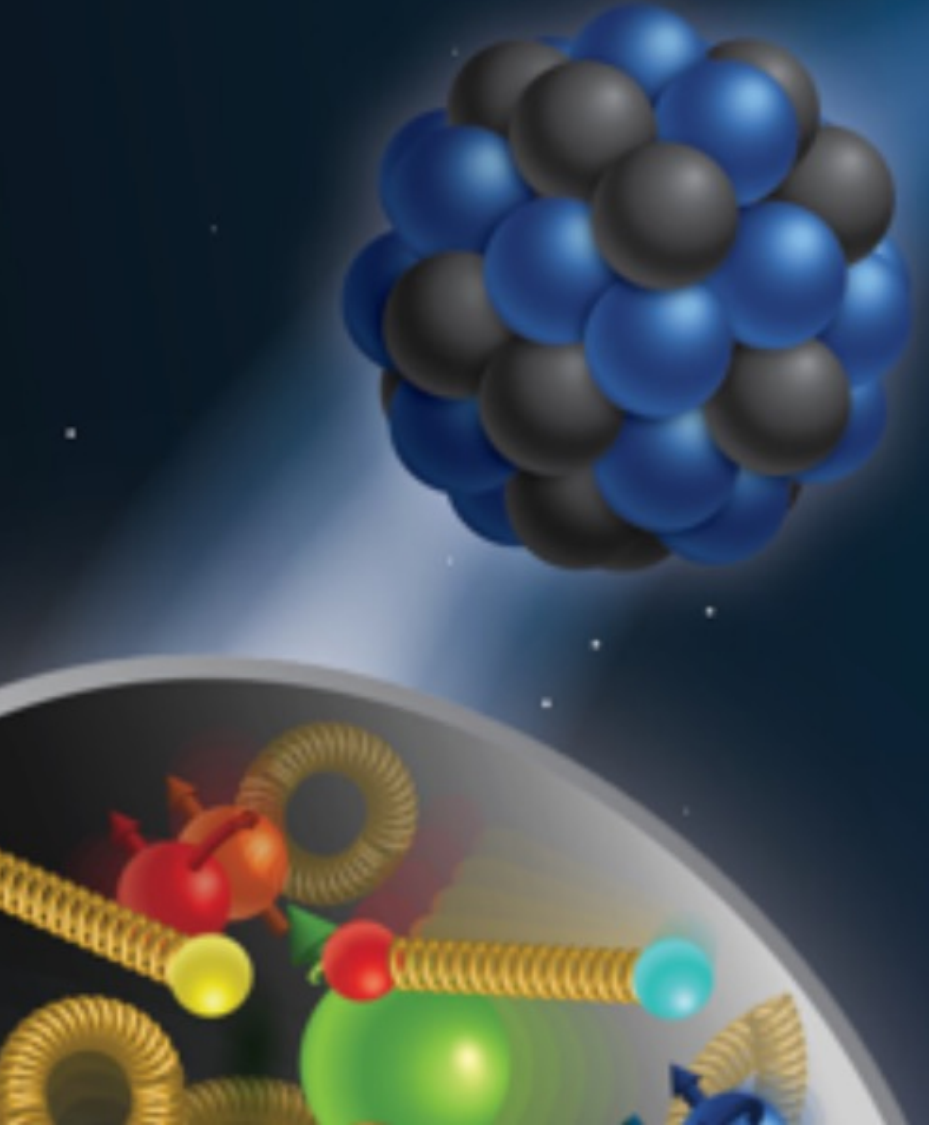


Software, Simulation & Physics studies

Salvatore Fazio

Università della Calabria & INFN Cosenza

EIC_net meeting with the referees

Bologna - August 31st , 2022

UNIVERSITÀ DELLA CALABRIA
Dipartimento di FISICA

INFN Gruppo Collegato di Cosenza
Istituto Nazionale di Fisica Nucleare

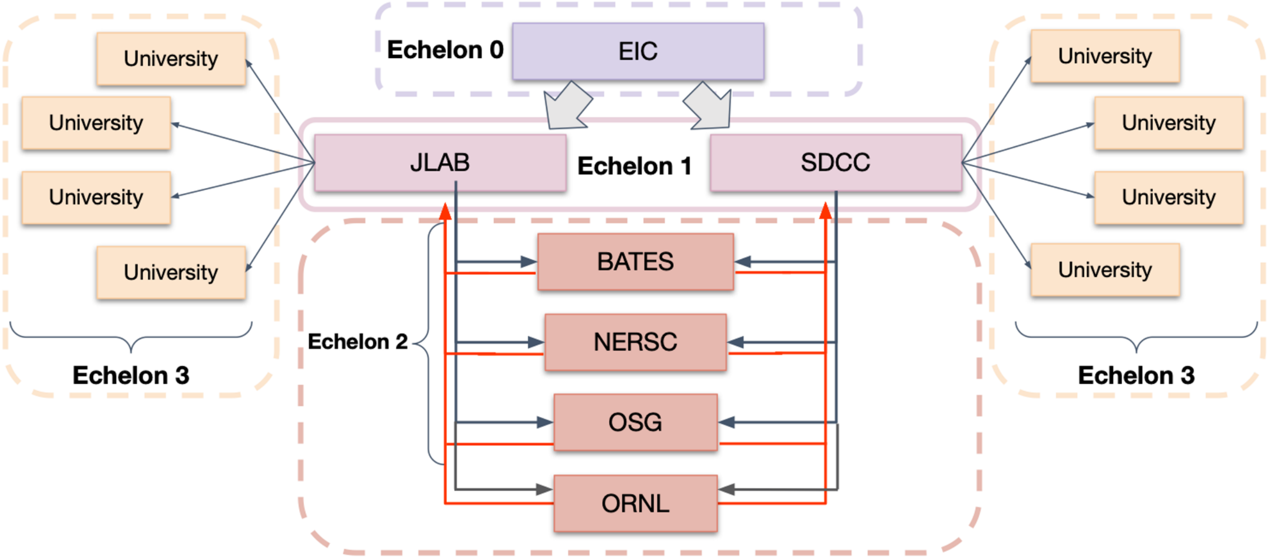
Simulation & Physics efforts in EIC_net

- **EIC_NET - Software and Simulation activities:**
  - Computing & Software infrastructure (EICUG & ePIC experiment)
  - dRICH simulation
  - Tracking perfomance studies
  - MC generators & physics studies
  - Bi-weekly meetings on Monday mornings
- ePIC experiment's common software frameork and tools have been endorsed:
  - Two Working Groups:
    - Computing & Software (A. Bressan WG convener of ATHENA → EPIC)
    - Simulation & Q.A.
  - Code repository: use GitHub as the primary repository, while using the eicweb GitLab instance for CI/CD
  - Geometry Description and Detector Interface: DD4hep (http://aidasoft.web.cern.ch/DD4hep)
  - Data Model: PODIO as the tool for managing the EDM. Adopt the EDM4hep Data model as the initial Data Model
  - Reconstruction Framework: JANA2 (https://jeffersonlab.github.io/JANA2/)
  - **Aim to have fully transitioned to the official software by October**

Slides by Andrea Bressan

COMPUTING Model (still under discussion)

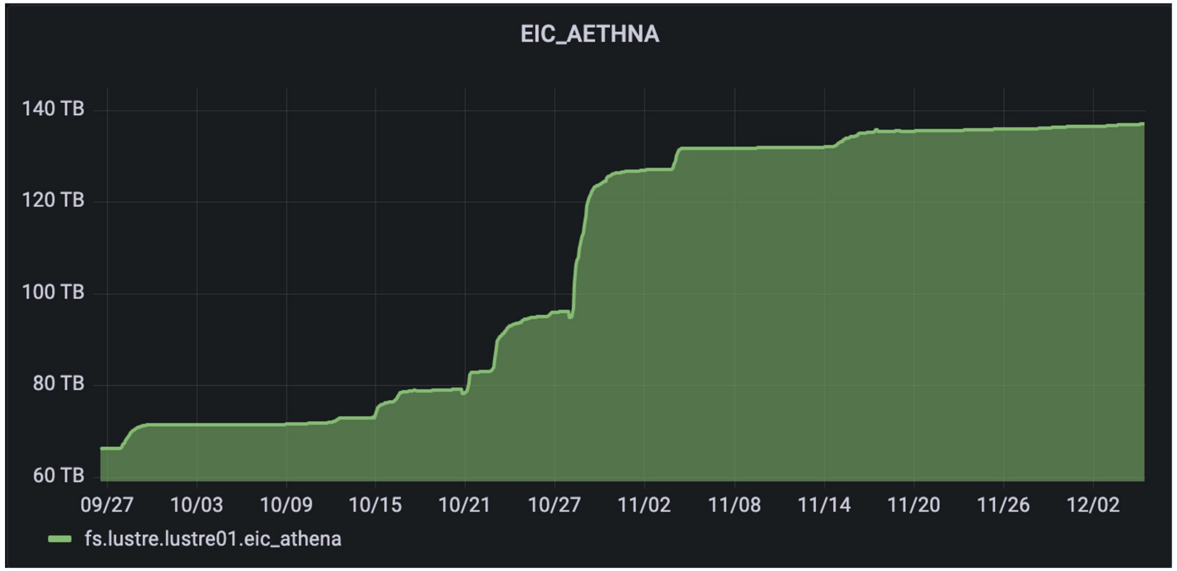
- **Federated computing architecture deployed by both proto-collaborations**
  - Very successful and desired moving forward
- **WLCG style architecture envisioned, utilizing e.g.**
  - Tier 1 sites - BNL and JLab
  - Tier 2 sites - Additional large compute sites, e.g. OSG, NERSC, others…
  - Tier 3 sites - Local universities/small compute sites
- **INFN presently trough OSG resources via CNAF, with limited resources requested.**
  - More will be discussed during/after elaborating the final model

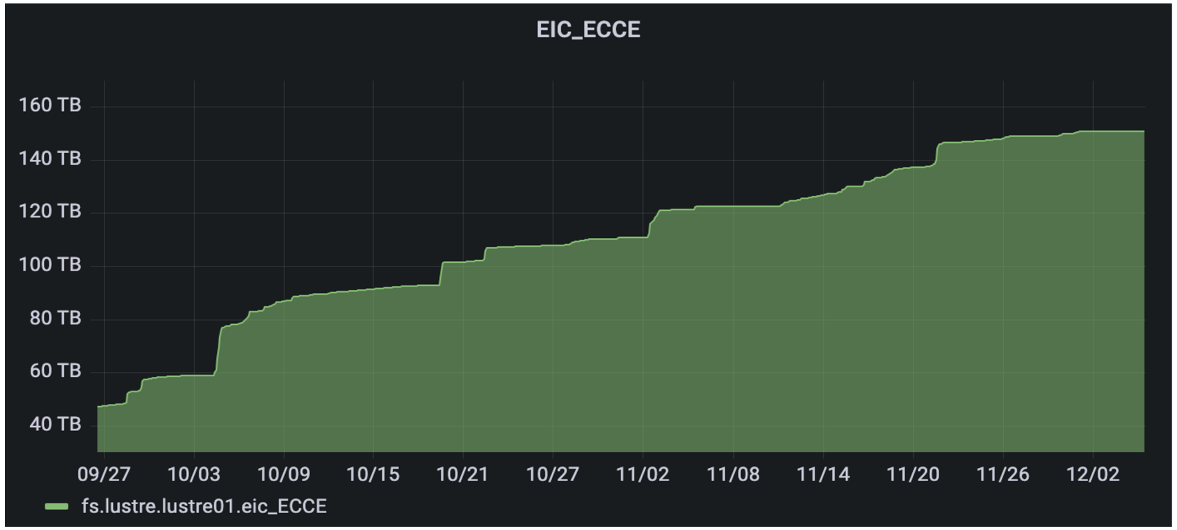


Slides by Andrea Bressan

During the detector proposals period

- ATHENA and ECCE proto-collaborations produced ~300 TB of simulation data, utilizing O(10M) CPU hours for O(100M) of physics events for analysis
- Carry-over liaisons from Physics/Detector Working Groups to communicate and request productions
  - Benefited from greater communication to physics working groups and wide variety of Monte Carlo Event Generators utilized for EIC science mission



