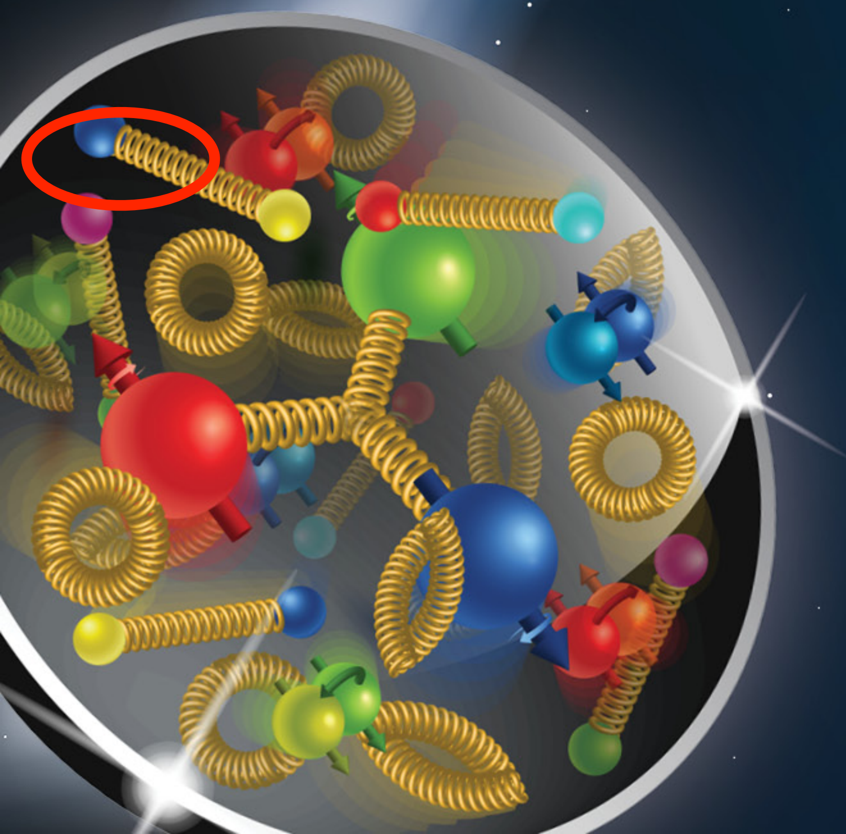
Sartre

A Generator for Diffractive Physics in ep and eA



Thomas Ullrich (BNL/Yale)

MC Event Generator for Future ep and eA Facilities

Regensburg, March 23, 2018

BROOKHAVEN NATIONAL LABORATORY

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Sartre

A Generator for Diffractive Physics in ep and eA

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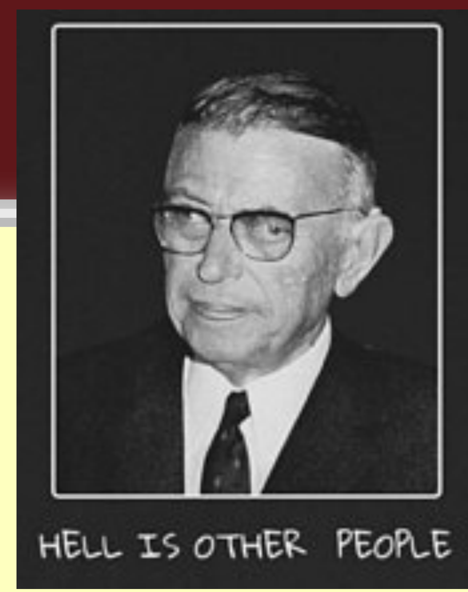
Satre



…re ep and eA Facilities

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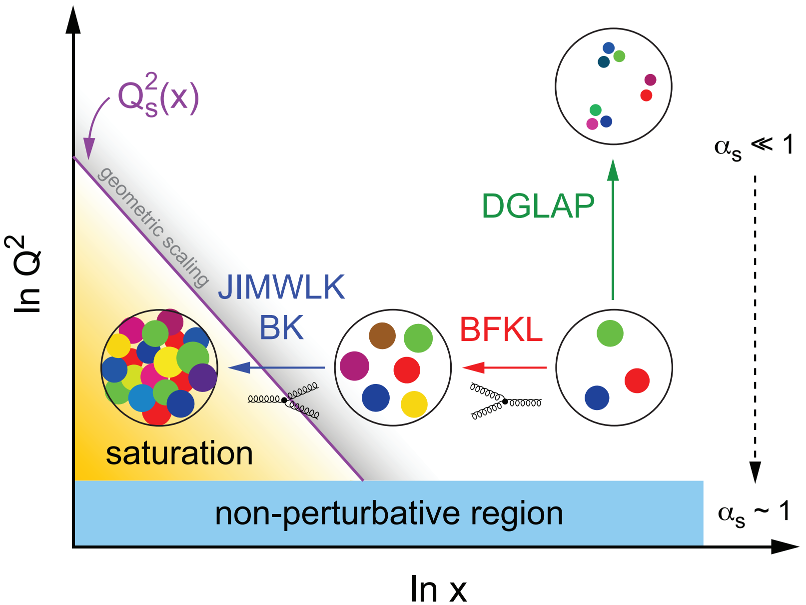
Motivation

Early efforts in the US to realize an Electron-Ion Collider

- 2010: 8 week INT workshop “Gluons and the quark sea at high energies” first comprehensive effort to make the physics case and set priorities.

Key Topic: 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?

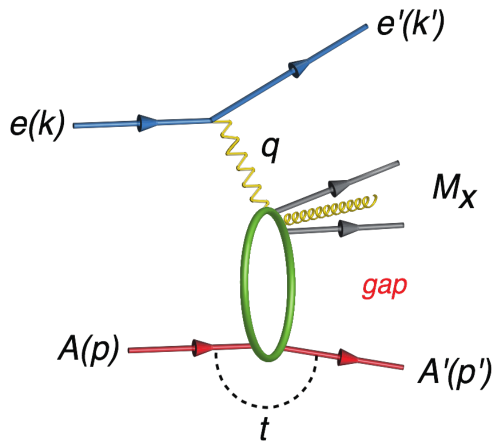


Qs in Nuclei: $(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x} \right)^{1/3}$

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

Key Measurements - Diffraction

Diffraction is the most precise probe of non-linear dynamics in QCD



Close relative of DIS:

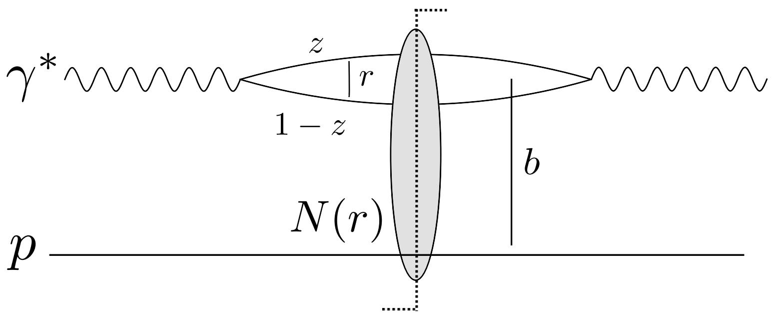
t : momentum transfer squared
M_X : mass of diffractive final-state
characterized by large **rapidity gap**
mediated by *color neutral exchange* (e.g. 2 gluons)

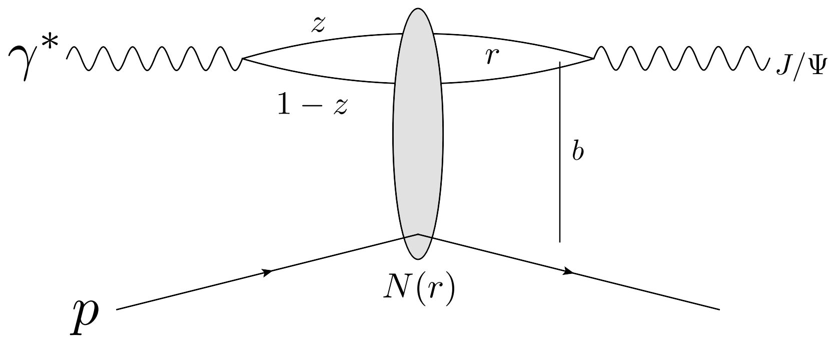
- Came into limelight with discovery at HERA: diffractive events (~15% of total DIS rate)
- Diffraction is very sensitive to (small-x) gluons
- High sensitivity to gluon density:
  - e.g. $\gamma^* H \rightarrow VH$: $d\sigma/dt|_{t=0} \sim [g(x,Q^2)]^2$
- Only known process where spatial gluon distributions can be extracted since *t* = Fourier conjugate to b_T

Diffractive Event Generators ?

- **Requirements:**
  - Must implement saturation and non-saturation picture
    - Comparison
    - Sensitivity to new physics
  - Systems
    - ep (cross-checks with existing data)
    - eA (broad range of nuclei)
  - Final State:
    - Highest priority: Exclusive vector meson production
    - Inclusive diffraction
- **Available Generators:**
  - Plethora of e+p generators from HERA times
    - not all with complete diffractive event generation mechanism
  - Little to nothing for eA, especially nothing on sat/no-sat

Sartre's Model: the Dipole Picture





Optical theorem:
$\sigma^{\gamma^* p} \sim$ dipole amplitude

$\sigma^{\gamma^* p \to Vp} \sim |\text{dipole amplitude}|^2$

Universal dipole amplitude:

- QCD dynamics is included in the dipole amplitude N, needed for DIS
- Diffraction
- Particle spectra in pp/pA ...

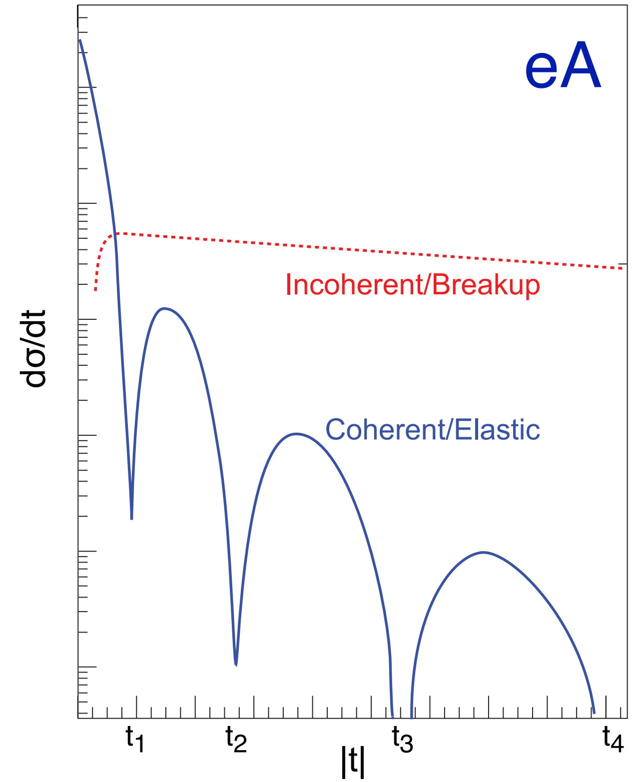
Many dipole models on market:

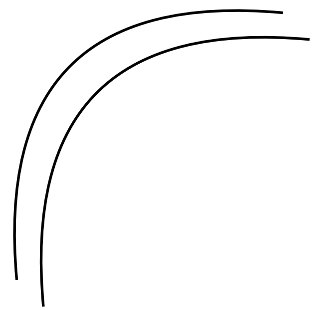
- GBW, VCGC, FS, BGBP, CGC, b-CGC, bSat (IPSat), …
- Non-perturbative input from fit to HERA F_2 data

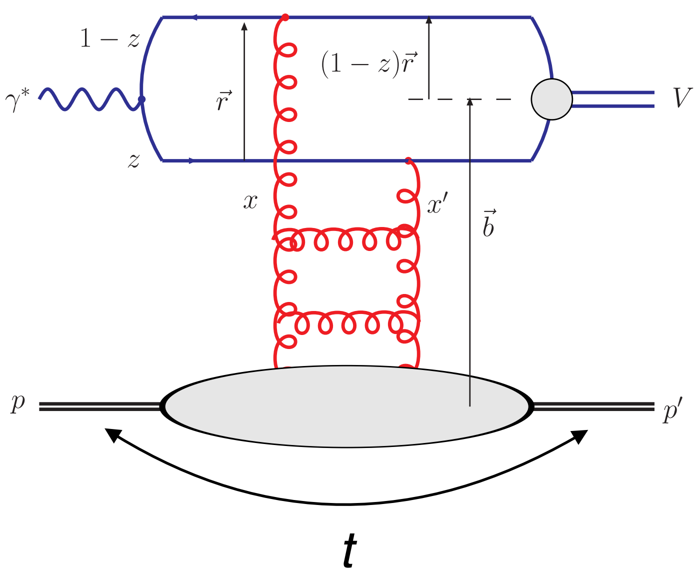
Sartre's Origin: Kowalski, Motyka, Watt

Complete Description:

- bSat (a.k.a IPSat) & CGC model
  - Parameters from fit to "old" Hera F_2
- ep and extension to eA
  - Added b_T dependence
- Many details worked out







