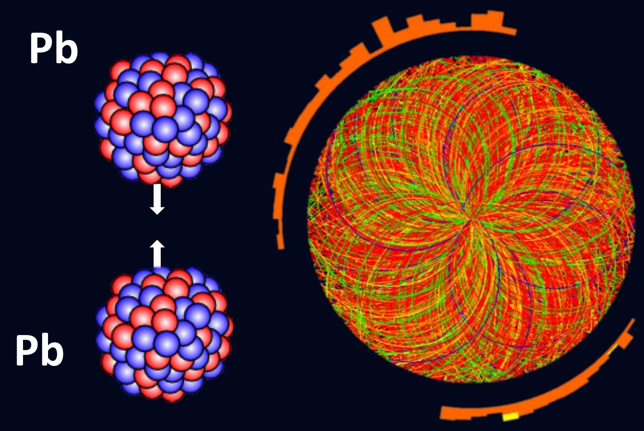
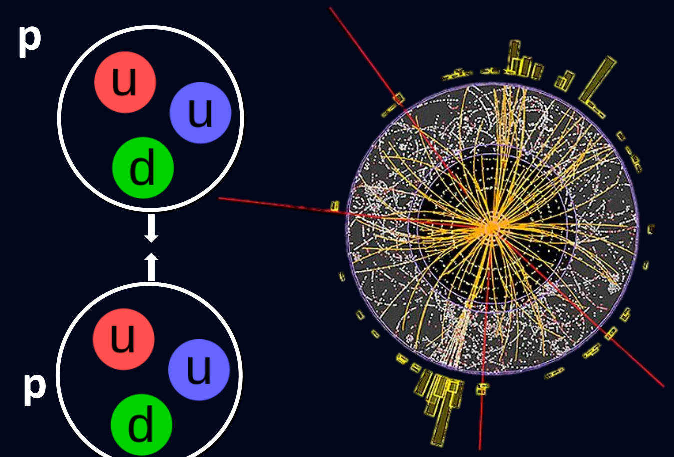




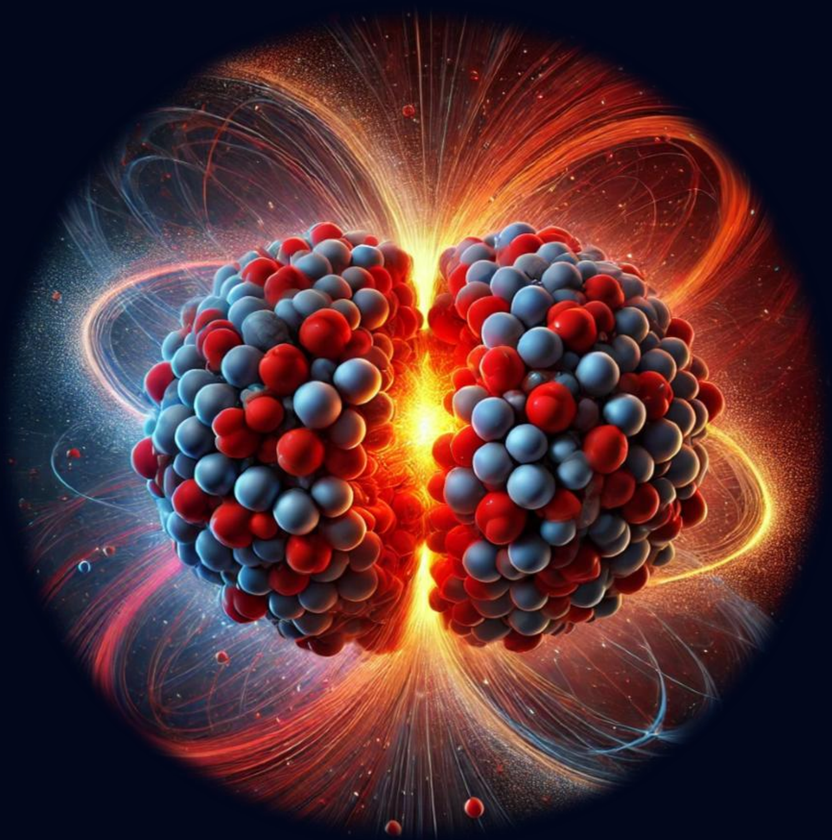
Bottom-up approach to describe groomed jet data in heavy-ion collisions

EQCD 2026, Granada

Diogo Costa (U. Granada)
Alba Soto-Ontoso (U. Granada), Liliana Apolinário (U. Lisboa)

UNIVERSIDAD DE GRANADA
High Energy Theory
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
AGENCIA ESTATAL DE INVESTIGACIÓN

Outline



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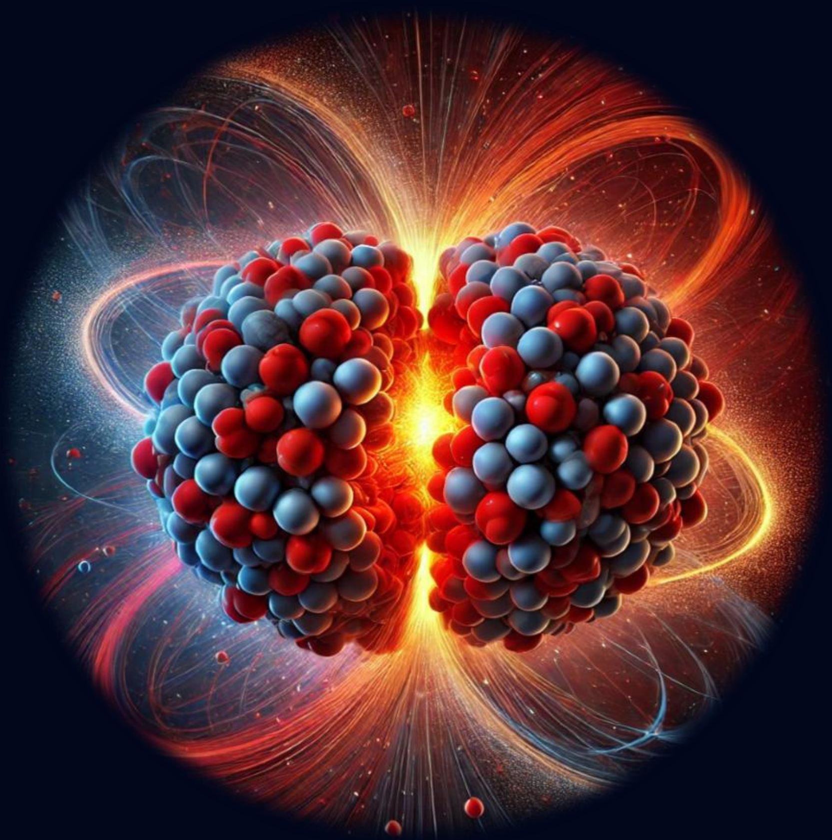

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Nuclear Matter at Extreme Conditions

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Hunt for **fundamental particles & symmetries** in the last century
Discovery of leptons, quarks, bosons… culminated into the **Standard Model**

Meanwhile…
another story unvealing..

What happens when ***nuclear matter*** *is probed at extreme* ***temperatures*** *and* ***densities****?*

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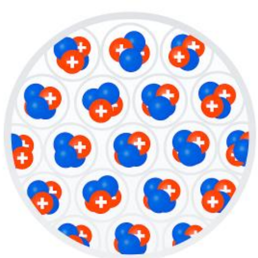
60s (Nuclear)

Thermodynamics
+Nuclear Models

Phase Transition¿?



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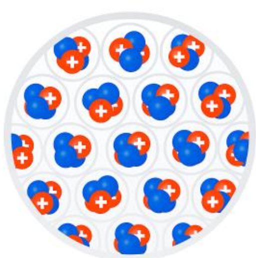

+

70s (Quantum)
Quantum Chromodynamics
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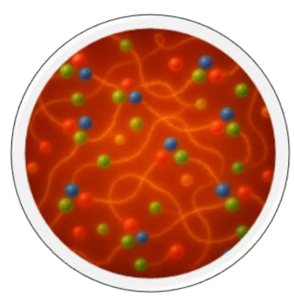

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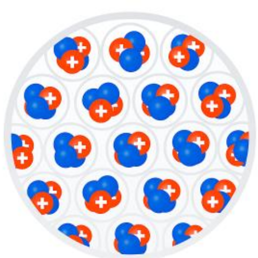

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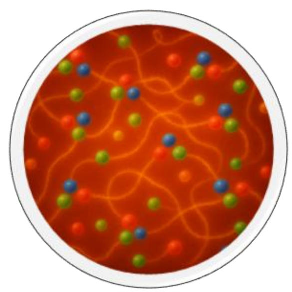
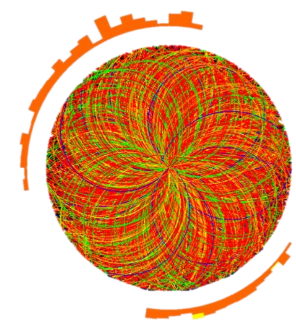


…2000s (Detection)

Ultra-Relativistic Heavy-Ion Collisions



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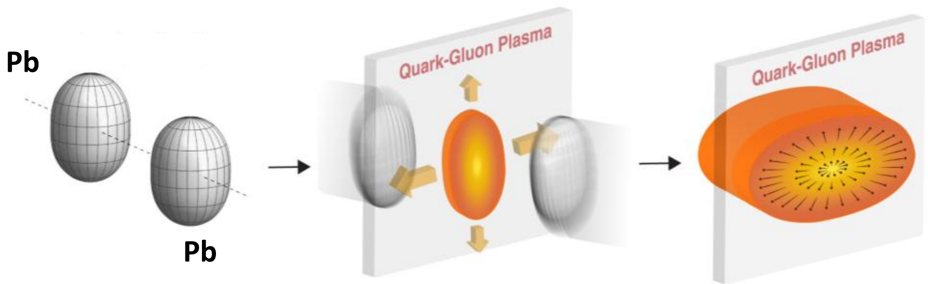
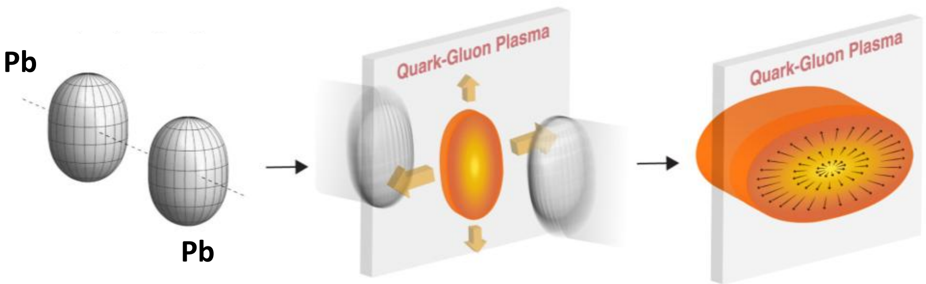


'Smoking guns'

CERN: **Enhancements** of **strange** bound states.

BNL: Azimuthal **asymmetry** in the bulk **hadron distribution.**

HI Collisions



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Properties

Strongly coupled hot fluid

Low viscosity

Short formation time…

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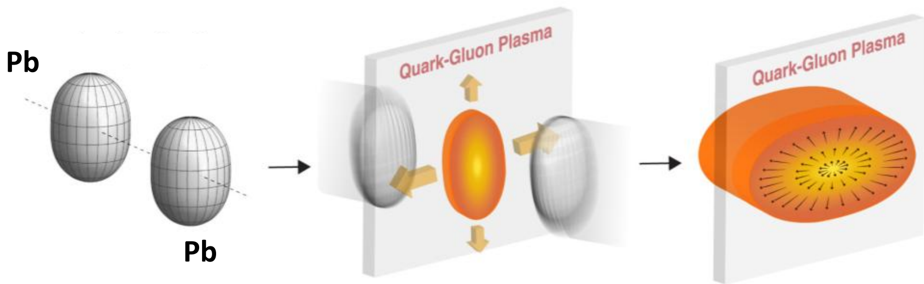

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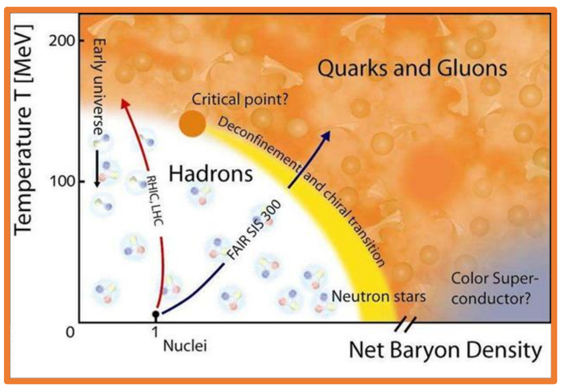


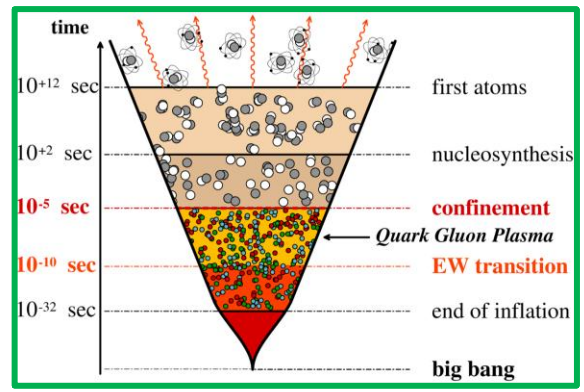
Strongly coupled hot fluid

Low viscosity

Short formation time…

Local assymptotic freedom

Primordial complex matter



Multifield problem

The QGP is characterized by a **rapid evolution** towards thermal equilibrium ($\sim 1\ fm/c$) and freeze-out at around ($\sim 10\ fm/c$)

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⬇

Unfeasible direct QGP measurement !

