Physics and challenges of exclusive J/ψ in e+A at the EIC
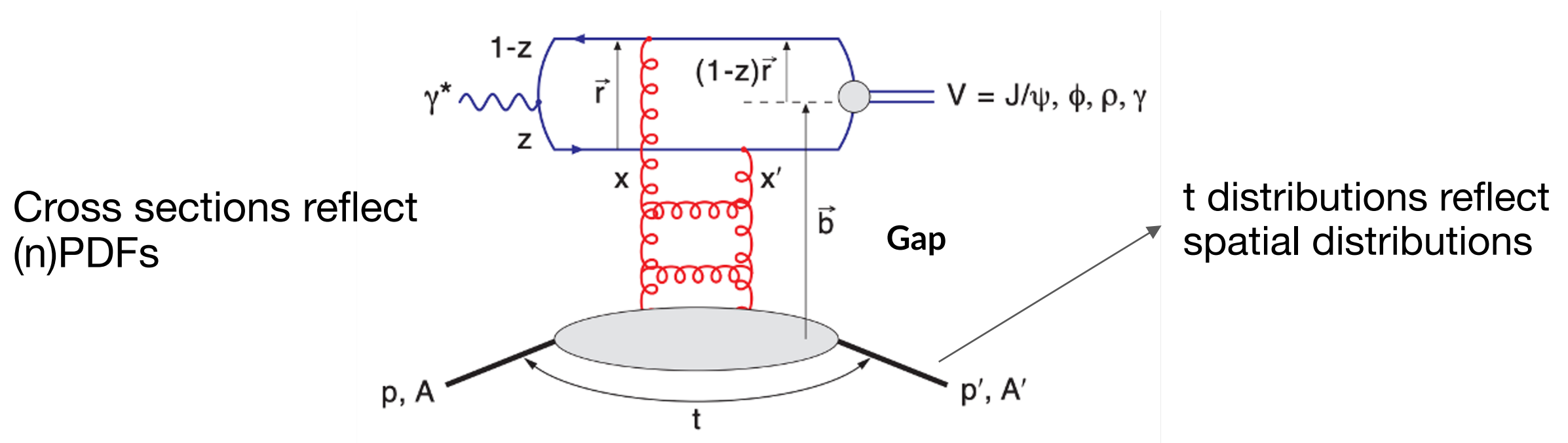
Thanks to many for direct and indirect help with this work, including:
Mark Baker, Bill Li, Alex Jentsch, Kong Tu, Axel Schmidt, Or Hen, Justin Frantz,
Dhevan Gangadharan, Thomas Ullrich, Tobias Toll, ePIC exclusive/diffractive/tagging WG…

Peter Steinberg, BNL / CFNS eA workshop / 6 July 2023

Diffraction in eA

- **Crucial to the NAS report (2018) and Yellow Report (2021) are two important questions for the EIC program**
  - Can we probe the low-x structure of the nucleus, and especially address the questions of parton saturation?
  - Can we elucidate the spatial parton structure of nuclei?

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

Cross sections reflect (n)PDFs

t distributions reflect spatial distributions

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

Coherent vs. incoherent

- **The diagram shown before is the coherent process, with no nuclear breakup**
  - This is of course the shadow of the incoherent process

- **The basic physical picture comes from Good & Walker, esp. as elucidated by Mietenlin & Pumplin (and following Klein):**
  - Total cross section goes as $\langle |A(K, \Omega)|^2 \rangle$
    - *Sum over target configurations Ω*
  - Coherent cross section goes as $|\langle A(K, \Omega)\rangle|^2$
    - *Sum over configurations before squaring, since target is unmodified*
  - Incoherent is the difference $\langle |A(K, \Omega)|^2 \rangle - |\langle A(K, \Omega)\rangle|^2$
    - *Reflects fluctuations in the target*

- **Renewed interest in our field from work of Schenke & Mantyasaari, interpreting HERA ep data in terms of a proton "hot spot" model**

Coherent processes: Sartre

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

$$\mathcal{A}_{T,L}^{\gamma^* p}(x_P, Q, \Delta) = i \int dr \int \frac{dz}{4\pi} \int d^2\mathbf{b} \left[(\Psi_V^* \Psi)(r,z) \right] 2\pi r J_0([1-z]r\Delta) e^{-i\mathbf{b}\cdot\Delta} \frac{d\sigma_{q\bar{q}}^{(p)}}{d^2\mathbf{b}}(x_P, r, \mathbf{b})$$
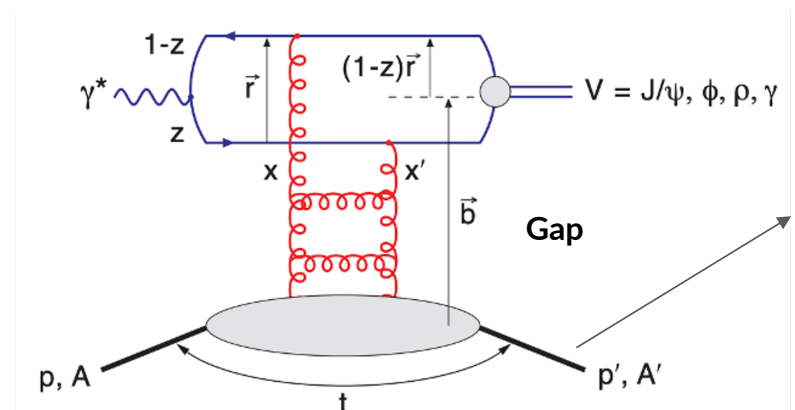
with the e+A
dipole cross section

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

and the final production cross section

$$\frac{d\sigma_{T,L}^{\gamma^* A}}{dt} = \frac{1}{16\pi} \left\langle \left| \mathcal{A}^{\gamma^* p}(x_P, Q^2, t) \right|^2 \right\rangle_\Omega$$
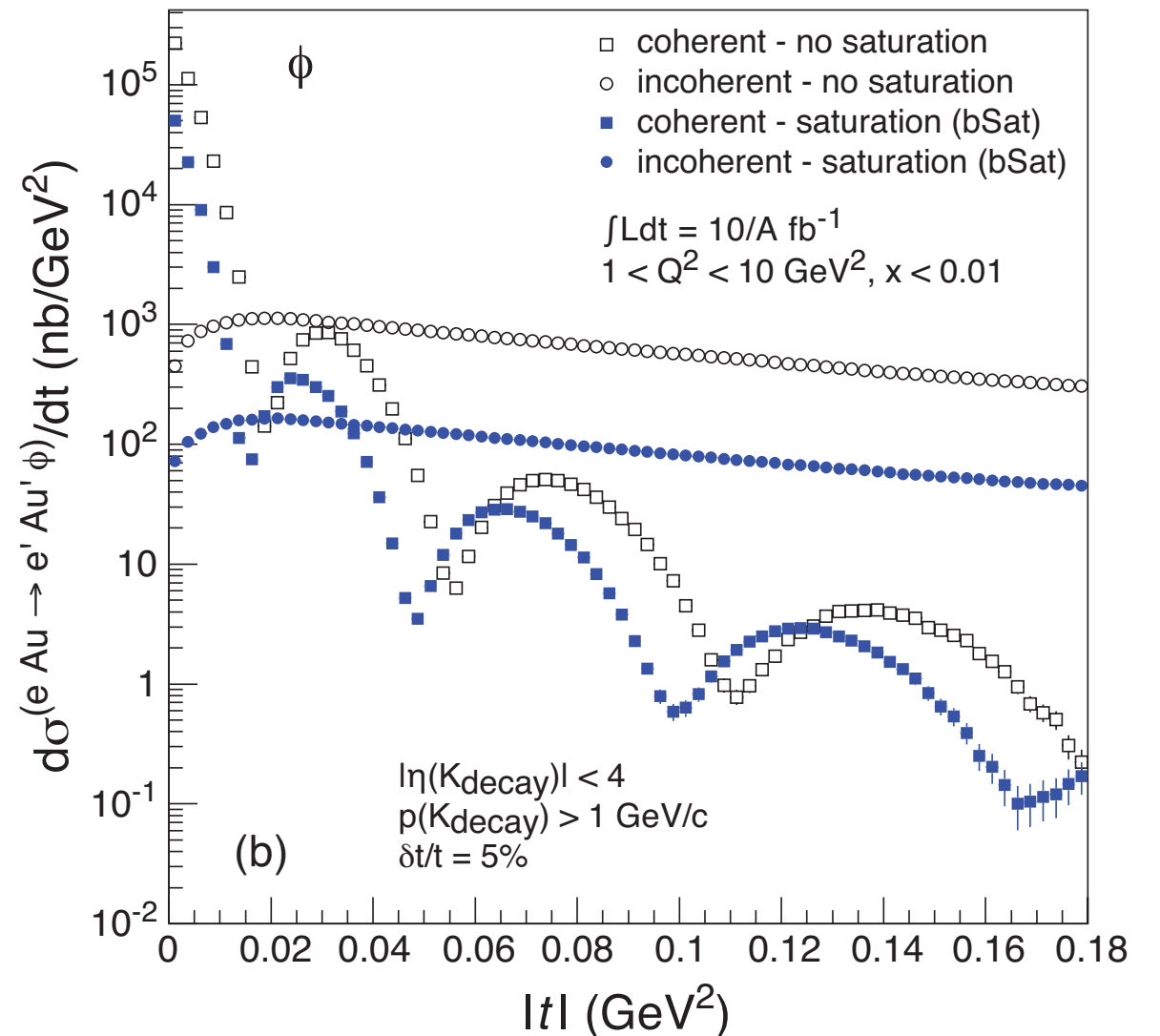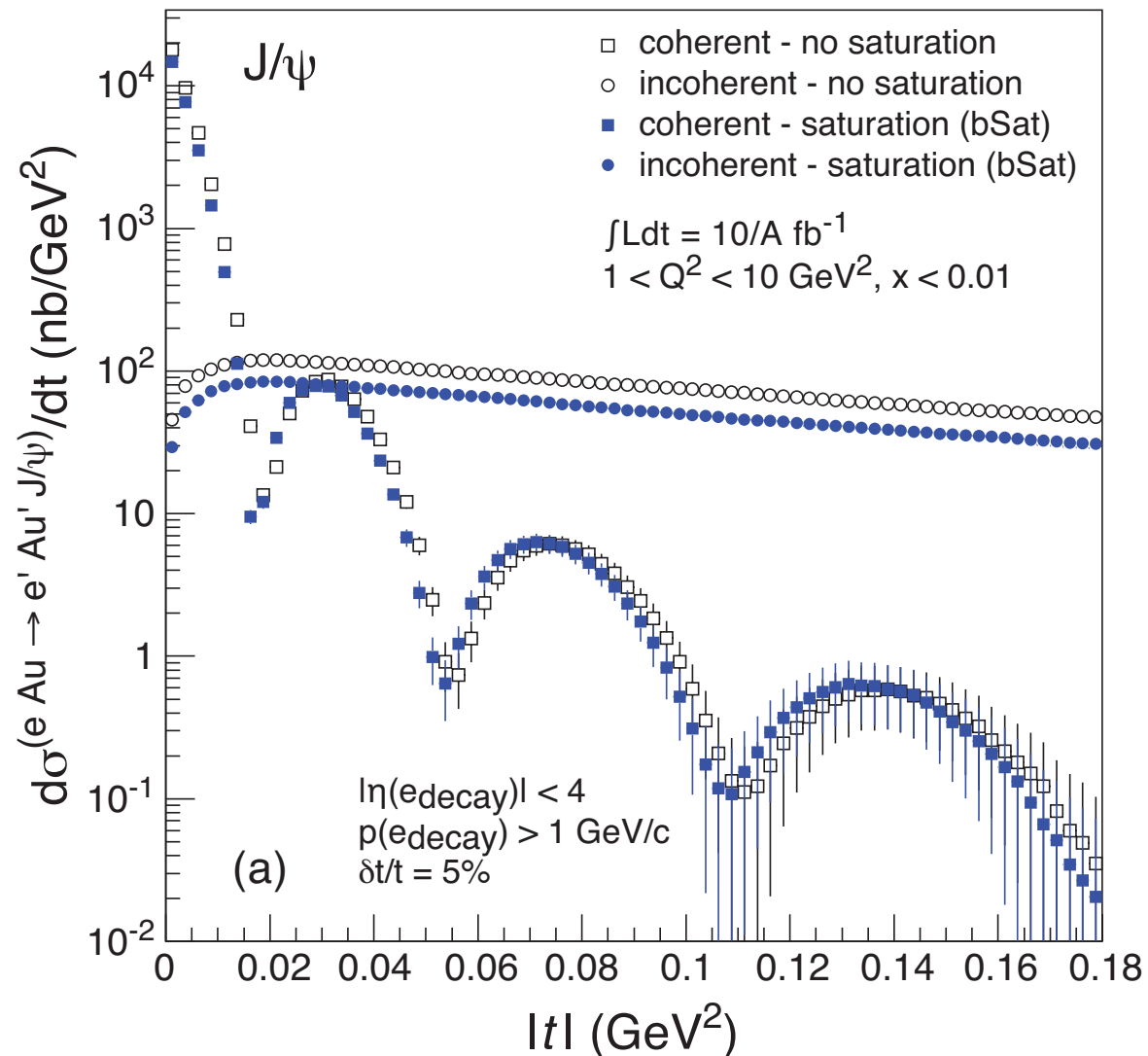
- **Here only used for coherent reactions, with no nuclear breakup**
  - Incoherent contributions only utilized for their cross sections

The basic task:

