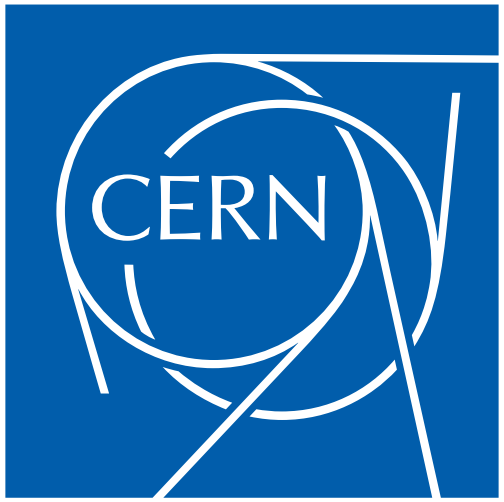
Jet quenching and jet-medium interactions

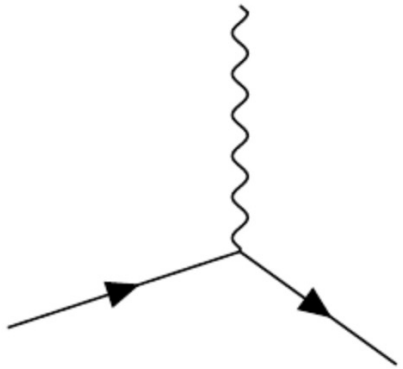
Jasmine Brewer

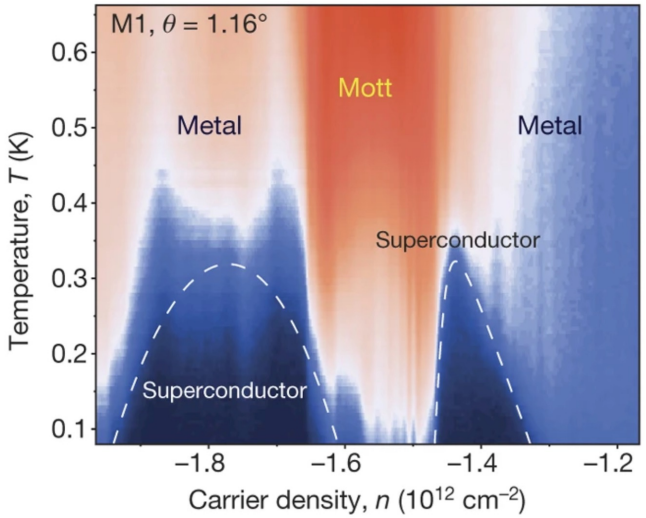


Quark Matter 2022

Special thanks to Gian Michele Innocenti, Aleksas Mazeliauskas,
Wilke van der Schee, Laura Serksnyte, Krishna Rajagopal, Urs Wiedemann, and Nima Zardoshti

QED

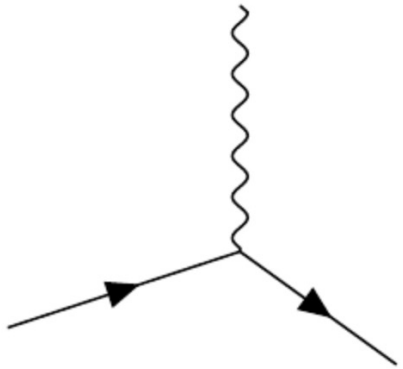


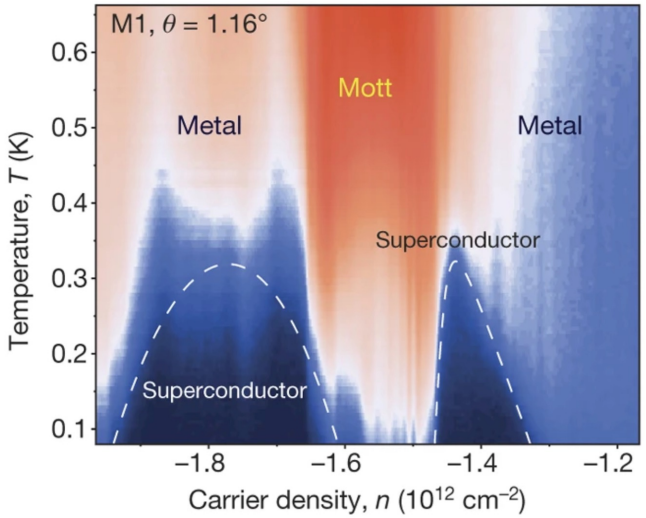


Magic angle graphene

Cao et. al. *Nature* **556**, 43–50 (2018)

QED





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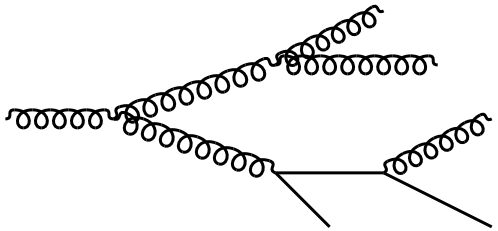
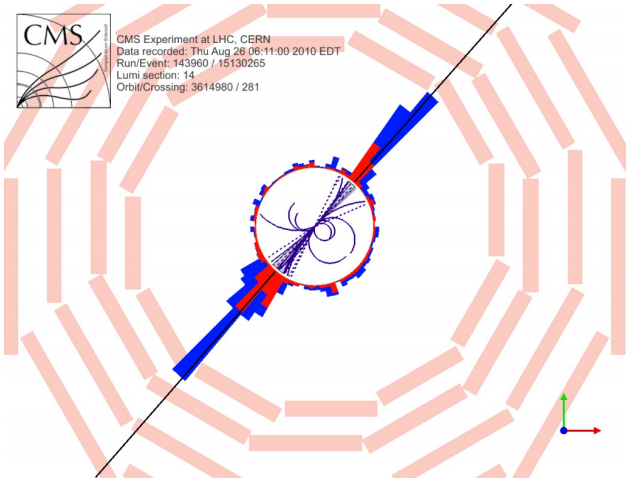
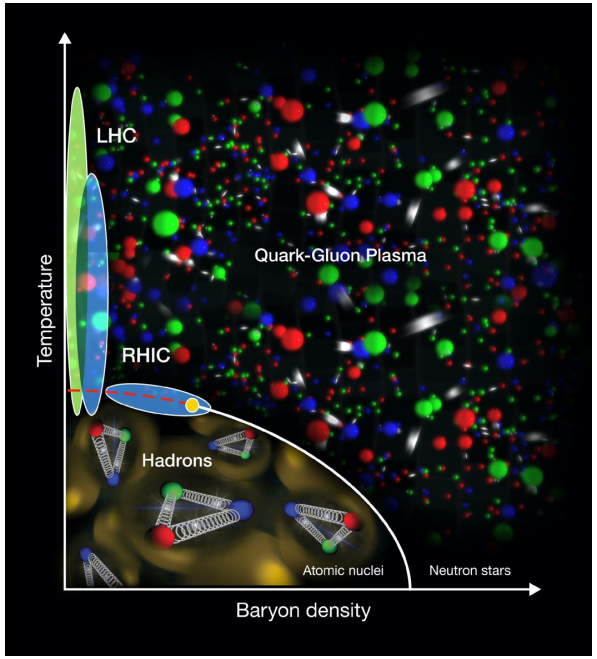
QCD



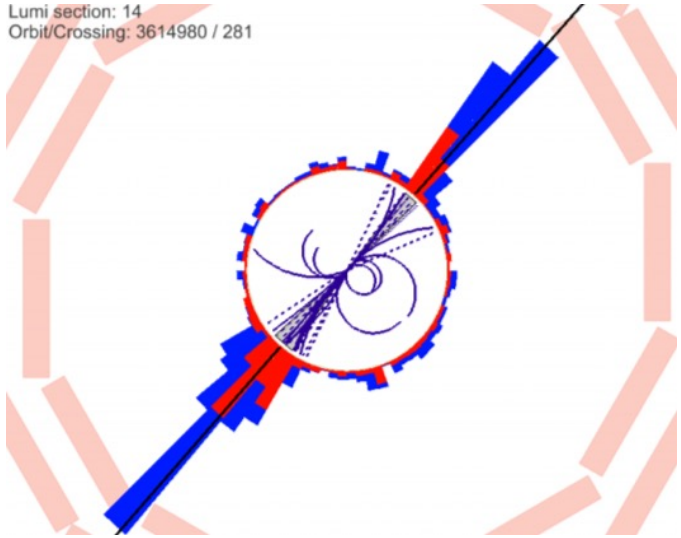




Understanding the fundamental interactions is just the beginning!

Modification of jets as a probe of quark-gluon plasma

proton–proton



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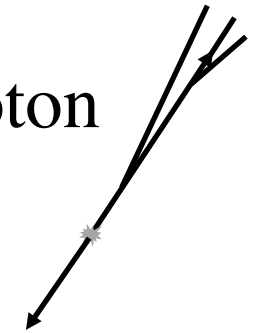
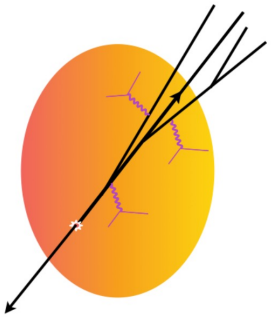
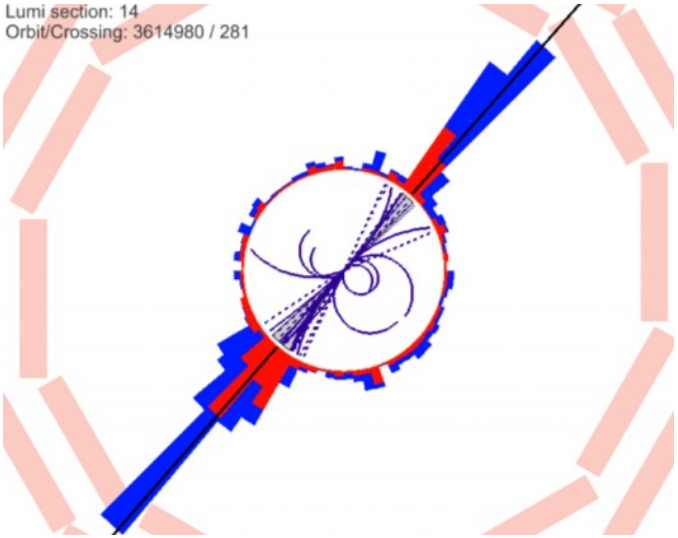
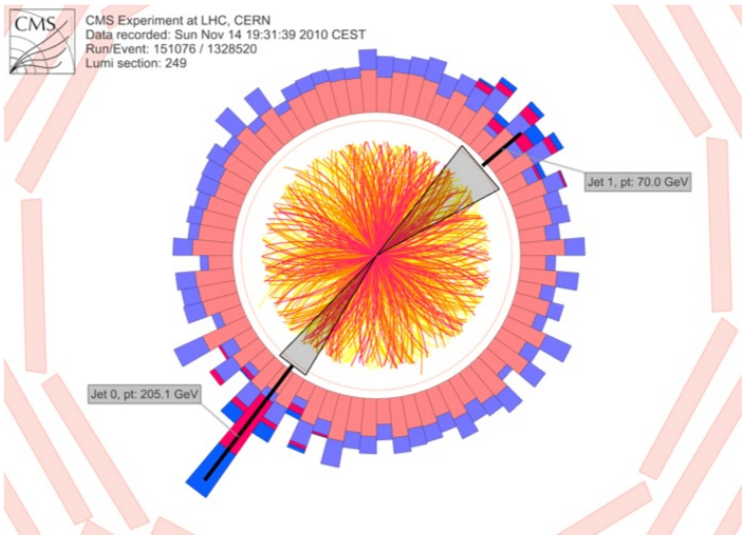


