Università di Genova

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Future Challenges & Opportunities for QCD at Colliders

LFC22: STRONG INTERACTIONS FROM QCD TO NEW STRONG DYNAMICS AT LHC AND FUTURE COLLIDERS

ECT* Trento 29th August - 2nd September 2022

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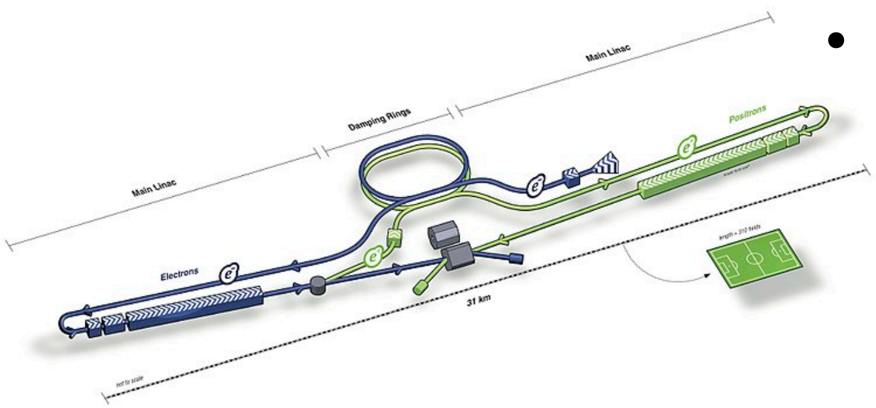
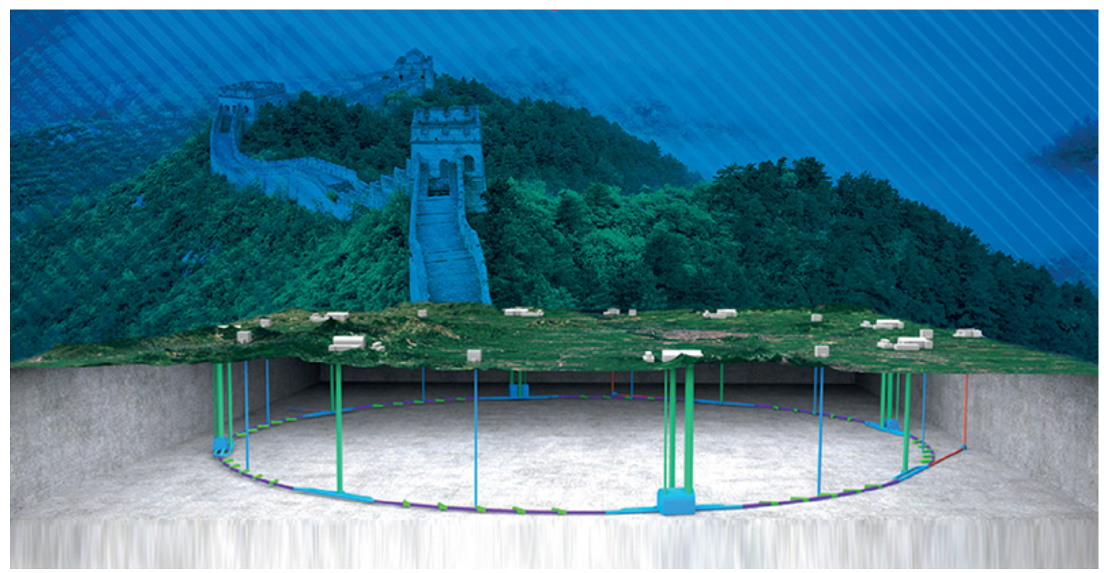
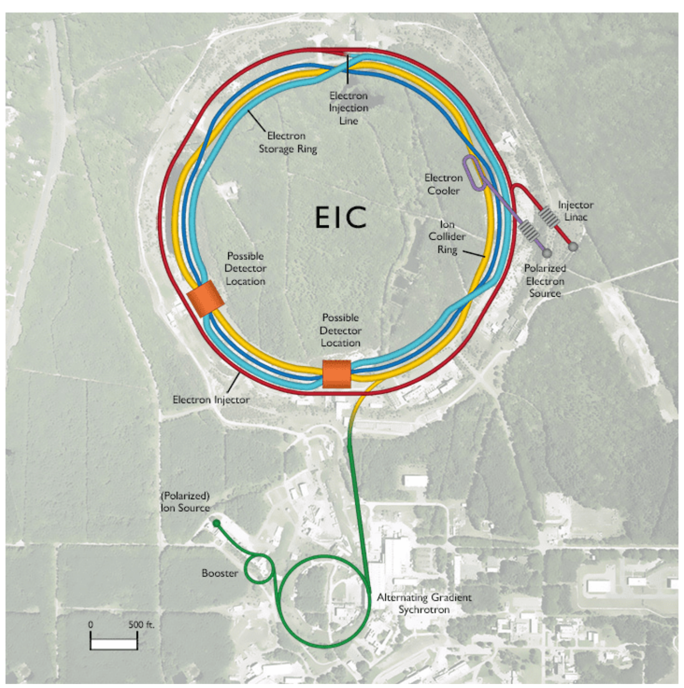
Colliders of the future

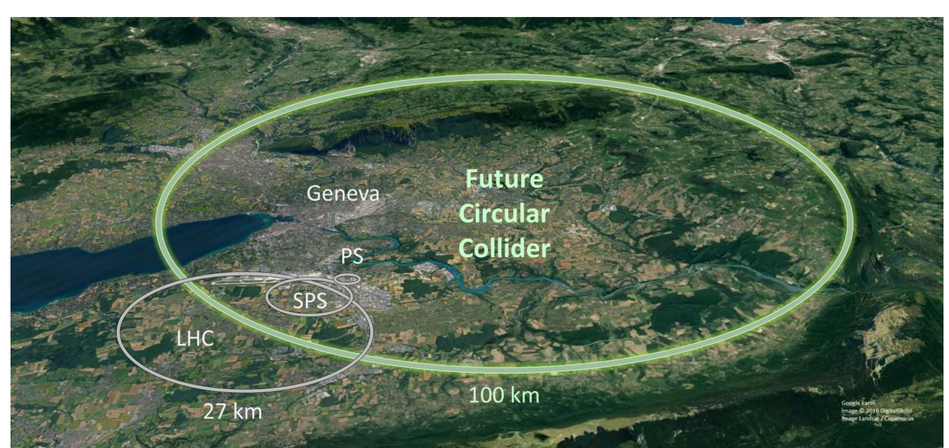
- technology is continuously advancing
- new experiments have started or are around the corner
- more will come (?)





- can we build better and better tools to analyse and understand the data?

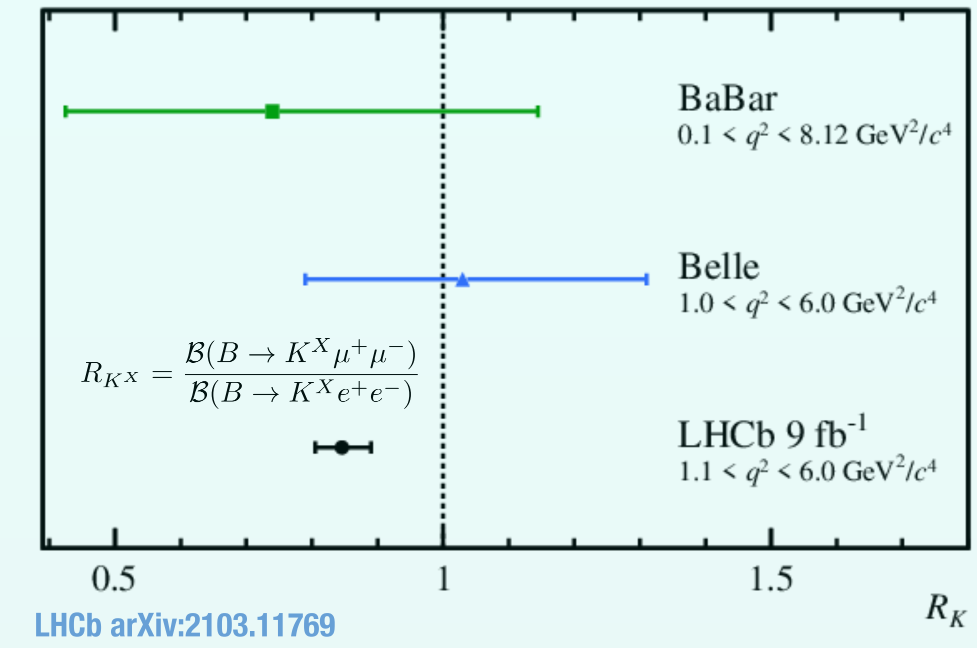


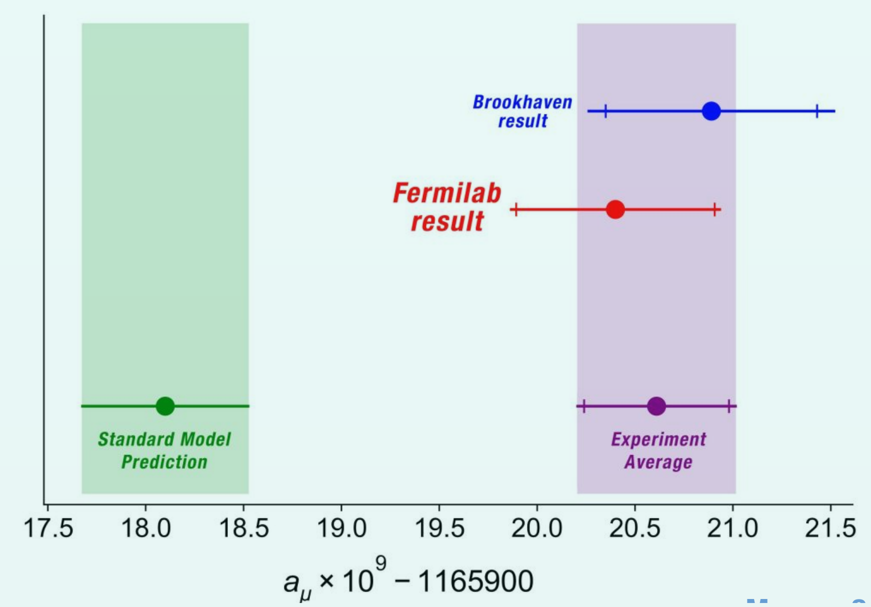


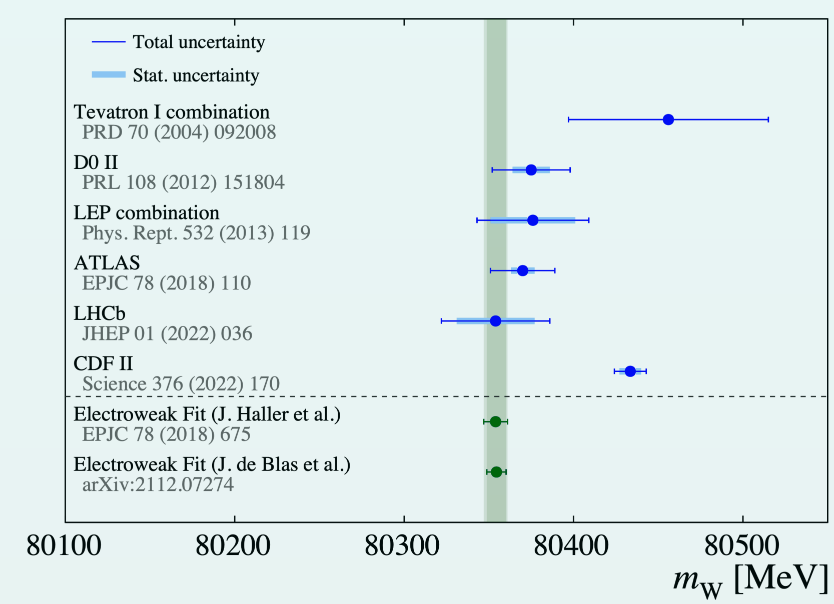
- what are the challenges that the (QCD) theory community is facing? What progress has been made recently?
- need to be creative (I): examples of cross-pollination
- need to be creative (II): understanding new tools

Sharpening our tools

to be able to address fundamental issues

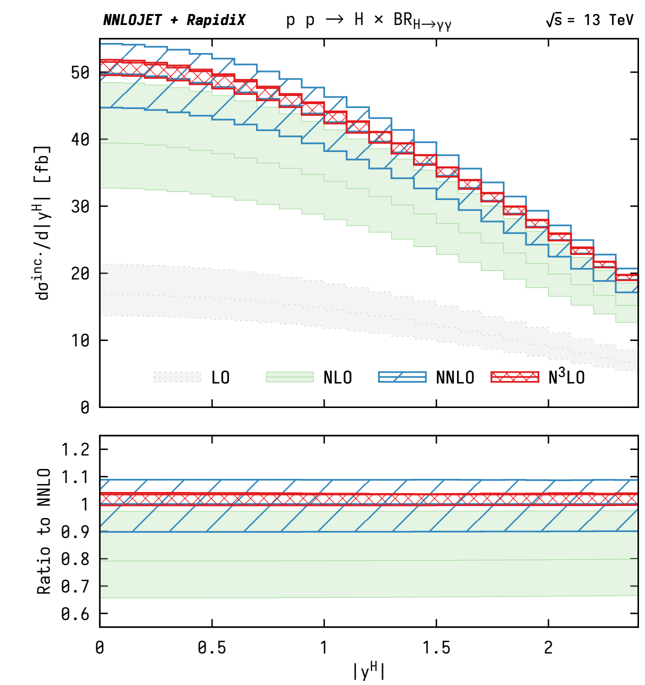




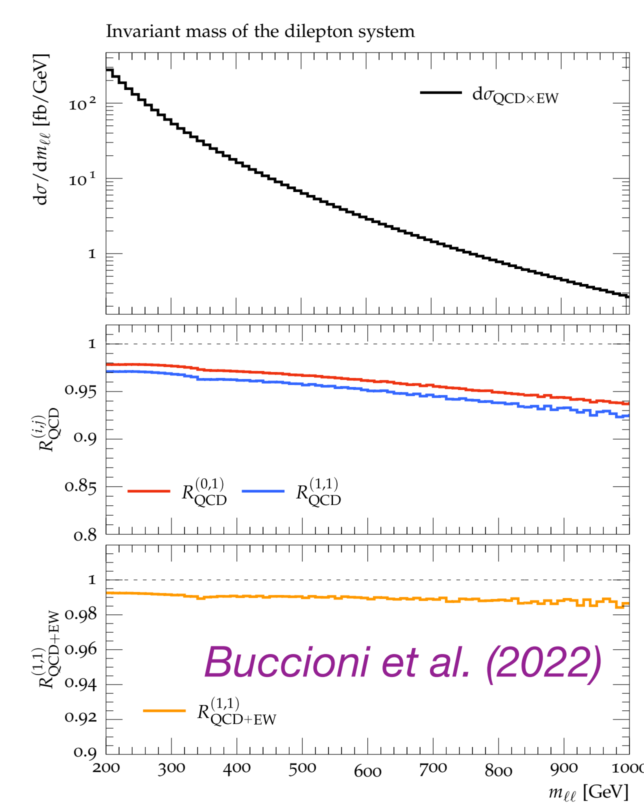


Fixed-order calculations

- QCD@NNLO
    - colour-singlet, *jj* and $t\bar{t}$ obtained with more than one technology. Often matched to parton shower to obtain precise and realistic predictions
    - colour-singlet plus jet also well-studied
    - progress towards 3-jet observables
- QCD@N³LO
    - inclusive x-sec and differential distributions for standard candles with simple kinematics (VBF-H, gg-H, DY)
- mixed QCD - EW corrections



Chen et al. (2021)

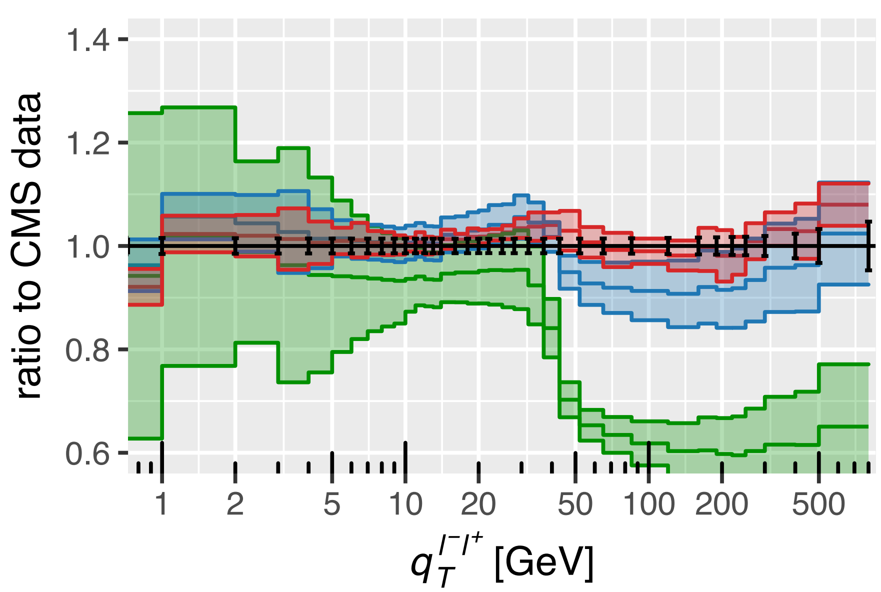


Buccioni et al. (2022)

Resummation

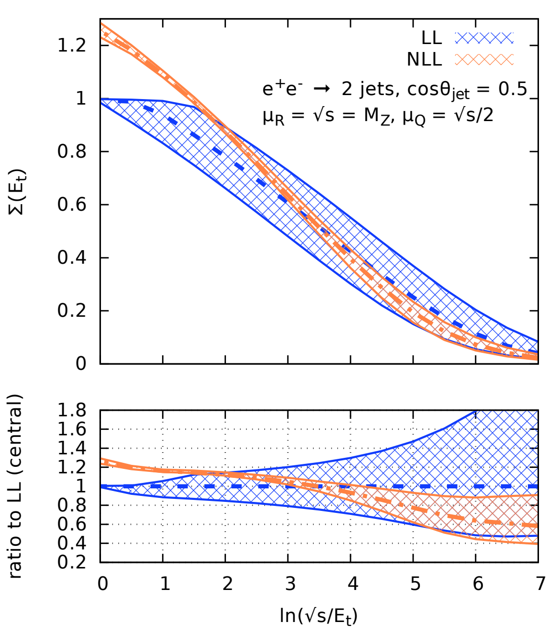
- when hierarchy of scales appears, fixed-order no longer enough, we need to resum to all orders

- high-precision (N³LO+aN⁴LL) for selected observables: transverse momentum Z boson (relevant for m_W)

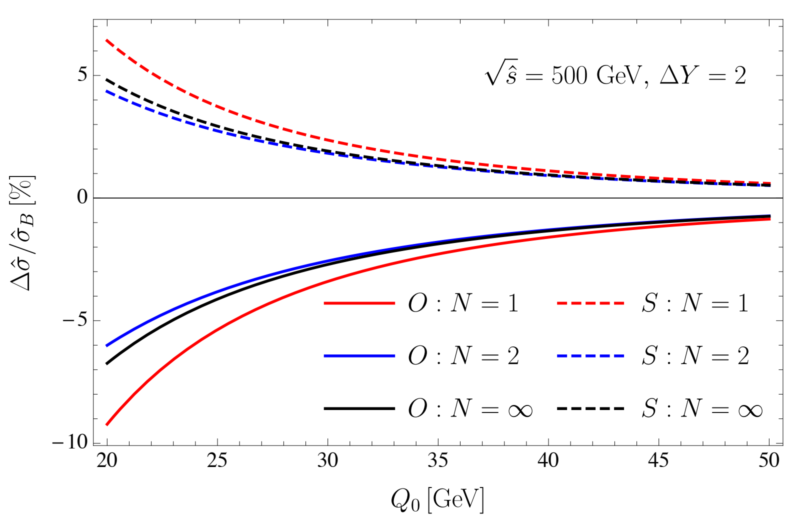


Campbell, Neumann (2022)