(Need indirect probes to infer about its properties…)

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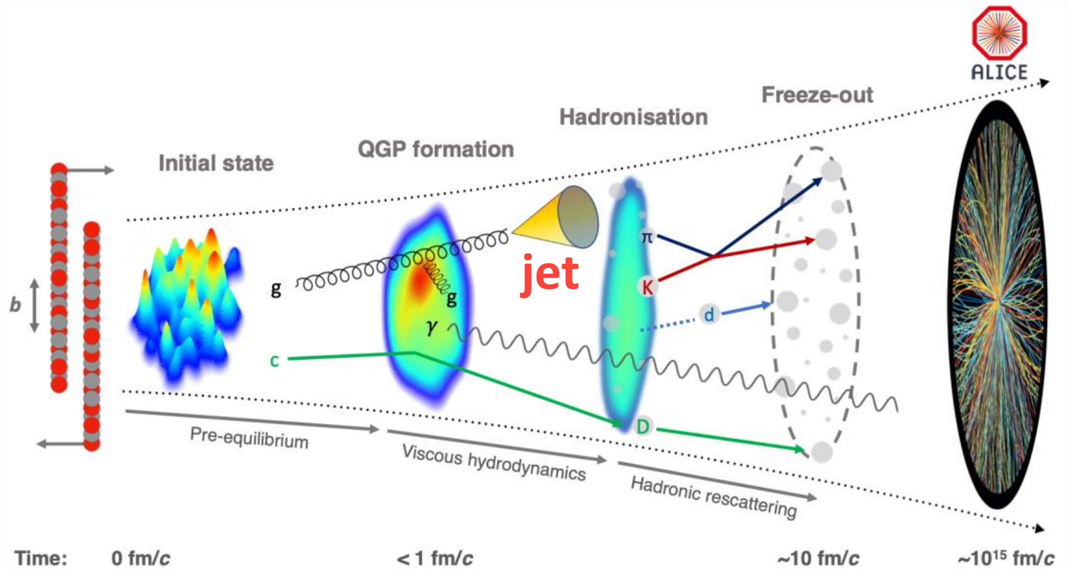

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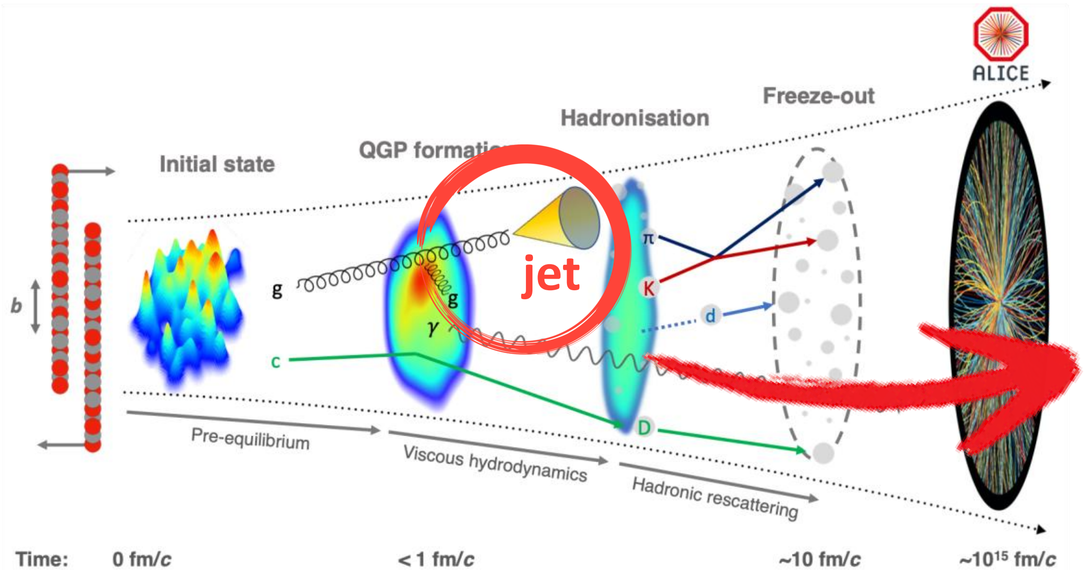

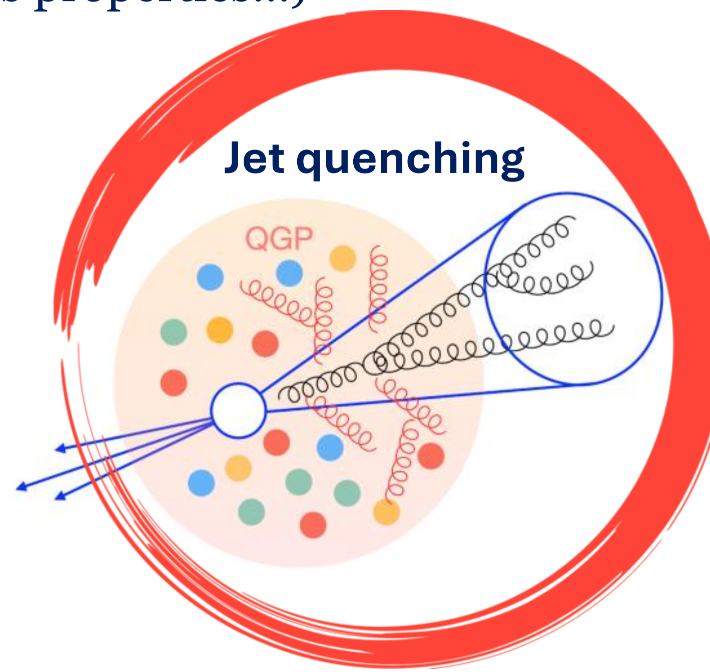

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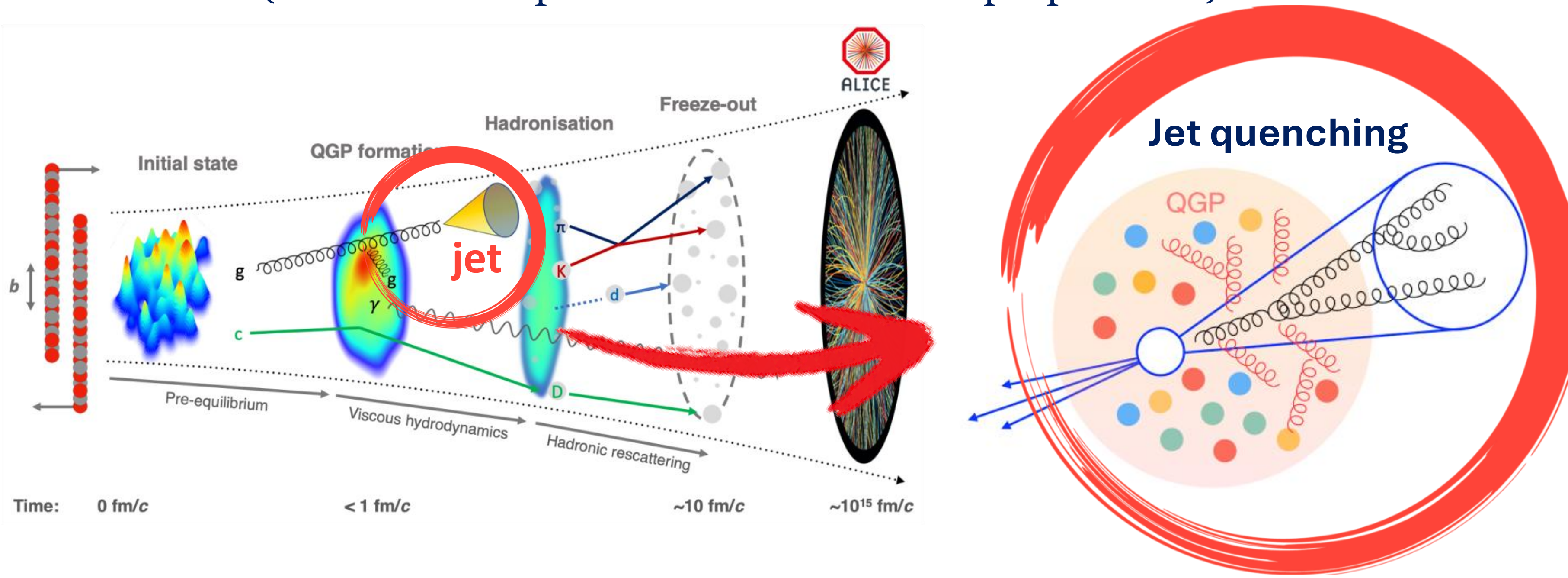
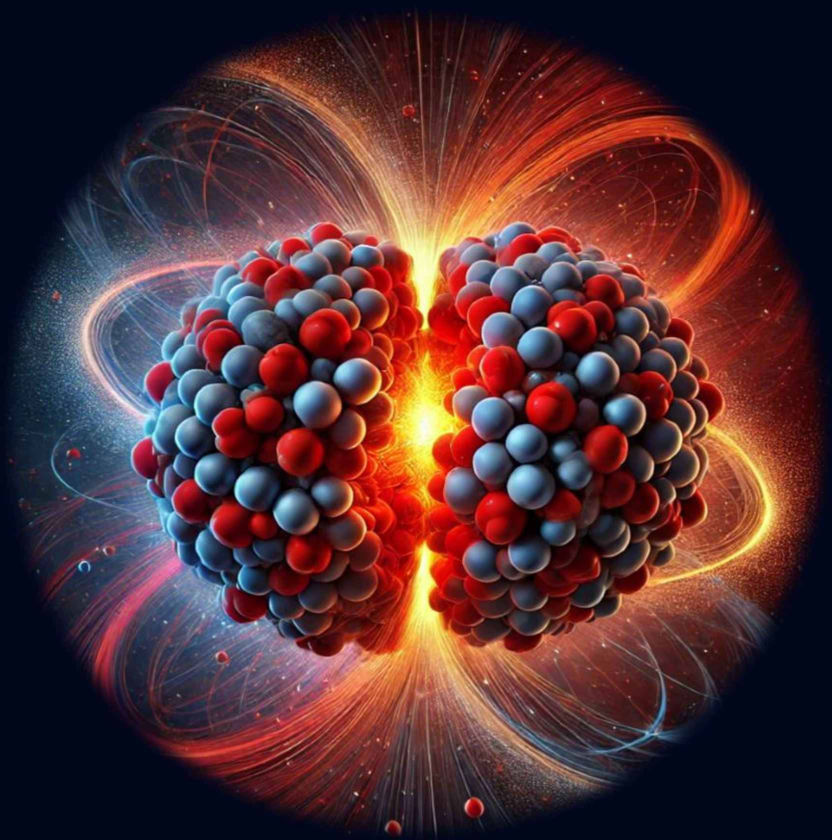


Jets allows to probe the QGP at different scales

Analyzing its substructure allows to probe the QGP dynamics

Outline



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Traversing the QGP

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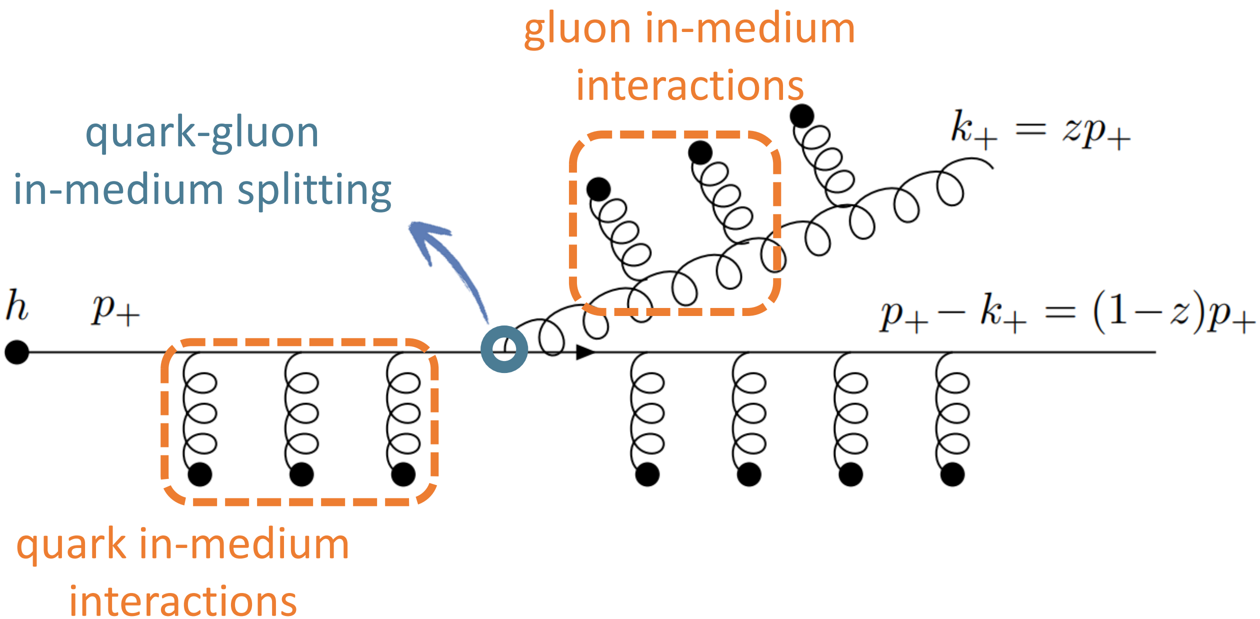
Feynman diagram of one quark interaction vertex



Contributes to:

- Additional (broad) emissions
- Broadening of the emitted particles

Traversing the QGP

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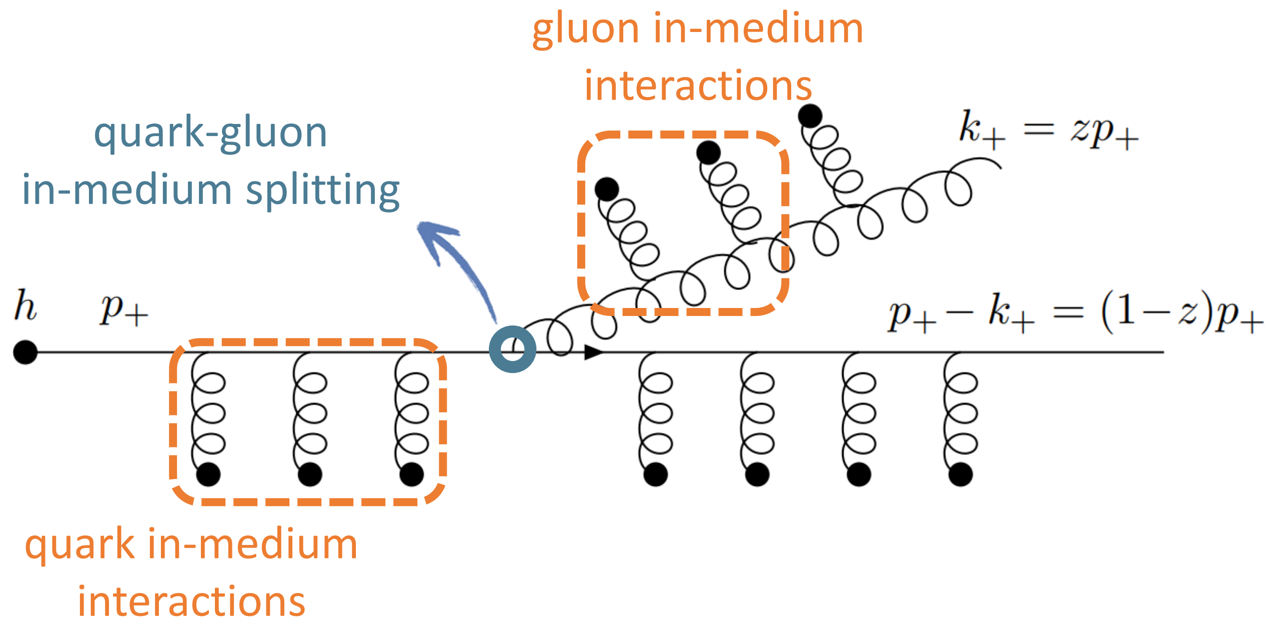

Contributes to:

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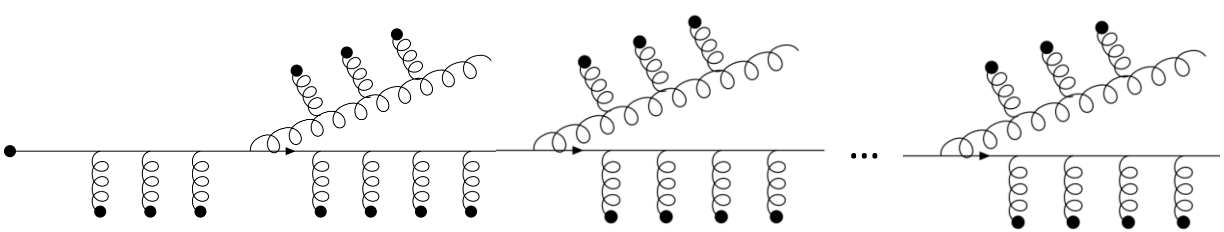
Broadening of the emitted particles

Jet quenching

To obtain an associated partonic Eloss one further performs resummation



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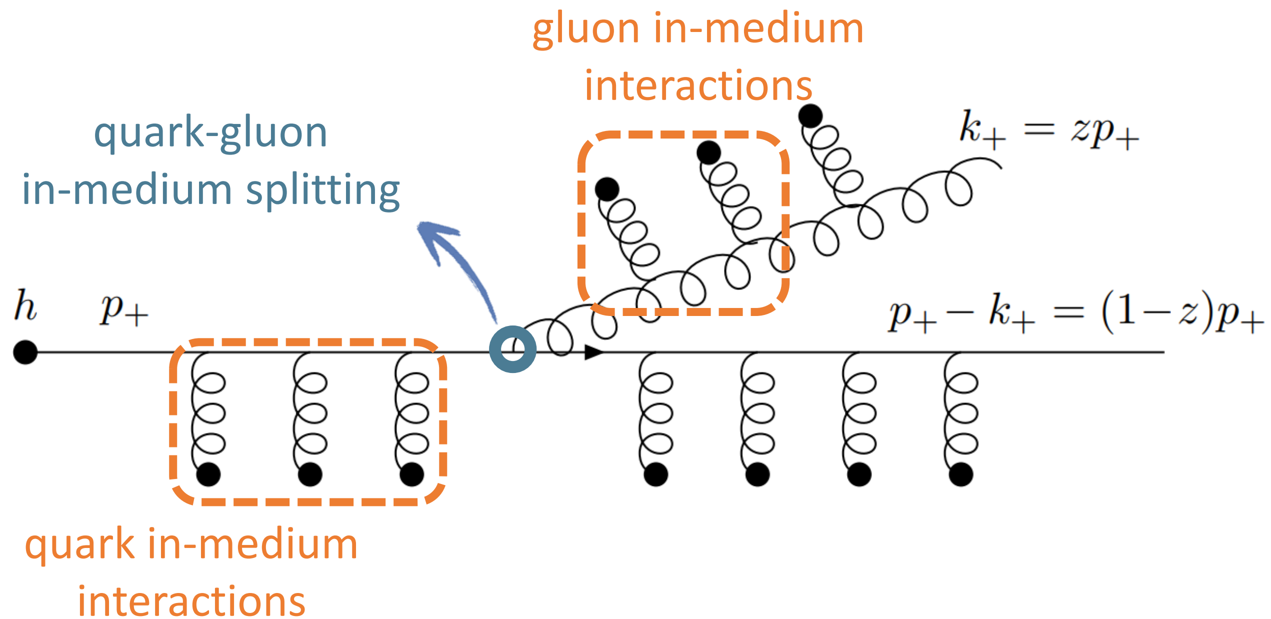