heavy-ion



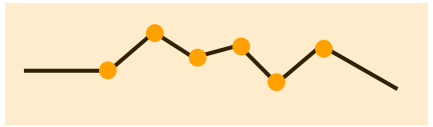




“baseline” jet properties

Energy loss of a parton in finite-temperature QCD

Parton undergoes transverse momentum diffusion

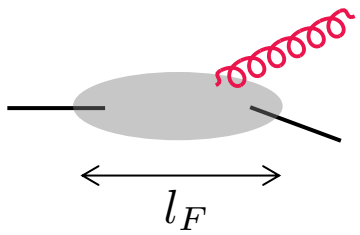


$\updownarrow k_\perp$

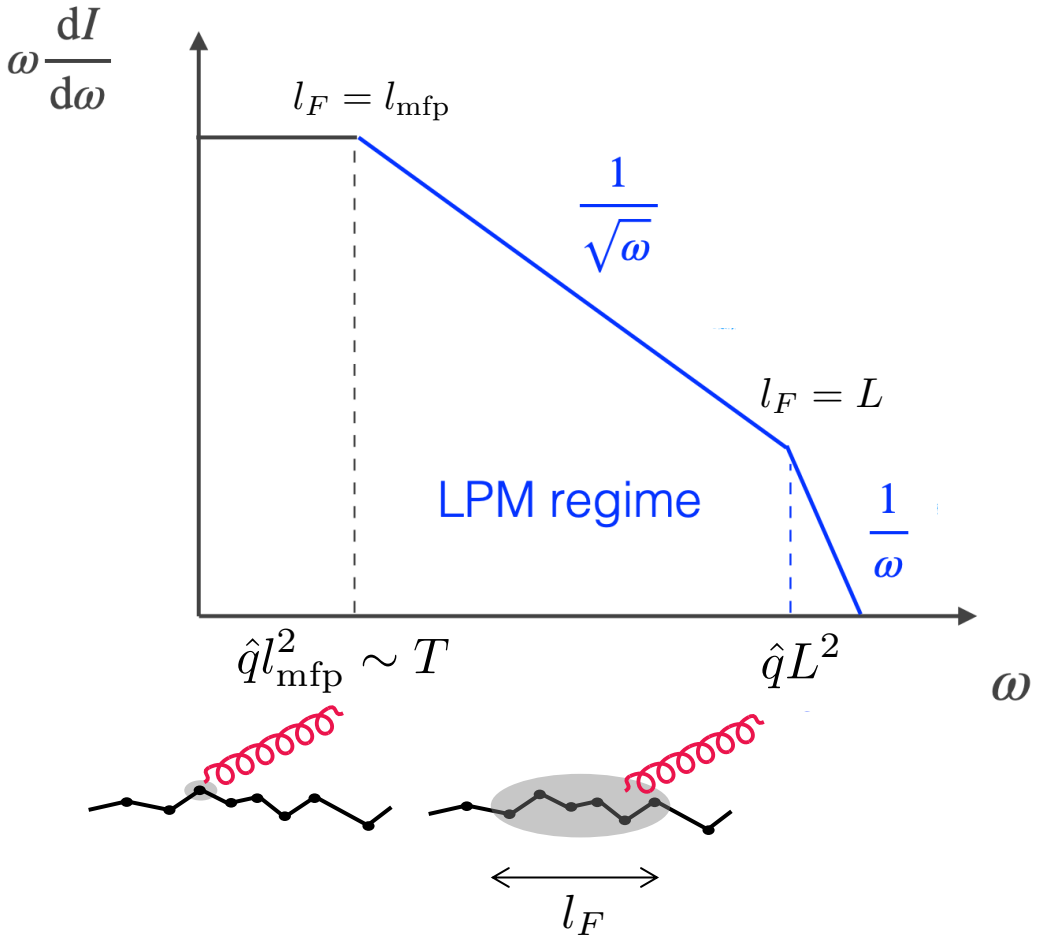
$$\hat{q} \equiv \frac{\mathrm{d}\langle k_\perp^2 \rangle}{\mathrm{d}t}$$

Kicks occasionally induce gluon radiation

Radiation can't be resolved instantaneously



$$l_F \propto \sqrt{\omega}$$



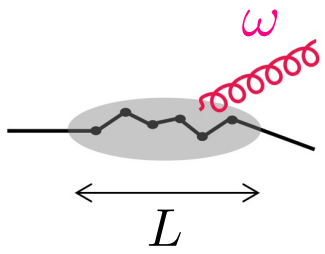
Baier, Dokshitzer, Mueller, Peigne, Schiff (1996), Zakharov (1996)
Arnold, Moore, Yaffe (2003)

Fig: adapted from Yacine Mehtar-Tani QM'19

Recent progress: Energy loss of a parton in finite-temperature QCD

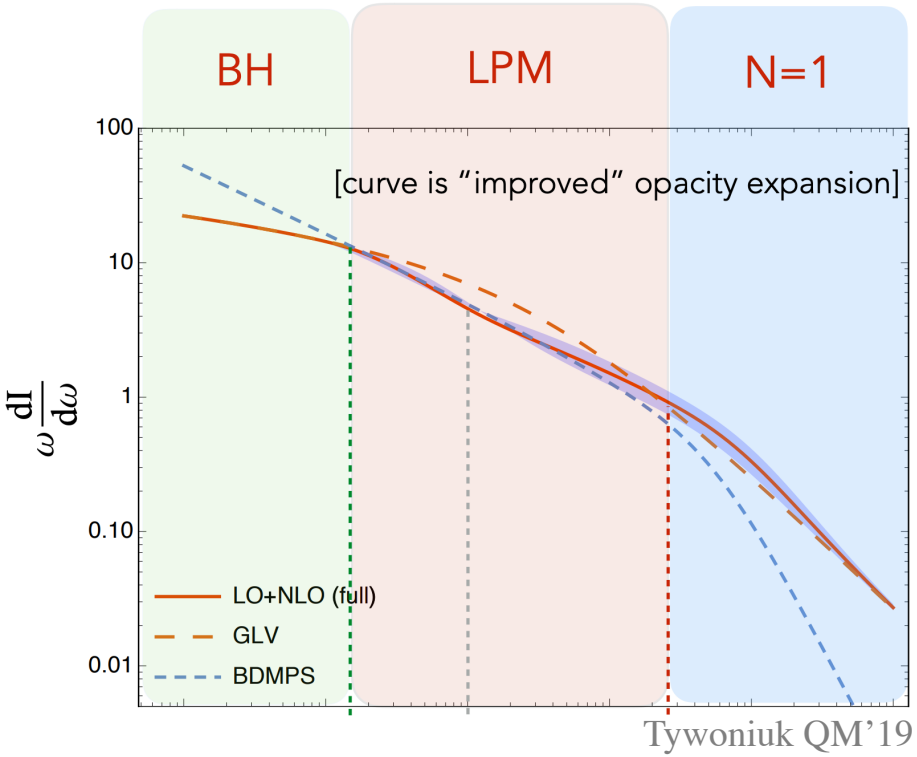
- Connecting multiple soft and single hard emission regimes

Multiple soft scatterings



Single hard scattering

Mehtar-Tani, Tywoniuk [1910.02032]
Mehtar-Tani [1903.00506]



Tywoniuk QM'19

Improved accuracy of radiation spectrum

Andres, Apolinario, Dominguez, Martinez [2011.06522, 2002.01517]

Expanding and inhomogeneous media

Barata, Sadofyev, Salgado [2202.08847] ; Andrey Sadofyev (talk)

Carlota Andres (talk); Souvik Adhya (talk)

See Jacopo Ghiglieri (plenary)

Recent progress: Energy loss of a parton in finite-temperature QCD

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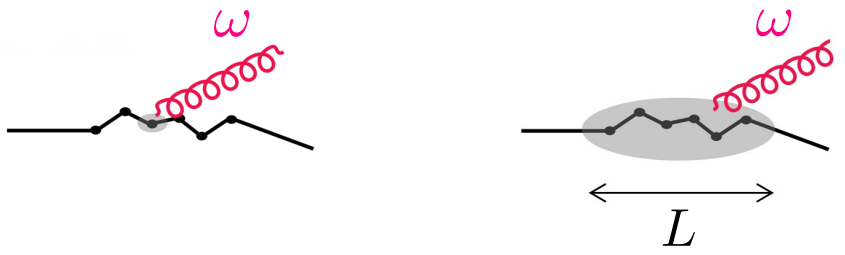


Multiple soft scatterings Single hard scattering

Mehtar-Tani, Tywoniuk [1910.02032]
Mehtar-Tani [1903.00506]

- Modification of vacuum structure with overlapping formation times

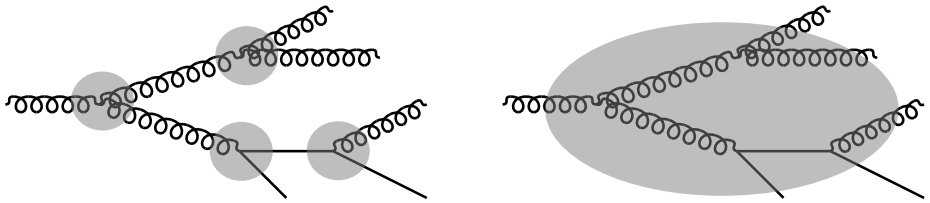
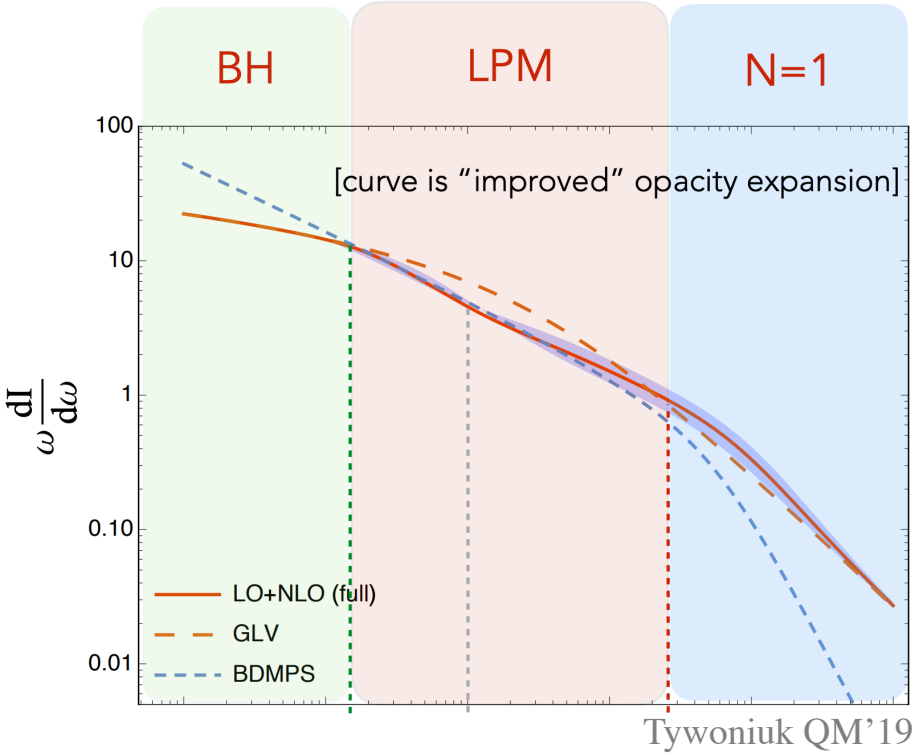


Fig: adapted from Arnold INT 2021
Arnold [2111.05348]



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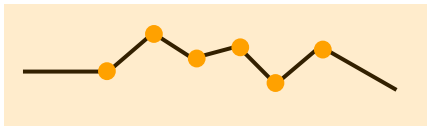
Probing the medium through parton energy loss



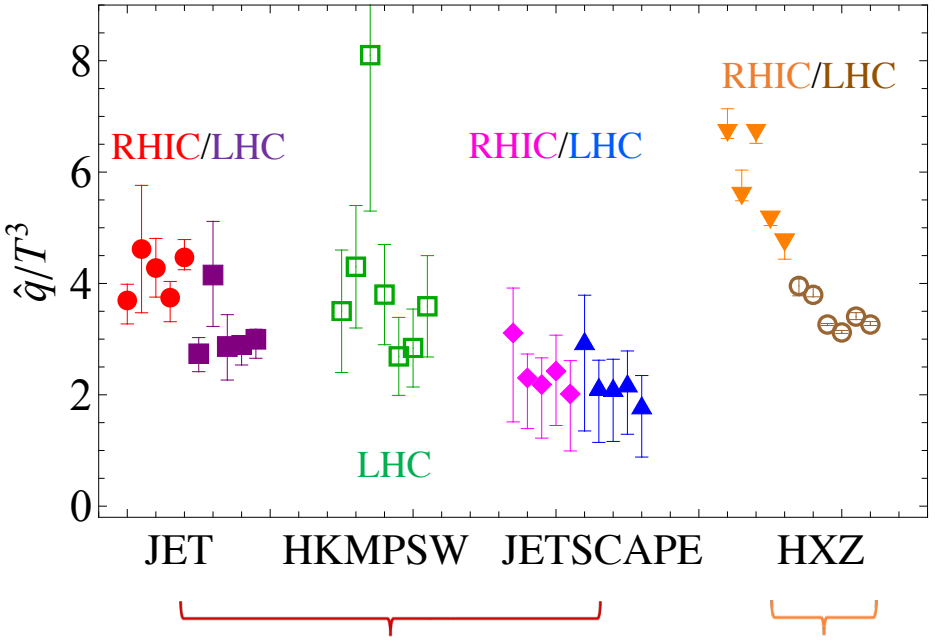
L

$\updownarrow k_\perp$

$$\hat{q} \equiv \frac{\mathrm{d}\langle k_\perp^2 \rangle}{\mathrm{d}t}$$

medium parameter

Global fits to hadron spectra



Extracting $\hat{q}$ depends on many assumptions, including

- Hadron fragmentation functions
- starting time of quenching
- ...

