Exclusive production of Quarkonia and Heavy Flavors to access gluon Generalized Parton Distributions, from medium to high energy experiments

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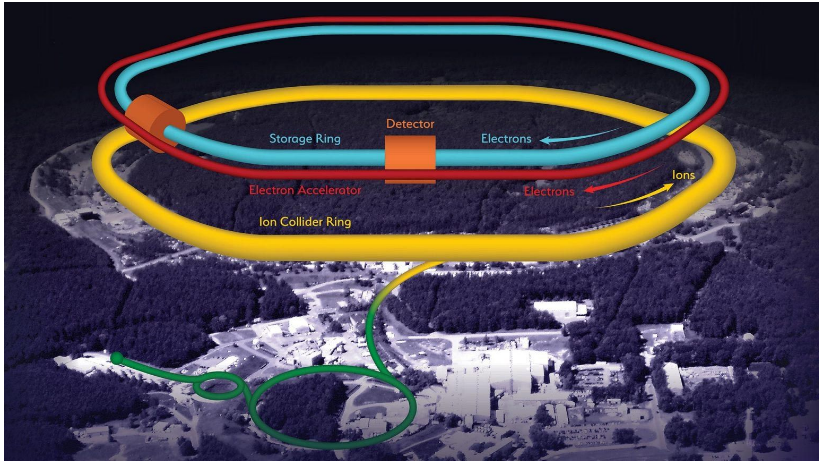
A Tale of Two Fields

Computational

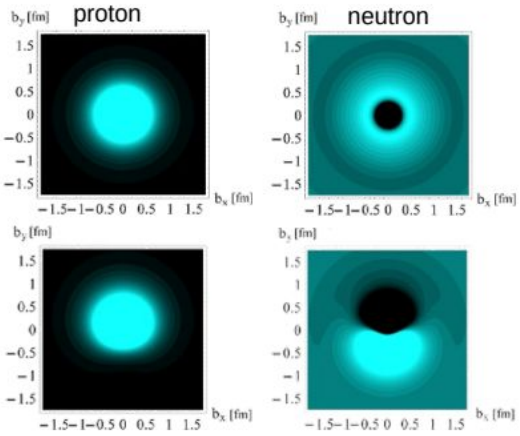
```
JPsiMeson::JPsiMeson(double stdDev, double lowerBound, double upperBound, double CSR) {
    distribution = new TF1("mesonDistribution", "gaus(0)", lowerBound, upperBound);
    distribution->SetParameters(1 / (stdDev * TMath::Sqrt(2 * TMath::Pi())), 3.0969, stdDev);

    EGammaMin = 0;
    EGammaMax = 10000;
    TMin = 0;
    TMax = 100;
    PhiMin = 3.;
    PhiMax = 363.;
    ThMin = 30.;
    ThMax = 155.;
    PhisMin = 0.;
    PhisMax = 360.;
    PsisMin = 0.;
    PsisMax = 360.;

    crossSectionRatio = CSR;

    cdfTable.setct11(cdfTablePath);
}
```

Experimental



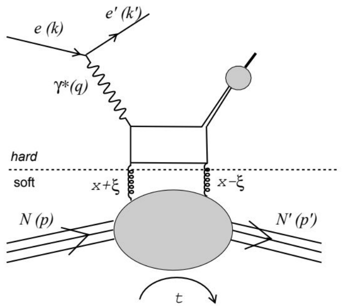
Purpose

- Understand **structure of nucleon**
  - Modern description in terms of Generalized Parton Distributions (GPDs)
  - Describes correlation between longitudinal momenta and transverse distribution
- Focus on **hard exclusive heavy quarkonia production**
  - Direct access to **gluon GPDs**
  - Specific focus on **vector mesons**



source: Marc Vanderhaeghen

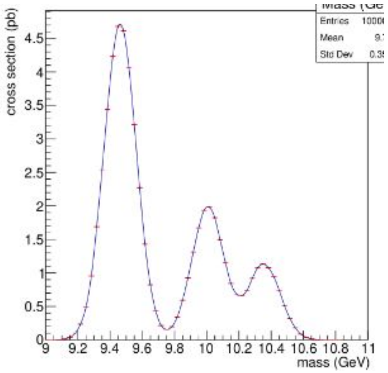
Purpose



- Two domains:
  - **Low energy (JLab):** polarized J/Ψ
    - Near threshold, dominated by 3-gluon interaction?
    - Factorization is unclear
  - **High energy (EIC, EICC):** access gluon GPDs at high energy
    - J/Ψ and ϒ
    - Factorization has been demonstrated (Collins, 2004)
    - Focus on photoproduction & electroproduction into e^+e^-, $\mu^+\mu^-$ pairs

DEEPGen and DEEPSim

- **Flexible event generators** designed for **exclusive reactions**
- **DEEPGen:** designed for Jefferson Lab
  - Fixed target, low energies
  - Projections used for experiments in Halls A, C, D
- **DEEPSim:** extension for **modern high energy colliders**
  - Discussed in EIC/ECCE exclusive working group
  - Still undergoing cross-checks
- Developed by Marie Boer & VT group



Supported reactions

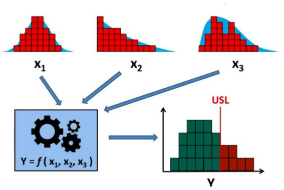
DEEPGen:

- Hard exclusive processes:
  - DVCS
  - TCS
  - DDVCS
- Other processes:
  - VCS
  - Elastic scattering
  - DIS
  - Low energy pion
  - Low energy kaon

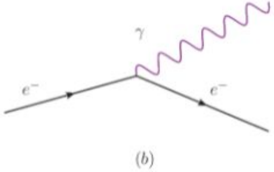
DEEPSim (in progress):

- Hard exclusive processes:
  - DVCS
  - TCS
  - DDVCS
  - HEMP
    - ρ
    - J/Ψ
    - Υ
  - More coming soon!

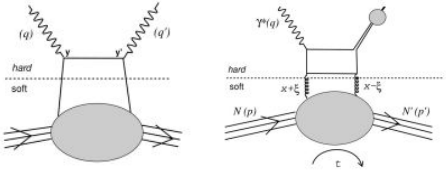
Generic Event Generation



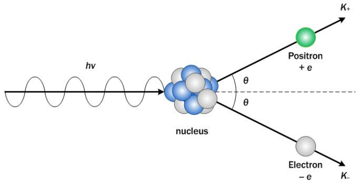
1. Randomize initial conditions within user-defined ranges



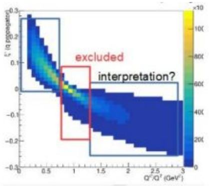
2. Boost to proton frame & emit virtual photon

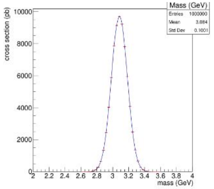


3. Boost to CM frame & generate outgoing photon (or meson, or...)

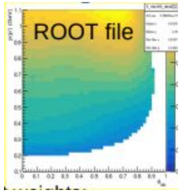


4. Boost to decay frame & generate lepton pair



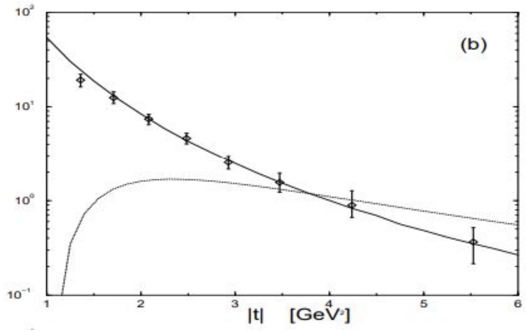


5. Apply kinematic cuts & weight by cross-section



6. Save all relevant values to ROOT/HEP file

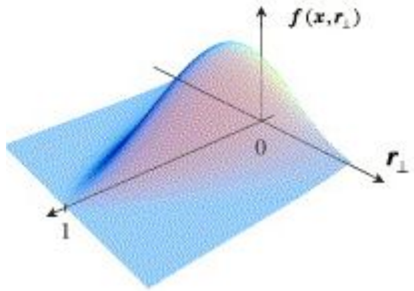
Quarkonia Production



- **Flexible framework** for meson production
- Hard exclusive **J/Ψ** production
  - User provides ratio between **two-gluon** and **three-gluon** cross-sections
  - Two-gluon dominates at EIC et al, three-gluon near threshold
    - Three-gluon gives more flexible momentum transfer
- Hard exclusive **ϒ** production
  - Currently using similar model to J/Ψ
  - Plan to compare w/ numerical BKFL xsec: $\mathcal{F}_{BFKL}(s',t) = \frac{t^2}{(2\pi)^3}\int d\nu \frac{\nu^2}{(\nu^2+1/4)^2} e^{\chi(\nu)z} I_\nu^{q^*}(Q_\perp) I_\nu^{\gamma V}(Q_\perp),$
  - Handles 1S, 2S, 3S resonances
- Currently extending to **other vector mesons**