Image nuclear spatial structure using diffractive peaks

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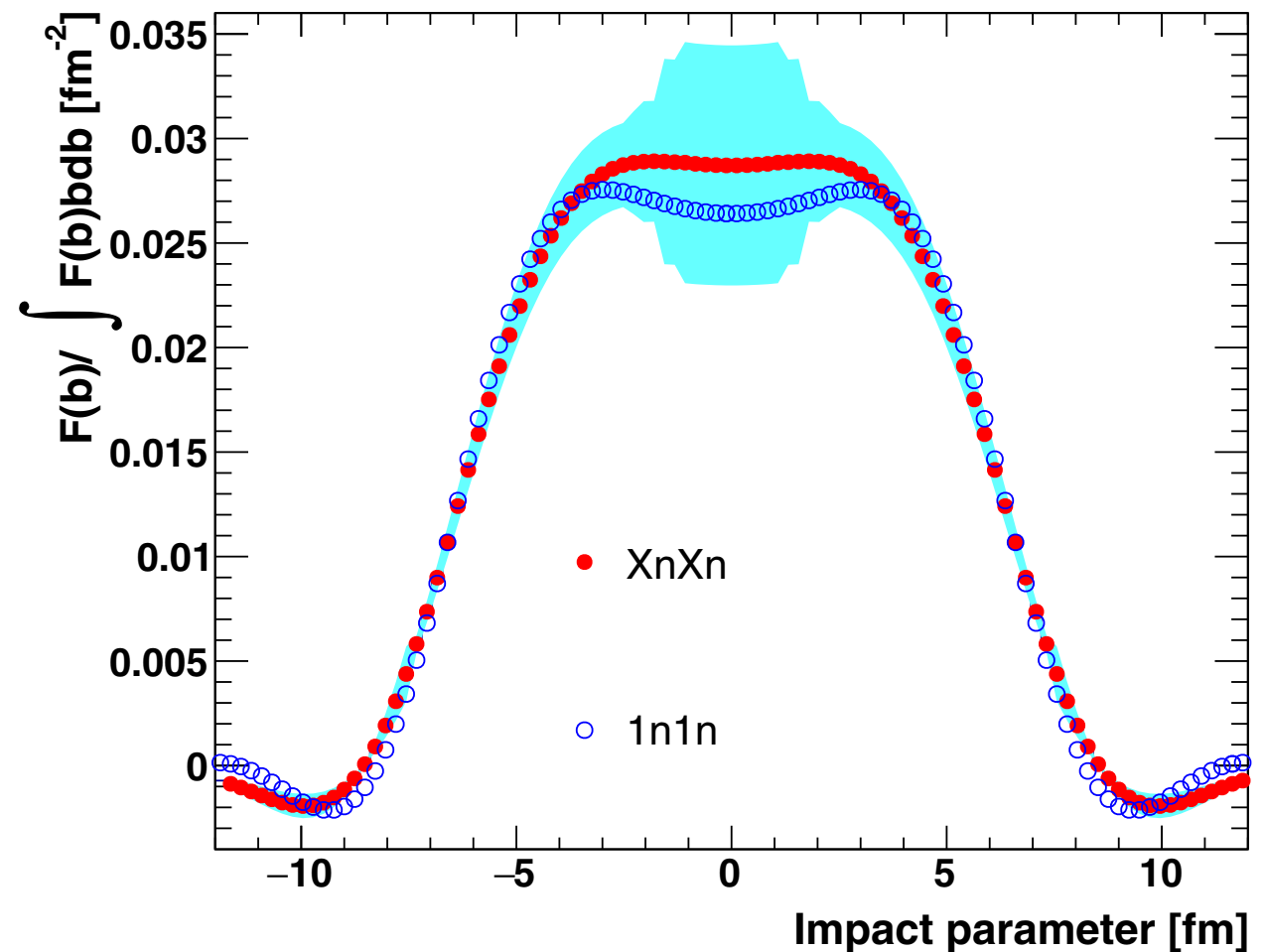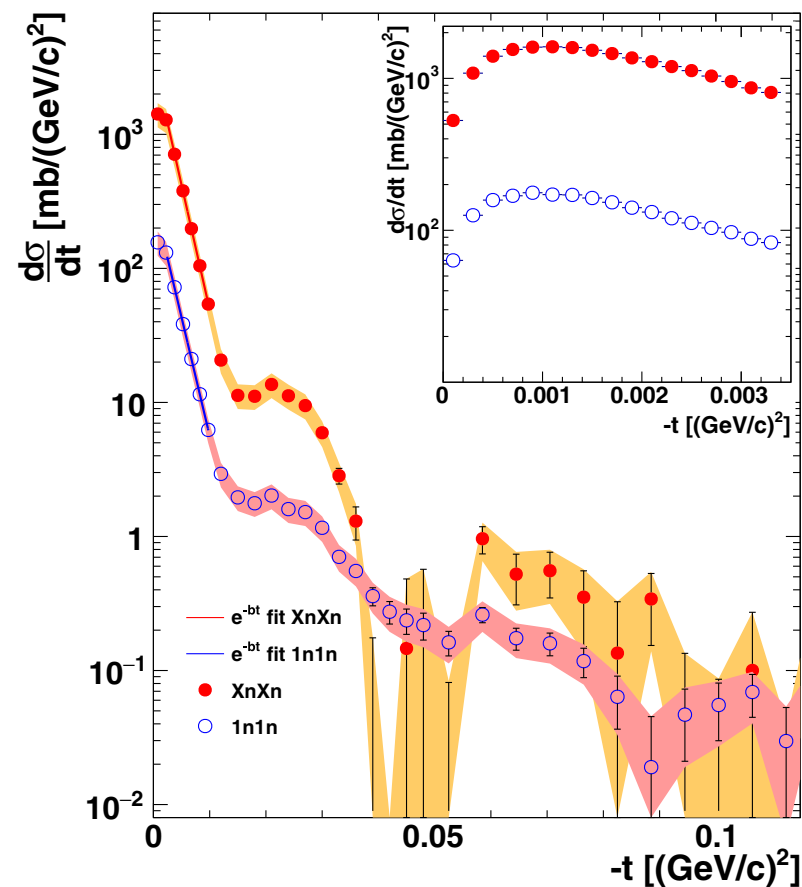φ is a much more sensitive saturation probe
But how deep will the dips be, in practice? Do HO processes fill them?
And how do we remove the incoherent contributions, large at large t
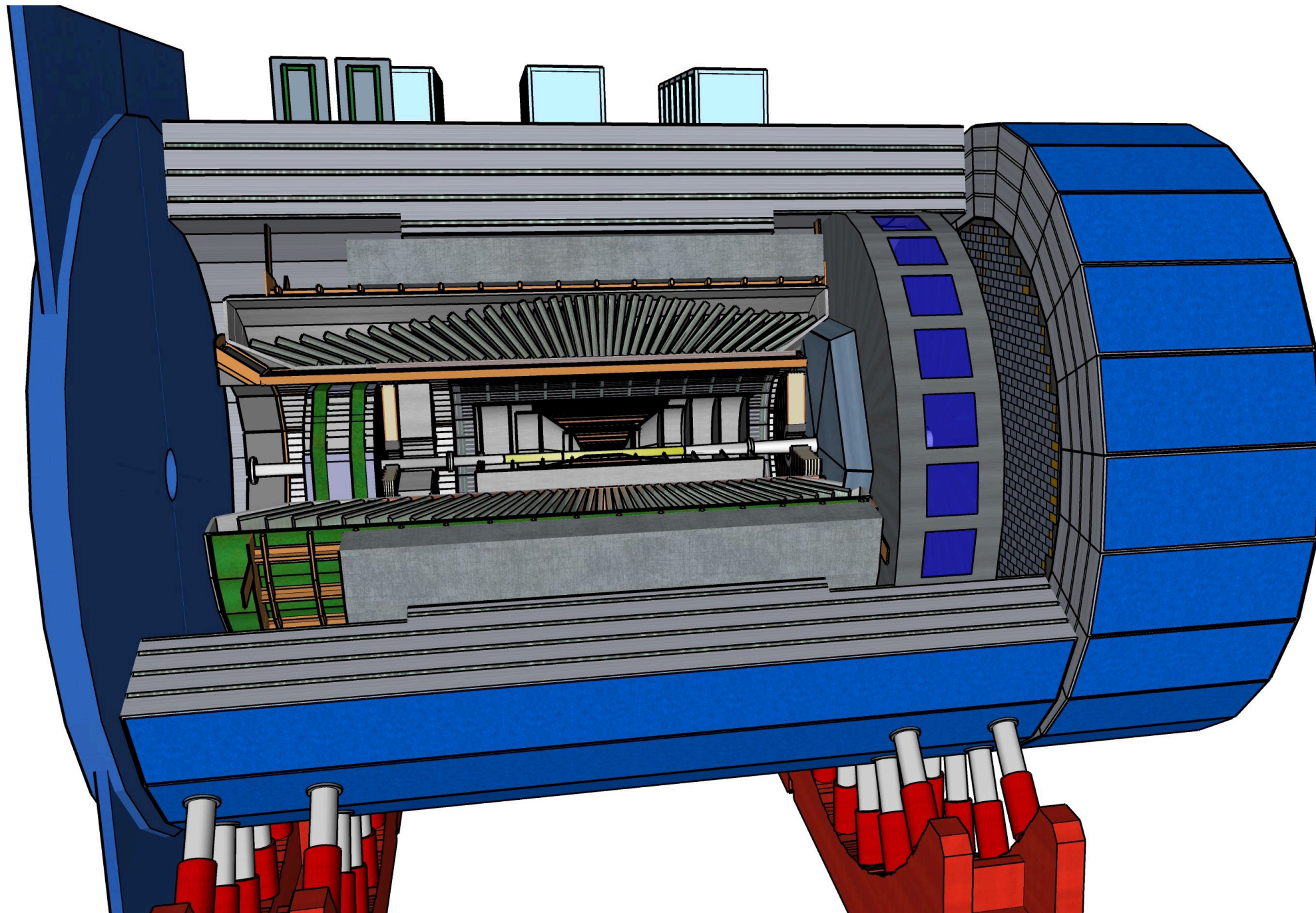
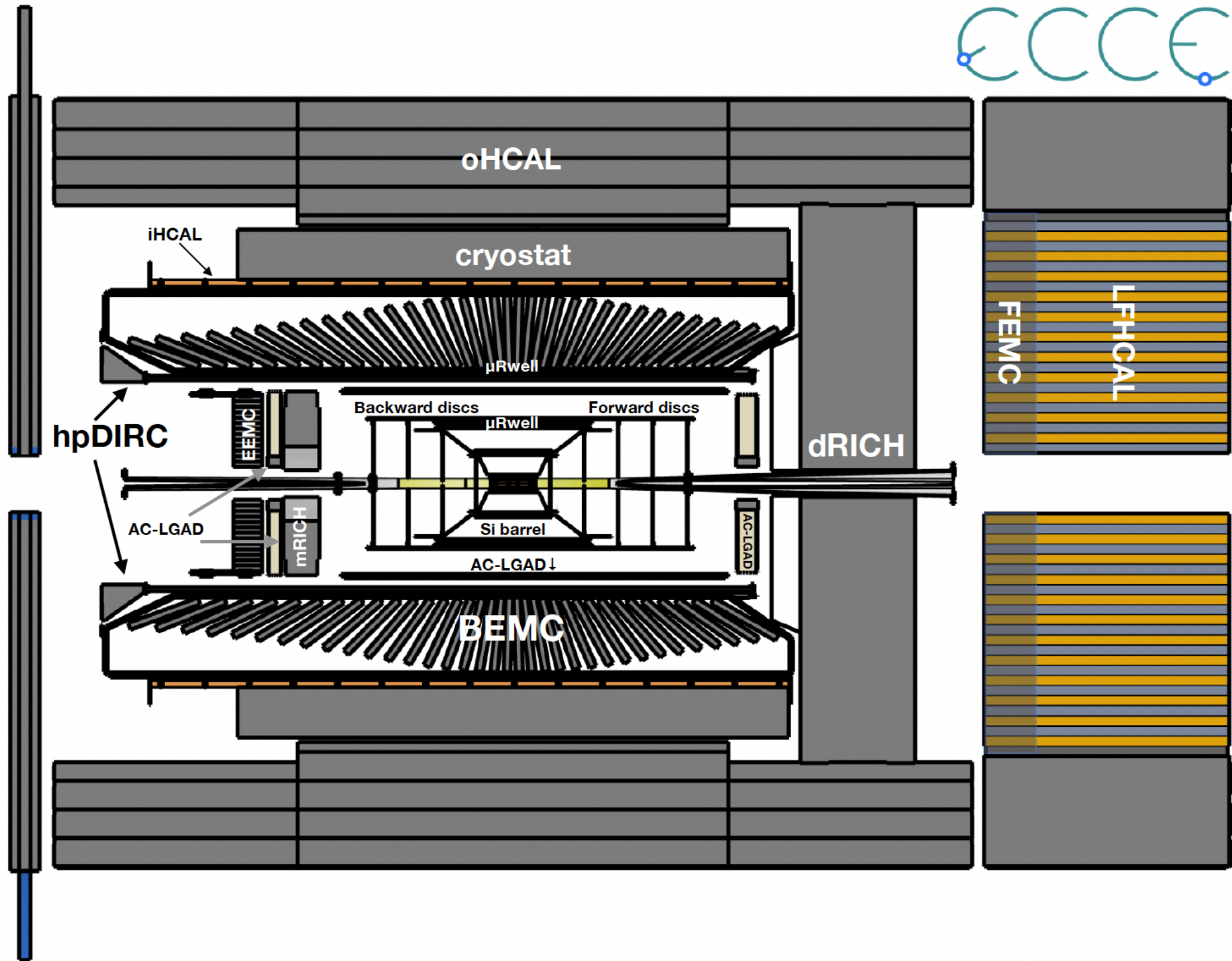# Existence proof :)

STAR @ RHIC

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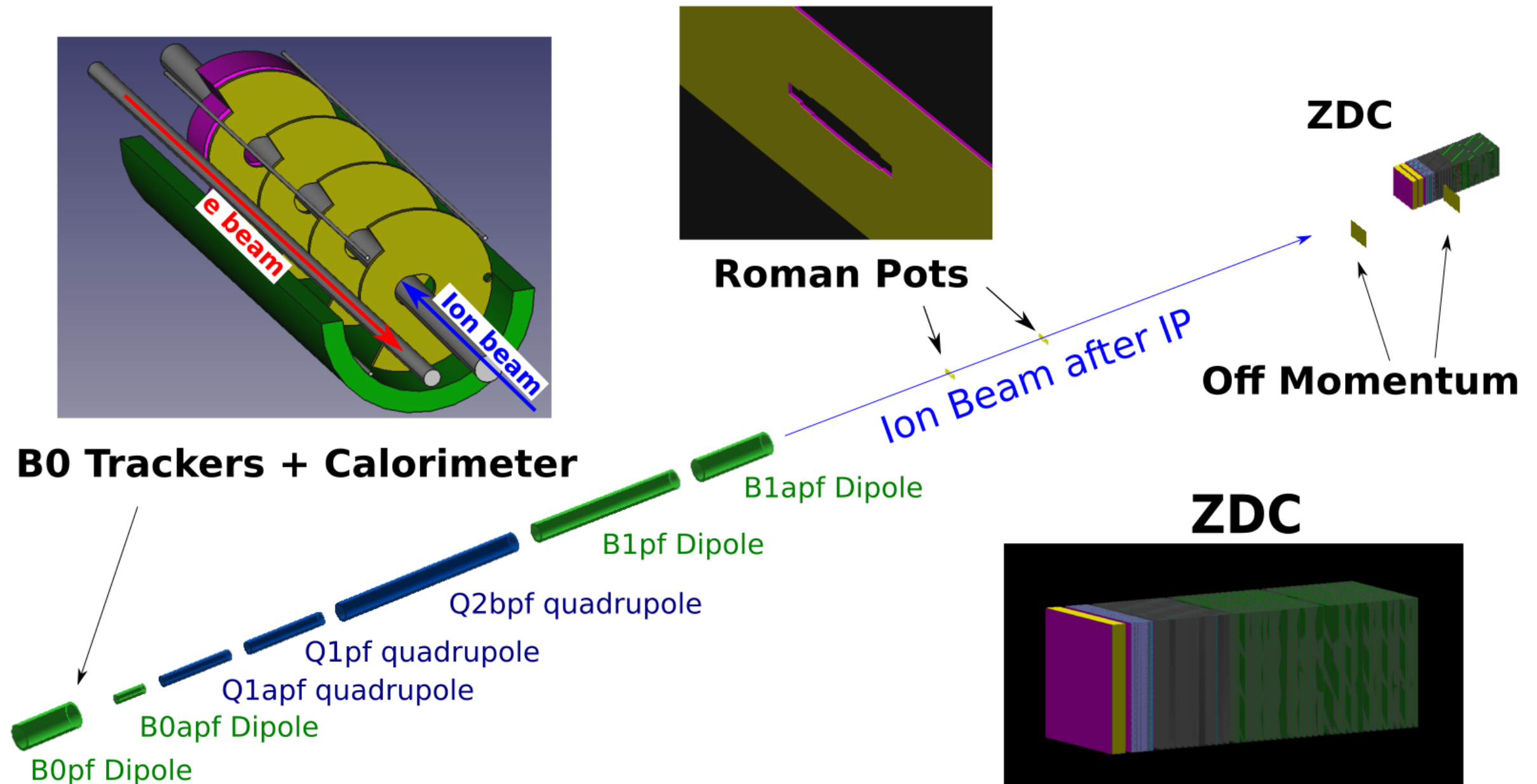but lighter mesons lack hard scale

Proposed ECCE experiment

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

ECCE far forward

ZDC

**Roman Pots**

Ion Beam after IP

Off Momentum

B0 Trackers + Calorimeter

B1apf Dipole

B1pf Dipole

Q2bpf quadrupole

Q1pf quadrupole

Q1apf quadrupole

B0apf Dipole

B0pf Dipole

ZDC

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

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see talk by A. Jentsch later today

Incoherent processes: BeAGLE

Parton level interaction, parton shower and jet fragmentation from PYTHIA. Multinucleon shadowing available in BeAGLE.
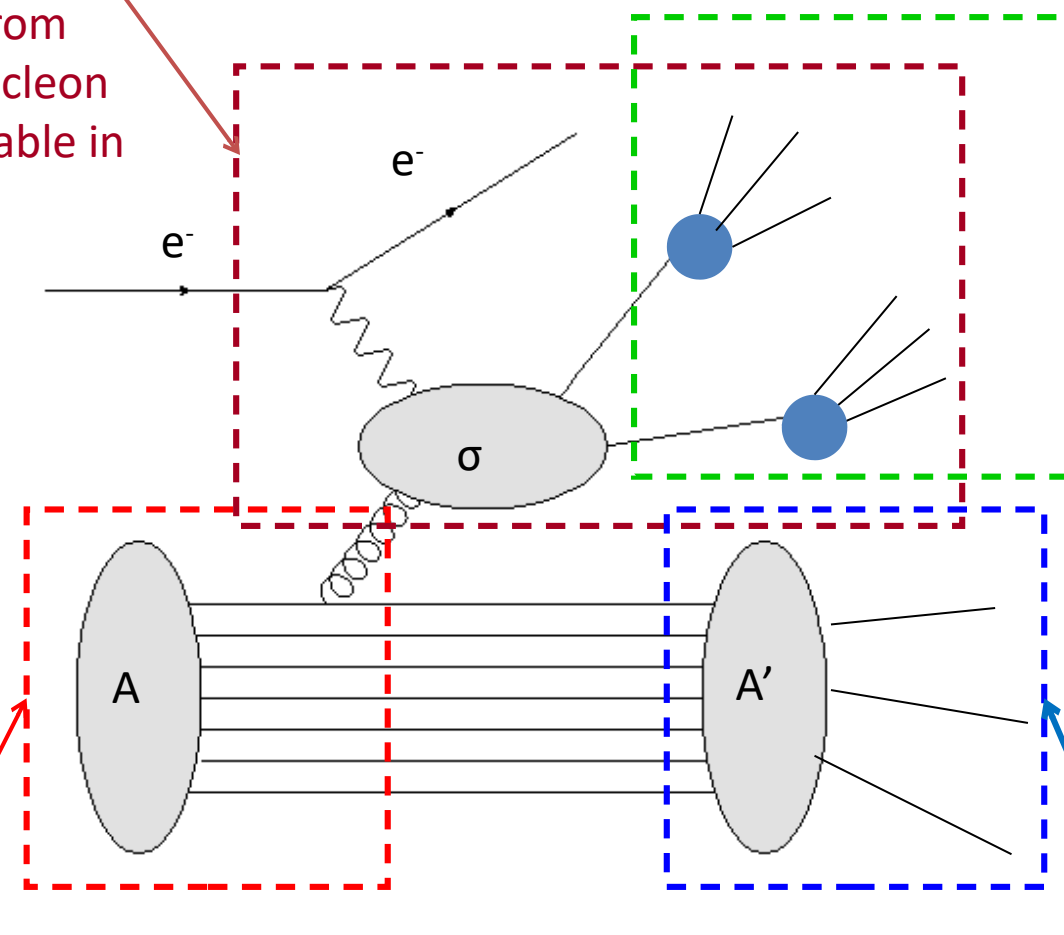
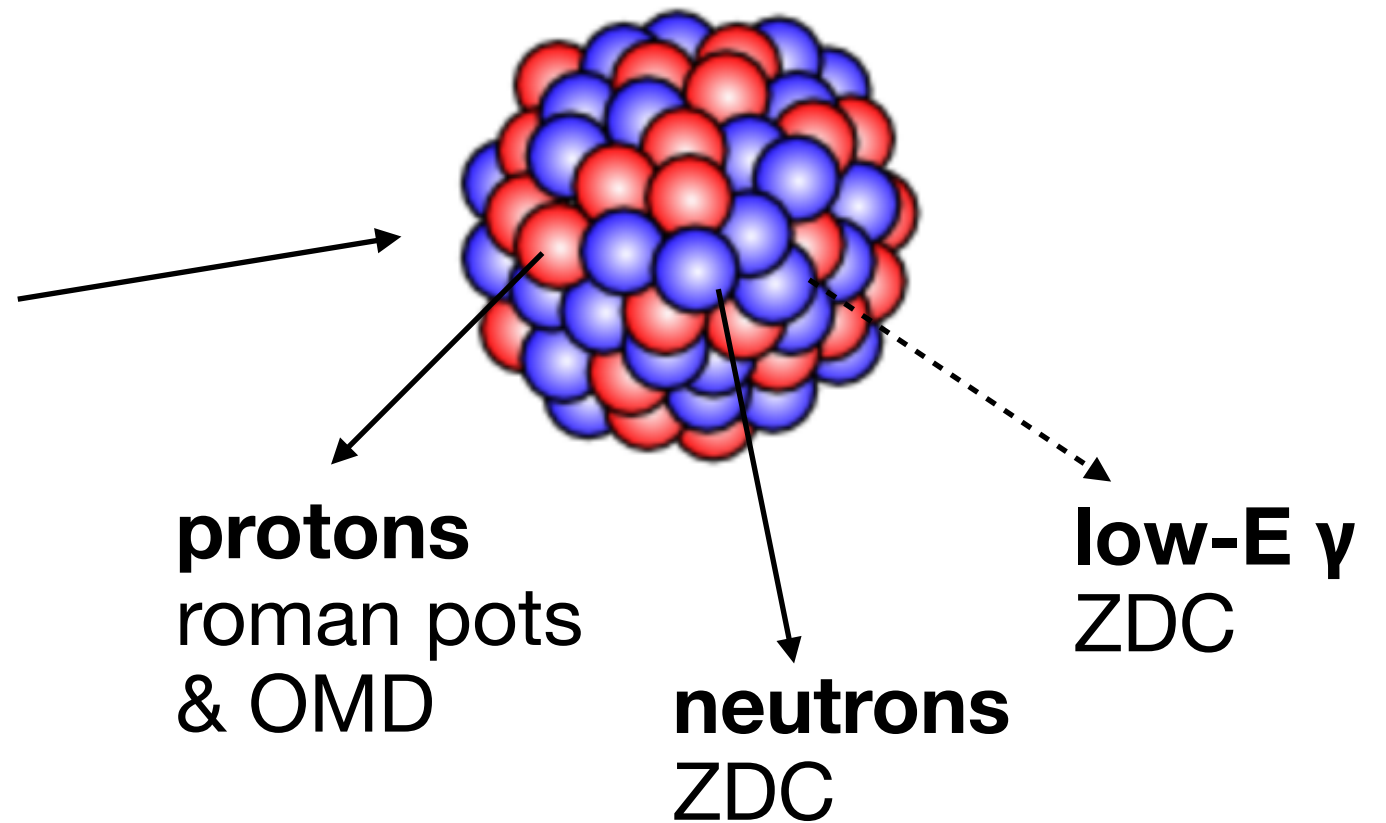Intranuclear Cascade from DPMJet. Optional Energy loss effect from extended BDMPS in PyQM.
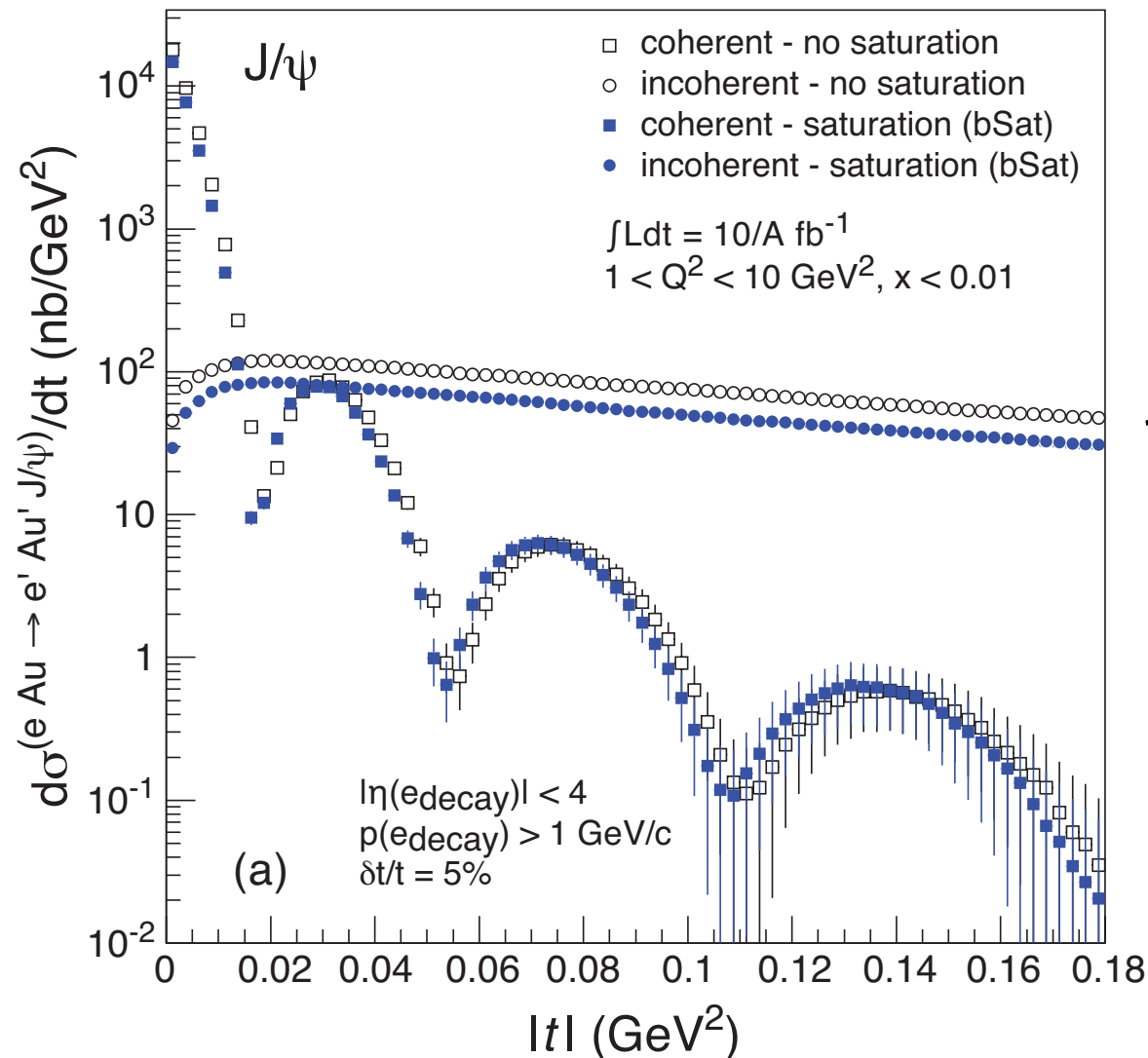