- H. Kowalski, L. Motyka and G. Watt: Exclusive diffractive processes at HERA , arXiv:hep-ph/0606272
- H. Kowalski, L. Motyka and G. Watt: Impact parameter dependent colour glass condensate dipole mode, arXiv:0712.2670

Sartre

Event Generator

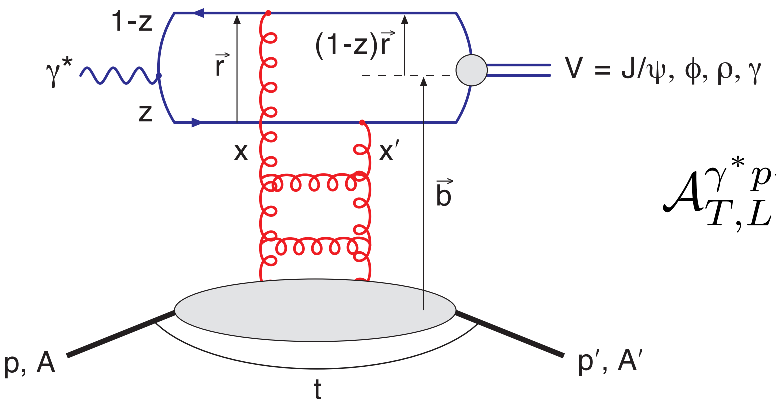
- Hosted at Hepforge: //sartre.hepforge.org (svn repository)
- Published: Phys. Rev. C87, 02491 (2013), Comput. Phys. Commun. 185 (2014) 1835-1853
- Developer: Tobias Toll, TU
- Input from: M. Baker, T. Lappi, H. Mantysaari, P. Zurita
- C++ class library (similar to Pythia8)
- External library: ROOT (4-vectors & TMath), GSL, UNU.RAN
- Packages included: Cuba (integration), Gemini++
- Currently only exclusive VM production

Issues addressed beyond KMW

- Coherence (averaging over configurations)
  - Required generation of tables and lots of CPU power to generate them
- Nuclear breakup in incoherent diffraction (eA)

Sartre: Approach

Use Dipole Model: bSat (bNonSat) $\Delta = \sqrt{-t}$



Amplitude in *ep*:

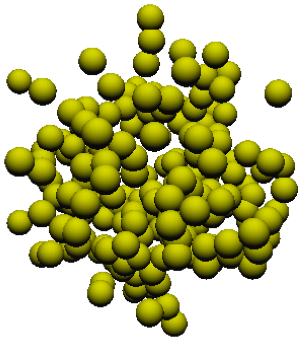
$$\mathcal{A}_{T,L}^{\gamma^* p \to V p}(x, Q, \Delta) = i \int \mathrm{d}r \int \frac{\mathrm{d}z}{4\pi} \int \mathrm{d}^2\mathbf{b} \left(\Psi_V^* \Psi\right)(r, z)$$

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

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

- Add photon flux → p.d.f.: $\dfrac{d^3\sigma}{dt\ dQ^2\ dW^2}$
- Sample p.d.f. → t, W, Q^2
- Final state generation → 4-Momenta of e', p', V, γ*

Sartre: eA adds complexity

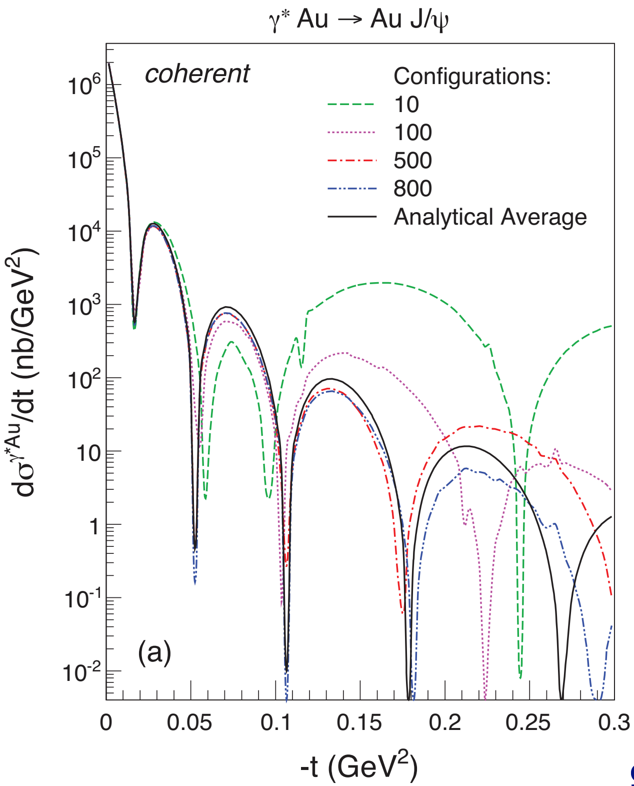


Nucleus:

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

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

- Analytic average not exact
- Need ~ 800 configuration, more at large *t*
- Use Wood-Saxon as source distribution



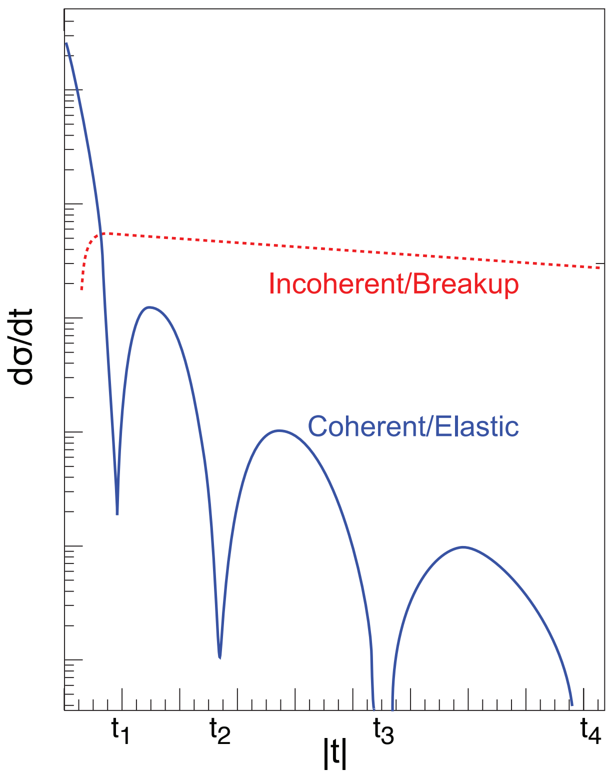
eA Incoherence - Interesting in its Own Right

