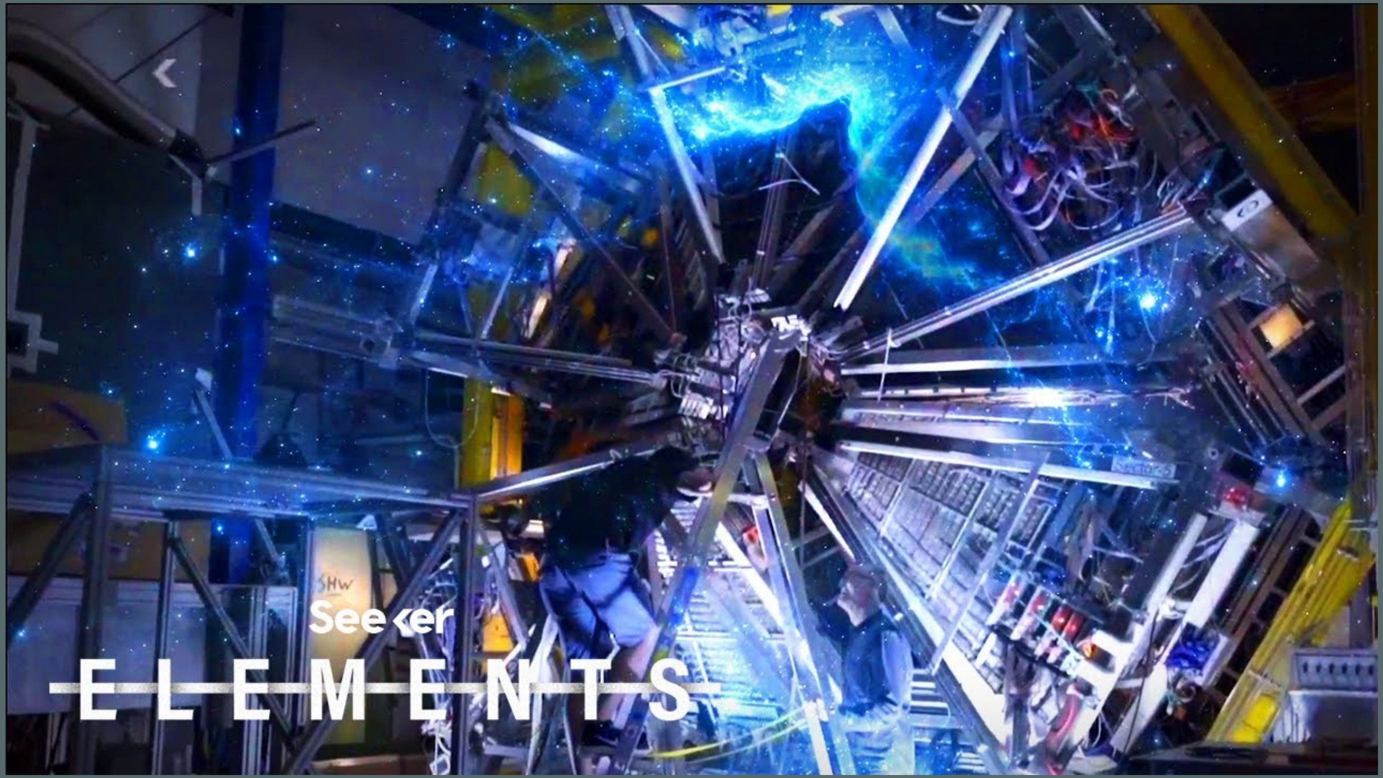
Photon-photon correlations in Ag+Ag collisions at $\sqrt{S_{NN}} = 2.55$ GeV



Mateusz Grunwald for the HADES Collaboration

HADES

GSI

Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

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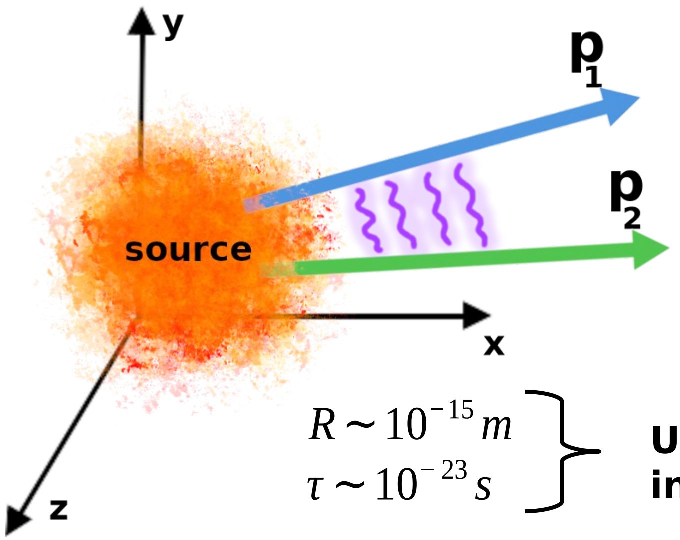
RESEARCH UNIVERSITY
EXCELLENCE INITIATIVE

NATIONAL SCIENCE CENTRE
POLAND

26.06.2023

Femtoscopy – measure source area



$R \sim 10^{-15} m$
$\tau \sim 10^{-23} s$ } **Unmeasurable in a direct way**

Definitions

4-momentum: $\bar{p}$

4-position: $\bar{x}$

Source function: $S(\bar{x}, \bar{p})$

2-particle wave function: $\Psi(\bar{x}_1, \bar{p}_1; \bar{x}_2, \bar{p}_2)$

Momentum difference: $q = |\bar{p}_1 - \bar{p}_2|$

Theory

Single particle emission function: $P(\bar{p}) = \int S(\bar{x}, \bar{p})\, d^4\bar{x}$

Two particle emission function: $P(\bar{p}_1, \bar{p}_2) = \int S(\bar{x}_1, \bar{p}_1; \bar{x}_2, \bar{p}_2) |\Psi(\bar{x}_1, \bar{p}_1; \bar{x}_2, \bar{p}_2)|^2 d^4\bar{x}_1 d^4\bar{x}_2$

Correlation Function: $CF(\bar{p}_1, \bar{p}_2) = \frac{P(\bar{p}_1, \bar{p}_2)}{P(\bar{p}_1) P(\bar{p}_2)}$

Experiment

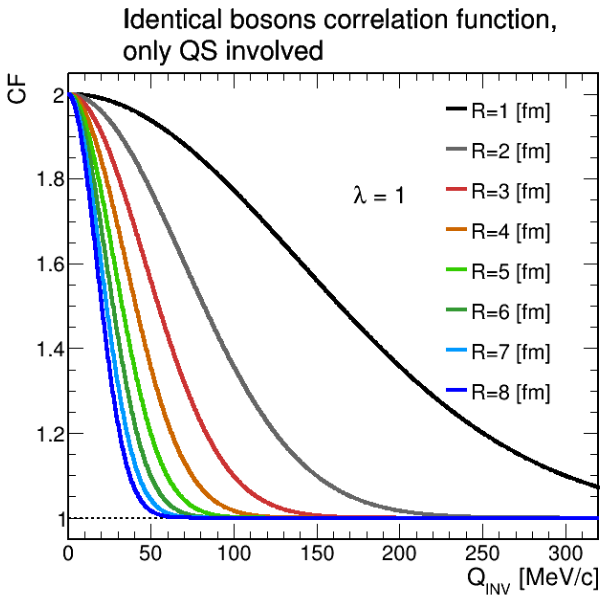
Same-event q distribution: $Sgn(q)$

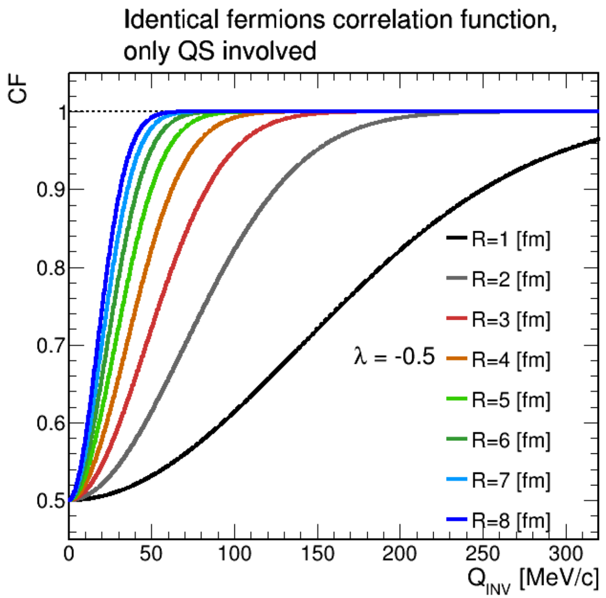
Mixed-event q distribution: $Bck(q)$

Correlation Function: $CF(q) = \frac{Sgn(q)}{Bck(q)}$

Femtoscopy – measure source area

Only quantum statistics (identical particles)



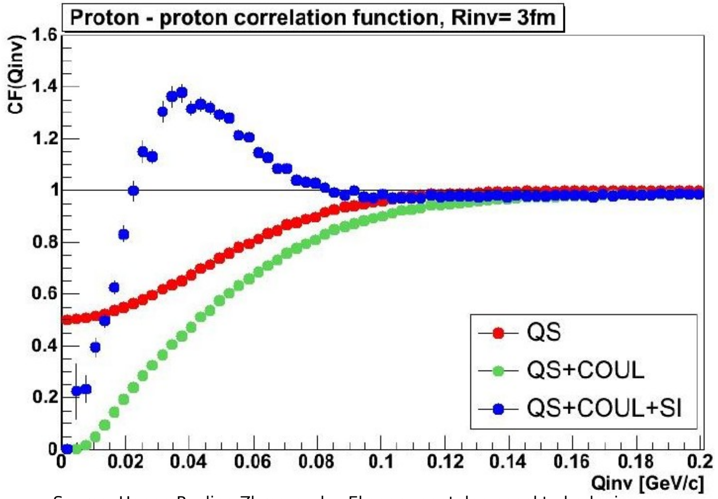


$$CF(q) = 1 + \lambda e^{-q^2 R^2}$$

R - homogenity length* (aka "source radius")

λ - correlation strenght ([0,1] for bosons, [-0.5, 0] for fermions)

More complex case → proton-proton correlation

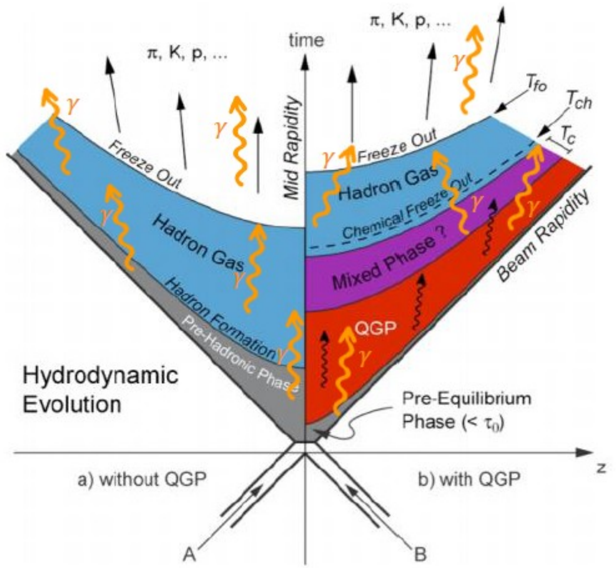


Source: Hanna Paulina Zbroszczyk, „Eksperymentalne aspekty badania korelacji femtoskopowych w zderzeniach relatywistycznych ciężkich jonów"

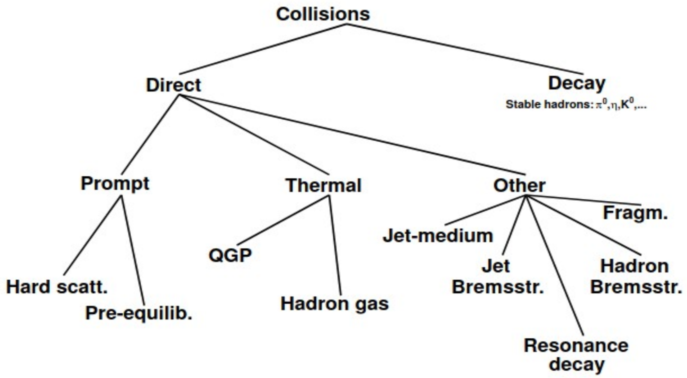
QS – quantum statistics
COUL – coulomb force
SI – strong interactions

* S.V.Akkelin, Yu.M.Sinyukov, THE HBT-INTERFEROMETRY OF EXPANDING, IN HOMOGENEOUS SOURCES, Kiev - 1995

Why photon femtoscopy?



