RD 2012-5 Physics Simulations: Progress report

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EIC Generic R&D Advisory Committee Meeting
December 13, 2012

BROOKHAVEN
NATIONAL LABORATORY

RD 2012-5: the first 7 month

- January 23, 2012: provided revised prioritized plan in *1st Quarter EIC R&D Report* as requested by Committee
- May 2/3, 2012: official start of RD 2012-5 (Tobias Toll paid out of R&D funds)
- May - August: heavy use of new generator Sar*t*re for EIC White Paper.
  - large fraction of studies for eA section make use of new set of generators (Sartre & eA-Hybrid)
- November 13, 2012: first paper on physics that went into Sar*t*re submitted to PRC (also arXiv:1211.3048)
- December 7, 2012: White Paper posted on archive (arXiv: 1212.1701)
- November - December: Sar*t*re documentation finalized, latest nuclear breakup code included, Cascade further evaluated

eA Event Generator for EIC

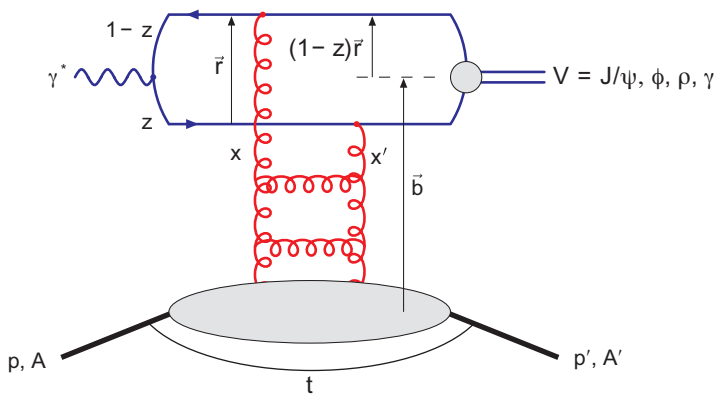
- Requirements
  - Generator has to reproduce existing *ep* (Hera) data
  - Encapsulate saturated ***and*** non-saturated models
    - difference ⇒ physics case
  - Reused generators must be:
    - freely available, well documented, supported

	DIS		Diffractive	
	saturated	non-saturated	saturated	non-saturated
exclusive	✗	✓	VM & DVCS ✓	VM & DVCS ✓
	✗	✓		
inclusive	✗	✓	✗	✗
	✗	✓		

Diffractive ep/eA Physics: Sar*t*re

- Highest priority because:
  - Diffractive events are most sensitive to saturation
    - $\sigma \sim G(x,Q^2)^2$
  - Only known way to learn about spatial distribution of glue
- Event generator Sar*t*re
  - exclusive diffractive vector meson production and DVCS
    - only way to measure $\boldsymbol{t} = (p_A - p'_A)^2$ at an EIC
  - based on dipole model
    - saturation: bSat
    - non-saturated: bNonSat
  - includes nuclear breakup (Gemini++) for incoherent events
  - ep, eA (O, Al, Ca, Cu, Cd, Au, and Pb)
  - authors: TU & Tobias Toll
  - status: (almost) ready for distribution

Sartre: Physics



Total (coherent+incoherent) cross-section:

$$\frac{\mathrm{d}^3\sigma_{\mathrm{total}}}{\mathrm{d}Q^2\mathrm{d}W^2\mathrm{d}t} = \sum_{T,L} \frac{R_g^2(1+\beta^2)}{16\pi} \frac{\mathrm{d}n^{\gamma}_{T,L}}{\mathrm{d}Q^2\mathrm{d}W^2} \left\langle |\mathcal{A}_{T,L}|^2 \right\rangle_{\Omega}$$

Coherent cross-section:

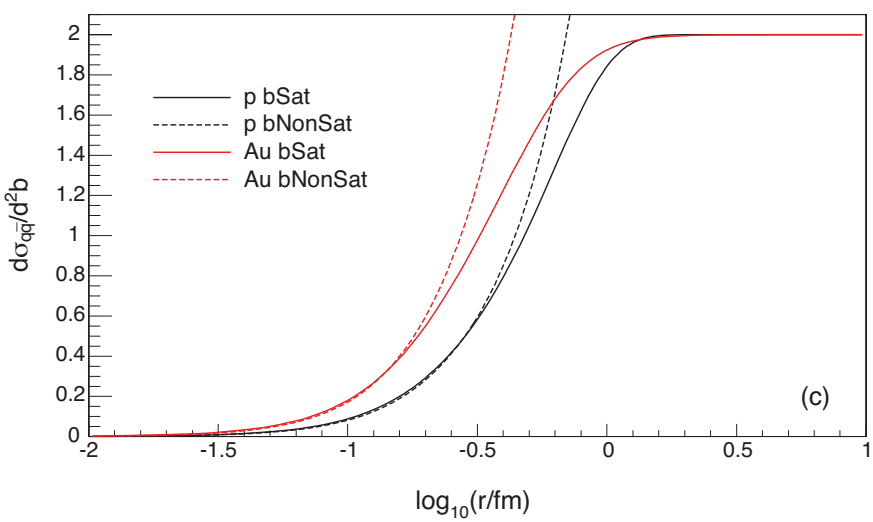
$$\frac{\mathrm{d}^3\sigma_{\mathrm{coherent}}}{\mathrm{d}Q^2\mathrm{d}W^2\mathrm{d}t} = \sum_{T,L} \frac{R_g^2(1+\beta^2)}{16\pi} \frac{\mathrm{d}n^{\gamma}_{T,L}}{\mathrm{d}Q^2\mathrm{d}W^2} \left| \langle \mathcal{A}_{T,L} \rangle_{\Omega} \right|^2$$

Amplitude:

$$\mathcal{A}_{T,L}(Q^2,\Delta,x_{I\!P},\Omega_i) = \int r\mathrm{d}r \frac{\mathrm{d}z}{2} \mathrm{d}^2\mathbf{b}\, (\Psi_V^*\Psi)_{T,L}\,(Q^2,r,z)$$

$$\times J_0([1-z]r\Delta) e^{-i\mathbf{b}\cdot\mathbf{\Delta}} \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}}(x_{I\!P},r,\mathbf{b},\Omega_i) \quad (19)$$

Dipole cross-section:



For the second moment of the amplitude, no analytical expression exists. Need to average over many (500-1000) nuclear configuration!

Sar*t*re: Implementation

- Prohibitive:
  - average over ~500 configurations on the fly
  - multiple 6D integration for each
- Technique
  - Create tables for $\langle A_{T,L} \rangle$ and $\langle A_{T,L}^2 \rangle$ and ship with Sar*t*re
    - Sartre on US Grid: 167,932 EIC jobs for 695,536 CPU hours and transferred 3.2TB of data
  - Generator reads tables, calculates cross-section $d^3\sigma/(dQ^2\, dW\, dt)$ and generates for each event Q^2,W, t
  - Q^2,W, t and beam energies fully determine final state
- Code
  - C++ class library, example programs, tables, documentation
  - External packages: Unuran (3D random numbers), Cuba (integration), Gemini (nuclear breakup), ROOT

Sartre: Documentation

Sartre Documentation

Sartre Documentation

file:///Users/ullrich/Physics/xdvmp/sartre/docs/index.html

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Sartre 1.0 Documentation

Getting Started	Sartre Basics	API Reference
• Overview • Downloading & Installing Sartre	• Event Generator Users Guide • Example Program • Event Record • Table Generator Documentation (experts only)	• Reference Guide • Runcard Reference • Table & Table Tools
The Physics Behind the Model	**What's New?**	**Troubleshooting**
• The Dipole Model • ep and eA Mode • Generation of Final State Particles • Publications • References		• Known problems • To-do list

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Sartre: Documentation

Sartre – Download & Installation

file:///Users/ullrich/Physics/xdvmp/sartre/docs/download_install.html

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Download

Sartre can be downloaded as a compressed tar archieve and has to be built following the instruction below.

- Version 1.0 (sartre-1.00.tgz)

Building Sartre

Supported platforms

Although Sartre is written in ISO C++ and we made sure to adhere to strict standards in our code we can only guarantee that it runs on the two platforms we tested it on, Mac OS and Linux (Red Hat) systems.

Unpacking the downloaded tar ball

```
tar -xzvf sartre-<version>.tgz
```

This will create a directory `sartre-<version>` with several subdirectories containing source code, include files, tables, as well as directories for (provided) external programs such as Cuba and Gemini++ that are required to built Sartre.

Required additional packages

Sartre requires two additional packages to be installed: ROOT and the GNU Scientific Library (GSL). If not already on your system please install them before you continue. Note that ROOT must contain the *Unuran* and *MathMore* components. The binary distributions available on the ROOT web site contain them already. If you install ROOT yourself make sure you select them during configuration. In case you want to generate tables for specific models and nuclei not already contained in the latest Sartre distribution **and** you want to do so in multithreaded mode (see below) you will need the Boost library. For most users this is in general not needed nor recommended.

Sartre is using Cmake for building and installation. If this package is not present please install it before continuing.

Building and installing Sartre

Cmake will lookup the locations of the required libraries. If ROOT and GSL are not installed in standard locations it is recommended to ensure that the following environment variables are defined. This helps cmake to locate the required libraries and include files:

```
# example using bash
export ROOTSYS=/usr/local/root          # must contain lib/ include/ bin/
export GSL_DIR=/usr/local/bin           # must contain gsl-config
# use only when creating tables in multithreaded mode: export Boost_Dir=...
```

Now building and installing Sartre is easy:

```
cd sartre-<version>
```

Reference

leshooting

Last Update: November 30, 2012

Sartre: Documentation

Sartre – Users Guide

file:///Users/ullrich/Physics/xdvmp/sartre/docs/usersGuide.html

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Users Guide

Sartre is a class library that lets you easily assemble a program that fits your needs. Typically your setup will consist of a main program and a runcard, *i.e.*, a text file with instruction read by Sartre, that defines various parameters such as beam energies, what model to use, what vector meson species to generate, the number of events, and much more. Sartre has a built-in mechanism to take care of this. The main class the user has to deal with is Sartre. Necessary subclasses can be obtained via access functions of Sartre. The class EventGeneratorSettings deals with the setup parameters and the complete structure of the generated event is returned in an instance of the Event class. Sartre has no predefined output format. The provided example program `sartreMain.cpp` contains an example on how to store the generated events in a ROOT file for later processing.