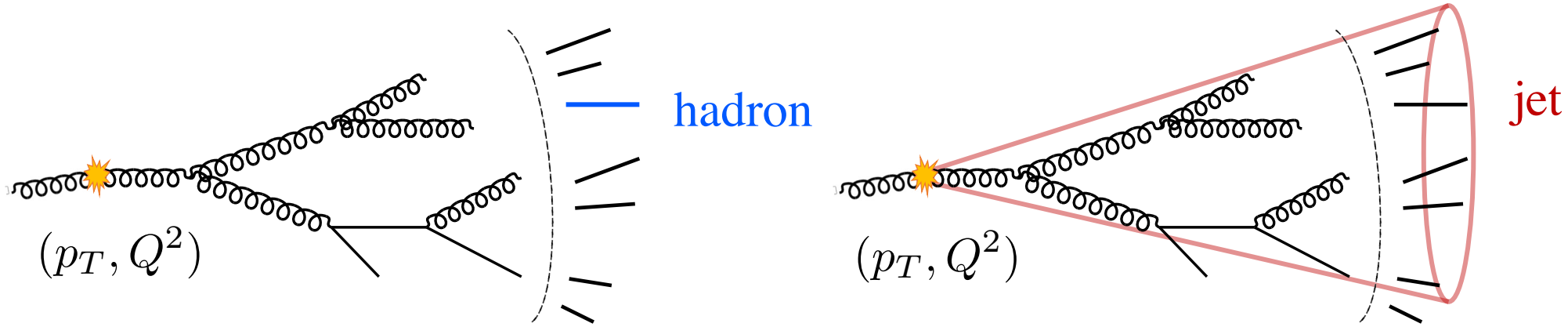
Vary: quenching model hadron fragmentation functions

Thanks to Aleksas Mazeliauskas and Wilke van der Schee

See also Andres, Armesto, Niemi, Paatelainen, Salgado [1902.03231]

JET [1312.5003];
Huss, Kurkela, Mazeliauskas, Paatelainen, van der Schee, Wiedemann (HKMPSW) [2007.13758];
JETSCAPE [2102.11337];
Han, Xie, Zhang (HXZ) [2201.02796]

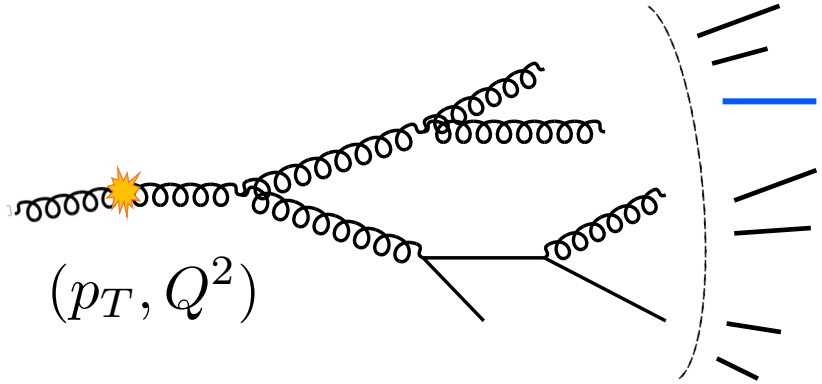
From hadrons to jets



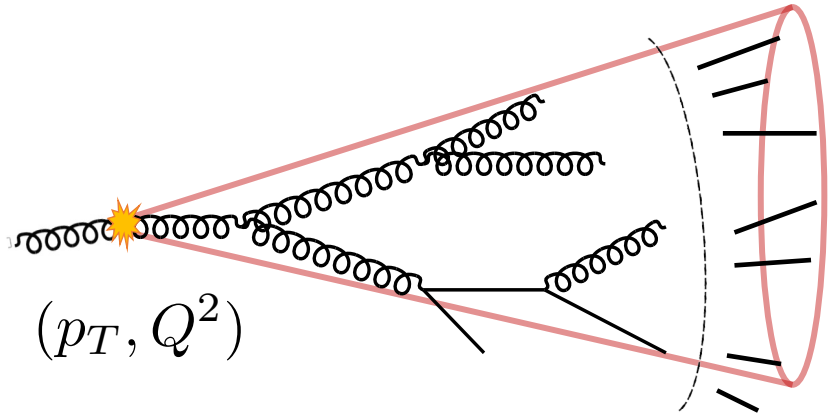
Advantages of jets

- (More) robust probes of hard splitting (p_T, Q^2,…)
- Access (in principle) to the whole shower
- Less sensitive to hadron fragmentation functions
- Under better perturbative control

From hadrons to jets



hadron



jet

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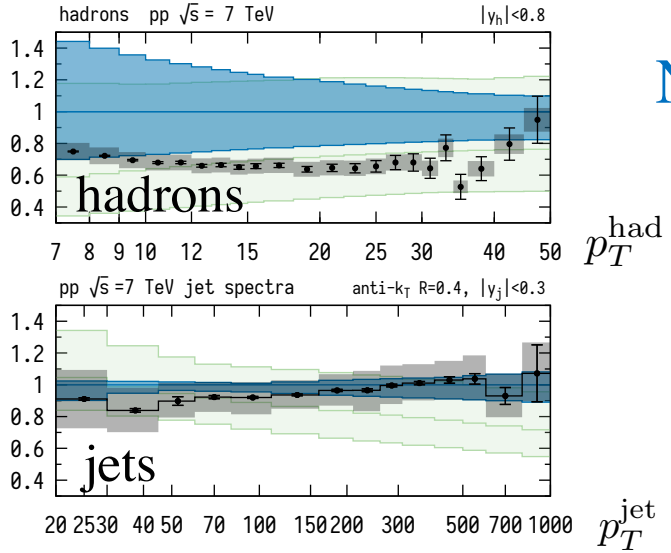
ratio of pp spectra to NLO pQCD

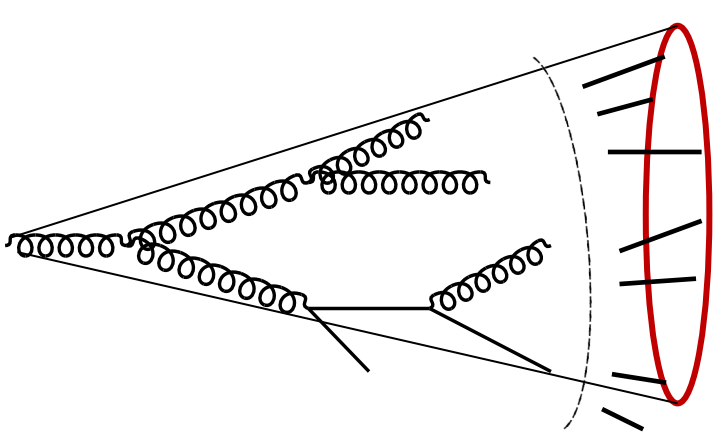


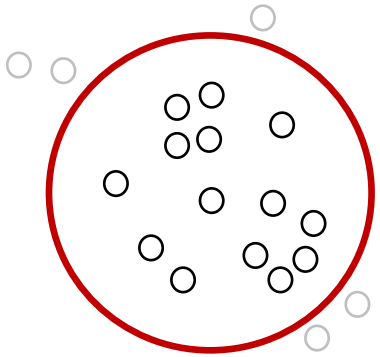
NLO

LO

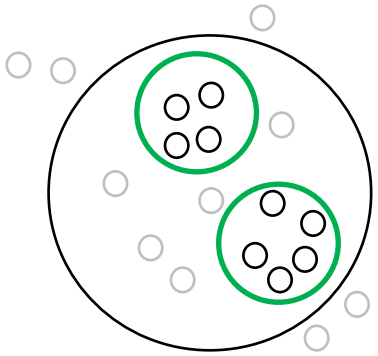
Brewer, Huss, Mazeliauskas, van der Schee [2108.13434]

Jets in principle give access to detailed structure of the shower

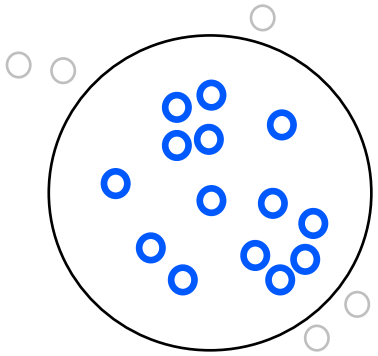




jet



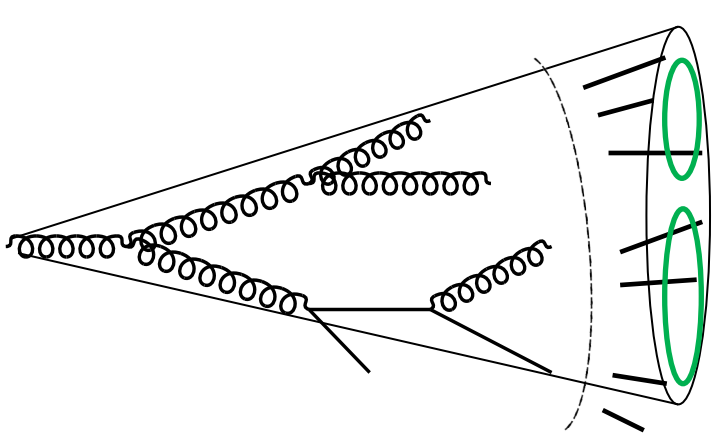
substructure

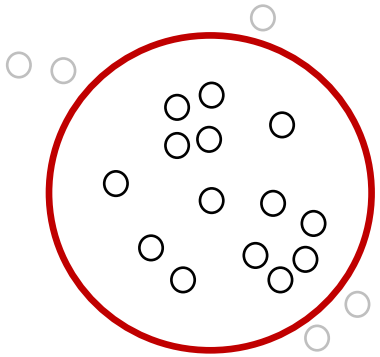


constituents

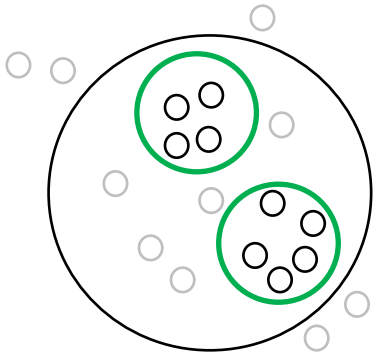
Graphic: Yi Chen QM'19

Jets in principle give access to detailed structure of the shower

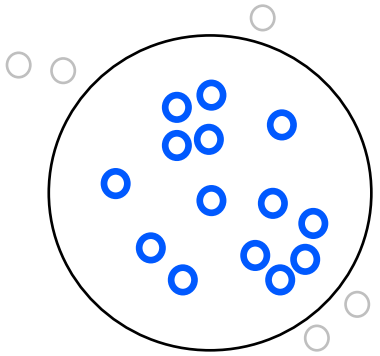




jet



substructure



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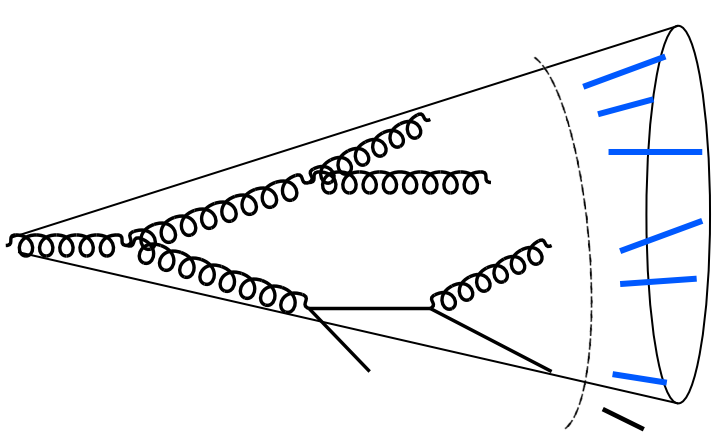
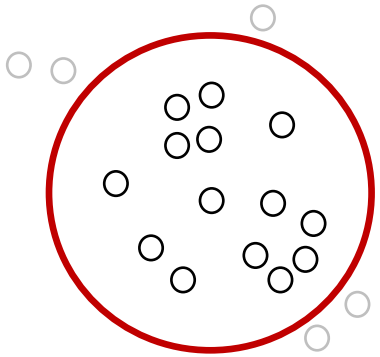
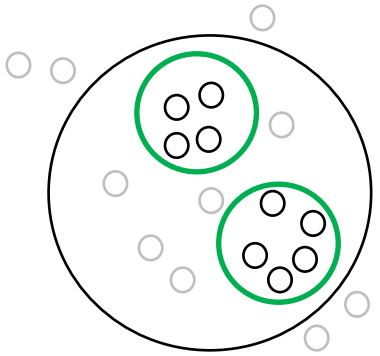
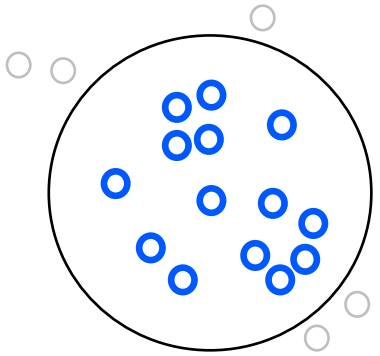