- all-order structure of complicated final-states: inter-jet energy flow
  - non-global logarithms at NLL (large N_c)
  - super-leading logarithms (N_c suppressed)



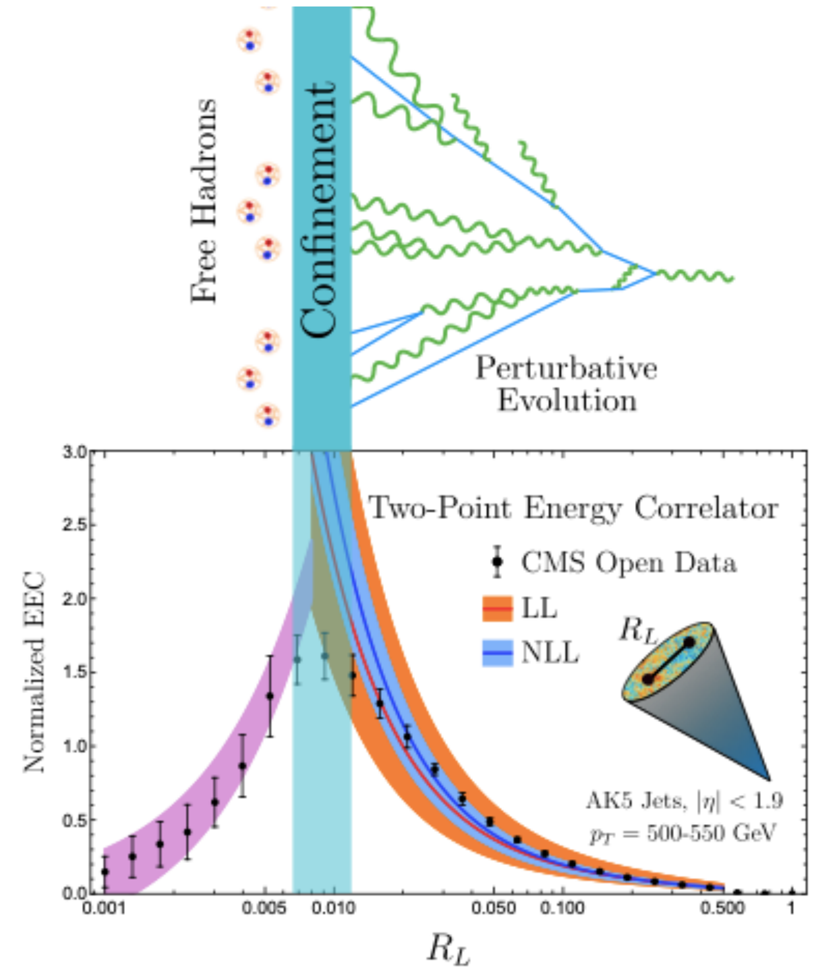
Banfi, Dreyer, Monni (2021)

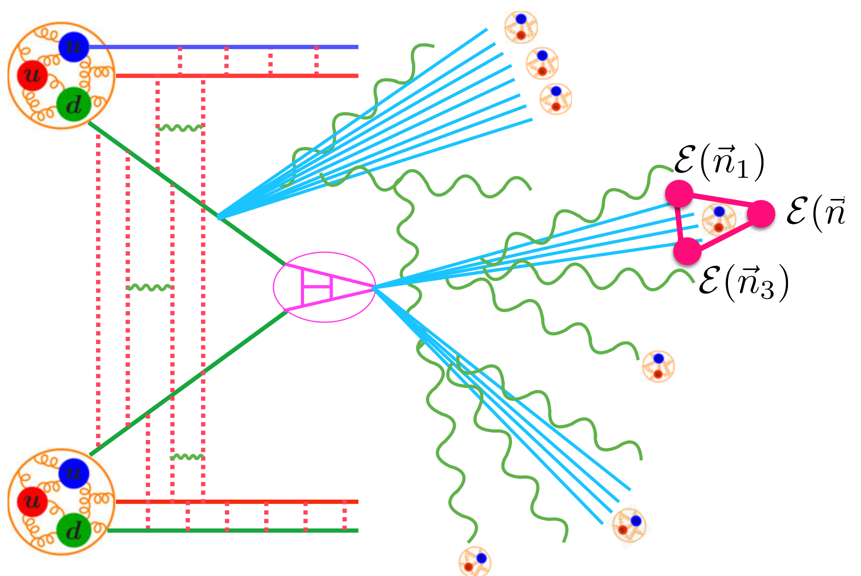


Becher, Neubert, Shaw (2021)

Energy Correlators

- In 2008 a seminal paper by Hoffman and Maldacena developed the use CFT methods to study correlators in collider physics
- Many intriguing results from CFT (OPE expansion scaling)
- Until recently, not very much investigated in collider phenomenology
- Many interesting developed by Ian Moult and collaborators
    - EEC are natural objects in field theory
    - energy weight make reduce sensitivity to soft physics
    - simple(r) analytic properties than standard observables (e.g. jet mass)



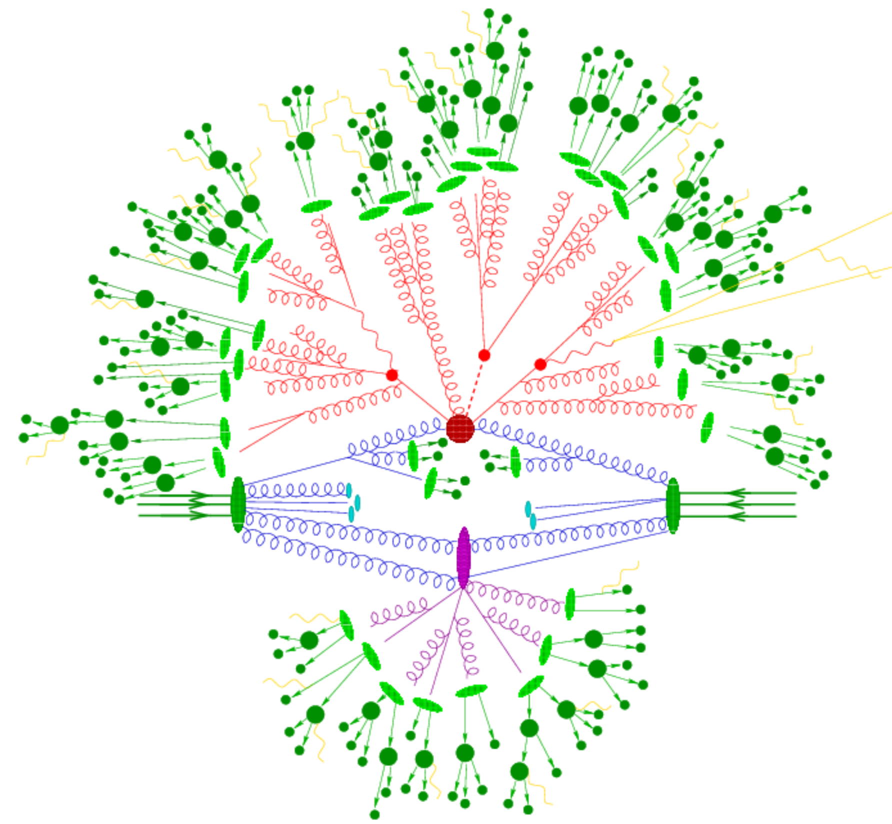


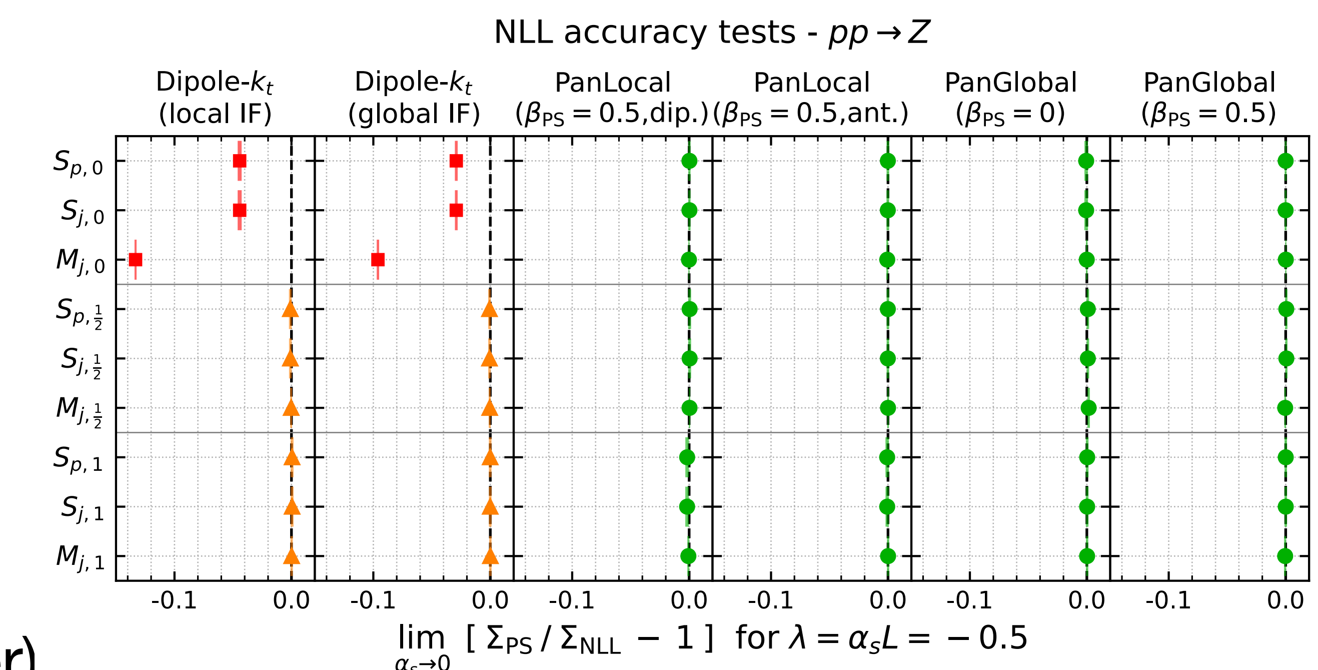
$$\langle \Psi \mid \varepsilon(\overrightarrow{n}_1)\varepsilon(\overrightarrow{n}_2) \mid \Psi \rangle$$

$$\sim \sum \theta^{\gamma_i} \mathcal{O}_i(\overrightarrow{n}_1)$$

Event generators

- Monte Carlo Event Generators (e.g. Pythia, Herwig, Sherpa) are the backbone of collider phenomenology
- Need to simulate complex environment, from perturbative to non-perturbative physics: many building blocks
- Push in recent years to improve the perturbative part (parton shower)
  - matching to NNLO
  - higher-order evolution kernels
  - spin correlation
  - treatment of colour and amplitude-level showers (Deductor, CVolver)
  - well-defined logarithmic accuracy (NLL) wide class of observables (PanScales showers, new Sherpa shower)

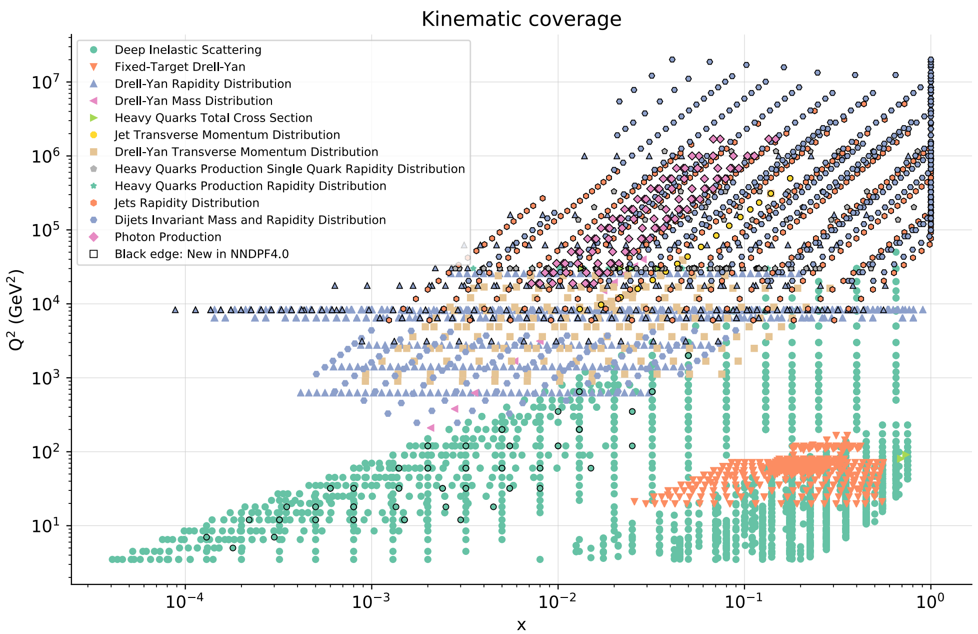




PanScales collaboration (2022)

Parton distribution functions

- PDFs are an essential ingredients for hadron colliders. Improvements in their determination come from different directions

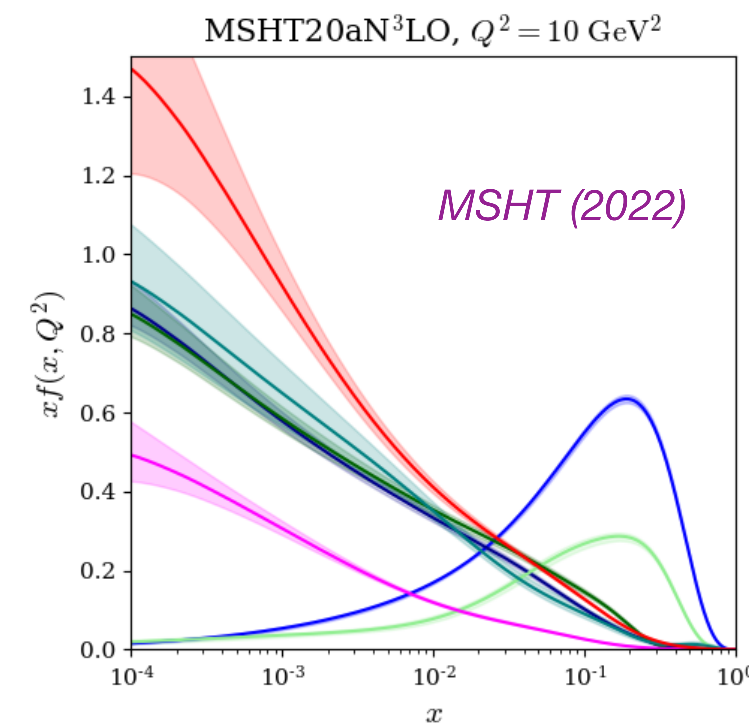


$N_{\rm dat} \sim 4500$

more data

better theory

- (fast) theory predictions for more complicated final states
- phase-space in resummation region
- high accuracy and theory uncertainties



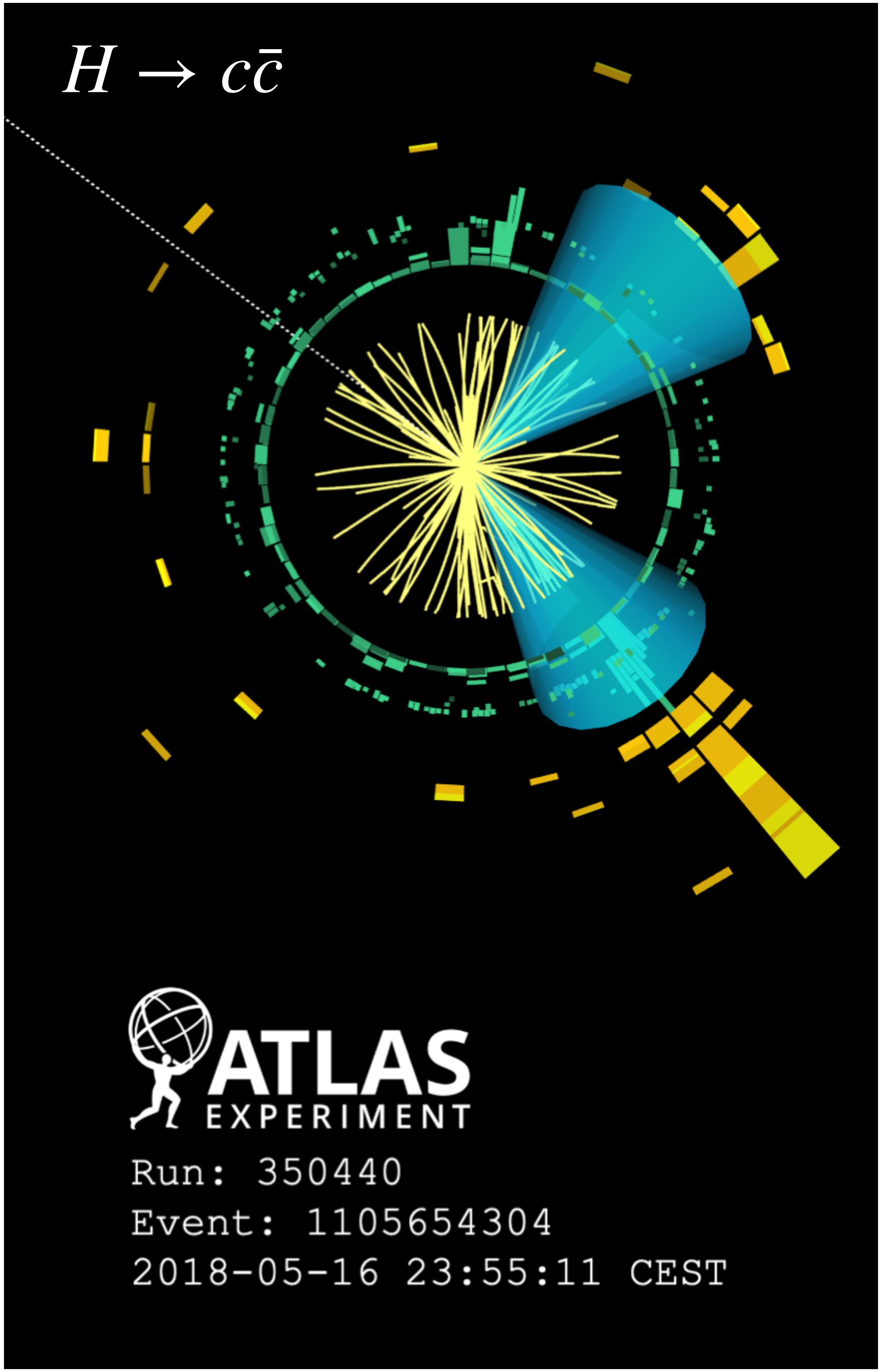
improved methodology

NNPDF (2021)

NNPDF3.1	NNPDF4.0
Genetic Algorithm optimizer	Gradient Descent optimization
one network per PDF	one network for all PDFs
sum rules imposed outside optimization	sum rules imposed during optimization
C++ monolithic codebase	Python object-ordiented codebase
fit parameters manually chosen (manual optimization)	fit parameters automatically chosen (hyperoptimization)
in-house ML framework	complete freedom in ML library choice (e.g. tensorflow)
private code	fully public open-source code

