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

In collaboration with Yang-Ting Chien, Daniel Reichelt and Steffen Schumann

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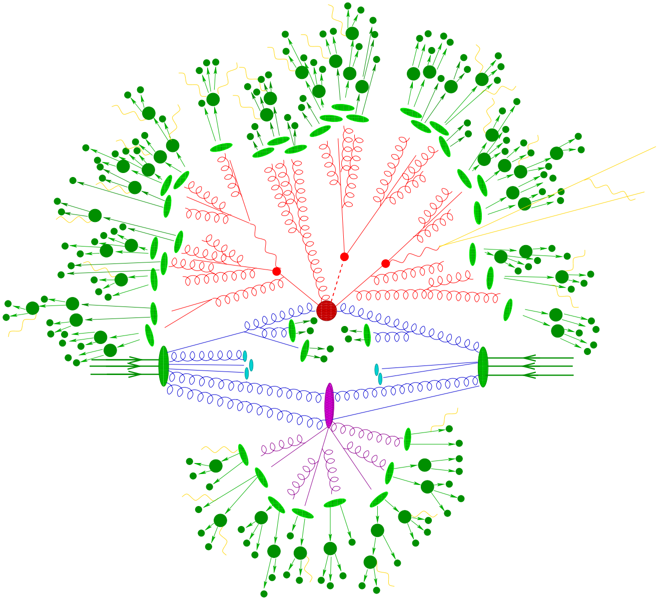
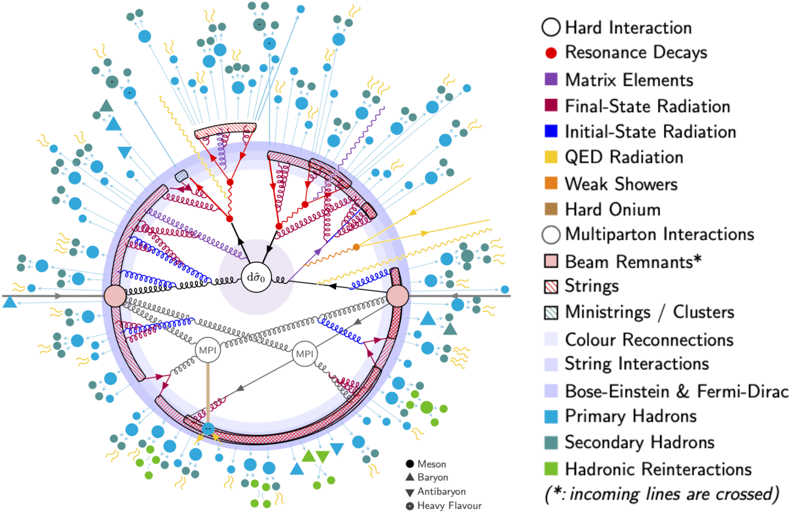
October 16, 2023

QCD is complicated!



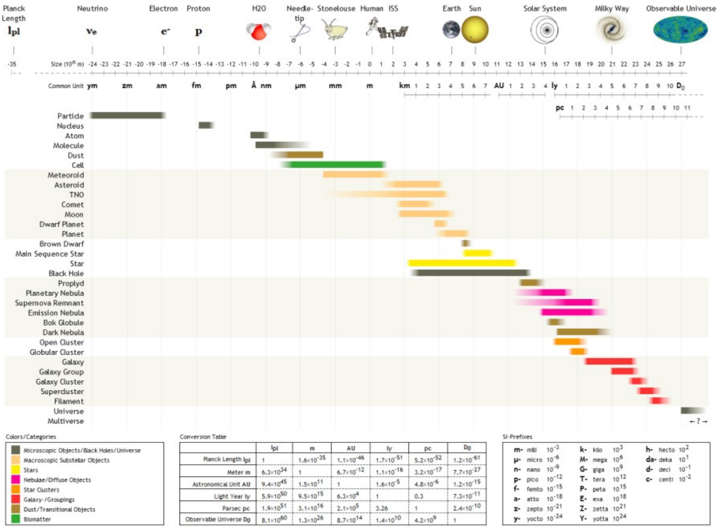
"Old event representation", credit: arXiv:0811.4622.

QCD is very complicated!



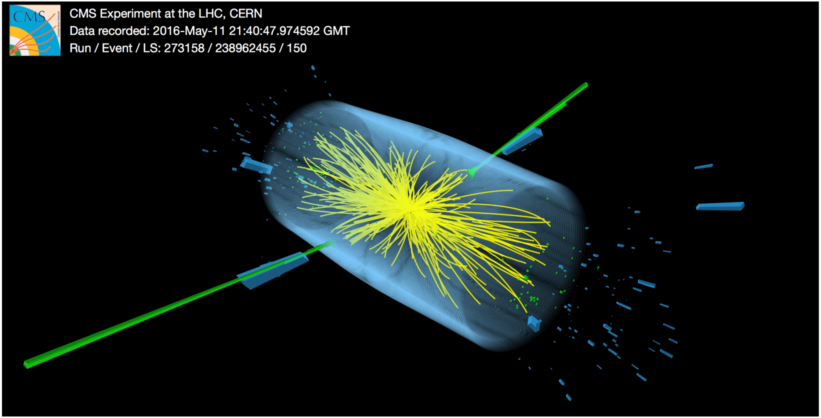
"New event representation", credit: Peter Skunds.

Physics is all about scales!



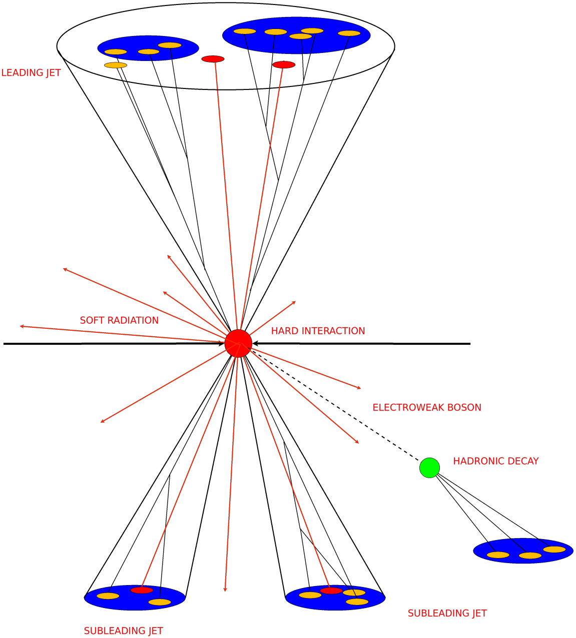
Typical scales of this Universe (credits: Wikipedia)

By studying hadrons inside jets we try to learn more about partons and their interactions

