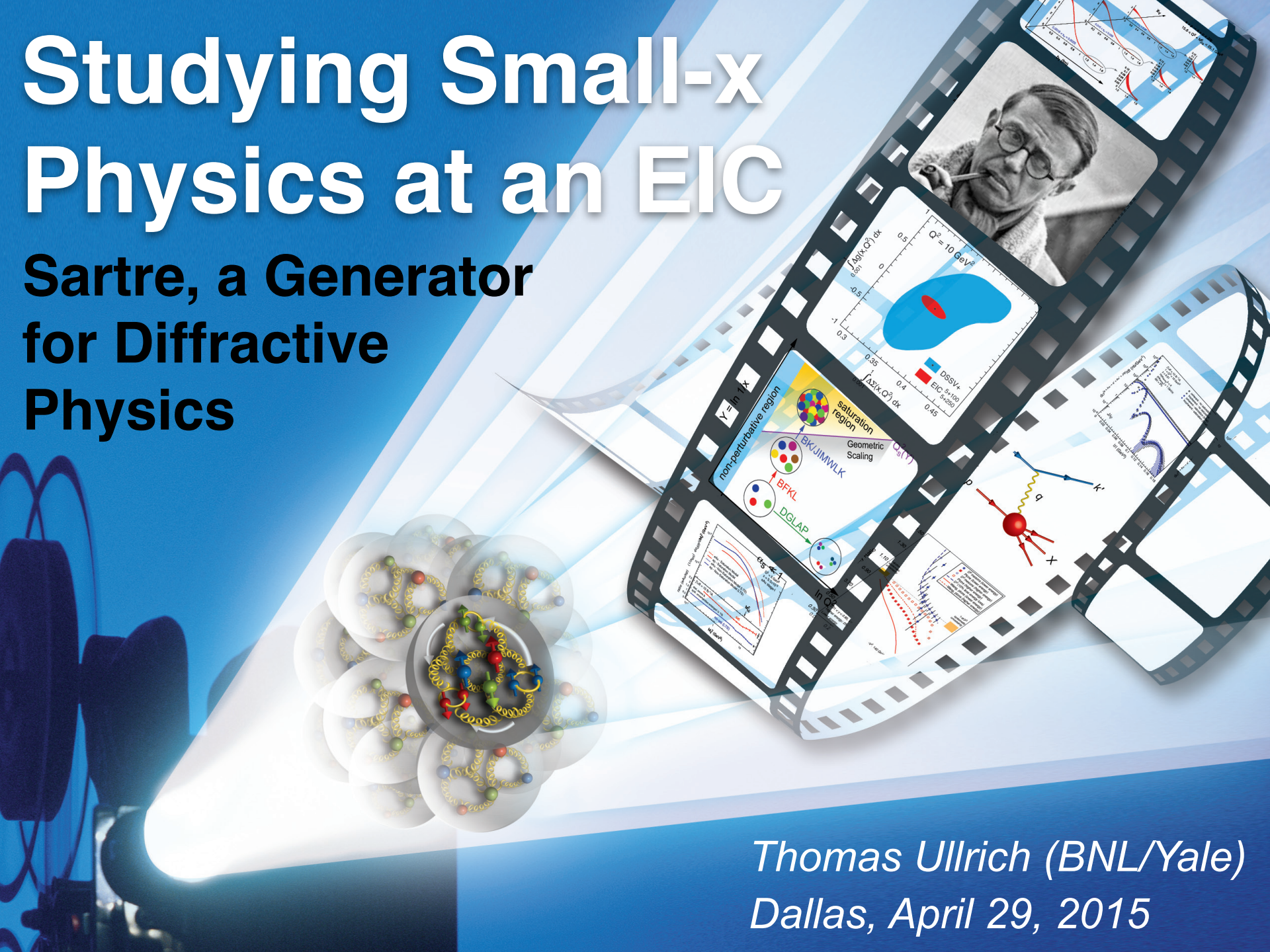
Studying Small-x Physics at an EIC

Sartre, a Generator for Diffractive Physics



Thomas Ullrich (BNL/Yale)

Dallas, April 29, 2015

Electron-Ion Collider

Investigate with precision universal dynamics of gluons

Ultimate QCD machine:

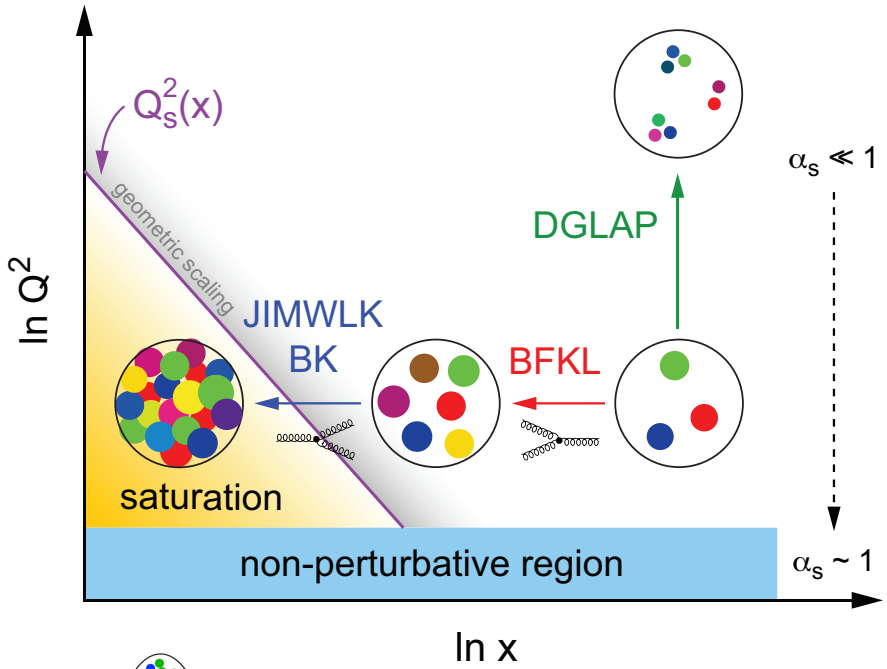
- The world's first polarized electron-polarized proton collider
- The world's first electron-heavy ion collider
- Luminosities: a hundred to up to a thousand times HERA
- Fine resolution inside proton down to 10^{-18} meters

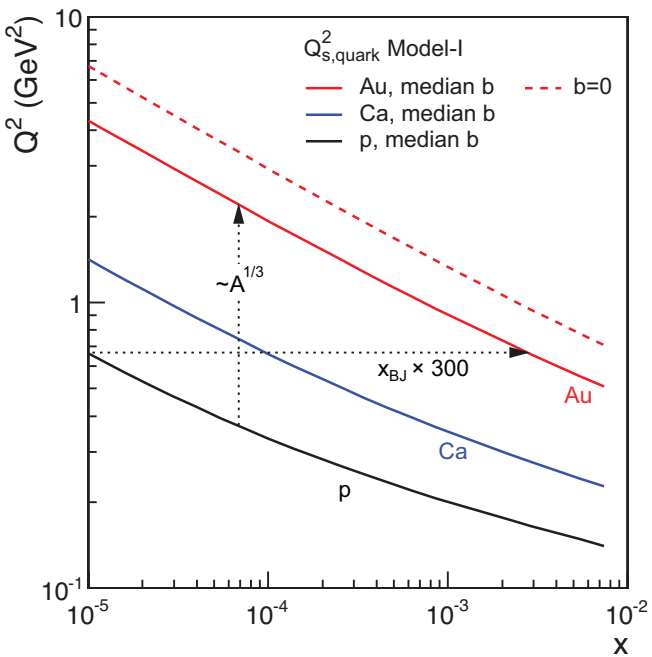
EIC:

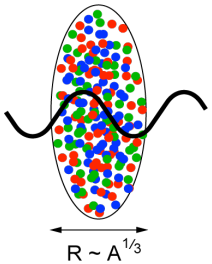
- NP Long Range Plan Resolution Meeting (April '15): Green Light
- Possible sites: BNL (eRHIC), JLab (MEIC)
  - Add ERL+FFAG Recirculating e Rings to RHIC facility
  - Figure-8 Ring-Ring Collider, use of CEBAF

What Drives Interest In e+A Collisions?

- **Gluon Saturation**
  - Can we find experimentally evidence of non-linear QCD dynamics?
  - What is the dynamics of gluon saturation? How does it evolve?
  - Is the Color Glass Condensate the correct theory in this realm?





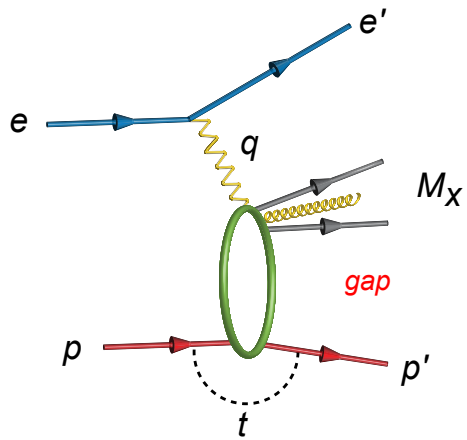


$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

Enhancement of Q_S with A: saturation regime reached at significantly lower energy in nuclei (and lower cost)

Key Measurements - Diffraction

Diffractive physics will be ***the*** major component of the e+A program at an EIC

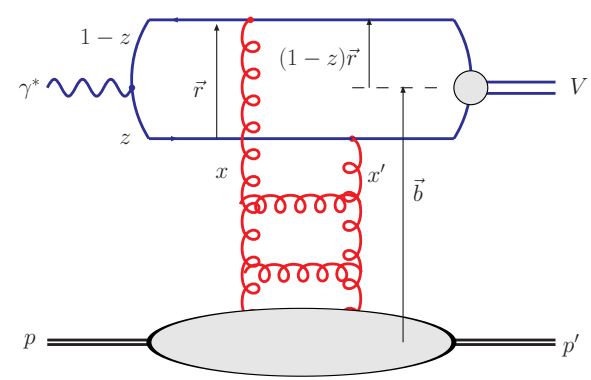


Close relative of DIS

t : momentum transfer squared
M_X : mass of diffractive final-state characterized by large **rapidity gap** mediated by *color neutral exchange* (e.g. 2 or more gluons)

- Came into limelight with discovery at HERA: diffractive events (~15% of total DIS rate)
- High sensitivity to gluon density: $\sigma \sim [g(x,Q^2)]^2$ due to color-neutral exchange
- Only known process where spatial gluon distributions can be extracted

Dipole Model:



Issue: Missing Event Generators

- Requirements:
  - DIS Events
  - Diffractive Events

  }
  - saturation and non-saturation picture
  - e+p (cross checks with existing data)
  - e+A incl. nuclear effects

