Evolution and fluctuations of chiral chemical potential in the heavy ion collisions

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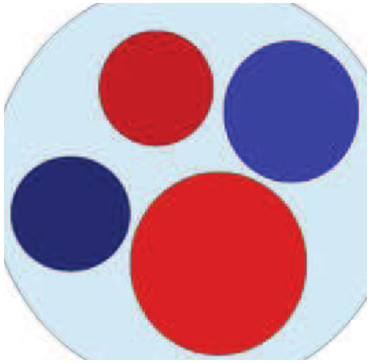
CP violation in QCD

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^{\mu\nu,a} G^a_{\mu\nu} + \bar{q}(i\gamma^\mu D_\mu - m)q,$$

$$D_\mu = \partial_\mu - igG^a_\mu \lambda^a, \quad G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g f^{abc} G^b_\mu G^c_\nu$$

- θ-term $\quad \Delta\mathcal{L}_\theta = \theta \frac{g^2}{16\pi^2} \mathrm{Tr}\left(G^{\mu\nu} \widetilde{G}_{\mu\nu} \right)$
- strong CP problem $\quad \theta \lesssim 10^{-9}.$
- P − and CP − odd bubbles may appear in a finite volume due to large topological fluctuations in a hot medium
- Gauge field configurations can be characterized by an integer topological (invariant) charge



A.A. Andrianov, V.A. Andrianov, D. Espriu, X. Planells, Phys. Lett. B 2012, 710, 230-235
A.A. Andrianov, V.A. Andrianov, D. Espriu, X. Planells, Proc. Sci., QFTHEP2013,025.
A.A. Andrianov, V.A. Andrianov, D. Espriu, X. Planells, AIP Conf.Proc. 1701 (2016) 1

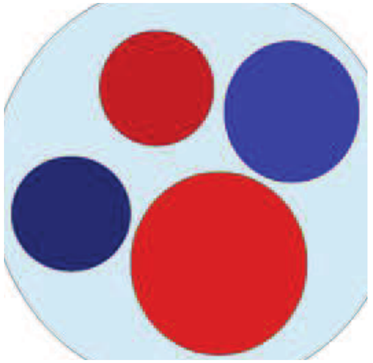
CP violation in QCD

- In QCD topologically non-trivial configurations of gauge fields can exist (instantons)
- Gauge field configurations can be characterized by an integer topological (invariant) charge

$$T_5 = \frac{g^2}{16\pi^2} \int_{t_i}^{t_f} dt \int_{\text{vol.}} d^3x \, \mathrm{Tr}\left(G^{\mu\nu}\widetilde{G}_{\mu\nu}\right) \in \mathbb{Z}$$

- Statistical treatment: with chemical potential μ

The local partial conservation of the axial current is afflicted by gluon anomaly



$$\partial^\mu J_{5,\mu} - 2i\bar{q}\hat{m}_q\gamma_5 q = \frac{N_f g^2}{8\pi^2}\mathrm{Tr}\left(G^{\mu\nu}\widetilde{G}_{\mu\nu}\right)$$

$$\frac{d}{dt}(Q_5^q - 2N_f T_5) \simeq 2i\int_{\text{vol.}} d^3x\, \bar{q}\hat{m}_q\gamma_5 q\ , \quad Q_5^q = \int_{\text{vol.}} d^3x\, \bar{q}\gamma_0\gamma_5 q.$$

$$\langle T_5\rangle = \frac{1}{2N_f}\langle Q_5^q\rangle \quad \Longleftrightarrow \quad \mu_5 = \frac{1}{2N_f}\mu_\theta.$$

It must survive for a sizeable lifetime in a heavy-ion fireball,

$$\langle \Delta T_5 \rangle \neq 0 \quad \text{for} \quad \Delta t \simeq \tau_{\text{fireball}} \simeq 5 \div 10 \text{ fm/c};$$

A.A. Andrianov, V.A. Andrianov, D. Espriu, X. Planells, Phys. Lett. B 2012, 710, 230-235
A.A. Andrianov, V.A. Andrianov, D. Espriu, X. Planells, Proc. Sci., QFTHEP2013,025.
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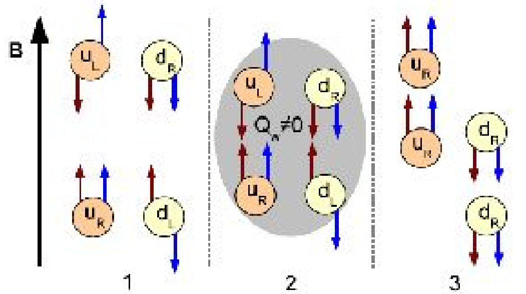
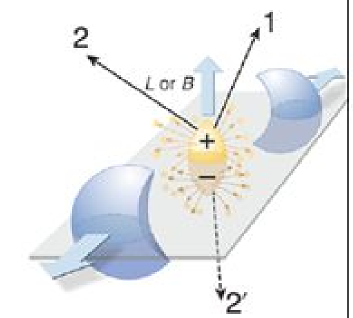
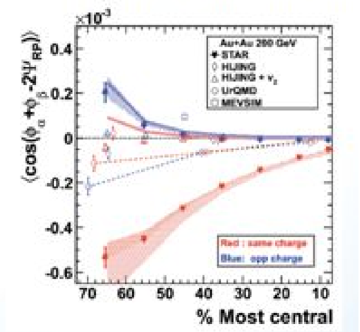
Observables for Local parity violation in QCD

Chiral Magnetic Effect (CME)





(STAR Collaboration)



. Kharzeev, L. McLerran, H. Warringa, 2007

. Fukushima, D. Kharzeev, and H. Warringa. Phys. Rev. D, 78, 074033 (2008).

Parity forbidden decays of light scalar mesons

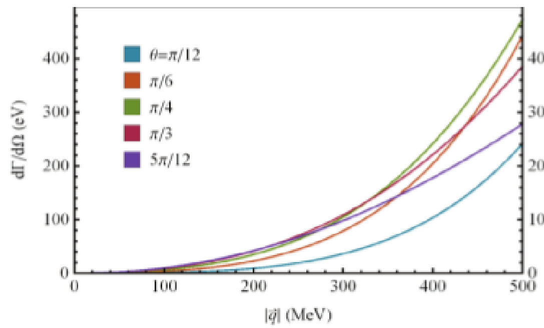
Effective meson theory in a medium with LPB

$$\mathcal{L} = \frac{1}{2}(\partial a_0)^2 + \frac{1}{2}(\partial \pi)^2 - \frac{1}{2}m_1^2 a_0^2 - \frac{1}{2}m_2^2\pi^2 - 4\mu_5 a_0 \dot{\pi},$$

$$m_1^2 = -2[M^2 - 2(3\lambda_1 + \lambda_2)v_q^2 - \lambda_2 v_s^2 - c v_s + 2\mu_5^2]$$

$$m_2^2 = \frac{2m}{v_q}B.$$

The decays $\tilde{a}_0^{\pm} \to \tilde{\pi}^{\pm}\gamma$.

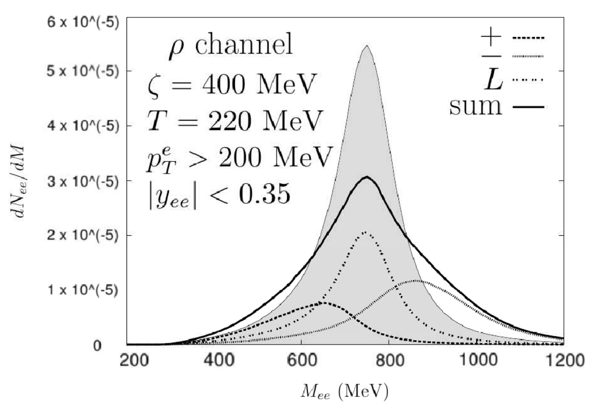


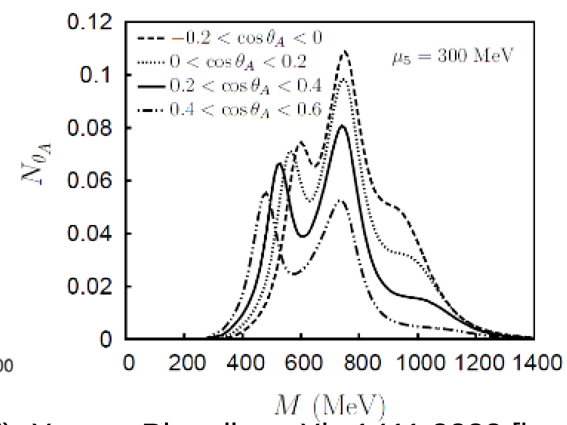
A. A. Andrianov, V. A. Andrianov, D. Espriu, A.V. Iakubovich, A.E. Putilova EPJ Web of Conf. 158, 03012 (2017)

Vector meson polarization splitting: angular analysis in di-lepton decays

VMD

$+ \mathcal{L}_{CS}$





A. Andrianov, V. Andrianov, D. Espriu, EPJ Web of Conferences 137 , 01005 (2017), Xumeu Planells, arXiv:1411.3283 [hep-ph]

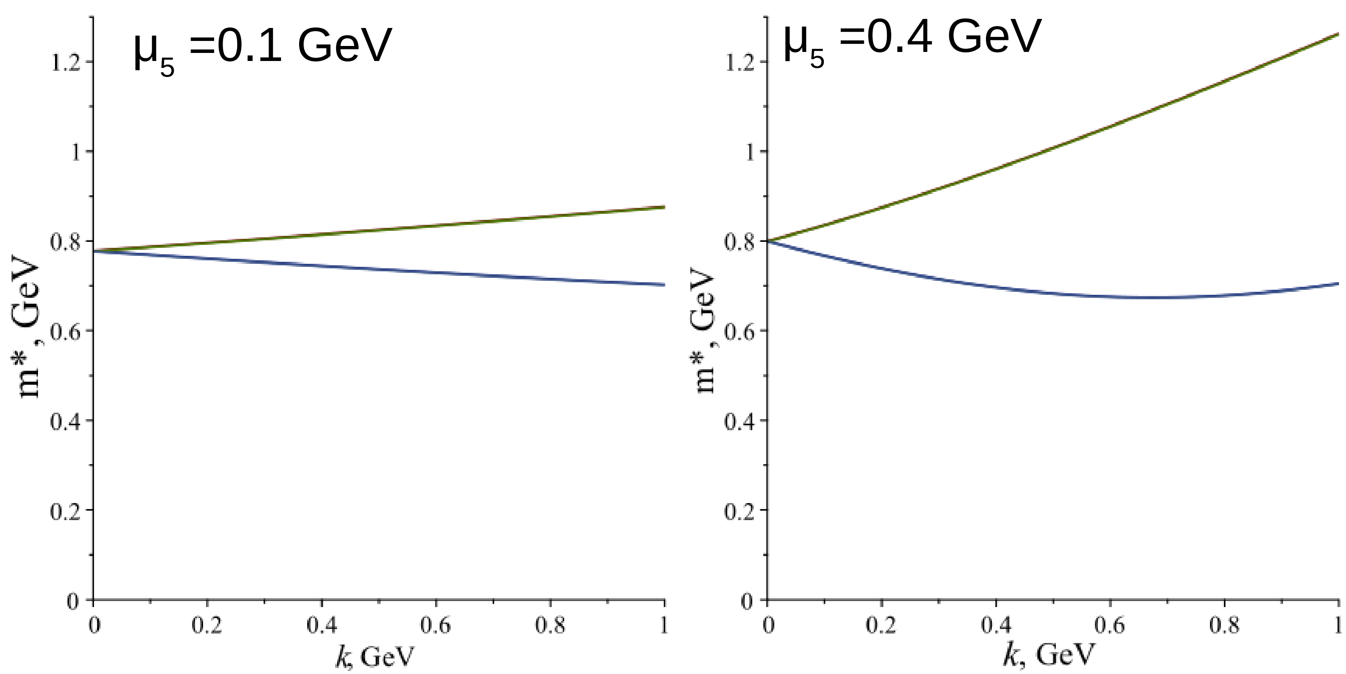
Vector meson dominance in LPB medium

$$\mathcal{L}_{\text{int}} = \bar{q}\gamma_\mu V^\mu q; \quad V_\mu \equiv -eA_\mu Q + \frac{1}{2}g_\omega \omega_\mu \mathbf{I}_q + \frac{1}{2}g_\rho \rho_\mu \lambda_3 + \frac{1}{\sqrt{2}} g_\phi \phi_\mu \mathbf{I}_s,$$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{kin}} - \frac{1}{4}\varepsilon V_{\mu\nu} \varepsilon V^{\mu\nu} + \frac{1}{2}\varepsilon m^2 V_\nu V^\nu + \varepsilon \frac{b^\lambda b^\nu}{2b^2} V_{\lambda\rho} V^\rho_\nu - \frac{N_c}{8\pi^2} b_\mu V_\nu \epsilon^{\mu\nu\lambda\nu} V_{\lambda\nu}$$

