Physics in the Lund plane(s)

Gregory Soyez, with Frederic Dreyer, Andrew Lifson, Gavin Salam and Adam Takacs
based on arXiv:1807.04758, arXiv:2007.06578 and arXiv:2112.09140

IPhT, CNRS, CEA Saclay

Flowing into the future, SCGP Jet Workshop, March 21-25 2022

Flows and trees

- 2 historical pictures to see jets
  1. Energy flows (e.g. Sterman-Weinberg, SISCone)
  2. Branching trees (e.g. anti-k_t, k_t, Cambridge/Aachen)
- Both pictures are physically sound; both pictures have pros and cons

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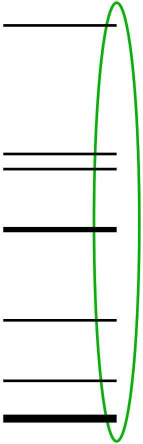
This talk

Show the virtues and breadth of branching trees
through a single "magic wand": the Lund jet plane(s)/tree
Including: basic intuition, pQCD calculations, MC developments, Deep Learning, ...

See Jesse's talk for the virtues and breadth of E flows

The Lund plane(s) representation (1/3)

use Cambridge/Aachen to iteratively recombine the closest pair



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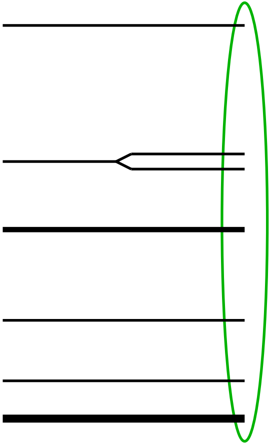

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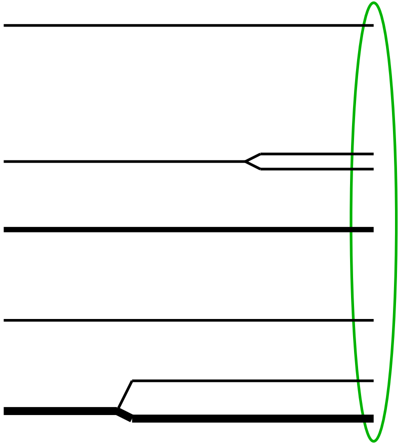

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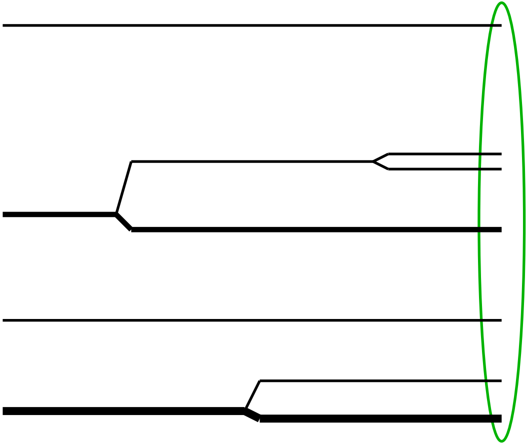

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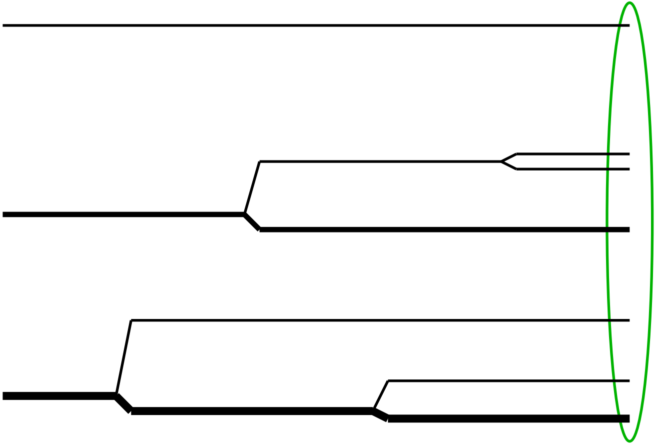

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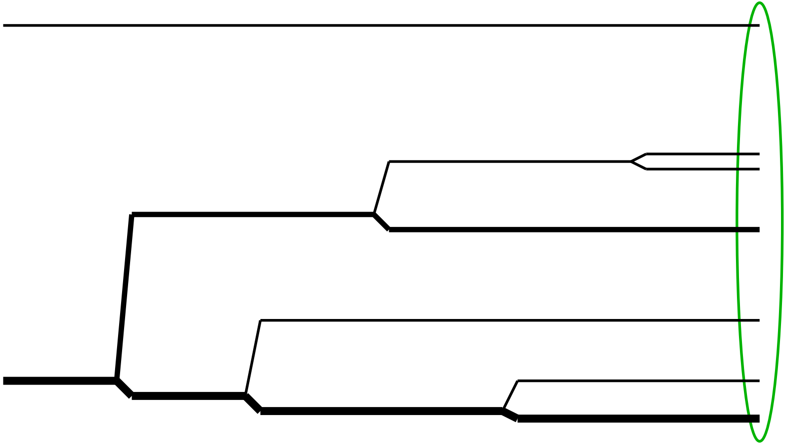

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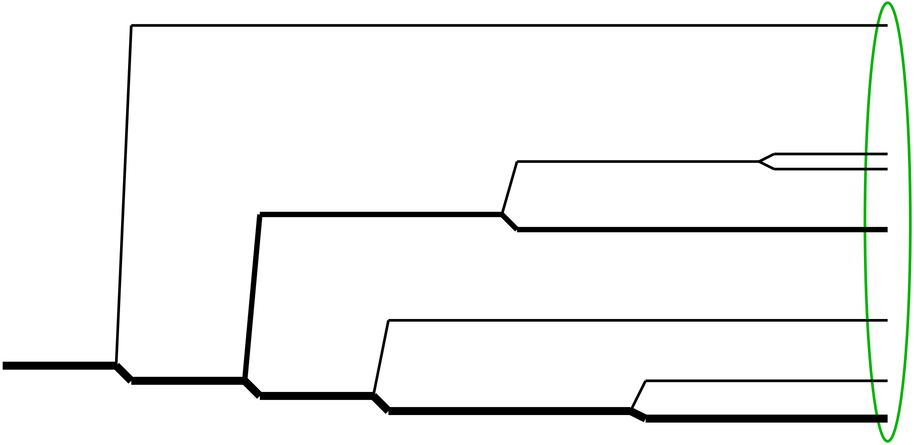