Source: J. Stachel. K. Reygers, QGP physics SS2015 6., „Space-time evolution of the QGP”



Source: : http://dx.doi.org/10.1088/1361-6633/ab6f57

Pros

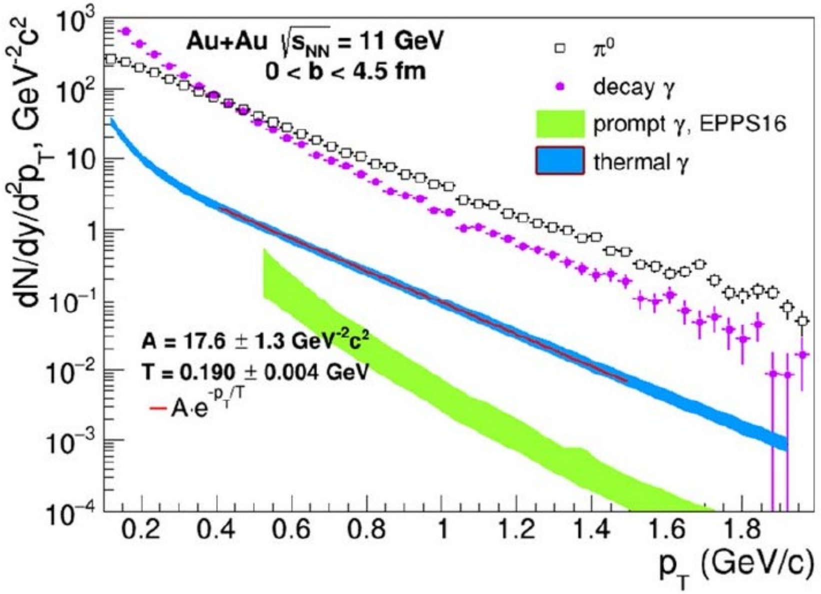
- No interactions (Coul,Si) and large mean free path → undistorted signal
- Emission through whole source evolution → information from different stages (not only freeze-out!)
- Plausible way to hunt direct ɣ
- Many different sources
- Easy parametrization of correlation function (only QS)
- Easy “quality benchmark” since:

3-momentum: p

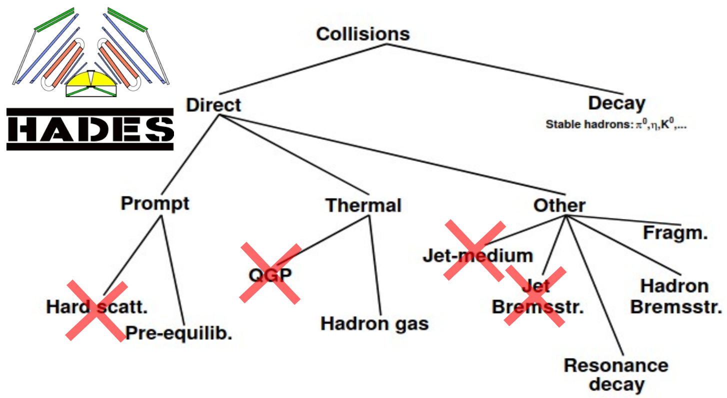
$$Q_{INV}=\sqrt{|p_1-p_2|^2-(E_1-E_2)^2}$$
$$M_{\gamma\gamma}=\sqrt{(E_1+E_2)^2-|p_1+p_2|^2}$$
$$m_\gamma=0 \Rightarrow E_\gamma=|p_\gamma|$$

$$Q_{INV}=M_{\gamma\gamma}$$
$$M_{\gamma\gamma}=\sqrt{2E_1E_2(1-\cos\alpha_{1,2})}$$

Why photon femtoscopy?



Source: : D.Blau, D.Peresunko. Physics of Particles and Nuclei (2021) 52(4):681-685

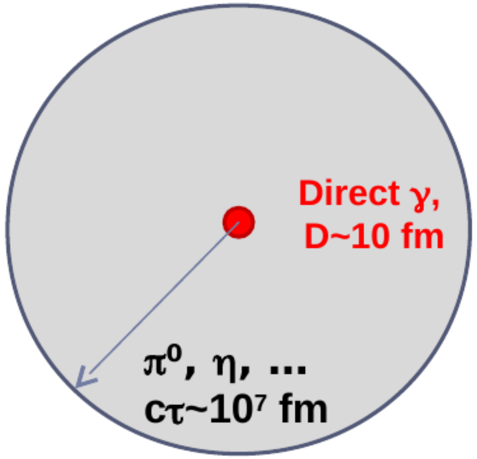


Source: : http://dx.doi.org/10.1088/1361-6633/ab6f57

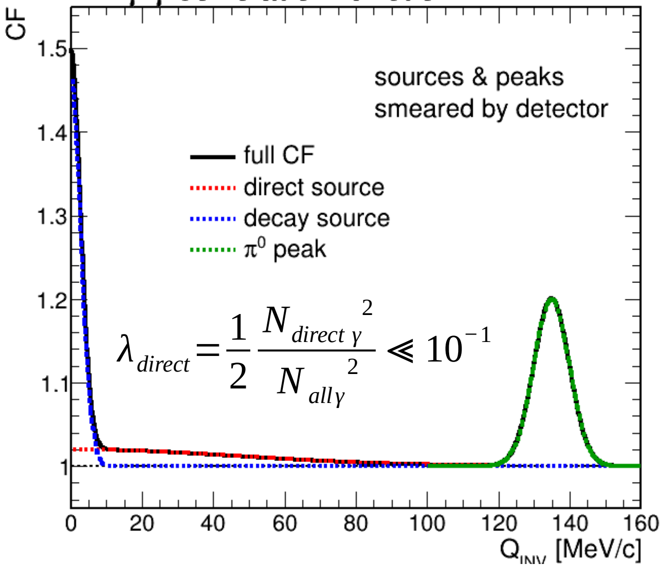
Cons

- Hard to detect in experiment → low statistics or(and) complex reconstruction
- Yield highly dominated by π^0 decay (post-freeze-out photons)
- Difficult/implausible distinguishment between decay(π^0, η) and direct ɣ
- Lack of some sources in low energy collision (f.eg. QGP or jets)
- No straight-forward transport model comparison for low energies (low scattering cross-sections, not all sources present)

What do we (probably) expect?



Cartoonish idea of experimental γ-γ correlation function



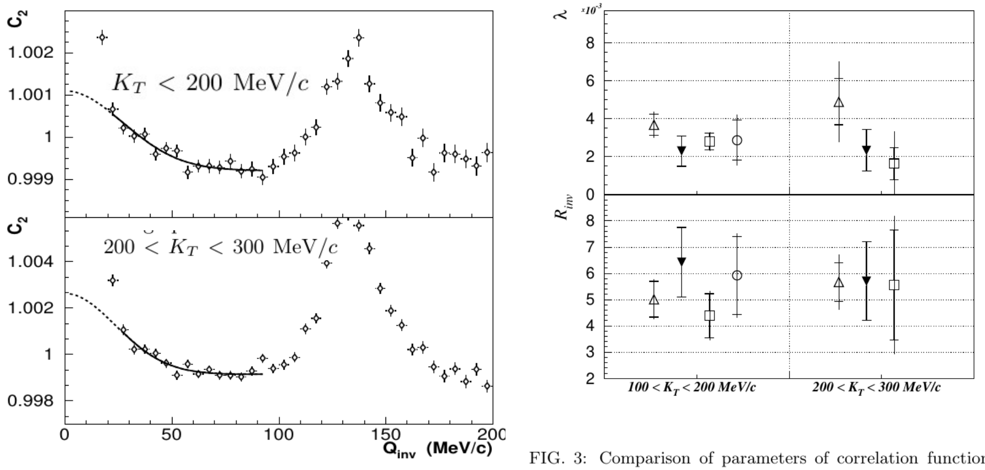
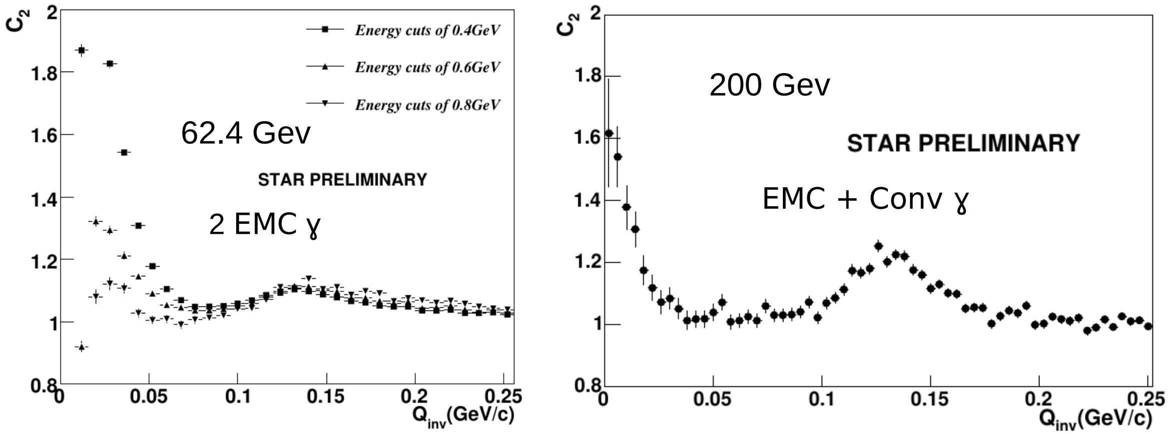


FIG. 3: Comparison of parameters of correlation functions with different particle identification criteria: △ - all clusters, ▼ - narrow electromagnetic, □ - all neutral, ◯ - narrow neutral electromagnetic (no significant result for high K_T).

Source: Interferometry of Direct Photons in Central 280Pb+208Pb Collisions at 158A GeV, WA98 Collaboration: M.M.Aggarwal, arXiv:nucl-ex/0310022v1

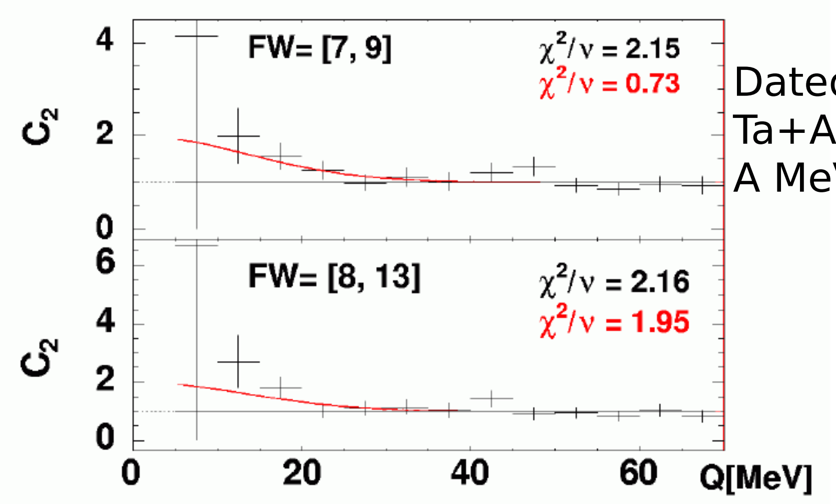
Dated: 2003, Pb+Pb @ 158 A GeV, real data



Source:„Preliminary Results on Direct Photon-Photon HBT Measurements in SNN = 62.4 GeV and 200 GeV Au+Au Collisions at RHIC", Debasish Das et al., https://arxiv.org/abs/nucl-ex/0511055v1

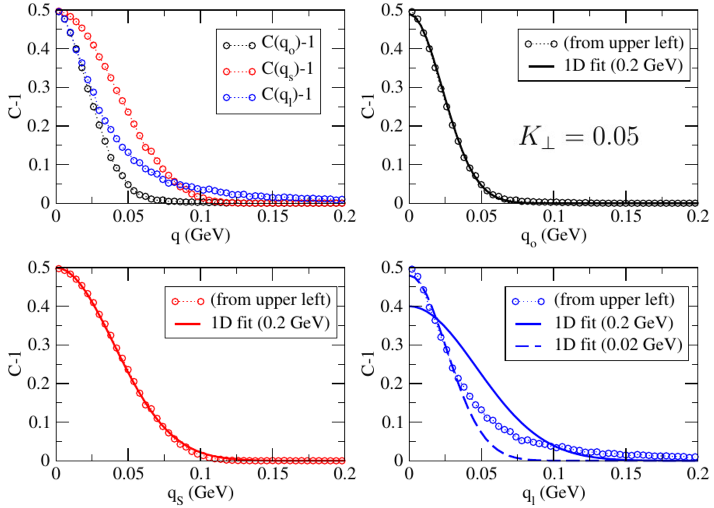
Dated: 2003, Au+Au @ 62.4/200 GeV, real data

What do we (probably) expect?



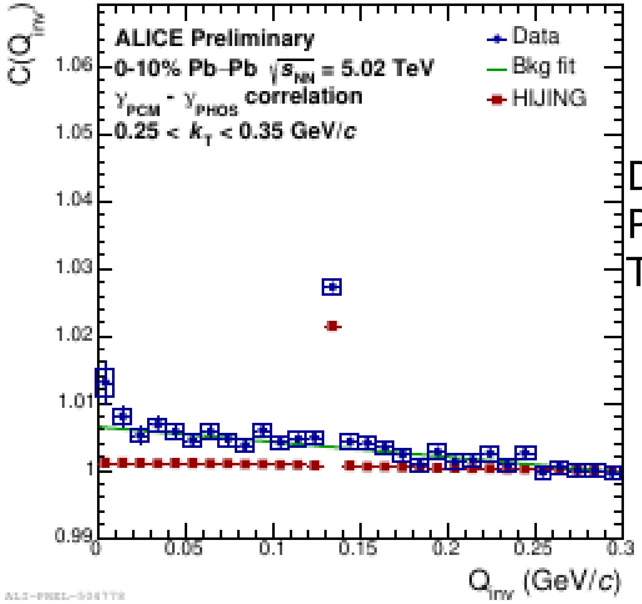
Dated: 2005, Ta+Au @ 39.5 A MeV, real data

Source:Krzysztof Piasecki, Interferometria intensywności wysokoenergetycznych fotonów ze zderzeń jader atomowych, PhD thesis, UJ, 2005



Dated: 2008, Au+Au @ 200 GeV, implementation of the Parton Cascade Model by Geiger (VNI)

