

Jets in QCD matter: Monte Carlo approaches

Liliana Apolinário



Many thanks to:

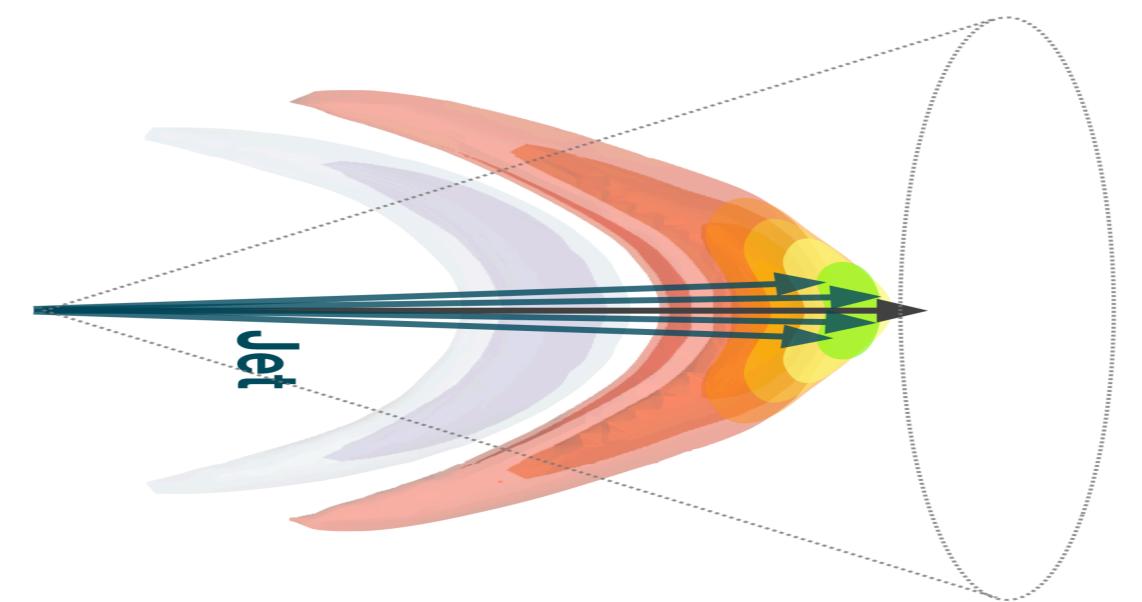
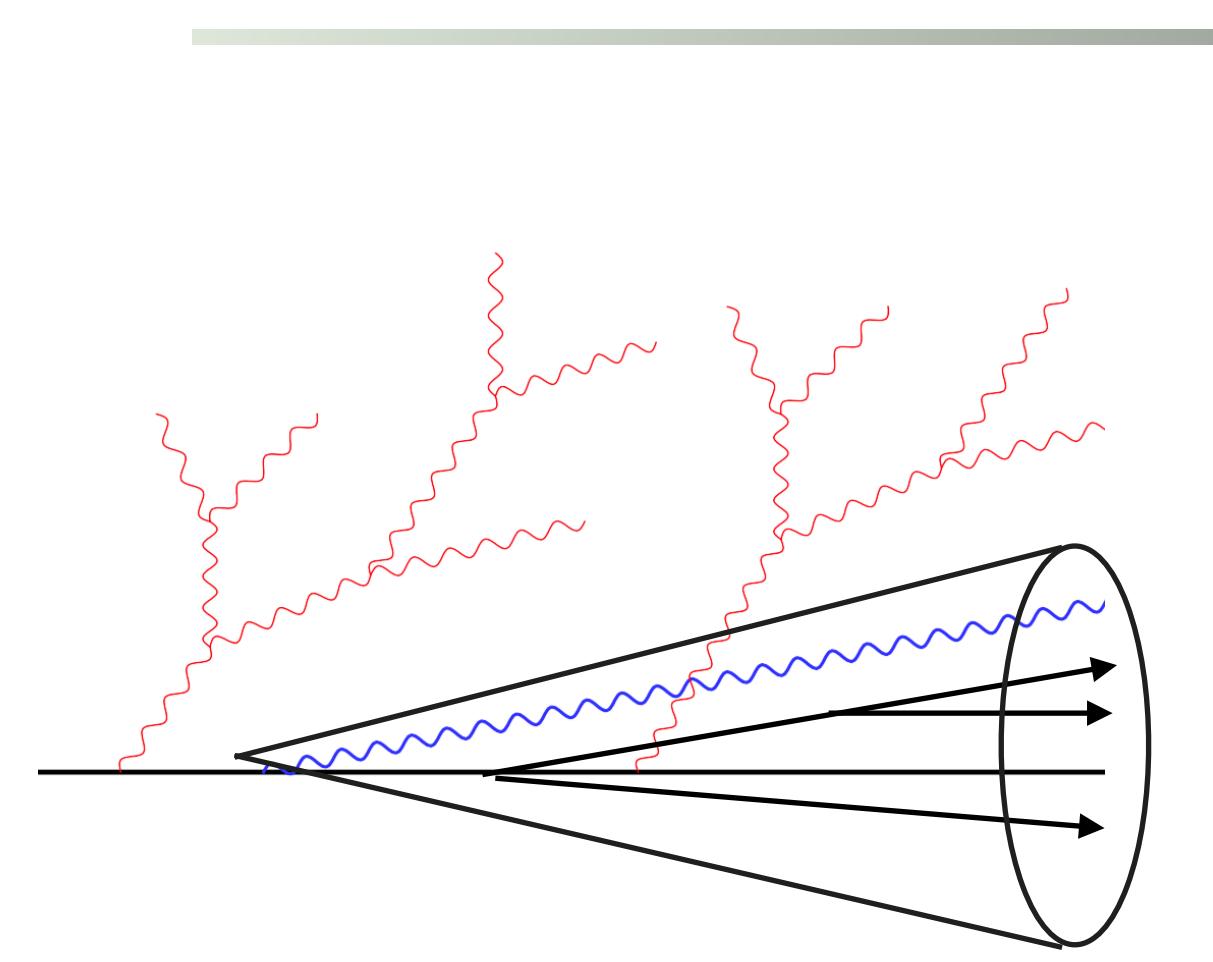
Néstor Armesto, Leticia Cunqueiro, Guilherme Milhano, Carlos Salgado and Marta Verweij

Outline

- ◆ Jets: analytical approach vs Monte Carlo approach
- ◆ Jet Quenching Monte Carlo:
 - ◆ What do we need to build one?
 - ◆ What have we learned so far?
- ◆ Summary

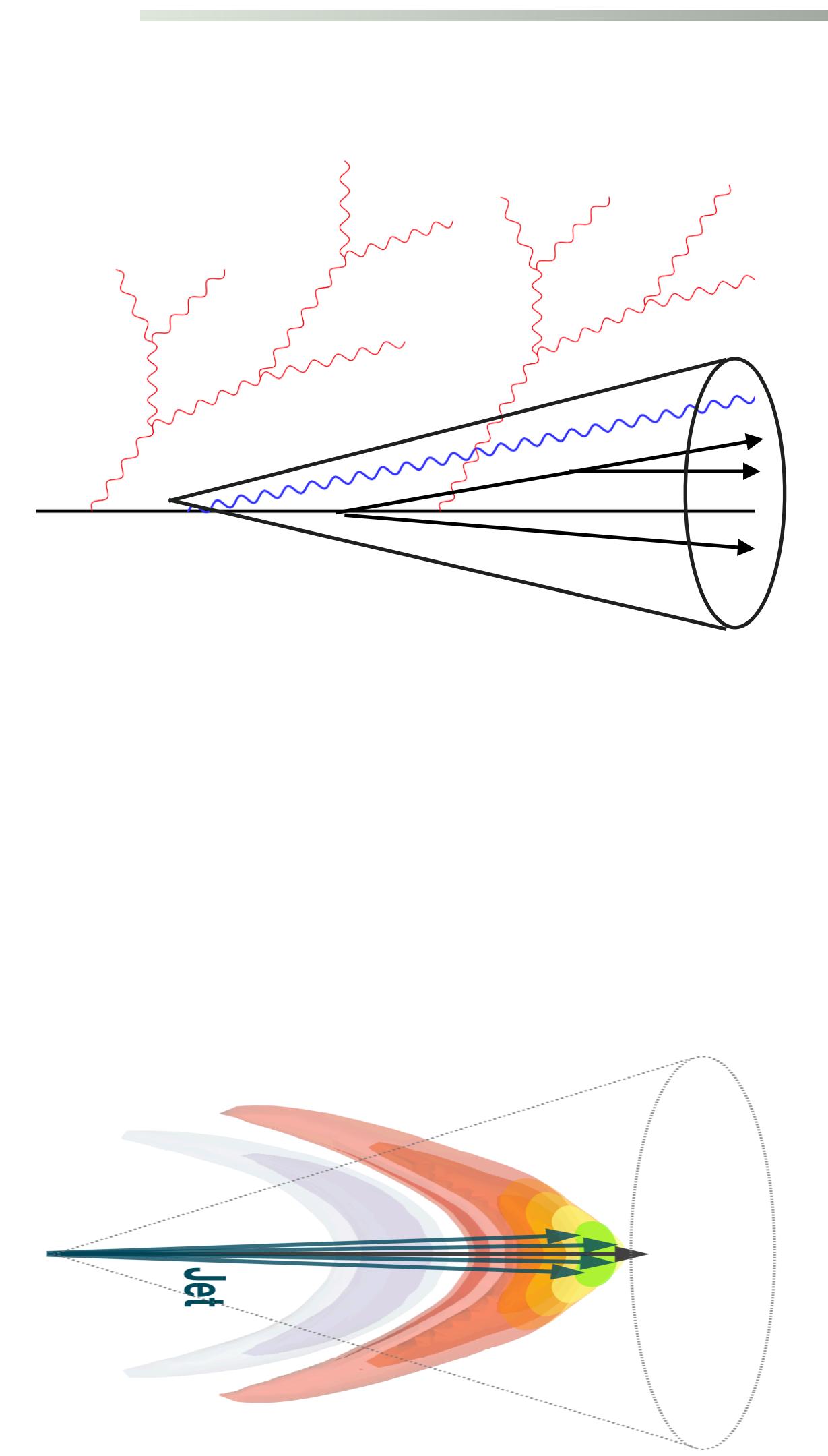
Jets in heavy-ions

- ◆ What is a jet in heavy-ion collisions?
- ◆ Multi-scale process:
- ◆ High momentum particles (typically from vacuum-like parton shower)
- ◆ “**Semi-hard**” & **Soft** medium-induced radiation
- ◆ **Soft** jet-induced medium response



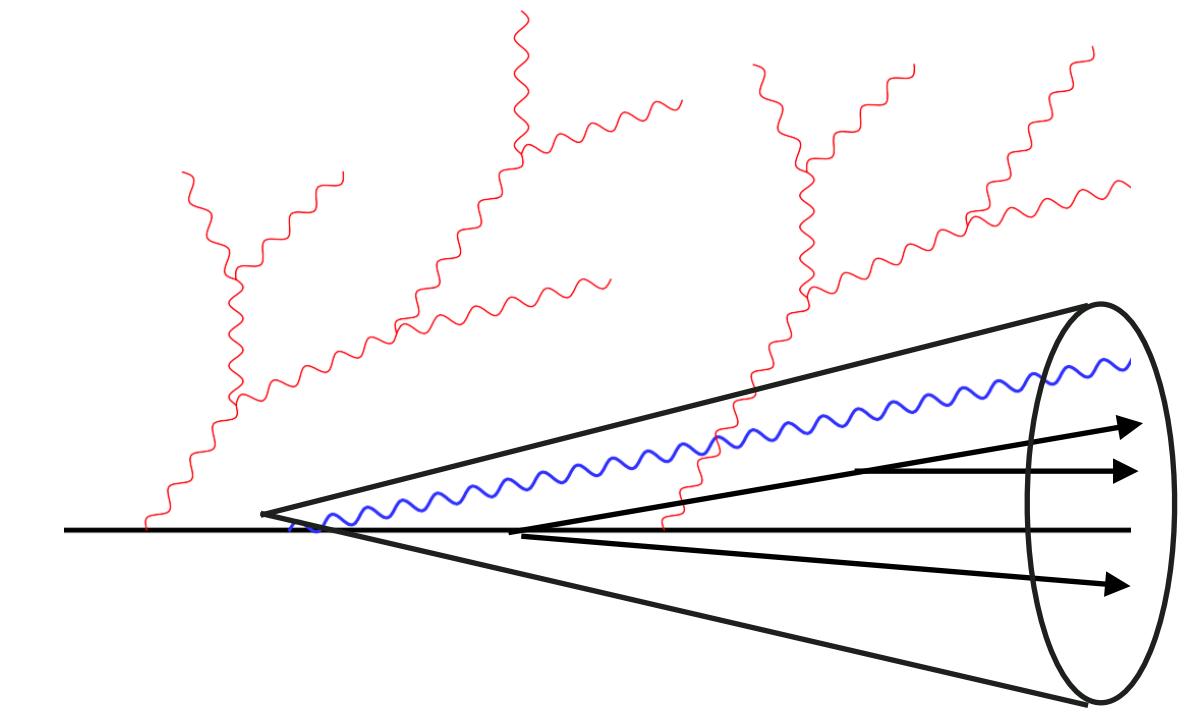
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- ❖ Space-temporal evolving structure:
 - ❖ parton fragmentation and parton re-scattering with medium constituents at some time

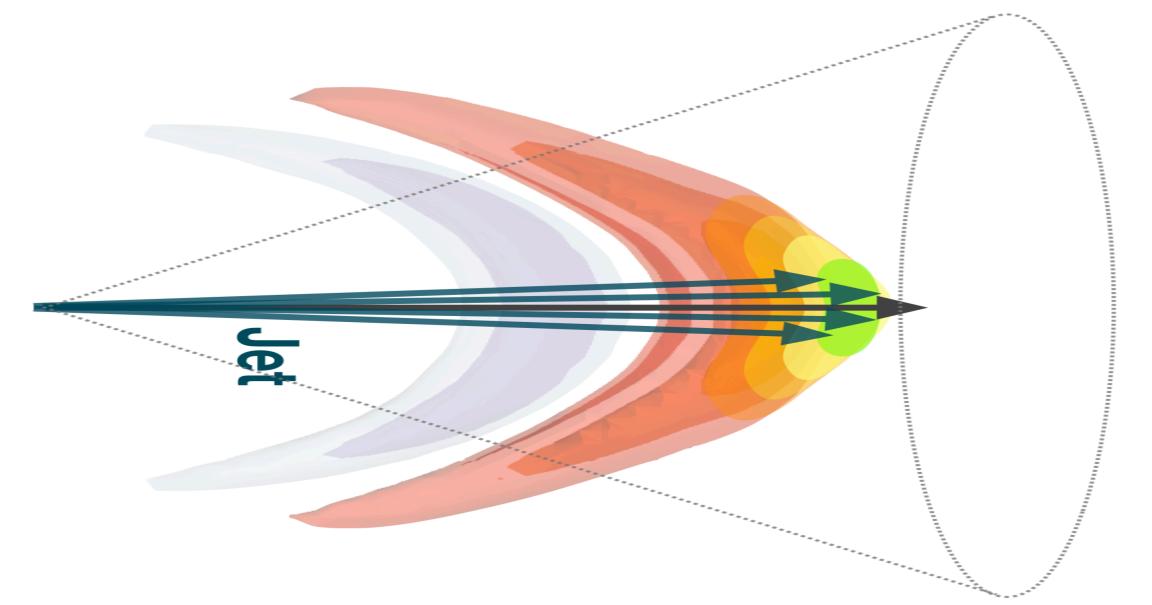


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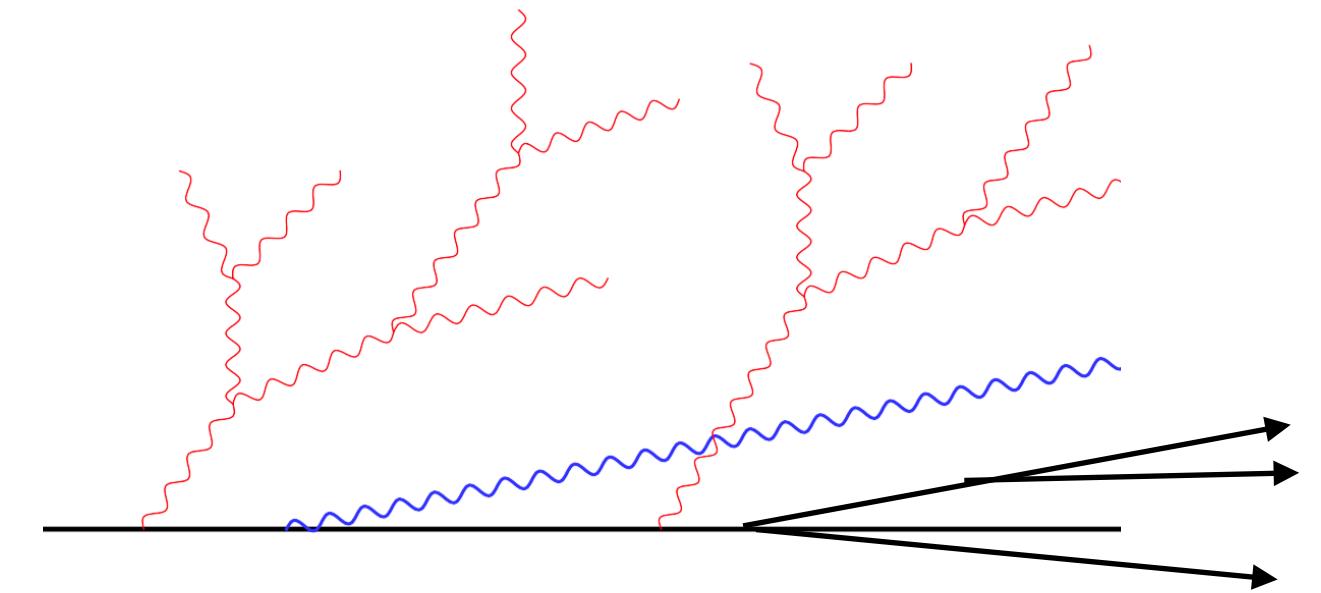


“Hard”
Problem!



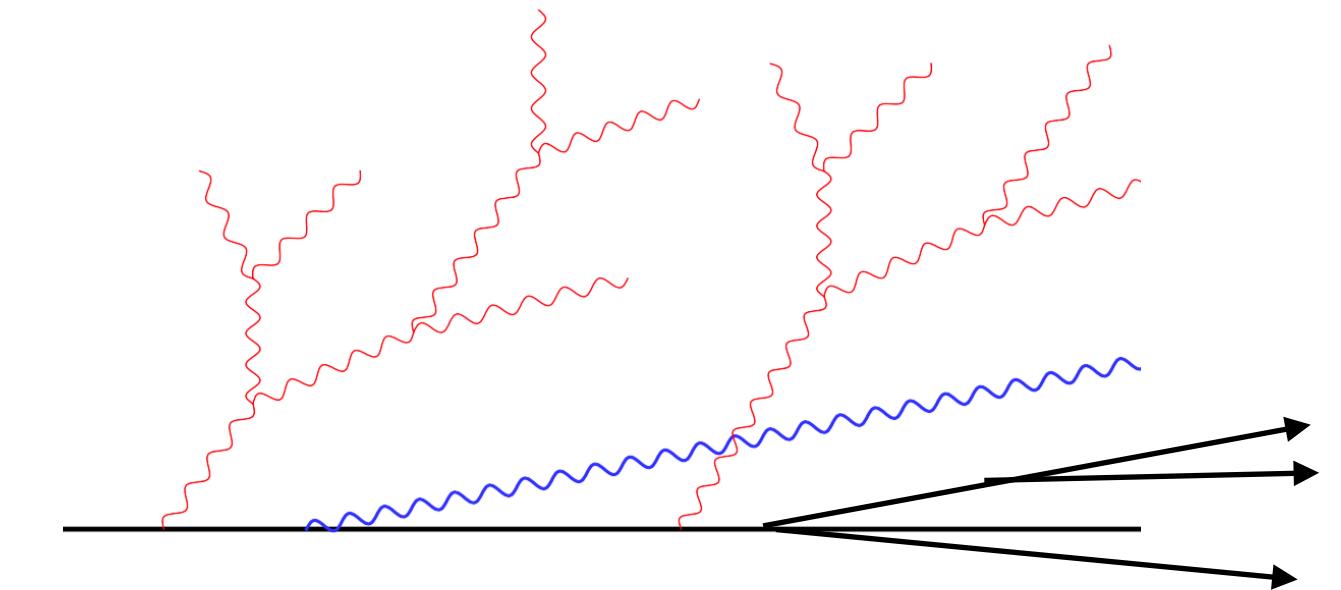
Analytical Approach

- ◆ How to describe a jet?
- ◆ Analytical approaches (pQCD or non-pQCD):
- ◆ Based on first principle calculations that address elementary processes at parton level;
- ◆ Carried out observable-by-observable...
- ◆ Several advances, **but** still towards a consistent treatment of:
 - ◆ Vacuum-like and Medium-like emissions: P. Caucal (Thursday)
 - ◆ Back-reaction (QGP response)...



Analytical Approach

- ◆ How to describe a jet?
Lattice/EFT: M. Escobedo (today)
Heavy-Quarks: S.Cao, M.Nardi (today)
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See also:

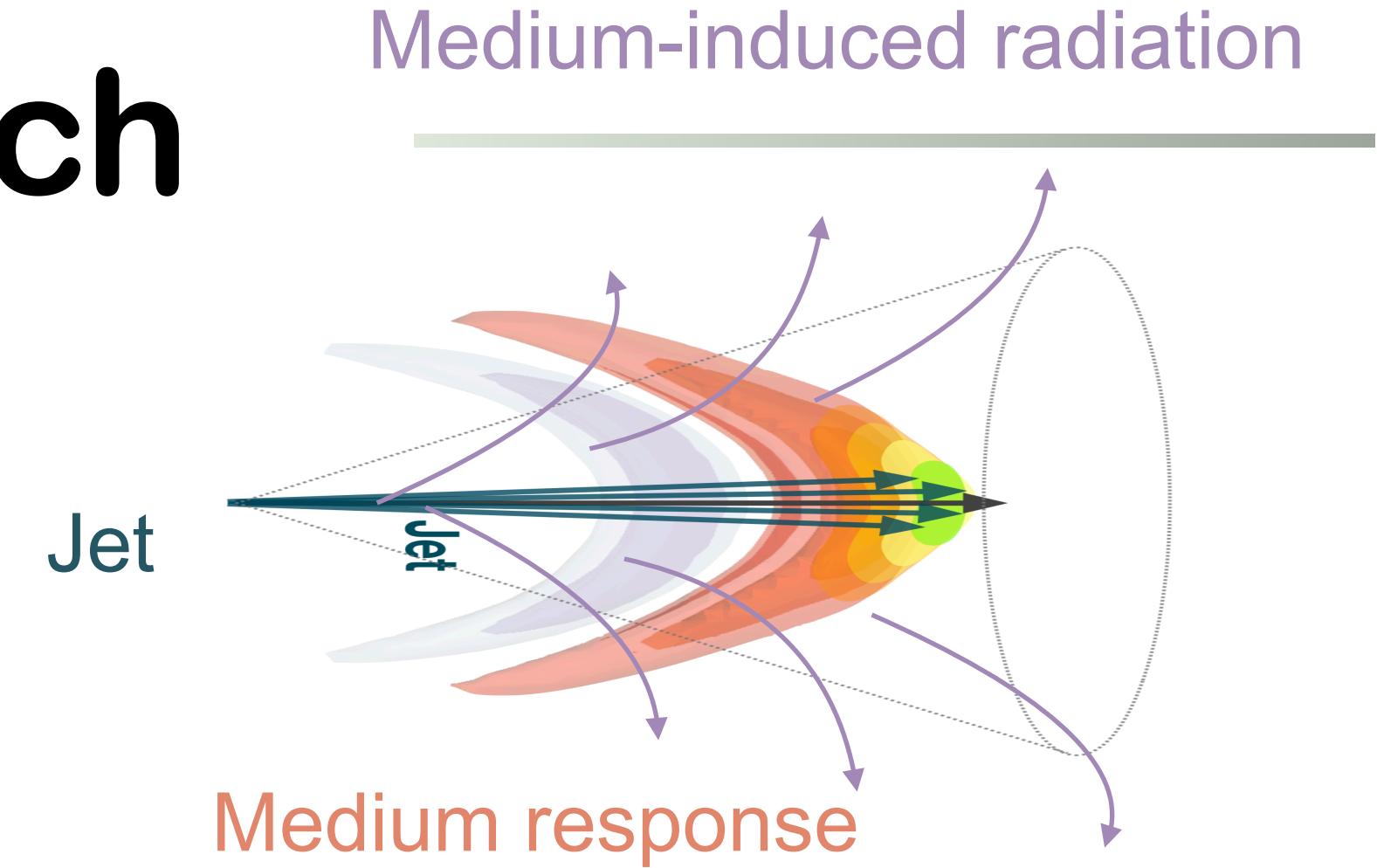
Tuesday: S. Adhya, B Blagojevic, N-B. Chang, H. Li, Y. Mehtar-Tani, W. van der Schee, V. Vila, B. Wu

Wednesday: Y-T. Chen, G. Qin, S. Schlichting

Thursday: A. Kumar, C. Sirimanna, Y. Zhang

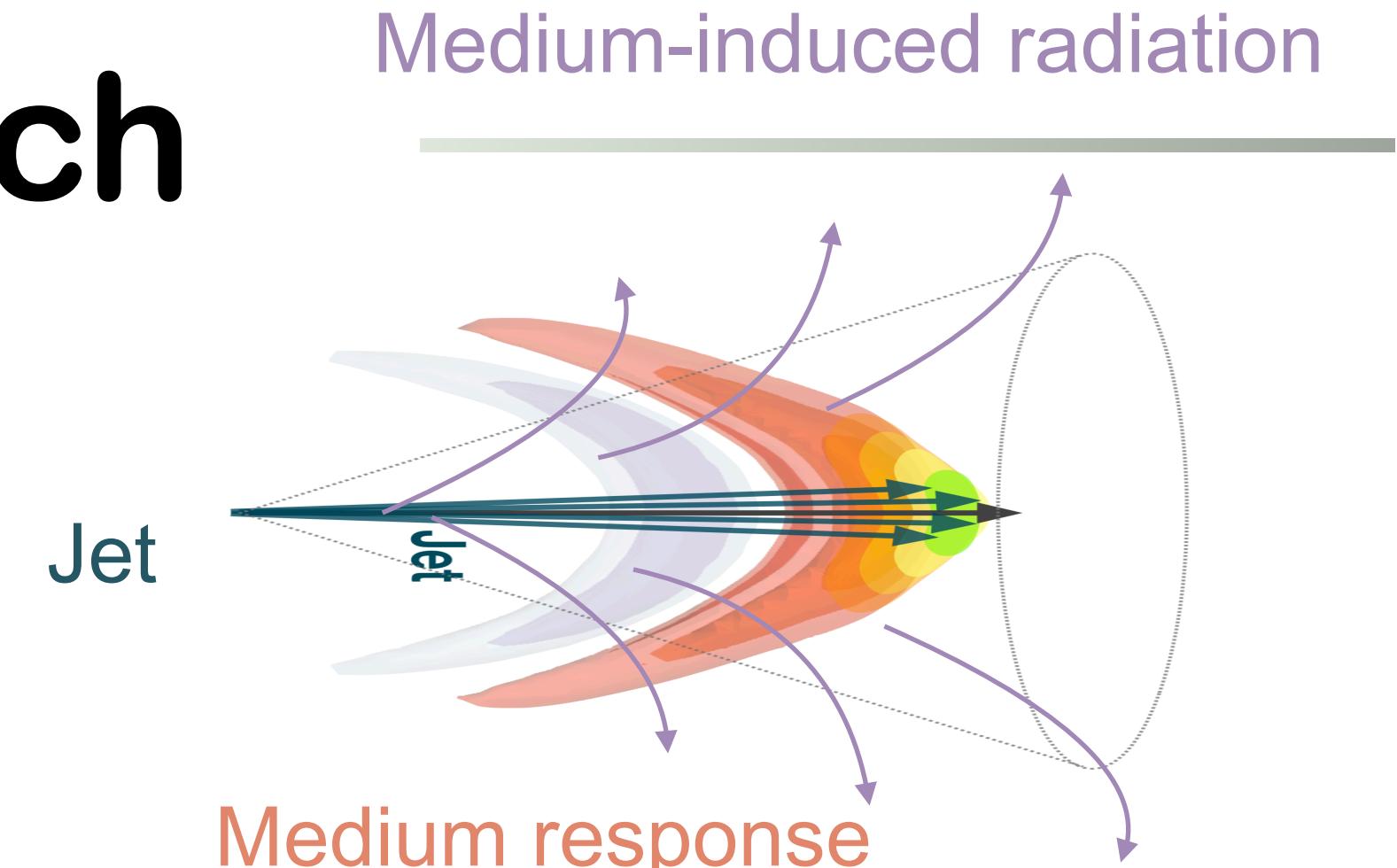
Monte Carlo Approach

- ◆ How to describe a jet?
- ◆ Monte Carlo approaches:
- ◆ Based on a factorisation of processes/scales
- ◆ Allow theory-data comparison on a large multi-particle complex set of observables
- ◆ Can go beyond analytical calculations (full jet shower evolution + evolving medium) but:
 - ◆ Inherits its limitations...
 - ◆ Further phenomenological assumptions



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See also:

Tuesday: G. Bíró (HIJING++)
W- Chen (Co-LBT)
M. Rohrmoser (Heavy-quarks)
F. Senzel (BAMPS)

Wednesday: Y. Tachibana (JETSCAPE)
X-N. Wang (LBT)

Thursday: P. Gossiaux(EPOS-HQ)
D. Pablos (Hybrid strong-strong-weak coupling)
C. Park (JETSCAPE)

Analytical vs MC

- ❖ How to describe a jet?

Analytical approaches

Based on first principle calculations
that address elementary jet processes

✓ Able to build up a clear qualitative picture

⚠ Sometimes difficult to compare with
complex multi-particle observables

Monte Carlo approaches

Can consider the full jet shower
evolution and evolving medium

⚠ ✓ Rely on analytical results

⚠ ✓ Require further modelling (beyond
kinematic approximations)

Jet Quenching Monte Carlos

- ◆ Several jet quenching Monte Carlo models: See references in the backup slides

Q-PYTHIA

JEWEL

PYQUEN

HIJING++

AMPT

MATTER

MARTINI

Hybrid strong/weak coupling

HYDJET++

LBT

...

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Q-PYTHIA



Wednesday, Thursday

MARTINI

JEWEL

MATTER

LBT

Wednesday

PYQUEN

Co-LBT
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HIJING++
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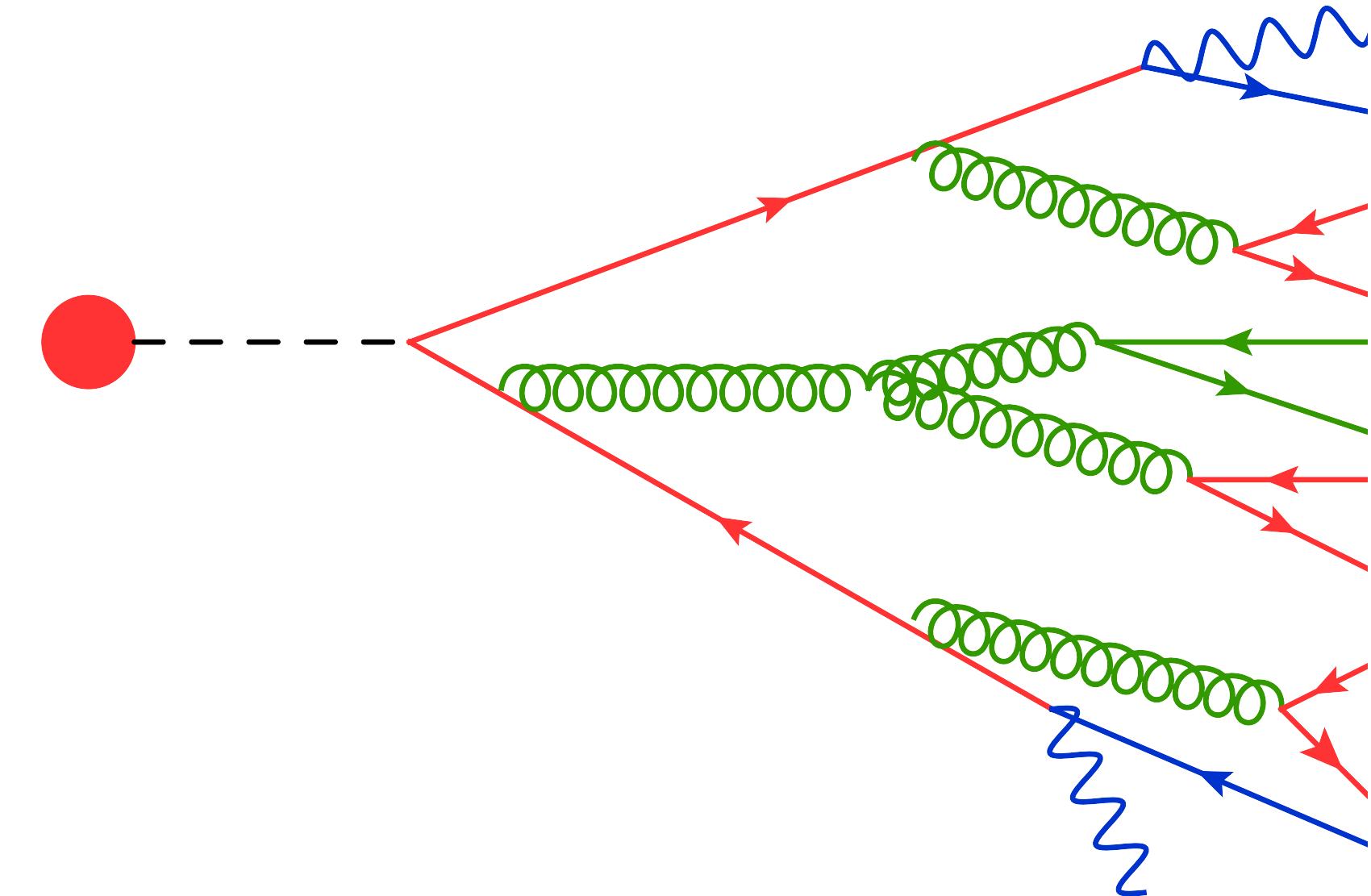
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Jet Quenching Monte Carlos

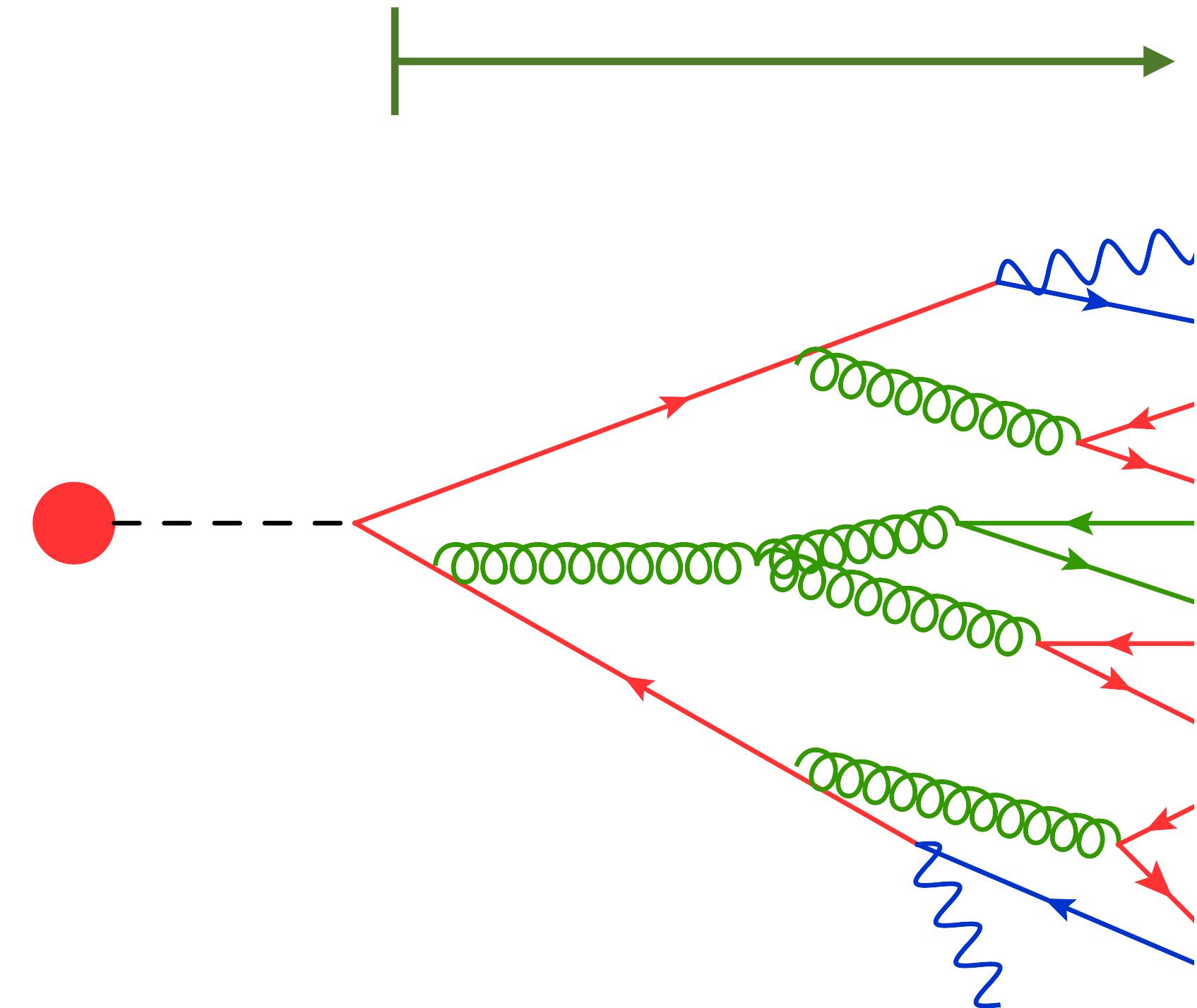
♦ Why so many?