GPD parameterizations

- **Easy to swap GPDs in and out** by design
    - Using generic model for EIC projections (GPD = PDF * *t*-dependent dipole)
    - Includes both quark & gluon GPDs
    - VGG model for JLab projections
- Current reference: CTEQ 2018 data for PDFs
    - *t* dependence experimentally set to $e^{1.13t}$ (Brodsky et. al, 2000)
    - May require tuning for high energies at EIC (fits from HERA, etc.)
- Use meson mass as factorization scale



Production modes

- J/Ψ: Both **photoproduction** (JLab) & **electroproduction** (EIC et. al) handled by **same cross-sections (**varying 2-3 gluon ratio)
- Beam:
    - Quasi-photoproduction & electroproduction for EIC: scale by **flux factor** (HERA collab. Z)
    - JLab: not factorized for electroproduction, using quasi-real photon flux + Bremsstrahlung (dep. on target) for quasi-photoproduction
    - Real photoproduction possible at JLab
- Spin:
    - Currently handle all polarization possibilities for JLab
    - Will soon handle for EIC
- Measuring both J/Ψ and ϒ through lepton decay modes (e^+e^-, $\mu^+\mu^-$)

Generator Internals

- DEEPGen and DEEPSim are **weighted generators**
  - Avoid peaks & spikes in regions that are less physically interesting
- **Multi-weighting system**
  - 2 gluon only, BH only, meson+BH interference only,..
  - Allow tuning at analysis level
  - Saves significant **CPU time** (same file into Geant4)
- **DEEPSim only:** Crossing angle corrections (optional)
- **DEEPGen (DEEPSim TBA):**
  - Radiative corrections and polarization vectors
  - Polarized cross sections

Adding Mesons in 5 Minutes

Step 1: Add meson object with mass distribution & kinematic ranges

```
UpsilonMeson::UpsilonMeson(double* stdDevs, double lowerBound, double upperBound) {
    double scalars[3] = {22./40., 11./40., 7./40.};
    double masses[3] = {9.465, 10.01, 10.36};
    distribution = new TF1("mesonDistribution", "[0] * gaus(1) + [4] * gaus(5) + [8] * gaus(9)", lowerBound, upperBound);
    for(int a = 0; a < 3; a++) {
        distribution->SetParameter(4 * a, scalars[a]);
        distribution->SetParameter(4 * a + 1, 1. / (stdDevs[a] * TMath::Sqrt(2 * TMath::Pi())));
        distribution->SetParameter(4 * a + 2, masses[a]);
        distribution->SetParameter(4 * a + 3, stdDevs[a]);
    }

    EGammaMin = 0;
    EGammaMax = 10000;
    TMin = 0;
    TMax = 100;
    PhiMin = 3.;
    PhiMax = 363.;
    ThMin = 30.;
    ThMax = 155.;
    PhisMin = 0.;
    PhisMax = 360.;
    PsisMin = 0.;
    PsisMax = 360.;

    cdfTable.setct11(cdfTablePath);
}
```

Adding Mesons in 5 Minutes

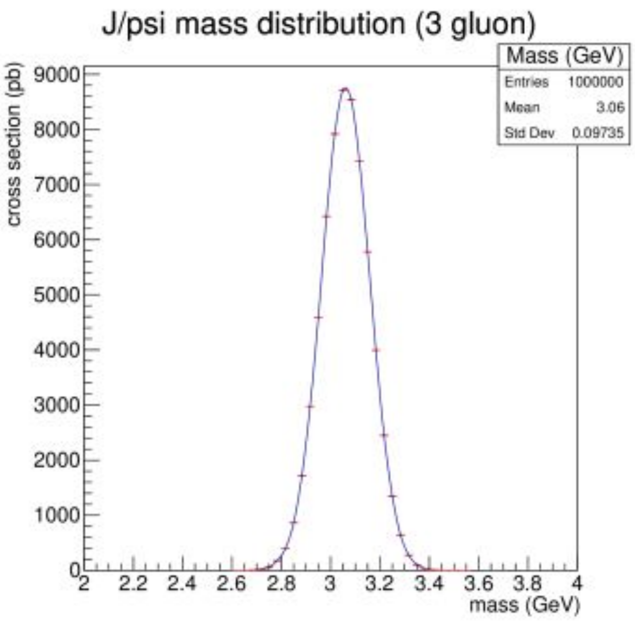
Step 2: Implement cross-section and GPDs

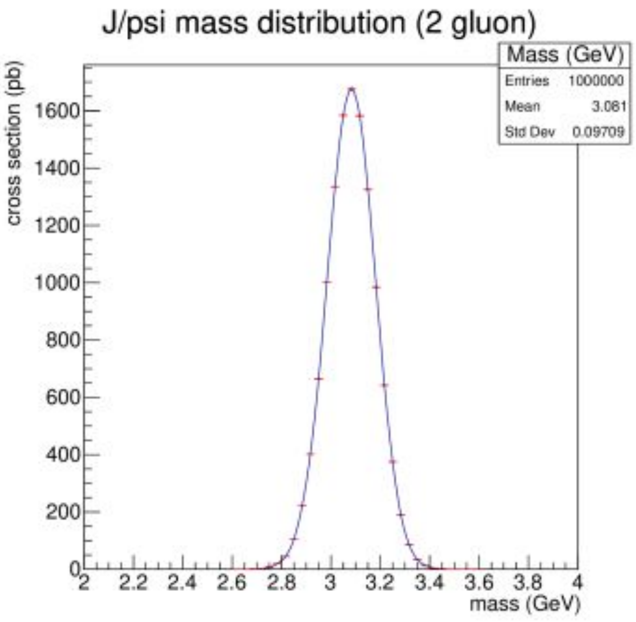
```
double UpsilonMeson::xsecPhotonUnpol(double x, double Q, double t, double Qp2) {
    // cout << "x: " << x << " Q: " << Q << " t: " << t << " Qp2: " << Qp2 << "| Gluon PDF: " << cdfTable.parton(0, x, Q) << endl;
    double firstSummand = ((4 * pow(n_colors, 4)) / (pow(pow(n_colors, 2) - 1, 2))) * exp(1.13 * t) * cdfTable.parton(0, x, Q);
    double secondSummand = 0;

    for(int f = 1; f <= 3; f++) {
        secondSummand += exp(1.13 * t) * abs(cdfTable.parton(f, x, Q) + cdfTable.parton(-f, x, Q));
    }

    return 1000 * (firstSummand + secondSummand) * quarkXsecPhotonUnpol(t, Qp2); // 1000x converts from nb to pb
}

double UpsilonMeson::quarkXsecPhotonUnpol(double t, double Qp2) {
    double tau = -t / Qp2;

    double C = sqrt(3 * electronDecayWidth * pow(sqrt(Qp2), 3) / alphaEM);
    double Iqq = 1 / n_colors;

    double firstFactor = (4 * pow(tau, 2)) / (1 - pow(tau, 2));
    double secondFactor = log(pow(1 + tau, 2) / (4 * tau));
    double phaseSpaceFactor = PI / (4 * pow(t, 4));

    return phaseSpaceFactor * pow(abs(C * pow(Iqq, 2) * firstFactor * secondFactor), 2);
}

double UpsilonMeson::xsecElectronUnpol(double y, double Q2, double x, double Q, double t, double Qp2) {
        return fluxFactor(y, Q2) * xsecPhotonUnpol(x, Q, t, Qp2);
}
```

Adding Mesons in 5 Minutes

Step 3: There is no step 3.