Mass of the transverse polarisations for ρ and ω mesons

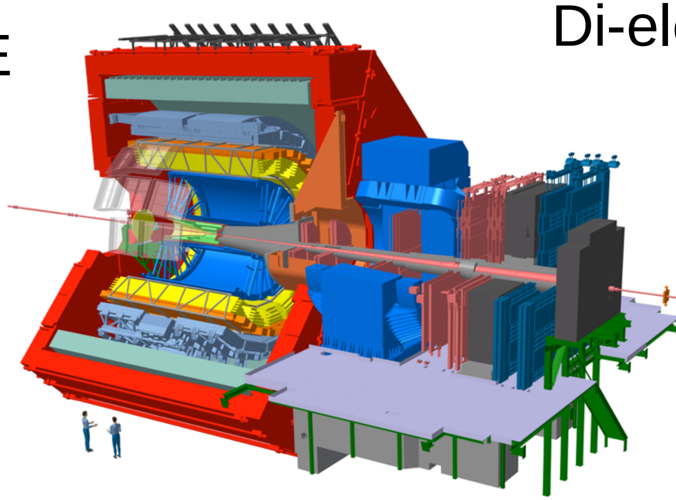
$$m*^2 = \bar{m}^2 \pm \zeta b_0 |\vec{k}| + \xi b_0^2 |\vec{k}|^2 / m^2$$



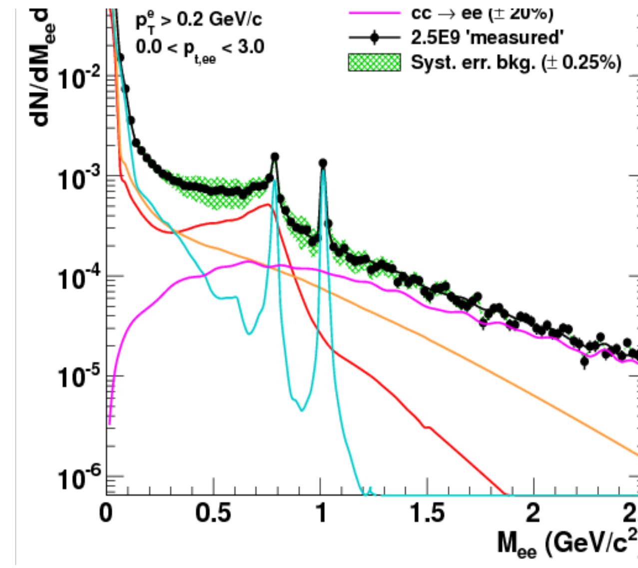
Vladimir Kovalenko, Alexander Andrianov, Vladimir Andrianov,
J. Phys.: Conf. Ser. 1690, 012097 (2020), arXiv:2010.13238 [hep-ph]

Experimental possibilities in heavy ion collisions at the LHC

ALICE



Di-electrons

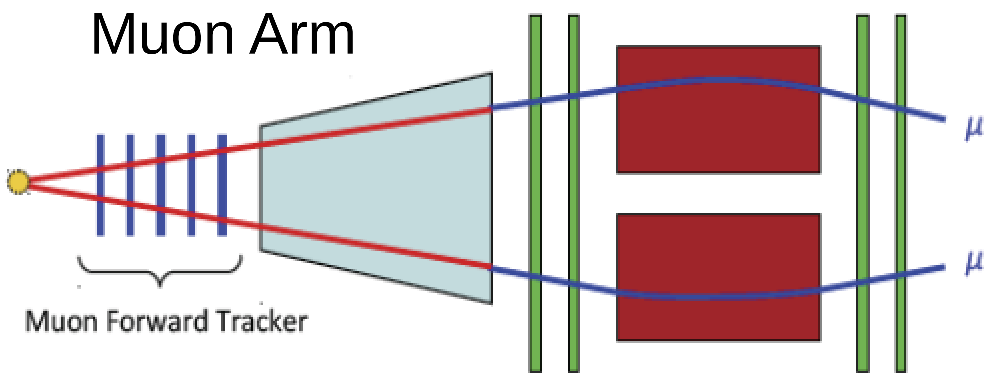


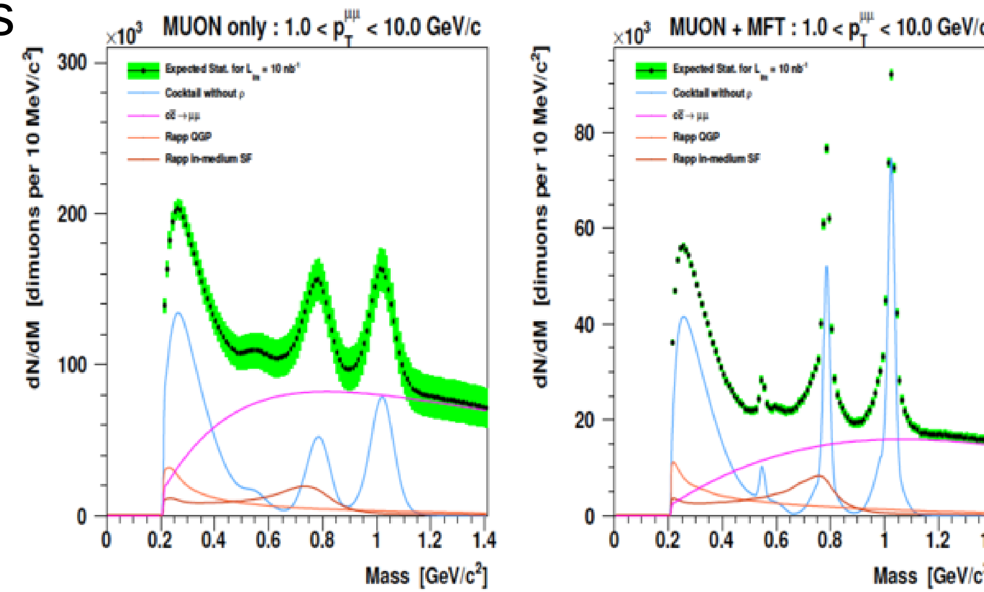
e+ e- in ITC+TPC,
combied PID + MVA (ml) methods

Technical Design Report for the Upgrade of the ALICE Inner Tracking System

Di-muons

Muon Arm



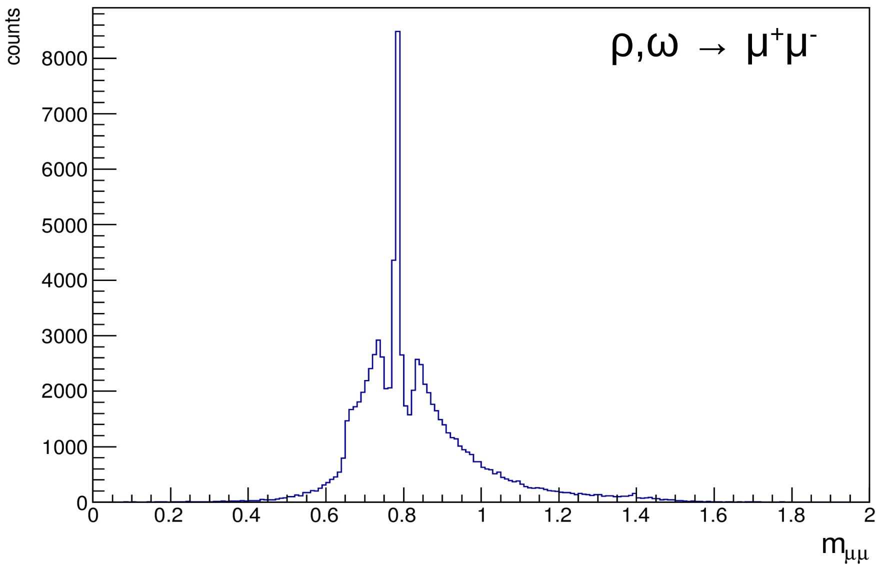


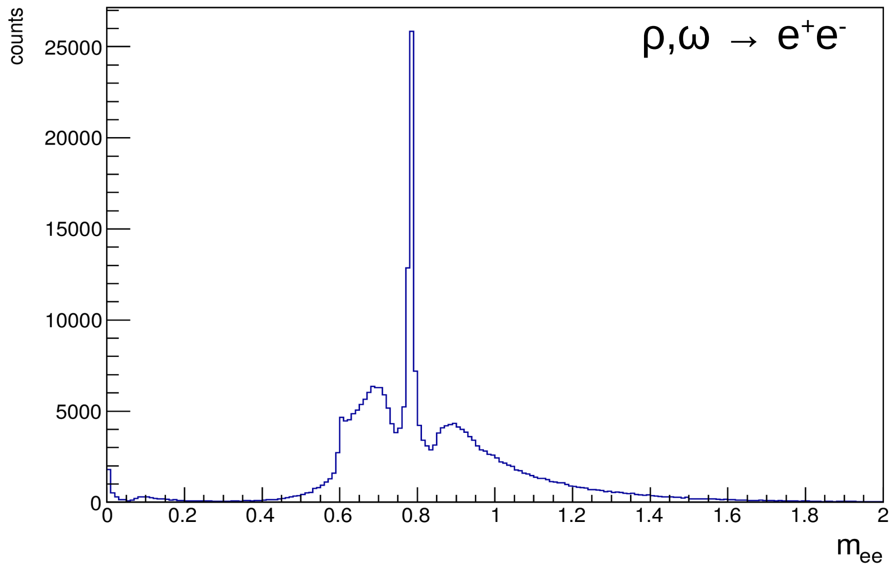
E. Garcia-Solis for the ALICE Collaboration, Nuclear and Particle Physics Proceedings 267–269 (2015) 382–391;
Technical Design Report for the Muon Forward Tracker

Pythia 8.2, Monte Carlo results (perfect detector response) - Pb-Pb at 5.02 TeV

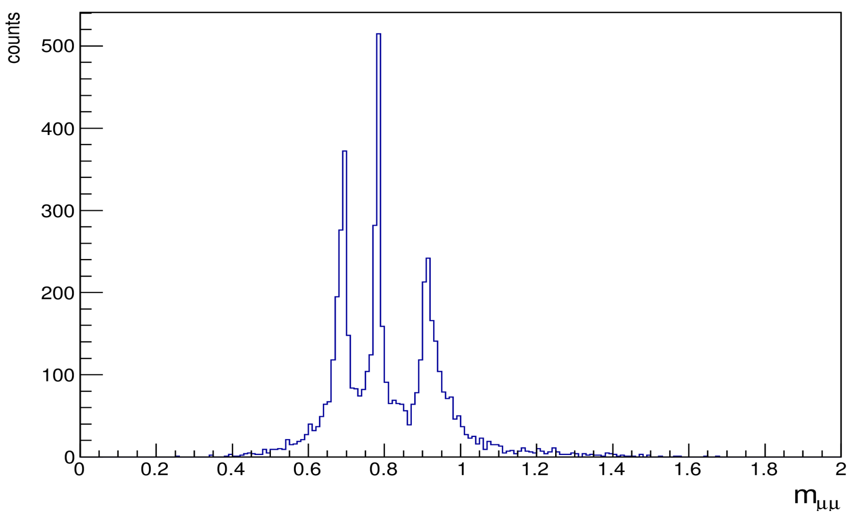
All: μ_5= 0.1 GeV

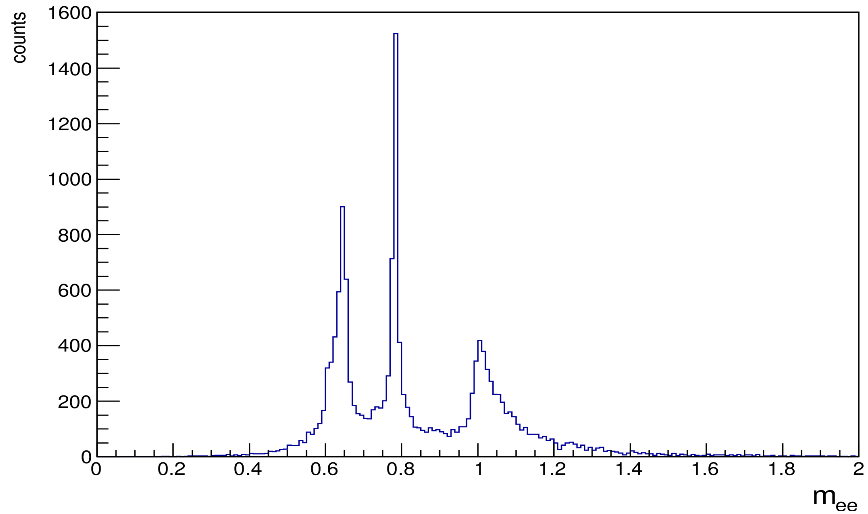
No angular θ_A selection





$0.4<\cos\theta_A<0.5$ (for muons — boost to midrapidity applied)





