

# Constraining mechanisms of jet-medium interaction via studies of energy dependencies of angular two-particle correlations

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# Motivation

# QGP studies via hard probes

## Why hard partons/mesons?

Energy scales:  $E \gg \Lambda_{\text{QCD}}$

$\Rightarrow$

- created at early stages,
- do not thermalize,
- but still interact with QGP (via strong interaction).

Same for heavy quarks/mesons

+ heavy quarks labeled by their large masses:

$m_c \approx 1.5 \text{ GeV}$ ,  $m_b \approx 4.5 \text{ GeV}$

$\implies$  "natural triggers".

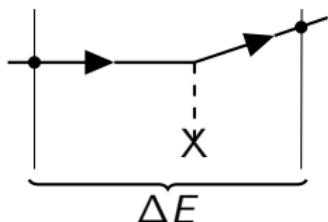
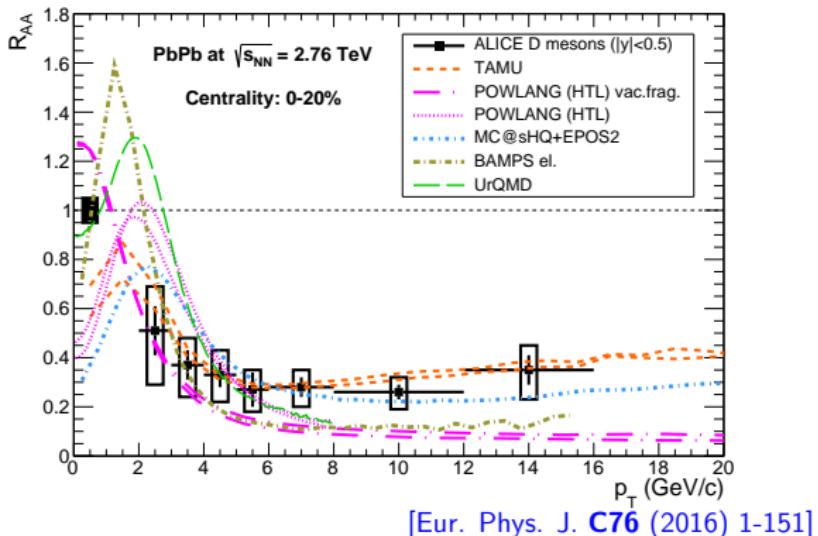
Types? highly energetic (hard) partons/mesons, heavy quarks/mesons, ... jets, heavy quark jets.

# Nuclear modification factor $R_{AA}$

$$R_{AA}(p_T) := \frac{N_{AA}(p_T)}{\langle T_{AA} \rangle \sigma_{pp}(p_T)}.$$

Motivation  
Jets  
Correlations  
Conclusions

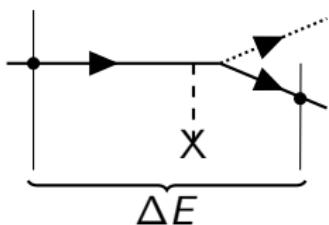
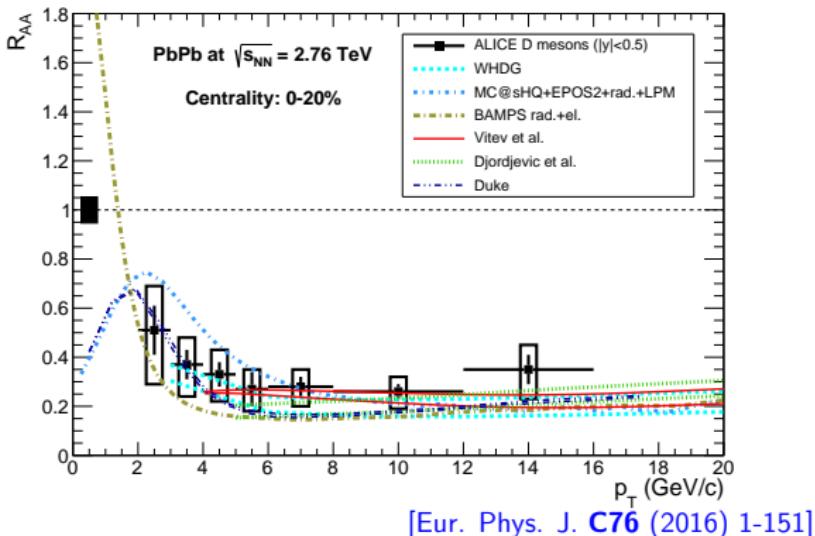
## Collisional Energy Loss:



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Collisional & Radiative Energy Loss:

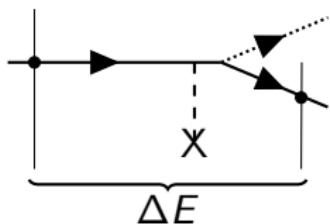
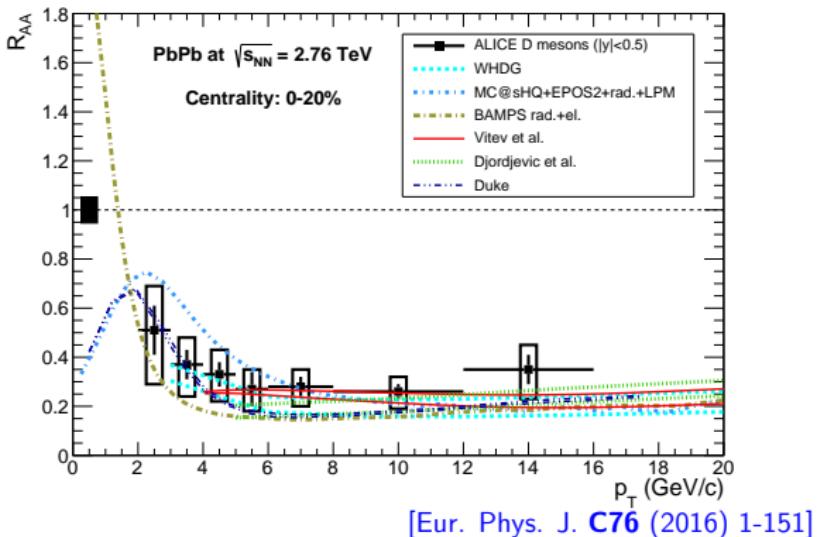


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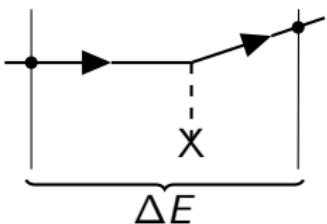
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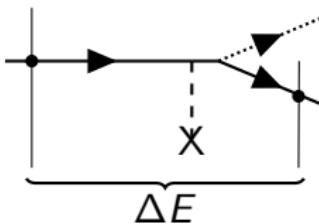
⇒ Need for more discriminative observables!

# Collisional vs. Radiative Processes

collisional:



radiative:



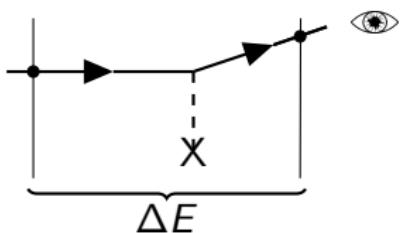
$$\Delta E \Rightarrow R_{AA},$$

i.e.: Observables for sets of individual particles

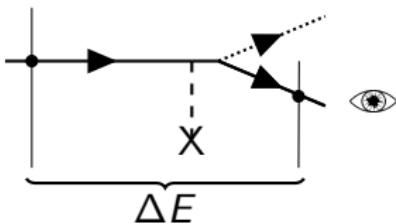
Different Two-Particle Correlations!

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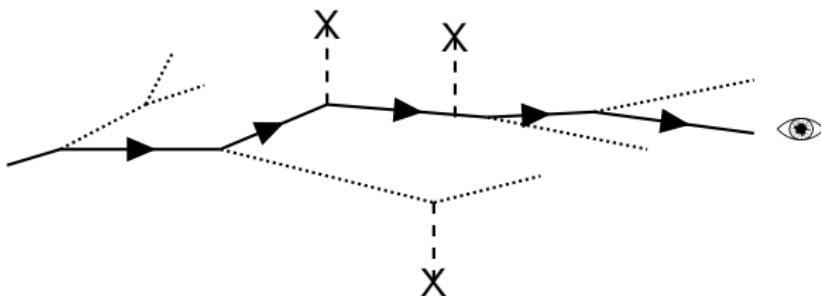
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Hard particles:  
Part of Jets  $\Rightarrow$  Correlated to other jet particles  
 $\Rightarrow$  Additional information from pairs of jet-particles!



