Quarkonium production at the EIC and LHC

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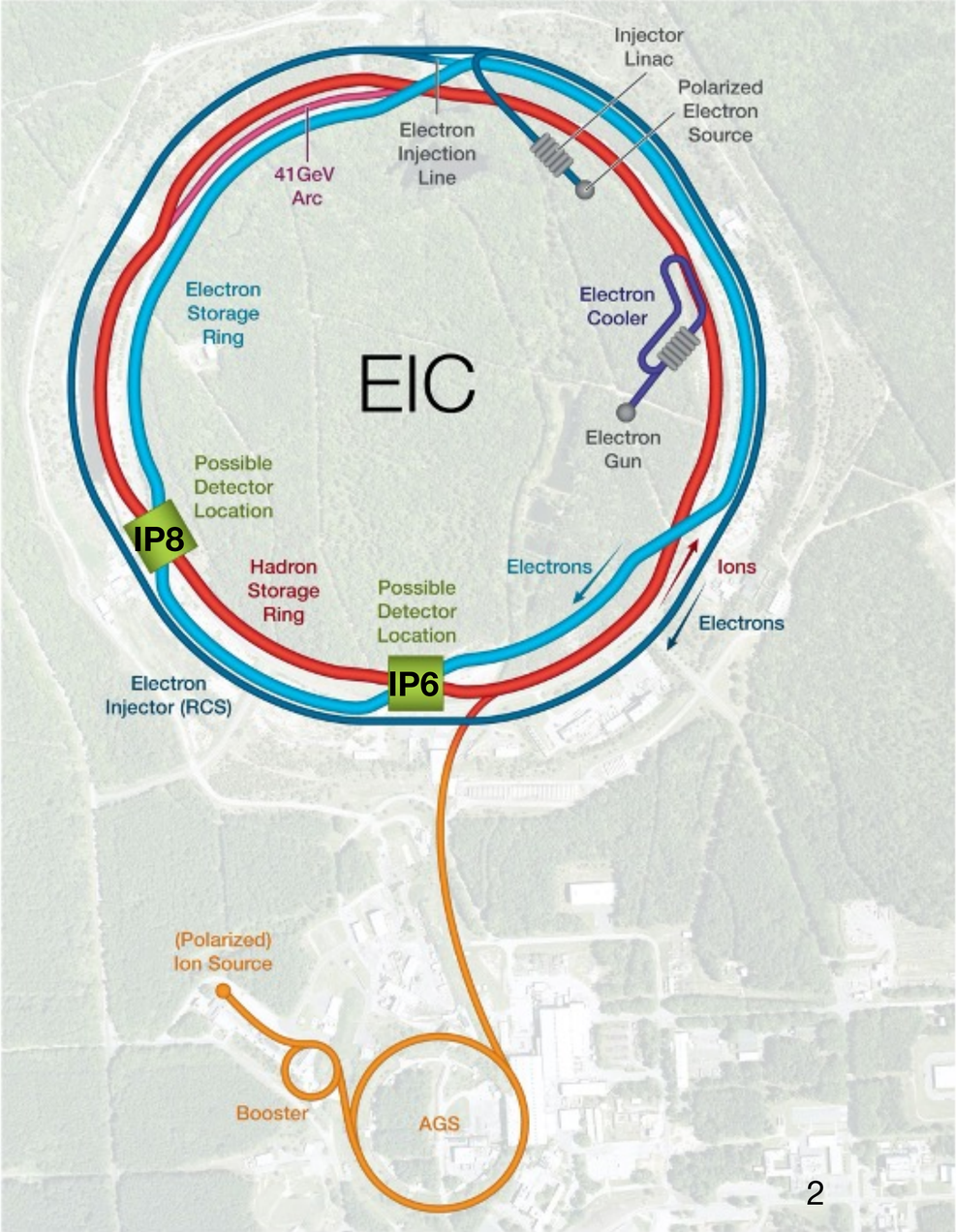
University of Alcalá de Henares

AdTCM

HF2022: Heavy Flavours from Small to large systems joint with Strong202-
Institut Pascal, Orsay, France
03 Oct – 21 Oct 2022

The electron-ion collider



$\vec{e} + \vec{p}^{\uparrow}/A$, with A=D, …, Au, Pb

~ 70% polarisation

$\mathcal{L} = 10^{33-34}\mathrm{cm}^{-2}\mathrm{s}^{-1} \leftrightarrow \mathcal{L}_{\mathrm{int}} = 10 - 100\ \mathrm{fb}^{-1}/\mathrm{year}$

$\sqrt{s} = 20\text{–}141\ \mathrm{GeV}$

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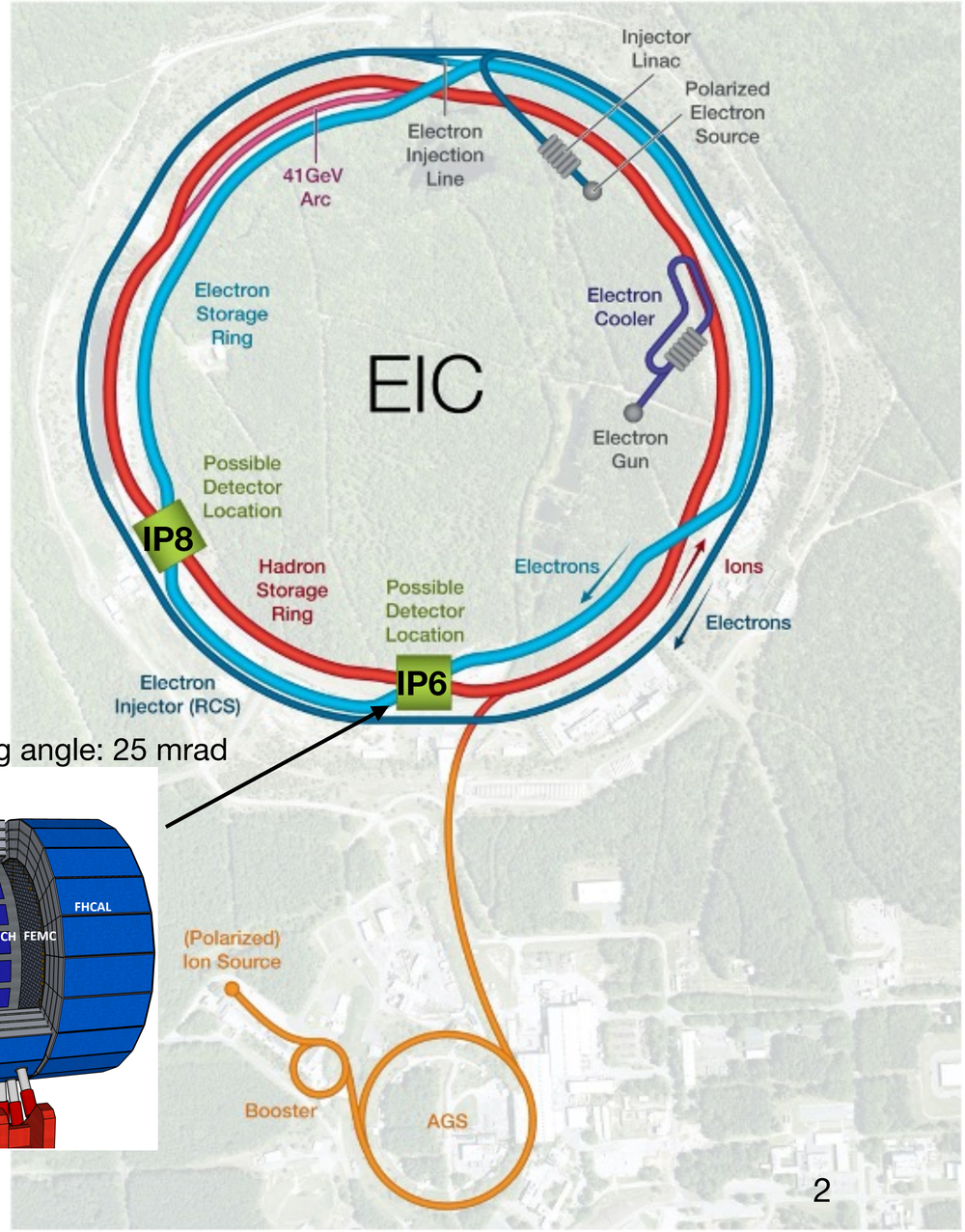
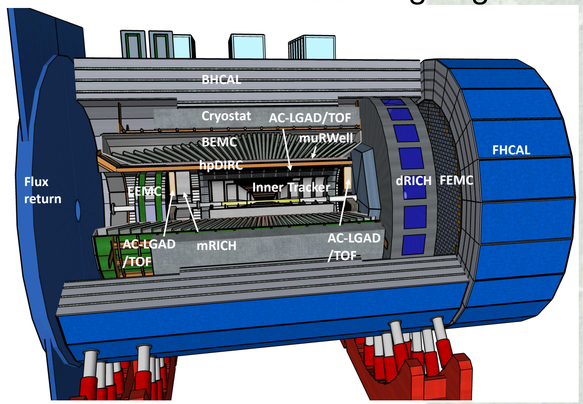


crossing angle: 25 mrad



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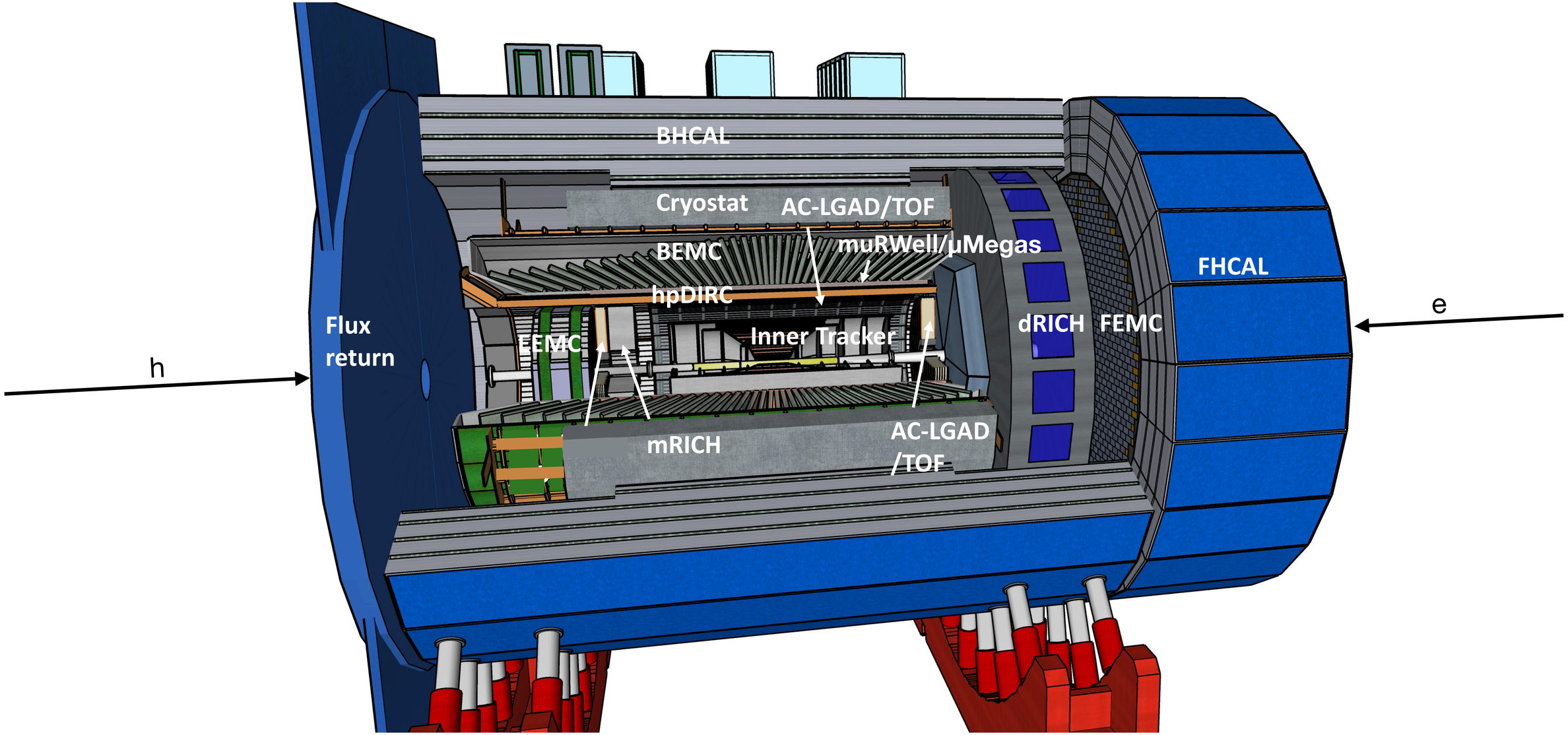
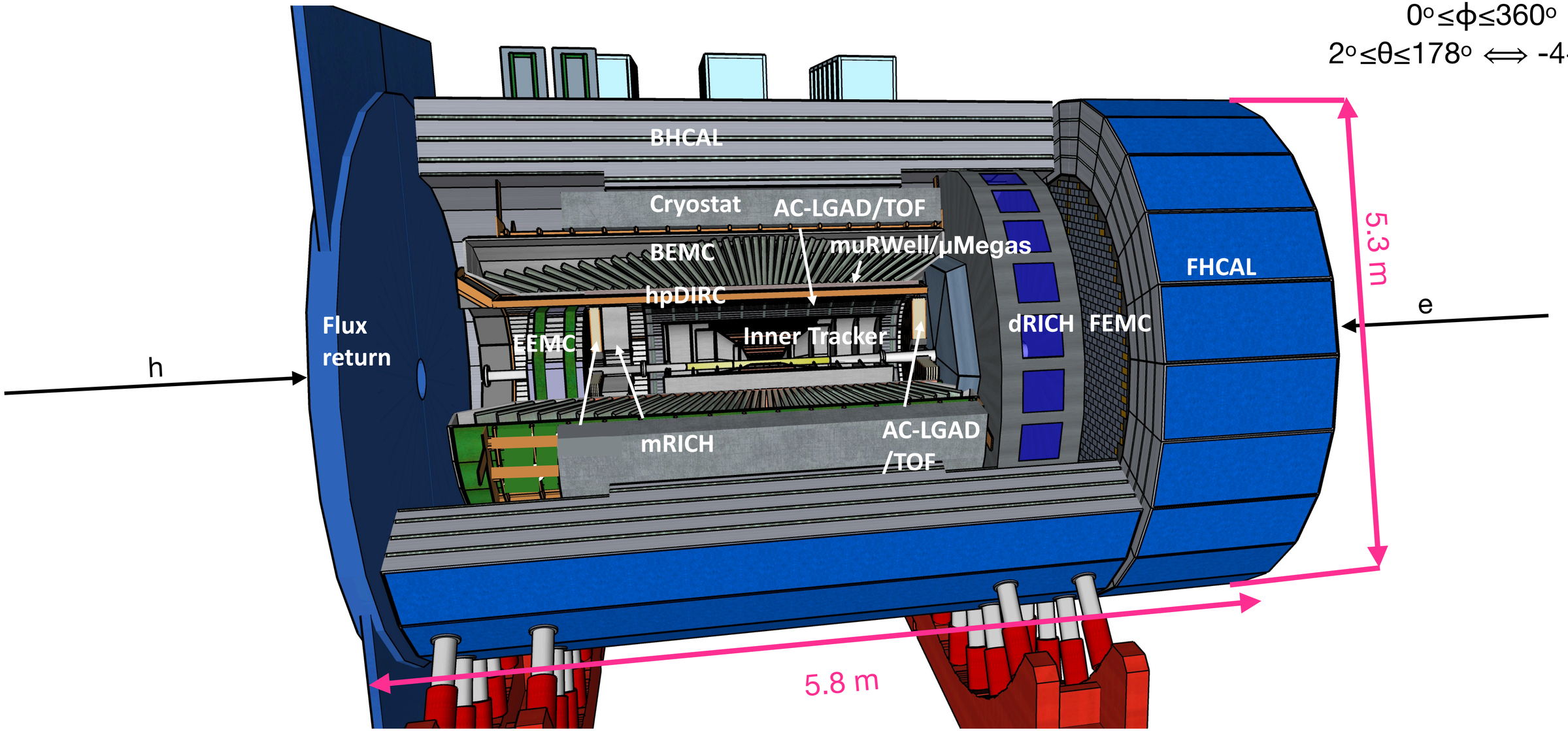
The electron-proton/ion collider (ePIC) detector (current status)



The electron-proton/ion collider (ePIC) detector (current status)

hermetic coverage:
$0^o \leq \phi \leq 360^o$
$2^o \leq \theta \leq 178^o \iff -4<\eta<4$



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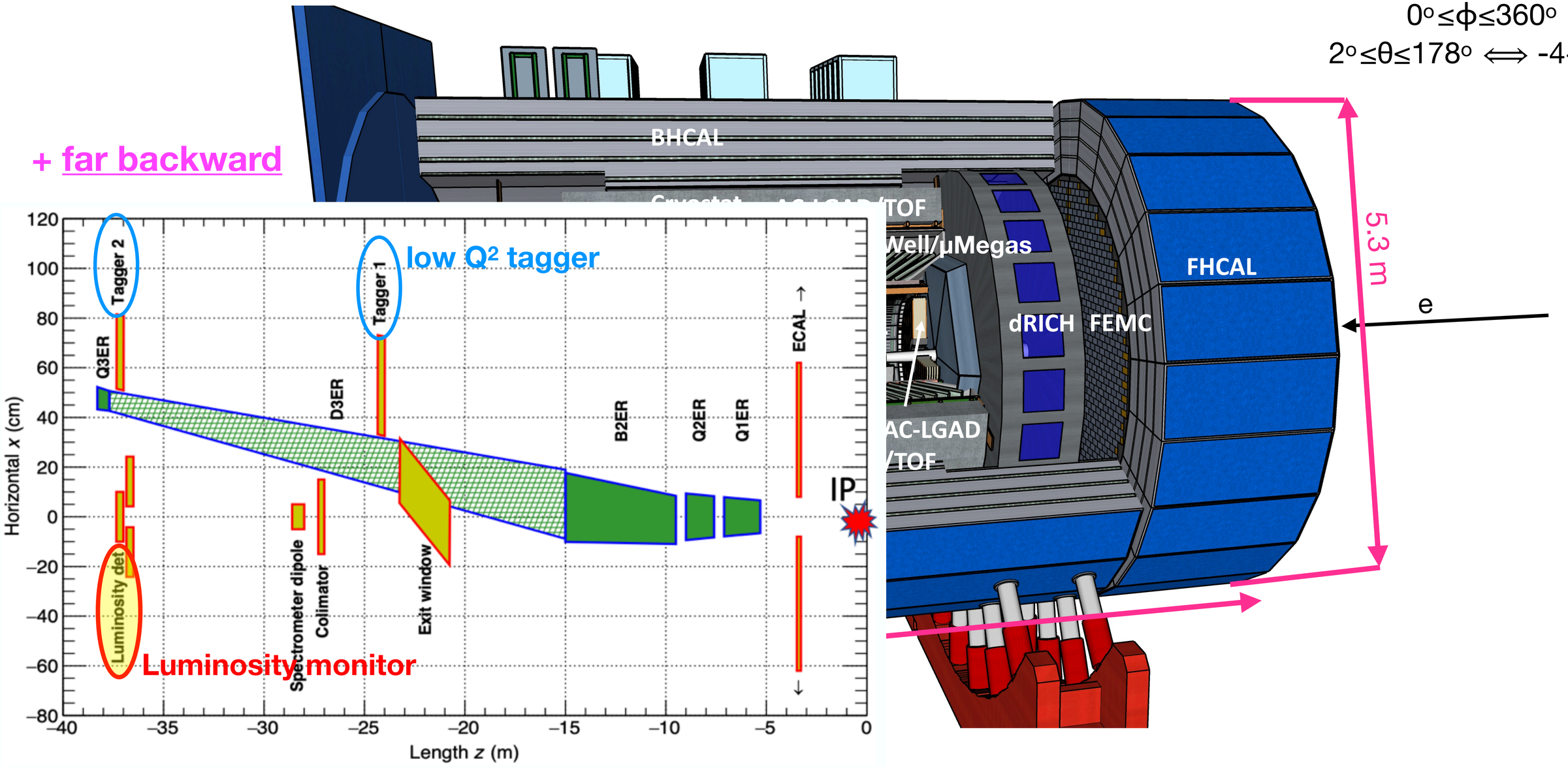
+ far backward



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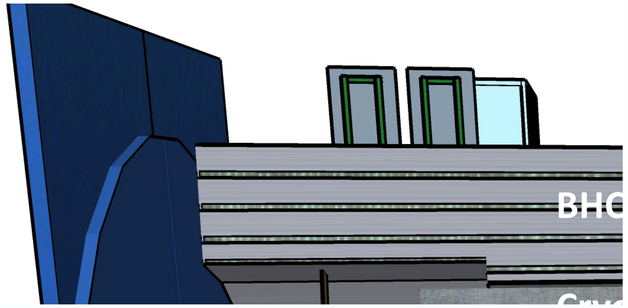
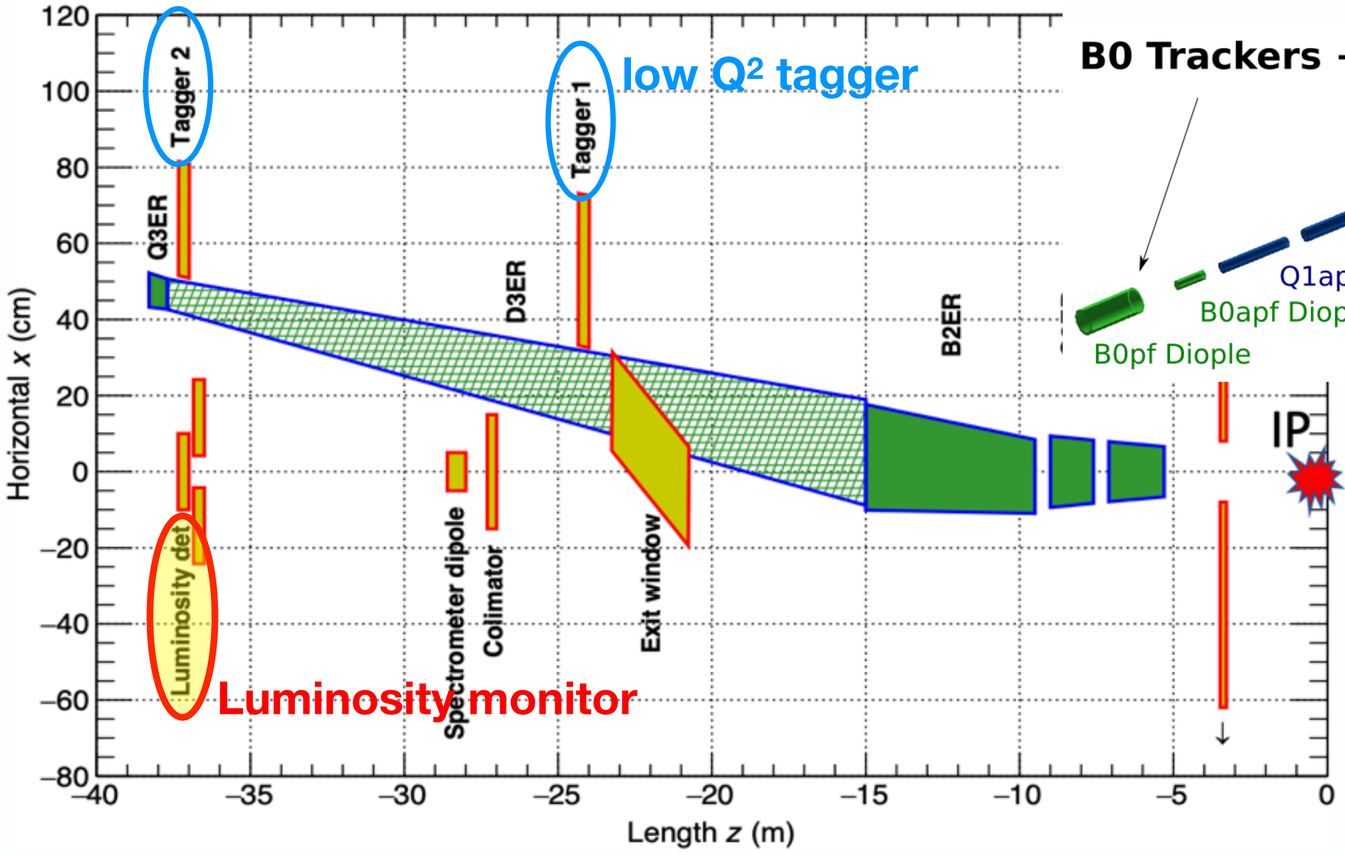
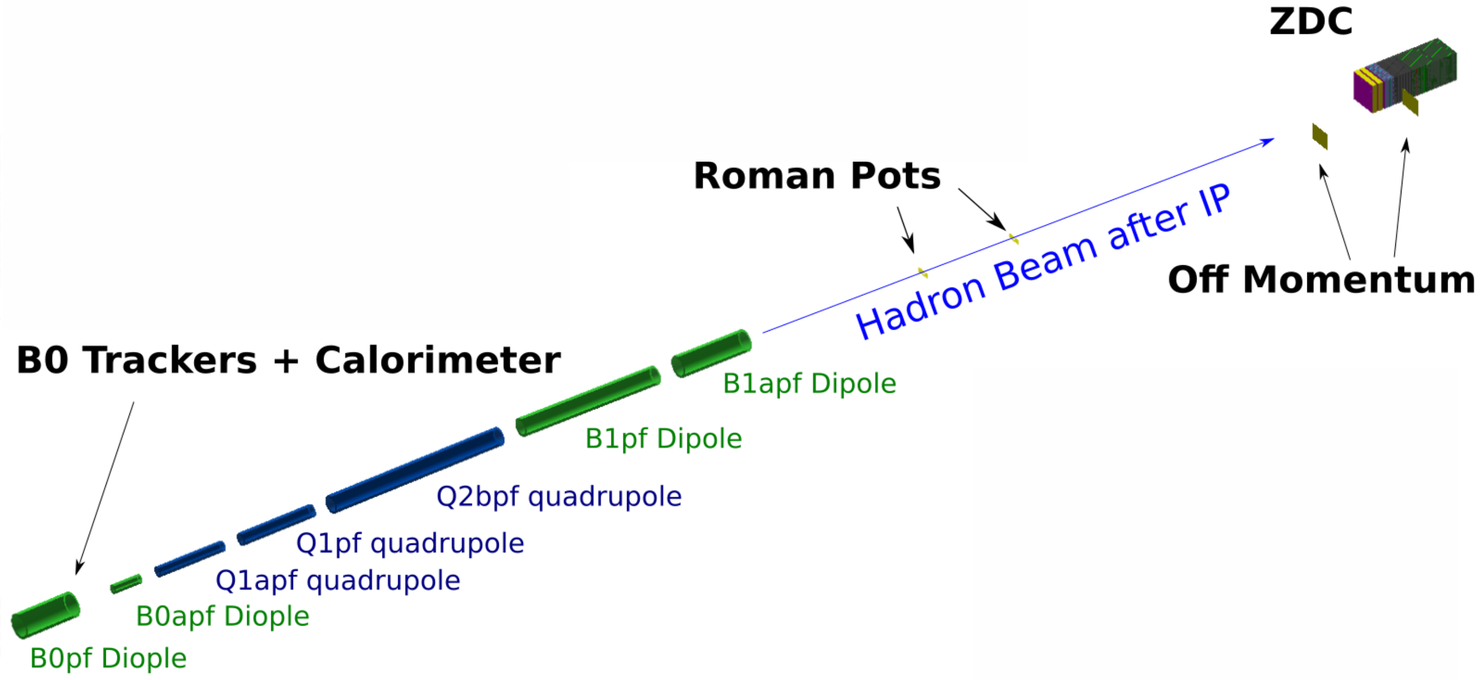
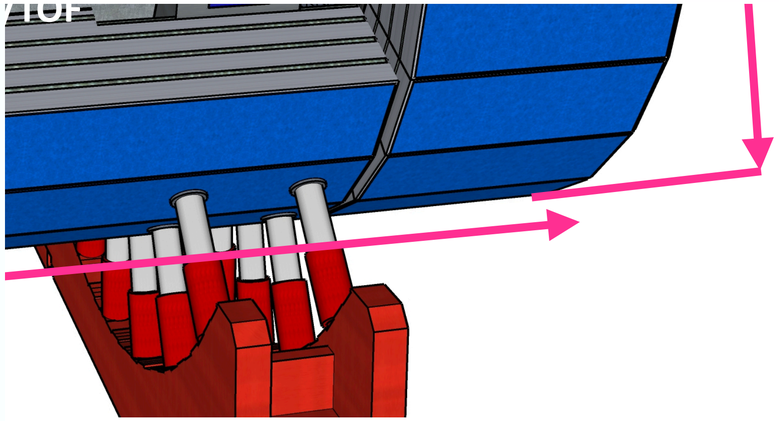
+ far forward