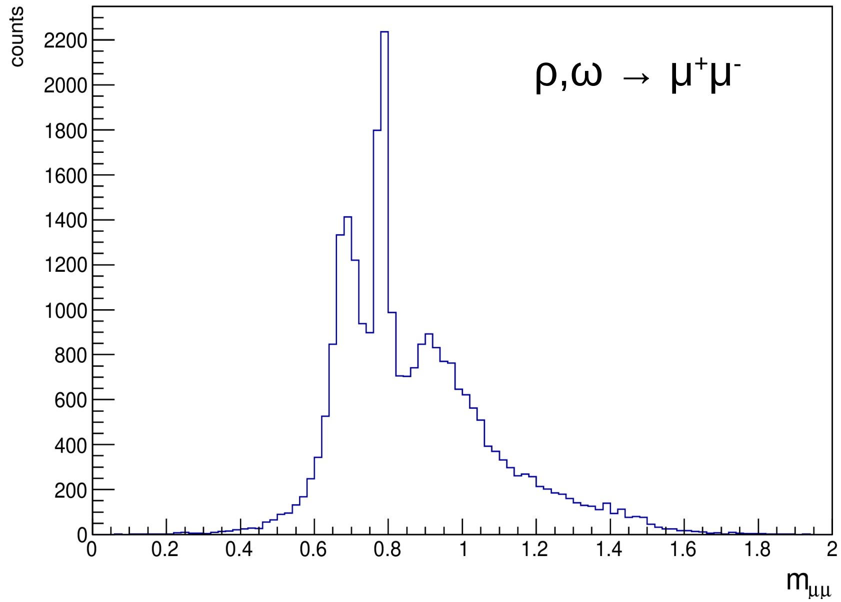
$p_{T\mu}$>0.2 GeV, $p_{T\mu\mu}$>0.4 GeV

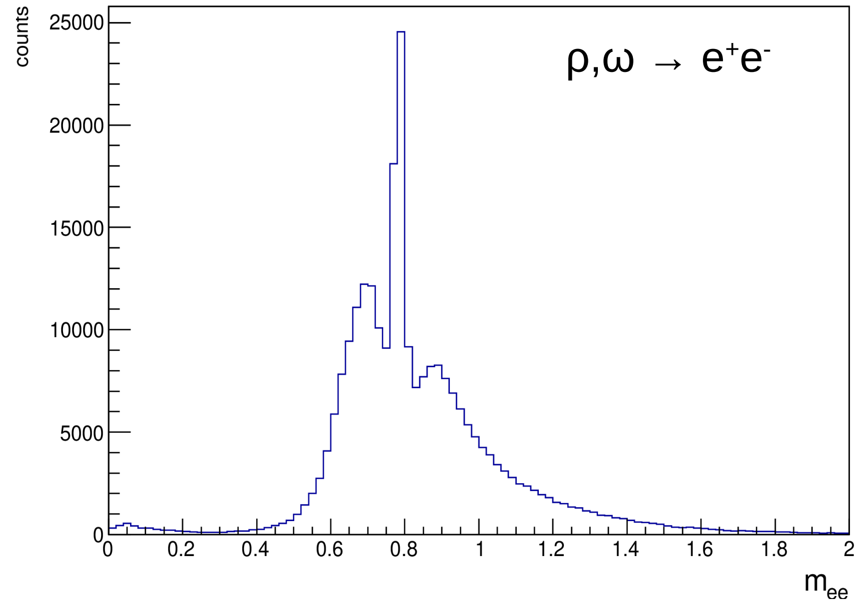
p_{Te}>0.1 GeV, p_{Tee}>0.4 GeV

Monte Carlo in ALICE Run 3 conditions (with detector responce resolution)

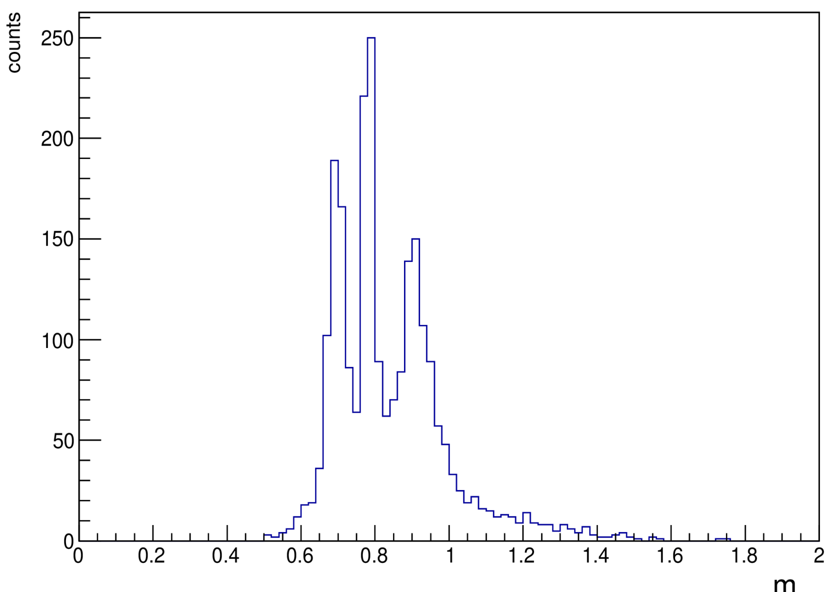
All: μ_5= 0.1 GeV

No angular θ_A selection



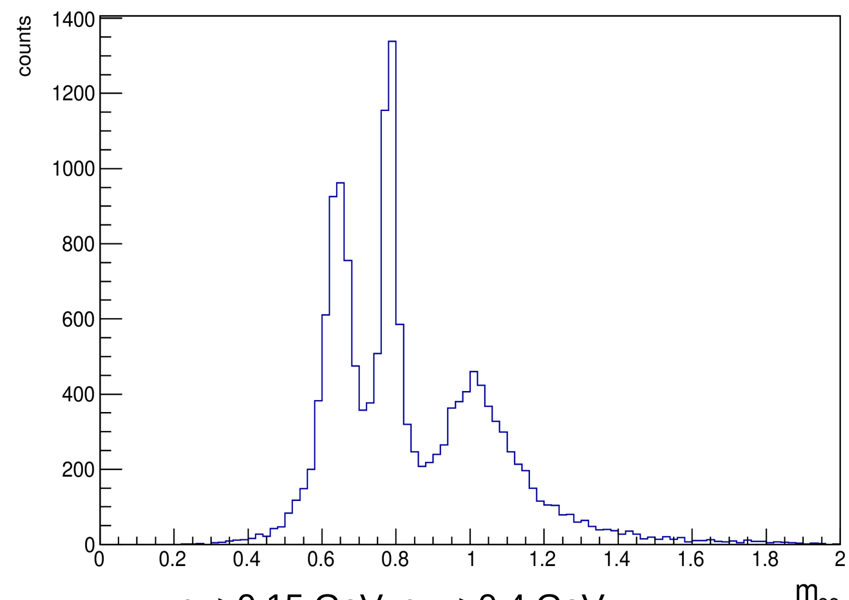


0.4<cos θ_A <0.5



$p_{T\mu}$>0.5 GeV, $p_{T\mu\mu}$>0.5 GeV

0.4<cos θ_A <0.5

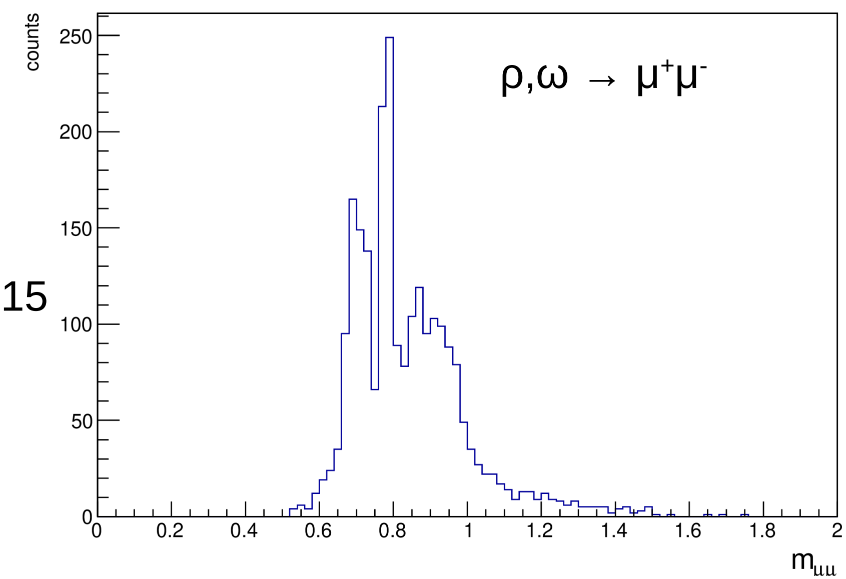


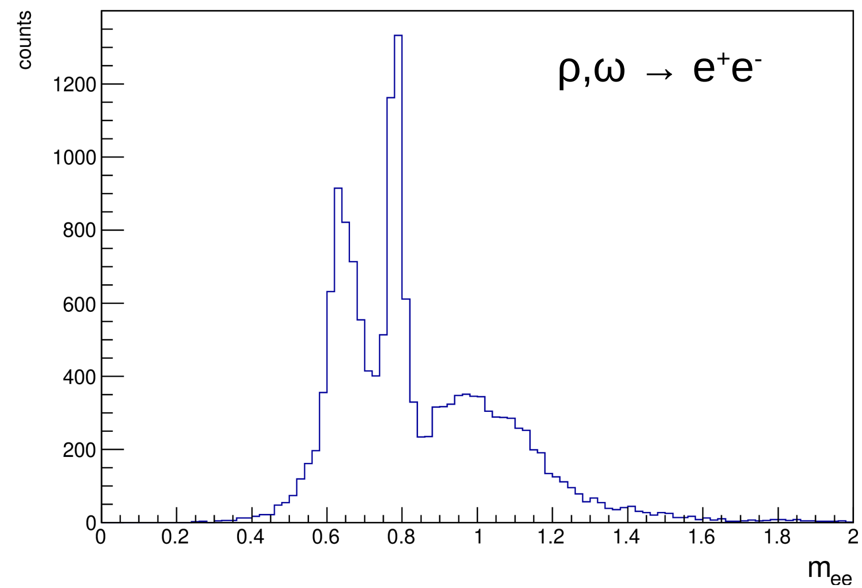
p_{Te}>0.15 GeV, p_{Tee}>0.4 GeV

Influence of the fluctuation of μ_5 (ALICE Run 3 conditions)

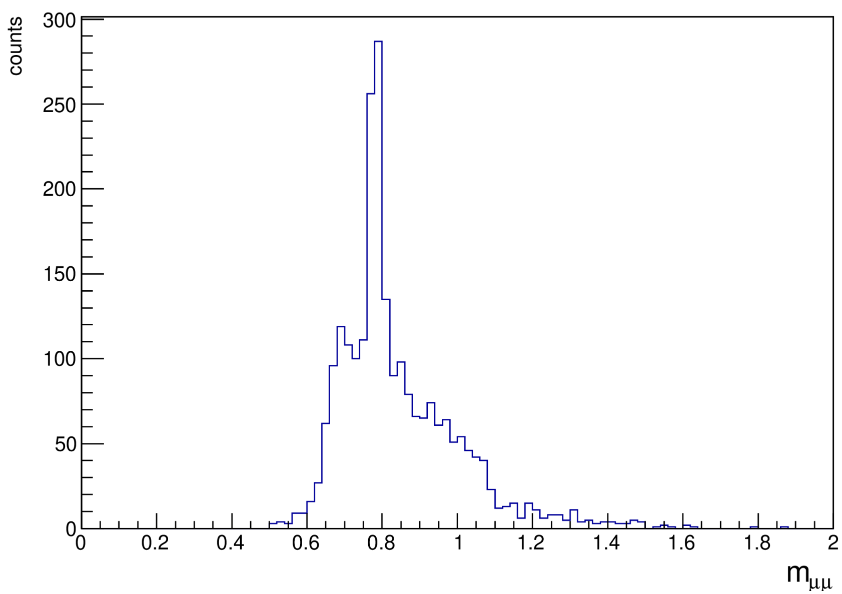
All: $0.4<\cos\theta_A<0.5$

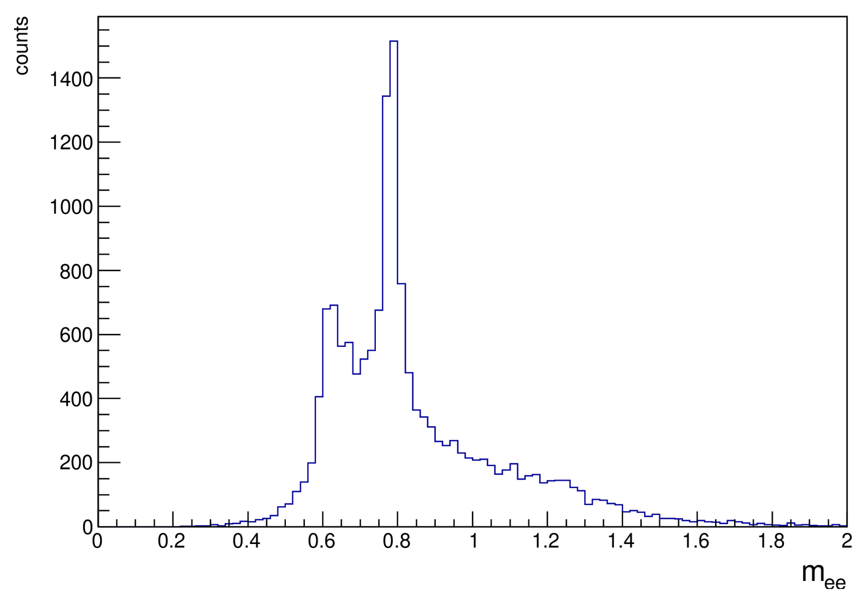
Uniform: $0.05<\mu_5<0.15$ [GeV]