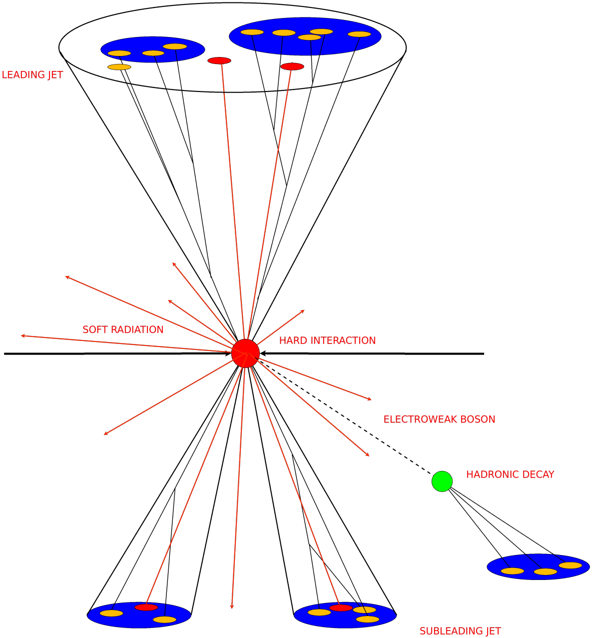


A di-jet event recorded by CMS collaboration (credits: CERN)

Looking inside jets



SoftDrop groomer: $\frac{\min(p_{ti}, p_{tj})}{p_{ti}+p_{tj}} > z_{\rm cut} \left(\frac{\Delta R_{ij}}{R}\right)^{\beta}$



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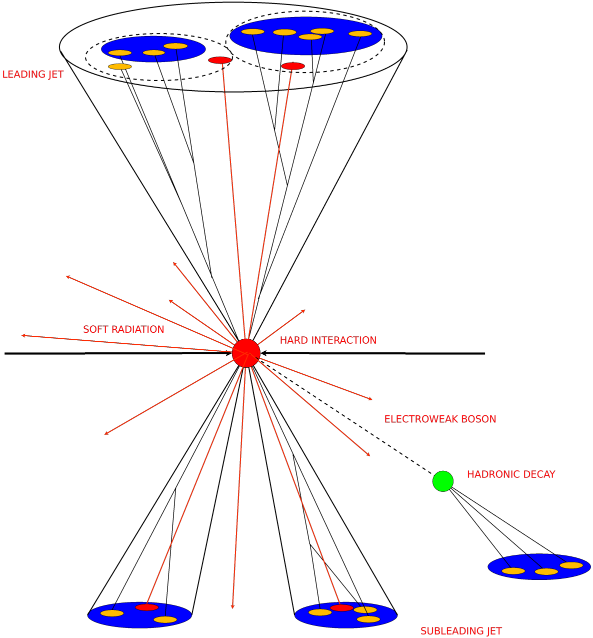

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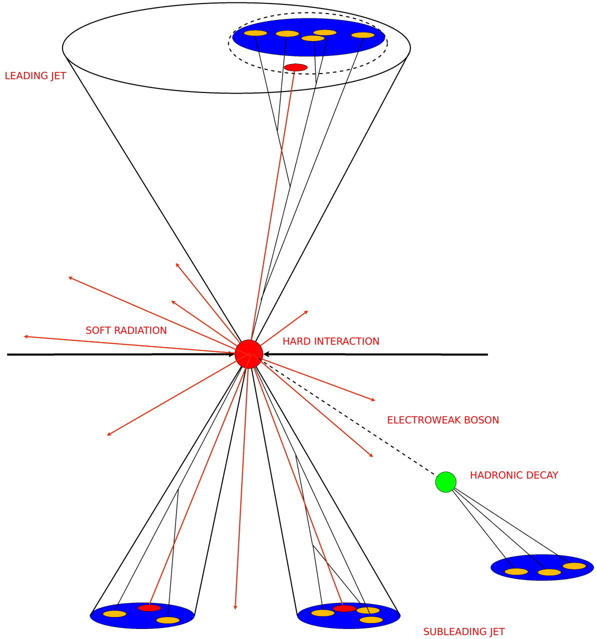

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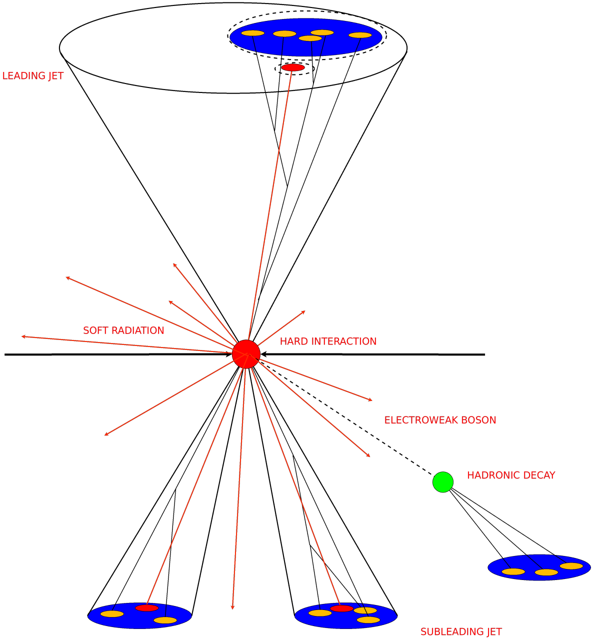

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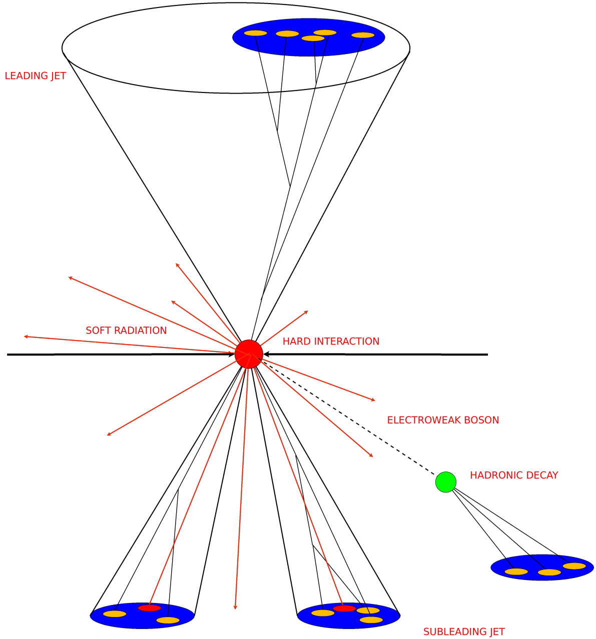
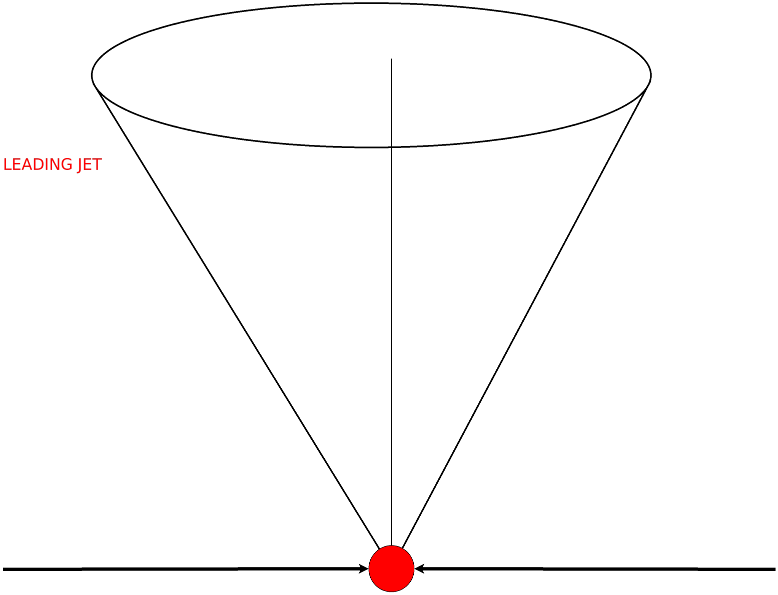


