Challenges in measurements of exclusive J/ψ at the EIC

Thanks to many for direct and indirect help with this work, including:
Mark Baker, Bill Li, Alex Jentsch, Kong Tu, Axel Schmidt, Or Hen, Justin Frantz,
Dhevan Gangadharan, Thomas Ullrich, Tobias Toll, ePIC exclusive/diffractive/tagging WG…

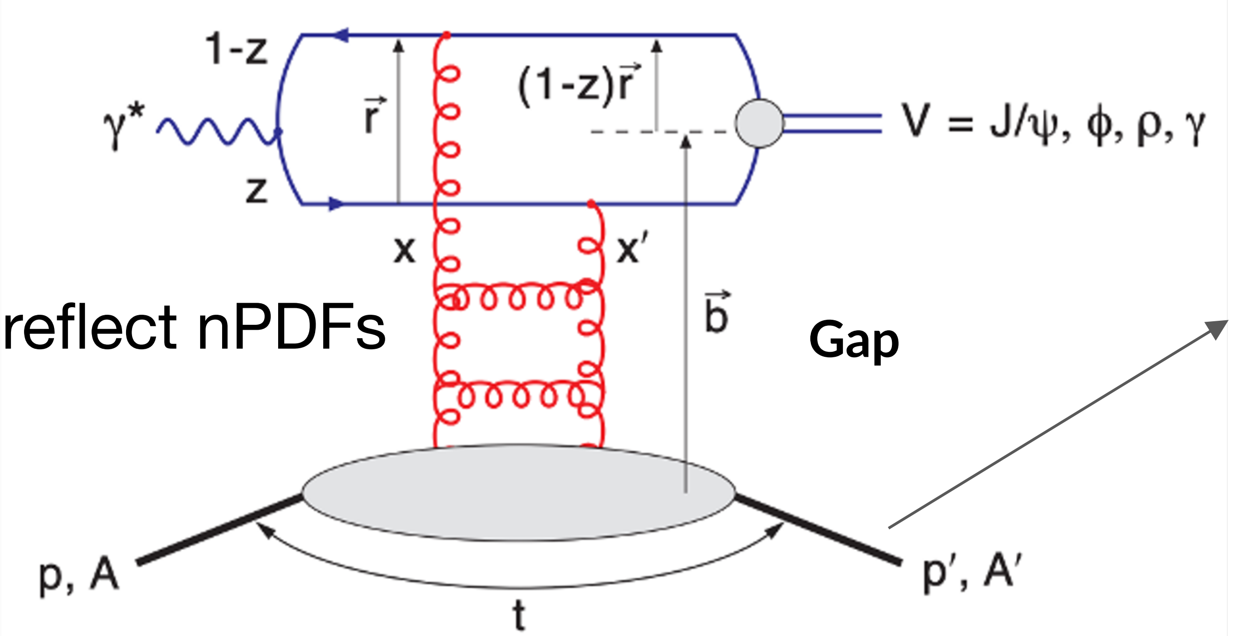
Peter Steinberg, BNL / EIC Theory WG / 16 Feb 2023

Diffraction in eA

- **I don't think I need to give the full case, but two major issues from the NAS report and subsequent Yellow report are relevant for this discussion**
  - Can we probe the low-x structure of the nucleus, and especially address the questions of parton saturation?
  - What do we know about the spatial parton structure of nuclei?

- **Vector meson production addresses both of these**

Cross sections reflect nPDFs



t distributions reflect spatial distributions

https://arxiv.org/pdf/1307.8059.pdf

Coherent processes: Sar*t*re

- **The Sar*t*re model (Toll & Ullrich, 2013) implements the dipole model in a form usable for experimentalists (i.e. with final state particles!)**

$$\mathcal{A}^{\gamma^* p}_{T,L}(x_{\boldsymbol{P}}, Q, \Delta) = i\int \mathrm{d}r \int \frac{\mathrm{d}z}{4\pi}\int \mathrm{d}^2\mathbf{b}\,[(\Psi_V^*\Psi)(r,z)]\,2\pi r J_0([1-z]r\Delta)\, e^{-i\mathbf{b}\cdot\Delta}\frac{\mathrm{d}\sigma^{(p)}_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}}(x_{\boldsymbol{P}}, r, \mathbf{b})$$

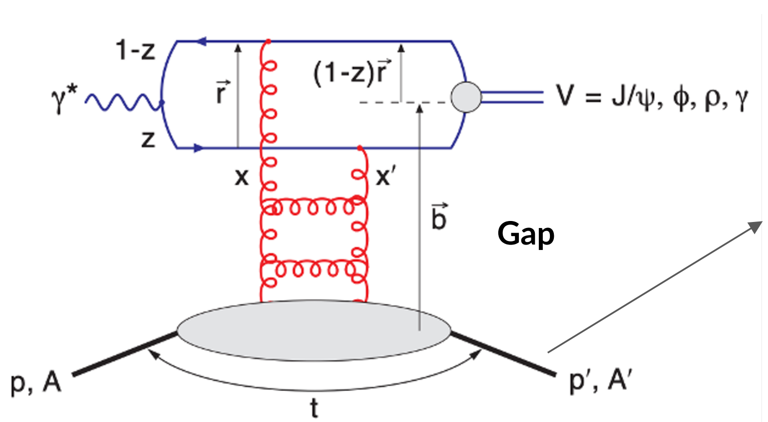
with the e+A dipole cross section

$$\frac{1}{2}\frac{\mathrm{d}\sigma^{(A)}_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}}(x_{\boldsymbol{P}}, r, \mathbf{b}, \Omega_j) = 1 - \exp\left(-\frac{\pi^2}{2N_C} r^2 \alpha_S(\mu^2) x_{\boldsymbol{P}} g(x_{\boldsymbol{P}}, \mu^2)\sum_{i=1}^{A} T(|\mathbf{b}-\mathbf{b}_i|)\right)$$

and the final production cross section

$$\frac{\mathrm{d}\sigma^{\gamma^* A}_{T,L}}{\mathrm{d}t} = \frac{1}{16\pi}\left\langle \left|\mathcal{A}^{\gamma^* p}(x_{\boldsymbol{P}}, Q^2, t)\right|^2\right\rangle_{\Omega}$$

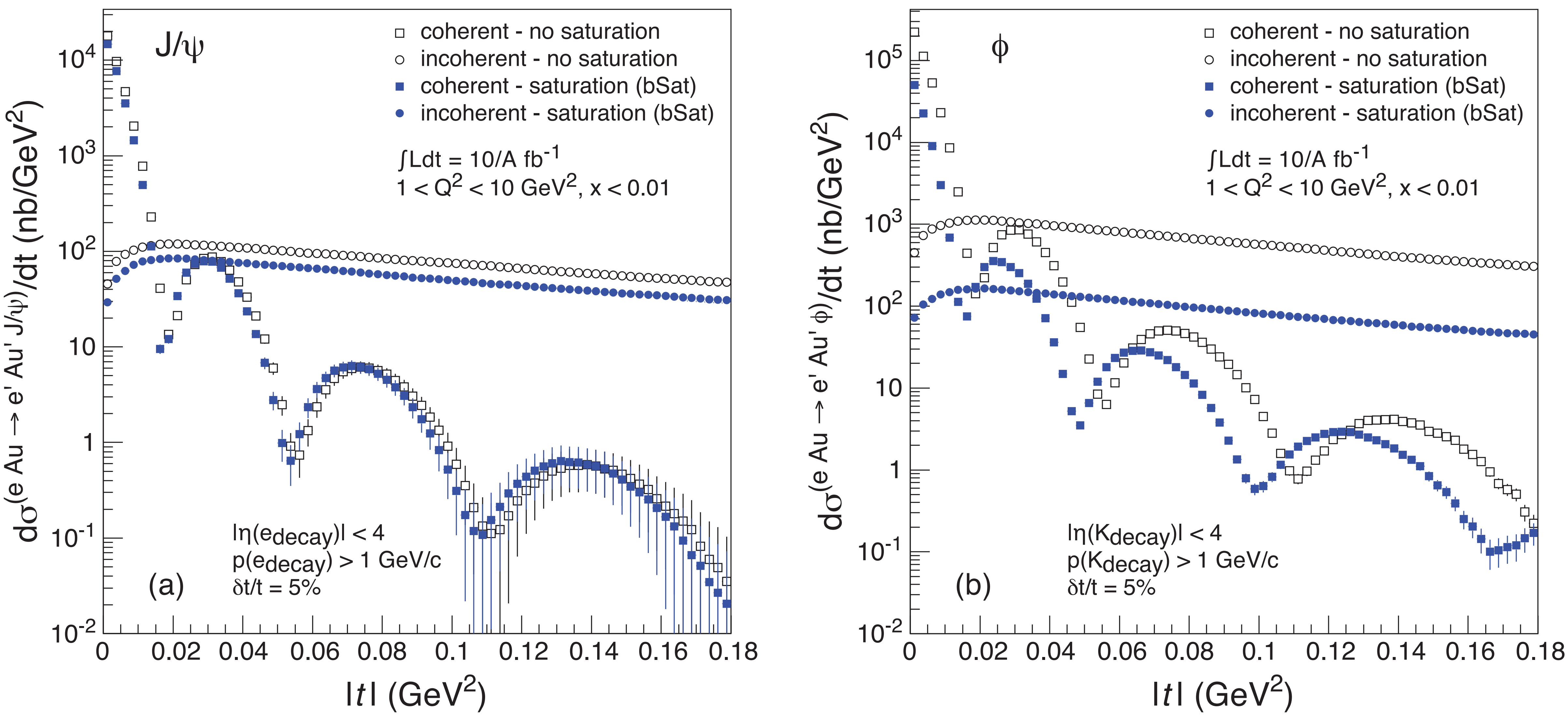
- **Here only used for coherent reactions, with no nuclear breakup**
    - Incoherent contributions only utilized for their cross sections



The basic task:

Toll & Ullrich
Phys. Rev. C **87**, 024913

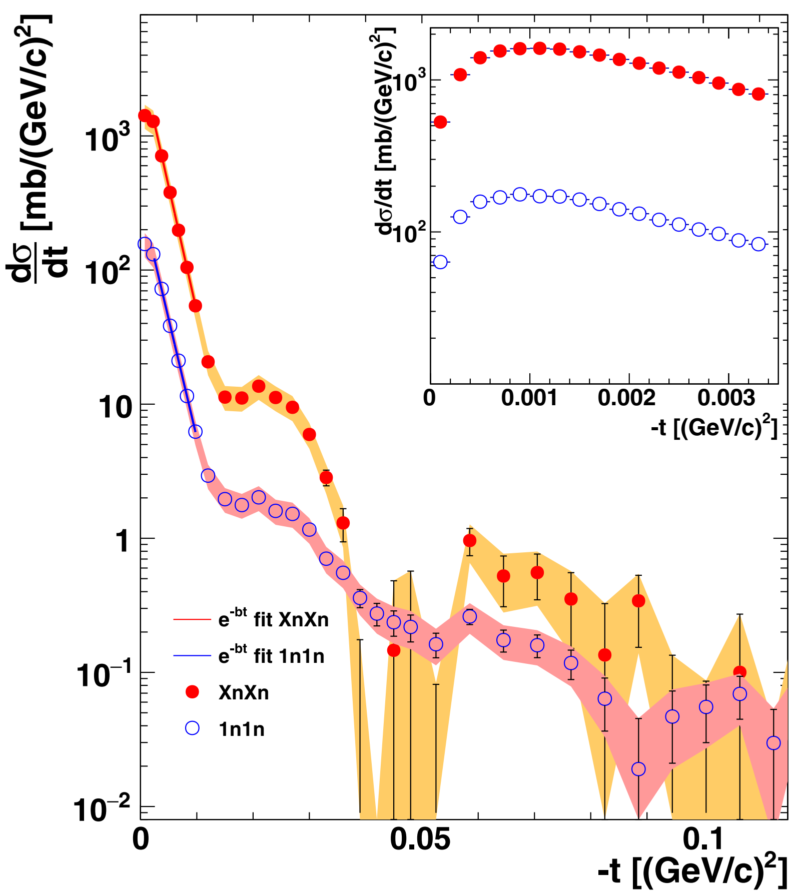
Image nuclear spatial structure using diffractive peaks



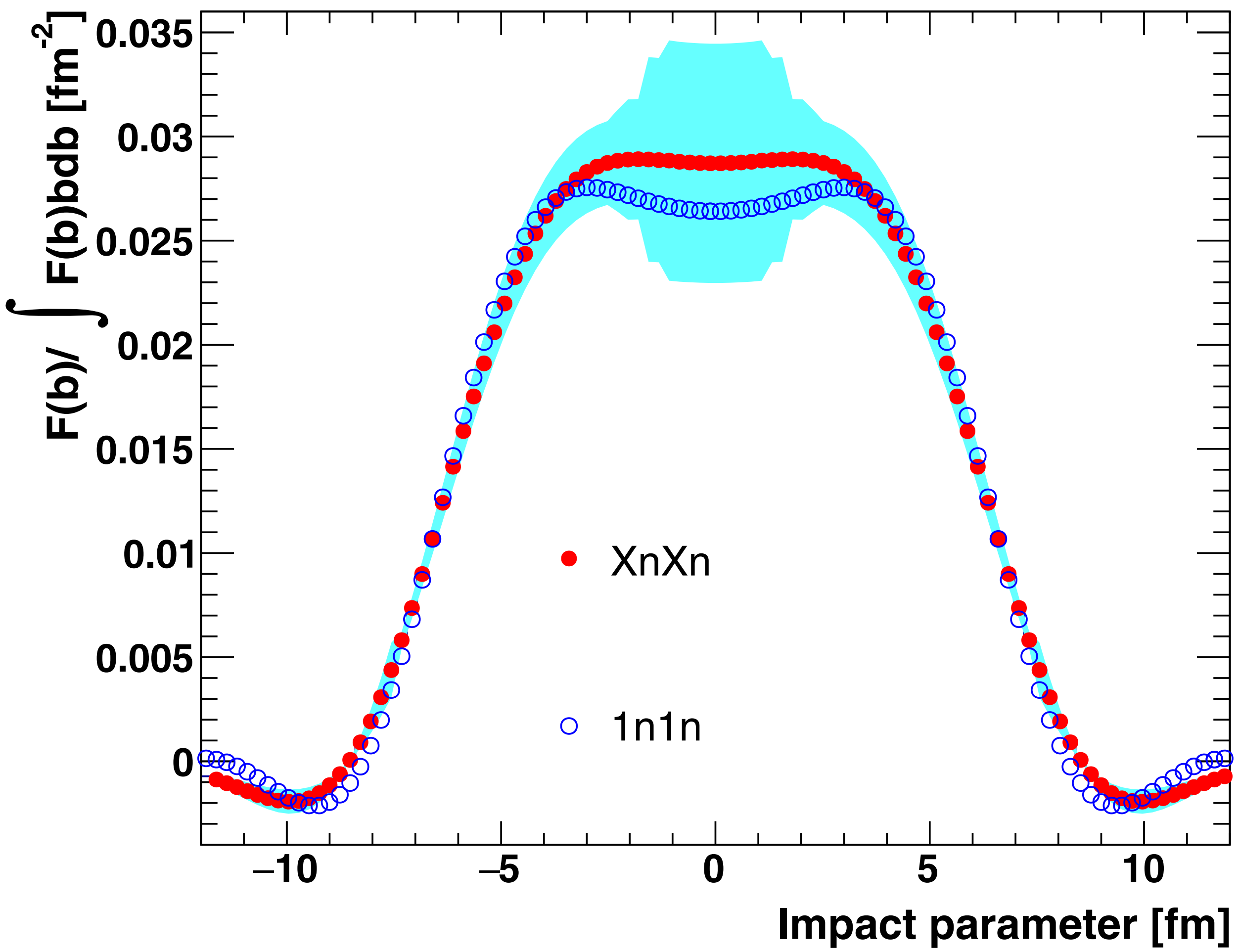
J/ψ will be a more reliable means to image the nucleus
ϕ is a much more sensitive saturation probe
But how deep will the dips be, in practice? Do HO processes fill them?
And how do we remove the incoherent contributions, large at large *t*