Jet Quenching Monte Carlos

- ♦ Why so many?

parton shower: fully in-medium dynamic or afterburn?

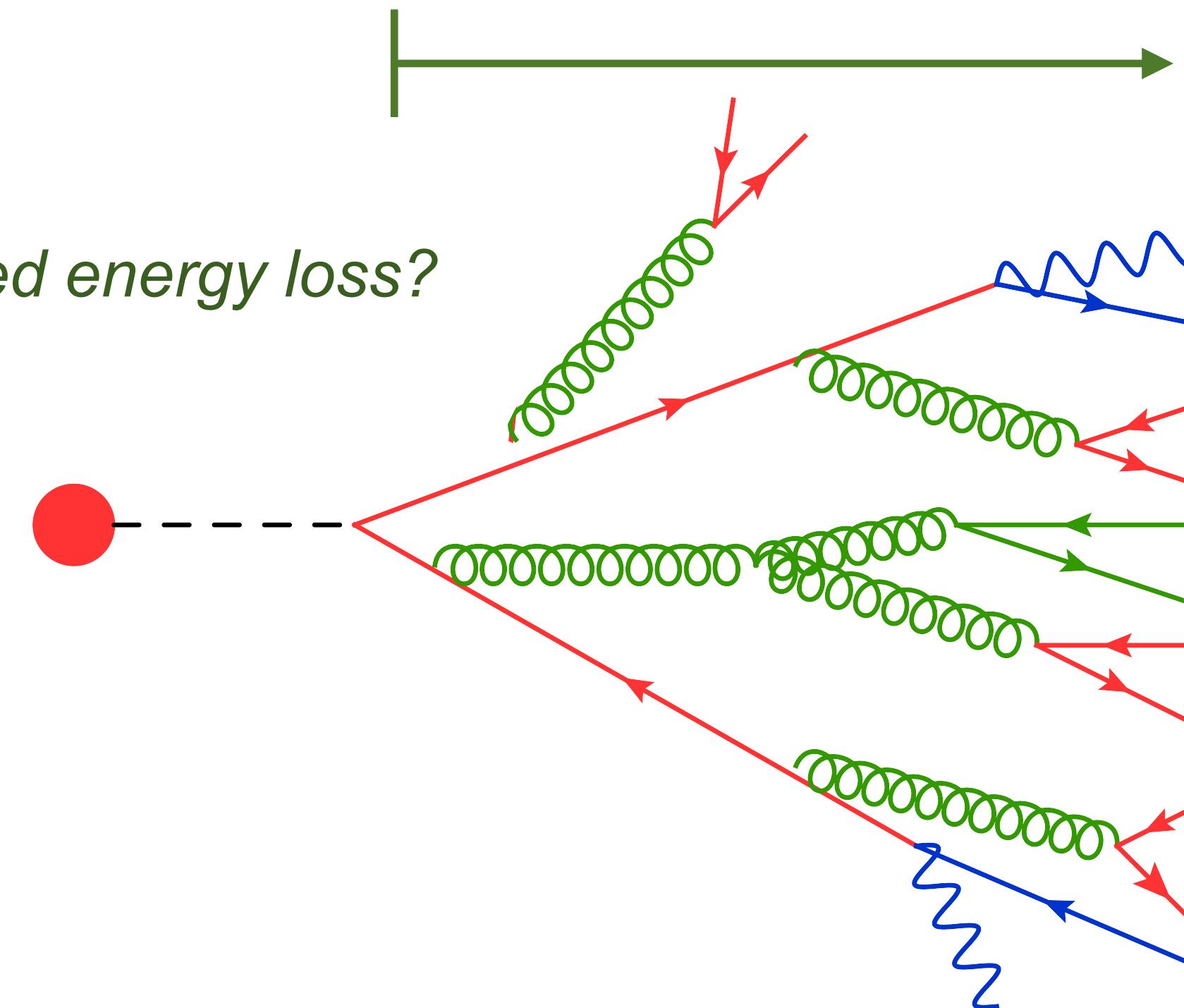


Jet Quenching Monte Carlos

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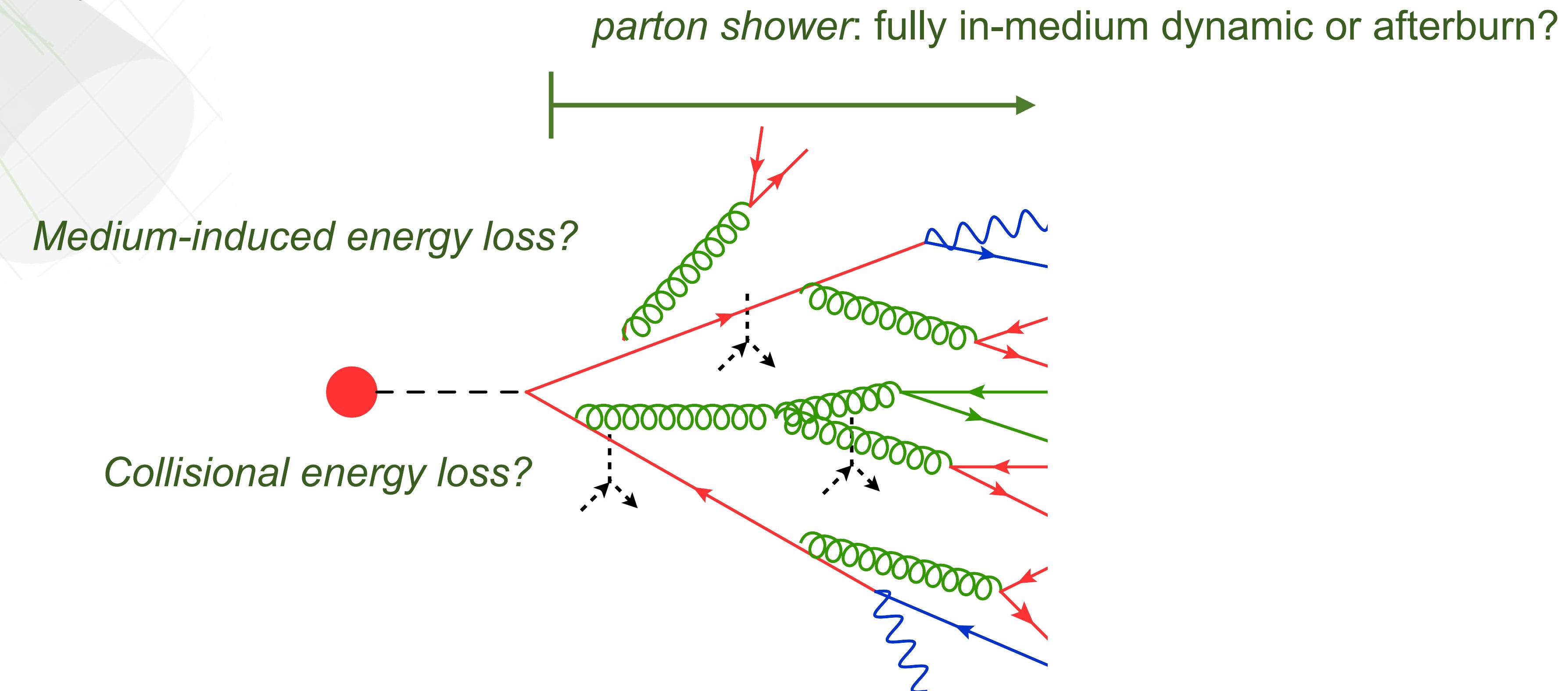
Medium-induced energy loss?

parton shower: fully in-medium dynamic or afterburn?



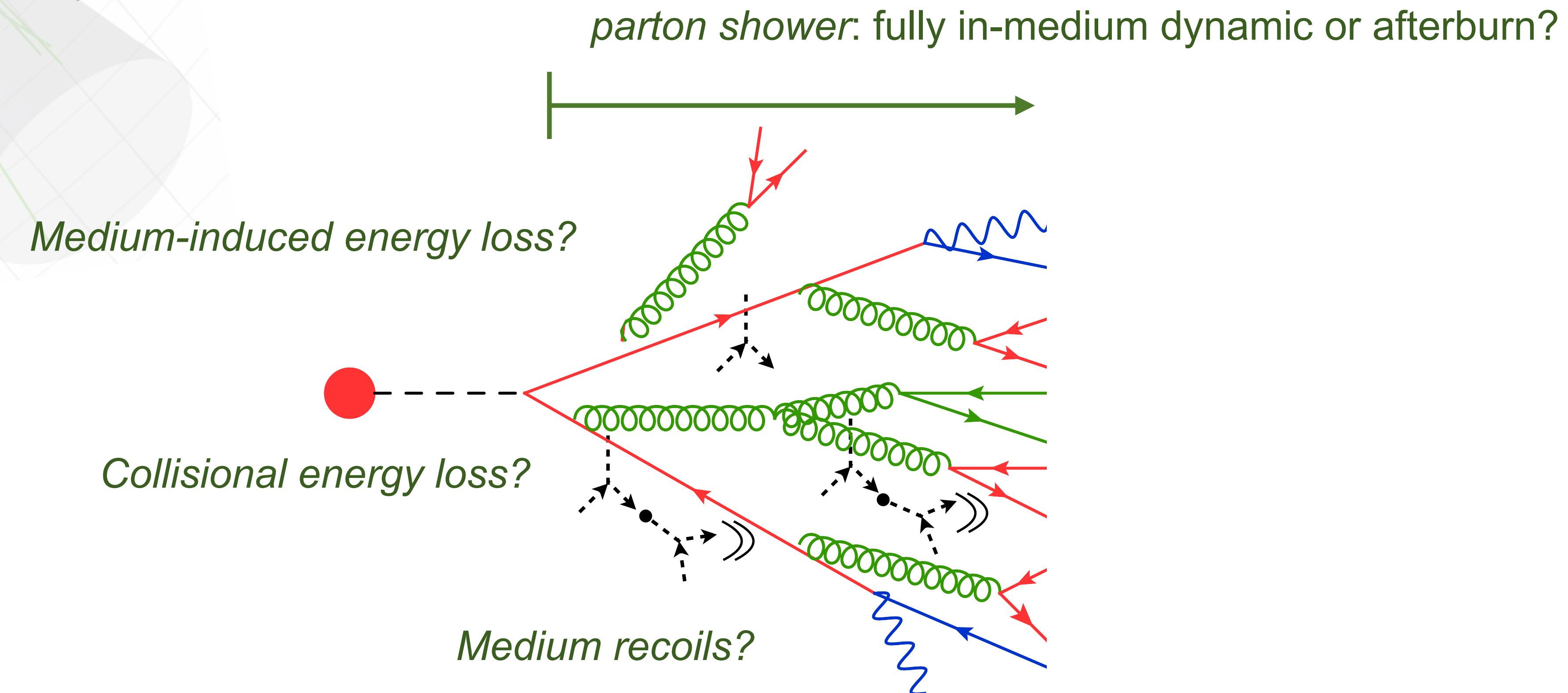
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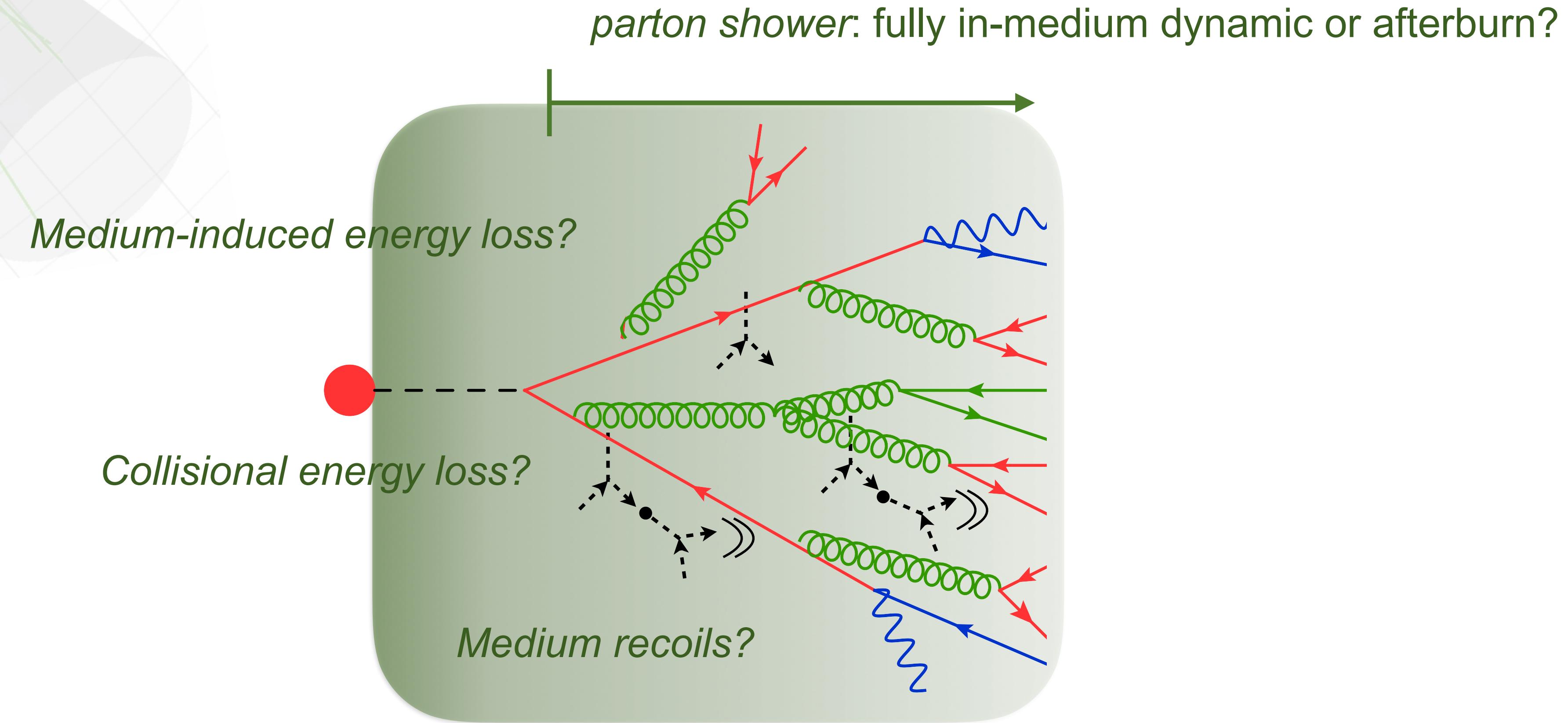
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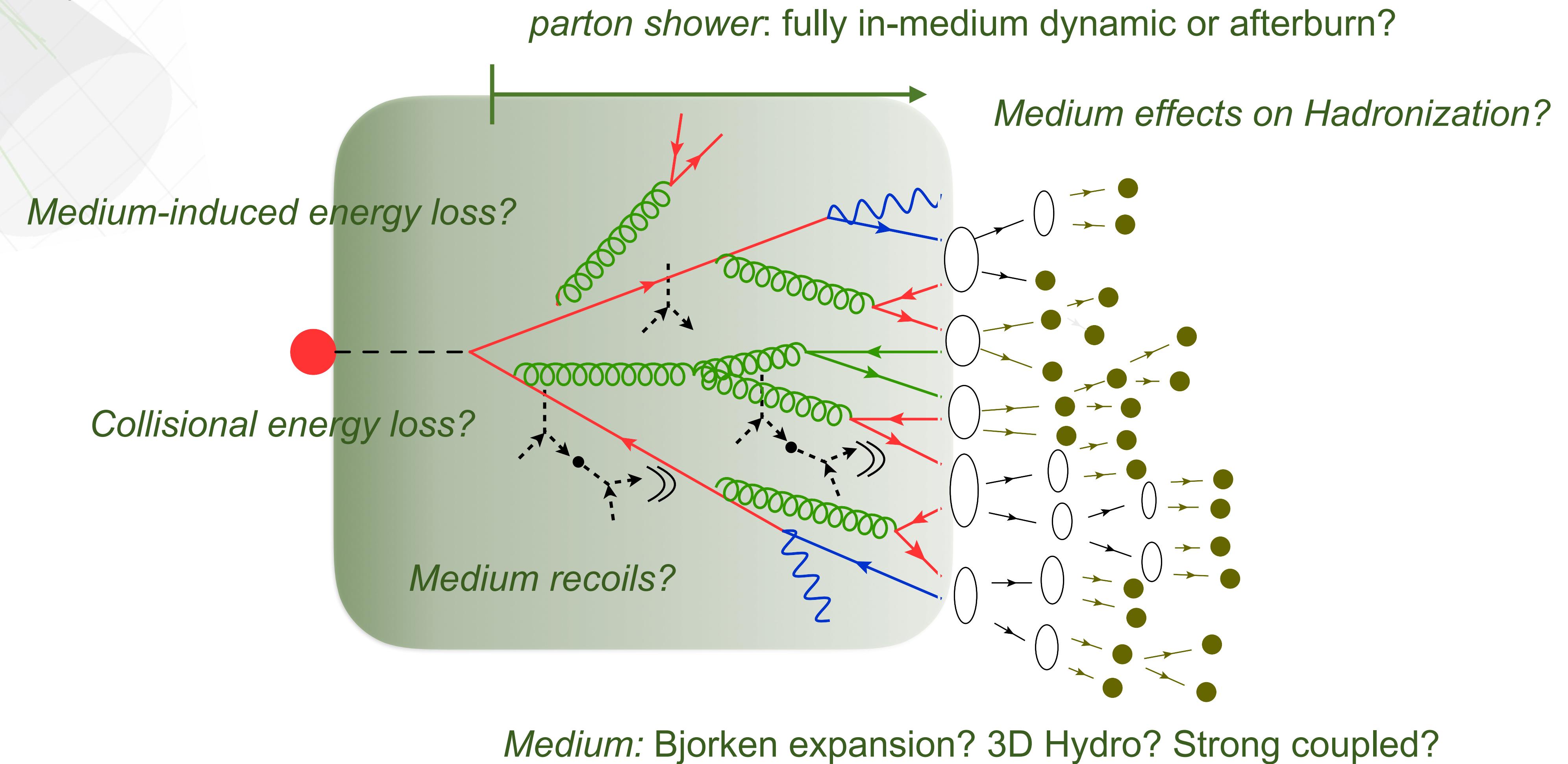
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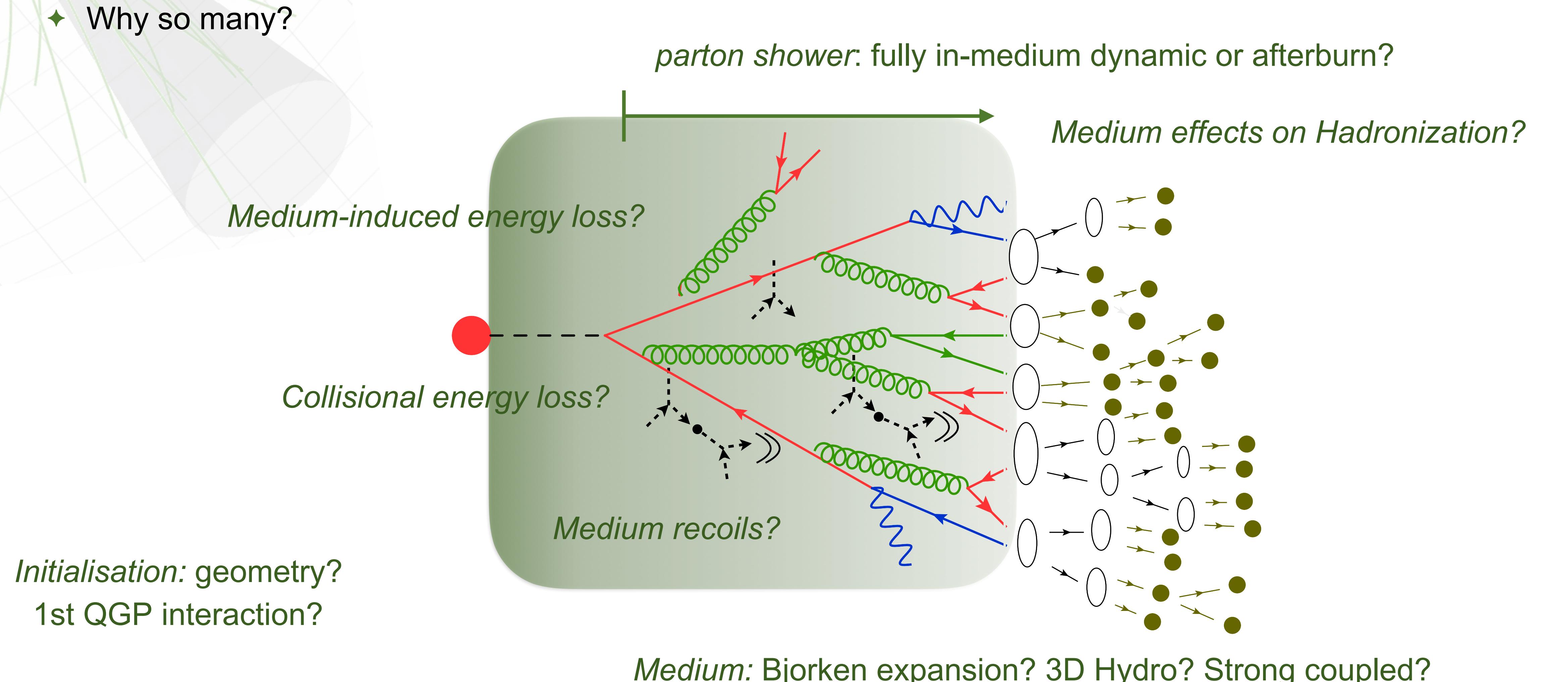
Medium: Bjorken expansion? 3D Hydro? Strong coupled?

Jet Quenching Monte Carlos

- Why so many?

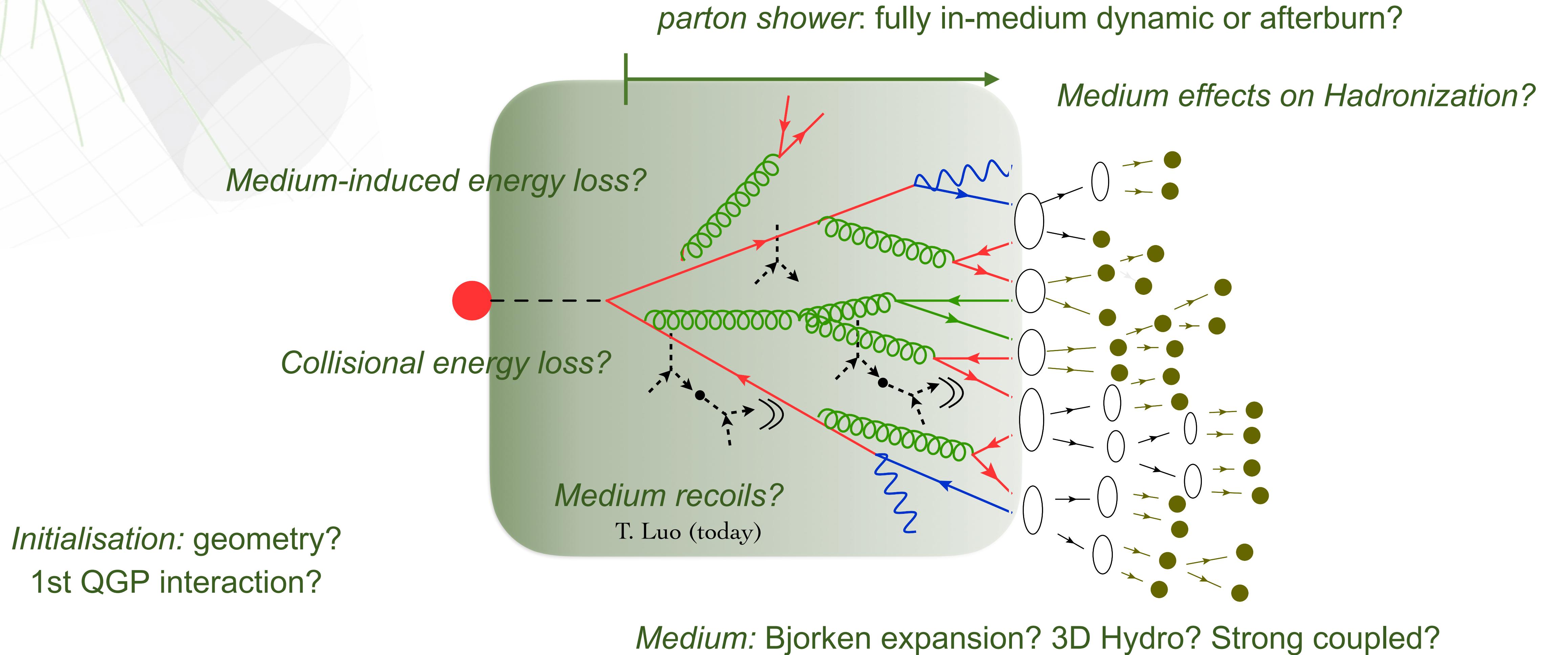


Jet Quenching Monte Carlos



Jet Quenching Monte Carlos

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Jet Quenching Monte Carlo

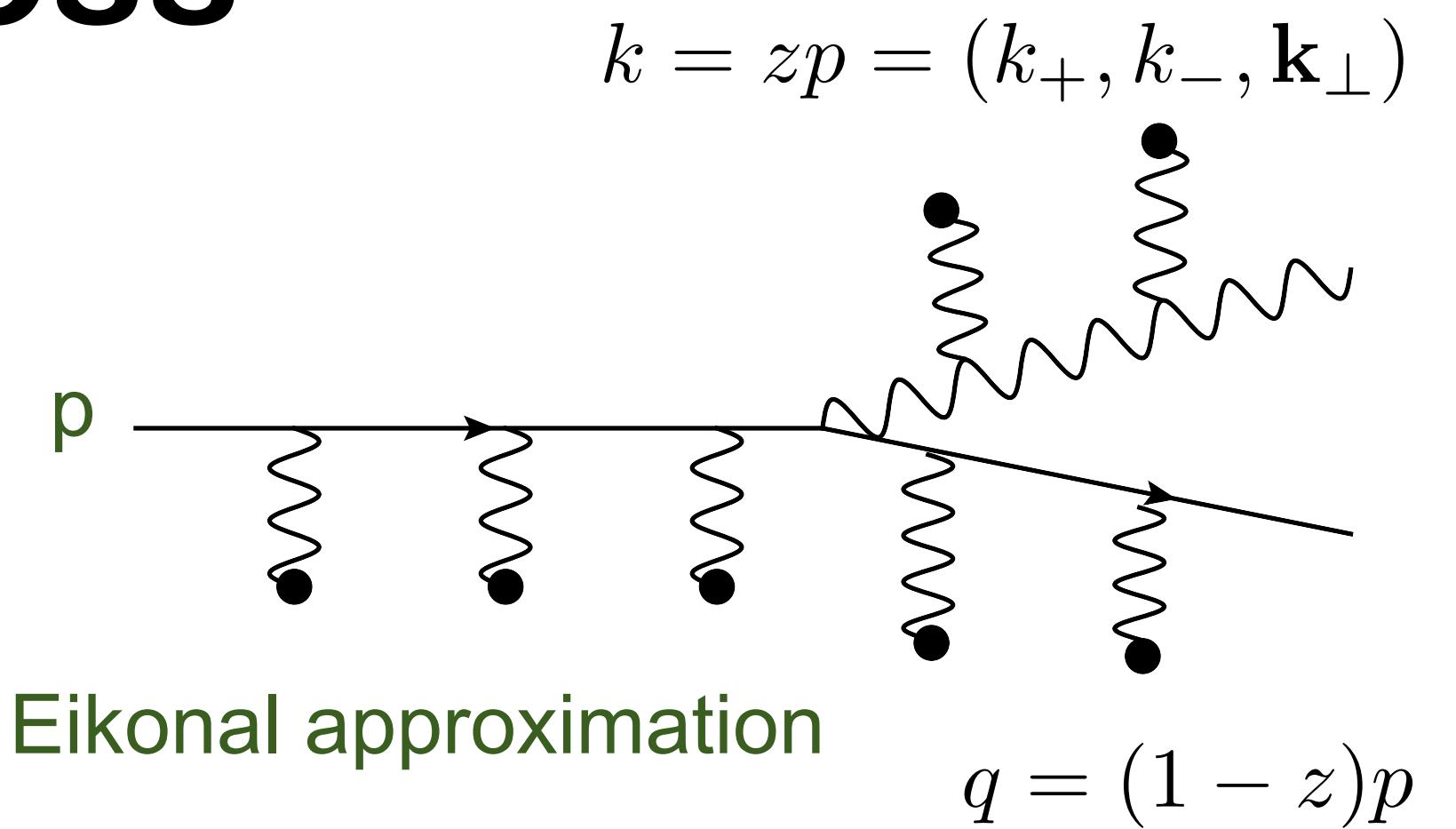
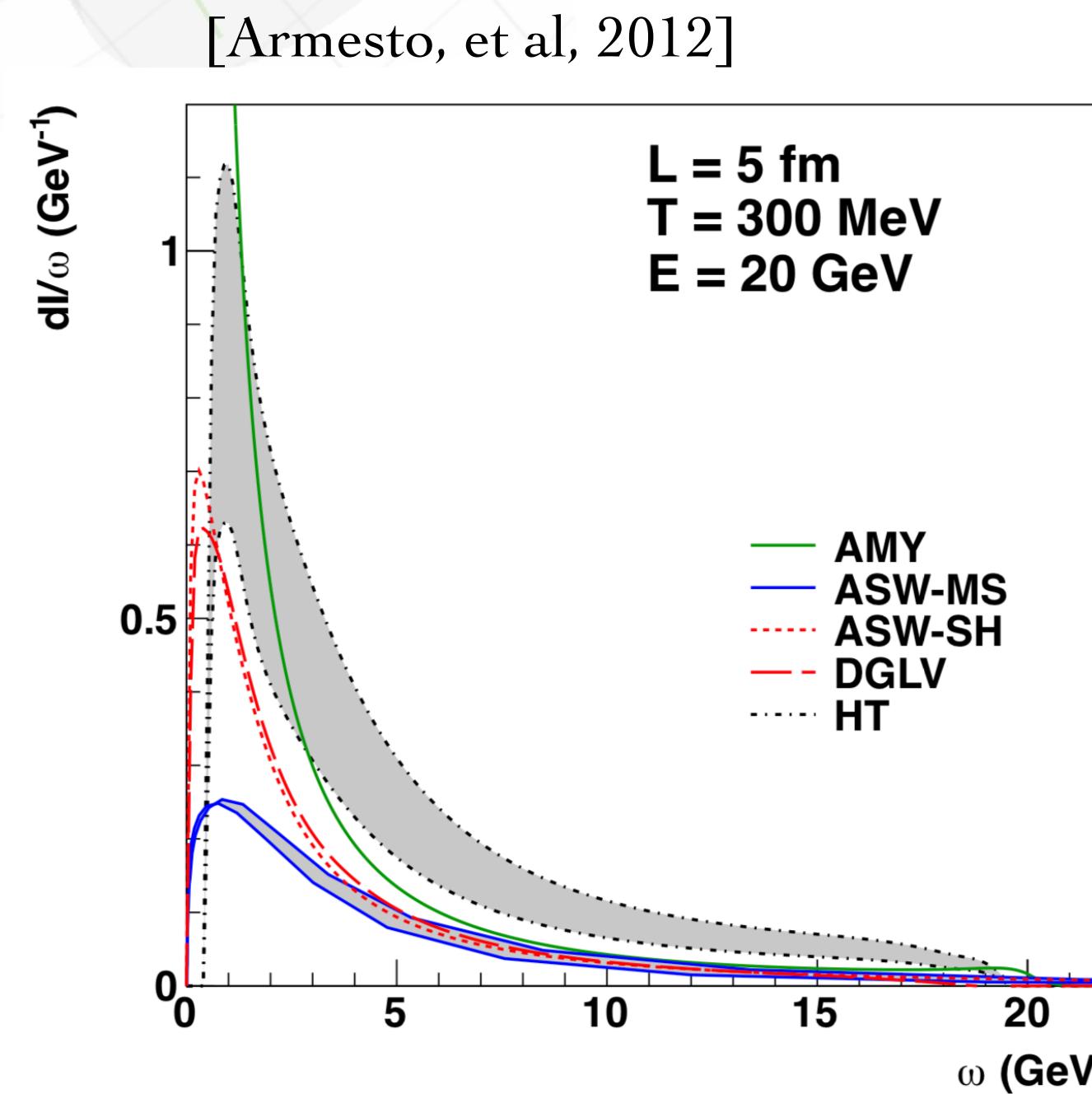
What do we need?