- Plethora of e+p generators from HERA times
  - PYTHIA6, LEPTO, CASCADE, HERACLES, DJANGOH, …
- Many p+p/p+A/A+A generators (RHIC, LHC)
  - HIJING, DPMJET, EPOS, …
- e+A
  - …

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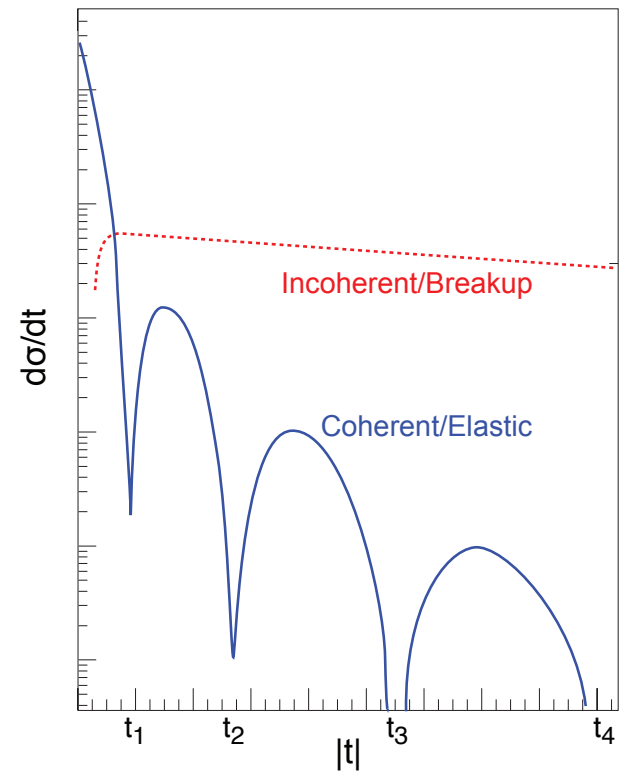
  - HIJING, DPMJET, EPOS, …
- e+A
  - …
- EIC community ⇒ do-it-yourself
  - Sartre 1 for exclusive diffractive VM production (T. Toll and TU)
  - Sartre 2 for inclusive diffractive events (T. Toll)
  - DIS event generator pending
    - currently: patch of PYTHIA6+DPMJet+Fluka

Sartre 1: Diffractive Vector Meson Production

Incoherent: nucleus dissociation ($f \neq i$)

$$\begin{aligned}\sigma_{\rm incoh} &\propto \sum_{f\neq i} \langle i|\mathcal{A}|f\rangle^\dagger \langle f|\mathcal{A}|i\rangle \\ &= \sum_{f} \langle i|\mathcal{A}|f\rangle^\dagger \langle f|\mathcal{A}|i\rangle - \langle i|A|i\rangle^\dagger \langle i|A|i\rangle \\ &= \langle i|\,|\mathcal{A}|^2|i\rangle - |\langle i|\mathcal{A}|i\rangle|^2 = \langle|\mathcal{A}|^2\rangle - |\langle\mathcal{A}\rangle|^2\end{aligned}$$



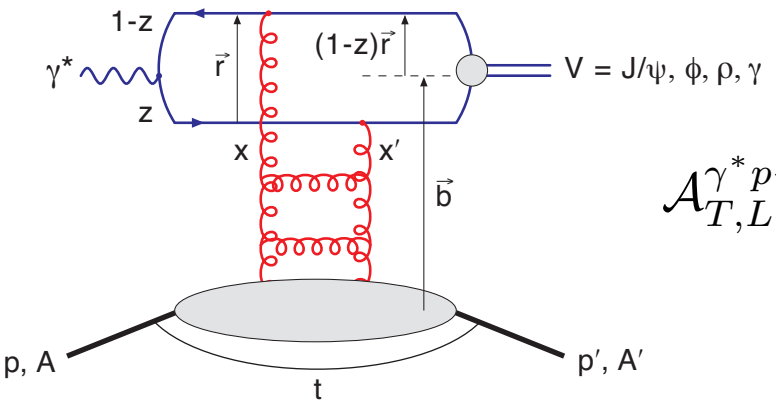
Incoherent CS is variance of amplitude
$\Rightarrow$ measure of fluctuating source density
Coherent CS reflects the average source density

$$\frac{\mathrm{d}\sigma_{\rm total}}{\mathrm{d}t} = \frac{1}{16\pi}\langle|\mathcal{A}|^2\rangle \qquad \frac{\mathrm{d}\sigma_{\rm coh}}{\mathrm{d}t} = \frac{1}{16\pi}\,|\langle\mathcal{A}\rangle|^2$$

Sartre 1: Diffractive Vector Meson Production

Use Dipole Model: bSat and bNonSat

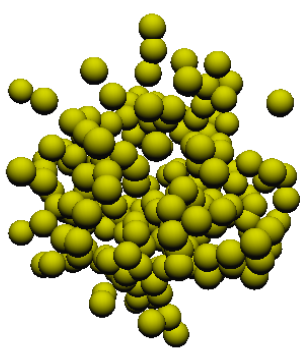
$\Delta = \sqrt{-t}$



Amplitude in *ep*:

$$\mathcal{A}_{T,L}^{\gamma^* p \to V p}(x, Q, \Delta) = i \int \mathrm{d}r \int \frac{\mathrm{d}z}{4\pi} \int \mathrm{d}^2\mathbf{b} (\Psi_V^* \Psi)(r, z)$$

$$\times 2\pi r J_0([1-z] r \Delta) e^{-i\mathbf{b}\cdot\Delta} \frac{\mathrm{d}\sigma_{q\bar{q}}^{(p)}}{\mathrm{d}^2\mathbf{b}}(x, r, \mathbf{b})$$



Sartre:
Wood-Saxon

Nucleus:

- small x ⇒ large λ ⇒ coherently probes whole nucleus for x ≪ $A^{-1/3}$ m_N/R_N ~ 10^{-2}
- Position of nucleon in nucleus is not an observable
- To calculate CS need to average over all possible states of nucleon configurations Ω

$$\frac{\mathrm{d}\sigma^{\gamma^* \mathrm{A}}}{\mathrm{d}t}(x, Q^2, t) = \frac{1}{16\pi} \frac{1}{C_{\max}} \sum_{i=1}^{C_{\max}} \left| \mathcal{A}(x, Q^2, t, \Omega_i) \right|^2$$

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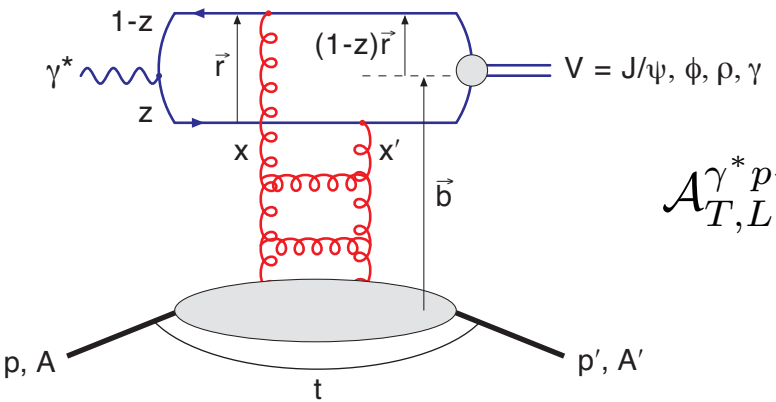

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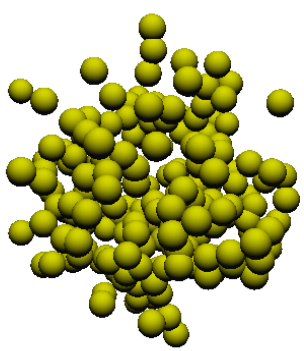
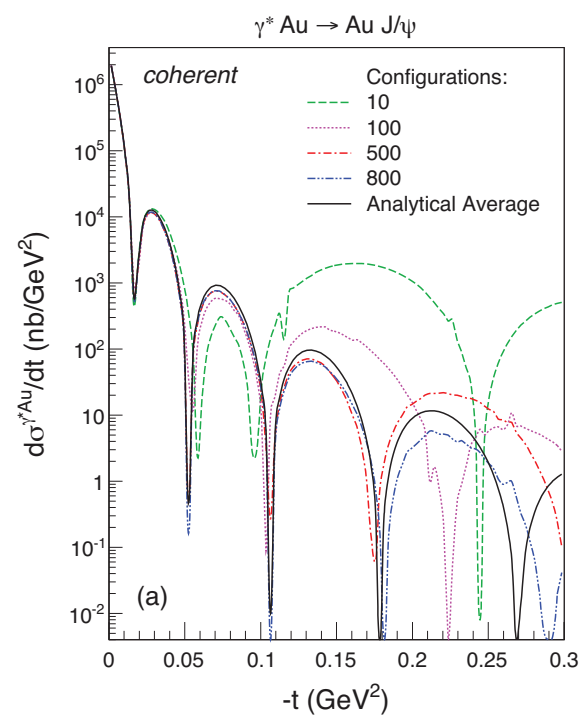


Sartre:
Wood-Saxon

- Analytic average not exact
- Need C_{max} ~ 800, more at large *t*



$$\frac{\mathrm{d}\sigma^{\gamma^* \mathrm{A}}}{\mathrm{d}t}(x, Q^2, t) = \frac{1}{16\pi} \frac{1}{C_{\max}} \sum_{i=1}^{C_{\max}} \left| \mathcal{A}(x, Q^2, t, \Omega_i) \right|^2$$