Nuclear geometry by BeAGLE & PyQM plus EPS09 nuclear PDF provided in LHAPDF.

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

J/ψ

- □ coherent - no saturation
- ○ incoherent - no saturation
- ■ coherent - saturation (bSat)
- ● incoherent - saturation (bSat)

$\int$Ldt = 10/A fb^{-1}
$1 < Q^2 < 10$ GeV^2, x < 0.01

|η(e$_{decay}$)| < 4
p(e$_{decay}$) > 1 GeV/c
δt/t = 5%

(a)

$d\sigma^{(e\ Au \to e'\ Au'\ J/\psi)}/dt$ (nb/GeV^2)

|t| (GeV^2)

protons
roman pots
& OMD

neutrons
ZDC

low-E γ
ZDC

Incoherent processes are "backgro
coherent processes - they hide the
structure - but they are also signal:
spatial fluctuations, e.g. "hotspot"

Pb > Au due to photon de-excitation

Schenke & Mäntysaari (2016)
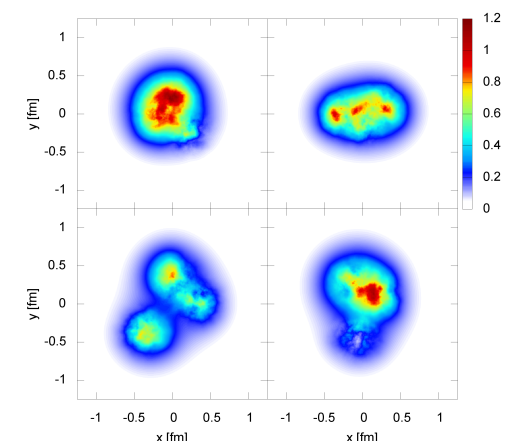
Initial studies of eA in ECCE

- **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)
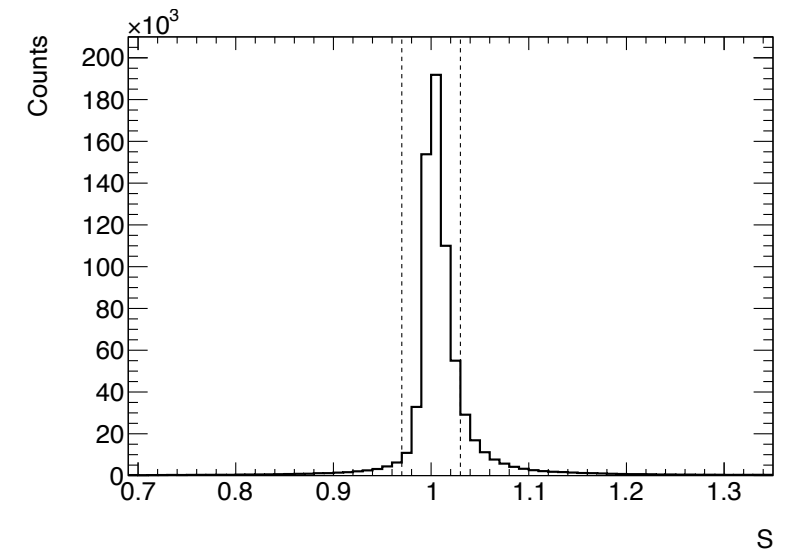low x_V (not x)
$10\ fb^{-1}/A = 50\ pb^{-1}$
ee and μμ modes

Initial studies in eA, contd.

- **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*

Further challenges!

- **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*
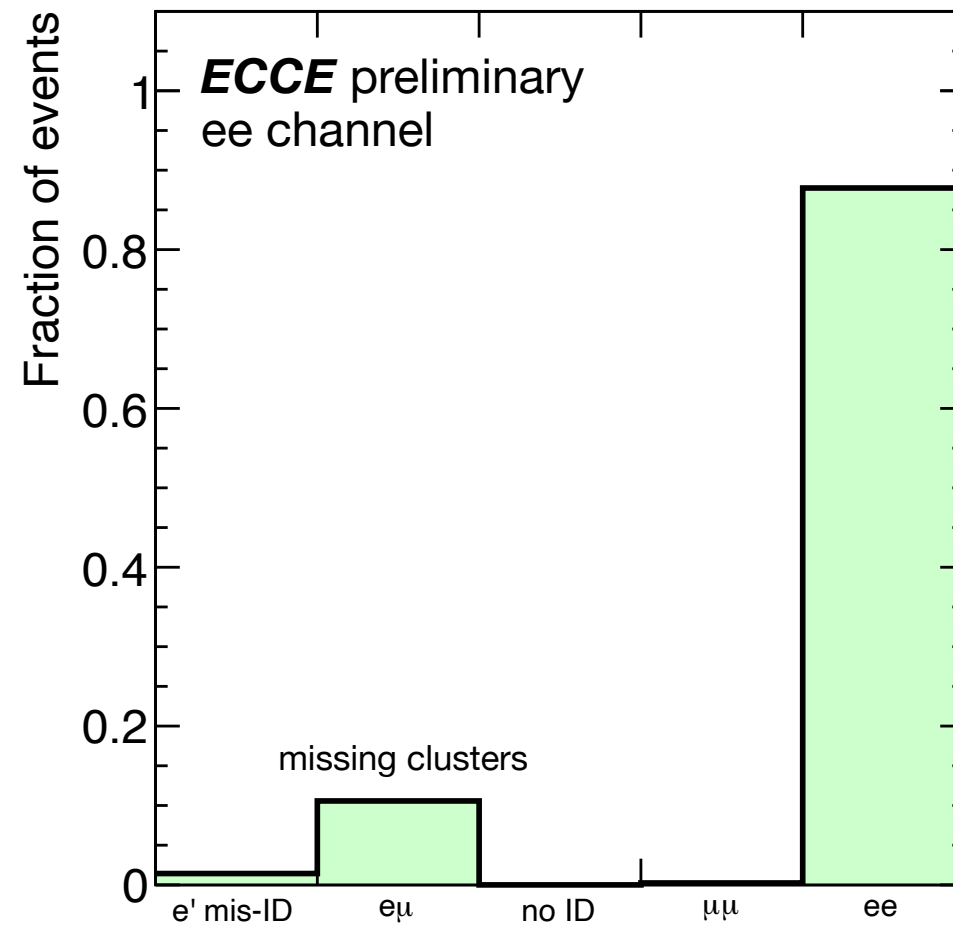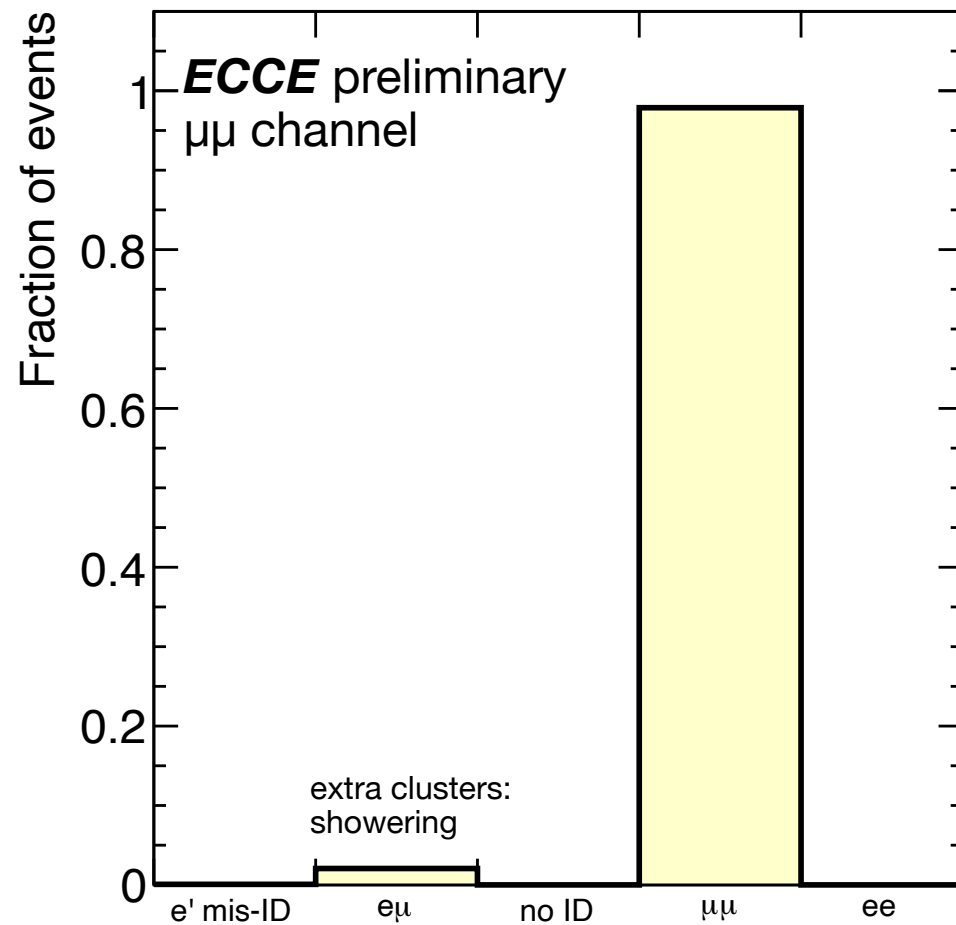
PID efficiency

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 GeV²**
  - 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?
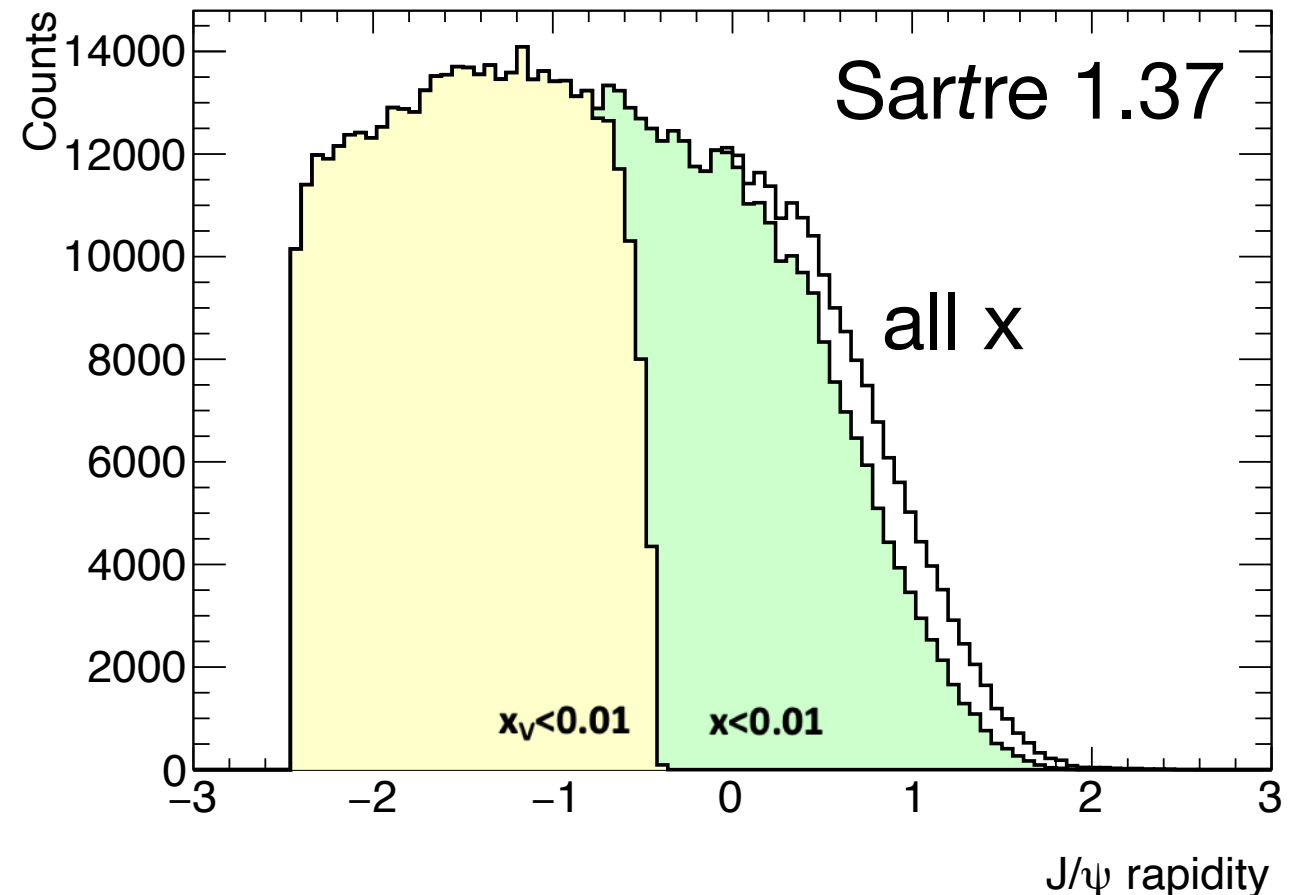
J/ψ decay kinematics   1<Q²<10 GeV², x<0.01
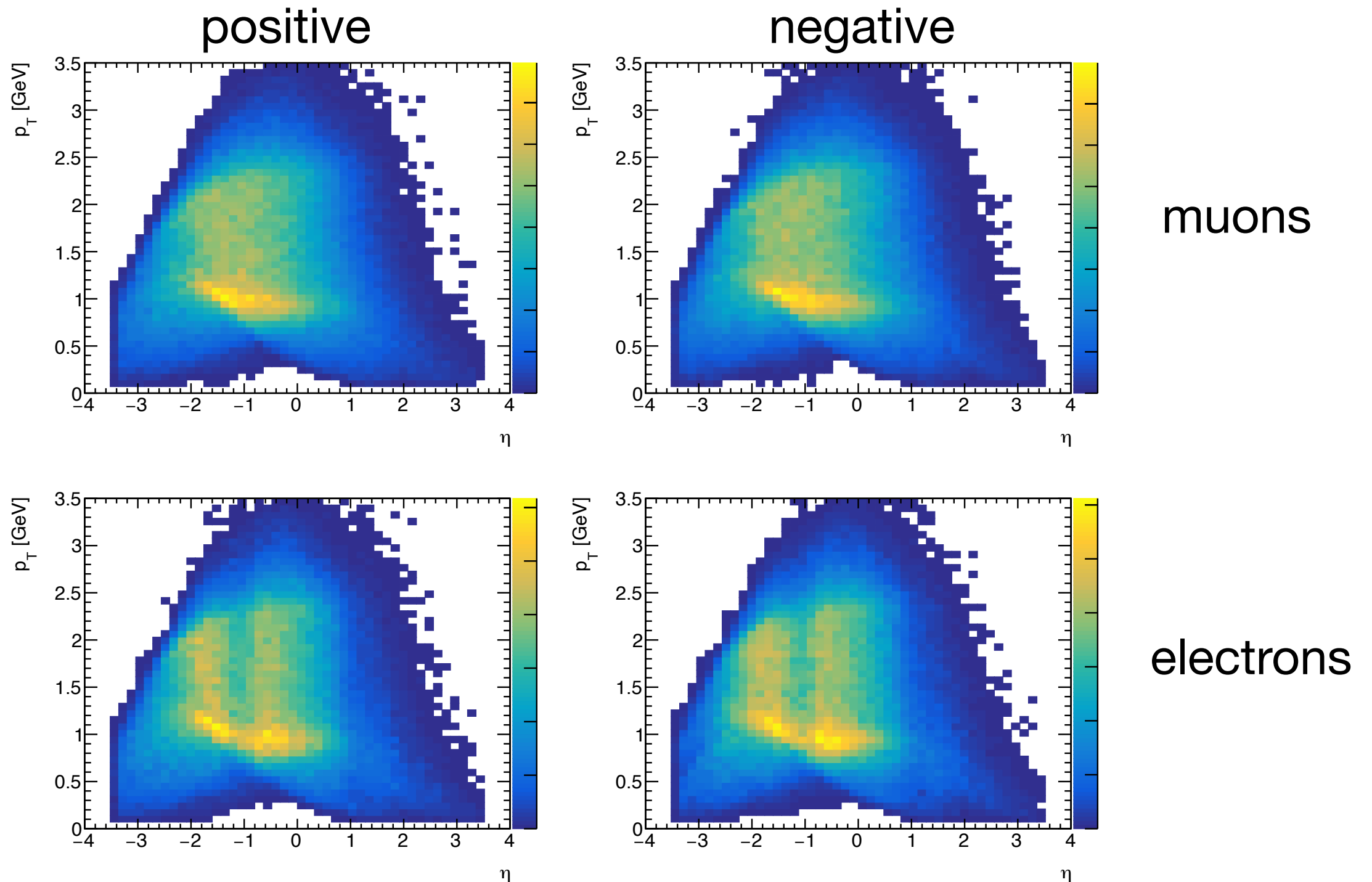
Tracks accepted within |η|<3.4 and p$_T$>0.1 GeV

