Jet substructure at RHIC and LHC

Oleh Fedkevych
in collaboration with Yang-Ting Chien, Daniel Reichelt and Steffen Schumann

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Jefferson Lab
Exploring the Nature of Matter

Georgia State University

Center for Frontiers
in Nuclear Science

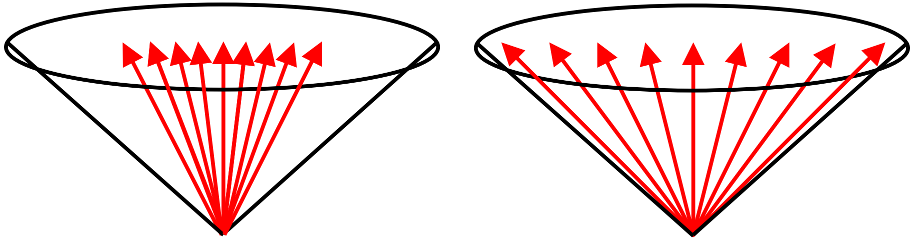
Observable definition: jet angularity

Jet angularity is defined as

$$\lambda_\alpha = \sum_{i\in \text{jet}} \frac{p_{t,i}}{p_{t,\text{jet}}} \left(\frac{\Delta R_{ij}}{R}\right)^\alpha, \quad \kappa = 1, \quad \alpha > 0$$

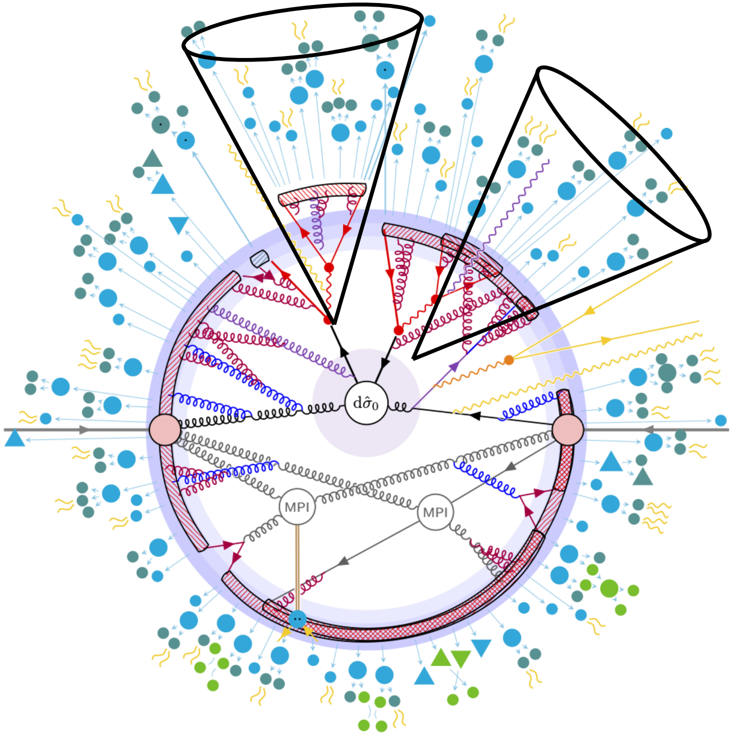
- Sum runs over all particles inside the jet
- Jet radius R
- Rapidity-azimuth distance $\Delta R_{i,\text{jet}}$
- IRC (infrared and collinear) safe observable!

- LHA (Les Houches Angularity): $\alpha = 1/2$
- Jet Width: $\alpha = 1$
- Jet Thrust: $\alpha = 2$



CMS: 1808.07340, 2109.03340; ALICE: 2107.11303; ATLAS: 1702.00674

Impact of Multiple Partonic Interactions



- Protons are composite objects so several (semi-)hard partonic interactions can occur per one pp collision!

Image credit: 2203.11601

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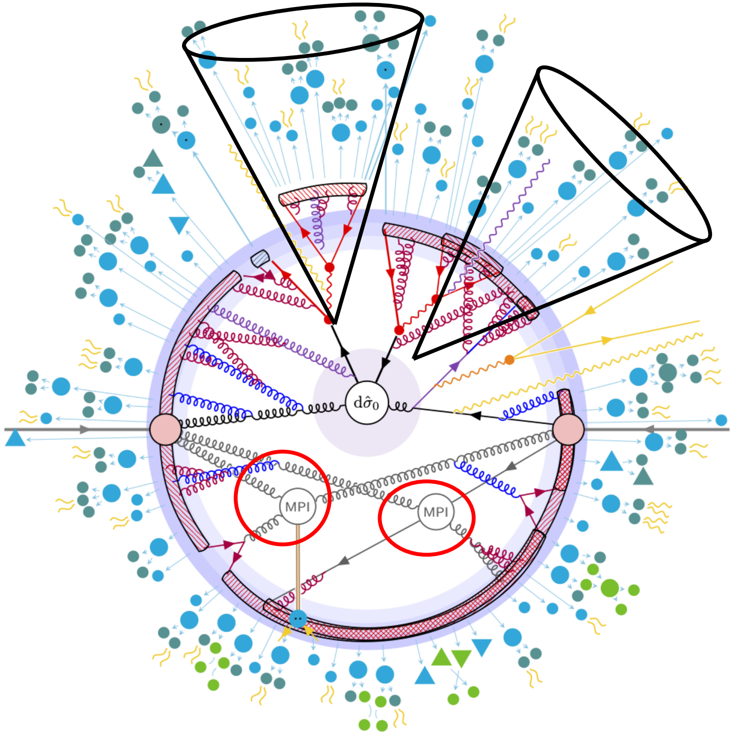

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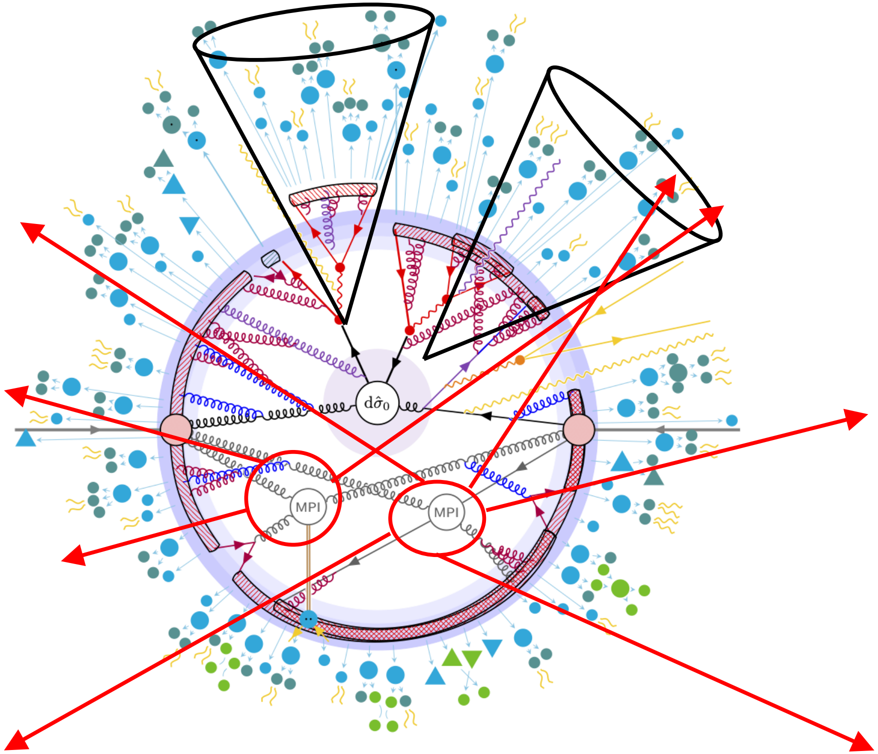

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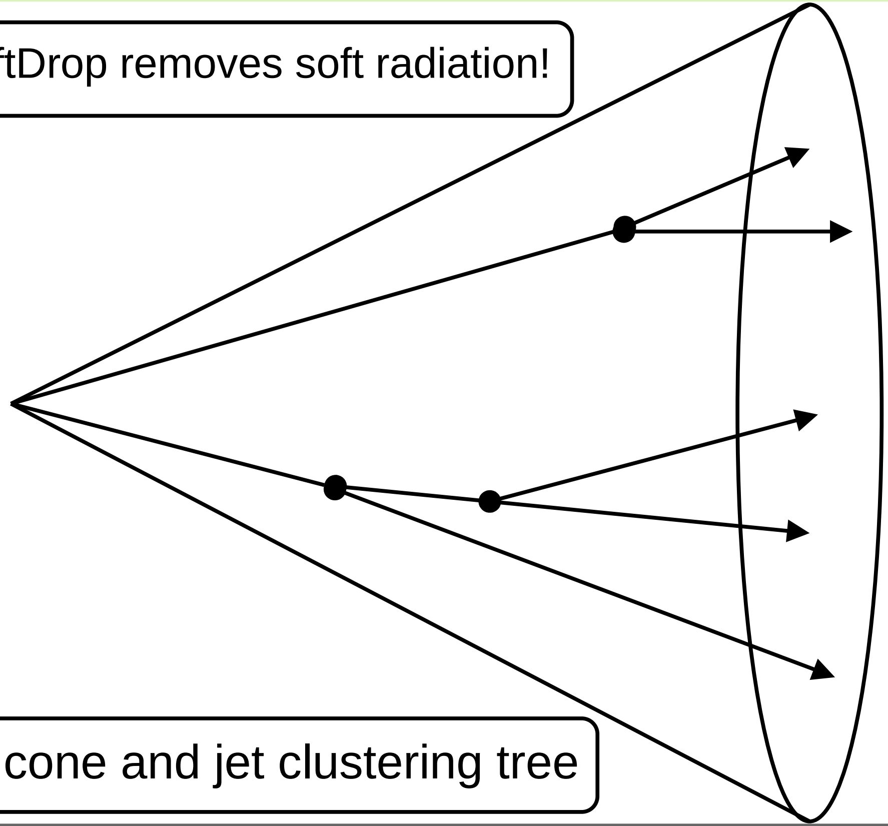
- Protons are composite objects so several (semi-)hard partonic interactions can occur per one pp collision!
- Such processes generally know as Multiple Partonic Interactions (MPI)
- MPI cause multiple uniform soft emissions which “contaminate” jet substructure

SoftDrop algorithm:

SoftDrop removes soft radiation!



Jet cone and jet clustering tree

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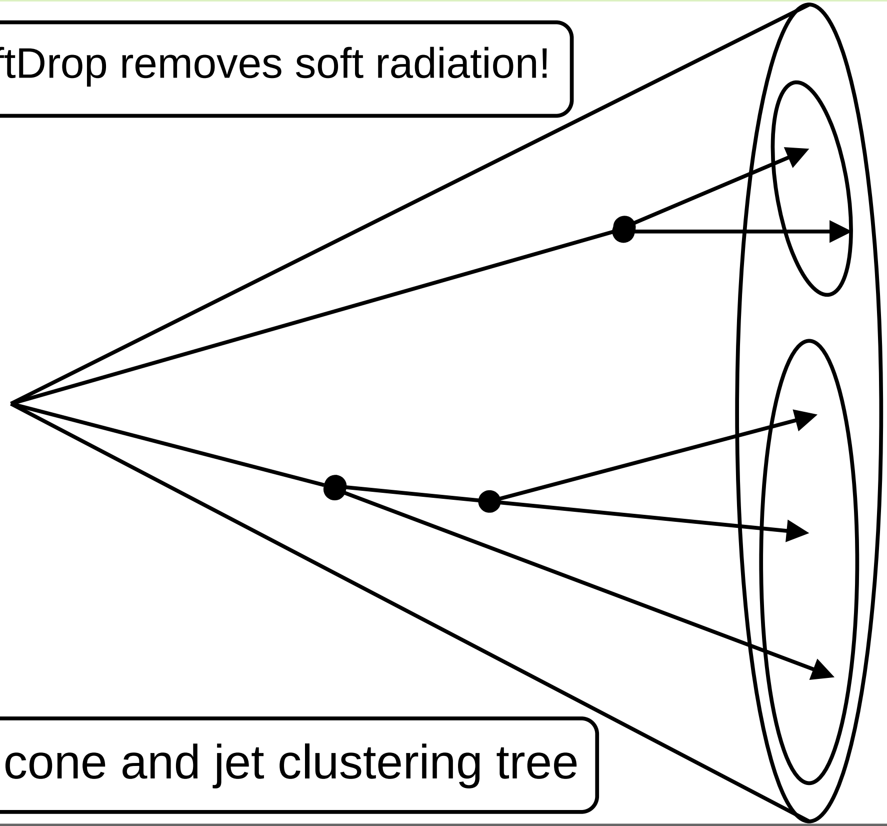

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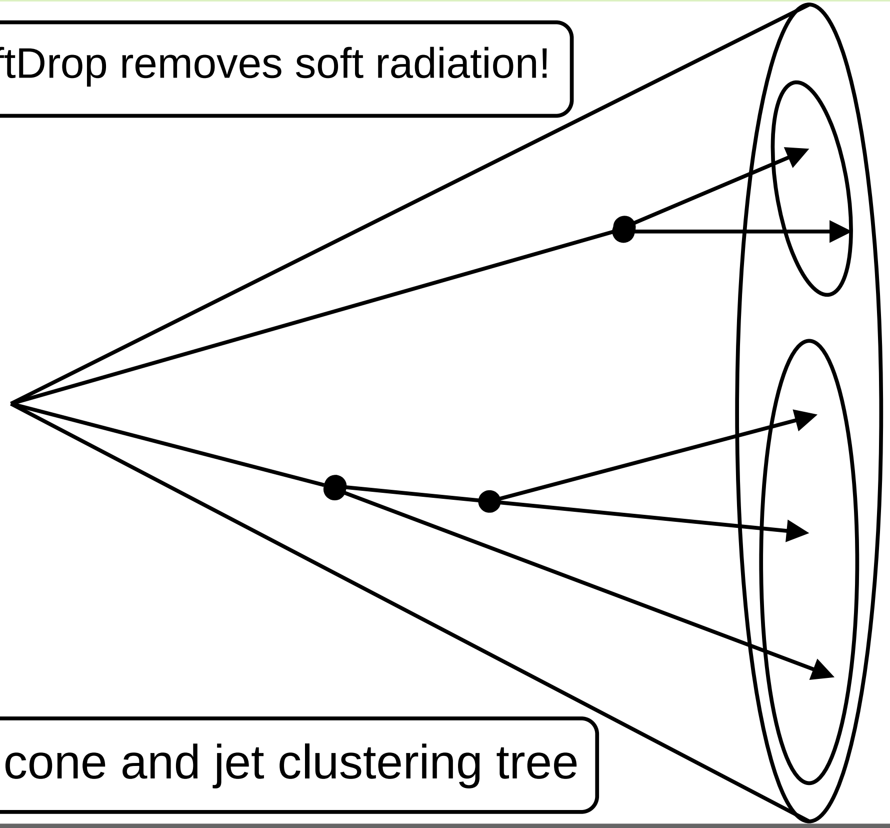