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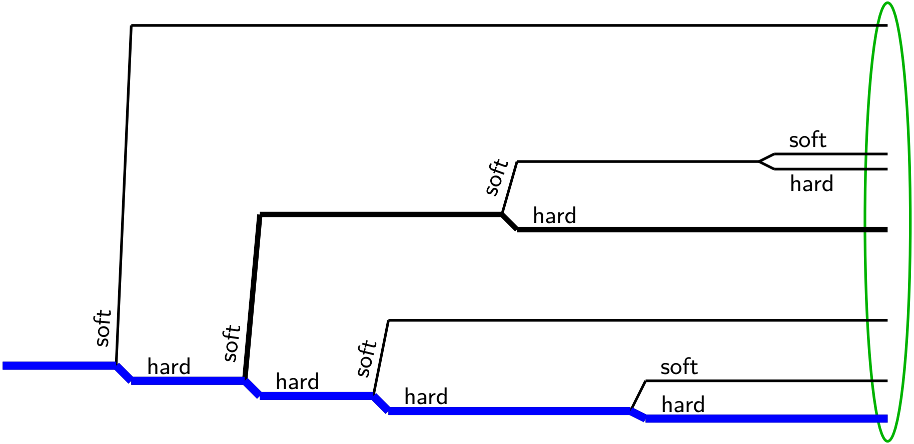
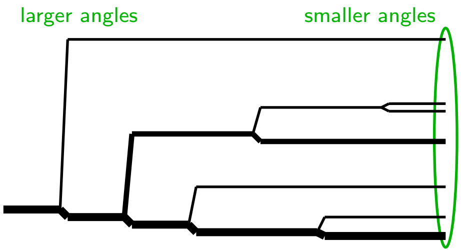


E.g.: conceptually the largest-energy (p_t or z) branch $\equiv$ emissions from the "leading parton"

The Lund plane(s) representation (2/3)



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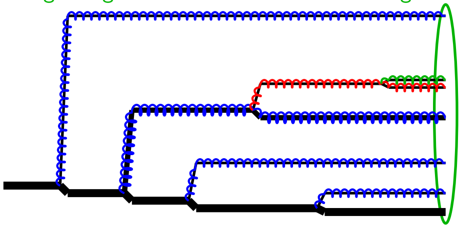
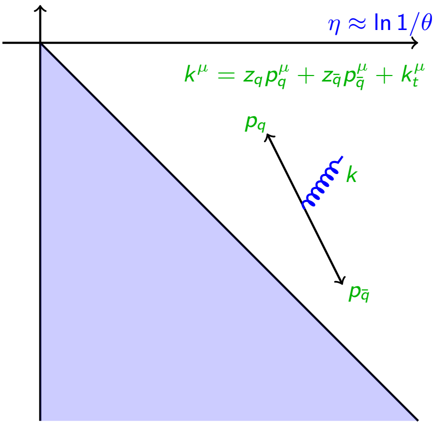
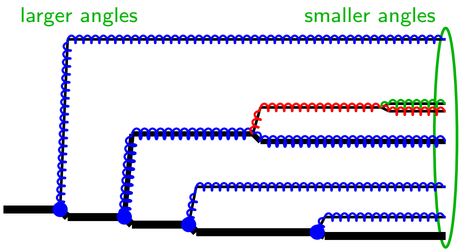


- closely follows our beloved angular ordering
- i.e. mimics partonic cascade
- can be organised in Lund planes

$k_t \equiv$ momentum transverse to a dipole
$\eta \equiv \frac{1}{2} \ln z_q/z_{\bar{q}}$ (longitudinal component)
$\phi \equiv$ azimuthl angle



$$d\mathcal{P} = \frac{\alpha_s(k_t) C_F}{\pi^2}\, d\eta\, \frac{dk_t}{k_t}\, d\phi$$



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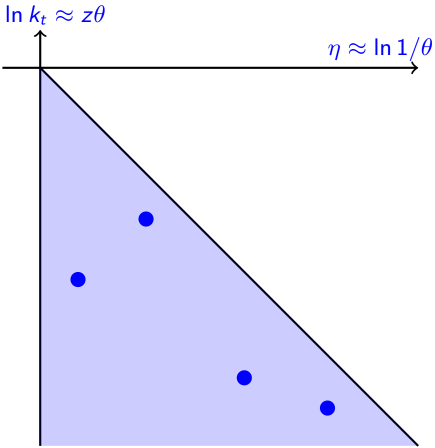
  - primary



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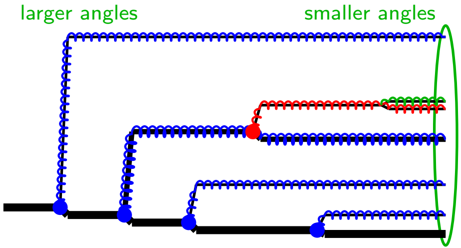
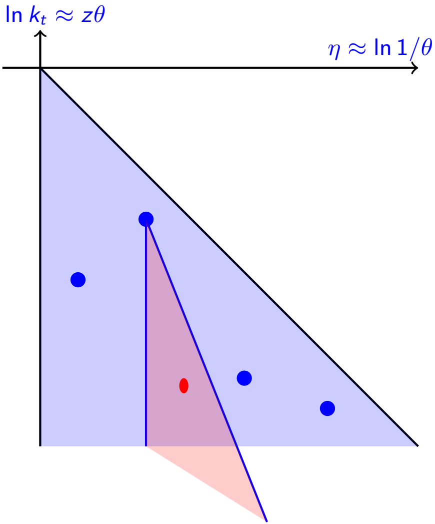


- closely follows our beloved angular ordering
- i.e. mimics partonic cascade
- can be organised in Lund planes
  - primary
  - secondary



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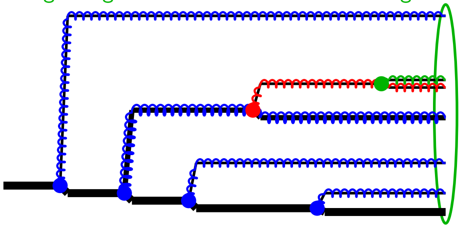

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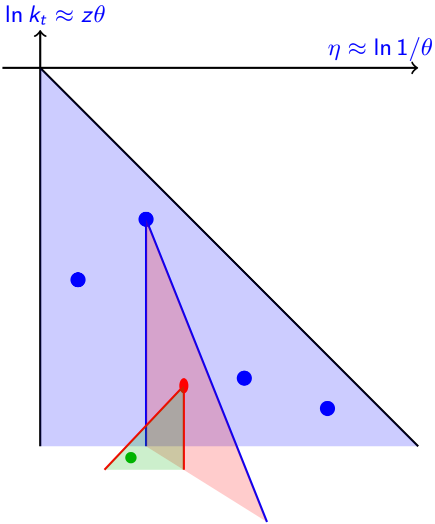

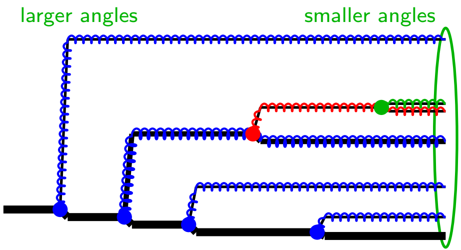

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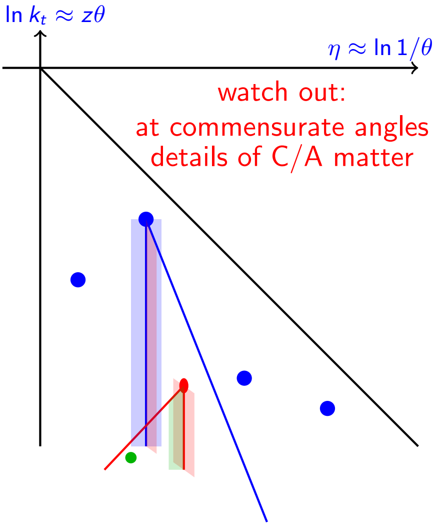
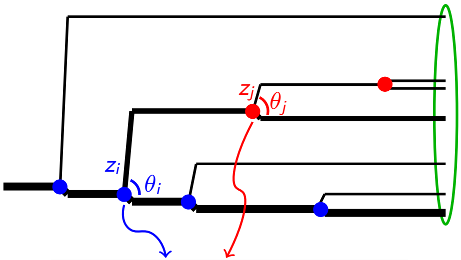