The big picture

Most programs have a similar structure:

1. Create an instance of Sartre
2. Pass setup parameters to the created object
3. Initialize
4. Loop and generate events

Typically you only need one instance of Sartre that you can initialize multiple times if needed. There are two ways of passing the setup parameters to Sartre: (i) using a runcard or (ii) programatically. The advantage of a runcard is that you can change the setup without re-compiling the program; it als makes batch processing easier. Here's the example with a runcard:

```
#include "Sartre.h"

int main() {
    Sartre sartre;
    bool ok = sartre.init("myRuncard.txt");

    // generate events if ok == true
    // ....

    return 0;
}
```

For details on runcard syntax and available commands see the runcard reference. To setup the run programatically you need to define every parameter through an instance of EventGeneratorSettings that can be obtained from the instance of Sartre as shown here:

```
#include "Sartre.h"
#include "EventGeneratorSettings.h"

int main() {
    Sartre sartre;

    EventGeneratorSettings* settings = sartre.runSettings();
```

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Sartre: Documentation

Sartre – Users Guide

file:///Users/ullrich/Physics/xdvmp/sartre/docs/usersGuide.html

Sartre – Reference Guide

file:///Users/ullrich/Physics/xdvmp/sartre/docs/referenceGuide.html

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Reference Guide

Constants	Enumerations	Classes
• electronMass • electronMass2 • protonMass • protonMass2 • alpha_em • hbarc • hbarc2	• DipoleModelType • GammaPolarization • AmplitudeMoment • DiffractiveMode	• BreakupProduct • Event • FrangibleNucleus • EventGeneratorSettings • Nucleus • Particle • Sartre • Settings

Note that only a fraction of the classes in Sartre is documented here. For the first release we only included the most relevant classes.

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```
Sartre sartre;

EventGeneratorSettings* settings = sartre.runSettings();
```

Sartre: Documentation

Sartre – Nucleus Class Reference

file:///Users/ullrich/Physics/xdvmp/sartre/docs/refNucleus.html

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Nucleus Class Reference

Virtual base class that describes the nucleus used in eA collisions. More...