Uniform: $0<\mu_5<0.2$ [GeV]





$p_{T\mu}>0.5$ GeV, $p_{T\mu\mu}>0.5$ GeV

$p_{Te}>0.15$ GeV, $p_{Tee}>0.4$ GeV

Setup

> Relativistic viscous hydrodynamics MUSIC* (boost-invariant mode)

> Glauber initial conditions

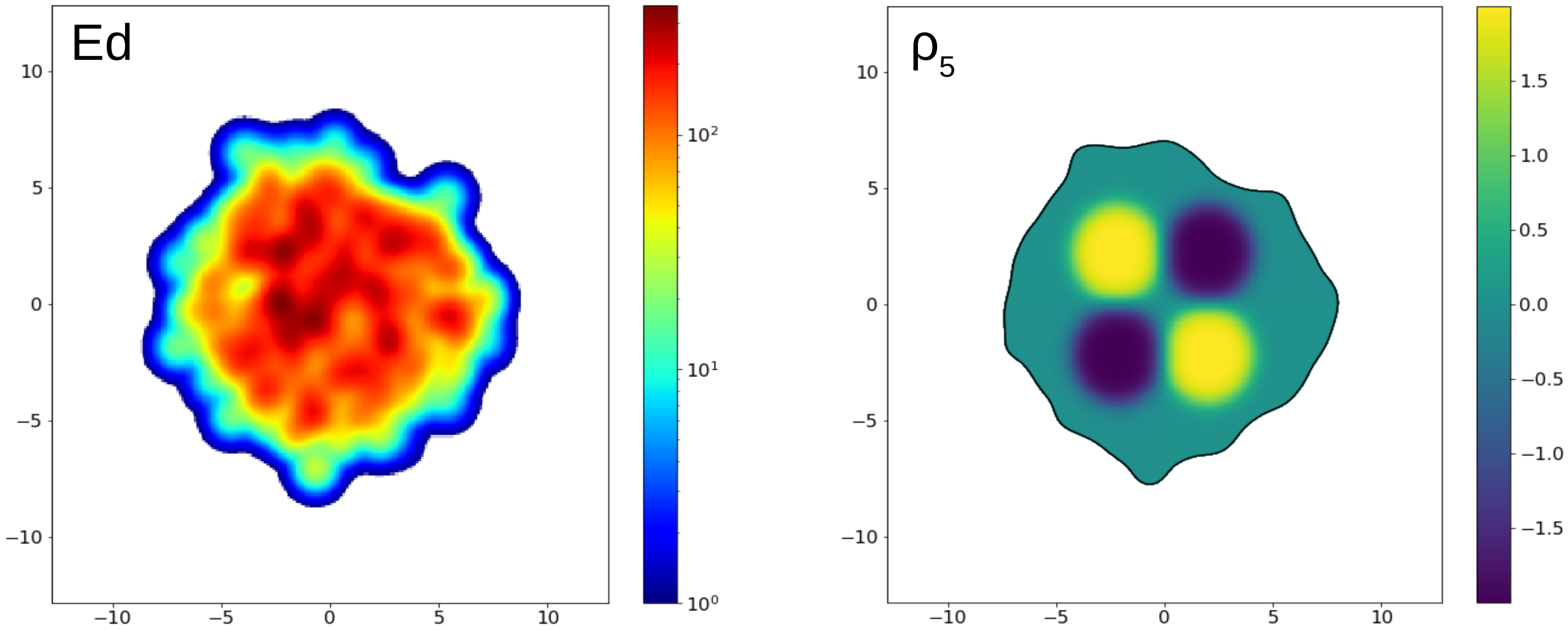
> Central Pb-Pb collisions at 5.02 TeV (0<b<2 fm)

> Lattice EOS hotQCD (no dependence in EOS on μ_5 assumed)

> Freeze-out at Ed=0.18 GeV/fm^3.

> Axial charge bubbles in the initial conditions

Initial energy density and topological charge density distributions in the transverse plane:

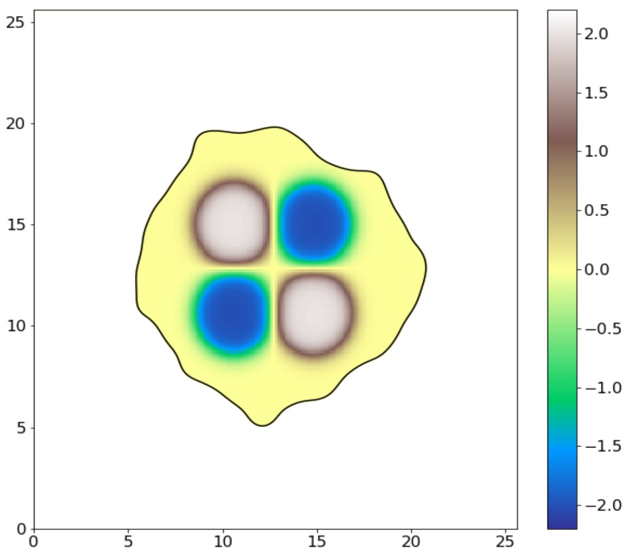


* Bjoern Schenke, Sangyong Jeon, and Charles Gale, Phys. Rev. C 82, 014903 (2010).

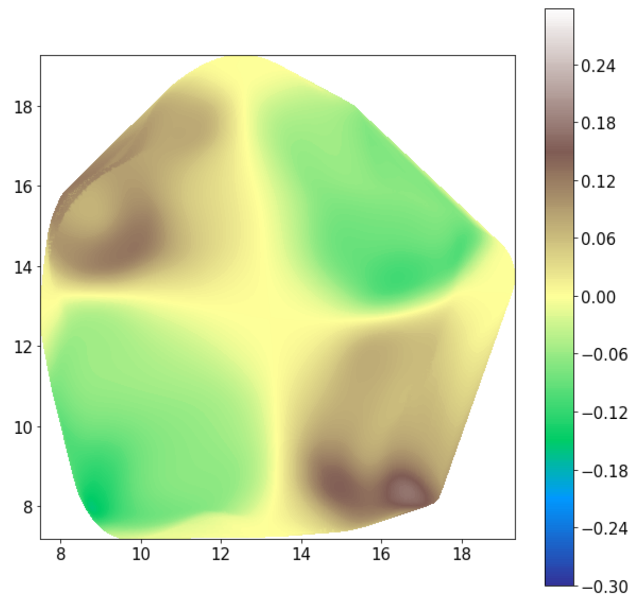
Axial charge density evolution

> example event

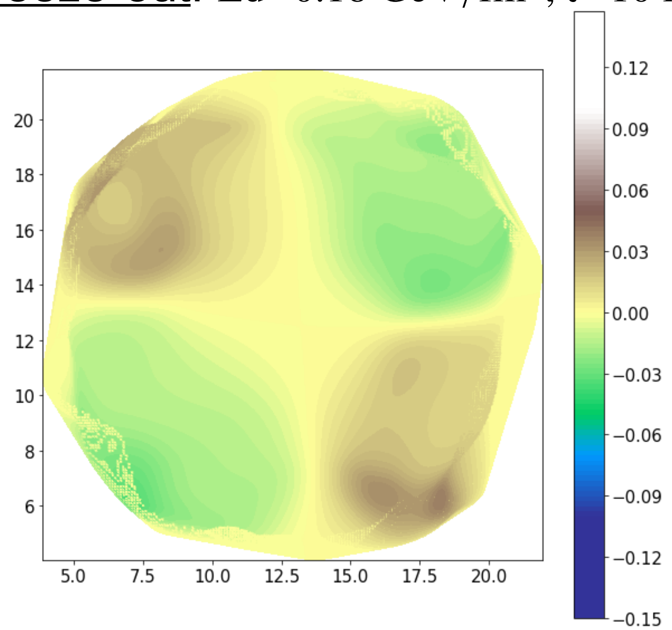
Initial $Ed \sim 60\ \mathrm{GeV/fm^3}\ \tau = 0.6\ \mathrm{fm}$



$Ed = 0.98\ \mathrm{GeV/fm^3},\ \tau \approx 6\ \mathrm{fm}$



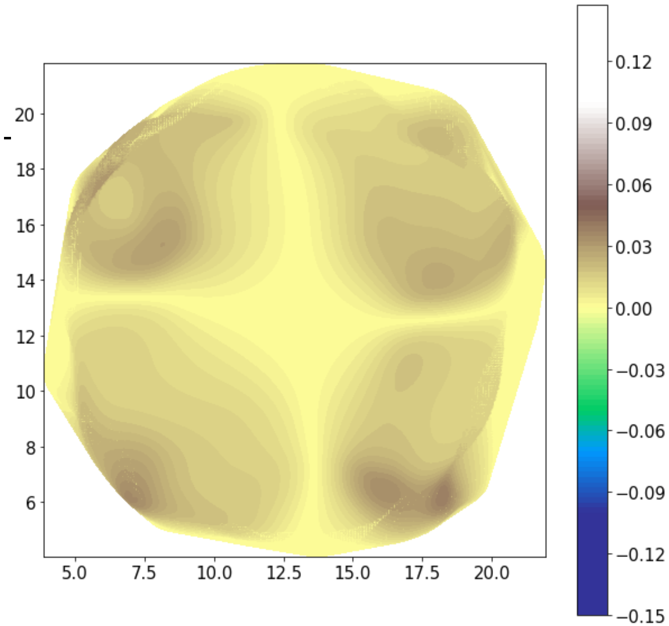
freeze-out: $Ed = 0.18\ \mathrm{GeV/fm^3},\ \tau \approx 10\ \mathrm{fm}$

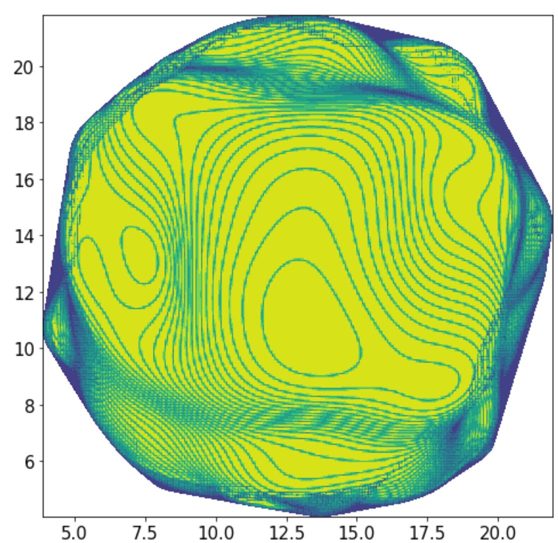


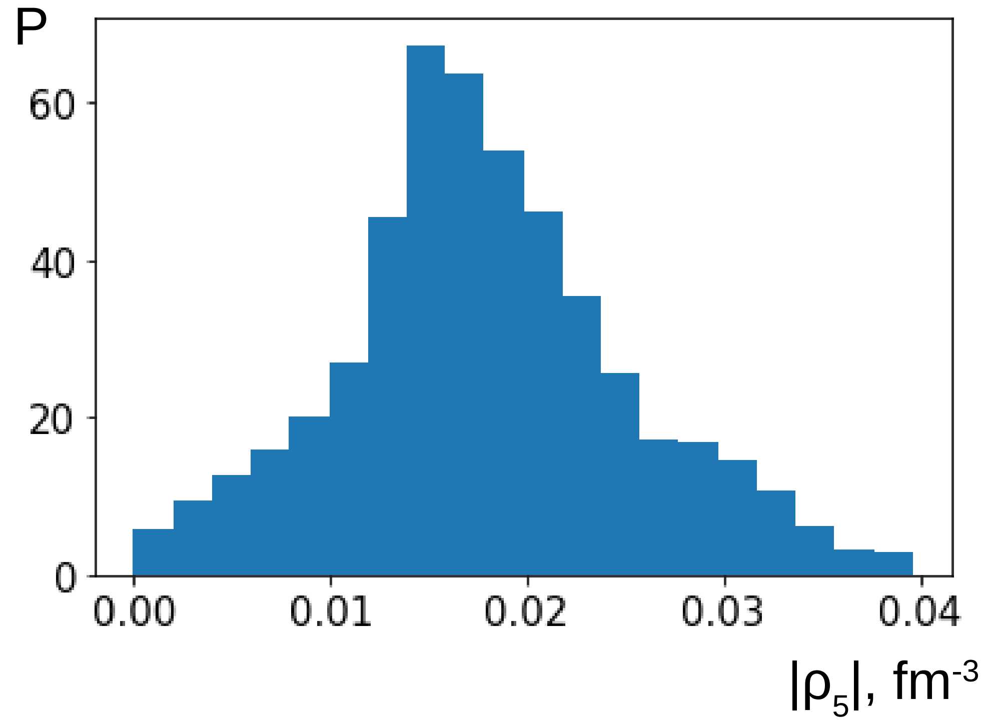
Regions of local axial charge excess stays throughout the entire hydro-dynamical evolution of the medium

Axial charge distribution at freeze-out

> $|\rho_5|$ distribution in transverse plane:







$\langle|\rho_5|\rangle = 0.018$ fm^{-3}, $\sigma = 0.007$fm^{-3} .