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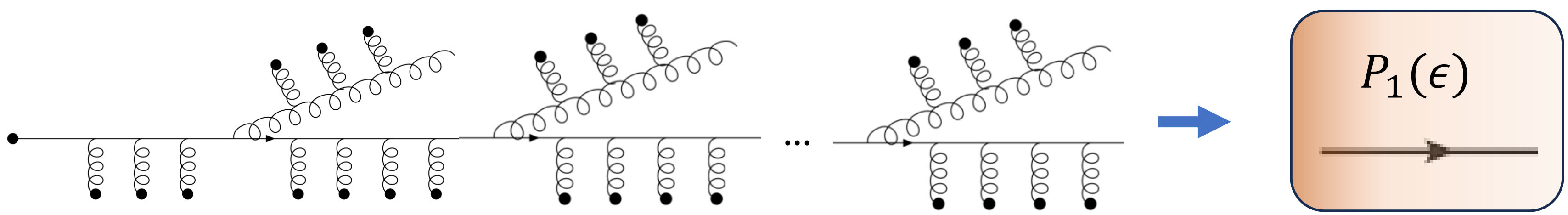
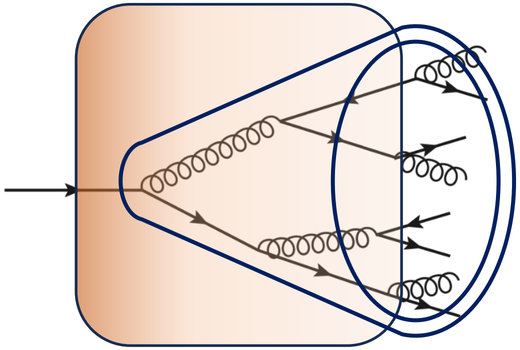


1st Gen. Measurements: Inclusive measurements



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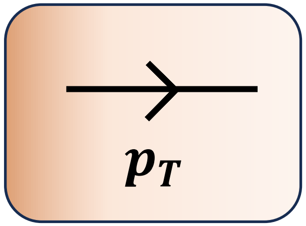

Approach

Jet as a singular structure integrated over all radiation phase-space

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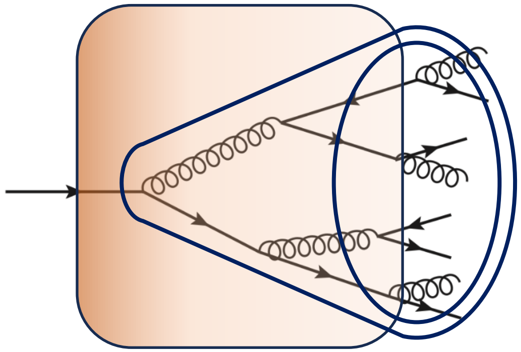

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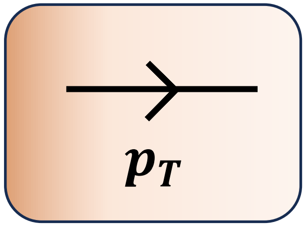

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Experimentally

Jet p_T suppression (RAA)

Jet quenching measurements

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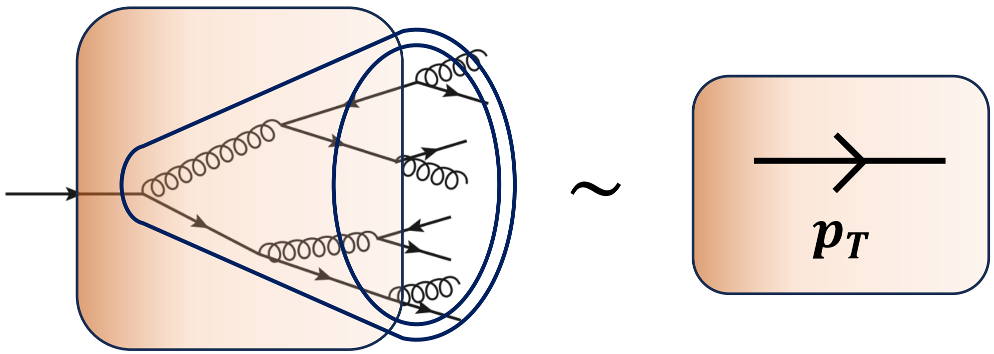

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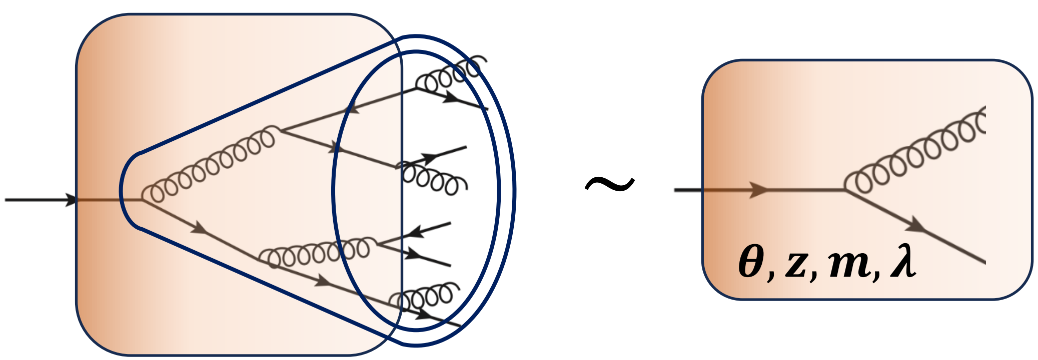
2nd Gen. Measurements Substructure measurements



Approach

Jet as a multi-scale structure, differential on phase-space

Jet quenching measurements

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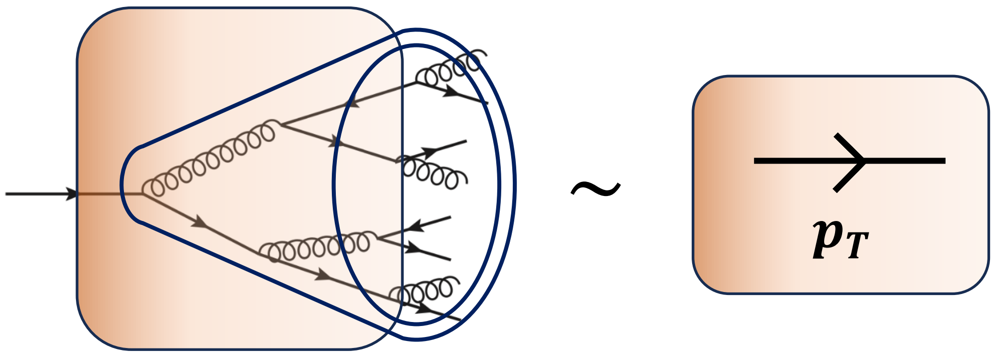
1st Gen. Measurements: Inclusive measurements



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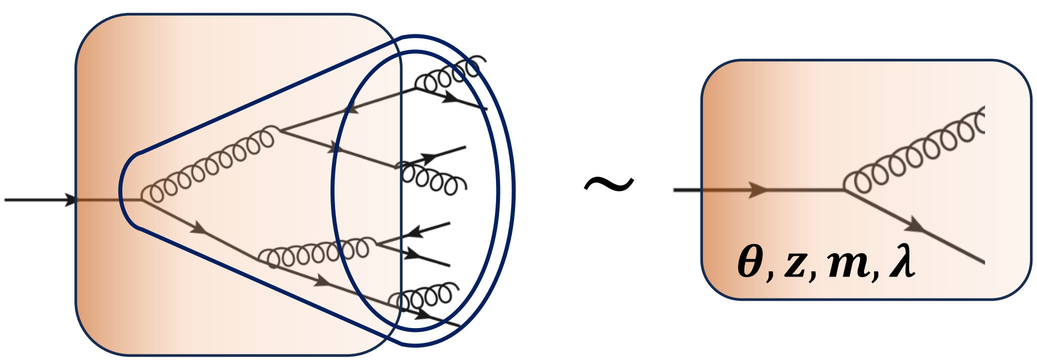

Approach

Jet as a multi-scale structure, differential on phase-space

Experimentally

Collinear enhancement

What's the physical origin?

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Many *competing* effects

qg fraction composition

Modified splitting kernels

Colour coherence

Medium response

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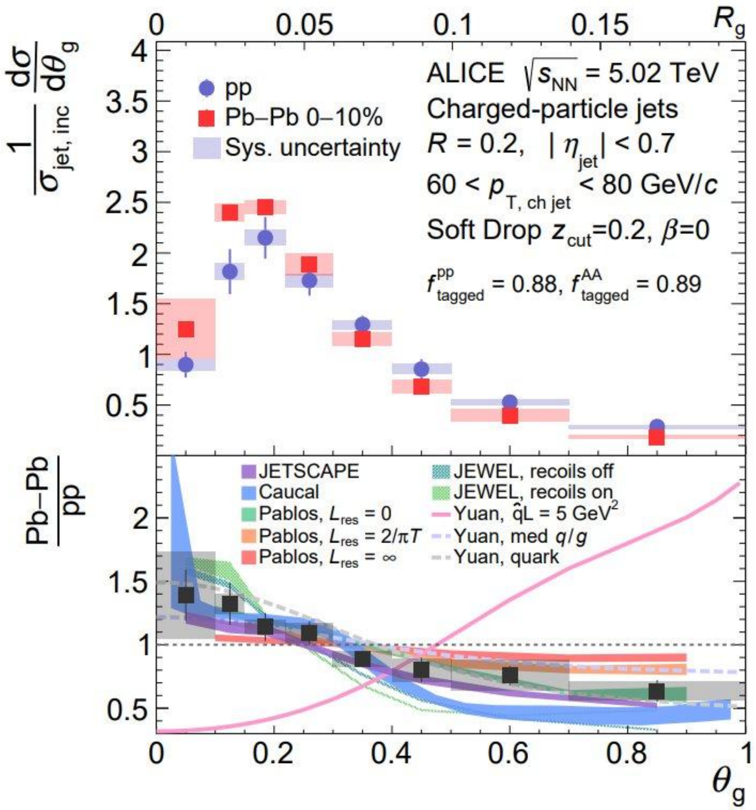
Many *competing* effects

qg fraction composition	Modified splitting kernels
Colour coherence	Medium response

Caveat..

We don't need them all to explain current exp. data!



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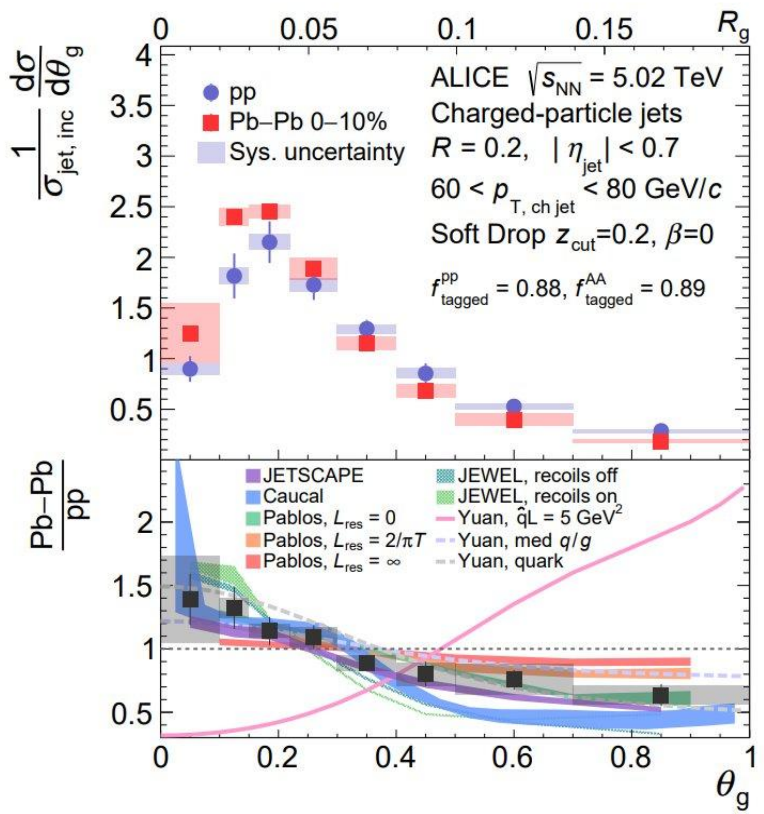

Jet quenching

$$\left[\textbf{HI collisions} \;/\; \textbf{pp collisions} \right]$$

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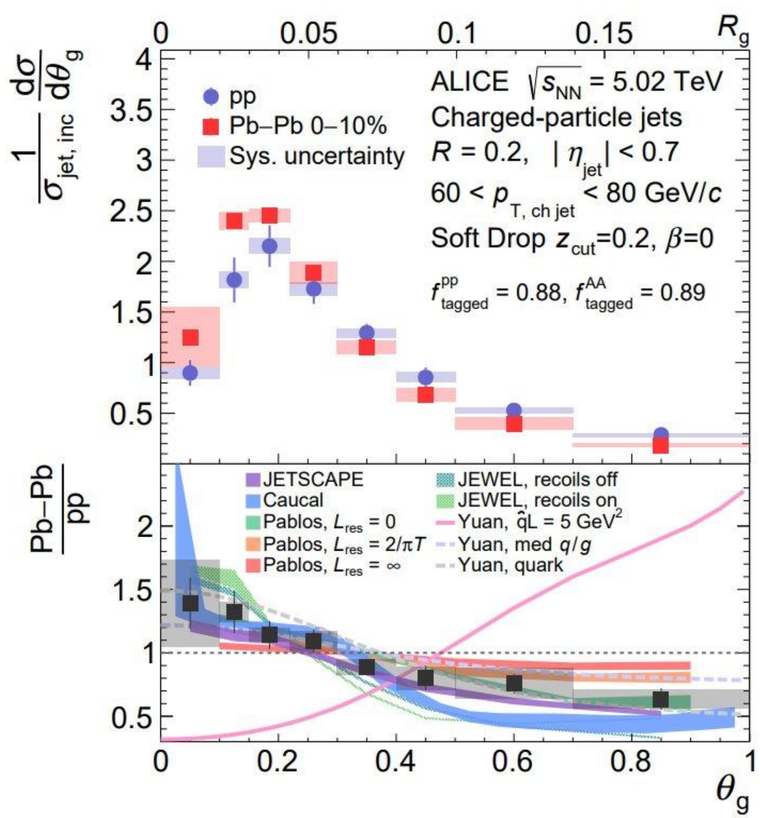


