Prospects for Jet Measurements

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ALICE USA meeting at Yale

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Open Questions

- What are the properties of QGP?
- How does the hydrodynamization happen and how QGP is created?
- How does hadronization happen in low and high parton density environment?

Answers with Hard Probes

- What are the properties of QGP?

  Extract its properties from slow (diffusion) and fast moving hard probes (energy loss / elastic scatterings)

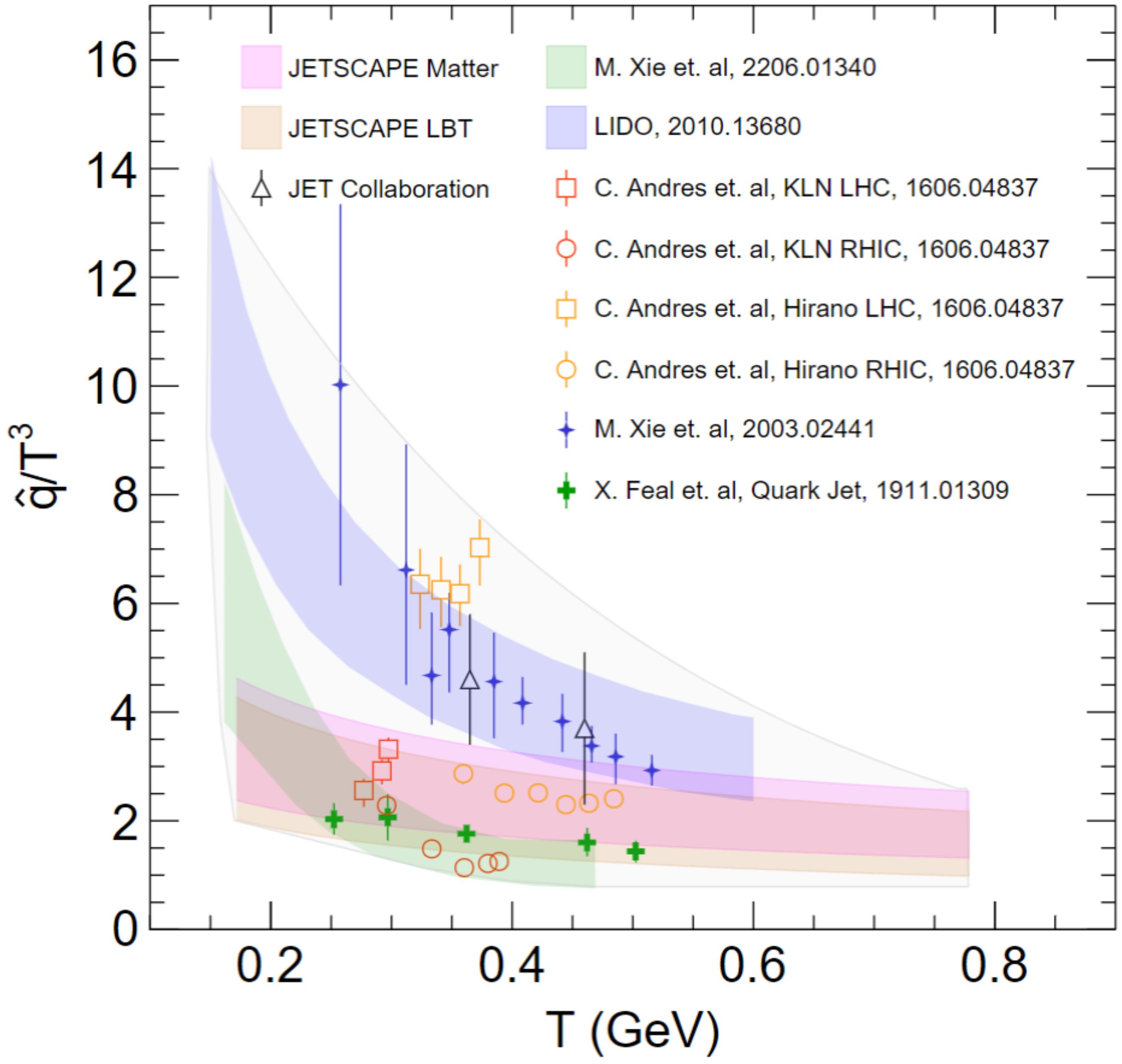
- How does the hydrodynamization happen and how QGP is created?

  Start from probes that are far from hydrodynamization
  Excite QGP response and see how it evolves

- How does hadronization happen in low and high parton density environment?

  Study how heavy quarks and jets hadronize

QGP Transport Properties with RHIC and LHC Run 2 Data



Compilation by YJL, Michael Winn, Liliana Apolinario arXiv:2203.16352
Progress in Particle and Nuclear Physics, 103990 (2022)

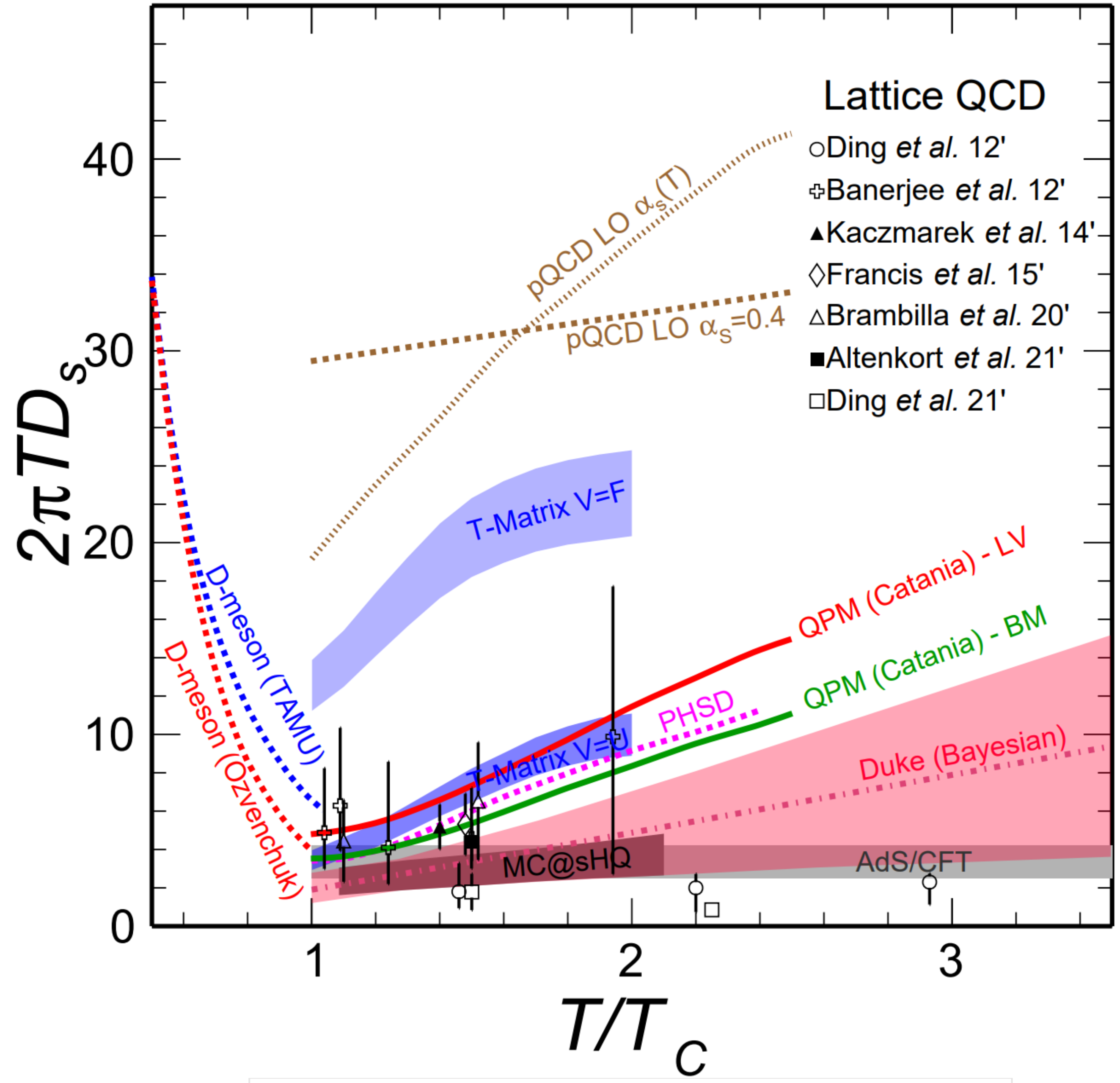
Jet Quenching Parameter $\hat{q}$

- Extracted mainly from charged hadron spectra R_{AA} data
  - Some analyses included γ-hadron and di-hadron data
  - Expansion to include jet observables has started
- $\hat{q}$ /T^3 : decreasing trend vs. T
- Extracted values differ by up to a factor of 7

Remaining Issues:

- Different jet quenching mechanisms in theoretical models
- Different QGP media used in calculations
- Hadron re-scattering in the hadron gas phase
- Hadronization of fast moving partons
- Role of initial stages

QGP Transport Properties with RHIC and LHC Run 2 Data



Xin Dong, YJL, Ralf Rapp, Ann.Rev.Nucl.Part.Sci. 69 (2019) 417-445

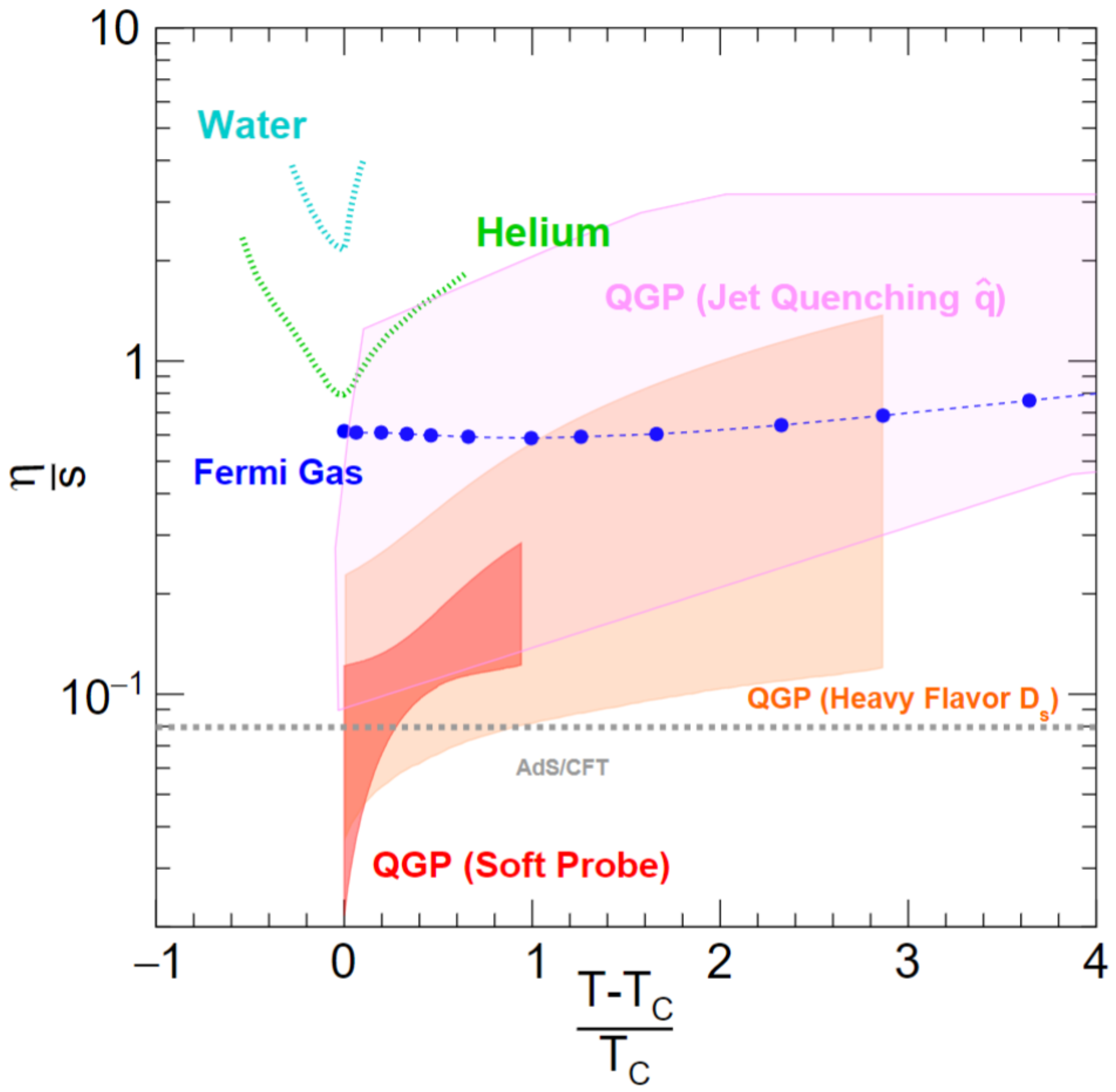
Charm diffusion coefficient D_s

- Bayesian analysis from D meson R_{AA} and v_2
- pQCD calculations at LO are ruled out by the data
- Non-perturbative calculations with a potential close to the HQ free energy from LQCD are not viable
- Increasing trend of $2\pi TD_s$ vs. T in various models

Remaining Issues:

- Hadronization of charm quarks
- Charm diffusion mechanism
- Different QGP media used in various calculations
- Precision of the experimental data

Medium Properties from Soft and Hard Probes



Compilation by YJL, Michael Winn, Liliana Apolinario arXiv:2203.16352
Progress in Particle and Nuclear Physics, 103990 (2022)

Specific viscosity has been extracted from **soft probes**

- Via identified hadron dN/dη, $<p_T>$, v_2, v_3 and v_4
- Main uncertainties from initial state and early time dynamics

To get the big picture of the QGP properties with Run 2 + RHIC data, one could compare the inputs from soft and hard probes:

- **HQ D_s** could be related to specific viscosity by

$$\frac{\eta}{s} = \frac{D_s(2\pi T)}{4\pi k}$$

R. Rapp, H. van Hees, 0903.1096
X. Dong, YJL, R. Rapp, 1903.07709

Where the scale factor k ranges between 1 (strong-coupling limit) and 2.5 (weak coupled)

- **Jet quenching parameter $\hat{q}$** could be related to specific viscosity in the limit of multiple soft scattering by