Radiative Energy Loss

- Based on single gluon emission in some kinematic approximation...

BDMPS-Z/ASW; AMY, Higher-Twist; GLV

[Baier, et al (97-00), Zakharov (96), Wiedemann (00); Arnold, Moore, Yaffe (01); Guo, Wang (00); Gyulassy, Levai, Vitev (00)]



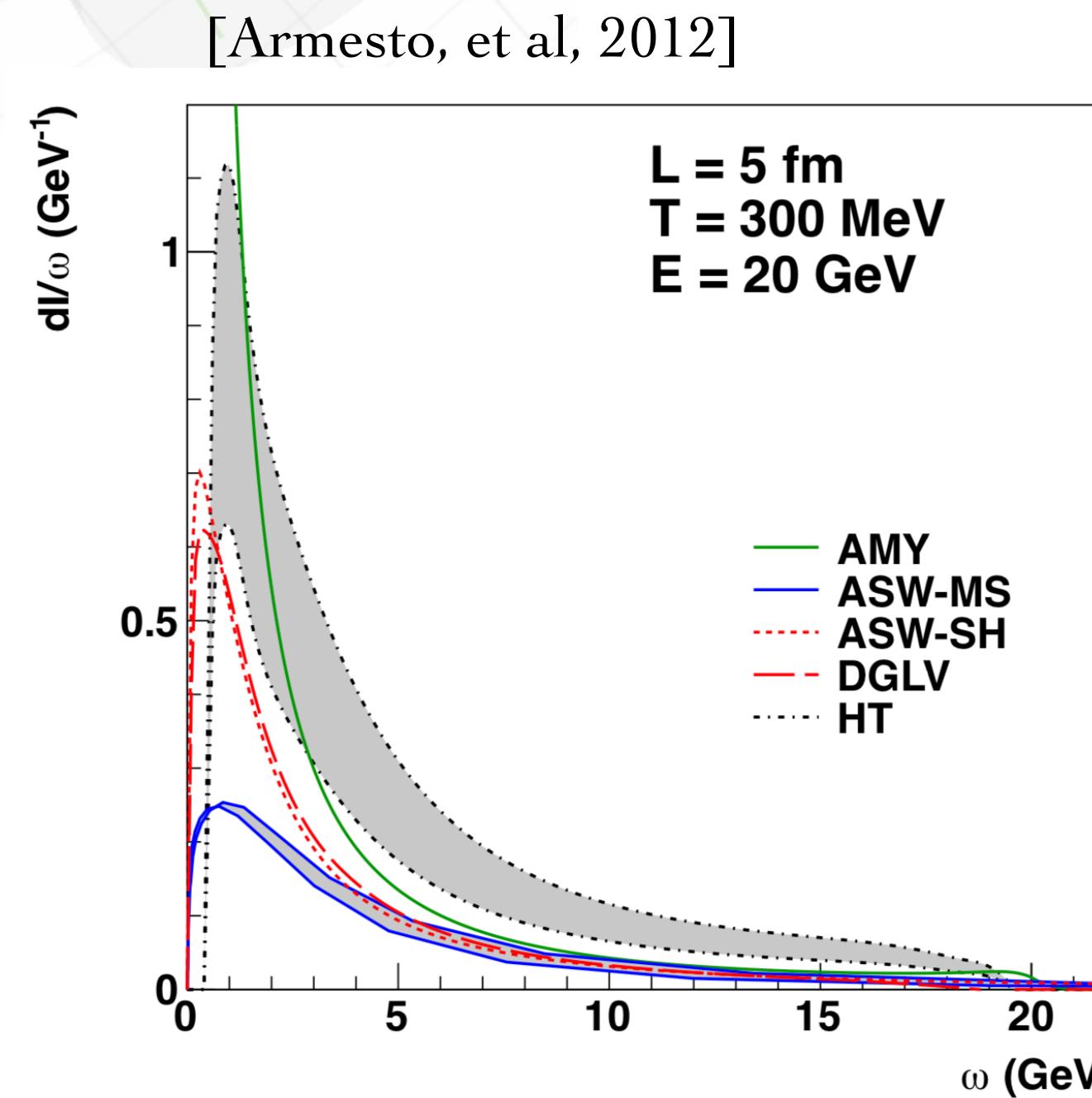
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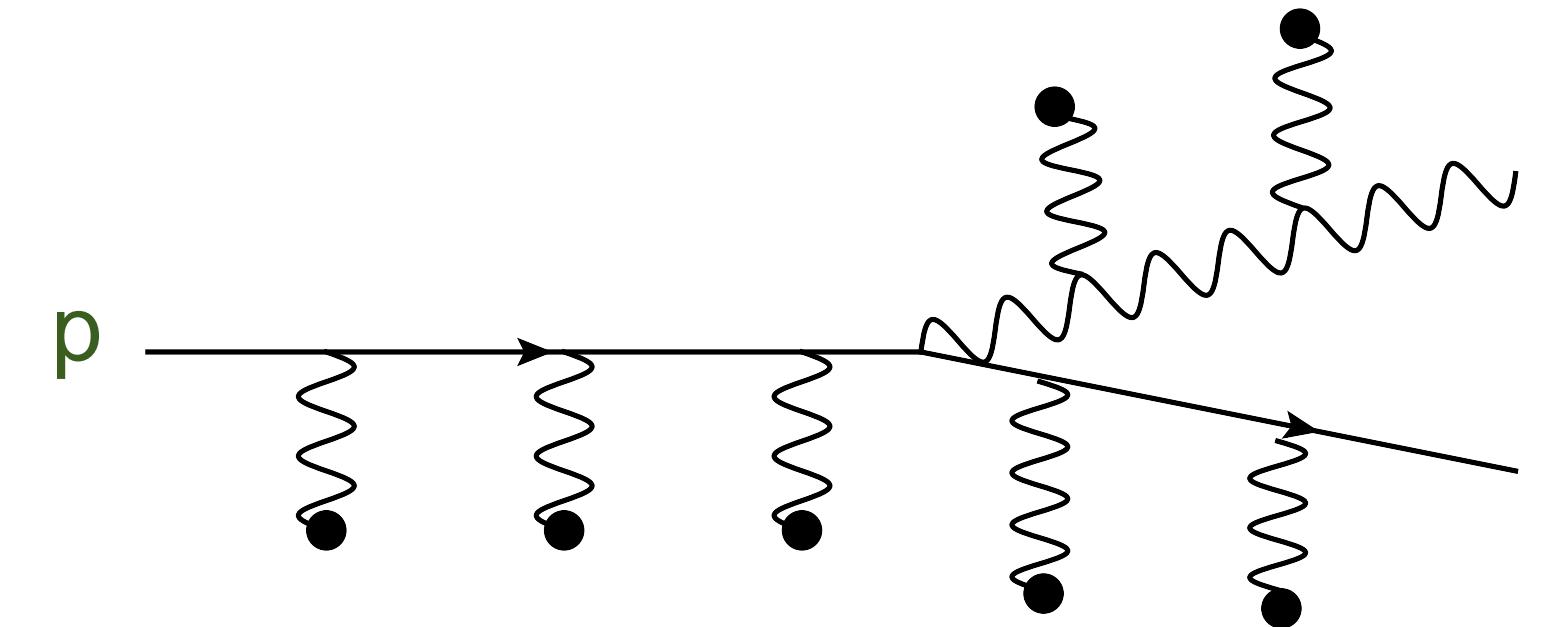
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- ... and extrapolated to account for all kinematics and full parton shower.

How to modify existing vacuum shower?

$$k = zp = (k_+, k_-, \mathbf{k}_\perp)$$



Eikonal approximation

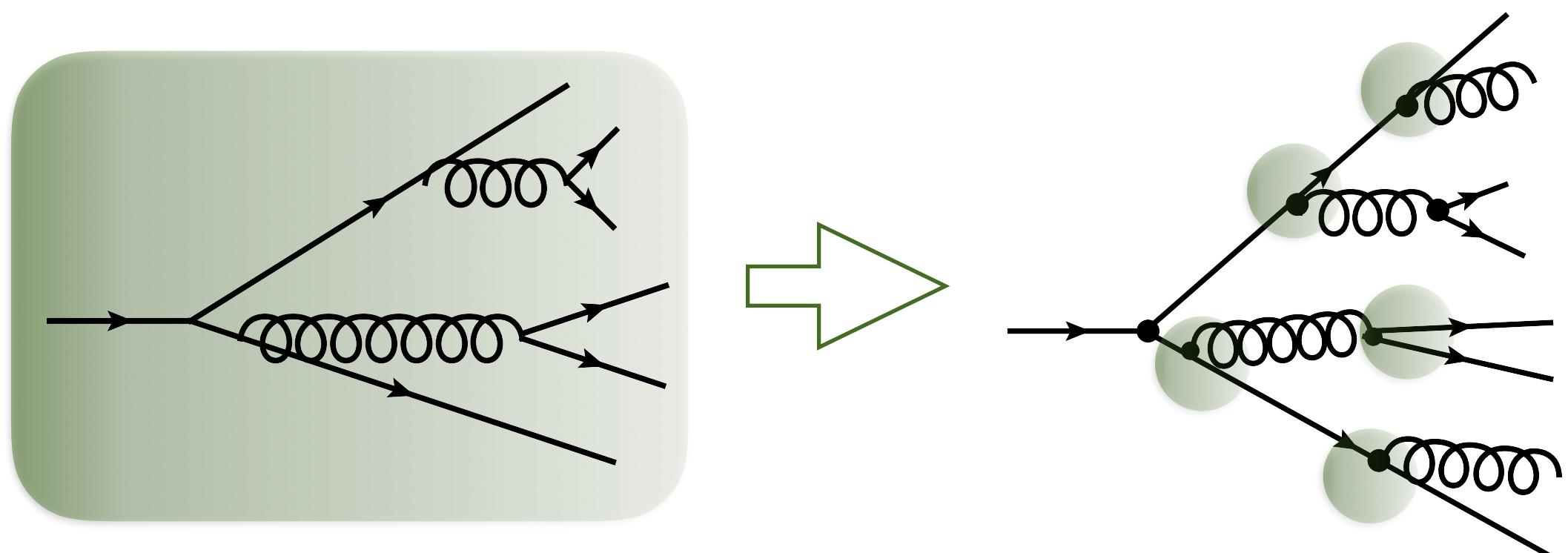
$$q = (1 - z)p$$

Vacuum + Medium effects

- From single gluon emission to full jet shower:

Change in the jet evolution:

E.g: Q-PYTHIA: $P^{tot}(z) = P^{vac}(z) + \Delta P^{med}(z)$



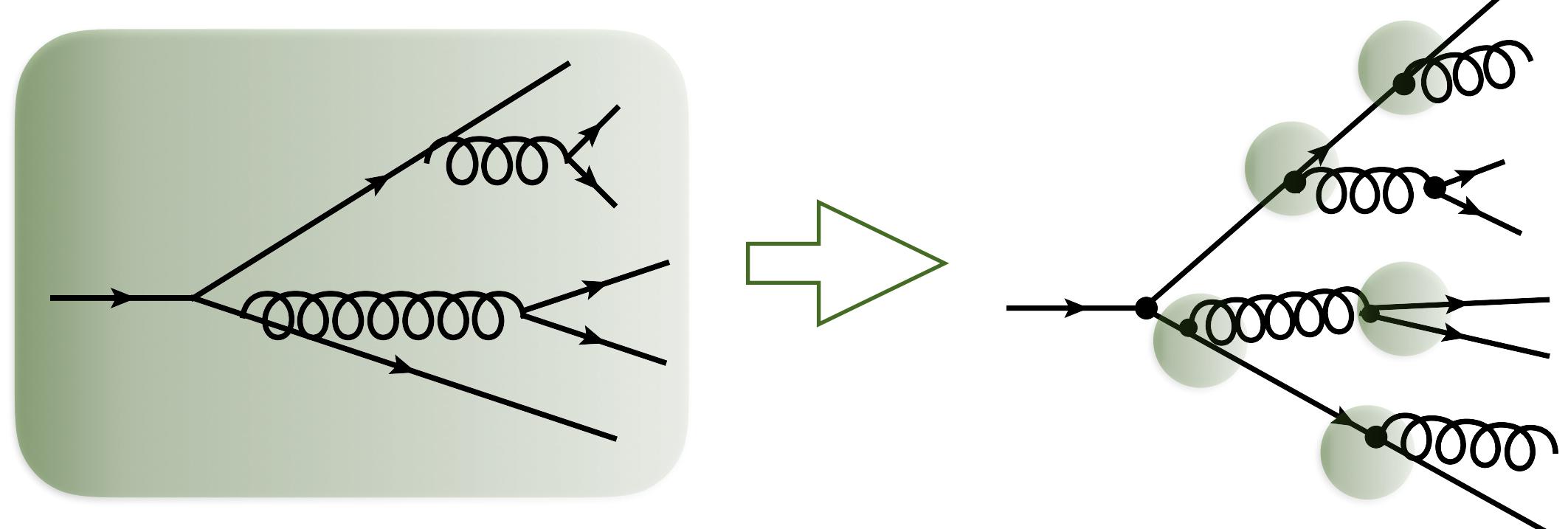
Similar models: MATTER, JEWEL,...

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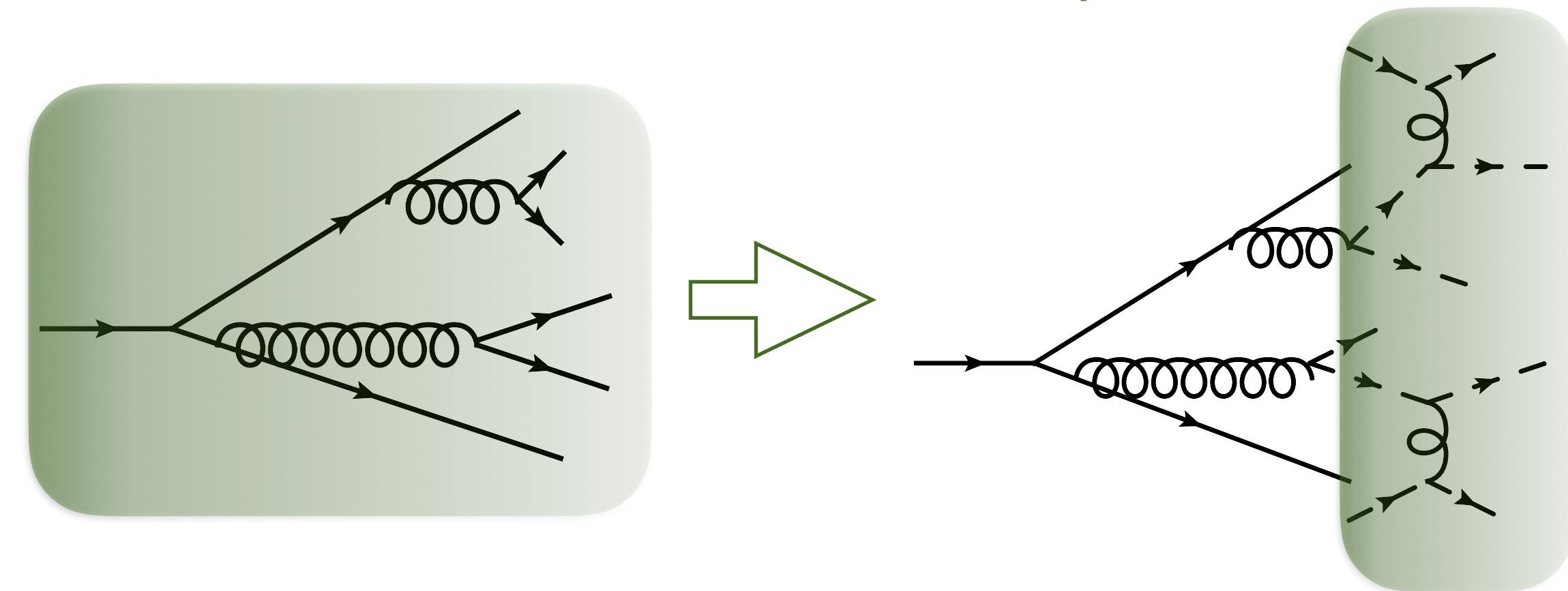
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Modifications on a developed shower

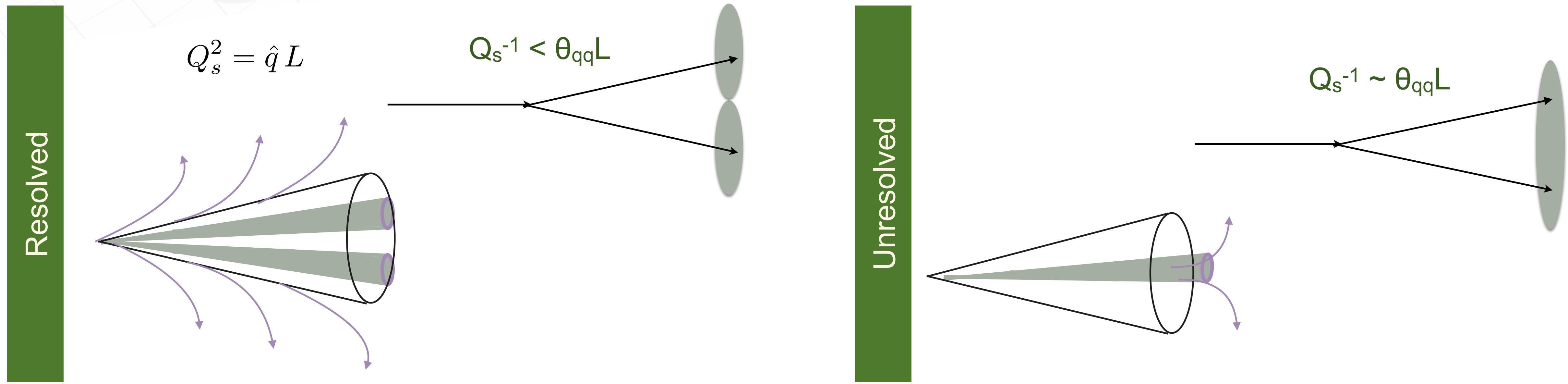
E.g: MARTINI: Vacuum Shower (up to a scale) + AMY Rate equations



Similar models: PyQUEN, Co-LBT, Hybrid,...

Latest Th Developments

- ◆ Qualitative picture evolved significantly! E.g:
 - ◆ In-medium coherence effects
 - ◆ Anti-Angular Ordering effects



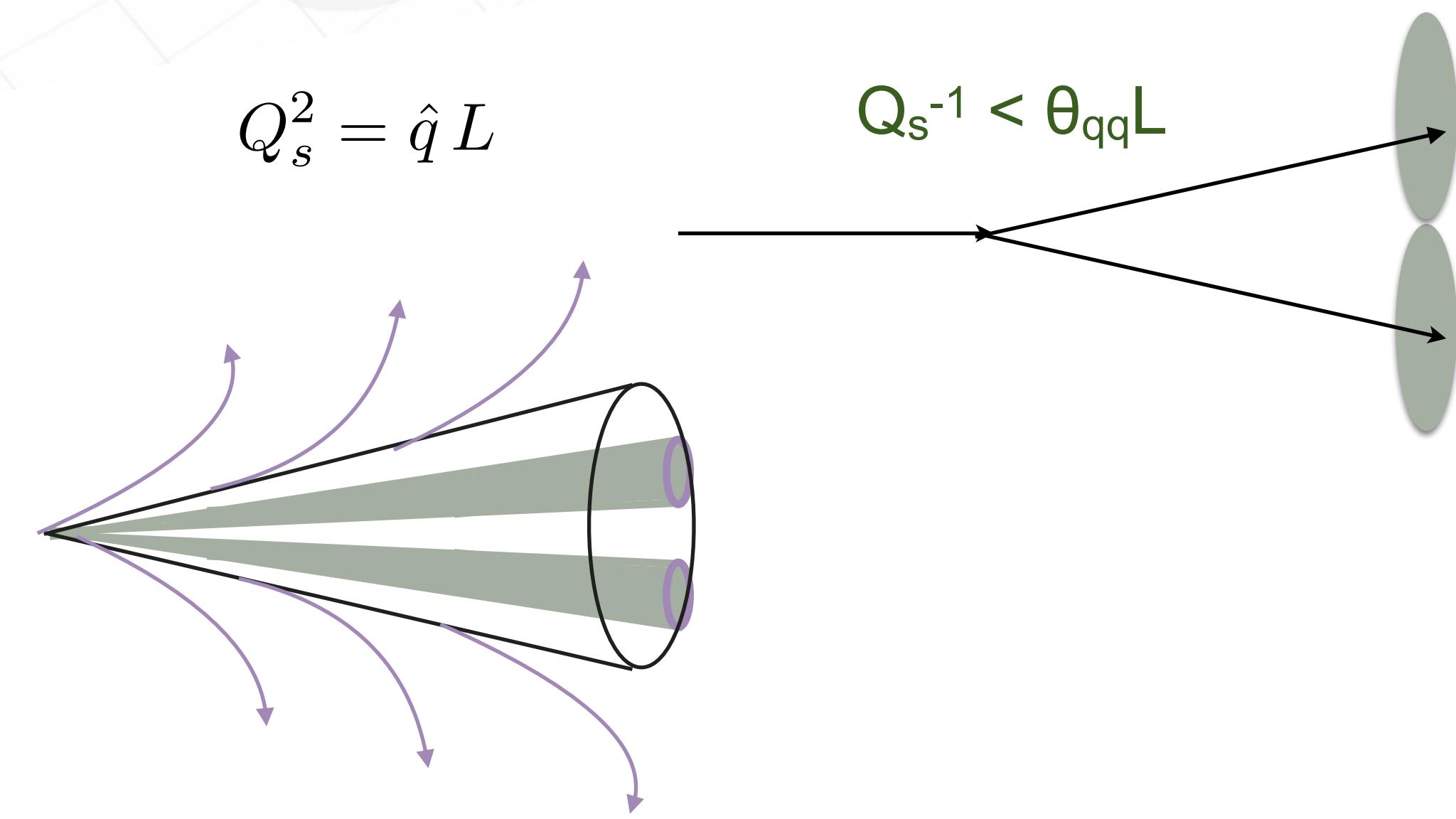
[Mehtar-Tani, Salgado, Tywoniuk (10-11), Casalderrey-Solana, Iancu (11), Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk (13)]

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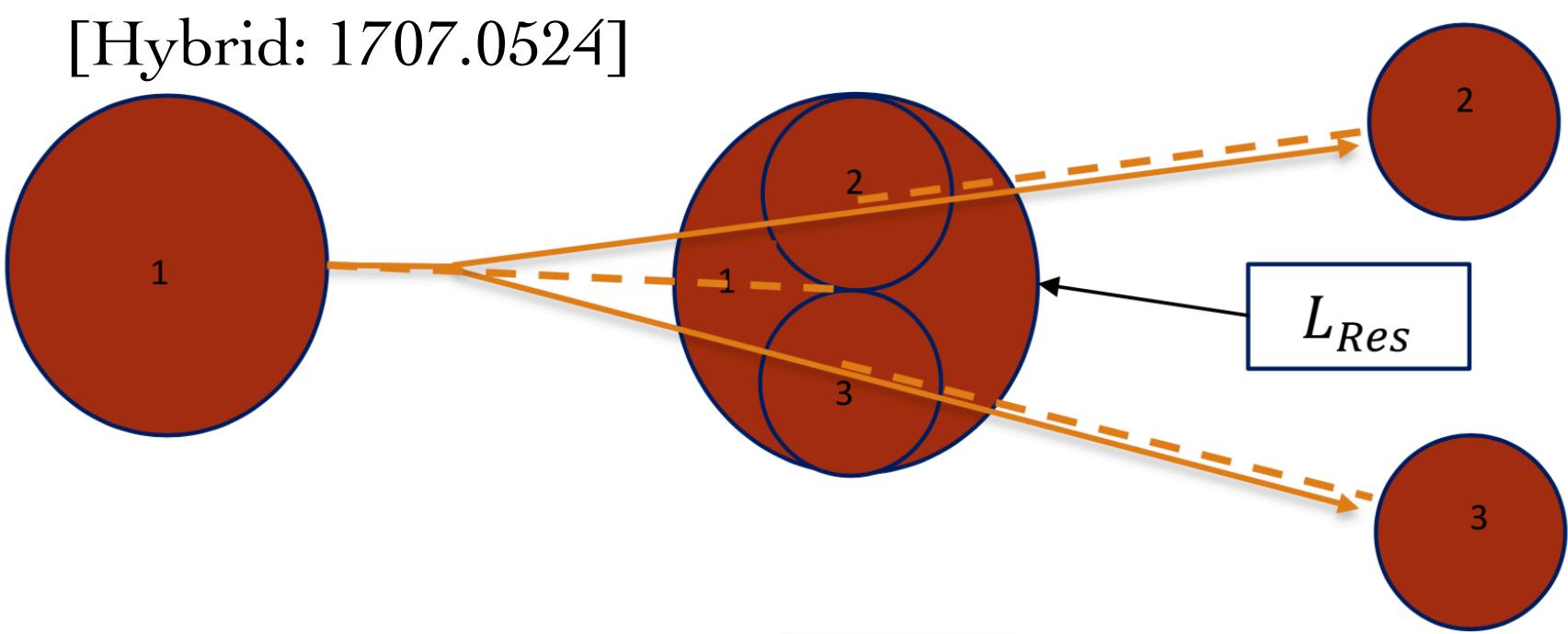
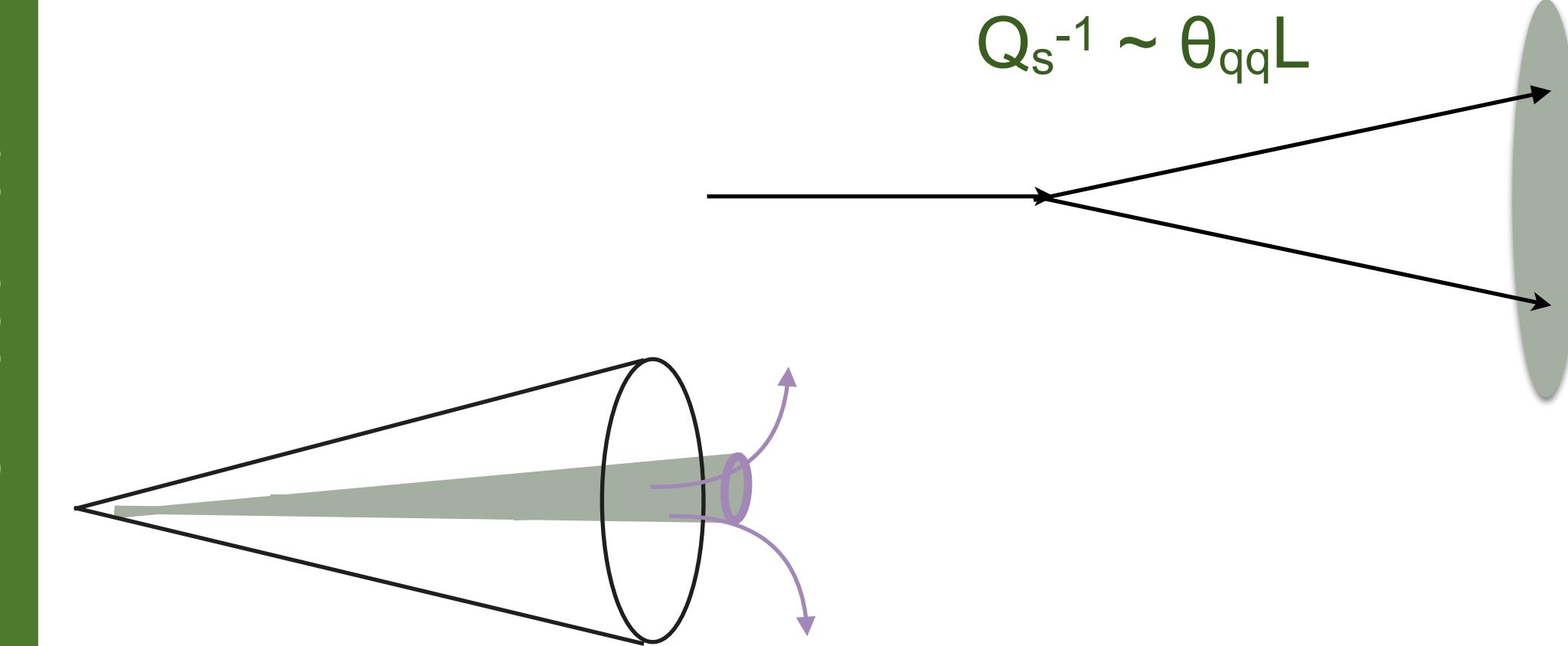
- ◆ Qualitative picture evolved significantly! E.g:
- ◆ In-medium coherence effects Only Hybrid so far...
- ◆ Anti-Angular Ordering effects Not accounted for...

Resolved

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



Unresolved

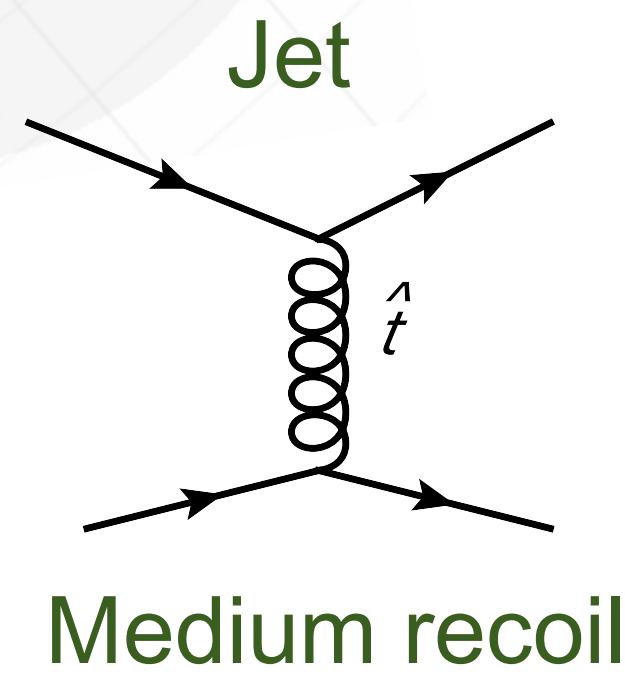


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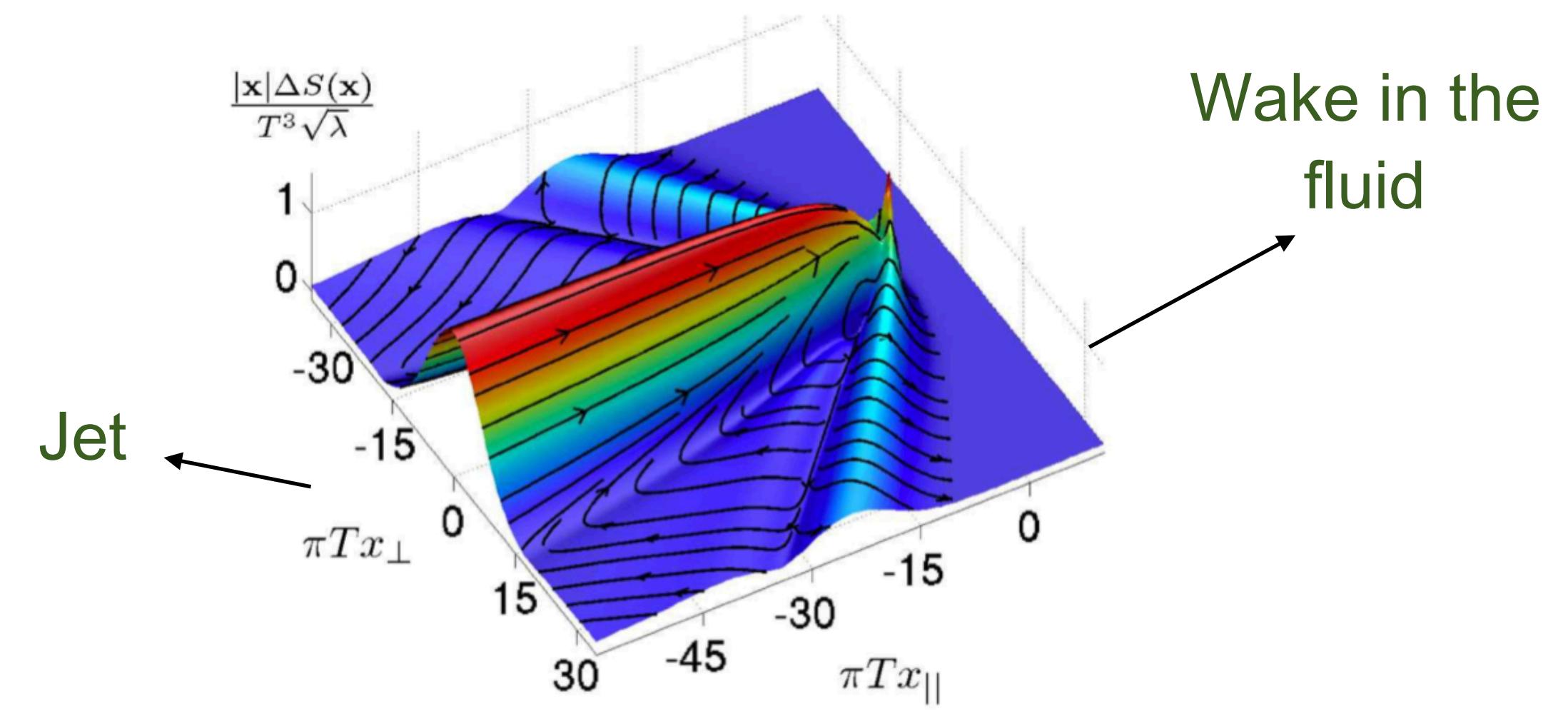
Elastic Energy Loss

- ◆ Elastic scatterings with medium constituents or drag effect?

pQCD perspective



AdS/CFT perspective



$$\text{E.g: JEWEL } \frac{d\hat{\sigma}}{d\hat{t}}(\hat{s}, |\hat{t}|) \simeq \frac{C_R 2\pi \alpha_s^2}{(|\hat{t}| + \mu_D^2)^2}$$

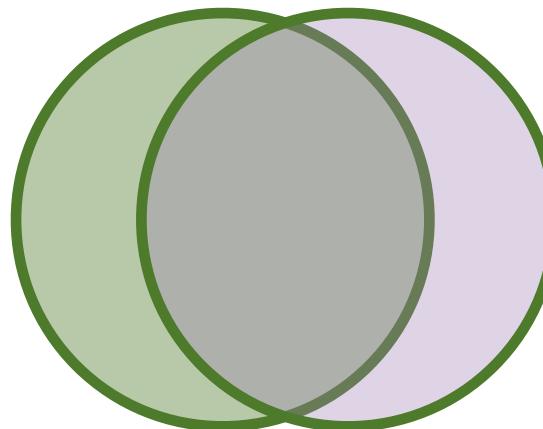
Similar models: MARTINI, Co-LBT...

$$\left. \frac{dE}{dx} \right|_{\text{strongly coupled}} = -\frac{4}{\pi} E_{\text{in}} \frac{x^2}{x_{\text{stop}}^2} \frac{1}{\sqrt{x_{\text{stop}}^2 - x^2}}$$

Hybrid:

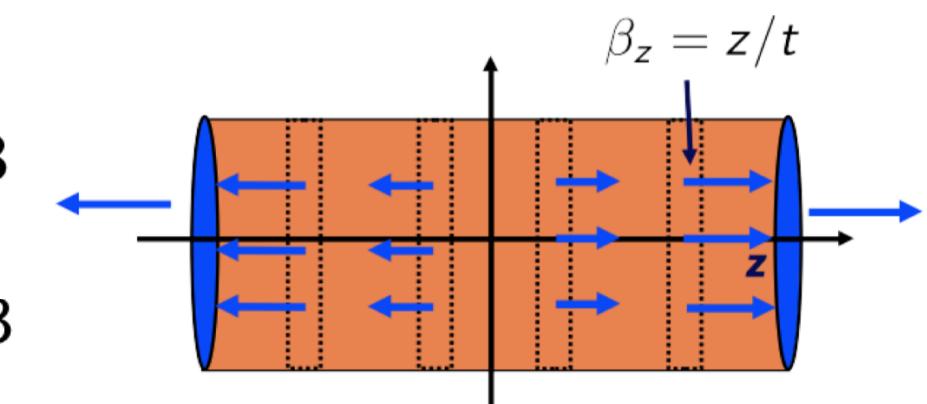
And still more...