+ far backward









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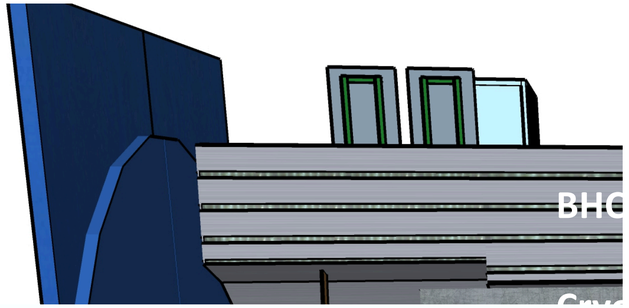
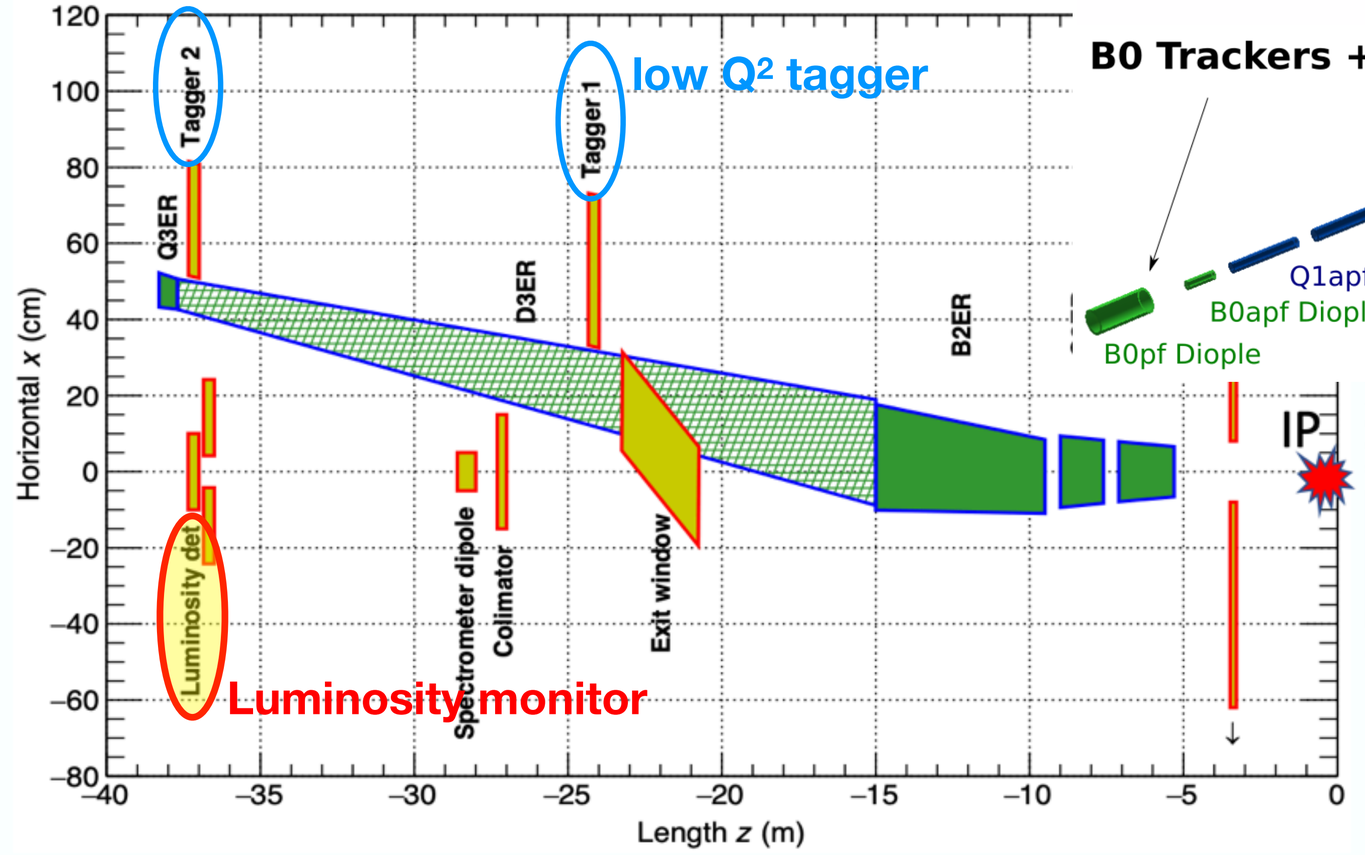
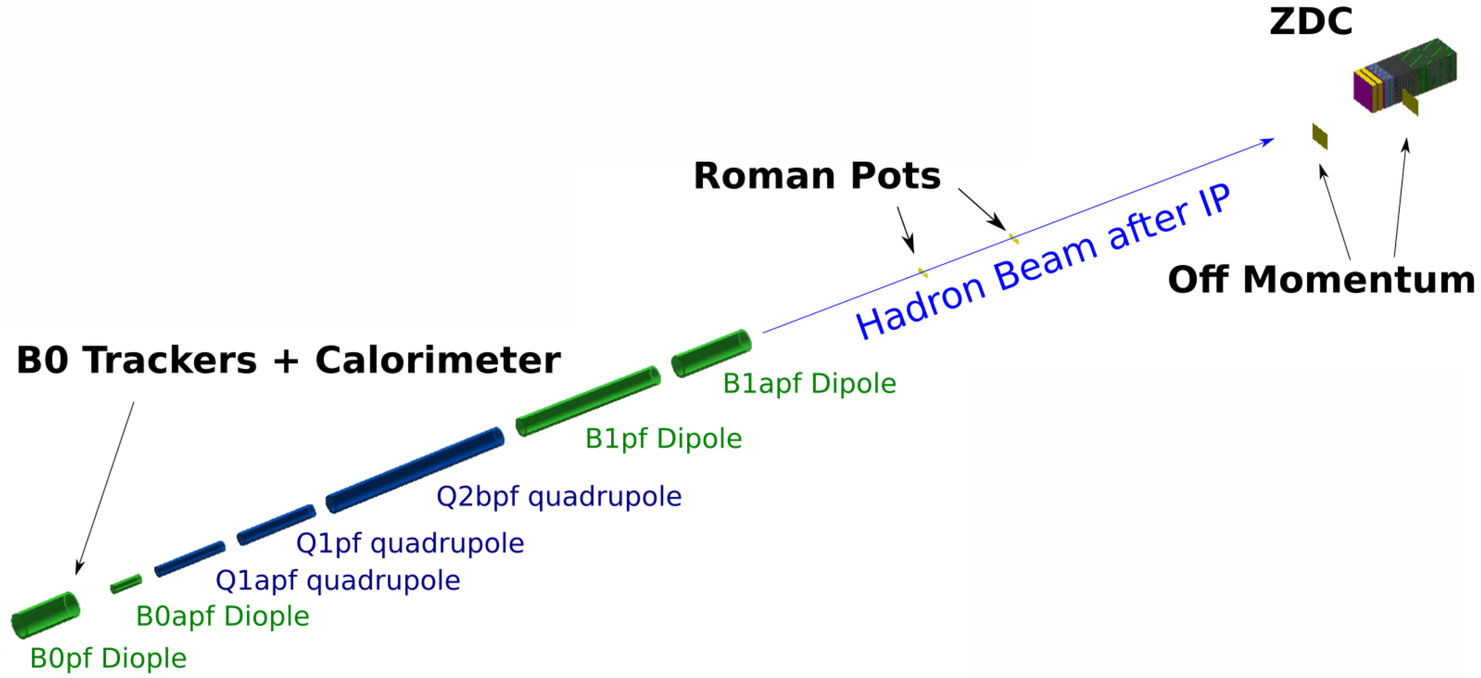
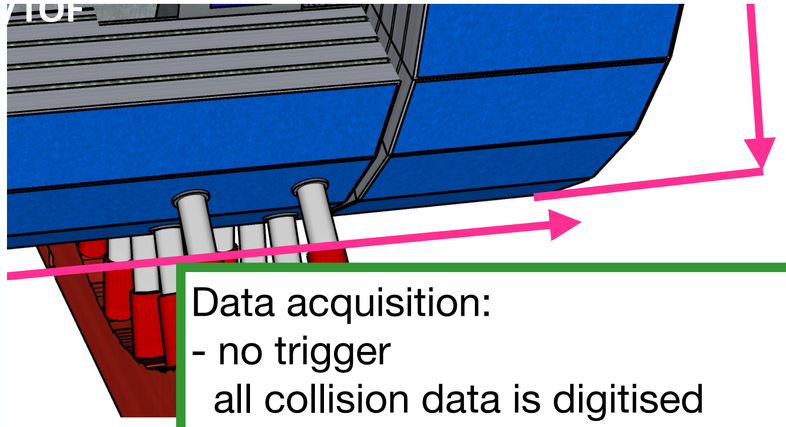


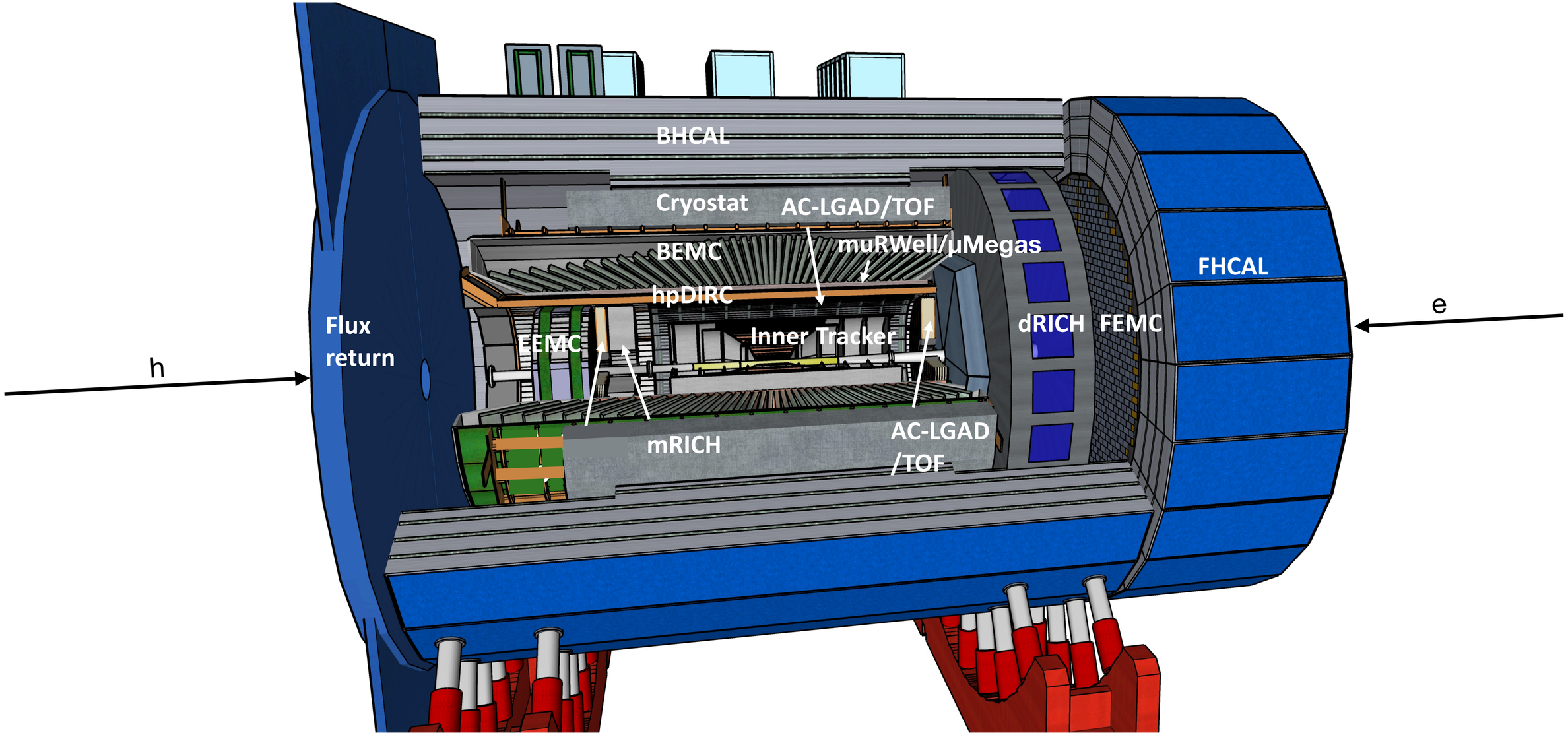






Data acquisition:
- no trigger
  all collision data is digitised
  with strong zero-suppression at front-end electronics

The ePIC central detector (current status)



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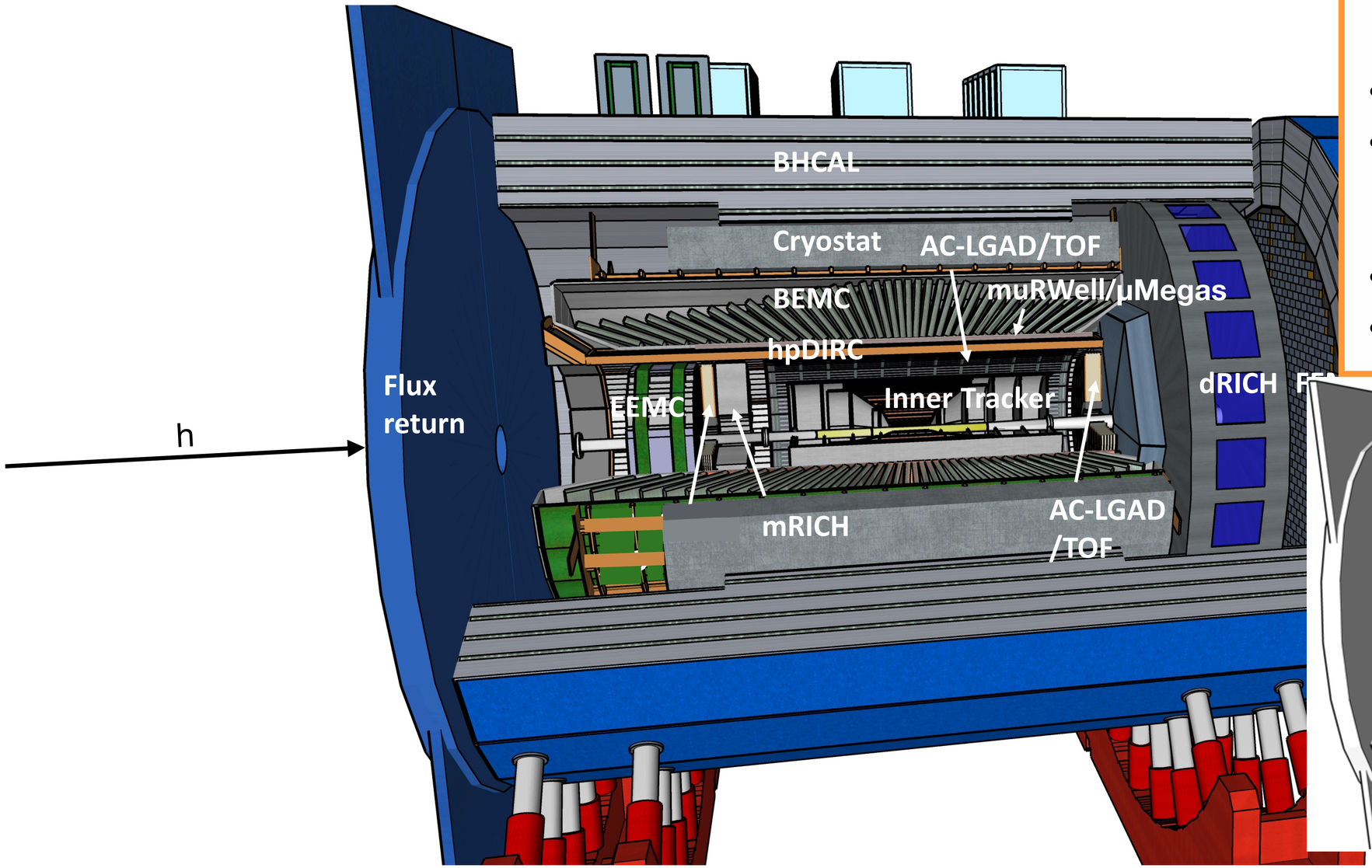
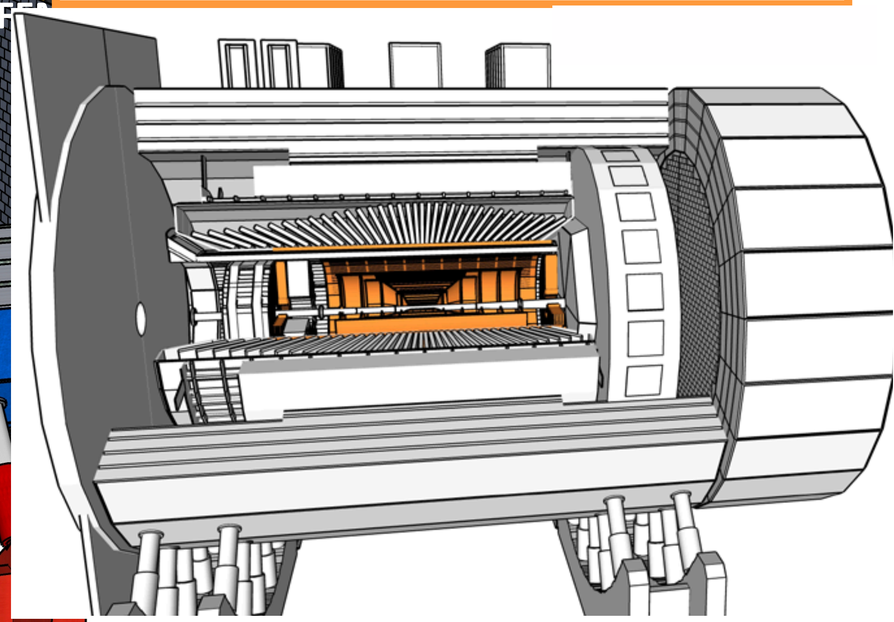


Tracking

- 1.7 T magnet
- Monolithic Active Pixel Sensor (MAPS) Silicon vertexing/inner tracker
- μRWell/microMegas
- AC-LGAD/TOF



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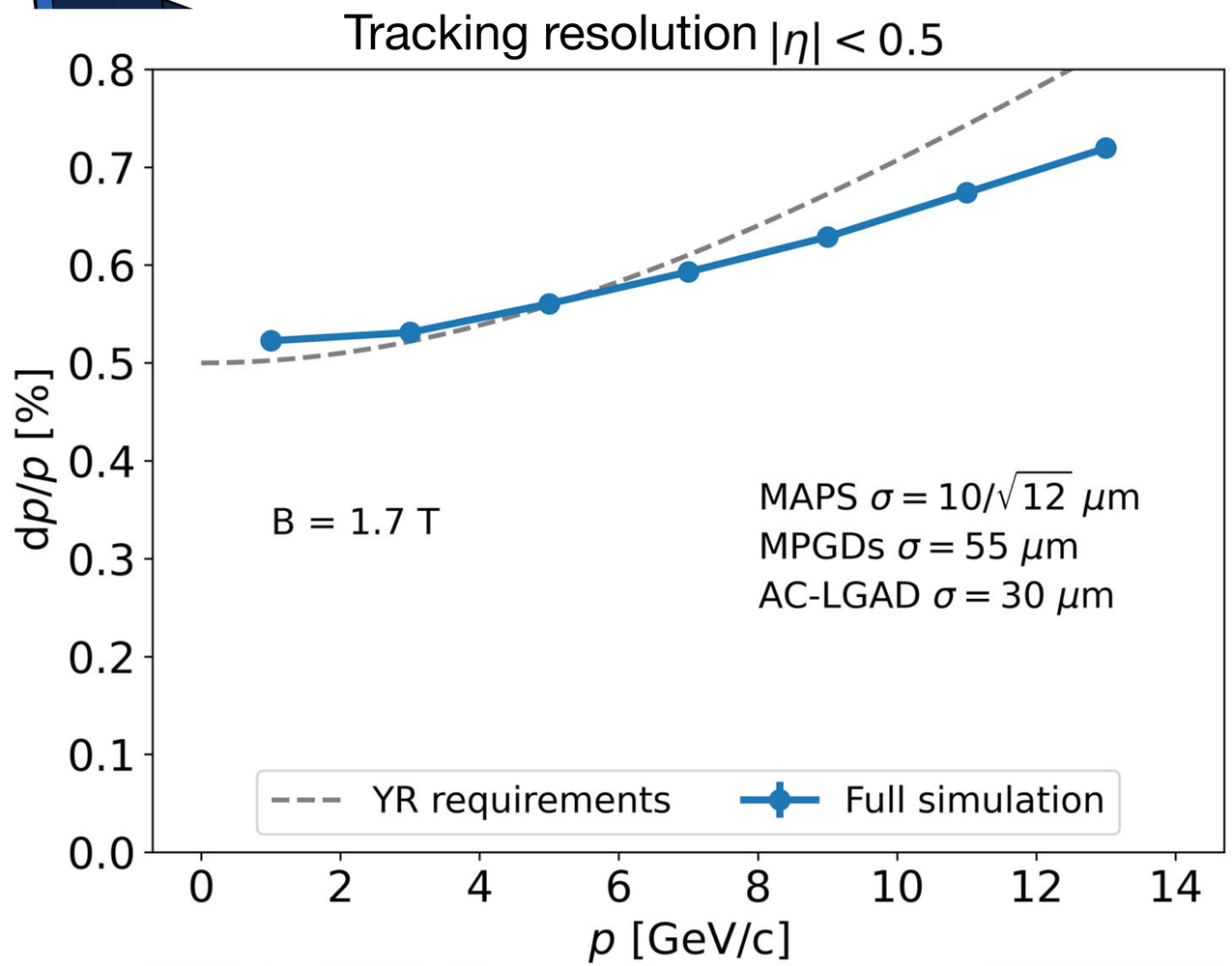

