Jet substructure in proton-proton and nucleus-nucleus collisions

Georgia State University and CFNS

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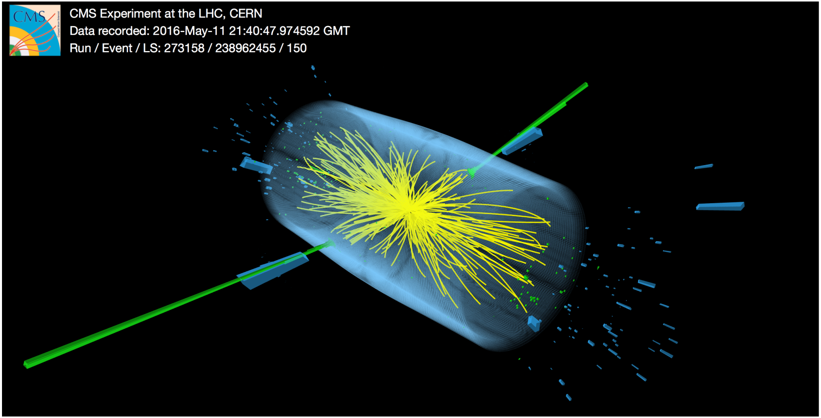
April 6, 2023

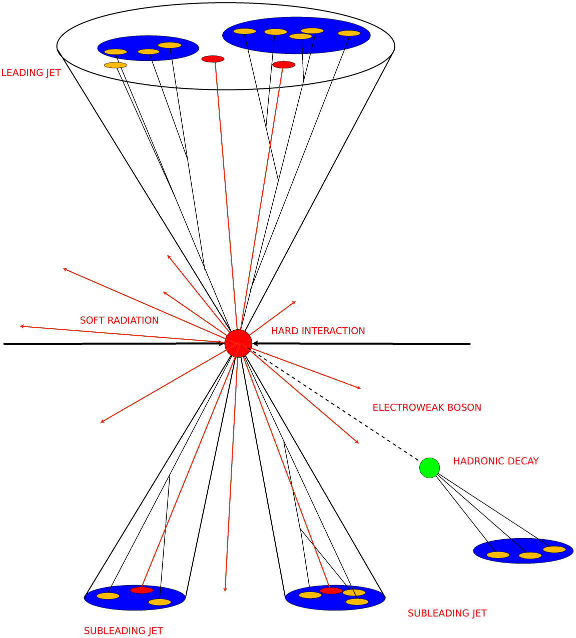
Based upon 2104.06920, 2112.09545, 2108.10024 and 2202.05082

Why do we study jets?

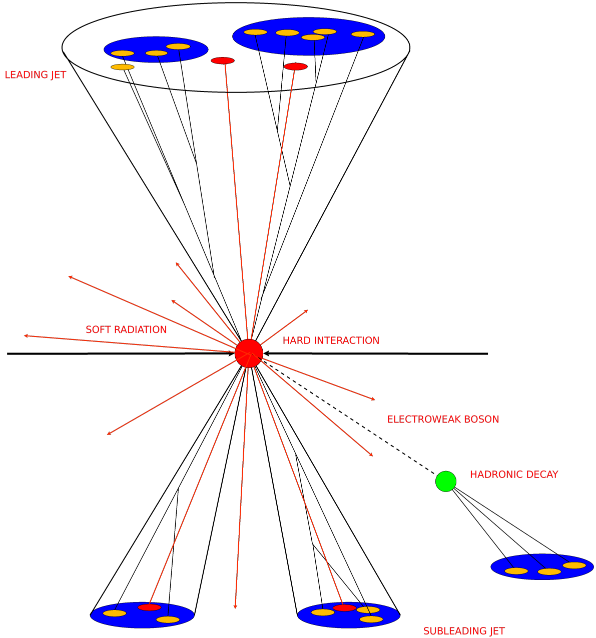


A di-jet event recorded by CMS collaboration (credits: CERN)

Looking inside jets



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



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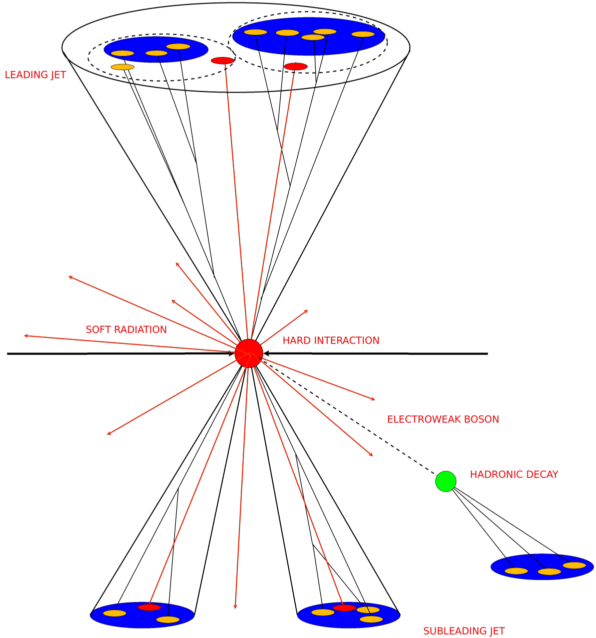

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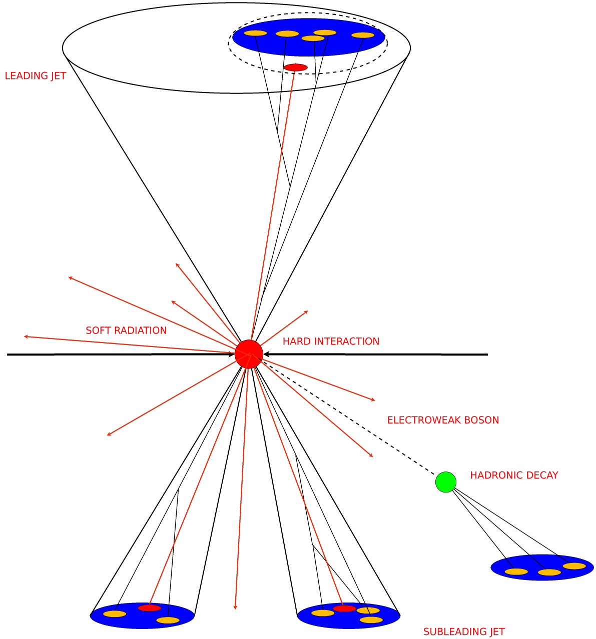