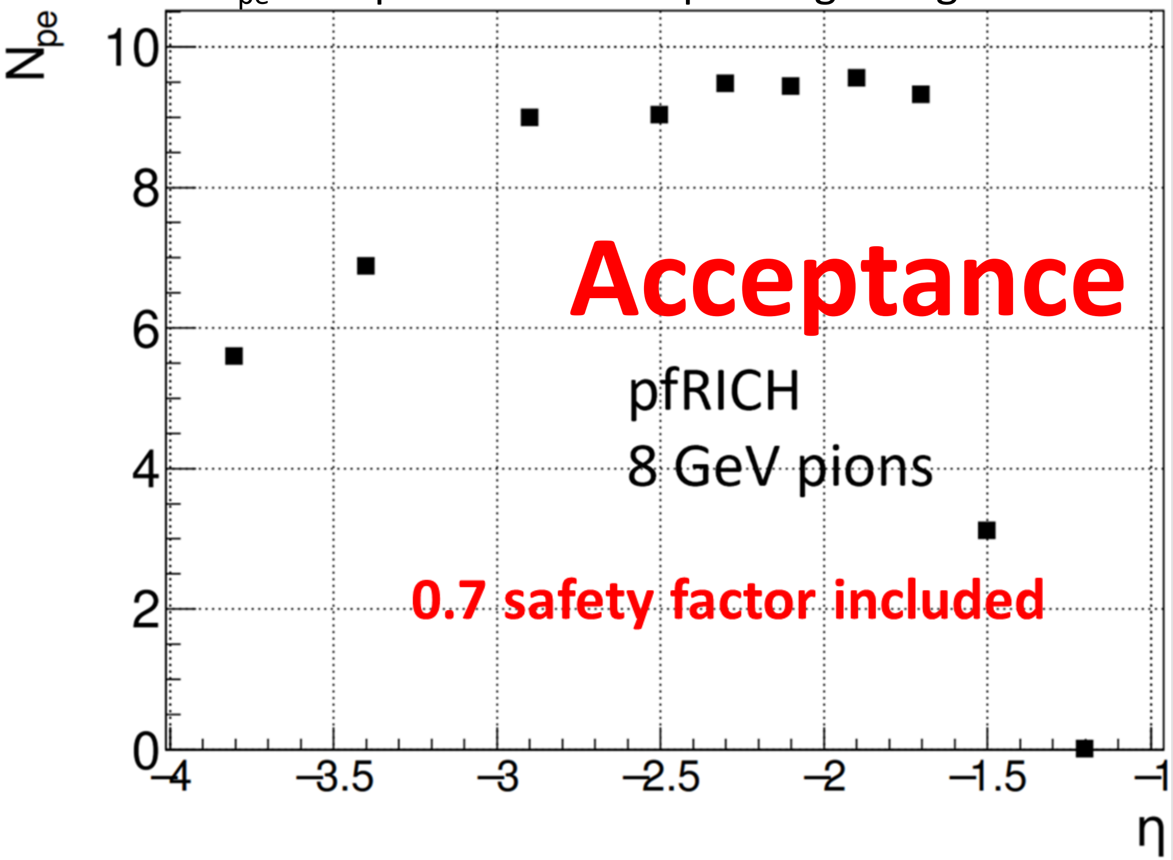


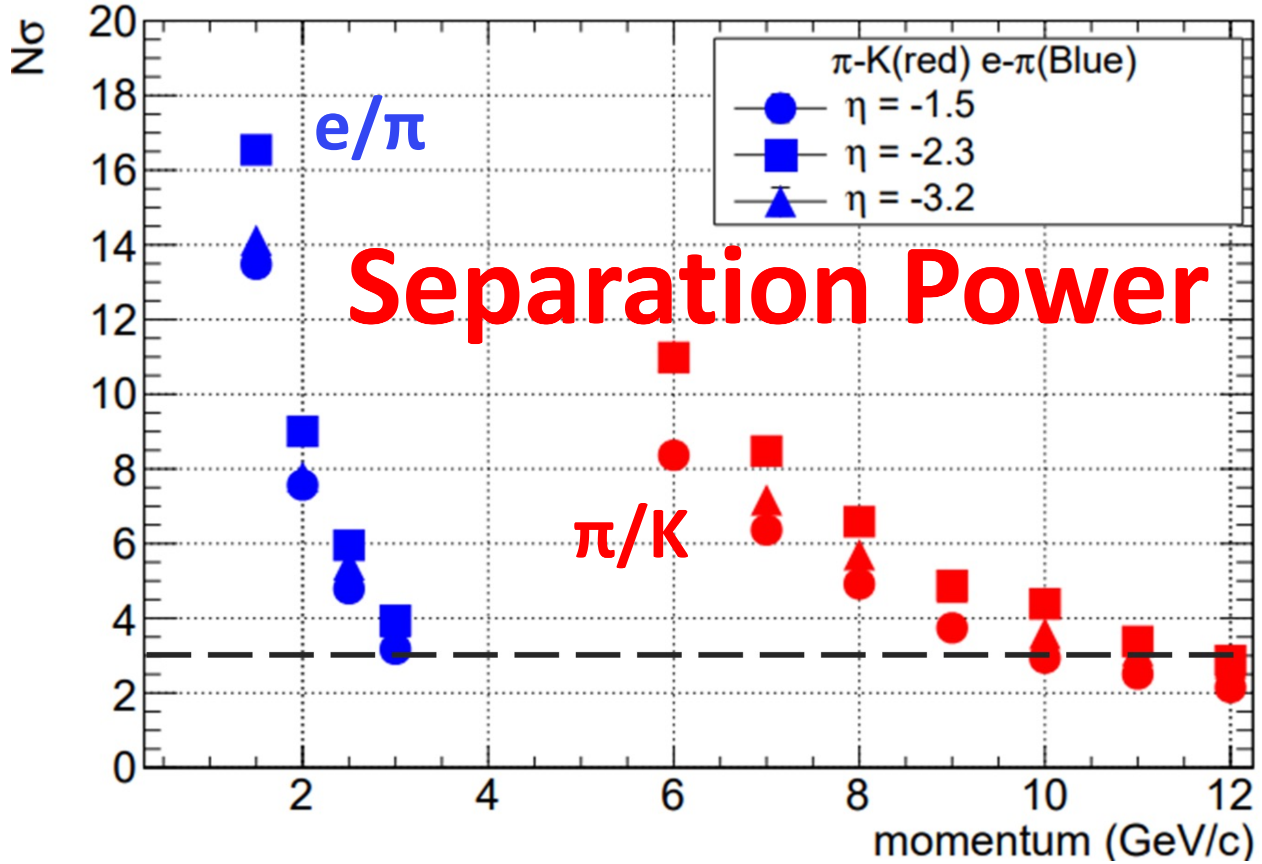
RICH simulation
Performance study for ATHENA Proposal

pfRICH – acceptance & separation-power

Backward direction

N_{pe} → # photoelectrons per single ring





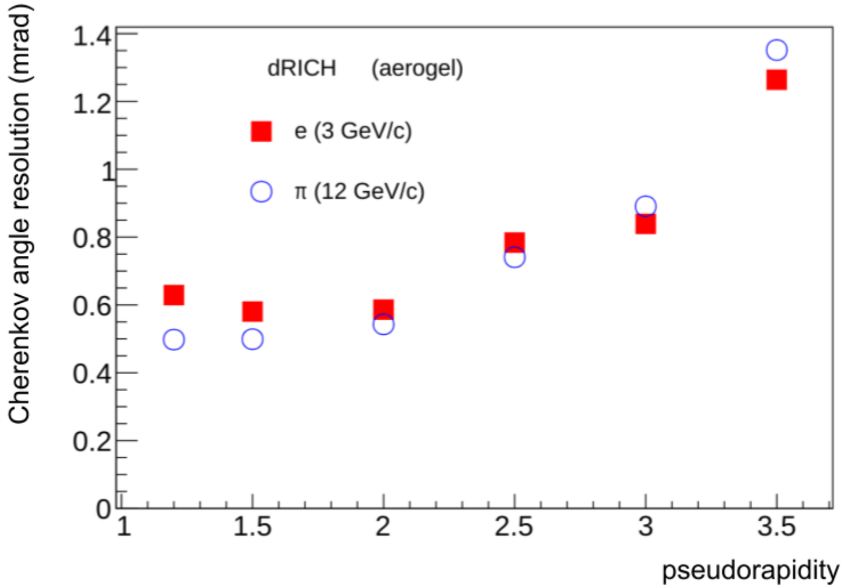
YR requirement achievable

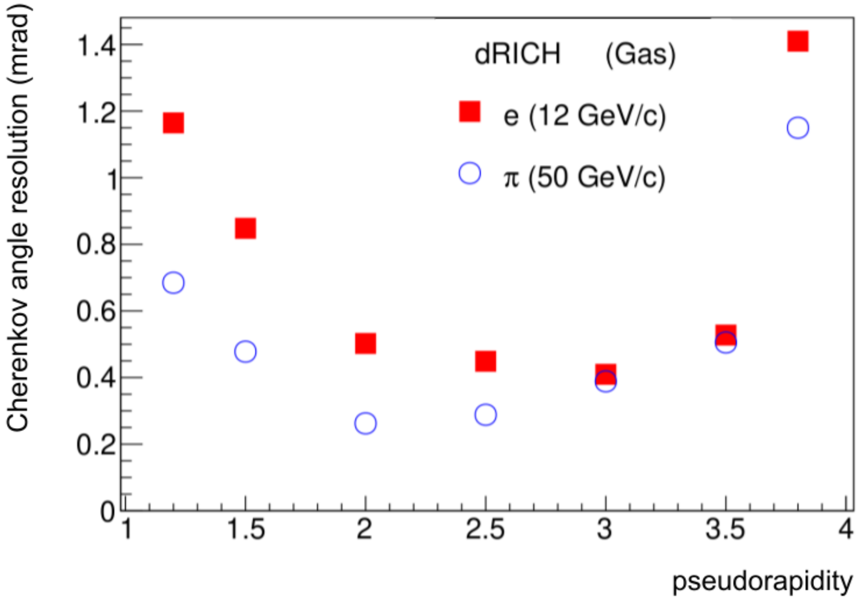
Yellow Report requirement:
hadron PID in the electron-going endcap better than 3σ π/K separation up to 10 GeV/c