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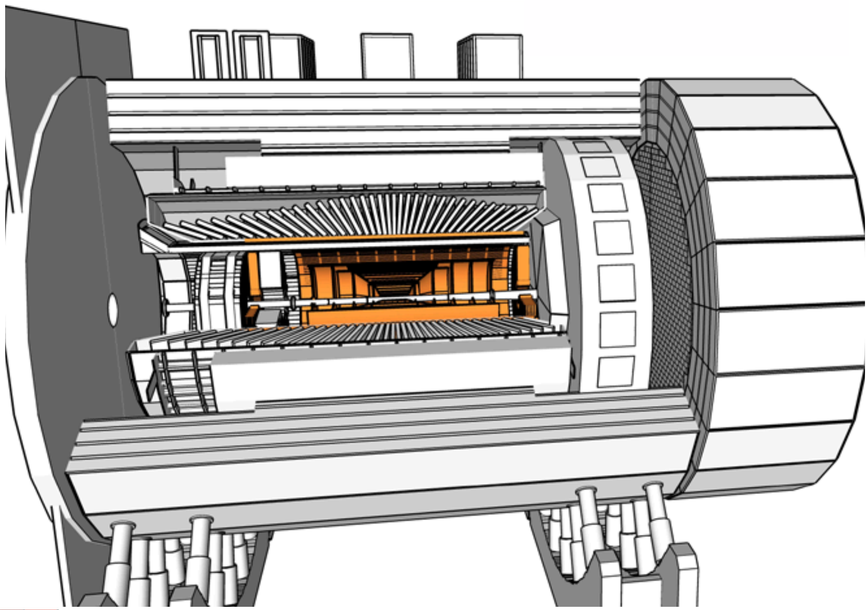
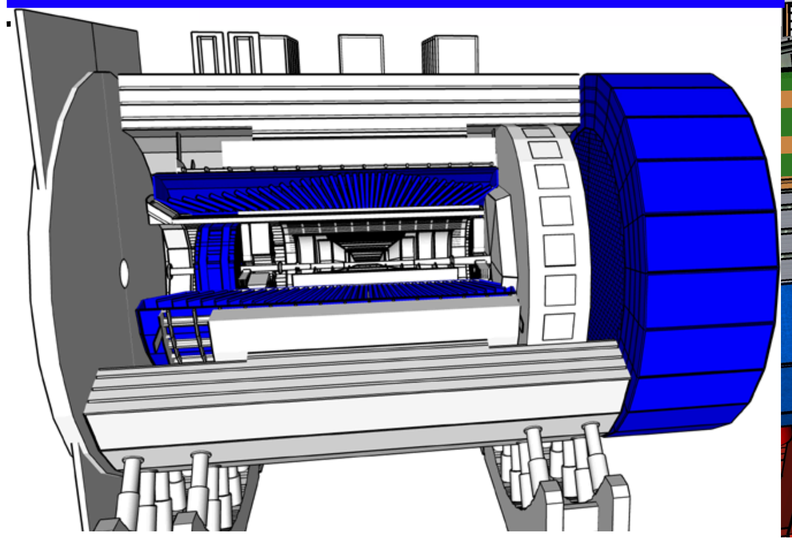
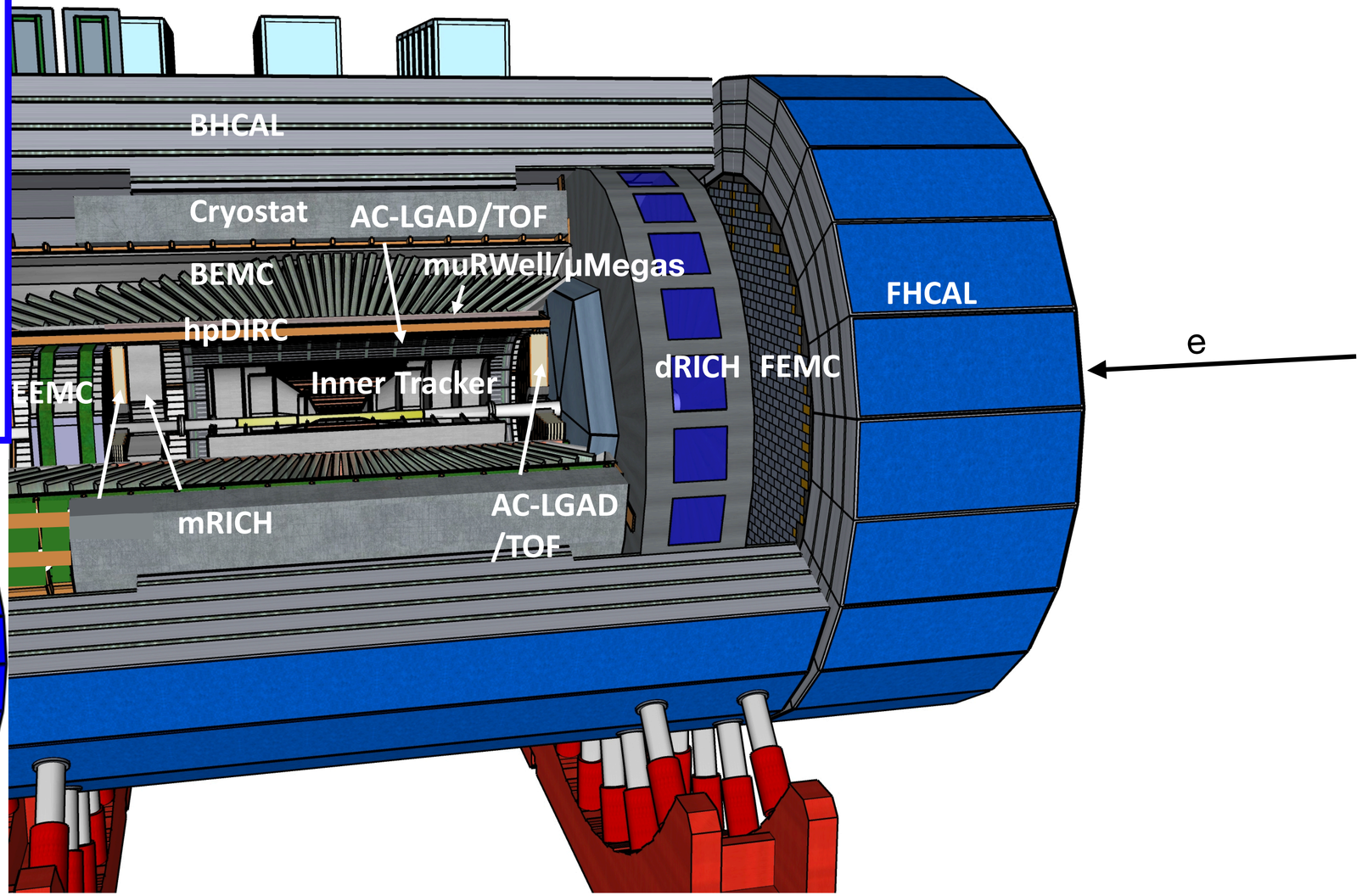


The ePIC central detector (current status)

EM CAL

- Electron-endcap EM cal (EEMC): high-precision $PbWO_4$+SiPMs
- Barrel EM cal (BEMC): SciGlass/Imaging EM cal
- Forward EM cal (FEMC): Finely segmented W-SciFi

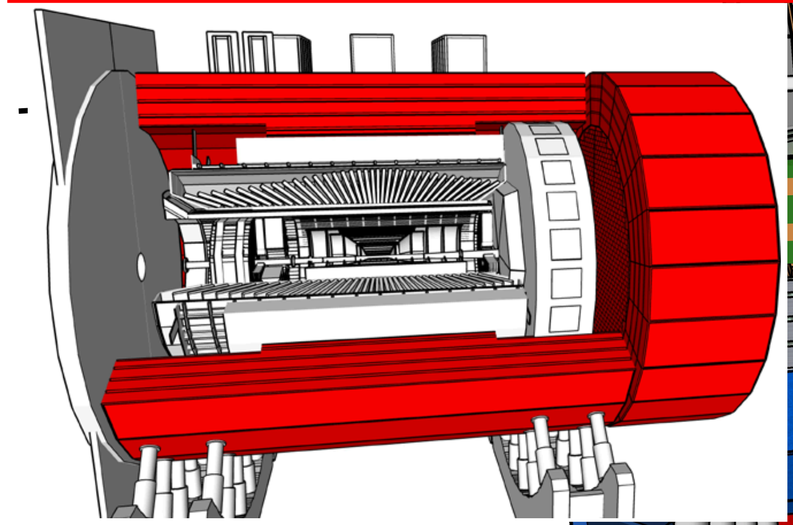


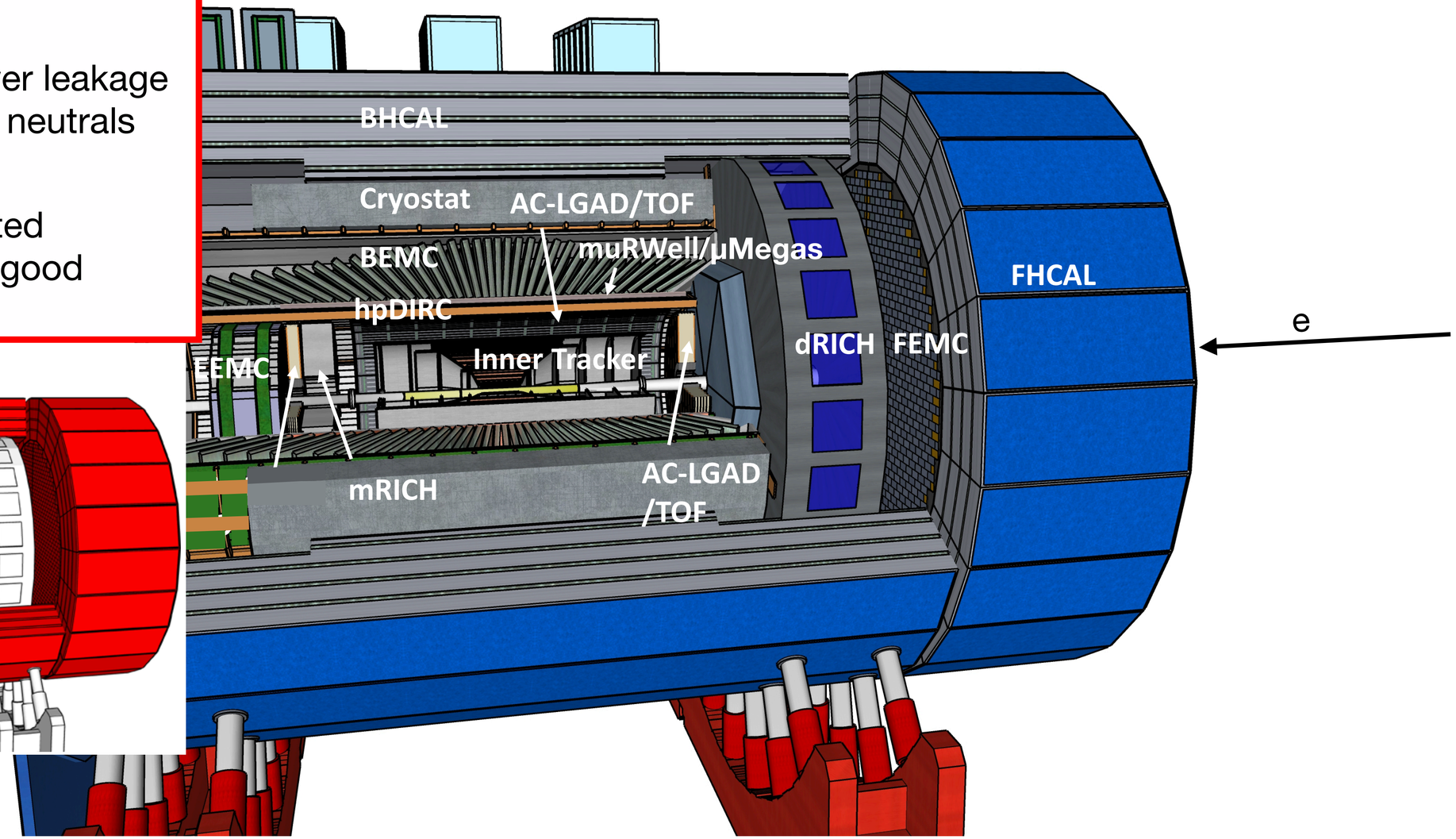


The ePIC central detector (current status)

HCAL

- Inner+outer HCAL: steel+Sci: control shower leakage (inner) and detection of neutrals
- FHCAL: finally segmented steel+tungsten+Sci for good energy resolution





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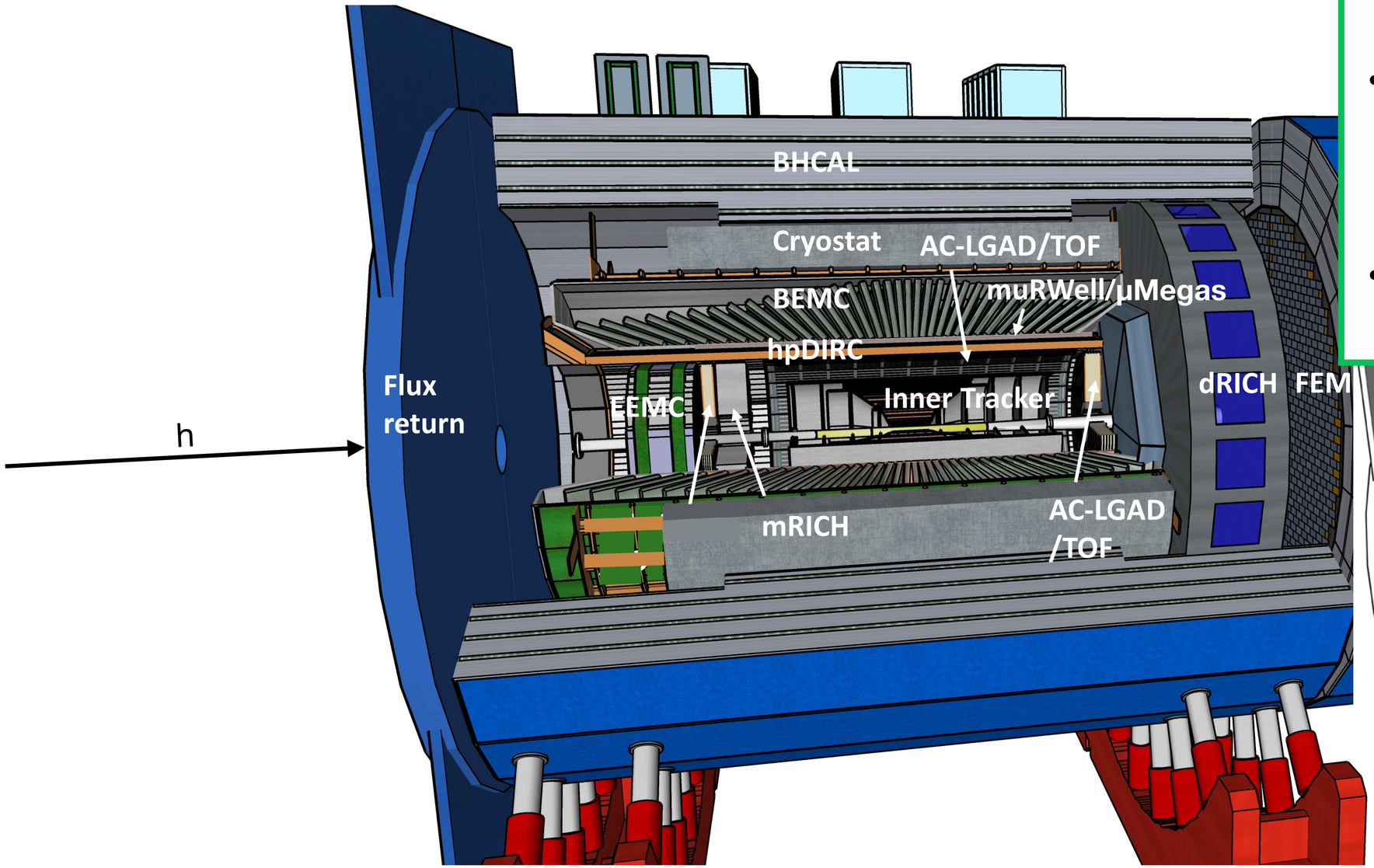
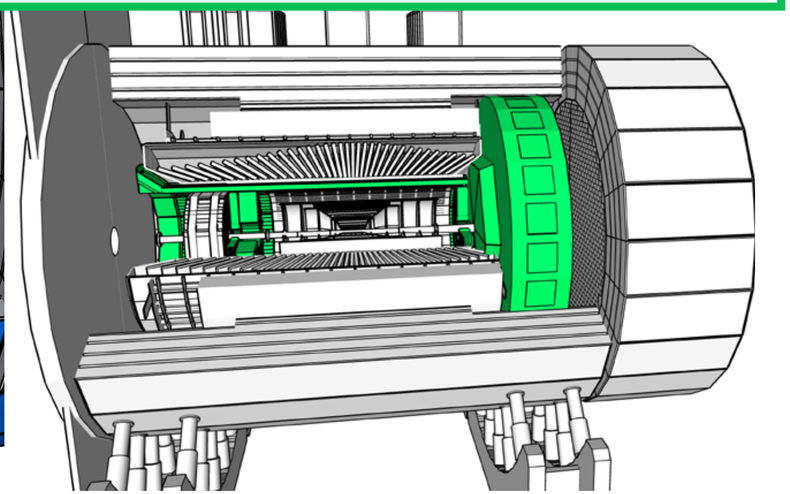


PID

- Cherenkov detectors: mRICH/pfRICH, hpDIRC, dRICH
  ~ 1 GeV/c<p<50 GeV/c
- AC-LGAD/TOF:
  ~ p < 0.5 – 3 GeV/c



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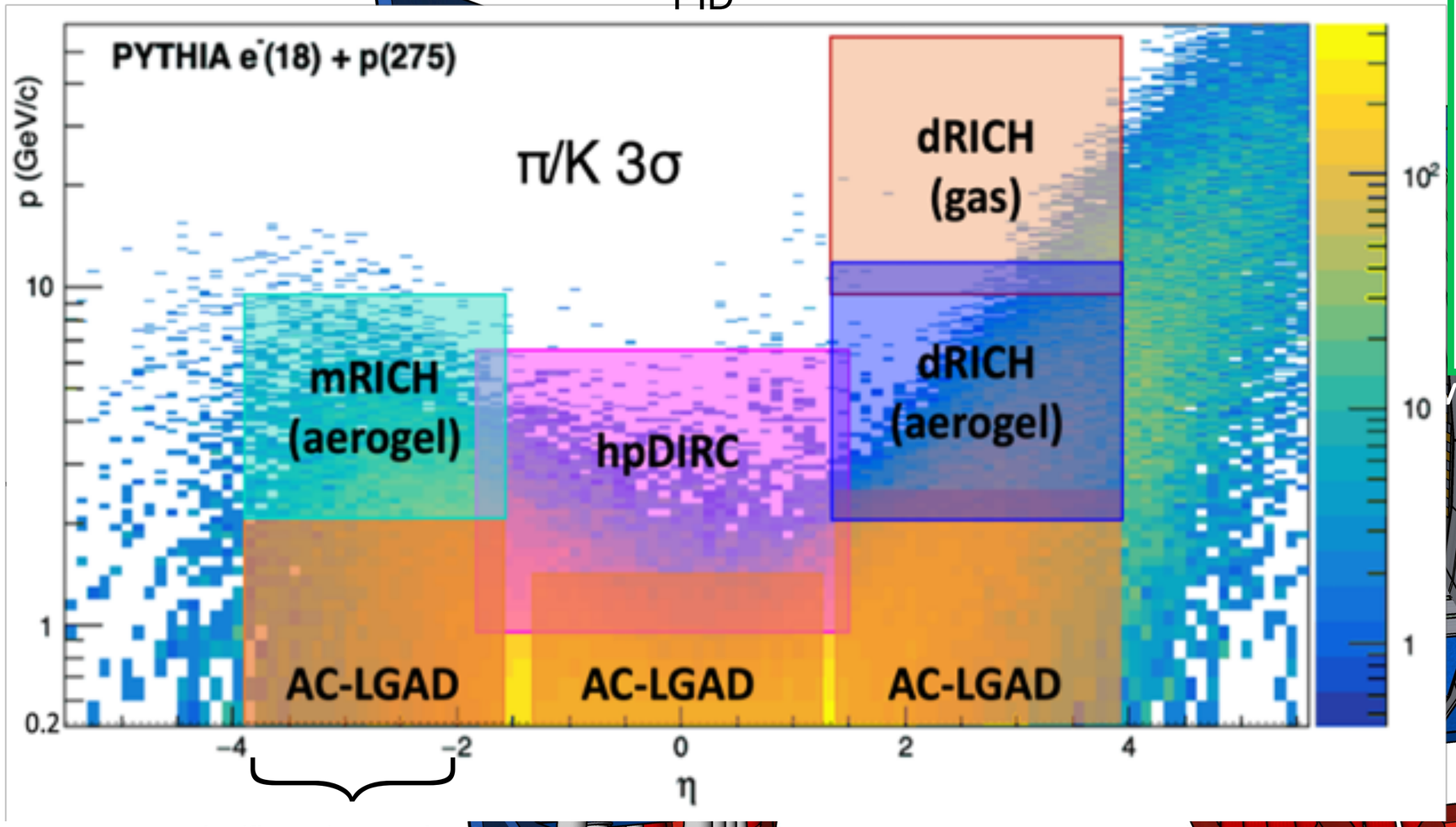

significant integration issues
work in progress

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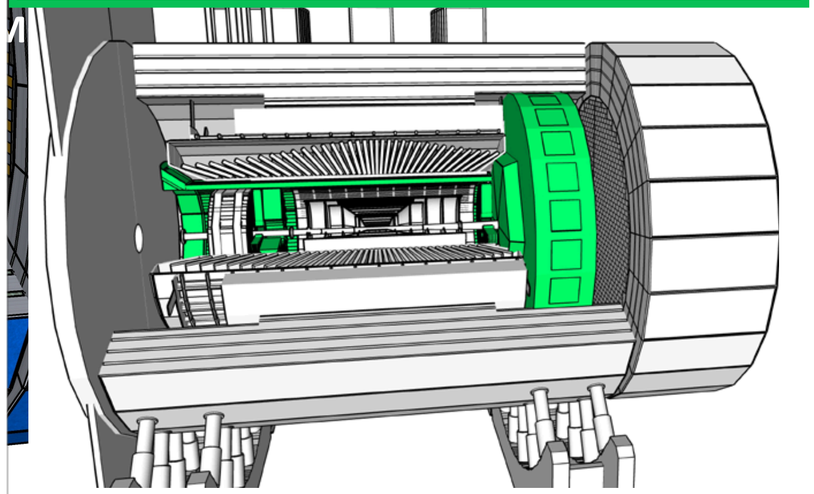
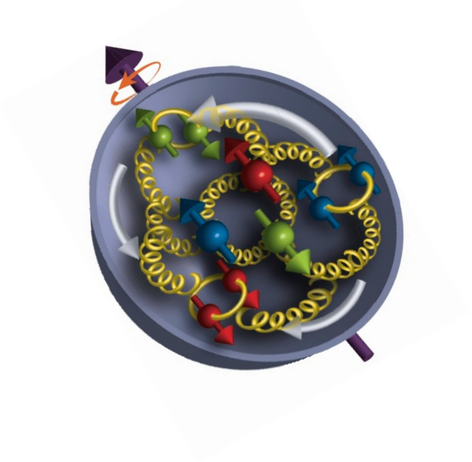
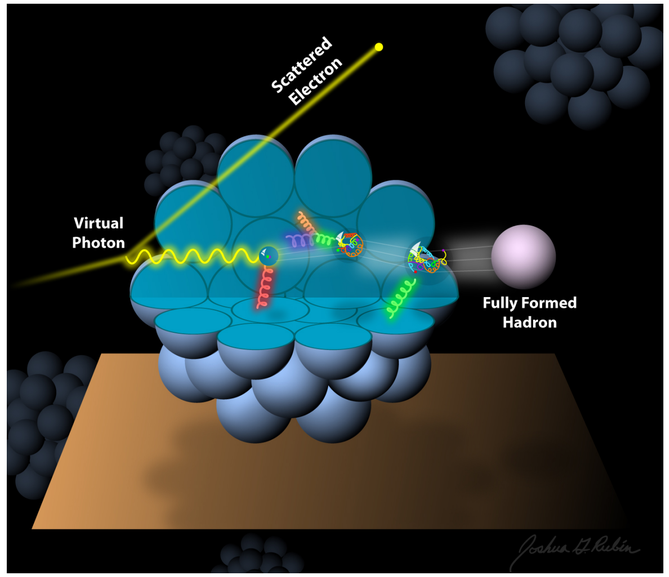