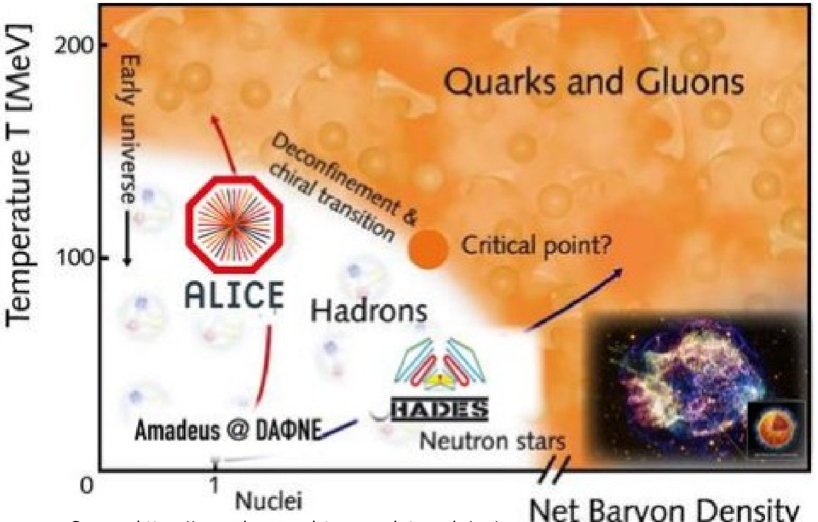
Source:Evan Scott Frodermann, A VIEW OF HEAVY-ION COLLISION DYNAMICS AND GEOMETRY THROUGH ELECTROMAGNETIC SIGNATURES, PhD thesis, Ohio State University, 2008



Dated: 2022, Pb+Pb @ 5.02 TeV, real data

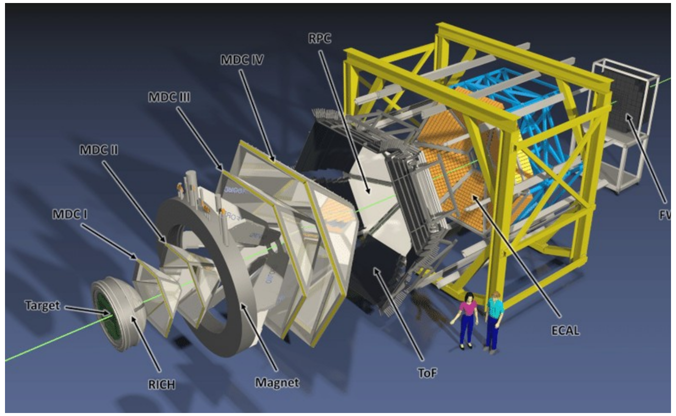
Source:Direct photon HBT correlations in pp and Pb-Pb collisions at sNN = 5.02 TeV, Mike Sas for the ALICE Collaboration, Quark Matter 2022

HADES experiment

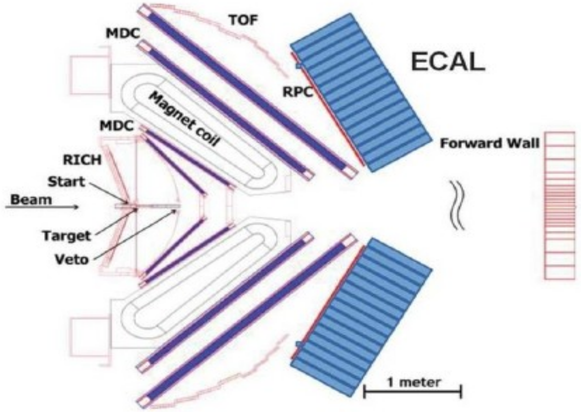


Source: https://www.denseandstrange.ph.tum.de/en/research/

- High Acceptance Di-Electron Spectrometer
- Fixed target, few (1-2) GeV beam kinetic energy
- Measurement of dilepton pairs from vector mesons (ω, φ, ρ)
- High angular acceptance ($0° < \varphi < 360°$, $18° < \theta < 85°$) split into 6 sectors.
- High $e^{\pm}$ reconstruction efficiency and $\pi^{\pm}$ /p separation (RICH, ECAL).



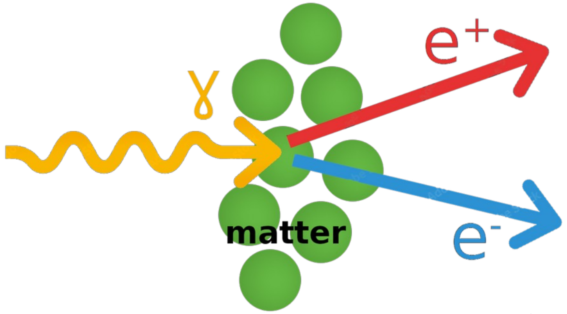
Source: Spies, Simon. (2022). HADES Overview: Recent results from Ag+Ag collisions at √ S NN = 2.55 GeV measured by HADES. EPJ Web of Conferences. 259. 01007. 10.1051/epjconf/202225901007.

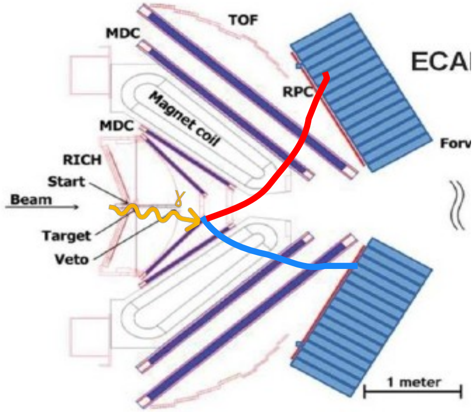


Source: https://www-hades.gsi.de

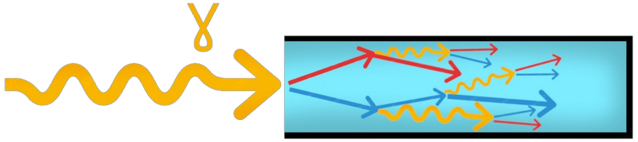
Photon detection at HADES

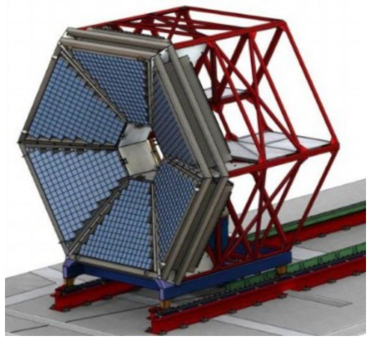
Photon Conversion Method (PCM)





Electromagnetic calorimeters (ECAL)





- High momentum and angular resolution
- Good lepton reconstruction efficiency at HADES
- Pure sample of photons

- 2-step reconstruction (leptons → photons) → low efficiency
- Low conversion probability
- Lepton close track effects due to small opening angle

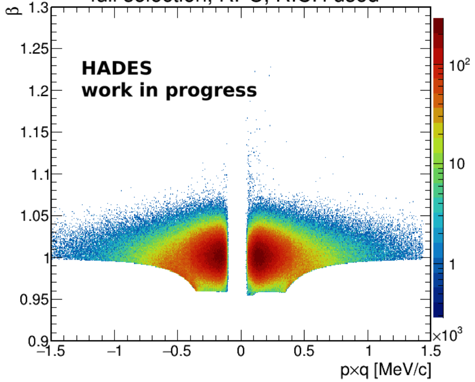
- Great efficiency due to 1-step photon reconstruction
- Covers wider energy range than PCM
- Decently pure sample with suitable criteria

- Finite granularity (each module is ~ 2.2° wide)
- Module to module differences
- Merging/splitting of clusters at low opening angles

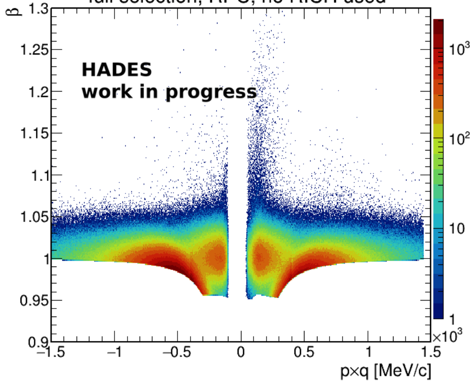
Photon detection at HADES (PCM, simulation)

Data (charged tracks) → Lepton selection → Leptons → Photon selection → Photons

β vs momentum× charge, all e^+e^-, full selection, RPC, RICH used

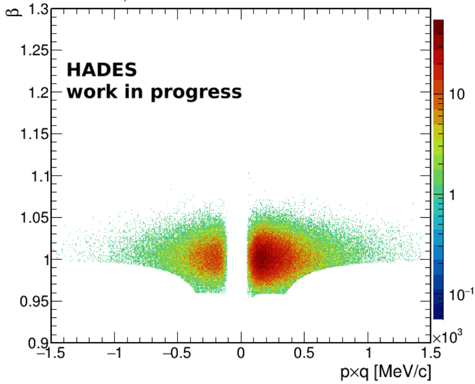


β vs momentum × charge, all e^+e^-, full selection, RPC, no RICH used

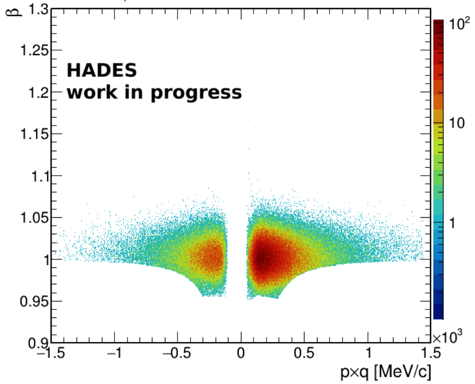


Photon selection →

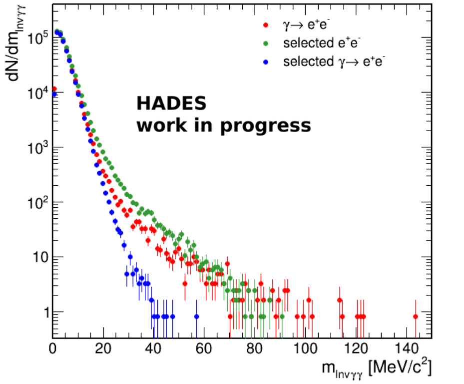
β vs momentum× charge, selected $\gamma \rightarrow e^+e^-$, RPC, RICH used



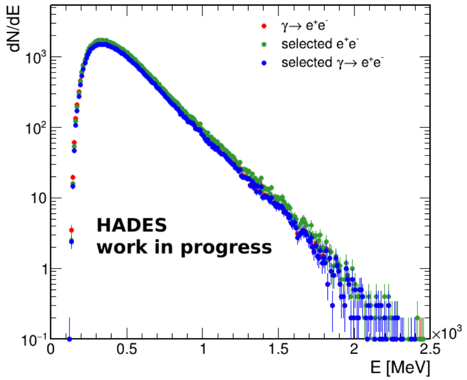
β vs momentum× charge, selected $\gamma \rightarrow e^+e^-$, RPC, no RICH used



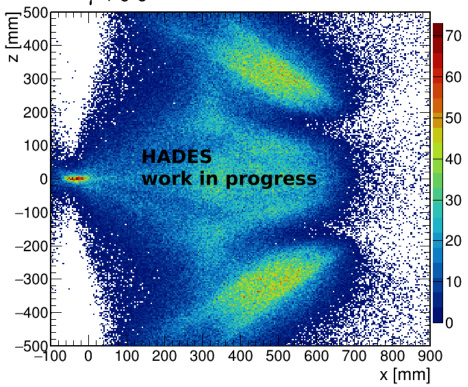
Invariant mass, separate Vtx.z cuts



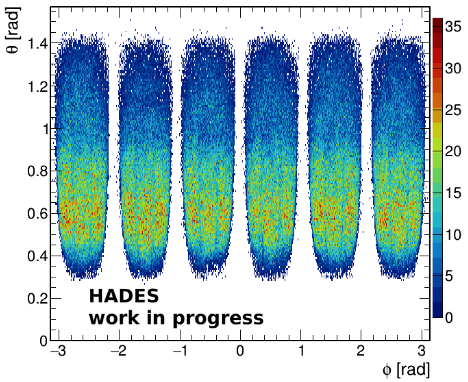
Energy distribution



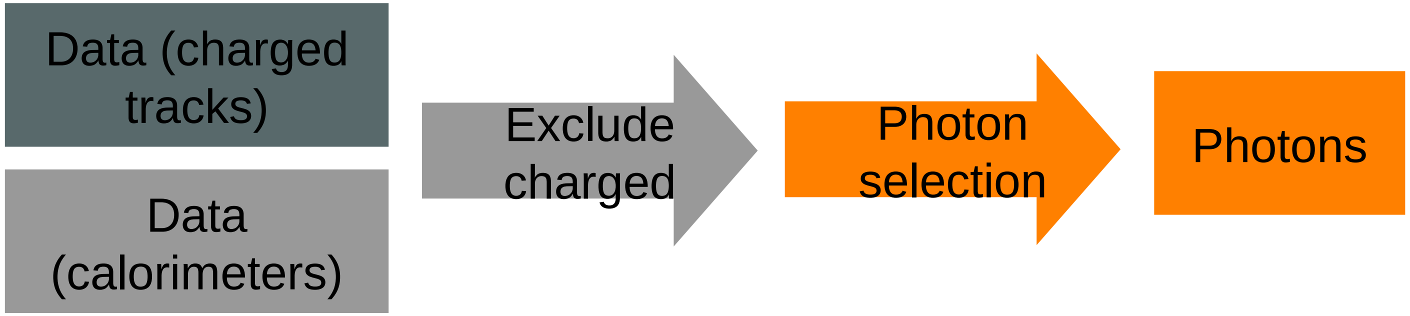
Conversion vertex x vs z coordinates, $\gamma \rightarrow e^+e^-$