```
#include "Nucleus.h"
```

Inheritance

Inherited by GeneratorNucleus.

Public Member Functions

	Nucleus()
	Nucleus(unsigned int A)
	Nucleus(const Nucleus&)
virtual	~Nucleus()
Nucleus&	operator=(const Nucleus&)
virtual void	init(unsigned int A)
double	T(double b) const
double	TofProton(double b)
unsigned int	A() const
unsigned int	Z() const
float	spin() const
double	radius() const
string	name() const
int	pdgID() const
int	pdgID(int Z, int A) const
double	atomicMass() const
void	normalizationOfT()

Detailed Description

The Nucleus class contains the necessary information about the nucleus (name, radius, spin, mass, ...) as well as the referring Woods-Saxon distribution to describe its density as a function of impact parameter. This class is used in the generation of amplitude tables as-is (see here for details), while a derived class GeneratorNucleus is used for event generation in class Sartre. The user does not have to care about the class or its initialization since it is handled internally in Sartre. However, it is always available through a call of Sartre::nucleus().

At the moment this class is able to describe the following nuclei: H (p), O, Al, Ca, Cu, Cd, Au, and Pb.

Classes

- BreakupProduct
- Event
- FrangibleNucleus
- EventGeneratorSettings
- Nucleus
- Particle
- Sartre
- Settings

the most relevant classes.

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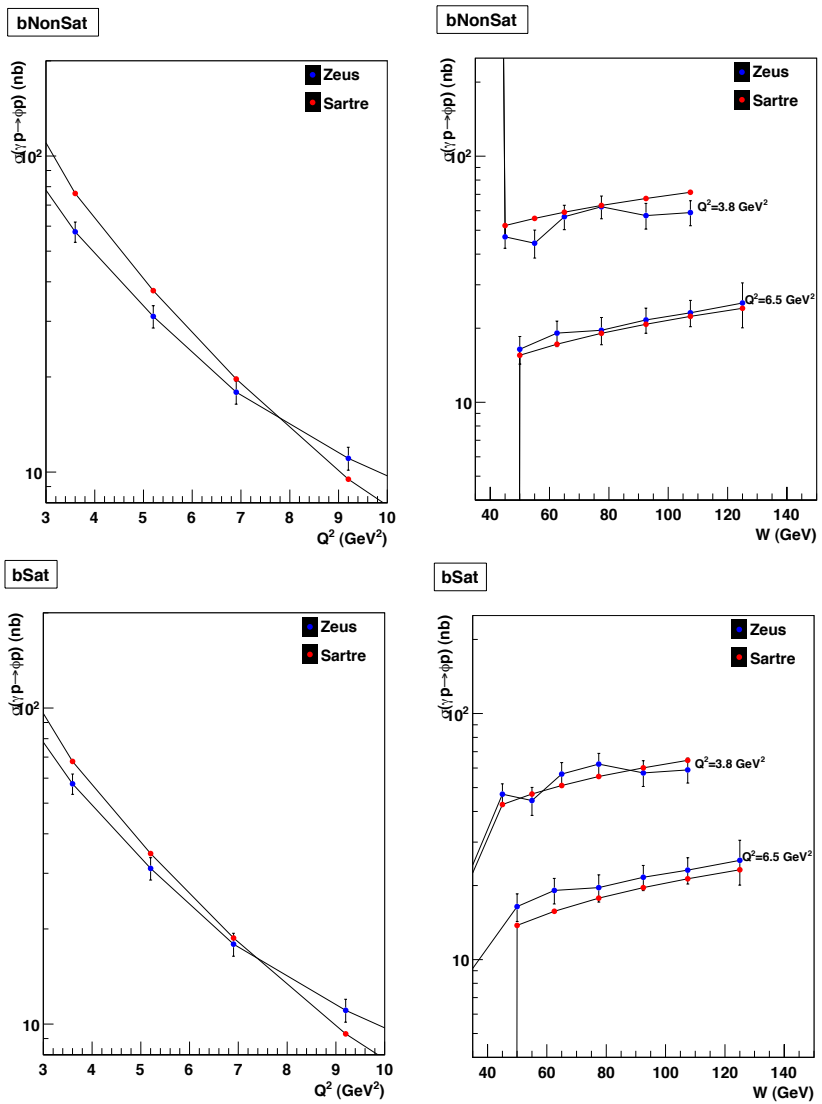
Sartre: HERA Comparison

Example: e p → e′ p′ ϕ

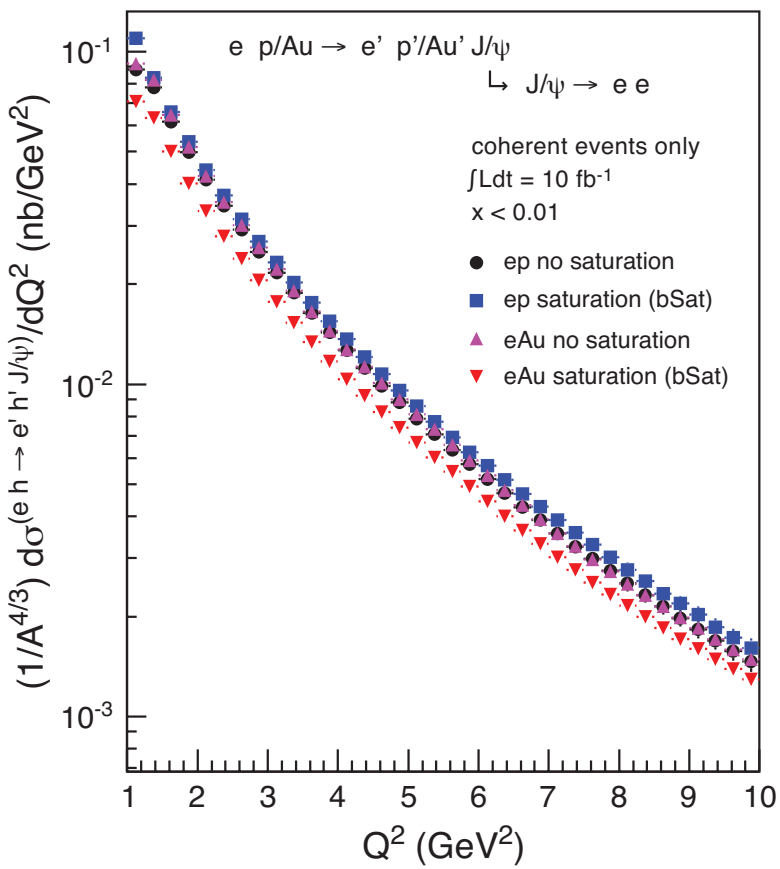


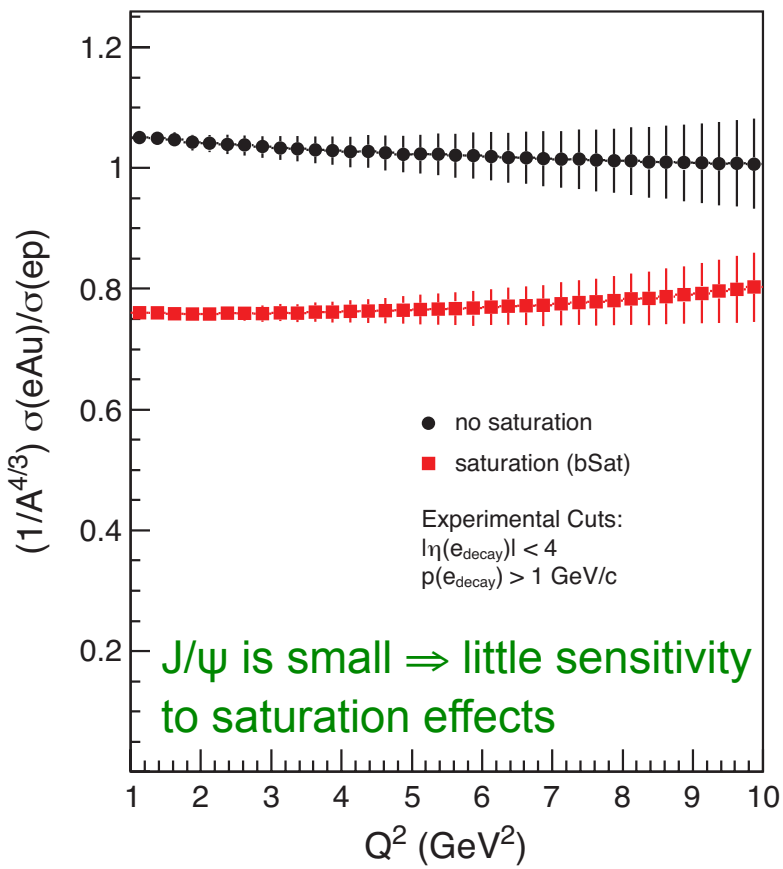
- Describes HERA data on ρ, ϕ, J/ψ, and γ (DVCS) well for saturated and non-saturated case
- Not surprising since models (and parameters) were tuned to describe HERA (KMW, Phys. Rev. D74)
- New parameters in the works from efforts at BNL (R. Venugopalan et al.)
- ep: No distinguishing power between bSat and bNonSat