Physics with EIC

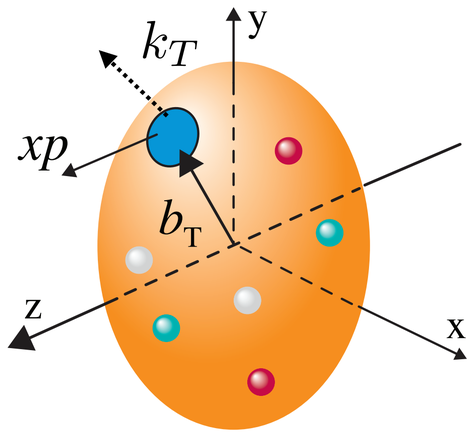
Nucleon spin



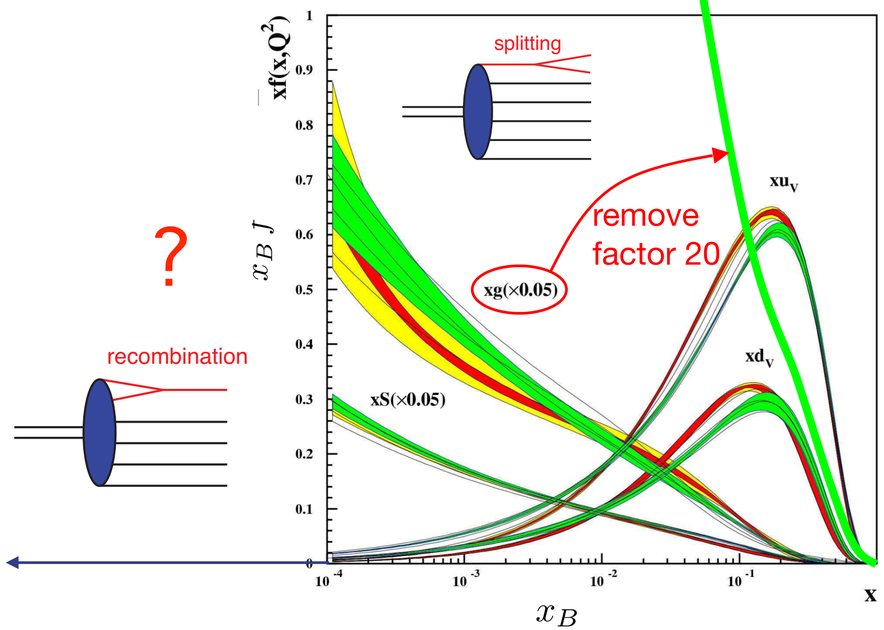
Hadronisation



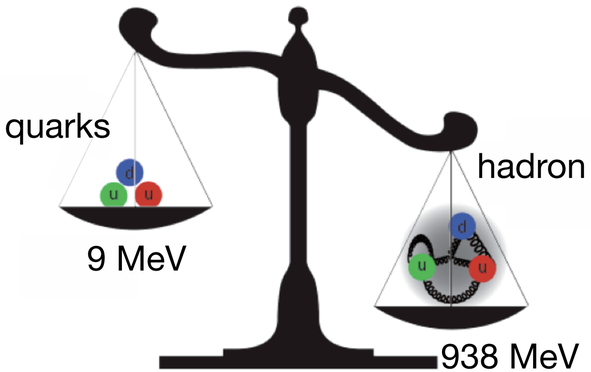
Nucleon multi-dimensional structure



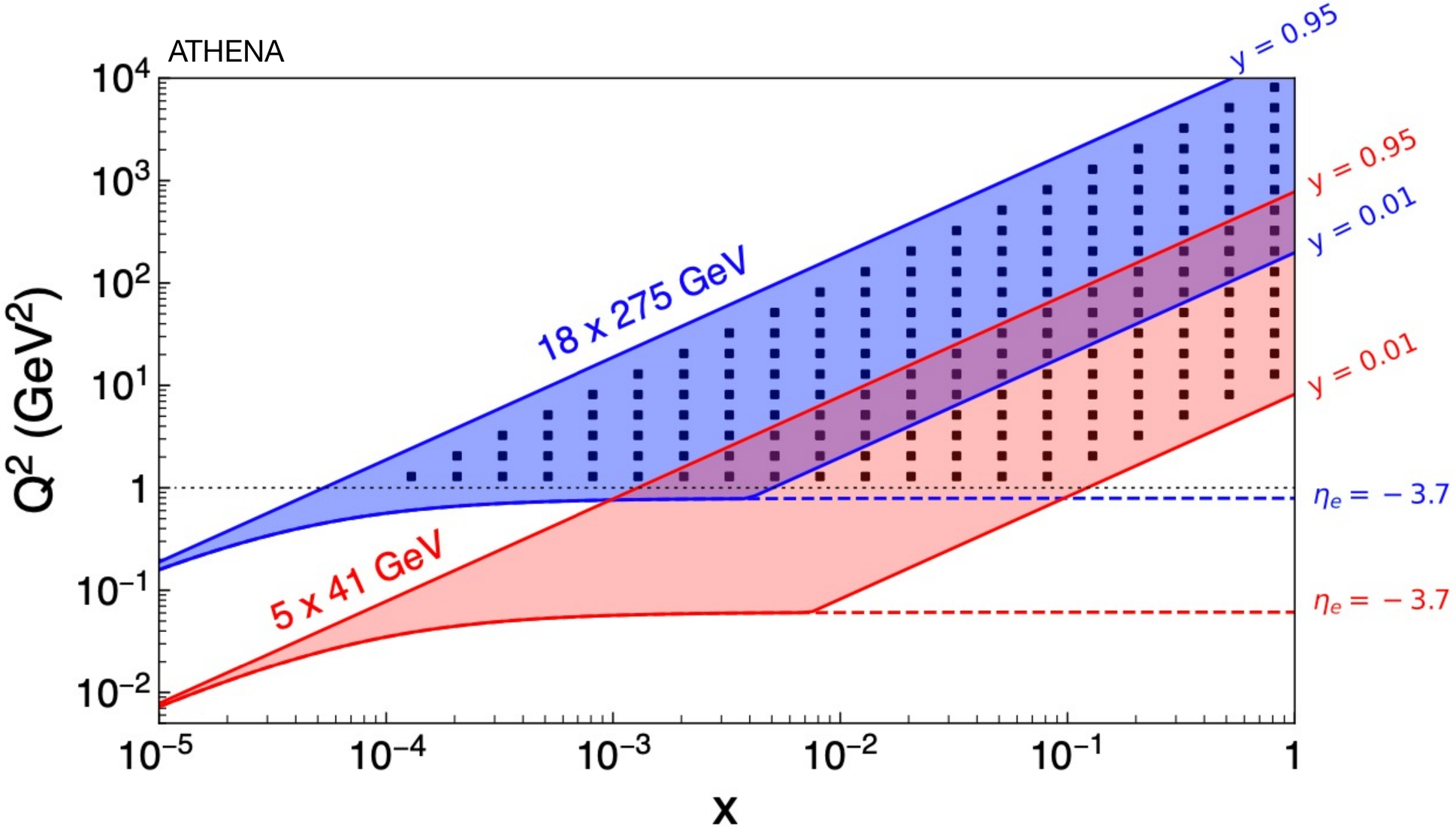
Search for gluon saturation



Hadron mass



Kinematic coverage for DIS



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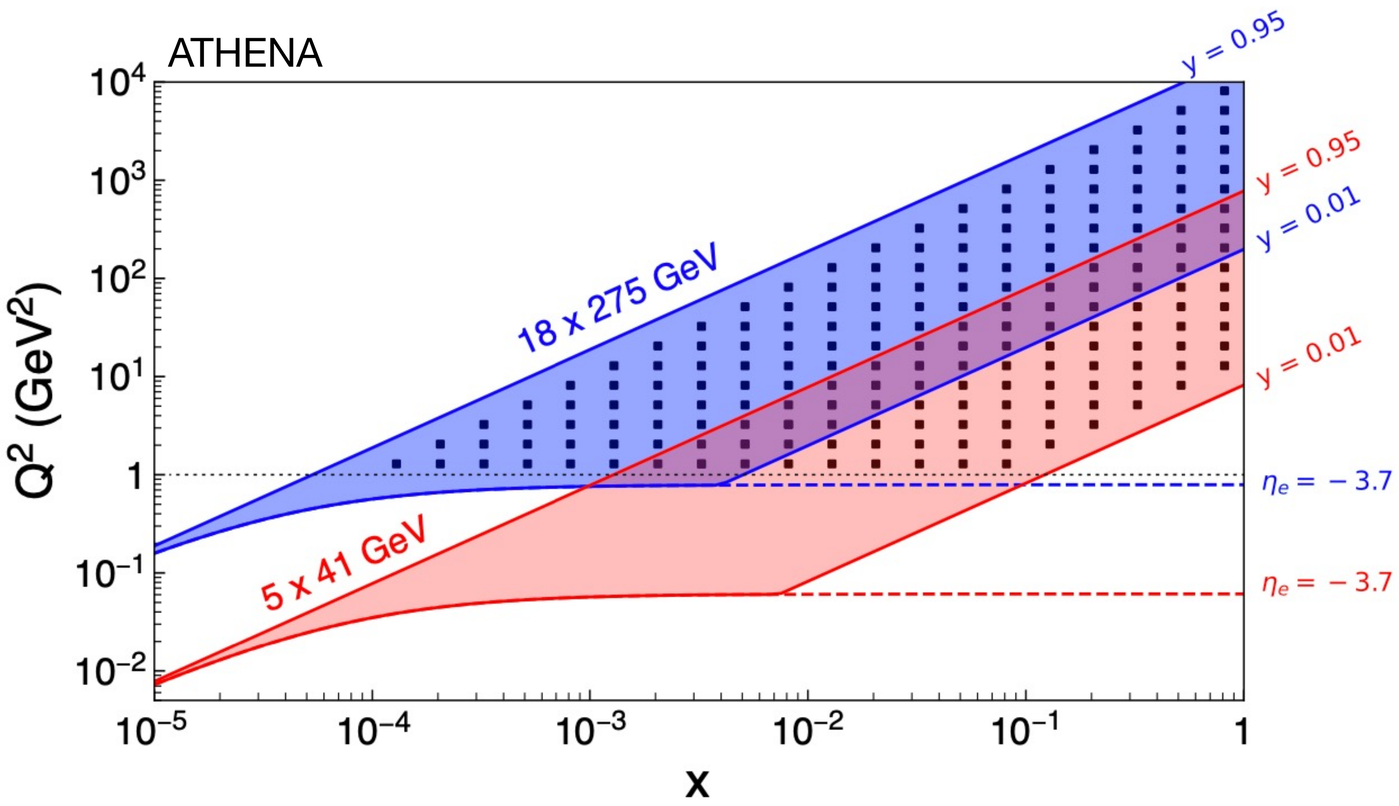
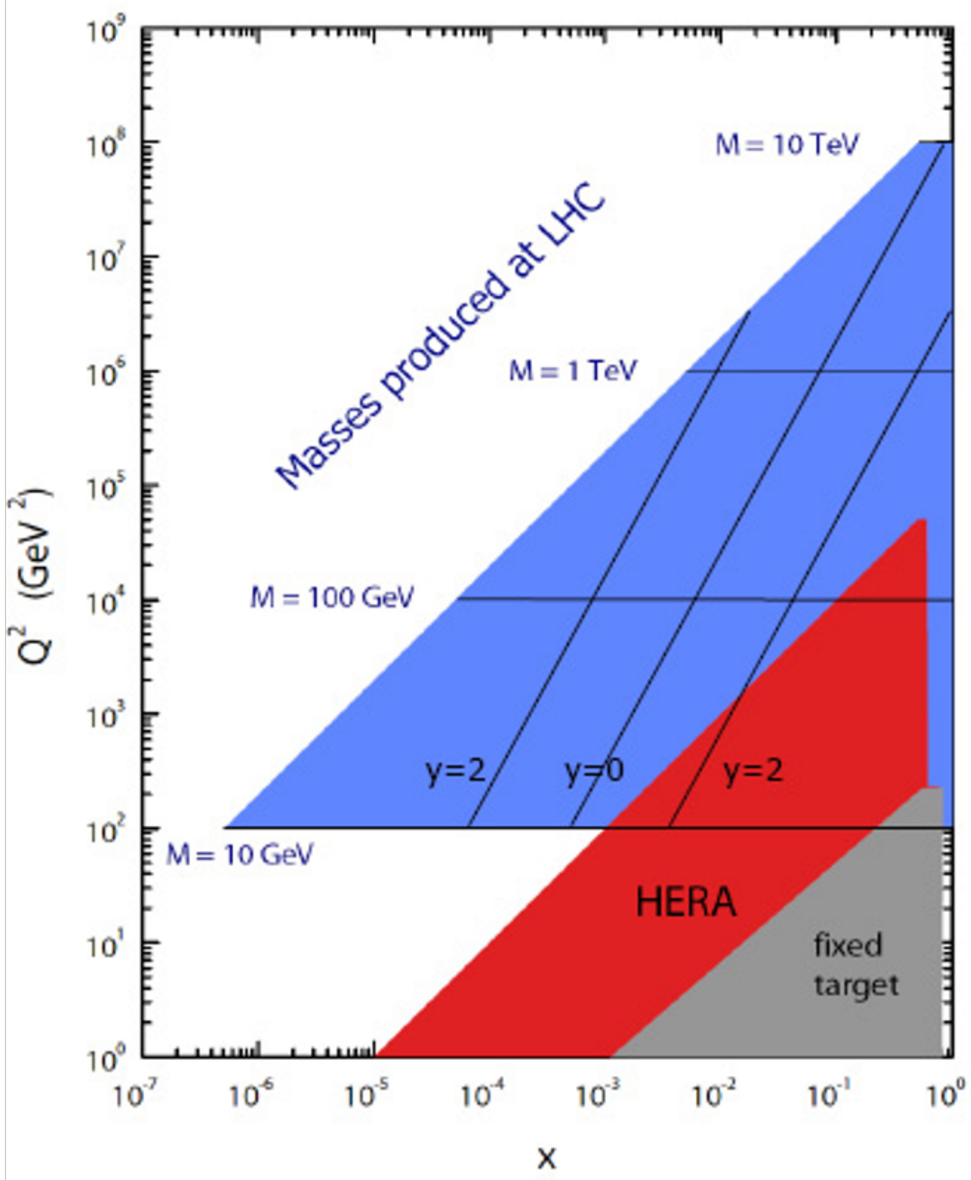
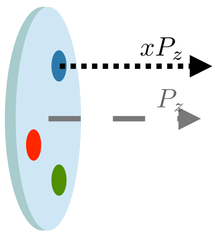


EIC



LHC, pp di-jets at

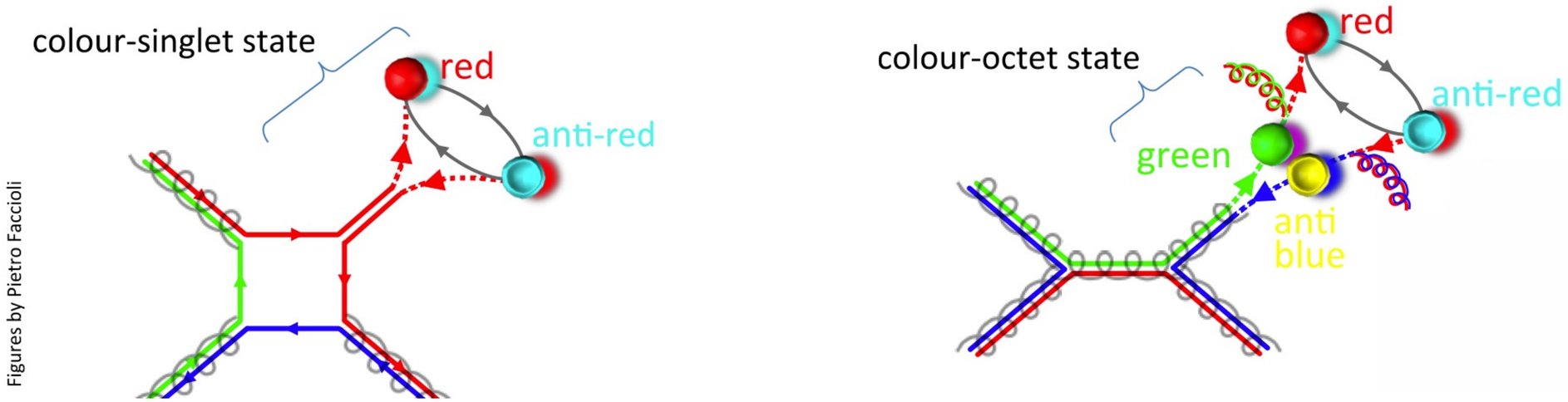
Quarkonium production (at the EIC)



→ Access to production mechanism of quarkonia, which is not yet understood

- Usual assumption: factorisation between $Q\overline{Q}$ formation and $Q\overline{Q}$ hadronisation
- Different approaches for hadronisation: colour-evaporation model, colour-singlet model, non-relativistic QCD (NRQCD)

NRQCD



Figures by Pietro Faccioli

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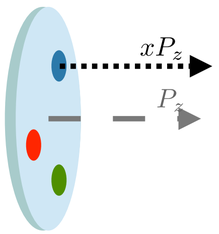

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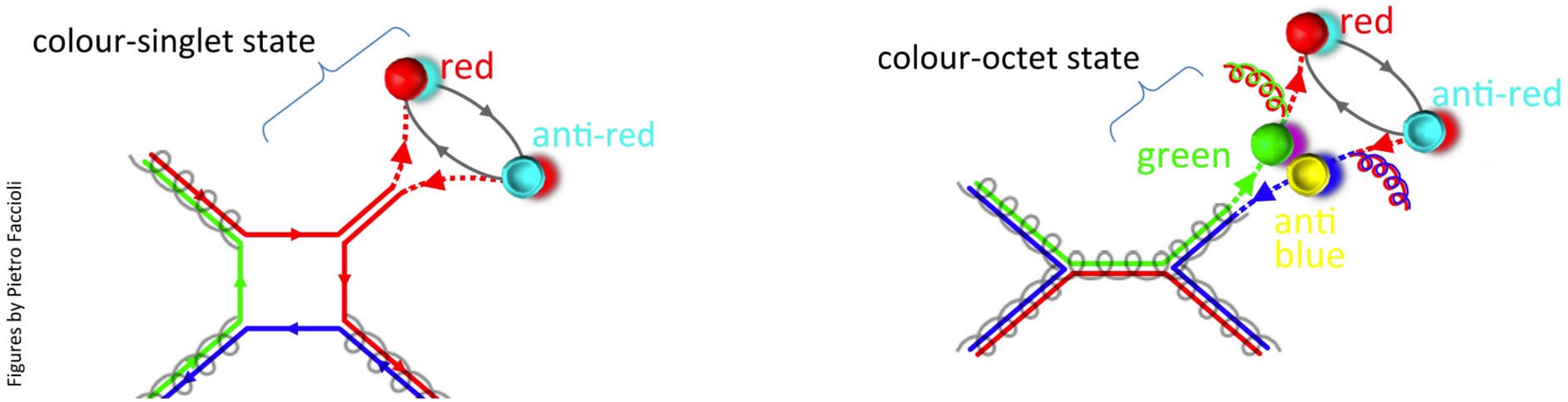
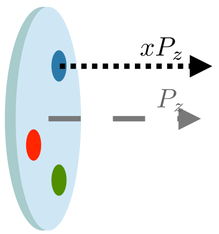
NRQCD

