Phenomenology of Heavy Ion Collisions

Liliana Apolinário

LIP **IST**

Phenomenology @ LIP

✦ Who are we?

✦ Group of physicists (theorists, phenomenologist and experimentalists) dedicated to make the bridge between data and theory:
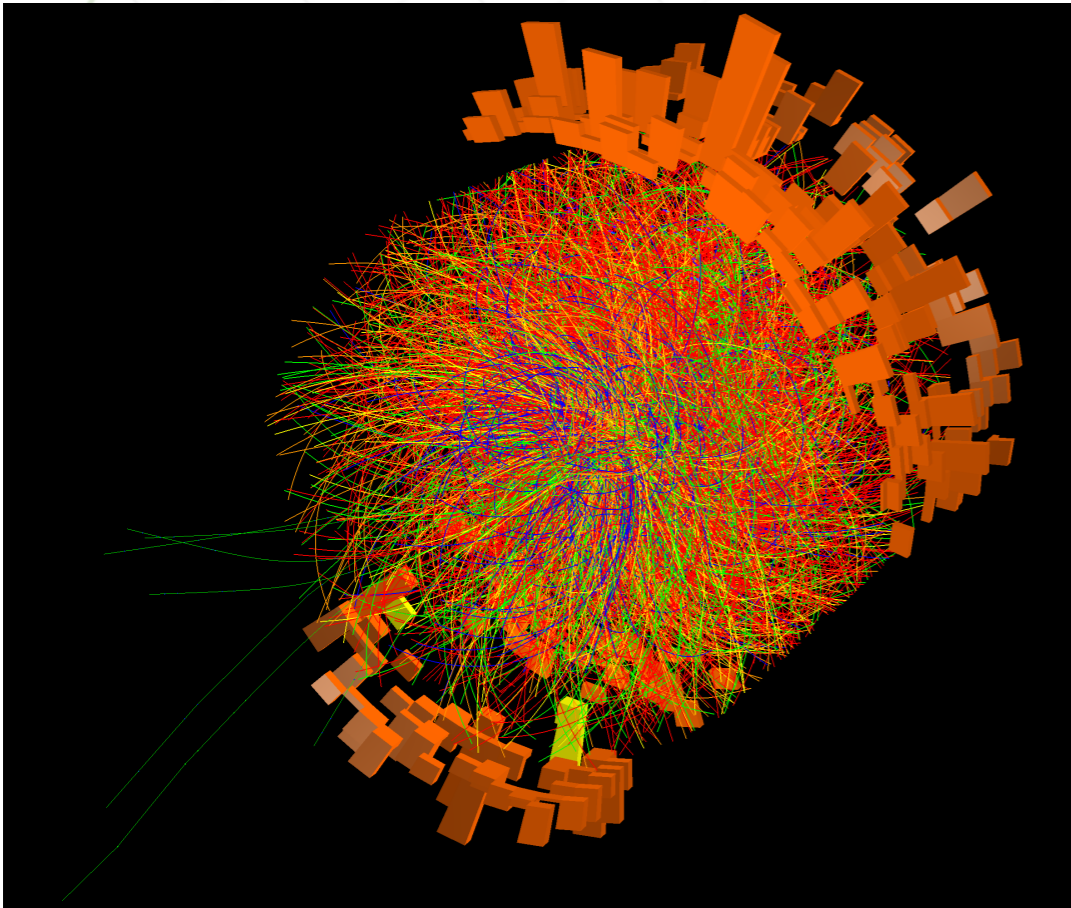
Phenomenology @ LIP

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$$\mathcal{L}_{SM} = -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$$

$$\frac{ig}{2\sqrt{2}}W^+_\mu\left((\bar\nu^\lambda \gamma^\mu(1+\gamma^5)U^{lep}_{\lambda\kappa}e^\kappa) + (\bar u^\lambda_j \gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) +$$
$$\frac{ig}{2\sqrt{2}}W^-_\mu\left((\bar e^\kappa U^{lep\dagger}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) +$$
$$\frac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar\nu^\lambda U^{lep}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar\nu^\lambda U^{lep}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) +$$

$$\frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar u^\lambda_j \gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar d^\lambda_j \gamma^5 d^\lambda_j)$$

Phenomenology @ LIP

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Phenomenology @ LIP

✦ Who are we?