The Lund plane(s) representation (3/3)



$$\mathcal{T}_i \equiv \{\theta_i, k_{t,i}, z_i, \psi_i, m_i, \dots\}$$

for *ee events*: (similar for *jets in pp*)

$$\eta = -\ln\tan\frac{\theta_i}{2}$$

$$k_t = E_{\text{soft}}\sin\theta \qquad z = \frac{E_{\text{soft}}}{E_{\text{parent}}}$$

$$\psi \equiv \text{azimuthal angle}$$

Two different Lund ($\mathcal{L}$) structures

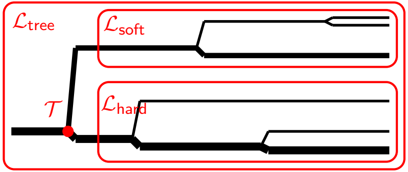
"primary plane" (follow hard branch)

$$\mathcal{L}_{\text{prim}} \equiv \{\mathcal{T}_i\}$$

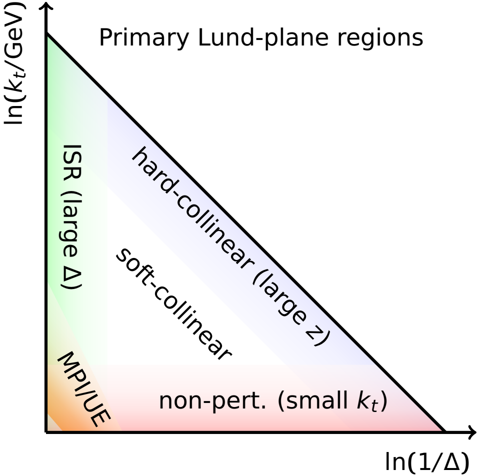
OR

full (de-)clustering tree

$$\mathcal{L}_{\text{tree}} \equiv \{\mathcal{T}, \mathcal{L}_{\text{hard}}, \mathcal{L}_{\text{soft}}\}$$



Main features



Separated physics regions

Different physics in different regions

- pQCD above $k_t \gtrsim \Lambda_{\text{QCD}}$ (data: 5–10 GeV)
- pQCD split: soft v. soft+coll v. hard-coll
- NP effects at low k_t (hadr & MPI)

Central observation

Lund diagrams are useful to do resummations, MC developments

Lund diagramd/trees/planes can actually be reconstructed in practice

The rest of this talk covers several applications:

- ✓ Calculations (and measurements)
- ✓ Tagging (incl. machine learning)
- ✓ Monte-Carlo developments
- (✓) Heavy-ion collisions: possible and interesting but not covered here

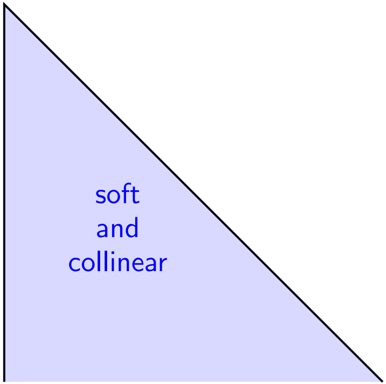
Application #1: QCD calculations

Primary Lund plane multiplicity

Average number of emission at given k_t, Δ:

[A. Lifson, G. Salam, GS, arXiv:2007.06578]

$$\rho = \frac{1}{N_{\text{jets}}} \frac{d^2 N}{d \ln \Delta \, d \ln k_t}$$



- Double-logarithmic behaviour:

$$\rho = \frac{2\alpha_s(k_t) C_R}{\pi}$$

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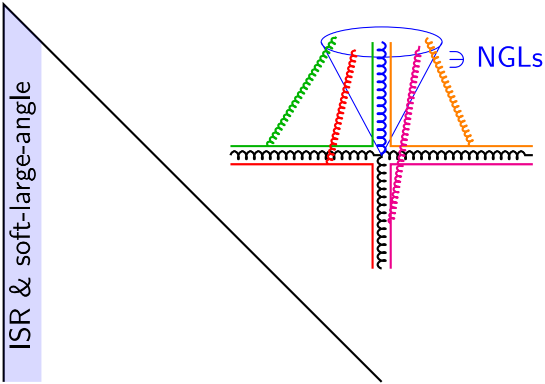

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- Single-log calculation including
  - ✓ Running-coupling (trivial)
  - ✓ ISR+large angle

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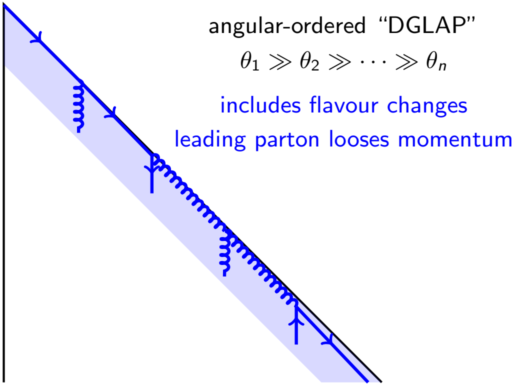

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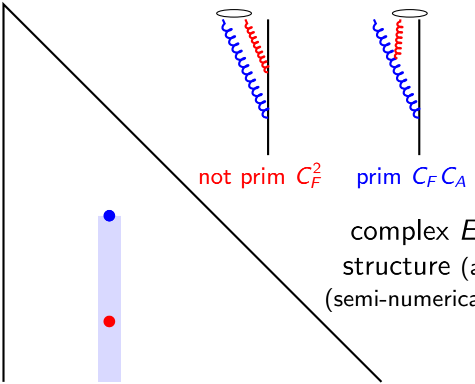

complex E-ordered structure (akin NGLs)
(semi-numerical treatment)

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from NLOJet++
(some non-trivial details)

$2 \to 3$ at NNLO would greatly help!
[M.Czakon,A.Mitov,R.Poncelet106.05331]

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- + Matching to NLO ($\sim$ top)

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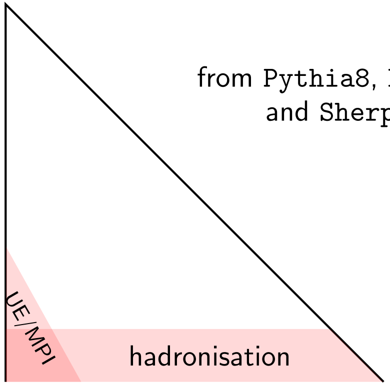

