Jet quenching in heavy ion collisions

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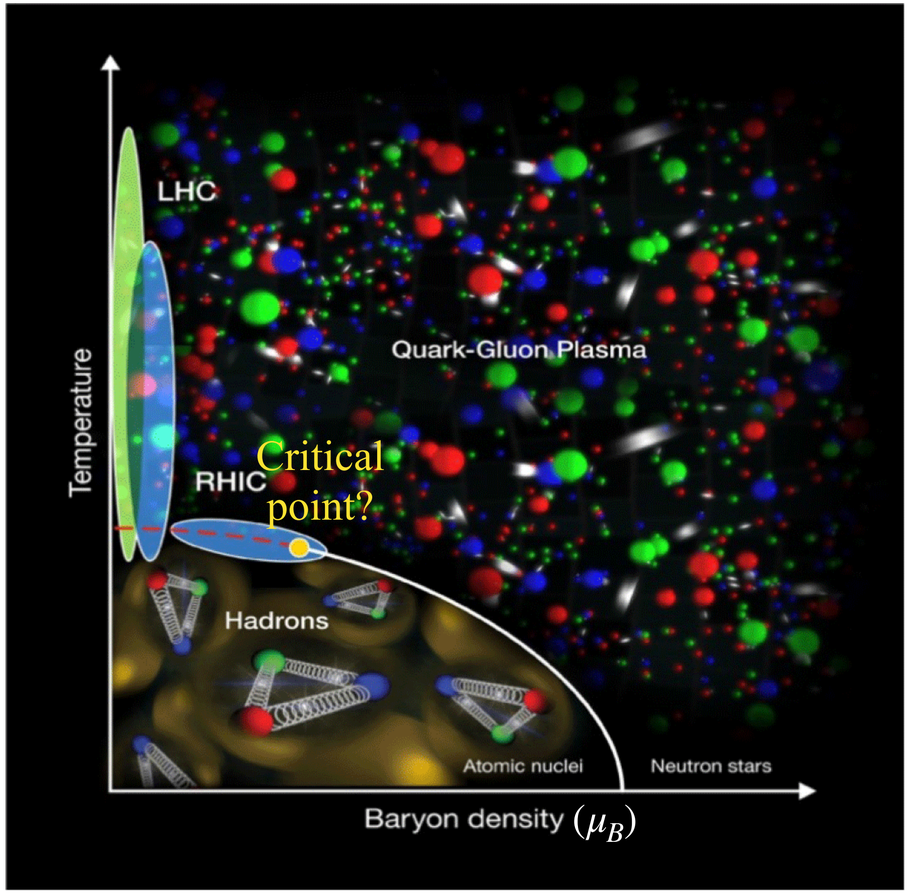
LIP, Lisbon

Present and future perspectives in Hadron Physics
Frascati, June 17-19, 2024

QCD phase diagram

- Hot QCD emergent dynamics at reach in collider experiments!



QCD phase diagram

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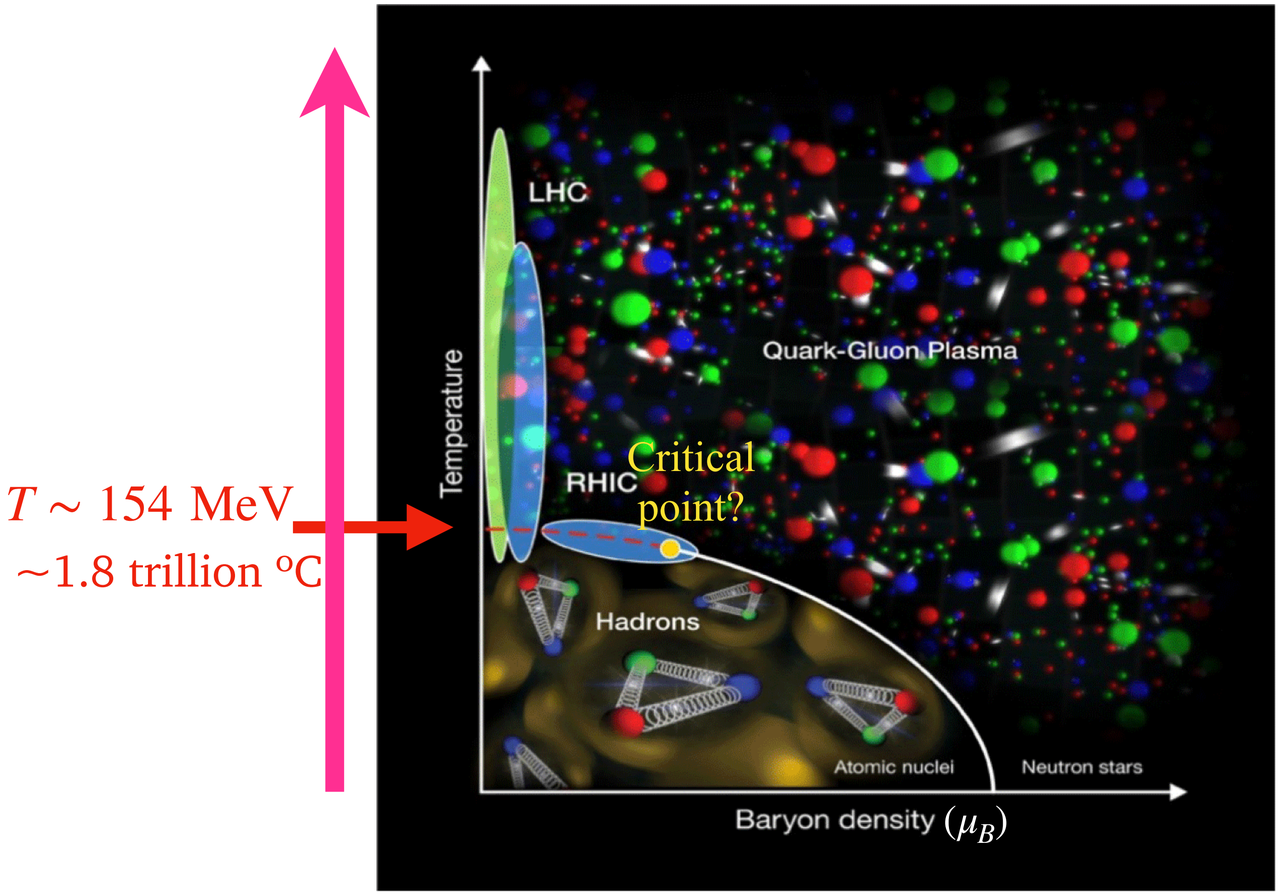
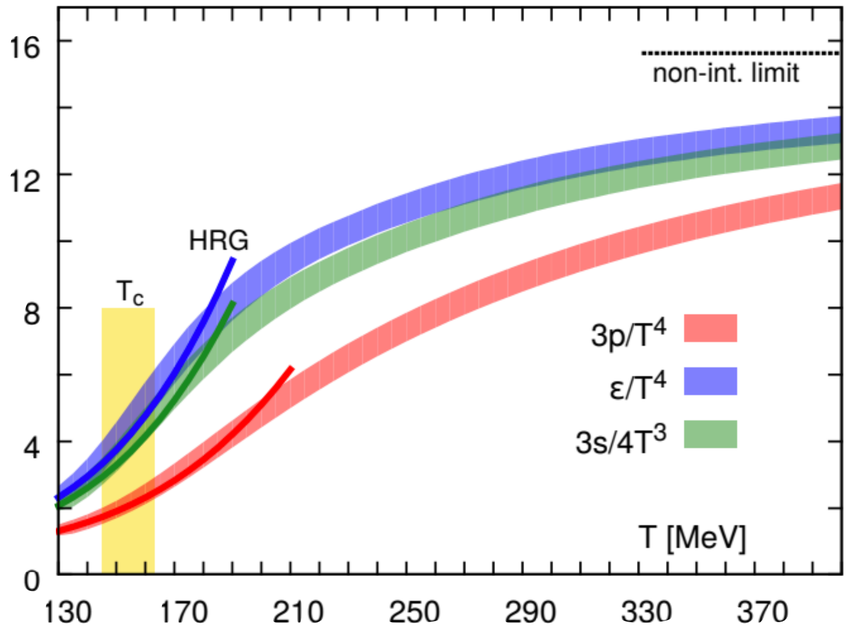


Lattice QCD ($\mu_B = 0$)



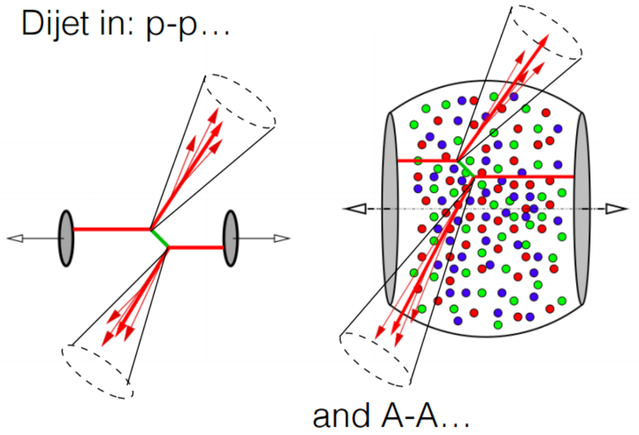
HotQCD Collaboration
Phys. Rev. D 90 (2014) 094503

Why jets?

- Production of high-energy partons unlikely to interfere with the medium formation

- Sensitive to the QGP dynamics through **jet quenching: jets interact with the QGP getting modified w.r.t p-p jets**

- In principle: under control in p-p collisions



- **Multi-scale** objects: broad range of momentum and spatial scales involved in the jet evolution

- **Multi-observable**: different observable jet properties sensitive to different QGP scales and properties?

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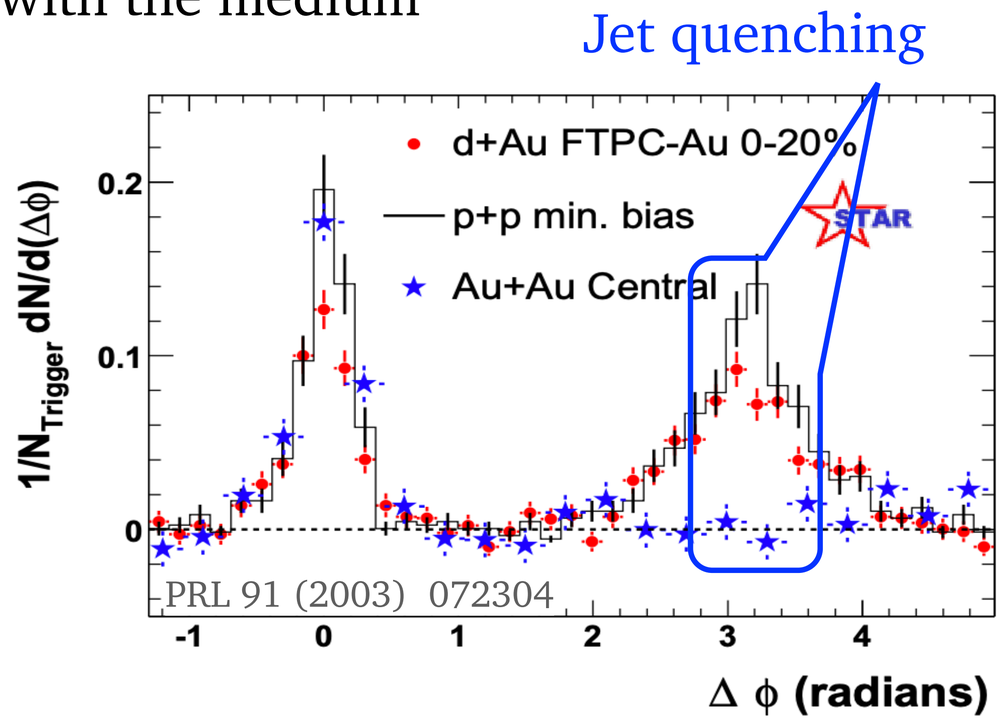

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Medium-induced radiation

- The main contribution to energy loss in the **QGP** is radiative energy loss

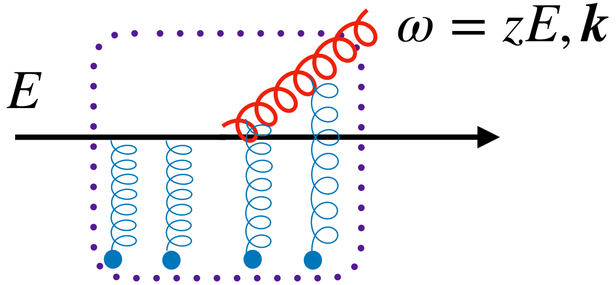
  Dominant for light quarks and gluons

High-energy partons experience **multiple scatterings with the medium** which induce **extra gluon radiation** (w.r.t. p-p)

- During the formation time of the gluon **multiple scatterings** act **coherently**

LPM effect

$$t_f \sim \frac{\omega}{k^2}$$



Landau, Pomeranchuk, Migdal for QED

Suppression of the spectrum for **large formation times**

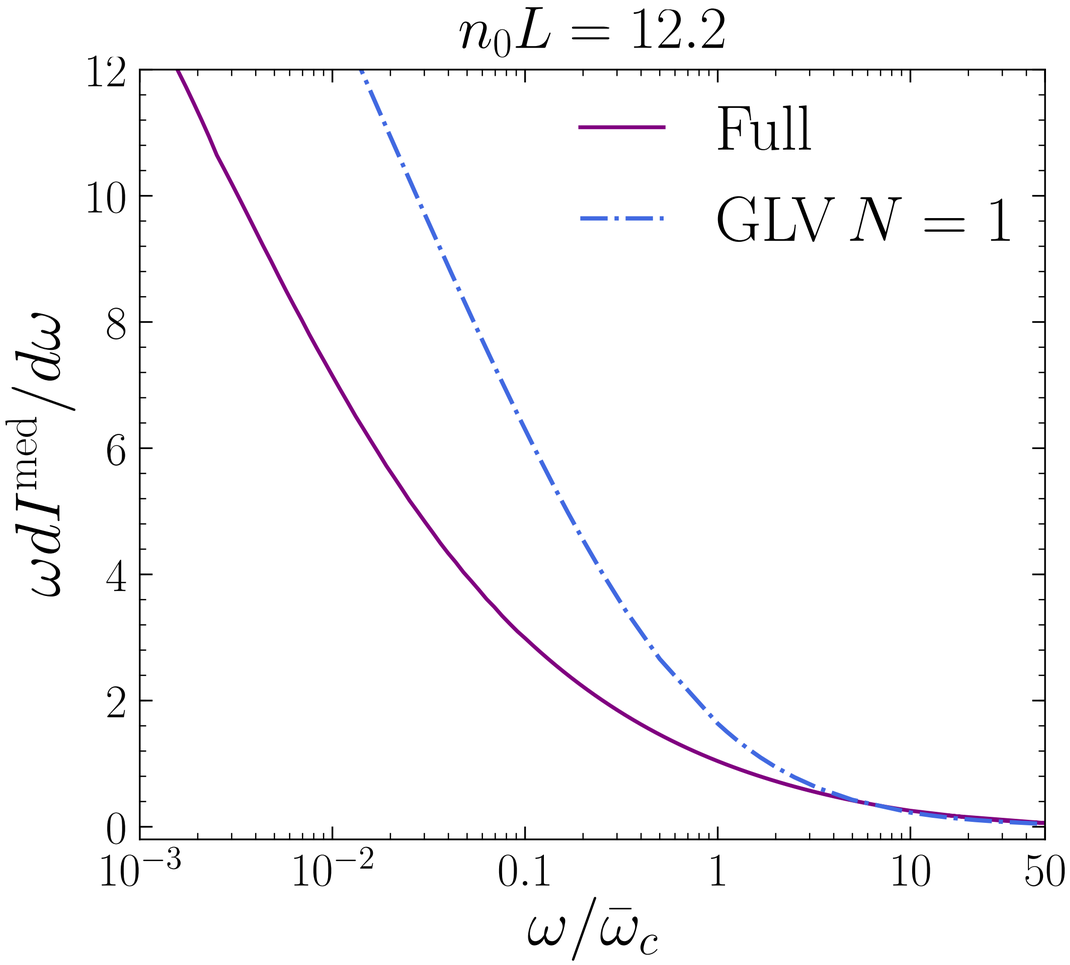
- Resummation of multiple scatterings: **BDMPS-Z formalism (1990's)**