Sar*t*re: Results I (White Paper)

Extensive simulations for White Paper Electron Ion Collider: *The Next QCD Frontier - Understanding the glue that binds us all* (arXiv:1212.1701)

Example: Q^2 dependence of ϕ and J/ψ production:





J/ψ is small ⇒ little sensitivity to saturation effects

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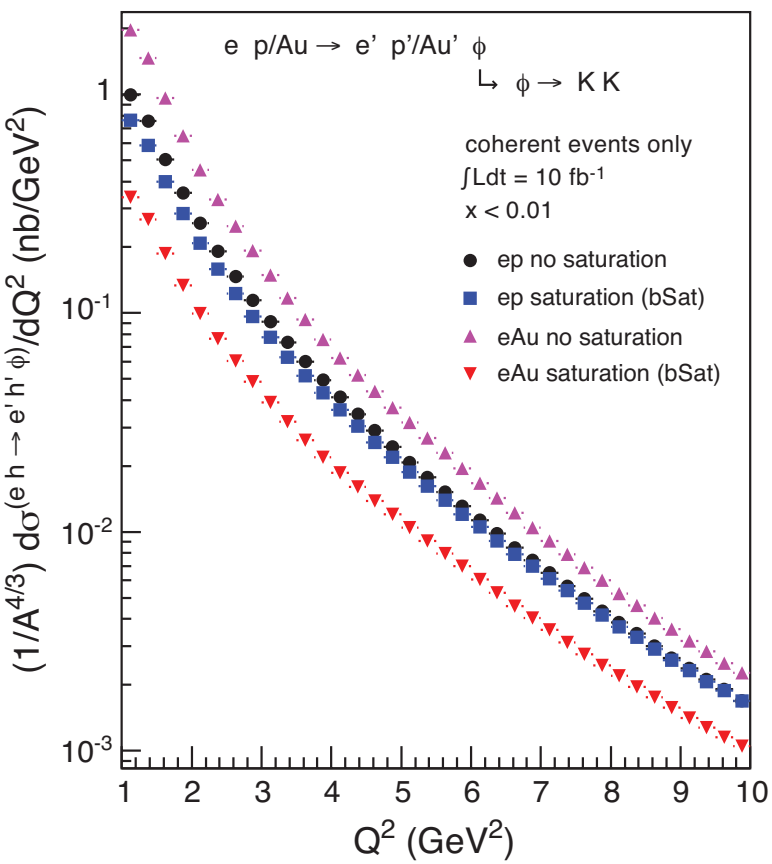
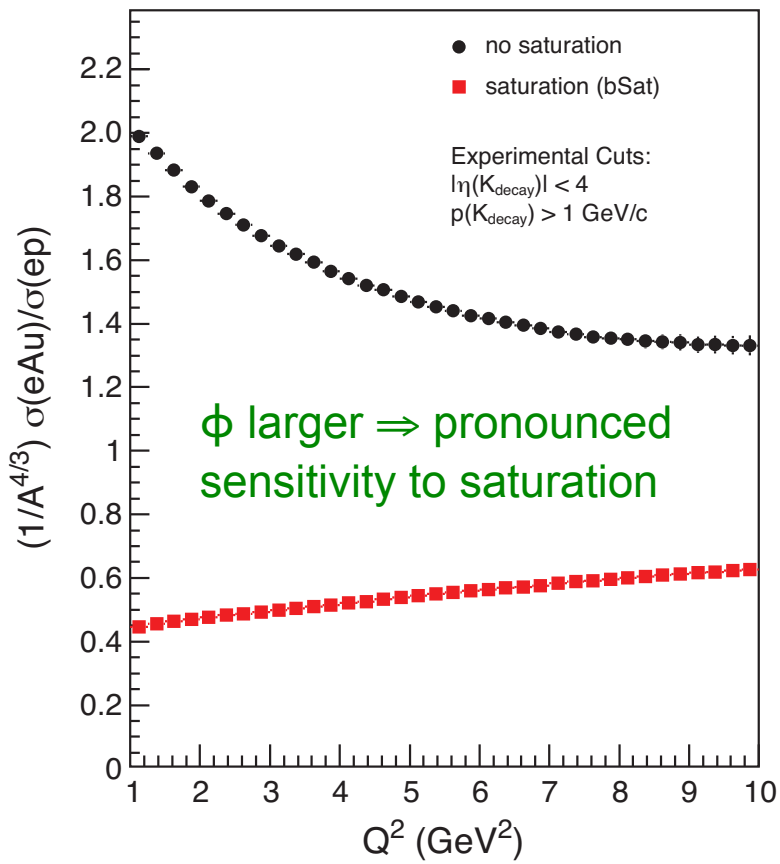
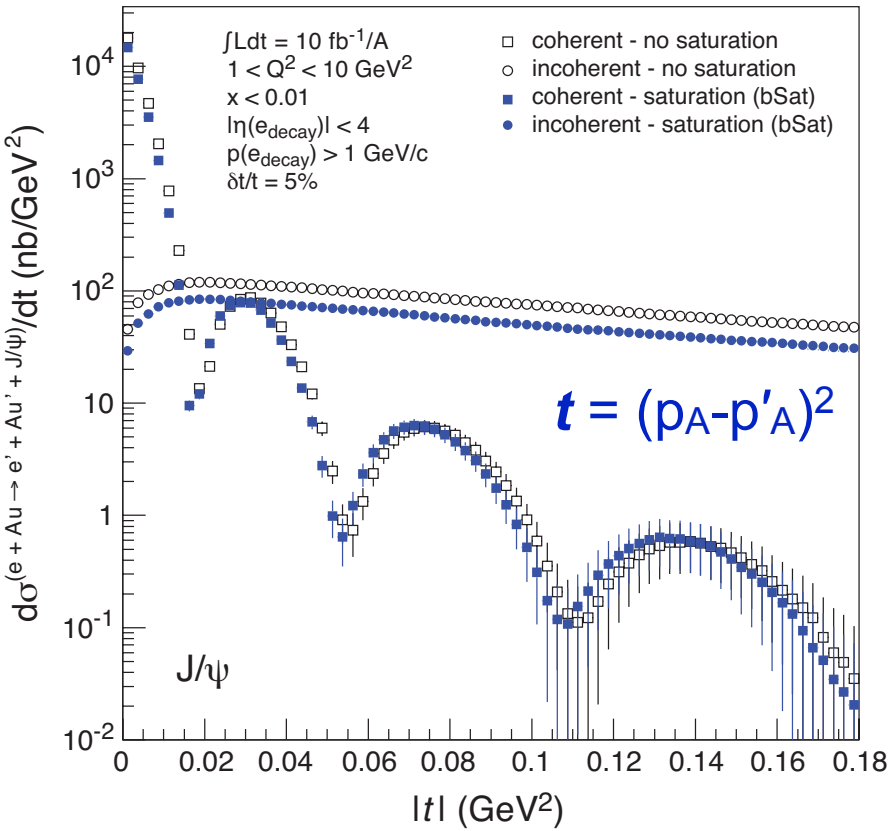


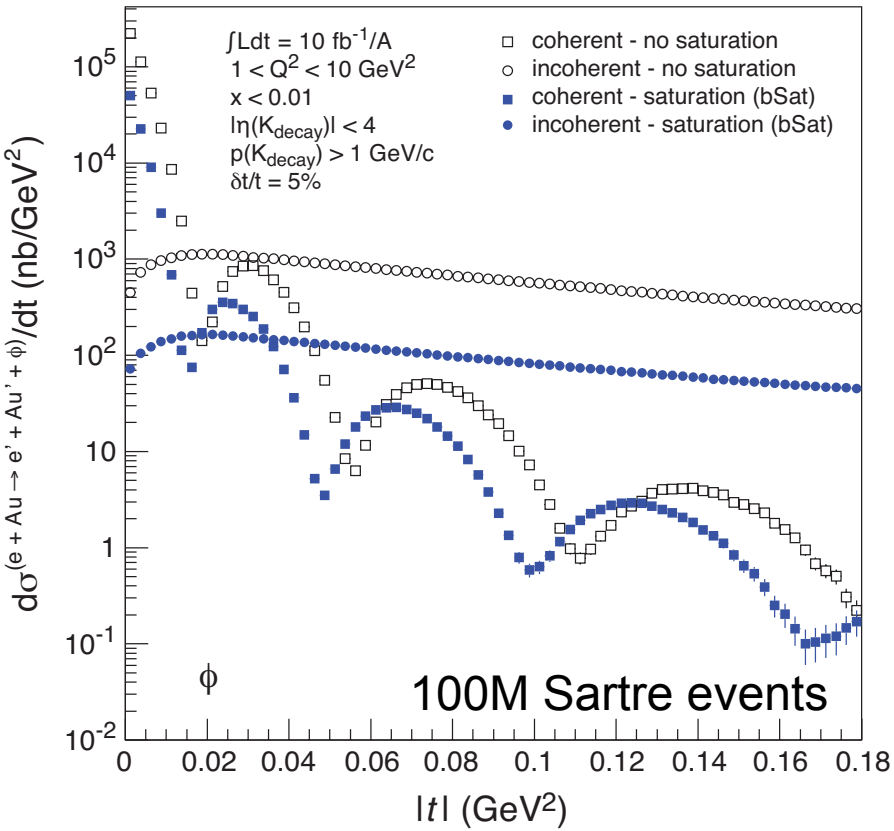


Sartre: Results II (White Paper)

$$e + Au \rightarrow e' + J/\Psi + Au'$$



$$e + Au \rightarrow e' + \phi + Au'$$



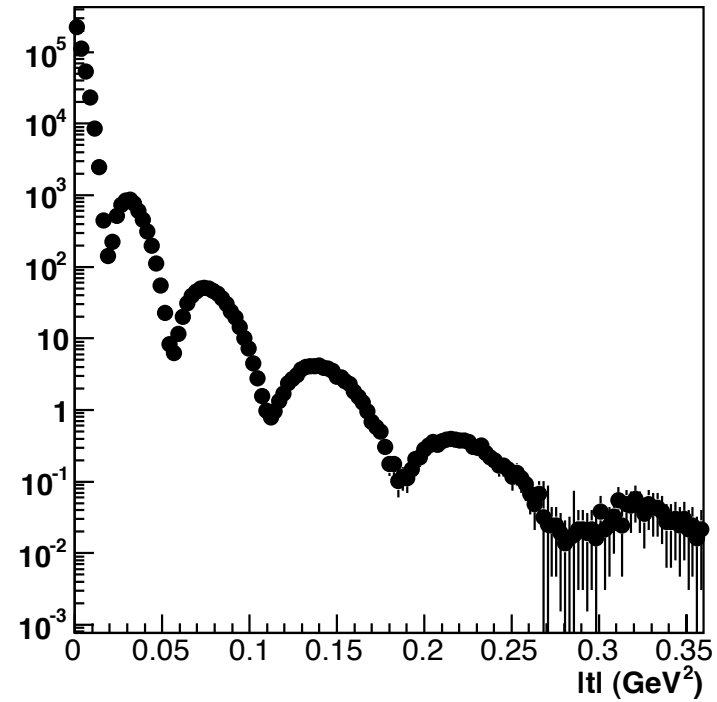
- Simulation showed that one can separate coherent from incoherent
  - Nuclear breakup (incoherent case) produces enough neutrons that can be detected with Zero-Degree-Calorimeter
  - Results affect IR design

Sartre: Results III (towards CDR)

Spatial source distribution from dσ/dt:

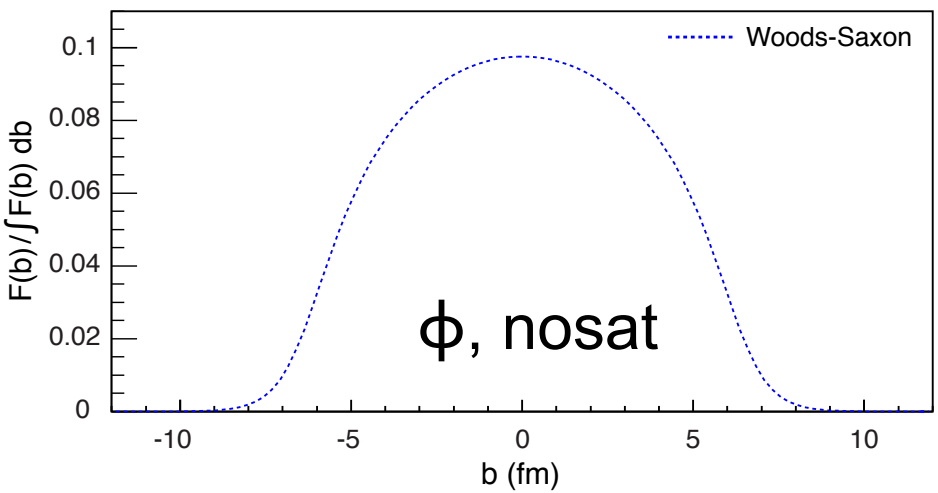
$$F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

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



Initial concerns:

- Measured range in Δ (t)
- Statistical errors on data
- Problematic in ep



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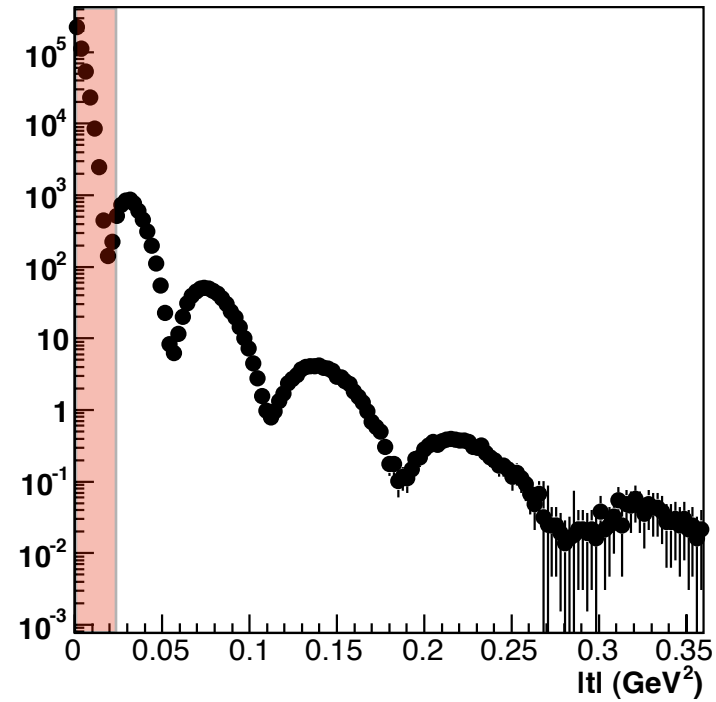

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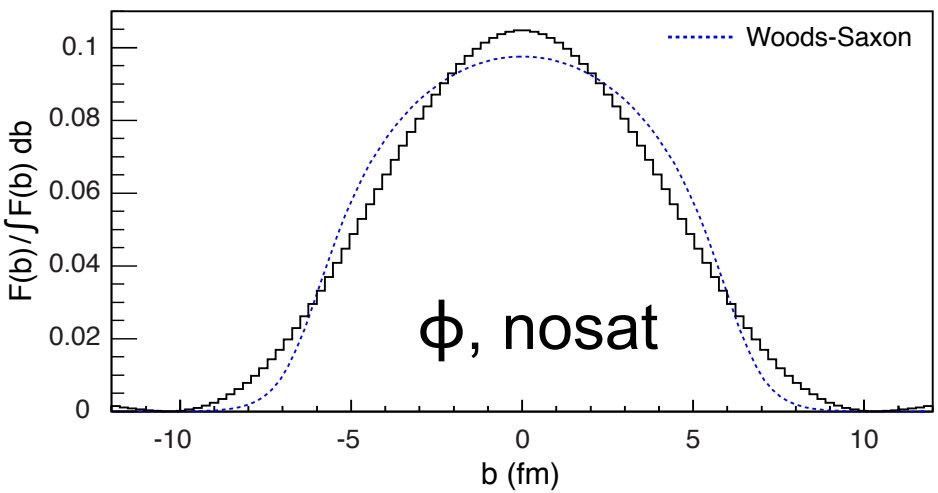

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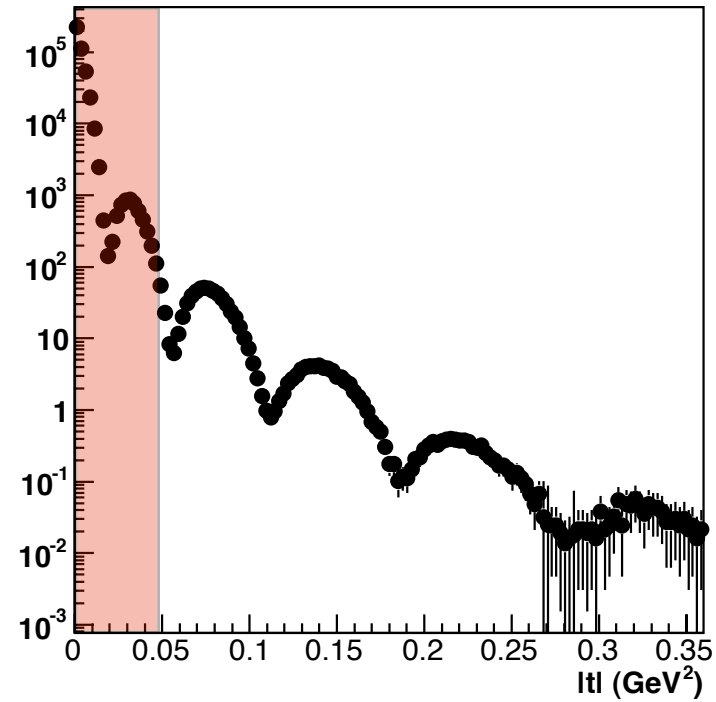

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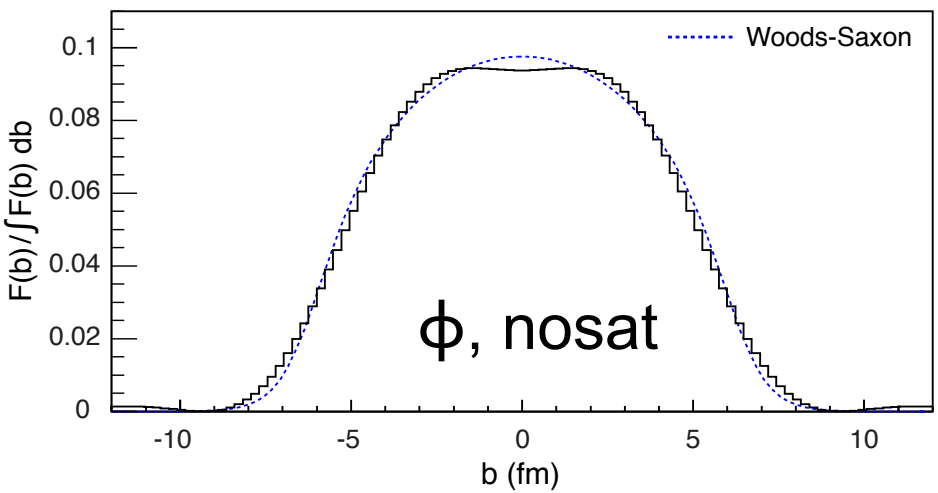

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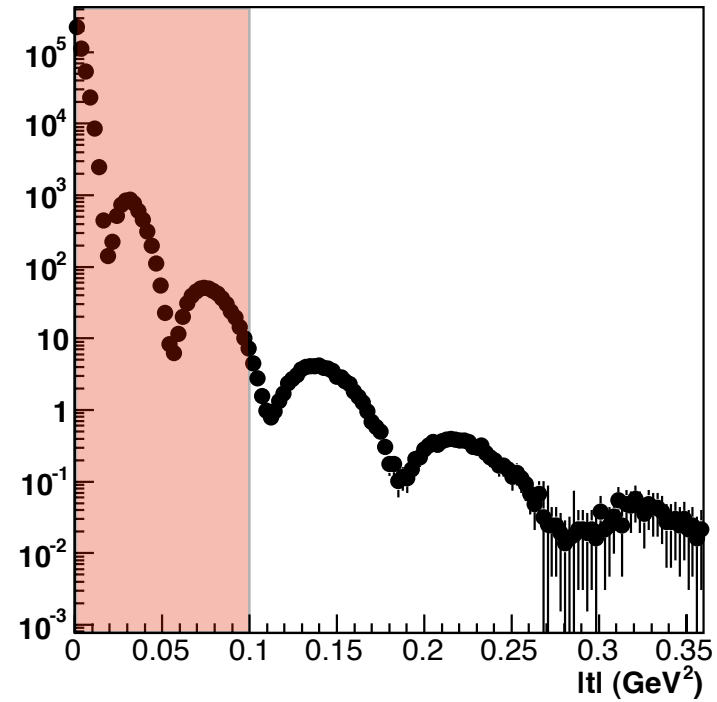

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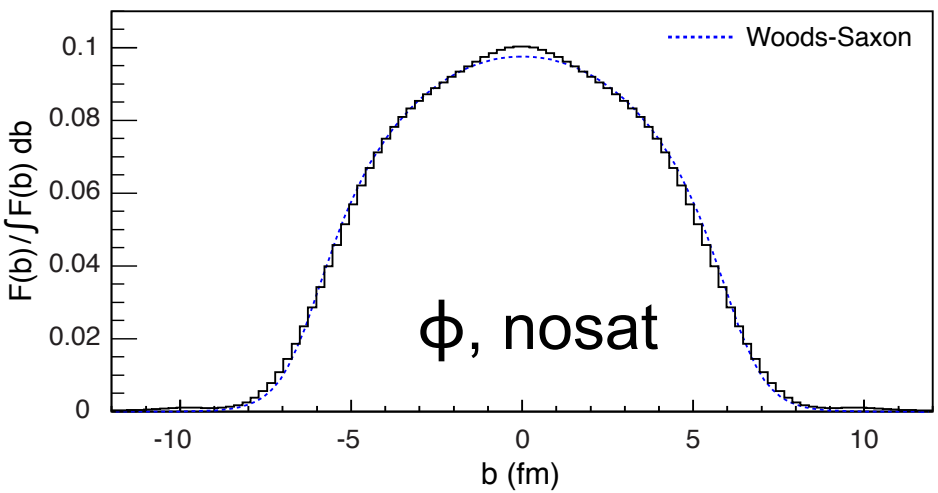

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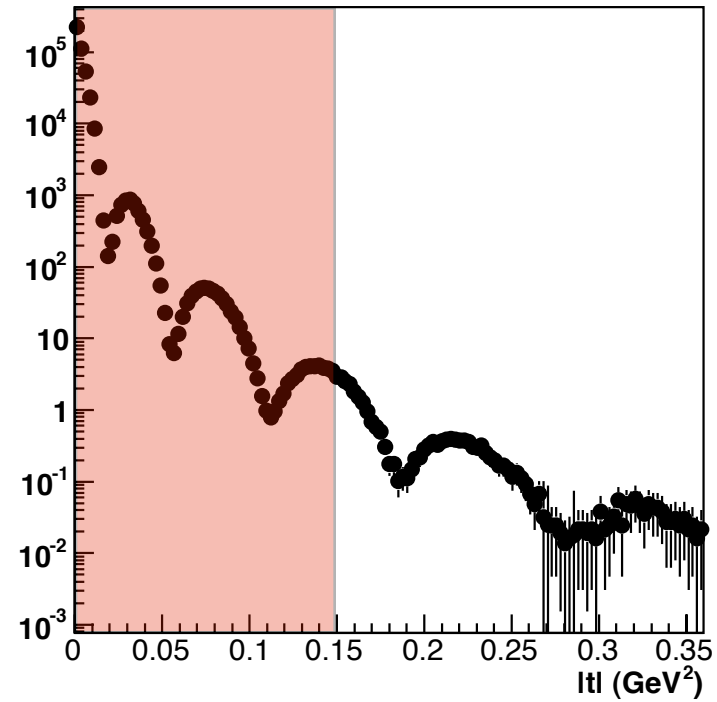