- ◆ Medium evolution (time decreasing \hat{q}):
 - ◆ 1D nuclei overlap (e.g: PQM [Dainese, Loizides, Paic (04)])
 - ◆ Longitudinal (Bjorken expansion) and/or transverse (flow) expansion
 - ◆ Hydrodynamics



$$\omega_c |_{\text{effective}} \equiv \frac{1}{2} \langle \hat{q} \rangle L^2 = \int_0^\infty \xi \hat{q}(\xi) d\xi$$

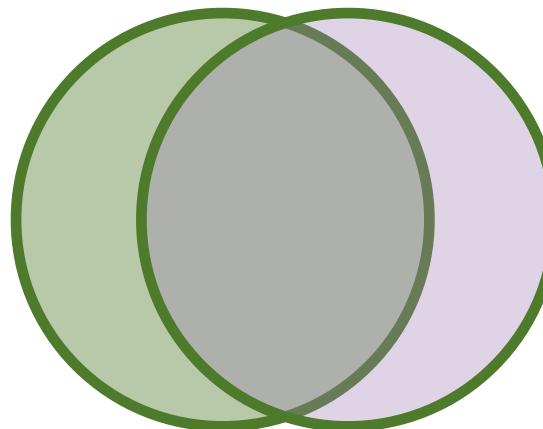
$$T(\tau) \propto \tau^{-1/3}$$
$$n(\tau) \propto \tau^{-1} \quad \& \quad \epsilon(\tau) \propto \tau^{-4/3}$$



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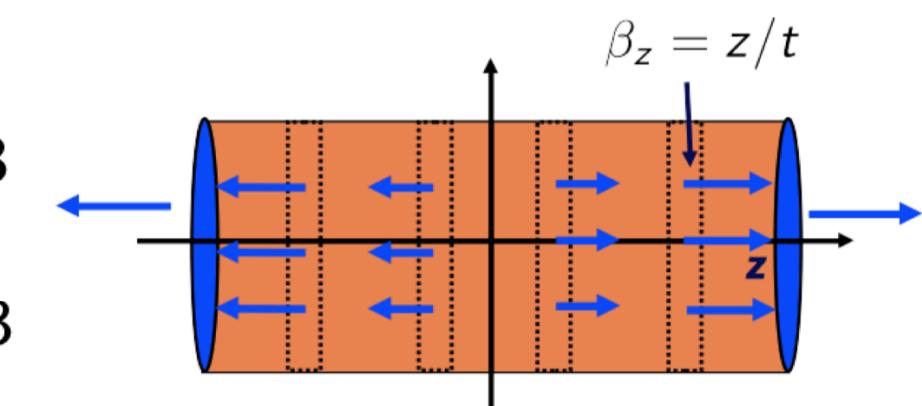
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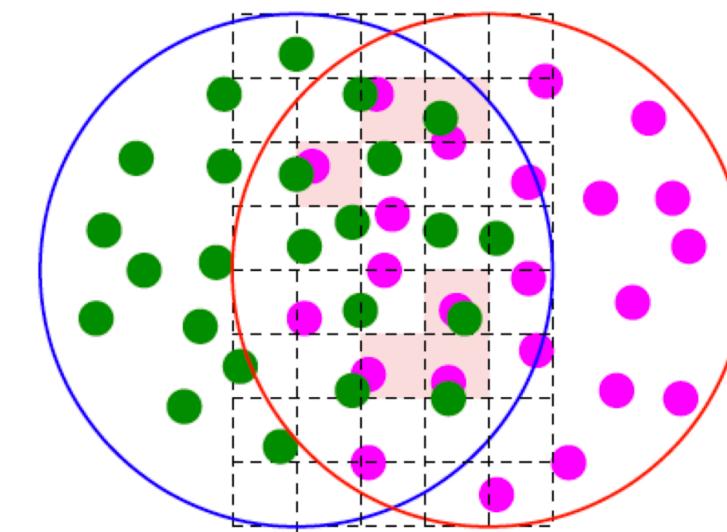
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- ◆ Hydrodynamics

- ◆ Production point (for path-length dependence):

- ◆ Sampled from initial nuclei overlap



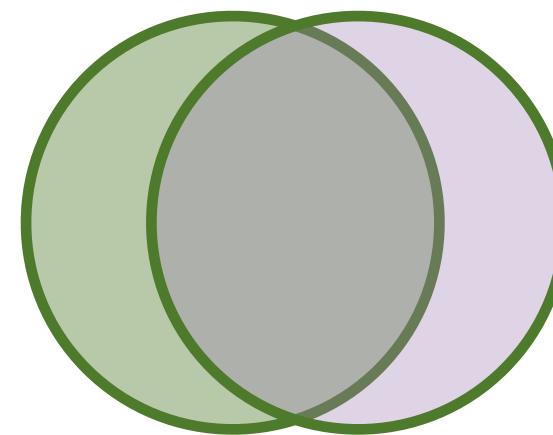
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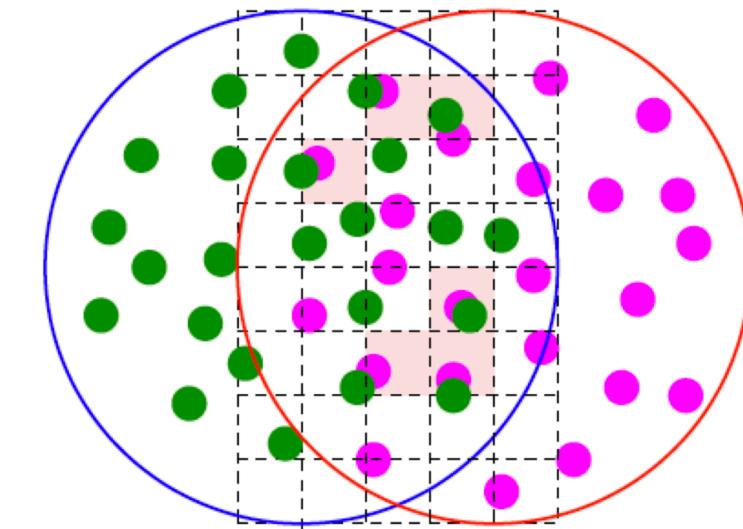
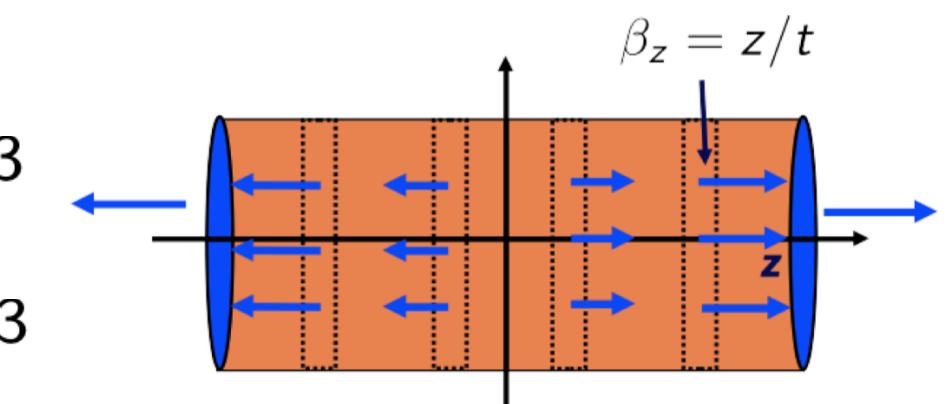
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- ◆ Hadronization:
 - ◆ Usually taken from pythia (might include recoiled particles)

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JQ MC: (Partial) Summary

	Model	Parton Shower	Radiative energy Loss	Collisional Energy Loss	Medium Response	Thermalization	Jet-induced effects
Fully Dynamic	Q-PYTHIA	Pythia 6 with Modified Sudakov	BDMPS	X	X	X	X
	MATTER	Virtuality ordered with Modified Sudakov	Higher-Twist	X	X	X	X
	JEWEL	Pythia 6 with medium scatterings	pQCD + LPM effect	pQCD	Yes	X	X
Afterburners	PYQUEN	Pythia 6 Shower + Energy Loss	BDMPS	pQCD	X	X	X
	MARTINI	Pythia 8 initialisation + MC Rate Equations	AMY	pQCD	Yes	Yes	X
	Co-LBT	Pythia 6 Shower + Energy Loss	Higher-Twist	pQCD	Yes	Yes	Yes
	Hybrid	Pythia 6 Shower + Energy Loss	X	AdS/CFT	Yes	Yes (resulting effect at the final spectra)	
Analytical Approach	Coupled Jet-Fluid	Pythia 6 initialisation + jet Evolution Equations	Higher-Twist	pQCD	Yes	Yes	Yes

...

(sorry for the ones that are not in this list...)

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	MARTINI Pythia 8 initialisation + MC Rate Equations	AMY	pQCD	Yes	Yes	X
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Analytical Approach (not MC)	Coupled Jet-Fluid	Pythia 6 initialisation + jet Evolution Equations	Higher-Twist	pQCD	Yes	Yes

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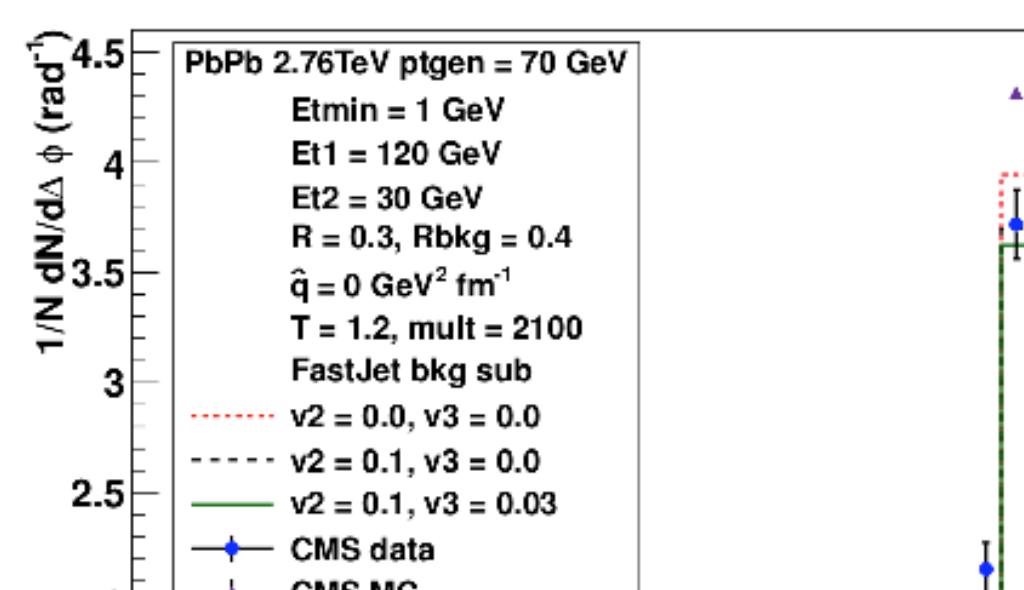
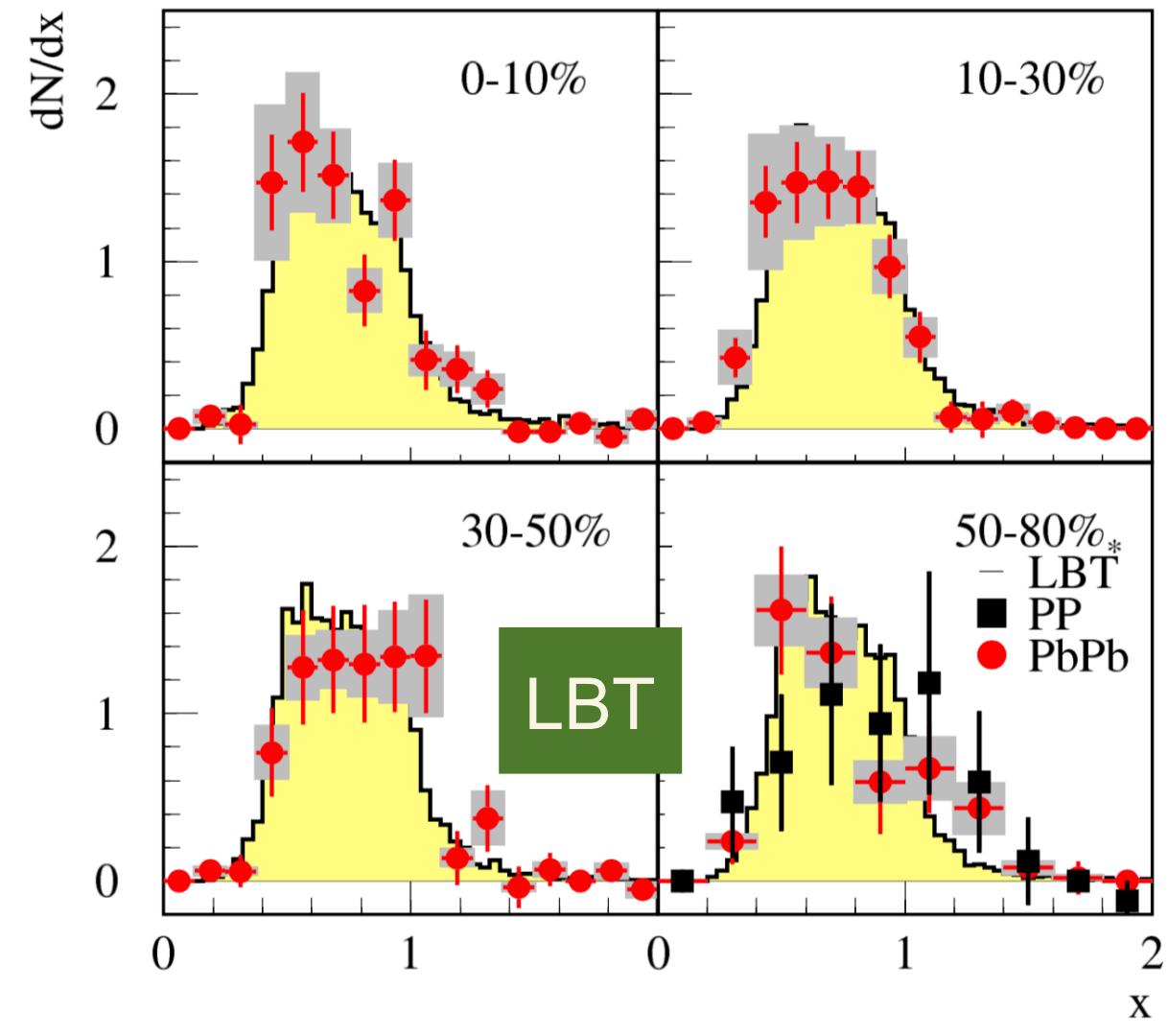
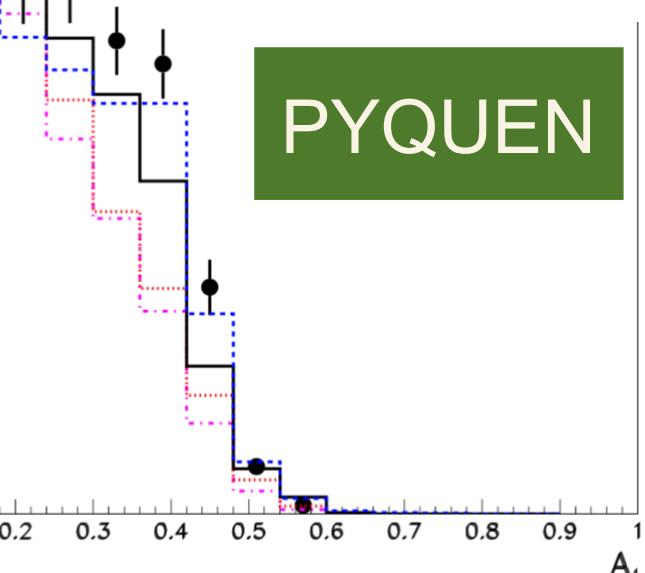
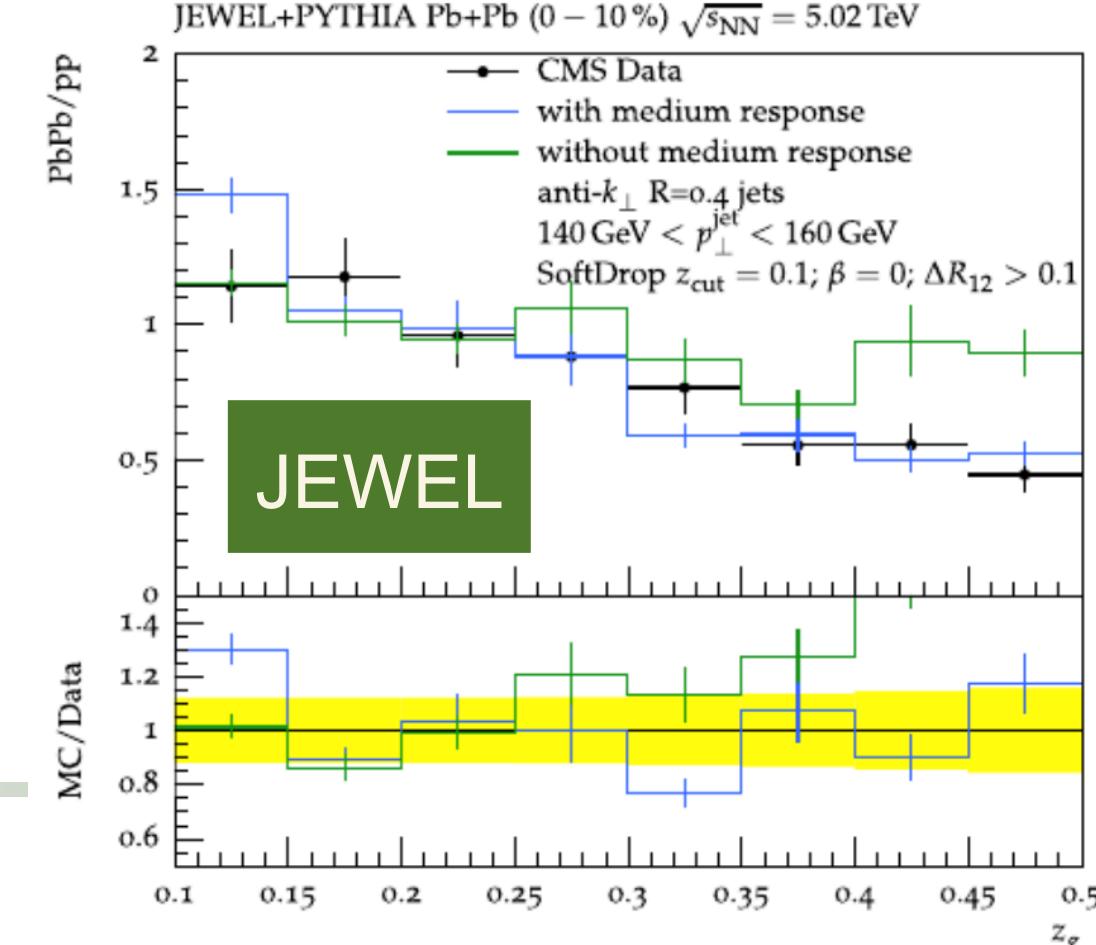
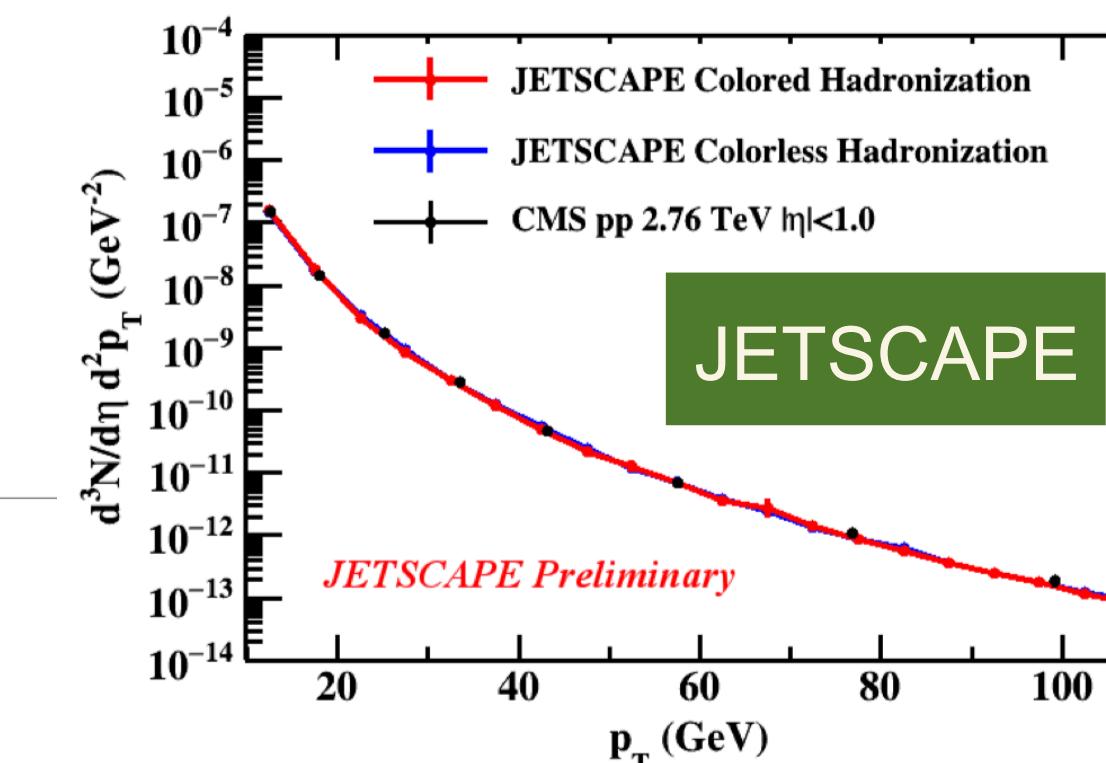
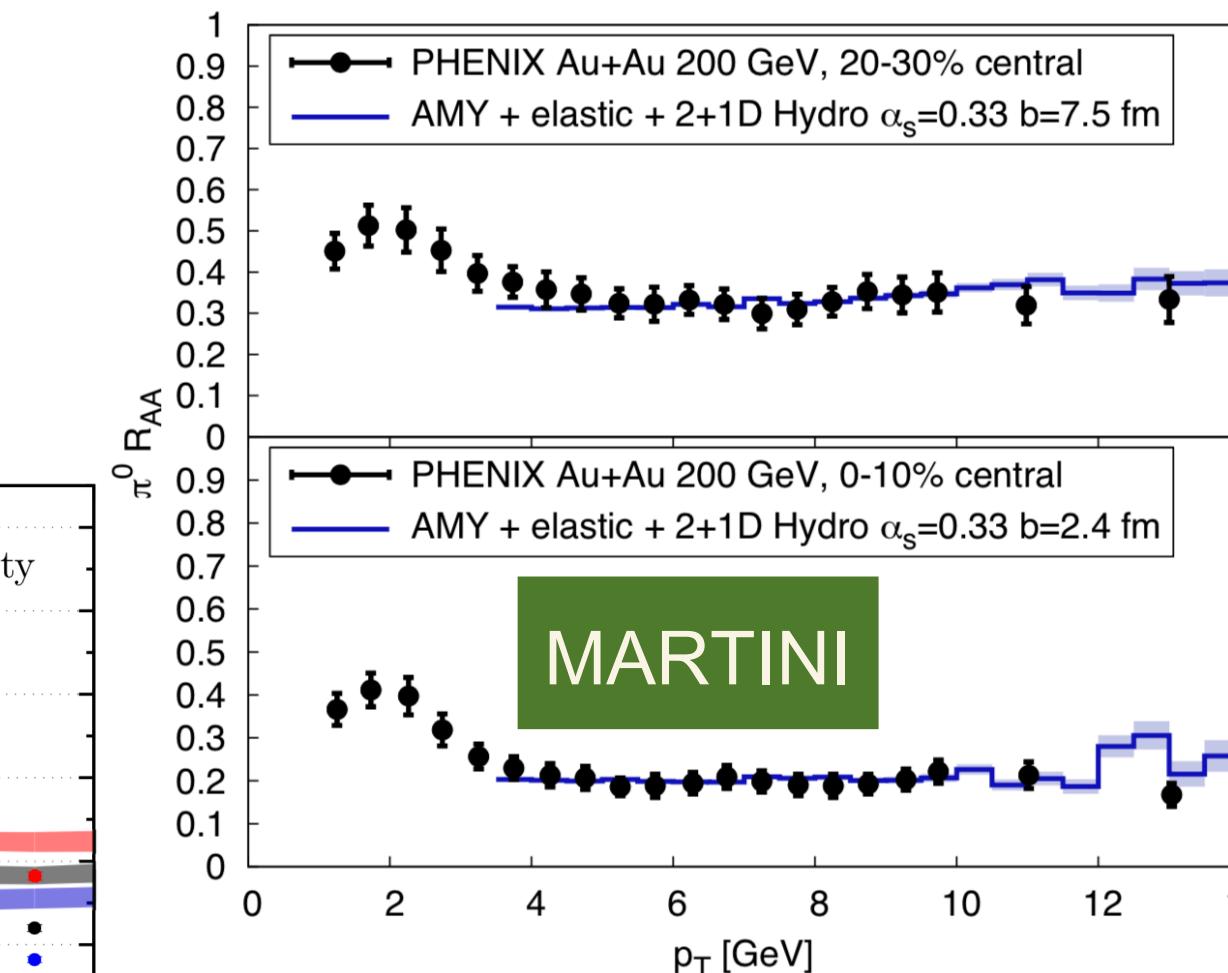
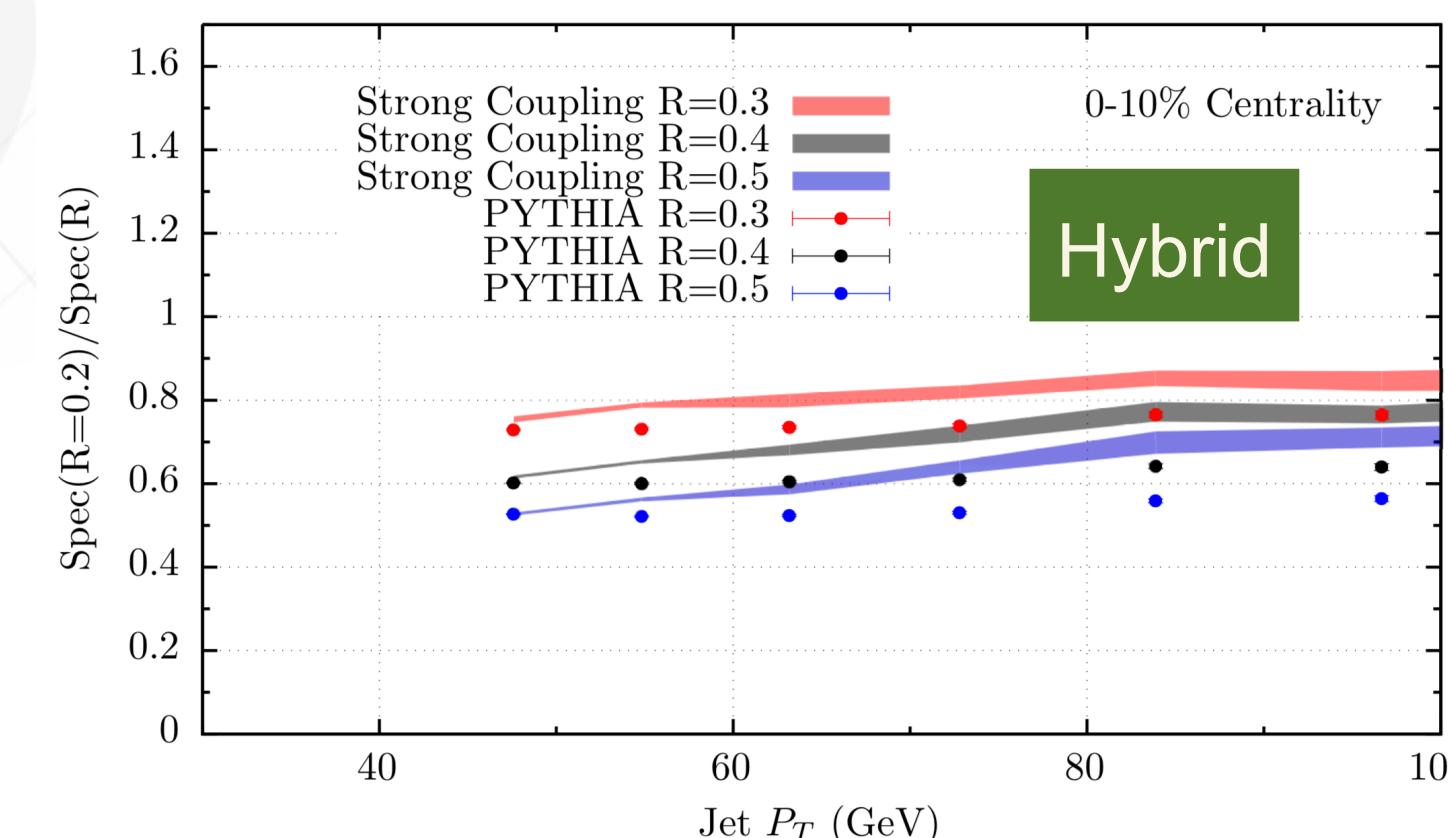
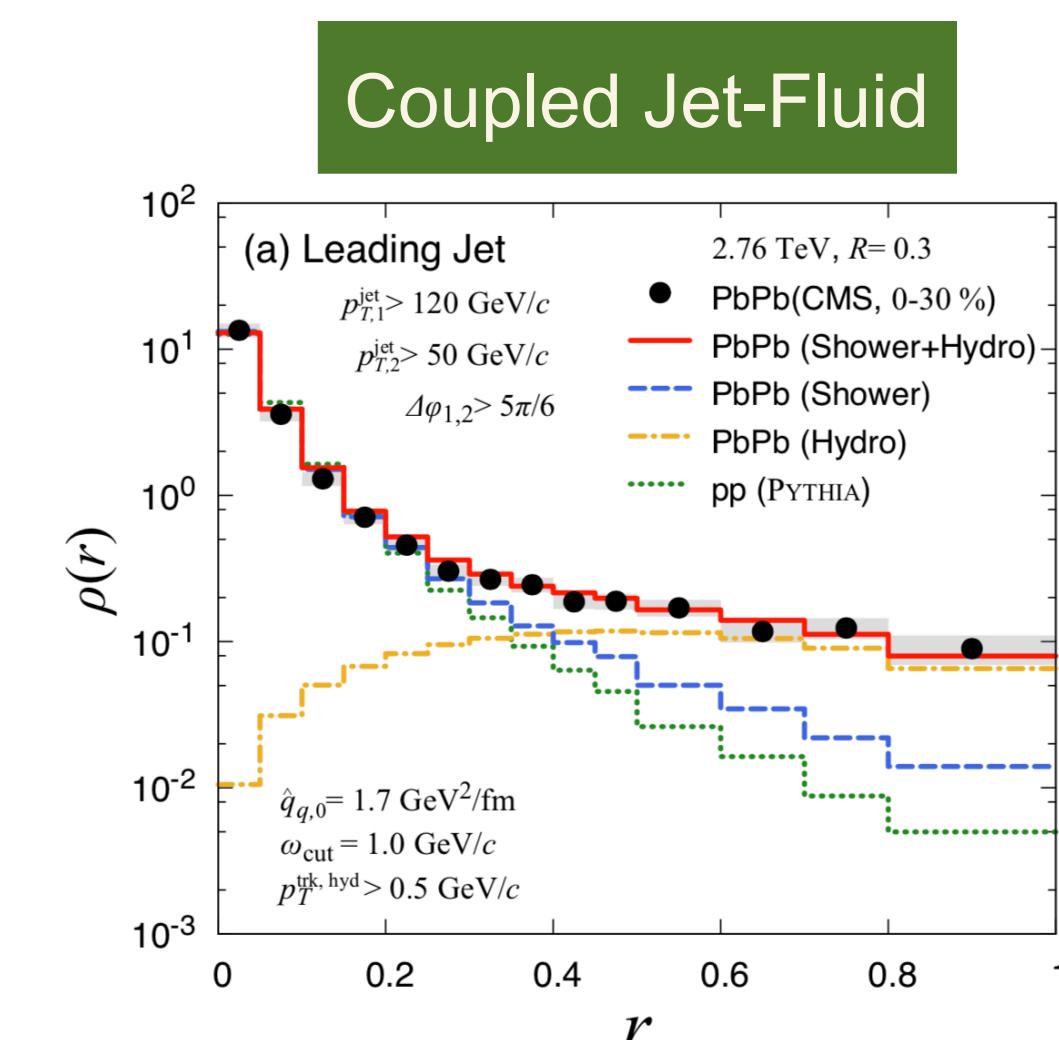
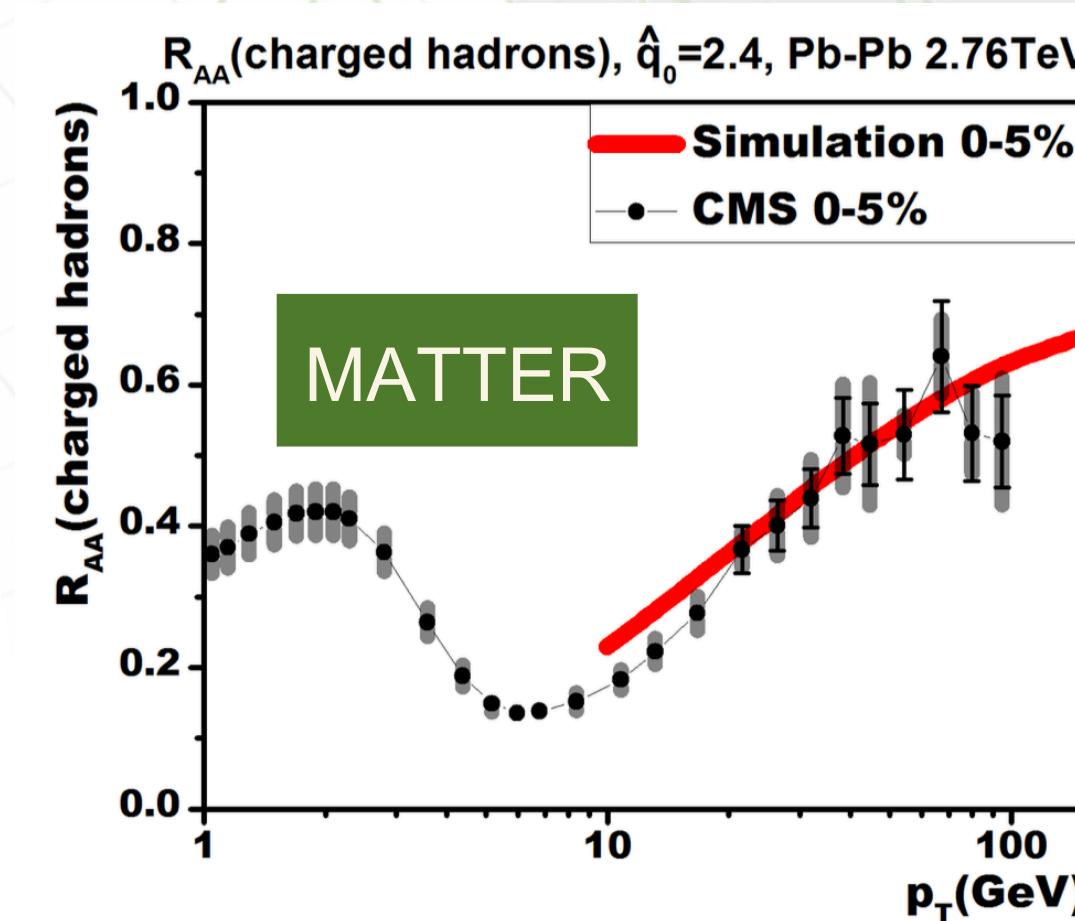
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Jet Quenching Monte Carlo