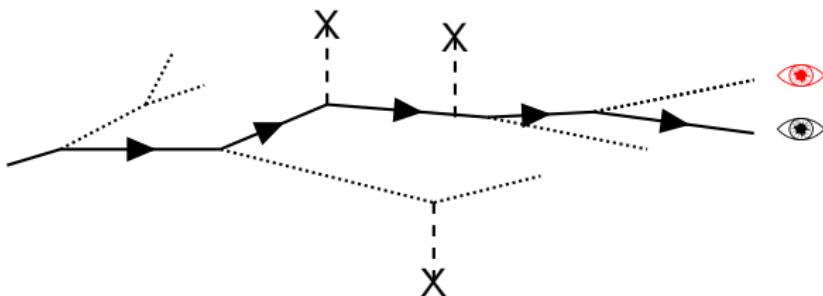
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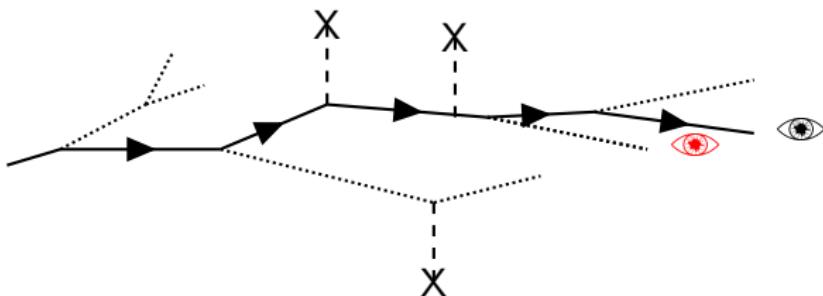
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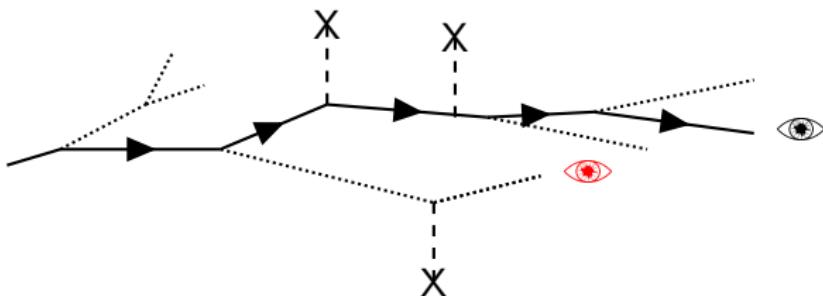
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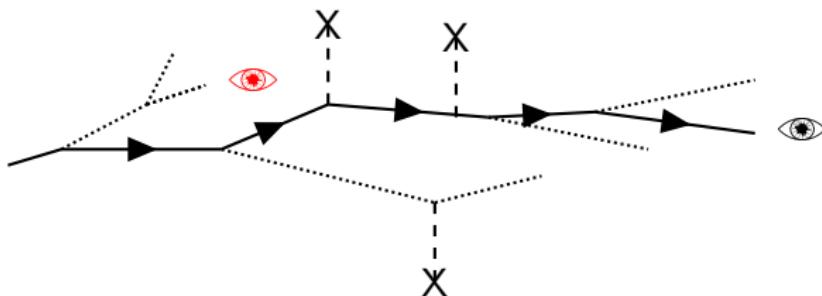
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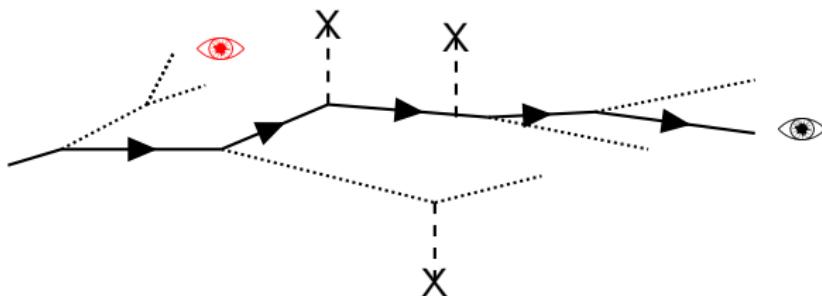
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# Descriptions of Jets in the Vacuum

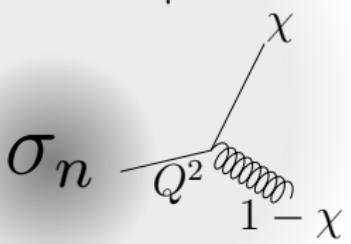
# Factorization and DGLAP evolution

Production of **multiple partons**:  
soft and/or **collinear** emissions dominant!  $\longrightarrow$  They factorize:

Number Distribution for particles:  
 $D(x, Q, m)$ .

Probability density for splitting:  
 $P(x)$

**DGLAP equations:**



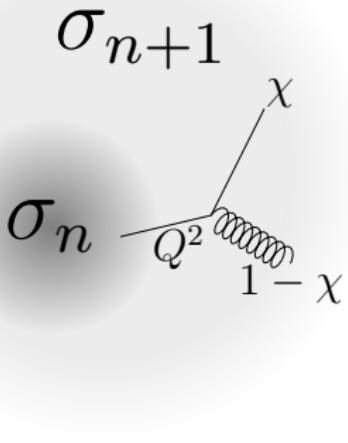
$$\frac{\partial D_i(x, Q, m)}{\partial \ln(Q^2)} \simeq \sum_j \int \frac{dz}{z} D_j\left(\frac{x}{z}, Q, m\right) P_{ij}(z).$$

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$\rightarrow$  Monte-Carlo Simulation of DGLAP-equations for jets between scales:  $Q_\uparrow$ ,  $E_{\text{ini}}$ , and  $Q_\downarrow$

# Applications and Limitations

## Applications:

- Parton cascades from:
  - $e^+ + e^-$  collisions,
  - pp-collisions (final state radiation),started by an initial parton.
- Allows to extract correlated parton pairs  
→ 2-particle correlations !

## Limitations:

- $Q_\uparrow, E_{\text{ini}}$  dependencies: No PDFs, no hard initial process, no initial state radiation,
- No multiple jet events,
- $Q_\downarrow$  dependence: No hadronization model.

Conclusion? → need to fix  $Q_\downarrow$ ! Use (IRC) stable observables!

## Validation:

Event-shape observables (Thrust), Humped-Back plateau distribution, cf. Zapp [[Eur.Phys.J. \(2009\) C60, 617-632](#)].

# Models of Jet-Medium Interaction

## "Inelastic" model A

Using a basic assumption of the YaJEM-model:  
 [Phys. Rev. C78 (2008), 034908]

Virtuality  $Q$  increases in the medium over time  $t$ :

$$\frac{dQ^2}{dt} = \hat{q}_R(t)$$

$Q$  increase  $\Leftrightarrow$  More parton splittings:

Implementation (steps  $t \mapsto t + \Delta t$ ):

$$\begin{aligned} Q &\mapsto \sqrt{Q^2 + \hat{q}_R \Delta t}, \\ \vec{p} &\mapsto \vec{p}, \\ \Rightarrow E &\mapsto \sqrt{E^2 + \hat{q}_R \Delta t}. \end{aligned}$$

...extra radiation!

## "Elastic" model B

Transport coefficients:

$$\vec{A}(t) := -\frac{d}{dt} \langle \vec{p}_{||} \rangle, \quad \hat{q}_C(t) := \frac{d}{dt} \langle \vec{p}_{\perp} \rangle^2.$$

drag force	(squared) transverse
deterministic	momentum transfers
	stochastic

**Thermalized medium:** relation between  $\vec{A}$  and  $\hat{q}_C$

We use:

$$\frac{\hat{q}_C}{A} \approx 0.56 + 1.44 \frac{T}{T_C}$$

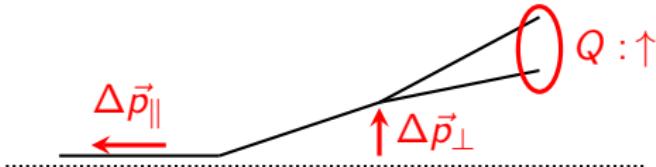
cf. Berrehrah et al. [Phys. Rev. C90 (2014) 064906, arXiv:1405.3243[hep-ph]]

$\hat{q}_C \sim T^3$  ... cf. Jet-Collaboration [Phys. Rev. C90 (2014) 014909, arXiv:1312.5003]

Assumption:  $\hat{q}_C = \hat{q}_R$

...energy transfer to the medium!