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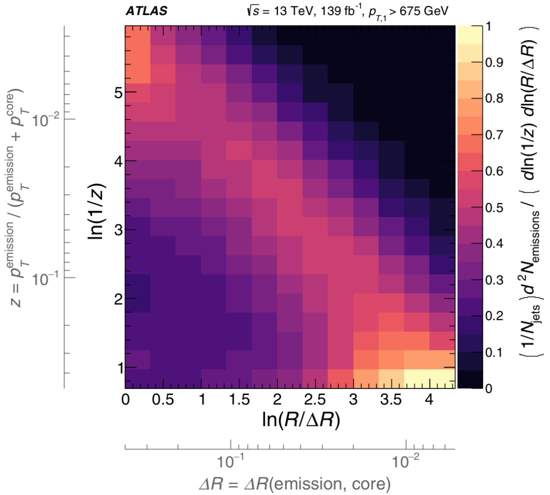
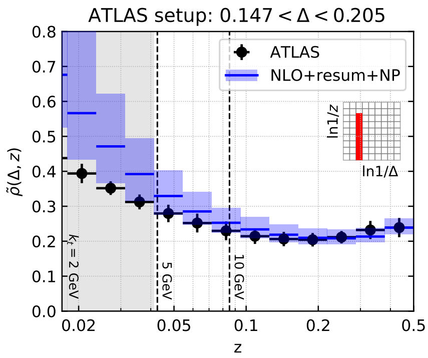
- \+ Matching to NLO ($\sim$ top)
- \+ NP corrections ($\sim$ bottom)

Data v. theory



[ATLAS, 2004.03540]



- good agreement (particularly for $k_t \gtrsim 5$ GeV)
- commensurate exp.&th. uncert.
- Can we get α_s from this?

[see Ben's talk]

Lund multiplicity (1/2)

Lund multiplicity

count the (average) number of Lund declusterings (in the full tree) with $k_t \geq k_{t,\text{cut}}$

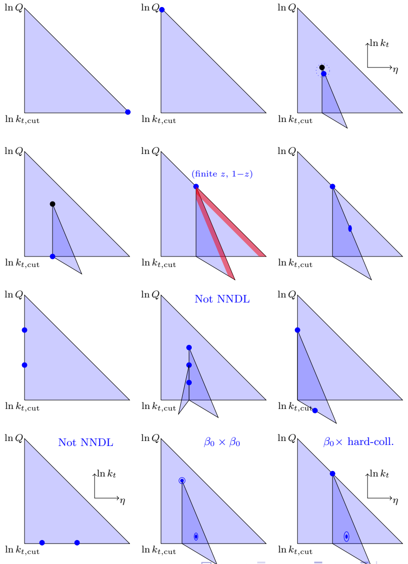
All-order structure ($L = \ln \frac{Q}{k_{t,\text{cut}}}$):

$$\langle N^{\text{LP}}(L,\alpha_s)\rangle = \underbrace{h_1(\alpha_s L^2) + \sqrt{\alpha_s}\, h_2(\alpha_s L^2)}_{\text{Since 1992}} + \underbrace{\alpha_s h_3(\alpha_s L^2)}_{\text{New NNDL!!}} + \dots$$

[R. Medves, A. Soto, GS, soon]

$$\begin{aligned}2\pi h_3^{(q)} = {} & D_{\text{end}}^{q\to qg} + \left(D_{\text{end}}^{g\to gg} + D_{\text{end}}^{g\to q\bar q}\right)\frac{C_F}{C_A}(\cosh\nu - 1) + D_{\text{hme}}^{qqg}\cosh\nu + \frac{C_F}{C_A}\left[(1-c_\delta)D_{\text{pair}}^{q\bar q}(\cosh\nu-1) + \left(K + D_{\text{pair}}^{gg} + c_\delta D_{\text{pair}}^{q\bar q}\right)\frac{\nu}{2}\sinh\nu\right] \\ & + C_F\left[\left(\cosh\nu - 1 - \frac{1-c_\delta}{4}\nu^2\right)D_{\text{clust}}^{(\text{prim})} + (\cosh\nu-1)D_{\text{clust}}^{(\text{sec})}\right] + \frac{C_F}{C_A}\left[D_{\text{e-loss}}^{g}\frac{\nu}{2}\sinh\nu + \left(D_{\text{e-loss}}^{q} - D_{\text{e-loss}}^{g}\right)(\cosh\nu - 1)\right] \\ & + \frac{C_F}{C_A}\frac{\pi^2\beta_0^2}{8C_A}\left[3\nu(2\nu^2-1)\sinh\nu + (\nu^4+3\nu^2)\cosh\nu\right] + \frac{C_F}{2}\Big\{(B_{gg}+c_\delta B_{gq})^2\nu^2\cosh\nu + 8\left[2c_\delta B_{gg} - 2c_\delta B_q - (1-3c_\delta^2)B_{gq}\right]B_{gq}\cosh\nu \\ & + \left[4B_q(B_{gg}+(2c_\delta+1)B_{gq}) - (B_{gg}+c_\delta B_{gq})(B_{gg}+9c_\delta B_{gq})\right]\nu\sinh\nu + 4(1-c_\delta^2)B_{gq}^2\nu^2 + 8\left[2c_\delta B_q - 2c_\delta B_{gg} + (1-3c_\delta^2)B_{gq}\right]B_{gq}\Big\} \\ & + \frac{C_F}{C_A}\frac{\pi\beta_0}{2}\Big\{(B_{gg}+c_\delta B_{gq})\nu^3\sinh\nu + \left[2B_q - 2B_{gg} + (6-8c_\delta)B_{gq}\right]\nu\sinh\nu + 2(B_q+B_{gg}+B_{gq})\nu^2\cosh\nu - 4(1-c_\delta)B_{gq}(2\cosh\nu - 2 + \nu^2)\Big\}\end{aligned}$$

Side product: NNDL Cambridge multiplicity for $y_{\text{cut}} = k_{t,\text{cut}}^2$



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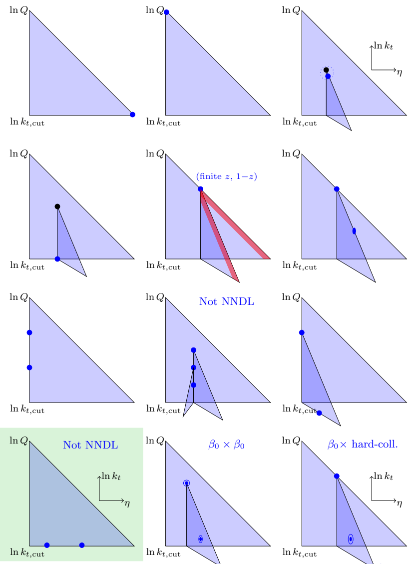
& + \frac{C_F}{C_A}\frac{\pi\beta_0}{2}\Big\{(B_{gg}+c_\delta B_{gq})\nu^3\sinh\nu + \left[2B_q - 2B_{gg} + (6-8c_\delta)B_{gq}\right]\nu\sinh\nu + 2(B_q+B_{gg}+B_{gq})\nu^2\cosh\nu - 4(1-c_\delta)B_{gq}(2\cosh\nu - 2 + \nu^2)\Big\}
\end{aligned}$$

No "long-distance effect" $\Rightarrow$ simpler than k_t



Lund multiplicity (2/2)