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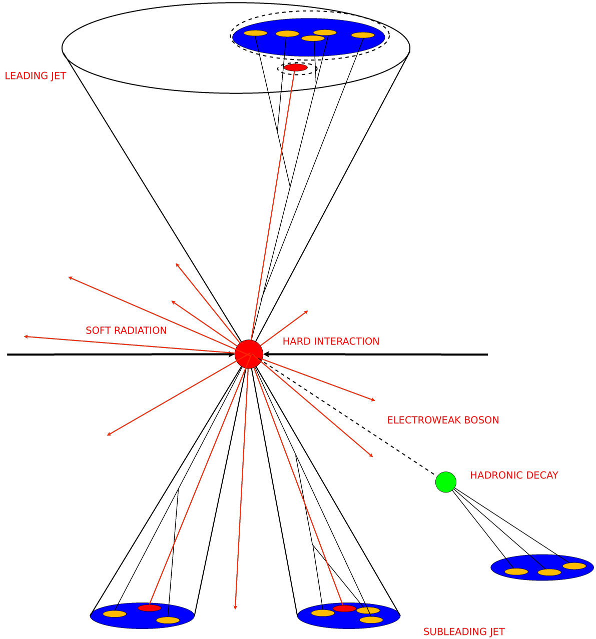

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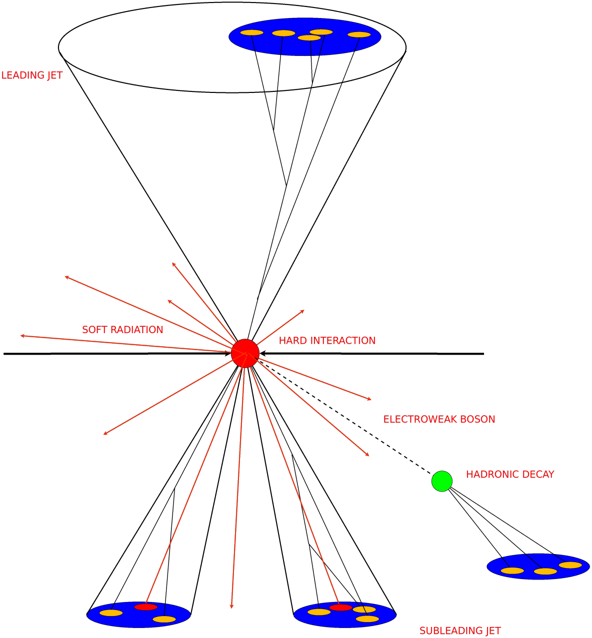
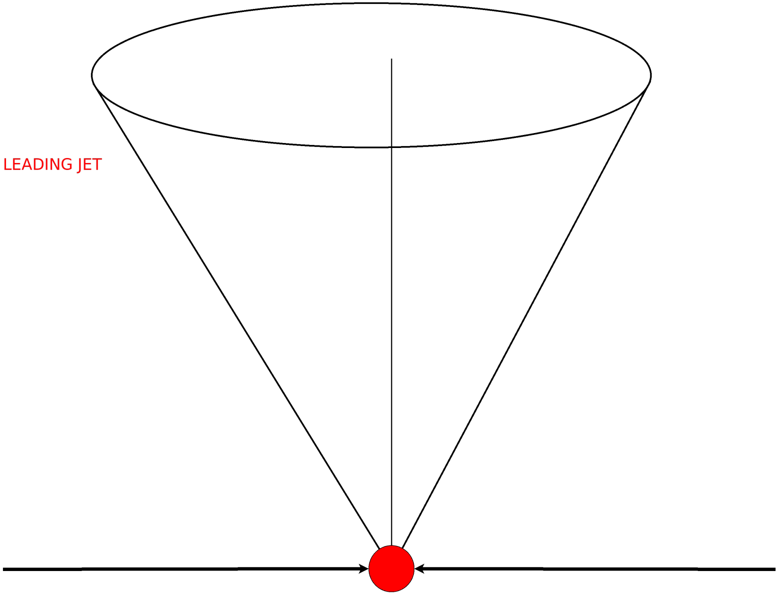
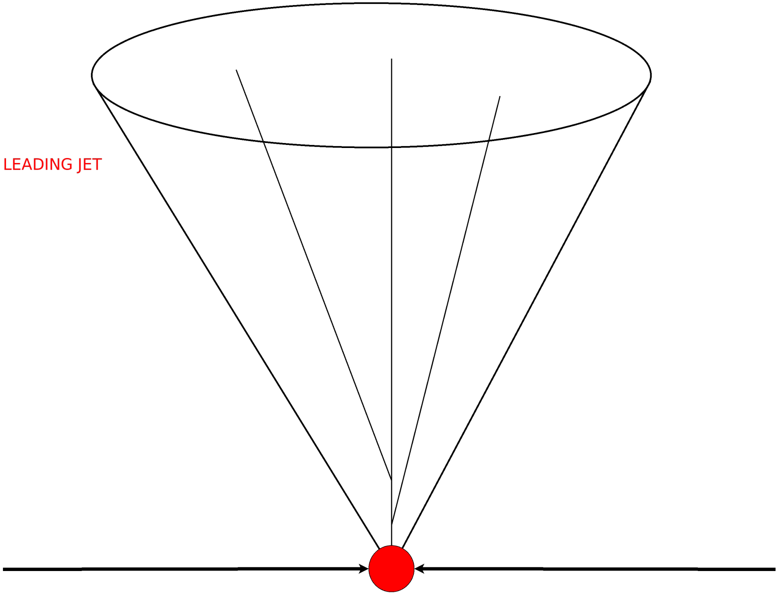