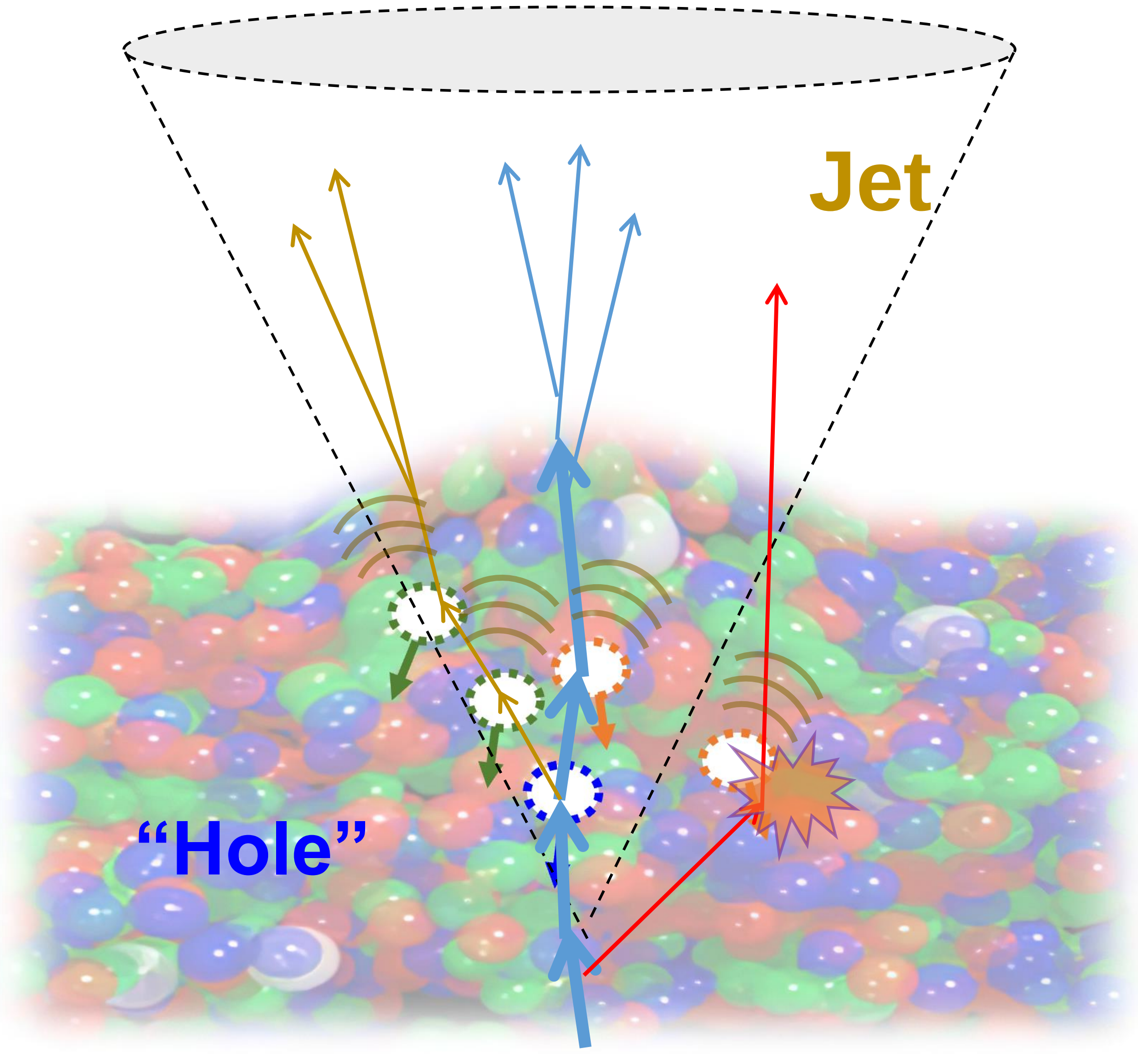
$$\frac{\eta}{s} = C\frac{T^3}{\hat{q}}$$

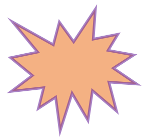
Where the scale factor C is varied between 1.25 and 2.5

A. Majumder, B. Muller, Xin-Nian Wang PRL 99 (207) 192301
B. Muller PRD 104 (2021) 7, L071501

Medium properties extracted from **Jet Quenching** and **Open Heavy Flavor** are consistent with the results from **Soft Probes**, but within rather large uncertainties

QGP Transport Properties and Structure with Jets



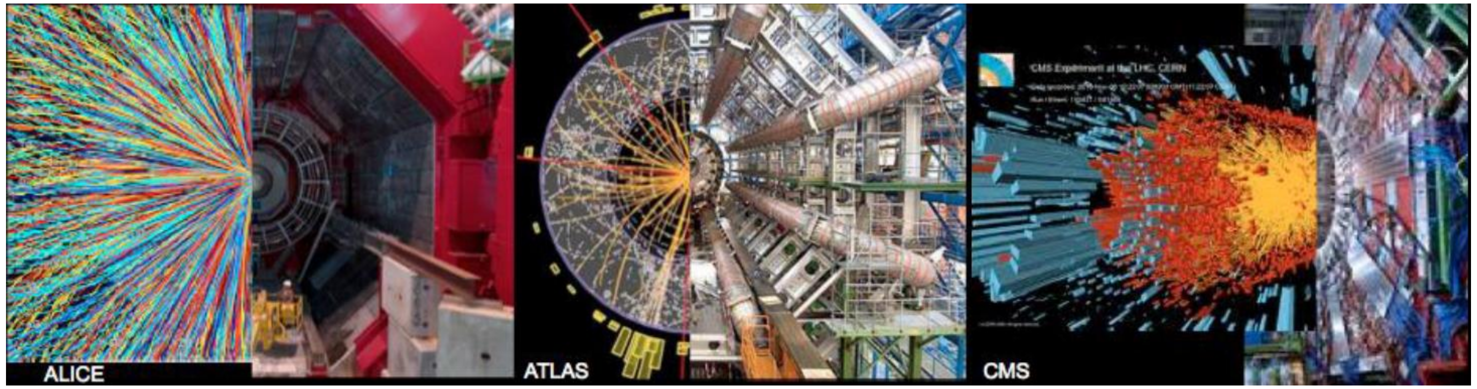
- Jet broadening effects from multiple soft scattering ($\hat{q}$) and induced radiation
- Contribution from medium response 
- Reveal medium recoil (the propagation of QGP holes) 
- With the precise understanding of the phenomena above, one could reveal the QGP structure with Moliere scattering 

Lessons learned from Jet Data

- **Jet quench** in large collision system, quenched energy recovered only when we include **low p_T particles** up to **very large angle (ΔR ~ 2)**

- **Jet quenching depends on the color charge and parton shower shape**: broad showers are more quenched and results in apparent narrowing of inclusive jet

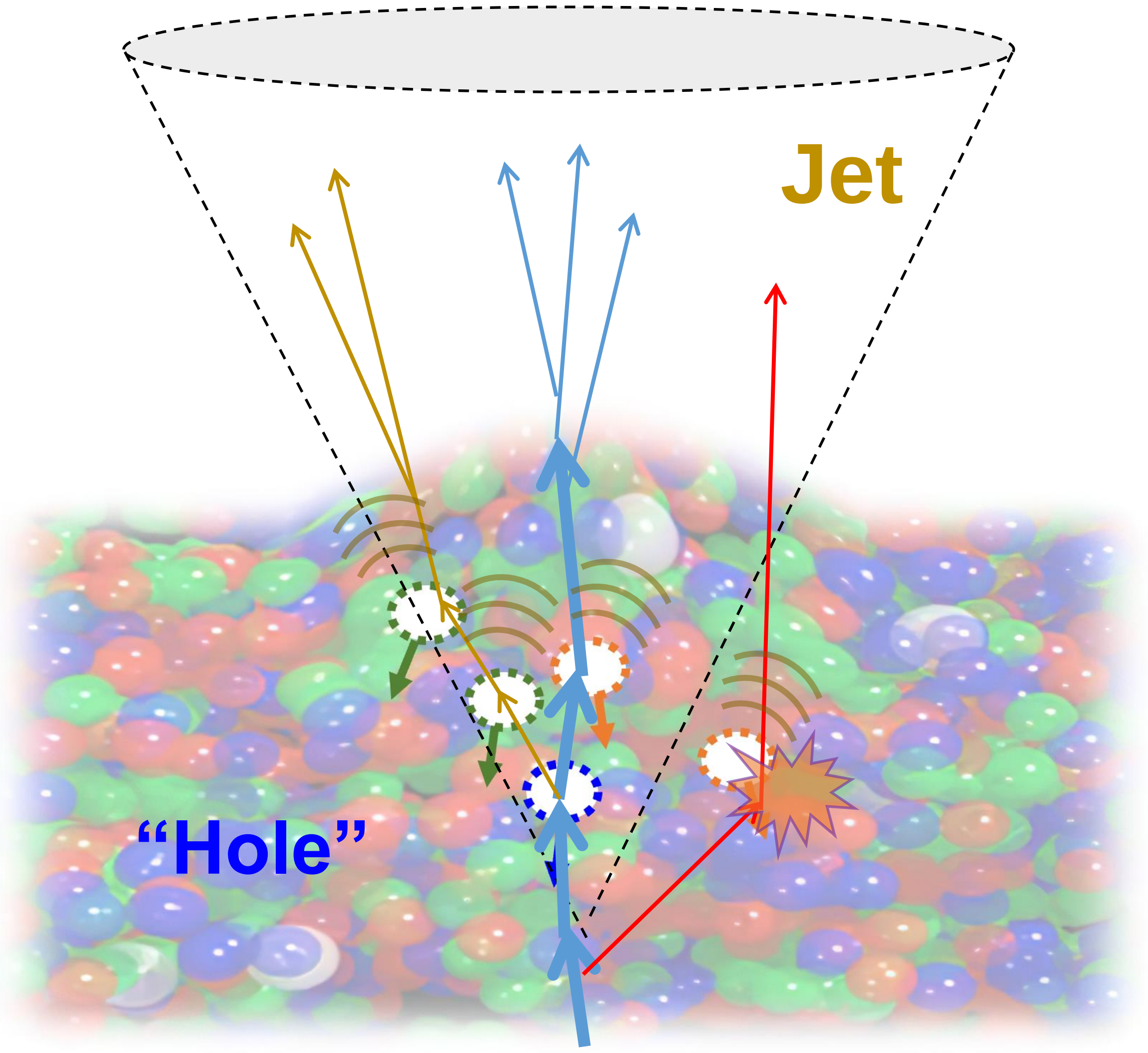
- No sign of jet quenching in smallest collision systems through jet spectrum and substructure



MSS and Induced Radiation

- Jet broadening effects from multiple soft scattering $(\hat{q})$ and induced radiation:
  - Indirect constraints from hadron spectra (ongoing efforts, for instance, from JETSCAPE to include jet data)
  - Lack of direct measurements of multiple soft scattering
  - High precision inclusive jet measurements affected by the survival bias effects
  - Low precision photon-tagged and Z-tagged jet data has large room for improvements
  - Ambiguity between induced radiation and medium response

Prospects for Jet Measurements



(1) Observables that are only / maximally sensitive to medium response

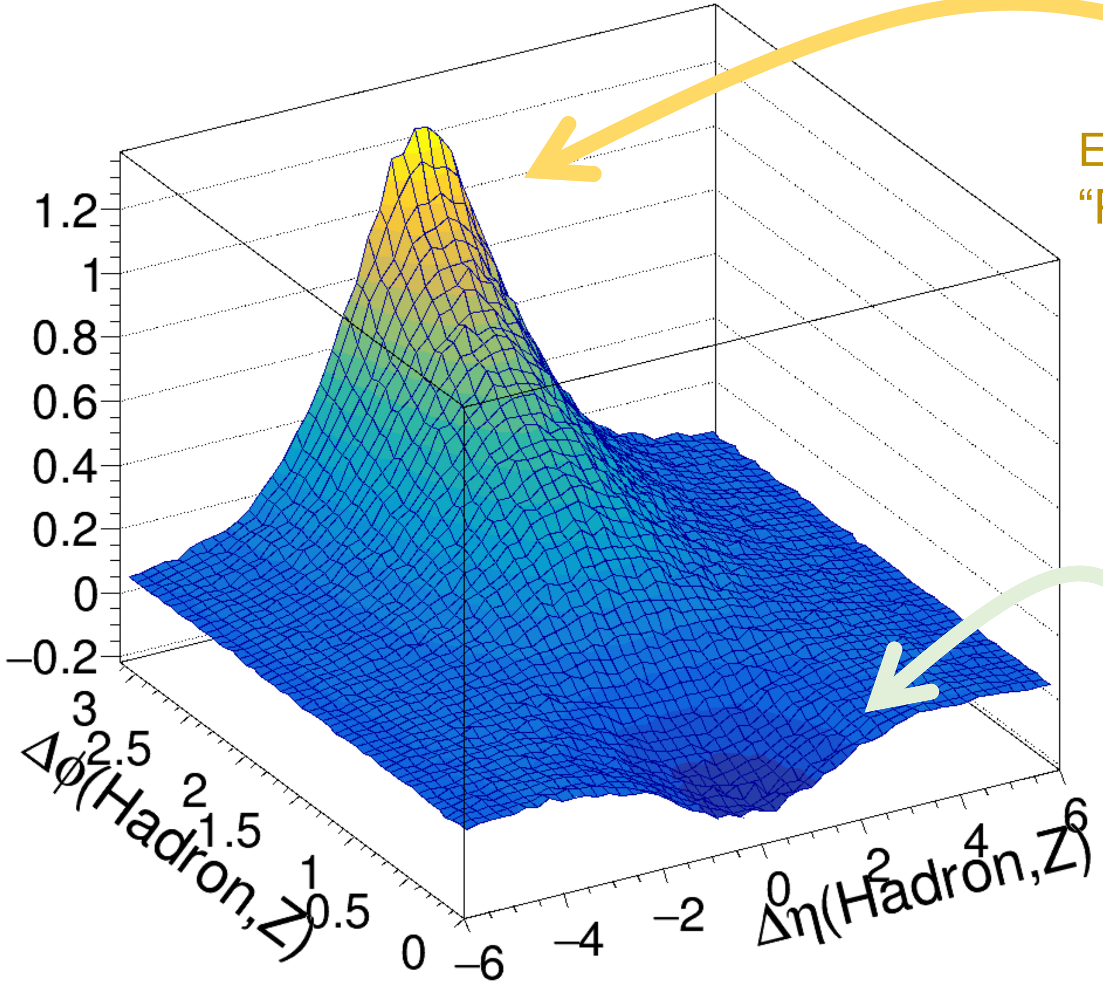
(2) Initial parton virtuality tagging and EEC

(3) Comprehensive survey of the jet splitting with Lund plane. Correlate the observables designed from different phase space on Lund plane.

