An overview of MC Tools at BNL for an EIC

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Brookhaven National Lab

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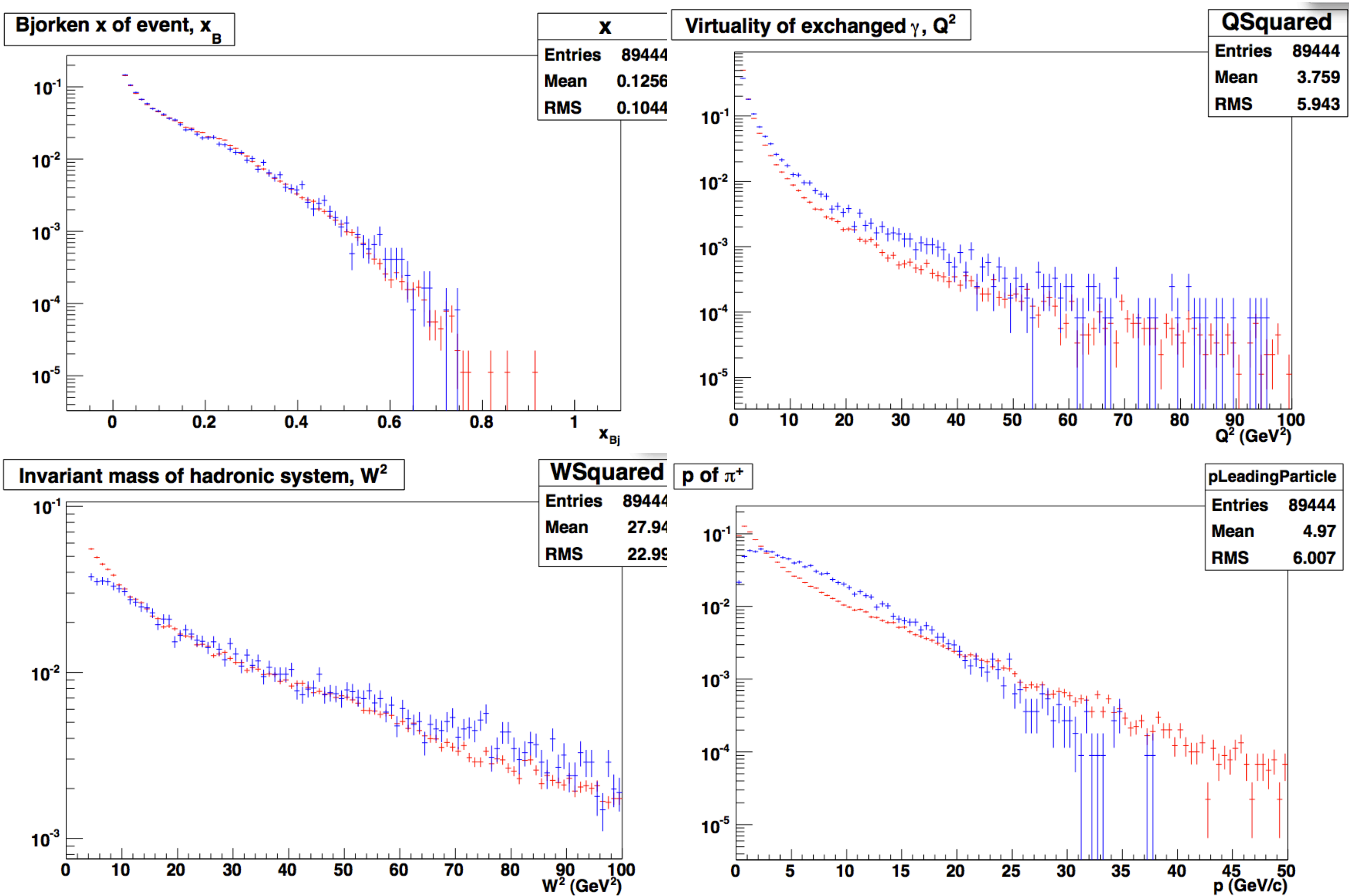
EIC Task Force at Brookhaven

- Task Force Leaders
  - ➡ Elke Aschenauer (Spin); Thomas Ullrich (Heavy Ions)
- Active Task Force Members
  - ➡ MACL, Ramiro Debbe, Jamie Dunlop (Heavy Ions)
  - ➡ J-H. Lee, Wlodek Guryn (pp2pp - Roman Pot expertise)
  - ➡ Pavel Nevski (Simulation framework)
- New Post-doc hires
  - ➡ Thomas Burton + 1 other (spin)
  - ➡ Tobias Toll (theory) - student of Hannes Jung in Hamburg and background with Lund group
- Students from Stony Brook
  - ➡ Michael Savastio, Anders Kirleis, Will Foreman and Peter Schnatz
- + large contribution from Collider-Accelerator Department (CAD)
  - ➡ led by Vadim Ptitsyn, Vladimir Litvinenko + many others

gmc_trans code (spin physics)

- https://wiki.bnl.gov/eic/index.php/Gmc_trans
- gmc_trans: MC generator for SIDIS
  - ➡ simulates single hadron production from lepton scattering off a transversely polarised hadron
  - ➡ includes the hadron transverse spin (transversity) distribution and transverse-momentum dependent (TMD) distributions, e.g. Sivers function
- Code developed for HERMES (27.57 GeV electron on stationary proton target)
  - ➡ Code re-written by Tom Burton for collider kinematics for arbitrary electron/proton energies
  - ➡ Code written in Fortran with small amount of "C"
    - "C" used to interface with Gnu Scientific Library's VEGAS integration routine

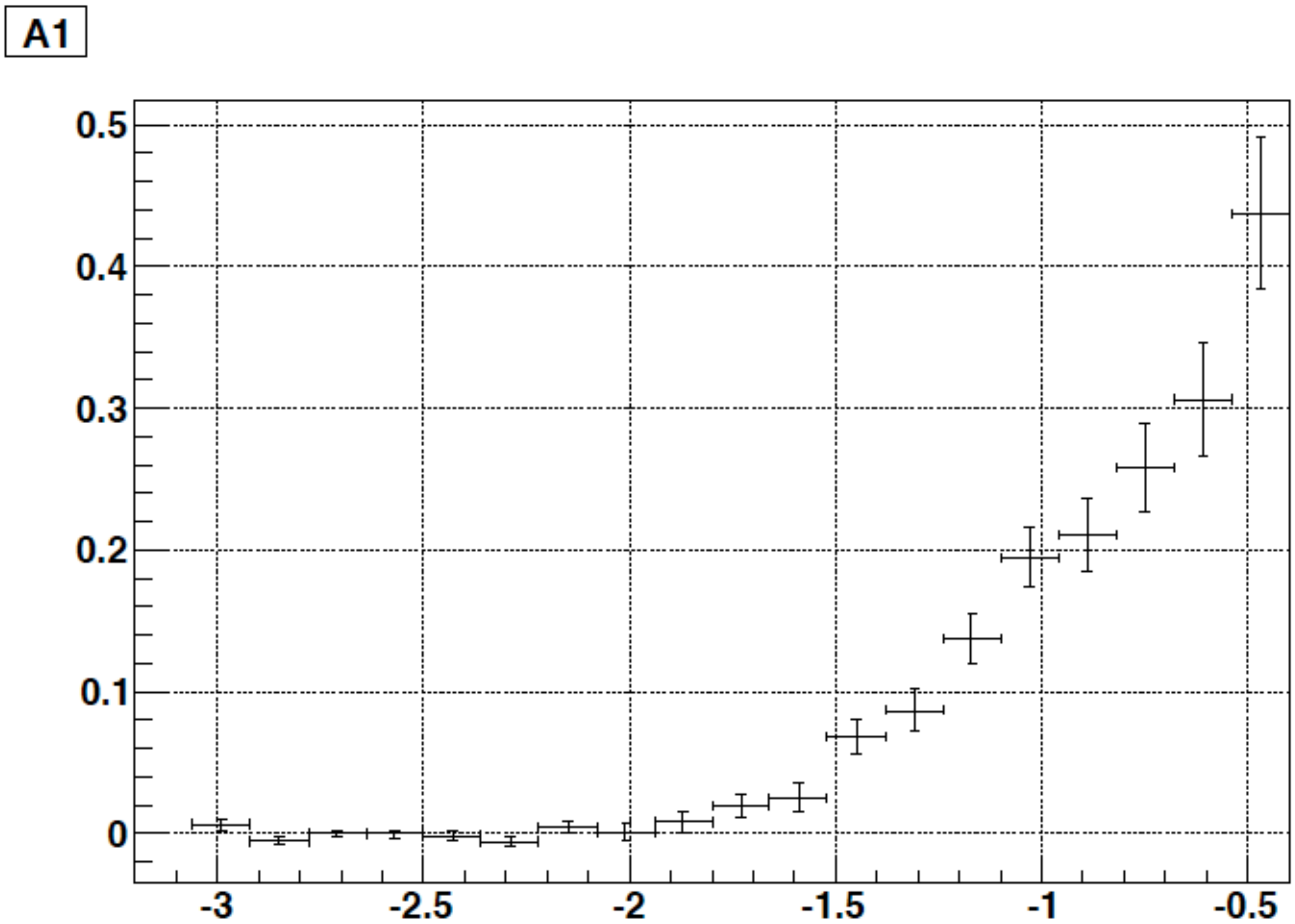
gmc_trans code (spin physics)



PEPSI - Polarised Electron Proton Scattering Interaction

- MC code for polarised deep inelastic lepto-production via EM interaction based on LEPTO
  - ➡ Generates hard γ^*-parton scattering according to polarisation dependent cross-section
  - ➡ Has inbuilt $\Delta q(x)$ and $\Delta g(x)$ distributions and supports user-implemented distributions

PEPSI - Polarised Electron Proton Scattering Interaction

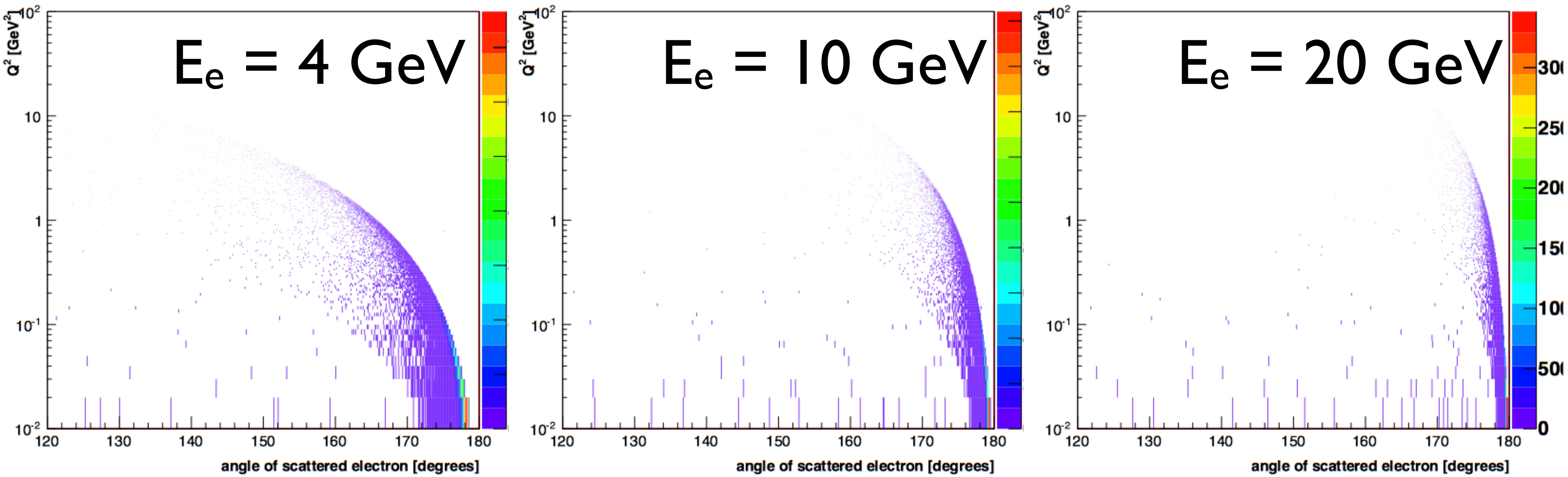


A1 - helicity asymmetries in γ* absorption cross-section

PYTHIA MC Generator

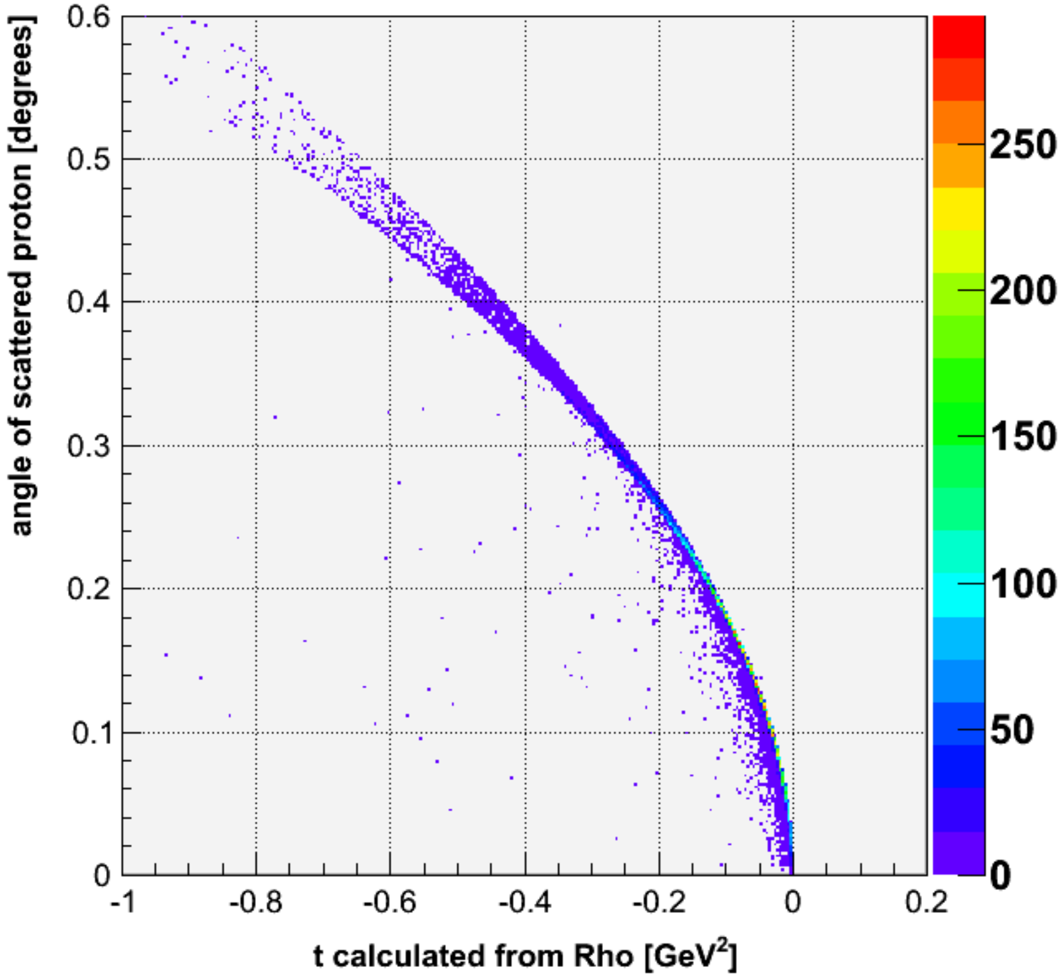
- https://wiki.bnl.gov/eic/index.php/PYTHIA
- MC generator for both DIS and diffractive e+p collisions (no rapidity gaps)
  - ➡ Using version 6.4.13 of PYTHIA for e+p collisions
    - e+p collisions not implemented in version 8 (C++)
  - ➡ Radiative corrections are included (radgen)
  - ➡ Lots of processes can be simulated
    - elastic VMD, diffractive VMD, LO DIS, QCDC, PGF ….

PYTHIA MC Generator - diagnostic plots

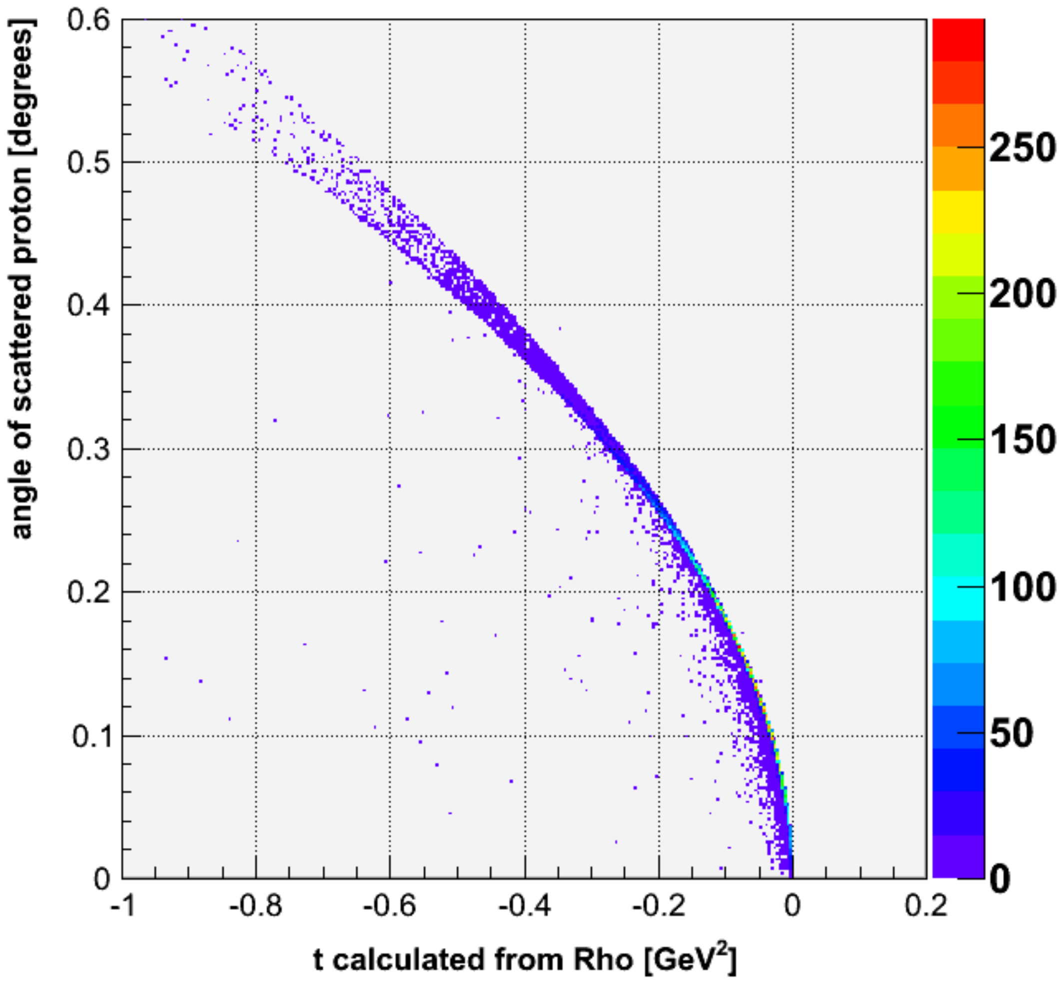


- Analysis of electron scattering angle in PYTHIA
  - ➡ higher energy electrons go at smaller angles wrt beam axis
    - harder to detect!!
    - independent of hadron energy

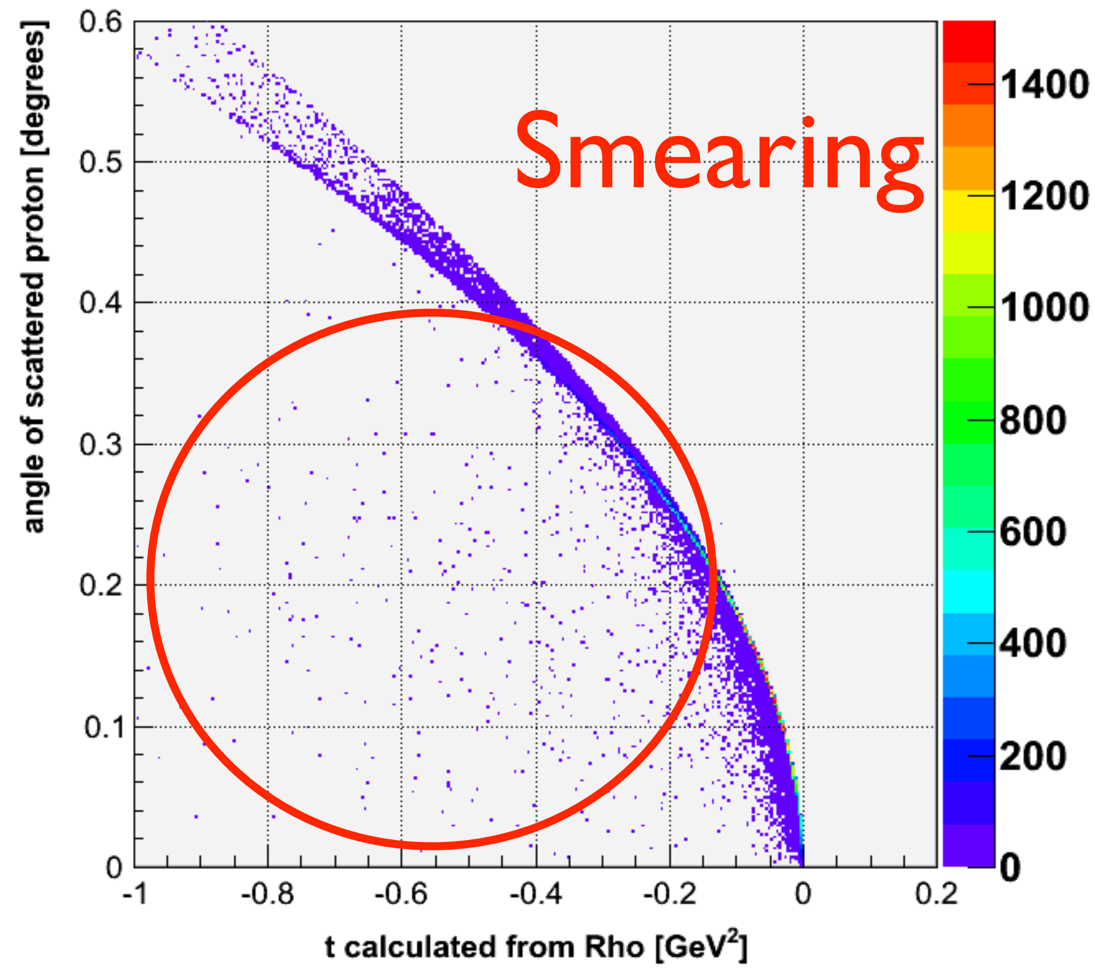
PYTHIA MC Generator - radiative corrections



PYTHIA MC Generator - radiative corrections



with radiative corrections



- Radiative corrections (via RADGEN)
  - ➡ Smear the t calculation at the ρ vertex
  - ➡ t calculated from the proton vertex is unaffected but harder to measure experimentally
    - need a proton spectrometer

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RAPGAP MC Generator

- https://wiki.bnl.gov/eic/index.php/RAPGAP
- MC generator for both DIS and diffractive e+p collisions (with rapidity gaps).
  - ➡ Diffractive collisions described by:
    - 2 gluon exchange (pQCD)
    - SATRAP
      - Saturation model (colour dipole) implemented by Henri Kowalski
  - ➡ Radiative corrections are included (utilising HERACLES)
- Need to use Rapgap version 3.2-beta-01 (released Feb 2010)
  - ➡ problem with proton kinematics we discovered has been corrected

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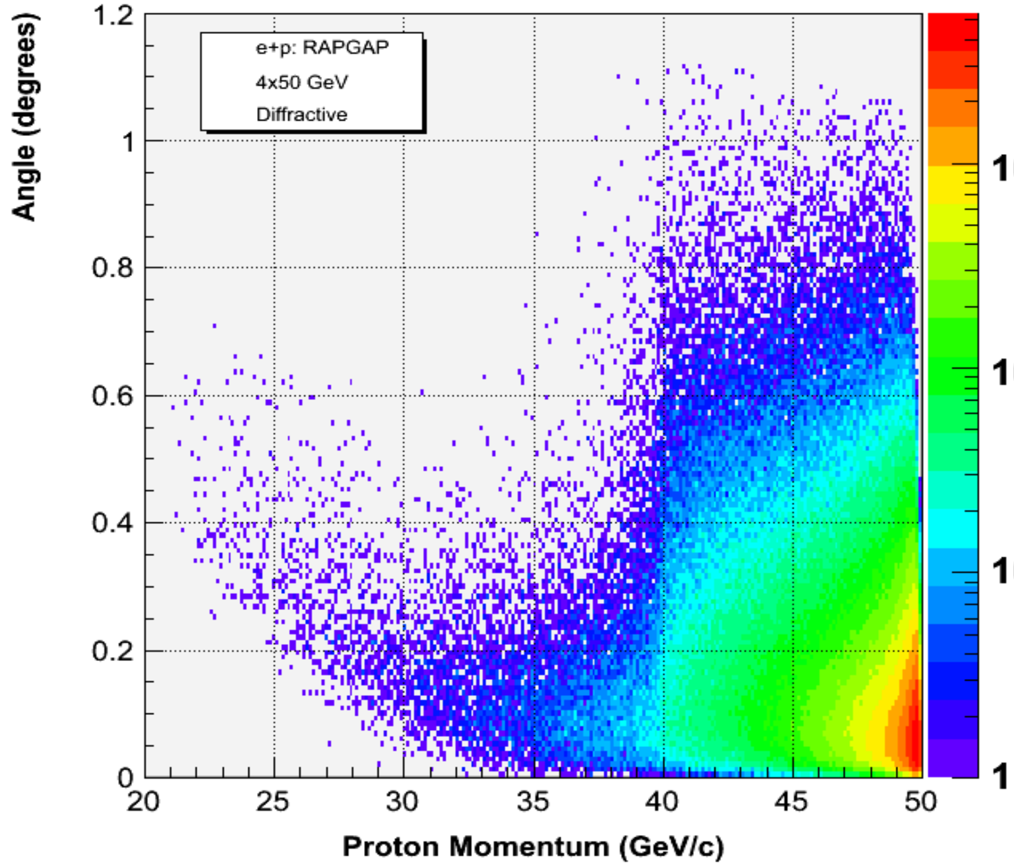
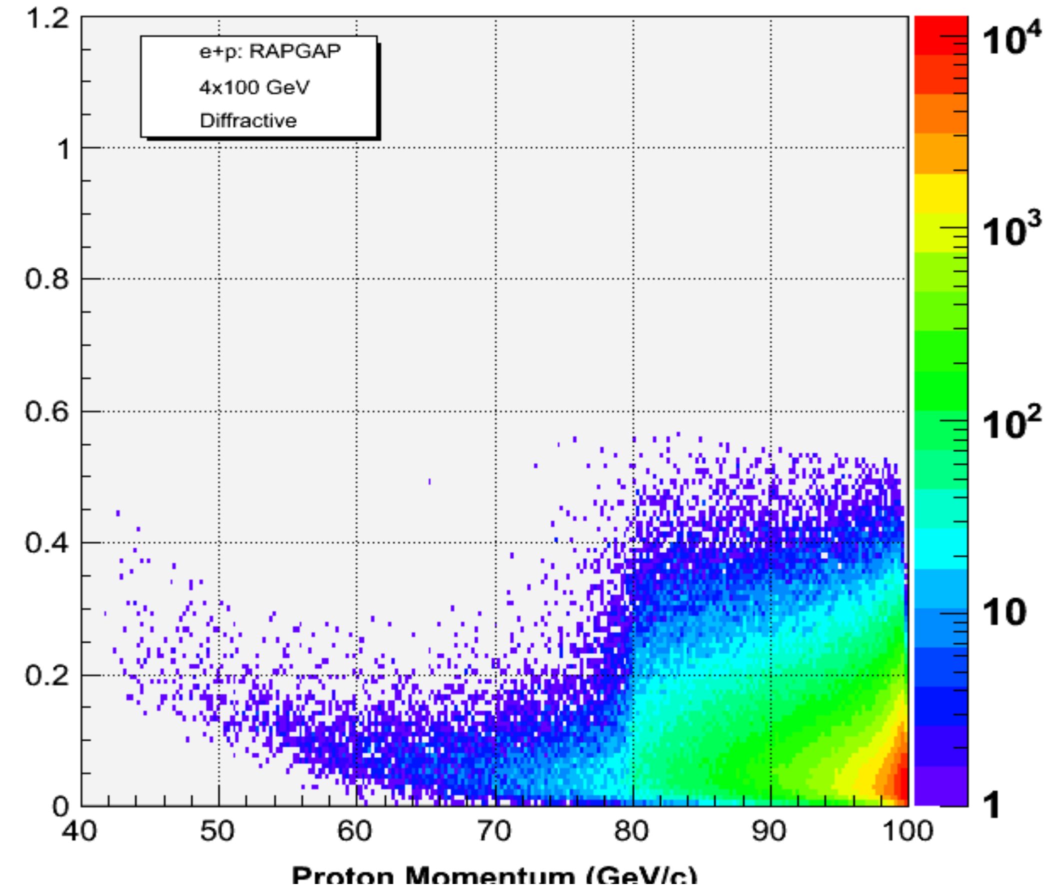
RAPGAP kinematics: scattered proton (diffractive)

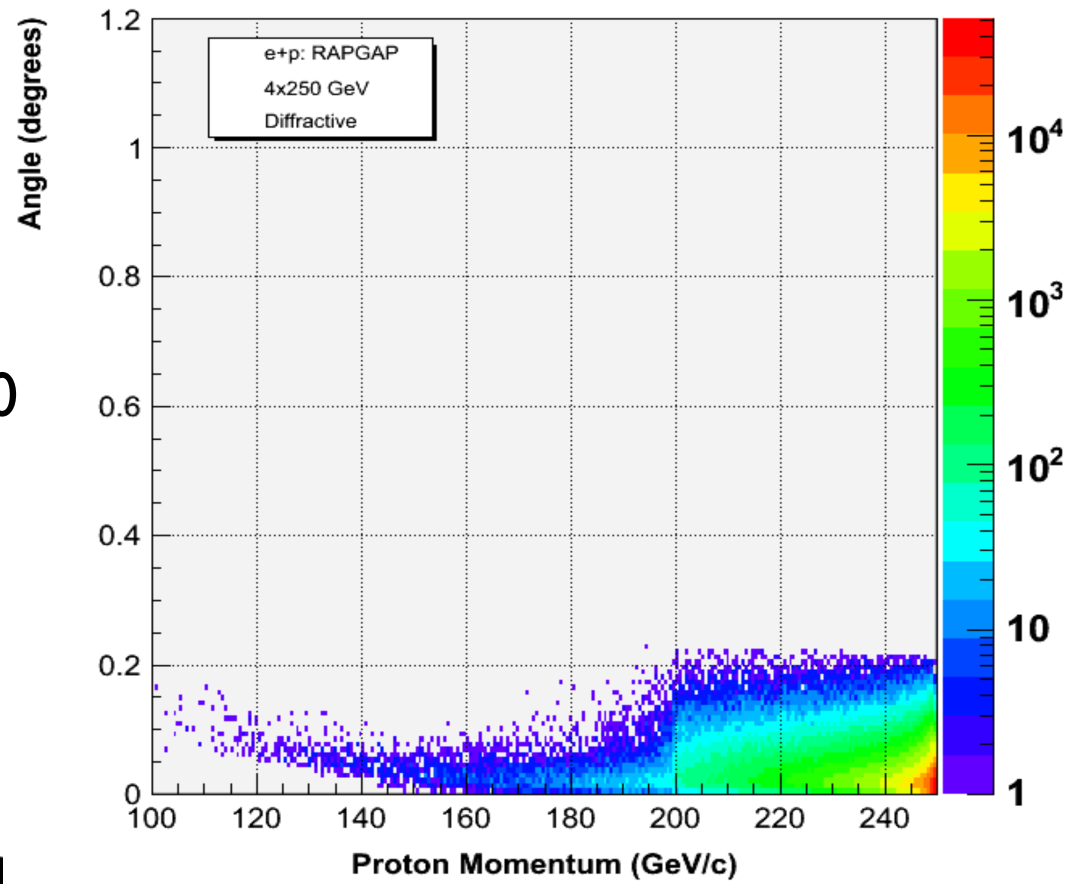
4x50



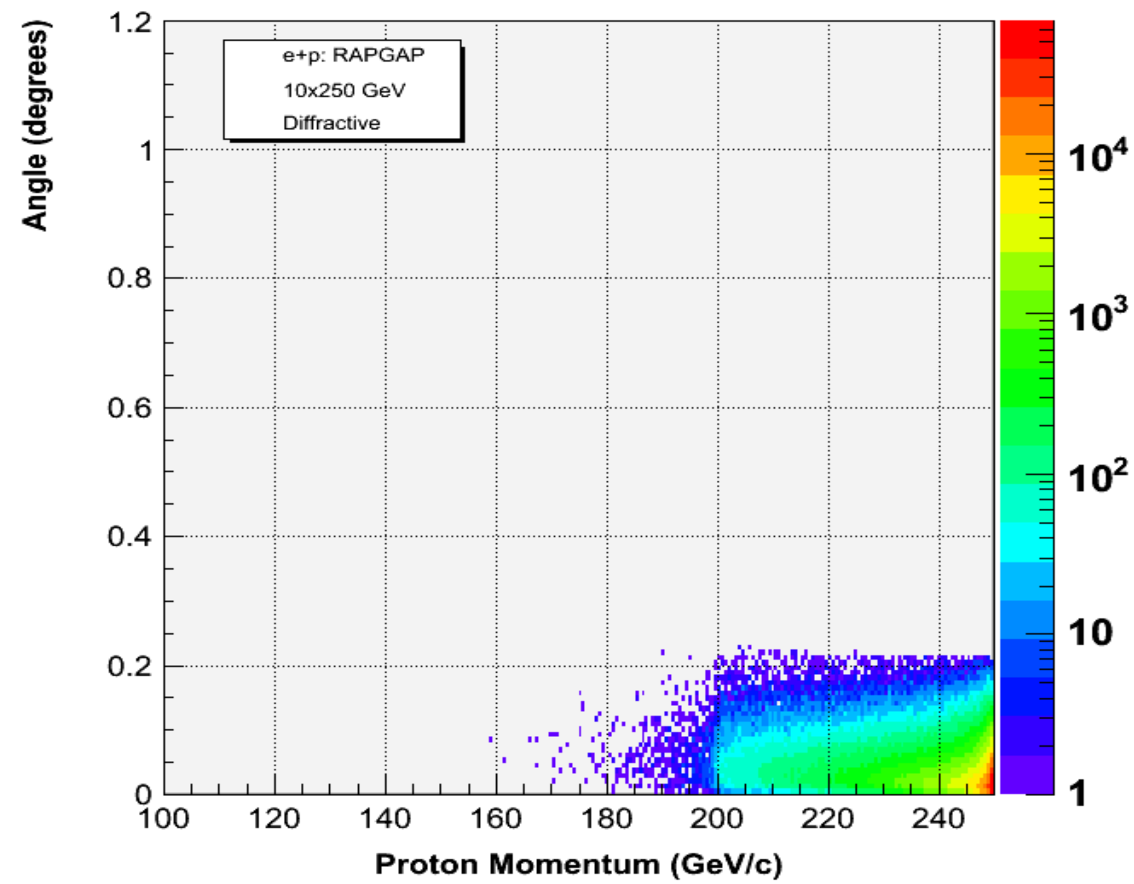
4x100



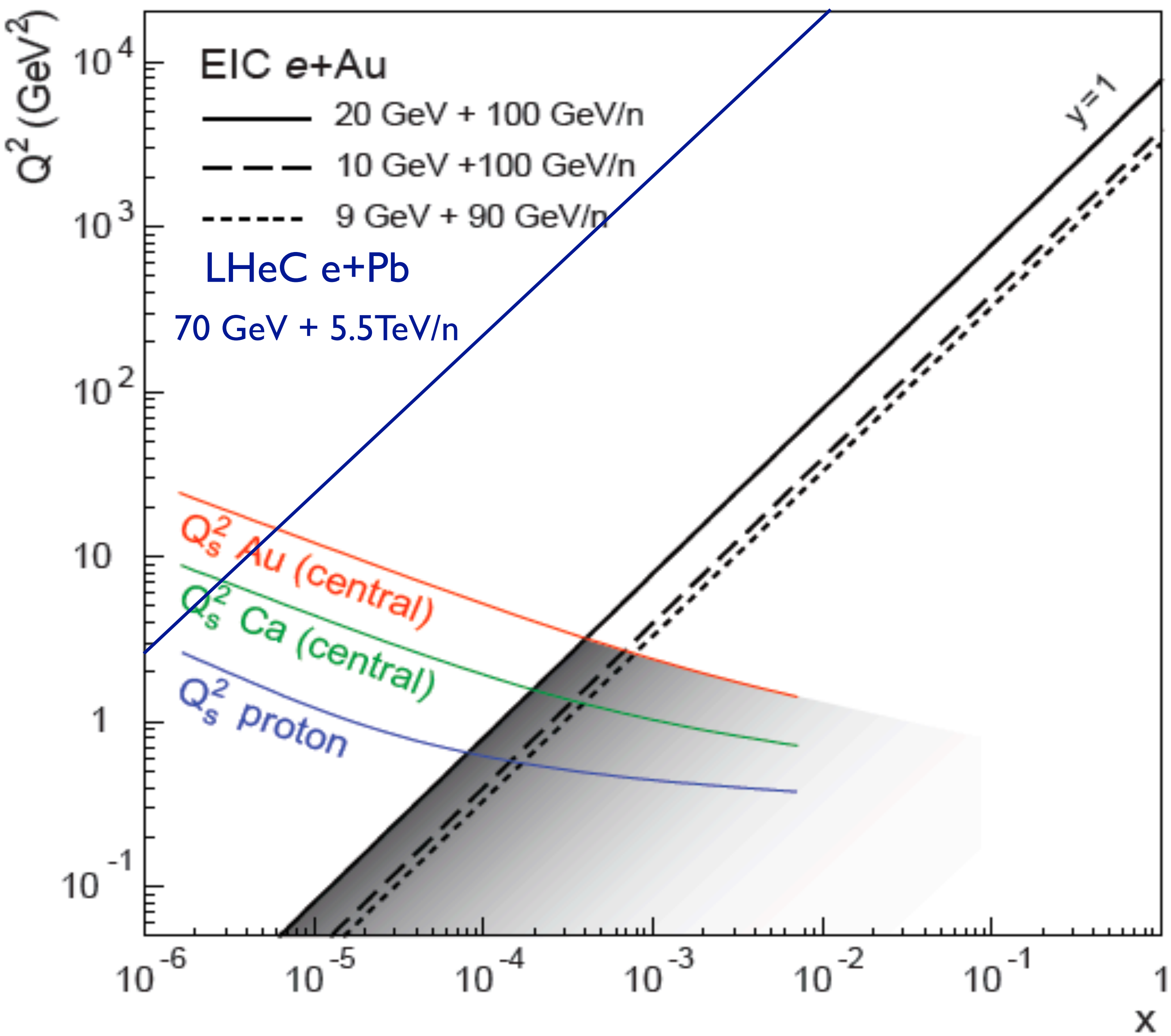
4x250



10x250



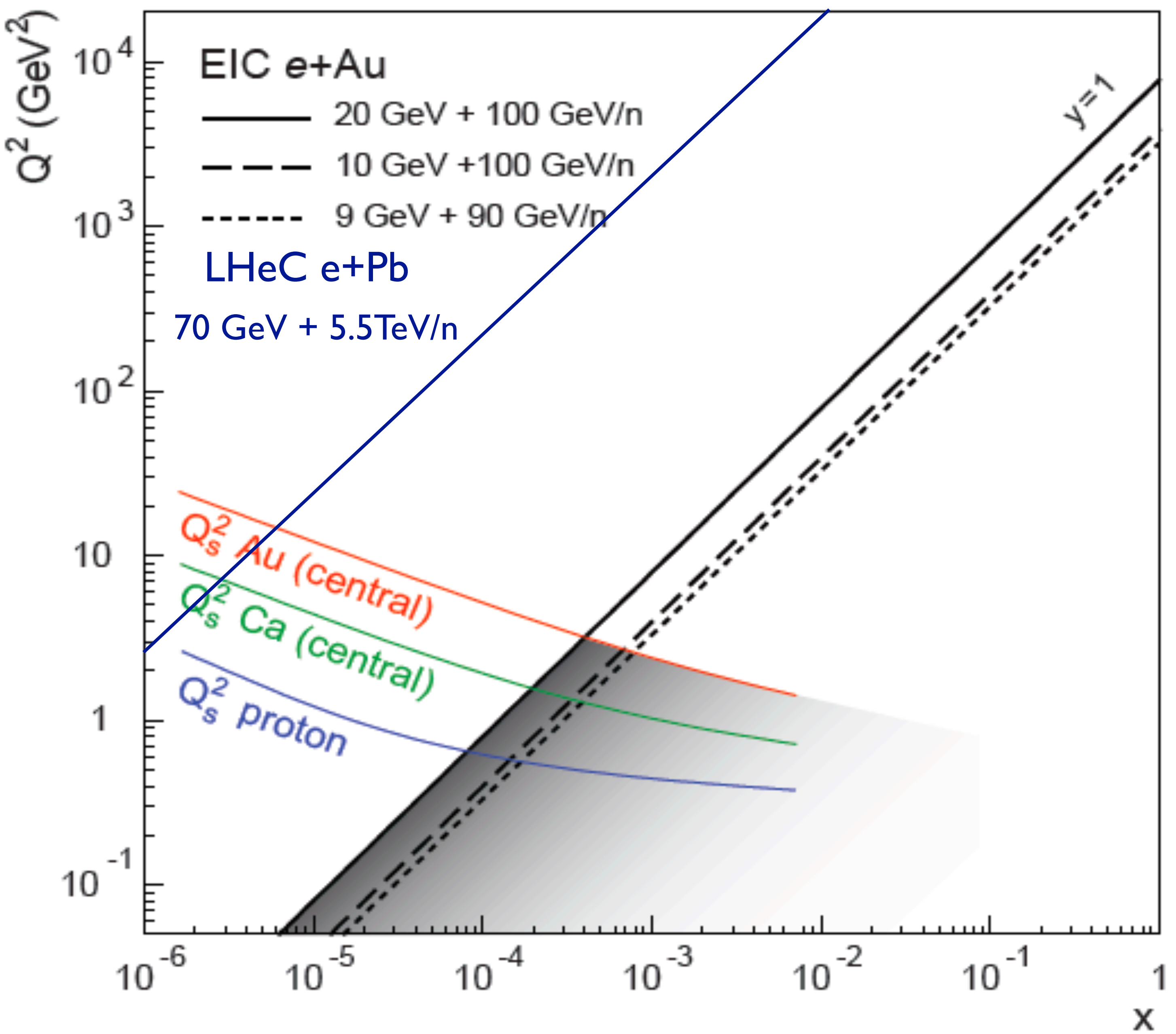
Phase-space coverage of an e+p/h experiments



- Large coverage in x-Q^2 phase space
- Results from both collider and fixed-target experiments complement each other

- Onset of saturation possibly observed in collisions at HERA at very low-x
- calculations are difficult at small Q_s^2 (< 2 GeV^2)

Phase-space coverage of an e+p/h experiments



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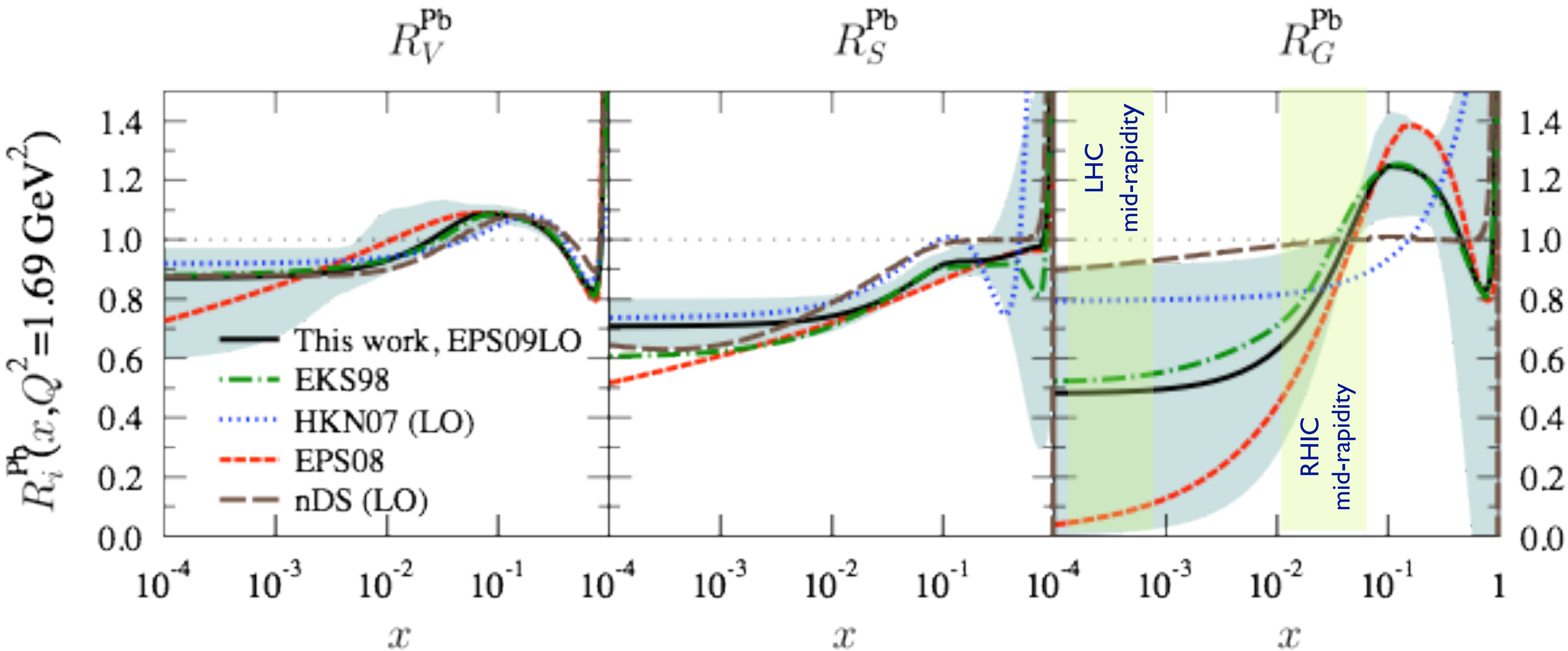
Electron Ion Collider:

- $\mathcal{L}$(EIC) > 100 × $\mathcal{L}$(HERA)
- Electrons
  - E_e = 3 - 20 GeV
  - polarised
- Polarised *p*

How well are gluons understood in nuclei?



