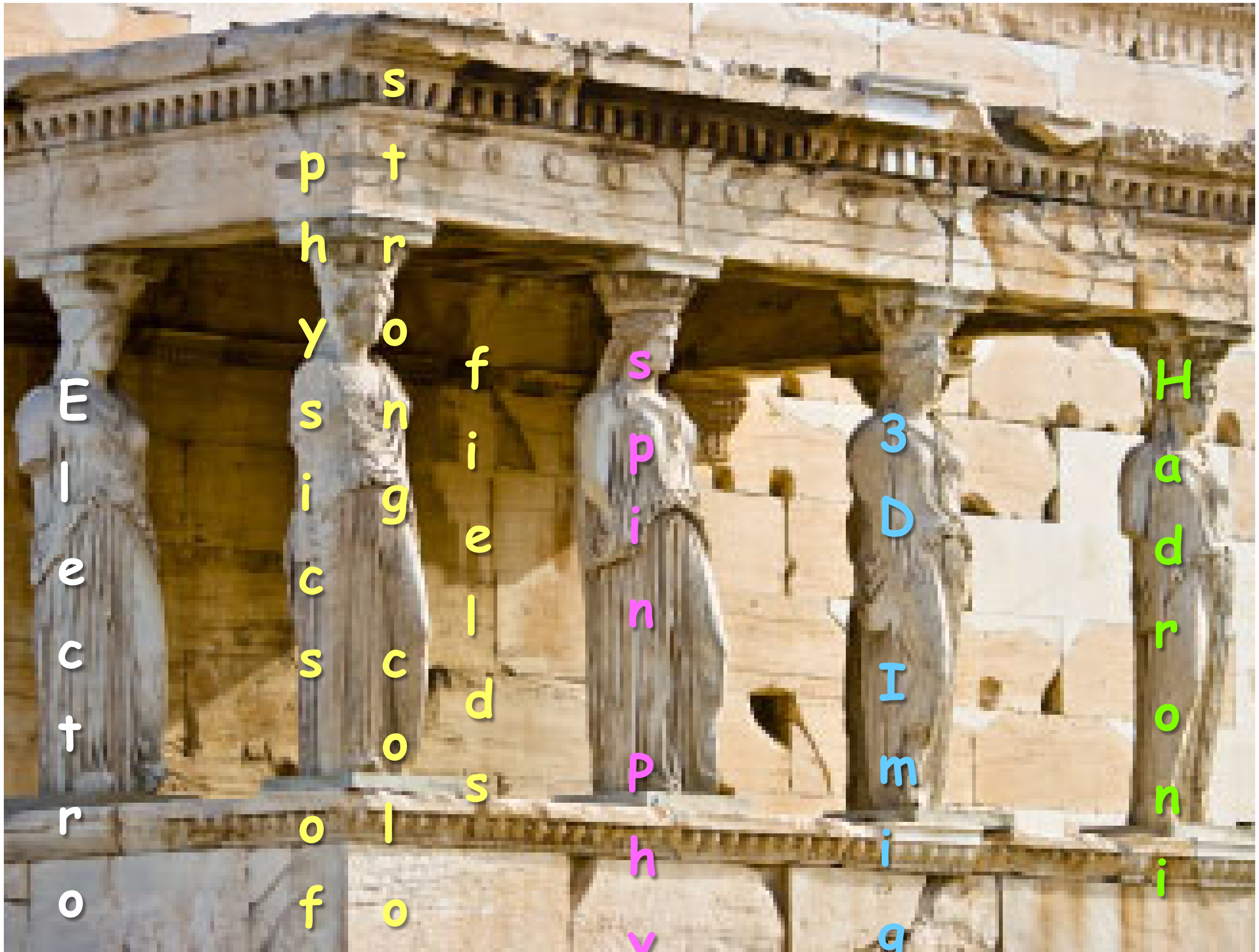
IR- and Detector Design Considerations

The Pillars of the eRHIC Physics program



Wide physics program with high requirements on detector and machine performance

Golden Measurements: Physics of strong color fields

Science Deliverable	Basic Measurement	Detector Requirements	Machine Requirements
integrated gluon distributions nuclear wave fct. saturation, Q_s	inclusive DIS $F_{2,L}$	→ very good electron ID → very good momentum and angular resolution for e'	need to reach x~10^{-4} large x,Q^2 coverage → medium lumi → highest √s
k_T-dependent gluons; gluon correlations non-linear QCD evolution/universality	semi-inclusive DIS di-hadron correlations	very similar to inclusive DIS → excellent particle ID → wide coverage range in η	need to reach x~10^{-4} large x,Q^2 coverage → medium lumi → highest √s
transport coefficients in cold nuclear matter parton energy loss; shower evolution energy loss mechani[sm]	semi-inclusive DIS; light and heavy hadrons (c,b), Jets	→ very good electron ID → very good momentum and angular resolution for e' → excellent particle ID → excellent vertex resolution	large x,Q^2 coverage multi-dim binning → medium - high lumi → low - high √s

Golden Measurements: Spin Physics

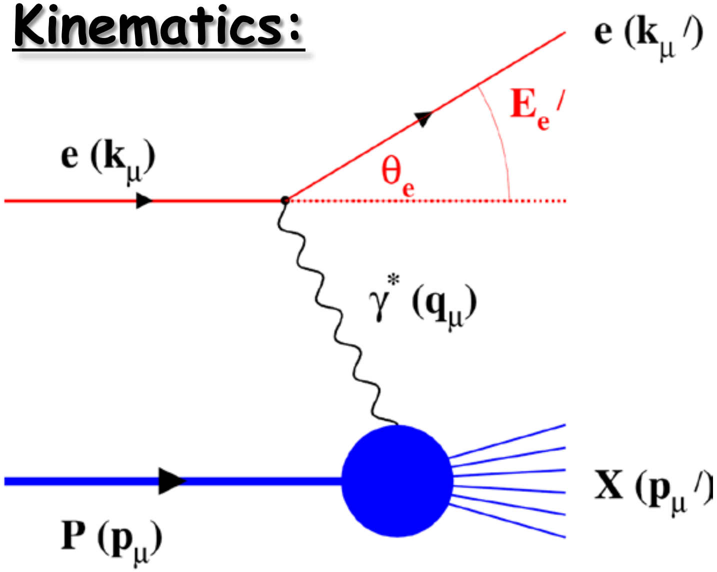
Science Deliverable	Basic Measurement	Detector Requirements	Machine Requirements
spin structure at small x contribution of Δg, $\Delta\Sigma$ to spin sum rule 	inclusive DIS	→ very good electron ID → very good momentum and angular resolution for e'	need to reach $x=10^{-4}$ large x,Q^2 coverage about $10 fb^{-1}$ → medium lumi → high $\sqrt{s}$
full flavor separation in large x,Q^2 range strangeness, $s(x)-\bar{s}(x)$ polarized sea 	semi-inclusive DIS	very similar to inclusive DIS →excellent particle ID separate π, K, p over a wide range in η	need to reach $x=10^{-4}$ large x,Q^2 coverage polarized ^{3}He beam medium lumi → high $\sqrt{s}$
electroweak probes of proton structure flavor separation electroweak parameters 	very high Q^2 hadronic final state	→ very good coverage for hadronic final state → kinematic from q-jet	20x250 to 30x325 positron beam polarized ^{3}He beam → high lumi → highest $\sqrt{s}$

Golden Measurements: 3D-Imaging in b_T / k_T

Science Deliverable	Basic Measurement	Detector Requirements	Machine Requirements
Sivers + unpol PDF valence, sea quarks & *gluons* • **quantum interference** • **multiparton correlations** • **spin-orbit correlations & role of OAM** • **matching low-high p_T**	semi-inclusive DIS **transverse nucl. pol.** ***di-hadron/(di-jets)*** ***heavy-flavor production***	→ very good electron ID → very good momentum and angular resolution for e' → excellent particle ID separate π, K, p over a wide range in η → full Φ-coverage around γ^* → excellent vertex res.	large x,Q^2 coverage 5D binning → high lumi → low - high $\sqrt{s}$
chiral odd fcts. valence, sea quarks & *gluons* • transversity & IFF • Collins-FF • Boer-Mulders fct.	semi-inclusive DIS	**as above**	**as above**
quark and gluon imaging via GPDs in b_T-space access to L_q and L_g	exclusive DIS DVCS, J/Ψ, ρ, Φ	→ very good electron ID → very good momentum and angular resolution for e' → exclusivity and high resolution in t → Roman pots	large x,Q^2,t coverage 4D binning polarized beams → high lumi → low - high $\sqrt{s}$

Deep Inelastic Scattering

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 2E_e E'_e(1-\cos\Theta_{e'})$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

e- → ← p/A

0° 180°

$$\text{Hadron}: z = \frac{E_h}{\nu};$$

p_t : with respect to γ^*

Challenge:

need to cover wide range in beam energies

lepton: 5 - 30 GeV

hadron (p/Au) 100 – 325 GeV / 25 – 130 GeV

Resolution in x, Q^2 dominated how well the scattered lepton is measured

low momentum: Multiple scattering → low material

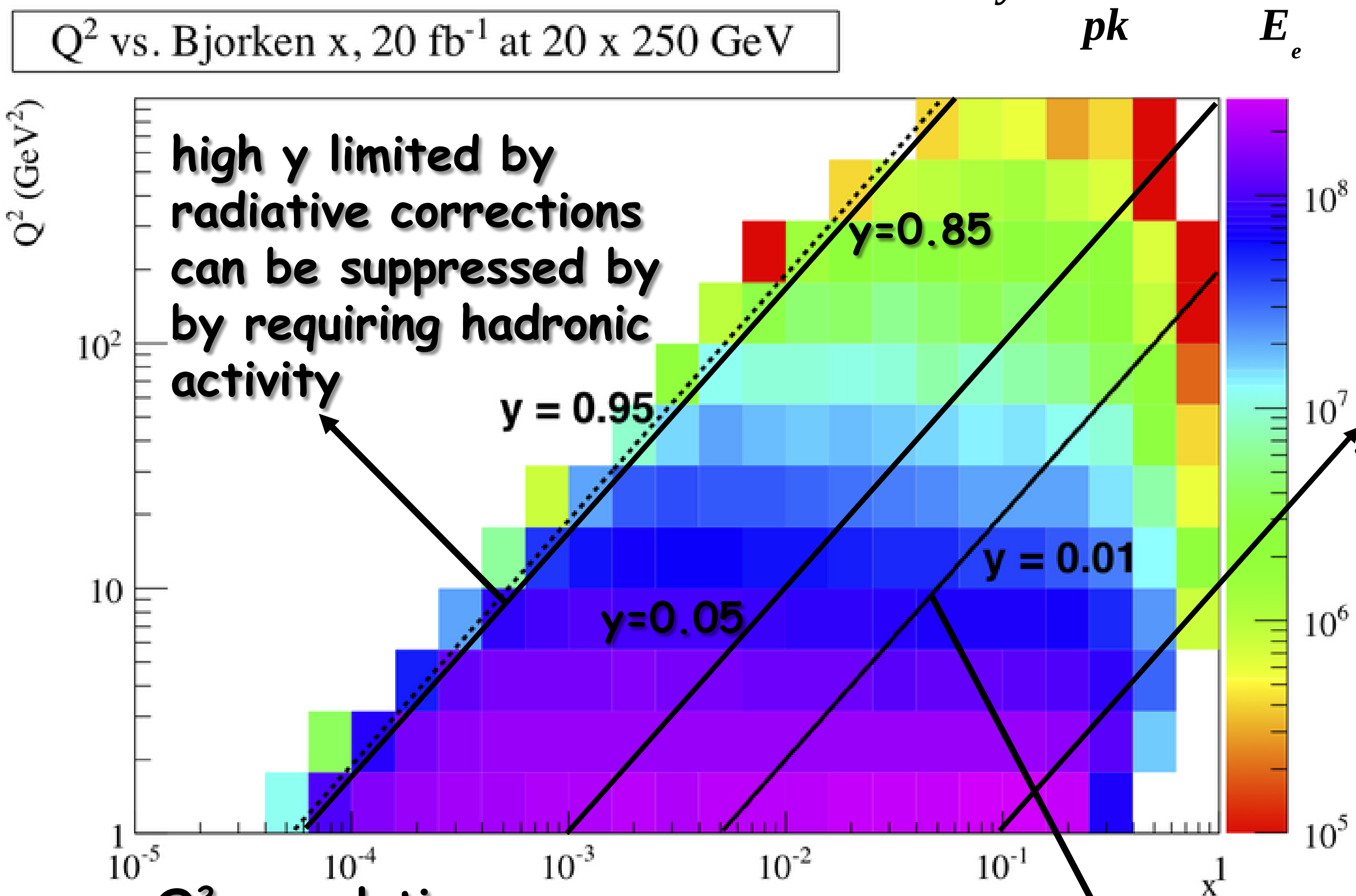
high momentum: position resolution from tracking detector

all momenta: Brems-strahlung → low material

DIS Kinematics

Potential limitations in kinematic coverage:

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

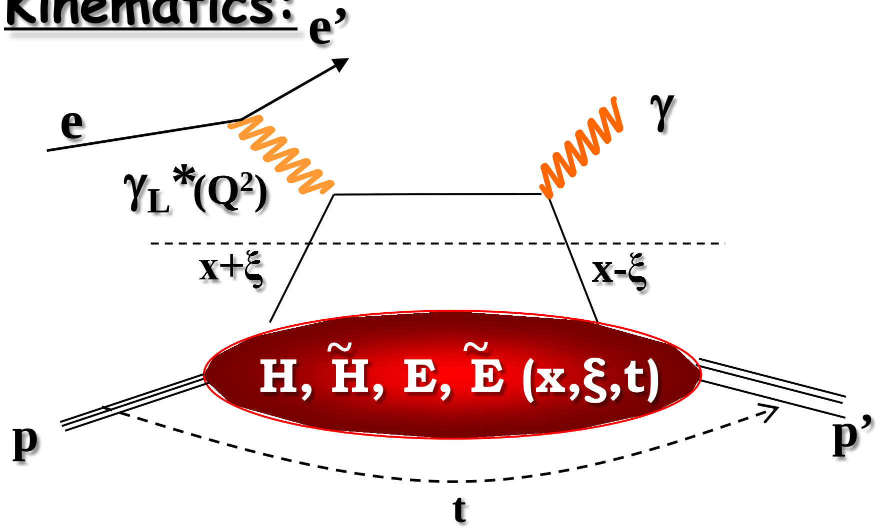


- Strong x-Q^2 correlation
  - high x → high Q^2
  - low x → low Q^2

low y limited by theta resolution for e'
→ use hadron method

Deep Inelastic Scattering

Kinematics:



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Measure of resolution power

$$Q^2 = 2E_e E'_e (1 - \cos\Theta_{e'})$$

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x_B = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

$$t = (p - p')^2, \xi = \frac{x_B}{2 - x_B}$$

Exclusive events:

e+p/A → e'+p'/A'+γ / J/ψ / ρ / ϕ

detect **all** event products in the detector

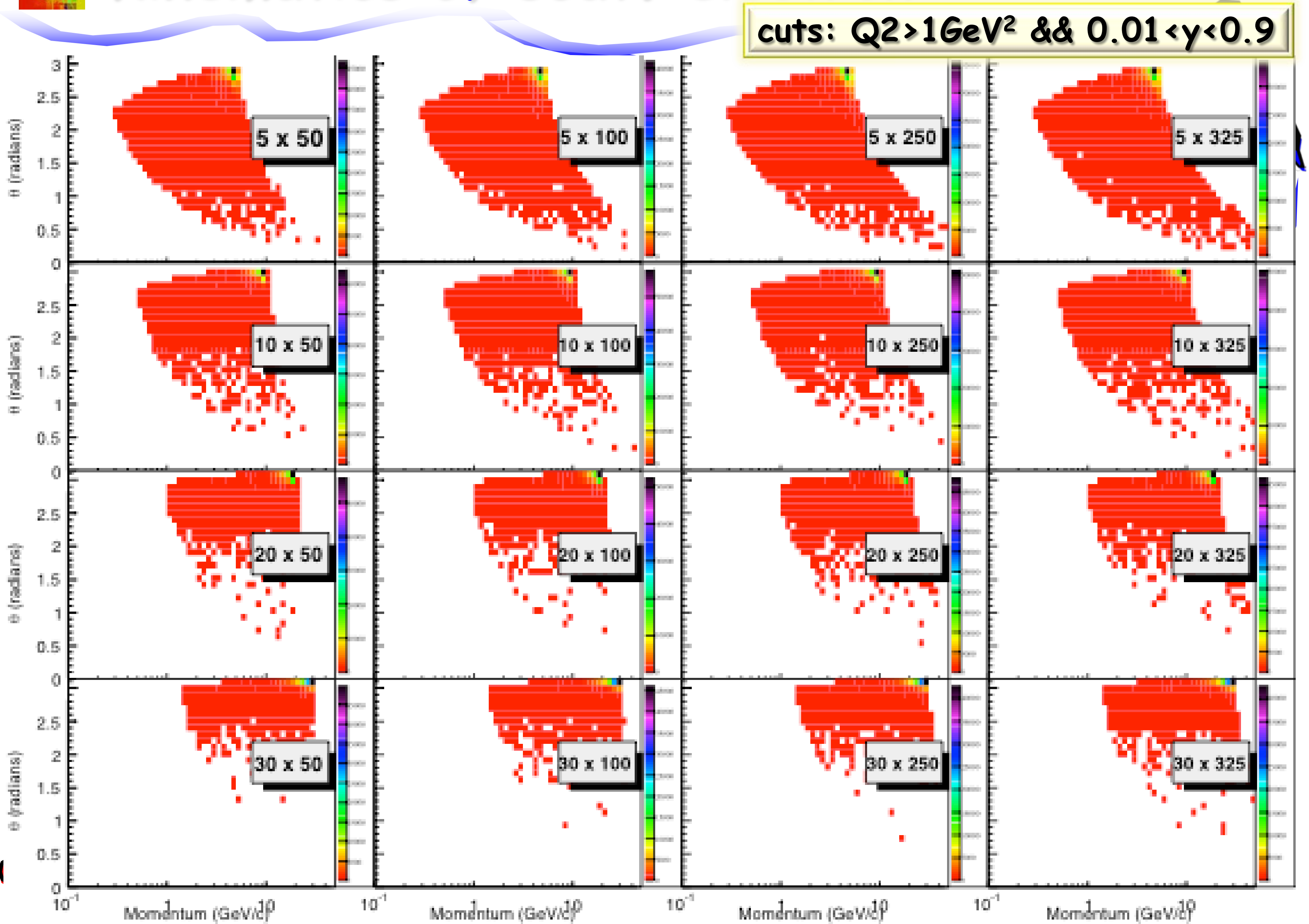
Special sub-event category **rapidity gap events**

e+p/A → e'+γ / J/ψ / ρ / ϕ / jet

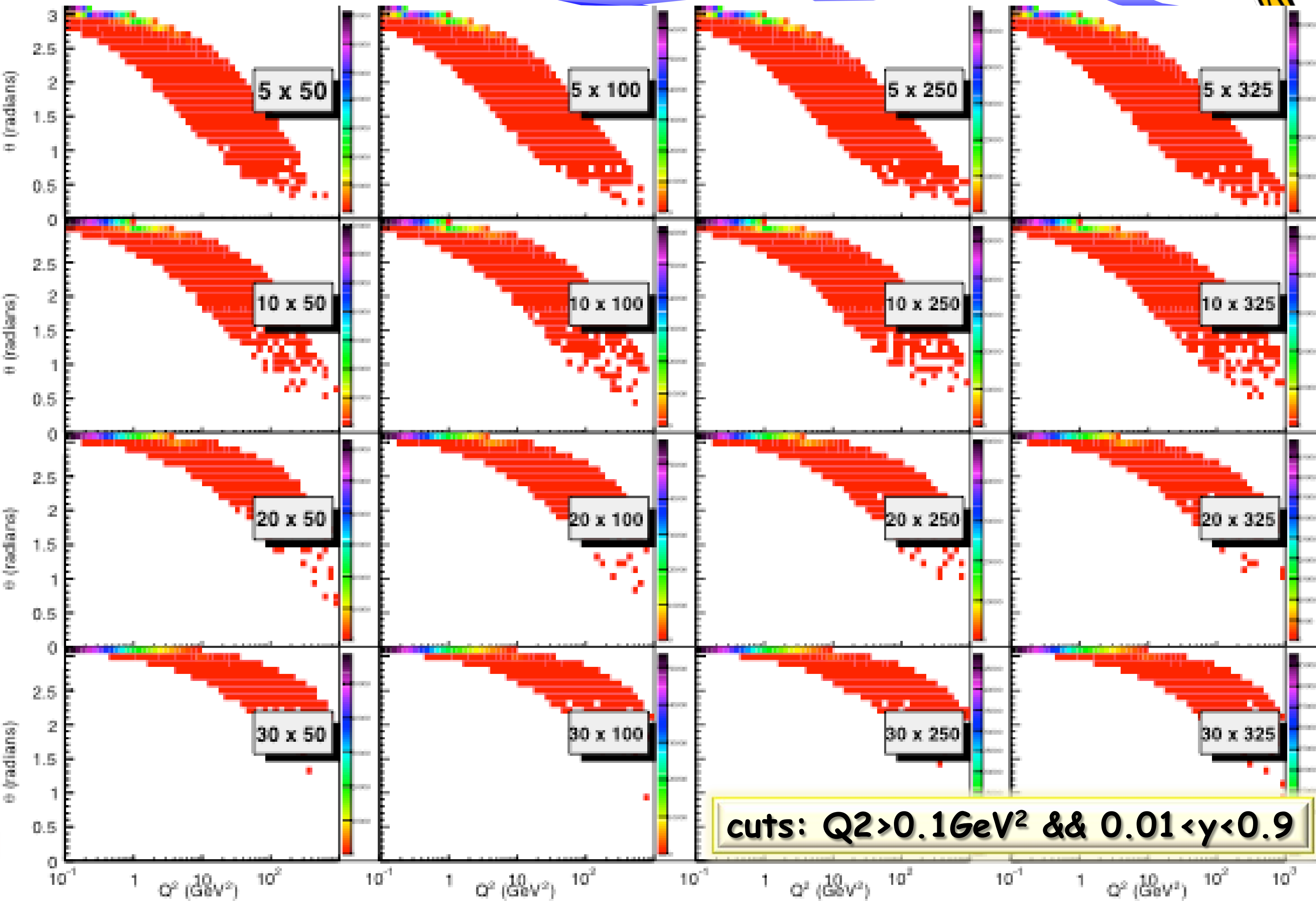
don't detect p' → HERA: 20% non-exclusive event contamination