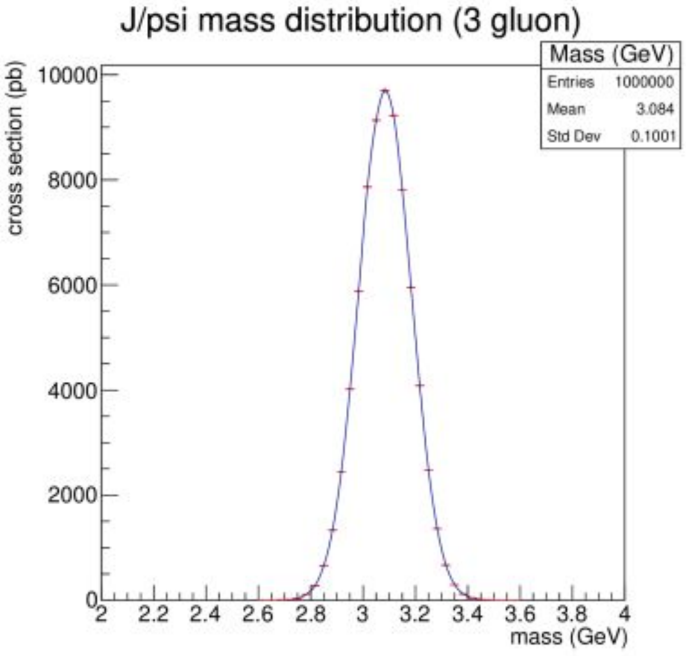
Projections (J/Ψ, near threshold)

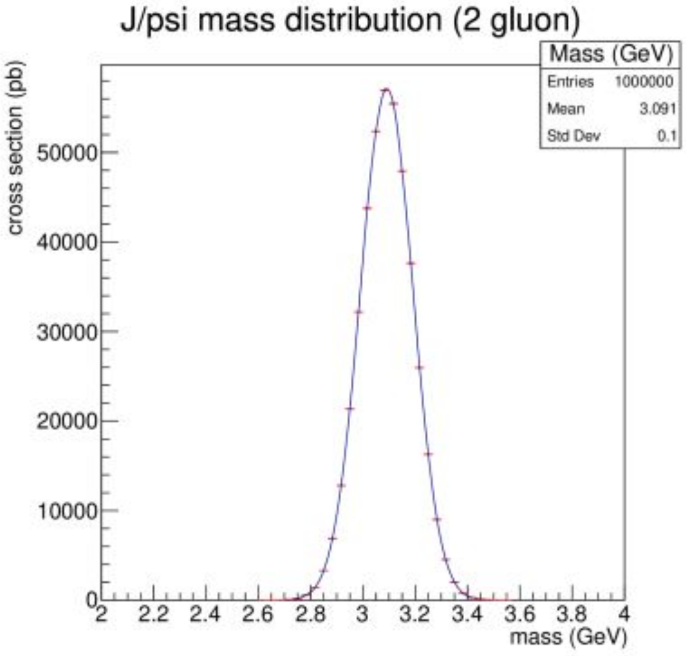




(photoproduction, 10% smearing) At low energy, 3-gluon dominates in our model

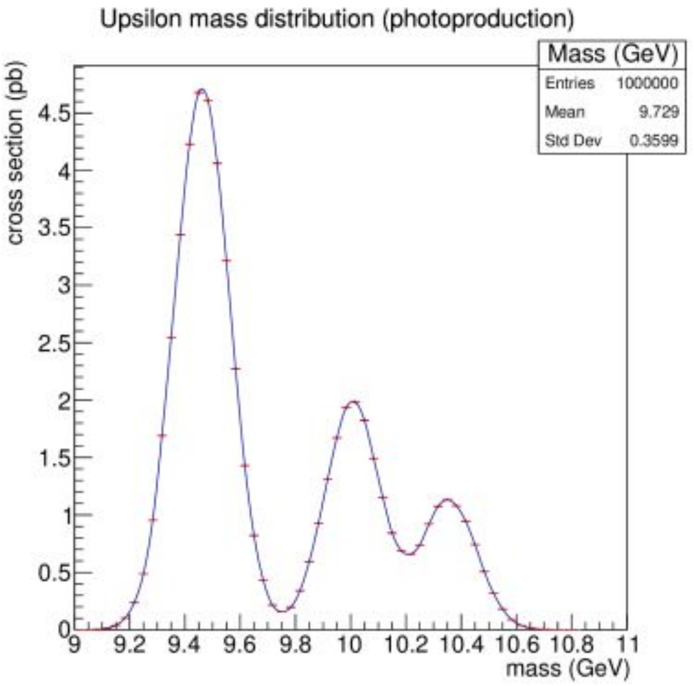
Projections (J/Ψ, high energy)

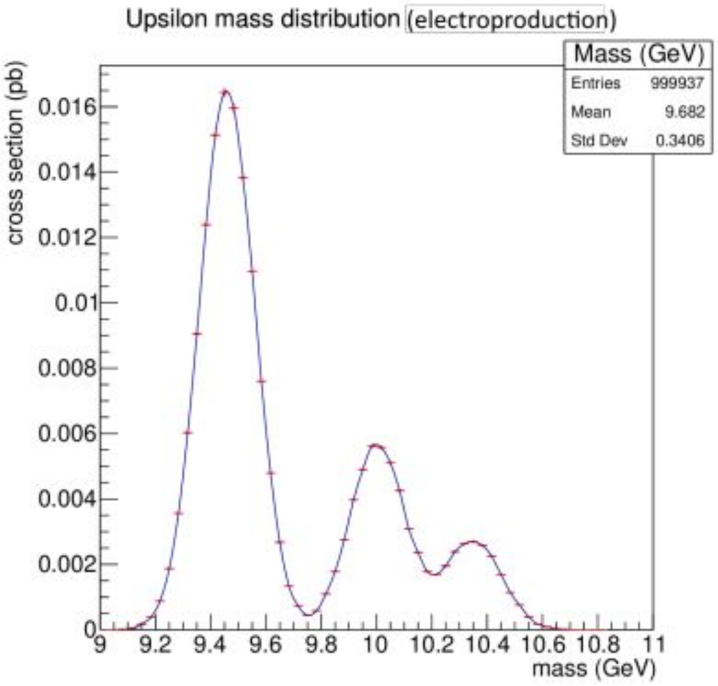




(photoproduction, 10% smearing) At higher energies, 2-gluon dominates in our model

Projections (Υ)





(1S, 2S, 3S normalization extrapolated from LHC)

What's possible?

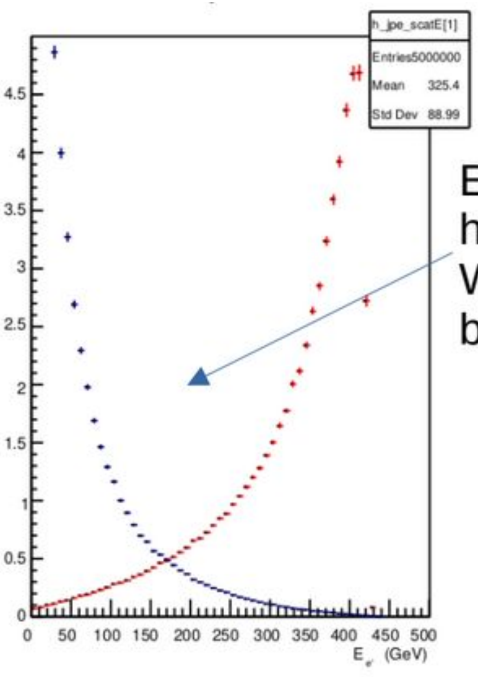
- **DEEPSim** generator can guide experiments to **probe gluon GPDs**, but there are constraints.
- Must ensure decay leptons live in **different phase space** than beam leptons (if two electrons)
- Tools at generator level to perform kinematic and physics studies:
    - Avoid region where $M_m \sim Q^2$
    - Must cut out **Bethe-Heitler peaks**
    - Must **detect outgoing proton** to screen out associated productions that don't touch GPDs