CA, Apolinario, Martinez, Dominguez, JHEP 07 (2020) 114, JHEP 03 (2021) 102

Mehtar-Tani, Barata, JHEP 07 (2019) 057, JHEP 10(2020) 176

Schlichting, Soudi, Phys. Rev. D 105 (2022) 076002

BDMPS-Z spectrum



$$\bar{\omega}_c = \frac{1}{2}\mu^2 L$$

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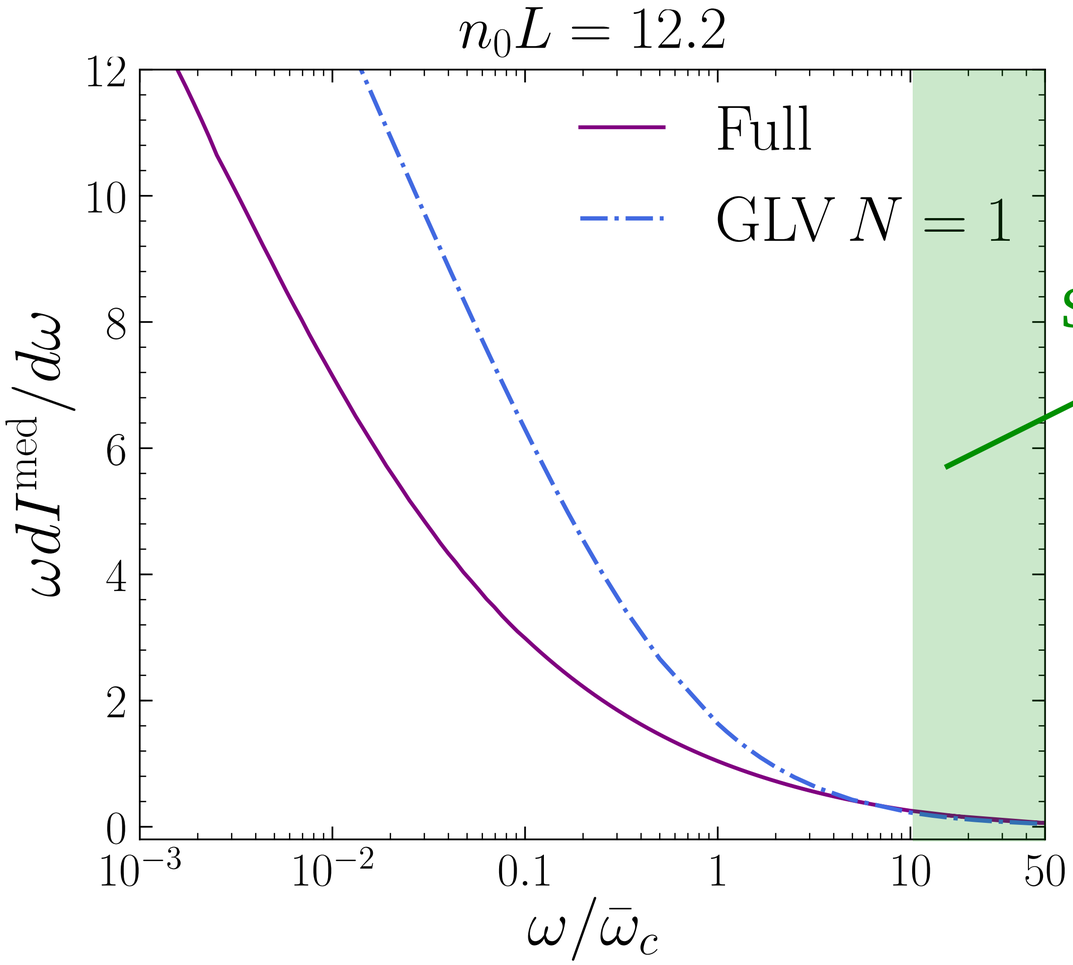

Single hard scattering regime

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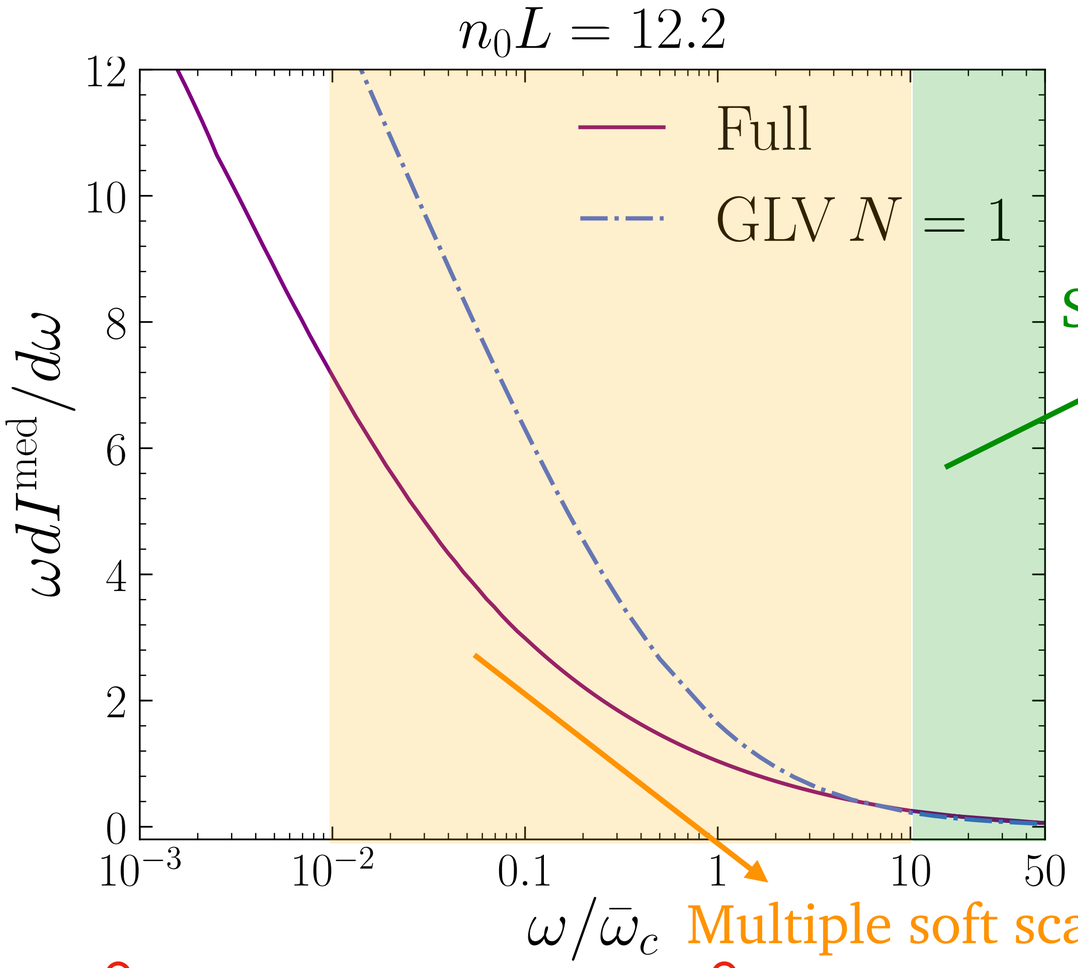
BDMPS-Z spectrum



Single hard scattering regime

Multiple soft scattering regime: LPM effect

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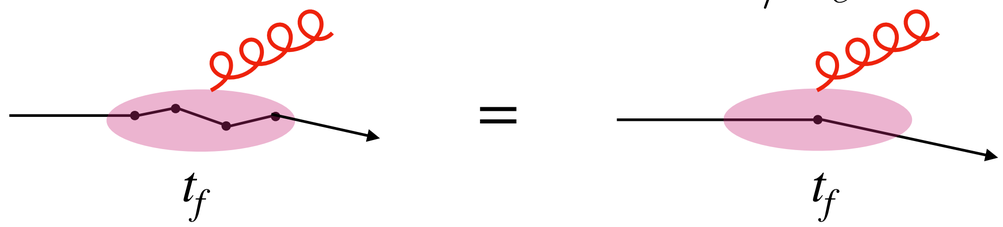
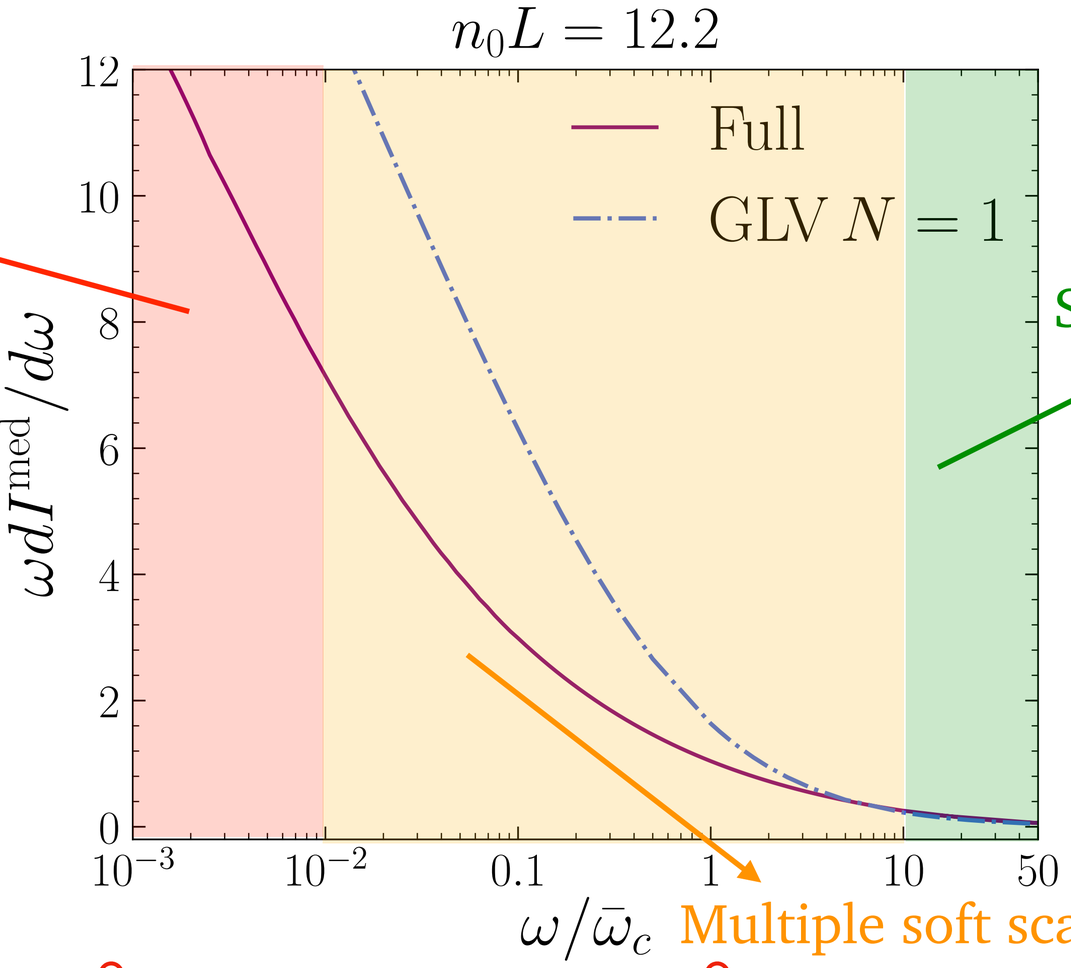


LPM effect

BDMPS-Z spectrum



Bethe-Heitler regime

Single hard scattering regime

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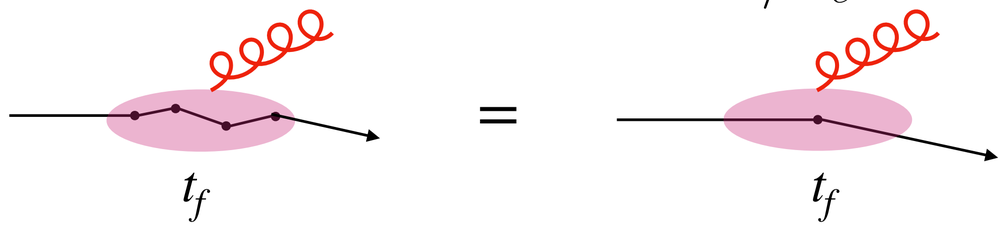
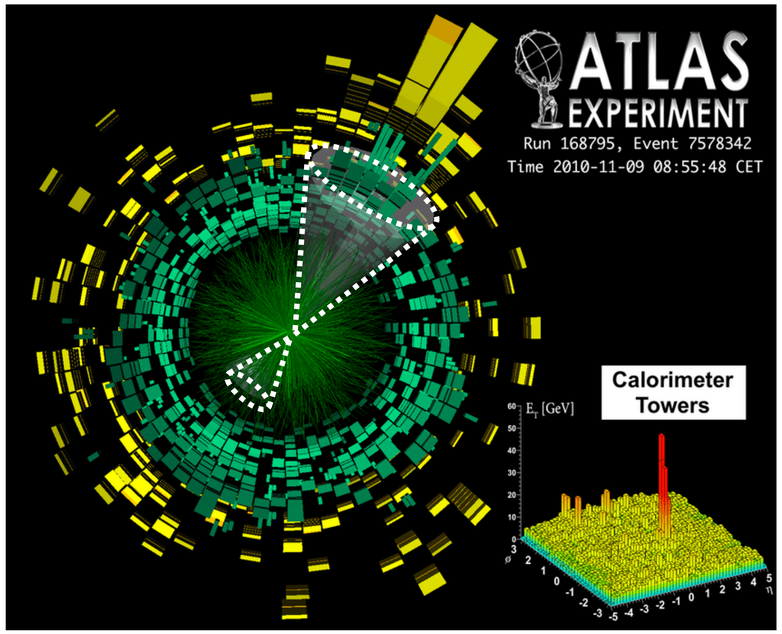
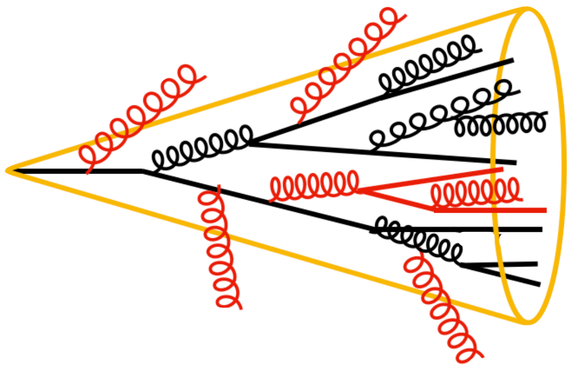


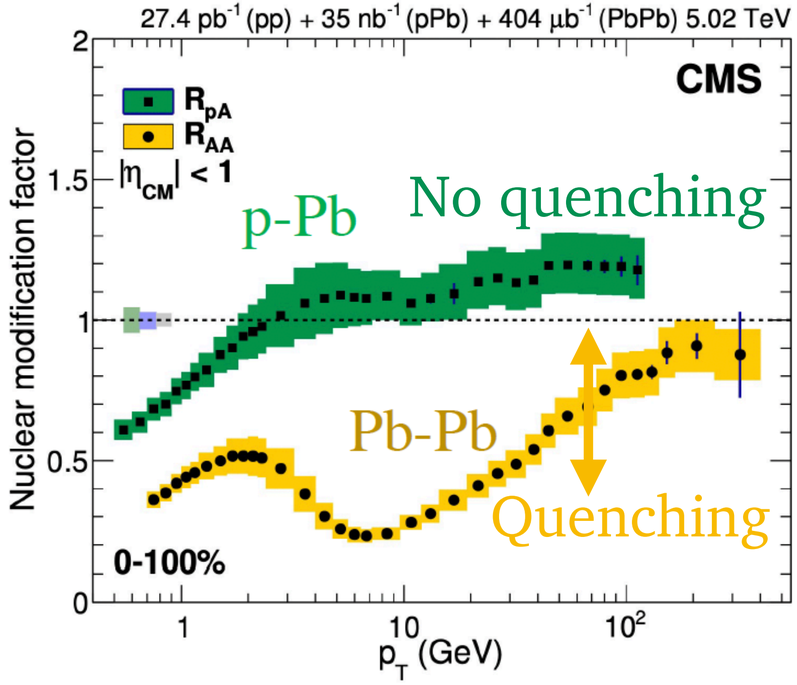
LPM effect

Jet quenching





$$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled} \otimes \text{pp}}$$



JHEP 04, 039 (2017)