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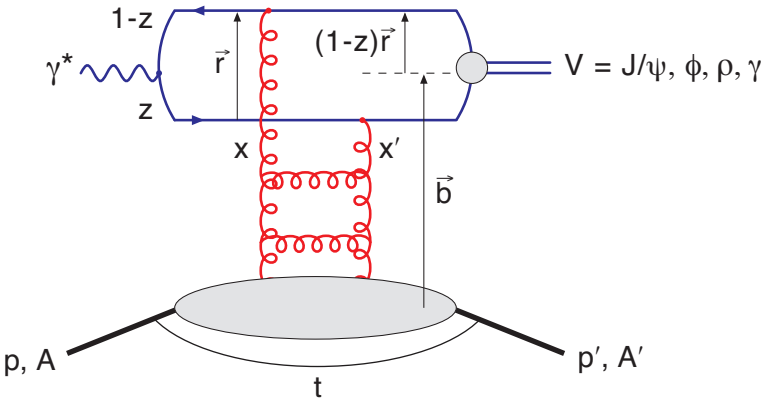
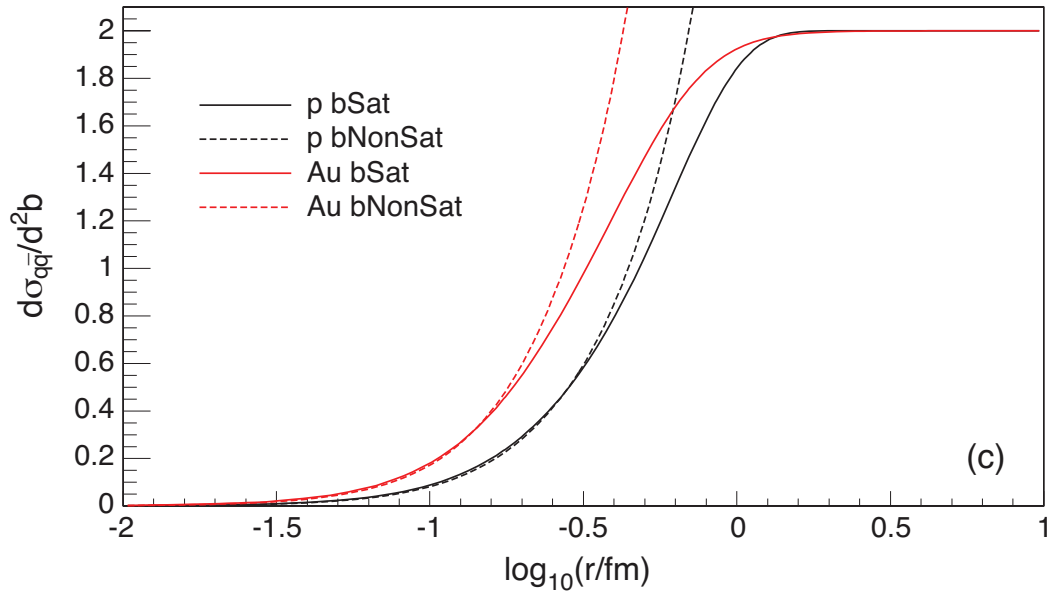


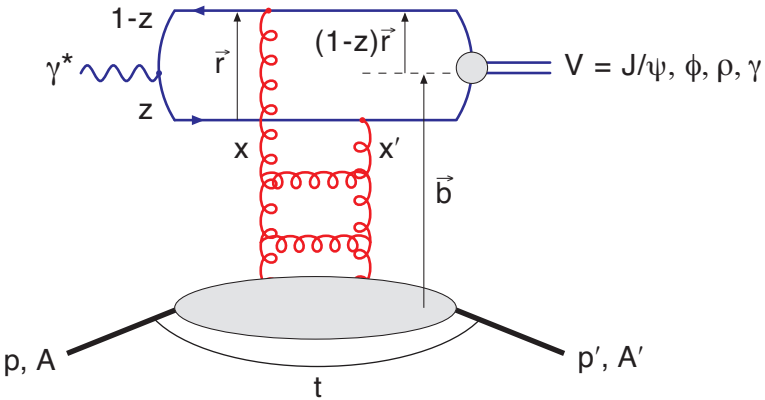


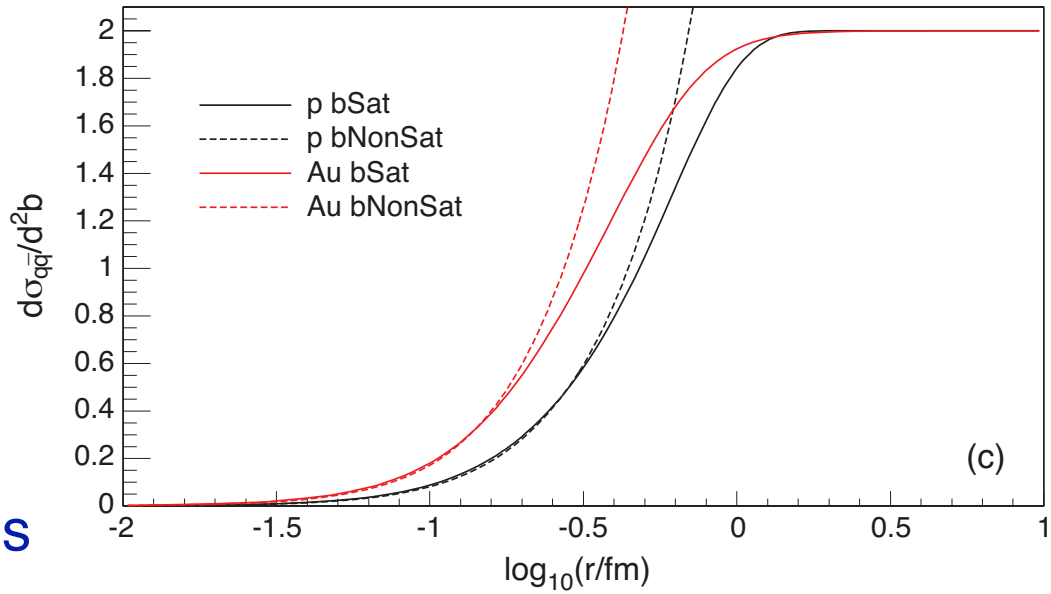
Dependence on nucleon configurations in the amplitude is entirely contained in this dipole cross-section.

bSat: $$\frac{1}{2}\frac{\mathrm{d}\sigma_{q\bar{q}}^{(A)}}{\mathrm{d}^2\mathbf{b}}(x,r,\mathbf{b},\Omega) = 1 - \exp\left(-\frac{\pi^2}{2N_C}r^2\alpha_S(\mu^2)xg(x,\mu^2)\sum_{i=1}^{A}T(|\mathbf{b}-\mathbf{b}_i|)\right)$$

bNonSat: $$\frac{\mathrm{d}\sigma_{q\bar{q}}^{(A)}}{\mathrm{d}^2 b} = \frac{\pi^2}{N_C}r^2\alpha_s(\mu^2)xg(x,\mu^2)\sum_{i=1}^{A}T(|\mathbf{b}-\mathbf{b}_i|)$$

Sartre 1: Diffractive Vector Meson Production





Wave overlap function $\Psi^*\Psi$ falls steeply for large dipole radii

- J/ψ not sensitive to saturation.
- Need to look at ϕ, or ρ that "see" more of the dipole amplitude

$$\mathcal{A}_{T,L}^{\gamma^* p \to V p}(x,Q,\Delta) = i \int \mathrm{d}r \int \frac{\mathrm{d}z}{4\pi} \int \mathrm{d}^2\mathbf{b} (\Psi_V^* \Psi)(r,z)$$

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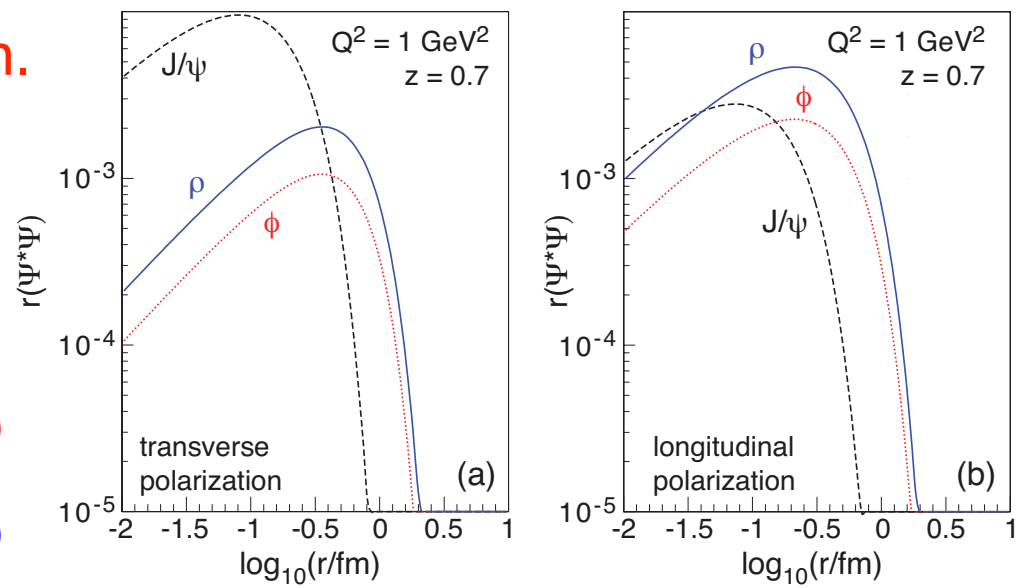

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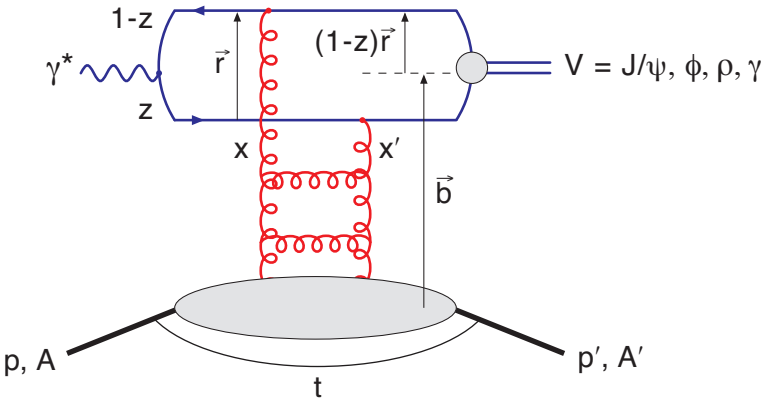