Leptoproduction of lepton pairs

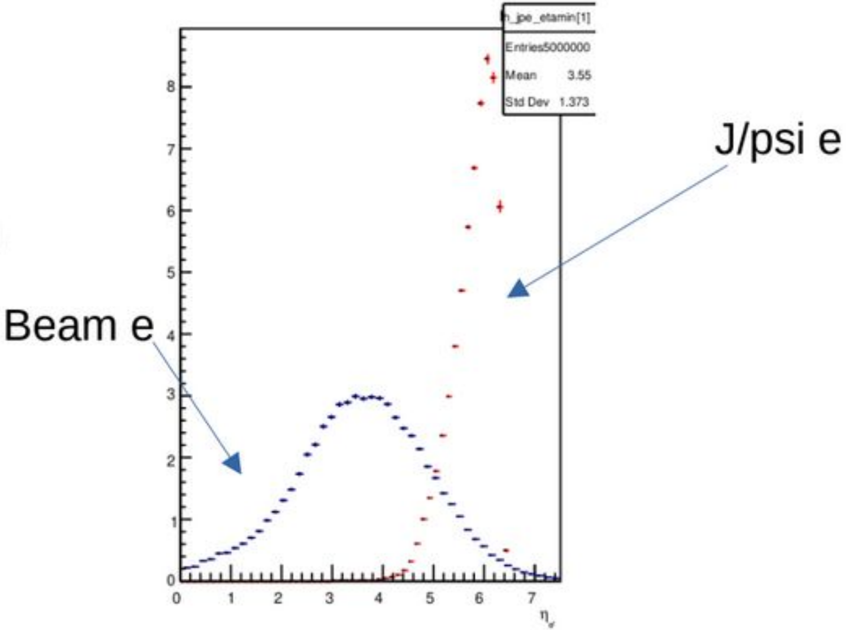
- **JLab and EIC have electron beam**
- If final leptons are electrons, we have 2 identical leptons!
    - Need antisymmetrization of wavefunction (hard to extract GPDs)
    - Cannot experimentally define the kinematics
- At EIC: use the **rapidity gap**
    - Beam electrons can be **backward**
    - For very specific kinematics, we assume small interference
    - Ideally, assumption can be checked with e+e- vs. mu+mu-
- At JLab: **not possible** because two electrons have same kinematics
- Large **rapidity gap** (EIC) or **photoproduction** (JLab+EIC w/ hard scale provided by meson mass) and **muon detectors**

Leptons share a kinematic range

Projections for J/Ψ production at EIC range (5 GeV electron, 41 GeV photon)

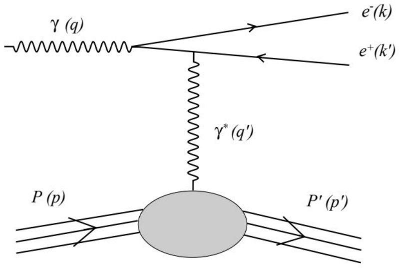


Even if the 2 electrons have a different distribution
We cannot distinguish them based on it

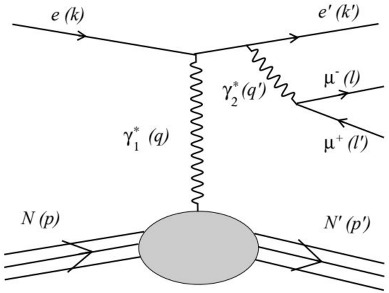


Interference with Bethe-Heitler

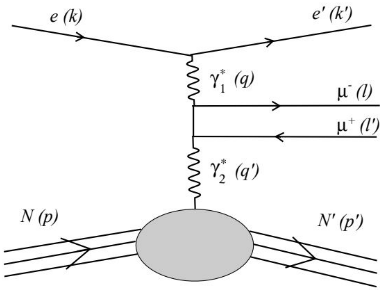
- **Bethe-Heitler:** competing process for J/Ψ (and all dilepton processes)
  - Produces lepton pair via photon exchange with proton (**no GPDs**)
- Avoid this by cutting away the peaks & not placing detectors near beam
- Cut is **not trivial** – function of E_γ, t, Q'^2
- One outgoing lepton tends to be **collinear with beam**
  - Dynamic cuts for integration range in θ
  - Don't want detectors too close to beam



photoproduction
(also interferes with TCS)

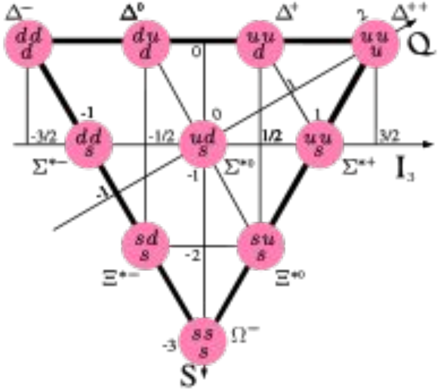


Electroproduction
(similar behavior to BH in DVCS)



Electroproduction
(similar behavior to BH in TCS)

Other Backgrounds

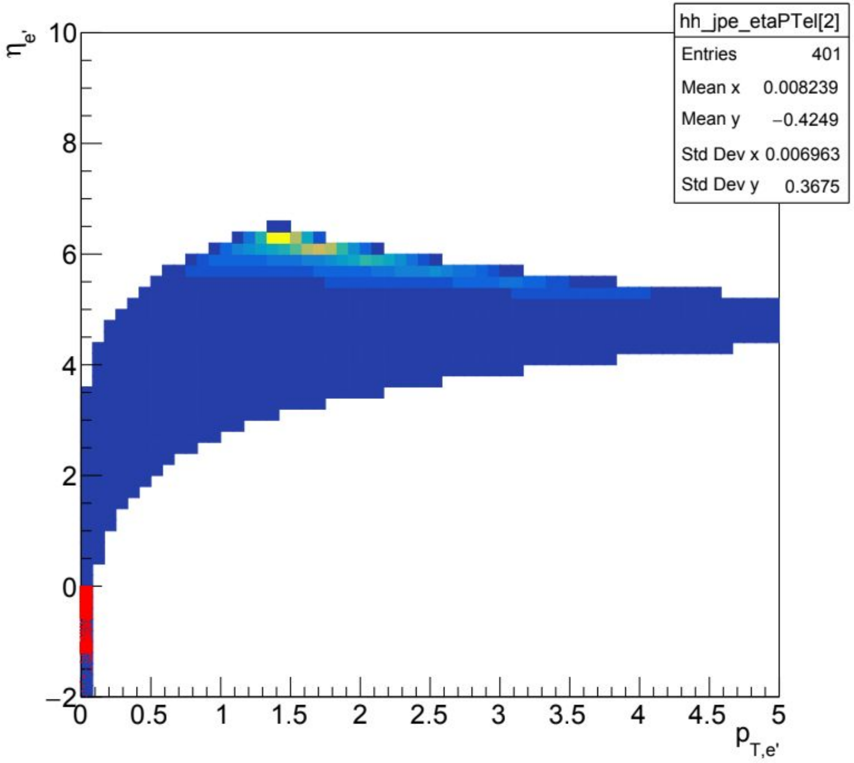


- **Must detect outgoing proton** as well as leptons, or there's too much background
  - Soft pion emission
  - Other associated production
  - pi+pi- pairs (seen as leptons)
  - Semi-inclusive background (dominant for EIC)
  - **Low background** at JLab

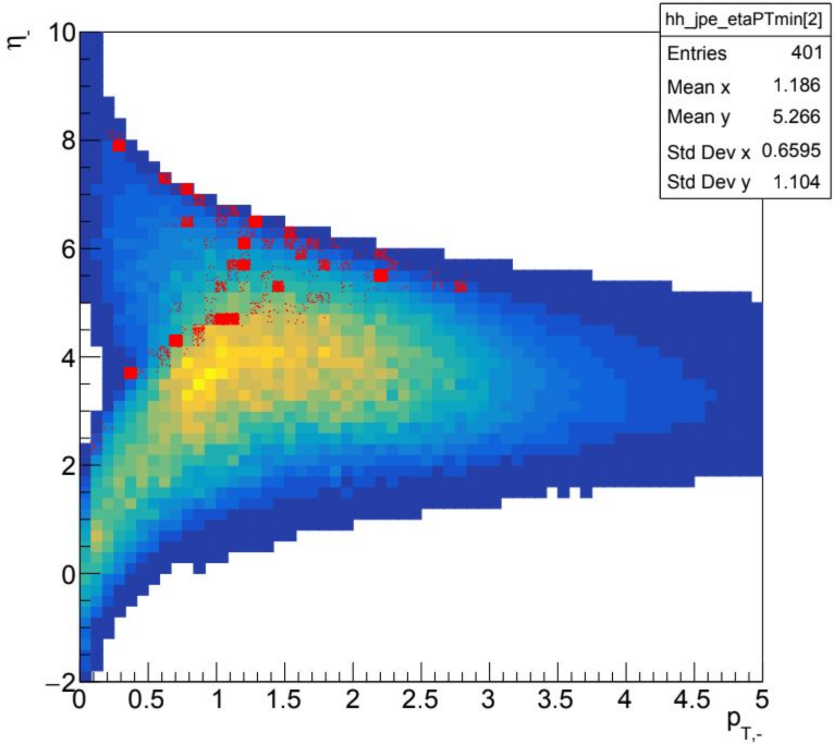
- For electroproduction, **must cut at** $W^2 \approx 2$ **GeV**
  - Resonance of proton with delta particles
  - Stops us from seeing GPDs

