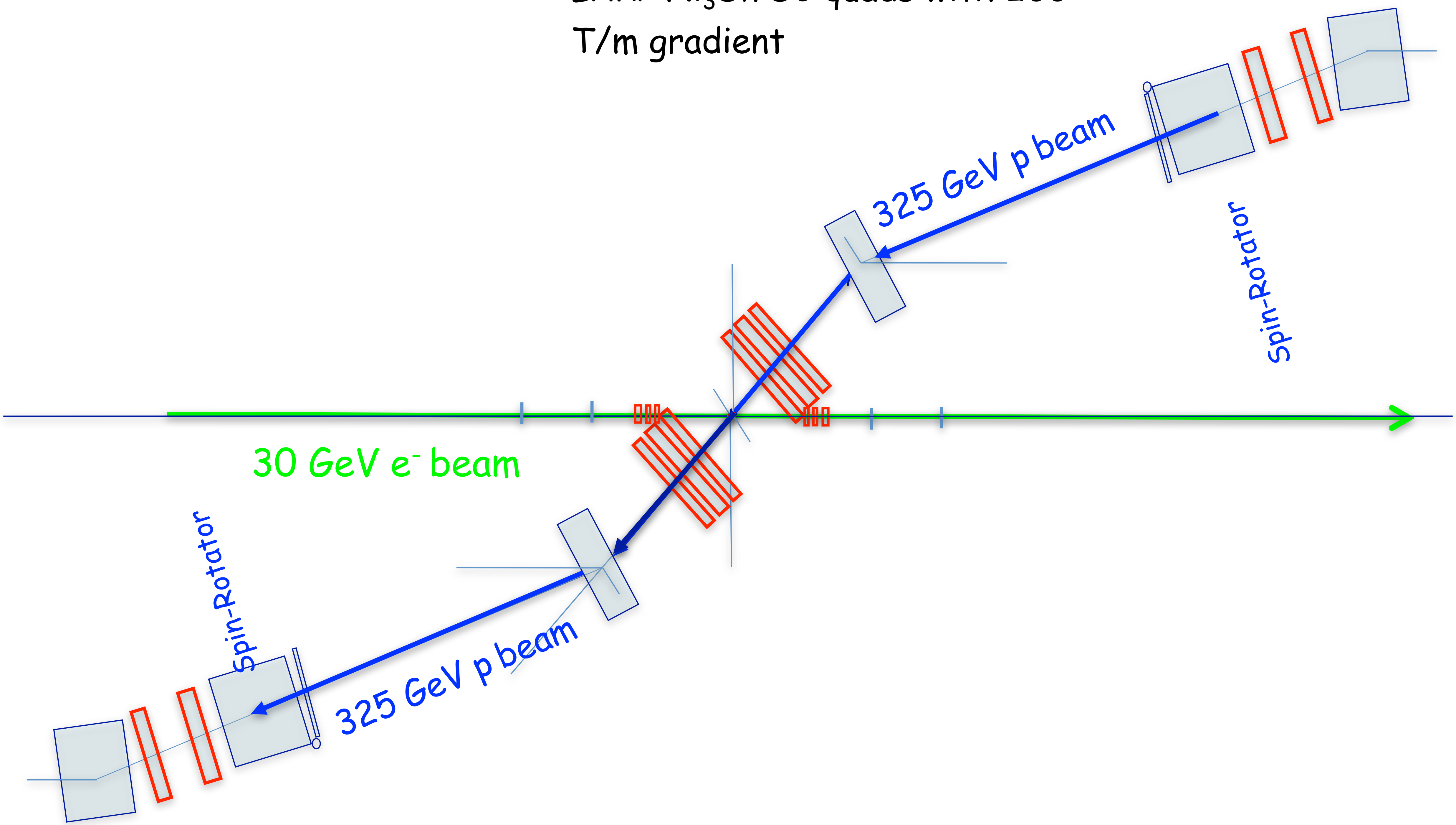
Implemented with exponential damping to control this.