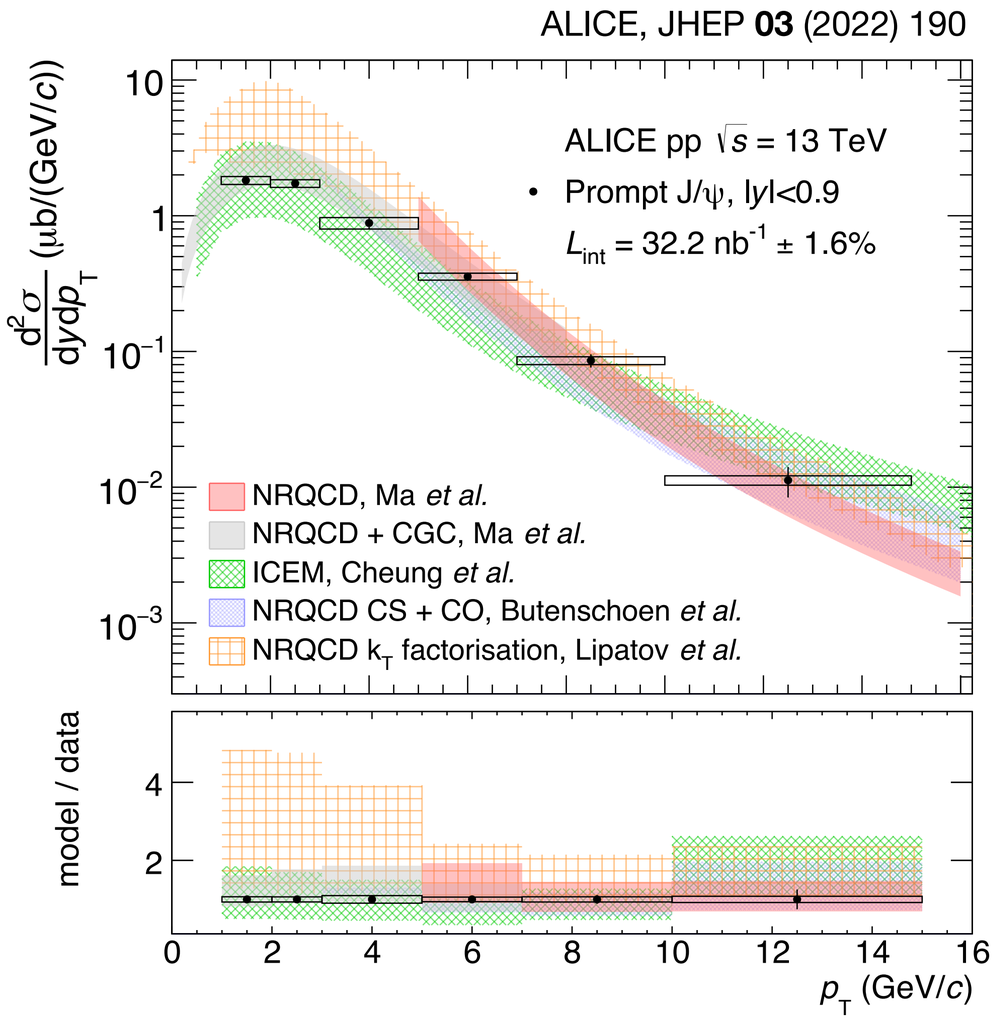


Figures by Pietro Faccioli

→ Access to gluon distributions

Inclusive J/ψ production





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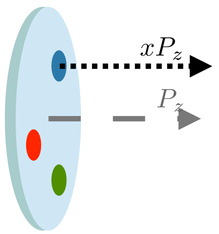
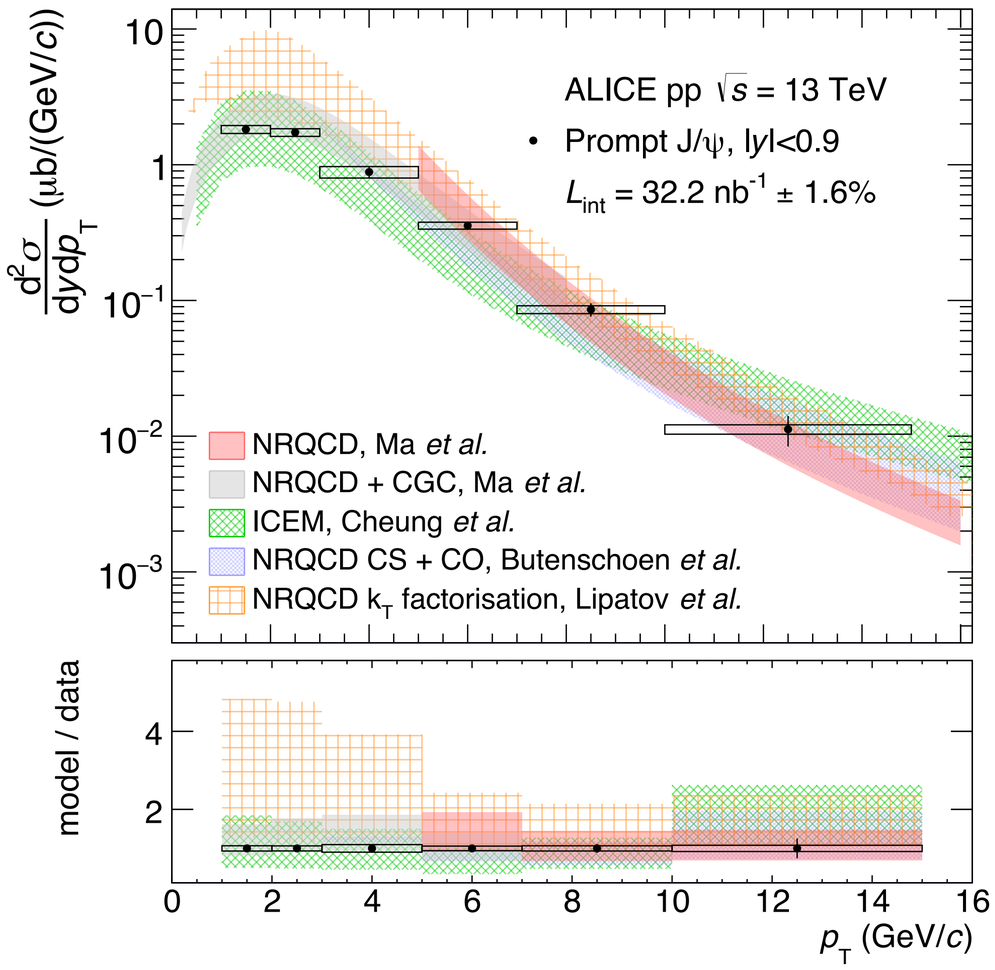
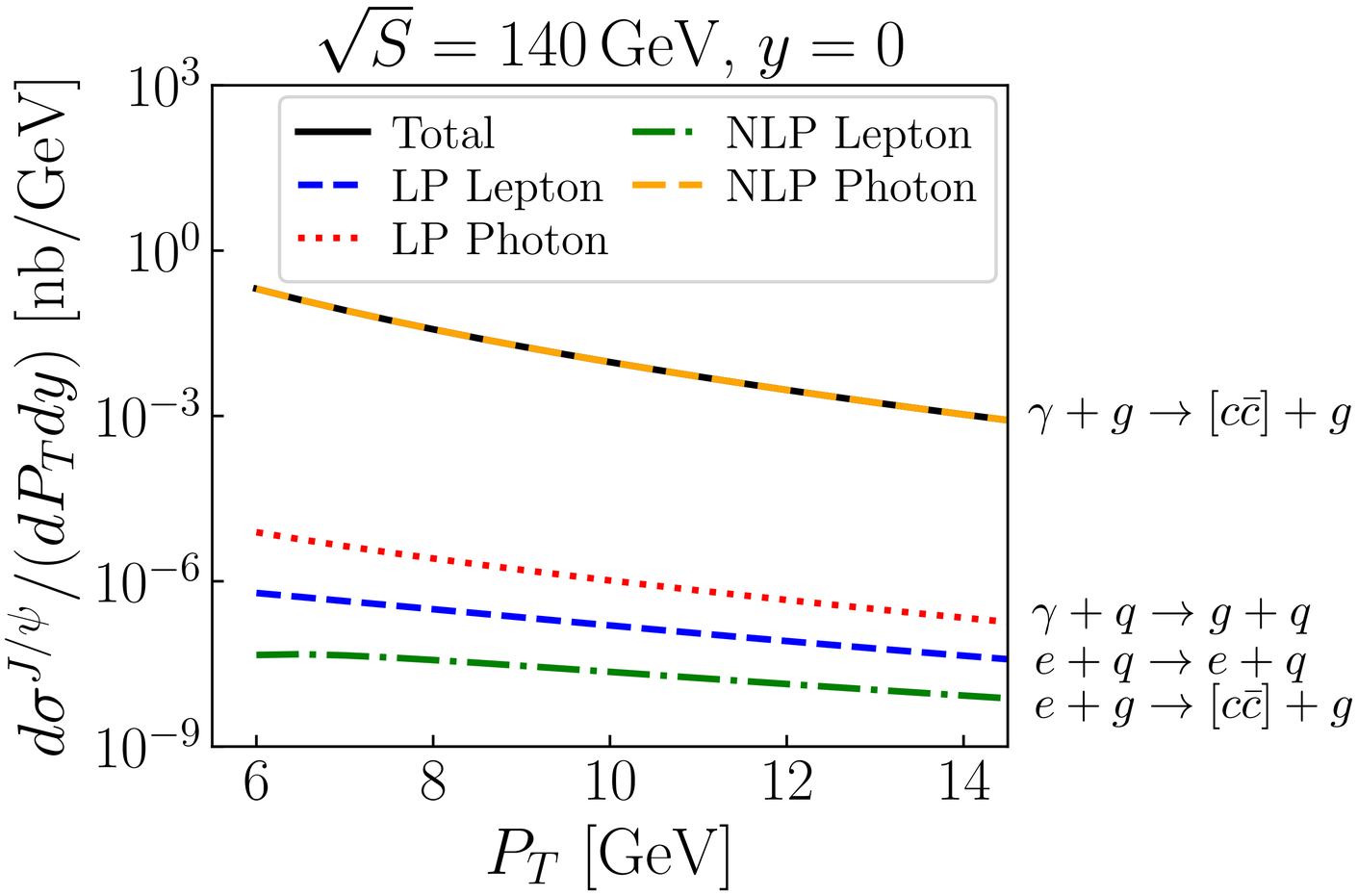


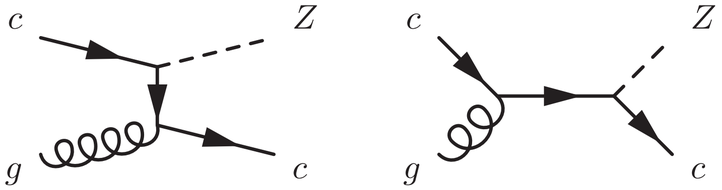
ALICE, JHEP **03** (2022) 190





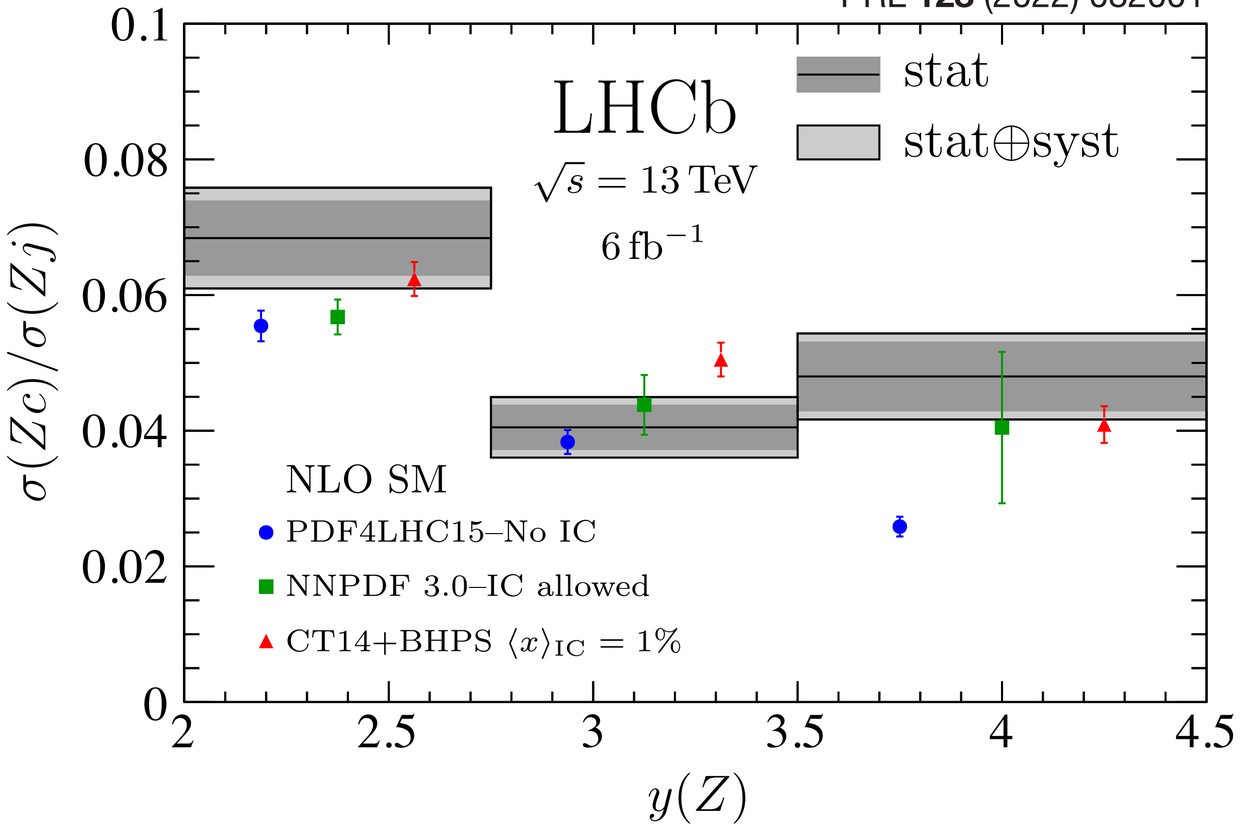
D. Boer et al., *Physics case for quarkonium studies at the Electron Ion Collider*

Intrinsic charm at the LHC



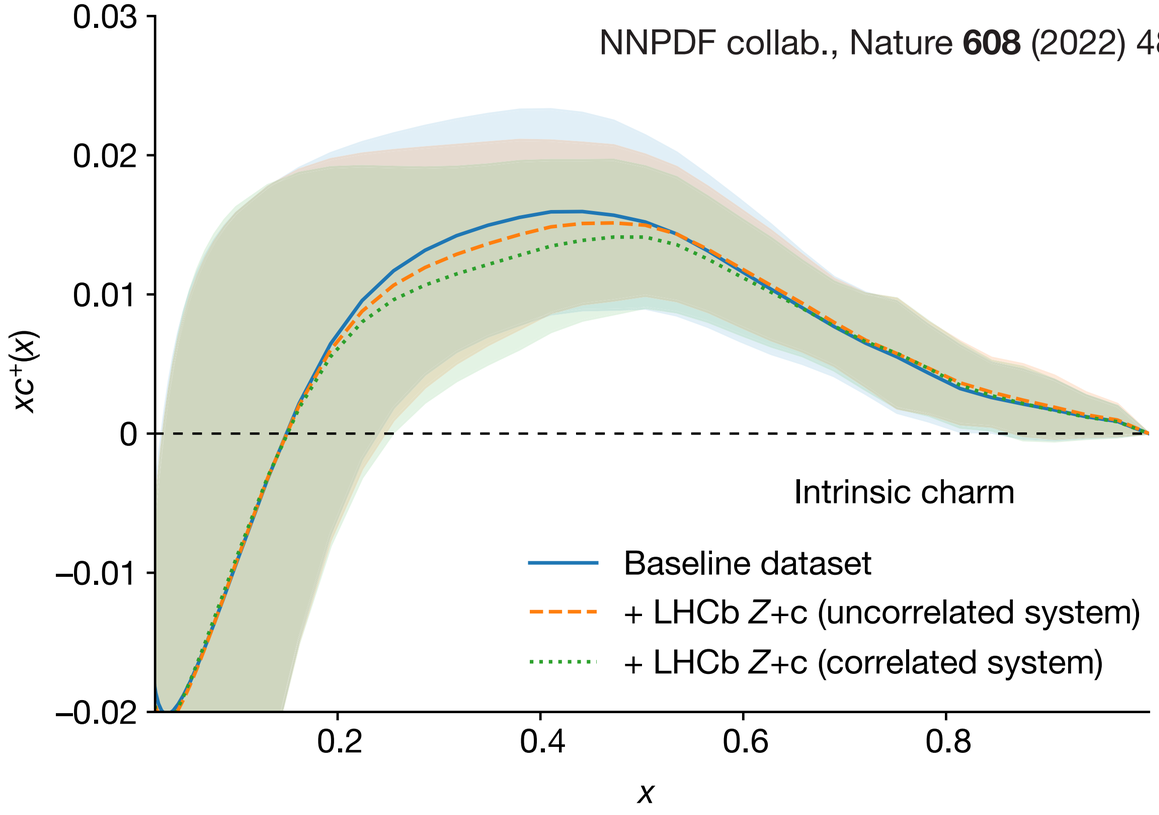
Ratio x-section Z+c-tagged jets/Z+jets

PRL **128** (2022) 082001



Intrinsic charm PDF

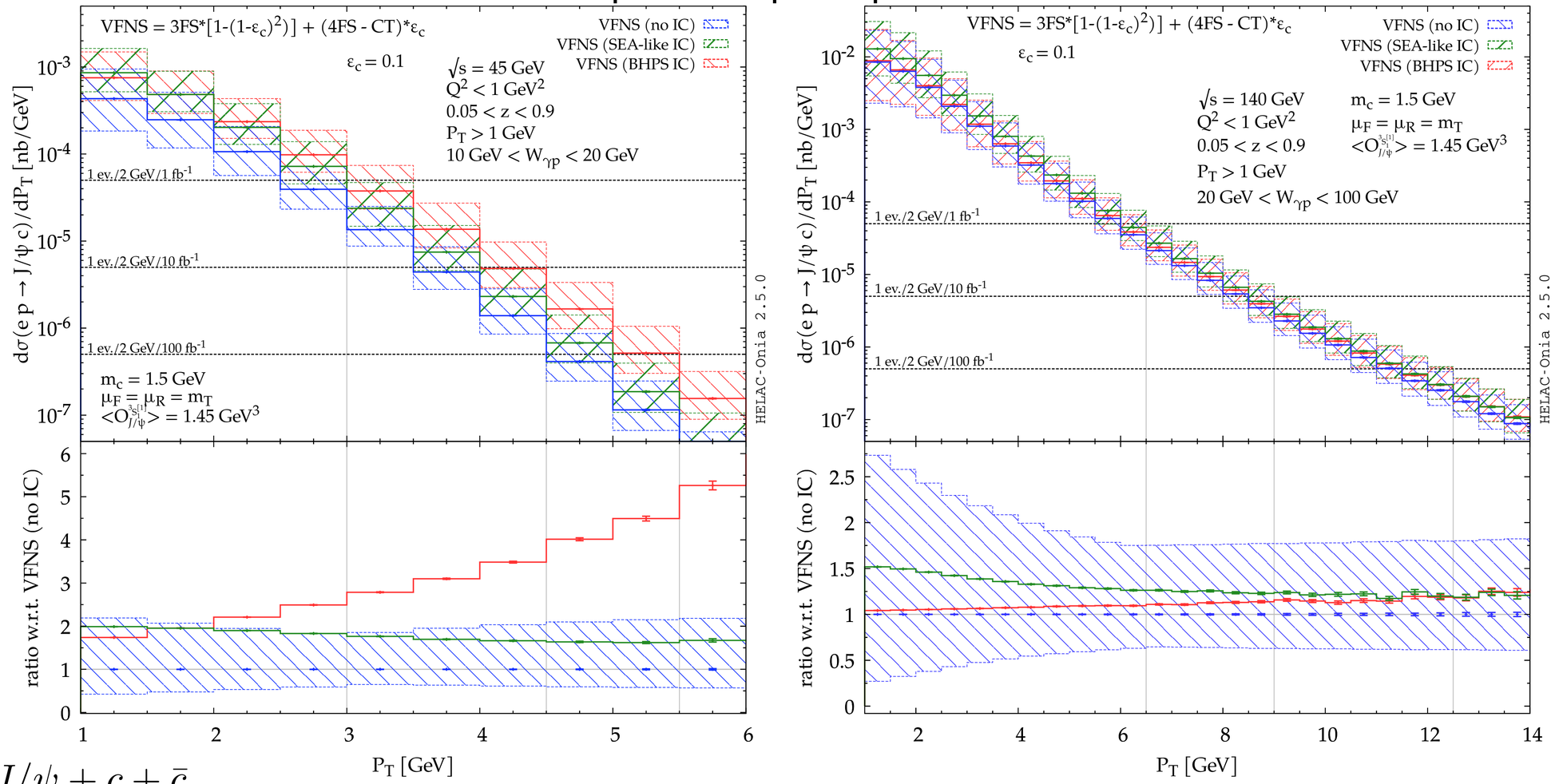
NNPDF collab., Nature **608** (2022) 483-487



Intrinsic charm at the EIC

J/ψ+charm photoproduction

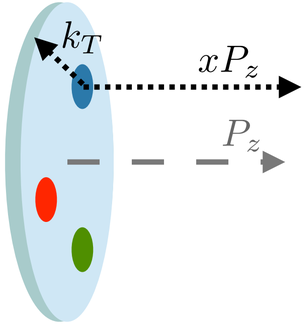
C. Flore et al., Phys. Lett. B **811** (2020) 135926



3FS: $\gamma + g \to J/\psi + c + \bar{c}$

4FS: $\gamma + [c, \bar{c}] \to J/\psi + [c, \bar{c}]$

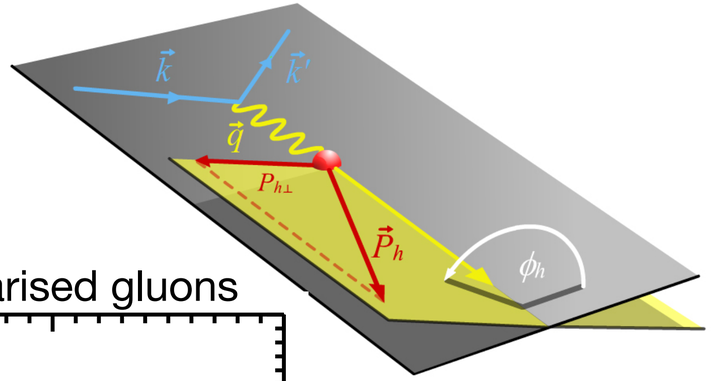
TMD PDFs in unpolarised protons



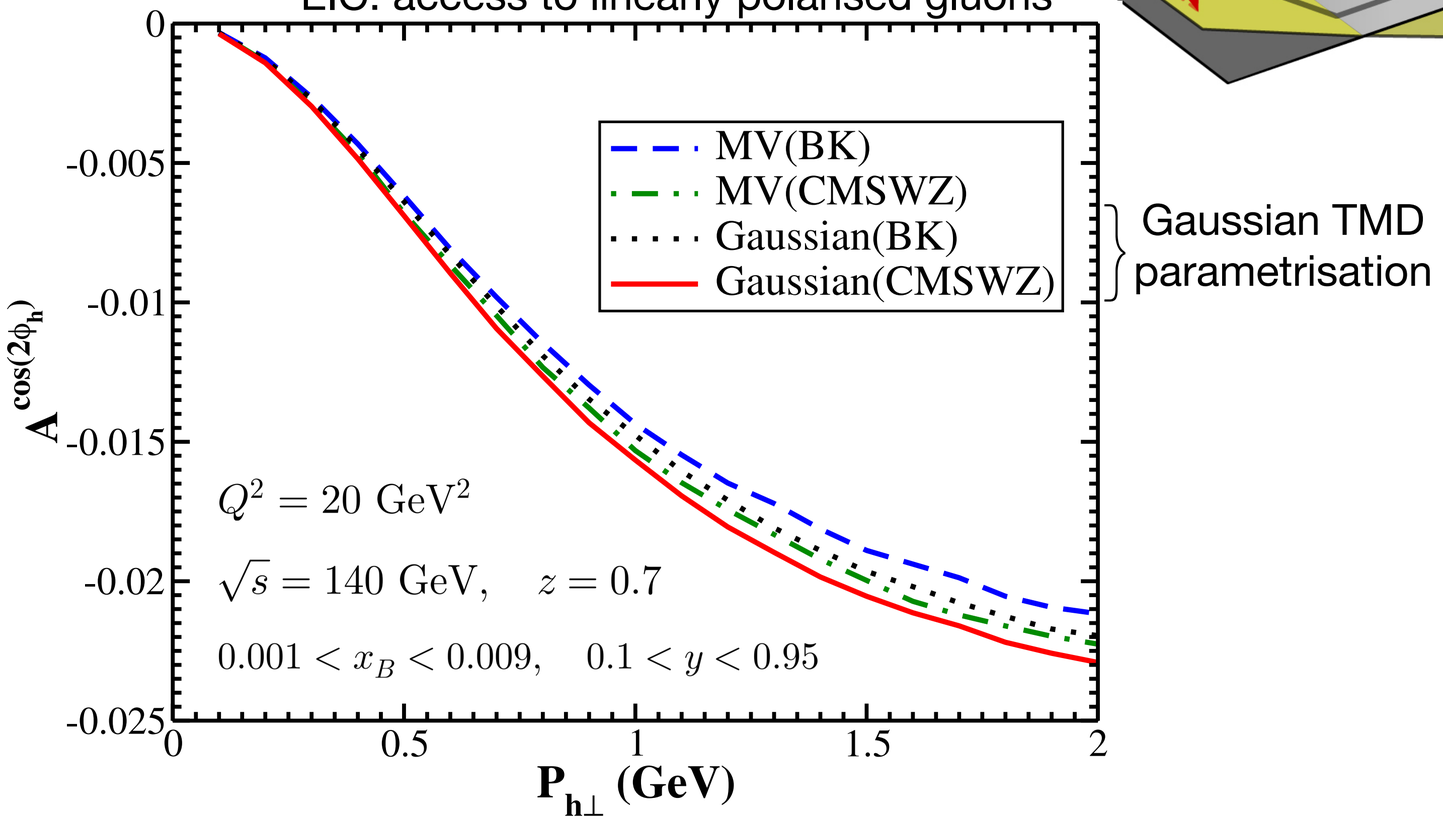
$e + p \to e + J/\psi + X$, leading sub-process: $e + g \to e + [c\bar{c}]$

→ probe gluon distribution

→ $p_{T J/\psi, \gamma^*}$: mostly from gluon k_T



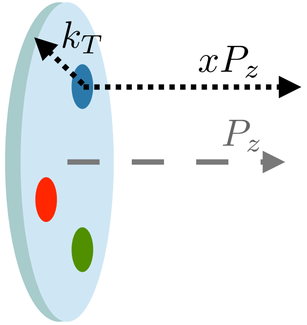
EIC: access to linearly polarised gluons



Gaussian TMD parametrisation

D. Boer et al., *Physics case for quarkonium studies at the Electron Ion Collider*

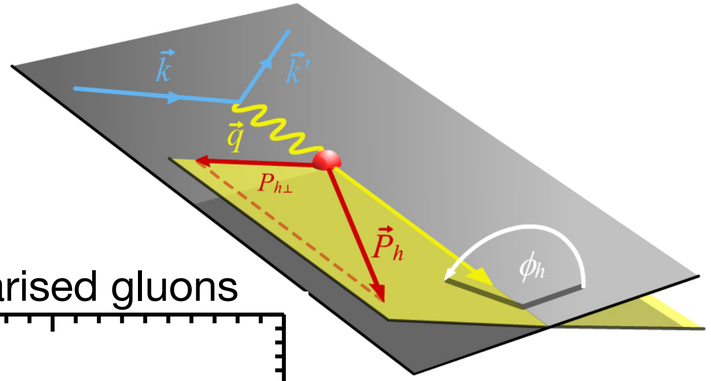
TMD PDFs in unpolarised protons



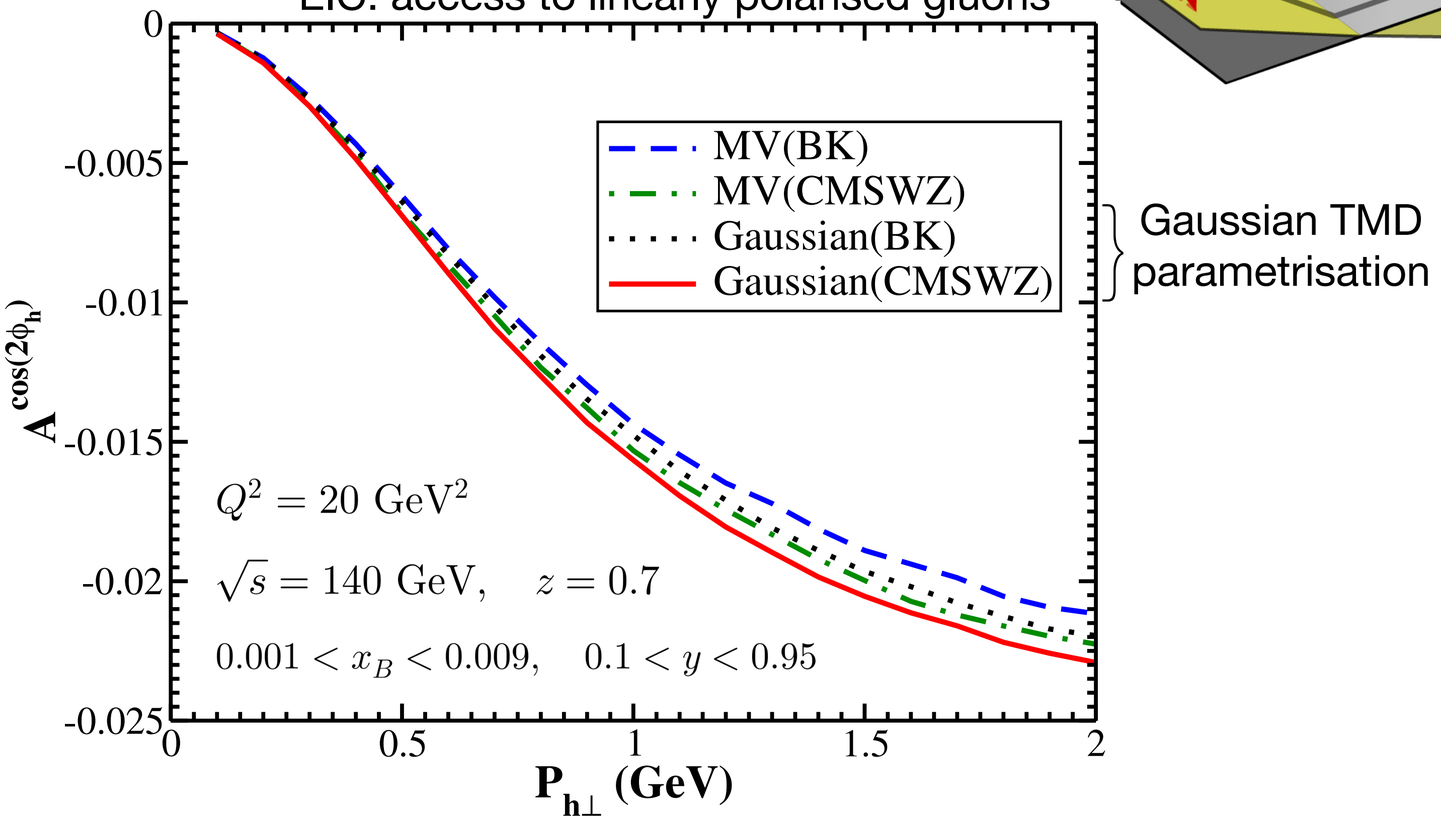
$e + p \to e + J/\psi + X$, leading sub-process: $e + g \to e + [c\bar{c}]$