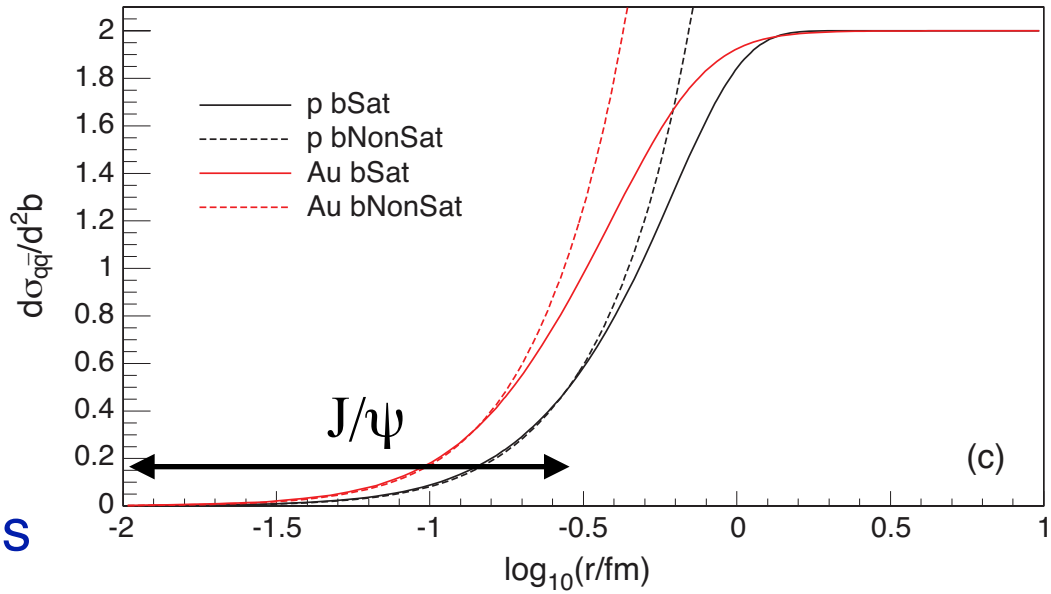

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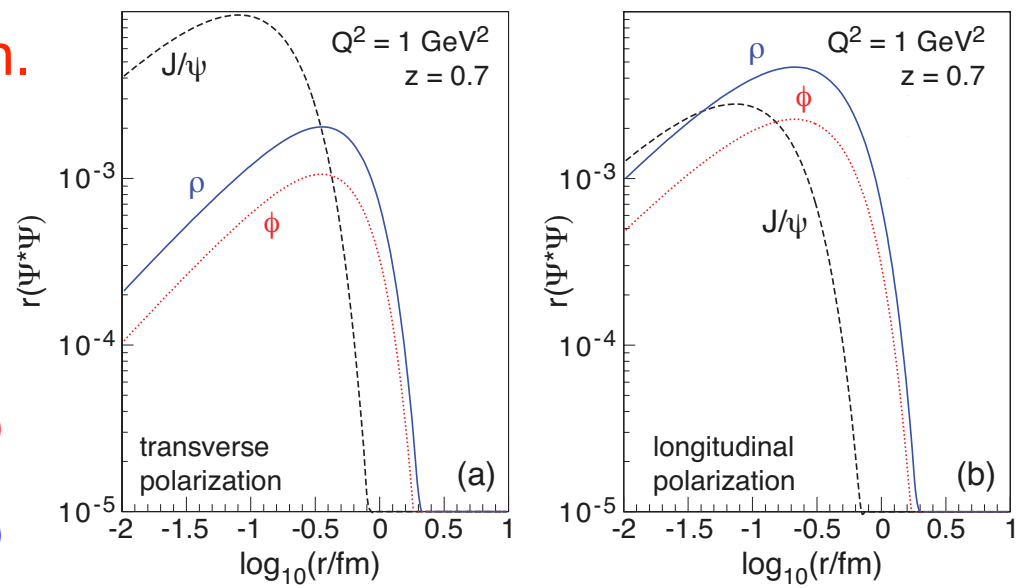

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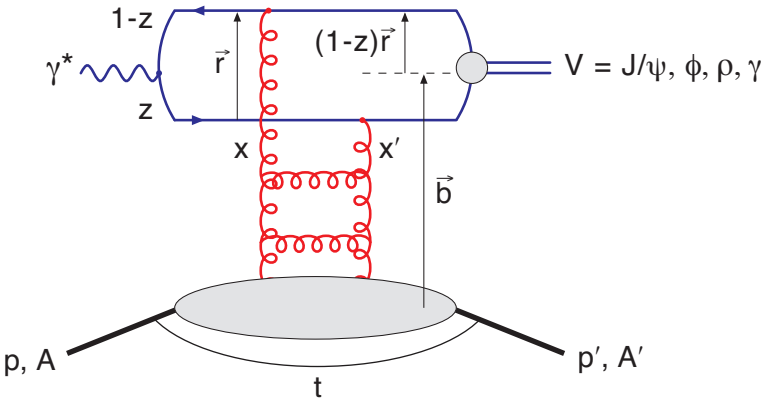

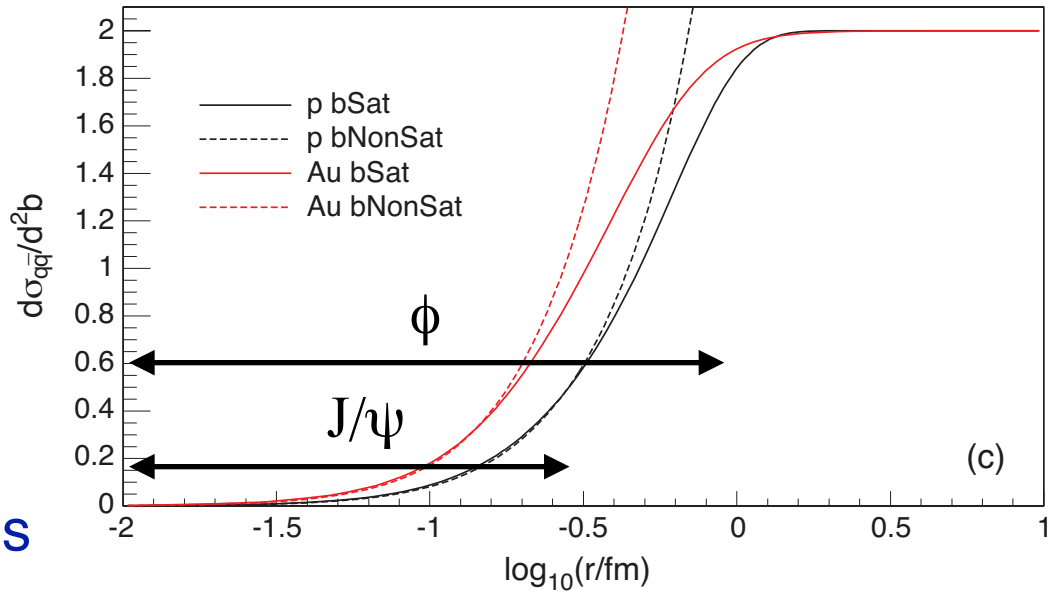

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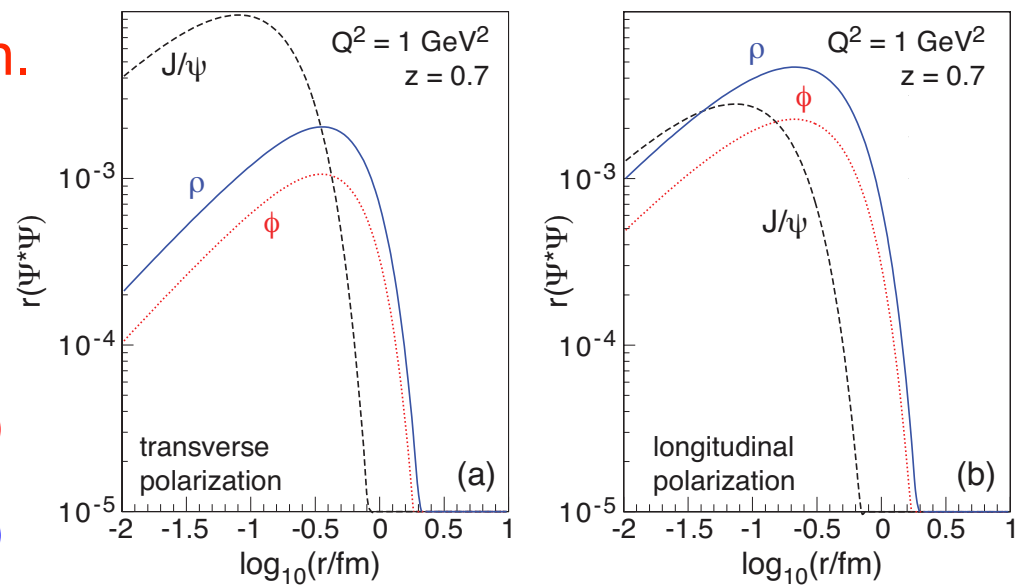
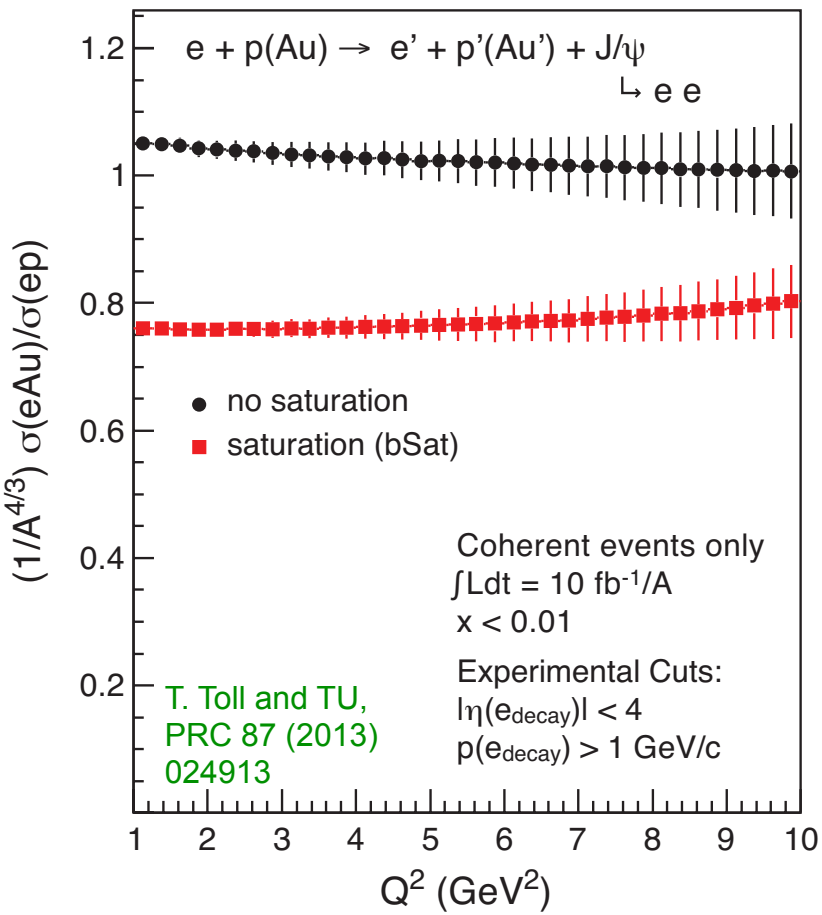
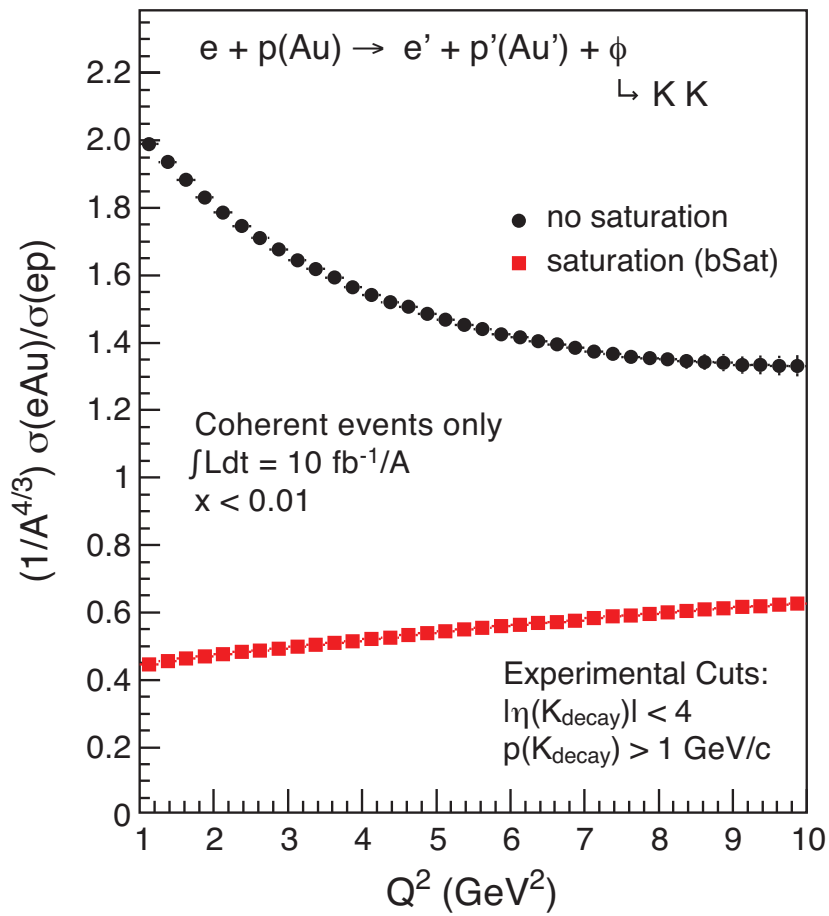