Resummation vs. Monte Carlo

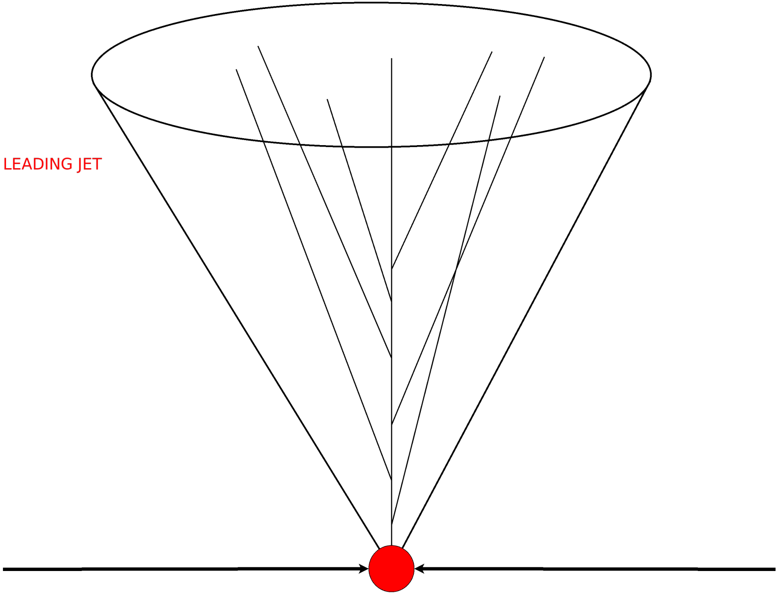


Resummation vs. Monte Carlo

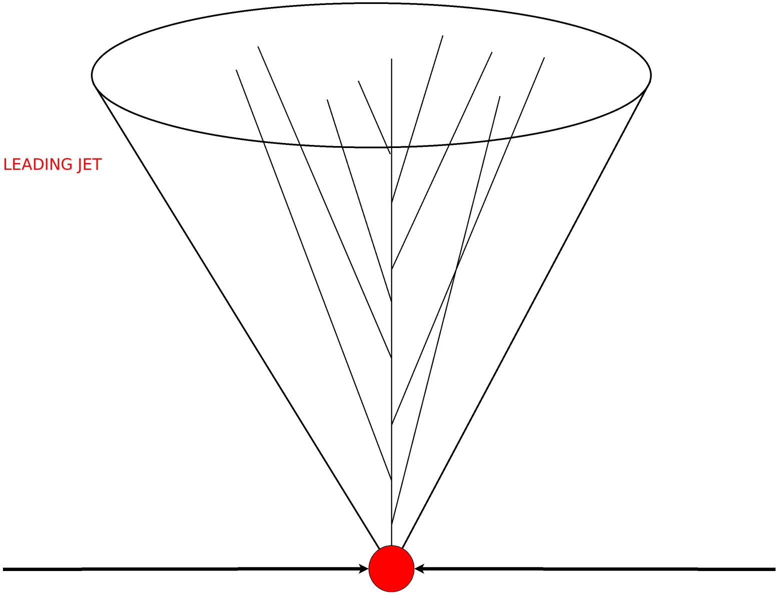
LEADING JET



Resummation vs. Monte Carlo



Resummation vs. Monte Carlo



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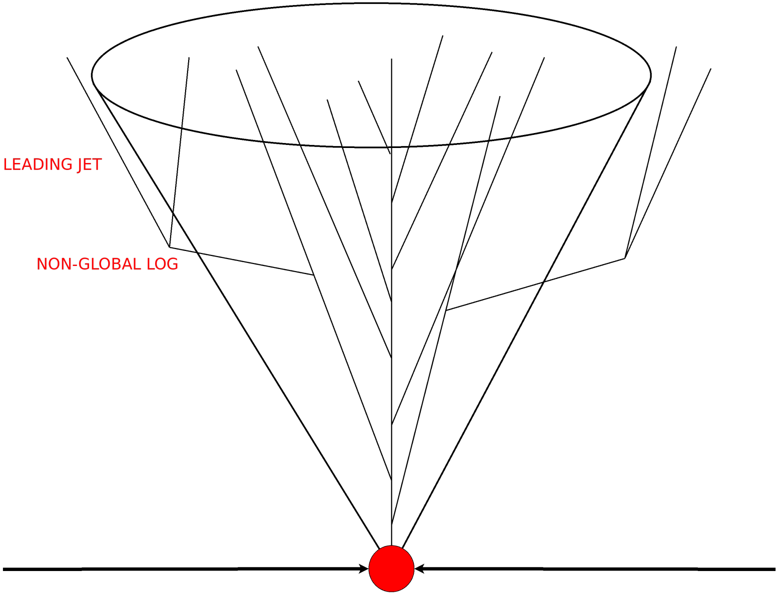

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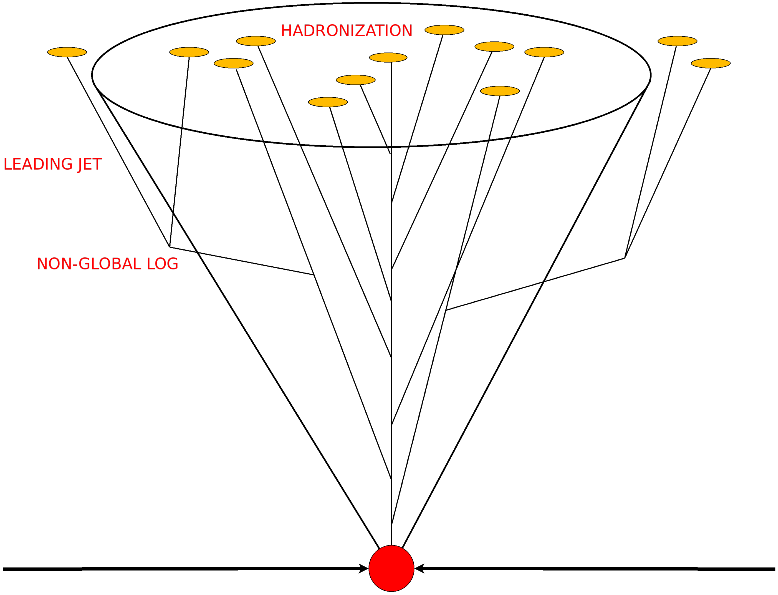

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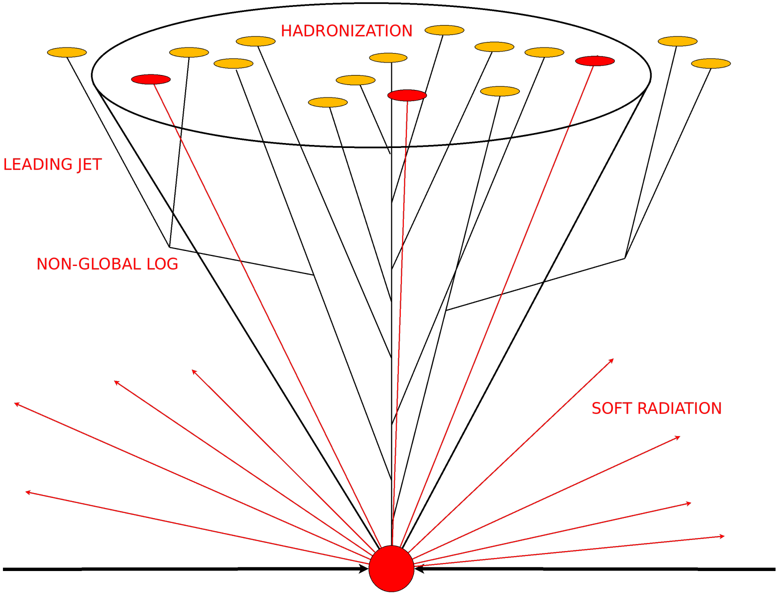

