Università
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# Jets for LHC Run 3

CERN QCD seminar
Friday 11th November 2022

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# Introduction

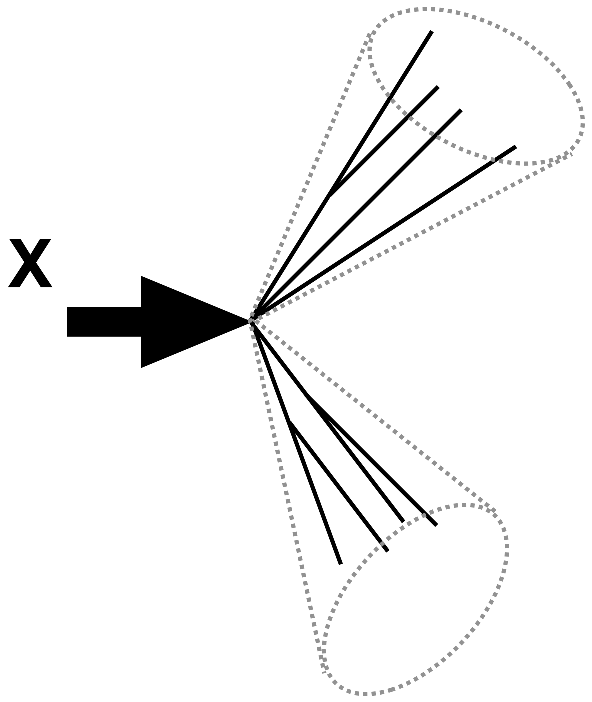
- LHC Run3 does not give us any substantial increase in energy: but we will have more and more data;
- the theoretical focus is on making our tools better and better
  - NNLO calculations as the new standard (loop-results for at least $2\to3$ topologies; more flexible subtraction schemes; interface with parton showers and/or resummation);
  - parton-shower simulations upgraded to the precision club (log accuracy, colour, higher-order splitting functions);
  - state-of-the art predictions for standard candles (e.g. $N^3LO$, $N^3LL$ resummation, effects on parton densities);
- one of the challenges ahead is to find new and more efficient ways to interrogate the data and **jet physics offers us exciting opportunities**

**CROSS-POLLINATION**

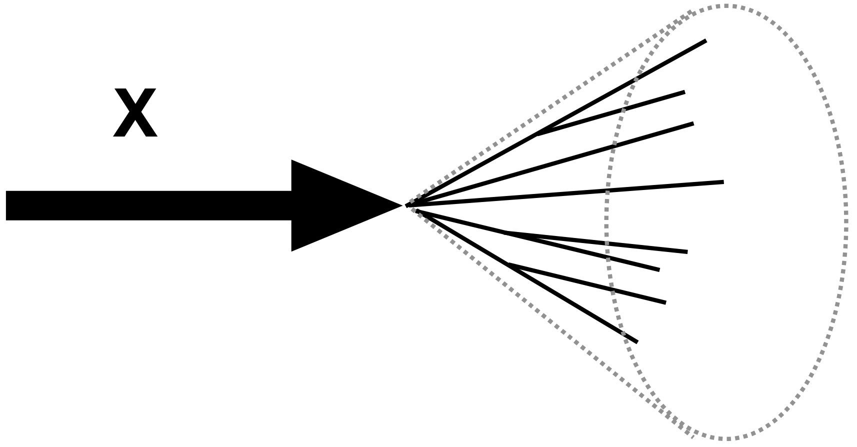
**UNDERSTANDING NEW TOOLS**

# An introduction to jet substructure

*starting mostly as a tool for new physics searches, jet substructure techniques are now mainstream*



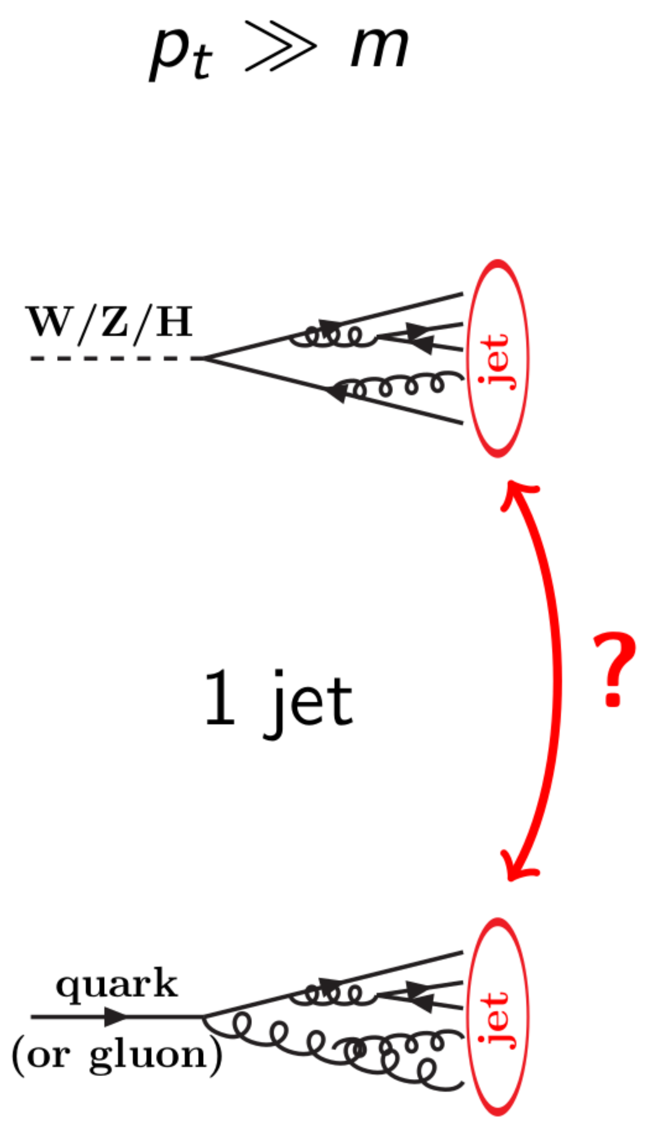
X is at rest and its decay products are reconstructed in two jets



X is boosted and its decay products are reconstructed in one jet

# Looking inside jets

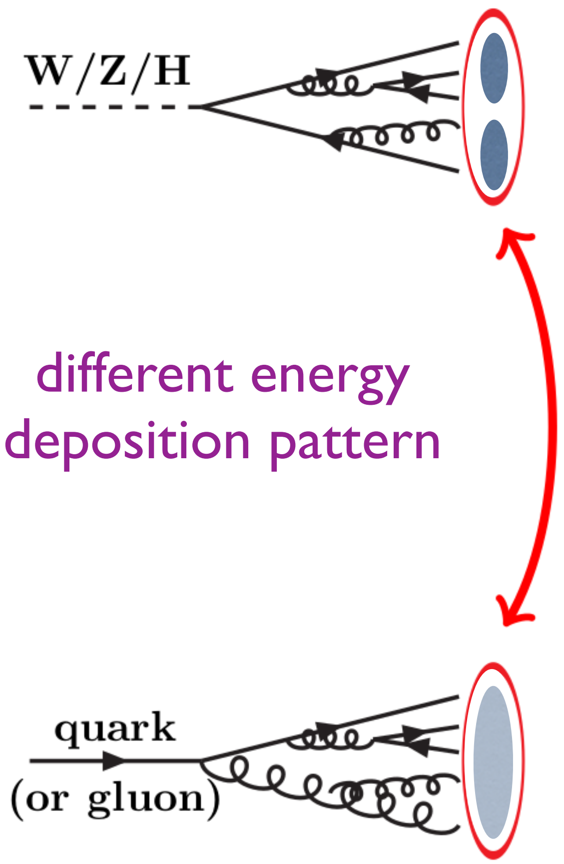
- the two major goals of the LHC
- search for new particles
- characterise the particles we know
- jets can be formed by QCD particles but also by the decay of massive particles (if they are sufficiently boosted)
- how can we distinguish signal jets from background ones?



# Jet substructure in a nutshell

- the final energy deposition pattern is influenced by the originating splitting
- hard vs soft translates into 2-prong vs 1-prong structure
- picture is mudded by many effects (hadronisation, underlying event, pileup)
- two-step procedure:
  - grooming: clean the jets up by removing soft radiation
  - tagging: identify the features of hard decays and cut on them

$p_t \gg m$

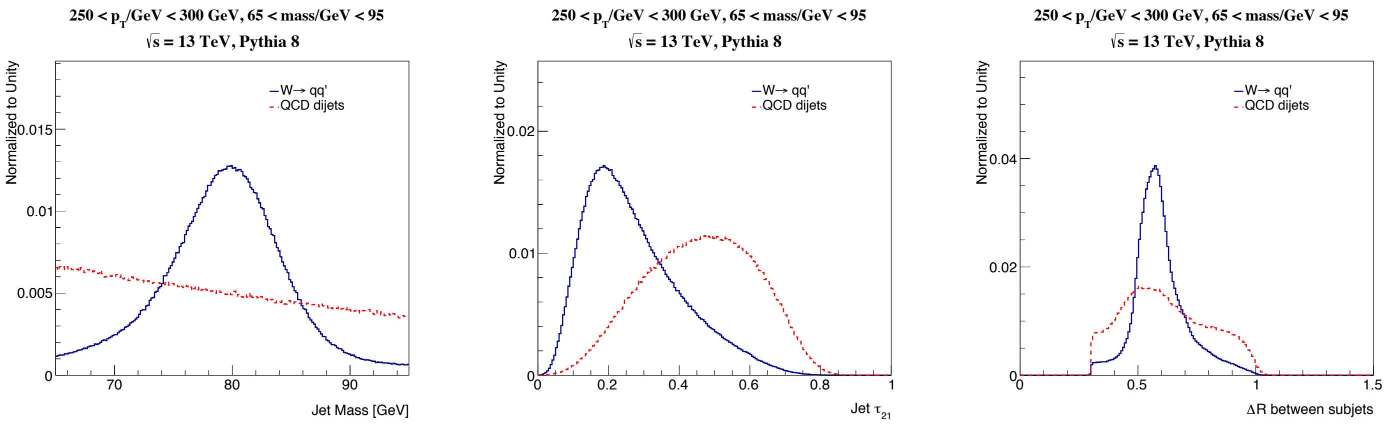


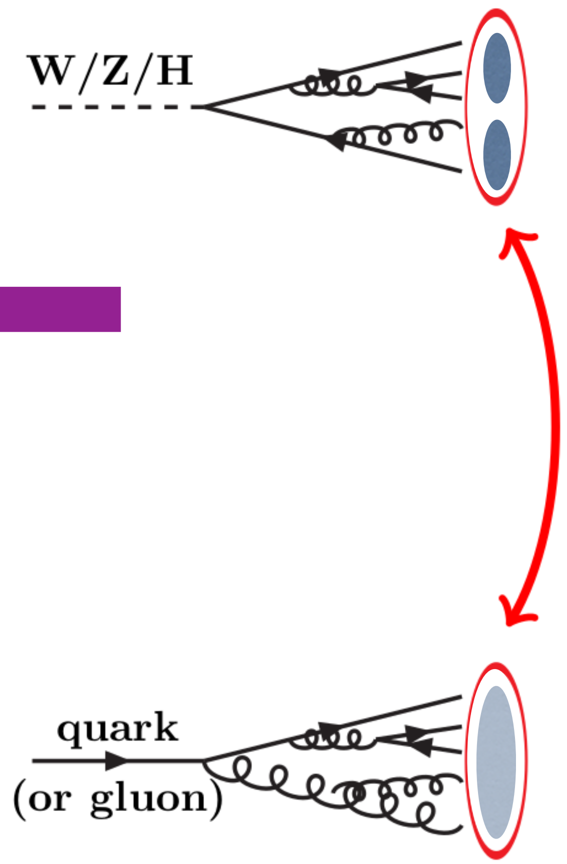
different energy deposition pattern

# A theorist's job

- devise clever ways to project the multi-dimensional parameter space of final-state momenta into suitable lower dimensional (typically 1-D) distributions

$p_t \gg m$





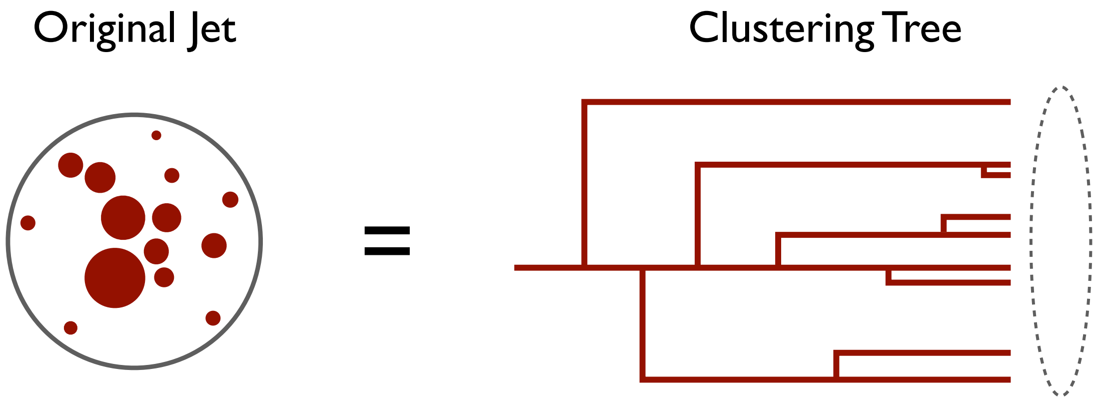
*for an introduction see SM, Soyez, Spannowsky*
*"Looking inside jets"*

- in the past decade, our understanding of jets has improved tremendously

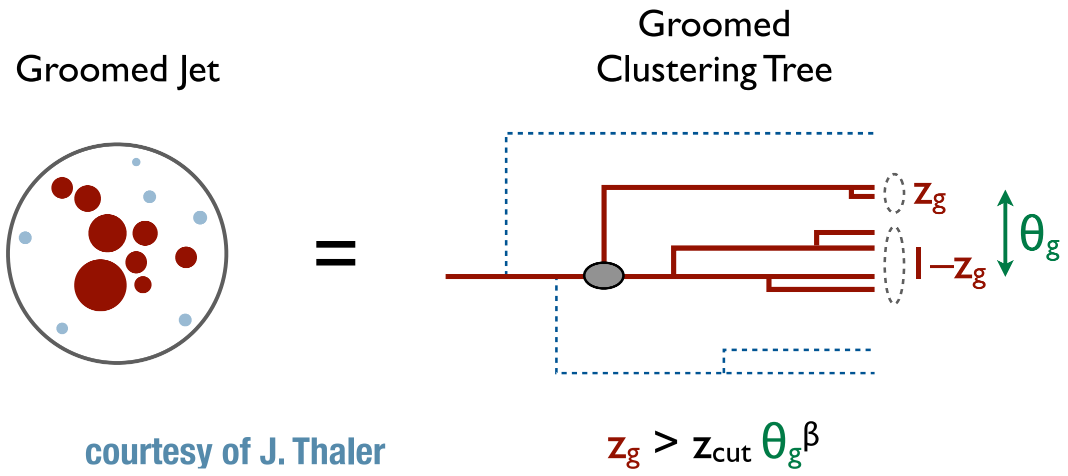
- so it is time to ask ourselves if jet substructure can play a role in the wider LHC physics program

# An example: Soft Drop

- efficient and robust *grooming* and *tagging* a have been developed and exploited at the LHC
- Soft Drop aims to clean up a jet by removing soft radiation



courtesy of J. Thaler



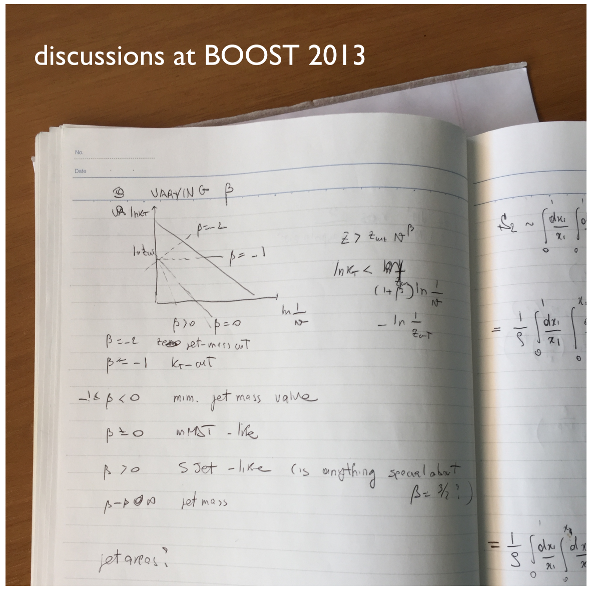
courtesy of J. Thaler

- compute momentum sharing and if it fails the soft drop condition, remove the branch

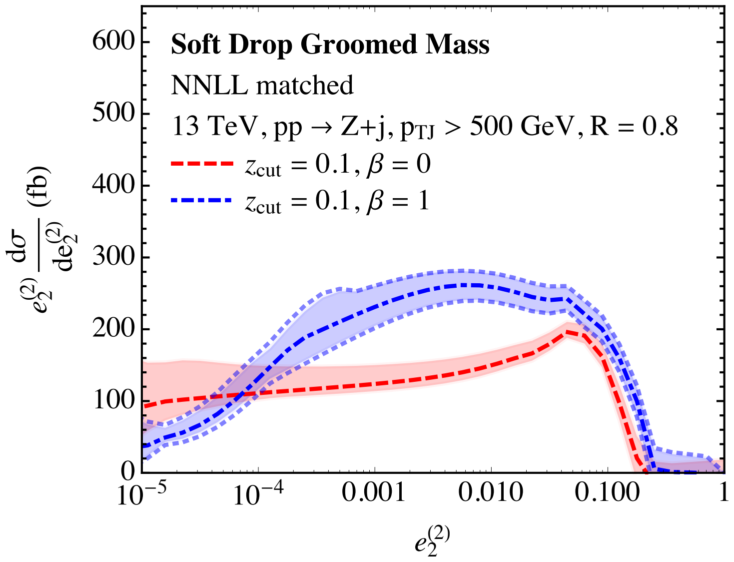
$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} \qquad z_g < z_{\rm cut}\,\theta_g^{\beta}$$

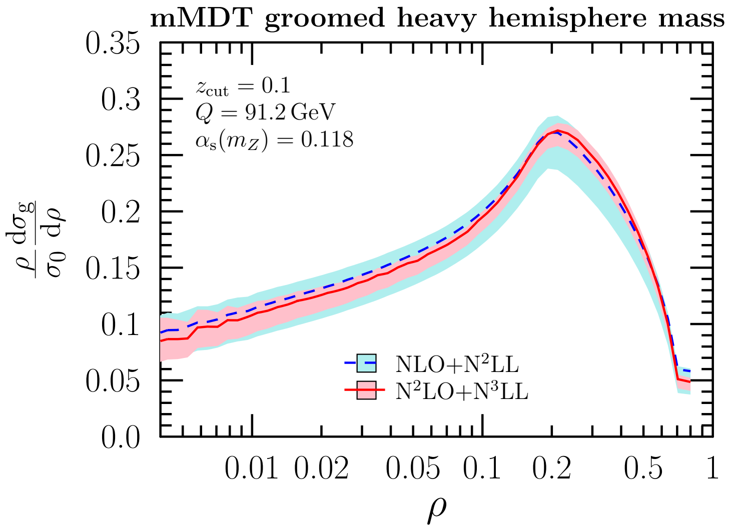
*Larkoski, SM, Soyez, Thaler (2014)*

# From ideas to precision



discussions at BOOST 2013





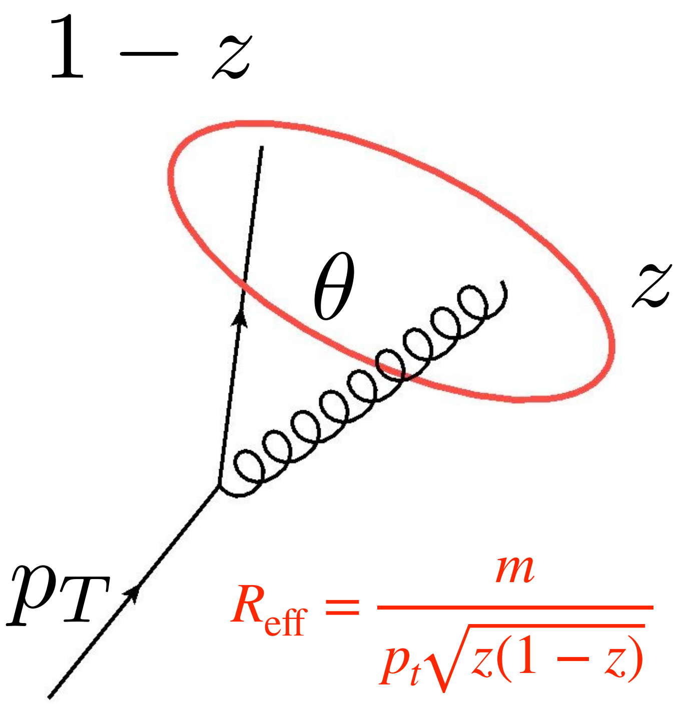
*Frye, Larkoski, Schwartz, Yan (2016)*

*Kardos, Larkoski, Trocsanyi (2020)*

*Dasgupta, El-Menoufi, Helliwell (2022)*

- good perturbative properties (convergence, absence of intricate soft effects such as non-global logs)
- what about sensitivity to non-perturbative corrections?

# Hadronisation corrections



$$R_{\rm eff} = \frac{m}{p_t\sqrt{z(1-z)}}$$

- we have to take into account (at least) two effects:
  - a non-perturbative mass shift

$$\delta m^2 = C_F \Lambda_{\rm NP} p_t R_{\rm eff}$$

  - a non-perturbative $p_t$ shift (loss)

$$\delta p_t = -\, C_A \Lambda_{\rm NP} / R_{eff}$$

*Dasgupta, Magnea, Salam (2008)*

- both contribute with the same leading-power correction to the jet mass distribution (assuming $1/m$ behaviour):

$$\left.\frac{d\sigma}{dm}\right|_{\rm NP} = \left.\frac{d\sigma}{dm}\right|_{\rm pert} \left(1 + f(z_{\rm cut}, \beta) \frac{p_t \Lambda_{\rm NP}}{m^2} \left(\frac{m}{p_t}\right)^{\frac{2}{2+\beta}}\right)$$

- standard result
- soft-drop reduction

*Dasgupta, Fregoso, SM, Salam (2013);*

*SM, Schunk, Soyez (2018)*

- detailed field-theory analysis confirms and expands on this picture

*Hoang, Pathak, Mantry, Stewart (2019);*

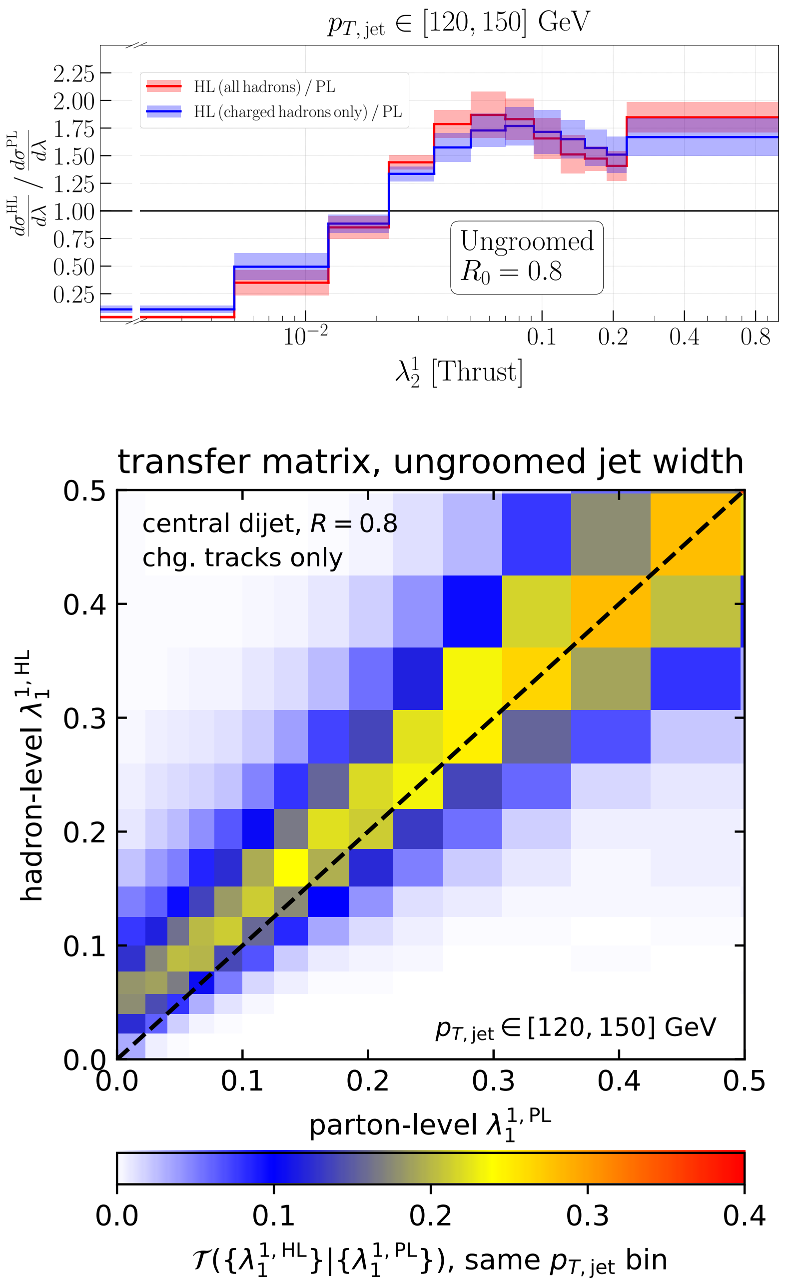
*Pathak, Vaida, Stewart, Zoppi (2020)*

# Size of the corrections

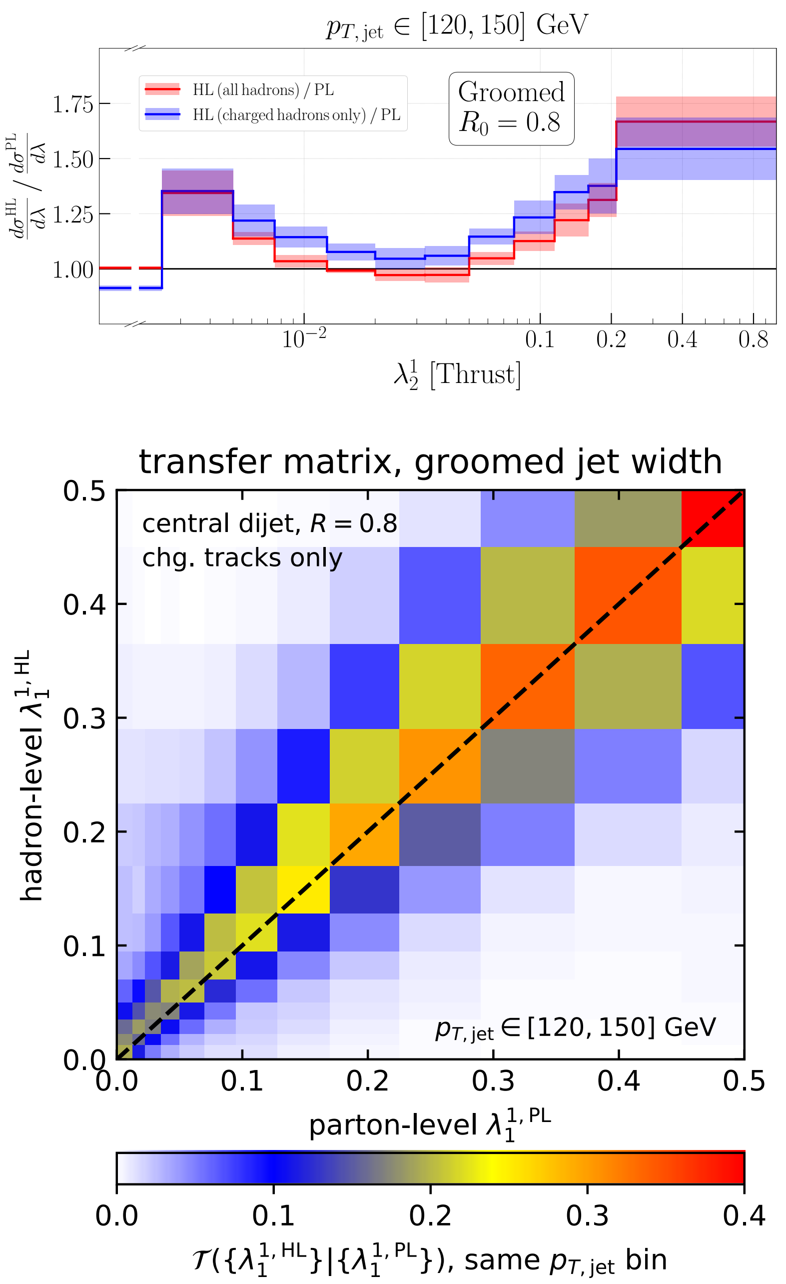
- simple analytic arguments confirmed by detailed MC simulations (with both hadronisation and underlying event)

$$\lambda_\alpha^\kappa = \sum_{i\in\text{jet}} \left(\frac{p_{ti}}{p_t}\right)^\kappa \left(\frac{\Delta_i}{R}\right)^\alpha$$

- grooming reduces onset, size and migration effects due to non-perturbative corrections!