EIC: Exclusive Vector Meson Production





- Sartre event generator (bSat & bNonSat = linearized bSat)
- As expected: big difference for ϕ less so for J/ψ
- Note: $A^{4/3}$ scaling strictly only valid at large Q^2

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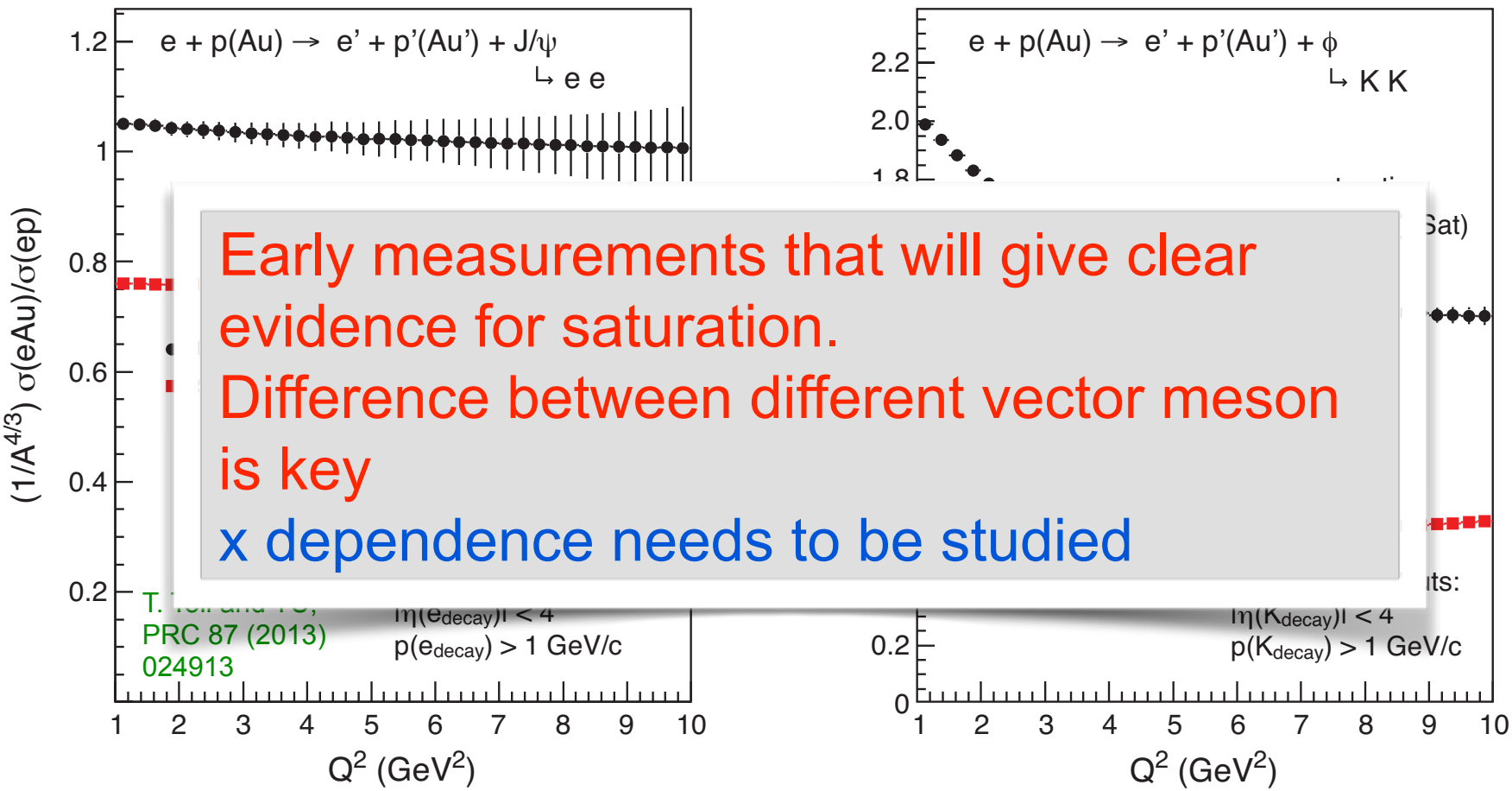
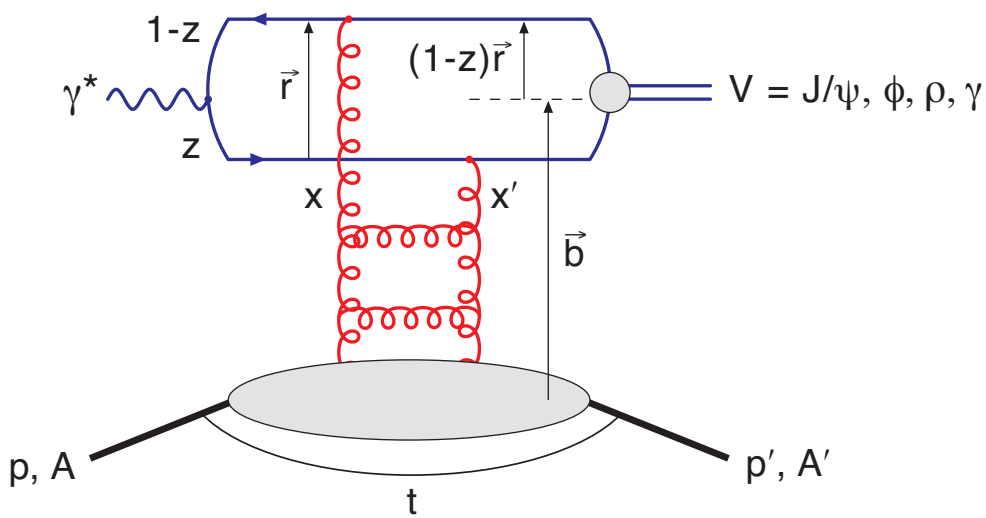


Early measurements that will give clear evidence for saturation.
Difference between different vector meson is key
x dependence needs to be studied

- Sartre event generator (bSat & bNonSat = linearized bSat)
- As expected: big difference for ϕ less so for J/ψ
- Note: $A^{4/3}$ scaling strictly only valid at large Q^2

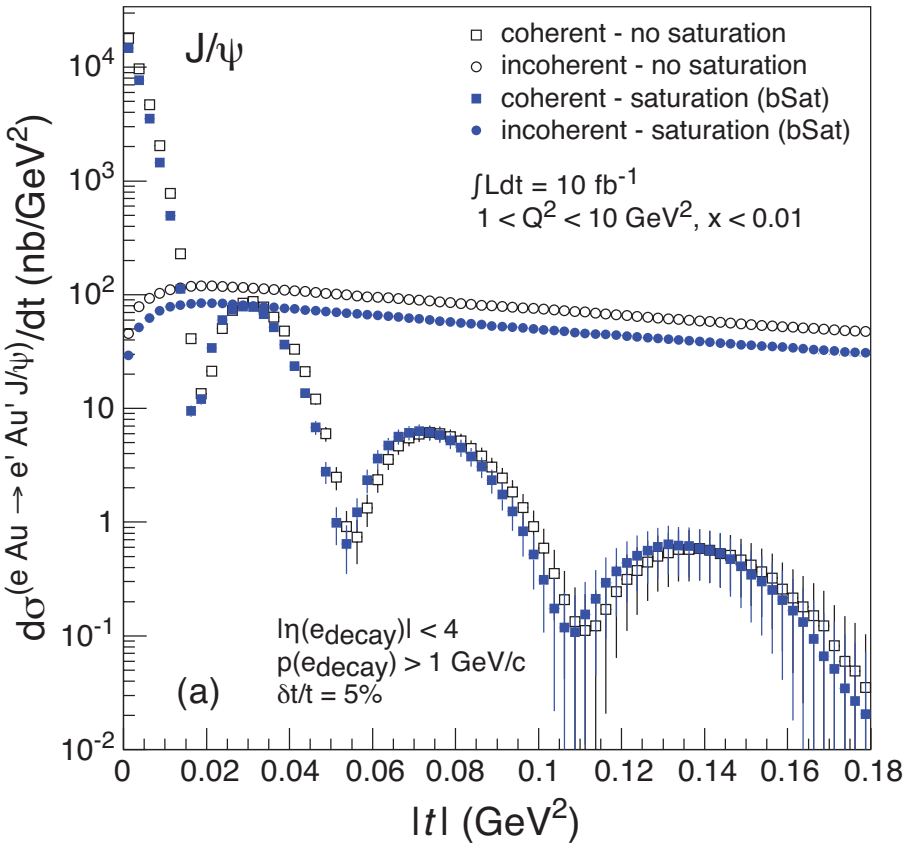
Exclusive Diffractive VM Production: dσ/d*t*