# Effective Models of Jet-Medium Interaction



⇒ 4 models:

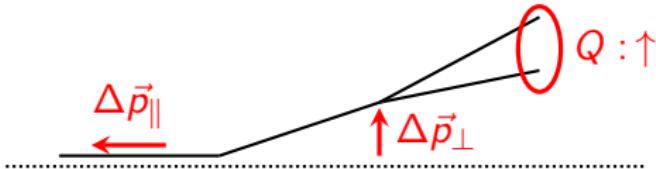
model	$Q$	$\vec{p}_{\parallel}$	$\vec{p}_{\perp}$	$E$
A (radiative/YaJEM-like)	↑	=	=	↑
B (collisional)	=	↓	↑	↓↑
C (hybrid/no transverse force)	↑	↓	=	↓↑
D (hybrid/transverse force)	↑	↓	↑	↓↑

**Disadvantages:** Simplifying assumptions; lack of microscopic interactions.

**Advantage:** Consistent framework for studying collisional and radiative mechanisms.

Jet-medium interaction:  $\Delta Q^2 := \int_0^L dt \hat{q}_{C,R}(t) \dots [\text{GeV}^2]$ .

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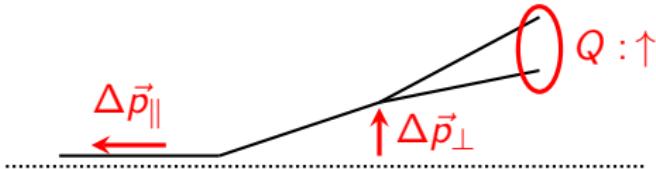
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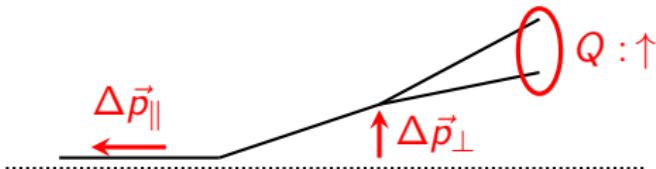
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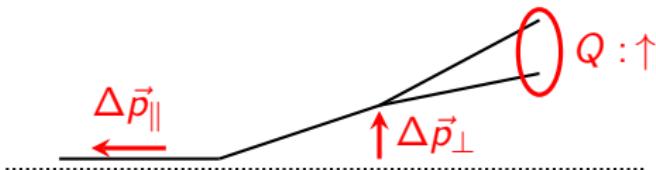
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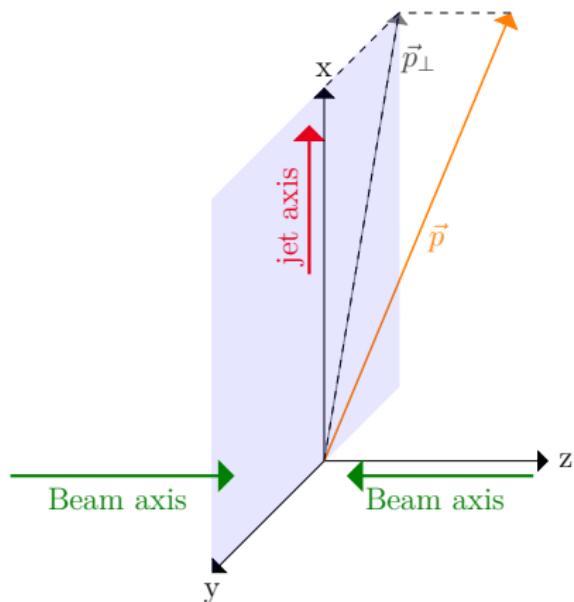
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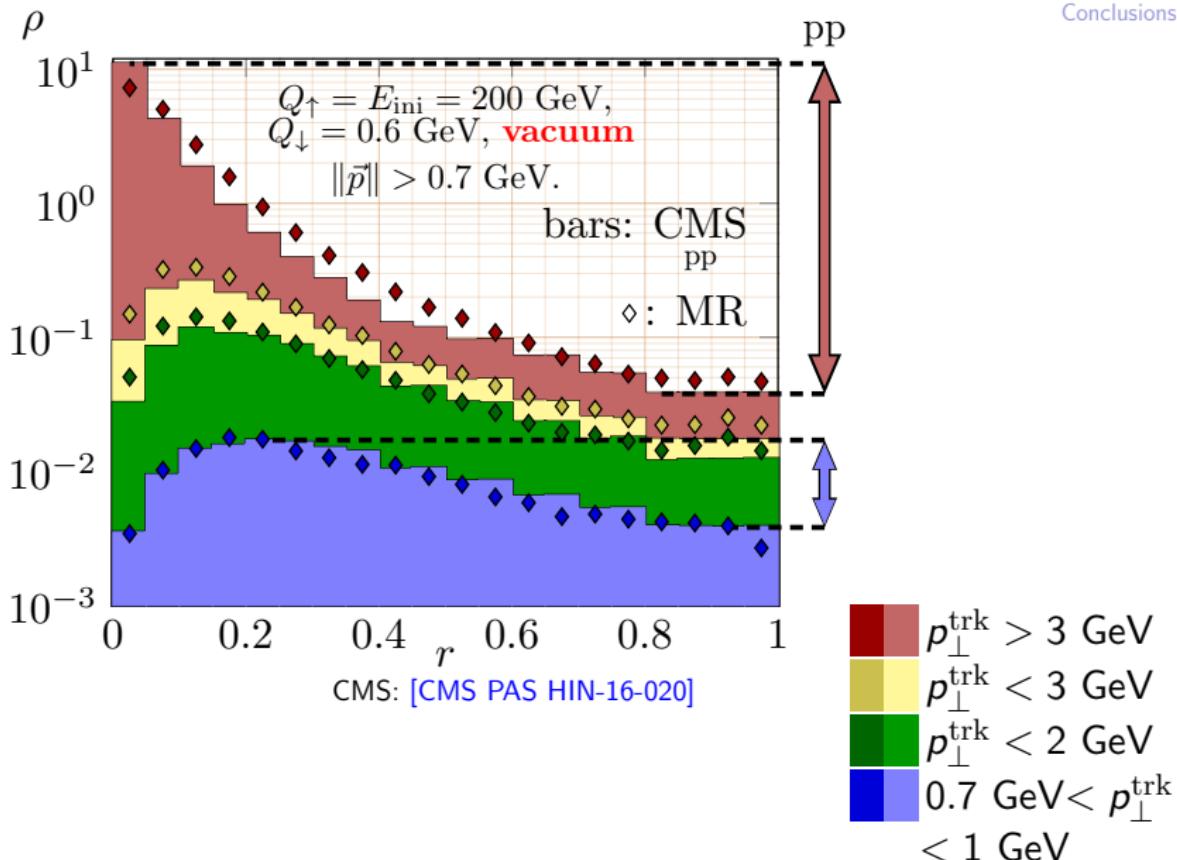
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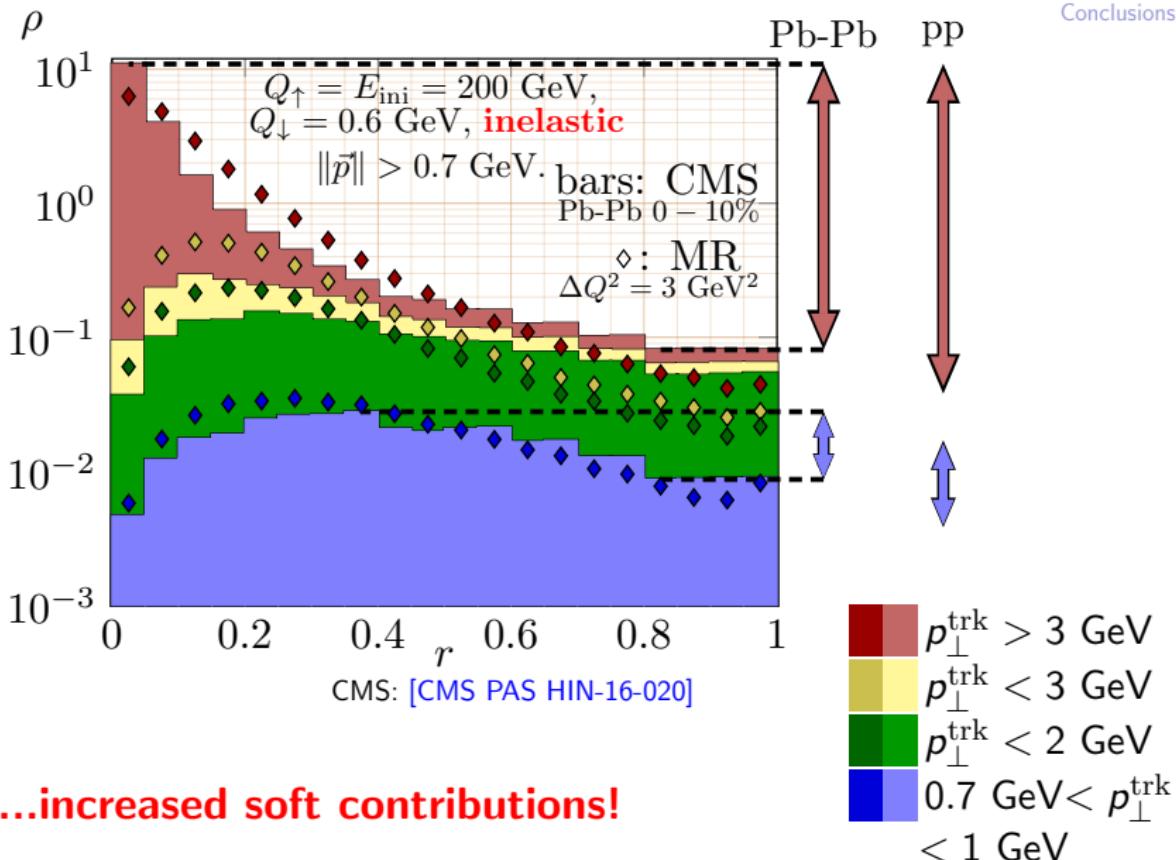
# Single Particle Observables