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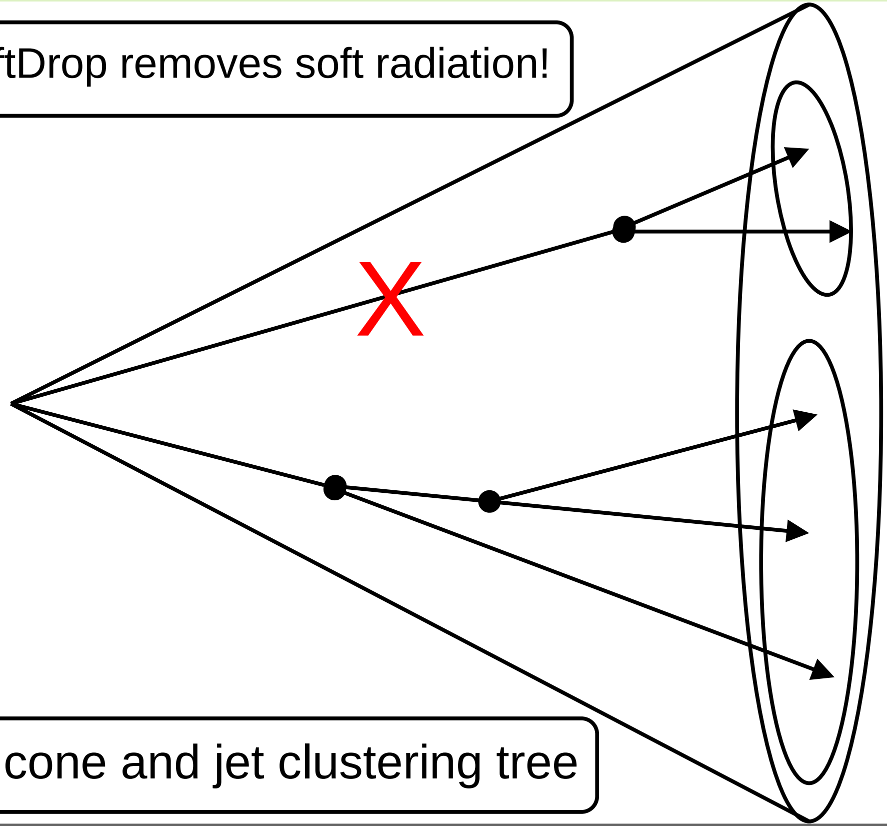

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Here z_{cut} and β control the intensity of grooming

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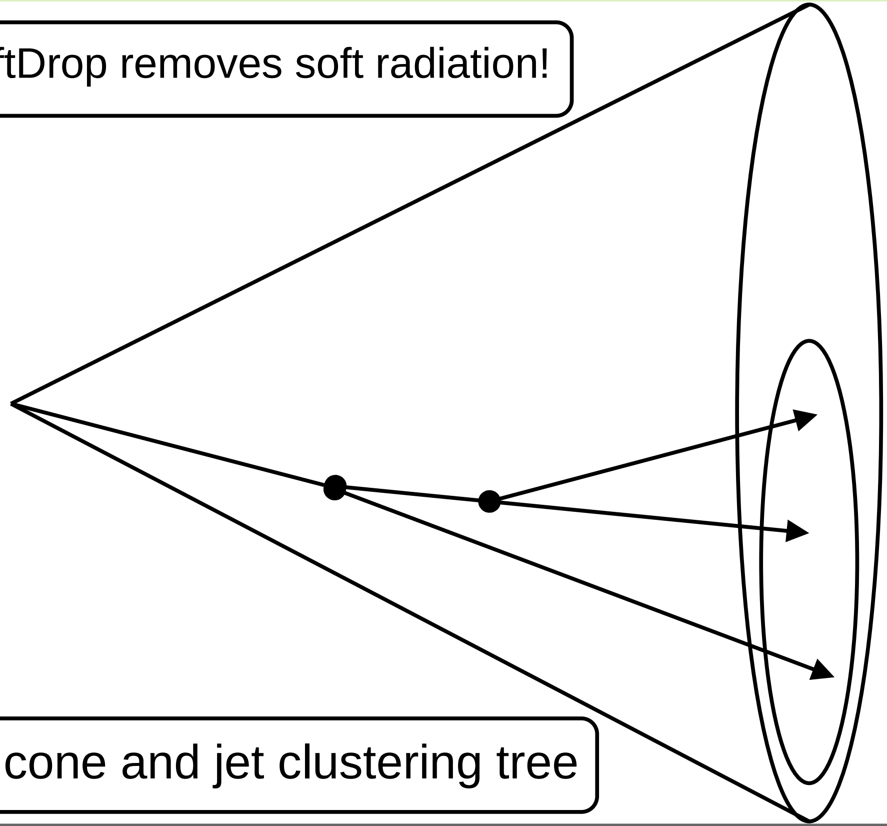

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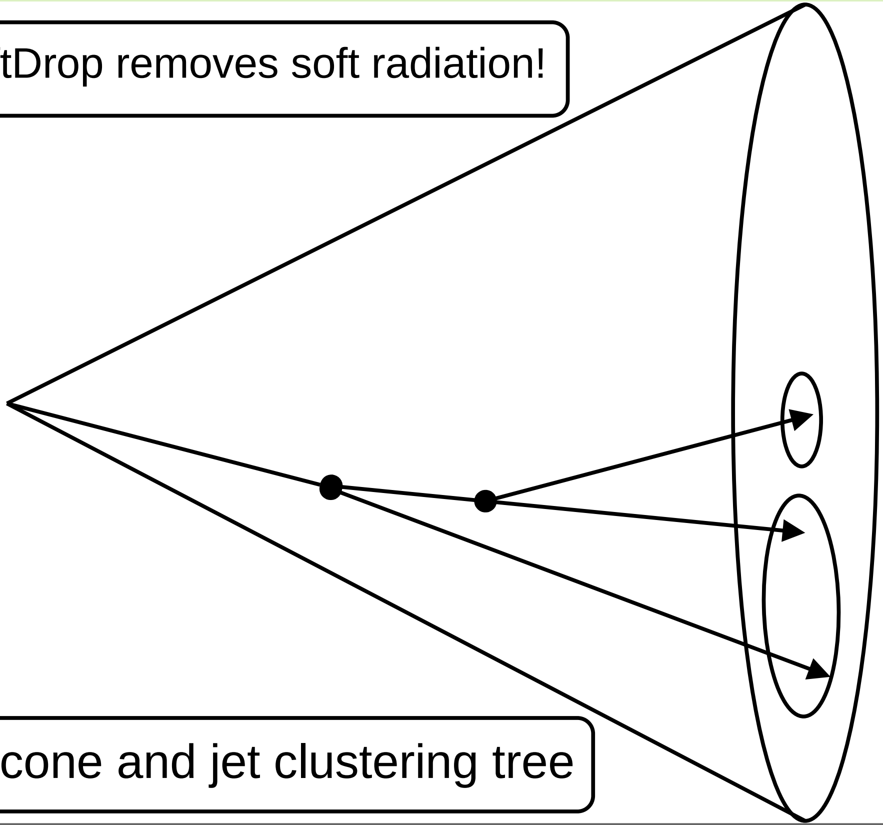

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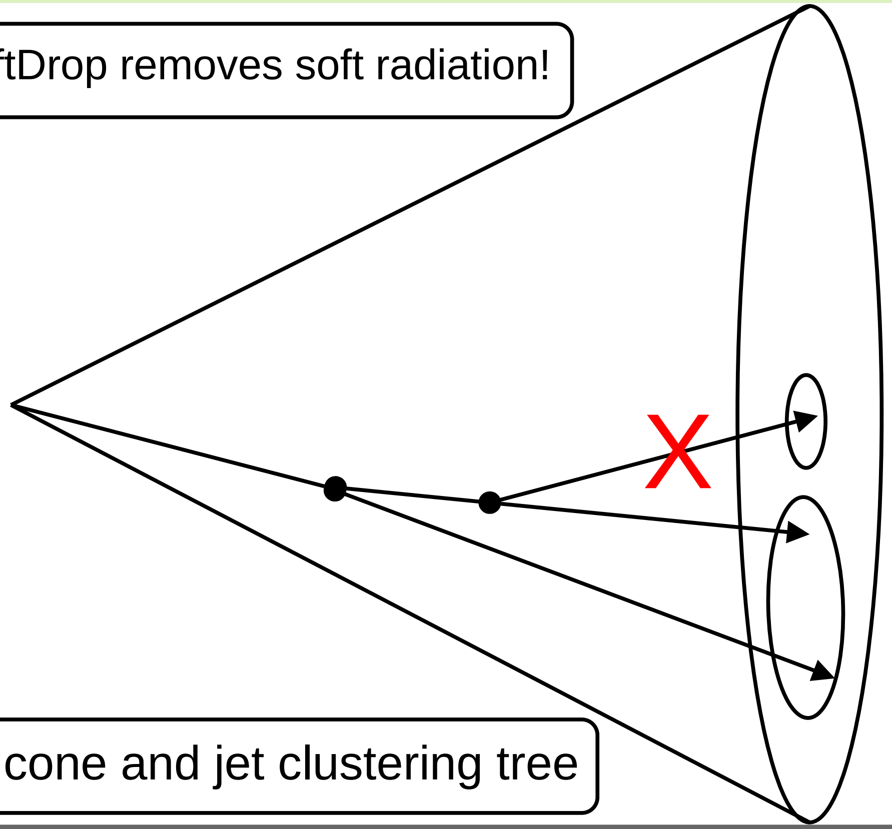

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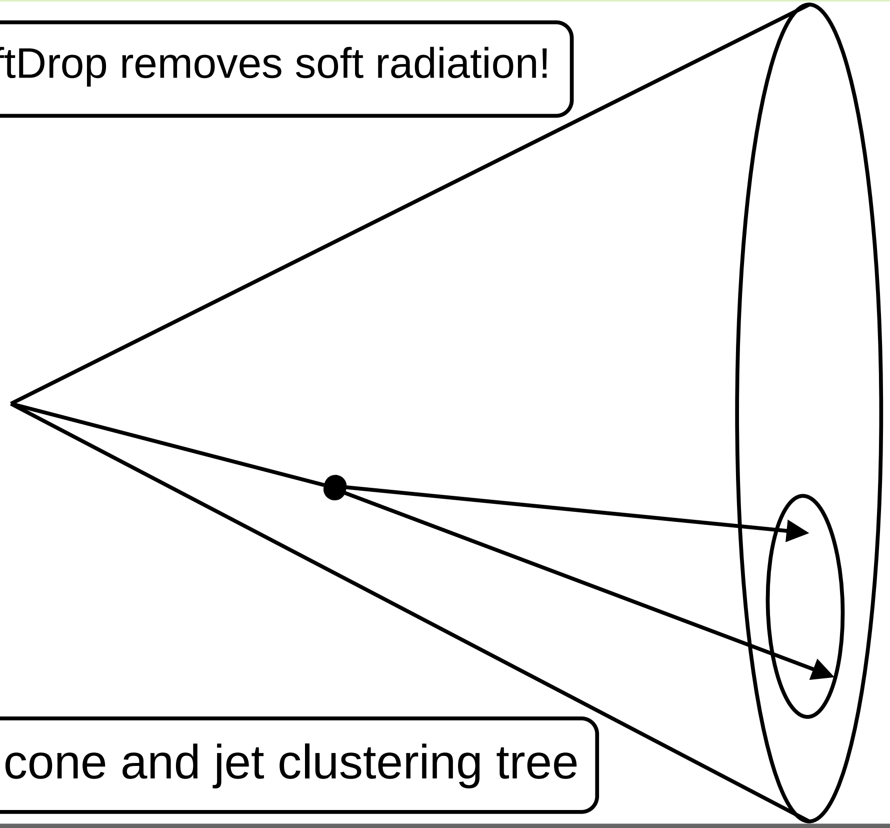

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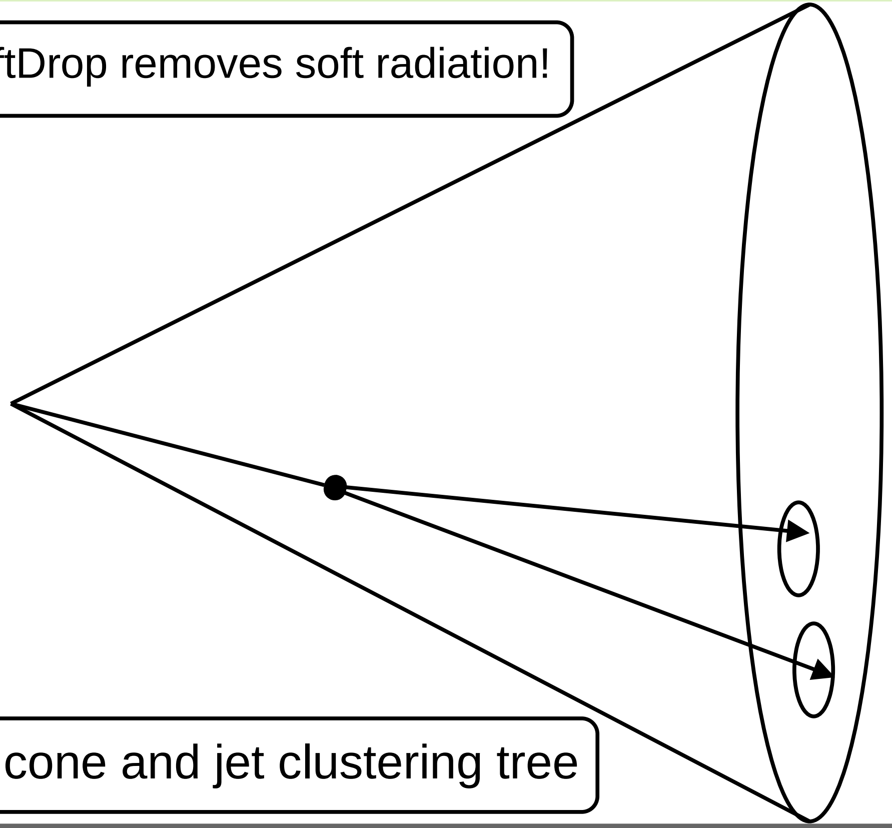