Existence proof :)

STAR @ RHIC



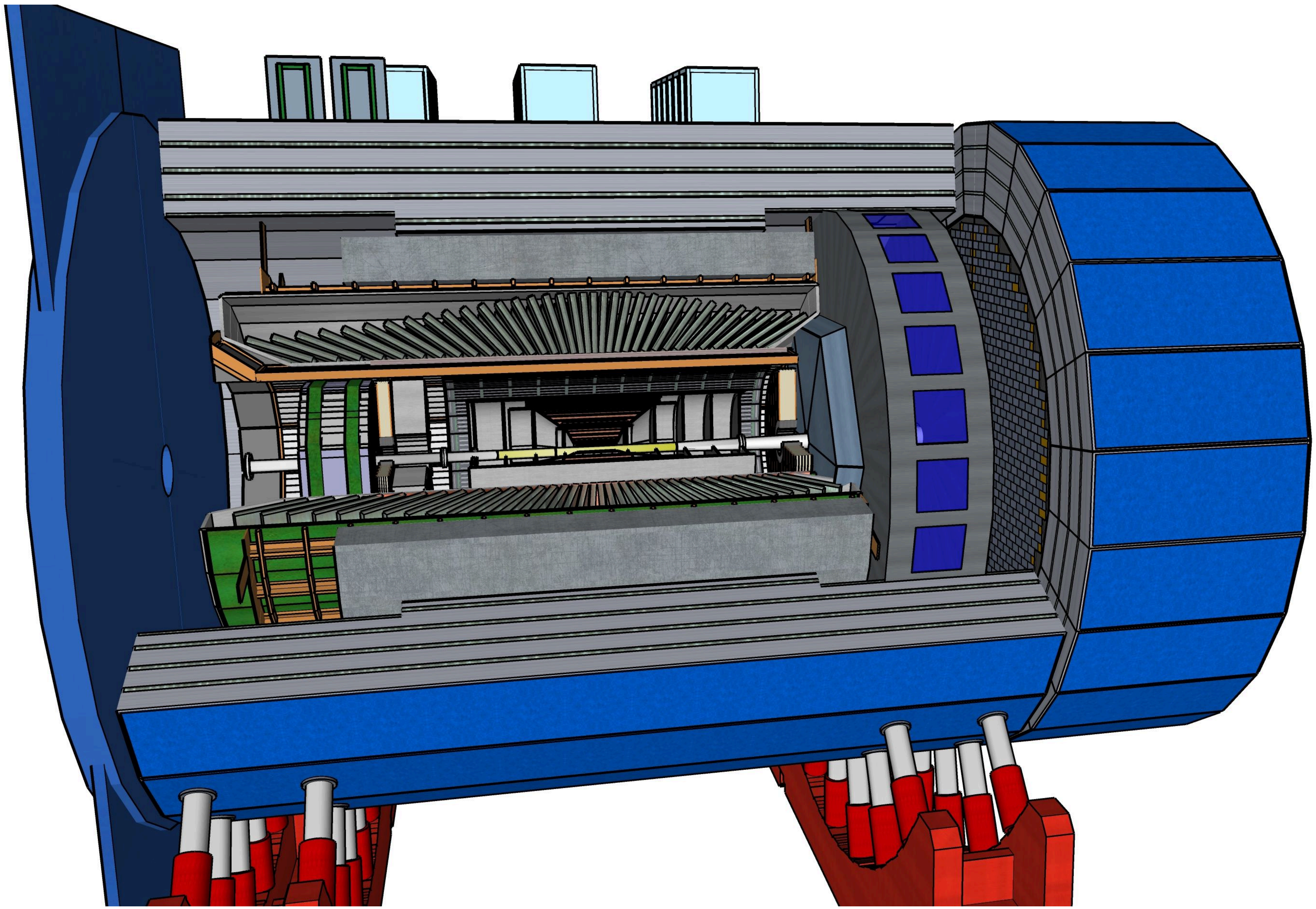
PHYSICAL REVIEW C **96**, 054904 (2017)

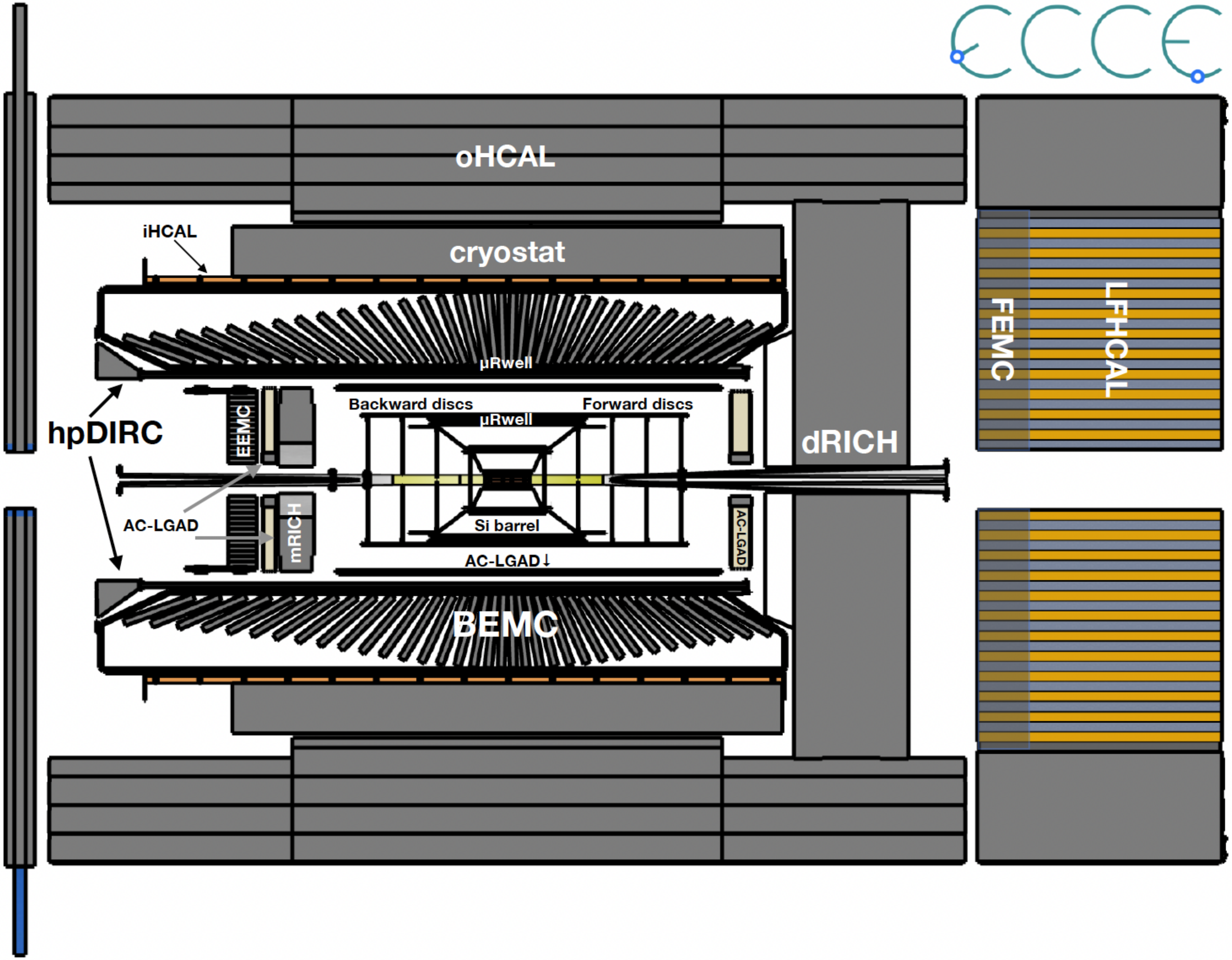


UPC vector meson photo production already shows that the diffractive structure is measurable in principle, but lighter mesons lack hard scale

Proposed ECCE experiment

December 2021

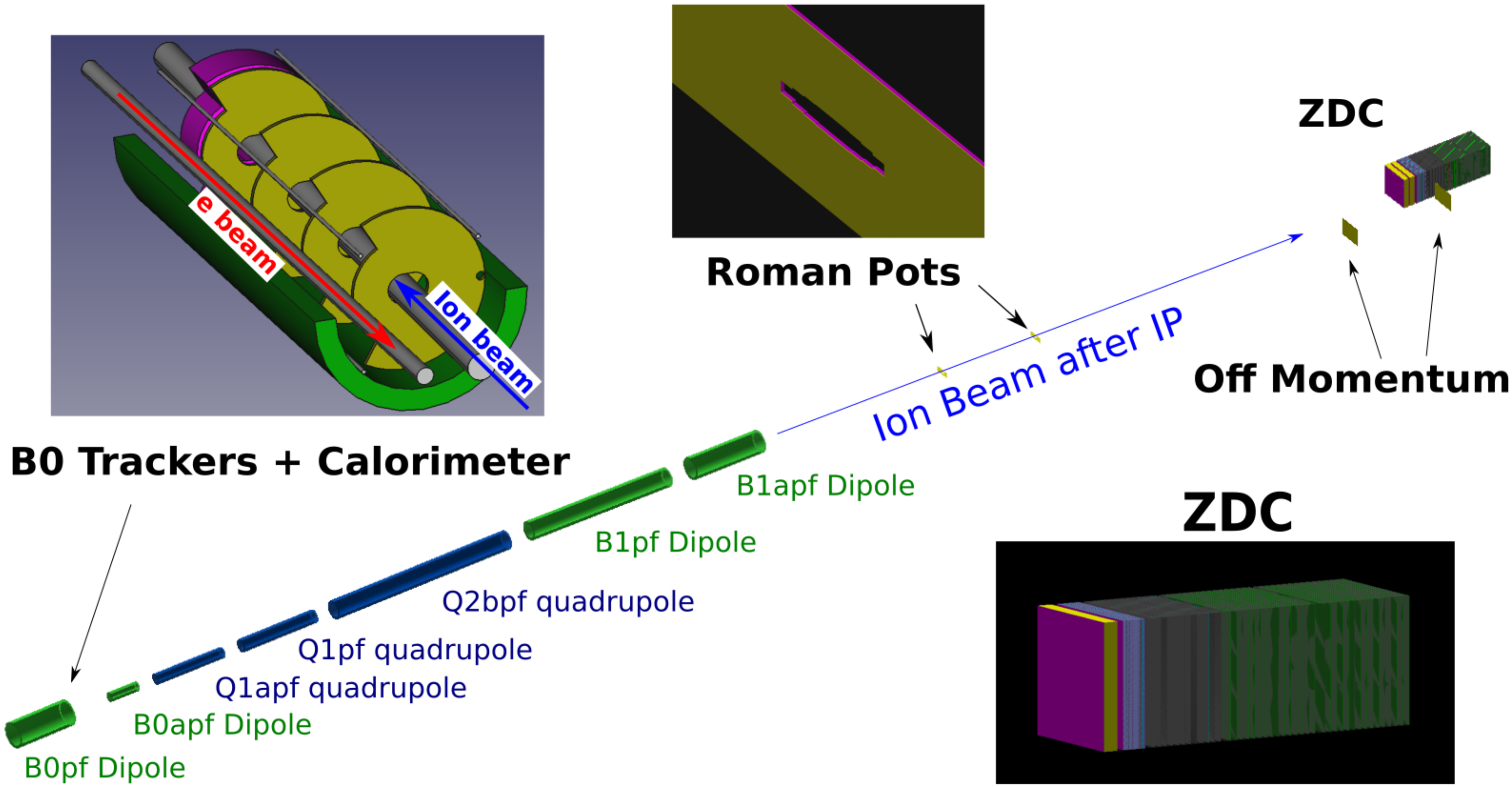




acceptance out to |η|<3.5, augmented by far forward systems, based around the BaBAR/sPHENIX 1.5T solenoid

ECCE far forward

ECCE far-forward program
(except this work!)
https://arxiv.org/abs/2208.14575



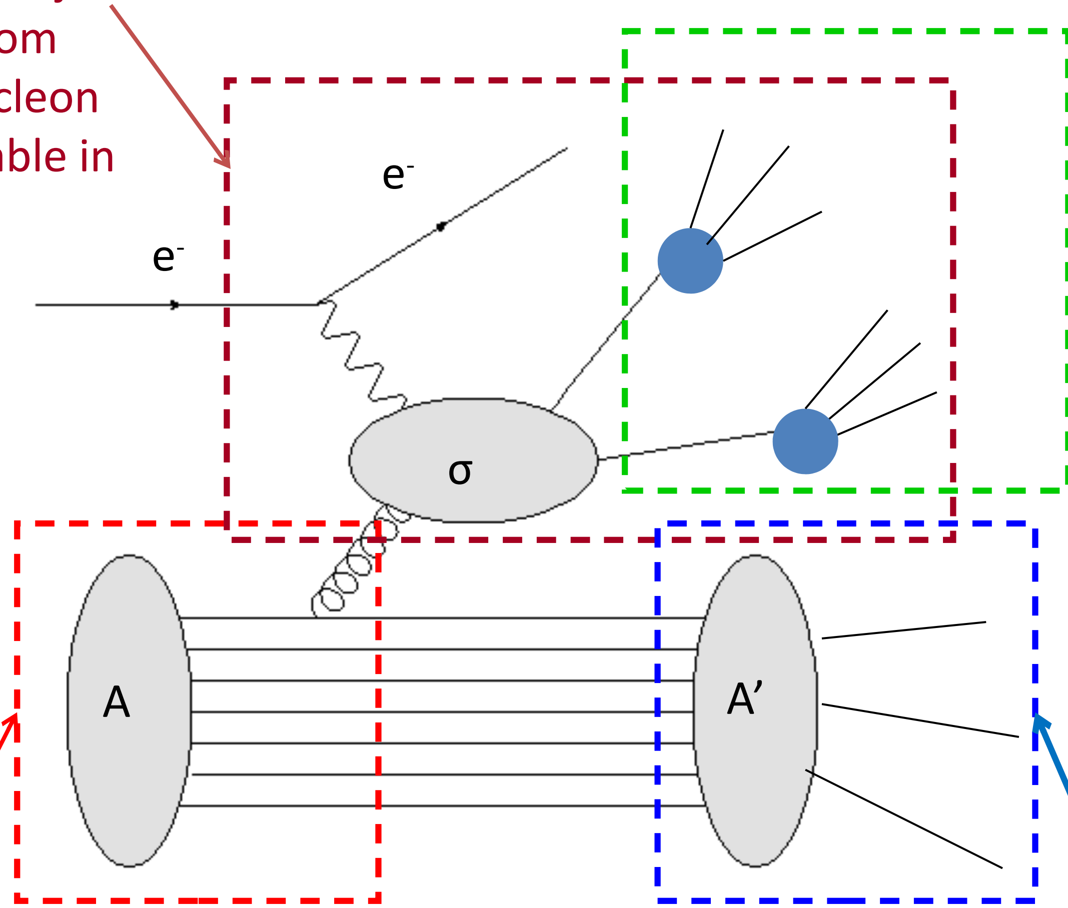
These are ECCE implementations based on the existing beam line plans provided by EIC project, implemented into ECCE Geant4 geometry

Chang et al, Phys. Rev. D **106**, 012007

Incoherent processes: BeAGLE

Parton level interaction, parton shower and jet fragmentation from PYTHIA. Multinucleon shadowing available in BeAGLE.

