Comparison of Simulation Data for Different Center-of-Mass Energies

(and calculating “t” in RAPGAP)

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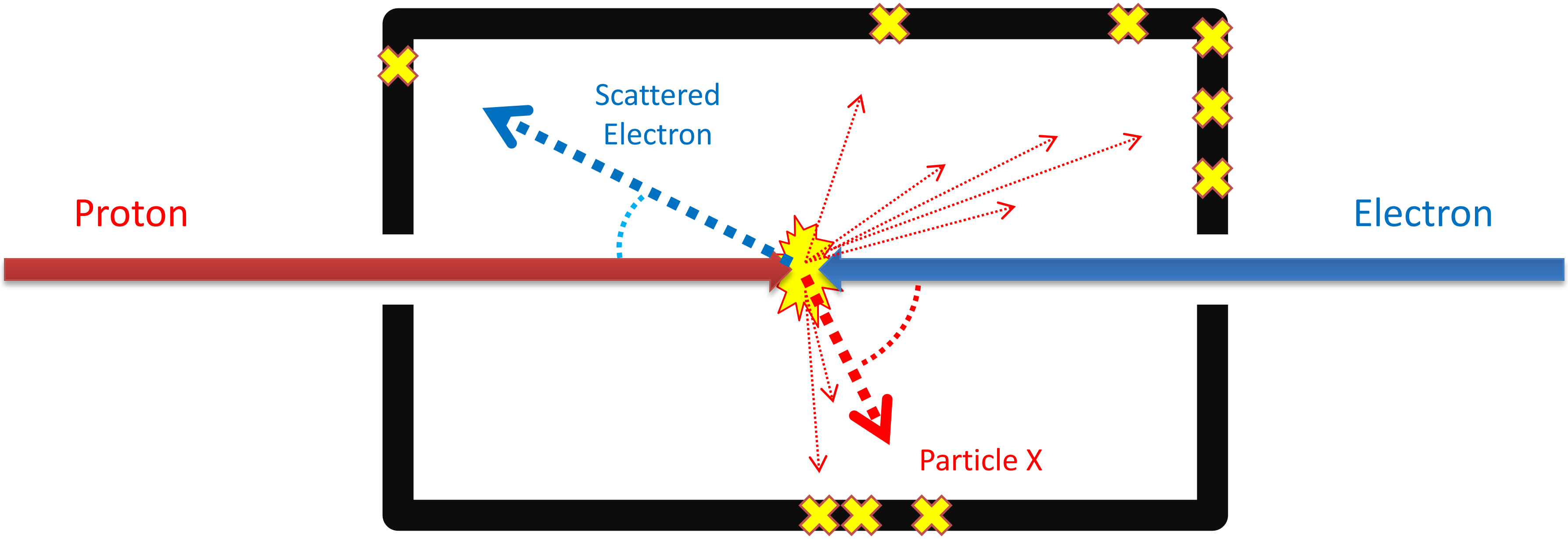
Designing a detector – the basics

- What we need to know:
  - The types of particles produced in electron-ion collisions
  - Multiplicity of particles
  - Where these particles go after a collision (angle and direction)
  - The momentum/energy these particles have



Event Generators

- We get this information from computer simulations or “event generators”
- Monte-Carlo Simulator
  - Random sampling used to create output data distributions that mimic what is seen in real experiments
  - **RAPGAP**
    - Main author Hannes Jung
    - ~12,000 lines of code
    - simulates e+p collisions

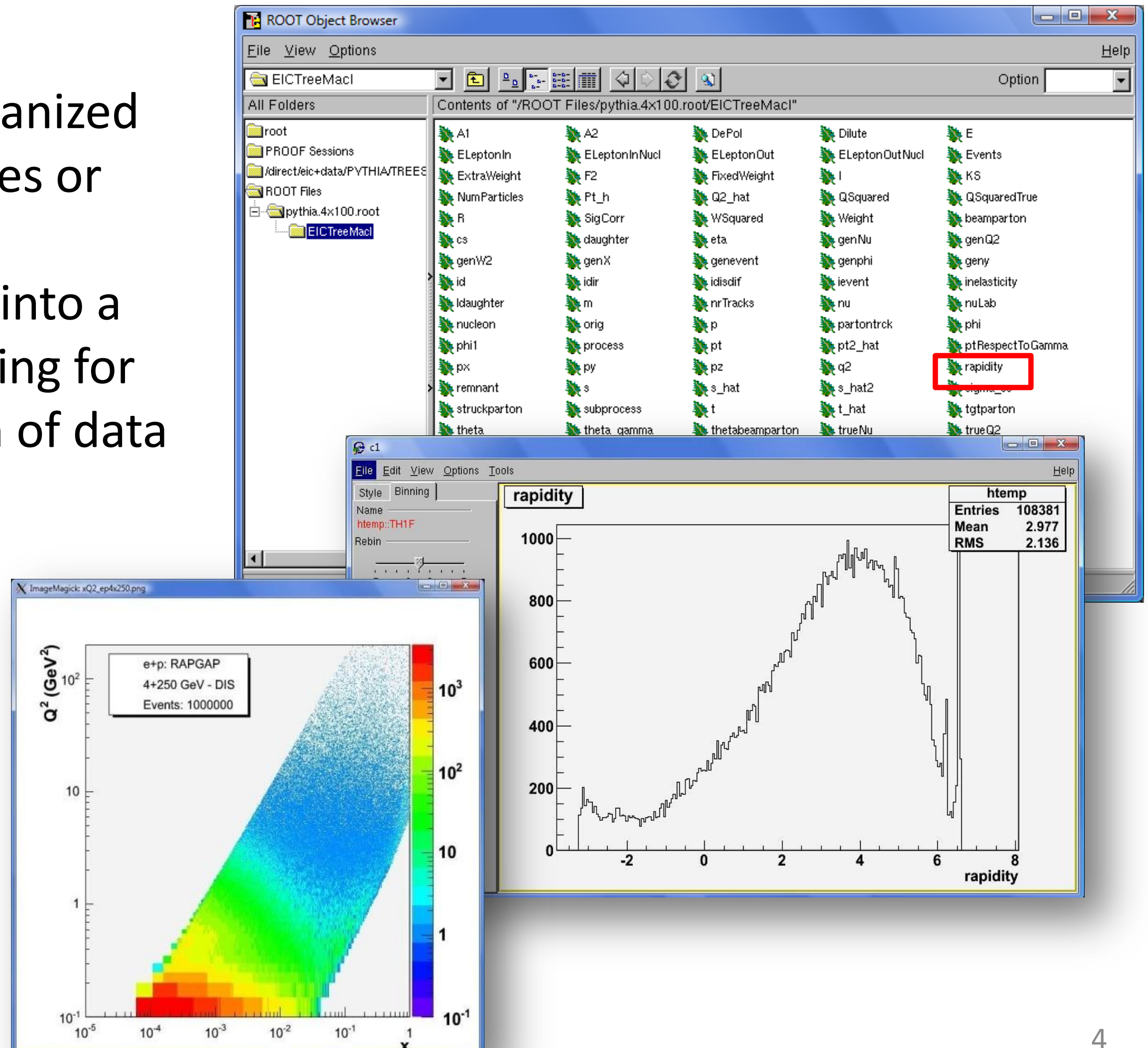
wforeman@rssh02:~

```
                        Event listing (summary)

  I particle/jet KS     KF  orig    p_x      p_y      p_z       E        m

  1 !e-!         21     11    0    0.000    0.000   -4.000    4.000    0.001
  2 !p+!         21   2212    0    0.000    0.000  250.000  250.002    0.938
  3 !Z0!         21     23    1   -0.196    0.302   -0.294    0.277   -0.373
  4 e-            1     11    1    0.196   -0.302   -3.706    3.723    0.001
  5 !u!          21      2    2   -0.440   -0.072    0.456   -0.108    0.000
  6 !u!          21      2    5    0.399   -0.232    0.226    0.514    0.000
  7 !u!          21      2    3    0.301   -0.082   -0.105    0.466    0.330
  8 (u)        A 12      2    7    0.301   -0.082   -0.105    0.466    0.330
  9 (ud_0)     V 11   2101    2   -0.498    0.384  249.811  249.812    0.579
 10 (string)     11     92    8   -0.196    0.302  249.706  250.279   16.917
 11 (pi0)        11    111   10   -0.202   -0.084    0.012    0.257    0.135
 12 (a_1+)       11  20213   10    0.289   -0.246    3.382    3.654    1.330
 13 (K0)         11    311   10    0.349    0.279    5.476    5.517    0.498
 14 (K*-)        11   -323   10   -0.517    0.338   58.343   58.353    0.865
 15 (pi0)        11    111   10   -0.309    0.134   26.043   26.046    0.135
 16 p+            1   2212   10    0.194   -0.119  156.575  156.578    0.938
 17 (rho0)       11    113   12    0.421   -0.281    3.316    3.448    0.798
 18 pi+           1    211   12   -0.106    0.028    0.045    0.183    0.140
 19 K_L0          1    130   13    0.351    0.279    5.457    5.498    0.498
 20 (Kbar0)      11   -311   14   -0.136    0.281   23.748   23.755    0.498
 21 pi-           1   -211   14   -0.379    0.056   34.423   34.425    0.140
 22 pi-           1   -211   17    0.107   -0.191    2.892    2.904    0.140
 23 pi+           1    211   17    0.286   -0.082    0.386    0.507    0.140
 24 K_L0          1    130   20   -0.138    0.281   23.874   23.881    0.498
 25 gamma         1     22   11   -0.169   -0.096   -0.036    0.198    0.000
 26 gamma         1     22   11   -0.033    0.012    0.048    0.059    0.000
 27 gamma         1     22   15   -0.064   -0.019    3.170    3.171    0.000
 28 gamma         1     22   15   -0.245    0.153   22.873   22.875    0.000
                sum:  0.00         0.000    0.000  246.000  254.002   63.253
 event: IPRO =   12
```

