# Precision jet substructure studies for the Relativistic Heavy Ion Collider with the sPHENIX detector

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In collaboration with D. Reichelt and S. Schumann.

## Introduction and motivation

- The jet substructure studies allow to test fundamental properties of QCD.
- Our ultimate goal is to use jet substructure to achieve improved understanding of hadronization and jet quenching in $AA$ collisions.
- In order to understand jet substructure in $AA$ collisions we need to make sure that we understand the $pp$ case. Therefore, we need high accuracy level theoretical predictions (beyond one-loop level) for various jet substructure observables.
- Due to complexity of calculations beyond one-loop accuracy level one needs a framework which allows to automate analytical computations.
- At LHC jet substructure was intensively studied however just a few measurements are available at RHIC [1].
- What is the difference between LHC and RHIC physics and how it will affect the jet substructure?
- We aim to use our available high accuracy level LHC results to make reliable phenomenological predictions for future RHIC measurements.

## Observable definition and grooming technique

### Observable definition:

- Jet angularity is defined as $\lambda_\alpha^\kappa = \sum_{i \in \text{jet}} \left(\frac{p_{T,i}}{p_{T,\text{jet}}}\right)^\kappa \left(\frac{\Delta R_{ij}}{R}\right)^\alpha, \quad \alpha > 0 \;\; \kappa > 0.$
- Angular decorrelation is defined as an azimuthal angle between two jets $\delta_\varphi$.
- For the LHC measurements of $\lambda^1_{1/2}$, $\lambda^1_1$ and $\lambda^1_2$ see [2].
- The $\text{NLO} + \text{NLL}'$ [3, 4] and NNLL [5] accuracy level theoretical predictions are available for $\lambda^1_\alpha$ and $\delta_\varphi$ correspondingly.
- The results of [3, 4] are available as the CAESAR resummation plugin to SHERPA MC generator [6].

### SoftDrop groomer:

- Allows to remove "contamination" from soft wide-angle emissions, hence reduces a non-perturbative contribution.
- Decluster jet into two subjets $i$ and $j$.
- Check if SoftDrop condition $\frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}} > z_{\text{cut}} \left(\frac{\Delta R_{ij}}{R}\right)^\beta$ holds.
- If SoftDrop condition is satisfied do nothing.
- Otherwise discard the softest branch and repeat the whole procedure.

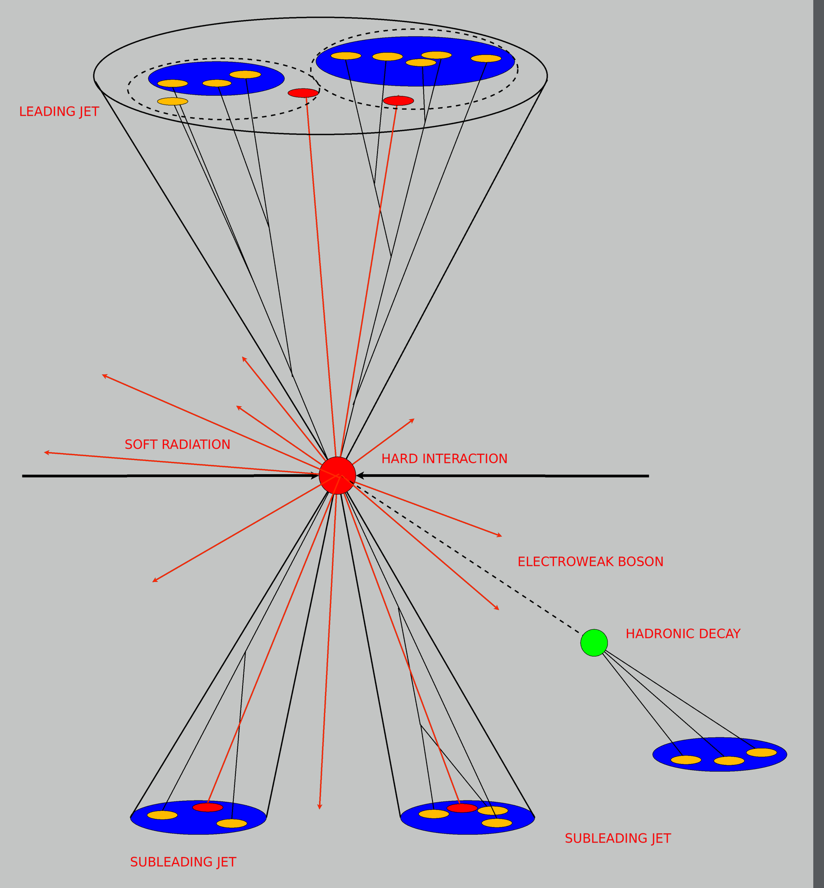


Figure 1: Schematic picture of the leading jet after declustering.