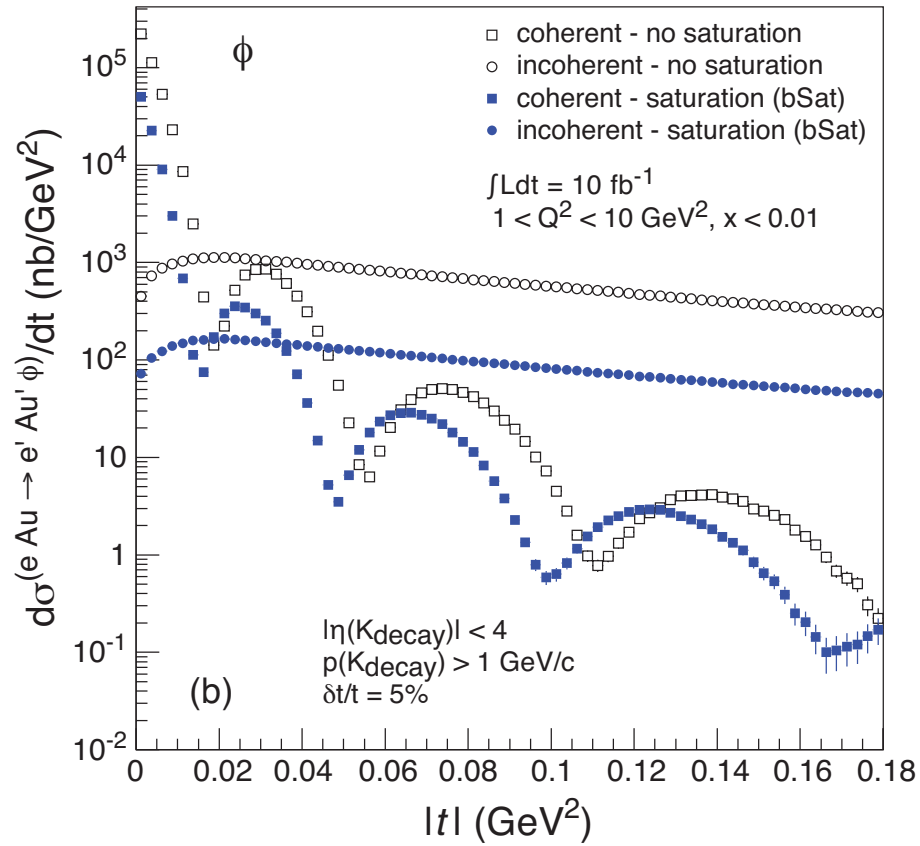
- In general in e+A: cannot detect the outgoing nucleus and measure its momentum
- Exception: exclusive VM production
  - Need only to measure e' and the VM



$$
\begin{aligned}
t &= (\boldsymbol{p}_A - \boldsymbol{p}_{A'})^2 = (\boldsymbol{p}_{\mathrm{VM}} + \boldsymbol{p}_{e'} - \boldsymbol{p}_e)^2 \\
&\approx (p_T^{e'} + p_T^{\mathrm{VM}})^2
\end{aligned}
$$

Vector Meson Production: dσ/d*t*



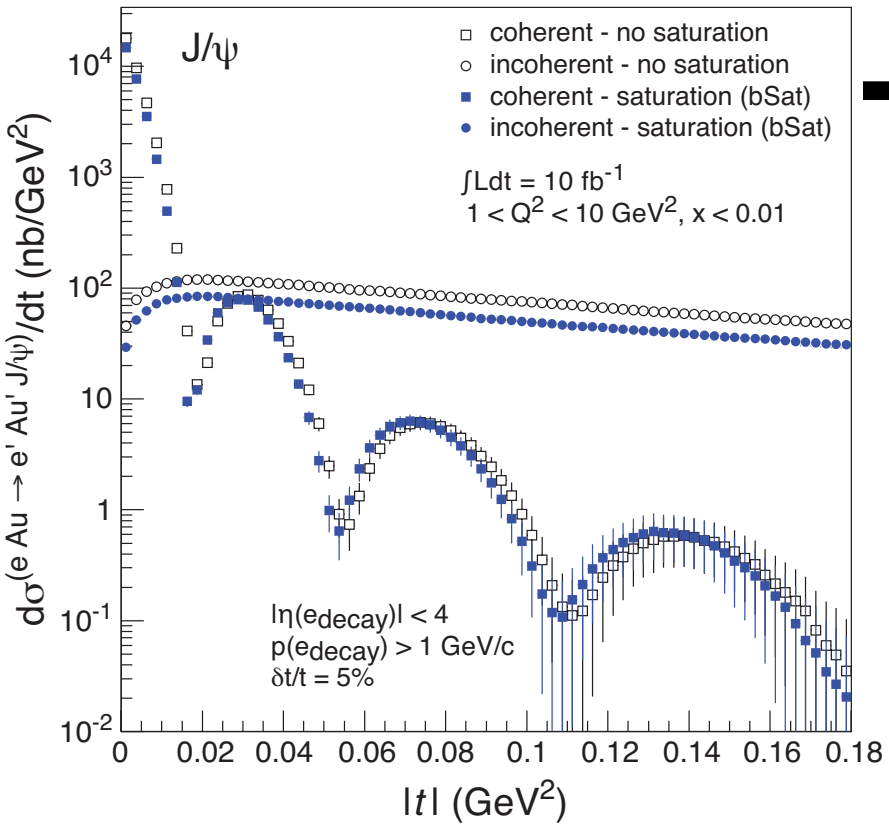


- Find: Typical diffractive pattern for coherent (non-breakup) part
- As expected: *J*/ψ less sensitive to saturation than ϕ
- Need this sliced in *x* bins ⇒ luminosity hungry
- Crucial: *t* resolution and reach

Spatial Gluon Distribution from dσ/d*t*

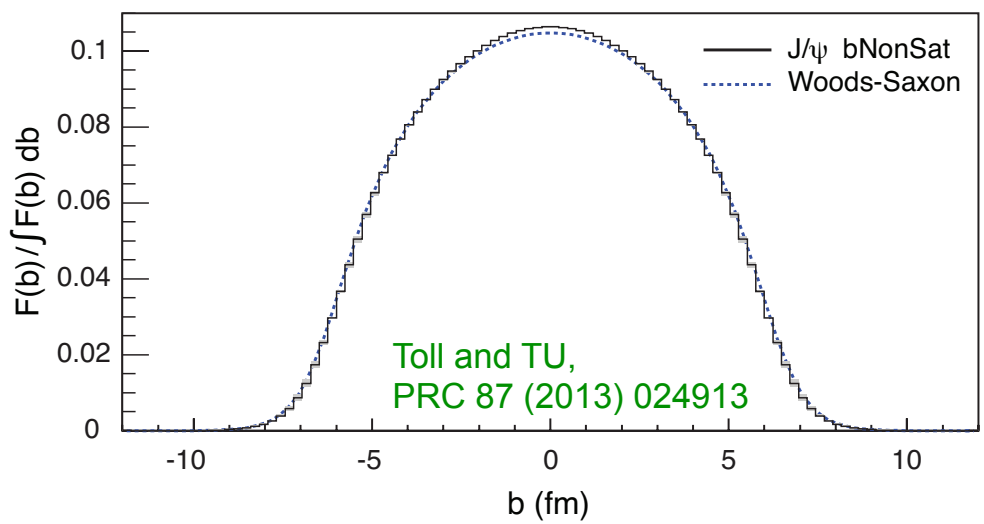
Diffractive vector meson production: e + Au → e′ + Au′ + J/ψ

- Momentum transfer $t = |\mathbf{p}_{Au}-\mathbf{p}_{Au'}|^2$ conjugate to b_T



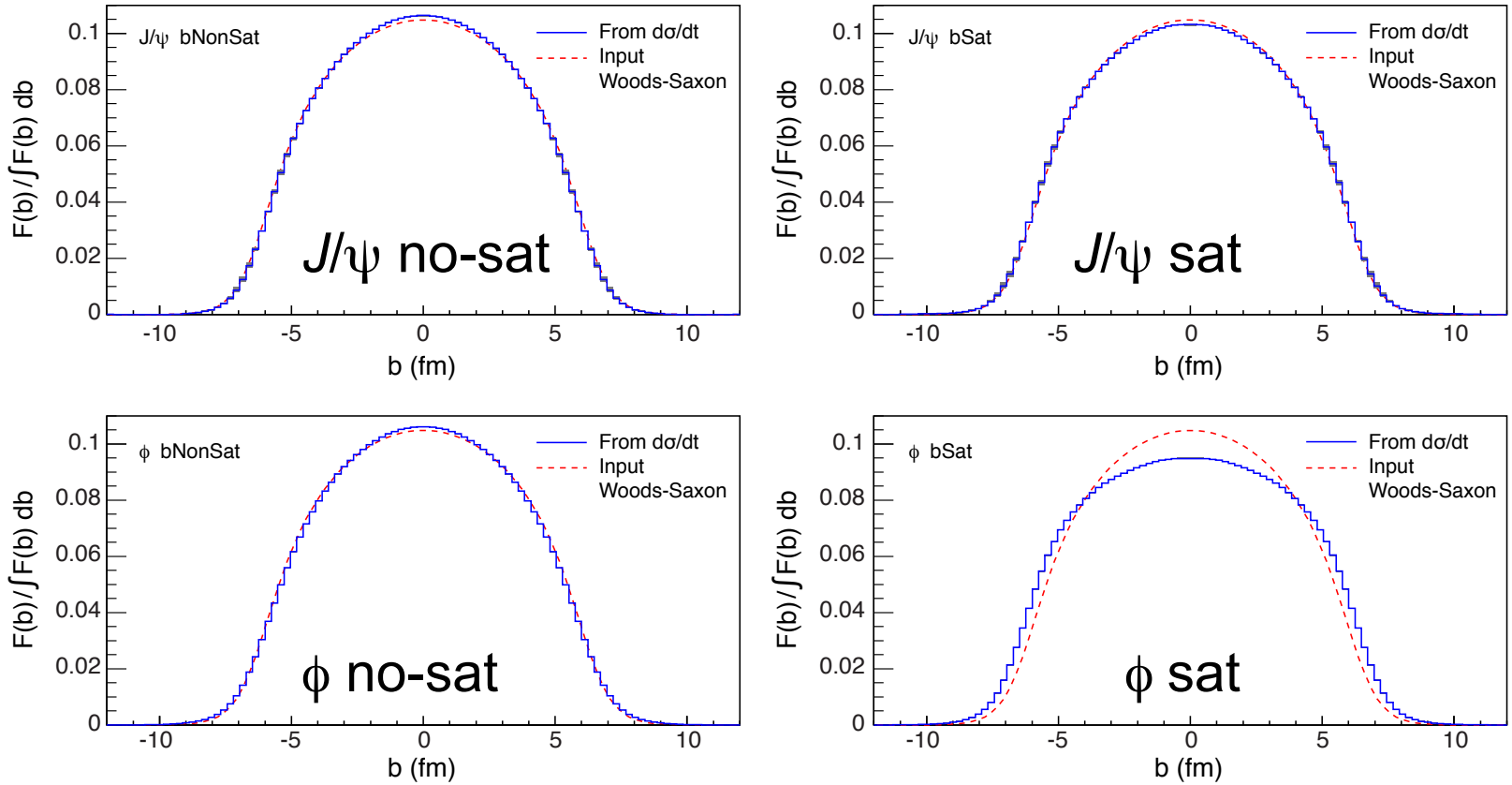
$$F(b) \sim \frac{1}{2\pi}\int_0^\infty d\Delta\,\Delta\,J_0(\Delta b)\sqrt{\frac{d\sigma}{dt}}$$