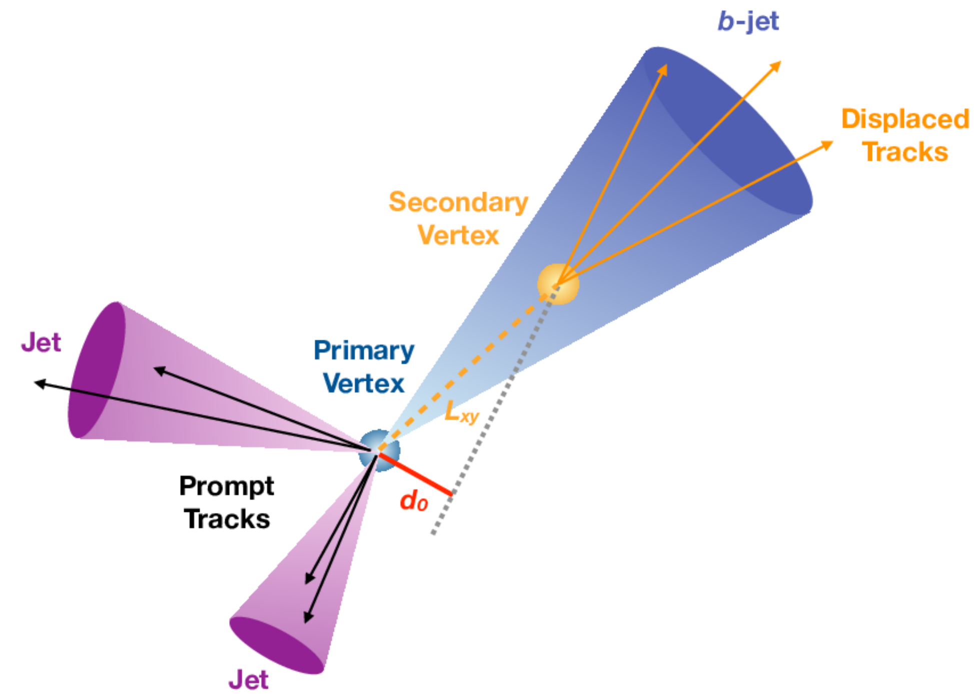
Cross-pollination

new ideas to study heavy flavours

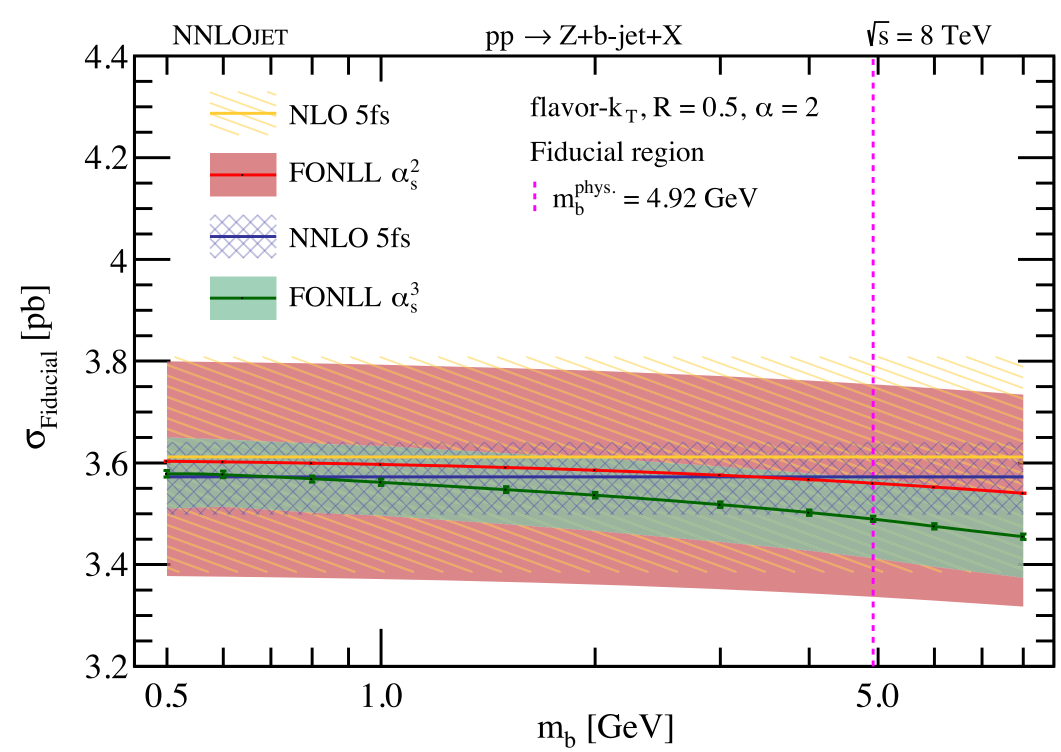


Heavy Flavour Jets

- 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 jet now exist



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



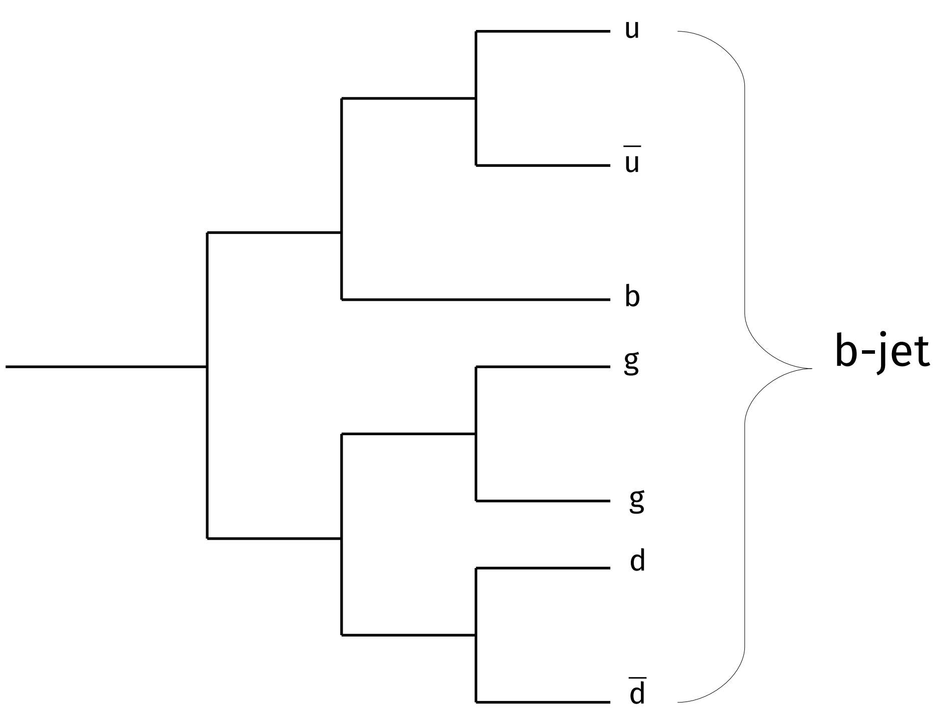
Gauld et a. (2020)

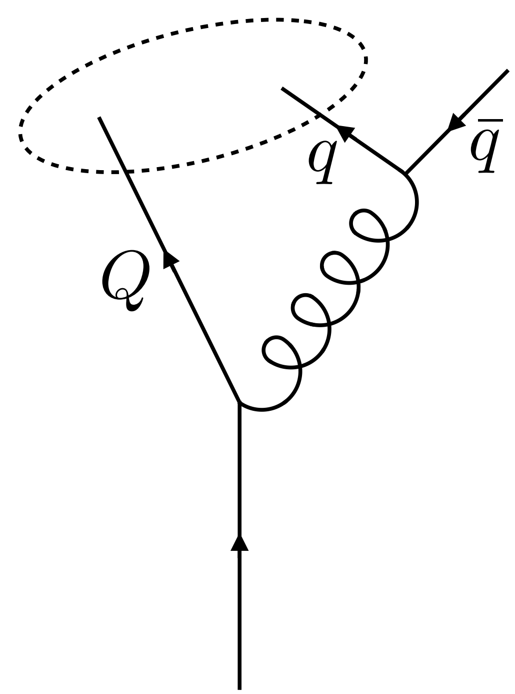
Experiment vs Theory (I)

- 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

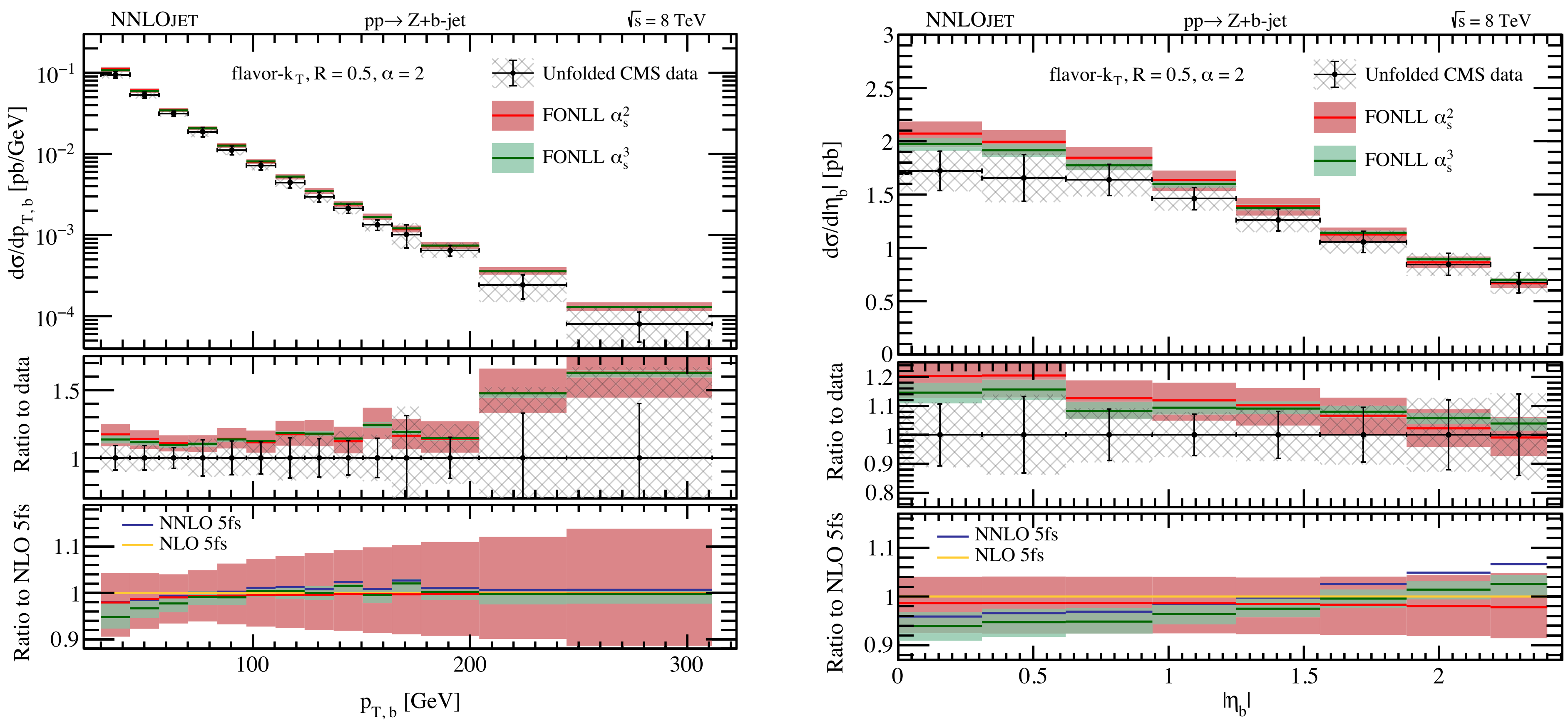
- however the use of BSZ in experimental analysis is far from straightforward:

  - 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

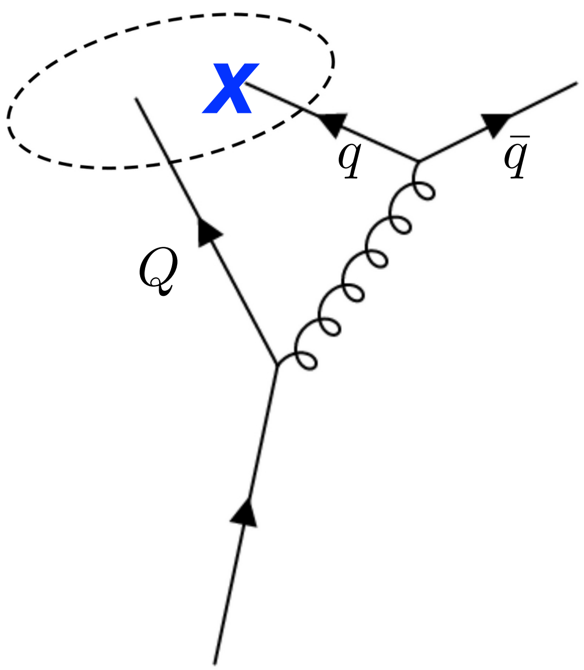


Gauld et a. (2020)

- 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

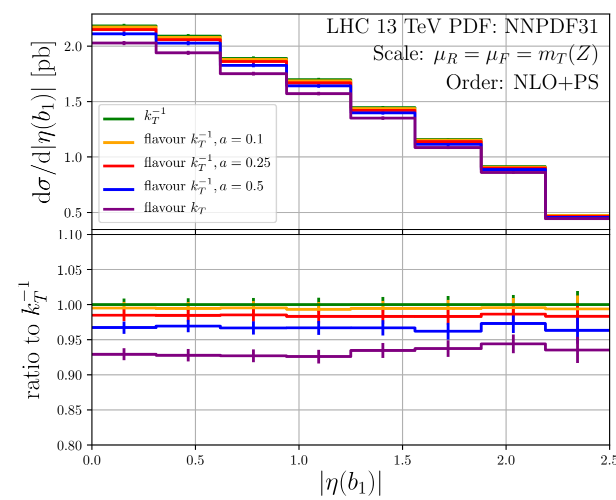


- needs JADE as reclusters, know to fail at three loops

Caletti, Larkoski, SM, Reichelt (2022)

- define a flavour algorithm that resembles anti-k_t

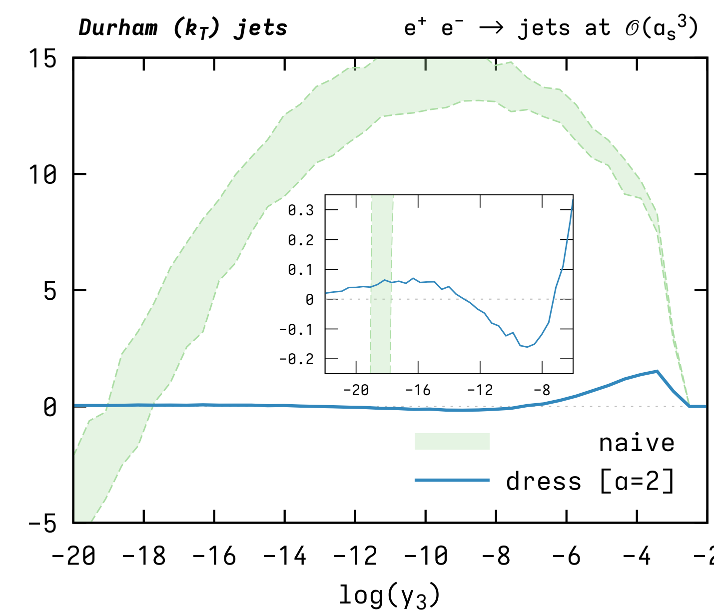
$$d_{ij}^{(F)} \equiv d_{ij} \times \begin{cases} \mathcal{S}_{ij}\,, & \text{if both } i \text{ and } j \text{ have non-zero flavour of opposite sign,} \\ 1\,, & \text{otherwise.} \end{cases}$$



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

Czakon, Mitov, Poncelet (2022)

- construct a flavour dressing for a given jet



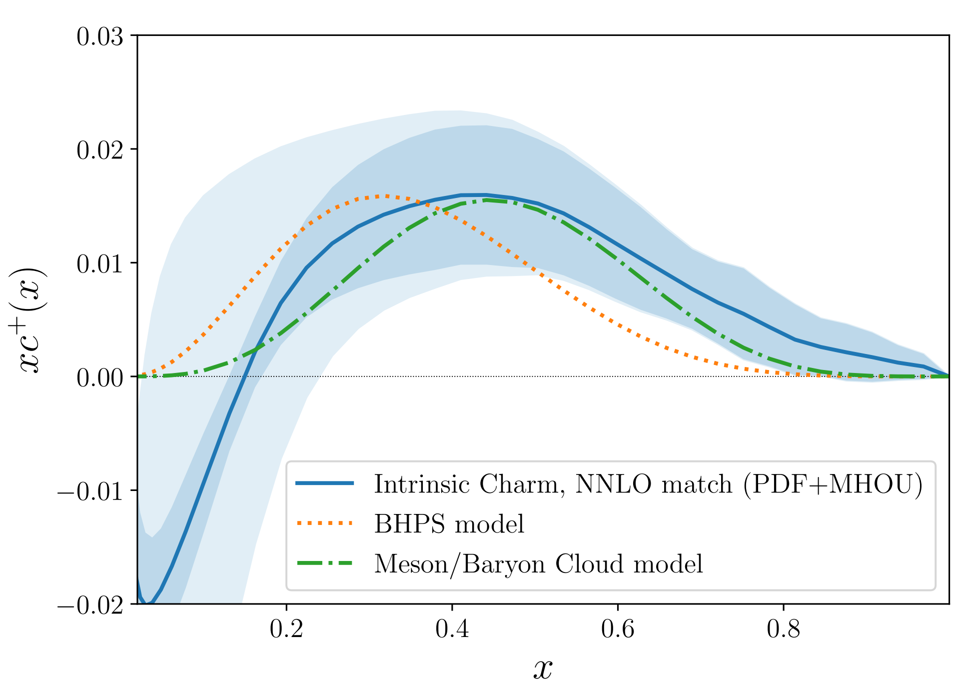
- needs flavour information of many (all?) particles in an event

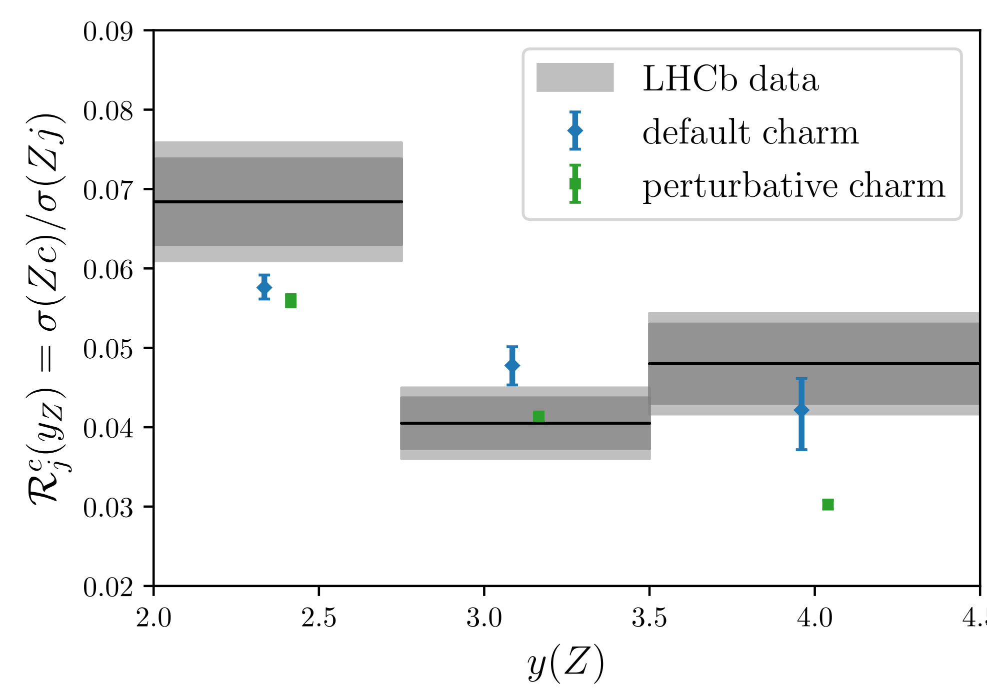
Gauld, Huss, Stagnitto (2022)

- it would be interesting to do a dedicated comparison!