Intranuclear Cascade from DPMJet. Optional Energy loss effect from extended BDMPS in PyQM.



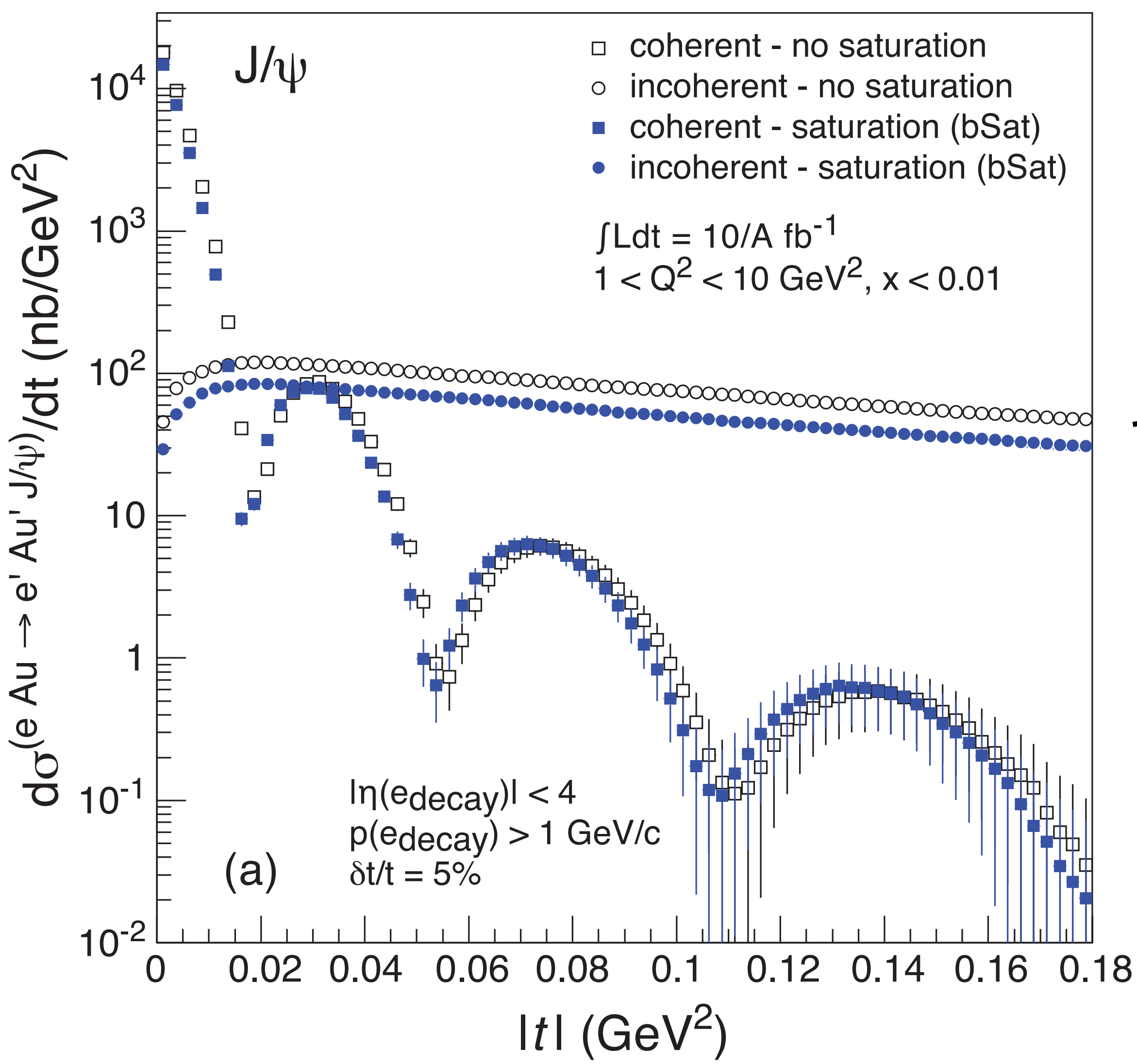
Nuclear geometry by BeAGLE & PyQM plus EPS09 nuclear PDF provided in LHAPDF.

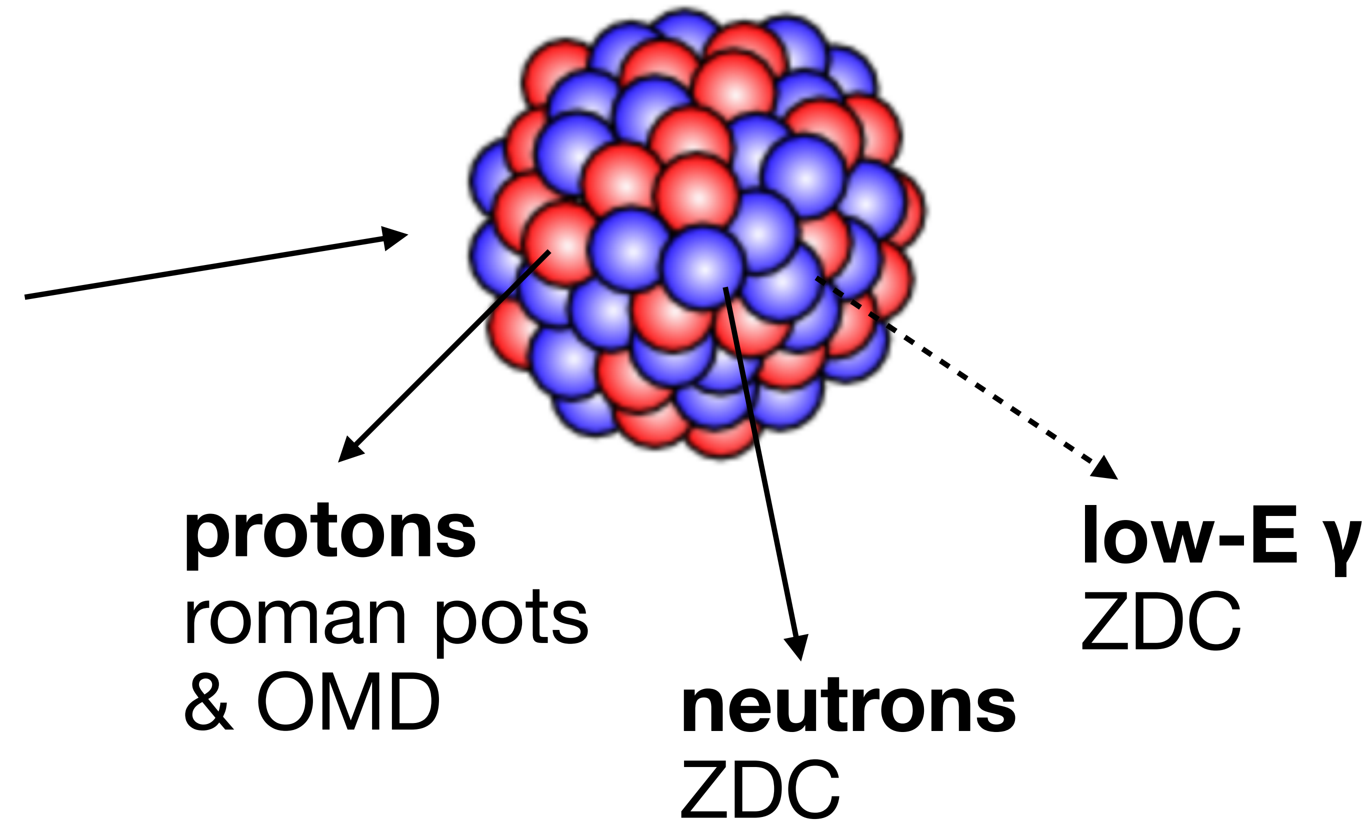
Nuclear evaporation, gamma dexcitation, nuclear fission & fermi break up treated by FLUKA.

Powerful tool, providing the only comprehensive eA generator on hand, and the only one that handles the full range of nuclear final states

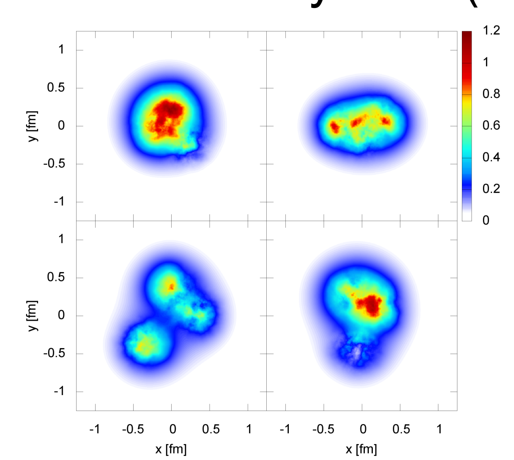
incoherent processes

Detailed study by Chang et al
Phys.Rev.D 104 (2021) 11, 114030





Schenke & Mäntysaari (2016)



Incoherent processes are “background” for coherent processes - they hide the diffractive structure - but they are also signal: sensitive to spatial fluctuations, e.g. “hotspot” structure

Pb > Au due to photon de-excitation

Focus of this work

- **Performed in the context of the ECCE proposal**
  - Last developed in mid January 2022
- **Incorporated responses to original proposal in Dec 2021**
  - Supersedes essentially all of the plots included there!
- **Homework provided by the DPAP committee, requesting a specific charge to make it easier to compare the proposals**

Projections for full physics processes (P):

P-1: diffractive electroproduction of J/Psi on nuclei.
e Pb -> e J/Psi + Pb and e Pb -> e J/Psi + X
Plot of the cross section vs t for the coherent and the incoherent process with the following settings (cf Figures 7.83 in the YR and 3.23 in the WP):

- 1 GeV^2 < Q^2 < 10 GeV^2
- x_V < 0.01 with x_V = (Q^2 + MJPsi^2) / W^2
- integrated luminosity 10 fb^{-1} / A
- beam energies 18 GeV on 110 GeV/A

Please indicate statistical and total errors separately. (e.g. by inner bars for statistical errors). If within the possibilities of your detector, provide separate plots for using the e+e- and the mu+mu- decay channels.

e+Pb
18+110 GeV/A (108.4)
low x_V (not x)
10 fb^{-1}/A = 50 pb^{-1}
ee and μμ modes

Primary challenges

- **Identifying exclusive processes**
  - In this context, treated as a simple problem
  - Events with a scattered electron and two opposite-charged tracks, satisfying mass constraint
    - *Tracks required to pass PID selections*
    - *Association with ECAL clusters used to tag electrons, with the absence of a tags identifying muons*
    - *With ee final state, the two tracks closest to M_{ψ} were assigned to J/ψ*

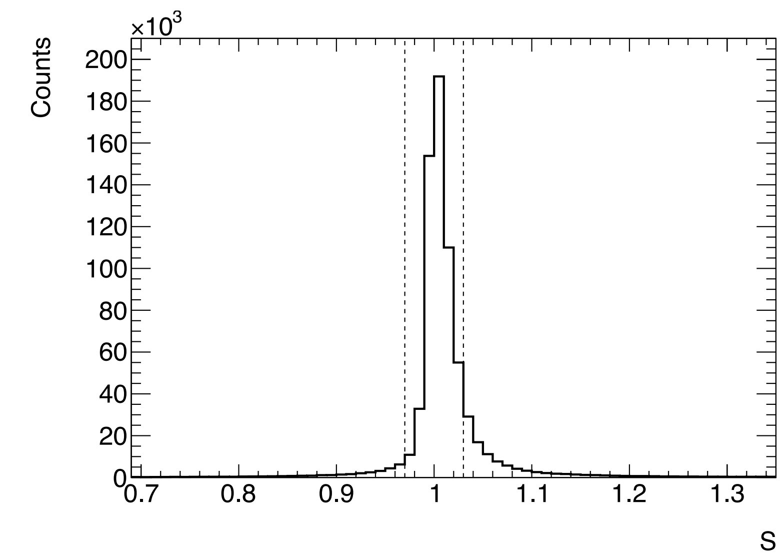
- **Measuring the scattered electron**
  - low Q^2 e’ emitted at small angles - most challenging region

- **Extracting t**
  - Cannot observe scattered nucleus, use t = e’ + J/ψ, approximated as its p_T^2

- **Background contributions - still not well known**
  - Hadronic contamination
    - *Not yet considered in this channel - will need to study high statistics inclusive PYTHIA6 sample*
  - Non-physics signals, e.g. from noise & synchrotron radiation
    - *Very hot issue, with simulation framework being developed for ePIC*

Other aspects of analysis

- **e’ energy adjusted to obey kinematic constraint (correct for coherent)**
  - Called method K
  - Scale factor applied to e’ 4-vector to satisfy nuclear mass constraint
    - *$e+A = e'+A'+J/\psi \rightarrow M^2_{A'} = (A - (Se'-e) - \psi)^2 = M^2_A$*
    - *Solve for S (just a bit of 4-vector algebra)*
  - Correction required to be small to guarantee well-reconstructed scattered electron
    - *$|S-1|<0.03$ - requires additional efficiency correction*