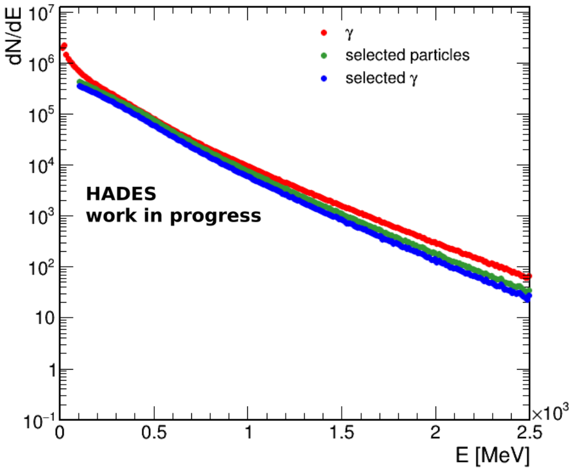
Conversion φ vs θ γ acceptance



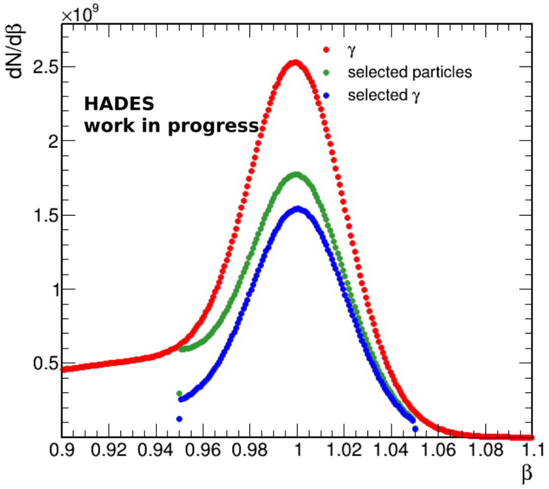
Photon detection at HADES (Ecal, simulation)



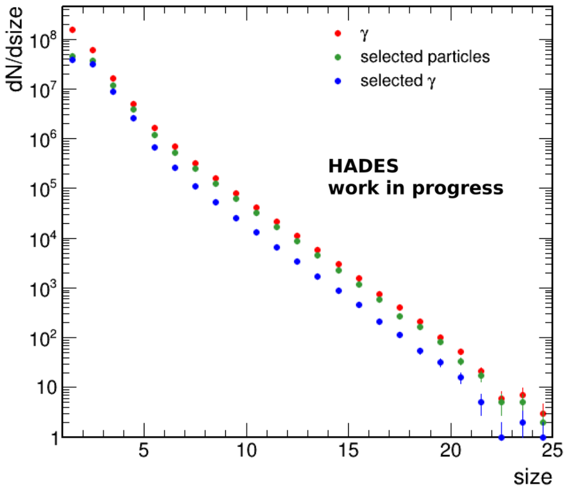
Ecal energy distribution



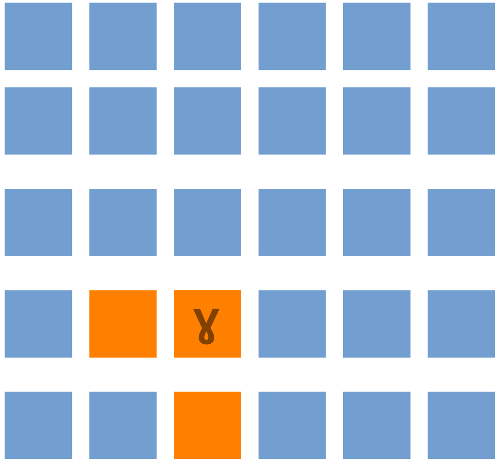
Ecal β distribution



Ecal cluster size distribution



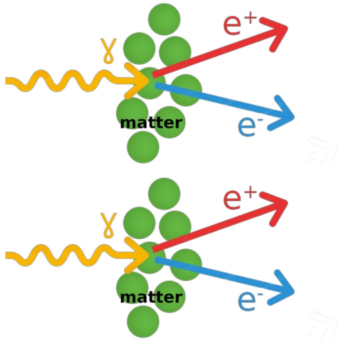
Ecal modules grid



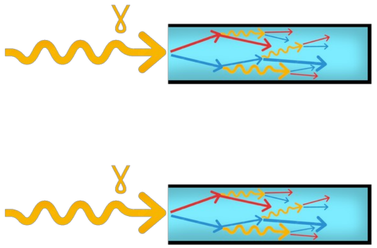
Photon triggers cluster of size 3

Plausible ways of building photon correlation function

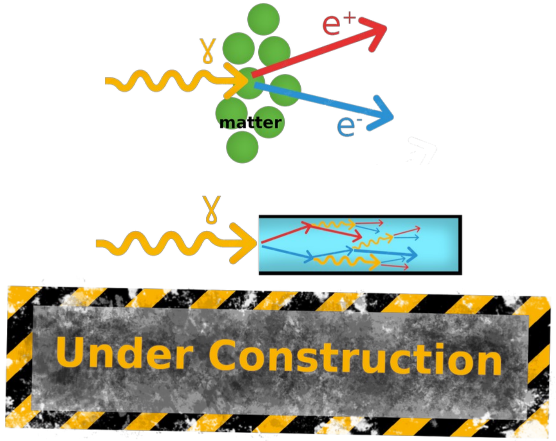
Conversion pair
(PCM + PCM)



Calorimeter pair
(ECAL + ECAL)



Hybrid pair
(PCM + ECAL)



Conversion pair (PCM + PCM)

- Good resolution
- Minimal impact of momentum smearing

- Very low statistics

Calorimeter pair (ECAL + ECAL)

- Good statistics → plausibility to check centrality dependence

- Strong impact of detector granularity

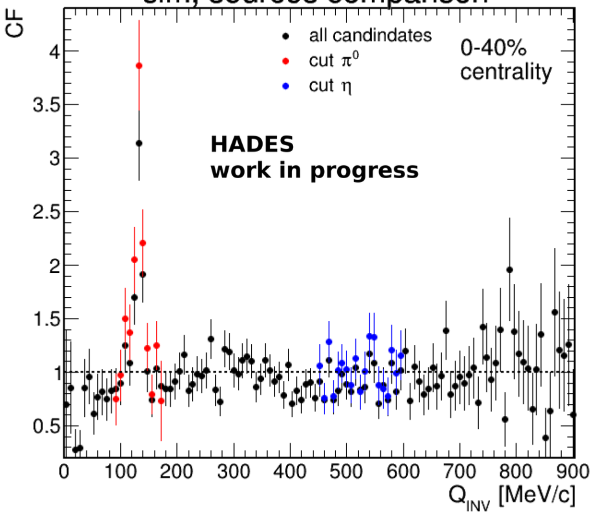
Hybrid pair (PCM + ECAL)

- Theoretically lowest opening angles plausible

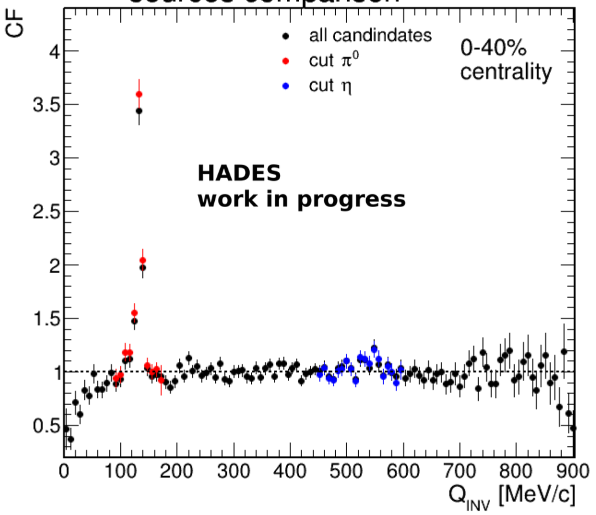
- Unpredictable effect of detector combinations

Photon correlation function – pure conversion

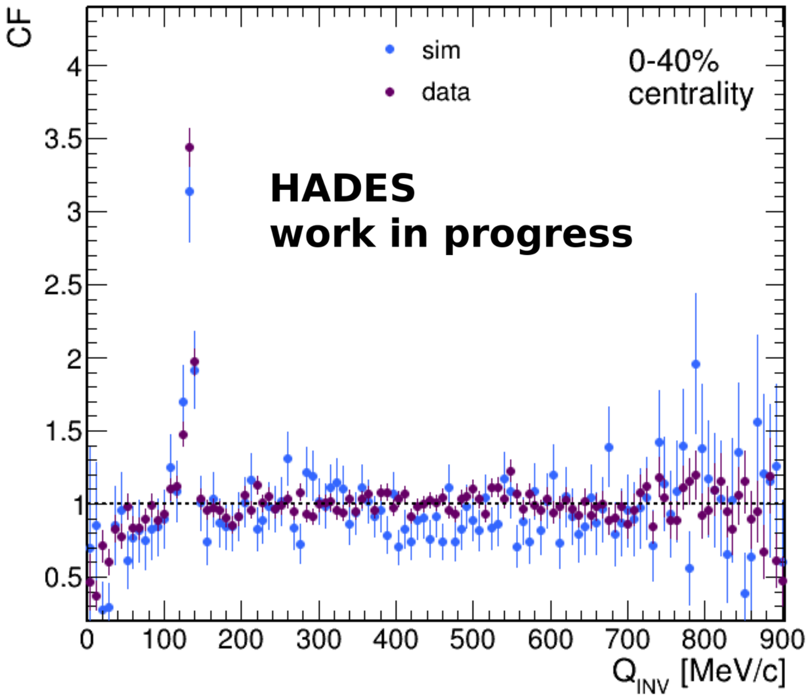
Two PCM γ candidates, sim, sources comparison



Two PCM γ candidates, data, sources comparison



Two PCM γ candidates, simulation vs data



Simulations – not enough data to draw any conclusion about correlation

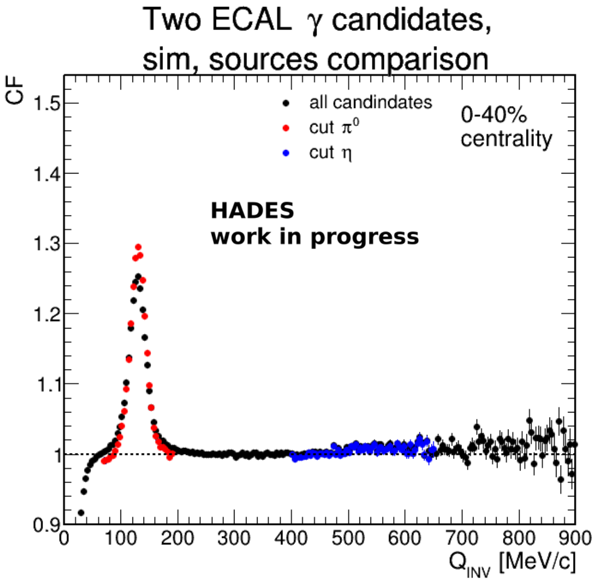
Real data – hint of close track effects visible (drop at $Q_{INV} \rightarrow 0$)

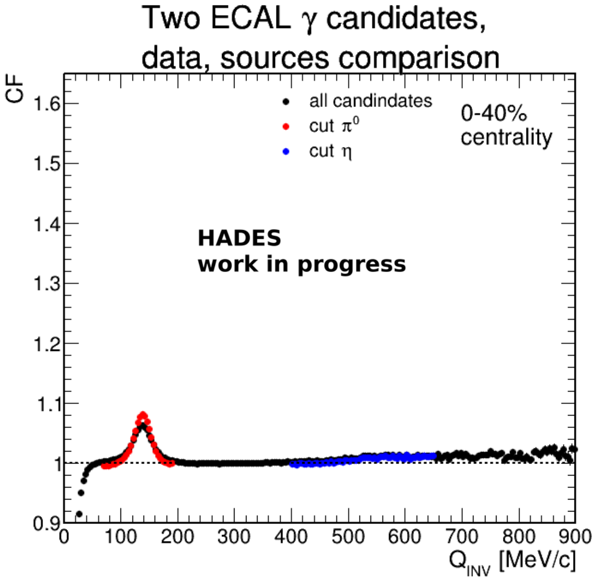
Sim – model + detector response (no QS effects, detector impact benchmark)

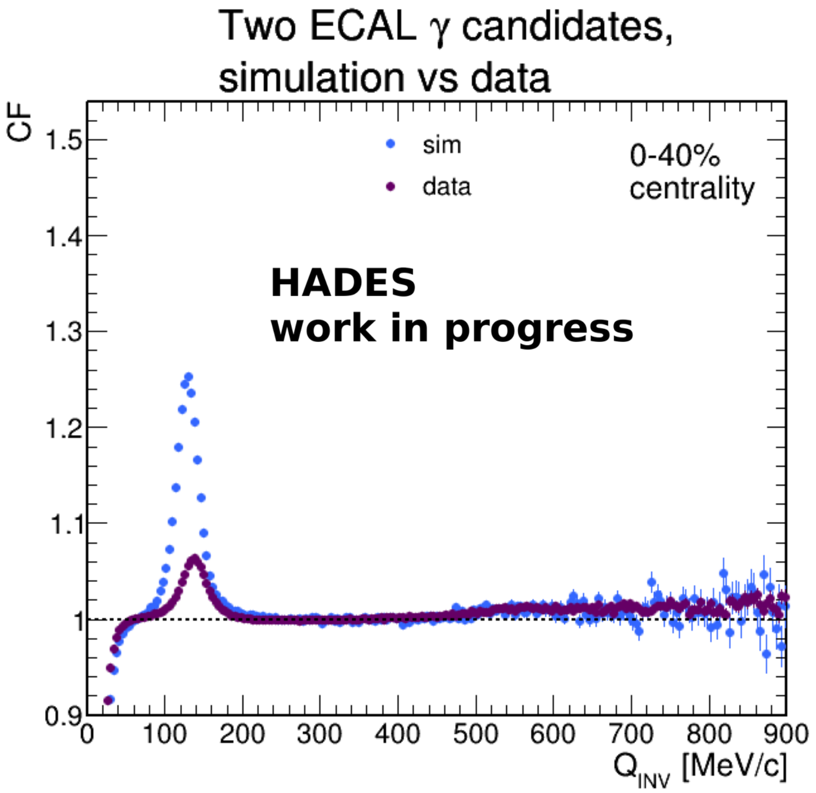
Data – real data (QS present)