The distribution of valence and sea quarks are relatively well known in nuclei - theories agree well

Large discrepancies exist in the gluon distributions from models for mid-rapidity LHC and forward RHIC rapidities !!

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xDVMP MC Generator

- A MC generator for exclusive diffractive vector meson production
  - ➡ Thomas Ullrich's implementation of the b-Sat/b-CGC model for e+p and e+A
- Exclusive diffractive vector meson production is one of the most promising ways to study saturation in ep/eA
  - ➡ Naive: $\sigma \sim G(x,Q^2)^2$
- Issues:
  - ➡ Experimentally difficult
    - rapidity gap, breakup, $\int L dt$ needed ?
    - reconstruction of t
    - detector requirements (resolution, acceptance)
    - sensitivity to physics (saturation)?
    - need to study in ep and eA

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Requirements for a new generator

- Simple, i.e. easy to use, manipulate and modify
  - ➡ single purpose: $e\ p \rightarrow e'\ p'\ V$
  - ➡ write only the necessary core
  - ➡ reuse what is available (and accessible)
- Based on a model that is known to describe data well
  - ➡ Dipole model (works well at Hera)
- Extendable to eA
  - ➡ Dipole model does that
- Modern
  - ➡ C++, integrates with ROOT and other tools
- Output should follow standards as much as possible
- Useful for detector/acceptance studies as well as physics studies (e.g., sensitivity to $xG(x,Q^2)$ etc.)

Dipole Model (I)

Cross-section for production of final state VM:

$$\frac{\mathrm{d}\sigma_{T,L}^{\gamma^* p \to Ep}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\mathcal{A}_{T,L}^{\gamma^* p \to Ep}\right|^2 = \frac{1}{16\pi}\left|\int \mathrm{d}^2\boldsymbol{r}\int_0^1 \frac{\mathrm{d}z}{4\pi}\int \mathrm{d}^2\boldsymbol{b}\,(\Psi_E^*\Psi)_{T,L}\,\mathrm{e}^{-\mathrm{i}[\boldsymbol{b}-(1-z)\boldsymbol{r}]\cdot\boldsymbol{\Delta}}\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\boldsymbol{b}}\right|^2$$

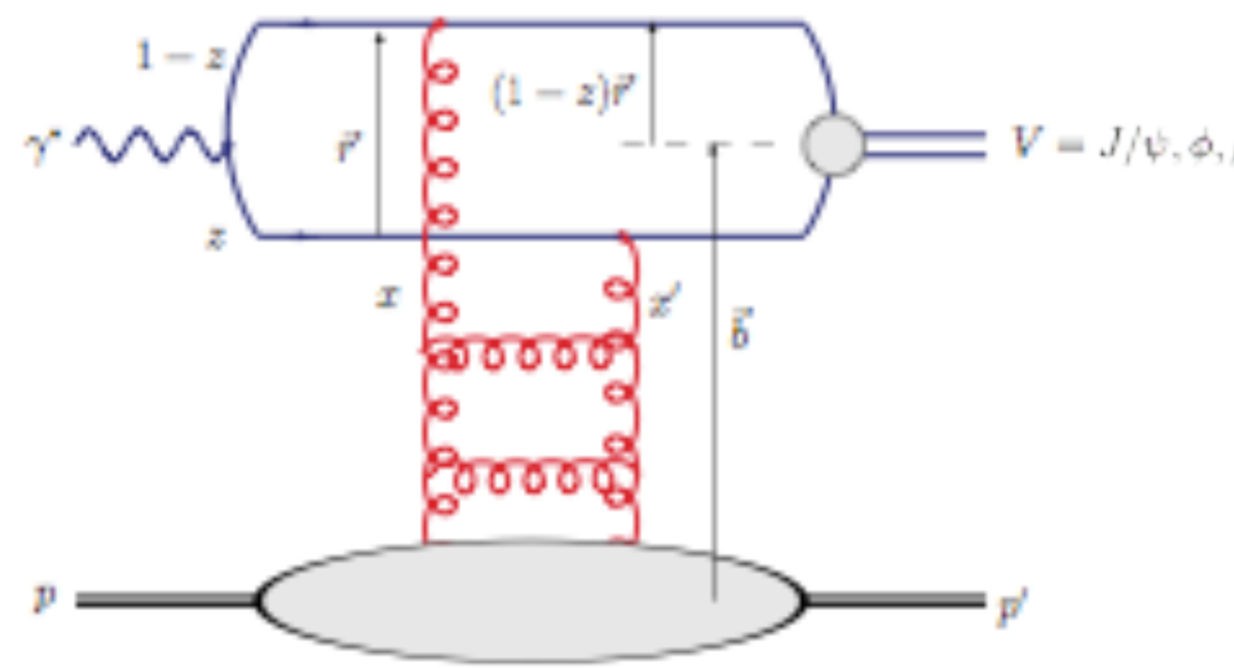
Amplitude

Overlap between photon and VM wave function

Dipole Cross-Section

Many dipole models on the market:

- Use : H. Kowalski, L. Motyka, G. Watt, Phys. Rev. D74, 074016
- Describes Hera data well
- has b-dependence
- Michael & TU have experience with it
- Henri is around to ask
- can be “easily” modified to do eA (via b-dependence)



Dipole Model (II)

Cross-section for production of final state VM:

$$\frac{d\sigma_{T,L}^{\gamma^* p \to Ep}}{dt} = \frac{1}{16\pi}\left|\mathcal{A}_{T,L}^{\gamma^* p \to Ep}\right|^2 = \frac{1}{16\pi}\left|\int d^2\boldsymbol{r}\int_0^1 \frac{dz}{4\pi}\int d^2\boldsymbol{b}\,(\Psi_E^*\Psi)_{T,L}\,e^{-i[\boldsymbol{b}-(1-z)\boldsymbol{r}]\cdot\boldsymbol{\Delta}}\frac{d\sigma_{q\bar{q}}}{d^2\boldsymbol{b}}\right|^2$$

Overlap between photon and VM wave function

Dipole Cross-Section

Wave function:

- Boosted Gaussian
  - ➡ Forshaw, Sandapen, Shaw
- GausLC
  - ➡ Dosch, Gousset, Kulzinger, Pirner, Teaney, Kowalski
- Parameters tuned for HERA are available
- any improved wave function can be easily plugged in

Dipole Cross-Section:

- b-Sat
  - ➡ uses DGLAP evolution from initial G (x,Q)
  - ➡ can be adapted for A (b-dependence)
- b-CGC
- Parameters tuned for HERA are available

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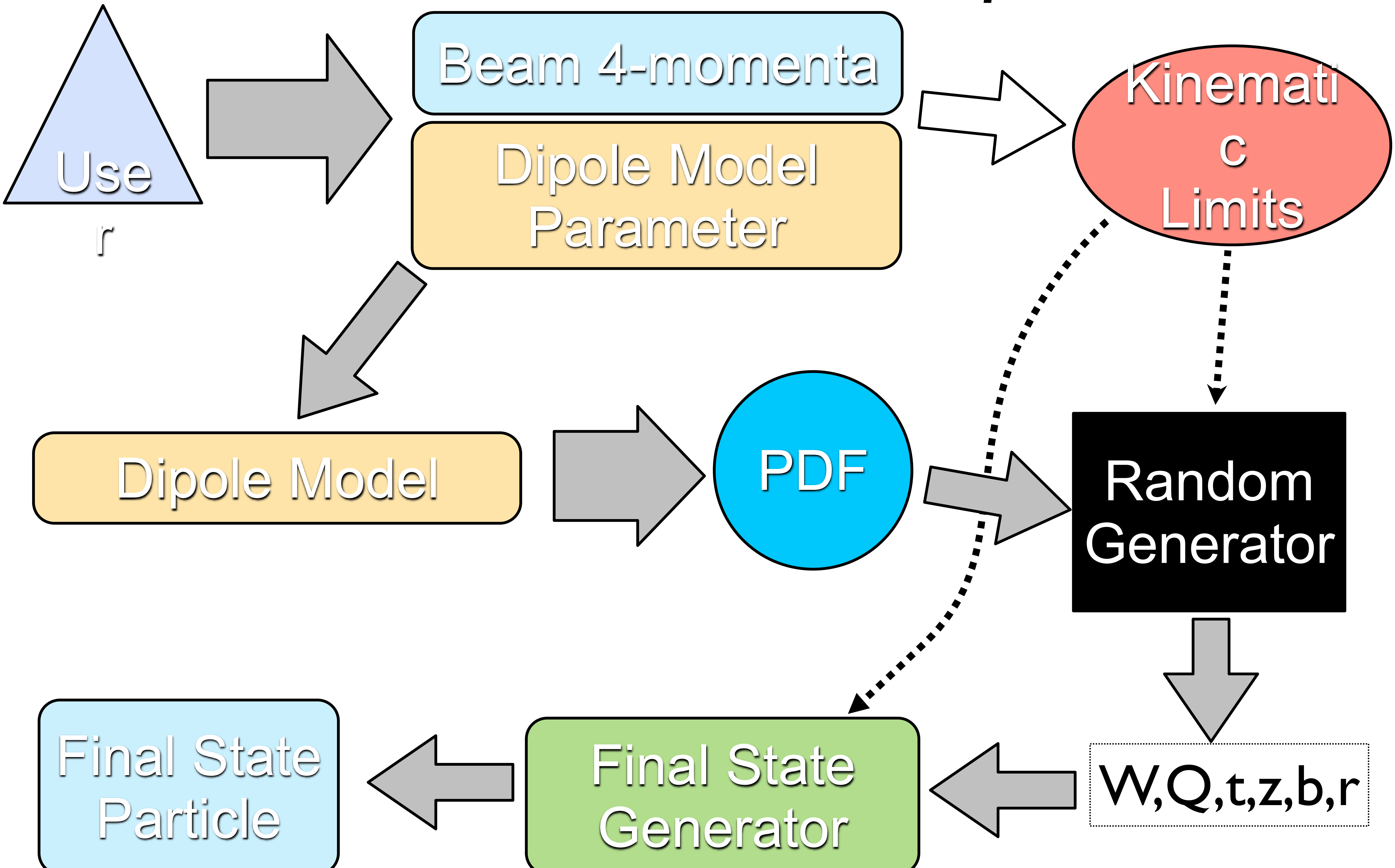
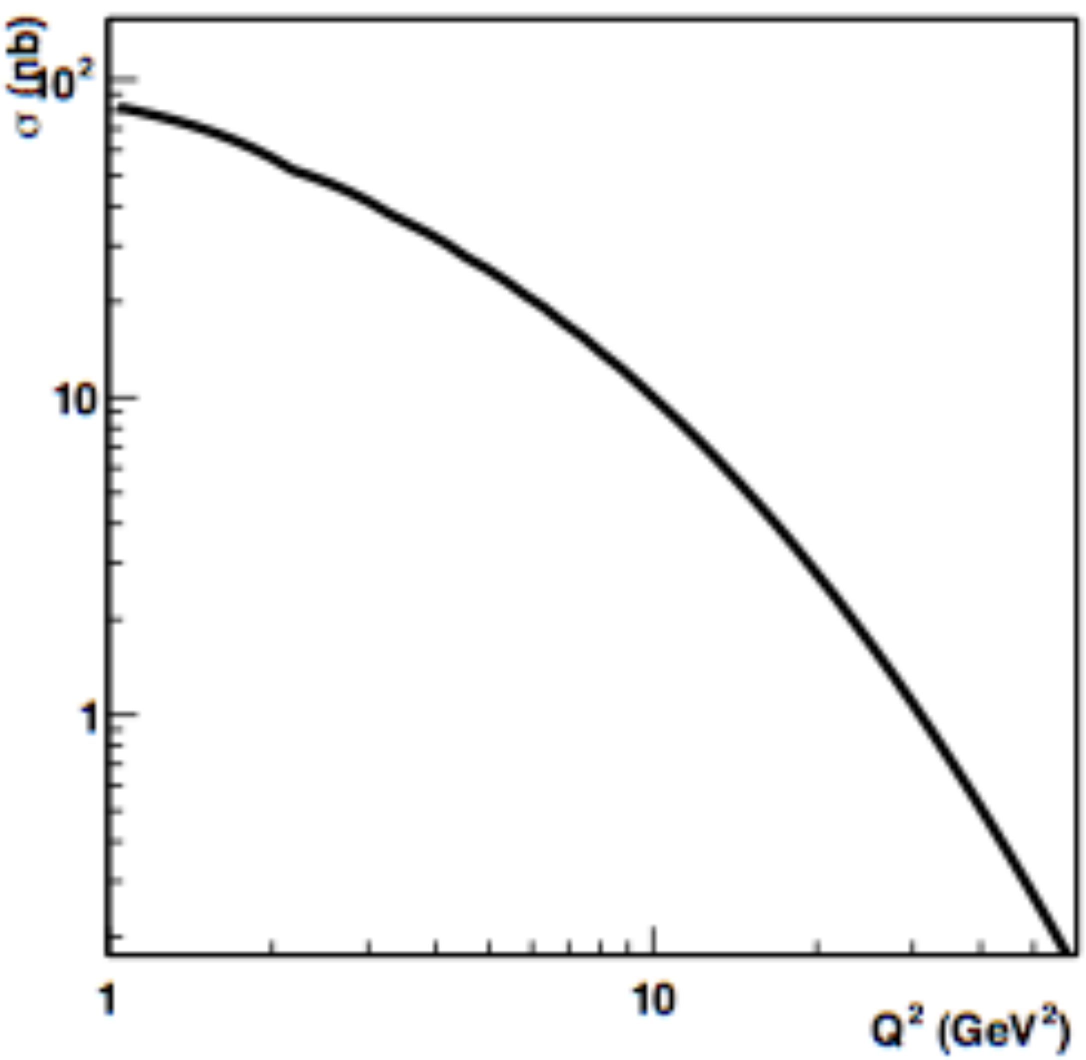
Basic scheme behind *xdvmpGenerator*



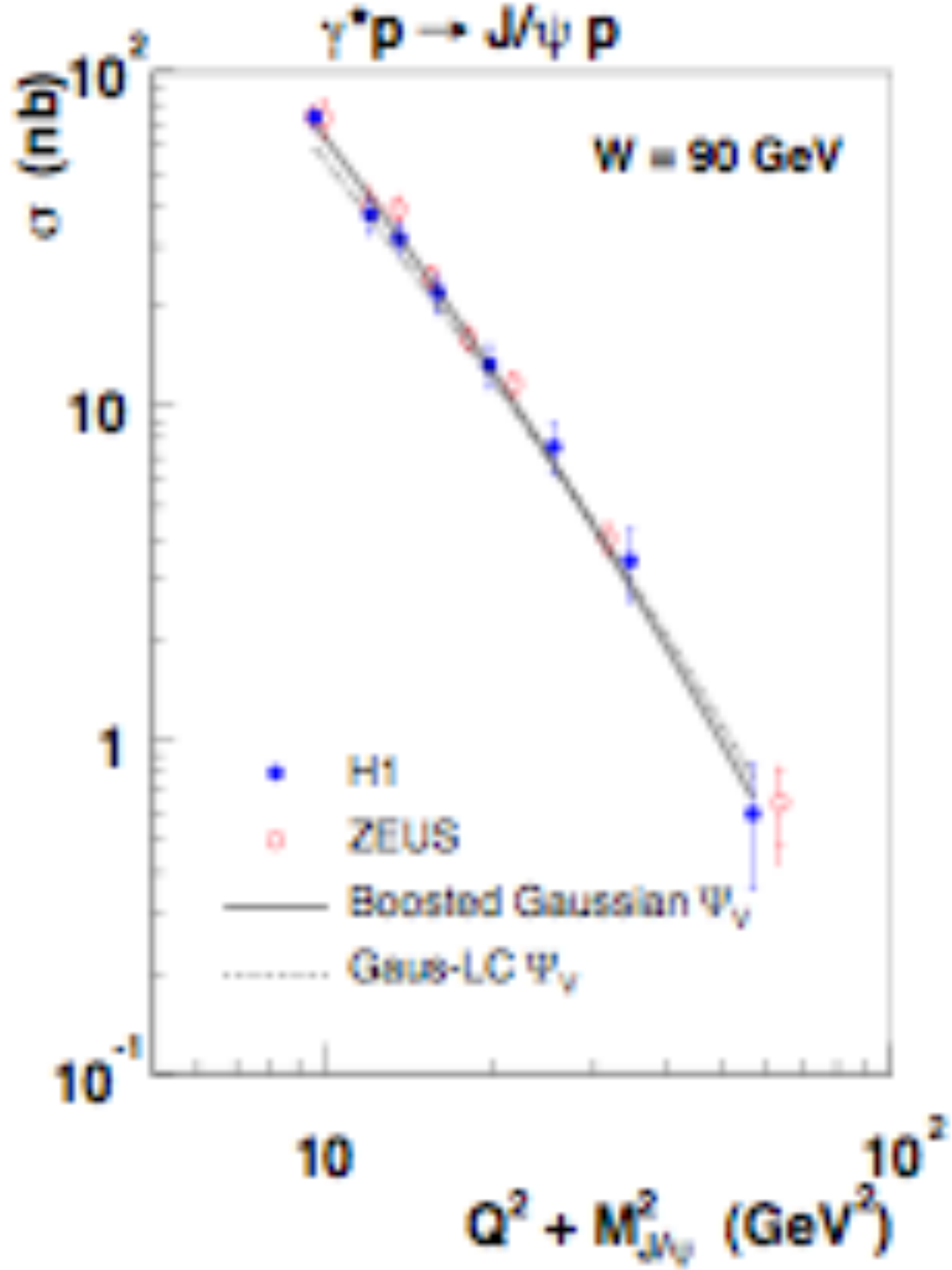
Implementation

- Follow Pythia8 philosophy
  - ➡ main program to be provided by user
  - ➡ *xdvmpGenerator* is a class with simple methods
    - init(), generateEvent(), printEventRecord(), ...
    - event record in plain structure (*xdvmpEvent*)
    - setup through runcard (txt file) or programmatically
  - ➡ *xdvmpGenerator* uses many other classes and functions
    - class *xdvmpDipoleModel* (dipole model implementation)
      - alphaStrong.cpp (fcts to calculate α_s - adapted from MRST, rewritten in C++)
      - laguerre.c, dglap.c (for DGLAP from F. Gelis)
    - class *xdvmpFinalStateGenerator* (generate final state particles from x, Q^2, s, t)
    - class *xdvmpSettings* (handle parameter & runcard parsing)
  - ➡ Total ~ 4200 lines of code only (requires only GSL, ROOT libs)

Dipole Model Test (I)



W = 90 GeV



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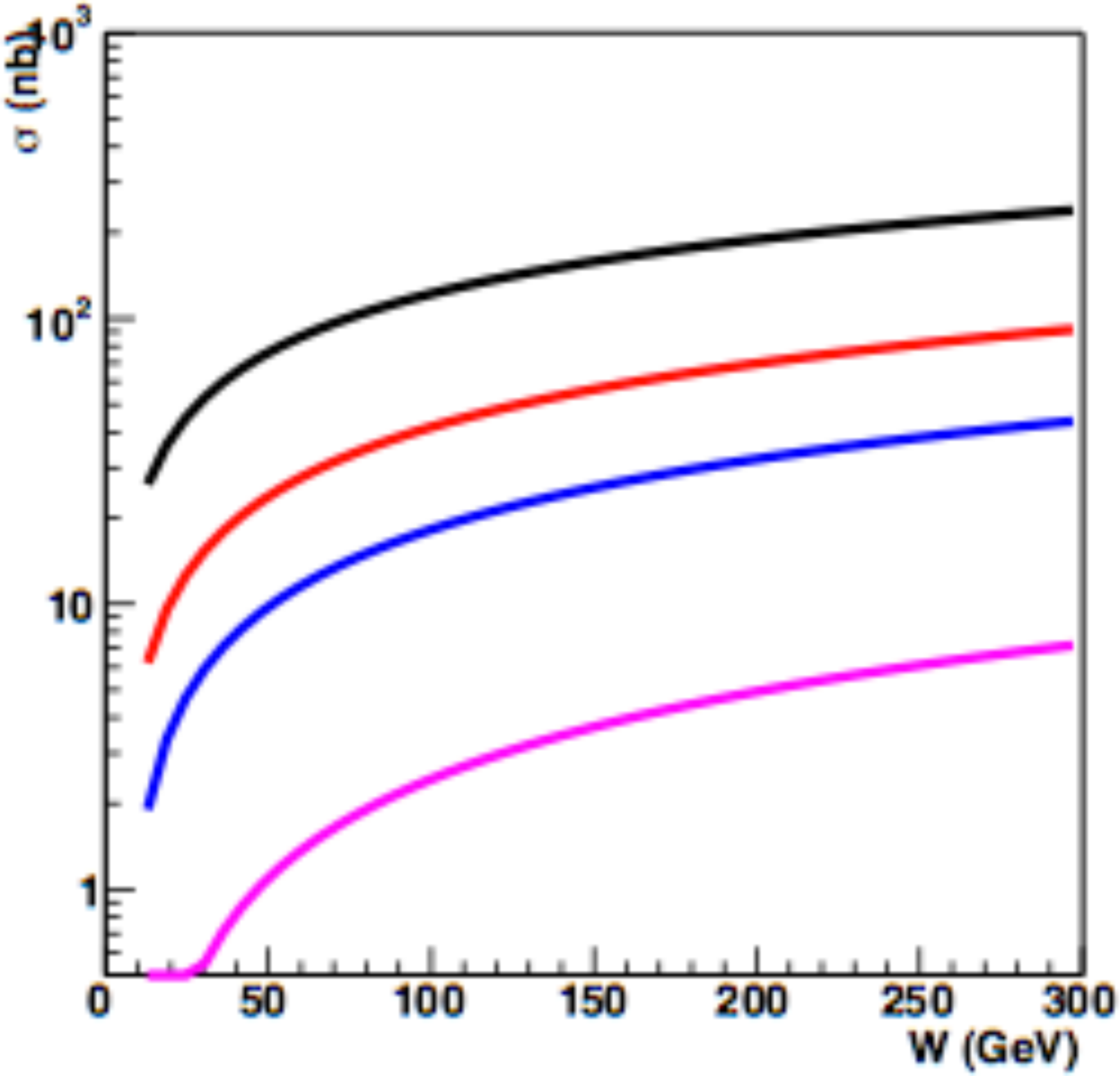
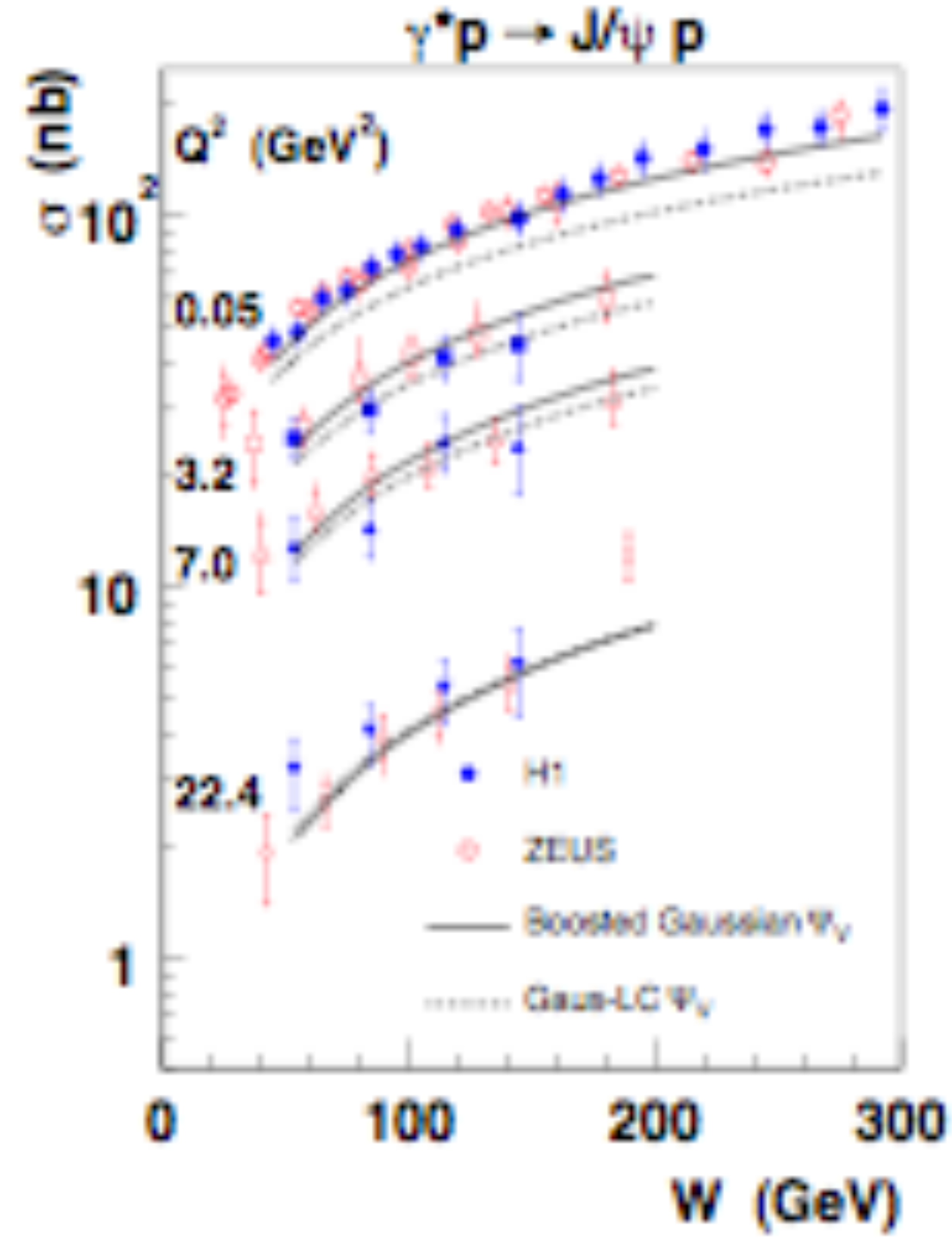
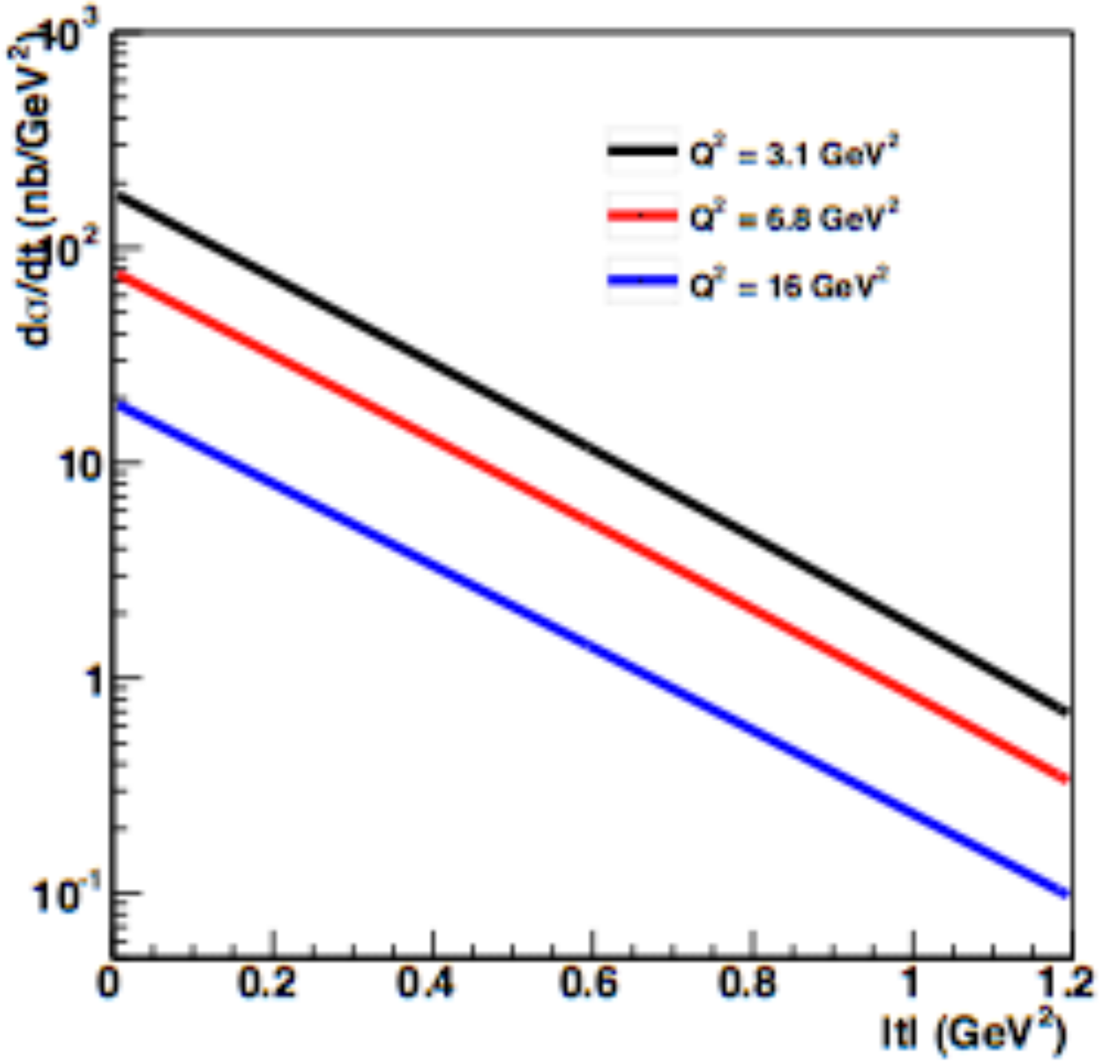
Dipole Model Test (II)

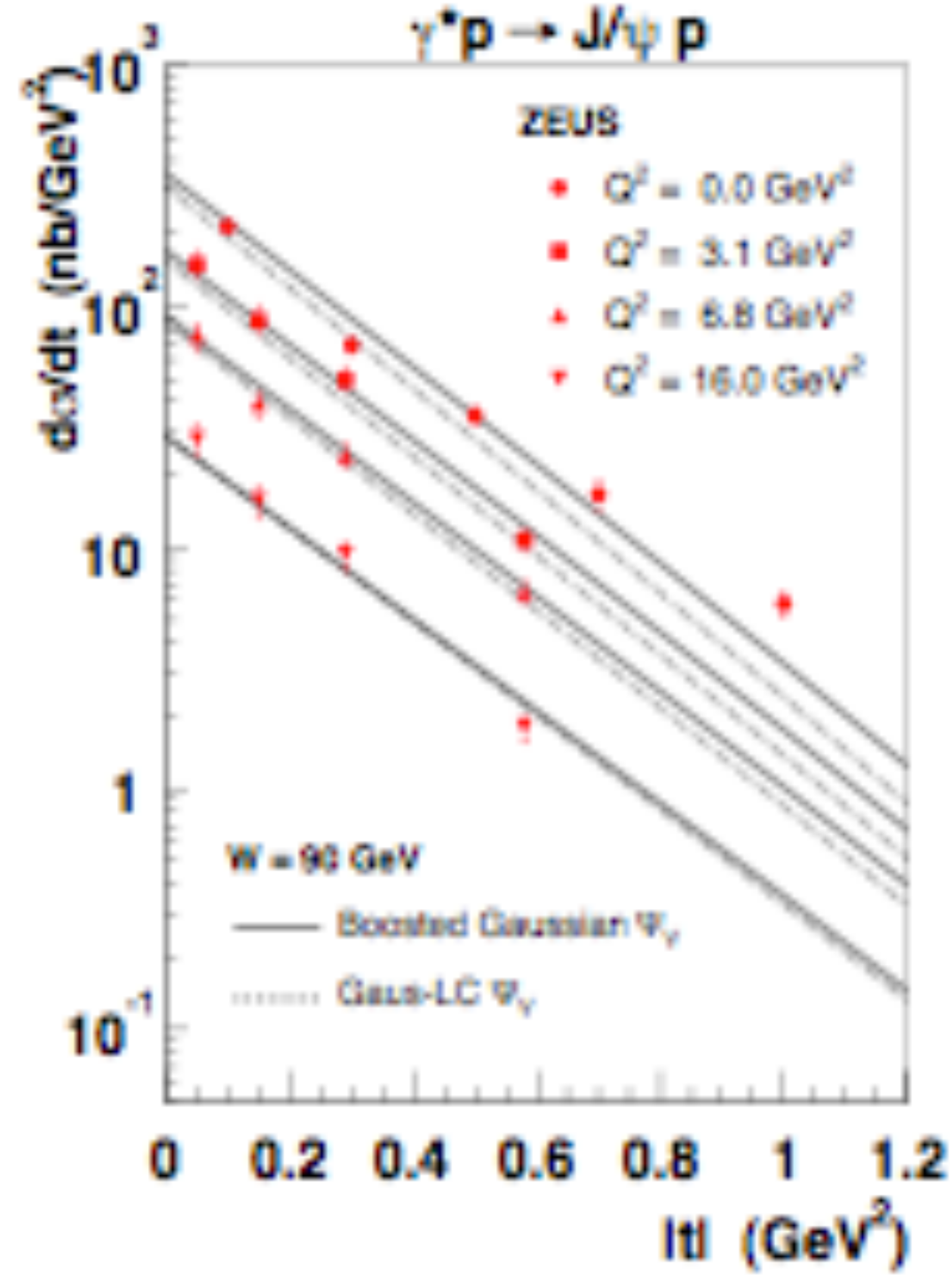




Q2 = 0.5, 3.2, 7.0, 22.4 GeV2

Dipole Model Test (III)





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xDVMP status

Home · Overview · API Reference · Event Generator

xdvmp Documentation

Getting started

- Overview
- Downloading
- Installing xdvmp

xdvmp Basics

- Event Generator
- Example program: xdvmpMain

API Reference

- Overview
- class xdvmpGenerator
- class xdvmpSettings
- class xdvmpDipoleModel
- class xdvmpFinalStateGenerator
- class xdvmpEvent (Event Record)
- Runcard Reference

The Physics Behind the Model

- The Dipole Model
- Generation of final state particles
- References & Credits

What's New?

Troubleshooting

- Known problems
- To-do list

Last Update: April 6, 20

Some final testing required before it is released into the wild ….

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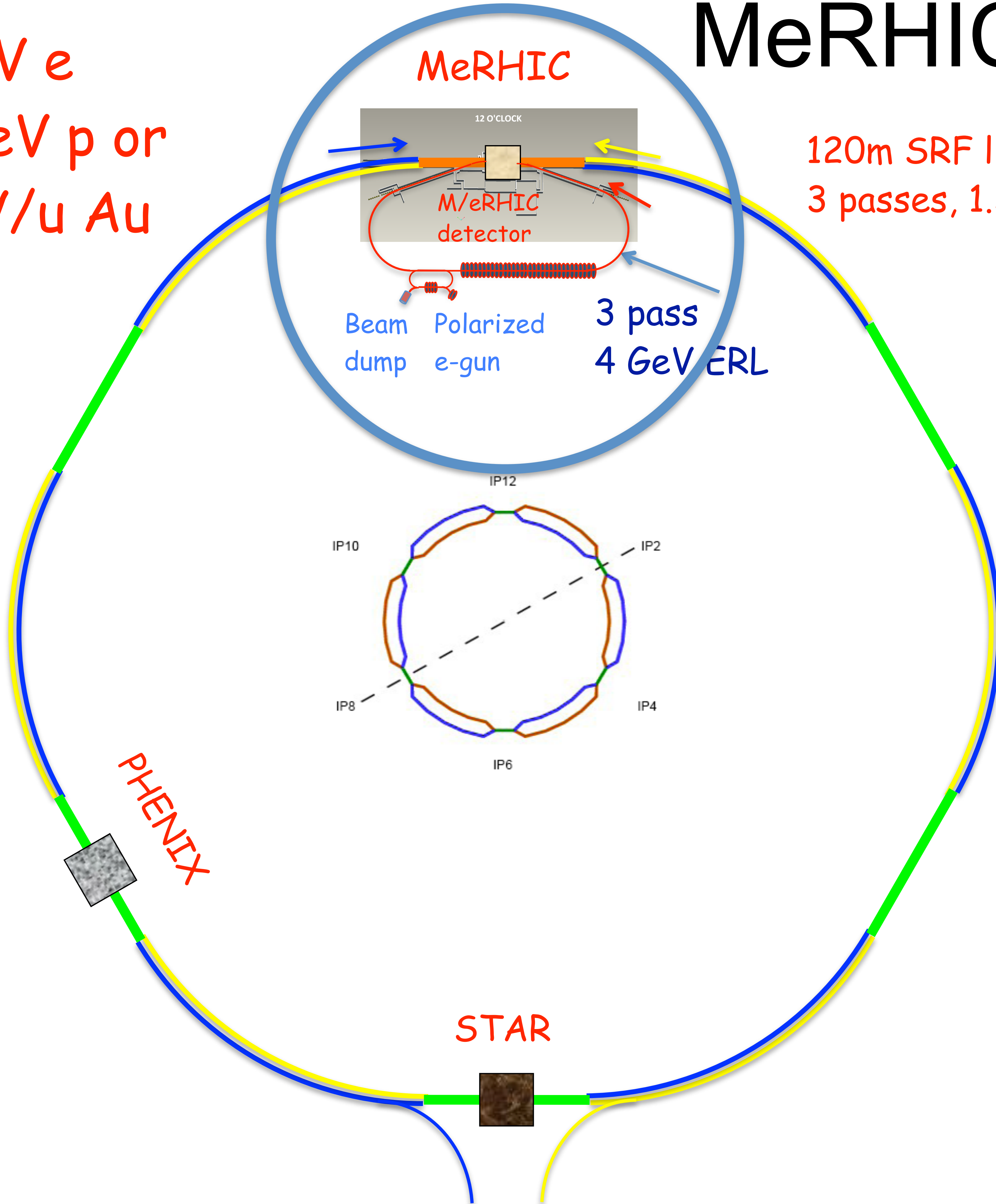
MeRHIC at BNL

4 GeV e
x 250 GeV p or
100 GeV/u Au

120m SRF linac
3 passes, 1.3 GeV/pass

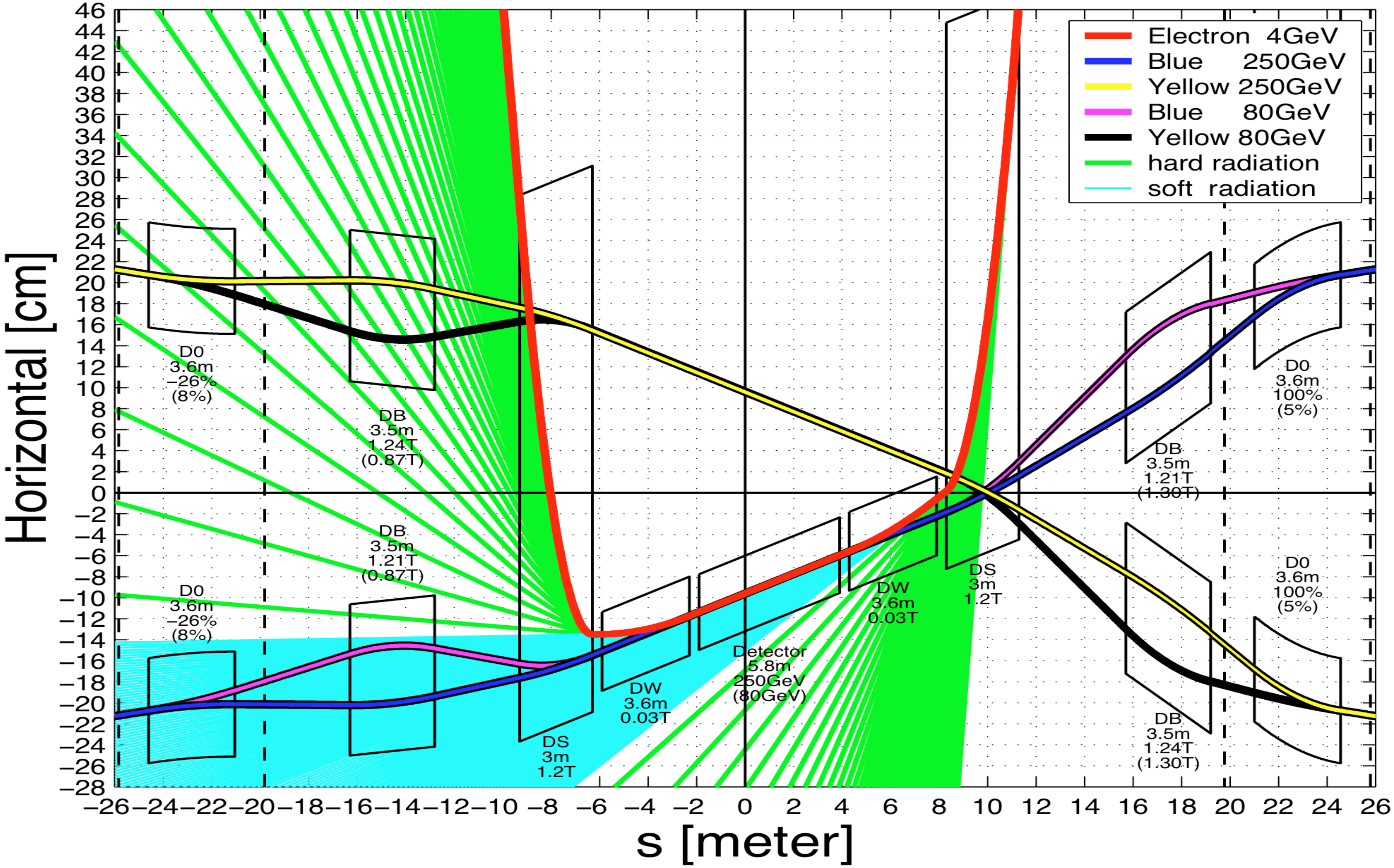


Detector requirements from physics

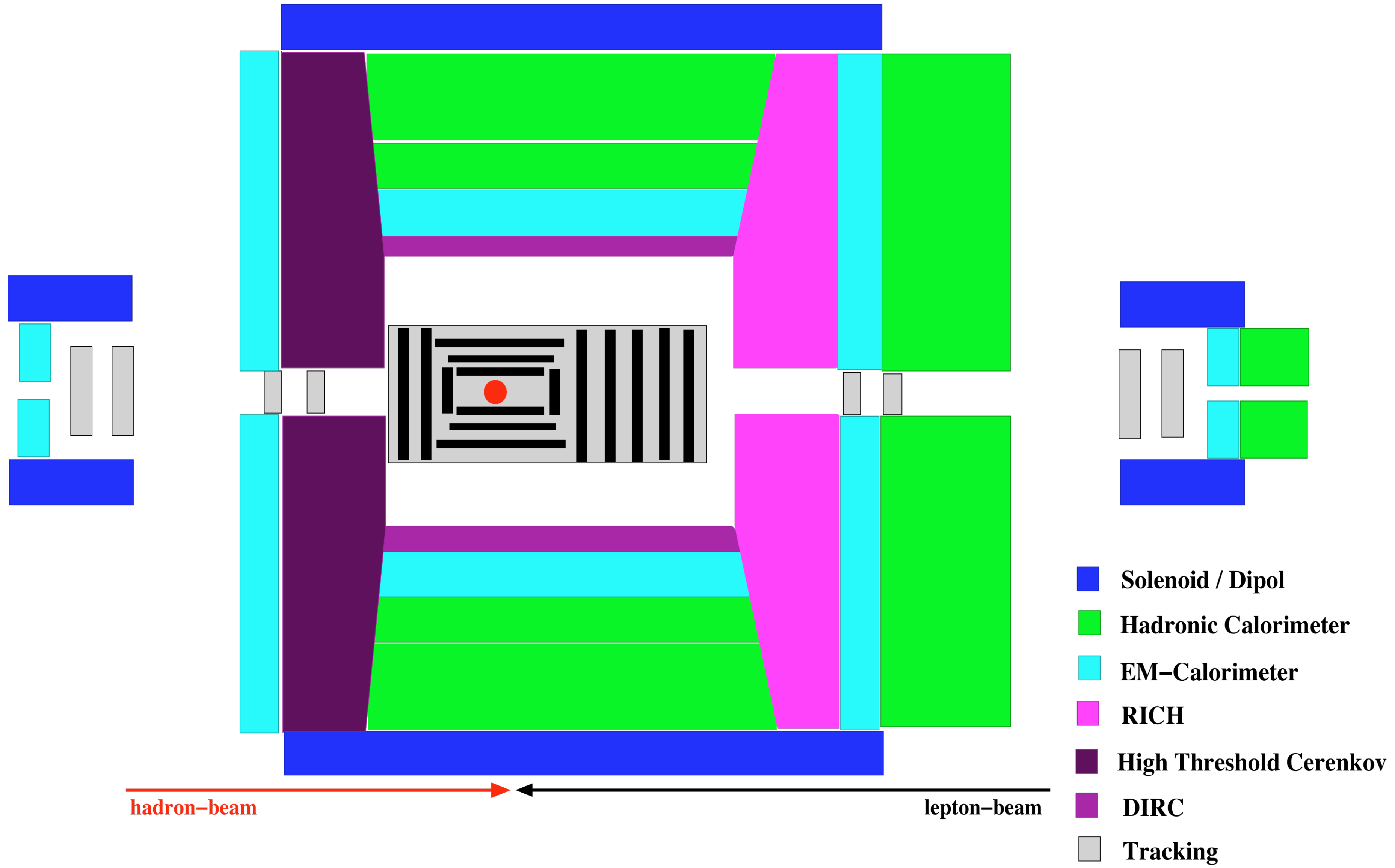
- e+p physics
  - ➡ Need the same detector for inclusive (ep → e'X), semi-inclusive (ep → e'X + hadrons) and exclusive (ep → e'p+π) reactions
    - Need to have a large acceptance (*both* mid- and forward-rapidity)
    - Crucial to have particle identification
      - e, π, K, p, n over wide momentum range and scattering angles
      - excellent secondary vertex resolution (charm)
    - small systematic uncertainty for e/p polarisation measurements
    - small systematic uncertainty for luminosity measurements
- e+A physics
  - ➡ most requirements similar to e+p guidelines
  - ➡ additional complication arises from the need to tag the struck nucleus in exclusive and diffractive reactions
- Also, important to have the same detector for all energies