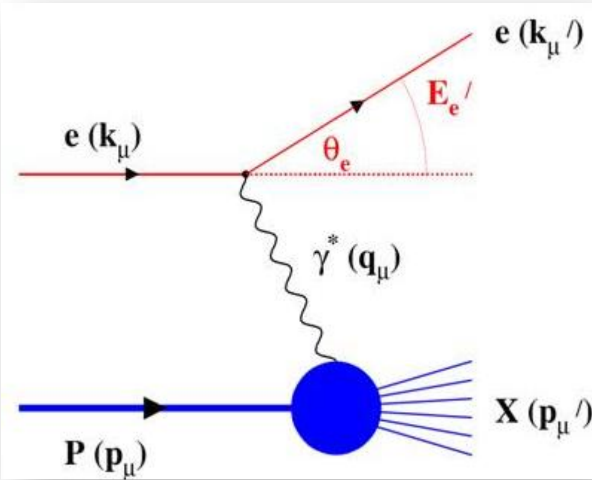
Dealing with data

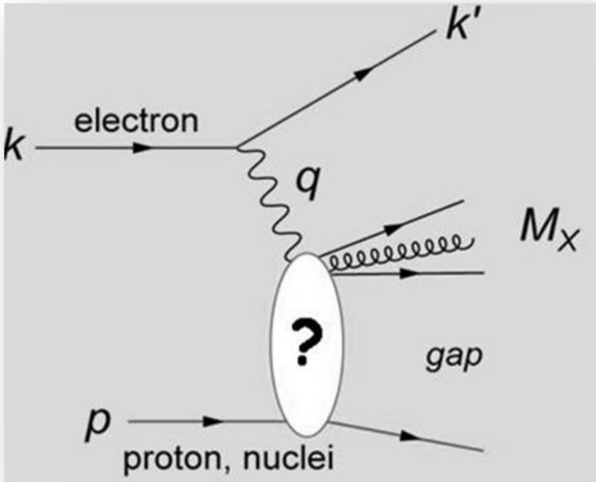
- RAPGAP output read/organized into **data trees** using codes or “macros” in C++/ROOT
  - Variables organized into a tree structure, allowing for simplified inspection of data

- **Trees are read by other custom macros to produce plots**



Deep Inelastic Scattering vs. Diffractive Scattering (in a nutshell)





Deep Inelastic Scattering (DIS):

Electron interacts with a parton inside proton, is scattered at angle θ_e with energy E_e', **proton fragments**

Diffractive Scattering:

Proton remains intact during the collision, "rapidity gap" in which no particles are ejected

- **RAPGAP simulates both processes**
- **Important to understand differences in data**

Kinematic Variables of DIS

E_e, E_p	initial electron/proton beam energies
$e = (0,0,-E_e, E_e)$	four momentum of incoming electron
$p = (0,0, E_p, E_p)$	four momentum of incoming proton
$e' = (E_e' \sin\theta_e', 0, E_e' \cos\theta_e', E_e')$	four momentum of recoil electron
$s = (e+p)^2 = 4E_e E_p$	square of total center-of-mass energy
$q^2 = (e-e')^2 = -2E_e E_e'(1+\cos\theta_e') = -Q^2$	square of total momentum transfer
$y = (q \cdot p)/(e \cdot p)$	fraction of energy transfer
$x = Q^2/(2\, q \cdot p) = Q^2/(y\, s)$	Bjorken scaling variable

Center-of-Mass Energy (CME) is square root of “s”

$$\sqrt{s} = \sqrt{(e+p)^2} = \sqrt{4E_e E_p} = 2\sqrt{E_e E_p} = 2\sqrt{(4 \text{ GeV})(100 \text{ GeV})} = 40 \text{ GeV}.$$

Energies Simulated in RAPGAP

Beam Energies $E_e + E_p$ [GeV]	Center-of-mass Energy [GeV]	Events Produced
4+50	28.3	↑
4+100	40.0	
10+50	44.7	
4+250	63.3	
10+100	63.3	One million
20+50	63.3	
20+100	89.4	
10+250	100	
20+250	141	↓

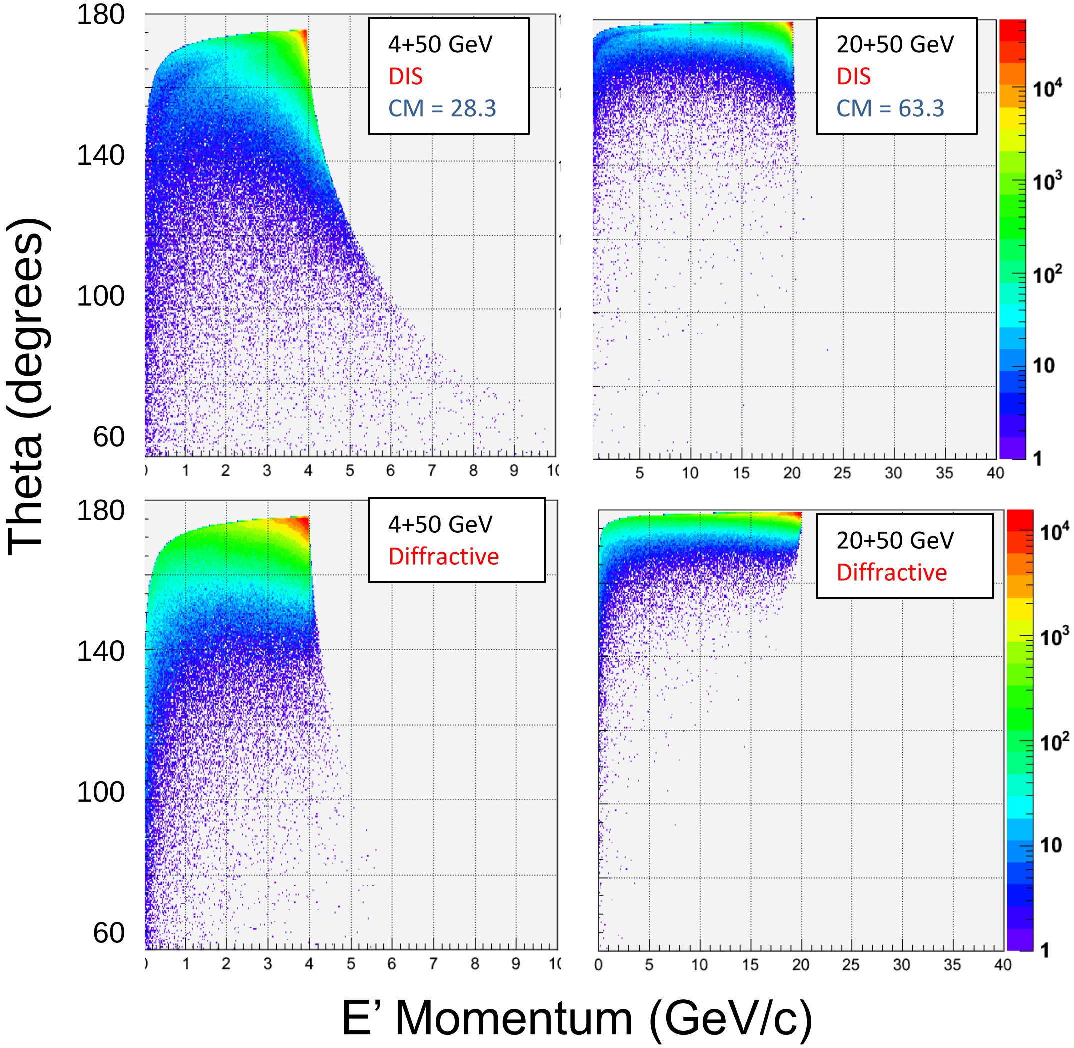
Energies Simulated in RAPGAP

- Simulation data available for wide range of CM energies (approx 30-140 GeV)

- 3 different combinations of beam energies yield the same CM
  - observe how changing energy balance between proton/electron (while maintaining same CM) affects data

10+250	100	
20+250	141	

Momentum vs. theta of scat. electron



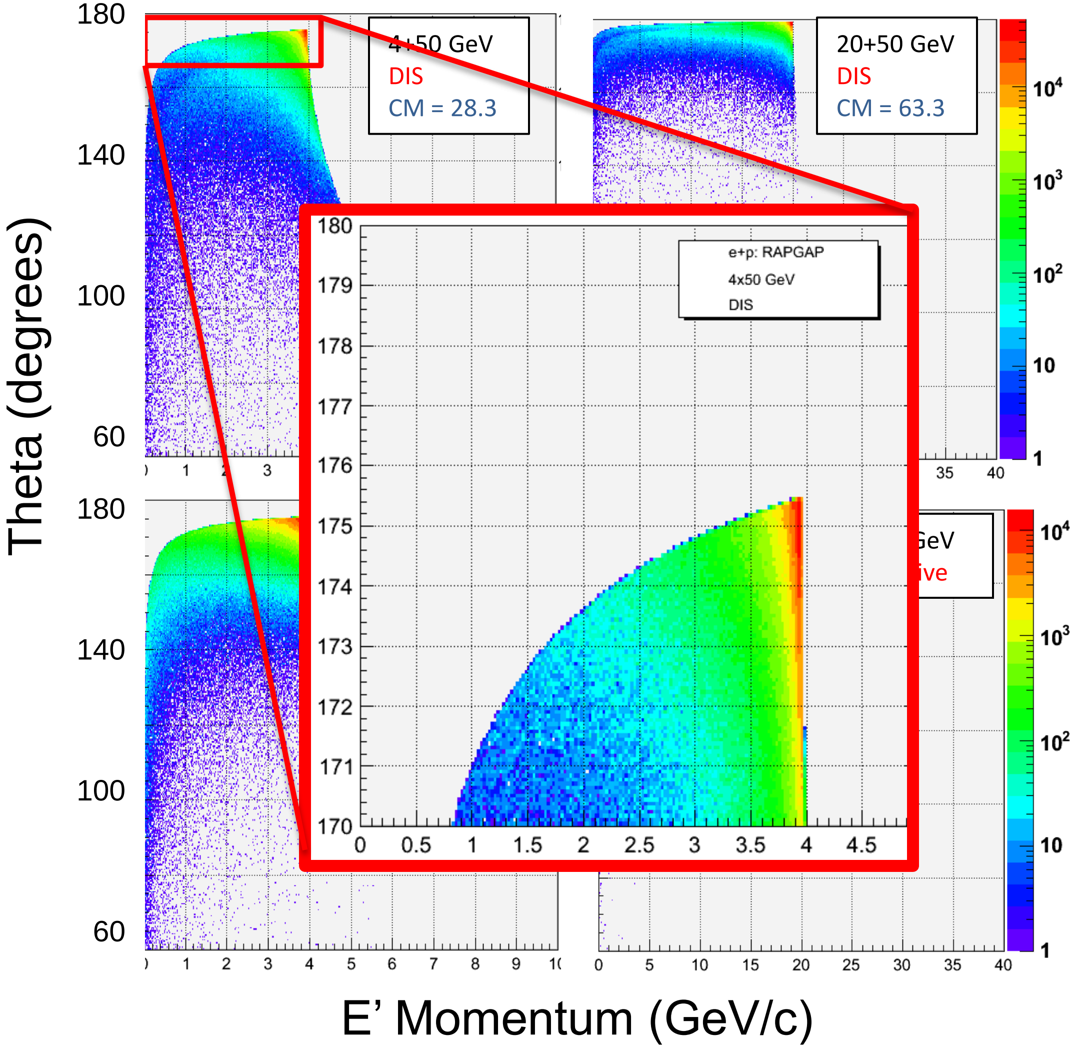
Proton beam kept constant (50 GeV)