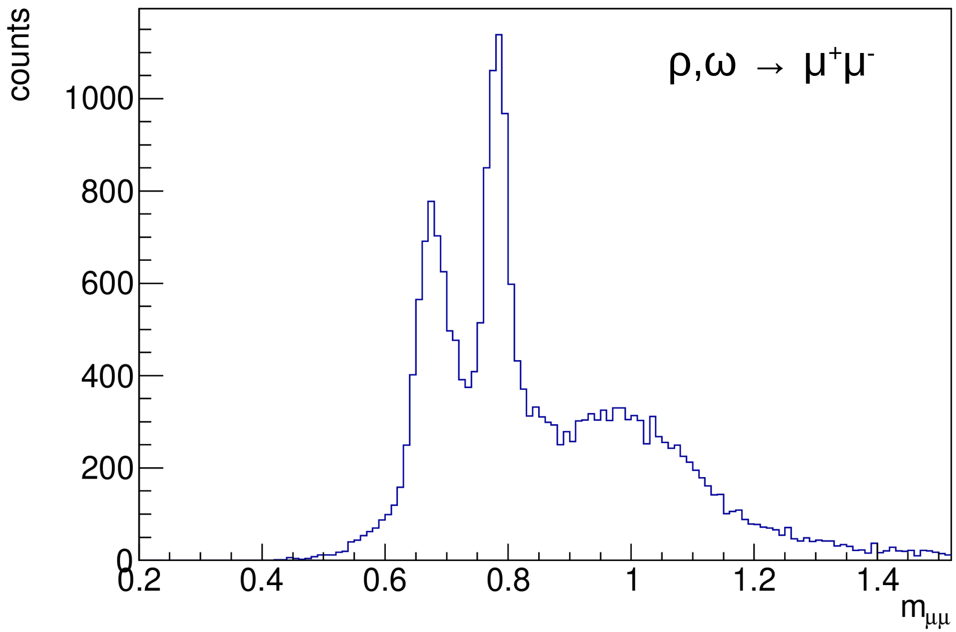
relative error $\sigma_{|\rho_5|}/\langle|\rho_5|\rangle = 0.4$

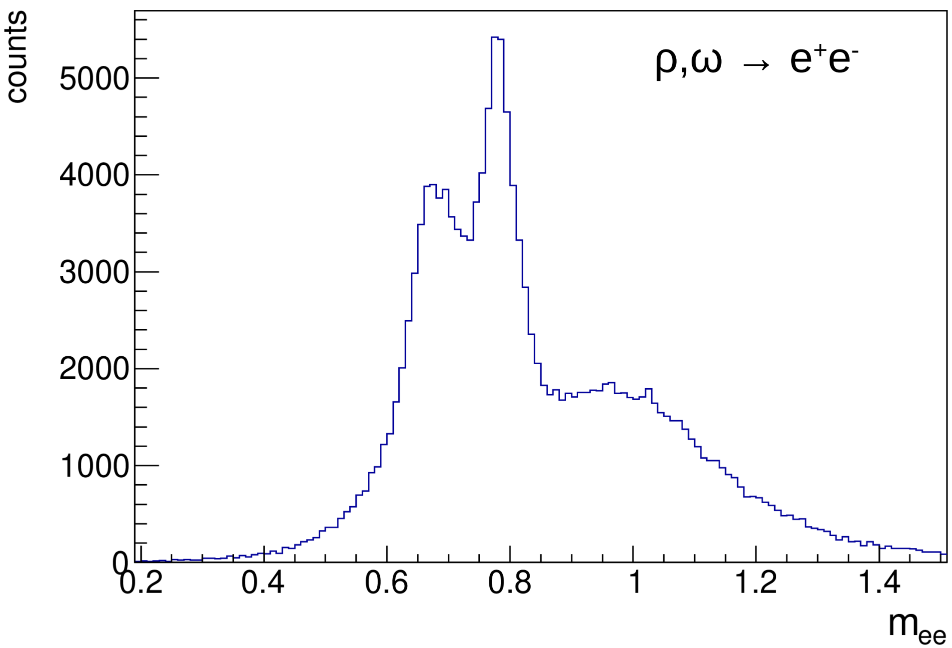
Uniform axial charge density at freeze-out is expected to keep during evolution in ideal relativistic hydrodynamics

$$-\frac{dV}{V}=\frac{ds}{s}=\frac{d\rho}{\rho}=\frac{dE_d}{E_d+p}$$

Influence of the μ_5 fluctuation on the observation of polarization splitting

> $\mu_5 \sim \exp\left(-\frac{1}{2}\frac{(\mu_5-\langle\mu_5\rangle)^2}{\sigma_{\mu_5}^2}\right)$ **with mean μ_5 =0.15 GeV and σ = 0.06 GeV**
(or $\sigma/\langle\mu_5\rangle$=0.4)





$p_{T\mu}$>0.5 GeV, $p_{T\mu\mu}$>0.5 GeV

$0.4<\cos\theta_A<0.5$

p_{Te}>0.15 GeV, p_{Tee}>0.4 GeV

$0.4<\cos\theta_A<0.5$

Conclusions

> The angular analysis of low-mass di-lepton production is sensitive to vector meson polarisation splitting
allowing to search for the local violation of spatial parity in QCD.

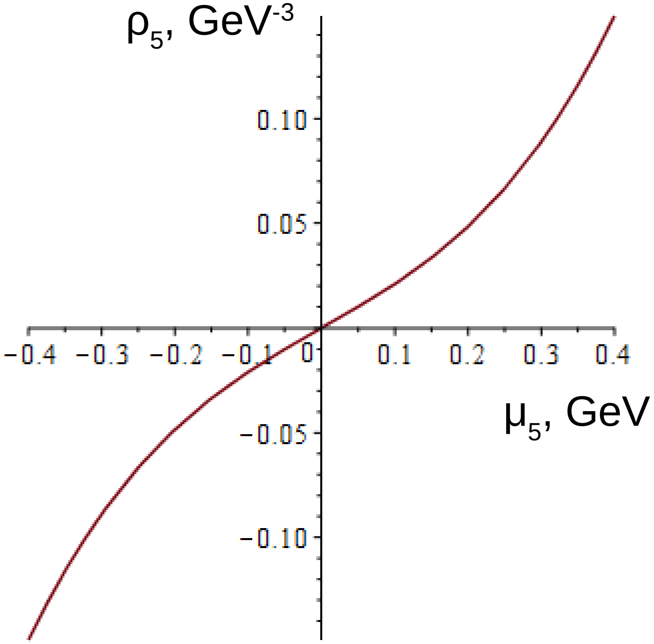
> Regions of local axial charge excess survive in the medium throughout the entire hydro-dynamical evolution up to freeze-out

> The of fluctuation of the axial chemical potential induced by the evolution of the medium in AA collisions is at the level of 40%, which leaves the room for the search of vector meson polarisation splitting in the LHC Run 3 data.

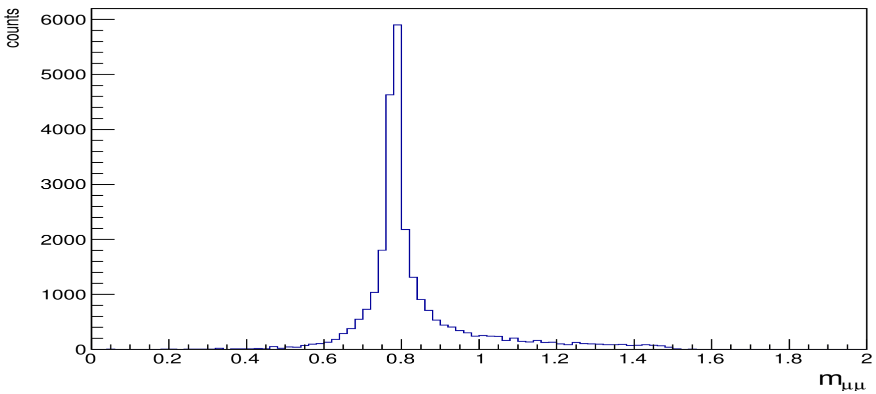
Backup

Backup

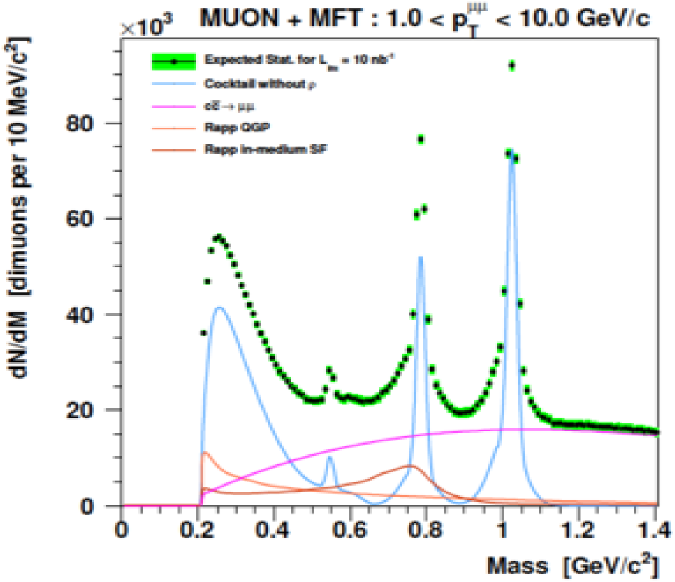
$$\rho_5 \sim \frac{1}{(2\pi)^3} \int_0^{\infty} \frac{2\ \pi\ p^2}{e^{\frac{\sqrt{m^2+p^2}-\mu}{T}}+1} dp - \int_0^{\infty} \frac{2\ \pi\ p^2}{e^{\frac{\sqrt{m^2+p^2}+\mu}{T}}+1} dp$$



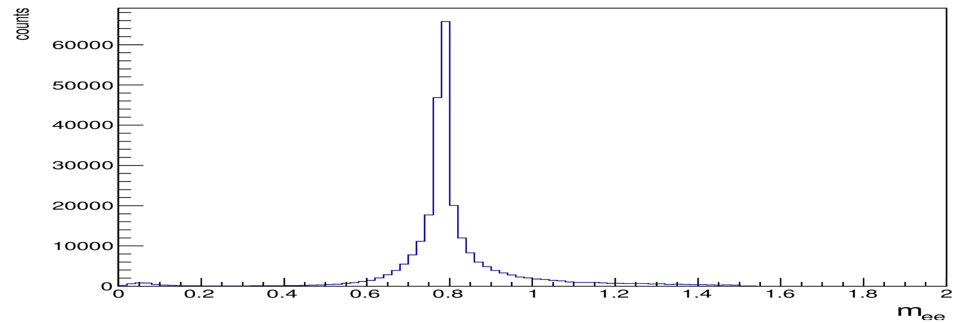
Backup



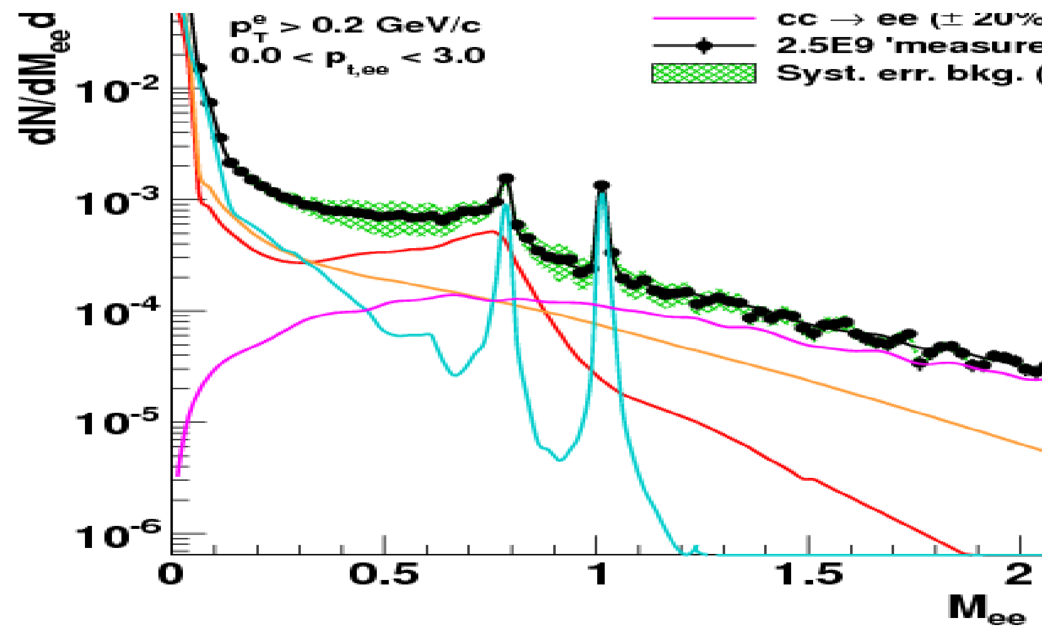
counts
$m_{\mu\mu}$



MUON + MFT : 1.0 < $p_T^{\mu\mu}$ < 10.0 GeV/c
Expected Stat. for L_{int} = 10 nb^{-1}
Cocktail without ρ
$c\bar{c} \rightarrow \mu\mu$
Rapp QGP
Rapp in-medium SF
dN/dM [dimuons per 10 MeV/c^2]
Mass [GeV/c^2]



counts
m_{ee}



p_T^e > 0.2 GeV/c
0.0 < $p_{t,ee}$ < 3.0
2.5E9 'measure
Syst. err. bkg. (
dN/dM_{ee}
M_{ee}