jet



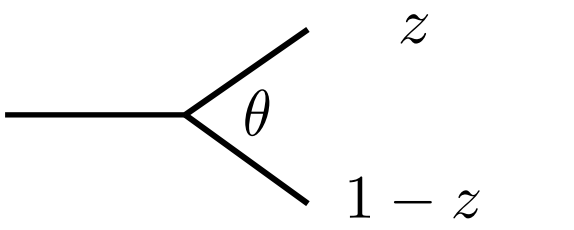
substructure



constituents

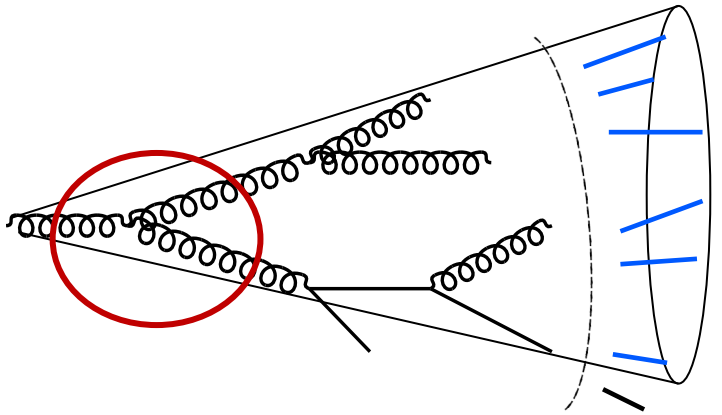
Graphic: Yi Chen QM'19

Jet substructure to access QCD splitting function



$$\mathrm{d}P_{i\to jk} = \frac{\mathrm{d}\theta}{\theta}\mathrm{d}z\, P_{i\to jk}(z)$$

Splitting functions



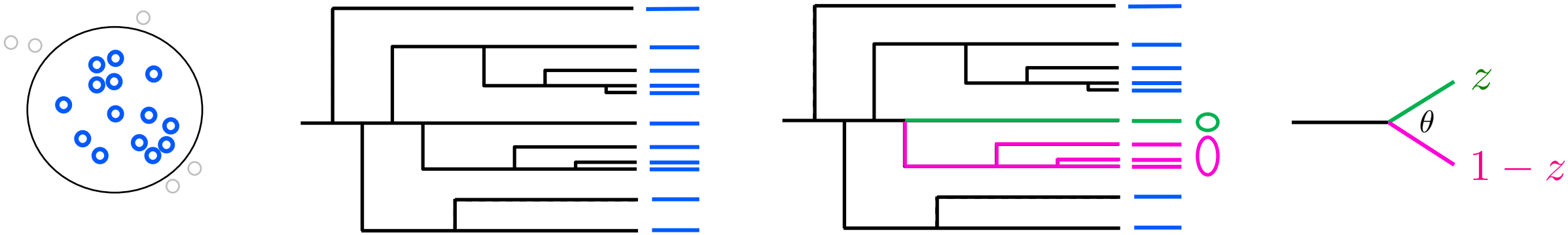
Parton showers in vacuum
Alba Soto-Ontoso (talk)

Modified splitting functions govern parton shower evolution in medium

How to access splitting function from jet substructure?

Jet substructure to access QCD splitting function

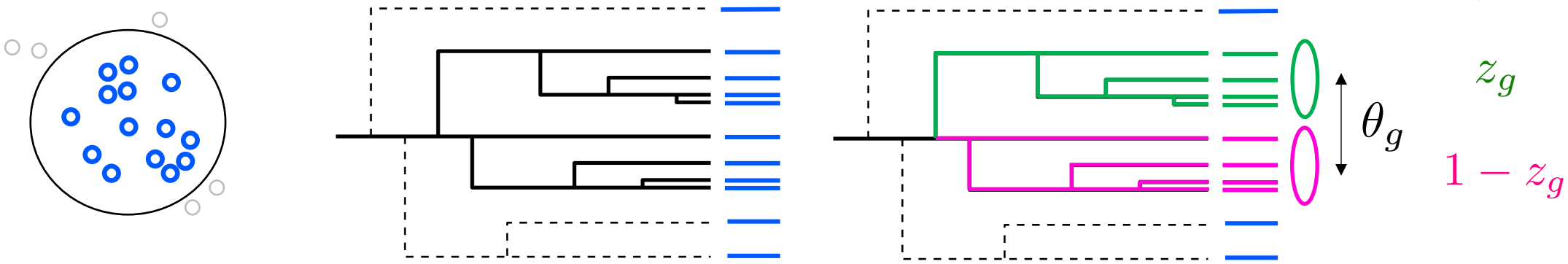
Use angular ordering of QCD to reconstruct shower from hadron level (“reclustering”)



Jet substructure to access QCD splitting function

"Soft Drop" grooming: reduce non-perturbative effects by removing soft/wide-angle radiation

Larkoski, Marzani, Soyez, Thaler [1402.2657]



First splitting with $z > z_{\text{cut}}\theta^{\beta}$

Measurements: Martin Rybar (plenary)

z_g distribution accesses splitting function in pp

Larkoski, Marzani, Thaler [1502.01719]
Larkoski, Marzani, Thaler, Tripathee, Xue [1704.05066]

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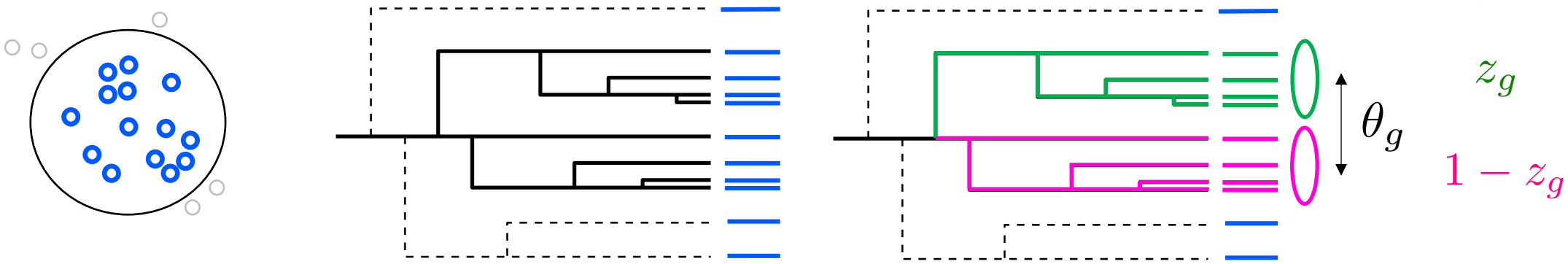

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z_g distribution accesses splitting function in pp

Larkoski, Marzani, Thaler [1502.01719]
Larkoski, Marzani, Thaler, Tripathee, Xue [1704.05066]

Digging into the physics of the modified shower

- "Dynamical grooming" to access shortest formation time, largest k_T

Mehtar-Tani, Soto-Ontoso, Tywoniuk [1911.00375]; Caucal, Soto-Ontoso, Takacs [2111.14768]; Paul Caucal (poster)

See also Apolinario, Cordeiro, Zapp [2012.02199] Pablo Rodriguez (poster)

Mapping emission phase space with substructure

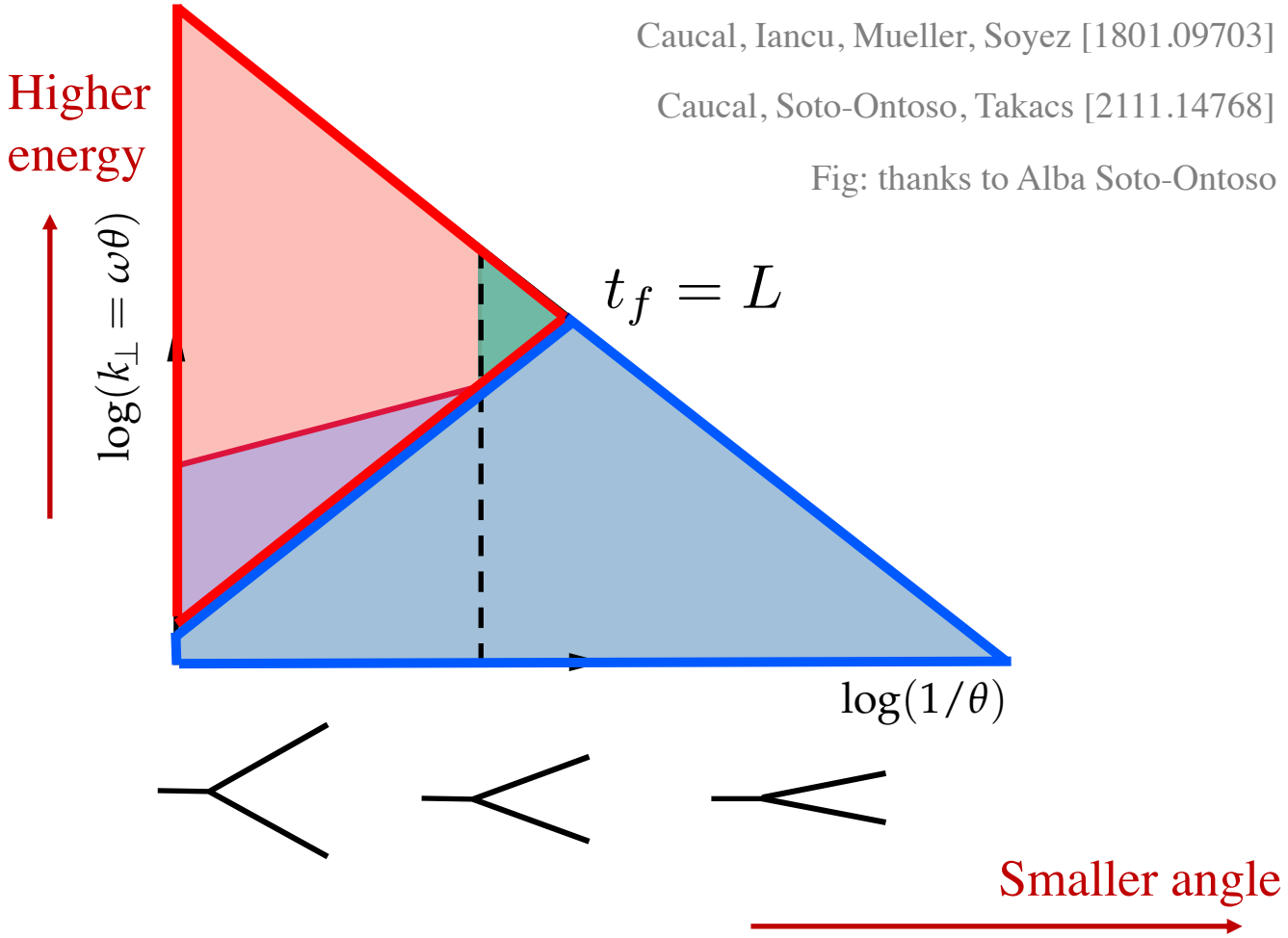
Emissions formed inside the medium

Vacuum-like splittings

Medium-modified splittings

Emissions formed outside the medium

Vacuum splittings



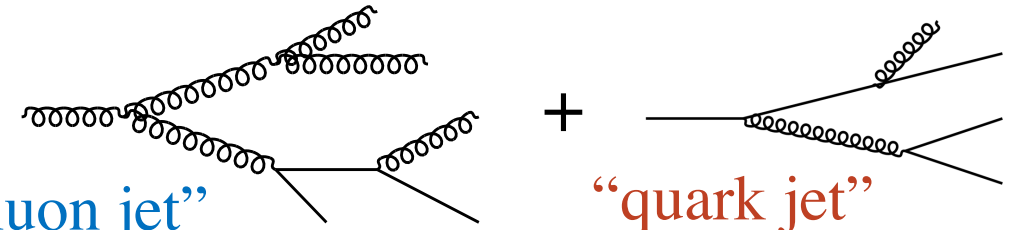
Caucal, Iancu, Mueller, Soyez [1801.09703]