Cut π^0/η – rough selection of decay residuals

Photon correlation function – pure Ecal





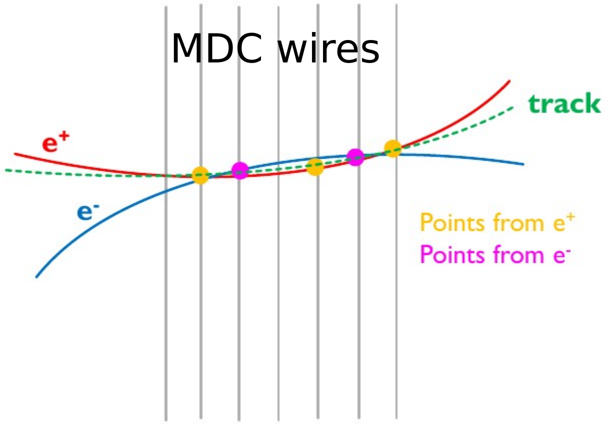


Small discrepancy between simulations and real data (π^0 peak shift)

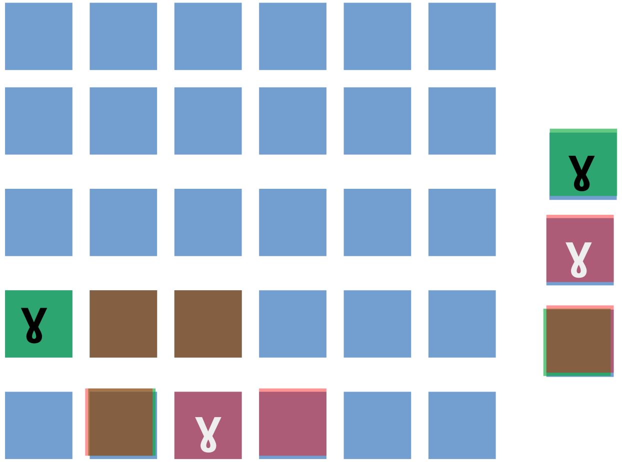
Well visible impact of granularity (drop at $Q_{INV} \rightarrow 0$)

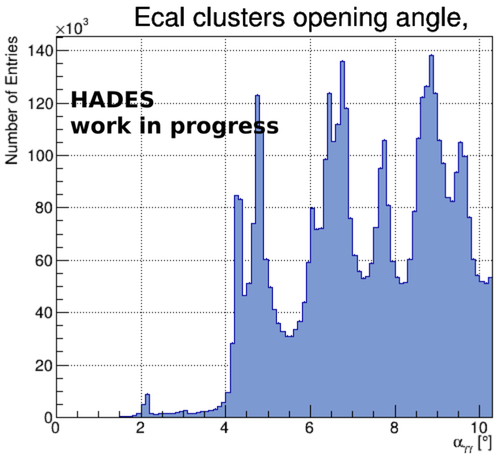
Detector effects impact

Merging

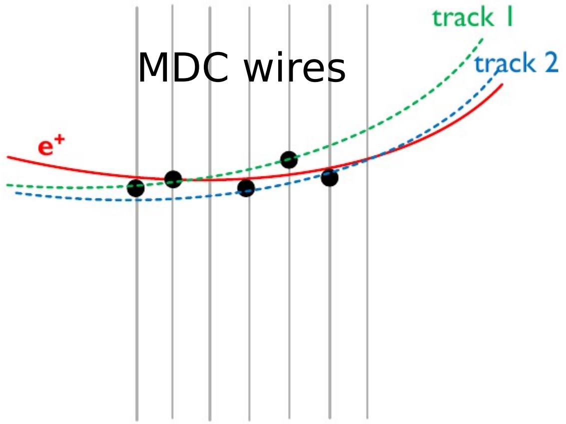


Ecal modules grid

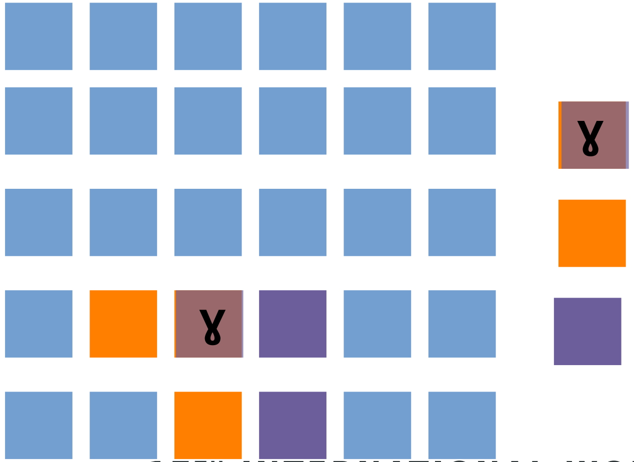


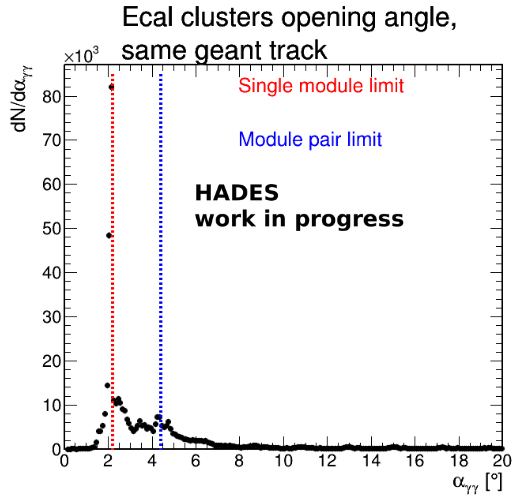


Splitting

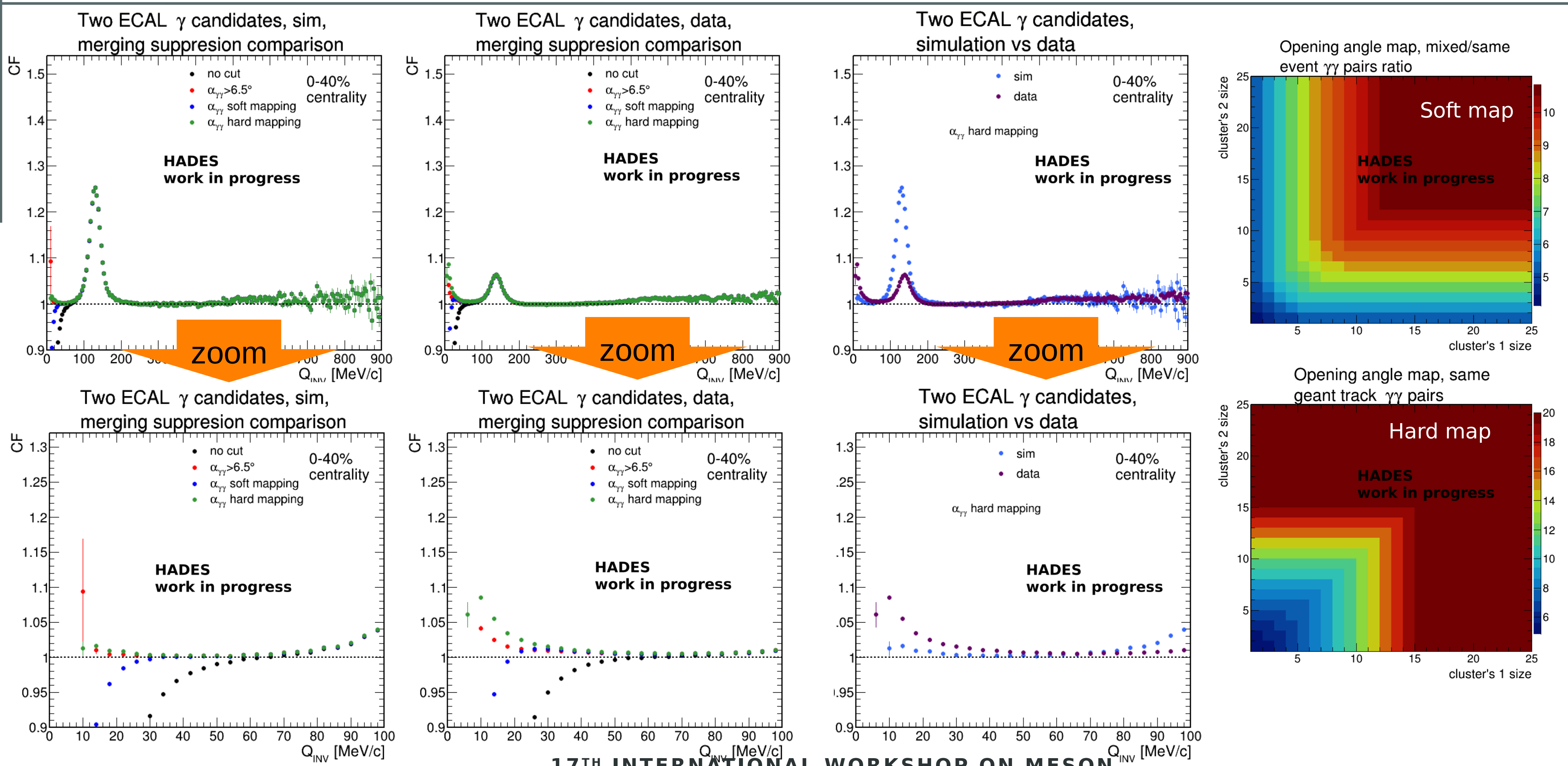


Ecal modules grid





Photon correlation function – pure Ecal



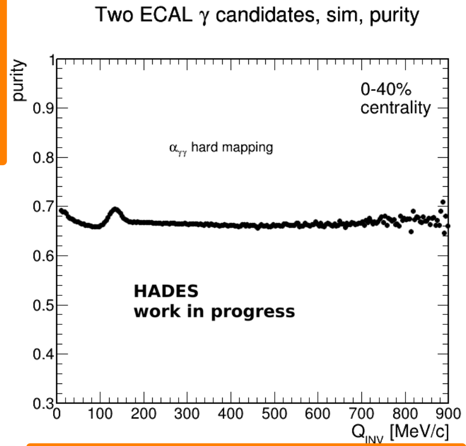
Photon correlation function – pure Ecal

Number of true ɣ pairs: $N_{\gamma\gamma}(q)$

Number of selected pairs: $N_{pair}(q)$

Purity (sim-based):

$$Purity(q) = \frac{N_{\gamma\gamma}(q)}{N_{pair}(q)}$$



CF from real data: $CF_{real\ data}(q)$

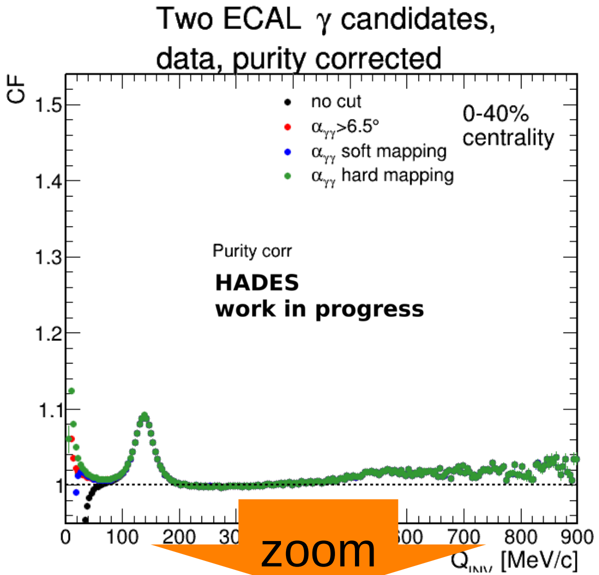
CF from simulation, with detector response and no QS: $CF_{sim\ no\ QS}(q)$

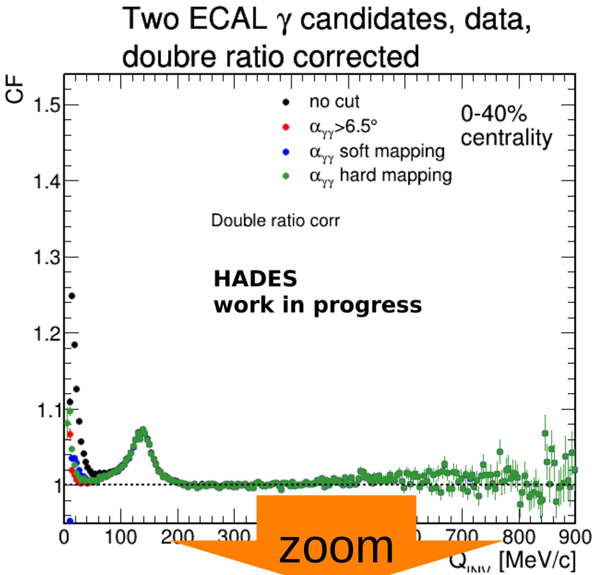
Purity correction:

$$CF_{corr}(q) = \frac{CF(q) - 1}{Purity(q)} + 1$$

Double ratio correction:

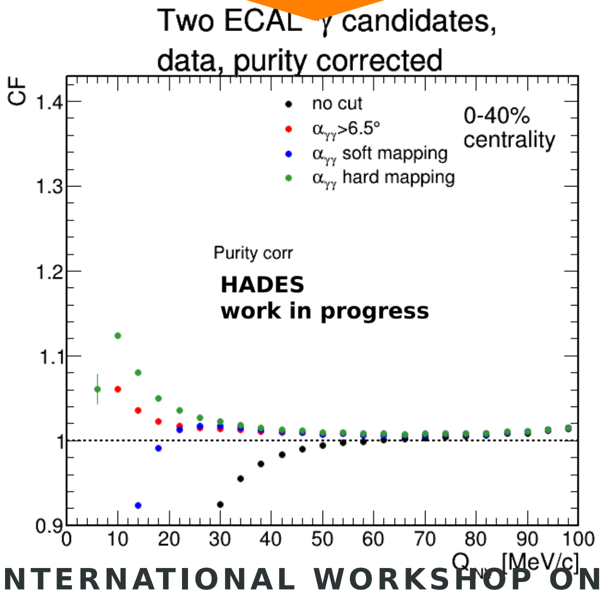
$$CF_{corr}(q) = \frac{CF_{real\ data}(q)}{CF_{sim\ no\ QS}(q)}$$