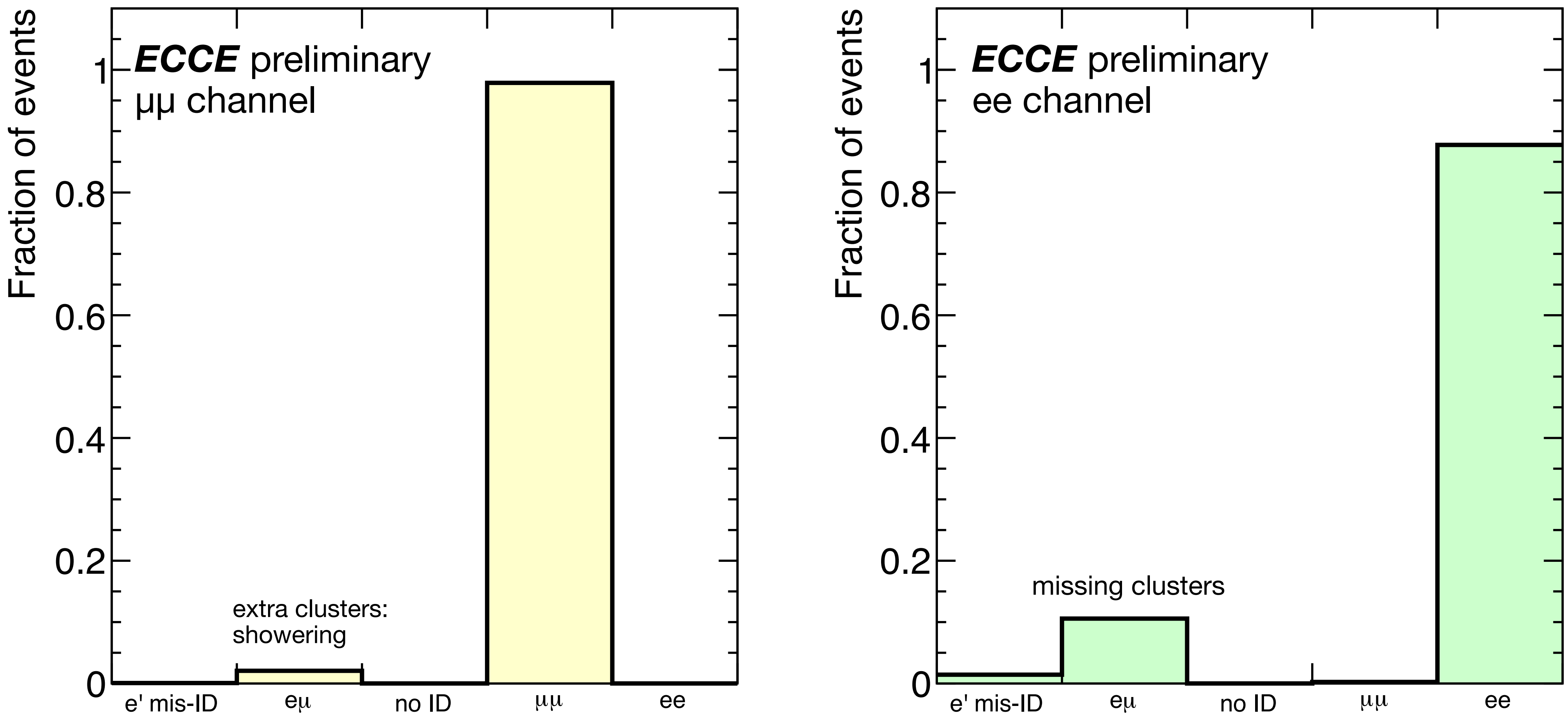


scale factor cut removes poorly measured e’

- **Simple efficiency corrections to arrive at cross sections**
    - *Coherent x-sect based on Sartre 1.37*
    - *Incoherent is BeAGLE 1.1 normalized to Sartre incoherent - full spectrum of final states*

- **Beam conditions slightly wrong**
  - Used pp values for beam divergence and crab divergence
  - No beam energy dispersion
  - Important to get details right!

PID efficiency

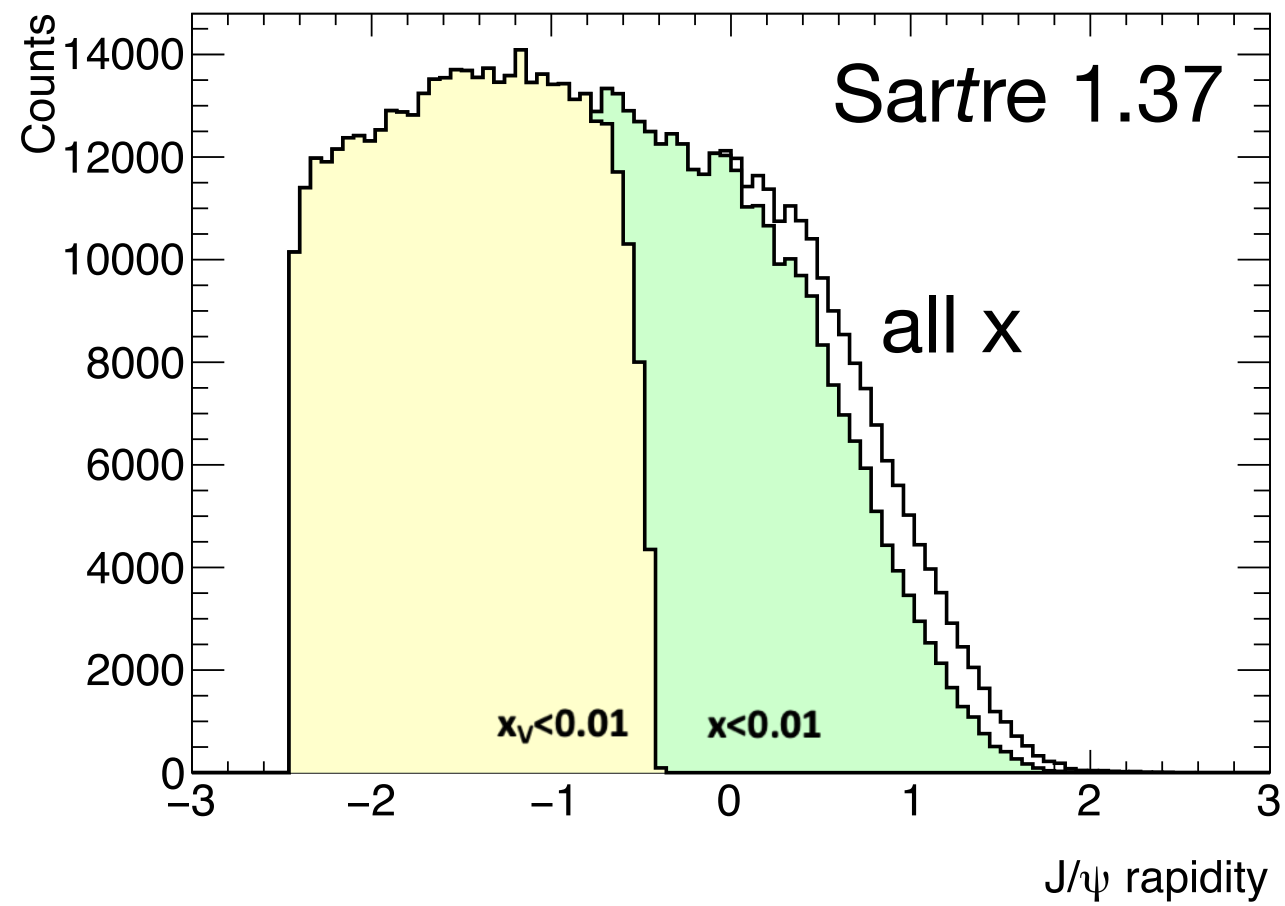


Accepted events required two positive tags on decay products and a confirmation of electron candidate - otherwise event is rejected

95% PID efficiency for μμ and 85% for ee (gaps in calo acceptance)
Electron/muon contamination after tagging both leptons found to be negligible.

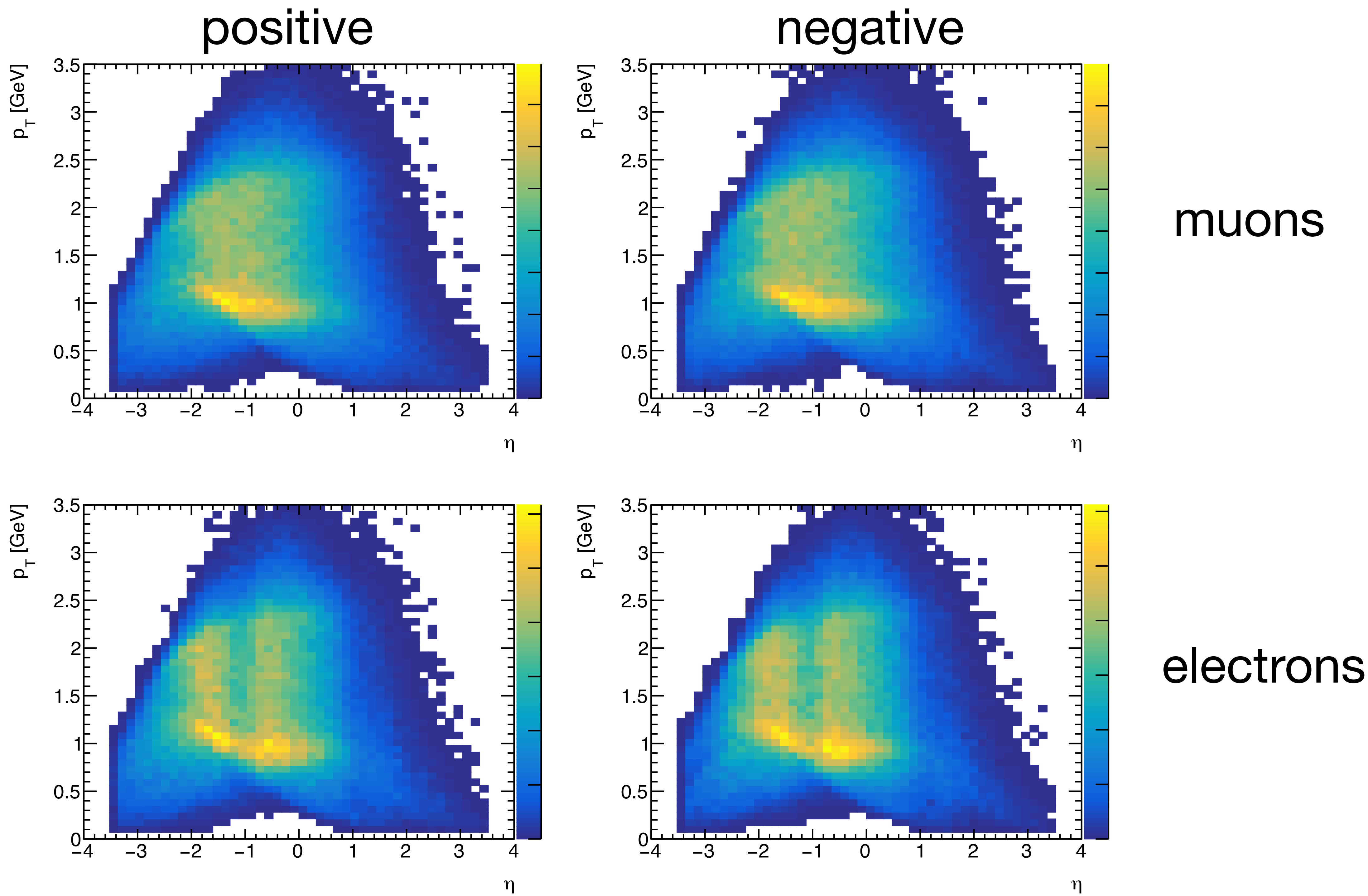
Kinematic selections

- **Q^2 and x_V calculated after correcting e' 4-vector**
- **Q^2 restricted to 1-10 GeV^2**
  - Some loss at boundaries due to this range also being applied to truth (a no-no for a proper unfolding)
- **x_V < 0.01 is a very tight selection on the J/ψ**
  - Nearly 40% of the cross section removed, relative to original selection x<0.01
  - Interesting question: is this stronger cut better for physics, e.g. saturation?



J/ψ decay kinematics

$1<Q^2<10$ GeV^2, $x<0.01$

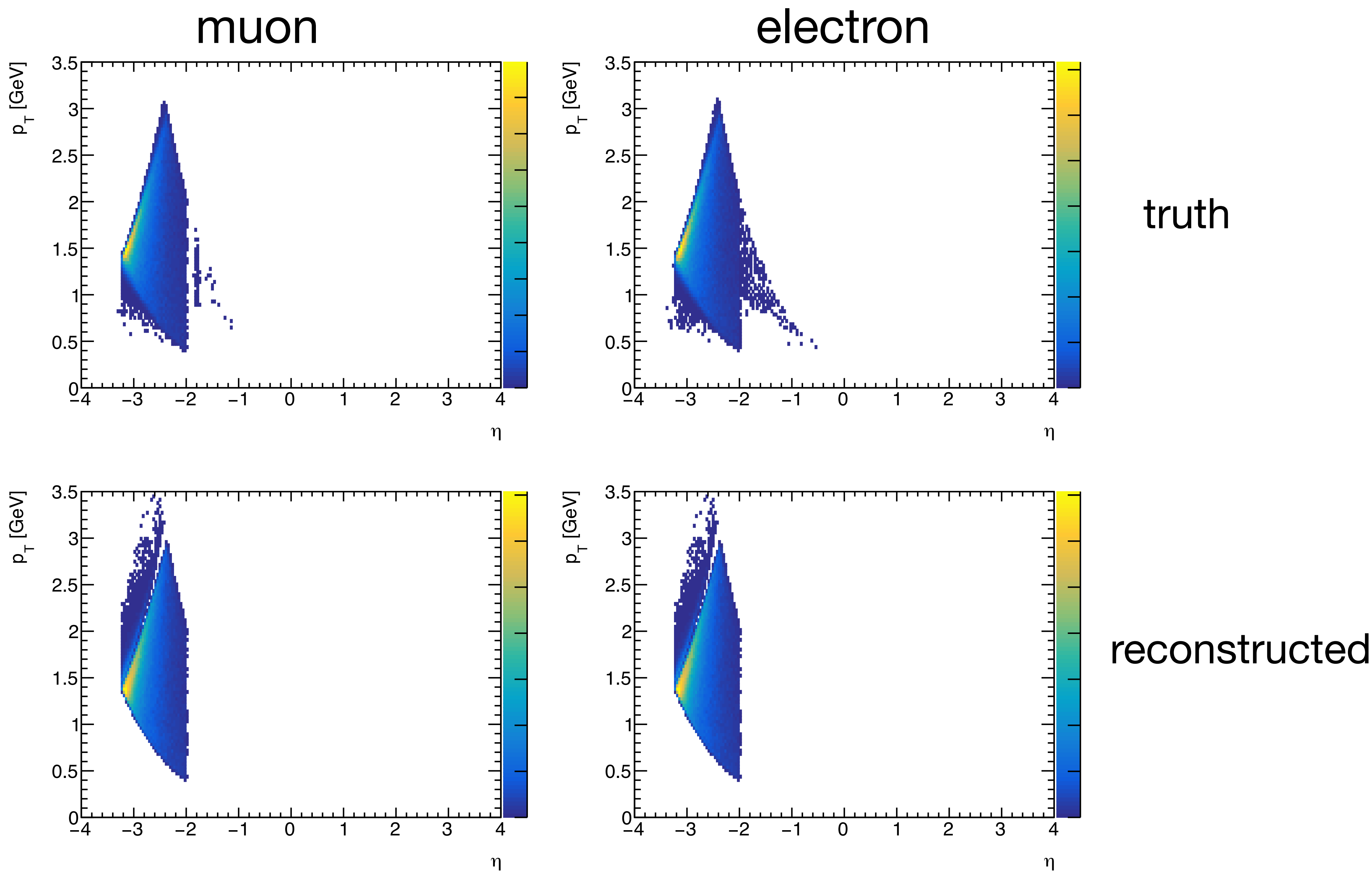


Tracks accepted within $|\eta|<3.4$ and $p_T>0.1$ GeV

some artifacts visible of my specific technique for selecting the scattered e’ in $\psi\to ee$