Caucal, Soto-Ontoso, Takacs [2111.14768]

Fig: thanks to Alba Soto-Ontoso

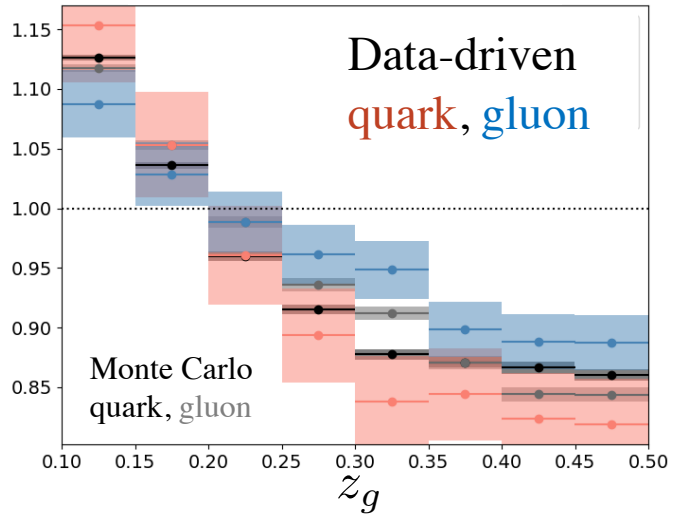
Flavor-dependent splitting functions

Inclusive jets



- Quark- and gluon-jet substructure modification

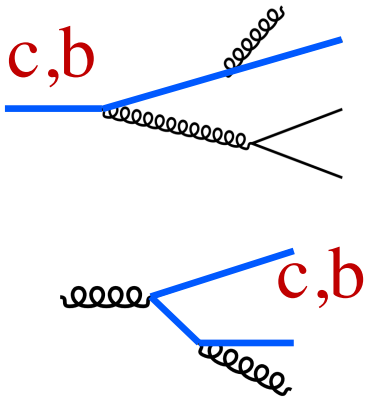
z_g dist. mod. (HI/pp)



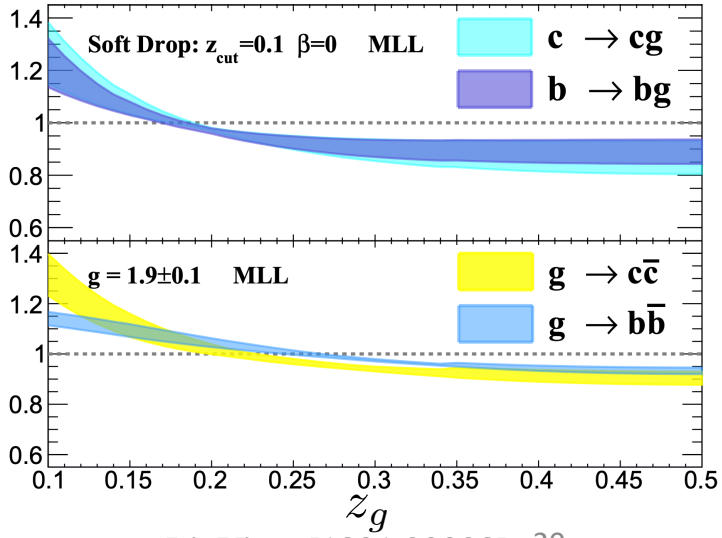
Ying, Brewer, Chen, Lee [2204.00641]
Yueyang Ying (poster)

Heavy flavor-tagged jets

- Unique mass-dependent substructure



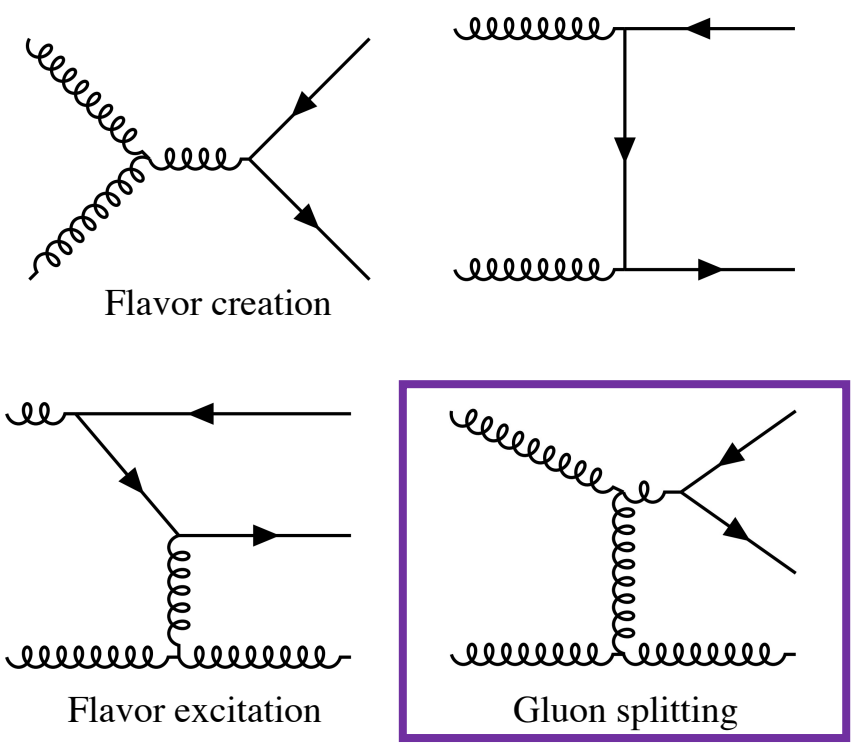
ALICE [2106.05713]
CMS Xiao Wang (talk)



Li, Vitev [1801.00008]

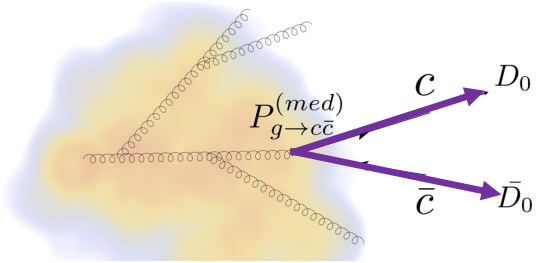
Heavy quarks as a probe of parton energy loss

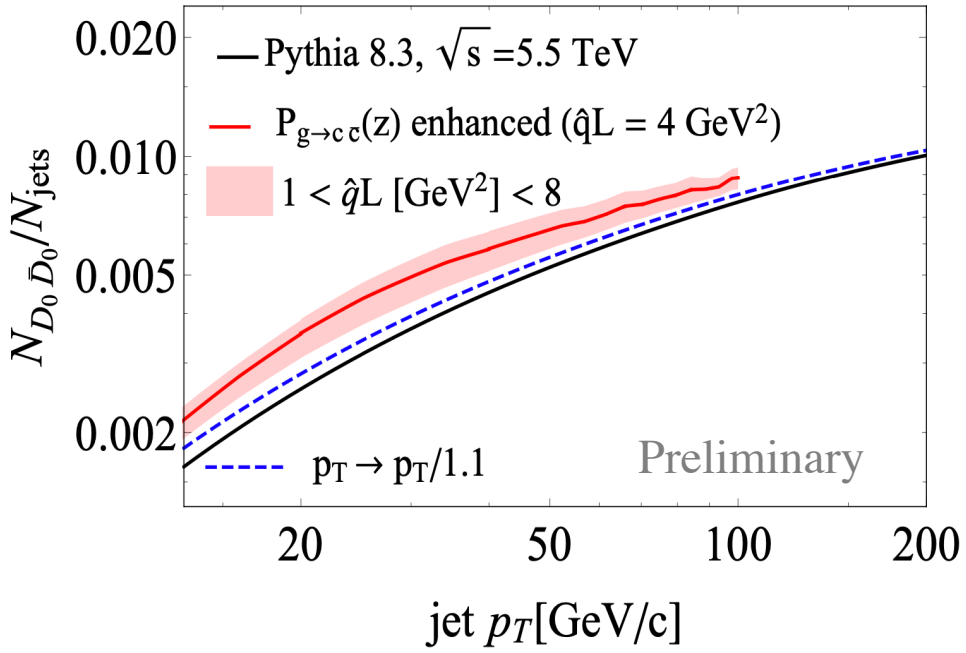
Leading processes for heavy quark production



Ilten, Rodd, Thaler, Williams [1702.02947]

(approximately) collinear



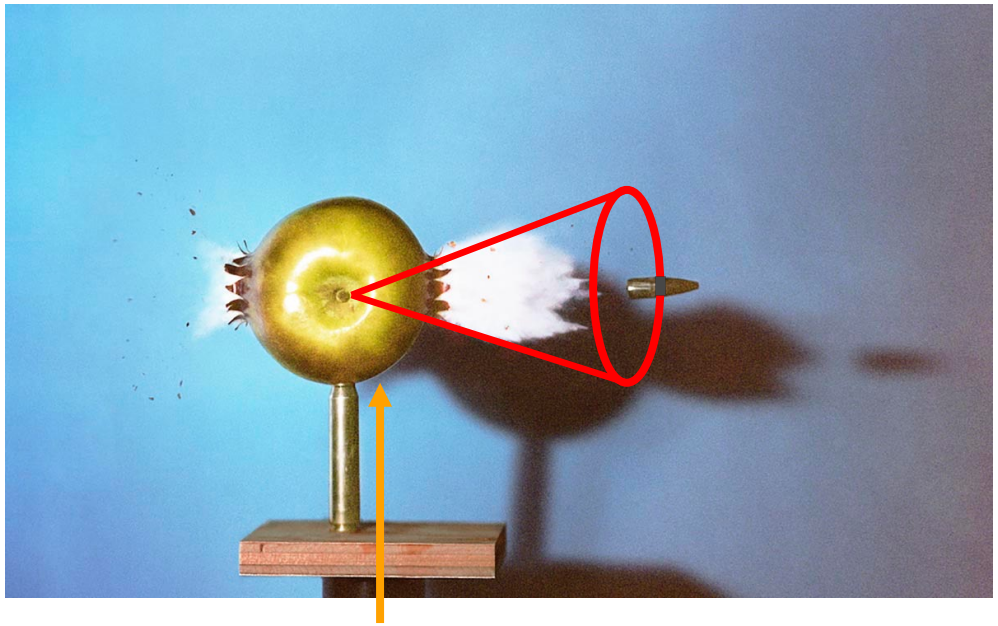


Attems, Brewer, Innocenti, Mazeliauskas, Park, van der Schee, Wiedemann; *forthcoming*

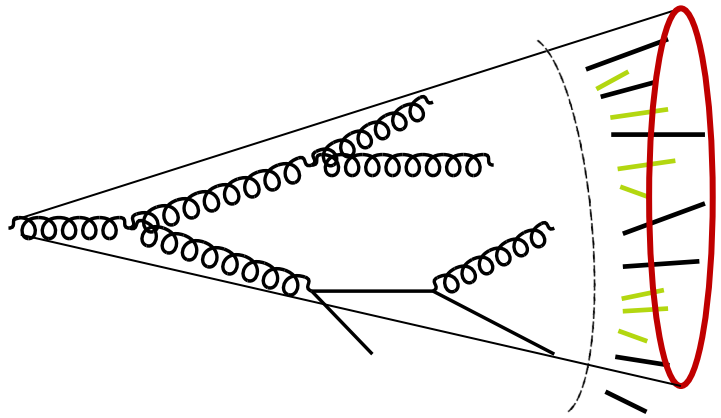
Gian Michele Innocenti (talk)