some artifacts visible of specific approach for selecting the scattered e' in ψ→ee

e' kinematics
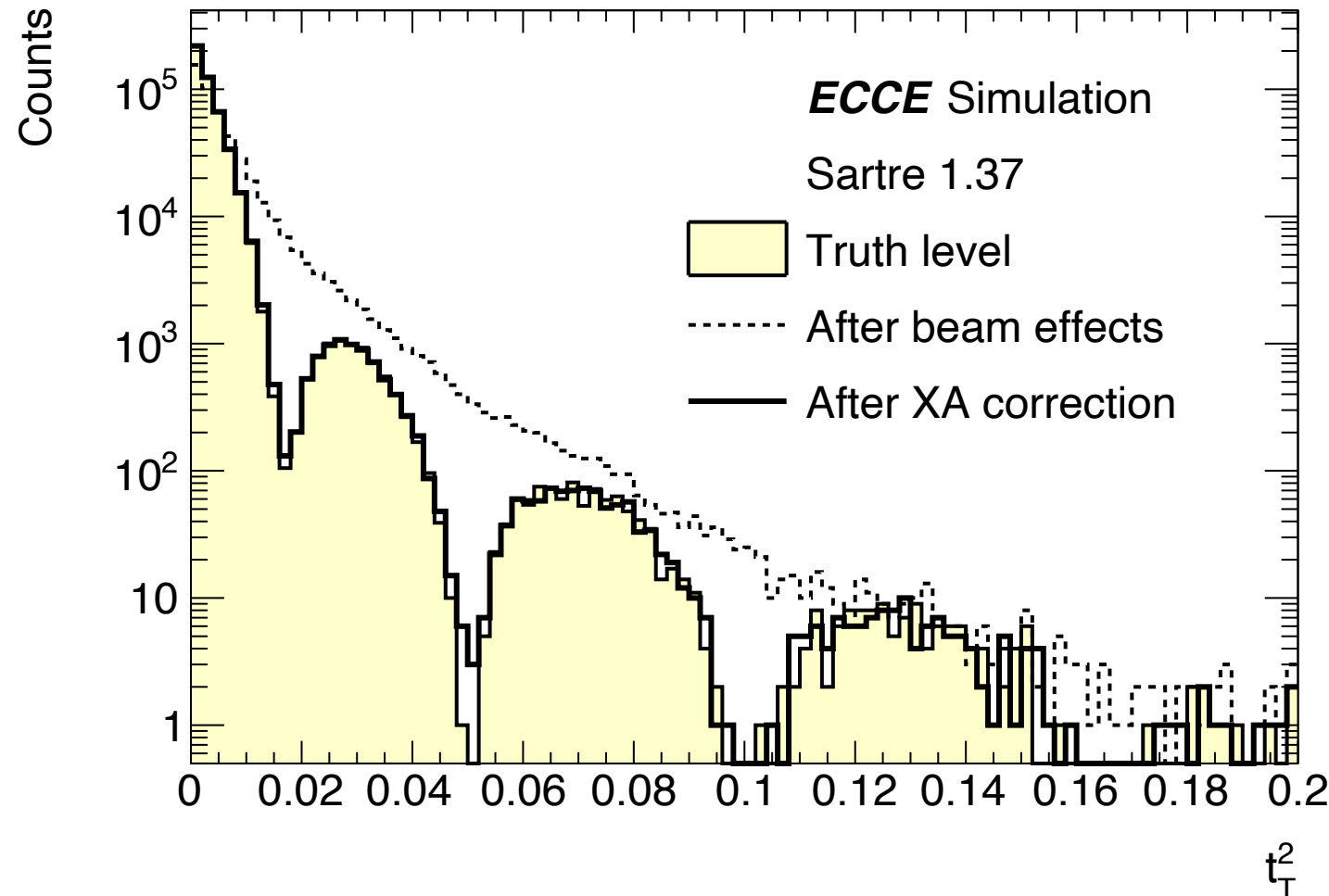
1<Q²<10 GeV², x<0.01

muon
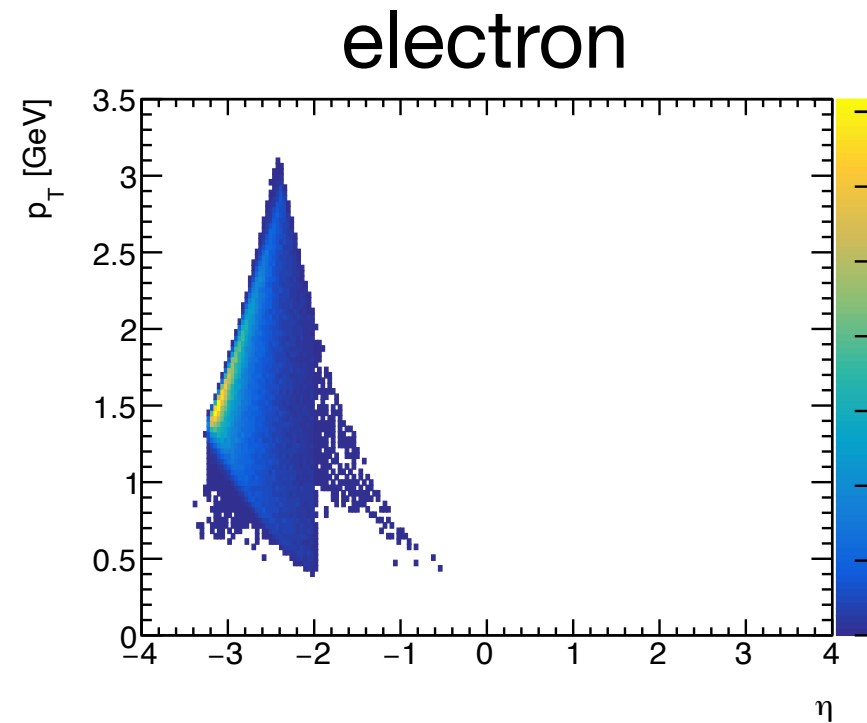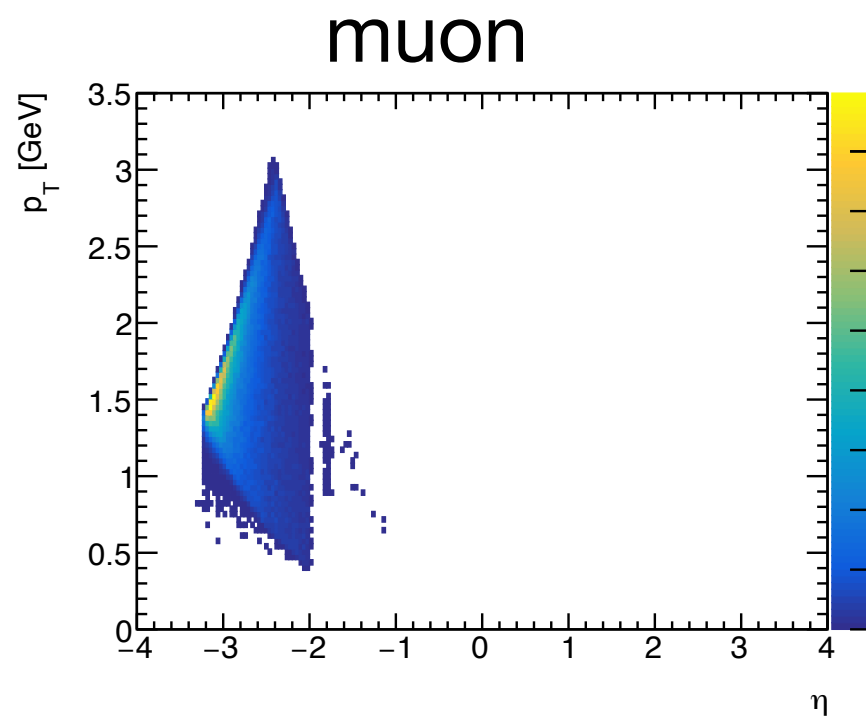
electron

truth
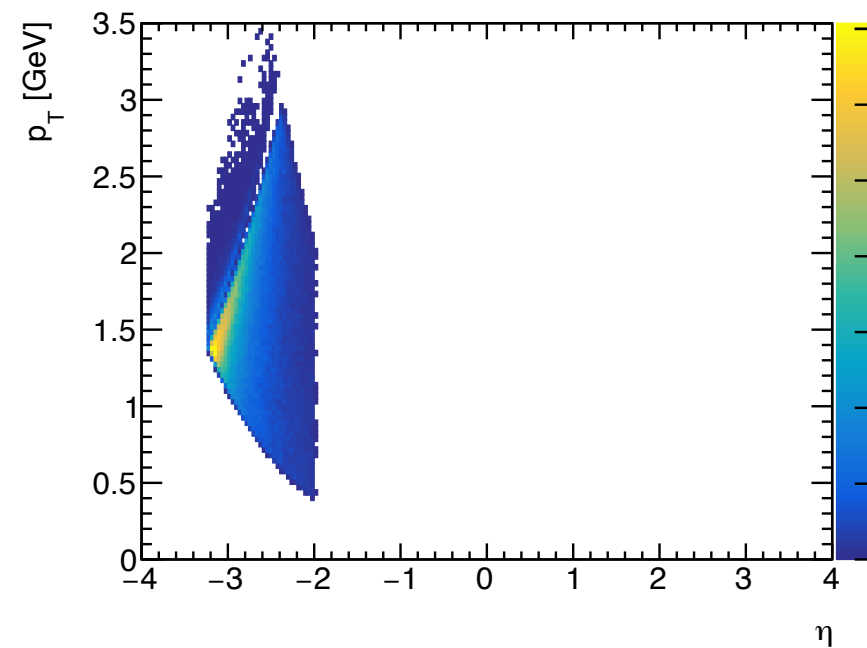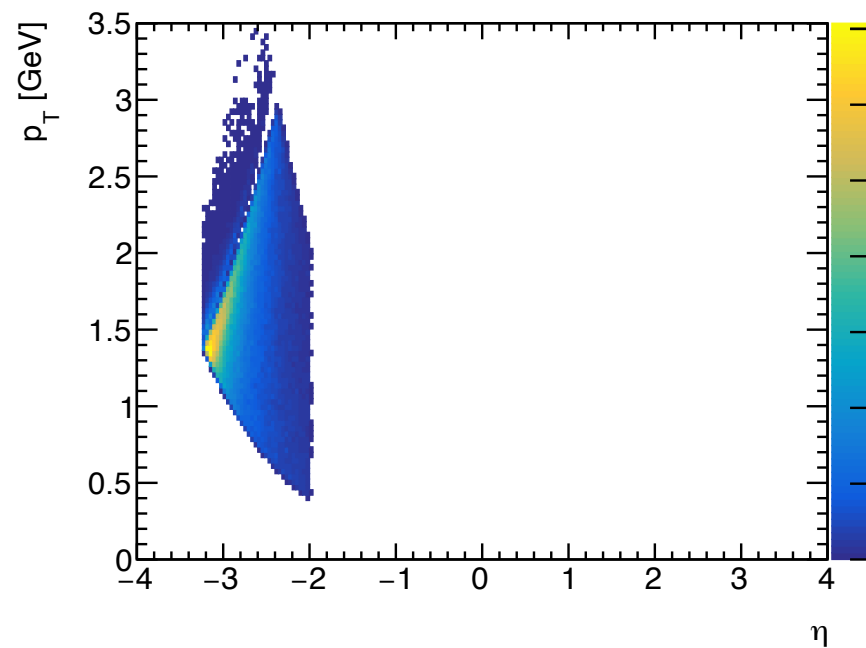
reconstructed

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

"response" P(reco)/P(truth)


p_T^2 [GeV^2]
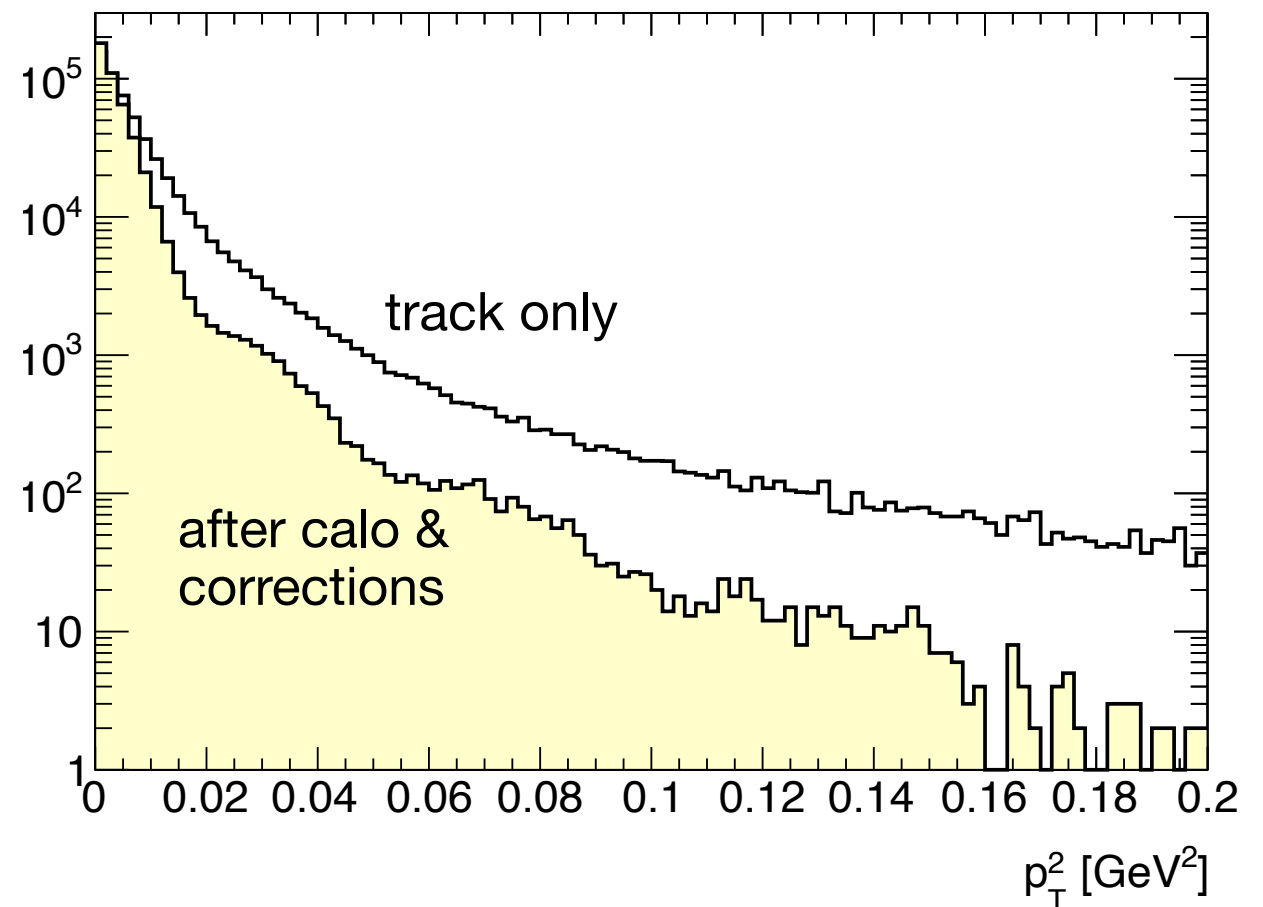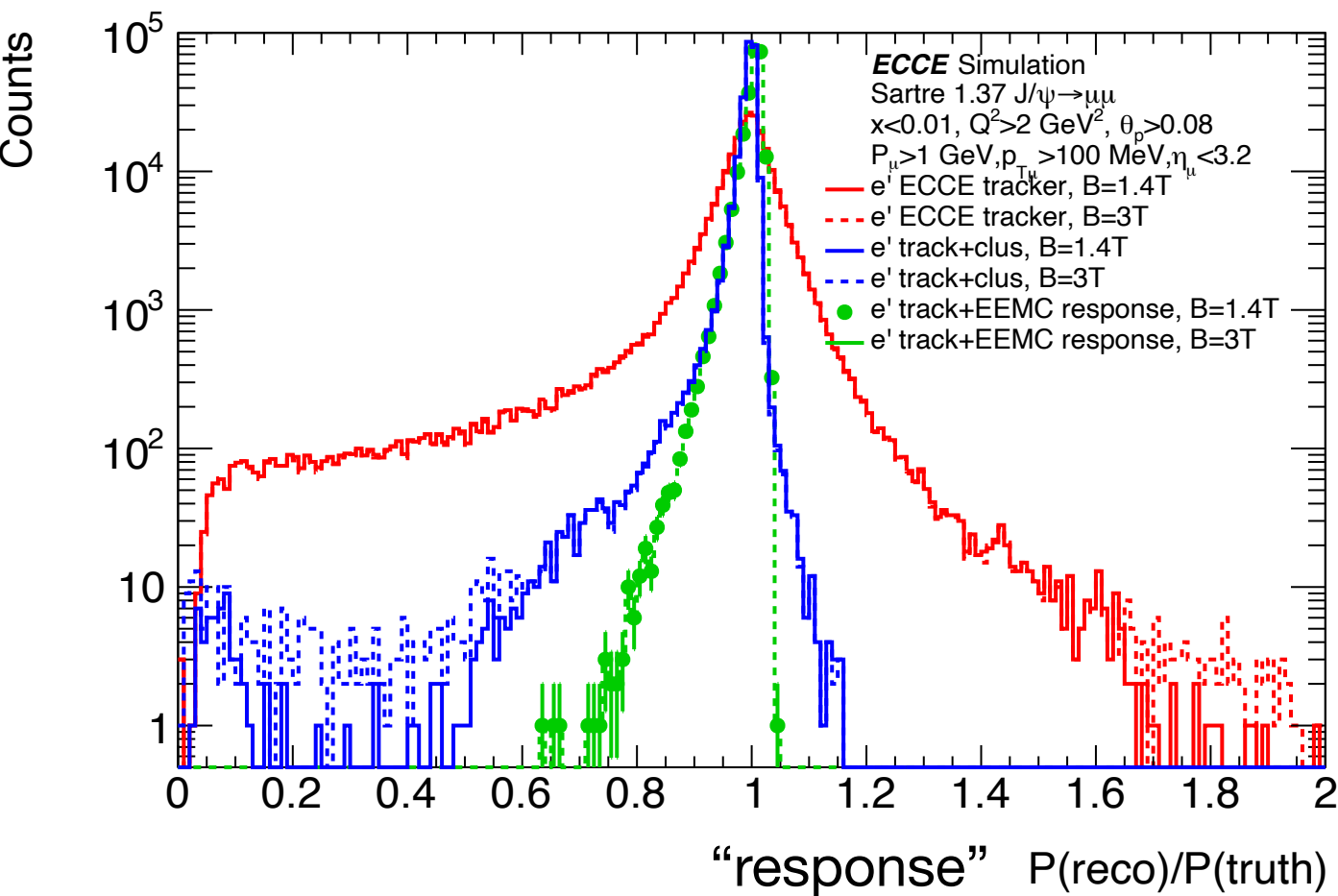
- Primary limitation on this measurement is the e' response:

- 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

- Limited improvement from "method L", kinematic constraint based on E+p_z
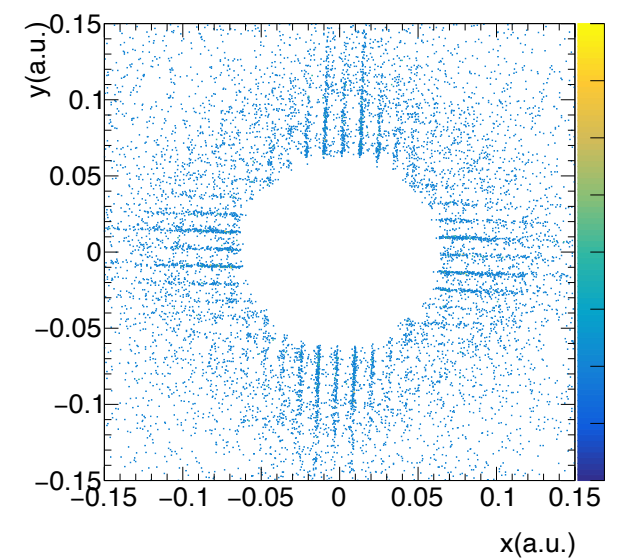
low momentum tails associated with cracks in backwards calorimeter!

Coherent-only cross section
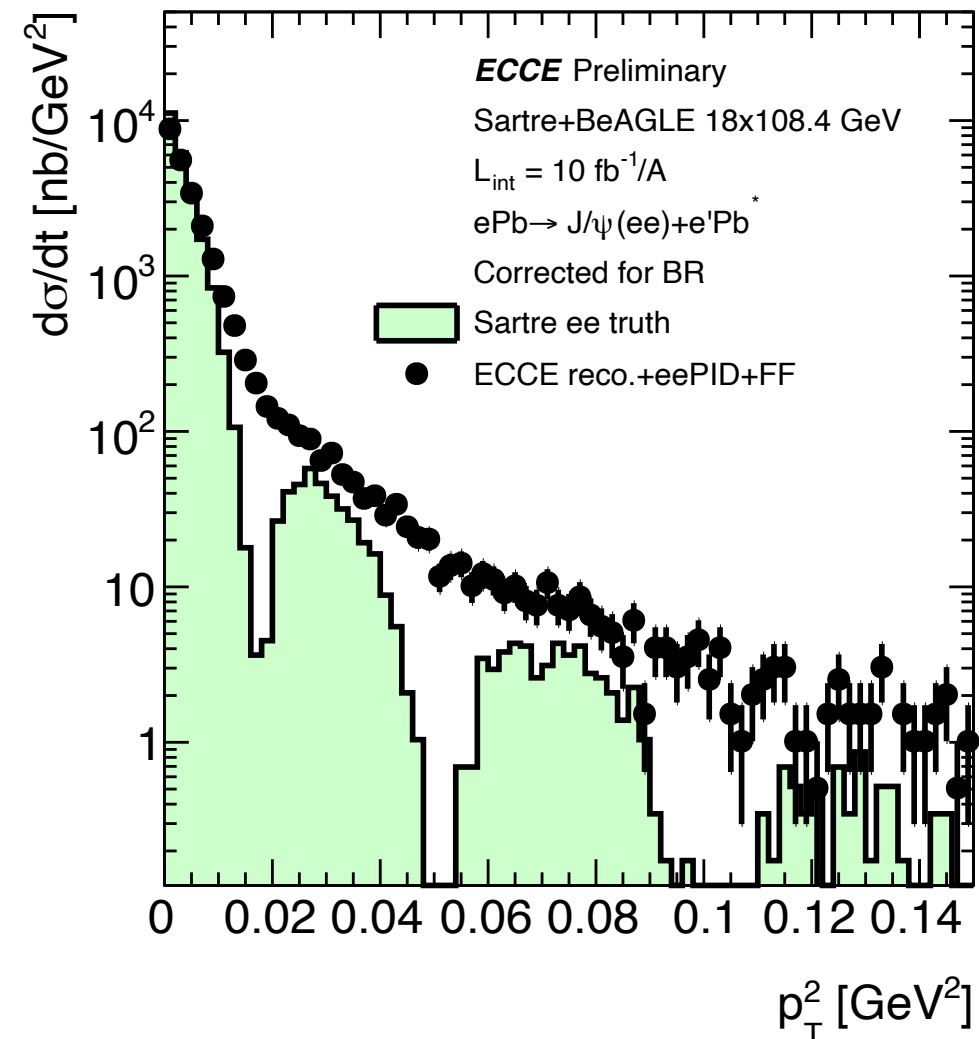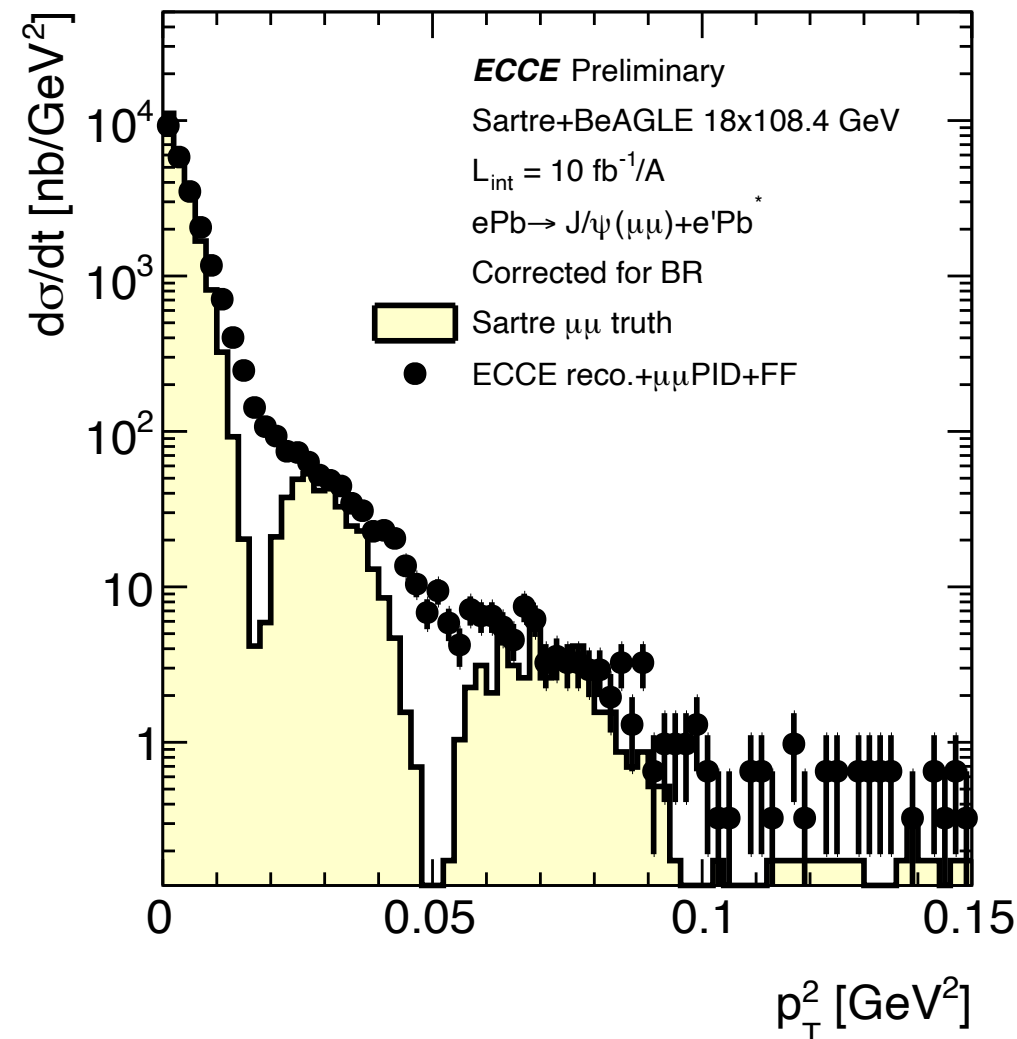
- Efficiency defined as simple integral of reconstructed counts over truth
- Efficiency vs Q^2 is mostly constant but composed of many parts
  - e' efficiency (track & cluster), charged decay products, PID cuts, kinematic constraints, etc.
  - 40% for ee, 60% for μμ
- Tracking resolution sufficient for observation of "kinks" in the μμ channel
  - Direct μID in detector 2 may be important, deserving of study (cf. Pavel's talk next!)
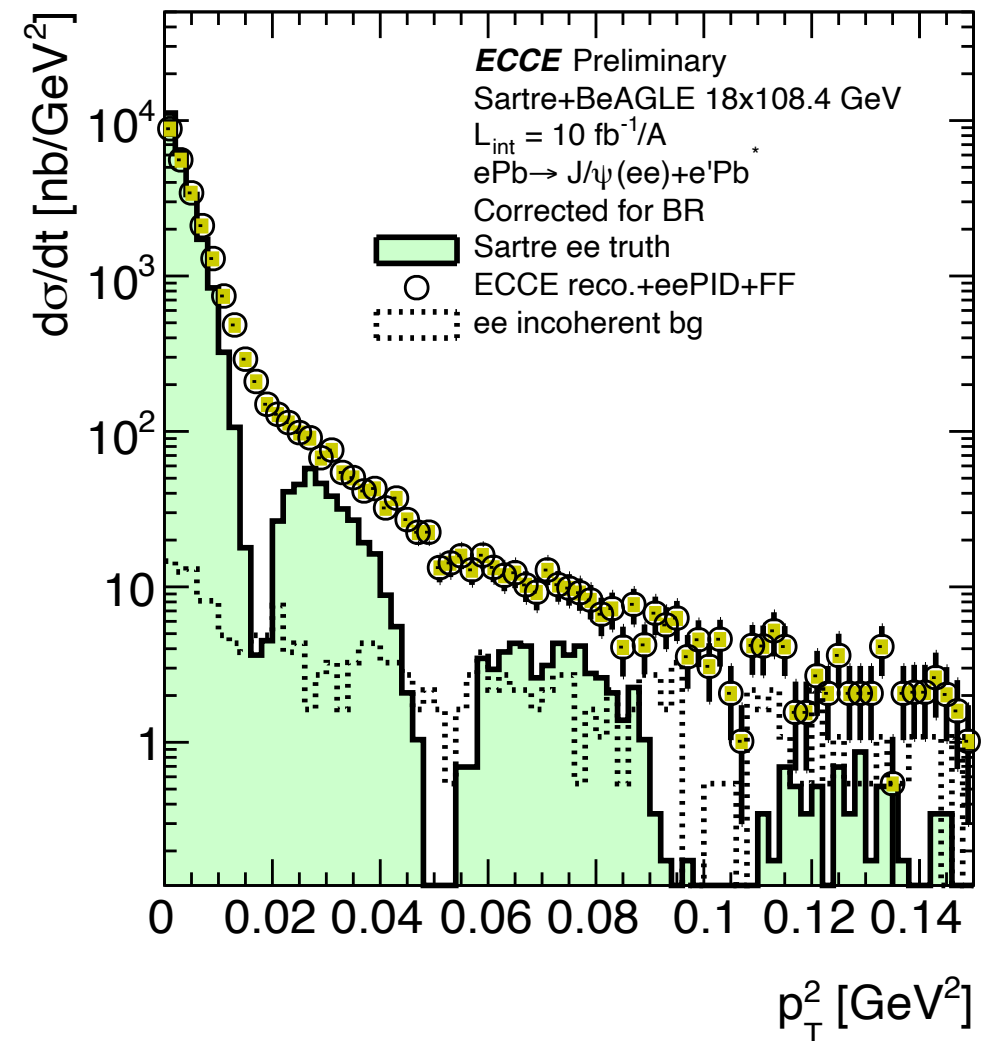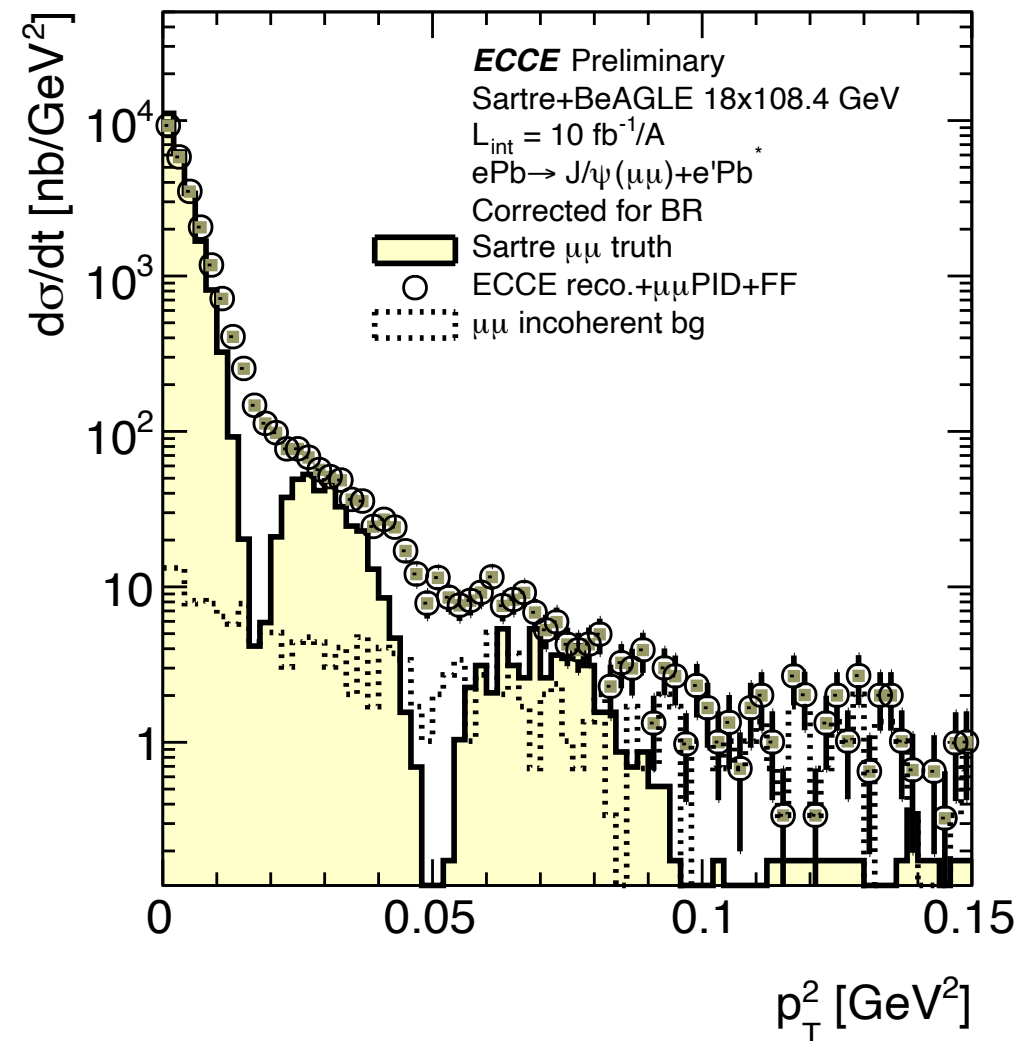
Cutting incoherent backgrounds
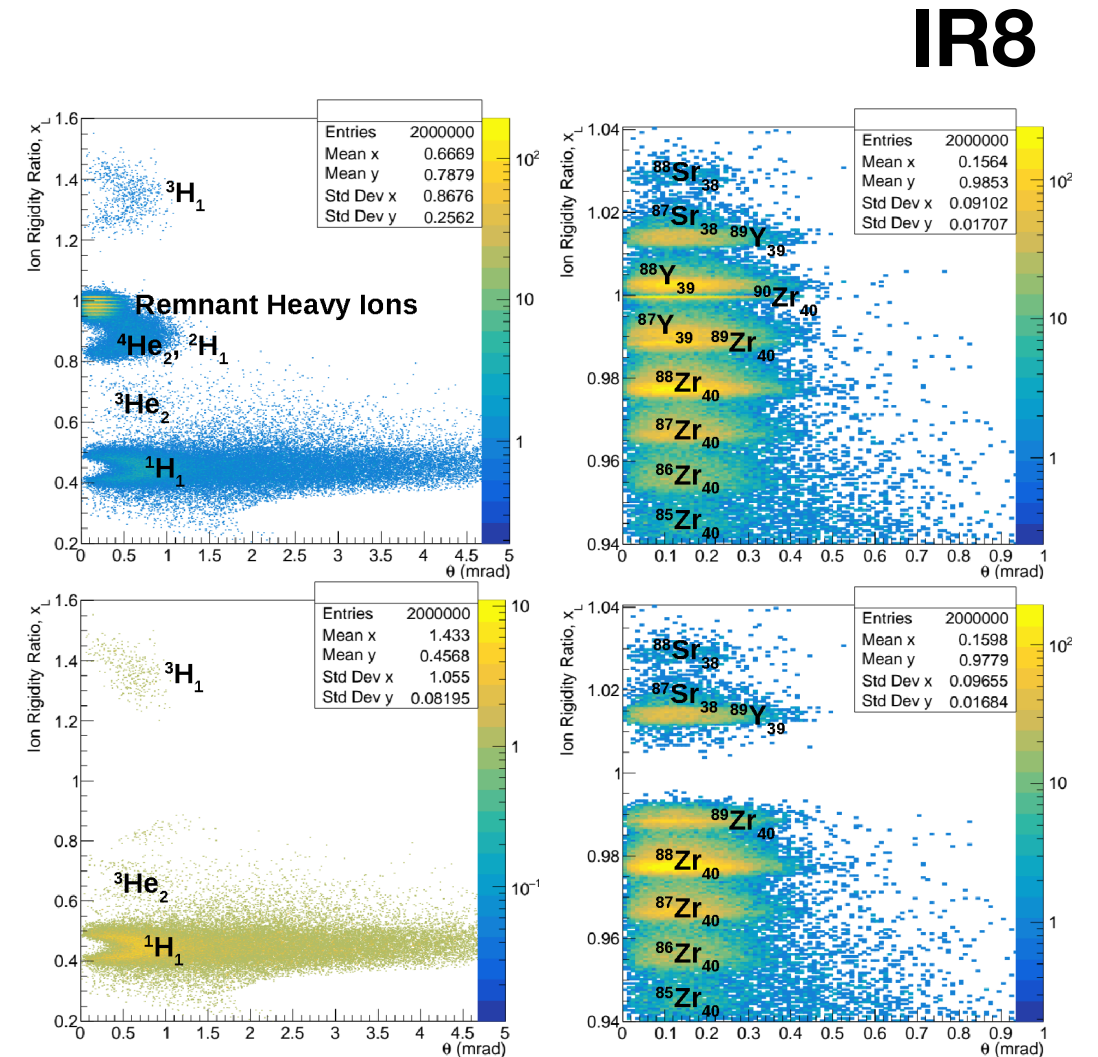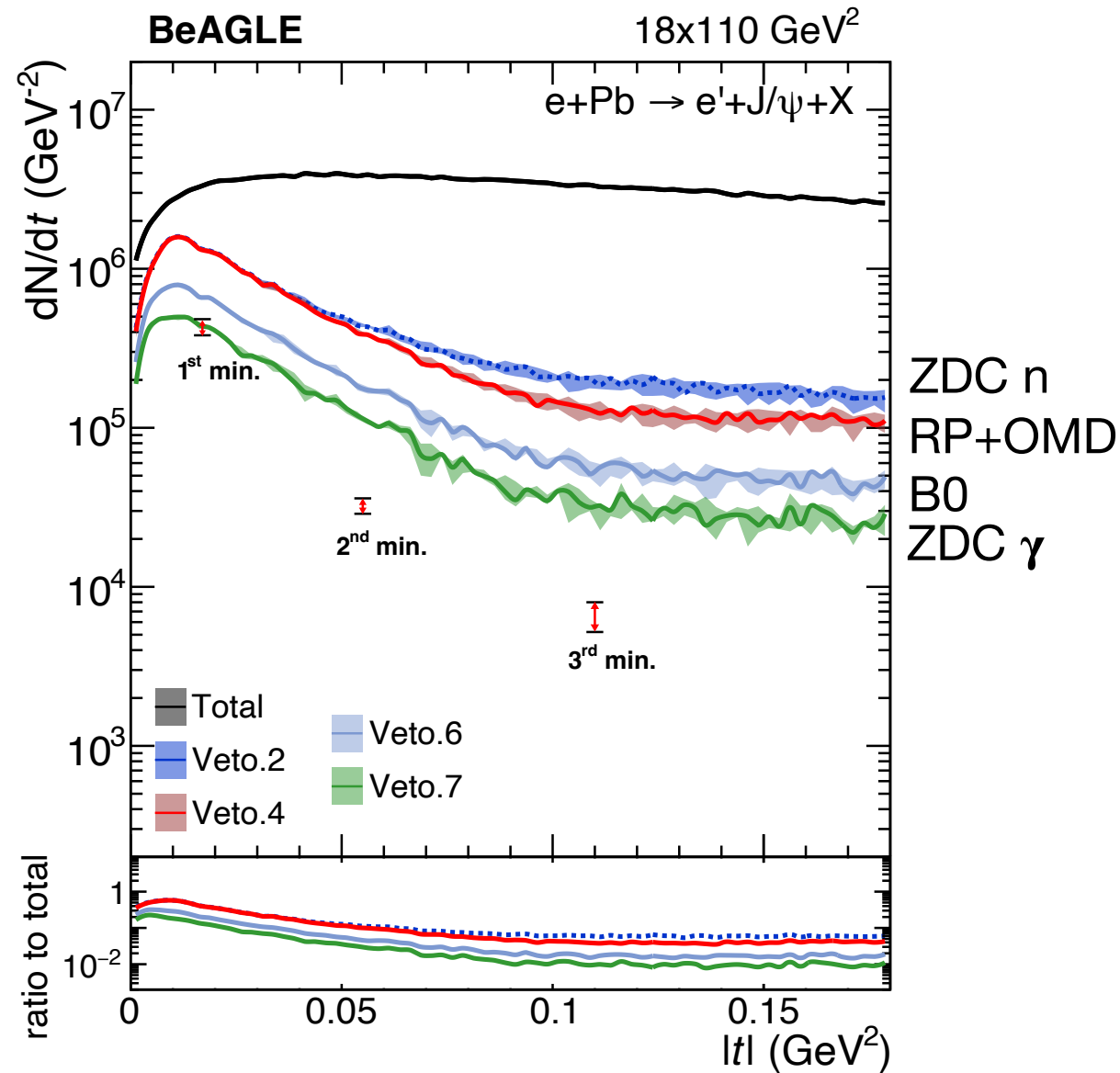
Incoherent contributions removed by successive application of selections
in the forward detector system: ZDC neutrons, RP+OMD, B0, ZDC photons (> 50 MeV)