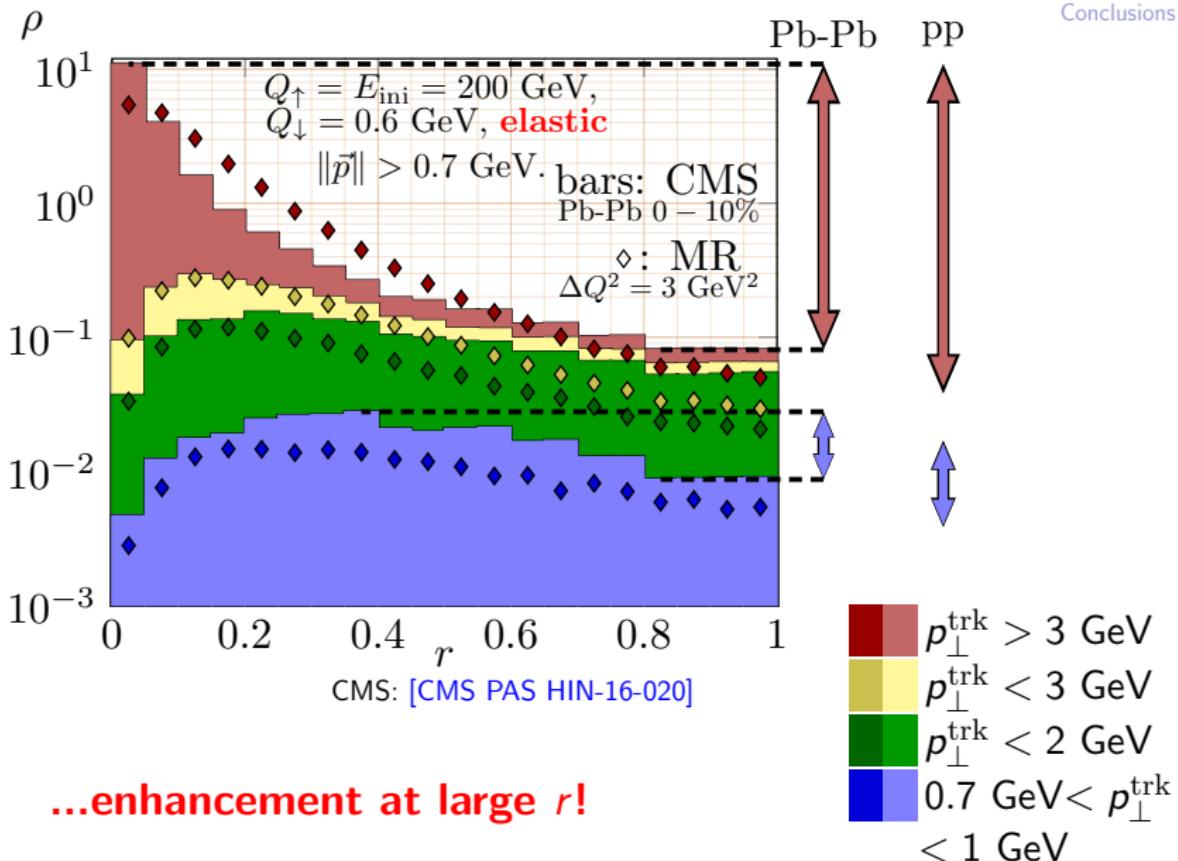
# Jet shapes: $\rho(r)$

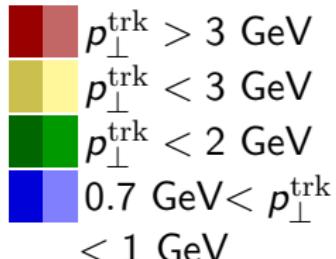
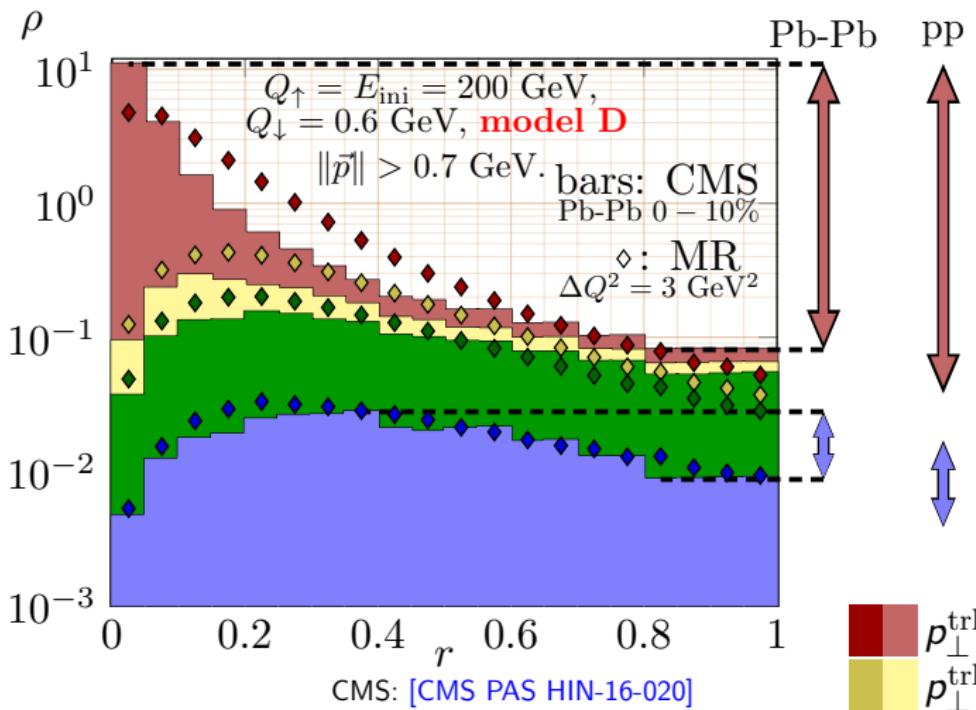
$$\rho(r) := \frac{1}{\delta r} \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{\sum_{\text{trk} \in [\mathbf{r}_a, \mathbf{r}_b]} p_{\perp}^{\text{trk}}}{p_{\perp}^{\text{jet}}}, \quad r = \sqrt{\Delta\phi^2 + \Delta\eta^2}.$$