The medium also responds to jets

Medium response

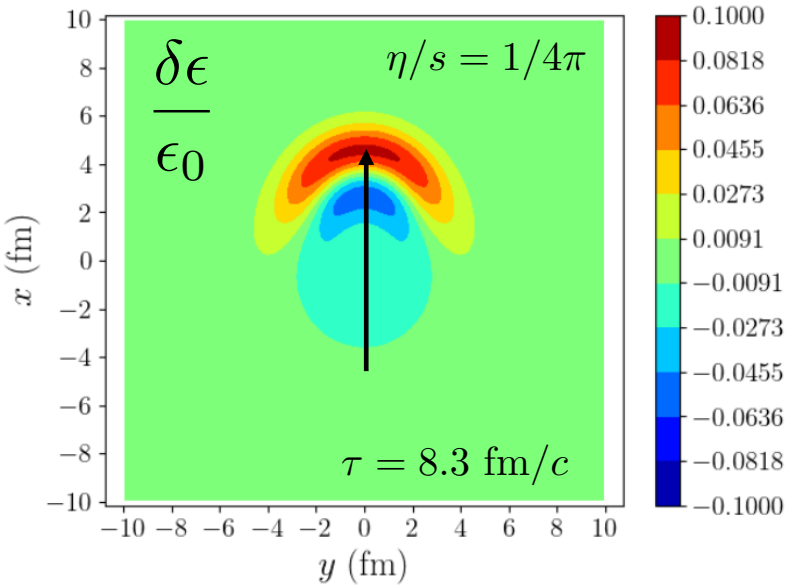


Average background can be subtracted



The intersection of jets and soft sector: medium response

High-energy parton deposits energy in hydro



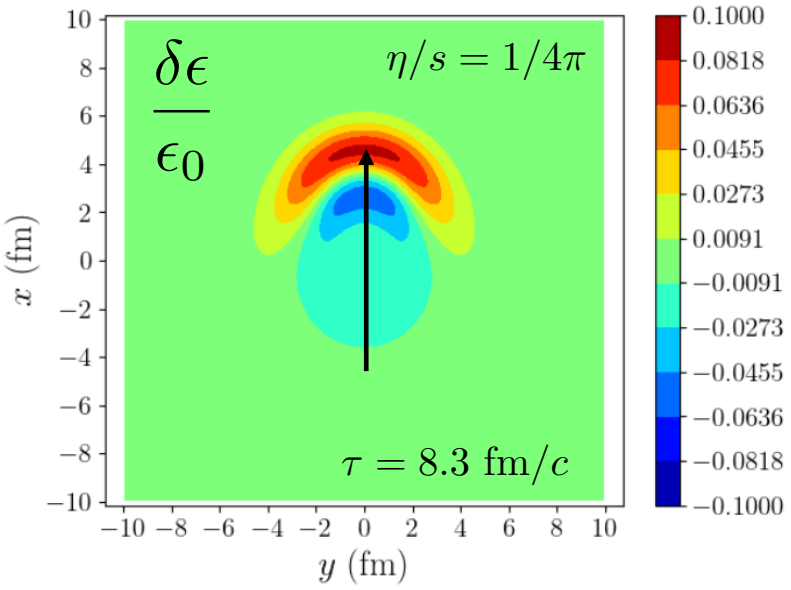
Casalderrey-Solana, Milhano, Pablos, Rajagopal, Yao [2010.01140]

Relatively simple picture for a single parton.
For jets, the picture is more complicated

- spacetime picture to the shower
- coherence of the shower
- hydrodynamic evolution of the wake
- ….

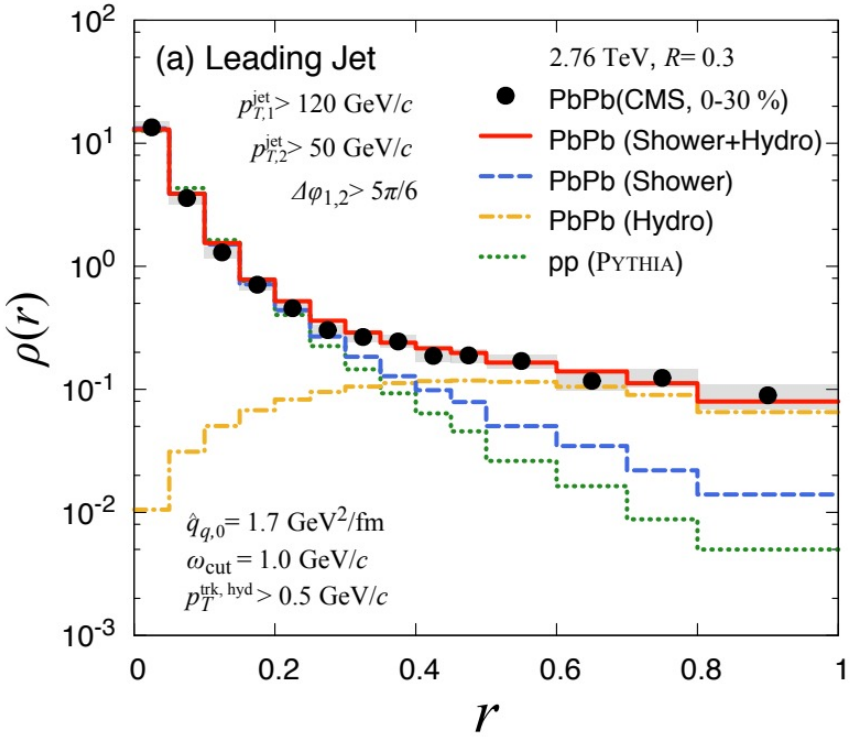
The intersection of jets and soft sector: medium response

High-energy parton deposits energy in hydro



Casalderrey-Solana, Milhano, Pablos, Rajagopal, Yao [2010.01140]

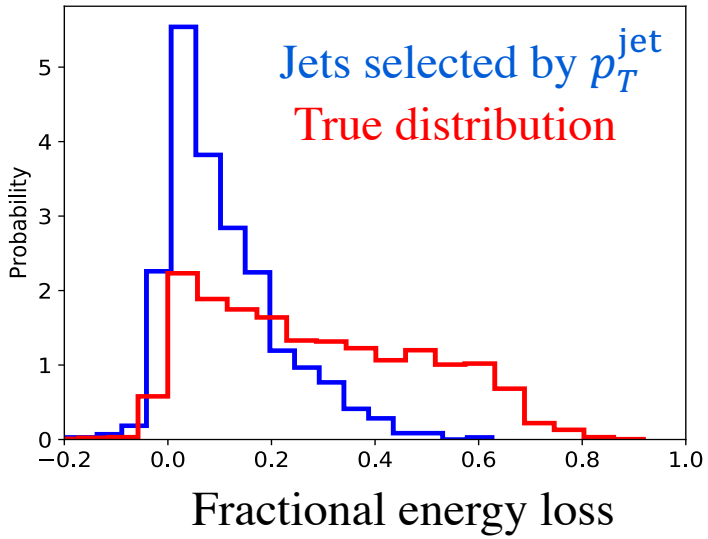
Jorge Casalderrey-Solana (talk)



Tachibana, Chang, Qin [1701.07951]

Generic enhancement of soft particles at large angles from the jet axis

More energy loss implies more medium response

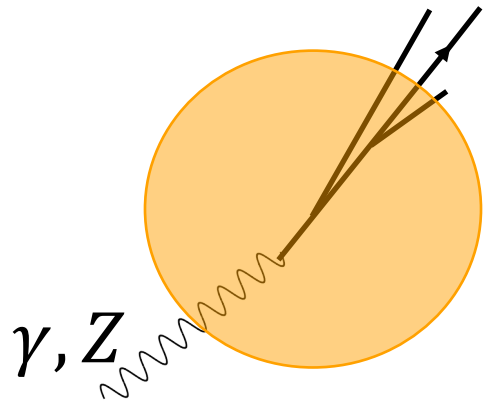


Brewer, Brodsky, Rajagopal [2110.13159]

Quinn Brodsky (poster)

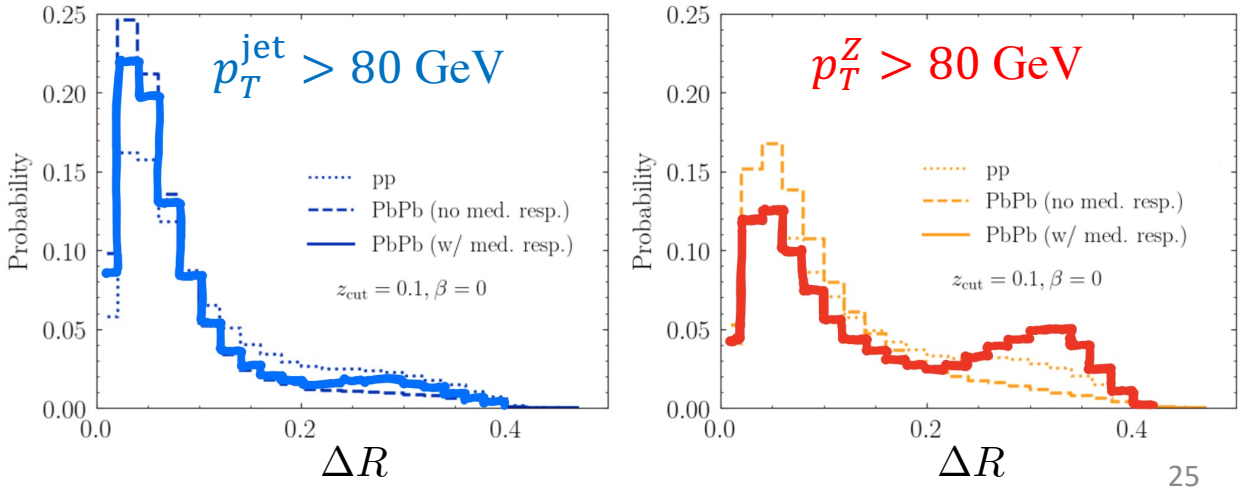
Similar effect from ISR: Korinna Zapp (talk)

Chen, Yang, He, Ke, Pang, Wang [2101.05422]



Jets selected by p_T^{jet}

Jets selected by $p_T^{\gamma,Z}$

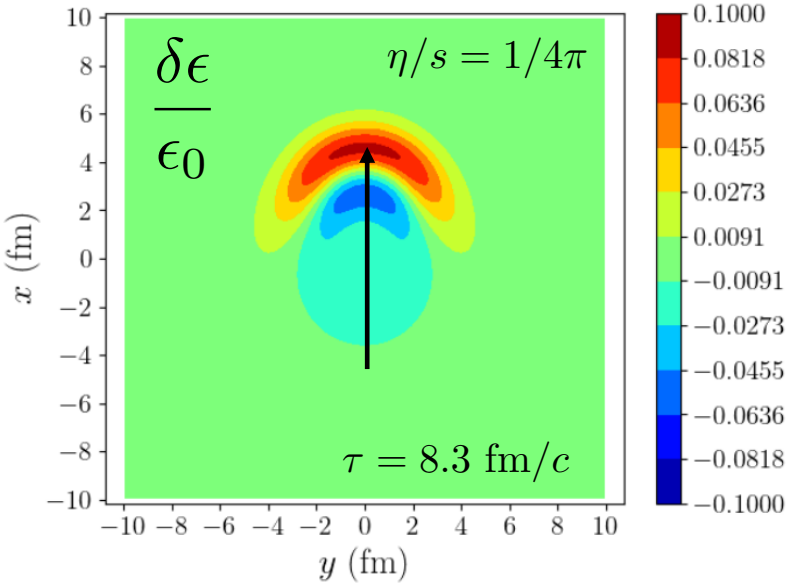


Medium response and diffusion wake

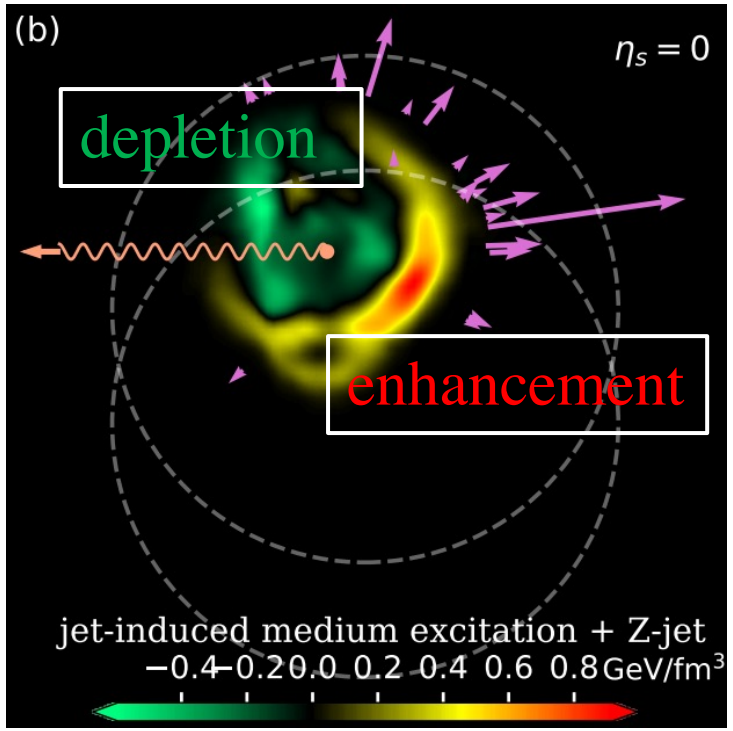
Medium response implies

- enhancement in the direction of the jet
- depletion *opposite* to the direction of the jet