## Parton-to-hadron level transition leads to bin migration and needs to be addressed carefully!

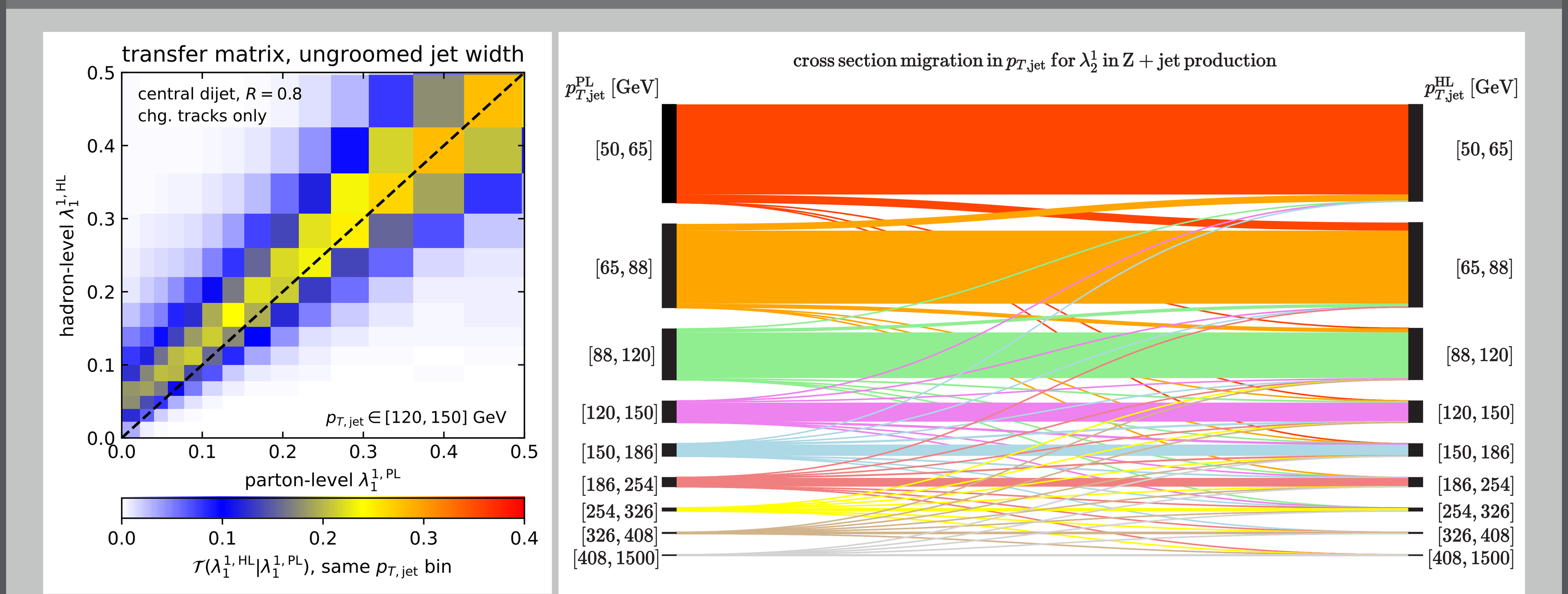


Figure 2: Left: Transfer matrix $\mathcal{T}(\lambda_1^{1,\text{HL}}|\lambda_1^{1,\text{PL}})$ for $\lambda_1^1$ for central dijet events with $R = 0.8$ and $p_{T,\text{jet}} \in [120, 150]$ GeV, $\sqrt{s} = 13$ TeV, $pp$ collisions. Right: Migration flow between different $p_T$-bins. From [4].