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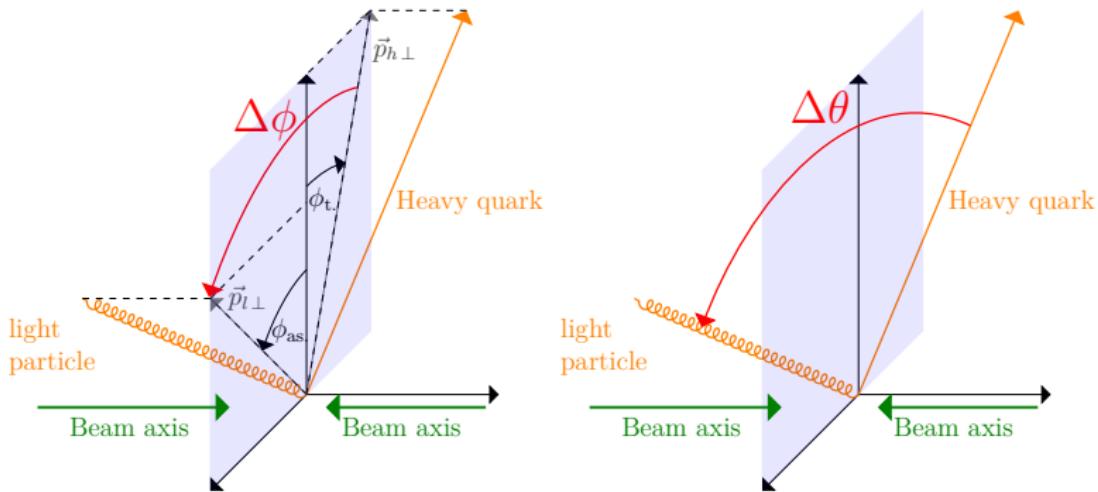
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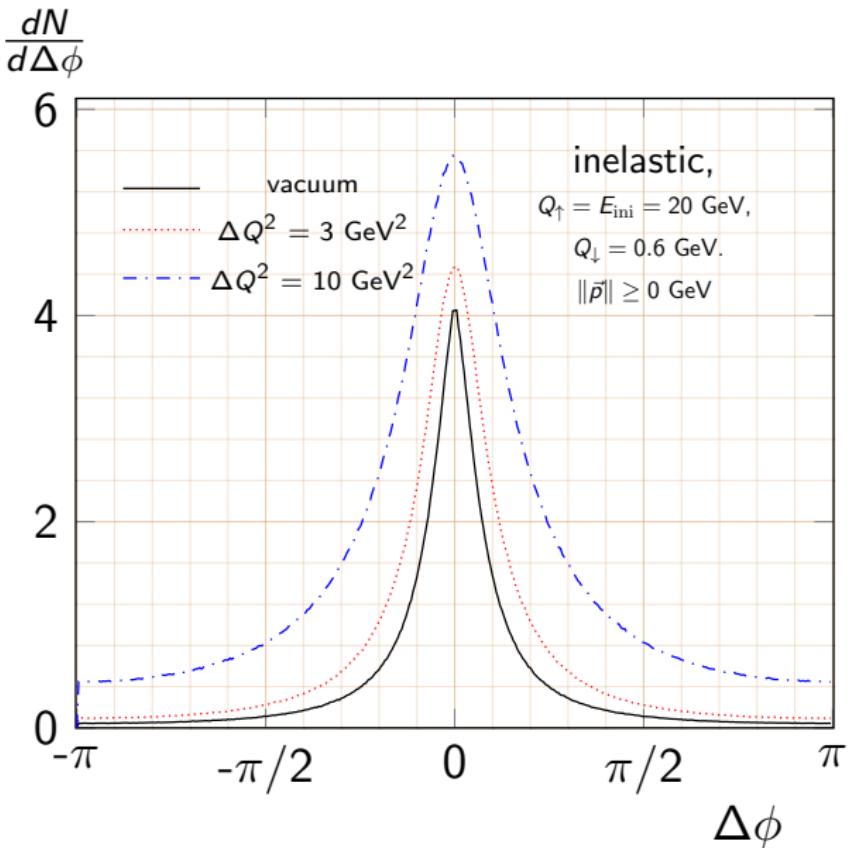
...combination of effects:  
Best behavior for soft contributions!