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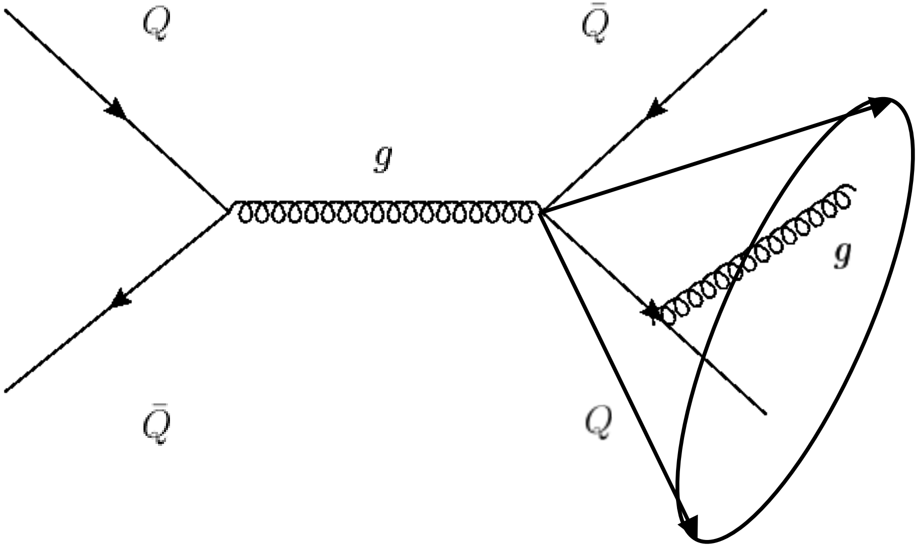
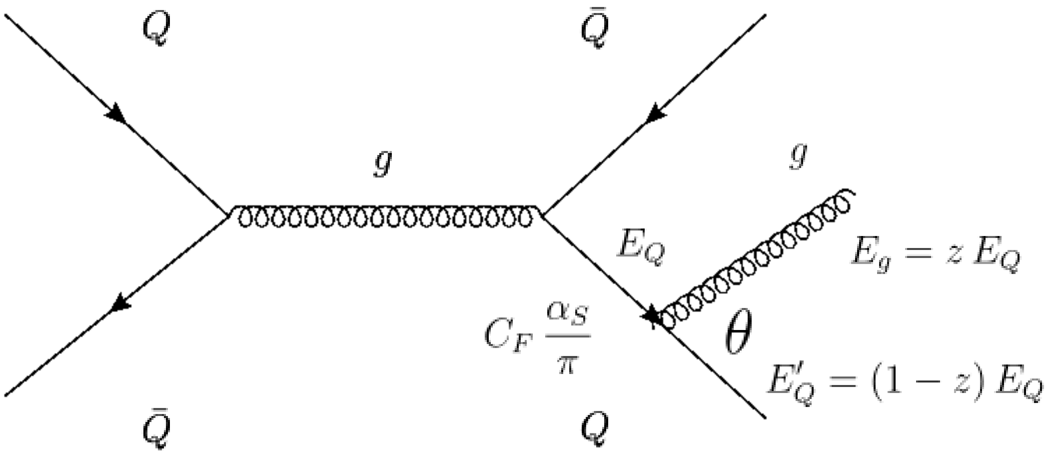
Fixed order (FO) jet substructure calculations



$$Q + \bar{Q} \longrightarrow Q + \bar{Q} + g$$

- A “standard” 2-to-2 QCD process cannot be used for jet substructure calculations (no substructure!)
- So one needs to take 2-to-2 process and add more emissions to it
- Jet substructure can be studied already for the 2-to-3 processes
- It is called fixed-order (FO) calculation.
- However, higher order corrections e.g. 2-to-4, 2-to-5 etc. in general are difficult to calculate

Resummation: leading log (LL)



$$Q + \bar{Q} \longrightarrow Q + \bar{Q} + g$$

2-to-3 cross section gets a di-log enhancement:

$$d\sigma \sim d(\log \theta^2)\, d(\log z)$$

Let's define a simple IRC safe jet substructure observable:

$$\tau = z\theta^2$$

In case of multiple emissions:

$$\tau = \sum_{i=\mathrm{gluon}} z_i \theta_i^2$$

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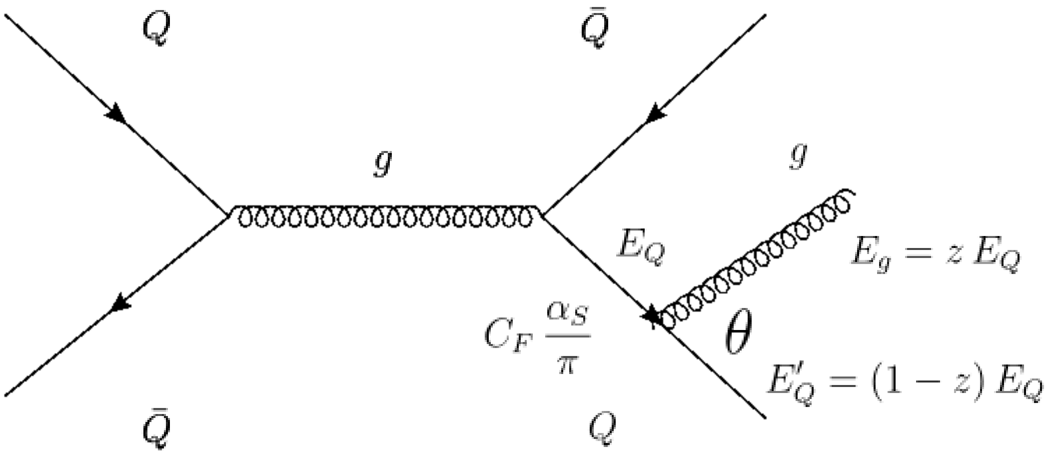

$$Q + \bar{Q} \longrightarrow Q + \bar{Q} + g$$

Multiple gluon emissions exponentiate:

$$P_q(x<\tau) = \exp\left(-\frac{\alpha_s}{\pi}\frac{C_F}{2}\log^2\tau\right)$$

Similar expression can be obtained for quark emissions:

$$P_g(x<\tau) = \exp\left(-\frac{\alpha_s}{\pi}\frac{C_A}{2}\log^2\tau\right)$$

Note that both expressions are finite if $\tau \to 0$ whereas FO result diverges!

For more details see: 1709.06195

Resummation: next-to-leading log (NLL)

In general:

$$P_{q/g} = 1 + \alpha_S \left(c_{22}L^2 + c_{21}L + ...\right) + \alpha_S^2 \left(c_{24}L^4 + c_{23}L^3 + ...\right) + ...$$

Both LL and NLL resummation can be performed separately for quark and gluon production channels!

Therefore, resummed expressions can be used to define “quark” and “gluon” jets!

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LL (the $c_{22}L^2$, $c_{24}L^4$ terms) NLL (the $c_{21}L$, $c_{23}L^3$ terms)

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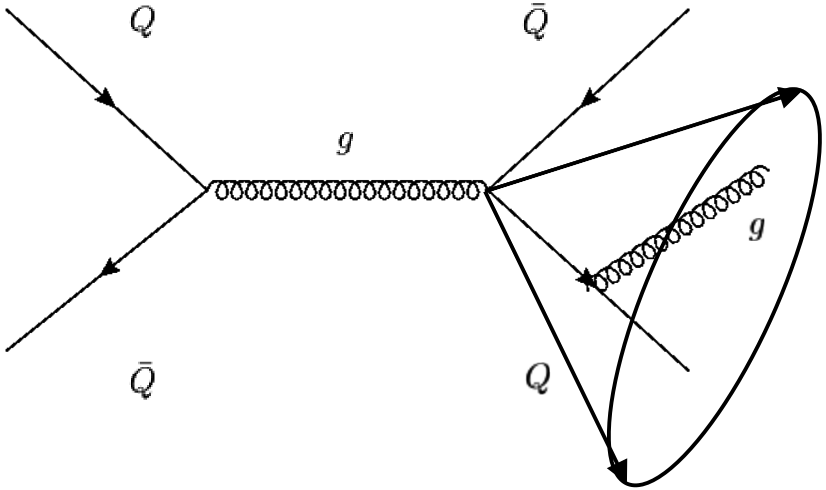
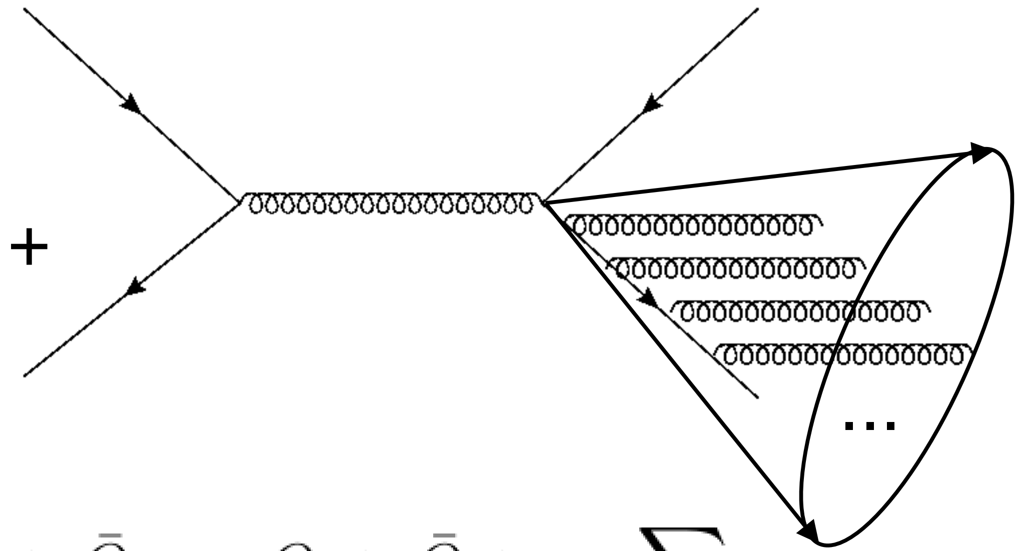
Resummation and matching to fixed order (FO) results

FO calculations



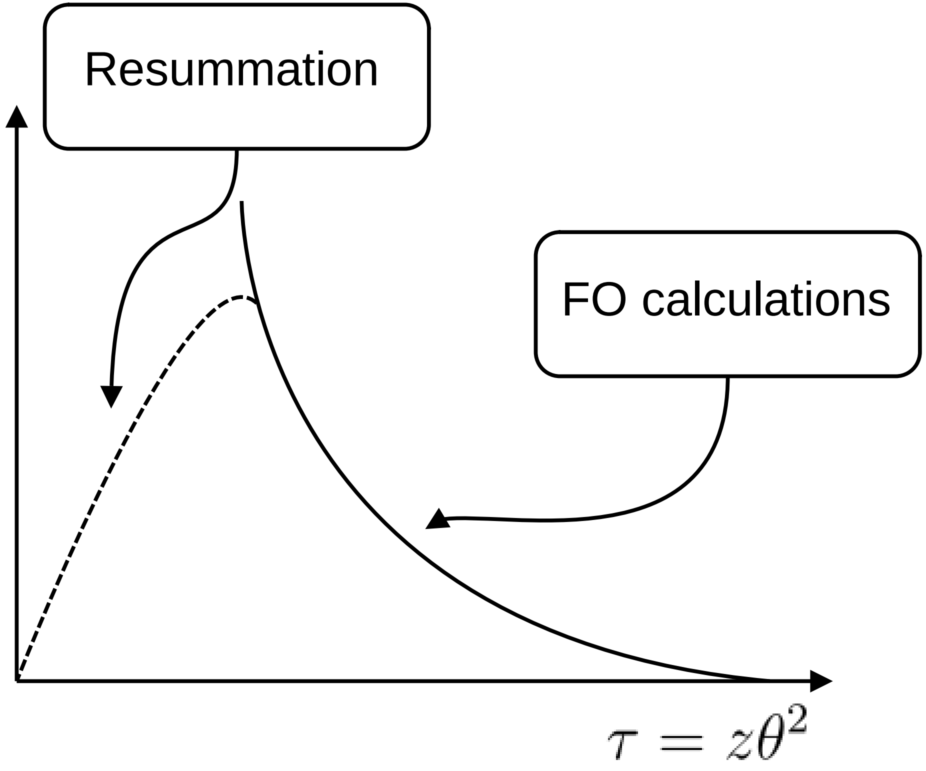
$$Q + \bar{Q} \longrightarrow Q + \bar{Q} + g$$

Resummation



$$Q + \bar{Q} \longrightarrow Q + \bar{Q} + \sum_{soft,\, collinear} g$$

Resummation and matching to fixed order (FO) results



Matching to FO results:

- Excludes double counting between overlapping phase space regions.
- Provides finite results at small values of observable of interest
- Matching “quark” and “gluon” jet contributions can be done separately which leads to NLL' accuracy level

CAESAR approach by Banfi, Salam and Zanderighi

CAESAR allows to automate resummation for each observable that can be parametrized as

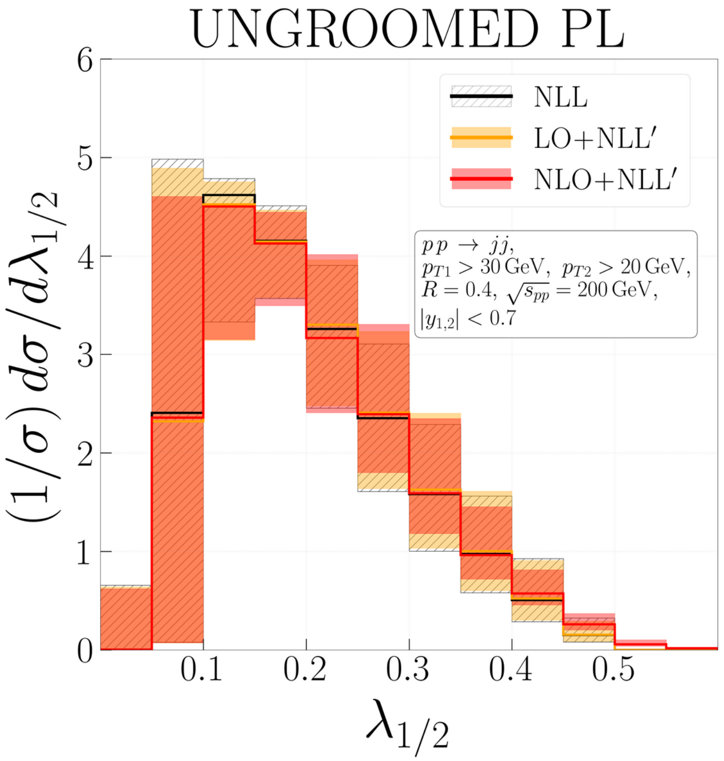
$$\Sigma_{\rm res}(v) = \sum_{\delta} \Sigma^{\delta}_{\rm res}(v)\,, \quad \text{with}$$

$$\Sigma^{\delta}_{\rm res}(v) = \int d\mathcal{B}_{\delta} \frac{d\sigma_{\delta}}{d\mathcal{B}_{\delta}} \exp\left[-\sum_{l\in\delta} R_l^{\mathcal{B}_{\delta}}(L)\right] \mathcal{P}^{\mathcal{B}_{\delta}}(L)\mathcal{S}^{\mathcal{B}_{\delta}}(L)\mathcal{F}^{\mathcal{B}_{\delta}}(L)\mathcal{H}^{\delta}(\mathcal{B}_{\delta})\,,$$