$t = \Delta^2/(1-x) \approx \Delta^2$



- Converges to input F(b) rapidly: $|t| < 0.1$ almost enough
- Fourier transformation requires $\int\mathcal{L}dt > 1\ \mathrm{fb}^{-1}/\mathrm{A}$

Spatial Gluon Distribution from dσ/d*t*



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- *J*/ψ perfect for obtaining *F*(*b*) in both cases sat and non-sat
- less so since coherence distorts *F*(*b*)
- Note: difference in *F*(*b*) of ϕ and J/ψ reveals saturation

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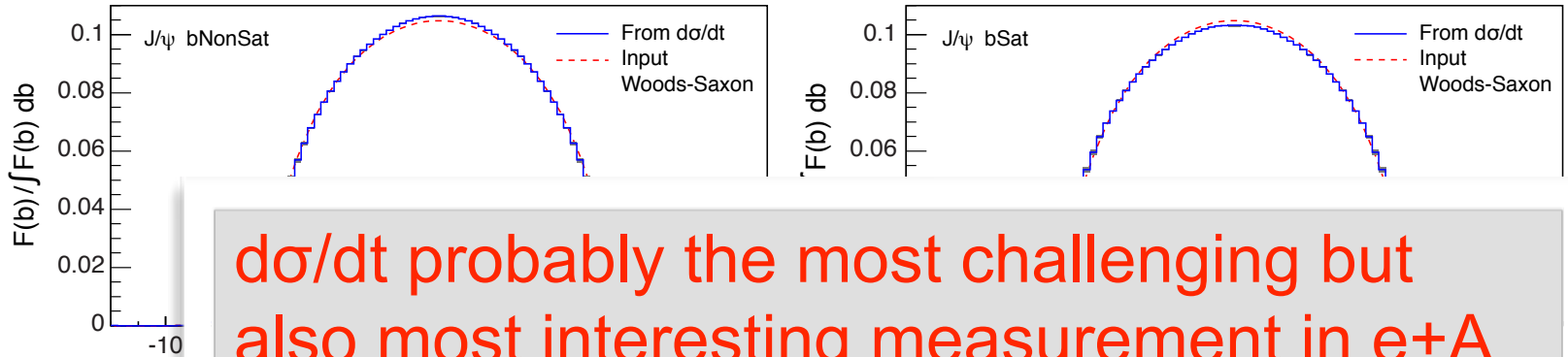

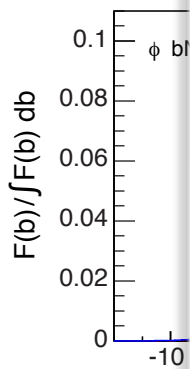

dσ/dt probably the most challenging but also most interesting measurement in e+A

It reveals:

- saturation
- spatial gluon distribution

x dependence needs to be studied

Luminosity hungry requiring $\int \mathcal{L} dt \sim 10\ fb^{-1}/A$

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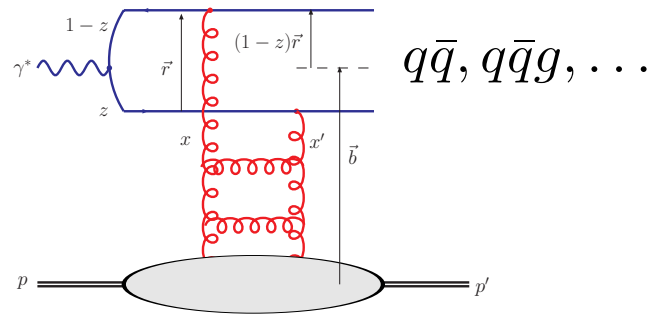
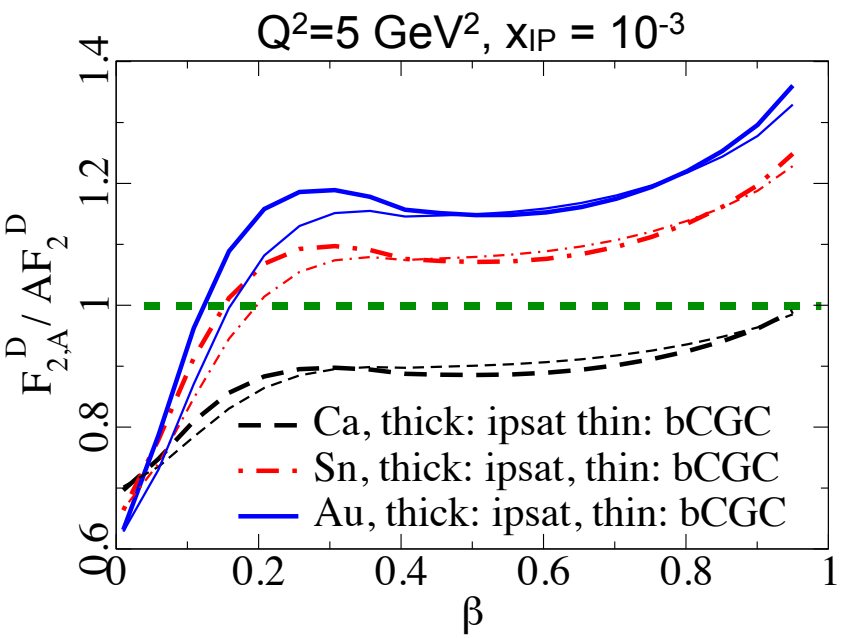
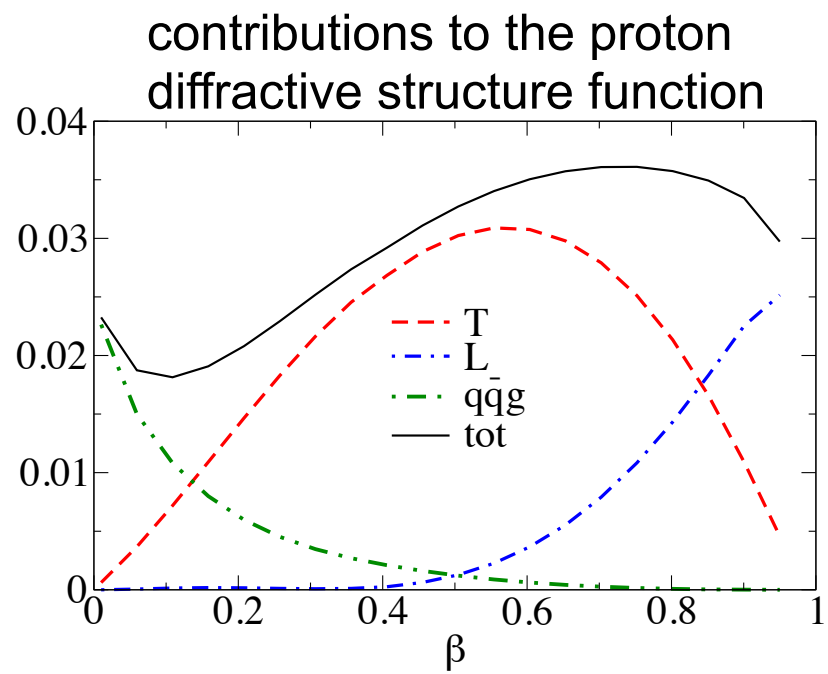
e+A: Diffractive over Total Cross-Section

- Predicted to be enhanced in e+A compared to e+p at large β, i.e. small M_X^2 ($\beta = xQ^2(Q^2-M_X^2)$)
  - β = momentum fraction of the struck parton with respect to the Pomeron





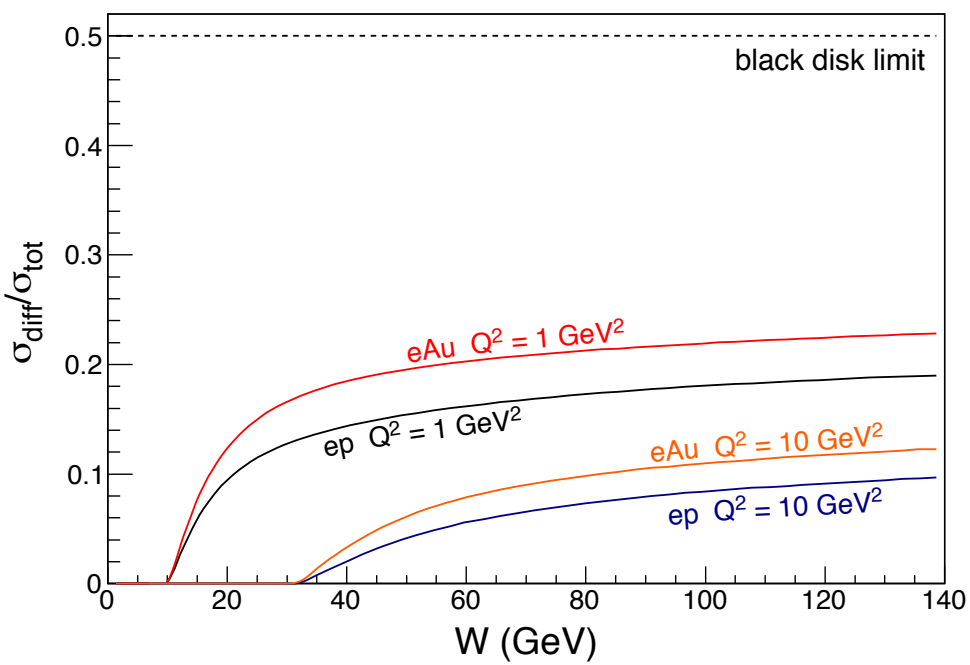
Kowalski et al. Phys.Rev. C78 (2008) 045201