Chen, Yang, He, Ke, Pang, Wang [2101.05422]
Yang, Luo, Chen, Pang, Wang [2203.03683]



Casalderrey-Solana, Milhano,
Pablos, Rajagopal, Yao [2010.01140]

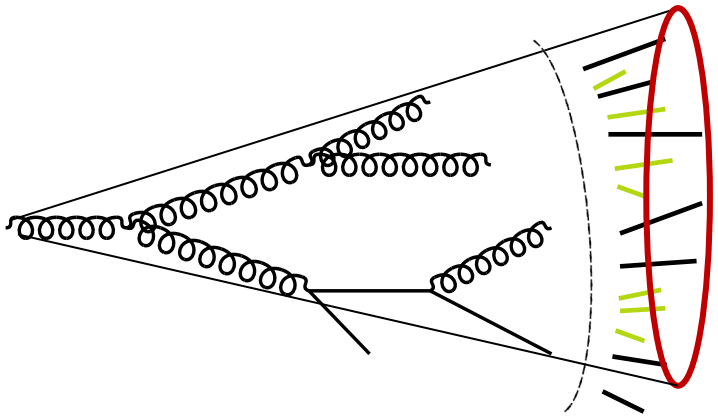


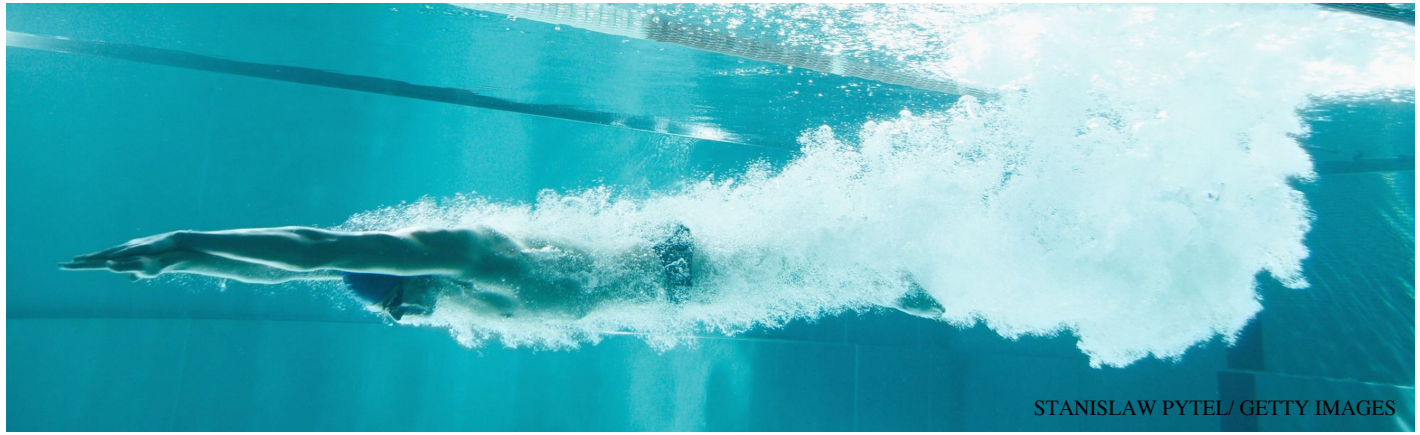
Chen, Yang, He, Ke, Pang, Wang [2101.05422]

Since Z does not radiate, clean signature of medium response

Jets as a probe of the far-from-equilibrium QGP

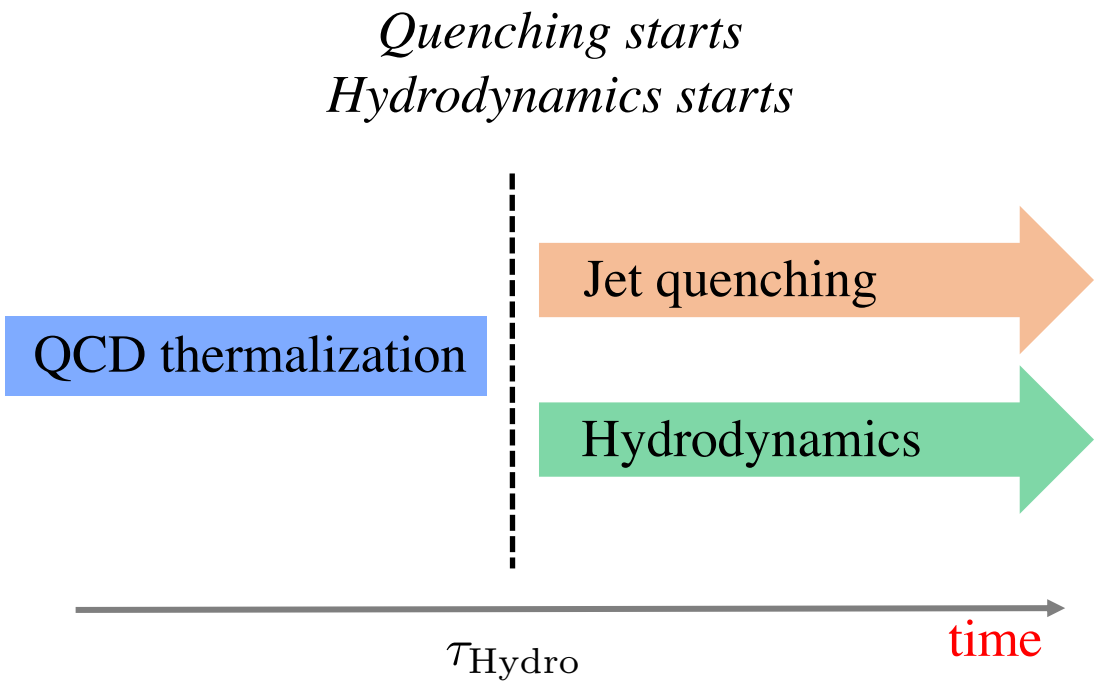
Description of soft-sensitive jet observables → Access to far-from-equilibrium QGP





Relevant for medium response and small systems

Thermalization in the soft sector happens through complex QCD interactions. Assumption: hard process doesn't participate

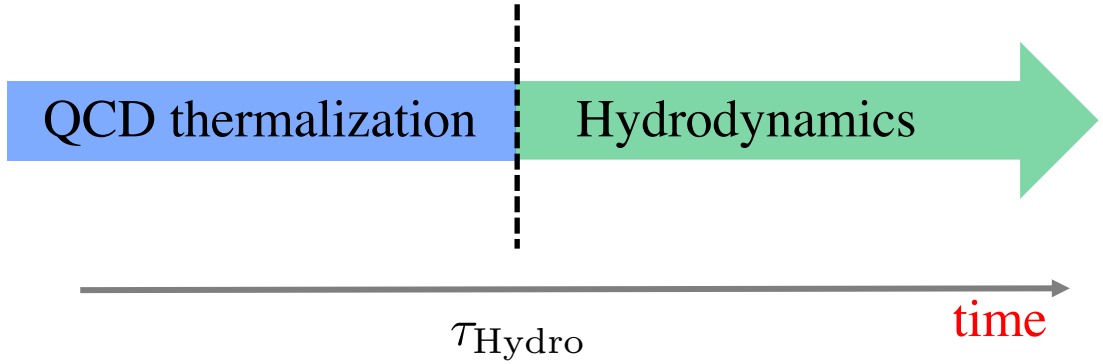


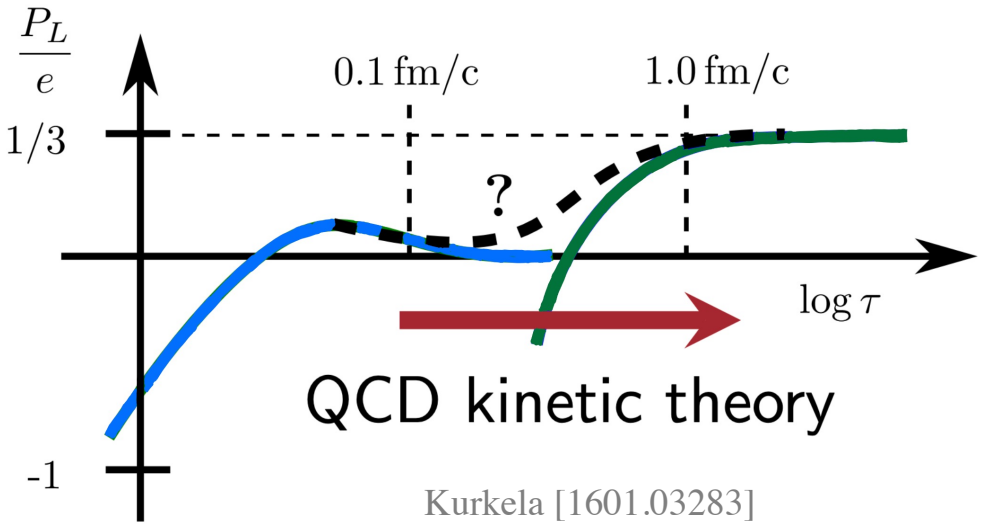
Even global quenching parameters like $\hat{q}$ can be sensitive to this assumption

Andres, Armesto, Niemi, Paatelainen, Salgado [1902.03231]

Hard process impacts thermalization process?

Extensive work on thermalization and hydrodynamization in kinetic theory



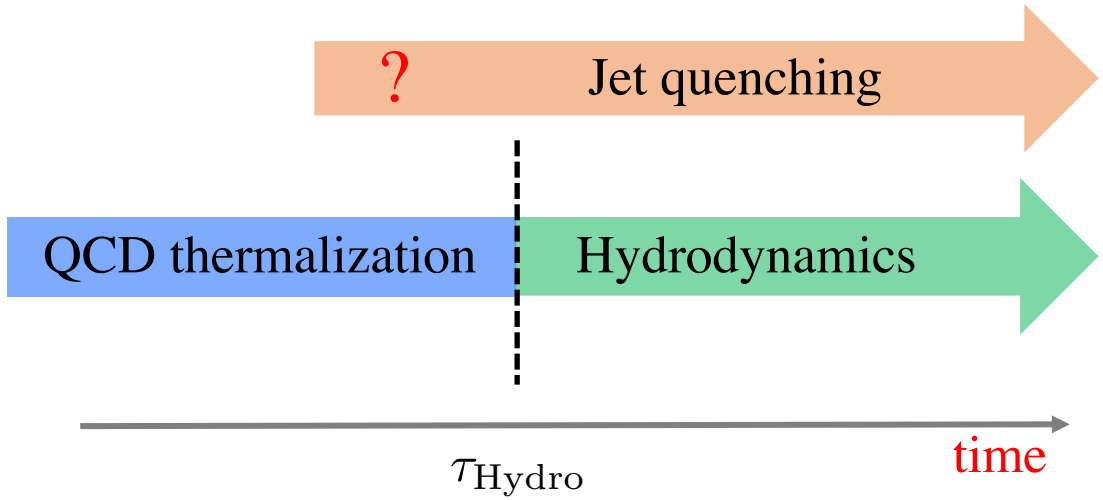


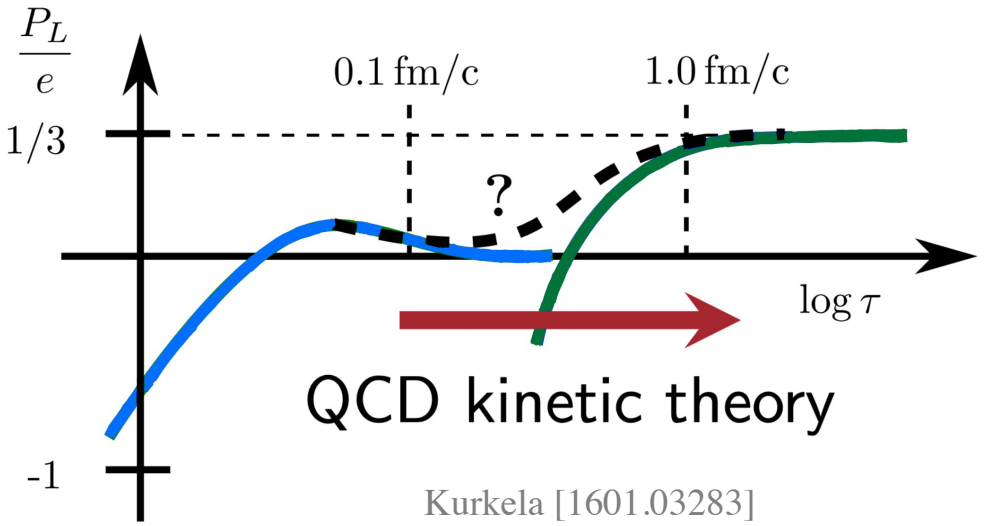
Kurkela [1601.03283]