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

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

Incoherent CS is variance of amplitude
⇒ measure of fluctuating source density

Coherent CS reflects the average source density



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

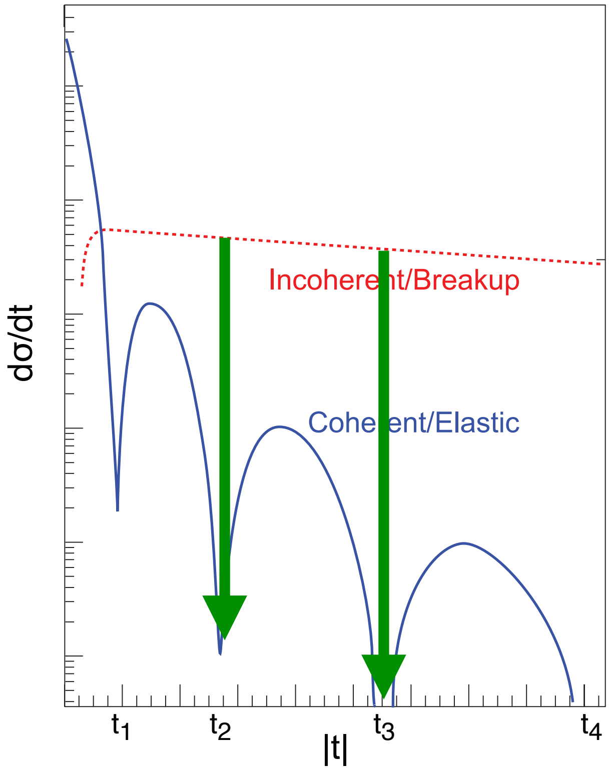
Sartre: Need for Amplitude Tables

- 800 configurations with 3D Integrals for longitudinal and transverse polarized photons and for coherent-total $\langle |A_L|^2 \rangle$, $\langle |A_T|^2 \rangle$, $|\langle A_L \rangle|^2$, $|\langle A_T \rangle|^2$
- CPU time for each sample prohibitive for all practical purposes
- Solution: Store amplitudes in 3D tables $A(Q^2, W, t)$
- Problems
  - Bridge kinematic range JLEIC → eRHIC → LHeC
  - Need to keep granularity
  - sat ⊗ no sat ⊗ 4 final states ⊗ ep and eA with different A
  - First round ~100k CPU core-hours (ep, eAu, eCa)
  - Next round with larger finer tables: ~1.5M CPU core-hours
- Optimization: flexible (grid-less) 3D table challenging (hardly any open code, Hollywood knows how but $$$$)
  - One issue: metric for closest neighbor (t, Q^2, W)

Incoherent Diffraction: Nuclear Breakup

Vital for experimental studies:

- distinguish incoherent from coherent
- ep: forward p detectors (HERA)
  - hadron dissociation mass follows $dN/dM_Y^2 \sim 1/M_Y^2$
- eA: more complex
  - lower t: nucleus breaks up into its constituents nucleons
  - larger t: nucleon breakup triggers nuclear breakup



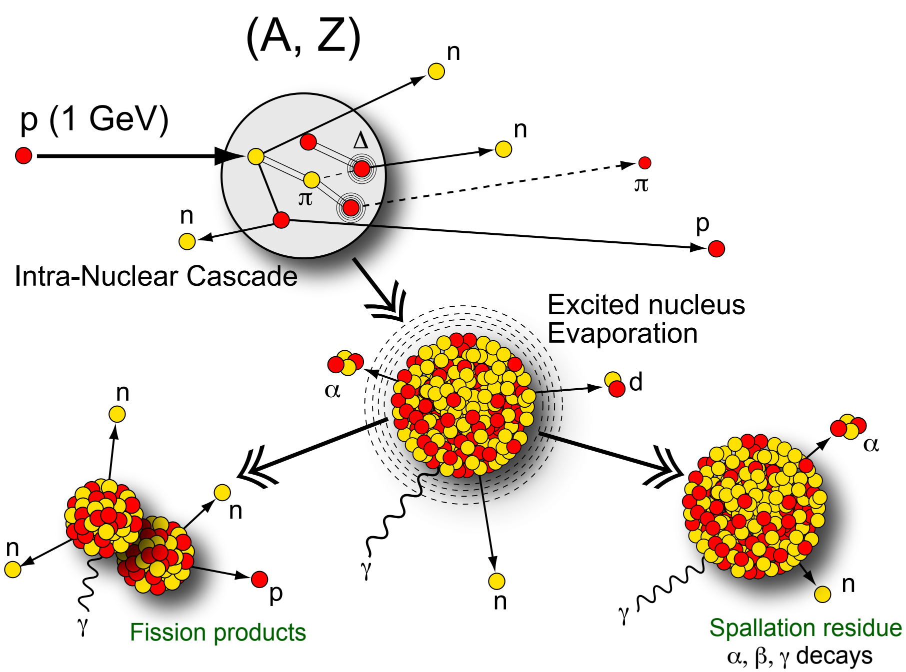
- eA: little is known about details of breakup and little theoretical guidance
- Experimental requirements
  - Required rejection factor: > 100
  - Required veto efficiency > 99%

Nuclear Breakup in Sartre

Need to detect breakup products through forward detectors (ZDC, Roman Pots, …) ⇒ need kinematics of breakup products

Proper treatment:

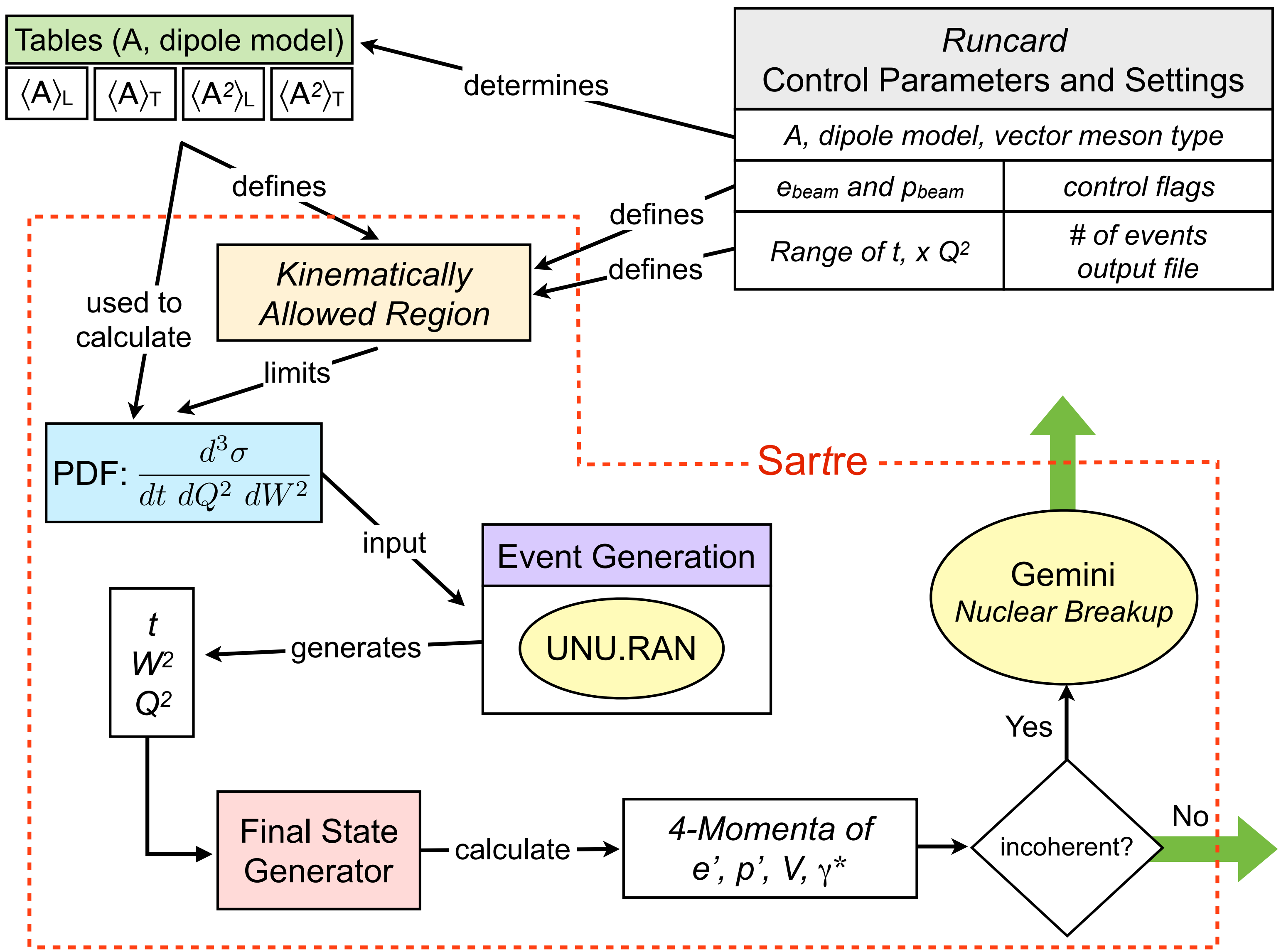
- Intra-Nuclear Cascade
  - studied in pA
  - Particle production
  - Remnant Nucleus (A, Z, E*, ...)
- De-Excitation
  - Evaporation
  - Fission
  - Residual Nuclei



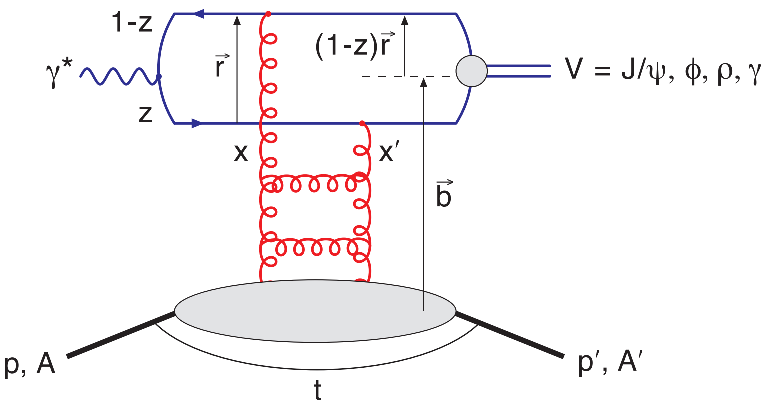
- Sartre (right now): skip INC, use evaporation MC Gemini++ (R. Charity). Derive excitation energy E* from M_Y => not complete.
  - Future: input from BEAGLE (see M. Baker's talk)