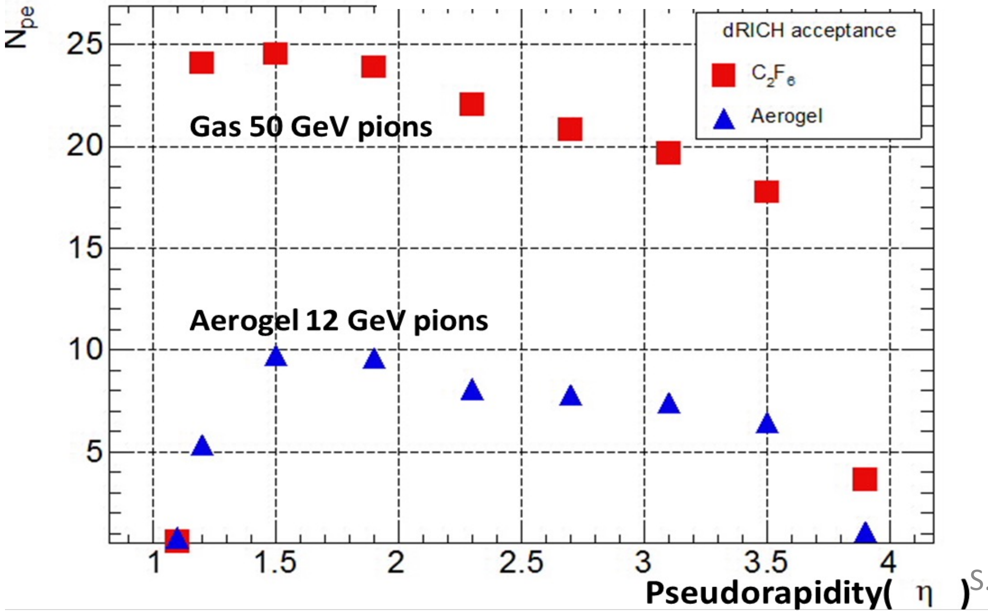
dRICH – Resolution & acceptance

Slides by Chandra Chatterjee

Forward direction







- **YR requirement: acceptance for the dRICH is 1.0 ≤ η ≤ 3.5**

These reference numbers were taken as a guidance for the ATHENA design

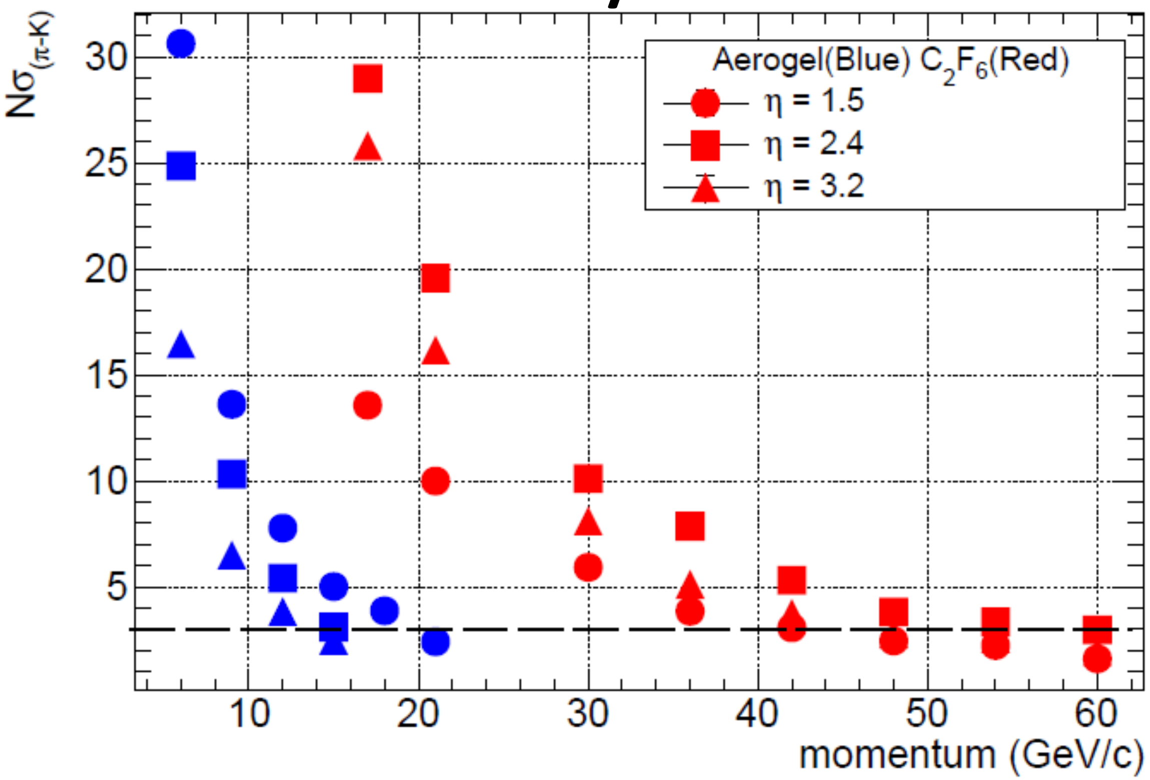
Slides by Chandra Chatterjee

dRICH - Nσ Separation

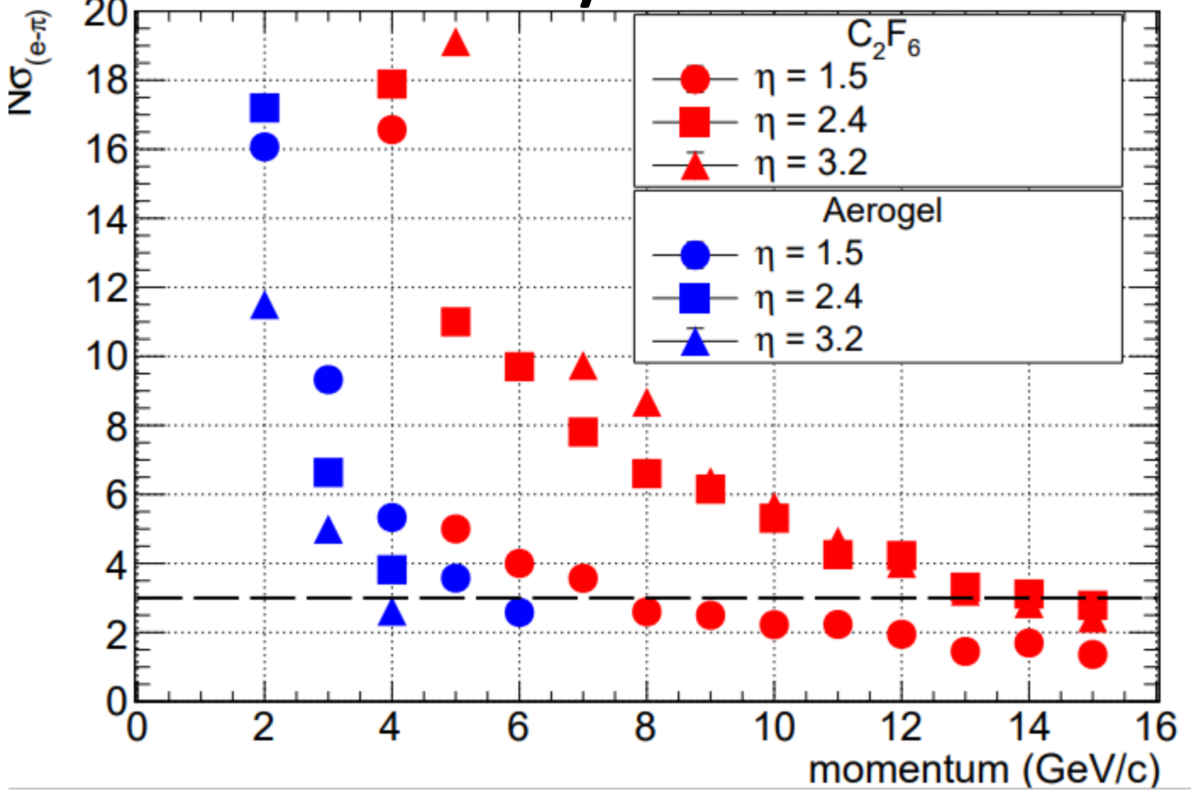
Forward direction

YR requirement: e-K-p separation up to 50 GeV/c

π/K



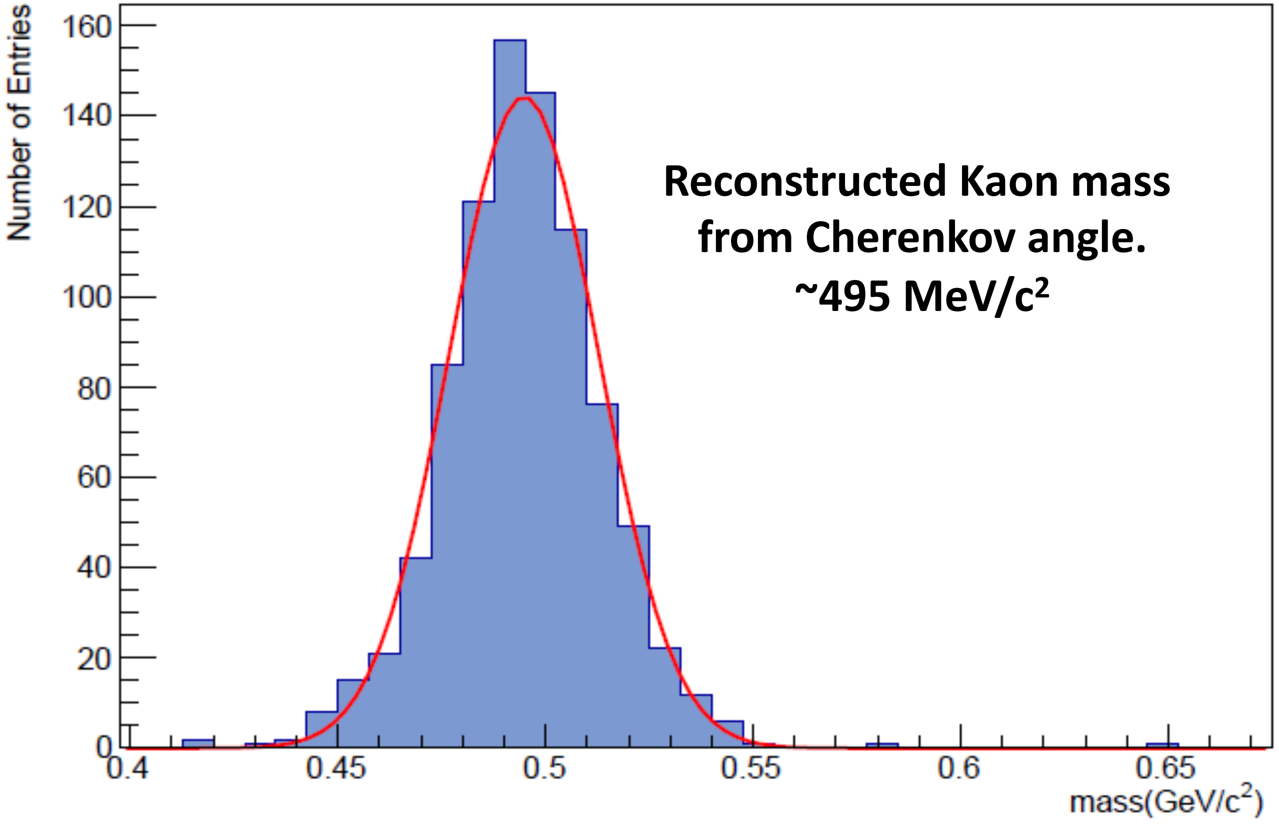
e/π



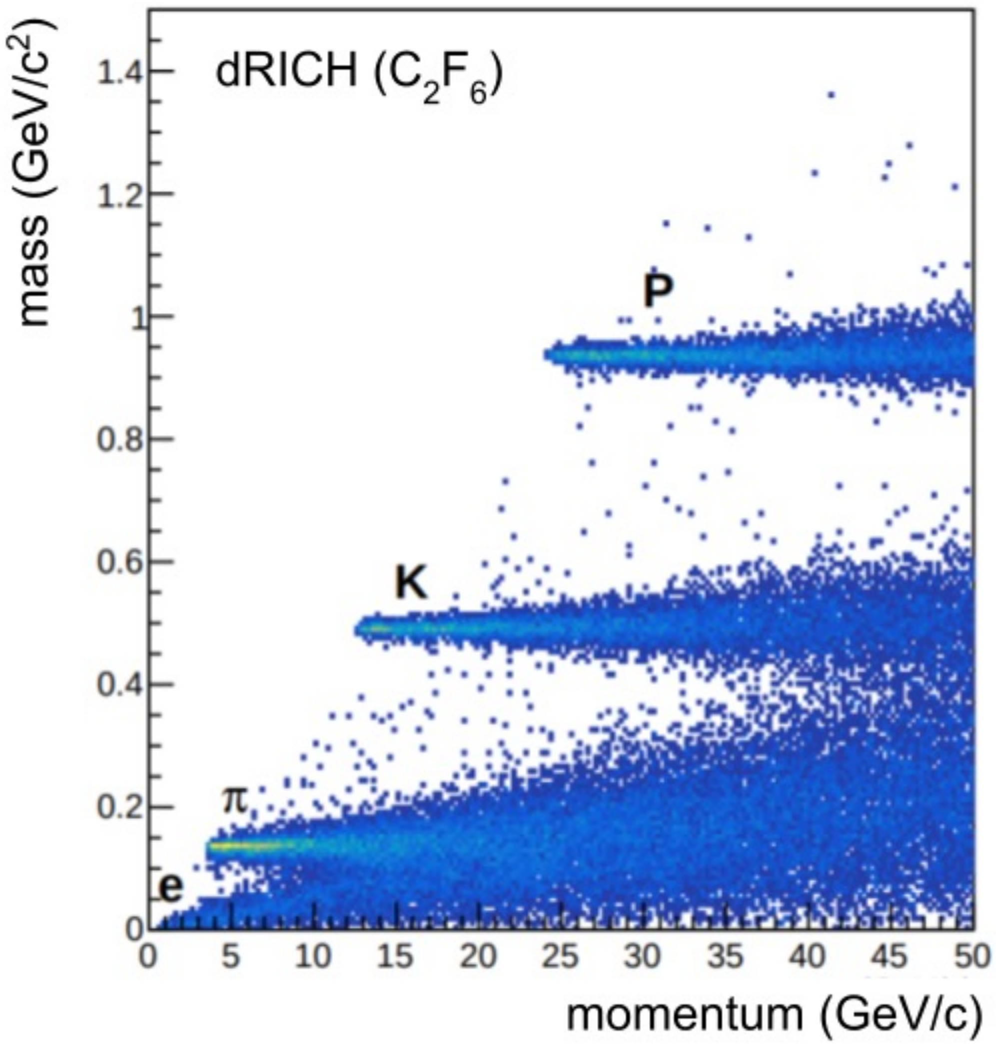
YR prescription achievable.

dRICH – reconstructed mass

Slides by Chandra Chatterjee



Particle Mass as a function of momentum retrieved from reconstructed Cherenkov angle



Migration
ATHENA → EPIC

Slides by Chandra Chatterjee

dRICH geometry – EPIC vs ATHENA

- ECCE's dRICH radiator length was shorter compared to the ATHENA radiator length
- Number of photons are of concern
  → We have increased the rad. Length by 20 cm (compared to ECCE) however the rad Length is not yet final
- Different geometries will be studied soon in terms of dRICH performance → Requires functioning full simulation chain

All Units are in cm!

ATHENA

DRICH_Length	=	140.000
DRICH_SnoutLength	=	4.000
DRICH_SnoutSlope	=	0.667
DRICH_aerogel_thickness	=	4.000
DRICH_create_irt_file	=	0.000
DRICH_debug_mirror	=	0.000
DRICH_debug_optics	=	0.000
DRICH_debug_sensors	=	0.000
DRICH_num_px	=	8.000