rho(r) [AU]
3500
3000
2500
2000
1500
1000
500
0
0
2
4
6
8
10
r [fm]


10^5
10^4
0
1
2
3
4
5
Nucleon Separation [fm]

eRHIC IRs, β*=5cm, l*=4.5 m

Plan to use newly commissioned LARP Ni_3Sn SC quads with 200 T/m gradient



eRHIC IRs, β*=5cm, l*=4.5 m

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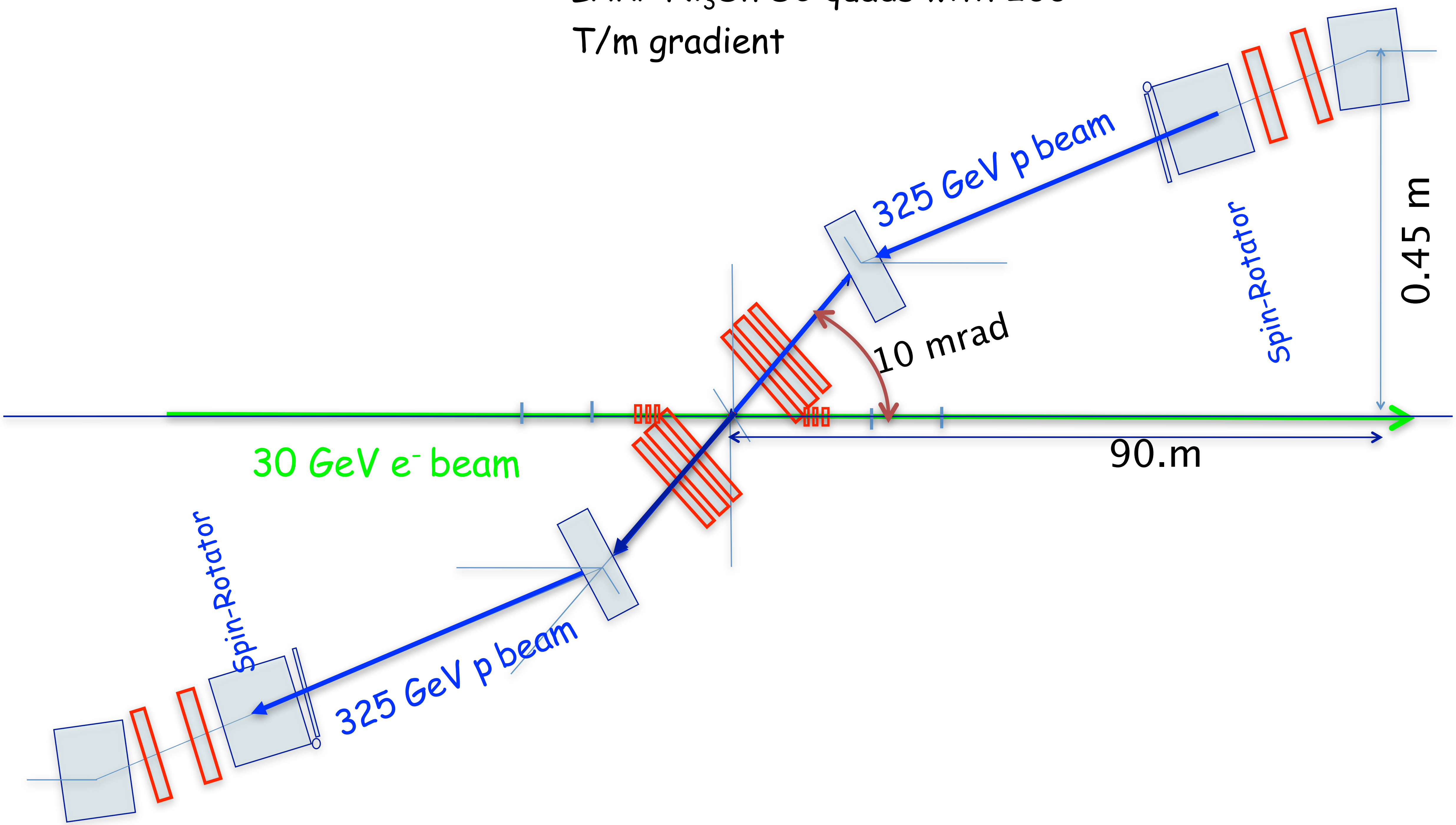

eRHIC IRs, β*=5cm, l*=4.5 m

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