Results of kinematic cuts

Beam electron rapidity vs. transverse momentum



Decay electron rapidity vs. transverse momentum



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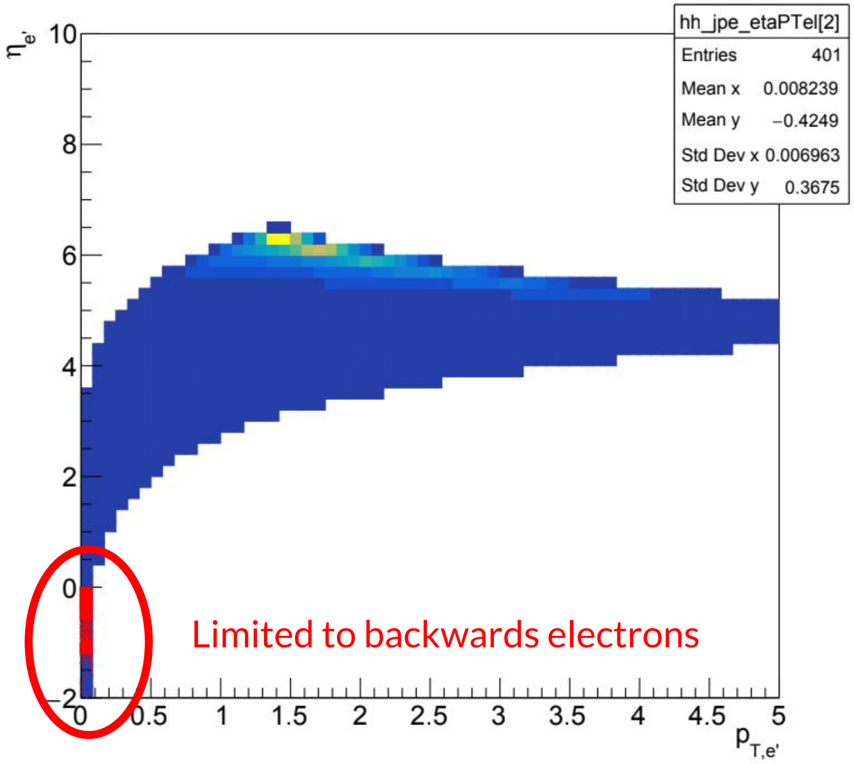

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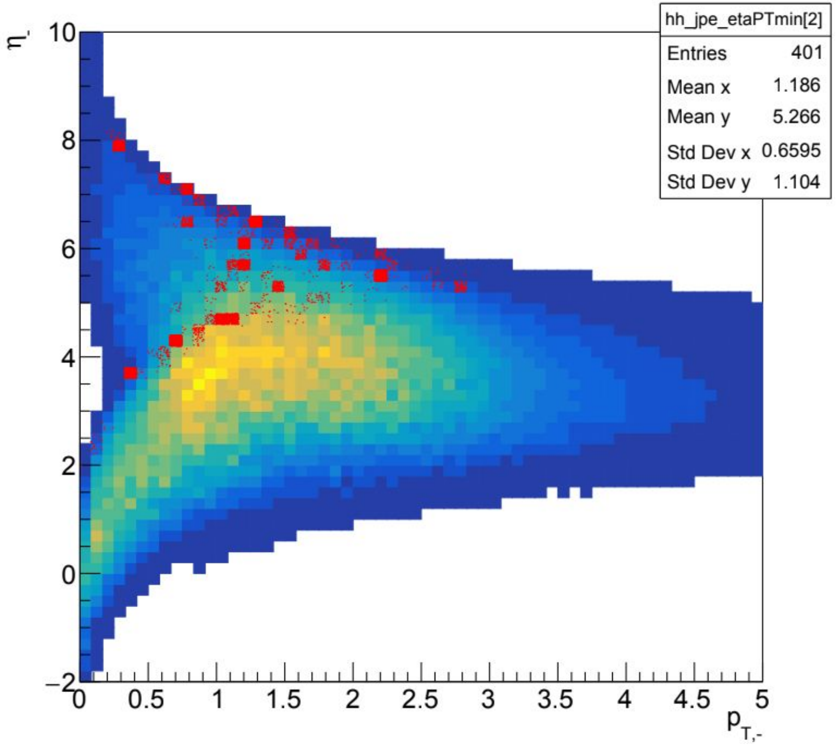

Results of kinematic cuts

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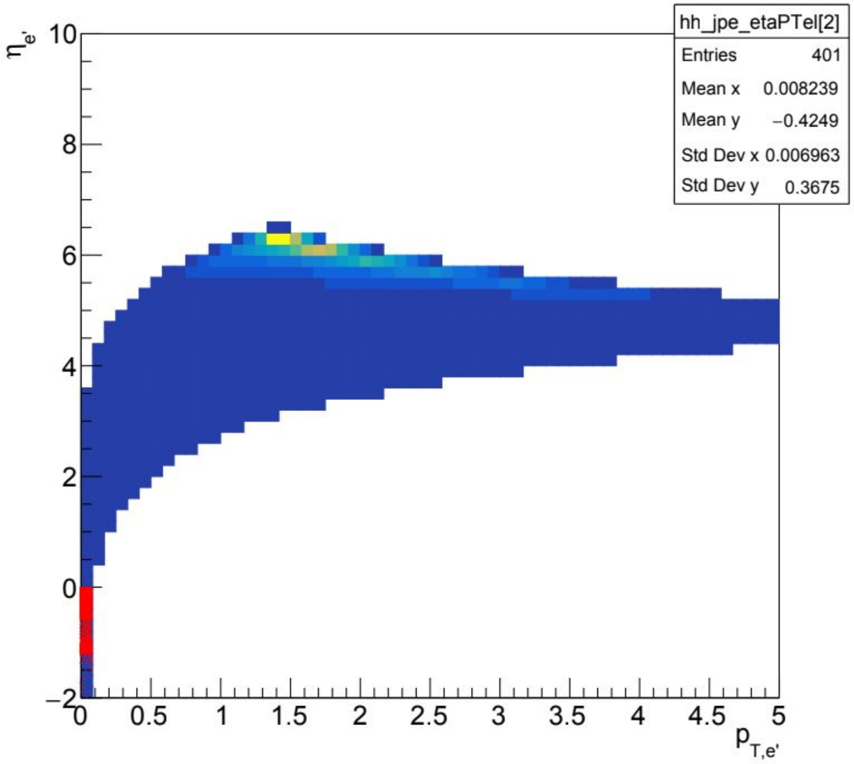
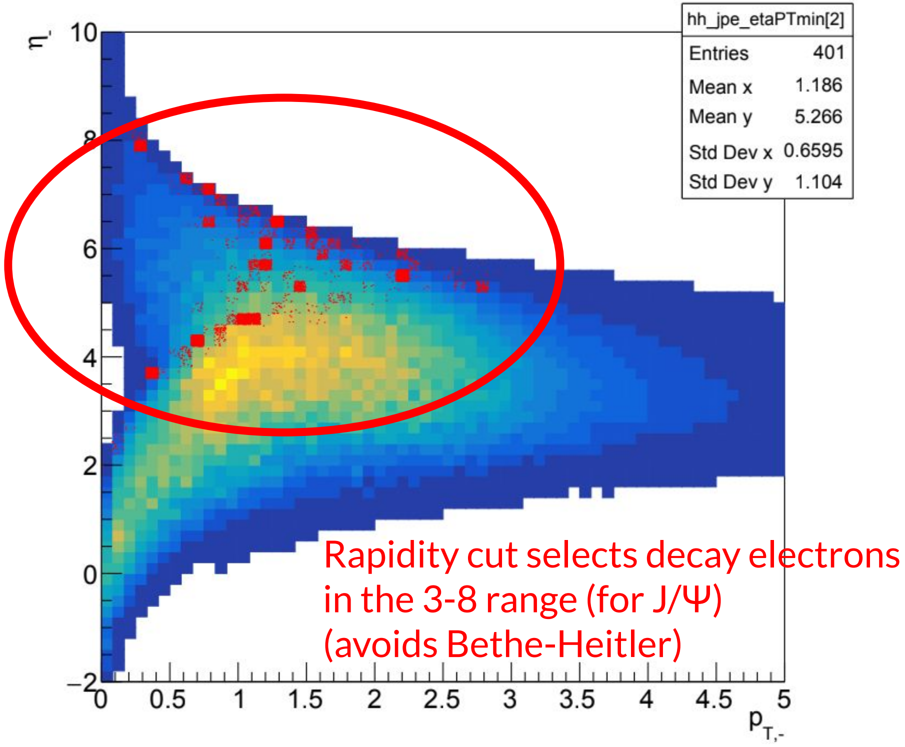
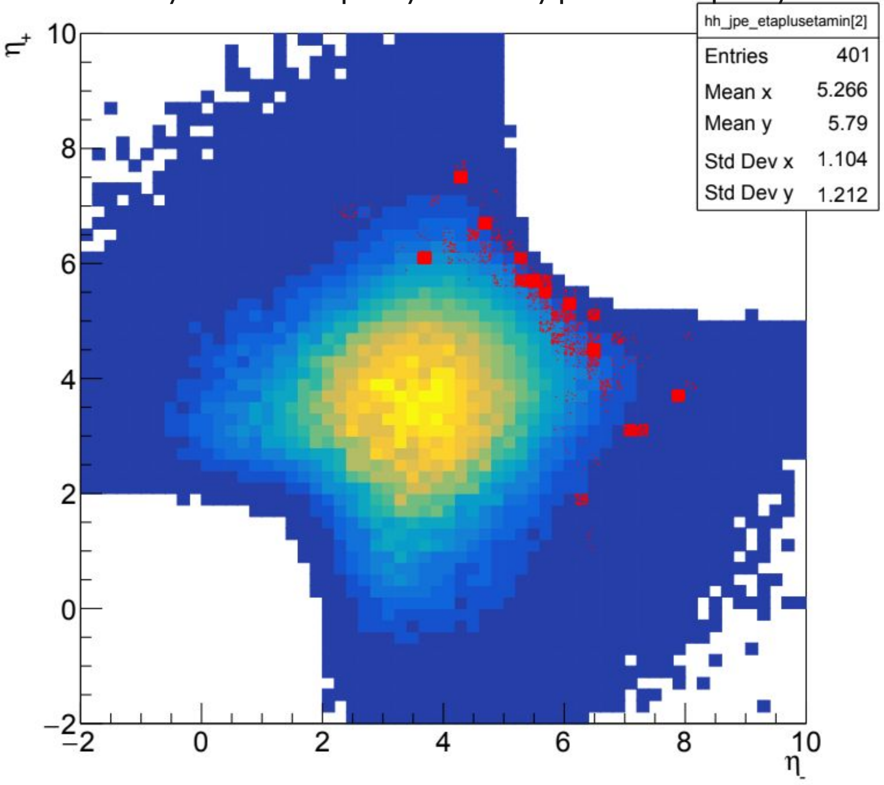