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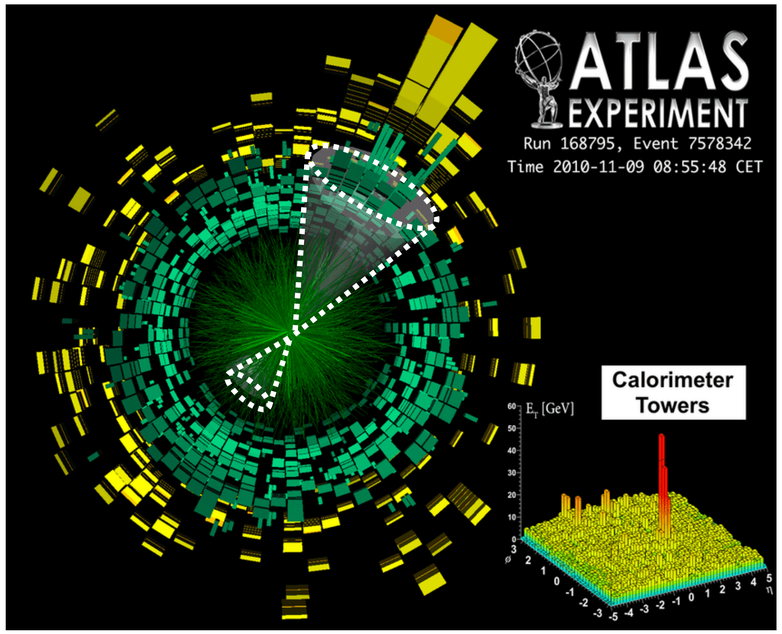

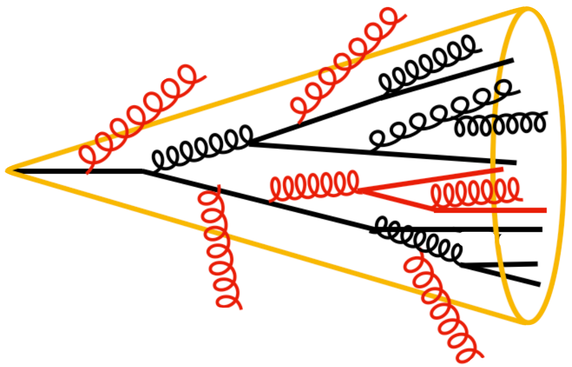

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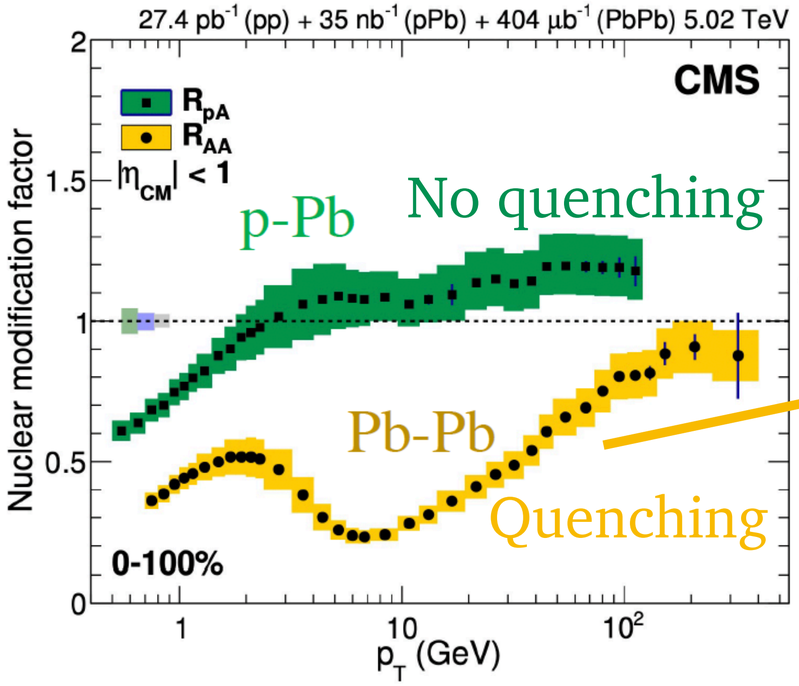

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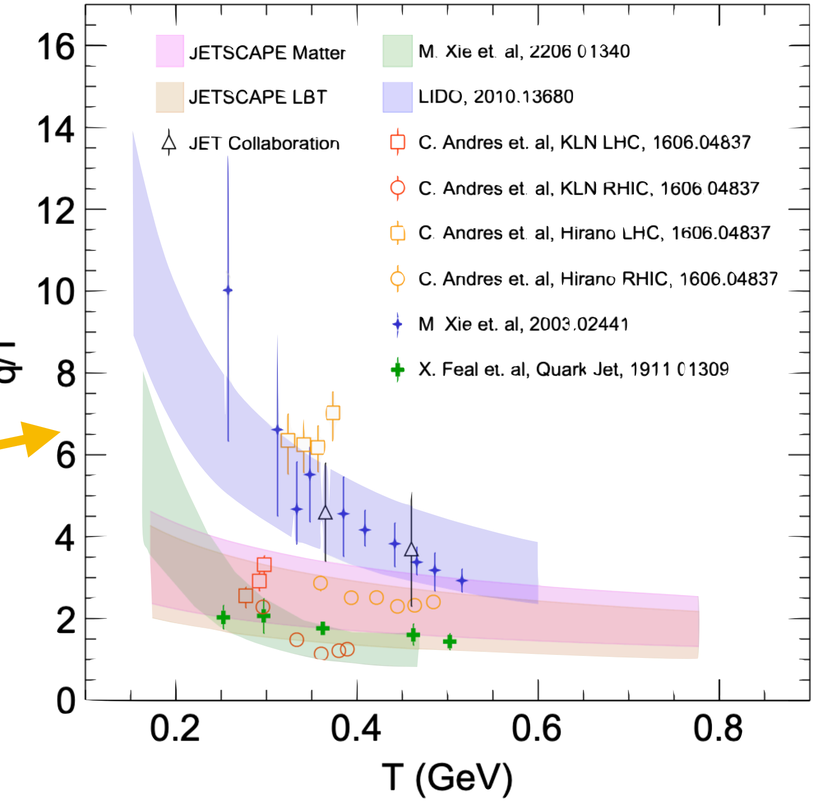
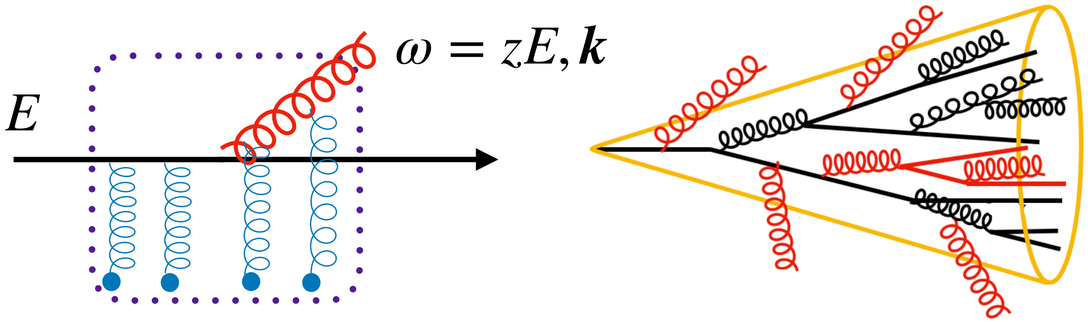
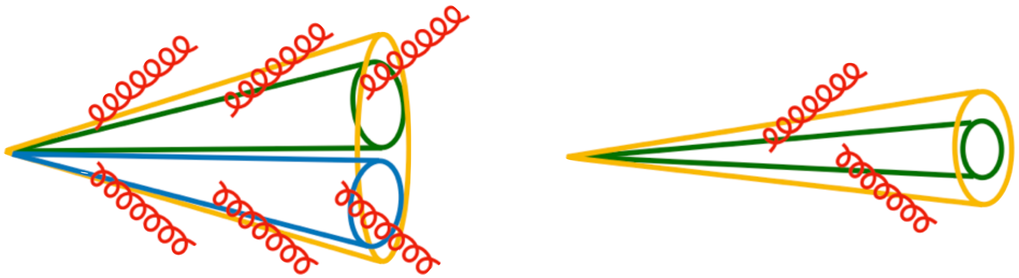


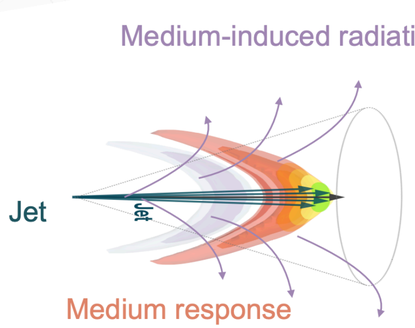
Apolinário et al., Prog. Part. Nucl. Phys. 127, 103990 (2022)

Jet modifications in heavy ions

- **Medium-induced** energy loss
  - Out-of-cone energy loss
  - Jet and hadron suppression
- **Color coherence** effects
  - Expected to modify the jet inner structure
  - Not yet unequivocally seen in observables
- **Medium response**
  - Medium recoils become part of the jet
  - Not yet unequivocally seen in observables



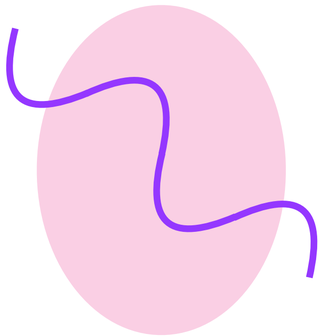




Jet substructure

Can we use jet substructure to probe the QGP at **various resolution scales?**

Fluid-like QGP



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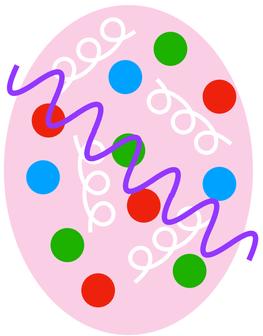
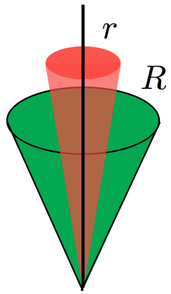
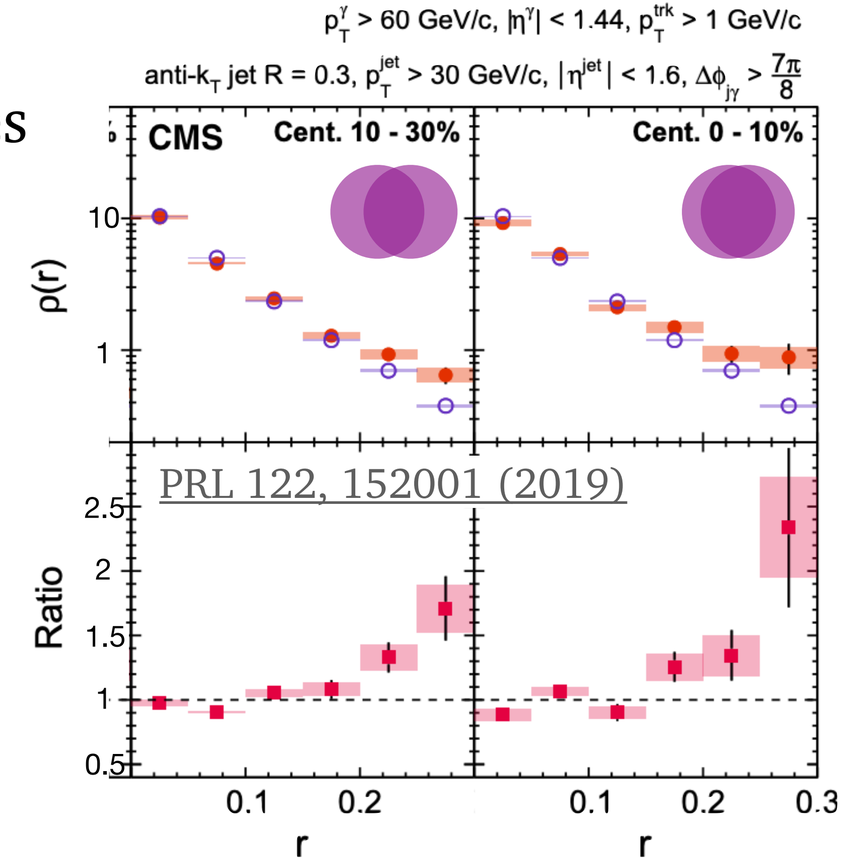


Increasing the resolution scale

Jet shapes





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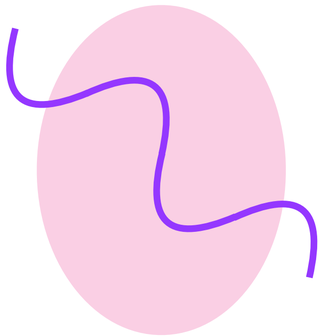

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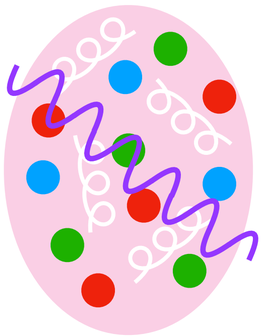

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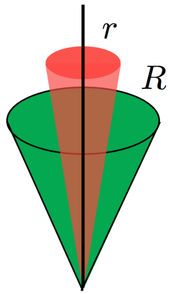
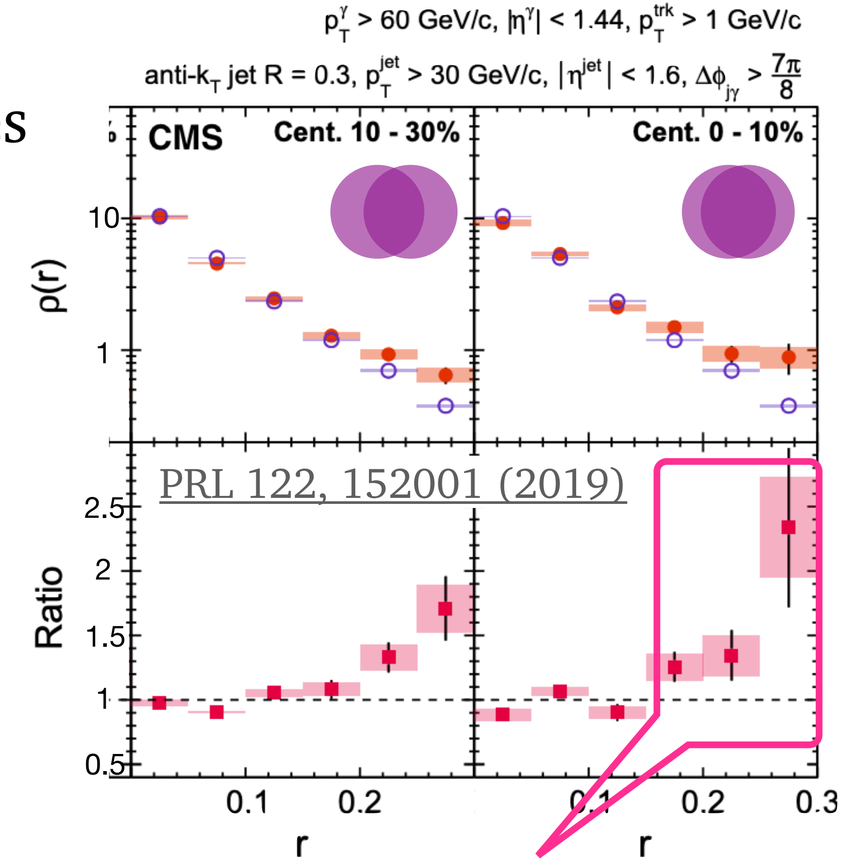
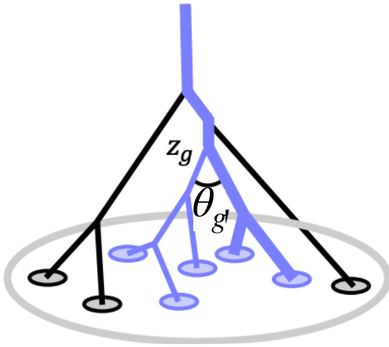




Pb-Pb jets **more energy toward the edge of the cone** than p-p jets

Jet substructure: grooming

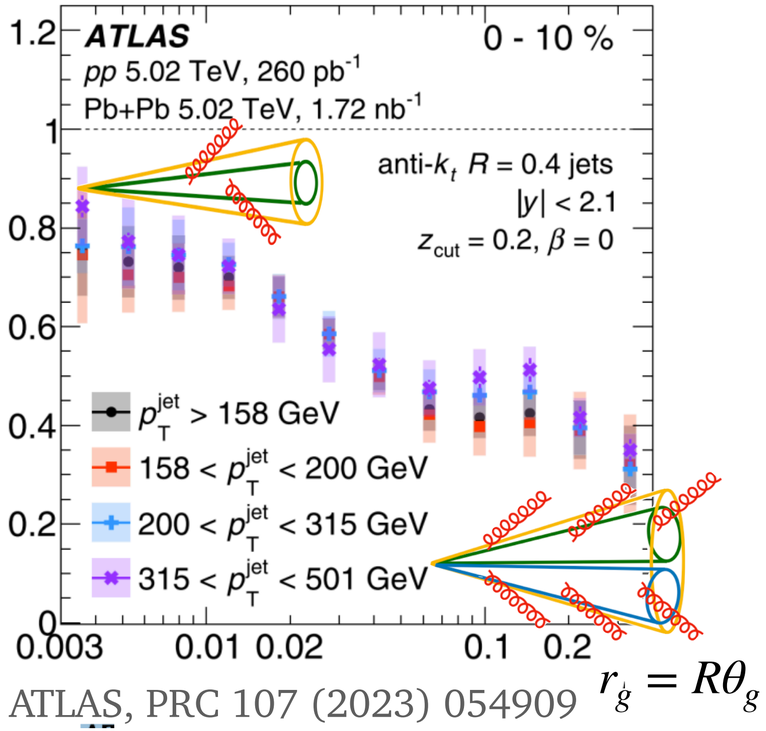


- What about grooming away soft physics?