DRICH_rmax0	=	126.667
DRICH_rmax1	=	129.333
DRICH_rmax2	=	220.000
DRICH_rmin0	=	8.273
DRICH_rmin1	=	16.062
DRICH_sensor_pixel_pitch	=	0.320
DRICH_sensor_pixel_size	=	0.300
DRICH_sensor_size	=	2.580
DRICH_sensor_thickness	=	0.050
DRICH_wall_thickness	=	0.500
DRICH_window_thickness	=	0.100
DRICH_zmin	=	190.000

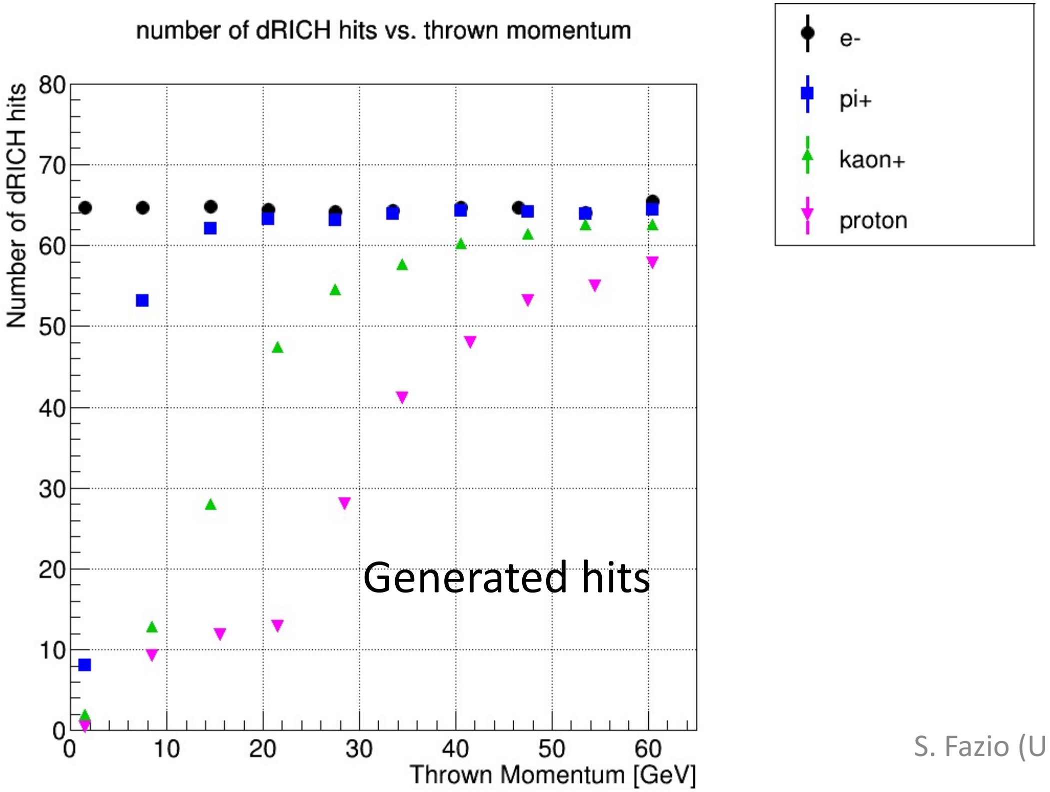
EPIC
(current version after increasing the radiator length of ECCE)

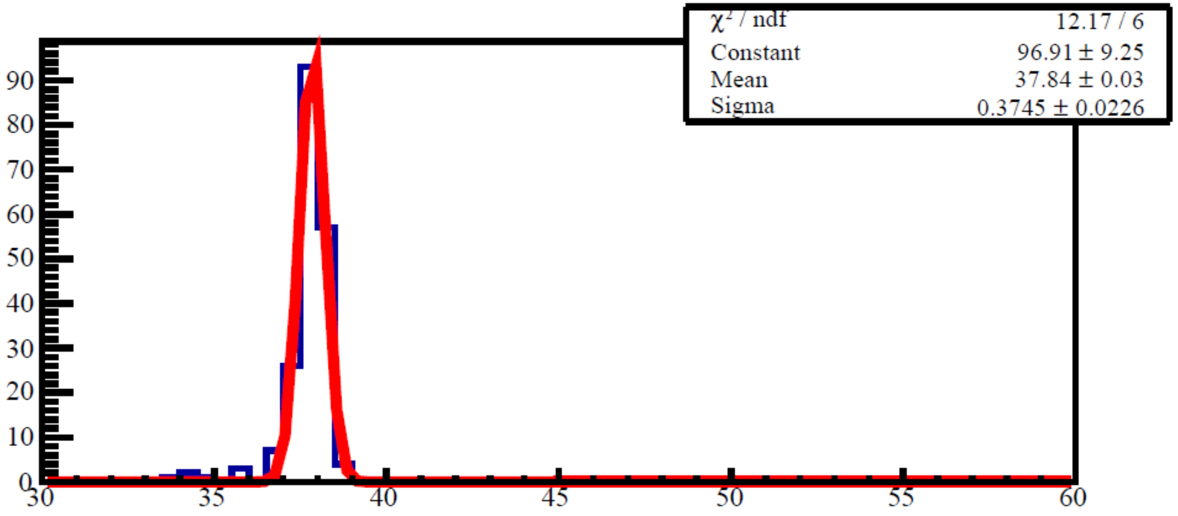
DRICH_Length	=	120.000
DRICH_SnoutLength	=	20.000
DRICH_SnoutSlope	=	0.487
DRICH_aerogel_thickness	=	4.000
DRICH_create_irt_file	=	0.000
DRICH_debug_mirror	=	0.000
DRICH_debug_optics	=	0.000
DRICH_debug_sensors	=	0.000
DRICH_num_px	=	8.000
DRICH_rmax0	=	95.000
DRICH_rmax1	=	104.744
DRICH_rmax2	=	180.000
DRICH_rmin0	=	8.490
DRICH_rmin1	=	15.332
DRICH_sensor_pixel_pitch	=	0.320
DRICH_sensor_pixel_size	=	0.300
DRICH_sensor_size	=	2.580
DRICH_sensor_thickness	=	0.050
DRICH_wall_thickness	=	0.500
DRICH_window_thickness	=	0.100
DRICH_zmax	=	315.000
DRICH_zmin	=	195.000

Slides by Chandra Chatterjee

dRICH – Status of full simulation

- Several changes upstream (data-model), therefore extensive modifications in the reconstruction are required to make the full chain running!
- New reconstruction framework supposed to be adopted (Juggler → Jana2). The algorithm must be ported in the new framework.
- Currently, we are able to run full simulation in the Juggler framework.