Latest IR Design for MeRHIC at IP2

- No DX magnet
- No synchrotron shielding included
- Height of beam from floor ~ 6 feet
- Allows p and A decay product tagging

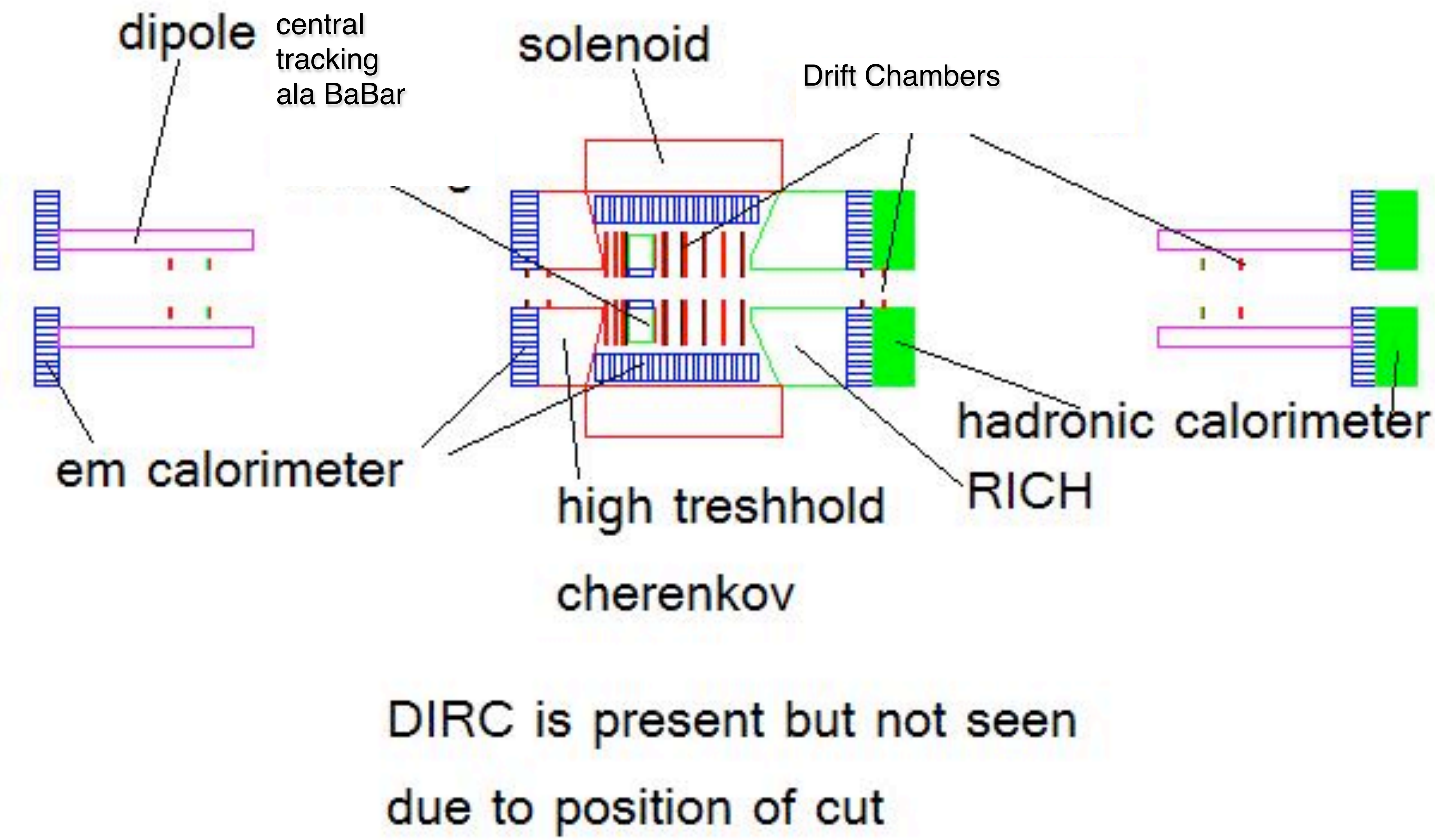


First attempt at detector design



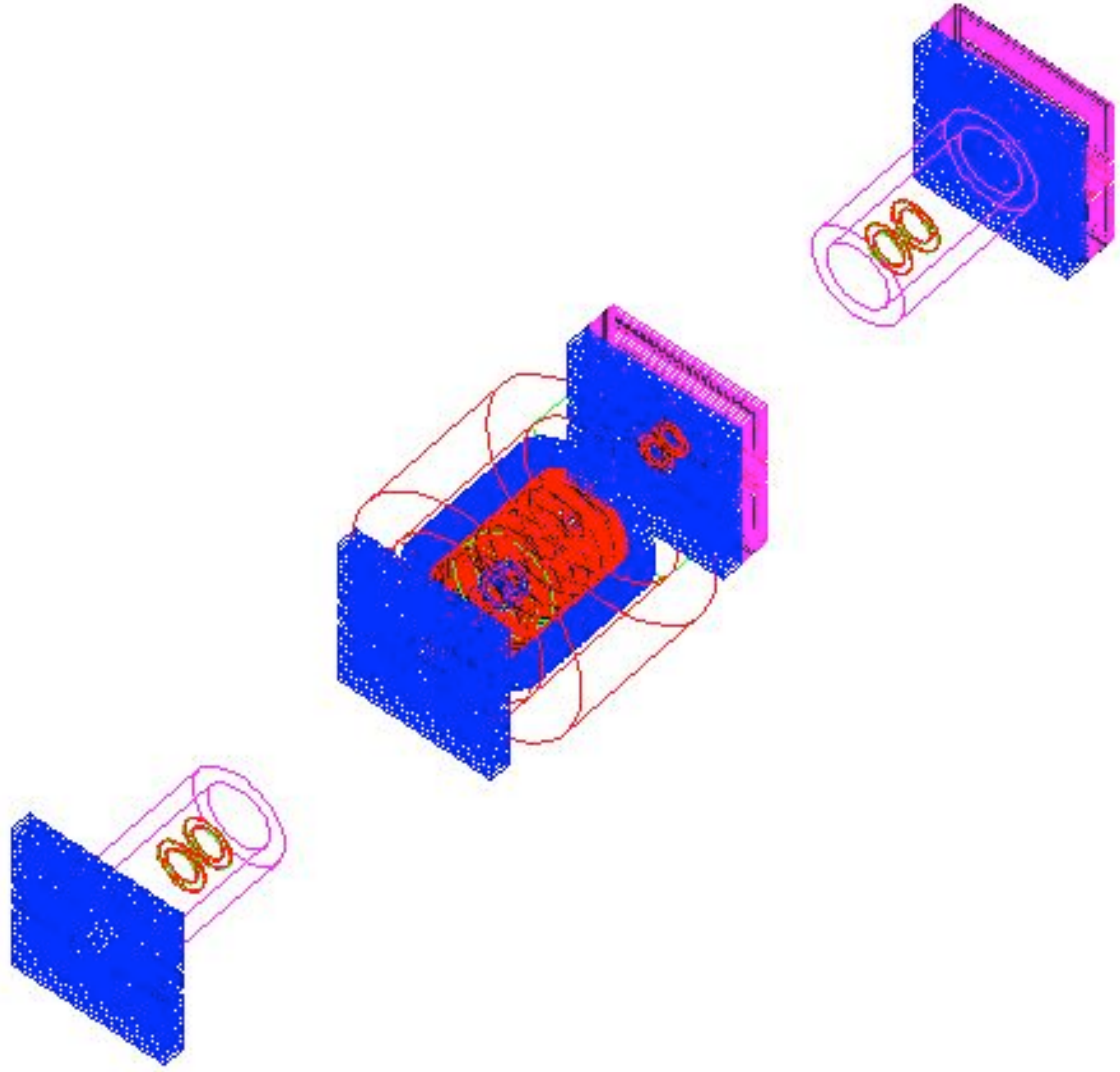
- Dipoles need to have good forward momentum resolution
  - ➡ Solenoid has no magnetic field for r → 0
- RICH, DIRC for hadron pid
- High threshold Cherenkov → fast trigger for scattered lepton
- Radiation length very critical → low lepton energies

MeRHIC Detector in Geant 3

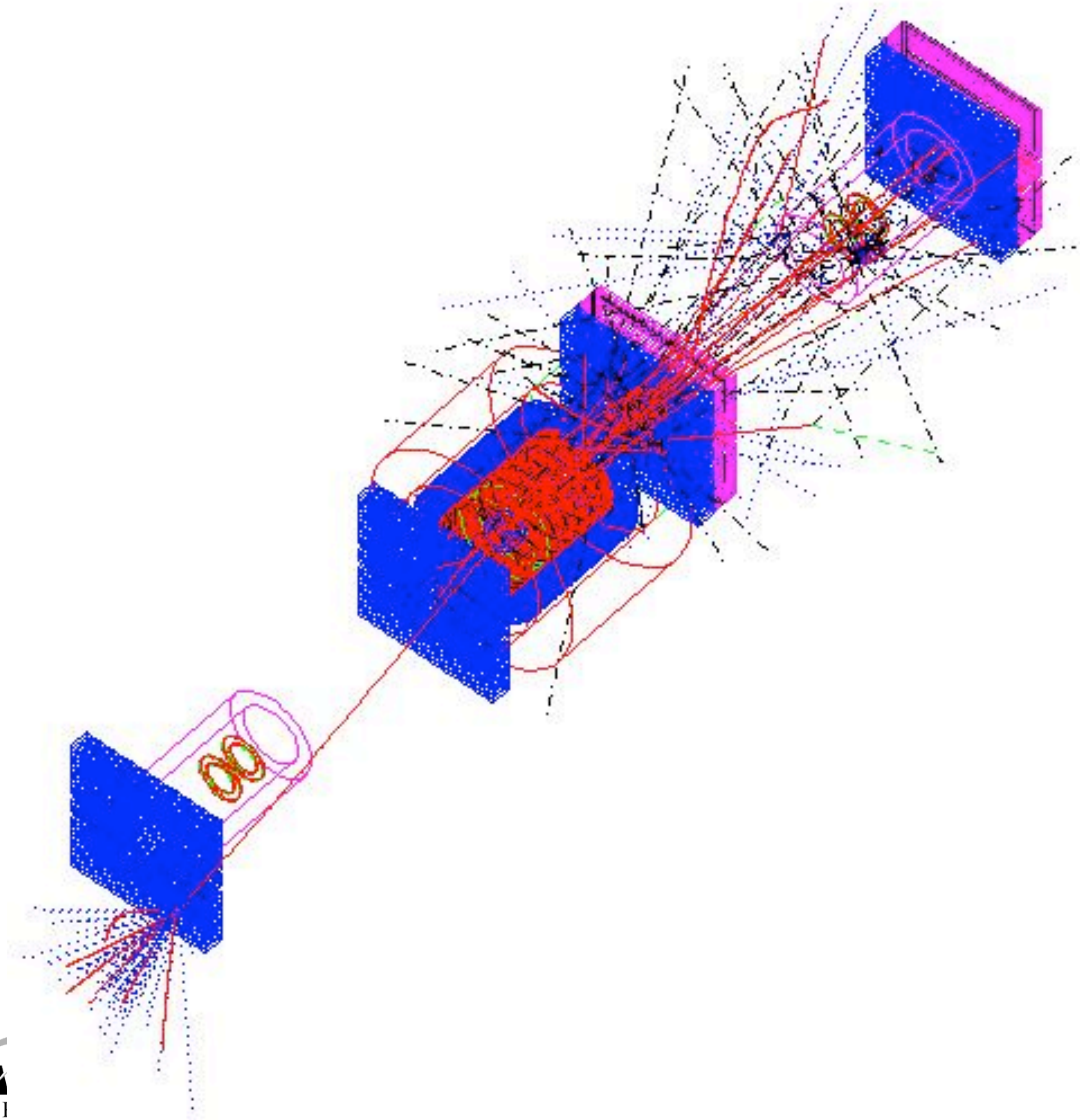


- Note - no hadronic barrel calorimeter due to height restrictions at IP2

MeRHIC detector in Geant 3

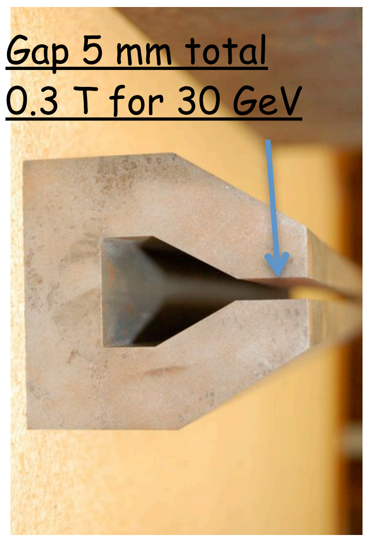


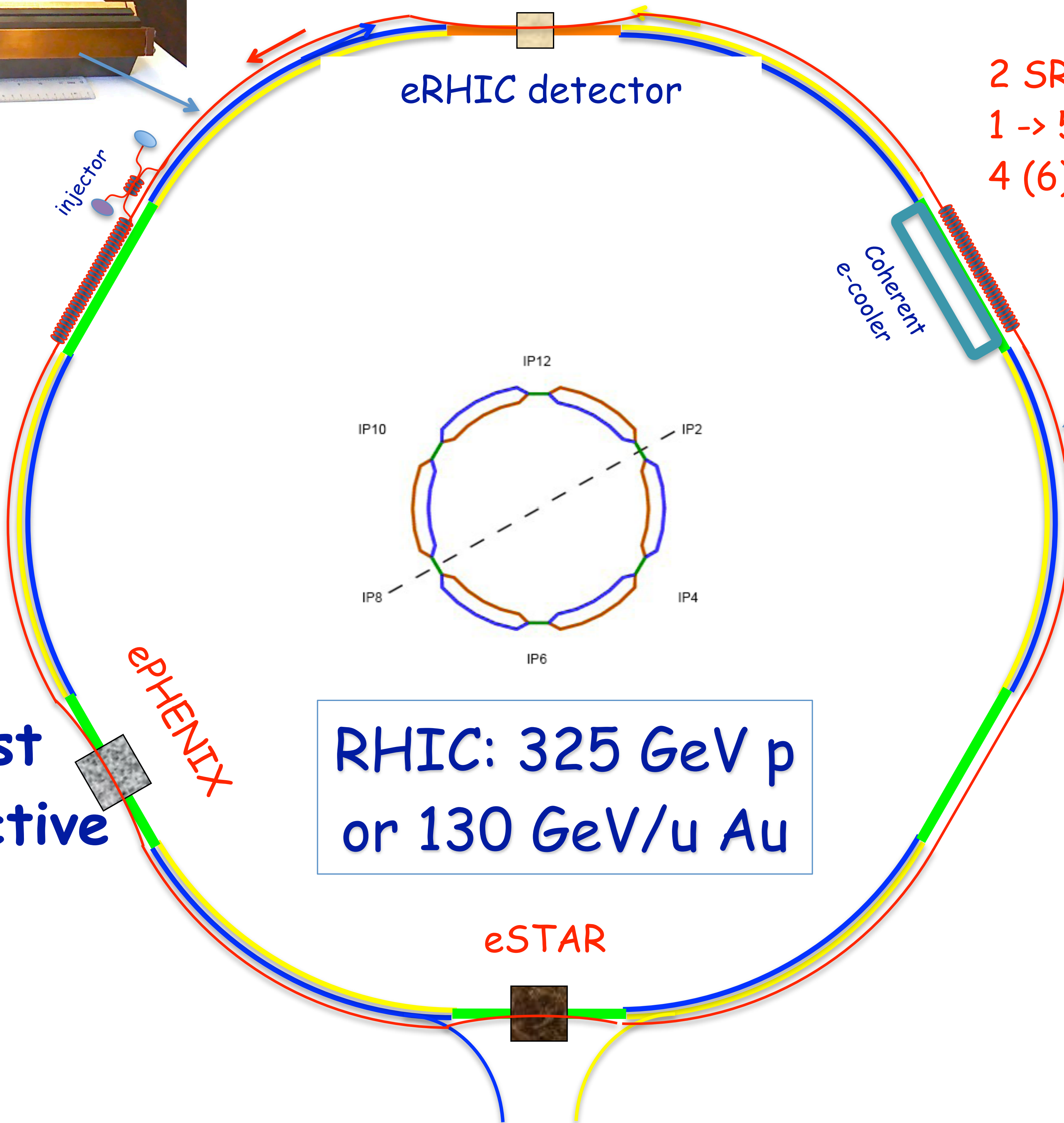
MeRHIC detector in Geant 3



Staging all-in tunnel eRHIC:

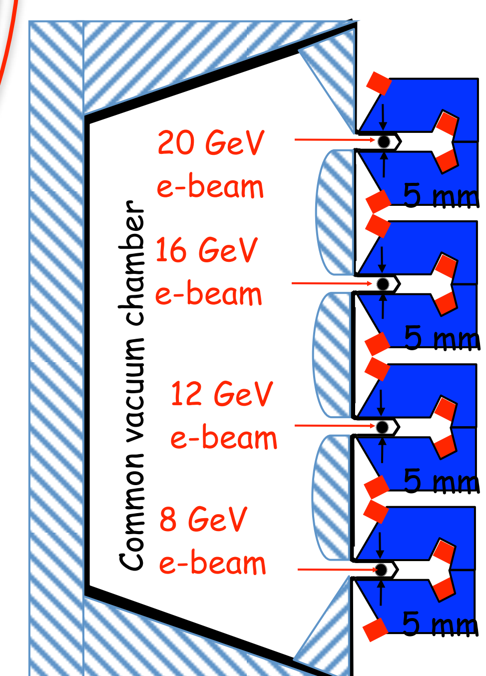
energy of electron beam is increasing from 5 GeV to 30 GeV by building-up the linacs





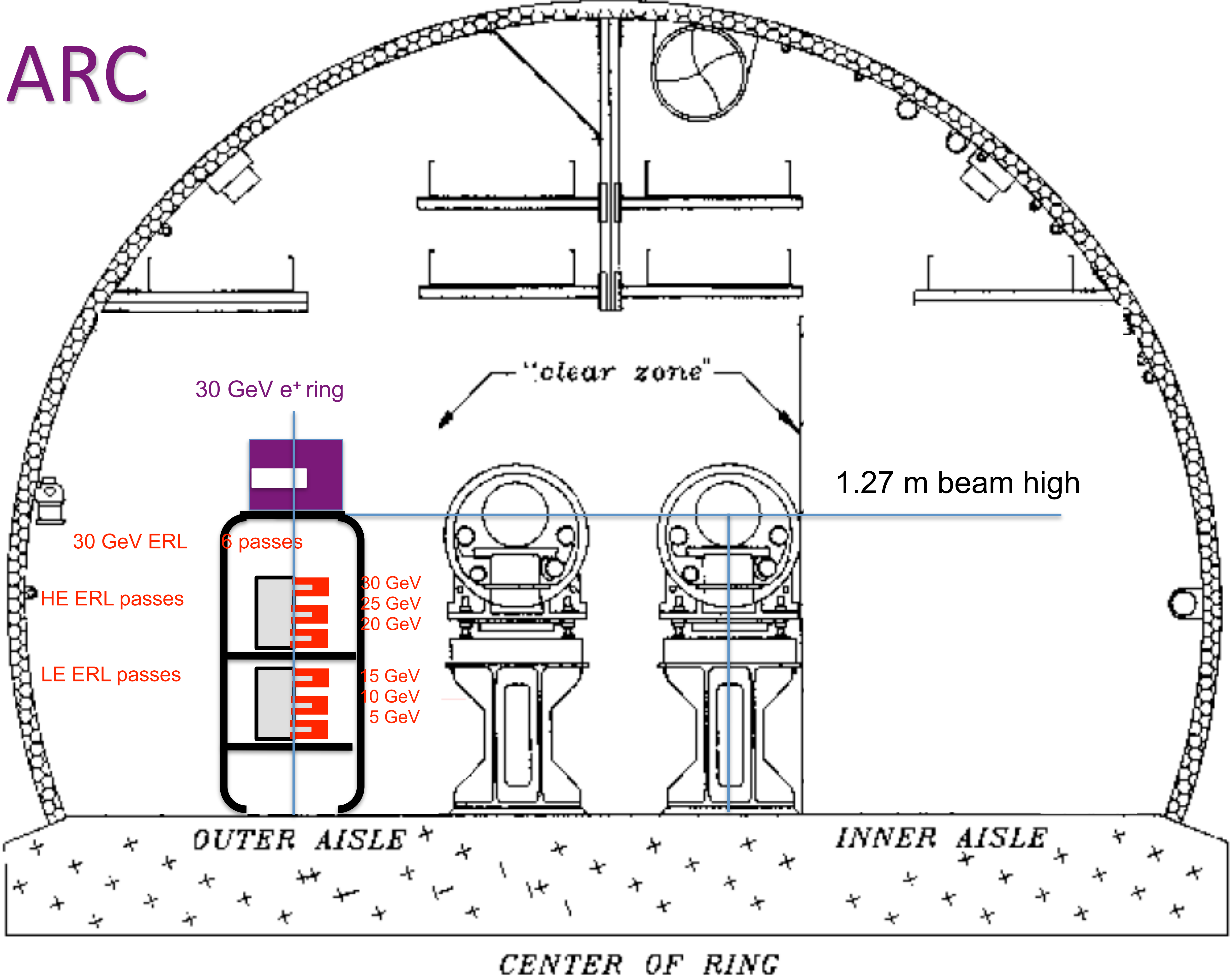
2 SRF linac
1 -> 5 GeV per pass
4 (6) passes

4 to 6 vertically separated recirculating passes. # of passes will be chosen to optimize eRHIC cost



The most cost effective design

ARC

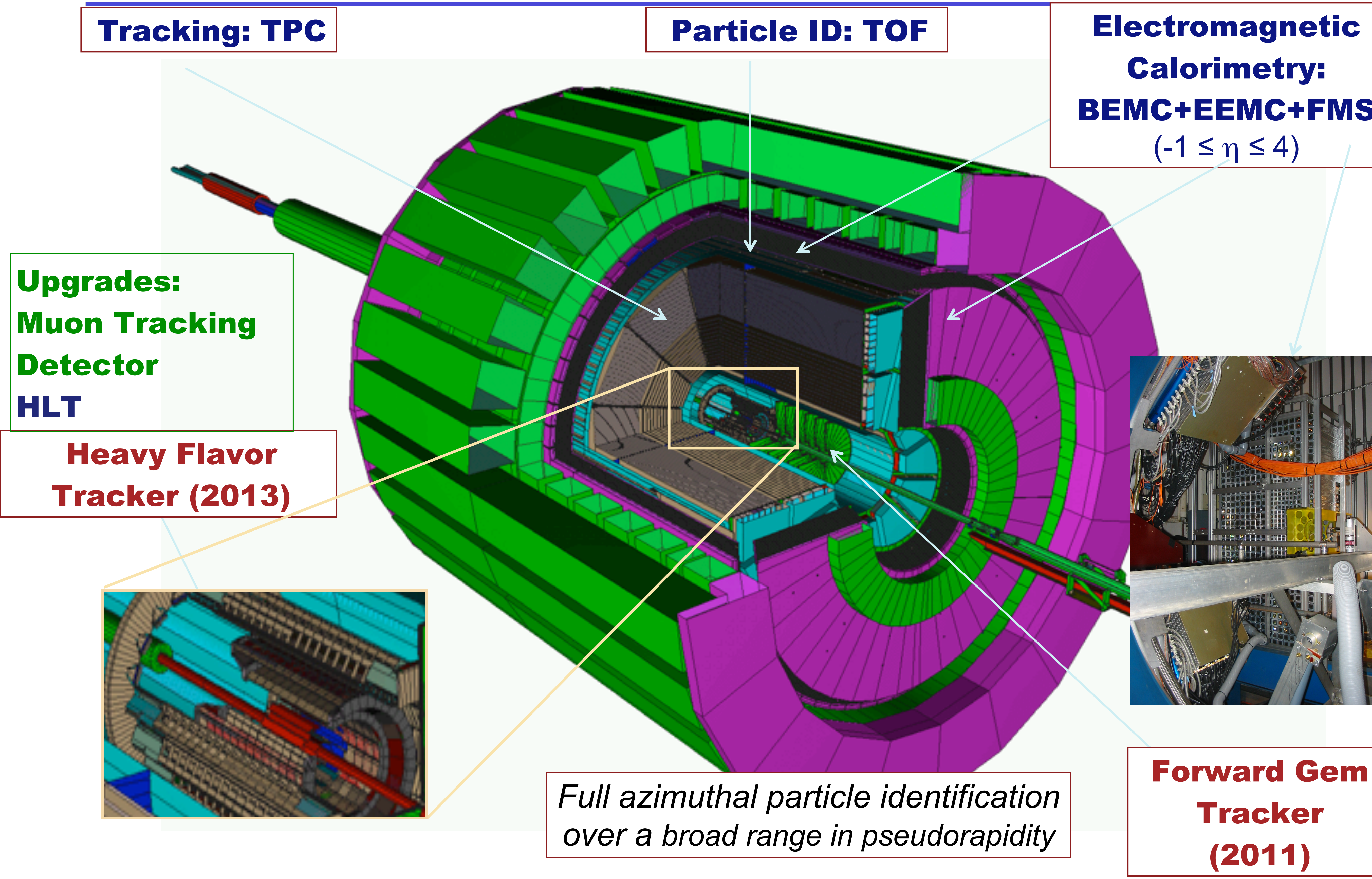


"clear zone"
30 GeV e+ ring
1.27 m beam high
30 GeV ERL
6 passes
HE ERL passes
30 GeV
25 GeV
20 GeV
LE ERL passes
15 GeV
10 GeV
5 GeV
OUTER AISLE
INNER AISLE
CENTER OF RING

Incorporating eSTAR and ePHENIX

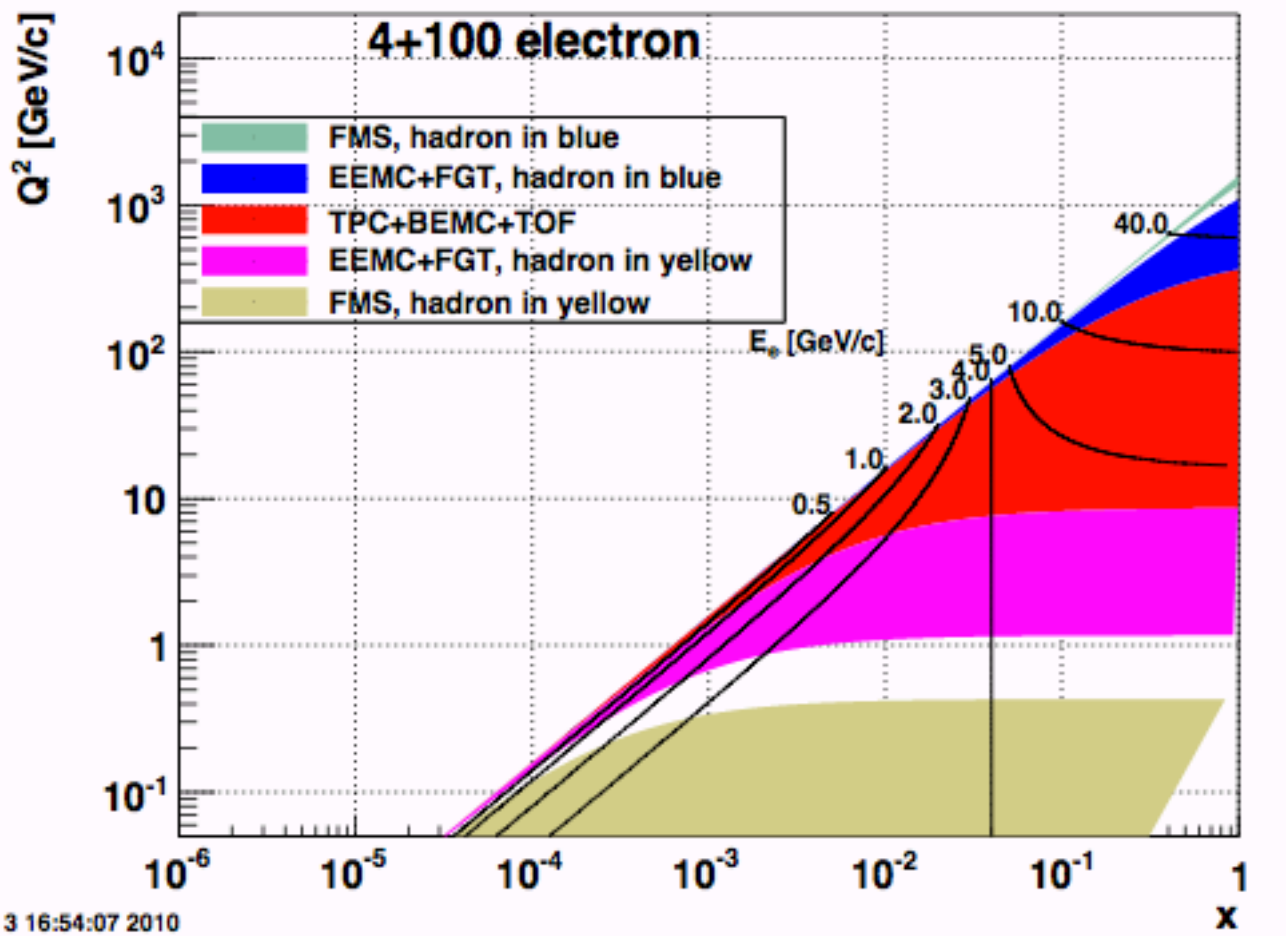
- **Without changing DX-D0 both the energy and luminosity will be low in electron-hadron collisions**
- **Parallel operation of hadron-hadron and electron-hadron collisions does not allow cooling of hadron beam, hence 10-fold lower luminosity for e-p and e-A**
- **Sequential operation of RHIC as a hadron collider and as an electron-hadron collider allows to have both full energy and full luminosities in al modes of operation, including coherent electron cooling**
- **CeC would provide 10-fold increases in e-p amd e-A luminosities and 6-fold increase in polarized p-p luminosity**
- **We have designs of two IR: low-x ($L \sim 3 \cdot 10^{33}$) and high-lumi ($L \sim 2 \cdot 10^{34}$)**
- **We suggest using crossing angle and crab-cavities to have identical energy-independent geometry of IRs and no synchrotron radiation in detectors**

STAR: A Correlation Machine

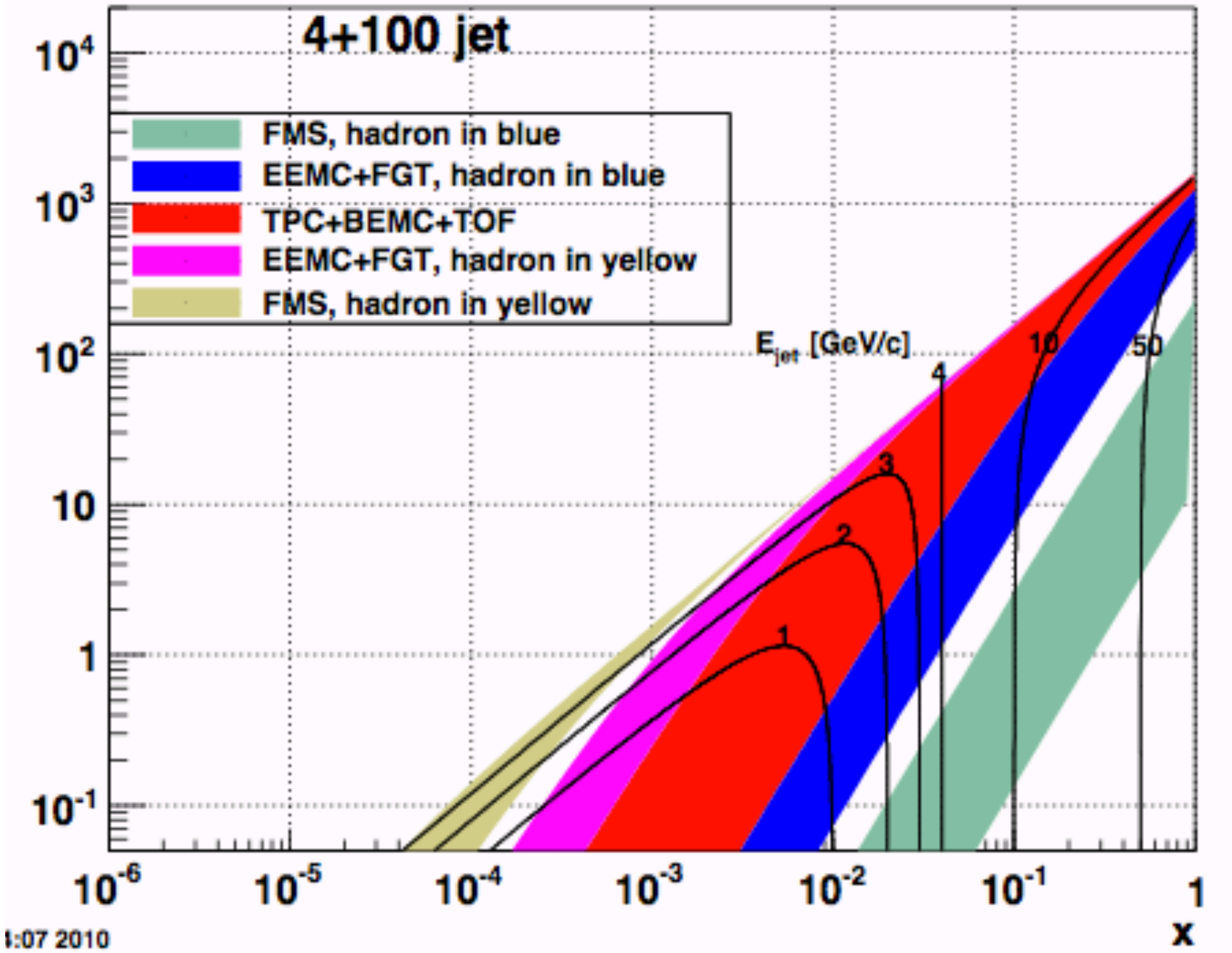


Kinematics at 4+100

Scattered electron



Scattered jet



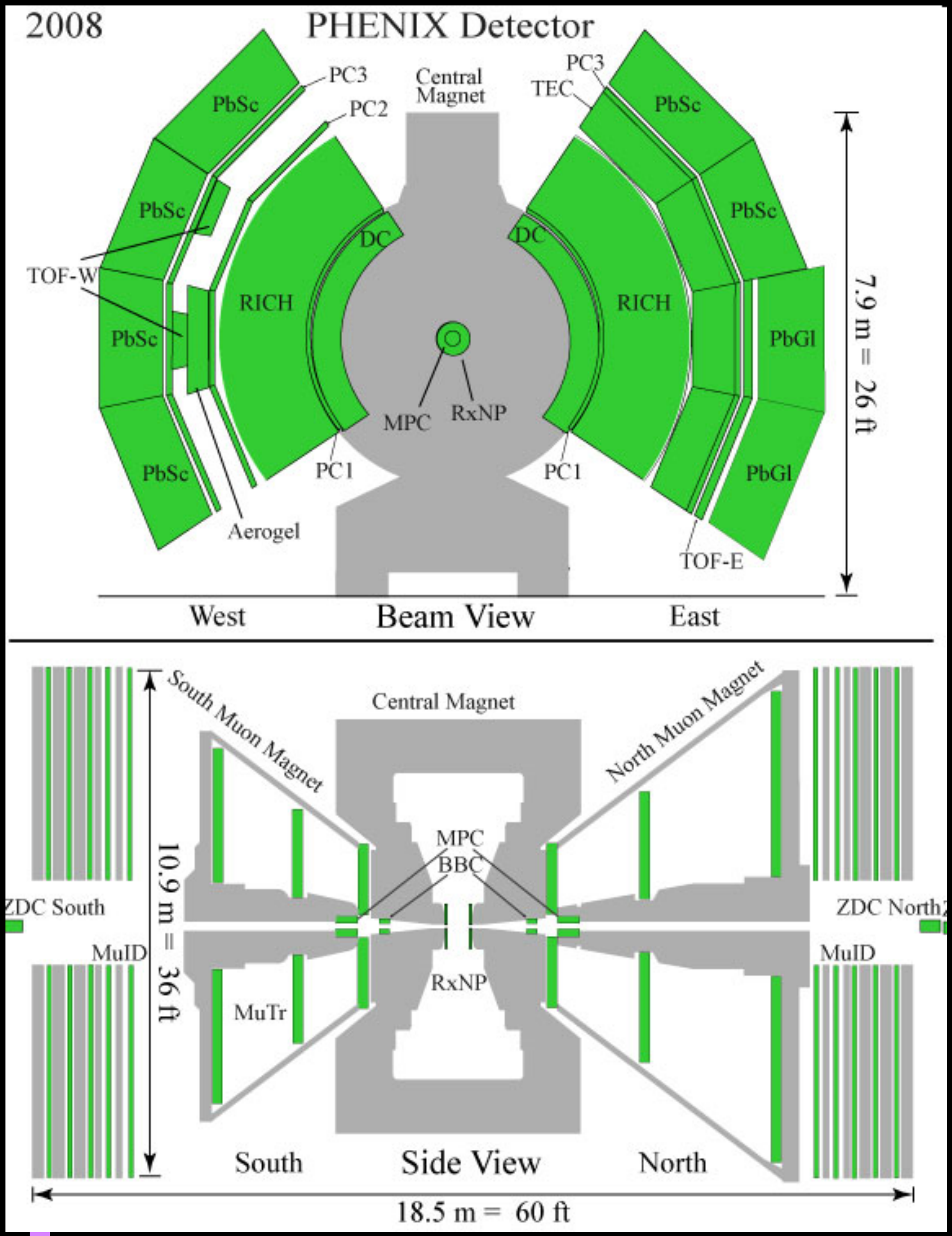
4+100 open kinematics: scatters the electron and jet to mid-rapidity

Forward region (FMS): Electron either Q^2 < 1 GeV, or very high x and Q^2

Jet either very soft or very hard

Note: current thinking has hadron in the blue beam: optimized for high x and Q^2

Current PHENIX Detector at RHIC

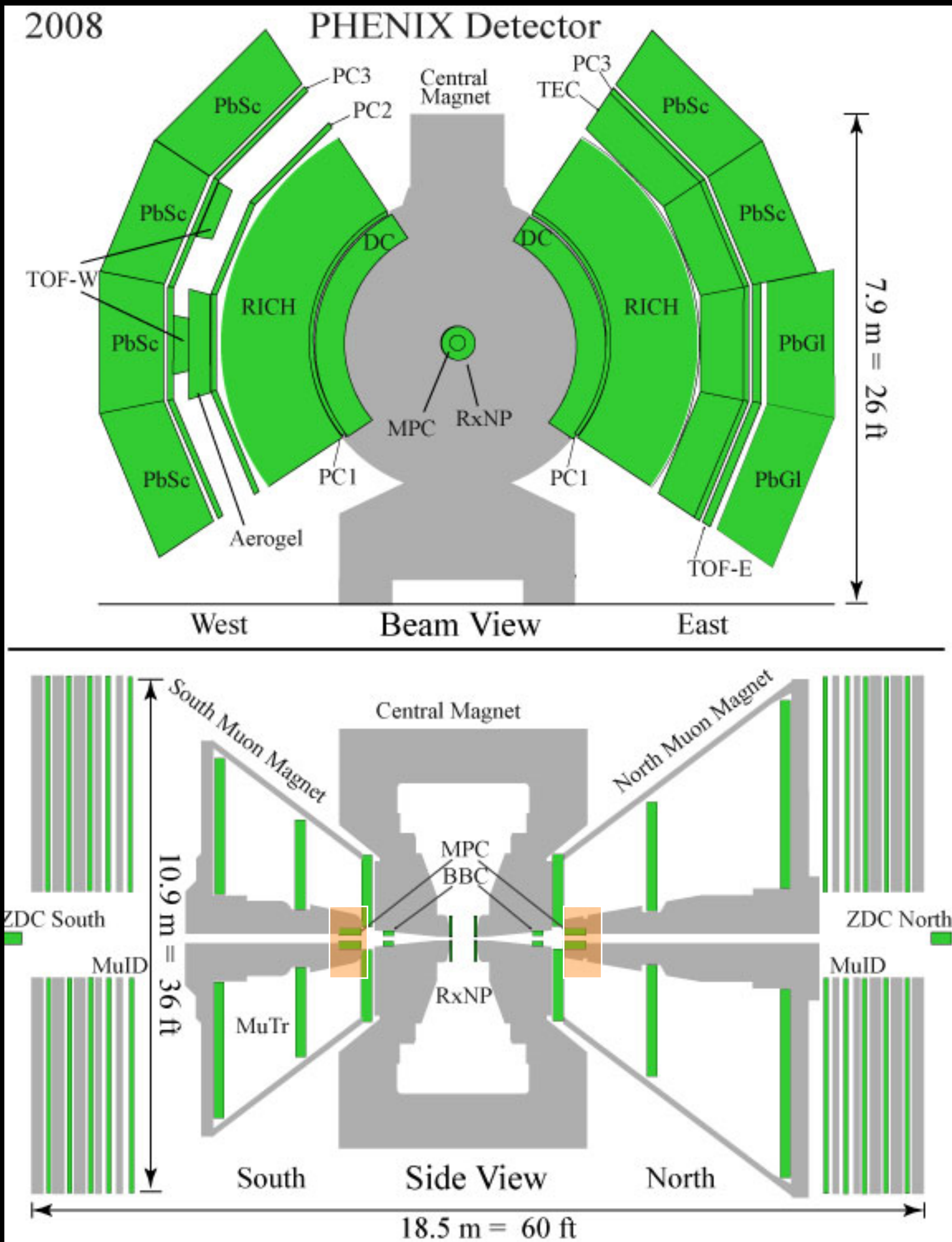


MPC	$3.1 < \|\eta\| < 3.9$
	$2.5^o < \Theta < 5.2^o$
Muon Arms	$1.2 < \|\eta\| < 2.4$
South:	$12^o < \Theta < 37^o$
North:	$10^o < \Theta < 37^o$
Central Arms	$\|\eta\| < 0.35$
	$60^o < \Theta < 110^o$

electrons will not make it
to the south muon arm
→ to much material

e-

Current PHENIX Detector at RHIC



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	$2.5^{\circ} < \Theta < 5.2^{\circ}$
Muon Arms	$1.2 < \vert\eta\vert < 2.4$
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Central Arms	$\vert\eta\vert < 0.35$
	$60^{\circ} < \Theta < 110^{\circ}$