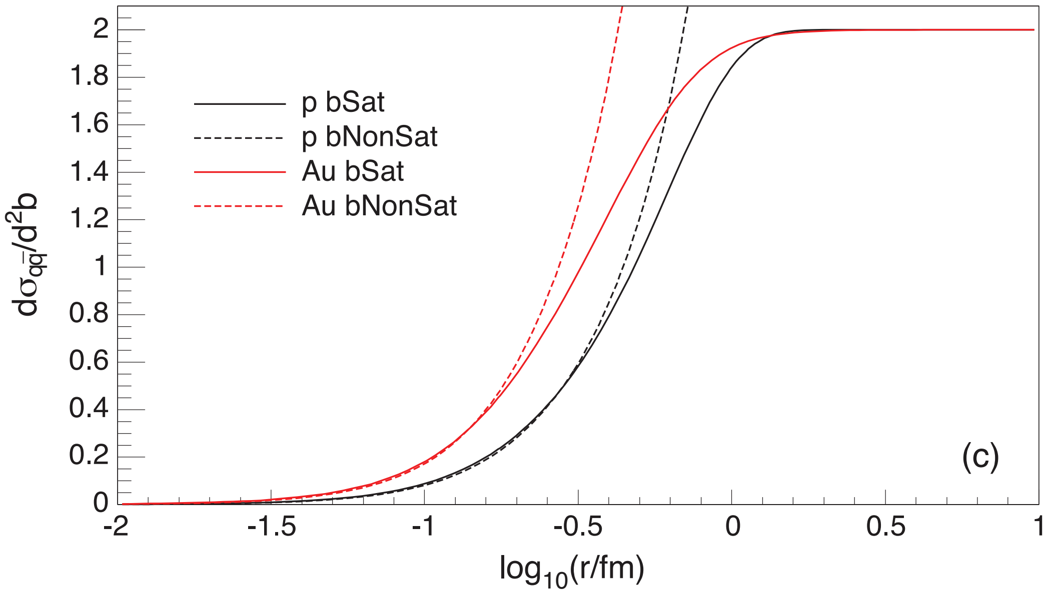
Sartre Workflow

Two parts: Table generator (experts), <u>Event generator</u>



Sartre: Vector Meson Production





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

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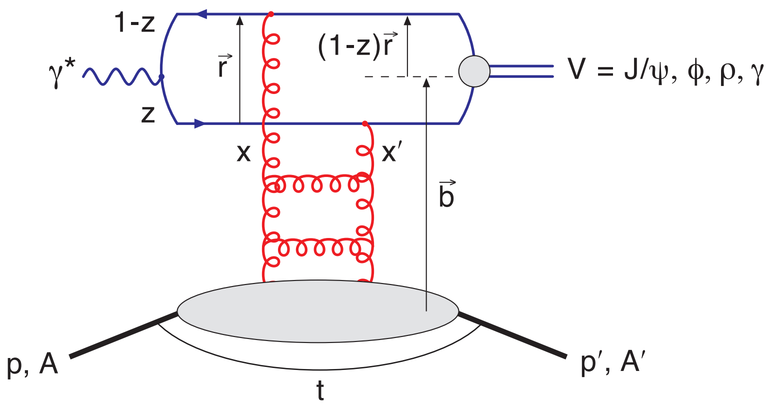
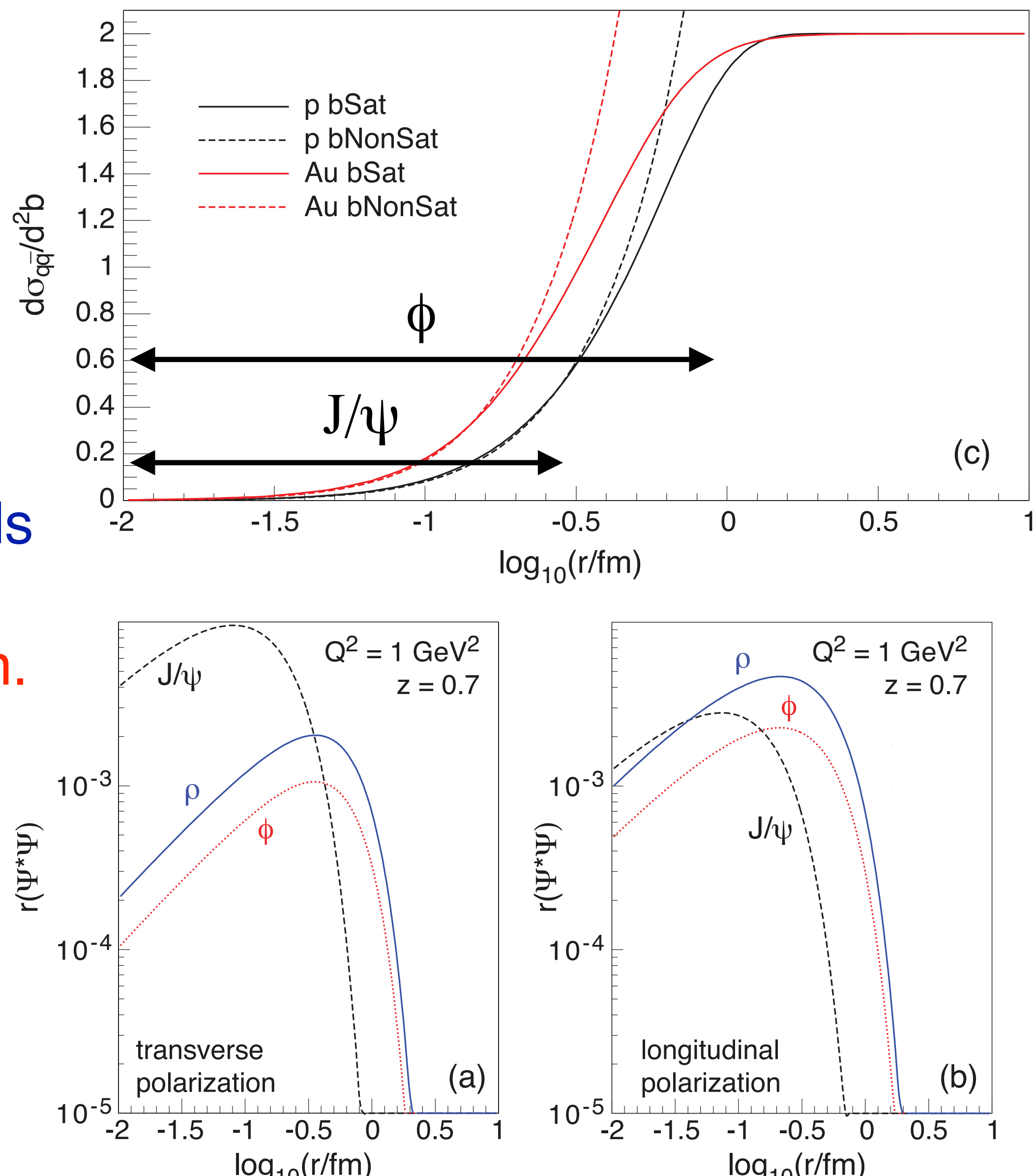