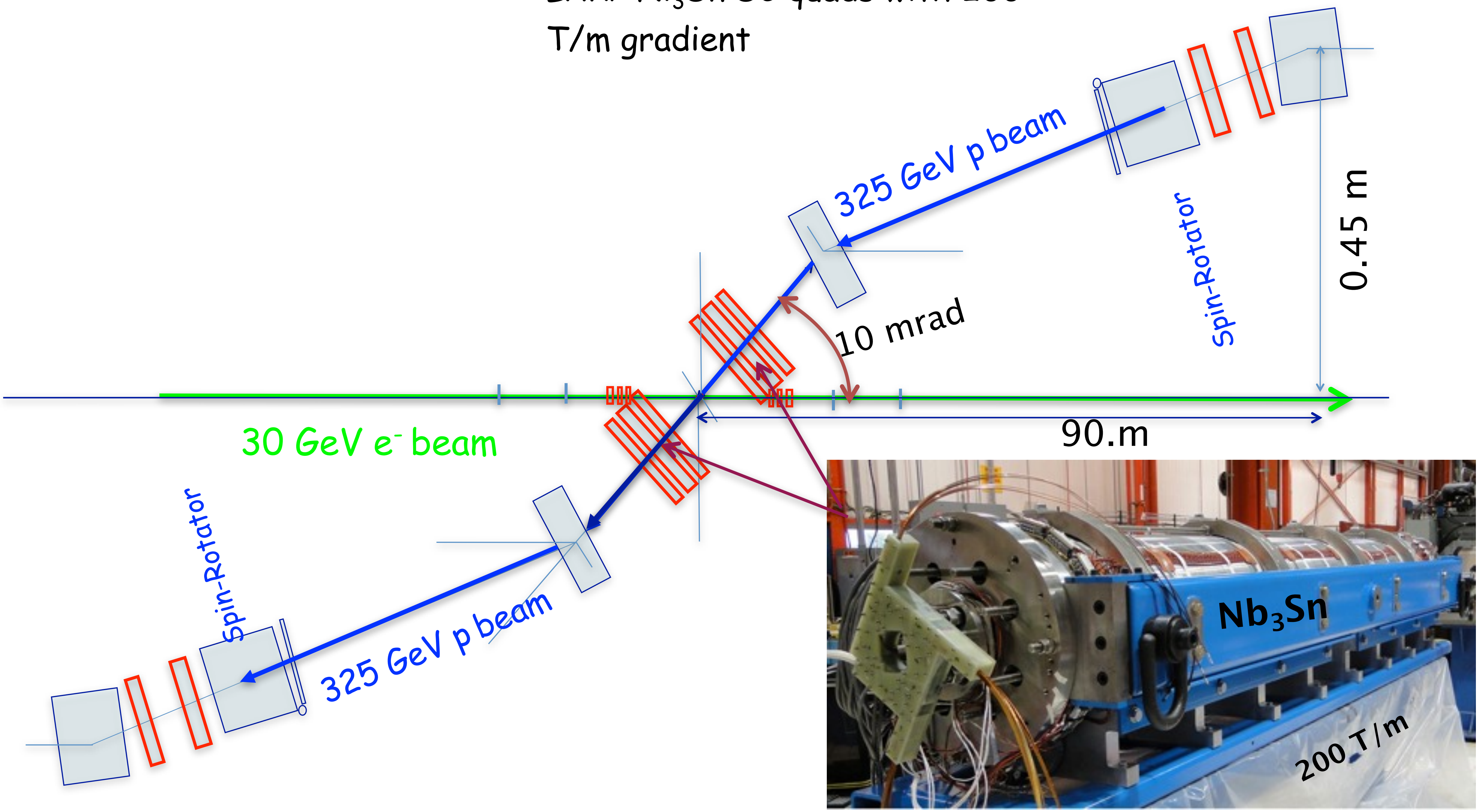
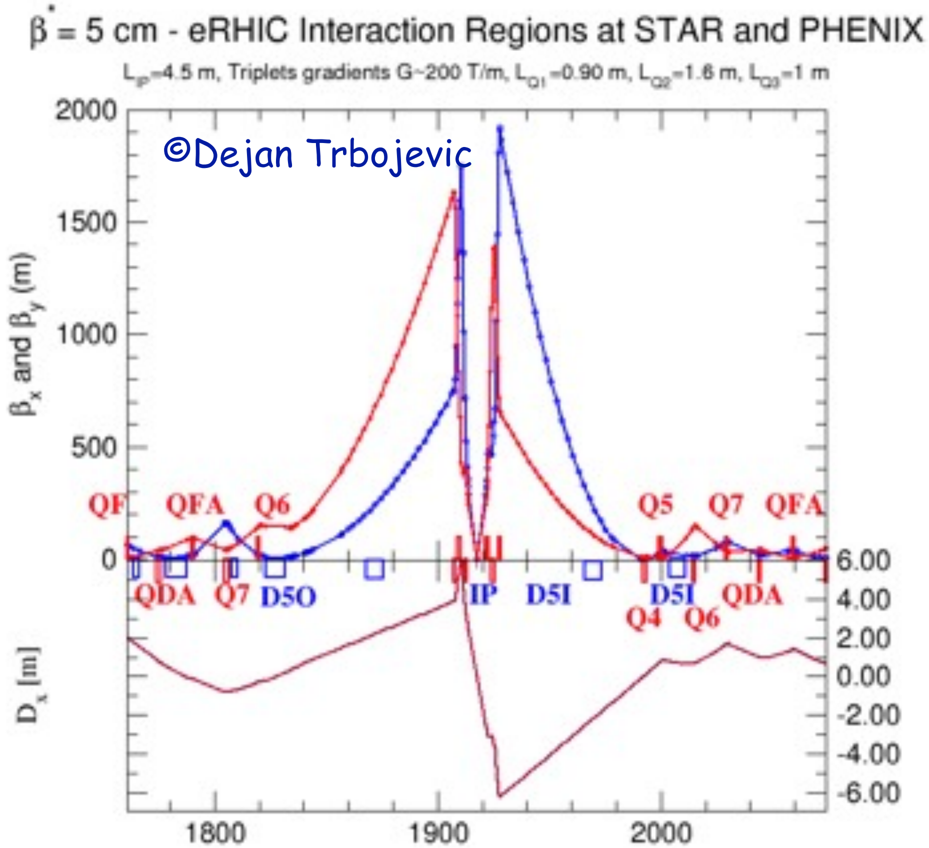


eRHIC IRs, β^*=5cm, l^*=4.5 m