Jet quenching

$$\left[\textbf{HI collisions} \;/\; \boxed{\textbf{pp collisions}} \right]$$

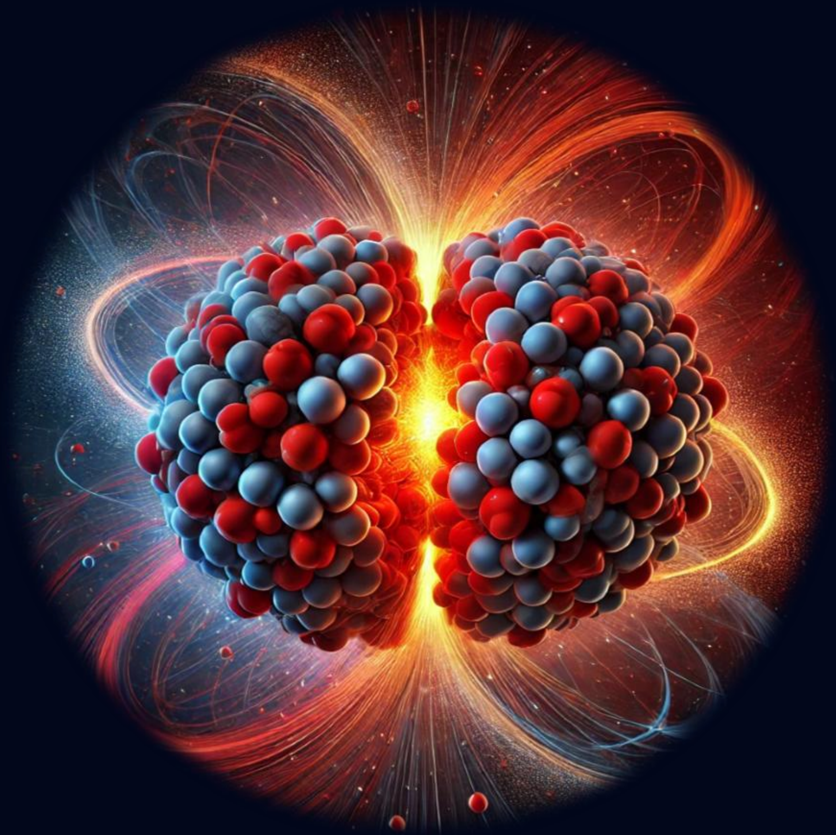
By simply improving the **baseline** we can improve quenching estimations

We computed the baseline at a precision **NLO + LL**

Hard-Scattering

Parton Shower

Outline



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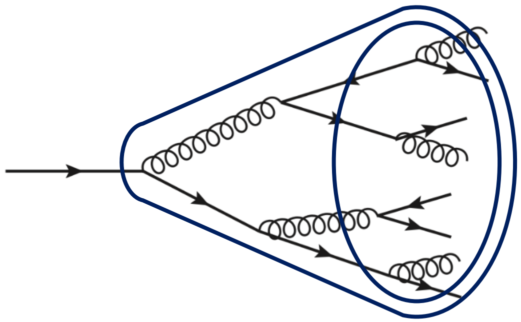
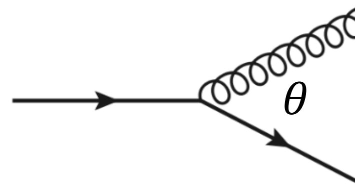
Jet quenching measurements

Bottom-up approach

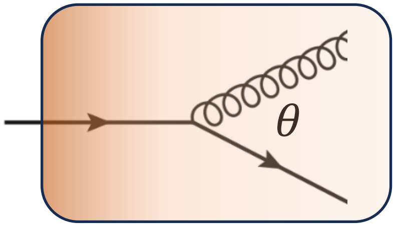
Starting from a NLO+LL baseline, we impose quenching effects a posteriori



(1) Clustering



(2) Grooming



(3) Quenching

Jet quenching measurements

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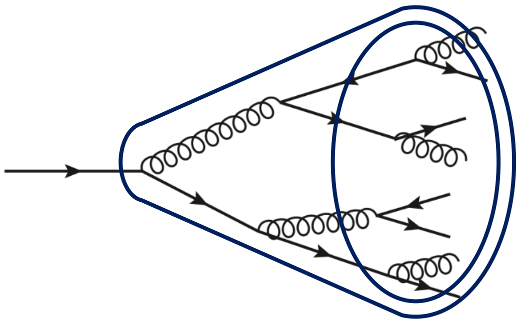

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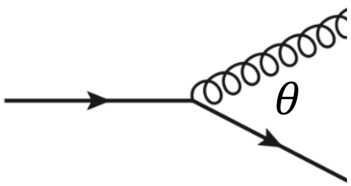

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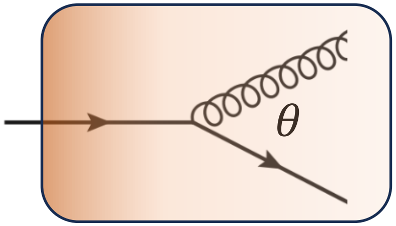


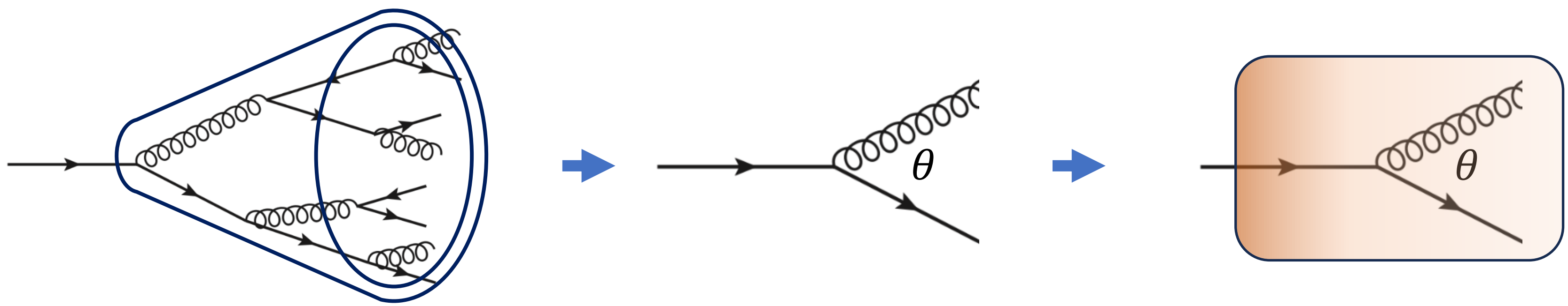
(3) Quenching

The goal is not to develop another state of the art quenching MC, but rather:

- Estimate the impact of NLO corrections
- Inspect the necessity to include **coherence effects** to explain data

Bottom-up approach

Starting from a NLO+LL baseline, we impose quenching effects a posteriori



(1) Clustering **(2) Grooming** **(3) Quenching**

The goal is not to develop another state of the art quenching MC, but rather:

- Estimate the impact of NLO corrections
- Inspect the necessity to include **coherence effects** to explain data

In practice...
Run a series of **theory-to-data comparisons** to **ALICE** and **ATLAS** data.
Note: I will only focus on one of the inspected observables

More in detail

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Baseline precision

Bottom-up approach

Compute the hard-scattering @ NLO

↓

Match exact-NLO with Parton Shower

Powheg-Box

PYTHIA 8

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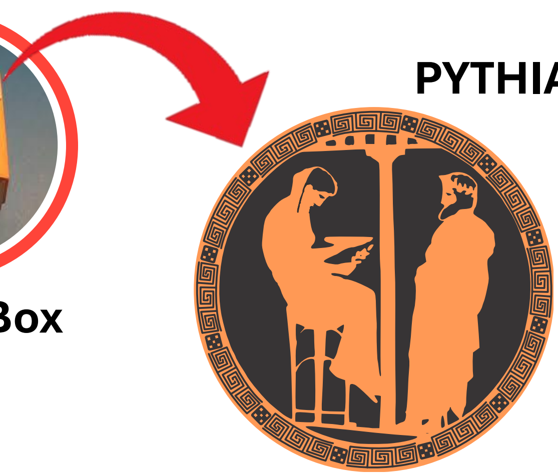
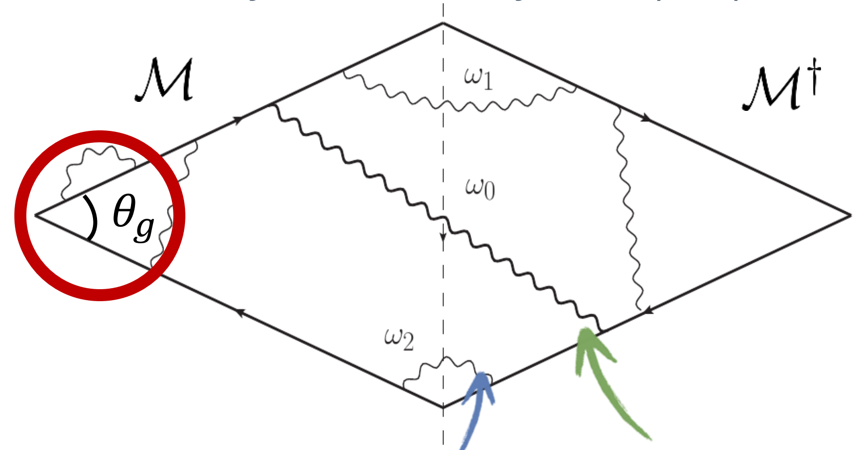


Medium Coherence

Consider interference effects

Y. Mehtar & K. Tywoniuk, Nucl.Phys.A 979 (2018) 165-203



$$P_2(\epsilon, \theta_g) = P_{\rm inc}(\epsilon) - P_{\rm coh}(\epsilon, \theta_g)$$

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Baseline precision

Bottom-up approach

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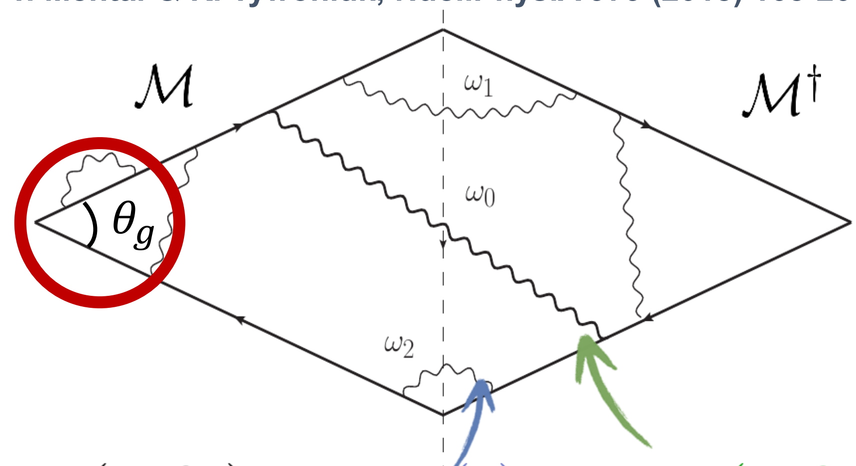

$$P_2(\epsilon, \theta_g) = P_{\rm inc}(\epsilon) - P_{\rm coh}(\epsilon, \theta_g)$$

E-loss sensitive to jet substructure!

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Eloss Models

1-parton Eloss

$$P_1^R(\epsilon) = \sqrt{\frac{2\omega_s^R}{\epsilon^3}} \exp\left[-\frac{2\pi\omega_s^R}{\epsilon}\right]$$

$$\omega_s^R = \frac{\alpha_s^{\mathrm{med}} C_R}{2\pi} \hat{q} L$$

Medium Length

Quenching parameter

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Eloss Models

1-parton Eloss

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$$\omega_s^R = \frac{\alpha_s^{\mathrm{med}} C_R}{2\pi} \hat{q} L$$

Medium Length

Quenching parameter

2-parton Eloss

$$P_2^{\mathrm{R}}(\epsilon) = \int_0^\infty d\epsilon_1 \int_0^\infty d\epsilon_2 P_1^R(\epsilon_1) P_{\mathrm{sing}}(\epsilon_2)\delta(\epsilon - \epsilon_1 - \epsilon_2)$$

$$P_{\mathrm{sing}}(\varepsilon, \theta_{12}, L) = P_1^{\mathrm{A}}(\varepsilon, L) - \int_0^L dt\, P_1^{\mathrm{A}}(\varepsilon, L - t) F(\varepsilon, L - t)\left[1 - \Delta_{\mathrm{med}}(t, \theta_{12})\right]$$

Quenching Model overview

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Eloss Models

1-parton Eloss

$$P_1^R(\epsilon) = \sqrt{\frac{2\omega_s^R}{\epsilon^3}} \exp\left[-\frac{2\pi\omega_s^R}{\epsilon}\right]$$

$$\omega_s^R = \frac{\alpha_s^{\mathrm{med}} C_R}{2\pi} \hat{q} L$$

Medium Length

Quenching parameter

2-parton Eloss

$$P_2^{\mathrm{R}}(\epsilon) = \int_0^\infty d\epsilon_1 \int_0^\infty d\epsilon_2 P_1^R(\epsilon_1) P_{\mathrm{sing}}(\epsilon_2) \delta(\epsilon - \epsilon_1 - \epsilon_2)$$

$$P_{\mathrm{sing}}(\varepsilon, \theta_{12}, L) = P_1^{\mathrm{A}}(\varepsilon, L) - \int_0^L dt\, P_1^{\mathrm{A}}(\varepsilon, L-t) F(\varepsilon, L-t) \left[1 - \Delta_{\mathrm{med}}(t, \theta_{12})\right]$$

$\Delta_{\mathrm{med}}(t) = 1 - \exp\left[-\theta_{12}/\theta_c(\hat{q}, L)\right]$ ~ ***Probability*** to resolve the Antenna

Critical Angle

Quenching Model overview

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Eloss Models

1-parton Eloss

$$P_1^R(\epsilon) = \sqrt{\frac{2\omega_s^R}{\epsilon^3}} \exp\left[-\frac{2\pi\omega_s^R}{\epsilon}\right]$$

$$\omega_s^R = \frac{\alpha_s^{\mathrm{med}} C_R}{2\pi} \hat{q} L$$

Medium Length

Quenching parameter

2-parton Eloss

$$P_2^{\mathrm{R}}(\epsilon) = \int_0^\infty d\epsilon_1 \int_0^\infty d\epsilon_2 P_1^R(\epsilon_1) P_{\mathrm{sing}}(\epsilon_2) \delta(\epsilon - \epsilon_1 - \epsilon_2)$$

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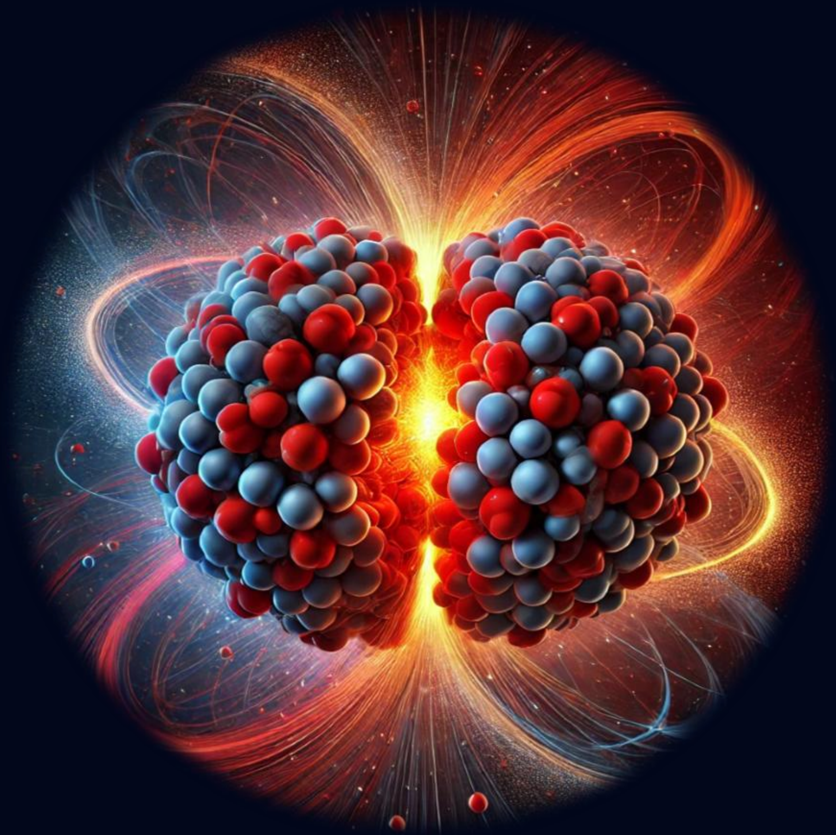
$\Delta_{\mathrm{med}}(t) = 1 - \exp\left[-\theta_{12}/\theta_c(\hat{q}, L)\right]$ ~ ***Probability*** to resolve the Antenna