Jet constituents are re-clustered (through C/A) and soft/wide angle radiation is rejected in this process

Groomed jet radius

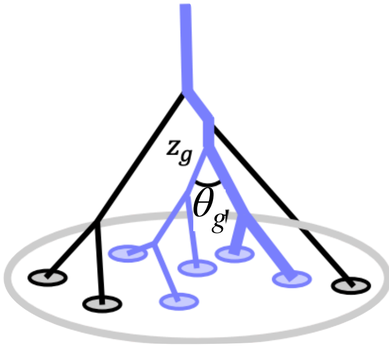
$$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled} \otimes \text{pp}}$$



ATLAS, PRC 107 (2023) 054909

Broad angular structures are more suppressed in PbPb collisions

Jet substructure: grooming



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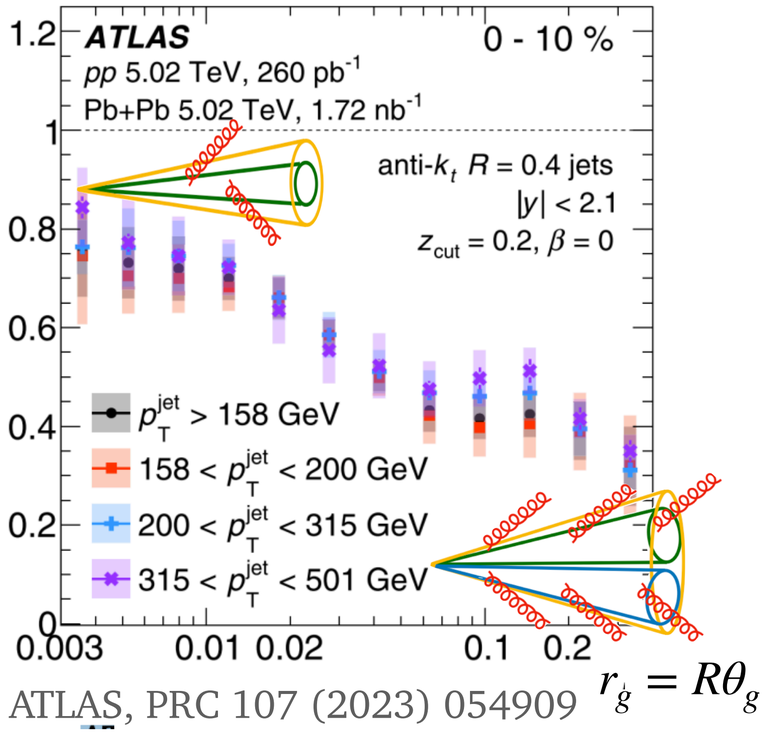

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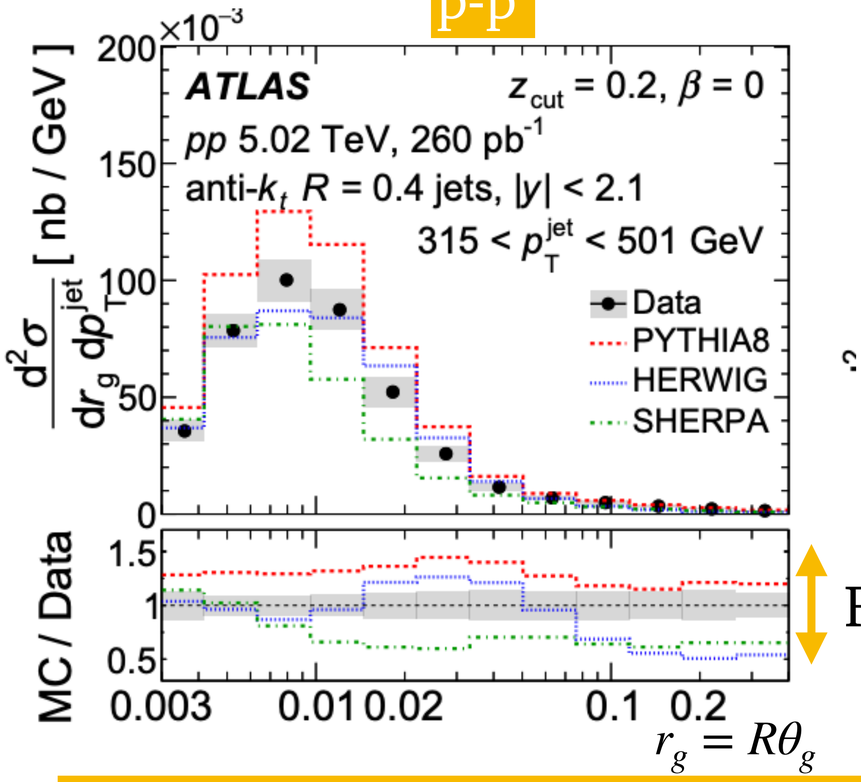
p-p



Factor 2

Large discrepancies between MC and data in p-p collisions

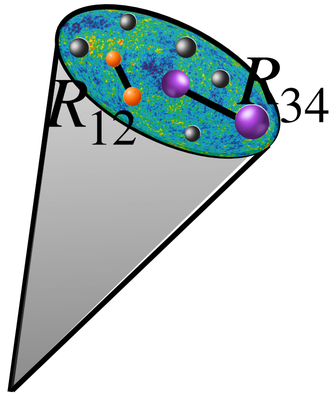
A new (old) idea?

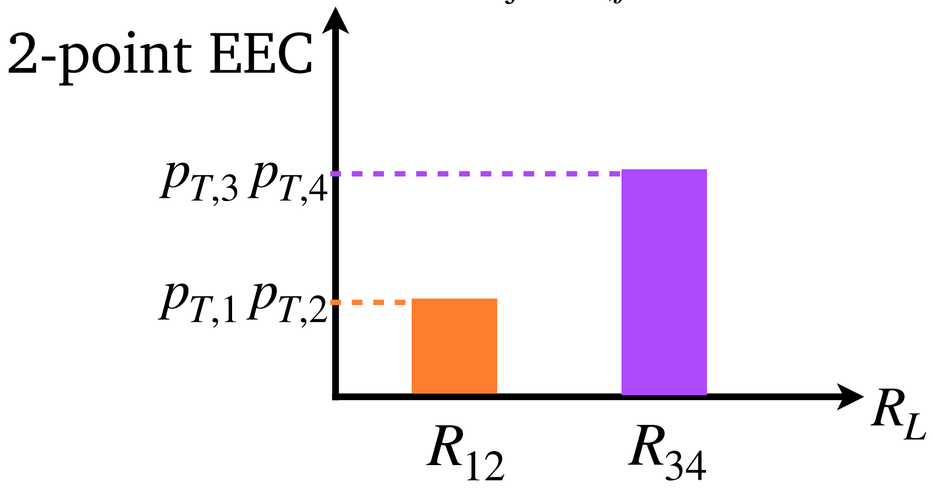
Energy-energy correlators

New tool: energy correlators

- Correlators $\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\cdots\mathcal{E}(\vec{n}_k)\rangle$ of the **energy flux**

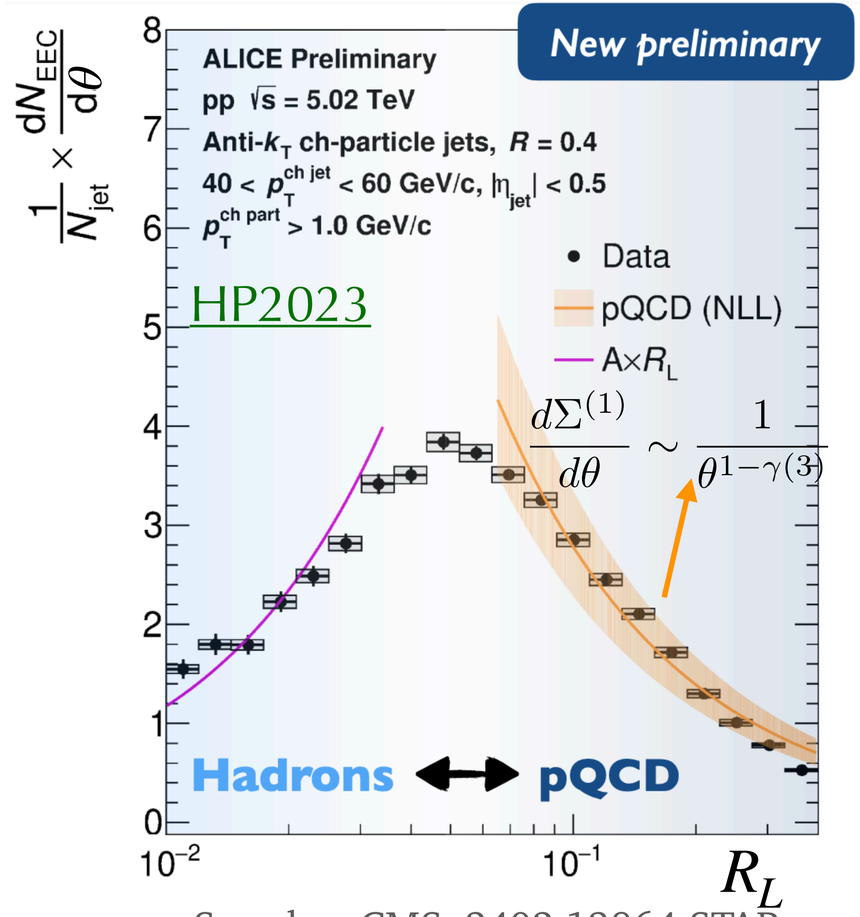
$$\text{2-point EEC} = \frac{1}{N_{\text{jets}}}\sum_{\text{jets}}\sum_{i,j}\frac{P_{T,i}\,P_{T,j}}{P^2_{T,\text{jet}}}\,\delta(R_{ij}-R_L)$$





- Excellent theoretical properties: good candidates for a heavy-ion substructure program

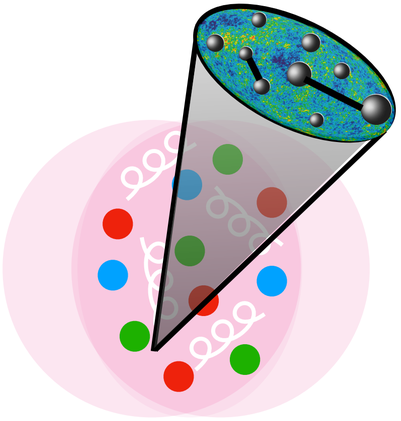
EEC in proton-proton



See also: CMS, 2402.13864 STAR, 2309.05761

EEC in heavy-ions

CA, Dominguez, Elayavalli, Holguin, Marquet, Moult
Phys. Rev. Lett. 130 (2023) 262301,
JHEP 09 (2023) 088



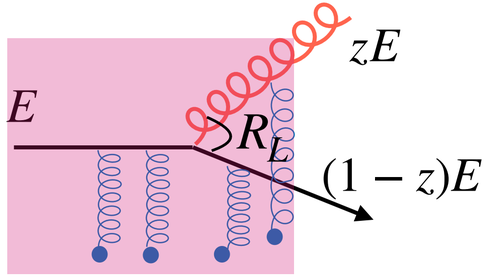
- EEC for a **massless quark jet**: $Q = E$

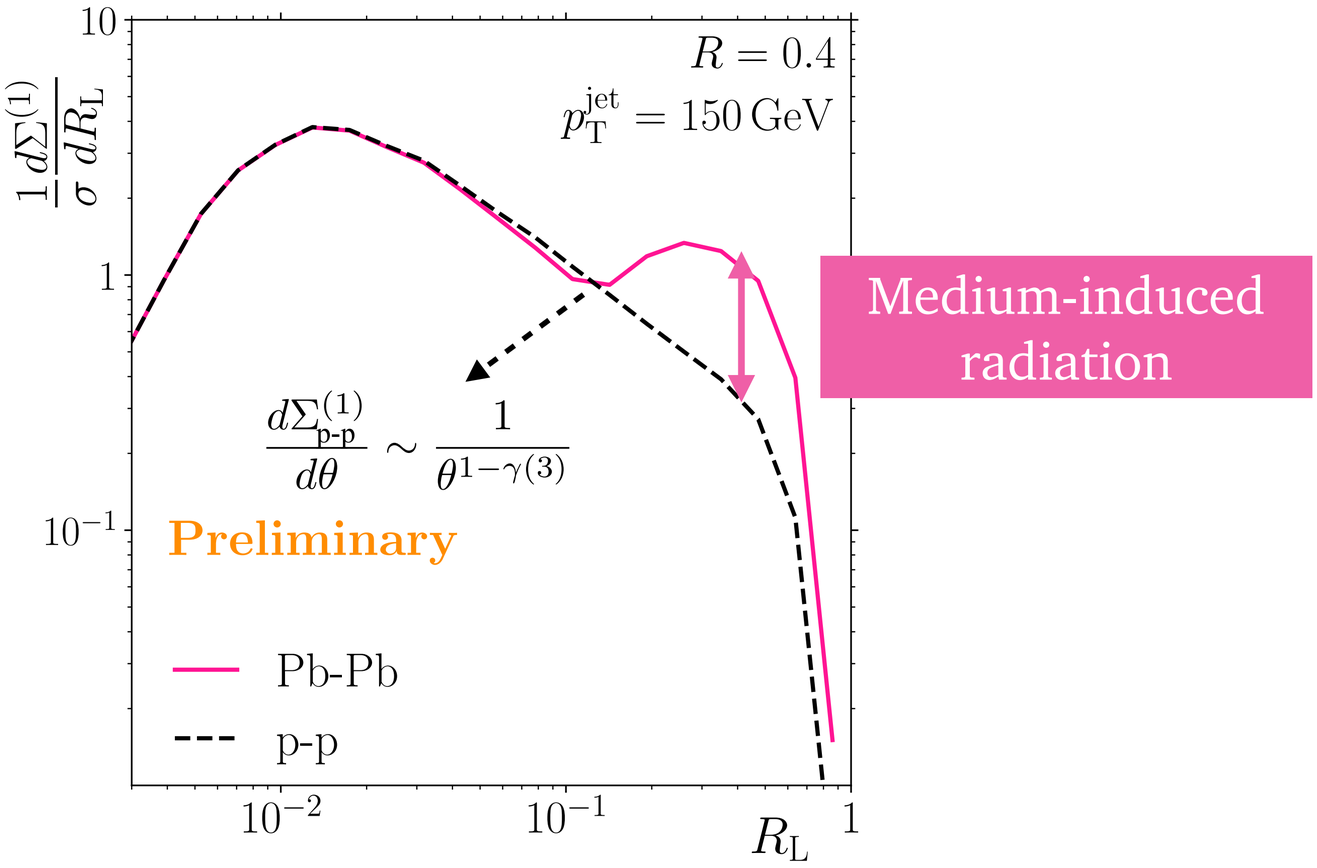
  We are assuming we know the initial jet energy E (γ/Z-jet)

$$\frac{\mathrm{d}\Sigma^{(n)}}{\mathrm{d}\theta} = \frac{1}{\sigma_{qg}} \int \mathrm{d}z \, \frac{\mathrm{d}\sigma_{qg}}{\mathrm{d}z\mathrm{d}\theta} \, z^n (1-z)^n + \mathcal{O}\left(\frac{\mu_s}{E}\right)$$

$$\frac{\mathrm{d}\sigma_{qg}}{\mathrm{d}\theta dz} = \frac{\mathrm{d}\sigma_{qg}^{\mathrm{vac}}}{\mathrm{d}\theta dz} + \frac{\mathrm{d}\sigma_{qg}^{\mathrm{med}}}{\mathrm{d}\theta dz}$$