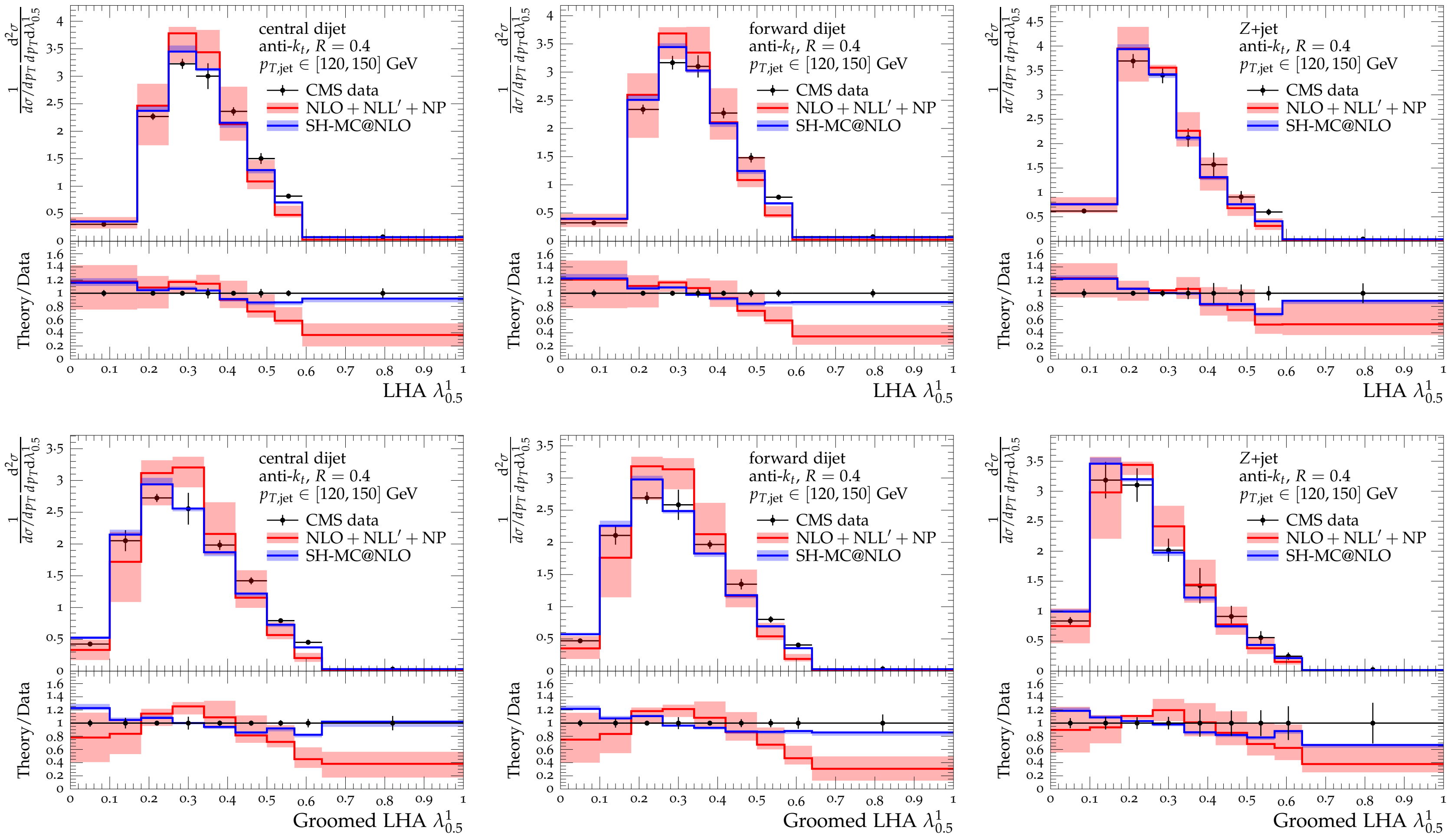
*Caletti, Fedkevych, SM, Reichelt, Schumann, Soyez, Theeuwes (2021)*



*Reichelt, Caletti, Fedkevych, SM, Schumann, Soyez (2021)*

# Comparison to data

- jet angularities allow us to probe the internal QCD dynamics of jets (set $\kappa = 1$ for IRC safety)
- multi-scale problem that requires resummation
- NLO+NLL’ implemented in the Sherpa-resummation plugin (efficient way to handle kinematics and colour)
- CMS performed detailed studies of jet angularities in Z+jet and dijet events



*CMS collaboration (2021)*

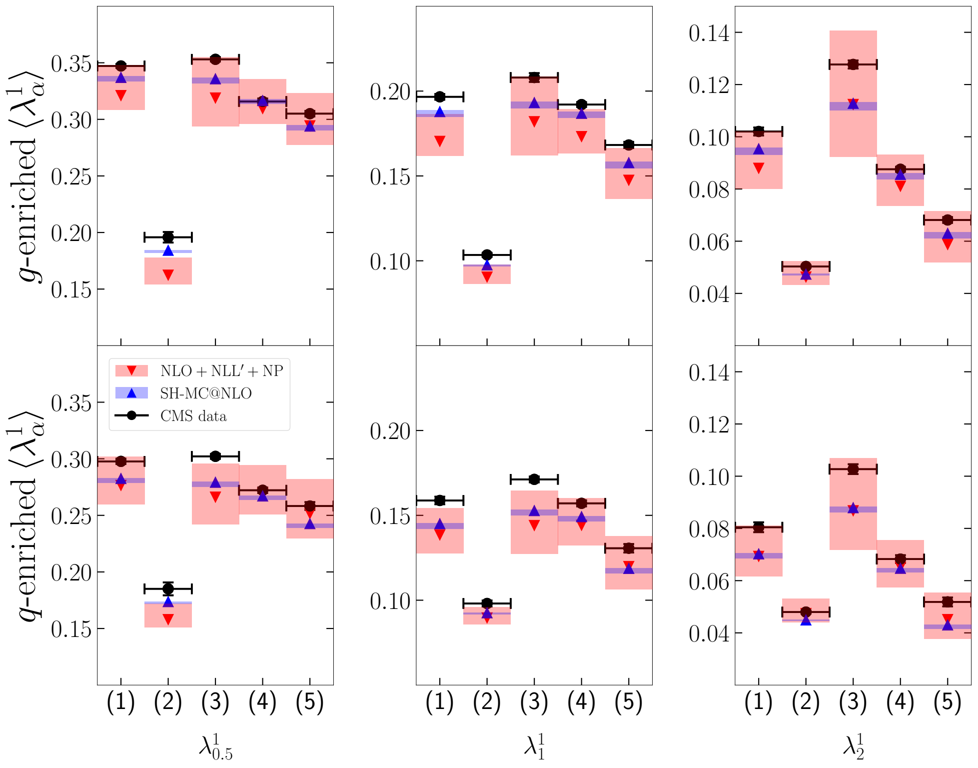
*Reichelt, Caletti, Fedkevych, SM, Schumann, Soyez (2021)*

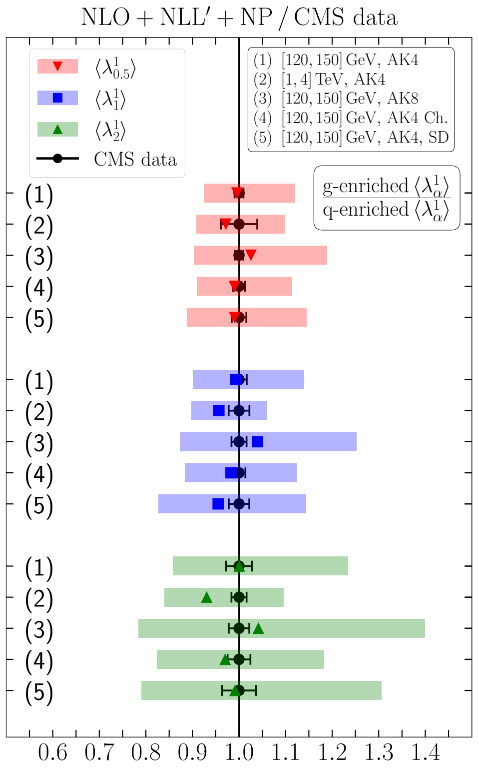
- a wealth of high-quality data combined with solid theory description
- a lot of phenomenology that can be done!

# Quark/gluon enriched samples

- angularities in $Z$+jet and dijets: different transverse momentum and rapidity bins allows us to probe samples with rather different quark/gluon components

| 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 |





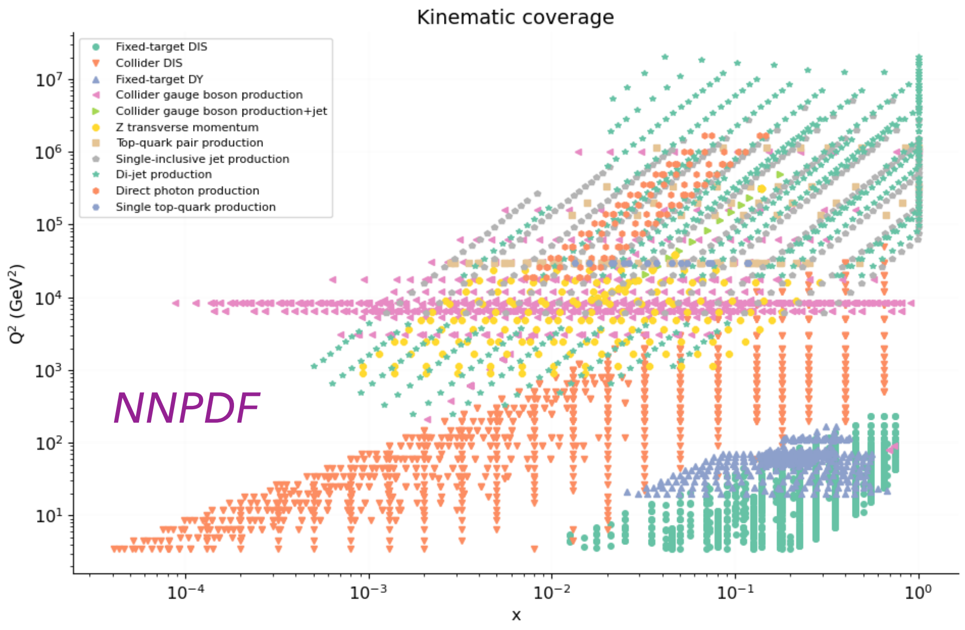
- mean values confirm standard picture: $g$'s radiate more than $q$'s
- our calculation tends to underestimate the mean values
- however, it does so democratically for $q$'s and $g$'s: no appreciable bias
- beware! NLO corrections can significantly alter $q/g$ fractions
- room for improvement: thanks to recent development NNLO+NNLL is not far away

*Reichelt, Caletti, Fedkevych, SM, Schumann, Soyez (2021)*

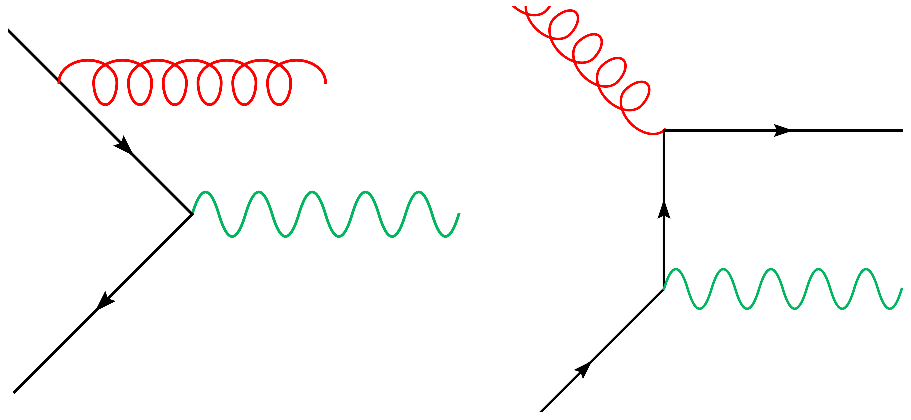
# *Quark/gluon* tagging for SM pheno

- *q/g* tagging traditional important for searches
- can it be useful in Standard Model studies?
- yes, but we need theoretically well-defined (IRC safe) taggers

- *Z* $p_T$ studies play a central role in SM phenomenology: probe of initial-state QCD dynamics
- *Z* $p_T$ recently entered global PDF fits: they provide info on the gluon PDF

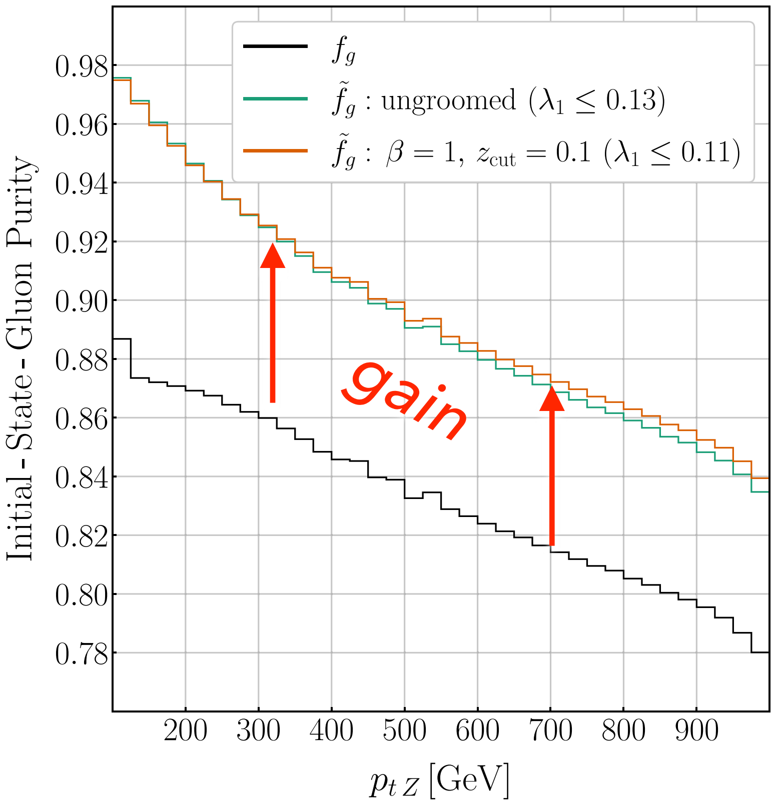


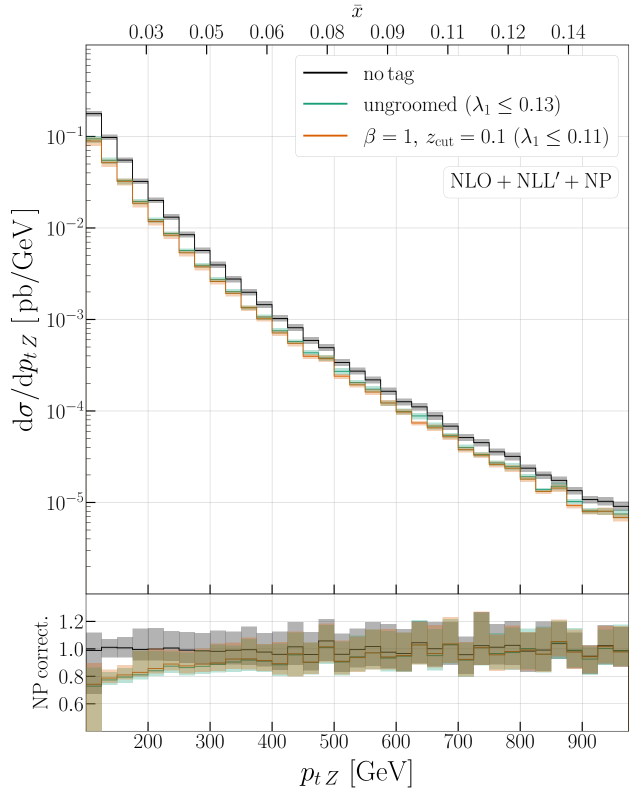
- the *Z* + jet process features a strong correlation between the flavours of initial- and final-state partons (100% at LO)



# Angularities as q/g taggers

- use jet angularities to select $Z$ + quark-jet events
- this selection ensures a higher initial-state-gluon purity
- measure Z $p_T$ on those events





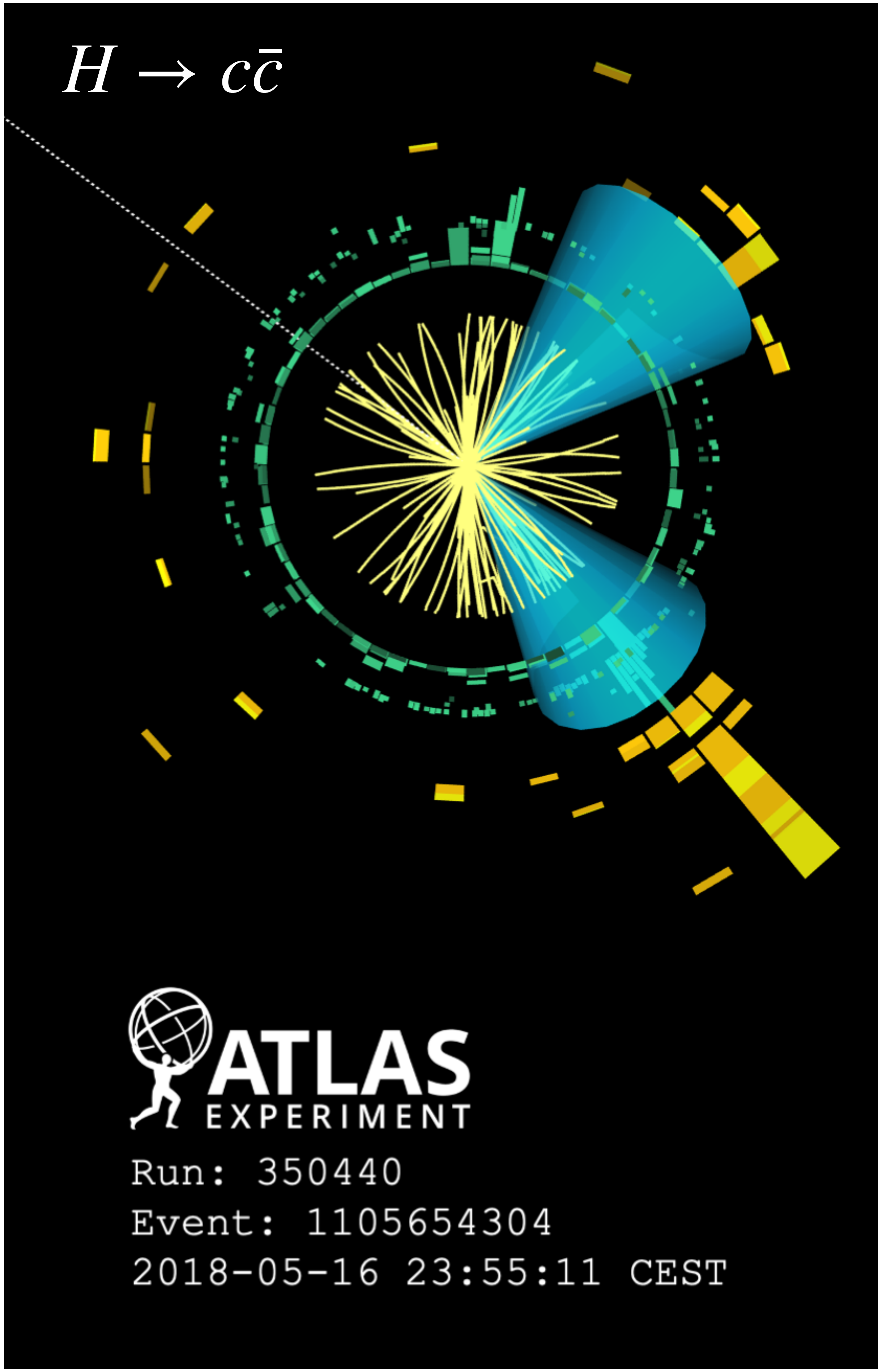
- need to assess the actual impact on the gluon PDF
- plenty of data!