MC Results vs Data

JQ Monte Carlo Results

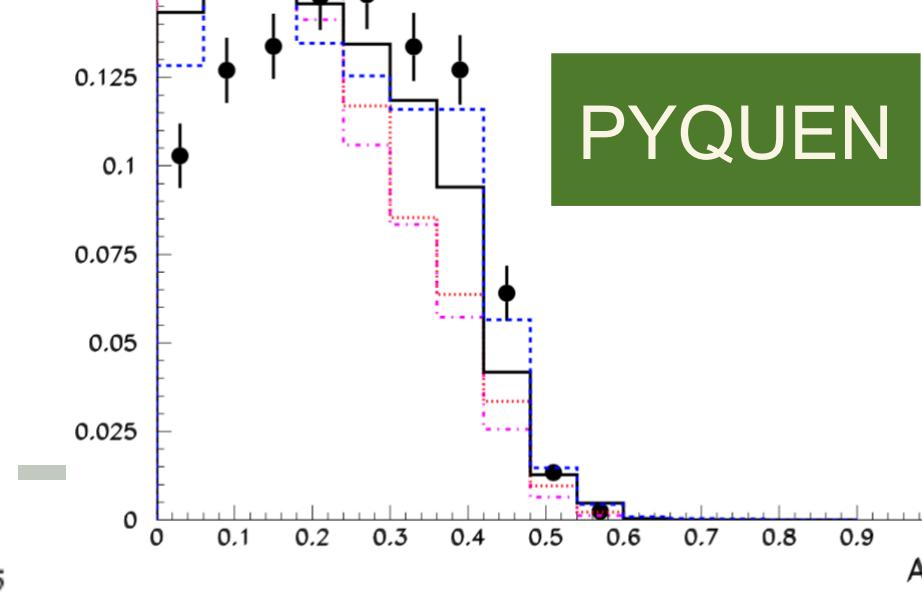
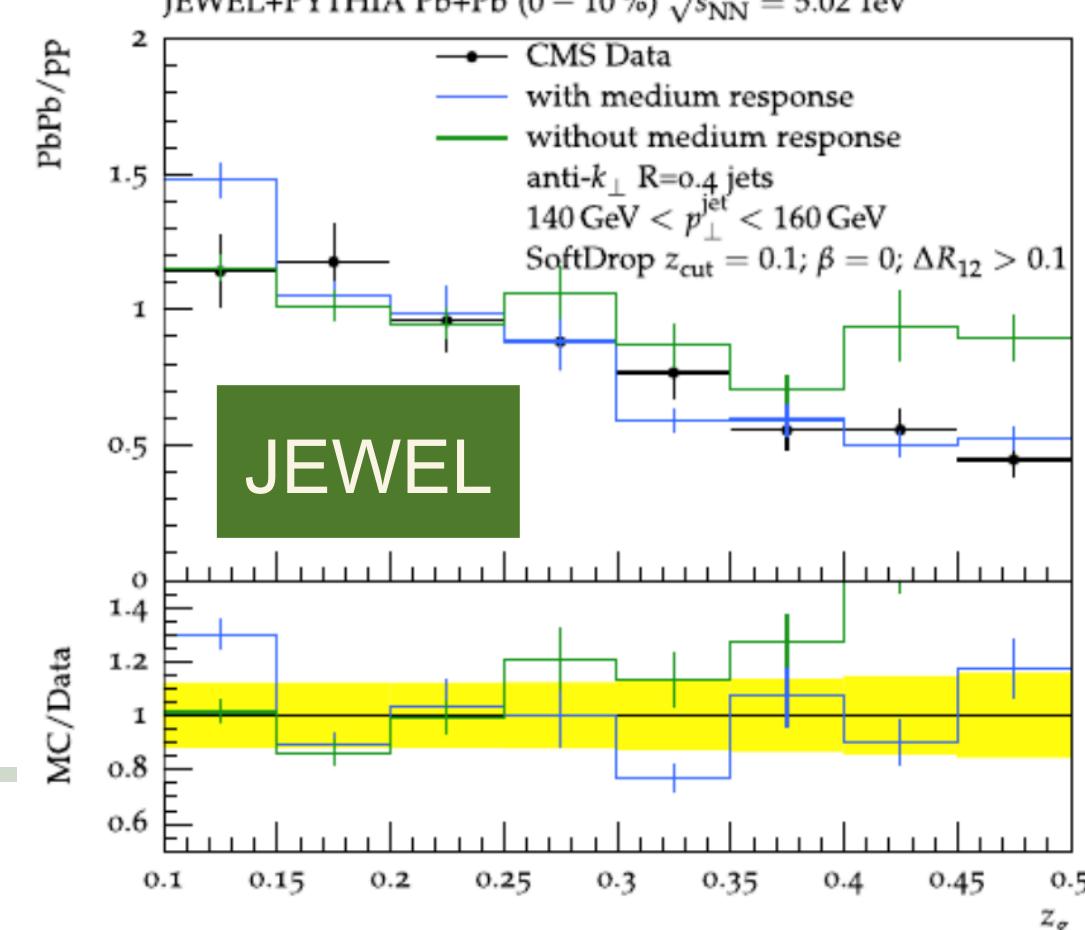
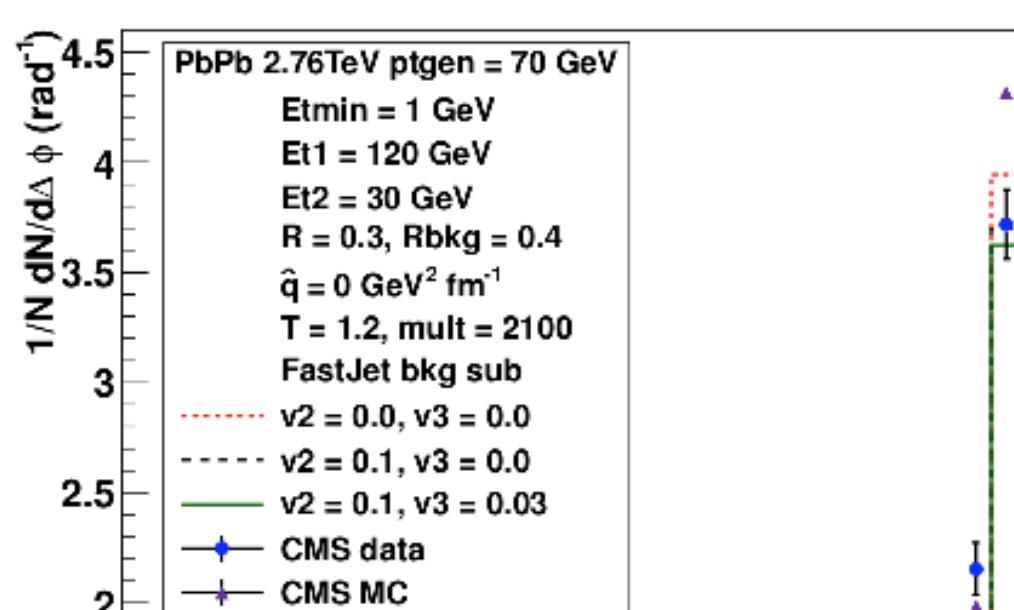
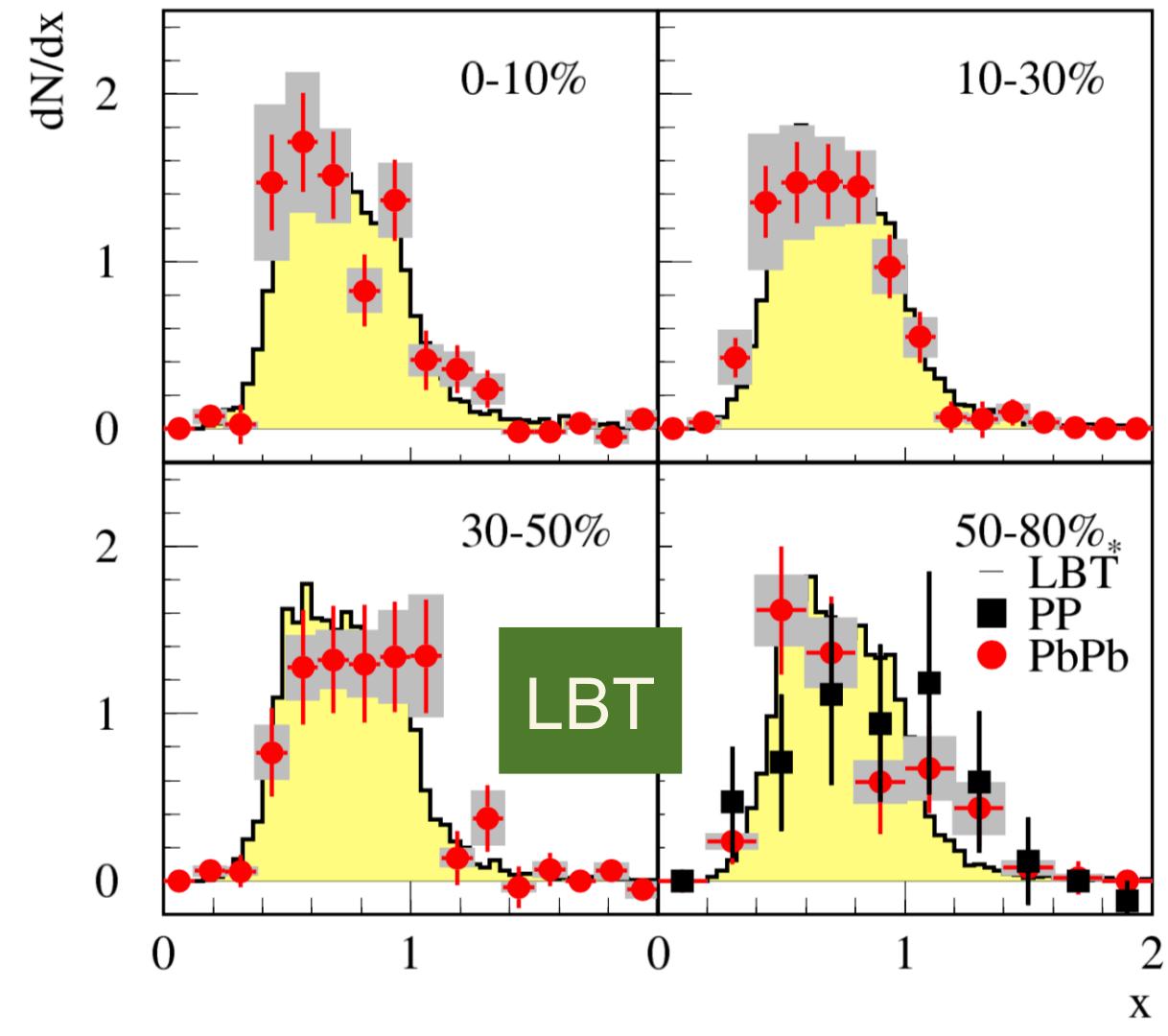
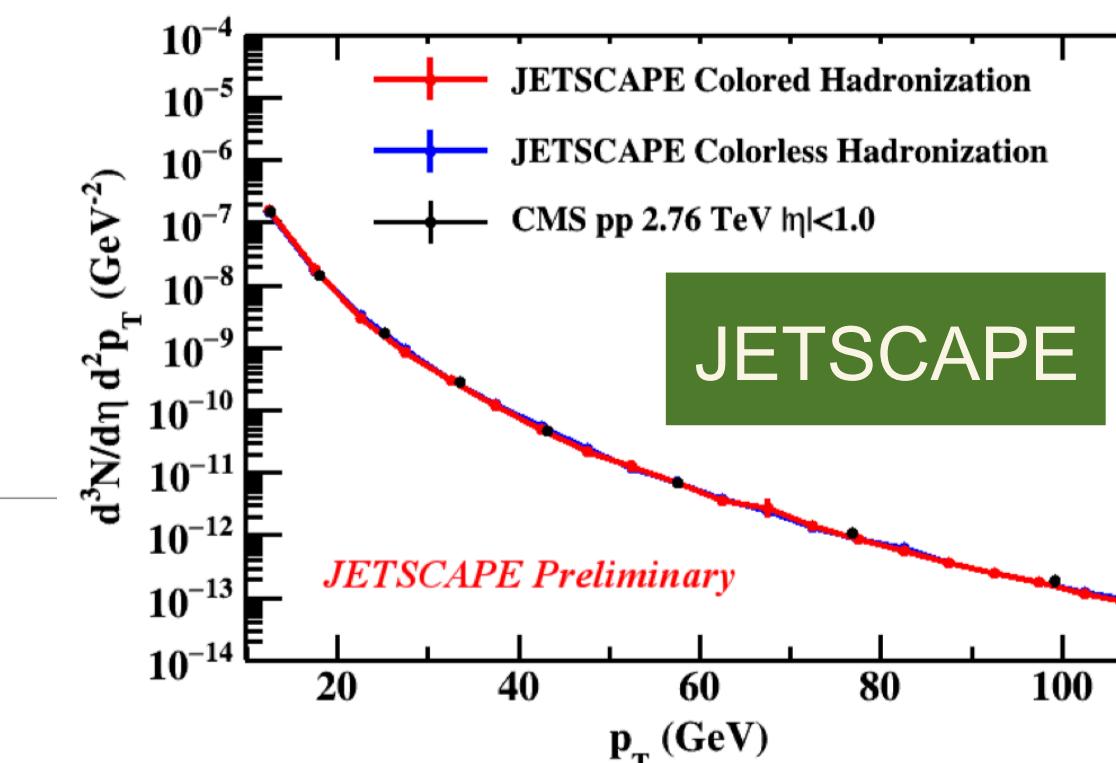
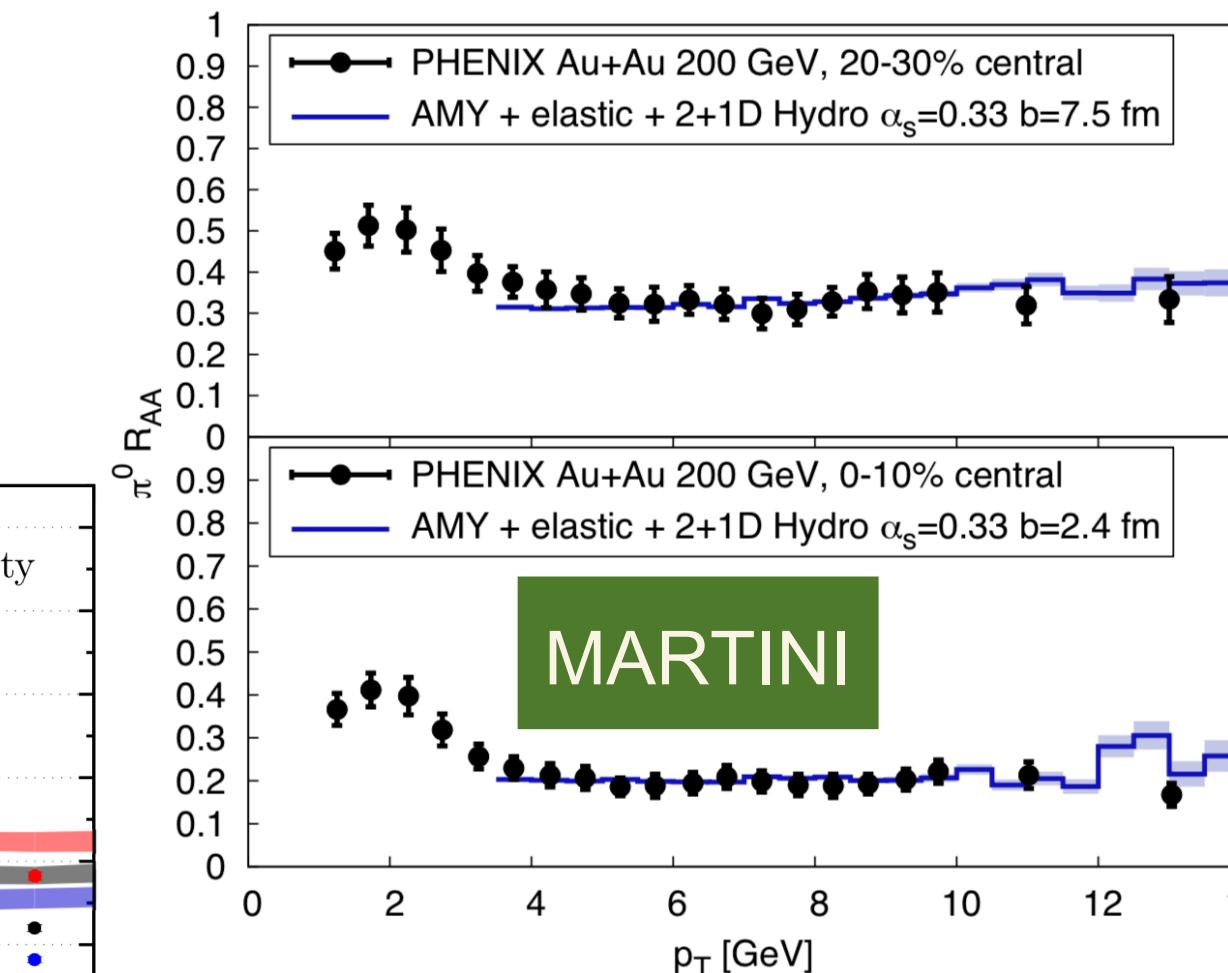
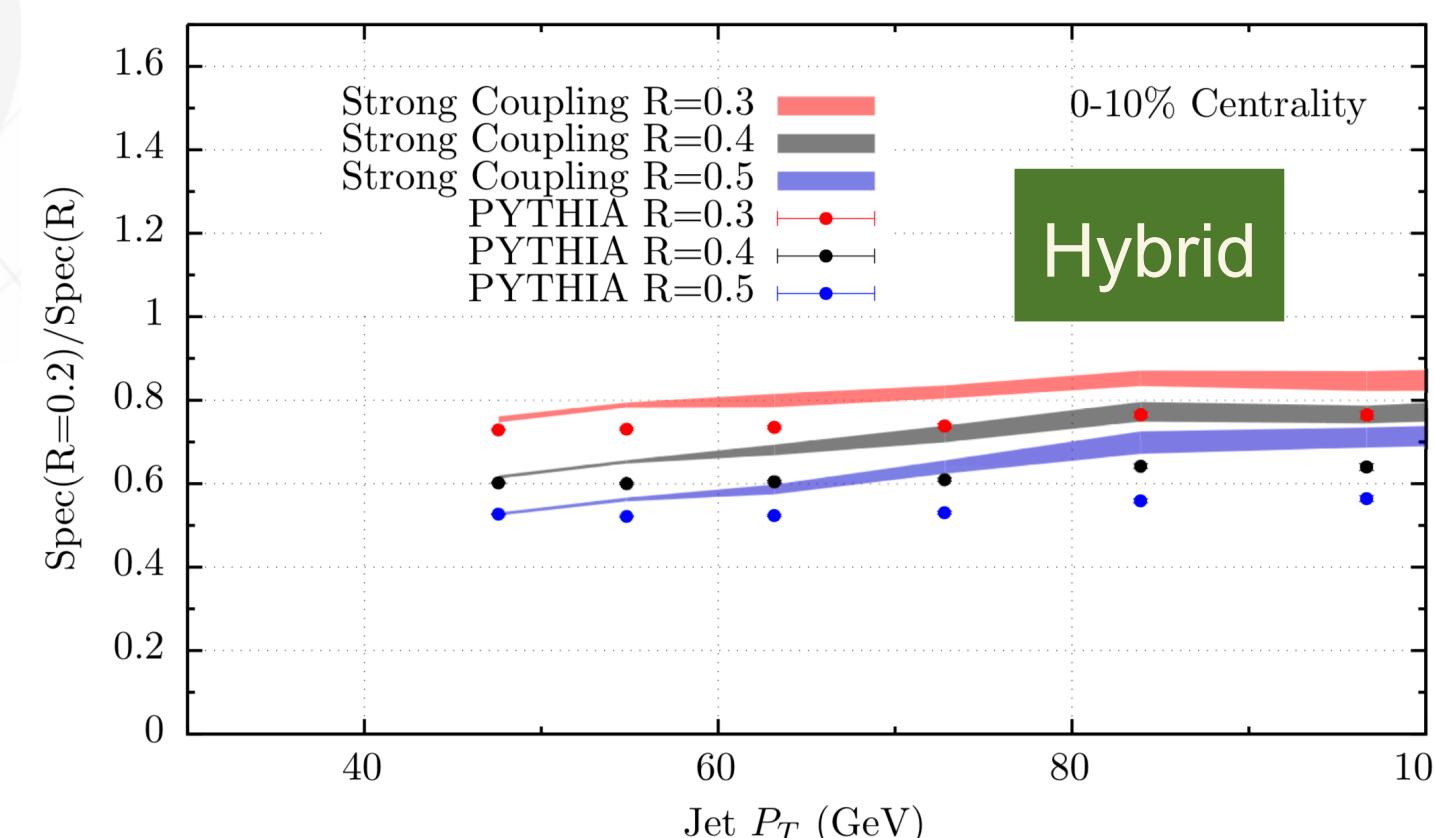
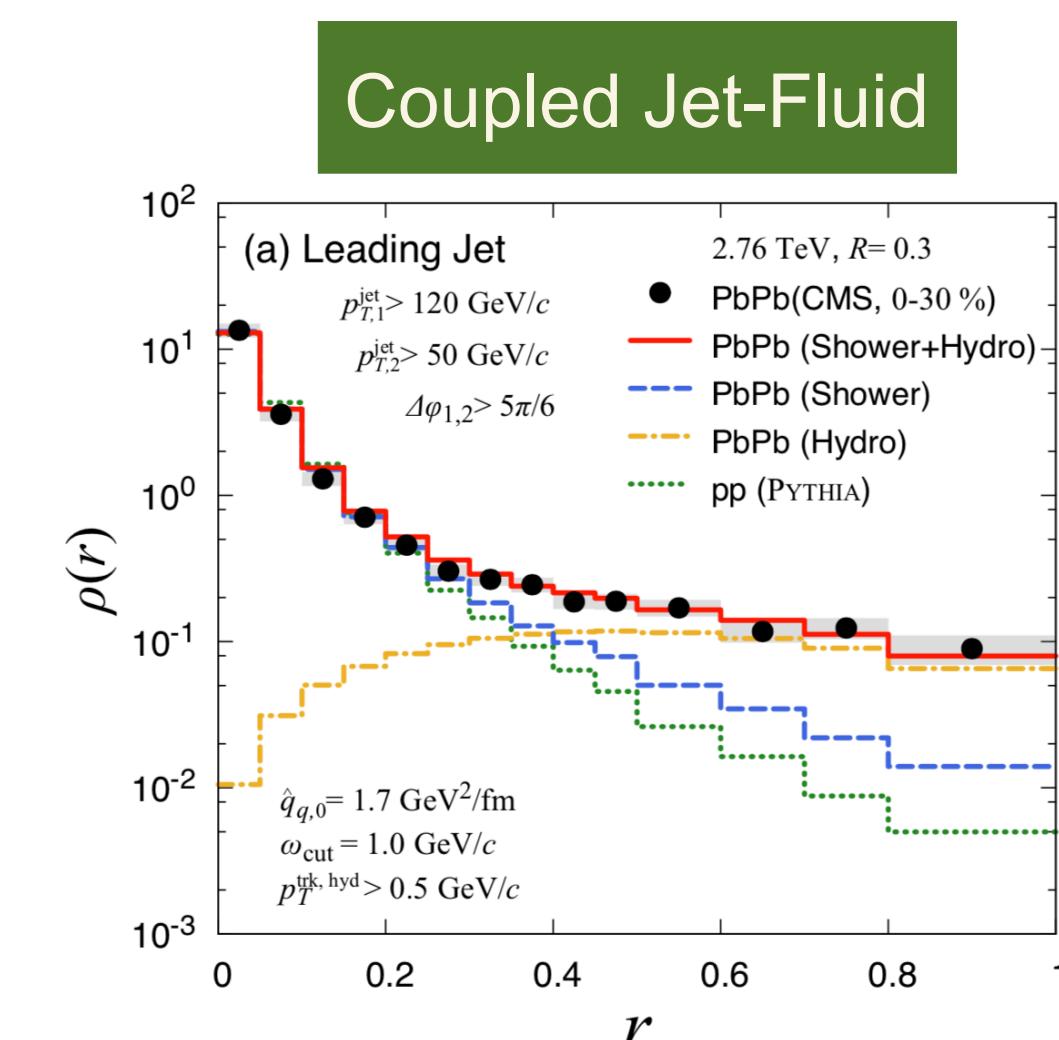
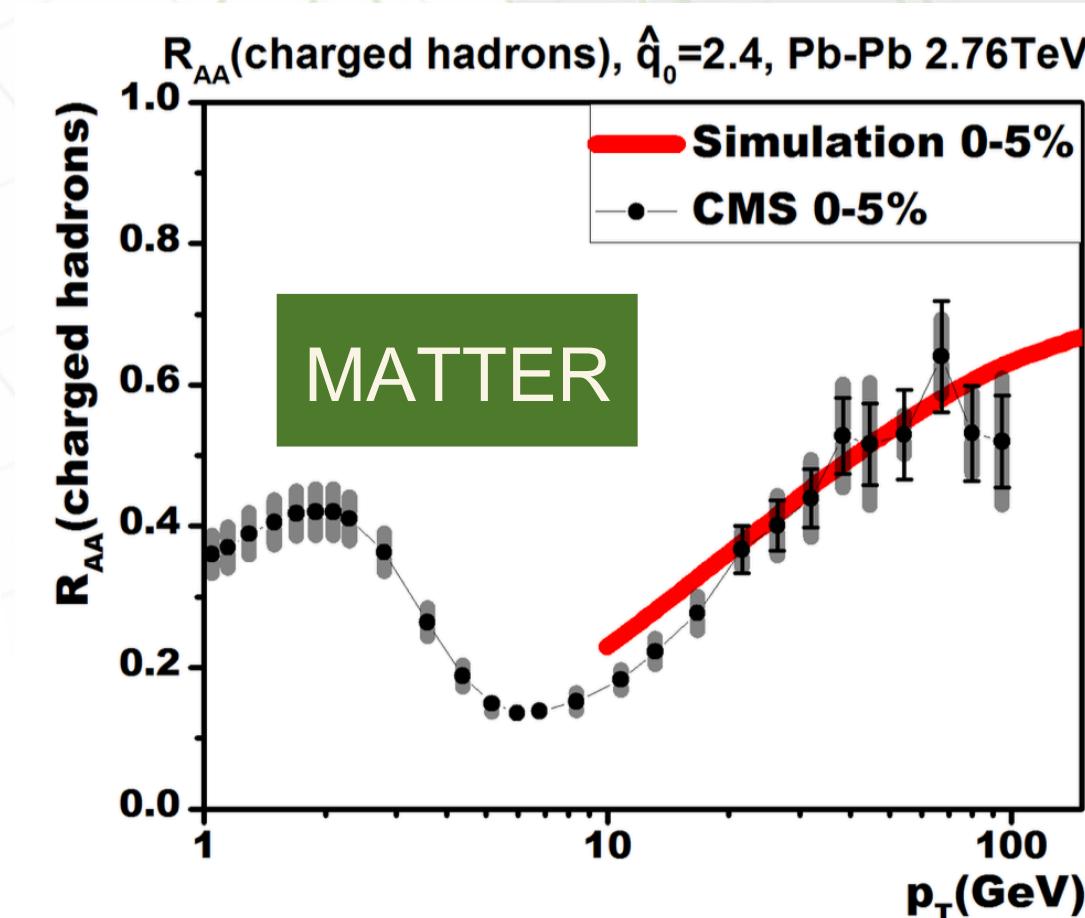
How well they do perform?



Jets in QCD matter: Monte Carlo approaches

JQ Monte Carlo Results

How well they do perform?



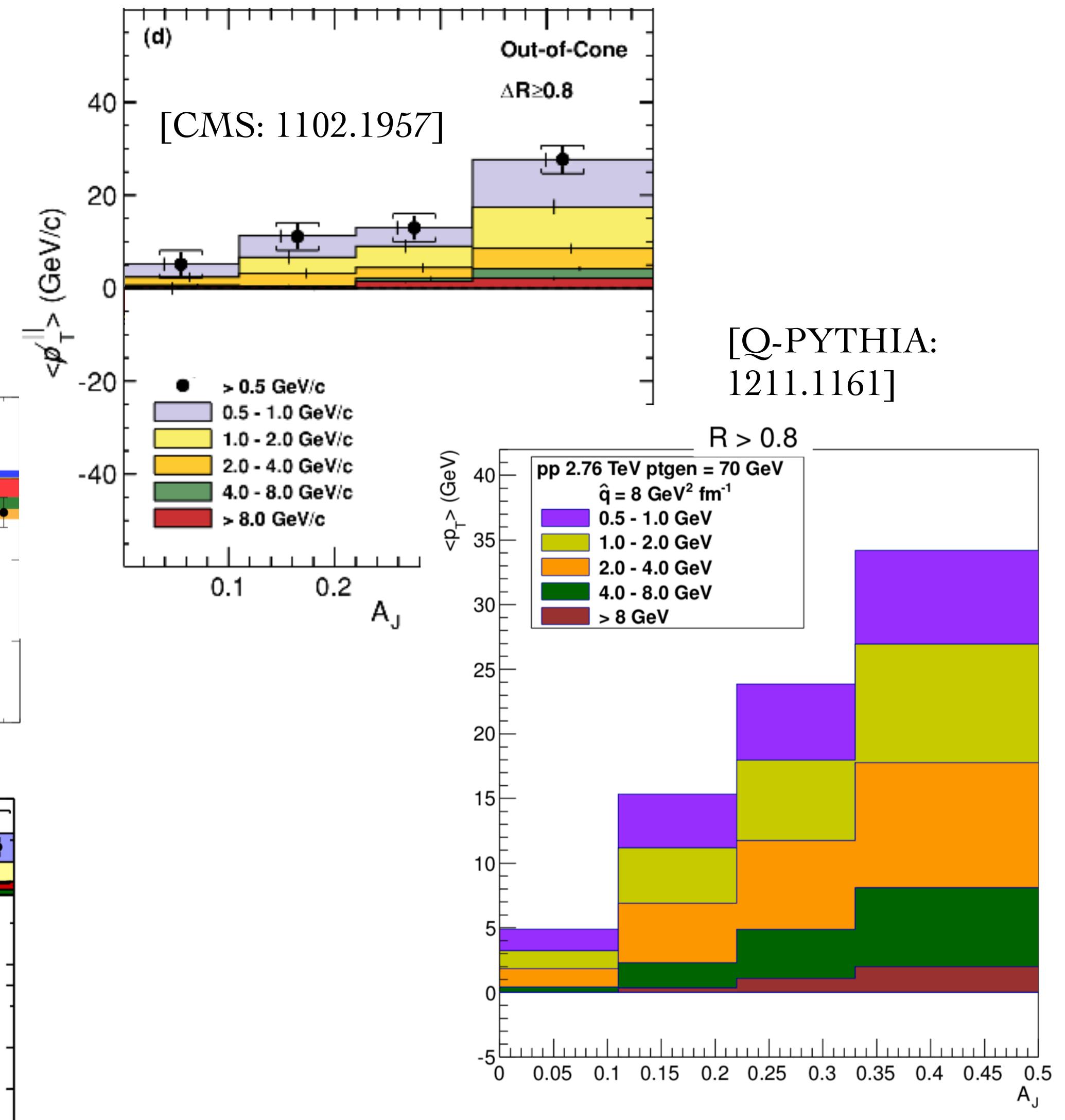
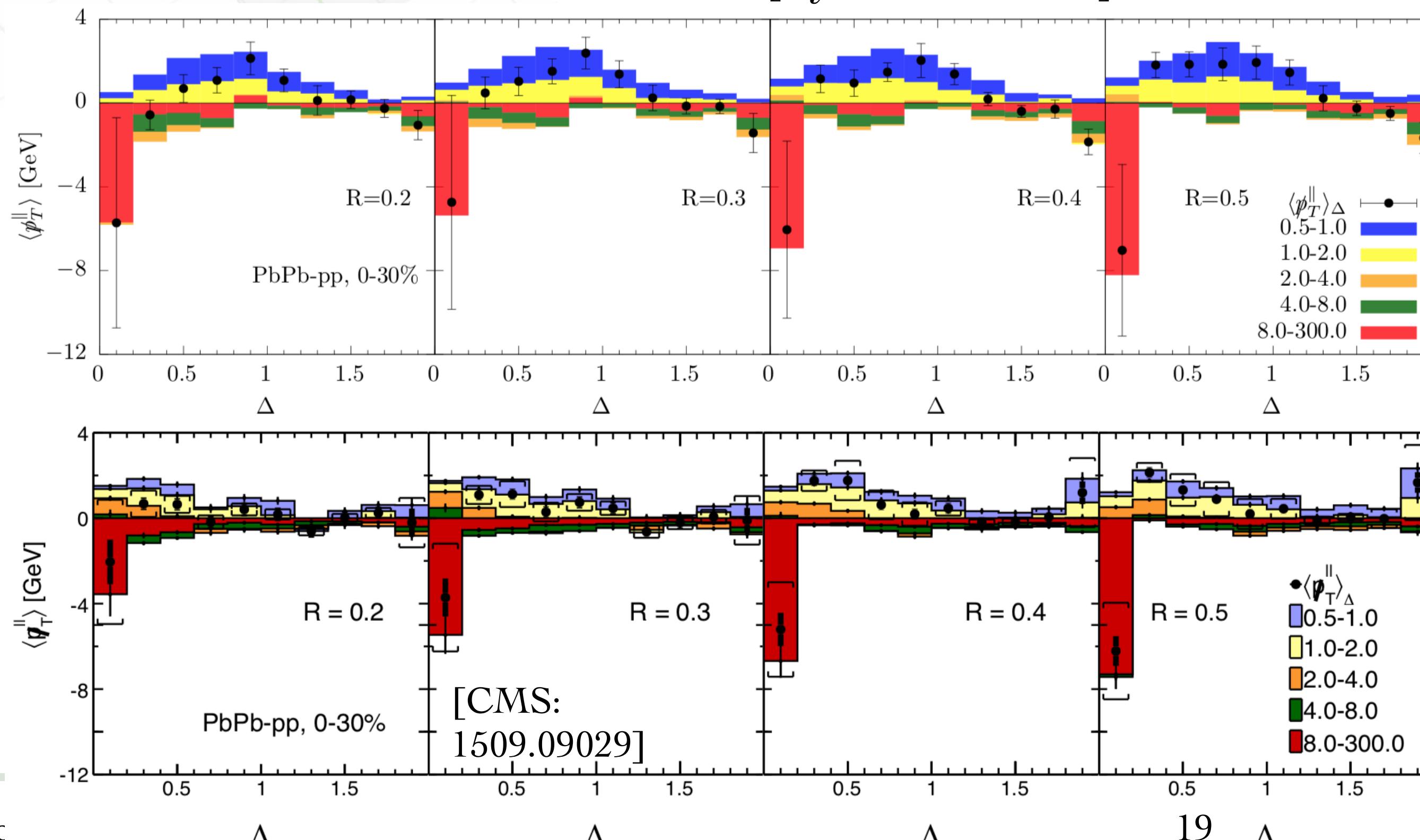
Fairly well!

but what have we (not) learned?