- Born cross section $\frac{d\sigma_{\delta}}{d\mathcal{B}_{\delta}}$
- Soft function $\mathcal{S}$
- Ratio of PDFs $\mathcal{P}$
- Multiple emission function $\mathcal{F}$
- Collinear radiator R_l
- Kinematic cuts $\mathcal{H}$

CAESAR = Computer Automated Expert Semi-Analytical Resummer, see the original paper by A.Banfi, G.Salam and G. Zanderighi 0407286

Parton-level (PL) CAESAR predictions



- ✓ The resummation is performed at NLL accuracy level
- ✓ The NLL results are matched to NLO FO results leading to NLO+NLL′ accuracy level
- ✓ The calculations are automated and are available as a CAESAR resummation plugin to SHERPA MC 2404.04168 , 2112.09545, 2104.06920

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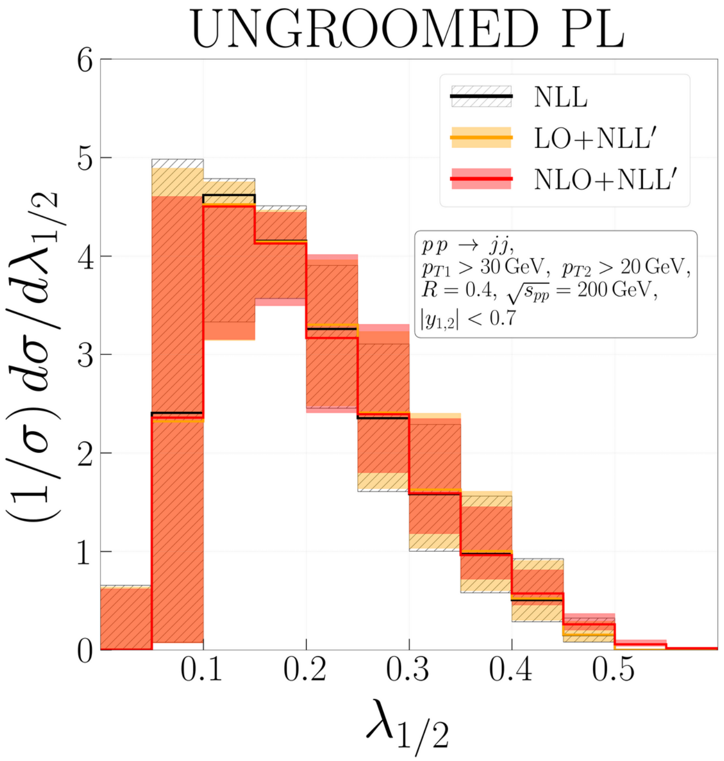
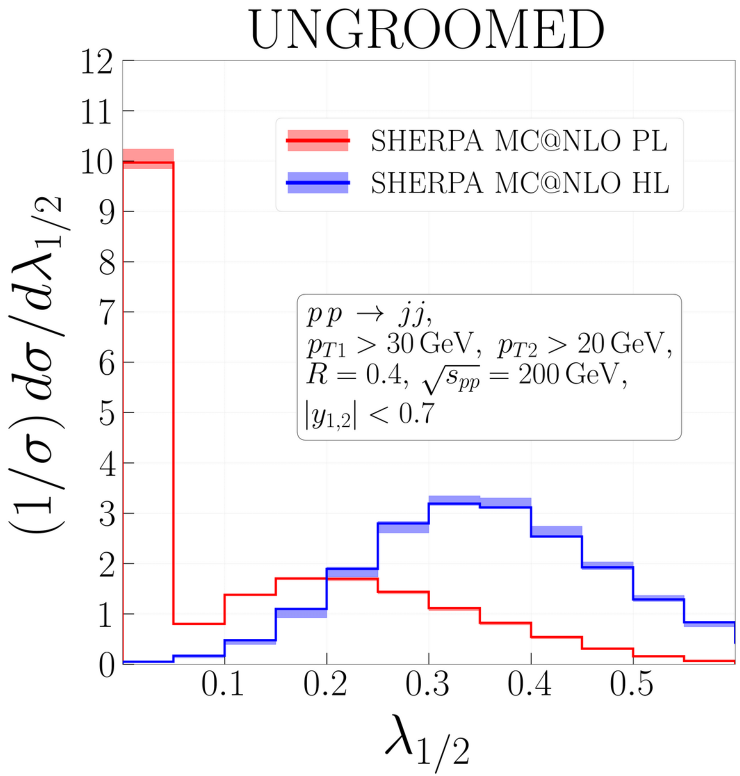


- ✓ Our results for jet angularities are at highest available accuracy NLO+NLL′ level
- ✓ Result are available for LHA, Jet Width and Jet Thrust (for ungroomed and groomed jets)
- ✓ The increase in accuracy of calculation reduces the size of uncertainty bands. Usually data has smaller errorbars (at least at the LHC) hence further improvement in accuracy of the calculation is desirable (though it is very challenging)

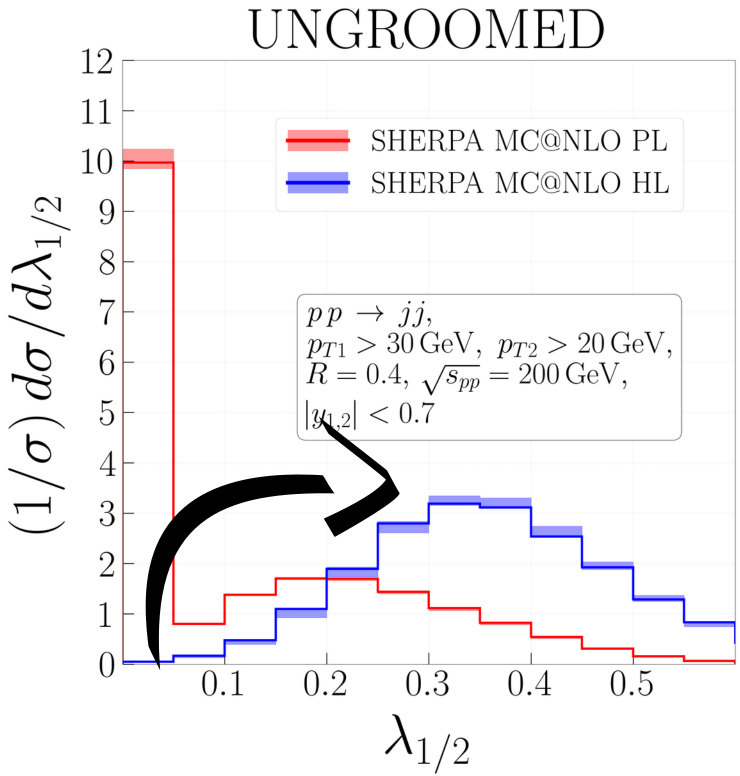
Parton-level (PL) vs. hadron-level (HL) distributions



Sherpa MC: parton level vs. hadron level

- Perturbative calculations do not describe physics at low energy scales
- Two major NP-contributions are due to MPI and hadronization
- Unlike the LHC case, at RHIC the NP-effects dominate

Parton-level vs. hadron-level distributions



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- Two major NP-contributions are due to MPI and hadronization
- Unlike the LHC case, at RHIC the NP-effects dominate
- Large NP-contirbutions are predominantly coming from fragmentation of jets made out of a single parton causing bin-bigration

MPI multiplicity at RHIC

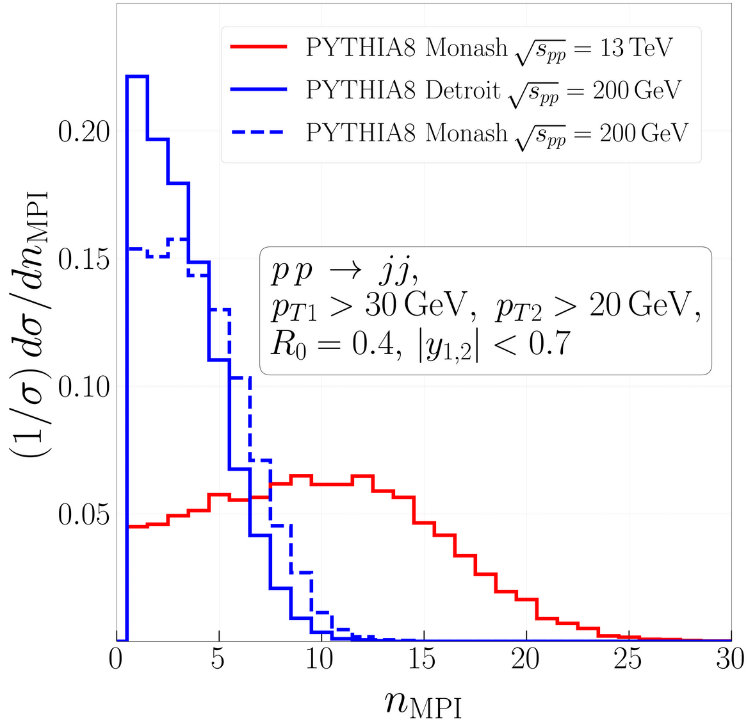

TABLE I. PYTHIA 8 settings and tuning parameters.

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PDF:pSet	13	17
MultipartonInteractions:ecmRef	7 TeV	200 GeV
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Tuning Parameter	**Default**	**Range**
MultipartonInteractions:pT0Ref	2.28 GeV	0.5-2.5 GeV
MultipartonInteractions:ecmPow	0.215	0.0-0.25
MultipartonInteractions:coreRadius	0.4	0.1-1.0
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ColourReconnection:range	1.8	1.0-9.0

Detroit PYTHIA tune (2110.09447)

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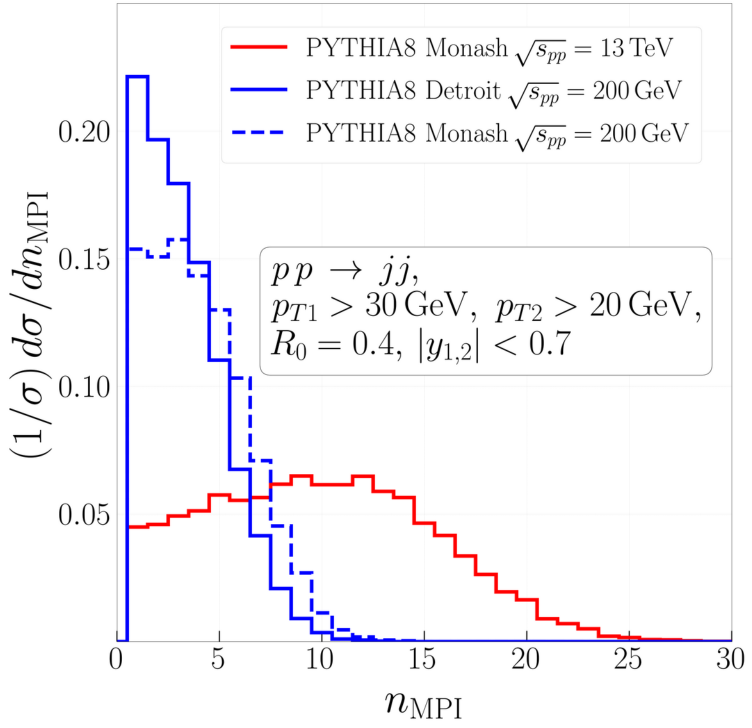

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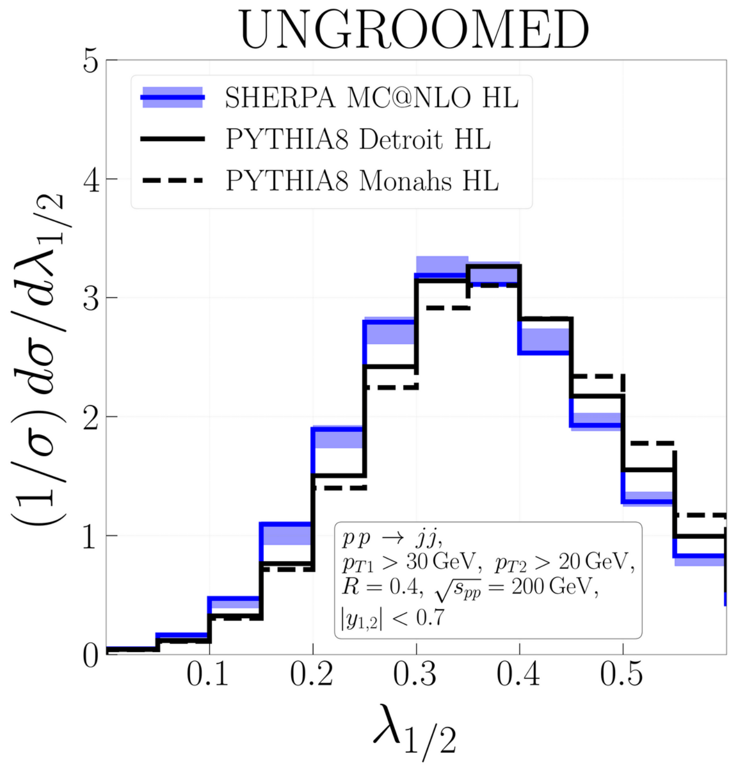
Detroit tune parameter choice essential means suppression of MPI production at RHIC!