(4) Search for elastic scattering with optimized observables and direct measurement of HQ diffusion

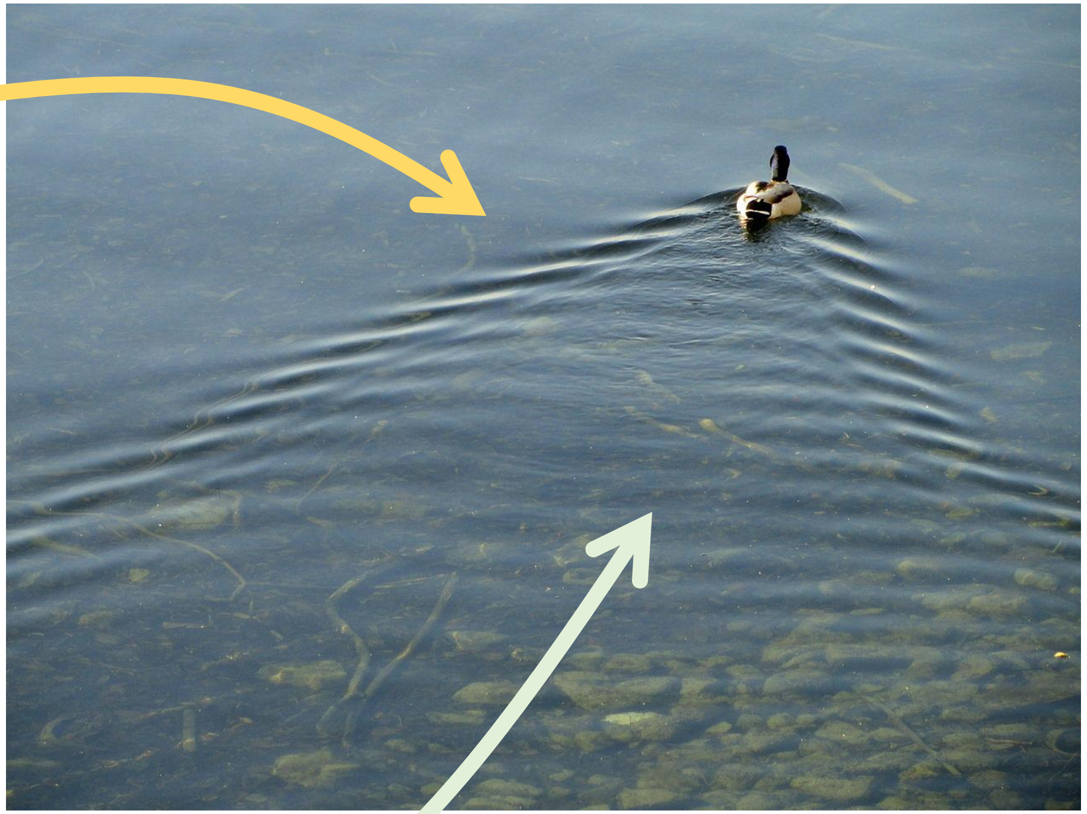
(5) Time dependence: Delay the starting time of the quenching effect with W/Z jet

(1) Reveal the Negative Wake Contribution



Enhancement of particle
“Positive wake”

Depletion of particle
“Recoil”
“QGP hole”
“Negative wake”



Position space

Z^0 and **wake hadron** correlation in Hybrid model

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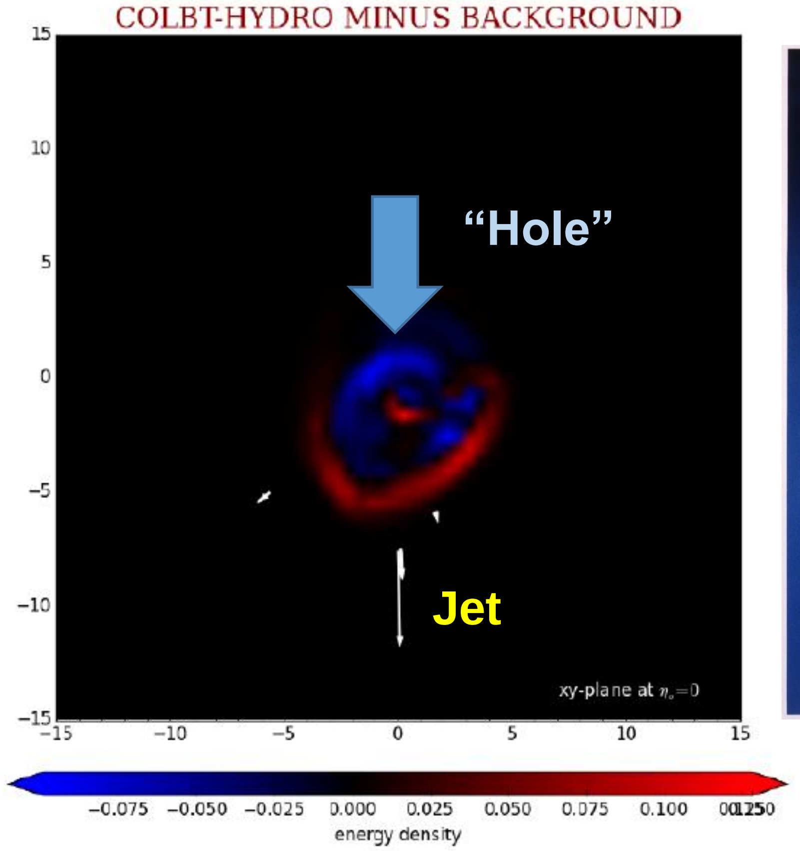
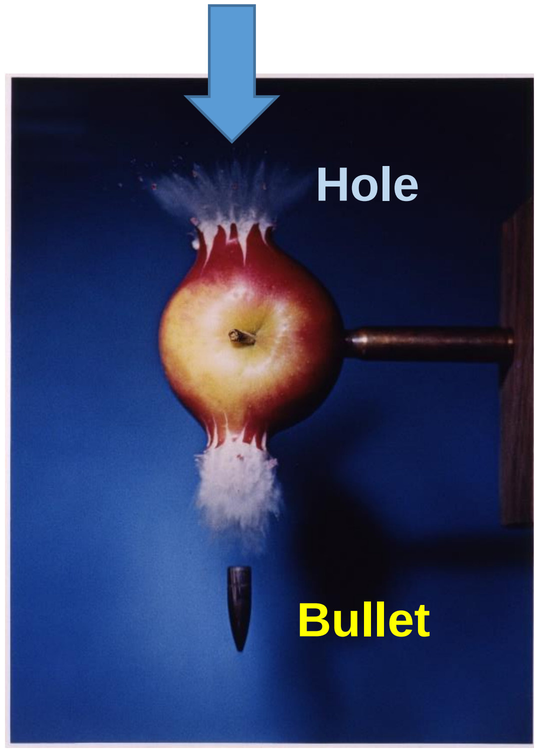
Momentum space

Measure the “Depletion” due to Medium Recoil

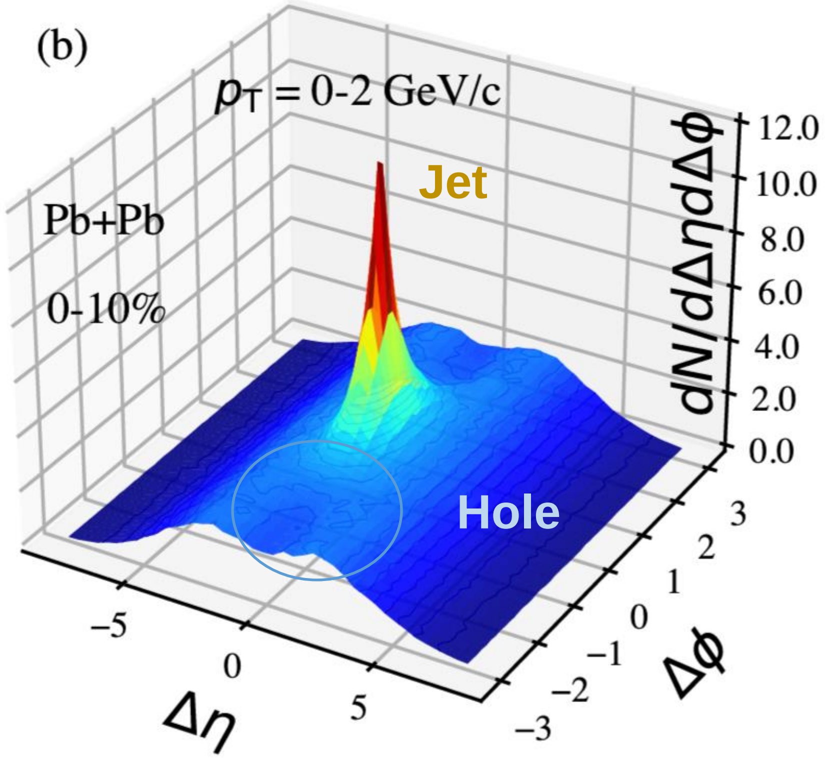
CoLBT

Tan Luo, Xin-Nian Wang



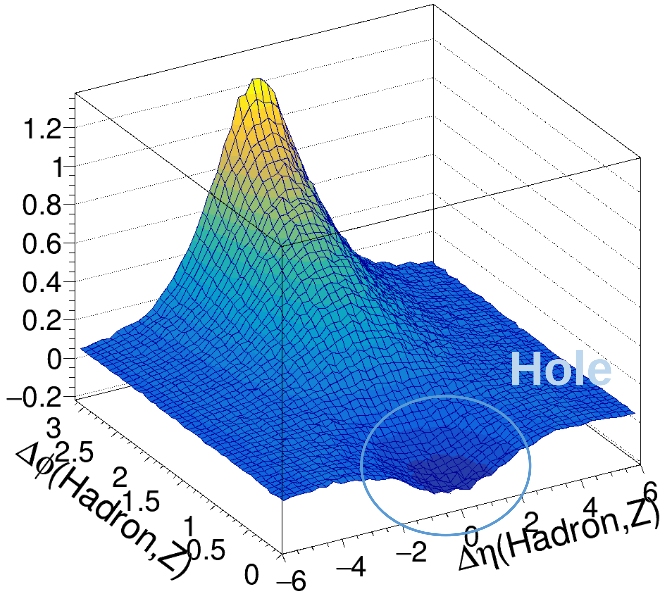


Photon tagged Jet-hadron correlation
Diffusion wake in CoLBT
PRL 130, 052301 (2023)
Zhong Yang, Tan Luo, Wei Chen, Longgang Pang, and Xin-Nian Wang



Z^0 - **wake hadron** correlation in Hybrid model

Daniel Pablo, Krishna Rajagopal, YJL



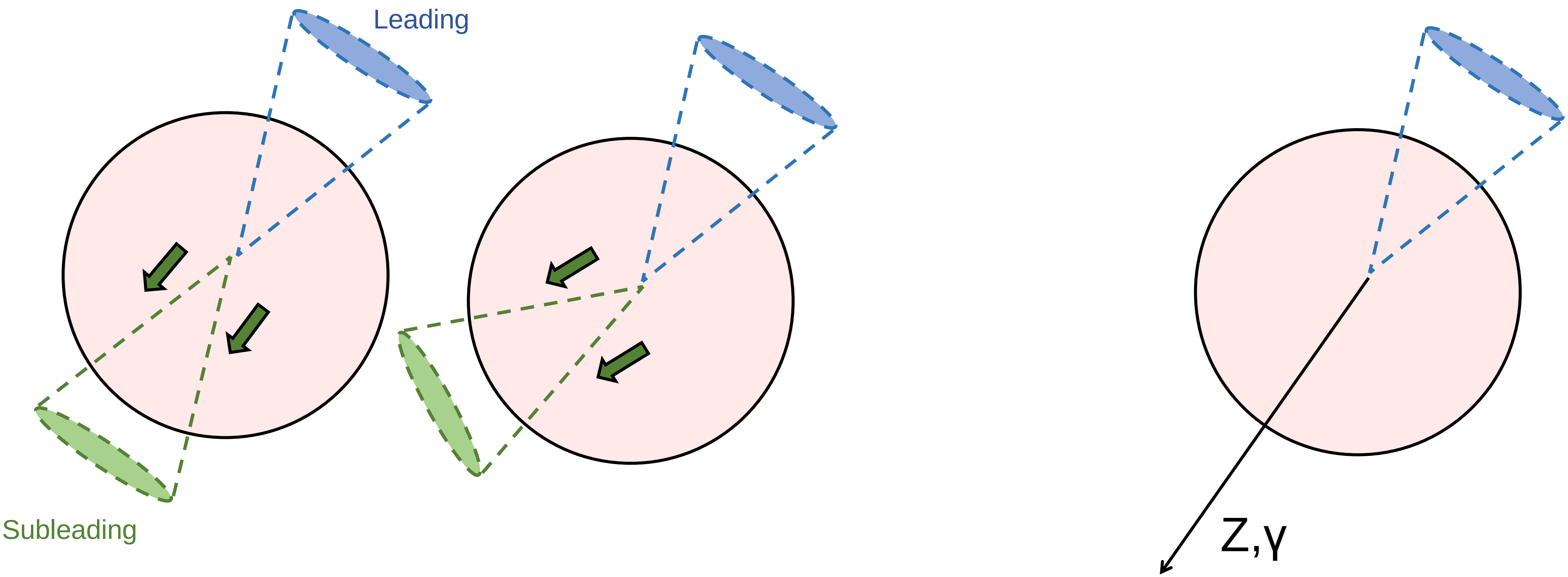
Measure the **boson-side associated yield** with Photon-jet and Z-jet

Reveal the Negative Wake Contribution

Receive back reaction effect from the **away side jet**

Receive **partial** back reaction from the away side jet

No back reaction from the electroweak boson



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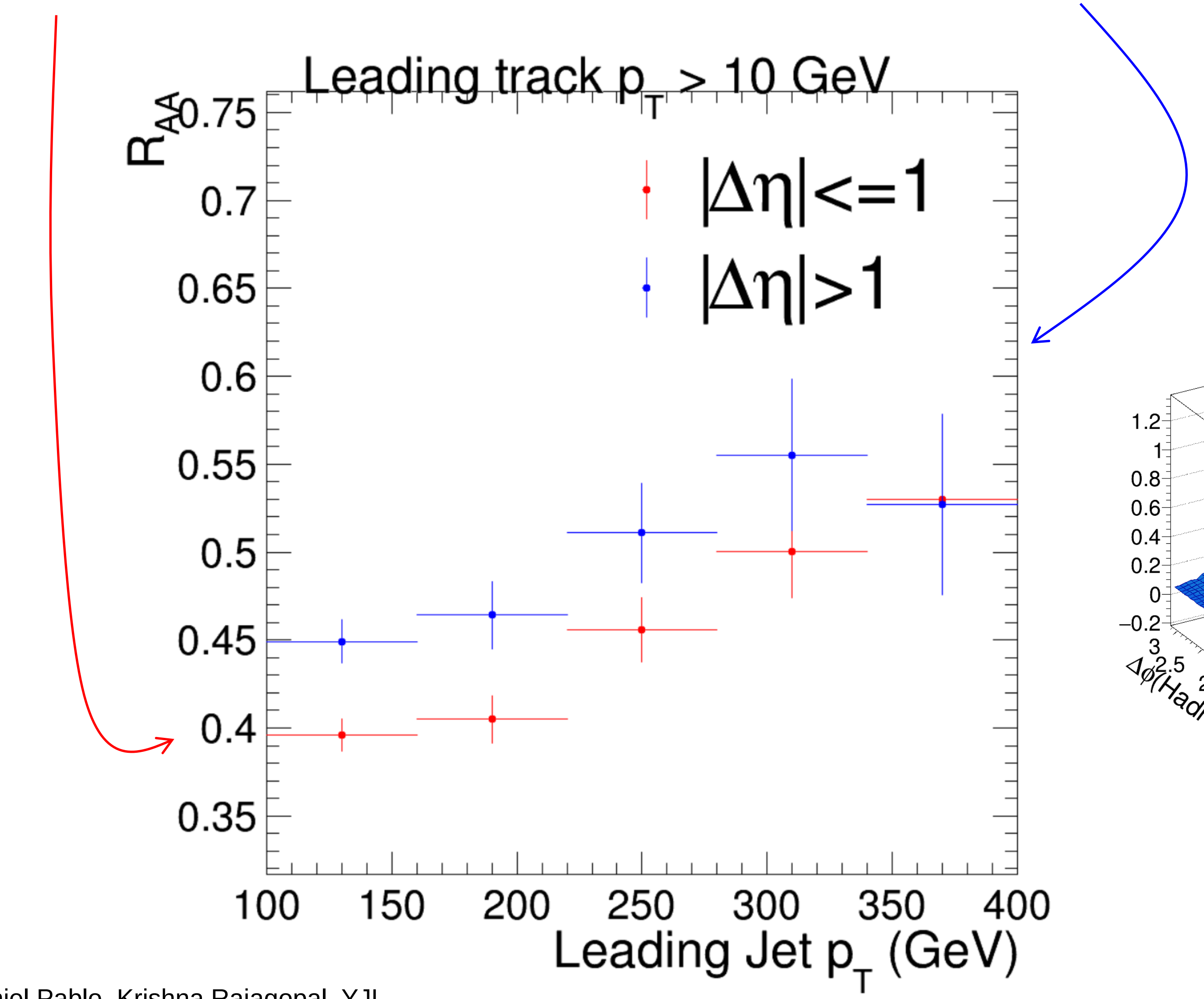