→ probe gluon distribution

→ $p_{T J/\psi,\gamma^*}$: mostly from gluon k_T



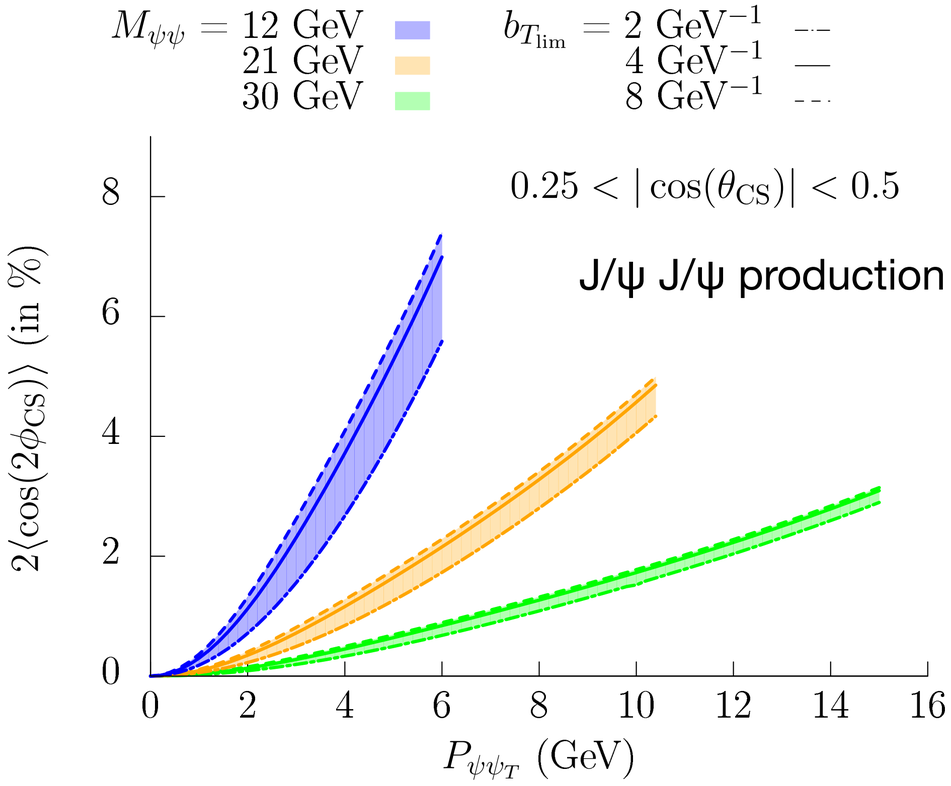
EIC: access to linearly polarised gluons



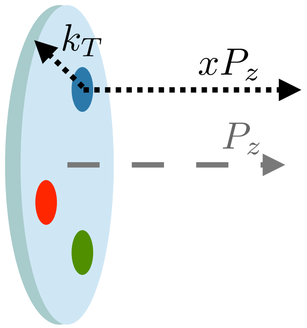
D. Boer et al., *Physics case for quarkonium studies at the Electron Ion Collider*

LHC: access to linearly polarised gluons

F. Scarpa et al., Eur. Phys. J. C**80** (2020) 87



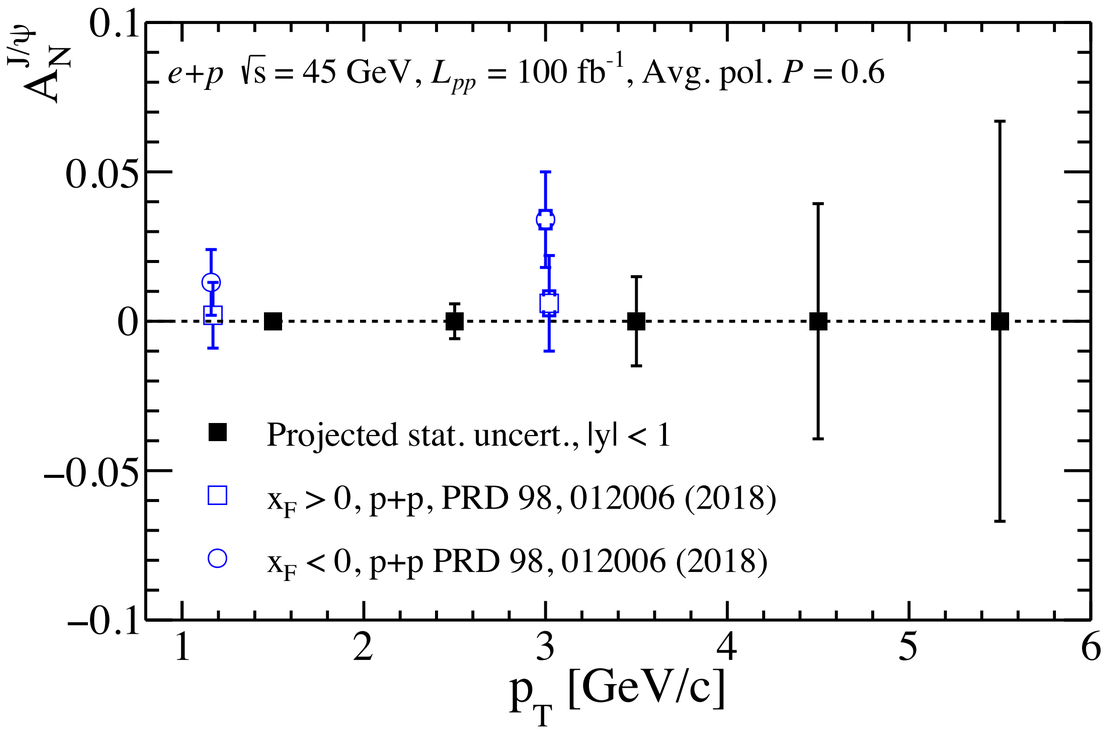
TMD PDFs in transversely polarised protons



→ gluon Sivers TMD

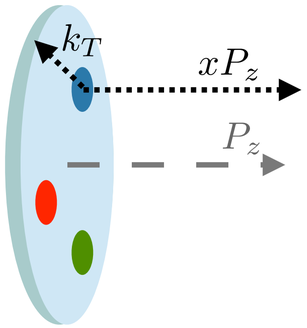
$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Predictions for EIC



D. Boer et al., *Physics case for quarkonium studies at the Electron Ion Collider*

TMD PDFs in transversely polarised protons



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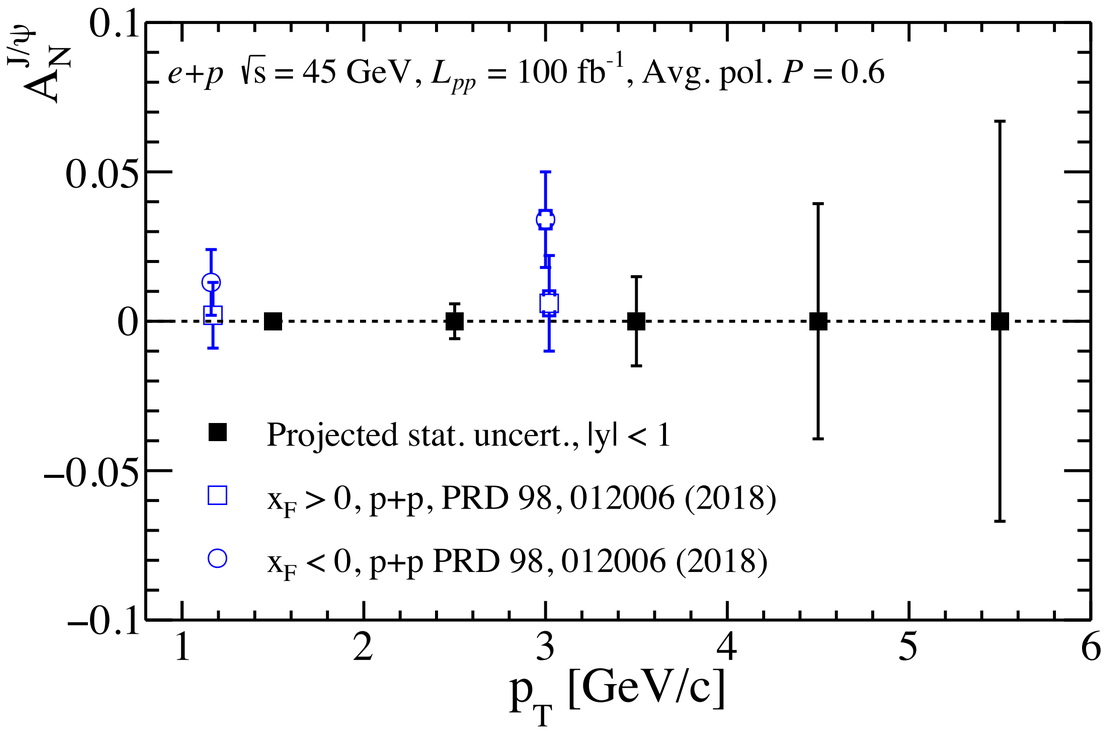
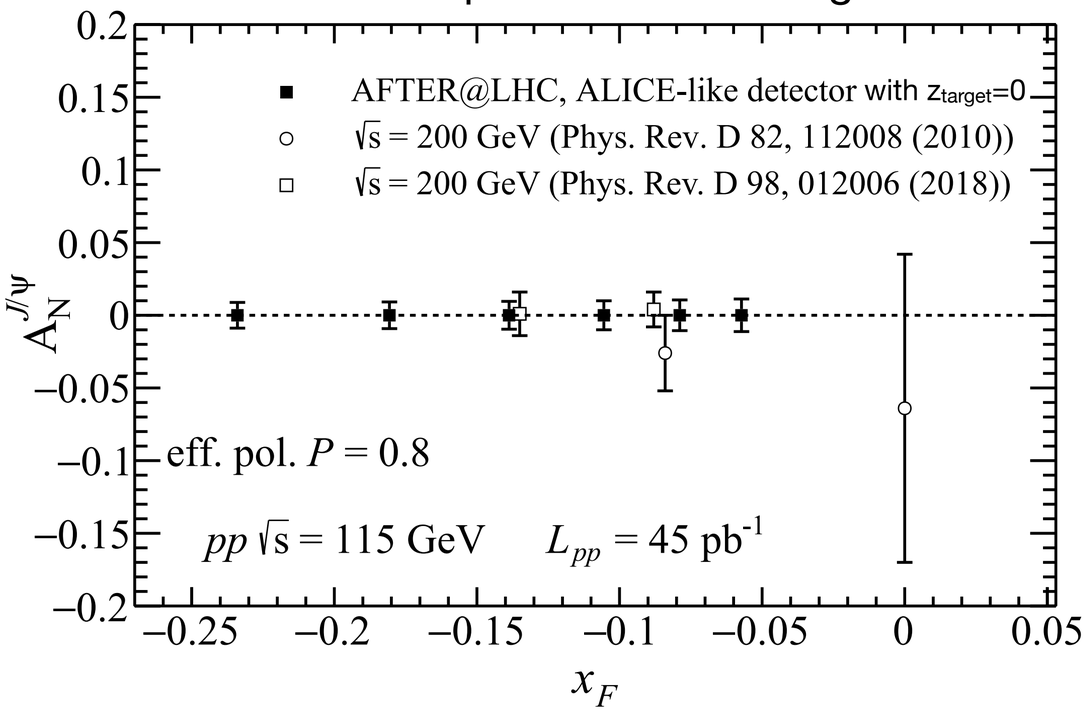


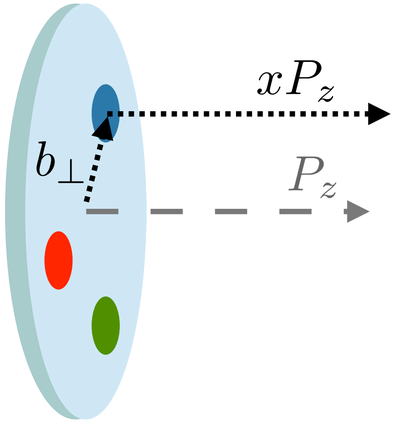
D. Boer et al., *Physics case for quarkonium studies at the Electron Ion Collider*

Predictions for polarised fixed target at LHC

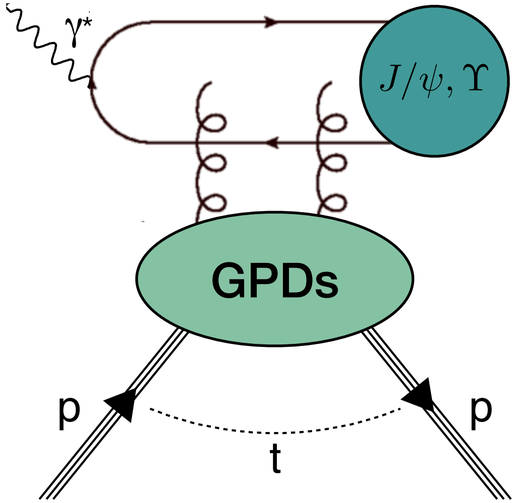


C.Hadjidakis et al., Phys. Rept. **911** (2021) 1–83

Exclusive measurements on protons



3D longitudinal-momentum
+ position structure



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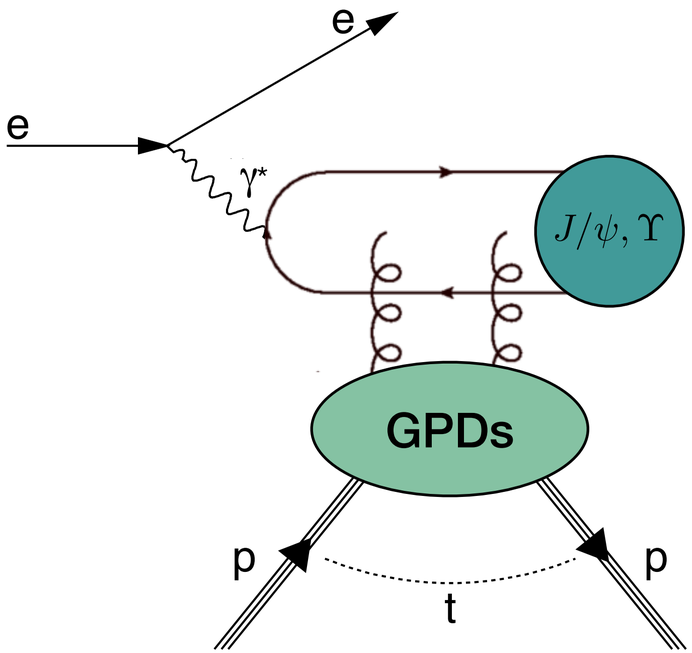

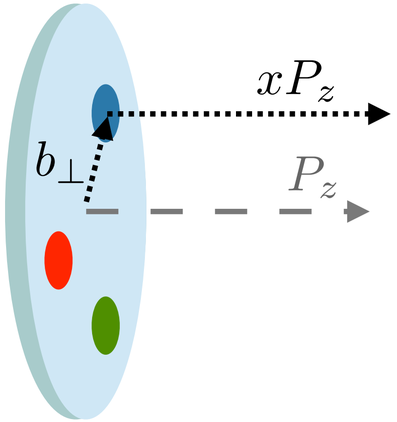

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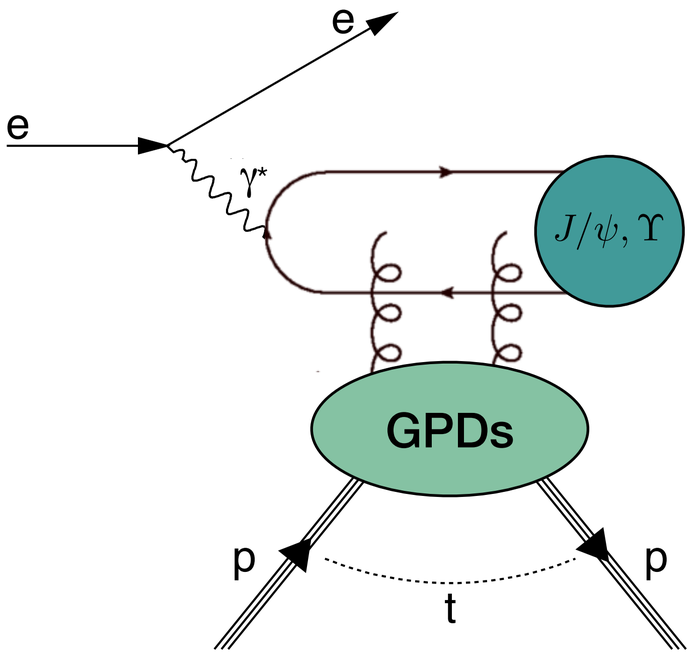

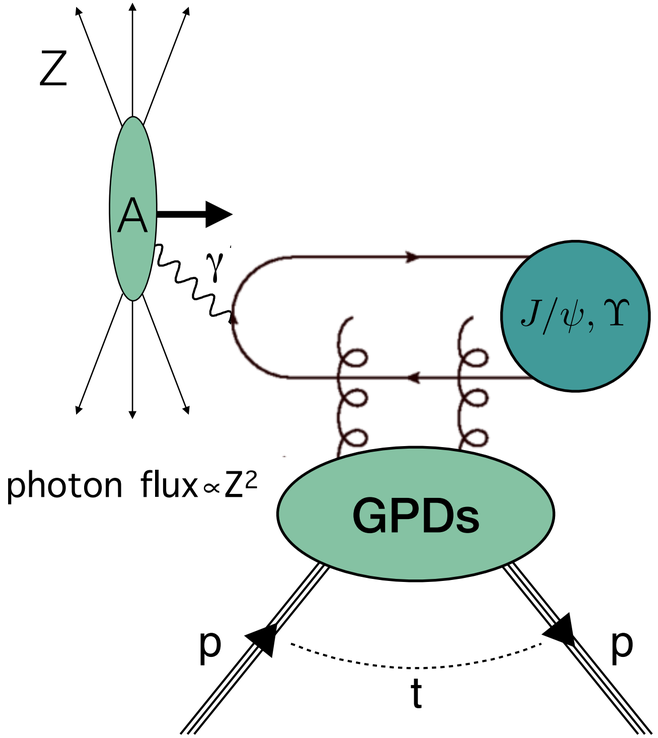

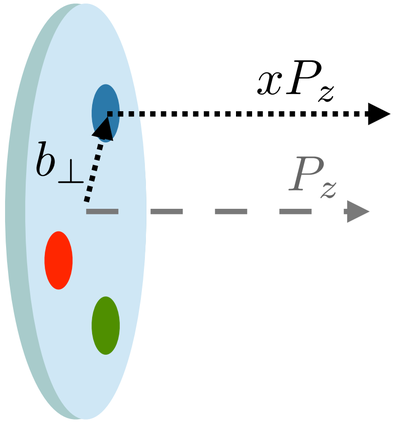

3D longitudinal-momentum
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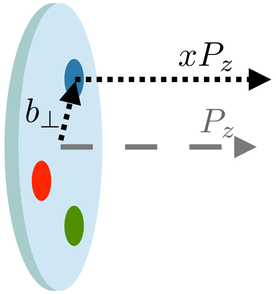
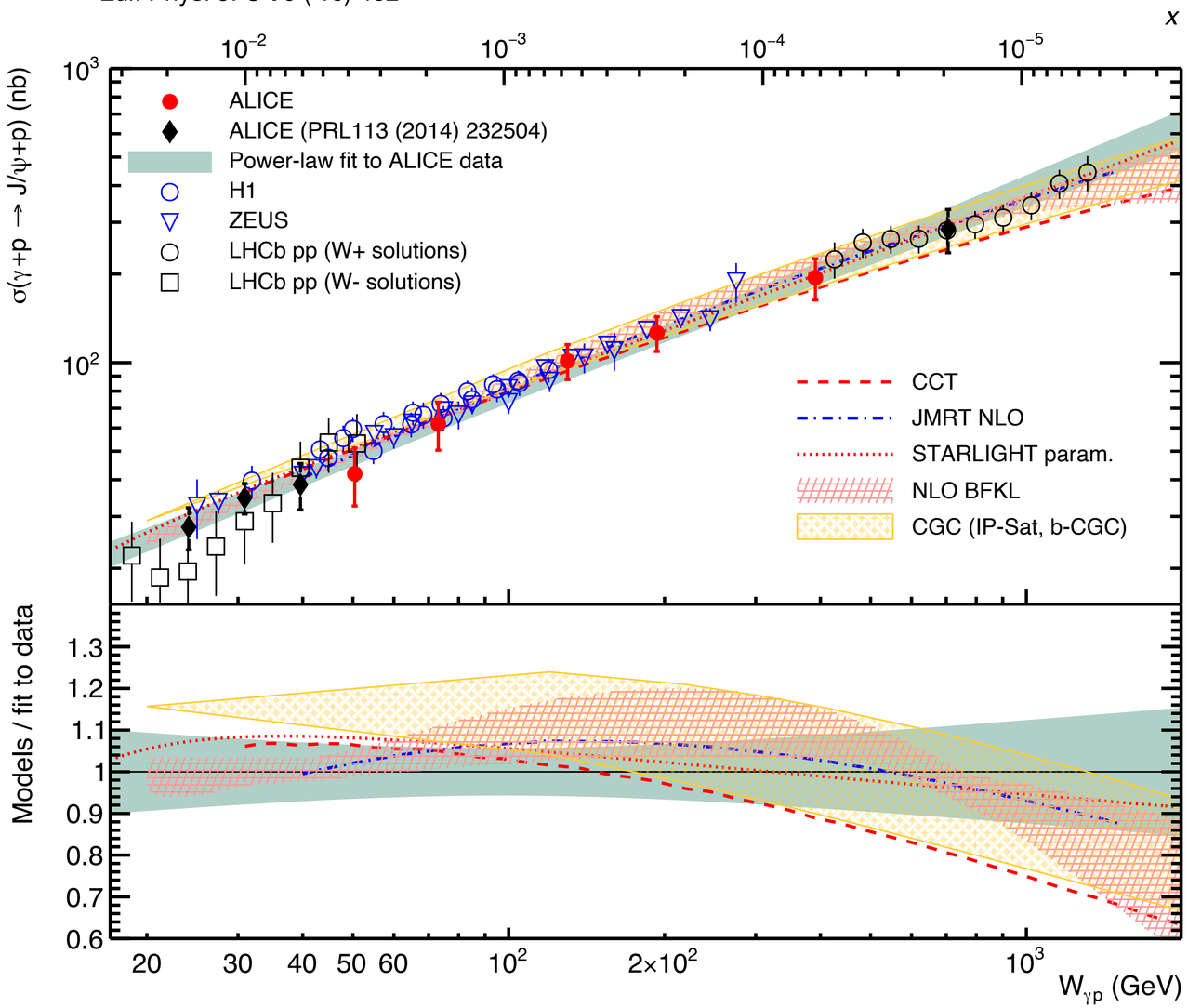
γp cross section: LHC



