Center for Frontiers in Nuclear Science

Dark Photons at the EIC

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Stony Brook University

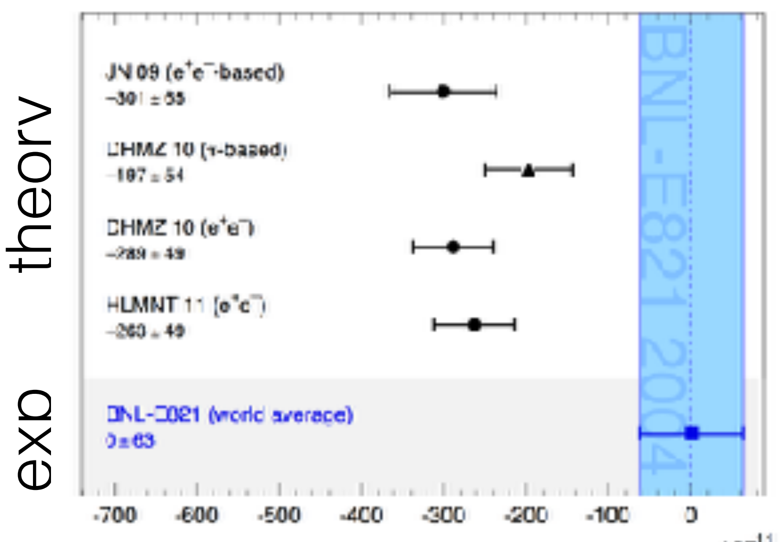
Outline

- Motivation
- Channels
- Kinematics
- Monte Carlo Studies
- Ongoing Work

Why a Dark Photon?

- Dark Matter Decay Mechanism?
- Anomalies:

Muon g-2



K.A. Olive et al. (PDG) Chin.Phys.C,38,090001 (2014).

X17 in 4He and 8Be

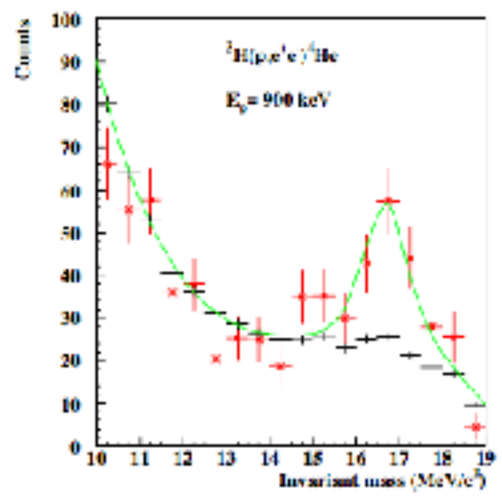
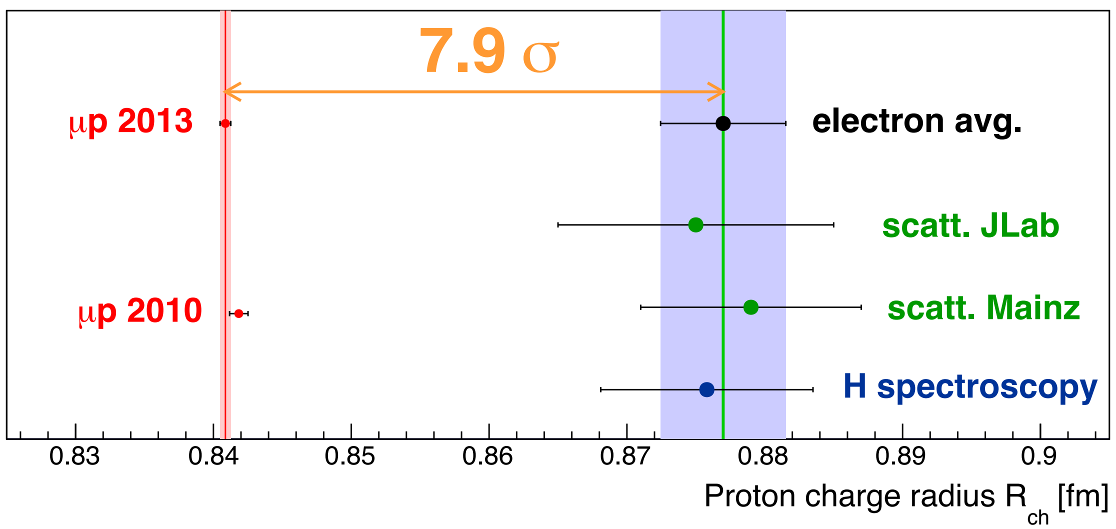


FIG. 3. Invariant mass distribution derived for the 20.49 MeV transition in ⁴He.

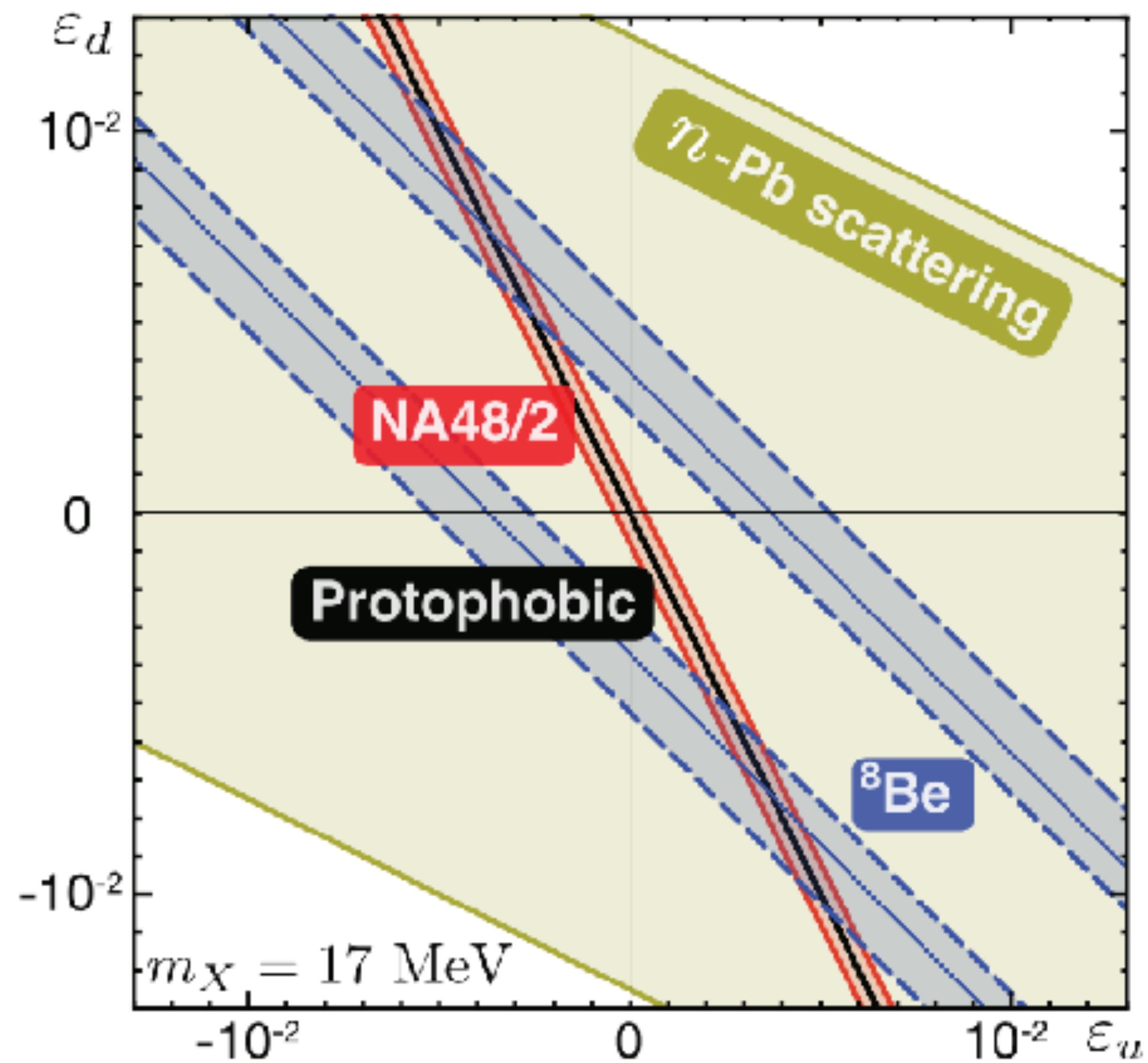
Proton radius puzzle



- Because we can write it: $$L \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

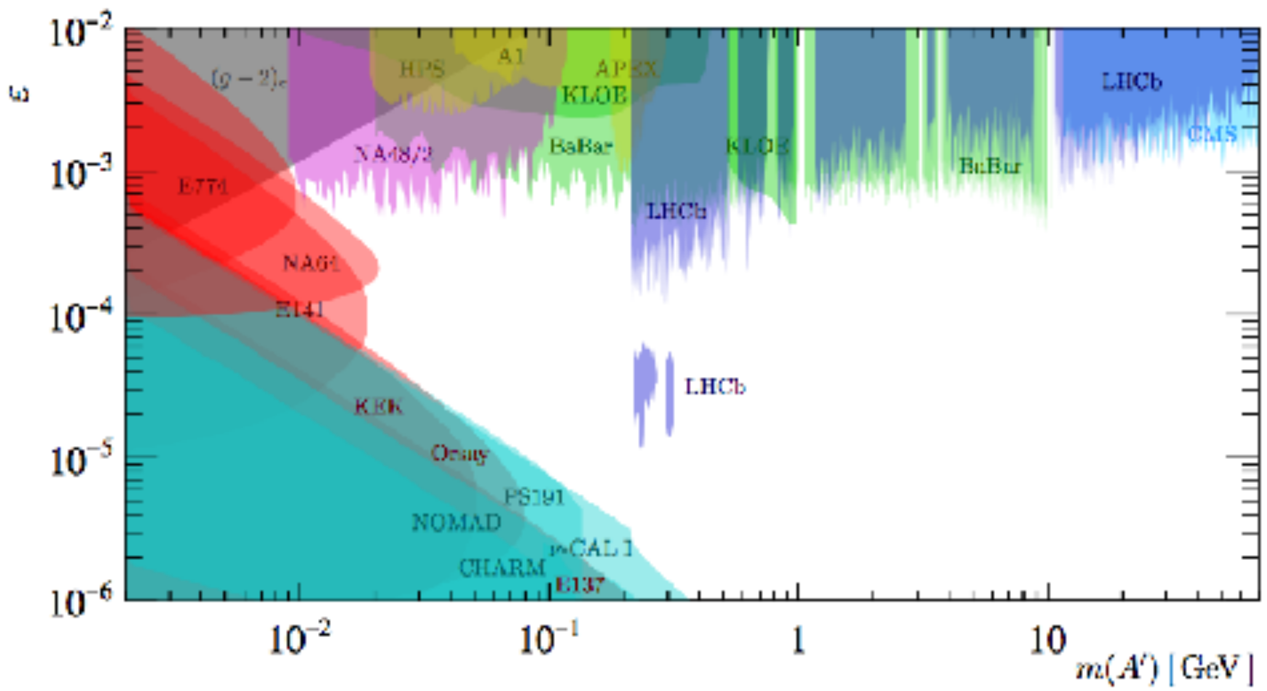
8Be/4He Anomalies

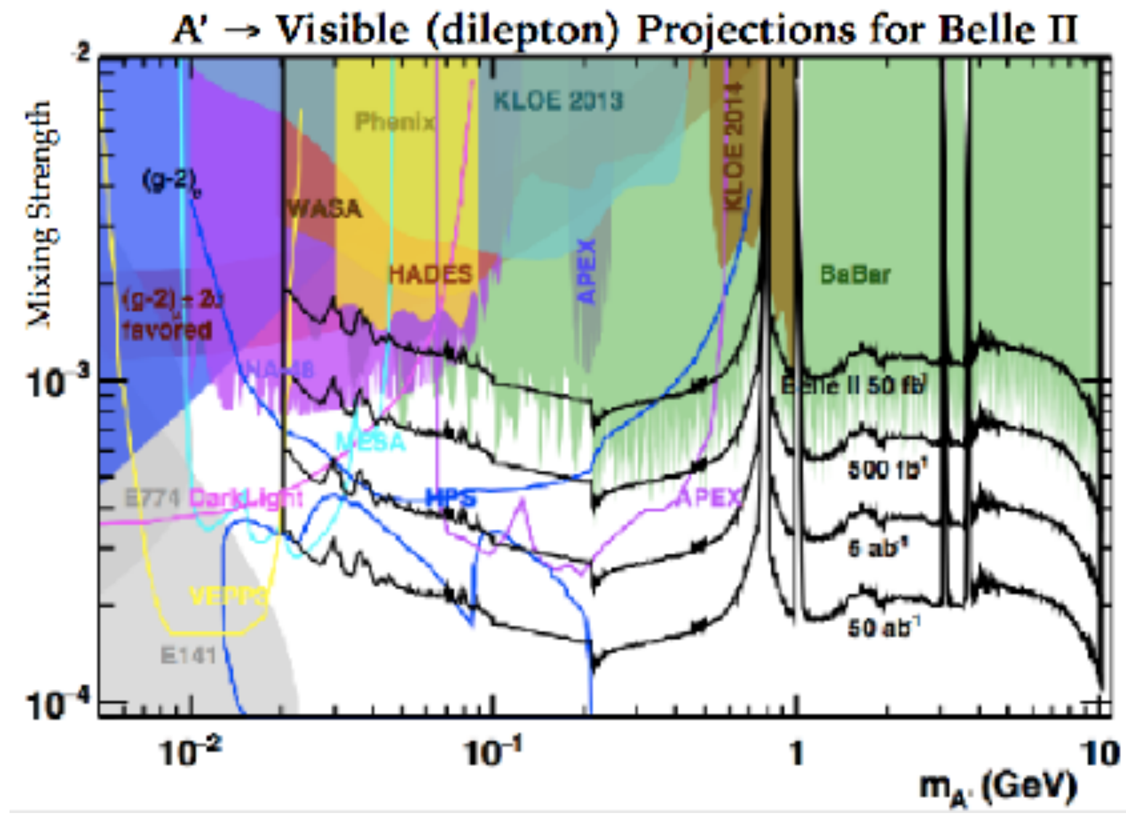
- Signal conflicts with simple charge-coupling model
- Allow particles to have independent couplings:
  - Simple Lagrangian term modified
  - Pion couplings suppressed
- Ratio of proton and neutron couplings no less 'natural' than for Z



arXiv:1604.07411

Existing Limits and Projections

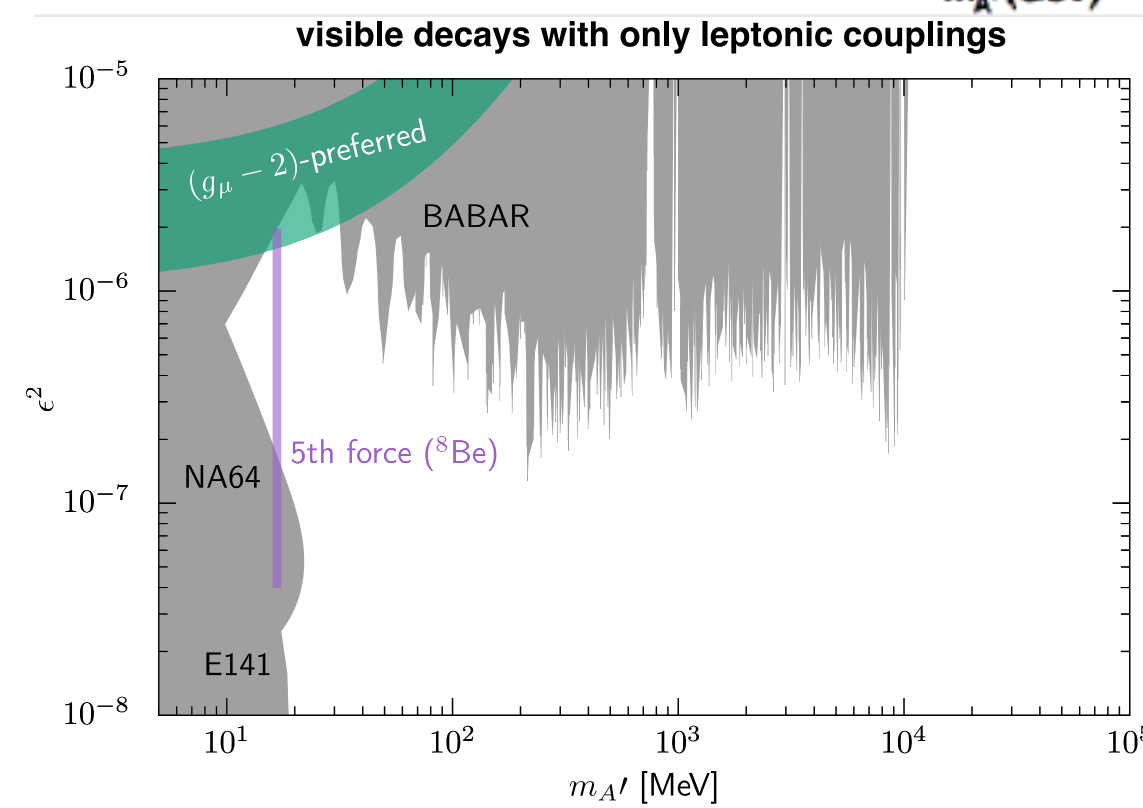




- In simple Kinetic Mixing Model:

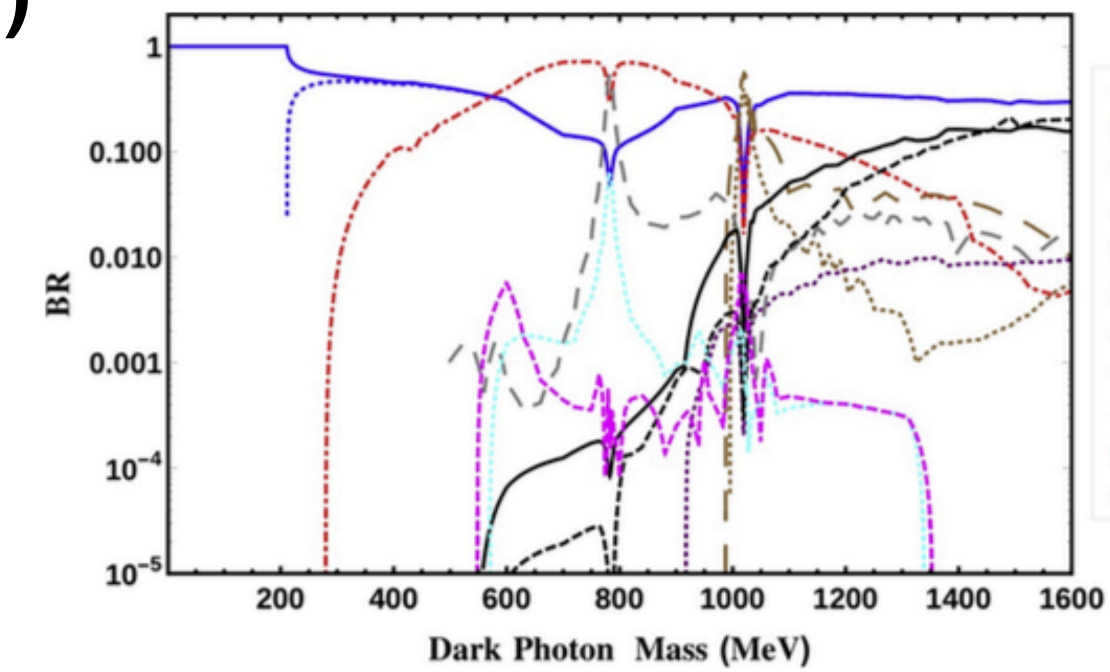
$$\alpha_D = \epsilon^2 \alpha_{EM}$$

- Want to explore the parameter space with purely leptonic couplings as well!
- (But keep the notation and name.)