Resummation vs. Monte Carlo



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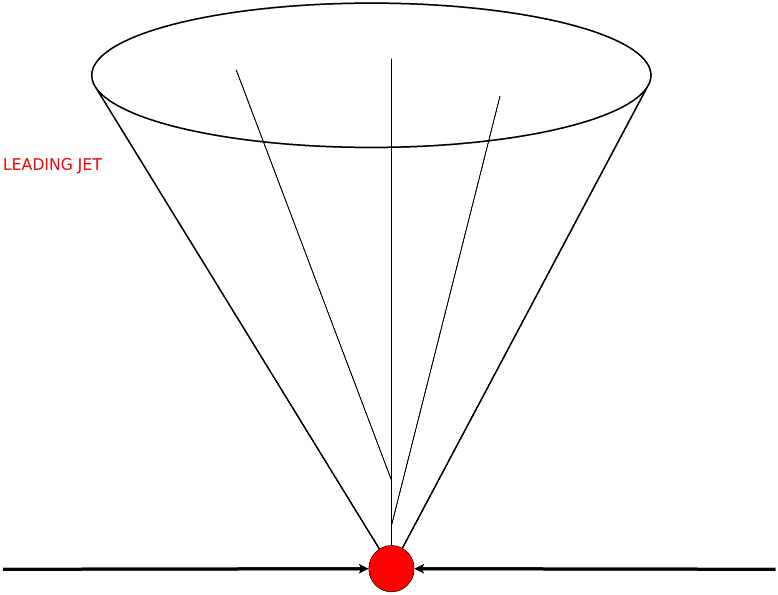

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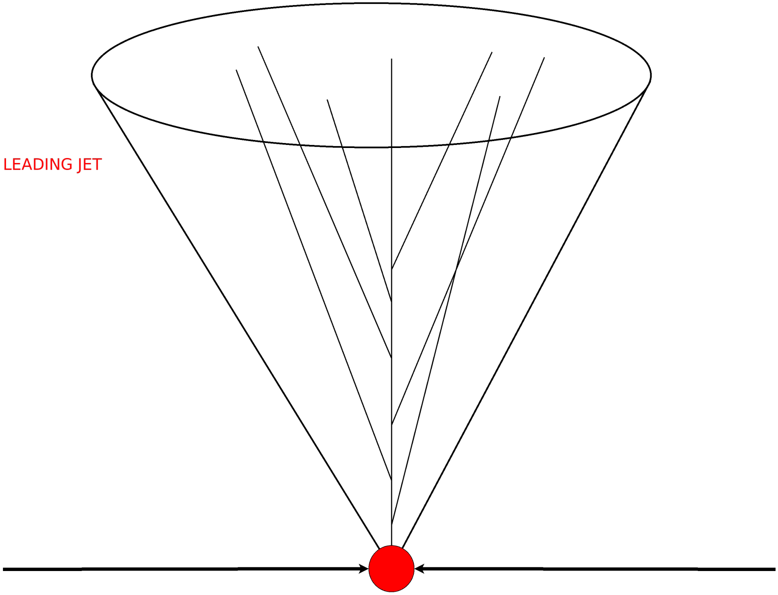

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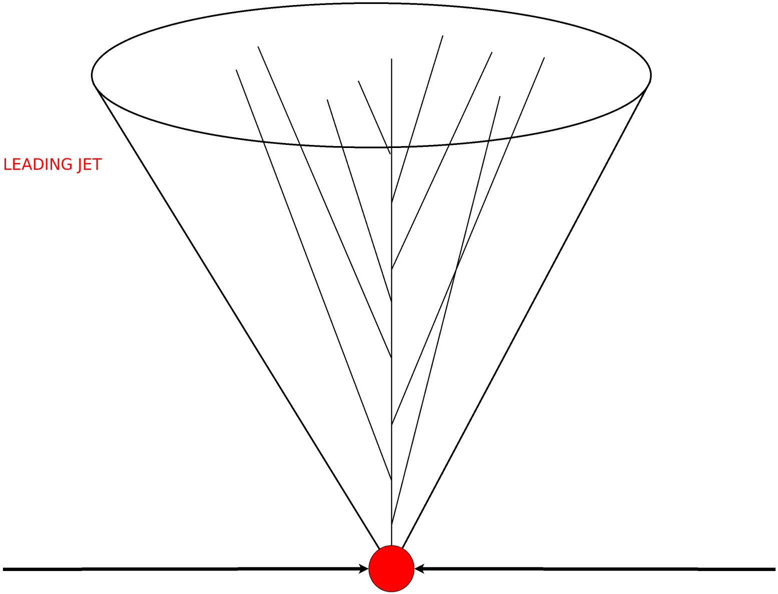