Medium-induced radiation





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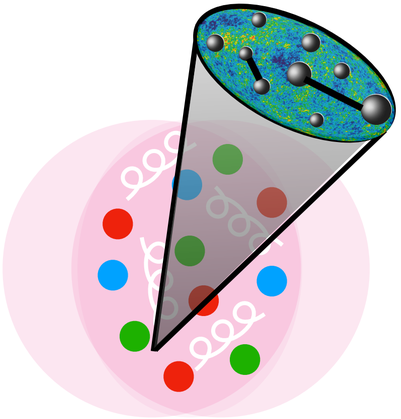

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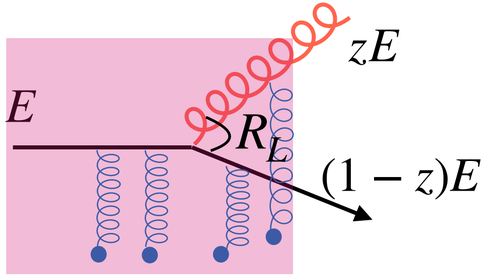
$$\frac{\mathrm{d}\sigma_{qg}}{\mathrm{d}\theta dz} = \frac{\mathrm{d}\sigma_{qg}^{\mathrm{vac}}}{\mathrm{d}\theta dz} + \frac{\mathrm{d}\sigma_{qg}^{\mathrm{med}}}{\mathrm{d}\theta dz}$$

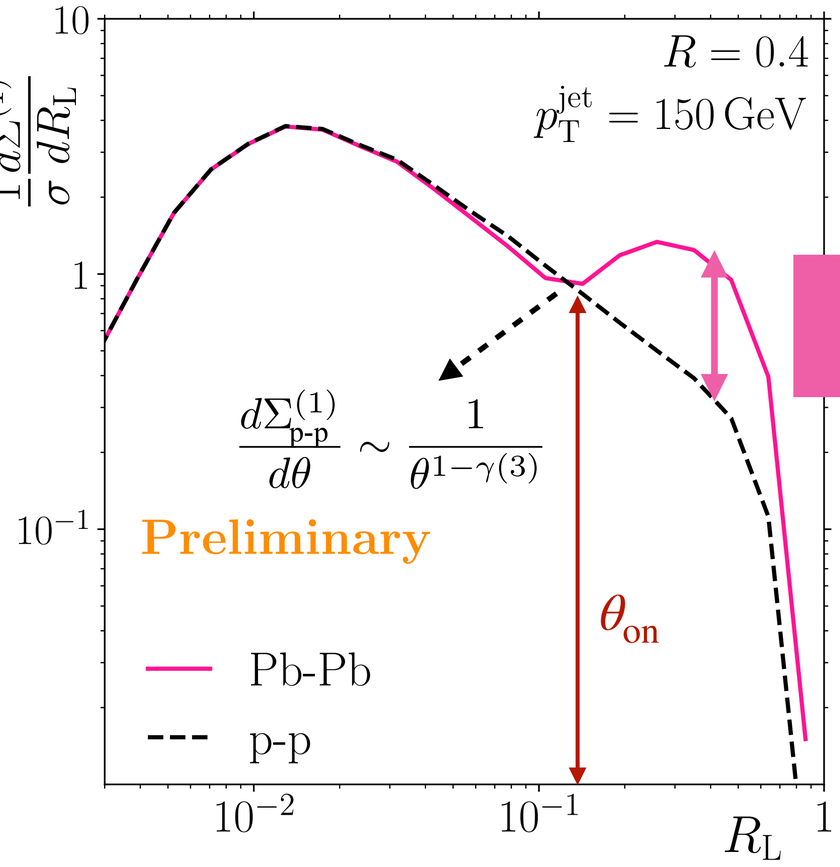
Medium-induced radiation



$$t_f = \frac{2}{z(1-z)ER_L^2}$$

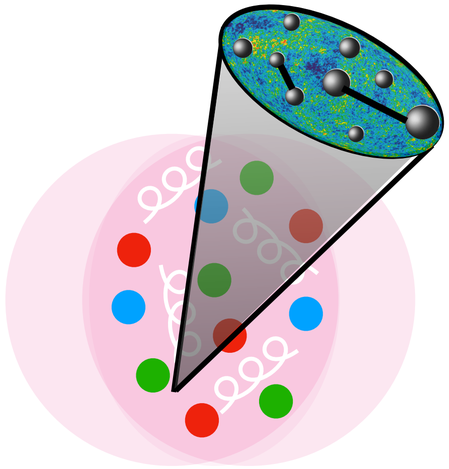
$$\downarrow \; t_f \leq L$$

$$\theta_{\mathrm{on}} \sim (EL)^{-1/2}$$



Medium-induced radiation

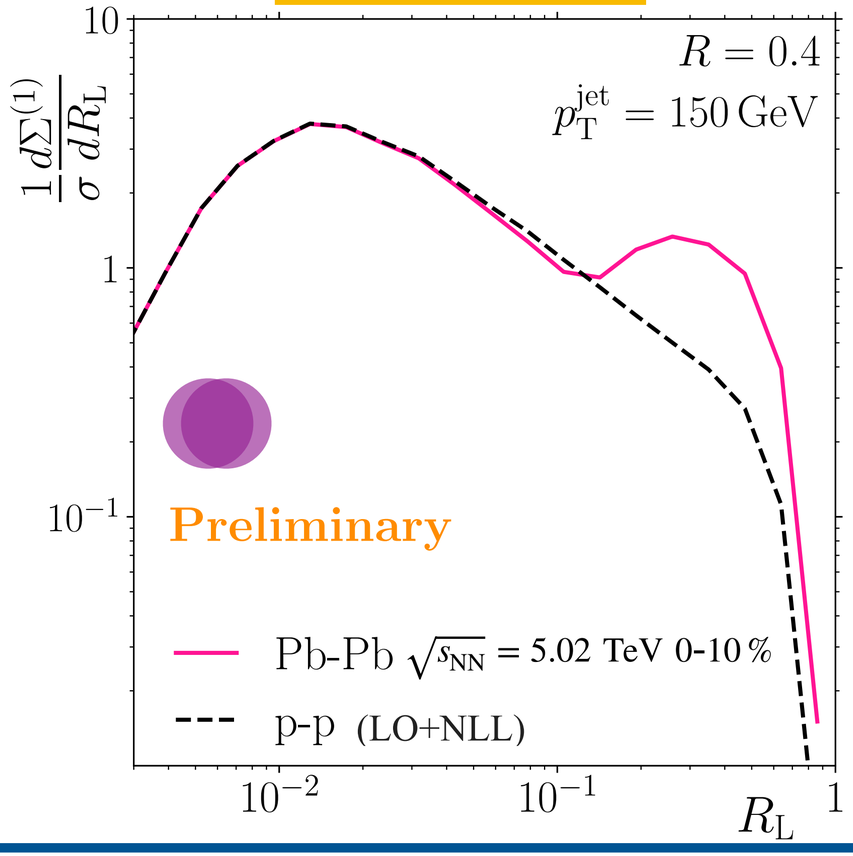
EEC in heavy-ions



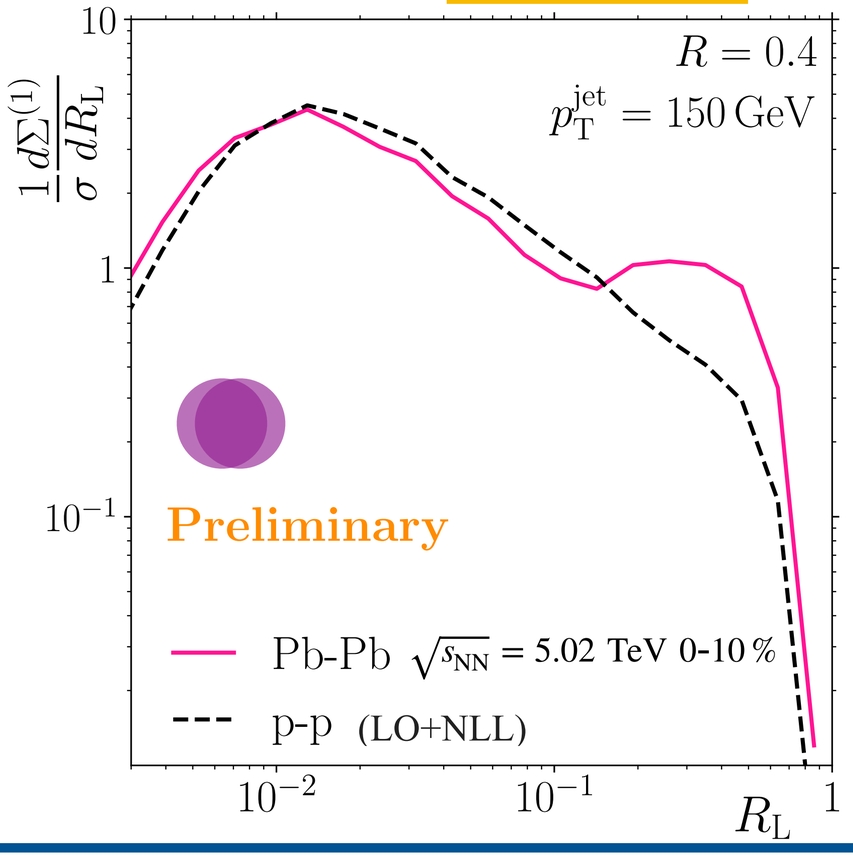
- Moving to inclusive jets

CA, Dominguez, Holguin, Marquet, Moult, in preparation

$\gamma-$tagged jets

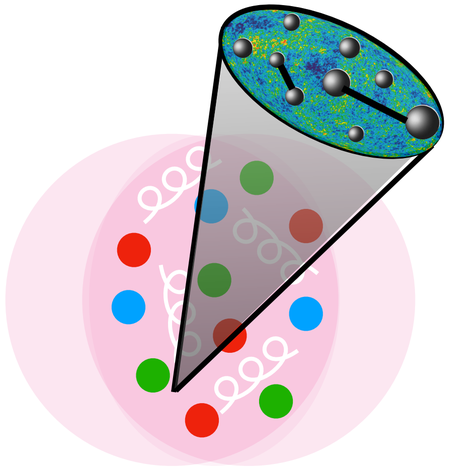


Inclusive



Results for inclusive jets from ALICE and CMS underway!

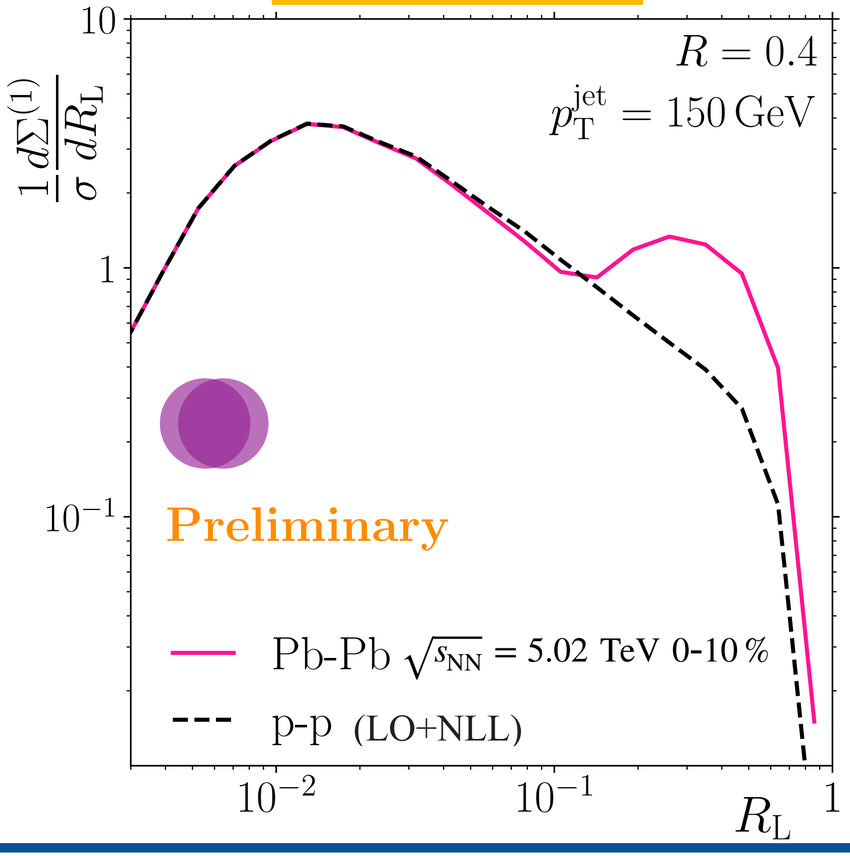
EEC in heavy-ions



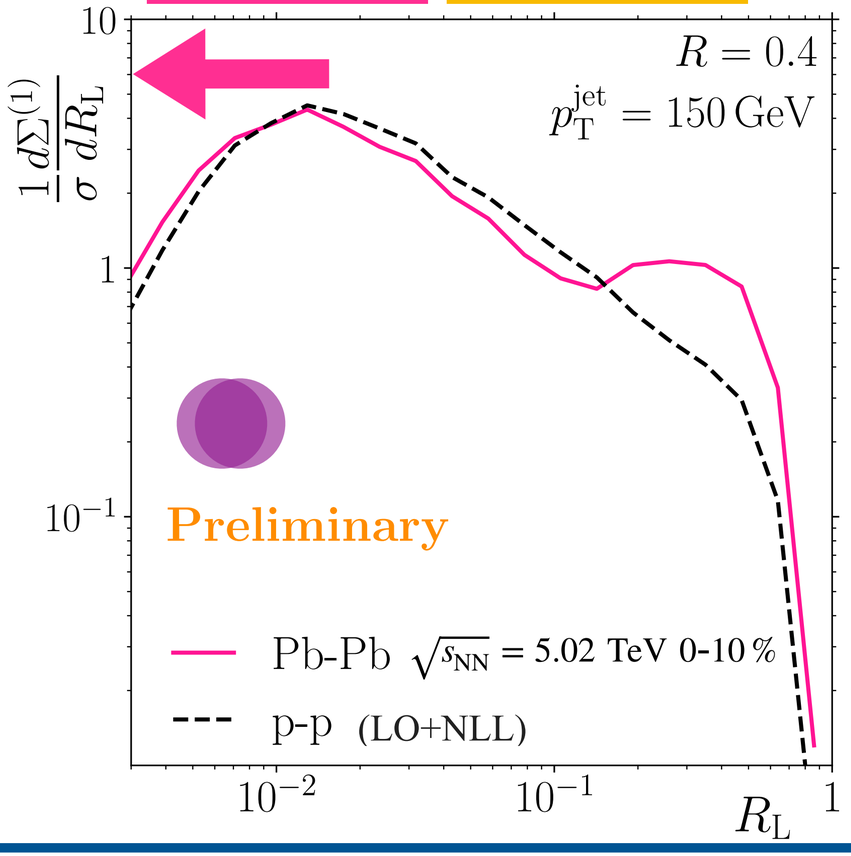
- Moving to inclusive jets

CA, Dominguez, Holguin, Marquet, Moult, in preparation

$\gamma-$tagged jets

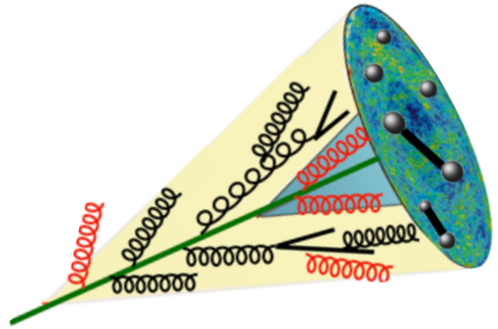


Energy loss Inclusive

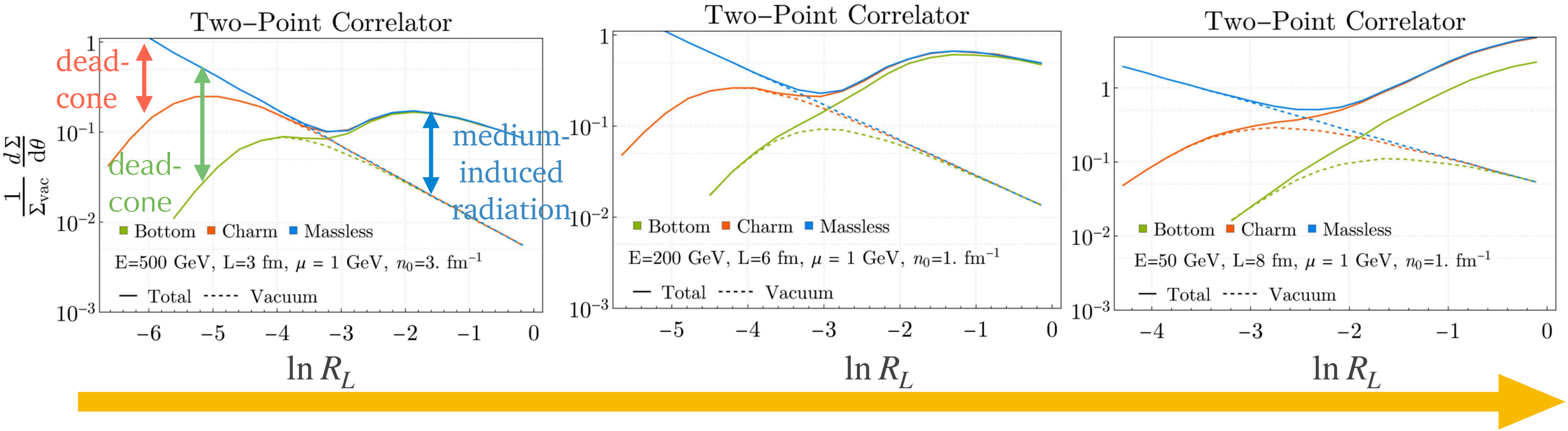


Results for inclusive jets from ALICE and CMS underway!