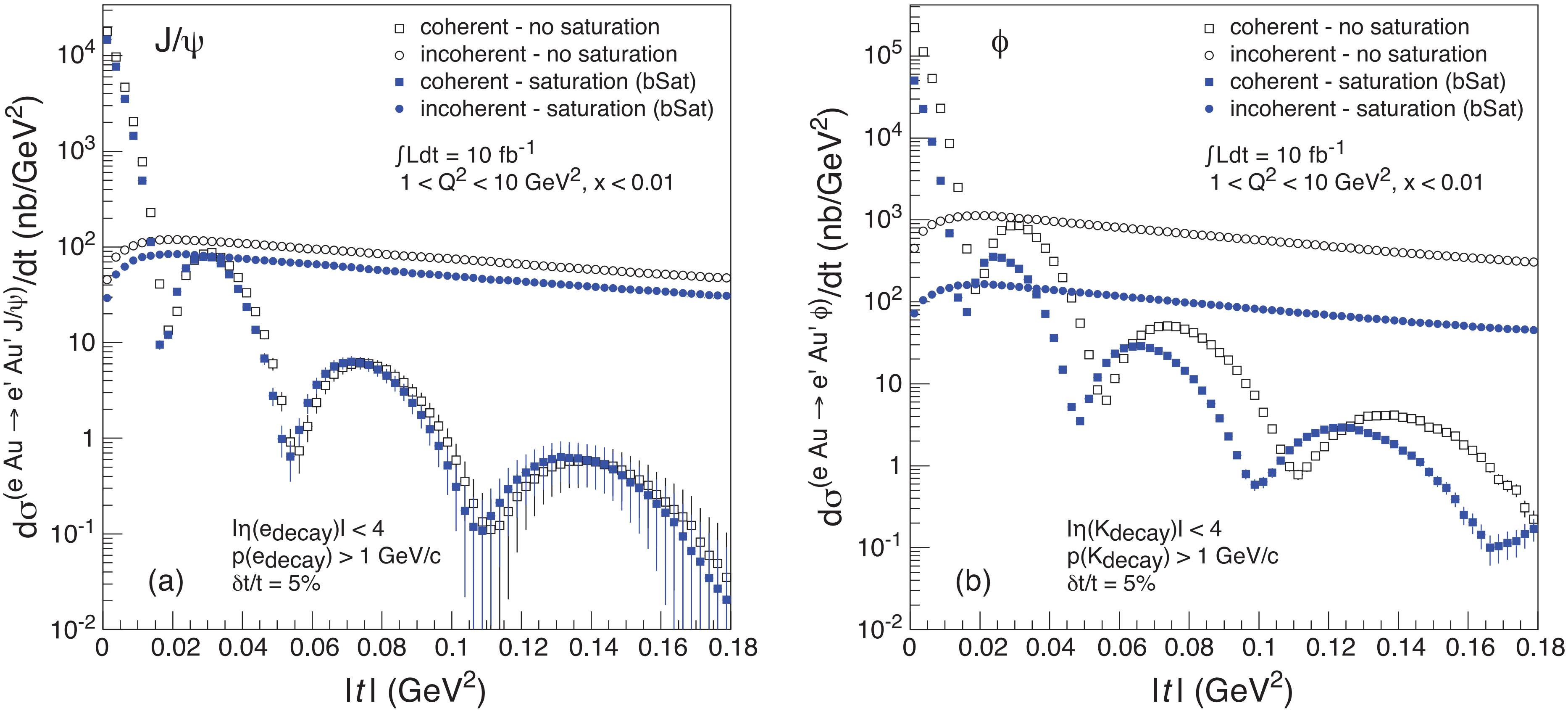


Wave overlap function Ψ*Ψ falls steeply for large dipole radii

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

$$\mathcal{A}_{T,L}^{\gamma^* p\to Vp}(x,Q,\Delta) = i\int \mathrm{d}r \int \frac{\mathrm{d}z}{4\pi}\int \mathrm{d}^2\mathbf{b}\,(\Psi_V^*\Psi)\,(r,z)$$
$$\times 2\pi r J_0([1-z]r\Delta)e^{-i\mathbf{b}\cdot\Delta}\frac{\mathrm{d}\sigma_{q\bar{q}}^{(p)}}{\mathrm{d}^2\mathbf{b}}(x,r,\mathbf{b})$$

Results: VM Production: dσ/dt

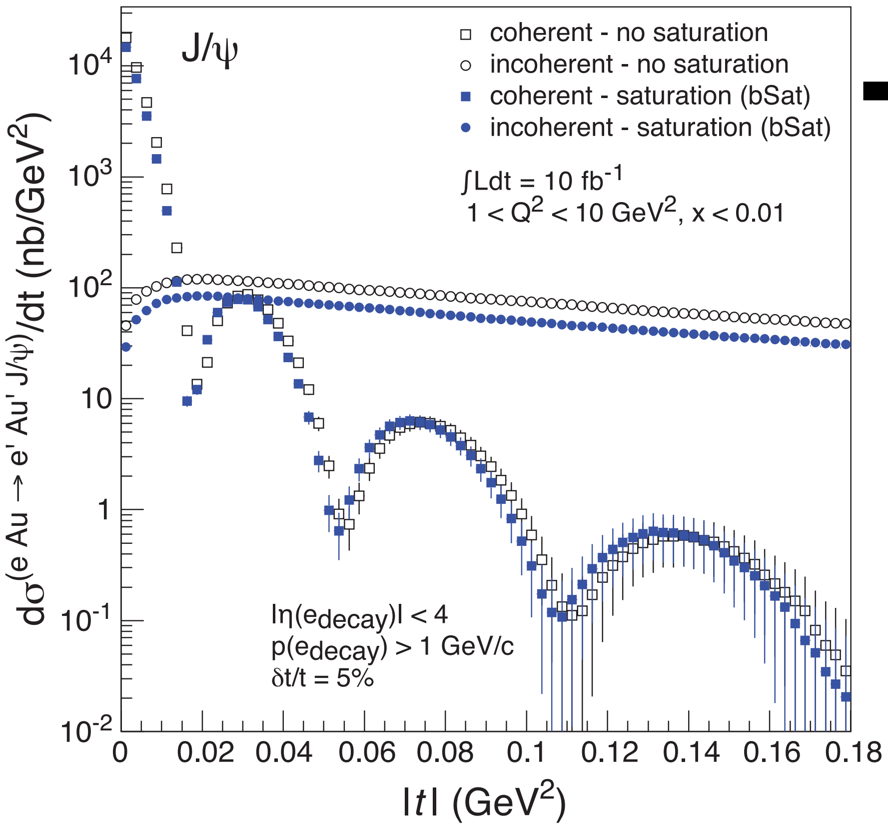


- Find: Typical diffractive pattern for coherent (non-breakup) part
- As expected: J/ψ less sensitive to saturation than ϕ
- Need this sliced in x bins ⇒ luminosity hungry
- Crucial: t resolution and reach

Results: Spatial Gluon Distribution from $d\sigma/dt$

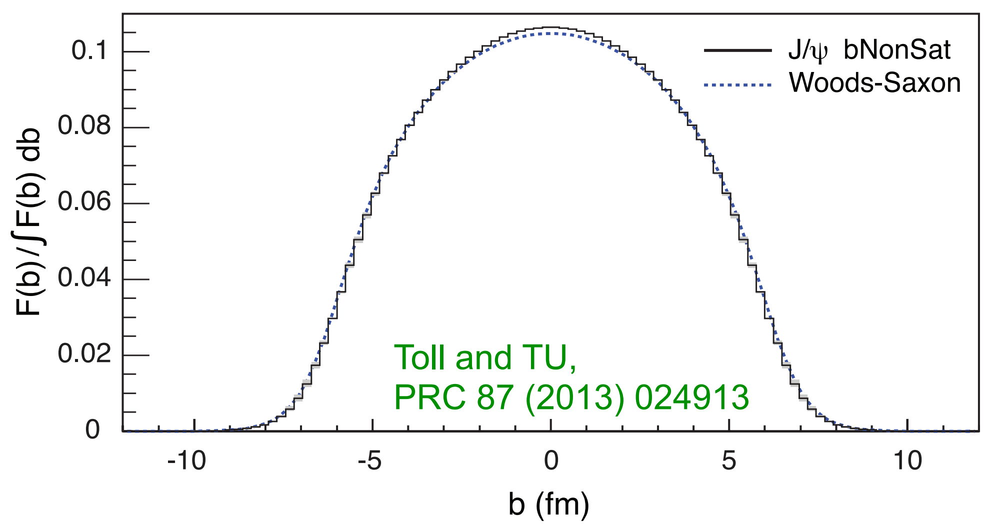
Diffractive vector meson production: $e + Au \rightarrow e' + Au' + J/\psi$