missing mass technique as for fixed target does not work → **resolution**

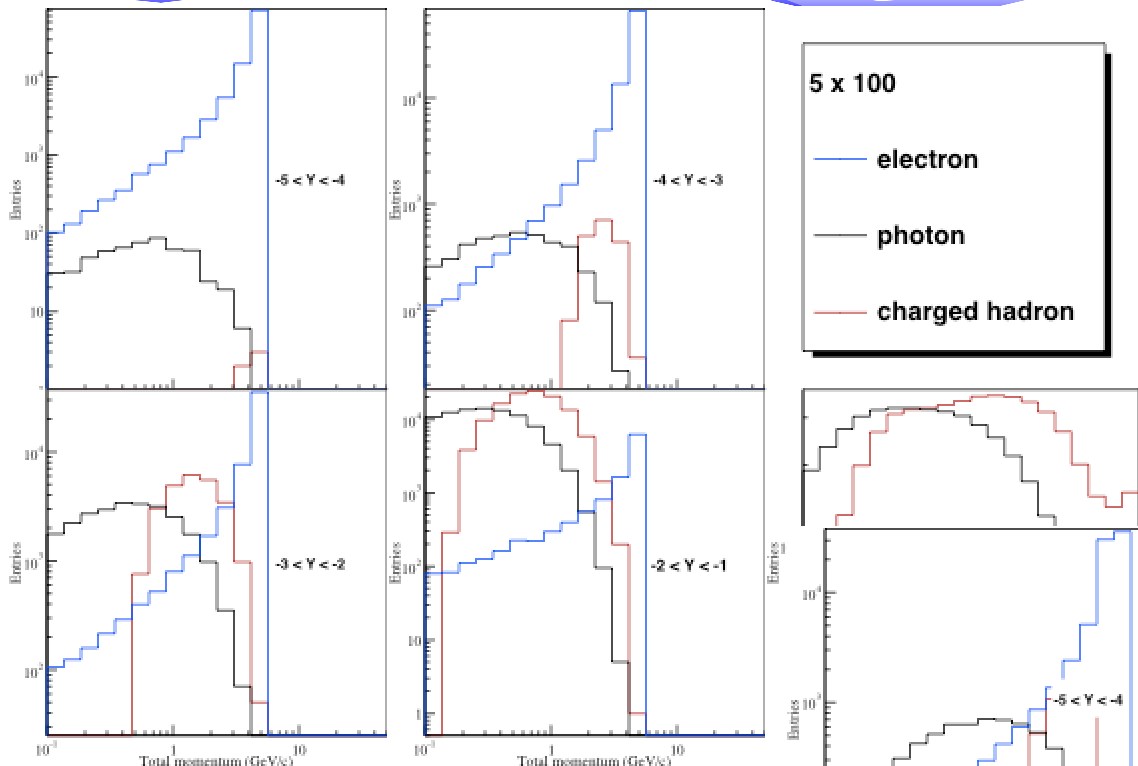
Kinematics of scat. electron

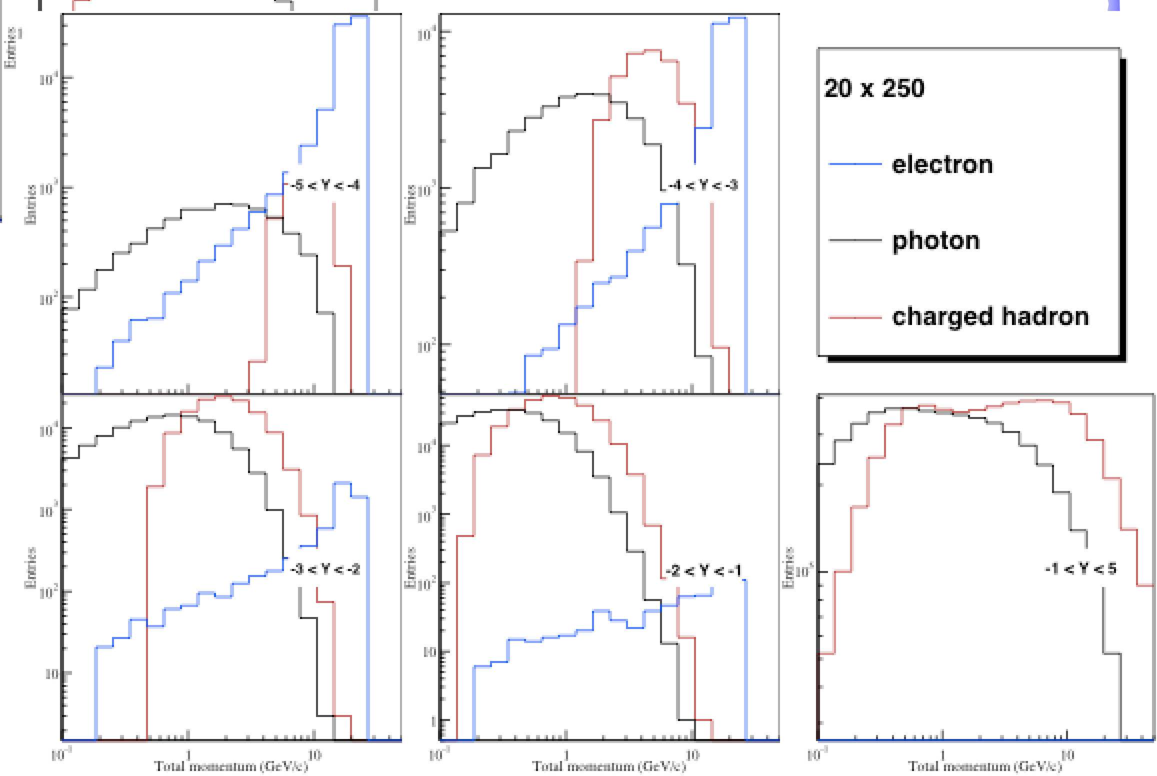


Kinematics of scat. electron



Required Lepton-Hadron Separation



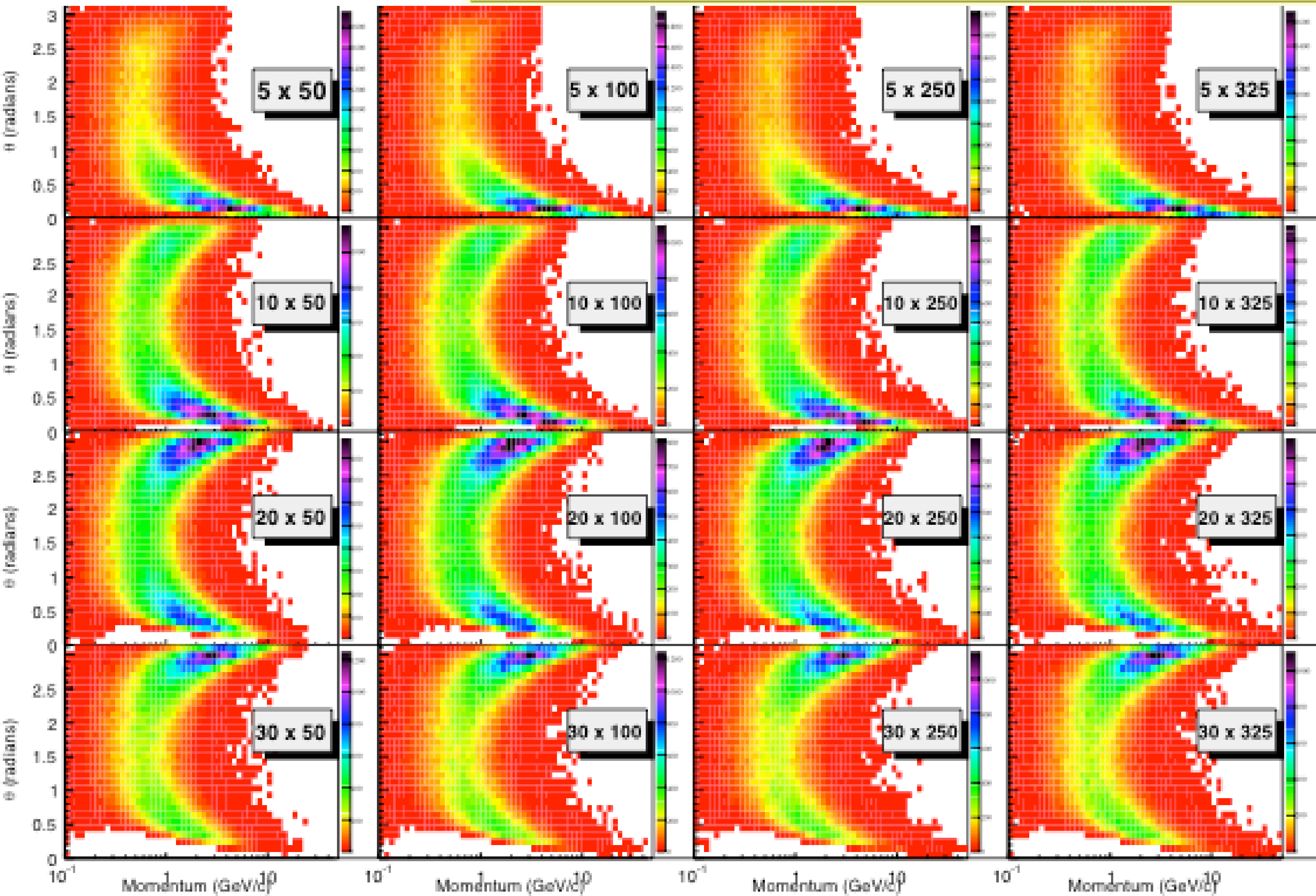


Need very good e-PID for high Q^2 events

Kinematics of semi-inclusive hadrons

PIONS:

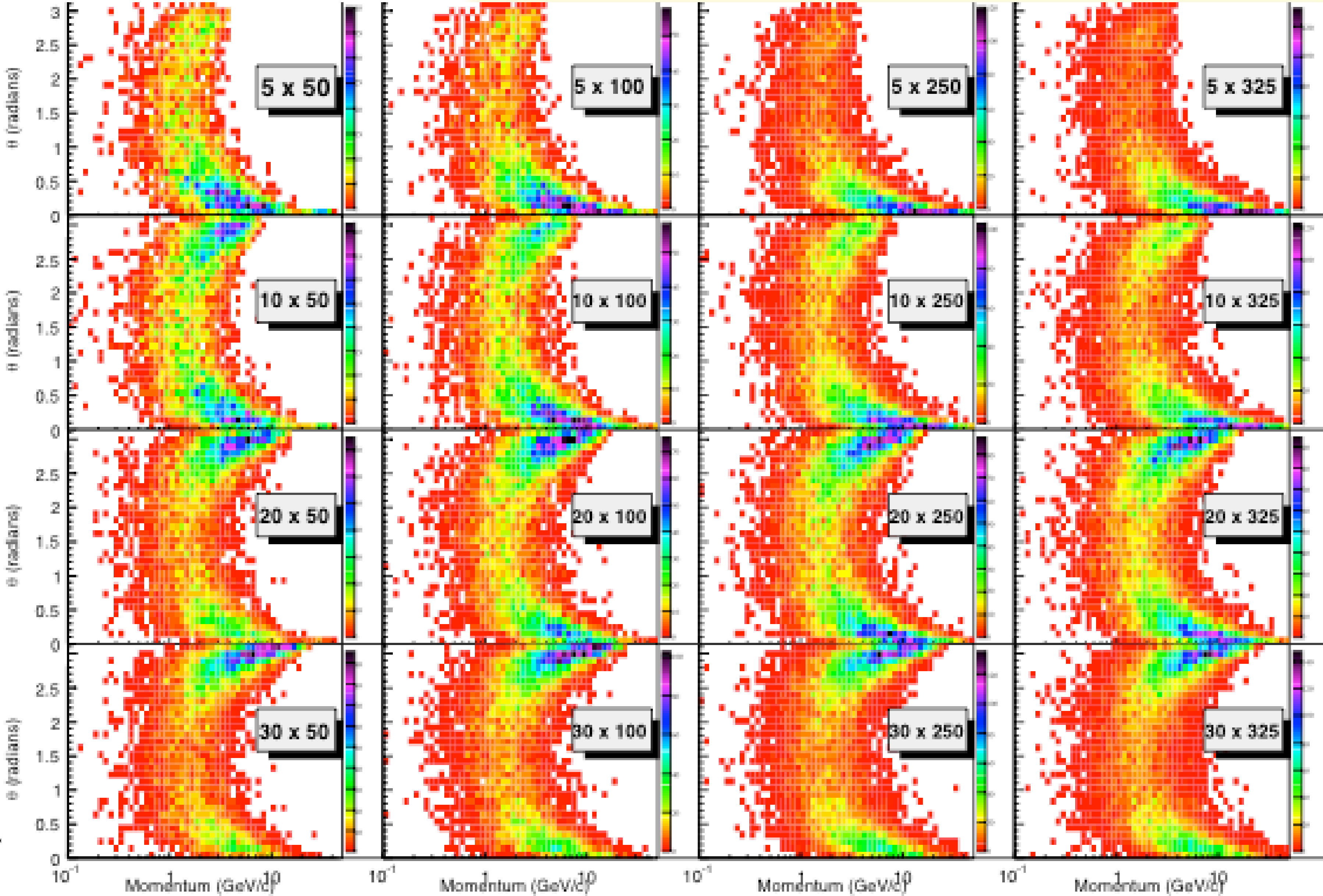
cuts: Q2>1GeV² && 0.01<y<0.9 && 0.1<z<0.9



Kinematics of semi-inclusive hadrons

KAONS:

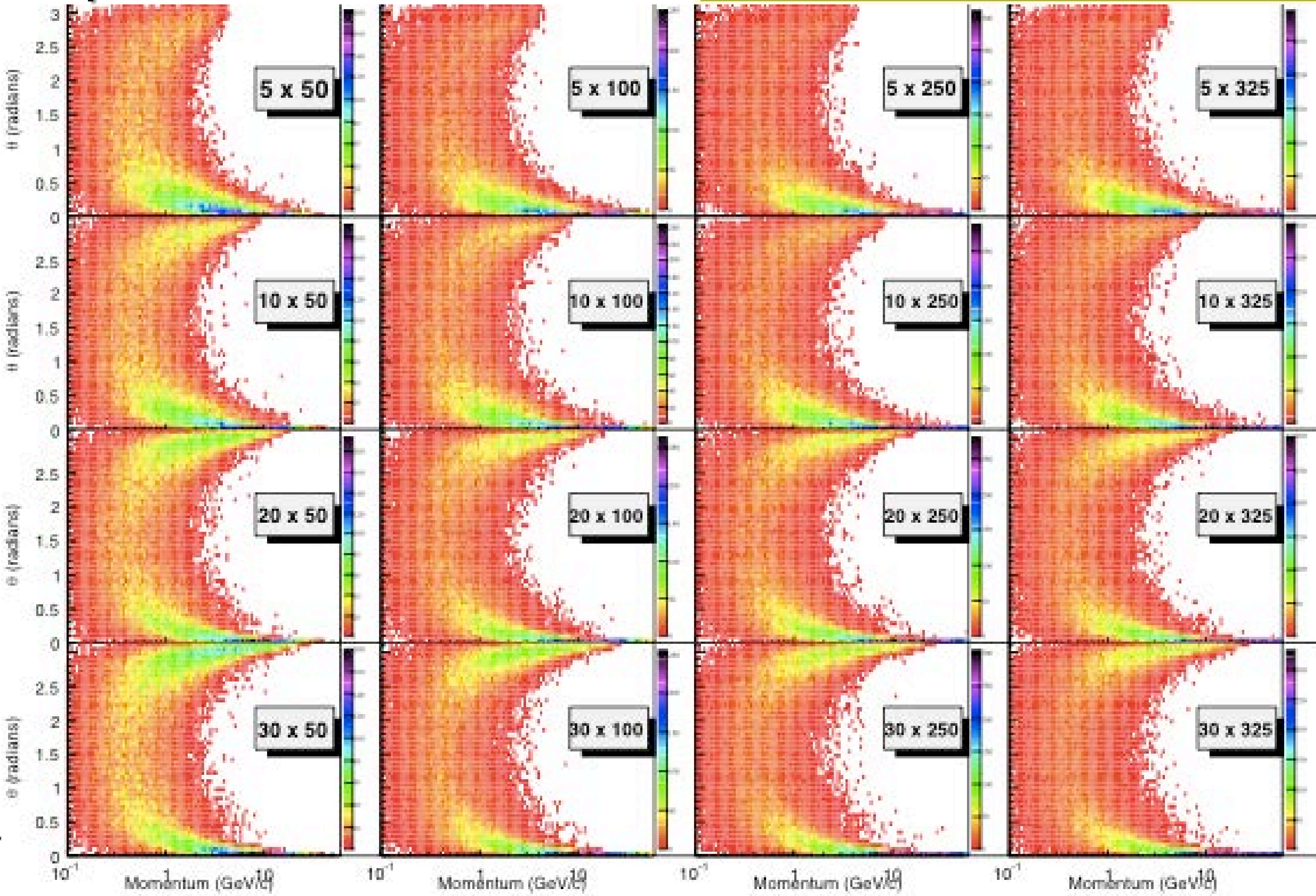
cuts: $Q2>1GeV^2$ && $0.01<y<0.9$ && $0.1<z<0.9$



Kinematics of exclusive hadrons

$\rho \rightarrow \pi^+ + \pi^-$:

cuts: $Q2>1.0GeV^2$ && $0.01<y<0.9$



Important for Detector Design

- DIS:
  - with increasing center-of-mass energy lepton goes more and more in original beam direction
  - high Q^2 events go into central detector
  - low Q2 events have small scattering angle and close to original beam energy

  need low forward electron tagger for low Q^2 events

  low-mass high resolution trackers over wide angular acceptance
- Semi-Inclusive DIS
  - hadrons go from very forward to central to even backward with lepton beam energy increasing

  good particle-ID over the entire detector ($1<p<30$-60GeV)
- Exclusive Reactions:
  - decay products from excl. ρ / ϕ / J/ψ go from very forward to central to even backward with lepton beam energy increasing

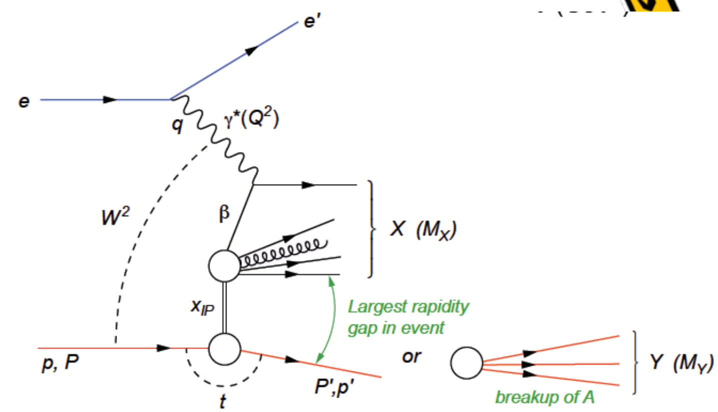
Additional Remarks

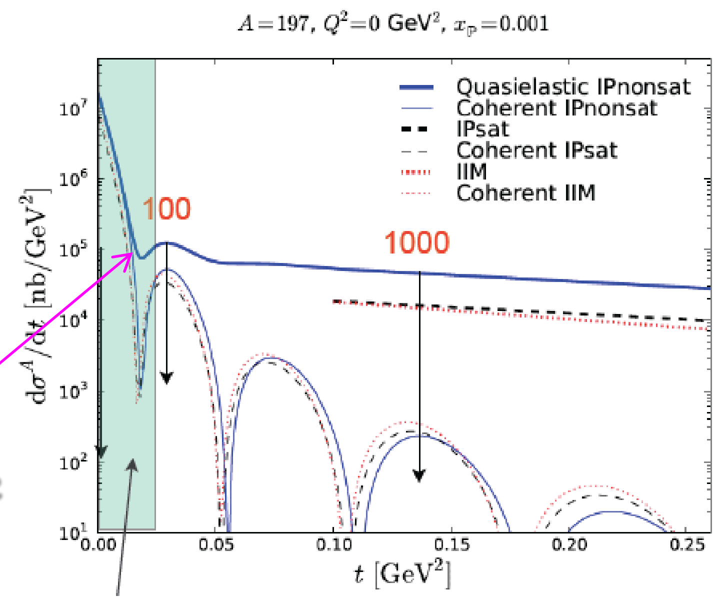
- Charm detection
  - structure functions
    - detecting lepton form decay in addition to scattered via displaced vertex should be enough
  - charm in fragmentation
    - need to reconstruct D^0 meson completely to measure its z
      → good PID

- Very high luminosity 10^{34} $cm^{-1}s^{-1}$
  - will be systematic limited basically in every measurement
  - needs a lot of care to account for this in the design
    - detector: alignment, ……
    - polarization measurements: bunch by bunch;
    - luminosity measurement
    - relative luminosity measurement

How to detect coherent/in-coherent events in ep/A ?