Critical Angle

By comparing P_1 with P_2 results, one can estimate the size of coherence effects in an unbiased manner

Outline



1. QGP
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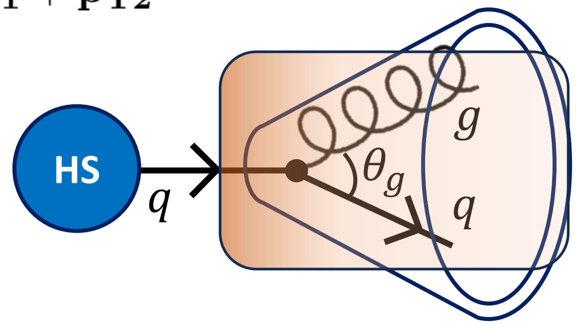
A Simple Exercise

As a first step one can compute the quenching modifications for an exact-NLO fixed-order dijet setup

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut}$$



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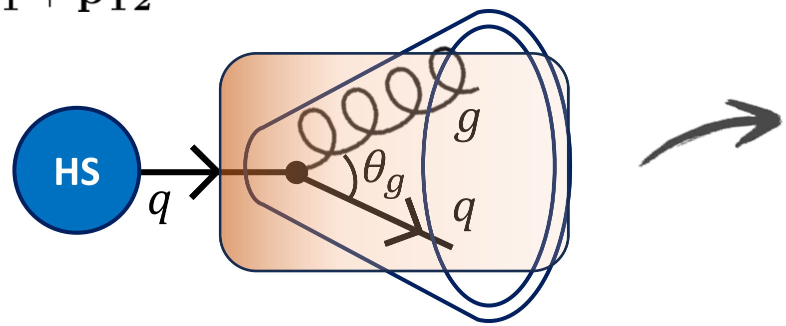
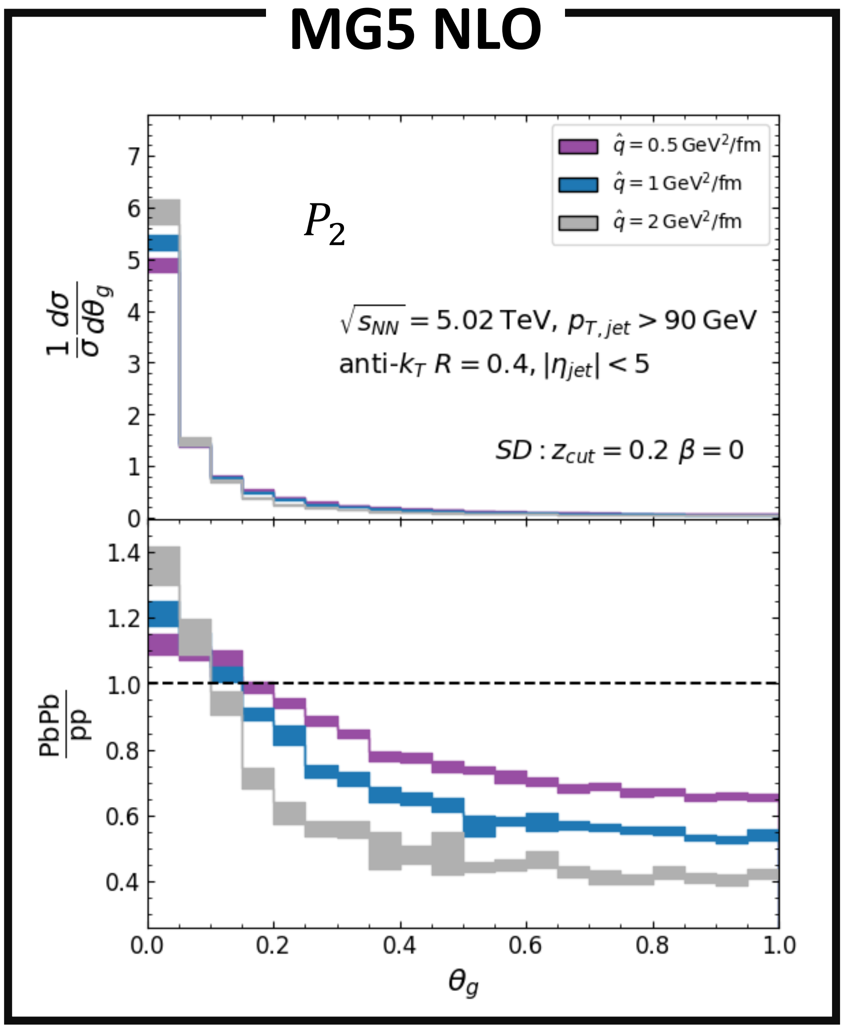


The results already show the narrowing trend observed in exp. data



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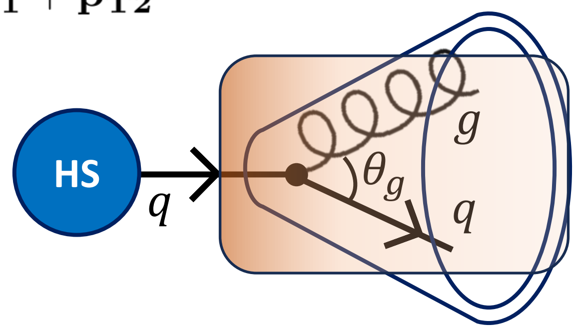

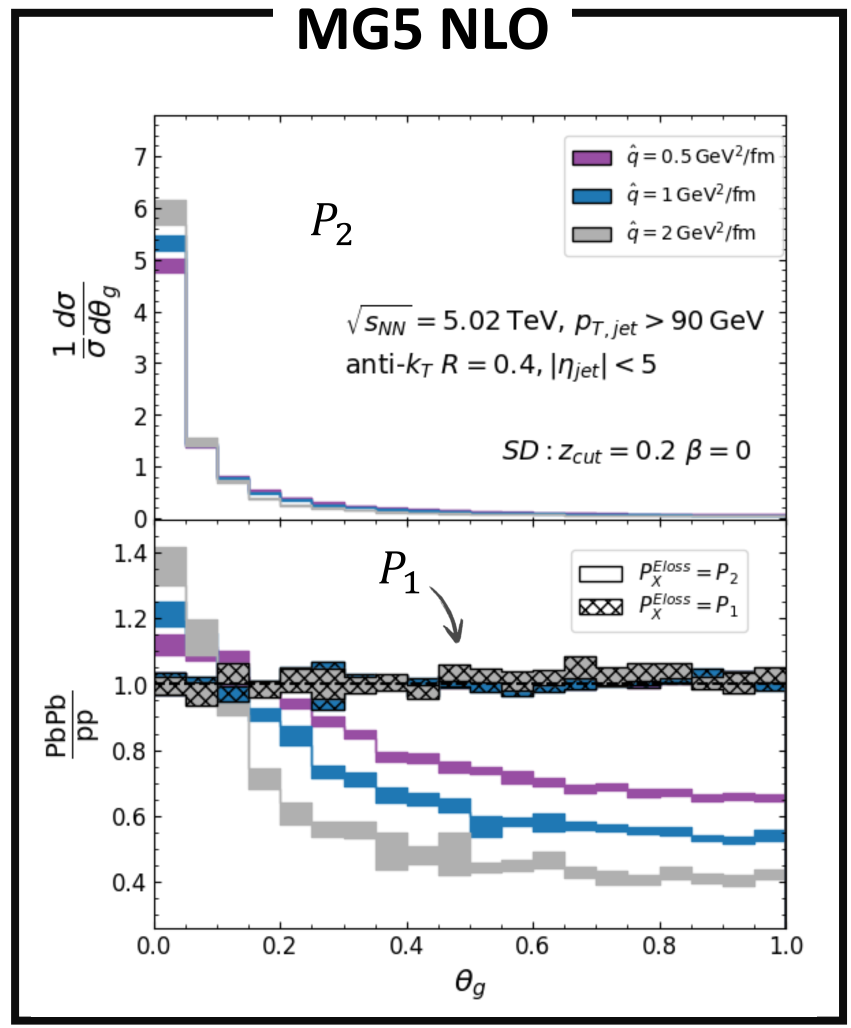

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But...

When using just P_1 (no coherence) there are no θ_g modifications...

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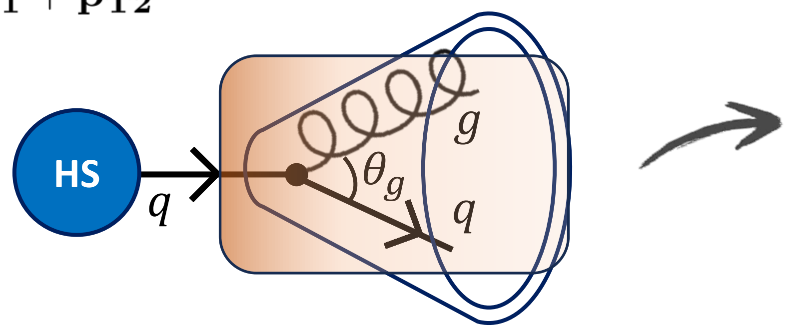
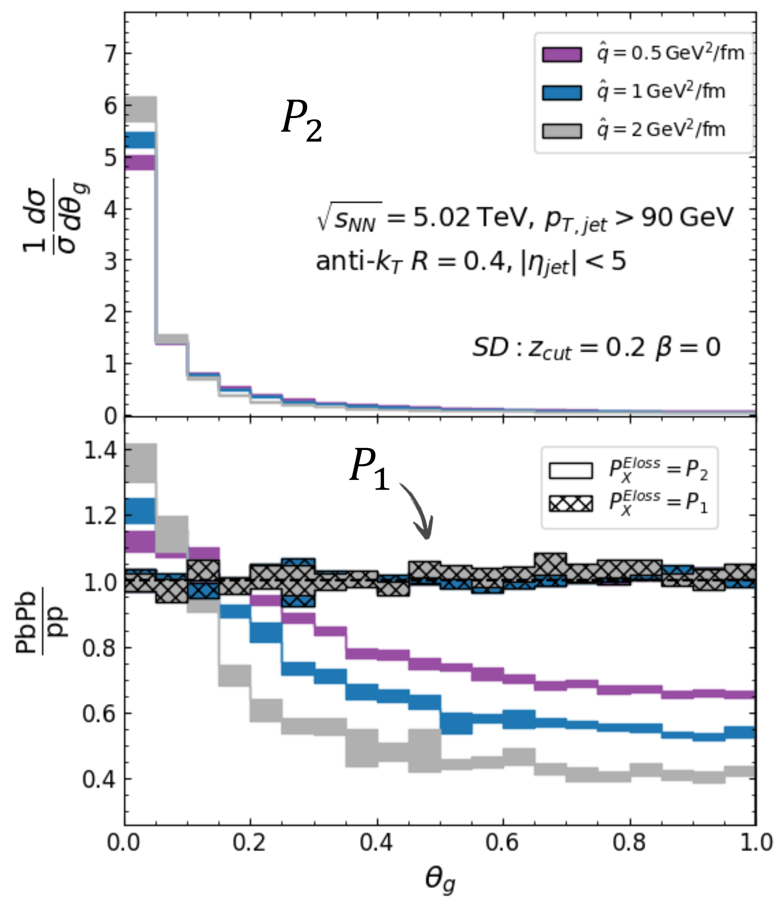


MG5 NLO



The results already show the narrowing trend observed in exp. data

But...

When using just P_1 (no coherence) there are no θ_g modifications...

Naively one expects: Coherence Effects + **qg selection bias**

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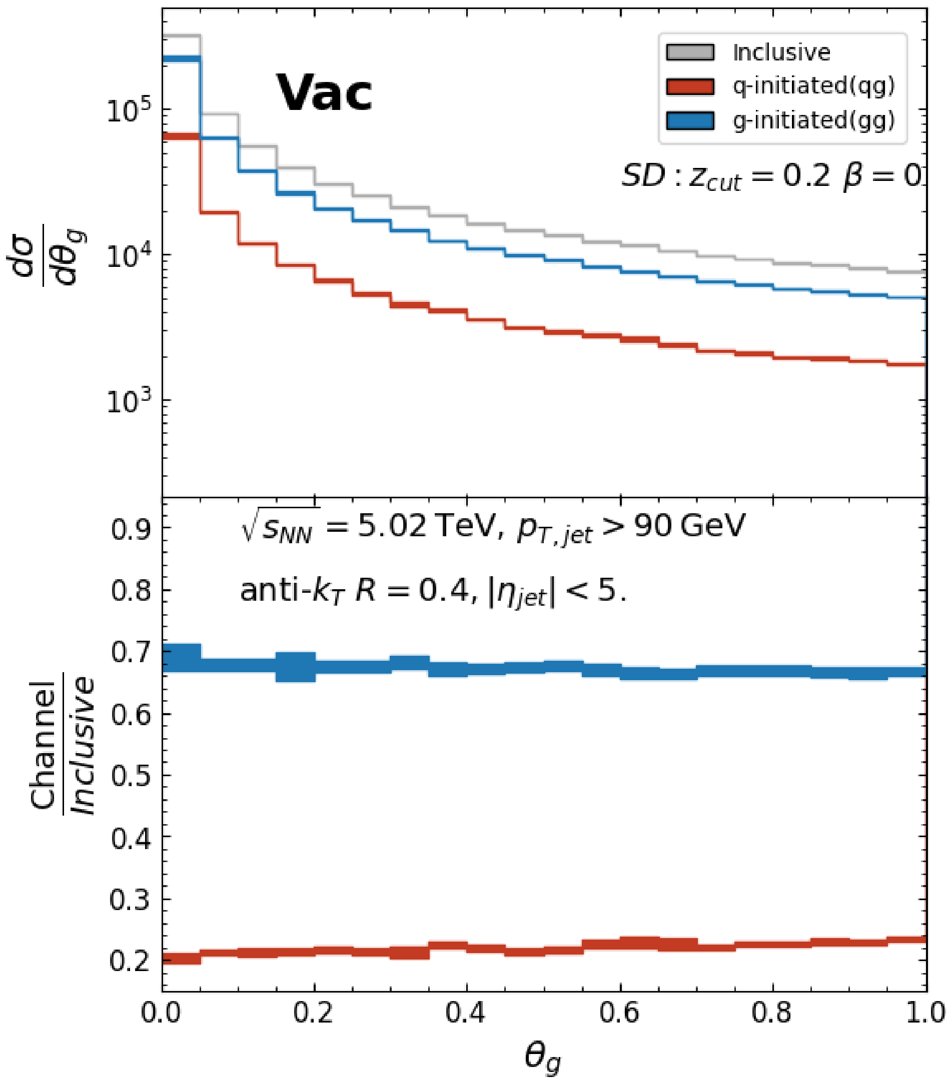
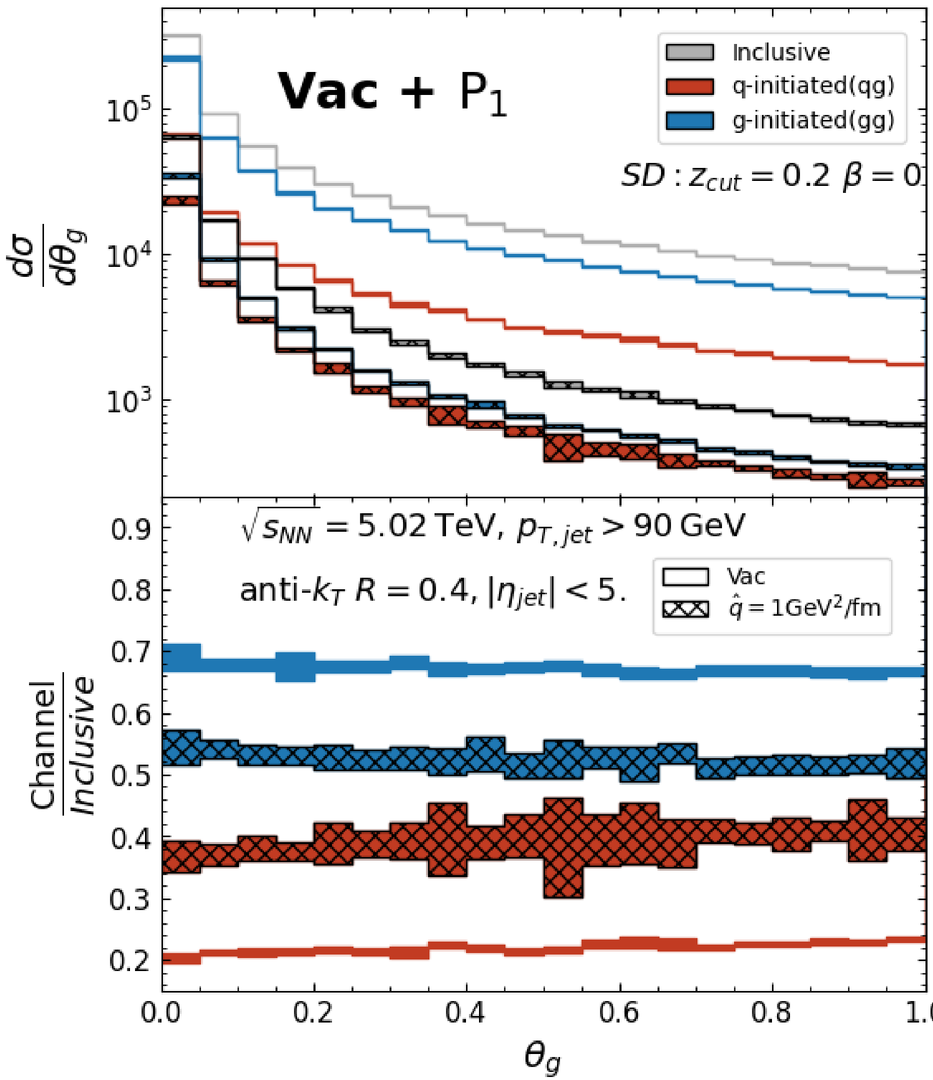