Decay electron rapidity vs. transverse momentum

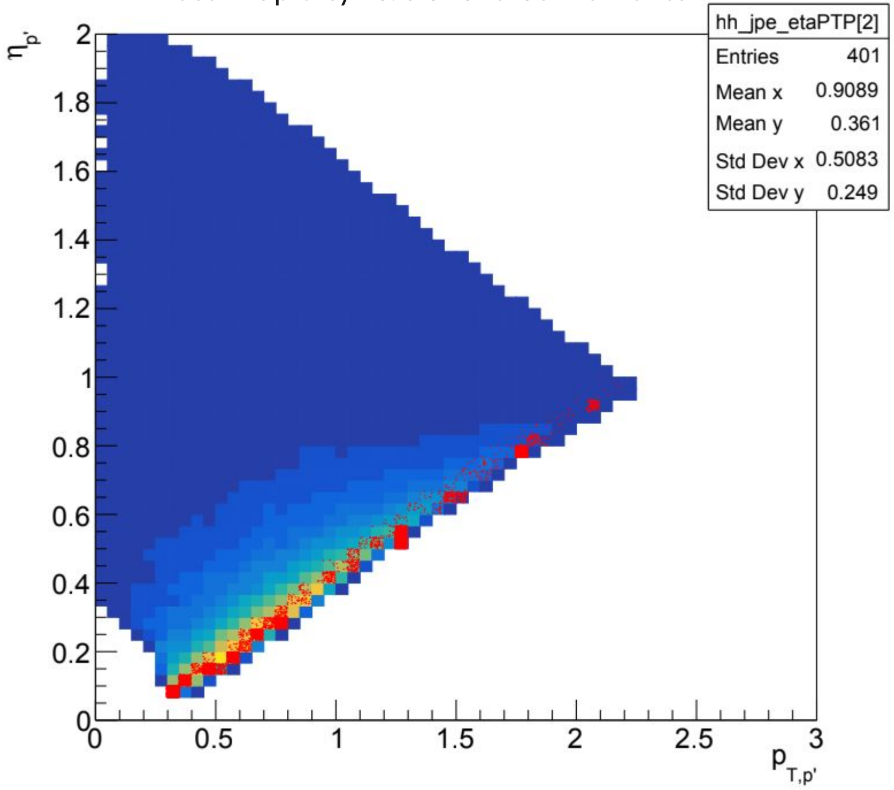


Results of kinematic cuts

Decay electron rapidity vs. decay positron rapidity

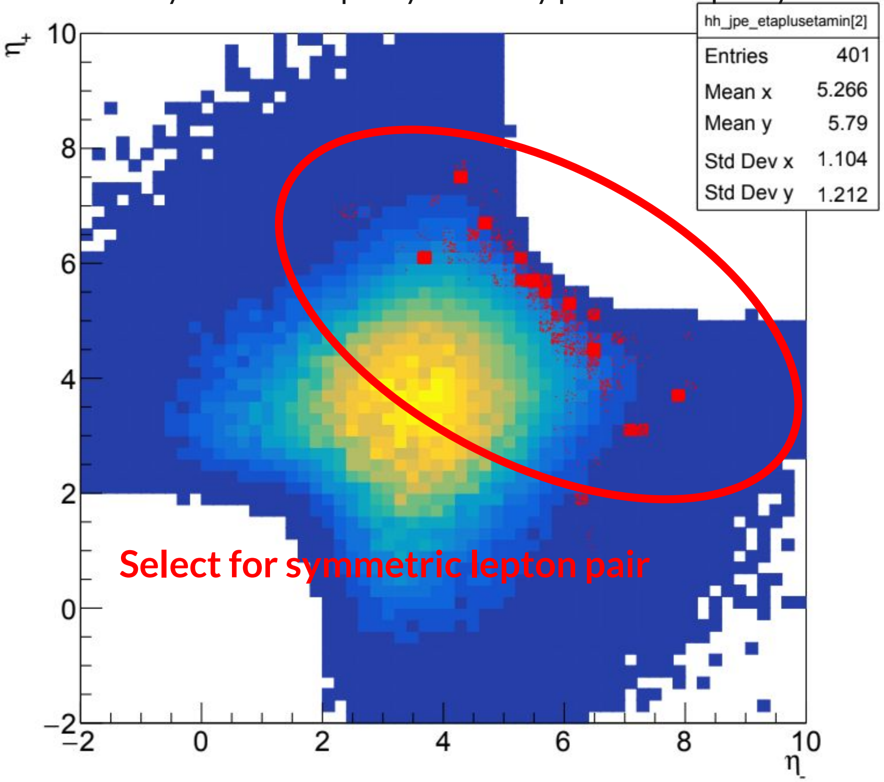


Proton rapidity vs. transverse momentum

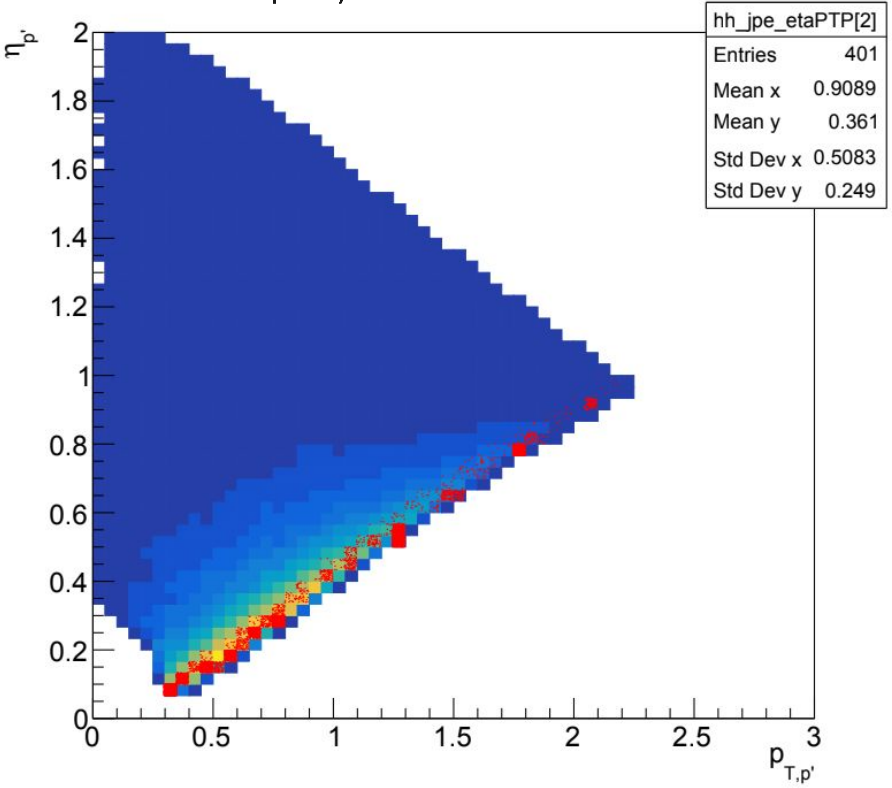


Results of kinematic cuts

Decay electron rapidity vs. decay positron rapidity

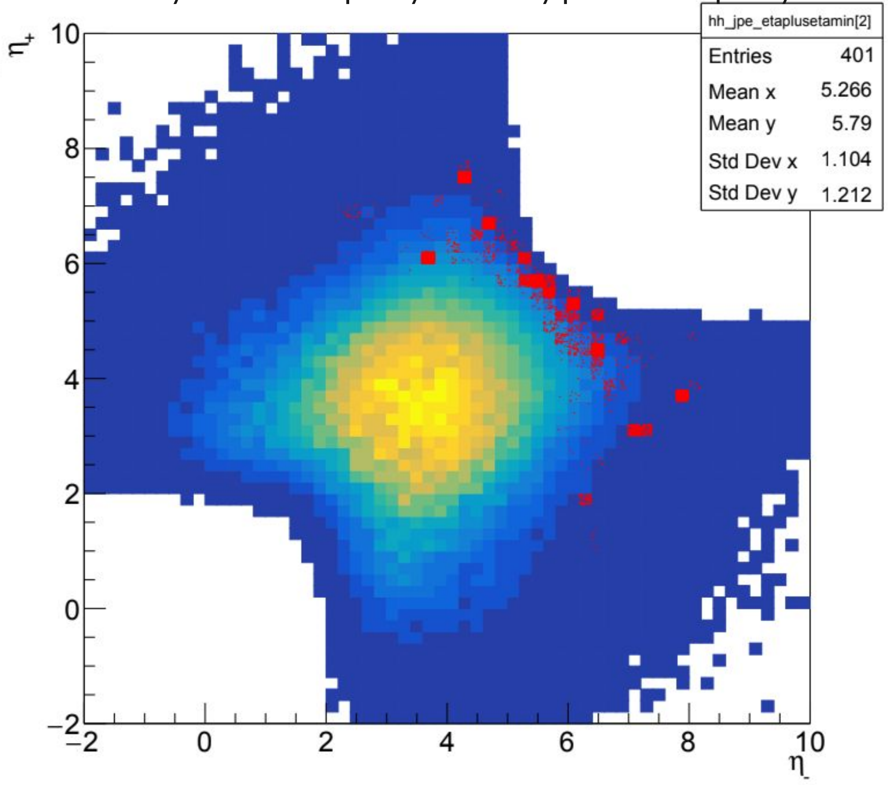


Proton rapidity vs. transverse momentum

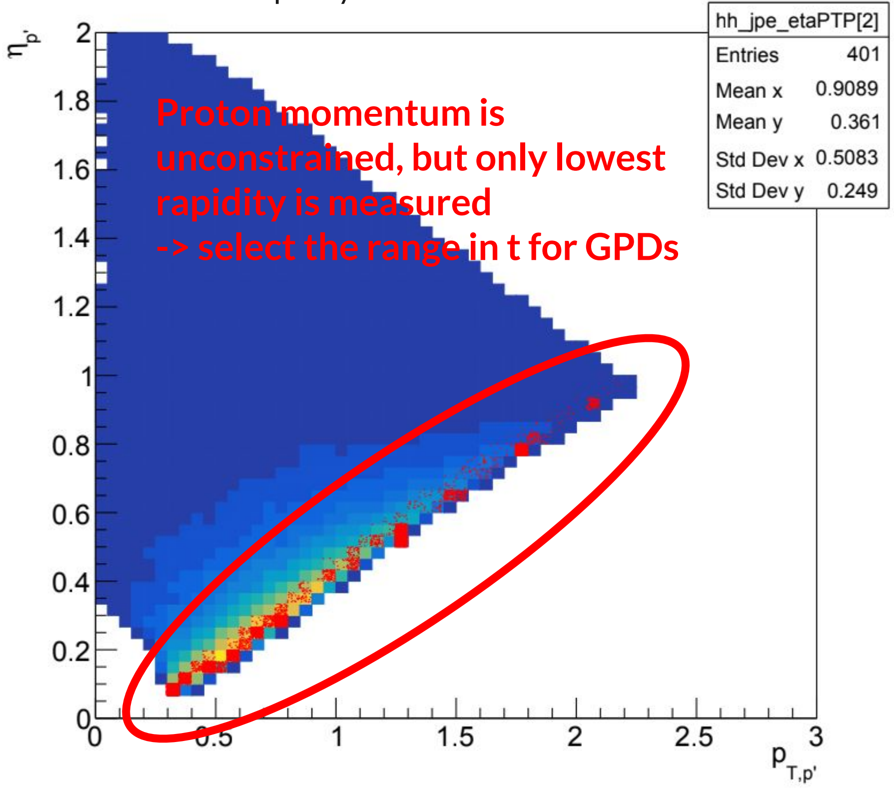


Results of kinematic cuts

Decay electron rapidity vs. decay positron rapidity



Proton rapidity vs. transverse momentum

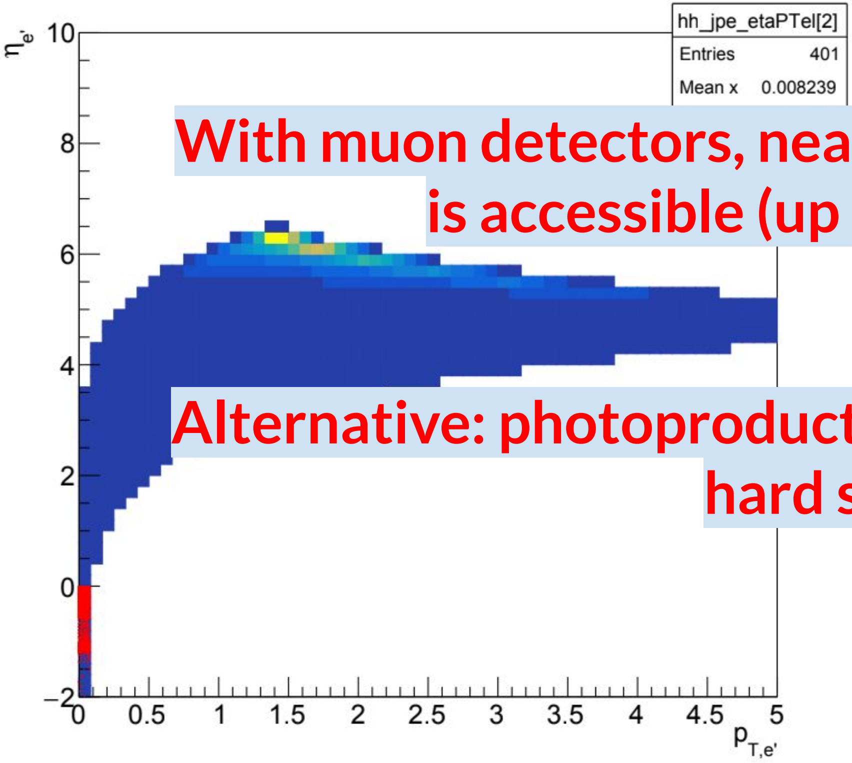


Conclusions

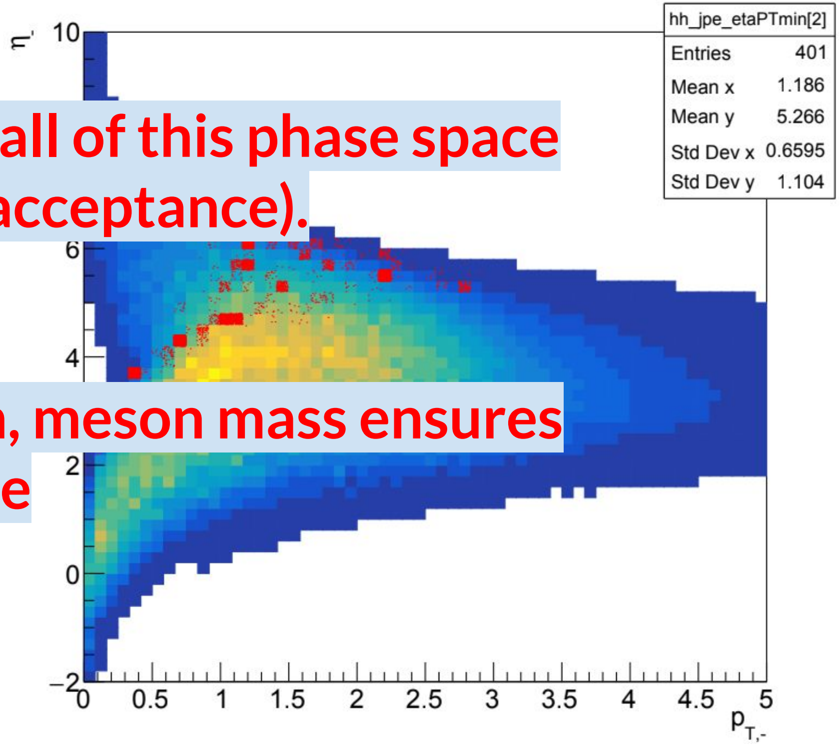
- Electroproduction into e^+e^- has **very limited kinematic access**
- **Two possible solutions:**