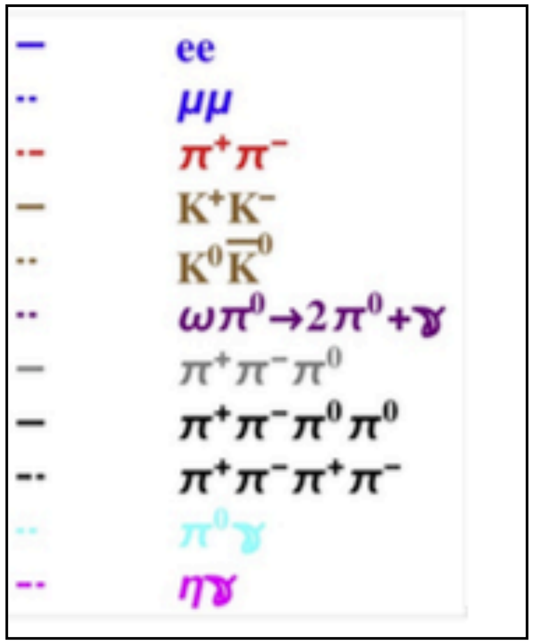


A' Channels

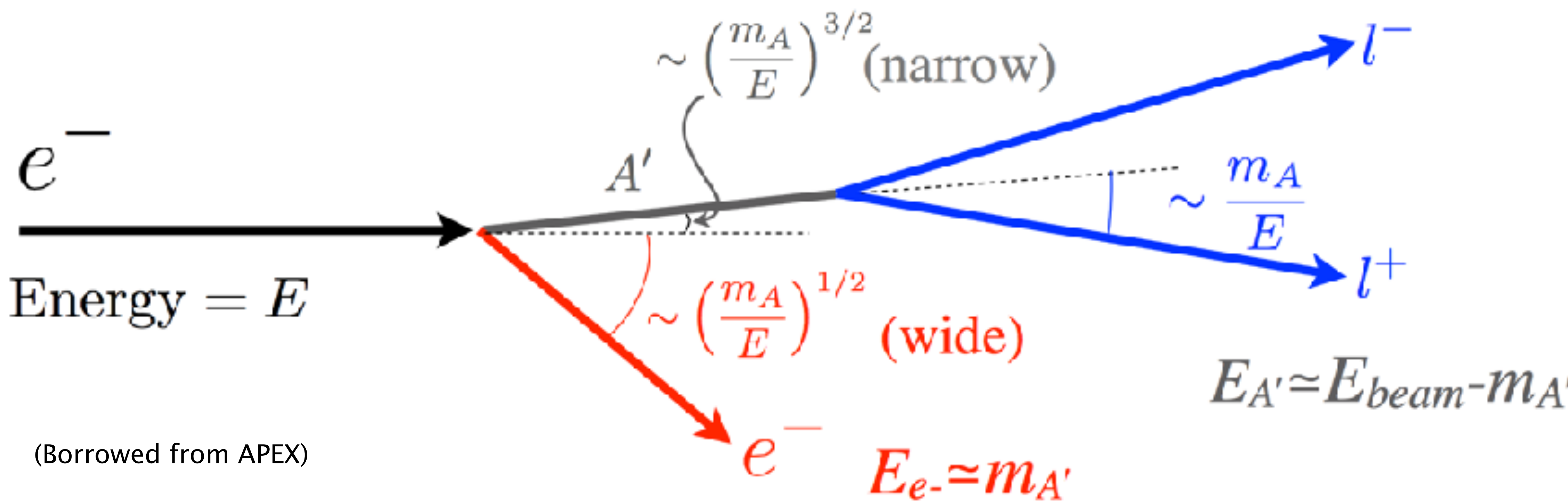
- Production:
  - **ISR (A'-strahlung from e- beam) ($m_A < \sqrt{s}$))**
  - Decay (on-shell A' replaces photon in decay chain) (m_A < parent)
- Final States:
  - **e+ e- pair ($m_A > 2m_e$)**
  - μ+ μ- pair ($m_A > 2m_\mu$, cleaner signal)
  - hadronic pair(s) (messier, harder)
  - invisible (much harder)
  - displaced vertices (cleaner, much harder)



Branching to:



Fixed-Target Kinematics

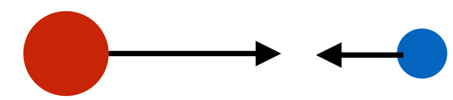


(Borrowed from APEX)

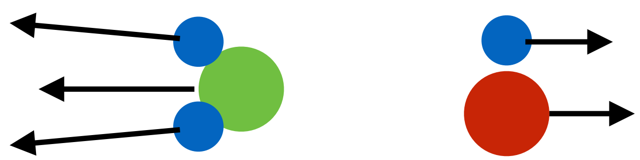
- A' carries large fraction of beam energy -- at large boost, decay products go forward.
- Recoil proton carries little energy

EIC Kinematics

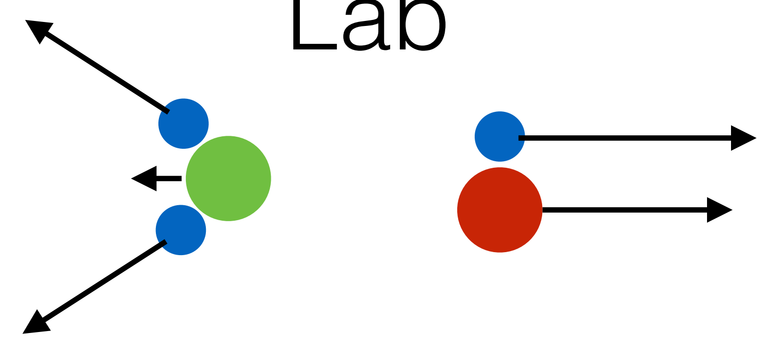
- at 20GeV x 250GeV, CM Boost substantially opens the angle between decay leptons:



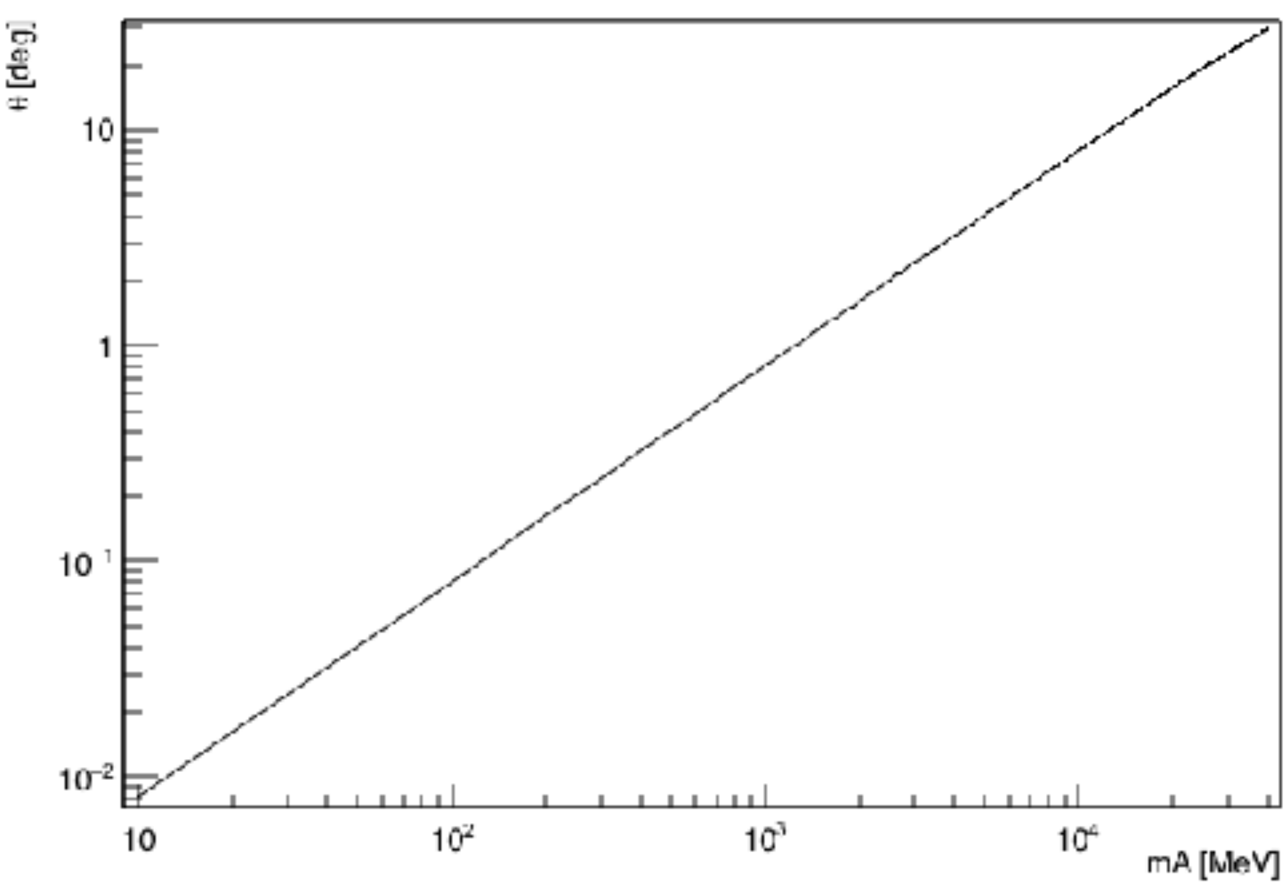
CM



Lab



CM frame symmetric θ for A' decay



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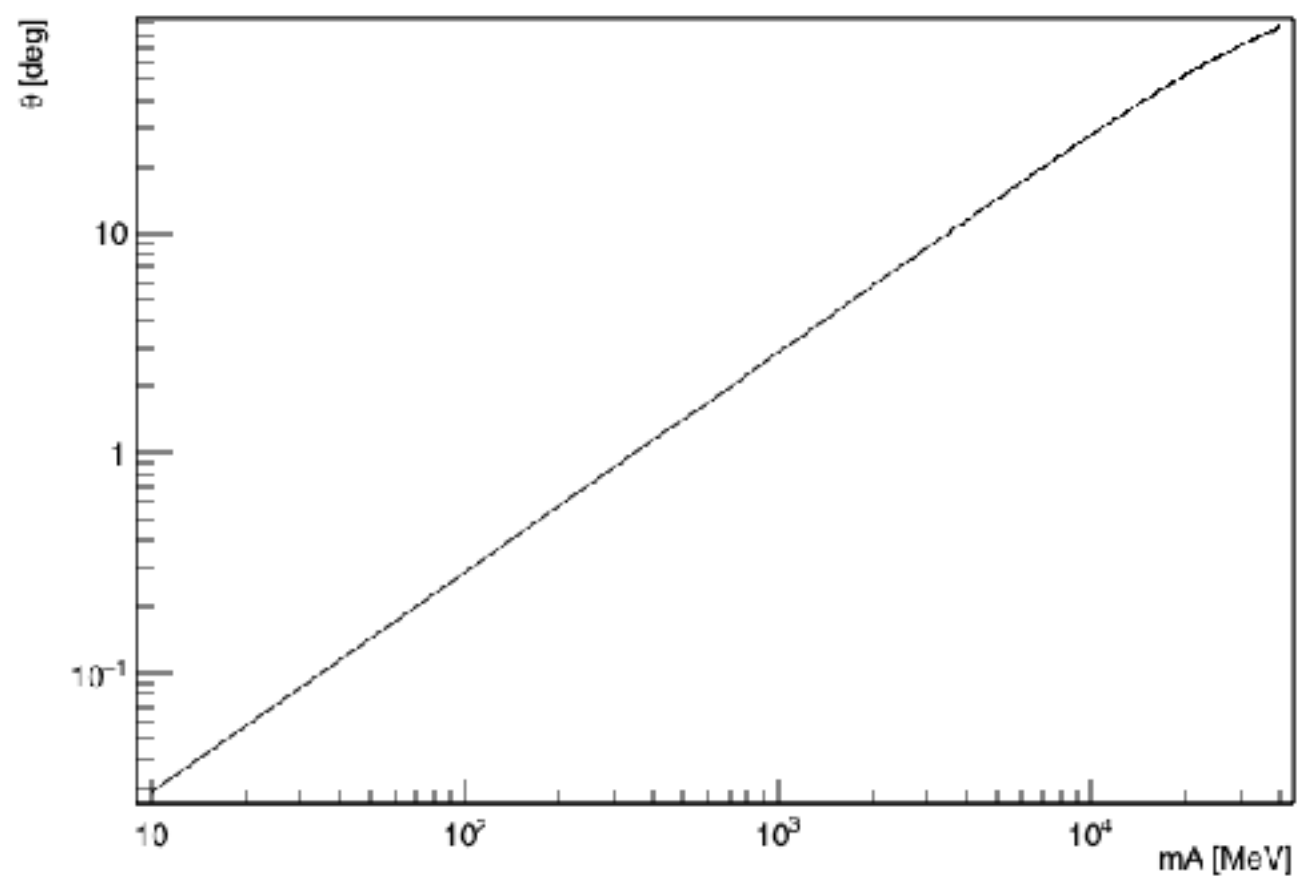
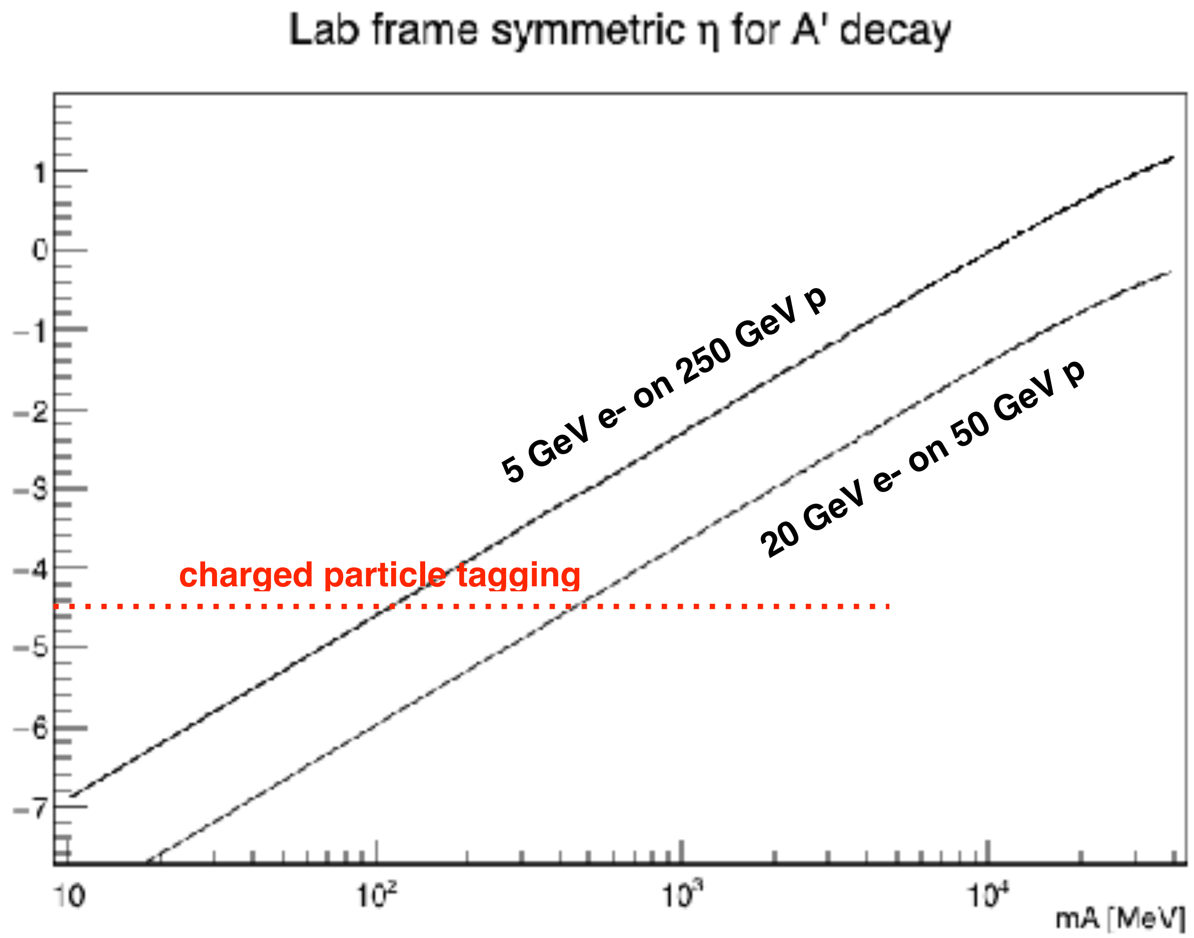
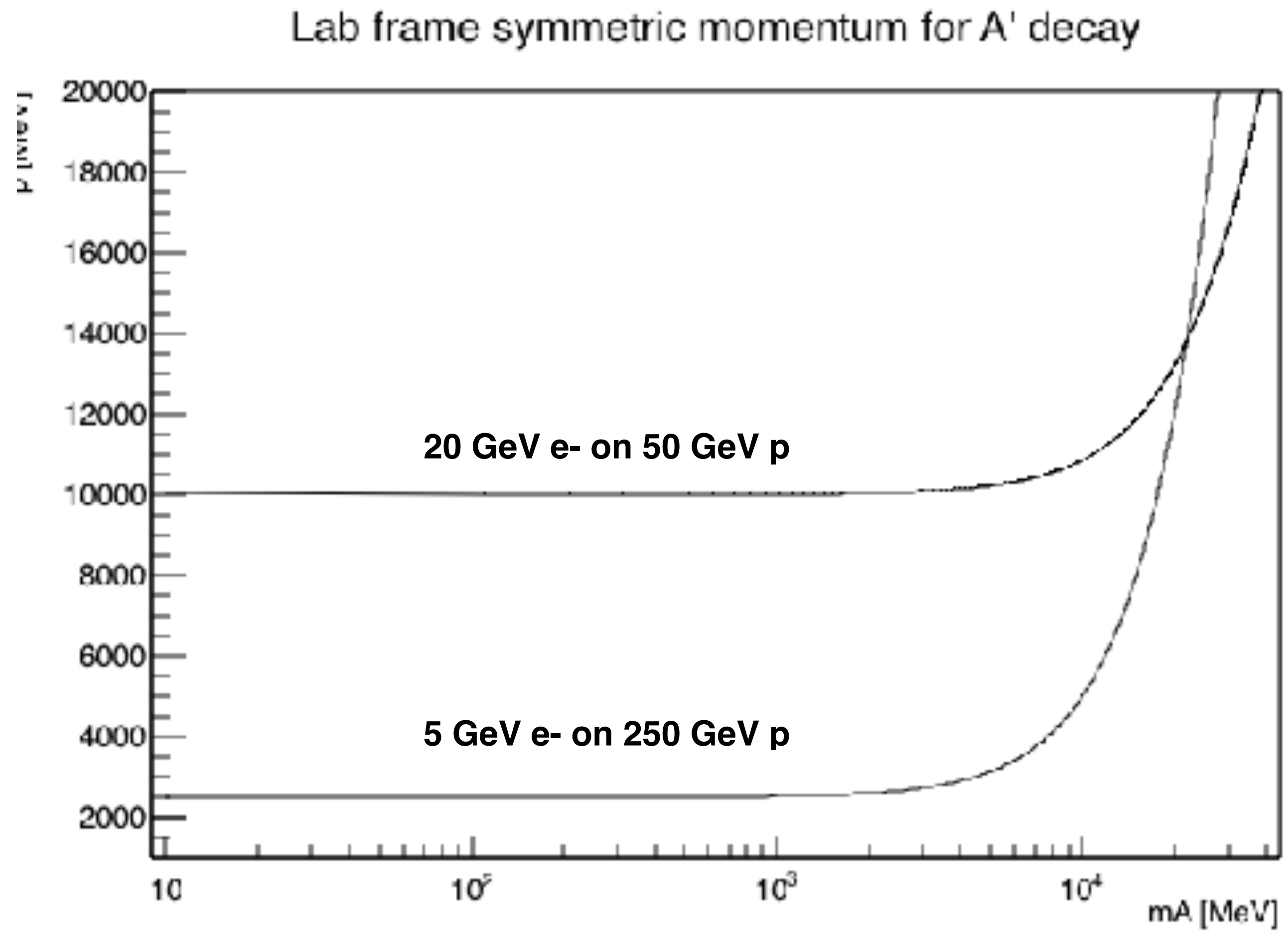
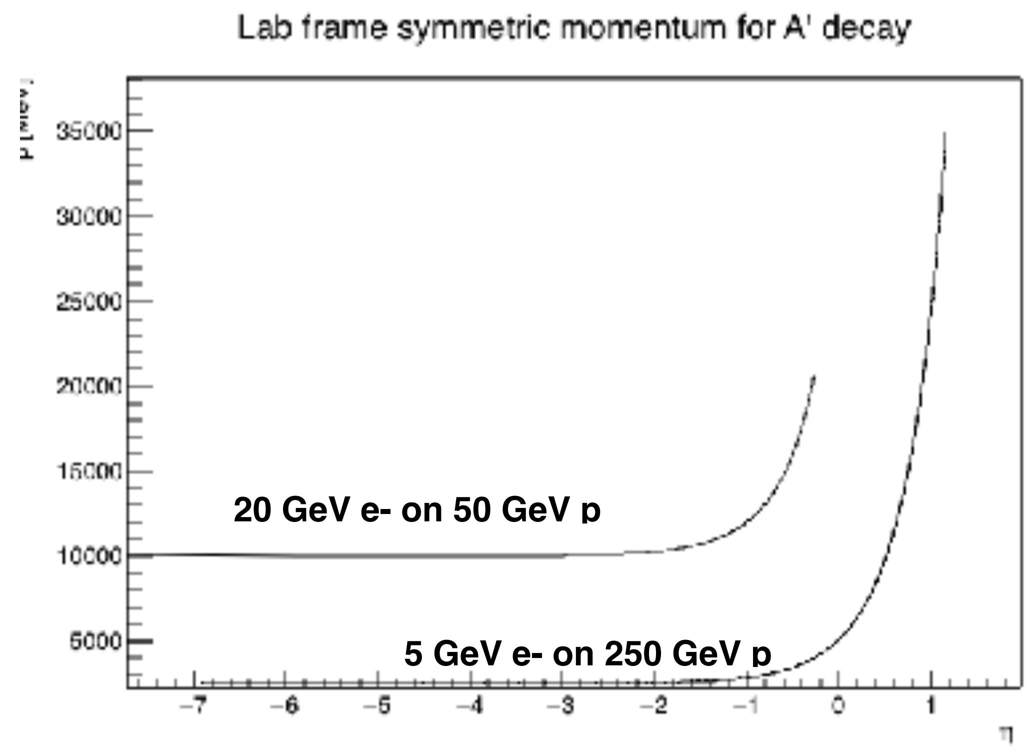


EIC Kinematics





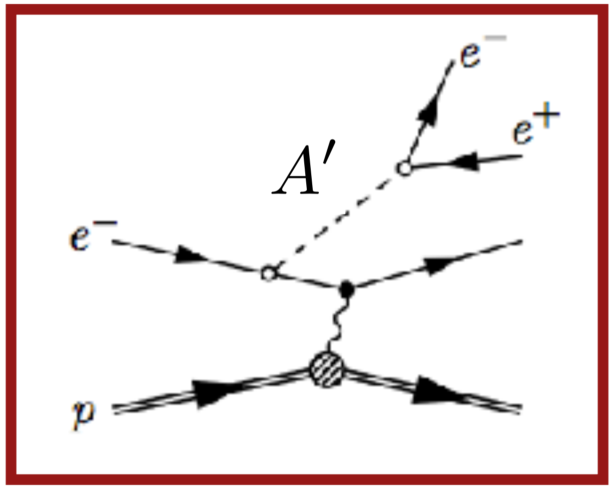


- For ep, handbook detector reaches down to O(100MeV)

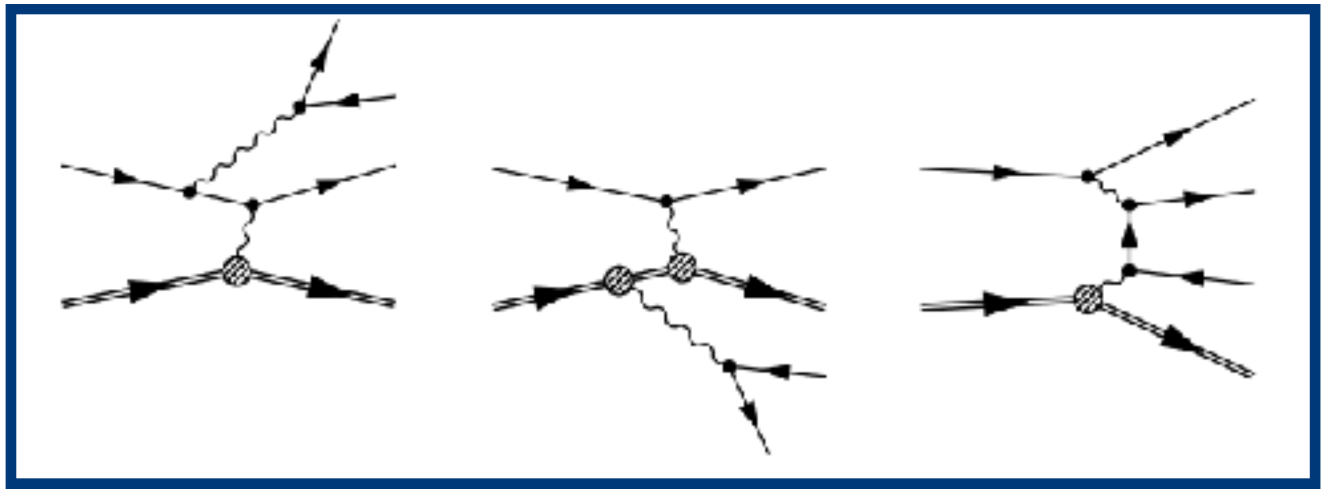
Generating Events

- Madgraph4.4 configuration:
  - custom (A',e,e) vertex
  - *ignores proton structure - xs must be modified for FF, but reaction prefers low Q^2*
  - ~10TeV e- on fixed proton target, boost to lab frame after generation (20x250 setting)
  - Gen-level cut at $1° < \theta_e < 179°$ wrt e- direction in lab ($0.001° < \theta_e < 30°$ wrt e- beam in p-rest)
  - generate leading order:
    Signal: ep->epA'->epee for various m_A
    Irred. Bg: ep->epγ*->epee

A' Signal

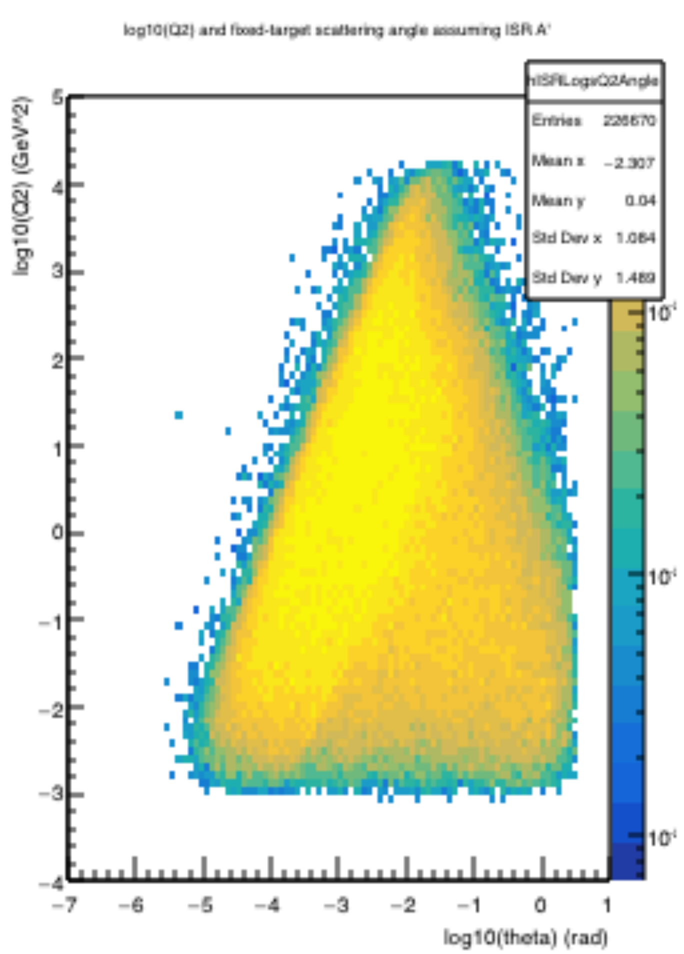


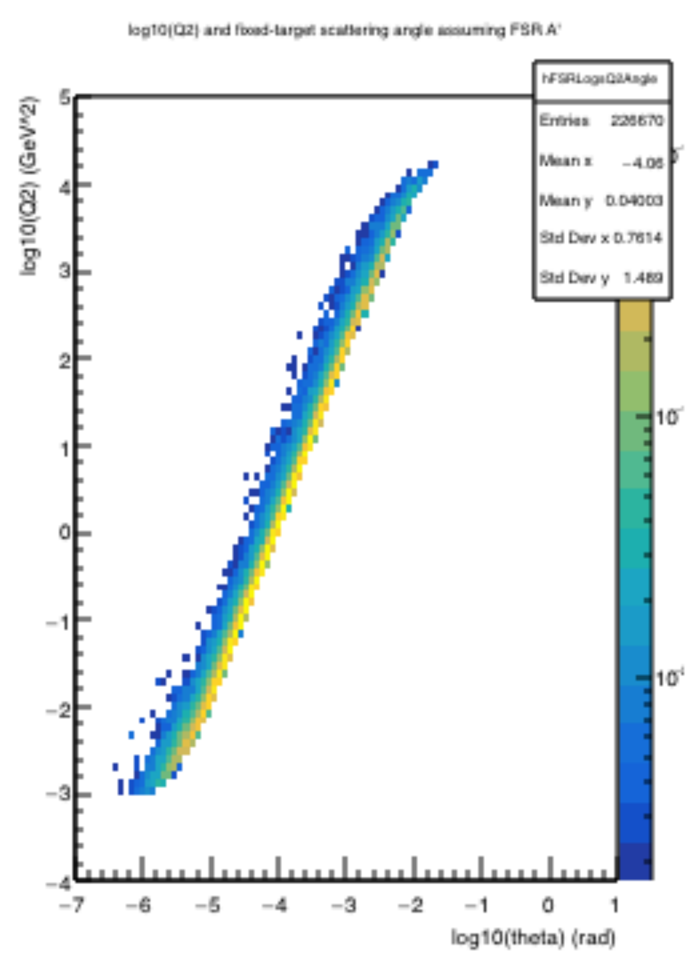
QED Background

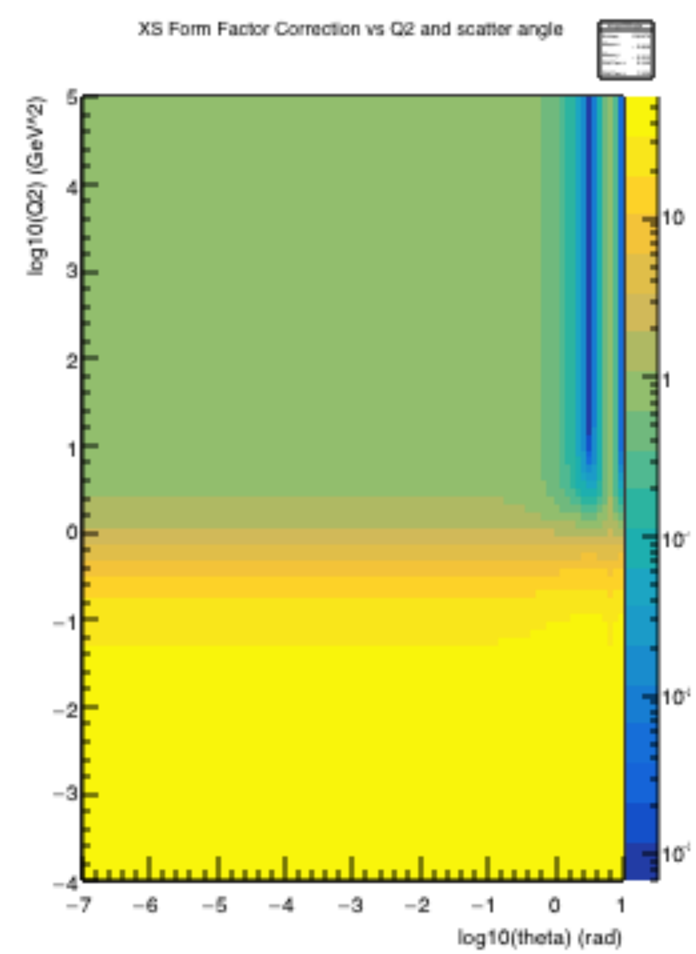


MC Scatter Kinematics (signal)