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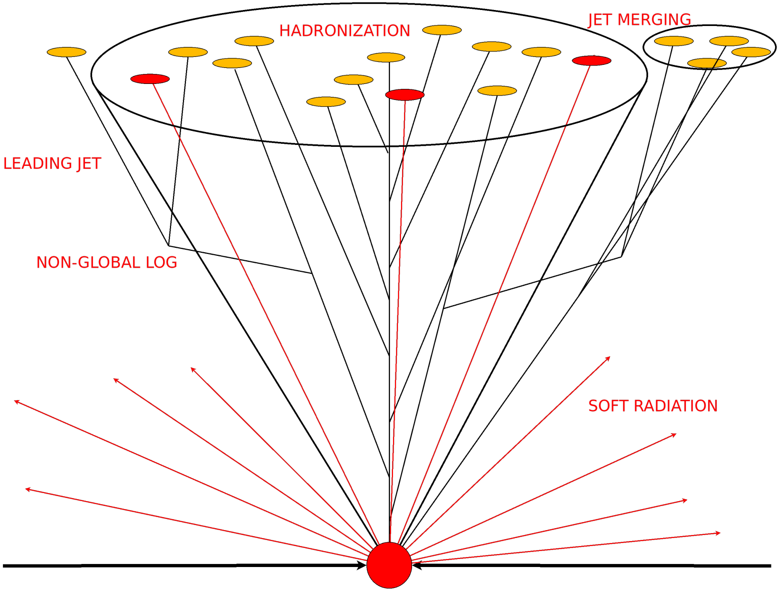
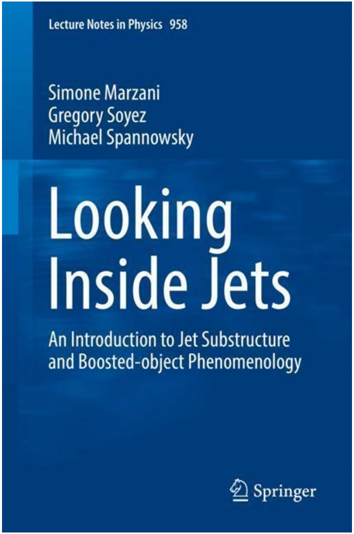


Looking inside jets

Various observables exist:

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



More info can be found here

We study jet angularities in Z+jet production

The jet angularities are defined as

$$\lambda_\alpha^\kappa = \sum_{i \in \text{jet}} \left(\frac{p_{T,i}}{\sum_{j \in \text{jet}} p_{T,j}} \right)^\kappa \left(\frac{\Delta_i}{R_0} \right)^\alpha ,$$

where

$$\Delta_i = \sqrt{(y_i - y_{\text{jet}})^2 + (\phi_i - \phi_{\text{jet}})^2} ,$$

is the Euclidean azimuth-rapidity distance of particle i from the jet axis.

- The concept of infrared and collinear (IRC) safety requires $\kappa = 1$ and $\alpha > 0$.
- We consider $\lambda_{1/2}^1$ (LHA), λ_1^1 (Width) and λ_2^1 (Thrust) cases.
- For the grooming we use SoftDrop with $\beta = 0$ and $z_{\text{cut}} = 0.1$.

We study jet angularities in Z+jet production

We use the selection cuts from the recent CMS measurements:

- We require all final state particles to have pseudo-rapidity $|\eta| < 5$
- Z-boson decays into muons. For both muon candidates we require $p_{T,\mu} > 26\ \mathrm{GeV}$, and $|\eta_\mu| < 2.4$
- The lepton pair has to pass the additional conditions $70\ \mathrm{GeV} < m_{\mu^+\mu^-} < 110\ \mathrm{GeV}$, and $p_{T,\mu^+\mu^-} > 30$ GeV
- The leading AK8 (AK4) jet has to satisfy $|y_{\text{jet}}| < 1.7$ and $p_{TJ} \in [50, 1500]$ GeV

Additionally, we impose the constraint

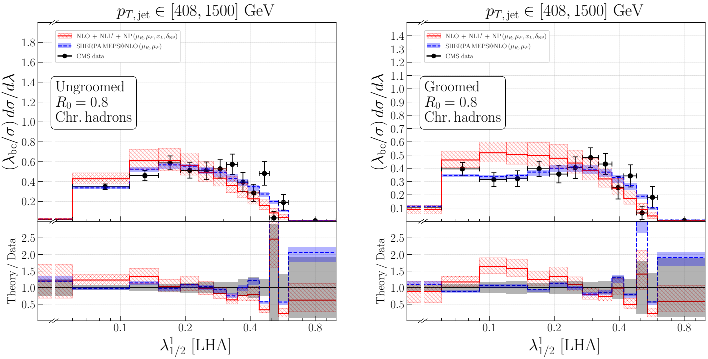
$$\Delta_{Z,\mathrm{jet}}^{p_T} \equiv \left| \frac{p_{T,\mathrm{jet}} - p_{T,\mu^+\mu^-}}{p_{T,\mathrm{jet}} + p_{T,\mu^+\mu^-}} \right| < 0.3 \,.$$

and require the Z-boson and the leading jet to be well separated in azimuthal angle

$$\Delta_{Z,\mathrm{jet}}^{\phi} \equiv |\phi_Z - \phi_{\mathrm{jet}}| > 2 \,.$$

CMS-SMP-20-010; 2109.03340

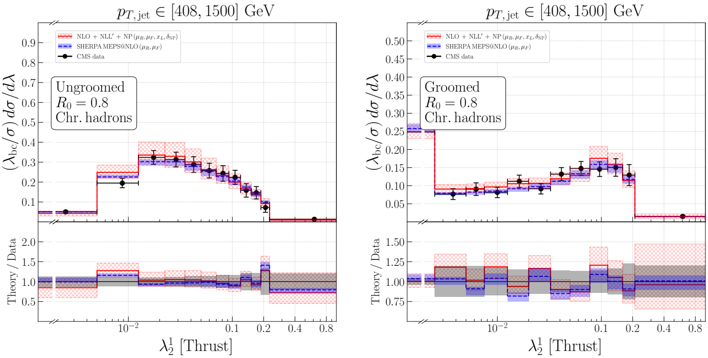
Theory vs. CMS data



Comparison against recent CMS data for the LHA angularity, $p_{T,\mathrm{jet}} \in [408, 1500]$ GeV.

CMS-SMP-20-010; 2109.03340

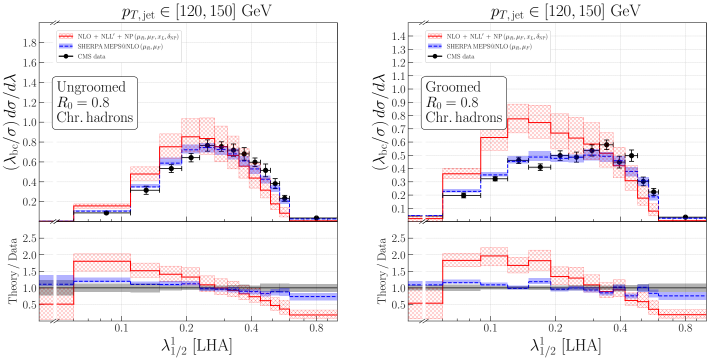
Theory vs. CMS data



Comparison against recent CMS data for the Jet Thrust angularity, $p_{T,\mathrm{jet}} \in [408, 1500]$ GeV.