Eur. Phys. J. C **79** ('19) 402



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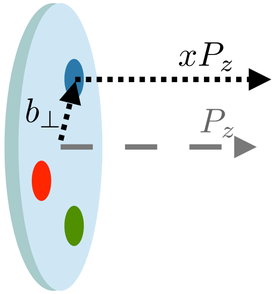
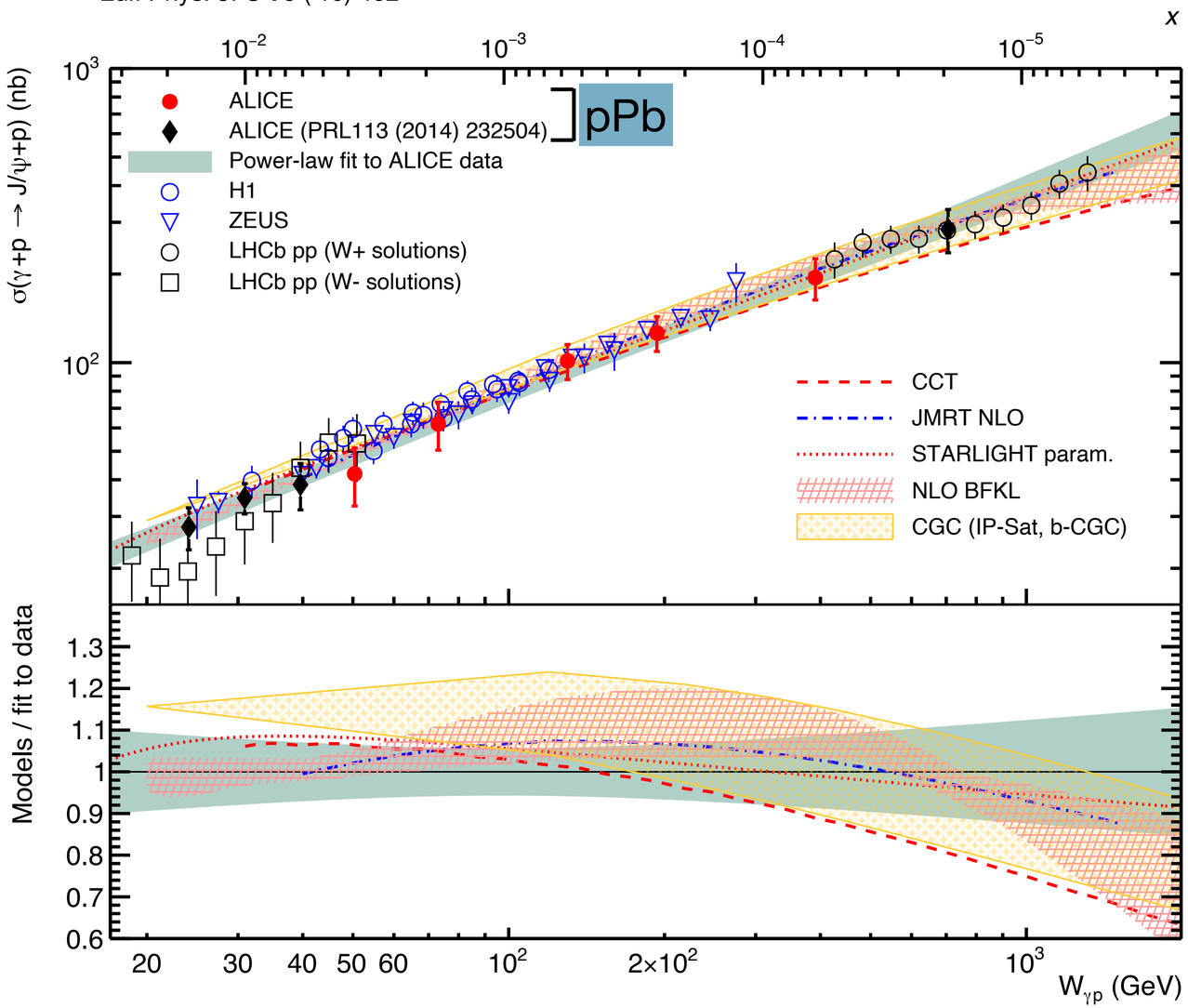


Eur. Phys. J. C **79** ('19) 402



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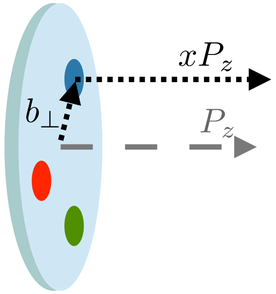

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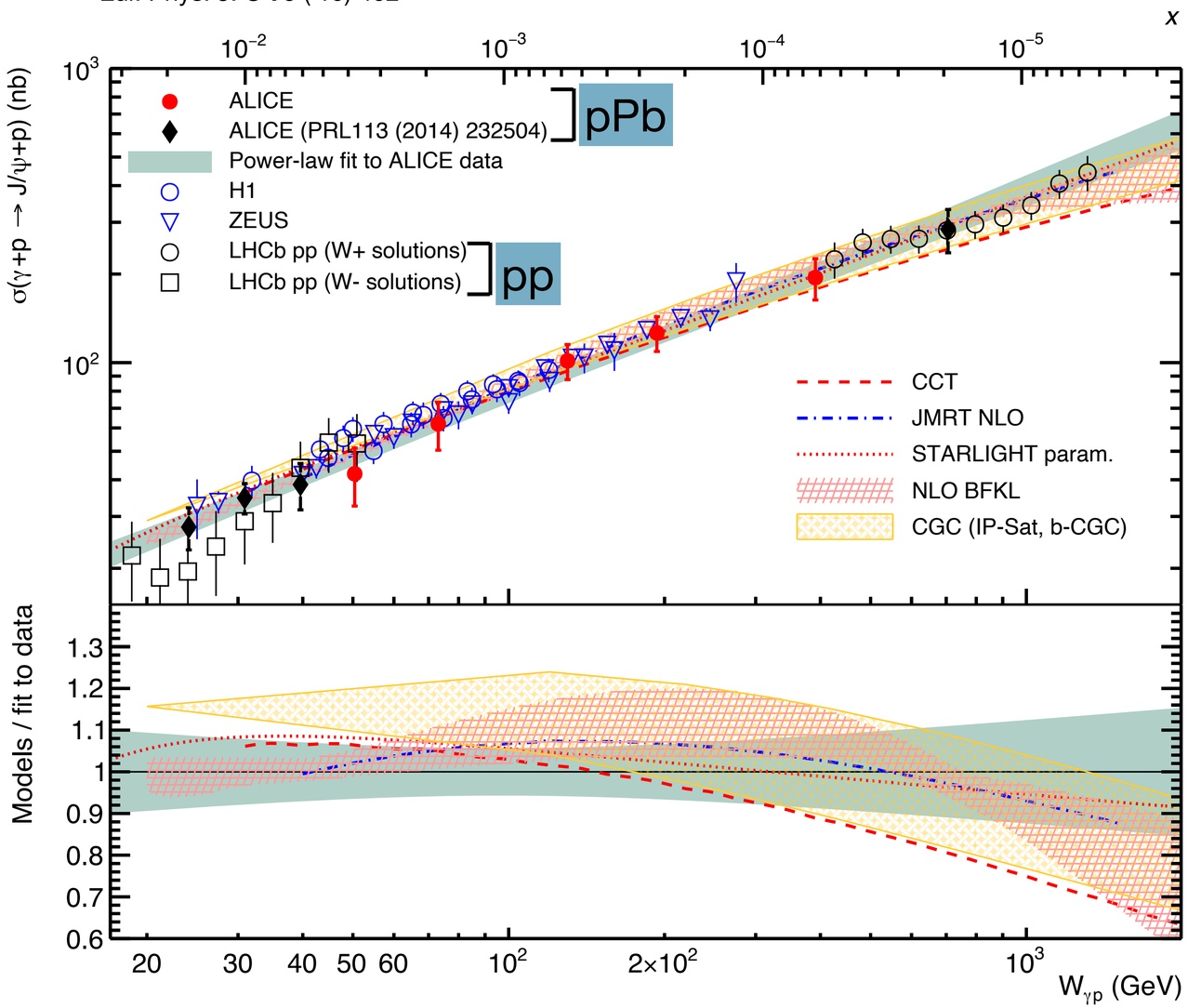

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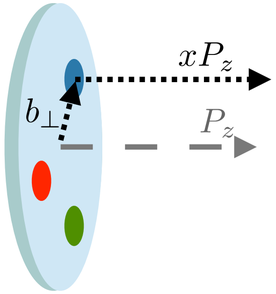

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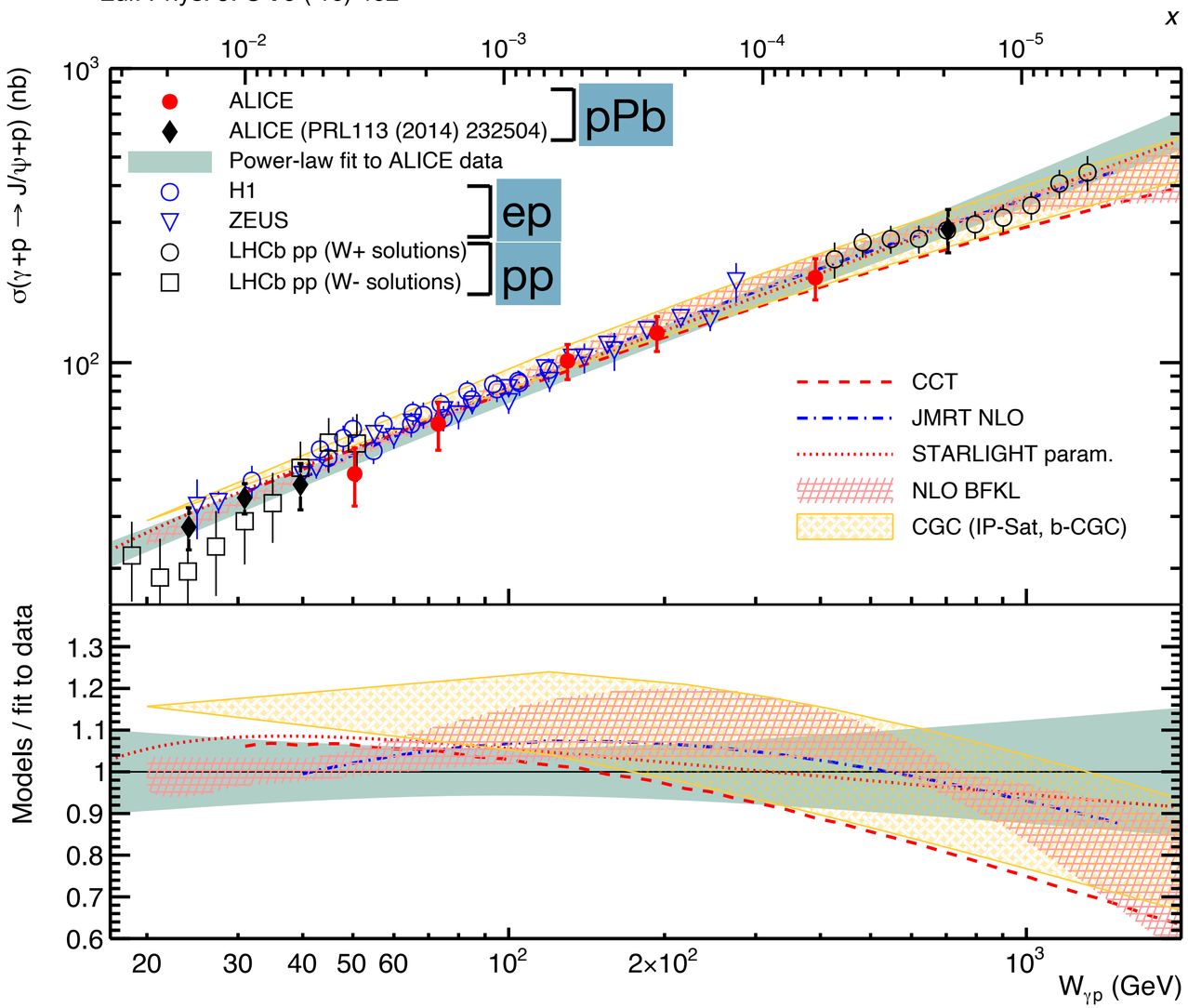
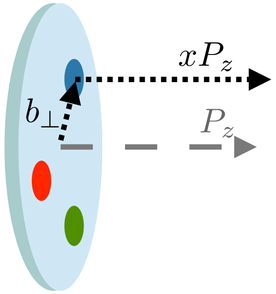
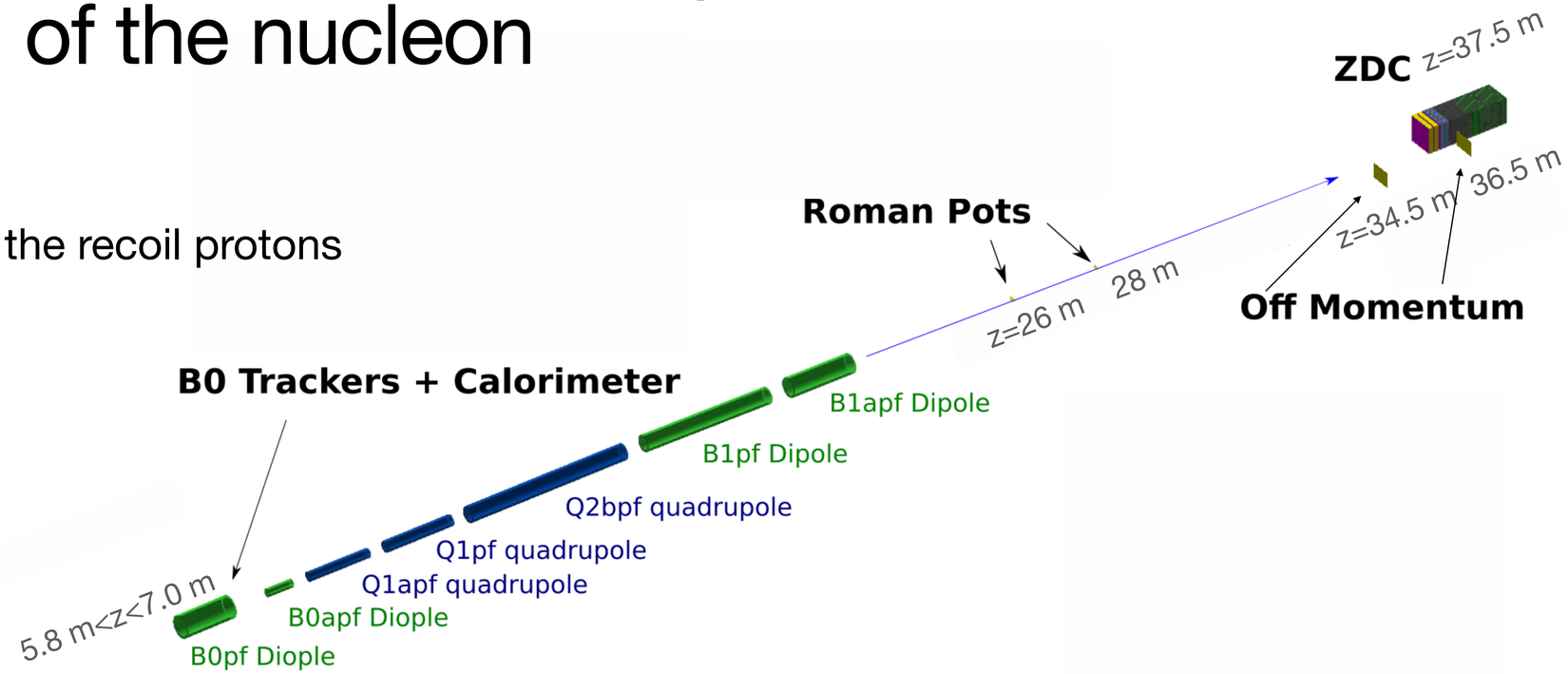
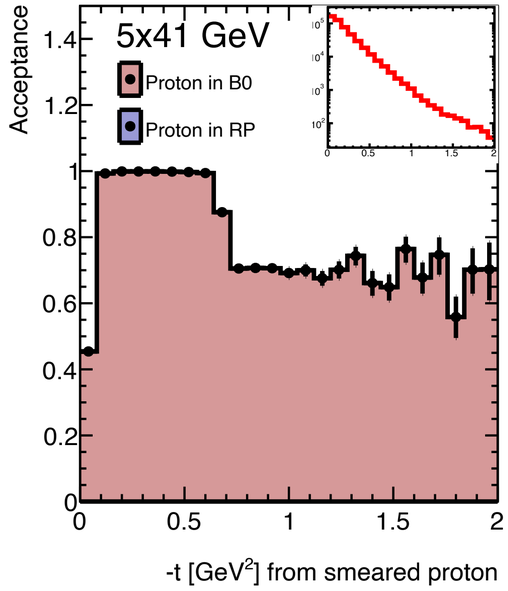


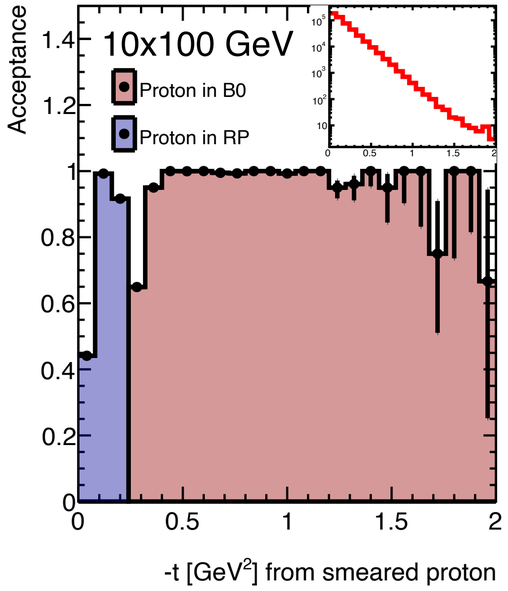
Exclusive measurements on p at EIC: detection of the nucleon

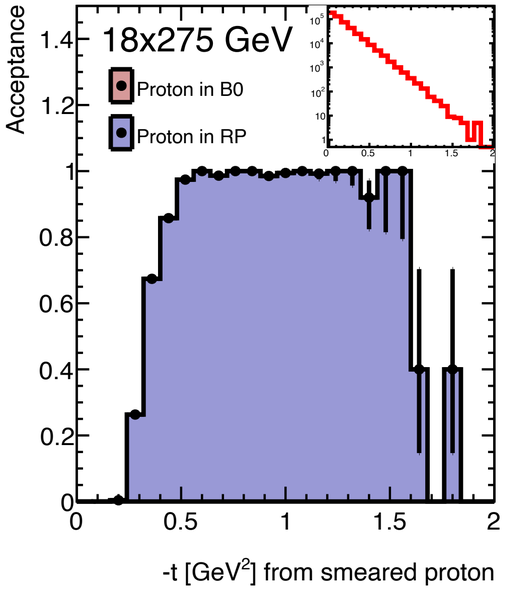


Detection of the recoil protons



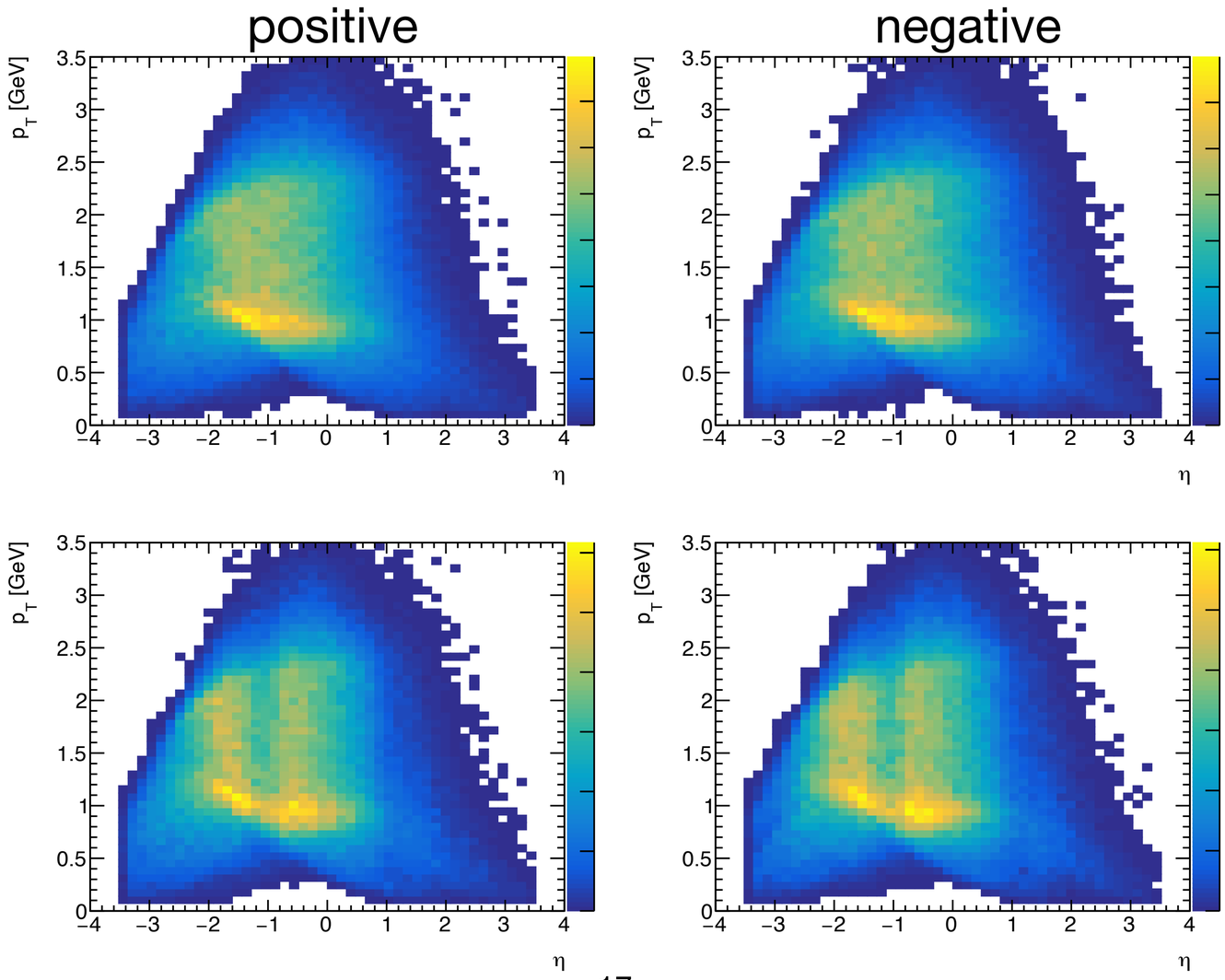






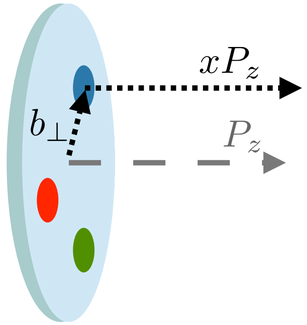
Reconstruction of J/ψ via electrons and muons

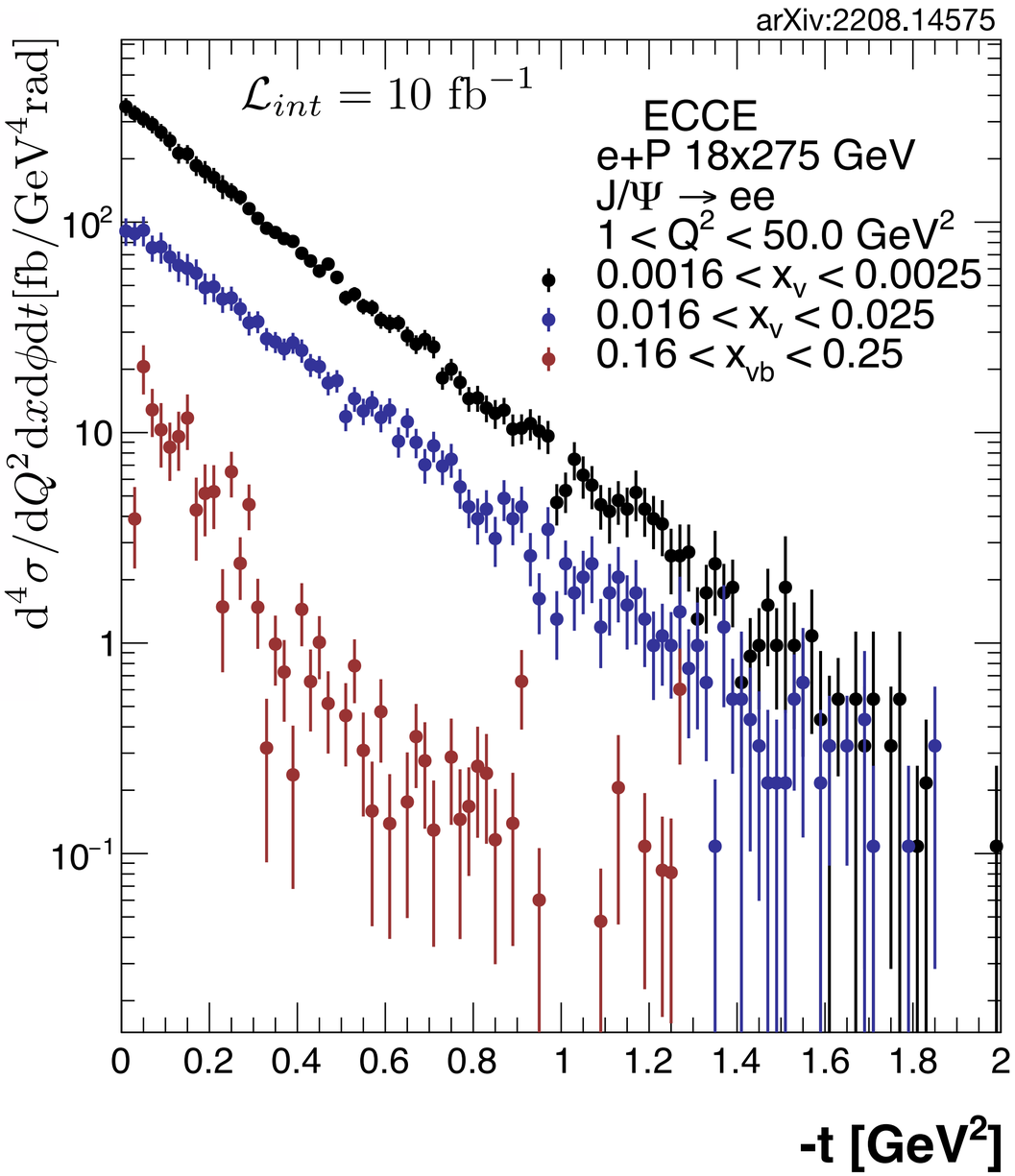
Distribution of electron and muons



(studies done for eA)

EIC: exclusive J/ψ production on p





Diffractive production on nuclei

→ probe gluon saturation (for not too heavy final states)

→ nuclear imaging in position space

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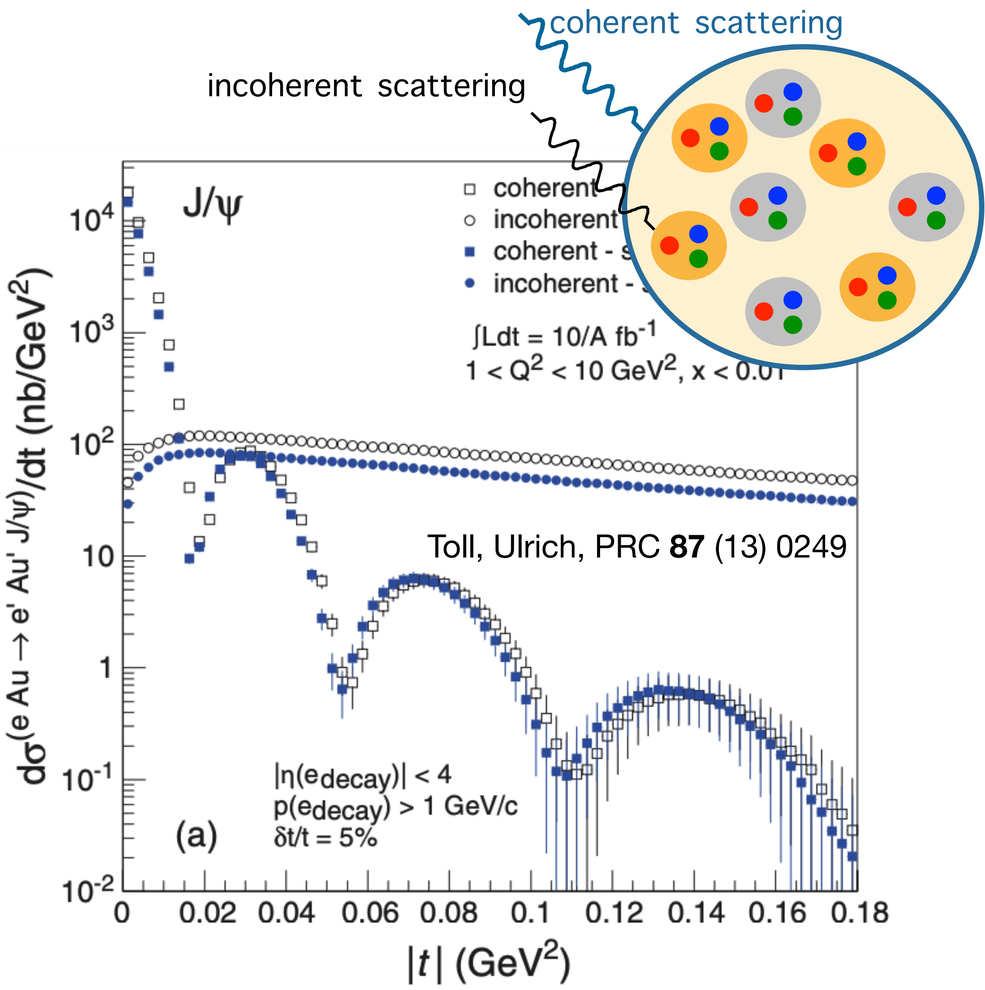
- Good separation of coherent and incoherent production. Not easy!



