Jet Theory Overview

Yacine Mehtar-Tani (BNL)

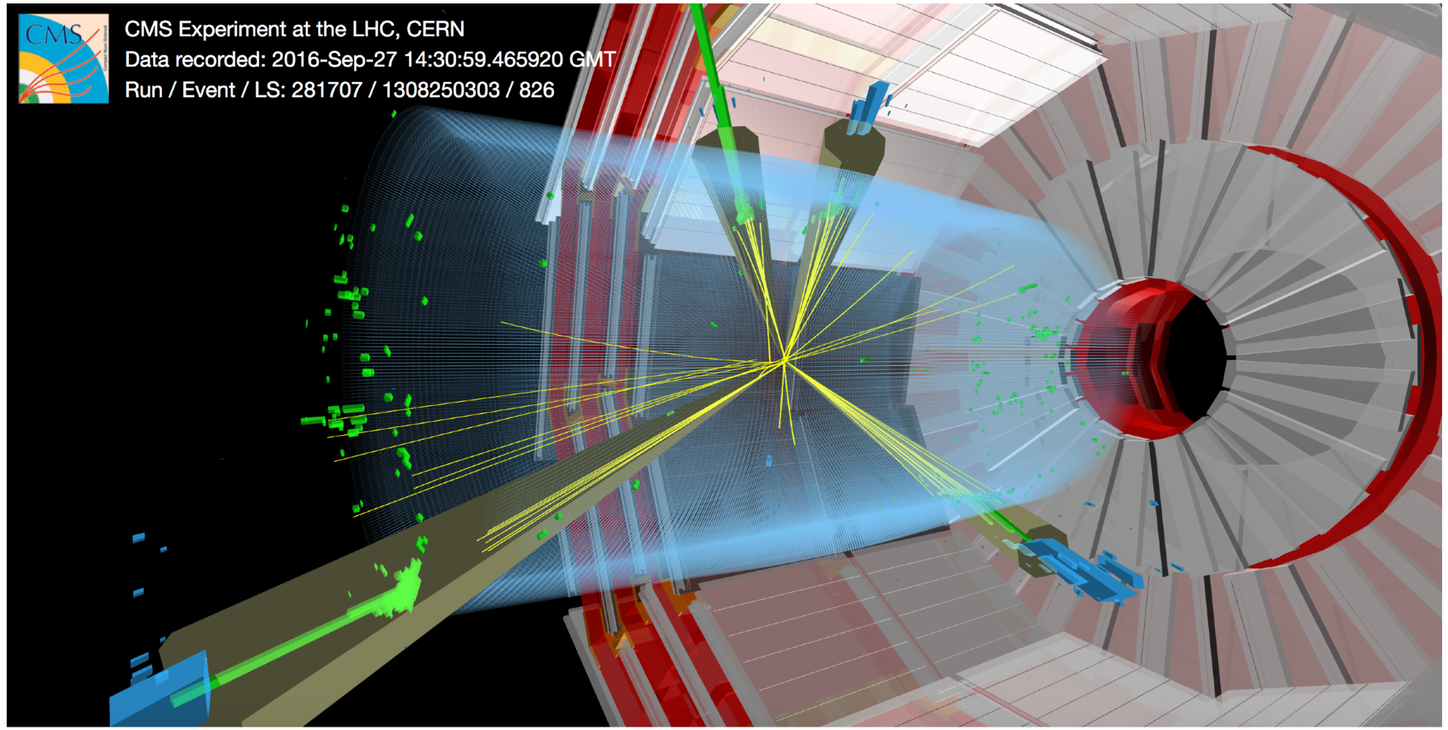
RHIC&AGS Users' Meeting @ BNL, June 11-12, 2024

Brookhaven National Laboratory

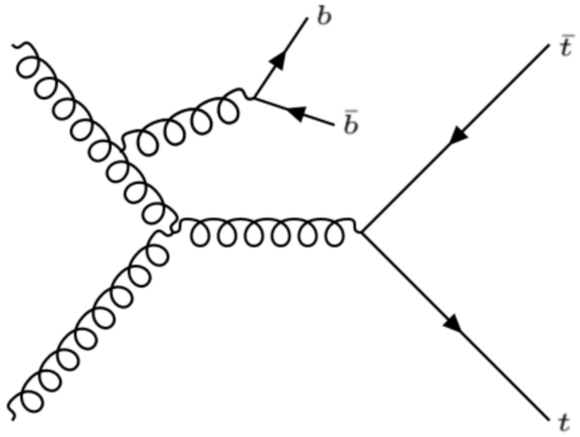
Introduction

Jets at Colliders

- QCD Jets are a direct manifestation of high energy quarks and gluons

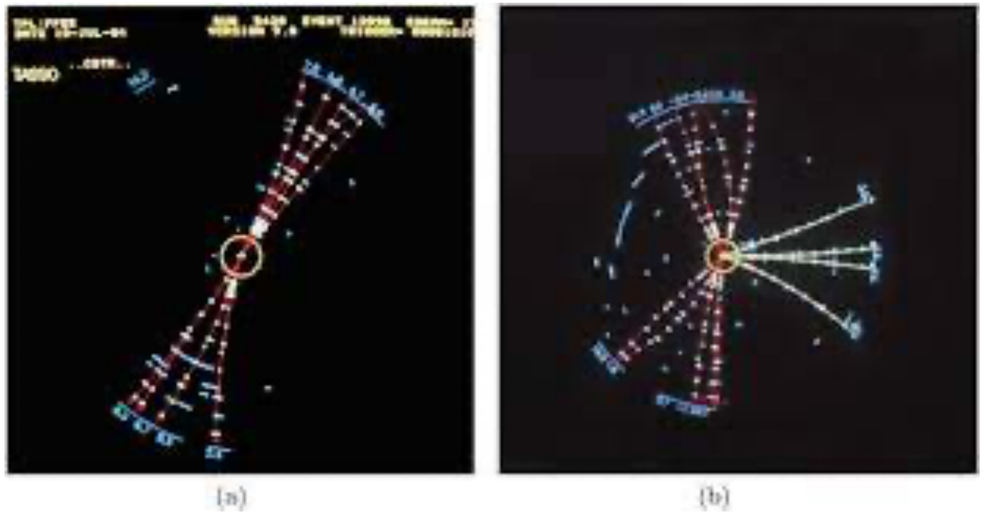


Multi-jet event at LHC

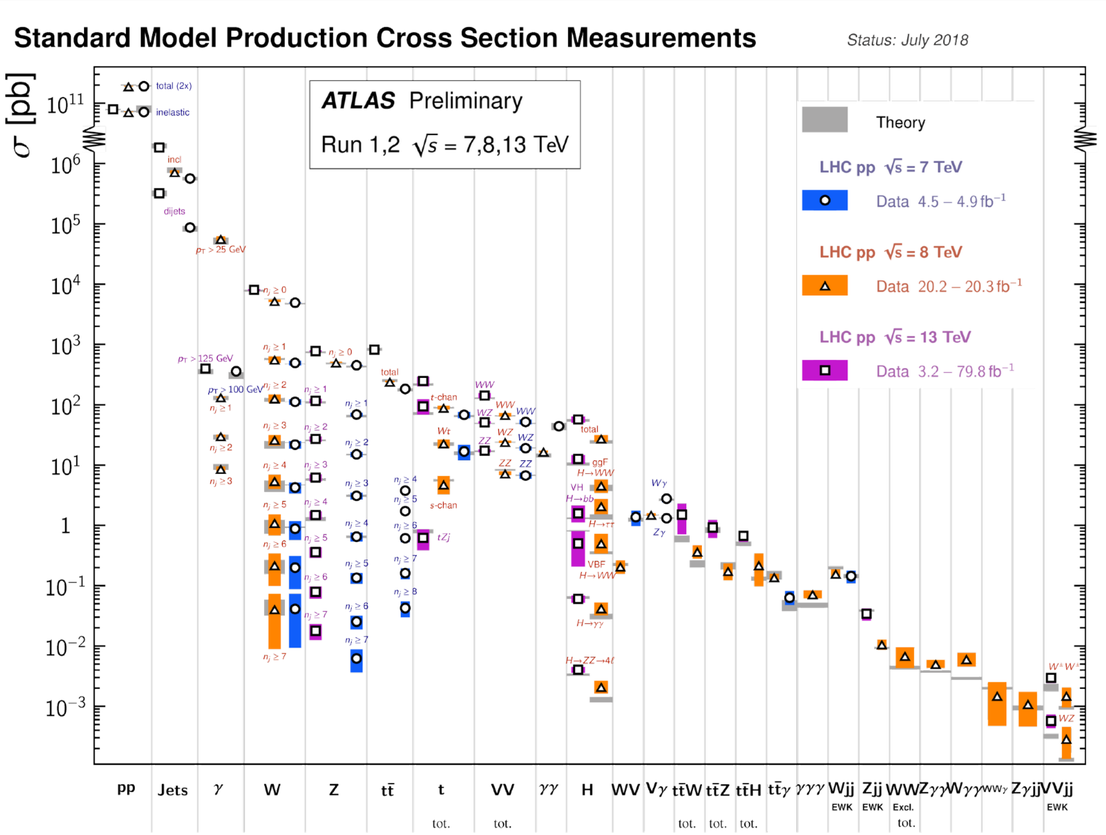


- Extensively studied: from the discovery of the gluon to precision tests of QCD

DESY 1979 - electron positron collisions



Early tests of QCD



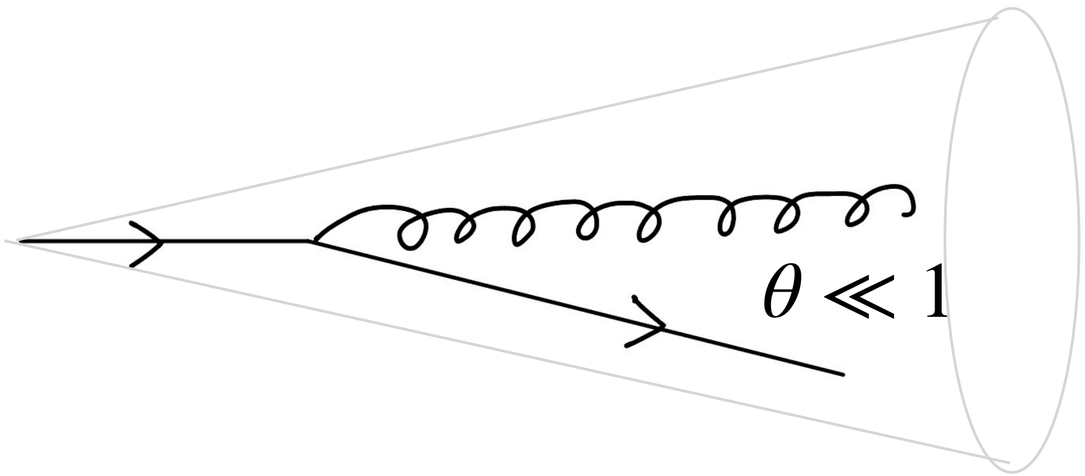
Today's theory accuracy $\gtrsim 5\,\%$

- Paramount for Higgs discovery and new physics searches

Why do we observe jets?