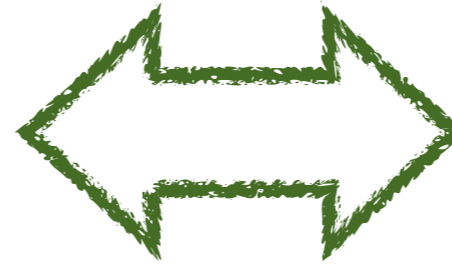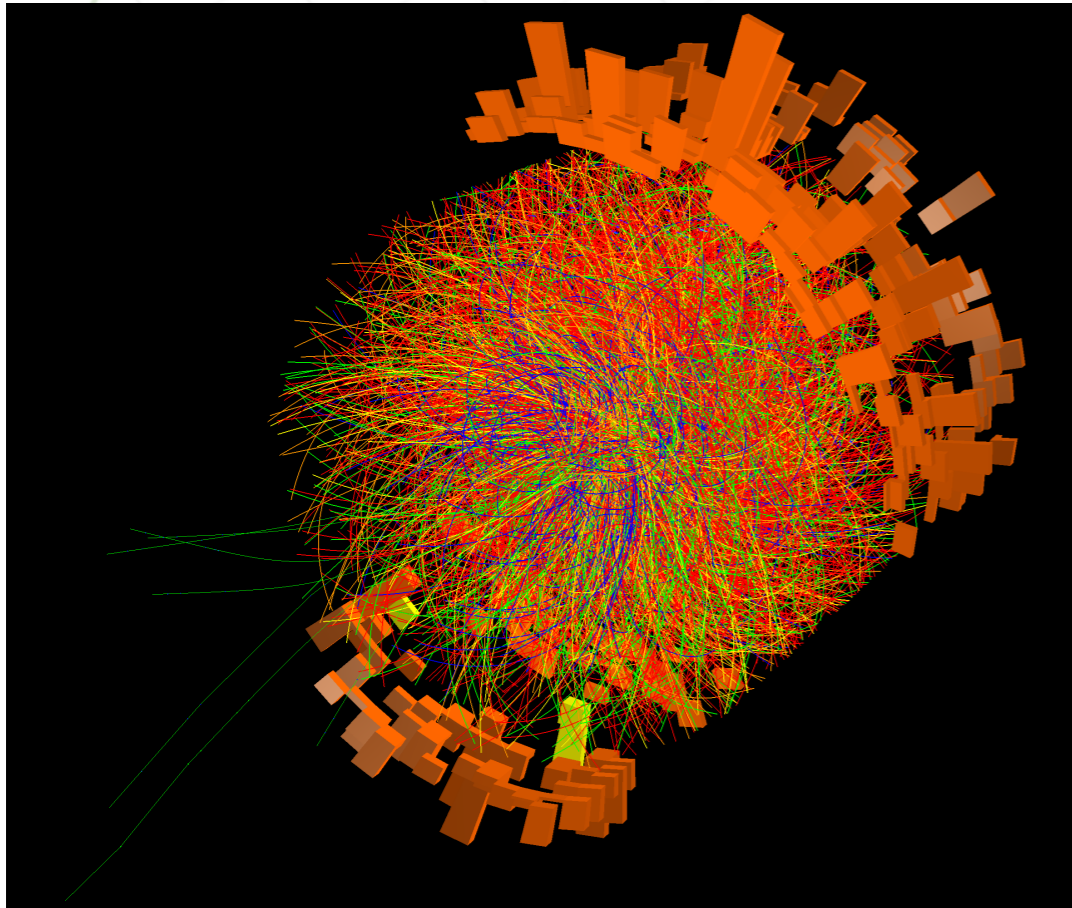✦ Group of physicists (theorists, phenomenologist and experimentalists) dedicated to make the bridge between data and theory:

Heavy-Ions @ Pheno

✦ Phenomenology of Heavy-Ions: Why?

   ✦ Unique window for corner of
QCD Phase Space

Heavy-Ions @ Pheno

✦ Phenomenology of Heavy-Ions: Why?

  ✦ Unique window for corner of
    QCD Phase Space

  ✦ Direct link to Early Universe
    ("Mini-bang" vs "Big-bang")
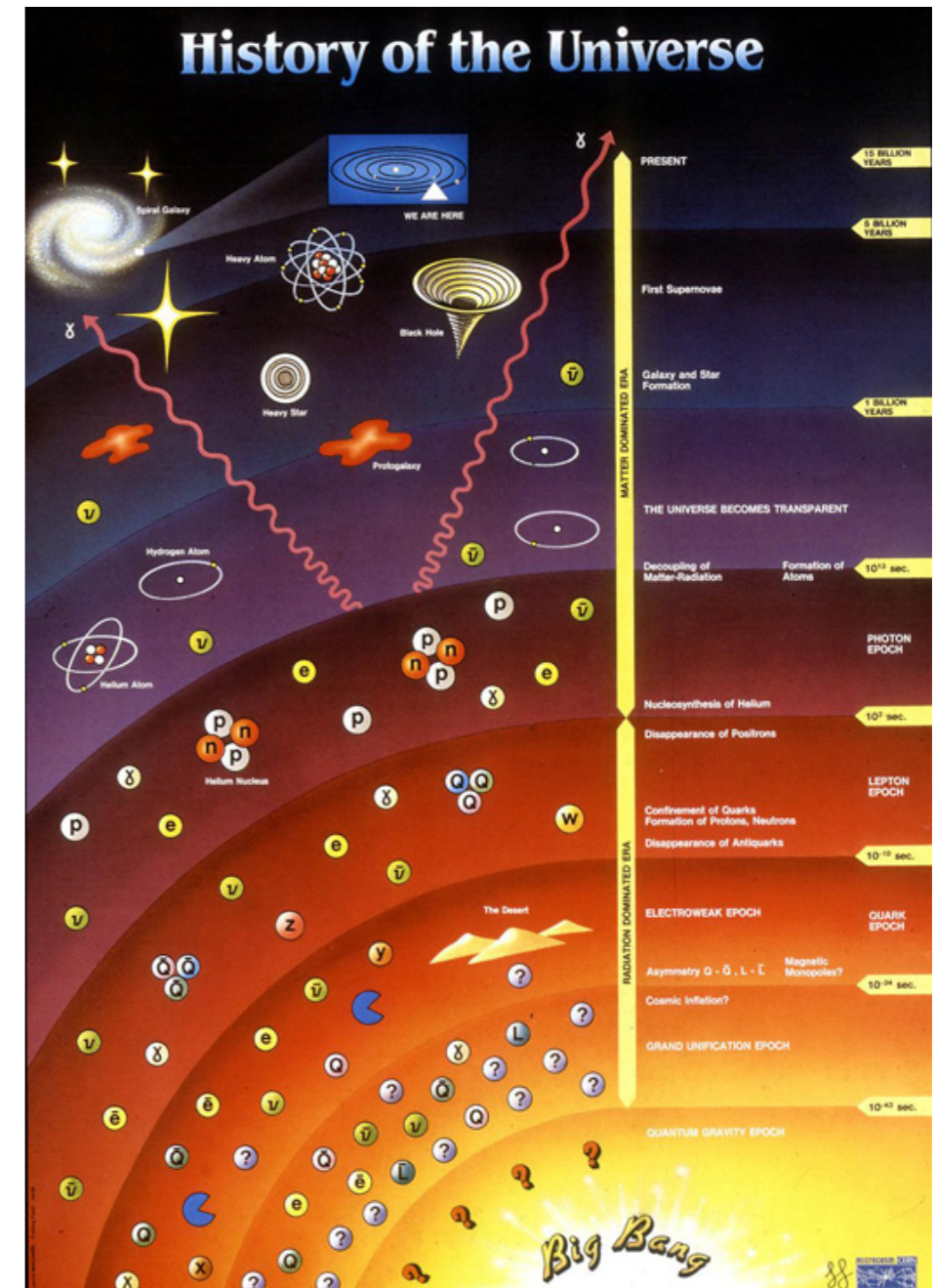
Heavy-Ions @ Pheno

✦ Phenomenology of Heavy-Ions: Why?