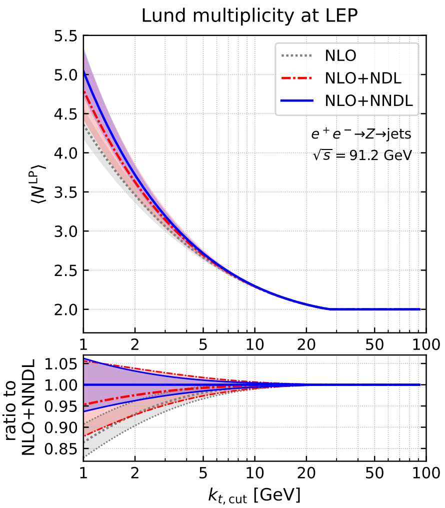
[R. Medves, A. Soto, GS, soon]

NNDL Matched to NLO

- Clear effect of resummation
- Clear effect compared to NDL (incl. uncert)

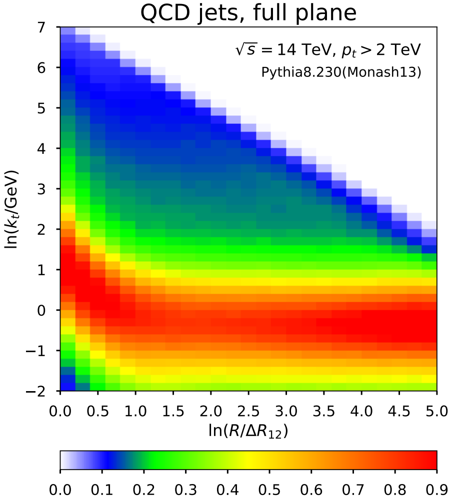
Several questions

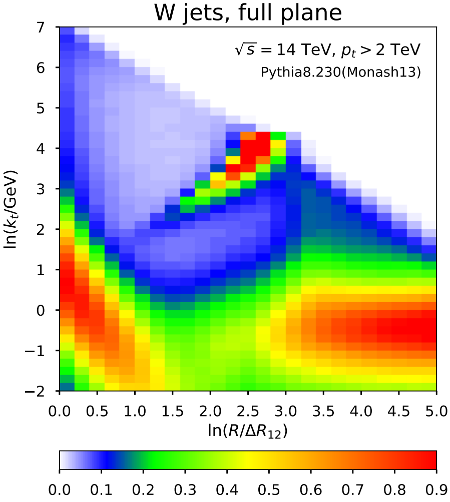
- LEP (ALEPH) measurement?
  cf. Yang-Ting's recent 2111.09914
- Upgrade to LHC jets?
- Can it lead to an α_s measurement?
- NNLO? N^{3}DL?

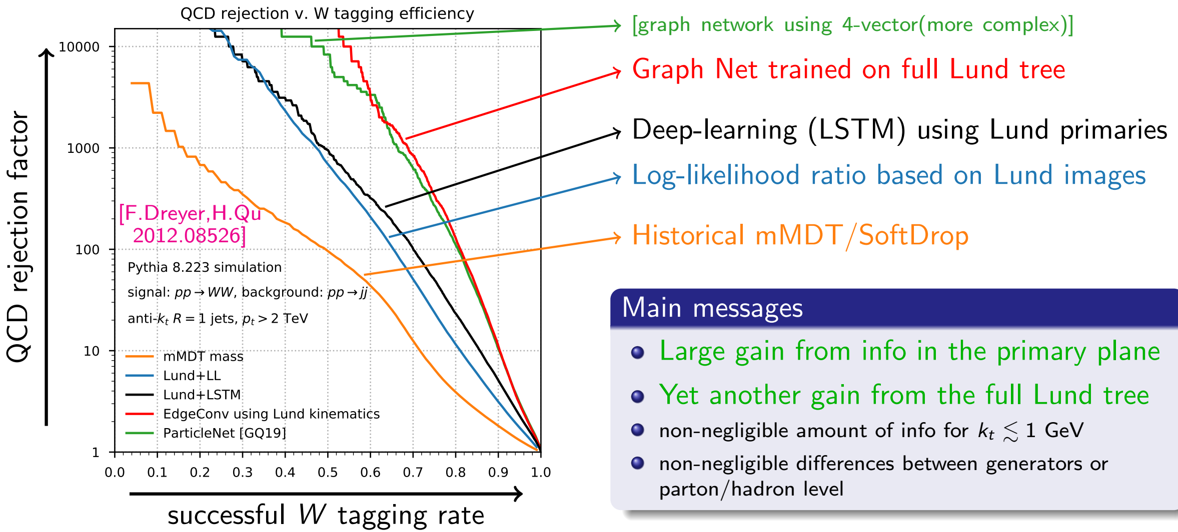


Application #2: Boosted object tagging

Clear potential on a simple image (also: many basic features recognised)



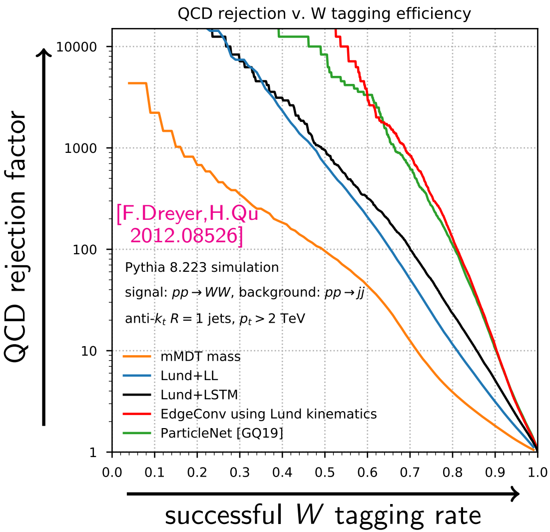


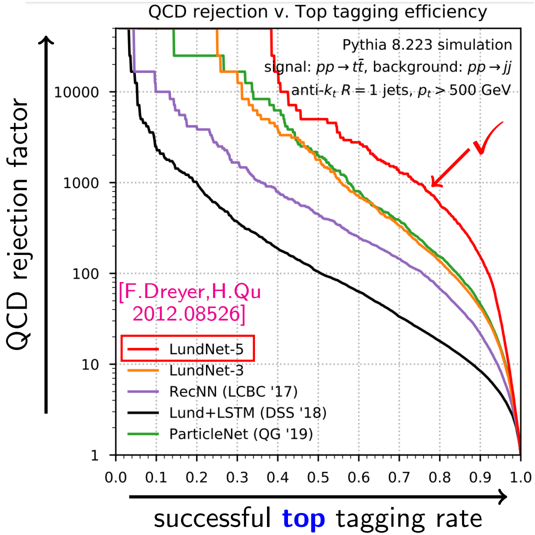


Main messages

- Large gain from info in the primary plane
- Yet another gain from the full Lund tree
- non-negligible amount of info for $k_t \lesssim 1$ GeV
- non-negligible differences between generators or parton/hadron level

Tagging boosted W bosons (v. QCD jets) [2/2]