QCD radiation pattern

- Highly virtual quarks or gluons tend to fragment and radiate with high probability
- Collinear Radiation enhanced



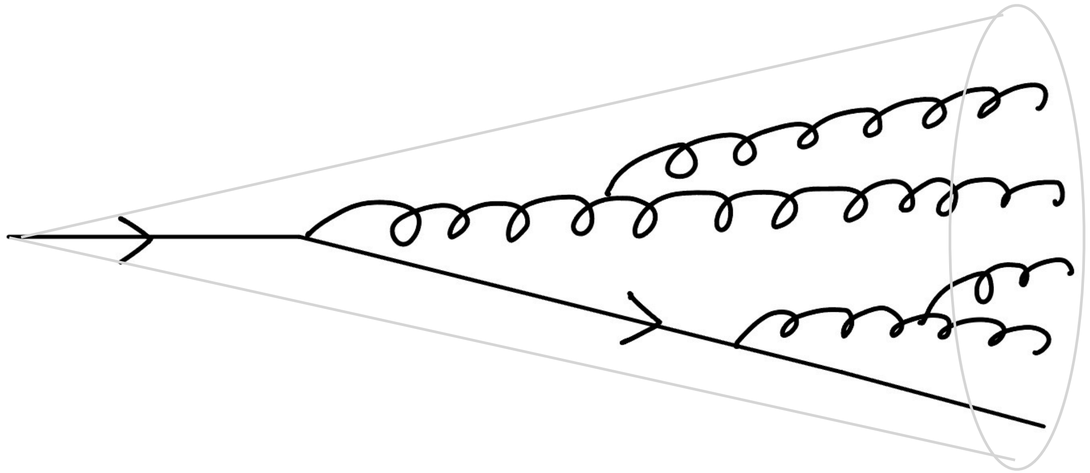
$$\mathrm{d}P \sim \alpha_s \frac{\mathrm{d}\theta}{\theta} \frac{\mathrm{d}\omega}{\omega}$$

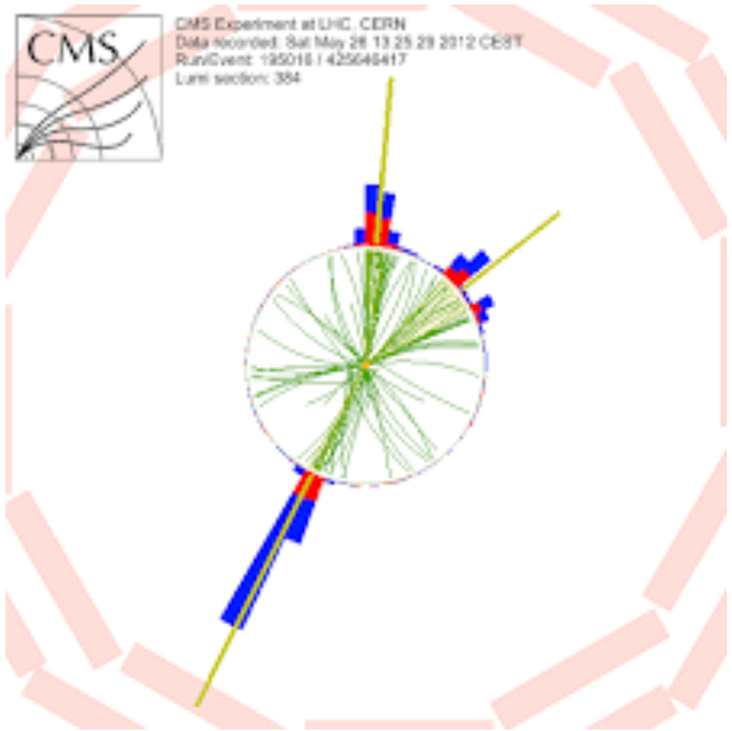
Large prob. when $\theta \to 0$

And $\alpha_s \ll 1$

QCD radiation pattern

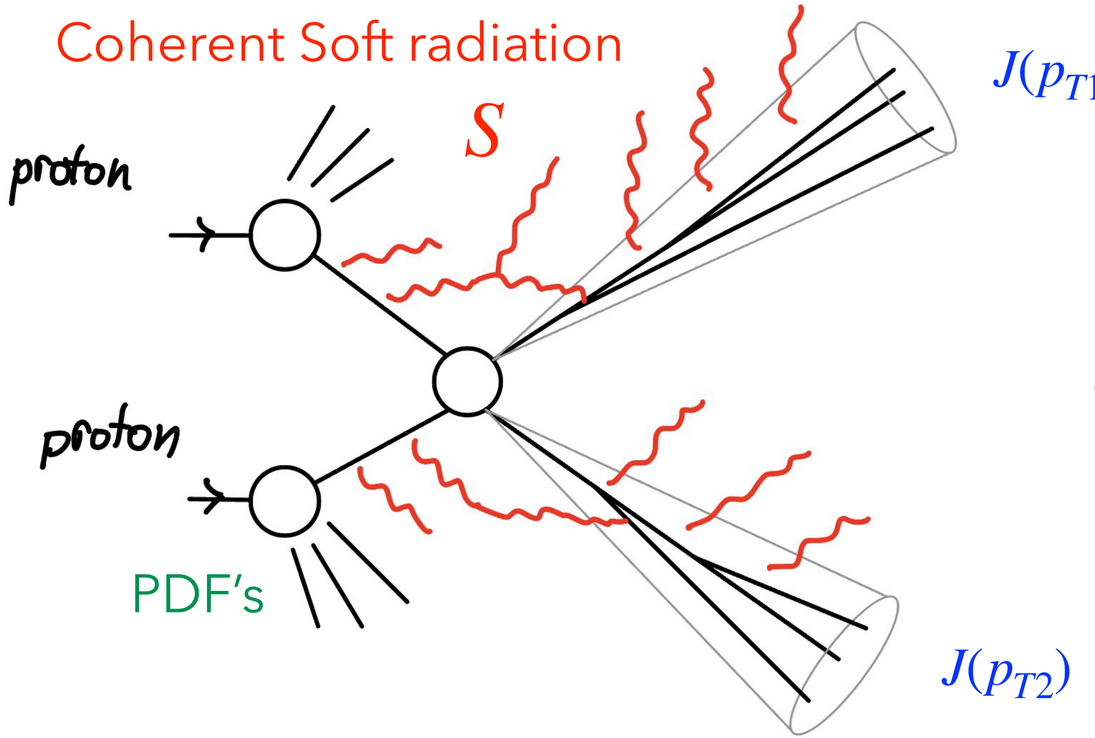
- Highly virtual quarks or gluons tend to fragment and radiate with high probability
- Collinear Radiation enhanced → high probability for numerous particle production along the jet





In a theorist's mind

- Powerful organizational tools: Factorization theorems and resummation



Collinear fragments

→ Typically, resums: $\ln \tau$

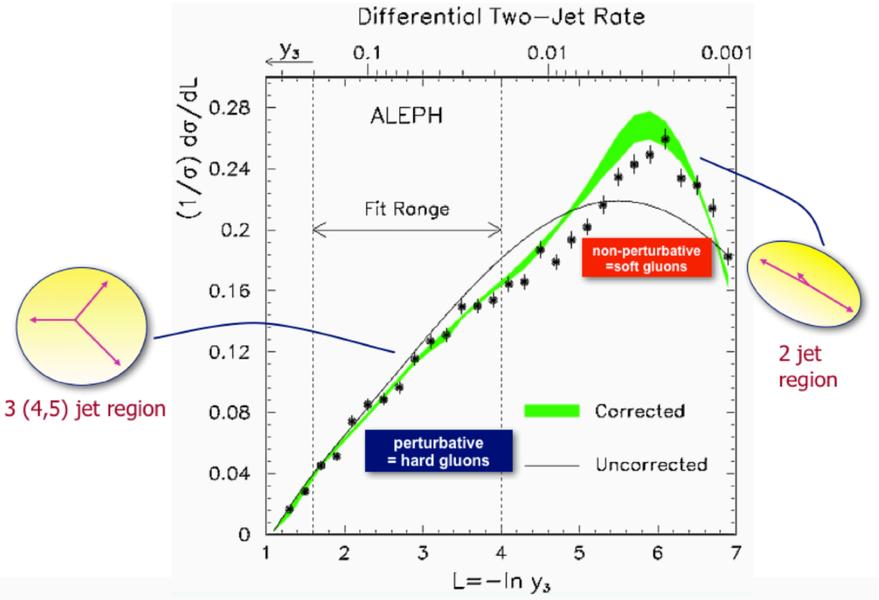
$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{T1}\mathrm{d}p_{T2}\,\mathrm{d}\tau} \equiv xf(x_1)\,xf(x_2) \otimes H(\mu^2) \otimes S \otimes J(p_1)\,J(p_2)\;\delta\left(\tau - \sum_{i\in\Omega} p_i\right)$$

