Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

NATIONAL SCIENCE CENTRE POLAND

Whispers of Baryons: A Femtoscopic Journey to High Baryonic Chemical Potential

Daniel Wielanek

Workshop on Particle Correlations and Femtoscopy, Tolouse

4th-8th November2024

Warsaw University of Technology

RESEARCH UNIVERSITY
EXCELLENCE INITIATIVE

Outline

- Motivation
- Current and future experiments at high baryonic density
- Femtoscopy – introduction
- Femtoscopy at high baryonic densities
- Summary

Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

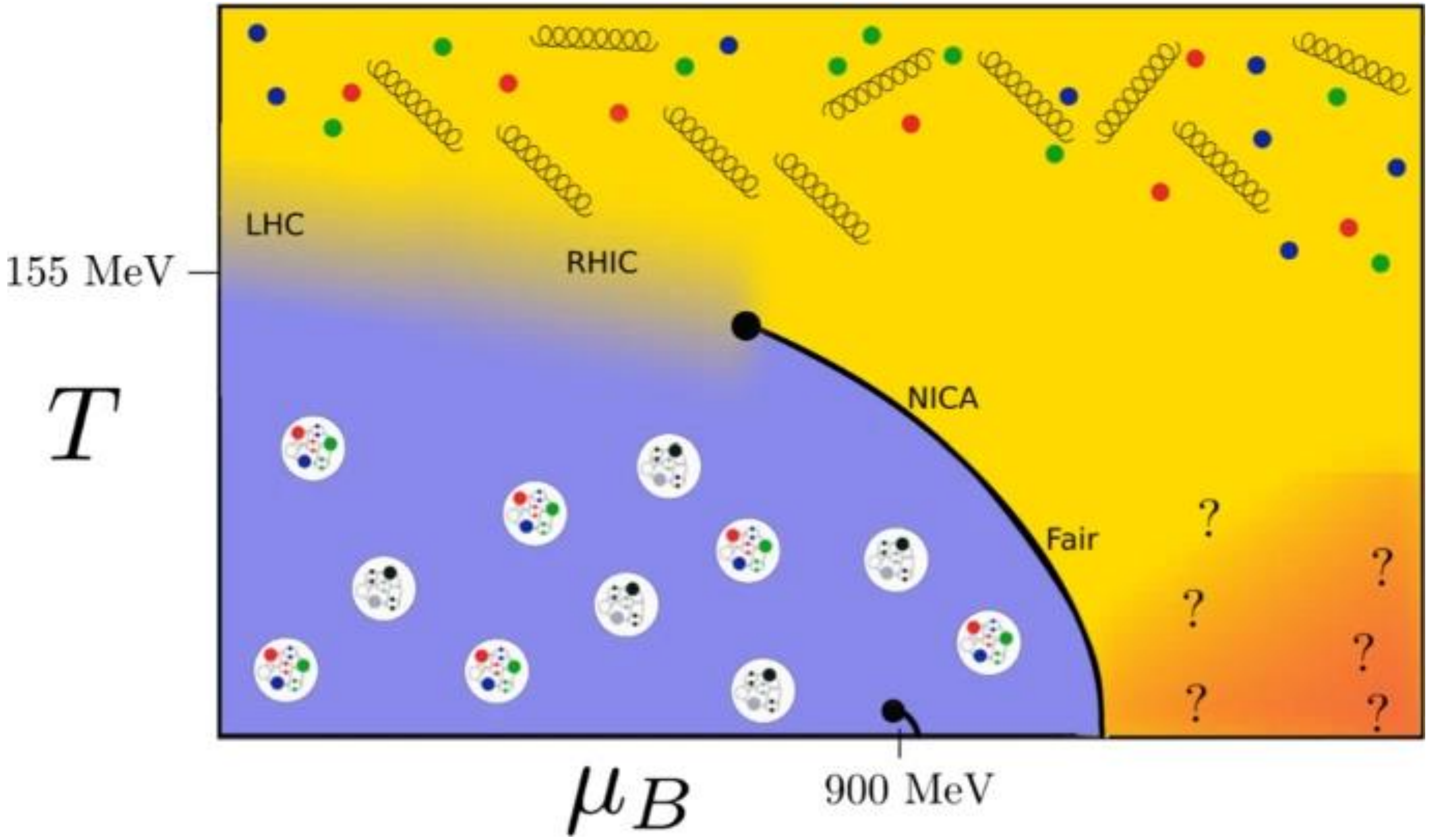
Motivation

Warsaw University of Technology

Motivation

Probing phase diagram of QCD matter

- High $\sqrt{s_{NN}}$ →high T, low μ_B
  - Lattice QCD calculations available
  - Crossover transition
  - Early Universe
- Medium $\sqrt{s_{NN}}$ → medium μ_B & T
  - Critical Point?
  - 1st order PT/crossover
- Low $\sqrt{s_{NN}}$ → high μ_B , low T
  - Neutron stars nature
  - Onset of deconfinement
- Different collision energies → probing QCD phase diagram



Overview of the QCD phase diagram, Recent progress from the lattice, The European Physical Journal A,
•Volume 57, article number 136, (2021) , Jana N. Guenther

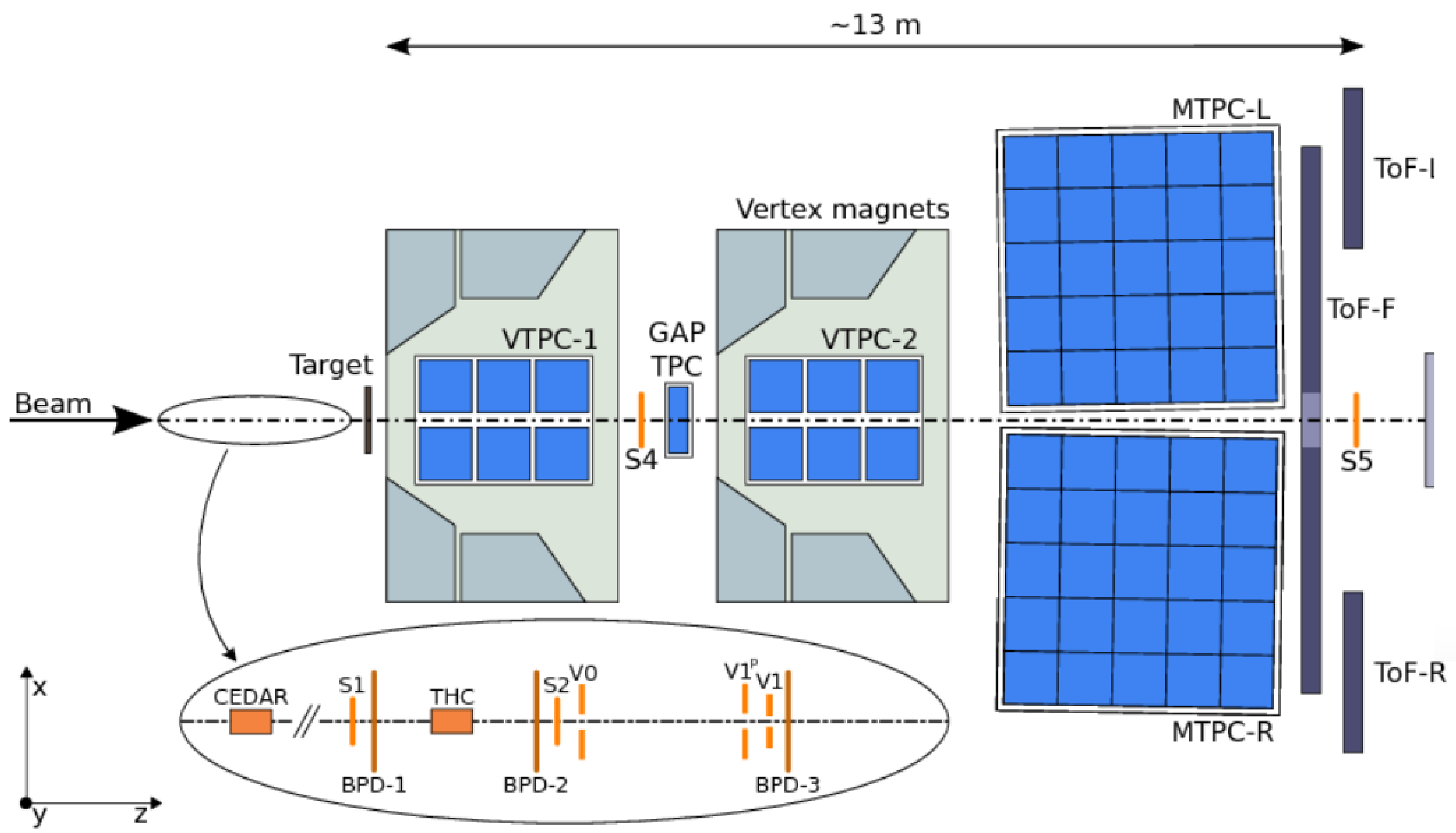
Faculty
of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

Current and future experiments dedicated to the measurements at high μ_B

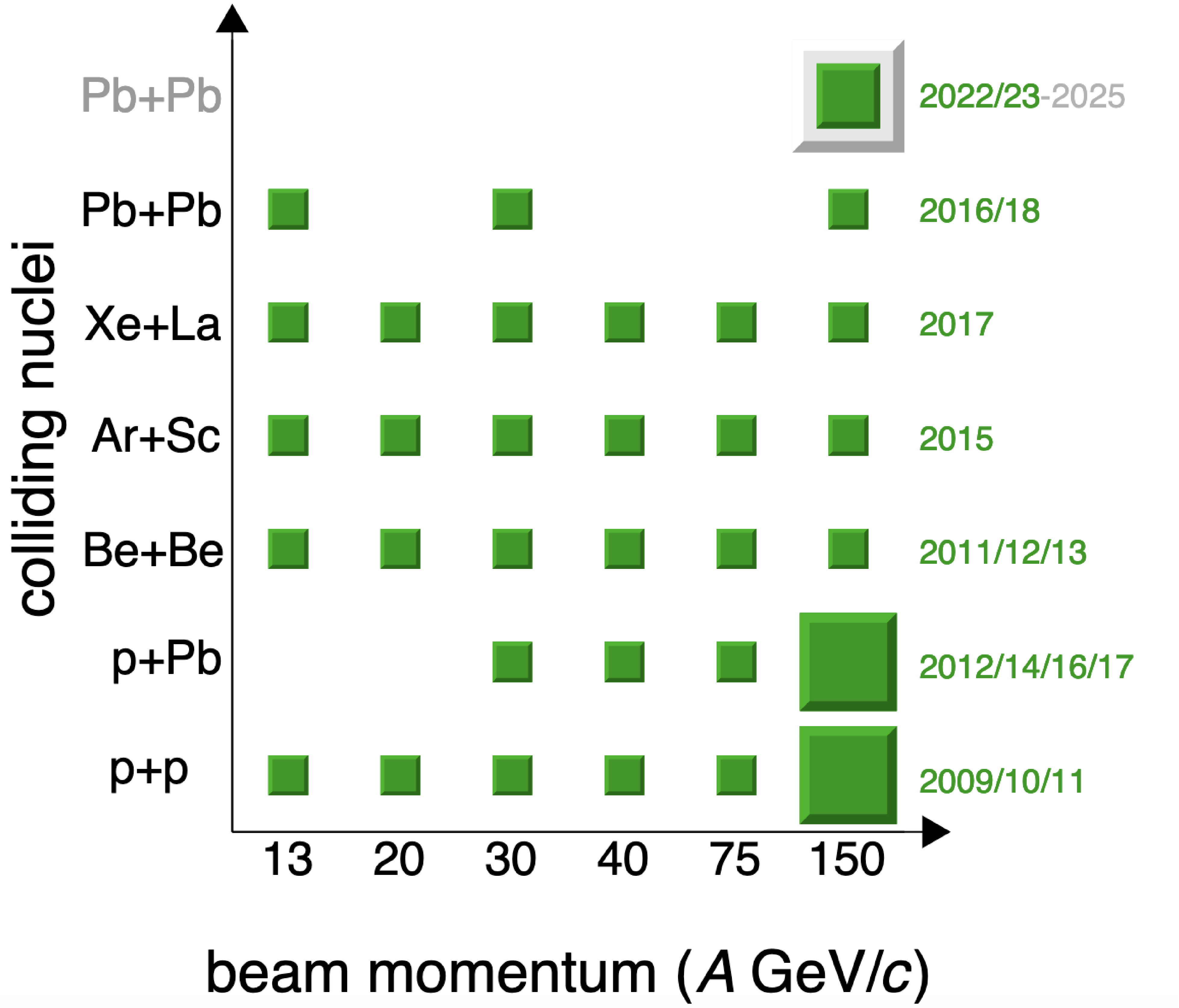
Warsaw University
of Technology

Current experiments (chosen)

- Na61/SHINE
  - Fixed target experiment at CERN
  - Dedicated to looking for CP
  - Energies $\sqrt{s_{NN}}$ ~5-17 GeV



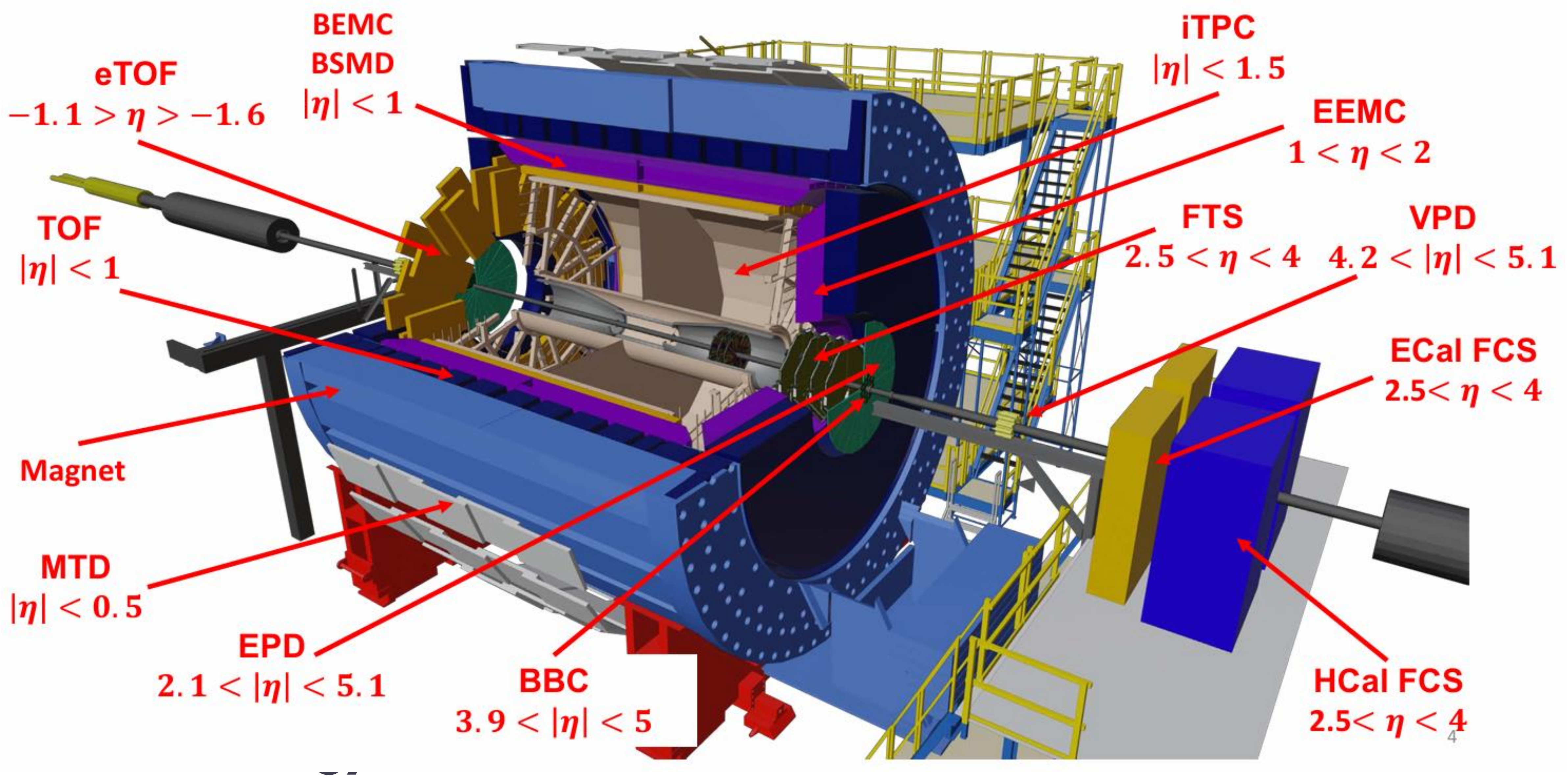
https://cds.cern.ch/record/2649393/files/1811.05522.pdf

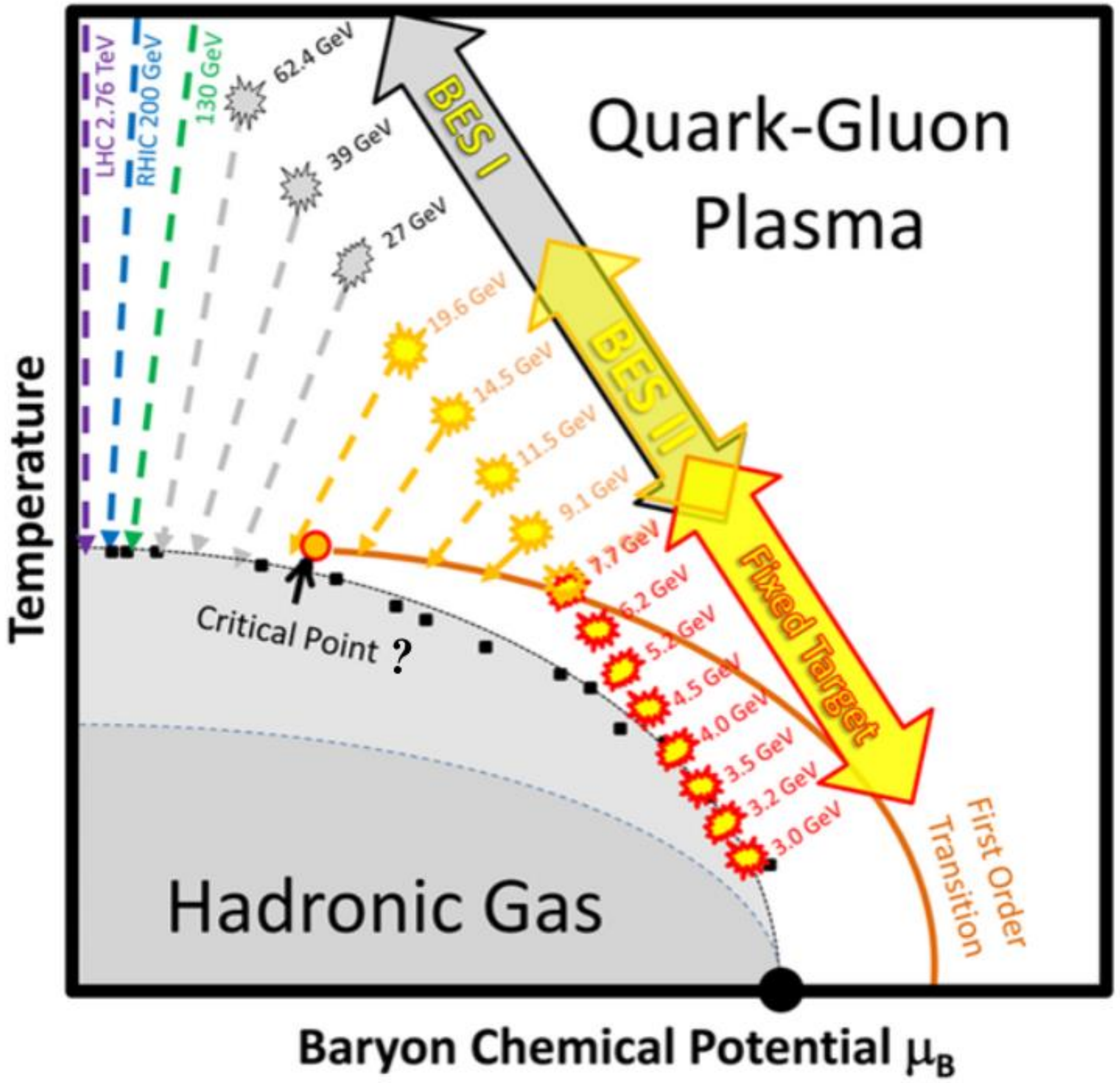


Energy scan results with L´evy type femtoscopy at NA61/SHINE XVIIth WPCF
Barnab´as P´orfy

Current experiments (chosen)

- STAR
  - Fixed target/collider experiment at BNL
  - Dedicated to looking for CP, Onset of Deconfinent, 1st order PT signature
  - Energies $\sqrt{s_{NN}}$ 3-200 GeV