Roman pot acceptance limited for e+Pb esp. in IR6, <u>much</u> improved for e+Zr in IR8 (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
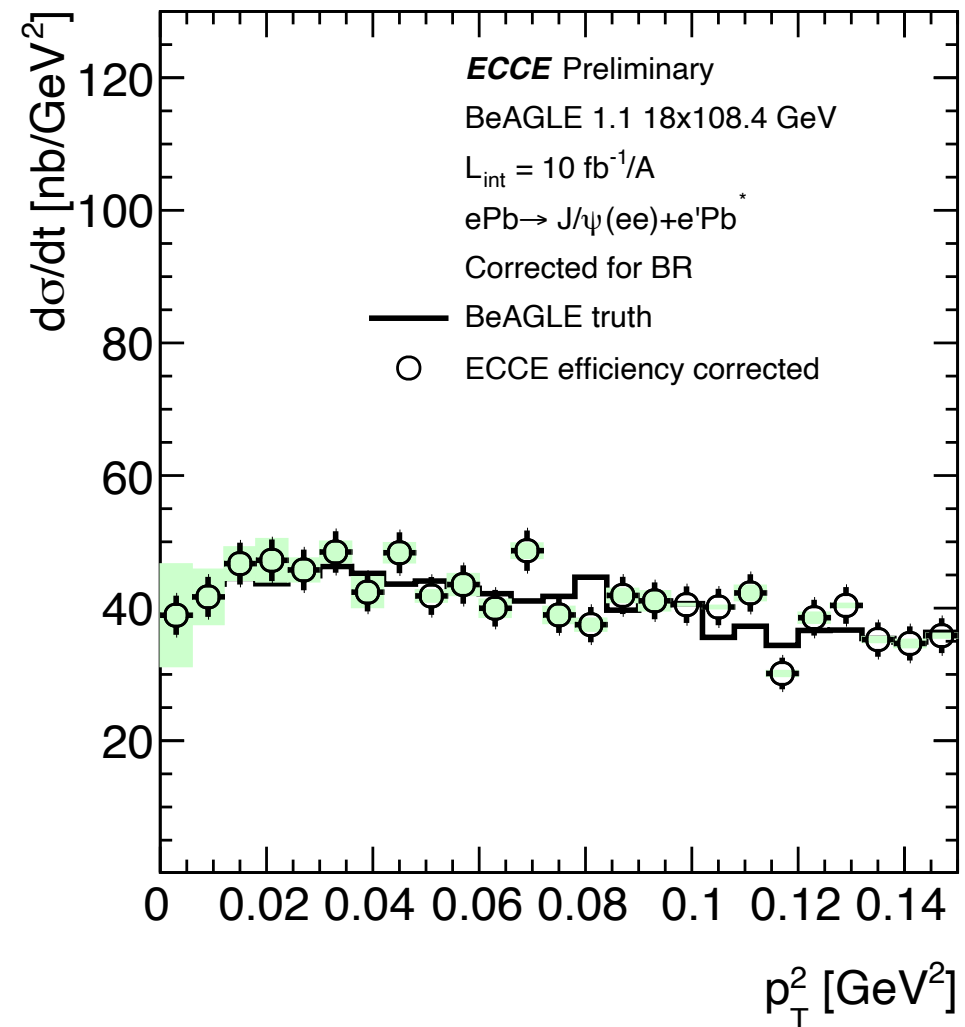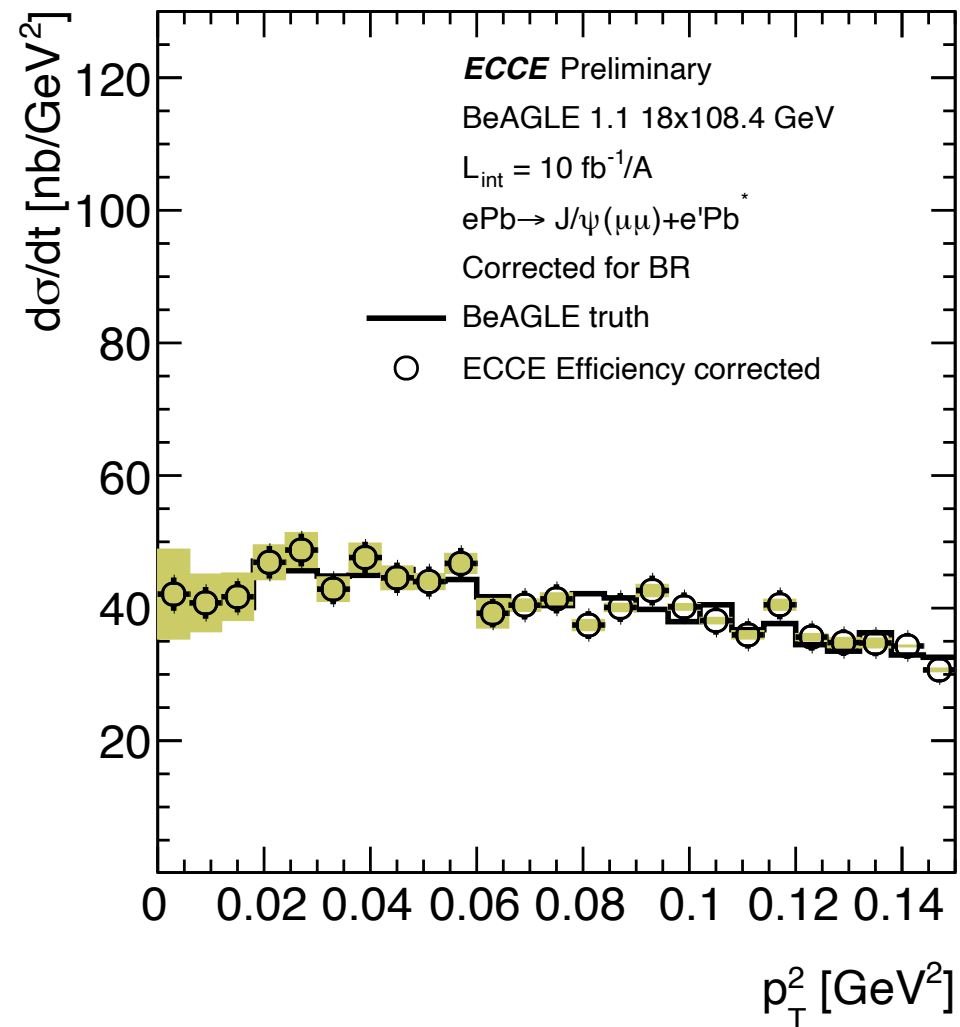
Events selected using "anti-veto" of the selections used for coherent x-sect.

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 $\mu\mu$, 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 ($\sim$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
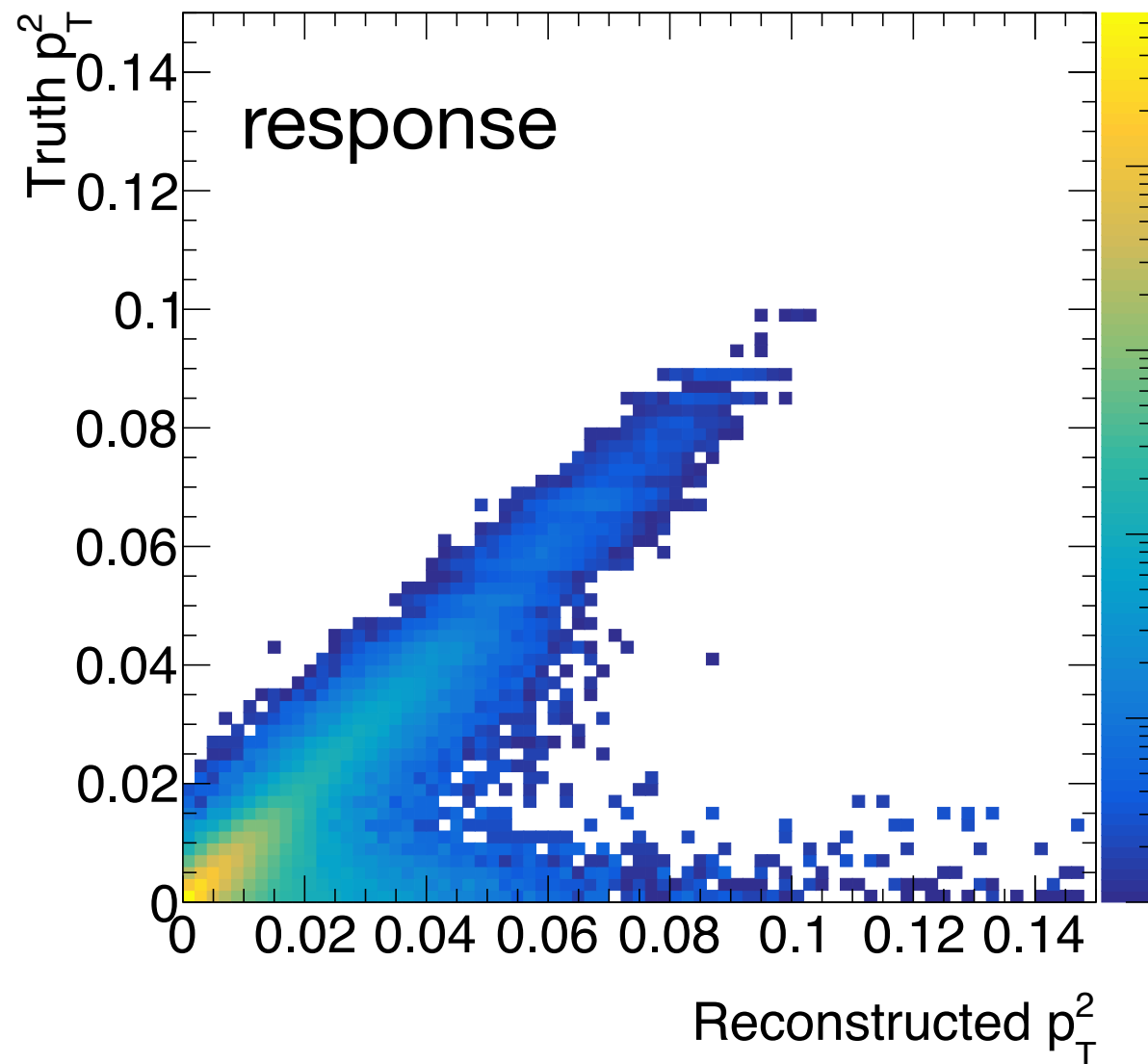measure (or even see)
diffractive dips