## Perturbative results must be "unfolded" (corrected for parton-to-hadron level transition)!

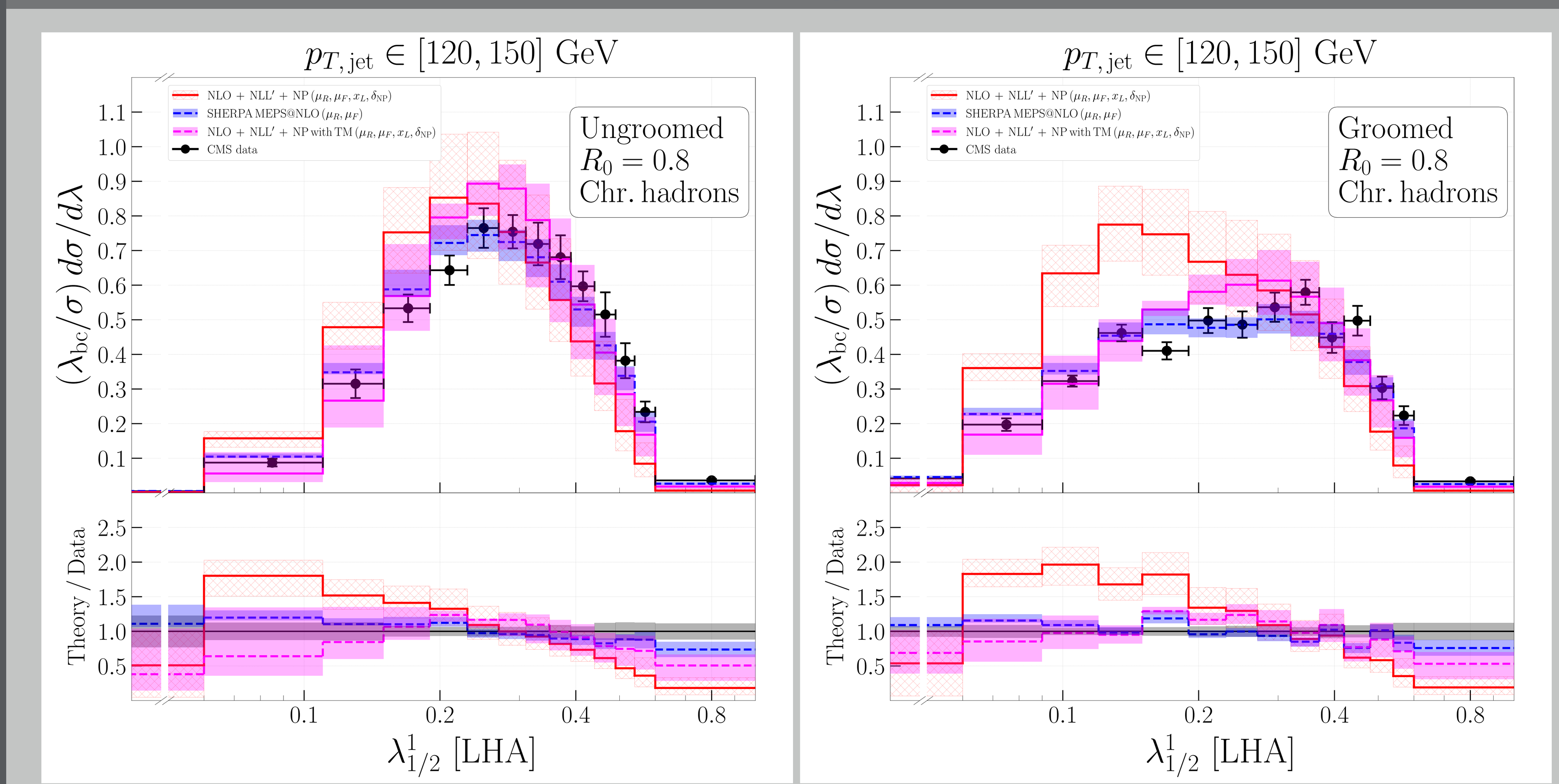


Figure 3: Comparison of the resummed predictions [3, 4] against CMS data [2] for ungroomed (left) and groomed (right) $\lambda^1_{1/2}$, $p_{T,\text{jet}} \in [120, 150]$ GeV, $\sqrt{s} = 13$ TeV, $pp$ collisions. Red band correspond to "naive" correction of perturbative results for non-perturbative effects without bin-migration. Magenta band correspond to transfer matrix approach taking bin-migration into account.