Reconstructed Cherenkov angle (mrad)
for50 GeV/c kaons

Slides by Chandra Chatterjee

dRICH simulation – ongoing work

- Validate the full software chain and fix residual bugs after the modifications made to accommodate upstream changes!
    - The validation work is ongoing. It aims to regenerate ATHENA proposal-like plots and checking the consistencies
    - Then we aim to characterize the EPIC's dRICH
- Accommodate robust PID algorithm and insert reasonable noise hits in order to study PID performance.
- A more realistic definition of photon-sensors in the simulation chain
    - the possibility to include G4SiPM package in the dd4hep is under discussion
- In order to study the possibility of thicker vessel window the effect of multiple scattering of the tracks has been initiated
    - Analytical estimates have been made
    - Detailed simulated studies will be done

Tracking performance studies

Tracking performance studies

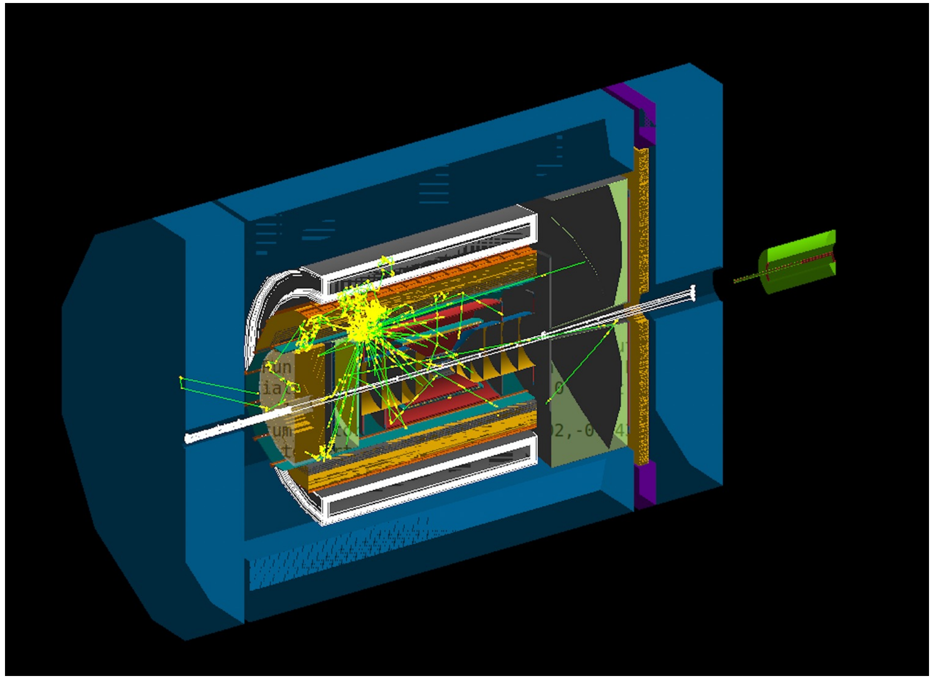
- Studies on the EPIC geometry
  - Target: vertex detector performance optimization
    - Momentum resolution as a function of p, p_T and η
    - Pointing resolution as a function of p, p_T and η
  - Development of a Fast Simulation Tool
    - Fast code that computes analytically the previous tracker performance observables:
    - Validation (3 step procedure)
      - Official software installed (fun4all, dd4hep) and full simulation performed (gun: 1 pion) to extract momentum and pointing resolution, and material budget vs η
      - FST code modified according to the geometry and the magnetic field.
      - Comparison on the results and further tuning
  - The FST tool allows for traking performance studies including also TPC
  - Performances compared with the Physics Working Group (PWG) requirement

Slides by Annalisa Mastroserio

Plots by Shyam Kumar

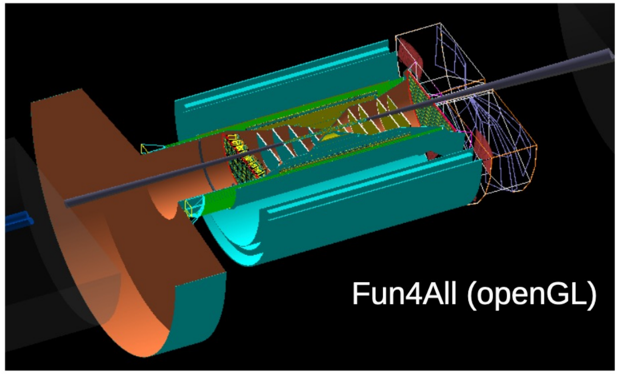
Geometry

ATHENA (DD4Hep)

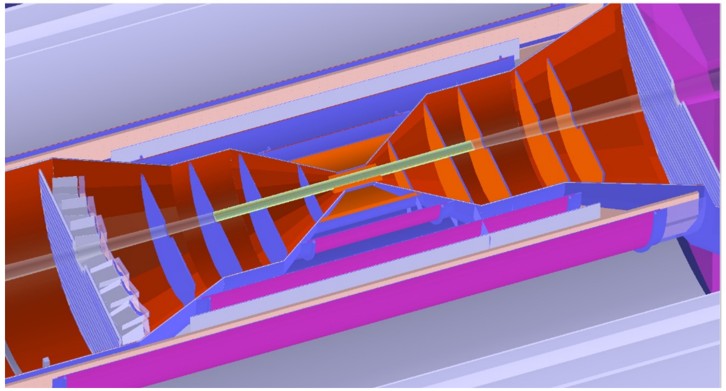


ECCE (Fun4All)

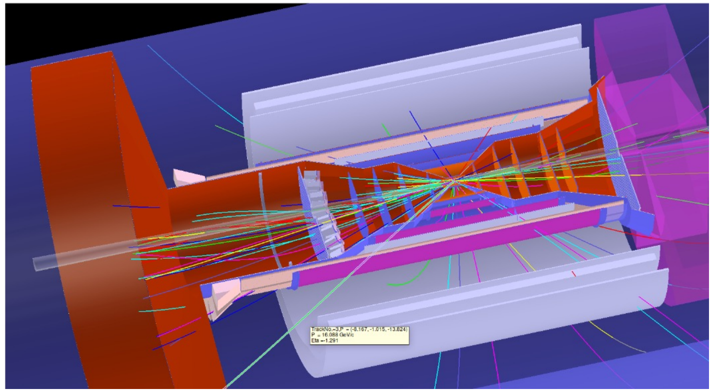
Geometry used for the simulation in Fun4All



EveManager



EveManager with tracks



Fast simulation tool results

Slides by Annalisa Mastroserio

Plots by Shyam Kumar

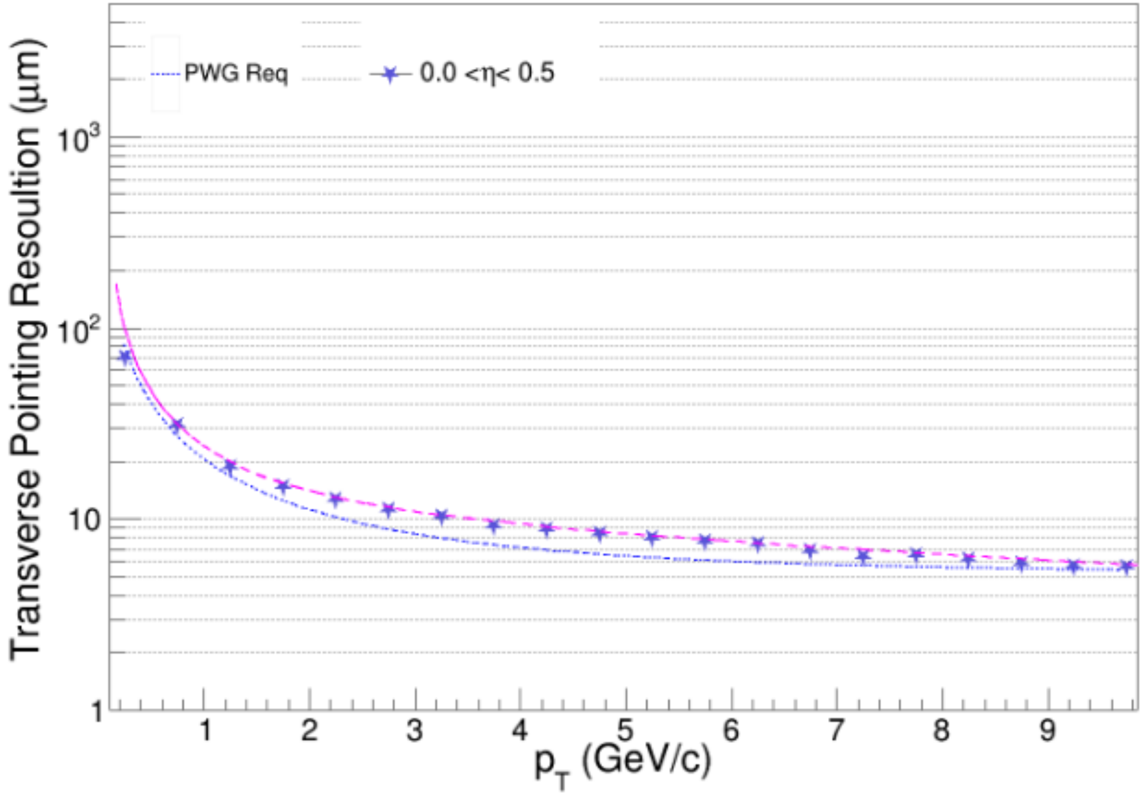
Internal parameters tuned to the ECCE's vertex detectors and B field

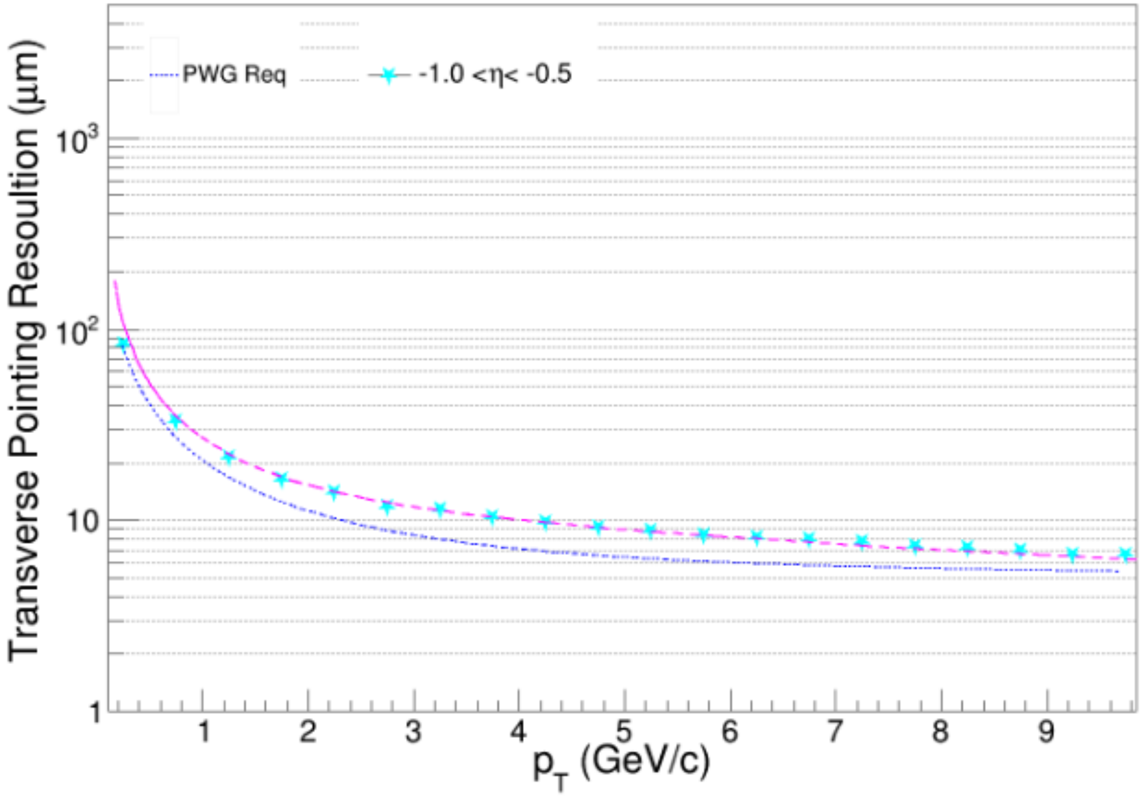
Blue points: Full simulation

Magenta line: Fast Simulation Tool

Blue line: PWG requirement

FS tool well under control





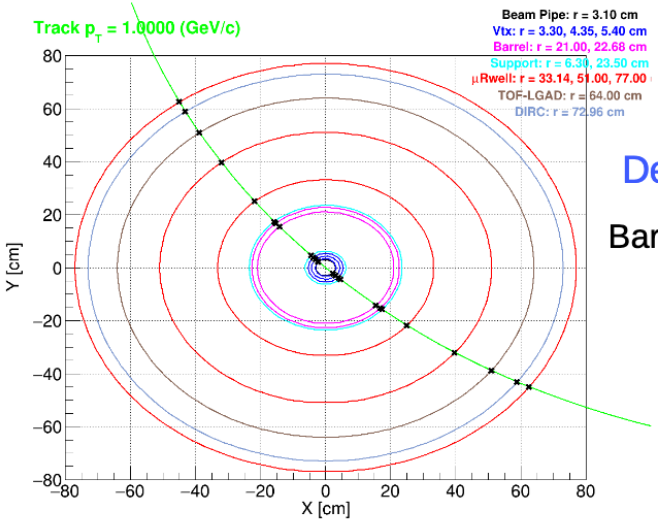
Fast simulation tool (Optimization studies)