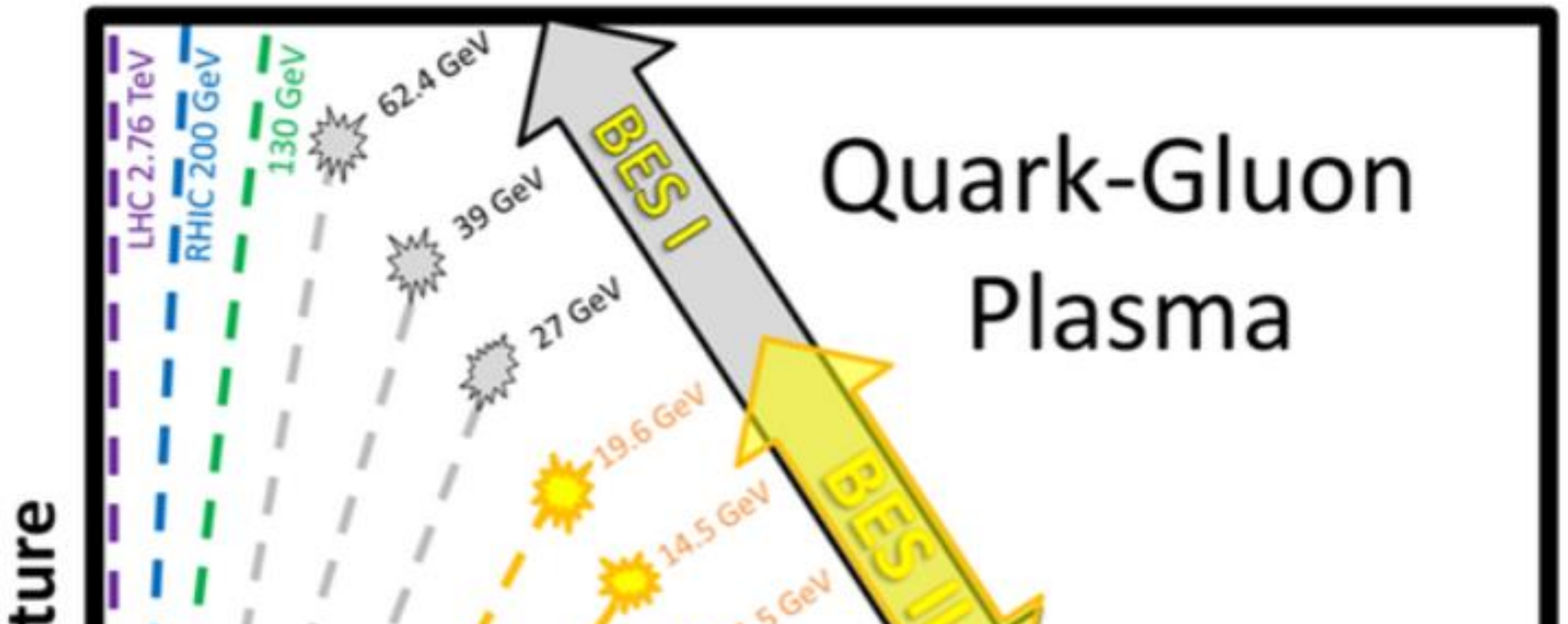


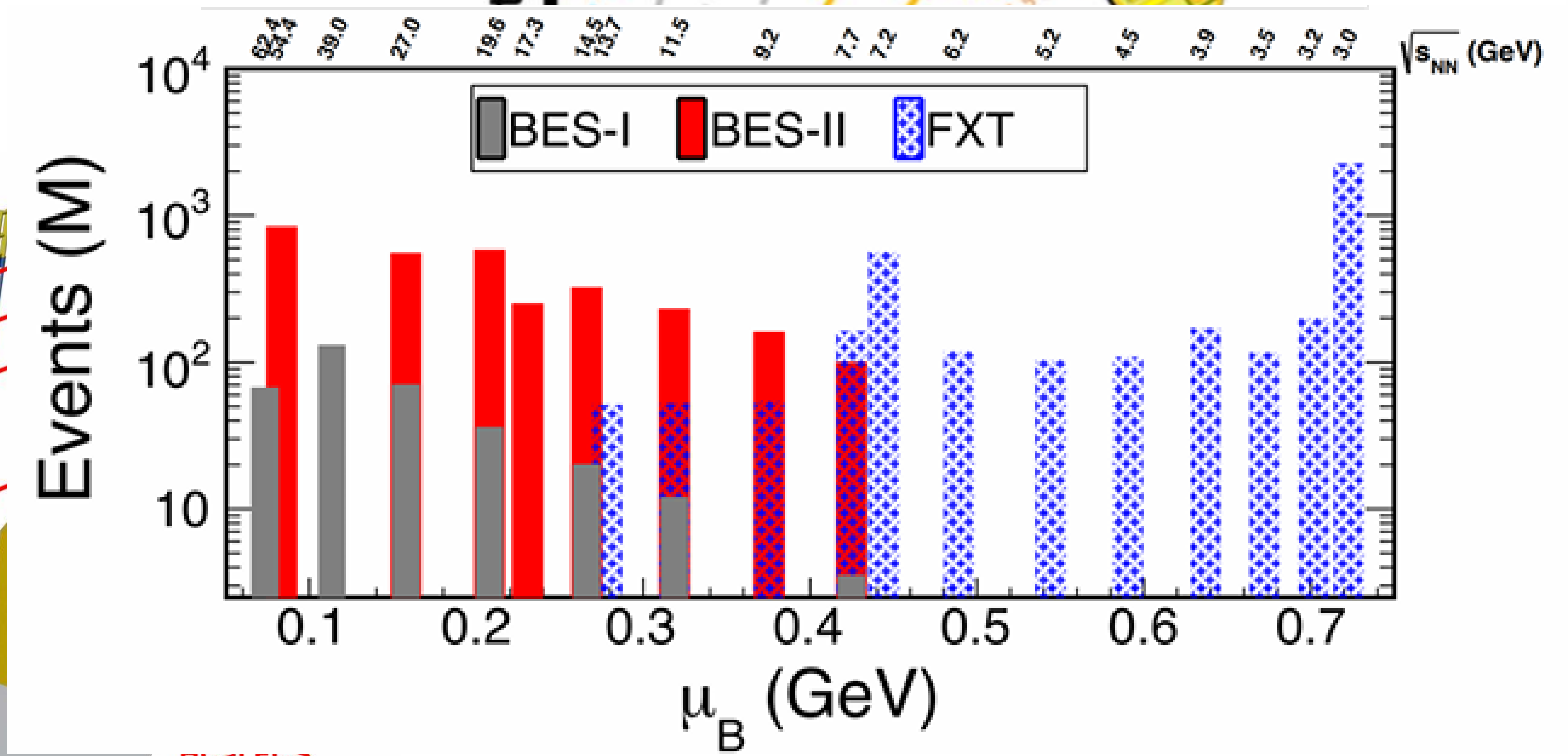


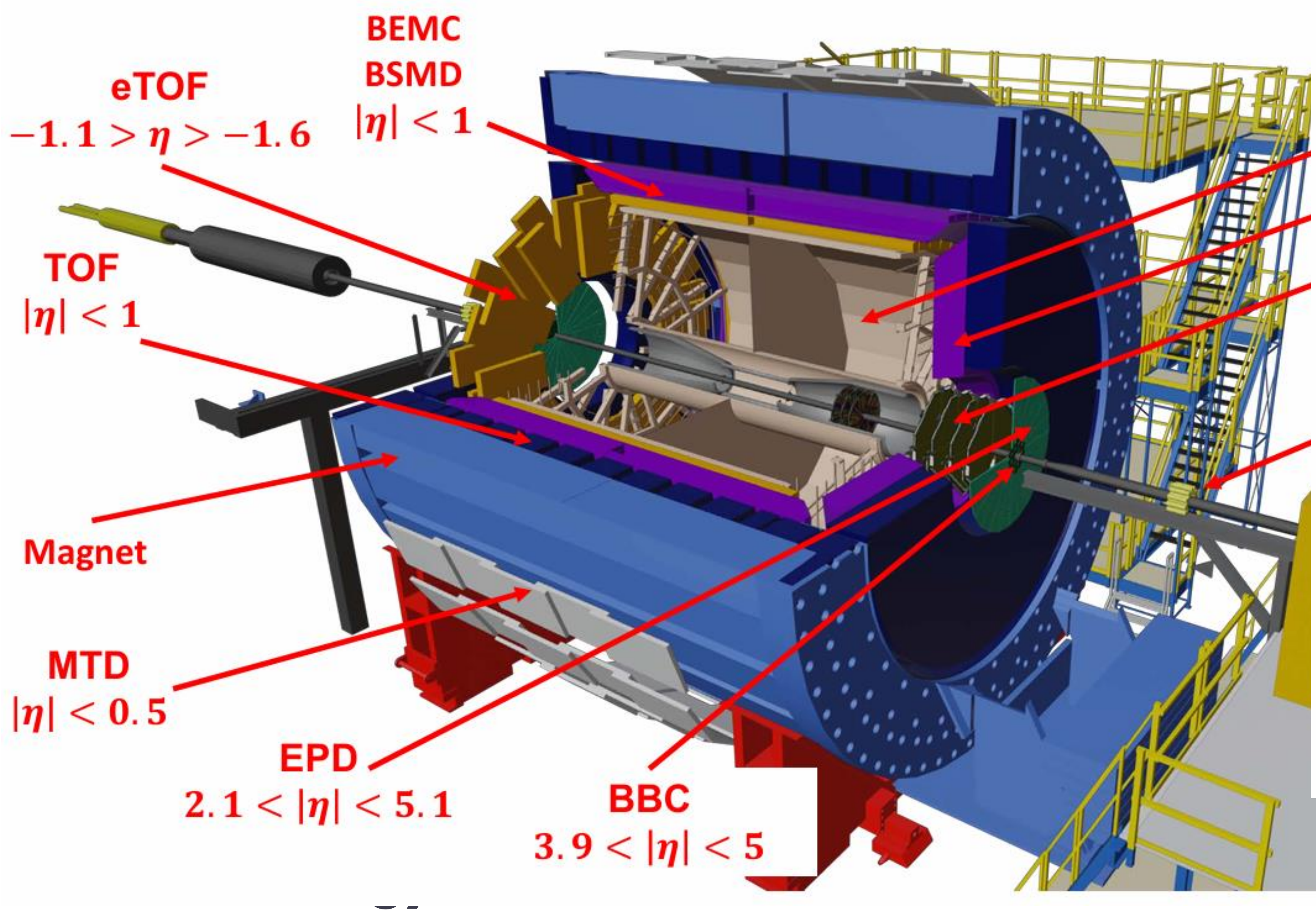
The STAR detector upgrade and future plan, Chi Yang

Current experiments (chosen)

- STAR
  - Fixed target/collider experiment at BNL
  - Dedicated to looking for CP, Onset of Deconfinent, 1st order PT signature
  - Energies $\sqrt{s_{NN}}$ 3-200 GeV

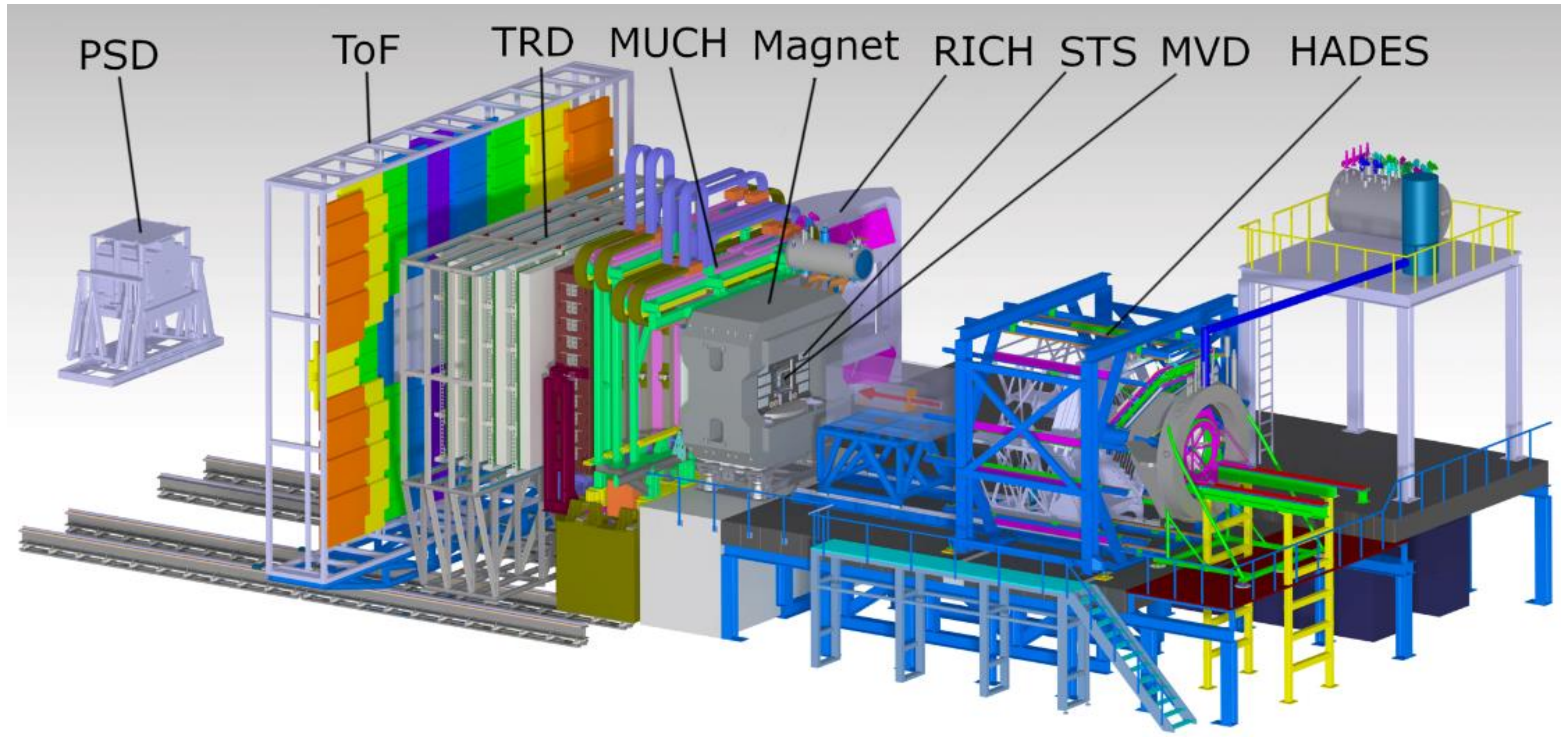


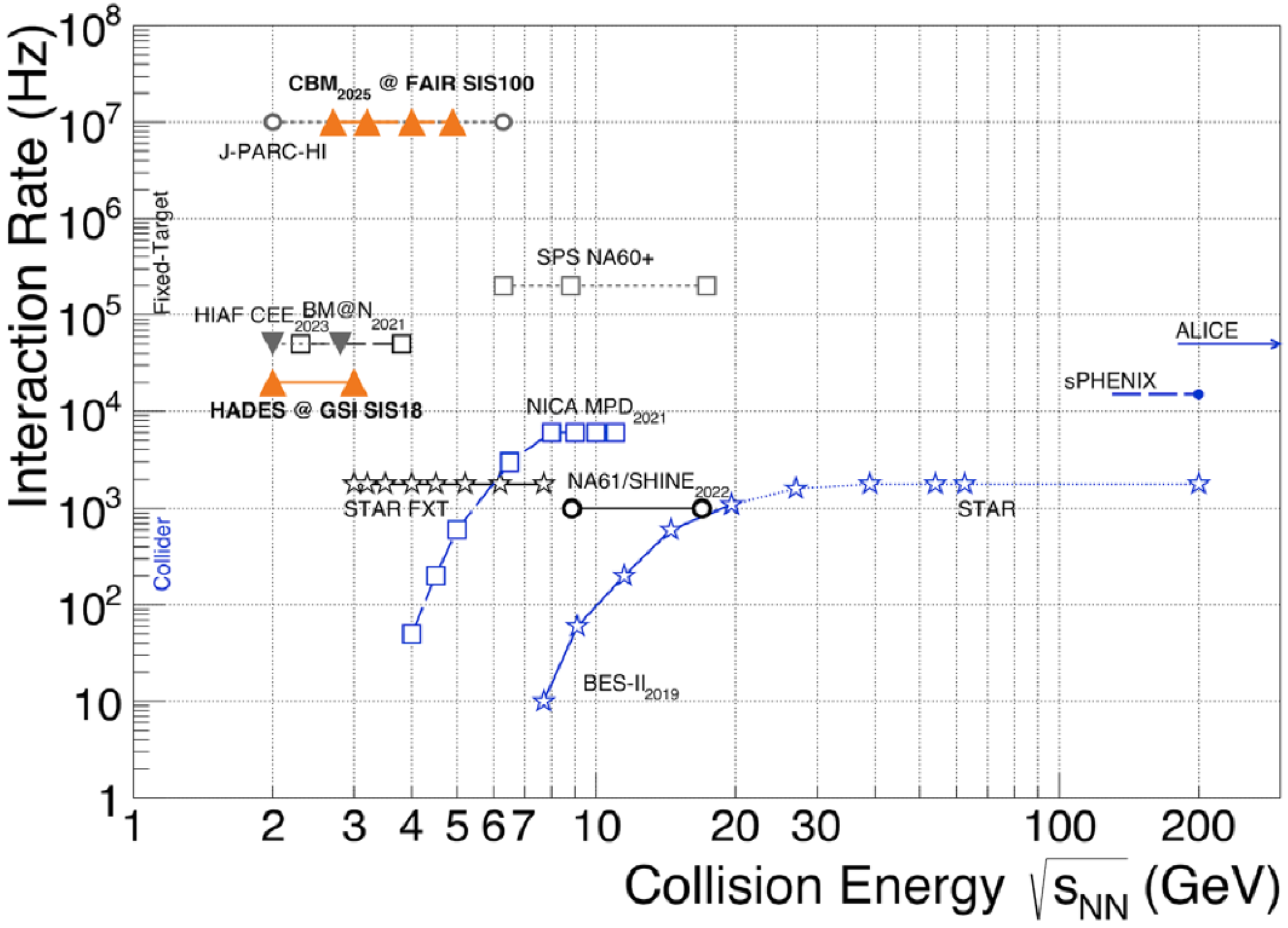




Future experiments

- J-PARC (Japain $\sqrt{s_{NN}}$ 2-5 GeV)
- NICA (Russia $\sqrt{s_{NN}}$ 2-11 GeV)
- GSI/FAIR CBM $\sqrt{s_{NN}}$ 2-5 GeV





Status and Perspectives of the CBM experiment at FAIR, N.. HerrMann, EPJ Web of Conferences 259, 2022

Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

Femtoscopy

Warsaw University of Technology

Femtoscopy

Femtoscopy uses the Correlation Function defined as:

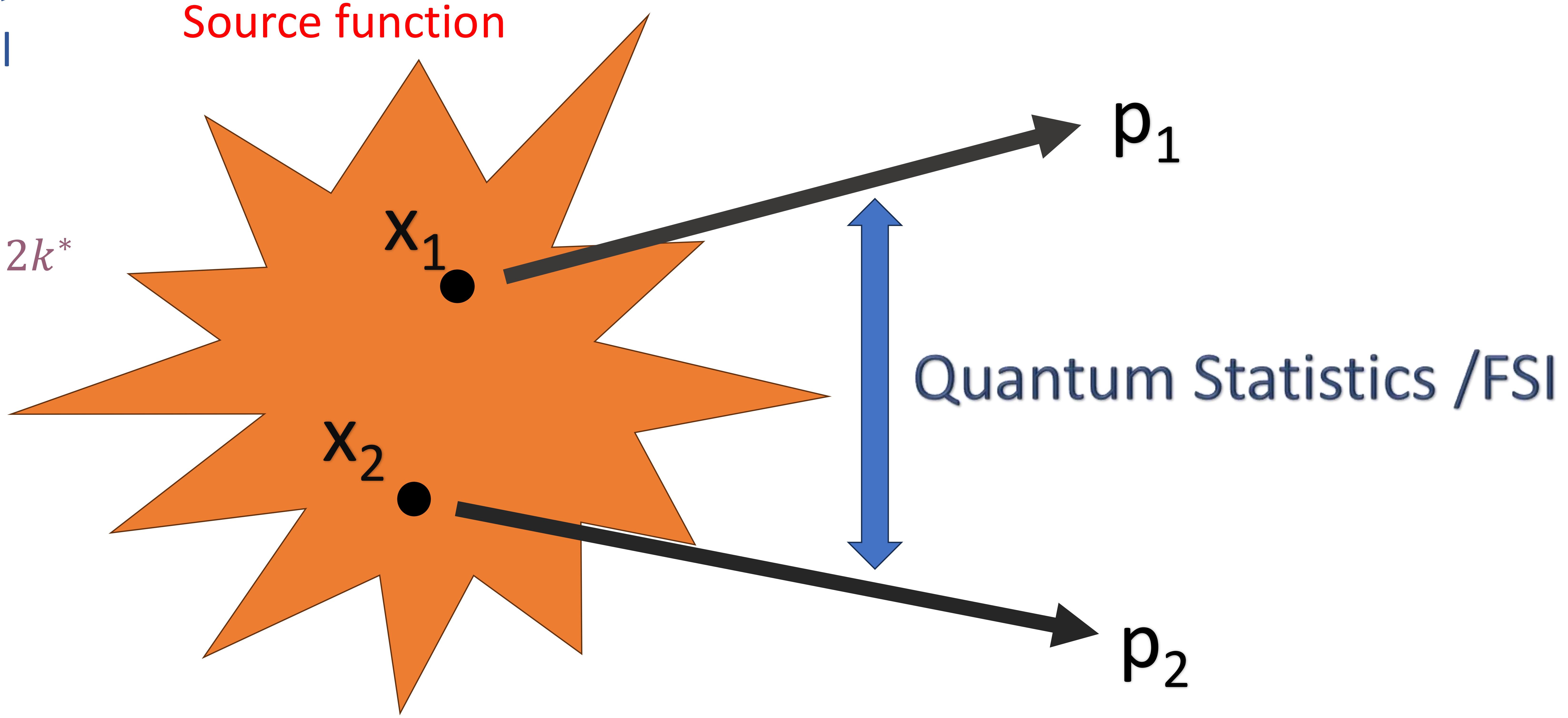
Two particle interactions/quantum effect

$$C(q) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} = \int \rho(x_1, p_1)\rho(x_2, p_2)\left|\Psi(x_1, p_1, x_2, p_2)\right|^2 dx_1 dx_2$$

Experimental definition

Source function

$$q = \sqrt{(p_1 - p_2)^2 - (E_1 - E_2)^2} = 2k^*$$



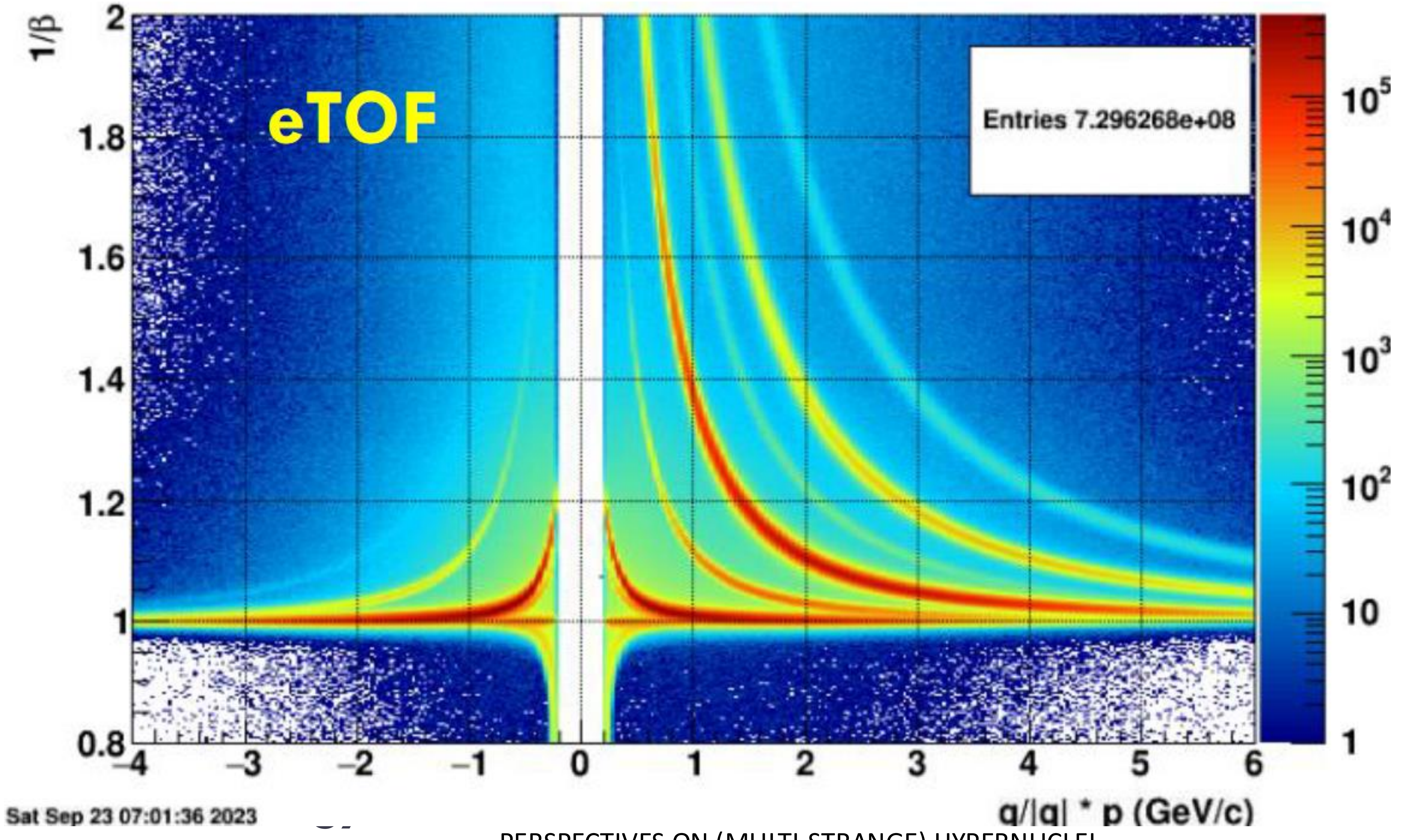
Faculty
of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

Femtoscopy at high baryonic densities

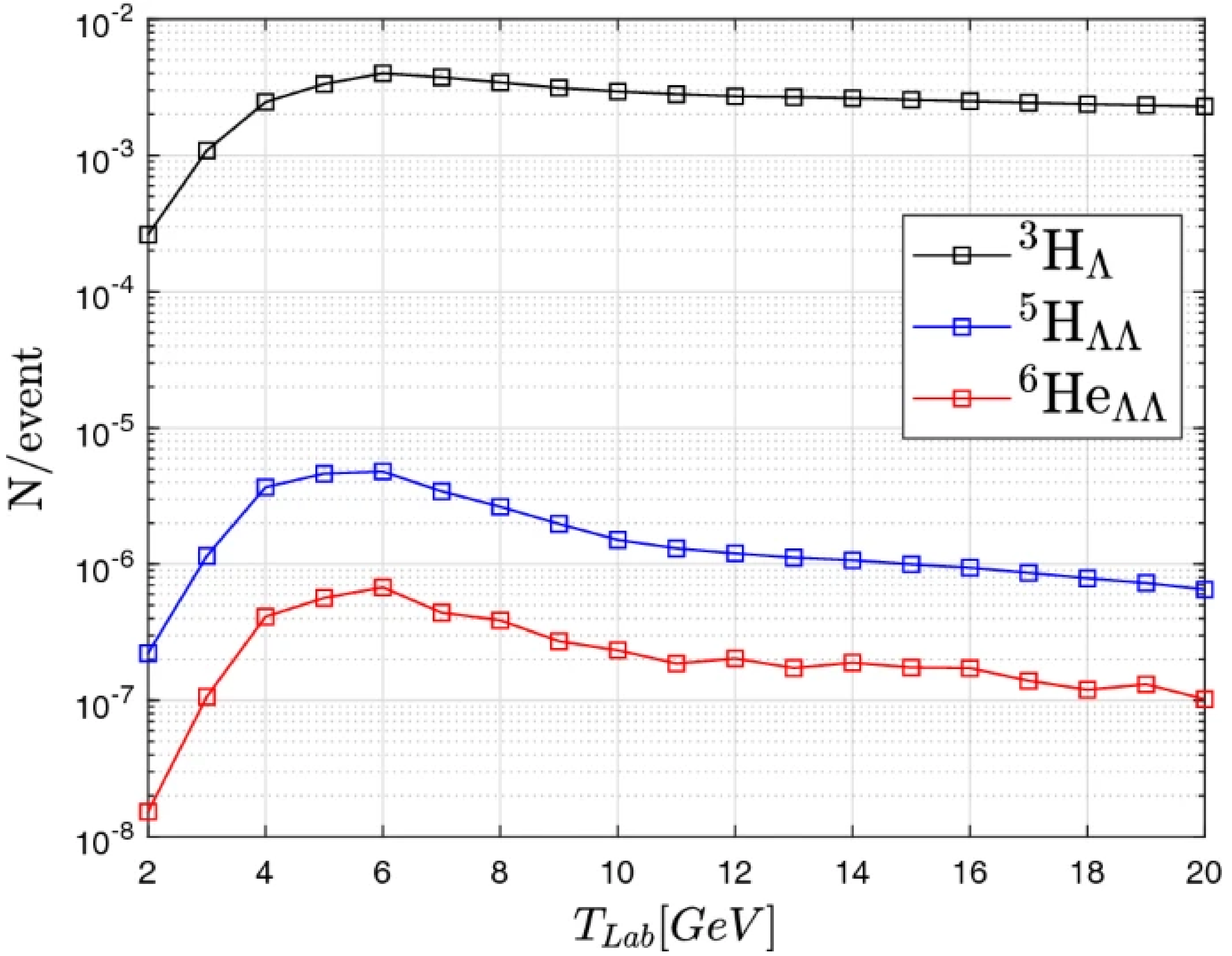
Warsaw University
of Technology

Lower collision energies

- Expected larger production of hypernuclei
- More protons (stopping)
- Equation of State
- Fragmentation etc.