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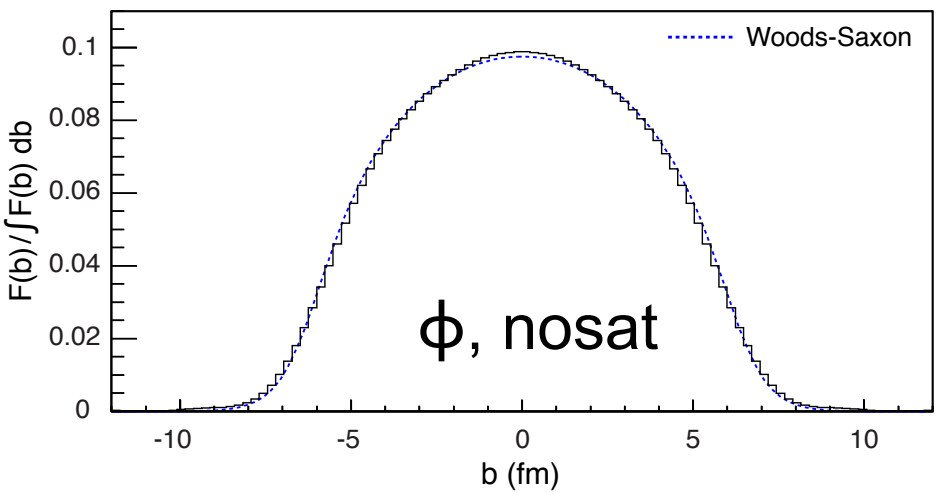

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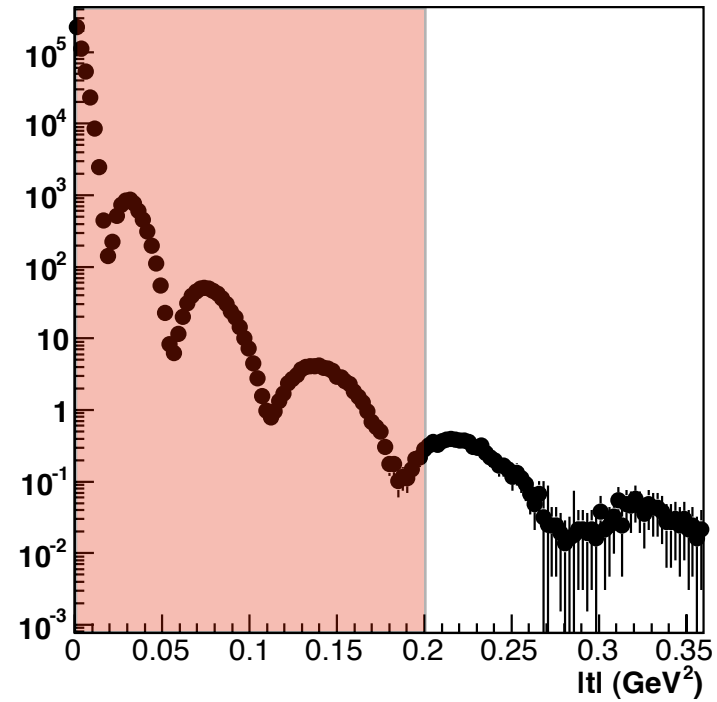

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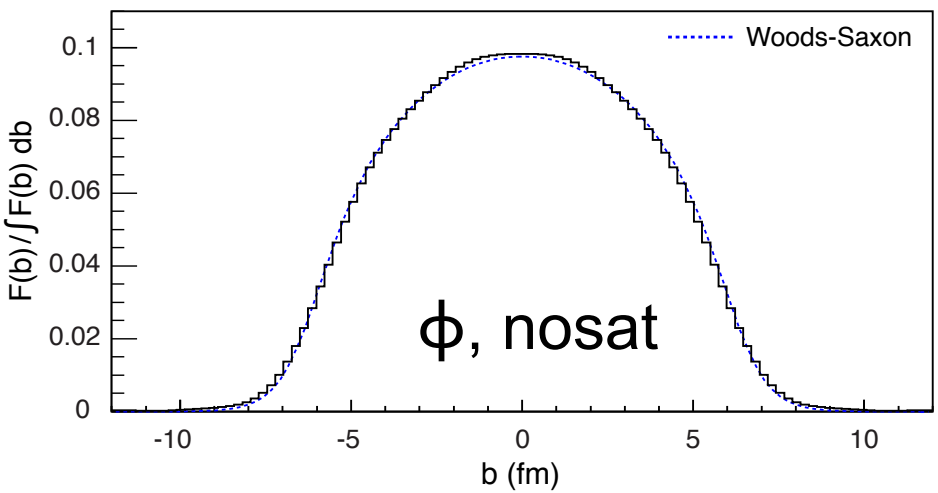

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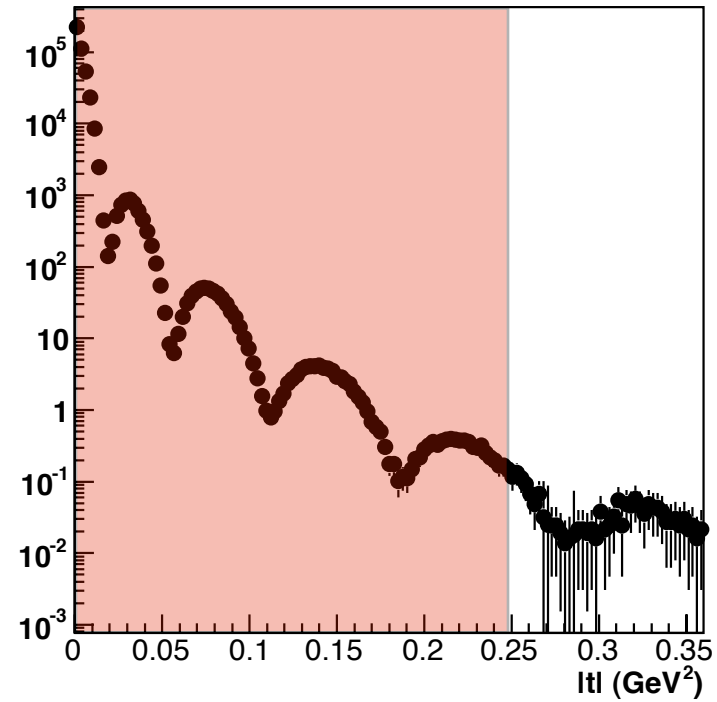

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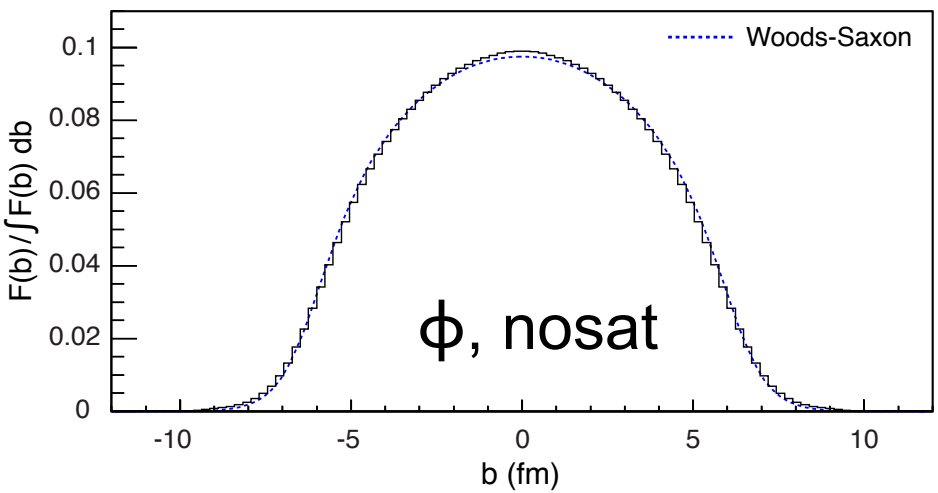

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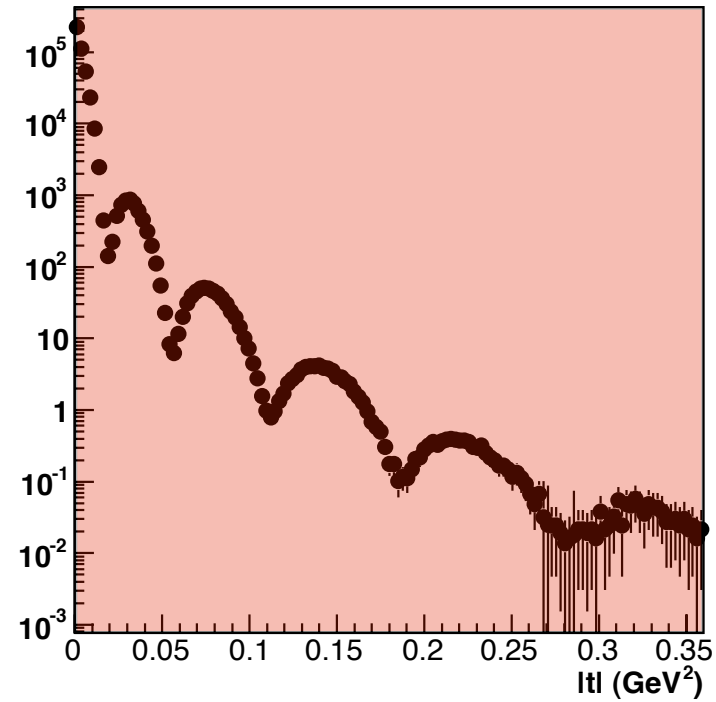

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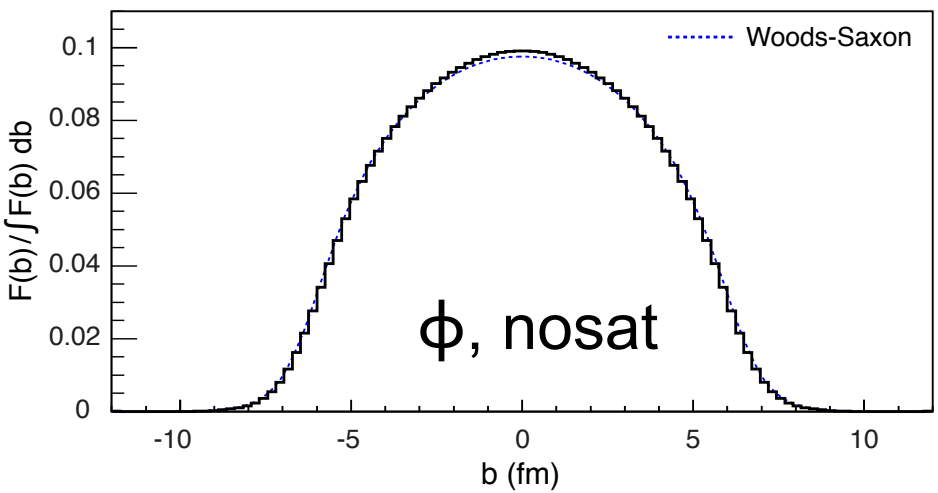
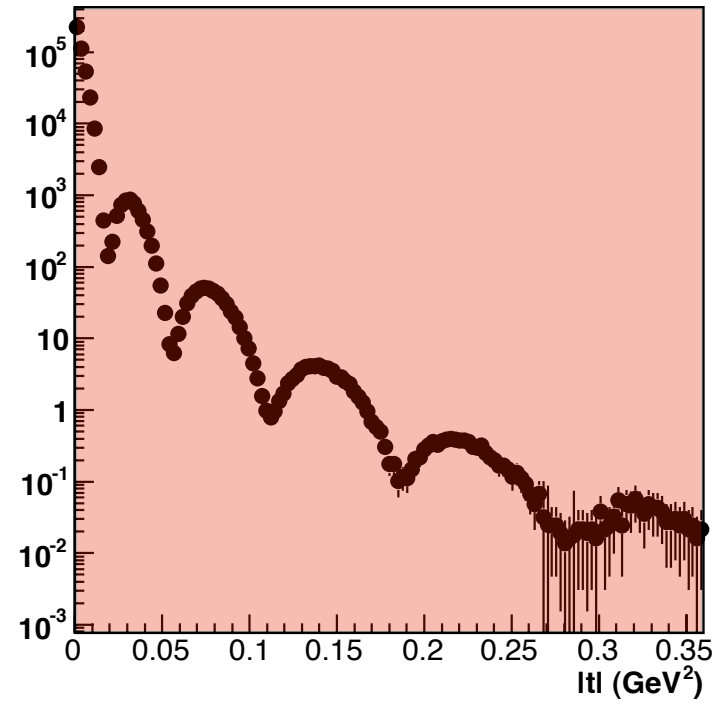


Sartre: Results III (towards CDR)

Spatial source distribution from dσ/dt:

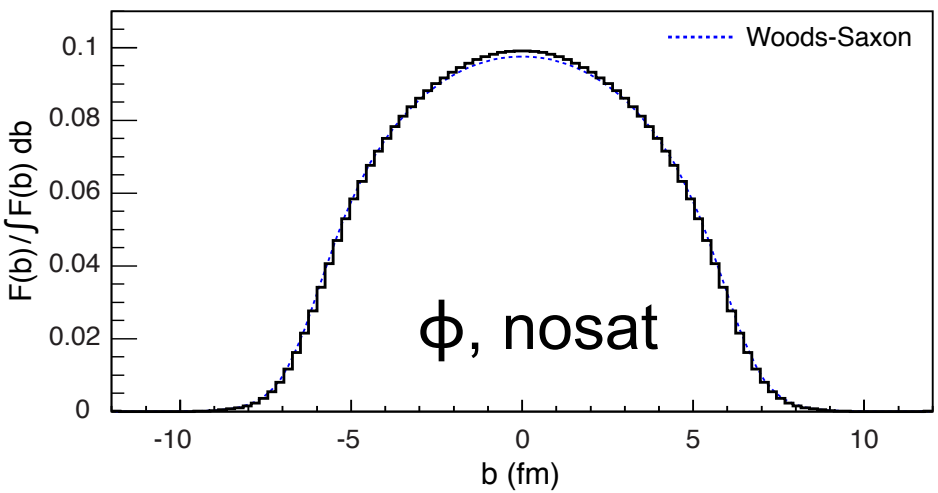
$$F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

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



Initial concerns:

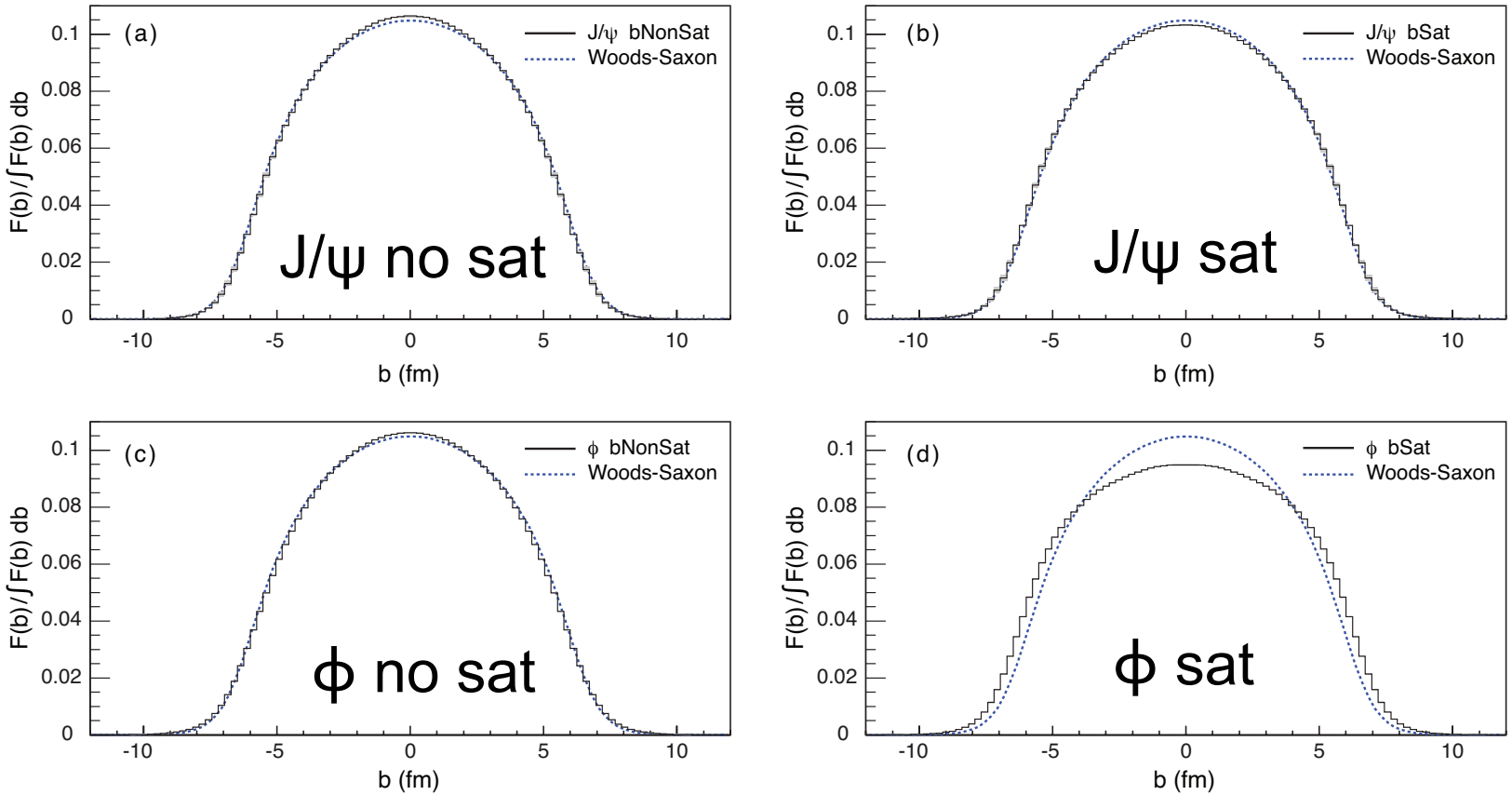
- Measured range in Δ (t)
- Statistical errors on data
- Problematic in ep



- Established golden eA measurement for EIC
- Sartre made feasibility studies possible

Sartre: Results IV (towards CDR)

all for 10 nb^{-1}/A



- J/ψ is the best suited probe to obtain spatial distribution independent of model
- Comparing J/ψ and ϕ reveals coherence effects (saturation)

Sar*t*re: Status & Summary

- Sar*t*re is tested and ready to go
- Few additions to documentation needed (1 week)
- Release with GNU Public License
- Need to solve remaining issue with Gemini++
  - Author has not thought about licensing (yet)

- Publication
  - T. Toll and TU: Exclusive diffractive processes in electron-ion collisions submitted to PRC (arXiv:1211.3048)
  - T. Toll and TU: Publication in Computer Physics Communications in preparation

Sar*tre*: What's Next?

	DIS		Diffractive	
	saturated	non-saturated	saturated	non-saturated
exclusive	✗	✓	VM & DVCS ✓	VM & DVCS ✓