There's charm in the proton!

- NNPDF collaboration has recently shown a 3σ 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!





Nature | Vol 608 | 18 August 2022 |

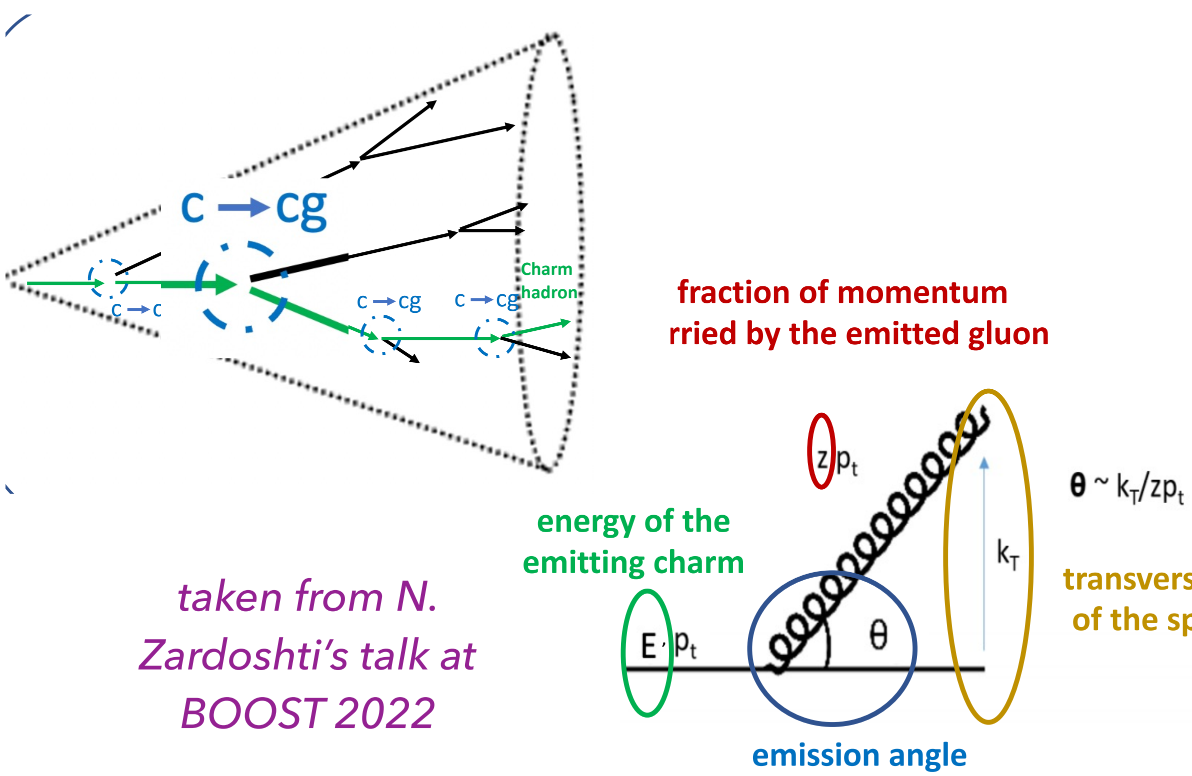
NNPDF (2022)

ALICE and the dead cone

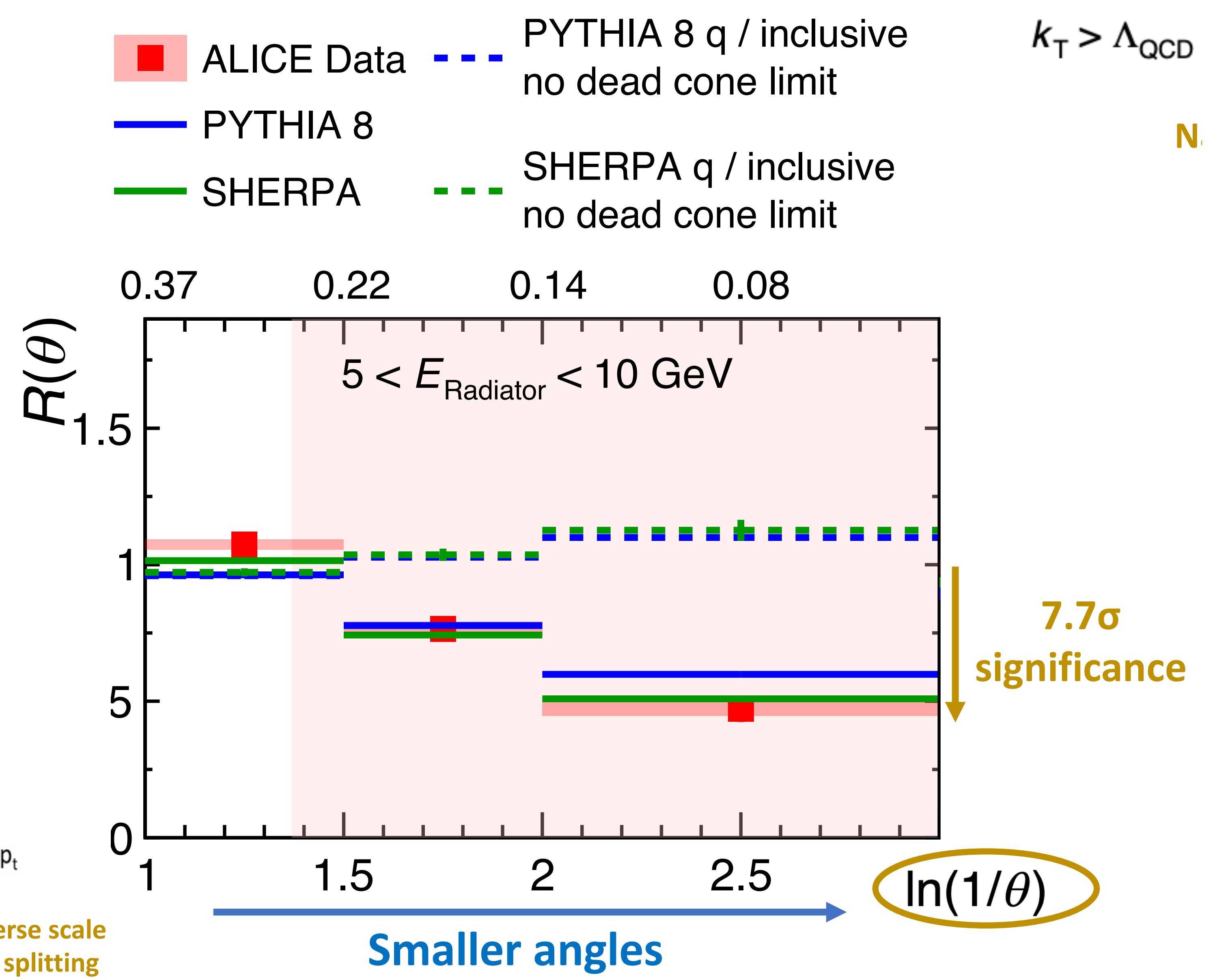
- ALICE recently exploited ideas from modern jet physics (e.g. reclustering) to perform the first direct measurement of the dead cone

- Charm jets are tagged using $D^0 \rightarrow K^-\pi^+$
- Jets are declustered and the splitting kinematics is recorded

Nature 605 (2022) 440-446



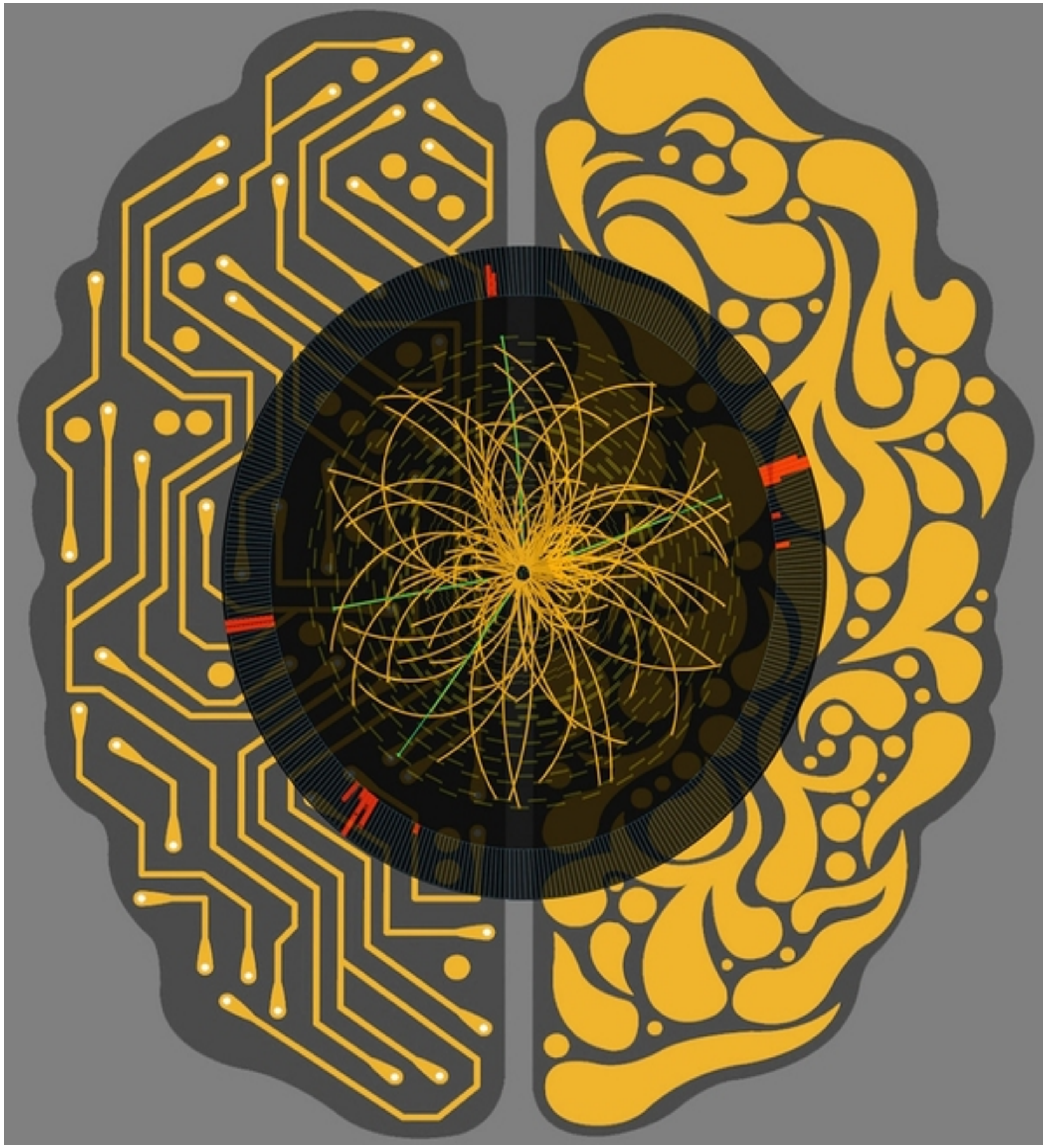
taken from N. Zardoshti's talk at BOOST 2022



Nature | Vol 605 | 19 May 2022 |

Understanding new tools

machine learning is reshaping the way we think analyses and searches

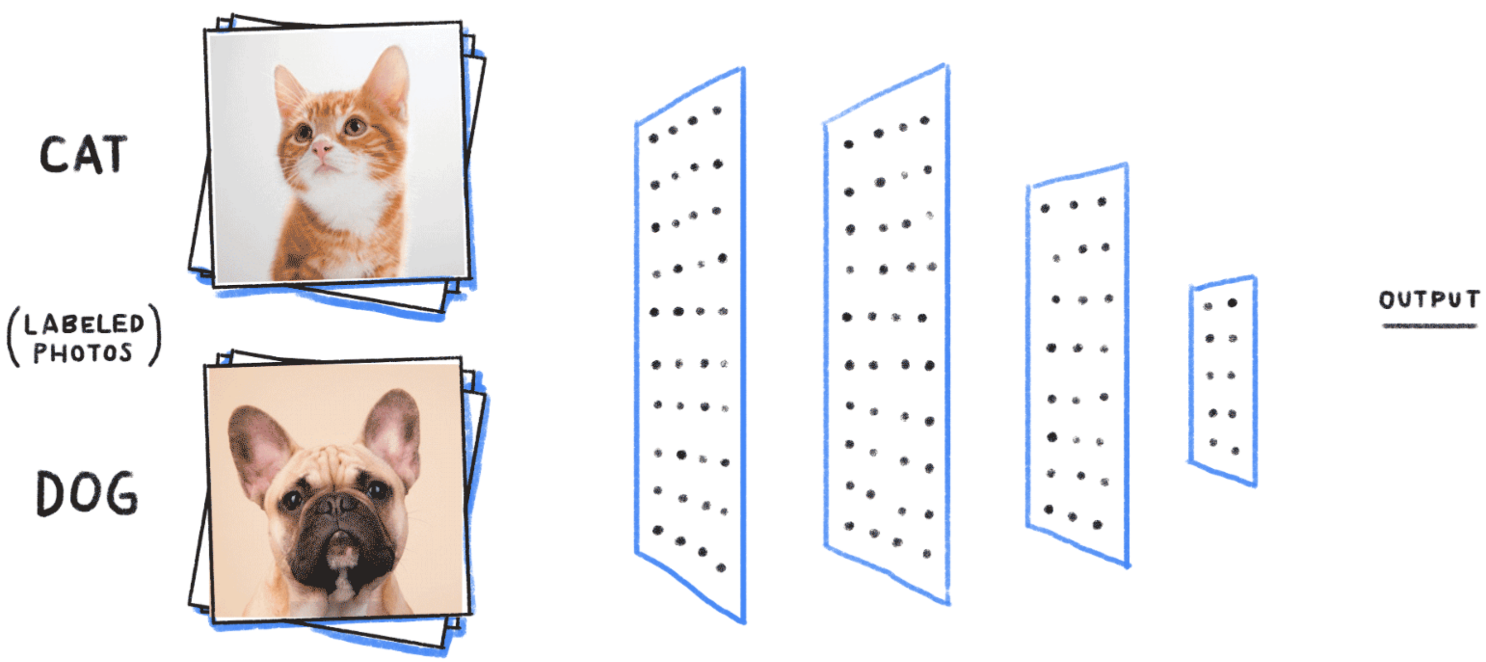


https://news.mit.edu/2019/boosting-computing-power-for-future-particle-physics-mit-lns-0819