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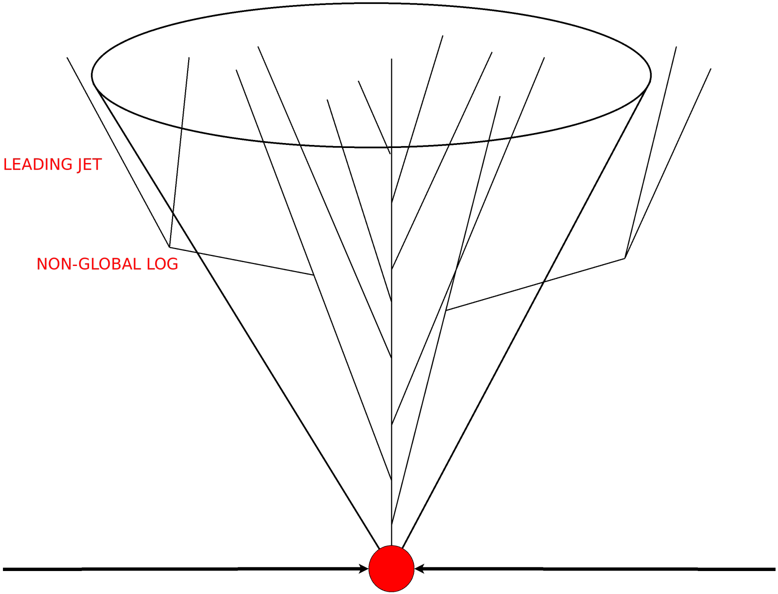

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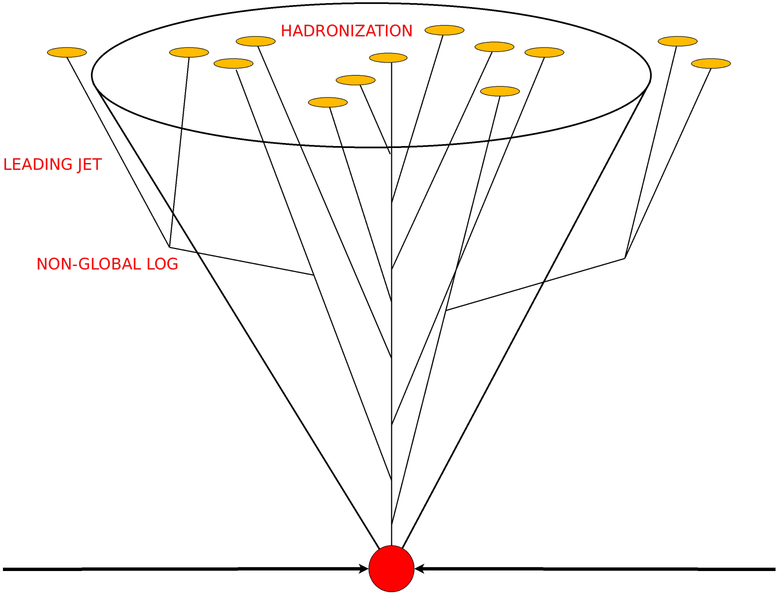

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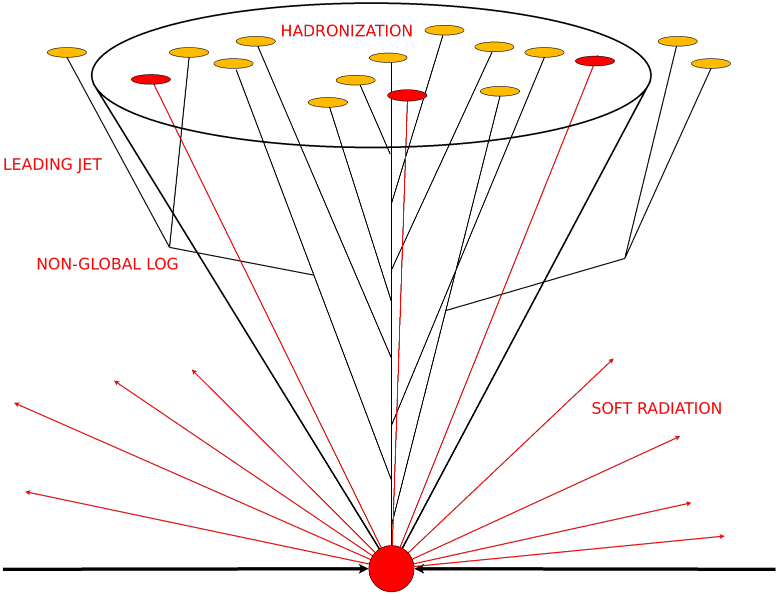

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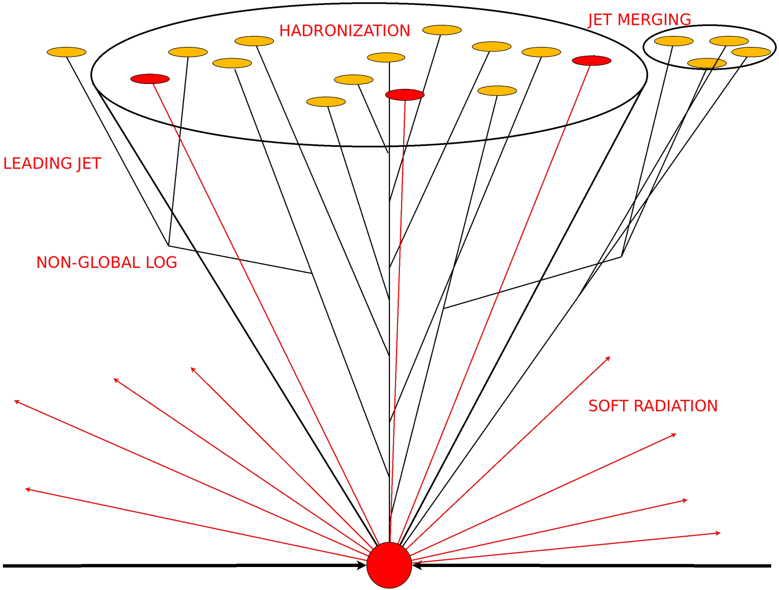
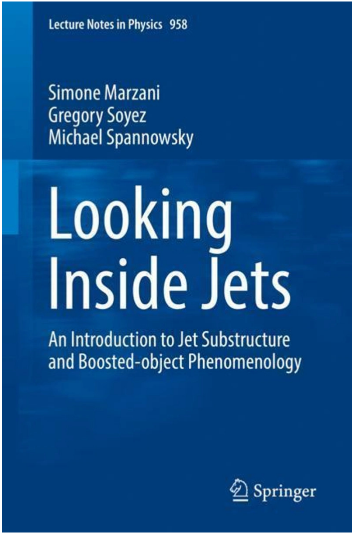


Looking inside jets

Various observables exist:

- N-subjettiness,
- **Jet angularities**,
- Energy-correlation functions,
- Lund plane projection,
- **Angular decorrelation**,
- and many others!



More info can be found here

Observable definition

The jet angularity is defined as

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

The angular decorrelation is defined as

$$\Delta\phi_{\mathrm{p}_1,\mathrm{p}_2} = \arccos\left(\frac{\vec{p}_1 \cdot \vec{p}_2}{|\vec{p}_1||\vec{p}_2|} \right)$$

SoftDrop grooming condition:

$$\frac{\min(p_{ti}, p_{tj})}{p_{ti} + p_{tj}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{ij}}{R} \right)^\beta$$

- The LHC measurements LHA ($\lambda_{1/2}$), Jet Width (λ_1), Jet Thrust (λ_2), see, for example, 2109.03340
- The theoretical predictions, see, for example 2112.09545, 2104.06920 and 2005.12279
- RHIC measurements?