	✗	✓		
inclusive	✗	✓	✗	✗
	✗	✓		

- Sartre only deals with exclusive vector meson & DVCS production
- Does not handle inclusive diffractive events (σ, F_2^D F_L^D studies)
- Requires upgrade of Sartre
  - we know how, but is considerable investment in time
- First release Sartre as is (leave upgrade for later versions)
- Not highest priority (DIS saturated case first)

DIS in eA (non-saturated): eA-Hybrid

	DIS		Diffractive	
	saturated	non-saturated	saturated	non-saturated
exclusive	✗	✓	VM & DVCS ✓	VM & DVCS ✓
	✗	✓		
inclusive	✗	✓	✗	✗
	✗	✓		

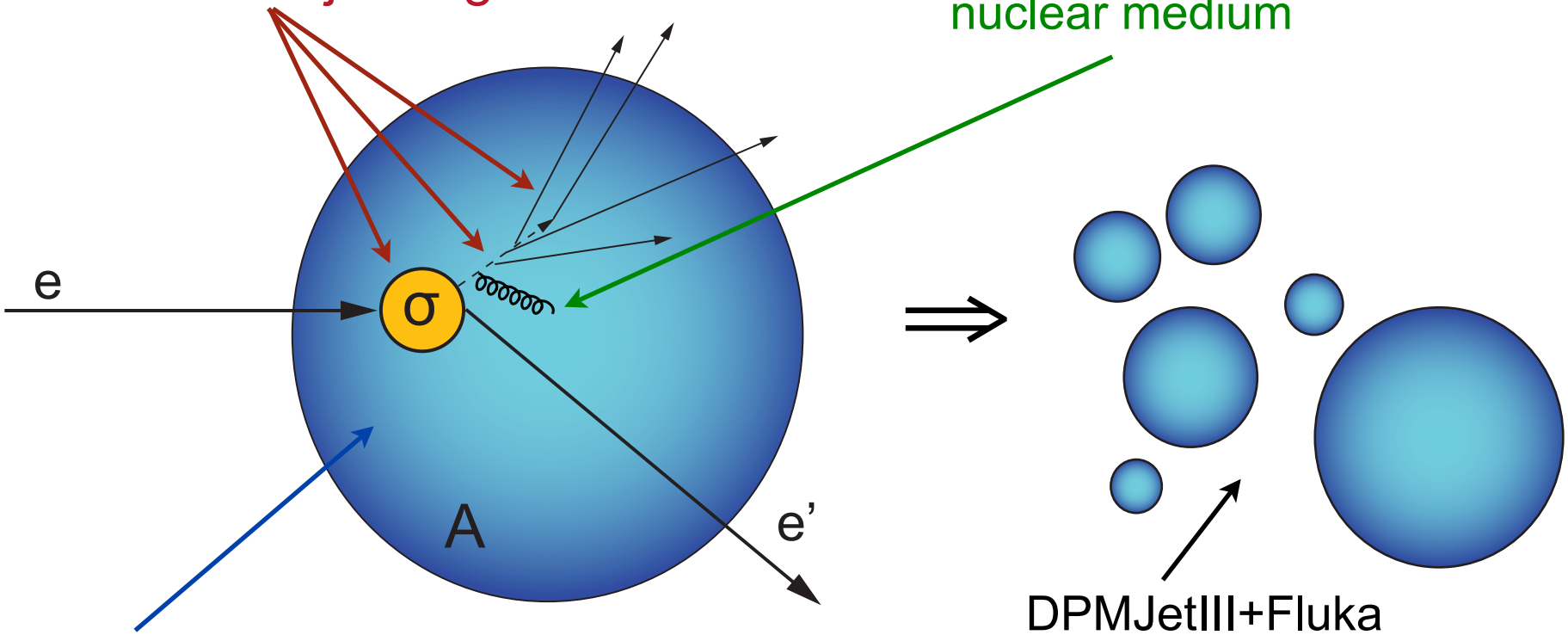
- A **hybrid** model
  - Reuse of existing generators with different level of support
  - New code only to interface generators
  - A non-saturation model only
  - DPMJetIII, FLUKA, PYTHIA6, EPS09 (nPDF)
  - Liang Zheng (CCNU student, located at BNL)

eA-Hybrid: Implementation

PYTHIA + nPDF (EPS09)

Parton level interaction, parton shower and jet fragmentation

Salgado-Wiedemann Energy loss effect for cold nuclear medium



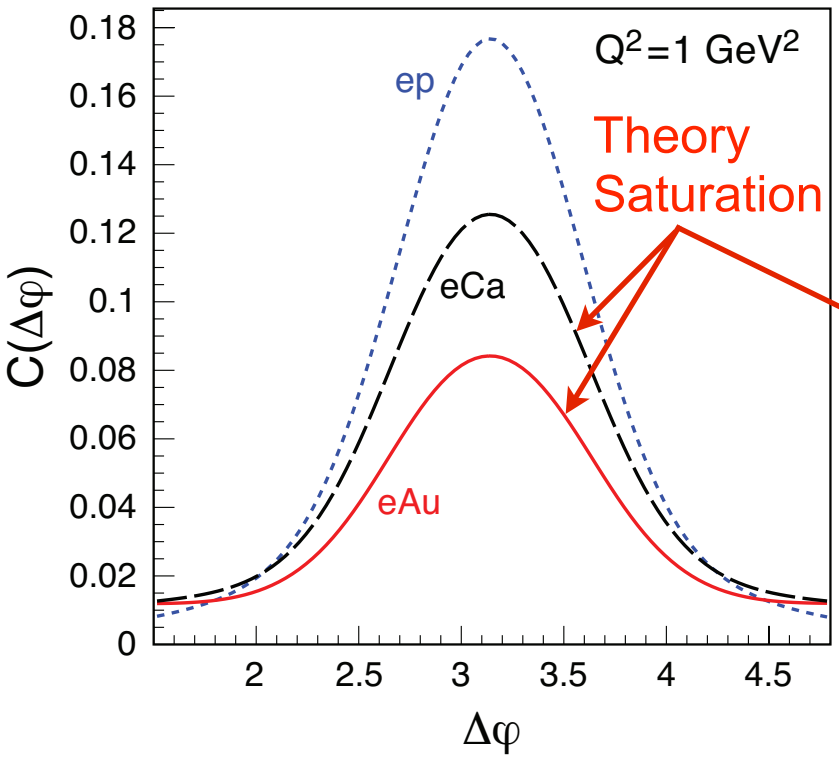
DPMJetIII Nuclear Geometry

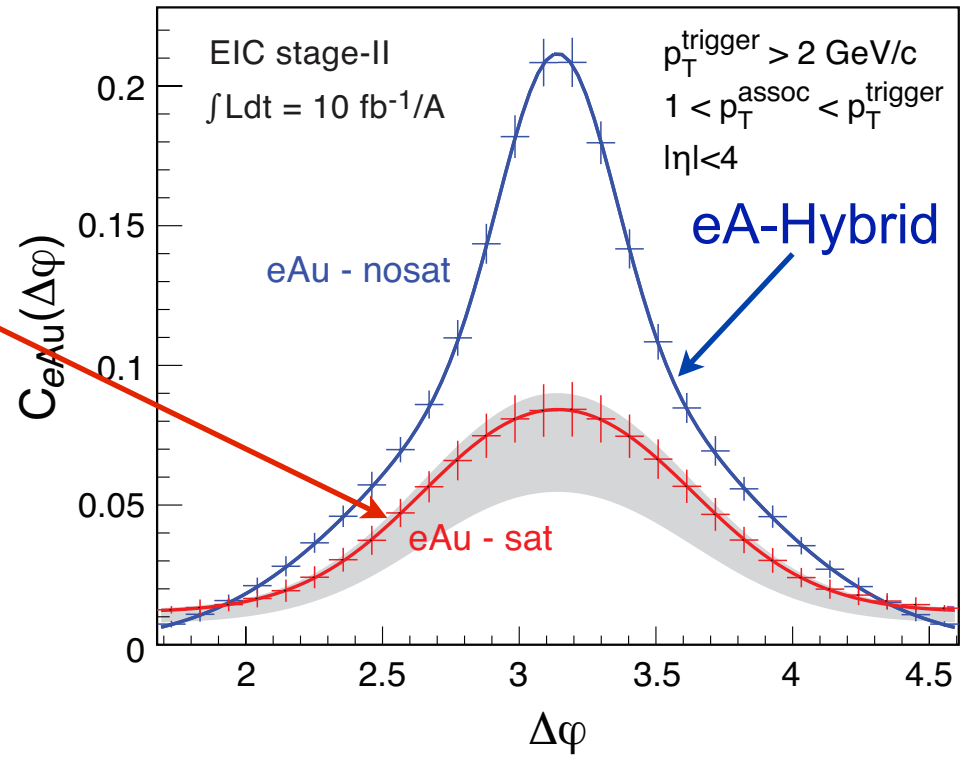
DPMJetIII+Fluka Nuclear Breakup & Evaporation

eA-Hybrid: Results I (White Paper)

Dihadron correlations h-h:

Study of away side peak (180°), compare saturation and non-saturation models

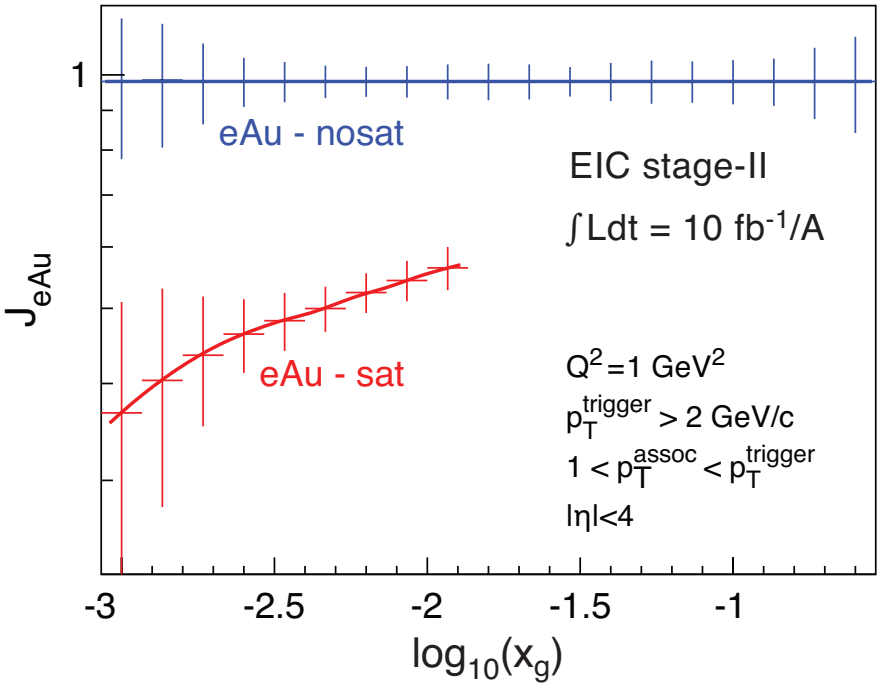


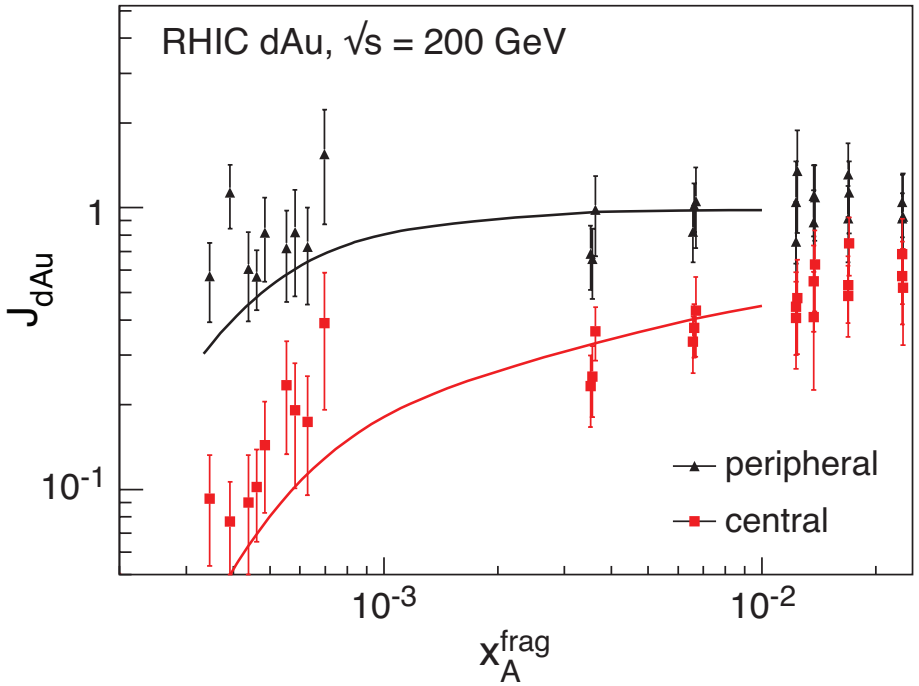


Simulations: Zheng, Theory: Xiao, Yan

eA-Hybrid: Results II (White Paper)

J_{eAu} = Away-side-yield(eAu) / Away-side-yield(ep)





- Established golden eA measurement for EIC
- Only possible by comparison of theory with “conventional” eA physics (including all nuclear effects)

What's Next?

	DIS		Diffractive	
	saturated	non-saturated	saturated	non-saturated
exclusive	✗	✓	VM & DVCS ✓	VM & DVCS ✓
	✗	✓		
inclusive	✗	✓	✗	✗
	✗	✓		