A rich family of observables

↪ Event Shapes: 1970-80's

- Characterize the shape of the event
- Thrust (jettiness), sphericity, Heavy jet mass, Jet broadening, EEC

$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}$$



A rich family of observables

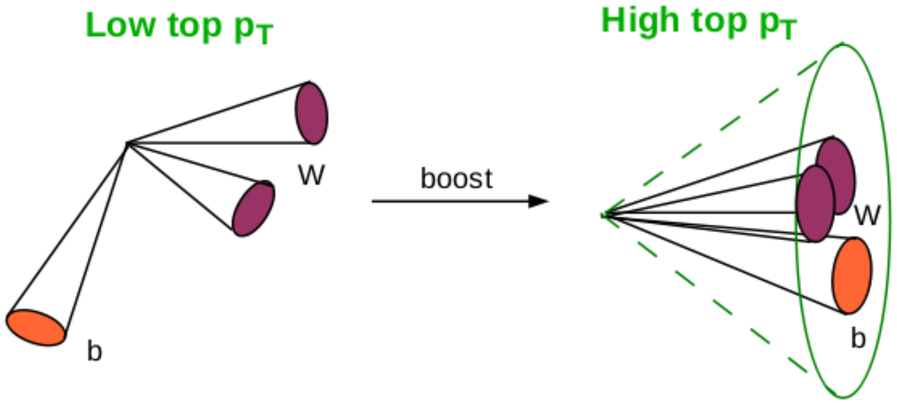
↪ Event Shapes: 1970-90's

- Characterize the shape of the event
- Thrust (jettiness), sphericity, Heavy jet mass, Jet broadening, EEC

↪ Jet substructure: 2010-20's

- Looks inside the jet
- Boosted topologies
- Pruning, Trimming, Grooming, SoftDrop
- N-subjetiness, jet angularities, jet mass, …

$$\lambda_\alpha^\kappa = \sum_{i \in \text{jet}} \left(\frac{p_{T,i}}{\sum_{j \in \text{jet}} p_{T,j}} \right)^\kappa \left(\frac{\Delta_i}{R_0} \right)^\alpha$$



A rich family of observables

↪ Event Shapes: 1970-80’s

- thrust (jettiness) , sphericity, Heavy jet mass, Jet brodening, EEC

↪ Jet substructure: 2010-20’s

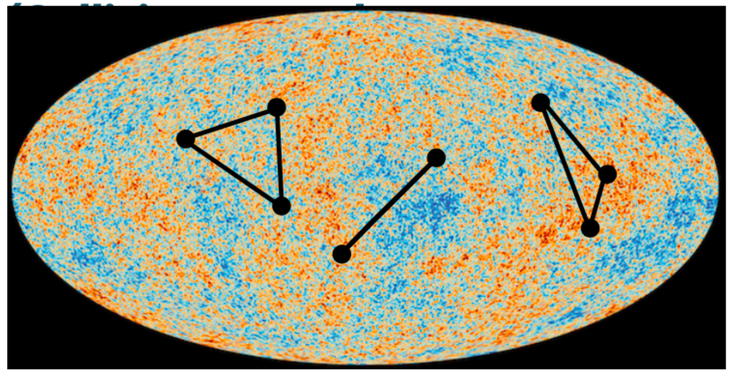
- Characterizes the inner structure of the jet
- Boosted topologies
- Pruning, Trimming, Grooming, SoftDrop
- N-subjetiness, jet angularities, jet mass, …

↪ Energy-Energy correlators: 2020’s

A rich family of observables

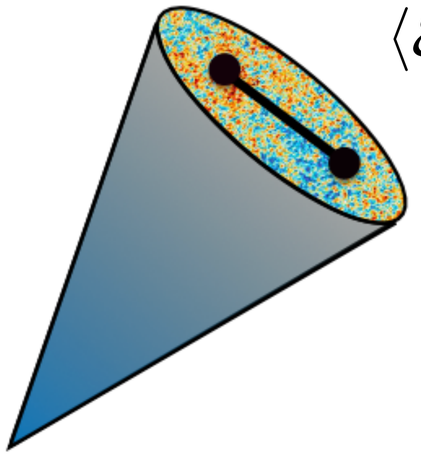
↪ Event Shapes: 1970-80's

- thrust (jettiness) , sphericity, Heavy jet mass, Jet brodening, EEC



2010-20's

oming, Softdrop



$\langle \mathcal{E}(\vec{n_1})\mathcal{E}(\vec{n_2})\rangle$

↪ Energy-Energy correlators: 2020's

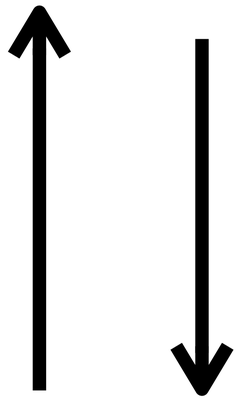
$\langle \mathcal{E}(n_1)\mathcal{E}(n_2)\cdots\mathcal{E}(n_k)\rangle$ Mesures energy flux of hadrons and their angular correlations

Two schools, two philosophies

Bottom up (traditional) 1970's - present

Direct computation of observables order by order in perturbation theory: resum perturbative series into factoraized functions

[Sterman, Collins, Soper, Marchesini, Basseto, Dokshitzer, Catani, Ciafaloni, Salam,…]



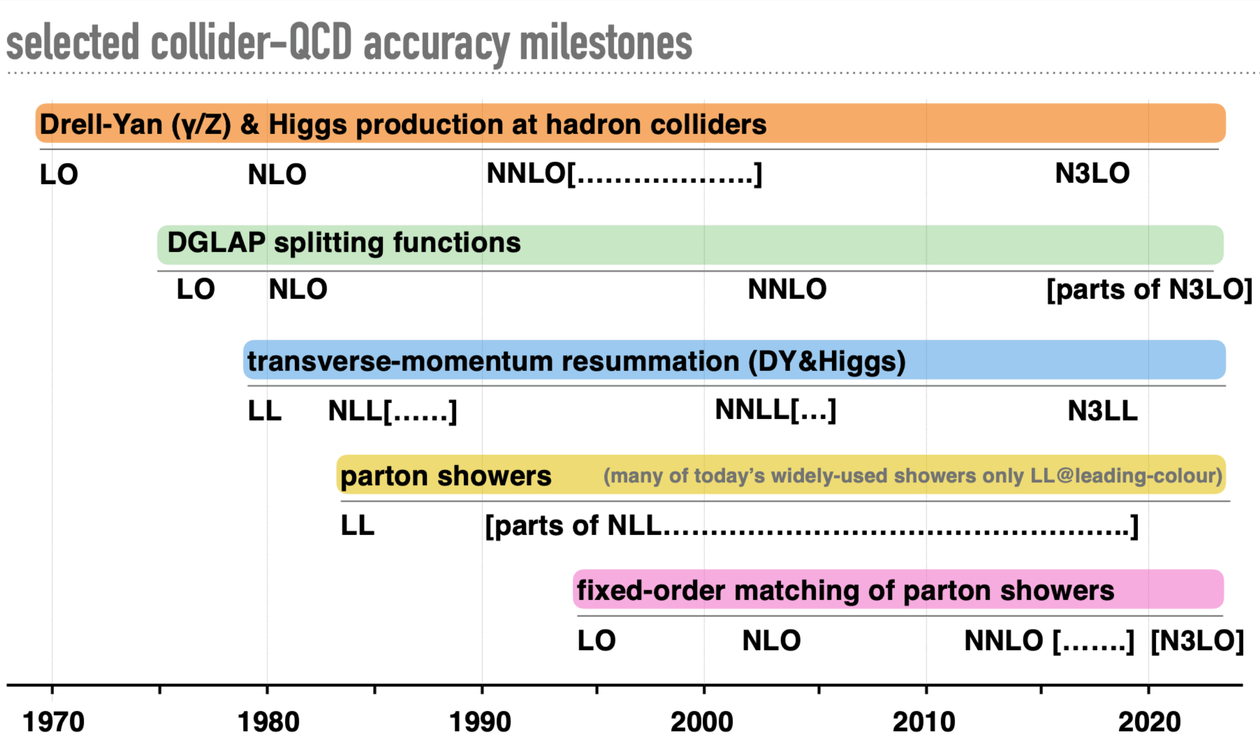
Top down (modern) 2000's - present

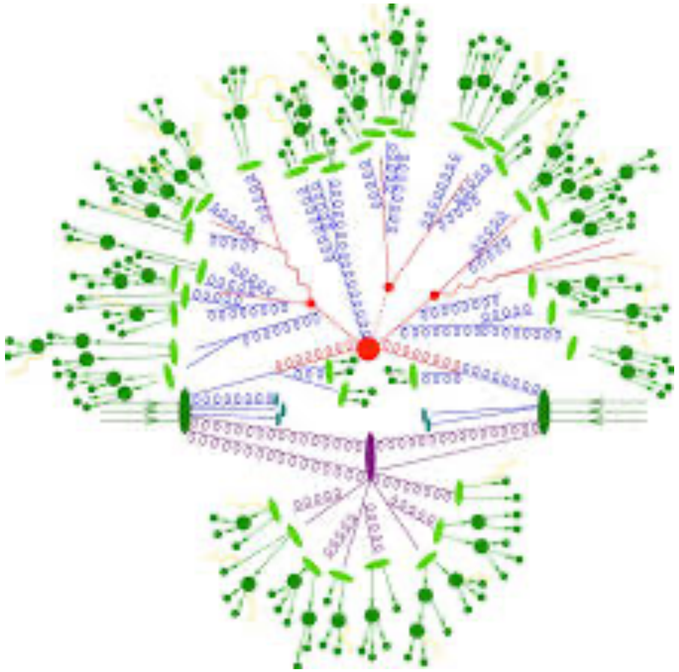
Derive an all order factorization theorems in soft-collinear effective field theory (SCET) then compute each factor in perturbation theory