HF jets: filling the dead-cone



CA, Dominguez, Holguin, Marquet, Moult, 2307.15110

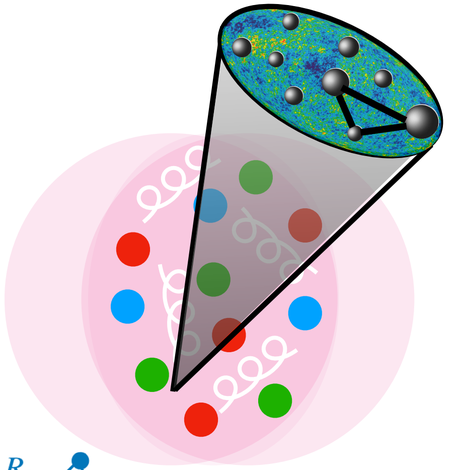


Armesto, Salgado, Wiedemann,
arXiv: hep-ph/0312106

$\frac{\theta_L}{\Theta_0} \to 1$: Filling the dead-cone

EEC sensitive to **two different scales**: HQ mass and onset of medium-induced radiation

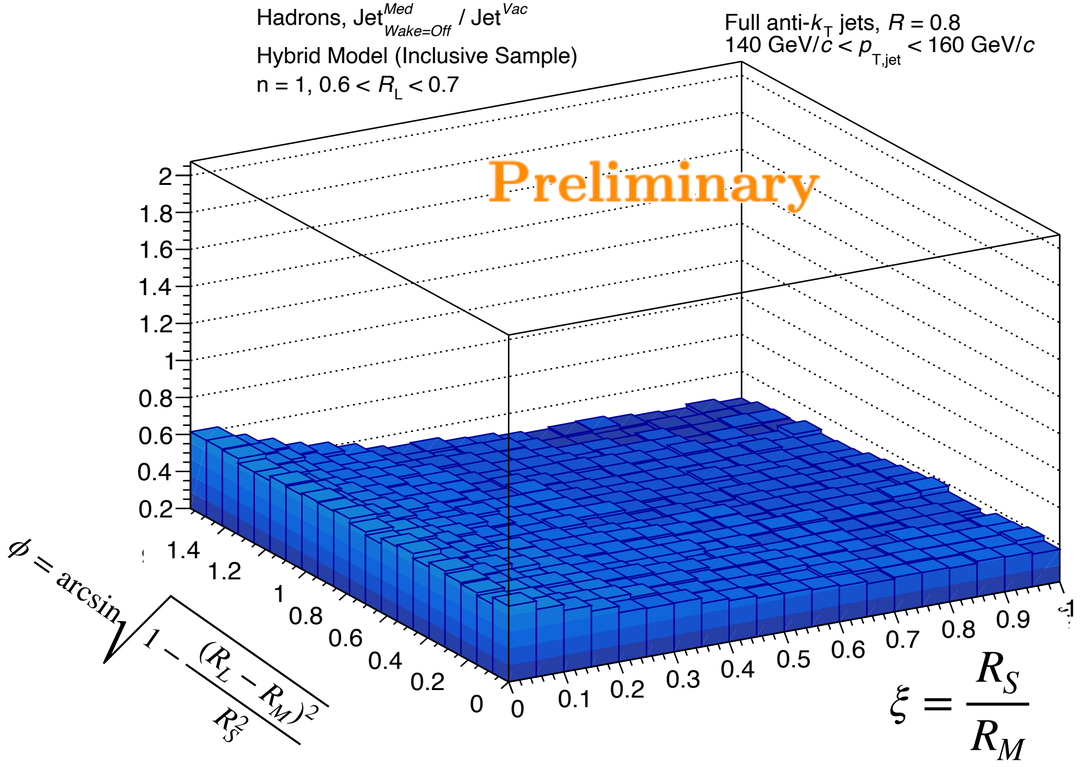
Energy correlators in heavy-ions



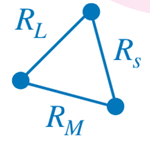
- First studies of the shape of the E3EC

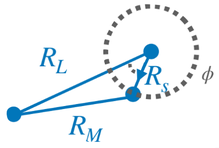
  Bossi, Kudinoor, Moult, Pablos, Rai, Rajagopal

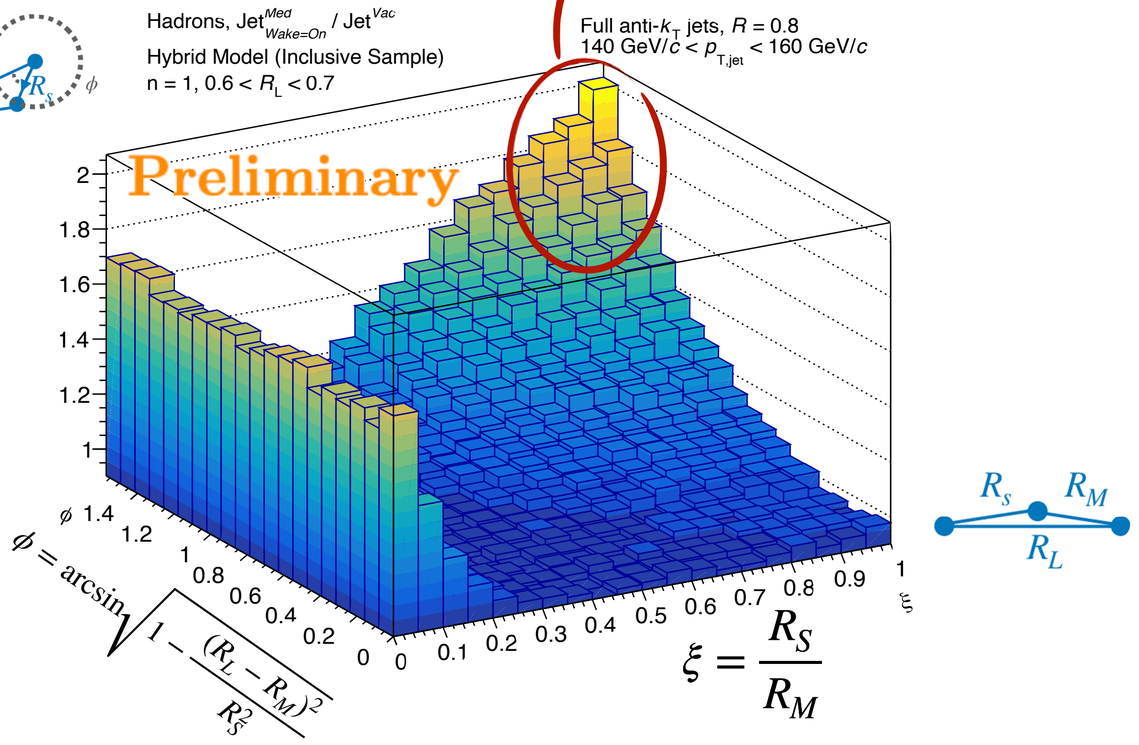
No wake/p-p



With wake/p-p







Conclusions

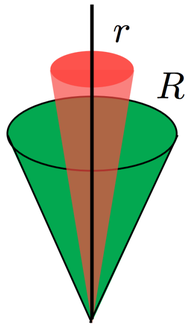
- **QCD collectivity at experimental reach** at RHIC and the LHC
  - Impressive progress on the study of the QGP and its pre-hydro stages
  - Many interesting questions to be answered in the next decade

How does a strongly-coupled fluid emerge from an asymptotically free gauge theory?

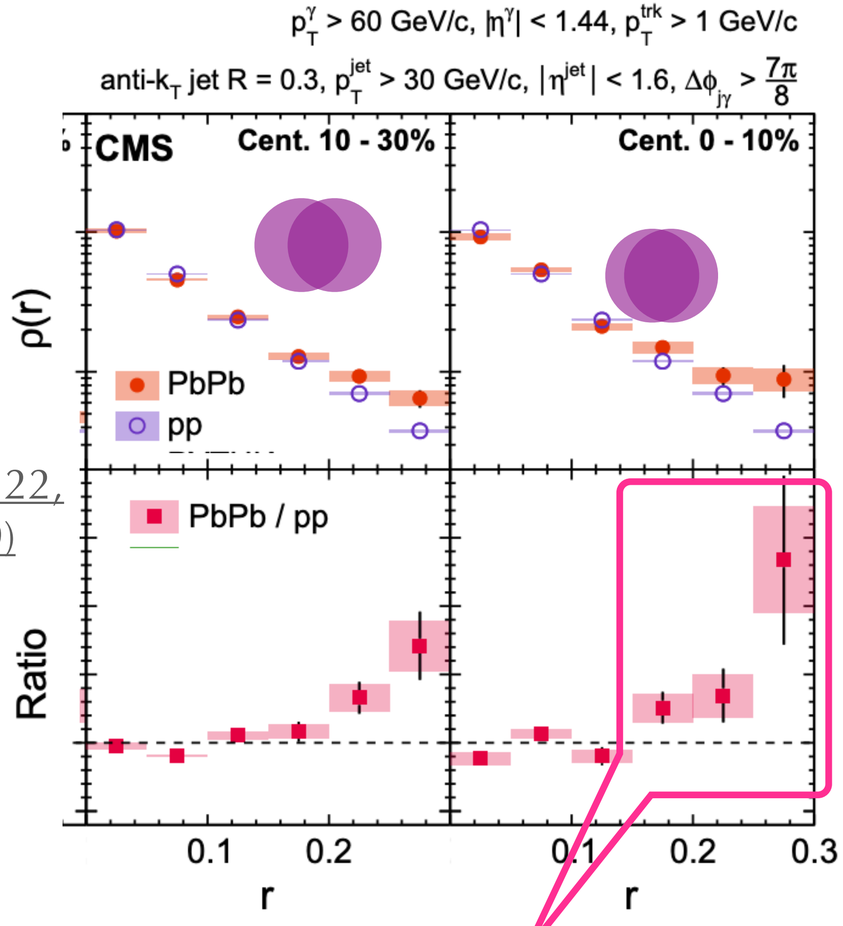
- Use **jets as *microscope* of the QGP**
- **Energy Correlators:** great potential for jet substructure studies of the QGP
- Many theoretical developments and experimental measurements on EECs to come!

Thank you!

Jet substructure

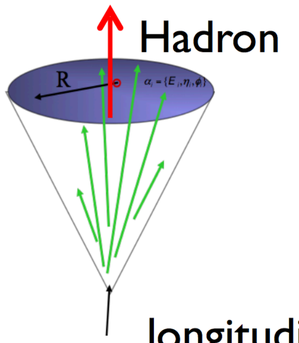


Jet shapes



Phys. Rev. Lett. 122, 152001 (2019)

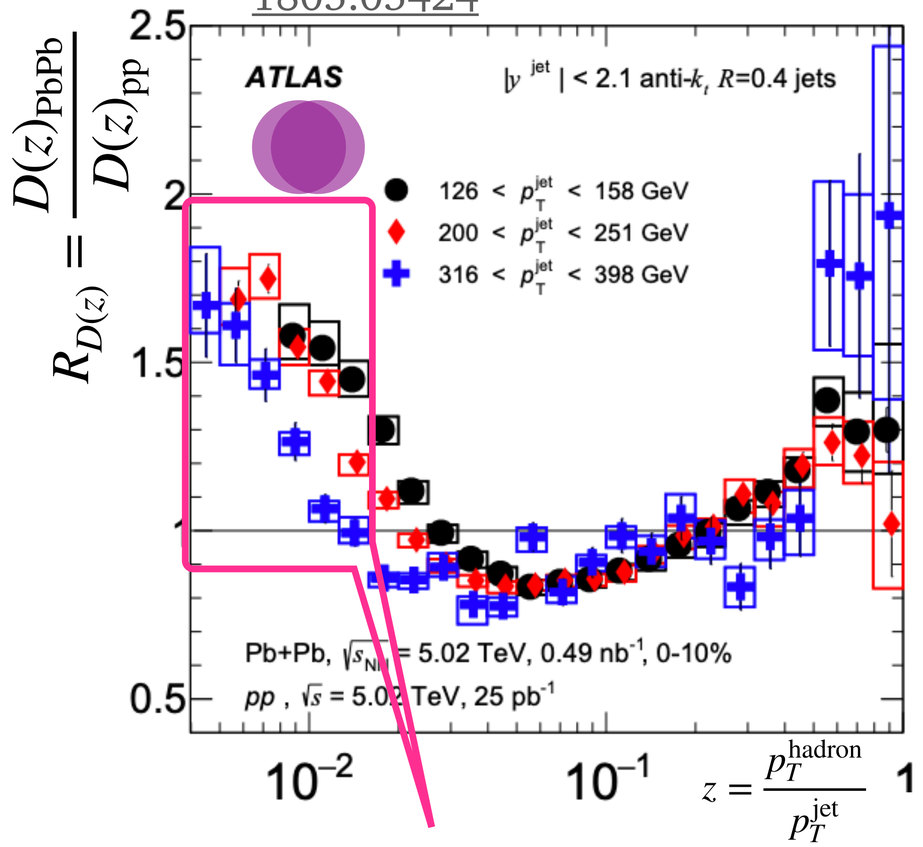
Pb-Pb jets **more energy toward the edge of the cone** than p-p jets