Vacuum

- Gluon dominated sample
- Almost no qg composition dependence on the phase-space

On the qg fraction selection bias



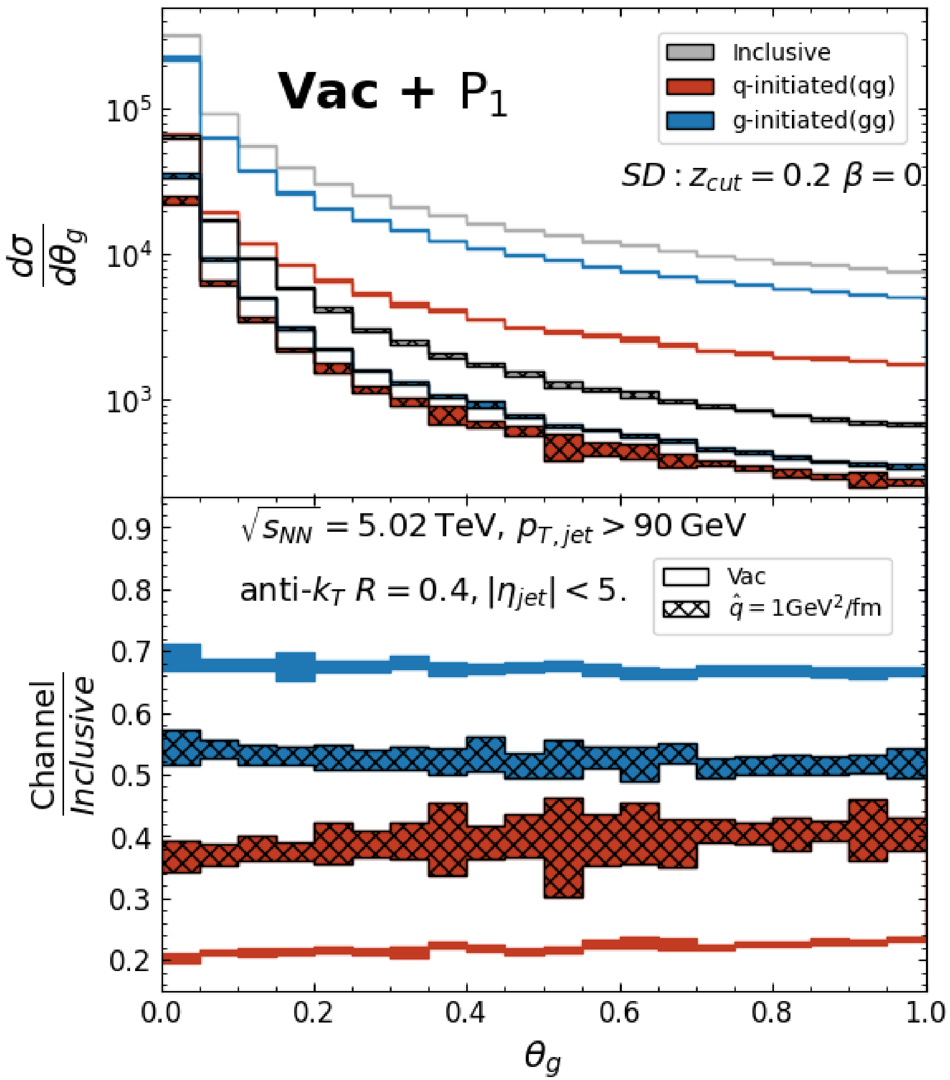
Vacuum

- ❑ Gluon dominated sample
- ❑ Almost no qg composition dependence on the phase-space

Medium

- ❑ Still almost constant qg fraction as a function of θ_g.
- ❑ As expected one obtains less g-jets in the final state

On the qg fraction selection bias



Vacuum

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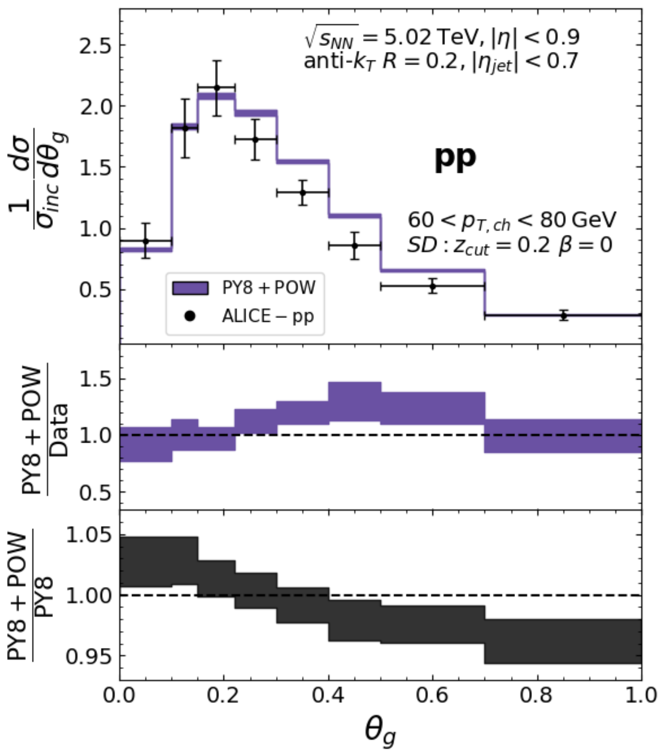
Medium

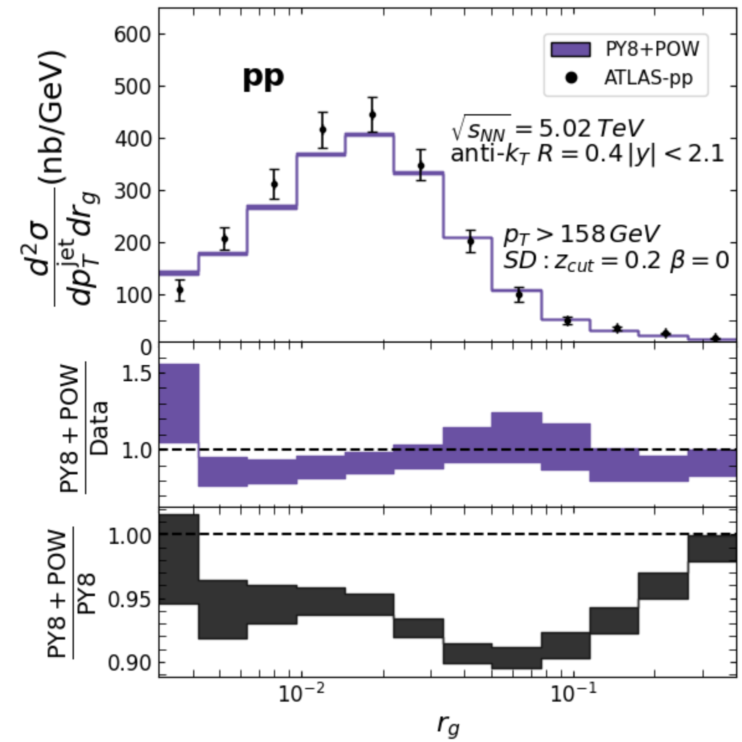
- ❑ Still almost constant qg fraction as a function of θ_g.
- ❑ As expected one obtains less g-jets in the final state

There is no apparent dependence on the initiator parton (q or g)

No qg selection bias effect is present in these conditions !

Vacuum baseline





Overall agreement with data for both baselines

NLO corrections correspond to 5-10% modification

PbPb - ALICE

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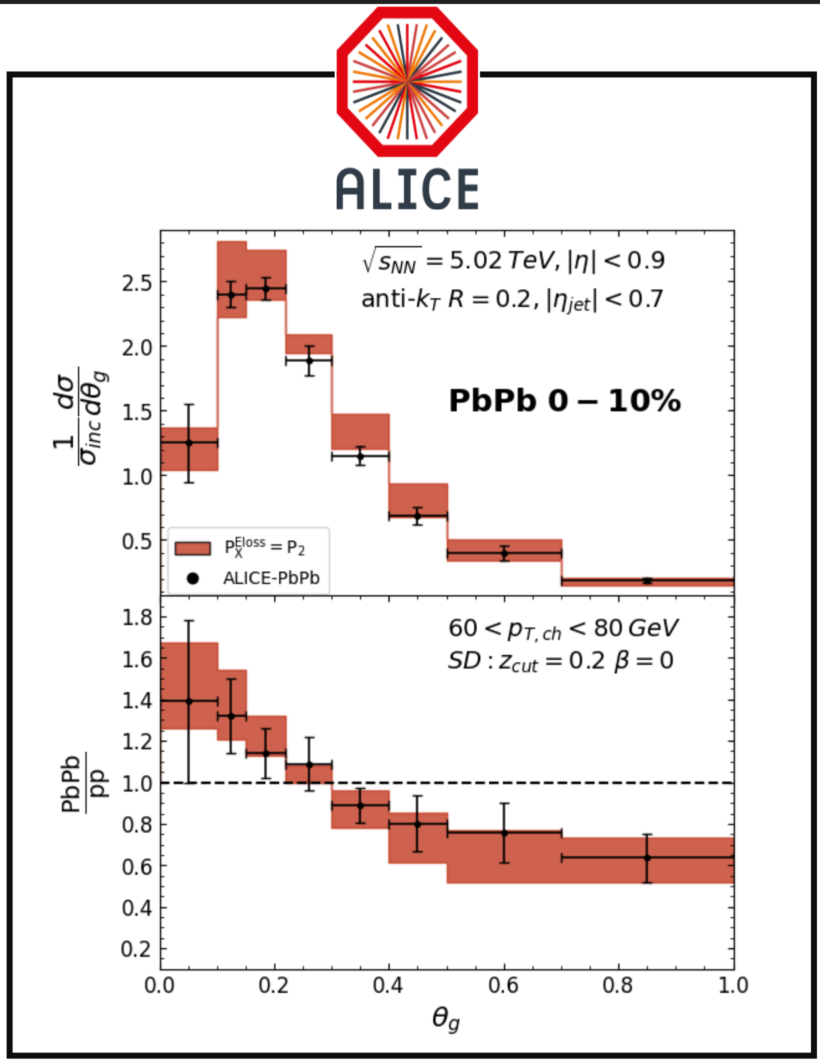
P_2

Overall success in describing the experimental data

Smaller theoretical uncertainties



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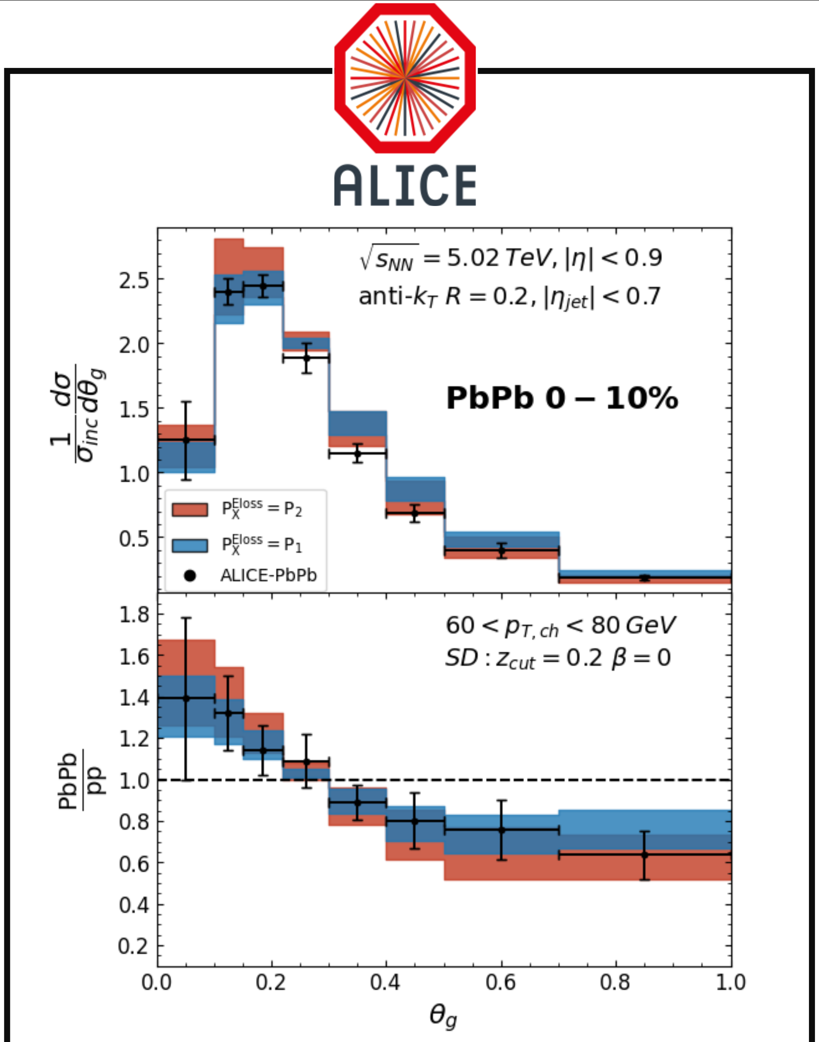

P_1

P1 model yields a flatter PbPb ratio

Still overall agreement with data

Overall agreement for both models

Difficult to conclude coherence for current exp. uncertainty..