- *pro's*: good gain, everything is IRC and calculable;
- *con's*: need to reconstruct the leading jet, acquired sensitivity to non-pert. corrections

*Caletti, Fedkevych, SM, Reichelt, (2021)*

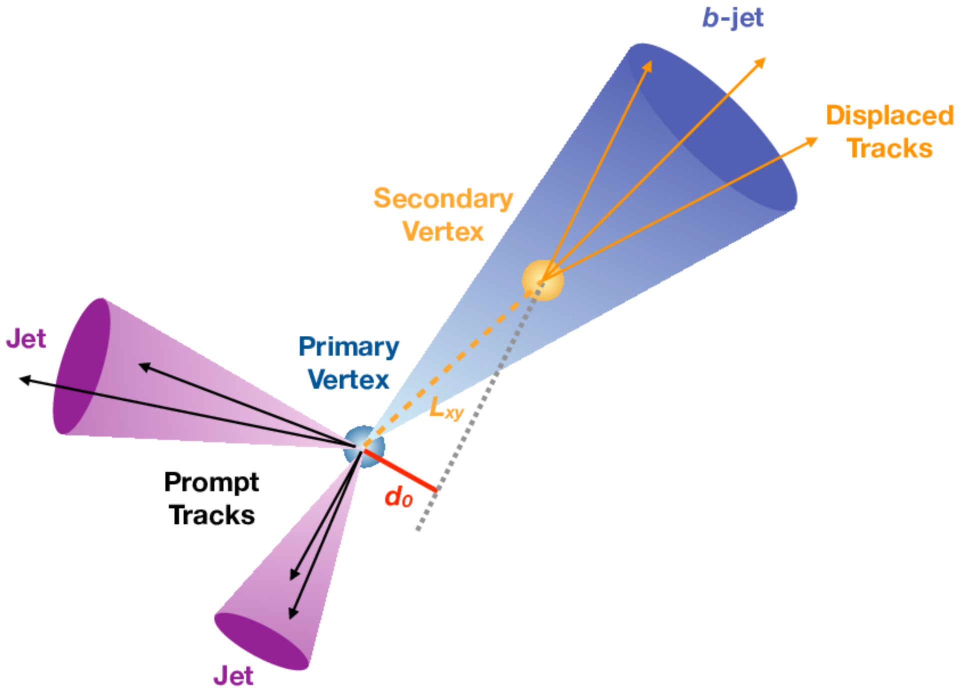
# Cross-pollination

*jet substructure inspires new ideas to study heavy flavours*

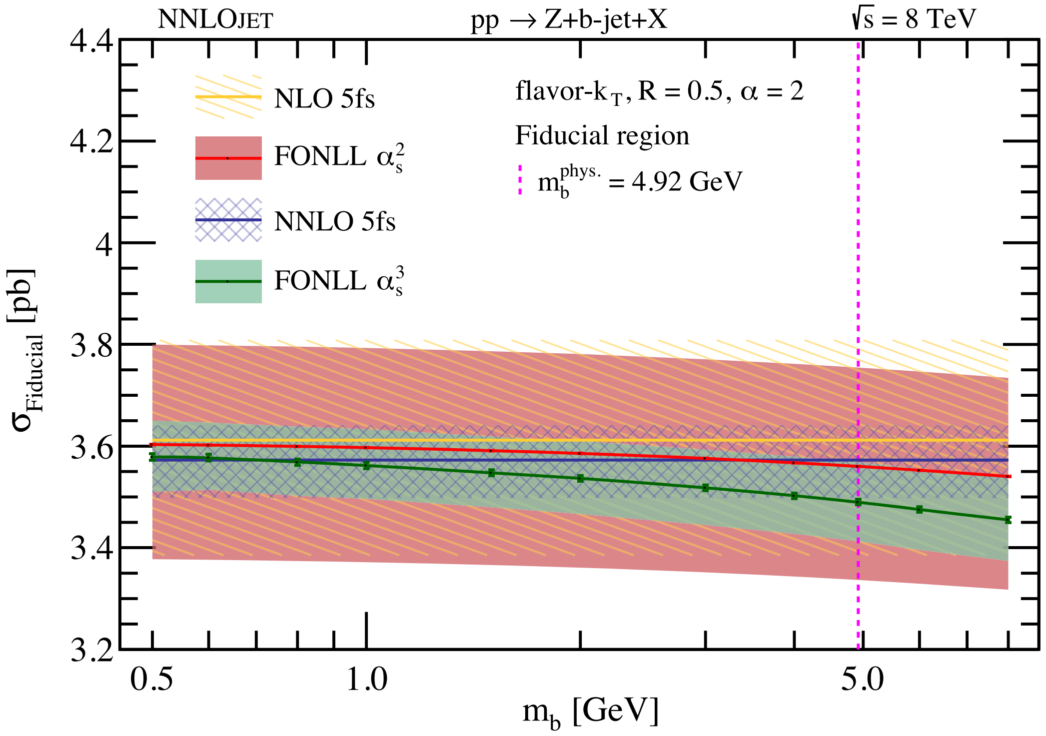


# Heavy Flavour Jets

- jets containing heavy flavours (charm and beauty) are central to the LHC Higgs program
- important for QCD studies too: PDFs, fragmentation etc.
- they are identified exploiting B hadron lifetime: displaced vertices
- from theory viewpoint, $m_b$ & $m_c$ set perturbative scales: high accuracy (NNLO) QCD calculations Z+b/c jet now exist



https://cds.cern.ch/record/2771727/plots

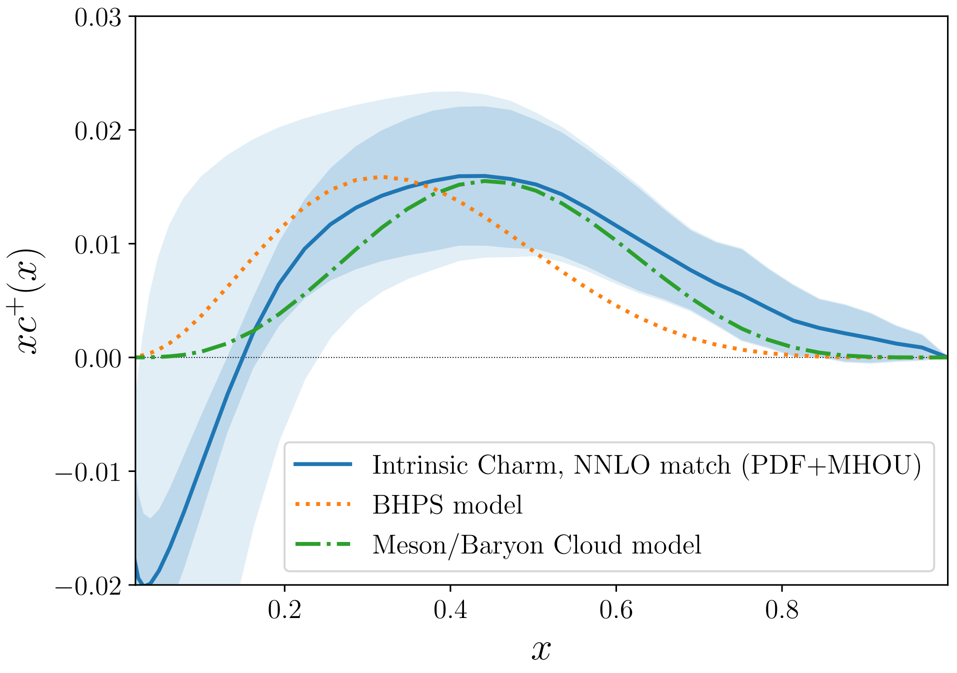


*Gauld et a. (2020)*

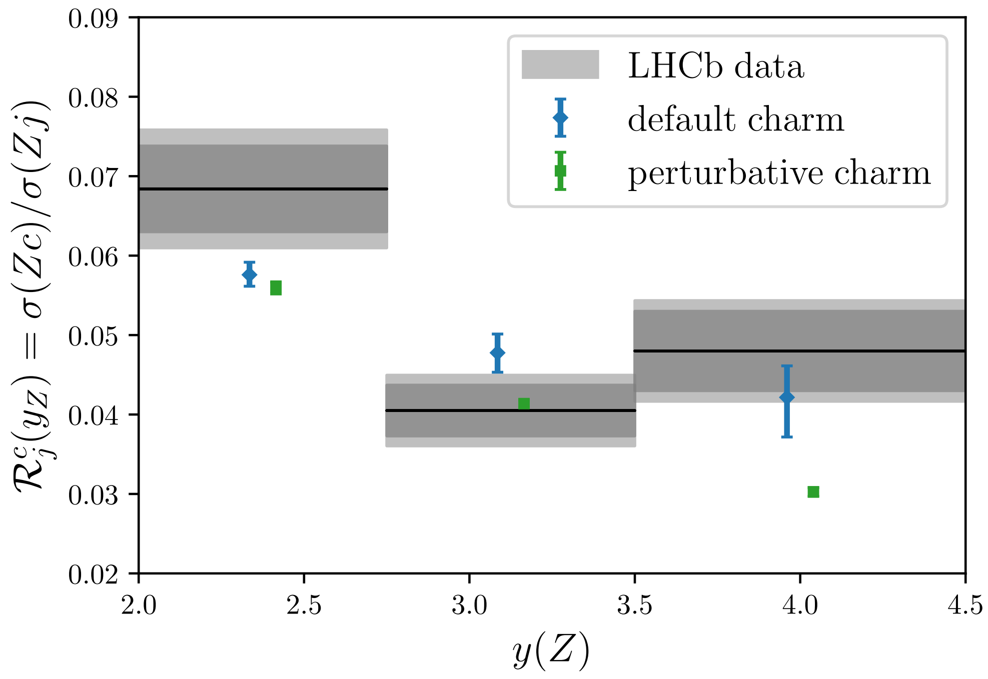
## two recent highlights…

# There’s charm in the proton!

- NNPDF collaboration has recently shown a 3$\sigma$ evidence of intrinsic charm in the proton
  - they fit the charm PDF in the 4-flavour scheme: charm is both radiative and intrinsic
  - they match to the 3-flavour scheme to extract the (only) intrinsic
- good agreement with theory models and and visible in Z+c data!



*NNPDF (2022)*



Nature | Vol 608 | 18 August 2022 |

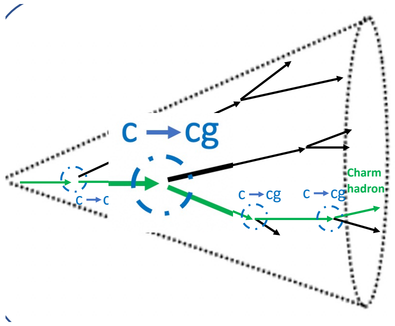
# ALICE and the dead cone

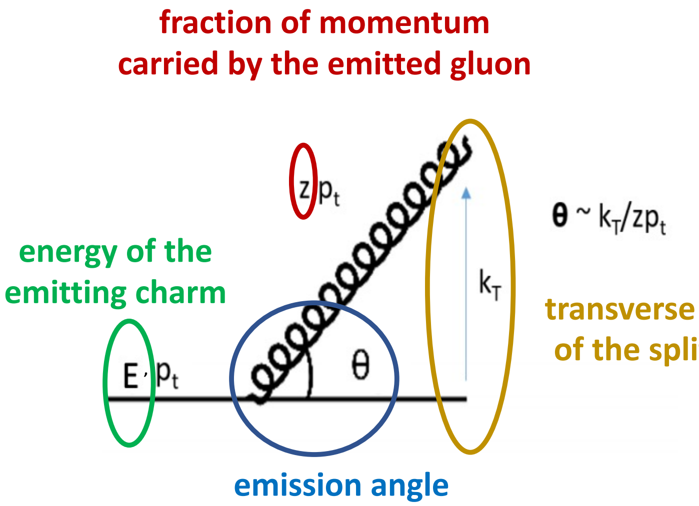
- ALICE recently exploited ideas from modern jet physics (e.g. reclustering) to perform the first direct measurement of the dead cone

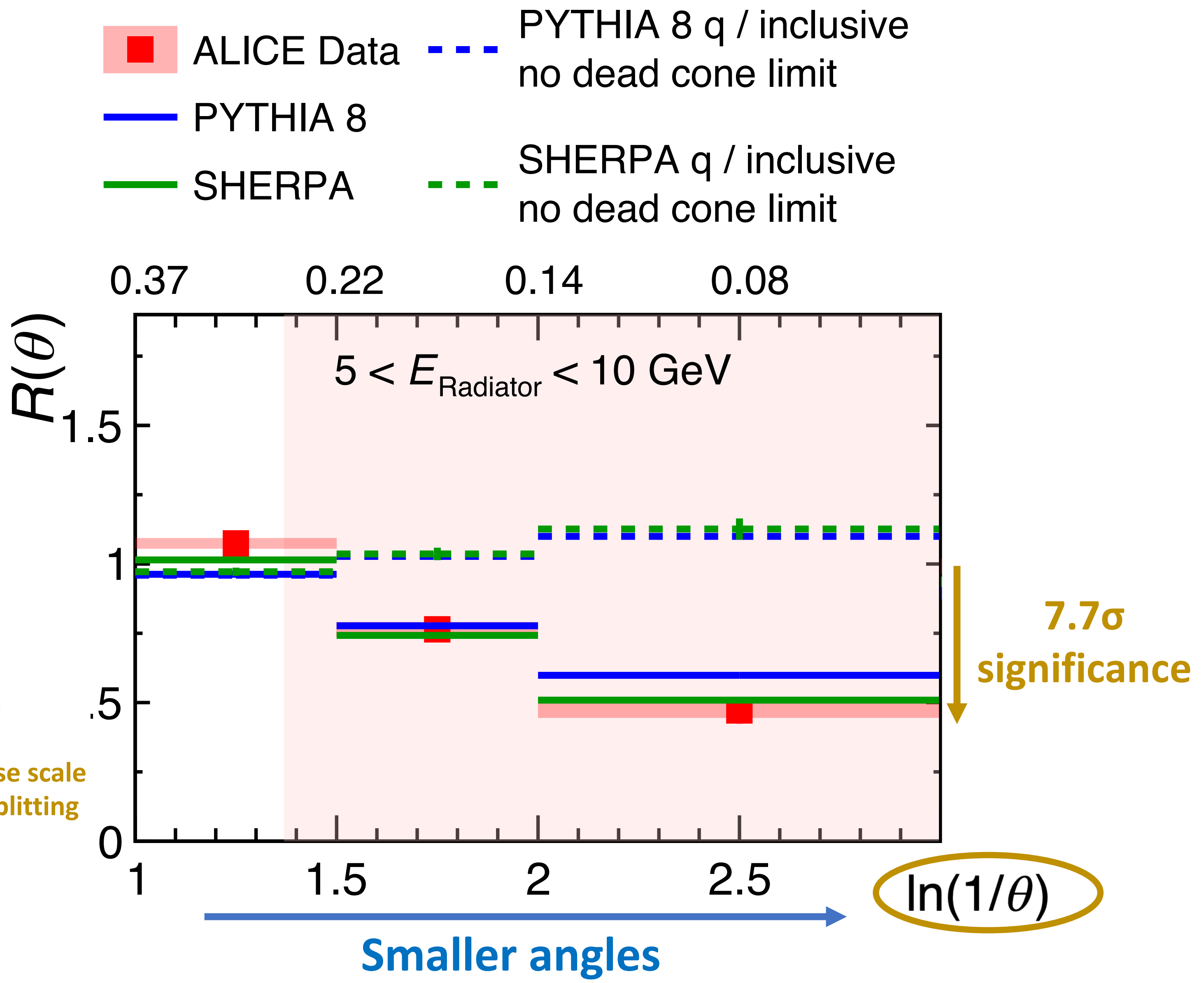
- charm jets are tagged using $D^0 \rightarrow K^- \pi^+$

- jets are declustered and the splitting kinematics is recorded

*Nature 605 (2022) 440-446*







Nature | Vol 605 | 19 May 2022 |

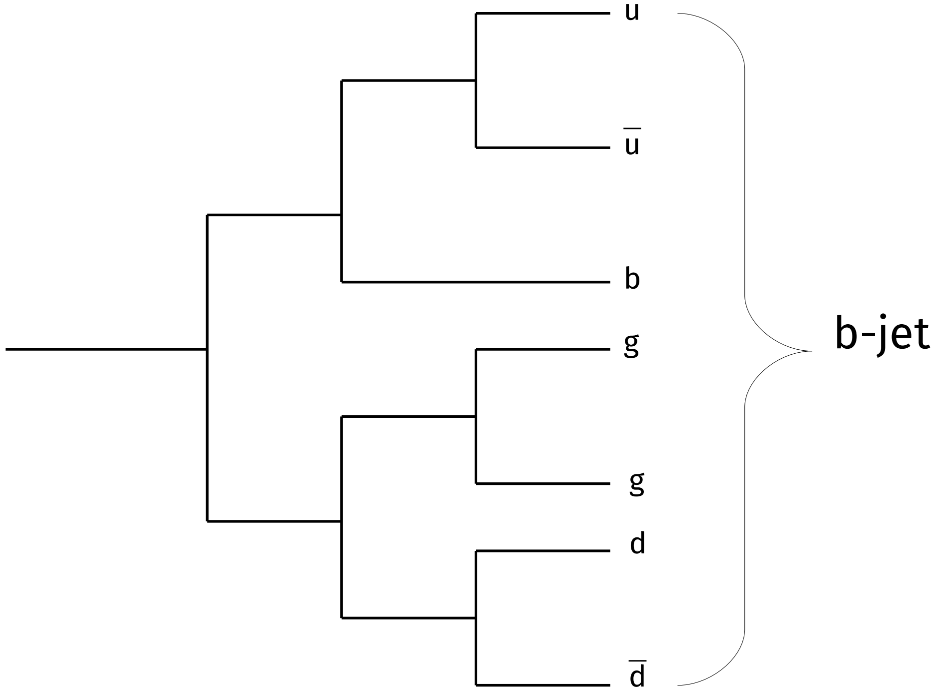
*taken from N. Zardoshti's talk at BOOST 2022*

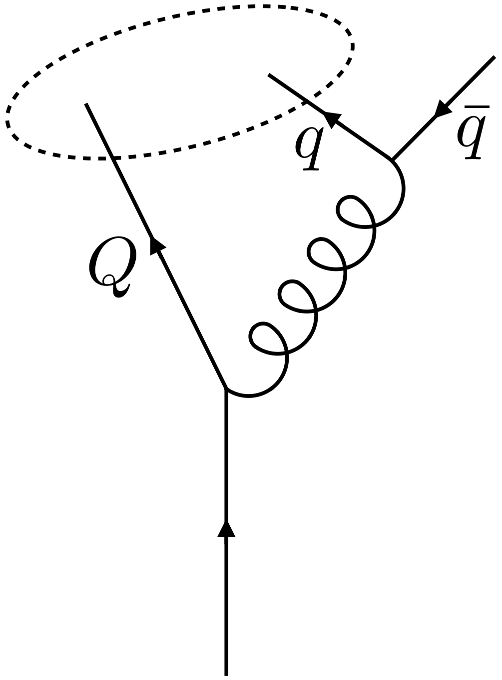
# Experiment vs Theory (I)

- Experimental procedure:
  - cluster jets using the anti-$k_t$ algorithm
  - run *b* (*c*)-tagging

- Theory calculation
  - compute real and virtual
  - cluster jets using an IRC safe (flavour) algorithm

BUT counting the flavour of an anti-$k_t$ jet is NOT IRC Safe beyond NLO!





splitting of a soft gluon can affect jet flavour

*Banfi Salam Zanderighi (2006)*

# BSZ flavour algorithm

- the flavour-sensitive metric reflects the absence of soft quark singularities:

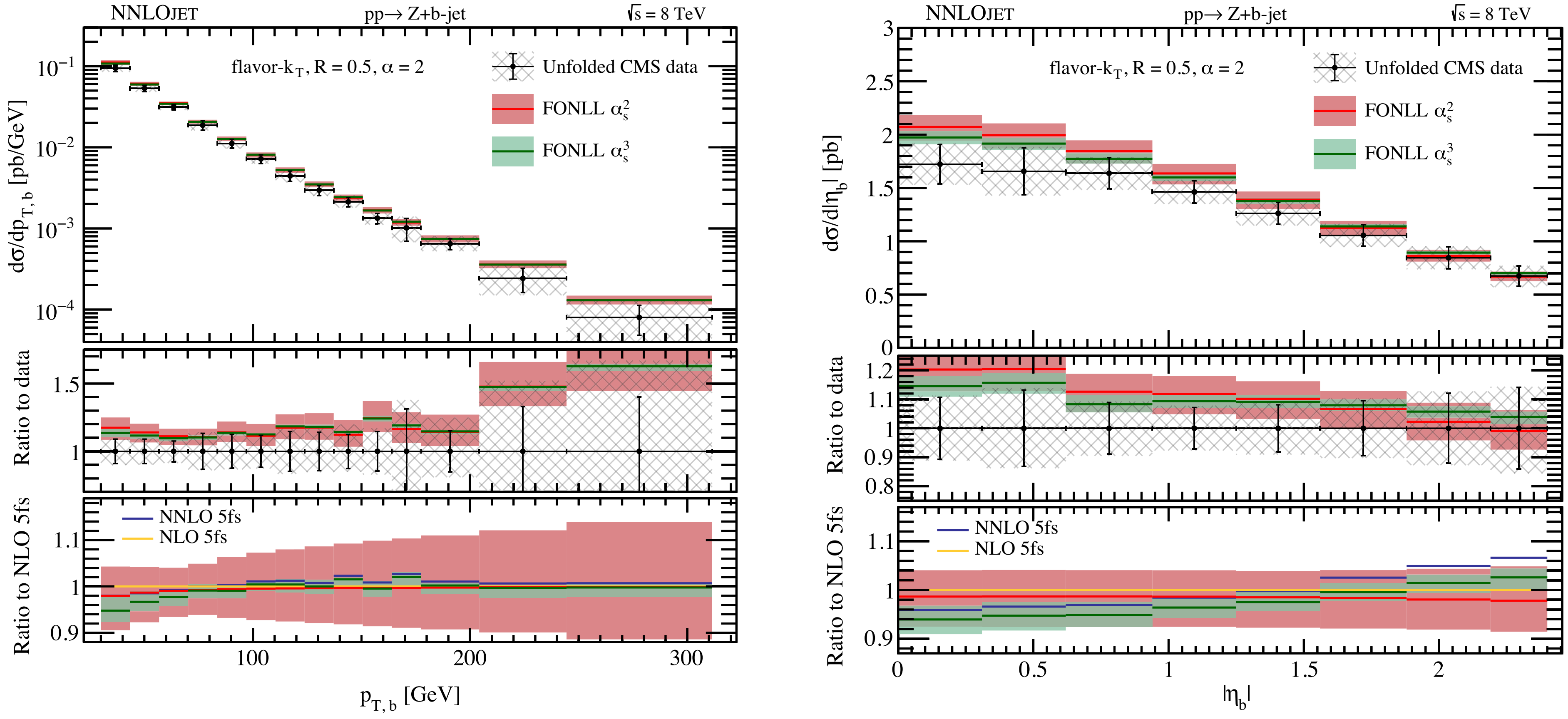
$$d_{ij}^{(F)} = (\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2) \times \begin{cases} \max(k_{ti}^2, k_{tj}^2)\,, & \text{softer of } i,j \text{ is flavoured,} \\ \min(k_{ti}^2, k_{tj}^2)\,, & \text{softer of } i,j \text{ is flavourless,} \end{cases}$$

- it is IRC safe because it tends to recombine together the problematic soft $q\bar{q}$ pair

- however the use of BSZ in experimental analysis is far from straightforward:
  - obviously, it's not anti-k$_t$
  - it requires knowledge of the flavour at each step of the clustering

# Experiment vs Theory (II)

- Comparison between theory and experiments requires to unfold the experimental data to the theory calculation performed with BSZ

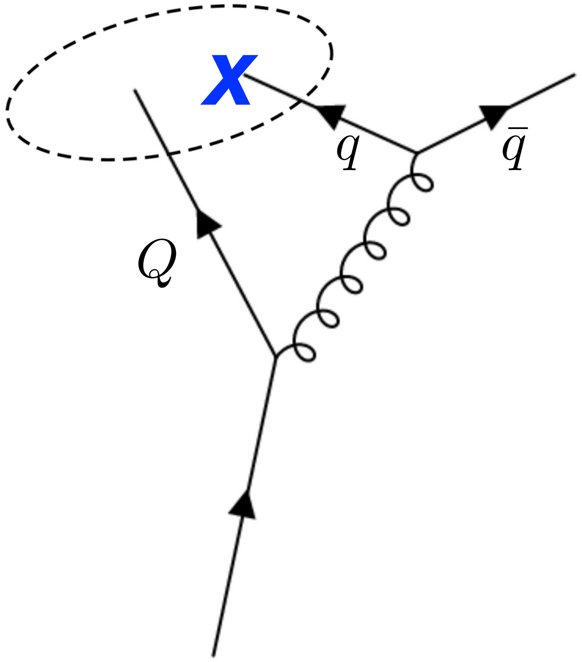


*Gauld et a. (2020)*

- it would be better to identify a common procedure in order to avoid this unfolding step

# 3* new ideas in the past 2 months!

- use Soft Drop to remove soft quarks

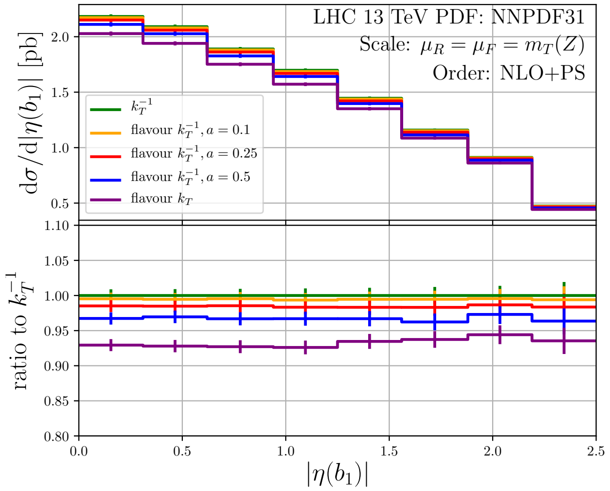


- needs JADE as reclusters, know to fail at three loops

*Caletti, Larkoski, SM, Reichelt (2022)*

- define a flavour algorithm that resembles anti-$k_t$

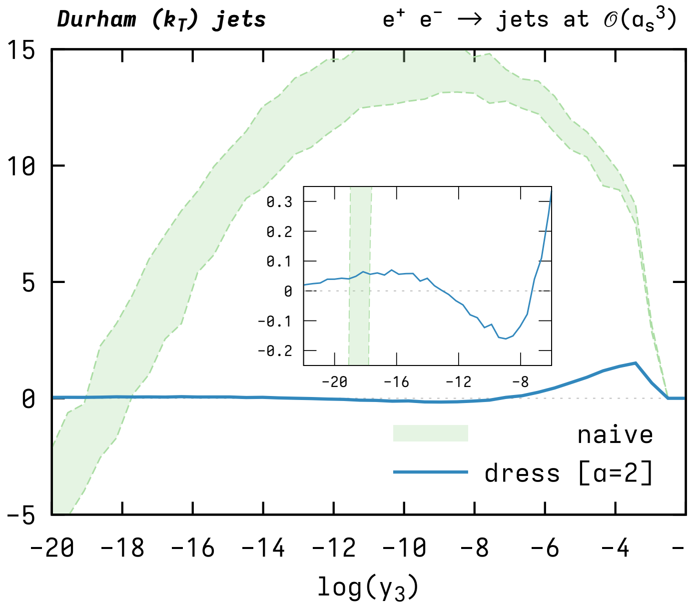
$$d_{ij}^{(F)} \equiv d_{ij} \times \begin{cases} \mathcal{S}_{ij}\,, & \text{if both } i \text{ and } j \text{ have non-zero flavour of opposite sign,} \\ 1\,, & \text{otherwise.} \end{cases}$$



- flavour-dependent metric, still needs some (small) unfolding

*Czakon, Mitov, Poncelet (2022)*

- construct a flavour dressing for a given jet



- needs flavour information of many (all?) particles in an event

*Gauld, Huss, Stagnitto (2022)*

- it would be interesting to do a dedicated comparison!