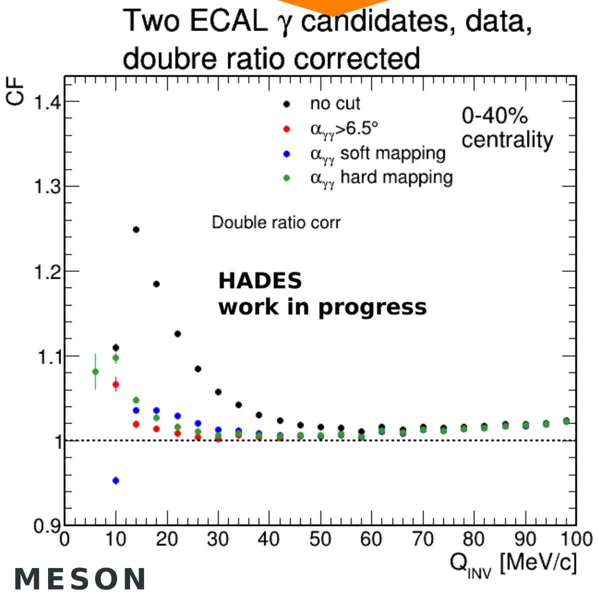




zoom

zoom





Summary

- Photon selection for PCM and ECAL works fine (confirmed by well visible π^0 peaks).
- Pure conversion CF has very low statistics and suffers from lepton close track effects (lower reconstruction efficiency for photons with small opening angle).
- Pure ECAL is promising, hard mapping suppresses detector effects well enough. HBT-like signal is observed.
- Hybrid approach, due to use of different detectors, suffers from hard to correct detector impact, which needs extra attention. Works is in progress.

Thank you

Mateusz Grunwald

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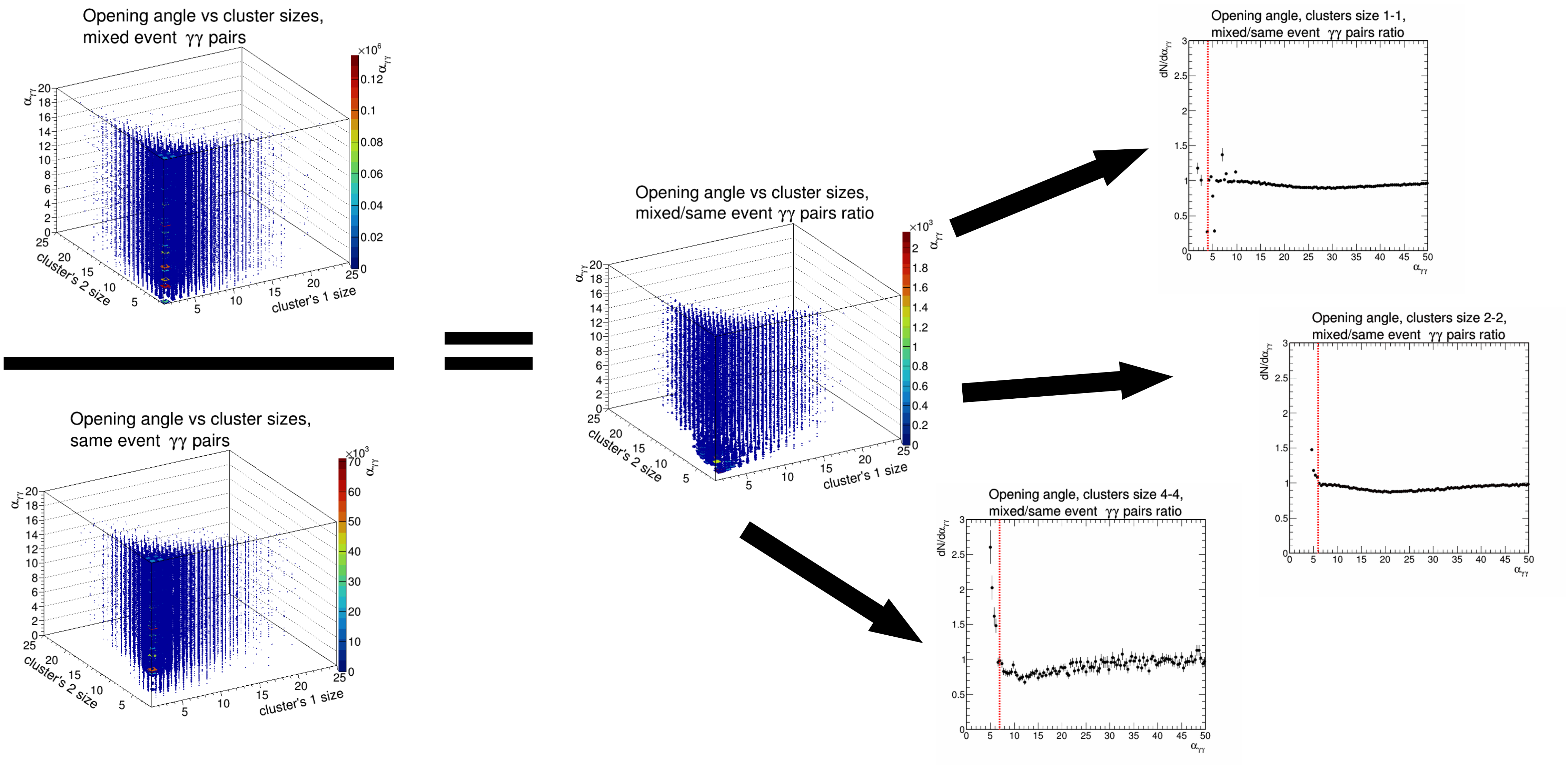
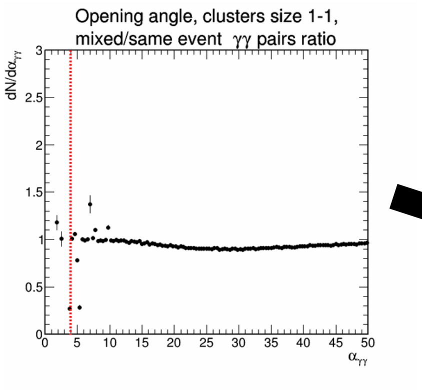
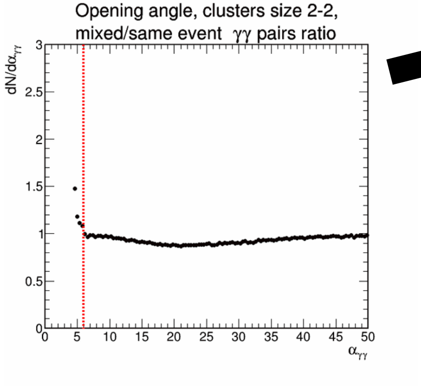
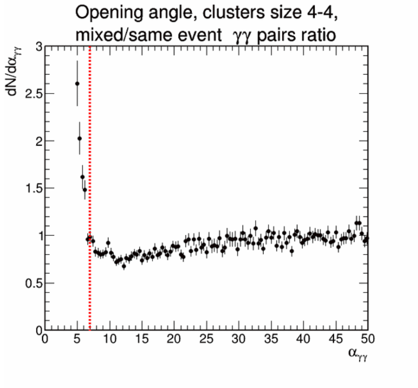
Backup – soft mapping

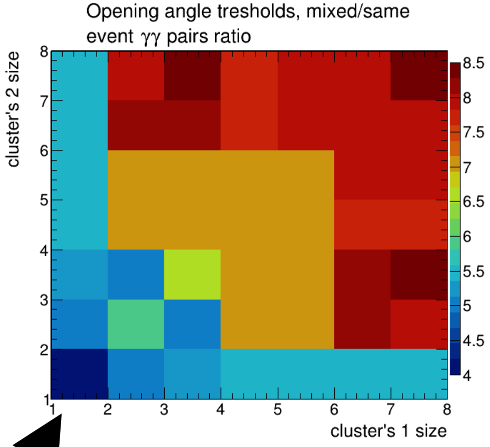


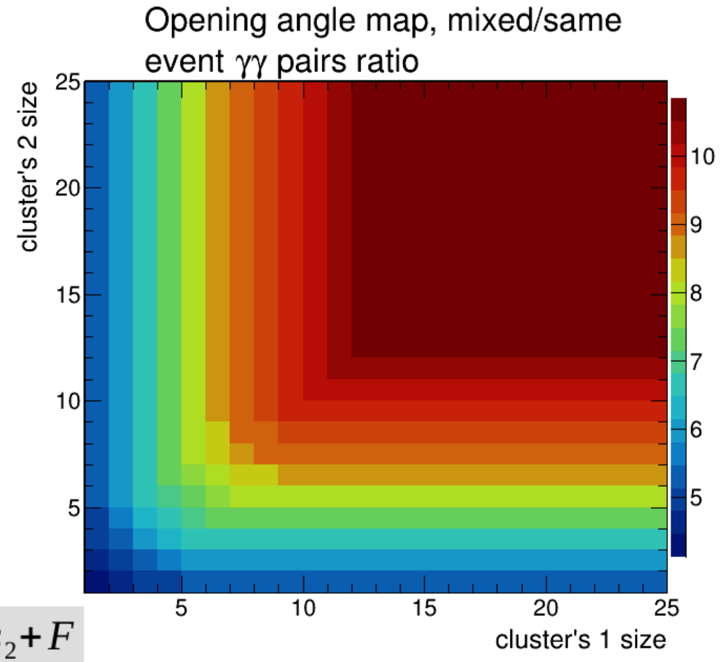
Backup – soft mapping







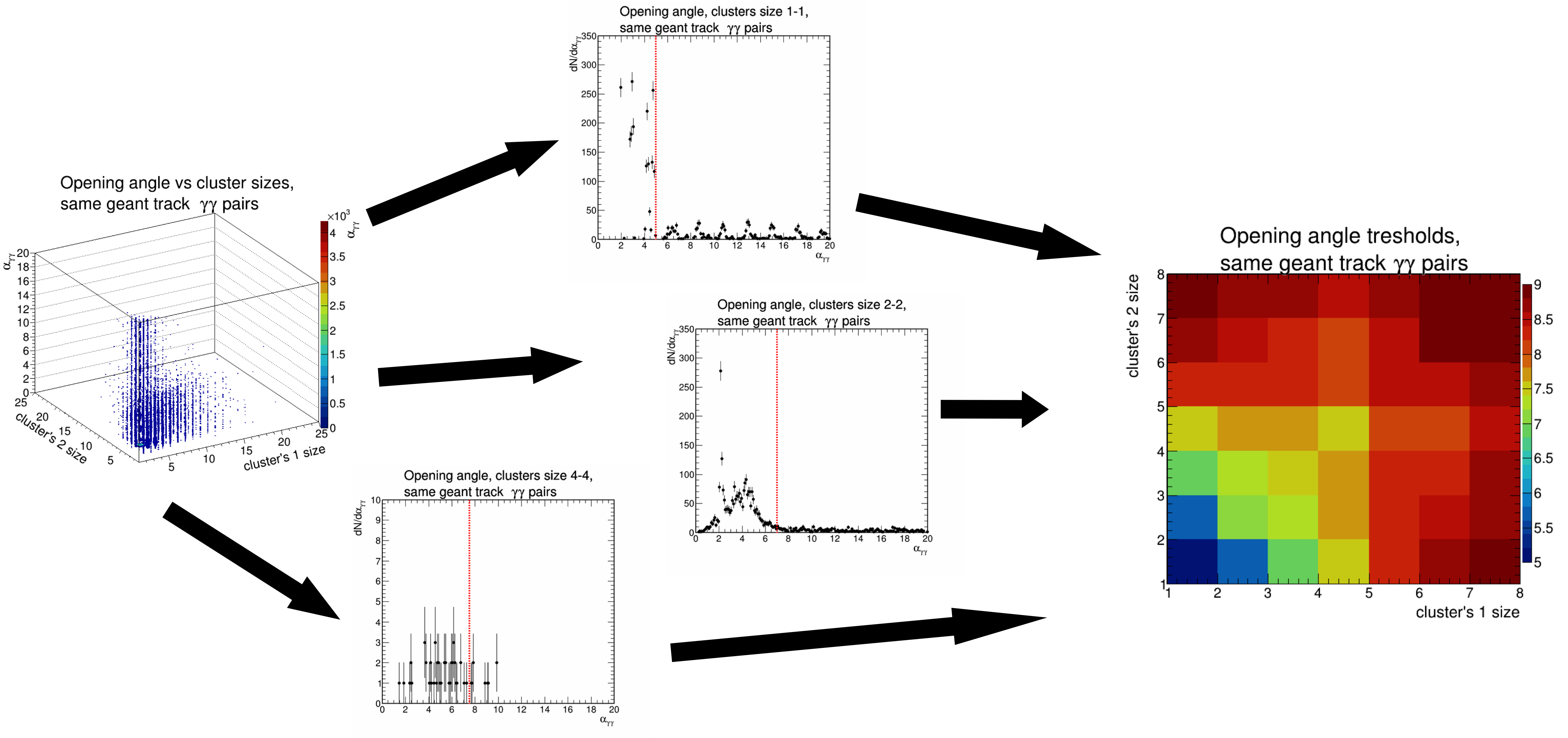




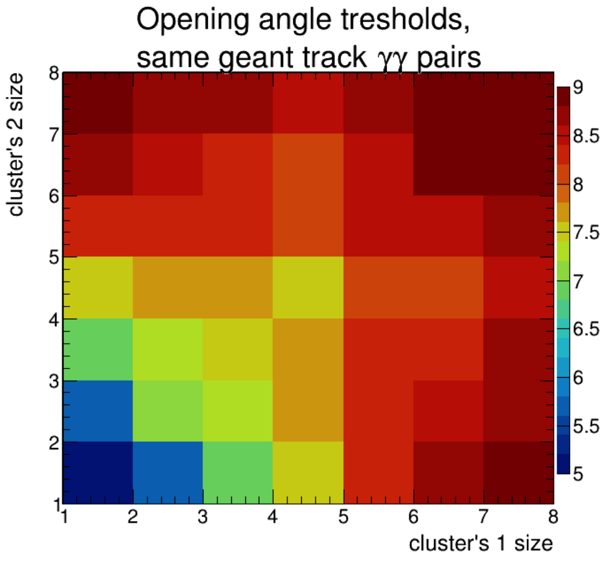
$$f(s_1, s_2) = As_1^2 + Bs_2^2 + Cs_1 s_2 + Ds_1 + Es_2 + F$$