- eA Physics case for EIC requires the **comparison** of established (non-saturated) models that nevertheless contain all nuclear effects **with** saturation models.
- Need a DIS version for saturation (best would be to have one approach for both)
- While eA-Hybrid works it doesn't fulfill this requirement

eA DIS generators: eA-Cascade

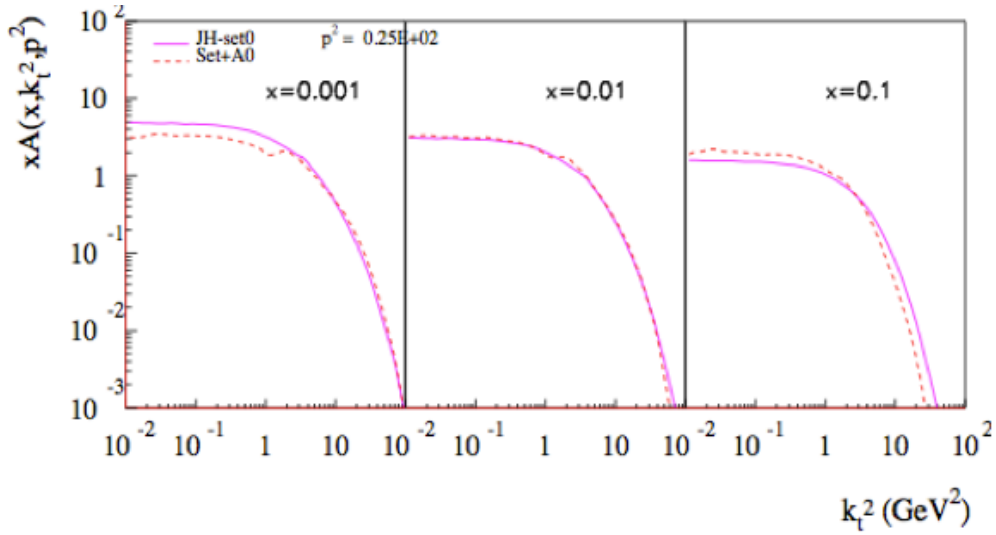
- Cascade
  - established generator by H. Jung for *ep*
  - uses CCFM evolution scheme
    - DGLAP-like for large x and BFKL-like for small x
- Requires unintegrated PDFs (uPDF)
- HERA F_2 data is now (combined F_2) precise enough to answer detailed questions about the CCFM evolution mandatory for the uPDF parametrization

- Extension of Cascade to eA is T. Toll's next project

eA-Cascade: Physics I

Saturation:

- Stop the evolution if k_t becomes smaller than saturation scale Q_S
- $Q_S \sim (A/x)^{\lambda}$



uPDF for ions:

Define uPDF:

$$x\mathcal{G}(x,Q^2) \equiv \int^{Q^2} \mathrm{d}k^2 \frac{\mathcal{A}(x,k^2)}{k^2}$$

Connection to dipole model:

$$\sigma_{q\bar{q}}(r,x) = \frac{8\pi^2}{N_C}\int \frac{\mathrm{d}k}{k^3}[1-J_0(kr)]\alpha_S \mathcal{A}(x,k^2) = 2\int \mathrm{d}^2\mathbf{b}\mathcal{N}(x,\mathbf{r},\mathbf{b})$$

uPDF from Scattering Amplitude:

$$\frac{\mathcal{A}(x,k^2)}{k^2} = \frac{C_F}{2\pi\alpha_S(k)k^2}\int \mathrm{d}r\mathrm{d}bJ_0(rk)\left(\frac{1}{r}\frac{\partial\mathcal{N}(x,r,b)}{\partial r} + \frac{\partial^2\mathcal{N}(x,r,b)}{\partial r^2}\right)$$

eA-Cascade: Physics II

Building ion scattering amplitude:

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

- Need:
  - b-dependent proton scattering amplitude that can be combined with the CCFM evolution in CASCADE
    - has to describe HERA F_2 data
- Only option GBW dipole model $\mathcal{N}(x, r) = \sigma_0 \left(1 - e^{-Q_s^2(x) r^2}\right)$
  - with Θ function b-dependence (cylindrical proton):

$$T_p(b) = \Theta(R_p - b) \Rightarrow \sigma_0 = \pi R_p^2$$