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

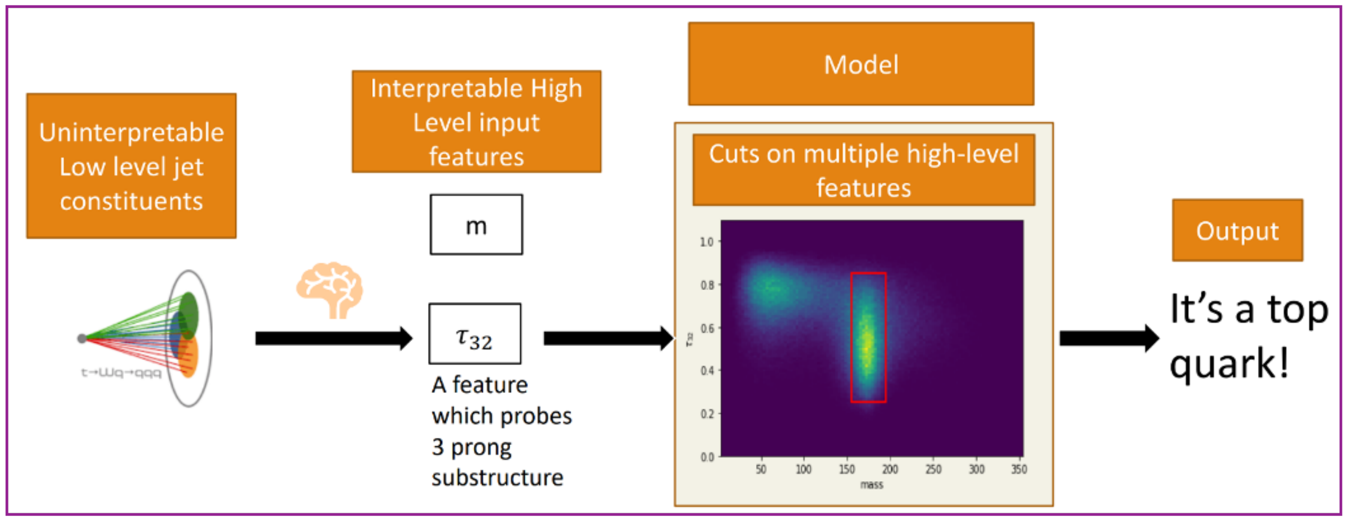


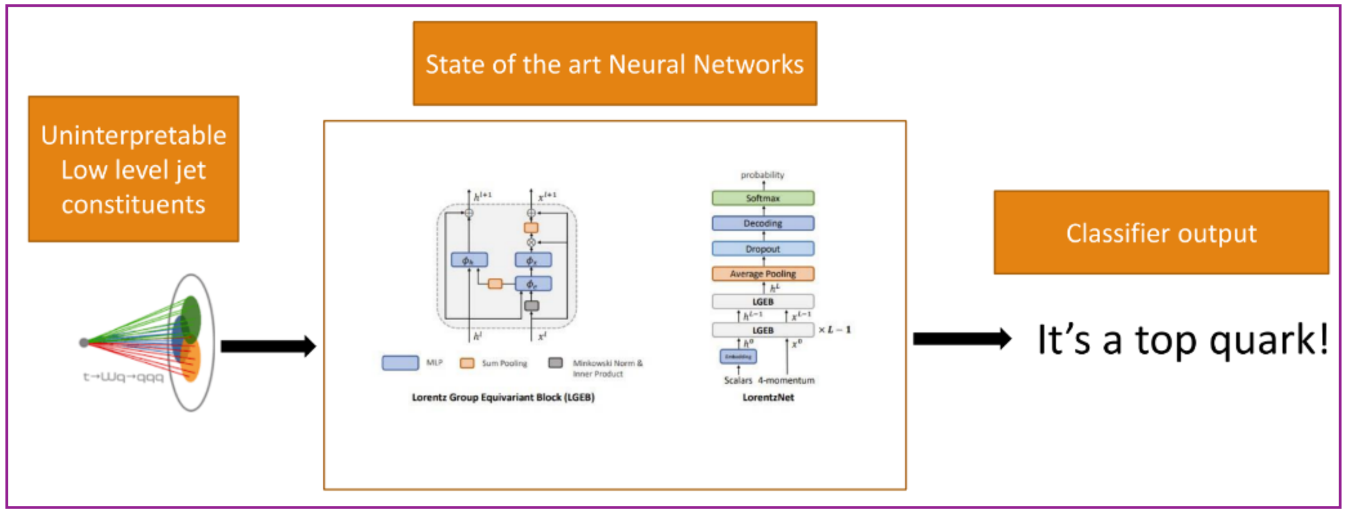
credits: becominghuman.ai

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

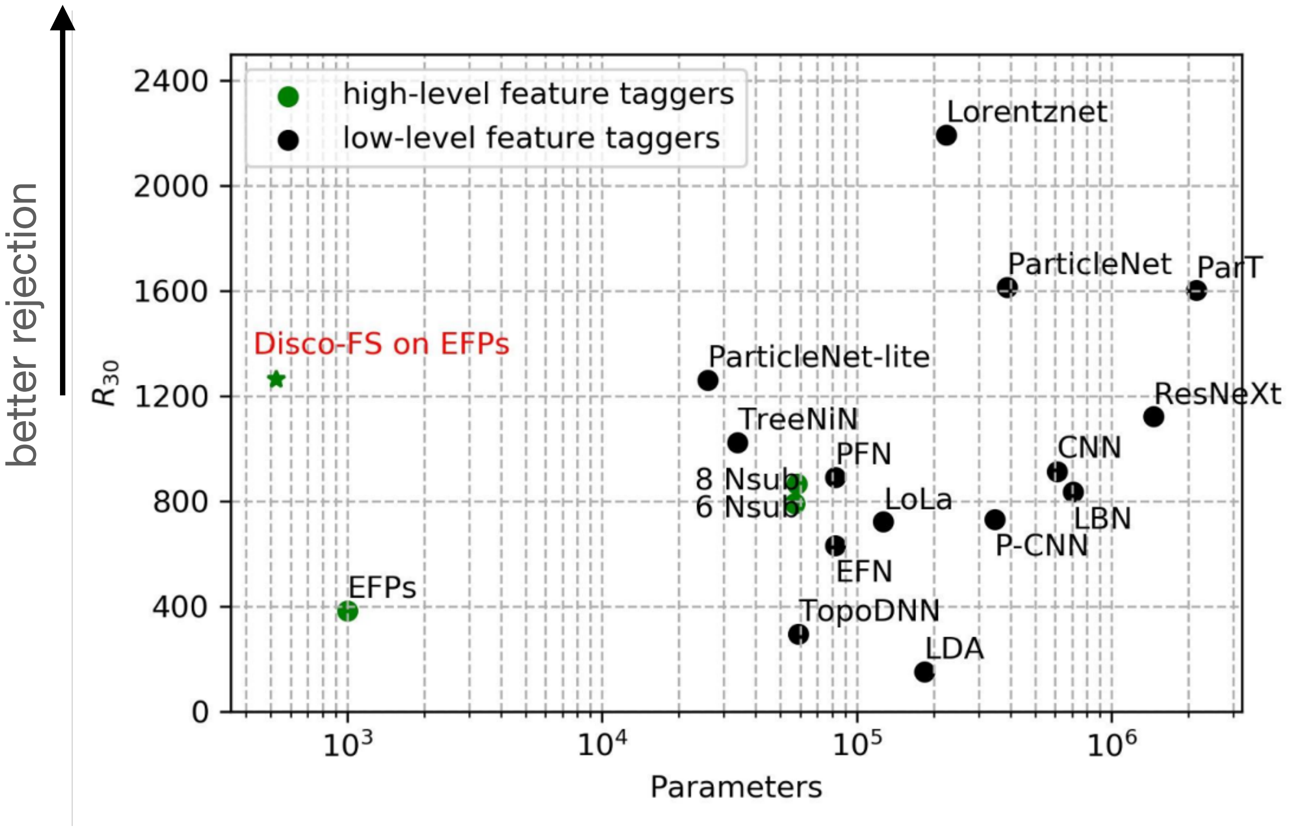
- very active and fast-developing field

High-level vs low-level





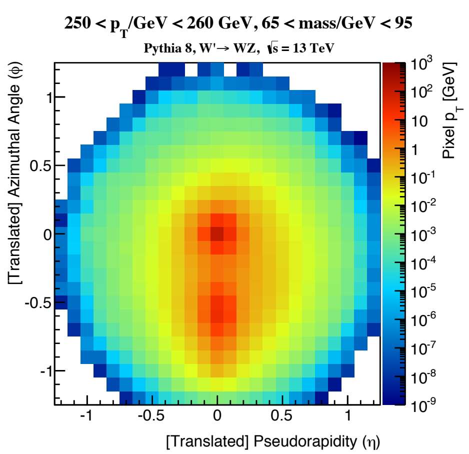
- traditionally, phenomenologists build “clever observables” that are able to capture the desired features of particle collisions
- neural networks and computational advances allow us to exploit low-level information (cal cells, momenta etc)
- what are pro’s and con’s of the two approaches? Can we combine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

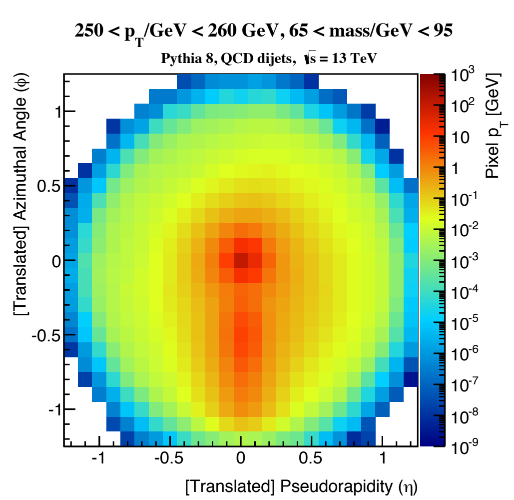


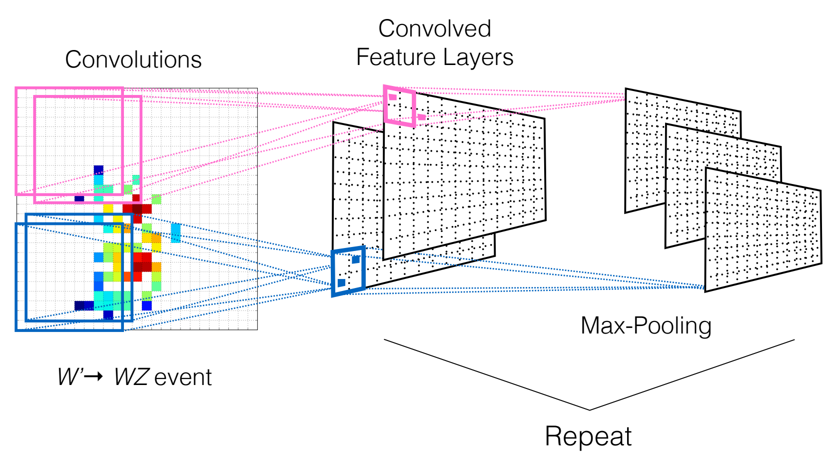
adapted from Ranit Das talk at BOOST 2022

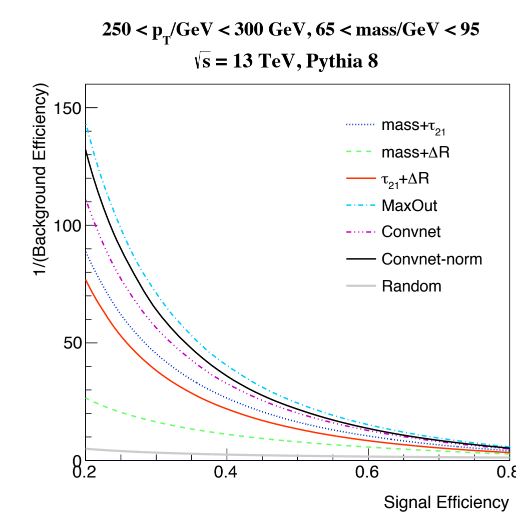
Jet images

- 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







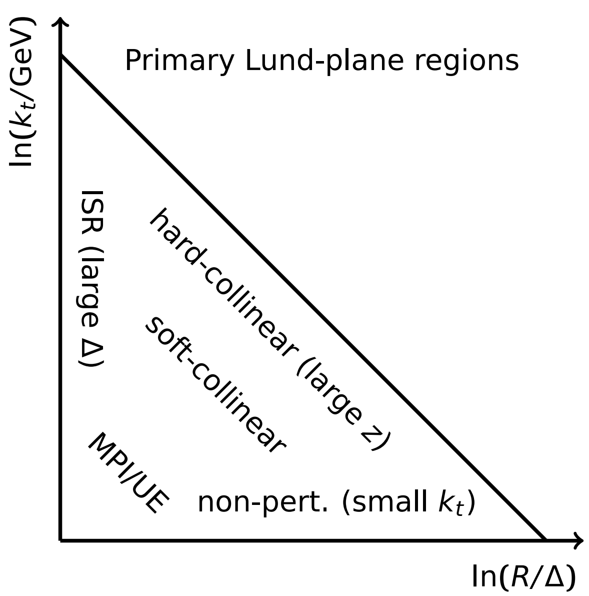


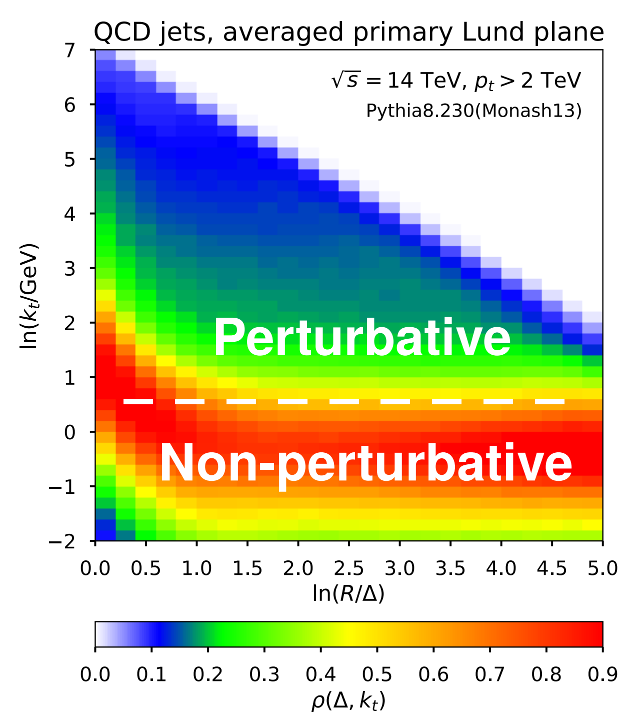
Cogan, Kagan, Strauss, Schwartzman (2015)
de Olivera, Kagan, Mackey, Nachman, Schwartzman (2016)

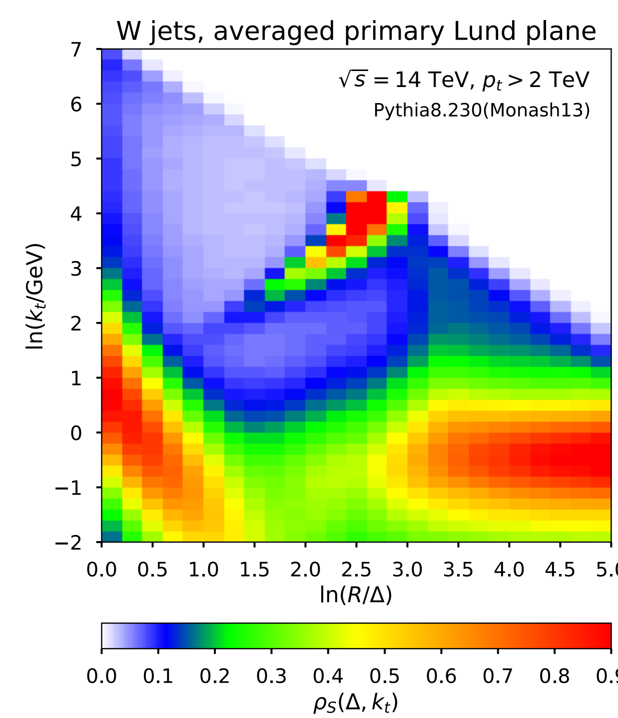
Theory inputs

- 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, Δ) at each step



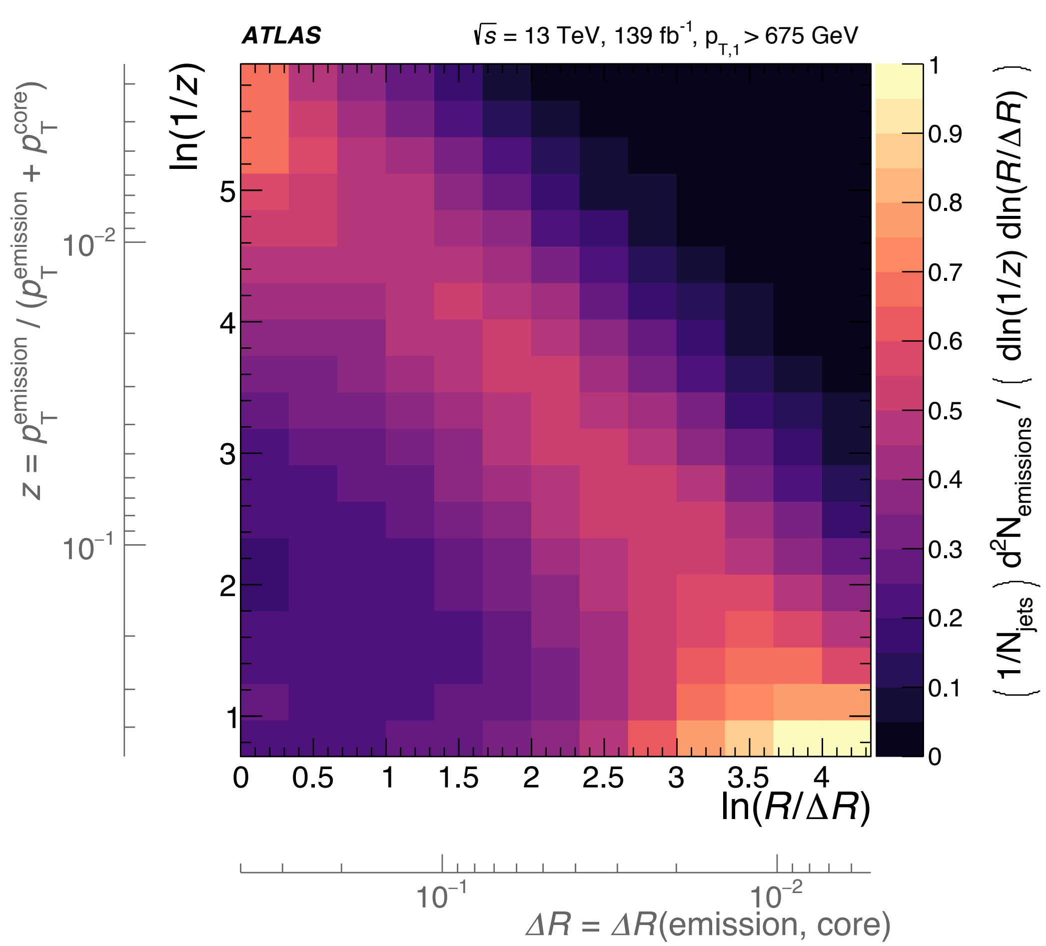




Dryer, Salam, Soyez (2018)

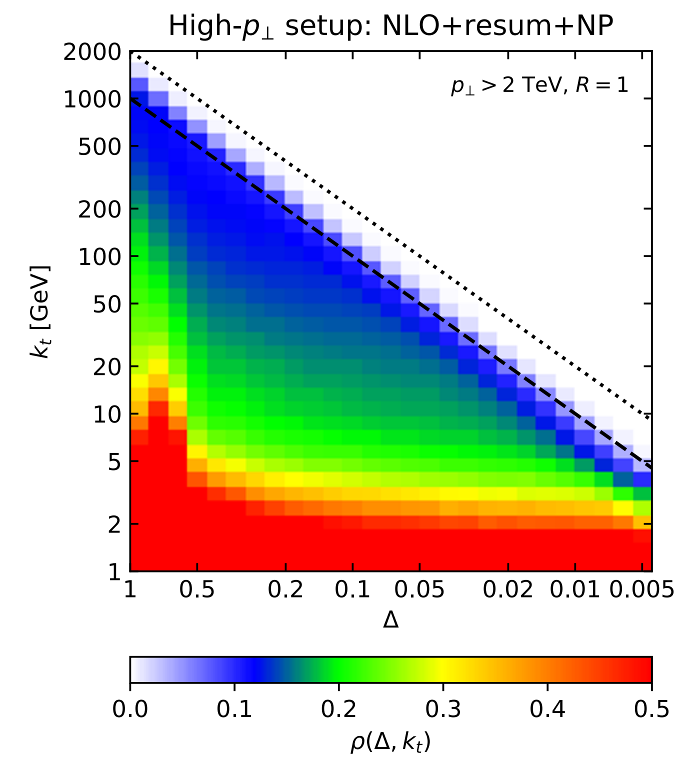
Mapping out the Lund plane

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

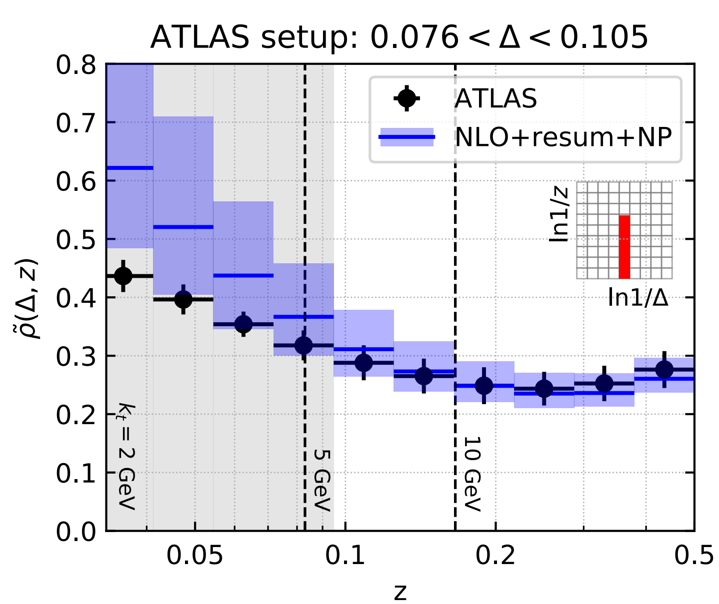


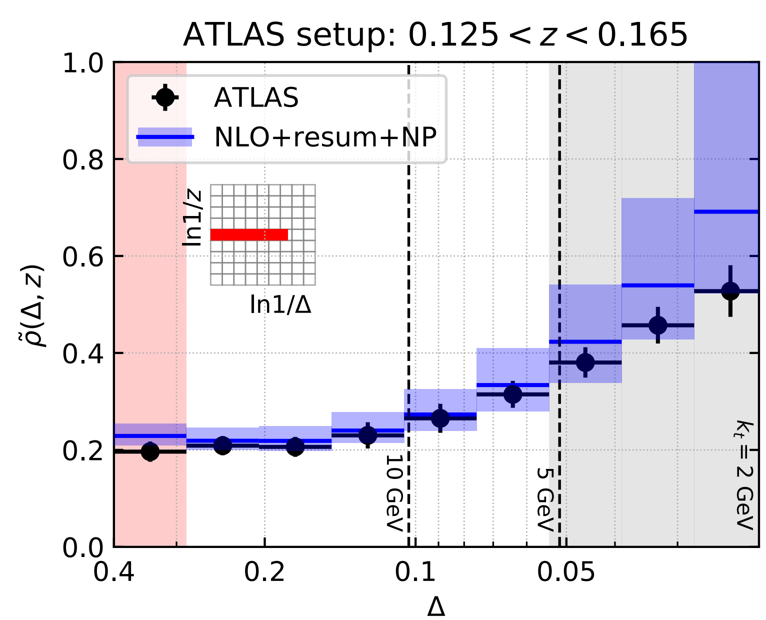
ATLAS (2020)