+ border cases

Backup – hard mapping

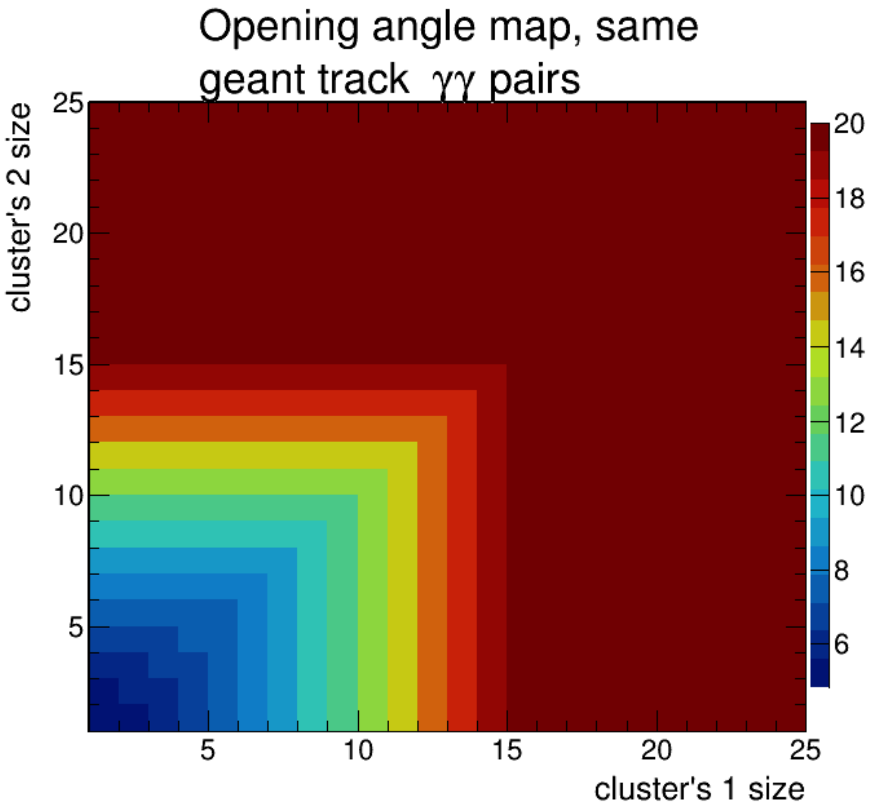


Backup – hard mapping



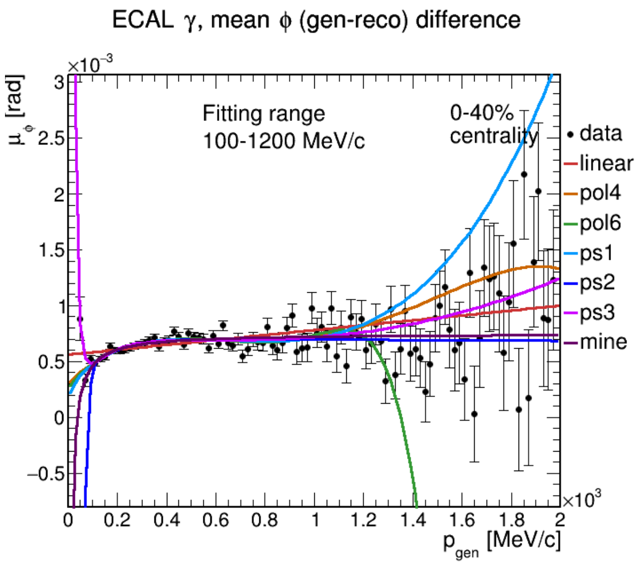
$$f(s_1, s_2) = As_1^2 + Bs_2^2 + Cs_1 s_2 + Ds_1 + Es_2 + F$$

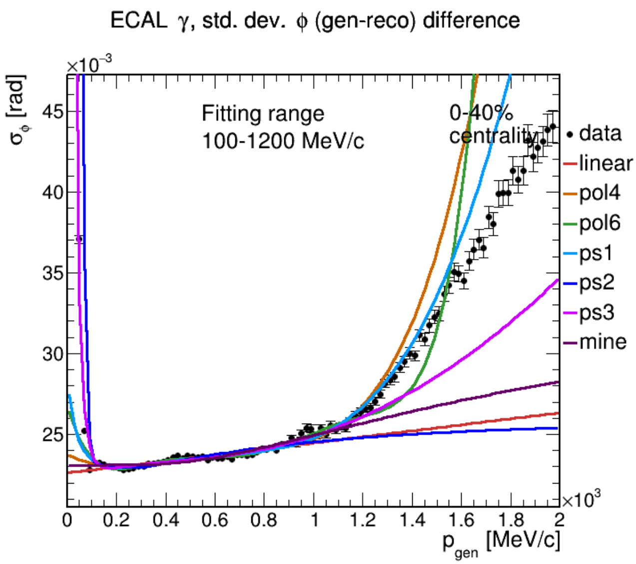
+ border cases



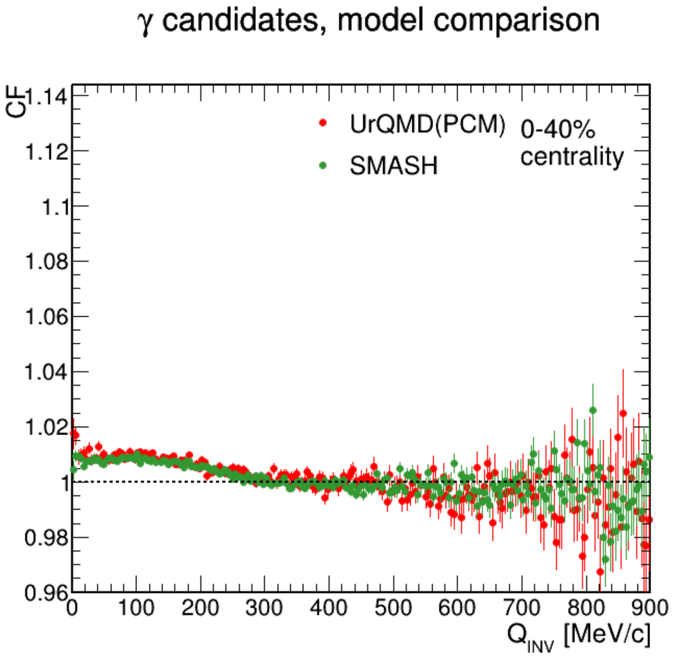
Backup – resolution estimation

- data → Difference between generated and reconstructed values, fitted with gauss & extracted mean and sigma
- linear → $l(p) = Ap + B$
- pol4 → $pol_4(p) = Ap^4 + Bp^3 + Cp^2 + Dp + E$
- pol6 → $pol_6(p) = Ap^6 + Bp^5 + Cp^4 + Dp^3 + Ep^2 + Fp + G$
- ps1 → $ps_1(p) = A + B\sqrt{p} + Cp + Dp^2 + Ep^3$
- ps2 → $ps_2(p) = A + \frac{B}{p} + \frac{C}{p^2} + \frac{D}{p^3} + \frac{E}{p^4}$
- ps3 → $ps_2(p) = A + \frac{B}{p} + \frac{C}{p^2} + Dp + Ep^2$
- mine → $m(p) = A + Be^{C/p}$

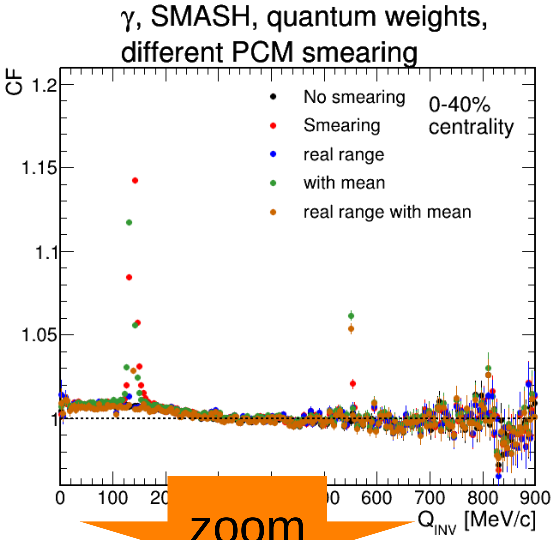


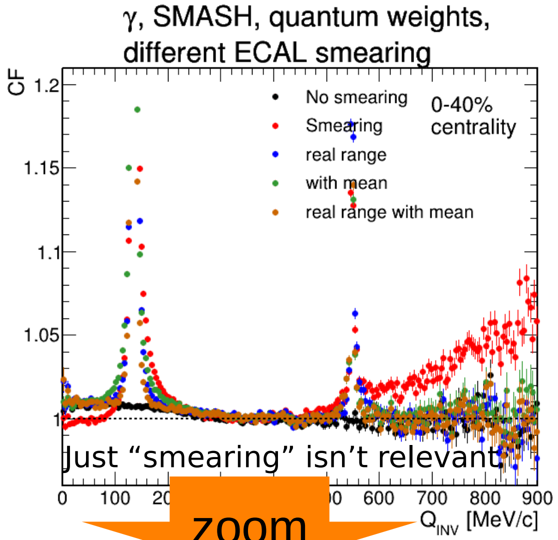


Backup – resolution impact & pure model



Pure model data comparison (no detector impact, no smearing)