[Bauer,Fleming, Pirjol, Stewart, Becher, Waalewijn, Rothstein, Neill,…]

Precision QCD and MC event generators

Monte Carlo event generators essential for data analysis at colliders and complement analytic approaches

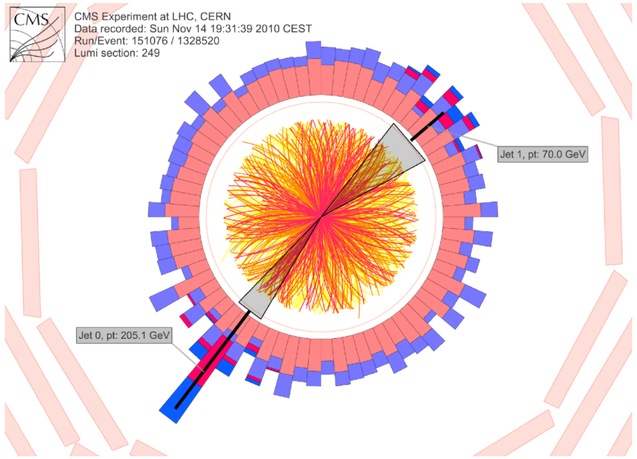


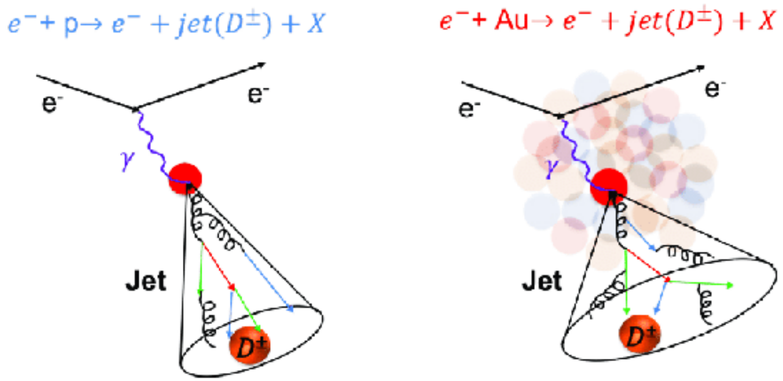


[G. Salam 2023]

Full NLL accuracy of parton showers under way…

New frontiers





Heavy Ion collisions

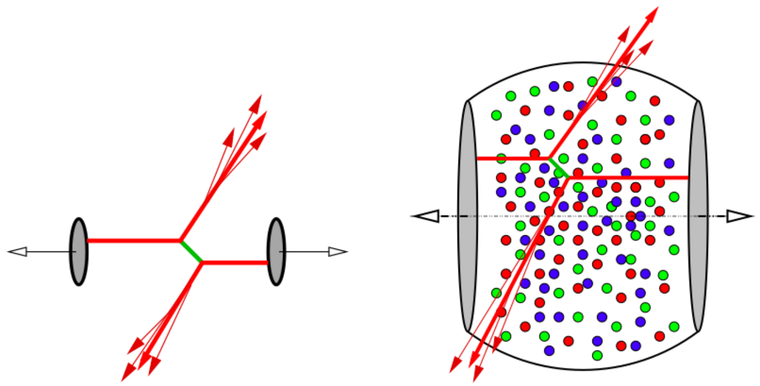
- Jet energy loss
- Jet modification
- Thermalization
- Heavy Flavor transport

Electron-Ion collider

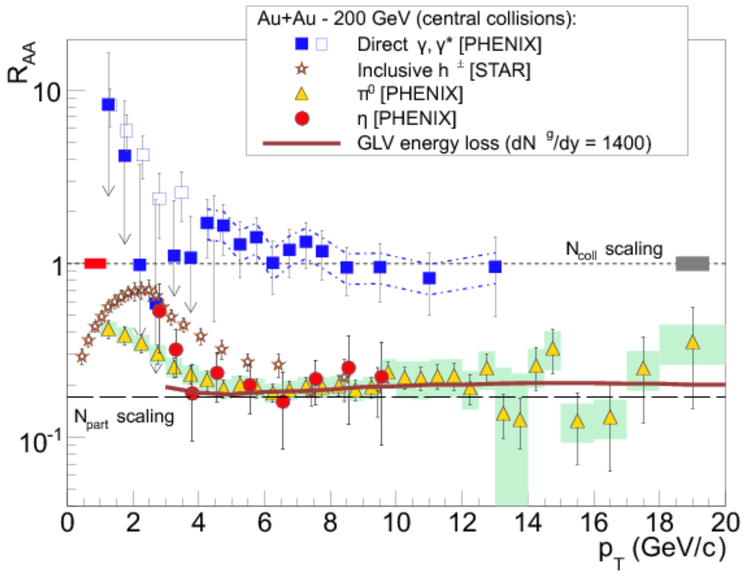
- 3D structure of the proton
- Gluon saturation
- Cold nuclear matter
- Polarization

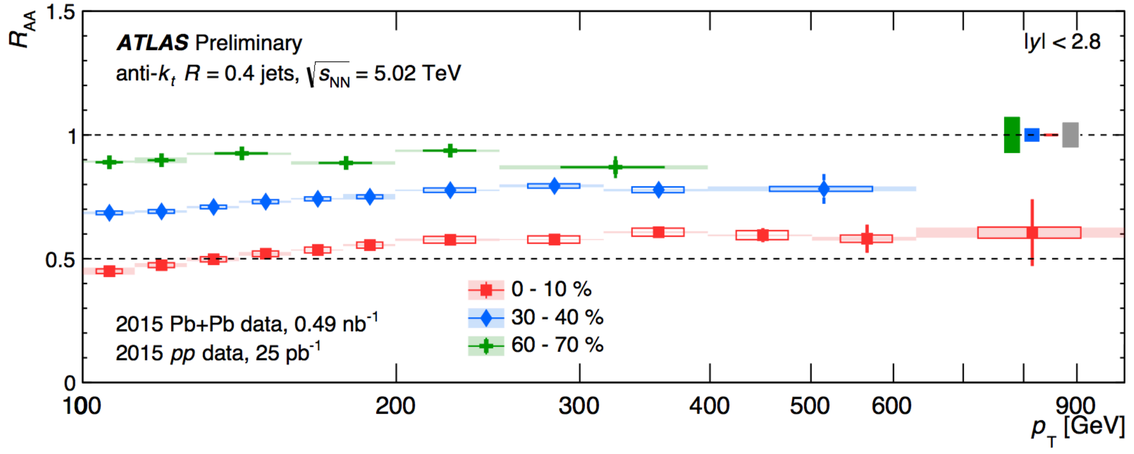
[Talk by F. Ringer]

Observation of jet quenching in HIC



- Substantial final state interactions: jets lose energy to the QGP constituents



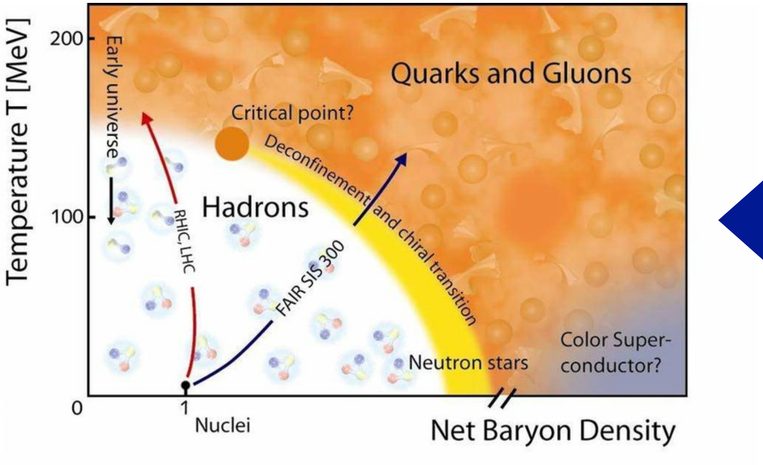


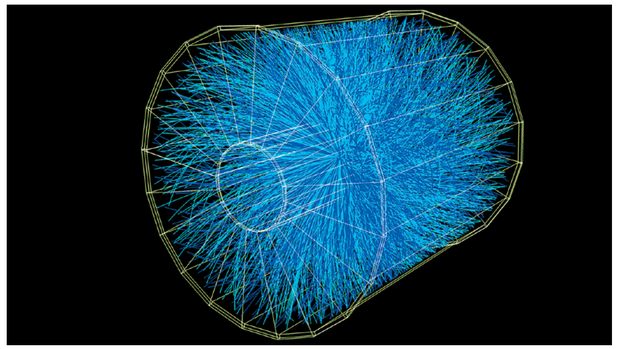
Multiscale dynamics

Thermal equilibrium (T≠ 0)