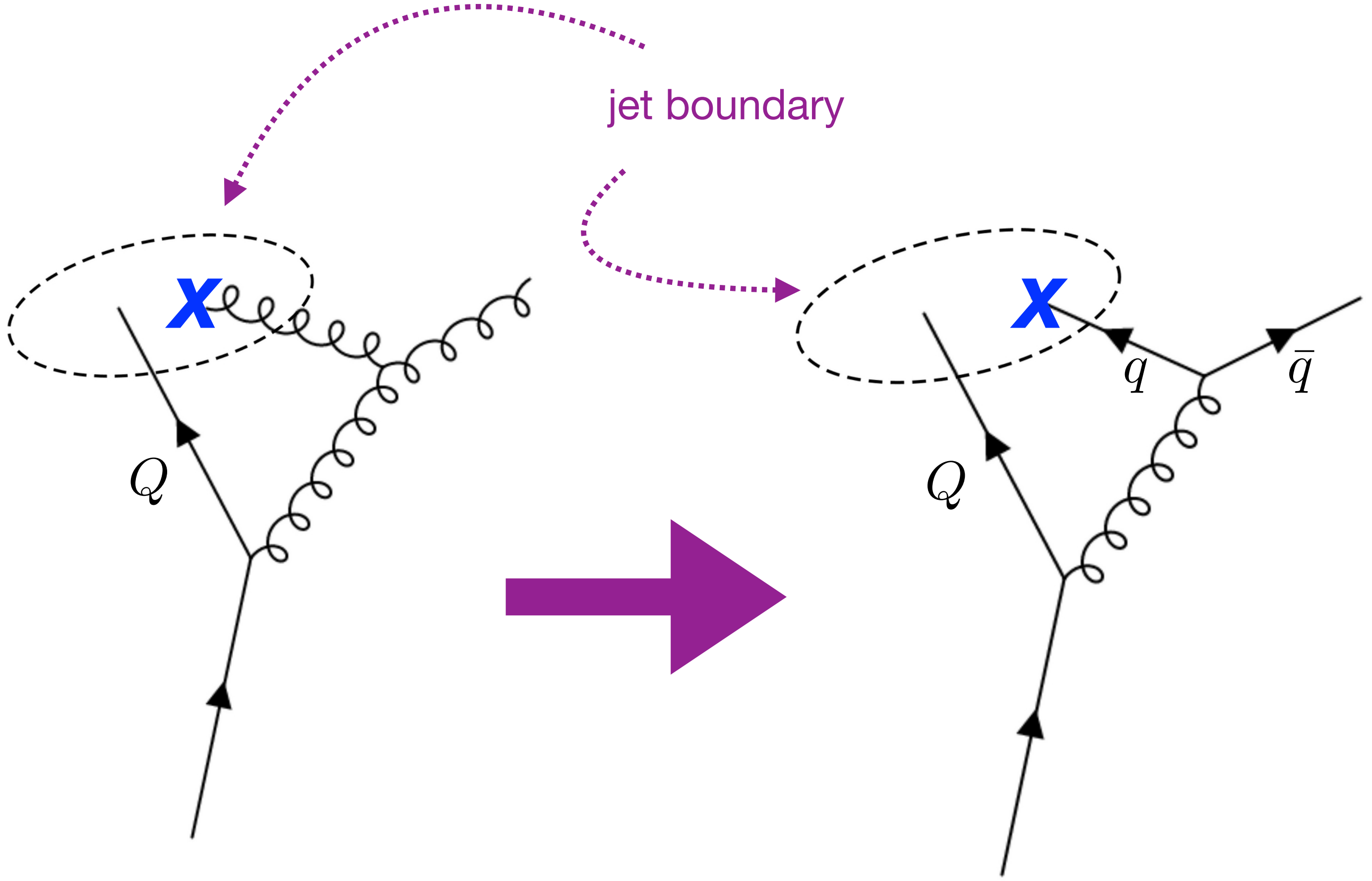
***4th proposal soon to appear**

# what about Soft Drop jets?

- grooming algorithms remove soft radiation from jets
- in particular is Soft Drop is beneficial in the context of non-global logarithms

*Larkoski, Marzani, Soyez, Thaler (2014)*

- the problematic configurations are similar



- so the idea is:
  - cluster jets with any algorithm you wish
  - apply Soft Drop and measure the flavour
- this is experimentally viable, it is IRC safe?

# Soft Drop flavour at NLO

- Through NLO even anti-k$_t$ flavour is IRC safe. Is there any subtlety with Soft Drop flavour?
- We concentrate on quark vs gluon, in *e*$^+$*e*$^-$
- LO:

$$P_g = 0 + \mathcal{O}(\alpha_s)$$

$$P_q = 1 + \mathcal{O}(\alpha_s)$$

- NLO:

q and g are in separate jets and gluon is harder

q and g are in the same jet and the q is groomed away

-

$$P_g = P_g^{(a)} + P_g^{(b)} = \frac{\alpha_s C_F}{2\pi}\left(\left(\frac{5}{8} - 2\log 2\right)\log R^2 + \frac{z_{\rm cut}}{\beta}\right) + \mathcal{O}(\alpha_s^2)$$

$$P_q = 1 - P_g = 1 + \frac{\alpha_s C_F}{2\pi}\left(\left(2\log 2 - \frac{5}{8}\right)\log R^2 - \frac{z_{\rm cut}}{\beta}\right) + \mathcal{O}(\alpha_s^2)$$

- so even at NLO, we must use Soft Drop with $\beta > 0$ (*perhaps not a surprise*)

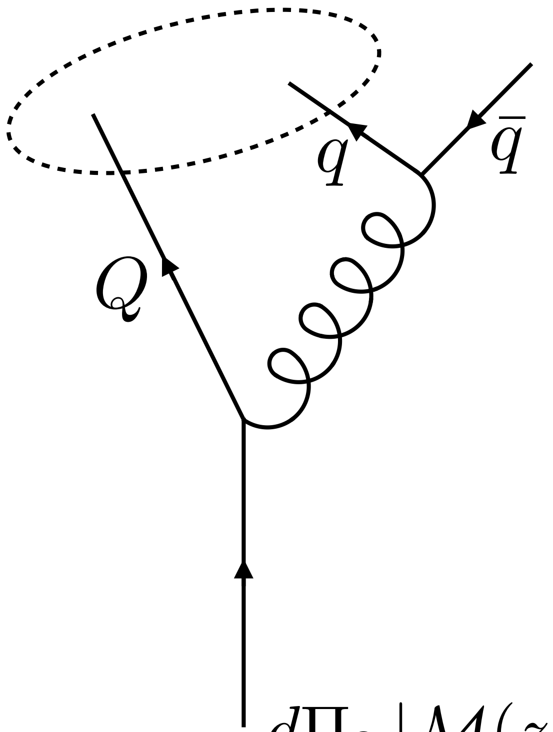
# Soft Drop flavour at NNLO

- if the dashed oval represents the jet boundary (NGLs configuration), Soft Drop screens the singularity
- if the dashed oval represents the effective grooming boundary (clustering log configuration), Soft Drop fails to screen the singularity

✓

Why is that?

✗



$$\Theta_{\mathrm{SD}}^{\mathrm{C/A}} = \Theta(\theta^2_{Q\bar{q}} - \theta^2_{Qq})\Theta(\theta^2_{q\bar{q}} - \theta^2_{Qq})\Theta\left(z_q - z_{\mathrm{cut}}\left(\frac{\theta^2_{Qq}}{R^2}\right)^{\beta}\right)\Theta\left(z_{\mathrm{cut}}\left(\frac{\theta^2_{Q\bar{q}}}{R^2}\right)^{\beta} - z_{\bar{q}}\right)$$

C/A clustering

quark passes Soft Drop

antiquark fails Soft Drop

$$d\Pi_3\,|\mathcal{M}(z_q, z_{\bar{q}})|^2\,\Theta_{\mathrm{SD}}$$

$$\simeq d\Pi_3\,|\mathcal{M}(x_q, x_{\bar{q}})|^2\,\Theta(\theta^2_{Q\bar{q}} - \theta^2_{Qq})\Theta(\theta^2_{q\bar{q}} - \theta^2_{Qq})\Theta\left(x_q - 1\right)\Theta\left(1 - x_{\bar{q}}\right)$$

rescaling: $z_q = x_q z_{\mathrm{cut}}\left(\frac{\theta^2_{Qq}}{R^2}\right)^{\beta}$

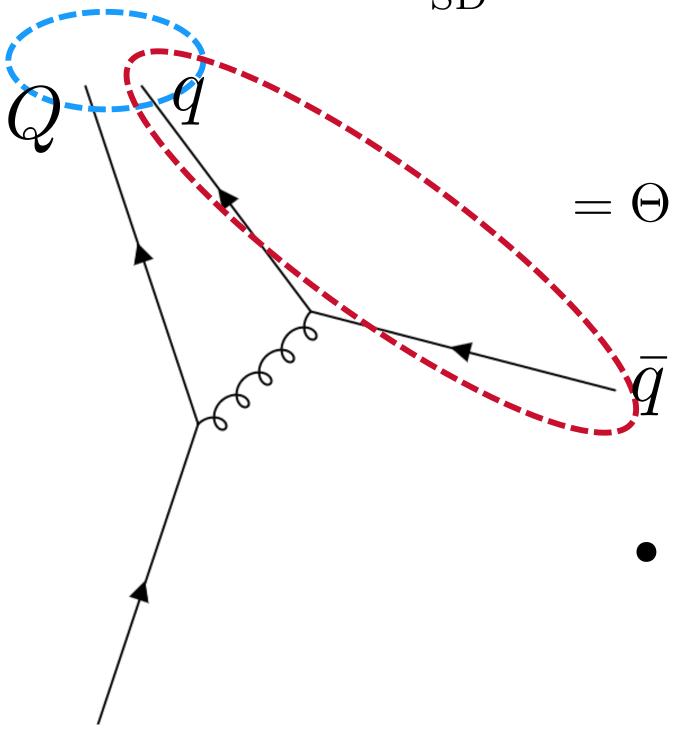
which is singular in the collinear limit

# Jade Soft Drop

- Can we modify Soft Drop to save the day?
- we can change the algorithm used for reclustering
- gen-$k_t$ algorithms do not cluster two soft particles together, if there is a hard particle around at smaller angle, but Jade does
- let's look at the problematic configuration with Jade reclustering

$$\Theta_{\mathrm{SD}}^{\mathrm{JADE}} = \Theta(m_{Q\bar{q}}^2 - m_{Qq}^2)\Theta(m_{q\bar{q}}^2 - m_{Qq}^2)\ \Theta\left(z_q - z_{\mathrm{cut}}\left(\frac{\theta_{Qq}^2}{R^2}\right)^{\beta}\right)\Theta\left(z_{\mathrm{cut}}\left(\frac{\theta_{Q\bar{q}}^2}{R^2}\right)^{\beta} - z_{\bar{q}}\right)$$

$$= \Theta\left(x_{\bar{q}}\theta_{Q\bar{q}}^{2(\beta+1)} - x_q\theta_{Qq}^{2(\beta+1)}\right)\Theta\left(x_{\bar{q}} z_{\mathrm{cut}}\left(\frac{\theta_{Q\bar{q}}^2}{R^2}\right)^{\beta}\theta_{q\bar{q}}^2 - \theta_{Qq}^2\right)\Theta\left(x_q - 1\right)\Theta\left(1 - x_{\bar{q}}\right)$$



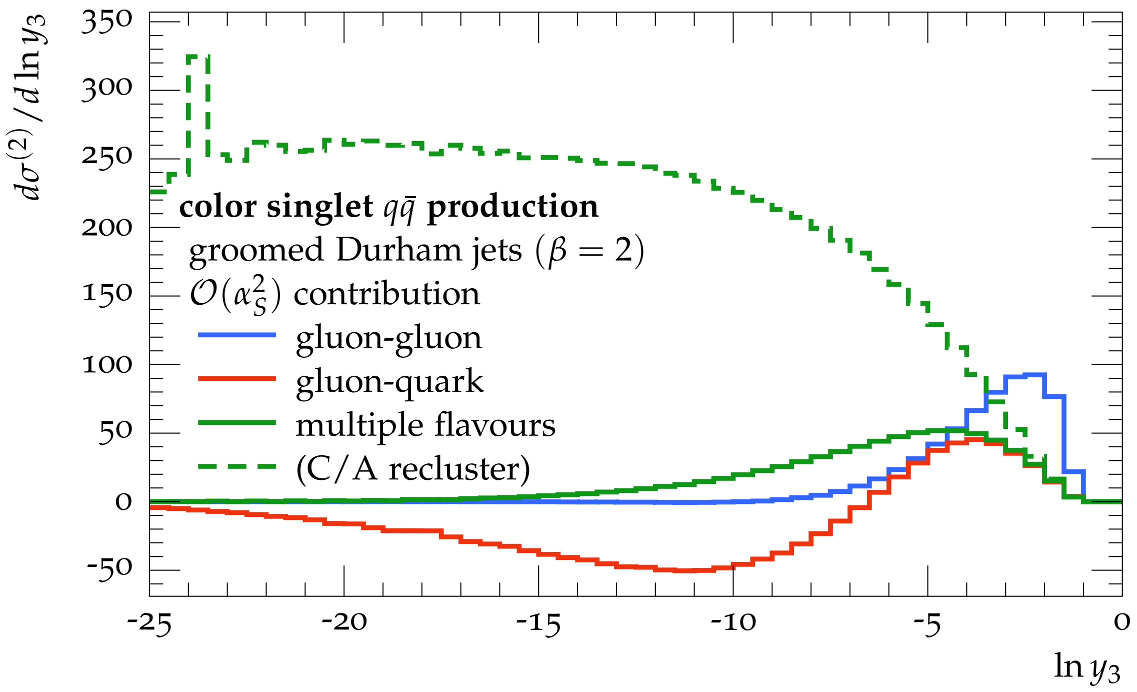
- with Jade reclustering energies and angles are coupled even after rescaling: the singularity is successfully screened

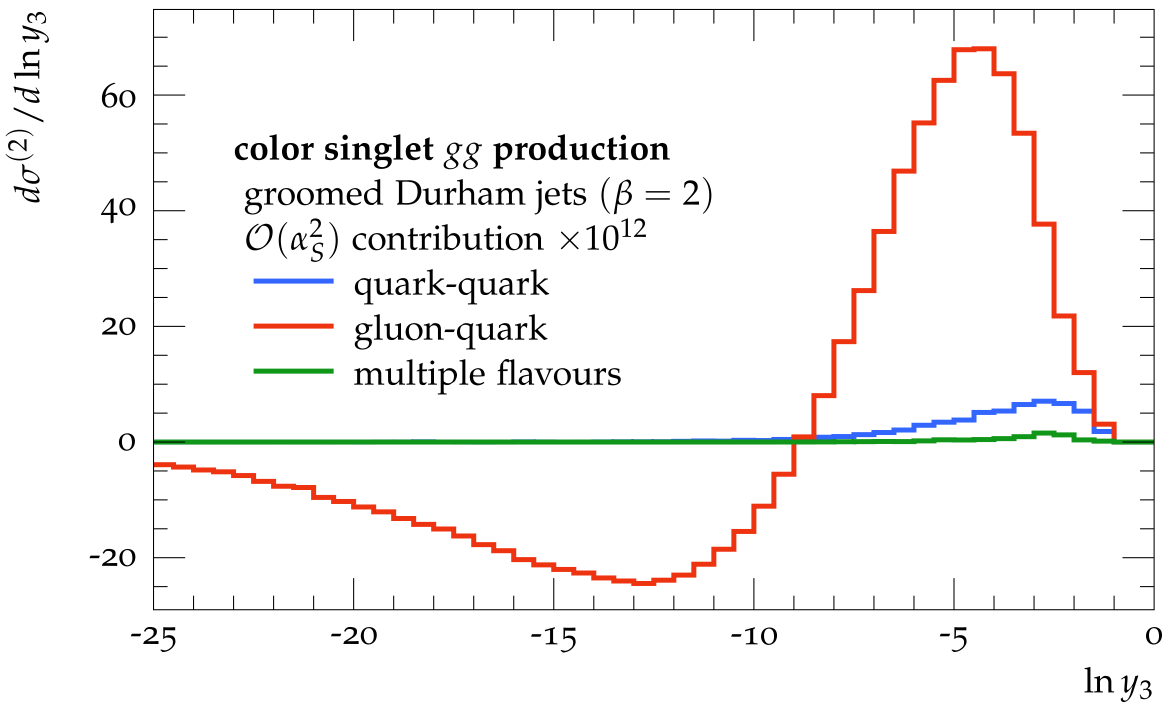
# Numerical checks

- introduce a resolution parameters to separate

$$\sigma^{\mathrm{NNLO}} = \int_0^{y_3} dy_3' \, \frac{d\sigma}{dy_3'} + \int_{y_3}^{y_{\max}} dy_3' \, \frac{d\sigma}{dy_3'}$$

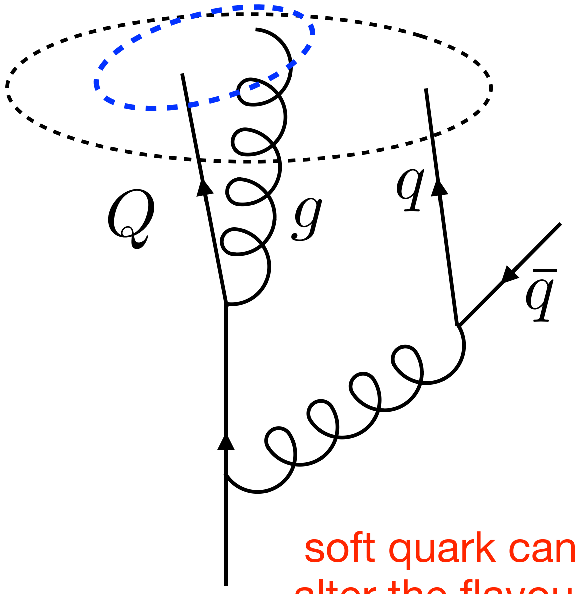
- following BSZ, we use the 3-jet resolution parameter
- distributions of non-Born configurations should be integrable as $y_3 \to 0$





# Problems at $N^3LO$ and beyond

- Jade Soft Drop allows us to formulate a definition of flavour which is
  - viable from an experimental view point (original jets can be anti-$k_t$ and the flavour algorithm is applied after jet clustering)
  - IRC safe through NNLO so that it can be used with state-of-the-art calculation
- however, the algorithm is unsafe at $N^3LO$: maybe one can think of applying recursive/iterative Soft Drop?

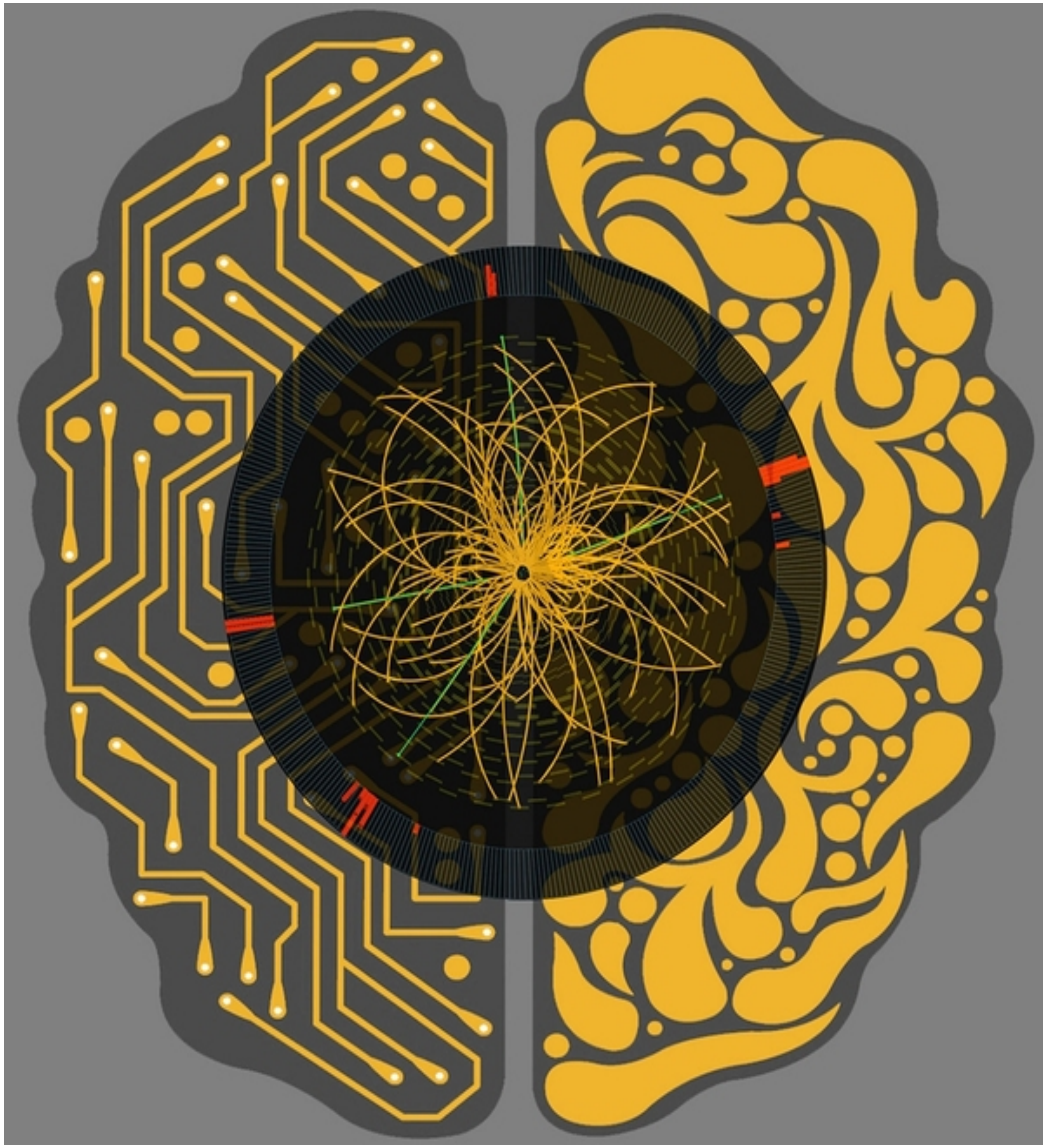


this system has the smallest invariant mass and passes SD

soft quark can alter the flavour

# Understanding new tools

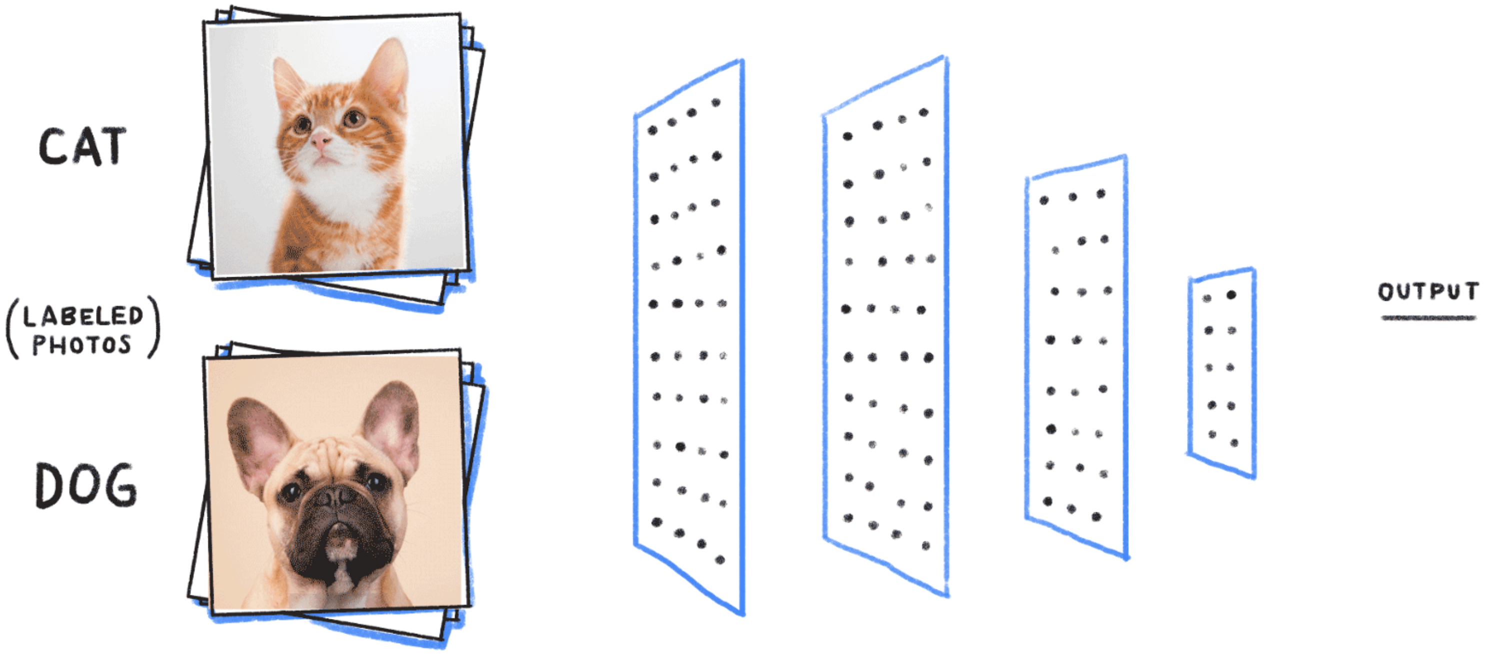
*machine learning is reshaping the way we think analyses and searches*



https://news.mit.edu/2019/boosting-computing-power-for-future-particle-physics-mit-lns-0819