Jet fragmentations

longitudinal

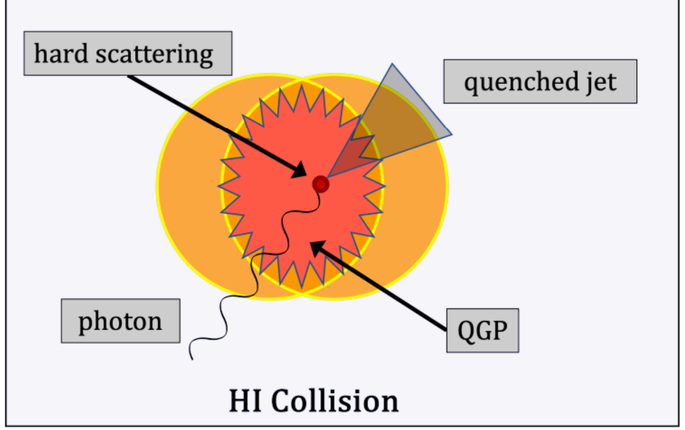
1805.05424



Pb-Pb jets contain **more low-p_T particles** than p-p jets

$$D(z) = \frac{1}{N_{jet}} \frac{dn_{ch}}{dz}$$

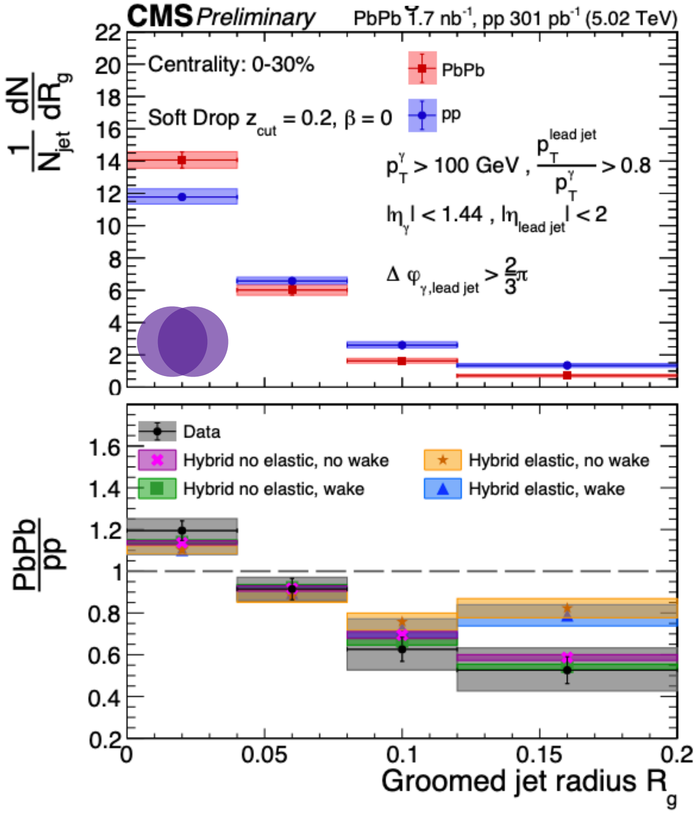
Jet substructure: grooming



- Use photon-tagged jets

$$p_T^{jet}/p_T^{\gamma} = x_{j\gamma} > 0.8$$

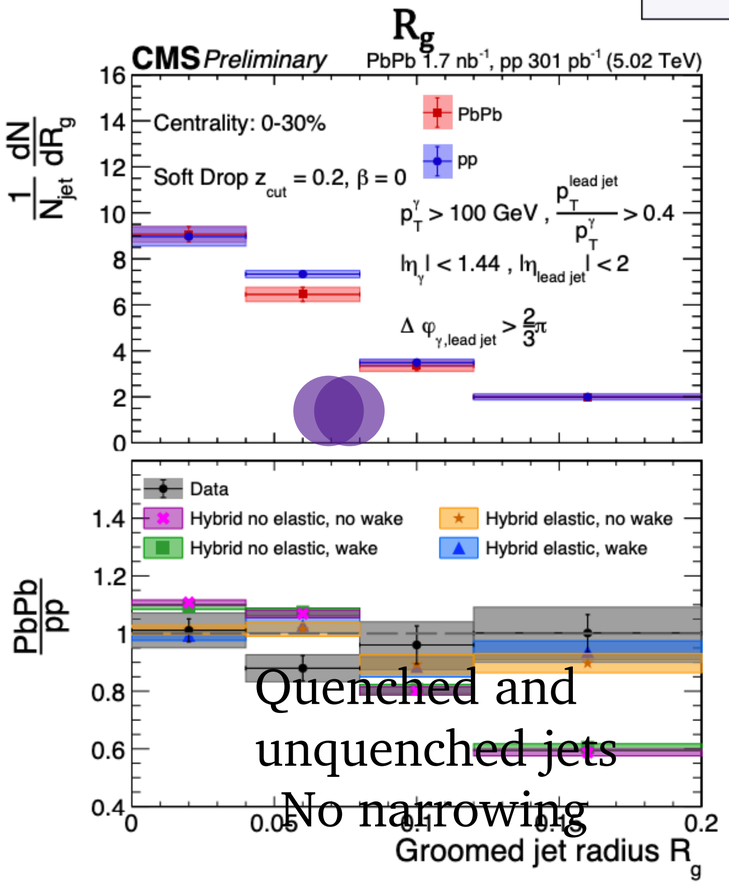
CMS-PA



Less quenched jets

Narrowing

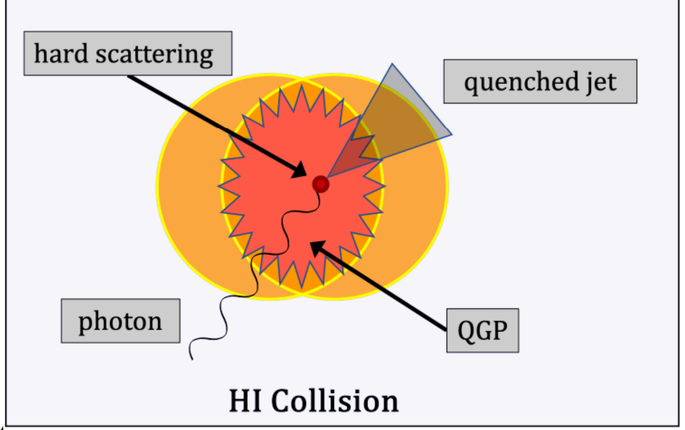
$$p_T^{jet}/p_T^{\gamma} = x_{j\gamma} > 0.4$$



Quenched and unquenched jets

No narrowing

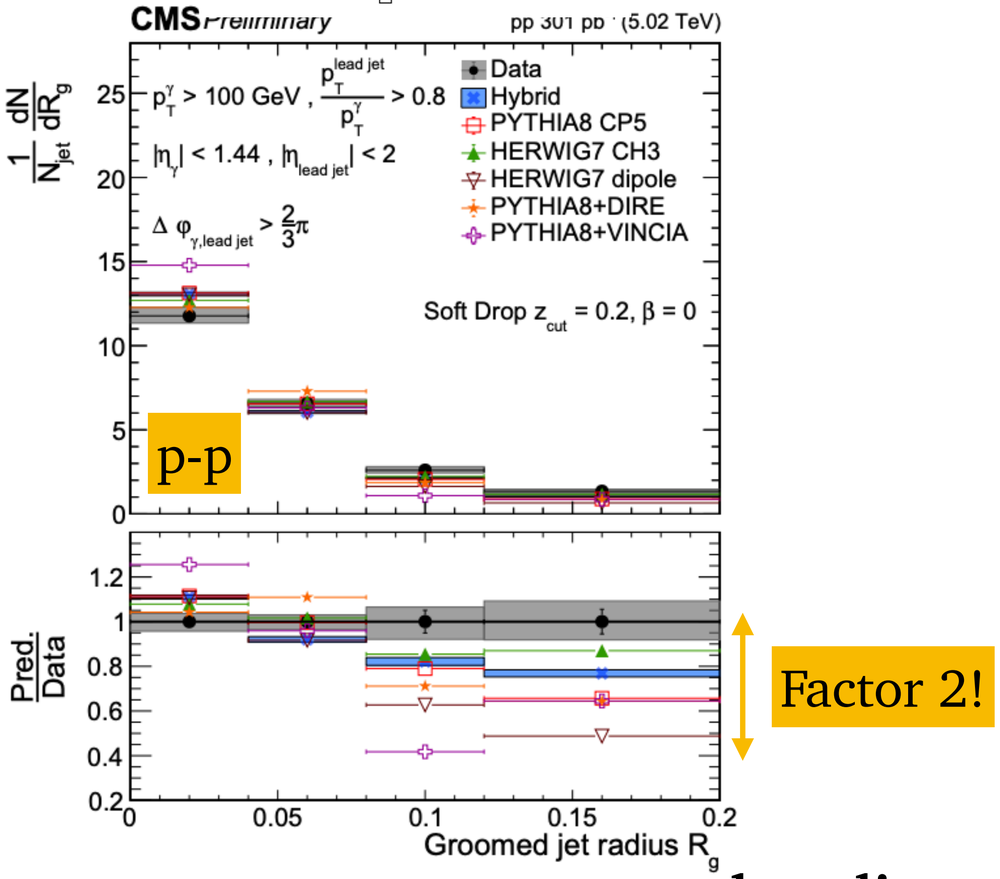
Jet substructure: grooming



- Use photon-tagged jets

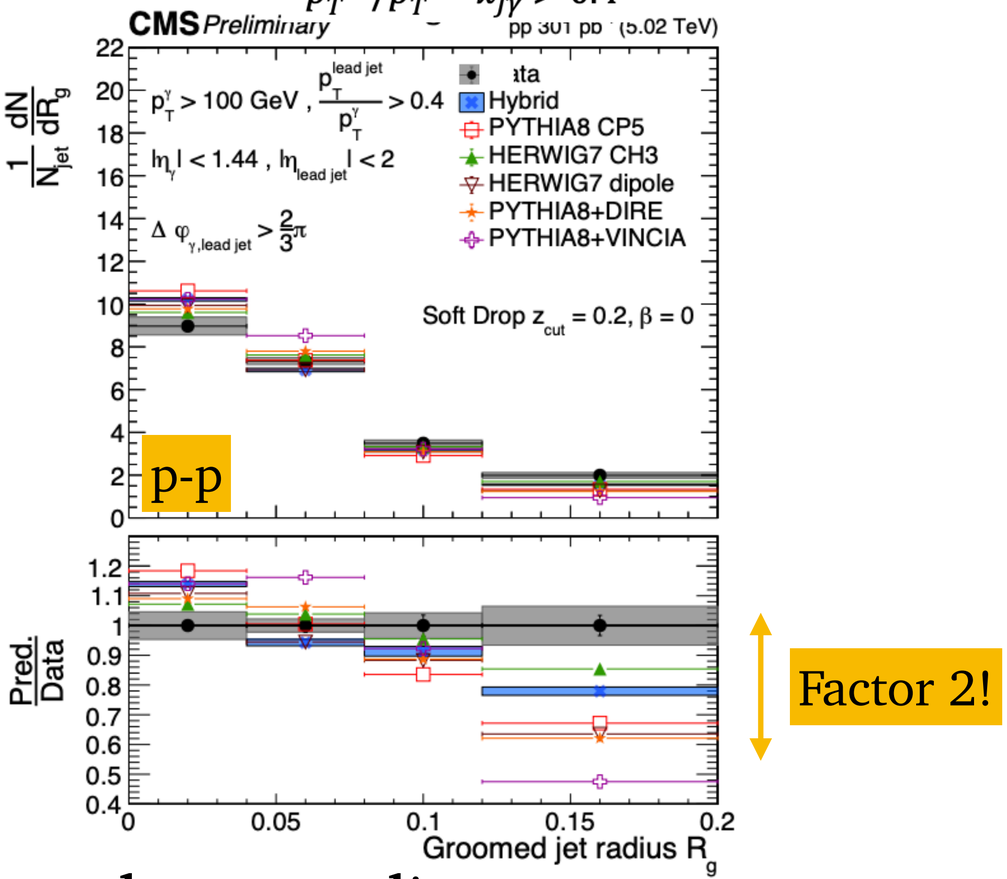
CMS-I

$p_T^{jet}/p_T^{\gamma} = x_{j\gamma} > 0.8$



Factor 2!

$p_T^{jet}/p_T^{\gamma} = x_{j\gamma} > 0.4$

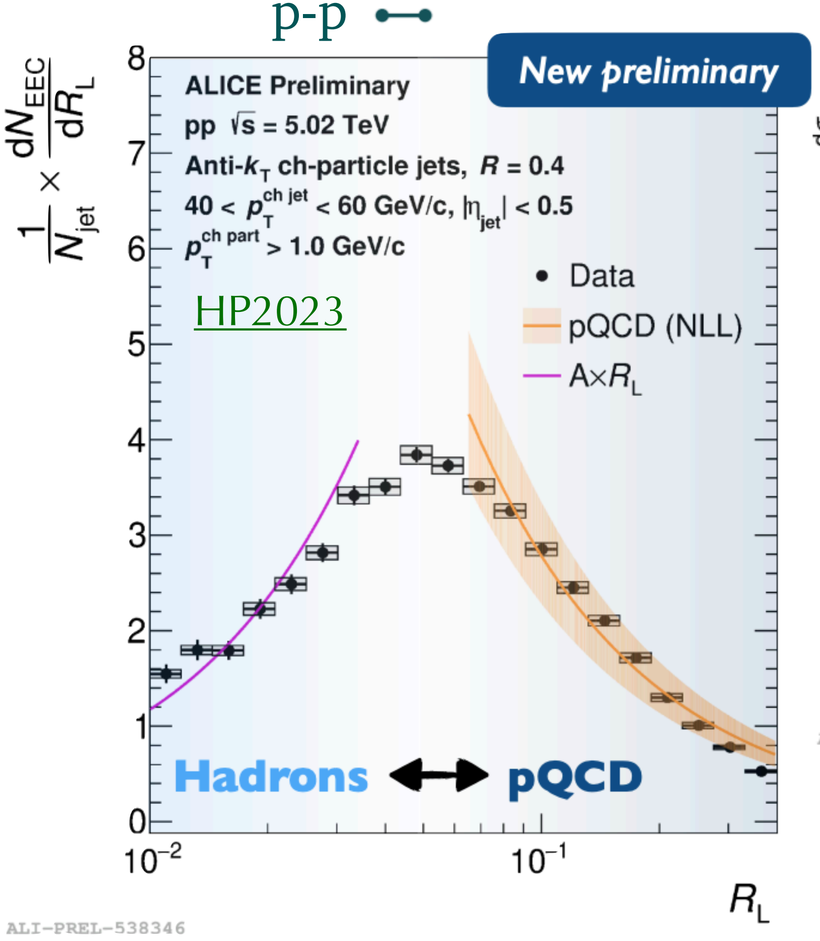


Factor 2!

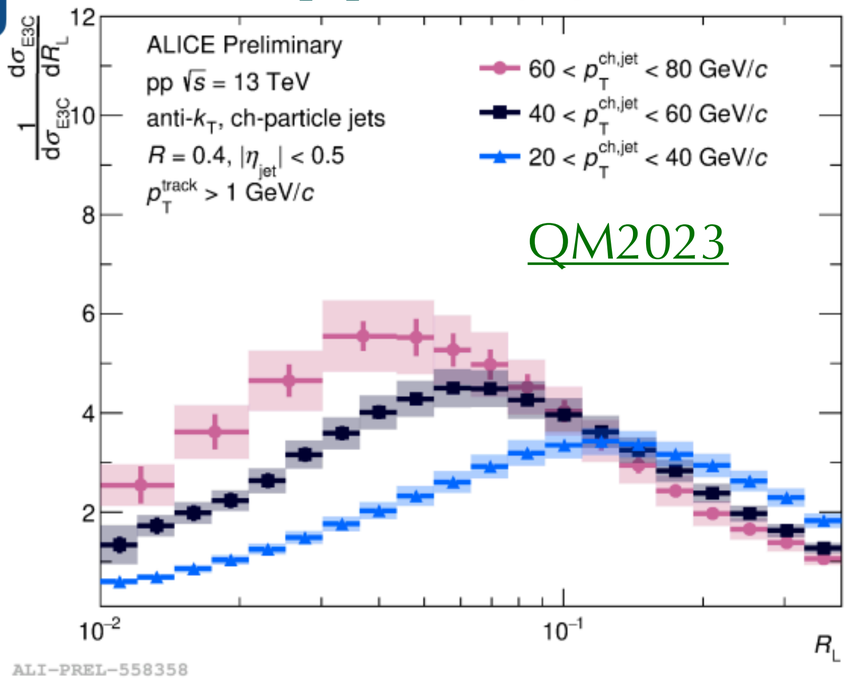
p-p baseline not under control!