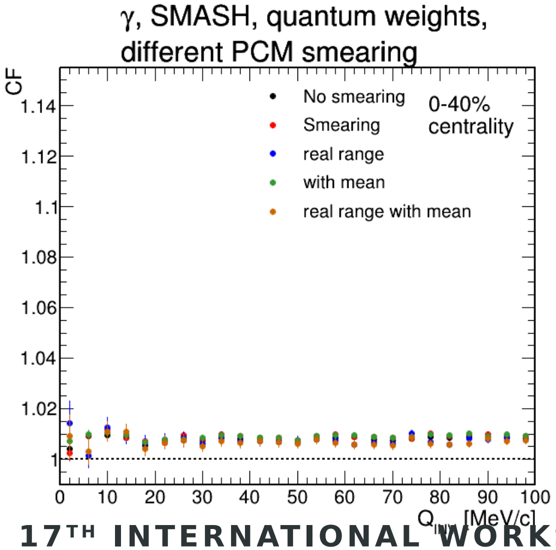


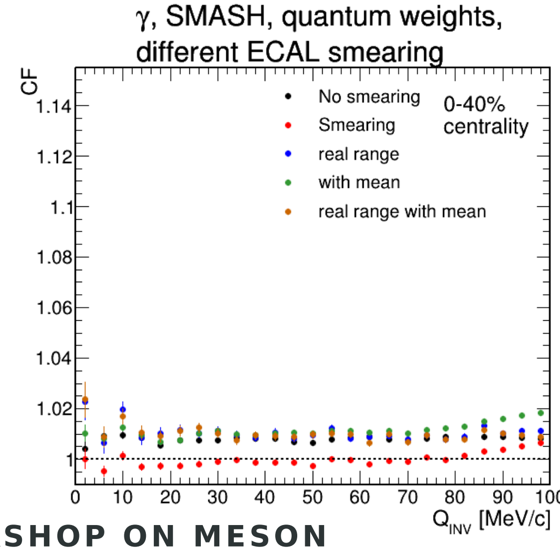


Just "smearing" isn't relevant

zoom

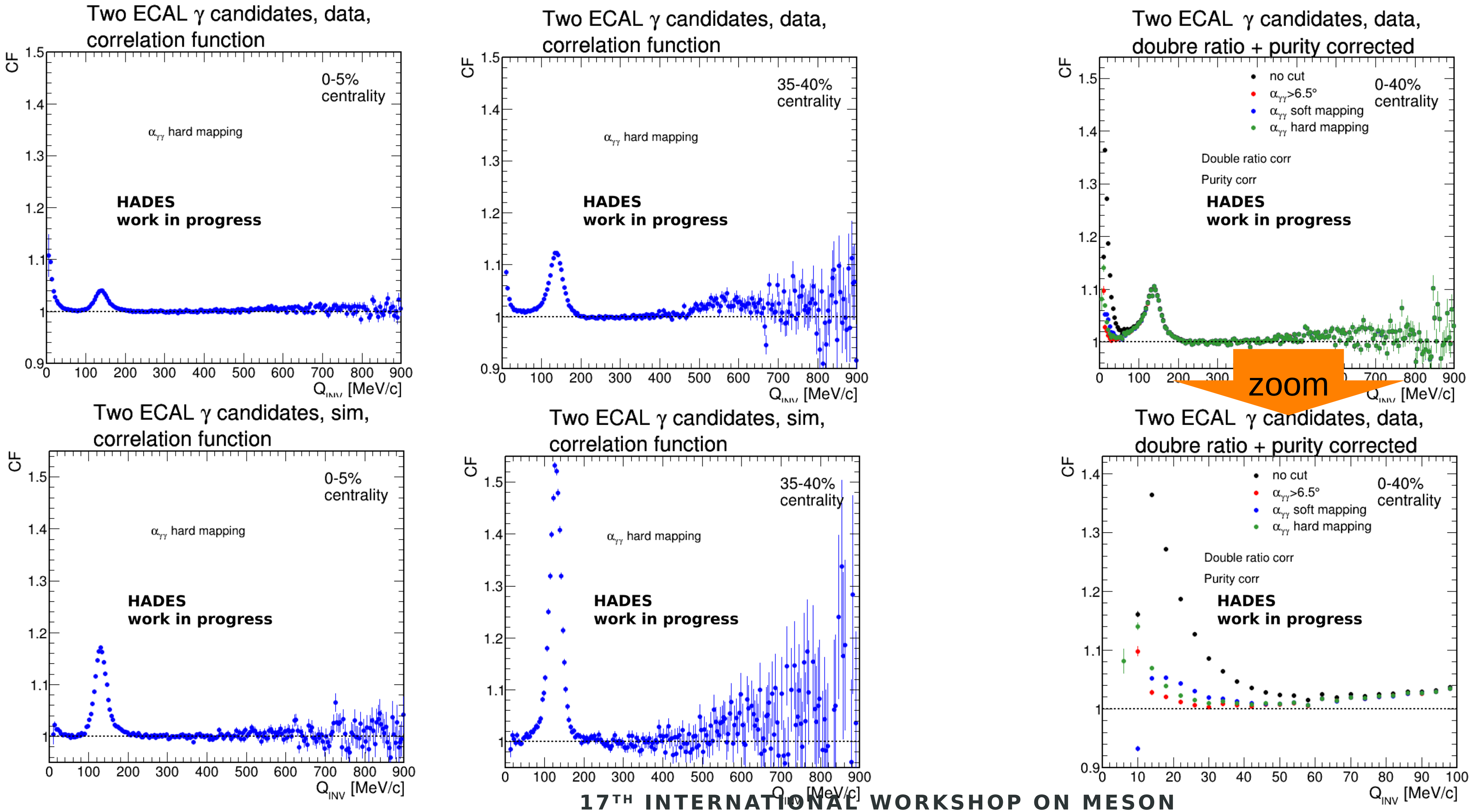
zoom



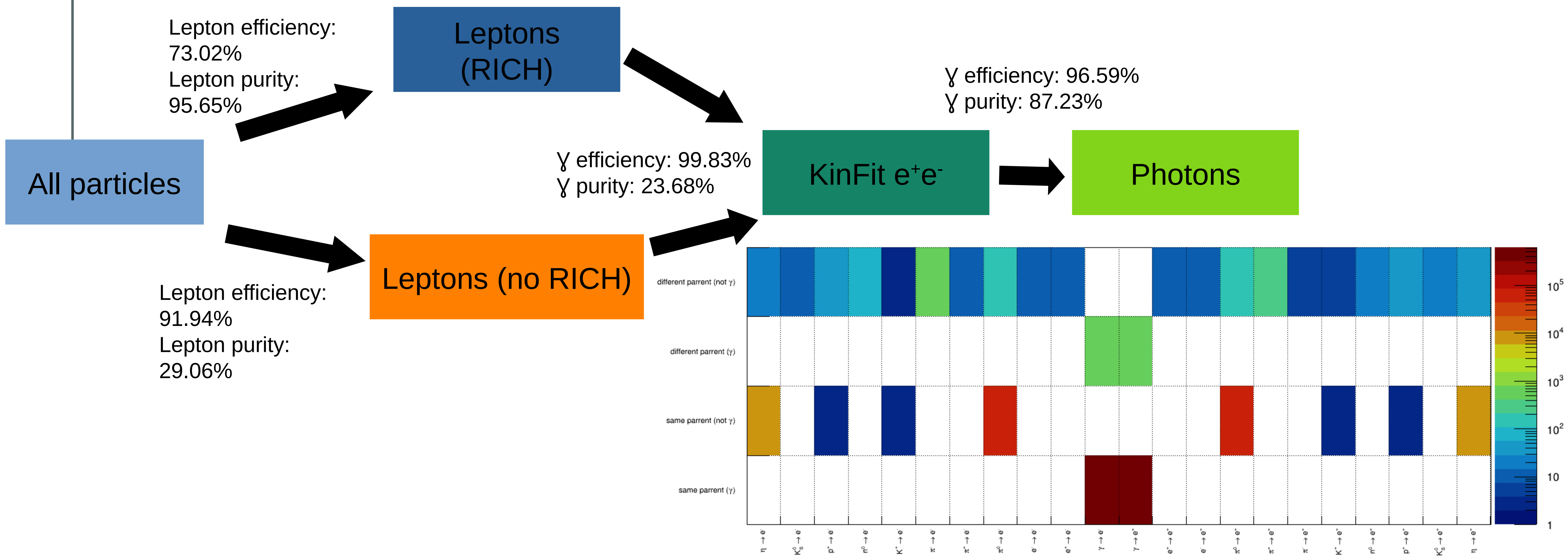


Smearing has negligible impact, at least it seems like

Backup – centrality & dual correction (Ecal)



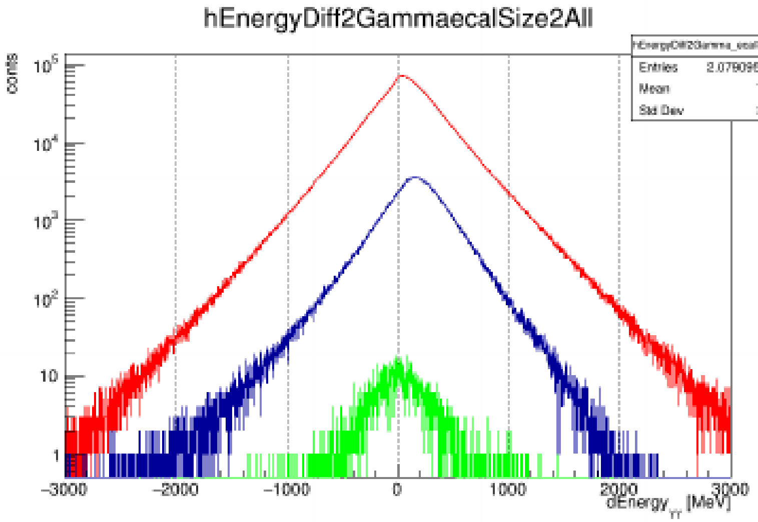
Backup – PCM photon selection

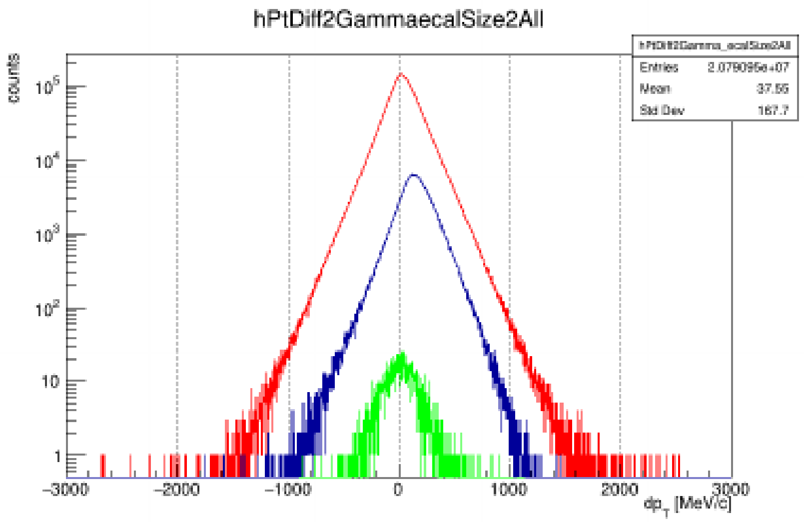


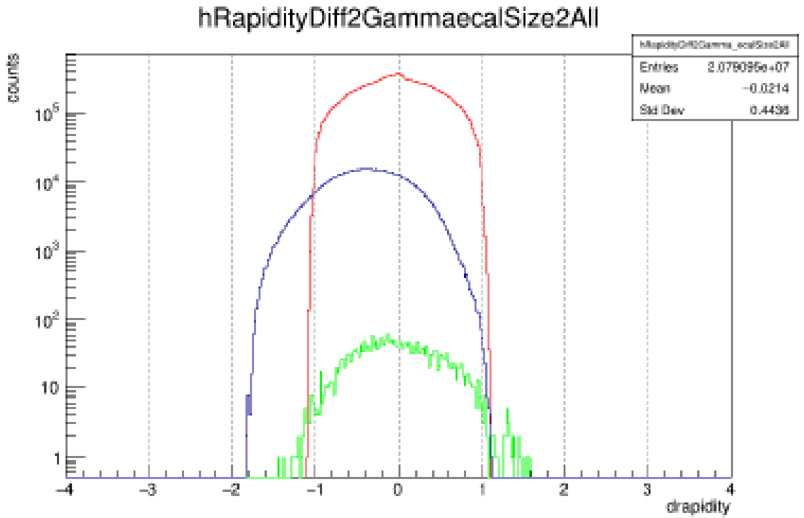
$\gamma \rightarrow e^+e^-$ (purity) ~ 87.9%, π^0 decay ~ 9.9%, η decay ~ 1.4%, rest ~ 0,8%,

Nγ ~ $6.2 \cdot 10^5$ (from $7.5 \cdot 10^7$ events) Efficiency ~ 93% * *(if both leptons are reconstructed)

Backup – hybrid issue



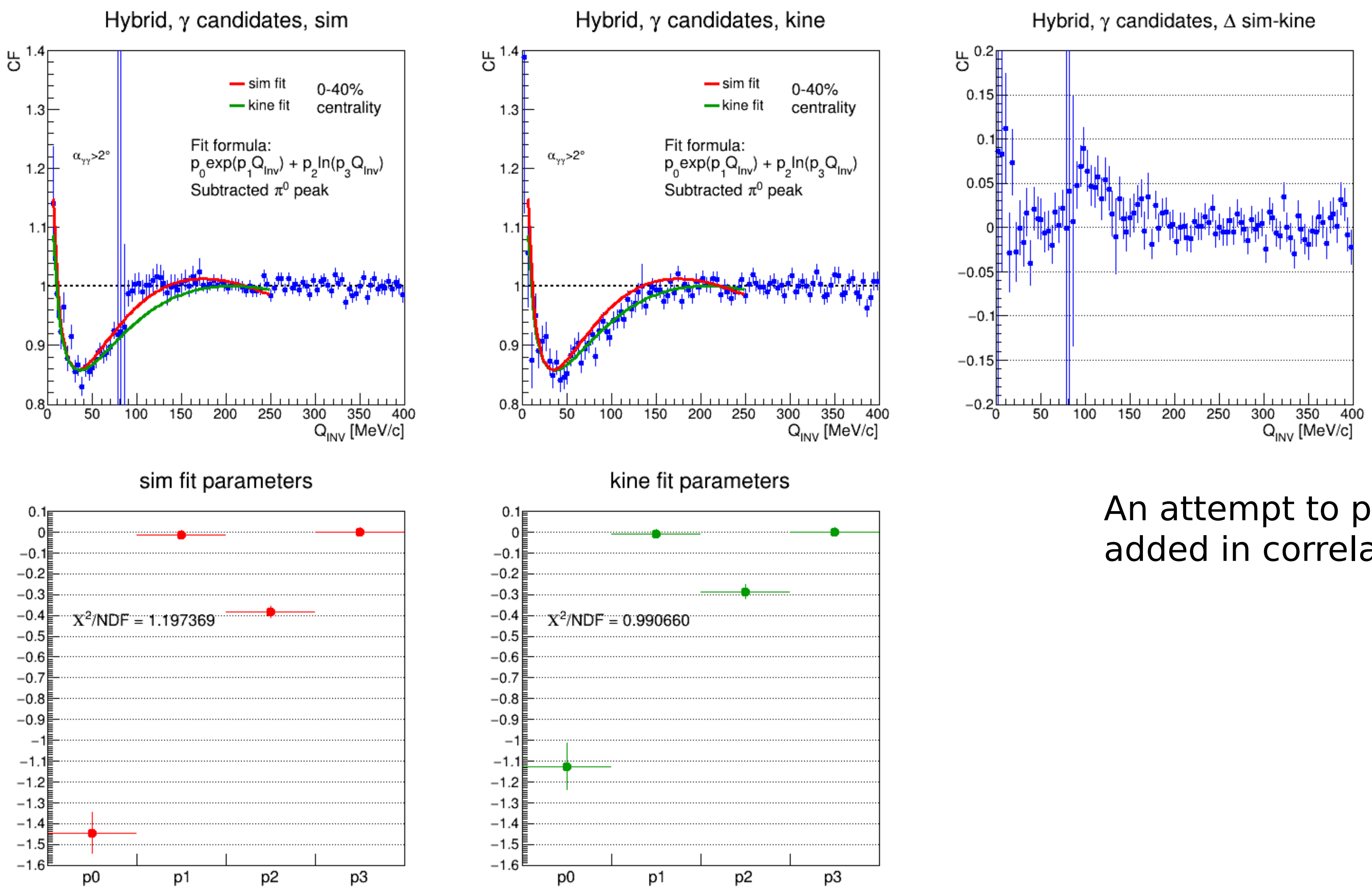




Mixing PCM and ECAL photons leads to offset in p_T,y and E differences. Is that a reason for having “the dip”? Maybe… But geometrical cuts doesn’t fix it, nor kinematical

Ecal
Hybrid
Conversion

Backup – hybrid "dip" estimation



An attempt to parametrize "the dip", to be added in correlation function (maybe)

Backup – veeeeery preliminaty fits