- $e+p/A \rightarrow e'+p'/A' + \gamma$ / J/ψ / ρ / φ / jet
- Challenges to detect p'/A'
  - Beam angular divergence limits smallest outgoing Θ_{min} for p/A that can be measured
  - Can measure the nucleus if it is separated from beam in Si (Roman Pot) "beamline" detectors
    - $p_{Tmin} \sim p_z^A \Theta_{min}$
      - For beam energies = 100 GeV/n and Θ_{min} = 0.1 mrad
  - Large momentum kicks, much larger than binding energy (~8 MeV)
    - For large A, coherently diffractive nucleus cannot be separated from beamline without breaking up
      → break up neutron detection
      → veto incoherent events





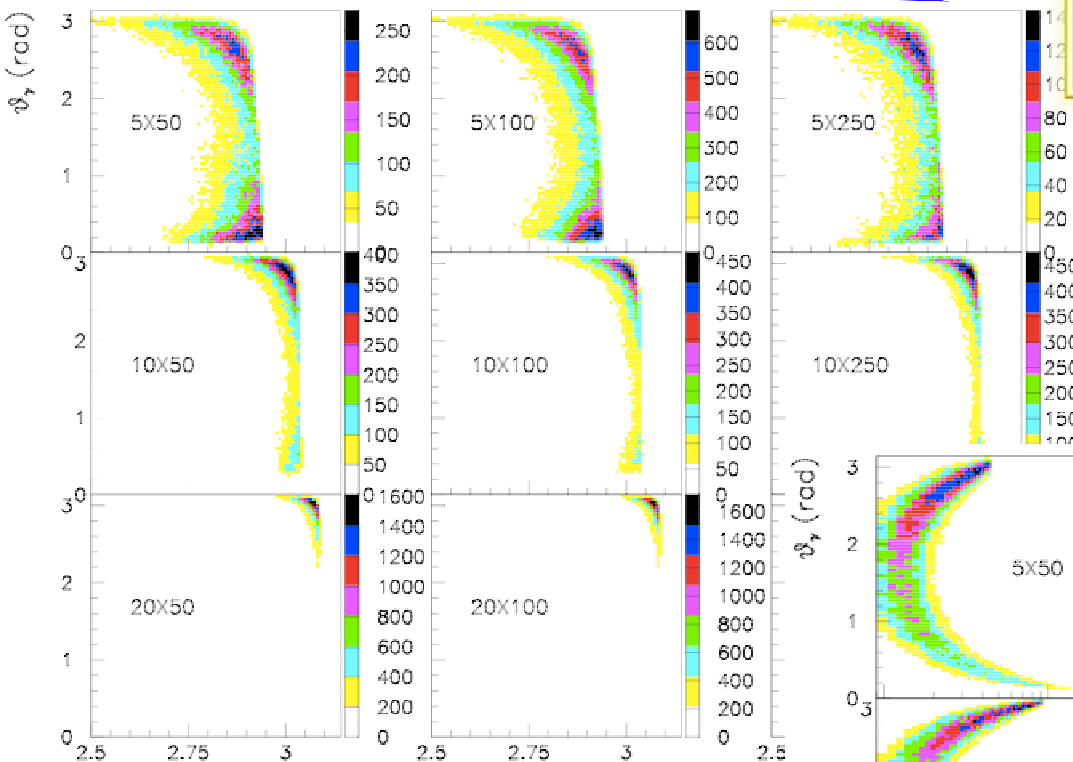
incoherent dominates at a t at 1/e of coherent cross section

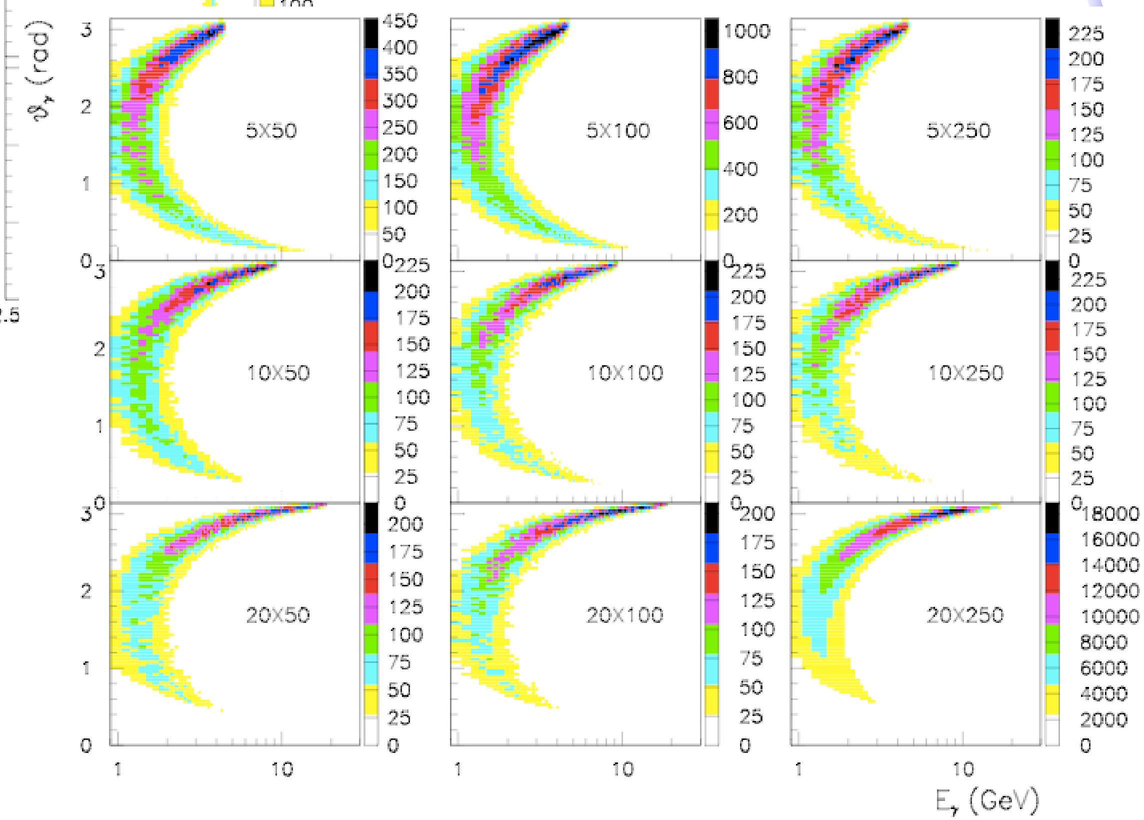
→ $p_t \ll p_{tmin}$

$p_t = \sqrt{t}$

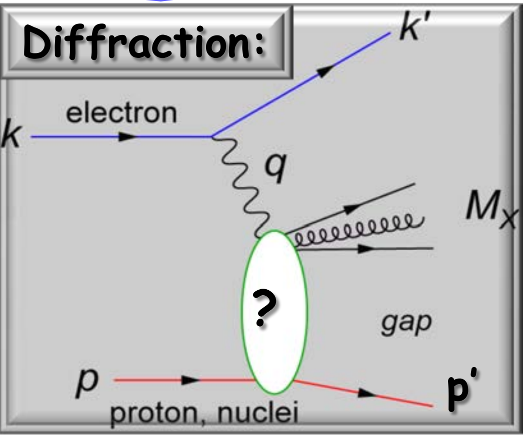
DVCS: $ep \rightarrow e'p'\gamma$

cuts: Q2>1.0GeV² && 0.01<y<0.9 && Eγ>1GeV



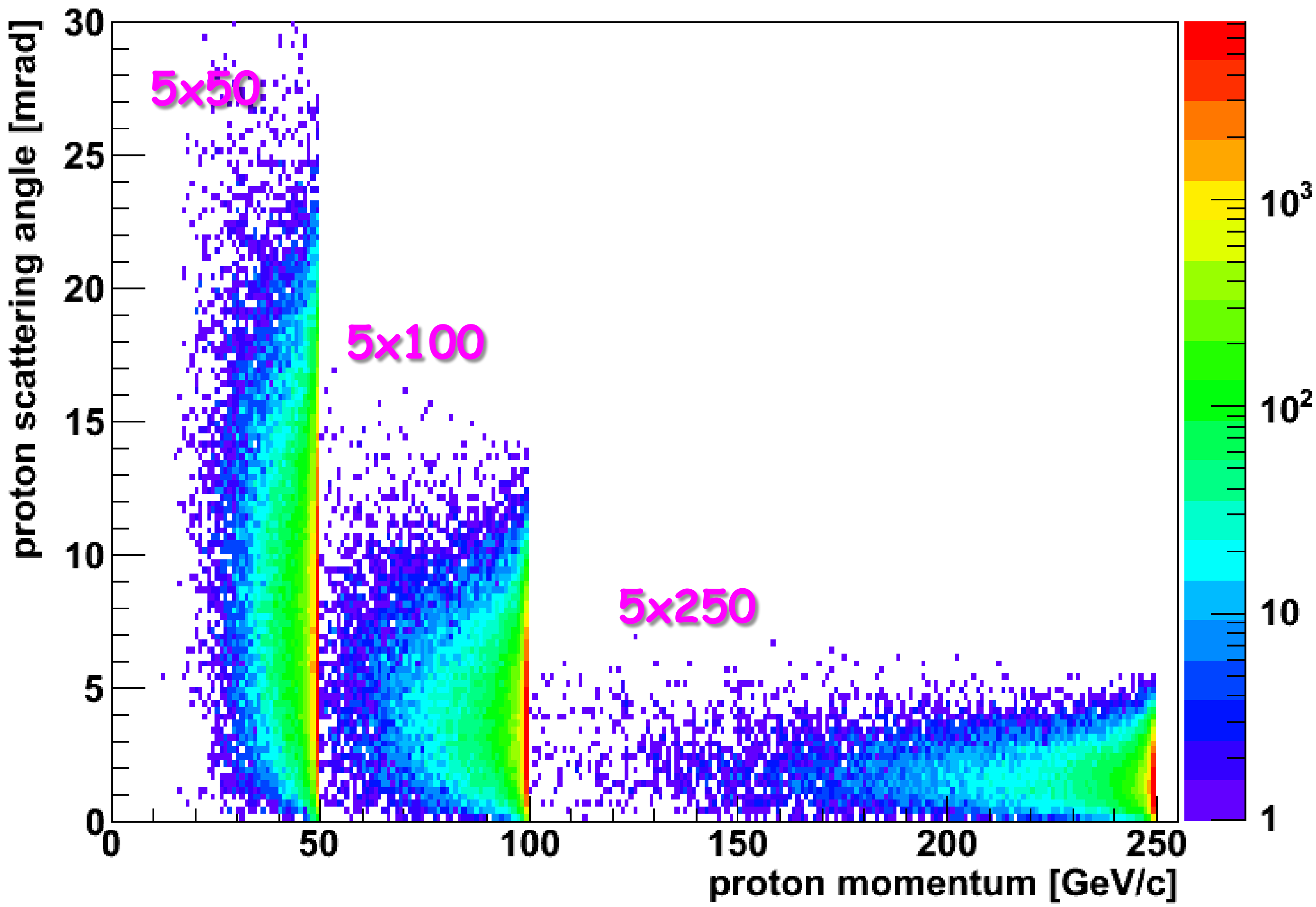


Diffractive Physics: p' kinematics



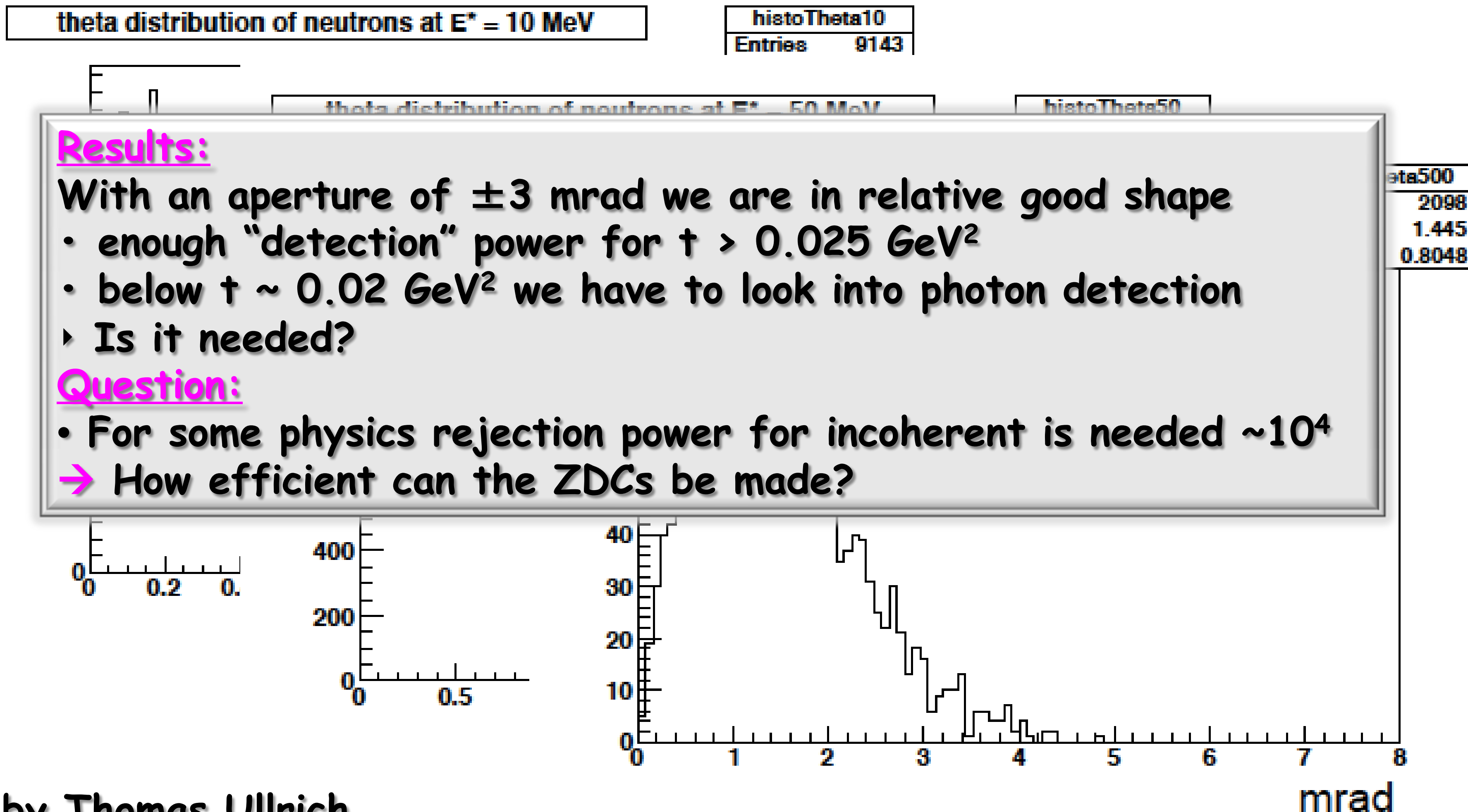
$t=(p_4-p_2)^2 = 2[(m_p^{in}.m_p^{out})-(E^{in}E^{out} - p_z^{in}p_z^{out})]$