# Deep learning revolution

- a wave of machine learning algorithms has hit HEP in the recent past
- ML algorithms are powerful tools for classification, and they have successfully applied to our tasks



credits: becominghuman.ai

- if an algorithm can distinguish pictures of cats and dogs, can it also distinguish QCD jets from boosted-objects?
- very active and fast-developing field

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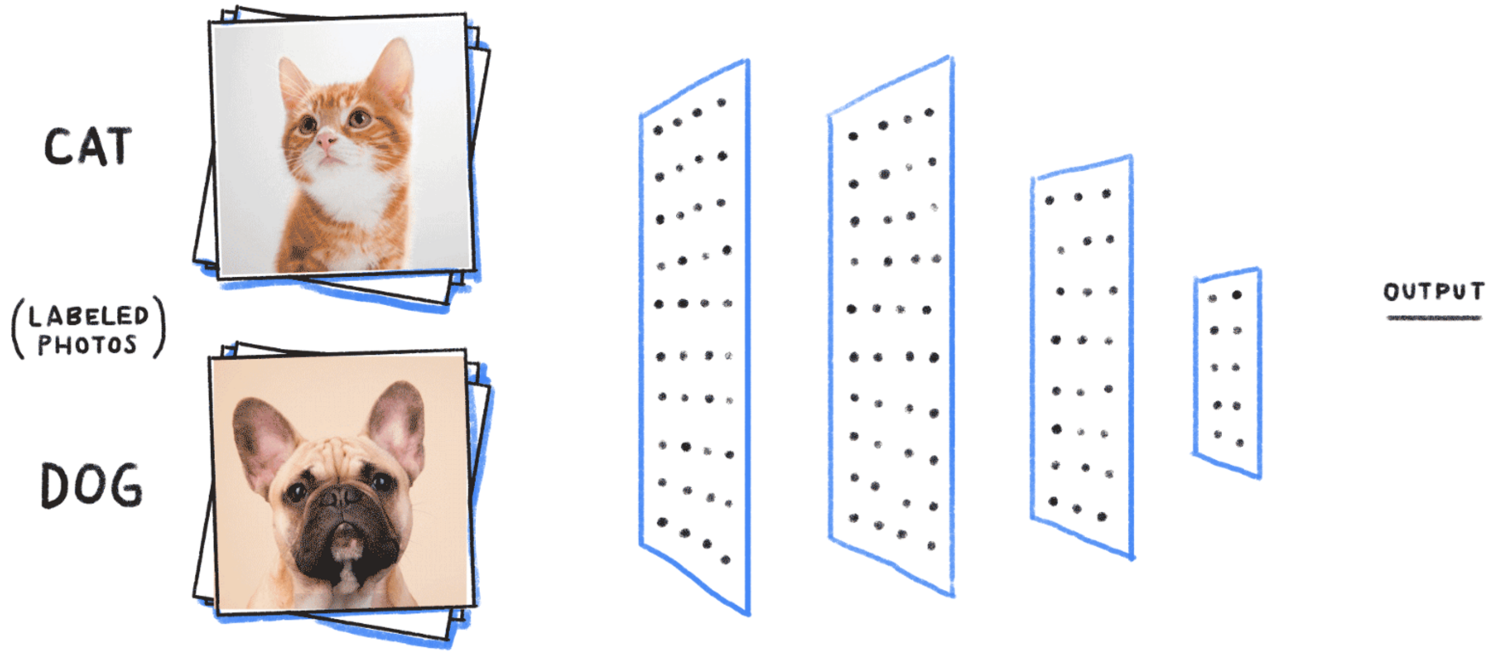

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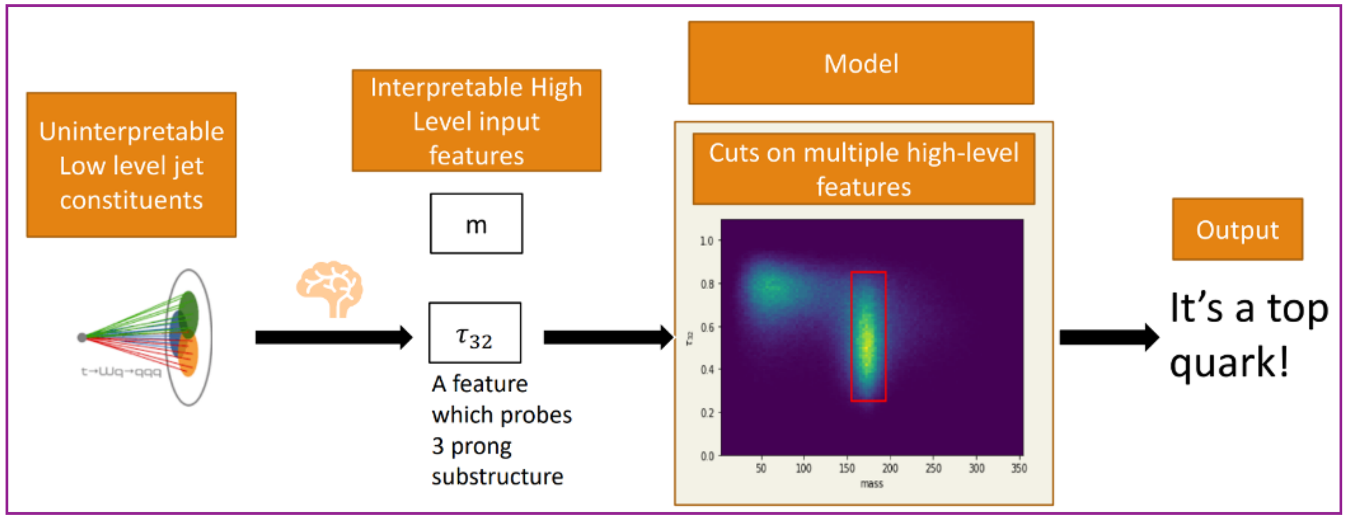
# High-level vs low-level



Uninterpretable Low level jet constituents

Interpretable High Level input features

m

$\tau_{32}$

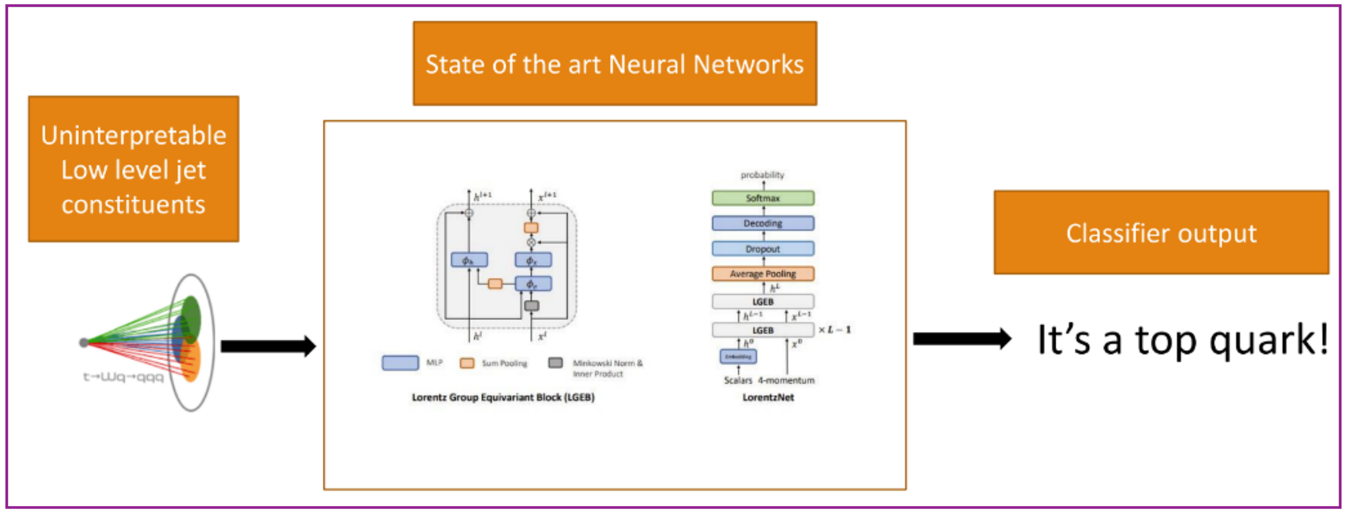
A feature which probes 3 prong substructure

Model

Cuts on multiple high-level features

Output

It's a top quark!



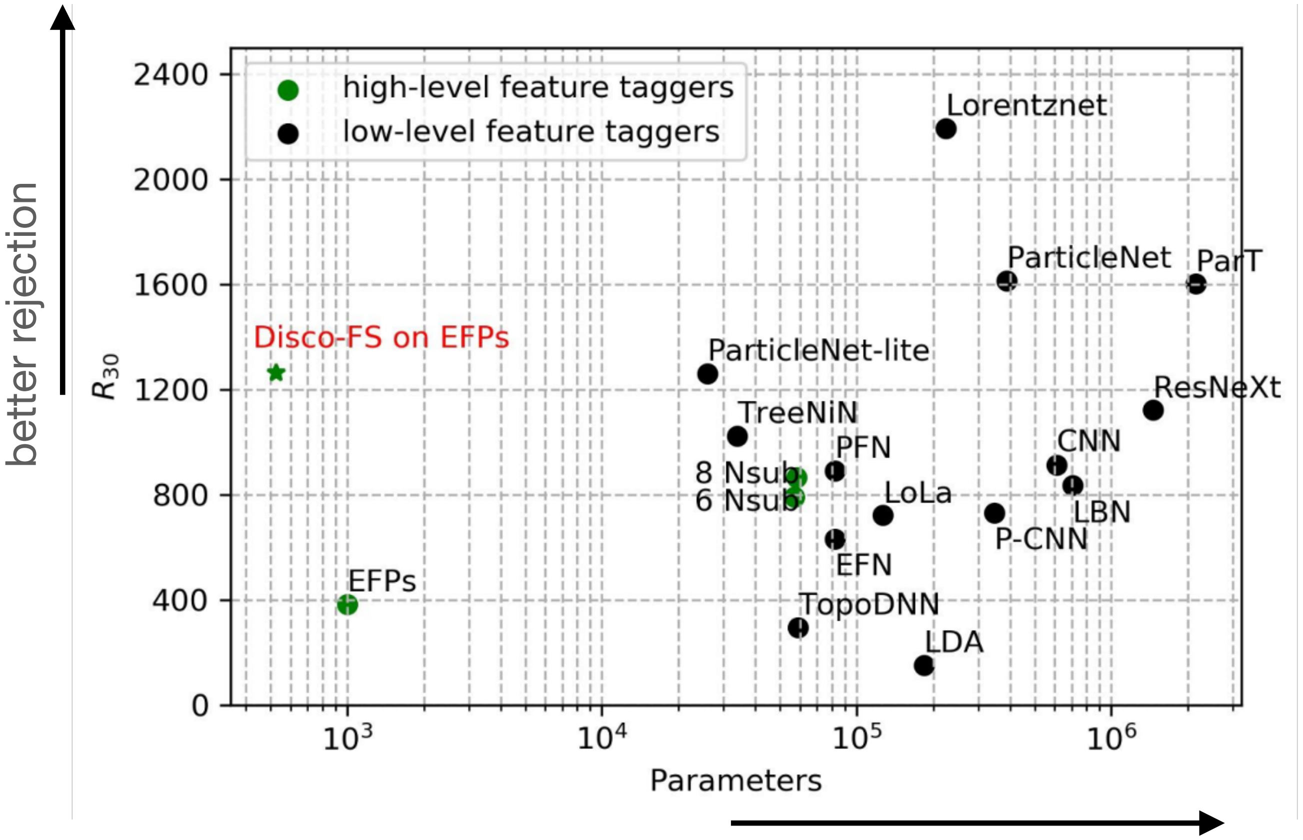
State of the art Neural Networks

Uninterpretable Low level jet constituents

Classifier output

It's a top quark!

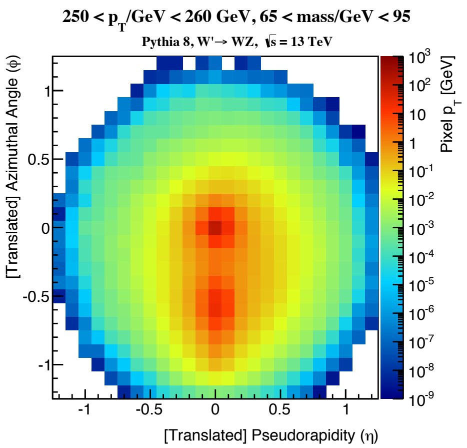
- traditionally, phenomenologists build “clever observables” that are able to capture the desired features of particle collisions
- neural networks and computational advances allow us to exploit low-level information (cal cells, momenta etc)
- what are pro’s and con’s of the two approaches?
- can we define a metric to measure robustness ?

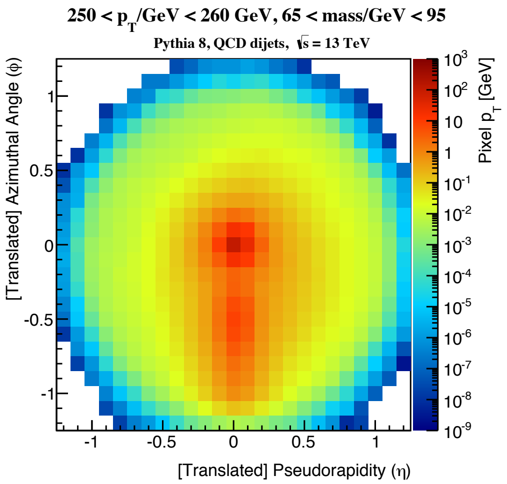


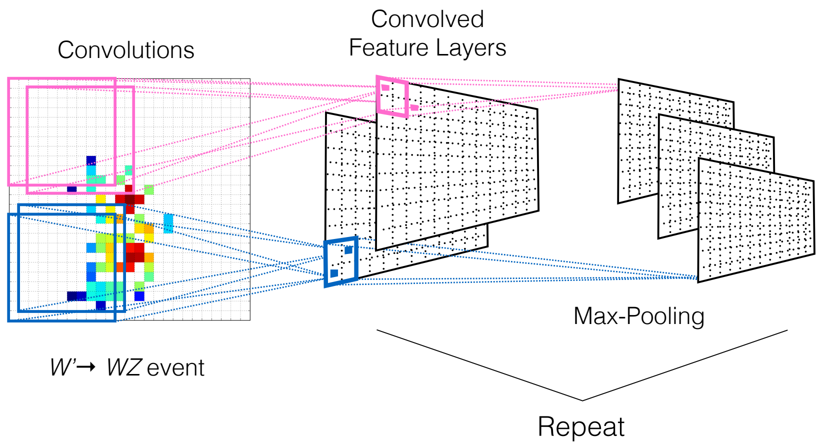
*adapted from Ranit Das talk at BOOST 2022*

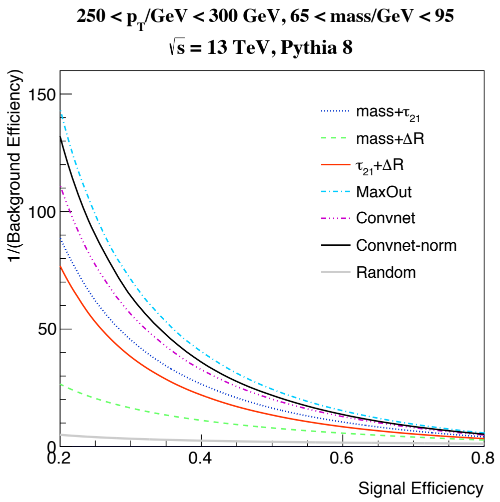
# Jet images

- jet images do what they say: project the jet into a $n \times n$ pixel image, where intensity is given by energy deposition
- use convolutional neural network (CNN) to classify
- right pre-processing is crucial for many reasons: we average over many events and Lorentz symmetry would wash away any pattern





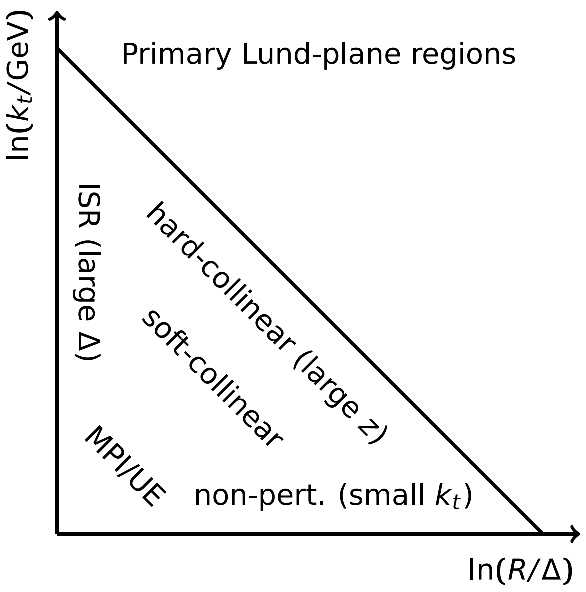


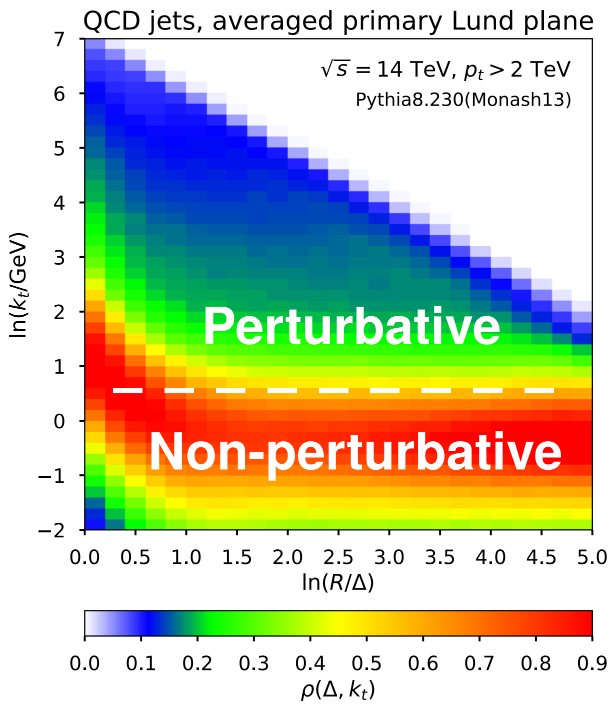


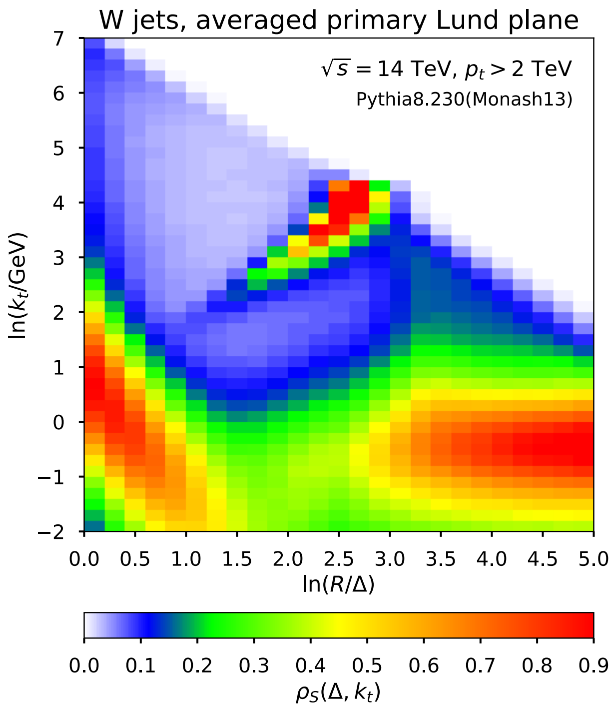
*Cogan, Kagan, Strauss, Schwartzman (2015)*
*de Olivera, Kagan, Mackey, Nachman, Schwartzman (2016)*

# Theory inputs

- physics intuition can lead us to construct better representations of a jet: the Lund jet plane
- the primary Lund jet plane is constructed by de-clustering the jet following the hard branch and record ($k_t$, $\Delta$) at each step



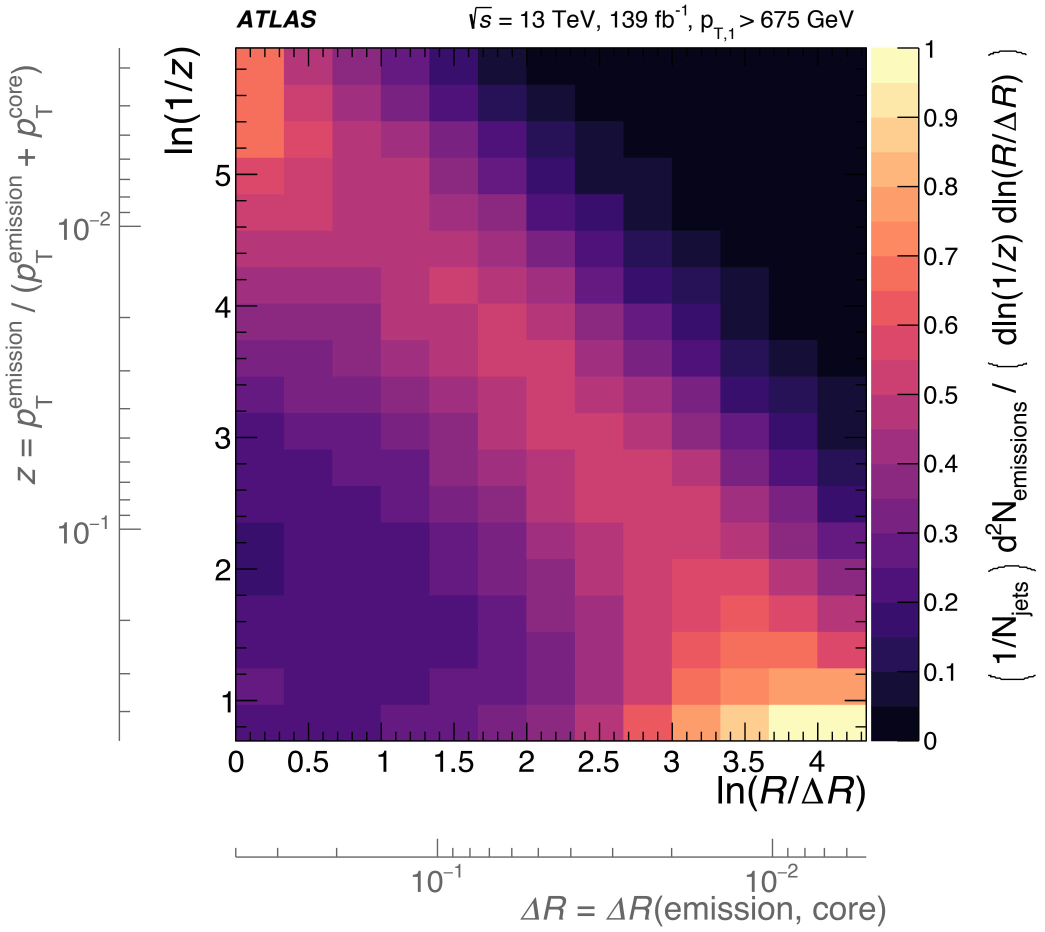




*Dryer, Salam, Soyez (2018)*

# Mapping out the Lund plane

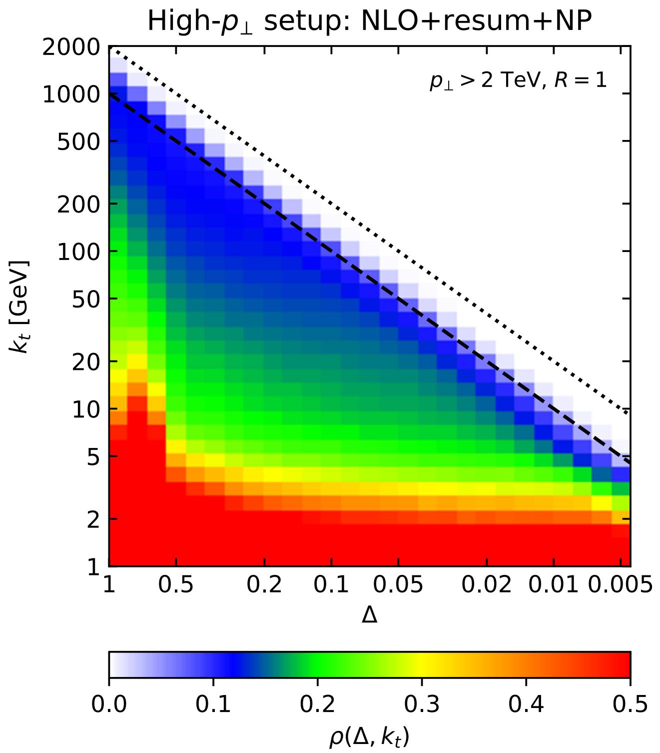
- ATLAS performed an unfolded measurement of the primary Lund plane density