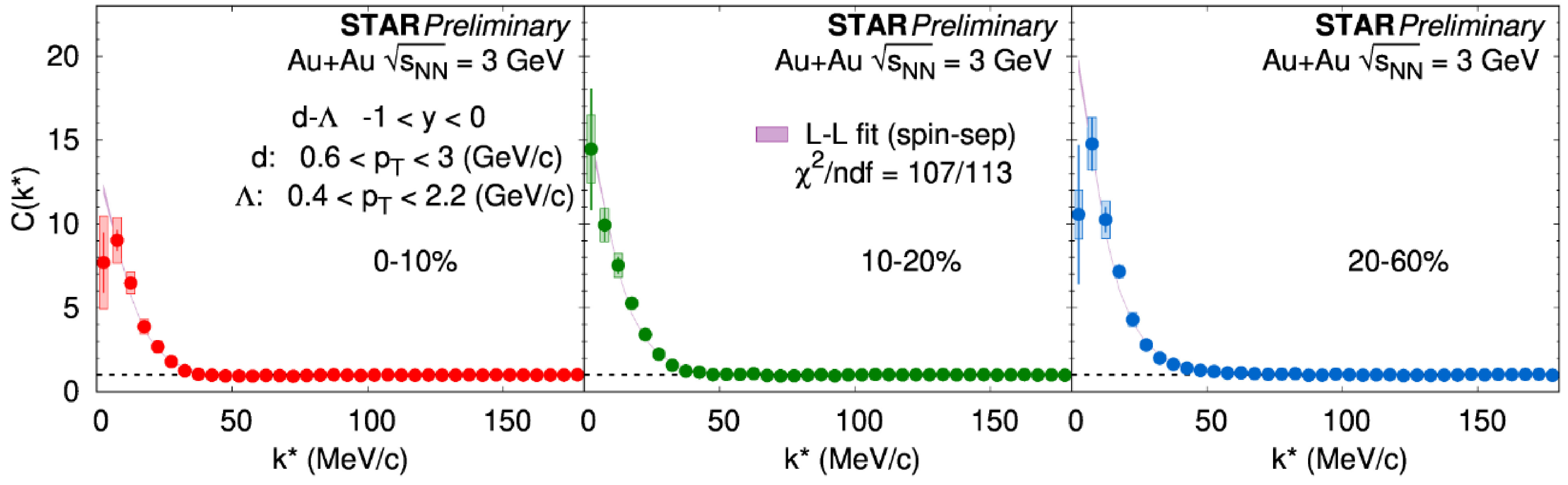


PERSPECTIVES ON (MULTI-STRANGE) HYPERNUCLEI PHYSICS WITH THE CBM EXPERIMENT AT FAIR, Iu. Vassiliev, SQM 2024

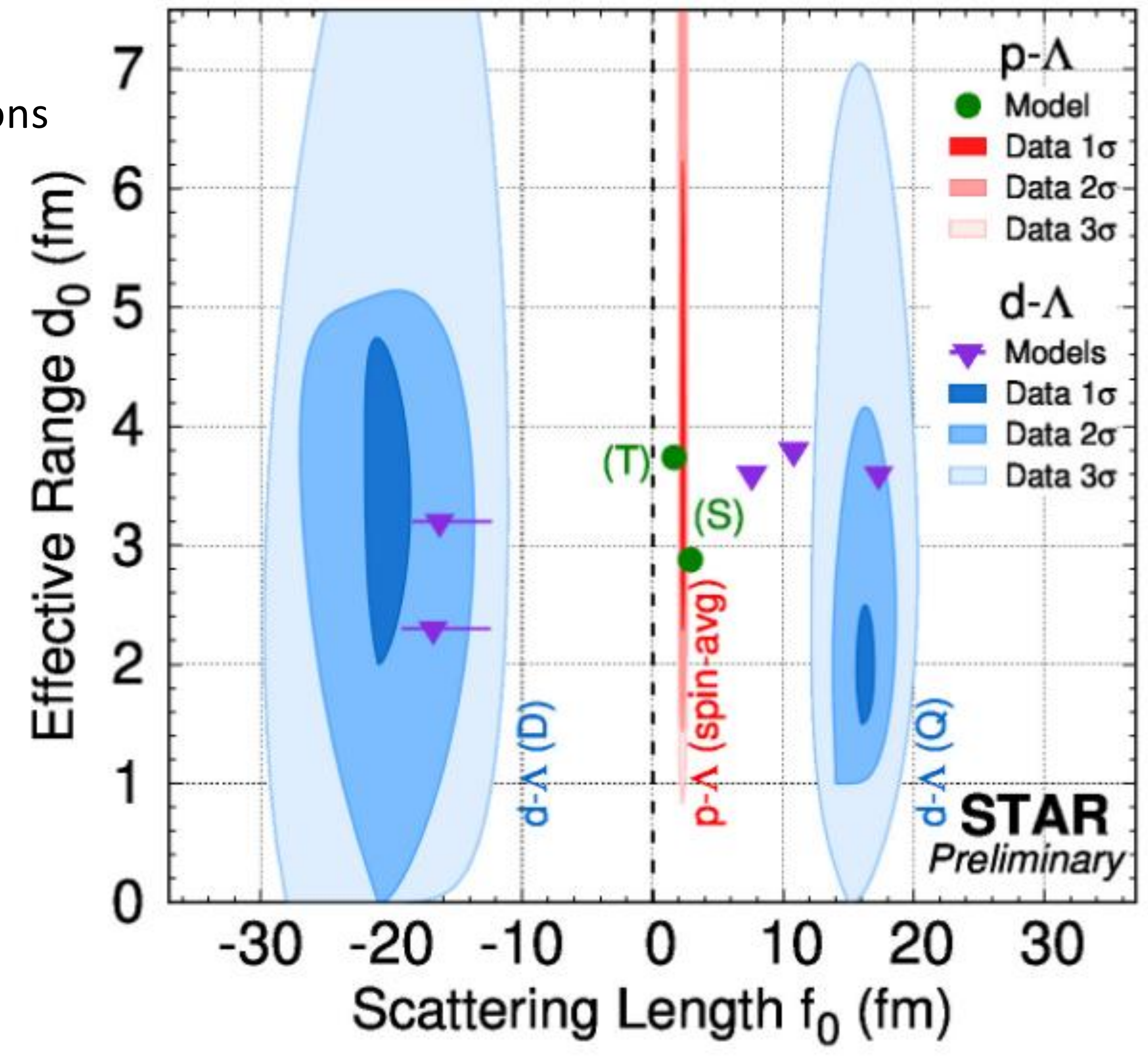


Hypernuclei production with a modified coalescence model in BUU transport calculations, Theoretical Physics ,Volume 59, article number 89, (2023), G. Balassa and Gyorgy Wolf

Probing interaction

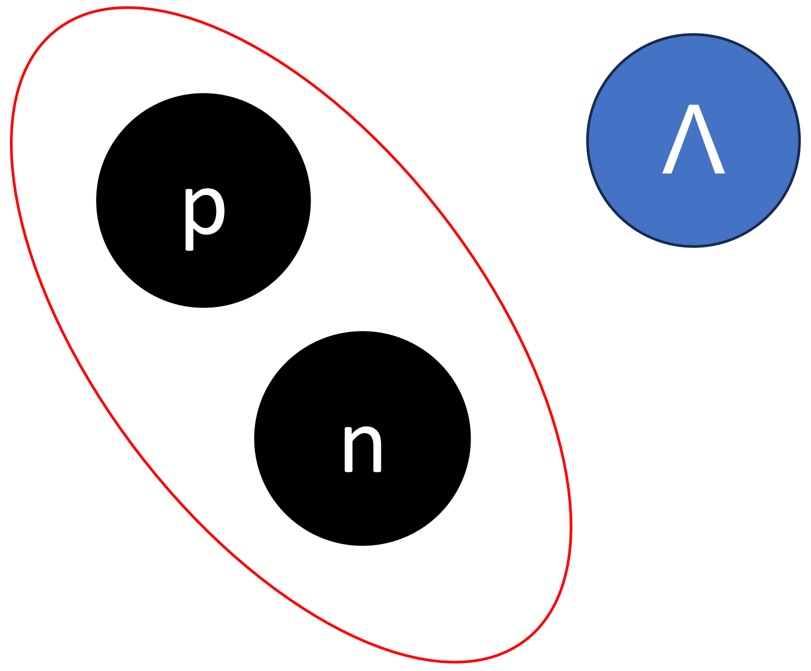


Measurements of p − Λ and d − Λ correlations in 3 GeV, Au+Au collisions at STAR, Yu Hu



Measuring deuteron-lambda interaction:

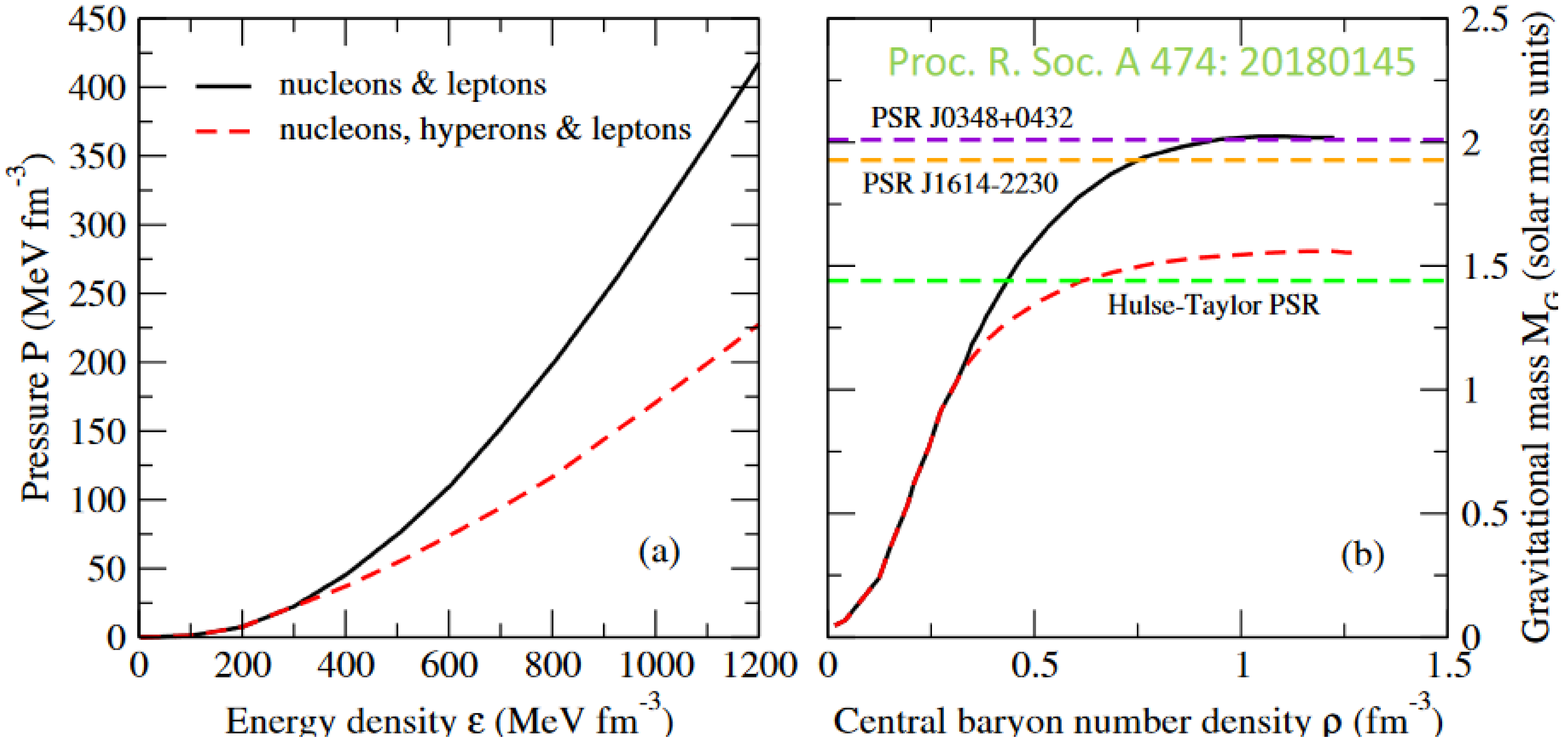
- Extraction of interaction parameters
- Extraction of binding Energy of hypertriton



Probing interaction

Hyperon puzzle:

- Hyperons might be present in the core of neturon stars
- They should soften EoS
- However this is not seen in astronomical observations
- YY repulsive potential? 3-body forces?



Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

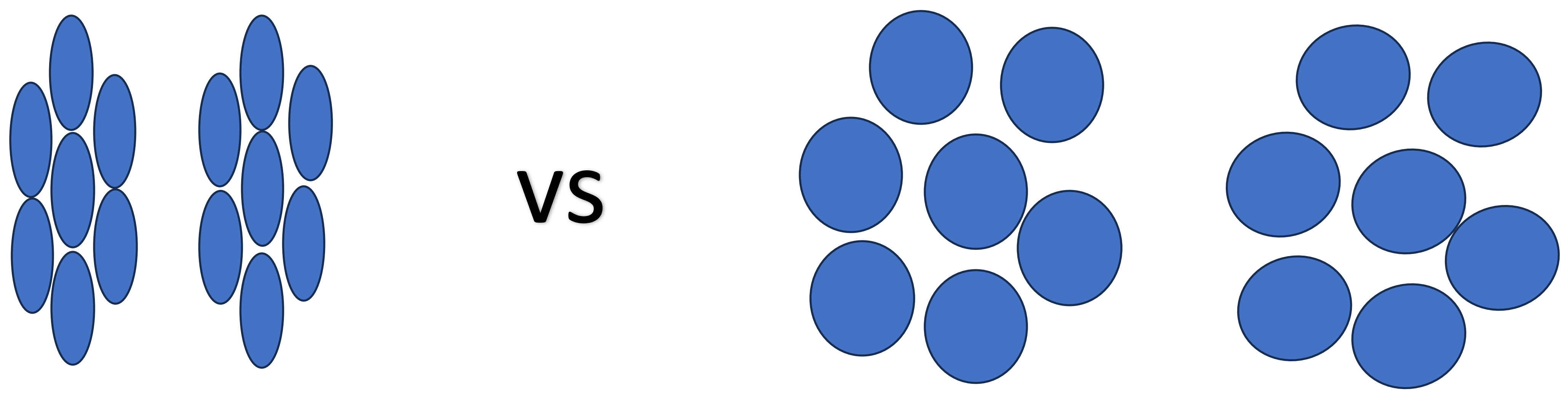
Challenges

Warsaw University of Technology

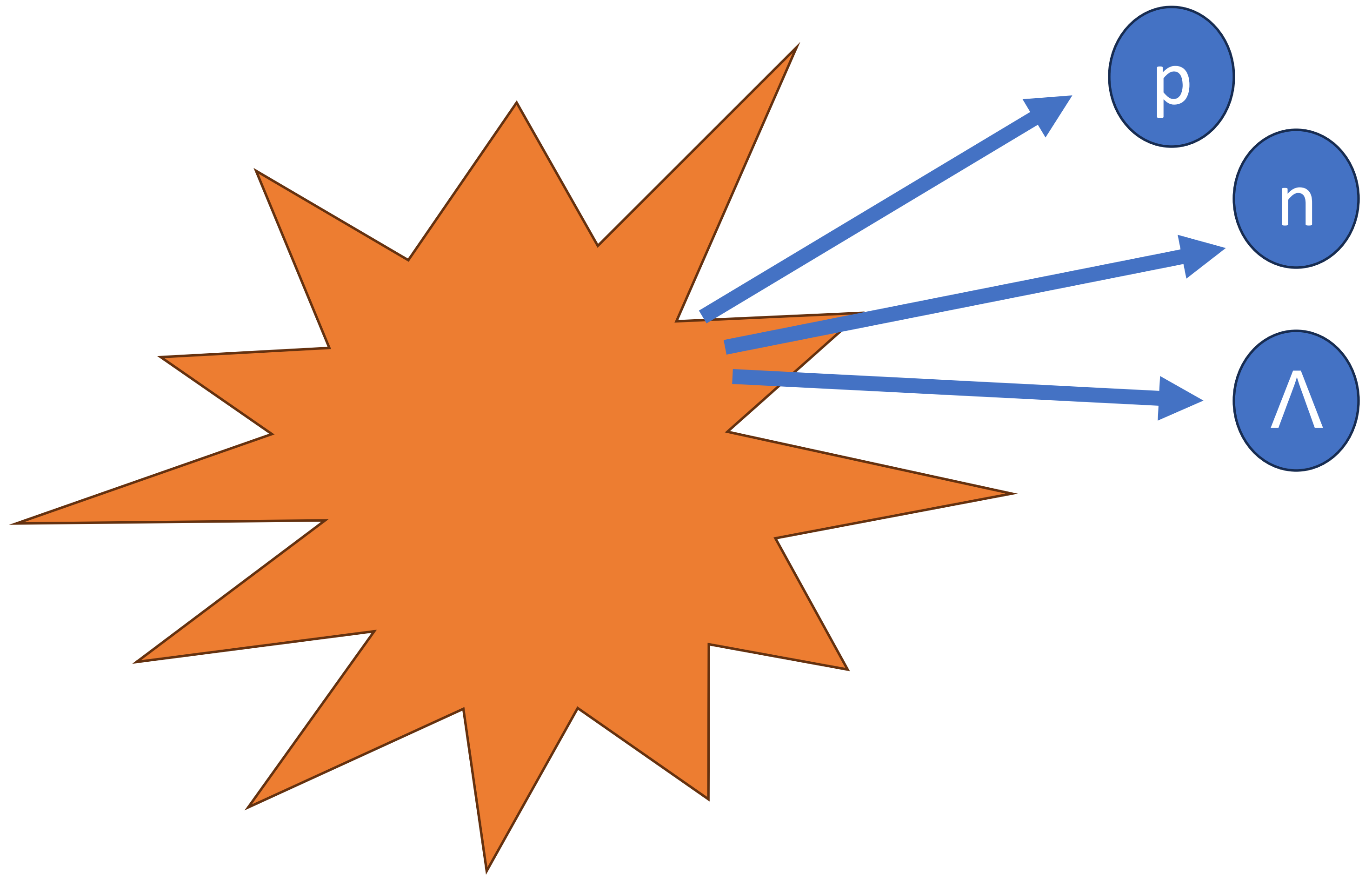
„Theoretical” challenges

Development of models for collisions at lower energies

- High collision energies = instant collisions
- Lower collision energies = continuous collision



Development of formalism for calculation of CF with taking into account 3-body interactions