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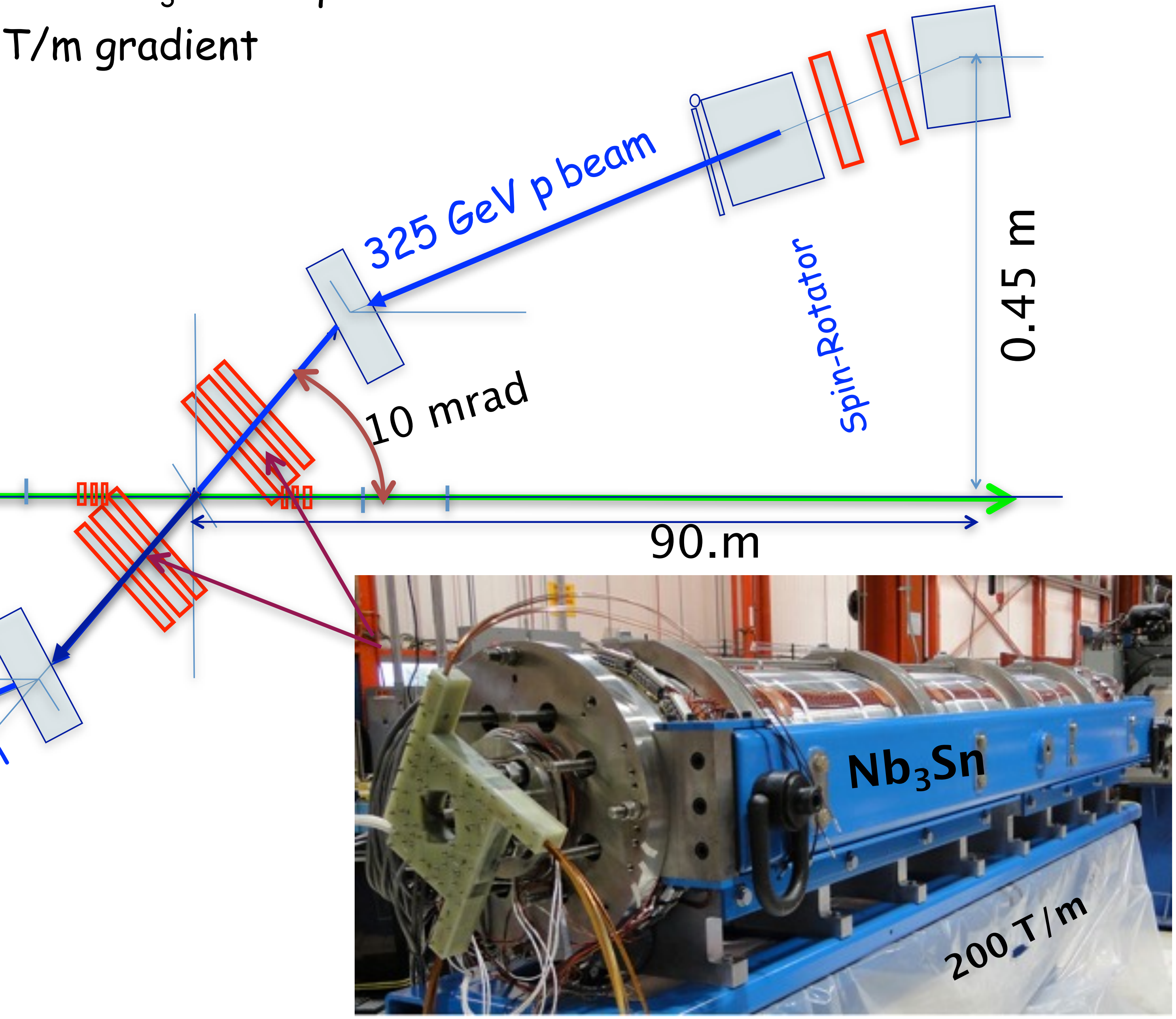
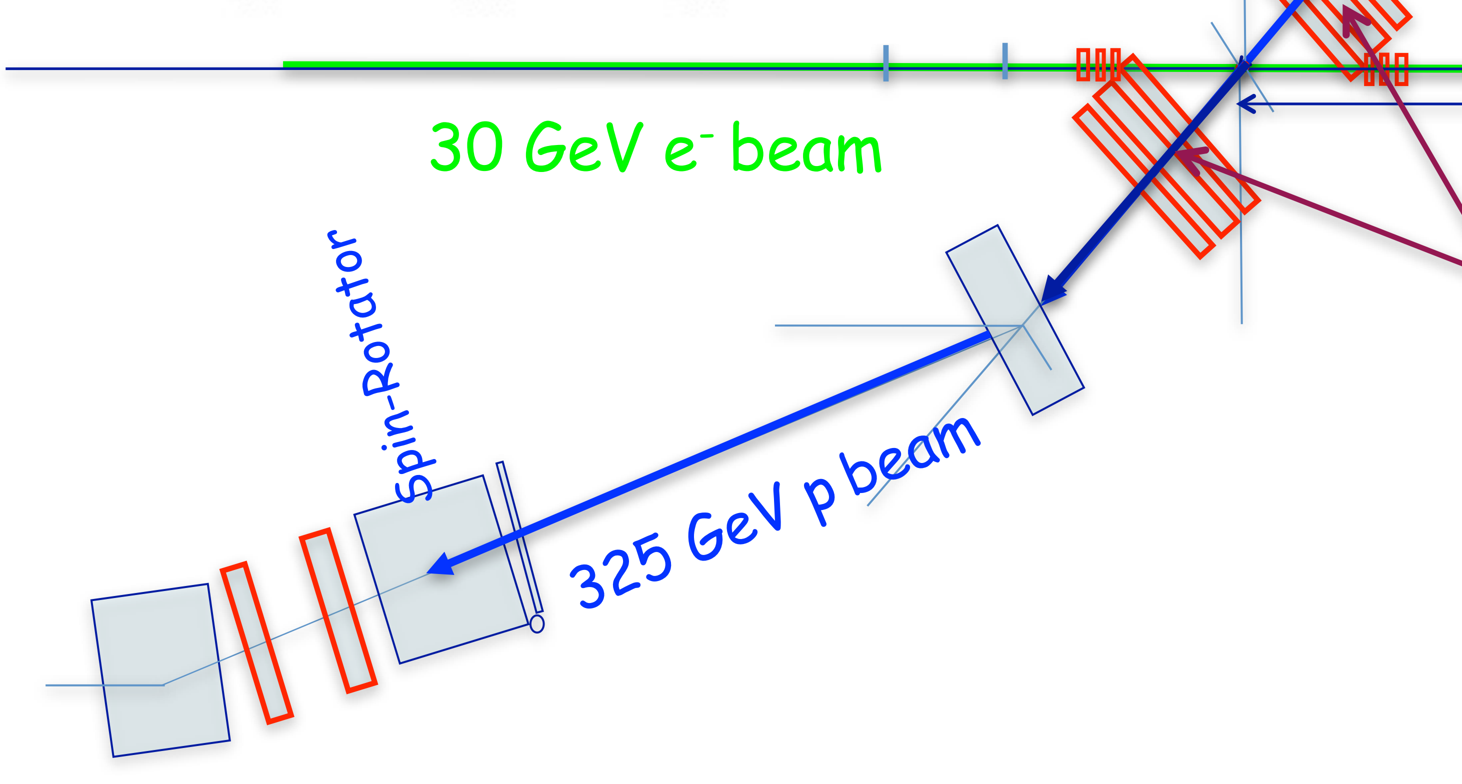