# Heavy-light Particle Correlations

# Angular Heavy-Light Particle Correlations

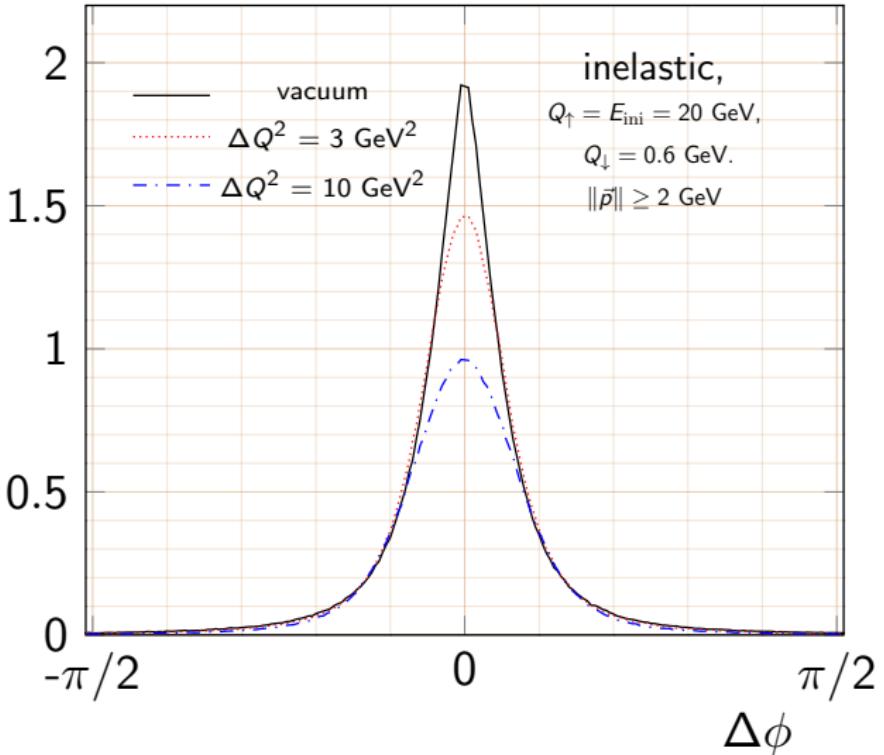


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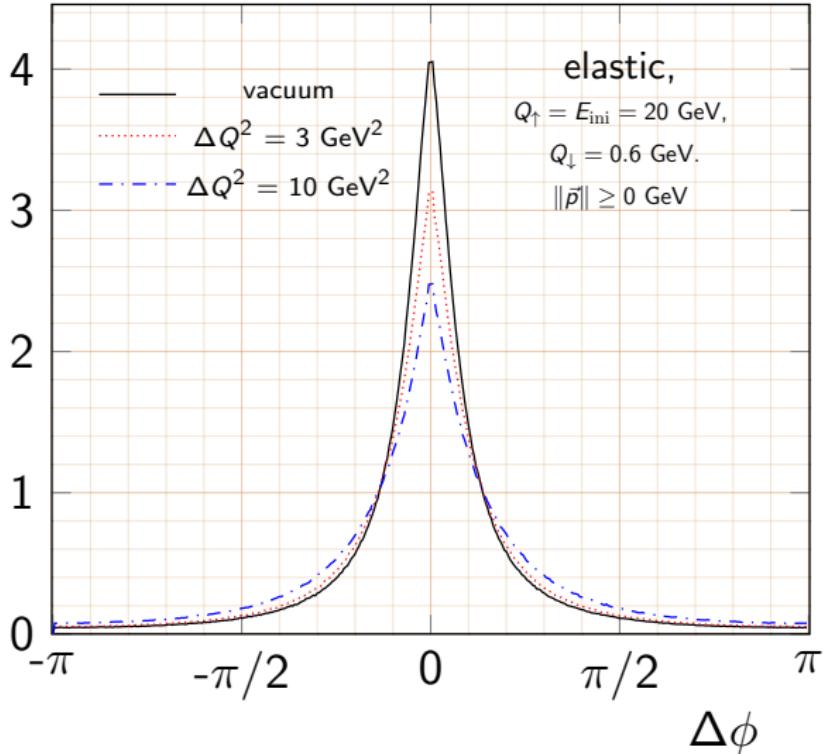
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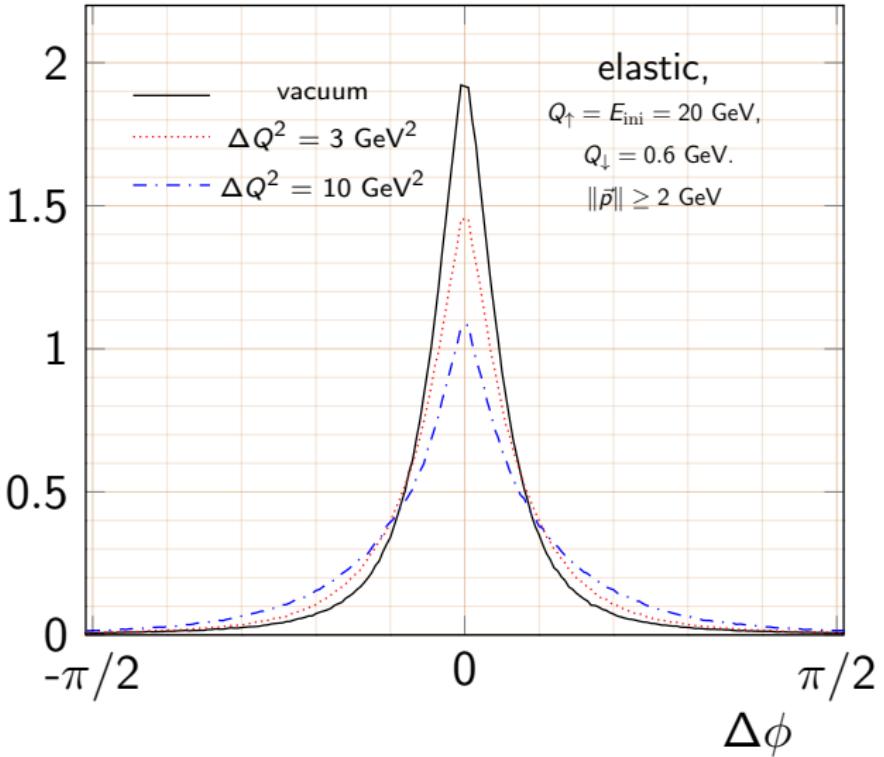
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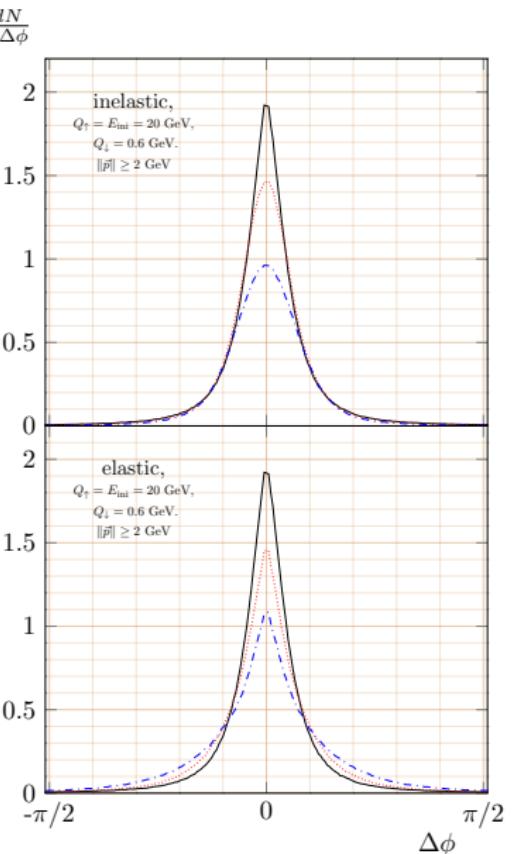
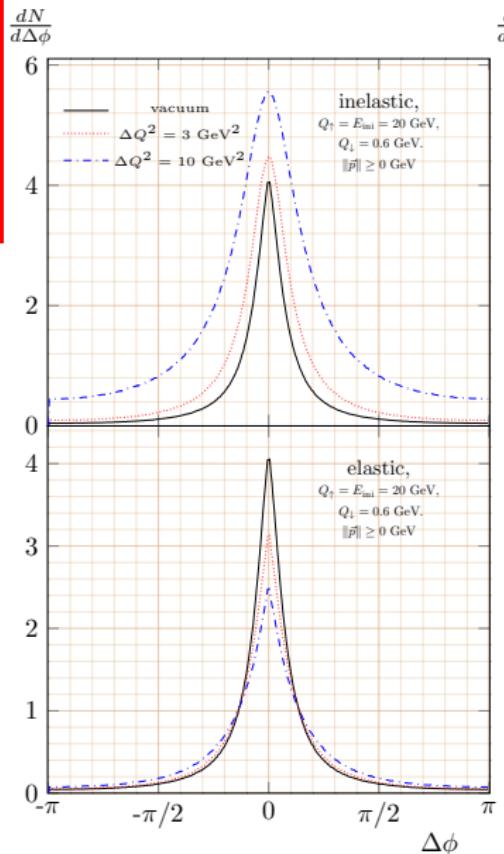


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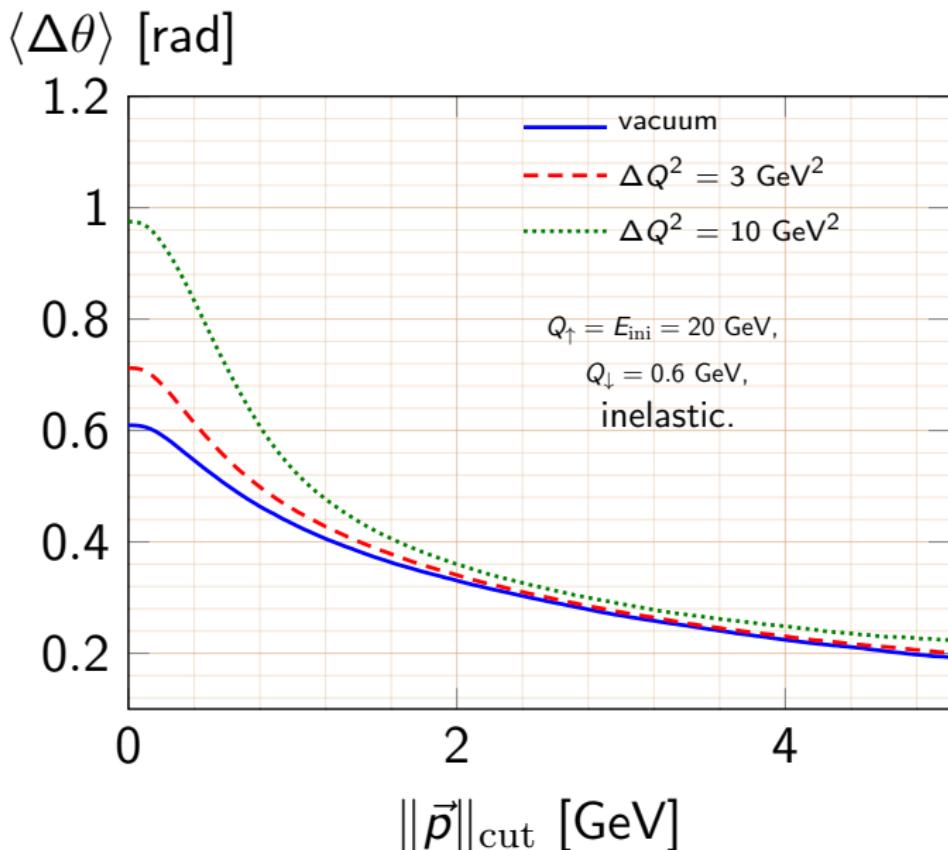