## Jet angularities $\lambda^1_\alpha = \sum_i z_i \left(\Delta_{i,jet}/R\right)^\alpha$ at RHIC collision energy, SHERPA Res. + MC

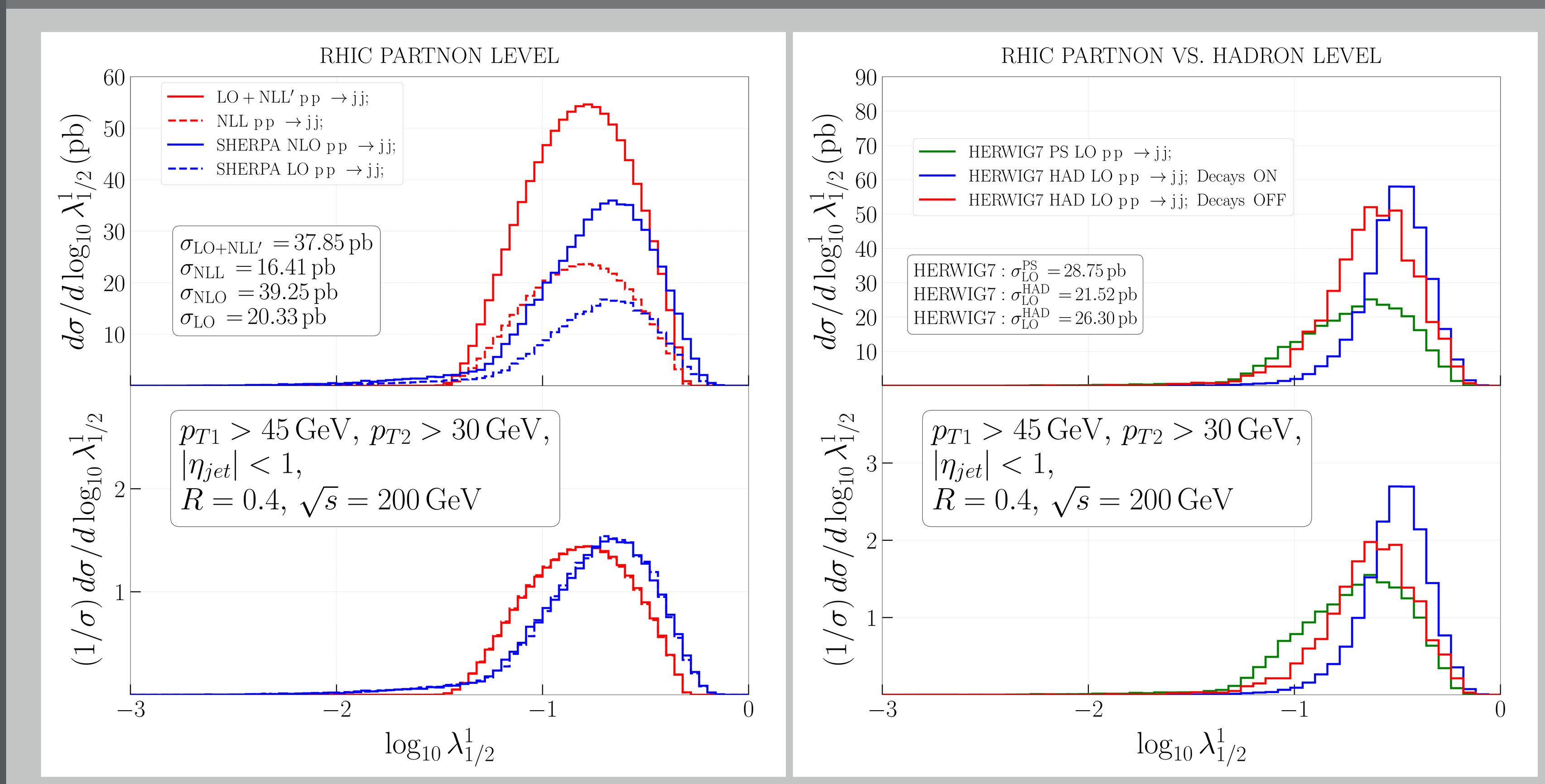


Figure 4: Left: comparison between $\text{LO} + \text{NLL}'$ predictions, LO and NLO MC simulations (CEASAR and SHERPA). Matching to fixed order results and higher order corrections change cross section but do not affect shape of $\lambda_\alpha$. Right: Impact of non-perturbative effects. In collaboration with D. Reichelt and S. Schumann (preliminary).