→ " Roman Pots" acceptance studies see later



Kinematics of Breakup Neutrons

Results from GEMINI++ for 50 GeV Au



Results:

With an aperture of ±3 mrad we are in relative good shape

- enough "detection" power for t > 0.025 GeV^2
- below t ~ 0.02 GeV^2 we have to look into photon detection
  - Is it needed?

Question:

- For some physics rejection power for incoherent is needed ~10^4

→ How efficient can the ZDCs be made?

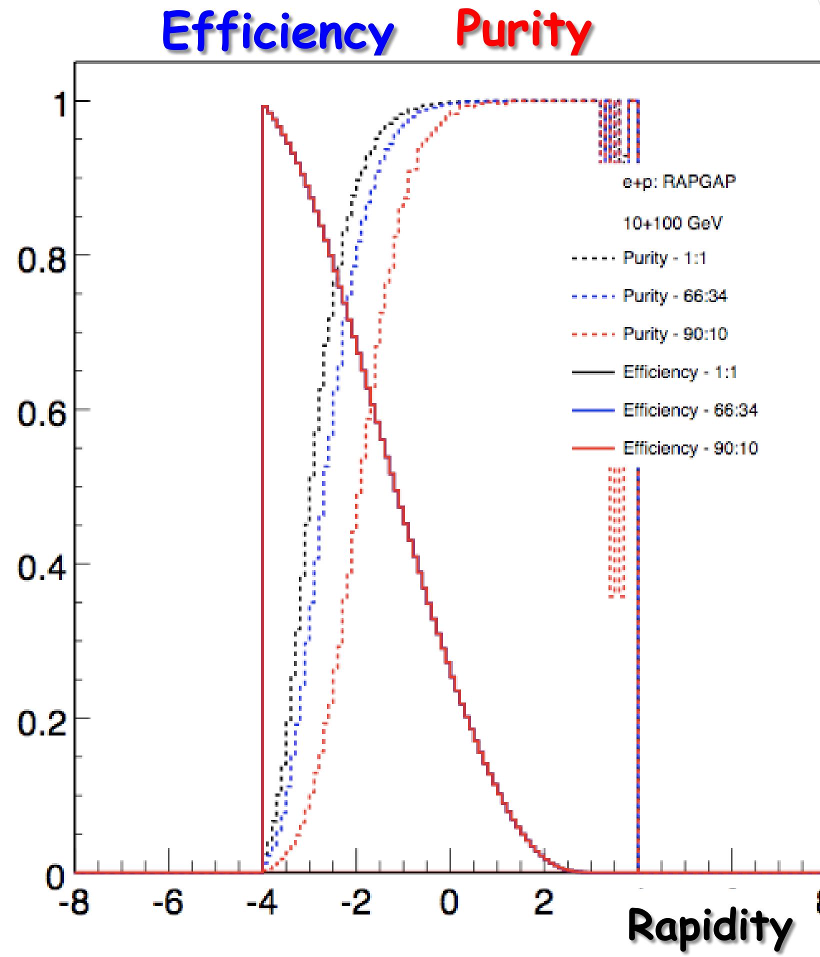
by Thomas Ullrich

→ +/-5mrad acceptance seems sufficient

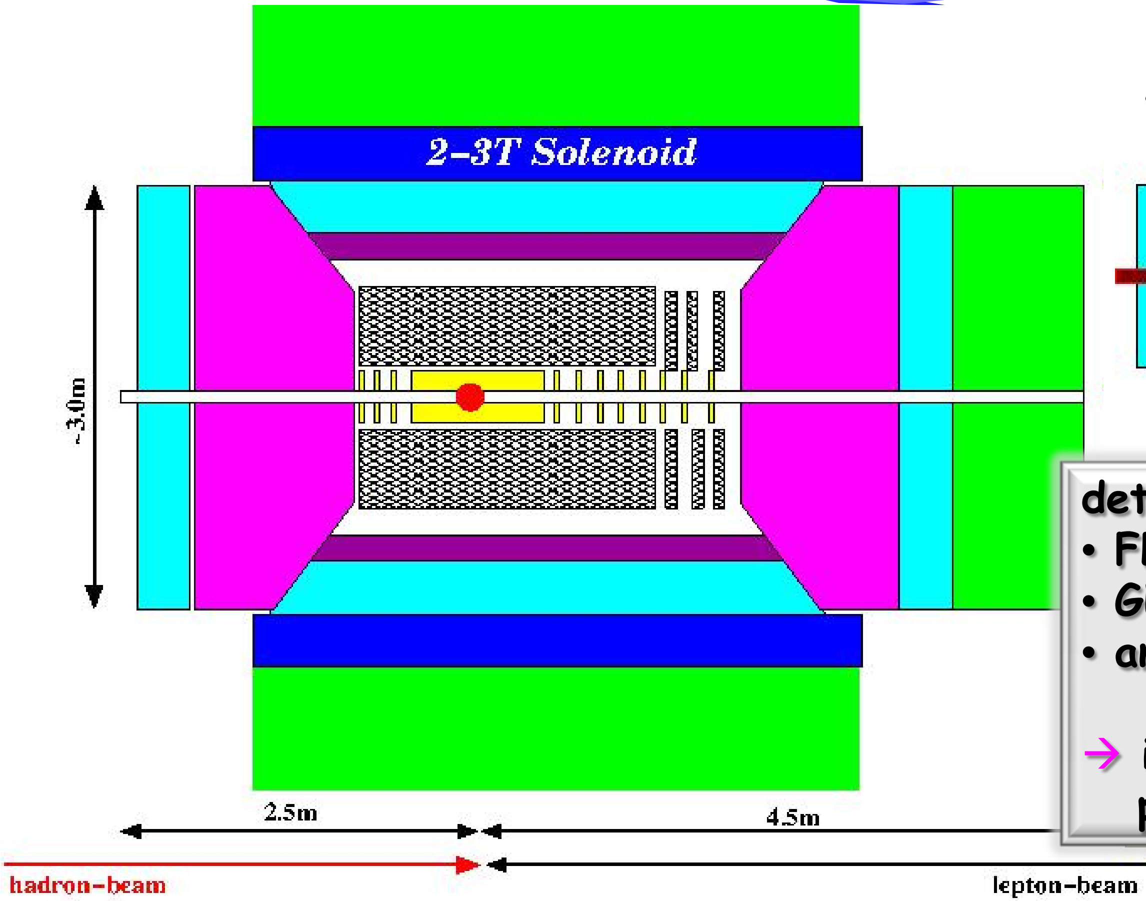
How to detect coherent/in-coherent events in ep/A ?

- **Rely on rapidity gap method**
  - simulations look good
    clear difference between DIS and diffractive events
  - high eff. high purity possible with gap alone
    - ~1% contamination
    - ~80% efficiency
  - depends critical on detector hermeticity
    - However, reduce the acceptance by 1 or 2 units of rapidity and these values drop significantly
  - improve further by veto on breakup of nuclei (DIS)

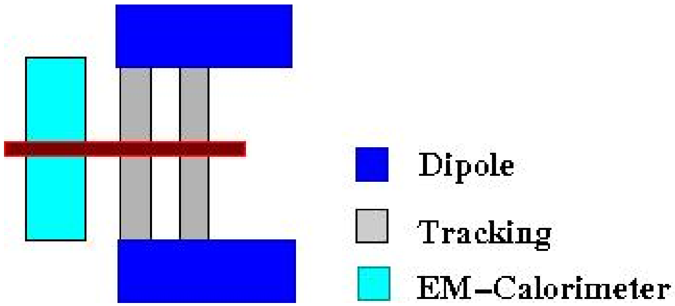
- **Very critical**
  - mandatory to detect nuclear fragments from breakup
  - n: Zero-Degree calorimeter
  - p, A frag: Forward Spectrometer



Emerging Detector Concept



Forward / Backward Spectrometers:



detector currently modeled in

- FLUKA
- GEANT-4
- and in a fast simulation
  - together with ZEUS and STAR

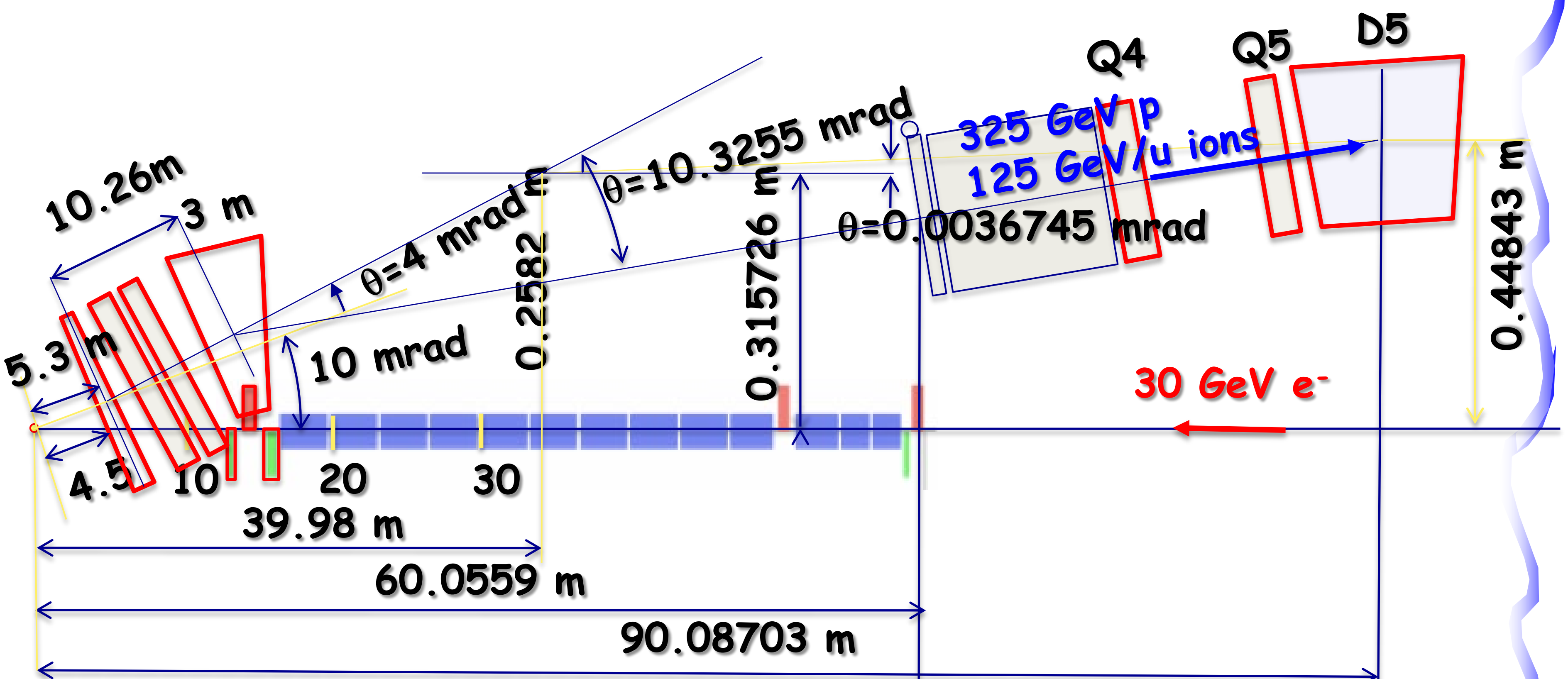
→ important for Detector R&D and physics capabilities

high acceptance $-5 < \eta < 5$ central detector
good PID (π,K,p and lepton) and vertex resolution (< 5μm)
tracking and calorimeter coverage the same → good momentum resolution, lepton PID
low material density → minimal multiple scattering and brems-strahlung
very forward electron and proton/neutron detection → maybe dipole spectrometers