- Can reconstruct Q2 of elastic e*p->ep (or ep->e*p) scatter from proton record
- Scattering angle is not uniquely determined, but both favor small scattering angles.
- Still working on how to apply this correction (esp. for QED background)

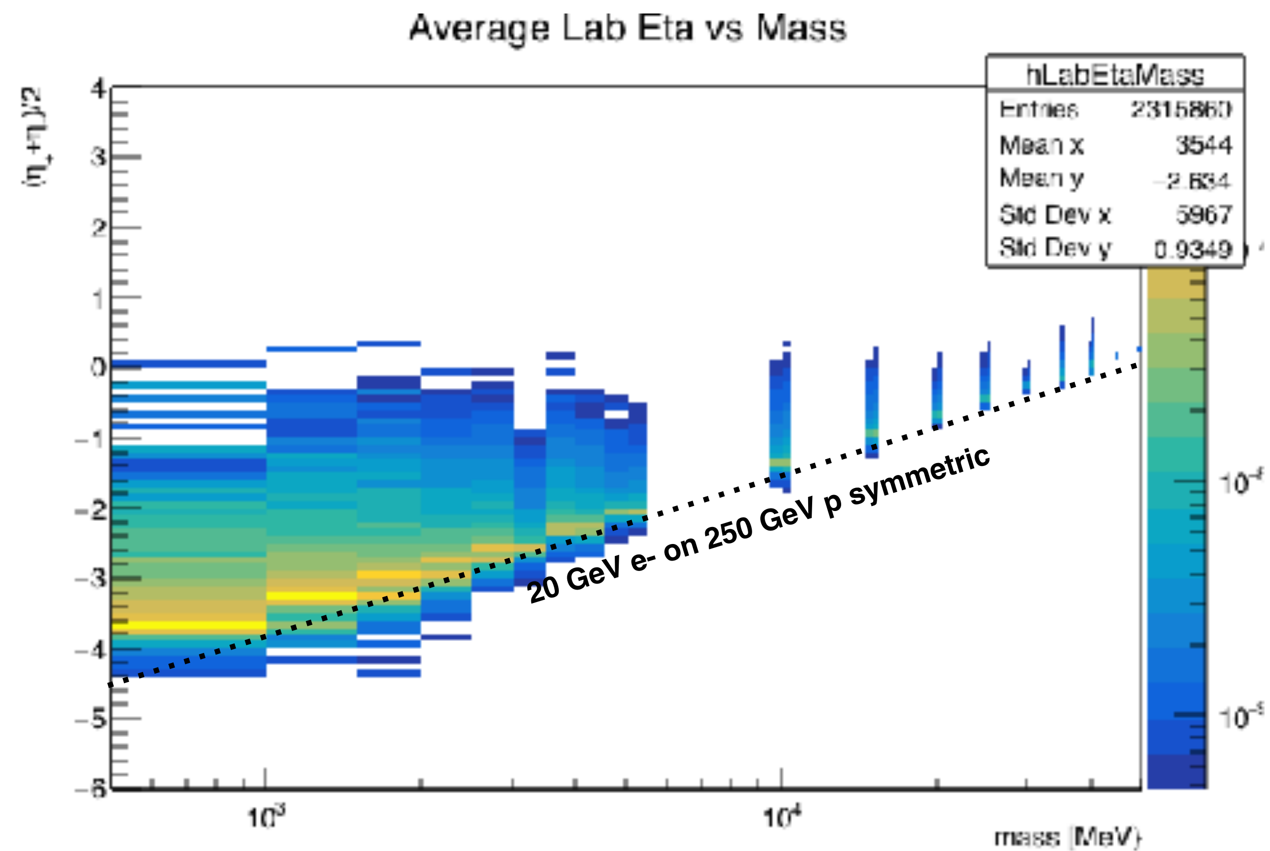


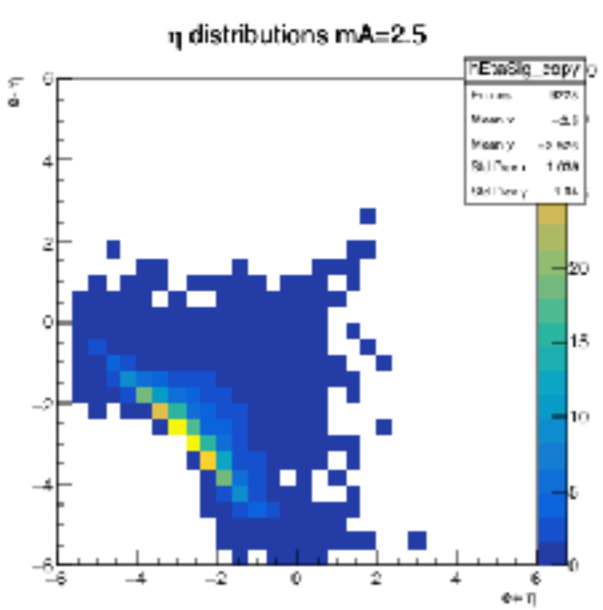


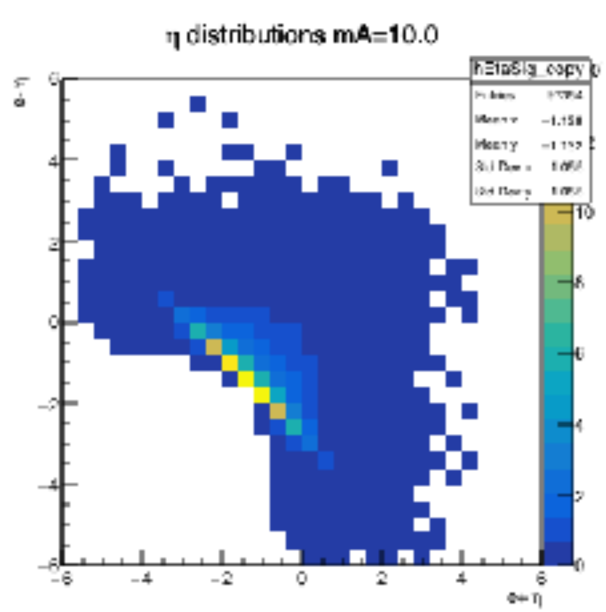


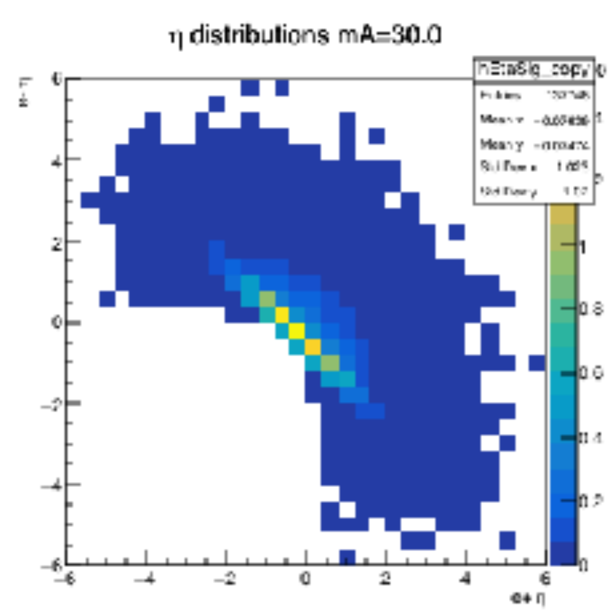
MC Decay Kinematics

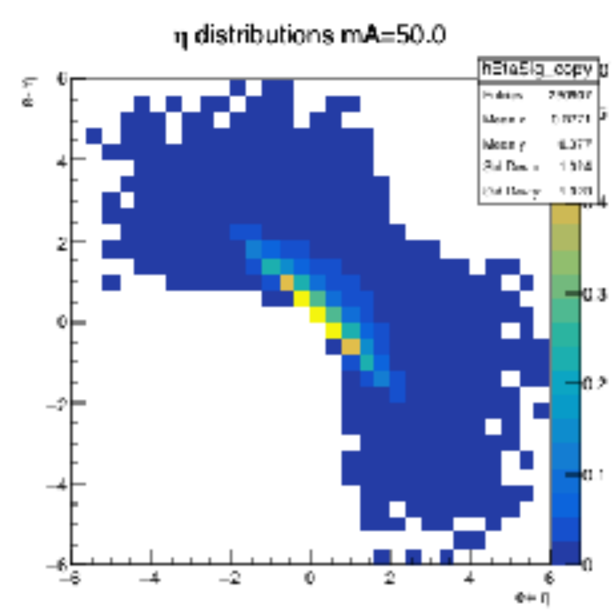
- Signal e+e- pairs track heuristic kinematics well
- Spectator e- is spread more broadly





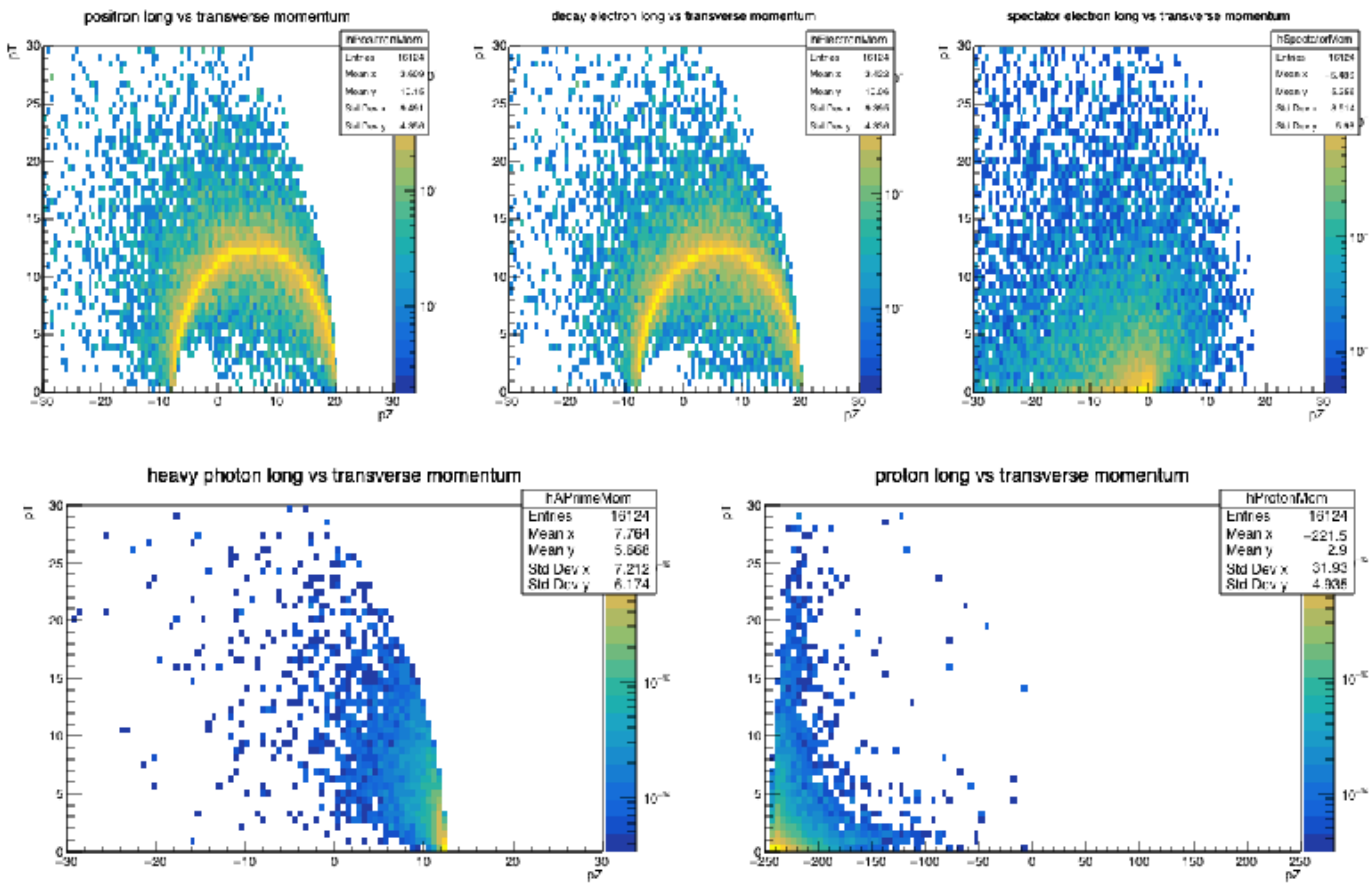






MC Decay Kinematics

- Spectator prefers to lose all its momentum, as expected
- A' prefers to carry forward momentum
- Low boost of A' produces relatively low boost e+e- decay pair.

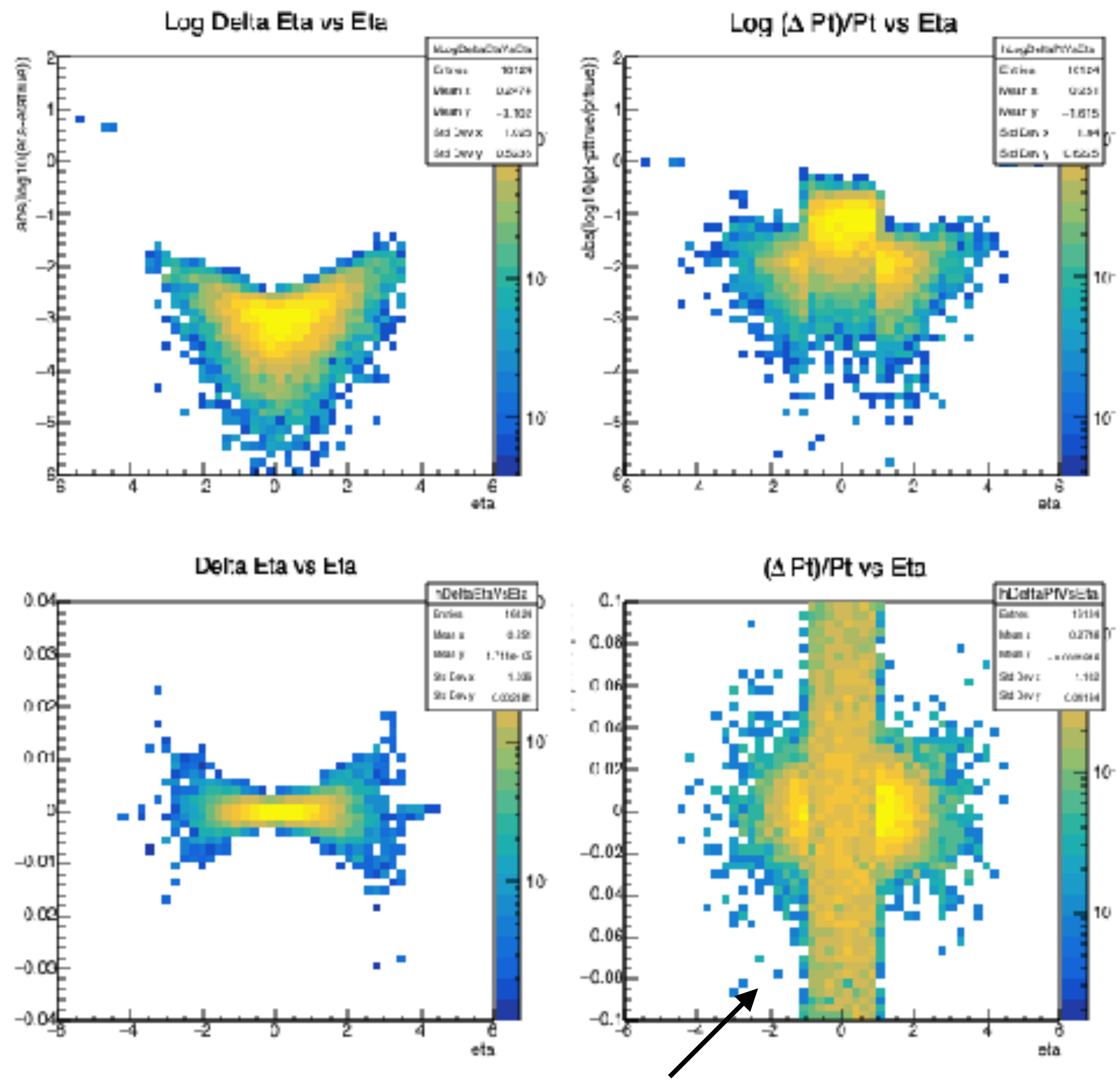


Detector Needs

- Mass resolution -- maximize FOM. Intrinsic width very narrow, so window dominated by detector.
- Charge sign reco/PID -- reduce combinatorics, fewer wrong-pairs to deal with
- Coverage -- higher (-) eta accesses lower masses