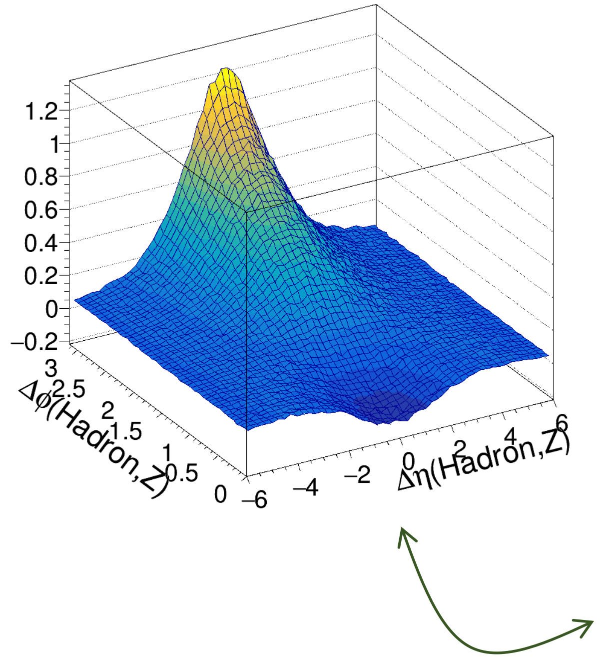

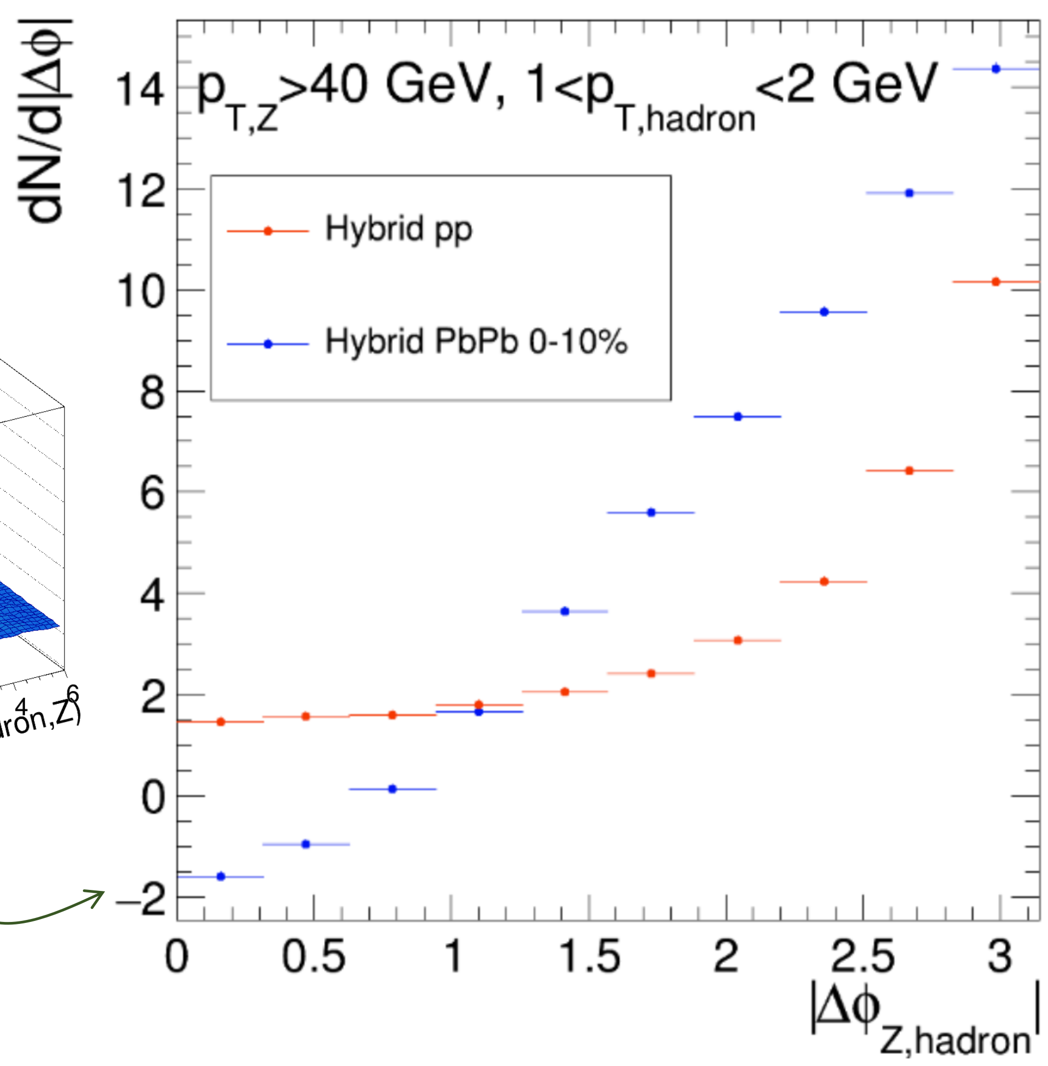

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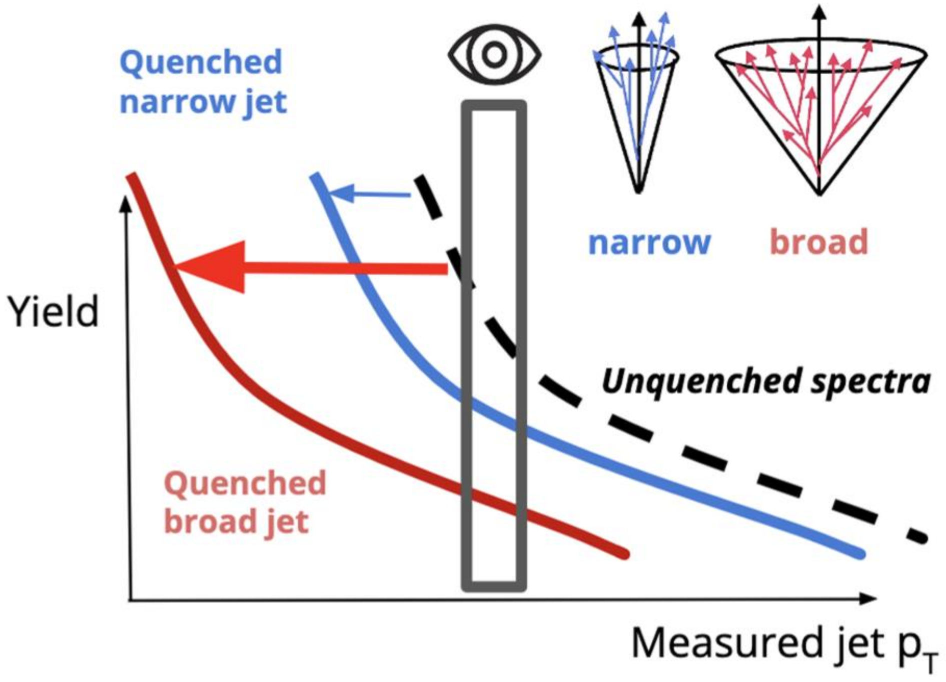
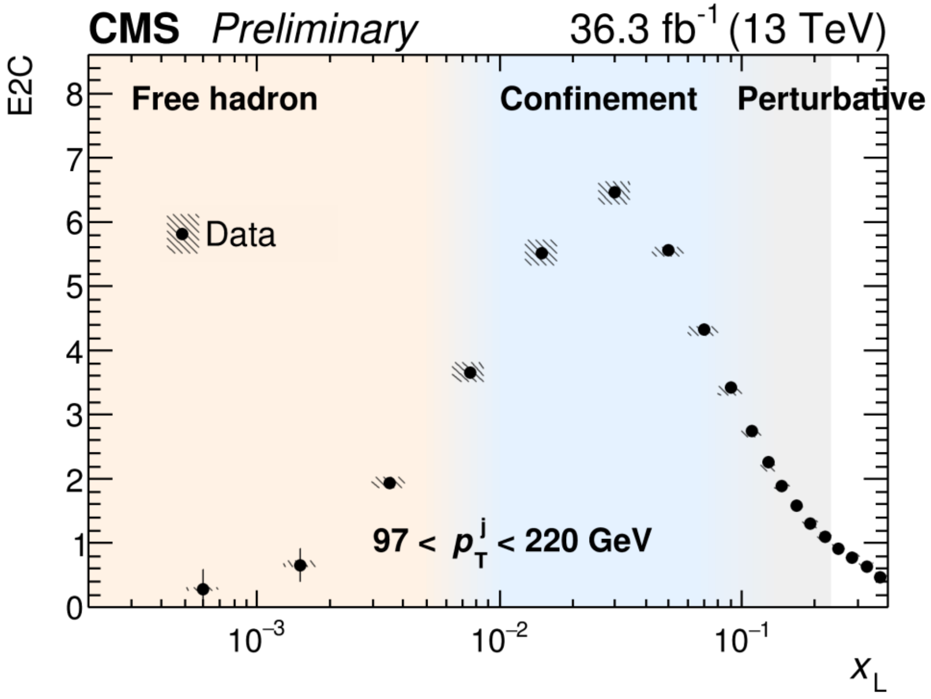
(2) Tag the (Initial) Parton Virtuality of a Jet

- Inclusive jet substructure studies show jets are narrowing, offering detailed insights per jet, advance from jet shape and FF. However, the measurements are significantly affected by selection bias.

- Highest priority on substructure observables that reduce survival-bias.

- Linking the (initial) virtuality of parton showers to jet measurements with **(photon/Z)-jet** or parton-shower based tagging for **inclusive jet**.



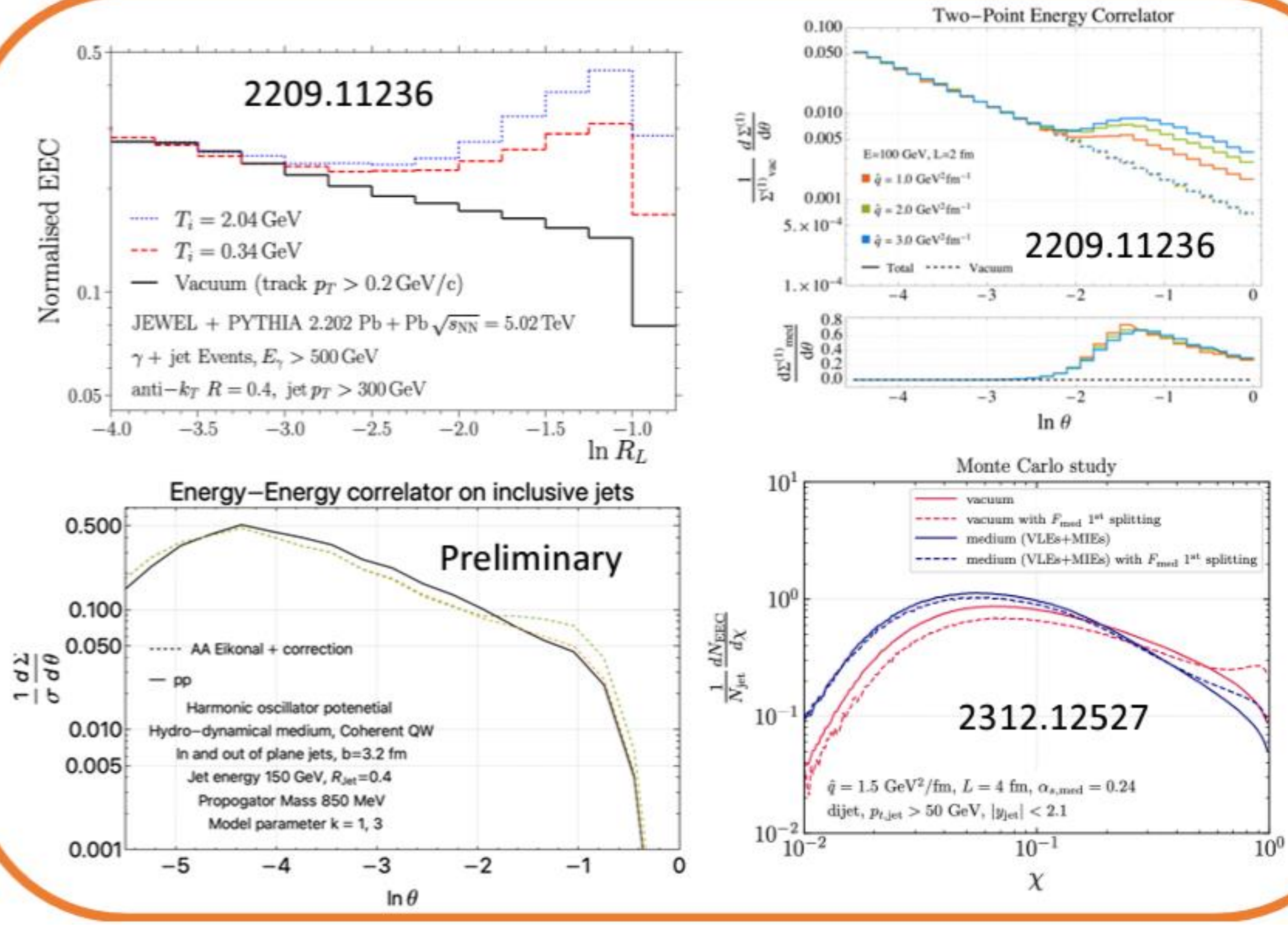


Energy-Energy Correlators

The pp baseline is extremely under control. No other observables, besides inclusive total cross-sections, have been computed with this level of analytic control.