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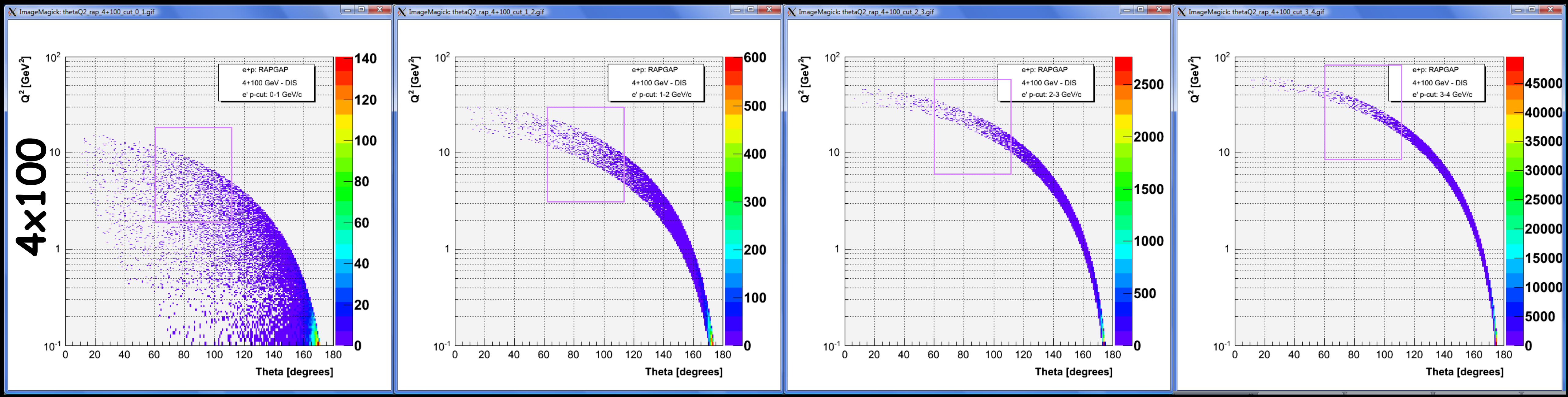
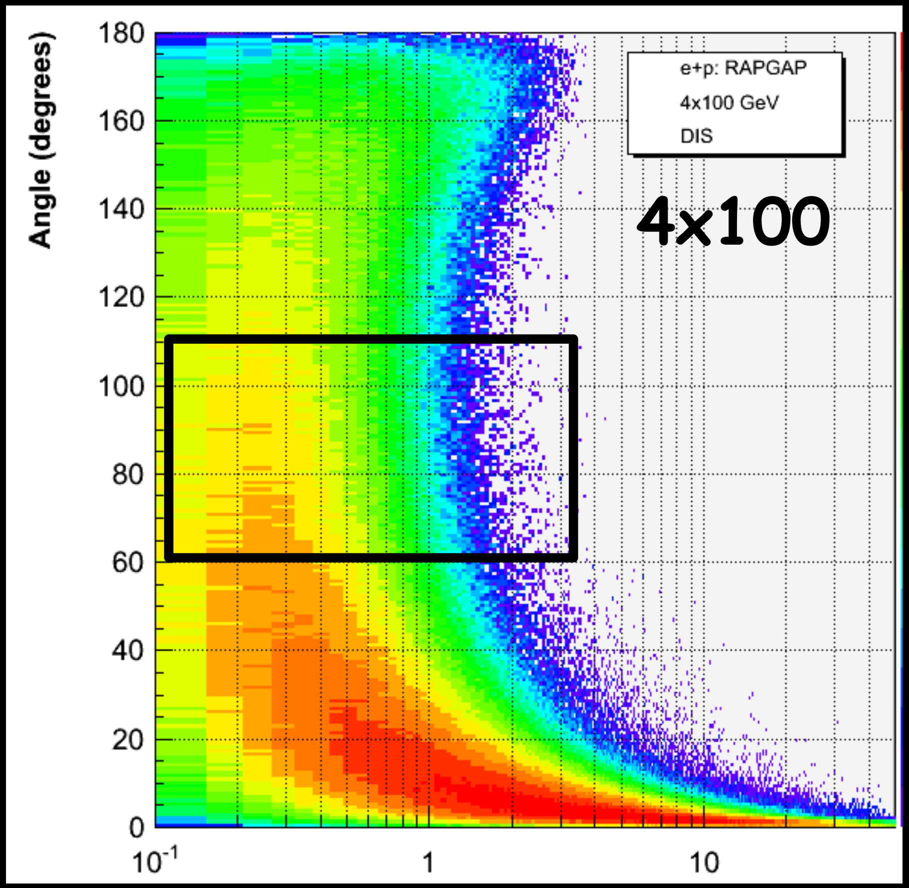
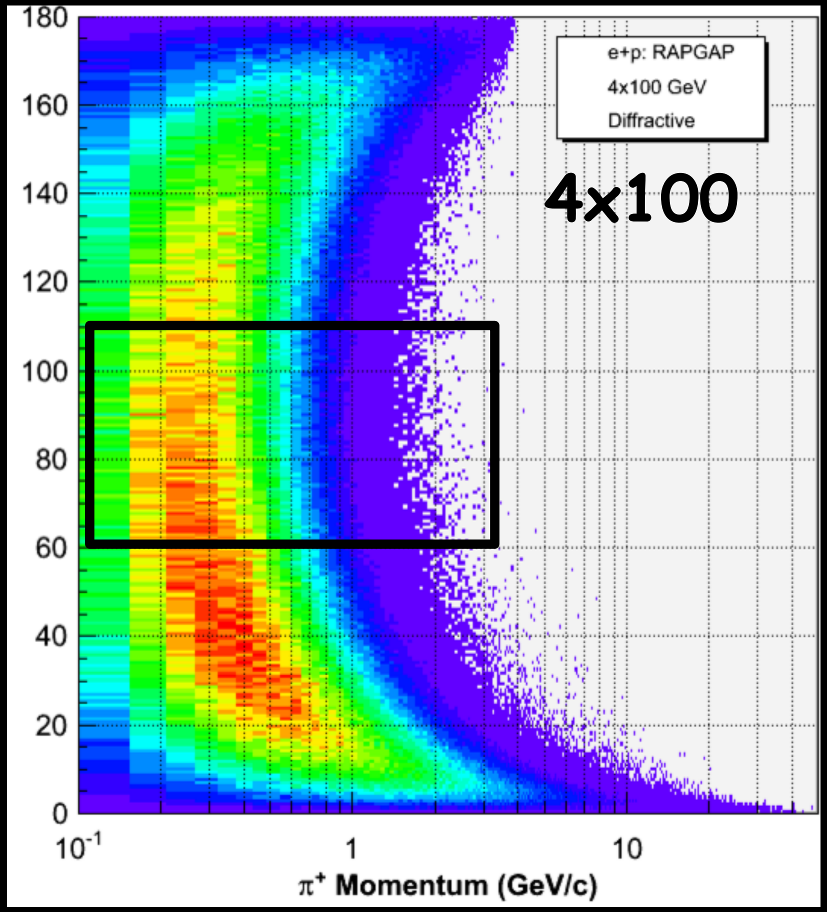
e-

What will the current PheniX see

p_e: 0-1 GeV p_e: 1-2 GeV p_e: 2-3 GeV p_e: 3-4 GeV

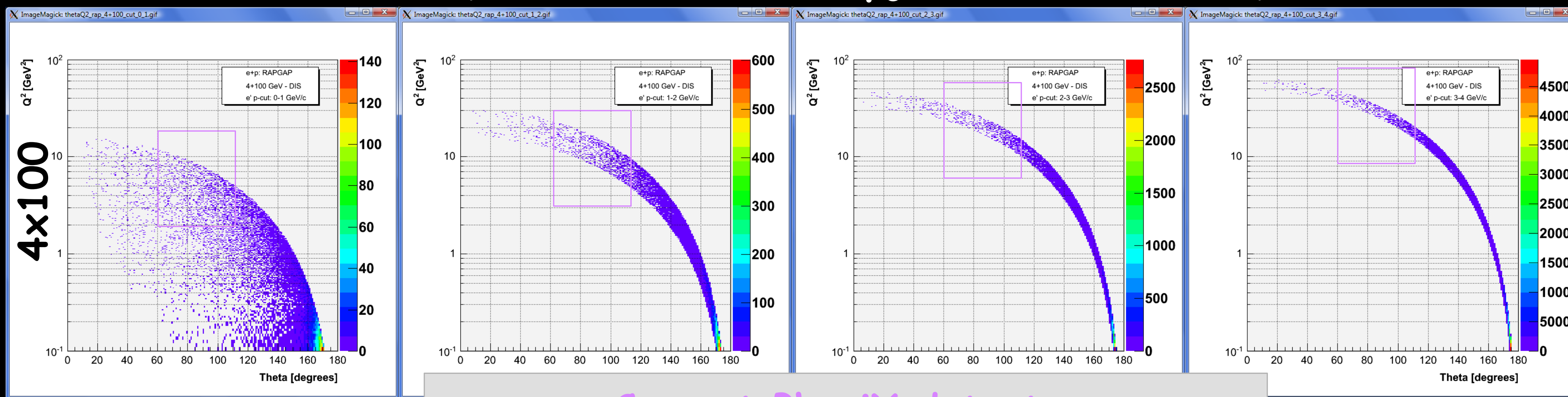




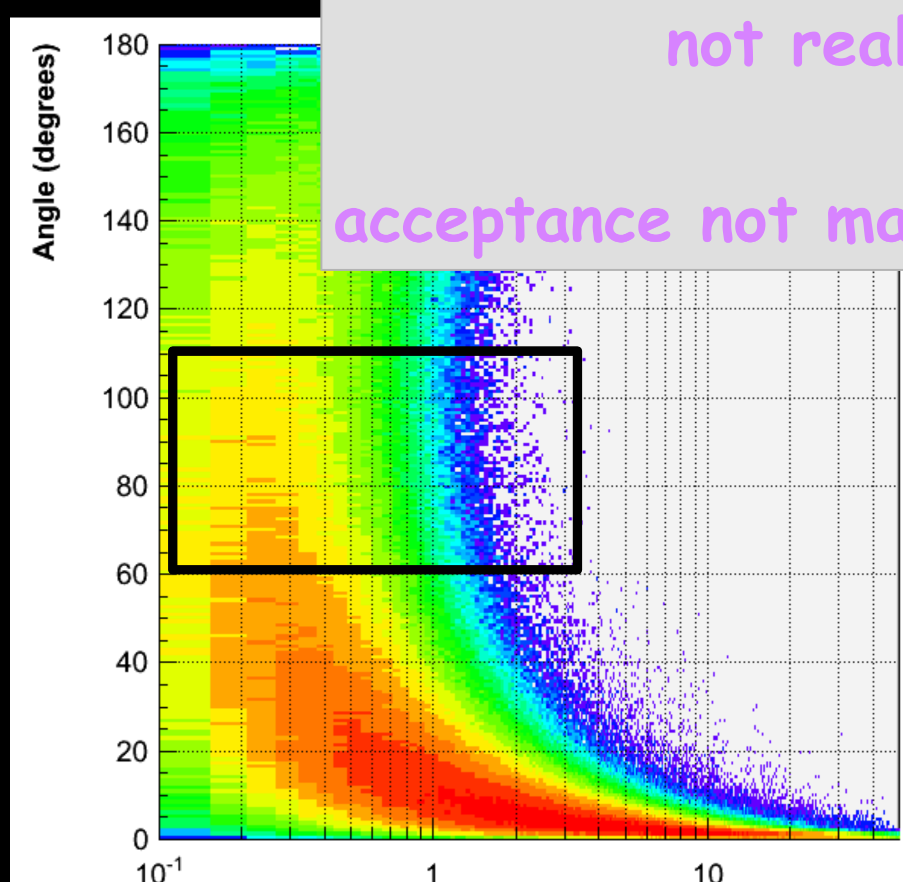


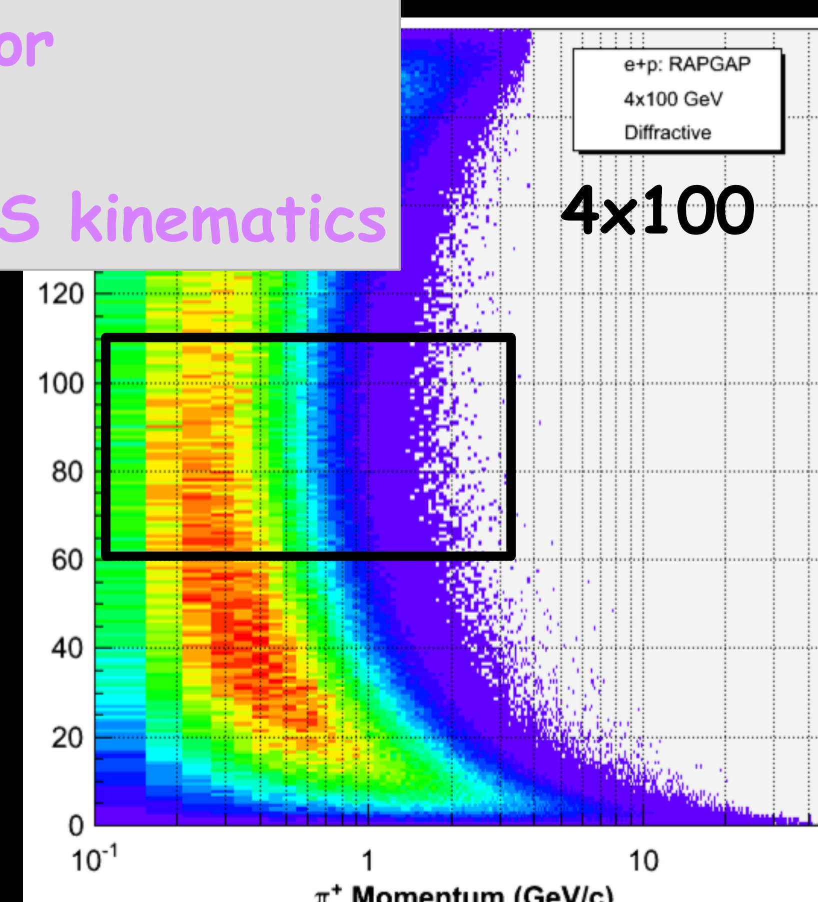
What will the current PheniX see

p_e: 0-1 GeV | p_e: 1-2 GeV | p_e: 2-3 GeV | p_e: 3-4 GeV



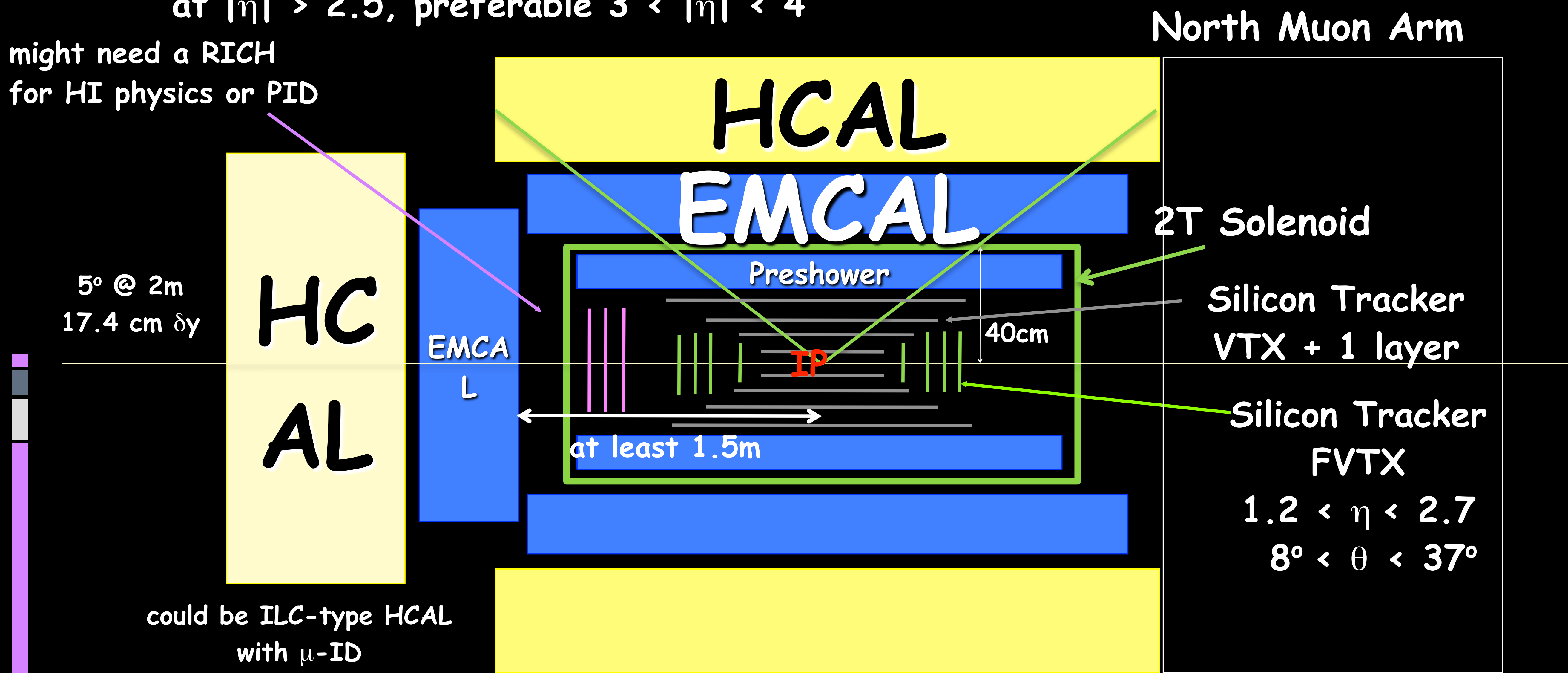
Current PheniX detector
not really useable for
DIS
acceptance not matched to DIS kinematics





How should a ePheniX look like

- Coverage in $|\eta| =< 3 \rightarrow 0.1 < Q^2 < 100$ (5^o – 175^o)
  - need an open geometry detector
  - planes for next decadal plan
    - replace current central detector with a new one covering $|\eta| =< 1$
    - replace South muon arm by a endcap spectrometer able to do DY at $|\eta| > 2.5$, preferable $3 < |\eta| < 4$



Summary and Outlook

- Lots of MC generators at BNL (anyone can use)
  - ➡ spin: gmc_trans, PEPSI; low-x: PYTHIA, RAPGAP; e+p, e+A: xDVMP
- xDVMP is a promising tool to look at exclusive diffractive vector-meson production in a saturated picture
  - ➡ currently works for e+p collisions, needs work to implement in e+A collisions
    - relatively straight forward
  - ➡ need to develop a more general e+A generator
    - Yasushi Nara just completed 1 month at BNL, Henri Kowalksi currently at BNL for 3 months, Tobias Toll is a new post-doctoral hire about to start
- Work underway in implementing detector designs in GEANT to study with the generated events
  - ➡ Looking at the possible use of eSTAR and ePHENIX concepts
    - eSTAR looks promising and the STAR geometry is in the same format as what we are using for our other studies

BACKUP SLIDES

Accelerator

MeRHIC parameters for e-p collisions

	not cooled		With cooling	
	p	e	p	e
Energy, GeV	250	4	250	4
Number of bunches	111		111	
Bunch intensity, 10^{11}	2.0	0.31	2.0	0.31
Bunch charge/current, nC/mA	32/320	5/**50**	32/320	5/**50**
Normalized emittance, 1e-6 m, 95% for p / rms for e	15	73	1.5	7.3
rms emittance, nm	9.4	9.4	0.94	0.94
beta*, cm	50	50	50	50
rms bunch length, cm	20	0.2	5	0.2
beam-beam for p /disruption for e	1.5e-3	3.1	0.015	7.7
Peak Luminosity, 1e32, $cm^{-2}s^{-1}$	**0.93**		**9.3**	

Luminosity for light and heavy ions
is the same as for e-p if measured per nucleon!

RHIC

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

Luminosity in eRHIC

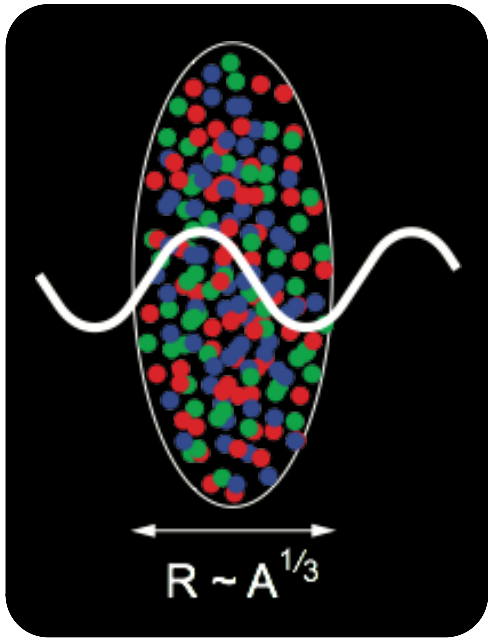
	eRHIC IR1		eRHIC IR2	
	p /A	e	p /A	e
Energy (max), GeV	325/130	20	325/130	20
Number of bunches	166	74 nsec	166	74 nsec
Bunch intensity (u) , 10^{11}	2.0	0.24	2.0	0.24
Bunch charge, nC	32	4	32	4
Beam current, mA	420	50	420	50
Normalized emittance, 1e-6 m, 95% for p / rms for e	1.2	25	1.2	25
Polarization, %	70	80	70	80
rms bunch length, cm	4.9	0.2	4.9	0.2
β*, cm	25	25	5	5
Luminosity, $cm^{-2}s^{-1}$	2.8×10^{33}		1.4×10^{34}	

Luminosity for 30 GeV e-beam operation will be at 20% level

Nuclear “Oomph”

The Nuclear "Oomph Factor"

- Enhancing Saturation effects:
  - Probes interact over distances $L \sim (2m_n x)^{-1}$
  - For probes where $L > 2R_A$ $(\sim A^{1/3})$ cannot distinguish between nucleons in front or back of the nucleus. Probe acts coherently with all nucleons!!



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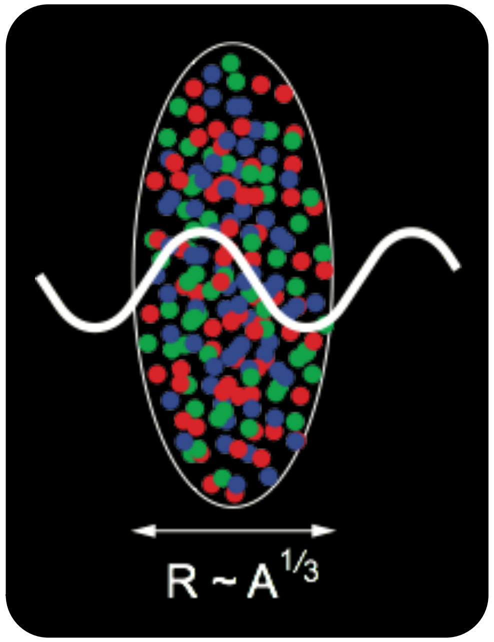

Simple geometric considerations lead to:

Nuclear "Oomph" Factor:

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

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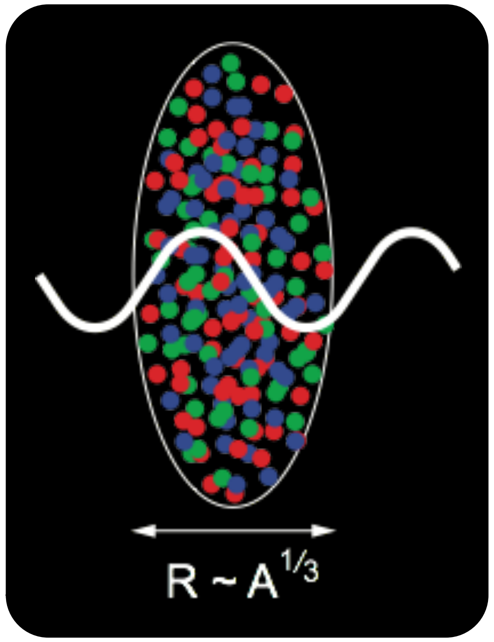

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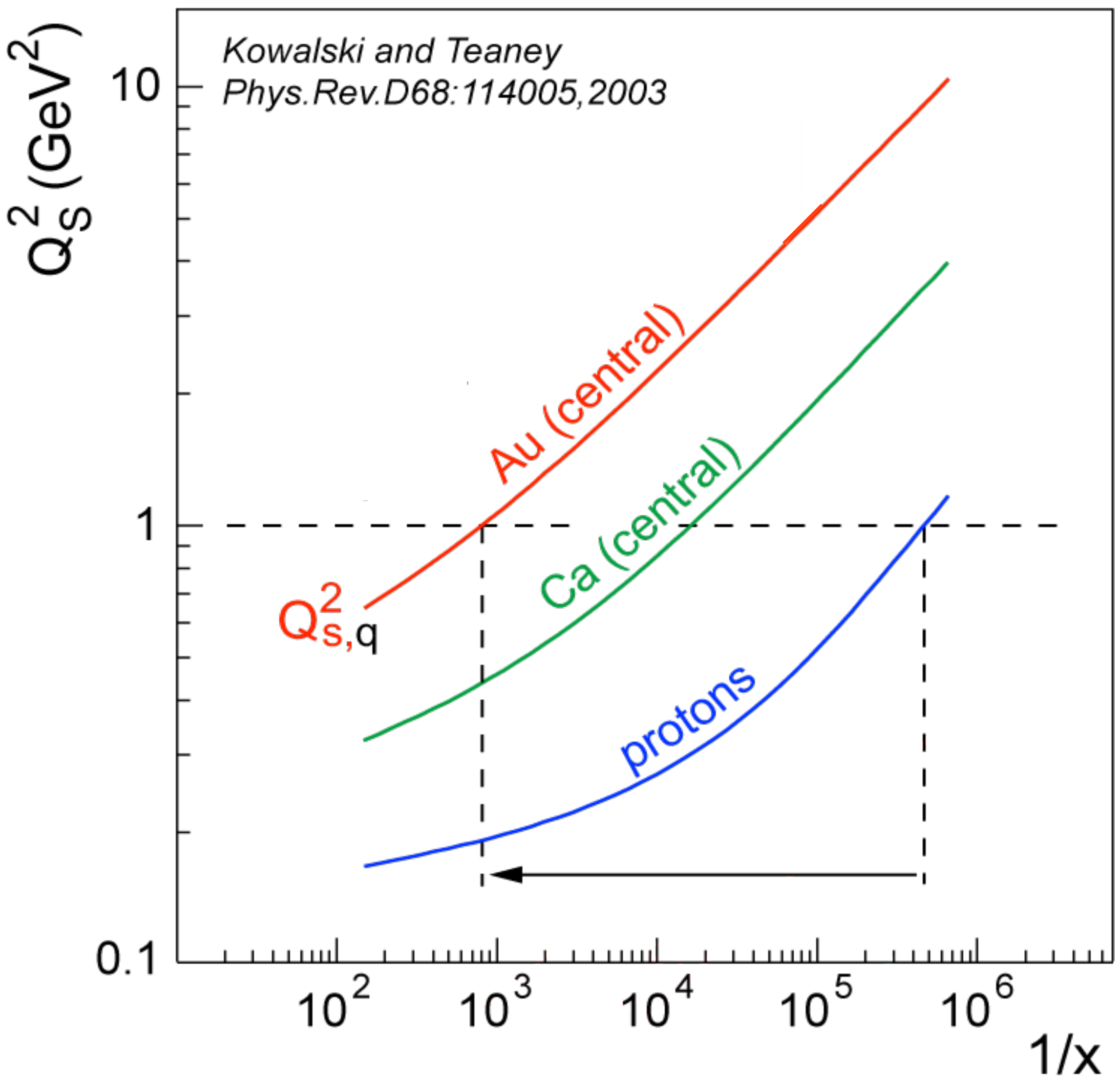

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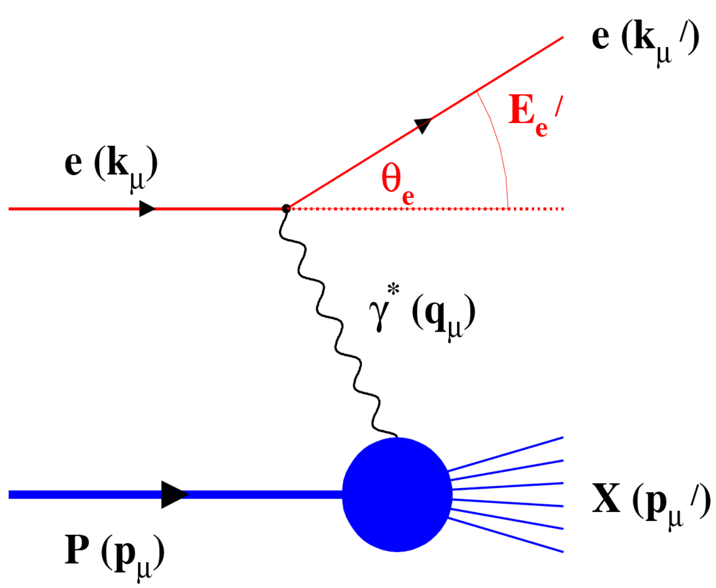
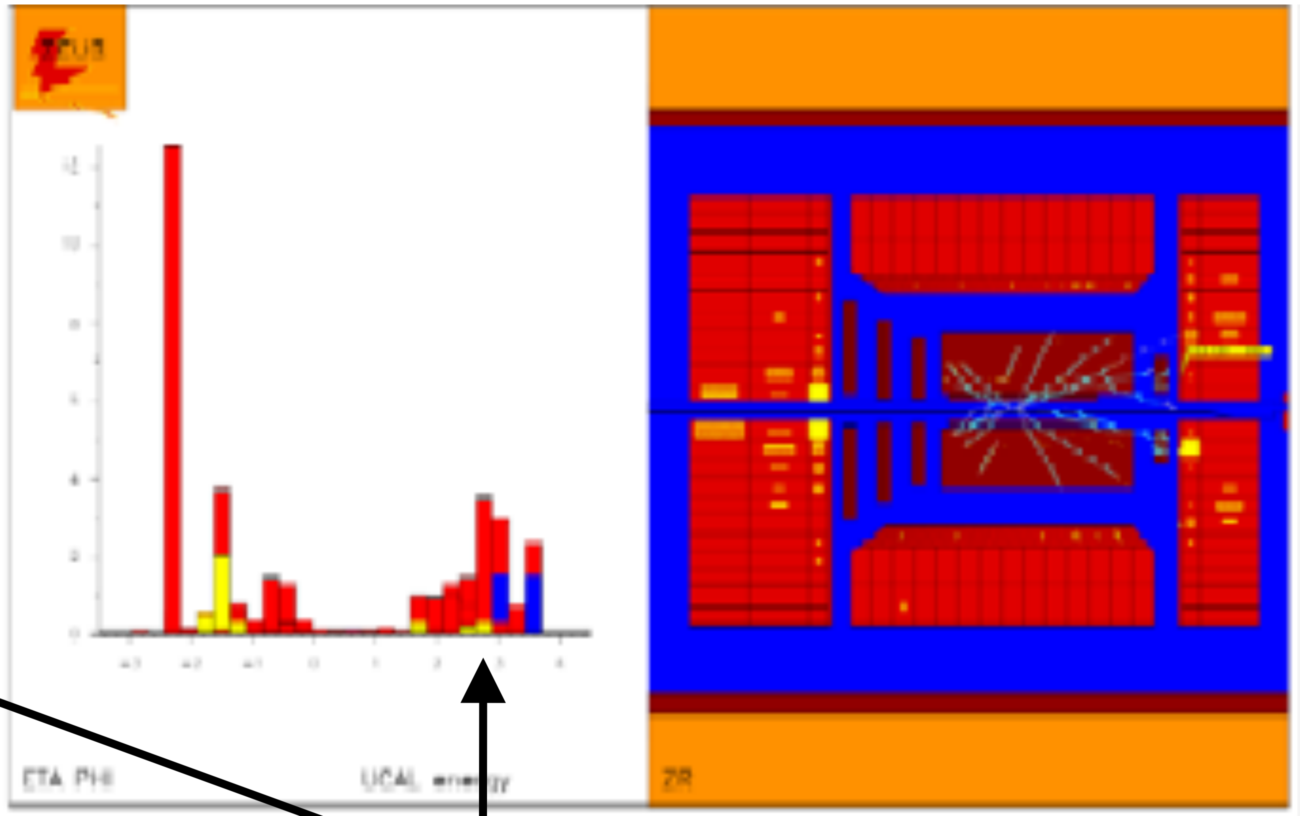
Diffractive

Diffractive Physics in e+A

'Standard DIS event'

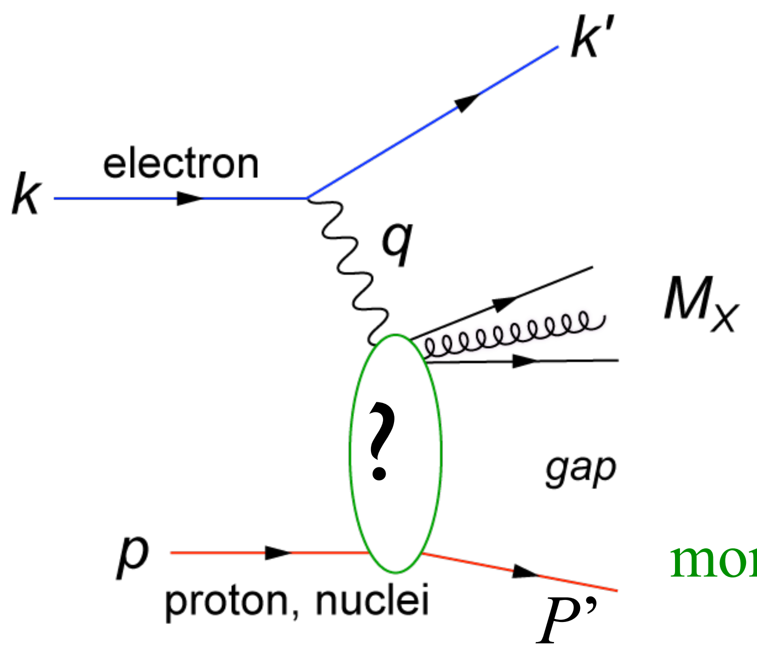




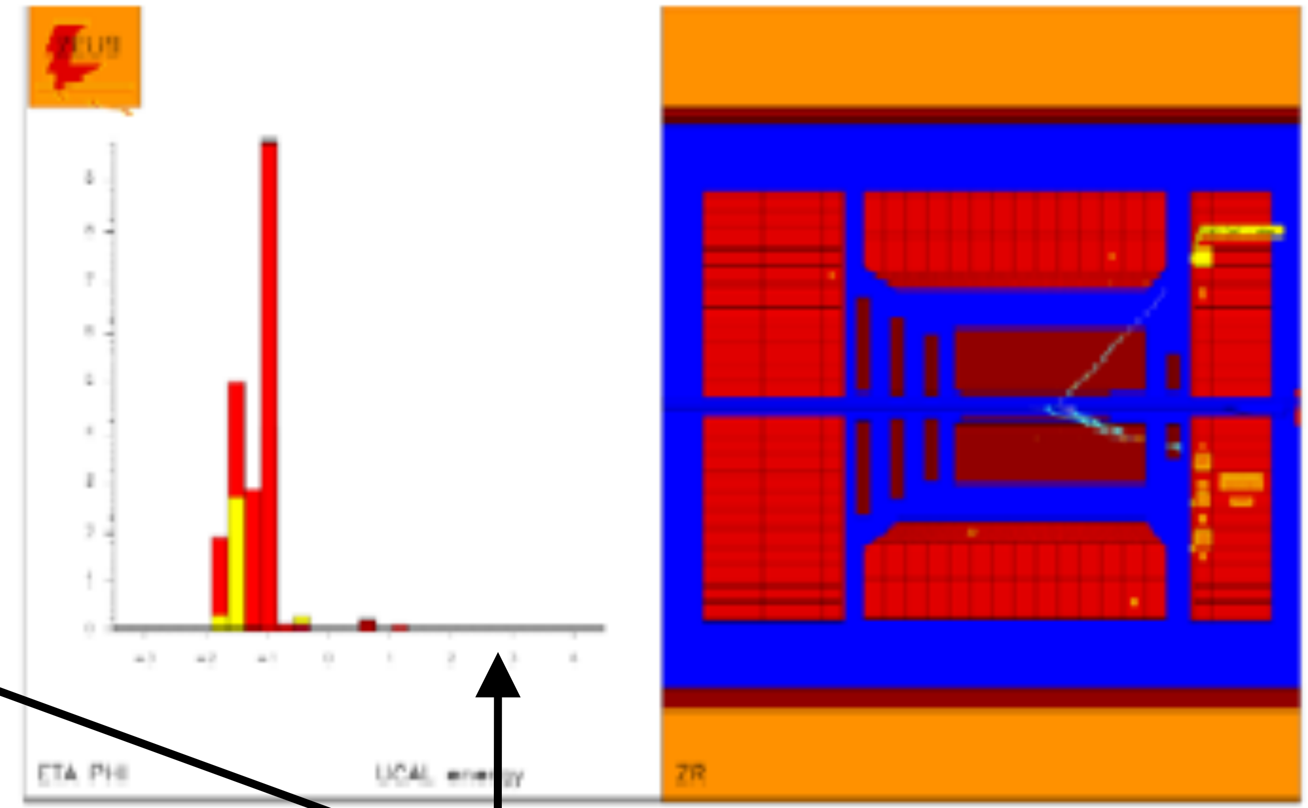
Activity in proton direction

Diffractive Physics in e+A

Diffractive event



momentum transfer:
$t = (P-P')^2$



Activity in proton direction

- HERA/ep: 15% of all events are hard diffractive
- Diffractive cross-section $\sigma_{diff}/\sigma_{tot}$ in e+A ?

➡ Predictions: ~25-40%?

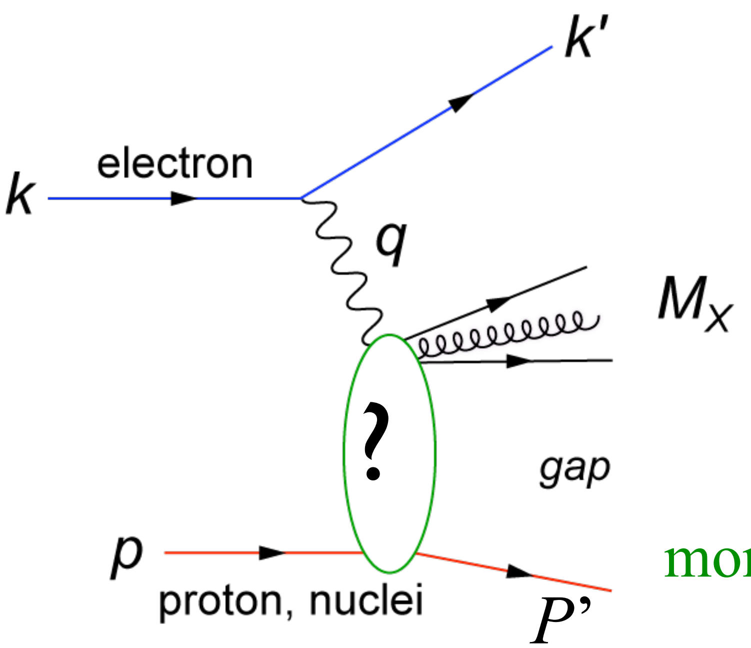
- Look inside the "Pomeron"

➡ Diffractive structure functions

➡ Exclusive Diffractive vector meson production: **$d\sigma/dt \sim [xG(x,Q^2)]^2$!!**

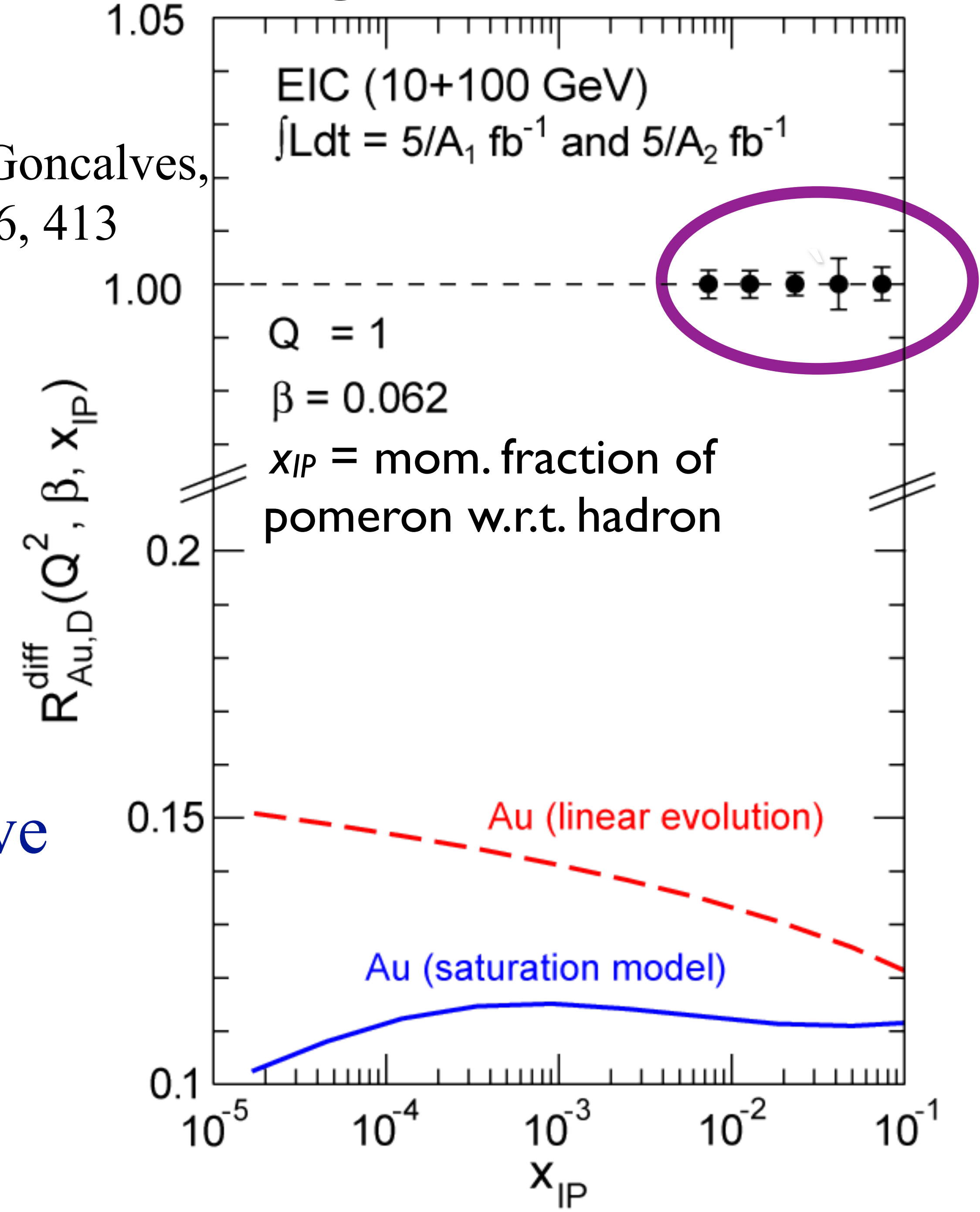
Diffractive Physics in e+A

Diffractive event



momentum transfer:
$t = (P-P')^2$

Curves: Kugeratski, Goncalves, Navarra, EPJ C46, 413



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➡ Exclusive Diffractive vector meson production: **dσ/d*t* ~ [xG(x,Q²)]² !!**

- Distinguish between linear evolution and saturation models

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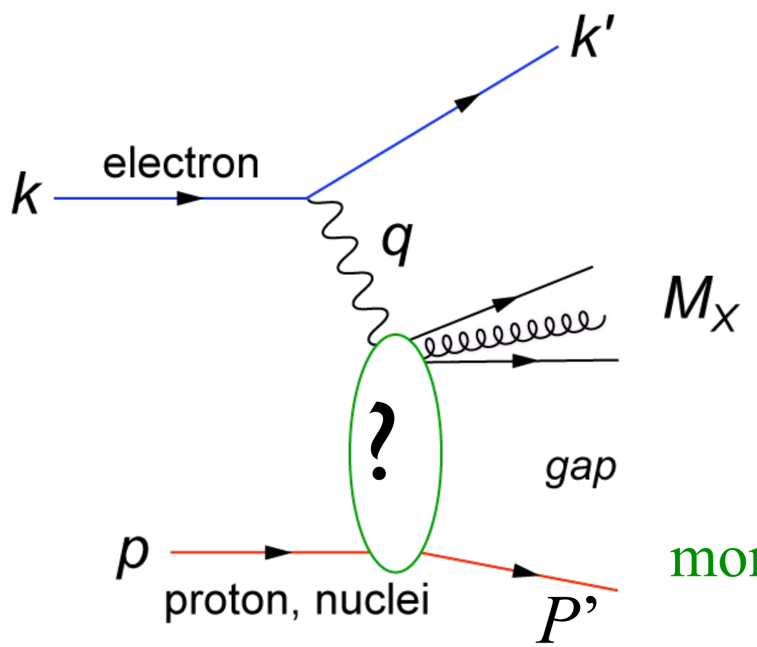
Diffractive Physics in e+A

Diffractive event



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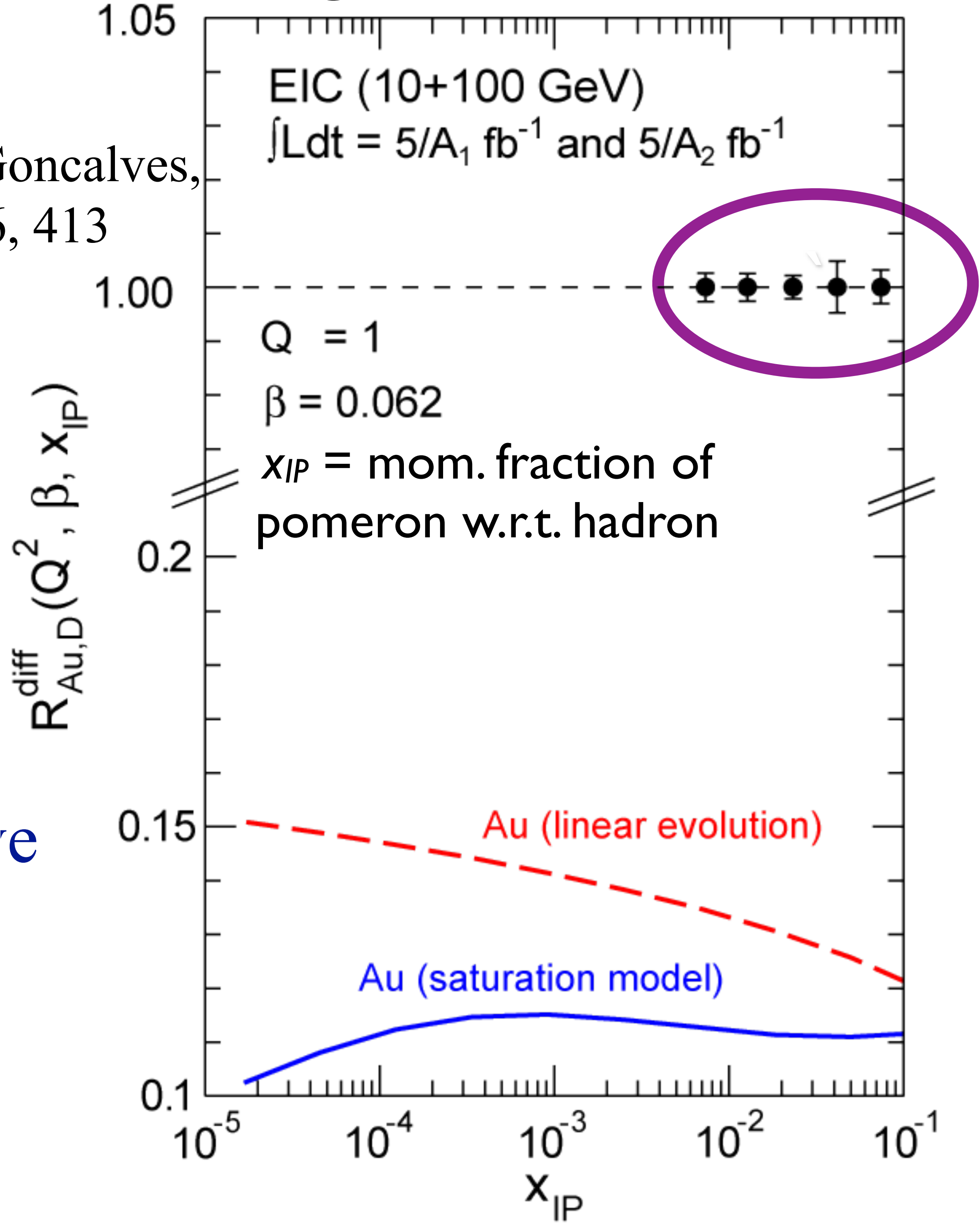
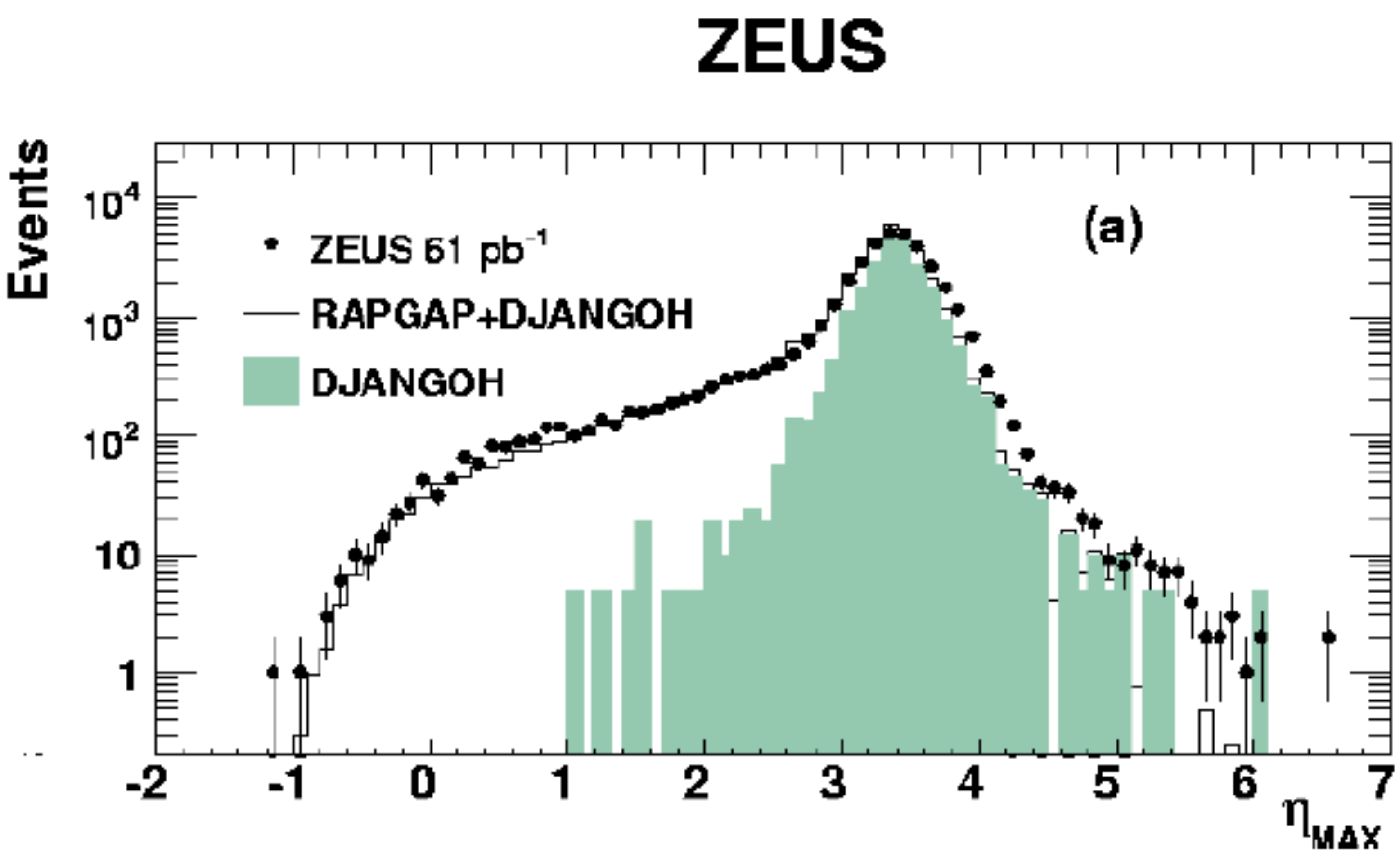