CMS-SMP-20-010; 2109.03340

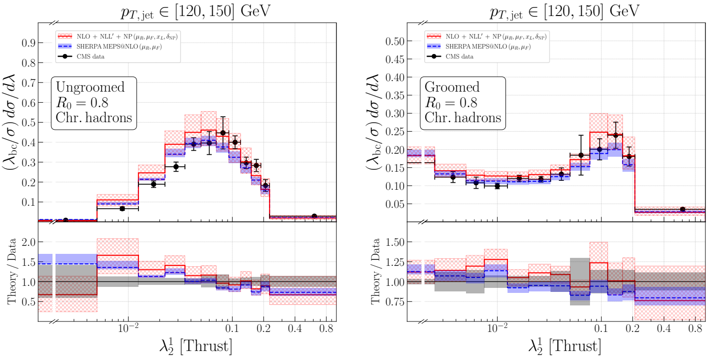
Theory vs. CMS data



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

CMS-SMP-20-010; 2109.03340

Theory vs. CMS data



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

CMS-SMP-20-010; 2109.03340

Conclusions on Z+jet results

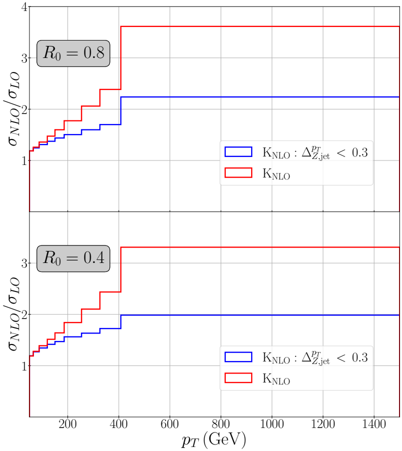
- We got a satisfactory agreement for the Jet Thrust observables.
- Resumed results fail to describe LHA angularity at low values λ.
- We demonstrated necessity to use state-of-the-art MC to describe LHC data.
- Our NLO+NLL′ results are embedded in the Sherpa framework and hence automated (available on request).
- For the di-jet production see 2112.09545
- For application to PDF studies see 2108.10024
- For b-tagging see 2202.05082
- **What about AA collisions ?**
- **What will happens at RHIC energies?**

Thank you for your attention!

This work has received funding from the grant “Using jets to challenge the Standard Model of particle physics” from Università di Genova.

A lot of backup slides

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.

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.

CAESAR formalism

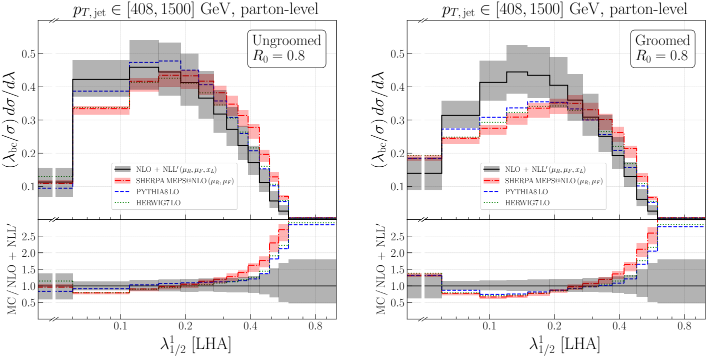
The cumulative cross section for a generic observable v can be written as a sum over partonic channels δ:

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

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

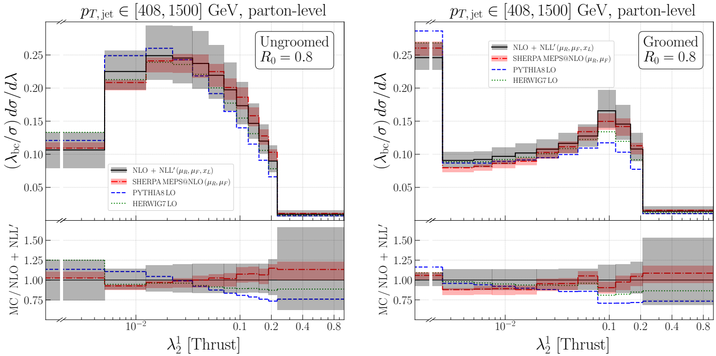
where $L = -\ln(v)$, $\frac{d\sigma_{\delta}}{d\mathcal{B}_{\delta}}$ is the differential Born cross section, R_l is the collinear radiator for the hard legs l, $\mathcal{P}$ is the ratio of PDFs, $\mathcal{S}$ is the soft function, $\mathcal{F}$ is the multiple emission function and $\mathcal{H}$ stands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

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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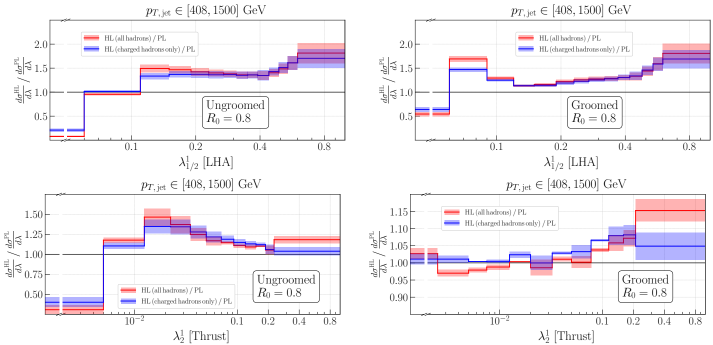
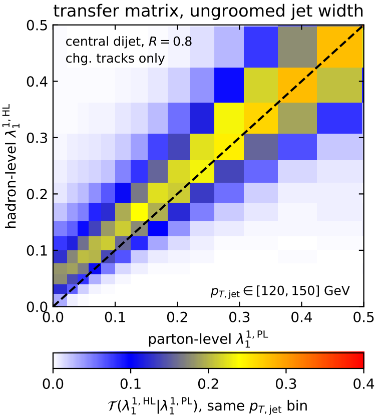
Impact of NP-corrections

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



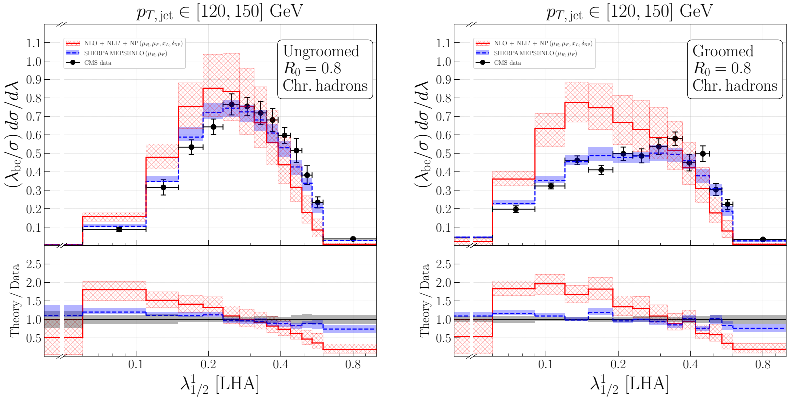
Hadron-to-parton-level ratios with associated uncertainties extracted from MC simulations (Pythia, Herwig and Sherpa). To some extent can be seen as a jet fragmentation function.