High electron beam energy

↓

smaller angle for scat. electron

Momentum vs. theta of scat. electron



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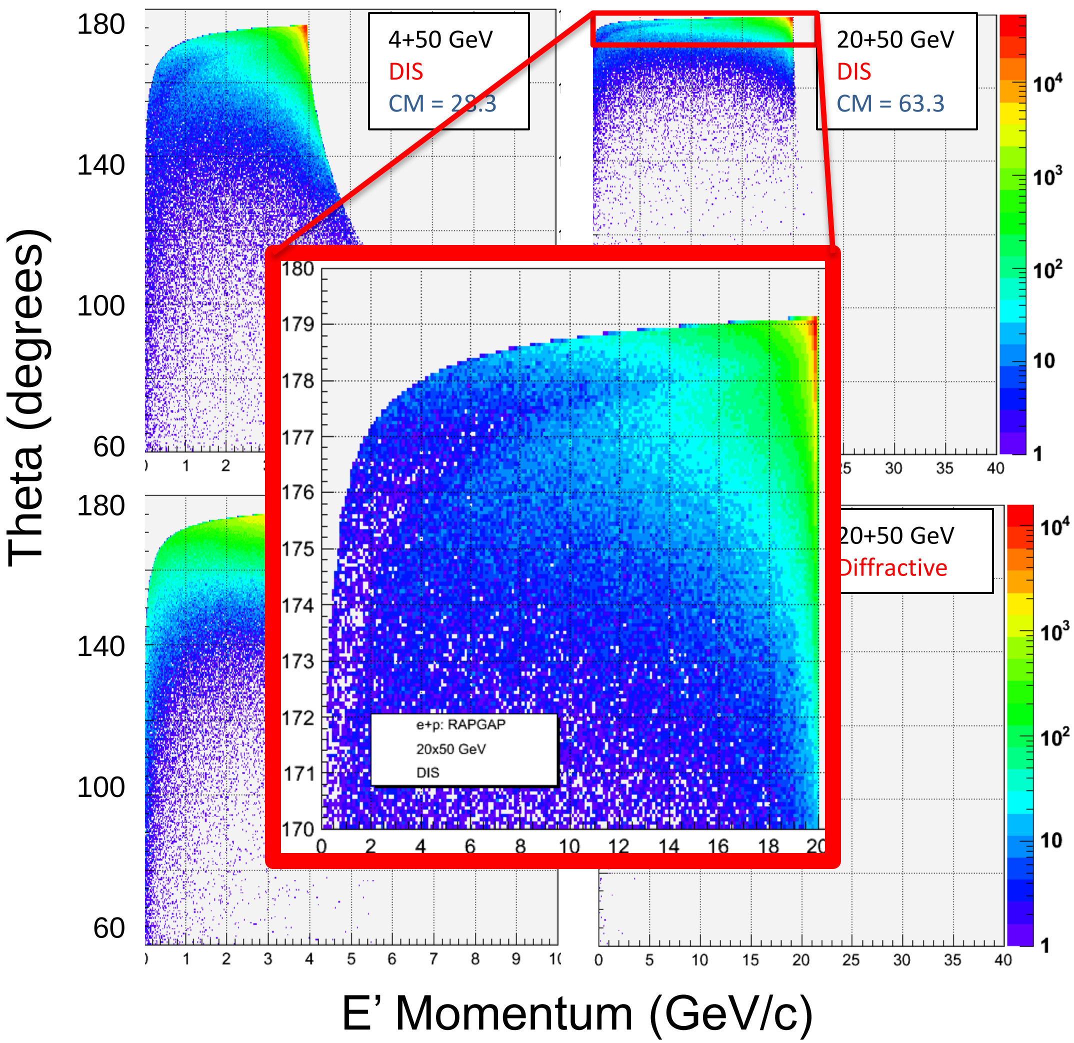

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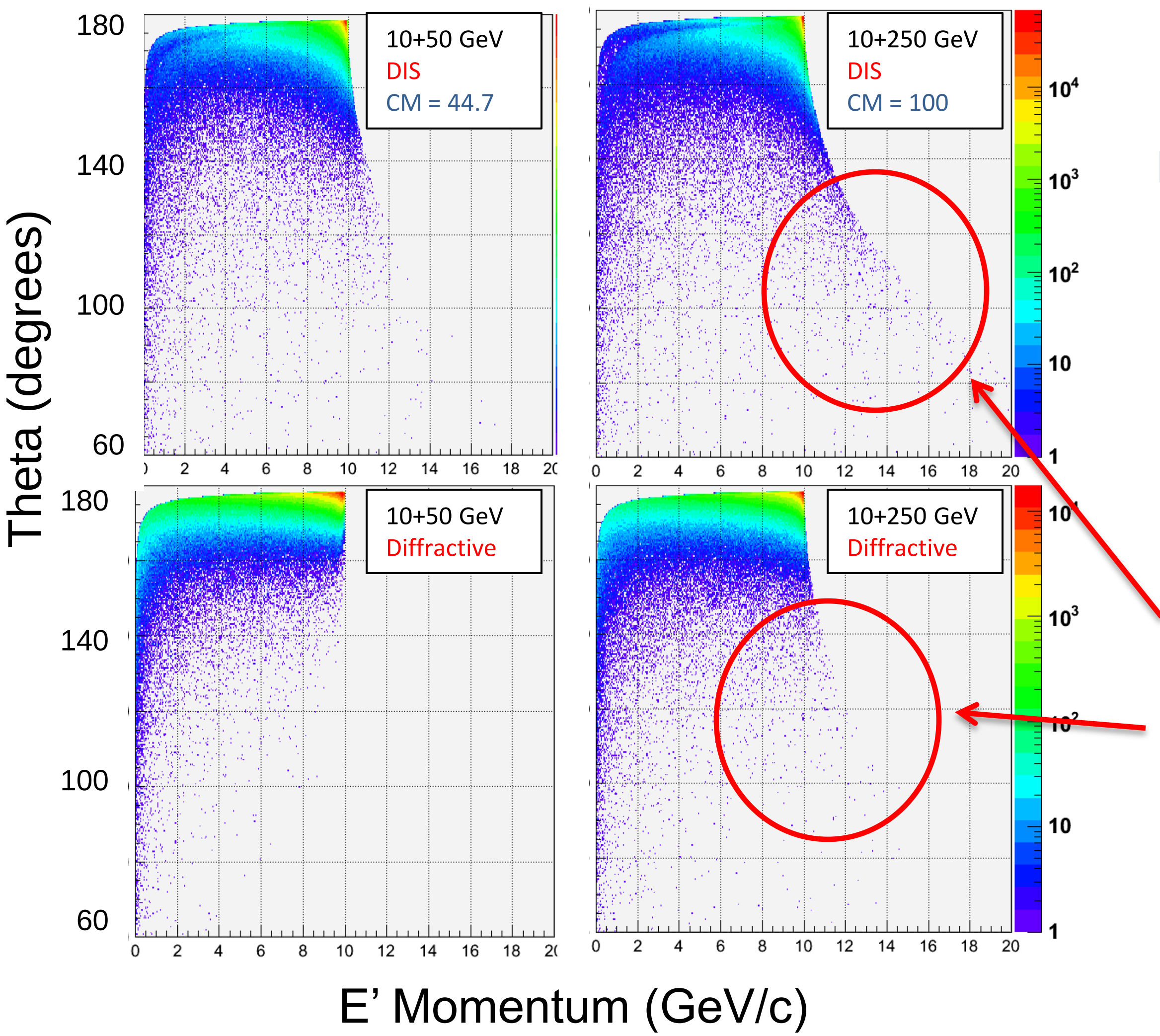
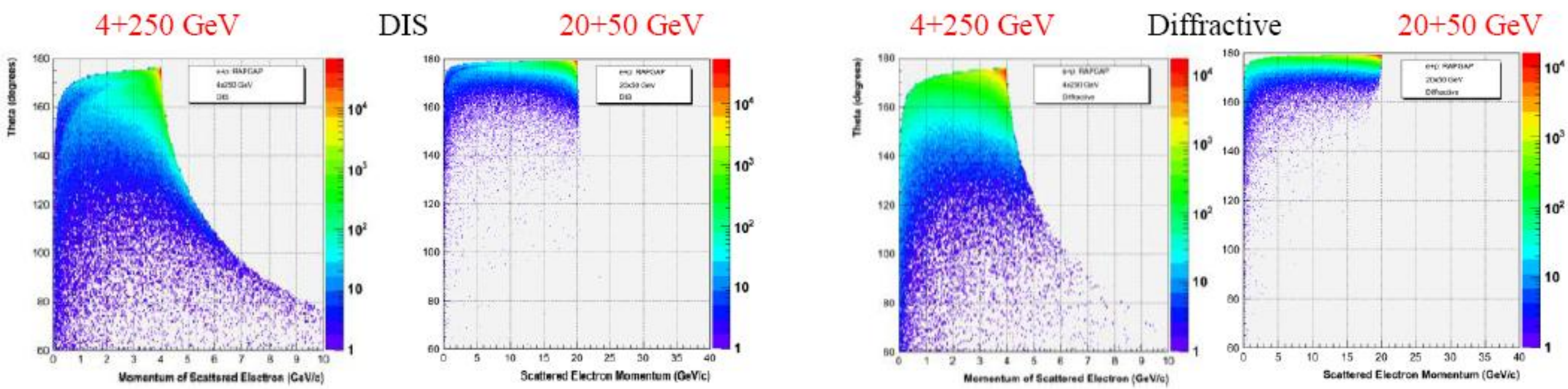