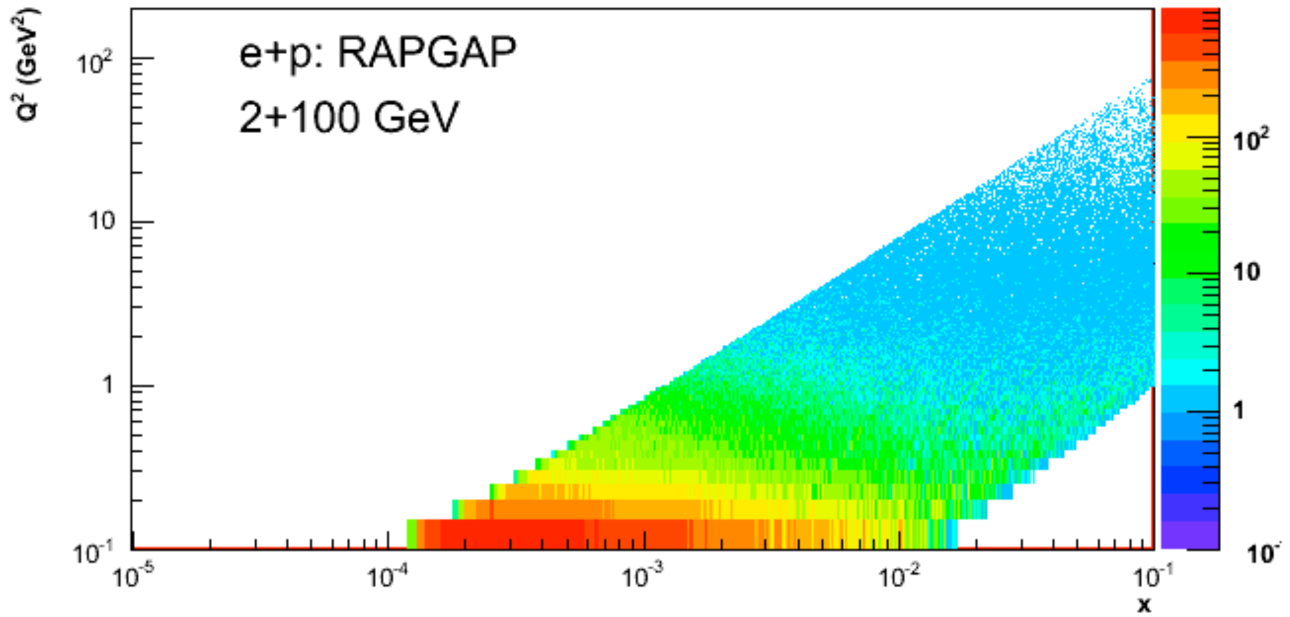
e

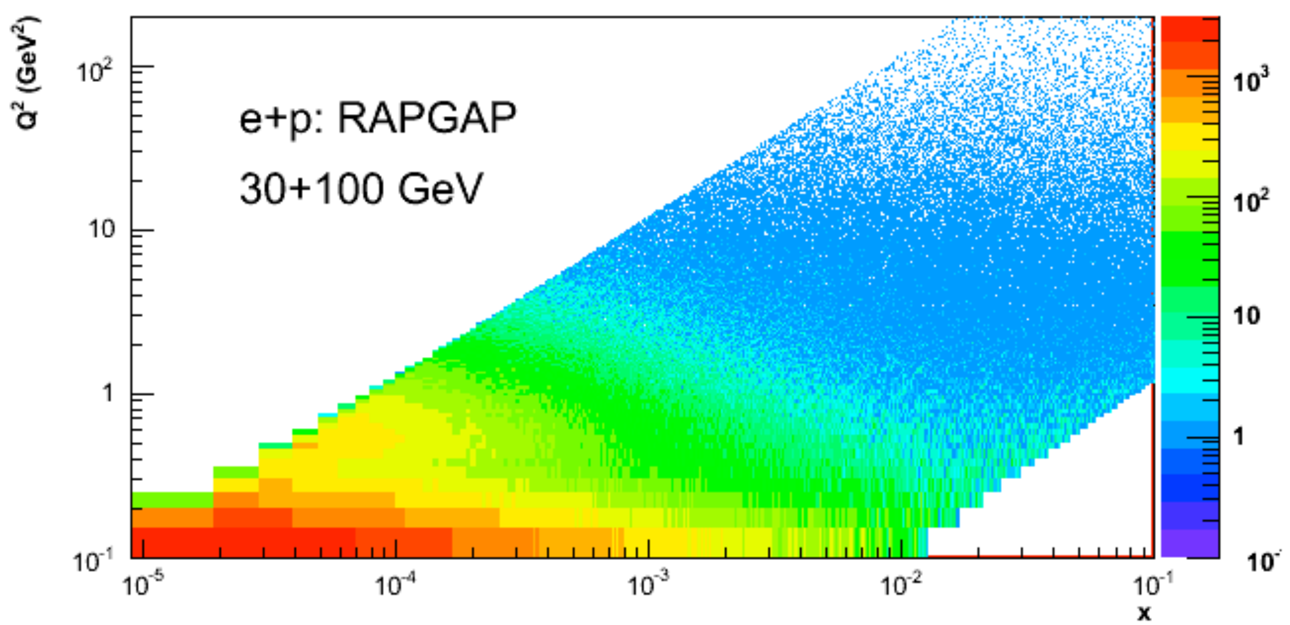
/dt ~ [xG(x,Q^2)]^2 !!

ation models

Diffractive Physics at an EIC

Generated 10^6 e+p events using RAPGAP for a variety of proposed EIC energies





Diffractive Physics at an EIC

- Significant coverage in x-Q^2
  - ➡ increases by ~ order of magnitude over EIC energies
- Plotted the distribution of the Most Forward Particle in the event for DIS and Diffractive events
  - ➡ significant gap between two classes of events
- Reproduce well the "ZEUS" plot
- Important - plot the efficiency vs purity
  - ➡ Can place a cut in rapidity for ~90% efficiency and ~90% purity !!

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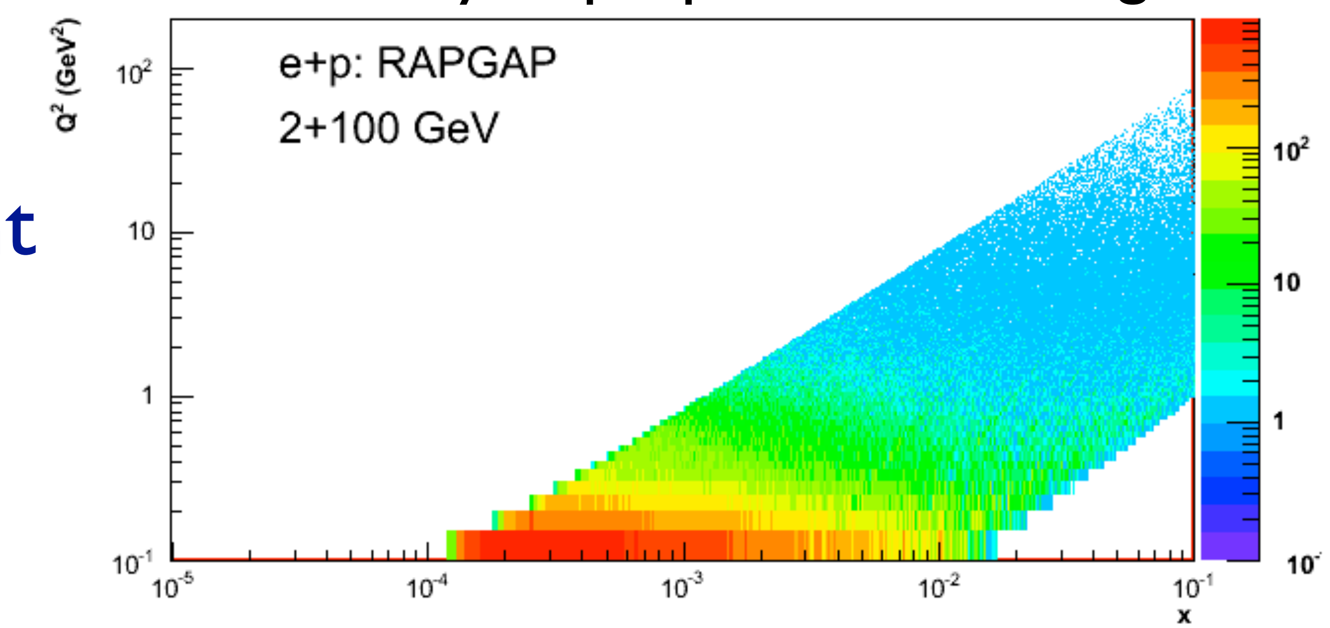

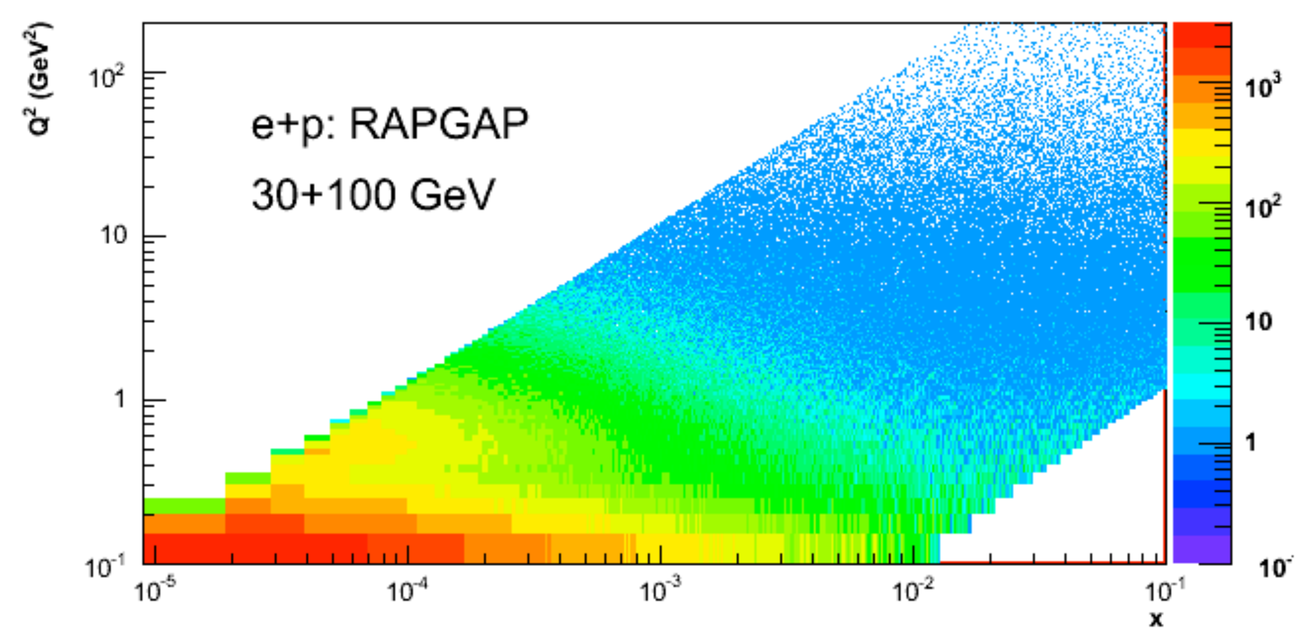

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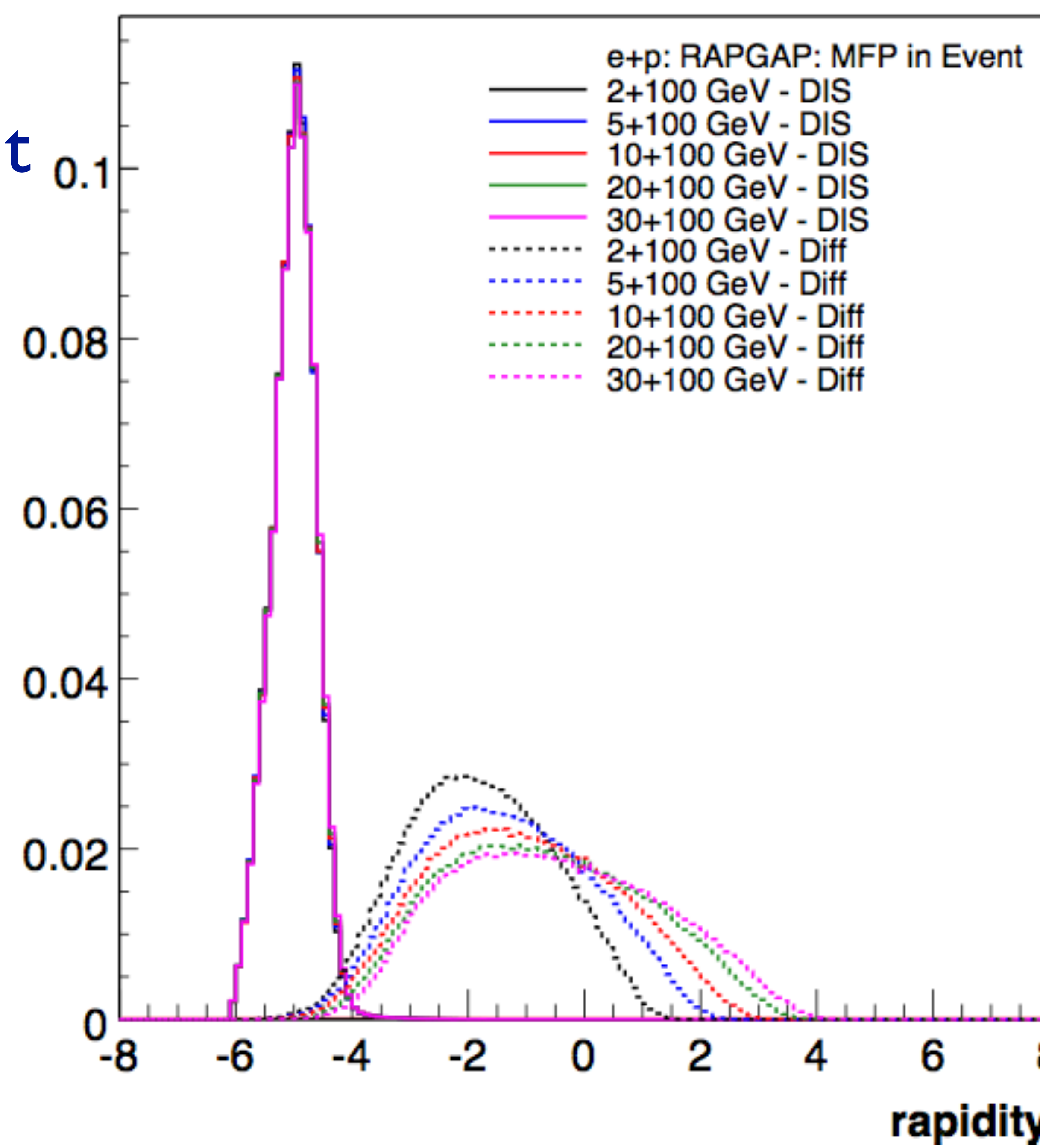

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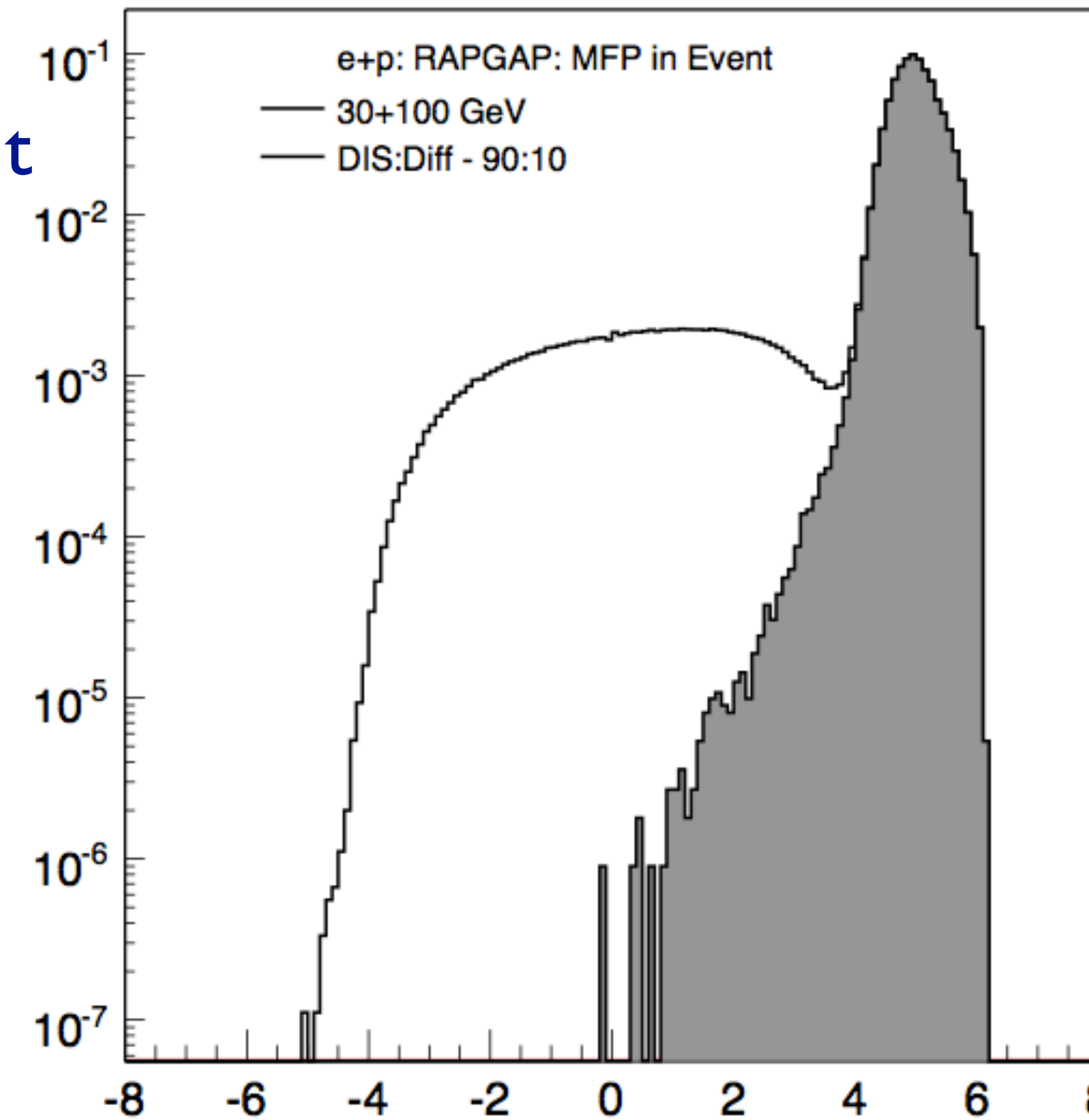

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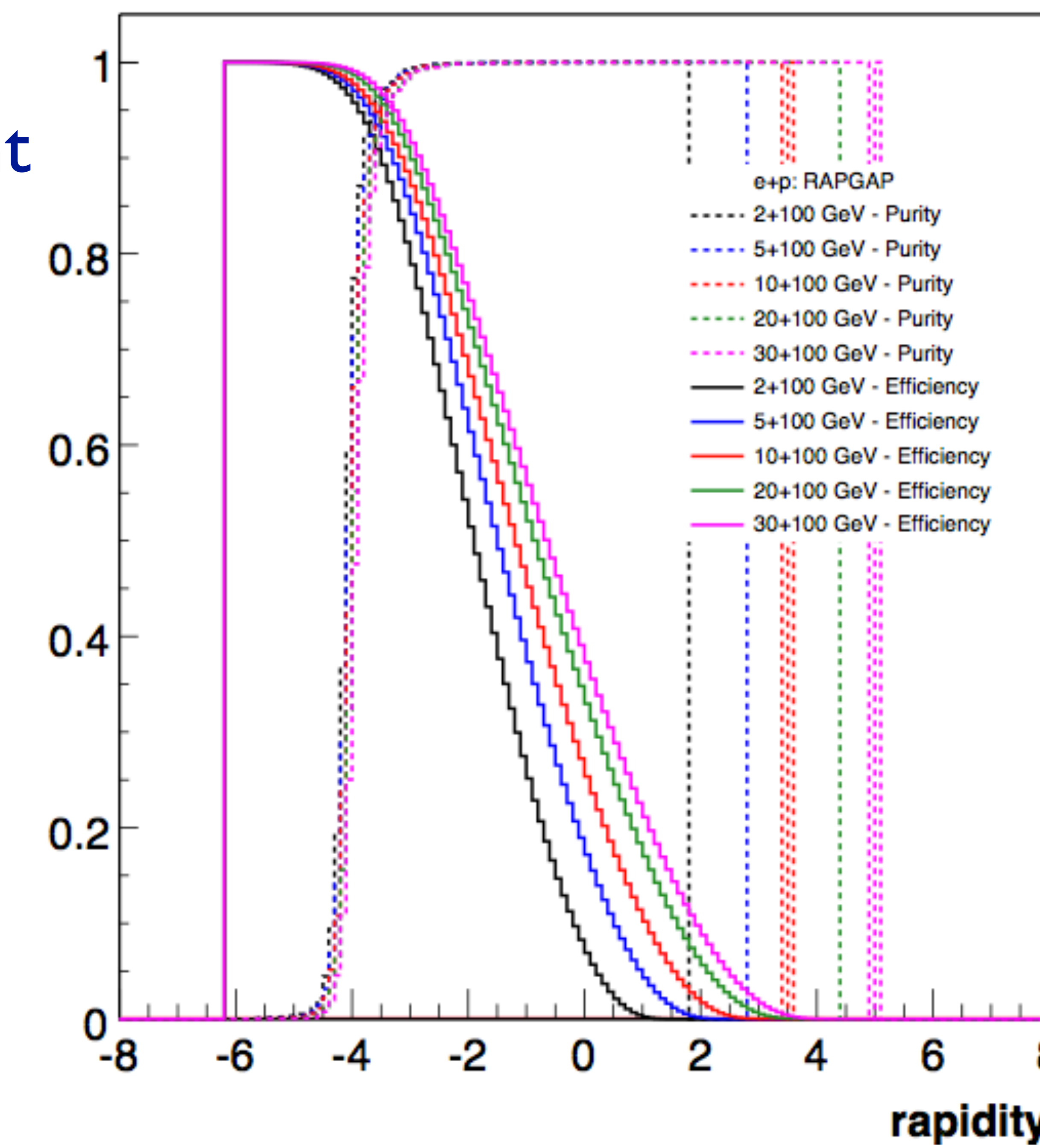

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Diffractive Physics at an EIC - Acceptance

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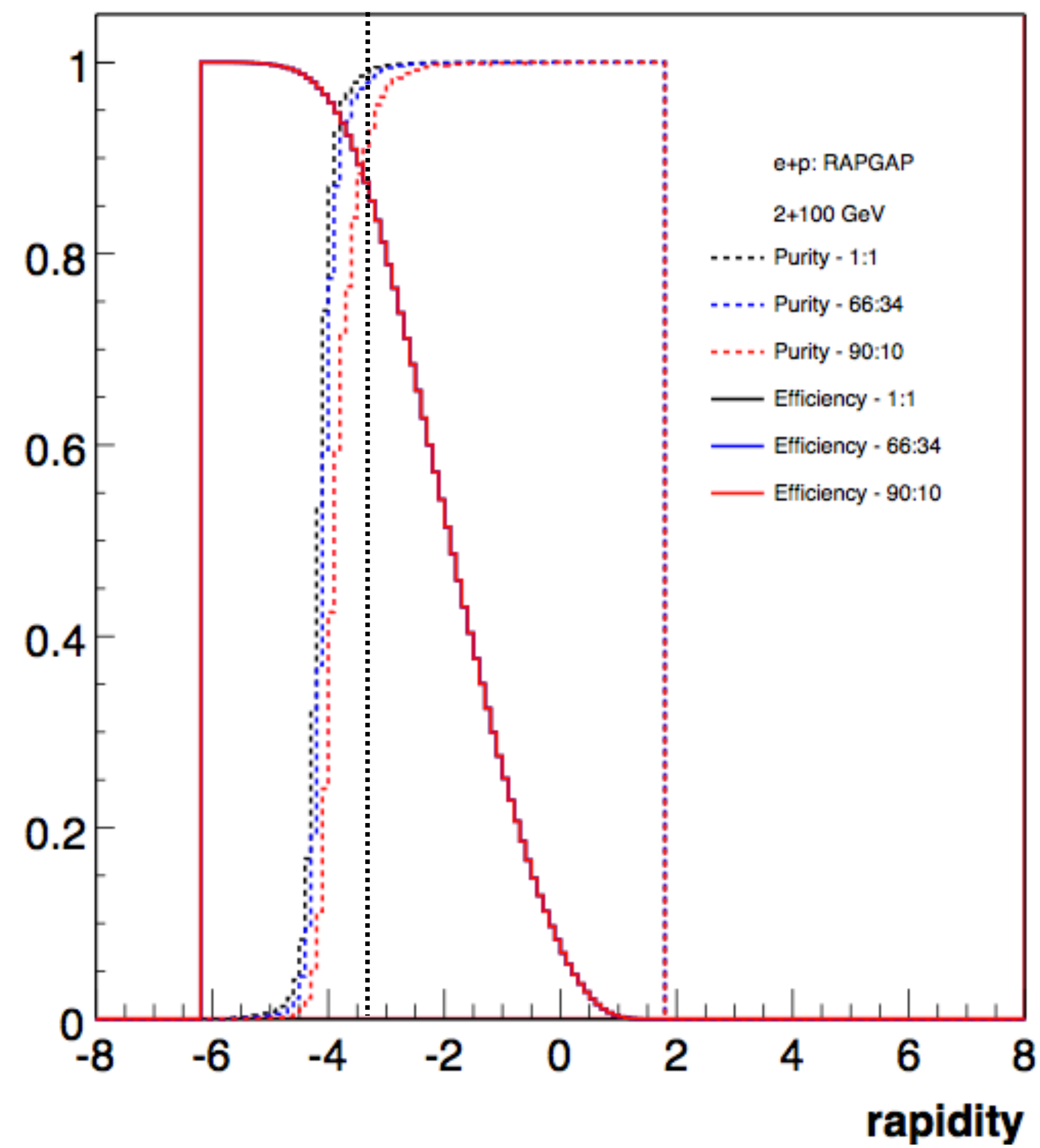

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Diffractive Physics at an EIC - Acceptance

- ZEUS had a gap in detector coverage (acceptance) of ~ 3 units.
- Studied this effect in the MFP distribution for EIC energies:
- Keeping the 90% Purity level has the following effect:
- 1 unit cut in rapidity
  - ➡ Efficiency falls by factor of 2, rapidity moves 2 units to right
- 2 unit cut in rapidity
  - ➡ Efficiency falls by a factor of 4, rapidity cut moves farther to right !!
- When designing a detector, it is essential to be as hermetic as possible !!!

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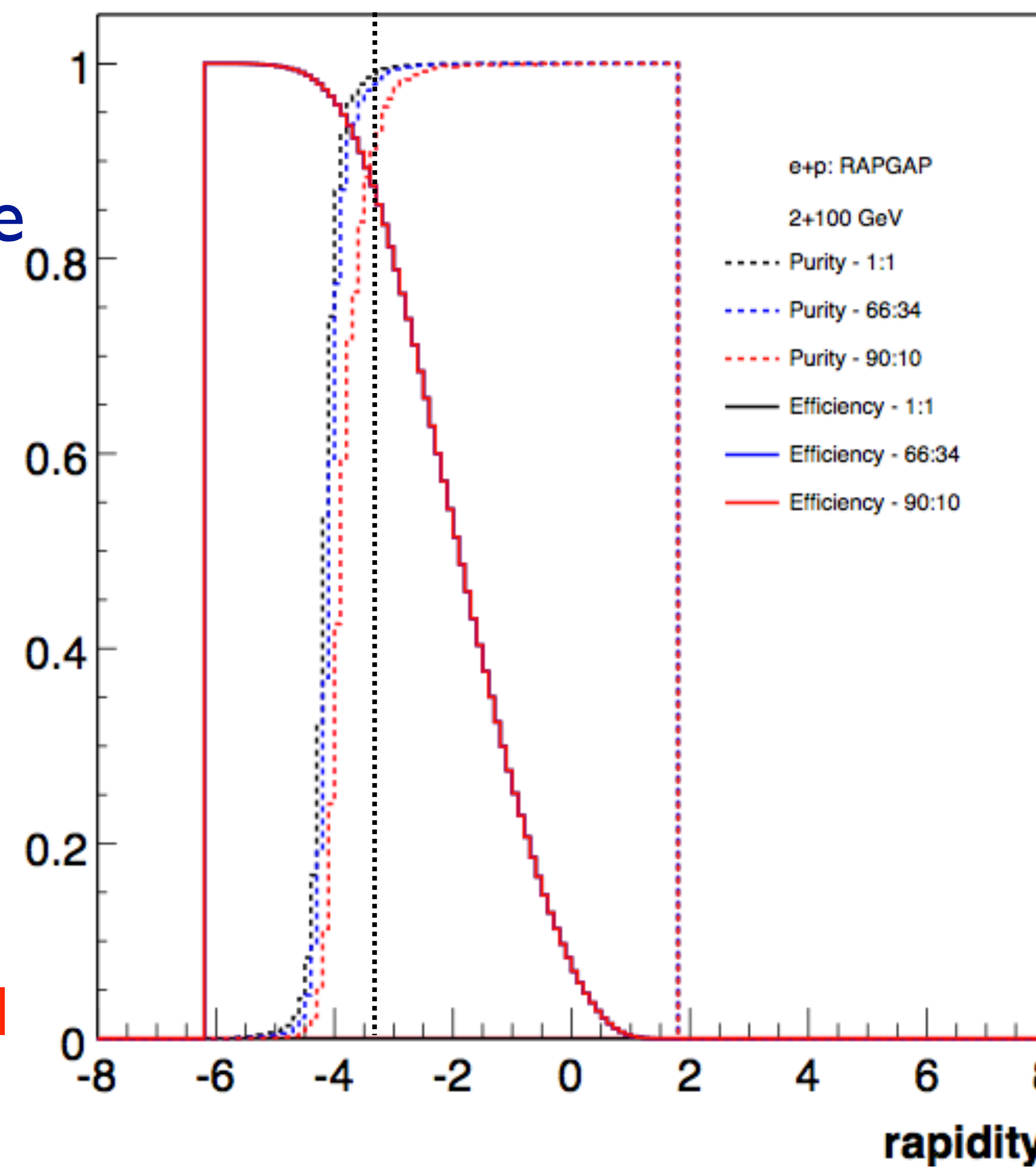

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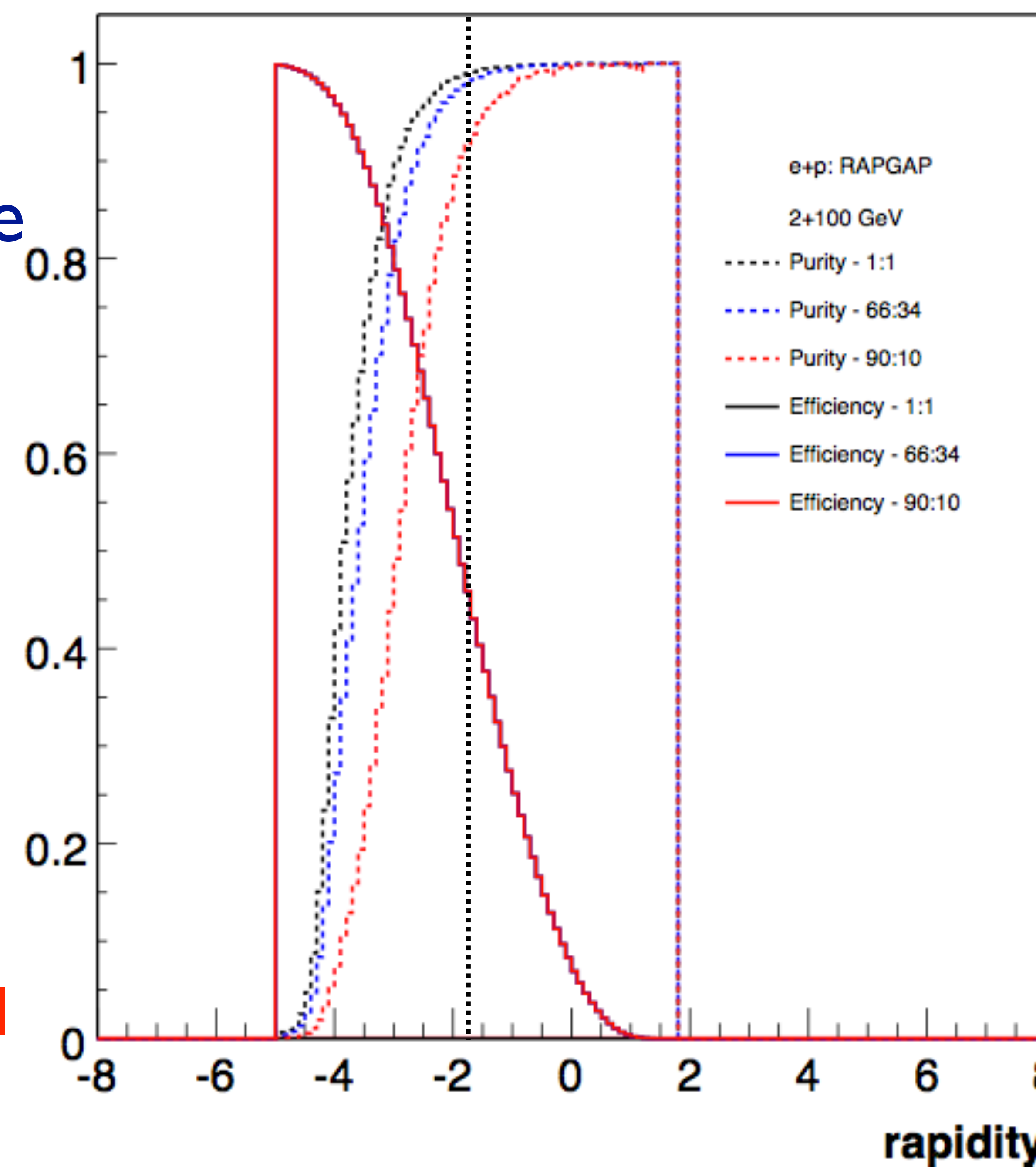

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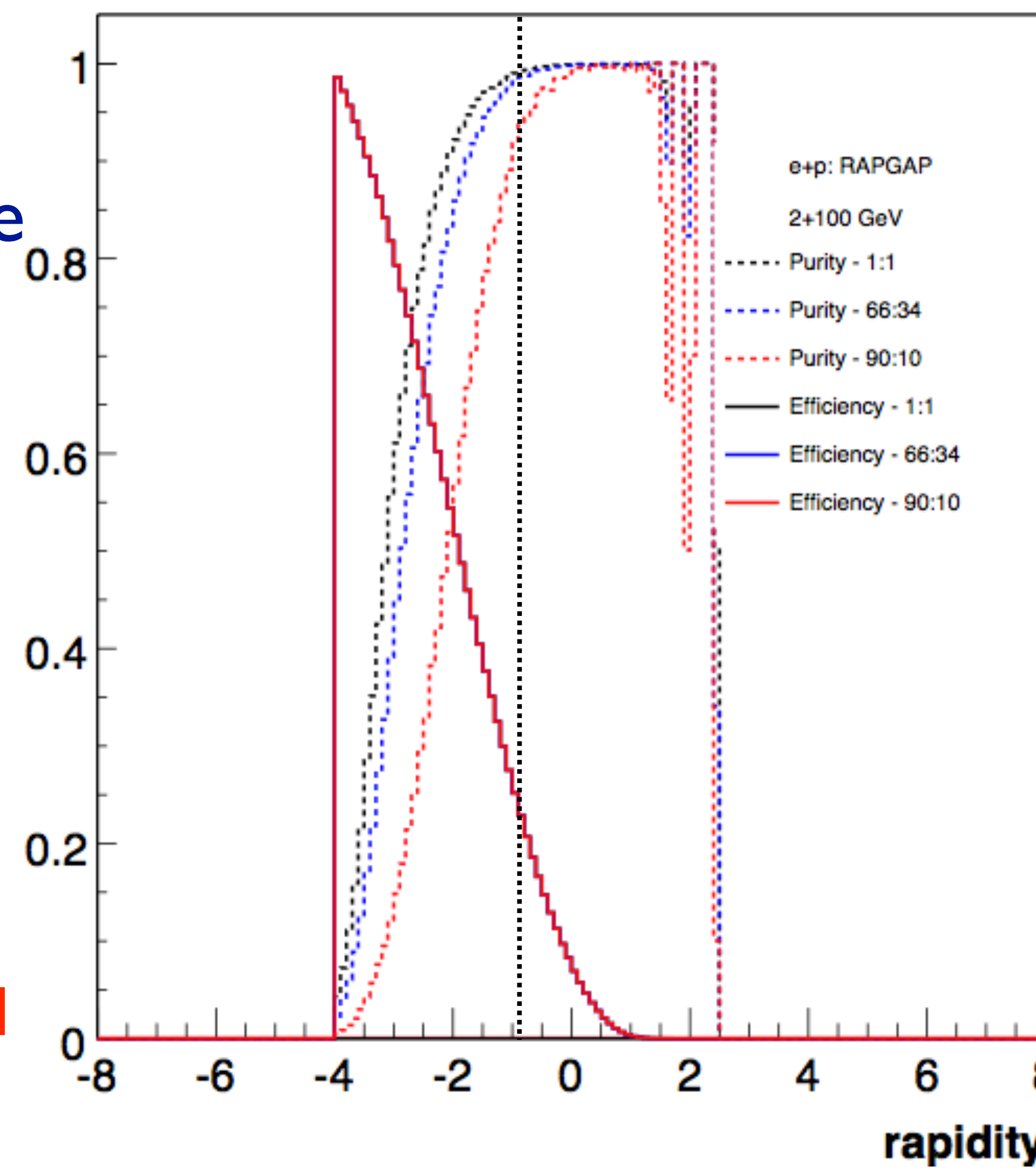

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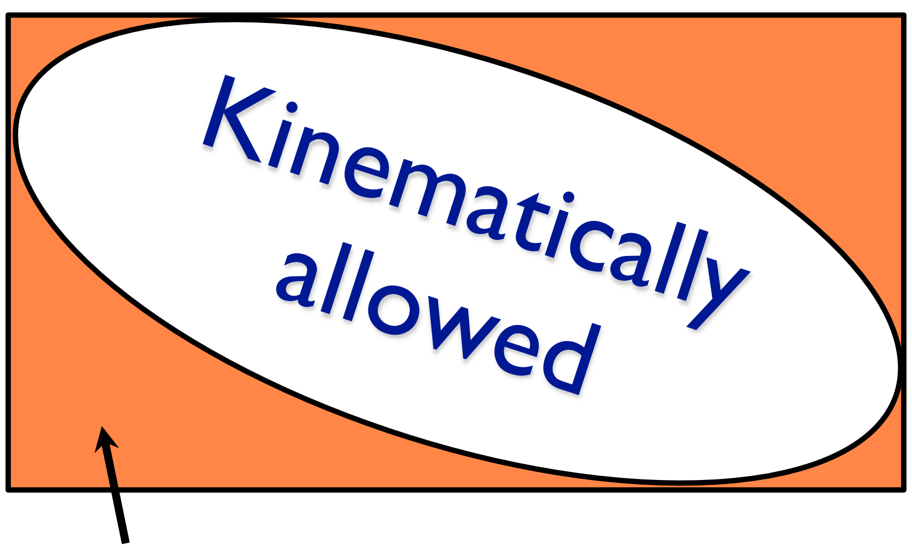
UNU.RAN Package

Universal Non-Uniform RANdom number generators
(Math Department University Vienna)

- ➡ provides tools to generate pretty much everything
- ➡ xdvmpGenerator:
  - Markov chain samplers for continuous multivariate distributions
  - HITRO: Hit-and-Run Sampler
- ➡ Bare minimum is implemented in Root/MathCore

- Issues:

Requires uniform limits (domains)



Kinematically not allowed but generated
Need to discard after generation (tries > events)

Requires to pass mode of pdf to UNURAN

- pdf is max at $|t| = |t|_{min}$, $x=x_{min}$, $Q=Q_{min}$
- less obvious for b, z, r

Use MINUIT (TMinuit2)

Random Generator

- Big Problem: generate random numbers according to a given distribution (here 6D PDF)
- Techniques (good overview in Pythia6 manual chapter 4):
  - ➡ Inverse transform method (invert cumulative PDF)
    - must integrate pdf and invert (note we have a DGLAP evolution in the PDF)
  - ➡ Acceptance-rejection method (Von Neumann)
    - good if pdf is too complex
    - rather easy in 1-D, nightmare in N-D
  - ➡ and many more
  - ➡ General recommendation in all text books for N-dim: factorize
    - Problem is we cannot do that since the 6 parameters are heavily intertwined
  - ➡ Largest fraction of code in most simulators is spent on this topic

UNURAN to the rescue (http://statmath.wu.ac.at/unuran/)

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Example Main Program

```
#include "xdvmpGenerator.h"


int main(int argc, char *argv[])

{

    xdvmpGenerator generator;

    bool ok = generator.init(“xdvmpRuncard.txt”);

    xdvmpSettings settings = generator.runSettings(); // for convinience

    TFile *hfile = new TFile(settings.rootfile().c_str(),"RECREATE");

    TH1D *histo_r = new TH1D("histo_r", "r distribution", 200, 0., 2.);


    int nPrint = settings.numberOfEvents()/settings.timesToShow();

    unsigned long maxEvents = settings.numberOfEvents();


    generator.printEventHeader(cout);
```

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Example Runcard

```
#==========================================================================
#  Comments start with a #
#  Name and value are separated by a "=":  name = value
#
#  The following settings are currently implemented:
#  eBeamEnergy:     electron beam energy (GeV)   (default = 10)
#  pBeamEnergy:     proton beam energy in (GeV)  (default = 250)
#  numberOfEvents:  number of events to generate (default = 10000)
#  vectorMeson:     rho | phi | jpsi  (default = rho)
#  waveFunction:    GausLC | BoostedGaussian (default = BoostedGaussian)
#  dipoleModel:     bSat | bCGC (default = bCGC)
#  timesToShow:     # of print-outs to tell how far we are (default=0)
#  rootfile:        name of root file for histos etc. (default ="")
#  xmin:            min x value (default = 1e-3)
#  Q2min:           min Q2 value (GeV^2)  (default = 1.)
#==========================================================================
eBeamEnergy = 10
pBeamEnergy = 250
vectorMeson = rho
dipoleModel = bSat
waveFunction = BoostedGaussian
numberOfEvents = 10000
timesToShow = 10;
rootfile = bla.root
Q2min = 1;
xmin = 1e-3;
```

Example Output (1)

```
#============================================================##
xdvmGenerator##  An event generator for exclusive diffractive vector
meson#  production using the dipole model.##  Code compiled on Jan
20 2010
16:50:46#=====================================================
=====Run started at Wed Jan 20 23:22:34 2010Runcard is
'xdvmpRuncard.txt'mXmin = 0.001Electron beam is: 0     0       -10
10      (0.000510999)Proton beam is:   0     0       249.998 250
(0.93827)sqrt(s) = 100.004Initializing the xdvmp dipole model:Vector
meson to generate: rhoDipole model used: bCGCWave function used:
BoostedGaussian
```