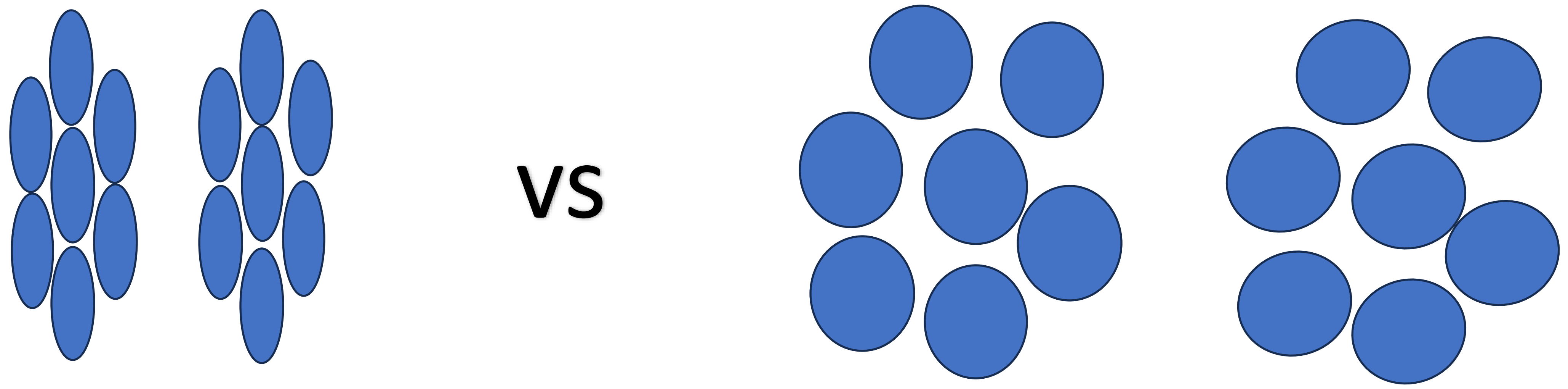


Warsaw University of Technology

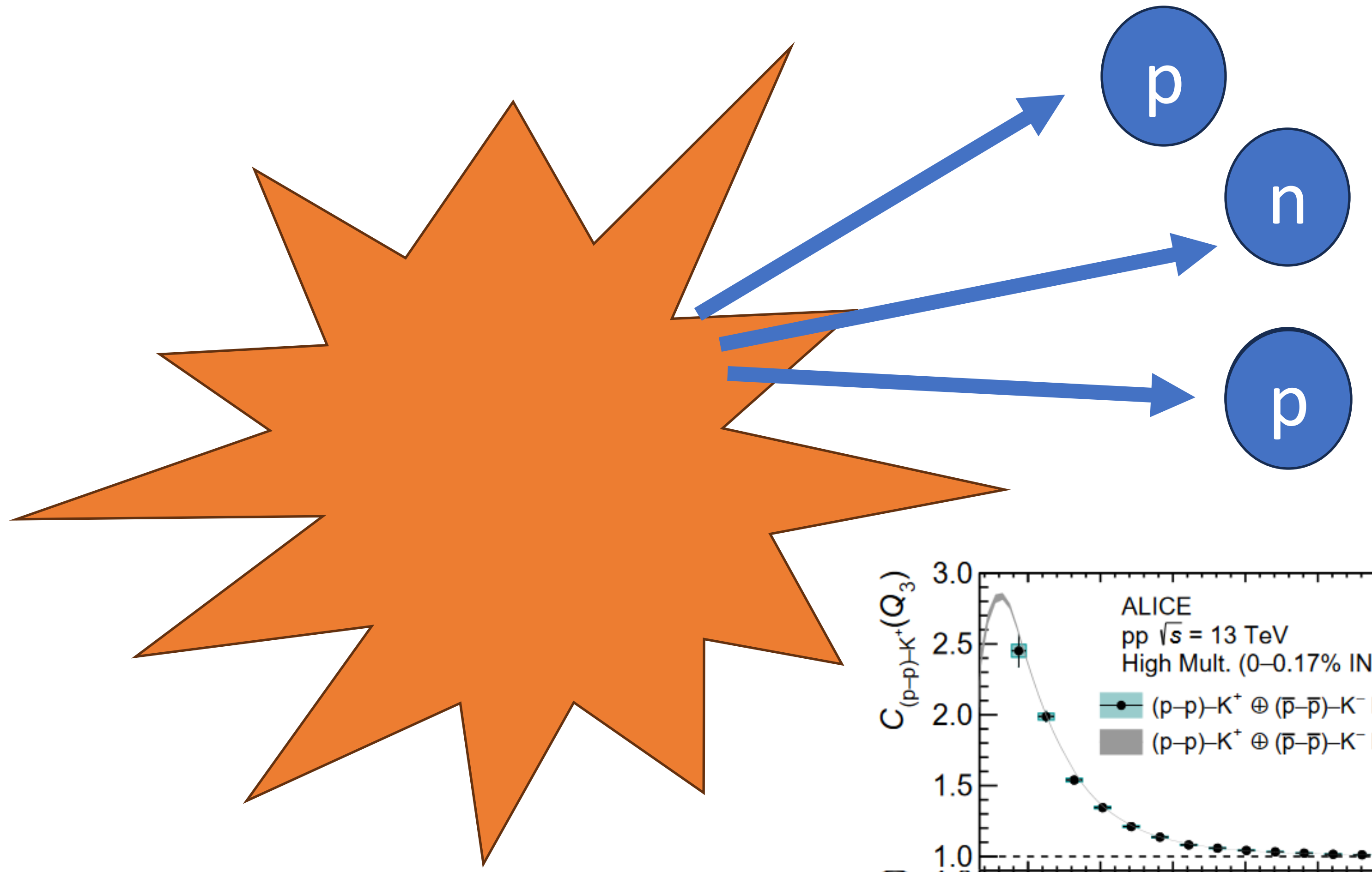
„Theoretical" challenges

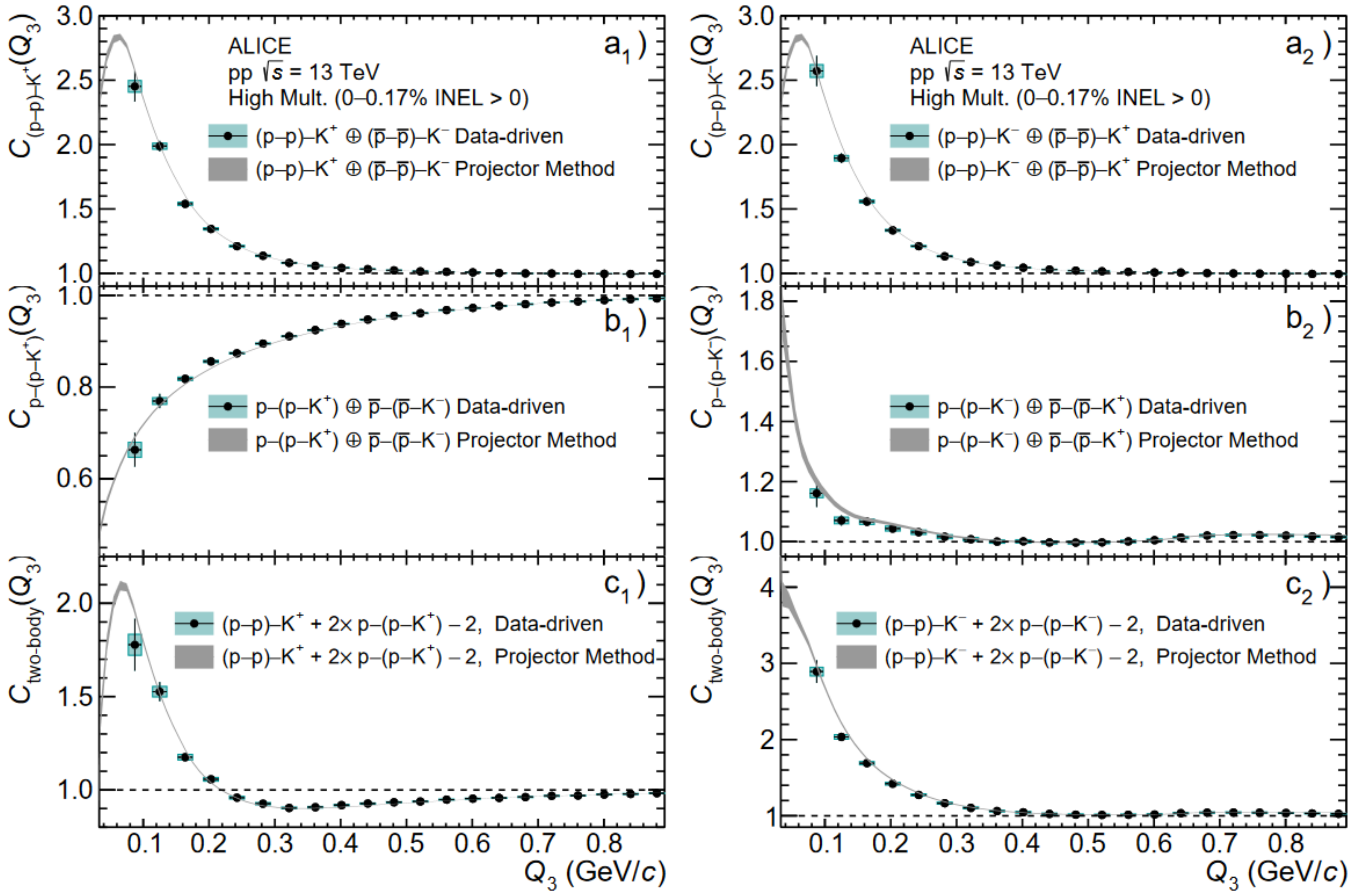
Development of models for collisions at lower energies

- High collision energies = instant collisions
- Lower collision energies = continuous collision



Development of formalism for calculation of CF with taking into account 3-body interactions





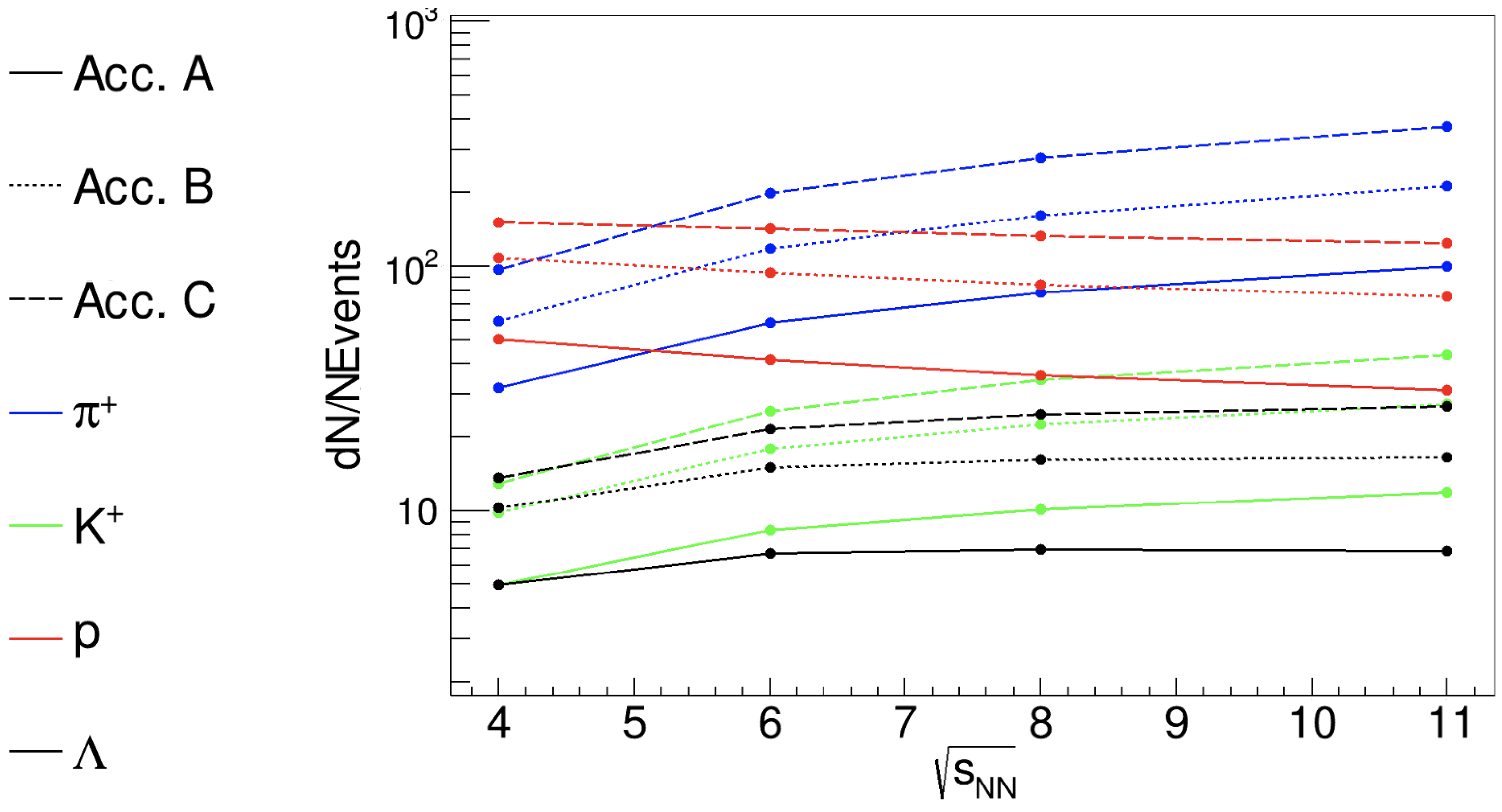
Study of the p−p−K+ and p−p−K− dynamics using the femtoscopy technique, ALICE Collaboration, Eur. Phys. J. A (2023) 59:298

Warsaw University of Technology

Experimental challenges

Taking sufficient amount of data e.g.:

- CBM interaction rate up to 10 MHz
  - How build event with continuous reading mode?
  - How trigger events?
  - How process data?

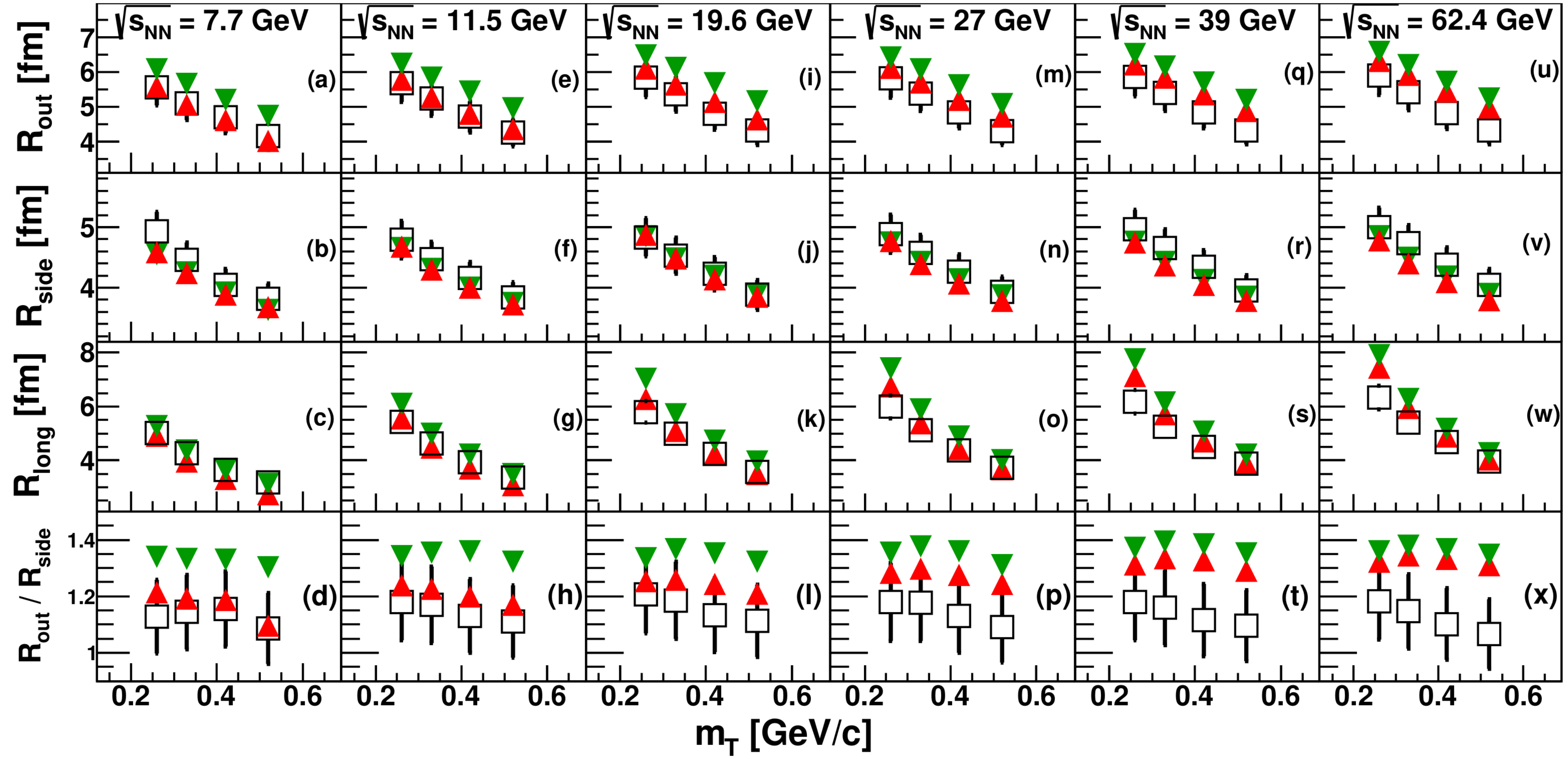


Production of particles in UrQMD model, D. Wielanek PhD thesis

Fitting measured correlation functions

- For pions & kaon – Bowler Sinukov
- What about non-gaussian sources?
  - Levy fits (M. Csanad +)
  - Imaging, deblurring techniques – no assumption about shape of the source! – still very exotic ☹ (Chi Kin Tam)
- What about protons?
  - New developments – **this talk**

Probing dynamics of the collision



vHLLE+UrQMD calculations:

- EoS affects the measured femtoscopic radii

Crossover EoS

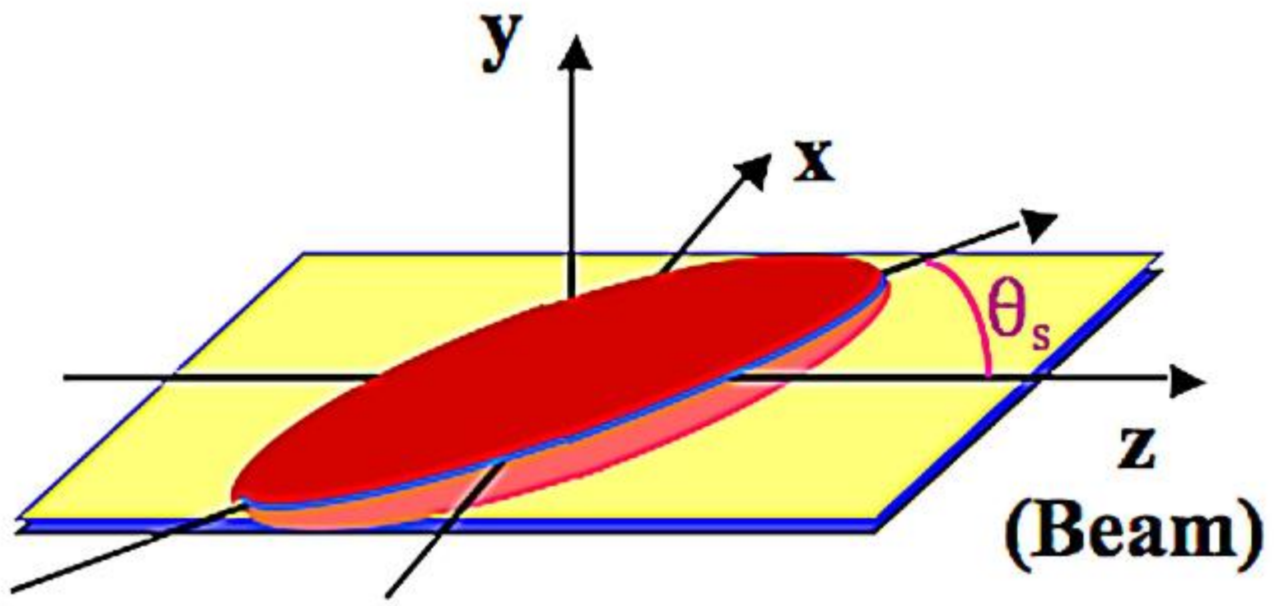
1st order EoS

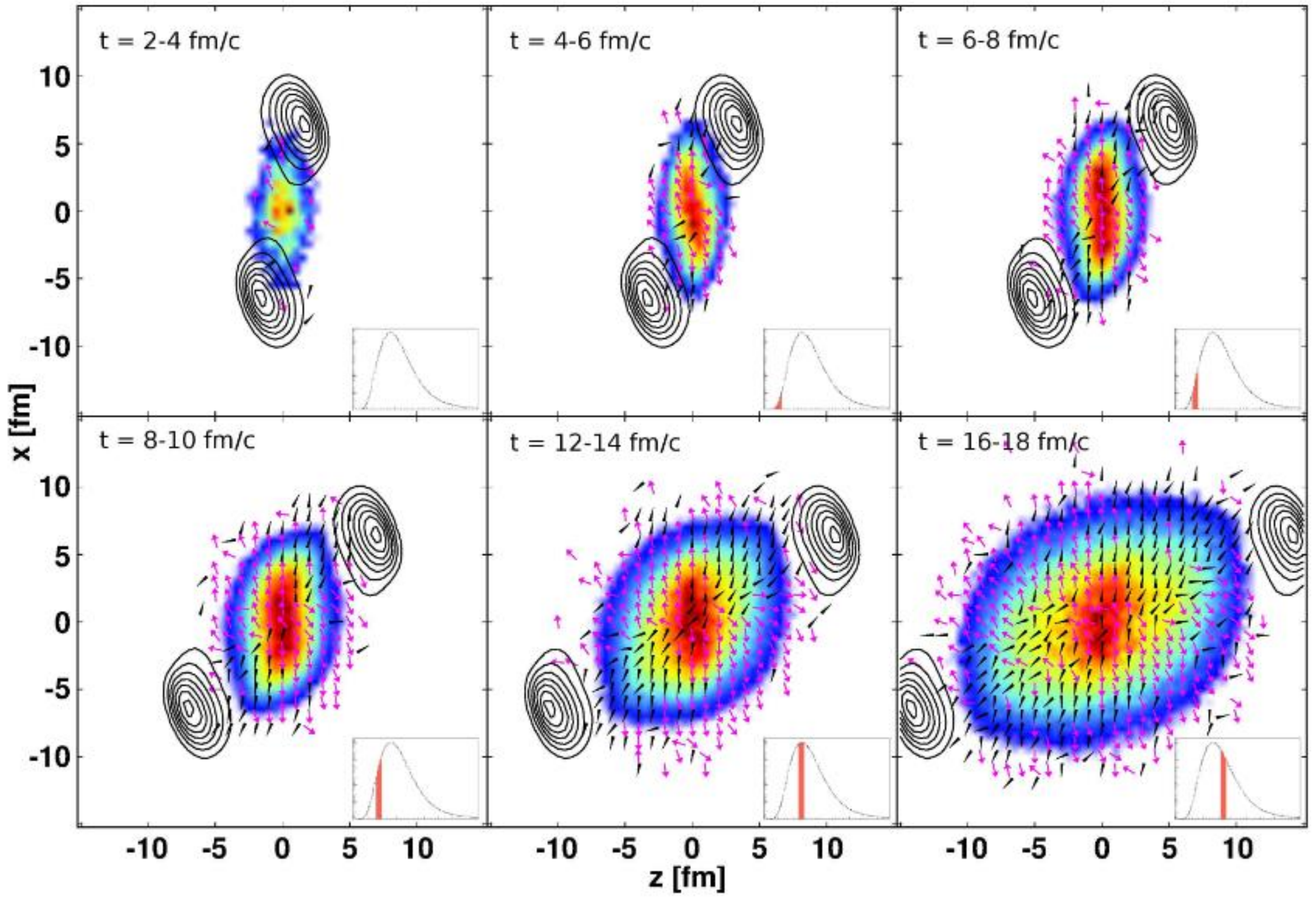
Correlation femtoscopy study at energies available at the JINR Nuclotron-based Ion Collider fAcility and the BNL Relativistic Heavy Ion Collider within a viscous hydrodynamic plus cascade model, P. Batyuk et al. Phys. Rev. C 96, 024911

J. Steinheimer, S. Schramm, and H. St¨ocker, J. Phys. G 38, 035001 (2011)

1PT Eos P. F. Kolb, J. Sollfrank, and U. W. Heinz, Phys. Rev. C 62, 054909 (2000).