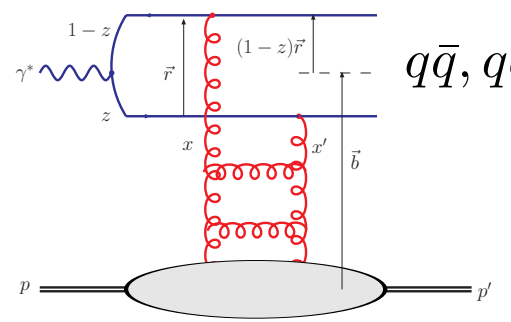


Inclusive Diffractive Events: Sartre 2

Sartre 2

- Allows for simulation of inclusive diffractive events
- Dipole model: $q\bar{q}, q\bar{q}g, \ldots$
- States handed over to Pythia 8 for parton showering

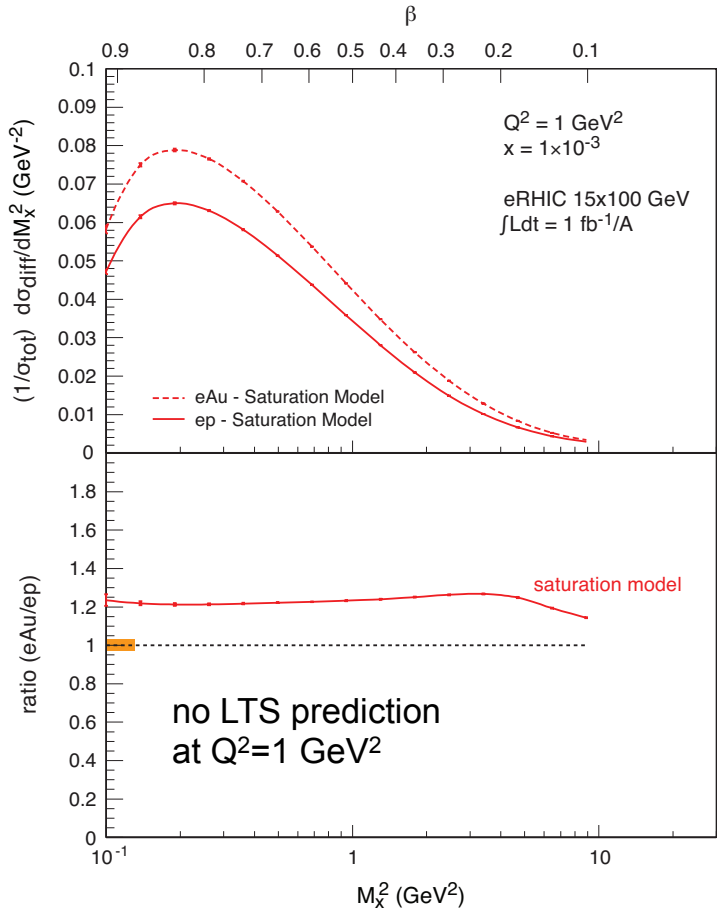


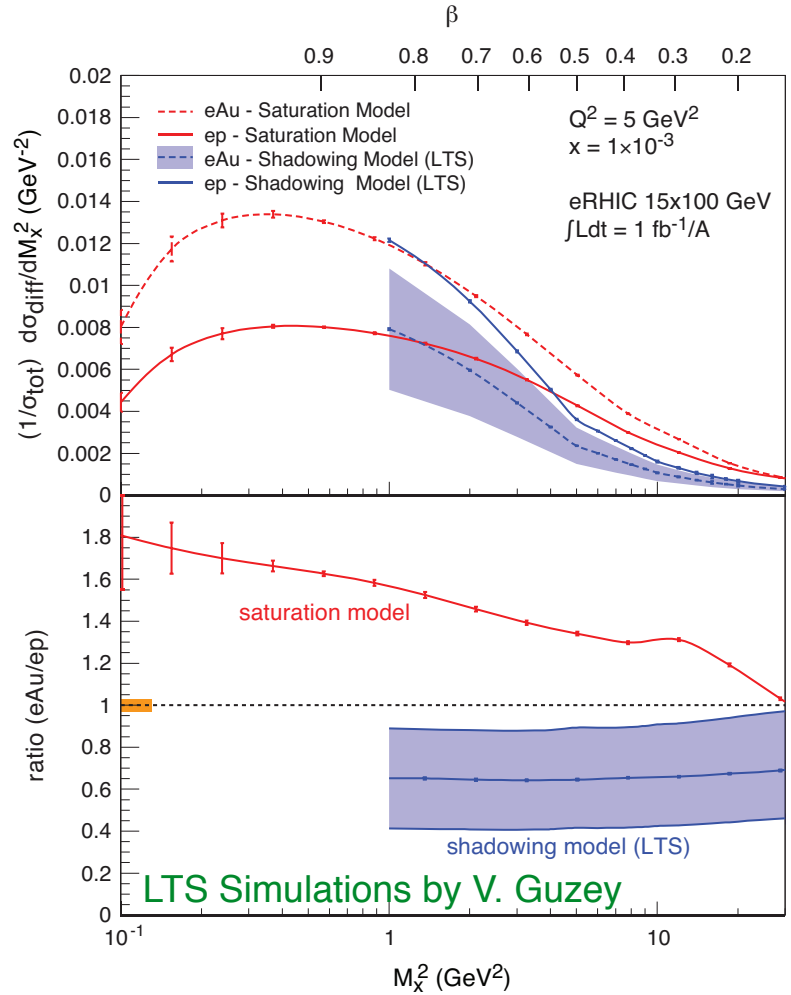


$q\bar{q}, q\bar{q}g, \ldots$

Simulations show little dependence on W (as observed at HERA)

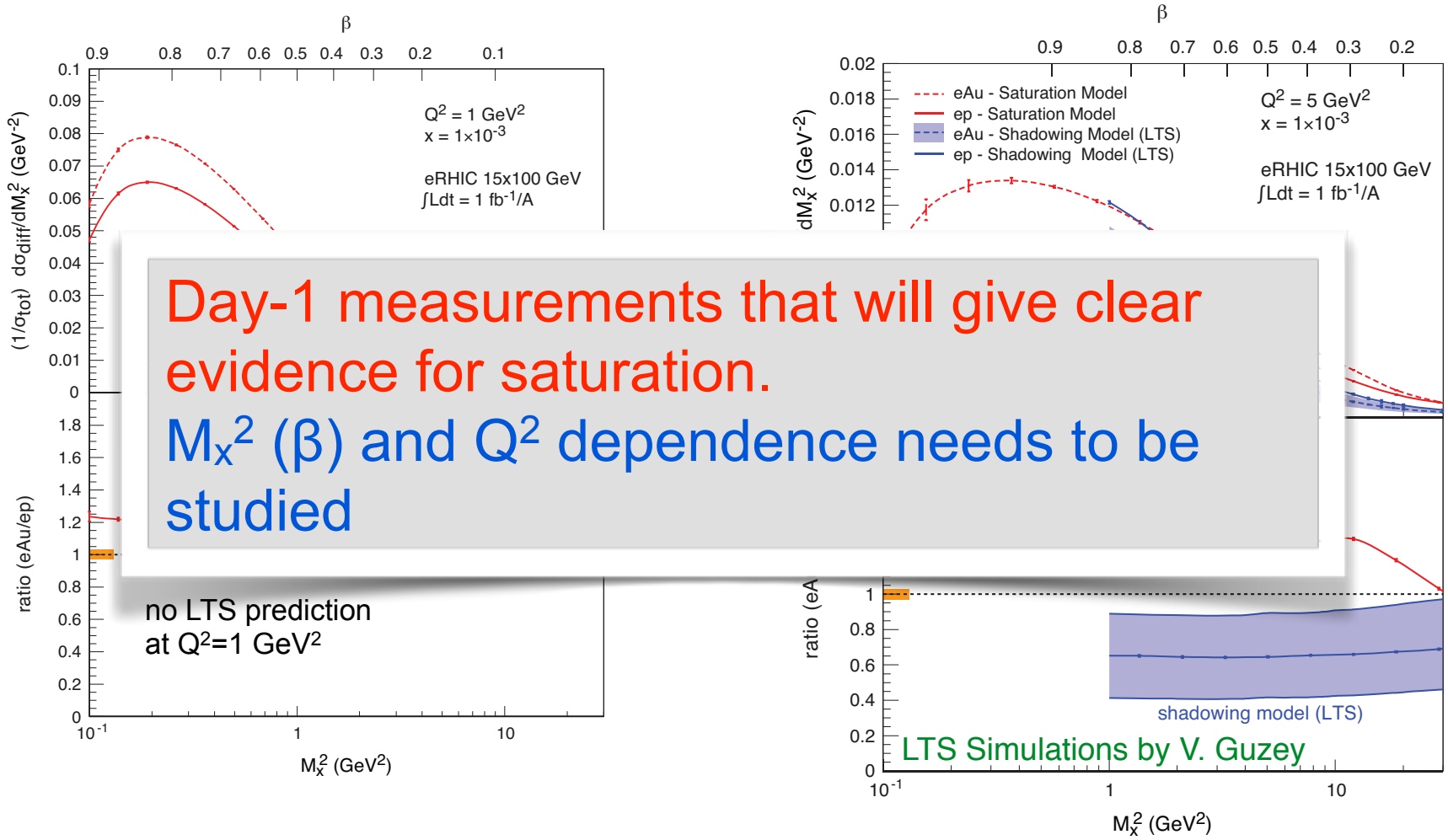
Sartre 2: Diffractive over Total Cross-Section





Saturation model calculations (Sartre event generator & analytic calculations by T. Lappi) now include $\bar{q}qg$ that affect the ratio at low β. Sat-simulations describe HERA results in ep.

Sartre 2: Diffractive over Total Cross-Section



Day-1 measurements that will give clear evidence for saturation.

M_X^2 (β) and Q^2 dependence needs to be studied

Saturation model calculations (Sartre event generator & analytic calculations by T. Lappi) now include $\bar{q}qg$ that affect the ratio at low β. Sat-simulations describe HERA results in ep.

Take Away Message

The diffractive physics e+A program at an EIC is unprecedented, allowing the study of matter in a new emergent regime.

- We developed a generator for diffractive events
  - in e+A and e+p
  - for saturation and non-saturation
  - exclusive vector mesons in Sartre 1
  - inclusive diffractive events in Sartre 2 (in progress)
- It helped us to simulate key measurements at an EIC
  - Indispensable for optimization of detector and IR design
- More work to do on DIS generators for e+A