   ✦ Unique window for corner of
      QCD Phase Space

   ✦ Direct link to Early Universe
      ("Mini-bang" vs "Big-bang")

   ✦ Major part of the physics
      program at current (LHC,
      RHIC) and future (FCC) high
      energy particle physics
      accelerators
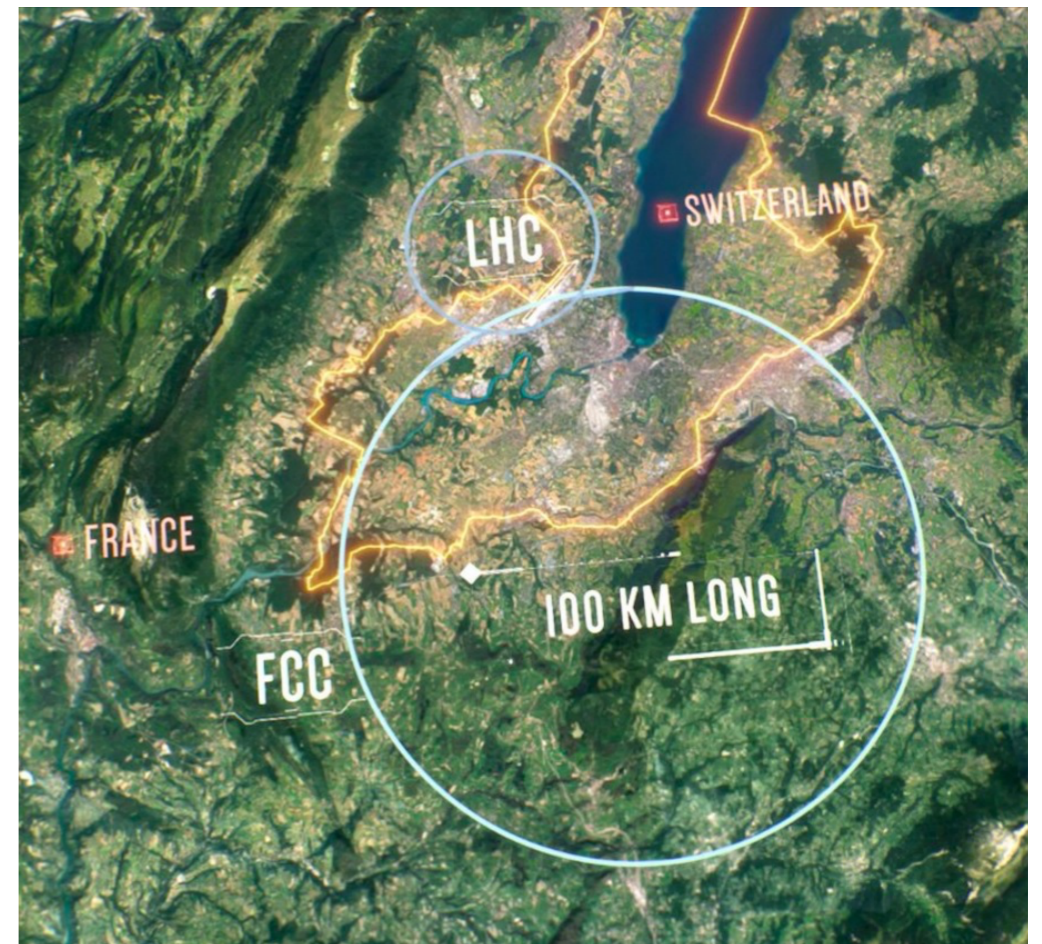
Group's main activities

what are we working on?

Probing the QGP

✦ Novel observables for Heavy-Ion collisions;

✦ Evaluate QCD jet-medium interactions

Novel subjet observables for jet quenching in heavy-ion collisions

Liliana Apolinário[1,2a], José Guilherme Milhano[1,2,3b], Mateusz Ploskon[4c], and Xiaoming Zhang[5d]