Azimuthally sensitive HBT

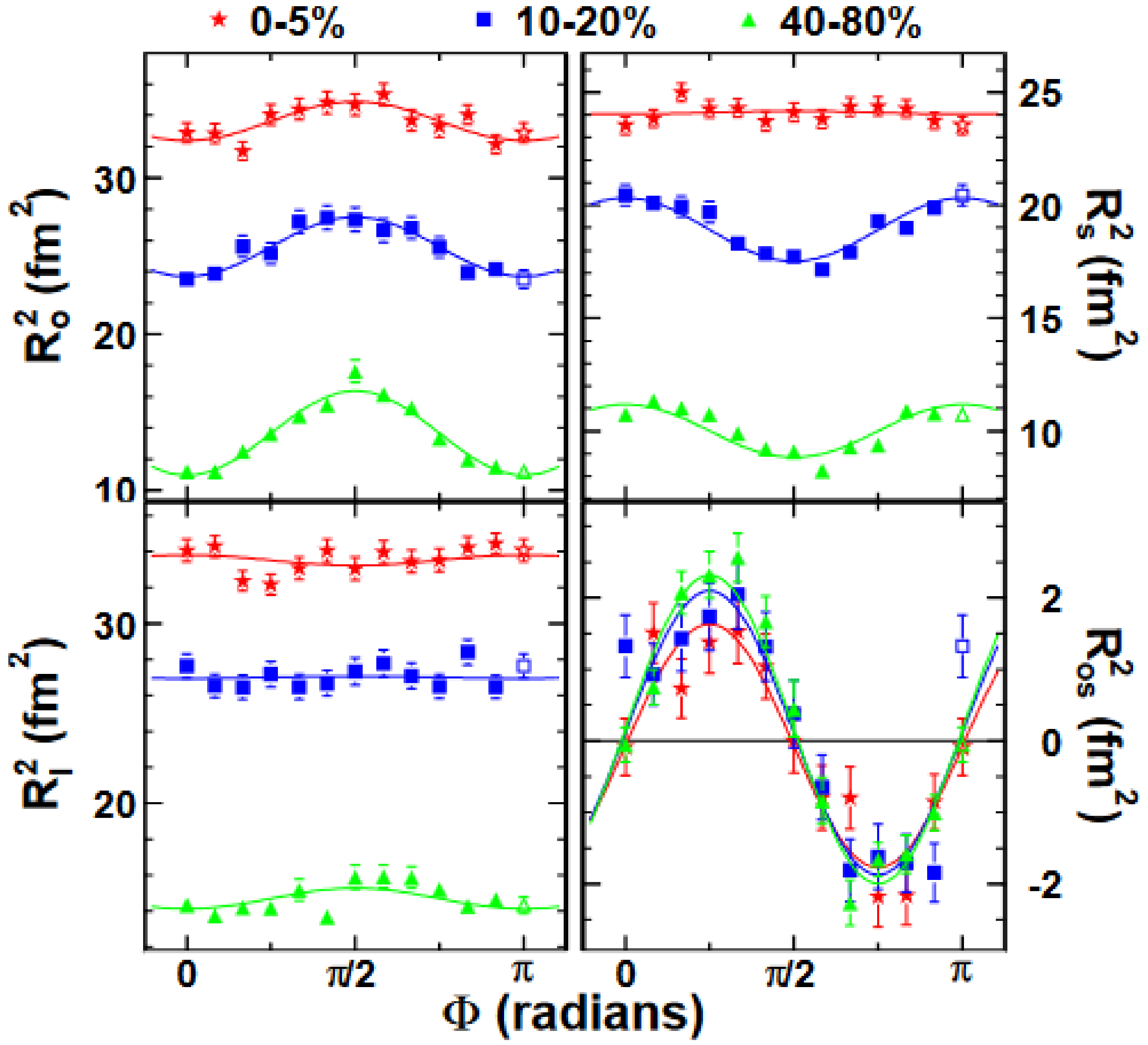




A twisted emission geometry in non-central Pb+Pb collisions measurable via azimuthally sensitive HBT, G. Graef, M. Lisa, M. Bleicher, Phys. Rev. C 89, 014903 (2014)

General idea:

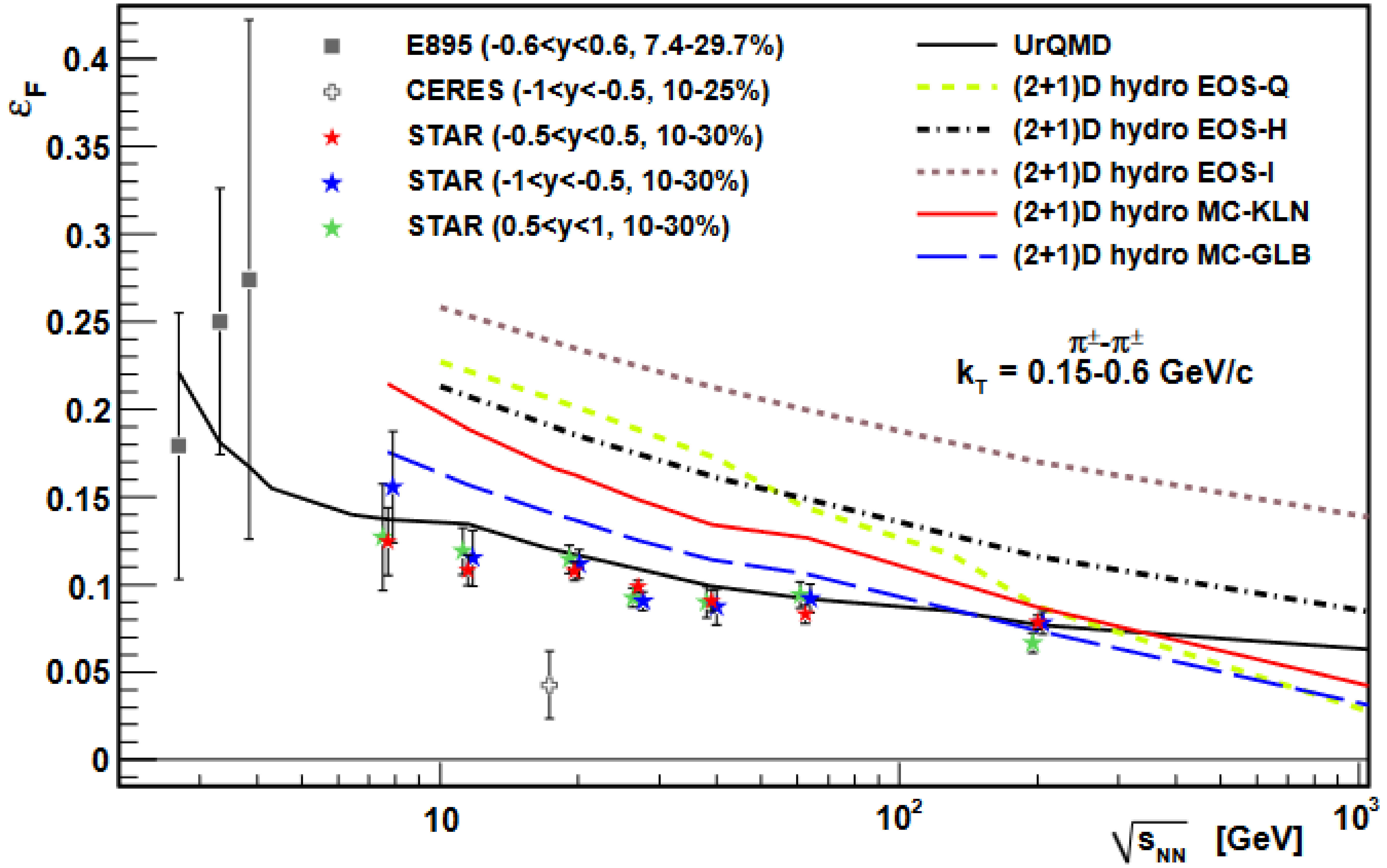
- Extension of HBT 3D measurements with respect to the reaction plane
- Extraction of tilt angle
- Probing dynamics of the collisions
- Done for pion @ STAR 7.7-200 GeV
- See Tilted geometry in the heavy-ion collisions tal Y. Khyzhniak (Monday)



HBT radii from the UrQMD transport approach at different energies, **The European Physical Journal Conferences,** Gunnar Graef &et al. 2011

Femtoscopy

- Probing spatio-temporal structure of the collision
  - STAR measurements done for various energies, reconstructed the eccentricity in Au+Au collisions at RHIC
  - Eccentricity reproduced by UrQMD model in cascade mode but non of the model listed in figure was able to reproduce all observables (spectra, HBT etc.)

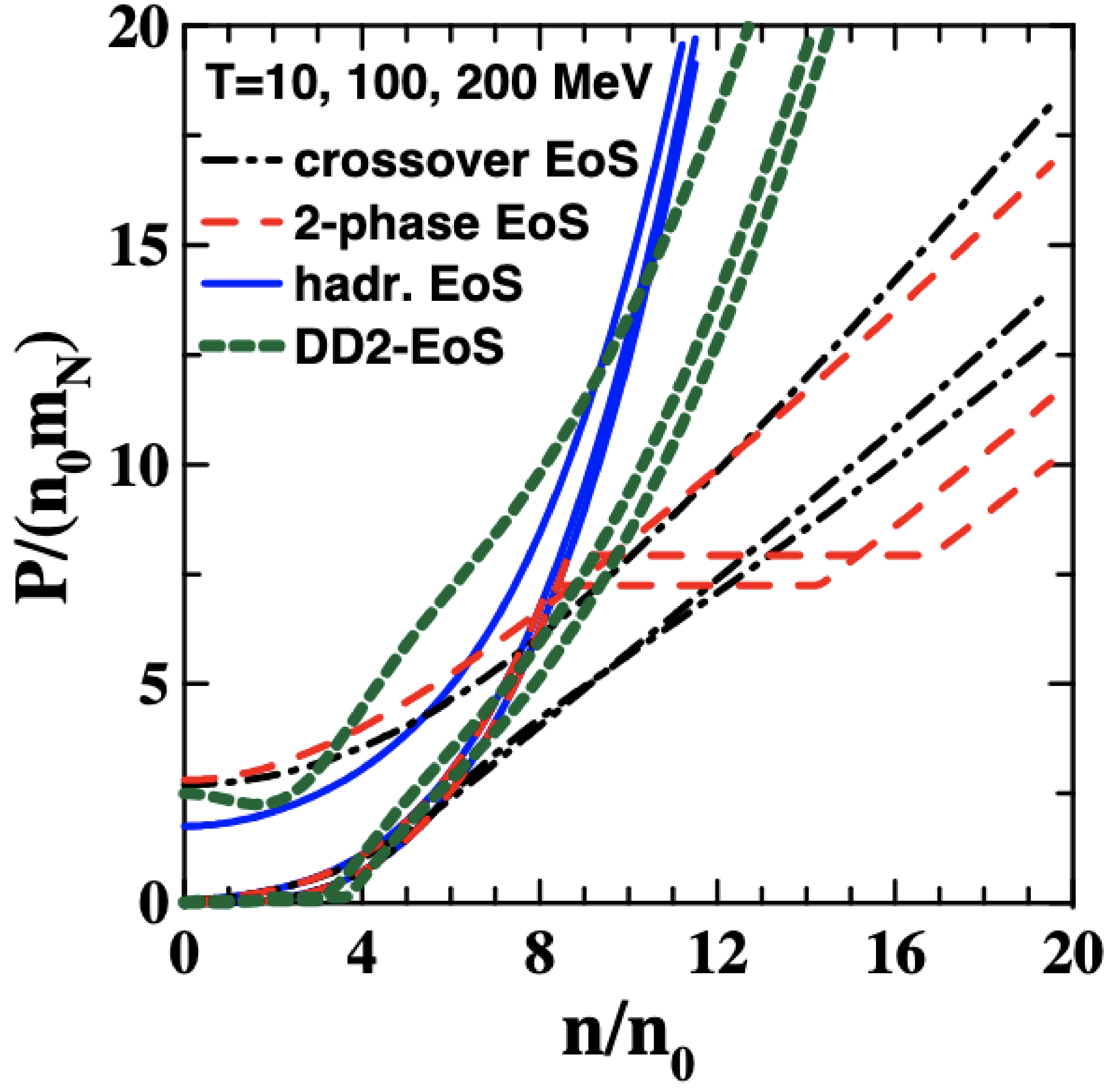


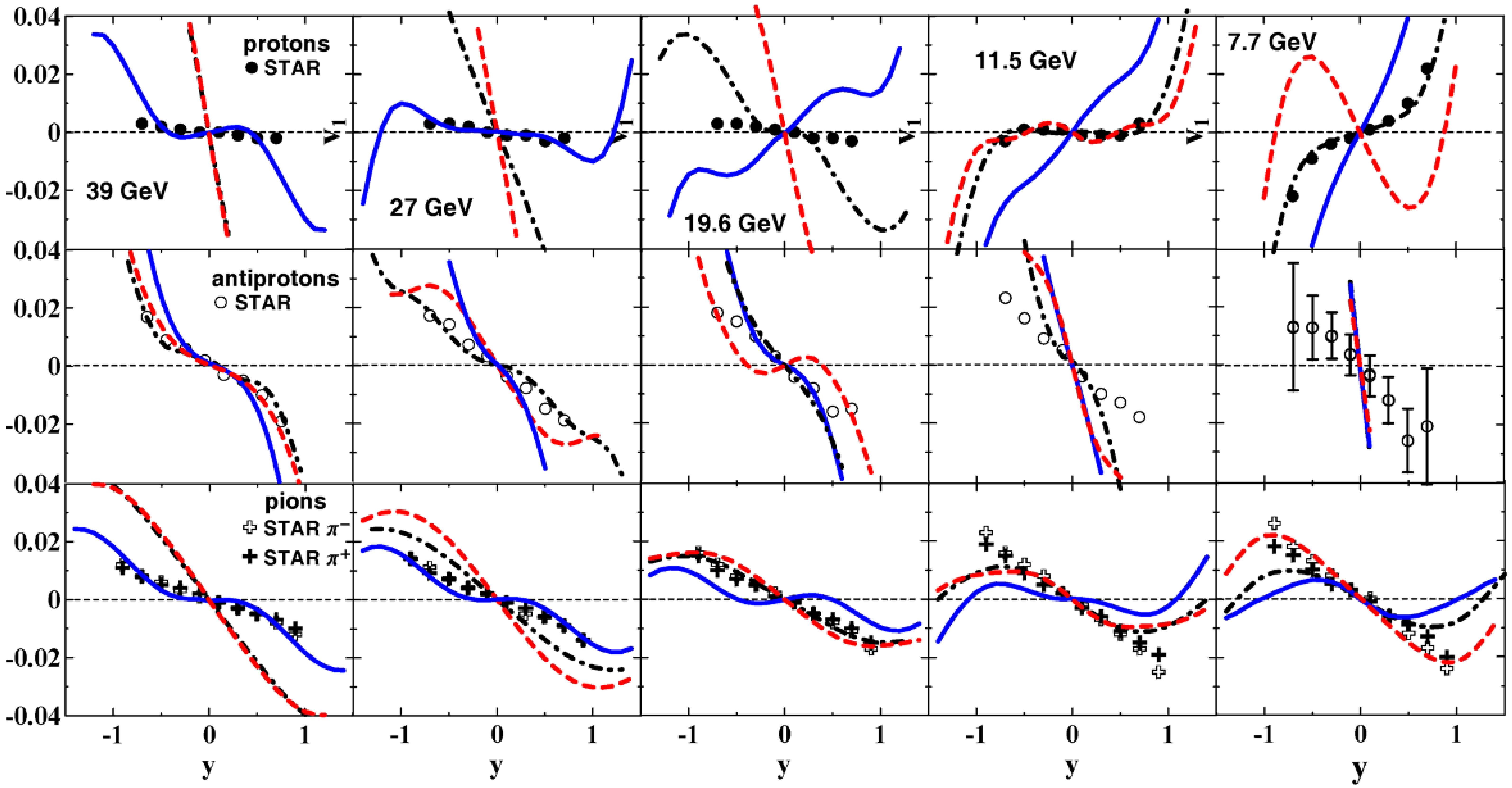
Size of fireball:
σ_x – in the reaction plane
σ_y – out of the reaction plane

$$\varepsilon_F = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2}$$

Beam energy dependent two-pion interferometry and the freeze-out eccentricity of pions in heavy ion collisions at STAR, STAR Collaboration, Phys Rev C 92, 2015

Azimuthally sensitive HBT





[Directed Flow in Heavy-Ion Collisions and Its Implications for Astrophysics](), Universe, STAR Collaboration, 2017

Faculty
of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

Towards new method of fitting correlation functions

Warsaw University
of Technology

Towards 3D protons

- Standard approach (CorrFit)
  - Generation of femtoscopic pairs from model (e.g., Therminator)
  - Calculation of theoretical function #1
  - Calculation of theoretical function #2
  - ....
  - Finding best fit
  - Paper ☺

$$C(q) = \int S(r^*, k^*)|\Psi(r^*, k^*))|^2 dr^* => \frac{2}{N(N-1)} \sum_{i=1}^{N} \sum_{j=i+1}^{N} |\Psi(r^*, k^*)|^2$$

- Pros:
  - Works with basically any pairs of particles
  - Works with complicated sources
  - Possible to include momentum resolution
  - ...
- Problems:
  - Time!

Towards 3D protons

Spherical Harmonics:

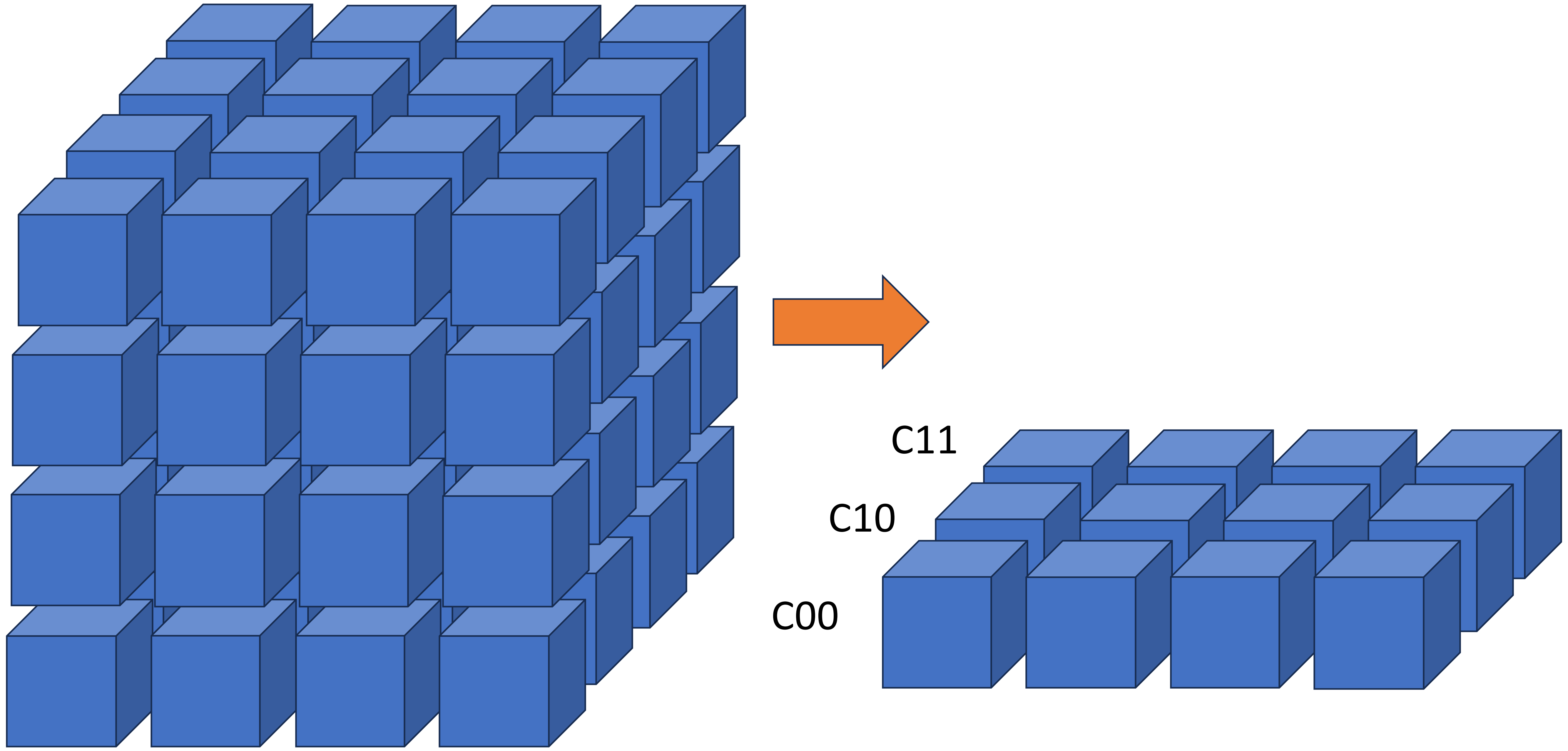
$$C(q) = \sum_{l,m} C(q) Y^*_{lm}\left(\Omega_q\right) d\Omega_q$$

Pros:

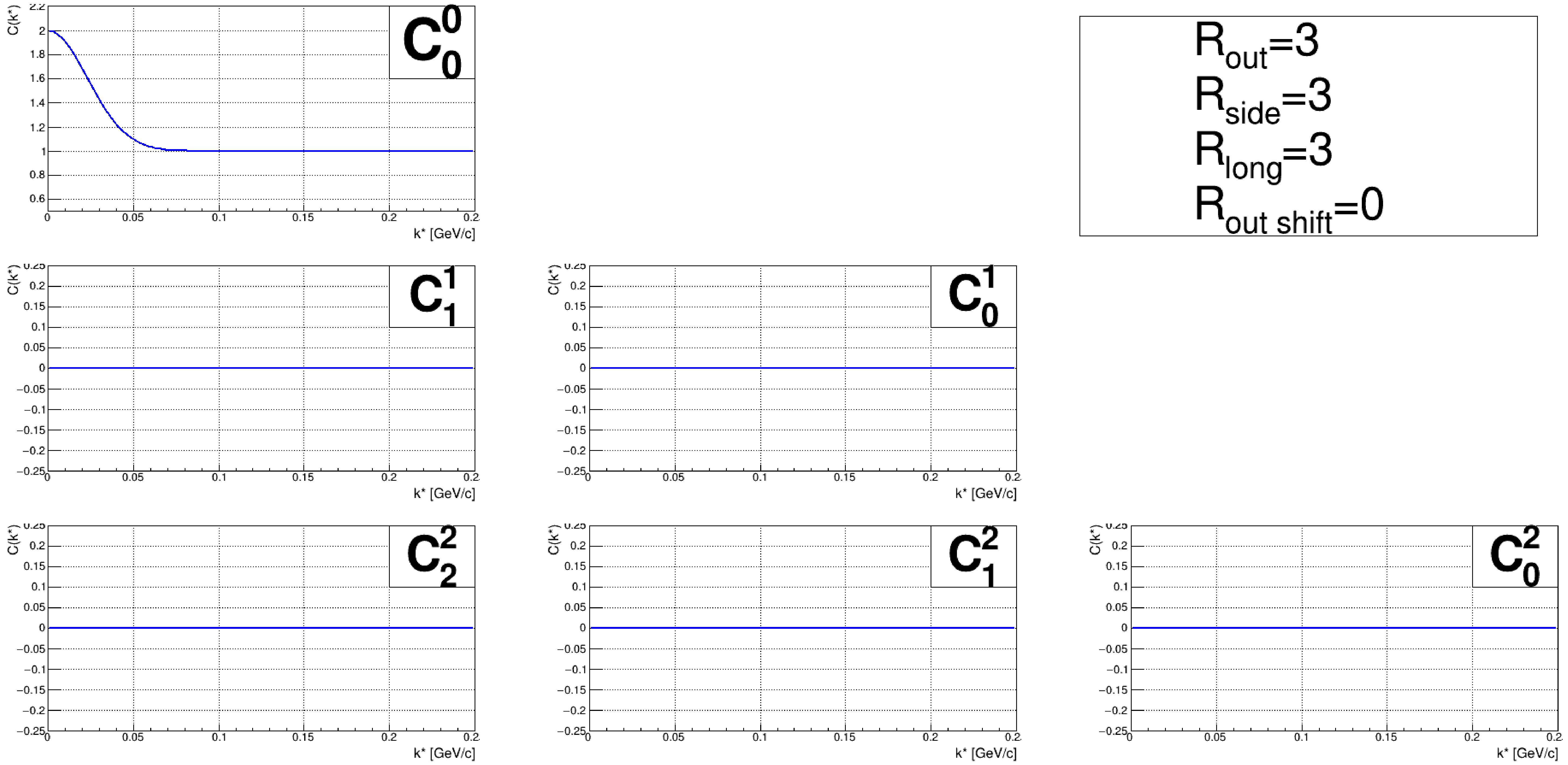
- Smaller number of bins – faster fitting
- 1D histogram – can be visualized

Cons:

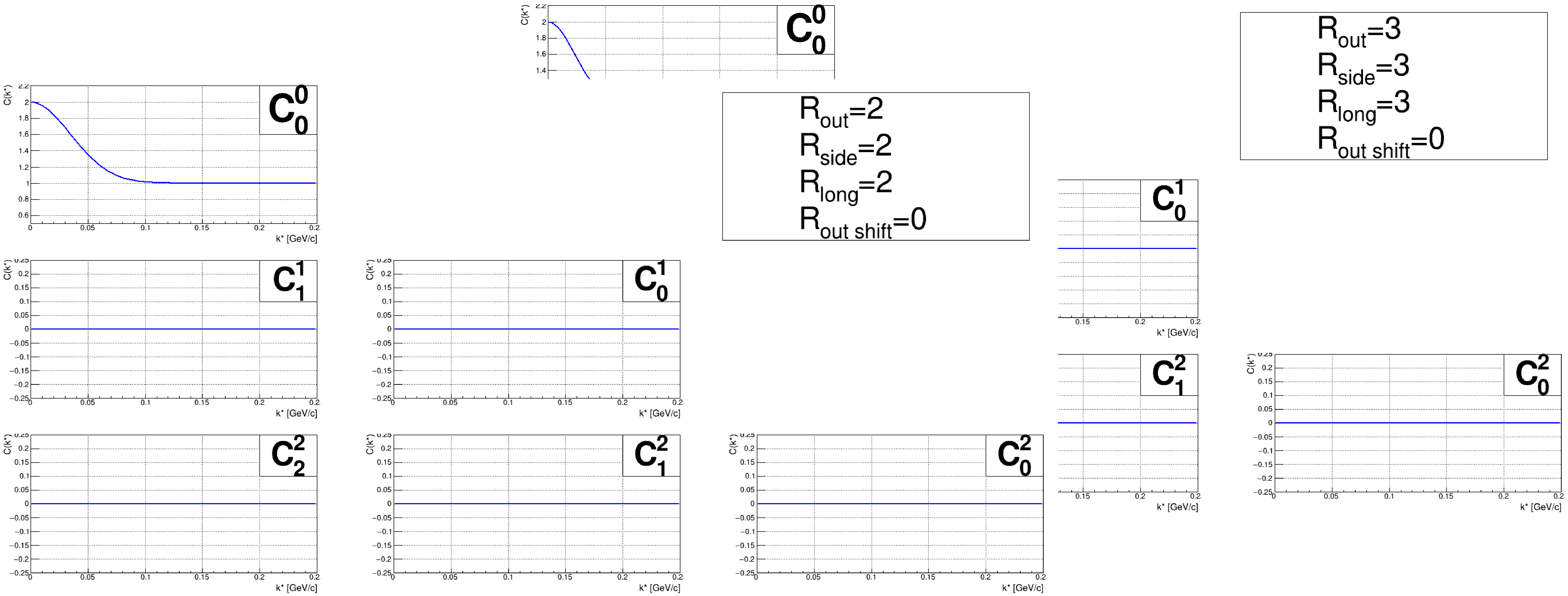
- Less intuitive
- More complicated math



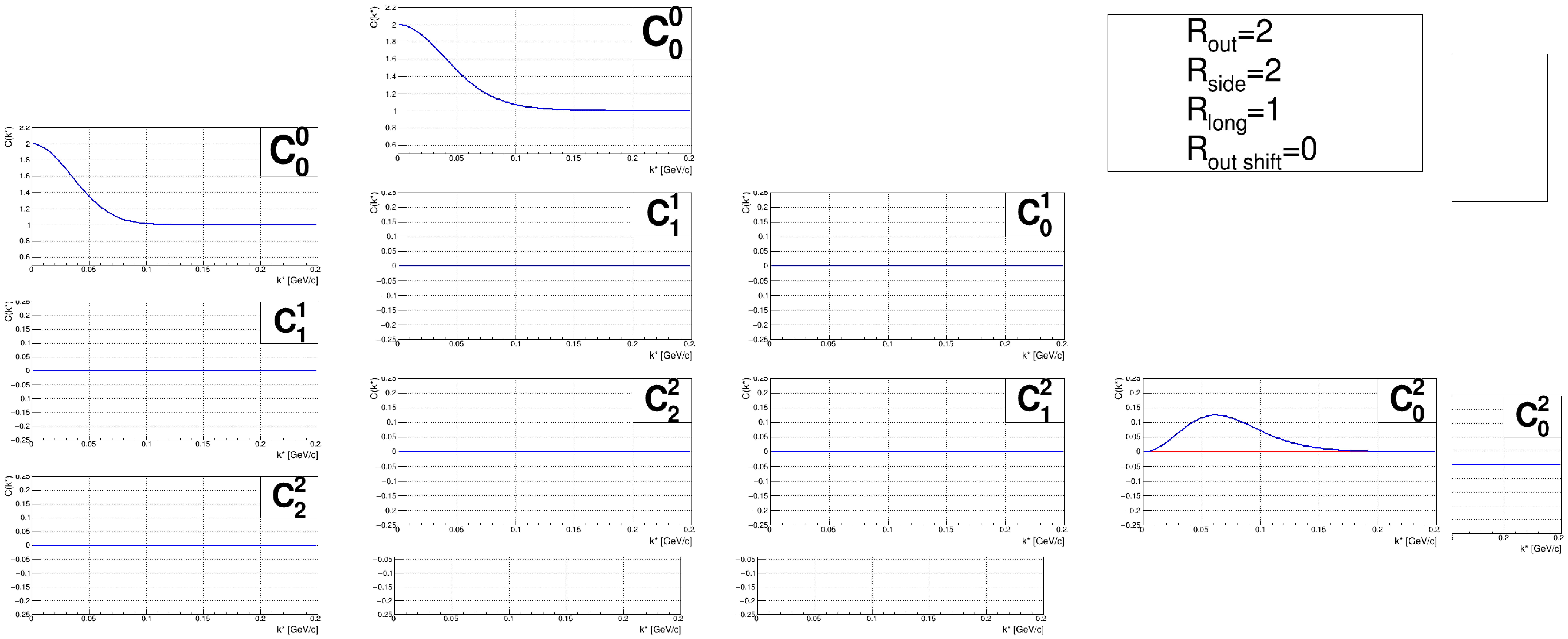
Towards 3D protons



Towards 3D protons

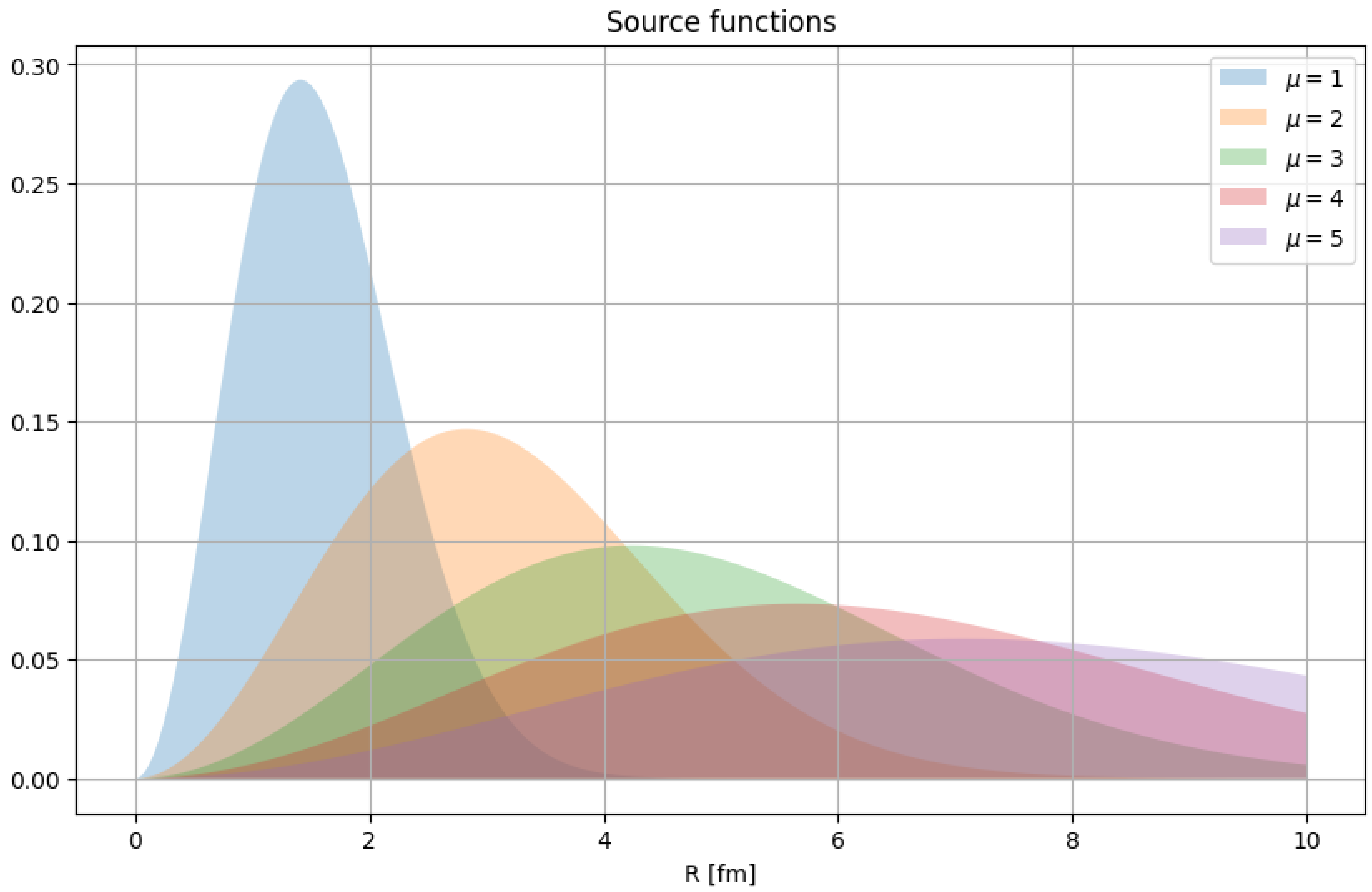


Towards 3D protons



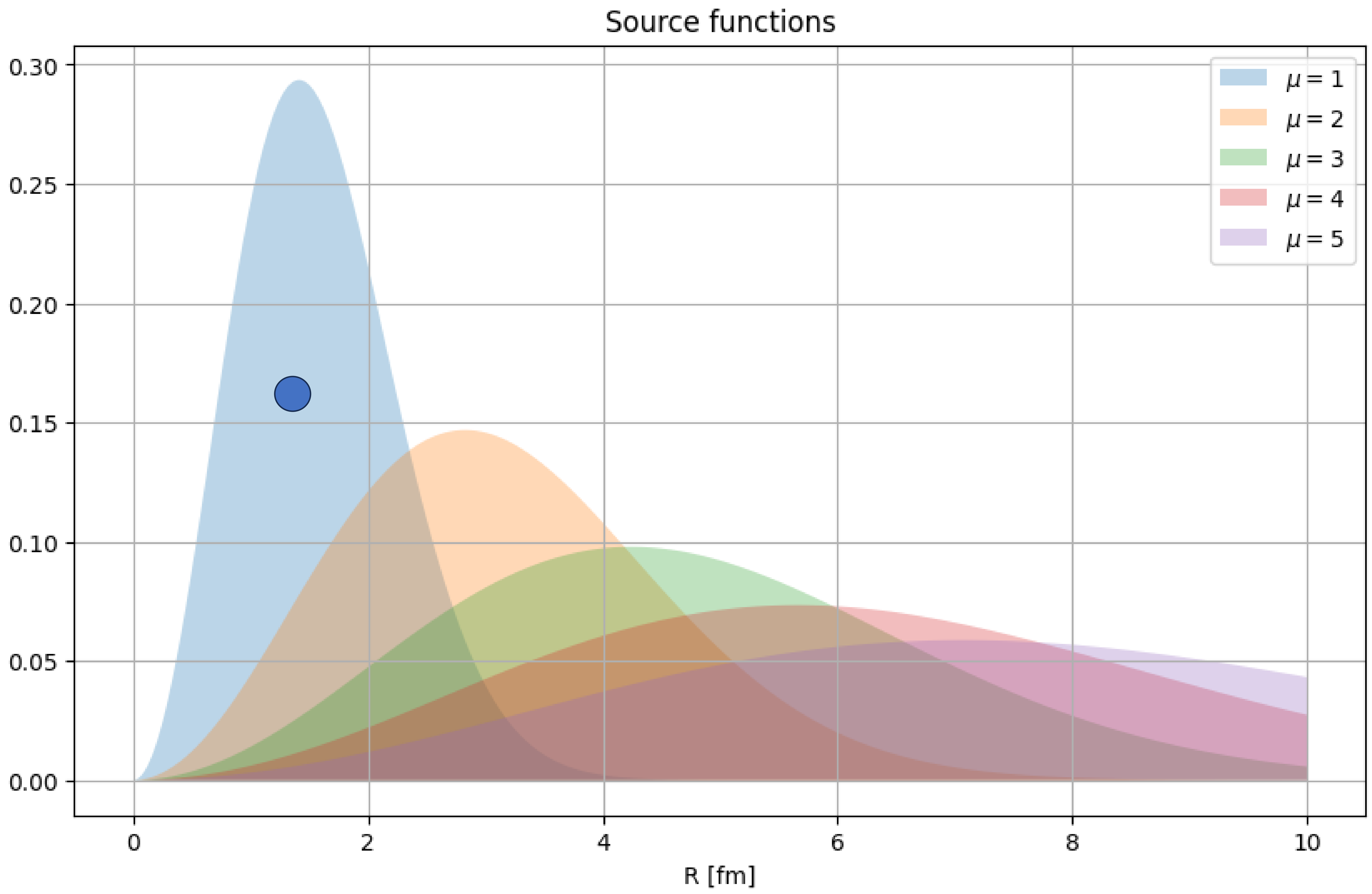
Towards 3D protons

- New approach (ROCO)
  - **R**eading pairs **o**nly once
  - **C**alculating of two-particle wave function only **o**nce
  - Computing time almost constant (depend only on number of pairs)



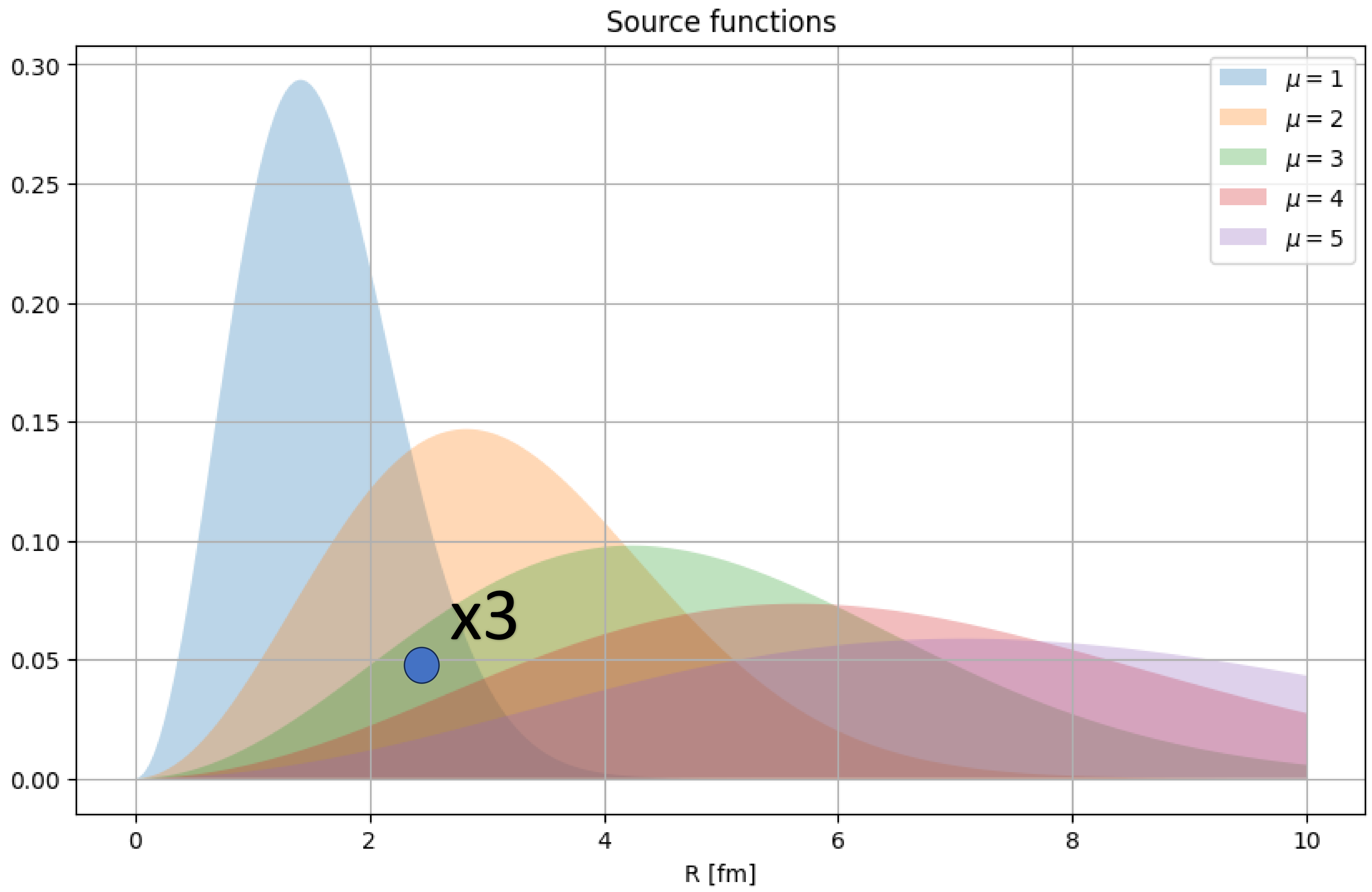
Towards 3D protons

- New approach (ROCO)
  - **R**eading pairs **o**nly once
  - **C**alculating of two-particle wave function only **o**nce
  - Computing time almost constant (depend only on number of pairs)



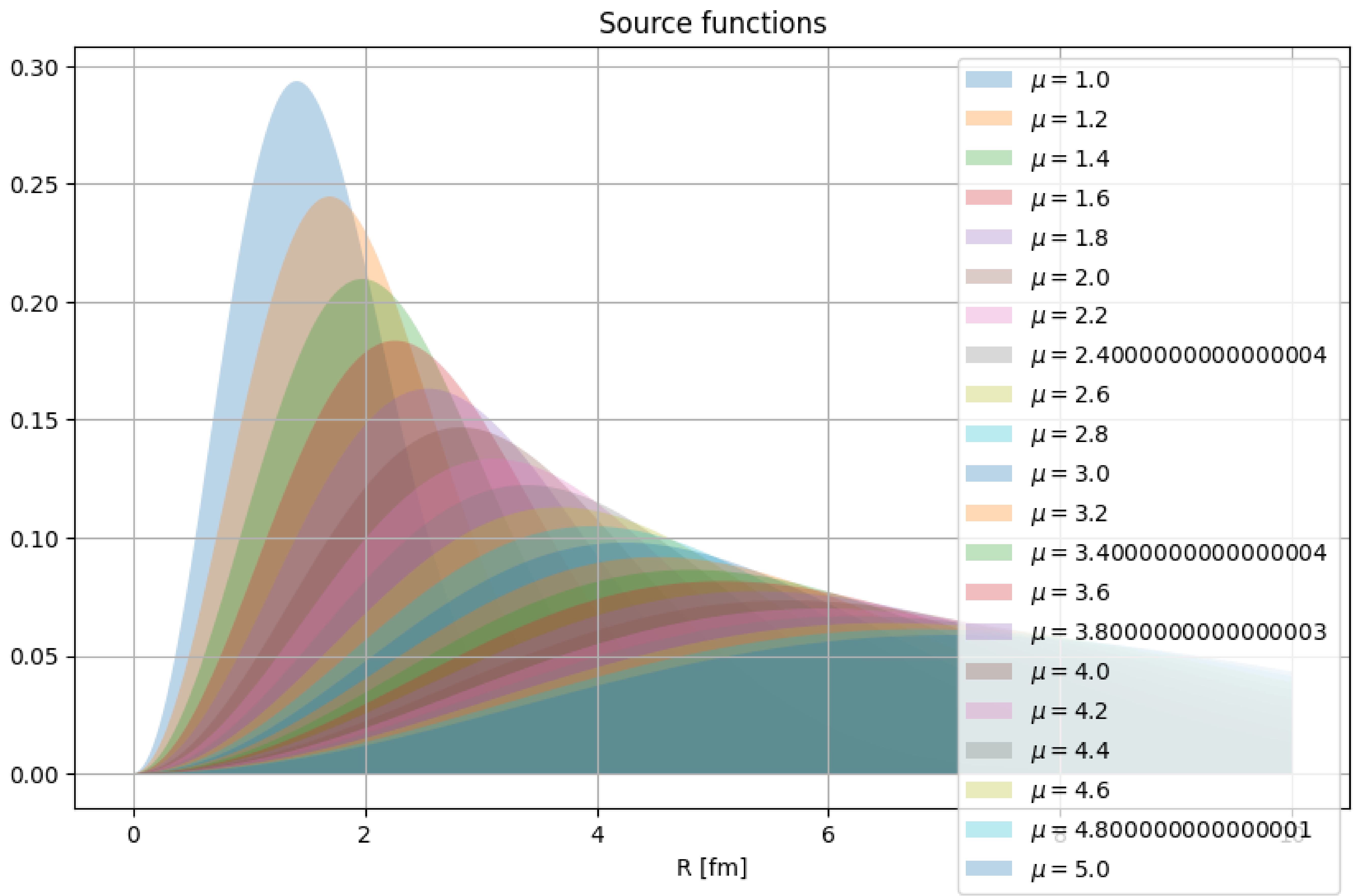
Towards 3D protons

- New approach (ROCO)
  - **R**eading pairs **o**nly once
  - **C**alculating of two-particle wave function only **o**nce
  - Computing time almost constant (depend only on number of pairs)



Towards 3D protons

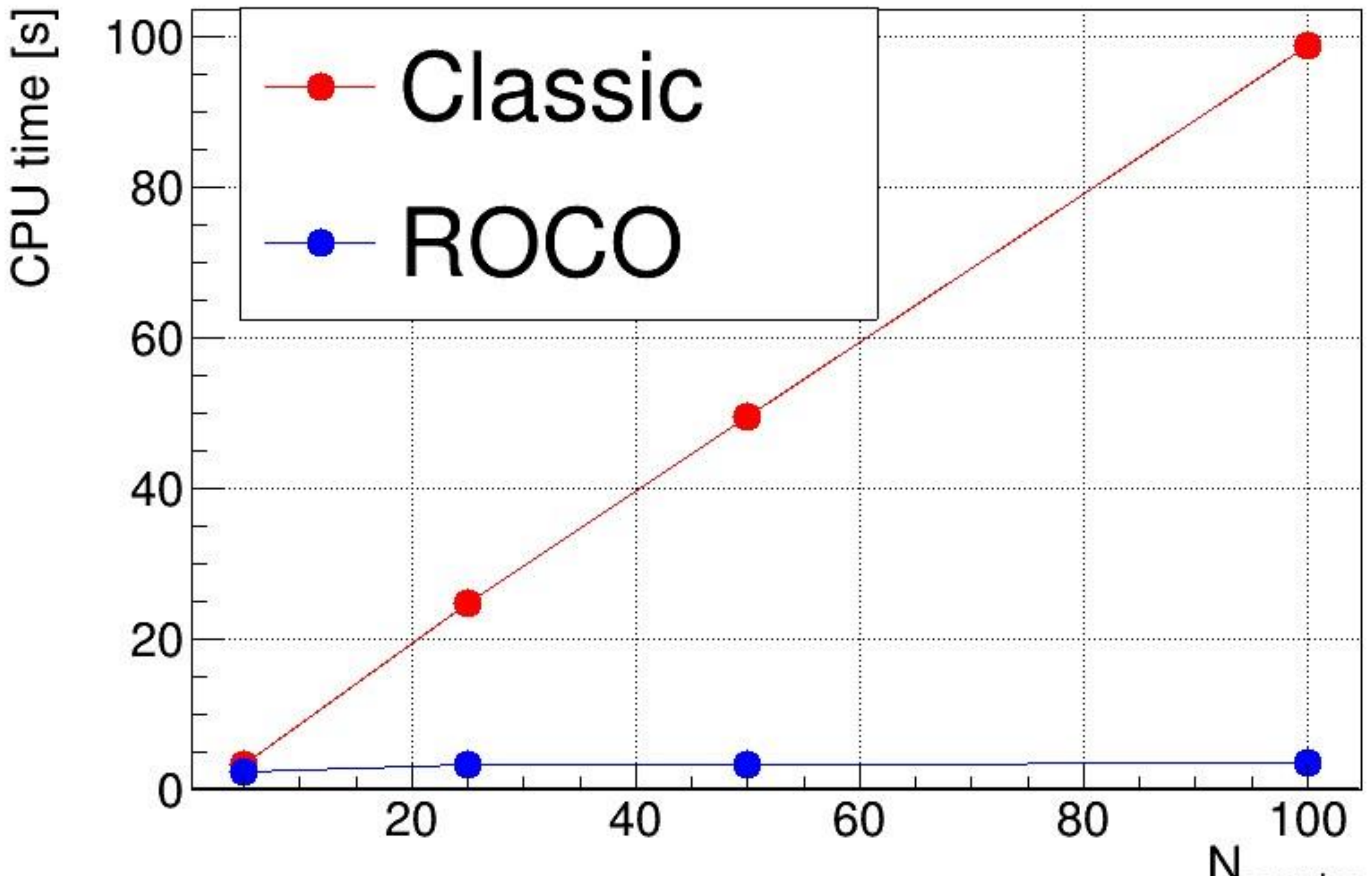
- New approach (ROCO)
  - **R**eading pairs **o**nly once
  - **C**alculating of two-particle wave function only **o**nce
  - Computing time almost constant (depend only on number of pairs)