Consistent description of initial state to onset of hydrodynamics

Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney [1805.01604, 1805.00961]

Extensive work on thermalization and hydrodynamization in kinetic theory





Kurkela [1601.03283]

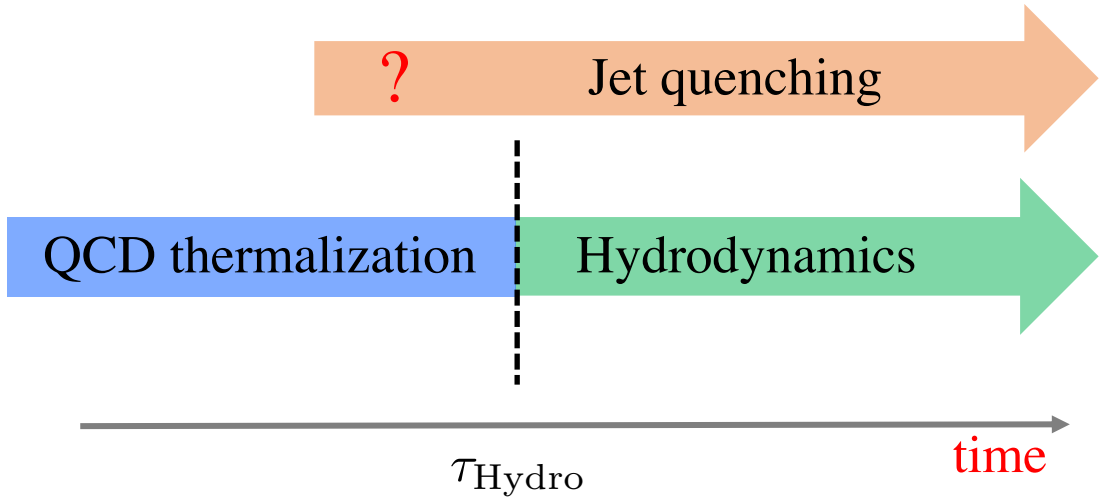
Consistent description of initial state to onset of hydrodynamics

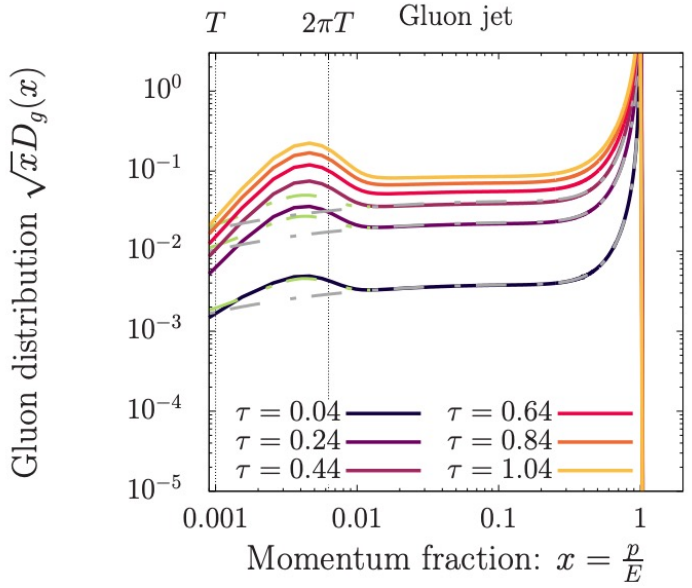
Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney [1805.01604, 1805.00961]

Toward the interplay of jet quenching and thermalization

Moore, Schlichting, Schlusser, Soudi [2105.01679]
Dai, Paquet, Teaney, Bass [2012.03441]

Extensive work on thermalization and hydrodynamization in kinetic theory





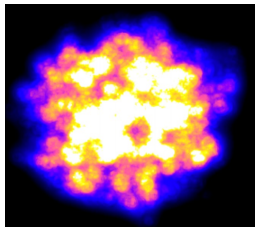
Schlichting, Soudi [2008.04928]
Ismail Soudi (talk)

See also Kurkela, Lu [1405.6318];
Mehtar-Tani, Schlichting [1807.06181]

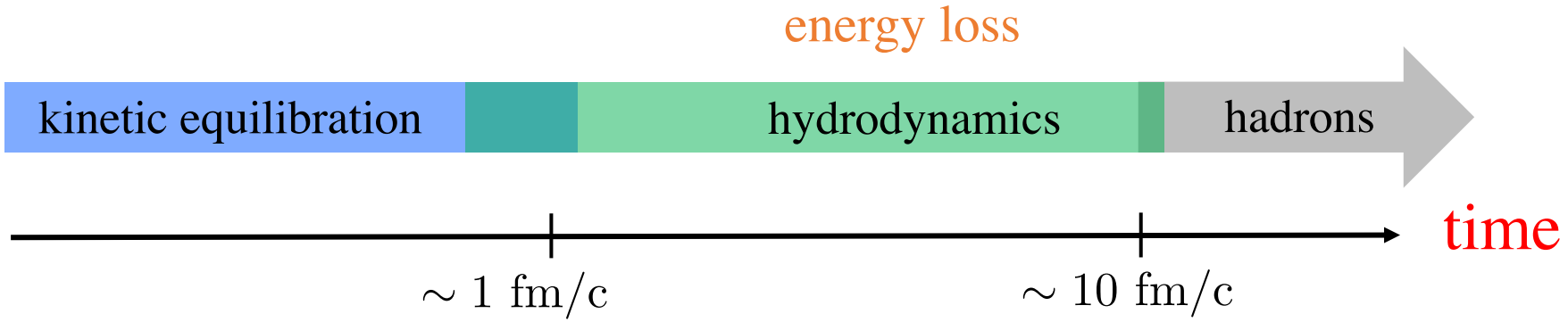
Toward the interplay of jet quenching and thermalization

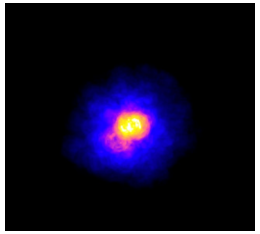
Moore, Schlichting, Schlusser, Soudi [2105.01679]
Dai, Paquet, Teaney, Bass [2012.03441]

Interplay of quenching and thermalization especially relevant in small systems

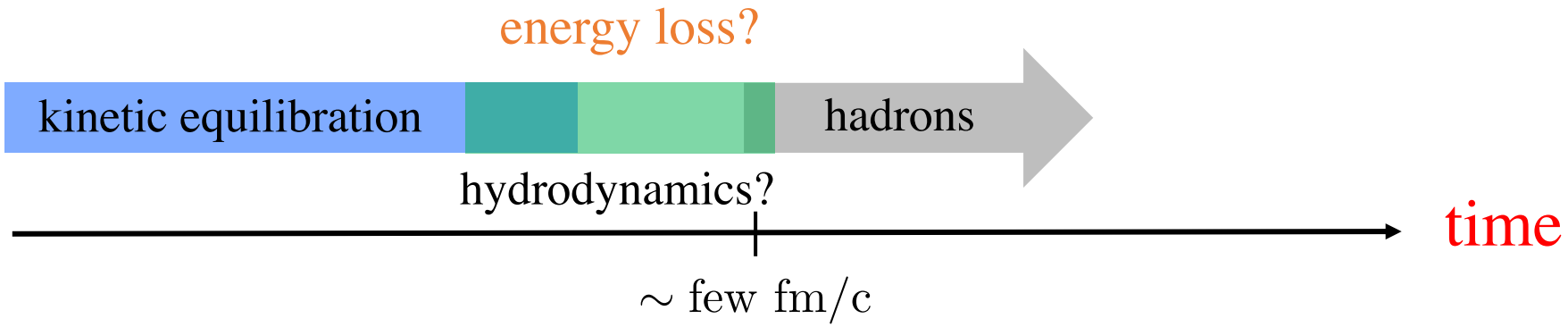


Heavy-ion collisions





Smaller systems (e.g. p-Pb)



Not just smaller versions of large systems!

Opportunities in small systems

- Experimental

2021	2022	2026-2027	>2030	
OO (200 GeV) in STAR	Short OO, pO run (~7 TeV) in LHC Run 3	Possibility of OO, ArAr in sPHENIX	Long run of intermediate nuclei (Ar, Kr) in LHC Run 5	time

In addition to high statistics pPb in Run 3+4 at LHC, pAu at RHIC

- Theoretical

  nPDFs and uncertainties have higher relative importance

  See Petja Paakinen (plenary)

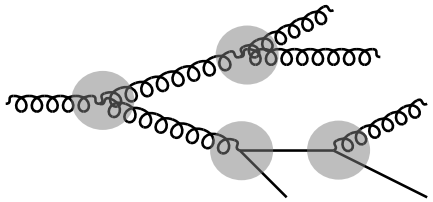
  Far-from-equilibrium effects in quenching

Predictions for quenching in OO

Brewer, Mazeliauskas, van der Schee [2103.01939]

Aleksas Mazeliauskas (talk); Ivan Vitev (poster)

Huss, Kurkela, Mazeliauskas, Paatelainen, van der Schee, Wiedemann [2007.13754, 2007.13758]

Physics goal	Theory outlook
Radiation and thermalization of hard processes in QCD 	Improved description of parton energy loss and broadening
Evolution of a parton shower in QCD media 	Medium modification of the structure of jets
Access to far-from-equilibrium QGP 	Integrated description of quenching and thermalization

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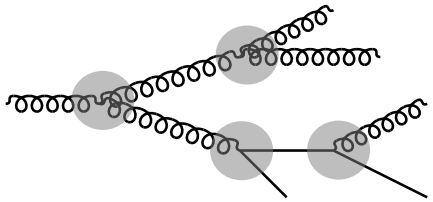
Evolution of a parton shower in QCD media 	Medium modification of the structure of jets
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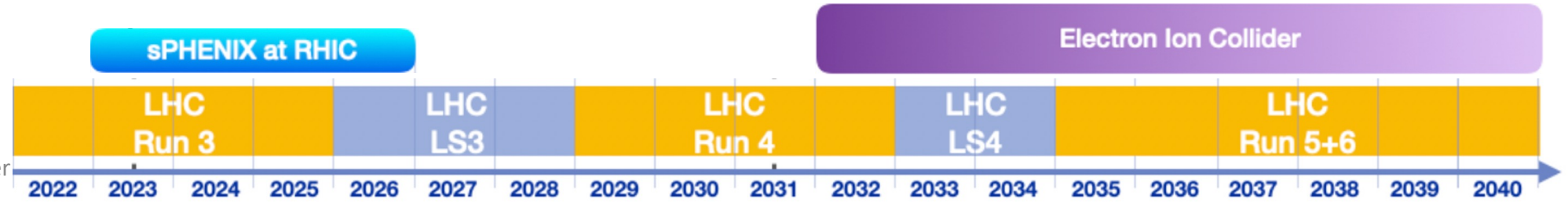
It's an exciting time to be a theorist!



Jasmine Brewer

Trip to donation center for Ukrainian refugees

Leaving from front of conference venue at 15:15

Needs: food, hygiene products, medications
(stop at supermarket on the way)