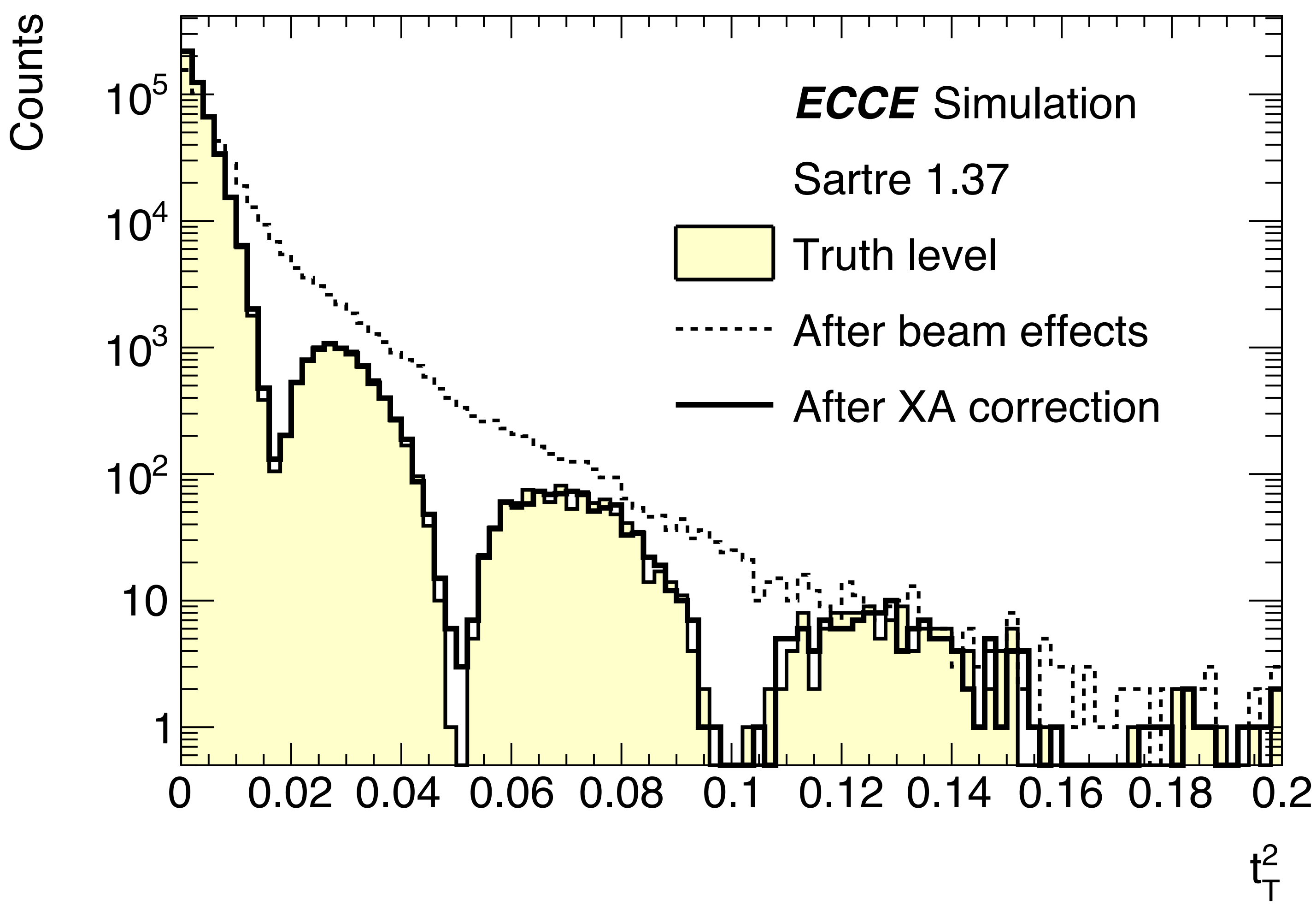
e’ kinematics

$1<Q^2<10$ GeV^2, $x<0.01$



some artifacts visible of my specific technique for picking the scattered e’

Crossing angle



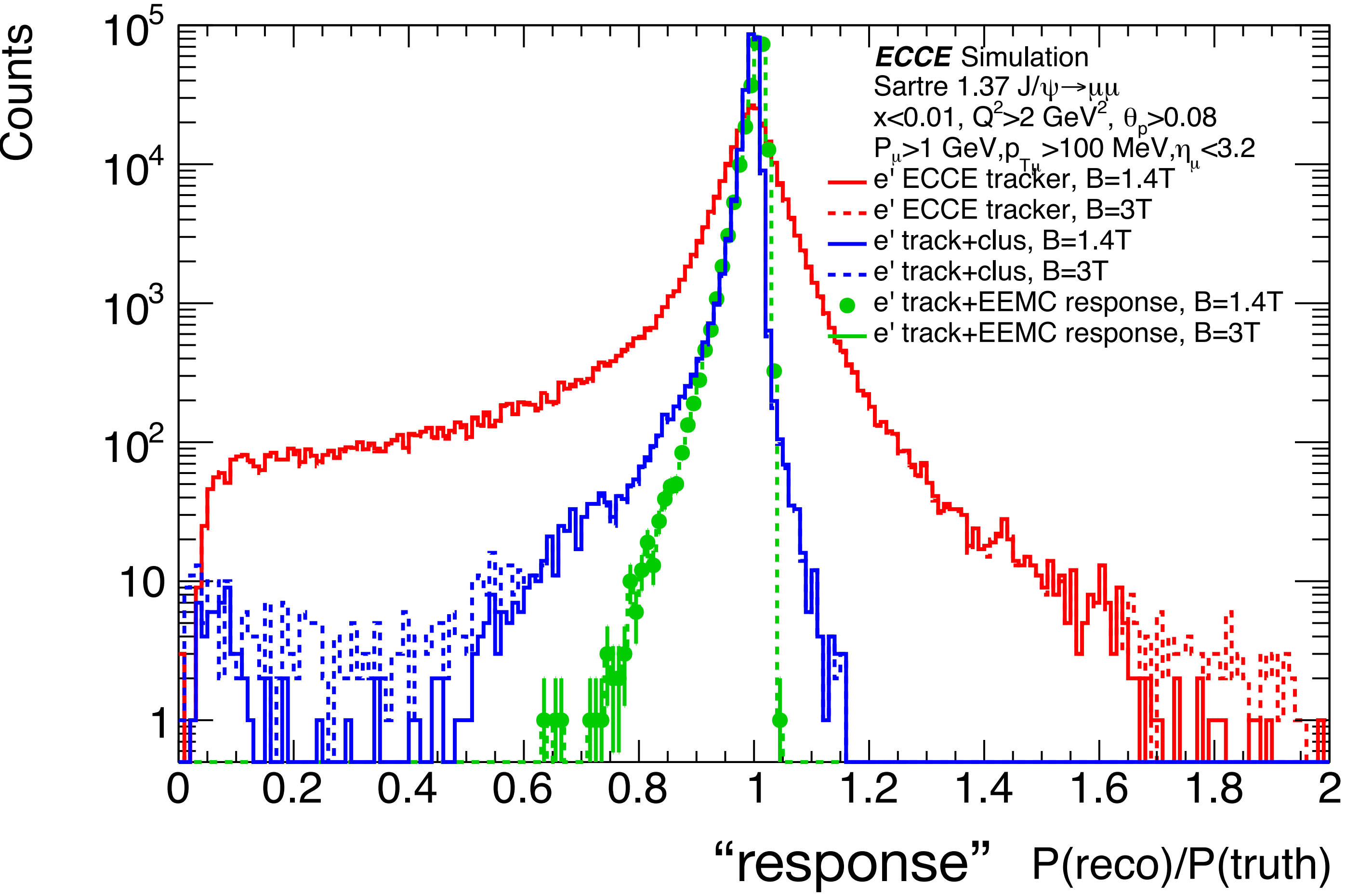
In this work, using approximation:

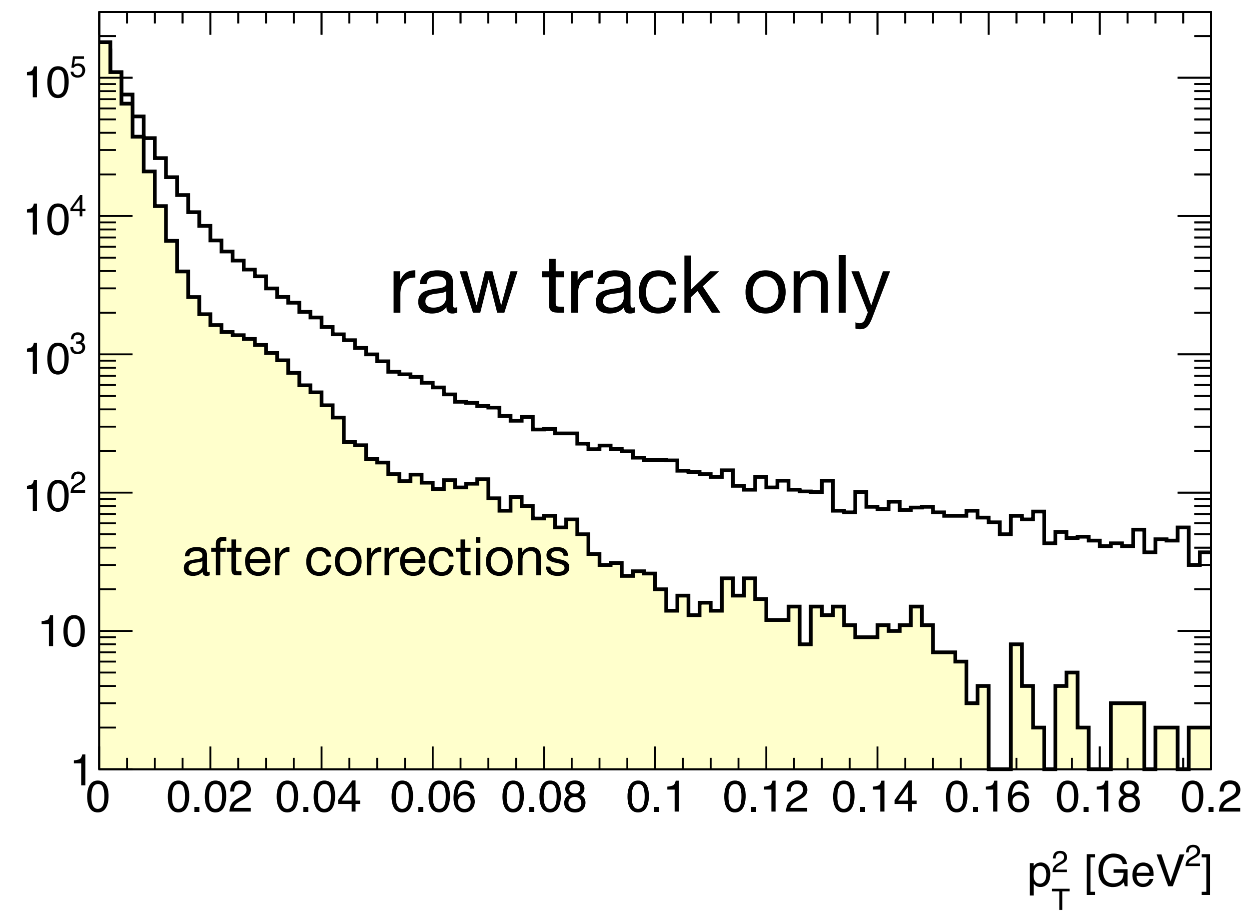
$t \sim p_T^2$

sometimes called t_T^2

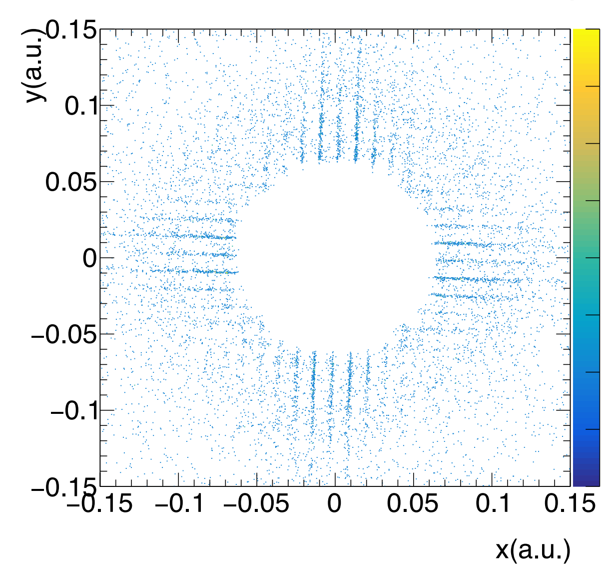
- **At IR6, EIC beams will cross at 25 mrad relative to each other**
  - Electron beam will be along Z axis, while hadron beam arrives and leaves 25 mrad off axis
- **Sounds like a detail, but an important one to be cognizant of!**
  - Many people were tricked at first when they looked at the output of their generators!
- **Everything simulation here has the angle applied (boost then rotation)**
  - Every kinematic quantity has the inverse transform (anti-rotation then anti-boost) applied before plotting!