Jets in QCD matter: Monte Carlo approaches

Radiation // Broadening // Recoils ?

- ◆ Large angle radiation provided by missing p_T : it is an effect of
 - ◆ Medium-induced radiation?
 - ◆ Medium response?



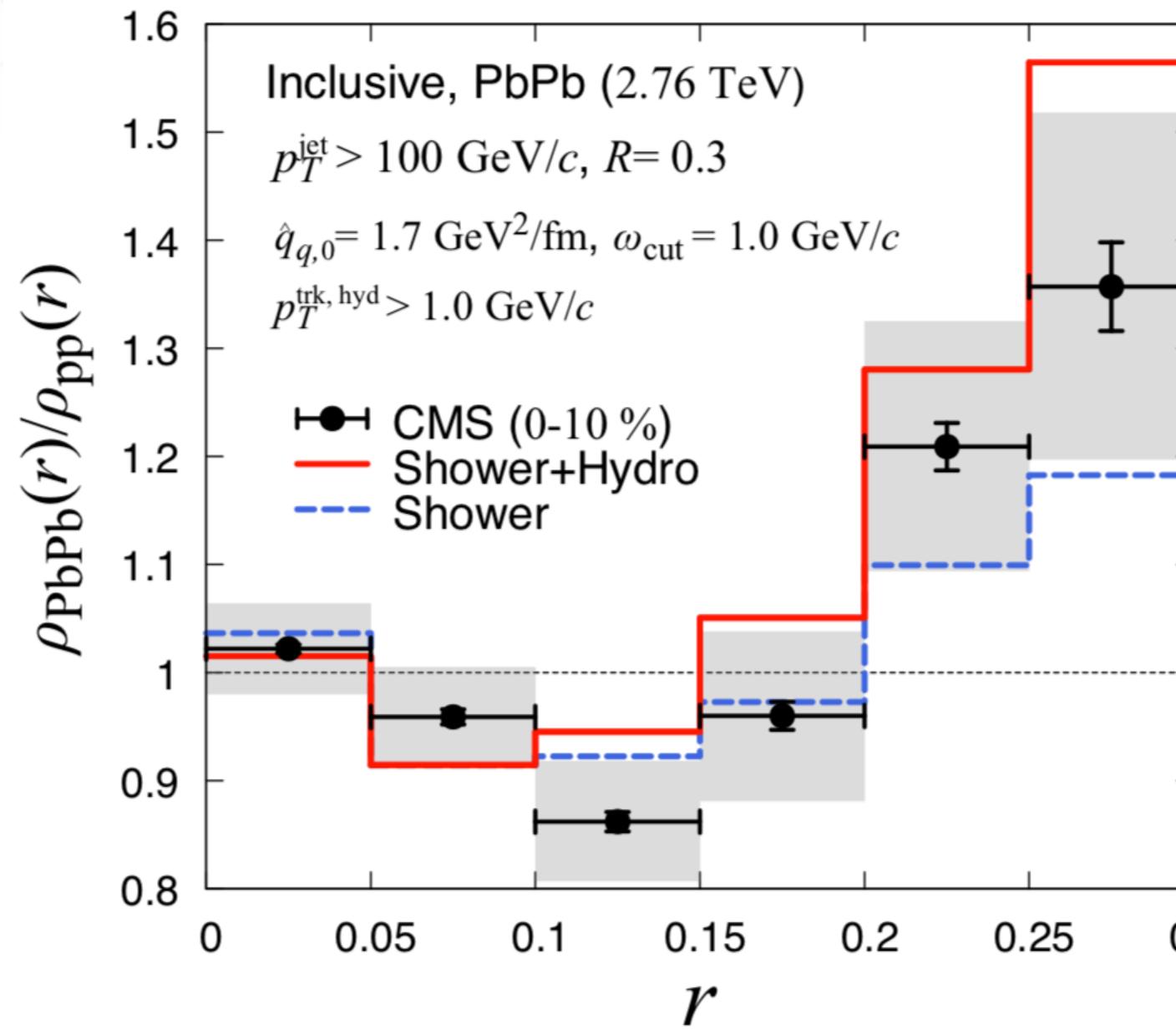
Fast or Slow Thermalisation?

[MARTINI:1807.06550]

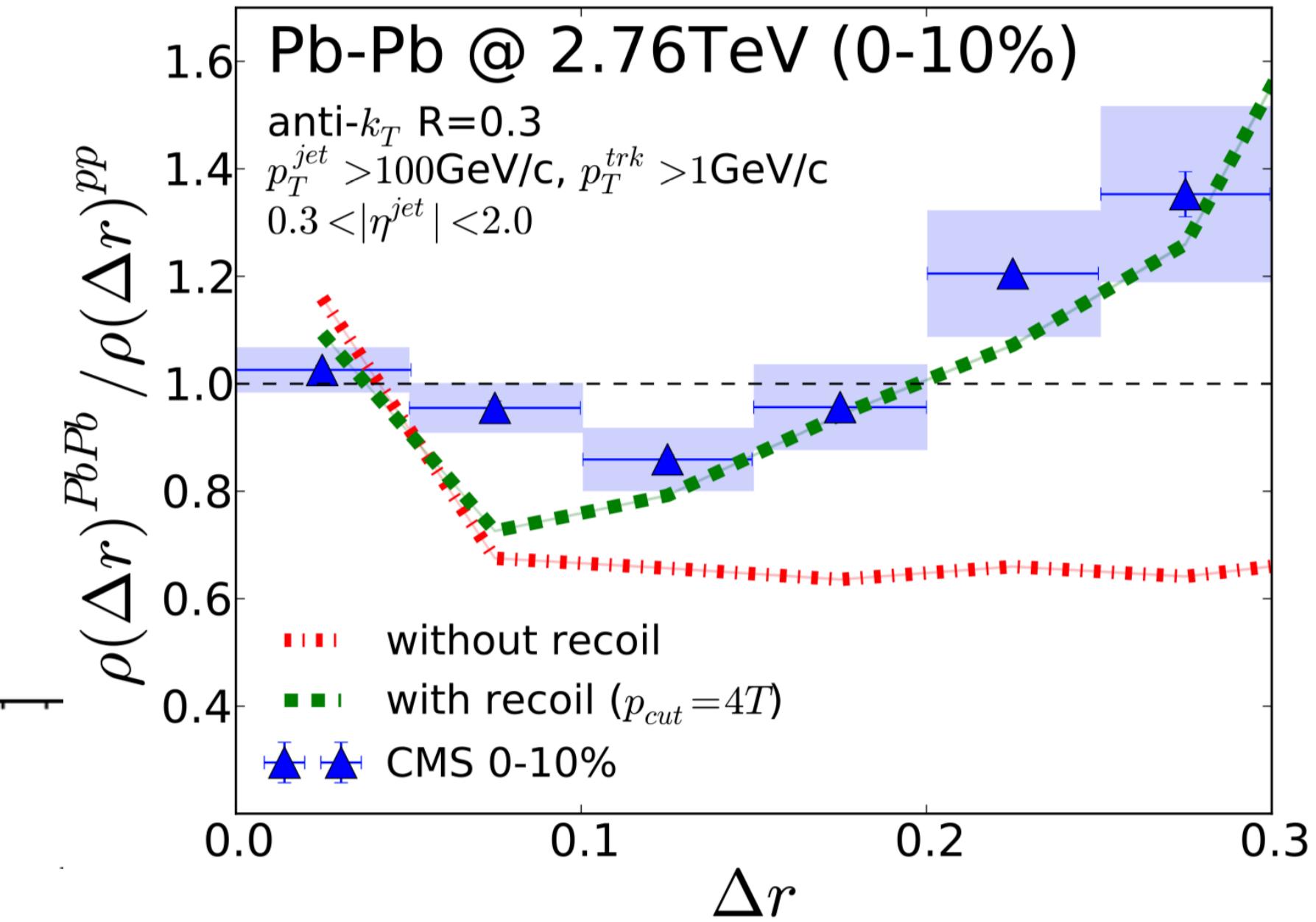
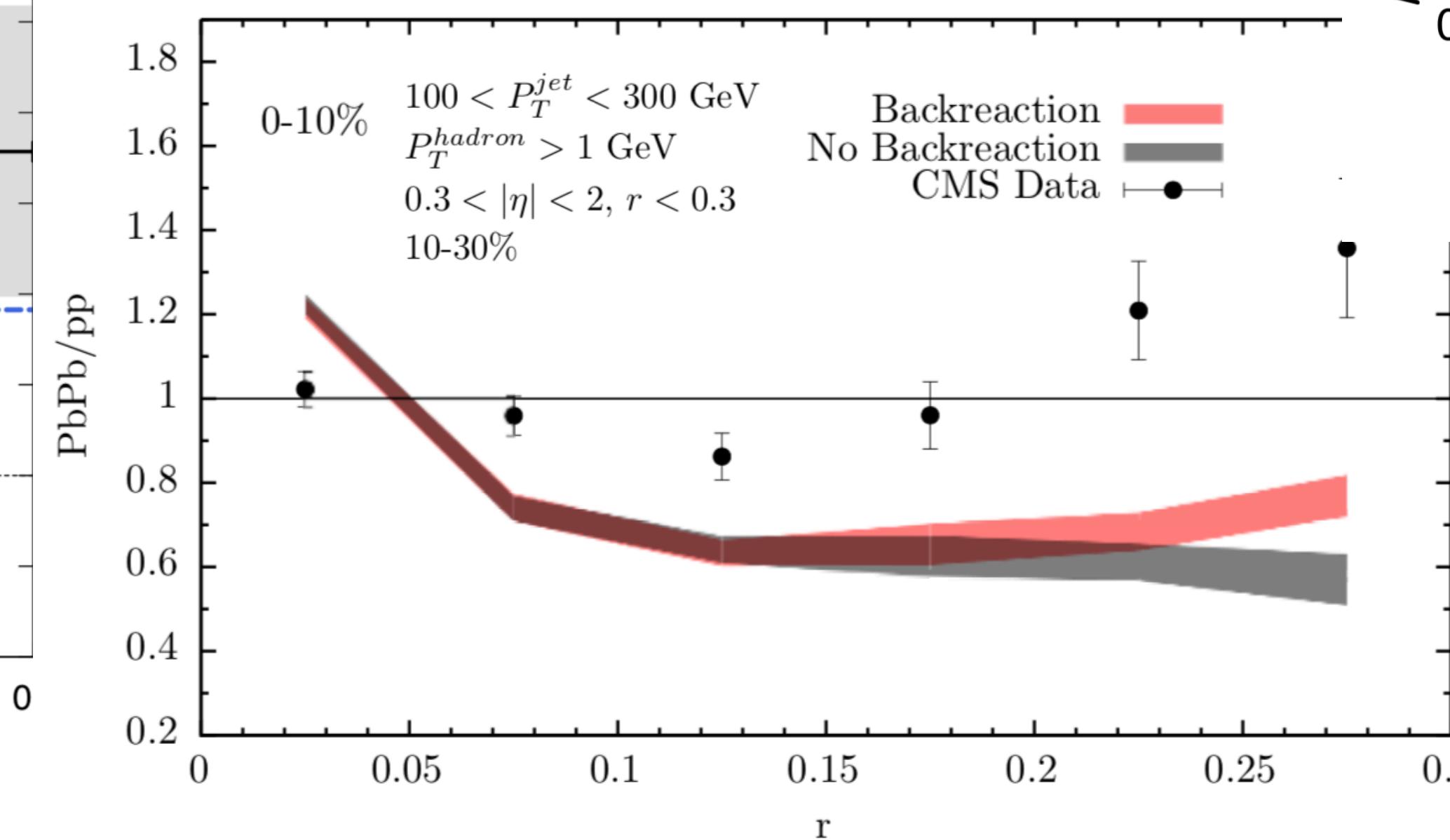
◆ Medium response:

◆ What exactly is the amount of medium response?

[Coupled Jet-Fluid: 1701.07951]

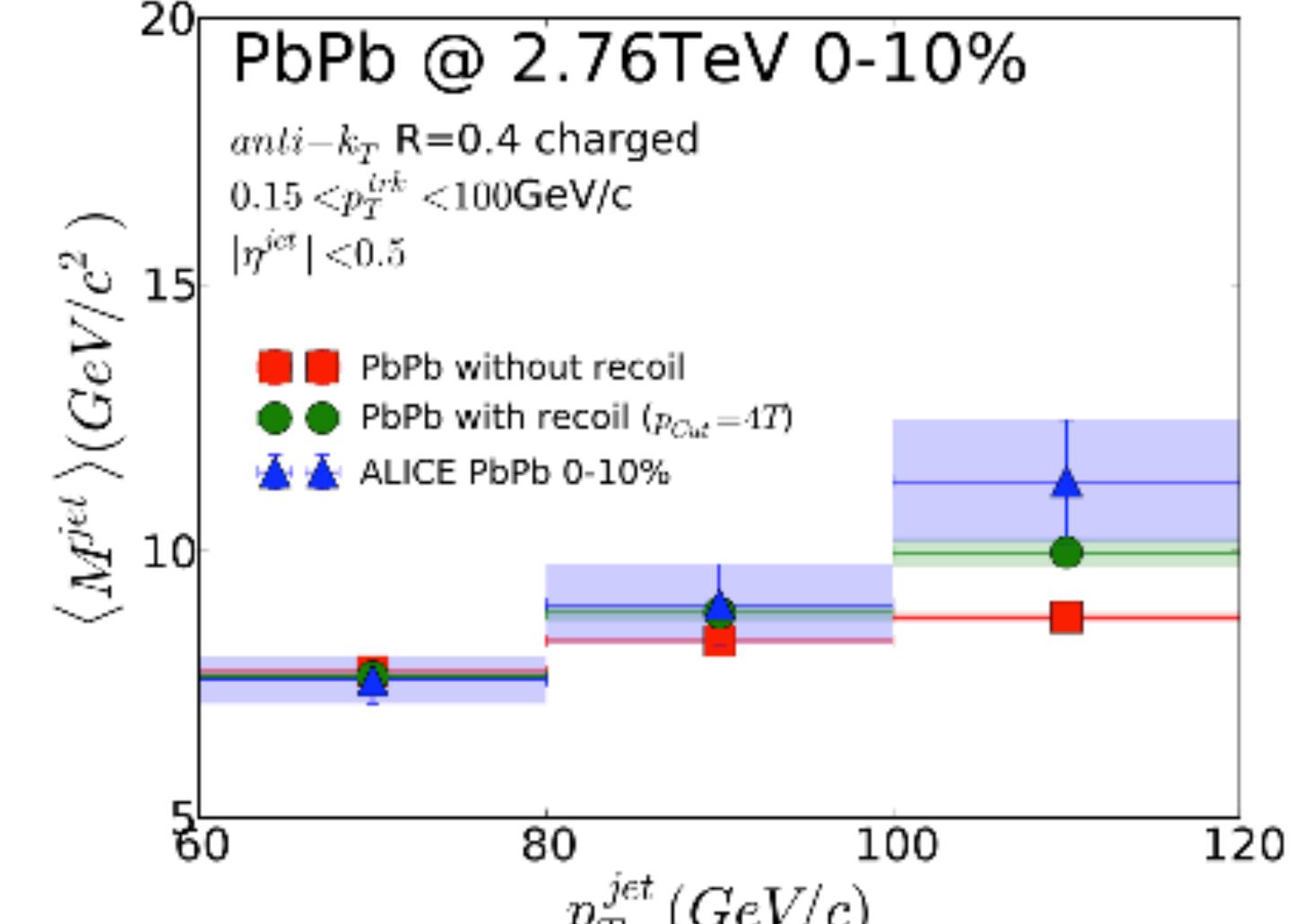
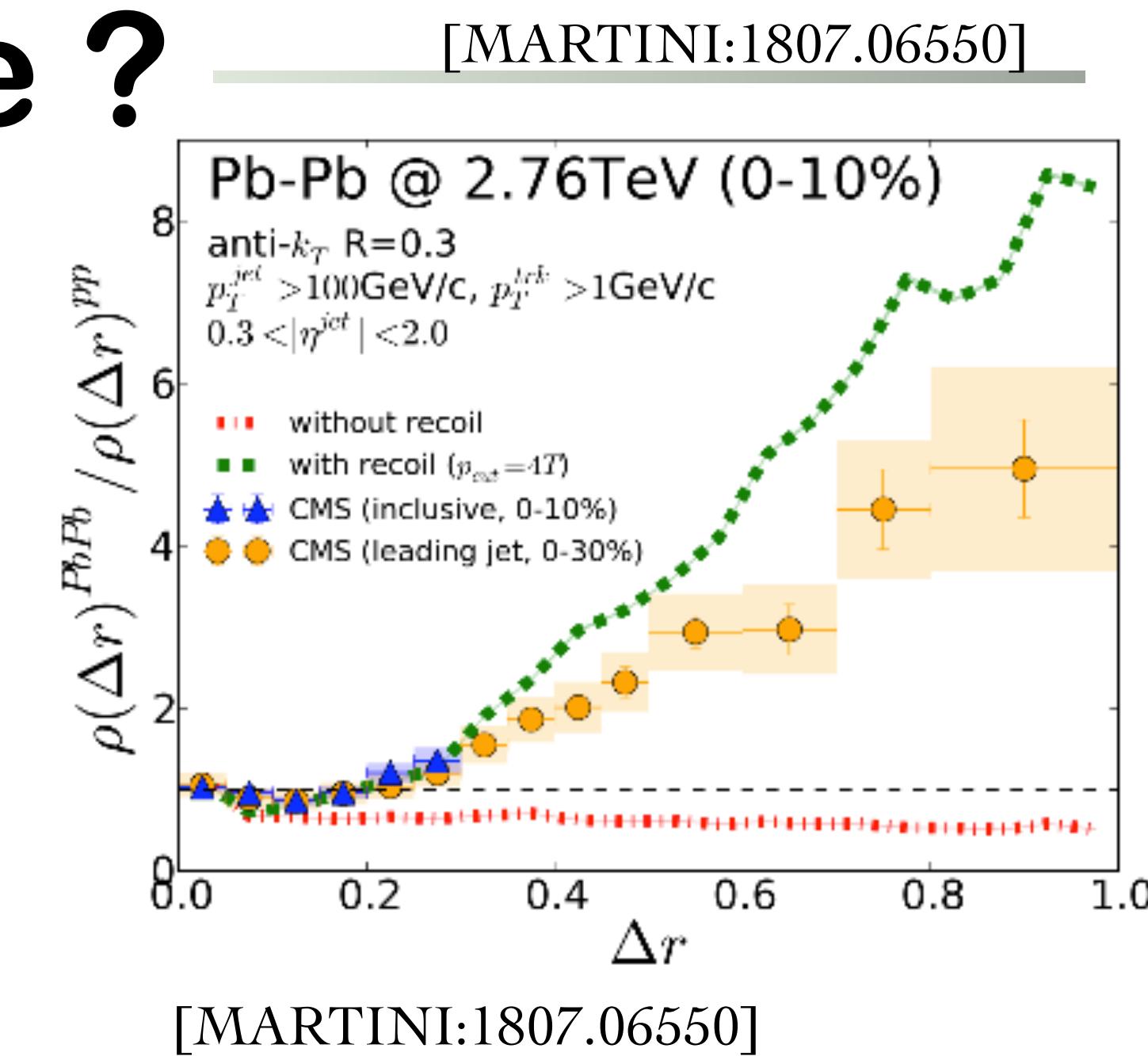
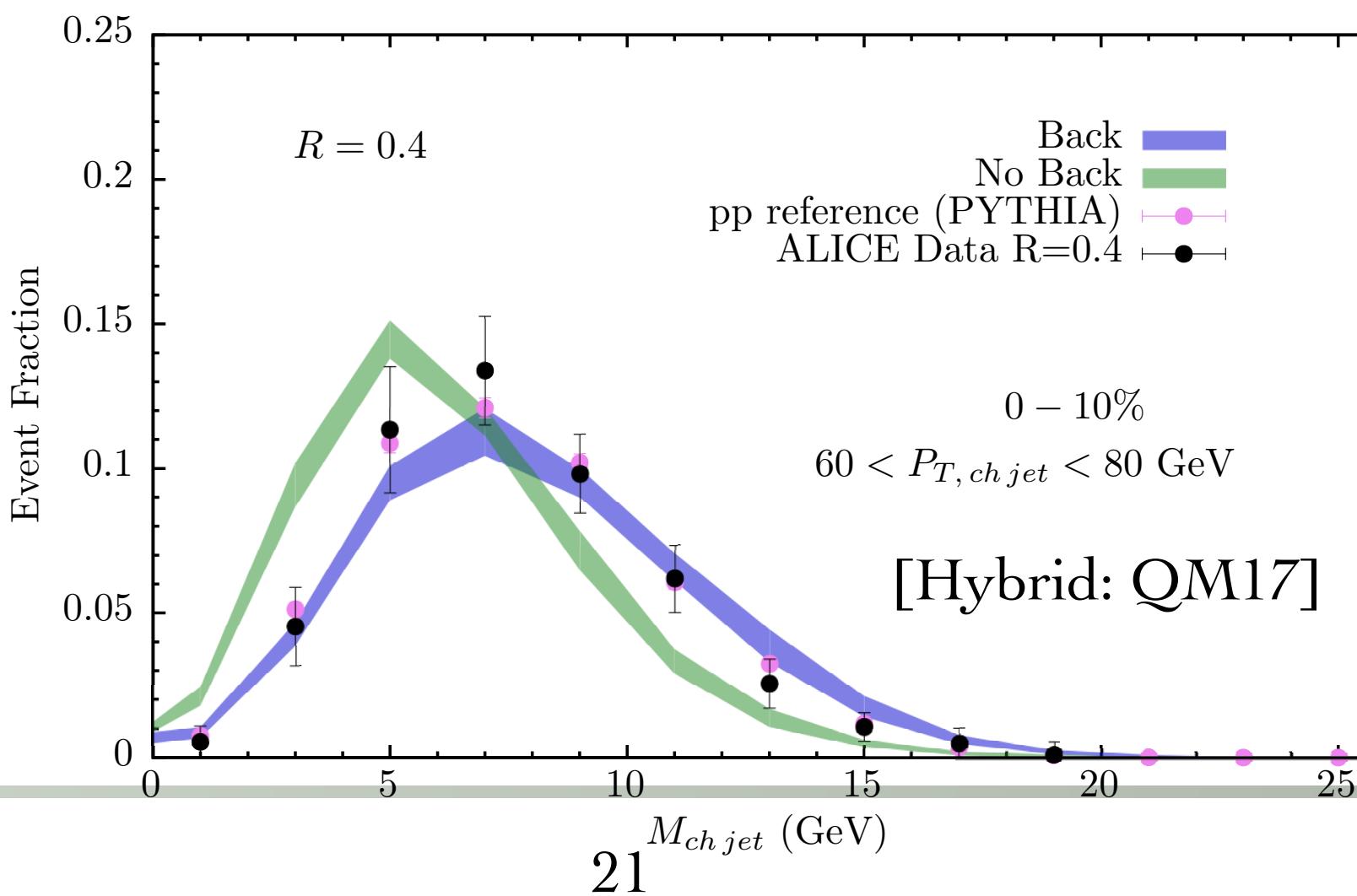
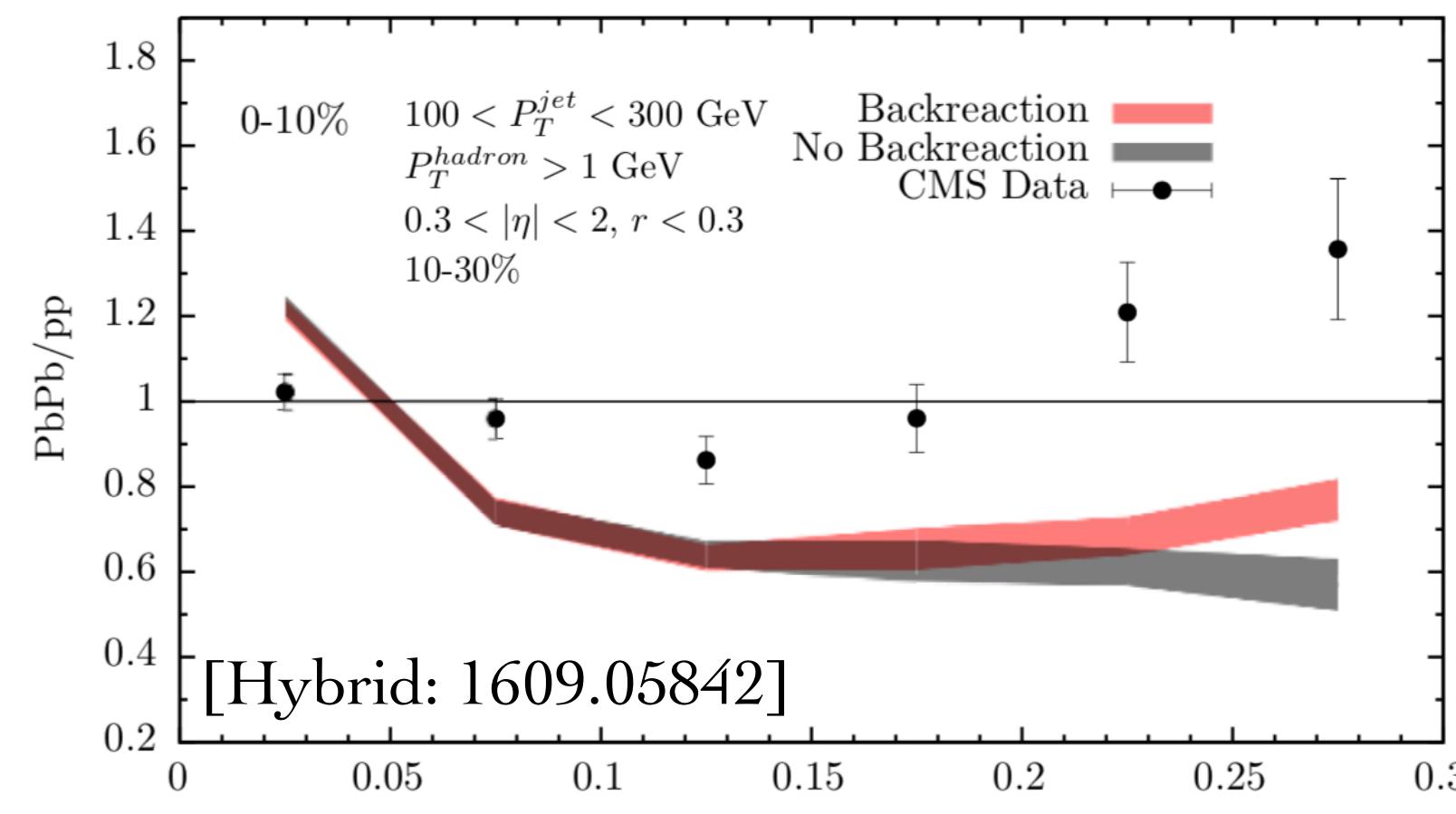
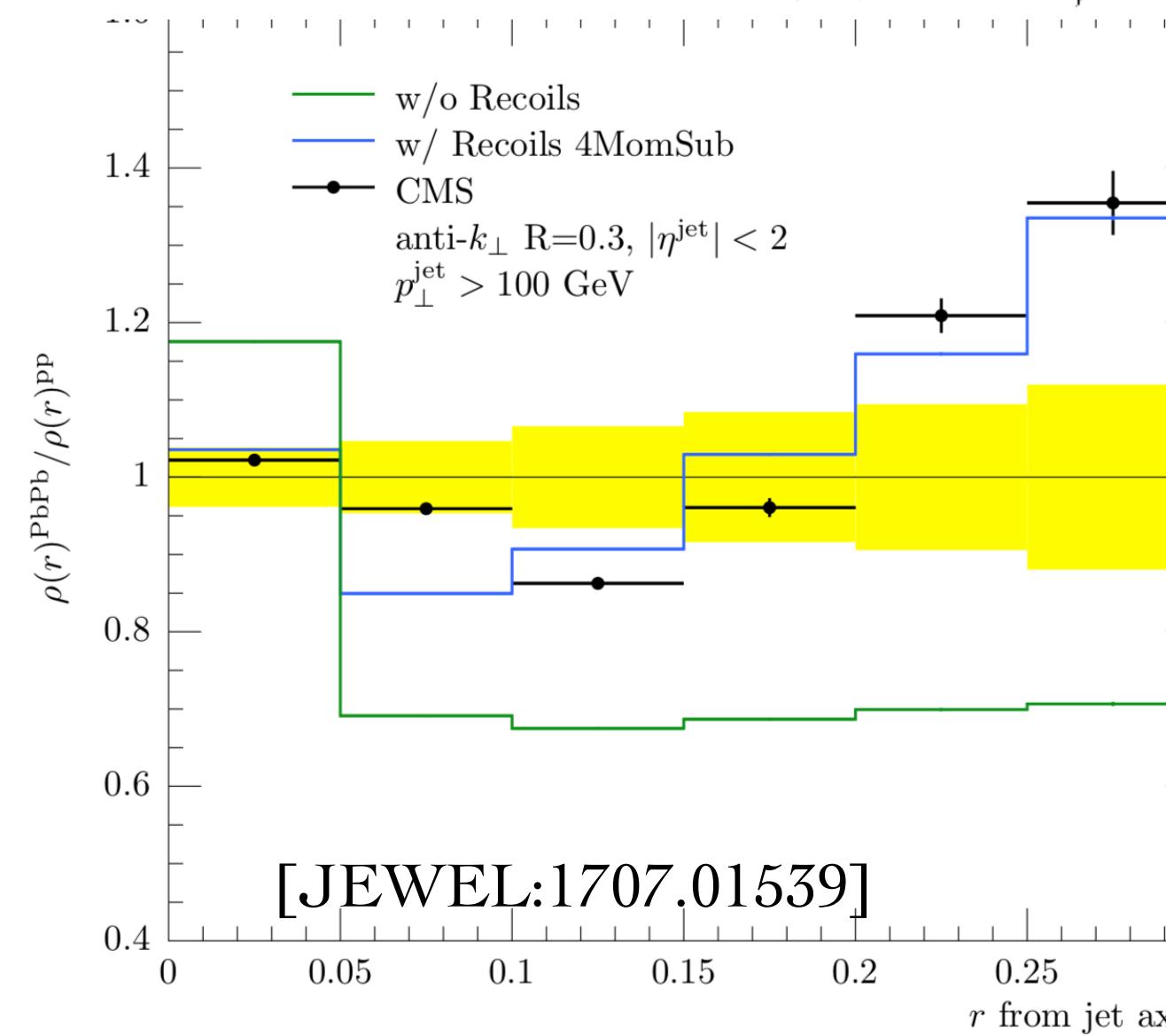
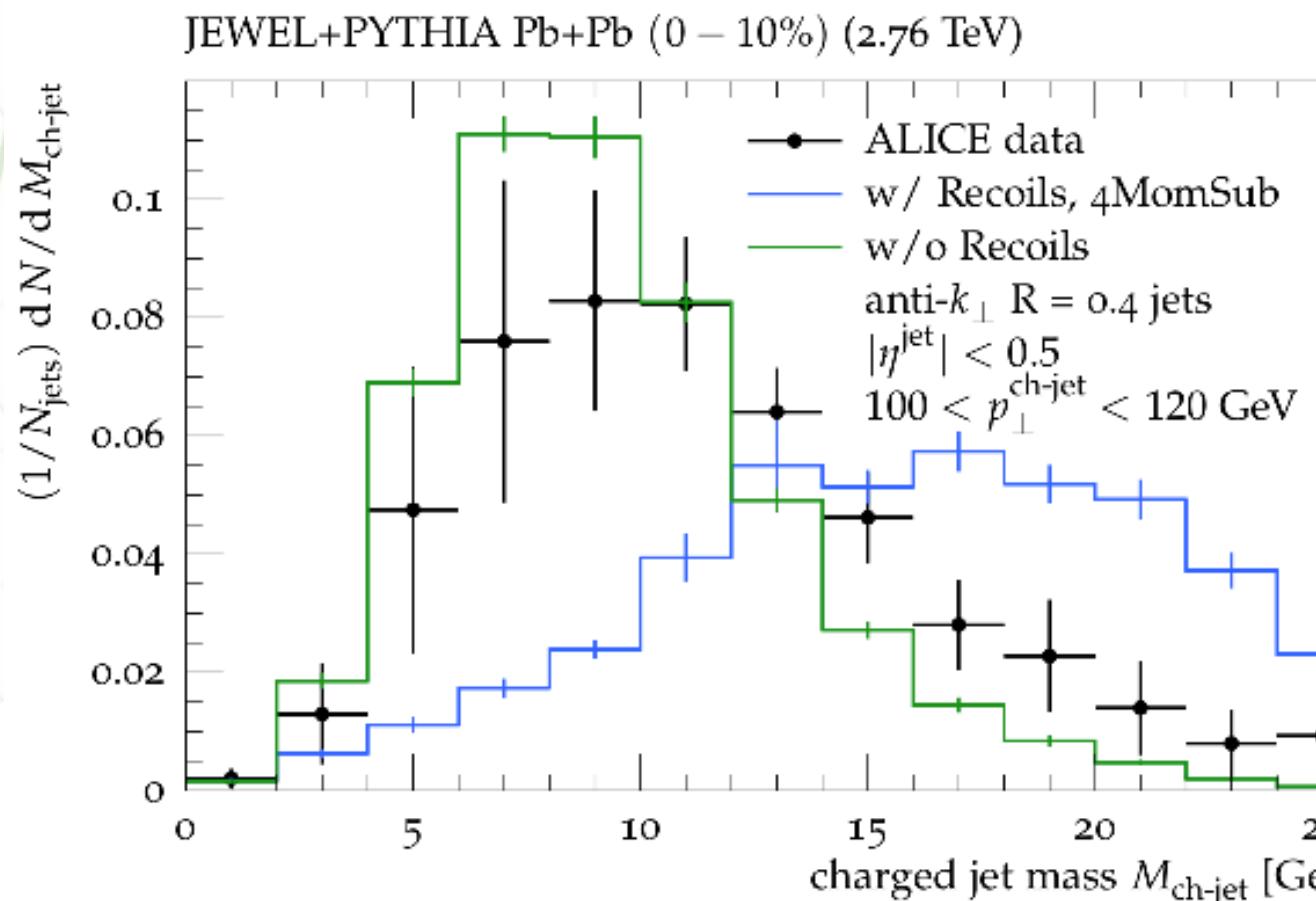