  - Measure GPDs from **photoproduction** into e^+e^-
    - Hard scale: mass of meson
    - Validity check: $P\,\gamma^* \to P'\,e^+e^-$ vs. $P\,\gamma^* \to P'\,\mu^+\mu^-$
  - Install **muon detectors** & measure muon decay mode
    - Allows access to **all of phase space** (up to acceptance)
    - Currently doing studies for J/Ψ and ϒ (various energies)
    - Preliminary results: phase space **severely diminished** if e^+e^- is only option!

Results of kinematic cuts

Beam electron rapidity vs. transverse momentum



Decay electron rapidity vs. transverse momentum

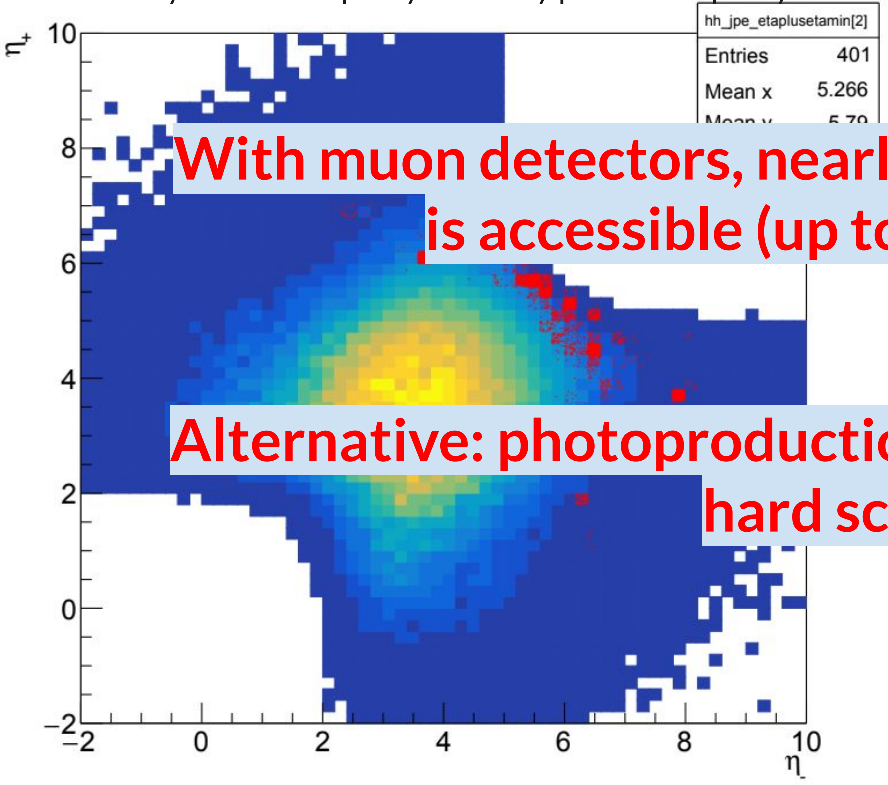


With muon detectors, nearly all of this phase space is accessible (up to acceptance).

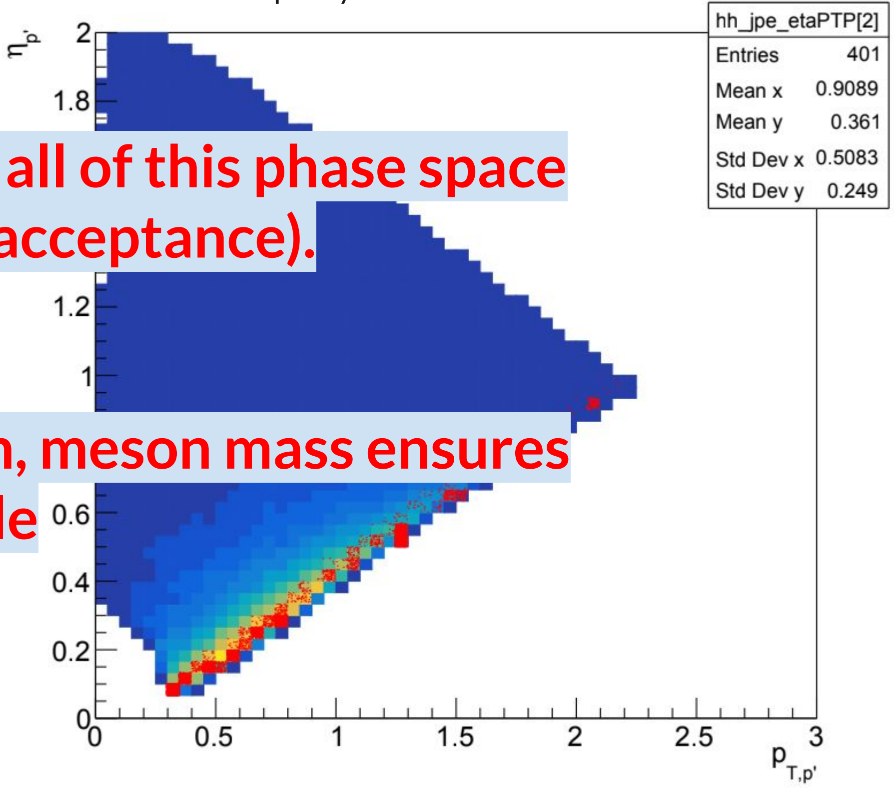
Alternative: photoproduction, meson mass ensures hard scale