Need for kinematic constraint



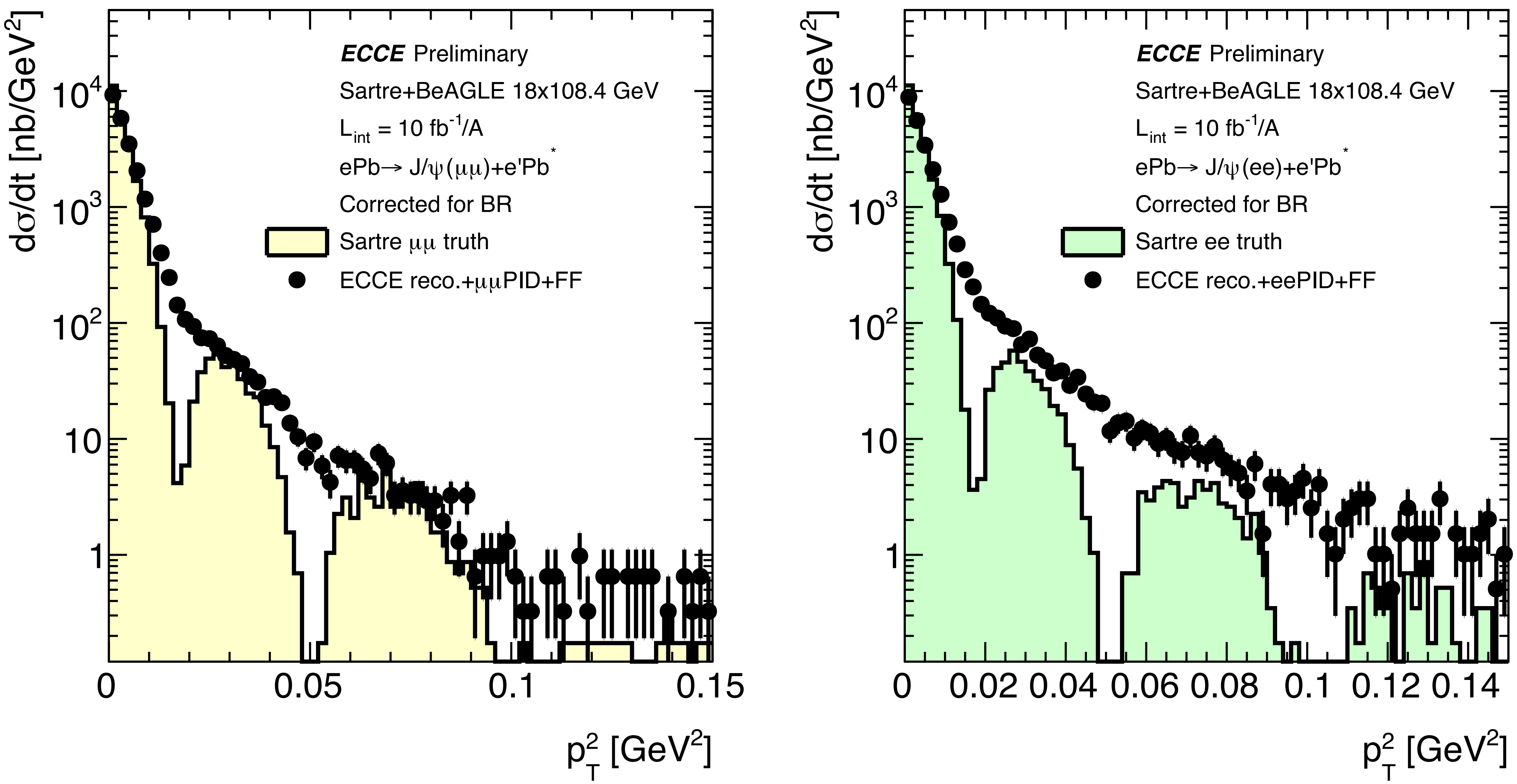


- Primary limitation on this measurement is the e’ response:
- Tracker alone has too poor a resolution in the far backward region
- EEMC simulation quite close to “ideal” PWO response (crystal ball, based on ECCE sims) but low energy tails induce larger t
- Selections on size of method K correction control tail contribution, at cost of requiring detailed data/MC agreement
- I implemented Method L, and so far it doesn’t seem to help as much — need more time to assess this



low momentum tails associated with cracks in backwards calorimeter!

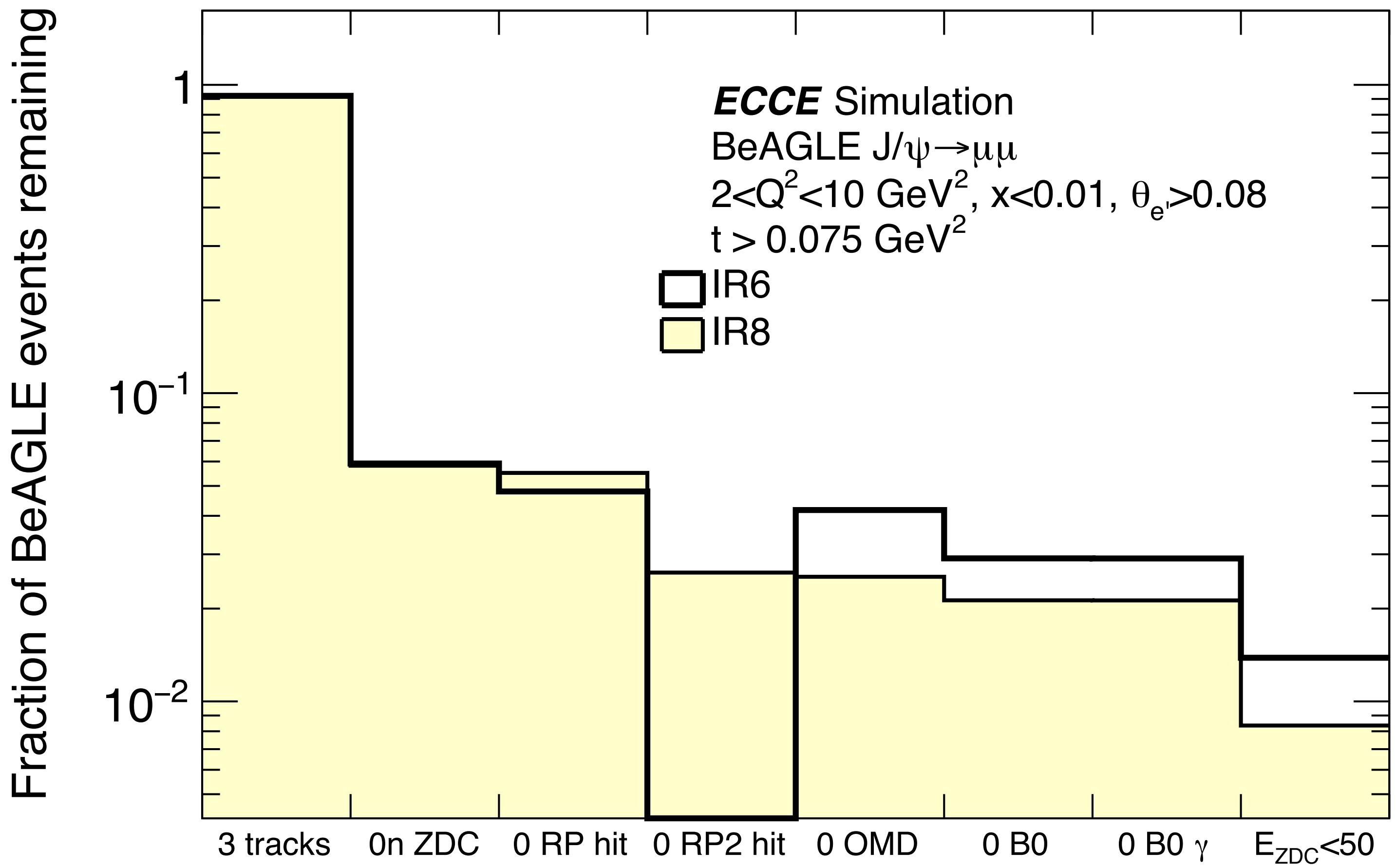
Coherent-only cross section

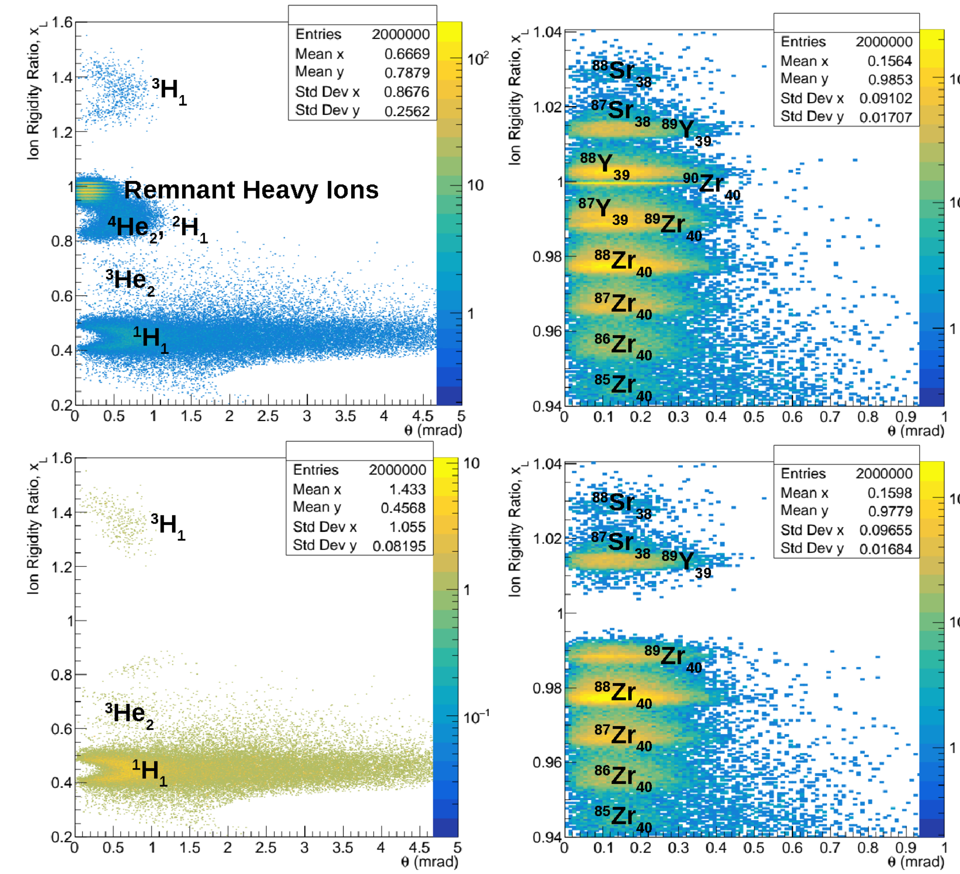


- Again, p_T^2 is used as proxy for *t*
- Correction is just simple integral of reconstructed counts over truth
- Efficiency vs Q^2 is mostly constant but composed of many parts: e' efficiency (track & cluster), charged decay products, PID cuts, kinematic constraints, etc.
- Aggregate efficiency is 40% for ee, 60% for μμ. Expect 15% systematics or better, as many efficiencies should be measurable in data using tag & probe technique
- Tracking resolution sufficient for observation of "kinks" in the μμ channel - weaker for ee

See Chang et al, for a complementary BeAGLE study
Phys.Rev.D 104 (2021) 11, 114030

Cutting incoherent backgrounds



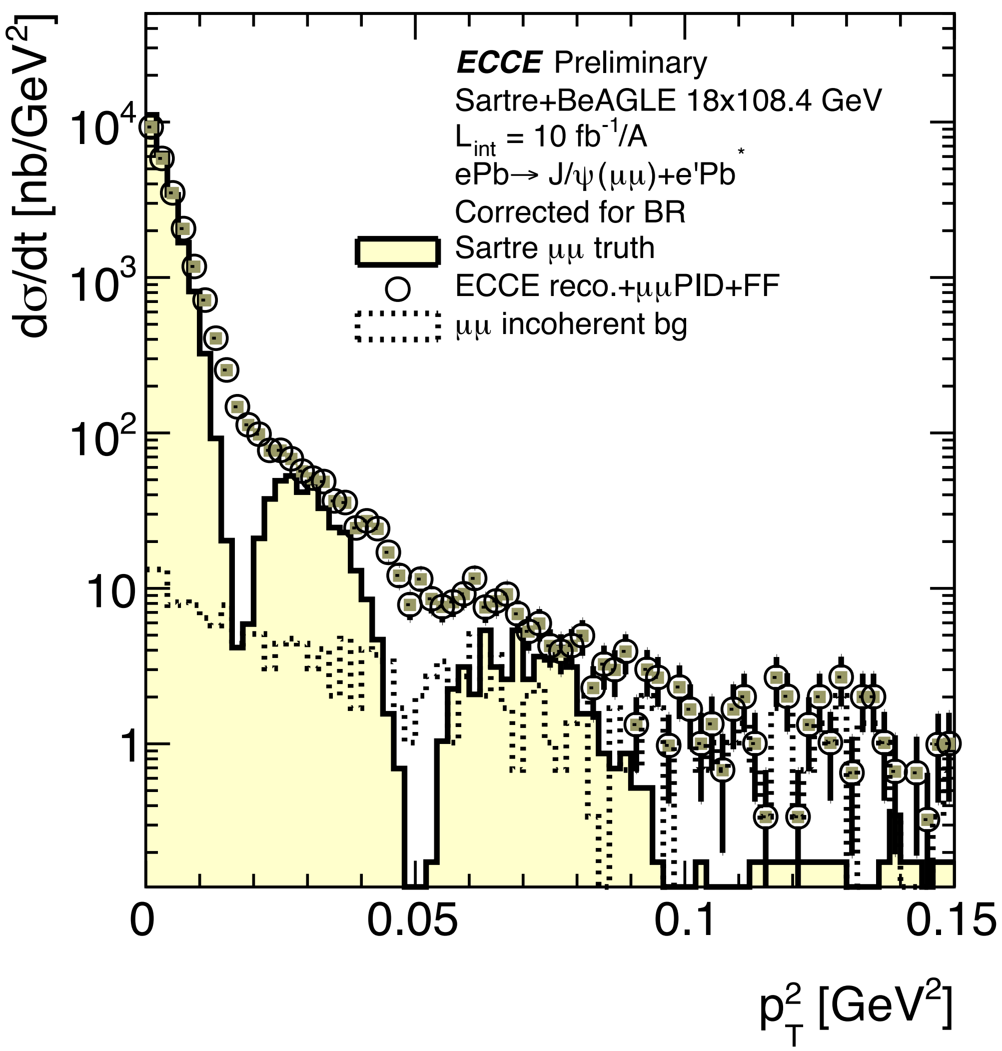


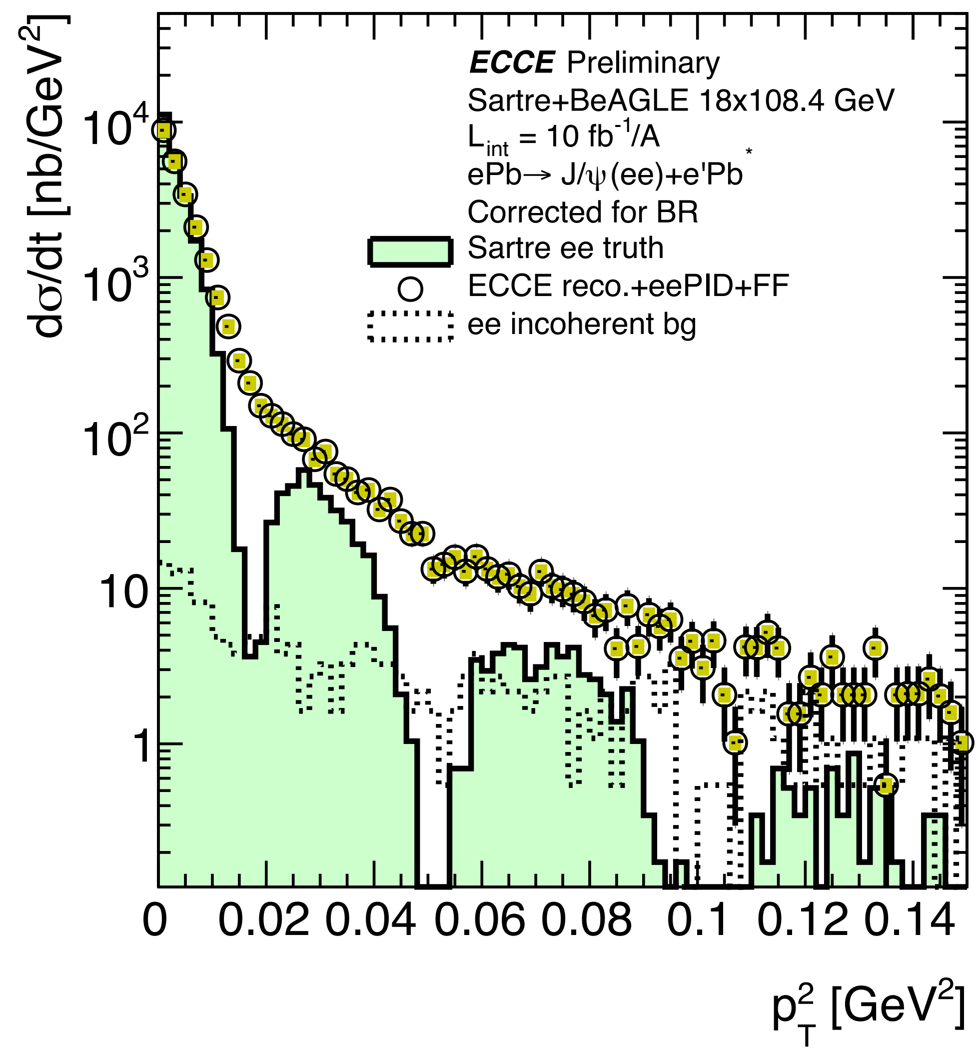
Simple representation of removing events with successive cuts
on the ECCE forward detectors, at moderate $t > 0.075$ GeV^2