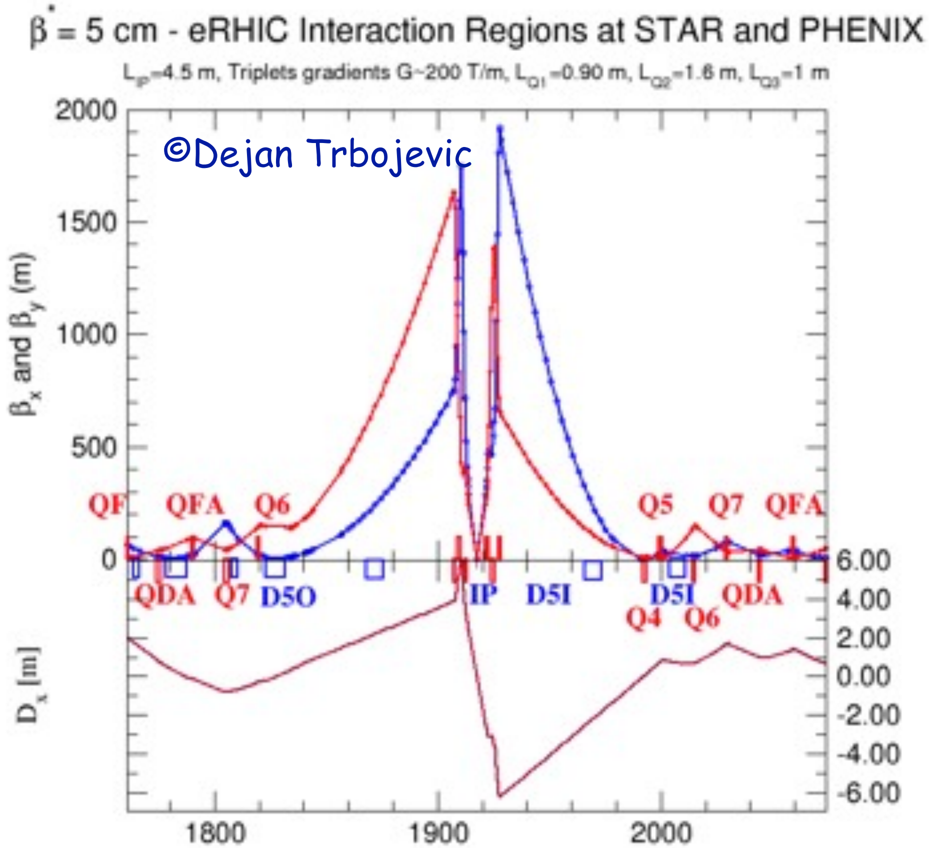




eRHIC IRs, β*=5cm, l*=4.5 m



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