## Hadronization and Lund string model

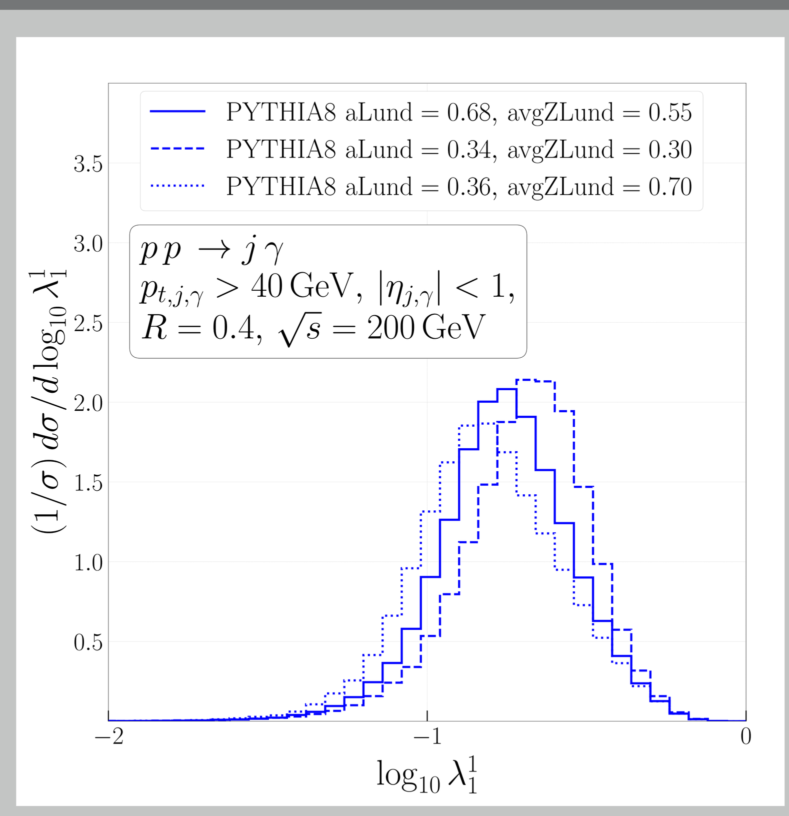


Figure 5: Impact of variation of the Lund String parameters in PYTHIA8 on the shape of jet angularity $\lambda^1_1$ (preliminary).

### New tunes?

- There is a Detroit PYTHIA tune [7] designed to describe RHIC data, but it mostly affect multiple partonic interactions (MPIs).
- However, MPIs are almost absent at RHIC energies because $\sqrt{S}$ is too small.
- Lund symmetric fragmentation function is given by

$$f(z) \sim \frac{(1-z)^a}{z} \exp\left(-bm_\perp^2/z\right).$$

- Hadron formation time

$$\langle \tau^2 \rangle = \frac{1+a}{b\kappa^2} \approx 2\,\text{fm}.$$

- At LHC jet angularities can be used to tune MPI models [4].
- At RHIC one can use jet angularities to tune hadronization models and, in perspective, to improve our understanding of hadronization.
- Reliable perturbative and non-perturbative predictions for jets produced in $pp$ collisions are needed (to be used as a baseline in comparison against $AA$ results).