Non-equilibrium

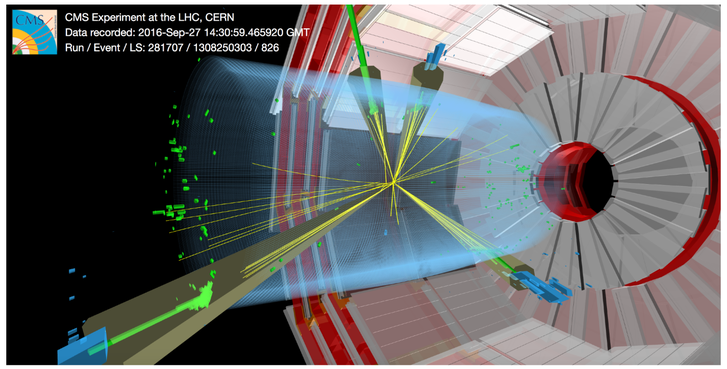
T=0



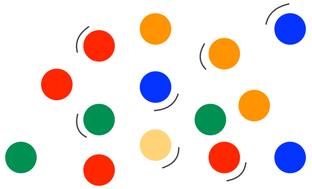


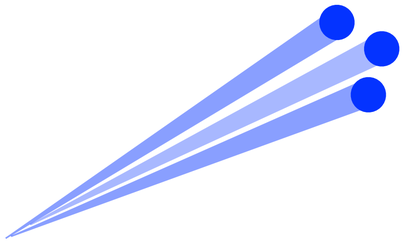
Heavy ion event

~ 1000's particles



Jets in pp





Energy

T ~ 1 GeV

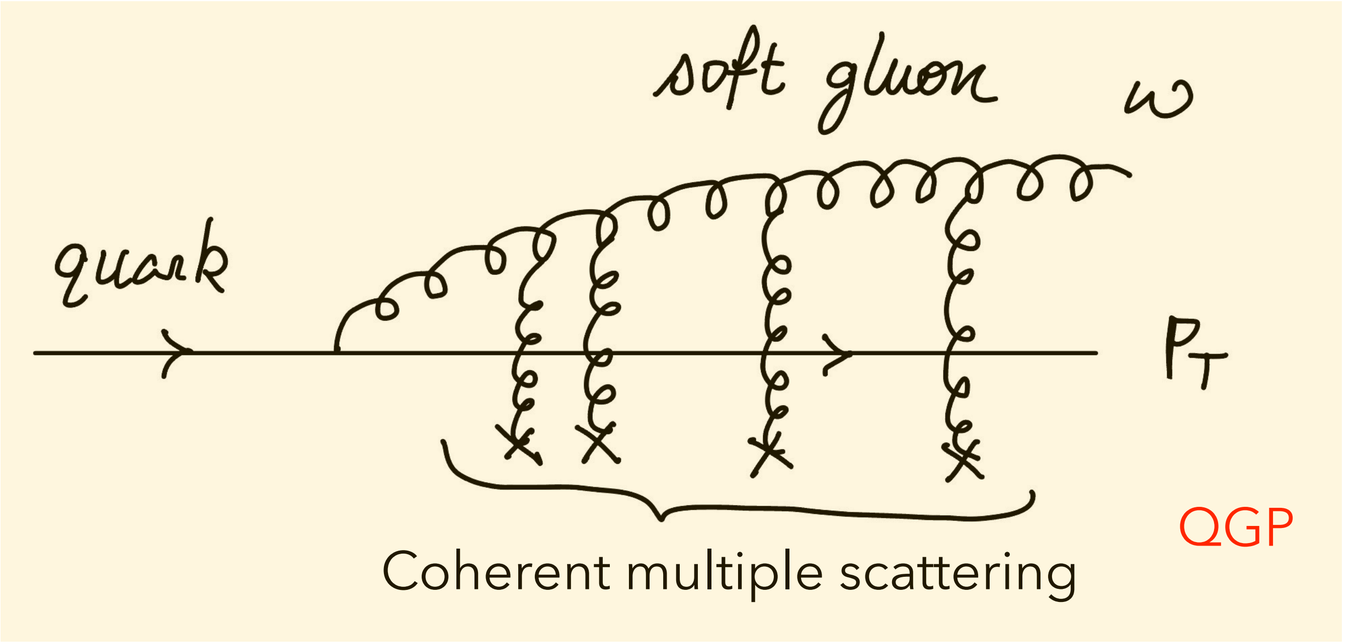
p_T ~ 1 TeV

Jet quenching timeline (epoch I)

↪ 1980: Bjorken predicts jet quenching

↪ 1990's parton radiative energy loss $E_{\text{loss}} \sim \hat{q} L^2$

Gyulassy, Wang (1990) Baier, Dokshitzer, Mueller, Peigne, Schiff (1996) Zakharov (1997)



Jet quenching timeline (epoch I)

↪ 1980: Bjorken predicts jet quenching

↪ 1990's parton radiative energy loss

Gyulassy, Wang (1990) Baier, Dokshitzer, Mueller, Peigne, Schiff (1996) Zakharov (1997)

↪ RHIC phenomenology (high pt hadrons) : 2000's

Guo, Wang (2000) Gyulassy, Levai, Vitev (2001) Wiedemann (2001) Arnold, Moore, Yaffe, (2000)

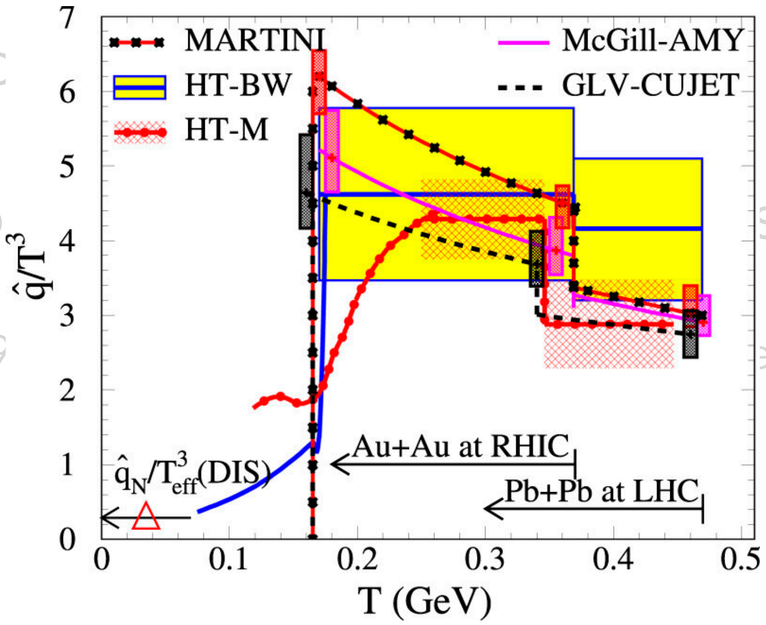
Salgado, Armesto, Wiedemann, Gale, Jeon, Schenke, Qin, Majumder, Horowitz, Wang, … (2000-2010)

Jet quenching timeline (epoch I)

↪ 1980: Bjorken p

↪ 1990's p ss

Gyulassy, Wang (199 e, Schiff (1996) Zakharov (1997)



Jet Collaboration (2014)

↪ RHIC phenomenology (high pt hadrons) : 2000's

Guo, Wang (2000) Gyulassy, Levai, Vitev (2001) Wiedemann (2001) Arnold, Moore, Yaffe, (2000)

Salgado, Armesto, Wiedemann, Gale, Jeon, Schenke, Qin, Majumder, Horowitz, Wang, … (2000-2010)

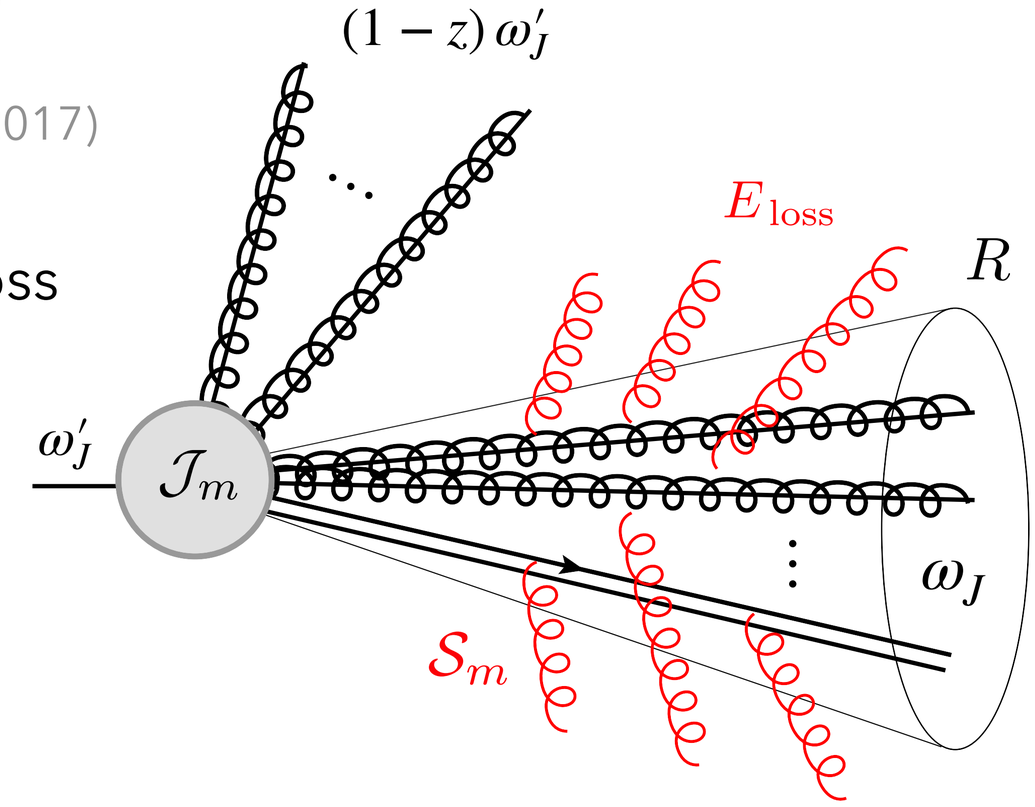
Jet quenching timeline (epoch II)

↪ 2010's Jet quenching theory

Color decoherence: MT, Tywoniuk, Salgado, Iancu, Casalderrey-Solana (2010) Blaizot, Dominguez, Iancu, MT (2013-2015)