Integration into Machine: IR-Design

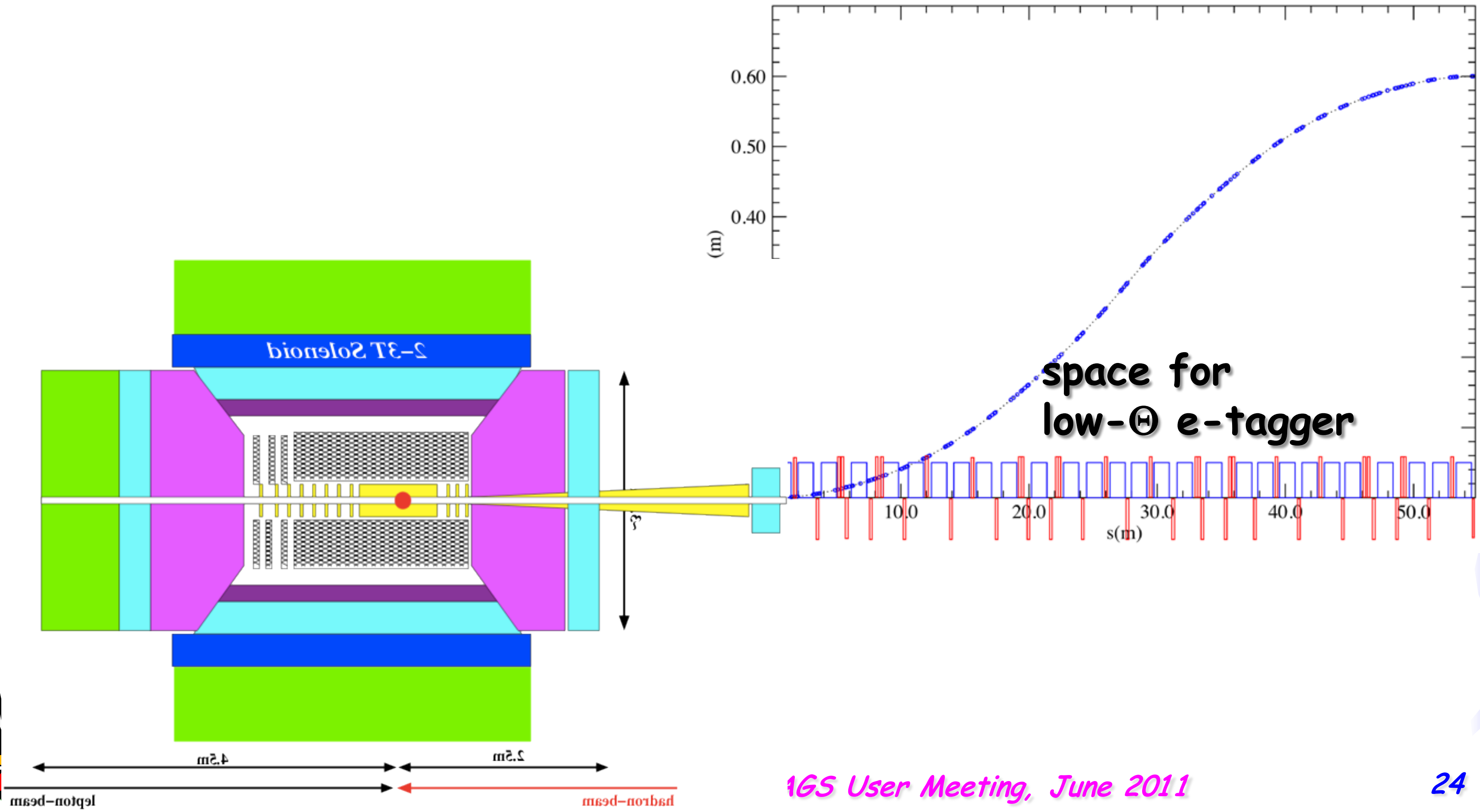
eRHIC - Geometry high-lumi IR with β*=5 cm, l*=4.5 m
and 10 mrad crossing angle → this is required for 10^{34} cm^{-2} s^{-1}

Outgoing Proton direction already far advanced



Integration into Machine: IR-Design

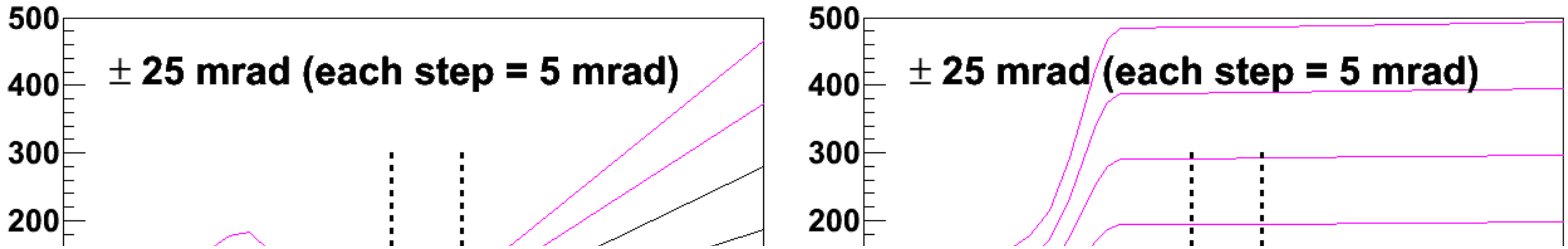
Outgoing electron direction currently under detailed design
→ detect low Q^2 scattered leptons
→ want to use the vertical bend to separate very low-Θ e' from beam-electrons
→ can make bend faster for outgoing beam → faster separation
→ for 0.1°<Θ<1° will add calorimetry after the main detector



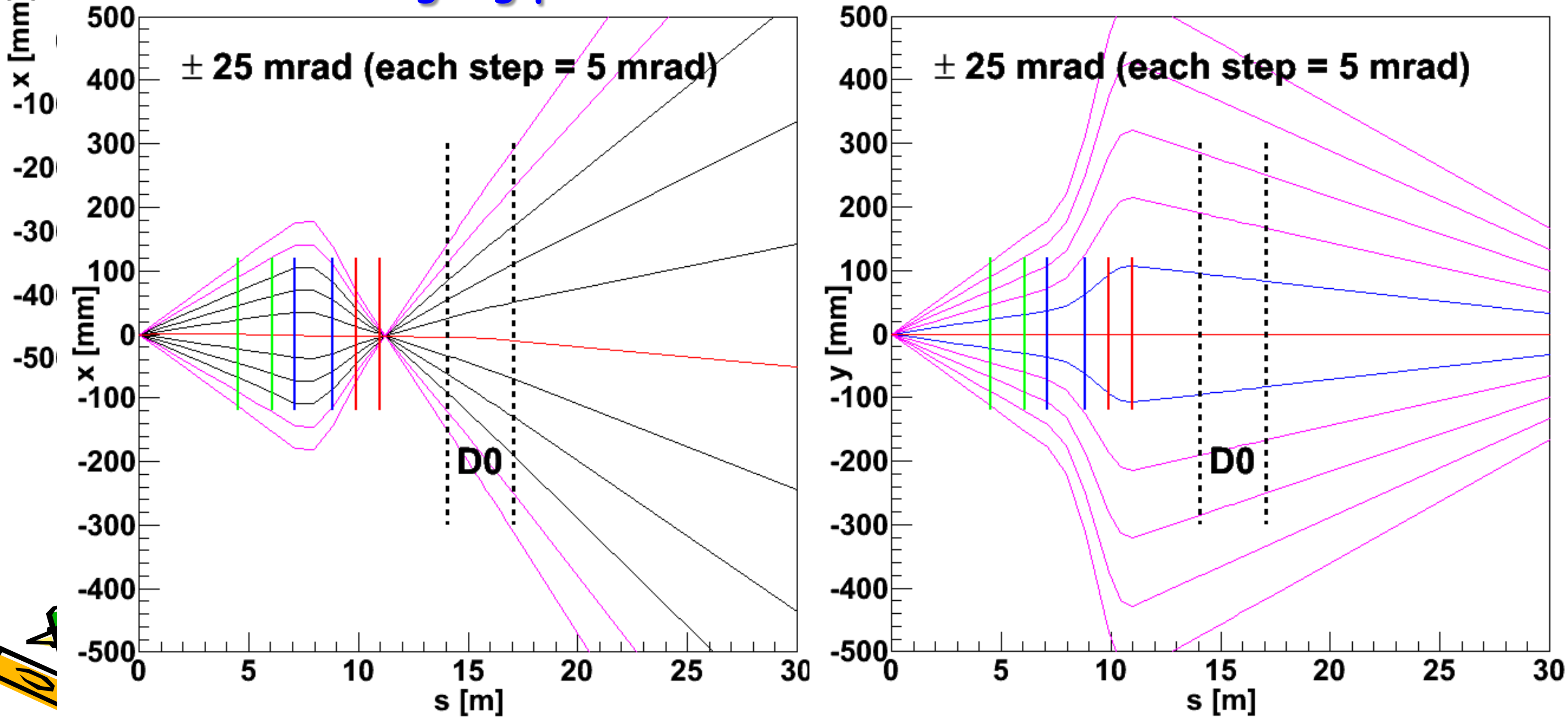
Latest beam optics for outgoing nominal protons

studies by JH

Beam transport using Hector:

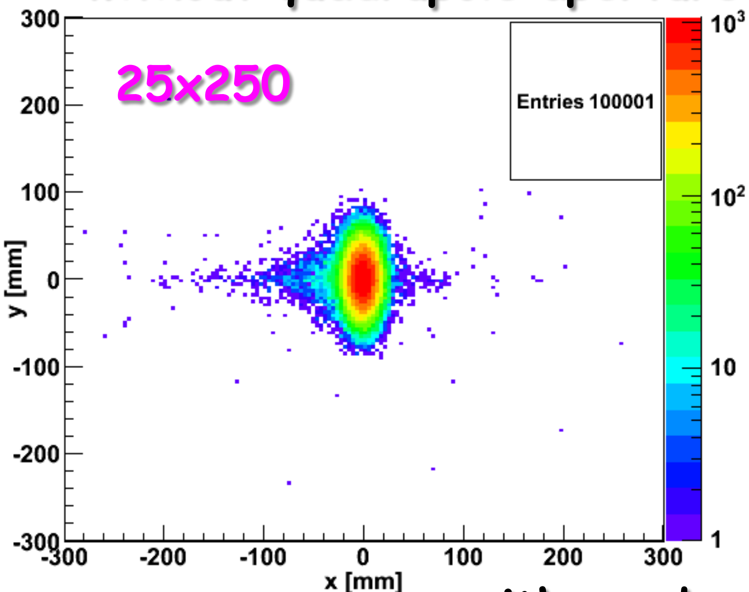


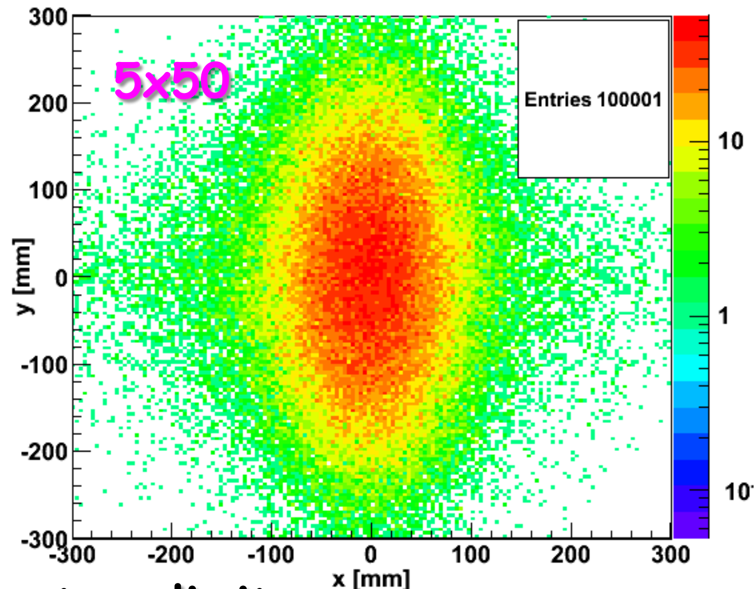
outgoing protons with 20% momentum loss



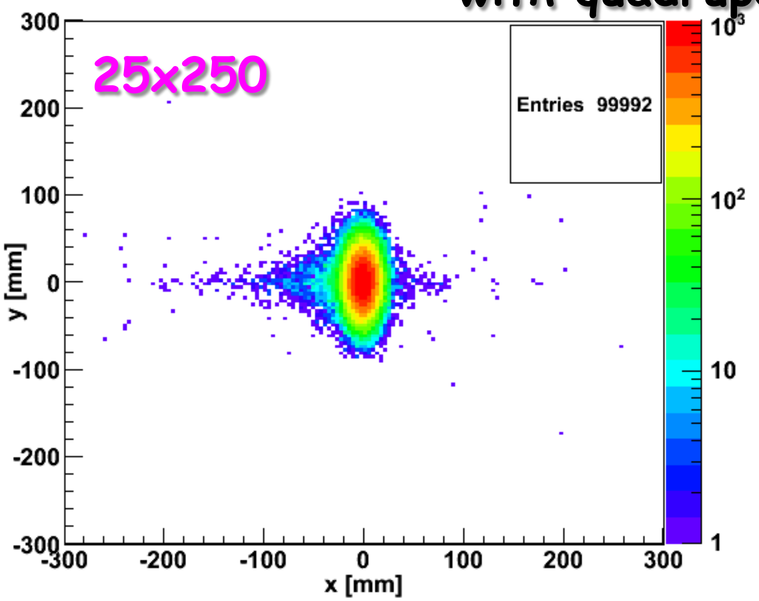
proton distribution in y vs x at s=20 m

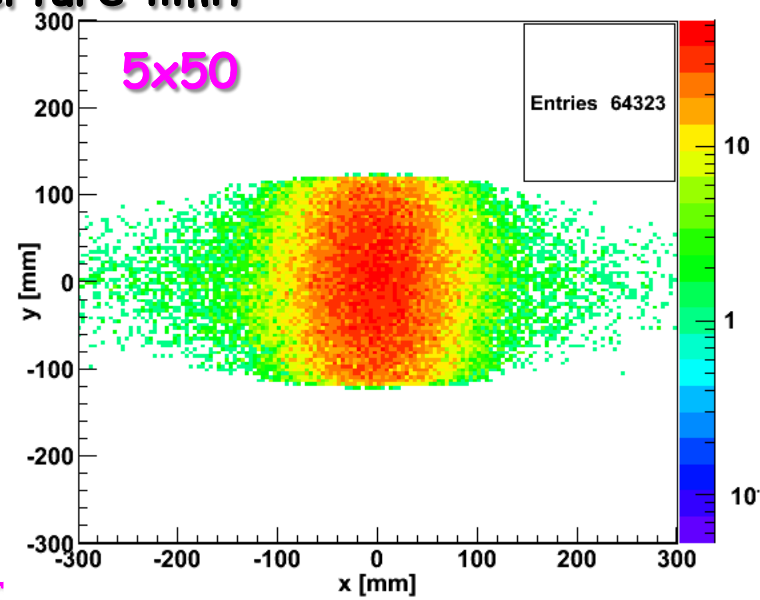
without quadrupole aperture limit



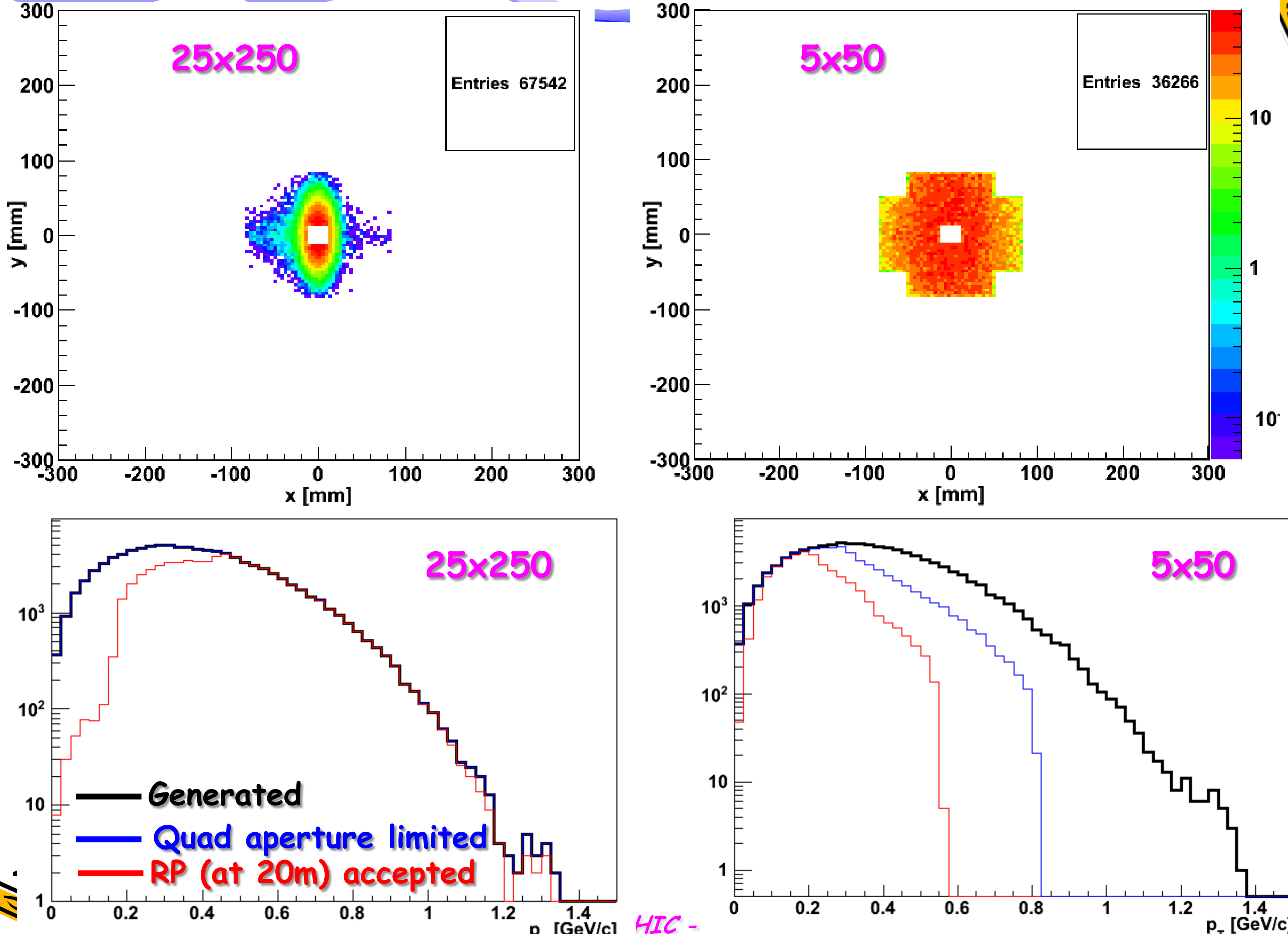


with quadrupole aperture limit

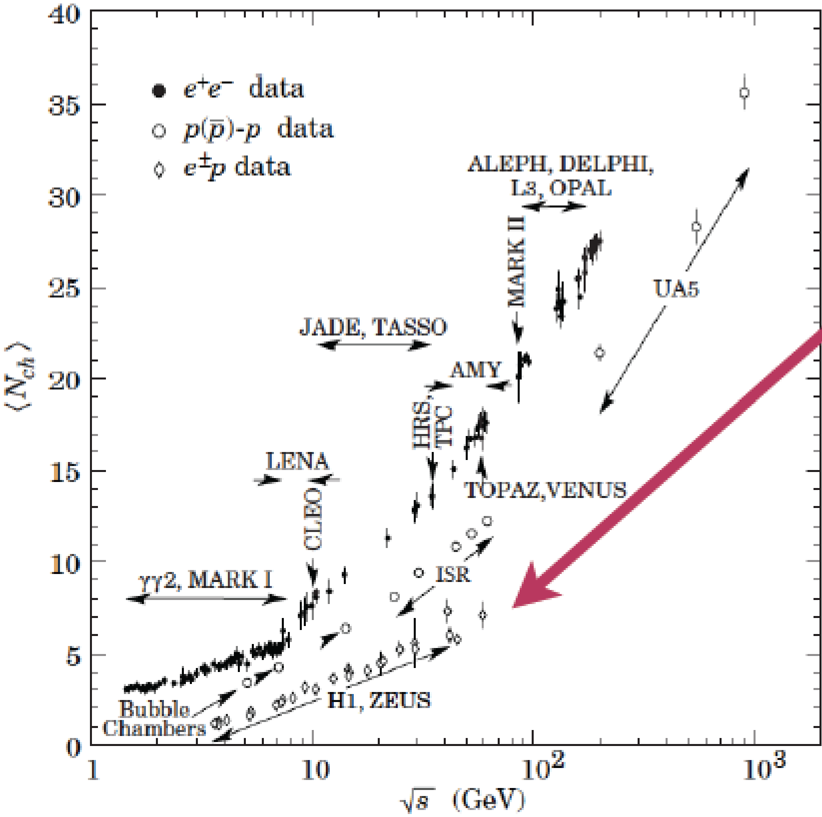




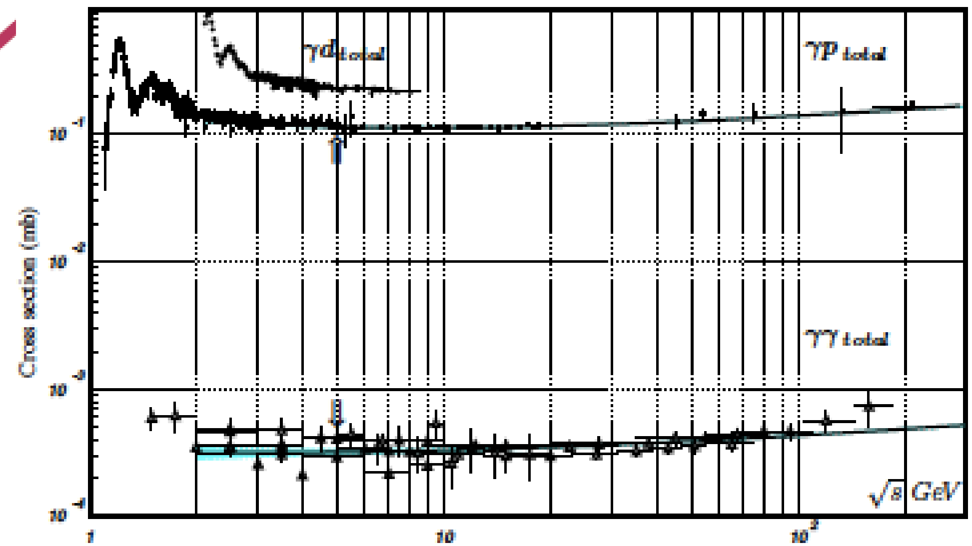
Accepted in "Roman Pot" (example) at s=20m



Some thought about rates



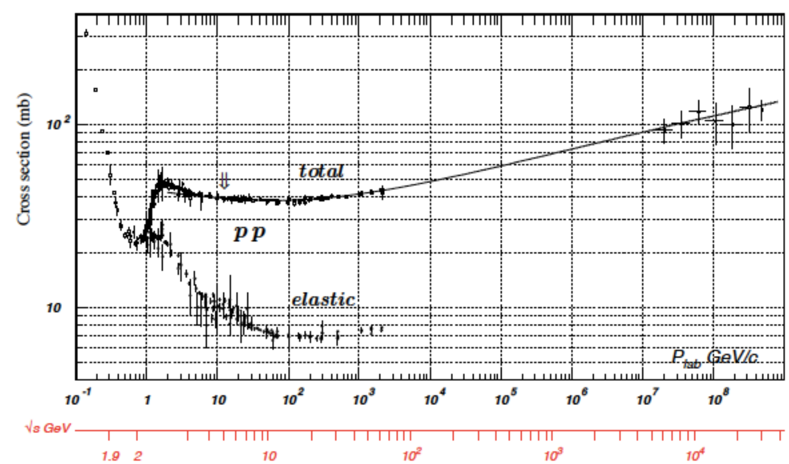
low multiplicity
4-6 $\sqrt{s}$ = 40-65 GeV
N_{ch} (ep) ~ N_{ch} (eA) < N_{ch}(pA)
→ no occupancy problem



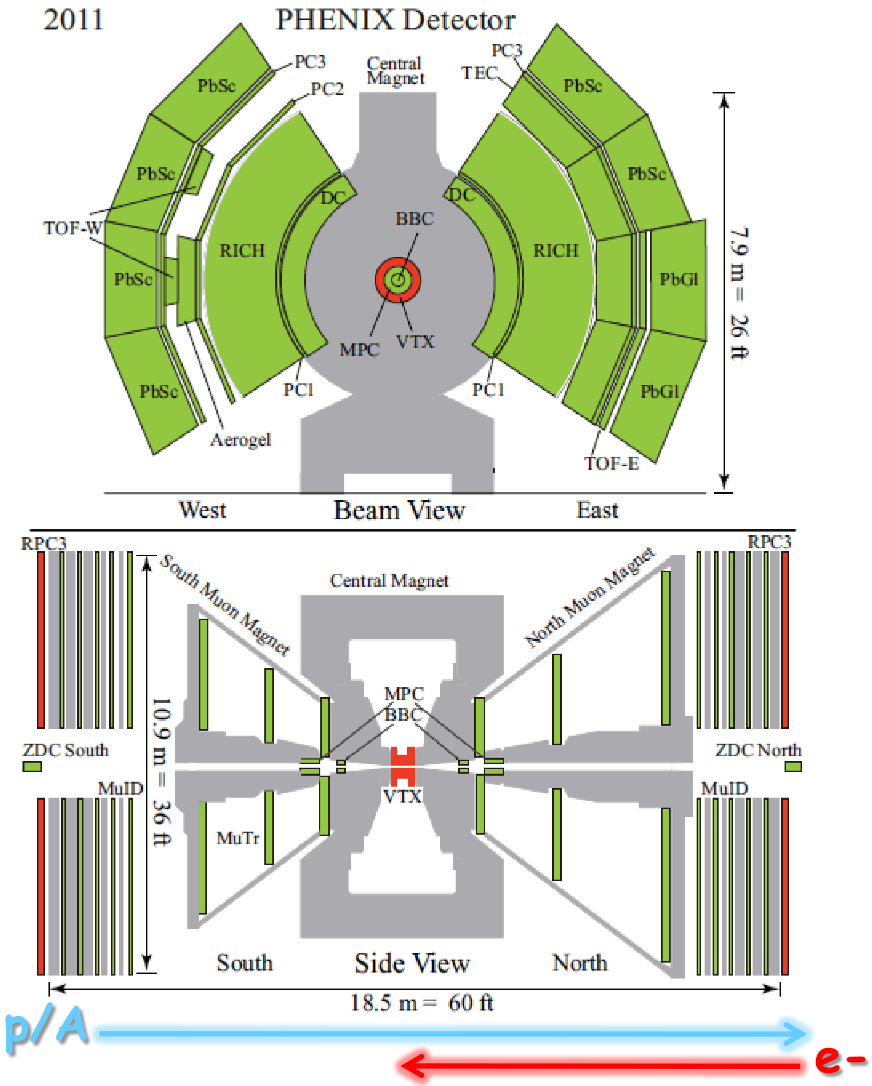
Cross section: $\sigma_{ep} < \sigma_{\gamma^* p} < \sigma_{\gamma p}$

Pythia σ_{ep}: 0.030 – 0.060 mb
Luminosity: 10^{34} cm^{-1} s^{-1} = 10^7 mb^{-1} s^{-1}

Interaction rate:
300 -600 kHz



What can PHENIX and STAR do?