Detector Smearing

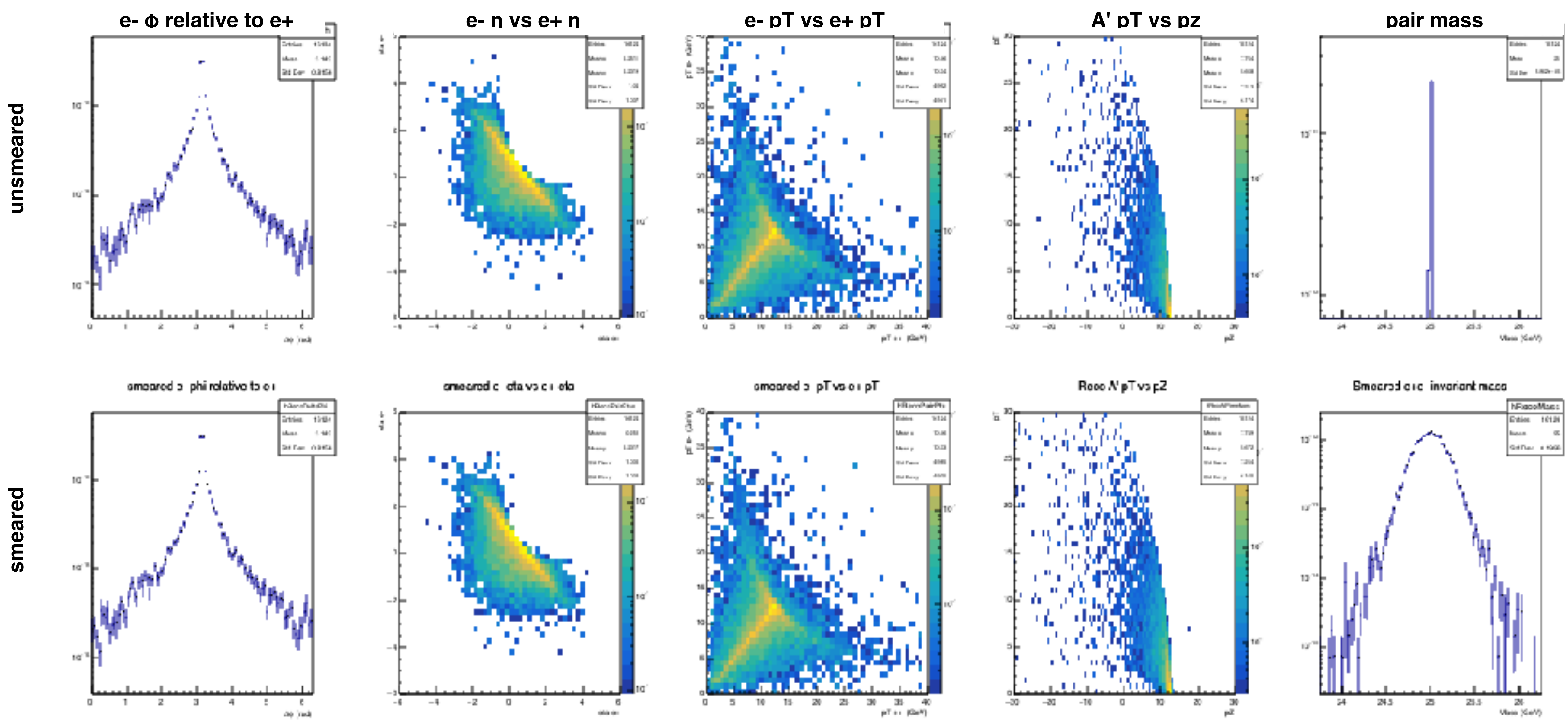
- Quick standalone smearing based on handbook resolutions
- Assume fourvector reconstructed from momentum, neglect particle rest mass
- Perfect charge ID
- No momentum acceptance cut
- Eta cut per defined detectors
- 100% efficiency



Intentionally degraded to check det. boundaries

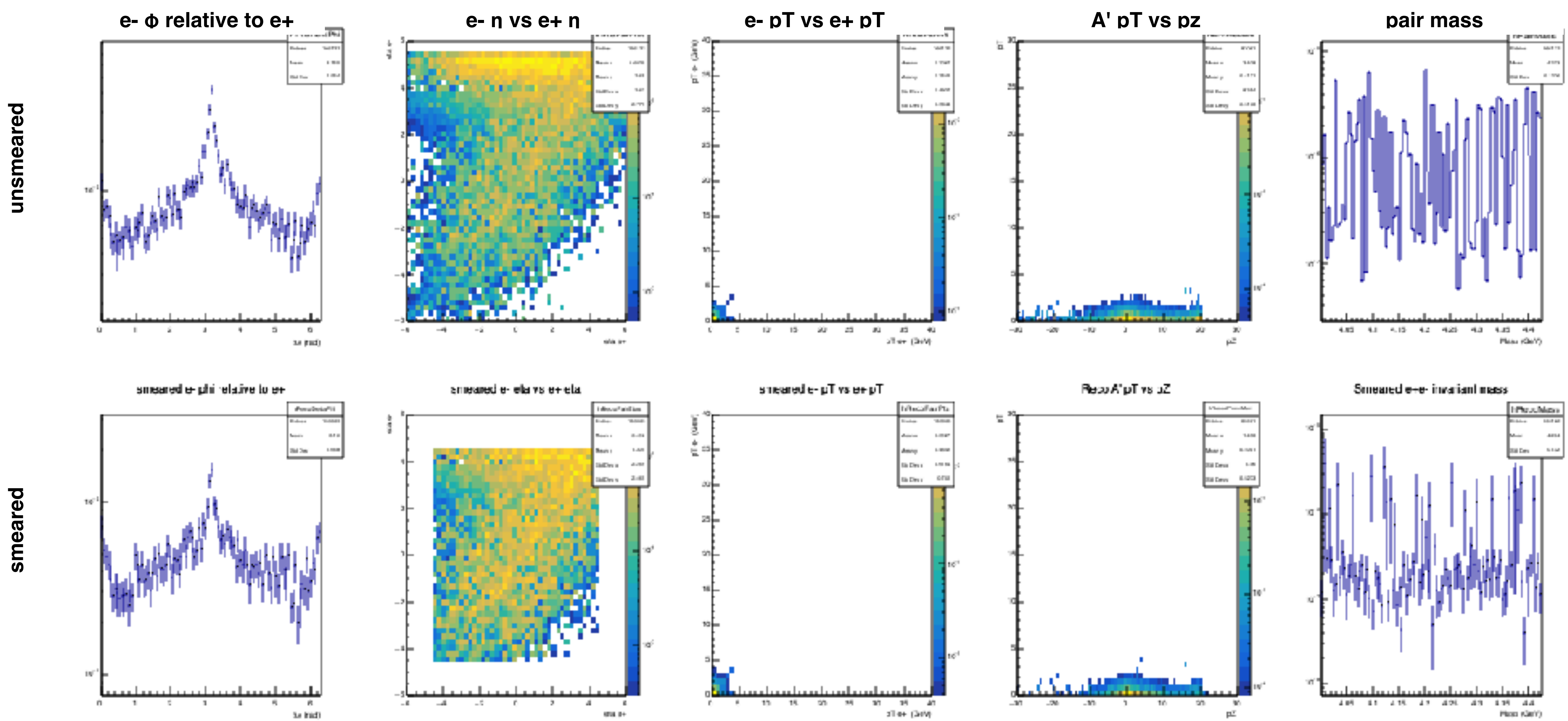
Smeared Events

- 25GeV A' signal sample shows main features: back-to-back, eta correlated, pT ~balanced



Smeared QED Background

- For BG, add both possible e+e- pairs. Expect similar structures for 'right' pair, no peak. (tridents different)



Reach Calculation

- Significance is signal size compared to fluctuation in irreducible background:

$$S = \frac{\sigma_A L}{\sqrt{\sigma_{QED} L}}$$

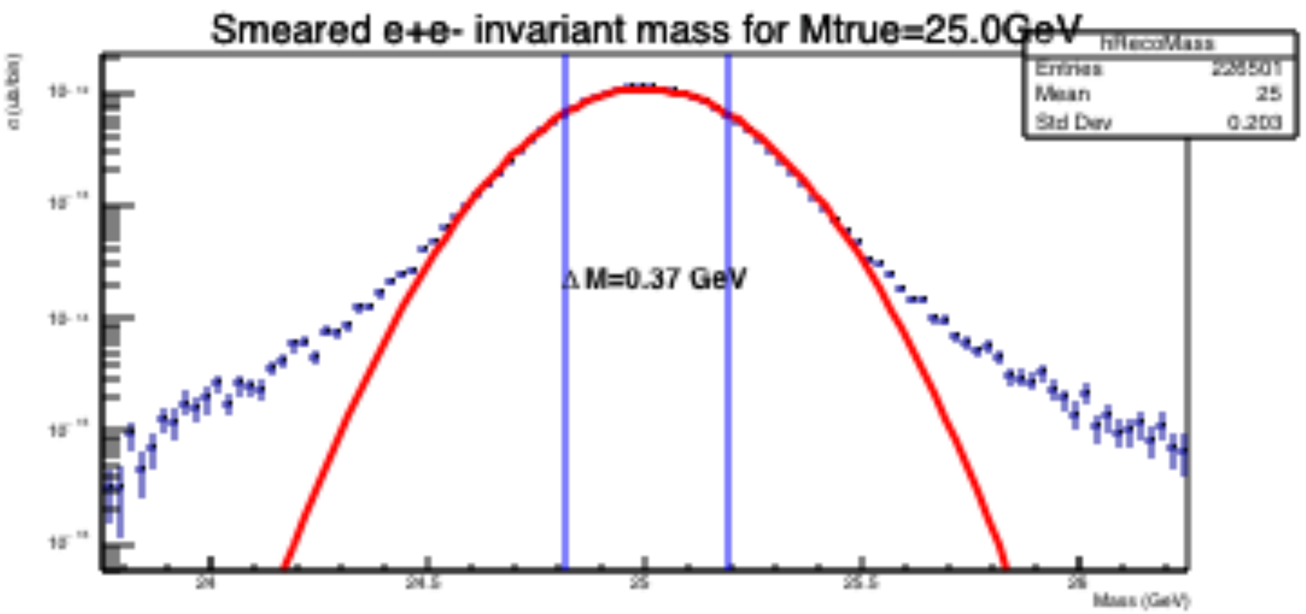
- Signal xs scales with coupling (ε^2):

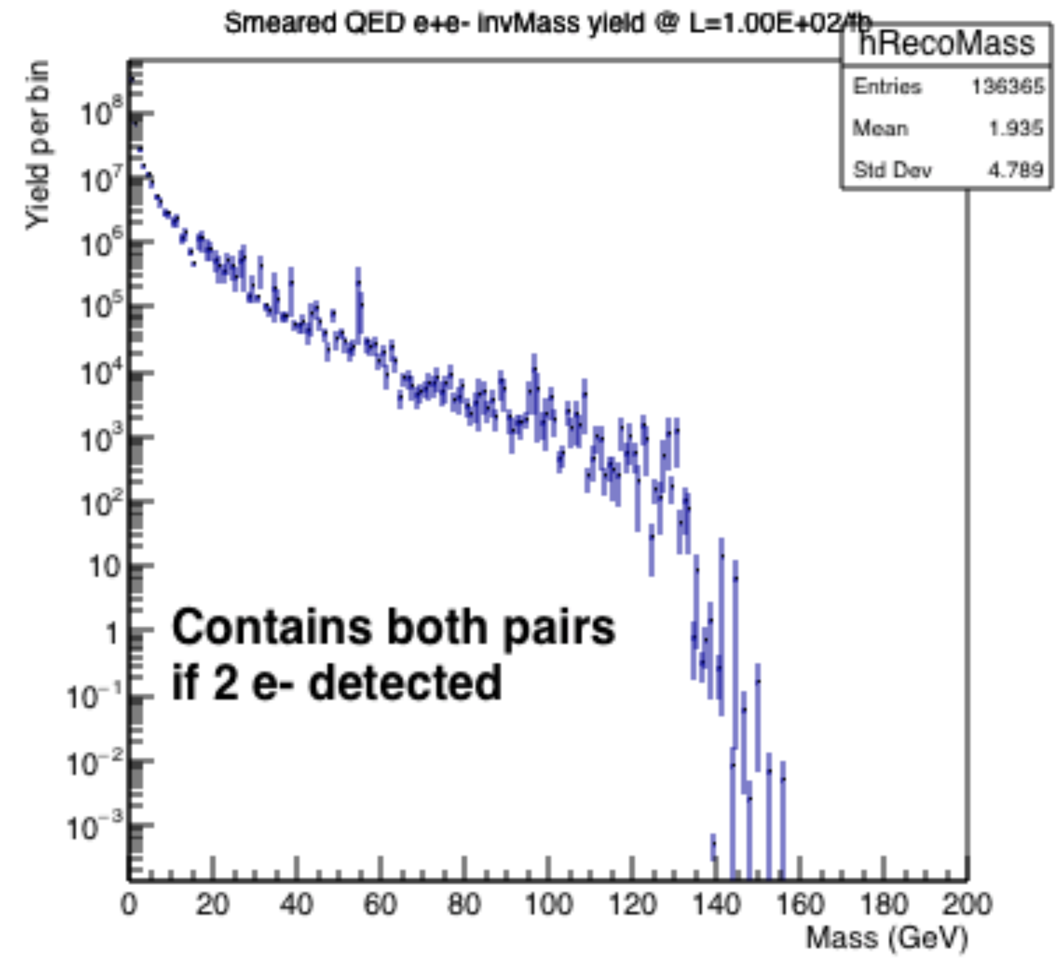
$$S = \sigma_{A0} \frac{\alpha_D}{\alpha_{D0}} \sqrt{\frac{L}{\sigma_{QED}}}$$

Reach defined by extrinsic factors and Sig/√Bg:

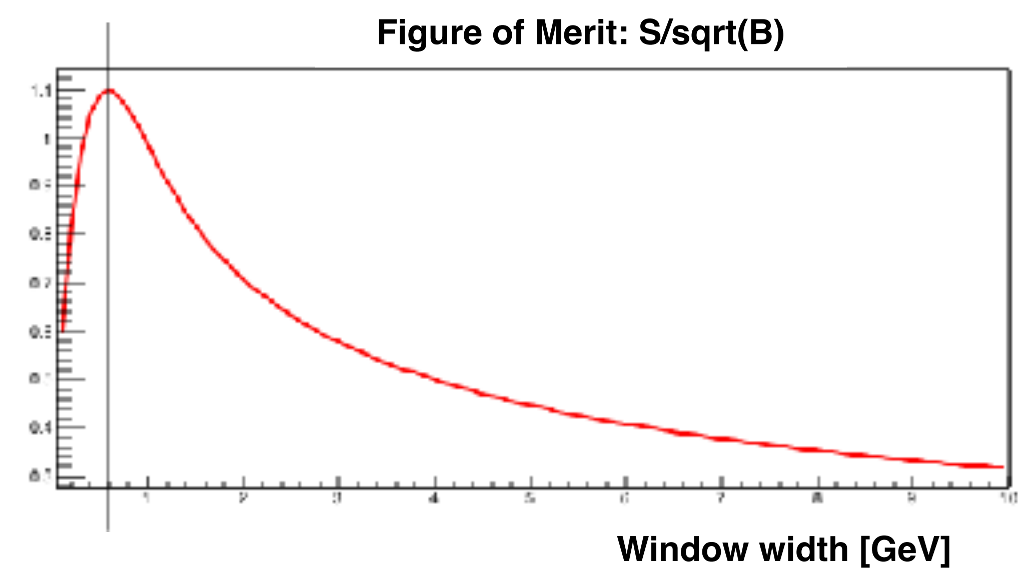
$$\alpha_D = S \frac{\alpha_{D0}}{\sqrt{L}} \frac{\sqrt{\sigma_{QED}}}{\sigma_{A0}}$$