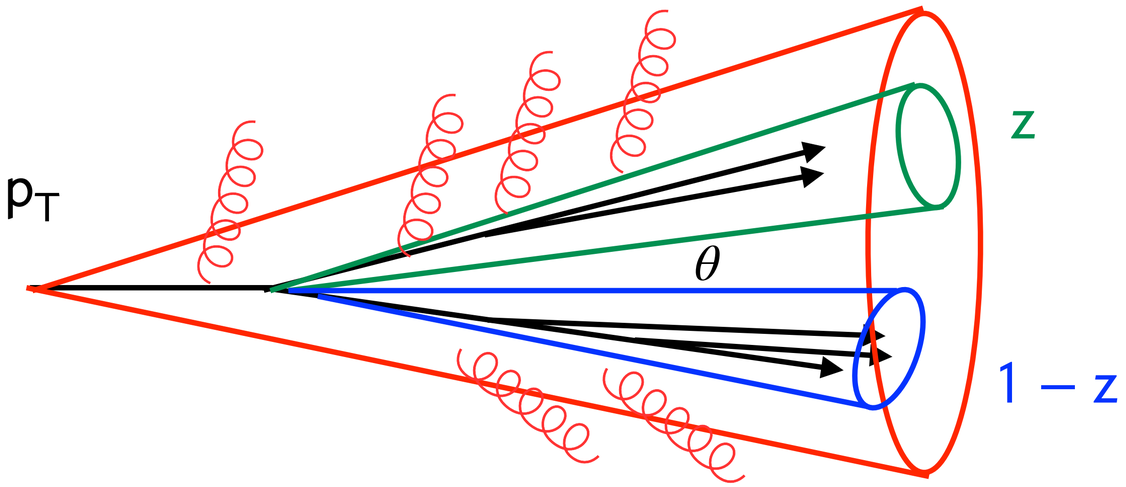
SCETg: Majumder, Vitev, Chien, Kang, Ringer, … (2010-2017)

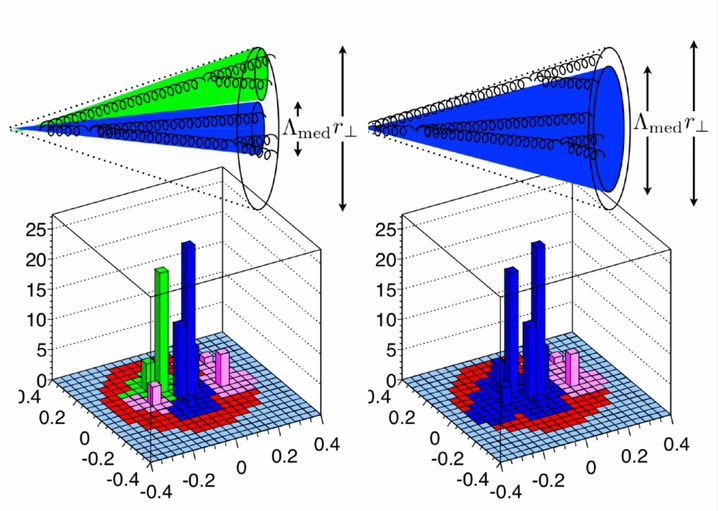
- From parton to multiple prong energy loss
- Color decoherence
- In-medium parton shower
- Radiative corrections
- Resummation
- Jet substructure…



Non-linear evolution of jet quenching

- Energy loss of a muti-parton system is sensitive to coherence effects: resolution angle $\theta_c = (\hat{q}L^3)^{1/2}$
- Quenching factor: $Q \sim R_{AA} < 1$





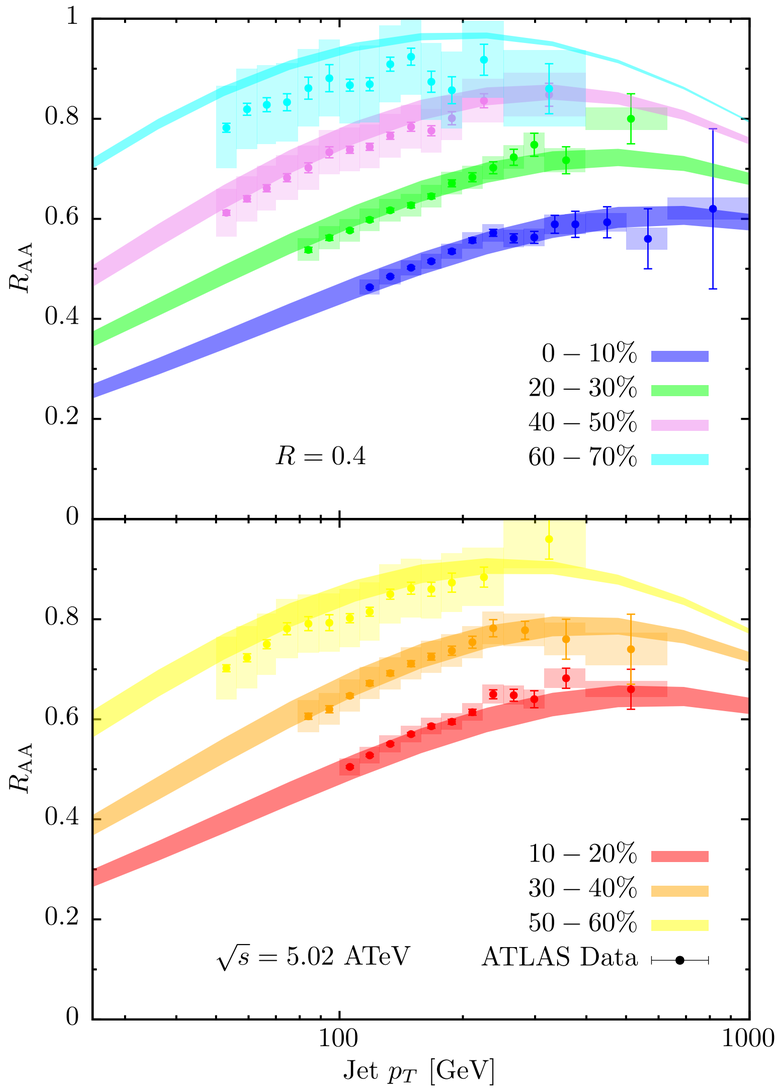
Two effective color charges

One effective color charge

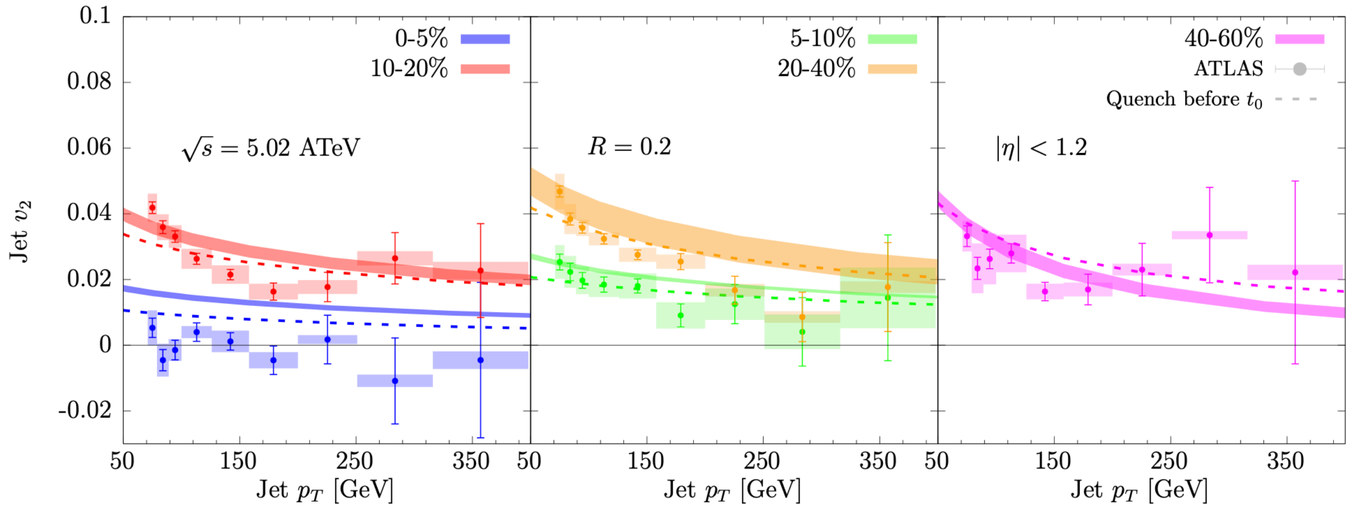
$$\frac{\partial}{\partial \ln\theta} Q_a(\theta, p_T) = \bar{\alpha} \int dz\, p^a_{bc}(z)\, \Theta_{res}(z,\theta) \left[Q_b(\theta, z p_T)\, Q_c(\theta, (1-z) p_T) - Q_a(\theta, p_T) \right]$$

MT, Tywoniuk (2017)

Inclusive jets and jet v2



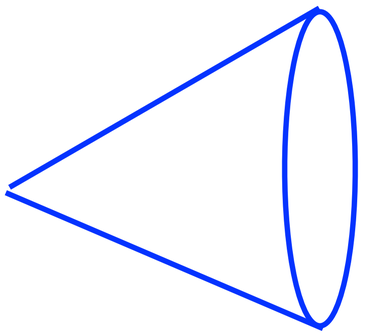
- Description of R, pt and centrality dependence
- Dominant theory uncertainties due parton shower accuracy



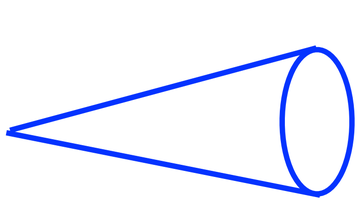
MT, Pablos, Tywoniuk (2021-2023)