Quark v. gluon jets: I. approach

Optimal discriminant (Neyman–Pearson lemma)

$$\mathbb{L}_{\text{prim,tree}} = \frac{p_g(\mathcal{L}_{\text{prim,tree}})}{p_q(\mathcal{L}_{\text{prim,tree}})}$$

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Approach #1

Deep-learn $\mathbb{L}_{\text{prim,tree}}$

LSTM with $\mathcal{L}_{\text{prim}}$ or Lund-Net with $\mathcal{L}_{\text{tree}}$

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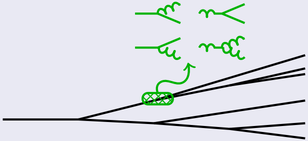
Approach #2

Use pQCD to *calculate* $p_{q,g}(\mathcal{L}_{\textbf{prim,tree}})$



- Consider $k_t \geq k_{t,\text{cut}}$ to stay perturbative
- Resum logs to all orders in α_s, up to single logs
  - single logs from "DGLAP" collinear splittings

$$P_q(\mathcal{L}_{\text{parent}}) = S_q(\Delta_{\text{prev}}, \Delta)\left[\tilde{P}_{qq}(z)p_q(\mathcal{L}_{\text{hard}})p_g(\mathcal{L}_{\text{soft}}) + \tilde{P}_{gq}(z)p_g(\mathcal{L}_{\text{hard}})p_q(\mathcal{L}_{\text{soft}})\right]$$

$$p_g(\mathcal{L}_{\text{parent}}) = S_g(\Delta_{\text{prev}}, \Delta)\left[\tilde{P}_{gg}(z)p_g(\mathcal{L}_{\text{hard}})p_g(\mathcal{L}_{\text{soft}}) + \tilde{P}_{qg}(z)p_q(\mathcal{L}_{\text{hard}})p_q(\mathcal{L}_{\text{soft}})\right]$$

  - some single logs for emissions at commensurate angles
- At double-log: $\frac{p_g}{p_q} = \left(\frac{C_A}{C_F}\right)^{n_{\text{prim}}} \Rightarrow$ reproduces the Iterated SoftDrop multiplicity

Quark v. gluon jets: II. ML validation

our analytic discriminant is exact/optimal in the dominant collinear limit $\theta_1 \gg \theta_2 \gg \cdots \gg \theta_n$
$\Rightarrow$ ML expected to give the same performance

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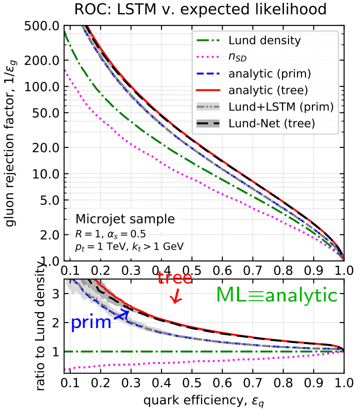
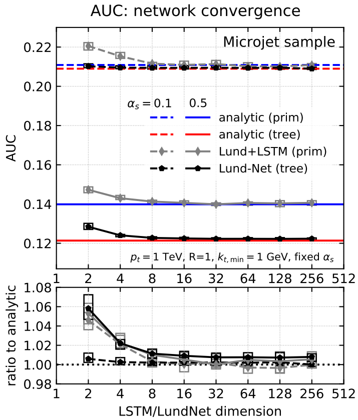


Microjet
≡
exact
pure-collinear

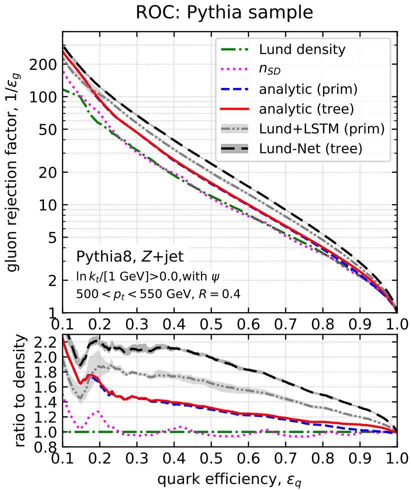


ROC curves agree

Converges for large-enough networks

Quark v. gluon jets: III. performance

$pp \to Zq$ v. $pp \to Zg$ $\quad (p_t \sim 500$ GeV, $R = 0.4)$



- clear performance ordering:
  1. Lund+ML > Lund analytic > ISD
  2. tree > prim

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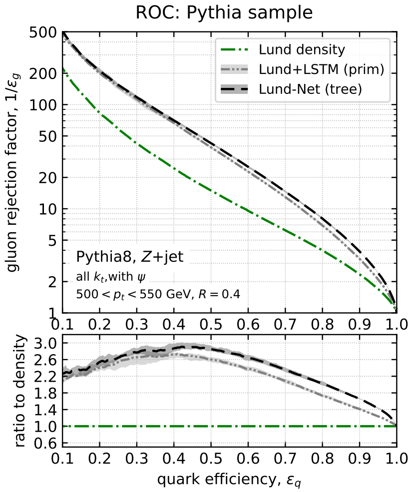

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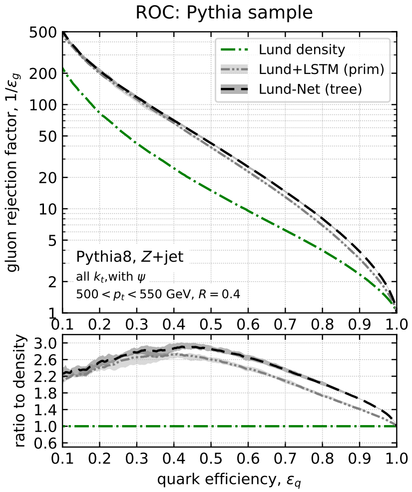
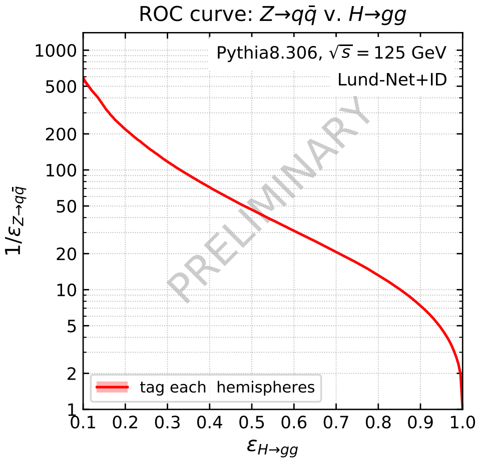


- clear performance ordering:
  1. Lund+ML > Lund analytic > ISD
  2. tree > prim
- larger gains with no k_t cut
- Interesting questions:
  - Analytic approach to NP?
  - Apply analytics to other systems ($W/Z/H$, top)

Towards full-event tagging

$e^+e^- \to Z \to q\bar{q}$ v. $e^+e^- \to H \to gg$ $(\sqrt{s} = 125$ GeV, no ISR)