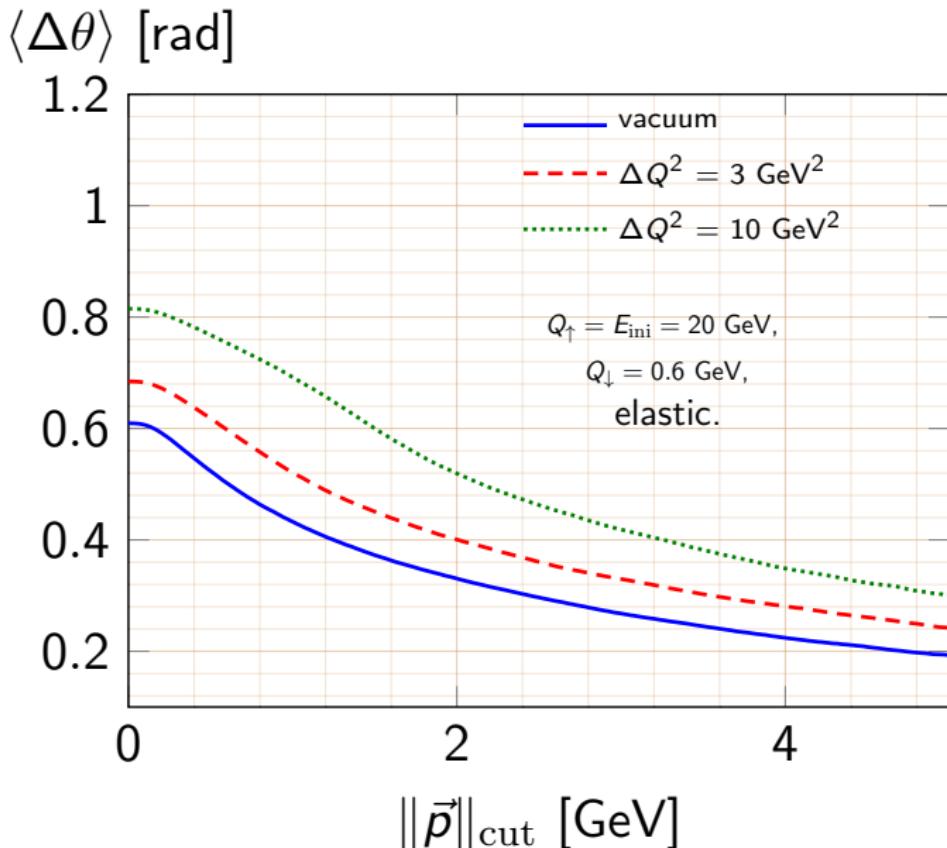
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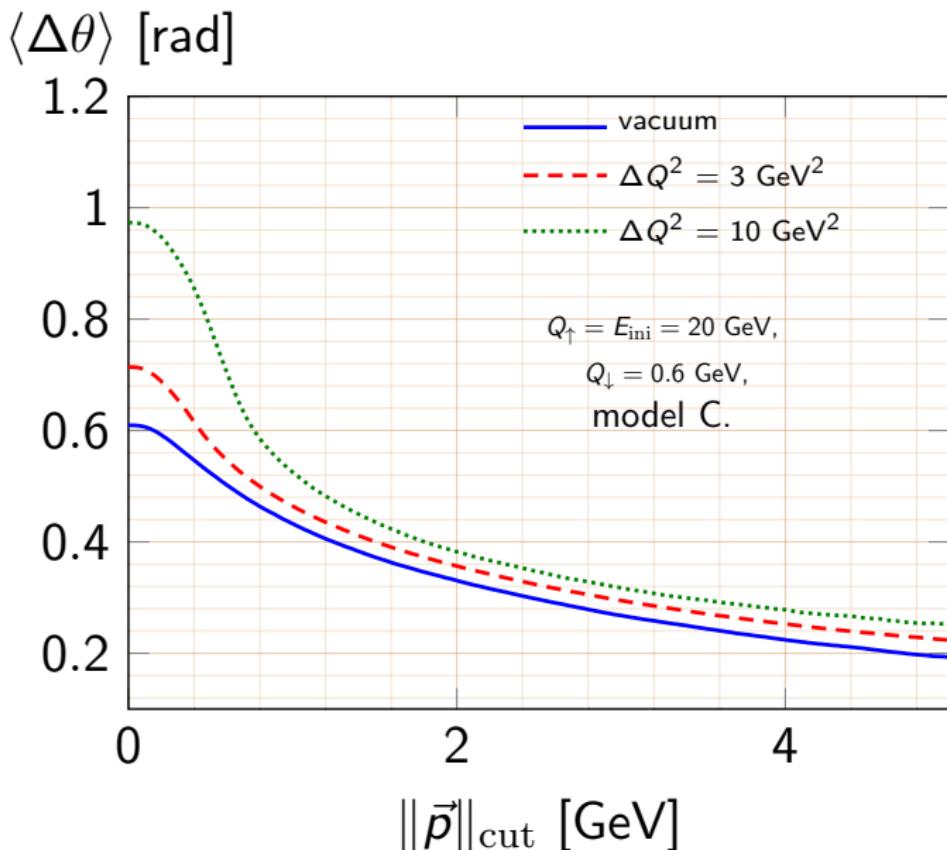


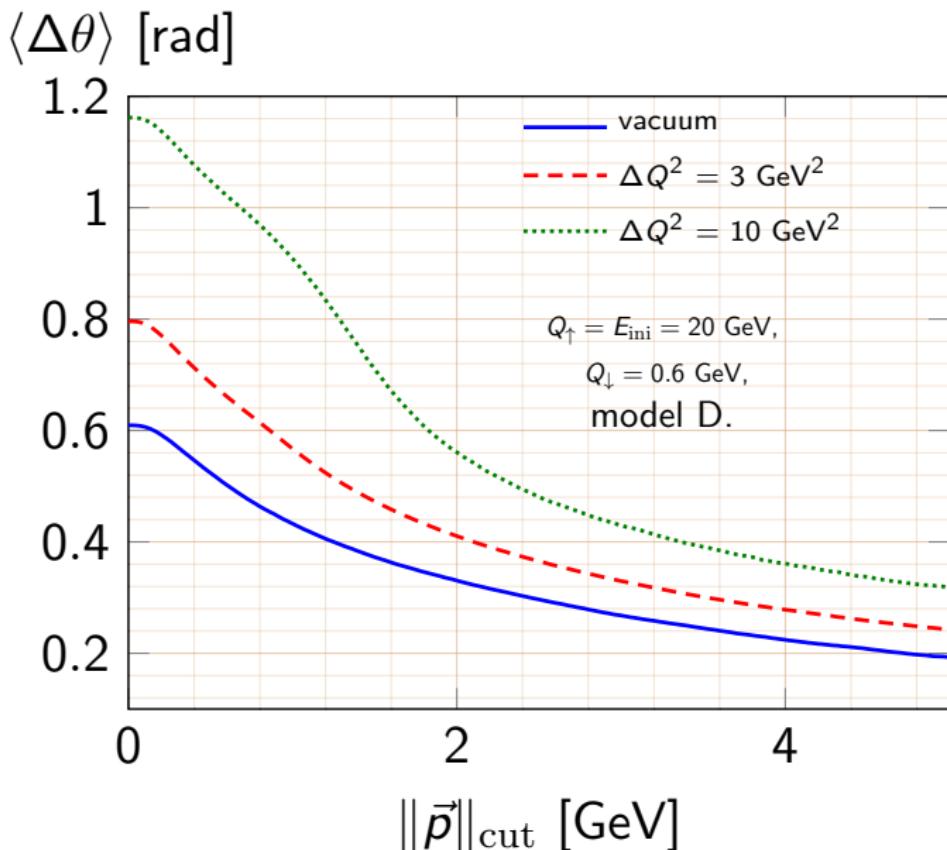
**Strong dependence on  $\|\vec{p}\|_{\text{cut}}$ !**