[Hybrid: 1609.05842]



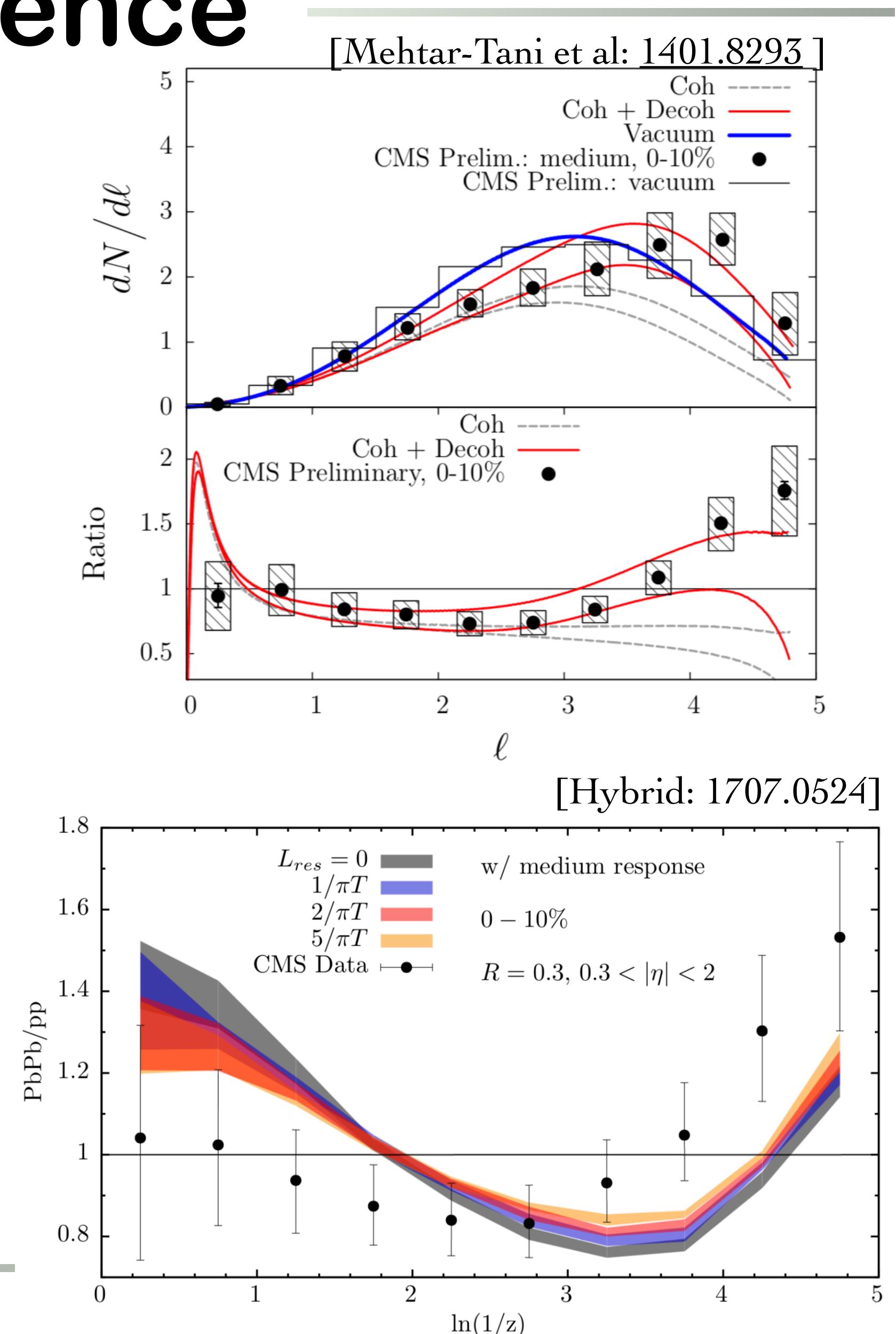
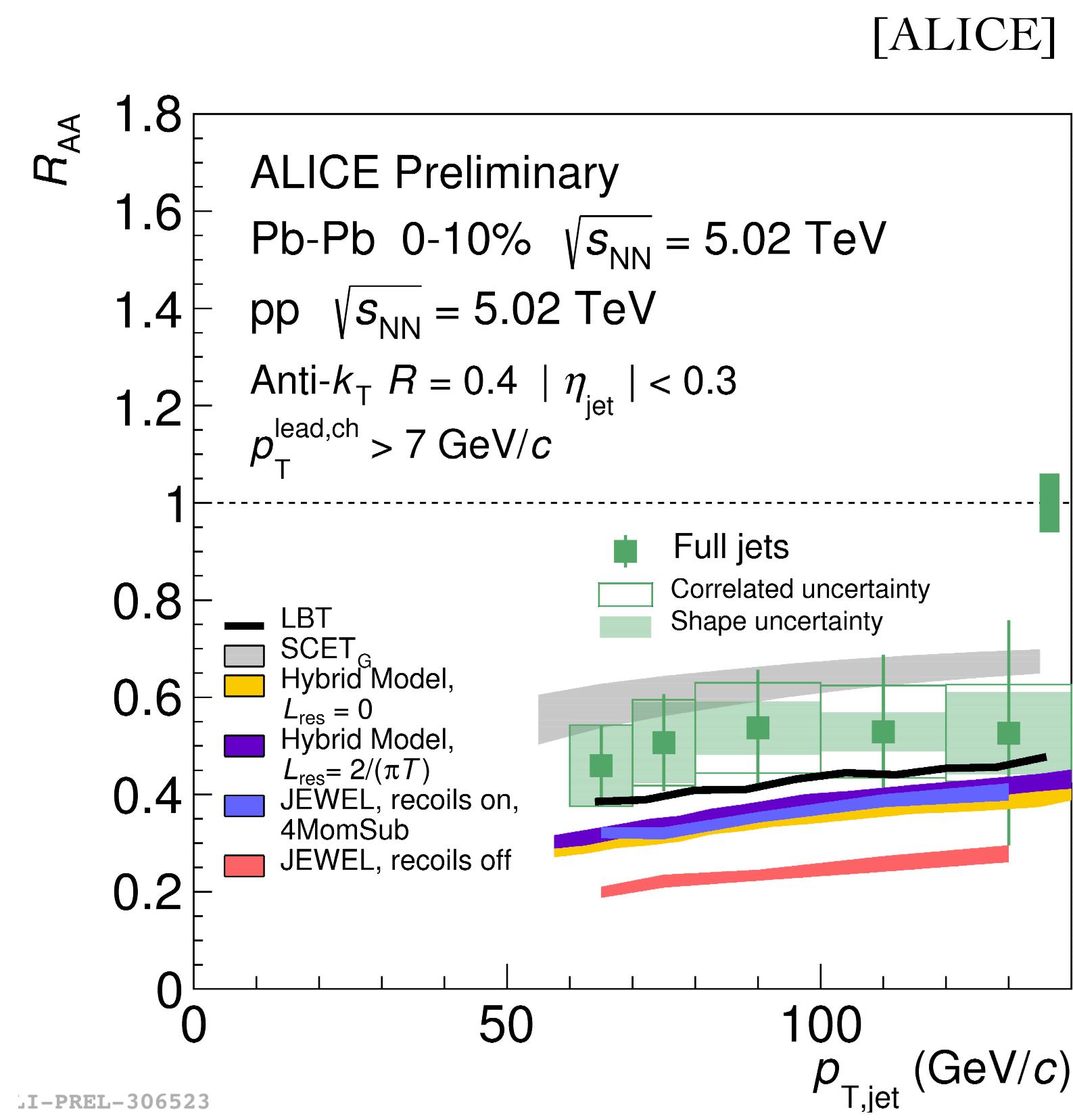
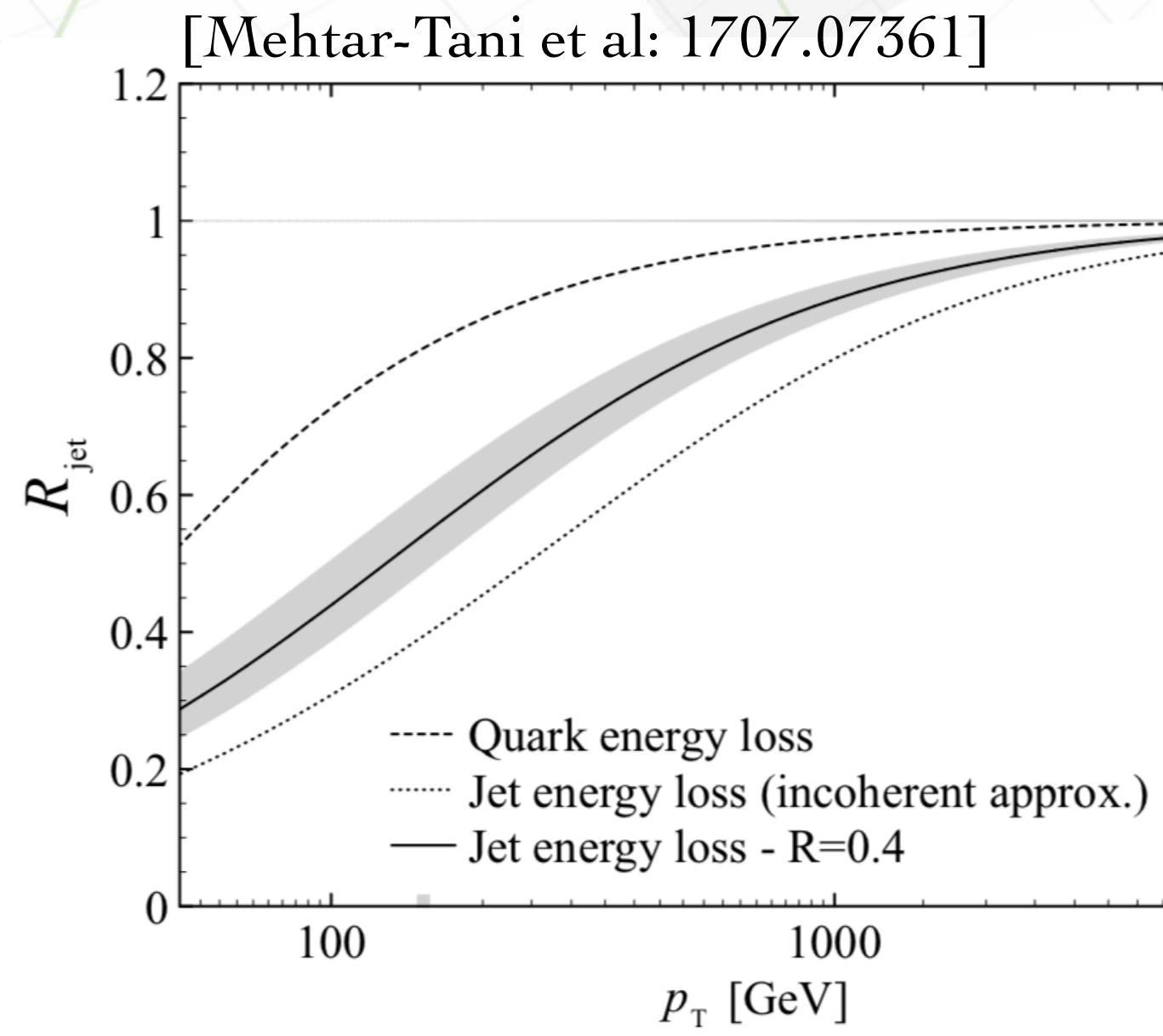
Jet Mass vs Jet p_T Profile ?

◆ How to describe simultaneously jet mass and jet transverse profile?



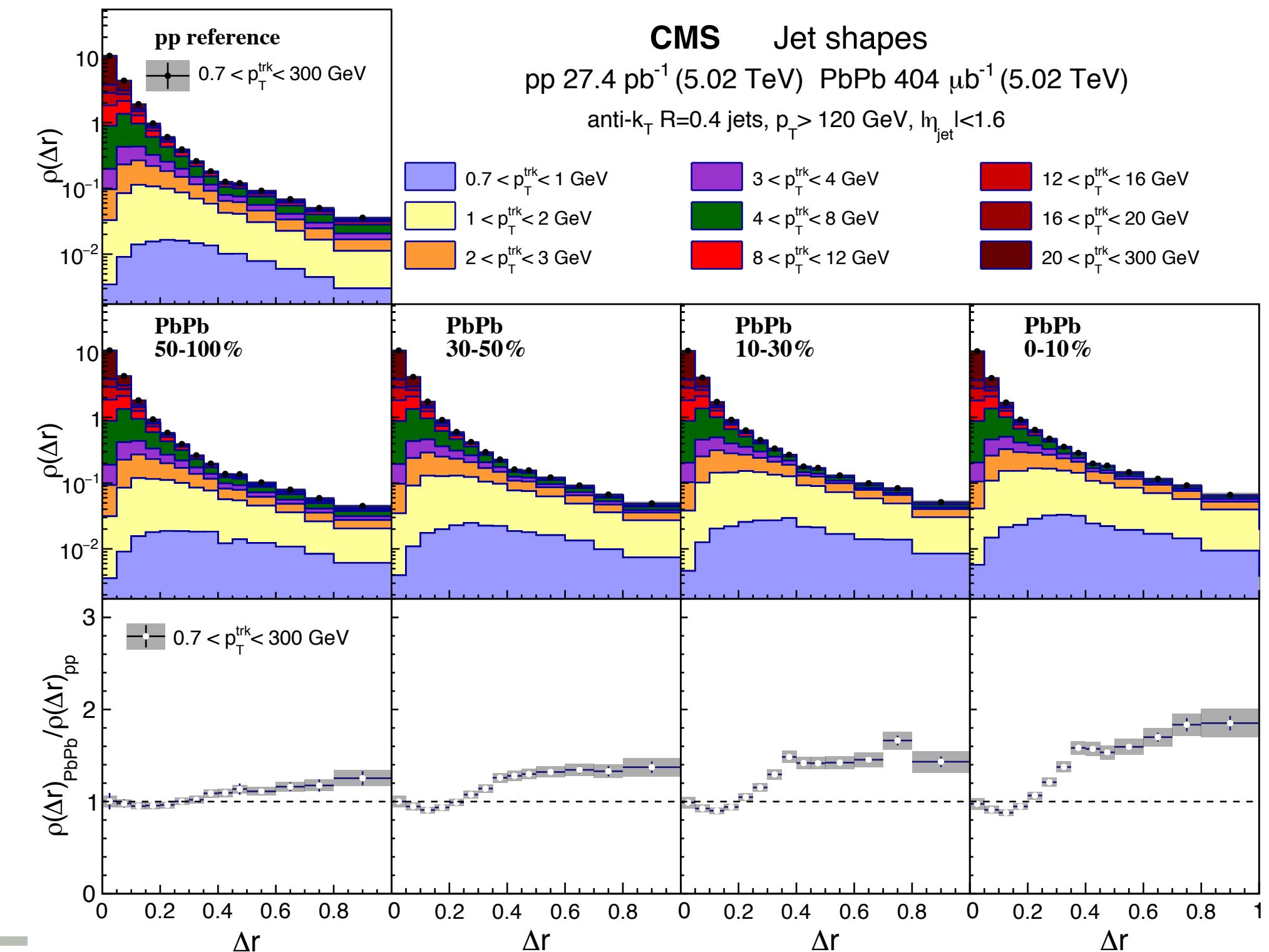
Looking for jet coherence

- Only Hybrid has a crude implementation of coherent energy loss...
- Difference between Analytics and Monte Carlo?



Outlook

- ◆ Systematic comparison of models to the same set of observables needed:
- ◆ Role of medium response not clear:
- ◆ Clear determination of p_T spectrum that is produced: jet shapes **with p_T bins information**



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 - ◆ Evaluation of the resulting hadronic species with and without medium response (**hadro-chemistry ratios**)

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Outlook

Future experiments: A. Dainese (Thursday)

Currently
difficult...
Currently
difficult...

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Summary

- ◆ Monte Carlo approach to describe jet quenching phenomena is powerful tool to take full advantage of RHIC and LHC data!
- ◆ Variety of JQ Monte Carlo models needed to estimate theoretical uncertainty!
 - ◆ But no consistent picture has emerged yet...
 - ◆ Towards new ways to further test and constrain Monte Carlo modelling:
 - ◆ JetScape Collaboration (several models in the same package): useful testing environment!
 - ◆ Observables sensitive to a particular QGP effect, a particular type of probe (q/g-jets) and/or different QGP timescales ⇒ Jet substructure!
 - ◆ Towards continuum development of Monte Carlo modelling;

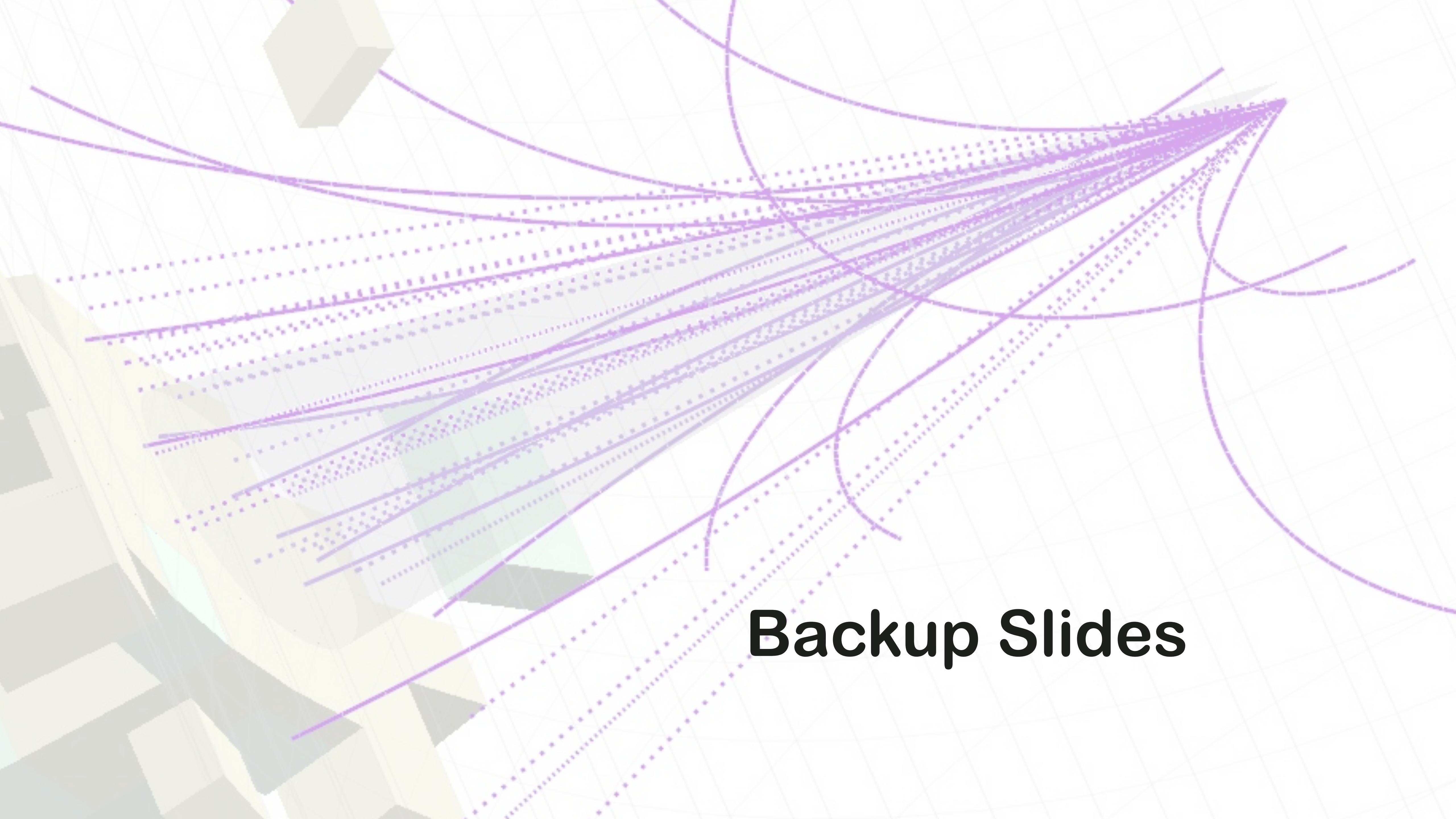
Thank you!!!

Acknowledgements



REPÚBLICA
PORTUGUESA





Backup Slides

Bibliography

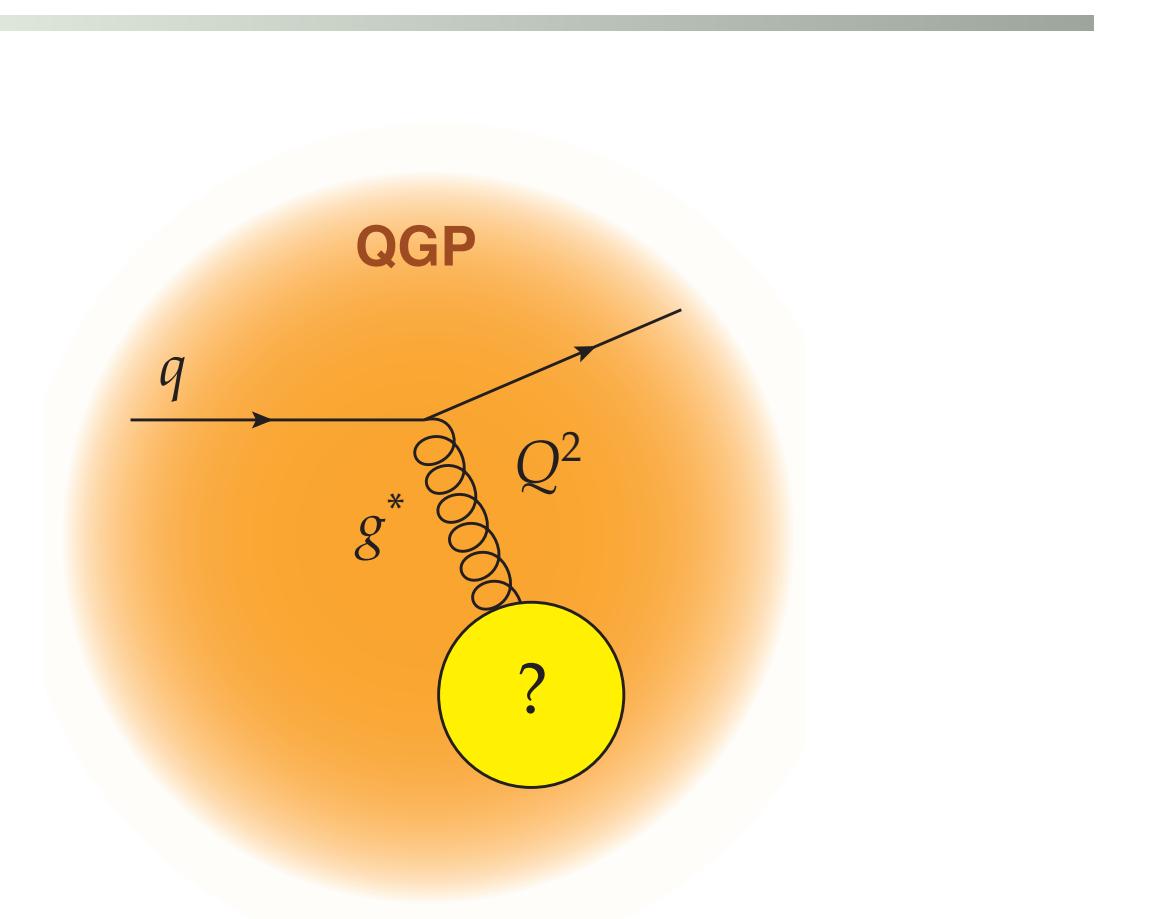
- ◆ Monte Carlo models for jet quenching:
 - ◆ Hybrid Strong/Weak coupling: [Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal (14;17); Helcher, Pablos, Rajagopal (18)]
 - ◆ JETSCAPE: [JETSCAPE Collab. (17)]
 - ◆ JEWEL: [Krauss, Wiedemann, Zapp(13); Zapp (14); Elayavalli, Zapp (16;17)]
 - ◆ LBT/Co-LBT: [Wang and Y. Zhu (16); Cao, Luo, Qin, Wang (15); He, Luo, Wang, Zhu (17);]
 - ◆ MARTINI: [Schenke, Gale, Jeon (09); Park, Jeon, Gale (18)]
 - ◆ MATTER: [Majumder (13); Kordell, Majumder (17); Cao, Majumder (18)]
 - ◆ PYQUEN: [Lokhtin, Snigirev (06)]
 - ◆ Q-PYTHIA: [Armesto, Cunqueiro, Salgado (09)]

Bibliography

- ◆ Monte Carlo models for heavy-ions:
 - ◆ **AMPT**: [Ko, Li, Lin, Pal, Zhang (00; 01)]
 - ◆ **BAMPS**: [Xu, Greiner (03; 07)]
 - ◆ **CUJET**: [Buzzatti and Gyulassy (11; 12)]
 - ◆ **HiJING/HIJING++**: [Gyulassy, Wang (91; 94); Barnaföldi et al (17)]
 - ◆ **HYDJET/HYDJET++**:
- ◆ Analytical approaches:
 - ◆ **Coupled Jet-Fluid**: [Tachibana, Chang, Qin (17)]

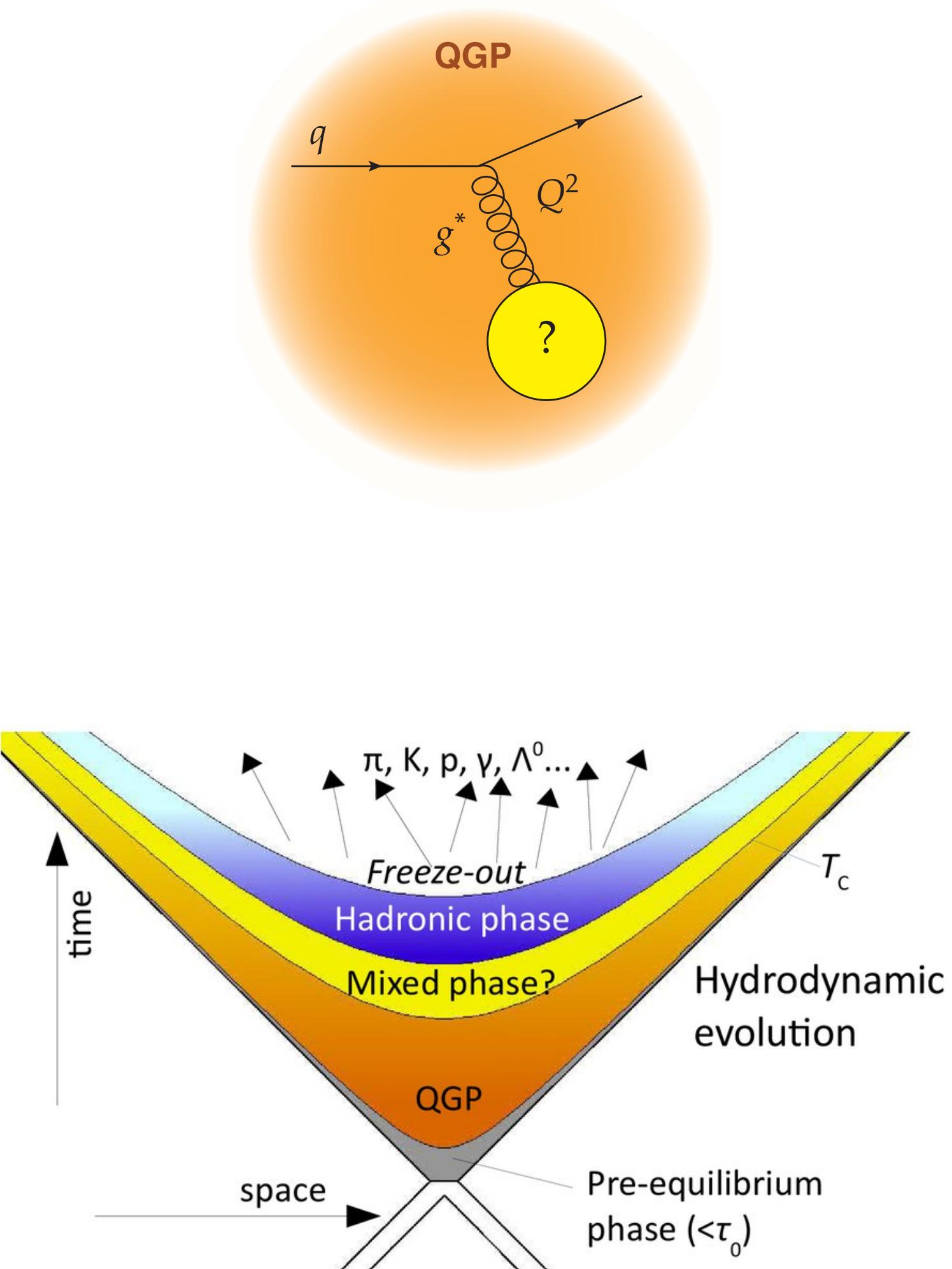
Jets & QGP

- ◆ Why do we care about jets?
- ◆ Can be used to learn about:
- ◆ QCD behaviour at all momentum scales (jet; jet-QGP; QGP):
 - ◆ QGP nature: strong coupled fluid, collection of quasi-particles...?;
 - ◆ Interplay between strong and weak coupling regimes;



Jets & QGP

- ◆ Why do we care about jets?
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- ◆ QCD behaviour at all momentum scales (jet; jet-QGP; QGP):
 - ◆ QGP nature: strong coupled fluid, collection of quasi-particles...?;
 - ◆ Interplay between strong and weak coupling regimes;
- ◆ QGP evolution:
 - ◆ Resolved or unresolved structures: QGP profile density,...
 - ◆ Thermalisation: same physics of QGP formation,...