Example Output (2)

```
Range of kinematic variables (domain) used in generator:t =
[-4, 0]Q = [1, 100.004]x = [0.001, 0.99]b = [0, 2]z =
[1e-12, 1]r = [0.001, 2]Finding mode of pdf:mode = (t=0,
Q=1, x=0.001, b=0.453883, z=0.5, r=0.526119; value of pdf =
107769)Initializing the random generator:Dimensions used:
6pdf in log: noNumber of events to process:
10000xdvmpGenerator is initialized.
```

For bCGC this takes < 1 s

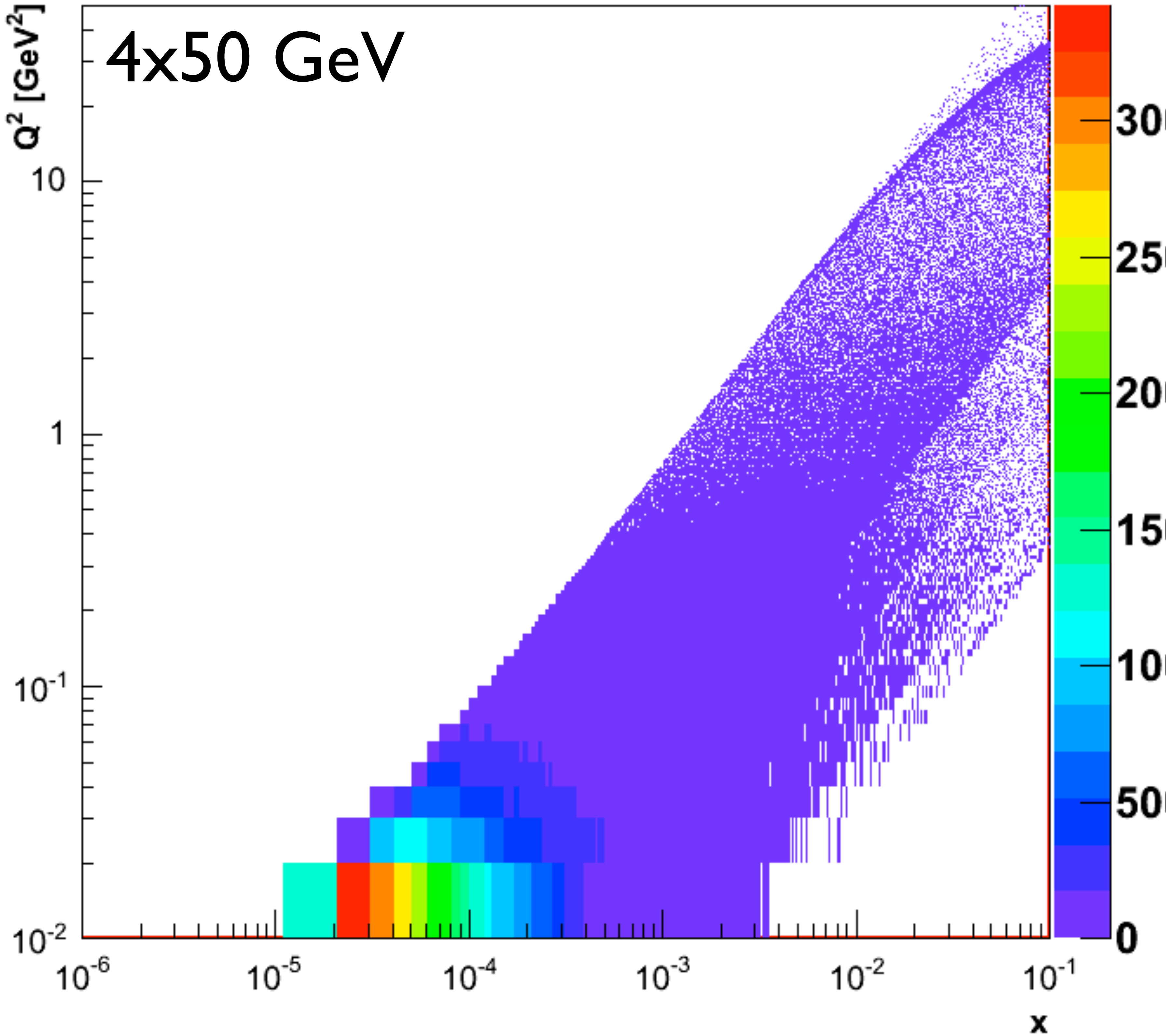
For bSat ~ 1-2 min (due to DGLAP setup)

Example Event Record

```
xdvmpGen event file============================================iEvent, t, Q2, x, y, b, z, r,
s============================================i, id, px, py, px, E, m, vx, vy,
vz============================================processed 0 events1       -0.171395       2.03611         0.00254752      0.0799258
0.525637        0.380722        0.344587        10000.8============================================1           11              0
0           -10             10   0.000510999            0             0             02          2212            0              0
249.998         250       0.93827             0             0             03            11   -0.00222092       1.36871
-9.14977        9.25157   0.000510999          0             0             04          2212       0.214882      0.352692
248.818         248.82      0.93827             0             0             05          113      -0.212661      -1.7214
0.33036       1.92867        0.776              0             0             0============= End Event Record =============2
-0.171395       2.03611         0.00254752      0.0799258       0.525637        0.380722        0.554715
10000.8============================================1           11              0             0             -10             10
0.000510999             0             0             02          2212            0             0           249.998         250
0.93827             0             0             03            11       1.34006       -0.278549      -9.14977        9.25157
0.000510999             0             0             04          2212       0.390437      -0.134496       248.769        248.771
0.93827             0             0             05          113       -1.7305       0.413045       0.379414       1.97772
0.776             0             0             0============= End Event Record =============
```

- Note the VM does not decay (GEANT can do this if needed)
- VM have zero width (should probably change that)
- The event record can be directly written into a ROOT Tree or any other format, the print-out shown here is optional
- Time to generate 1M events ~ 4 min on Thomas' 3y old MacBook Pro

x-Q^2 acceptance vs energy



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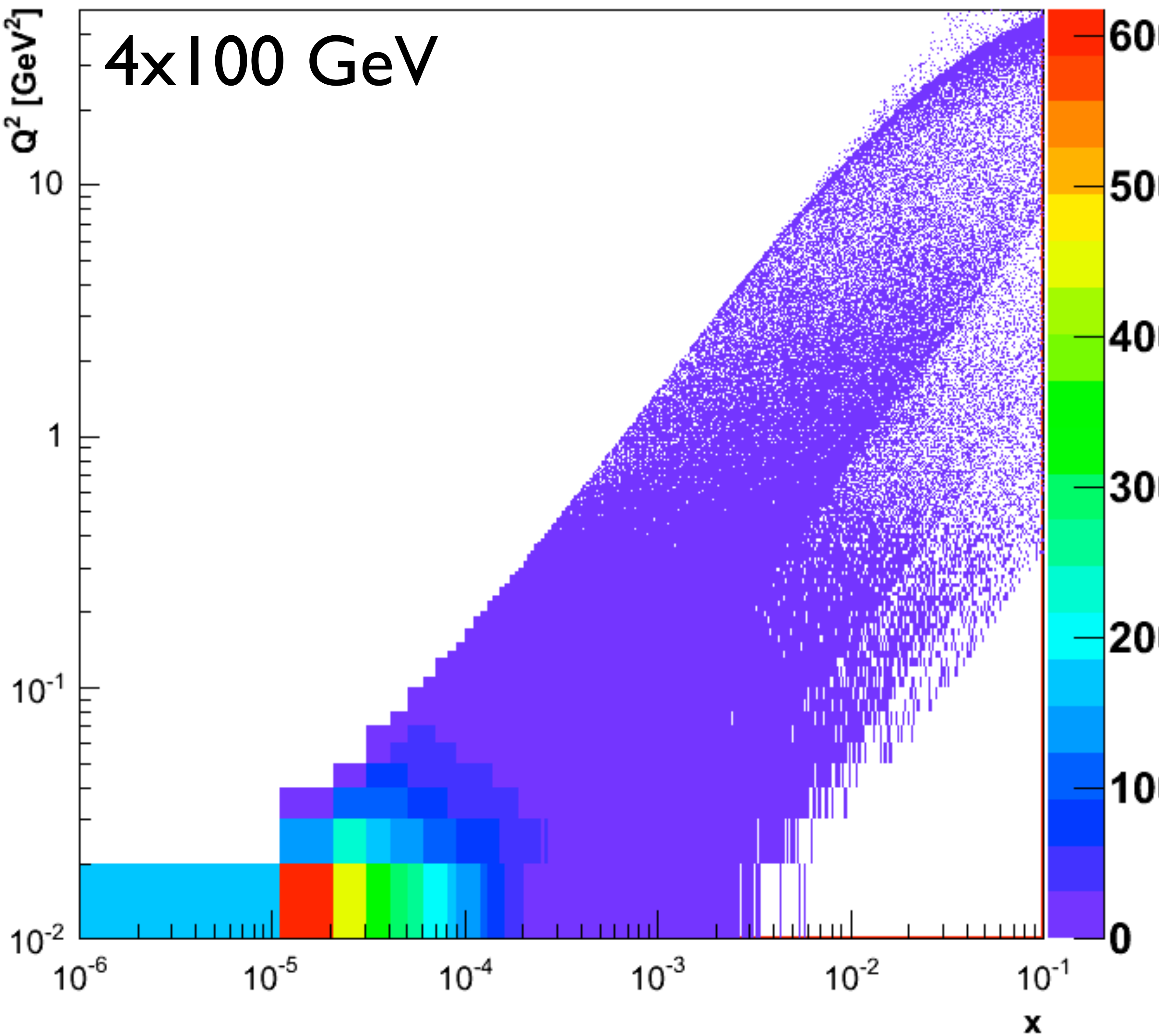

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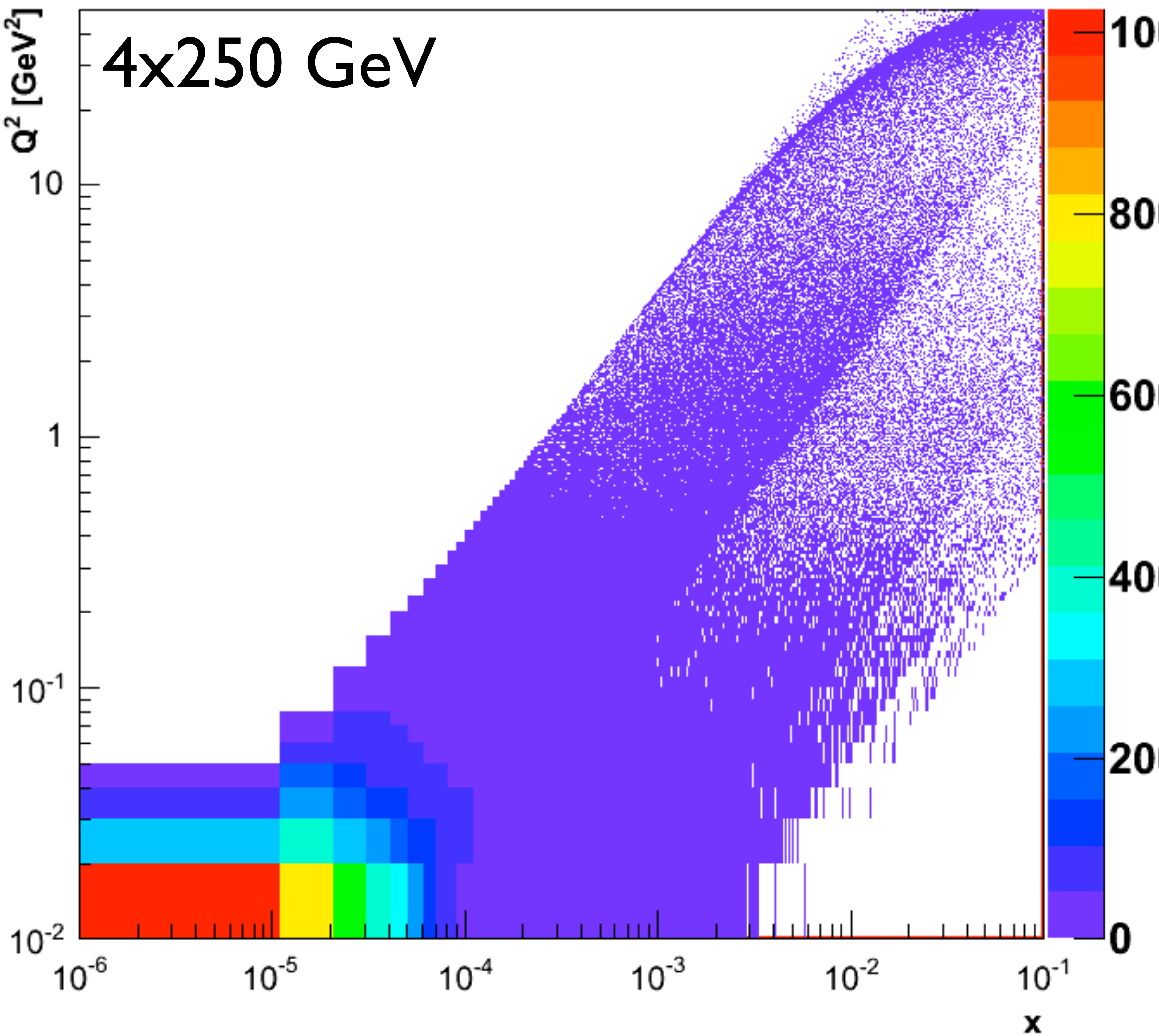

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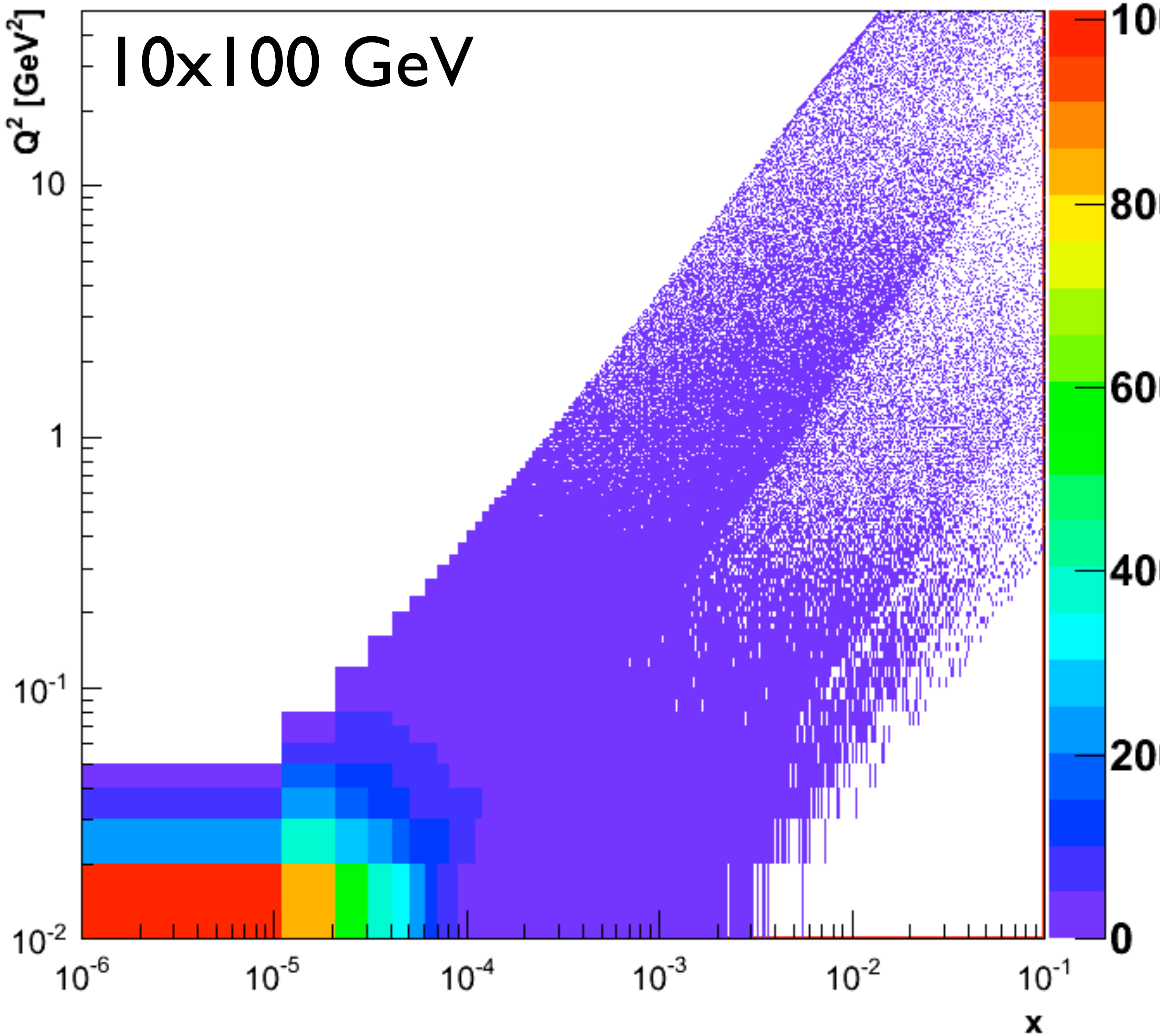

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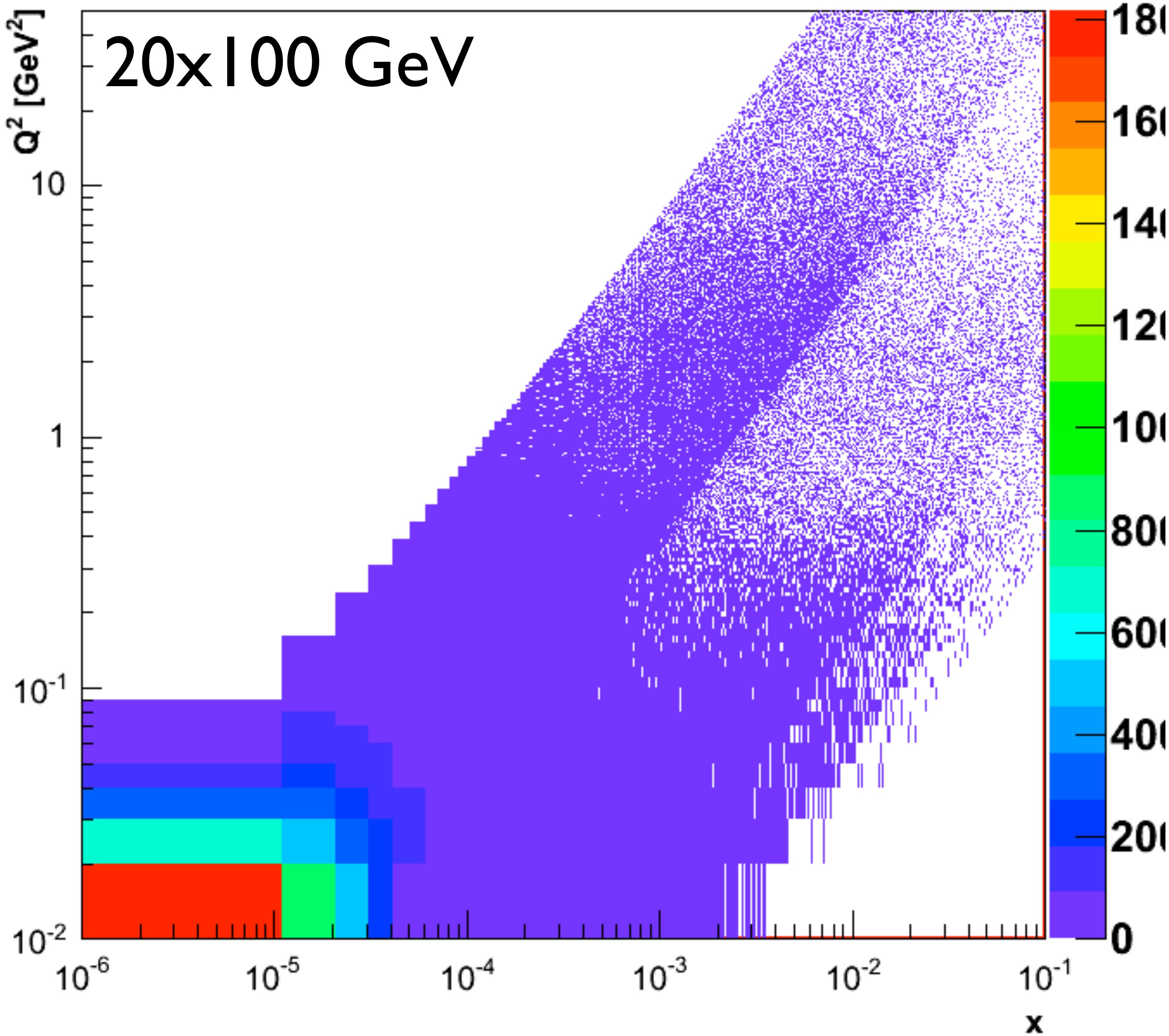

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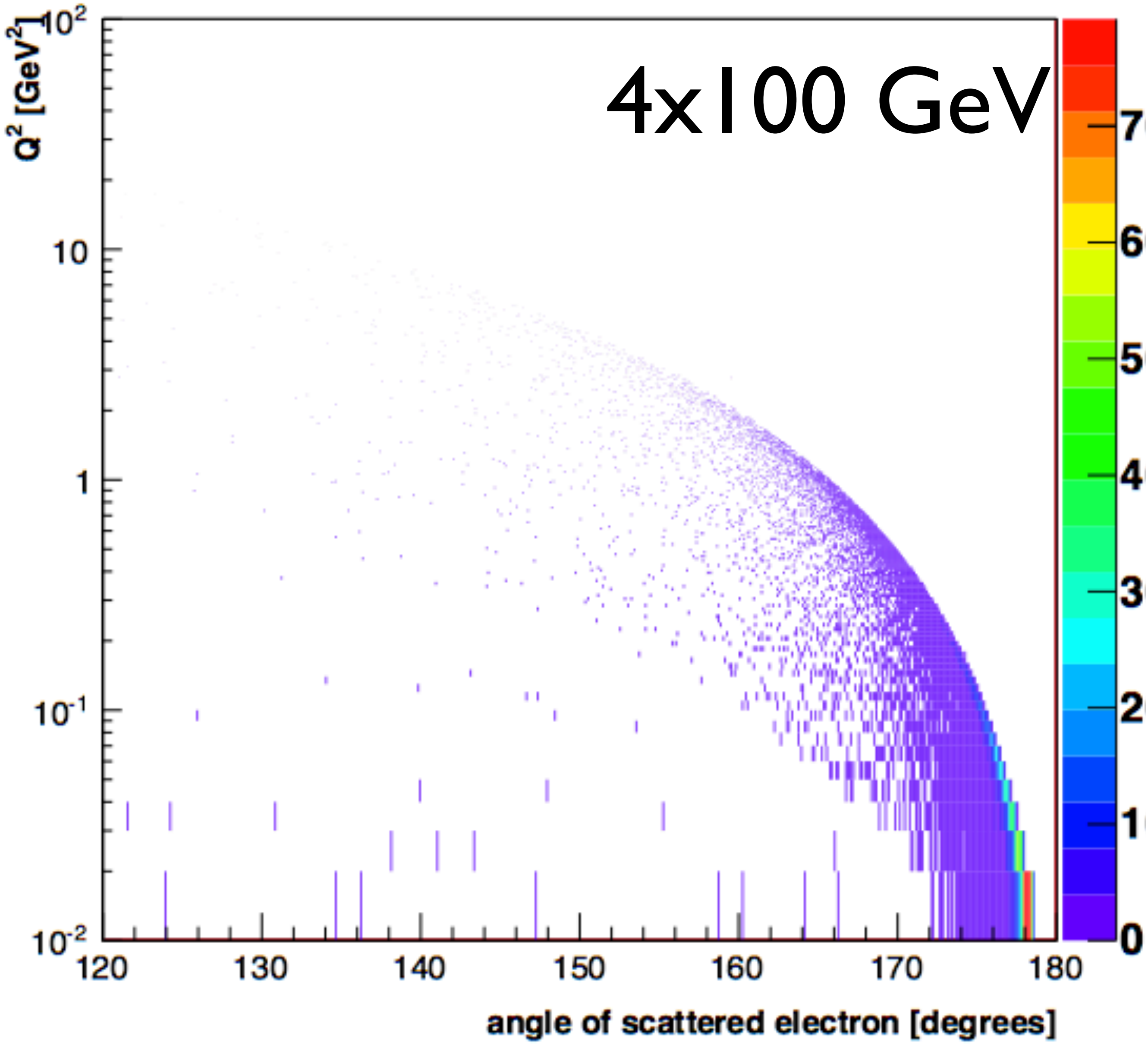
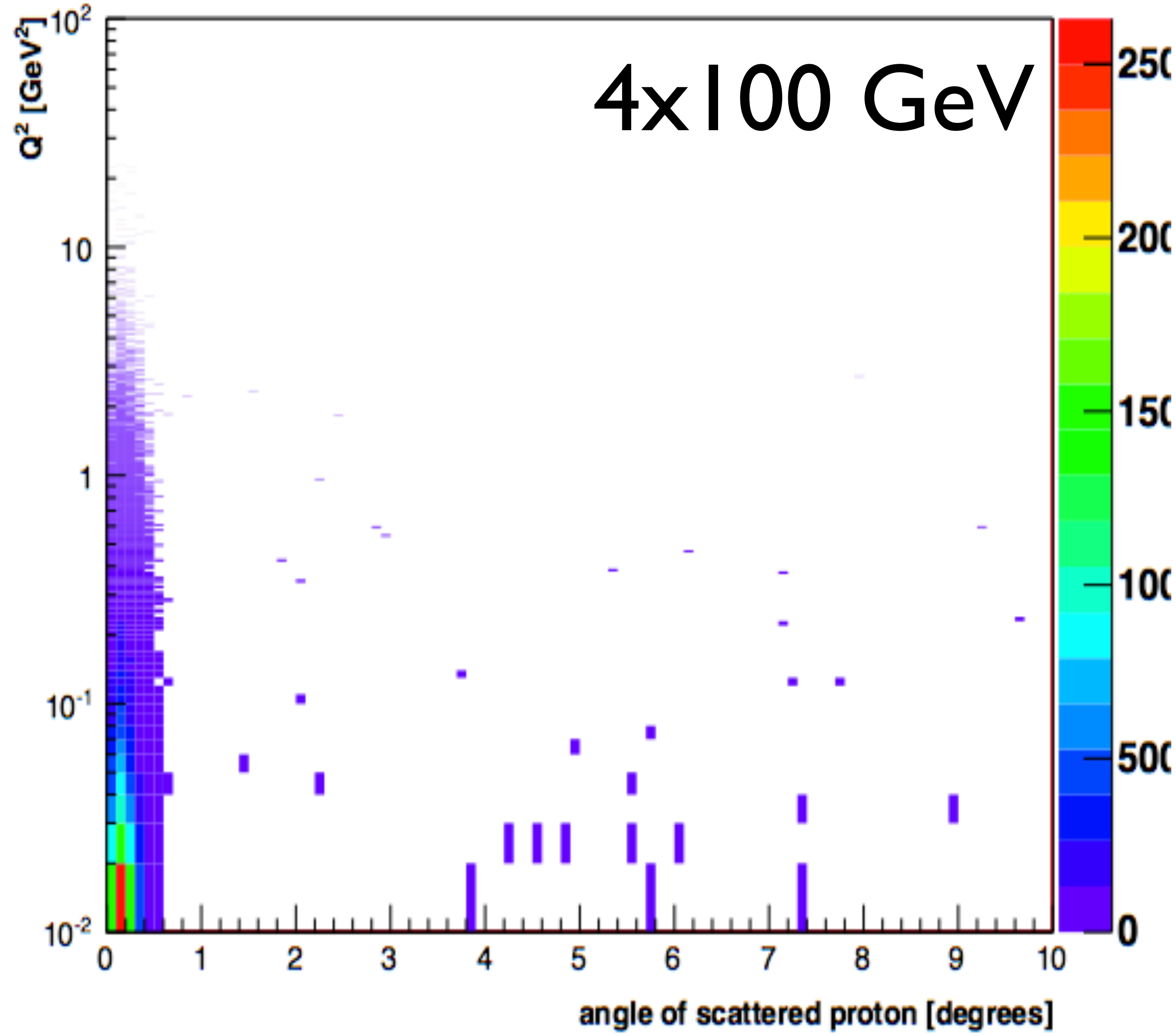
electron and proton angles vs Q^2

electron



proton



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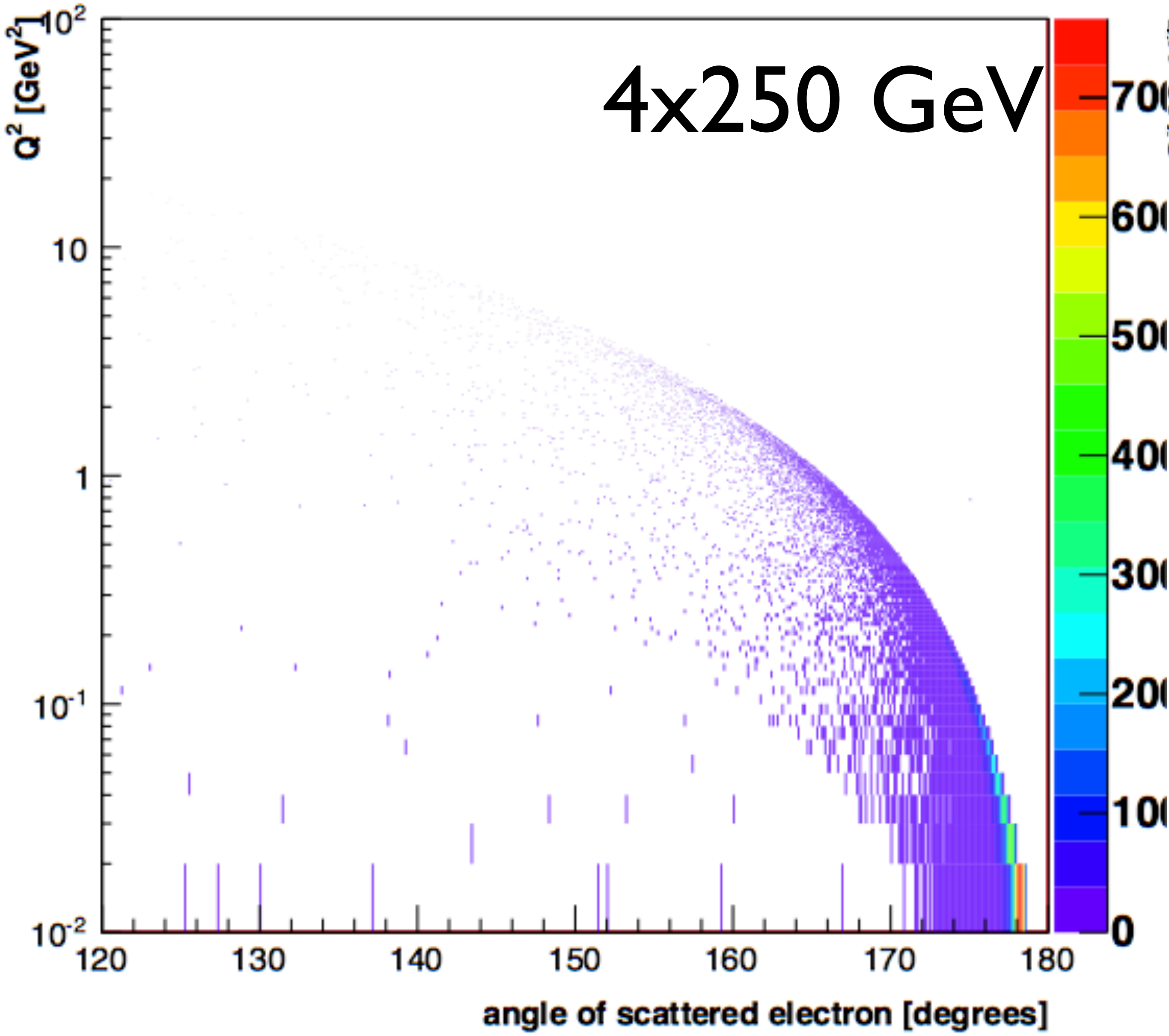

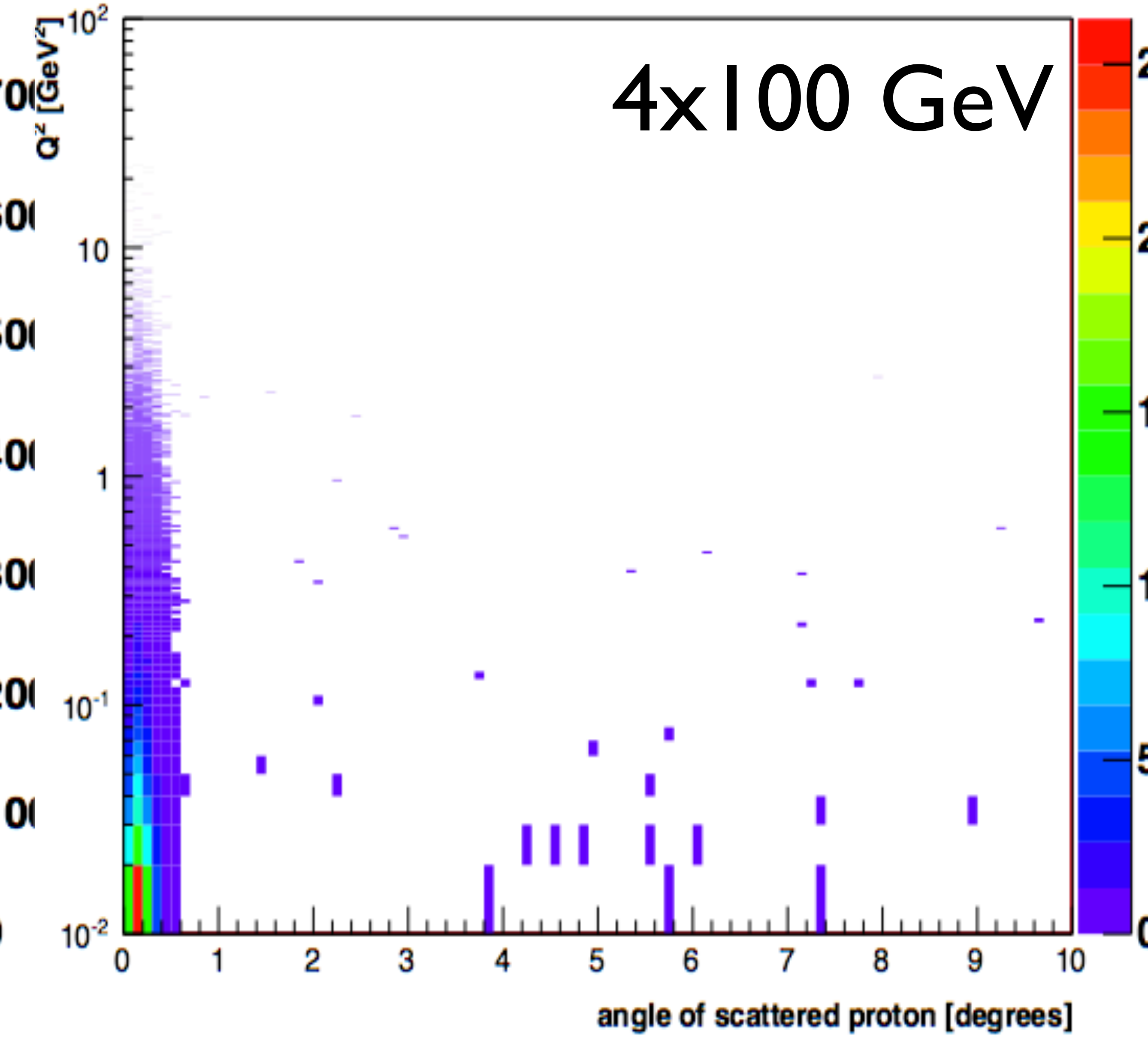

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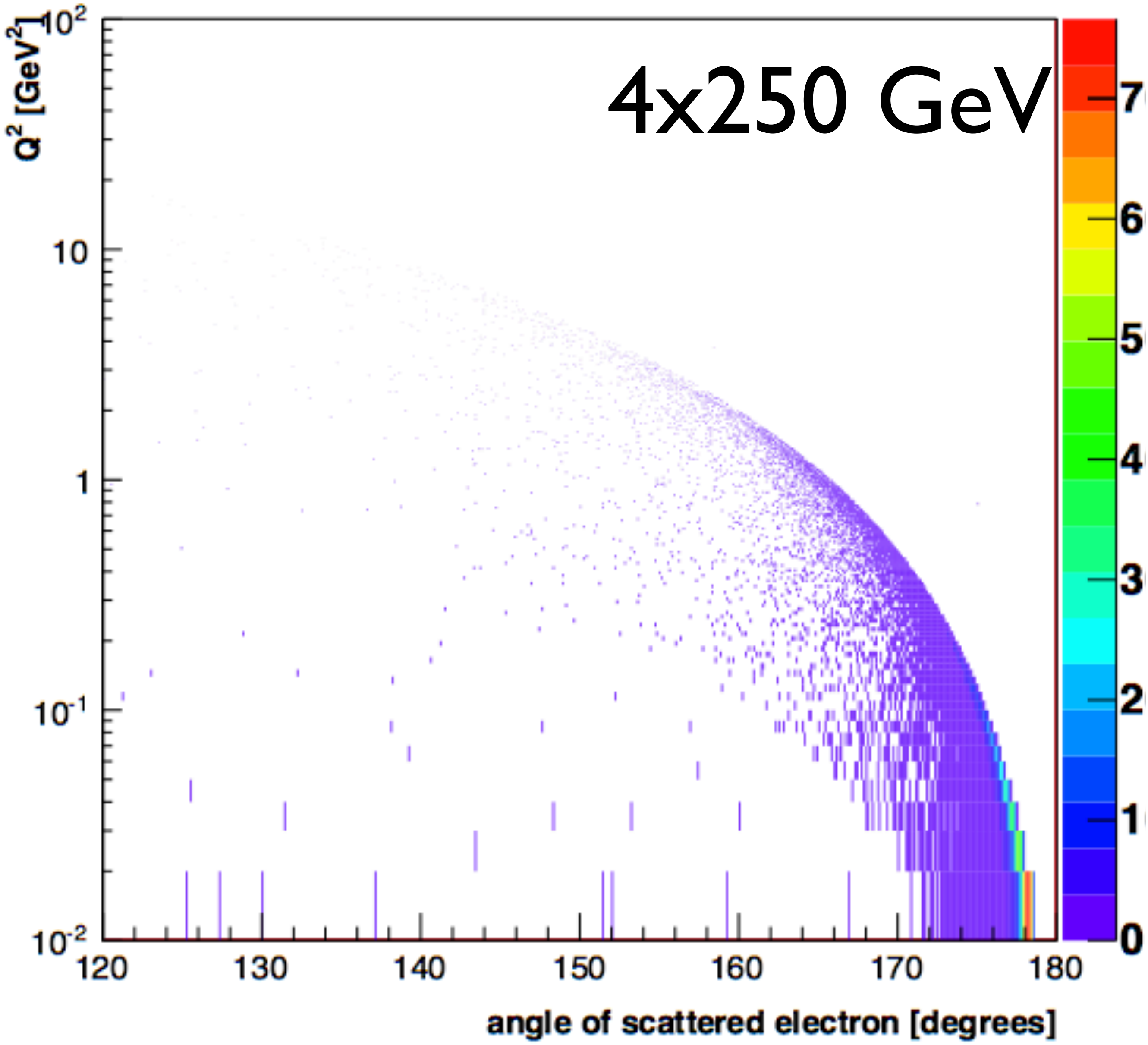

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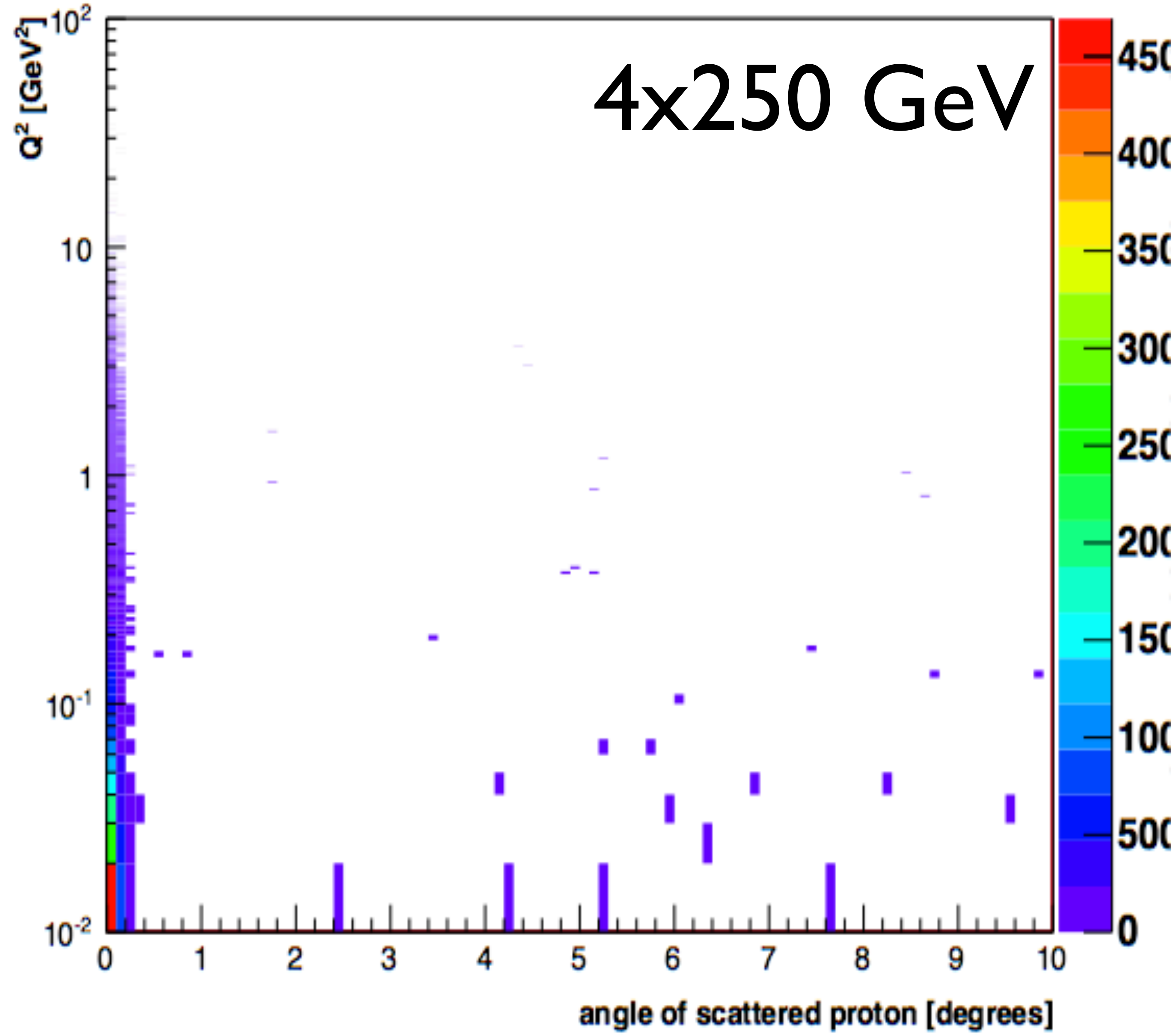