Electron beam kept constant (10 GeV)

- No significant dependence on proton beam energy
- Distributions virtually identical except more electrons scattered with larger momenta at larger angles as proton energy increases

Momentum vs. theta of scat. electron

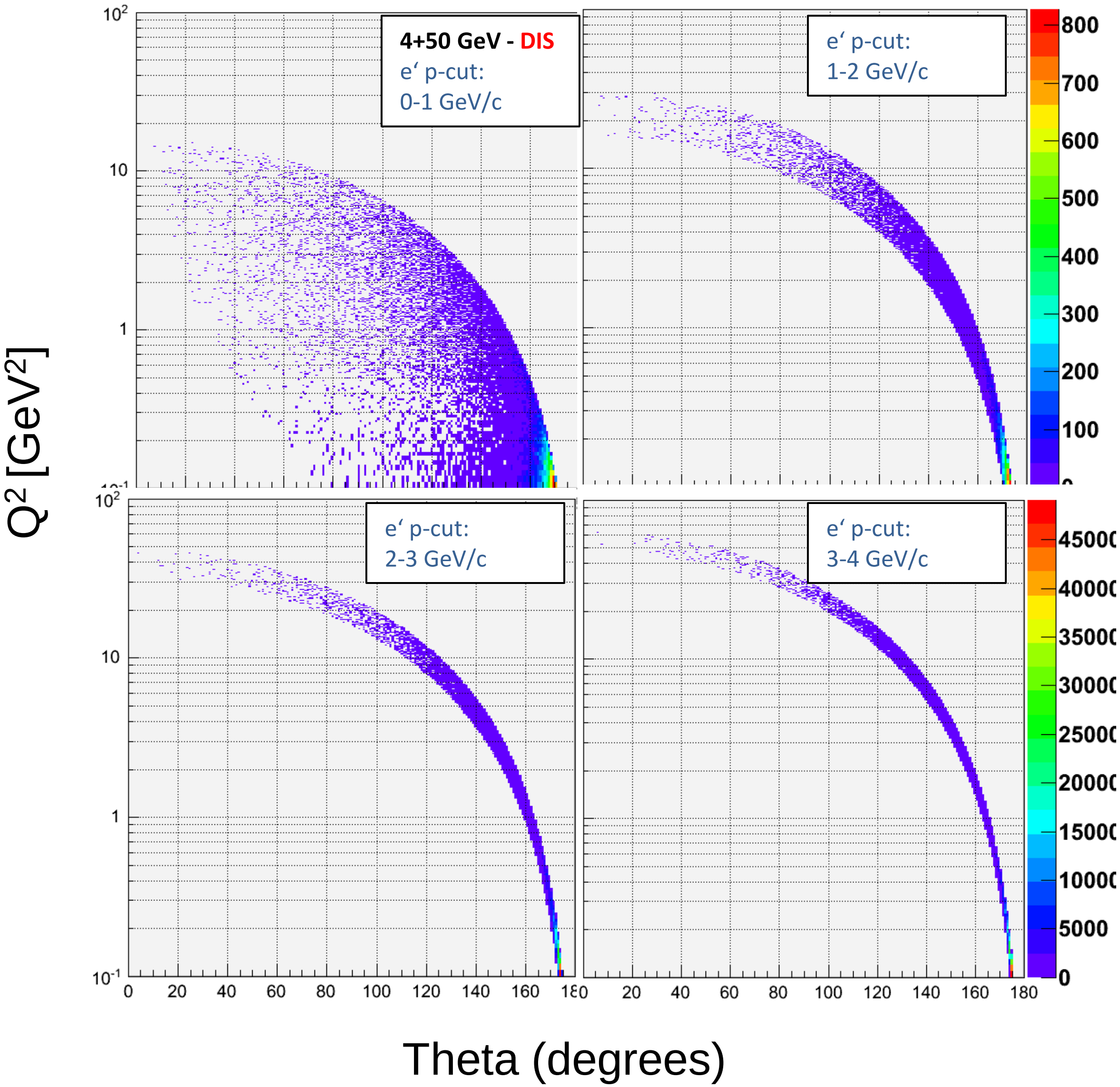


Same CM energy (63.3 GeV)

What we see:

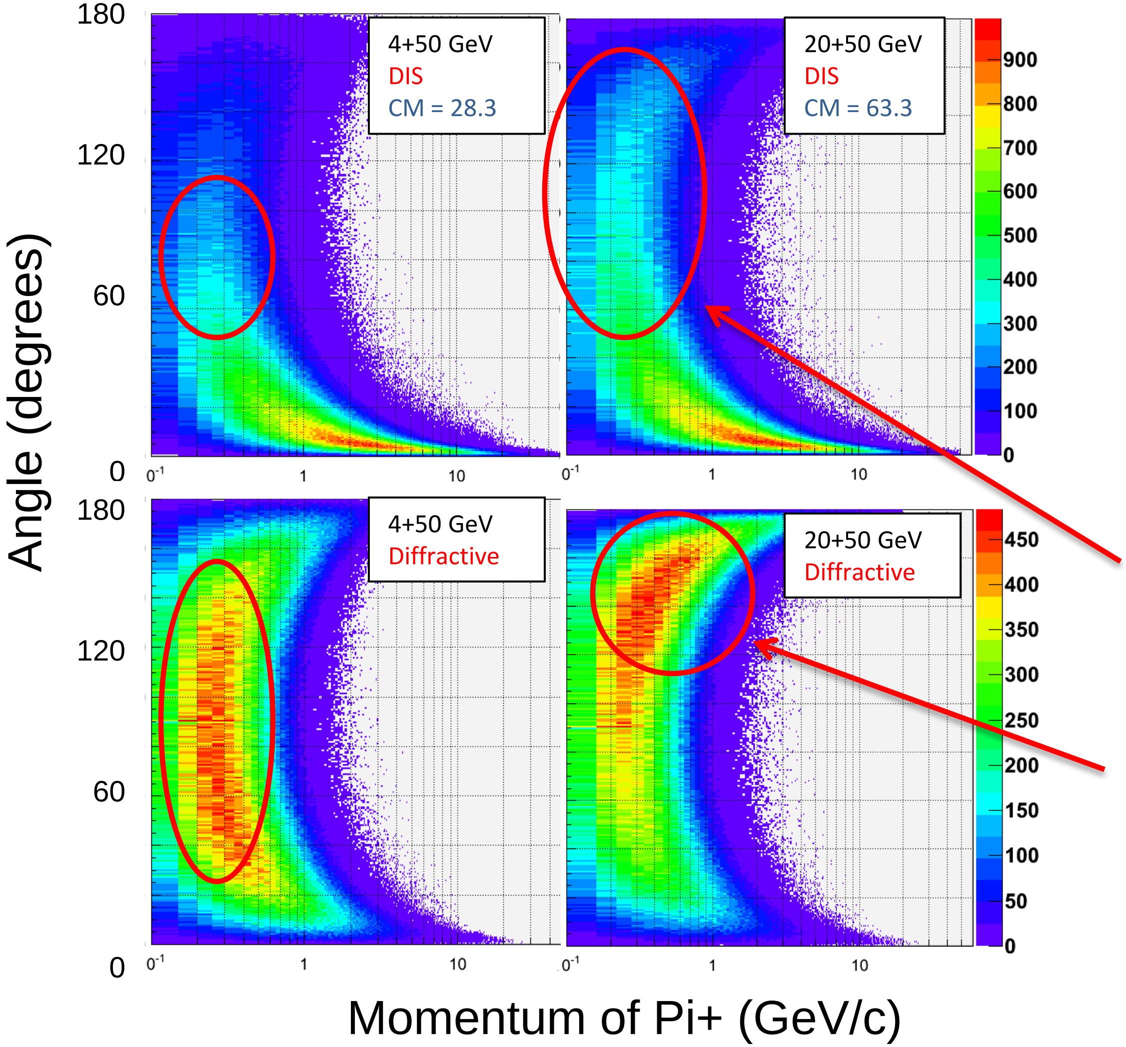
- More symmetric beam energies send scattered electrons at very small angles
- More favorable for measurement of e’ if proton dominating in energy

Momentum vs. theta of scat. electron



- No cuts on Q^2 for previous plots shown
- However: Theta vs. Q^2 plots shown here with cuts on momentum