Slides by Annalisa Mastroserio

Plots by Shyam Kumar

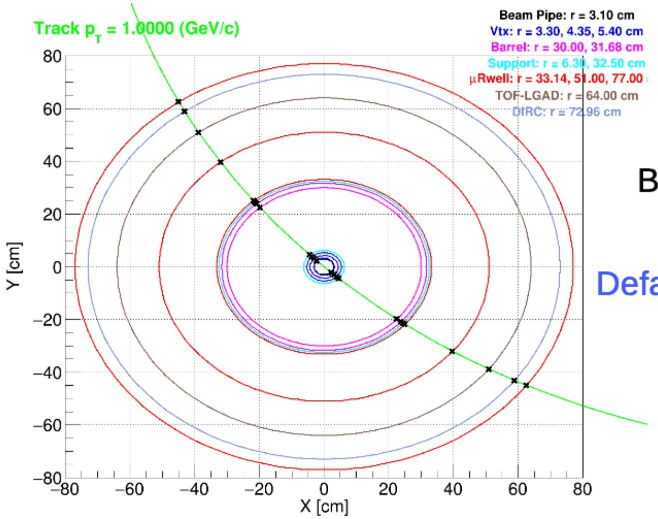
Several results on

- **Moving internal layers**
- **Changing their material budget**
- **Changing detector resolution**



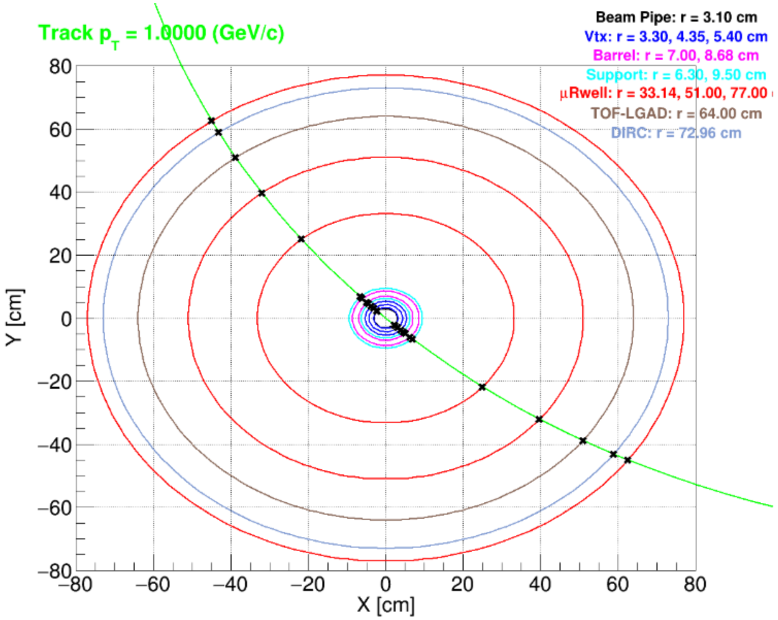
Default

$Barr_1$-Vtx_3 =15.6 cm



$Barr_1$-Vtx_3 =24.6 cm

Default+Sagitta Shift 9.0cm



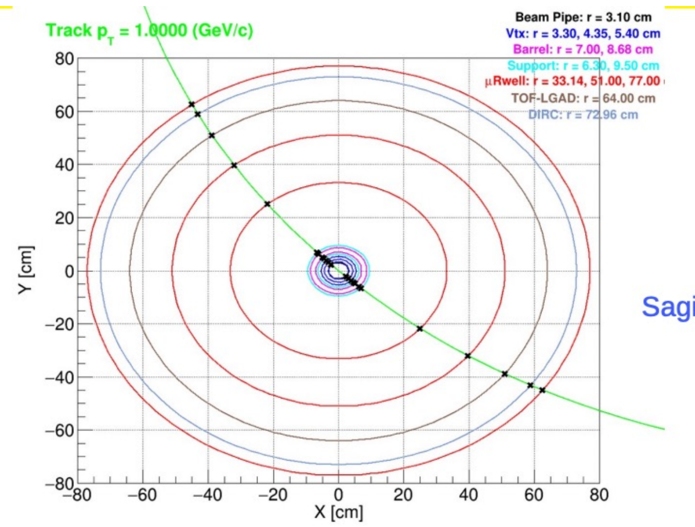
Default+Sagitta Shift -14.0cm

MM_1-$Barr_2$ = 24.46 cm

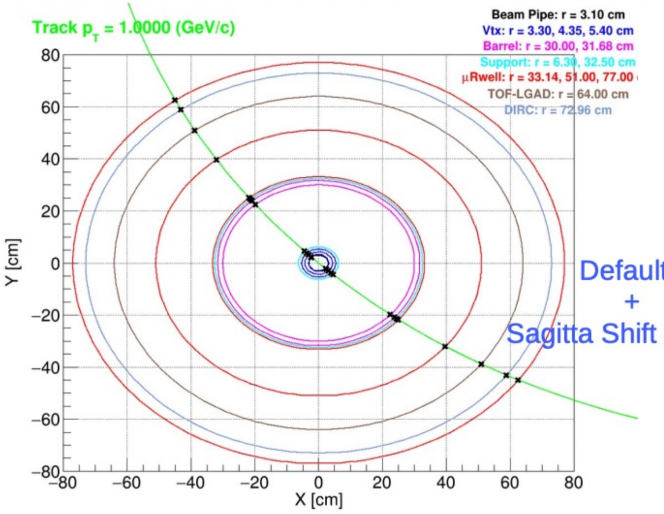
Material budget of sagitta layers = 0.55 % and also VTX_Support = 0.1 %

Slides by Annalisa Mastroserio
Plots by Shyam Kumar

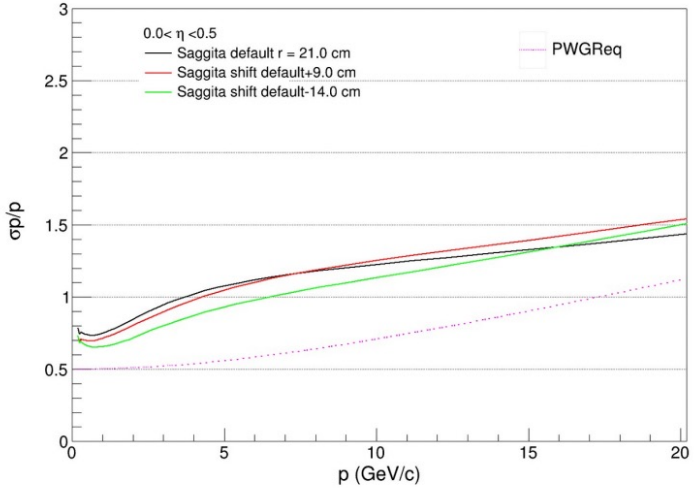
Fast simulation tool (Radii changes)

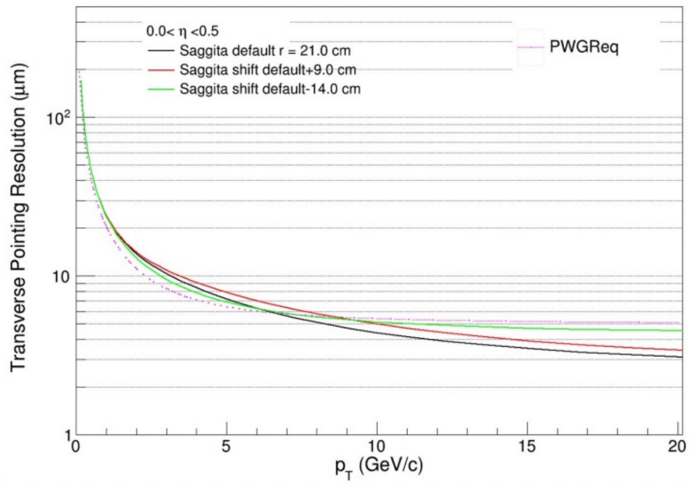


Default
+
Sagitta Shift -14.0cm



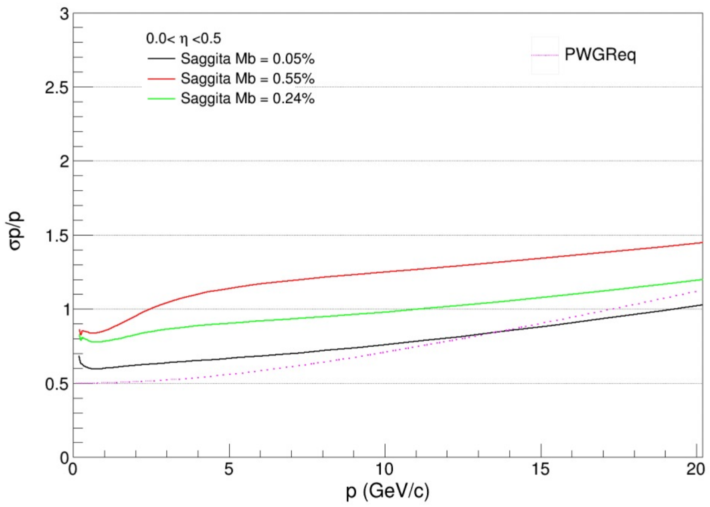
Default
+
Sagitta Shift 9.0cm

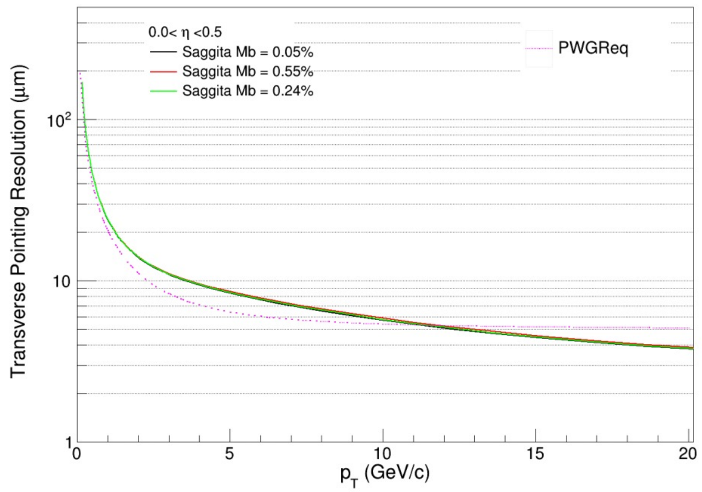




Slides by Annalisa Mastroserio
Plots by Shyam Kumar

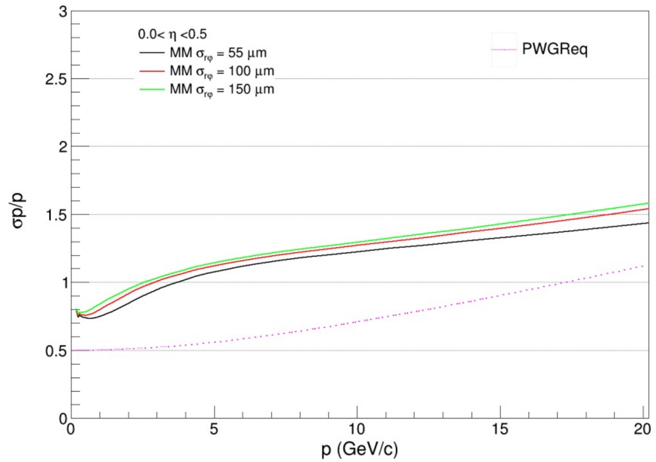
Versatile tool for tracking performance studies