PbPb - ATLAS

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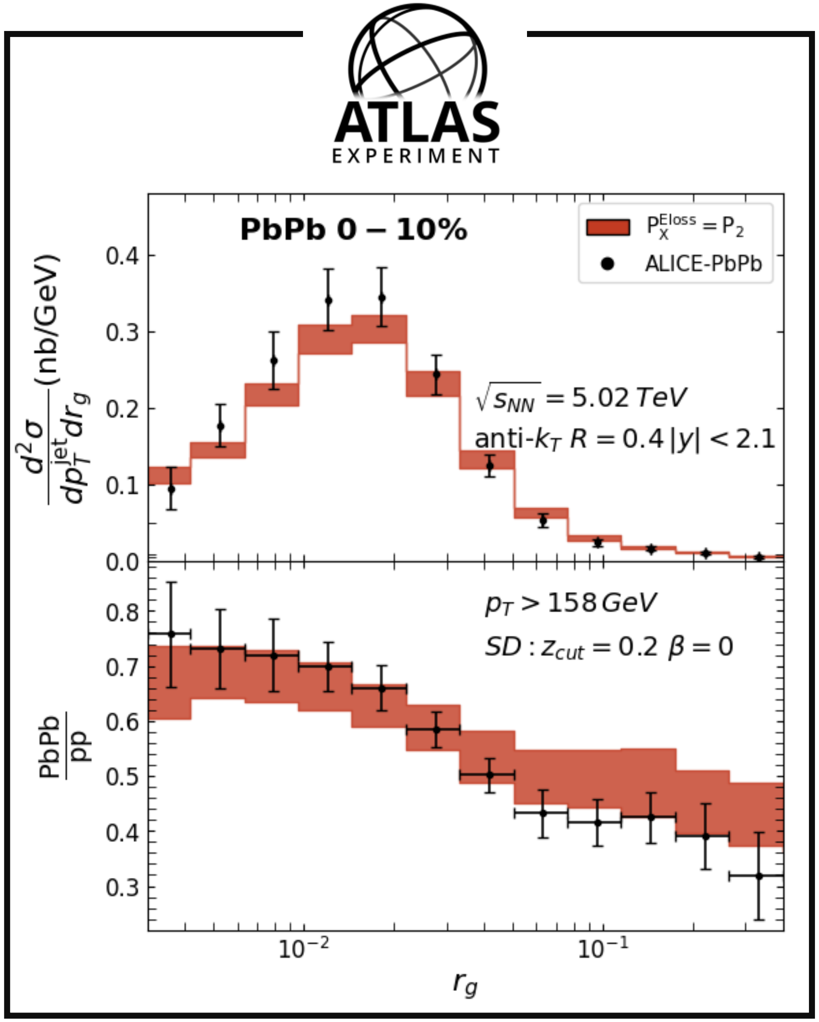

P_2

Overall success in describing the experimental data

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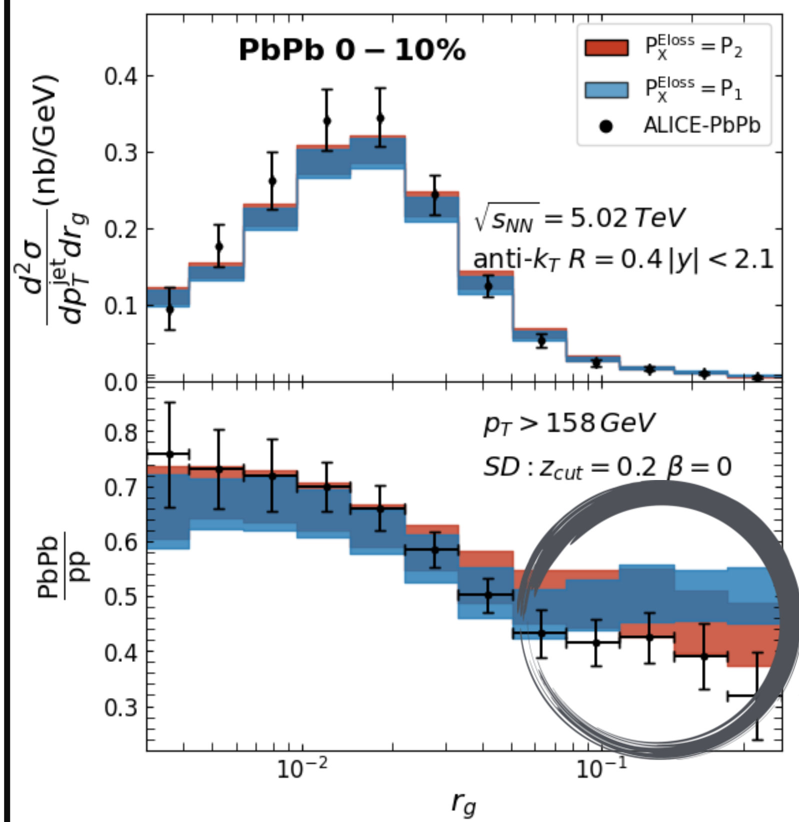
ATLAS EXPERIMENT

P_2

Overall success in describing the experimental data

Smaller theoretical uncertainties



P_1

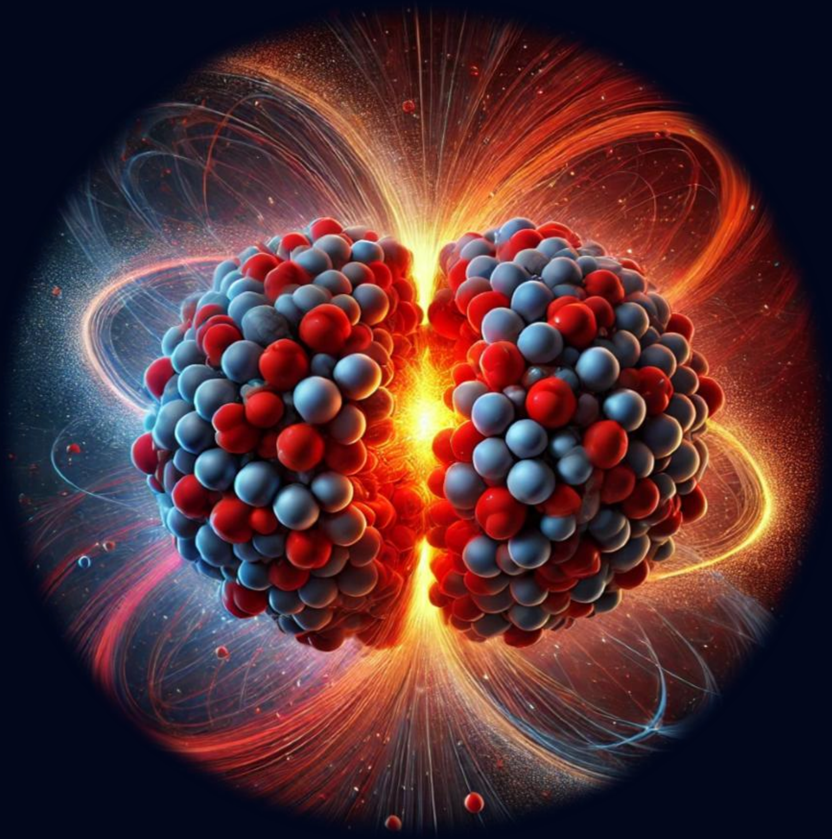
P1 model yields a flatter PbPb ratio

There is now a disagreement for higher rg

Same observable for different kinematics..

Result now shows an agreement towards coherence

Outline



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Conclusions

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NLO corrections improve the theory-to-data agreement and contribute up to 10%

Overall in-medium agreement for the $\boldsymbol{P_2}$ **model** with a **deviation** of up to 10% for the $\boldsymbol{P_1}$ **model**, **dependent on the kinematics.**

Conclusions

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Altogether… current **experimental uncertainties** pose a challenge.

Conclusions

NLO corrections improve the theory-to-data agreement and contribute up to 10%

Overall in-medium agreement for the P_2 **model** with a **deviation** of up to 10% for the P_1 **model, dependent on the kinematics.**

Altogether… current **experimental uncertainties** pose a challenge.

Some good news…

Upcoming LHC experimental update: High-Luminosity Phase

Future QGP measurements with unprecedent precision levels

Necessary to keep up current theoretical models!

Bottom-up approach to describe groomed jet data in heavy-ion collisions

EQCD 2026, Granada

Diogo Costa

Alba Soto-Ontoso, Universidad de Granada
Liliana Apolinário, Universidade de Lisboa

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High Energy Theory

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

AGENCIA ESTATAL DE INVESTIGACIÓN

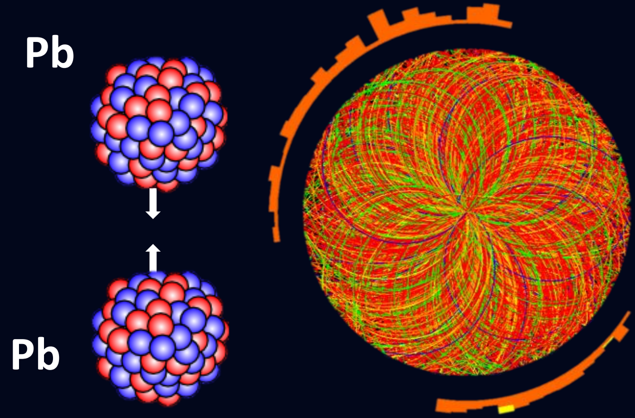
Hot Hadronic Matter (A Poetic Summary)

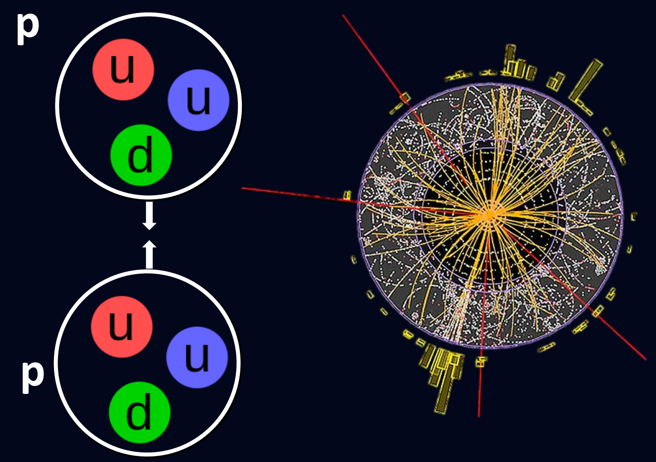
In days of old
a tale was told
of hadrons ever fatter.
Behold, my friends, said Hagedorn,
the ultimate of matter.

Then Muster Mark
called in the quarks,
to hadrons they were mated.
Of colors three, and never free,
all to confinement fated.

But in dense matter,
their bonds can shatter
and they can freely move around.
Above TH , their colors shine,
as the QGP is found.

Said Hagedorn,
when quarks were born
they had different advances.
Today they form, as we can see,
a gas of all their chances.





Backup Slides

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FTAE High Energy Theory

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ATLAS pp

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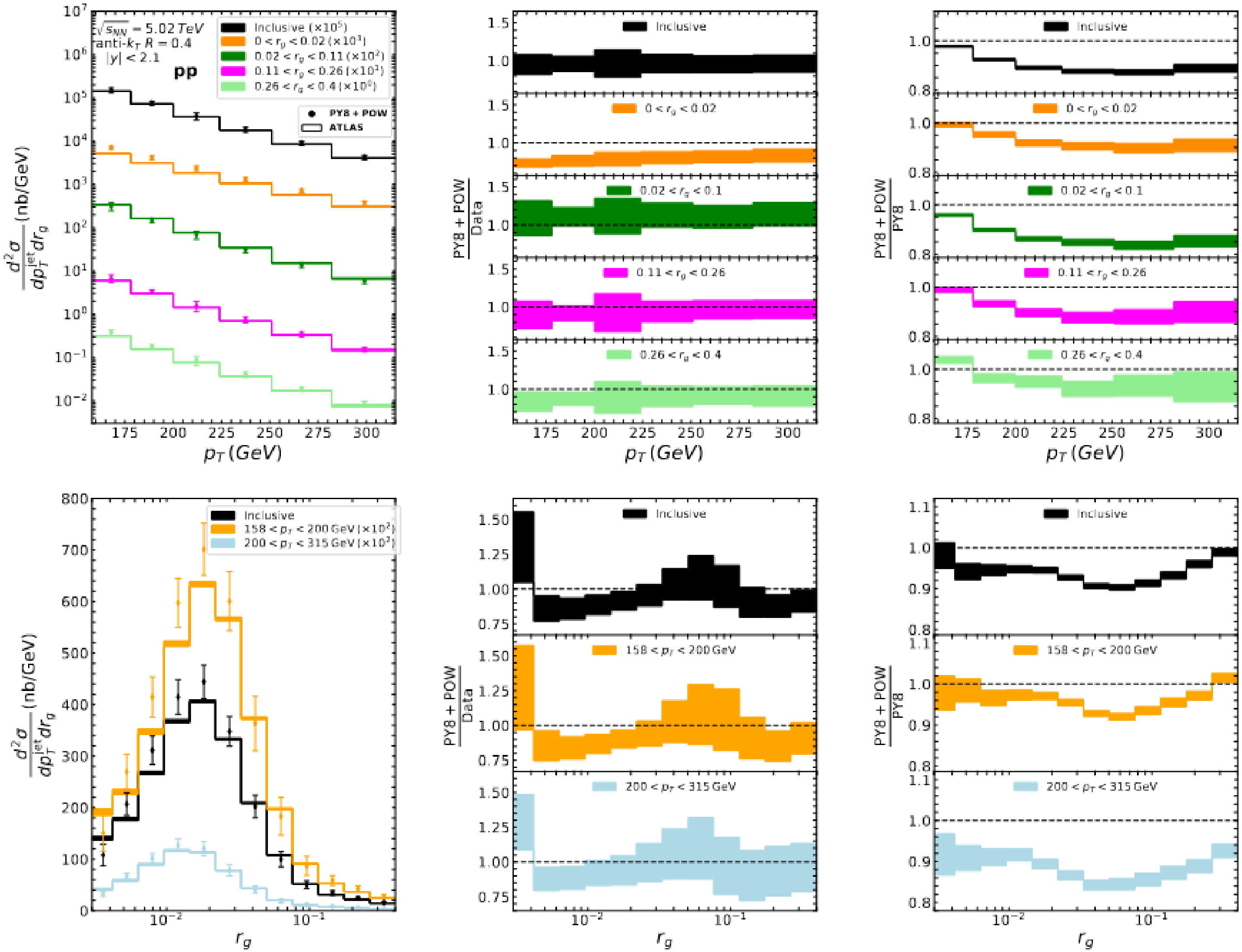
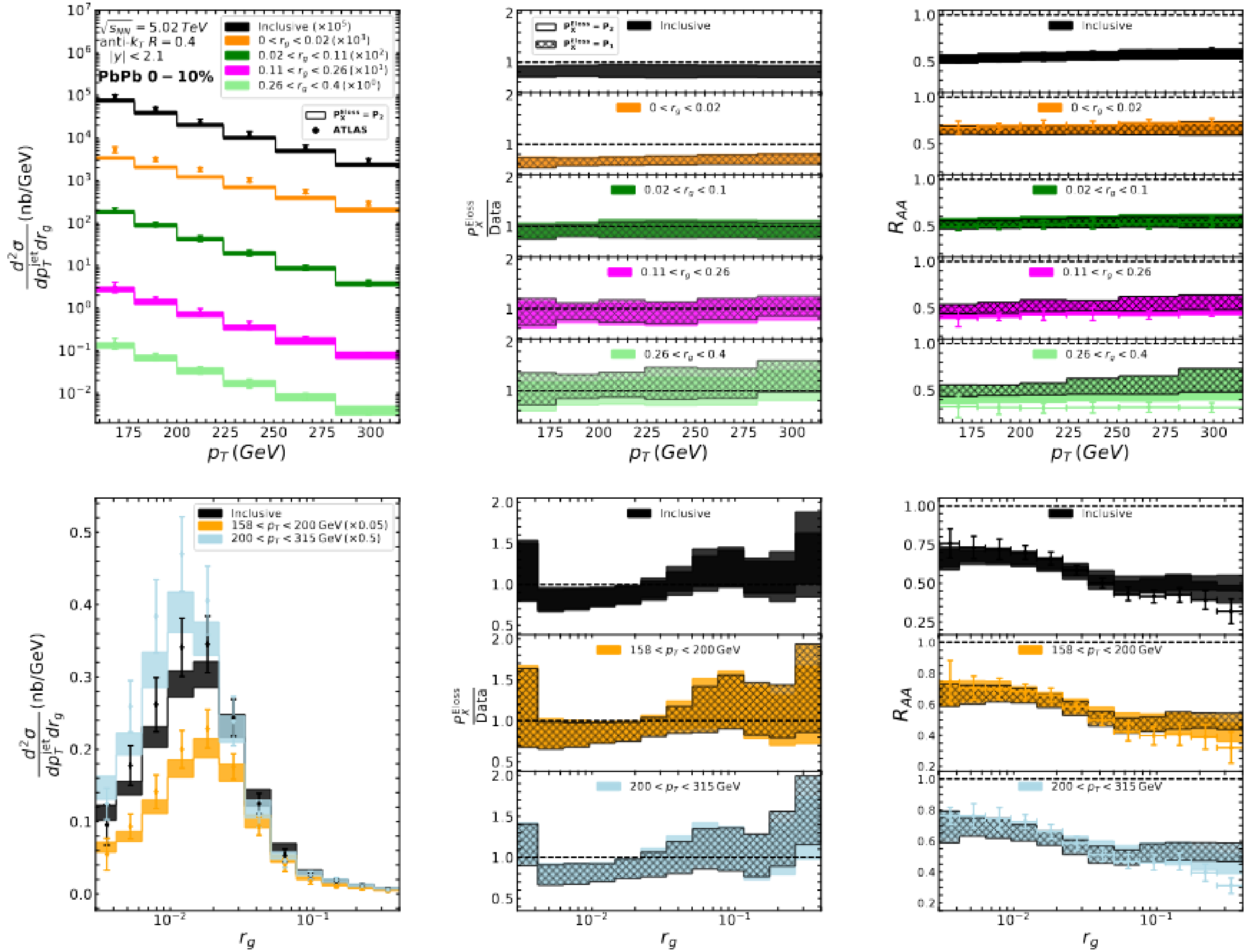
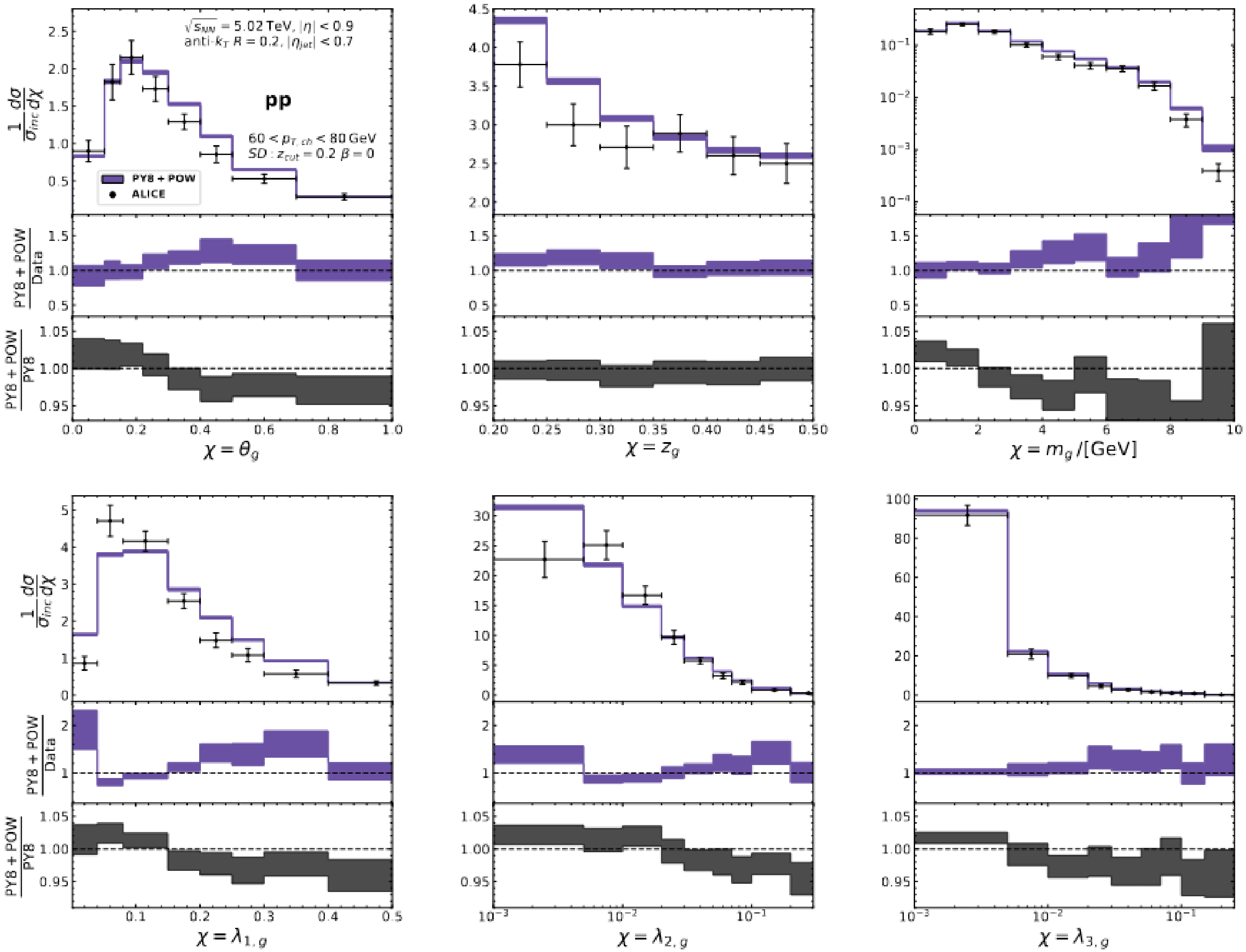