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

- scattered lepton can only be detected at mid-rapidity $|\eta| < 0.35$ very high Q^2
- no acceptance for TMD/GPD physics
- small acceptance for semi-inclusive physics

PHENIX:

in its current incarnation it is not suited for eRHIC physics

The New PheniX Spectrometer

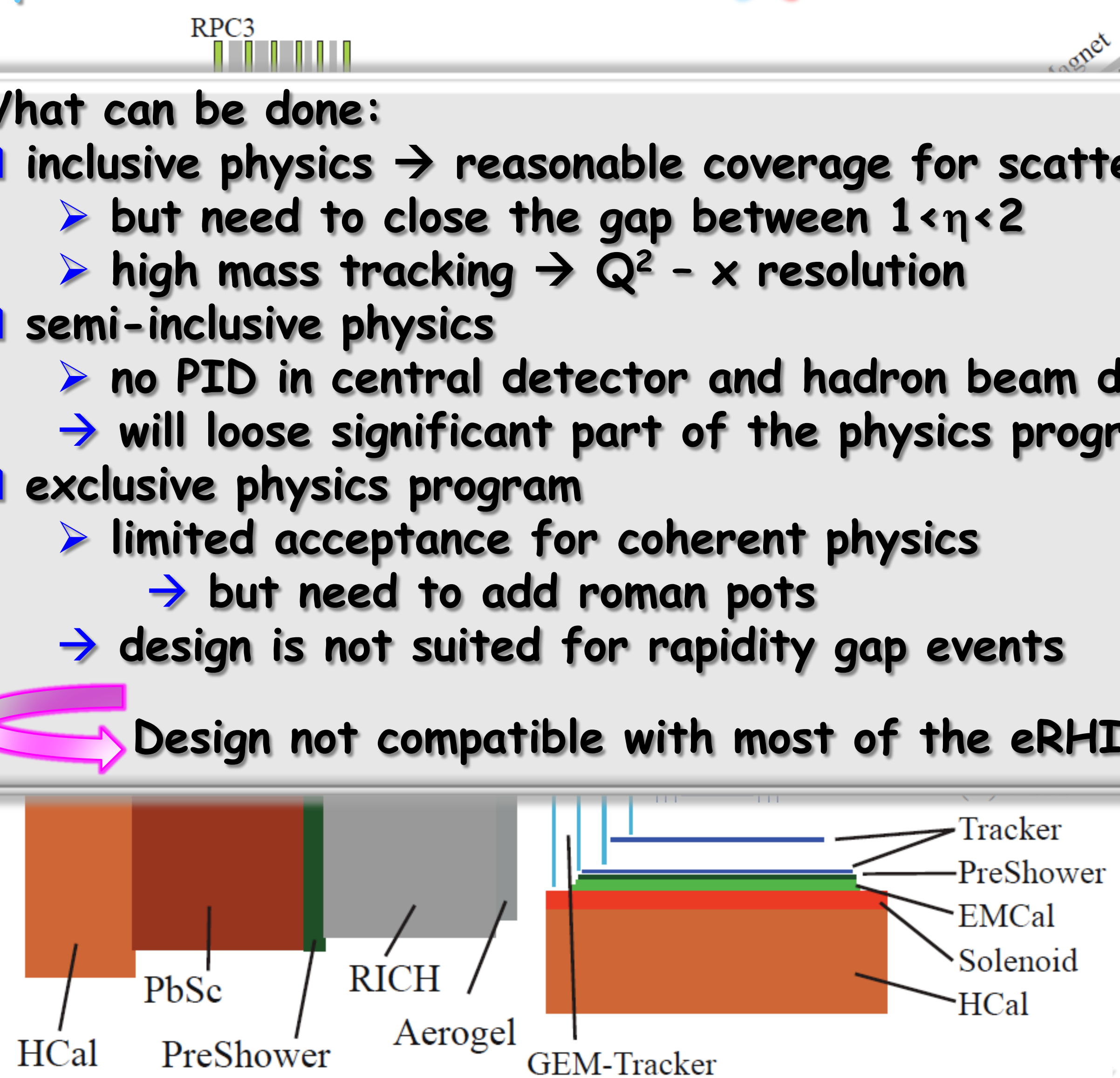
Design completely driven by AA, dA and pp physics program

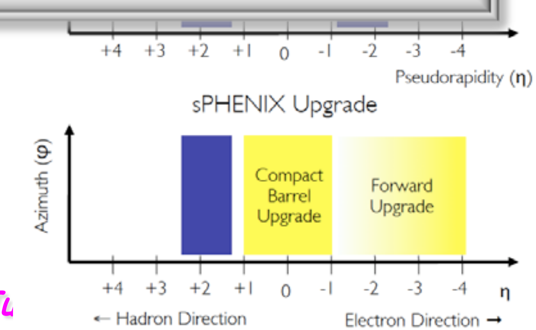
p/A → ← e-

What can be done:

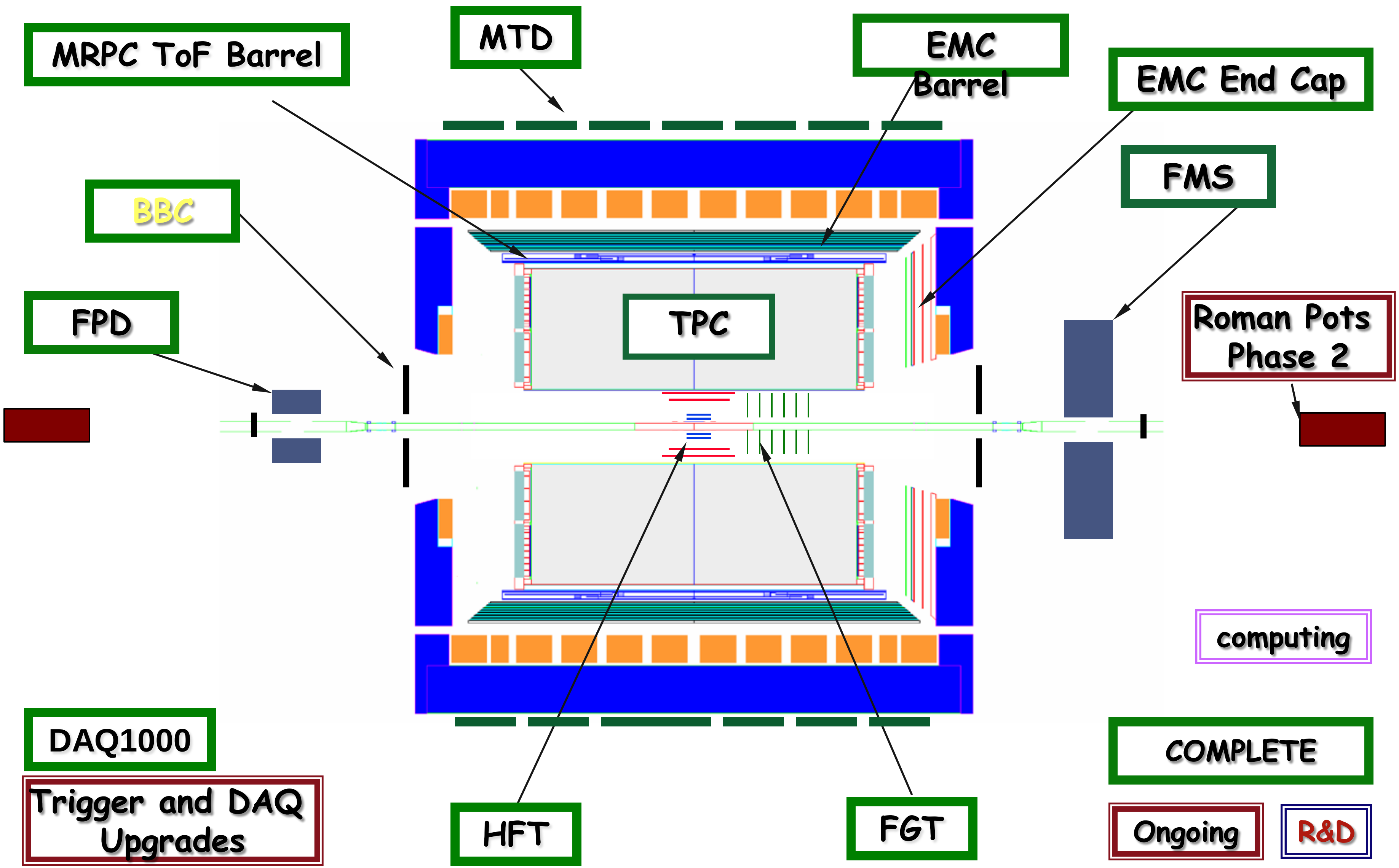
- inclusive physics → reasonable coverage for scattered lepton
  - but need to close the gap between $1<\eta<2$
  - high mass tracking → Q^2 – x resolution
- semi-inclusive physics
  - no PID in central detector and hadron beam direction
  - → will loose significant part of the physics program
- exclusive physics program
  - limited acceptance for coherent physics
    - → but need to add roman pots
  - → design is not suited for rapidity gap events

Design not compatible with most of the eRHIC physics program





STAR Experiment as of 2014

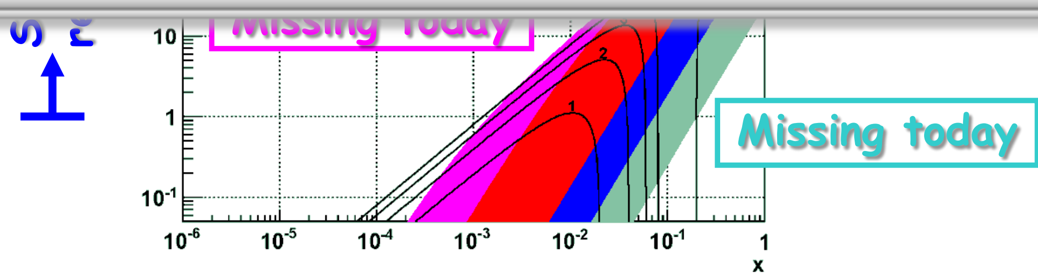


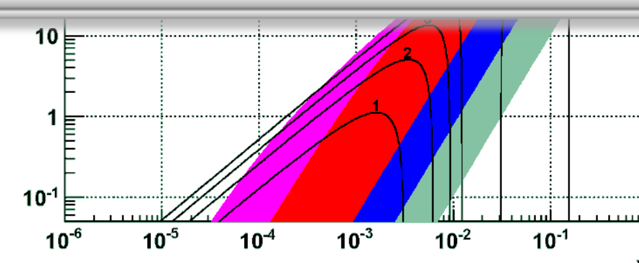
eRHIC phase 1: kinematic range

5 GeV e + 50 GeV/nucleon

5 GeV e + 325 GeV/nucleon

- Inclusive physics
  - "Forward" (-2.5 <~ η < -1) electron acceptance essential to span deep-inelastic (DIS) regime
- semi-inclusive physics
  - need to investigate how well PID coverage is matched to SIDIS kinematics
  - Both backward and forward hadron coverage valuable for SIDIS
- exclusive physics program
  - Need forward proton and expanded photon detection (→DVCS)
    - Roman pots (also valuable for spectator proton tagging in e+^{3}He)
  - EM calorimetry for -4 < η < -1
  - rapidity gap event acceptance needs to be checked





Evolving from STAR into eSTAR

proton nucleus/electron

Lepton Beam Direction:

ToF: π, *K* identification, t_0, electron

ECal: electrons and photons

GCT:
a compact tracker with enhanced electron capability
Combine high-threshold (gas) Cherenkov with TPC(-like) tracking

Hadron Beam Direction:

optimized for p+A and transverse spin physics

- Charged-particle tracking
- *e*/*h* and γ/π^0 discrimination
- Baryon/meson separation

- What is the momentum resolution at forward rapidity (B=0.5T too low?)

Design closer to eRHIC physics program needs
But: need to simulate golden measurements to understand the details

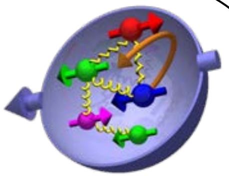
EIC Generic Detector R&D Panel:
GCT: LOI toward multi-institution R&D effort
HCal: R&D proposal

Outlook and Summary

- Challenges for both eSTAR and ePHENIX
  - IR design needs to be adopted → L* → impact on lumi
  - how can the 10 mrad crossing angle be integrated
- what is the minimum physics program ePHENIX and eSTAR need to be able to cover, to be an interesting option for phase I of eRHIC
- Dedicated detector is essential to do the full eRHIC physics program
  - essential to form a eRHIC community with new groups
- IR and detector design need to go hand in hand
- what is the cost for a new detector? How can it be staged?
  - reasonable technology choices → price
- need to start quantitative detector simulation
  - simulate golden experiments in detail
  - address question: what can a dedicated ep/eA detector do in pp, AA, pA collisions

Most Compelling Physics Questions

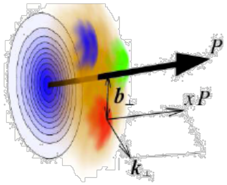
spin physics



- what is the polarization of gluons at small x where they are most abundant
- what is the flavor decomposition of the polarized sea depending on x

determine quark and gluon contributions to the proton spin at last

imaging

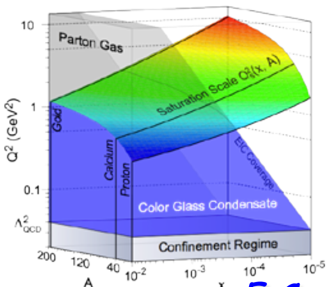


- what is the spatial distribution of quarks and gluons in nucleons/nuclei
- understand deep aspects of gauge theories revealed by k_T dep. distr'n

possible window to orbital angular momentum

physics of strong color fields

quantitatively probe the universality of strong color fields in AA, pA, and eA



- understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation
- how do hard probes in eA interact with the medium

Optimizing STAR for e+p and e+A collisions from 5+50 to 5+325 GeV

- Inclusive scattering over the entire deep-inelastic region
  - Key measurements
    - F_L in e+p and e+A: direct measure of gluon densities in nucleons and nuclei
    - g_1 in e+p and e+^{3}He: nucleon spin structure
    - F_2^A/F_2^d: parton distributions in nuclei (including gluons via Q^2 evolution)
  - Need electron detection, ID, and triggering over -2.5 <~ η < -1
    - Combined mini-TPC/threshold gas Cherekov detector
- Semi-inclusive deep-inelastic scattering over a broad (x,Q^2) domain
  - Key measurements
    - Flavor-separated helicity distributions, including strangeness
    - Collins, Sivers, Boer-Mulders, and other transverse spin distributions
    - Flavor-separated parton distributions in nuclei, including strangeness
    - Parton energy loss in cold nuclear matter
  - Need hadron detection and identification beyond the TPC/EEMC
    - Extend TOF to cover -2 < η < -1
    - GEM disks (from forward instrumentation upgrade) plus hadronic calorimetry in the region 2 < η < 3
- Deeply-virtual Compton scattering
  - Key measurement
    - GPDs
  - Need forward proton and expanded photon detection
    - Roman pots (also valuable for spectator proton tagging in e+^{3}He)
    - EM calorimetry for -4 < η < -1