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

Begs the question: can these
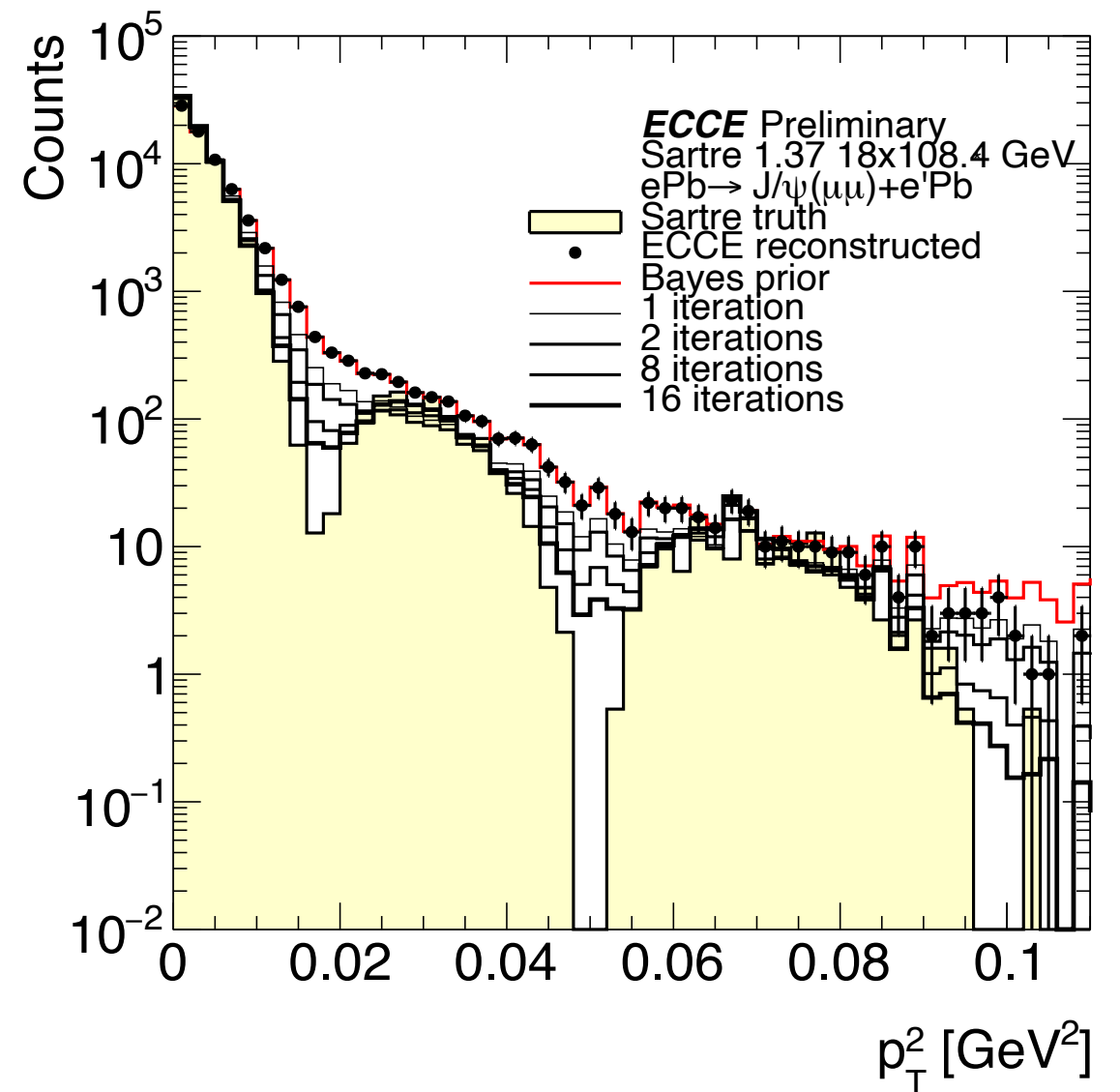distributions be unfolded?
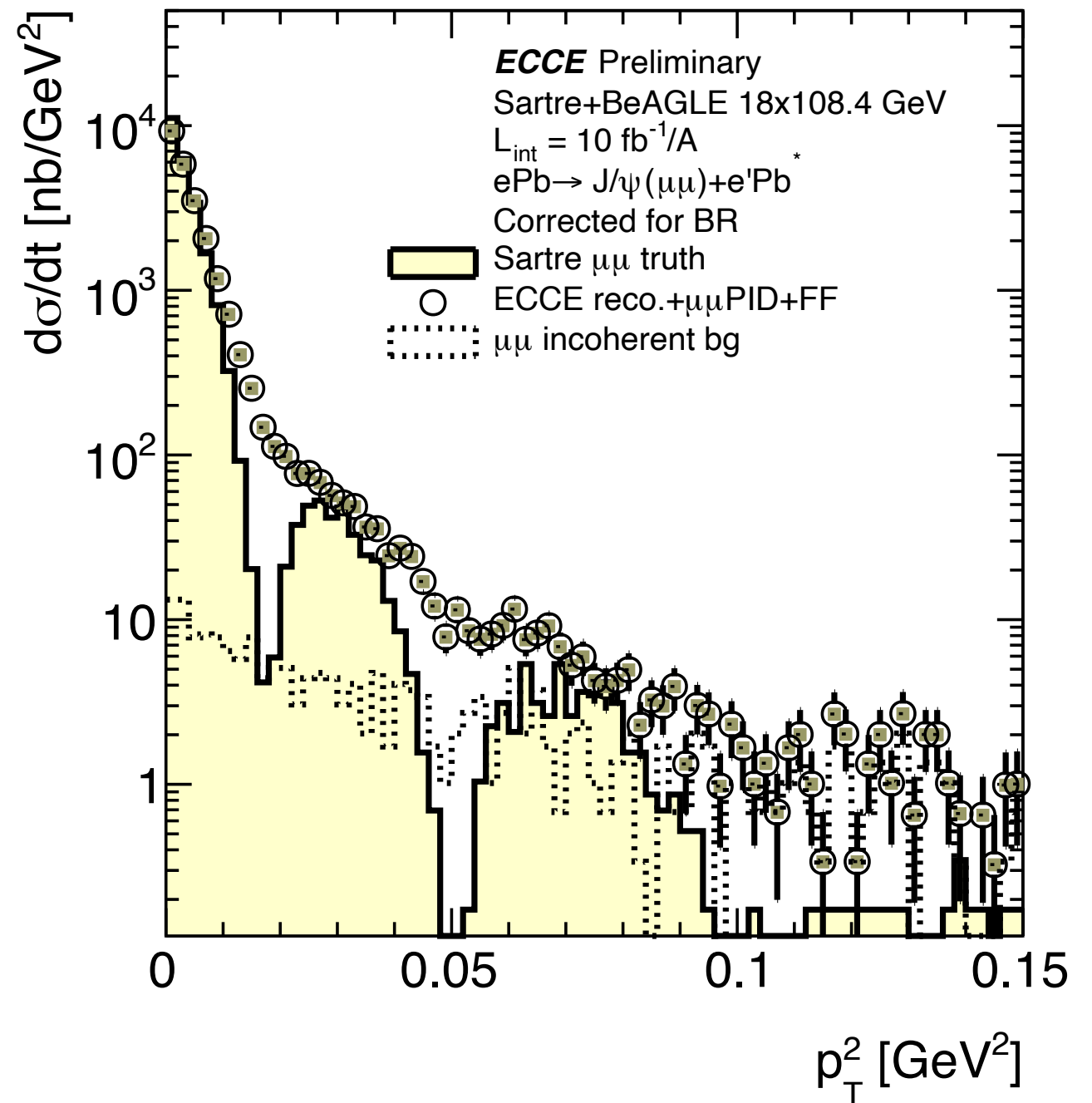
Unfolding

simple exercise, using Sartre only, and Bayesian unfolding (in ROOT)
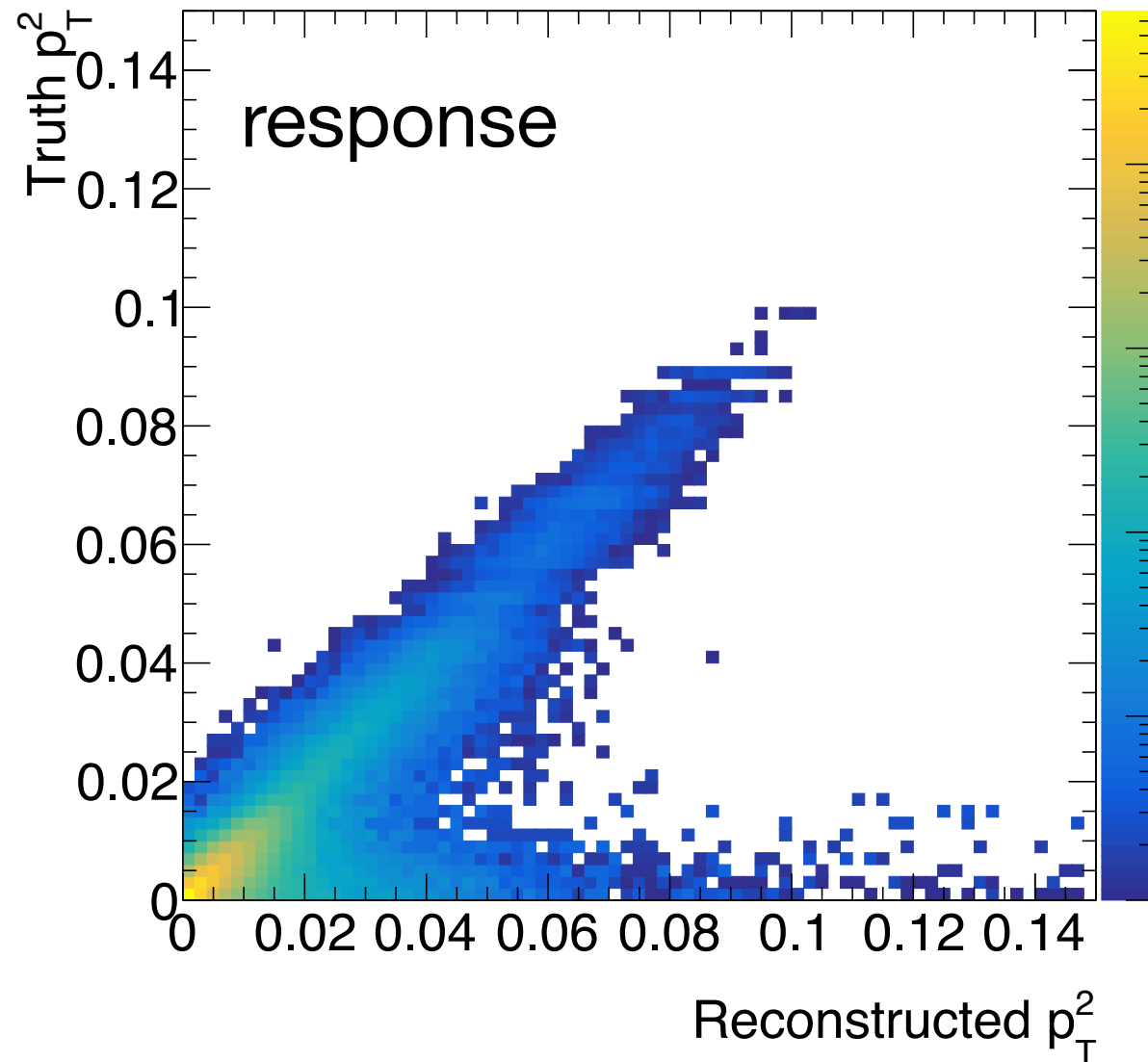

Sartre+BeAGLE, just to build response which populates both branches: truth reweighed to observed: identifies problem as tails extending from $t \sim 0$
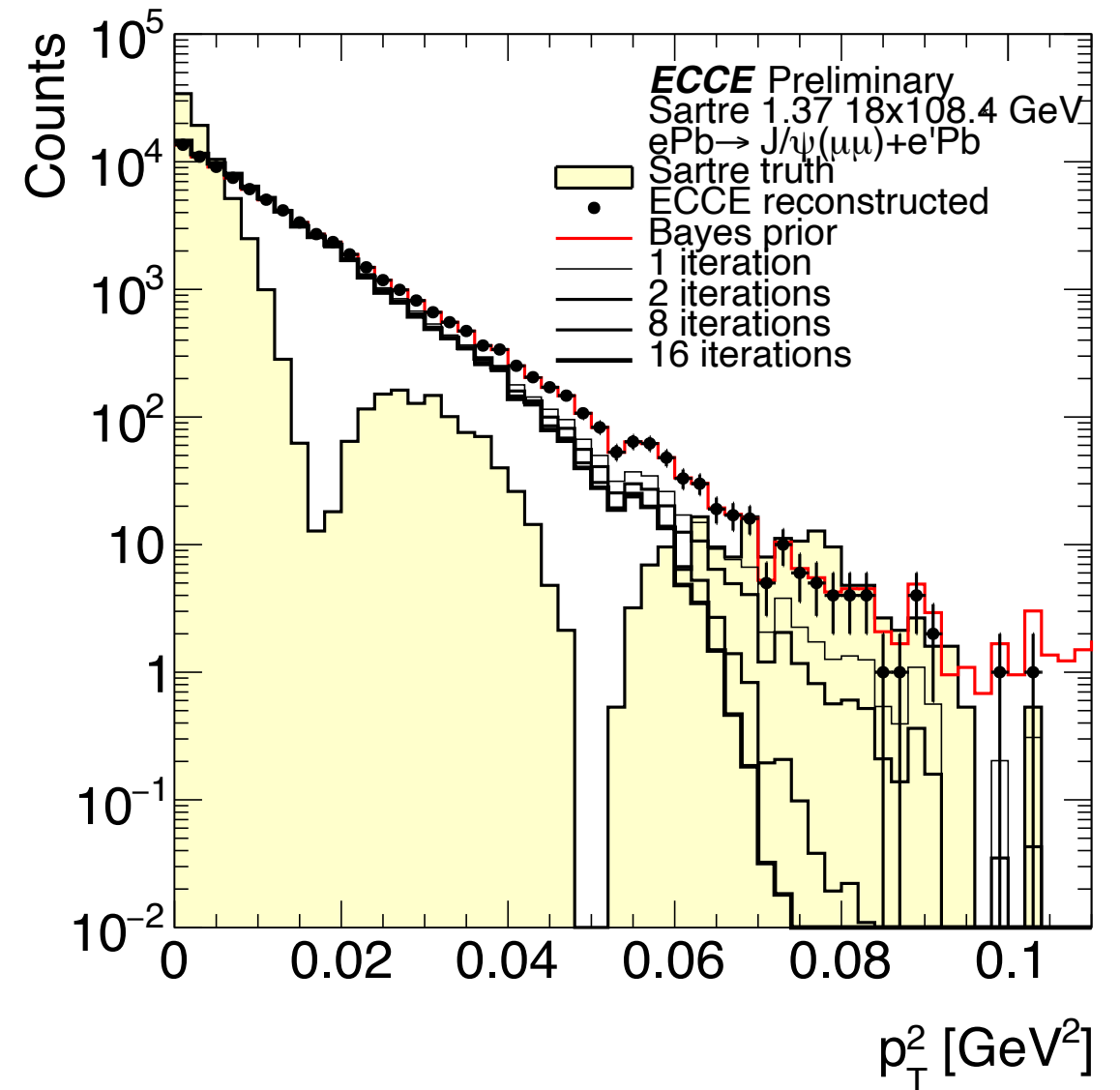

Kinks in final distributions sufficient to start unfolding in right direction, but no obvious convergence

Unfolding

Sar*tre*+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!)

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What can we do with incoherent at EIC?

- **Great interest in heavy ion physics about what we can study about deformed nuclei**
  - yet another application of imaging using the QGP!