Optimizing mass window

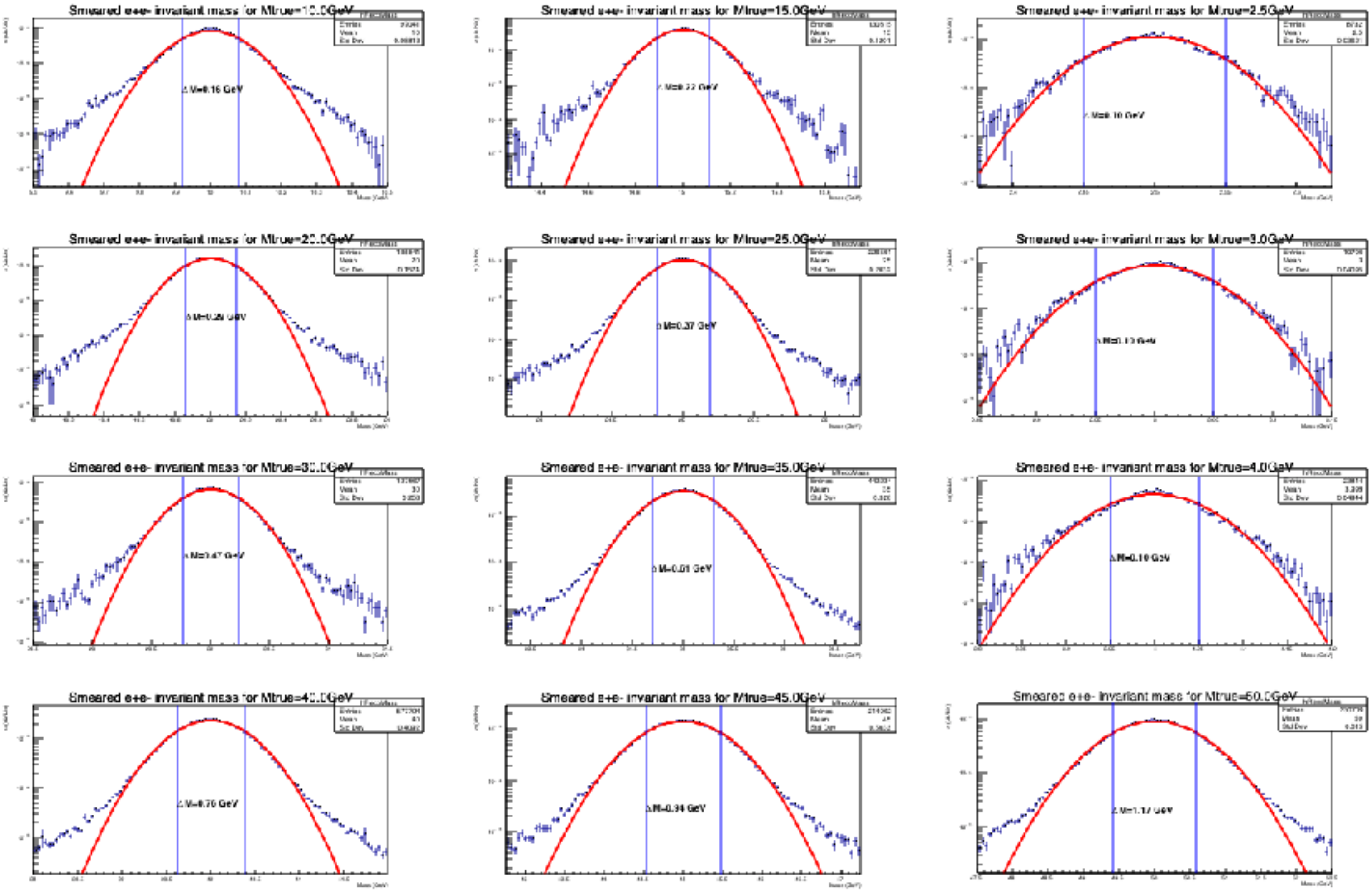




- Integrate yield in Signal and Bg samples in window of varying size, find local maximum (analytic if flat background)
- Inv Mass from e+ and spectator e- does not have a peak

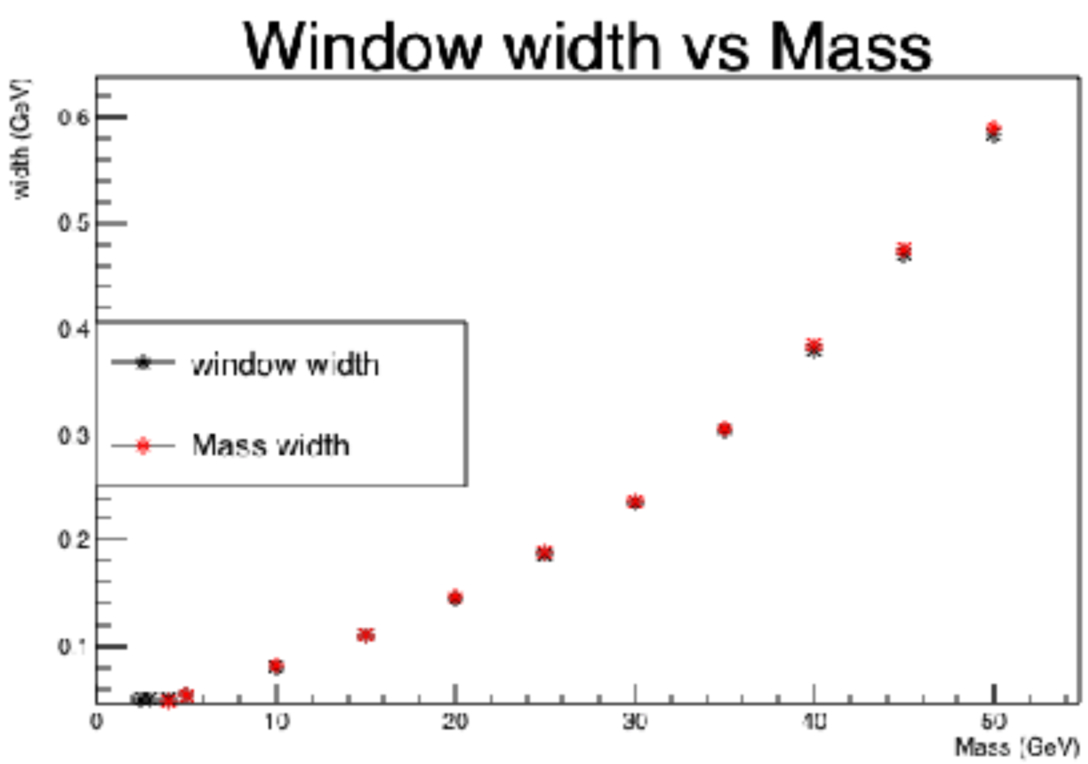


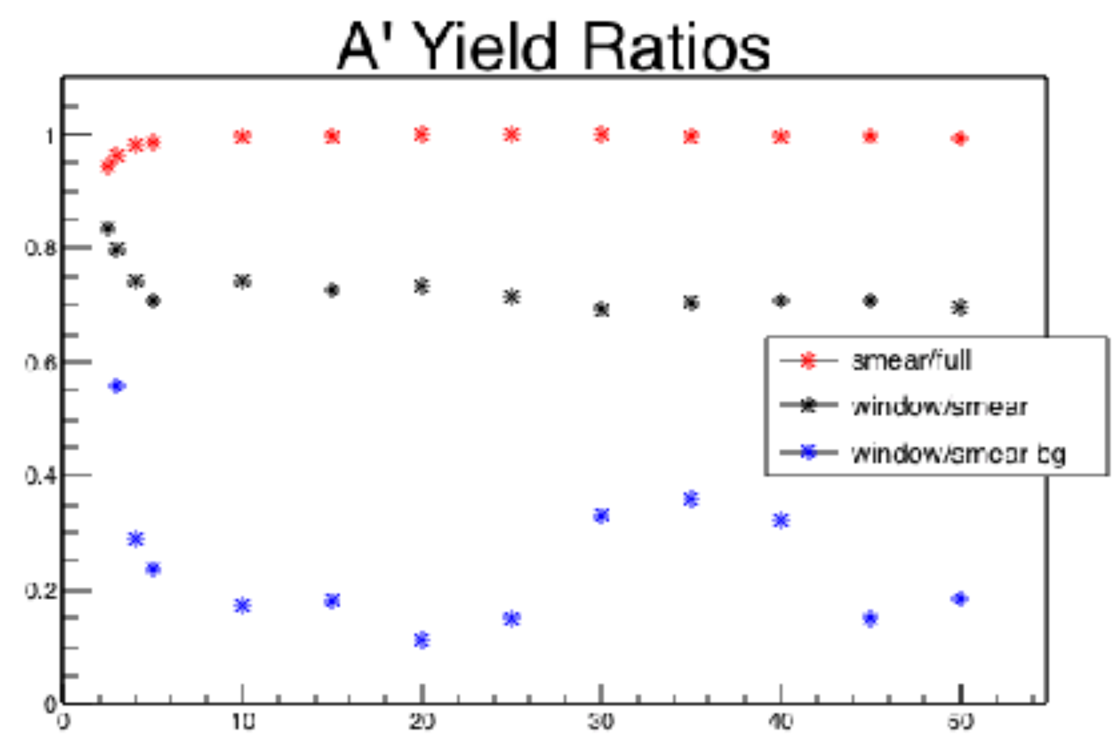
Repeat for multiple masses



Windows and Yields

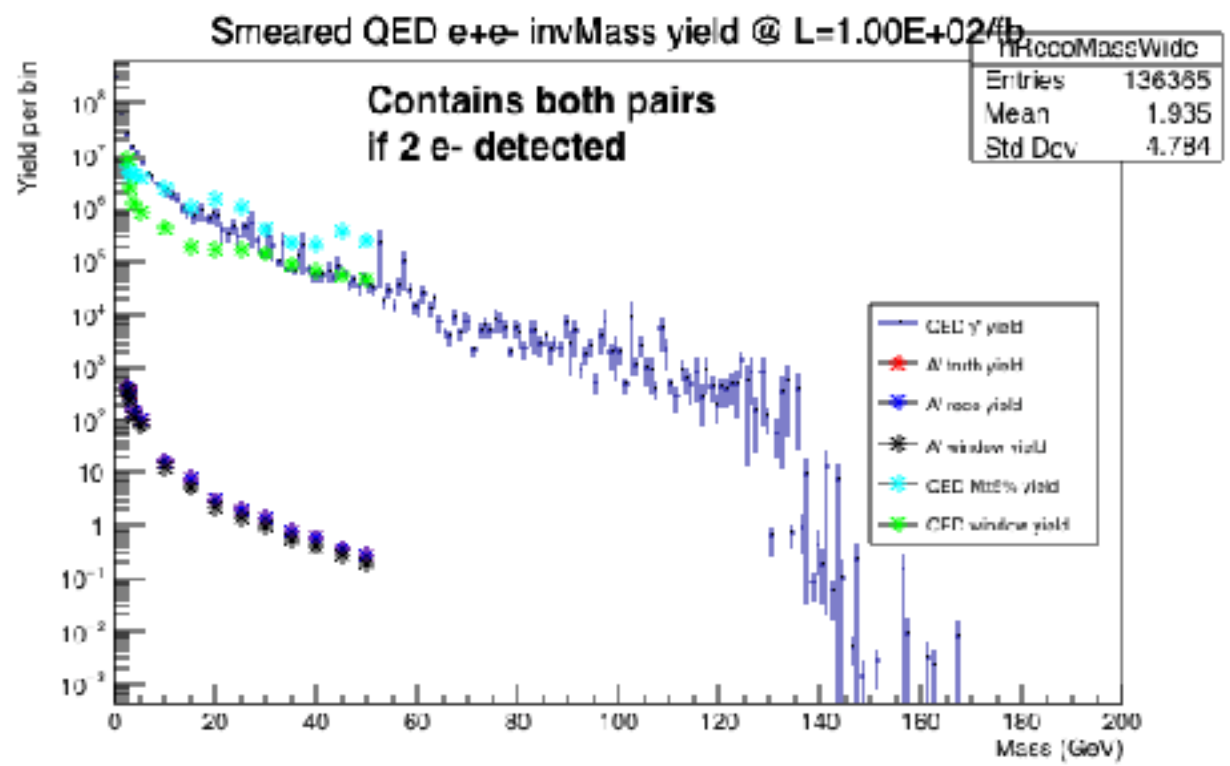
- Windows track the gaussian fit, signal acceptance stable over most of the studied mass range

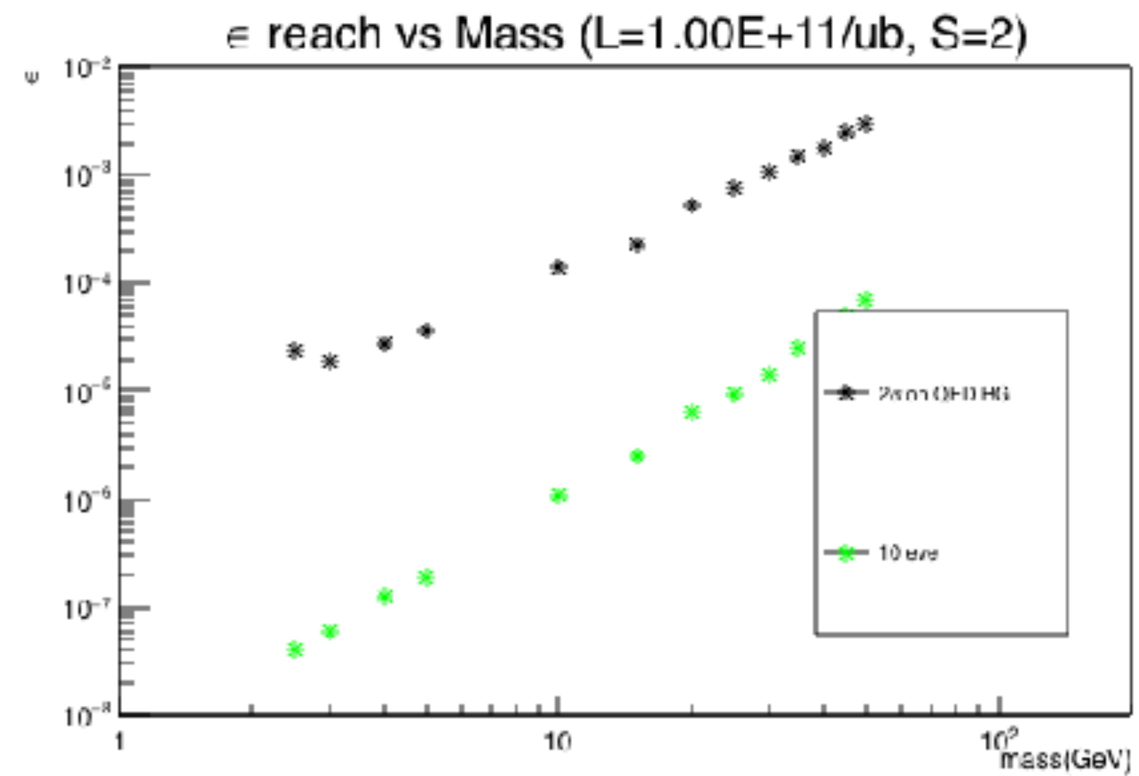




Performance at 100fb^{-1}

- Caveats first:
  - Weighting of some events may be off by more than order of magnitude (FF correction)
  - Only QED background considered
  - Branching ratio to mu, hadrons ignored
  - Resonances ignored
  - Detector complications not considered
- Default coupling set α_D=1e-8
- Performance vs QED bg and zero-bg performance limit shown
- Naive model looks very promising across broad range
- Expect gains from cuts
- Expect losses from other backgrounds





Future Work

- MC generator/datasets:
  - expand mass range, different beam configs
  - muons, *more efficient cuts*, heavy ion beam
  - hadronic couplings, proton structure
  - *other backgrounds*
- Algorithm
  - explore Sig/√Bg gains via mild cuts
  - explore displaced vertices
- Migrate to SmearHandbook
  - "free" improvements as detectors take shape

Summary

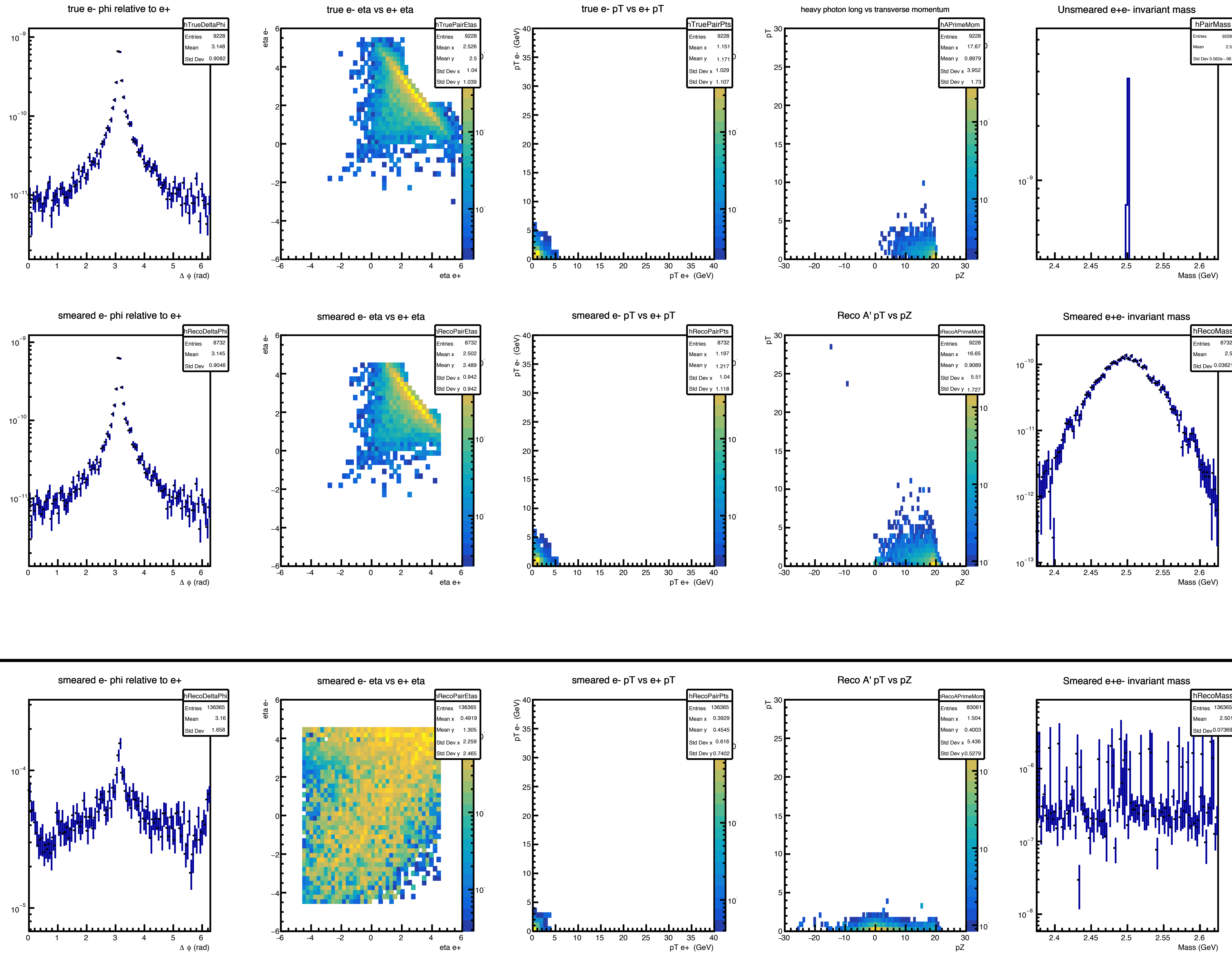
- Multiple probes desired to explore A' generalized parameter space
- Multiple approaches available at EIC:
  - ISR leptons - ~500MeV<mA<~50GeV from kinematics
  - Dalitz decays - mA<parent
  - hadronic decays?
- Boosted CM helps in ISR scenario
- Benefits from pid, charge, and resolution -- especially in electron-going direction
- First glimpse very promising, but still in development