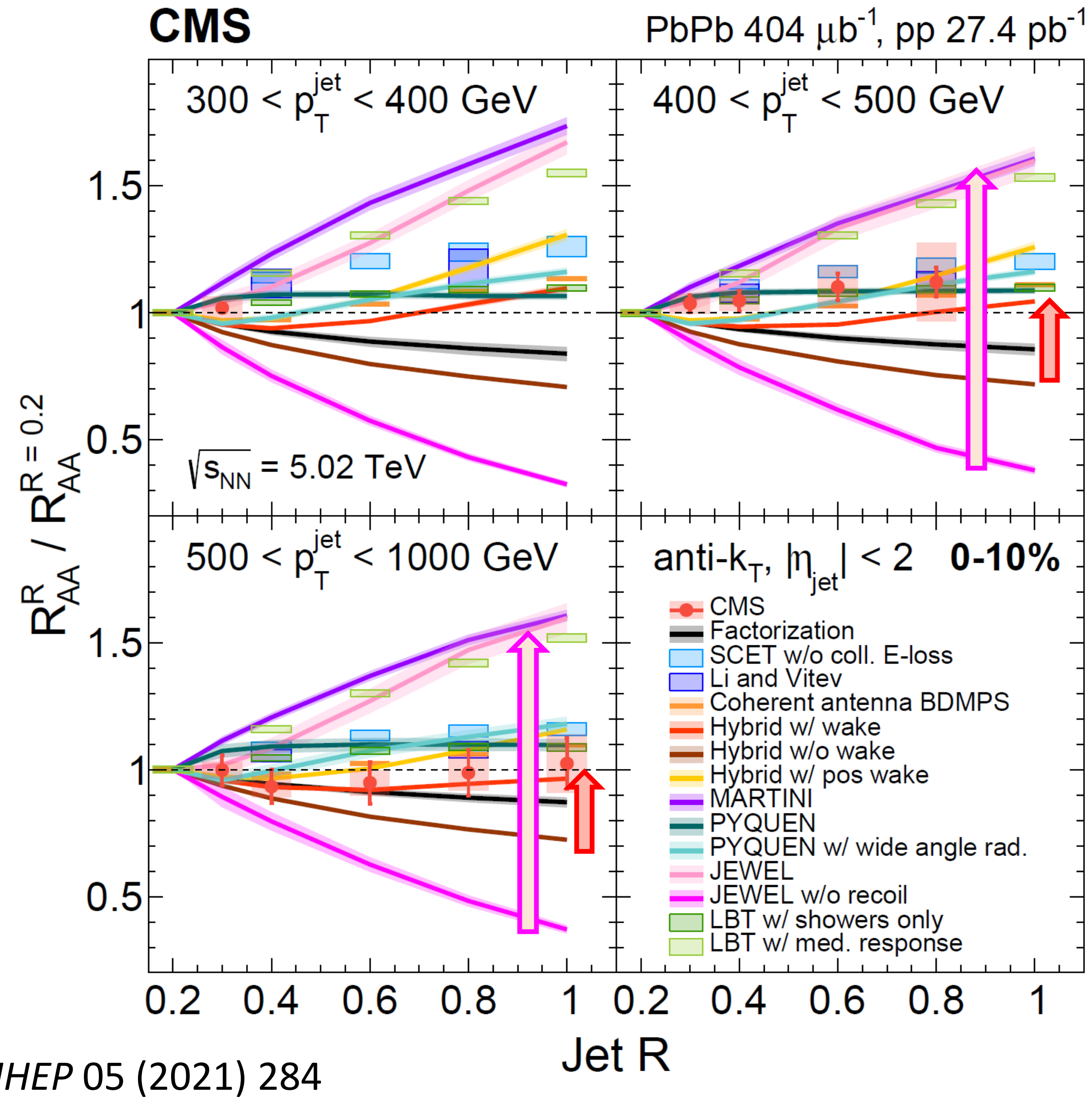
$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle$	$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\mathcal{E}(\vec{n}_3)\rangle$	$\langle \mathcal{E}(\vec{n}_1) \dots \mathcal{E}(\vec{n}_i)\rangle$
Complete NLO (2-loops) for colour singlet Dixon, Luo, Shtabovenko, Yang, Zhu arXiv:1801.03219	Complete LO (1-loop) for colour singlet Yang, Zhang arXiv:2402.05174	Tree-level
Small angle NNLL & NNNLL Dixon, Moult, Zhu arXiv:1905.01310 Gao, Li, Moult, Zhu arXiv:2312.16408	Small angle NLL Cheng, Moult, Zhu arXiv:2011.02492	Small angle NLL Cheng, Moult, Zhu arXiv:2011.02492

Moreover, EEC could be performed
with (inclusive jet based)
or
without jet reconstruction
(with photon or Z-tagged jets)

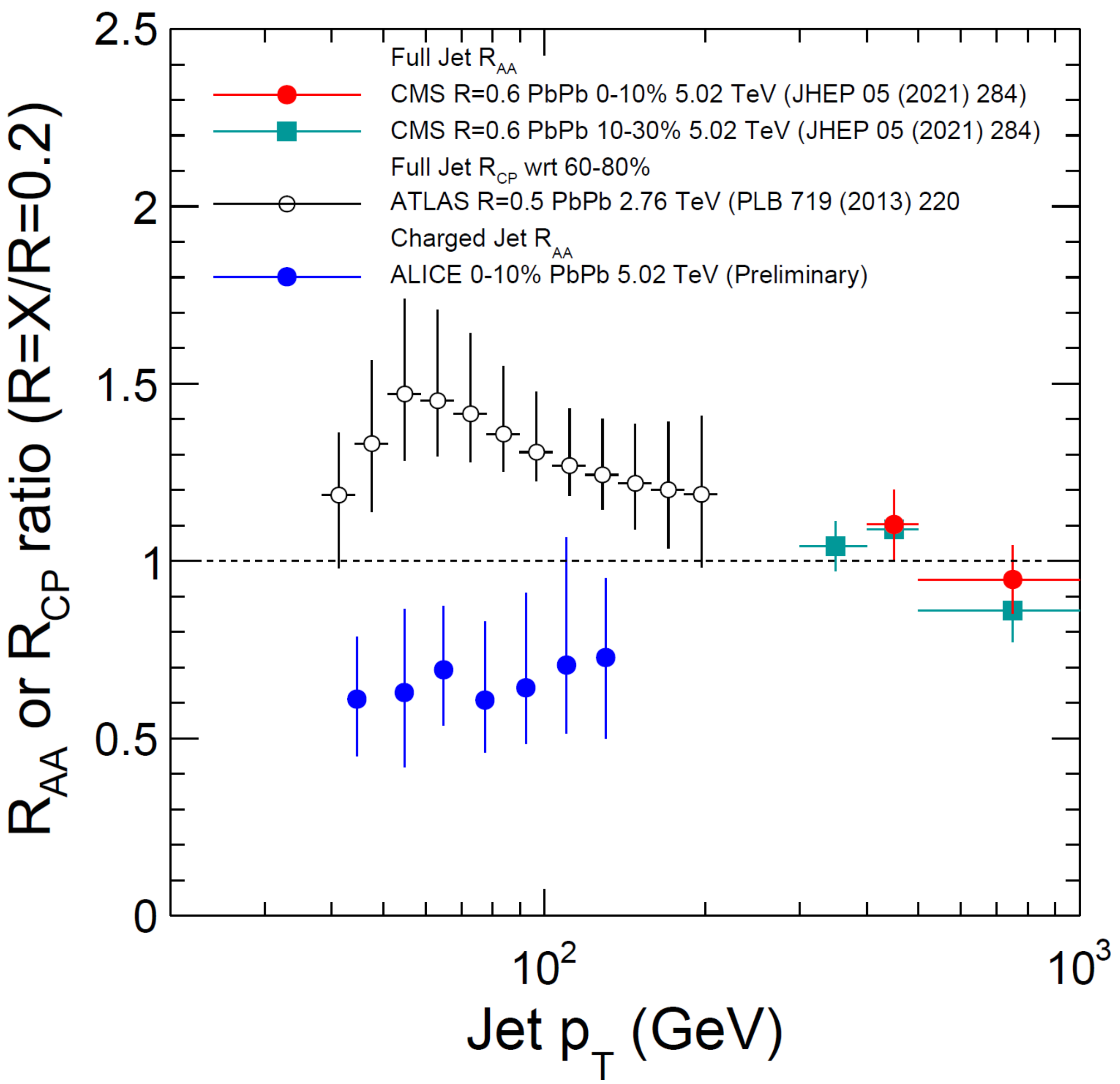


Compiled by Jack Holguin

Follow Up with the Large Area Jets

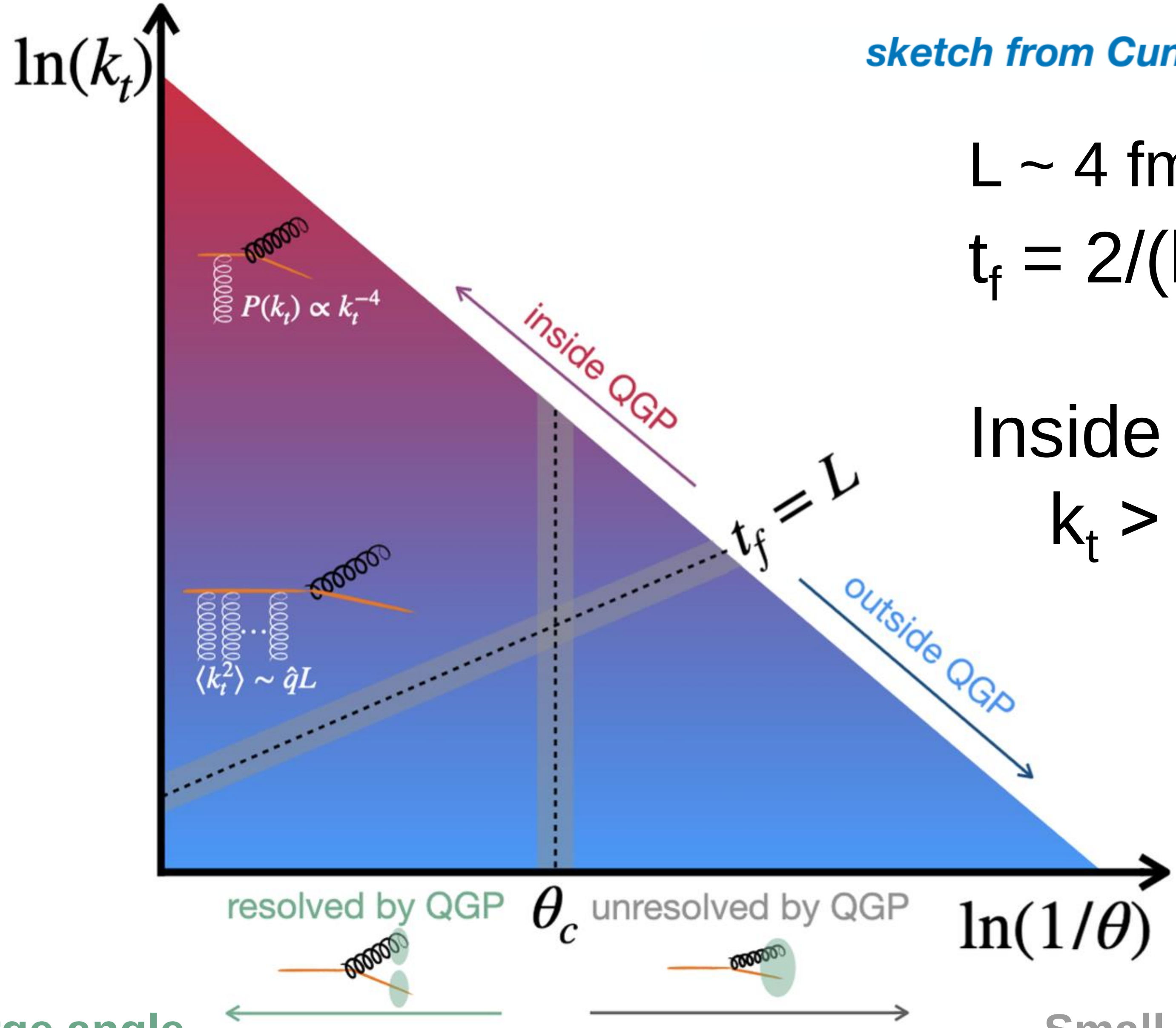


JHEP 05 (2021) 284



Need high precision measurement and resolution of the ATLAS / ALICE discrepancy

(3) Survey of the Jet Splitting with Lund Plane



sketch from Cunqueiro et al arXiv:2311.07643

L ~ 4 fm ~ 20 GeV^{-1}

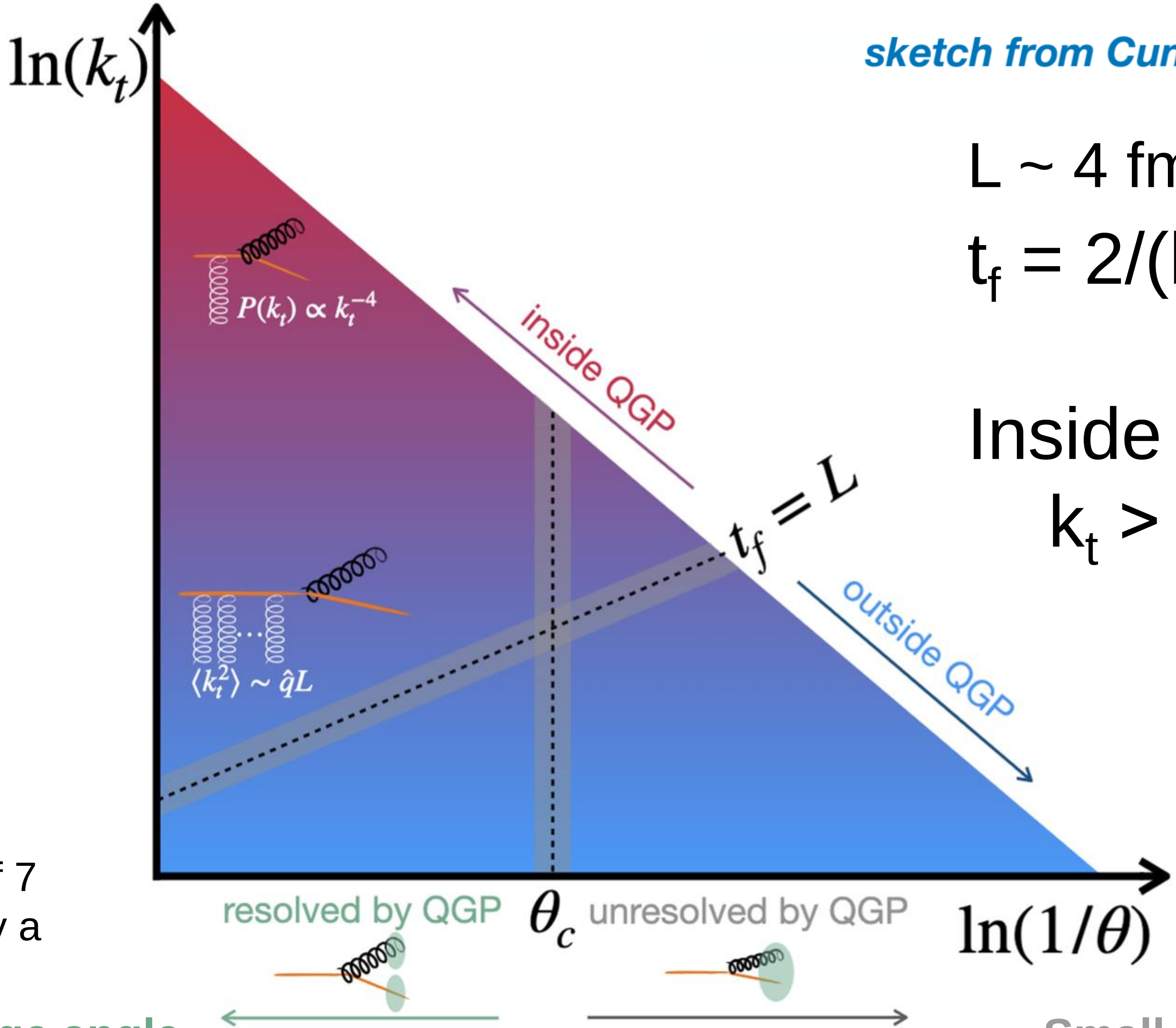
$t_f = 2/(k_t\theta) = L$

Inside QGP:

$k_t > 0.1/\theta$ (GeV)

Large angle **Small angle, collinear**

(3) Survey of the Jet Splitting with Lund Plane



sketch from Cunqueiro et al arXiv:2311.07643

$L \sim 4$ fm ~ 20 GeV^{-1}

$t_f = 2/(k_t\theta) = L$

Inside QGP:

$k_t > 0.1/\theta$ (GeV)

$$\theta_c = \frac{2}{\sqrt{\hat{q}L^3}}$$

PLB 725, 357 (2013)

➡ Varying $\hat{q}$ by a factor of 7
Meaning θ_c changed by a factor of ~ 2.7

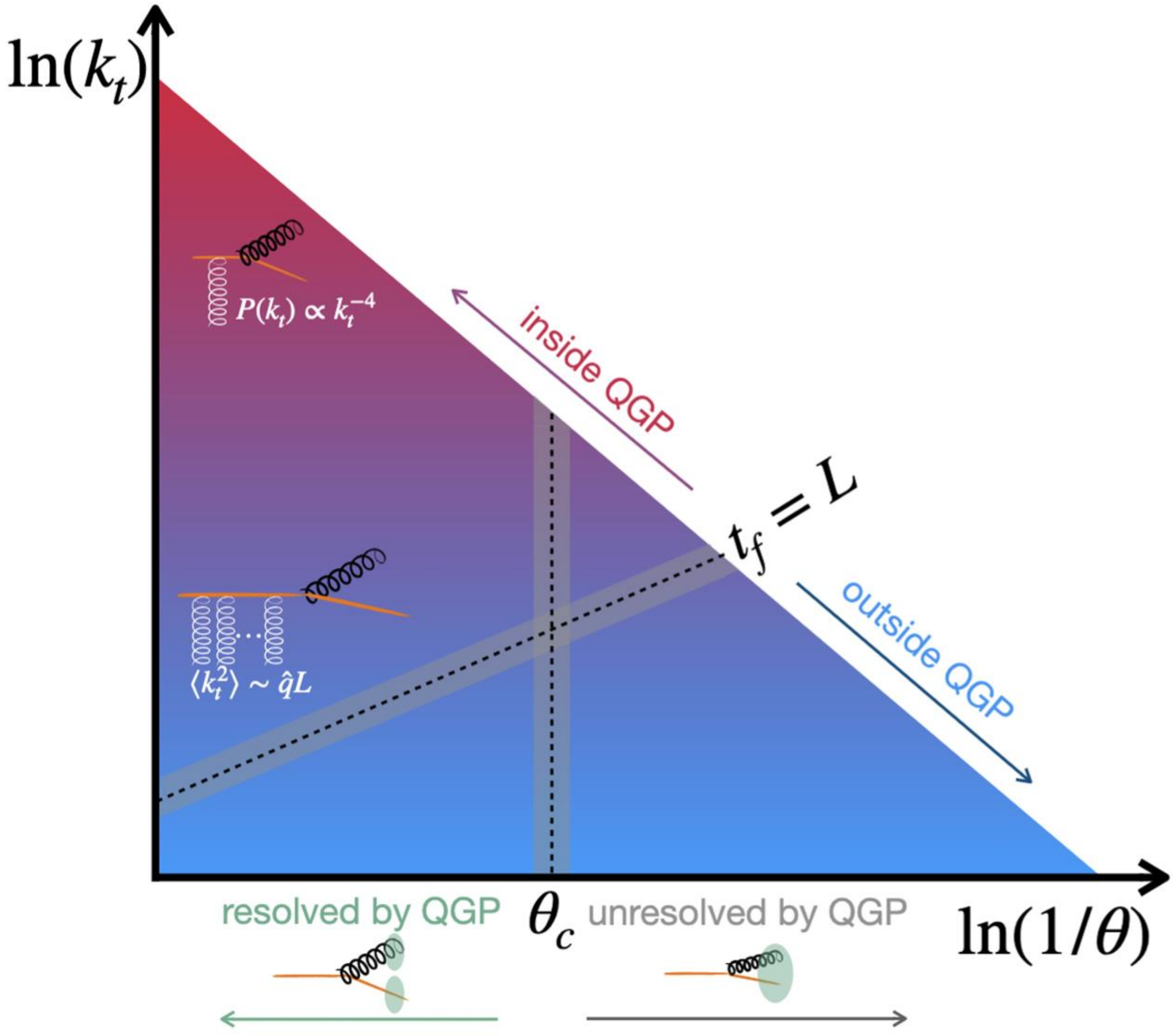
Large angle

Small angle, collinear

$\hat{q} = 1.5\ \mathrm{GeV^2/fm} \rightarrow$ $\theta_c \sim 0.04$

(3) Survey of the Jet Splitting with Lund Plane

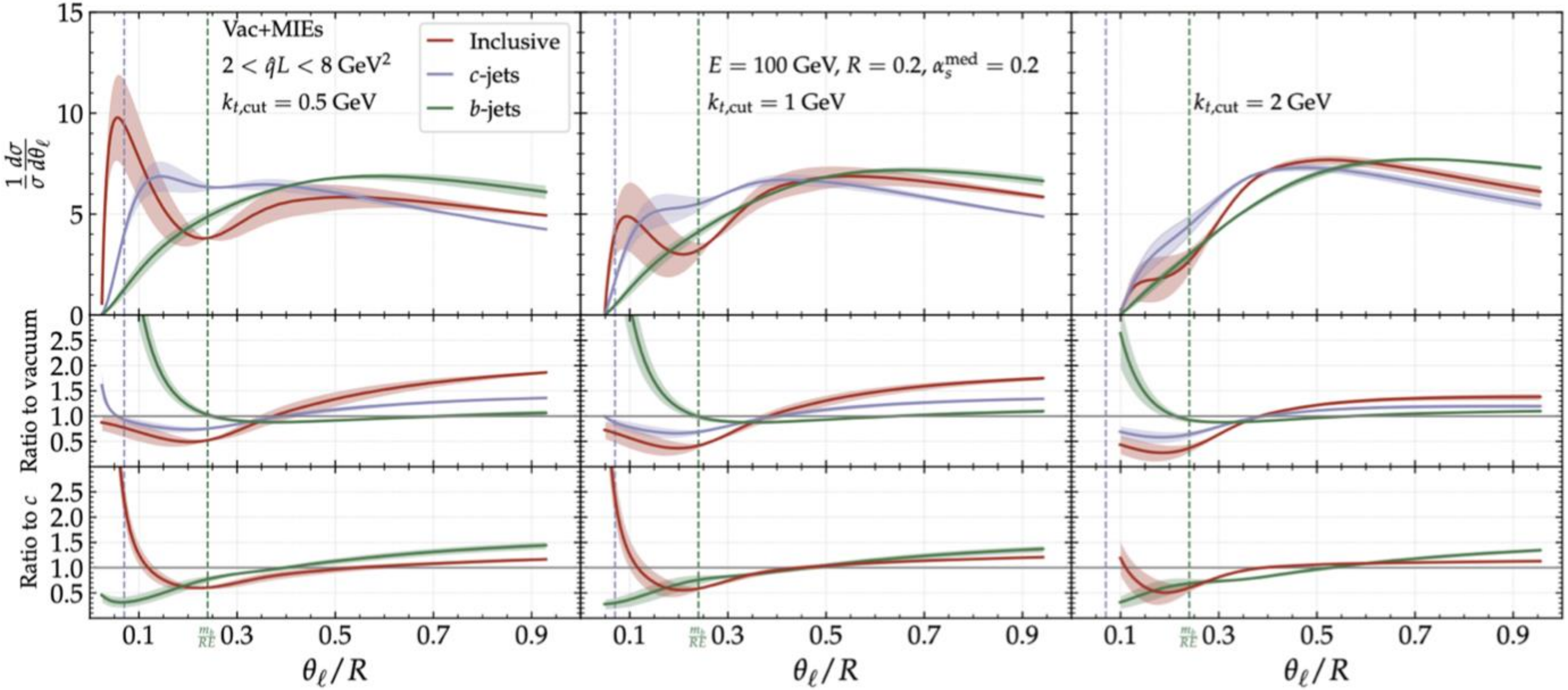
- Ideally we want to measure the full Lund plane with high p_T photon-tagged jets
- High statistics high p_T inclusive jet data are still to be measured.
- Validate our theoretical understanding of the splitting in different part of the phase space in Lund Plane
- Correlate the substructure derived from different regions in the Lund Plane (Controlled vs. Medium modified).



sketch from Cunqueiro et al arXiv:2311.07643

Dead cone in HIC using Jet Tree

medium



$\theta_C < \theta < \theta_{dead}$

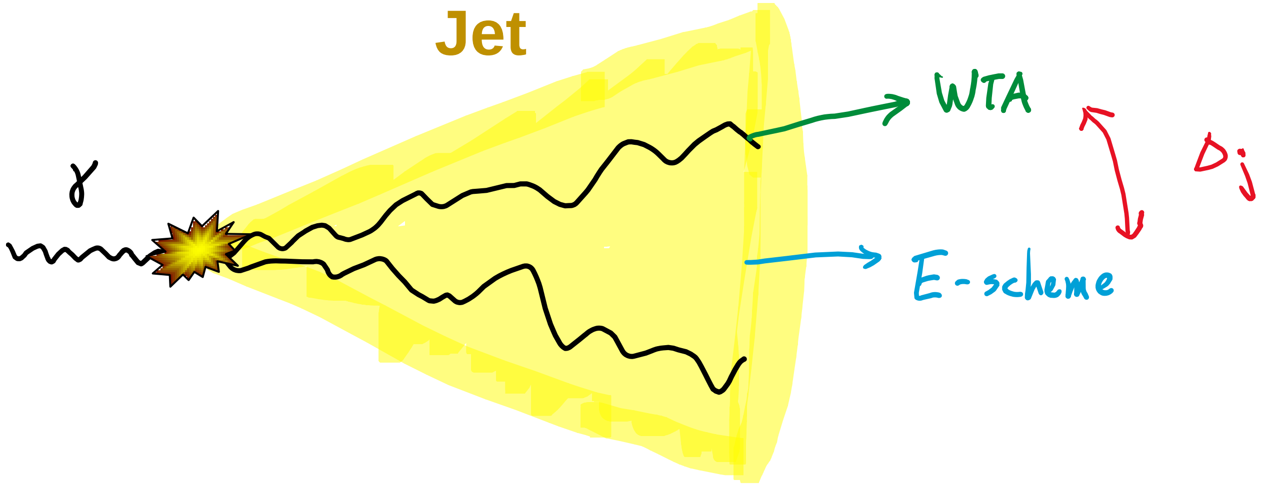
QGP-induced signal is expected to fill the dead cone for b-jets. Detectable signal!

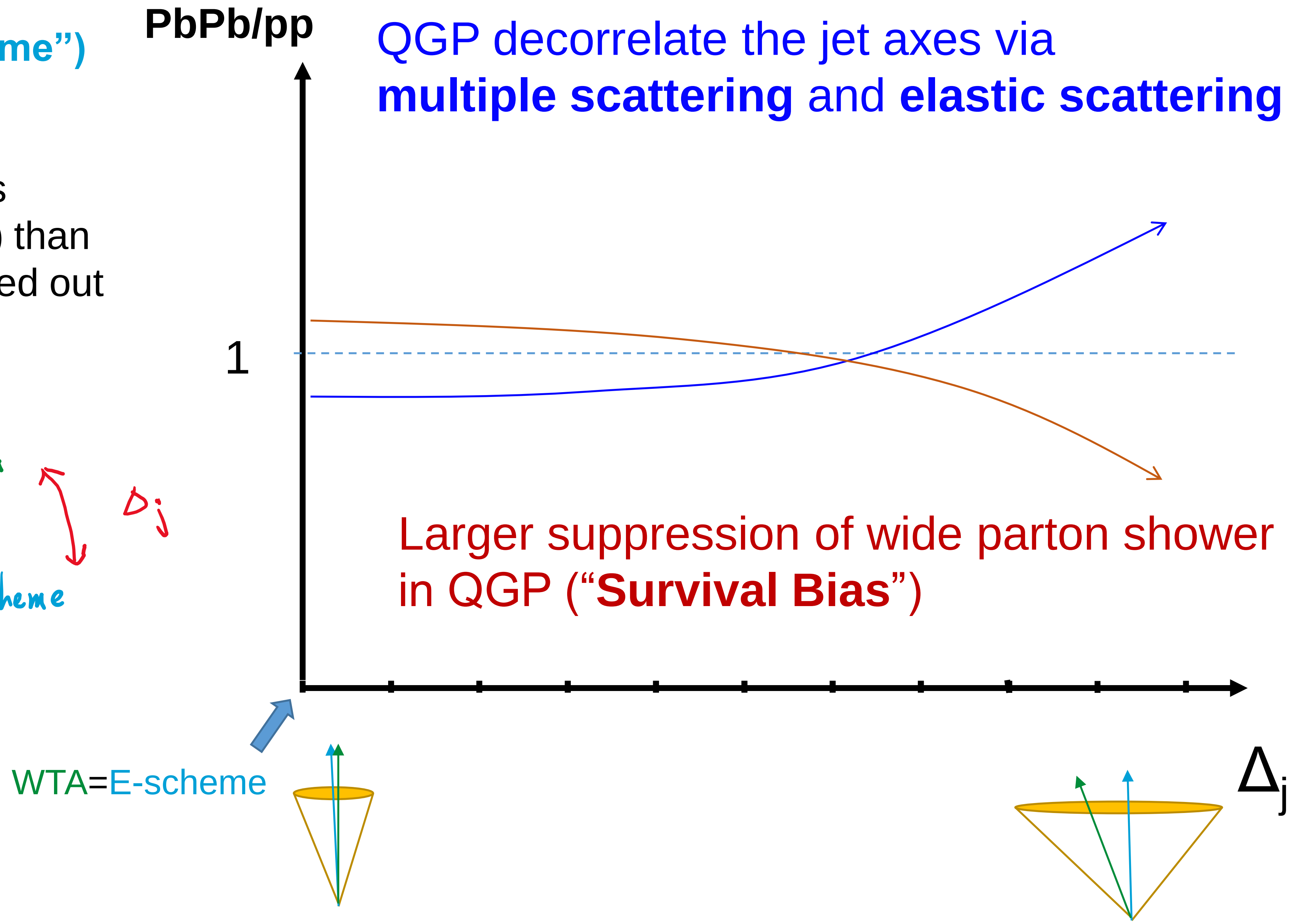
Leticia Cunqueiro

(4) MSS and Search for Elastic Scattering

- The angular separation of jet axes (Δ_j) calculated with **energy weight ("E-scheme")** and a **winner-take-all (WTA)** scheme