CP violation in QCD

Vafa-Witten theorem: vector-like global symmetries such as parity, charge conjugation, isospin and baryon number in vector-like gauge theories like QCD cannot be spontaneously broken while the θ angle is zero

However this theorem does not apply to dense QCD matter where the partition function is not any more positive definite due to the presence of a highly non-trivial fermion determinant. In addition, out-of-equilibrium symmetry-breaking effects driven by finite temperatures are not forbidden by the Vafa-Witten theorem.

Lorentz–non-invariant P -odd operators are allowed to have non-zero expectation values at finite density $\mu > 0$ and finite temperature if the system is out of Equilibrium.

P − and CP − odd bubbles may appear in a finite volume due to large topological fluctuations in a hot medium

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^{\mu\nu,a} G^{a}_{\mu\nu} + \bar{q}(i\gamma^{\mu} D_{\mu} - m)q,$$

$$D_{\mu} = \partial_{\mu} - igG^{a}_{\mu}\lambda^{a}, \quad G^{a}_{\mu\nu} = \partial_{\mu}G^{a}_{\nu} - \partial_{\nu}G^{a}_{\mu} + gf^{abc}G^{b}_{\mu}G^{c}_{\nu}$$

$$\theta\text{-term} \qquad \Delta\mathcal{L}_{\theta} = \theta \frac{g^2}{16\pi^2} \mathrm{Tr}\left(G^{\mu\nu}\widetilde{G}_{\mu\nu}\right)$$

$$\theta \lesssim 10^{-9}.$$

Chiral Magnetic Effect (CME)

Chiral Magnetic, Separation Effect:

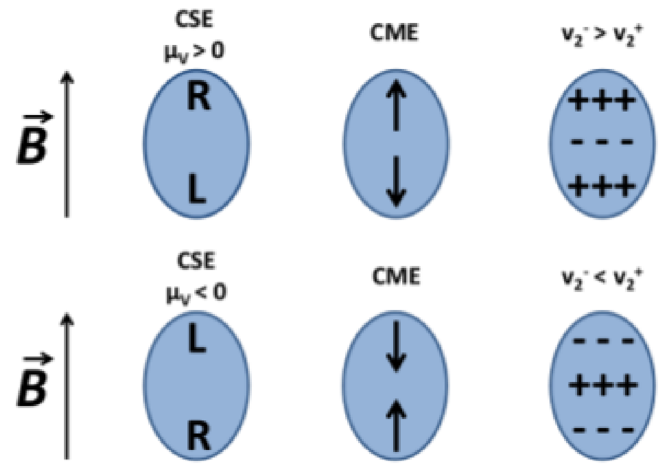
$$\vec{J}_V = \frac{N_c e}{2\pi^2}\mu_A \vec{B}, \quad \vec{J}_A = \frac{N_c e}{2\pi^2}\mu_V \vec{B}$$

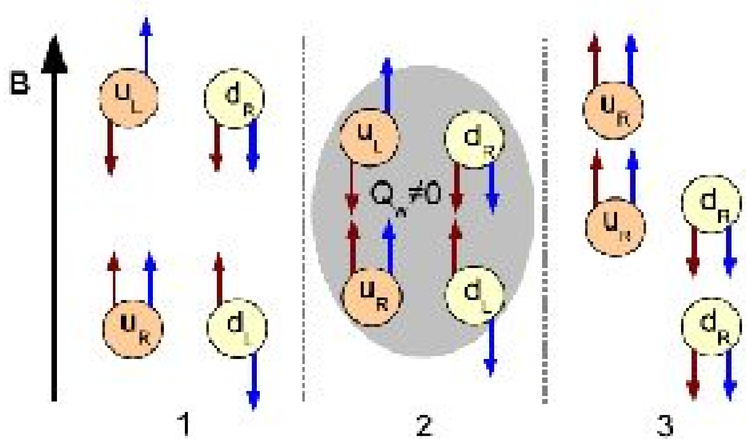
Thermodynamics:

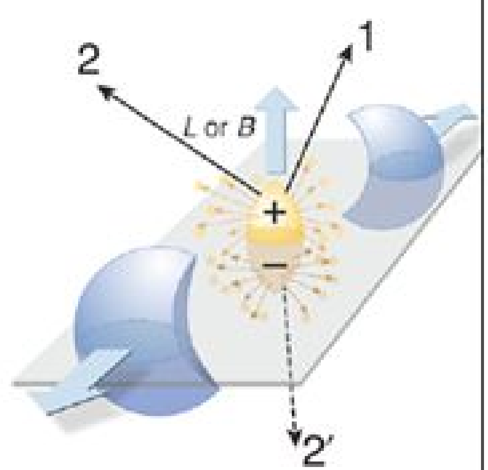
$$\vec{J}_V = \frac{N_c e}{2\pi^2}\chi\rho_A \vec{B}, \quad \vec{J}_A = \frac{N_c e}{2\pi^2}\chi\rho_V \vec{B}$$

Chiral basis:

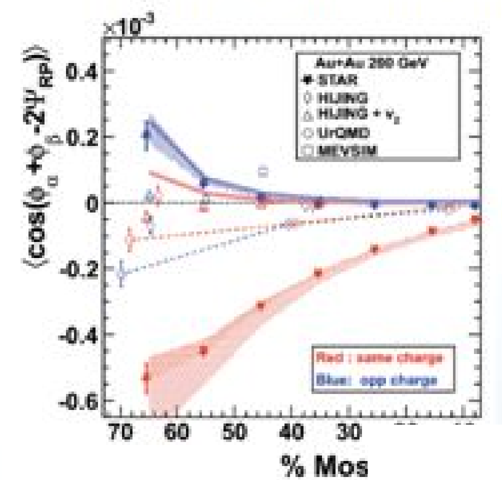
$$\vec{J}_L = -\frac{N_c e}{2\pi^2}\chi\rho_L \vec{B}, \quad \vec{J}_R = \frac{N_c e}{2\pi^2}\chi\rho_R \vec{B}$$







(STAR Collaboration)



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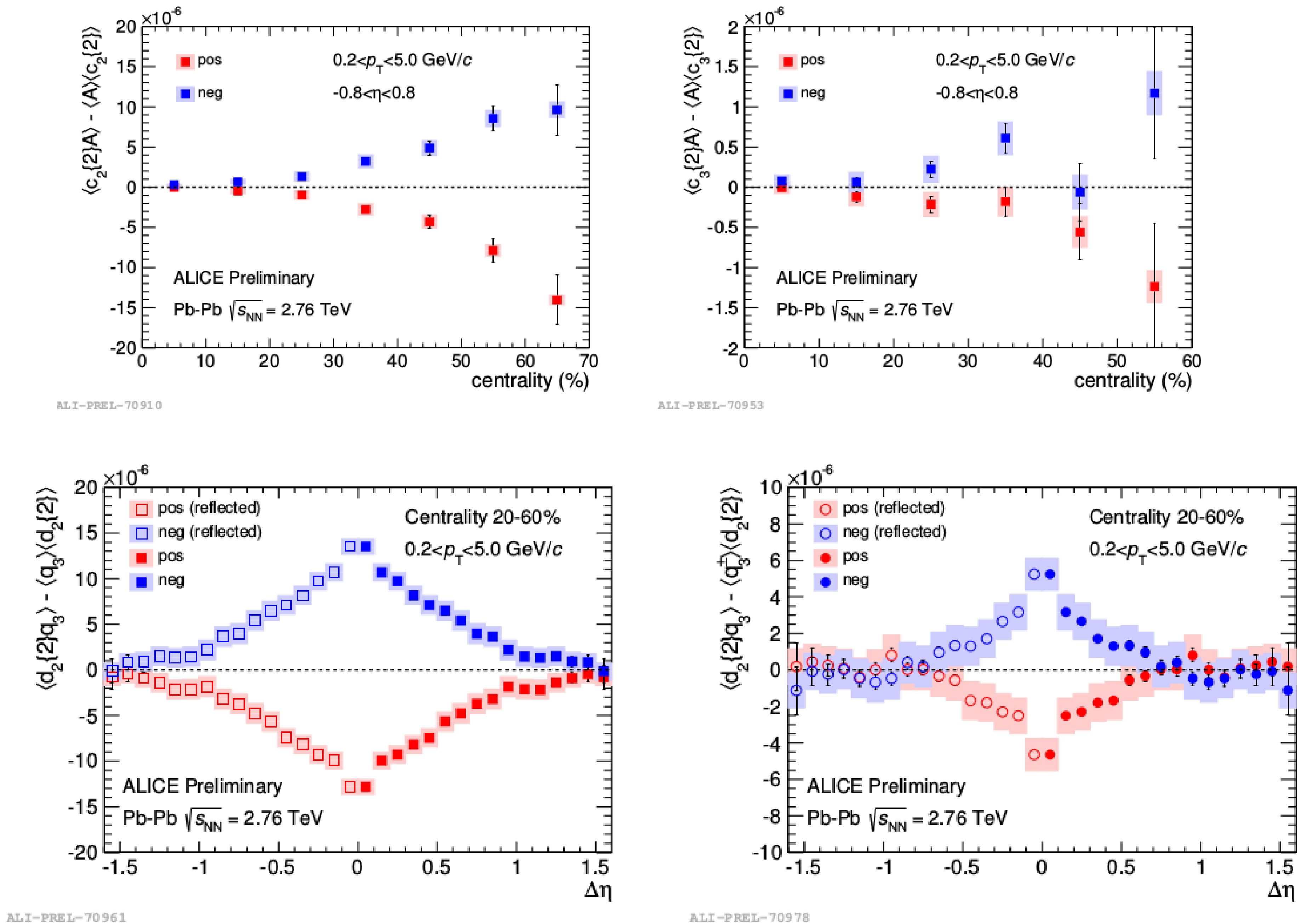
. Fukushima, D. Kharzeev, and H. Warringa. Phys. Rev. D, 78, 074033 (2008).