- First-principle calculation of the Lund plane density



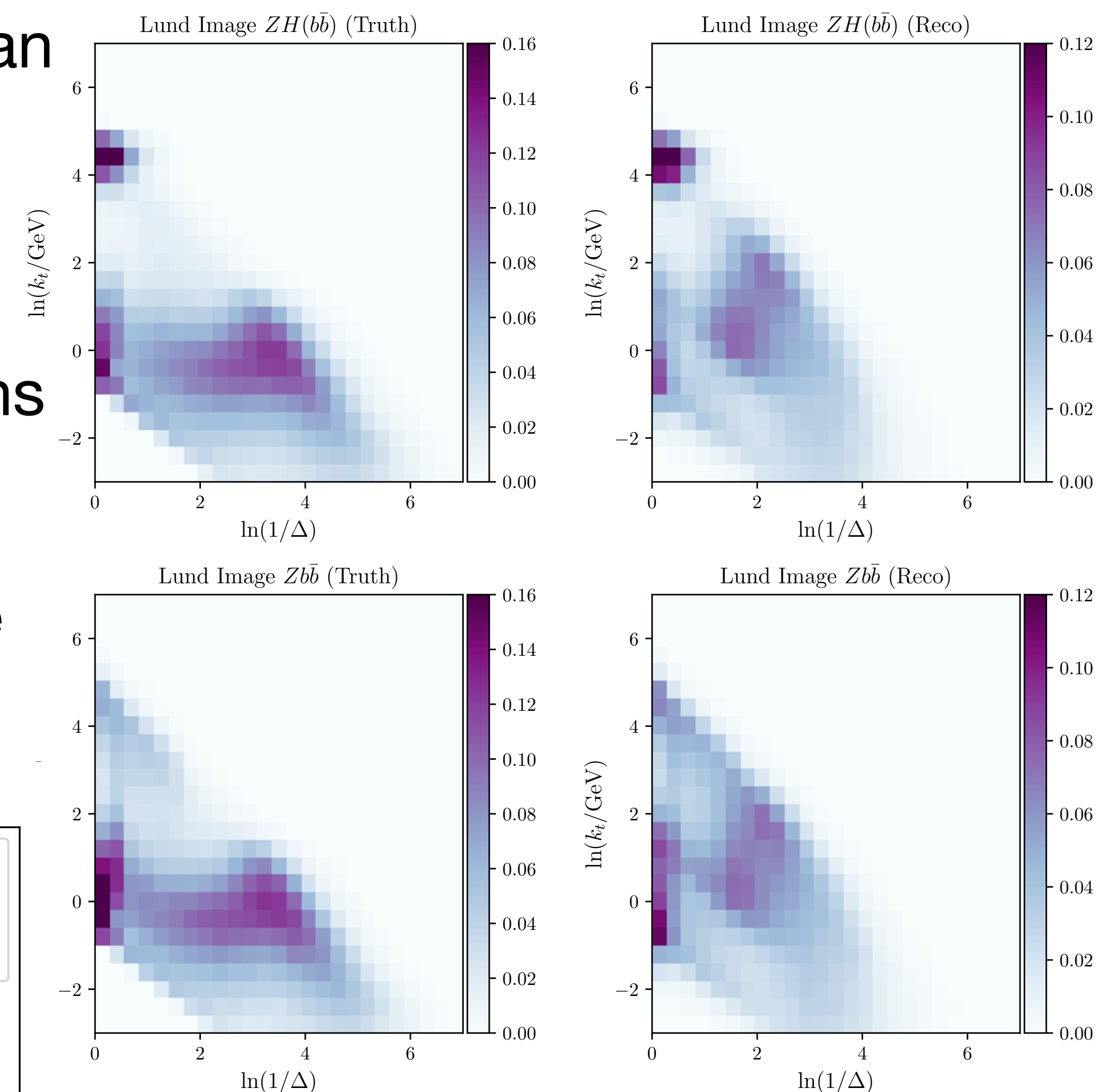
Lifson, Salam, Soyez (2020)

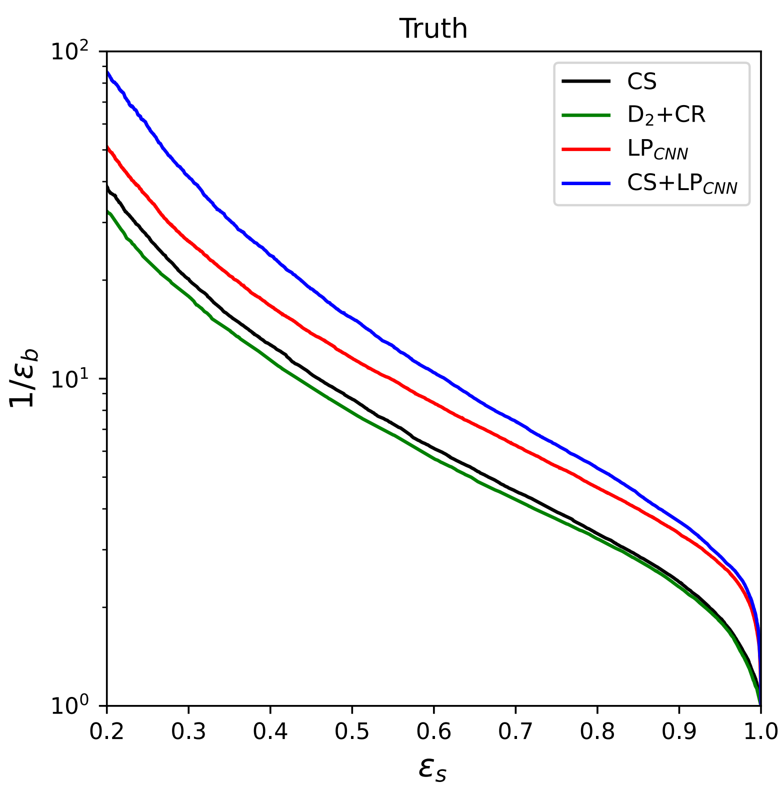


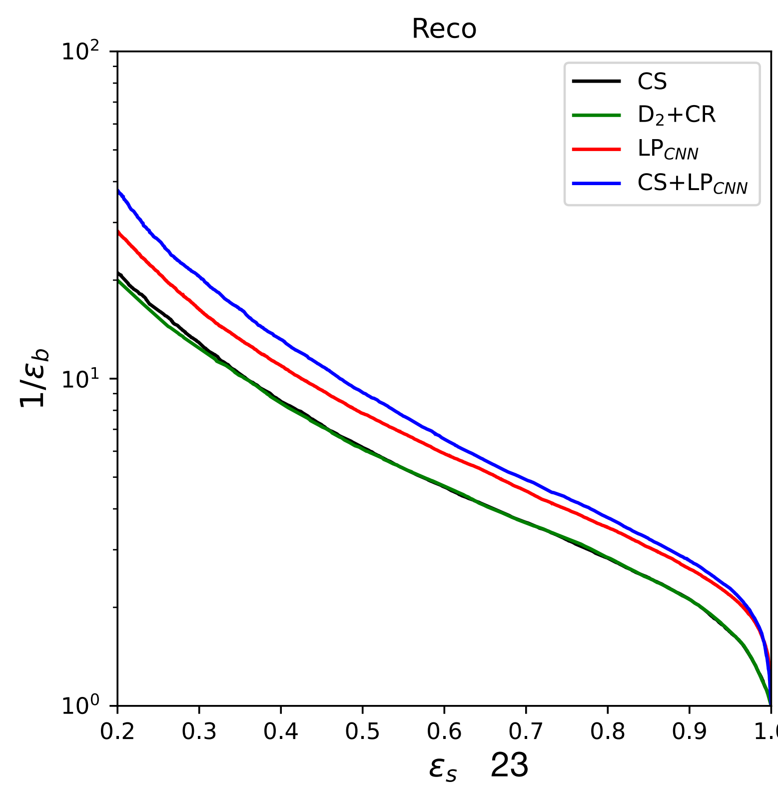


Lund plane images: Higgs

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



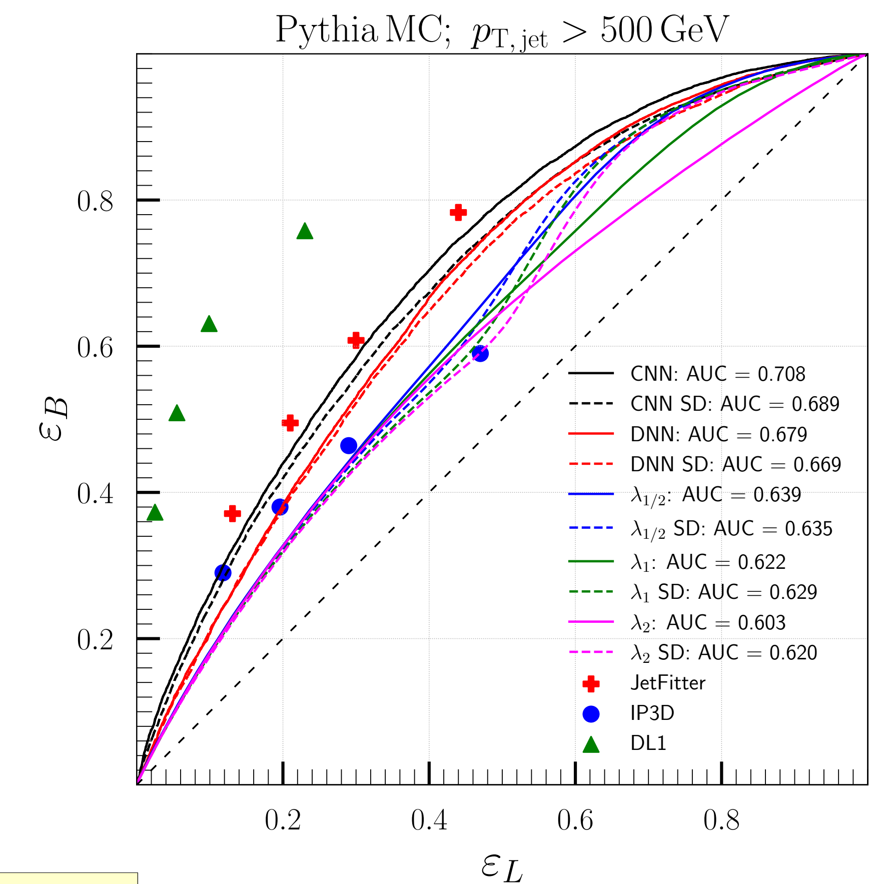


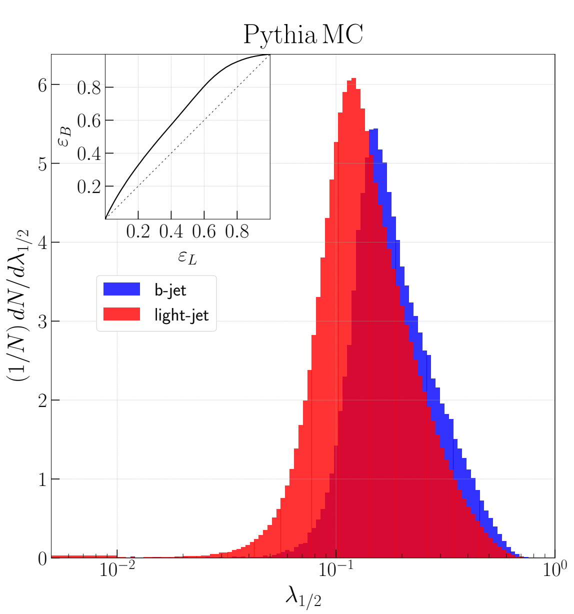


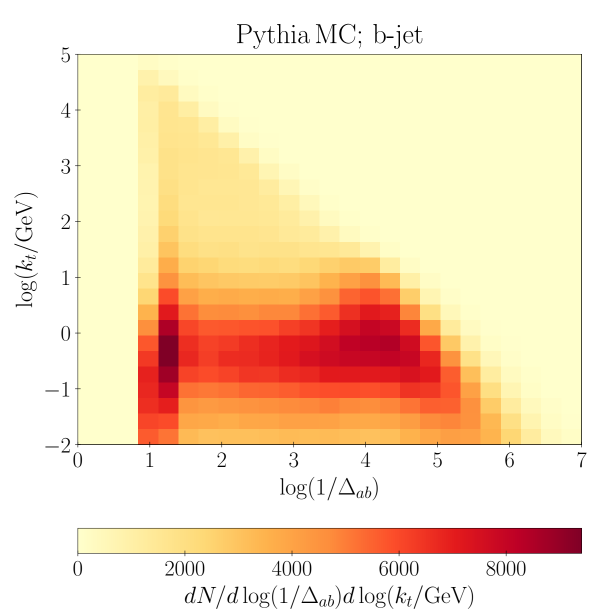
- good performance also for Higgs decay into light jets, where colour ring fails

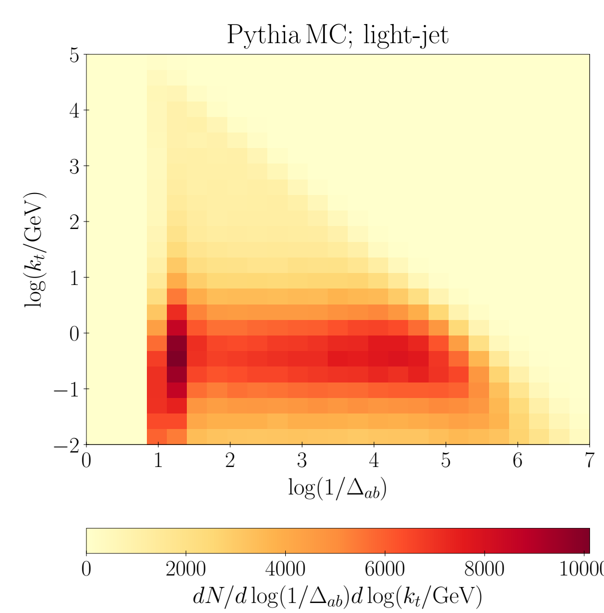
Lund plane images: heavy quarks

- 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)







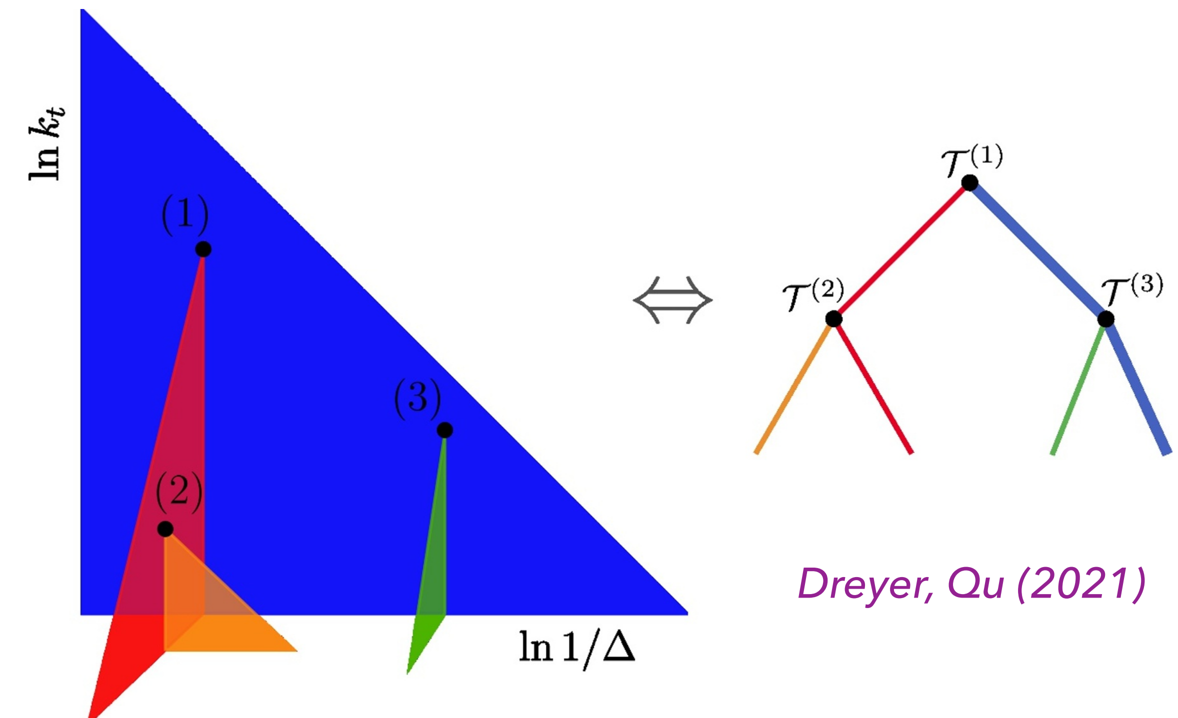


- work in progress to actually compute these distributions from first-principles

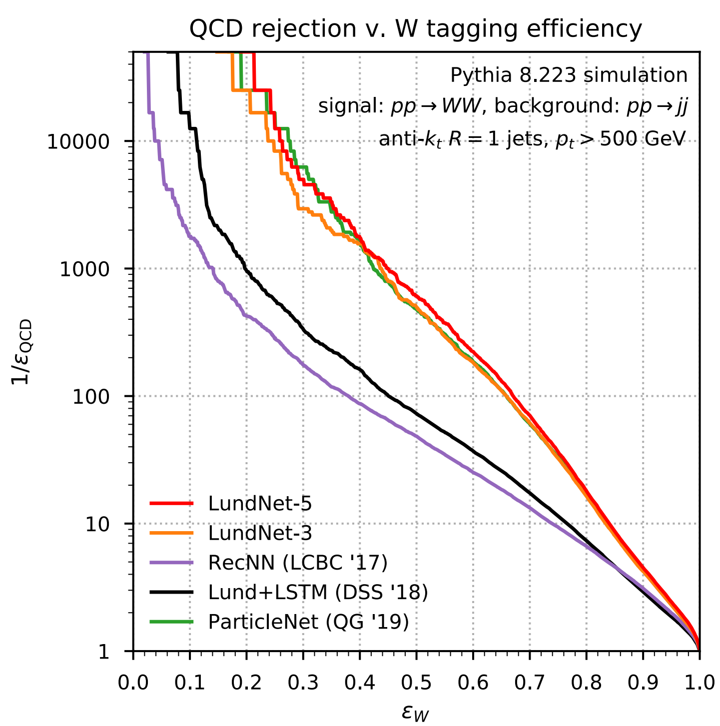
Fedkevych, Kaur, SM, Sforza (2022)