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



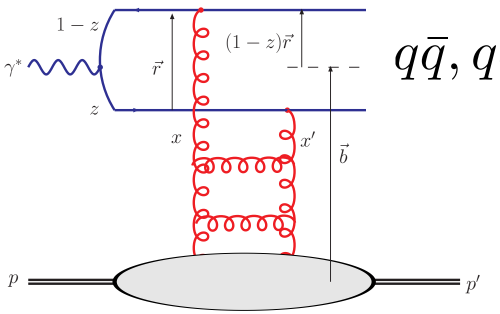
$$F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

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



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

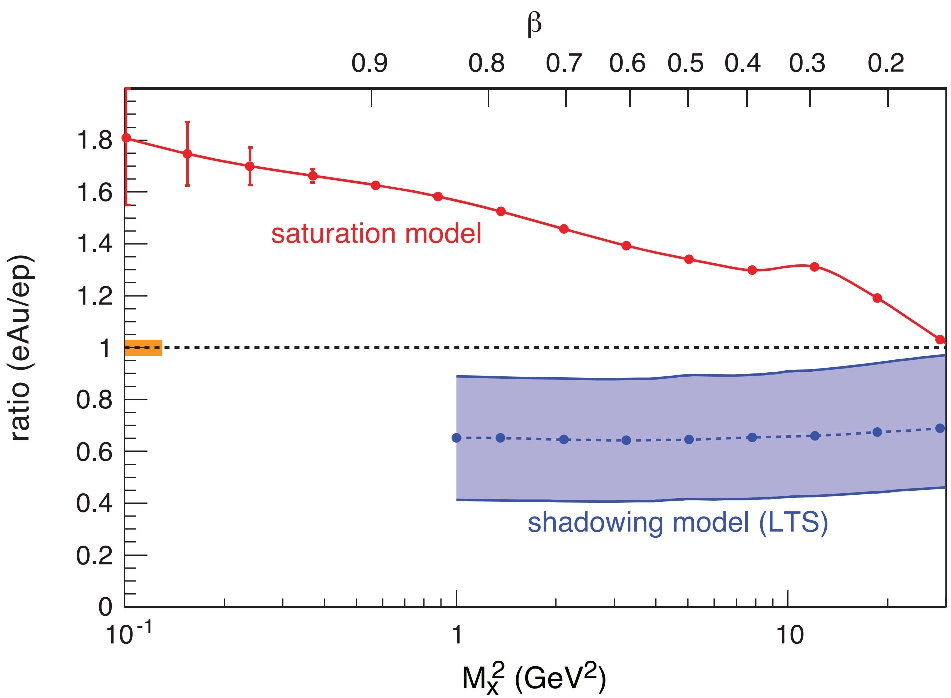
Work in Progress: Inclusive Diffraction



Work in progress:

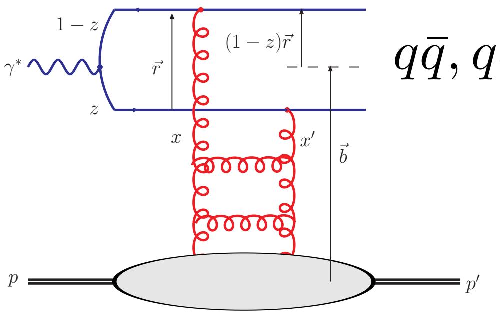
- Dipole model: $q\bar{q}, q\bar{q}g, \ldots$
- States handed over to Pythia 8 for parton showering

Example: $\sigma_{\text{diffractive}}/\sigma_{\text{total}}$



- Saturation models (CGC) predict up to $\sigma_{\text{diff}}/\sigma_{\text{tot}}$ ~ 25% in eA
- Ratio *enhanced* for small M_X and *suppressed* for large M_X
- Standard QCD predicts no M_X dependence and a moderate suppression due to shadowing.

Work in Progress: Inclusive Diffraction



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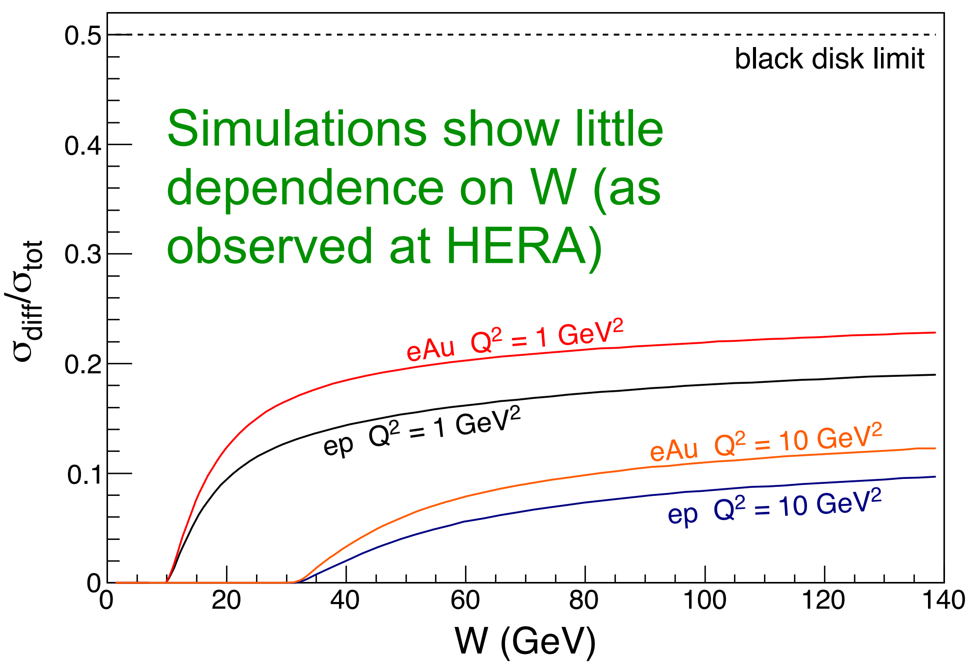

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Take Away Message

- Sartre an event generator for diffractive events
  - in e+A and e+p
  - for saturation and non-saturation
- Vital to simulate eA key measurements at an EIC
- Work in progress (weeks/few month)
  - New set of IPSat and IPNonSat parameters from fits to combined HERA F_2 data: H. Mantysaari, P. Zurita
  - Improve nuclear breakup model: M. Baker
  - New complete set of amplitude tables
- Longer term (hopefully all this year)
  - Complete extension to inclusive diffractive events
  - Add physics of UPC collisions (AA)
- Very long term
  - NLO Dipole Models (see POETIC talks from Henri Hänninen, Guillaume Beuf)
  - IPSat $\rightarrow$ BK (problem is b dependence)