## Is $\delta\varphi$ affected by NP-corrections?

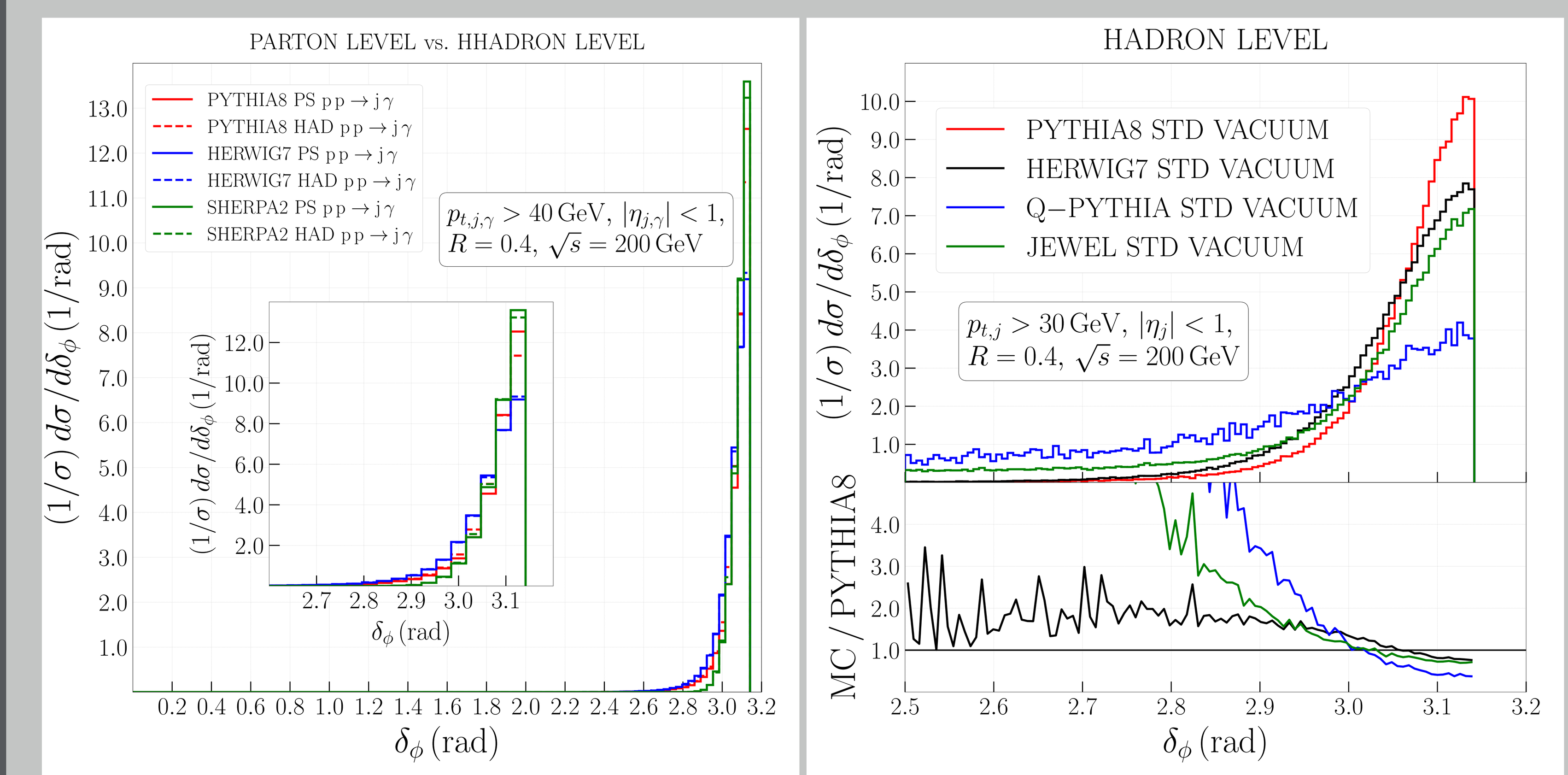


Figure 6: Left: Impact of hadronization and MPIs on $\delta\varphi$, comparison between PYTHIA8, HERWIG7 and SHERPA2 $pp$ collisions. Right: Impact of hadronization and MPIs on $\delta\varphi$, comparison between PYTHIA8, HERWIG7 and Q-PYTHIA and JEWEL, $pp$ collisions (preliminary).