Impact of MPI on jet substructure



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Different MPI tunes lead to somewhat different shapes of jet angularities

Incorporation of non-perturbative corrections

- Hadron level to parton level ratio:
  one simulates the same observable at parton and hadron levels then multiplies resummed predictions by the ratio

$$\lambda_\alpha^{\mathrm{HL}} = \lambda_\alpha^{\mathrm{PL}} \times \left(\frac{\lambda_\alpha^{\mathrm{HL,MC}}}{\lambda_\alpha^{\mathrm{PL,MC}}}\right)$$

- Shape functions, as in the work of Korchemsky, Sterman arXiv:hep-ph/9902341 where the hadron level result is given by a convolution

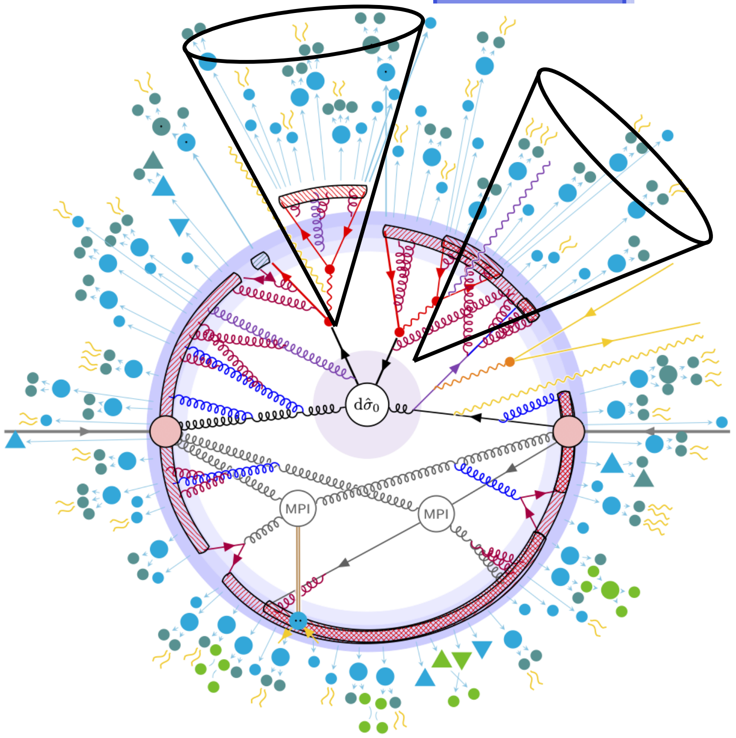
$$\frac{d\sigma}{d\lambda_\alpha^{\mathrm{HL}}} = \int d\epsilon\, f(\epsilon) \int d\lambda_\alpha^{\mathrm{PL}} \frac{d\sigma}{d\lambda_\alpha^{\mathrm{PL}}} \delta\left(\lambda_\alpha^{\mathrm{HL}} - \lambda_\alpha^{\mathrm{PL}} - C_\alpha^{\beta, z_{\mathrm{cut}}} \epsilon^{\gamma_\alpha^\beta}\right)$$

- Parton-to-hadron transfer matrices, see arXiv:2112.09545

$$\sigma^{\mathrm{HL}}(\vec{v}_h) = \mathcal{T}(\vec{v}_h | \vec{v}_p) \times \sigma^{\mathrm{PL}}(\vec{v}_p)$$

Parton-to-hadron transition via transfer matrices (TM)

- The transfer matrices can be extracted from MC simulations



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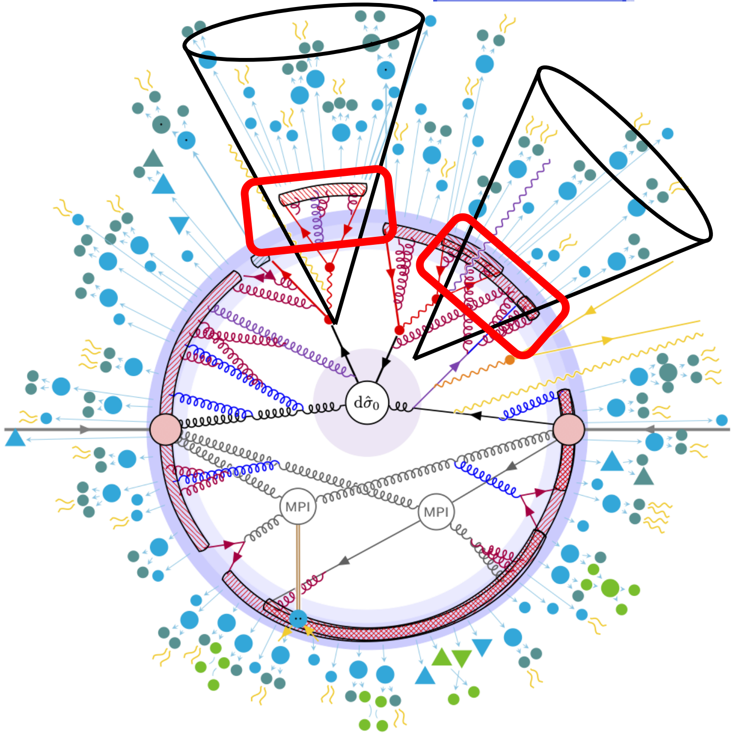

Parton-to-hadron transition via transfer matrices (TM)

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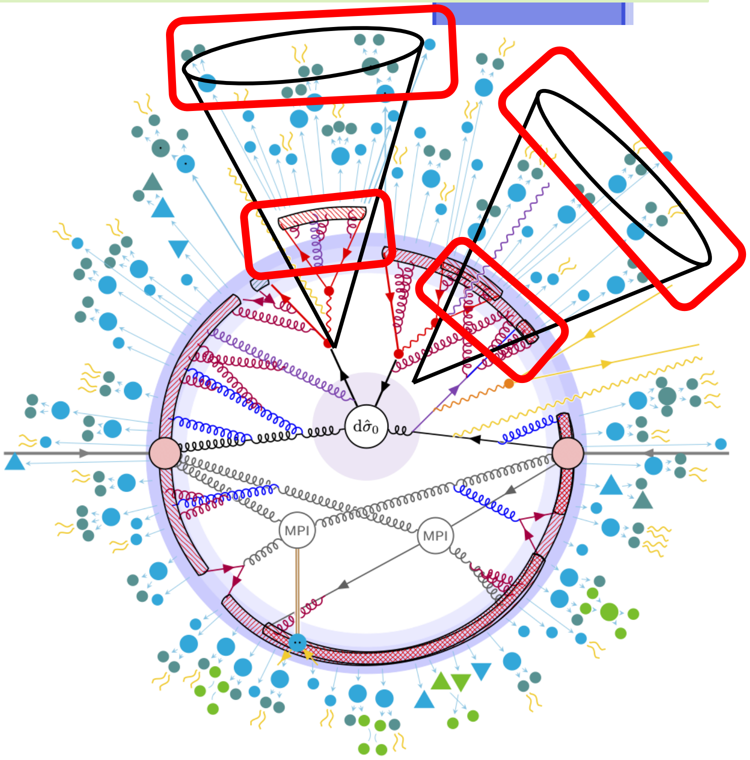
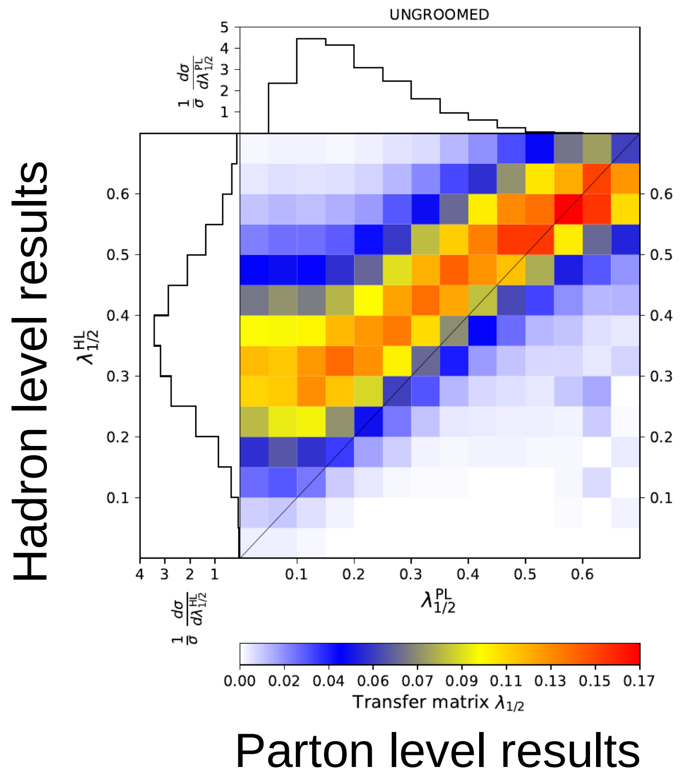
- One needs to "put event generation on pause" when parton shower reach non-perturbative scale and calculate $\lambda_\alpha^{\mathrm{PL}}$
- After that one "resume" event generation and calculate $\lambda_\alpha^{\mathrm{HL}}$
- The correlations between $\lambda_\alpha^{\mathrm{PL}}$ and $\lambda_\alpha^{\mathrm{HL}}$ are used to build TMs

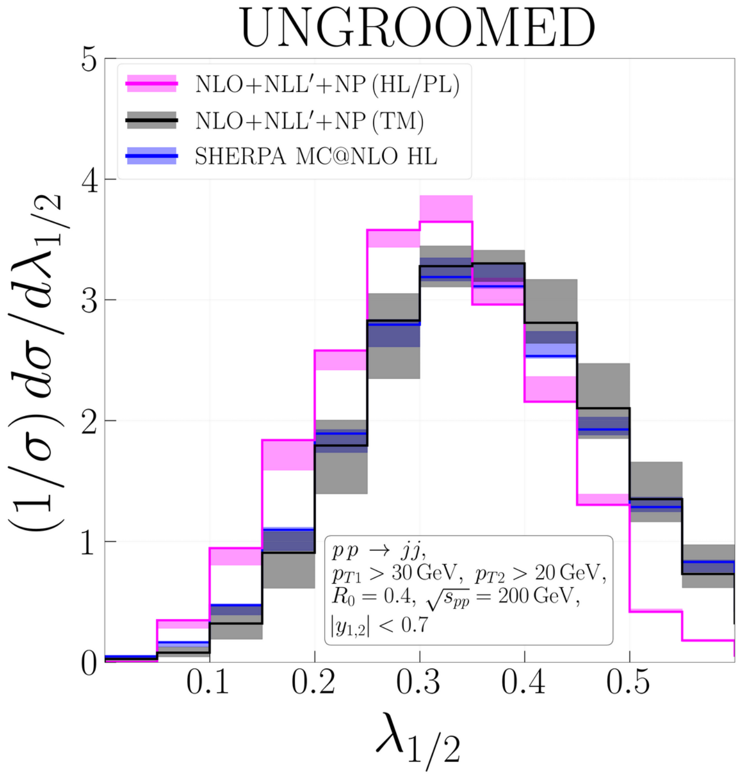


Transfer matrices (TM)



- Transfer matrices were obtained with SHERPA MC
- The information on correlation between partons and hadrons in each event is embedded
- The clearly visible off-diagonal structures indicate strong bin-migration caused by non-perturbative effects
- Unlike the approach of the shape functions the TM are not bounded to any particular functional form

TM vs. HL/PL ratio



- The approach based upon HL/PL ratio

$$\lambda_\alpha^{\mathrm{HL}} = \lambda_\alpha^{\mathrm{PL}} \times \left(\frac{\lambda_\alpha^{\mathrm{HL,MC}}}{\lambda_\alpha^{\mathrm{PL,MC}}} \right)$$

neglects bin migration

- Therefore, does nor provide correct shift of the distribution

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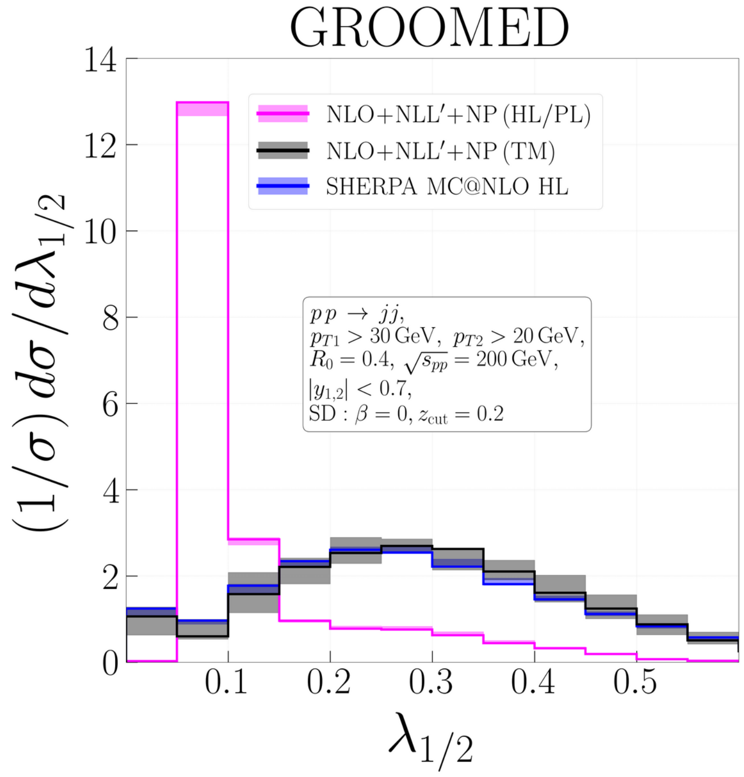

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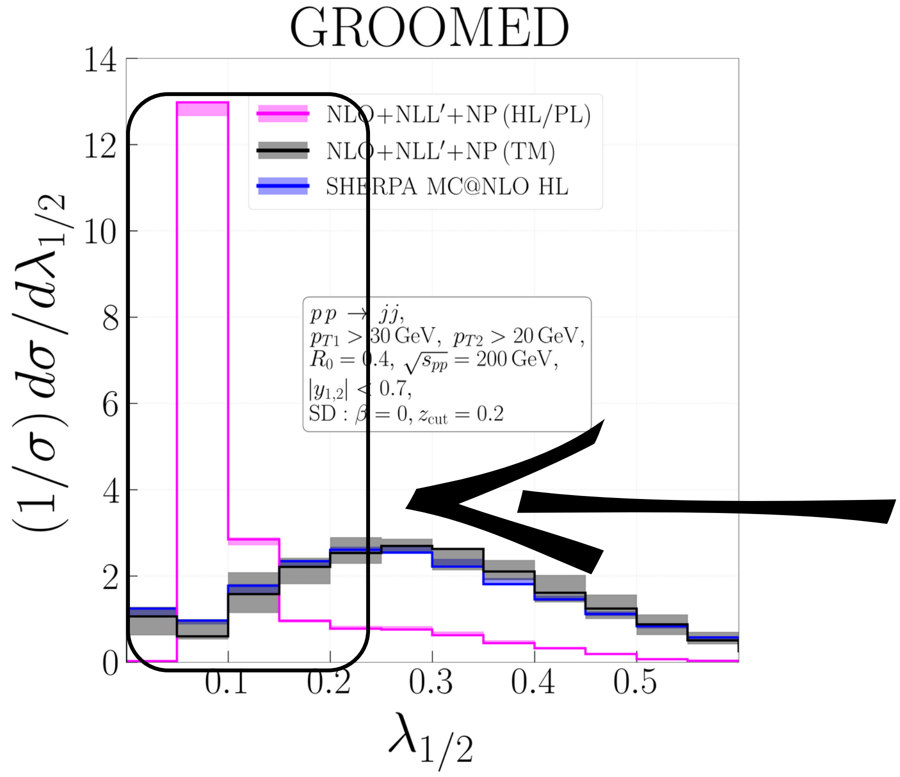
- Fails, especially for the groomed jets!