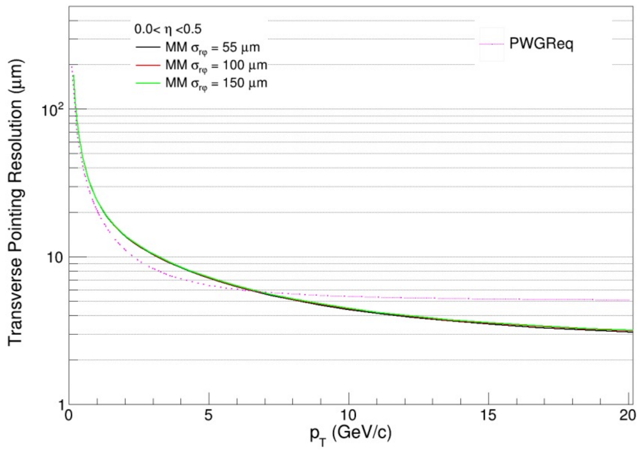




Changing Sagitta layer material budget

Changing Detector Resolution





INFN contribution EIC Software

- **Andrea Bressan: convenership**

- **Vertex and tracking:**
  - Development of a fast simulation tool
  - Support for the vertex detector layout in terms of tracking performance results
  - Studies on physics benchmark cases with the vertex detector: D^0 and Λ_c extraction
    Full simulation with good tracking algorithm is crucial
- **dRICH:**
  - Development of the code needed for the full simulation
  - Development and application of the IRT (Inverse Ray Tracing) algorithm for the Cherenkov angle reconstruction

Physics studies

Partonic tomography

A pillar of the Science Program for the future Electron-Ion Collider

Proton structure beyond one-dimension

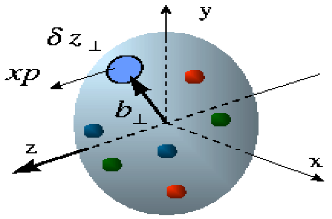
- **In a fast-moving nucleon the longitudinal size squeezes like a pancake but transverse size remains about 1 fm, but… PDFs do not resolve transverse coordinate**
- **The spatial distribution of quarks and gluons in nucleons/nuclei (and their correlations) is encoded in the Generalized Parton Distribution fct.s (GPDs)**

Wigner functions
$W(x, b_T, k_T)$

proton's "genetic code"

$\int d^2k_T$ →

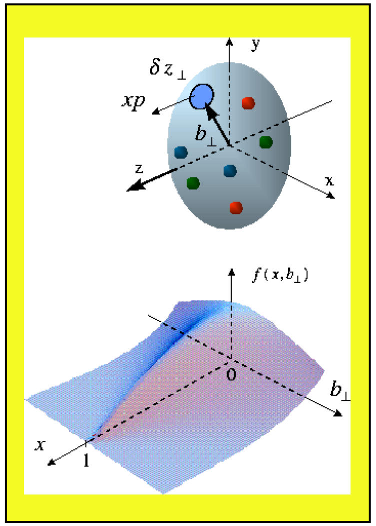
$GPDs(x, b_T)$



Spin-dependent
2D **transverse coordinate space** + 1D (p_L)
images

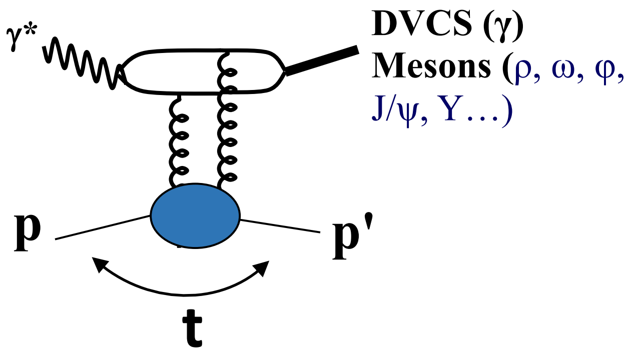
$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*for sum over parton helicities*
$\widetilde{H}^{q,g}(x,\xi,t)$	$\widetilde{E}^{q,g}(x,\xi,t)$	*for difference over parton helicities*
nucleon helicity conserved	*nucleon helicity changed*	

The nucleon (spin-1/2) has
four quark and gluon GPDs



Extracting GPDs

Exclusive Processes



momentum transfer
by the proton

❖ **Hard Exclusive processes probe specific components of GPDs**
- Real photon production (DVCS) -> quark GPDs (gluon via evolution or rad. corr. NLO)
- Time-like Compton scattering (TCS)-> gives the *real* part
- heavy vector mesons (J/ψ, Y) -> gluon GPDs
- light vector mesons (ρ^0; ρ^+; ω) -> quark flavors GPDs
- pseudoscalar mesons (π^+; π^0; η) -> helicity-flip GPDs
- DVCS on a neutron target (D; He^3) -> neutron GPDs, u/d separation

❖ **GPDs related to the energy-momentum tensor, *"last global unknown property"* of a hadron, related to distribution of forces inside the nucleon.** Through this tensor, gravity couples to matter and generates fundamental properties such as mass and spin

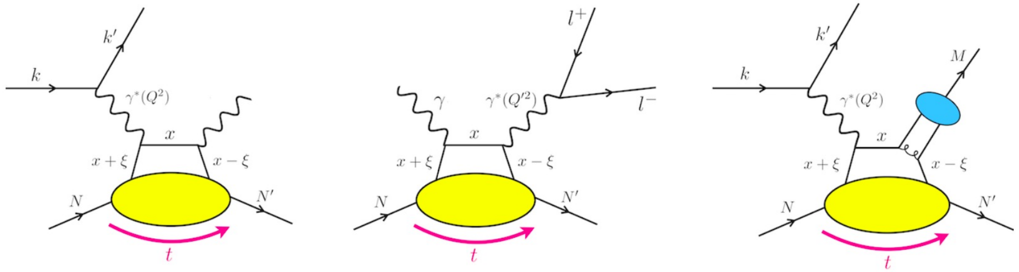
❖ **GPDs and exclusive processes also sensitive to:**
- Contribution from orbital angular momentum to **proton spin** (via Ji sum rule)
- Change with *x* of the gluon distribution: hints on the underlying **mechanism of saturation**

Challenges:

- Extraction via global fits → requires models which incorporate NLO evolution
- Model dependence to be evaluated → need common software platforms incorporating different models
- Initial- and final-state Radiative effects → needed for precise reconstruction of kinematics
- **The community needs a state-of-art GPD-based NLO Monte Carlo generator**

The EpIC generator

- **EpIC:** an event generator for exclusive reactions
  - Named after EIC and the philosopher *Epicurus*
  - Note: we inspired the name for EIC detecor-1 ☺
- *Ep*IC uses the PARTONS framework (http://partons.cea.fr), takes advantage of:
  - two state-of-art GPD models (GK, KM20)
  - flexibility for adding new models
- Multiple channels: DVCS, TCS, π^0
  - Initial and final state radiative corrections are implemented based on the collinear approximation
  - flexibility for adding all exclusive mesons



87 [hep-ph] 3 May 2022

EpIC: novel Monte Carlo generator for exclusive processes

E. C. Aschenauer[a1], V. Batozskaya[b2], S. Fazio[c3], K. Gates[d4], H. Moutarde[e5], D. Sokhan[f5,4], H. Spiesberger[g6], P. Sznajder[h2], K. Tezgin[i1]

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Received: date / Accepted: date

Abstract We present the EpIC Monte Carlo event generator for exclusive processes sensitive to generalised parton distributions. EpIC utilises the PARTONS framework, which provides a flexible software architecture and a variety of modelling options for the partonic description of the nucleon. The generator offers a comprehensive set of features, including multichannel capabilities and radiative corrections. It may be used both in analyses of experimental data, as well as in impact studies, especially for future electron-ion colliders.

like separations. In case there is no momentum transfer to the nucleon, *i.e.* in the forward limit, certain GPDs become equivalent to PDFs. Additionally, the first Mellin moments of GPDs are related to elastic form factors. In this regard, GPDs may be viewed as a unified concept of elastic form factors studied via elastic scattering processes and one-dimensional parton distribution functions studied via (semi-) inclusive scattering processes. Another key aspect of GPDs is their relation to nucleon tomography. The Fourier transform of GPDs are related to the impact parameter space distri-

arXiv:2205.01762

Accepted for publication on: EPJC

The E*p*IC generator

- EpIC uses mini FOAM to generate random events
- GPDs framework:

GPDs → CFFs → Observables

- Written in **C++**, XML interface for automated tasks, open source
- Flexible Architecture that utilises a modular programming paradigm
- Used for the ATHENA proposal: DVCS and TCS performance studies

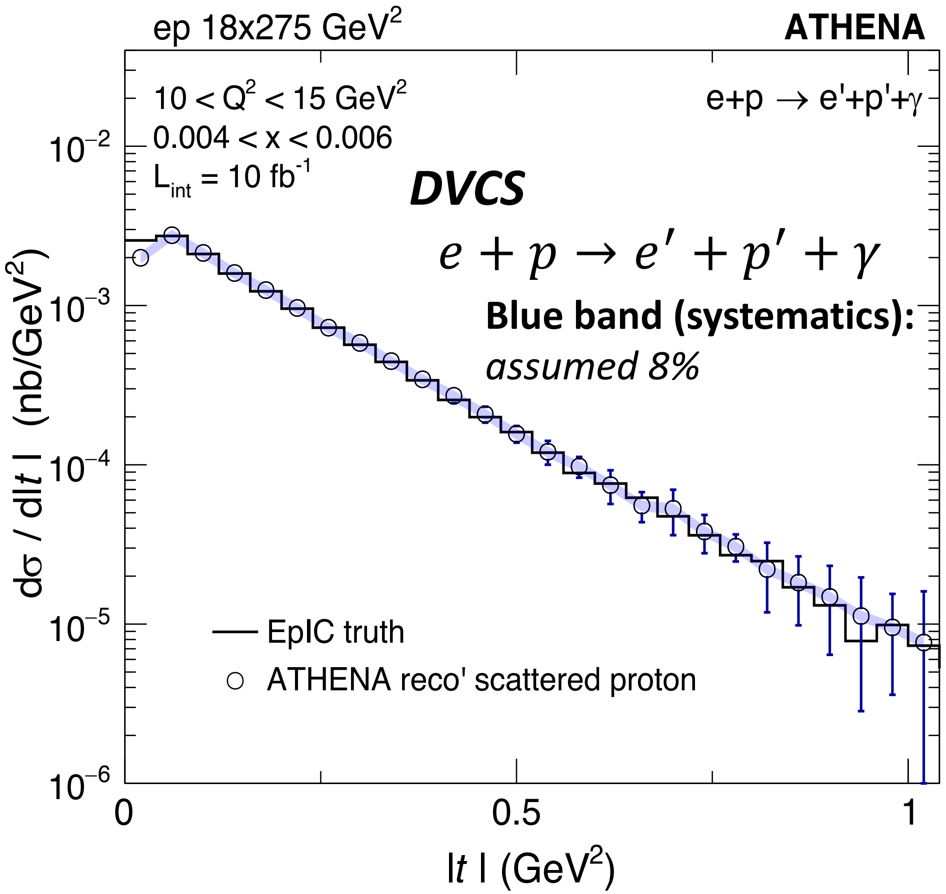
- **Input file:** model, model parameters, number of events, kinematic limits, beam and target type, beam helicity, target polarization, beam and target energy, mFOAM parameters
- **Output file:** 4-vectors of all particles