Diffractive production on nuclei

→ probe gluon saturation (for not too heavy final states)

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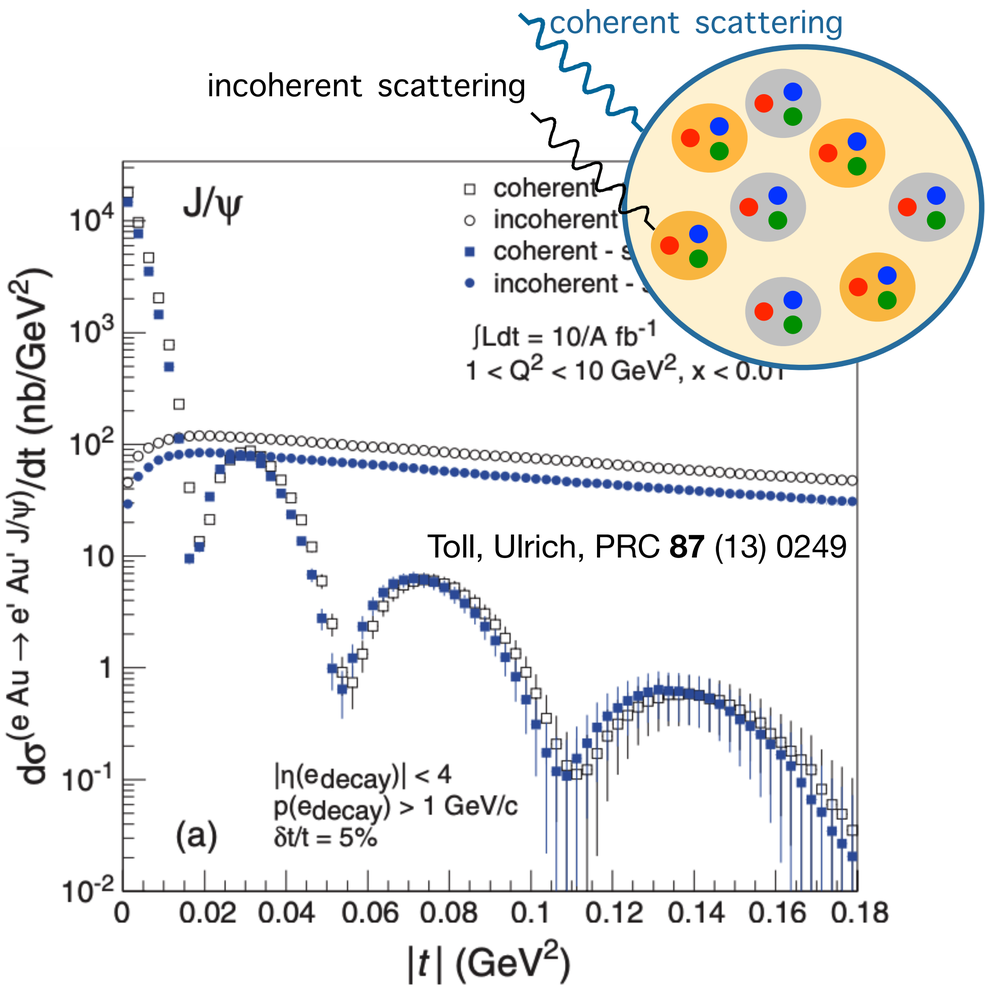
- Coherent production: measurements up to large t:
  - 3D or 2D (x independent) transverse position

$$\int_0^{\infty} d\Delta_\perp \; \mathrm{GPD}(x, 0, \Delta_\perp) \; e^{-ib_\perp \Delta_\perp}$$

Experimentally limited by maximum transverse momentum.
Need to extend p_T range as much as possible in measurement.
~third diffractive minimum.



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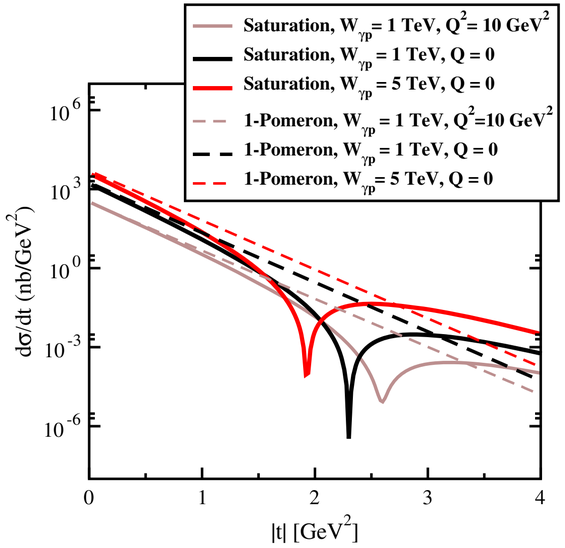
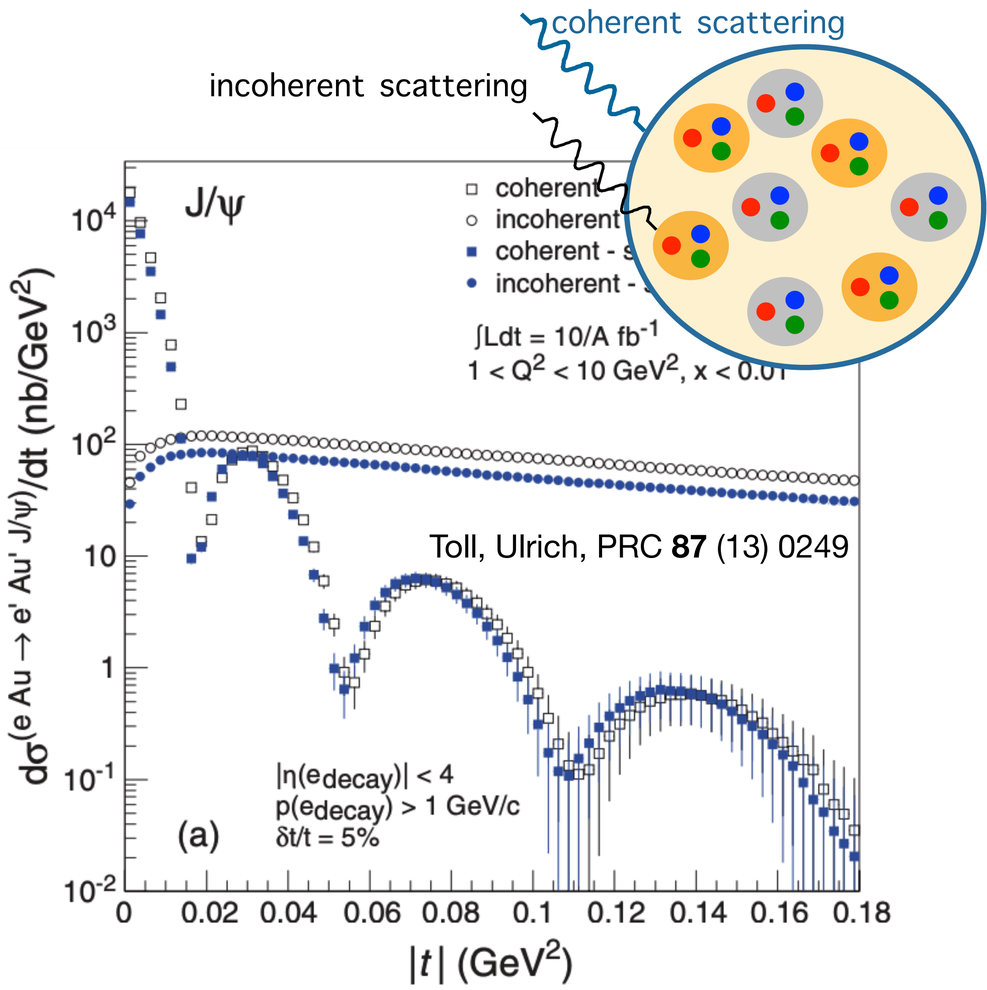
- Saturation:

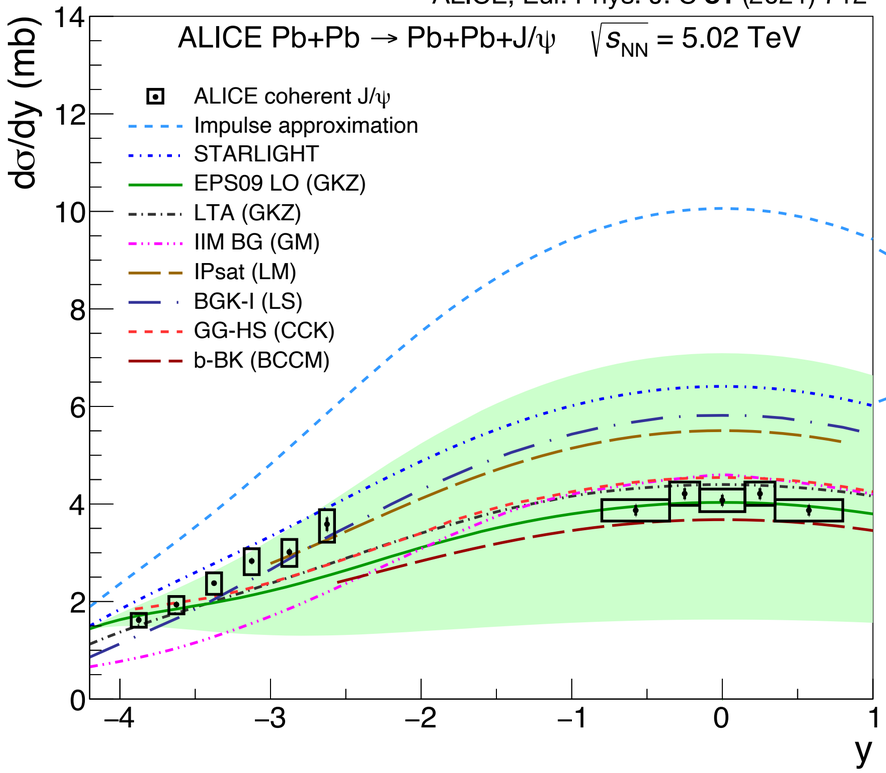
  determine dip position indirectly via slope and probe its dependence with $W_{\gamma p}$





Coherent photoproduction in PbPb at the LHC

ALICE, Eur. Phys. J. C **81** (2021) 712

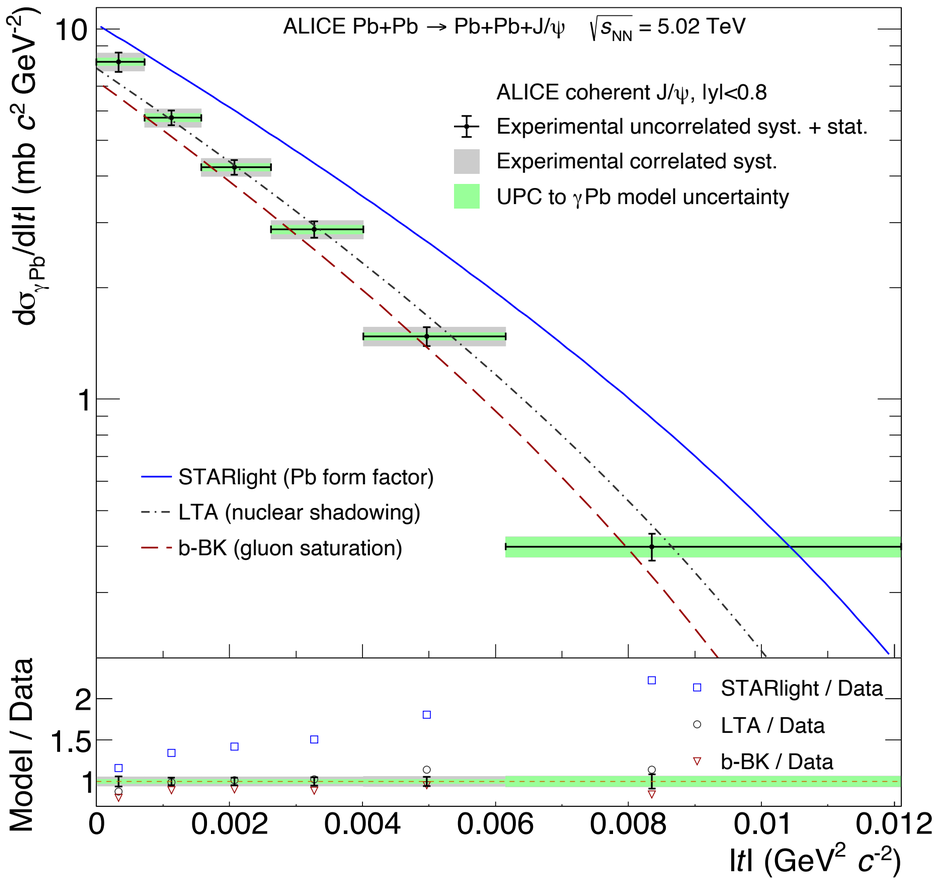


no gluon shadowing

-4.0<y<-2.5

|y|<0.8 ⟷ 0.3 x 10^{-3} < x_B < 1.4 x10^{-3}

ALICE, Phys. Lett. B **817** (2021) 136280



0.7 x 10^{-2} < x_B < 3.3 x10^{-2} (dominant)

1.1 x 10^{-5} < x_B < 5.1 x10^{-5}

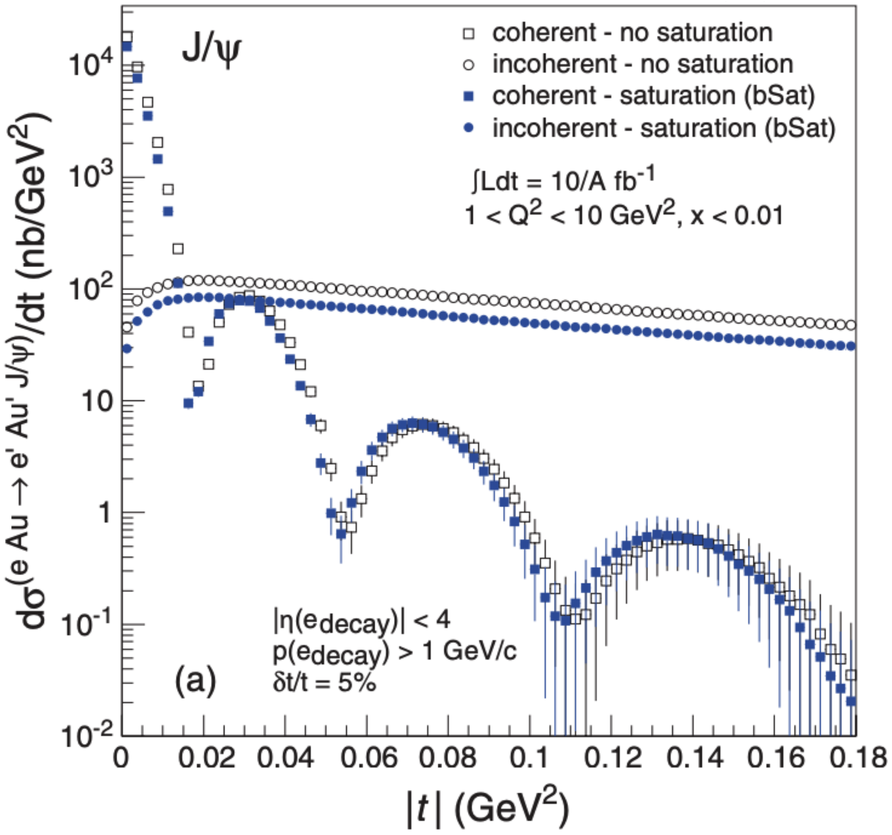
Results indicate shadowing in gluon PDF:

$$R_g = \frac{g^{Pb}}{A\, g^p} \approx 0.65 \text{ at } x \approx 10^{-3}$$

EIC: diffractive eA

→ resolving minima

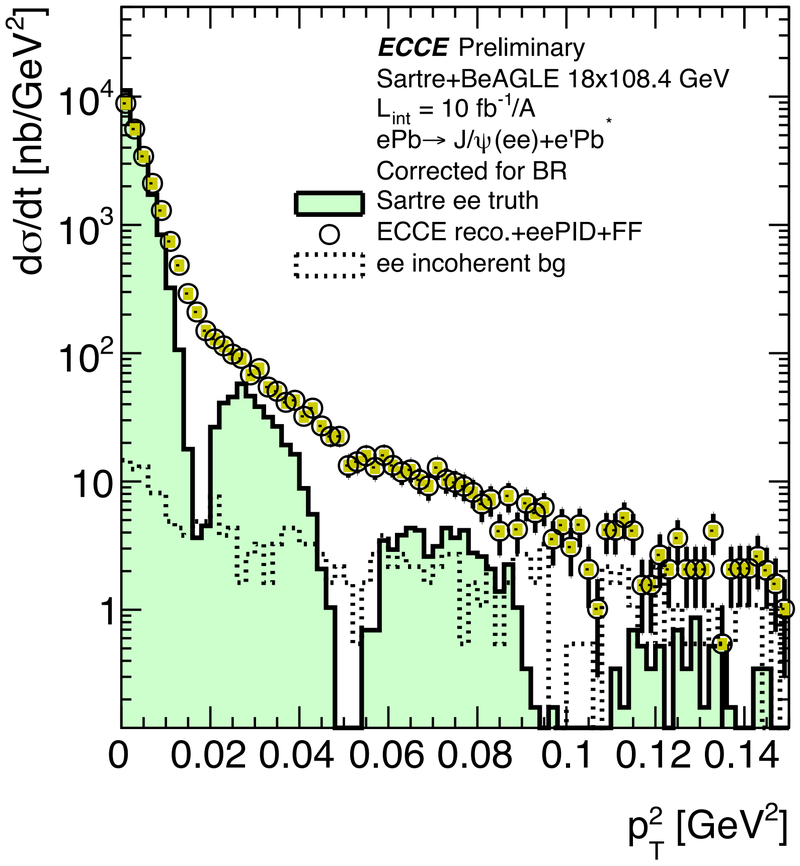
Toll, Ulrich, PRC **87** (13) 0249



- Need 90%, 99%, and > 99.8% veto efficiency for incoherent production, for the respective minima at increasing t.
- veto of events where nuclei break up
  → use entire far-forward detector systems
- Need precise determination of t.
- reconstruction via scattered lepton and exclusively produced vector meson/photon

Diffractive eA: study of exclusive J/ψ production in ePb

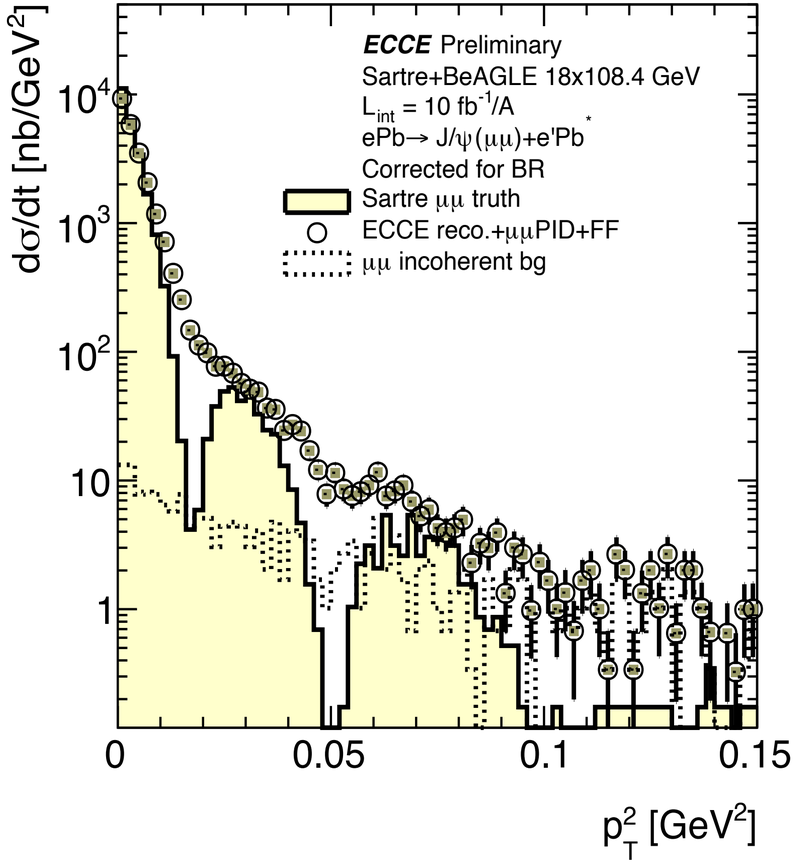
$J/\psi \to e^+e^-$



Extraction of coherent signal from coherent and incoherent production

Distinction of e and μ in present study:
E deposition in EEMC cluster/P_{track}:
>0.6 → e
<0.6 → μ

$J/\psi \to \mu^+\mu^-$



- Simulation: coherent (Sartre)+incoherent (Beagle, normalised to Sartre)
- No background simulation
- No simulation of the beam spread

t via scattered lepton and reconstructed vector meson $p_T^2 \approx (\vec{p}_{J/\psi,T} + \vec{p}_{e',T})^2$

Summary

- Quarkonium production at the EIC offers:
  - complementary information to probe the quarkonium production mechanism
  - excellent tool to probe the gluon content of nucleon,
    with the advantage of a clean probe, compared to the LHC
- Promising studies based on detector simulation for physics of exclusive measurements
- High potential for non-exclusive physics:
  - next step: further studies using full detector simulation

Back up

Diffractive eA: study of exclusive J/ψ production in ePb

On the importance of the EEMC for the scattered lepton