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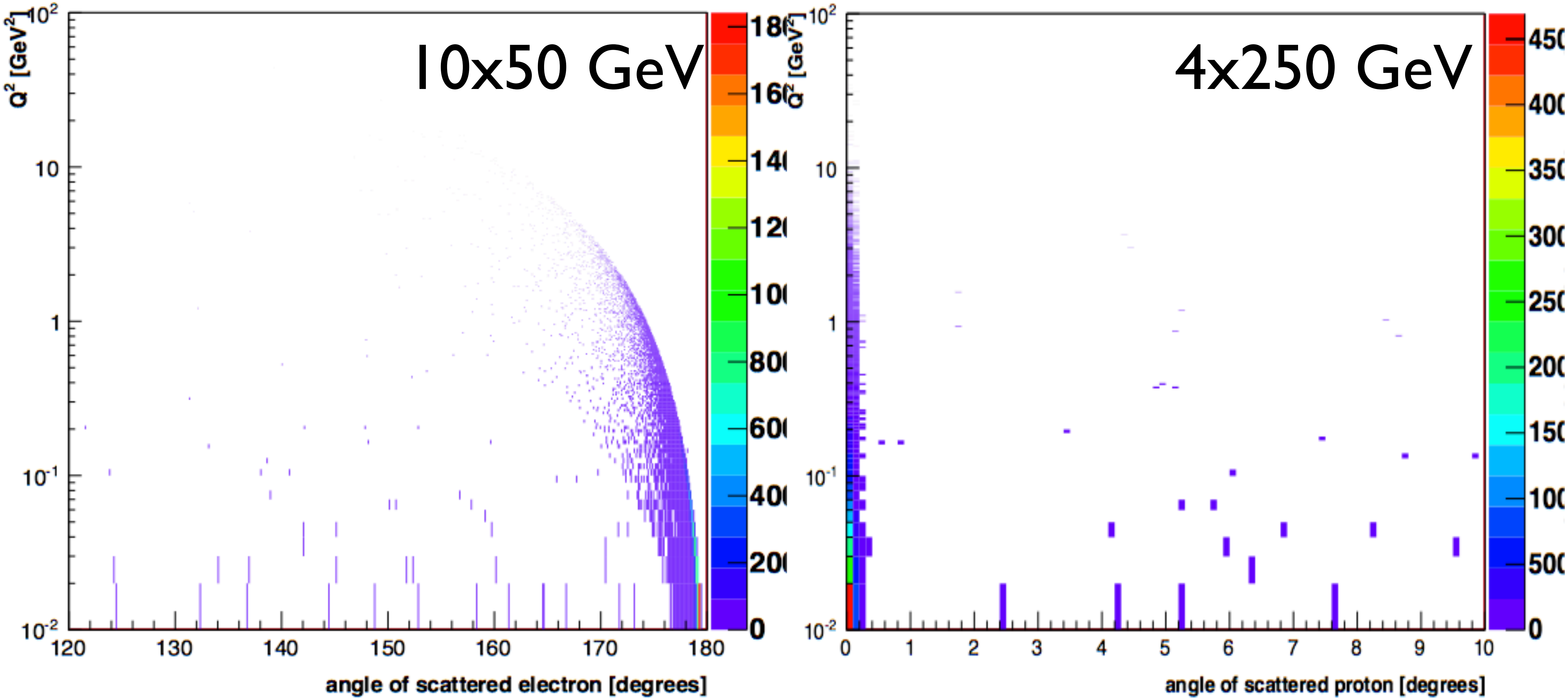
electron and proton angles vs Q^2

electron | proton



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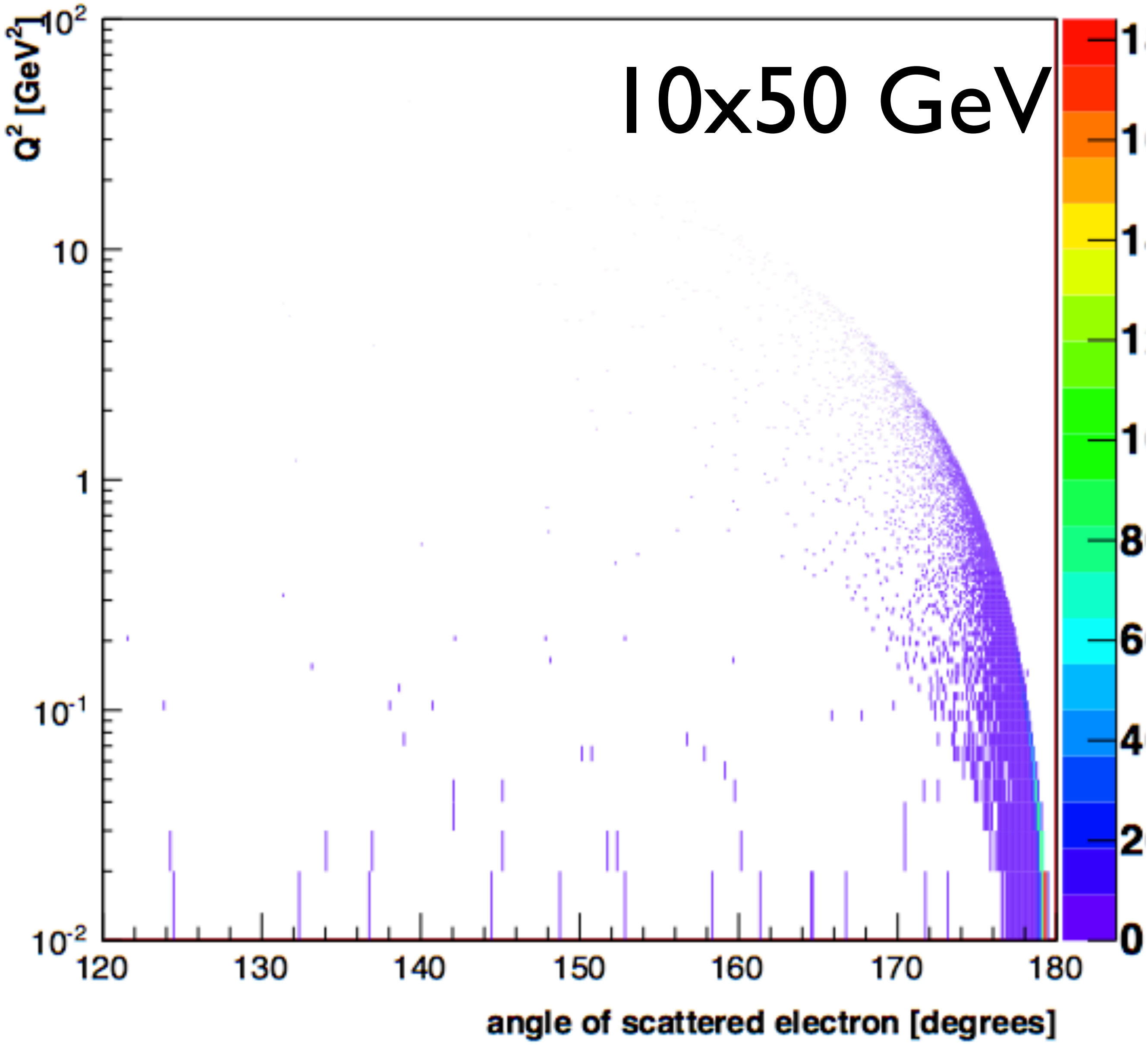

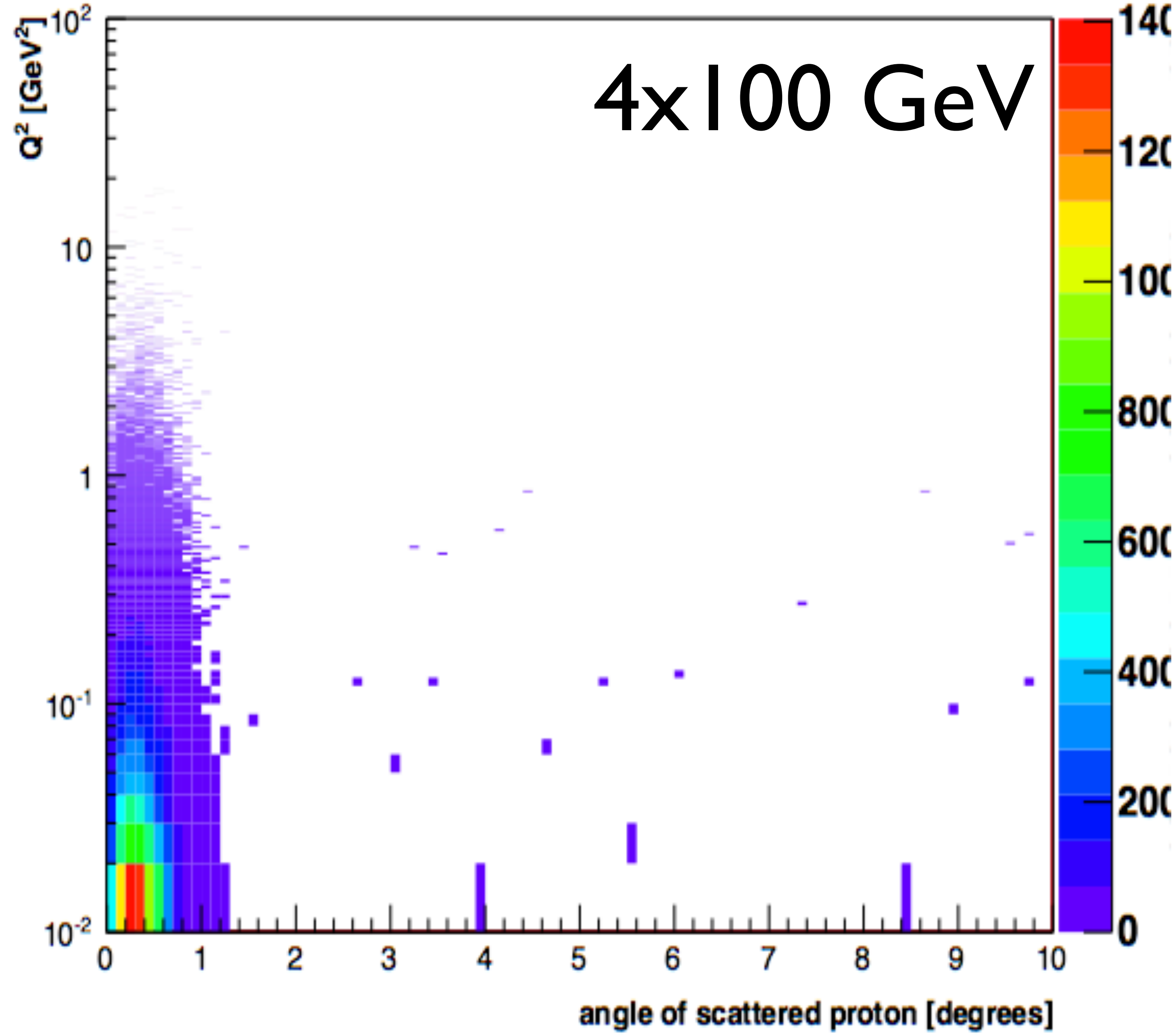

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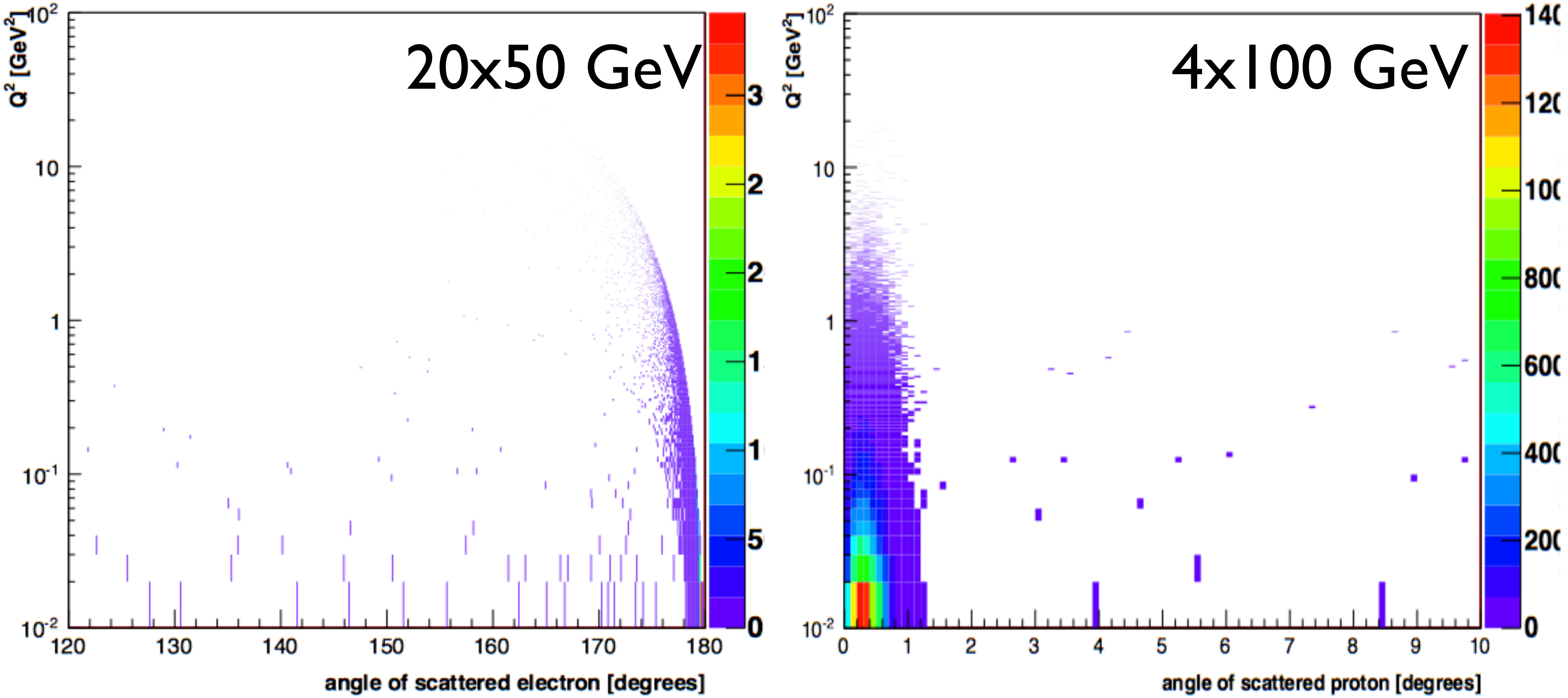

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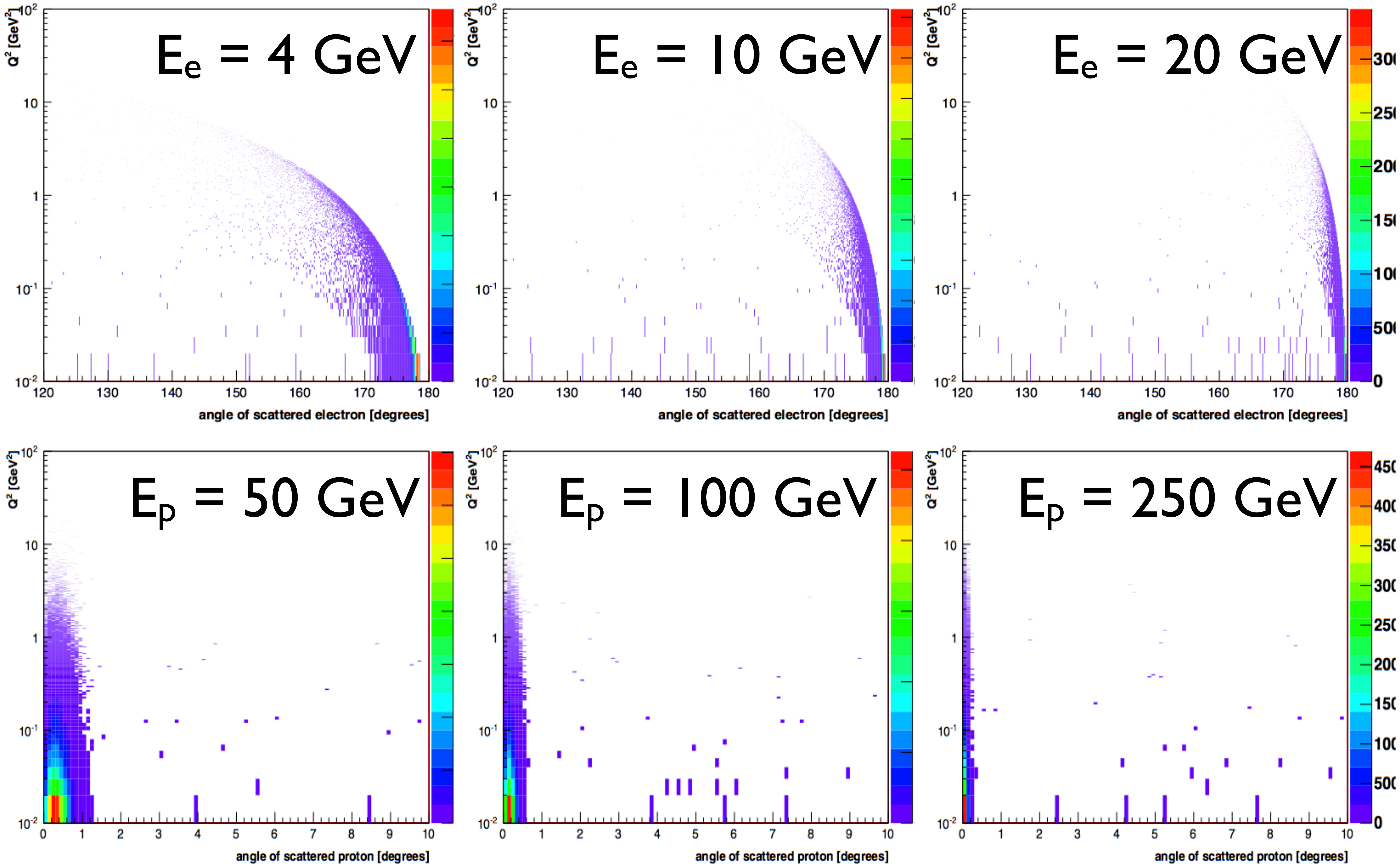
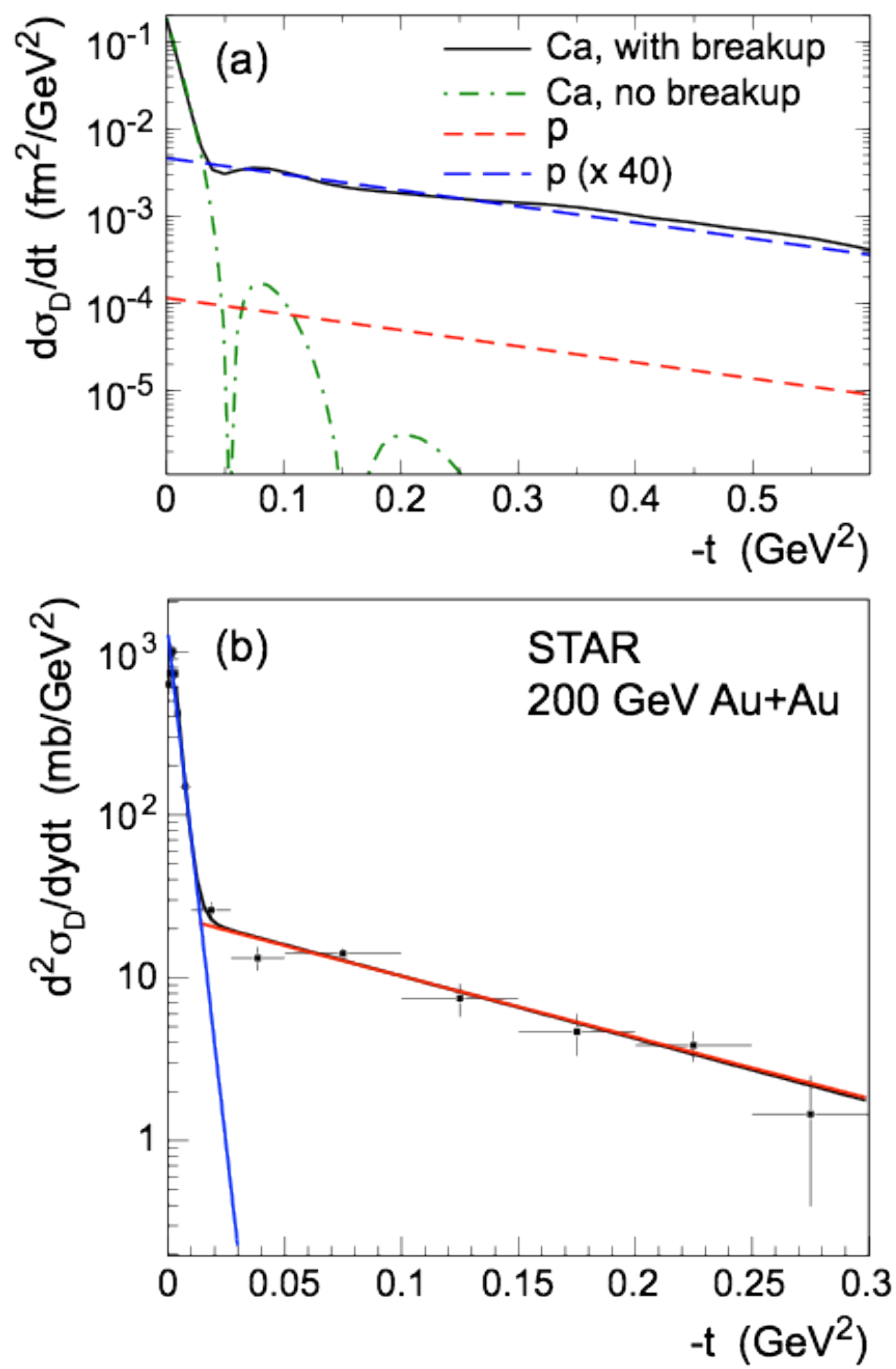


How to measure coherent diffraction in e+A ?

$$\frac{d\sigma}{dt}|_{t=0}(\gamma^* A \rightarrow VA) \propto \alpha_s^2[G_A(x,Q^2)]^2$$



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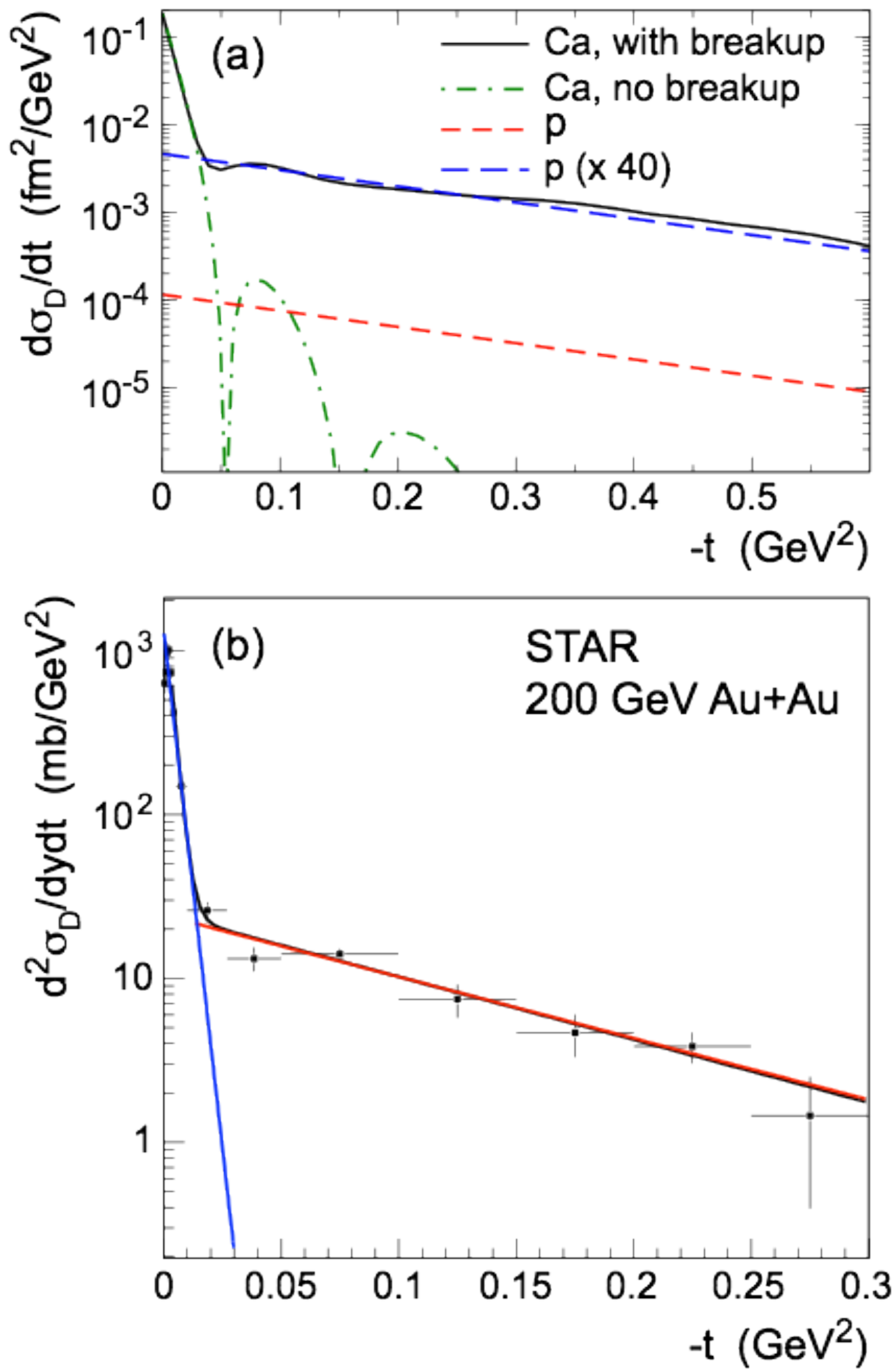
- Can measure the nucleus if it is separated from the beam in Si (Roman Pot) "beamline" detectors
  - ➡ $p_T^{min} \sim pA\theta_{min}$
    - For beam energies = 100 GeV/n and θ_{min} = 0.08 mrad:
- These are large momentum kicks, >> the binding energy (~ 8 MeV)



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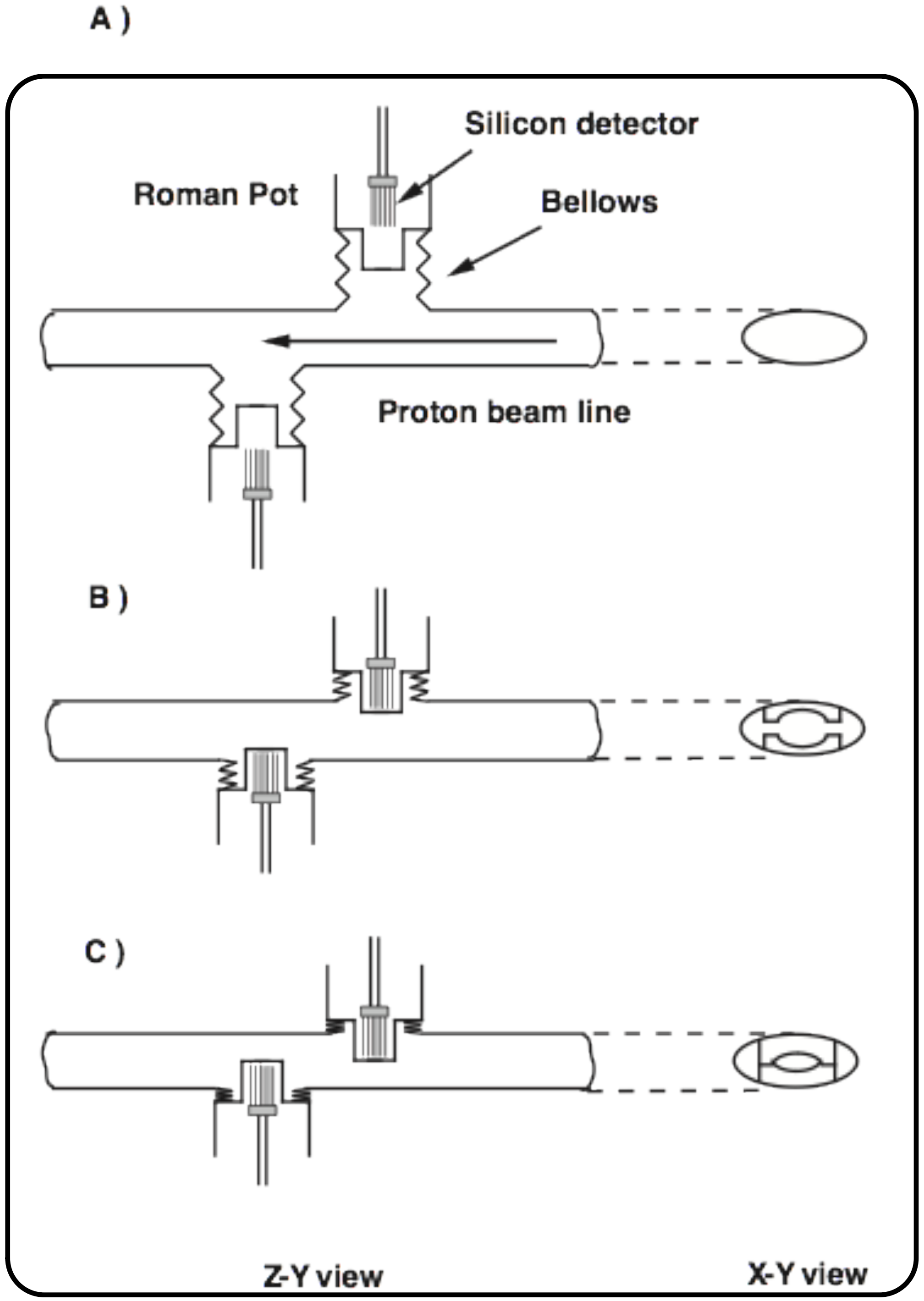

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d (2)	0.02
Si (28)	0.22
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For large A, nucleus cannot be separated from beam without breaking up

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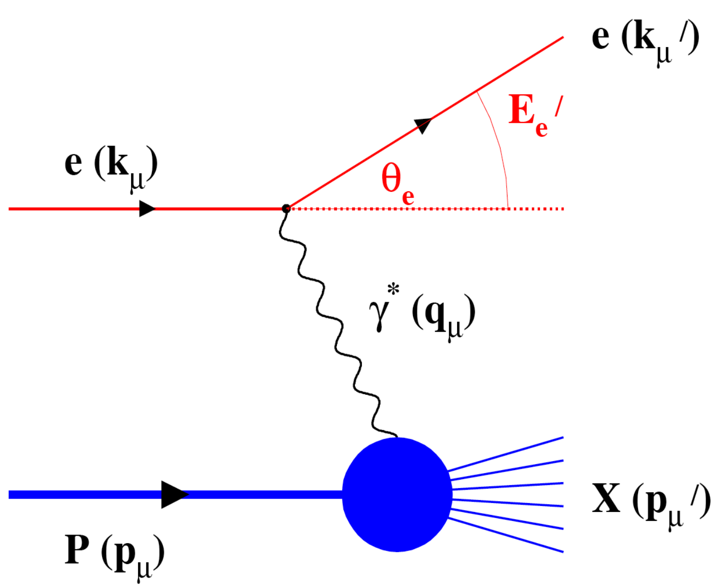
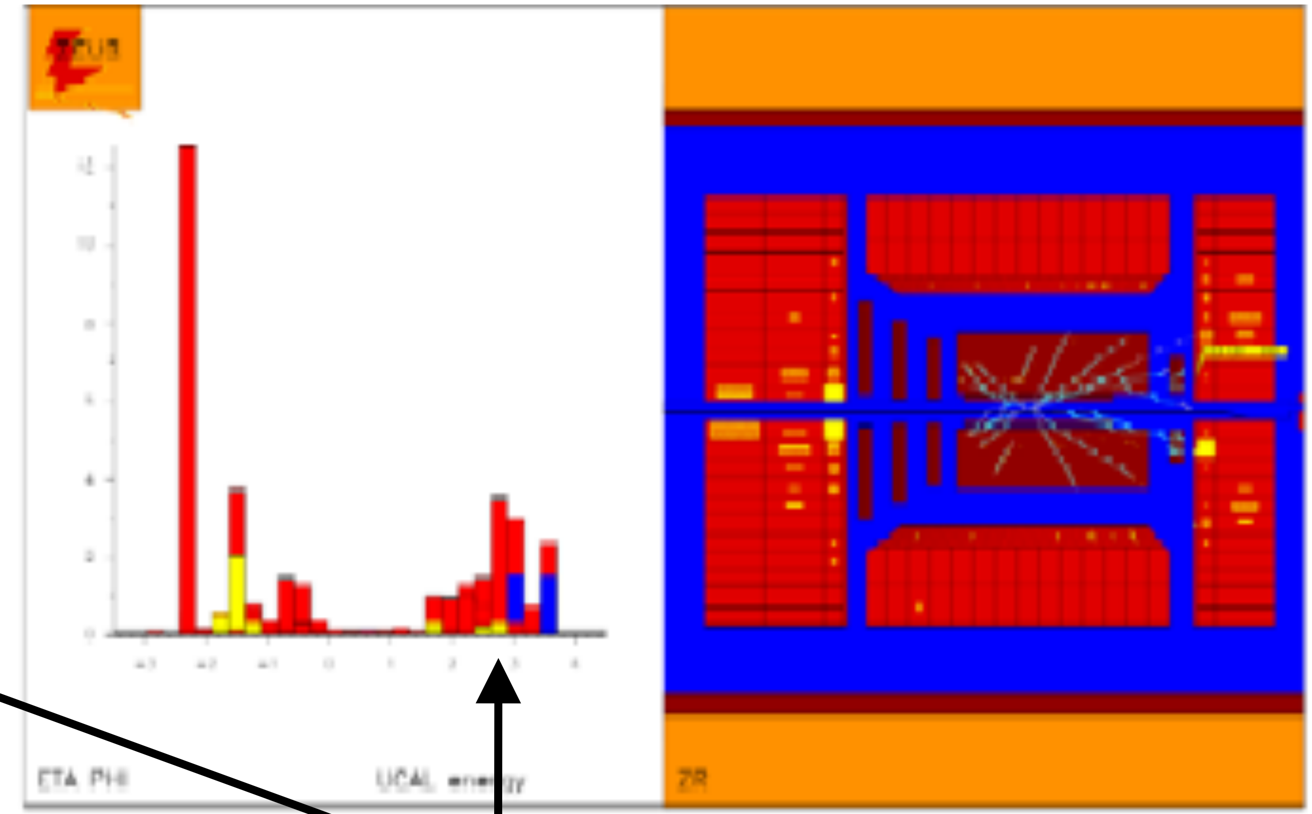
Diffractive Physics in e+A

'Standard DIS event'

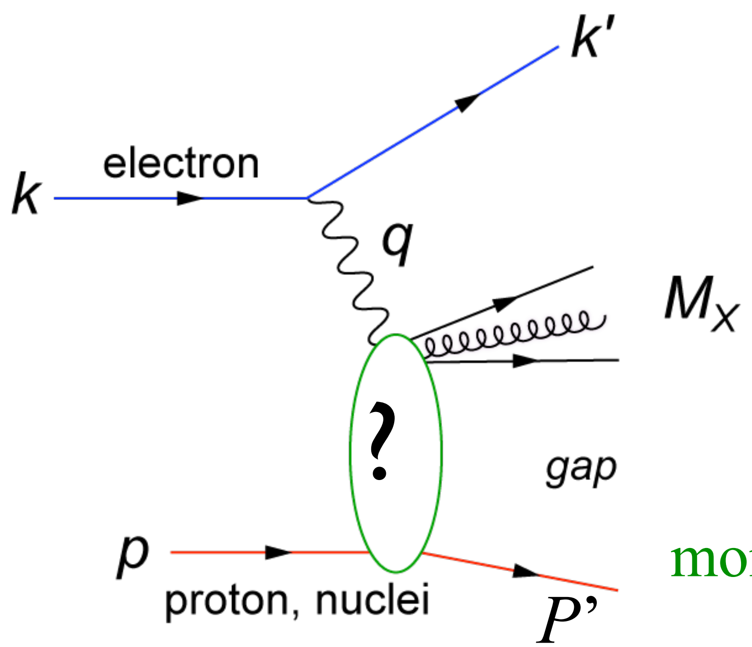




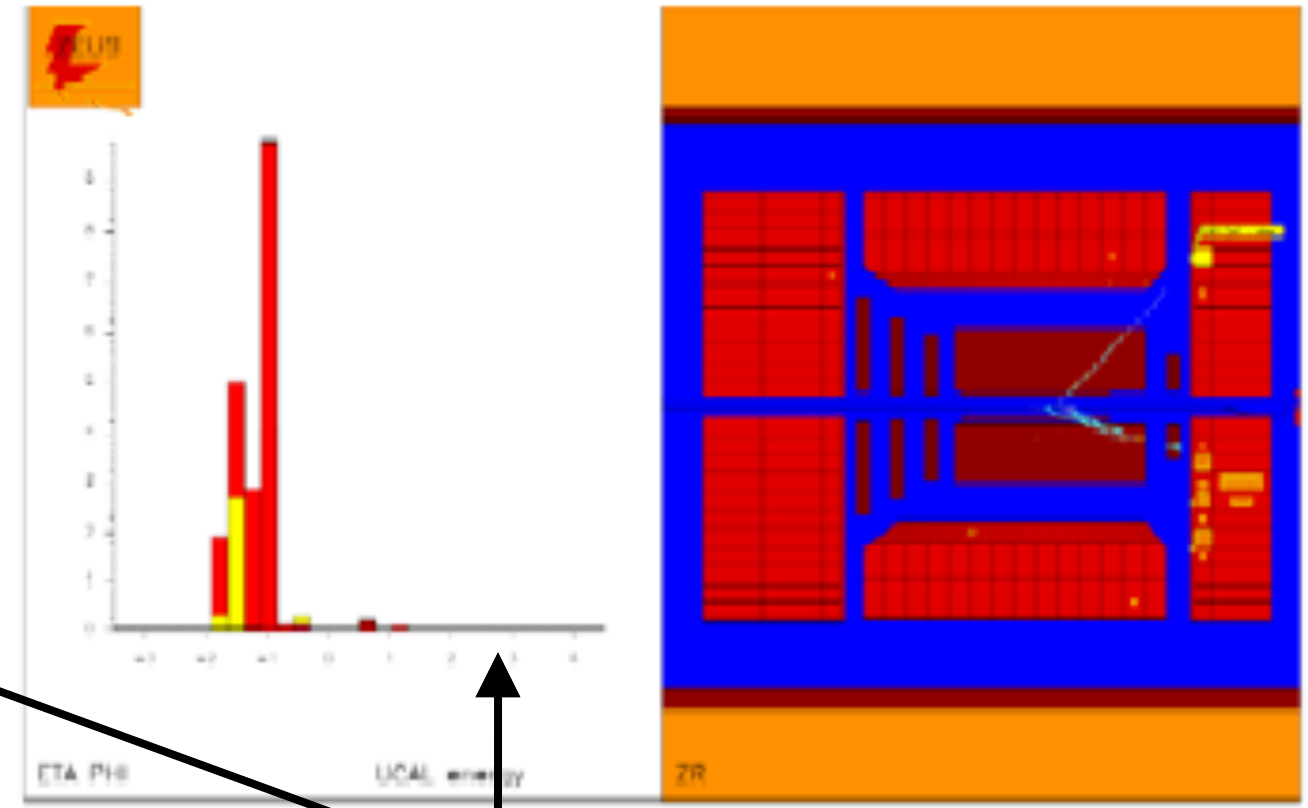
Activity in proton direction

Diffractive Physics in e+A

Diffractive event



momentum transfer:
$t = (P\text{-}P')^2$



Activity in proton direction

- HERA/ep: 15% of all events are hard diffractive
- Diffractive cross-section $\sigma_{diff}/\sigma_{tot}$ in e+A ?

➡ Predictions: ~25-40%?

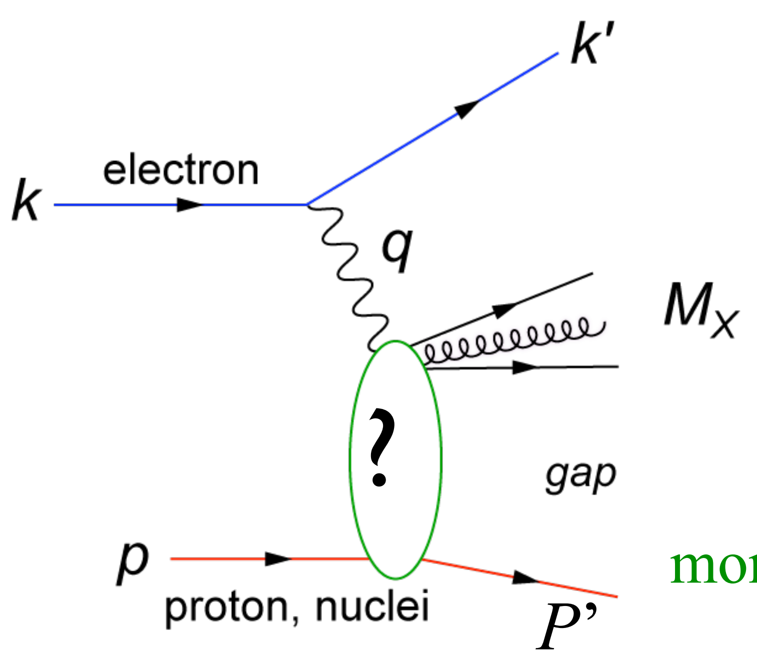
- Look inside the “Pomeron”

➡ Diffractive structure functions

➡ Exclusive Diffractive vector meson production: **dσ/dt ~ [xG(x,Q^2)]^2 !!**

Diffractive Physics in e+A

Diffractive event



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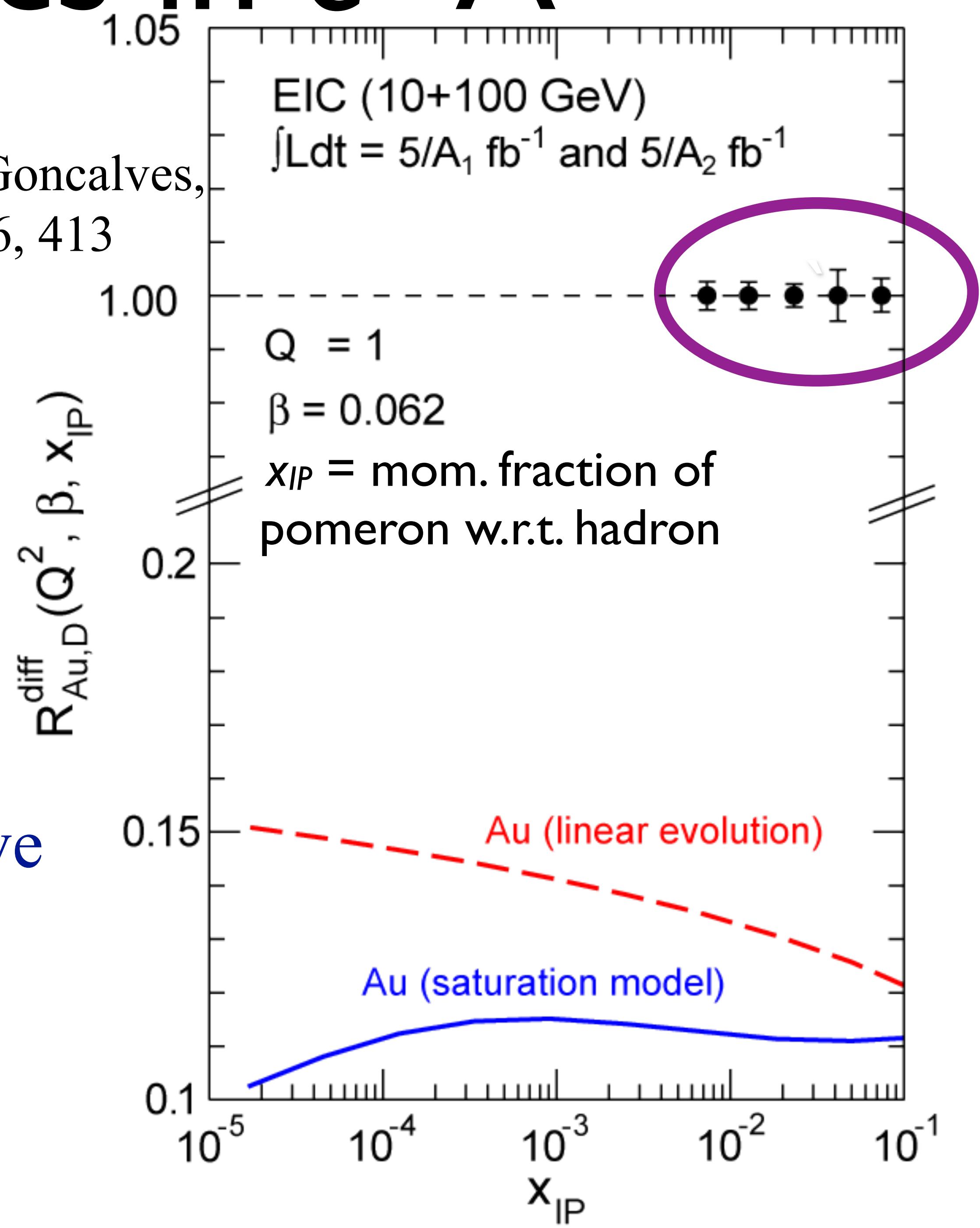
Curves: Kugeratski, Goncalves, Navarra, EPJ C46, 413



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- Distinguish between linear evolution and saturation models

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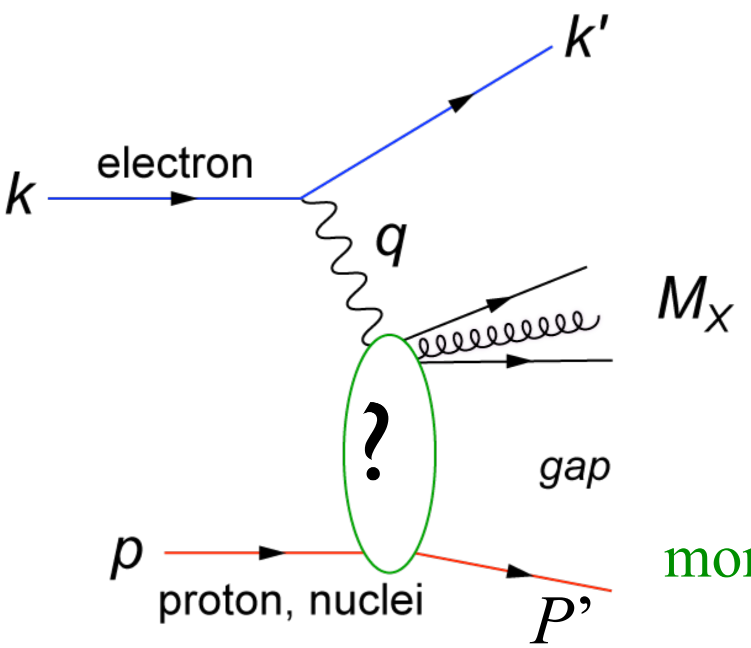
Diffractive event