LIP & Collaborators (2018)
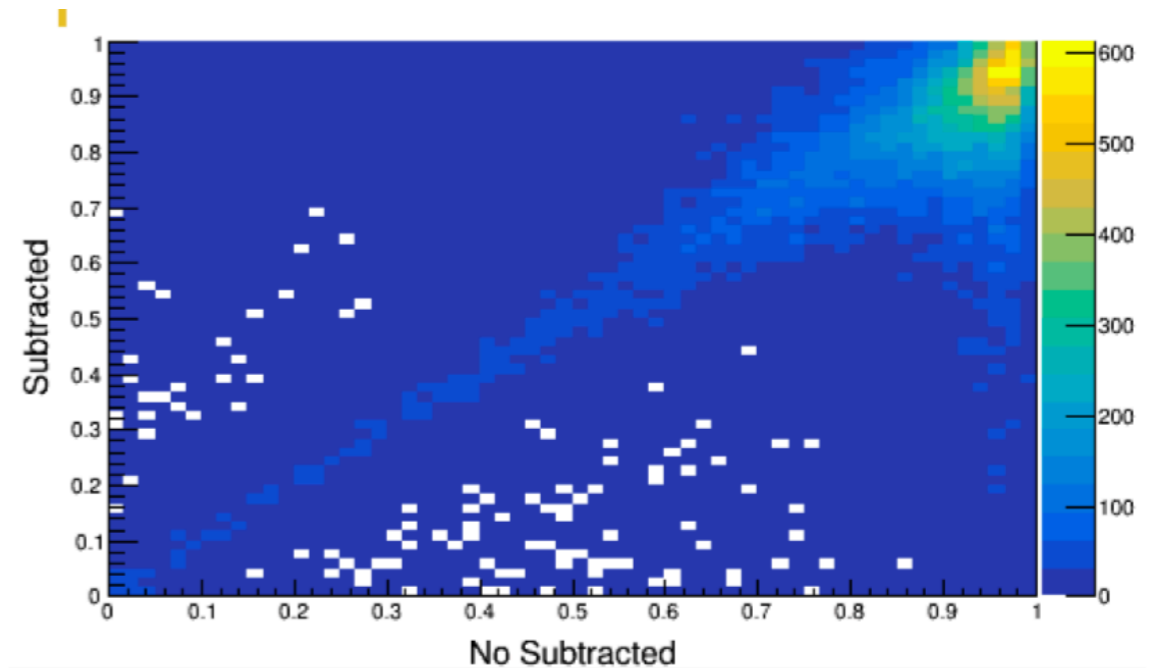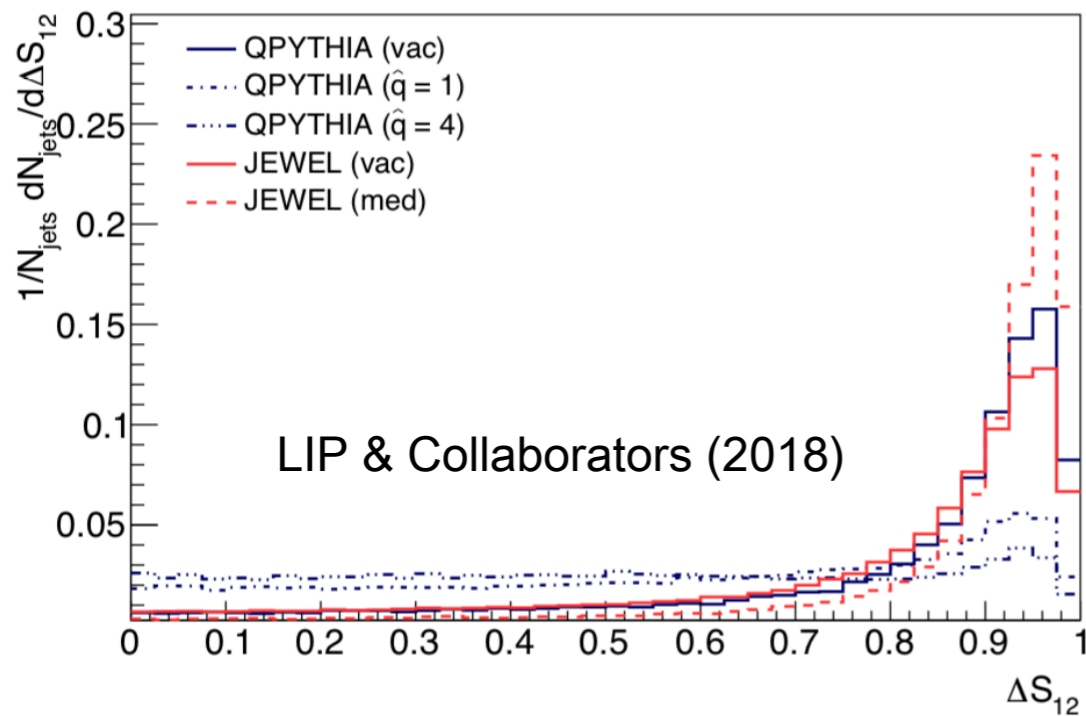
& João Diogo Mesquita (LIP Summer Internship 2018)
Results: 40th edition of Pulsar (NFIST)

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Probing the QGP

- ✦ Novel observables for Heavy-Ion collisions;

- ✦ Evaluate QCD jet-medium interactions

- ✦ Distinguish pp-like jets from AA-like jets

Novel tools and observables for jet physics in heavy-ion collisions
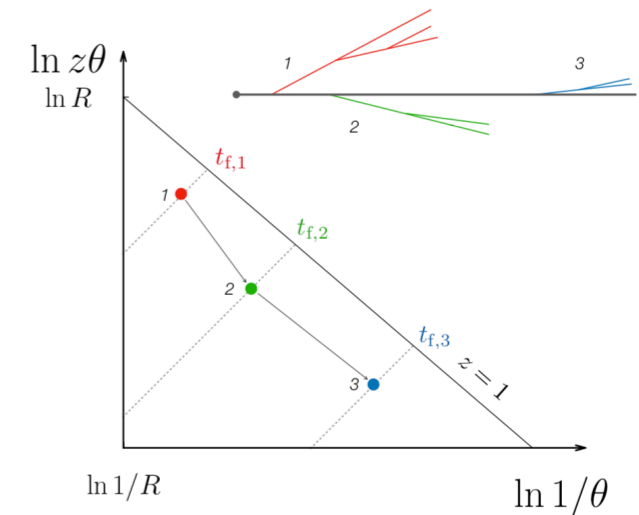
LIP & Collaborators (2018)