Momentum vs. angle of pions



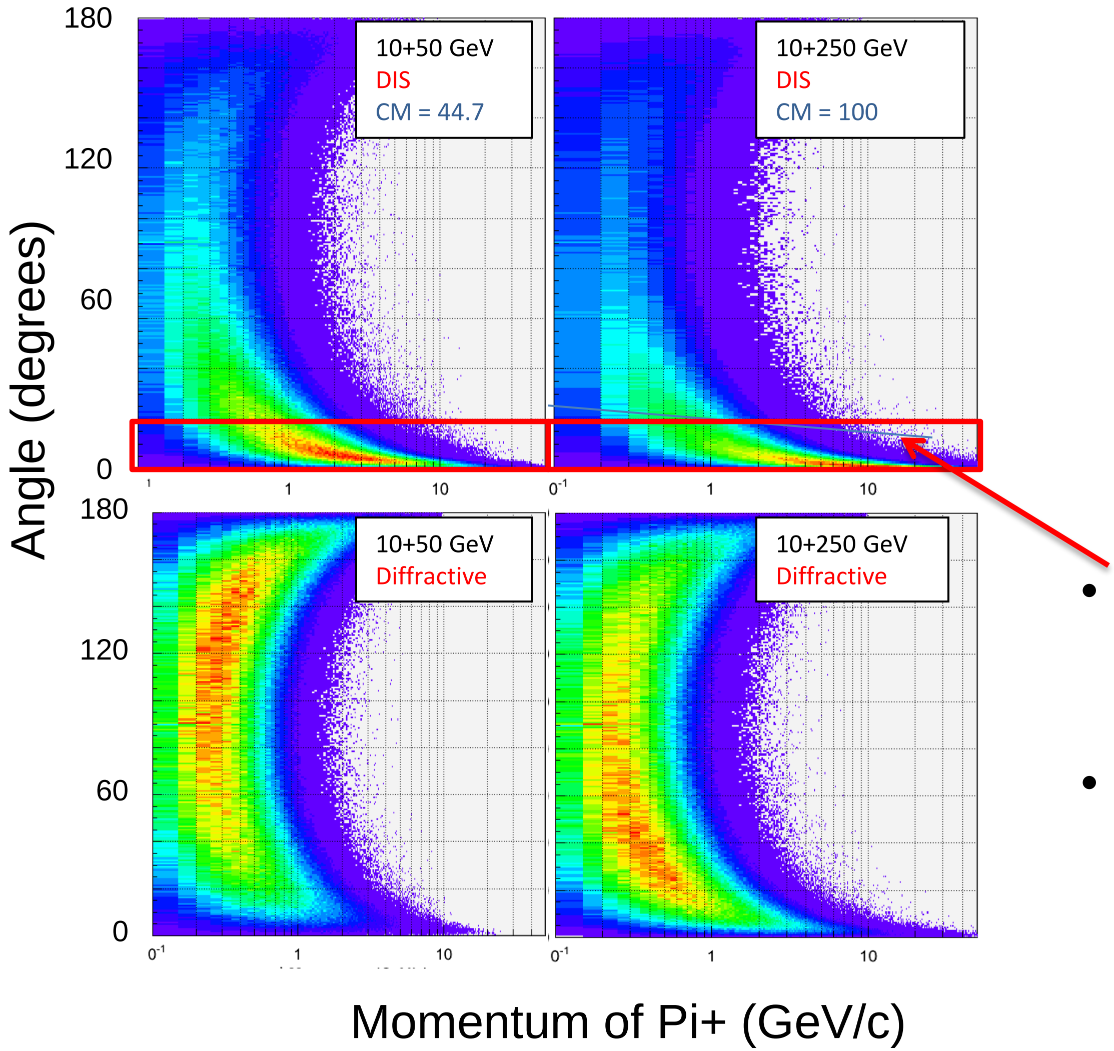
Proton beam kept constant (50 GeV)

High electron beam energy

↓

- Distribution is "smeared" to a larger angular extent in direction of electron
- Change more obvious for diffractive events

Momentum vs. angle of pions



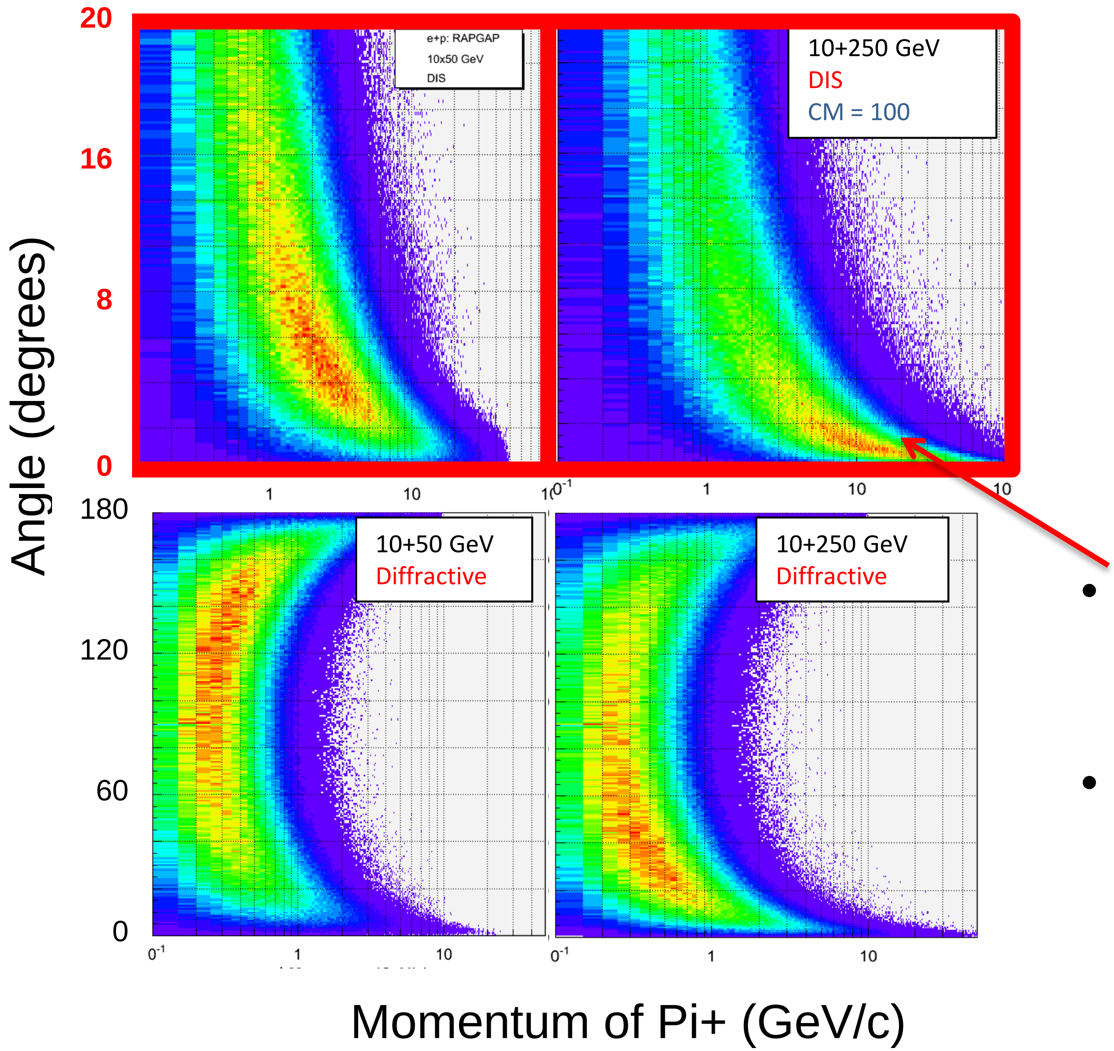
Electron beam kept constant (10 GeV)

High proton beam energy

↓

- Pions more concentrated at small angles (< 2 degrees) in forward direction
- For diffractive events, same effect, except pions always at reasonably accessible angles

Momentum vs. angle of pions



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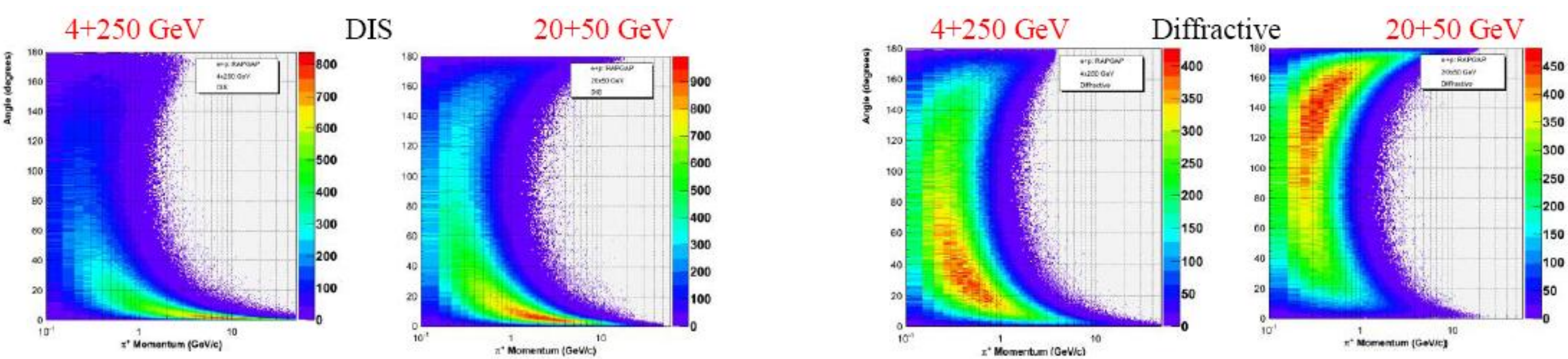
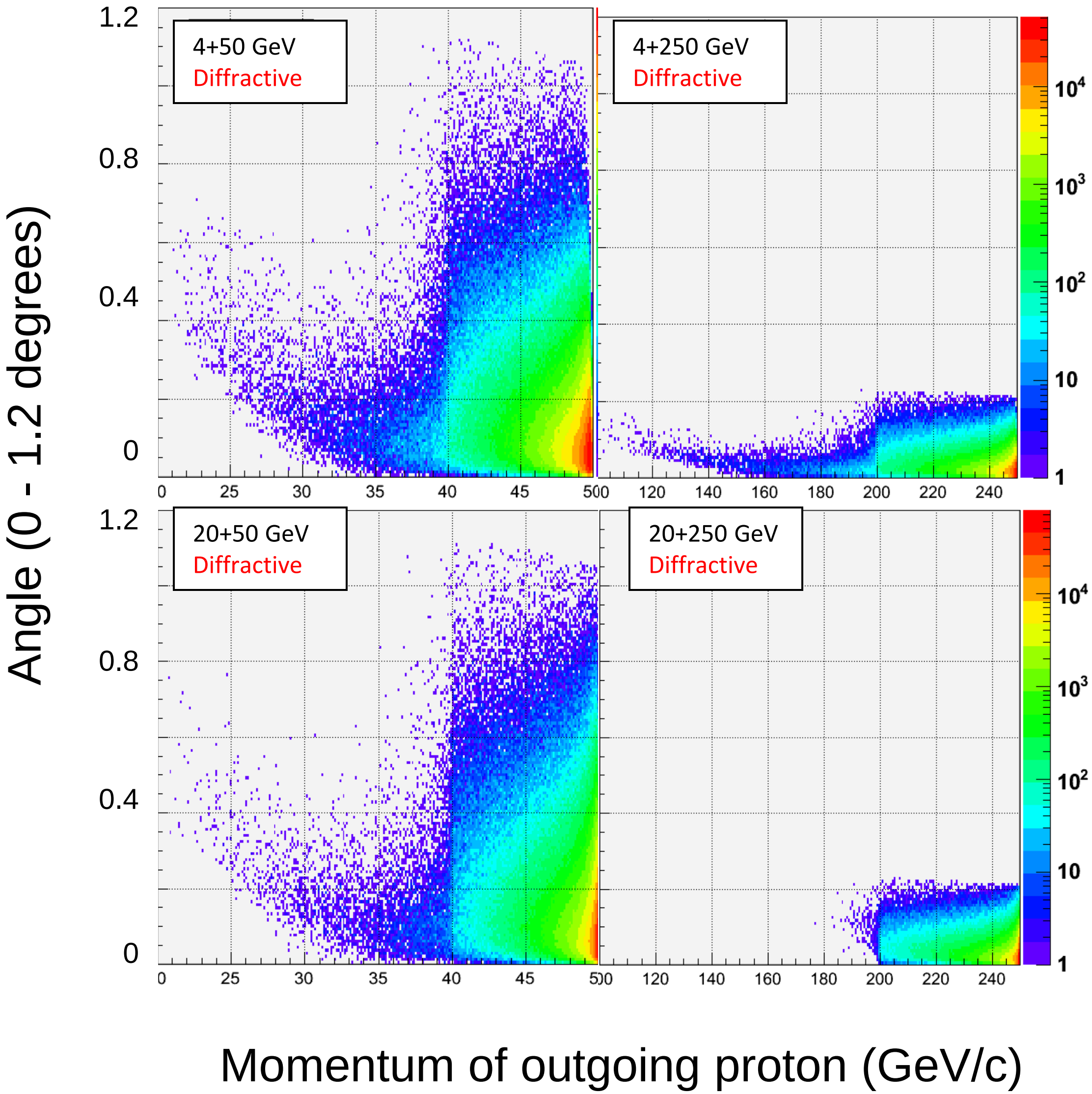