Much of the work done by the ZDCs, both neutrons and forward EM,
with B0 next in line (although B0 photon detection wasn't working…)

Roman pot acceptance insufficient for e+Pb, much improved for e+Zr (see 2208.14575)

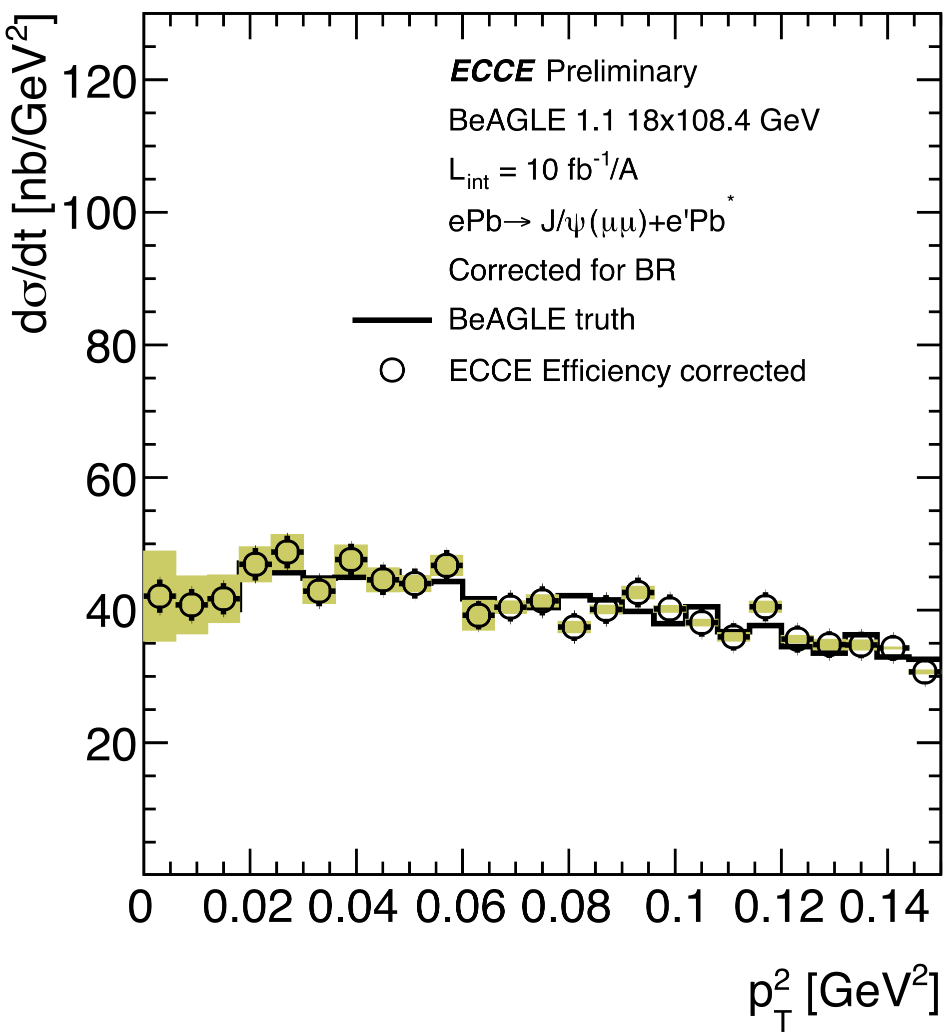
Coherent+incoherent background

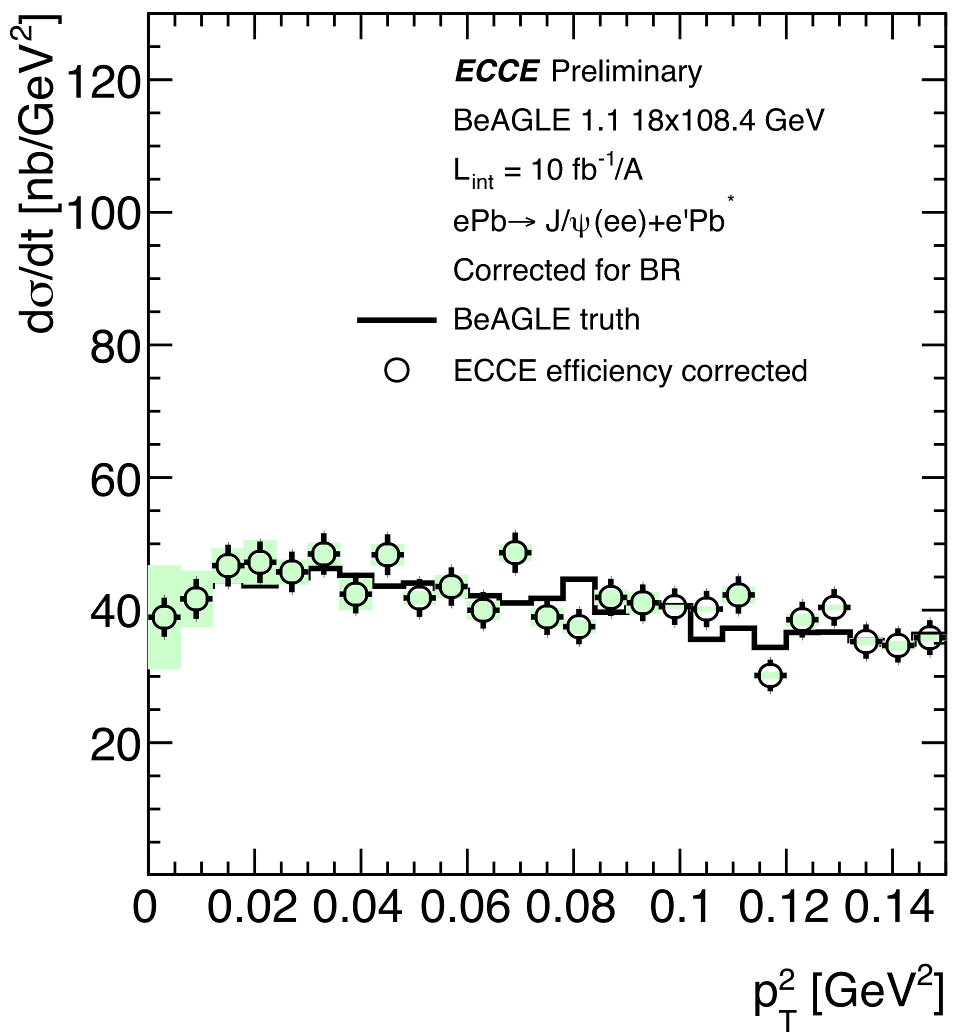




- **Total J/ψ yield compared to signal (filled) and incoherent (dashed histogram)**
  - Expect improvements with further optimization of detector design (e.g. B0 EMCal) and analysis methodology
- **Backgrounds modest up to second diffractive peak**
  - Cut more effective at larger t, but signal distribution drops rapidly

Incoherent cross section only





sensitive to "hotspot" structure

Events selected using "anti-veto" of the selections used for coherent x-sect.

Correction to convert reconstructed to final is a polynomial fit (for smoothing) to truth/reco of yield vs. p_T^2. Uncertainties are identical to coherent case.

~Flat distribution in t, so comparable performance for electrons and muons

Estimates of systematics

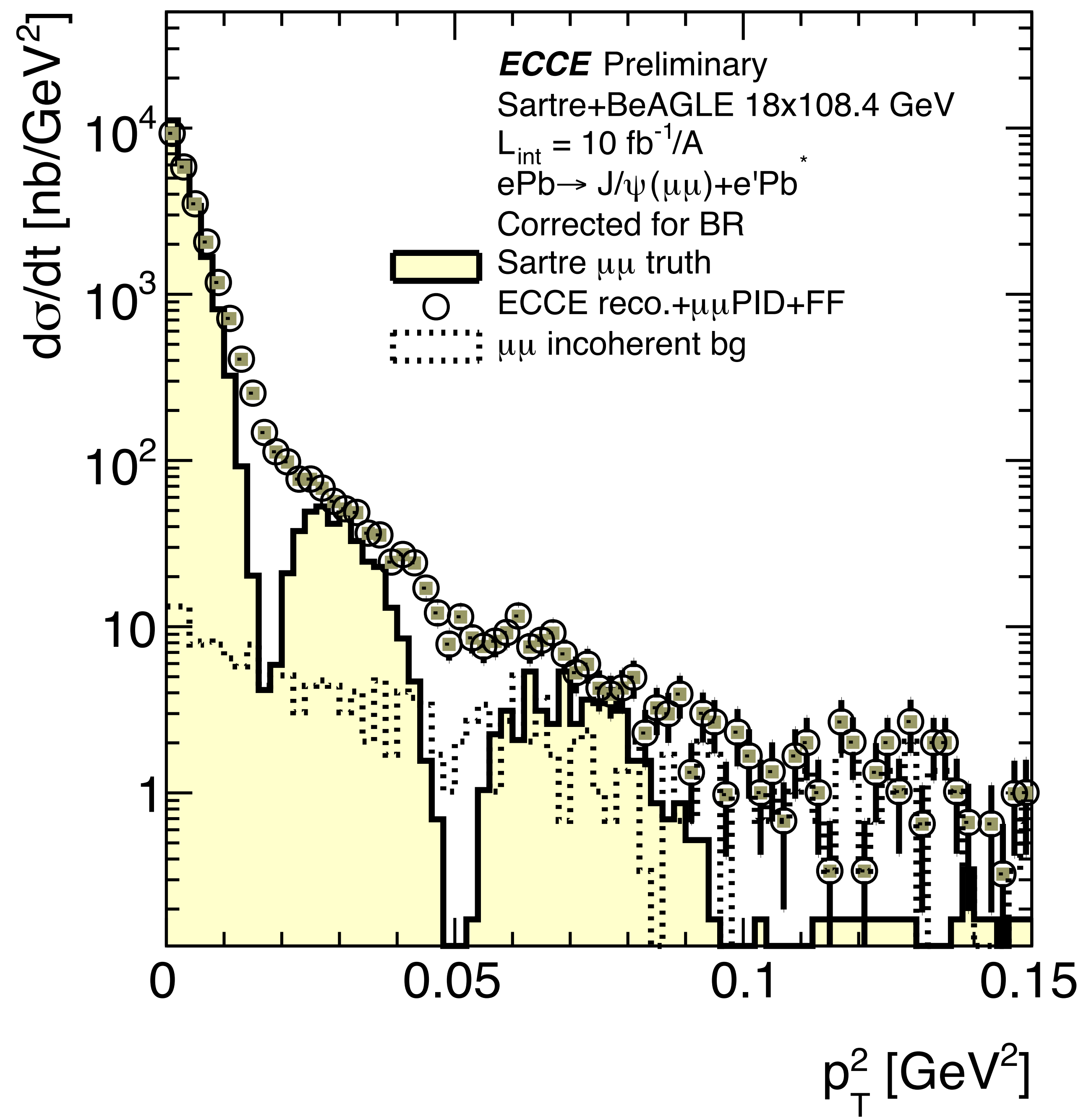
- General
  - Luminosity: 1%
  - Tracking efficiency: 2% (limited by tag & probe statistics)
  - e’ PID (cluster matching): 2% (EEMC spatial variations, gaps in calo system)
  - J/psi mass window: 2% for μμ, 5% for ee (variation on window size)
  - J/psi PID – 3% in ee (gaps in calo system)
  - Kinematic constraint to remove long tails from t=0 – 7% (variation of window)
- Incoherent process tagging
  - 10% on total cross section (from larger inefficiency at t=0), 5% on t dependence
  - Large O(50%) impact on cross sections at “high” t (~0.1 GeV^2) where residual incoherent backgrounds are similar in magnitude to coherent signal

Limits on observing dips

measurement resolution (both e' and J/ψ) limit ability measure (or even see) diffractive dips