Harry Arthur Andrews[1], Liliana Apolinario[2,3], Redmer Alexander Bertens[4], Christian Bierlich[5,6], Matteo Cacciari[7,8], Yi Chen[9], Yang-Ting Chien[10], Leticia Cunqueiro Mendez[11,4], Michal Deak[12], David d'Enterria[9], Fabio Dominguez[13], Philip Coleman Harris[14], Krzysztof Kutak[12], Yen-Jie Lee[14], Yacine Mehtar-Tani[15,16], James Mulligan[17], Matthew Nguyen[18], Chang Ning-Bo[19], Dennis Perepelitsa[20], Gavin Salam*[21], Martin Spousta[22], José Guilherme Milhano[2,3,21], Konrad Tywoniuk[21], Marco Van Leeuwen[23], Marta Verweij[24,25], Victor Vila[13], Urs A. Wiedemann[21], and Korinna C. Zapp[2,21]
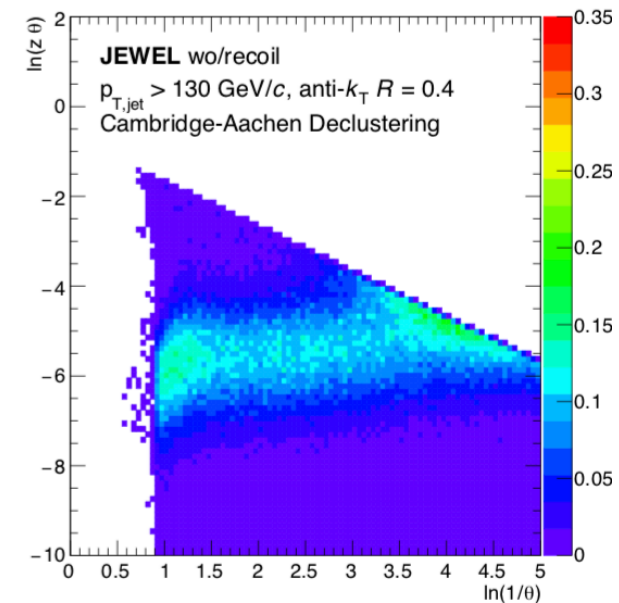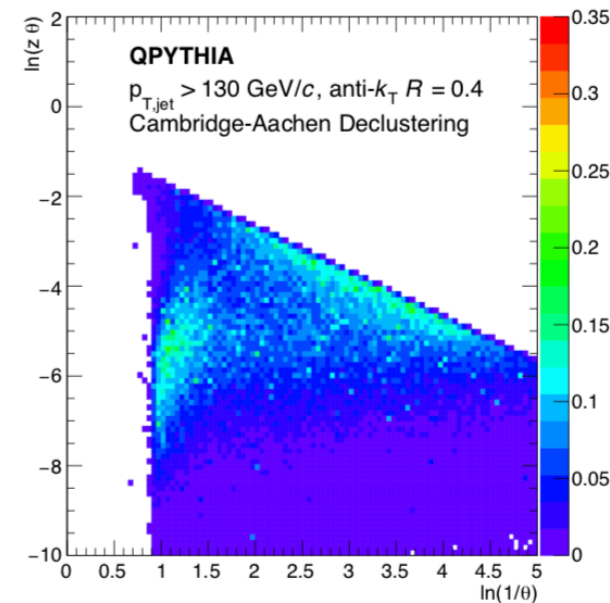
& Bruno Silva, Filipa Peres and João Gonçalves (currently working on their MsC thesis)

Monte Carlo Development

✦ Jet Quenching Monte Carlo event generators;

✦ Improve current model for jet-medium interaction

LIP & Collaborators (2014-…)

LIP & Collaborators (2013-…)

An analysis of the influence of background subtraction and quenching on jet observables in heavy-ion collisions

Angular Structure of Jet Quenching Within a Hybrid Strong/Weak Coupling Model

Liliana Apolinário[a,b], Néstor Armesto[a] and Leticia Cunqueiro[c,d]

Jorge Casalderrey-Solana,[a,b] Doga Can Gulhan,[c] José Guilherme Milhano,[d,e,f] Daniel Pablos,[b] Krishna Rajagopal[g]

(a) Dijet asymmetry A_J.
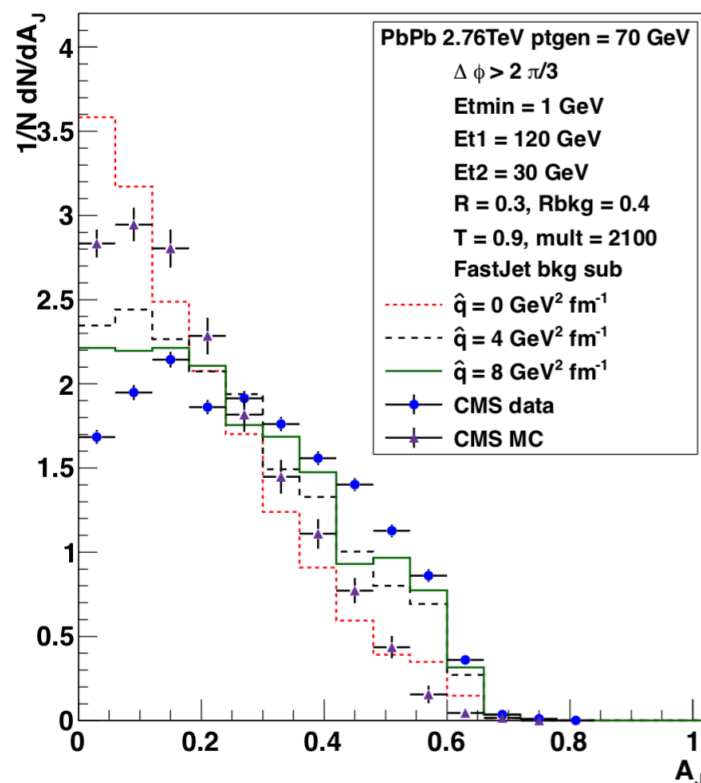
perturbative approach
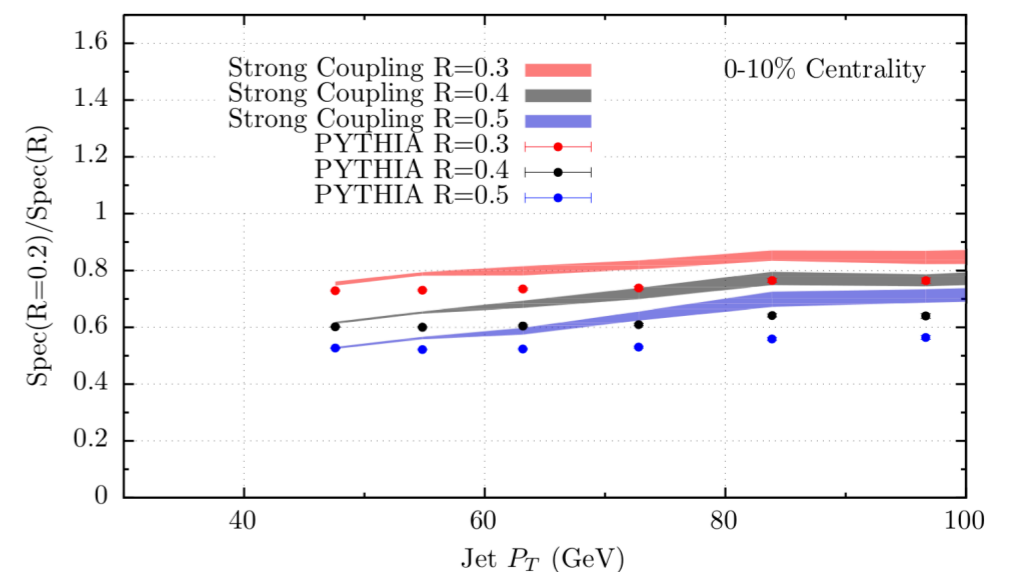
non perturbative approach