CAESAR formalism

The cumulative cross section for a generic observable v can be written as a sum over partonic channels δ:

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

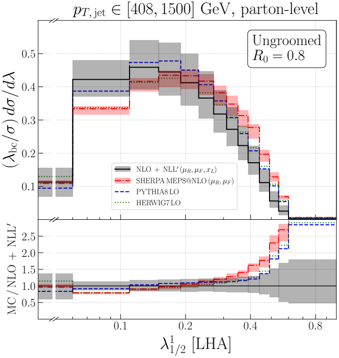
$$\Sigma_{\rm res}^{\delta}(v) = \int d\mathcal{B}_{\delta} \frac{d\sigma_{\delta}}{d\mathcal{B}_{\delta}} \exp\left[-\sum_{l\in\delta} R_l^{\mathcal{B}_{\delta}}(L)\right] \mathcal{P}^{\mathcal{B}_{\delta}}(L) \mathcal{S}^{\mathcal{B}_{\delta}}(L) \mathcal{F}^{\mathcal{B}_{\delta}}(L) \mathcal{H}^{\delta}(\mathcal{B}_{\delta})\,,$$

where $L = -\ln(v)$, $\frac{d\sigma_{\delta}}{d\mathcal{B}_{\delta}}$ is the differential Born cross section, R_l is the collinear radiator for the hard legs l, $\mathcal{P}$ is the ratio of PDFs, $\mathcal{S}$ is the soft function, $\mathcal{F}$ is the multiple emission function and $\mathcal{H}$ stands for the corresponding kinematic cuts on the Born process.

CAESAR resummation plugin to Sherpa

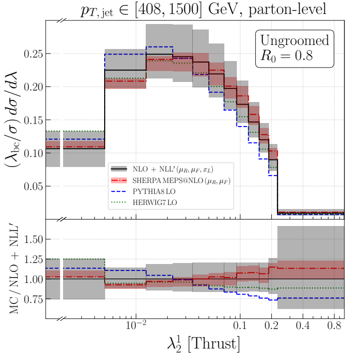
- Is using Comix matrix element generator as well as Sherpa machinery for phase-space integration and event generation.
- The NLO computations are performed using Catani-Seymour dipole subtraction.
- For the loop computations we use Recola and OpenLoops libraries.
- The resummed results are matched to the fixed order NLO computations using the multiplicative matching scheme.
- The final result is at NLO+NLL$'$ accuracy level + corrections for the non-perturbative effects.

Monte Carlo results: LHA



Comparison of hadron-level predictions for ungroomed and groomed jet-angularities in Zj production from Pythia and Herwig (both based on the LO Zj matrix element), and MEPS@LO as well as MEPS@NLO results from Sherpa. Here we use SoftDrop with $\beta = 0$ and $z_{\mathrm{cut}} = 0.1$.

Monte Carlo results: Jet Thrust



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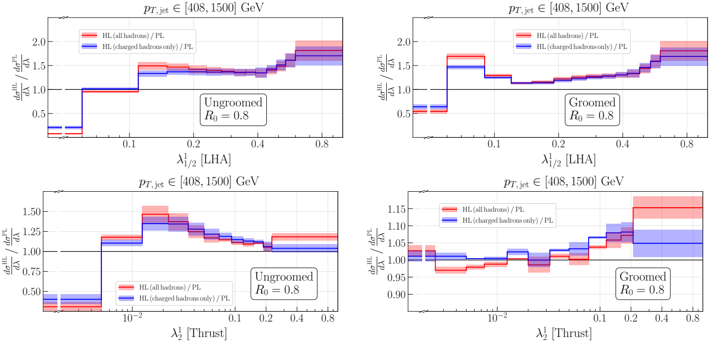
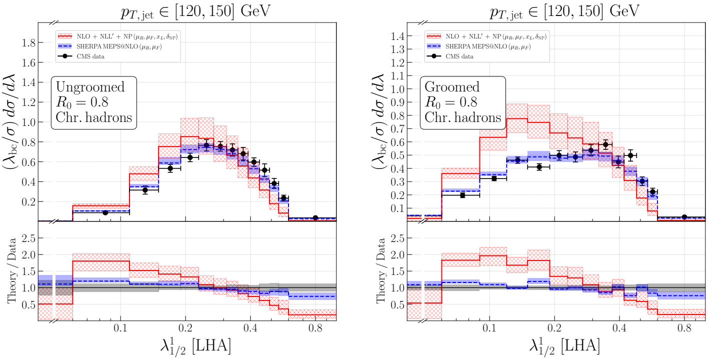
Impact of NP-corrections

One can estimate the impact of non-perturbative corrections using Monte Carlo simulations



Hadron-to-parton-level ratios with associated uncertainties extracted from MC simulations (Pythia, Herwig and Sherpa). To some extent can be seen as a jet fragmentation function.

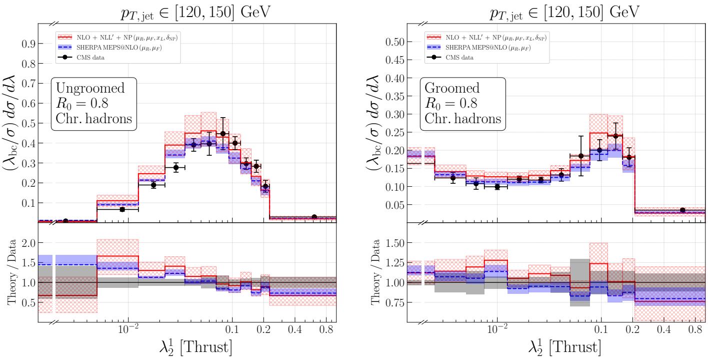
Theory vs. CMS data



Comparison against recent CMS data for the LHA angularity, $p_{T,\text{jet}} \in [120, 150]$ GeV.

Theory: 2112.09545, 2104.06920 (in collaboration with S. Caletti, S. Marzani, D. Reichelt, S. Schumann, G. Soyez, V. Theeuwes); CMS: 2109.03340

Theory vs. CMS data



Comparison against recent CMS data for the Jet Thrust angularity, $p_{T,\text{jet}} \in [120, 150]$ GeV.