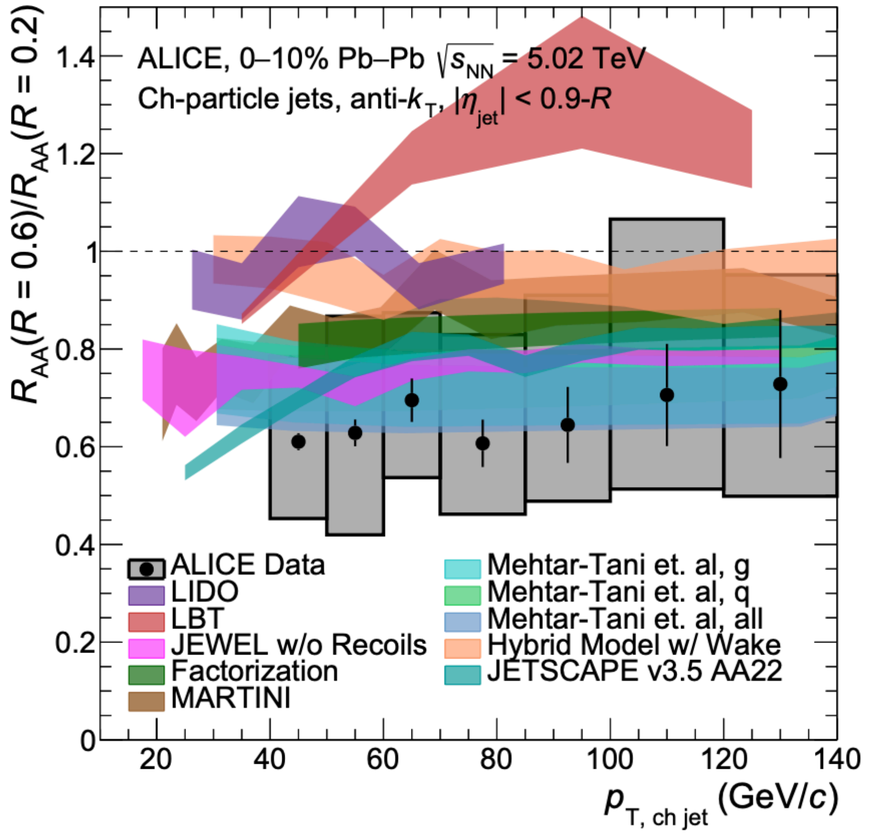
Predictions for R dependence

- R dependence encodes color coherence effects



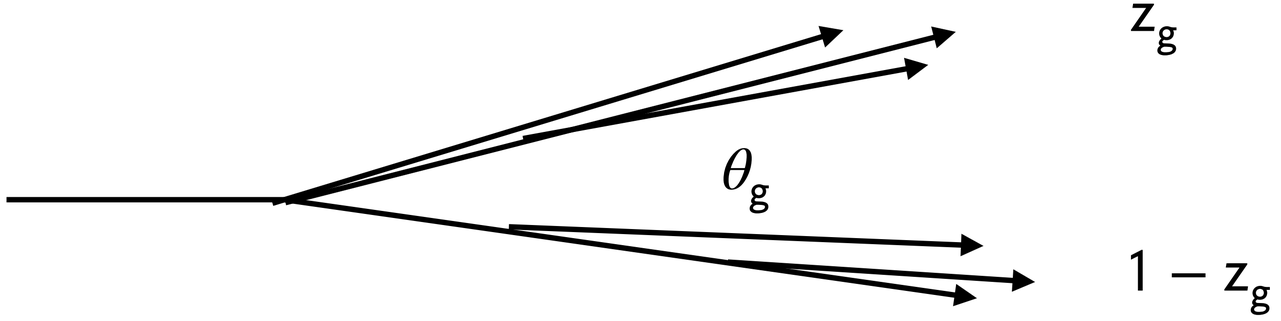
Vs.

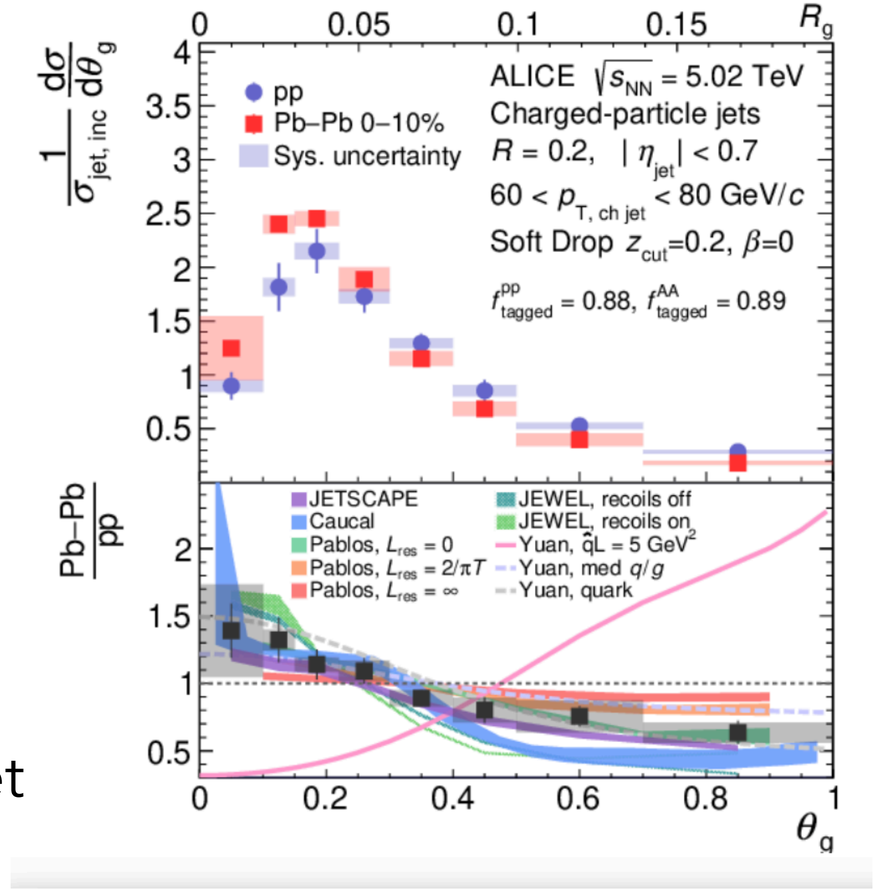




→ Good agreement with 2023 ALICE data as function of pT and jet cone size

Jet substructure with grooming





ALICE Collaboration (2021)

- Access the hard components of the jet by reducing soft contamination with Groomed jet observables: jet mass, θ_g, z_g ⇝ jet collimation observed
- Evidence for color decoherence: Two prongs lose more energy than one prong

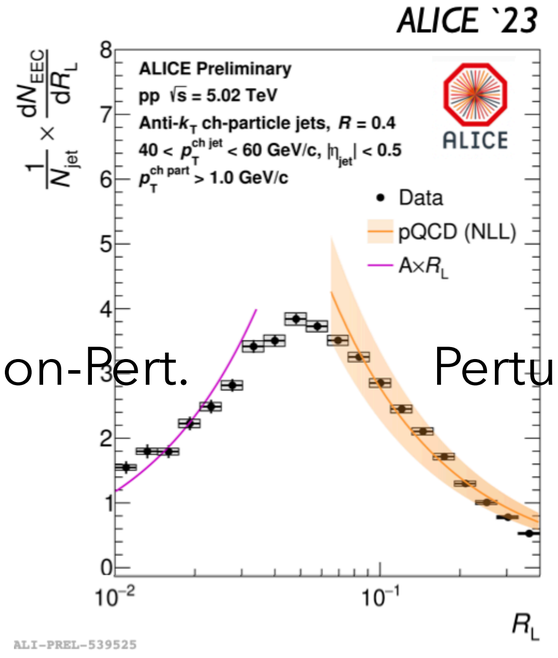
New observable: Energy-Energy correlator

- Energy flow correlations

$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\,\mathbb{O}_i(\hat{n}_1)$$

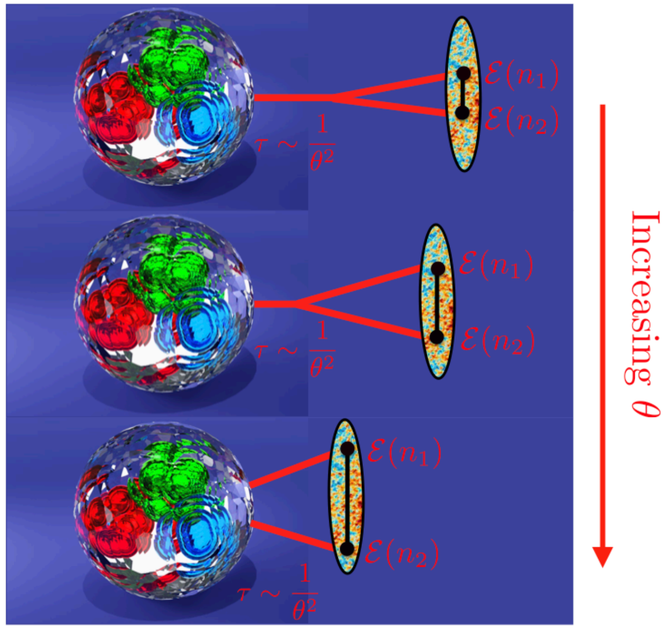
- Proposal: two-point EEC probes hard medium induced radiation

  [Andres, Dominguez, Holguin, Marquet, Moult, (2022)]



non-Pert. Perturbative

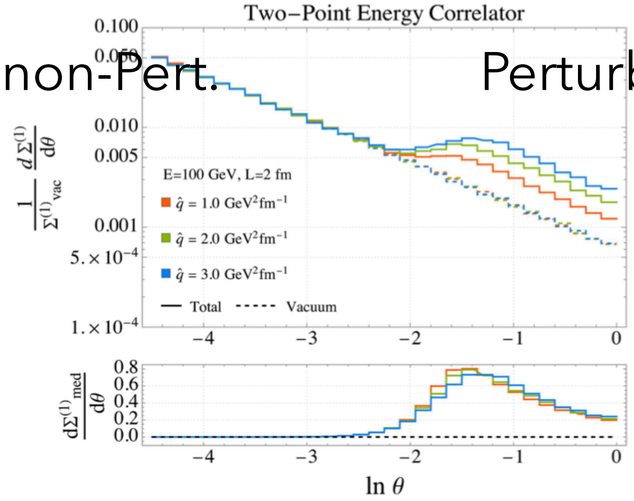
In pp collisions



(a)