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Theoretical improvements

✦ Jet Quenching description beyond current kinematic limitations:

✓ jet structure is modified by QGP

$$\mathcal{R}_q^{\mathrm{med}} \approx 4\omega \int_0^L dt' \int \frac{d^2\boldsymbol{k}'}{(2\pi)^2} \mathcal{P}(\boldsymbol{k} - \boldsymbol{k}', L - t') \sin\left(\frac{\boldsymbol{k}'^2}{2k_{\mathrm{f}}^2}\right) e^{-\frac{\boldsymbol{k}'^2}{2k_{\mathrm{f}}^2}}$$
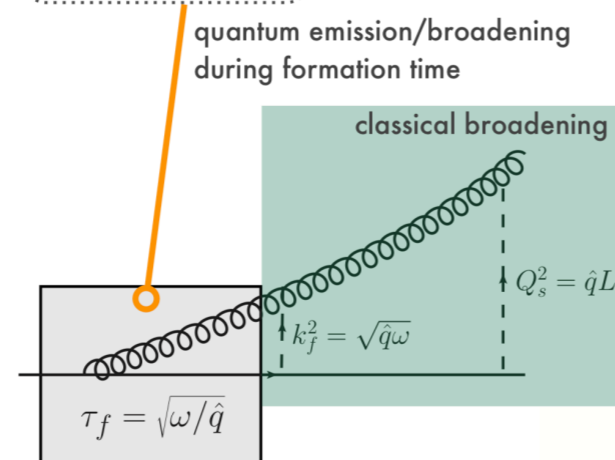
quantum emission/broadening
during formation time

classical broadening

$Q_s^2 = \hat{q}L$

$k_f^2 = \sqrt{\hat{q}\omega}$

$\tau_f = \sqrt{\omega/\hat{q}}$

Theoretical improvements

✦ Jet Quenching description beyond current kinematic limitations:

LIP & Collaborators (2017)

Factorization of in-medium parton branching beyond the eikonal approximation

✓ jet structure is modified by QGP

Liliana Apolinário[a], Néstor Armesto[b], José Guilherme Milhano[a,c], Carlos A. Salgado[b]

$$\mathcal{R}_q^{\text{med}} \approx 4\omega \int_0^L dt' \int \frac{d^2\boldsymbol{k}'}{(2\pi)^2} \mathcal{P}(\boldsymbol{k} - \boldsymbol{k}', L - t') \sin\left(\frac{\boldsymbol{k}'^2}{2k_{\text{f}}^2}\right) e^{-\frac{\boldsymbol{k}'^2}{2k_{\text{f}}^2}}$$

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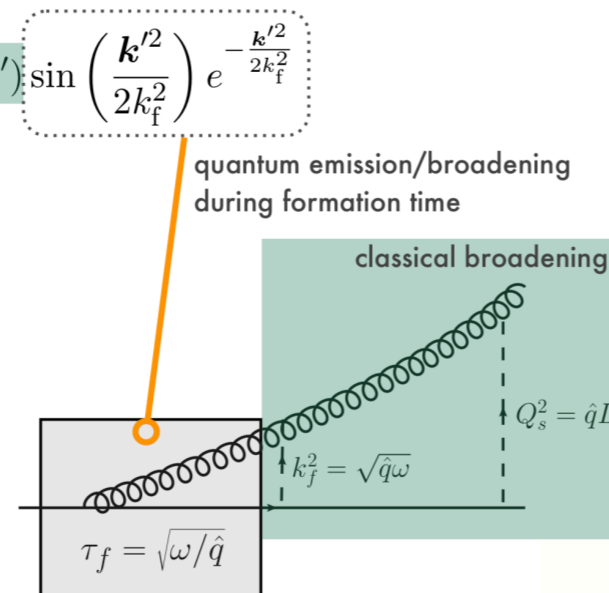
Quark and Gluon Jet Energy Loss

LIP & Collaborators (2018)

Liliana Apolinário[a,b], João Barata[*c] and Guilherme Milhano[a,b]

João Barata (former MsC student)

Angular ordering

$r_\perp$ Q_s^{-1}

$\Delta_{med} \to 0$
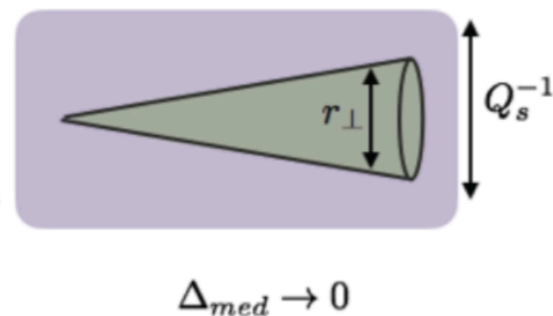
Anti-Angular ordering
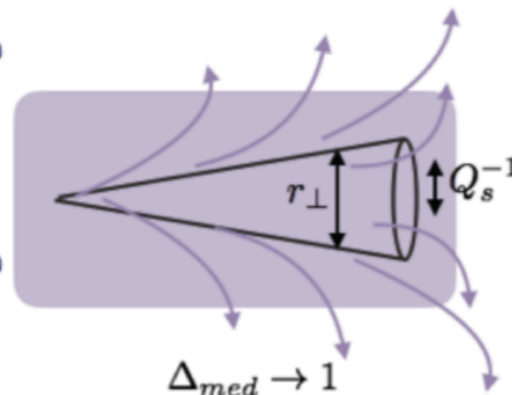
$r_\perp$ Q_s^{-1}