2.5GeV

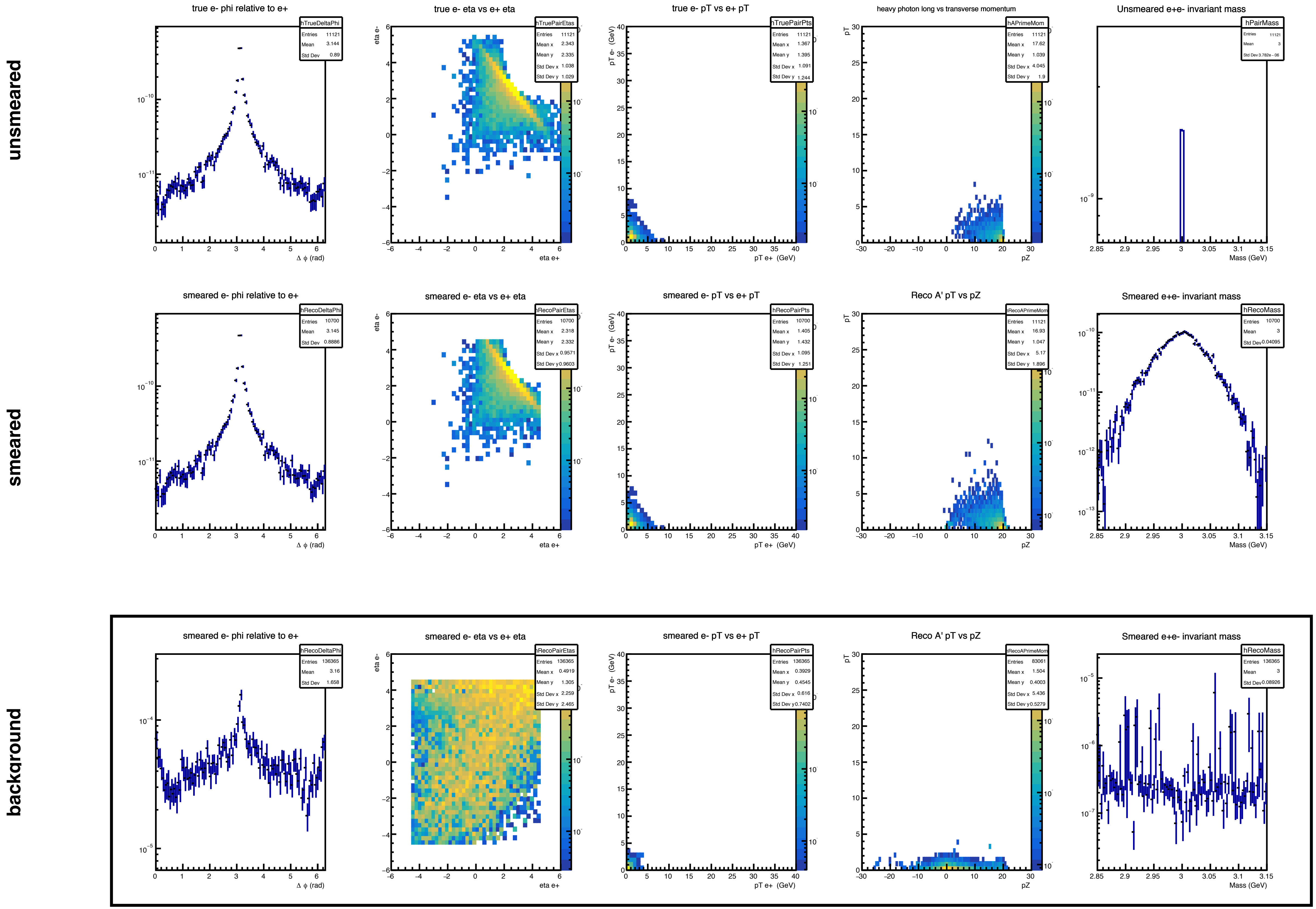
unsmeared

smeared

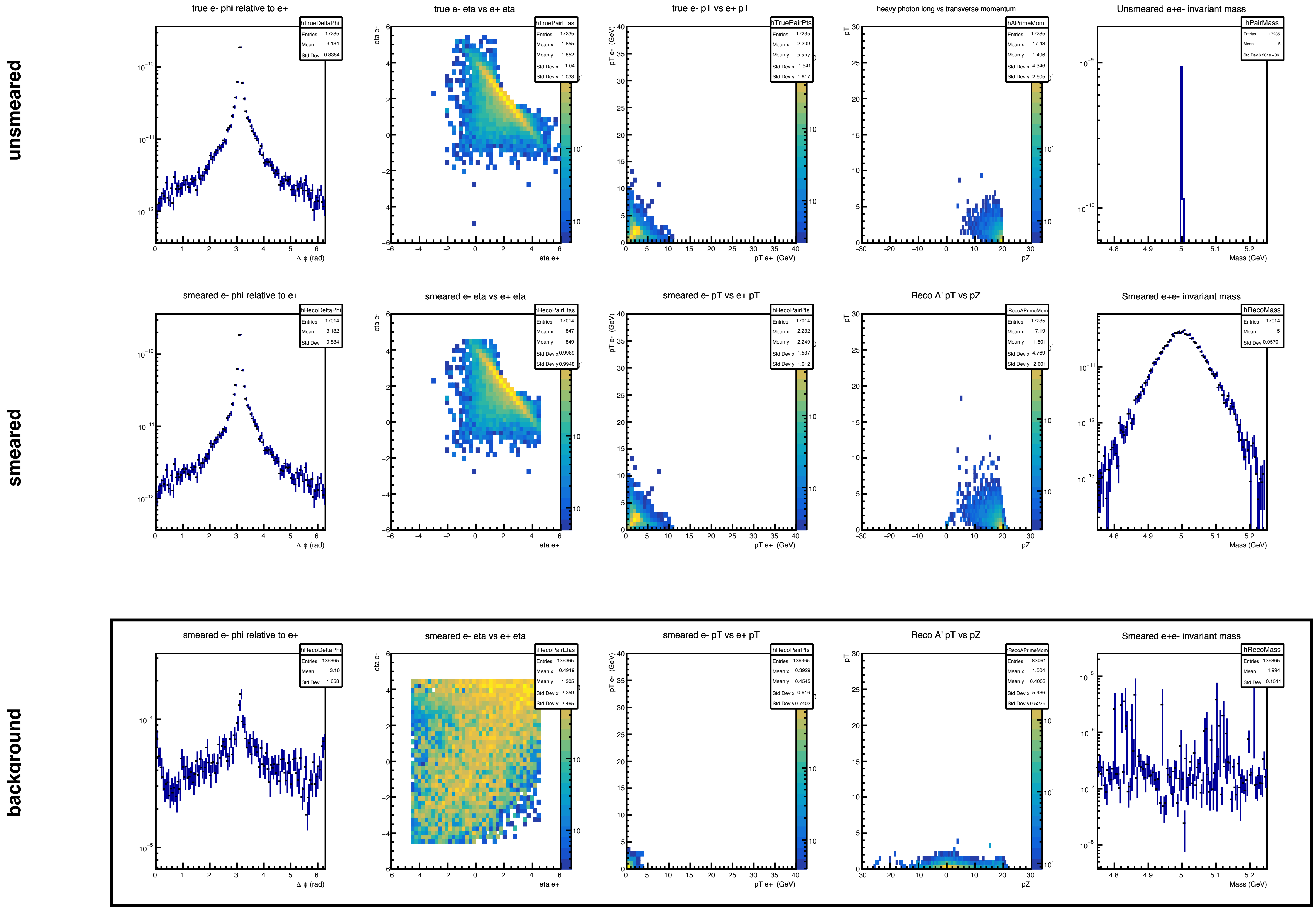
background



3GeV


unsmeared
smeared
background
true e- phi relative to e+
hTrueDeltaPhi
Δ φ (rad)
true e- eta vs e+ eta
hTruePairEtas
eta e-
eta e+
true e- pT vs e+ pT
hTruePairPts
pT e- (GeV)
pT e+ (GeV)
heavy photon long vs transverse momentum
hAPrimeMom
pT
pZ
Unsmeared e+e- invariant mass
hPairMass
Mass (GeV)
smeared e- phi relative to e+
hRecoDeltaPhi
smeared e- eta vs e+ eta
hRecoPairEtas
smeared e- pT vs e+ pT
hRecoPairPts
Reco A' pT vs pZ
hRecoAPrimeMom
Smeared e+e- invariant mass
hRecoMass

5GeV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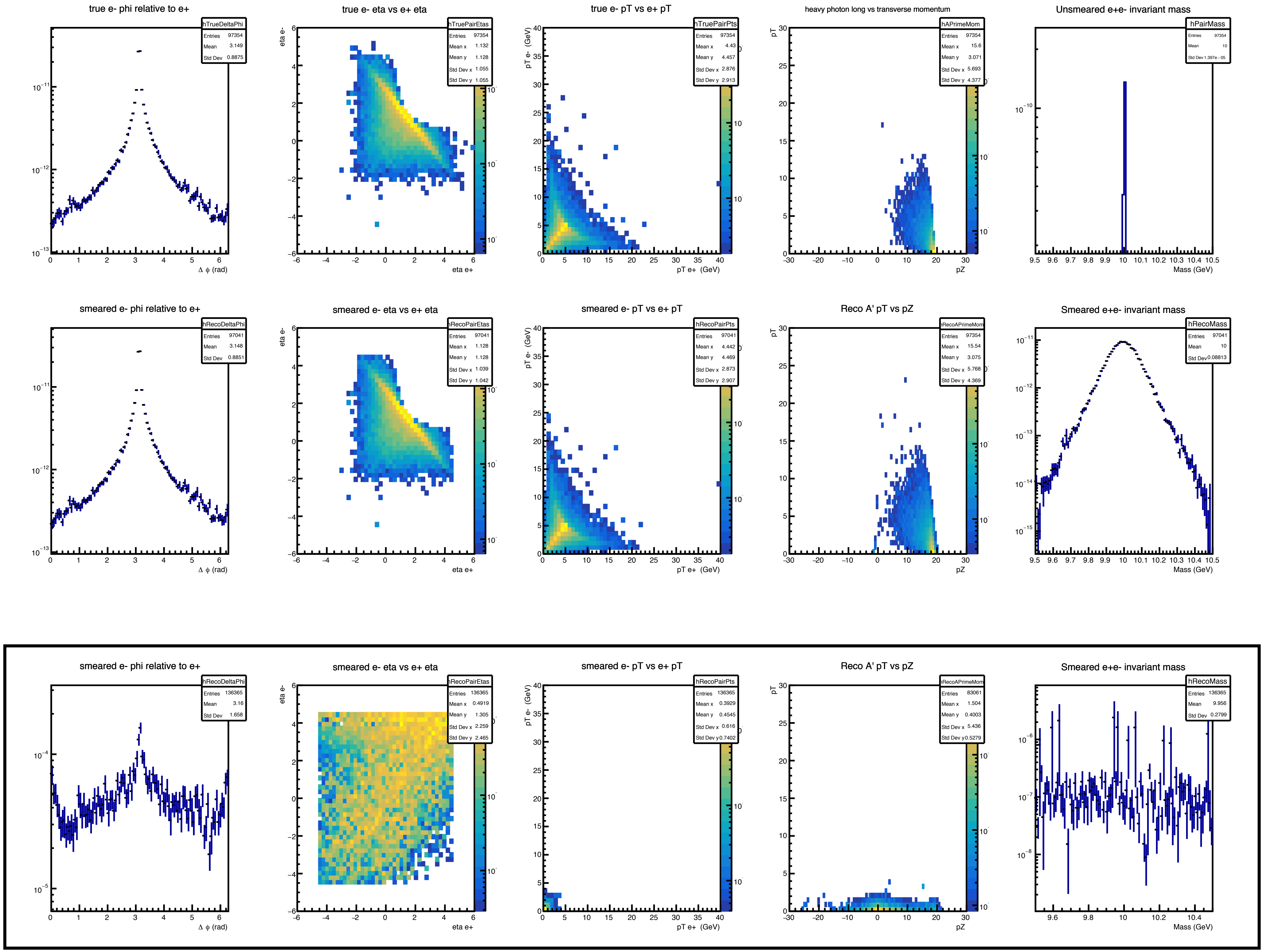
Smeared e+e- invariant mass
Δ φ (rad)
eta e+
eta e-
pT e+ (GeV)
pT e- (GeV)
pZ
pT
Mass (GeV)