Parton to hadron level transition; credits G. Soyez



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

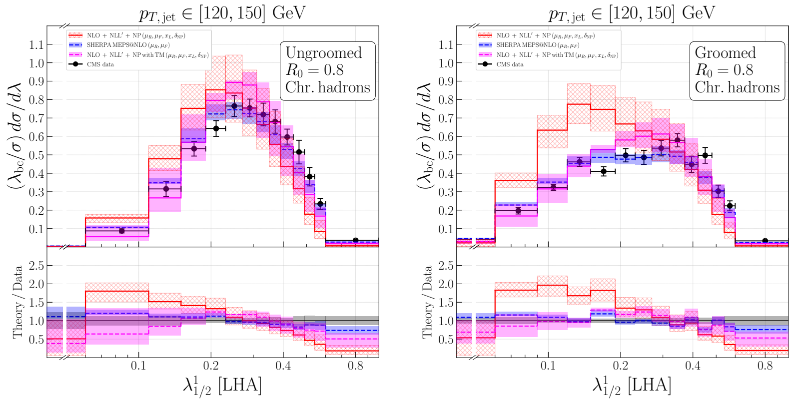
Theory (including TM) vs. CMS data



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.

CMS-SMP-20-010; 2109.03340

Theory (including TM) vs. CMS data



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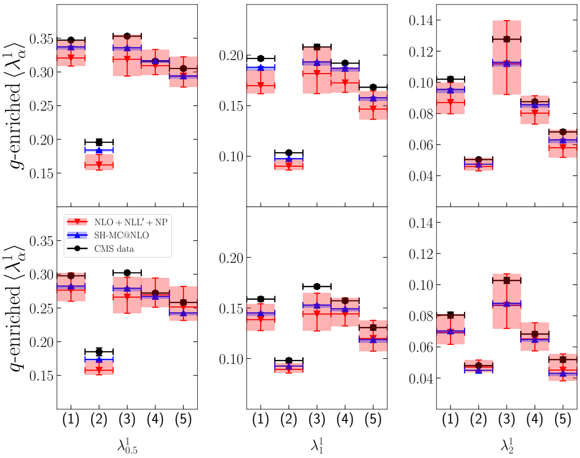
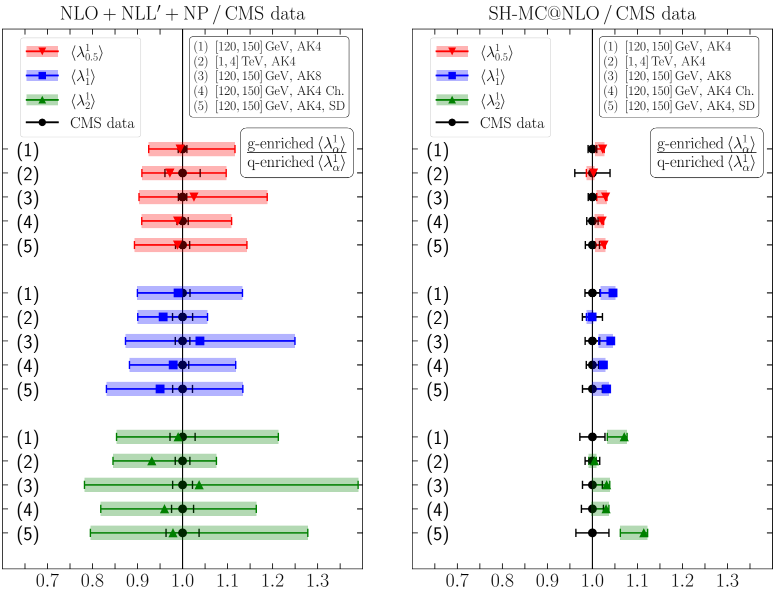
Comparison against CMS data



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

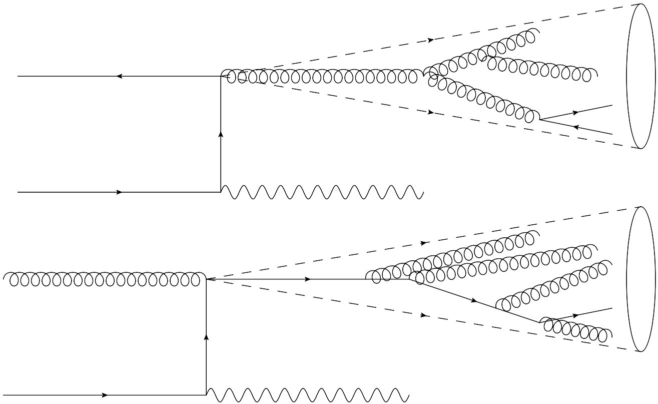
Comparison against CMS data



Conclusions on Z+jet and di-jet results

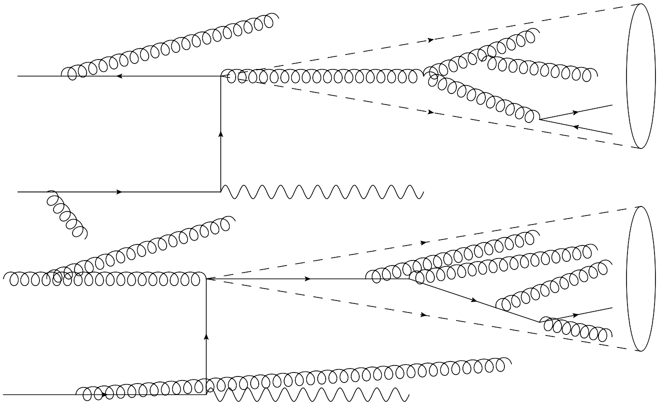
- Parton to hadron level transfer matrix improves agreement with the data.
- NLO+NLL$'$ di-jet resummation is also now implemented in Sherpa.
- Both Sherpa and resummed averaged results somewhat underestimate the data.
- However, the ratio of gluon-enriched to quark-enriched distributions describe the data better.
- Large uncertainty values of resummed predictions indicates necessity for further improvement in accuracy of our calculations (need for NNLL resummation ?).

Jet angularities as a tool for PDF fits



At leading order we have only two diagrams with only one diagram containing an initial-state gluon leg!