TM vs. HL/PL ratio



- The approach based upon HL/PL ratio

$$\lambda_\alpha^{\rm HL} = \lambda_\alpha^{\rm PL} \times \left(\frac{\lambda_\alpha^{\rm HL,MC}}{\lambda_\alpha^{\rm PL,MC}}\right)$$

  neglects bin migration

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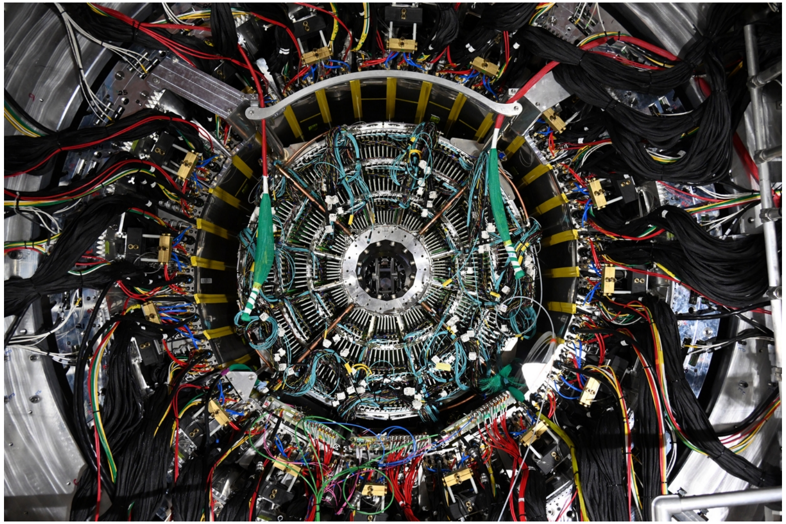
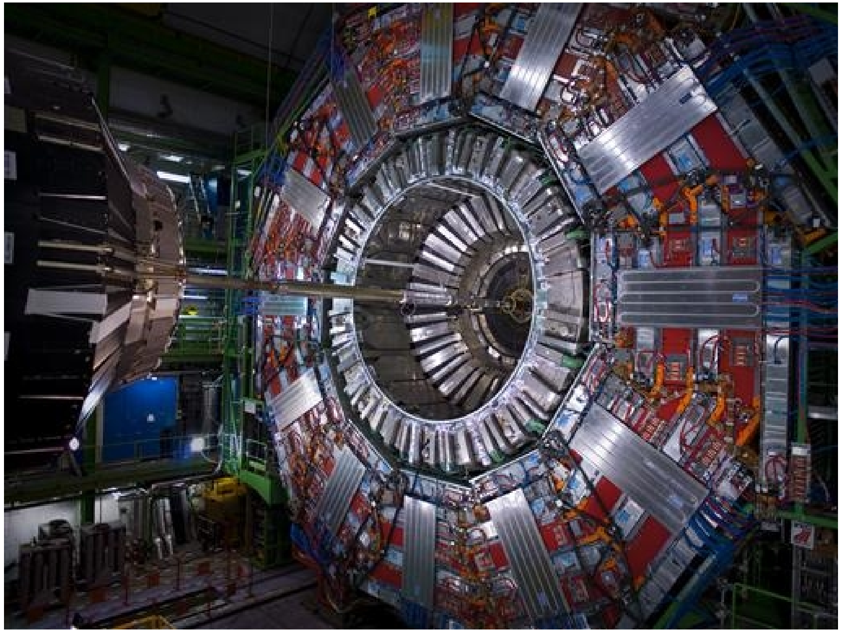
For the moment let’s move from RHIC to CMS

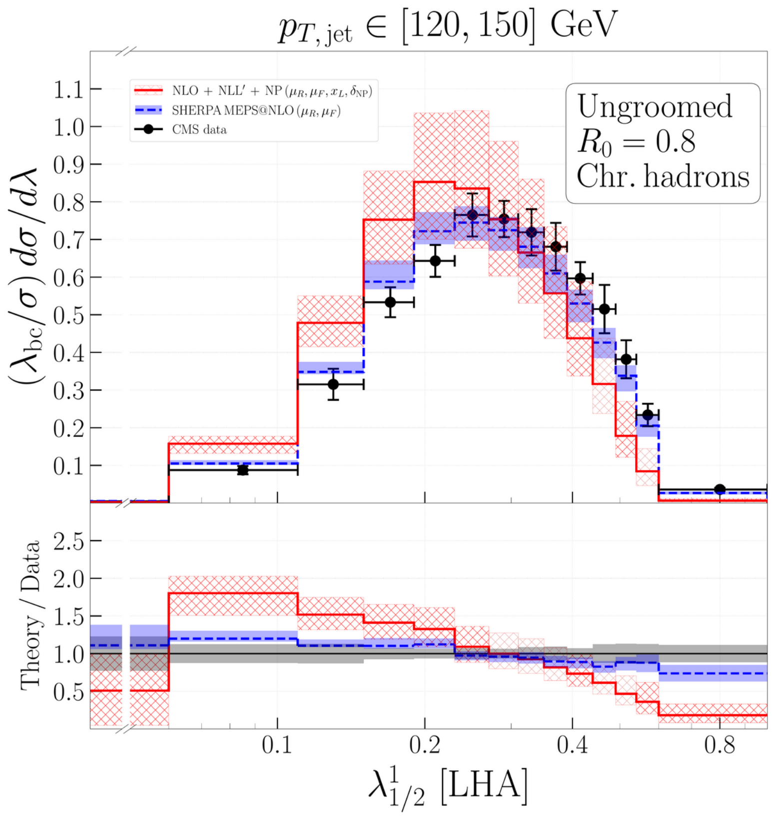


sPHENIX detector (credit: BNL)



CMS detector (credit: CERN)

TM vs. HL/PL ratio vs. CMS data (ungroomed jets)



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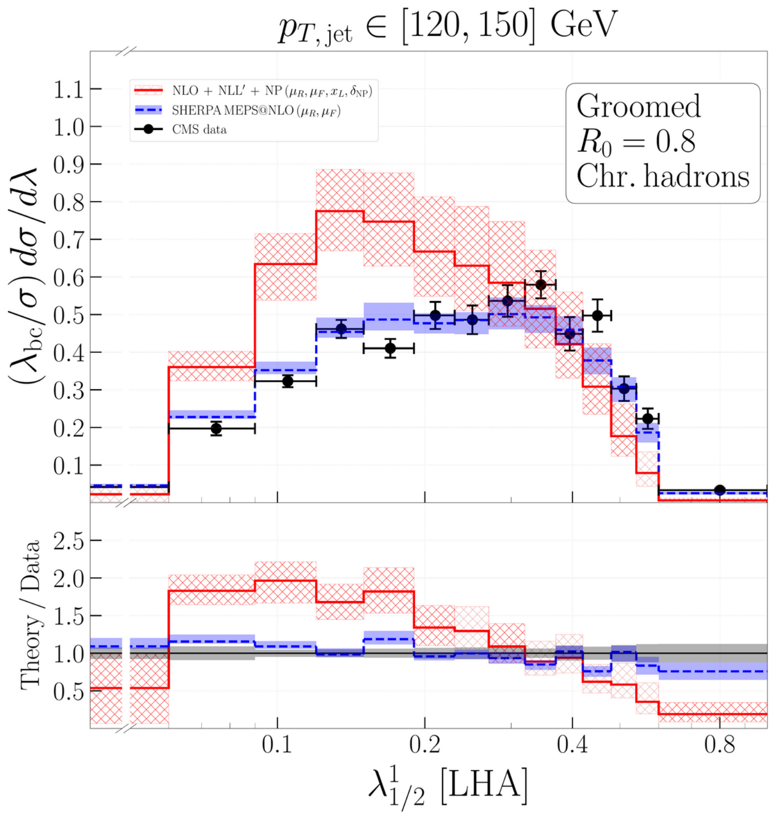
$$\lambda_\alpha^{\mathrm{HL}} = \lambda_\alpha^{\mathrm{PL}} \times \left(\frac{\lambda_\alpha^{\mathrm{HL,MC}}}{\lambda_\alpha^{\mathrm{PL,MC}}} \right)$$

neglects bin migration

- CMS data 2109.03340
- Theory 2112.09545 , 2104.06920

TM vs. HL/PL ratio vs. CMS data (groomed jets)



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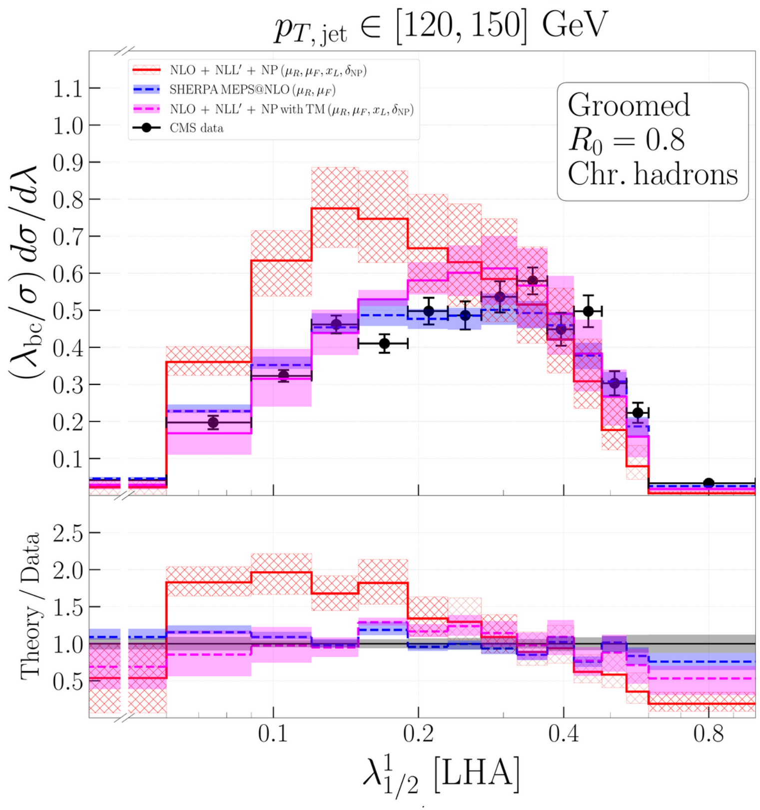

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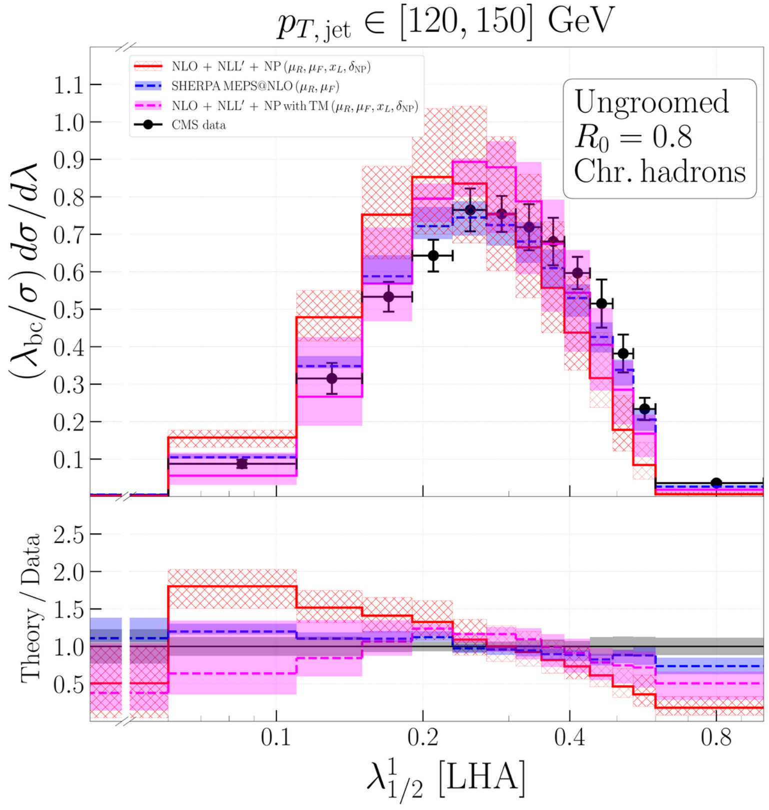

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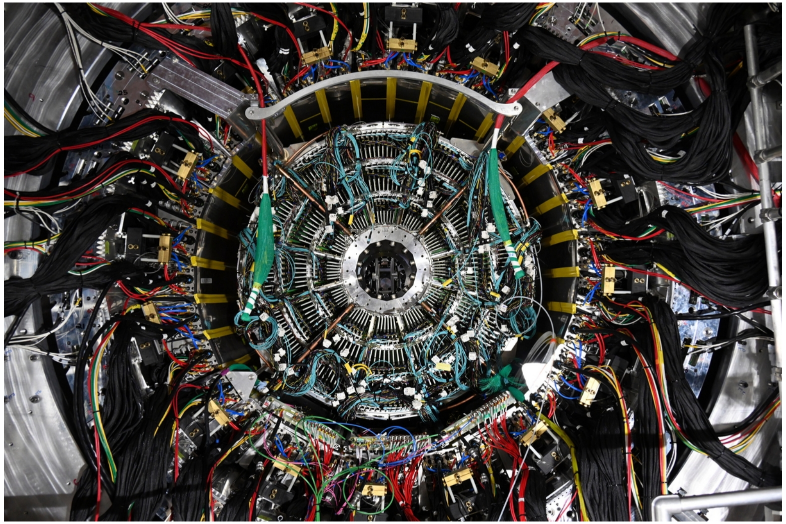
And now let's get back to sPHENIX