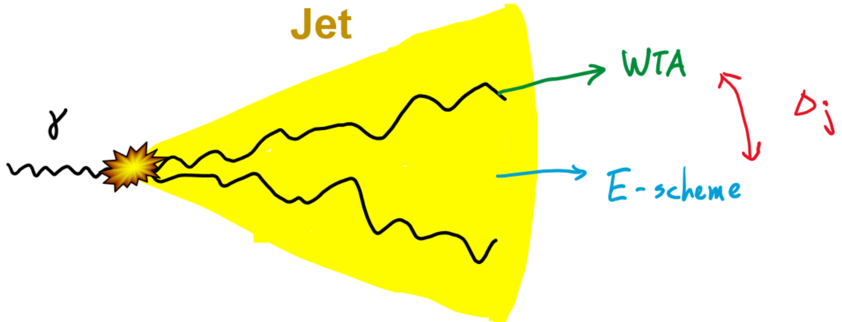
- **WTA** follows the leading energy flow, has larger sensitivity to $\hat{q}$ (multiple scattering) than **E-scheme**, where the effects are averaged out



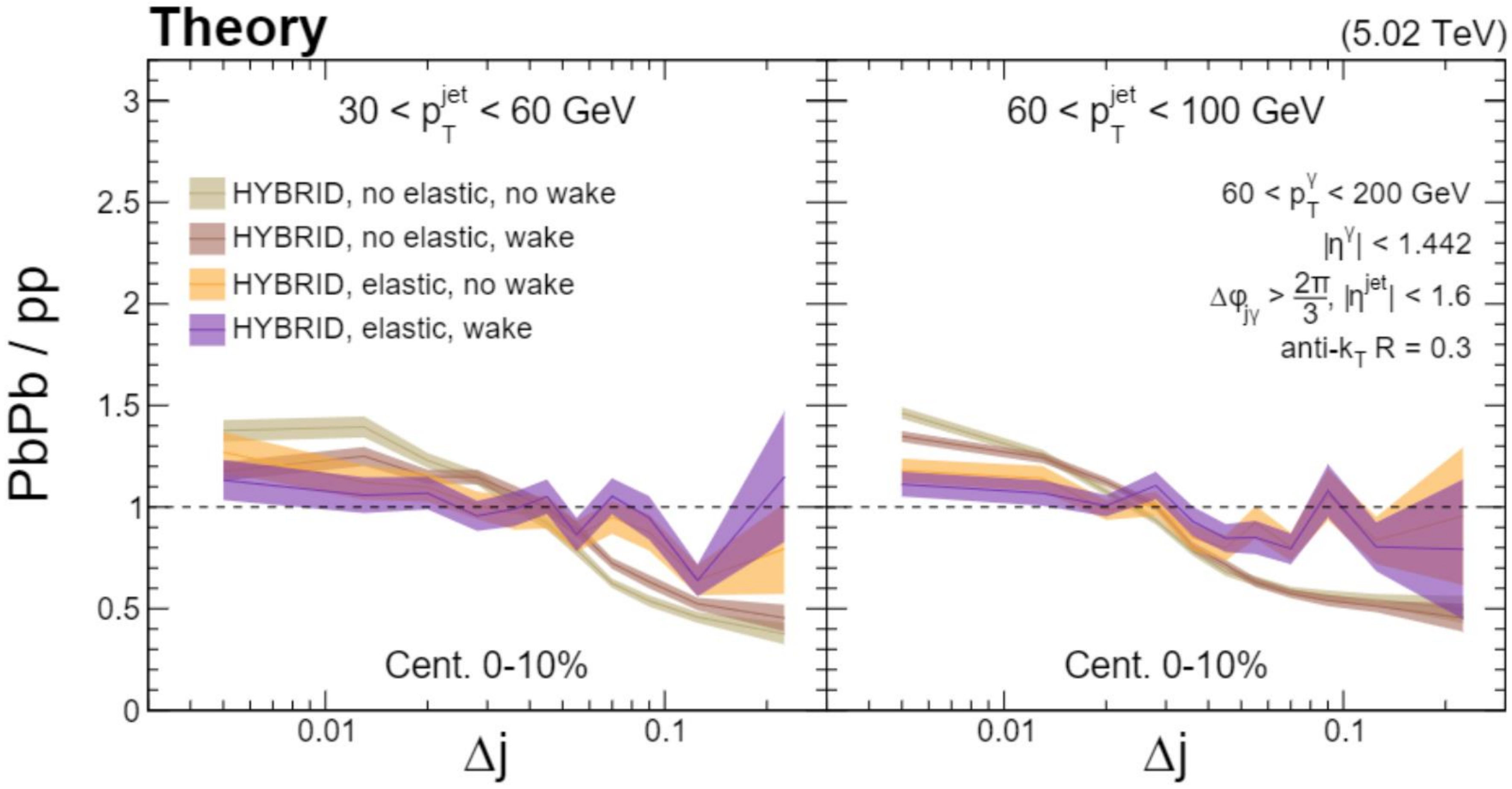


Photon-tagged Jet Δ_j (WTA, E-Scheme)

- At fixed photon p_T, different jet p_T intervals could be used as a proxy of the degree of quenching of the associated jets
- HYBRID model: Δj sensitive to elastic scattering and insensitive to wake effect
- Subjet multiplicity: sensitive variable based on HYBIRD



More quenched jets   Less quenched jets



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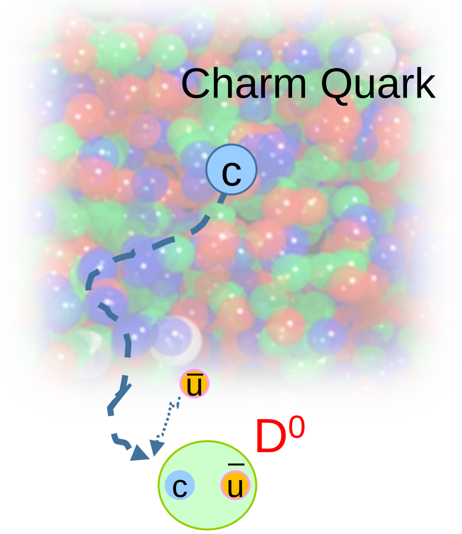
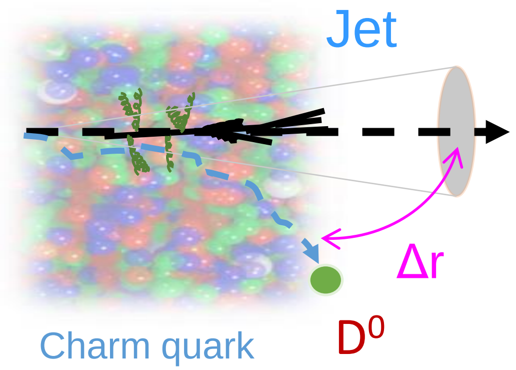
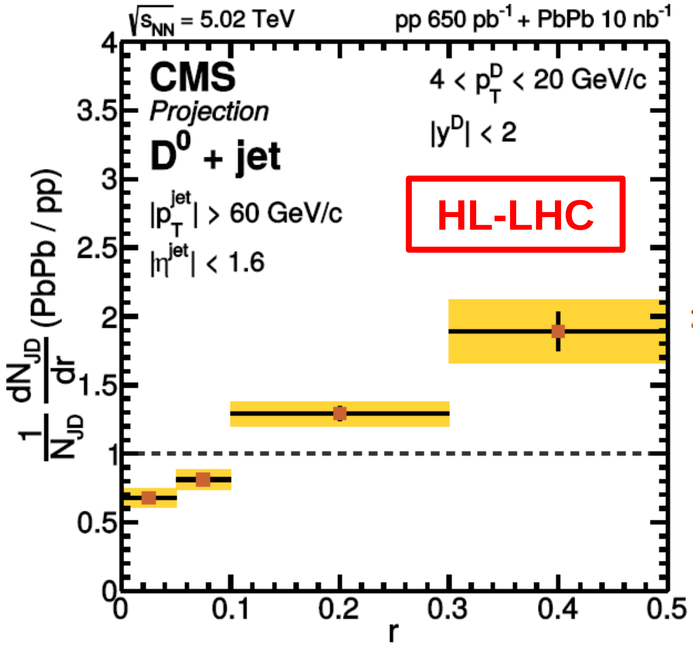
High Precision Measurement of HQ Diffusion



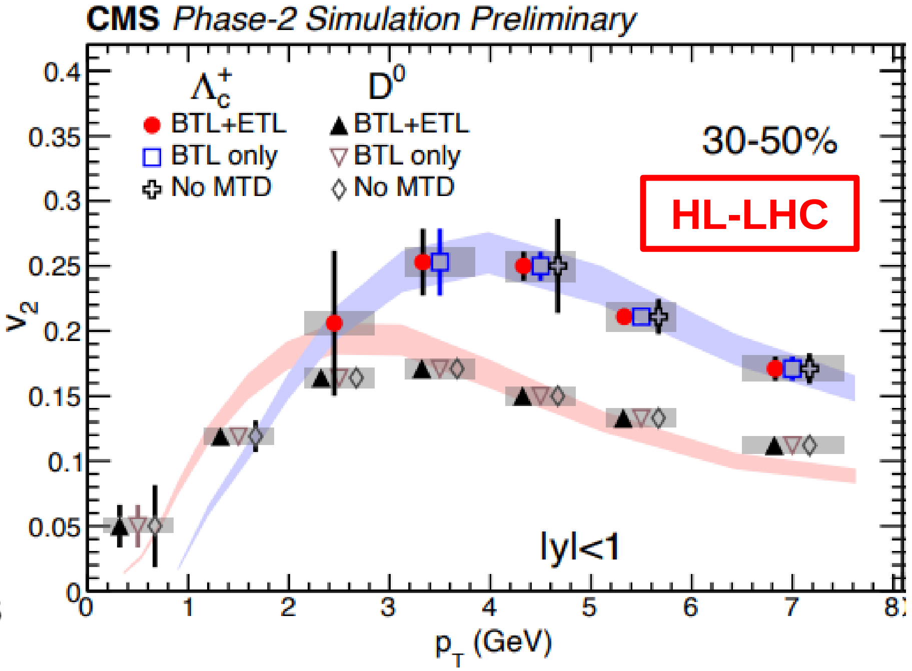


Jet-D^0 Correlation



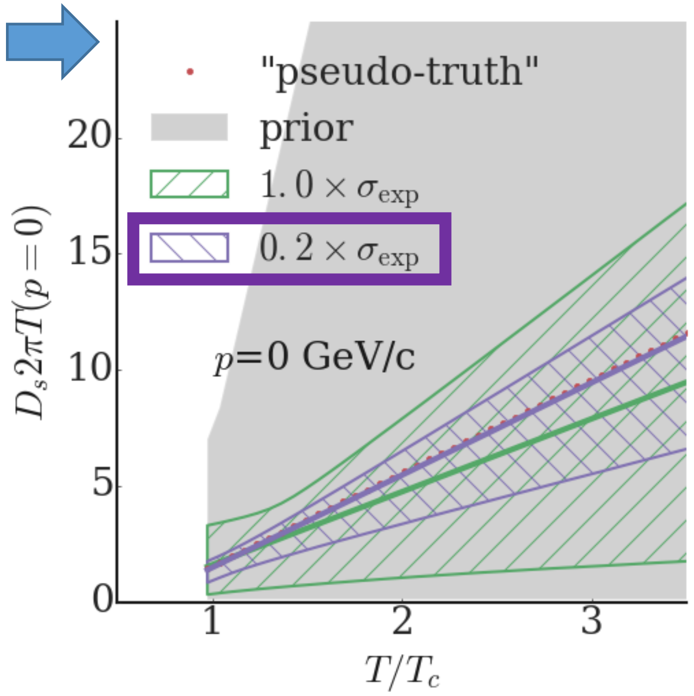
CMS PAS-FTR-18-025

D^0 and Λ_c v_2



CMS DP_2021_037

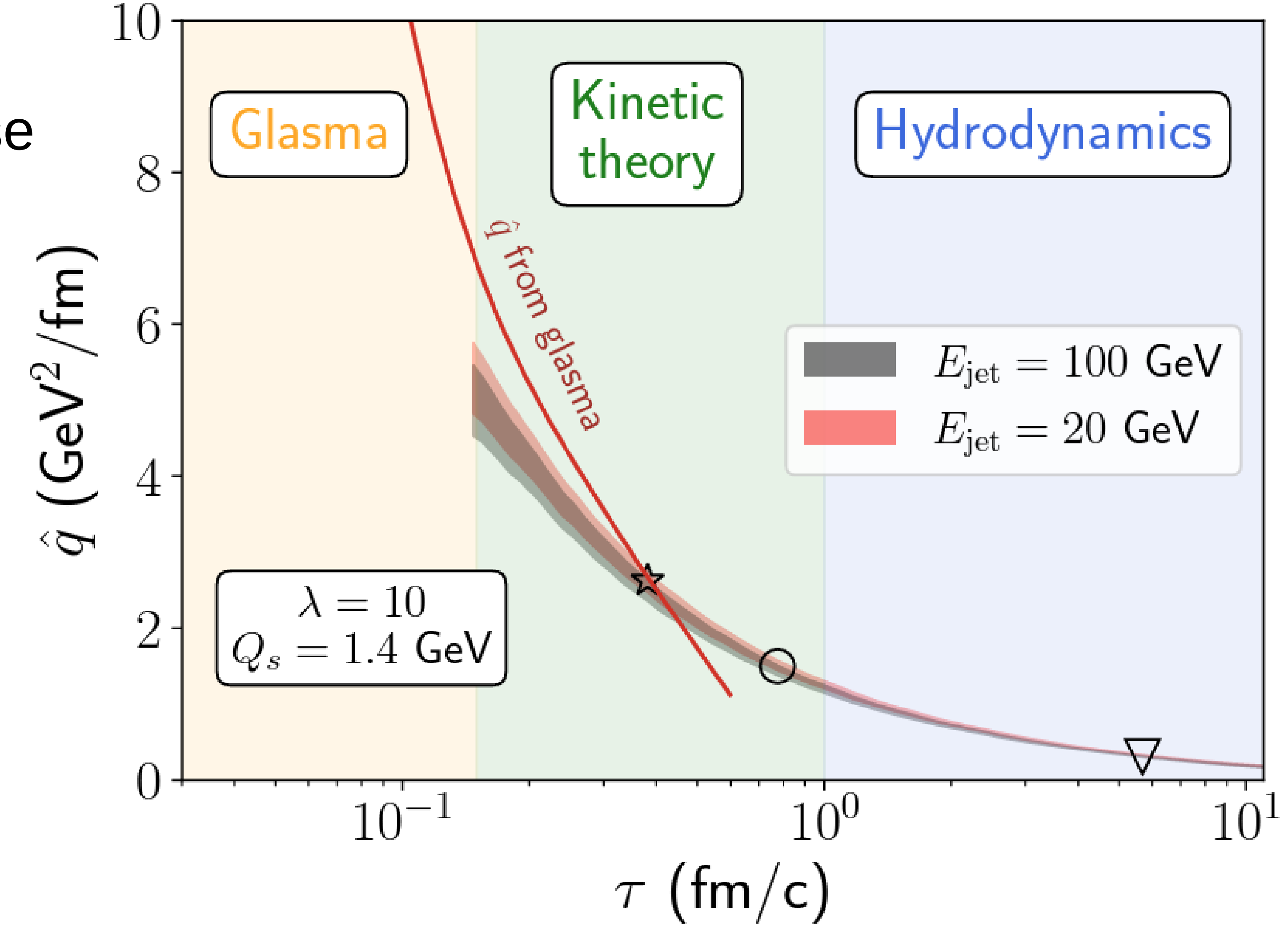
D_s vs. T



- Study how charm jet hadronized in different collision systems
- Direct observation of charm diffusion with D^0-Jet correlation
- Together with v_2 and R_{AA} :Strong constraint on the HQ diffusion coefficient $\mathbf{D_s}$