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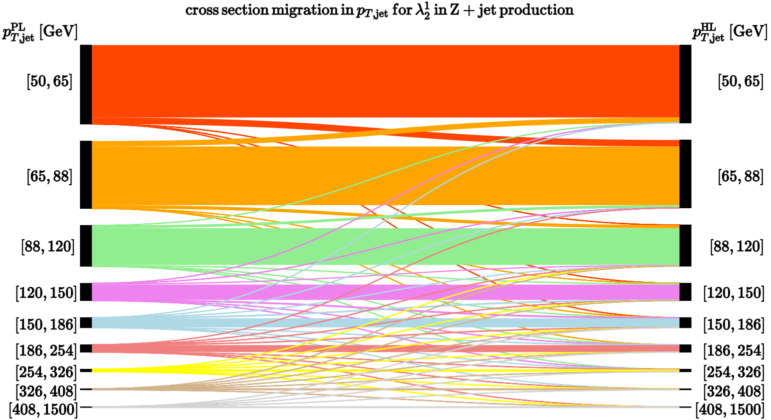
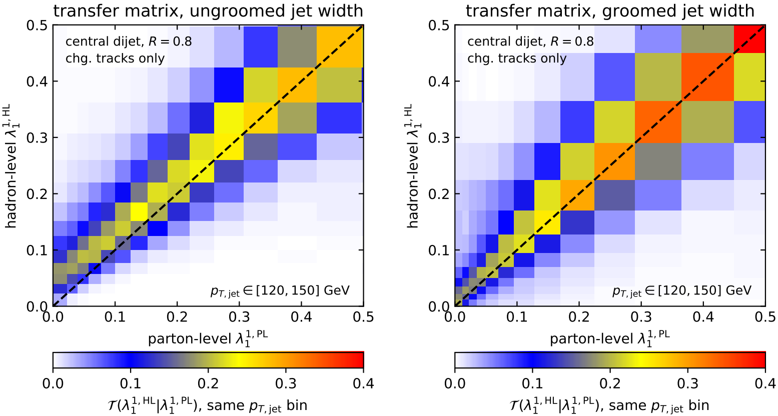
Migration between different p_T-bins; credit S. Schumann



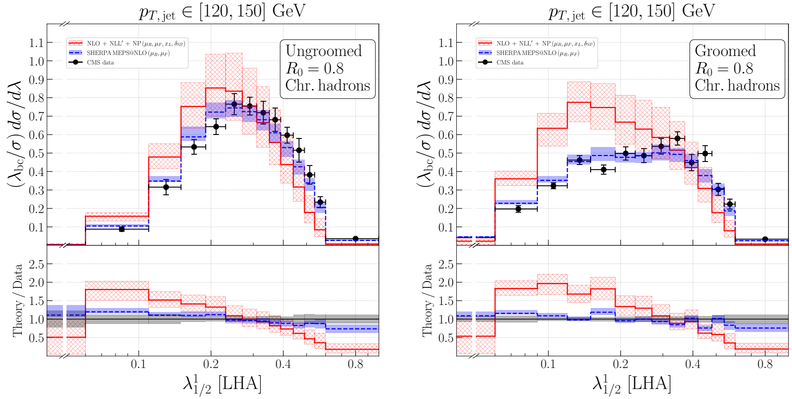
Hadronization can cause migration between different p_T-bins.

Parton to hadron level transition; credit G. Soyez



Transfer matrix $\mathcal{T}(\lambda_1^{1,\mathrm{HL}}|\lambda_1^{1,\mathrm{PL}})$ for the jet-width angularity for central dijet events with $R = 0.8$ and $p_{T,\mathrm{jet}} \in [120, 150]$ GeV.

Theory (including TM) vs. CMS data



Comparison against recent CMS data for the Jet Thrust angularity, $p_{T,\mathrm{jet}} \in [120, 150]$ GeV. Magenta band correspond to transfer matrix approach.

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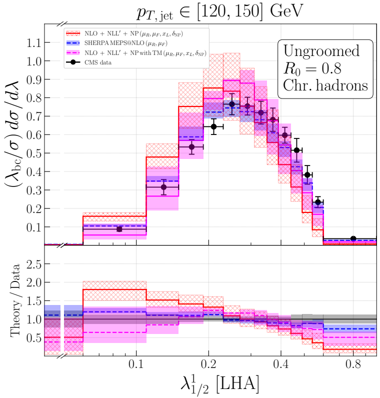
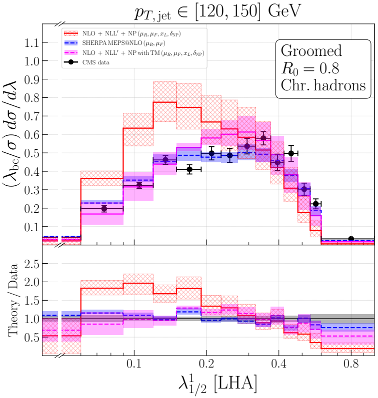
Theory (including TM) vs. CMS data





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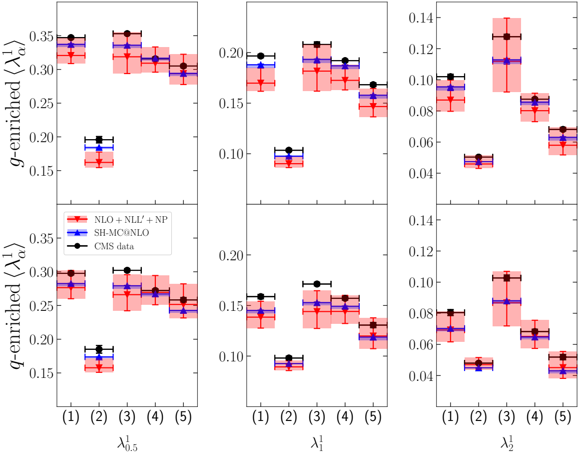
Comparison against CMS data



configuration	type of jet	$p_{T,\text{jet}}$ [GeV]	g-enriched	q-enriched
(1)	ungroomed $R = 0.4$	[120,150]	dijet central	Z+jet
(2)	ungroomed $R = 0.4$	[1000,4000]	dijet central	dijet forward
(3)	ungroomed $R = 0.8$	[120,150]	dijet central	Z+jet
(4)	ungroomed $R = 0.4$ (tracks only)	[120,150]	dijet central	Z+jet
(5)	SoftDrop ($\beta = 0$, $z_{\text{cut}} = 0.1$) $R = 0.4$	[120,150]	dijet central	Z+jet

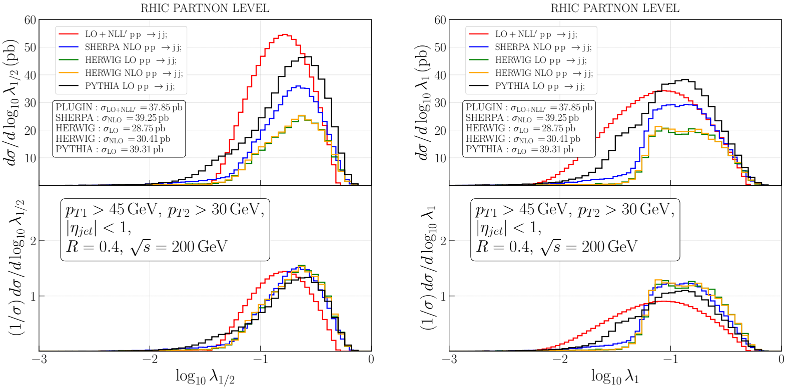
What about RHIC?