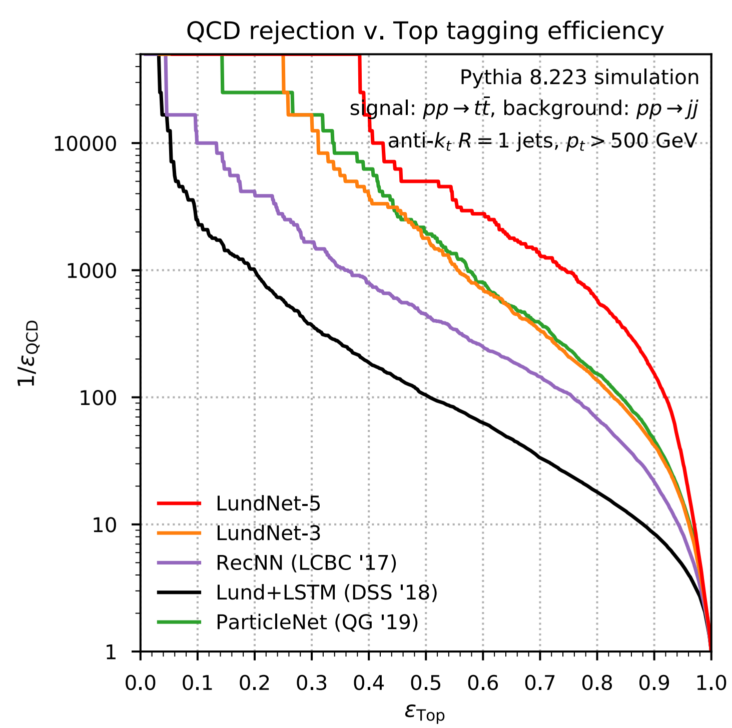
Exploring secondary planes

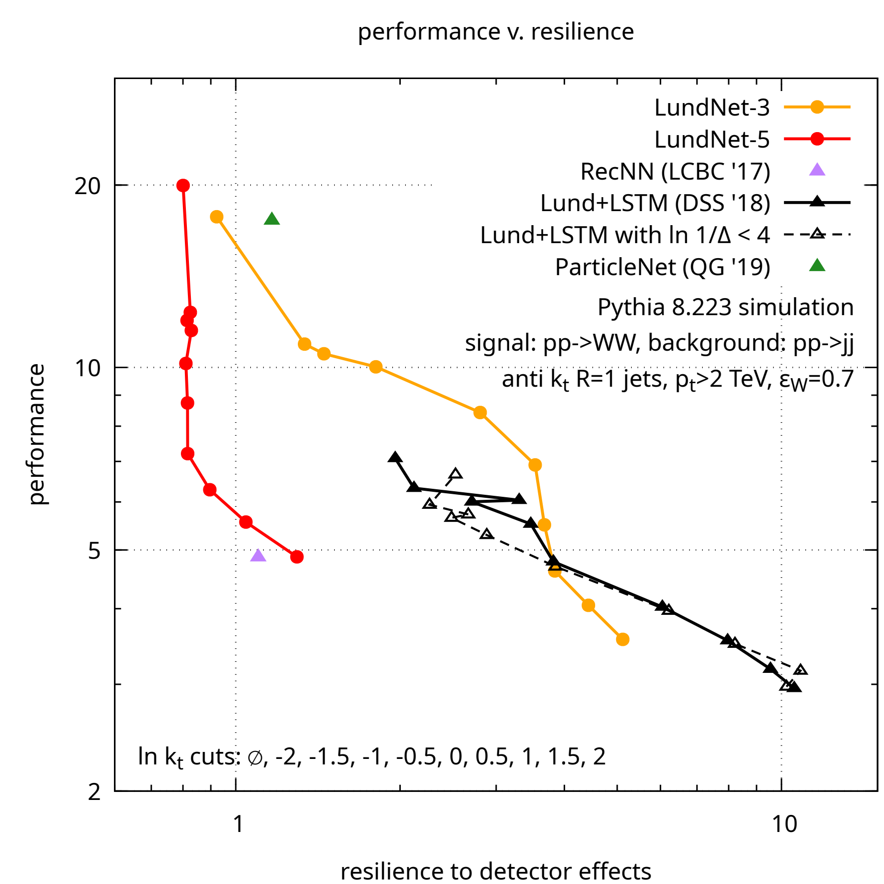
- so far we've discussed the primary Lund plane (always follow the hardest branch)
- it is possible to include information about leaves obtained following the softer ones
- the LundNet taggers make use of graph NN to digest the whole structure



Dreyer, Qu (2021)







Summary

- Collider phenomenology exploits a growing collection of sophisticated tools to understand data of outstanding quality
- Run3 of the LHC is here and we are ready!
- Continuous theoretical progress in many aspects of QCD makes us well-prepared for the challenges ahead
- We should also be creative and find new (robust) ways to interrogate the data and perhaps Nature will be kind enough to allow us to discover something new!

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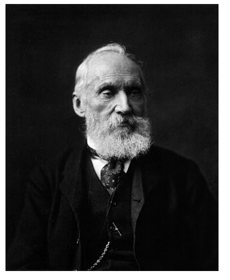
"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

attributed to Lord Kelvin, ca**1900**

hopefully, this will be proven wrong again

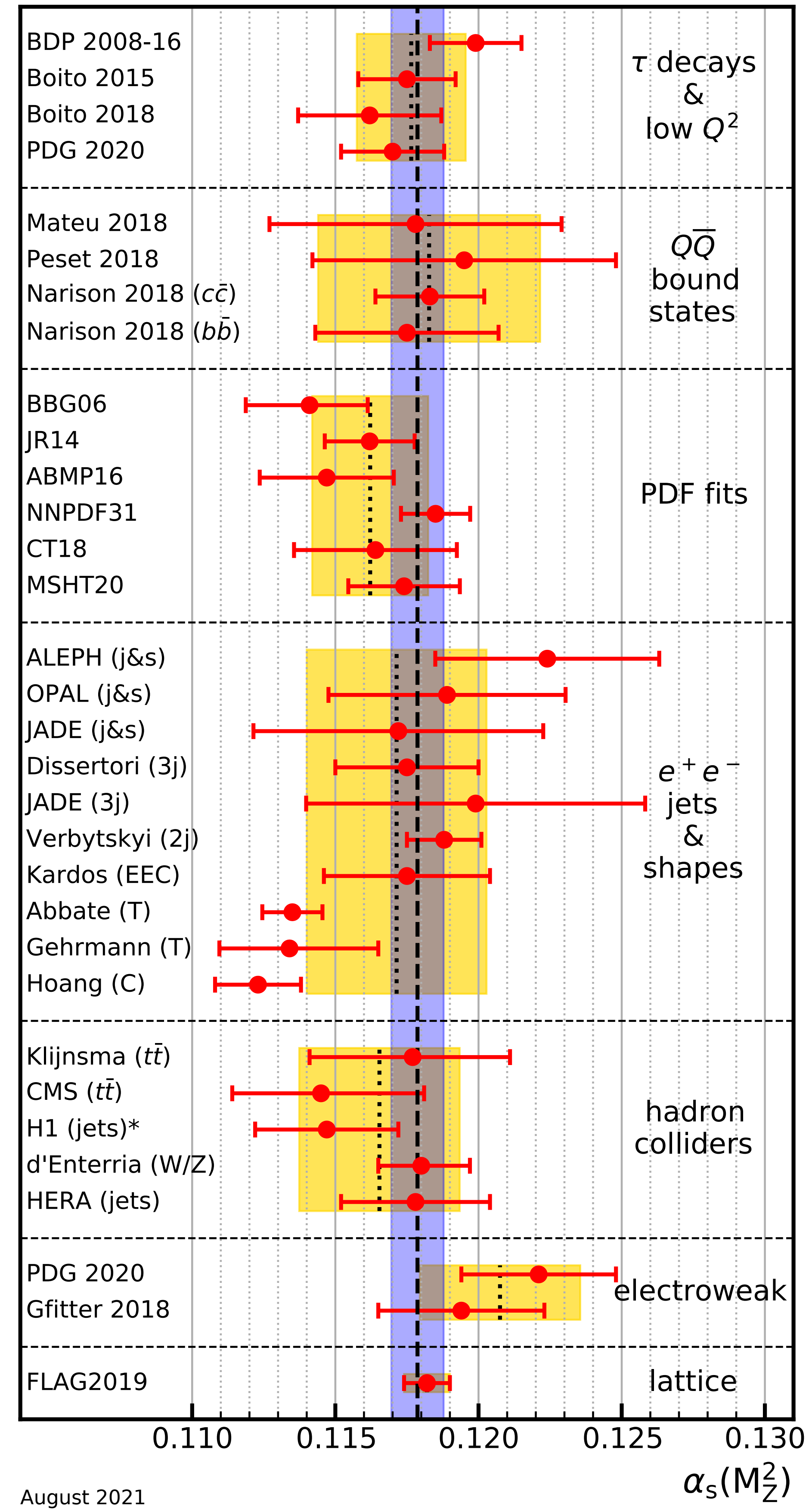


Thank you very much for your attention !

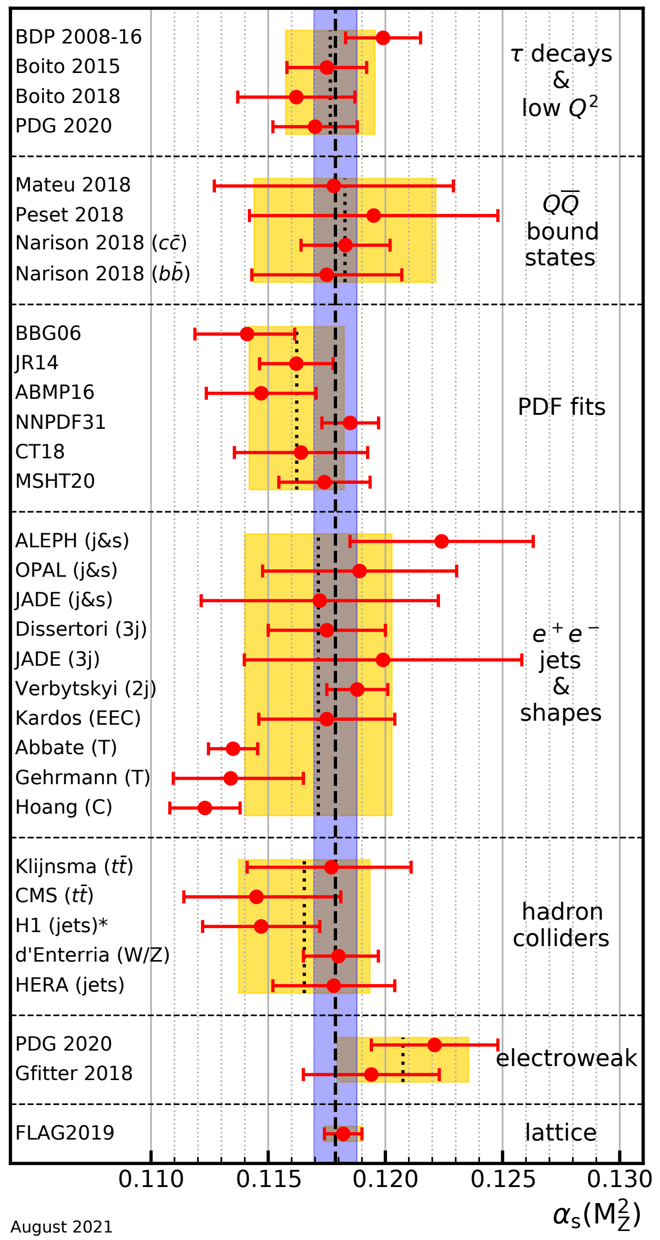
BACKUP

Cross-pollination (II)

the strong coupling



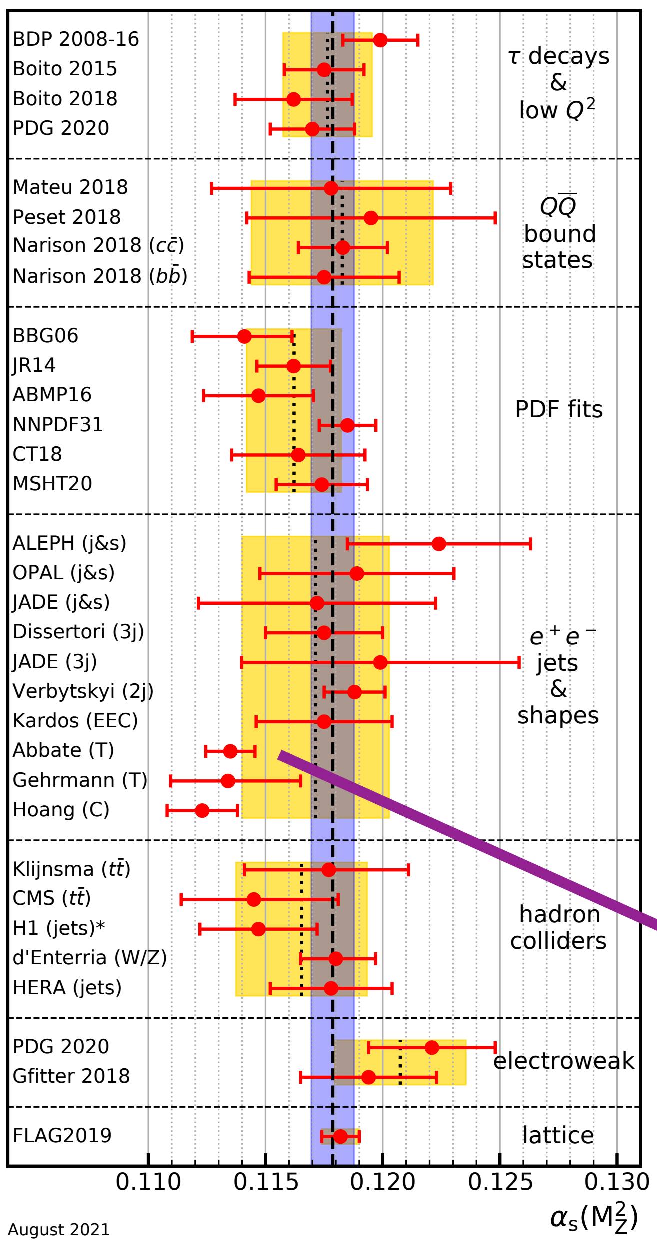
α_s from event shapes



- 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

α_s from event shapes



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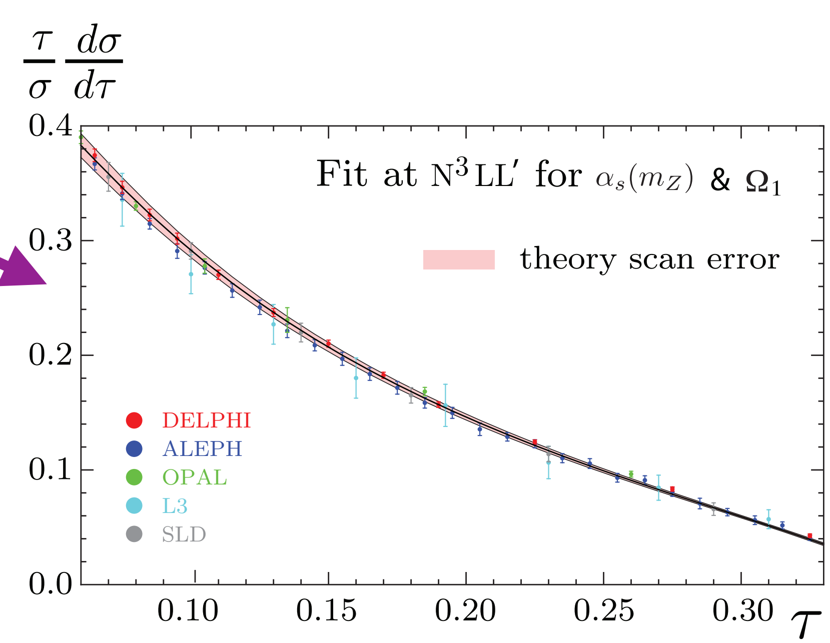

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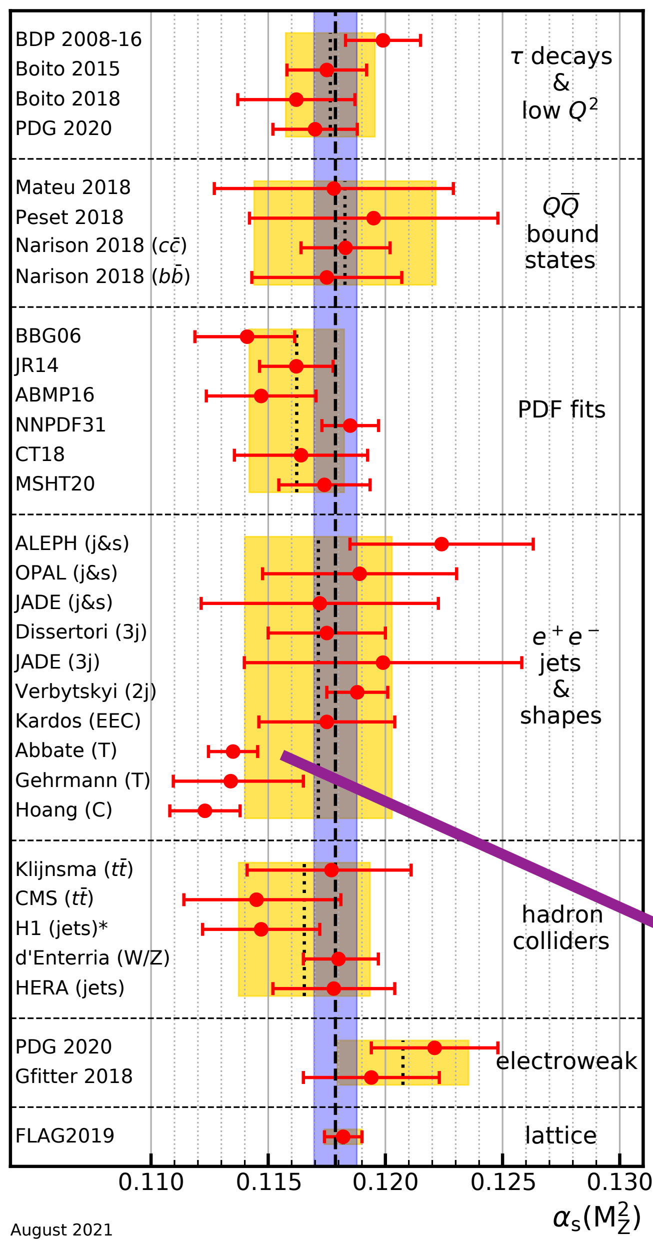

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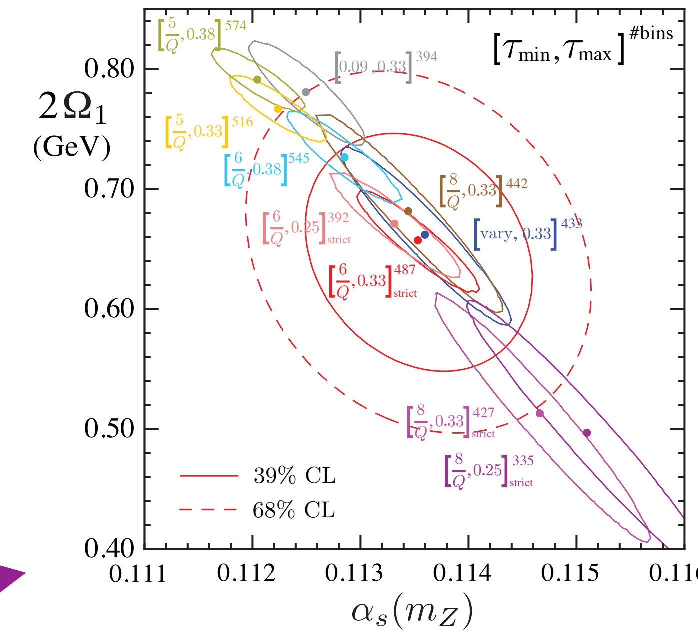