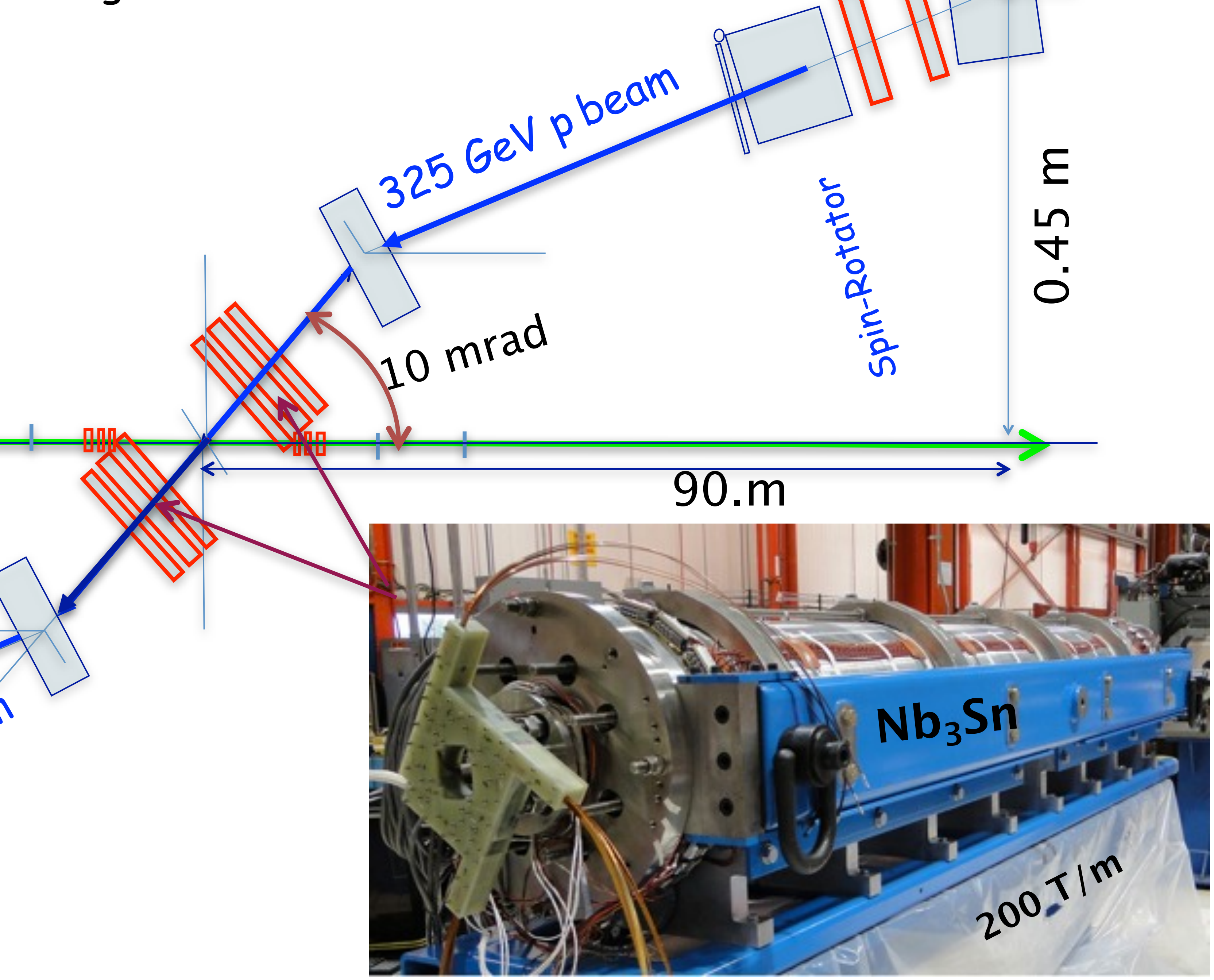

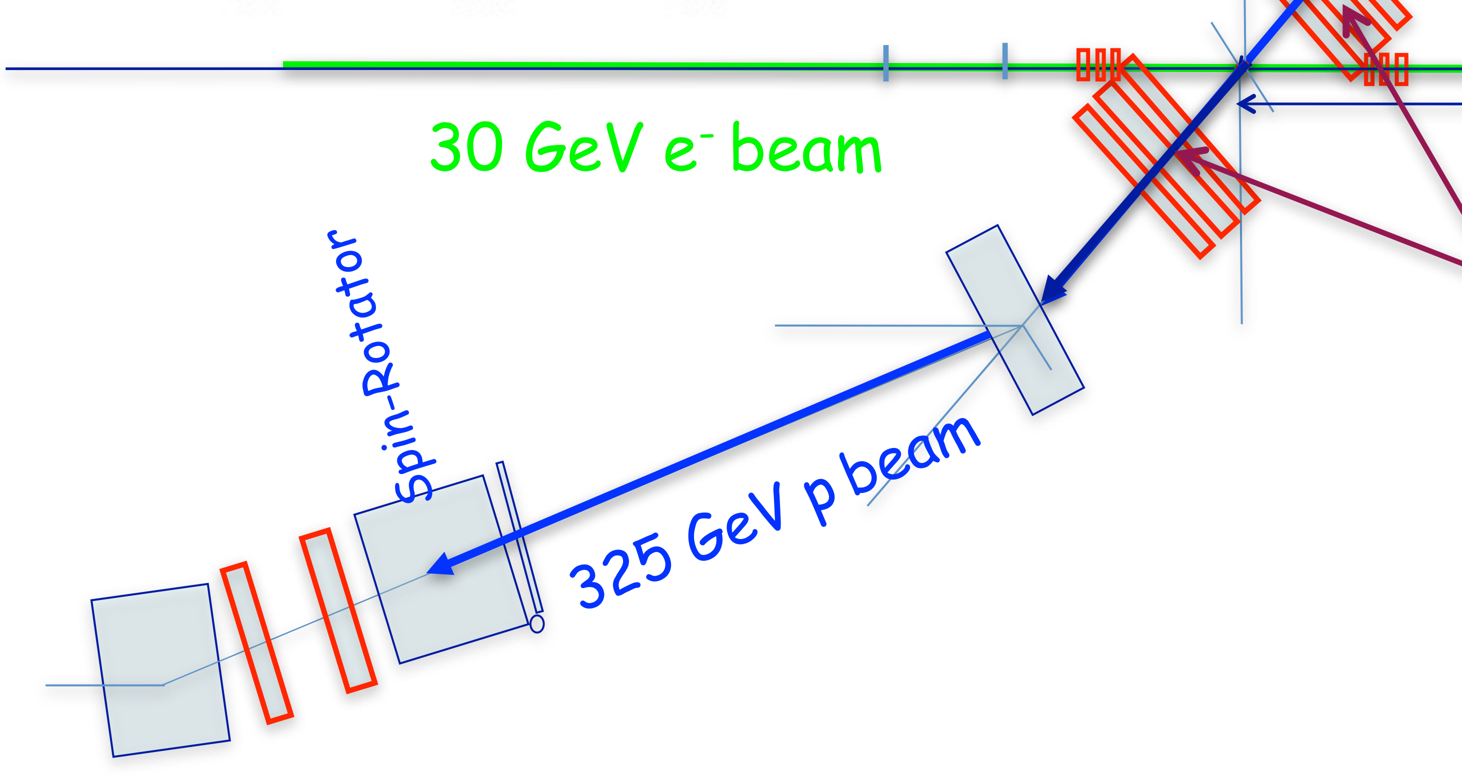

$L=1.4\times10^{34}cm^{-2}s^{-1}$, 200 T/m gradient