> And Now for Something Completely Different
>
> *Monty Python's Flying Circus*

At RHIC

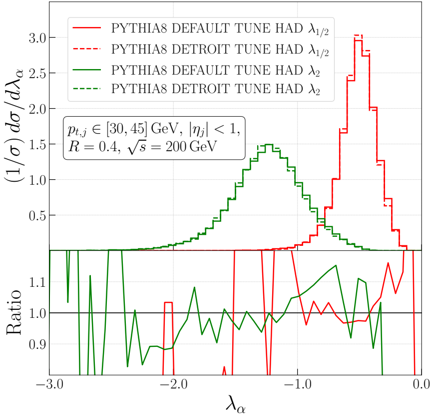
- MPIs are less relevant ($\sqrt{S}$ is small comparing to the LHC)
- Hadronization is more important (small $\sqrt{S}$ and small jet p_T)
- Completely different energy regime
- One can study jets in pp and AA
- Only few jet substructure studies (STAR) are available 1705.01974
- The sPHENIX data can be used to produce new tunes, to test currently available precise predictions, to get better understanding of hadronization

$\lambda_\alpha = \sum_i z_i \left(\frac{\Delta_{i,jet}}{R}\right)^\alpha$ at RHIC energy, Res. vs. MC



Comparison between resummed predictions matched to fixed order results (SHERPA $\mathrm{LO}+\mathrm{NLL}'$ accuracy level) against MC simulations (preliminary)

$\lambda_\alpha = \sum_i z_i \left(\frac{\Delta_{i,jet}}{R}\right)^\alpha$ at RHIC energy, Detroit PYTHIA tune

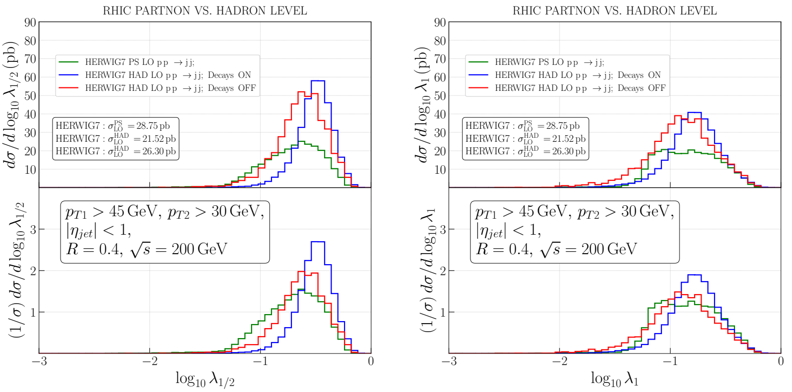


(preliminary)

Shall one make new tunes?

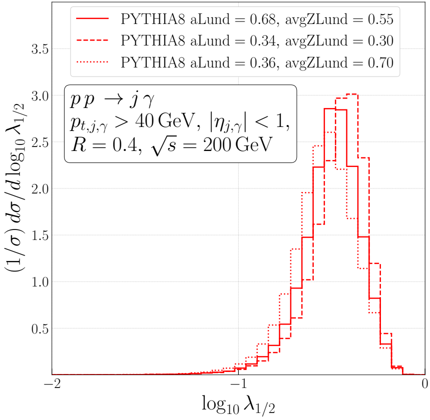
- There is a Detroit PYTHIA tune 2110.09447 for RHIC, but it mostly affect MPI
- However, MPI are almost absent at RHIC energies
- Main contribution comes from hadronization

$\lambda_\alpha = \sum_i z_i \left(\frac{\Delta_{i,jet}}{R}\right)^\alpha$ at RHIC energy, hadronisation and dacays



Angularities at RHIC energies are strongly affected by hadronization and decay of produced hadrons in case of jets containing a single hadron, see also Lee *et al* in 1901.09095. (preliminary)

Hadronization and Lund string model



(preliminary)

New tunes?

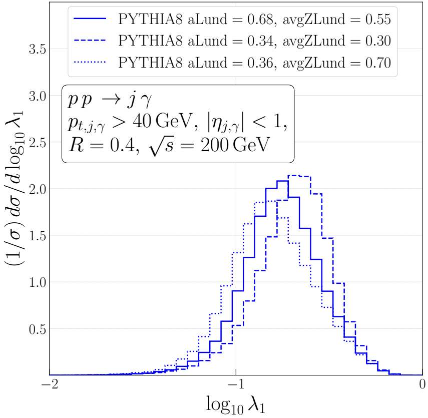
- There is a Detroit PYTHIA tune 2110.09447 designed to describe RHIC data, but it mostly affect MPI
- However, MPI are almost absent at RHIC energies $\sqrt{S}$ is too small.
- Lund symmetric fragmentation function

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

- Hadron formation time

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

Hadronization and Lund string model



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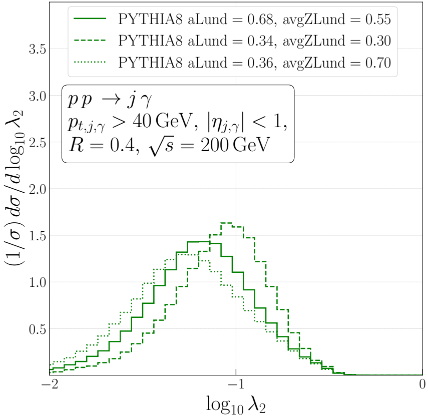

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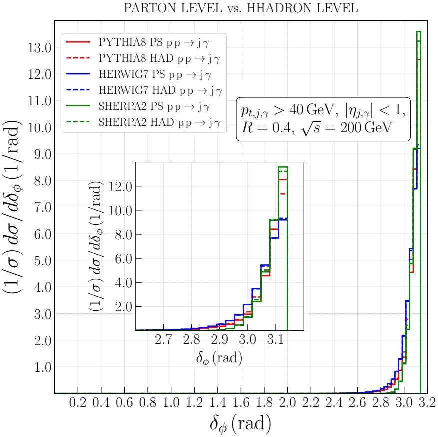
Is $\delta\phi$ affected by NP-corrections?



(preliminary)

Angular decorrelation

- $\Delta\phi$ is an azimthal angle between two most energetic jets (or between a leading jet and a leading photon)
- Unlike λ_α is more sensitive to radiation pattern
- Which PS-model would work better?