$\Delta_{med} \to 1$

Future Colliders

✦ Physics opportunities for future accelerators;

✦ Jet substructure to probe different QGP lifetimes

Probing the time structure of the quark-gluon plasma with top quarks

Liliana Apolinário,[1,2] José Guilherme Milhano,[1,2,3] Gavin P. Salam,[3,*] and Carlos A. Salgado[4]

Heavy ions at the Future Circular Collider

A. Dainese[1], U.A. Wiedemann[2] (editors), N. Armesto[3], D. d'Enterria[2], J.M. Jowett[2], J.-P. Lansberg[4], J.G. Milhano[5,2], C.A. Salgado[3], M. Schaumann[2], M. van Leeuwen[6,7] (section editors), J.L. Albacete[8], A. Andronic[9], P. Antonioli[10], L. Apolinário[5], S. Bass[11], A. Beraudo[12], A. Bilandzic[13], S. Borsanyi[14], P. Braun-Munzinger[9], Z. Chen[15], L. Cunqueiro Mendez[16], G.S. Denicol[17], K.J. Eskola[18], S. Floerchinger[19], H. Fujii[20], P. Giubellino[12], C. Greiner[21], J.F. Grosse-Oetringhaus[2], C.-M. Ko[22], P. Kotko[23], K. Krajczár[2,24], K. Kutak[25], M. Laine[26], Y. Liu[27], M.P. Lombardo[28], M. Luzum[29,3], C. Marquet[30], S. Masciocchi[9], V. Okorokov[31], J.-F. Paquet[32,33], H. Paukkunen[3,18,34], E. Petreska[30,3], T. Pierog[35], M. Ploskon[36], C. Ratti[37], A.H. Rezaeian[38], W. Riegler[2], J. Rojo[39], C. Roland[24], A. Rossi[40,1], G.P. Salam[2], S. Sapeta[25,2], R. Schicker[19], C. Schmidt[41], J. Stachel[19], J. Uphoff[21], A. van Hameren[25], K. Watanabe[42], B.-W. Xiao[42], F. Yuan[36], D. Zaslavsky[42], K. Zhou[21,15], P. Zhuang[15]

LIP & Collaborators (2017, 2018)

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Future Colliders

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LIP & Collaborators (2019)

& Rafael Orelhas (LIP Summer Internship 2018)