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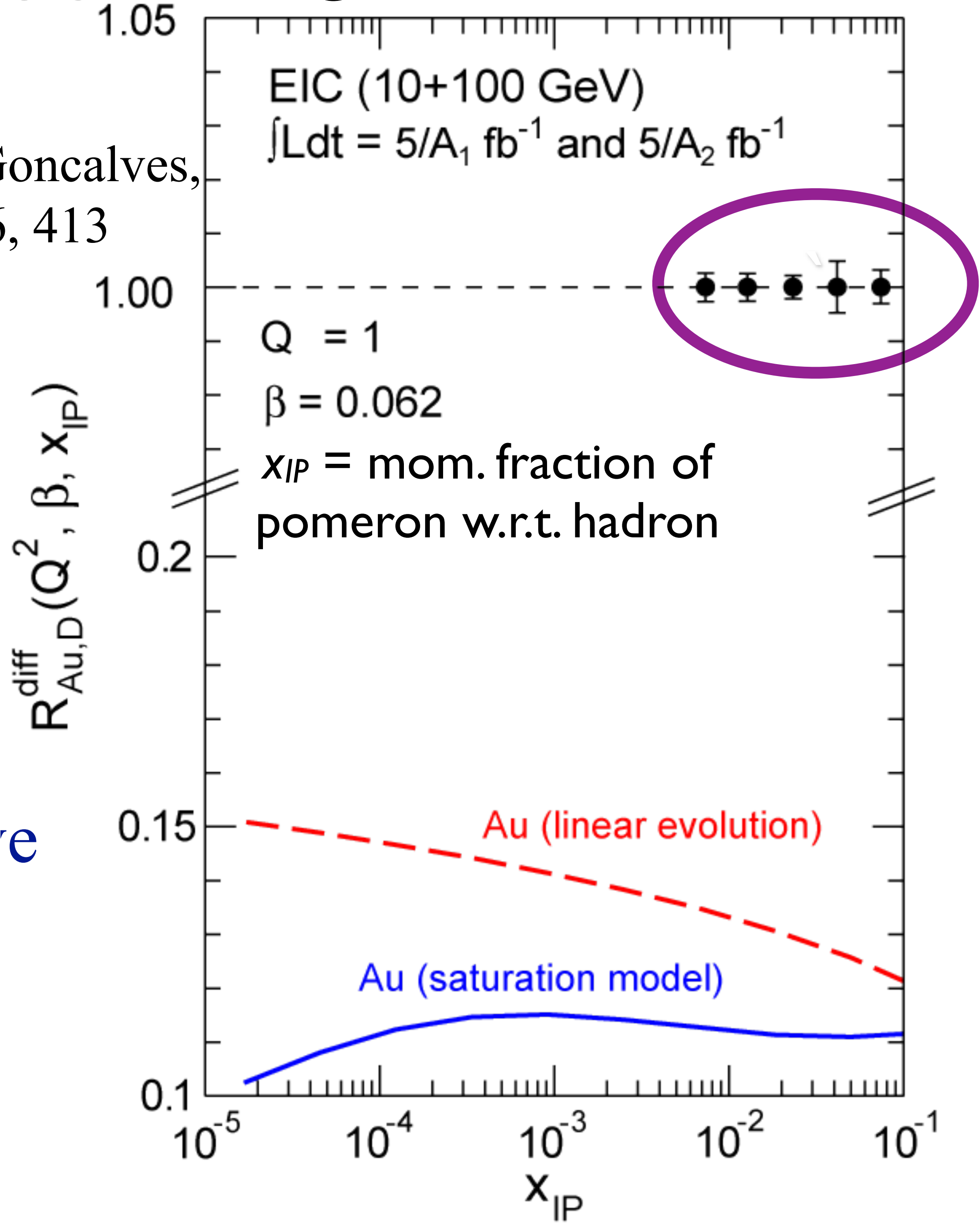
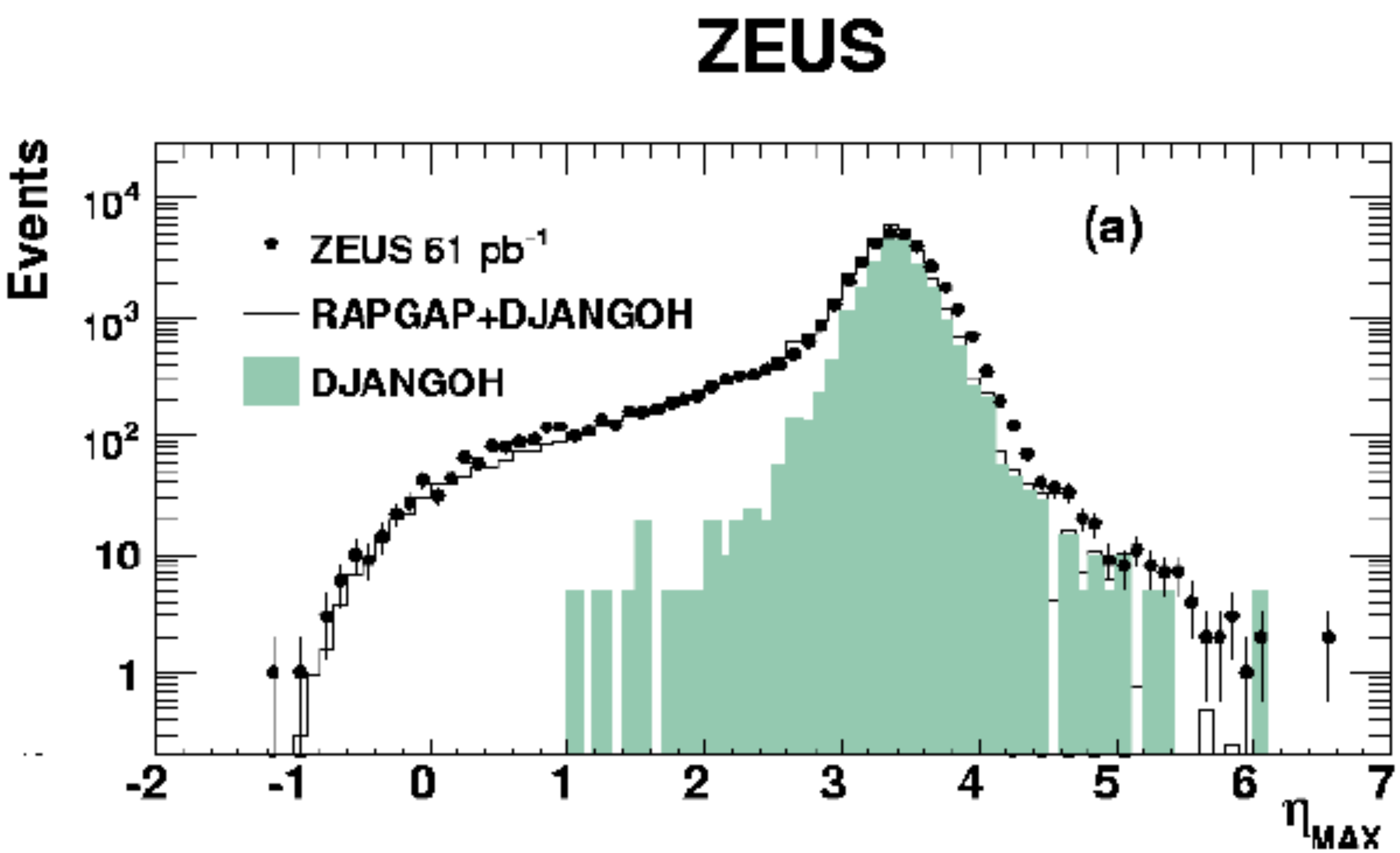




e

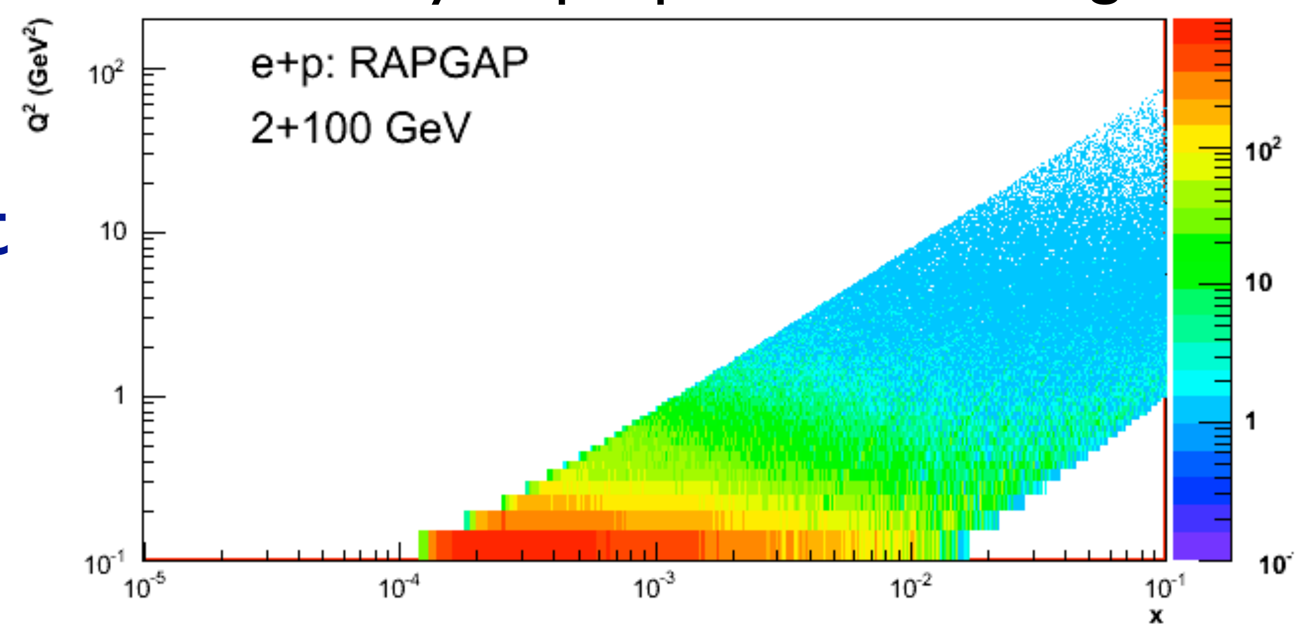
σ/d*t* ~ [xG(x,Q²)]² !!

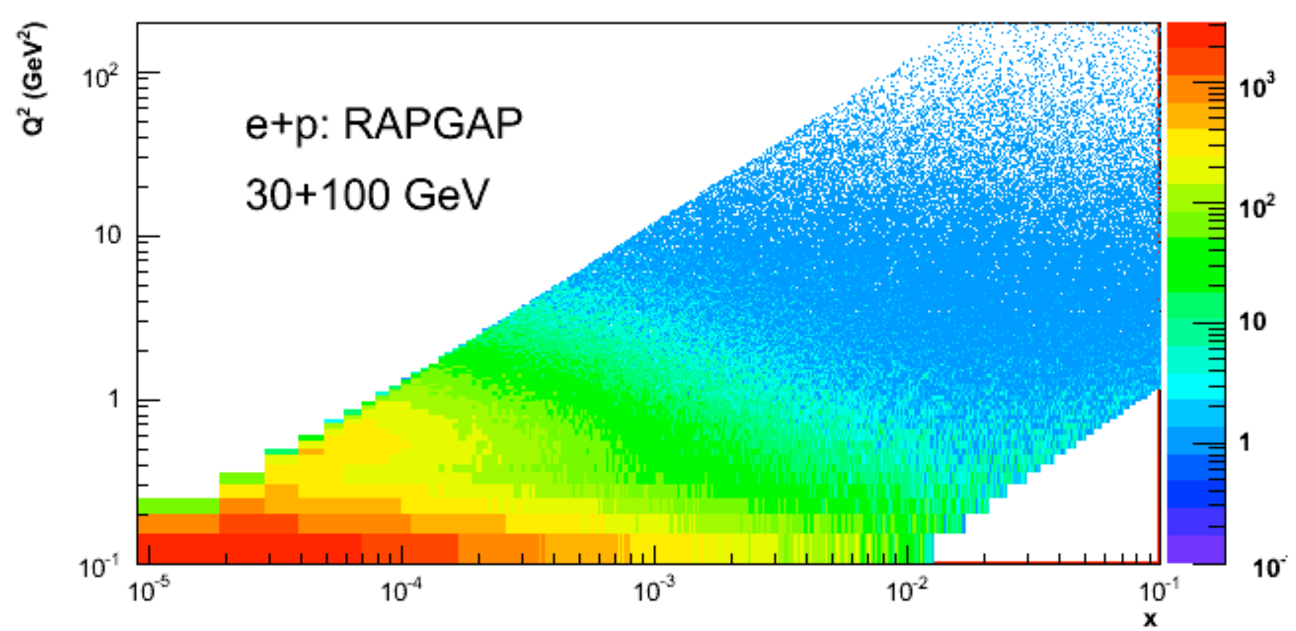
ation models

Diffractive Physics at an EIC

- Significant coverage in x-Q^2
  - ➡ increases by ~ order of magnitude over EIC energies
- Plotted the distribution of the Most Forward Particle in the event for DIS and Diffractive events
  - ➡ significant gap between two classes of events
- Reproduce the "ZEUS" plot?
- Important - plot the efficiency vs purity
  - ➡ Can place a cut in rapidity for ~90% efficiency and ~90% purity !!

Generated 10^6 e+p events using RAPGAP for a variety of proposed EIC energies





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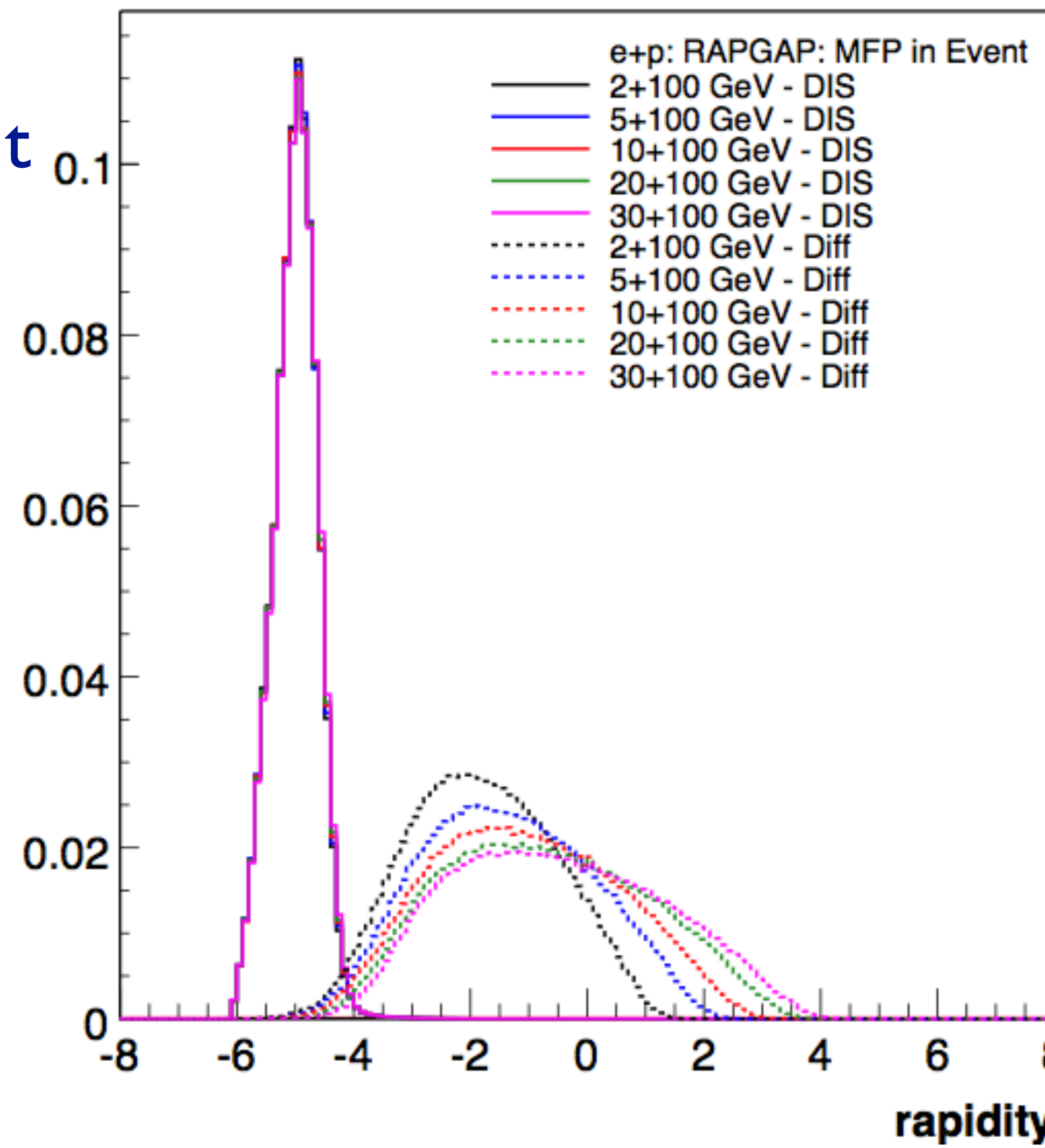

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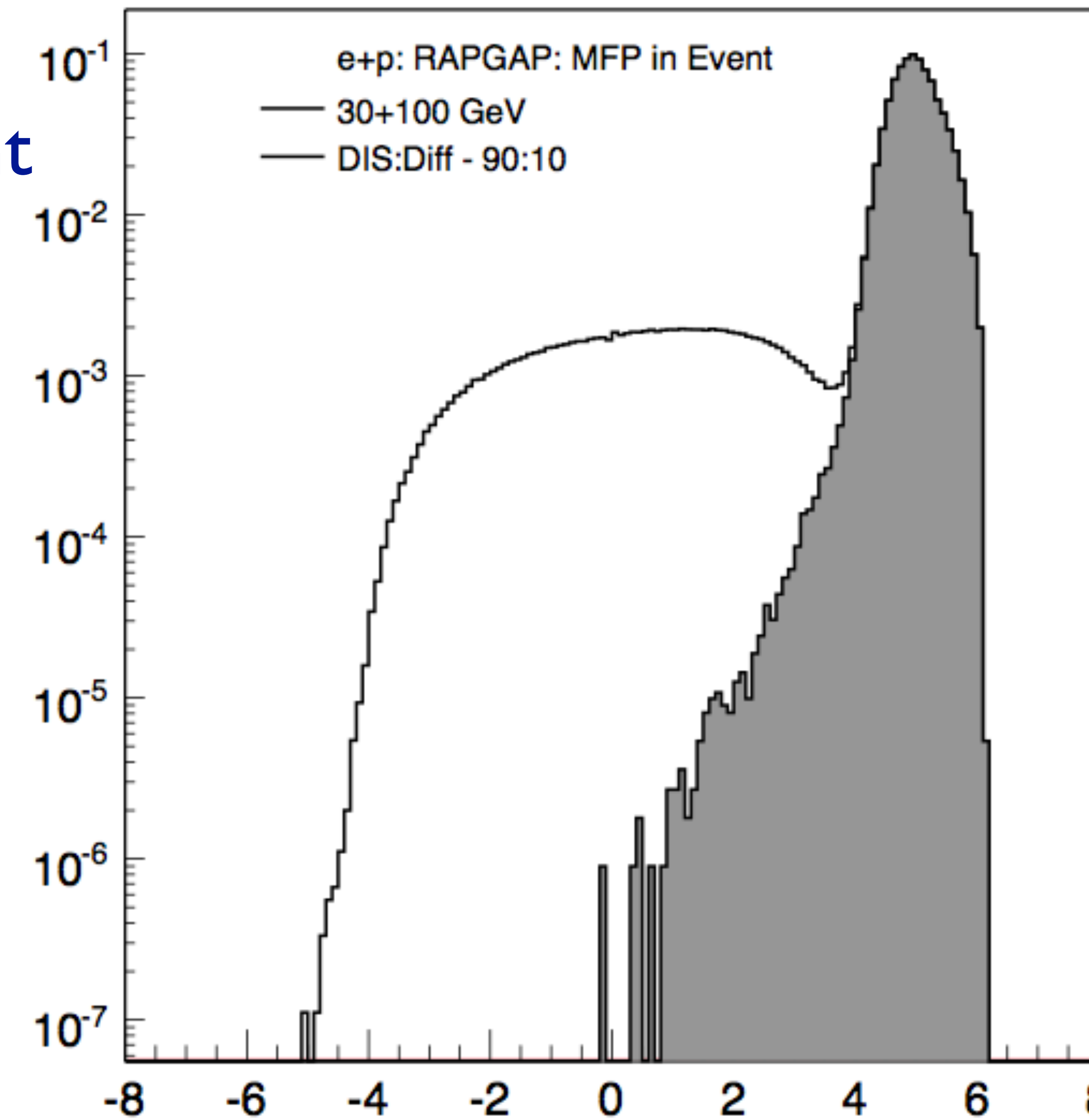

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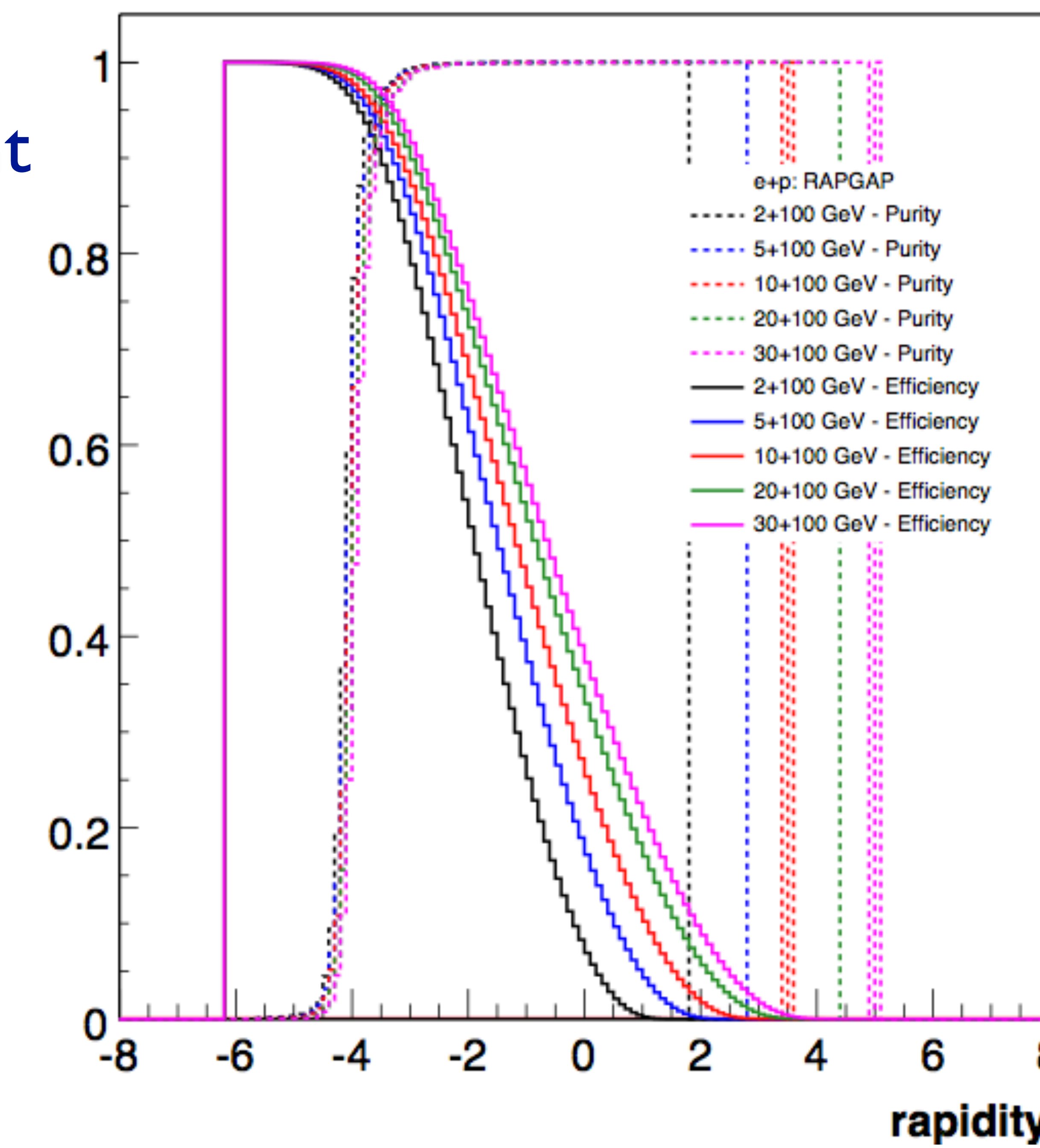

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Diffractive Physics at an EIC - Acceptance

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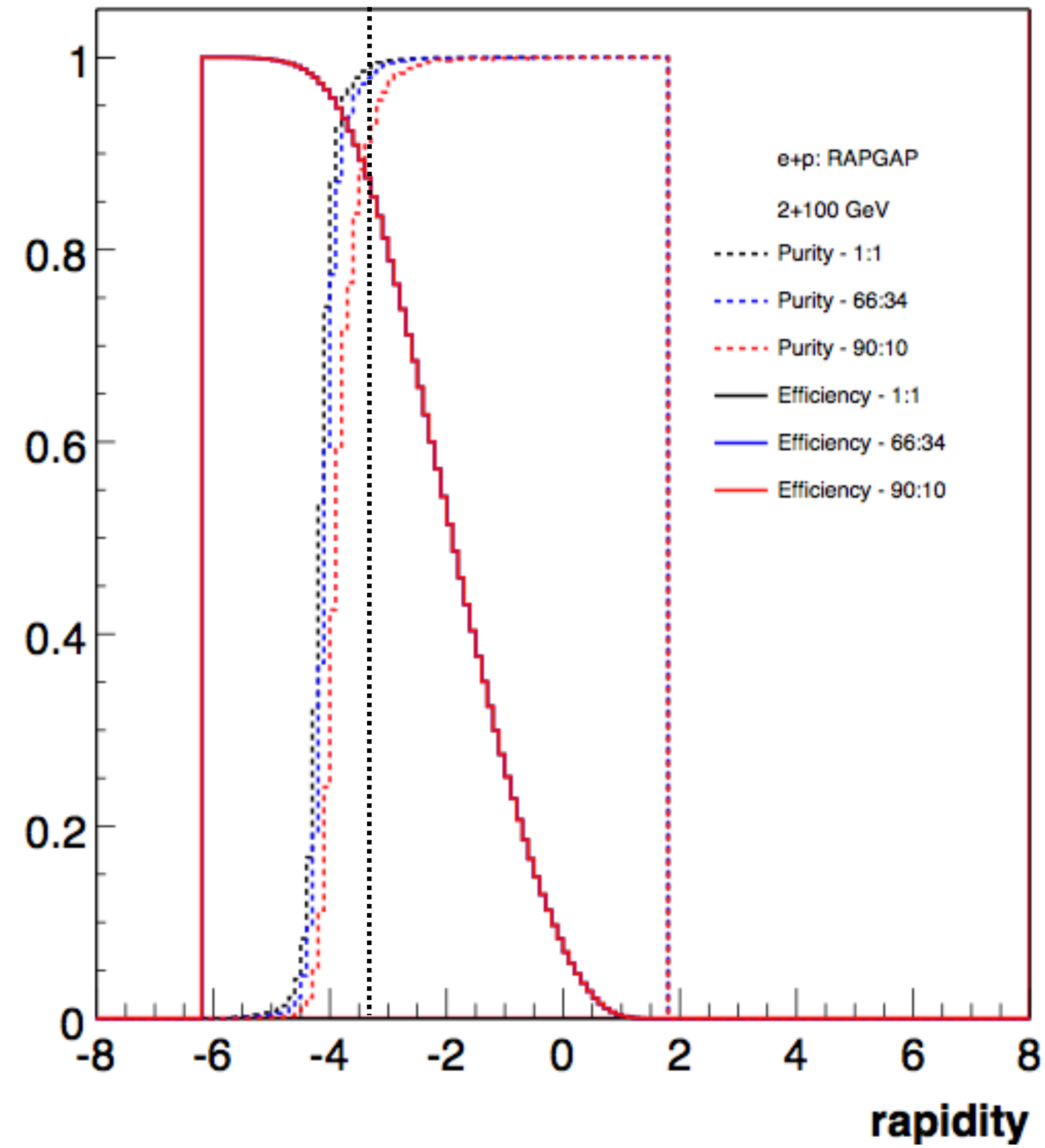

Diffractive Physics at an EIC - Acceptance

- ZEUS had a gap in detector coverage (acceptance) of ~ 3 units.
- Studied this effect in the MFP distribution for EIC energies:
- Keeping the 90% Purity level has the following effect:
- 1 unit cut in rapidity
  - ➡ Efficiency falls by factor of 2, rapidity moves 2 units to right
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- When designing a detector, it is essential to be as hermetic as possible !!!

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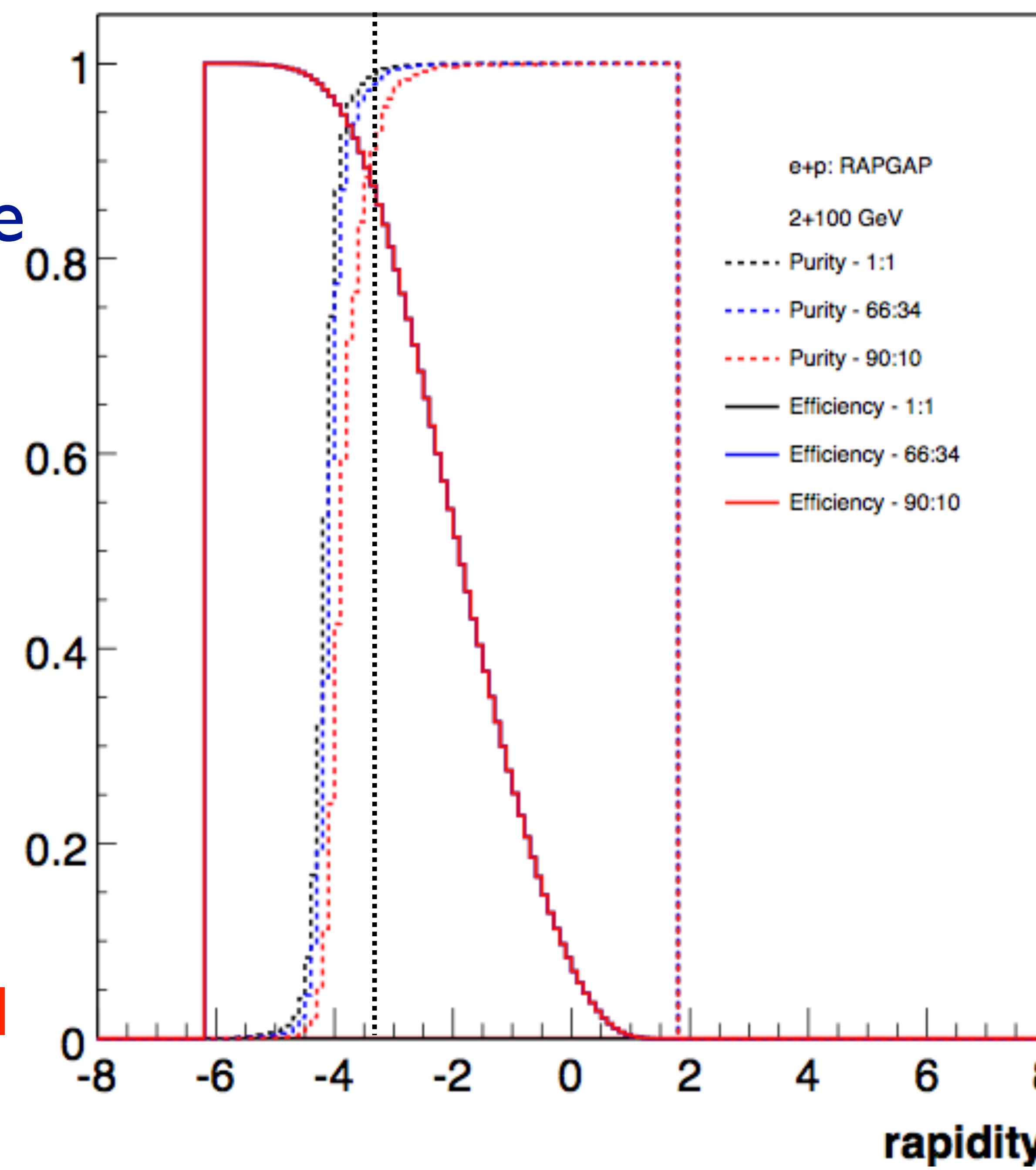

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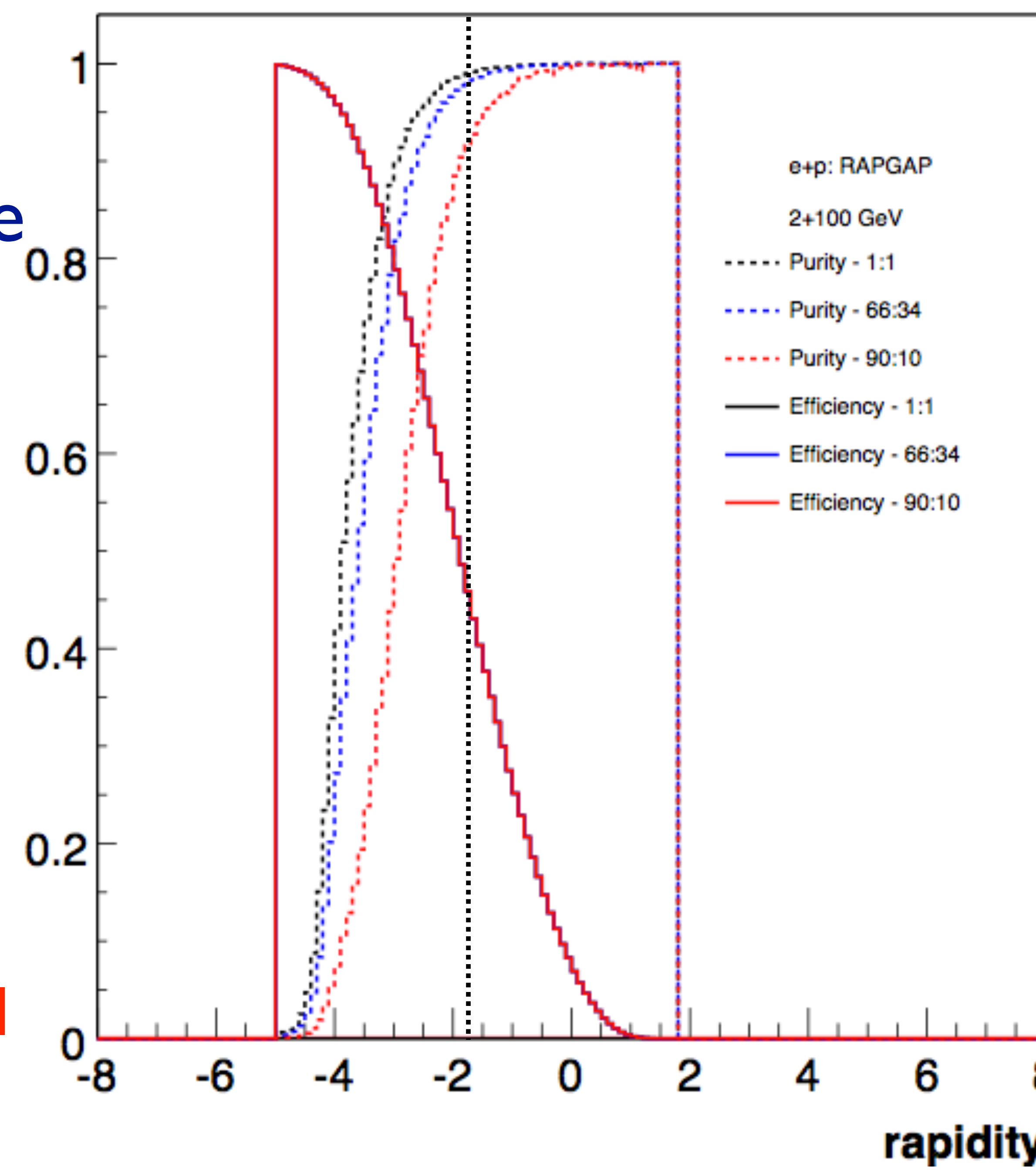

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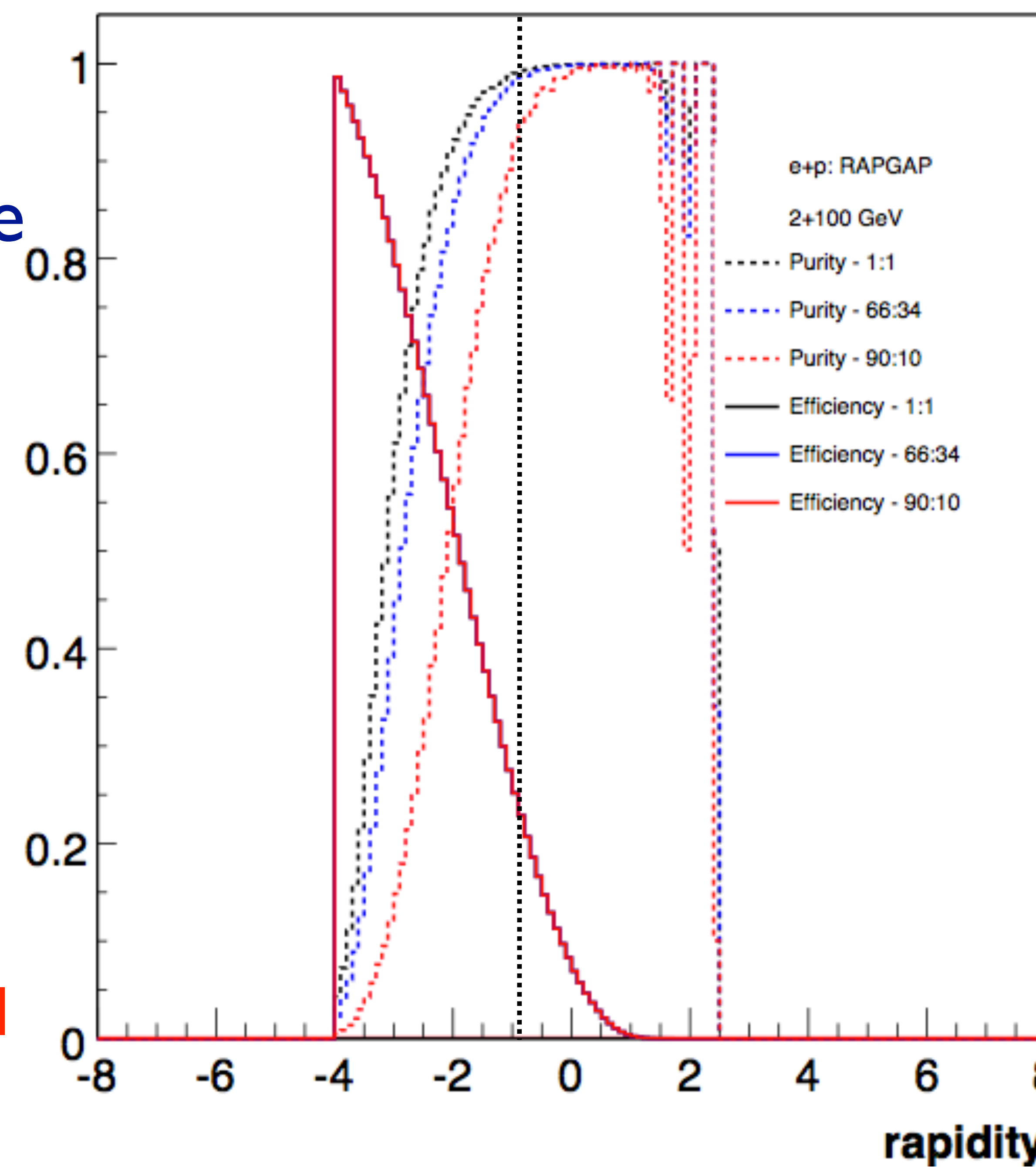

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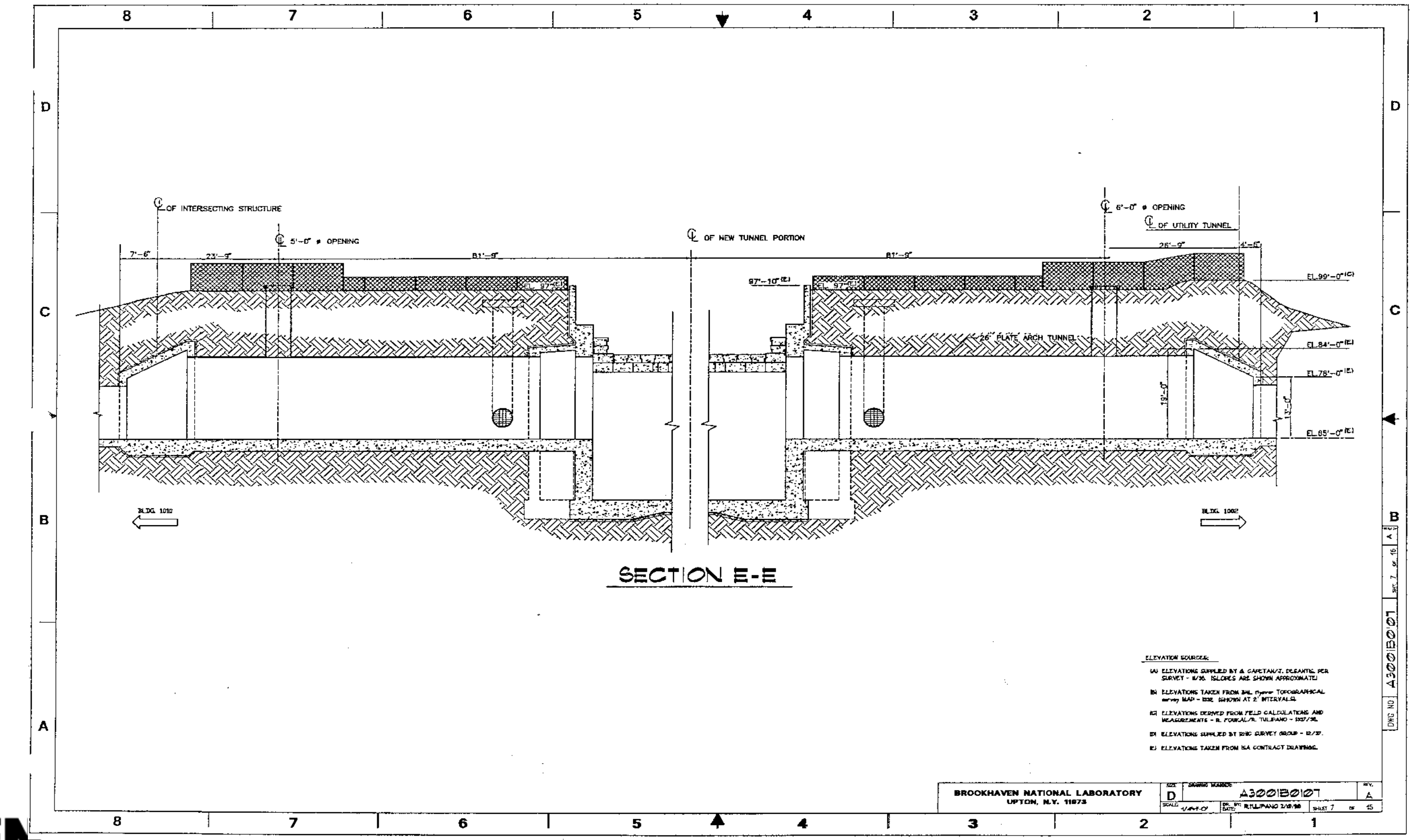
Why 2 o'clock and not 12 o'clock?

- Start at 12 o'clock originally:
  - ➡ Detector cost savings
    - fully staged detector from MeRHIC to eRHIC
      - vertical stage much bigger
      - need to buy magnets only once
      - can stage detector components (i.e. hadronic calorimeter)
      - no moving of detector



Summary and Outlook

- First steps made on detector design
- Optimisations needed
  - ➡ Do we need 4 T for solenoid and 3 Tm for dipole?
  - ➡ What radiation length can be tolerated for low energy electron?
  - ➡ Optimise the distance from solenoid to dipole
  - ➡ What is the impact of the beam lines through the detector on the physics?
  - ➡ Need to optimise acceptance at low scattering angle
    - Need acceptance down to 1 degree
- Need to add Roman Pots into detector configuration
- Need to include luminosity monitor and lepton polarimeter in IR design

Photon Flux

Dipole models provide $\sigma_{L,T}$ (γ^* p → p' V)

For generator we need to consider σ (e p → ε' p' V)

Need Photon Flux Γ_T , Γ_L

$\sigma^{e\,p \to \varepsilon'\,p'\,V} = \Gamma_L\, \sigma_L^{\gamma^*\,p \to p'\,V} + \Gamma_T\, \sigma_T^{\gamma^*\,p \to p'\,V}$

The full formula is rather complex

What is used is a simplification (not always justified):

For $Q^2/(4E^2) = 0$ and $Q^2/\nu^2 = 0$, $m_e = 0$

Pick 2 independent variables best for MC: x, Q^2

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{\alpha}{2\pi}\frac{1}{xQ^2}\left(\left[1+(1-y)^2-2(1-y)\frac{Q^2_{min}}{Q^2}\right]\sigma_T + 2(1-y)\sigma_L\right)$$

where $$Q^2_{min} = \frac{m_e^2 y^2}{1-y}$$

Jacobian!

Full Shebang ...

Dipole model calculations + flux give:

$$\frac{d^6\sigma}{dx\ dQ^2\ dt\ db\ dz\ dr}$$

- 6-dim Probability Distribution Function (PDF)
- all variables independent
- Given (input): beam energies **p**$_e$, **p**$_p$

Final State Particles

Given: $\mathbf{p}_e$, $\mathbf{p}_p$, s, t, x, Q^2, y

Need: $\mathbf{p}_{e'}$, $\mathbf{p}_{p'}$, $\mathbf{p}_{\gamma^*}$, $\mathbf{p}_{VM}$

Hannes Jung (DESY) gave me analytic solutions for all. After many checks: $\mathbf{p}_{e'}$, $\mathbf{p}_{\gamma^*}$ formulas are correct!

$\mathbf{p}_{p'}$ is not correct (possible source of problems in RAPGAP?)

New Ansatz:

- $t = (\mathbf{p}-\mathbf{p}')^2$, $m_{VM}^2 = (\mathbf{p}_{\gamma^*} + \mathbf{p}_p - \mathbf{p}_{p'})^2$, $|\mathbf{p}_{p'}| = m_p$
- allows to derive $\mathbf{p}_p$ numerically (root finder)
- use Hanne's analytic formula as first guess
  - fails at times since first guess is off by several GeV
- $\mathbf{p}_{VM}$ trough $\mathbf{p}_e + \mathbf{p}_p = \mathbf{p}_{e'} + \mathbf{p}_{p'} + \mathbf{p}_{VM}$
- solution obtained this way is fully consistent
  - $\mathbf{p}_{e'}$, $\mathbf{p}_{p'}$, $\mathbf{p}_{\gamma^*}$, $\mathbf{p}_{VM}$ $\Rightarrow$ s, t, x, Q^2, y

Kinematic Boundaries

Tricky since some formulas neglect masses others not (something to still work on)

$$s = \frac{Q^2}{xy} + m_p^2 + m_e^2$$

not just $Q^2 = s\,x\,y$

Currently implemented (but not sufficient):

$$0 < \quad x \quad < 1$$

$$0 < \quad y \quad < 1$$

$$\frac{m_e^2 y^2}{1-y} < \quad Q^2 \quad < s - m_e^2 - m_p^2$$

$$x_{IP} = \frac{m_V^2 + Q^2}{ys}$$

$$t \quad < -\frac{x_{IP}^2 m_p^2}{1 - x_{IP}}$$