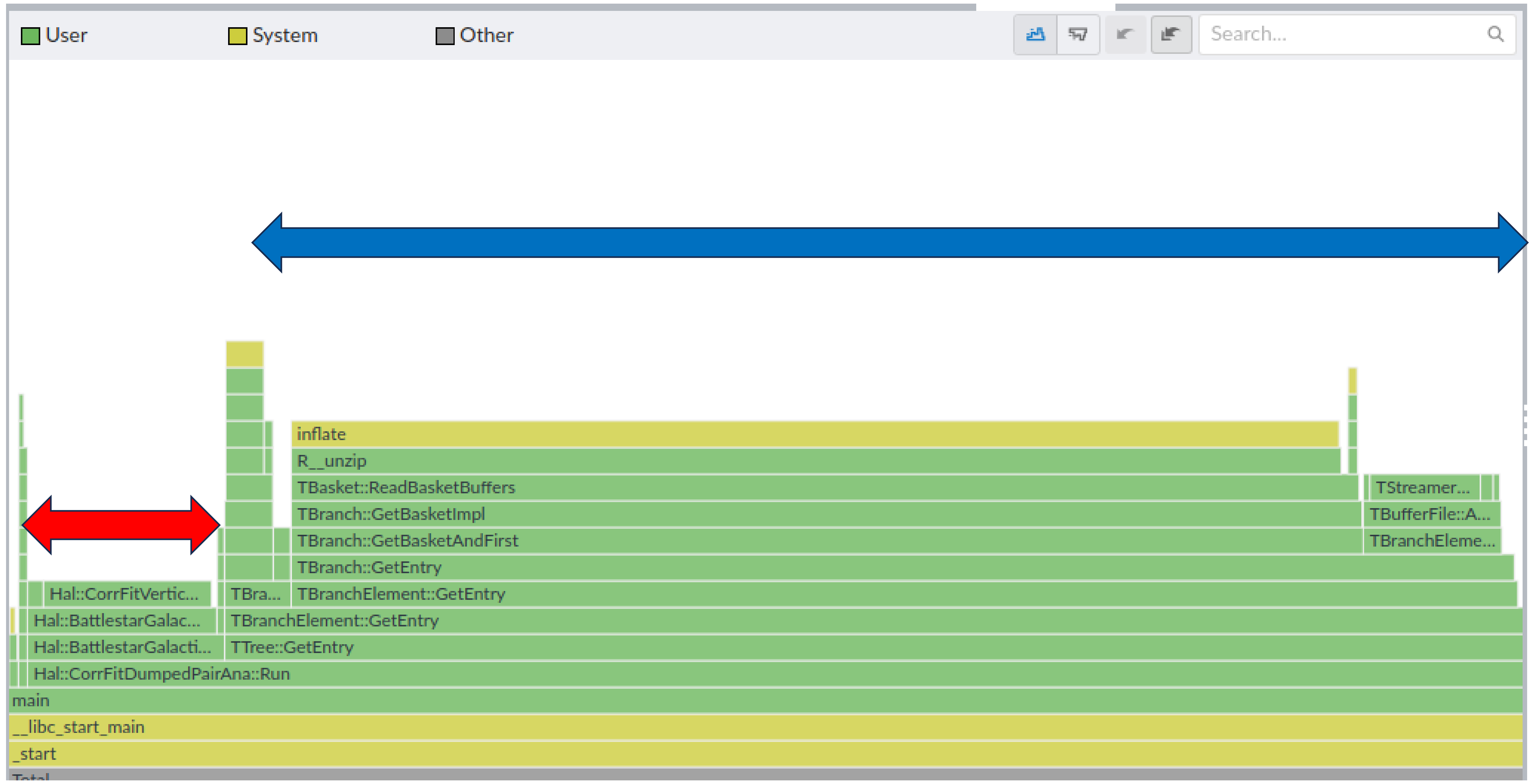
Towards 3D protons

Example of test of code

- Below comparion of ROCO vs classical method
- Similar improvement in 3D achieved



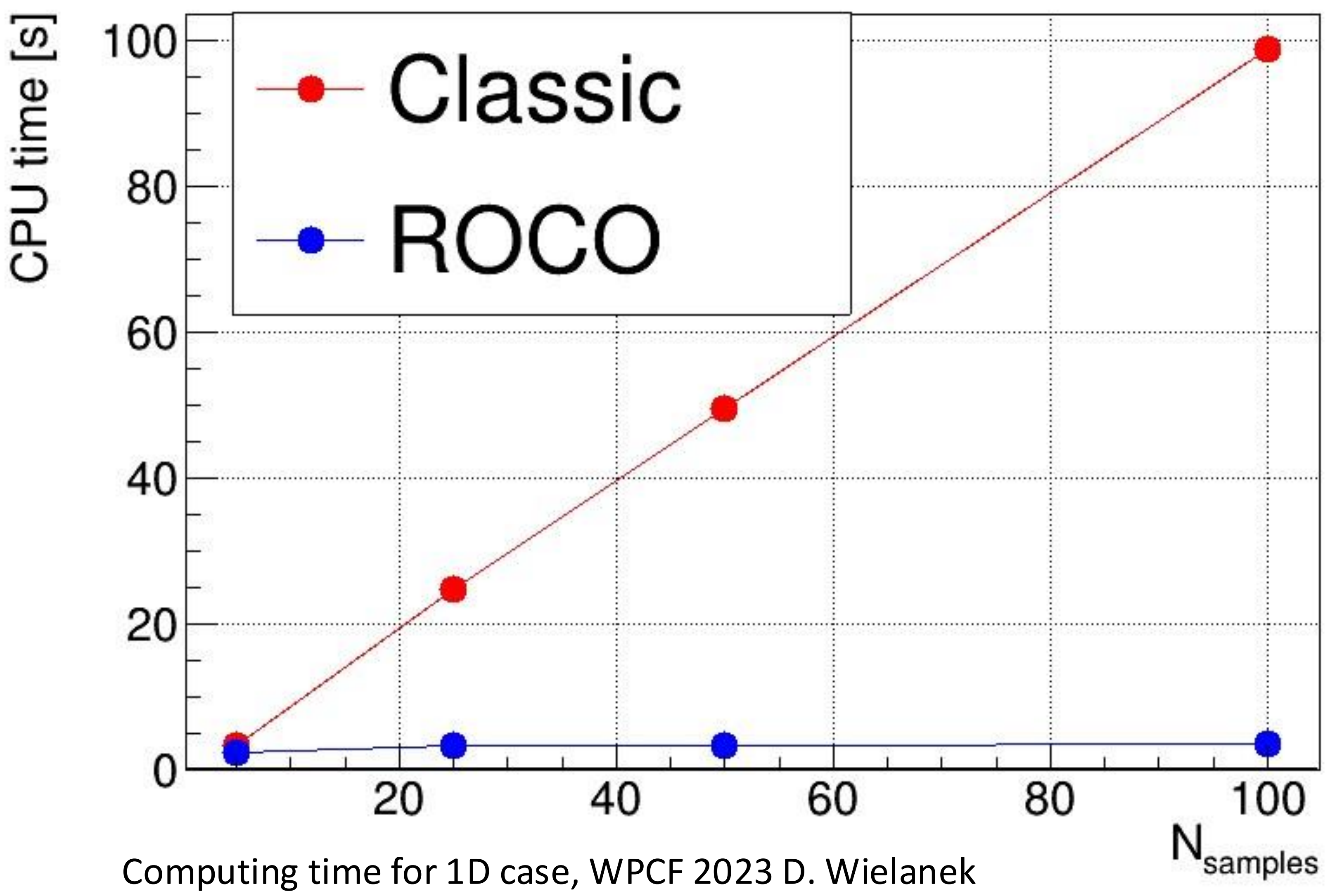
Computing time for 1D case, WPCF 2023 D. Wielanek



Towards 3D protons

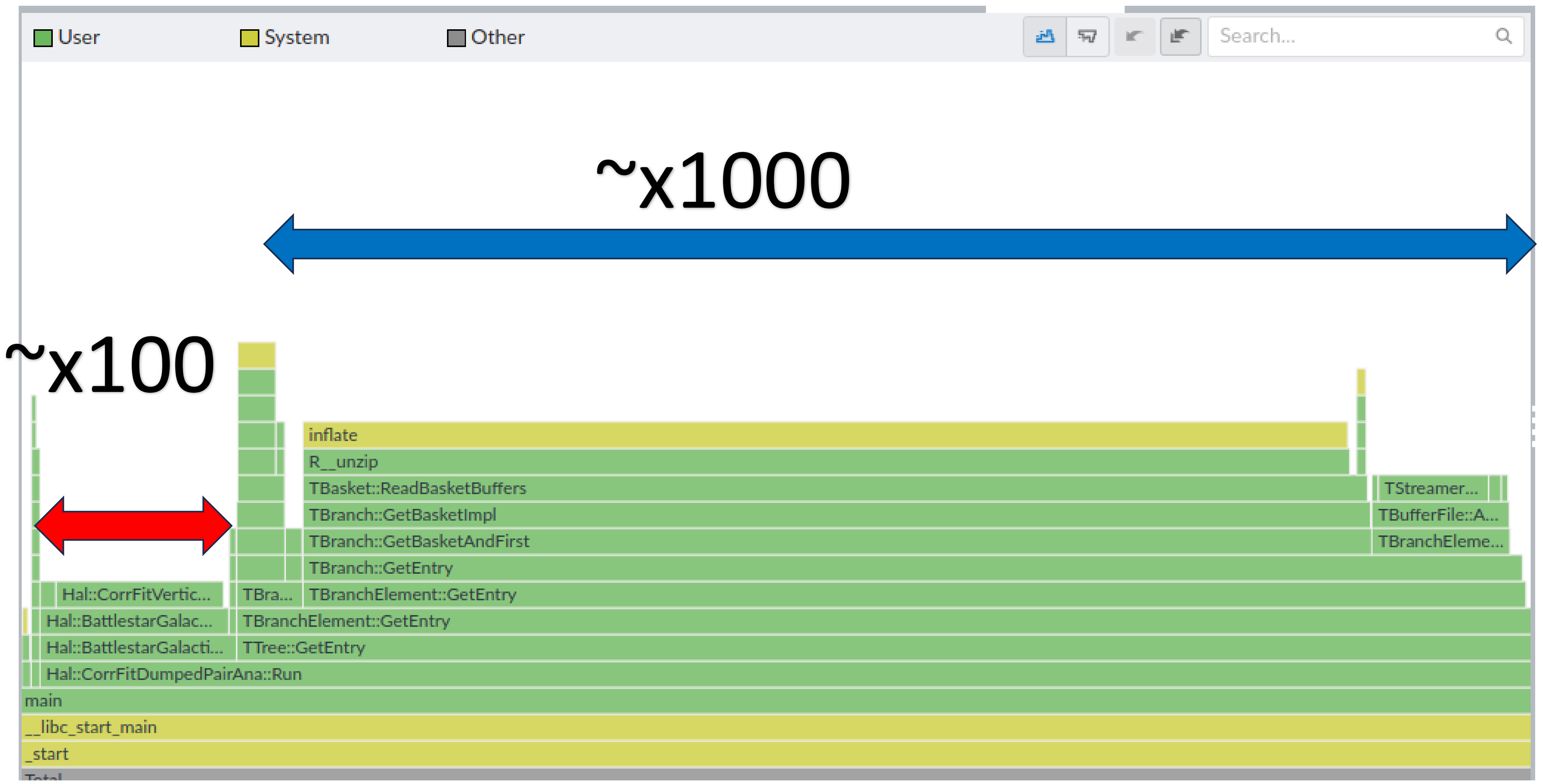
Example of test of code

- Below comparion of ROCO vs classical method
- Similar improvement in 3D achieved



Computing time for 1D case, WPCF 2023 D. Wielanek

N=1000



Towards 3D protons

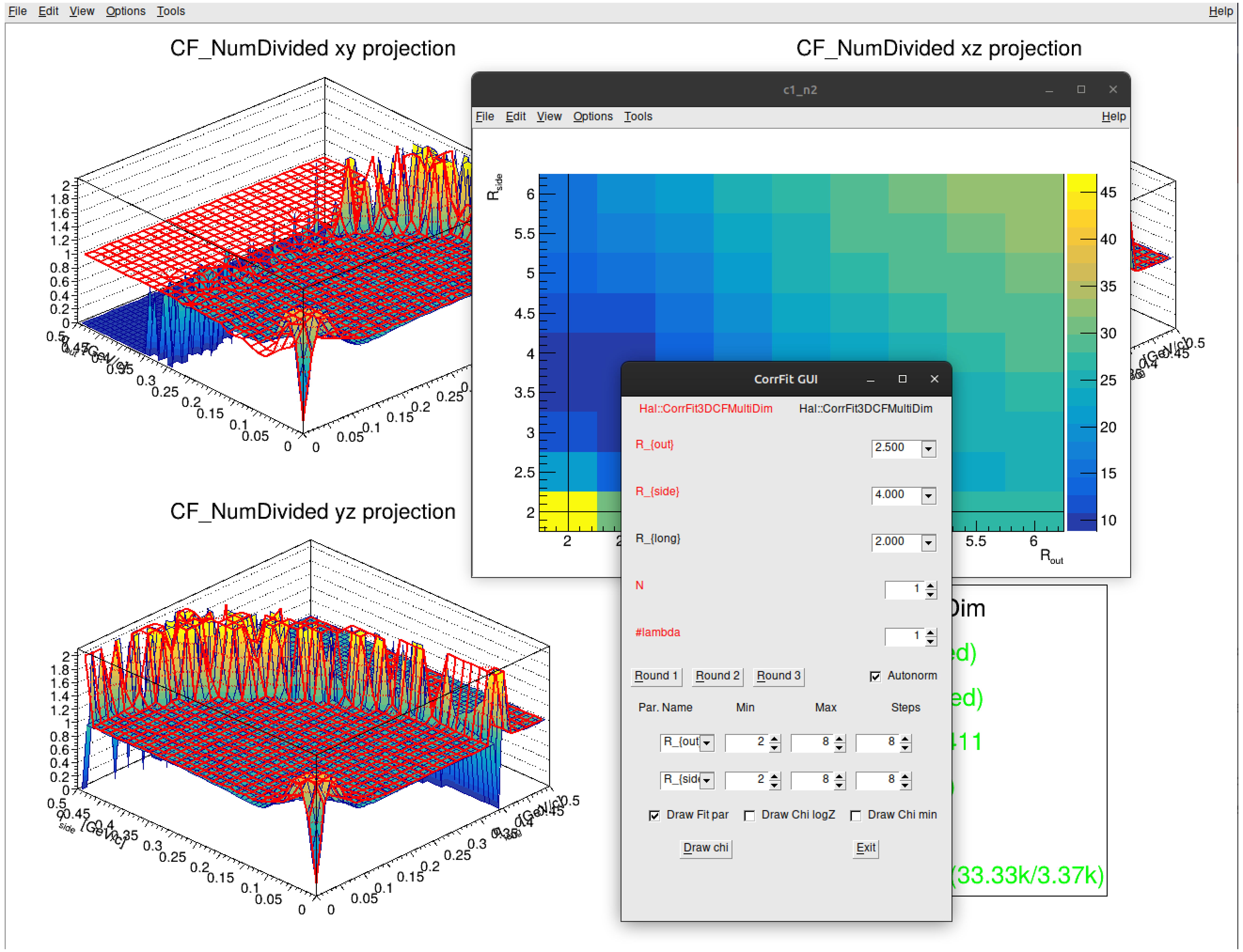
General way to fit the data:

- Prepare pair file
- call hal-corrfit 0 – prepare xml-template and macro for calculations, modify them
- Send jobs to computer farm (each calculates part of the CF)
- Call hal-corrfit 1 – check and combine numerators and denominators of CF
- Call hal-corrfit 2 – compress data (store CF)
- Download map to your local PC and fit data

```xml
<CorrfitConfig>
<Parameters>
        <Param name="R_{out}" min="1" max="10" step="1"></Param>
        <Param name="R_{side}" min="1" max="10" step="1"></Param>
        <Param name="R_{long}" min="1" max="10" step="1"></Param>
</Parameters>
<!-- full path to file with pairs-->
<PairFile>zz.root</PairFile>
<!-- optional part, use to configure dump pair analysis-->
<DumpAnalysisConf>
        <CorrelationFunction>
                <Name>CF</Name>
                <Frame>EKinematics::kLCMS</Frame>
                <Type>Femto3DCF</Type>
<!-- optional part, used only for spherical harmonics-->
                <L>3</L>
                <Xaxis bins="100" min="0.0" max="1.0"></Xaxis>
                <Yaxis bins="100" min="0.0" max="1.0"></Yaxis>
                <Zaxis bins="100" min="0.0" max="1.0"></Zaxis>
        </CorrelationFunction>
        <FreezoutGenerator>Hal::FemtoFreezoutGeneratorLCMS</FreezoutGenerator>
        <SourceModel>Hal::FemtoSourceModelGauss3D</SourceModel>
        <CalcOptions>
                <JobMultiplyFactor>1</JobMultiplyFactor>
                <WeightMultiplyFactor>1</WeightMultiplyFactor>
                <PreprocessMultiplyFactor>1</PreprocessMultiplyFactor>
                <!-- S/B/S+B for S(signal) B (background)  B+S (both)-->
                <CalcMode>S</CalcMode>
                <IgnoreSign>kTRUE</IgnoreSign>
        </CalcOptions>
        <WeightConf>
                <Type>Hal::FemtoWeightGeneratorLednicky</Type>
                <QuantumOn>kTRUE</QuantumOn>
                <StrongOn>kFALSE</StrongOn>
                <CoulombOn>kFALSE</CoulombOn>
                <PairType>211;211</PairType>
        </WeightConf>
</DumpAnalysisConf>
</CorrfitConfig>
```

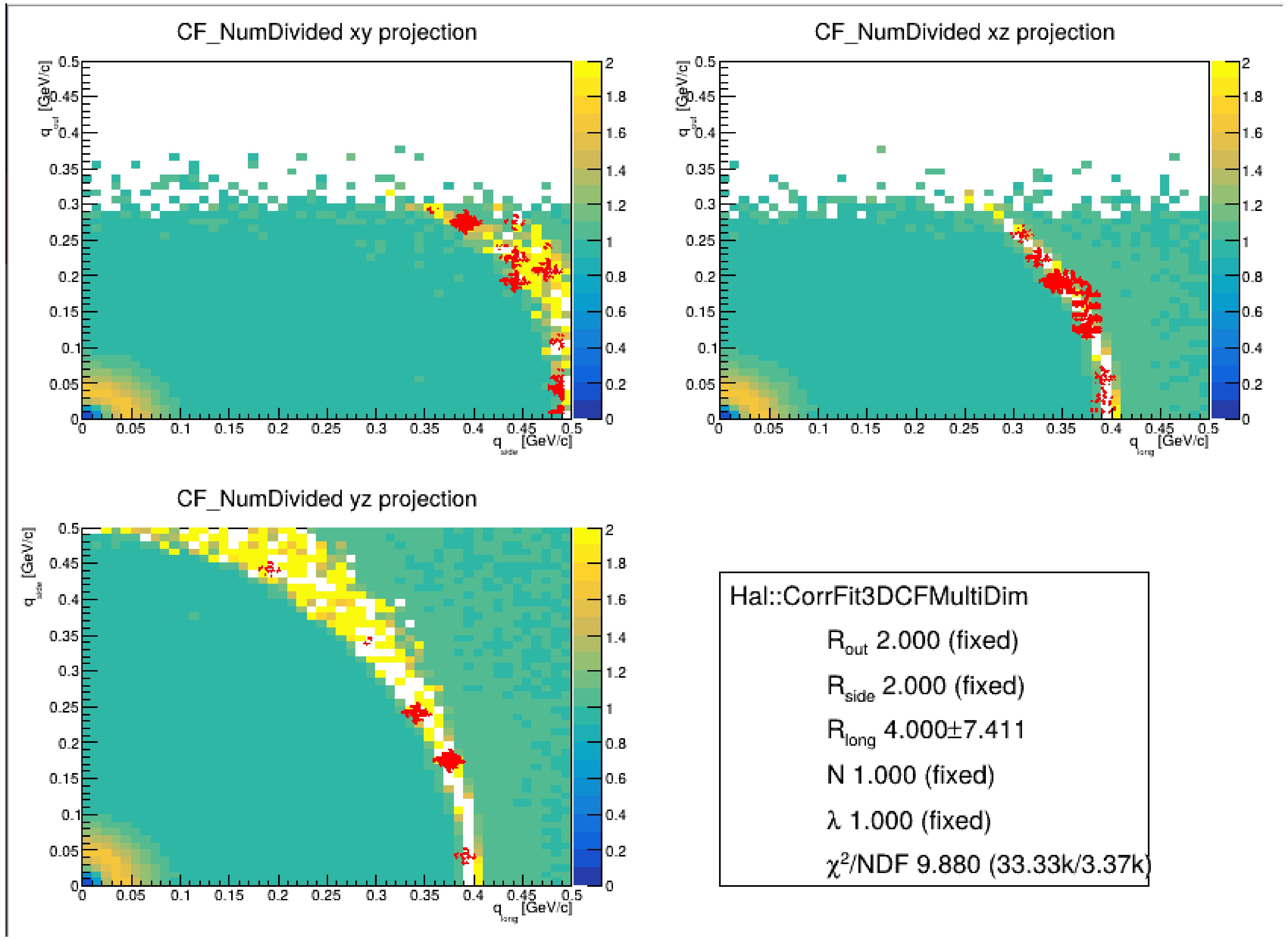
Towards 3D protons

Example of function with fit (3d options)



Towards 3D protons

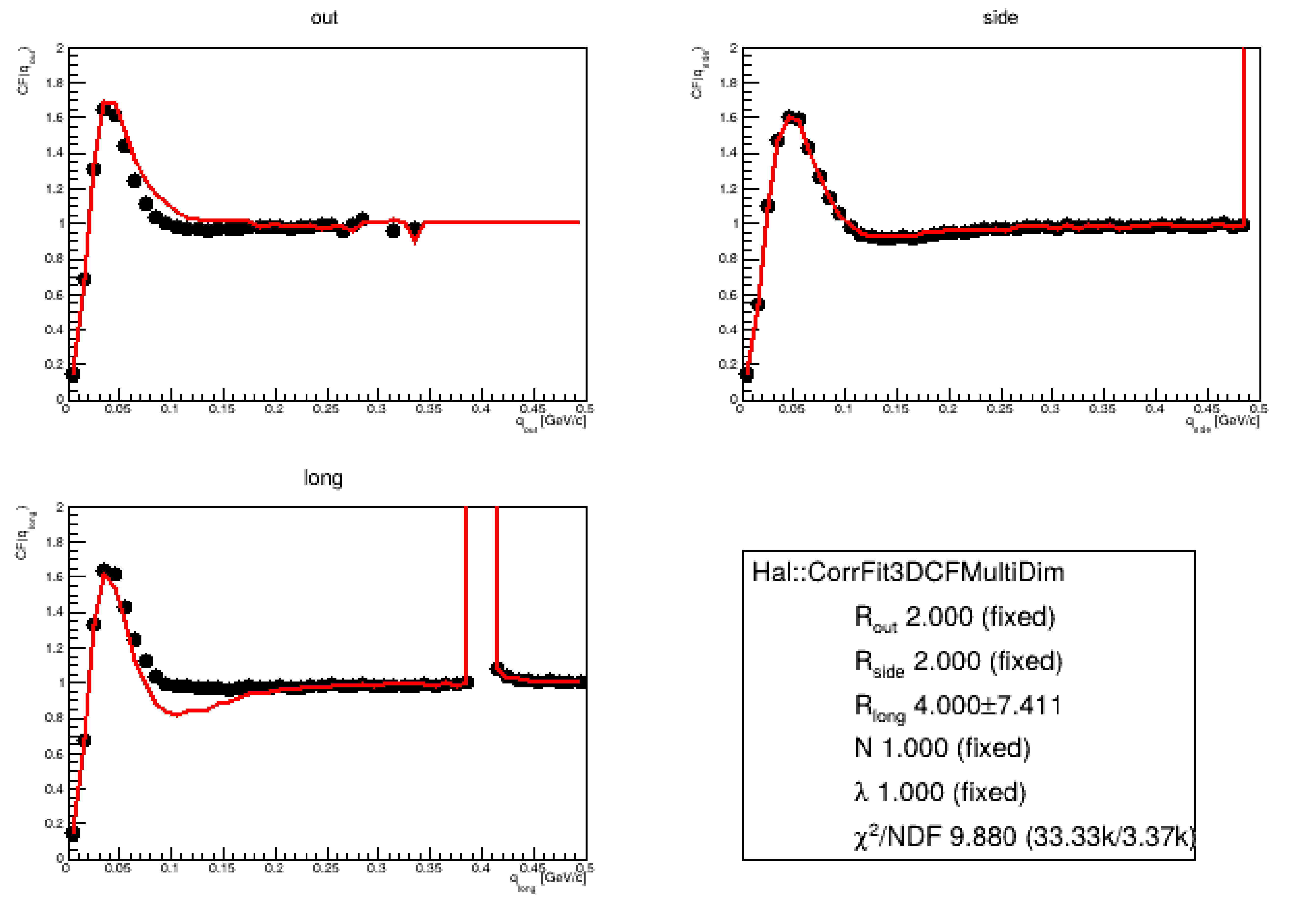
Example of visualization – 2d option



Towards 3D protons

Example of visualization – standard vis.