## How $\delta\varphi$ is affected by medium effects?

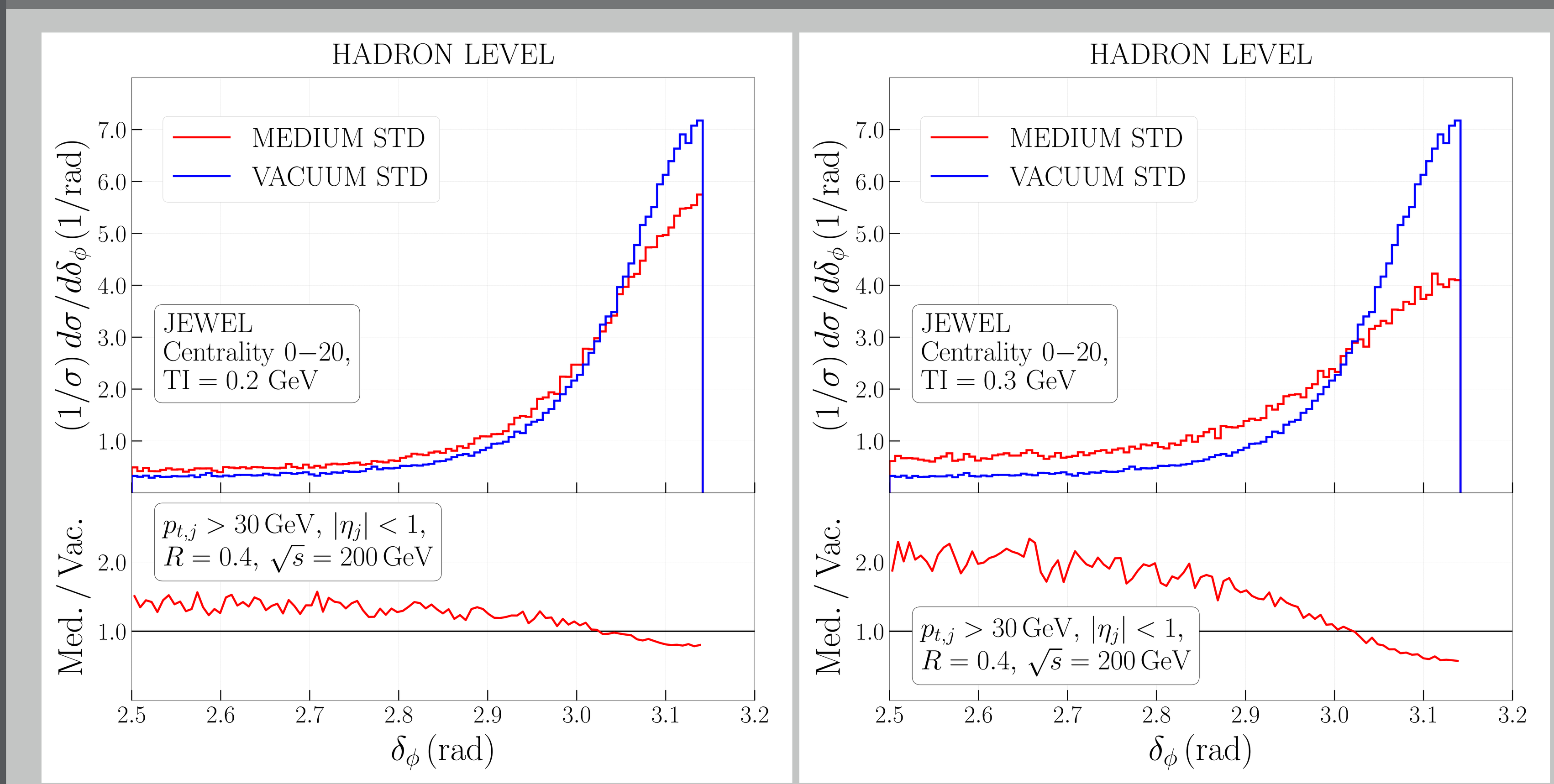


Figure 7: Impact of the medium interactions on $\delta_\varphi$ distribution. Left: JEWEL MC with 0.2 GeV initial medium temperature. Right: JEWEL MC with 0.3 GeV initial medium temperature (preliminary).

## Conclusions and next steps

- Resummed predictions for both groomed and ungroomed angularities $\lambda^1_\alpha$ ($\alpha \in [1/2, 1, 2]$) at $\text{LO} + \text{NLL}'$ are ready, the $\text{NLO} + \text{NLL}'$ prediction require some more CPU time.
- We found that angularities $\lambda^1_\alpha$ at RHIC energies can be used to study hadronization and produce new MC tunes.
- On the other hand, angular decorrelation $\delta_\varphi$ is less sensitive to hadronization and hence can be used to test various parton shower models.
- The JEWEL and Q-PYTHIA MC event generators predictions strongly differ from standard LHC MC event generators applied to RHIC setup.
- The $\delta_\varphi$ distributions simulated with JEWEL MC generator show strong dependence on the medium temperature.
- The resummed predictions must be corrected for non-perturbative effects using corresponding parton-to-hadron transition matrices.
- The deeper understanding of the source of the differences between Q-PYTHIA, JEWEL and LHC MC is required.
- Will Q-Pythia, JEWEL and Jetscape MC simulations agree / disagree with each other?
- The new RHIC measurements are needed!

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- The results from Refs. [3, 4] were obtained in collaboration with S. Caletti, S. Marzani, D. Reichelt, S. Schumann, G. Soyez and Vincent Theeuwes.

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