Same CM energy (63.3 GeV)

What we see:

- For DIS: distribution is more "smeared" as energy balance becomes more symmetric
- For diffractive: majority of pions at easily accessible angles, either forward or backward depending on proton/electron energy

Momentum vs. angle of protons

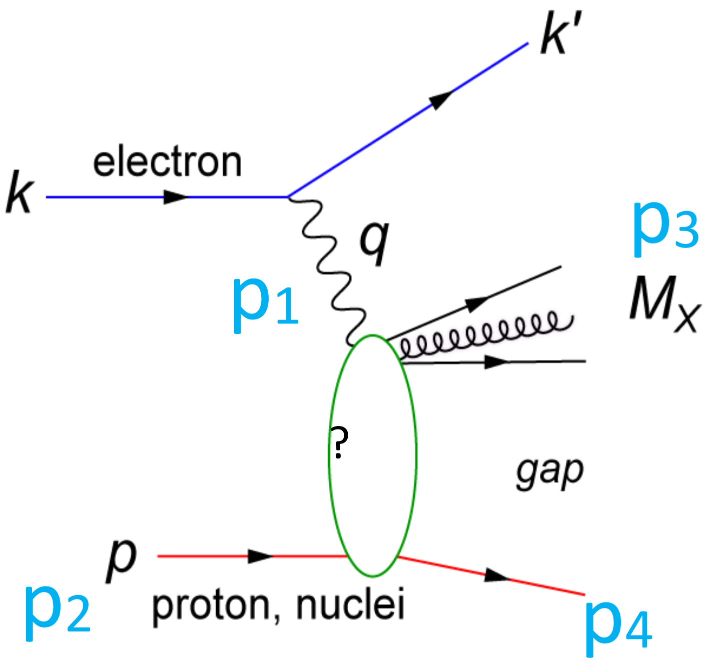


What we see:

- Larger initial proton energy = smaller scattered proton angle
- **Protons always at VERY small angles, difficult to detect** (but not impossible!)
- Increasing proton energy = exaggerated effect

Calculating “t” in RAPGAP

What is t?



Diffractive kinematics

Mandelstam variable “t”:

$t = (p_3 - p_1)^2 = (p_4 - p_2)^2$

ALWAYS NEGATIVE

- When Mx is exclusive vector meson (rho), $(p_3 - p_1)^2$ can be used
- Otherwise, we must use information from the the outgoing and initial proton, $(p_4 - p_2)^2$

t calculated from rho-gamma*

$$t_\rho = m_\rho^2 - Q^2 - 2\left(E_\rho E_{\gamma^*} - p_{x_\rho} p_{x_{\gamma^*}} - p_{y_\rho} p_{y_{\gamma^*}} - p_{z_\rho} p_{z_{\gamma^*}}\right)$$

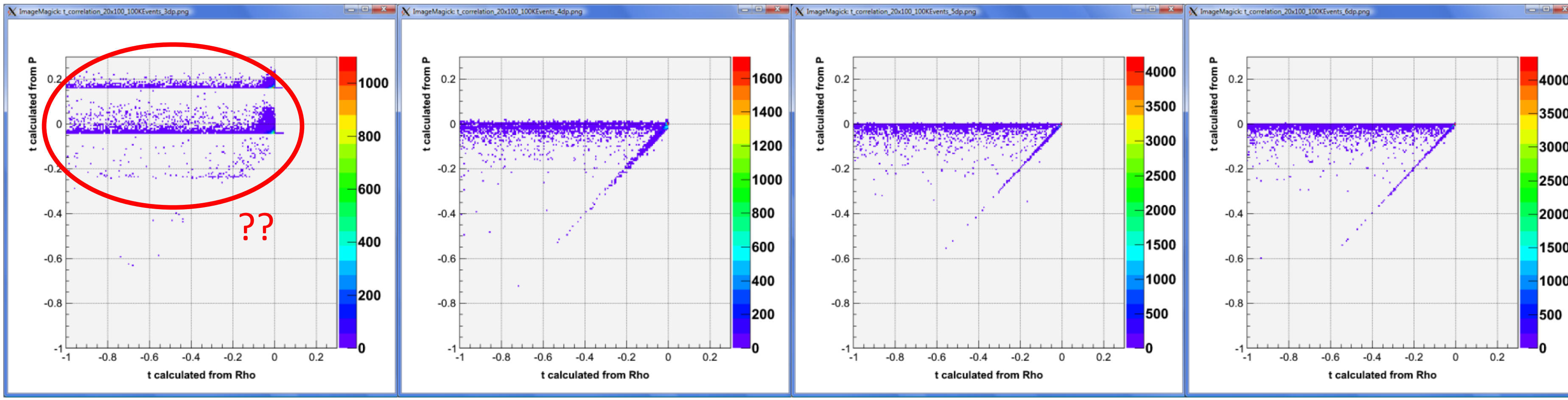
t calculated from P’-P

$$t_{proton} = 2m_p^2 - 2\left(E_P E_{P'} - p_{z_P} p_{z_{P'}}\right)$$

What we get from RAPGAP:

- Using p-p vertex, many positive “t” values even though it is **defined to be negative**
- “t” from p-p and gamma-rho vertices do not correlate, even at high precision

Precision Studies



3dp	4dp	5dp	6dp
Correlation: 13.98%	Correlation: 14.06%	Correlation: 14.12%	Correlation: 14.08%

RAPGAP default

- t_rho on x-axis, t_proton on y-axis, 20+100 GeV
- **Increasing precision has no real effect on correlation**
- Strange “banding” effect is resolved for dp > 3

The problem:

- **There appears to be an inherent bug in RAPGAP that affects exclusive vector meson events!!**
- In the next talk, Peter Schnatz will show how this bug is not apparent in data from PYTHIA, another MC generator similar to RAPGAP

Other Ongoing Work and Future Plans

- Anders Kirleis (Stony Brook & BNL)
  - eRHIC detector simulation in Geant3
  - Spoke earlier

- Peter Schnatz (Stony Brook & BNL)
  - Radiative corrections in PYTHIA
  - Next speaker..

Thank you

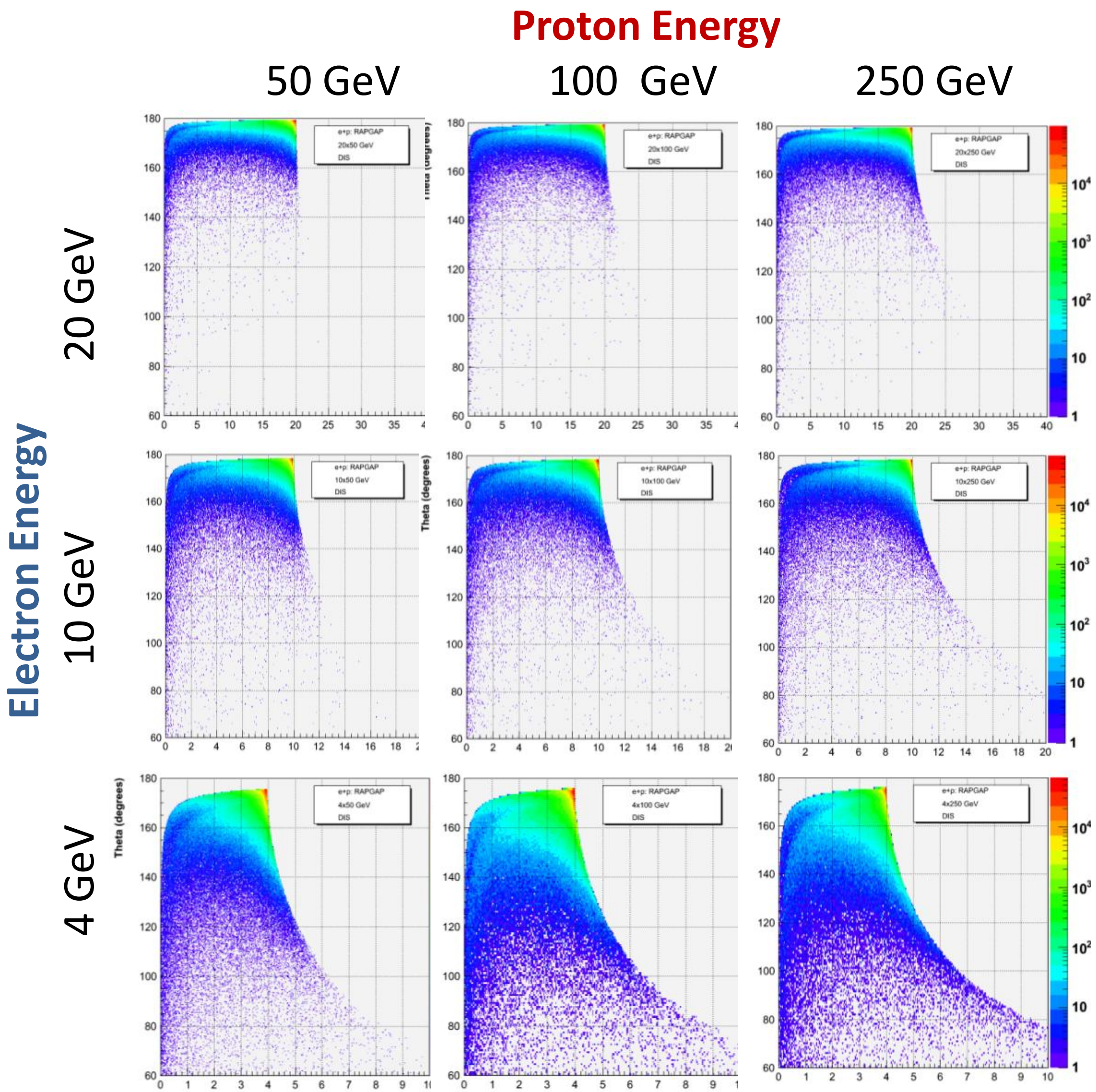
Acknowledgements:
Matt Lamont & Elke-Caroline Aschenauer
Abhay Deshpande
Anders Kirleis
Michael Savastio
Peter Schnatz