Jet Evolution

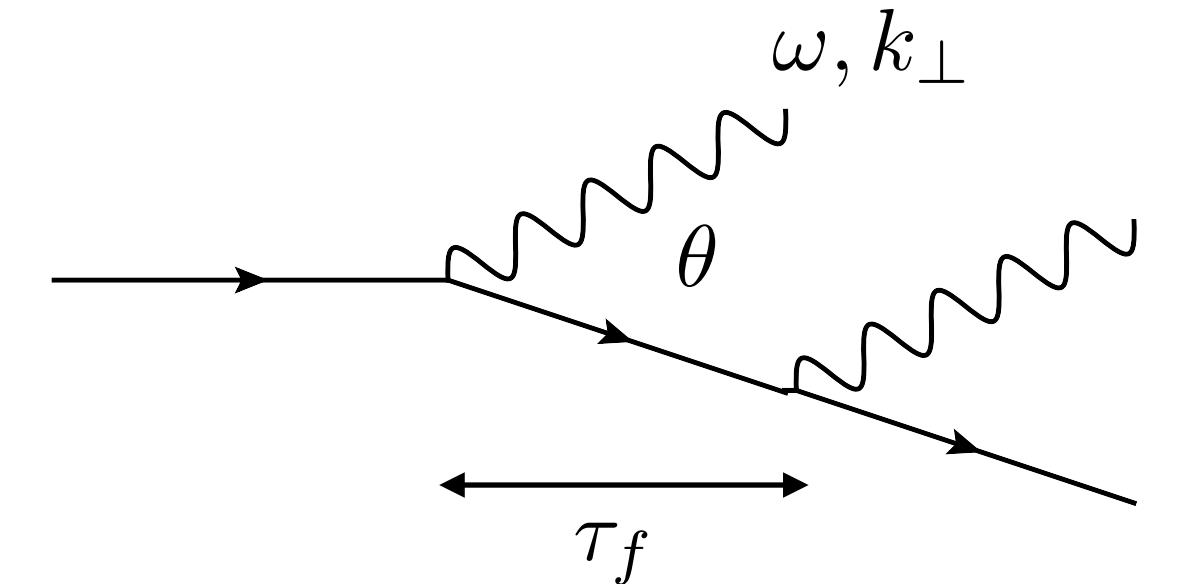
- Formation time of gluon radiation rules the parton shower development:

Vacuum Shower:

$$d\mathcal{P} \simeq \alpha_S \frac{d\omega}{\omega} \frac{d\theta^2}{\theta^2}$$

$$\tau_f \simeq \frac{\omega}{k_\perp^2} \simeq \frac{1}{\omega\theta^2}$$

$$k_\perp \sim \omega\theta$$

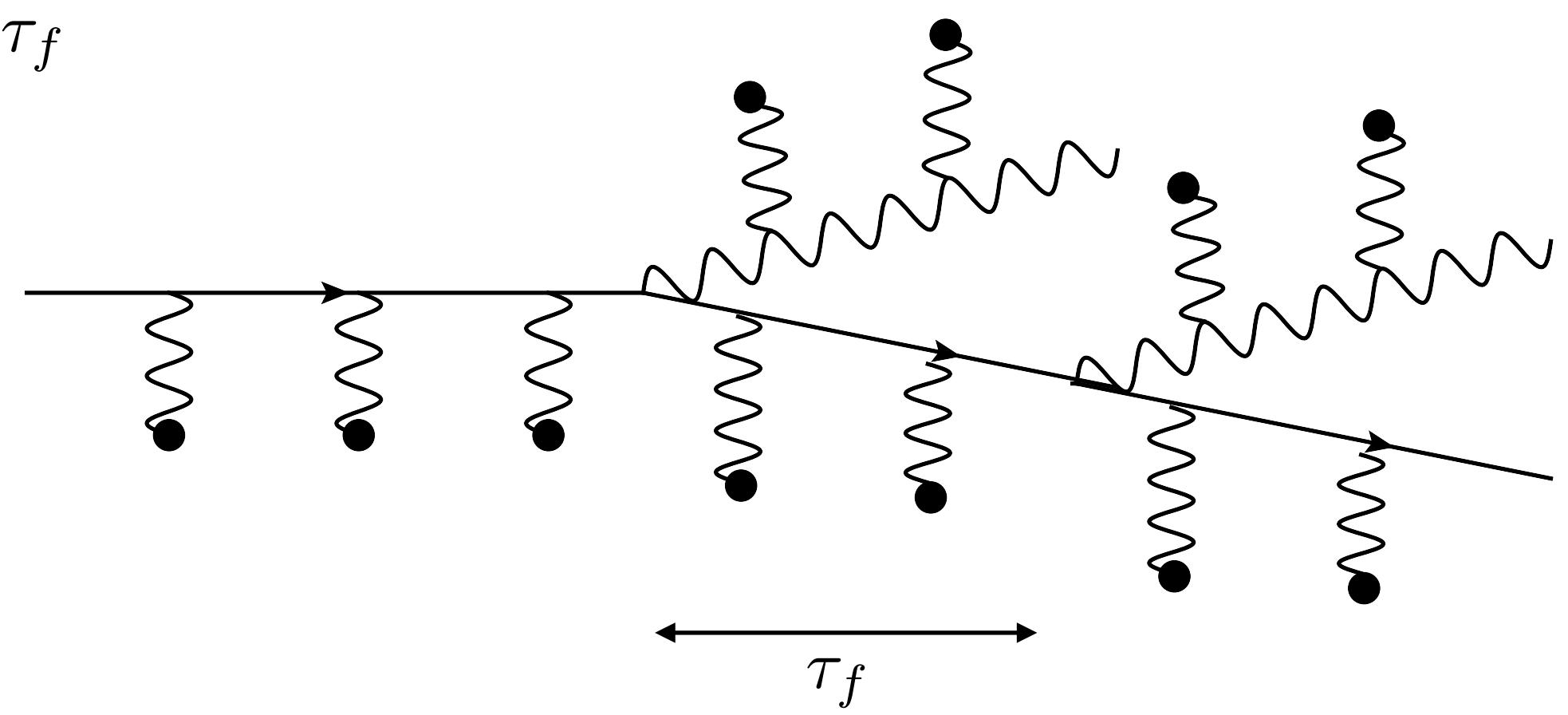


Medium Shower:

$$d\mathcal{P} \simeq \alpha_S \frac{d\omega}{\omega} \frac{L}{\tau_f} \simeq \alpha_s \sqrt{\frac{\hat{q}L^2}{\omega}} \frac{d\omega}{\omega}$$

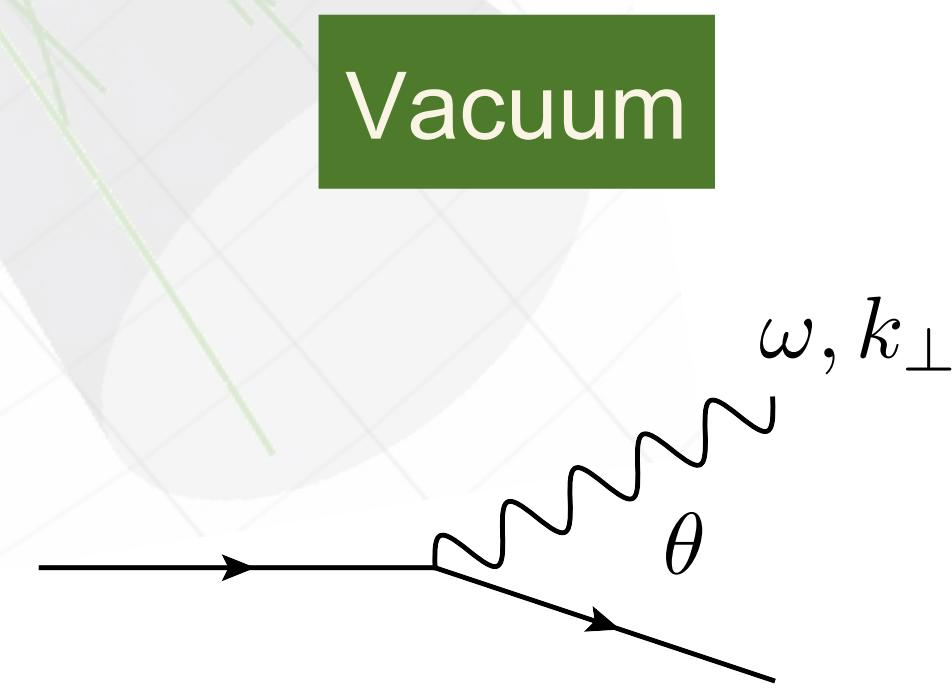
$$\tau_f \leq \sqrt{\frac{\omega}{\hat{q}}}$$

$$k_\perp \geq \hat{q}\tau_f$$



Radiative Energy Loss

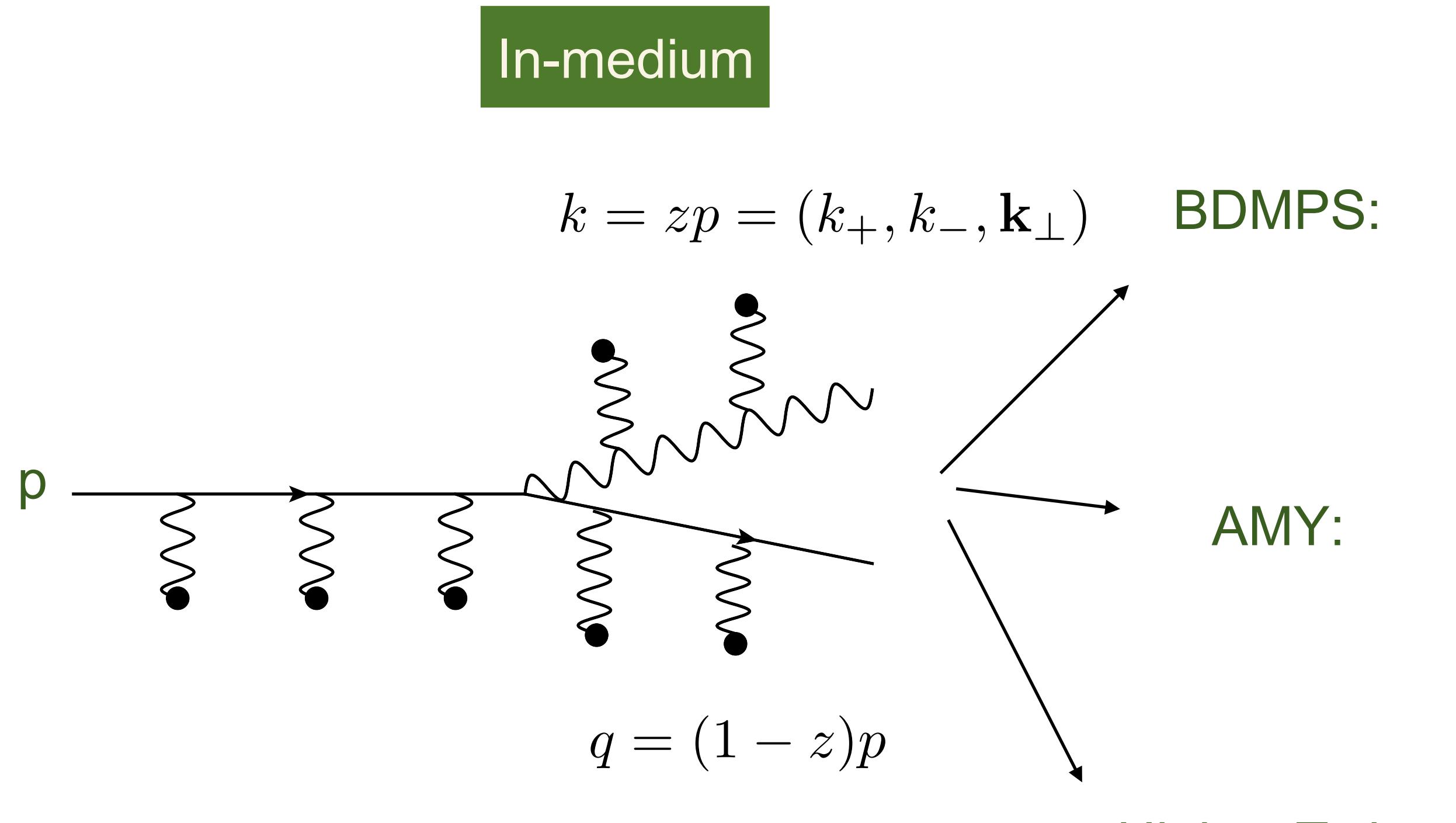
- From single gluon emission to full jet shower:



$$dP^{q \rightarrow qg} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{dk_\perp^2}{k_\perp^2}$$

Re-summation of multiple emissions

$$\Delta_i(t) \equiv \exp \left[- \sum_j \int_{t_0}^t \frac{dt'}{t'} \int dx \frac{\alpha_s}{2\pi} P_{i \leftarrow j}(x) \right]$$



BDMPS:

AMY:

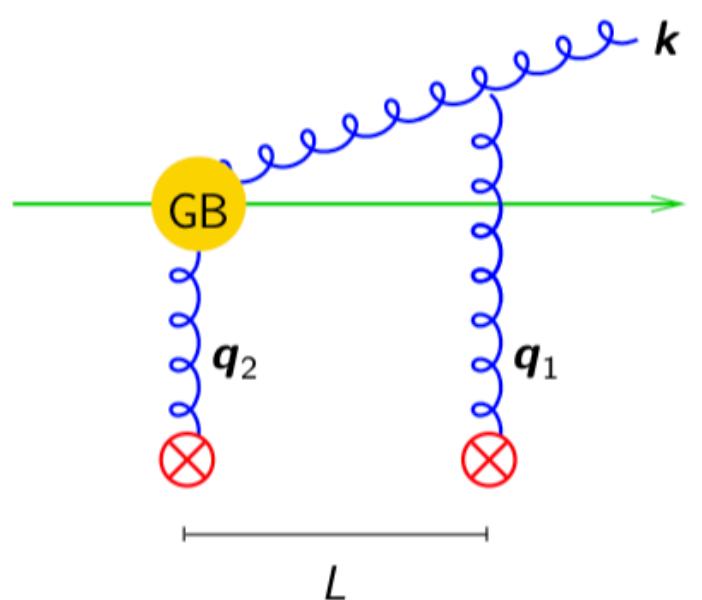
Higher-Twist:

LPM effect

- ◆ Jewel: probabilistic interpretation of the LPM effect
- ◆ Emission with the smallest formation time is the one that is realised

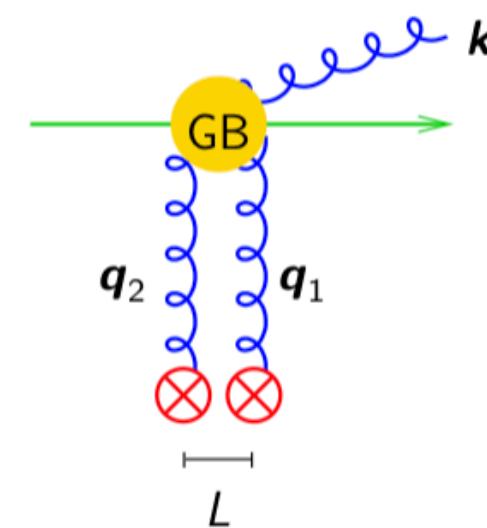
incoherent production

$$\tau_1 \ll L$$



coherent production

$$\tau_1 \gg L$$



JQ MC: (Partial) Summary

Model	Parton Shower	Radiative energy Loss	Collisional Energy Loss	Medium Response	Thermalization	Jet-induced effects
Fully Dynamic	Q-PYTHIA Pythia 6 with Modified Sudakov	BDMPS	X	X	X	X
	MATTER Virtuality ordered with Modified Sudakov	Higher-Twist	X	X	X	X
	JEWEL Pythia 6 with medium scatterings	pQCD + LPM effect	pQCD	Yes	X	X
Afterburners	PYQUEN Pythia 6 Shower + Energy Loss	BDMPS	pQCD	X	X	X
	MARTINI Pythia 8 initialisation + MC Rate Equations	AMY	pQCD	Yes	Yes	X
	Co-LBT Pythia 6 Shower + Energy Loss	Higher-Twist	pQCD	Yes	Yes	Yes
	Hybrid Pythia 6 Shower + Energy Loss	X	AdS/CFT	Yes	Yes (resulting effect at the final spectra)	

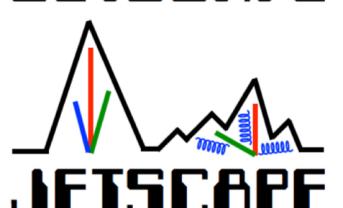
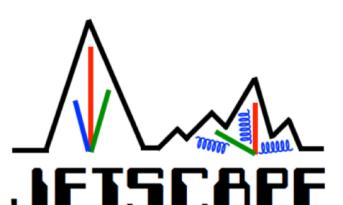
...

(sorry for the ones that are not in this list...)

New since HP16

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JEWEL	Pythia 6 with medium scatterings	pQCD + LPM effect	pQCD	Yes	X	X
PYQUEN	Pythia 6 Shower + Energy Loss	BDMPS	pQCD	X	X	X
MARTINI	Pythia 8 initialisation + MC Rate Equations	AMY	pQCD	Yes	Yes	X
Co-LBT	Pythia 6 Shower + Energy Loss	Higher-Twist	pQCD	Yes	Yes	Yes
Hybrid	Pythia 6 Shower + Energy Loss	X	AdS/CFT	Yes	Yes (resulting effect at the final spectra)	



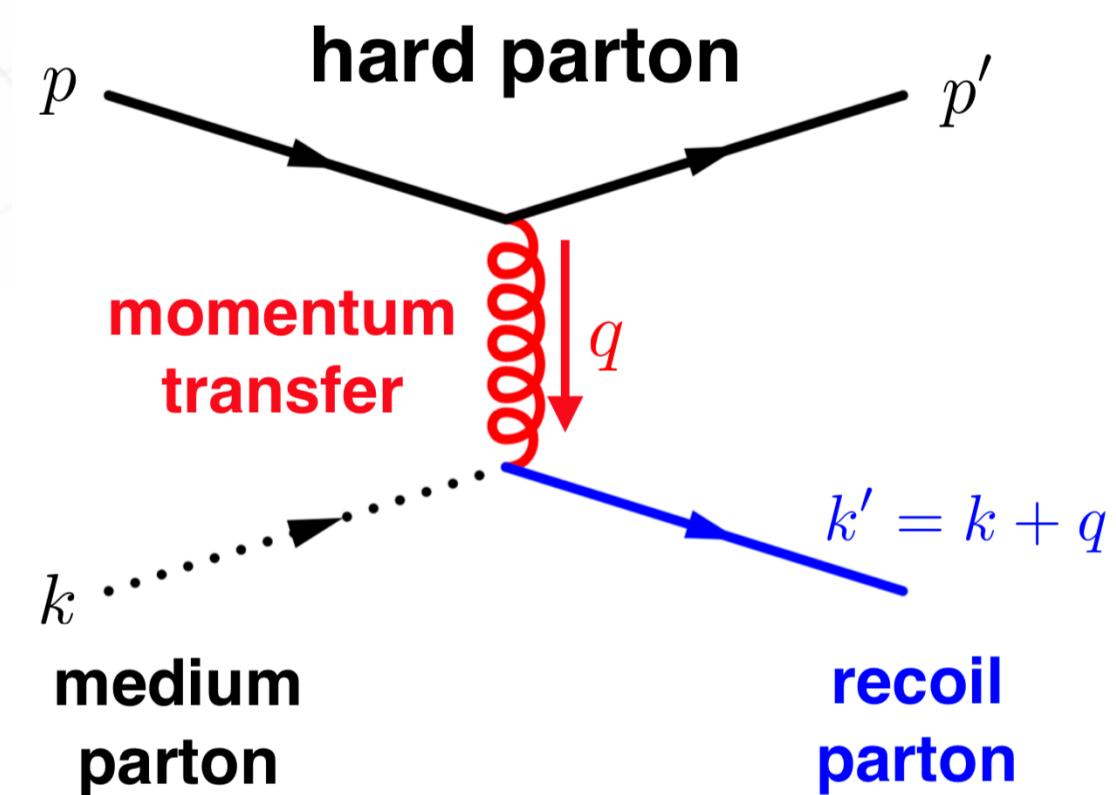
...

(sorry for the ones that are not in this list...)

Medium Recoils

- ◆ Medium constituents that became correlated with the jet, after interacting with it:

pQCD perspective



Sampled from a thermal distribution

May end part of the jet

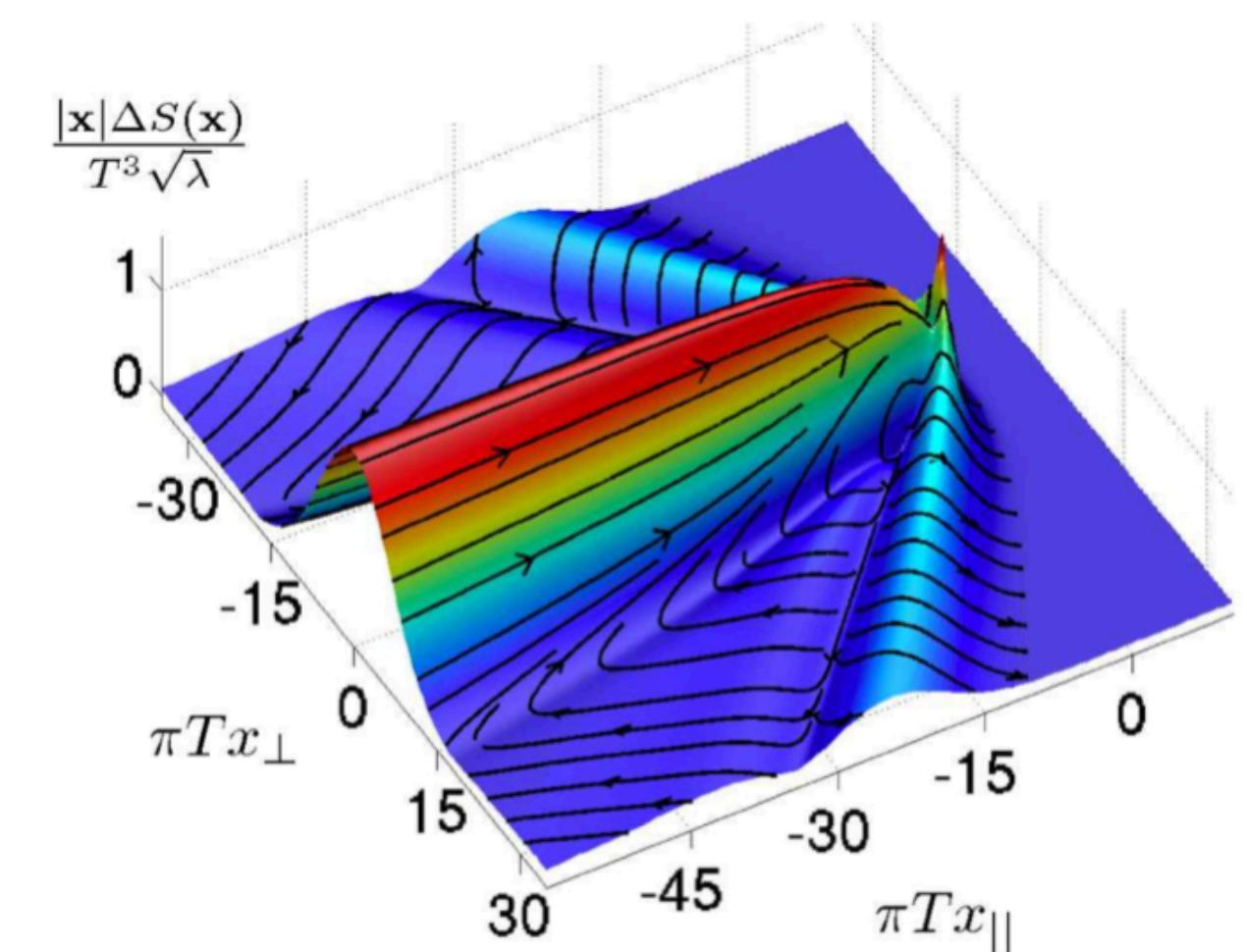
E.g: JEWEL,...

Continue to re-scatter with the medium:

E.g: MARTINI, Co-LBT,...

AdS/CFT perspective

Particles from a wake in the fluid



Jet-induced medium response

- ◆ How the medium reacts to the passage of a high energy jet?
- ◆ Energy deposited by the jet will change medium evolution
- ◆ Medium hydrodynamic evolution affected by a source (jet) term

$$\partial_\mu T_{\text{fluid}}^{\mu\nu} = J_{\text{jet}}^\nu(x)$$

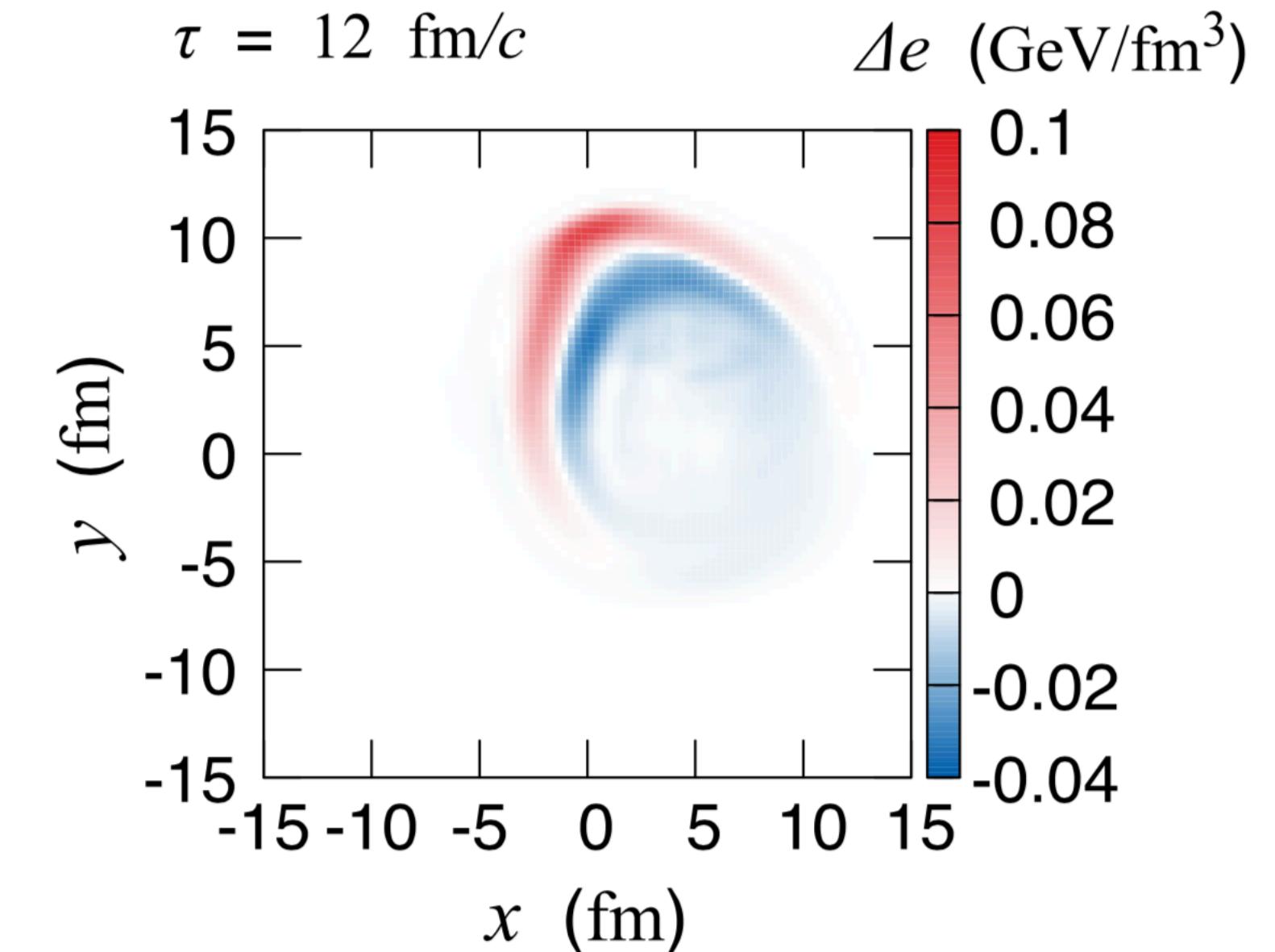
Energy-momentum tensor
of the QGP fluid

Energy and momentum
deposited from the jet

Ideal Hydro or Viscous Hydro

E.g: Coupled Jet-Fluid, Co-LBT,...

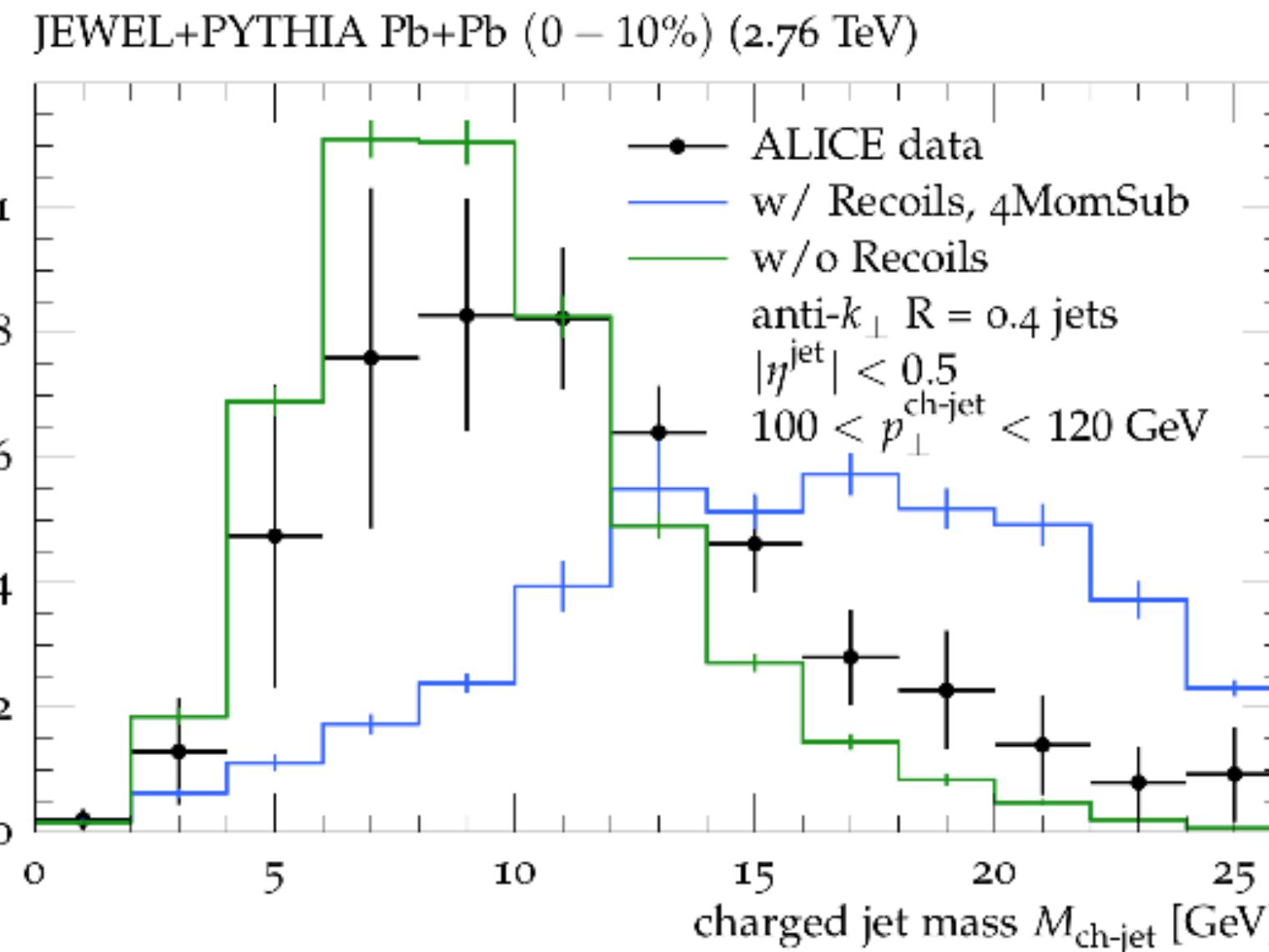
[Coupled Jet-Fluid: 1701.07951]



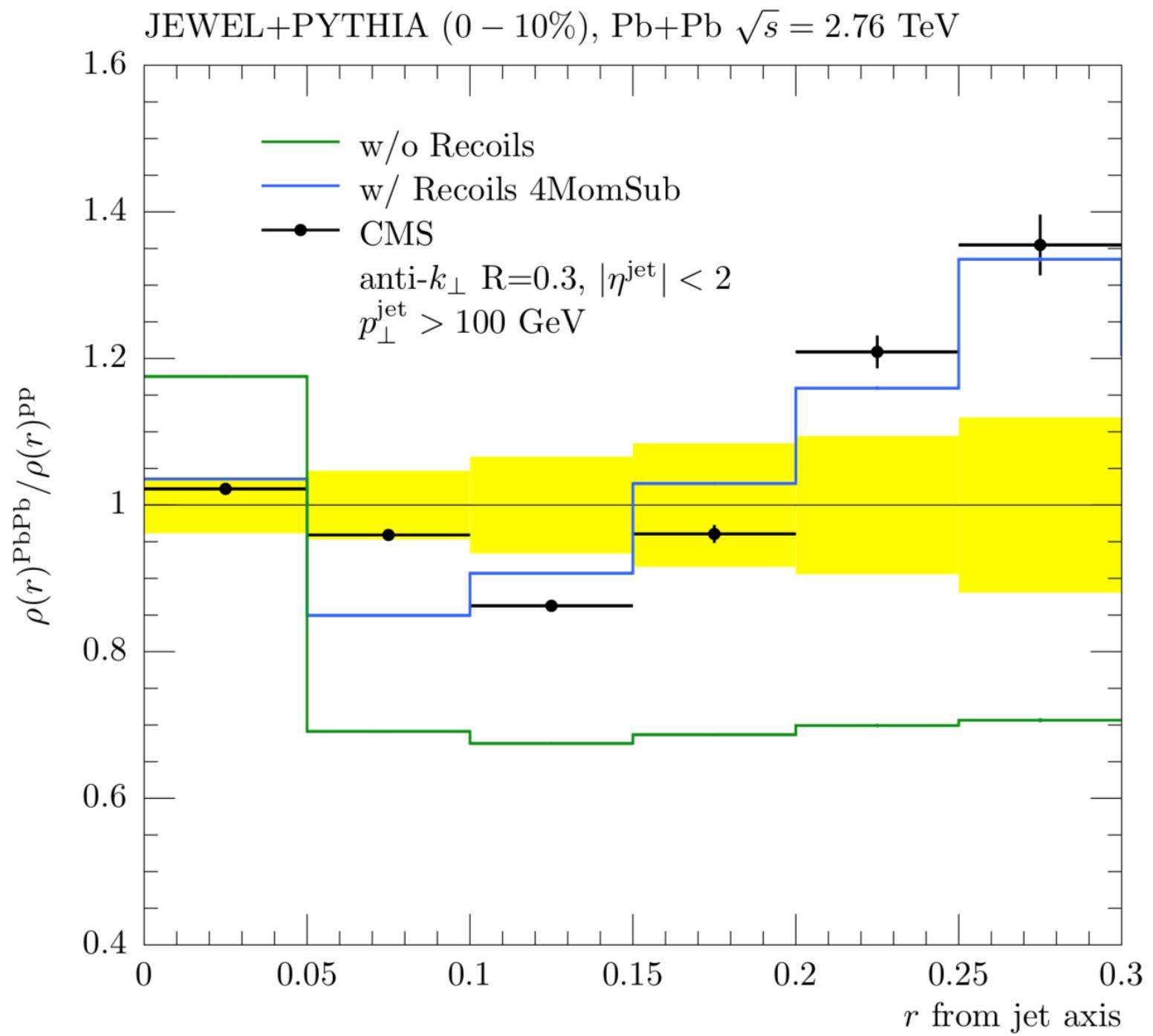
Jet Mass vs Jet p_T Profile?

♦ How to describe simultaneously jet mass and jet transverse profile?

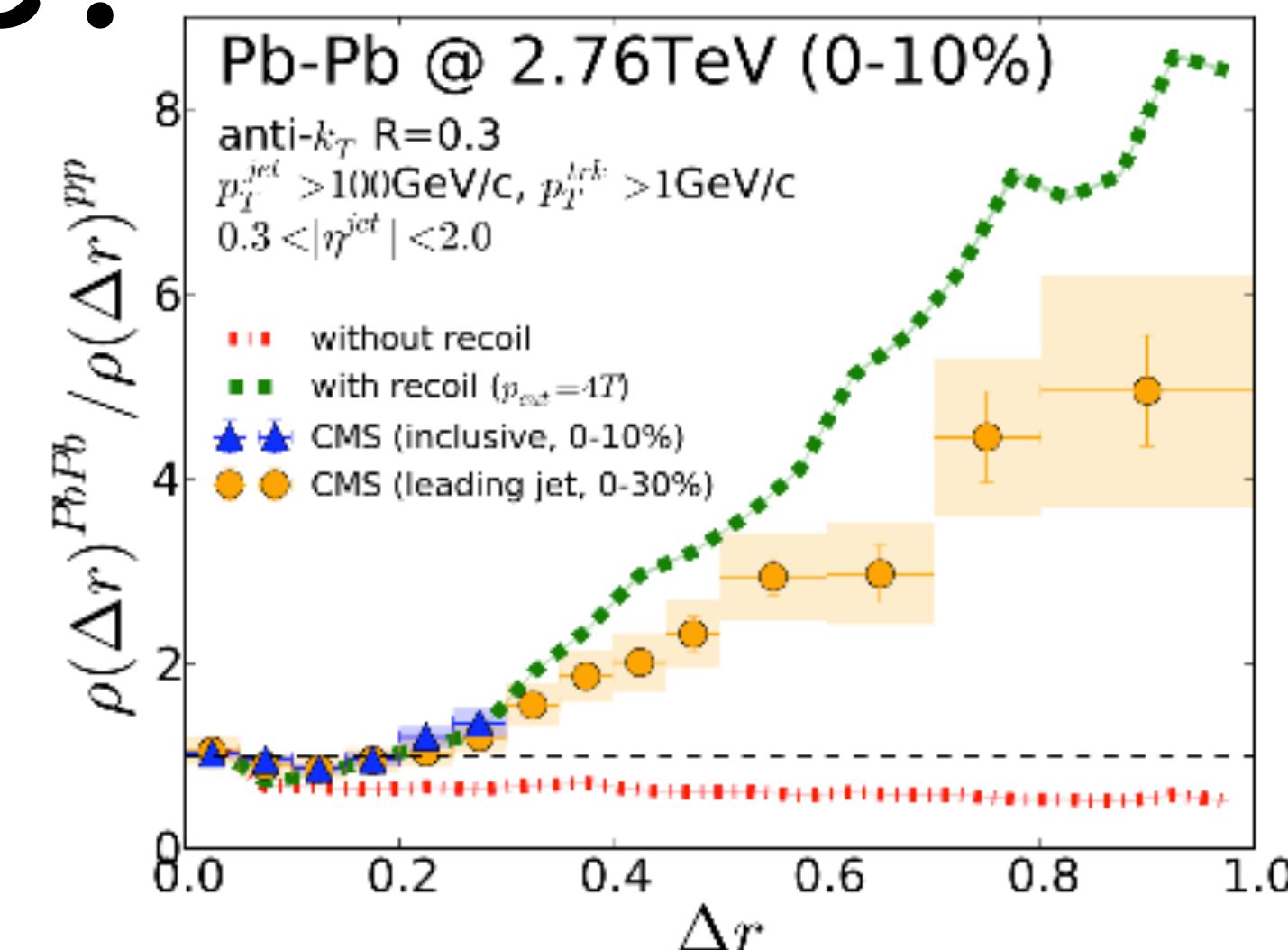
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[JEWEL:1707.01539]



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