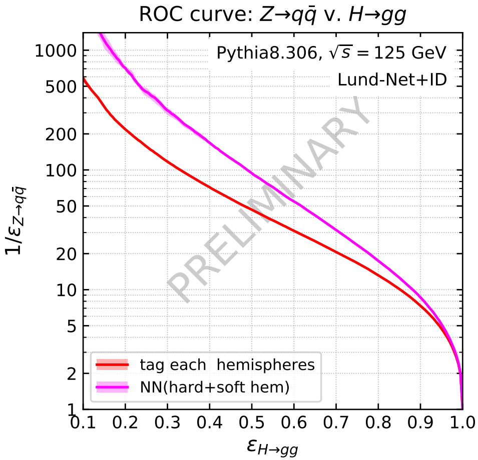
observed performance:

- tagging both hemispheres
  i.e. both jets should be tagged

  full event clearly worse that (jet)^2

Towards full-event tagging

$$e^+e^- \to Z \to q\bar{q} \text{ v. } e^+e^- \to H \to gg \qquad (\sqrt{s} = 125 \text{ GeV, no ISR})$$



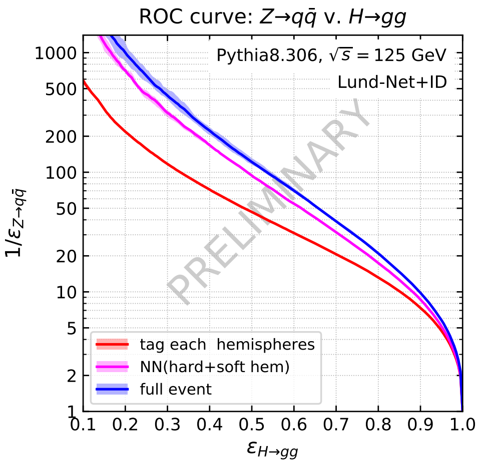
observed performance:

- tagging both hemispheres
- double Lund-Net tag
  train separately on hard & soft hemispheres
  use another NN (or MVA) to combine the two

  clear performance gain

Towards full-event tagging

$e^+e^- \to Z \to q\bar{q}$ v. $e^+e^- \to H \to gg$ $\quad (\sqrt{s} = 125$ GeV, no ISR)

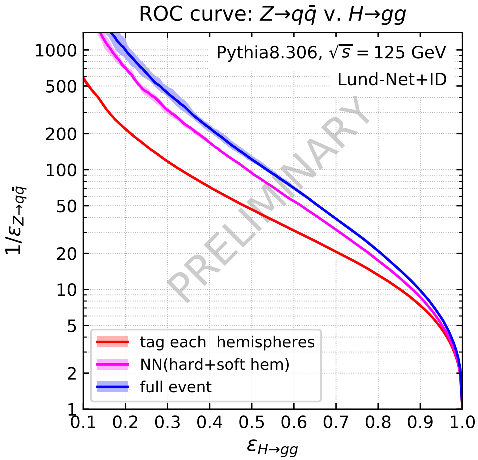


observed performance:

- tagging both hemispheres
- double Lund-Net tag
- Lund-Net for the full event
  Another performance gain

Towards full-event tagging

$e^+e^- \to Z \to q\bar{q}$ v. $e^+e^- \to H \to gg$ $(\sqrt{s} = 125$ GeV, no ISR$)$



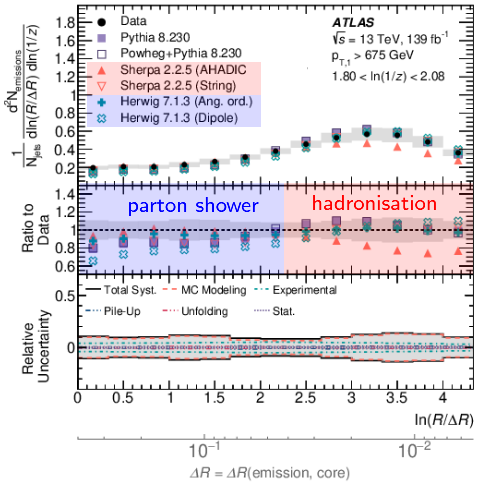
observed performance:

- tagging both hemispheres
- double Lund-Net tag
- Lund-Net for the full event
  Another performance gain

Open questions/work in progress

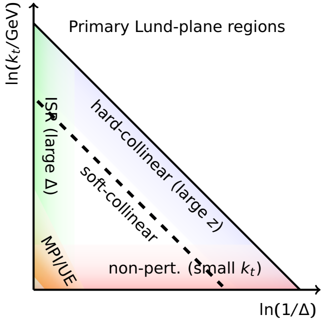
- How does the analytic do?
  e.g. what gain from full-event tagging?
- Applications to other cases (e.g. at the LHC)?

Application #3: MC development



"standard" data vs. Monte Carlo comparison

Recall that different Lund regions are sensitive to different physics:



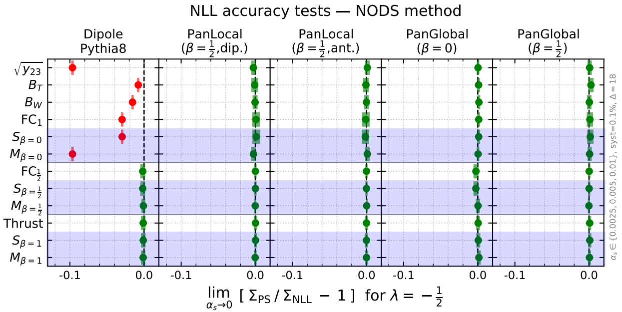
Revisiting substructure observables

- Equivalent to angularities/EECs:

$$S_\beta = \sum_{i\in\mathcal{L}} E_i \, e^{-\beta\eta_i}$$

$$M_\beta = \max_{i\in\mathcal{L}} E_i \, e^{-\beta\eta_i}$$

  - ✓ subjets allows for the use of "max"
  - ✓ sum≠max at NLL
  - ✓ can be defined in *pp*



[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,2002.11114]
[K.Hamilton,R.Medves,G.Salam,L.Scyboz,GS,2011.10054]

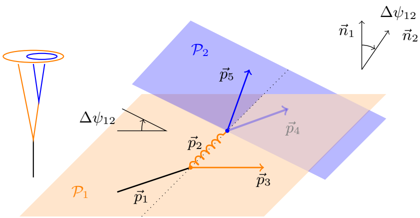
- N-subjettiness-like: sum excluding the N largest

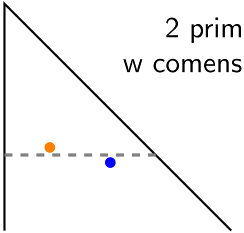
$$\tau_N^{\beta,\text{Lund}} = \sum_{i\in A_N} E_i \, e^{-\beta\eta_i} \qquad \text{with} \qquad A_N = \text{argmin}_{X\subset\mathcal{L},|\mathcal{L}\setminus X|=N-1}$$

  - ✓ Could replace sum by max (likely gaining a simpler resummation structure)
  - ✓ Could be defined on the primary plane only

Crafted observables

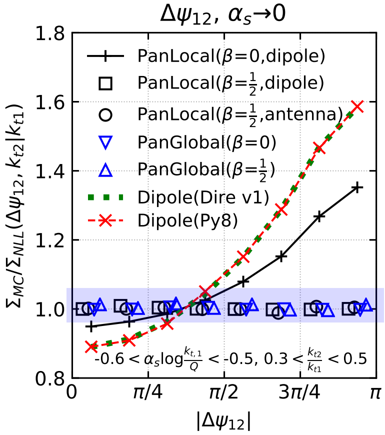
Azimuth between 1st and 2nd prim. declust.