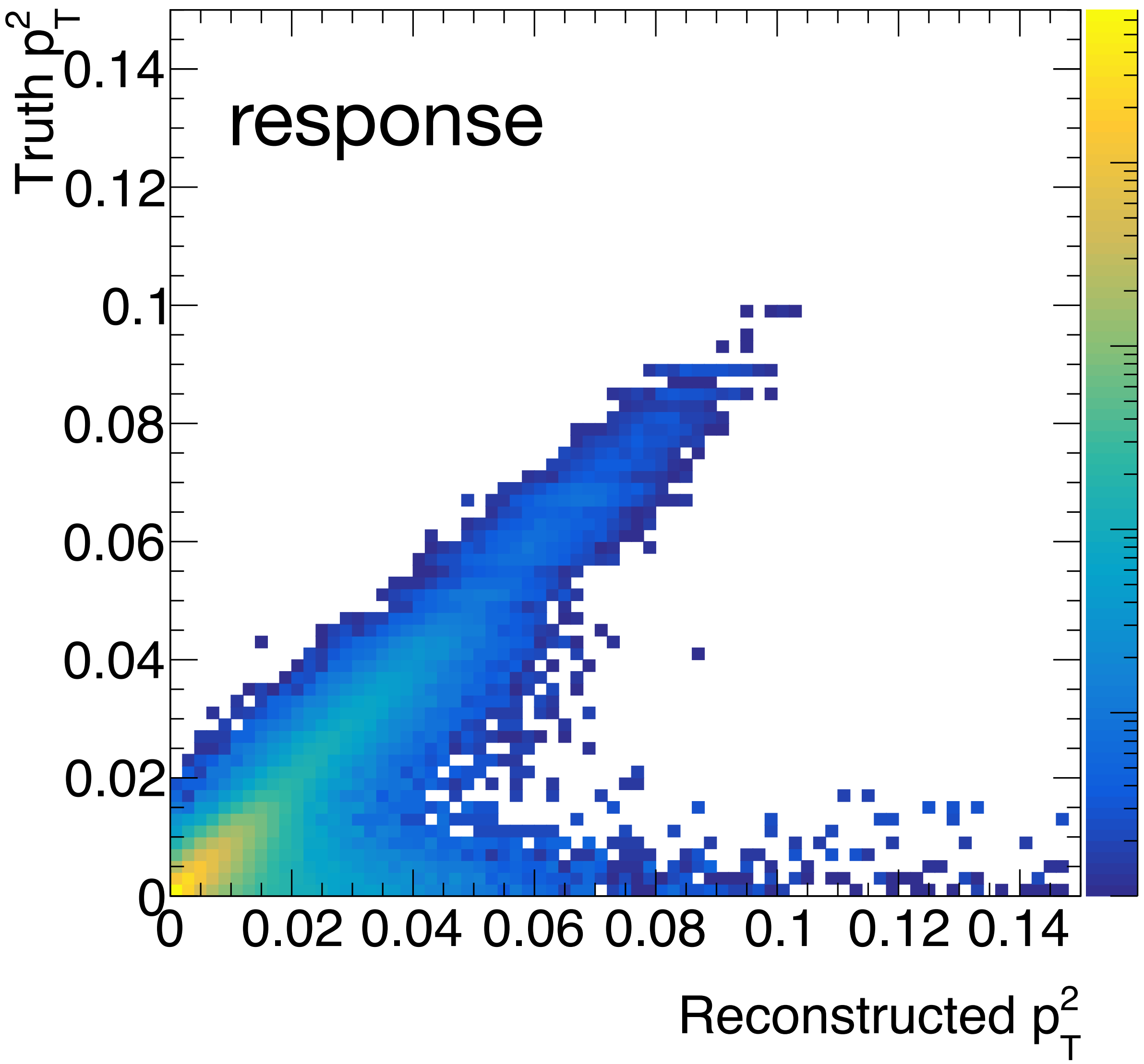
incoherent background can only be removed so much, esp. with acceptance of IP6 used here (ATHENA reported similar issues)

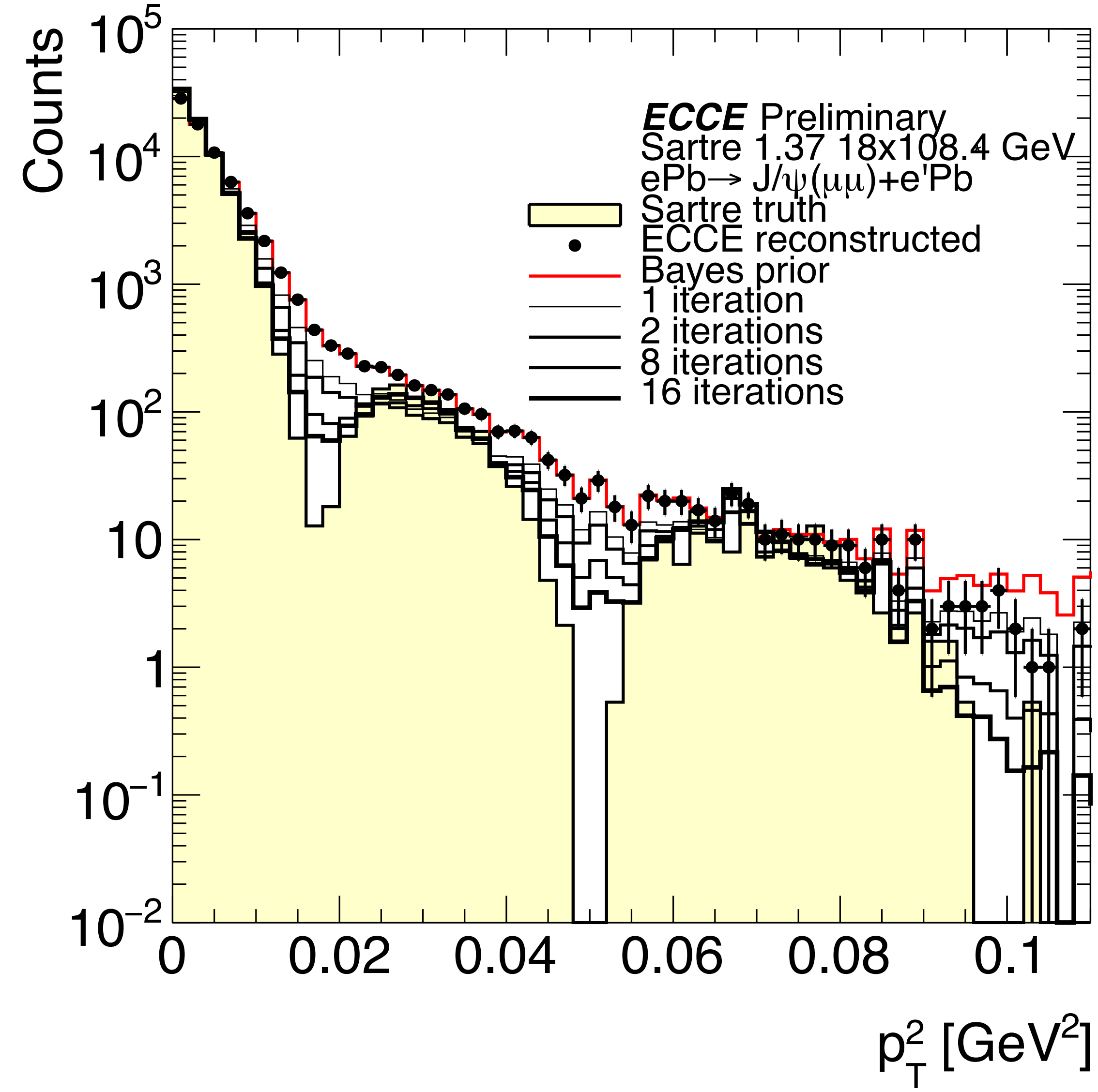
Begs the question: can these distributions be unfolded?



Unfolding

simple exercise, using Sar*t*re only, and Bayesian unfolding (in ROOT)

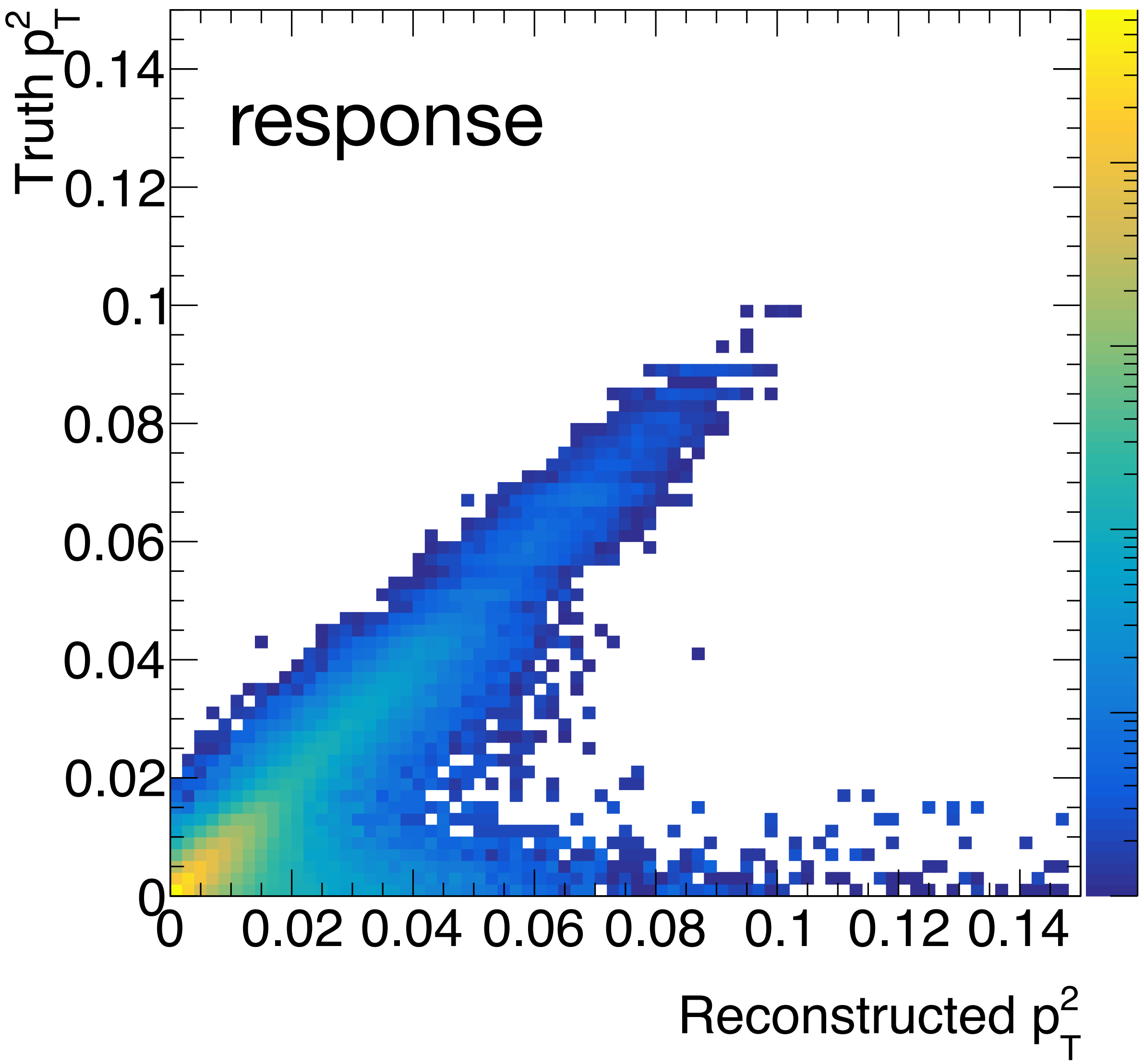


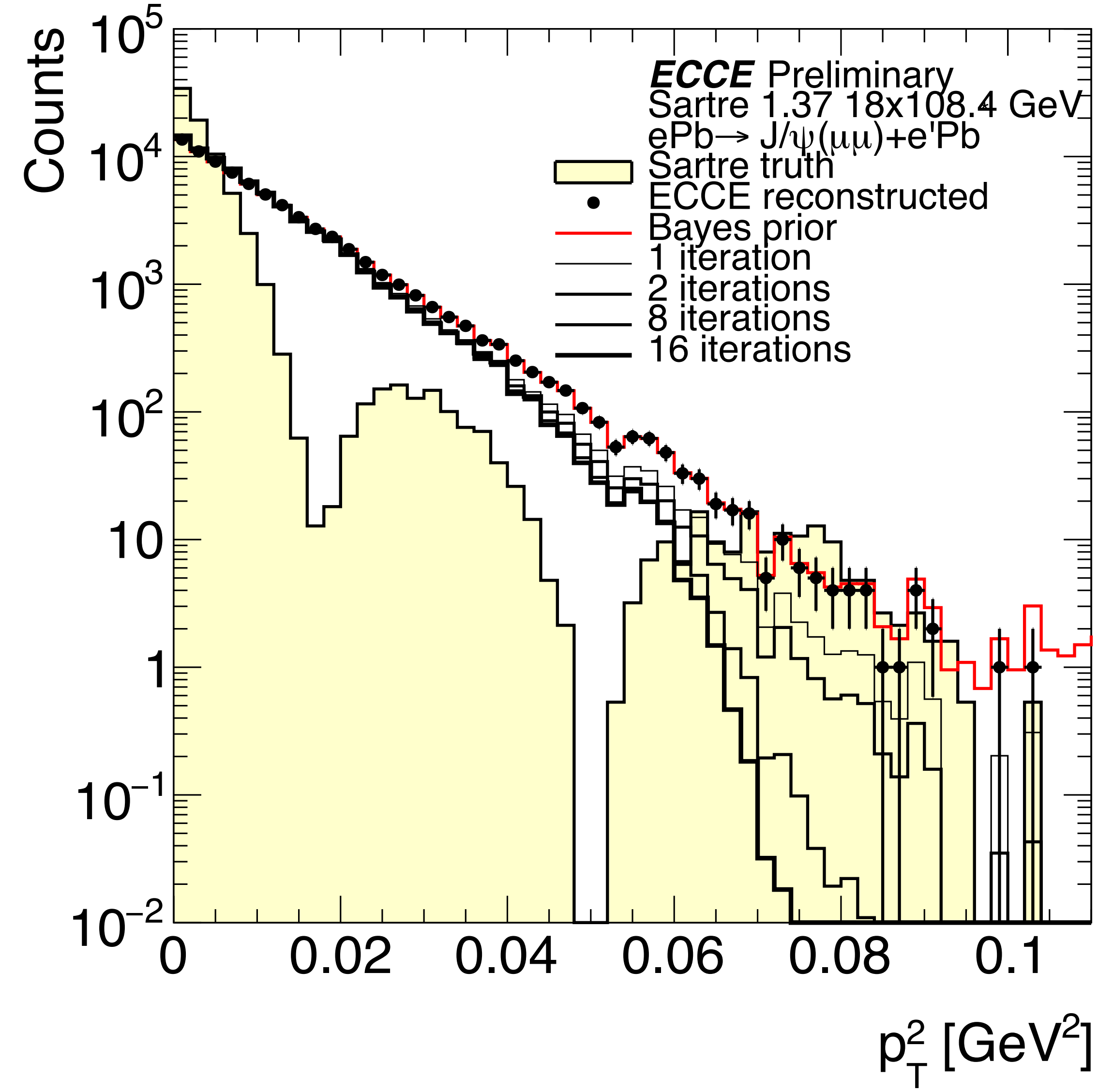


Sar*t*re+BeAGLE, just to build response which populates both branches: truth reweighed to observed: identifies problem as tails extending from t~0

Kinks in final distributions sufficient to start unfolding in right direction, but no obvious convergence

Unfolding





Sar*t*re+BeAGLE, just to build response which populates both branches: truth reweighed to observed: identifies problem as tails extending from *t*~0

Created fake data with no structure: and no dips created (phew!)

Prospects

- **This is now a topic of major interest for ePIC!**
  - Keep your eye on that work - Kong Tu, et al
- **Writing up baseline analysis for publication**
  - Long overdue, will also include phi - helpful to document what we learned
- **Expect some improvements, but work will mainly go to the new detector design**
  - Better material description
  - More detailed study of track properties (e.g. number of hits, goodness of track fit, etc.)
  - position-dependent EEMC energy scale corrections
  - Incorporation of state of the art response of FF detectors
- **More models?**
  - Lots of complaints during this process of the “reality” of the dips, and constraints imposed on detector based on them…
- **What about other diffractive processes, esp. inclusive**
  - No generators - great to see efforts developing in experimental community