Jet angularities as a tool for PDF fits



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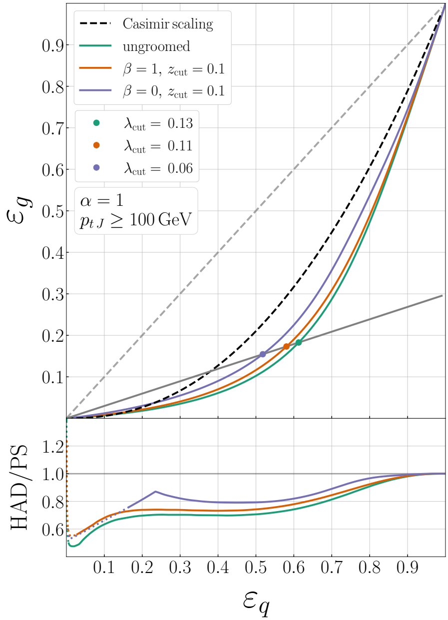
Defining our tagger (credits: S.Caletti)



Efficiencies:

$$\varepsilon_{q,g} = \frac{1}{\sigma_{q,g}} \int_0^{\lambda_{\rm cut}} d\lambda_\alpha \frac{d\sigma_{q,g}}{d\lambda_\alpha}$$

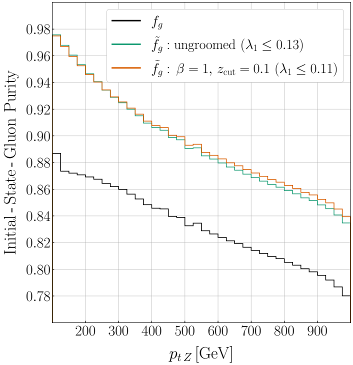
Gluon faction set $\lambda_{\rm cut}$:

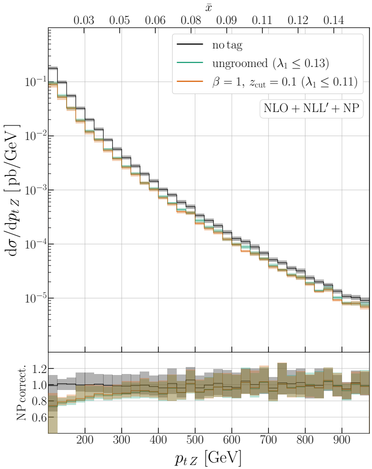
$$f_g = \frac{\sigma_{qg}}{\sigma_{qq} + \sigma_{qg}}$$

$$\tilde{f}_g = \frac{\varepsilon_q \sigma_{qg}}{\varepsilon_g \sigma_{qq} + \varepsilon_q \sigma_{qg}}$$

$$\varepsilon_g = \frac{f_g(1 - \tilde{f}_g)}{\tilde{f}_g(1 - f_g)} \varepsilon_q$$

Gluon fraction after tagging (credits: S.Caletti)





Left: the initial-state gluon purity before (f_g) and after tagging ($\widetilde{f_g}$), right: transverse momentum distribution of the Z boson in Z+jet events, with the leading jet tagged as quark-initiated.

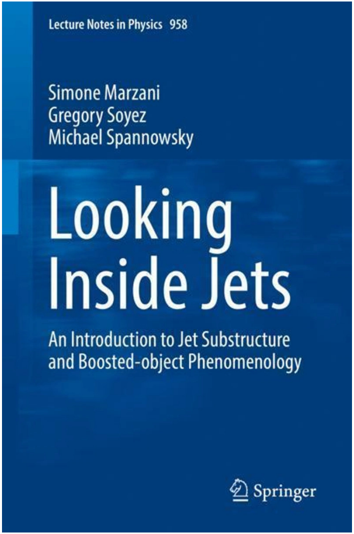
Conclusions on quark-gluon tagging

- The quark/gluon tagging procedure is realised by a cut on a jet angularity and it is therefore theoretically well-defined and exhibits infrared and collinear safety.
- By exploiting resummed perturbation theory, we are able to provide theoretical predictions for transverse momentum distributions at a well-defined and, in principle, systematically improvable accuracy.
- Tagging the leading jet as quark-initiated allows us to enhance the initial-state gluon contribution.

Looking inside jets

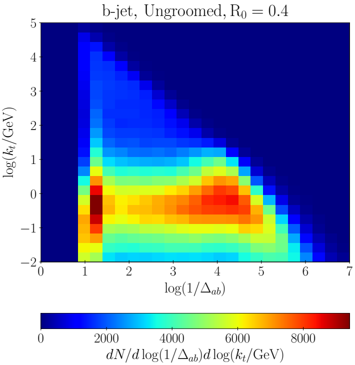
Various observables exist:

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



more info can be found here

Lund plane projection



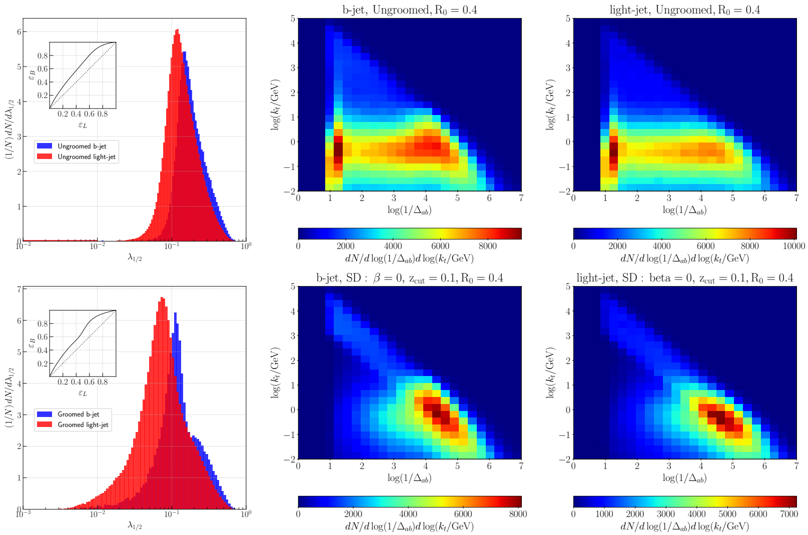
To build a Lund plane:

- Recluster your jet using CA algorithm
- Then compute:

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

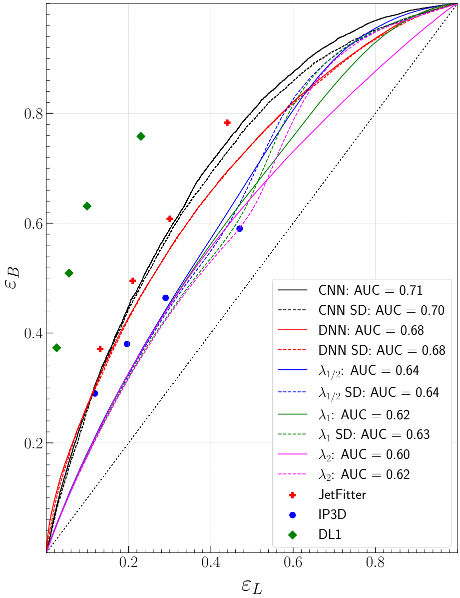
- Discard softest branch and repeat.

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.