10GeV

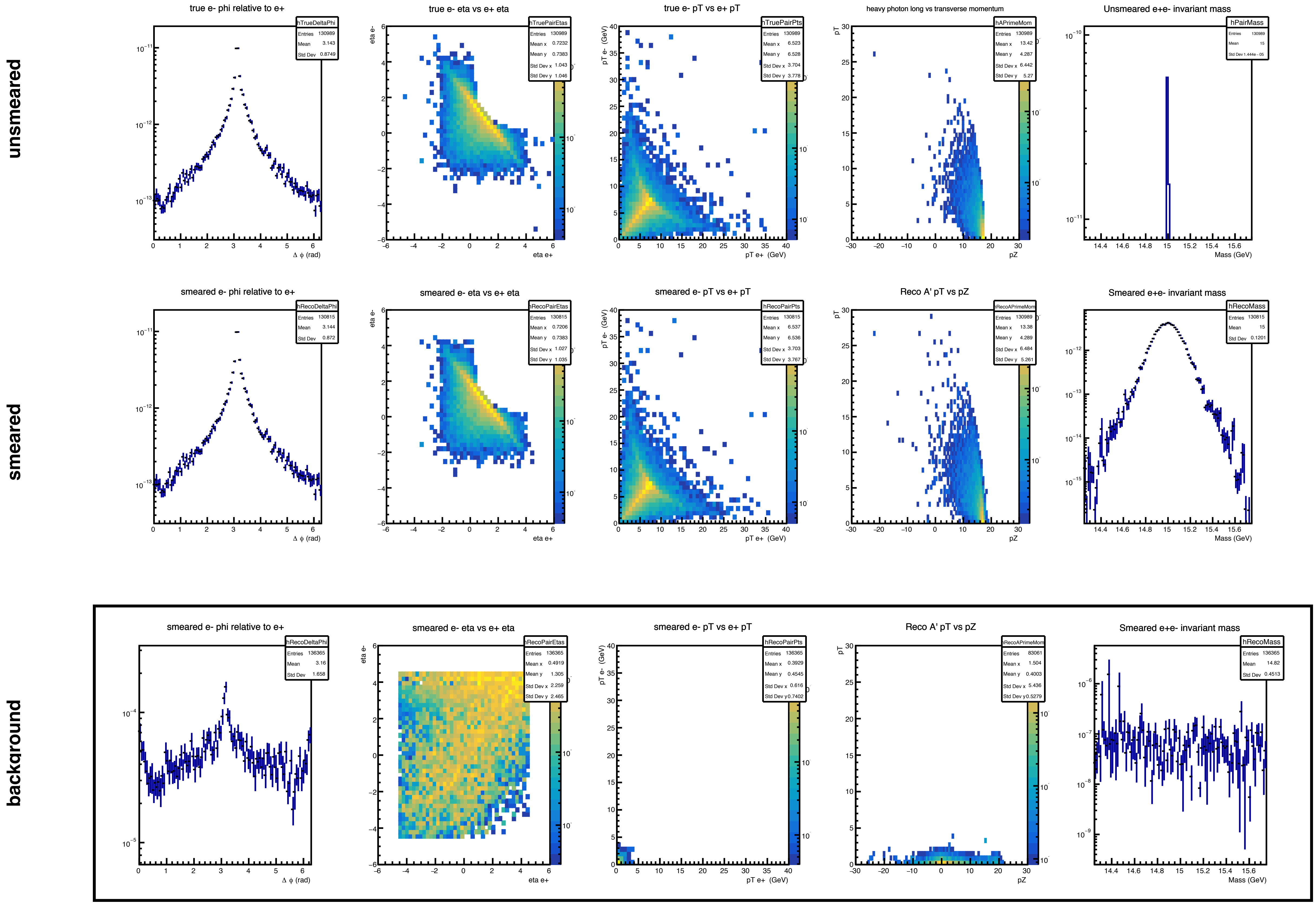
unsmeared

smeared

background



15GeV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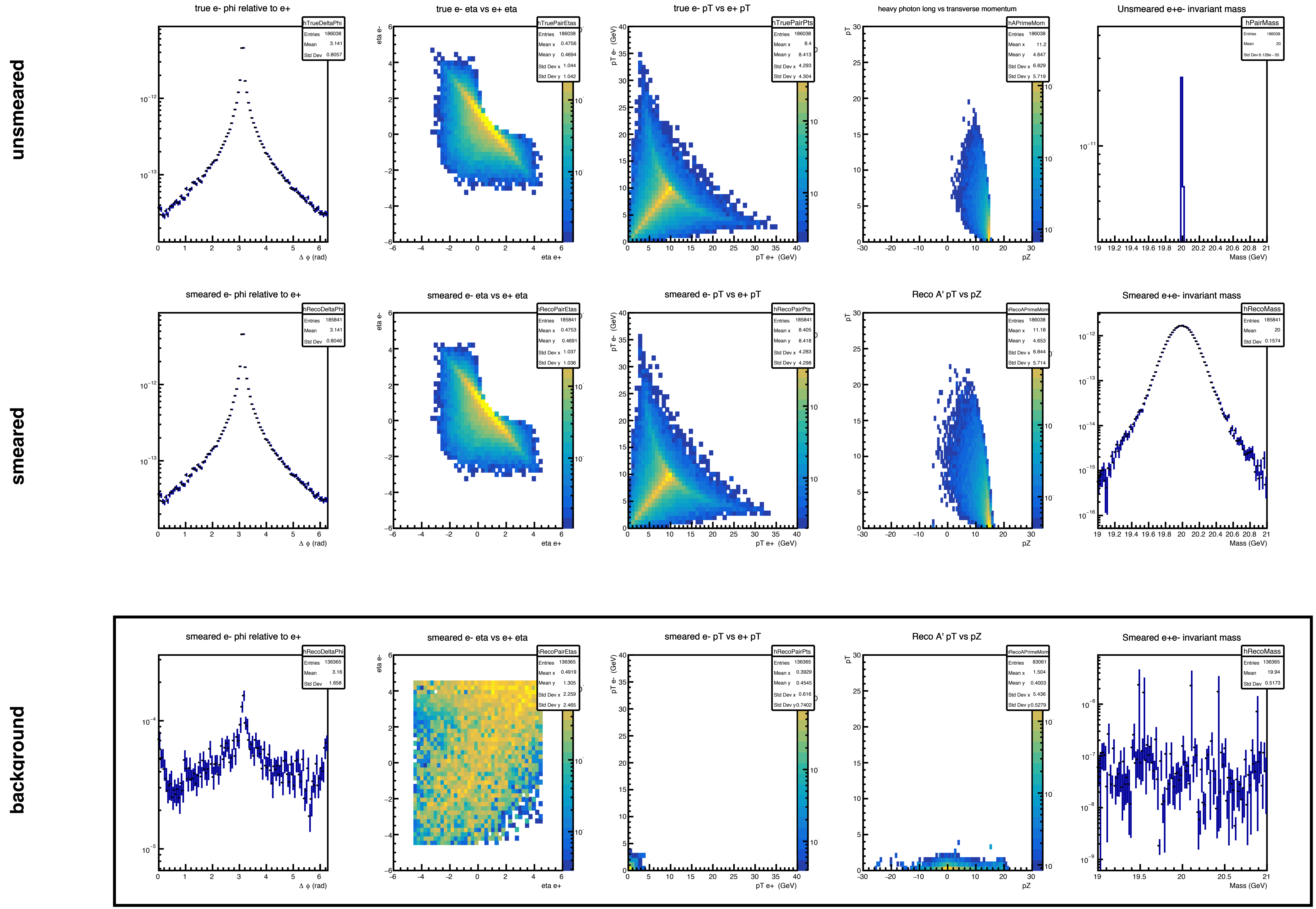
Smeared e+e- invariant mass
Δ φ (rad)
eta e+
eta e-
pT e+ (GeV)
pT e- (GeV)
pZ
pT
Mass (GeV)

20GeV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Unsmeared e+e- invariant mass
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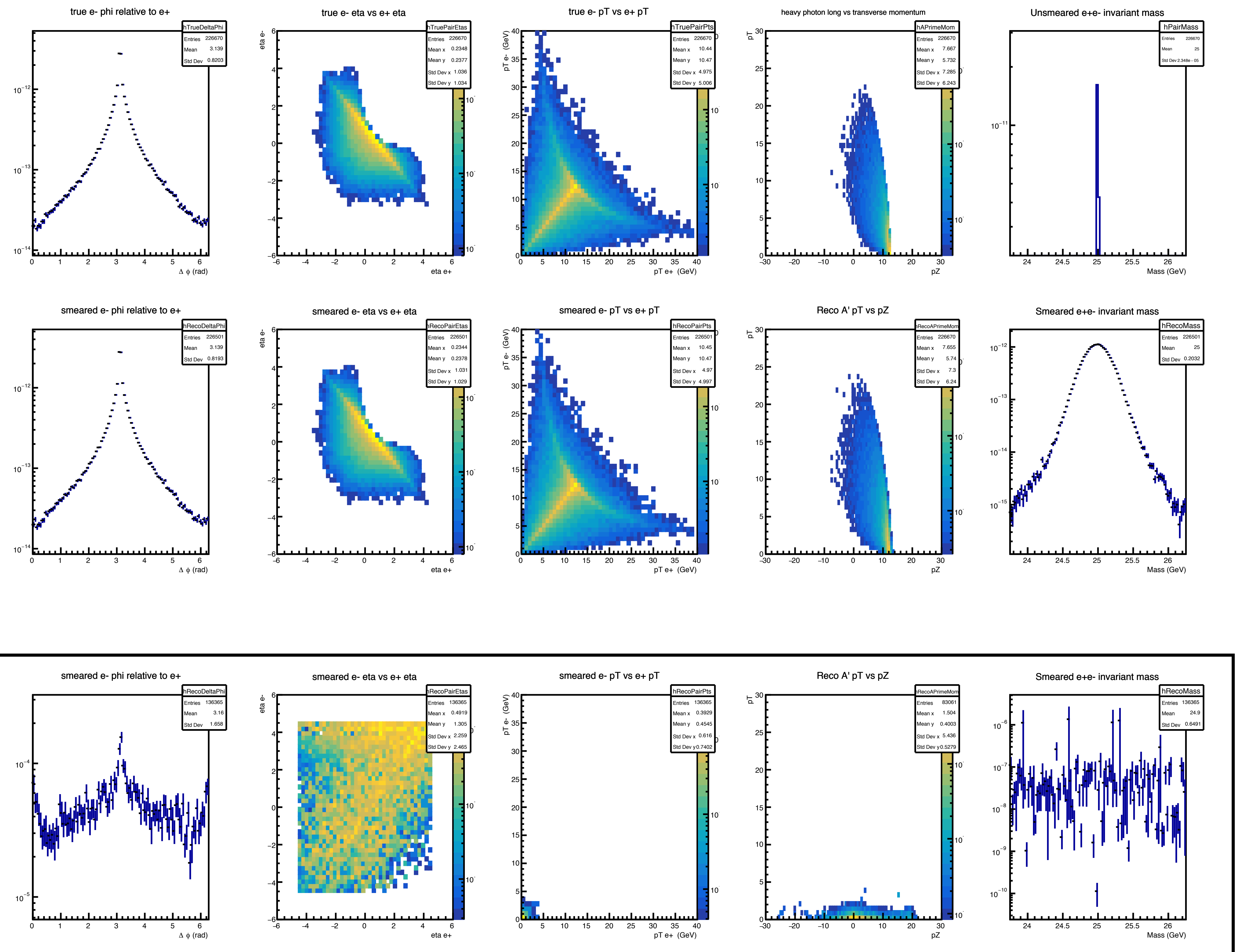
Smeared e+e- invariant mass
smeared e- phi relative to e+
smeared e- eta vs e+ eta
smeared e- pT vs e+ pT
Reco A' pT vs pZ
Smeared e+e- invariant mass
Δ φ (rad)
eta e-
eta e+
pT e- (GeV)
pT e+ (GeV)
pT
pZ
Mass (GeV)

25GeV

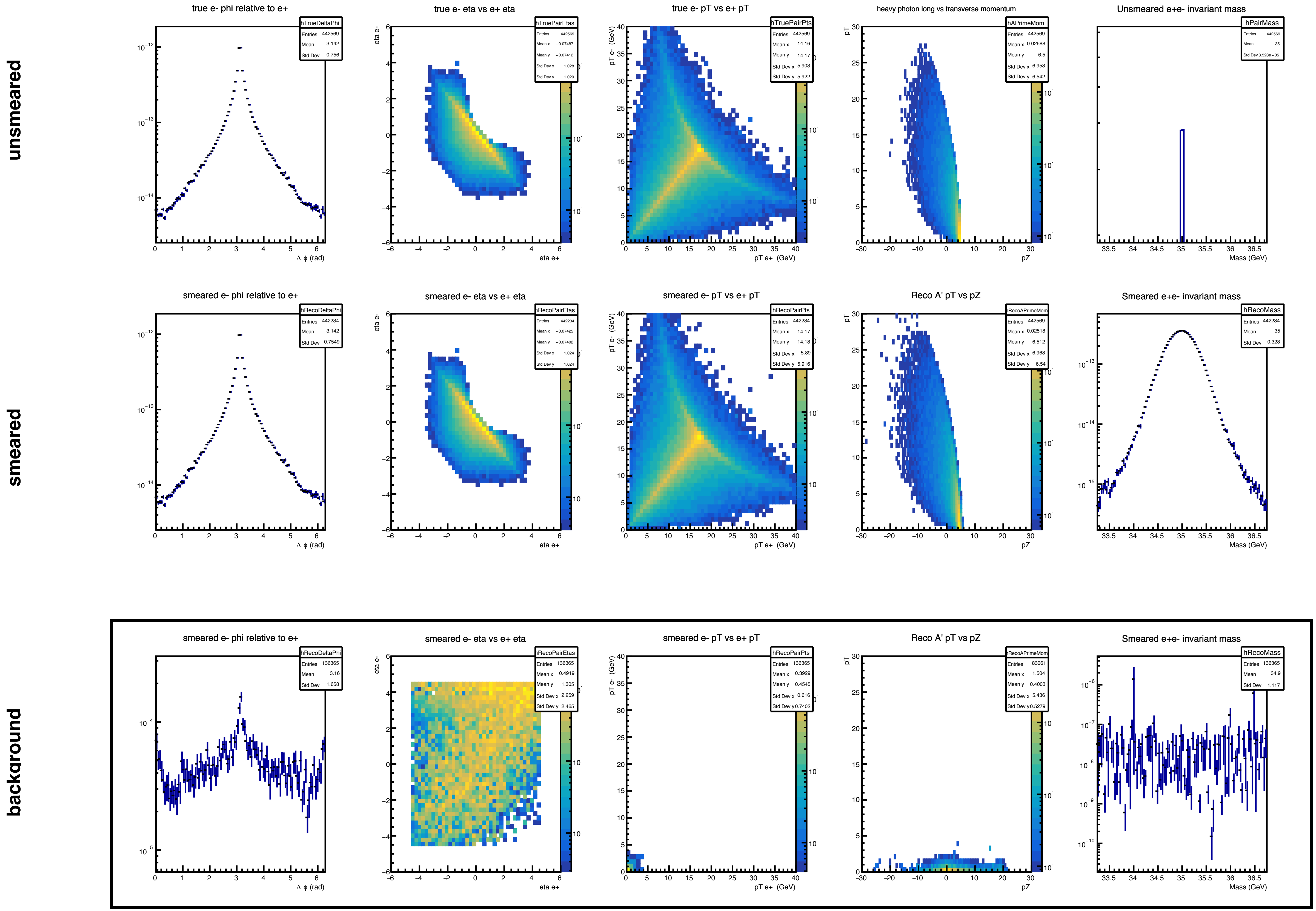
unsmeared

smeared

background



35GeV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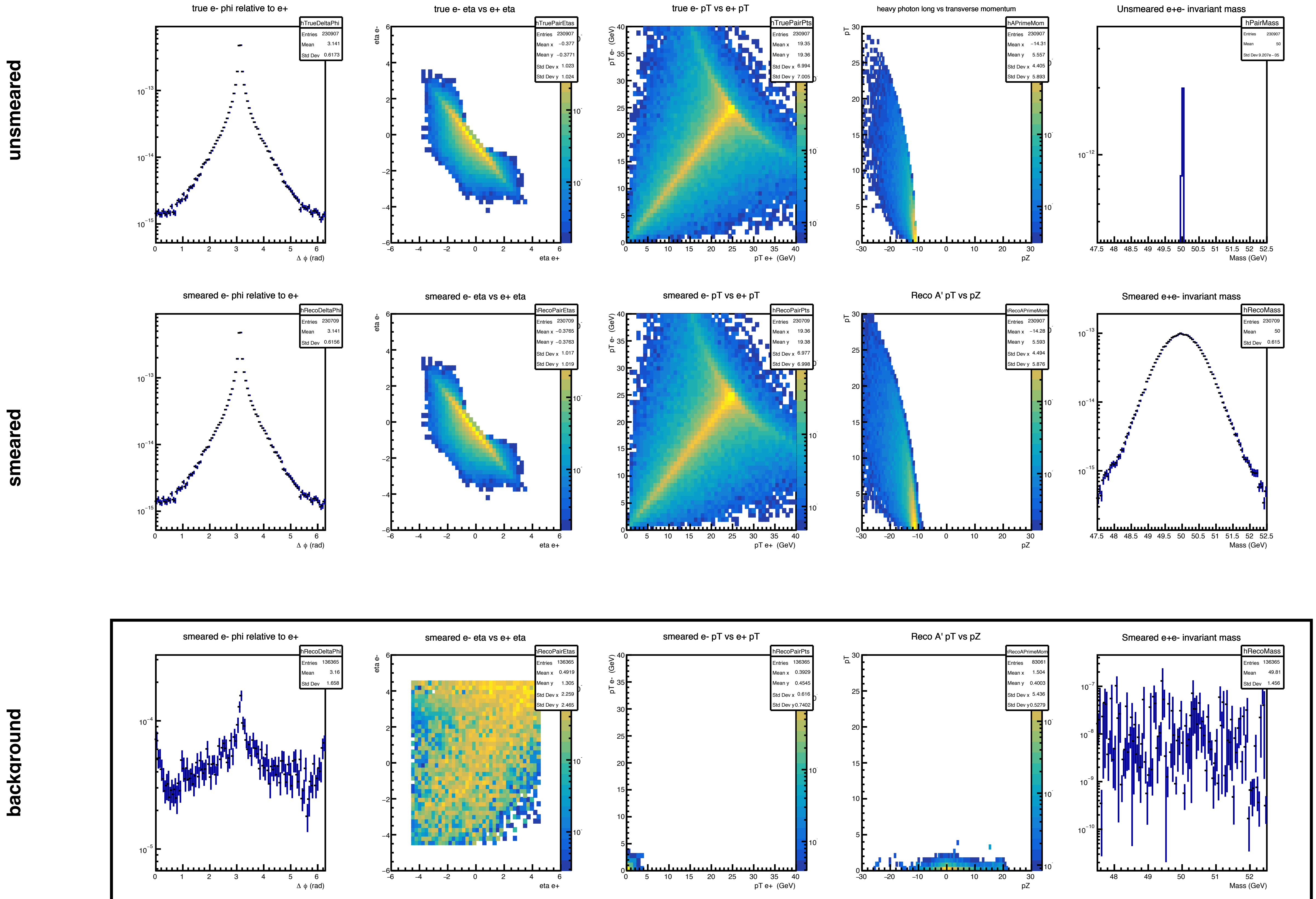
hRecoDeltaPhi
smeared e- eta vs e+ eta
hRecoPairEtas
smeared e- pT vs e+ pT
hRecoPairPts
Reco A' pT vs pZ
hRecoAPrimeMom
Smeared e+e- invariant mass
hRecoMass
Δ φ (rad)
eta e+
eta e-
pT e+ (GeV)
pT e- (GeV)
pZ
pT
Mass (GeV)

50GeV


unsmeared
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background
true e- phi relative to e+
true e- eta vs e+ eta
true e- pT vs e+ pT
heavy photon long vs transverse momentum
Unsmeared e+e- invariant mass
smeared e- phi relative to e+
smeared e- eta vs e+ eta
smeared e- pT vs e+ pT
Reco A' pT vs pZ
Smeared e+e- invariant mass
hTrueDeltaPhi
hTruePairEtas
hTruePairPts
hAPrimeMom
hPairMass
hRecoDeltaPhi
hRecoPairEtas
hRecoPairPts
hRecoAPrimeMom
hRecoMass
Δ φ (rad)
eta e+
eta e-
pT e+ (GeV)
pT e- (GeV)
pZ
pT
Mass (GeV)

Possible Cuts

- 50GeV signal vs QED background in nearby mass window