- **Vector meson photo production sensitivity depends on process**
  - Incoherent processes see different anisotropy orders in different t regions
  - Coherent processes have some sensitivity at high t
  - Inoherent/coherent ratio can be used to cancel our understanding of J/ψ wave function
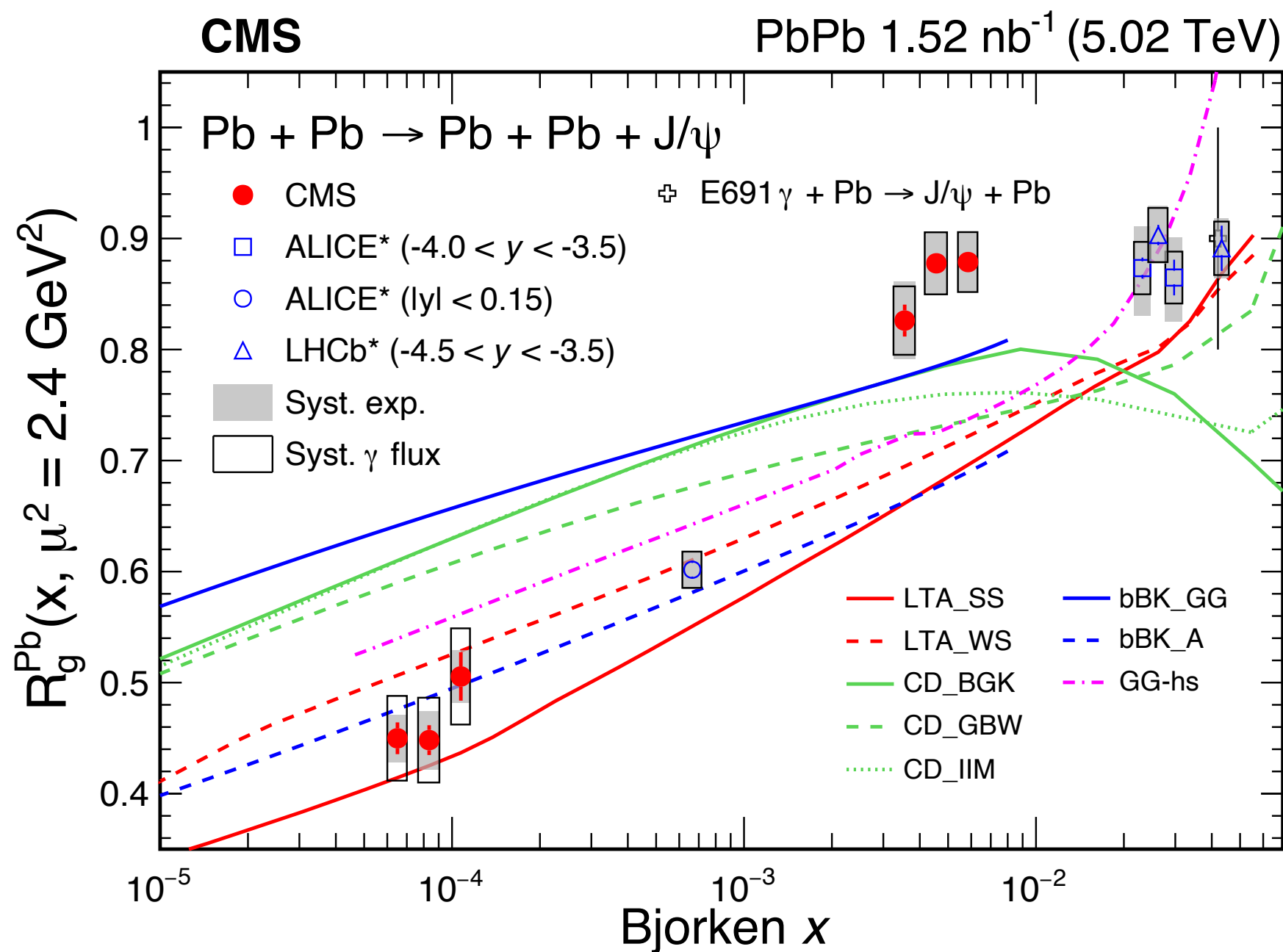
- **Will hear more from Bjoern tomorrow!**
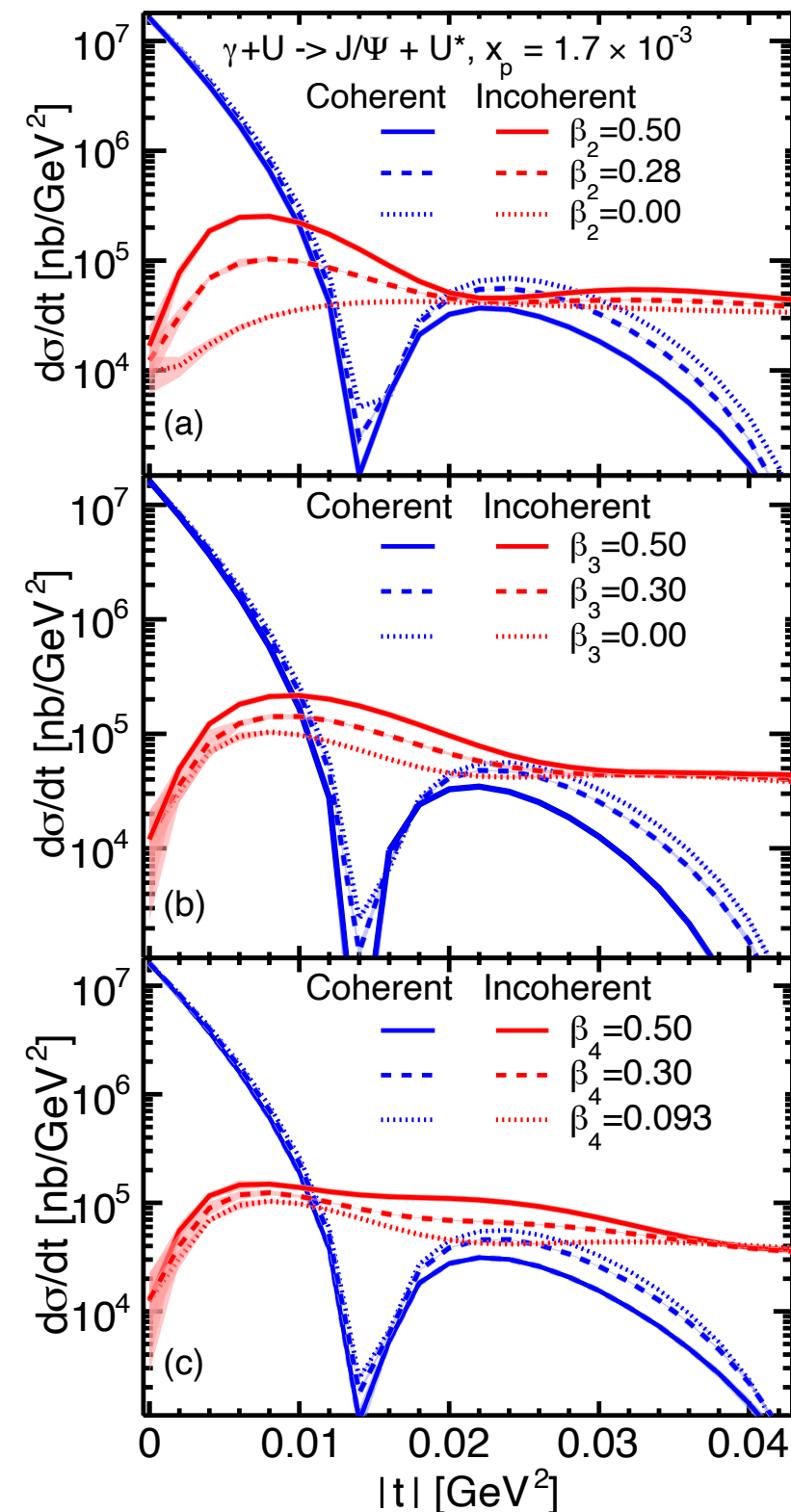
ALICE data on incoherent J/ψ
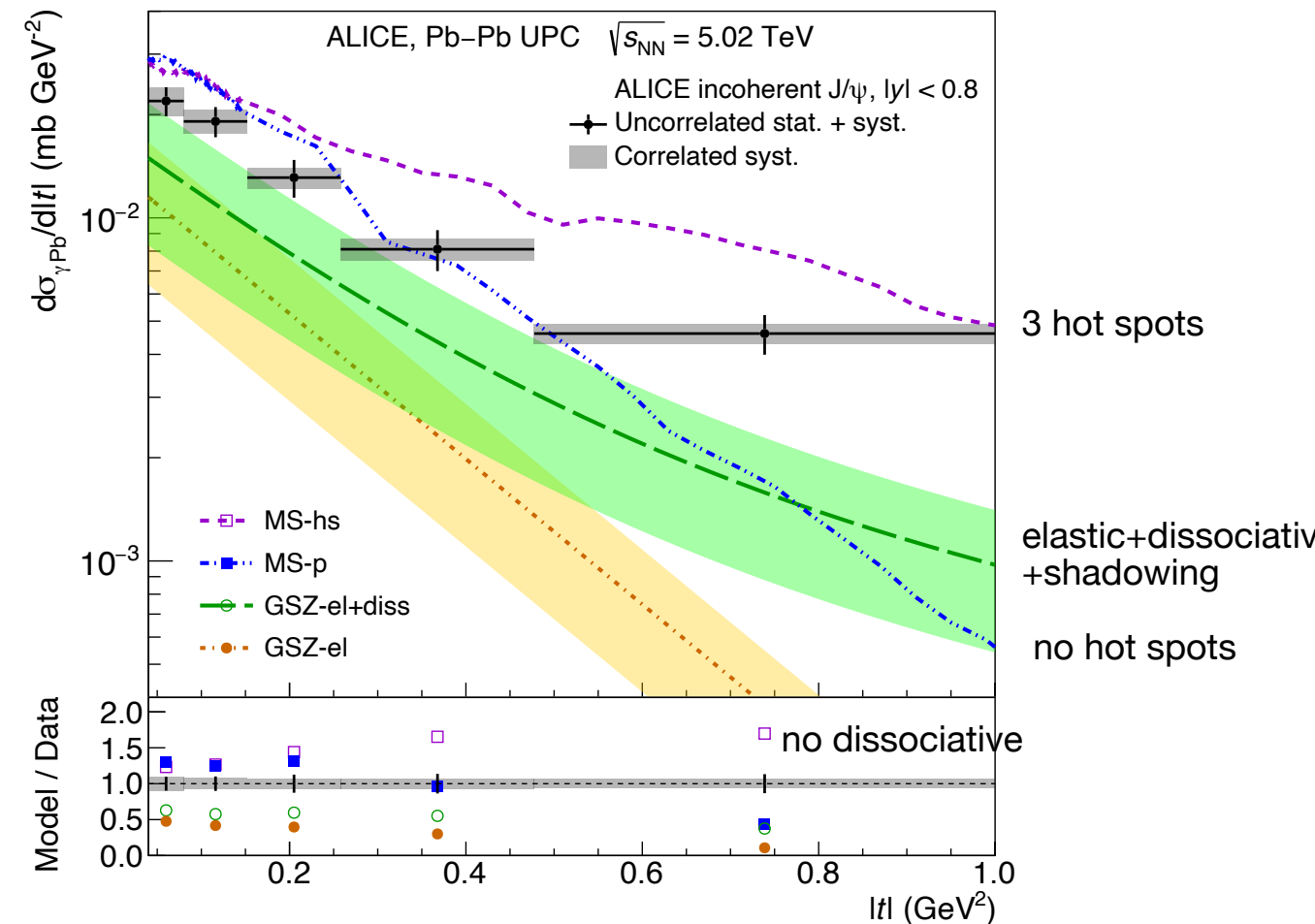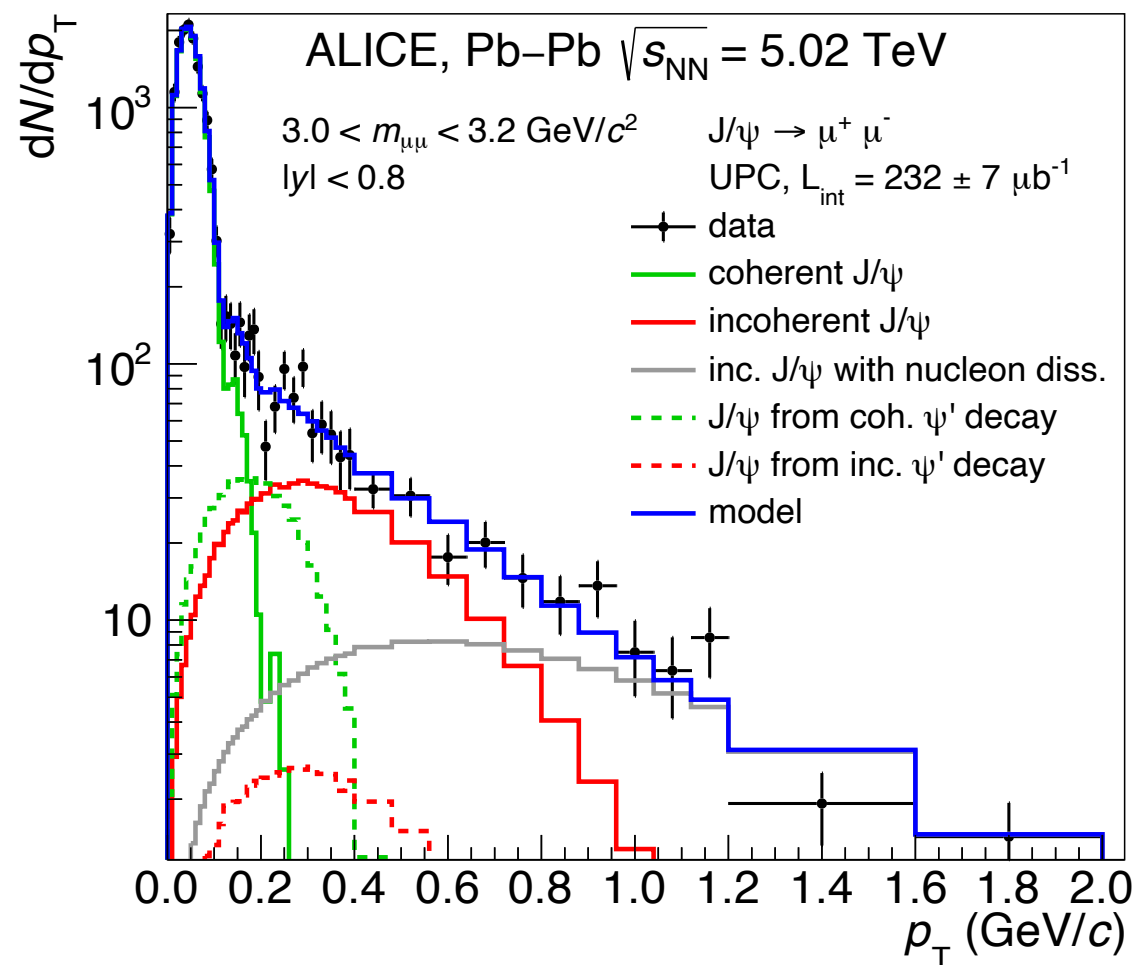
First results are already starting to appear from the LHC:
Incoherent J/ψ production from ALICE (in the μμ channel at |y|<0.8)
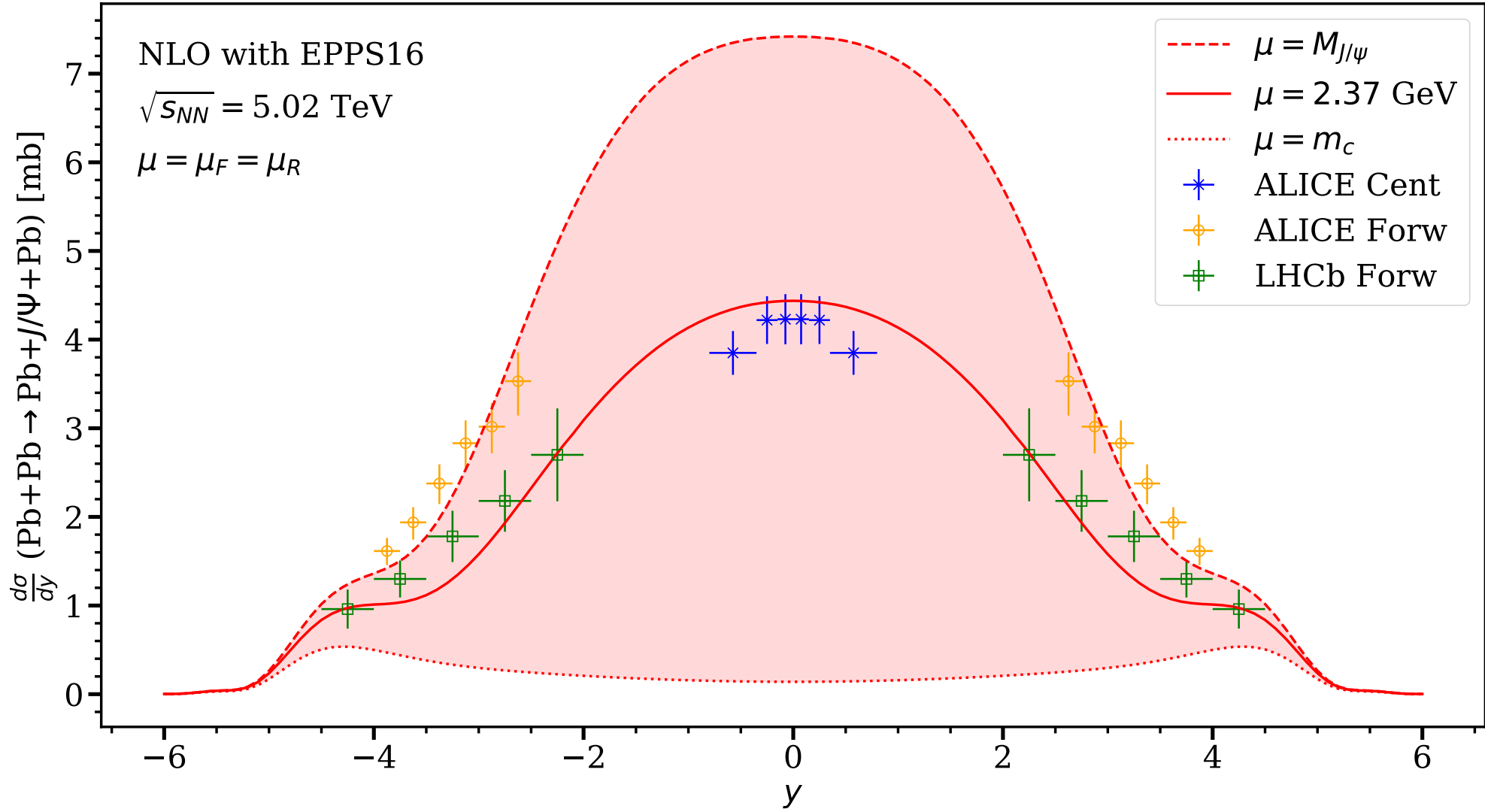can be extracted as a function of |t|=p$_T$², and compared to models.

No-one describes data completely, but sub nucleon structure appears
to be needed

Lots to learn about coherent J/ψ

New results on coherent J/ψ, disentangling the photon emitter
(and thus the kinematics) using the CMS ZDCs!

Especially theory…

NLO calculations clearly have a very strong scale dependence!
Many intertwining aspects of this problem - what about ϒ?
(challenging due to huge continuum background!)

Prospects

- **Enormous physics potential for J/ψ and other vector mesons at the EIC**

- **Topic of major interest for ePIC!**
  - see talk by Kong Tu later today!

- **Initial studies performed by ECCE & ATHENA for EIC detector proposals**
  - Expect improvements with more sophisticated detector design and reconstruction

- **Models already being developed using HERA data, and concepts being challenged by UPC data**
  - What else should RHIC & LHC be doing in next few years to help with this

- **Need more discussion on how deep the dips will be**
  - Lots of debate so far on whether well-known nuclear effect and more realistic calculations, will smear these out

- **What about other diffractive processes, esp. inclusive**
  - Golden channel for saturation
  - Exciting to see developments along these lines, both experimental and theoretical!
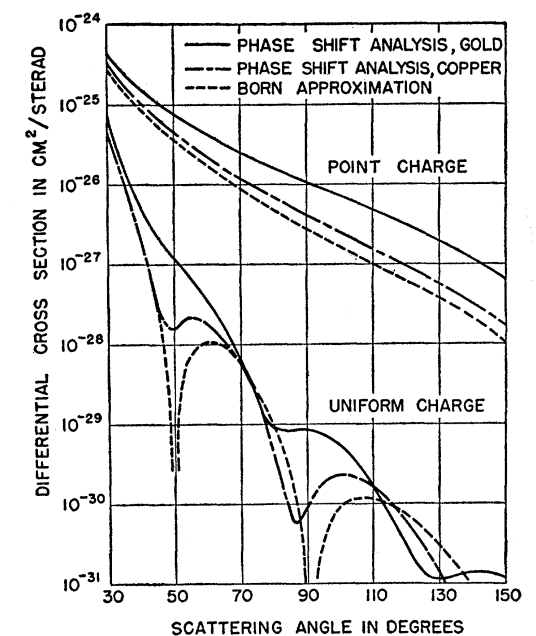
Hofstadter 1956

FIG. 5. Phase shift analyses by Yennie et al.[17,18] for uniform spherical models of gold and copper. The point charge curves are shown as well as Born approximation results for all cases. The data refer to gold at approximately 150 Mev and copper at 225 Mev.