Conclusions on b-tagging

- We found that one can use jet angularities and Lund plane projection as an input for DNN / CNN discriminators.
- Our DNN/CNN discriminators show performance compatible to JetFitter and IP3D taggers used by ATLAS.
- The discriminating features we use can be added to a list of already considered ones and, therefore, can be used to improve performance of *e.g.* DL1 tagger (which is NL trained upon multiple variables) .

Thank you for your attention!

This work has received funding from the grant "Using jets to challenge the Standard Model of particle physics" from Università di Genova.

Main DPS formula

Master x-section formula

$$\sigma_{AB} = \sum_{i,j,k,l} \int \prod_{a=1}^{4} dx_a \, d^2 b \, \hat{\sigma}_{ij\to A} \, \hat{\sigma}_{kl\to B} \, \Gamma_{ik}\left(x_1, x_2, b, Q_A, Q_B\right) \Gamma_{jl}\left(x_3, x_4, b, Q_A, Q_B\right)$$

where functions $\Gamma_{ik}\left(x_1, x_2, b, Q_A, Q_B\right)$ are called *generalized parton distribution functions* (gPDFs) and give a probability to find two partons, separated by transverse distance b, in a hadron (in case of *bare* gPDFs)

Assumption on factorization

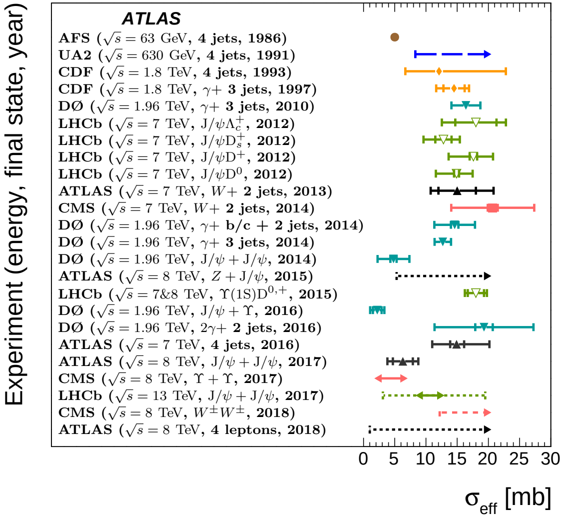
Assuming $\Gamma_{ik}\left(x_1, x_2, b, Q_A, Q_B\right) \approx f_i(x_1, Q_A) f_j(x_2, Q_B) F(b)$ one can write

$$\sigma_{AB} = \frac{1}{1+\delta_{AB}} \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

where we defined

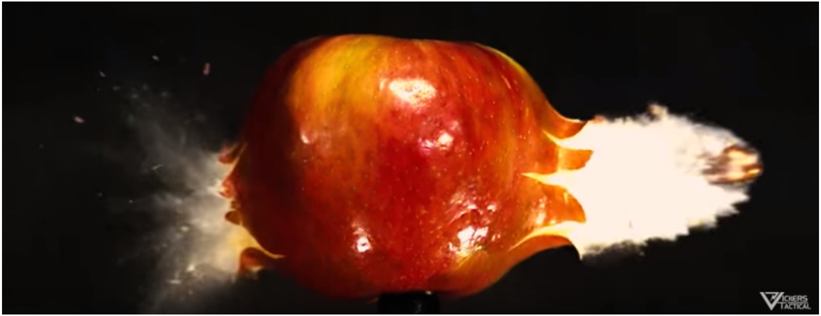
$$\frac{1}{\sigma_{eff}} \equiv \int d^2 b \left[F(b)\right]^2$$

“Measurements” of σ_{eff}



Different measurements of σ_{eff}, 1811.11094. See also recent *pp* 1909.06265 and *pA* 2007.06945 measurements.

The difference between pp and pA collisions



YouTube/Vickers Tactical

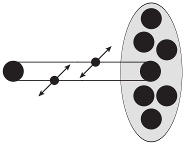
We expect that number of DPS events in pA collisions will grow!

The difference between pp and pA collisions

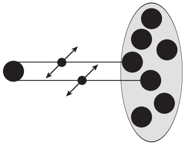
Unlike pp case several different DPS contributions are possible

"It is worthwhile to notice that by using targets with multiple nuclear composition, one can unambiguously separate the two production mechanisms [DPS and SPS] experimentally."

Goebel *et. al.* 1980.



DPS I



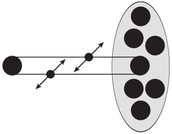
DPS II

Left panel: DPS occur between a proton and a single nucleon.
Right panel: DPS occur between a proton and two different nucleons.

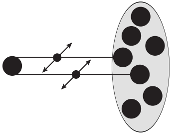
The difference between pp and pA collisions

Unlike pp case several different DPS contributions are possible

- Several authors have predicted the enhancement of the fraction of the DPS events in pA collisions in comparison with pp case (Treleani and Strikman 2001, d'Enterria and Snigirev 2012, Block, Strikman and Wiedemann 2013)

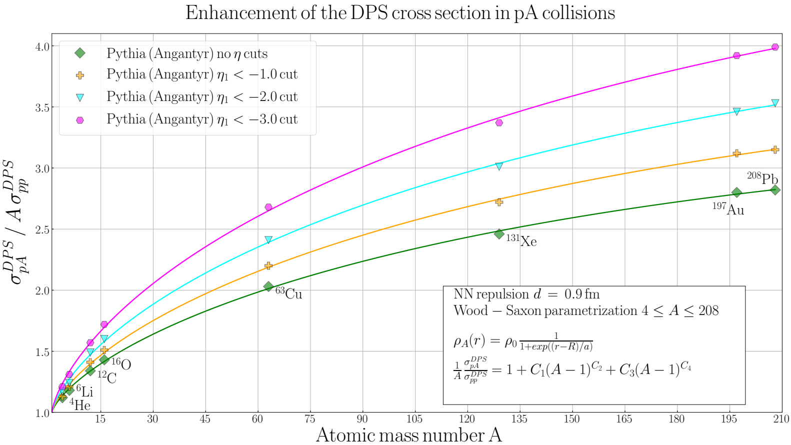


$$\sigma_{AB} \sim A \int \Gamma_p(x_1, x_2, \mathrm{b})\, \Gamma_p(x_3, x_4, \mathrm{b})$$



$$\sigma_{AB} \sim \frac{A-1}{A} \int D_p(x_1, x_2)\, f_p(x_3)\, f_p(x_4)\, \mathrm{T}_A^2(\mathrm{s})$$

DPS in pA collisions. Pythia (Angantyr)



The DPS enhancement factor $\sigma_{\rm pA}^{\rm DPS}/{\rm A}\,\sigma_{\rm pp}^{\rm DPS}$. Comparison between theoretical predictions of Strikman and Treleani and Pythia (Angantyr) simulations.

OF and L.Lönnblad, 1912.08733