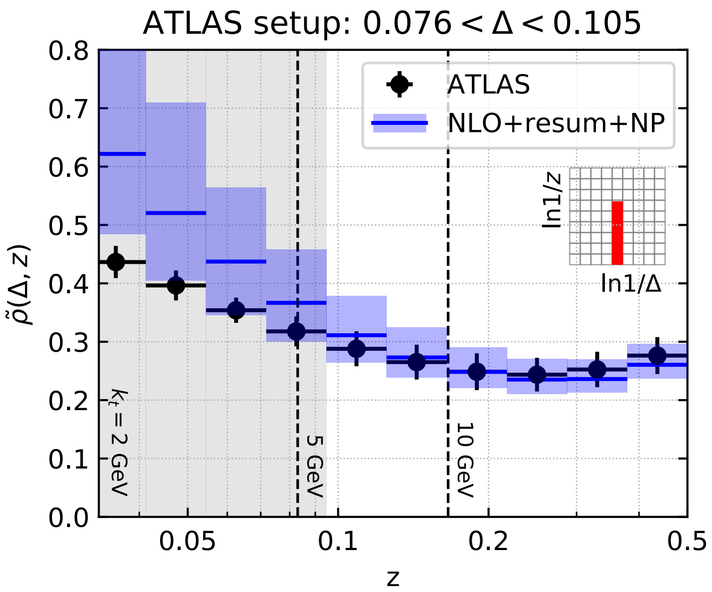


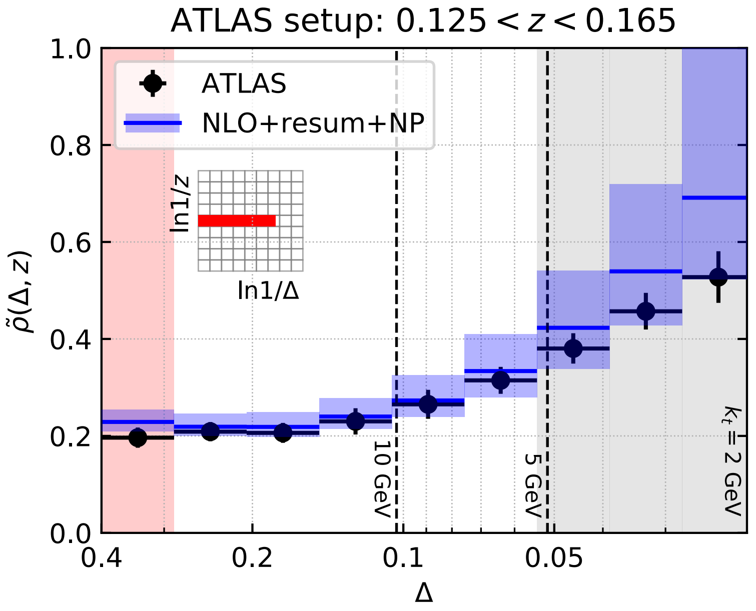
*ATLAS (2020)*

- First-principle calculation of the Lund plane density

*Lifson, Salam, Soyez (2020)*

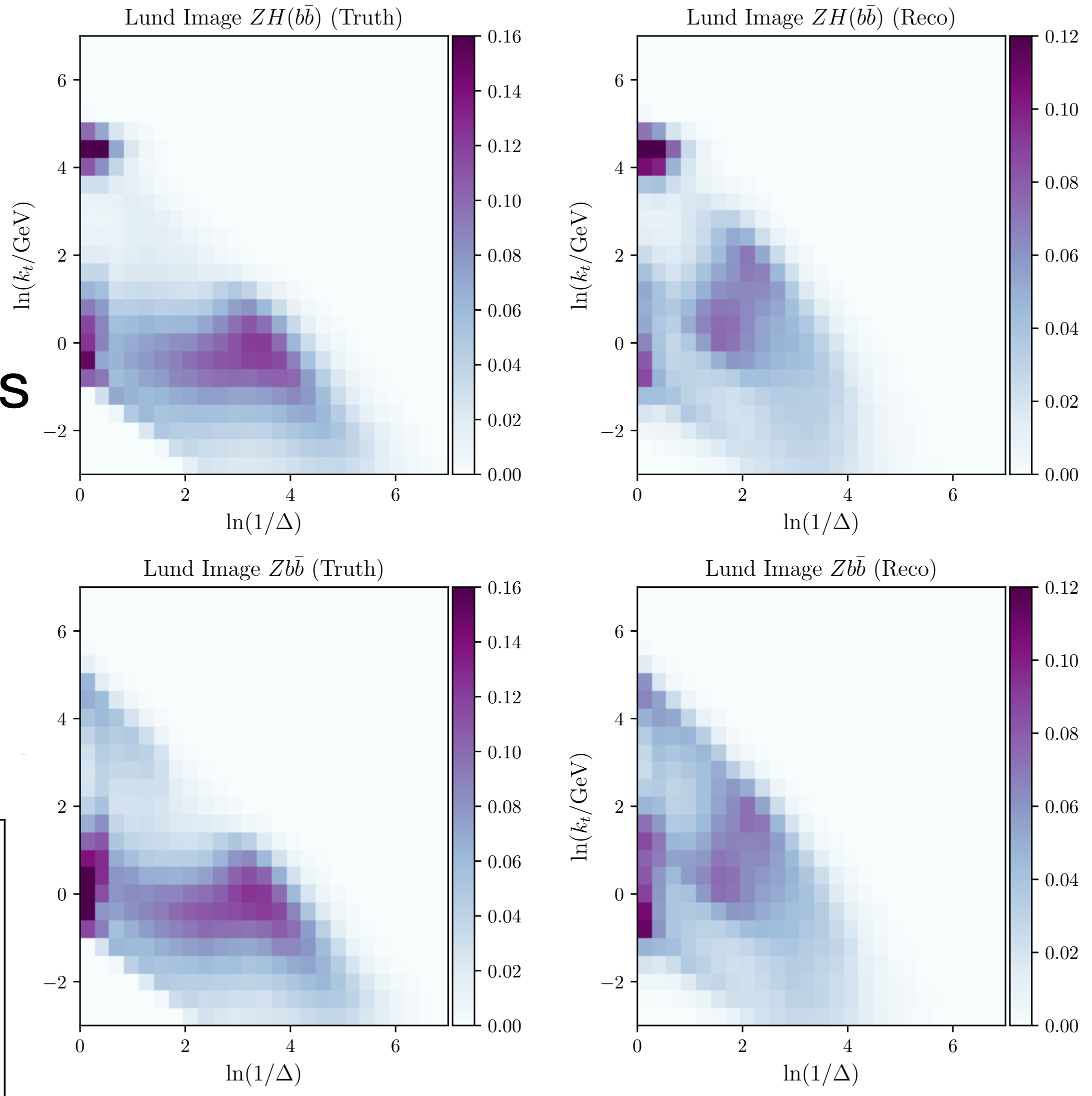


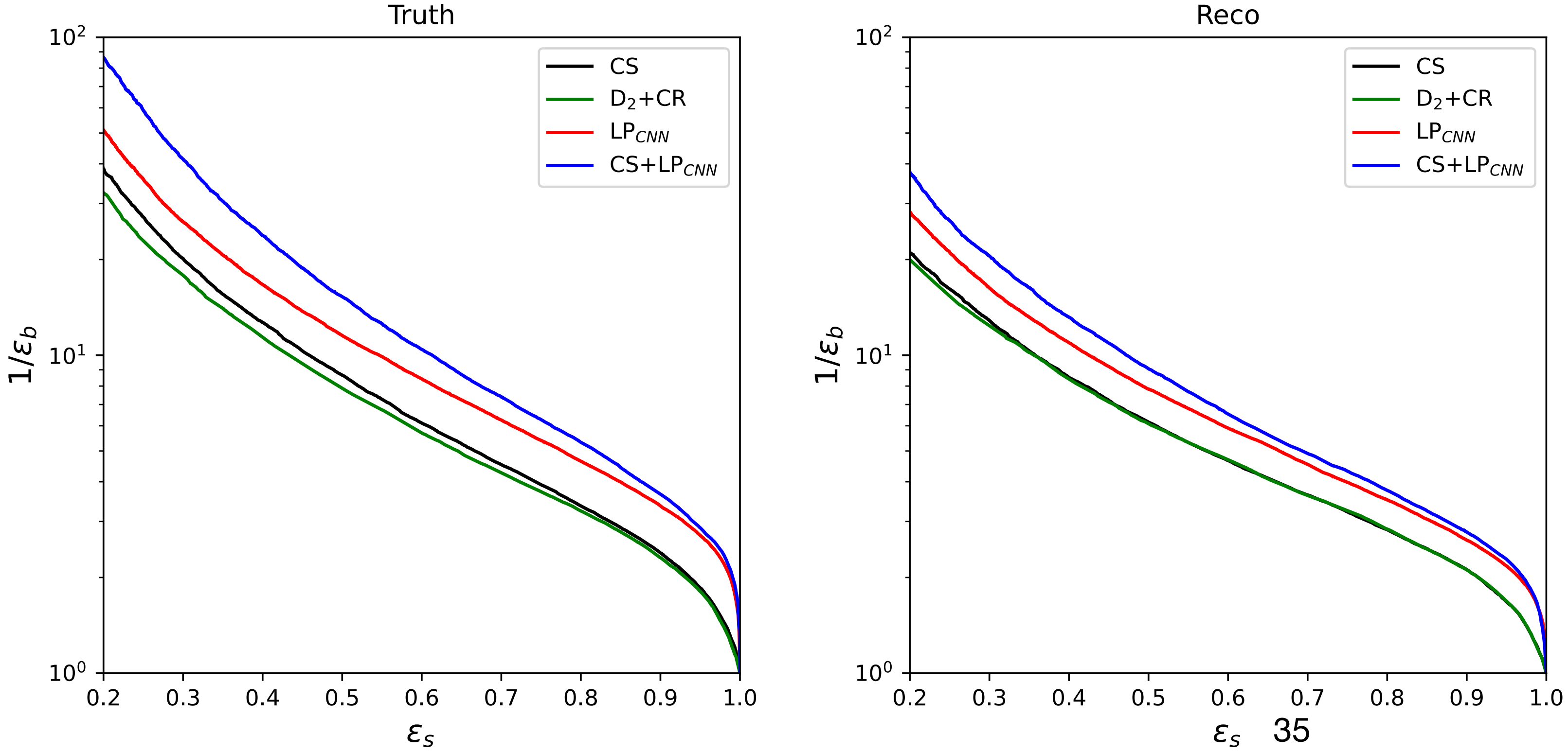




# Lund plane images: Higgs

- primary Lund plane provides us with an alternative jet image
- used as input to CNN to built taggers
- *Hbb* tagger that exploits different colour correlations between $H \rightarrow b\bar{b}$ vs $g \rightarrow b\bar{b}$
- improved performance wrt simpler colour-sensitive variables, such as the colour ring

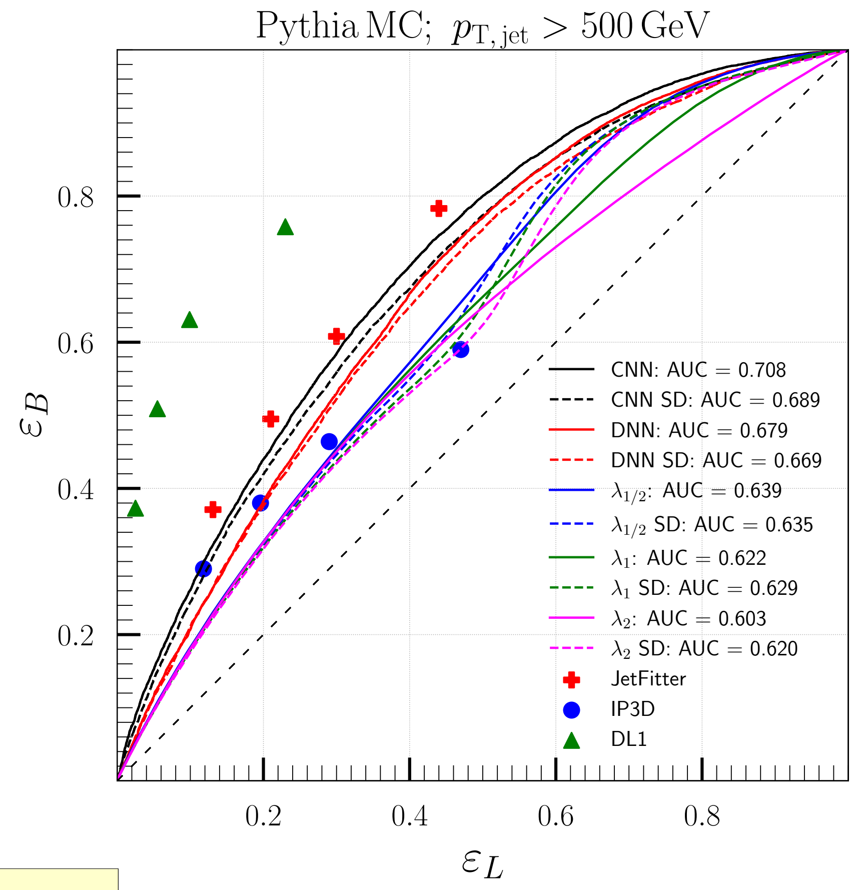


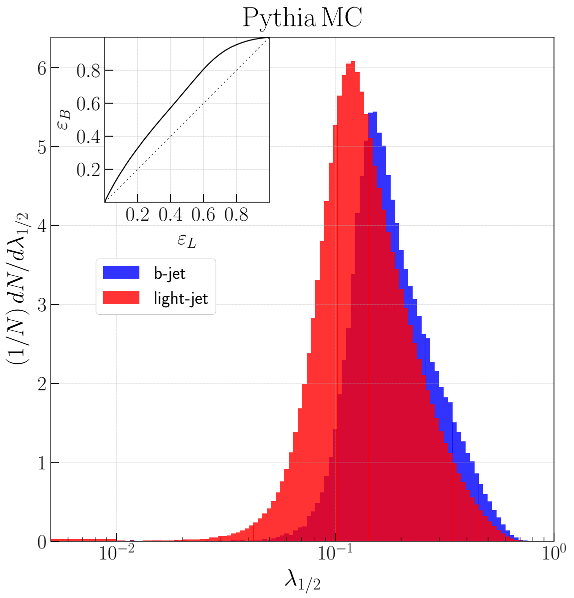


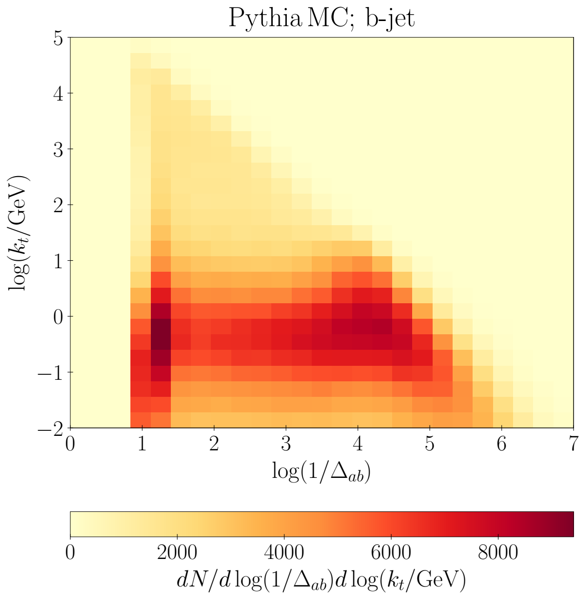
- good performance also for Higgs decay into light jets, where colour ring fails

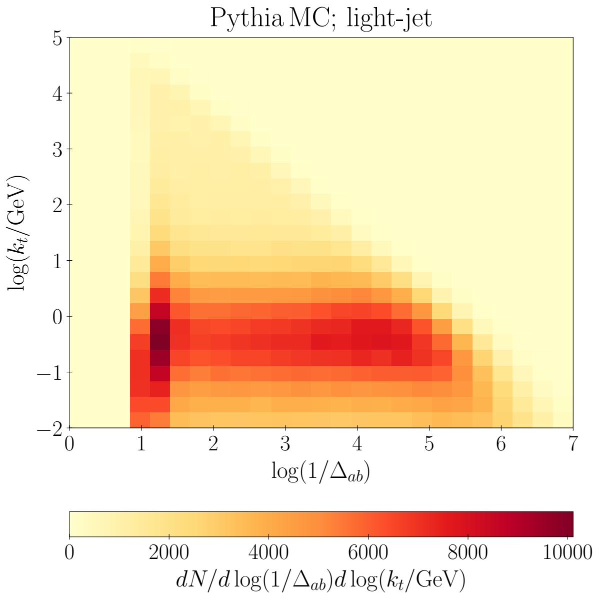
# Lund plane images: heavy quarks

- the presence of massive quarks alters the QCD radiation pattern (so-called dead-cone effect)
- we build a *b*-tagger which exploits orthogonal information to standard approach
- again we compare to simpler variables (here jet angularities)









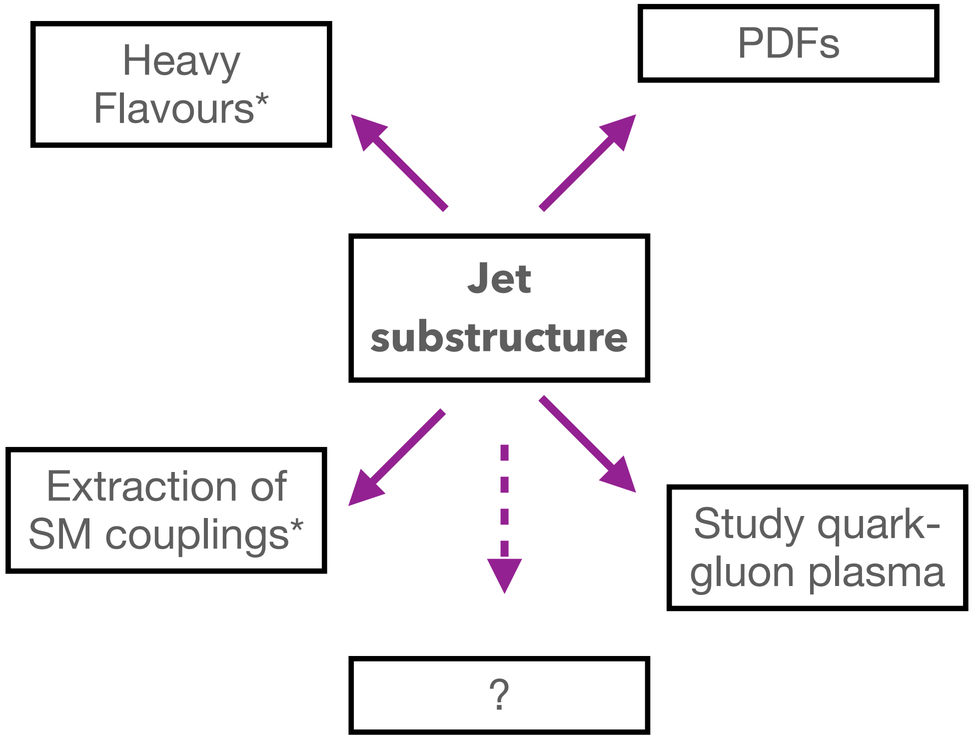
- work in progress to actually compute these distributions from first-principles
- resummed calculations with masses leads to nontrivial effects

*Fedkevych, Kaur, SM, Sforza (2022)*

*Gaggero, Ghira, SM, Ridolfi (2022)*

# Conclusions and Outlook

*Cross-pollination: bring field-specific developments to the broader pheno community*



Heavy Flavours*

PDFs

**Jet substructure**

Extraction of SM couplings*

Study quark-gluon plasma

?

*Understanding new tools: ML algorithms are reshaping the way we think analyses and searches*

What is the role of expert-knowledge in designing ML algorithms?

Can we understand what the algorithms are exploiting?

What is the right metric to measure “robustness”?

*more in the backup

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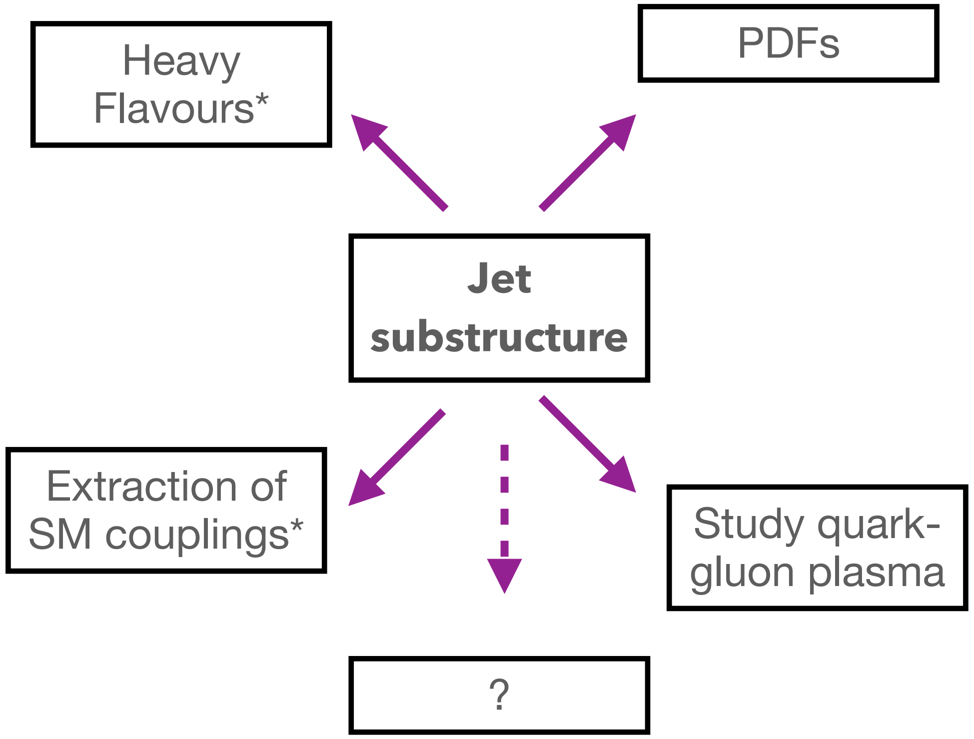

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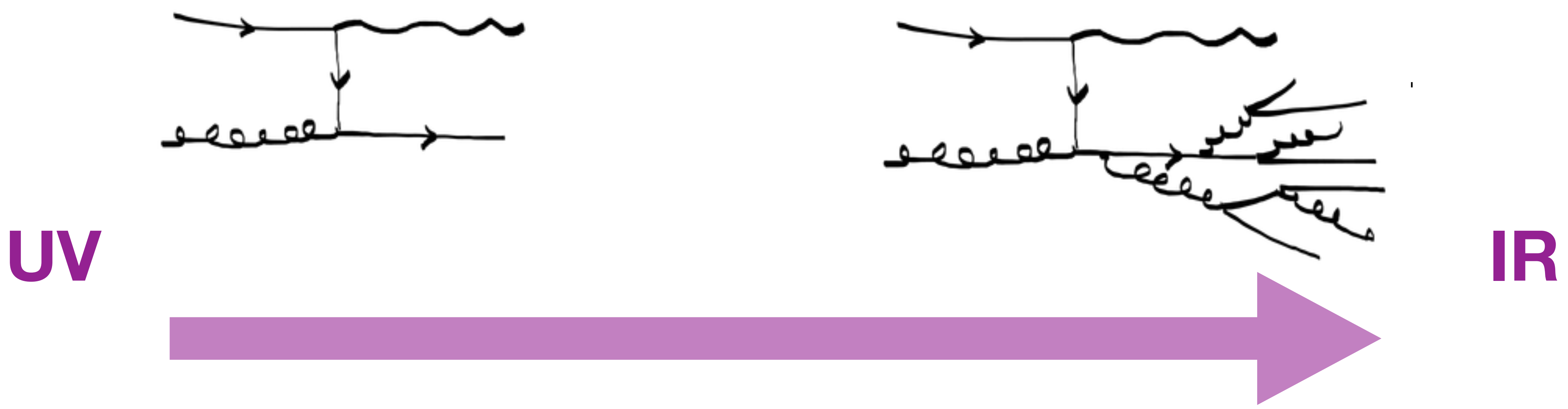
## Thank you very much for your attention !

*more in the backup

# BACKUP SLIDES

# A more physical approach

- “counting” (heavy) flavours may obscure the physical picture
- a more physical approach should try to link the flavour of the UV parton to the IR jet



- not a new idea: it has been suggested to use the flavour of the hardest micro-jet as a proxy for the UV flavour

*Dasgupta, Dryer, Salam, Soyez (2014)*

# Winner Take All axis

- Cluster and find jets in your collision event with any desired jet algorithm.
- On a given jet, recluster its constituents with a pairwise, IRC safe, algorithm, using the WTA recombination scheme. Specifically:
    1. For all pairs i and j of particles in your jet, calculate the pairwise metric $d_{ij}$ .
    2. For the pair i and j that corresponds to the smallest dij , recombine their momenta into a new massless particle ij such that $E_{ij}=E_i+E_j$ , and the direction of ij is along the direction of the harder between i and j.
    3. Replace particles i and j with their combination ij in the collection of particles in the jet.
    4. Repeat clustering until there is a single, combined particle that remains. The direction of this particle corresponds to the WTA axis of the jet.
- The sum of the flavour of all particles in the jet whose momenta lie exactly along the WTA axis is defined to be the flavour of the jet.