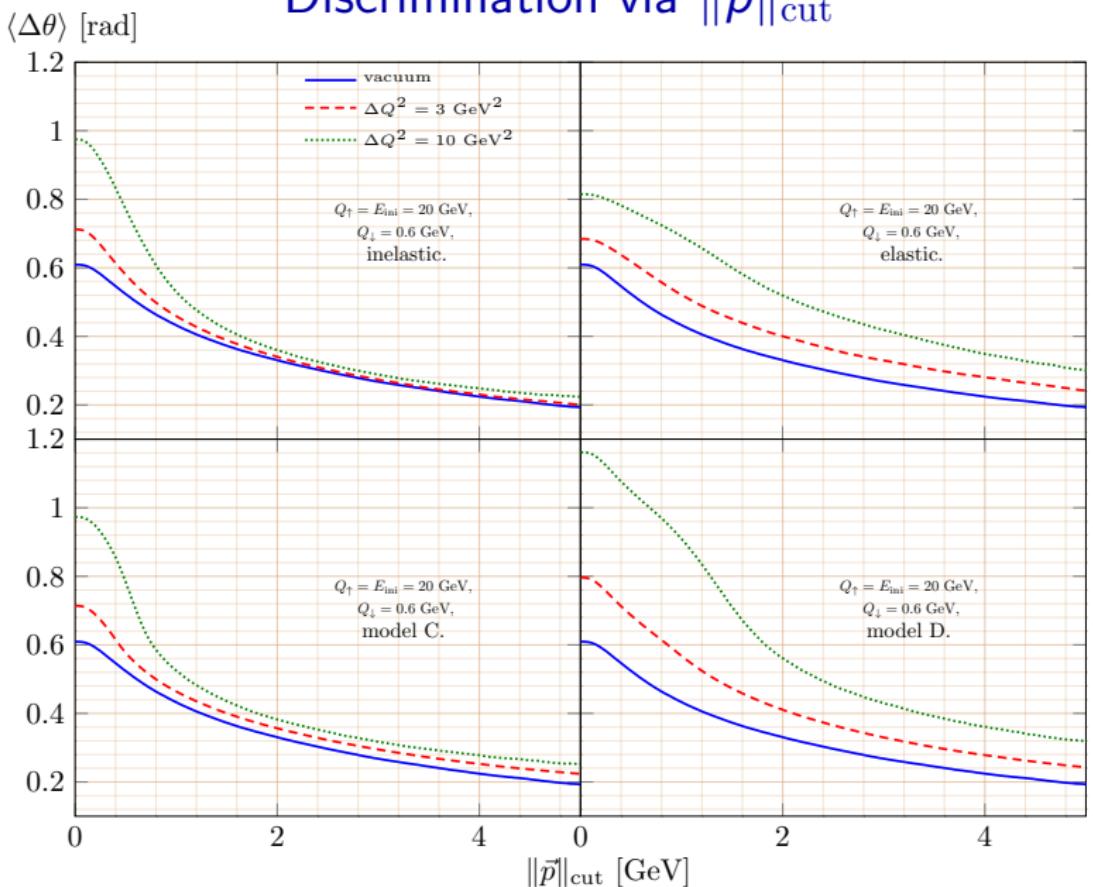
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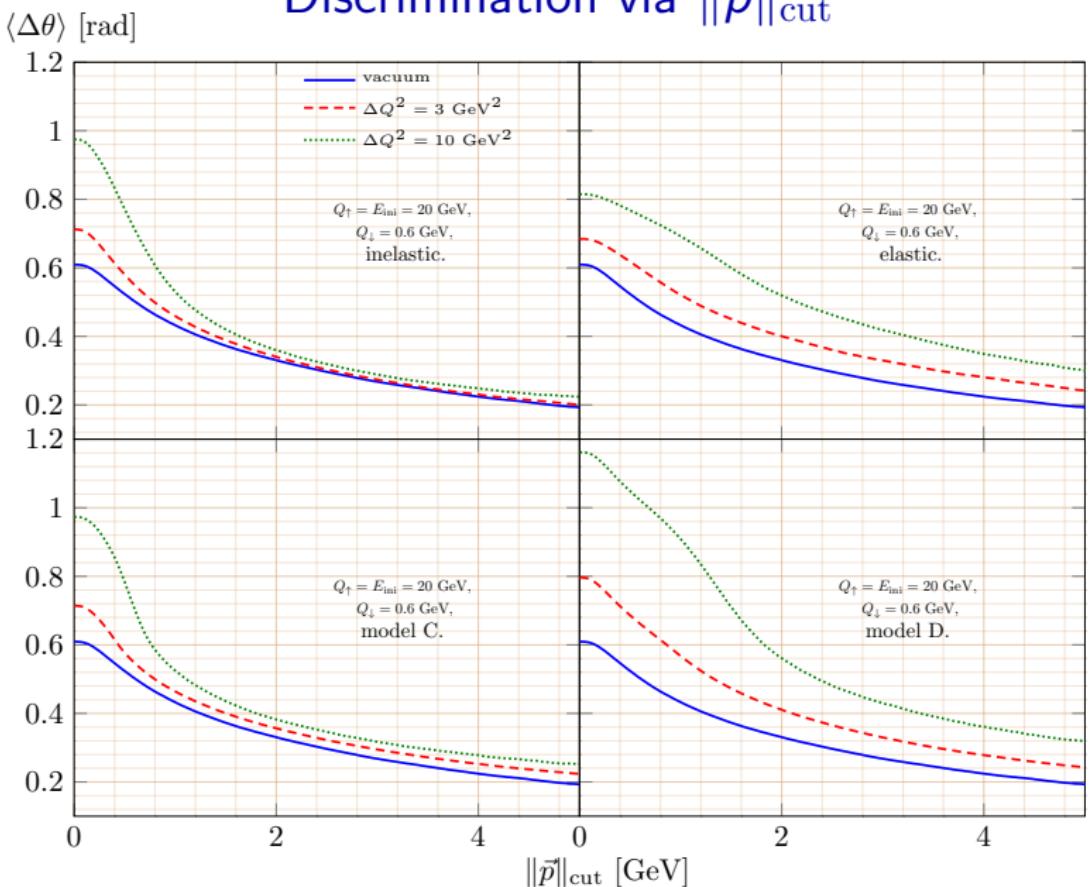
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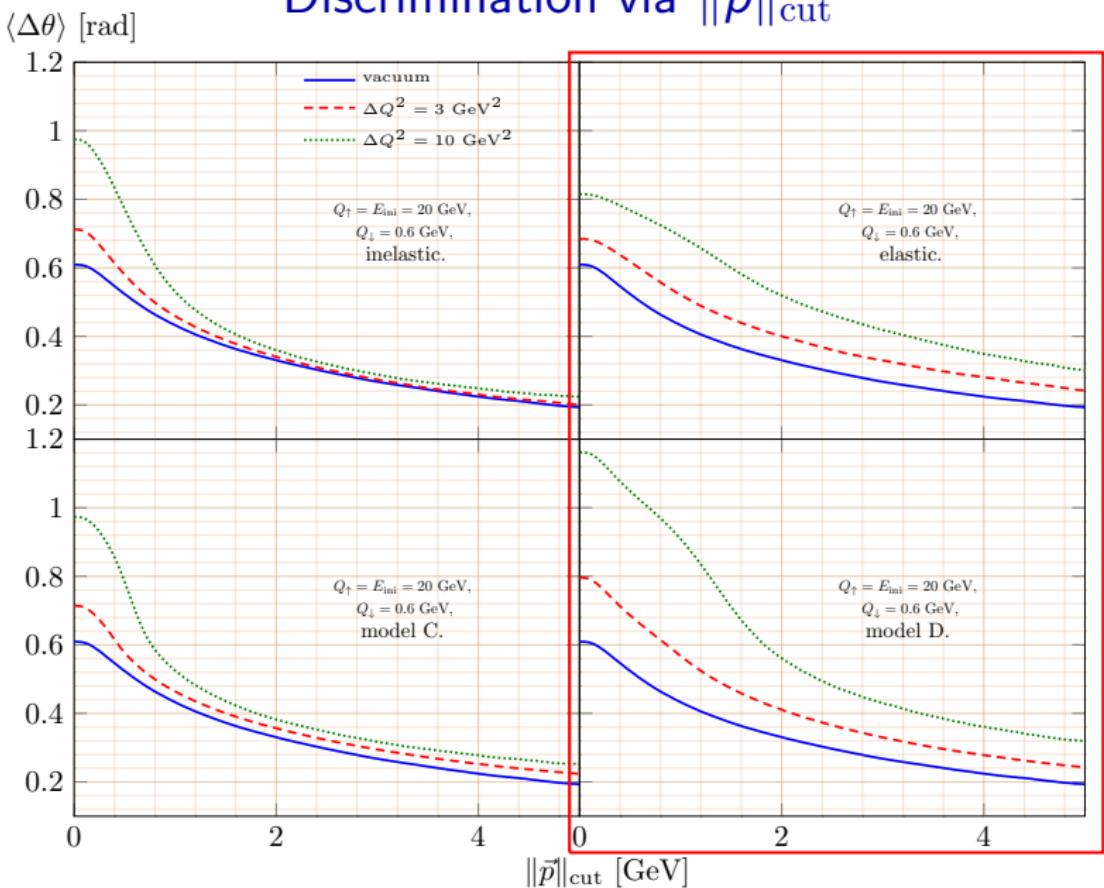
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## Key-Result:

Induced Radiation: broadening at small energies.  
Transverse forces: Broadening at all energies.

## Main Conclusion:

Angular Heavy-Light particle correlations allow to distinguish different mechanisms of in-medium parton-energy loss!

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