Chiral Magnetic Effect (CME) in ALICE



Jaroslav Adam , et al (ALICE Collab) Phys. Rev. C 93 (2016) 044903

New Possibilities

Parity forbidden decays

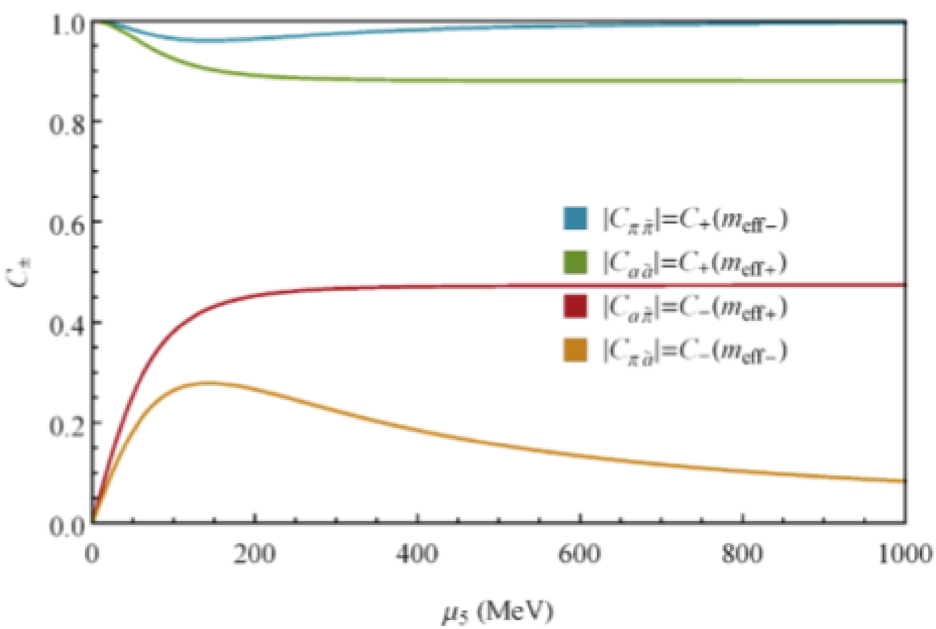
Effective meson theory in a medium with LPB

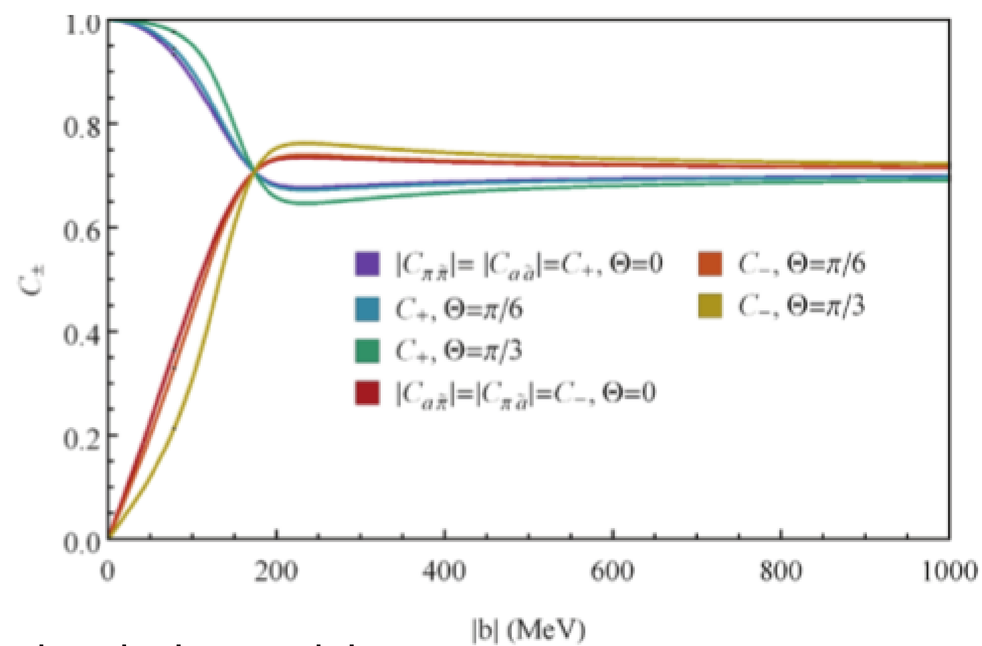
$$\mathcal{L} = \frac{1}{2}(\partial a_0)^2 + \frac{1}{2}(\partial \pi)^2 - \frac{1}{2}m_1^2 a_0^2 - \frac{1}{2}m_2^2\pi^2 - 4\mu_5 a_0 \dot{\pi},$$

$$m_1^2 = -2[M^2 - 2(3\lambda_1 + \lambda_2)v_q^2 - \lambda_2 v_s^2 - c v_s + 2\mu_5^2]$$

$$m_2^2 = \frac{2m}{v_q}B.$$

After diagonalization the new eigen-states appear: $\tilde{\pi}$ and $\tilde{a}_0$.





mixing coefficients dependence on chemical potential μ_5

A. A. Andrianov, V. A. Andrianov, D. Espriu, A.V. Iakubovich, A.E. Putilova EPJ Web of Conferences 158, 03012 (2017)

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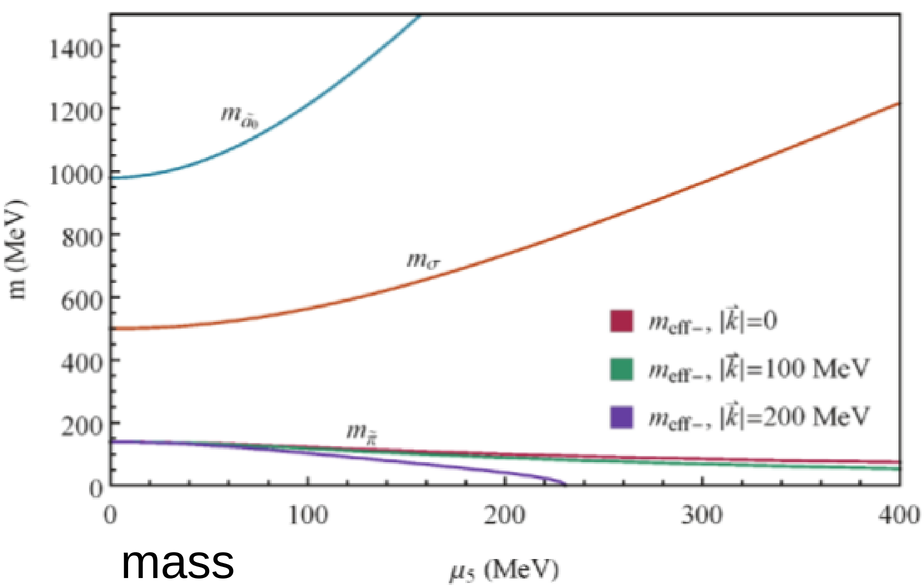
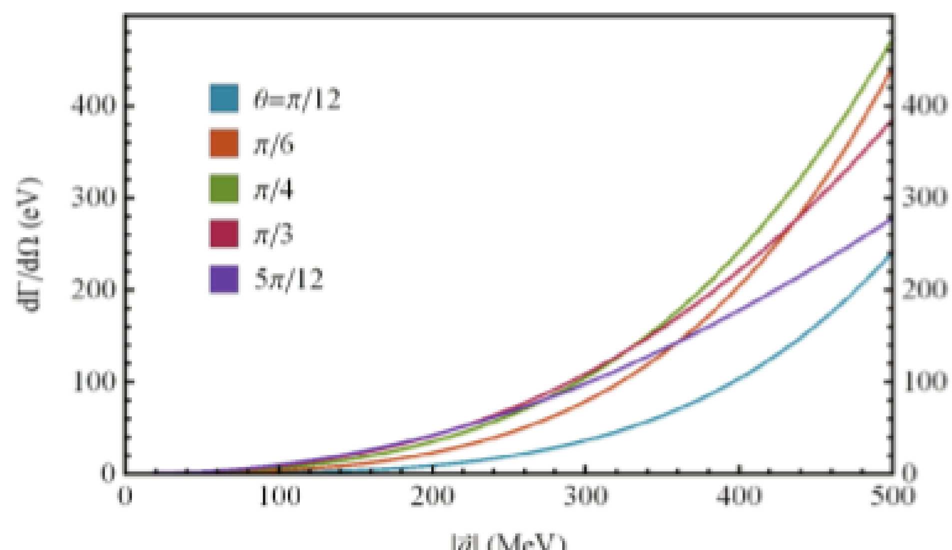
The decays $\tilde{a}_0^{\pm} \to \tilde{\pi}^{\pm}\gamma$,



mass



$\tilde{a}^{\pm}_0$ width

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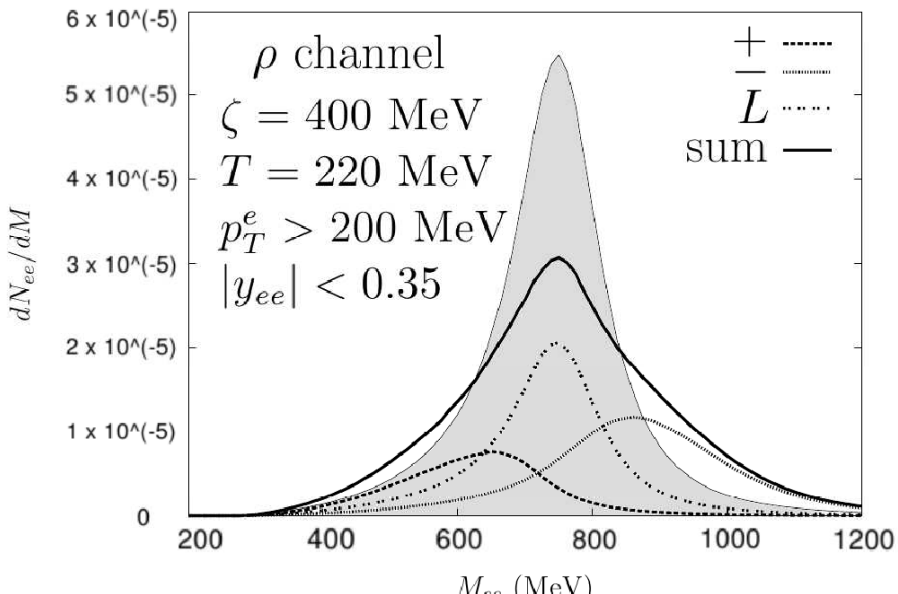
New Possibilities
DILEPTON POLARIZATION ANALYSIS
IN ρ ω → $l^+ l^-$ DECAYS

VDM + $\mathcal{L}_{\rm CS} = -\frac{1}{4}\varepsilon^{\mu\nu\rho\sigma}\,{\rm Tr}\left[\hat{\zeta}_\mu V_\nu V_{\rho\sigma}\right]$

The dilepton production from the $V(k) \to \ell^-(p)\ell^+(p')$ decays is governed by

$$\frac{dN_V}{dM} = \int \frac{d\tilde{M}}{\sqrt{2\pi}\Delta}\exp\left[-\frac{(M-\tilde{M})^2}{2\Delta^2}\right] c_V \frac{\alpha^2}{24\pi^2\tilde{M}}\Theta(\tilde{M}-n_V m_\pi)\left(1-\frac{n_V^2 m_\pi^2}{\tilde{M}^2}\right)^{3/2}$$
$$\times \int \frac{d^3\vec{k}}{E_k}\frac{d^3\vec{p}}{E_p}\frac{d^3\vec{p}'}{E_{p'}}\delta^4(p+p'-k)\sum_\epsilon \frac{m_{V,\epsilon}^4\left(1+\frac{\Gamma_V^2}{m_V^2}\right)}{\left(\tilde{M}^2-m_{V,\epsilon}^2\right)^2+m_{V,\epsilon}^4\frac{\Gamma_V^2}{m_V^2}}$$
$$\times P_\epsilon^{\mu\nu}(\tilde{M}^2 g_{\mu\nu}+4p_\mu p_\nu)\frac{1}{e^{\tilde{M}_T/T}-1}, \qquad \text{where } V=\rho,\omega \text{ and } n_V=2,0$$



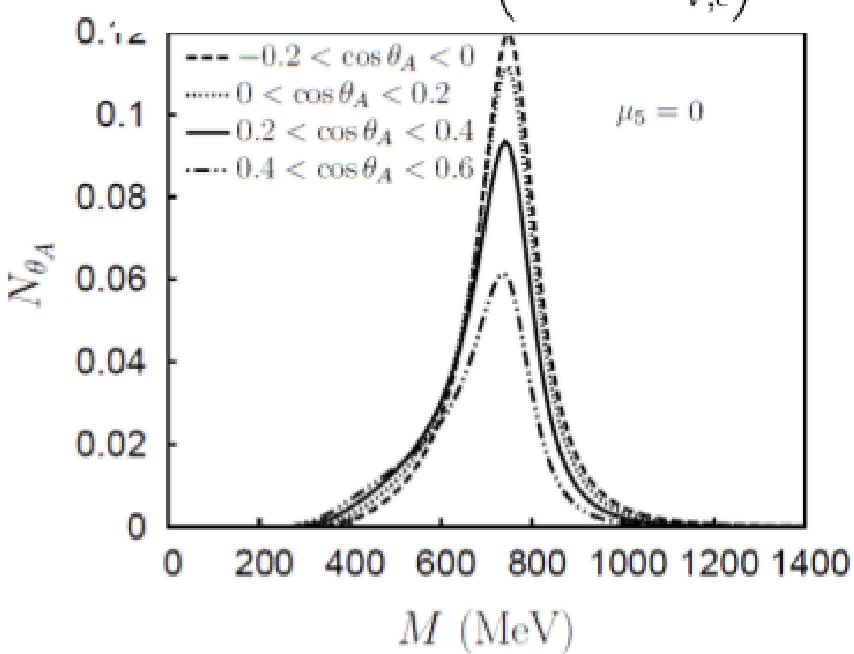
A. Andrianov, V. Andrianov, D. Espriu, EPJ Web of Conferences 137 , 01005 (2017)
Xumeu Planells, PhD thesis, November 2014, arXiv:1411.3283 [hep-ph]