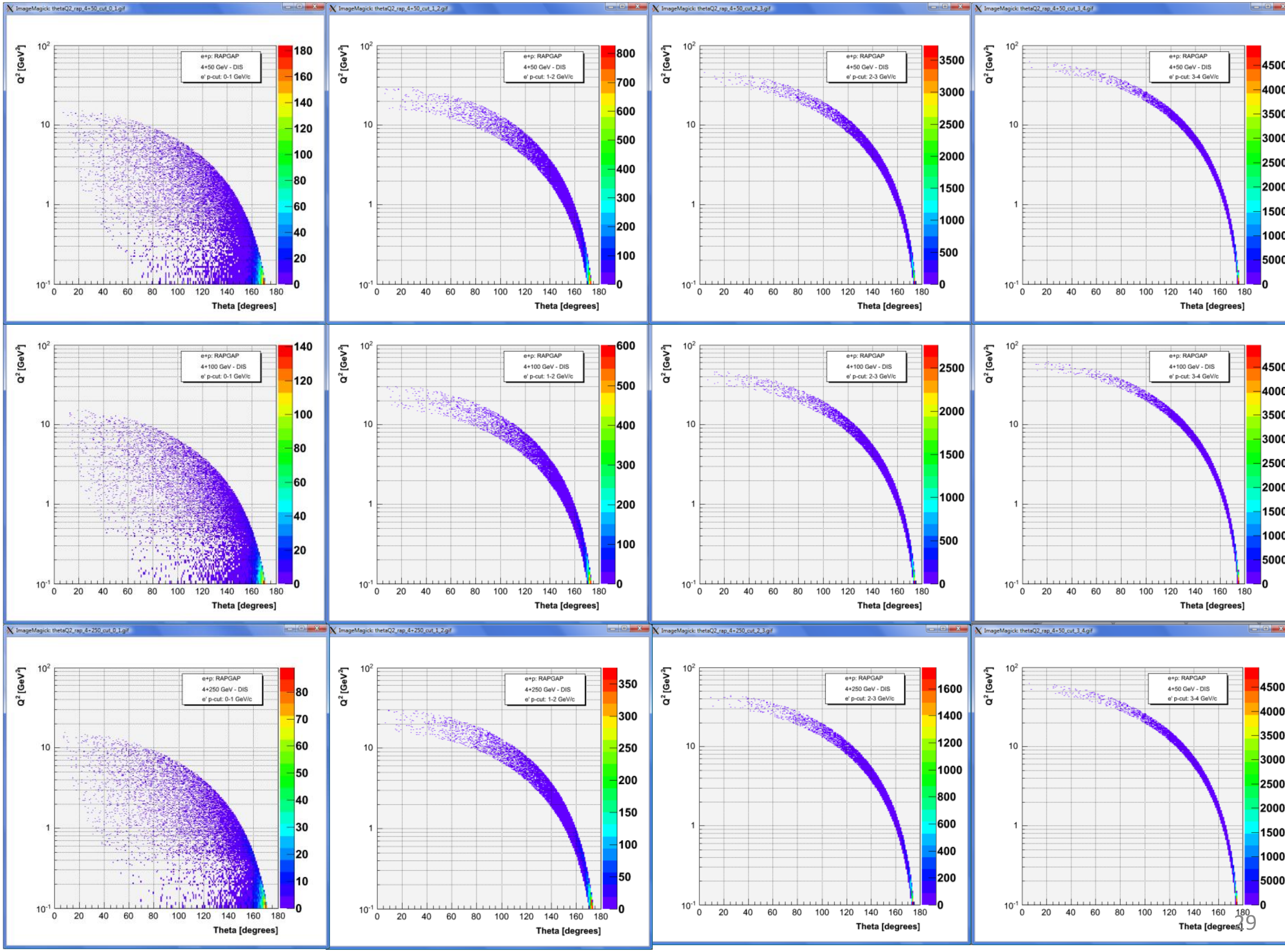
BROOKHAVEN NATIONAL LABORATORY

STATE UNIVERSITY OF NEW YORK STONY BROOK DEPARTMENT OF PHYSICS & ASTRONOMY

Backup

Momentum vs. theta of scat. electron




ImageMagick: thetaQ2_rap_4+50_cut_0_1.gif
e+p: RAPGAP
4+50 GeV - DIS
e' p-cut: 0-1 GeV/c
ImageMagick: thetaQ2_rap_4+50_cut_1_2.gif
e+p: RAPGAP
4+50 GeV - DIS
e' p-cut: 1-2 GeV/c
ImageMagick: thetaQ2_rap_4+50_cut_2_3.gif
e+p: RAPGAP
4+50 GeV - DIS
e' p-cut: 2-3 GeV/c
ImageMagick: thetaQ2_rap_4+50_cut_3_4.gif
e+p: RAPGAP
4+50 GeV - DIS
e' p-cut: 3-4 GeV/c
e+p: RAPGAP
4+100 GeV - DIS
e' p-cut: 0-1 GeV/c
e+p: RAPGAP
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e' p-cut: 1-2 GeV/c
e+p: RAPGAP
4+100 GeV - DIS
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e+p: RAPGAP
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e' p-cut: 3-4 GeV/c
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e+p: RAPGAP
4+250 GeV - DIS
e' p-cut: 0-1 GeV/c
ImageMagick: thetaQ2_rap_4+250_cut_1_2.gif
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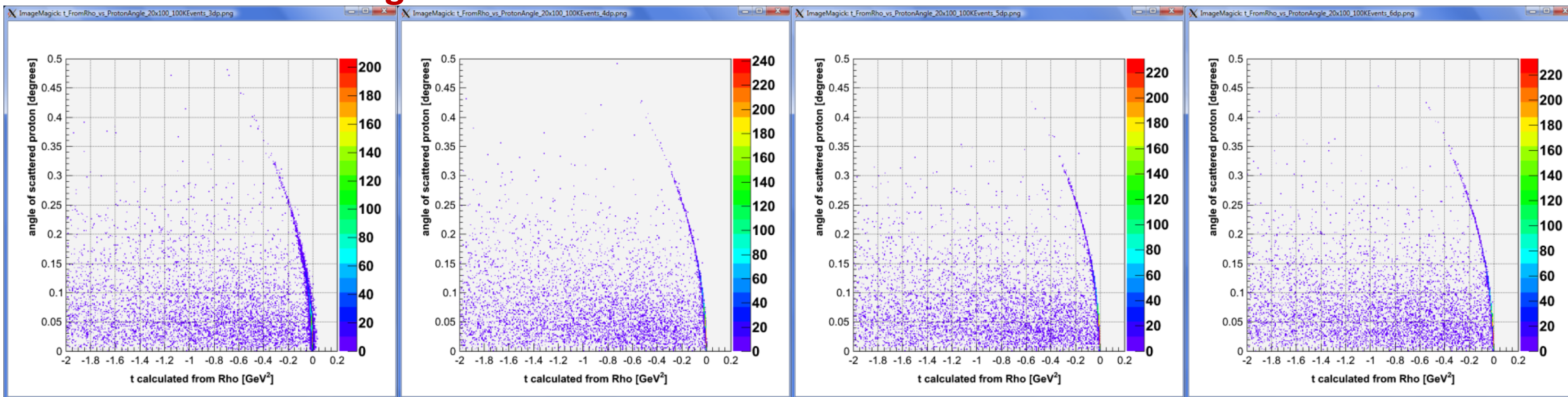
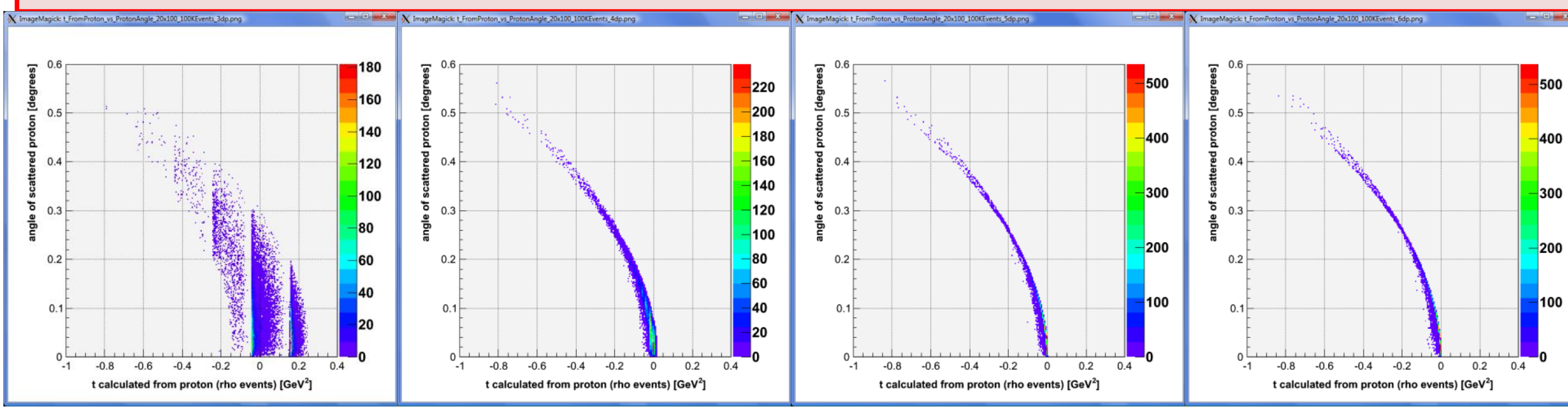
4+250 GeV - DIS
e' p-cut: 1-2 GeV/c
ImageMagick: thetaQ2_rap_4+250_cut_2_3.gif
e+p: RAPGAP
4+250 GeV - DIS
e' p-cut: 2-3 GeV/c
ImageMagick: thetaQ2_rap_4+50_cut_3_4.gif
e+p: RAPGAP
4+50 GeV - DIS
e' p-cut: 3-4 GeV/c
Q² [GeV²]
Theta [degrees]