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A. Dainese[1], U.A. Wiedemann[2] (editors), N. Armesto[3], D. d'Enterria[2], J.M. Jowett[2], J.-P. Lansberg[4], J.G. Milhano[5,2], C.A. Salgado[3], M. Schaumann[2], M. van Leeuwen[6,7] (section editors), J.L. Albacete[8], A. Andronic[9], P. Antonioli[10], L. Apolinário[5], S. Bass[11], A. Beraudo[12], A. Bilandzic[13], S. Borsanyi[14], P. Braun-Munzinger[9], Z. Chen[15], L. Cunqueiro Mendez[16], G.S. Denicol[17], K.J. Eskola[18], S. Floerchinger[19], H. Fuj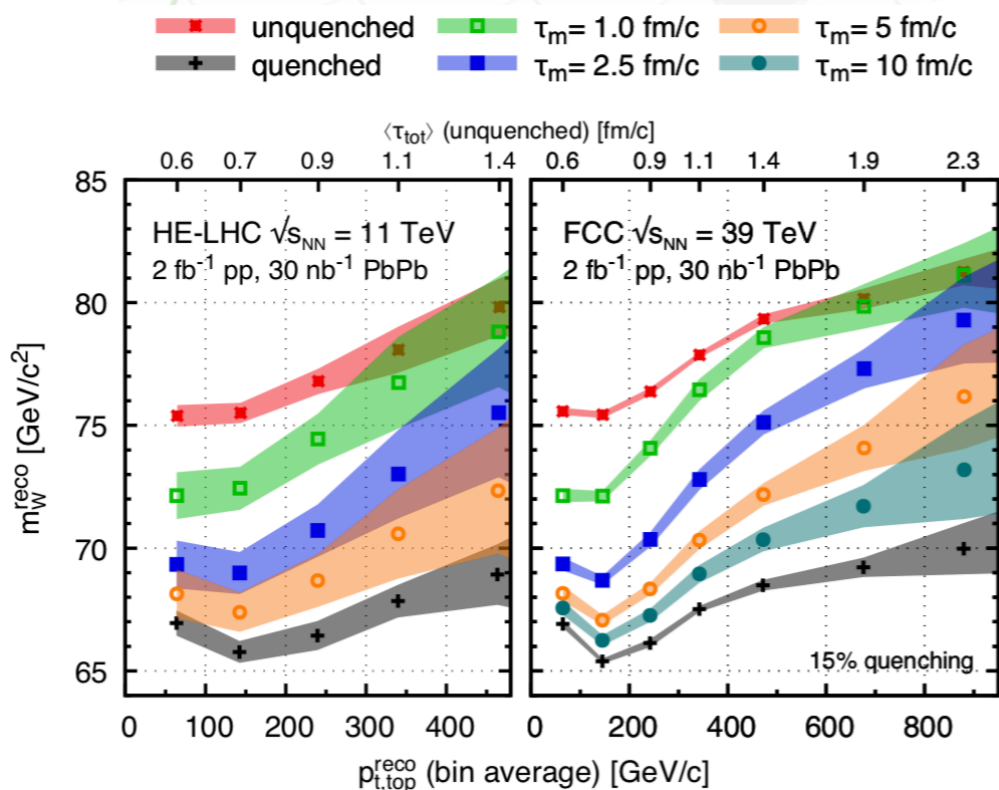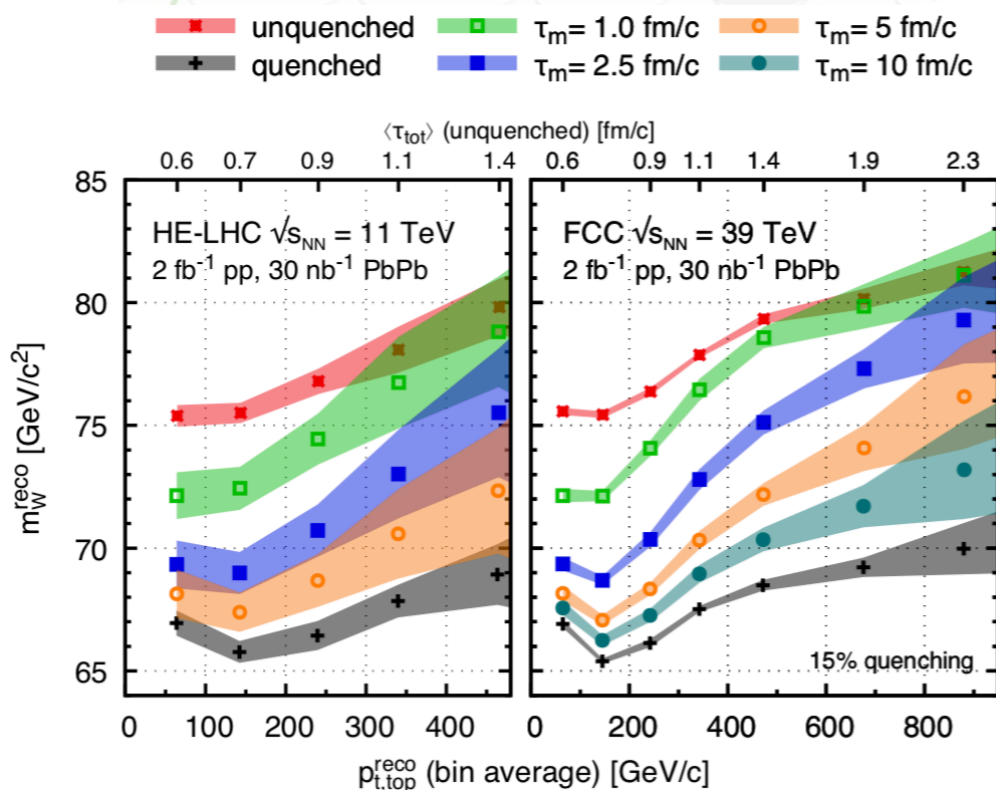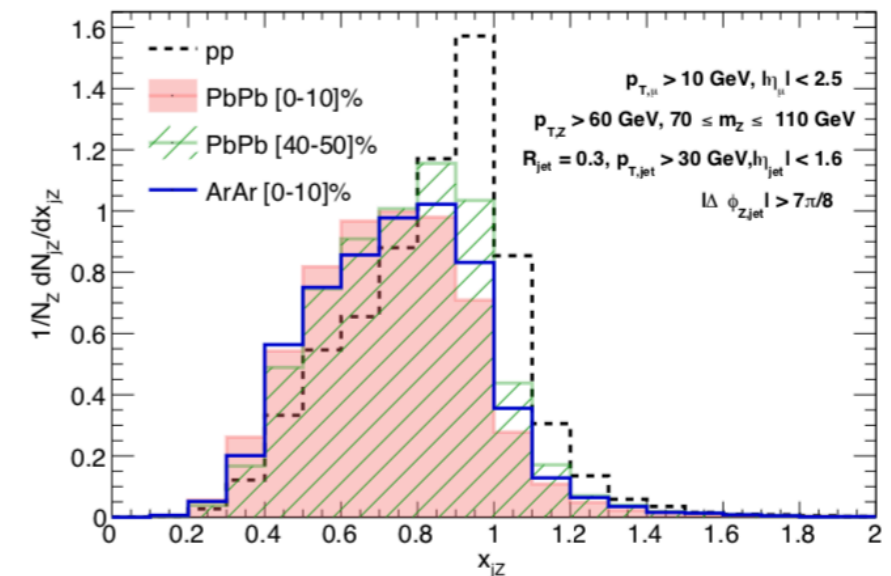ii[20], P. Giubellino[12], C. Greiner[21], J.F. Grosse-Oetringhaus[2], C.-M. Ko[22], P. Kotko[23], K. Krajczár[2,24], K. Kutak[25], M. Laine[26], Y. Liu[27], M.P. Lombardo[28], M. Luzum[29,3], C. Marquet[30], S. Masciocchi[9], V. Okorokov[31], J.-F. Paquet[32,33], H. Paukkunen[3,18,34], E. Petreska[30,3], T. Pierog[35], M. Ploskon[36], C. Ratti[37], A.H. Rezaeian[38], W. Riegler[2], J. Rojo[39], C. Roland[24], A. Rossi[40,1], G.P. Salam[2], S. Sapeta[25,2], R. Schicker[19], C. Schmidt[41], J. Stachel[19], J. Uphoff[21], A. van Hameren[25], K. Watanabe[42], B.-W. Xiao[42], F. Yuan[36], D. Zaslavsky[42], K. Zhou[21,15], P. Zhuang[15]

LIP & Collaborators (2017, 2018)

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

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Students @ Pheno

- If you want to do Jet Physics in the presence of a QGP:

    - Quantum Field Theory in a Hot and Dense medium;

    - Development of Monte Carlo event generators;

    - Design of novel experimental observables/physics analysis for heavy-ion collisions (present and future);

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Join us! :-)

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gmilhano@lip.pt

Thank you!

Acknowledgements