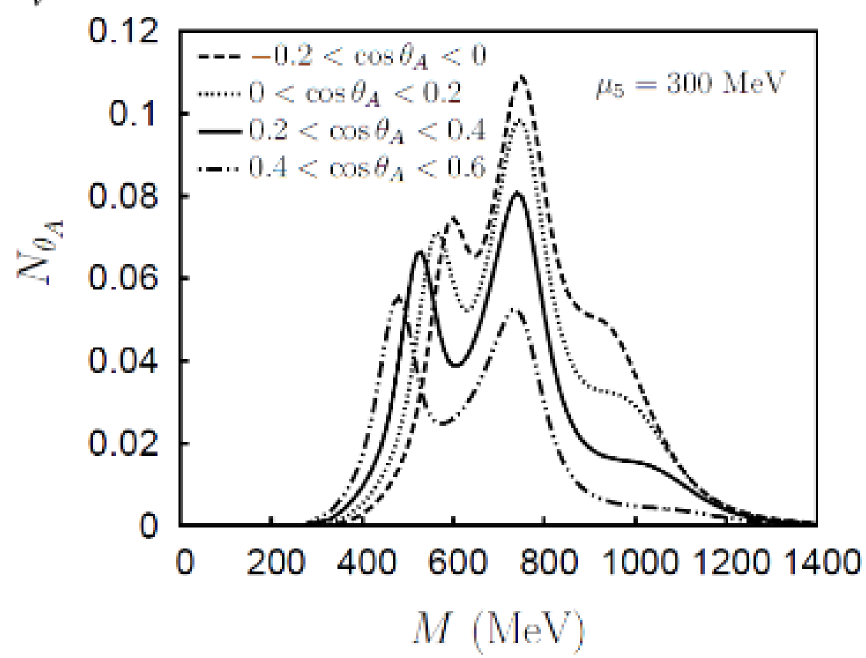
New Possibilities
DILEPTON POLARIZATION ANALYSIS
IN ρ ω → $l^+ l^-$ DECAYS

angle θ_A between the two outgoing leptons

$$\frac{dN_V}{dM\,d\cos\theta_A} = c_V \frac{\alpha^2}{6\pi M}\left(1-\frac{n_V^2 m_\pi^2}{M^2}\right)^{3/2}\int \frac{p^2 p'^2\, dp\, d\cos\theta\, d\phi}{E_p\sqrt{(M^2-2m_\ell^2)^2-4m_\ell^2(E_p^2-p^2\cos^2\theta_A)}}$$

$$\sum_\epsilon \frac{m_{V,\epsilon}^4\left(1+\frac{\Gamma_V^2}{m_V^2}\right)}{\left(M^2-m_{V,\epsilon}^2\right)^2+m_{V,\epsilon}^4\frac{\Gamma_V^2}{m_V^2}} P_\epsilon^{\mu\nu}(M^2 g_{\mu\nu}+4p_\mu p_\nu)\frac{1}{e^{M_T/T}-1},$$





A. Andrianov, V. Andrianov, D. Espriu, EPJ Web of Conferences 137 , 01005 (2017)
Xumeu Planells, PhD thesis, November 2014, arXiv:1411.3283 [hep-ph]

Monte Carlo setup

> Pythia 8.2 (Angantyr for heavy ion collisions, Pb+Pb, 5.02 TeV)

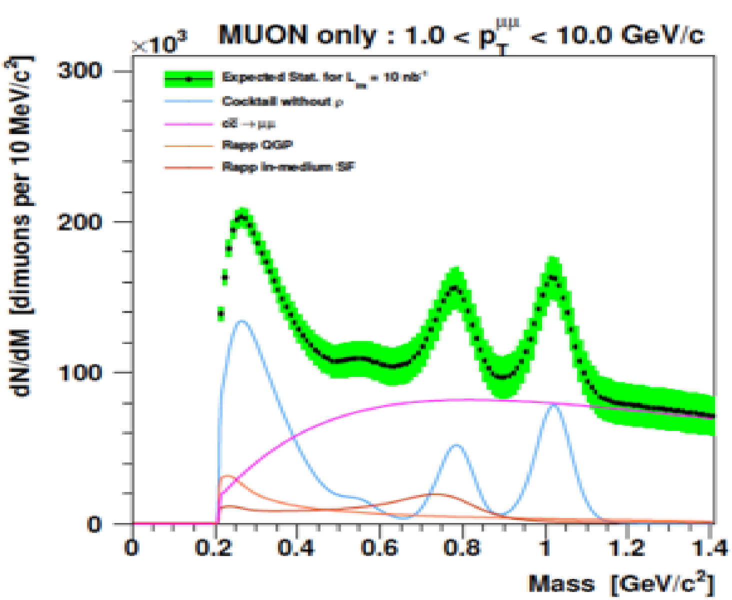
> Enhanced fraction of rho and omega leptonic decay channels

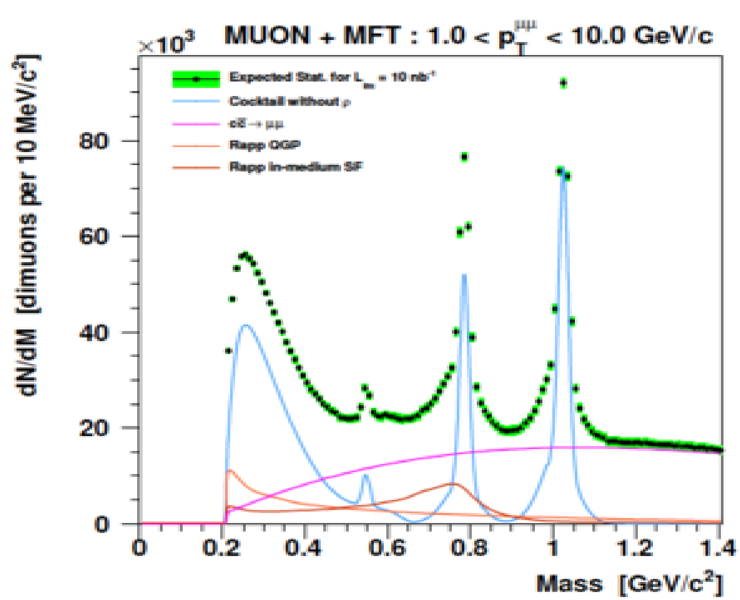
> Acceptance -0.8<eta<0.8 for di-Electrons, -3.6<eta<-2.45 for di-Muons

> Detector responce estimated using TDR resolutions/predictions (no fully detector modelling for this study yet)

> Focus on <u>resolution</u> of dimuon invariant mass studies (leaving significance/signal-over-background optimisation)

> Run 1+2 and Run 3 conditions

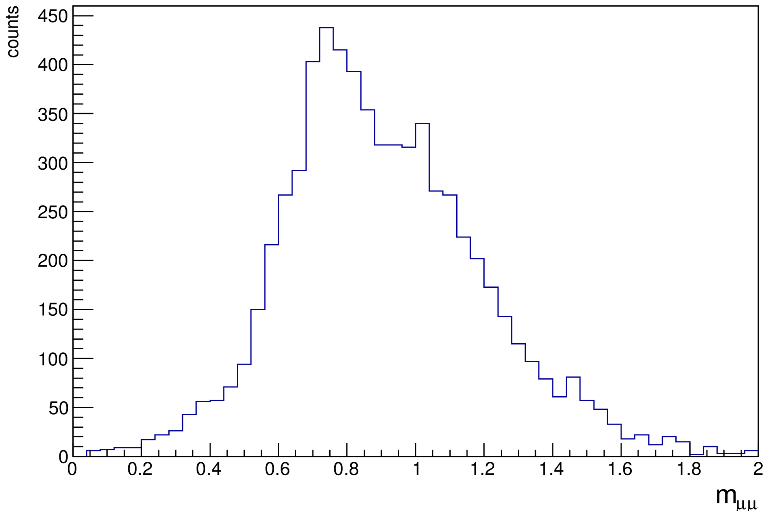


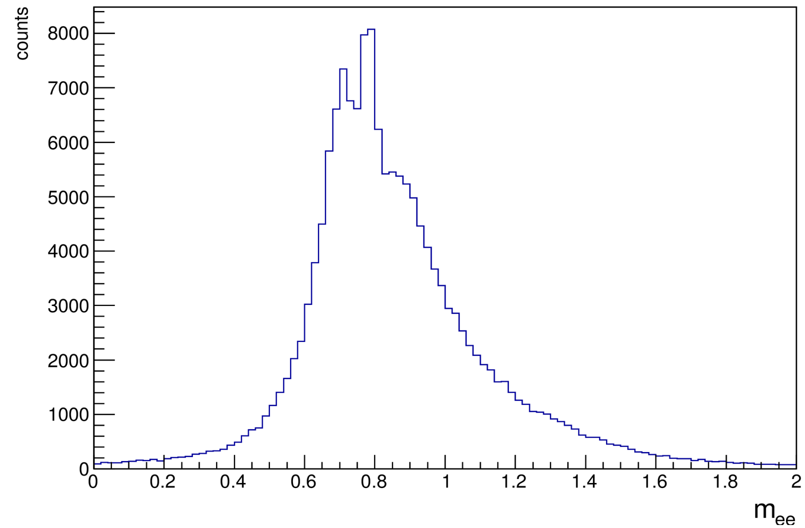


Monte Carlo with smearing (Run 1+2 conditions)

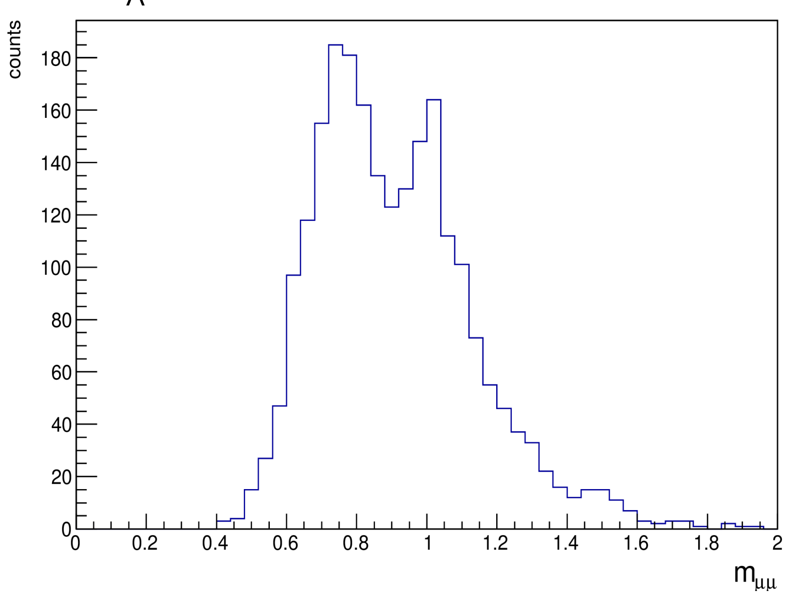
All: μ_5= 0.1 GeV

No angular θ_A selection



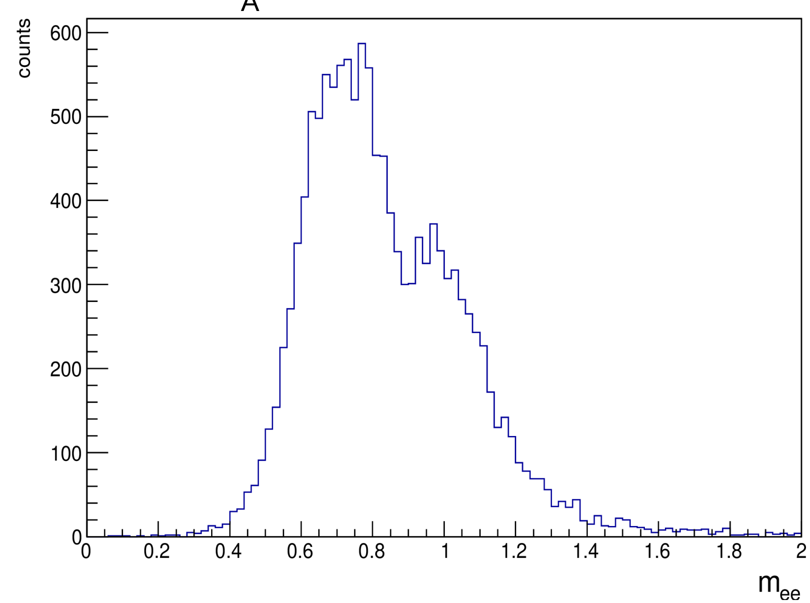


$0.4<\cos\theta_A<0.8$



$p_{T\mu}$>0.85 GeV, $p_{T\mu\mu}$>1.4 GeV

$0.4<\cos\theta_A<0.5$



p_{Te}>0.3 GeV, p_{Tee}>0.4 GeV

Future steps

> Full treatment of the statistical requirements and signal+background modelling

> Checking the effects of radial flow and its fluctuation (probably, other event generator will be needed)

> Full modelling of the detector response

> Analysis of real data

> Feasibility studies at NICA energy:

both theoretical (large μ_B +non-zero μ_5) and experimental/metodological