# Winner-Take-All Flavour

- instead of the hardest micro-jet, assign the flavour of the jet to be the flavour of the particle(s) lying along the Winner-Take-All axis (see backup for WTA definition)

- this definition is soft-safe, but collinear unsafe: we make use of WTA fragmentation functions

- unlike the micro-jet approach, the evolution equations are DGLAP-like and, hence, linear

$$Q^2 \frac{df_q(x,Q^2)}{dQ^2} = \frac{\alpha_S}{2\pi}\int_x^{\min[1,2x]} \frac{dz}{z}\left[P_{qg\leftarrow q}\left(\frac{x}{z}\right) f_q(z,Q^2) + P_{q\bar{q}\leftarrow g}\left(\frac{x}{z}\right) f_g(z,Q^2)\right]$$

$$Q^2 \frac{df_g(x,Q^2)}{dQ^2} = \frac{\alpha_s}{2\pi}\int_x^{\min[1,2x]} \frac{dz}{z}\left[P_{gq\leftarrow q}\left(\frac{x}{z}\right)\sum_{i=1}^{n_f}\left(f_{q_i}(z,Q^2) + f_{\bar{q}_i}(z,Q^2)\right) + P_{gg\leftarrow g}\left(\frac{x}{z}\right) f_g(z,Q^2)\right]$$

- interesting properties, e.g. IR fixed-point

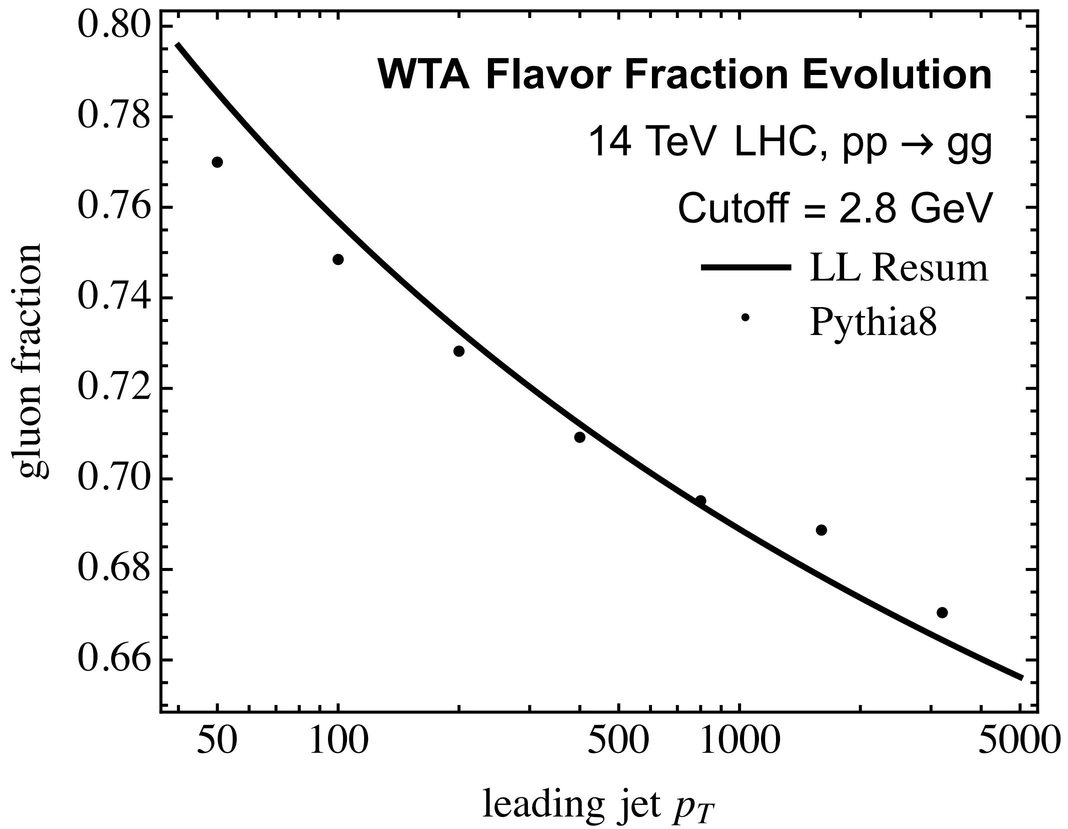
upper limits take into account the WTA condition

# Comparison to Parton Shower

- good agreement between LL evolution and Pythia parton shower

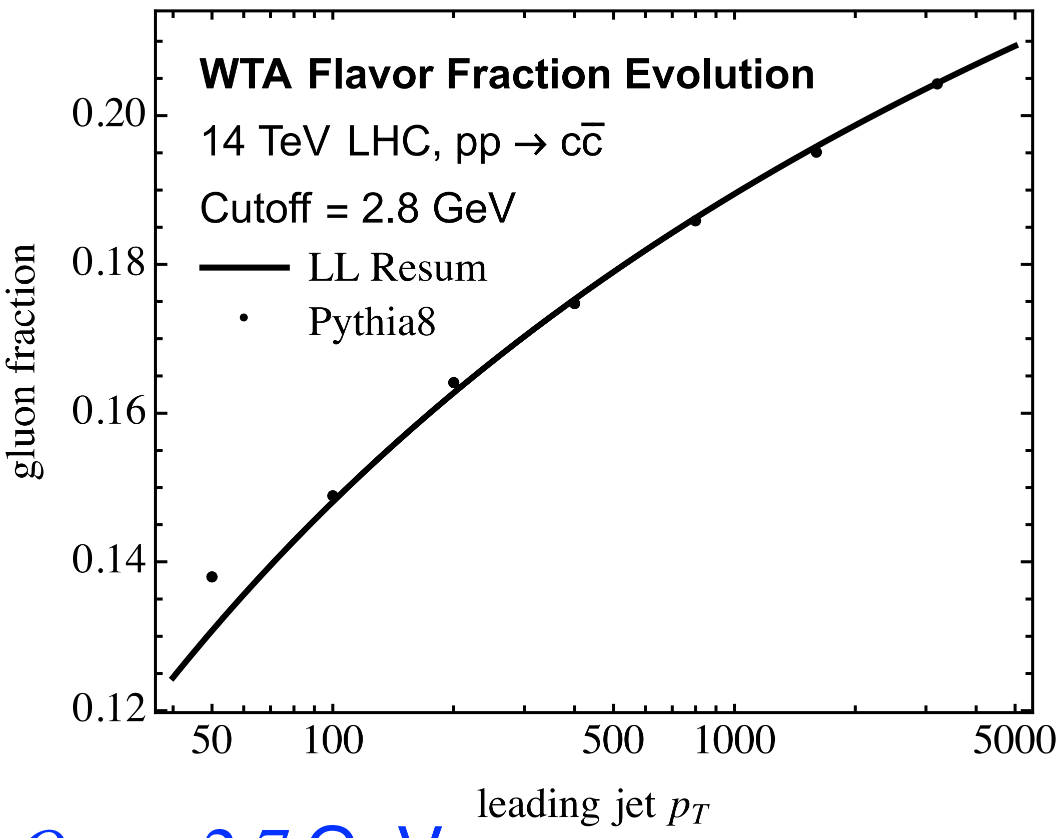
$$f_g(Q_{UV}) = 1,$$

$$f_q(Q_{UV}) = 0, \forall q$$



$$f_c(Q_{UV}) = 1,$$

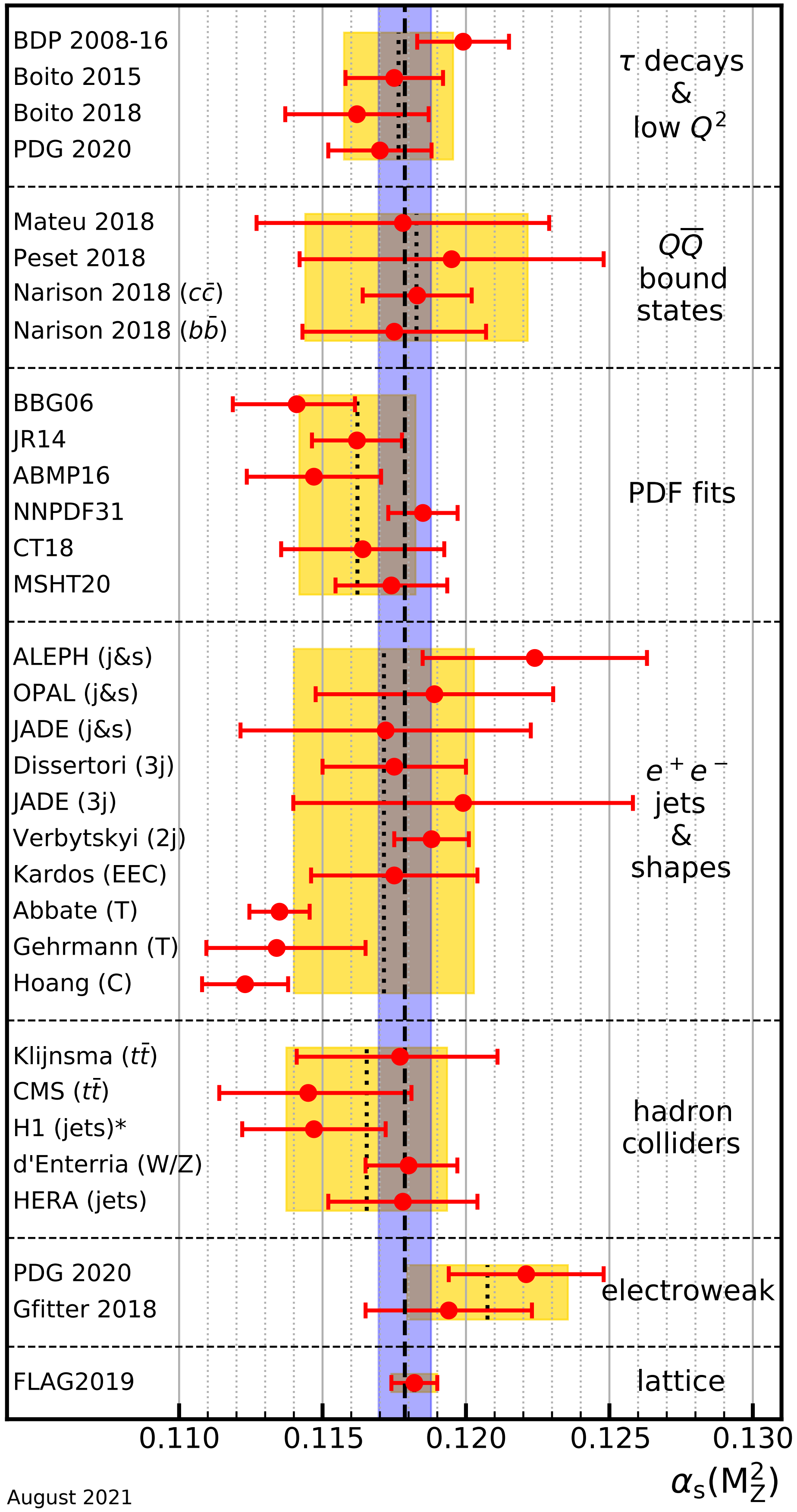
$$f_g(Q_{UV}) = f_q(Q_{UV}) = 0, \forall q \neq c$$



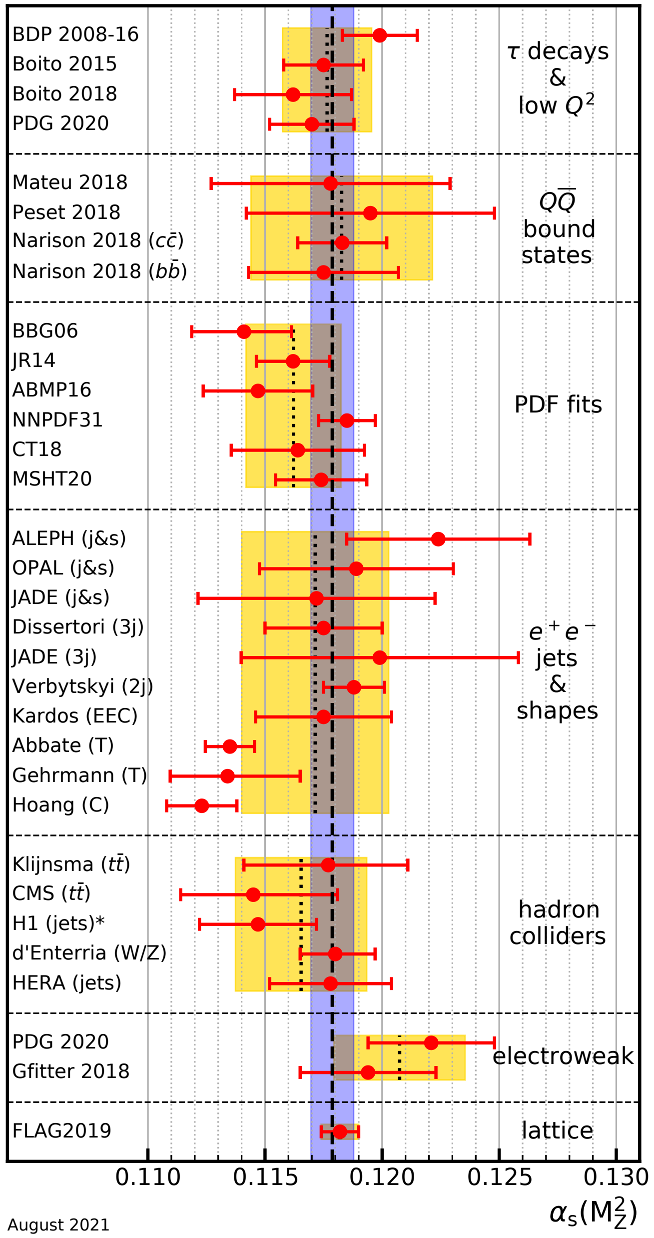
$$Q_{UV} = p_T, \quad Q_{IR} = 2.7\ \text{GeV}$$

# Cross-pollination (II)

## the strong coupling



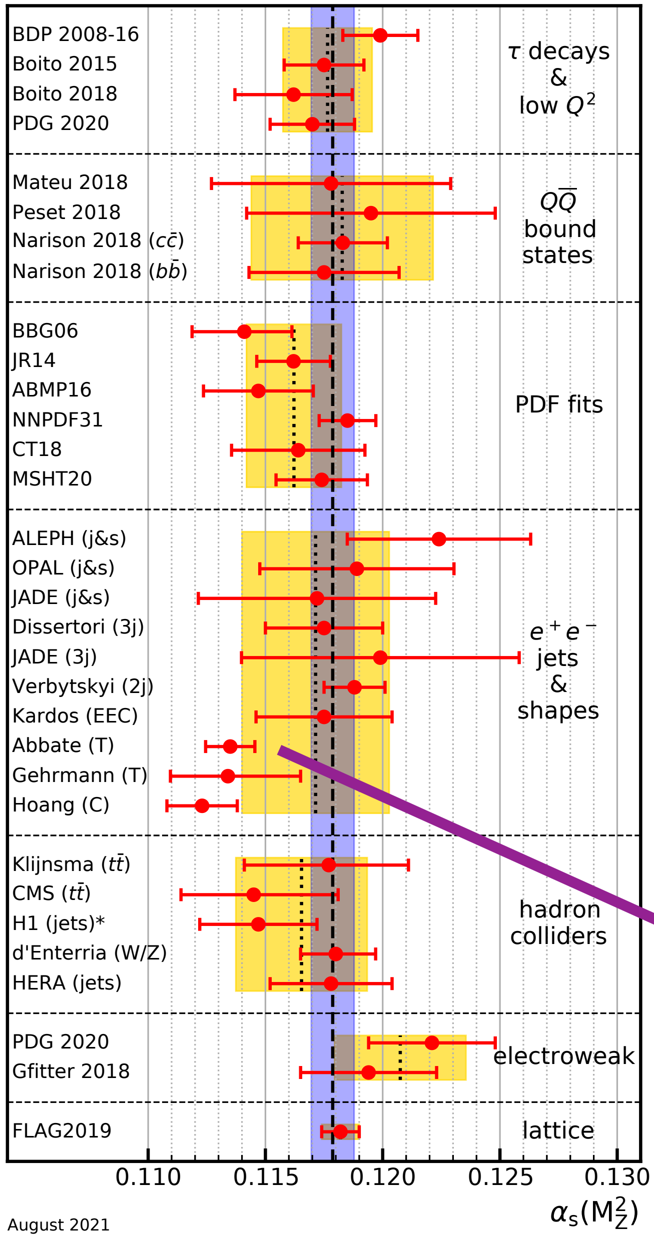
# $\alpha_s$ from event shapes



- current precision below 1%, dominated by lattice extractions
- LEP event shapes also very precise (5%)
- however they are in tension with the world average
- thrust (and C parameter) known with outstanding accuracy

- strong coupling correlated with non-perturbative parameters
- need better understanding of these effects
- or… we can try and reduce them

# $\alpha_s$ from event shapes



August 2021

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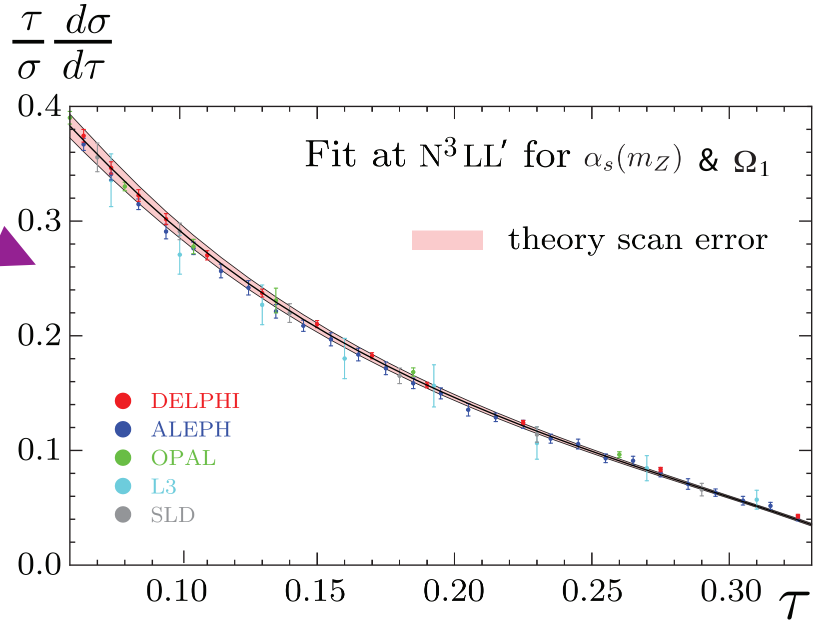

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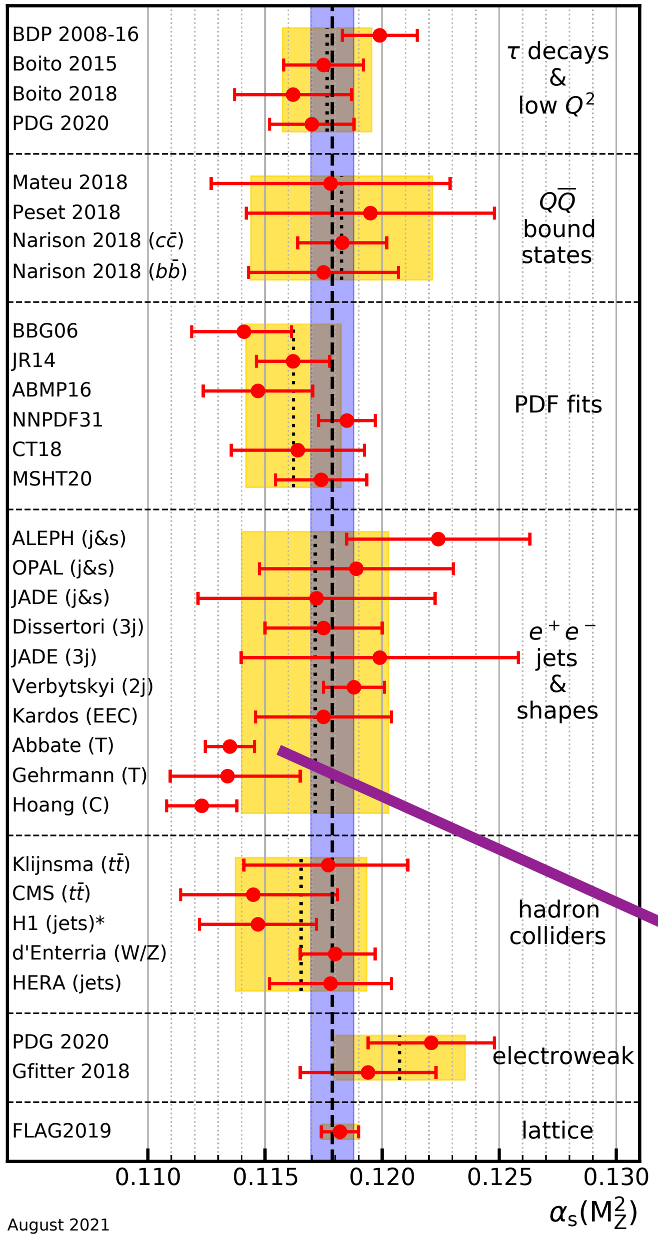

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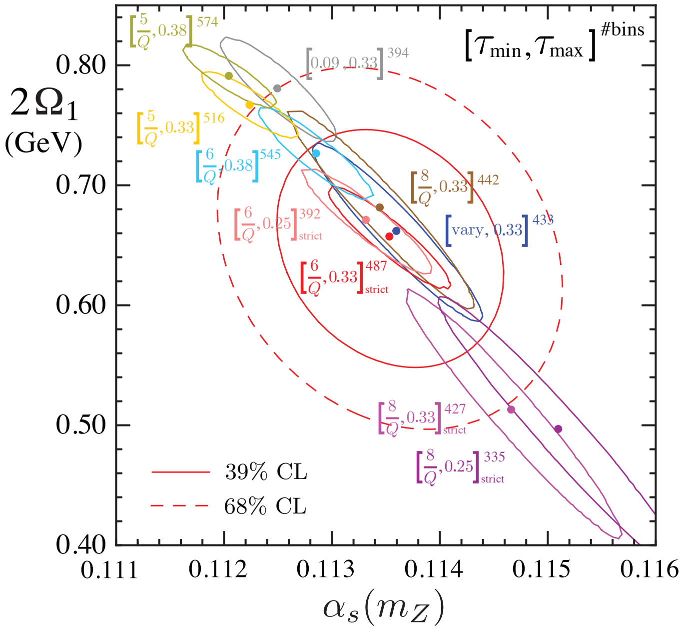

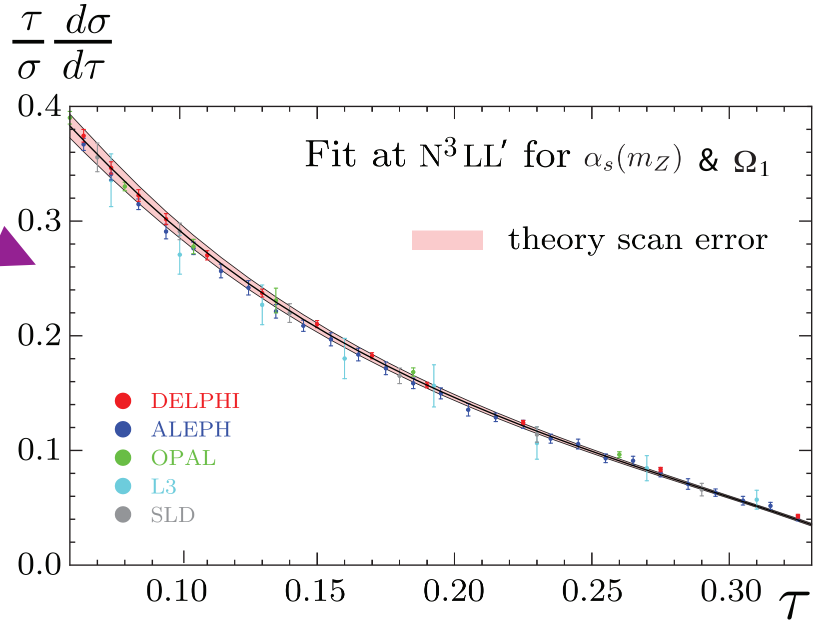

- strong coupling correlated with non-perturbative parameters
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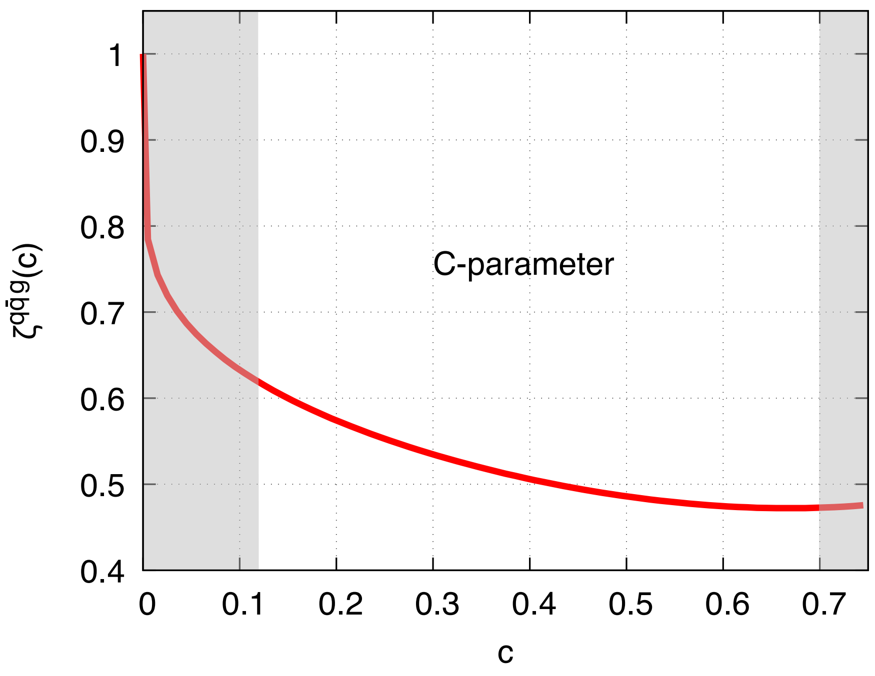
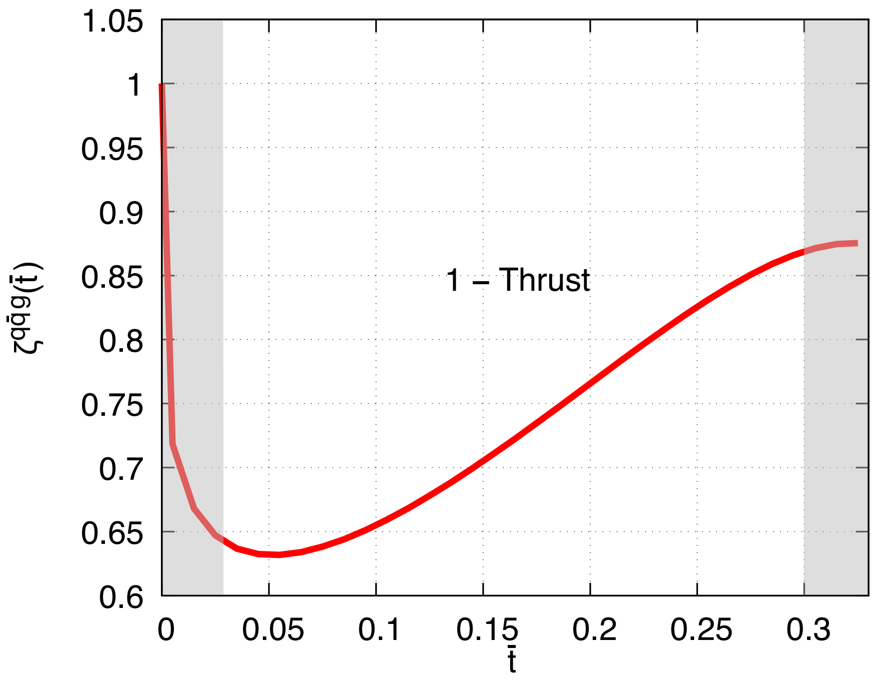
- or… we can try and reduce them

# A better understanding

- MC models of non-pert corrections are tuned with parton showers of limited accuracy
- analytic models of non-pert corrections are usually derived in the two-jet limit
- recently a full calculation of the leading non-pert corrections has been performed
- can these improvements alleviate the tension in strong coupling determinations using event shapes?