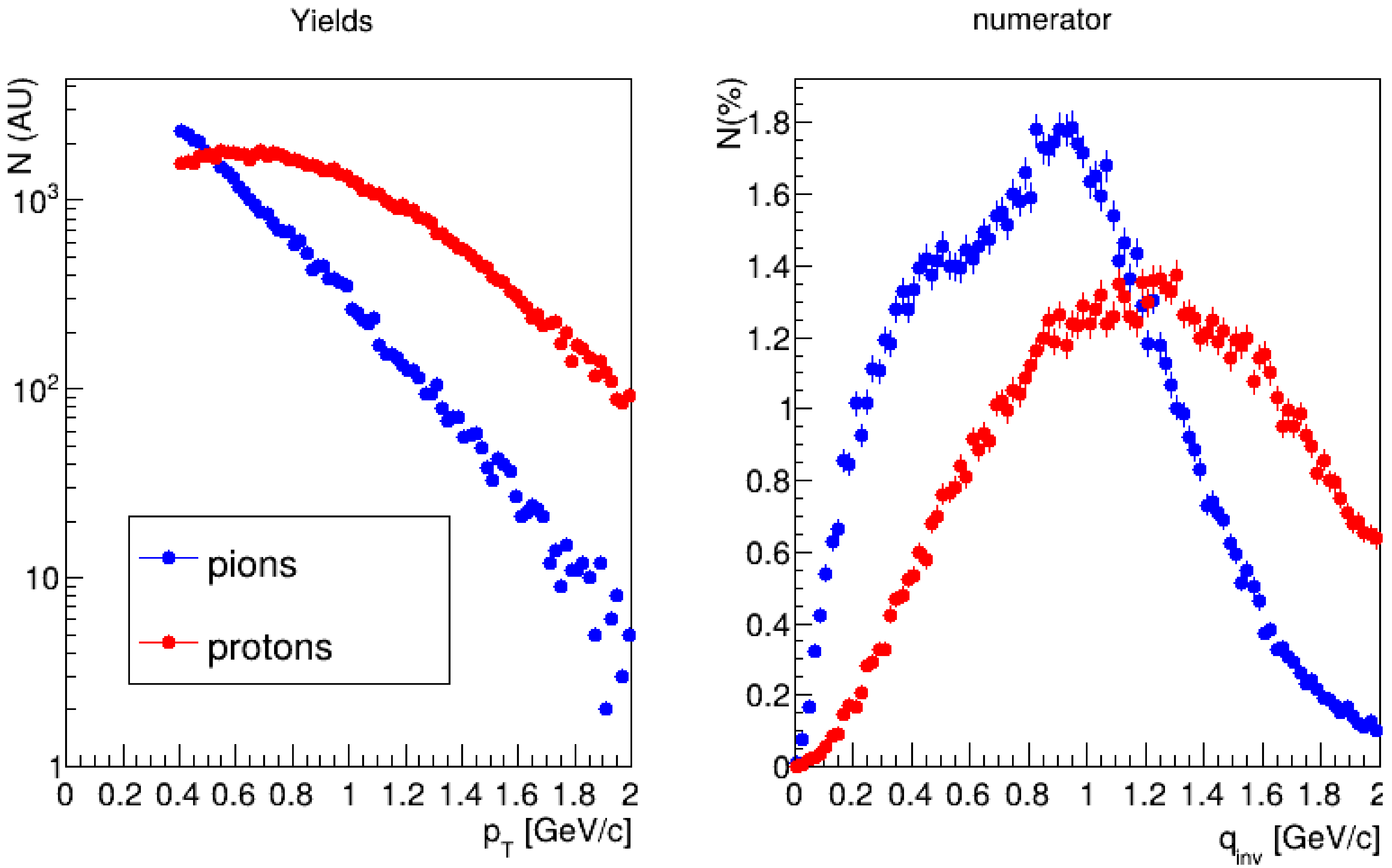
```
Hal::CorrFitMask3D* mask = new Hal::CorrFitMask3D(*cf);

// mask->ApplyThreshold(*cf->GetNum(), 100);
mask->Reset(0);
mask->ApplyRange(0, 0.15, 0, 0.15, 0, 0.15, kTRUE);
mask->SetBin(2, 2, 2, 1);
Hal::CorrFit3DCFMultiDim* mdim = new Hal::CorrFit3DCFMultiDim();

mdim->SetFunctorFromMap("/media/daniel/Baza1/data/corrfit_star/compressed_map.root");

auto minimizer = Hal::Minimizer::Instance();
Hal::MinimizerStepConf conf;
conf.LoadFromXML("dummy_conf.xml");
minimizer->SetParamConf(Hal::MinimizerStepConf(), kFALSE);
mdim->SetMinimizer(Hal::CorrFit::EMinAlgo::kHalScan);
mdim->FixParameter(mdim->NormID(), 0.05);
mdim->FixParameter(mdim->NormID(), 1);
mdim->SetParLimits(mdim->LambdaID(), 0.4, 0.8);
mdim->FixParameter(mdim->LambdaID(), 1);
mdim->FixParameter(mdim->RoutID(), 2);
mdim->FixParameter(mdim->RsideID(), 2);

// mdim->TraceFitting();

cf->FitDummy(mdim);
mdim->SetFittingMask(*mask);
mask->Init();

cf->Fit(mdim);
cf->Draw("{y=0,2}+{ang=45,145}");

mdim->Draw("norm+legend+chi2+{leg=0.1,0.1,0.8,0.8}");
new Hal::CorrFitGUI(mdim);
```



Towards protons in 3D

Current issues/limitations:

- Size of the maps (3D functions are huge)
- Might use more CPU nodes (better parallelization)
- Pair generation – time!
  - Partially improved by y-pt generation instead of „real MC model"
- Discretization – uncertainty estimation, need for fititng in steps
  - No as „automagic" as initially expected ☹



~5 bins is interesting

Data from: Phys. Rev. C **96** (2017) 44904

Summary

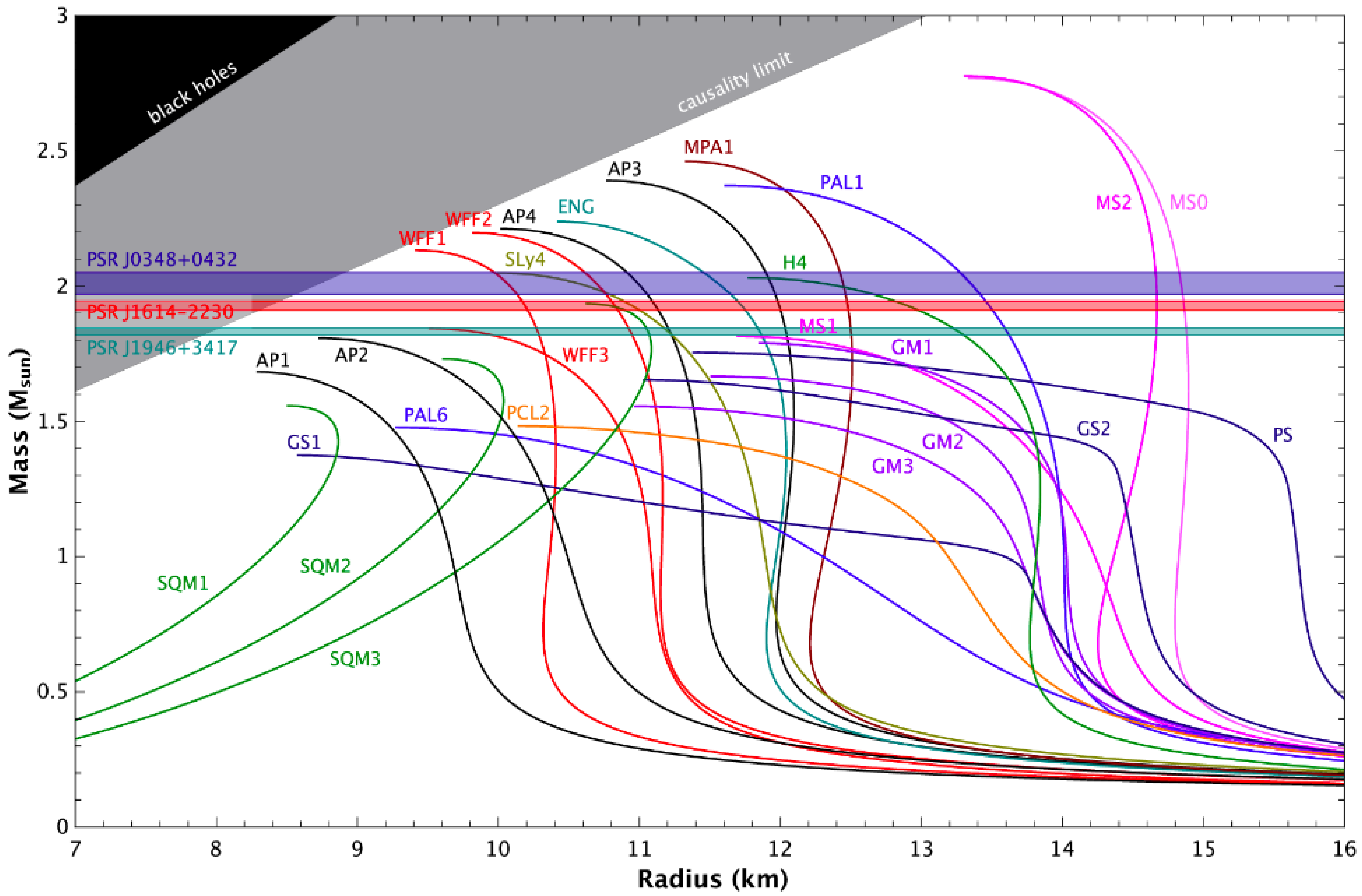
Summary

- Exploration of area of high baryonic densities:
  - Very interesting but also challenging
  - Understanding of proton correlations is important
- New algorithm for measurements of proton-proton correlation developed:
  - Significant improvement in performance
  - Still needs some improvements
  - Many (new) ideas need to be tested
  - All new ideas welcome!

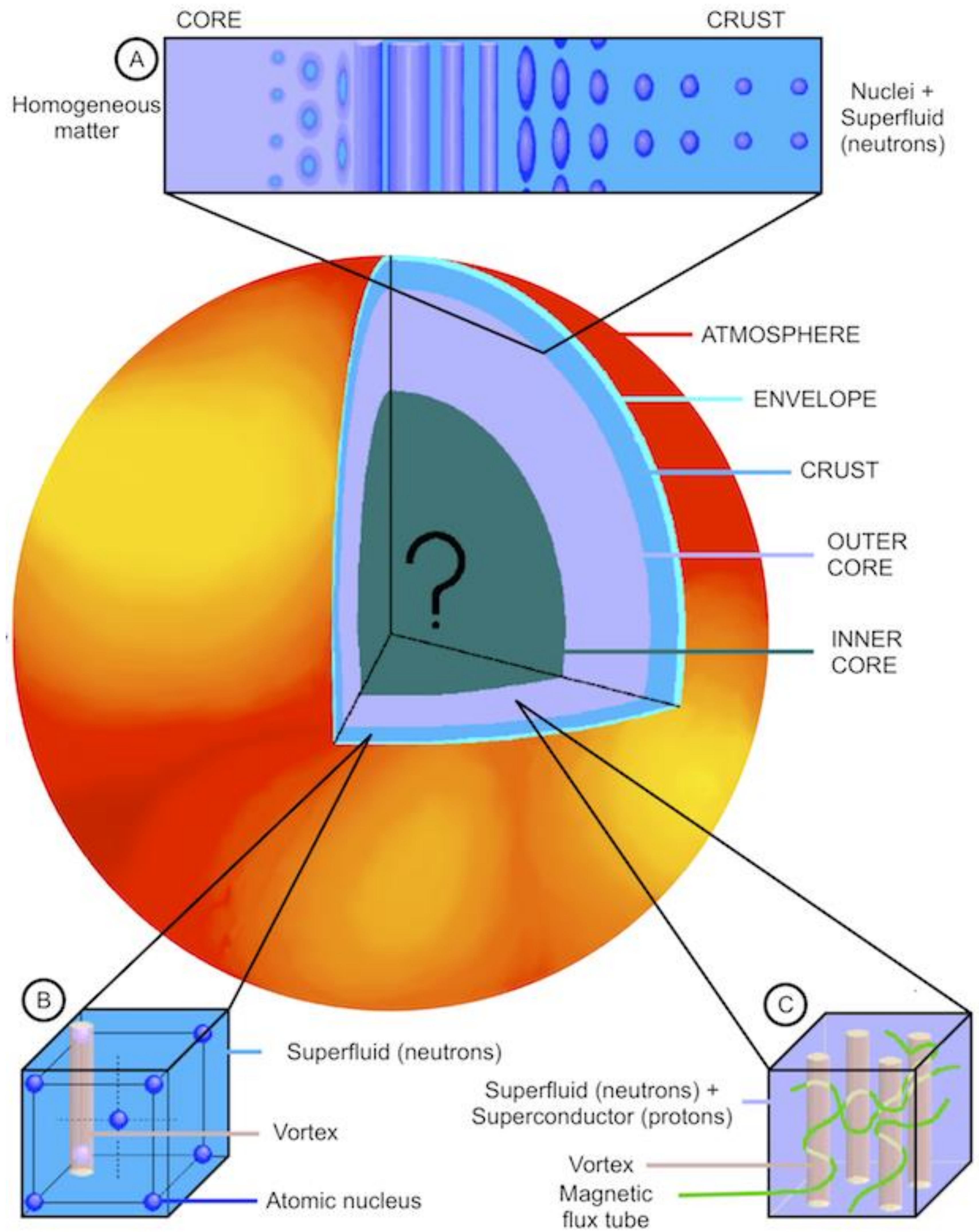
Thank you

Backup slides

Femtoscopy - baryons

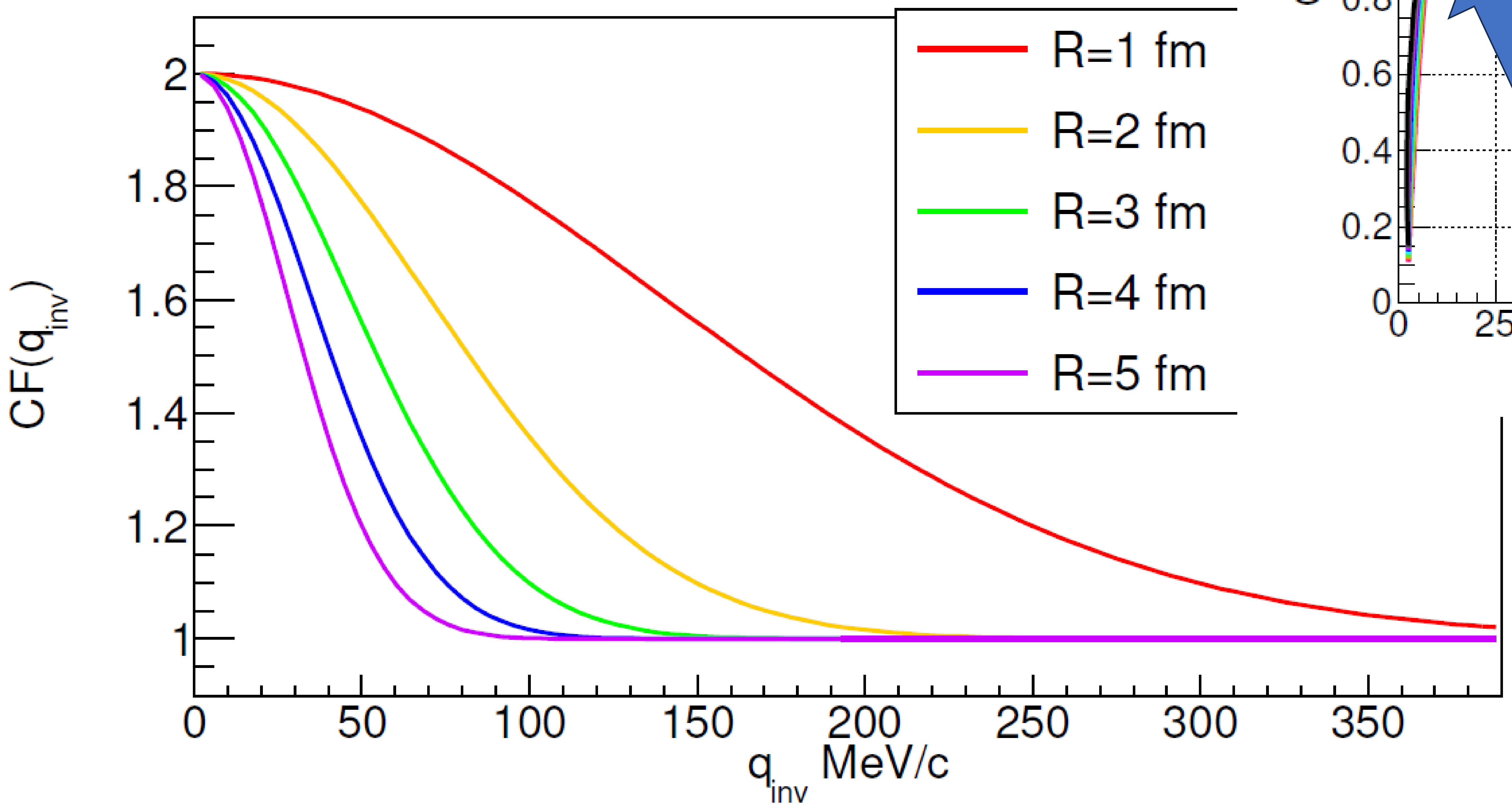


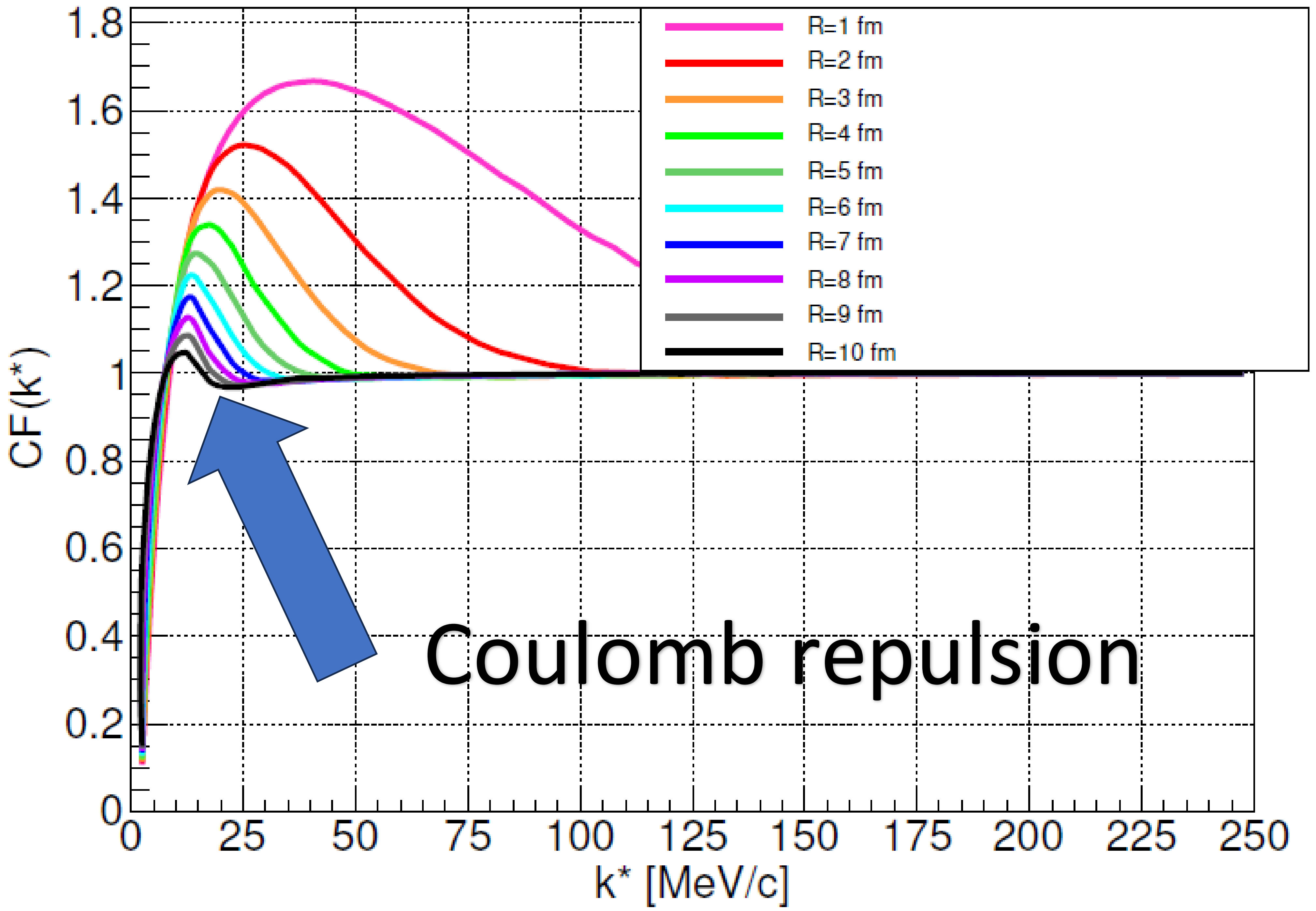
https://indico.cern.ch/event/592683/contributions/2393804/attachments/1386135/2109411/Karsai_Zimanyi.pdf



https://cxc.harvard.edu/newsletters/news_29/article1.html

Femtoscopy


R=1 fm
R=2 fm
R=3 fm
R=4 fm
R=5 fm
CF(q_inv)
q_inv MeV/c
0
50
100
150
200
250
300
350
1
1.2
1.4
1.6
1.8
2


R=1 fm
R=2 fm
R=3 fm
R=4 fm
R=5 fm
R=6 fm
R=7 fm
R=8 fm
R=9 fm
R=10 fm
CF(k*)
k* [MeV/c]
Coulomb repulsion