EECs in proton-proton by ALICE

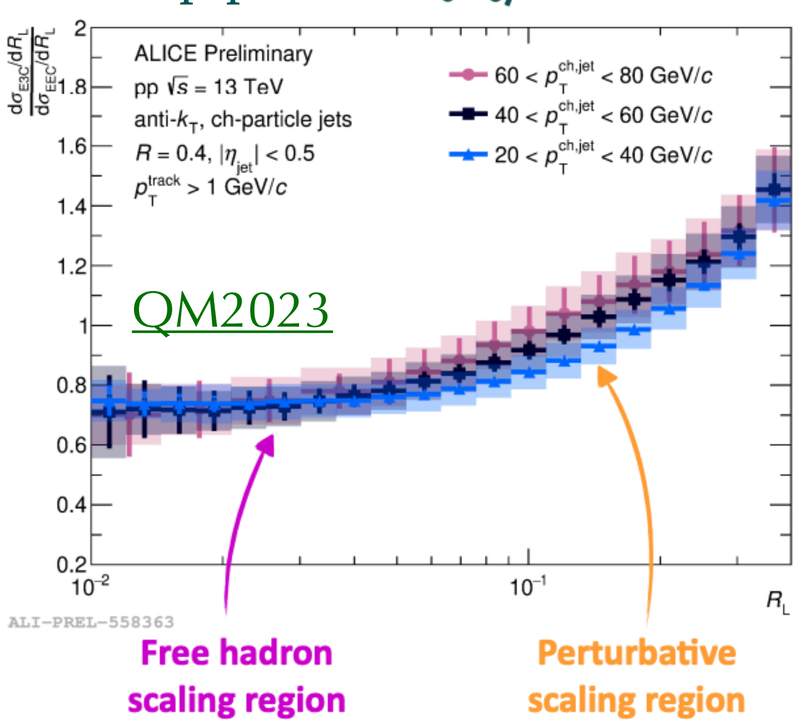
p-p



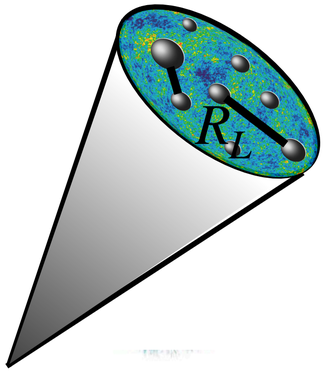
p-p E3C



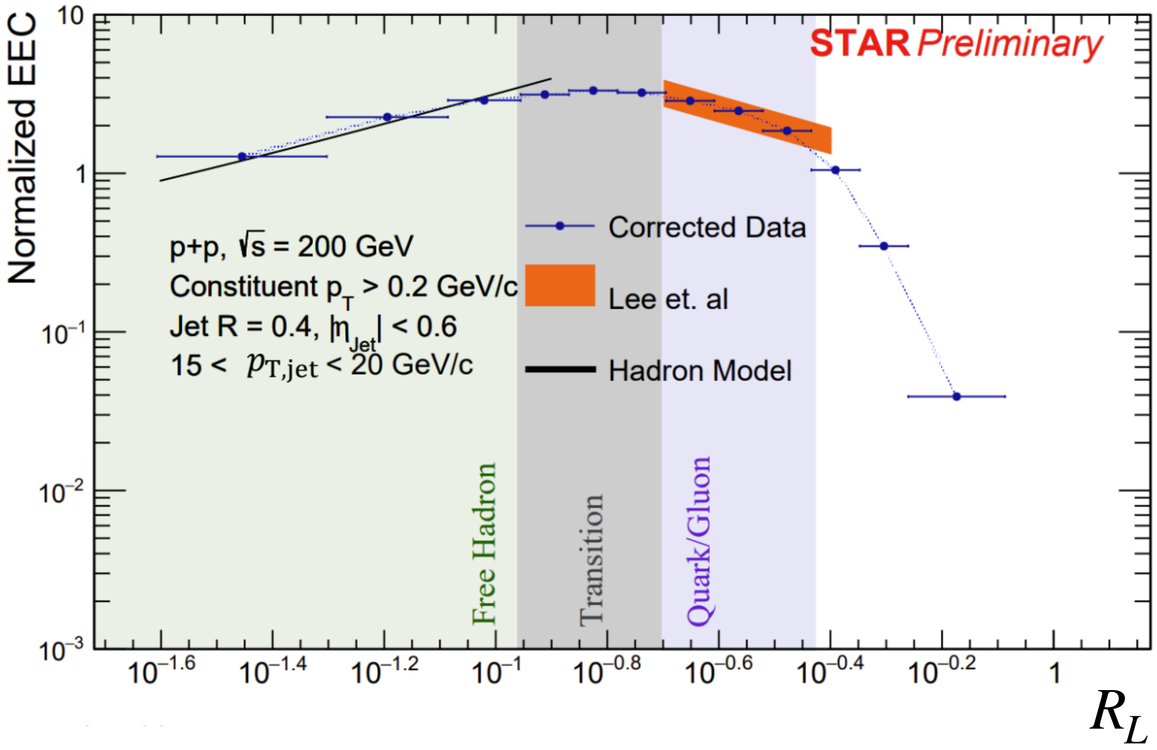
p-p E3C/EEC



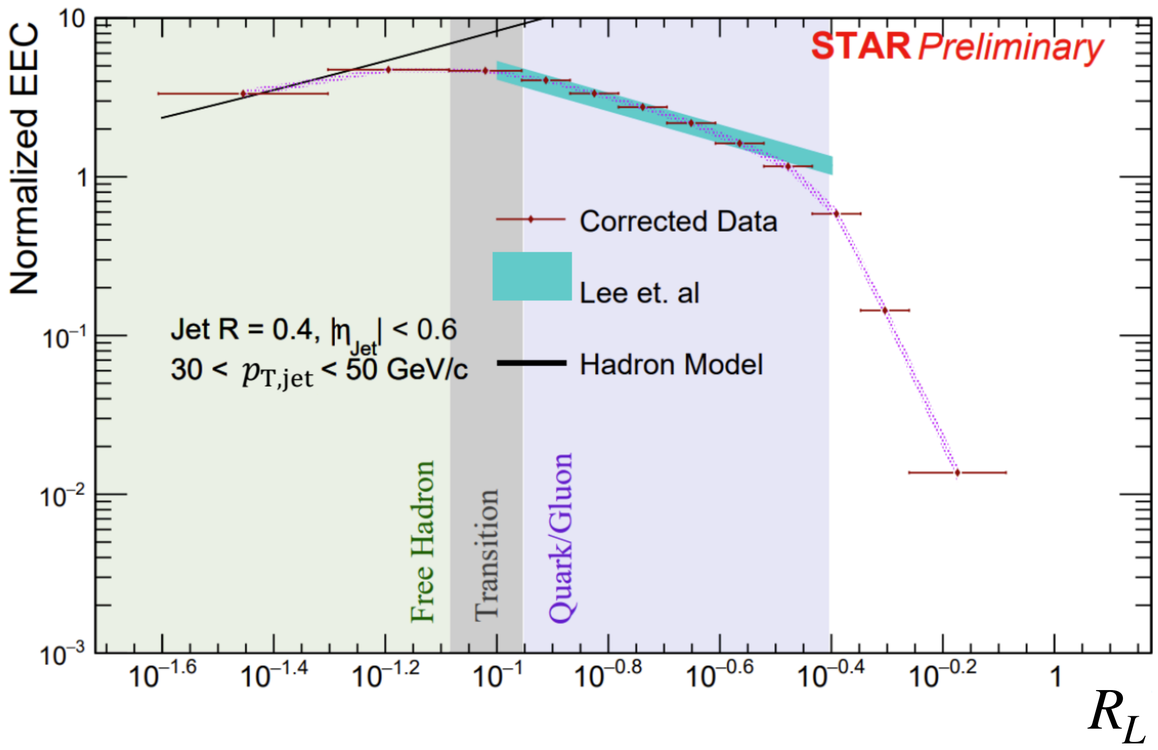
E2EC in proton-proton by STAR



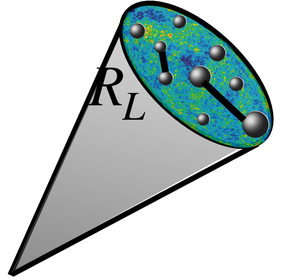
15 < Full Jet p_T < 20 GeV/c p-p

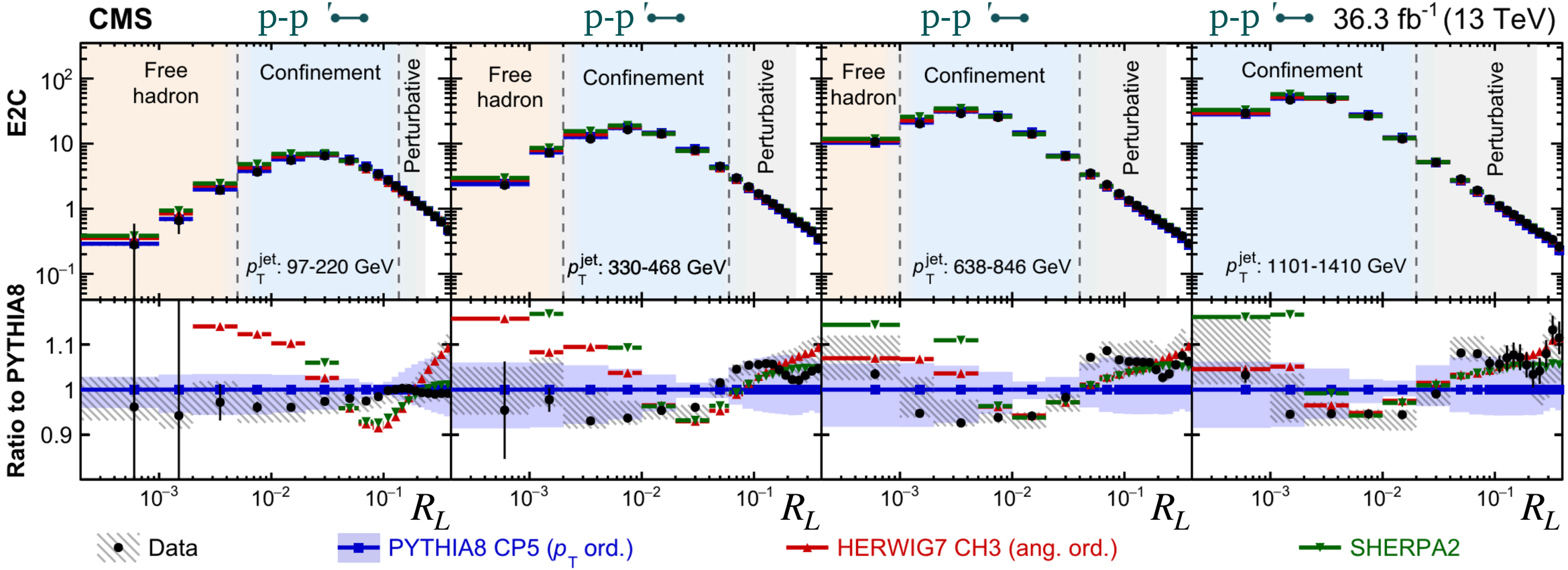


30 < Full Jet p_T < 50 GeV/c p-p



E2EC in proton-proton by CMS

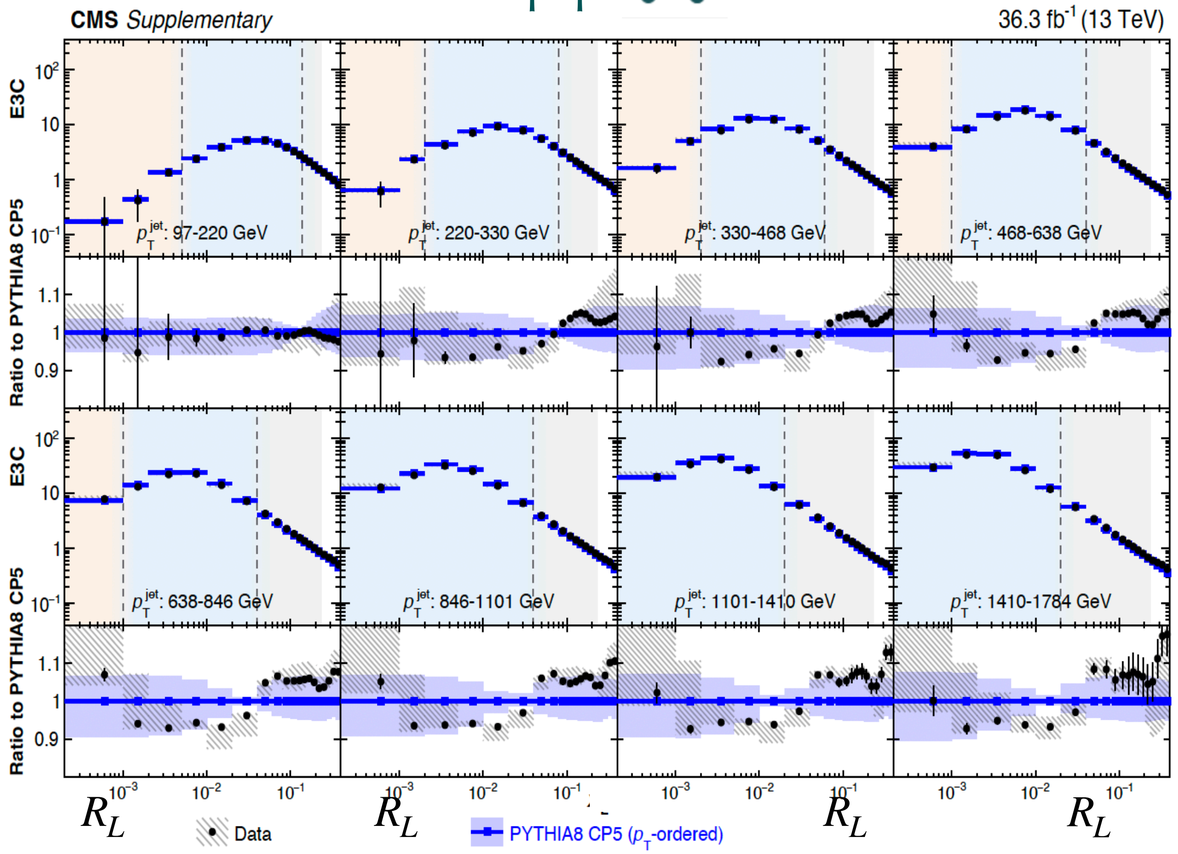




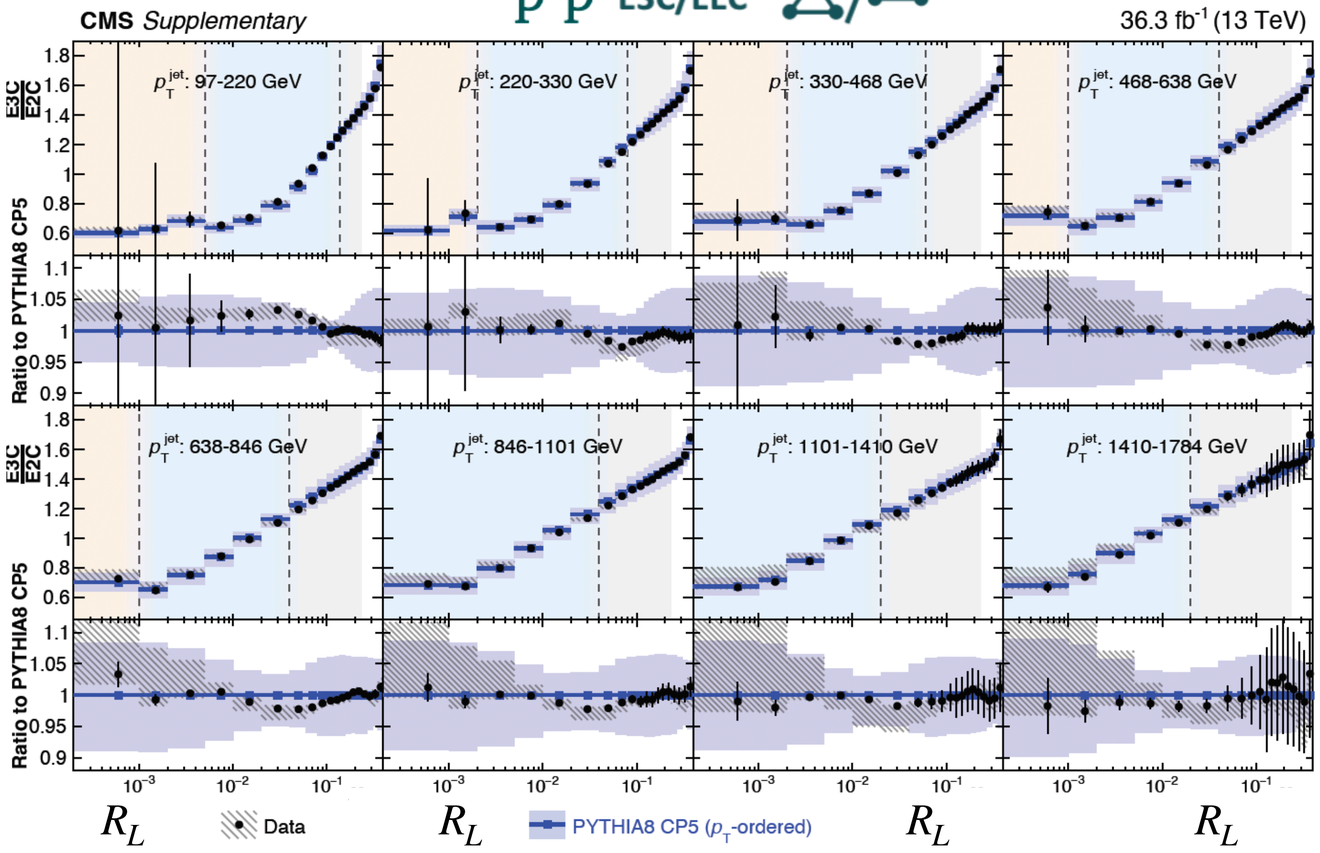
arXiv:2402.13864

E3EC in proton-proton by CMS

p-p



p-p E3C/EEC



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