*Luisoni, Monni, Salam (2021)*



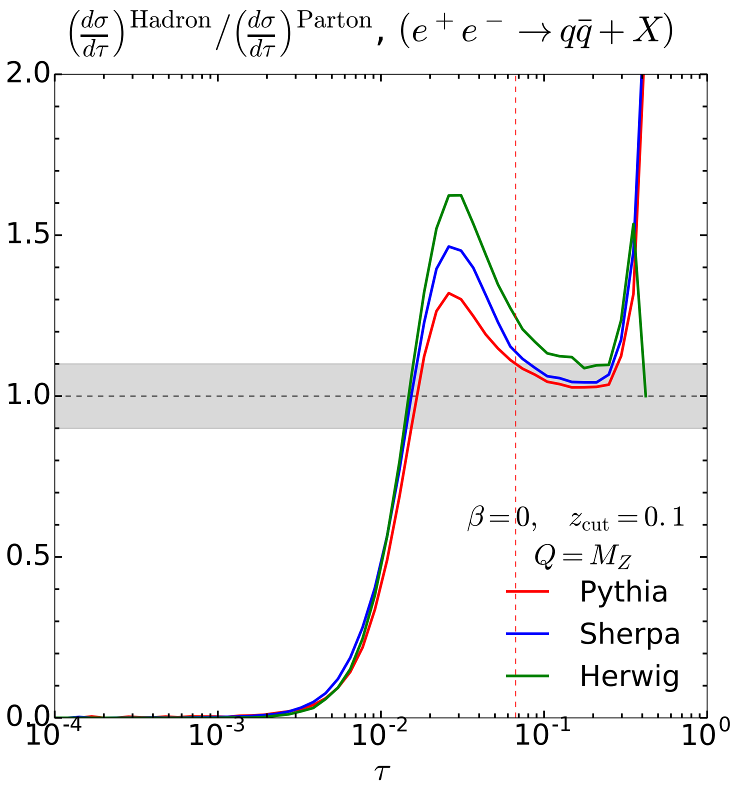
*Caola, Ferrario Ravasio, Limatola, Melnikov, Nason (2021)*

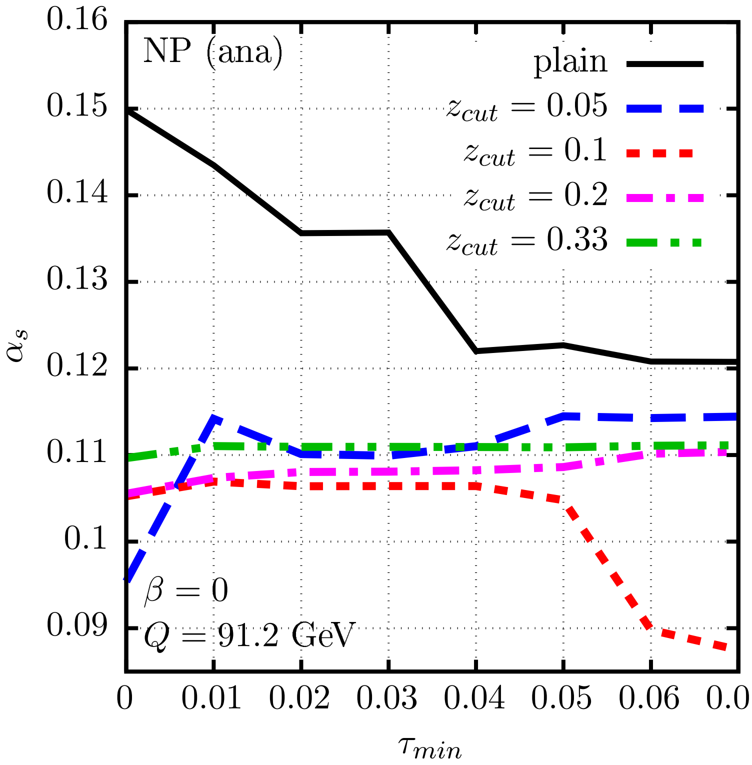
*Caola, Ferrario Ravasio, Limatola, Melnikov, Nason (2022)*

# Groomed event shapes

- in the past decade, our understanding of jets has improved tremendously
- efficient and robust grooming and tagging algorithms have been developed and exploited at the LHC
- Soft Drop aims to clean up a jet by removing soft radiation

*Larkoski, SM, Soyez, Thaler (2014)*

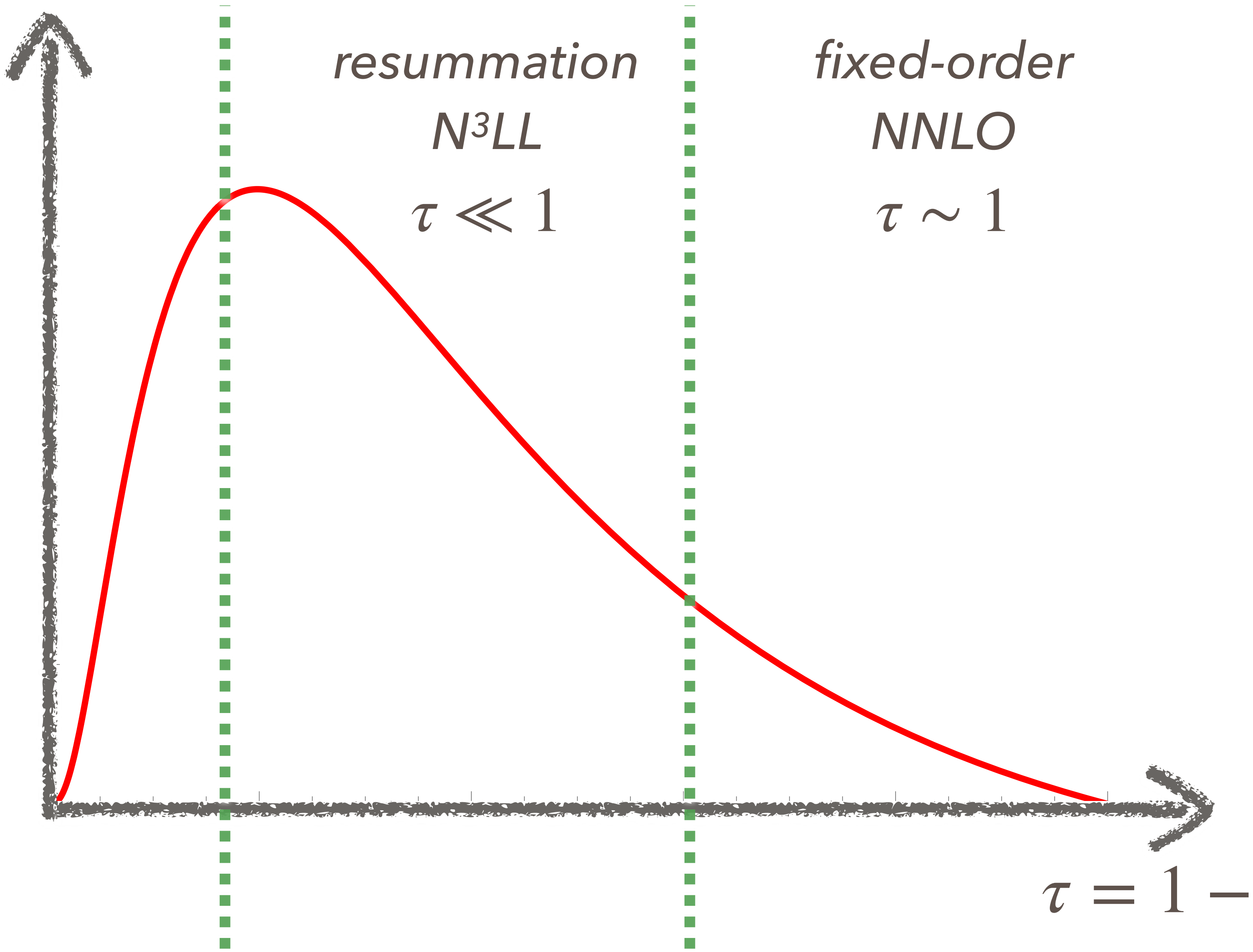




*Baron, SM, Theeuwes (2018)*

*SM, Reichelt, Schumann, Soyez, Theeuwes (2019)*

# Challenges for Soft Drop thrust



$$\frac{1}{\sigma}\frac{d\sigma}{d\tau}$$

*non-perturbative*

$$\tau \sim \frac{\Lambda_{\mathrm{NP}}}{Q}$$

*resummation*

*N$^3$LL*

$$\tau \ll 1$$

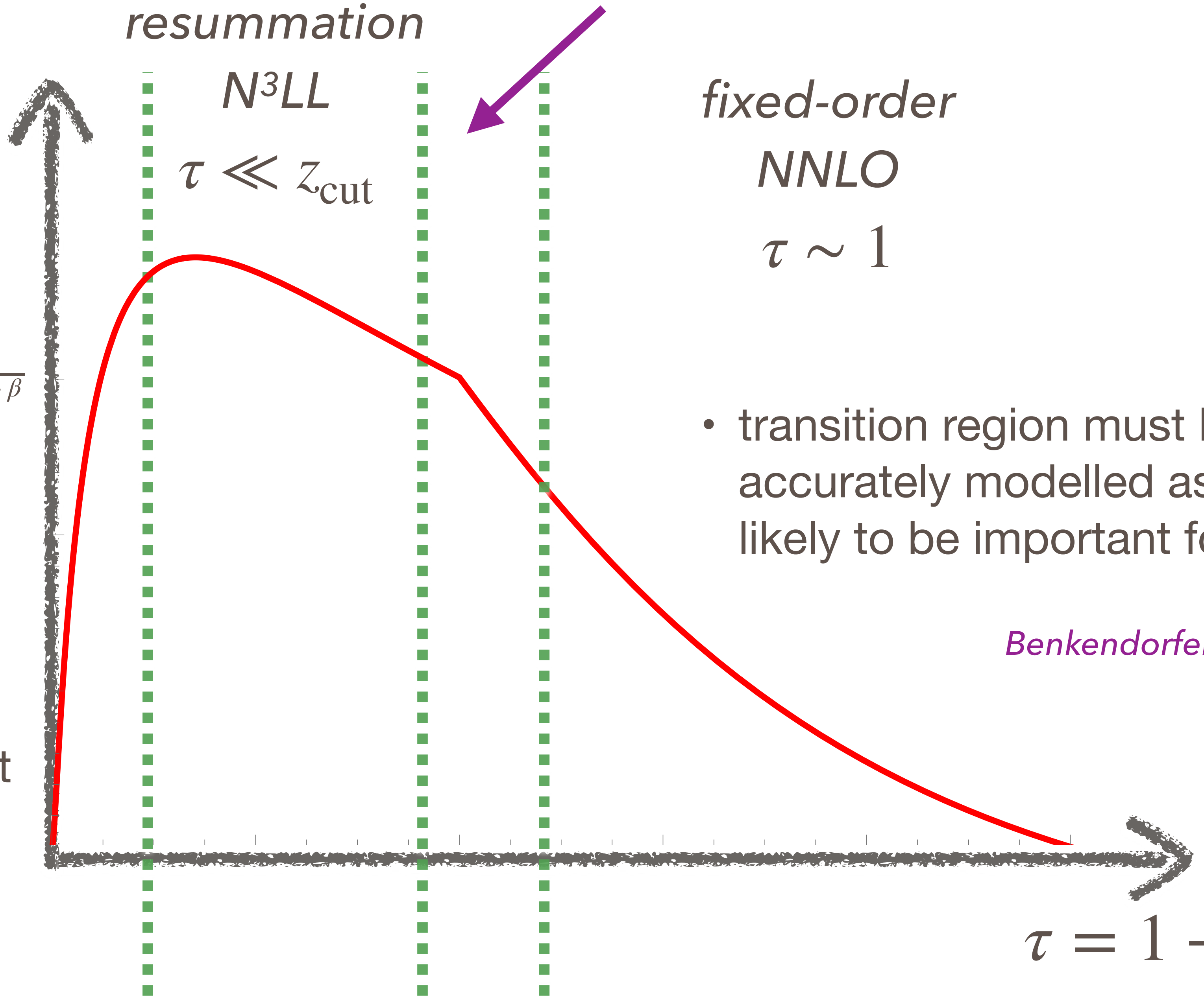
*fixed-order*

*NNLO*

$$\tau \sim 1$$

$$\tau = 1 - T$$

# Challenges for Soft Drop thrust



*transition region*

$\tau \sim z_{\rm cut}$

*resummation*

*N³LL*

$\tau \ll z_{\rm cut}$

*fixed-order*

*NNLO*

$\tau \sim 1$

$\frac{1}{\sigma}\frac{d\sigma}{d\tau}$

*non-perturbative*

$$\tau \sim \frac{\Lambda_{\rm NP}}{Q}\left(\frac{\Lambda_{\rm NP}}{Q z_{\rm cut}}\right)^{\frac{1}{1+\beta}}$$

$\tau = 1 - T$

- transition region must be accurately modelled as it is likely to be important for fits

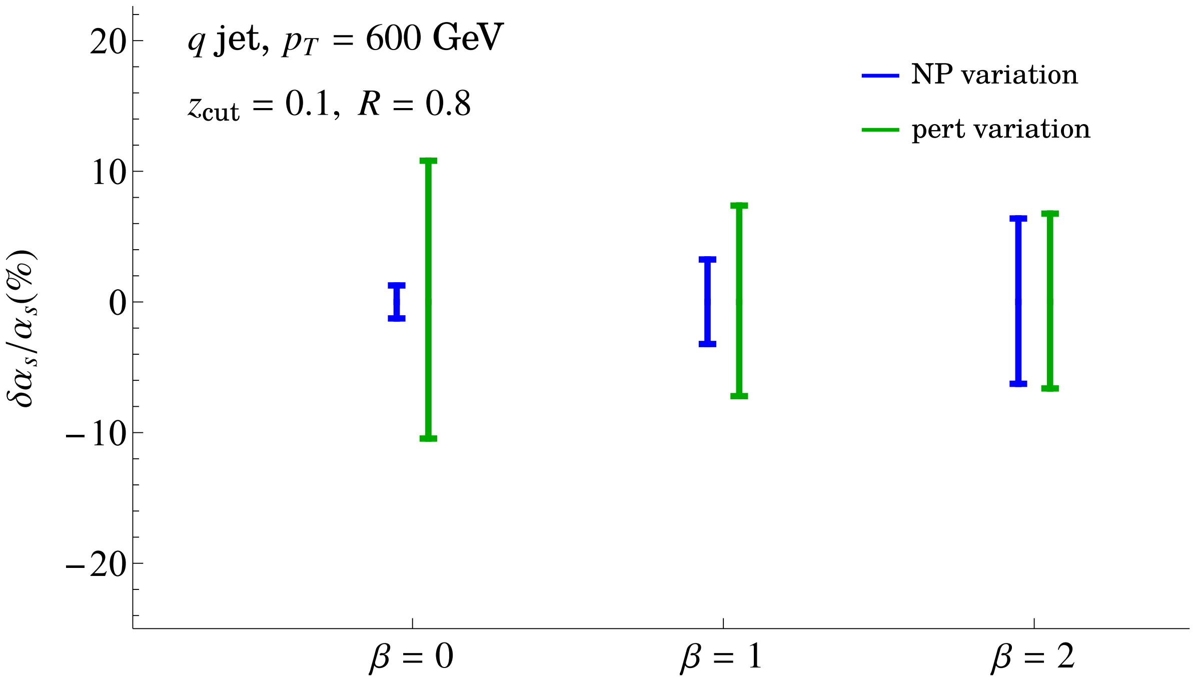
*Benkendorfer, Larkoski (2021)*

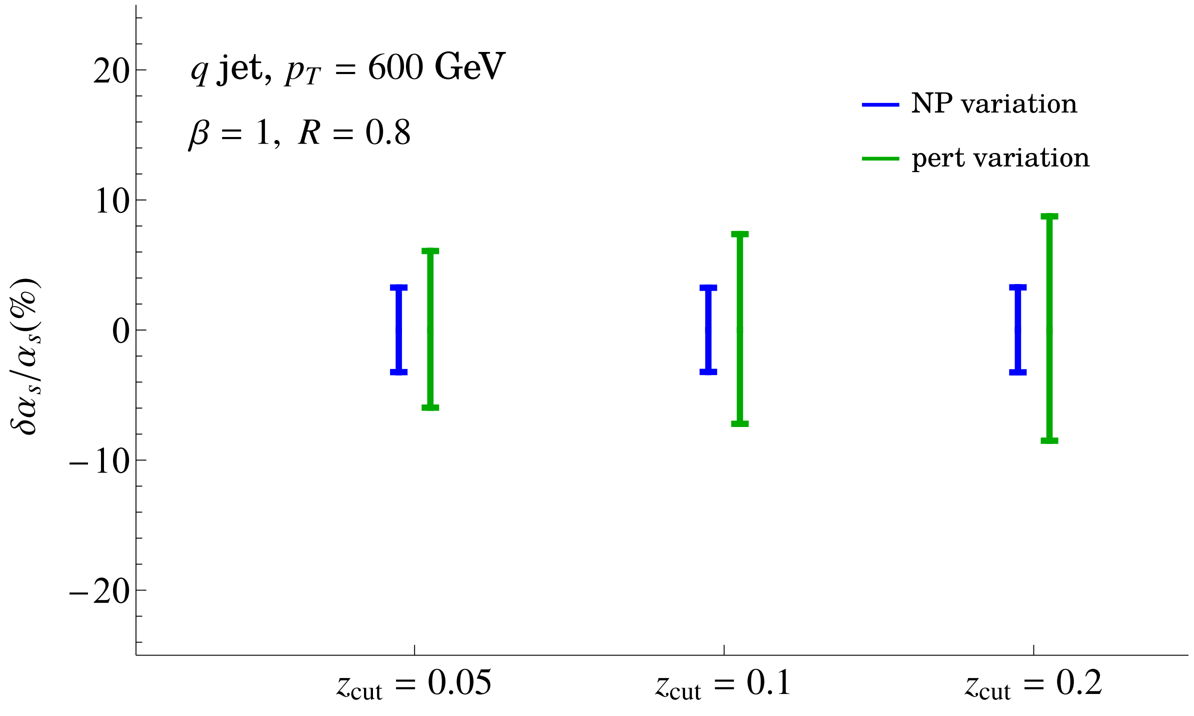
- non-pert region is pushed down, but it acquires a more complicated structure

*Hoang, Pathak, Mantry, Stewart (2019);*

*Pathak, Vaida, Stewart, Zoppi (2020)*

# Fitting for the strong coupling





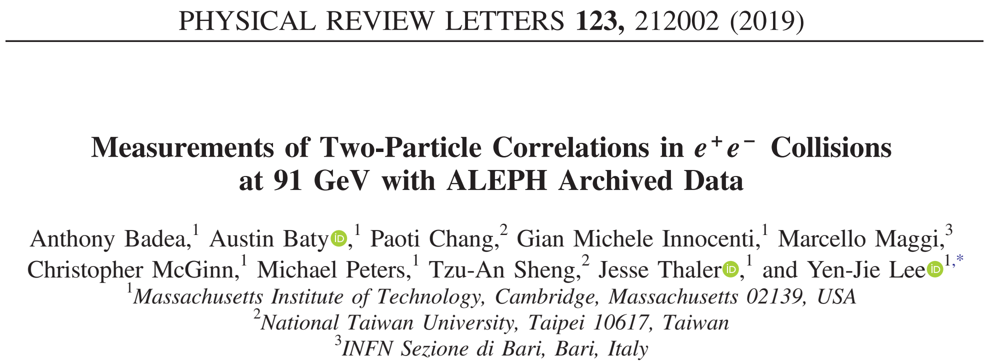
*Hannesdottir, Pathak, Schwartz, Stewart (2022)*

- Soft Drop mass more sensitive to pert. effects than non-pert ones (but choice of normalisation is important)
- in e+e- we essentially only have quark jets, while important limitation for *pp* is the correlations with quark/gluon fractions
- what about using energy correlators rather than grooming?

*Bianka Meçaj talk at BOOST 2022*

# It’s all very nice but we have no data

- groomed event shapes or other substructure variables can be used as high-precision observables for future lepton colliders
- reduced sensitivity to non-perturbative physics will allow for cleaner extractions of Standard Model parameters, including the strong coupling
- what can we do now? use LEP archived data!
- there is an MIT - led collaboration using ALPEH data, what about data from the other LEP experiments?


PHYSICAL REVIEW LETTERS **123,** 212002 (2019)

**Measurements of Two-Particle Correlations in $e^+e^-$ Collisions at 91 GeV with ALEPH Archived Data**

Anthony Badea,[1] Austin Baty,[1] Paoti Chang,[2] Gian Michele Innocenti,[1] Marcello Maggi,[3]
Christopher McGinn,[1] Michael Peters,[1] Tzu-An Sheng,[2] Jesse Thaler,[1] and Yen-Jie Lee[1,*]
[1]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
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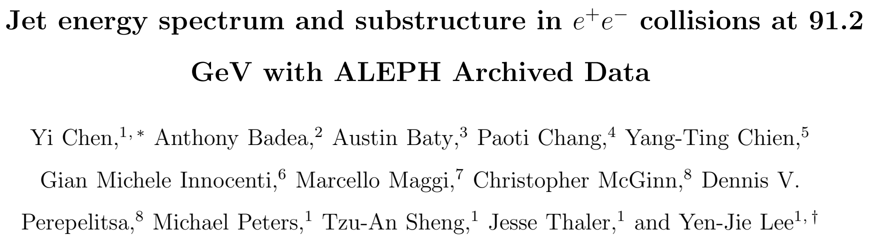
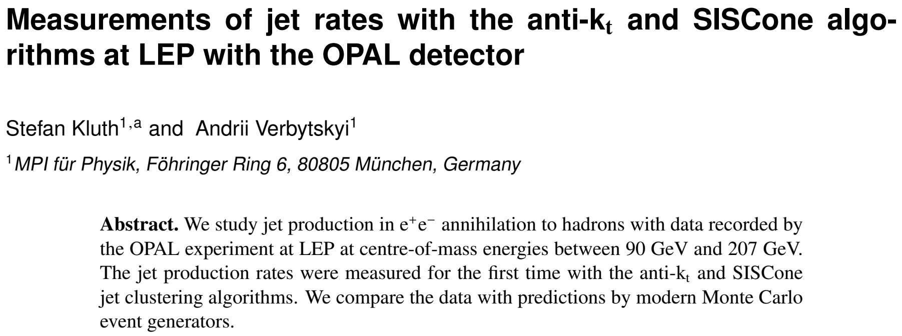
[3]*INFN Sezione di Bari, Bari, Italy*


**Jet energy spectrum and substructure in $e^+e^-$ collisions at 91.2 GeV with ALEPH Archived Data**

Yi Chen,[1,*] Anthony Badea,[2] Austin Baty,[3] Paoti Chang,[4] Yang-Ting Chien,[5]
Gian Michele Innocenti,[6] Marcello Maggi,[7] Christopher McGinn,[8] Dennis V.
Perepelitsa,[8] Michael Peters,[1] Tzu-An Sheng,[1] Jesse Thaler,[1] and Yen-Jie Lee[1,†]


**Measurements of jet rates with the anti-$k_t$ and SISCone algorithms at LEP with the OPAL detector**

Stefan Kluth[1,a] and Andrii Verbytskyi[1]
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**Abstract.** We study jet production in $e^+e^-$ annihilation to hadrons with data recorded by the OPAL experiment at LEP at centre-of-mass energies between 90 GeV and 207 GeV. The jet production rates were measured for the first time with the anti-$k_t$ and SISCone jet clustering algorithms. We compare the data with predictions by modern Monte Carlo event generators.