Signal at large angles

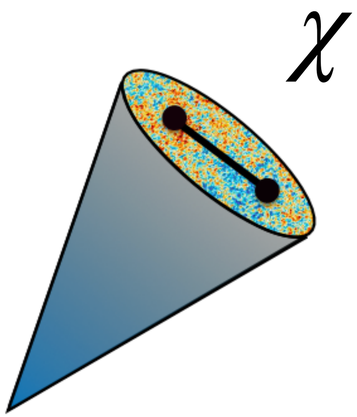
non-Pert. Perturbative



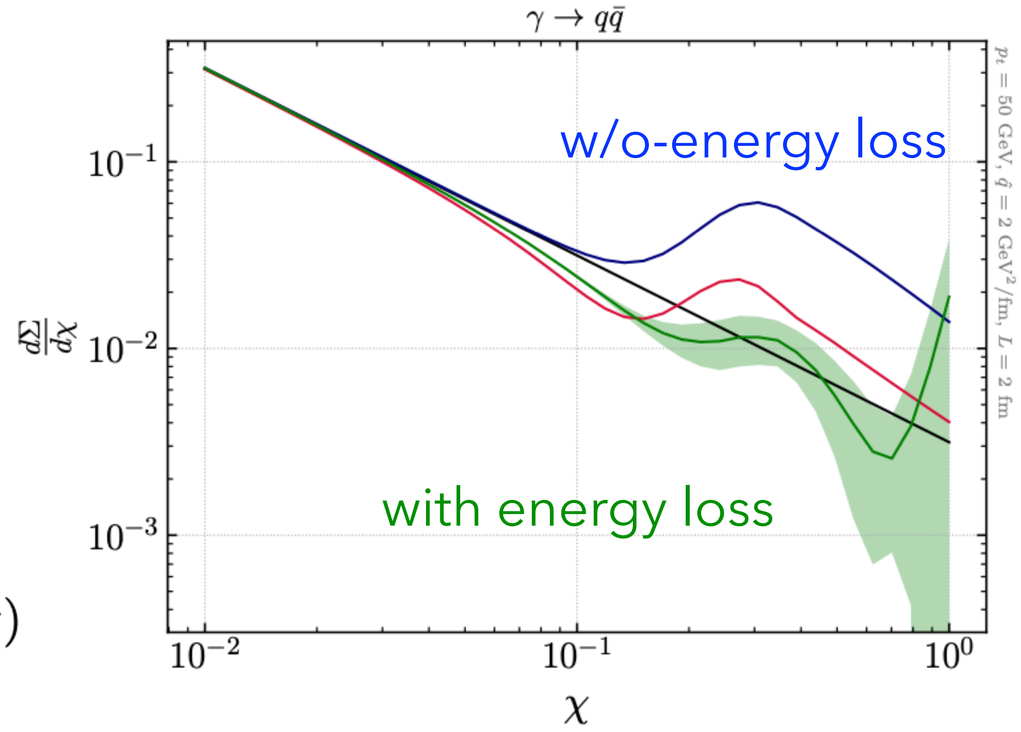
(b)

Basham et al (1978)… Dixon,Moult ,Zhu 2019

New observable: Energy-Energy correlators



$$\frac{\mathrm{d}\Sigma^{(n)}}{\mathrm{d}\chi} = \int_{\vec{n}_1,\vec{n}_2} \frac{\langle \mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\rangle}{Q^2}\delta(\vec{n_1}\cdot\vec{n_2} - \cos\chi)$$



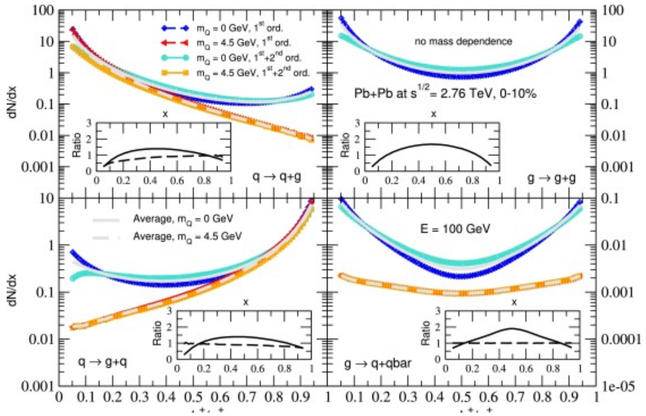
[Barata, Caucal, Soto-Ontoso, Szafron (2023)]

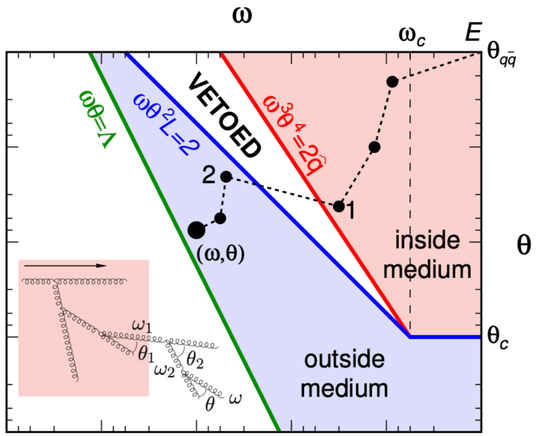
Energy loss effects and soft contamination mays suppress the signal

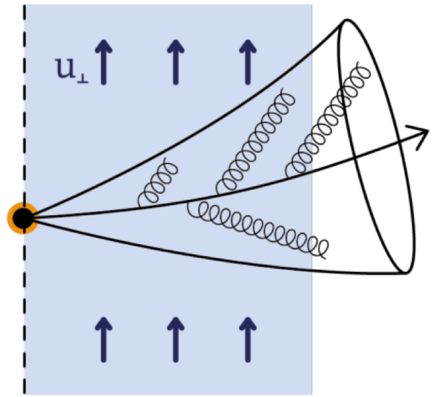
Towards precision computations

A lot of recent progress!

- Full gluon splitting and higher opacity expansion [Vitev, Sievert (2018)]
- Improved opacity expansion [Barata, MT, Soto-Ontoso, Tywoniuk 2019-2022]
- Monte Carlo prescription [Caucal, Soyez, Iancu, Mueller (2018-20)]
- Collective flow in the opacity expansion approach [Sadofyev, Sievert, Vitev (2021)

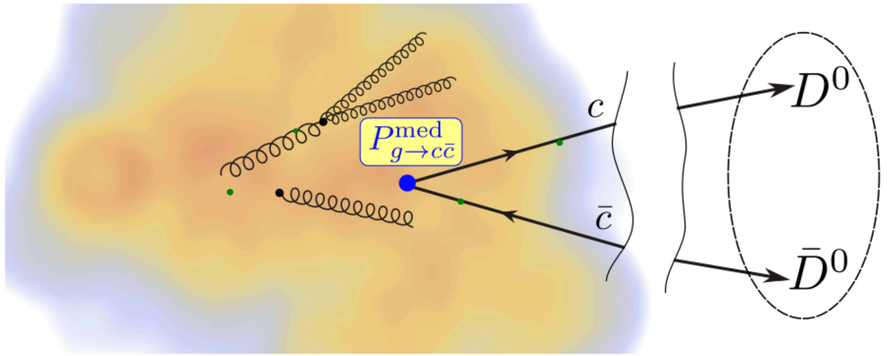


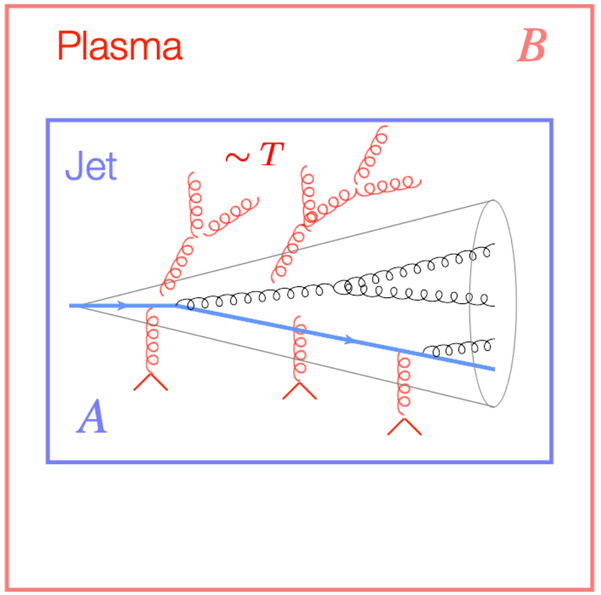




Towards precision computations

A lot of recent progress!

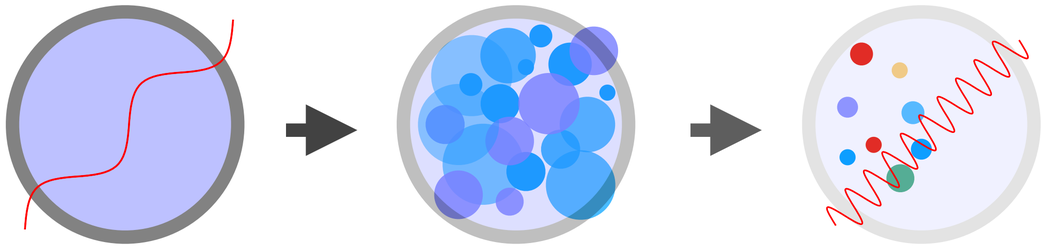




- $c\bar{c}$ enhancement in the medium [Attems, et al (2024)]
- Open quantum system description [Vaidya, Yao (2020-2021)]
- And a lot more! ….

Open questions

- Understanding thermalization with jets → sPHENIX
- Extract scale dependence of the quenching parameter → QGP PDF
- Factorization theorems for heavy ion collisions → precision theory
- Strong coupling (ideal fluid) to weak coupling transition
- Jet chemistry, heavy flavor transport, hadronization, …



Thank you!