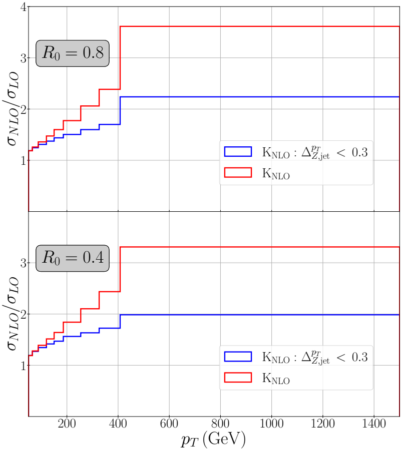
Summary and next steps:

Current results

- Resummed predictions for both groomed and ungroomed angularities λ_α ($\alpha \in [1/2, 1, 2]$) at $\mathrm{LO} + \mathrm{NLL}'$ are ready, the $\mathrm{NLO} + \mathrm{NLL}'$ requires some more (a way more) CPU time
- We found that angularities λ_α at RHIC energies can be used to study hadronization and potentially to produce new MC tunes
- On the other hand, angular decorrelation δ_ϕ, can be used to test various parton shower models
- $\delta\phi$ simulated with JEWEL shows strong dependence on the medium temperature
- Correct the resummed predictions for non-perturbative effects using corresponding parton-to-hadron transition matrices
- What about 2D observables, say primary Lund Plane?
- The sPHENIX data is needed!

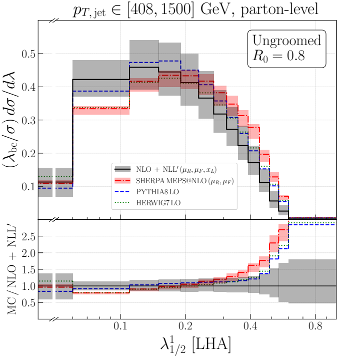
Thank you for your attention!

Monte Carlo result: K-factor



The NLO K-factor as a function of the p_{TJ} with and without $\Delta^{p_T}_{Z,\mathrm{jet}} = |(p_{T,\mathrm{jet}} - p_{T,\mu^+\mu^-})/(p_{T,\mathrm{jet}} + p_{T,\mu^+\mu^-})| < 0.3$ cut.

Monte Carlo results: LHA



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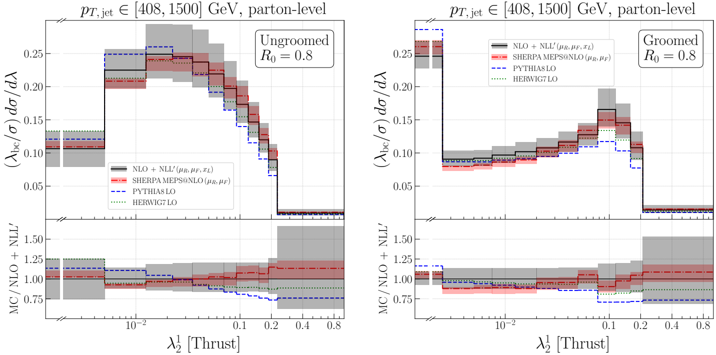
Monte Carlo results: Jet Thrust



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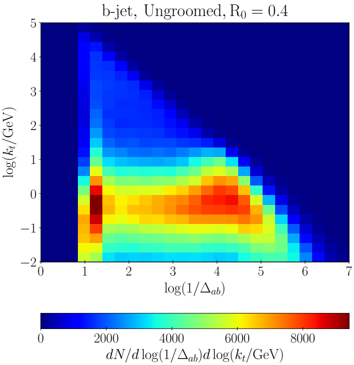
Lund plane projection



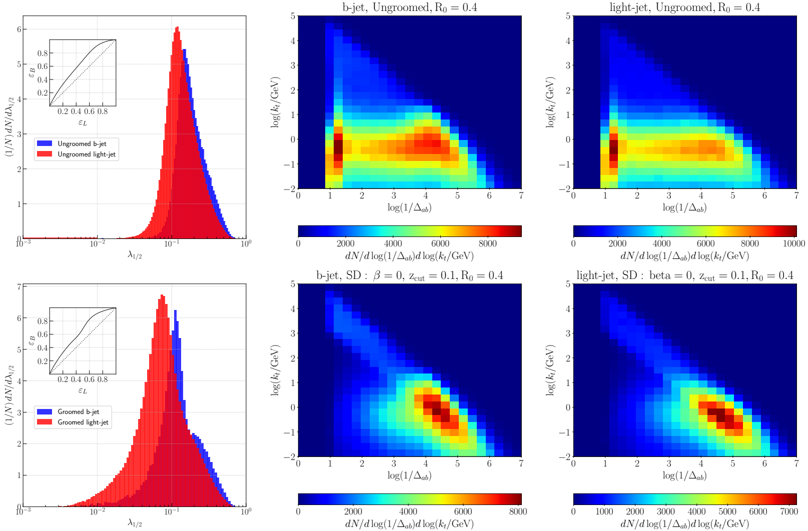
To build a Lund plane:

- Recluster your jet using CA algorithm
- Then compute:

$$\Delta_{ab} \equiv \sqrt{(y_a - y_b)^2 + (\phi_a - \phi_b)^2},$$
$$k_t \equiv p_{Tb}\,\Delta_{ab}.$$

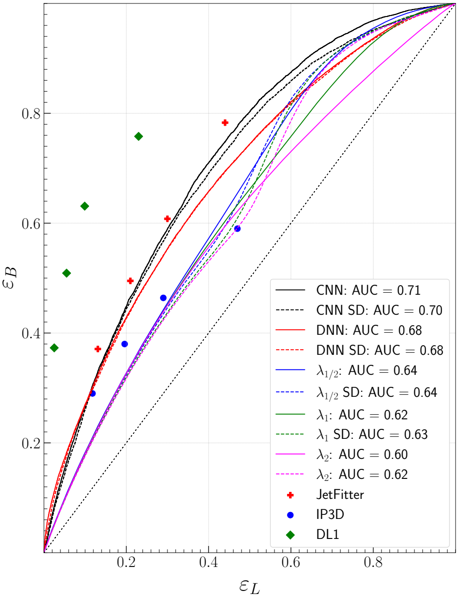
- Discard softest branch and repeat.

Lund plane projection



Observables we consider as an input for our DNN / CNN. Note that jet flavour is defined in an experimental way here.

Performance of our CNN / DNN



The ROC curves obtained for one-dimensional angularity distributions, multivariable DNN classification and Lund plane CNN classification. The single points correspond to ATLAS SV1, IP3D and DL1 *b*-tagging performance from CERN-EP-2019-132.