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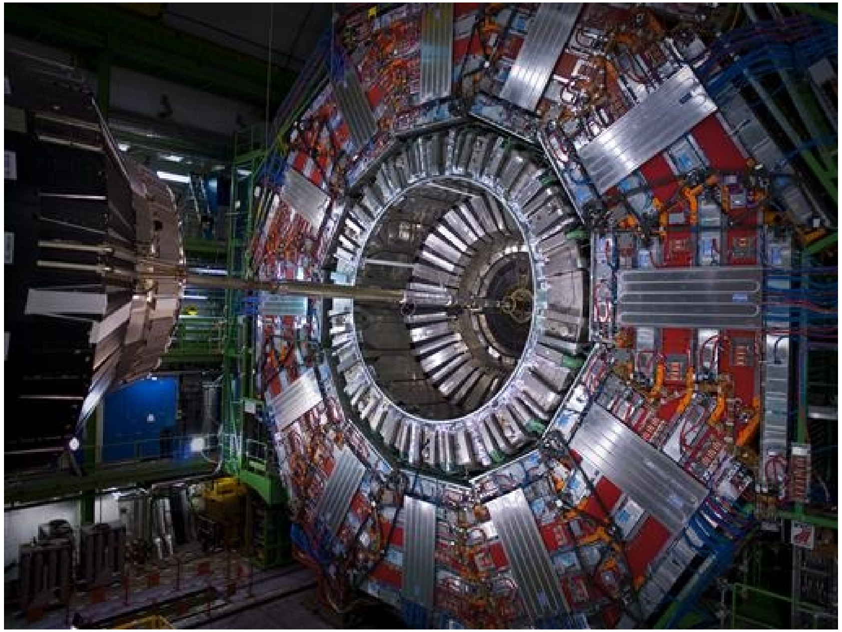
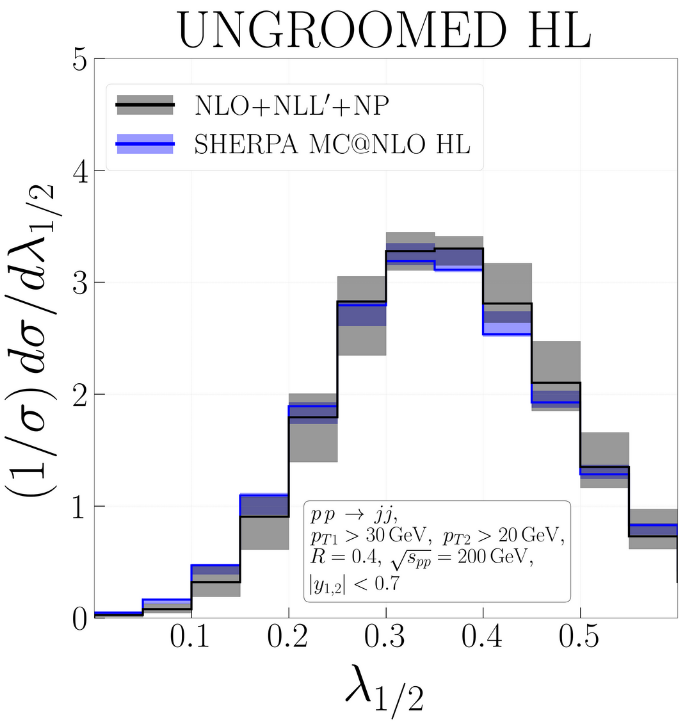


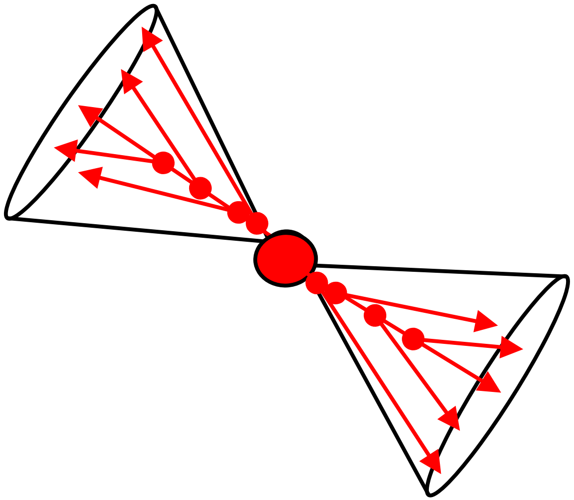
CMS detector (credit: CERN)

Main predictions: NLO+NLL'+NP results



- We corrected our NLO+NLL' results for non-perturbative effects using TM approach
- Our approach is more accurate than standard MC@NLO SHERPA simulations (SHERPA parton shower is at LL accuracy)
- Our uncertainty estimate is more accurate and includes variation of larger number of parameters
- Our results are automated and available as a resummation plugin to SHERPA

Impact of Quark-Gluon Plasma (QGP)



- We expect a new state of matter (called QGP) to born in AA and pA collisions
- Particles produced via hard QCD interaction and parton shower can interact with the QGP scattering centers

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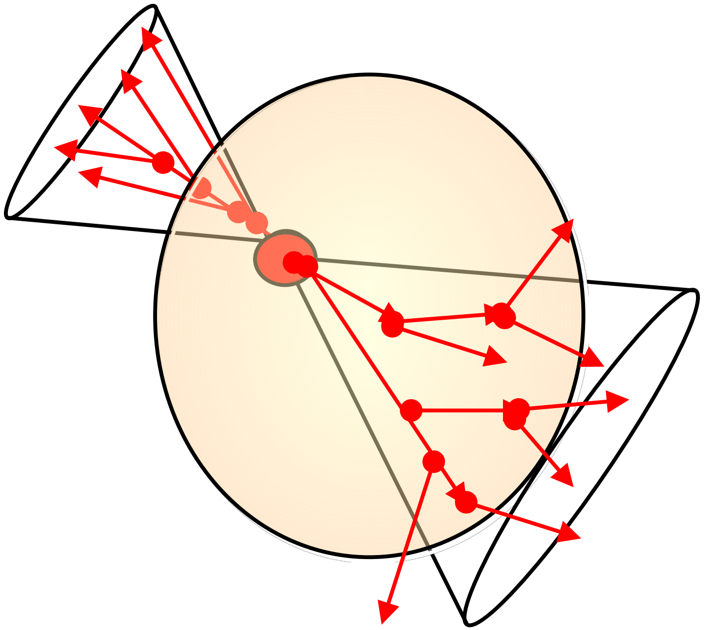

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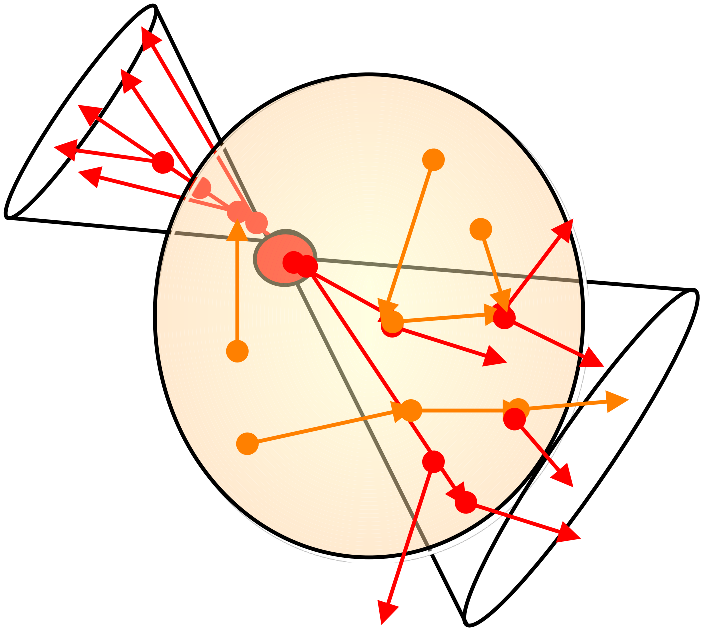

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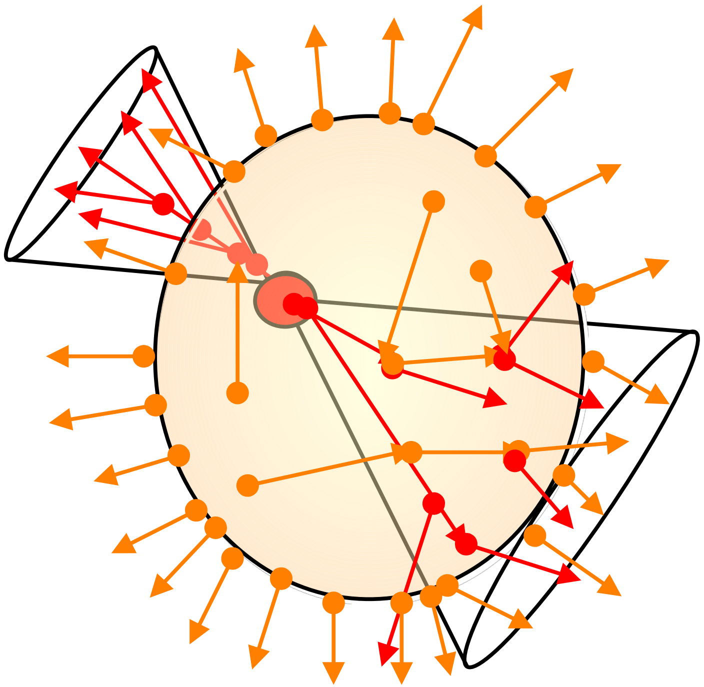
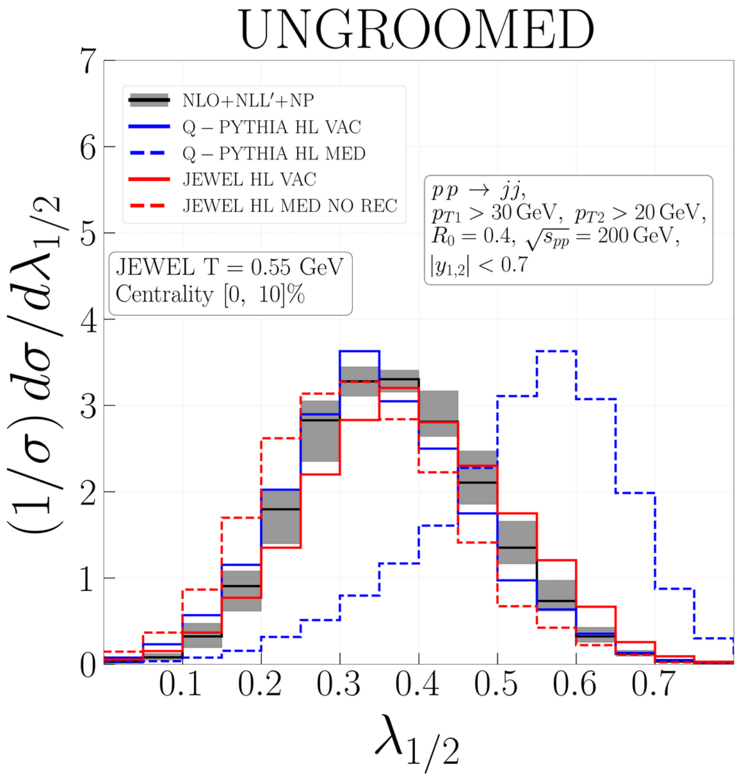


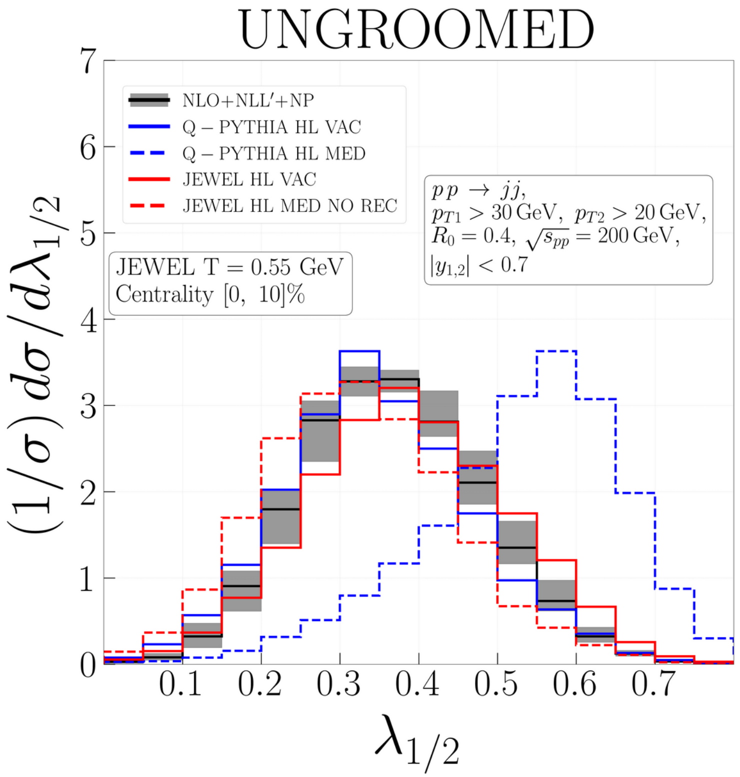
- We expect a new state of matter (called QGP) to born in AA and pA collisions
- QGP may have a significant impact on jet substructure generally known as jet quenching
- Particles produced via hard QCD interaction and parton shower can interact with the QGP scattering centers
- Thermalization of QGP creates a huge soft background

Impact of medium effects



- There are different MC models of jet-medium interactions, e.g. HIJING, JEWEL, PQM, HYBRID, JETSCAPE, Q-Pythia, LBT…
- We used two light-weighted Pythia6 based MC models: Q-Pythia and JEWEL
- Q-Pythia: is using modified Altarelli-Parisi splitting functions (BDMPS-Z formalism)
- JEWEL: 2-to-2 rescatterings between parton shower partons and QGP scattering centers is included in parton shower evolution

Impact of medium effects



- Q-Pythia is, essentially, Pythia-6 with modified parton shower
- Parton shower is unitary and hence conserves energy

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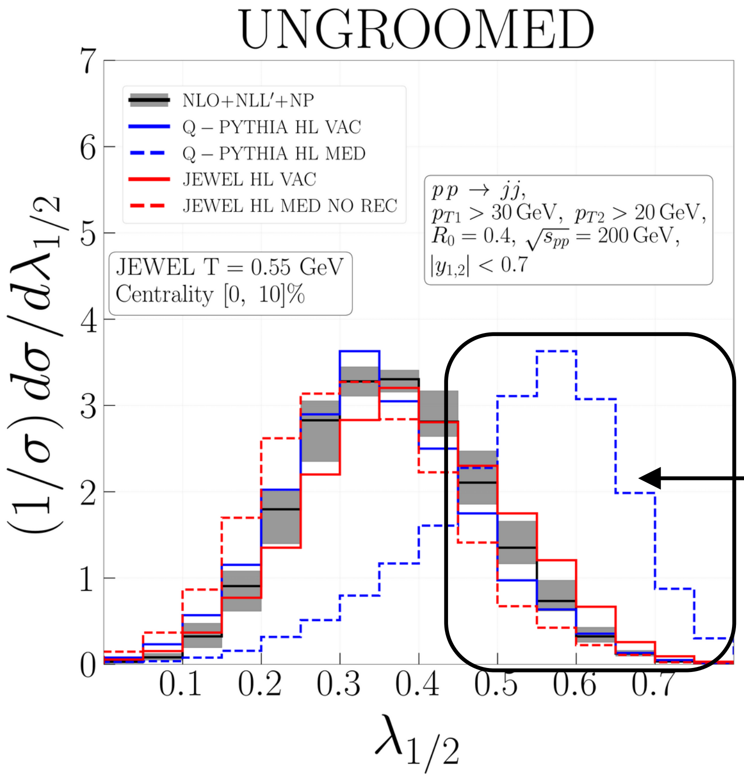