t vs. P’ angle

t calculated from rho-gamma*



t_rho > zero: 1.17%	t_rho > zero: 0.21%	t_rho > zero: 0.037%	t_rho > zero: 0.004 %
3dp	4dp	5dp	6dp
t_p > zero: **50%**	t_p > zero: 25.3%	t_p > zero: 3.0%	t_p > zero: 2.22%



t calculated from p-p’

t vs. P' angle

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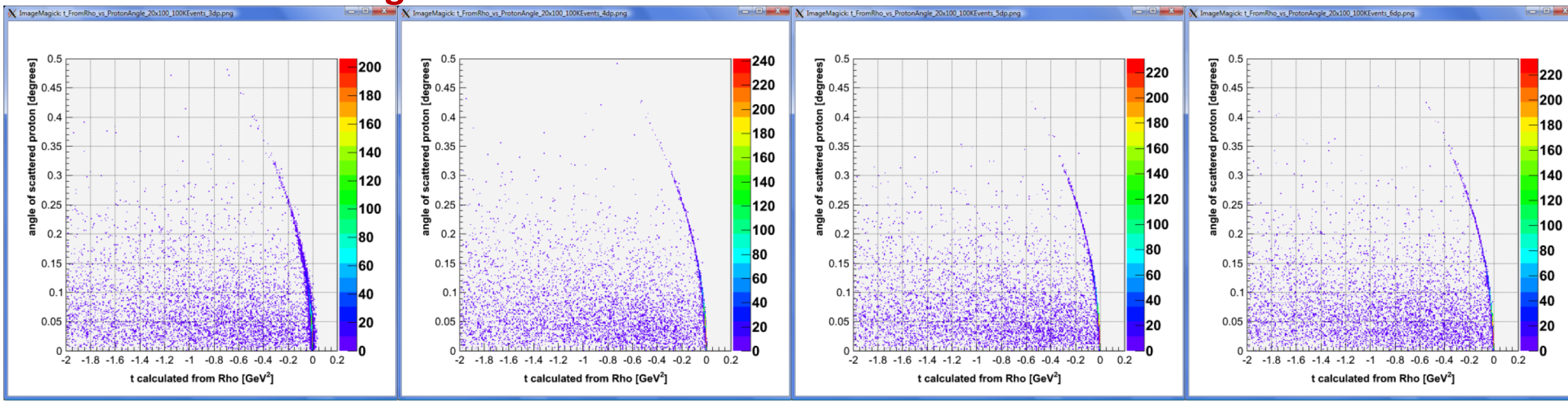

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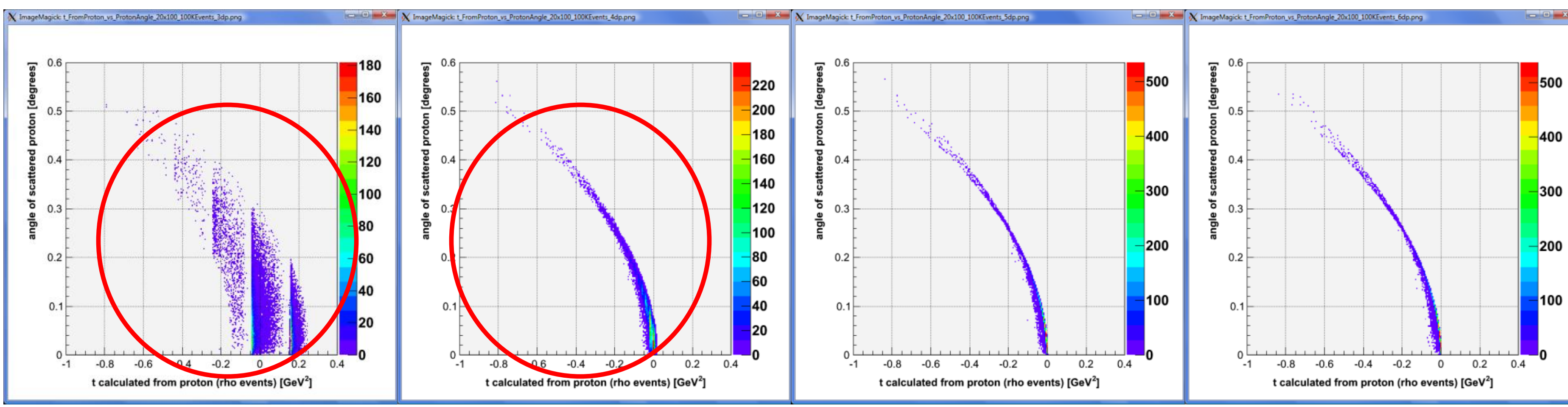

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t vs. P' angle

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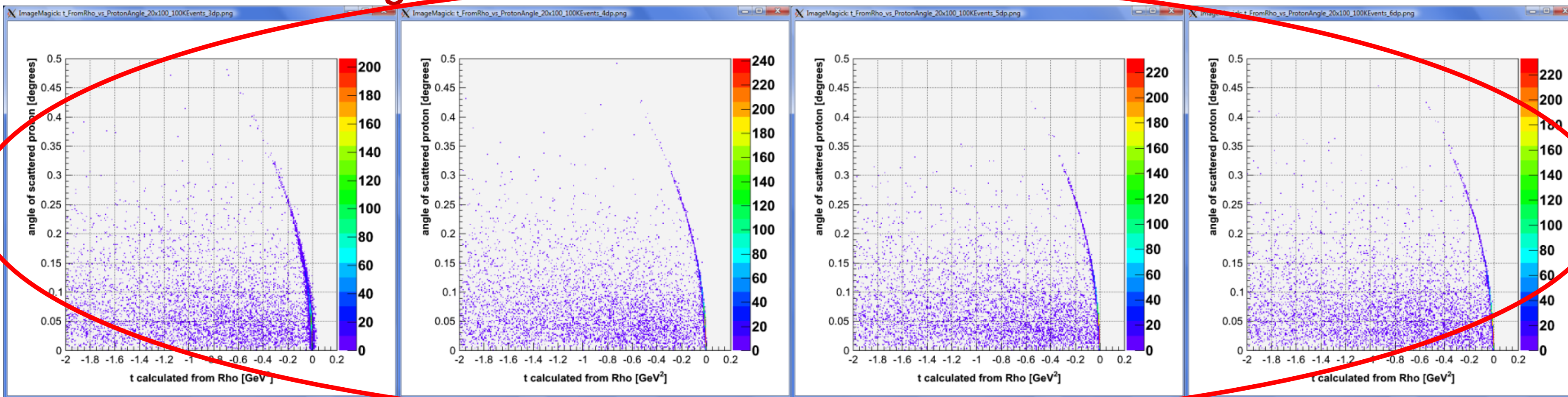

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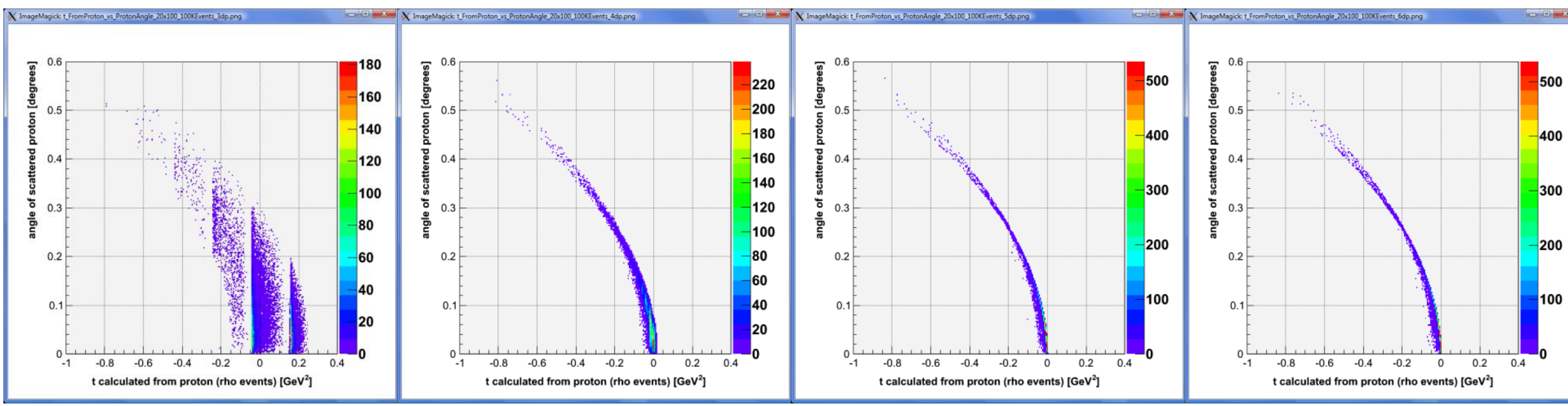

t calculated from p-p'