ATHENA – DVCS & TCS performance plots

- Plot made with full simulation
- DVCS & TCS events simulated using EpIC

Key detector requirements:

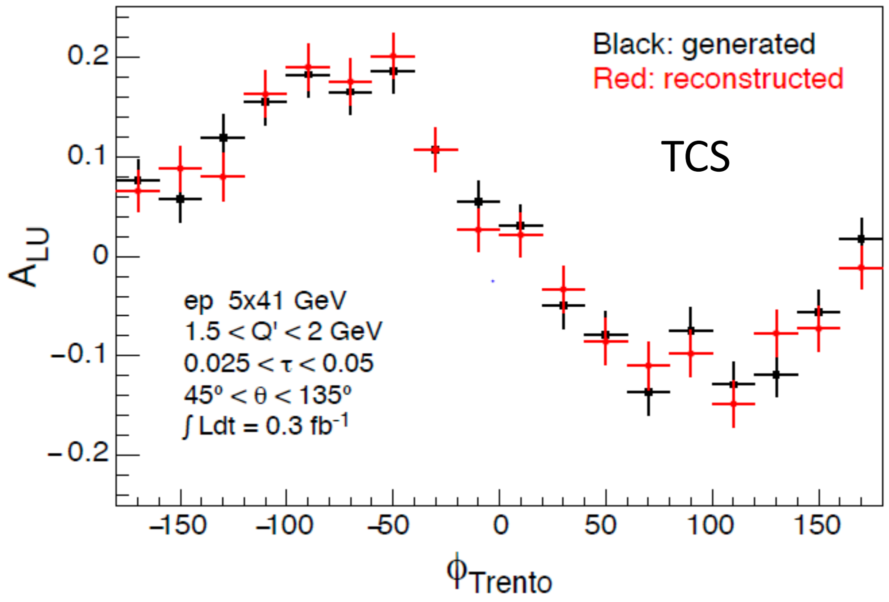
- Acceptance (including Far Forward)
- γ/π^0 separation in ECAL
- t- lever arm in FF spectrometers
- muon ID (for TCS)



DVCS

$$e + p \to e' + p' + \gamma$$

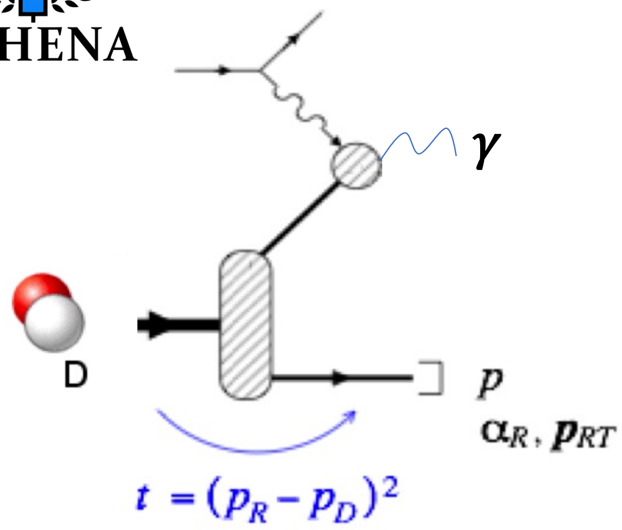
Blue band (systematics): *assumed 8%*



Timelike Compton Scattering (TCS) $\gamma p \to \gamma^* p \ (\gamma^* \to l^+ l^-)$

- Q': invariant mass of $l^+ l^-$
- $\tau = Q^2 = (s - m_p^2)$ equivalent to x_B

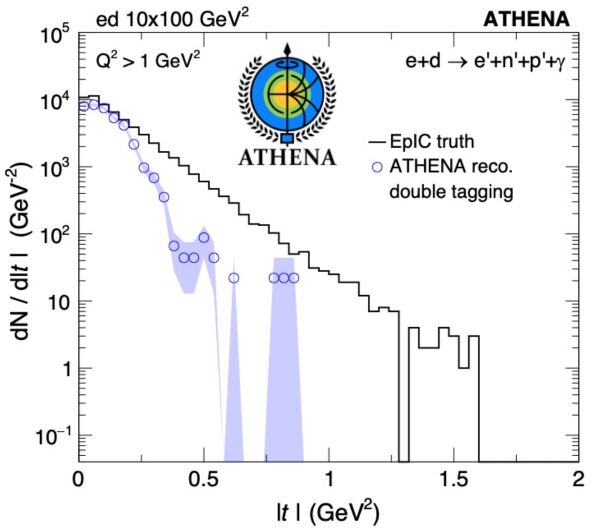
ATHENA – DVCS on deuterium

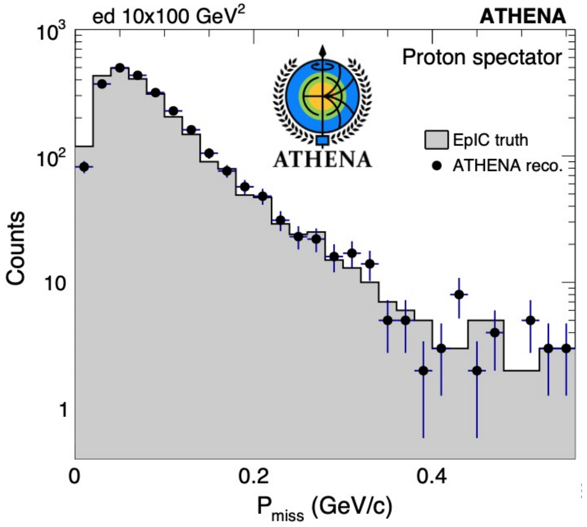


- Possibility to study neutron structure
- DVCS on neutron compared to proton is important for flavor u/d separation

DVCS on incoherent D (D breaks up) but coherent on the neutron, the "double tagging" method

- **Tag DIS on a neutron (by the ZDC)**
- **Measure the recoil proton momentum (in F.F. detectors)**
- **The recoil proton momentum cone is**
  - $\alpha_R = (E_R + p_{R||})/(E_D + p_{D||})$ **and** p_{RT}
- Gives you a free neutron structure, not affected by final state interactions





ATHENA – DVCS on e+D:

- 80-90% acceptance at low |t|,
- |t|-acceptance loss at higher value mostly due to the loss in tagging the active neutron in ZDC.
- Alternatively, |t| can be measured via scattered *e* and γ → higher acceptance at large |t|.
- Proton momentum is well reconstructed

Next step: EIC impact studies!

- We aim at performing new impact studies for extracting GPDs, similarly to what was done for the W.P. [E.C. Aschenauer, S.F., K. Kumericki, D. Mueller - JHEP09(2013)093], now with:
  - geant-4 simulation of the detector-1 response and realistic event reconstruction
  - state-of-art radiative effects implemented in the E*p*IC generator
  - BH and π^0 background subtraction
  - state of art models (GK and KM20)
- INFN people with longstanding experience in the field of partonic imaging: ZEUS@HERA, STAR@RHIC, EIC physics case and the EIC Yellow Report initiative
- People involved:
  - Simulation & analysis: E. Aschenauer, S.F., A. Jentsch, P. Sznajder (+ student), K. Tezgin
  - Theory guidance and global fits: K. & K.P. Kumericki, H. Spiesberger, H. Moutarde

Spatial 3D imaging – our goals!

✓ Milestone y21-22 release a novel, unique, Monte Carlo generator for hard exclusive processes based on available and upcoming GPD models, featuring first and second order initial- and final-state radiative effects

Milestone y23 extract GPDs by performing global NLO fits of various models in order to quantify the impact of the future Electron-Ion Collider at BNL in constraining CFFs and GPDs, from DVCS and TCS measurements

Future Goal 1 assess the feasibility of extracting the energy-momentum tensor, through which gravity couples to matter and generates fundamental properties such as mass and spin

Future Goal 2 include HEMP into the generator and explore the possibility of disentangling the contribution to GPDs from different partonic flavor

Longer term perspectives:

- Seed future topical collaborations
- Guide future executive decisions on the EIC second experimental apparatus

Diffractive PDFs

Slides by Marta Ruspa

- **Proton DPDFs not yet exploited for the EIC!**
  - good constrain on the gluon densities though scaling violation
- **A DPDF fit releasing the assumption or Regge factorization was never done**
  - though the HERA data might suggest a breaking.
- **PLAN: Evaluate the impact of the EIC to disentangle to which extent Regge factorization holds**
  - Understand the detector acceptance for inclusive diffractive processes
  - Full Monte Carlo chain generation-detector-reconstruction
  - Generation of pseudodata to be used in DPDF fit
  - Additional inclusion of the HERA data to evaluate the impact

Need to expand our involvement with EIC Physics

LOOKING FORWARD

EIC School proposal

Slides by Annalisa Mastroserio

School dedicated to Electron Ion Collider
[physics and detectors]

- Who: ~20 students both from master thesis / PhD
- When: spring/summer 2023 -> 3.5 days
- Where : LNF/Bertinoro/Maratea/Vieste/….
  - Decide by September (based also on possible contribution from local Institutions)
- What : lessons from theory, detectors, hands on sessions (MC simulations)

  → Availability of Abhay Deshpande (international VIP guest)

Preliminary ideas on lectures

- Deep Inelastic Scattering history (from SLAC-MIT to HERA)
- Detectors: detectors and technologies chosen for DIS measurements at HERA (ZEUS, H1, HERMES)
- JLAB e COMPASS: overview of physics results
- EIC Physics Program: Nucleon tomography, Spin physics, Mass of the nucleon, Hadron spectroscopy
- Hands-on session on data analisys and simulation

Costs & estimates

- Computing & Software infrastructure
  - TS: 2.5k€ travel for related S&C networking
- dRICH simulation
  - TS: included in the overall 2.5k€ travel request for dRICH-related networking
- Tracking performance
  - BA: included in the overall 5k€ travel request for networking
- Exclusive Physics & partonic 3D imaging - DPDFs
  - CS: 1k€ for the PARTONS network meeting + 1.5k€ network with BNL
- EIC School (5k€ RN + 2.5k€ others)
  - BO: 5k€ RN travel support for the EIC School
  - CS: 0.5k€ participation of a student
  - LNS: 0.5k€ participation of a student
  - PD: 0.5k€ participation of a student
  - SA: 1k€ participation of three students


KEEP
CALM
IT IS
DISCUSSION
TIME