  - Dipole model can be linearized ⇒ non-saturated version

eA-Cascade: Status

- We know how to extend Cascade to eA
- H. Jung interested in project
- Issues
  - Legacy F77 code
  - Need to add nuclear breakup (Gemini or as in eA-Hybrid)
  - Include cold matter E-loss (Salgado & Wiedemann)
  - Considerable effort

ep Generator Efforts

- ep generators vital for *ep* program at EIC
- While for detailed physics and detector studies the difference between ep and eA matters for several generic detector studies ep might be enough

Deliverables	Obserables	MC generator
Polarised gluon distribution Δg	Scaling violation in inclusive DIS	PEPSI+LEPTO
Polarised quark and antiquark densities	semi-incl. DIS for pions and kaons	PEPSI+LEPTO
Sivers and unpolarised TMDs for quarks and gluon	SIDIS with transv. polarisation/ions; di-hadron (di-jet) heavy flavours	gmc_trans
GPDs, 3D structure of quarks and gluon in b-p_L space	Exclusive DIS: vector mesons and DVCS	MILOU

T. Toll, EIC R&D Simulation Workshop BNL 10/8/12

ep Generator Efforts

- Developments in EIC community (BNL TF):
  - Pythia6 + Radiative Corrections (RADGEN) - Elke Aschenauer
  - PEPSI + Radiative Corrections (RADGEN) - Elke Aschenauer
  - MILOU - update and maintenance - Salvatore Fazio
  - LEPTO-PHI - Mark Baker
    - Adds "Cahn effect" (azimuthal asymmetry of outgoing hadrons even for unpolarized beams) implemented.

Summary

- Finished Sar*t*re - exclusive diffractive VM production
  - saturation & non-saturation
  - distribution soon, publication in progress
  - extensively used for studies in EIC White Paper
- eA-Hybrid
  - includes set of realistic nuclear effects, non-saturation only
  - based on combo of existing generators
  - non-saturation only
- Cascade
  - next project to address
  - saturation & non-saturation physics
  - possibly replace eA-Hybrid
- Sartre for inclusive diffraction
  - has to wait