ATLAS PbPb

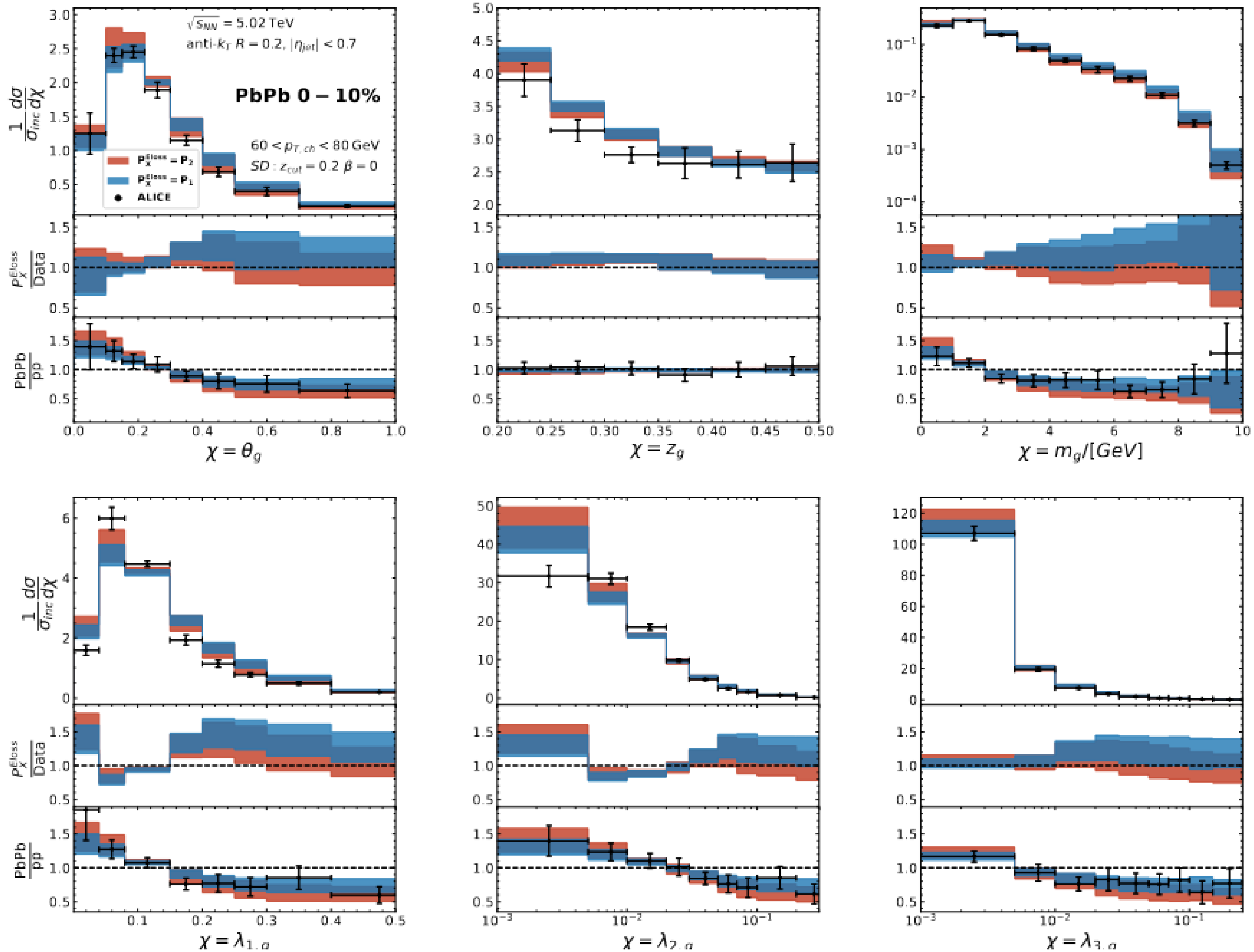


$\sqrt{s_{NN}} = 5.02$ TeV
anti-k_T $R = 0.4$
$|y| < 2.1$
PbPb 0 − 10%
Inclusive ($\times 10^5$)
$0 < r_g < 0.02$ ($\times 10^3$)
$0.02 < r_g < 0.11$ ($\times 10^2$)
$0.11 < r_g < 0.26$ ($\times 10^1$)
$0.26 < r_g < 0.4$ ($\times 10^0$)
$P_x^{\rm Eloss} = P_2$
$P_x^{\rm Eloss} = P_1$
ATLAS
$\frac{d^2\sigma}{dp_T^{\rm jet} dr_g}$ (nb/GeV)
$\frac{P_x^{\rm Eloss}}{\rm Data}$
R_{AA}
p_T (GeV)
Inclusive
$0 < r_g < 0.02$
$0.02 < r_g < 0.1$
$0.11 < r_g < 0.26$
$0.26 < r_g < 0.4$
$158 < p_T < 200$ GeV ($\times 0.05$)
$200 < p_T < 315$ GeV ($\times 0.5$)
$158 < p_T < 200$ GeV
$200 < p_T < 315$ GeV
r_g

ALICE pp


$\sqrt{s_{NN}} = 5.02$ TeV, $|\eta| < 0.9$
anti-k_T $R = 0.2$, $|\eta_{jet}| < 0.7$
pp
$60 < p_{T,ch} < 80$ GeV
$SD : z_{cut} = 0.2$ $\beta = 0$
PY8 + POW
ALICE
$\frac{1}{\sigma_{inc}} \frac{d\sigma}{d\chi}$
$\frac{PY8 + POW}{Data}$
$\frac{PY8 + POW}{PY8}$
$\chi = \theta_g$
$\chi = z_g$
$\chi = m_g / [\mathrm{GeV}]$
$\chi = \lambda_{1,g}$
$\chi = \lambda_{2,g}$
$\chi = \lambda_{3,g}$

ALICE PbPb



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ALICE
$\frac{1}{\sigma_{inc}}\frac{d\sigma}{d\chi}$
$\frac{P_X^{Eloss}}{Data}$
$\frac{PbPb}{pp}$
$\chi = \theta_g$
$\chi = z_g$
$\chi = m_g/[GeV]$
$\chi = \lambda_{1,g}$
$\chi = \lambda_{2,g}$
$\chi = \lambda_{3,g}$

Baseline corrections to in-medium params

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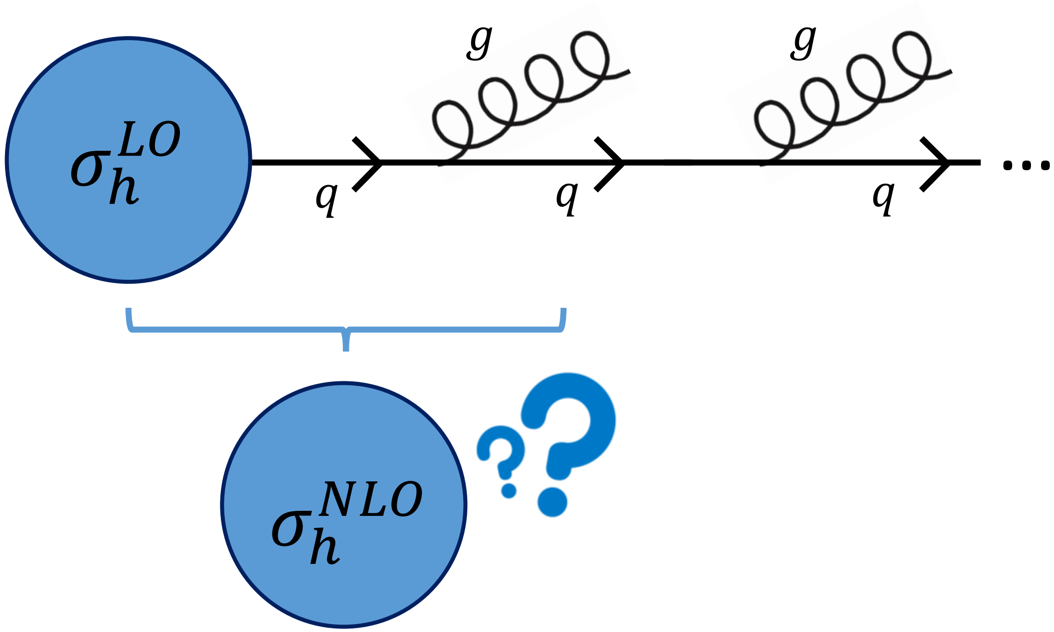
Different baselines give us different quenching parameter estimation

Dataset	$\hat{q}$ [GeV^2/fm]	$\delta\hat{q}_{\mathrm{vac}}$	$\delta\hat{q}_{\mathrm{E-loss}}$
ALICE	$[0.13, 0.40]$	$[20\%, 19\%]$	$[77\%, 125\%]$
ATLAS	$[0.18, 0.28]$	$[14\%, 27\%]$	$[94\%, 96\%]$

$$\delta\hat{q}_x = 100\left(\frac{\hat{q}_x}{\hat{q}} - 1\right)$$

Matching



Double counting of the radiation phase-space …

Need mechanism to remove/compensate the overlaping phase-space.

MADGRAPH

$$d\sigma^{\mathrm{NLO}}_{\mathrm{MC@NLO}} \sim d\sigma^{\mathrm{NLO}} - d\sigma^{\mathrm{MC}}$$

Additive Matching

POWHEG-BOX

$$d\sigma^{\mathrm{NLO}}_{\mathrm{POWHEG}} \sim \frac{d\sigma^{\mathrm{NLO}}}{d\sigma^{\mathrm{MC}}}$$

Multiplicative Matching

Antenna choice and colour tagging

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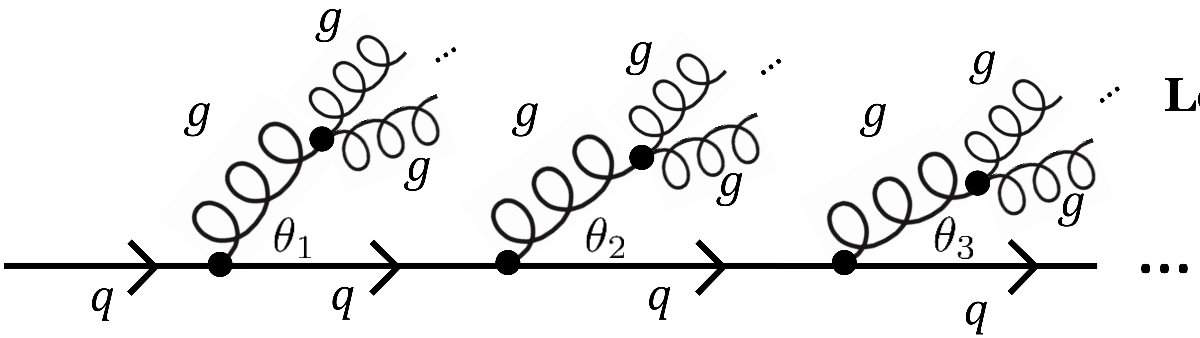
Antenna choice



Logarithmic Enhancement:

$$\theta_1 > \theta_2 > \theta_3$$

- ❑ SD algorithm will decluster first C/A shower algorithm step
- ❑ **First C/A** step corresponds to **emission** with **widest angle**

Colour tagging