- Q-Pythia is, essentially, Pythia-6 with modified parton shower
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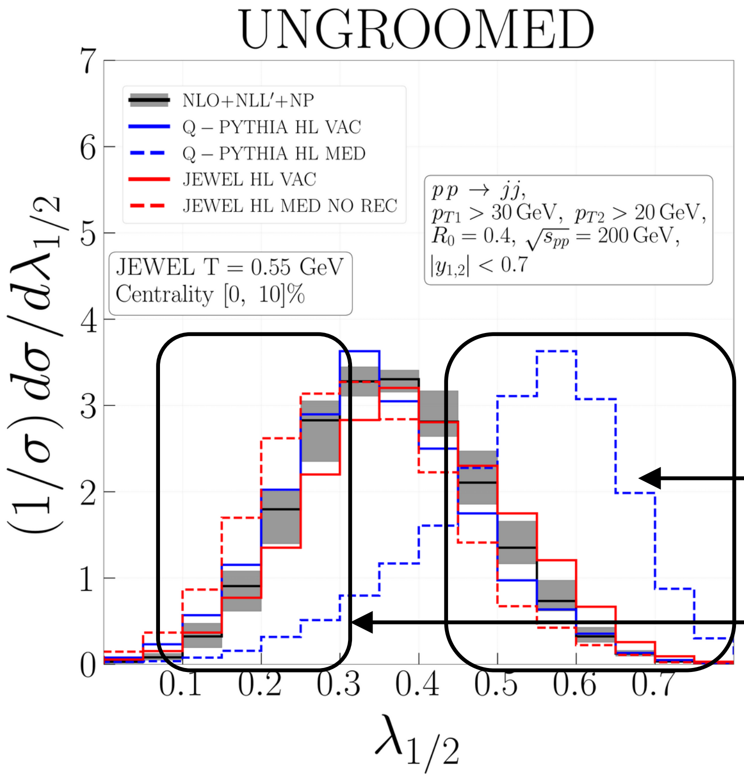
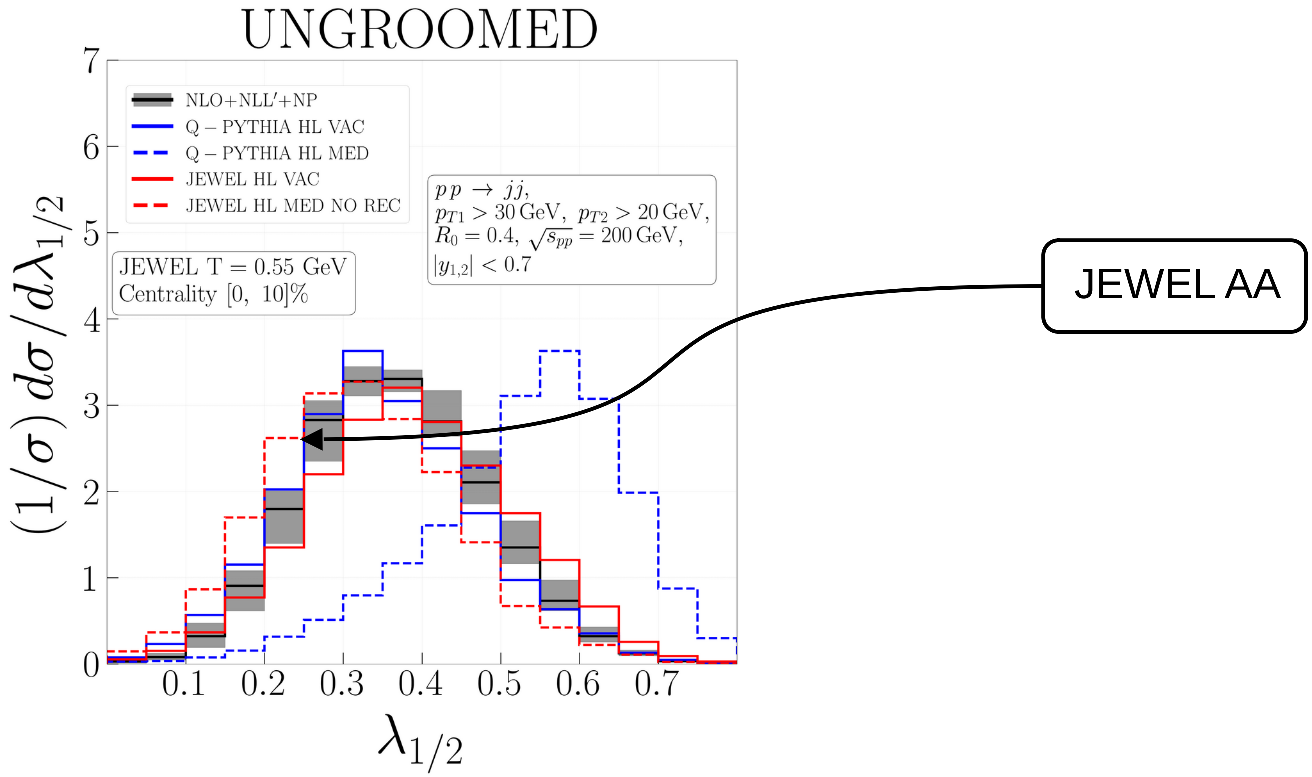


- Q-Pythia is, essentially, Pythia-6 with modified parton shower
- Parton shower is unitary and hence conserves energy
- As a consequence there is no energy exchange between “QGP medium” and parton shower which has drastic consequences
- JEWEL, in turn, “injects” QGP particles into parton shower evolution which leads to energy exchange between QGP and parton shower

Solid understanding of the vacuum case is required



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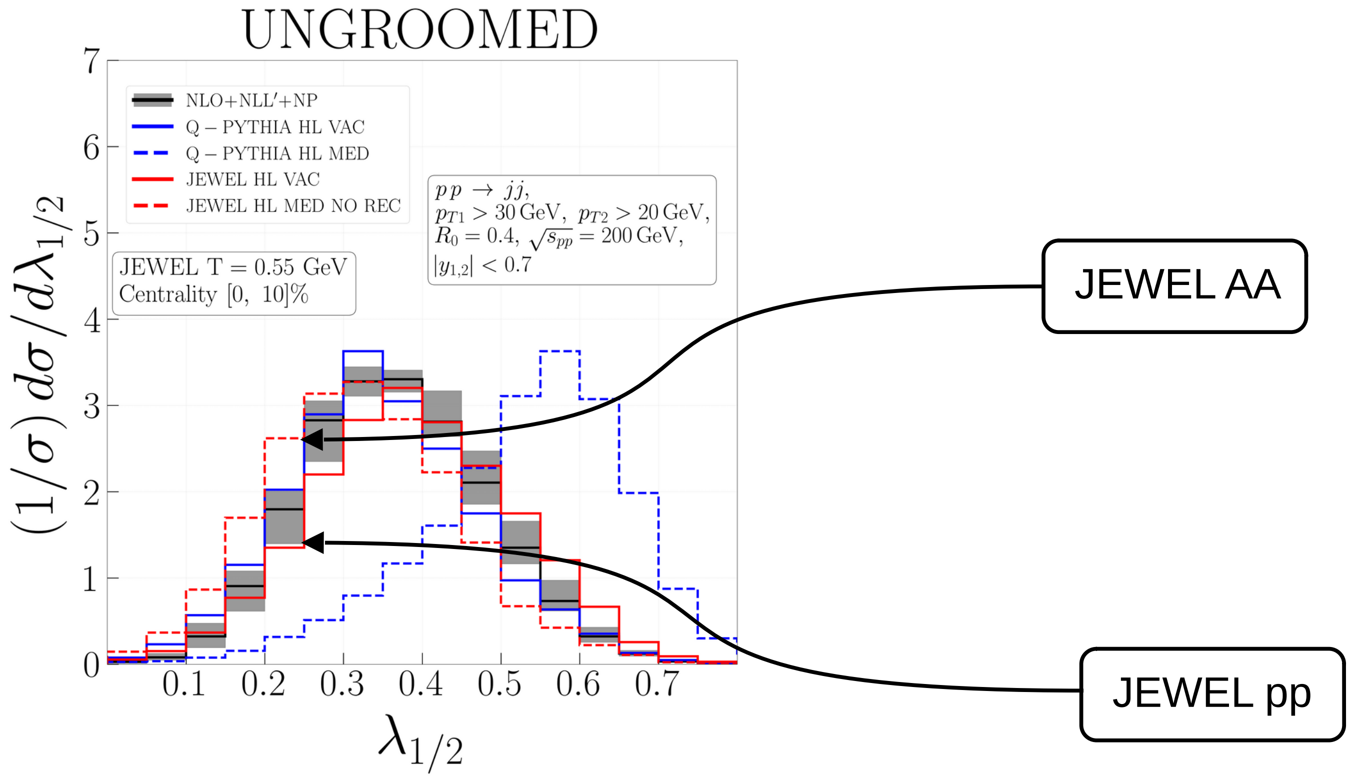

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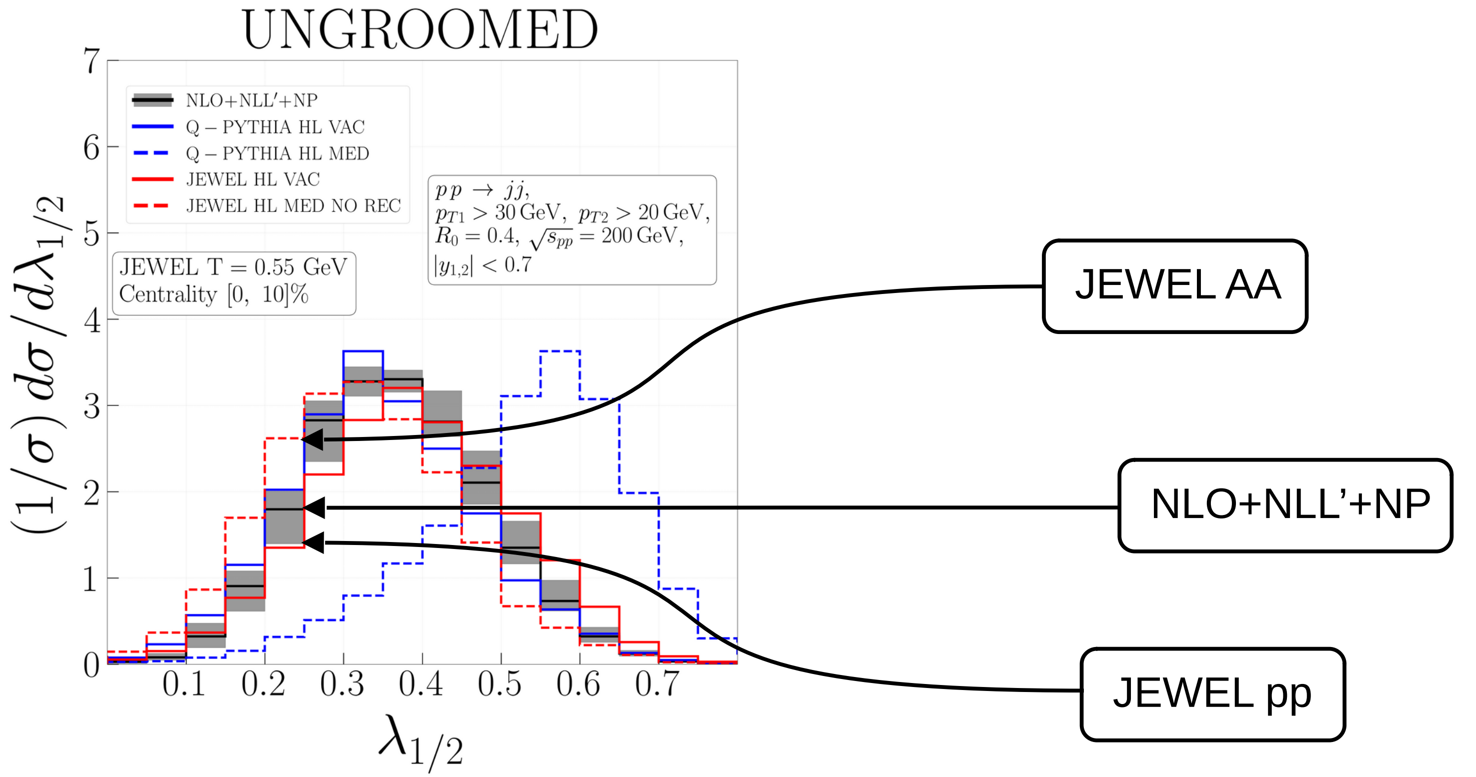

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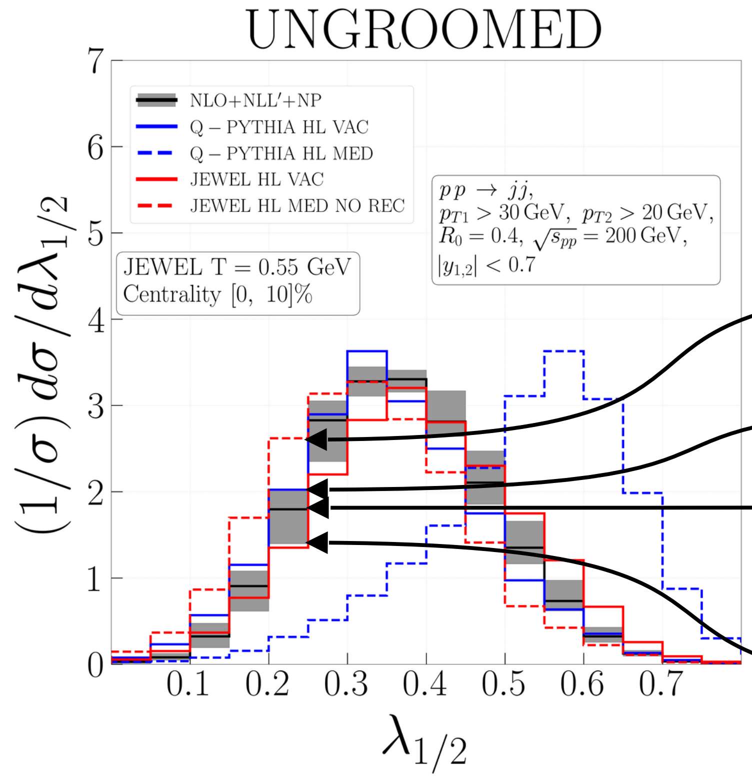

Neither Q-Pythia pp nor JEWEL pp predictions do not agree with our NLO+NLL'+NP results!

Summary

- We obtained NLO+NLL’ accuracy level results for 3 different types of jet angularities:

  Les-Houches Angularity (LHA), Jet Width and Jet Thrust for both groomed and ungroomed jets. These results are automated (as a SHERPA MC plugin) and are available on request
- We found that MPI at RHIC are strongly suppressed and the non-perturbative contribution to the jet substructure is given mostly by hadronization (fragmentation) effects.
- The hadronization corrections were incorporated via transfer matrices extracted from SHERPA MC
- At RHIC hadronization causes strong bin-migration (significantly off-diagonal transfer matrices)
- Jet substructure can be used to test jet quenching models however a solid understanding of the vacuum case is required.
- The obtained AA results suggest necessity to improve the Q-Pythia model

THANK YOU FOR LISTENING!