(5) Time Dependence of Jet Quenching

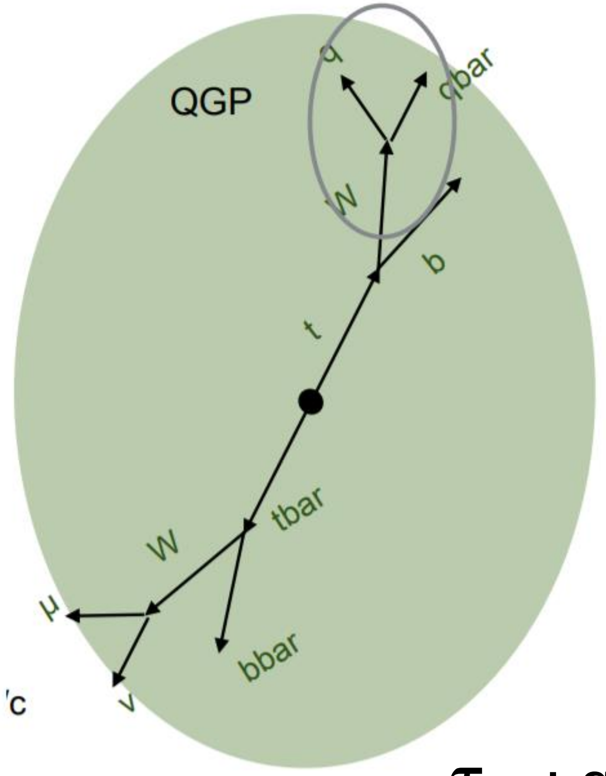
- Jet quenching parameter extracted from experiment mostly only in hydrodynamics phase
- To describe high p_T hadron **v_2** and **R_{AA}**, later quenching start time is preferred in models:
  - Carlota Andres et al. (R_{AA} and v_2, PLB 803 (2020) 135318) : $\tau_0 \sim 0.6$ fm/c
  - JETSCAPE (R_{AA}): $\tau_0 \sim$ 0-1 fm/c
- What is the role of the Glasma phase?



[2303.12595 [Boguslavski, Kurkela, Lappi, FL, Peuron]]

(5) Time dependence: Quenching effect with W/Z jet

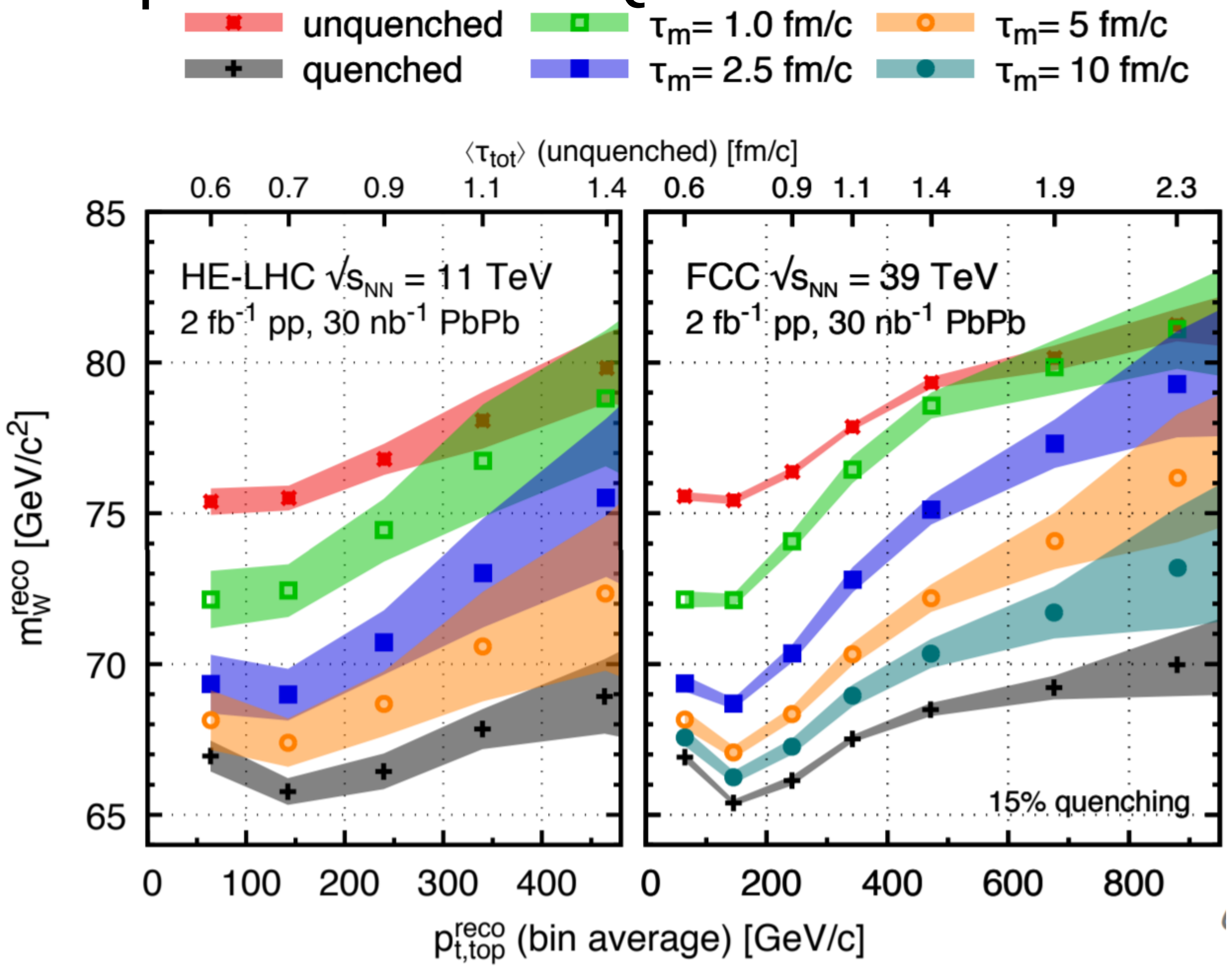
Negligible interaction between Top / W and the QGP



τ_{top}=0.15 fm/c

τ_{W}=0.10 fm/c

τ_m : quenching end time



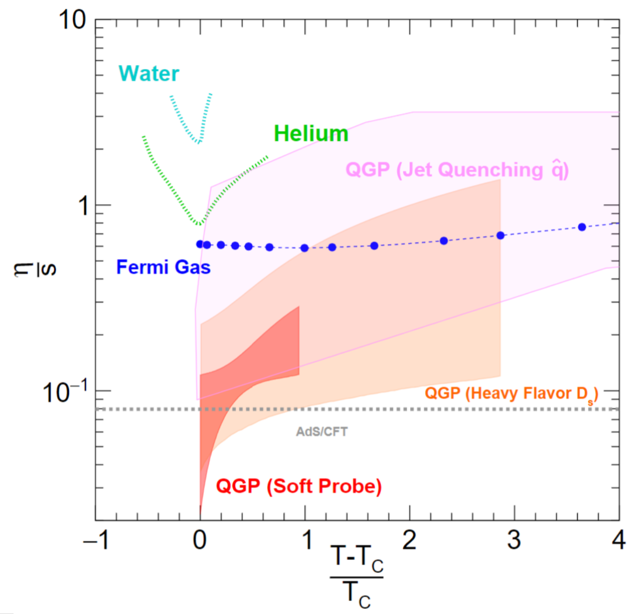
- Longer total delay time of the W (τ_{tot}) leads to smaller modification of W mass in heavy ion collisions
- Probe the "start" and "end" time of the QGP!!

"A Yoctosecond Chronometer." (Gavin Salam)

Summary

- Within the next decade, we expect significant progress on jet measurements
  - Detection of medium recoil effects
  - Detailed understanding of medium response and jet hadronization
  - Direct detection of MSS and color coherence effect in QGP
  - Improved understanding of shower shape dependence of jet quenching
  - Direct detection of charm and charge diffusion
  - Revealing elastic scattering in QGP
  - Limit or detection of jet quenching signal in small systems (e.g., OO)
  - Jet quenching start time with boosted W/Z jet

- Aim to greatly enhance the precision of QGP properties and study the consistency between extractions using soft and hard probes.

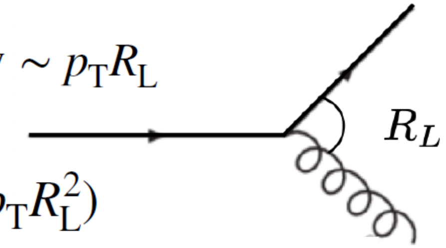


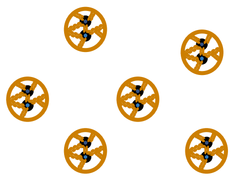
Backup slides

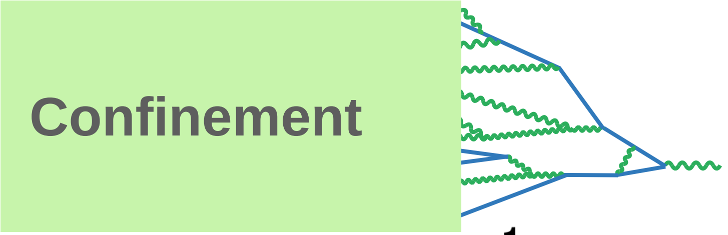
Unfolded EEC in pp at 13 TeV

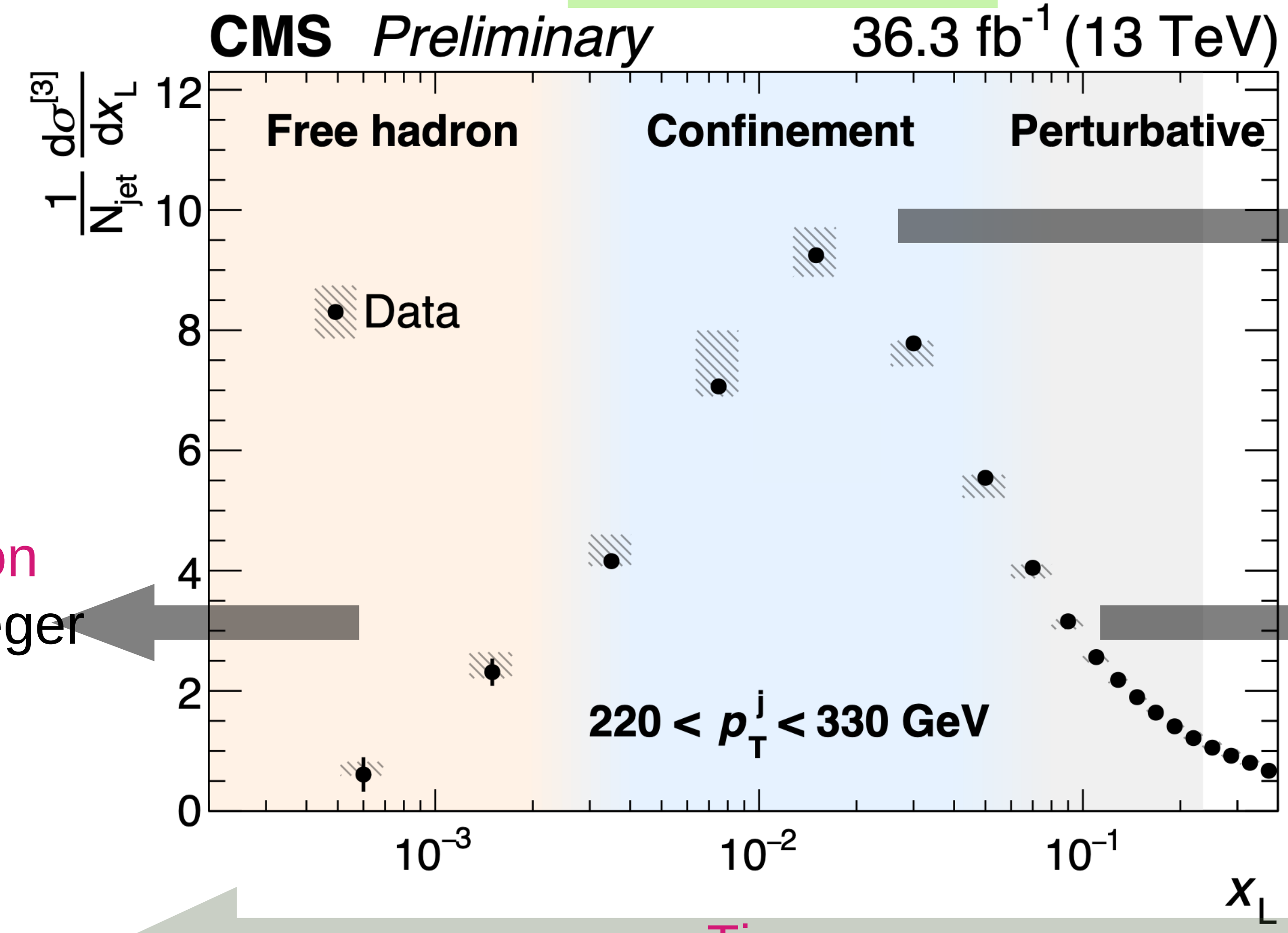
virtuality $\sim p_T R_L$

$\tau \simeq 1/(p_T R_L^2)$









Phase transition from parton to hadron

Non-interacting hadron random distribution integer power-law scaling

Interacting partons non-integer scaling

Time