2 primaries
w comensurate k_t

[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,2002.11114]



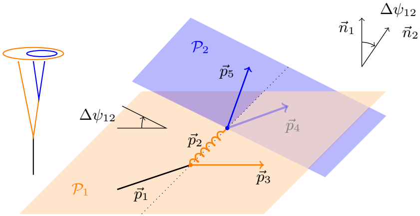
Expected ratio of 1 at NLL

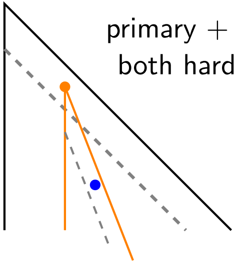
NLL failures for "standard" showers

"New" PanScales shower OK at NLL

Crafted observables

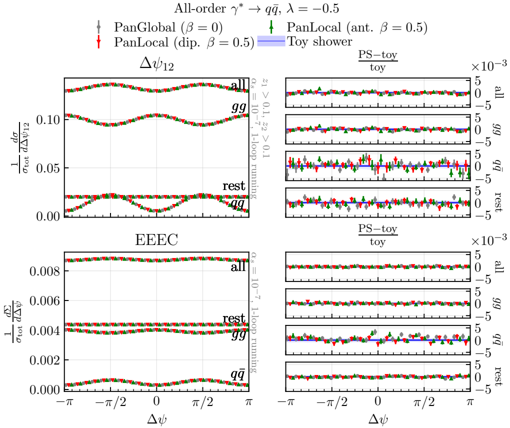
Azimuth between 1st and 2nd prim. declust.





primary + secondary
both hard-collinear

[A.Karlberg,G.Salam,L.Scyboz,R.Verheyen,2103.16526]

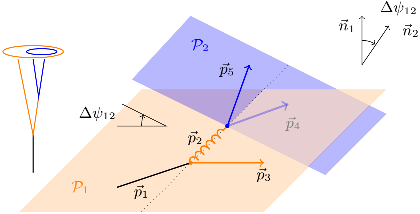


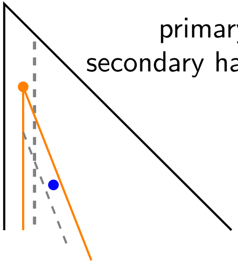
Sensitive to (collinear) spin
"New" PanScales shower have spin at NLL
agrees w EEEC from 2011.02492 (EEEC less sensitive)

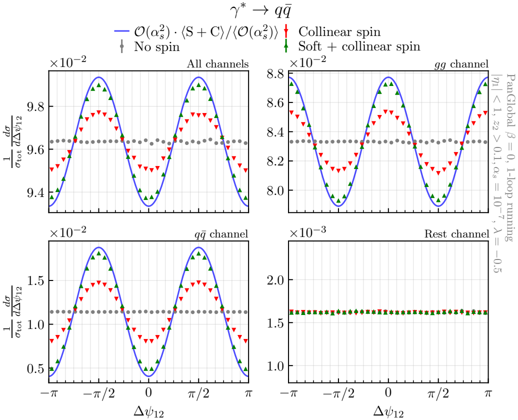
Crafted observables

[K.Hamilton,A.Karlberg,G.Salam,L.Scyboz,R.Verheyen,2111.01161]

Azimuth between 1st and 2nd prim. declust.







Sensitive to (soft) spin

"New" PanScales shower have spin at NLL

first all-order result

Conclusions

1. Lund diagrams have helped thinking about resummation and MCs
   Now they can be reconstructed in practice
2. They provide a view of a jet/event which mimics angular ordering
3. They provide a separation between different physical effects
4. Broad spectrum of applications:
   - Wide range of possible (p)QCD calculations
     Main limitation: (non-global) clustering logs; can we apply grooming-like techniques?
   - Large scope for crafting new observables for improved (p)QCD calculations
   - Large scope for crafting new observables for MC development/validation
   - More connections to deep learning, heavy-ion collisions, ...
5. Still many open questions and space for more applications in the future

Backup

Promoting to a practical tool

Construct the Lund tree in practice: use the Cambridge(/Aachen) algorithm

Main idea: Cambridge(/Aachen) preserves angular ordering

e^+e^- collisions

1. Cluster with Cambridge ($d_{ij} = 2(1 - \cos\theta_{ij})$)
2. For each (de)-clustering $j \leftarrow j_1 j_2$:

$$\eta = -\ln \theta_{12}/2$$
$$k_t = \min(E_1, E_2)\sin\theta_{12}$$
$$z = \frac{\min(E_1,E_2)}{E_1+E_2}$$
$$\psi \equiv \text{some azimuth},\ldots$$

Jet in pp

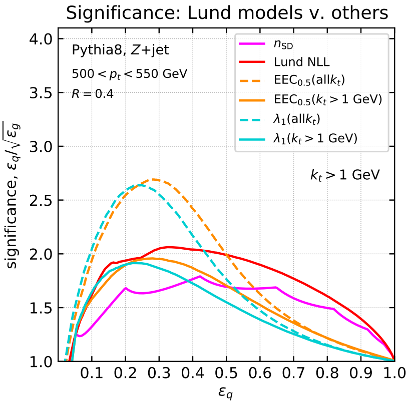
1. Cluster with Cambridge/Aachen ($d_{ij} = \Delta R_{ij}$)
2. For each (de)-clustering $j \leftarrow j_1 j_2$:

$$\eta = -\ln \Delta R_{12}$$
$$k_t = \min(p_{t1}, p_{t2})\Delta R_{12}$$
$$z = \frac{\min(p_{t1},p_{t2})}{p_{t1}+p_{t2}}$$
$$\psi \equiv \text{some azimuth},\ldots$$

Primary Lund plane

Starting from the jet, de-cluster following the "hard branch" (largest E or p_t)

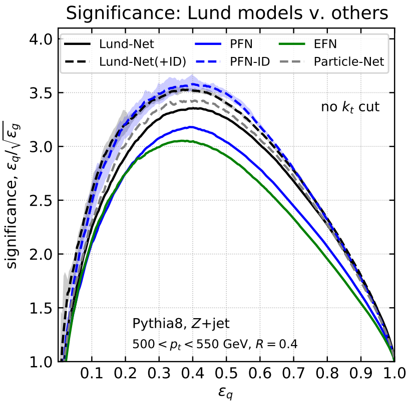
$pp \to Zq$ v. $pp \to Zg$ $(p_t \sim 500$ GeV, $R = 0.4)$



- Analytic approach shows gains for $k_t > 1$ GeV
  (shapes improve at small ε_q by adding smaller k_t)

Quark v. gluon jets: III. performance v. others

$pp \to Zq$ v. $pp \to Zg$ $(p_t \sim 500$ GeV, $R = 0.4)$



- Analytic approach shows gains for $k_t > 1$ GeV

  (shapes improve at small ε_q by adding smaller k_t)

- ML performance on par with PFN, slightly better than Particle-Net

  (treatment of PDG-ID could maybe be improved)