Results of kinematic cuts

Decay electron rapidity vs. decay positron rapidity



Proton rapidity vs. transverse momentum



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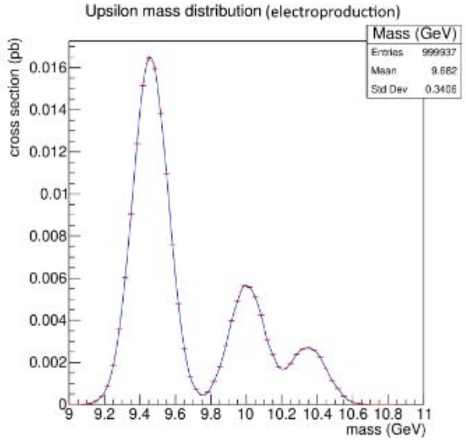
Summary



- **DEEPGen & DEEPSim:** Powerful, flexible generators for fixed target & collider production
    - Source released soon
    - Very easy to extend (new models welcome!)
    - Many more reactions on the horizon
- Current research
    - **High energy quarkonia production** (Marie/Tyler)
    - **Polarized J/Ψ studies** at JLab (Erik Wrightson)
    - Modelling both electro- and photoproduction
- **Installing muon detector** at JLab, EIC, et. al would **greatly improve studies** of HEMP & other dilepton decay reactions.

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