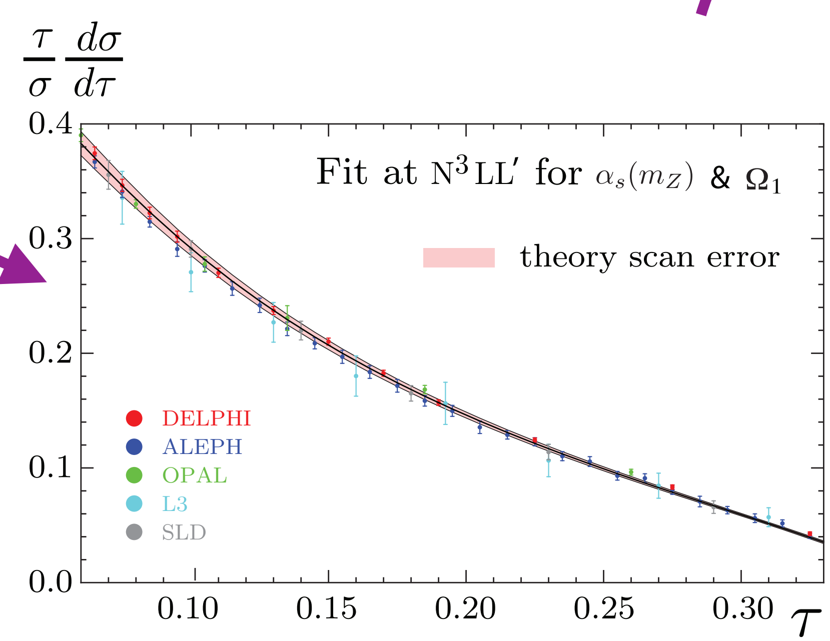

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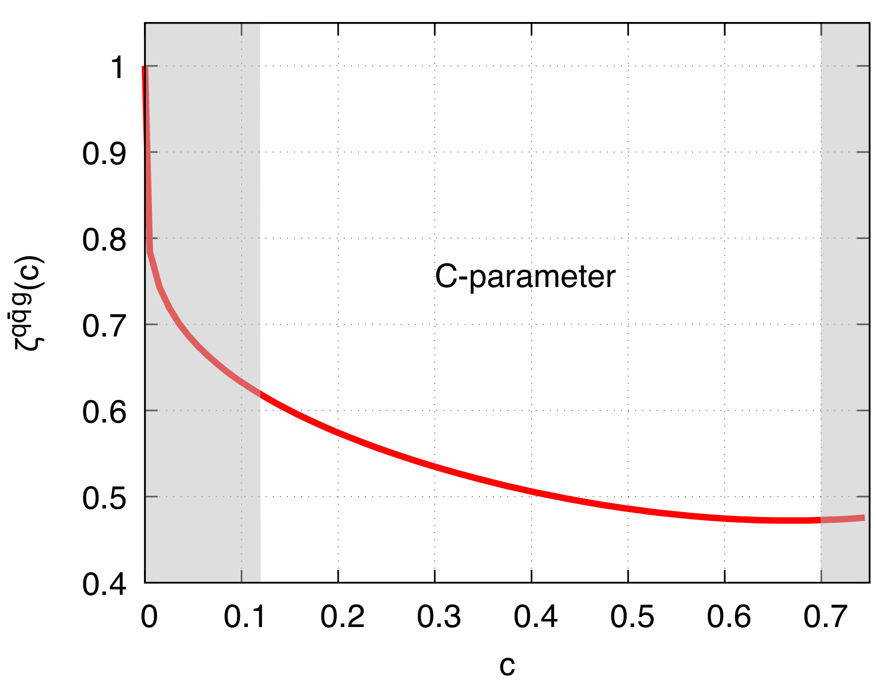
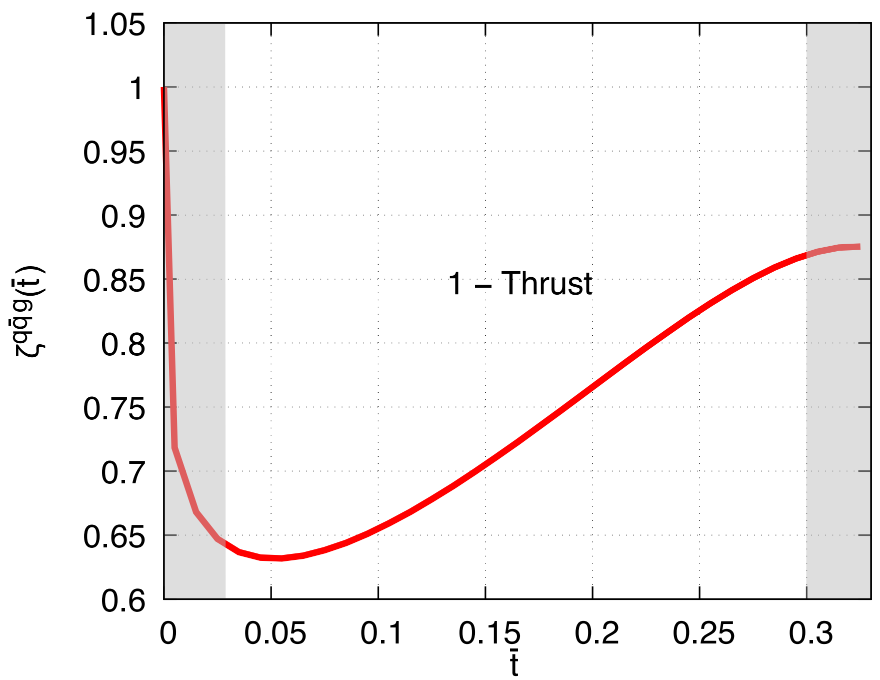
- need better understanding of these effects
- or… we can try and reduce them

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)

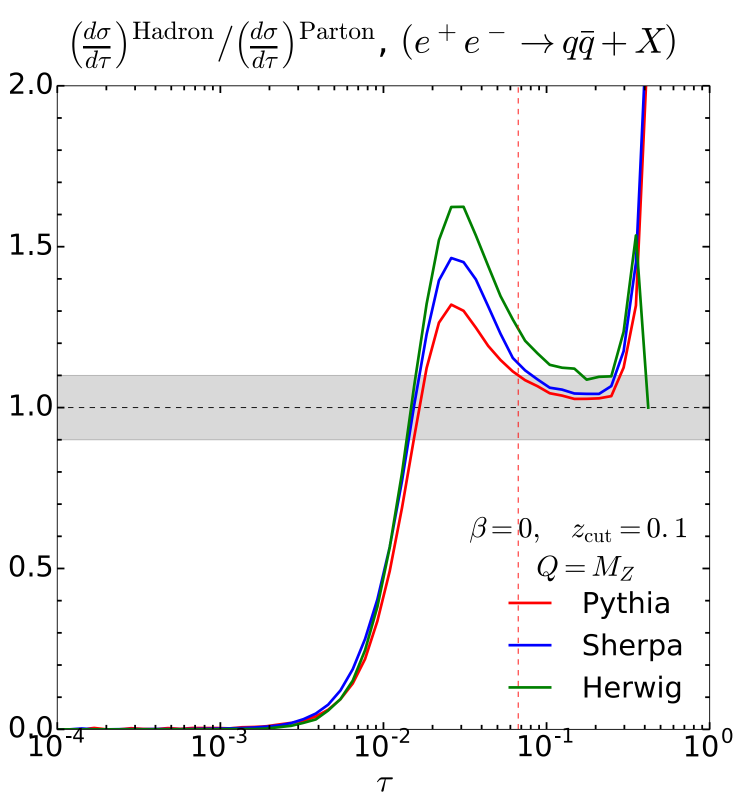
Caola, Ferrario Ravasio, Limatola, Melnikov, Nason (2021)

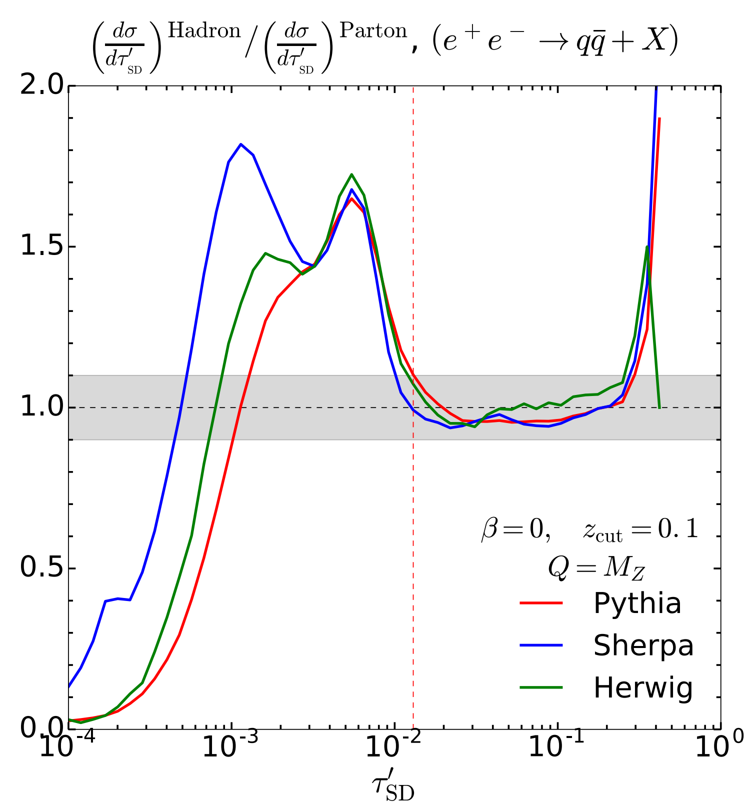
Caola, Ferrario Ravasio, Limatola, Melnikov, Nason (2022)

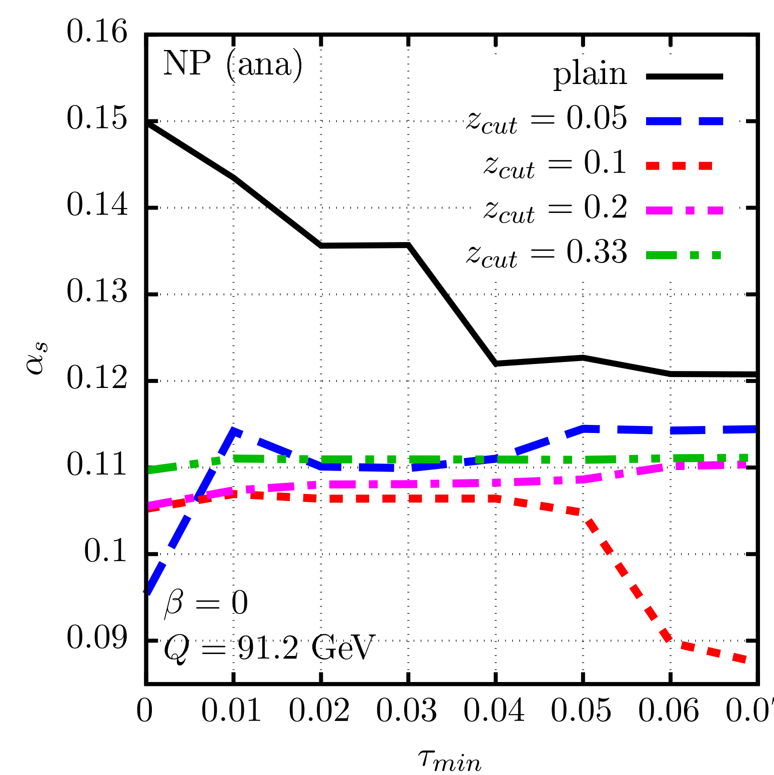
Groomed event shapes

- 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)



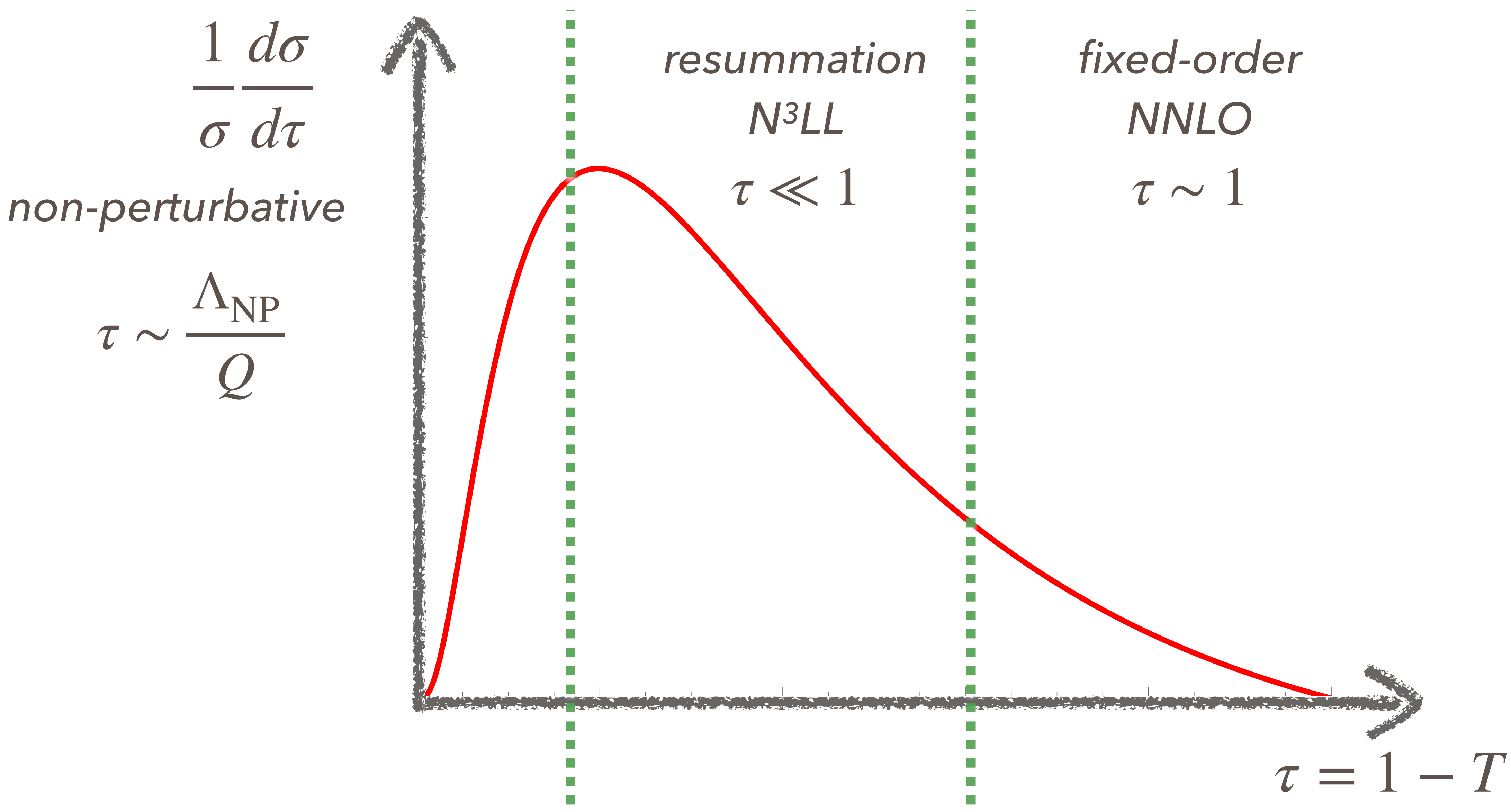




Baron, SM, Theeuwes (2018)

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

Challenges for Soft Drop thrust

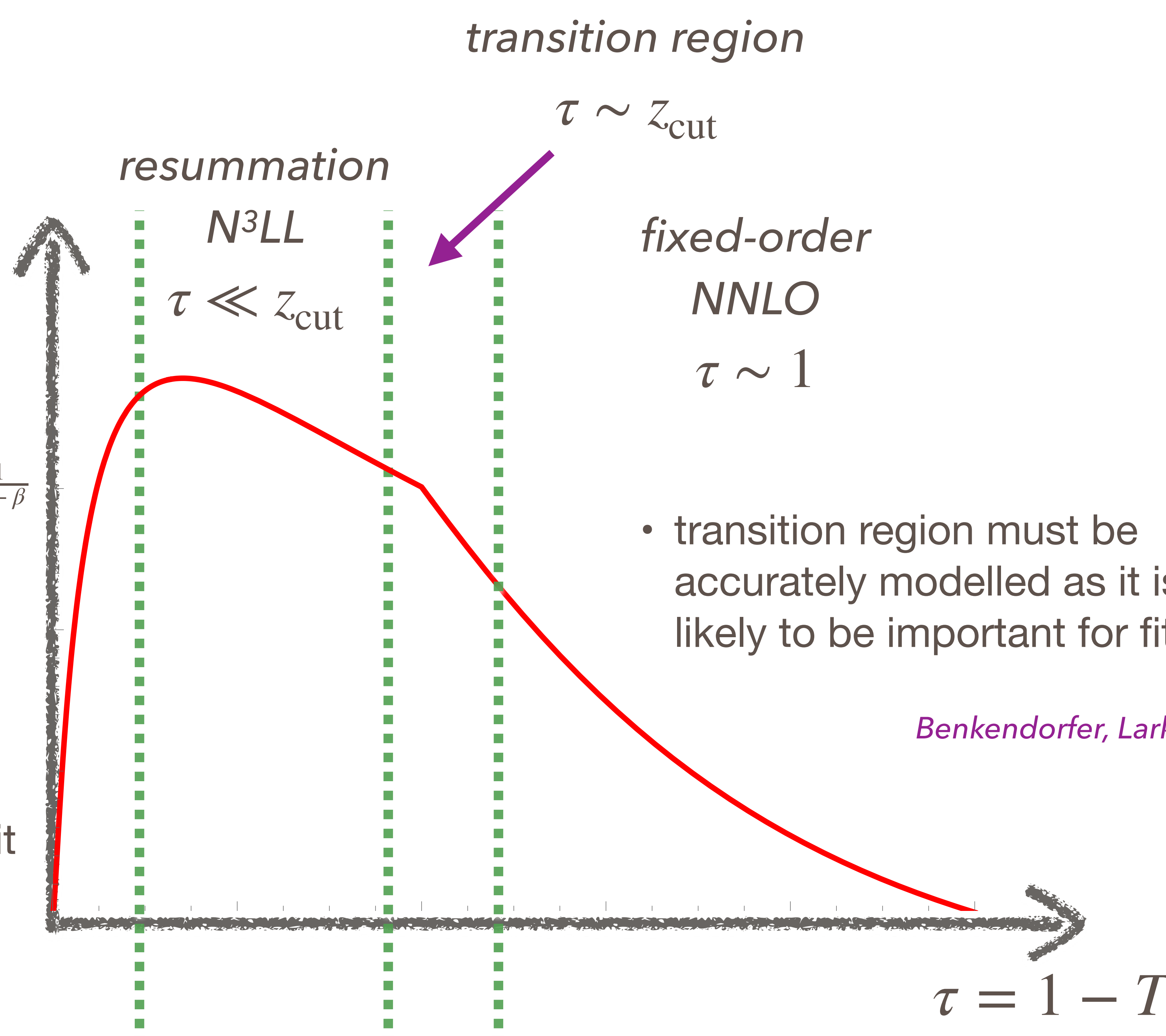


Challenges for Soft Drop thrust

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

non-perturbative

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



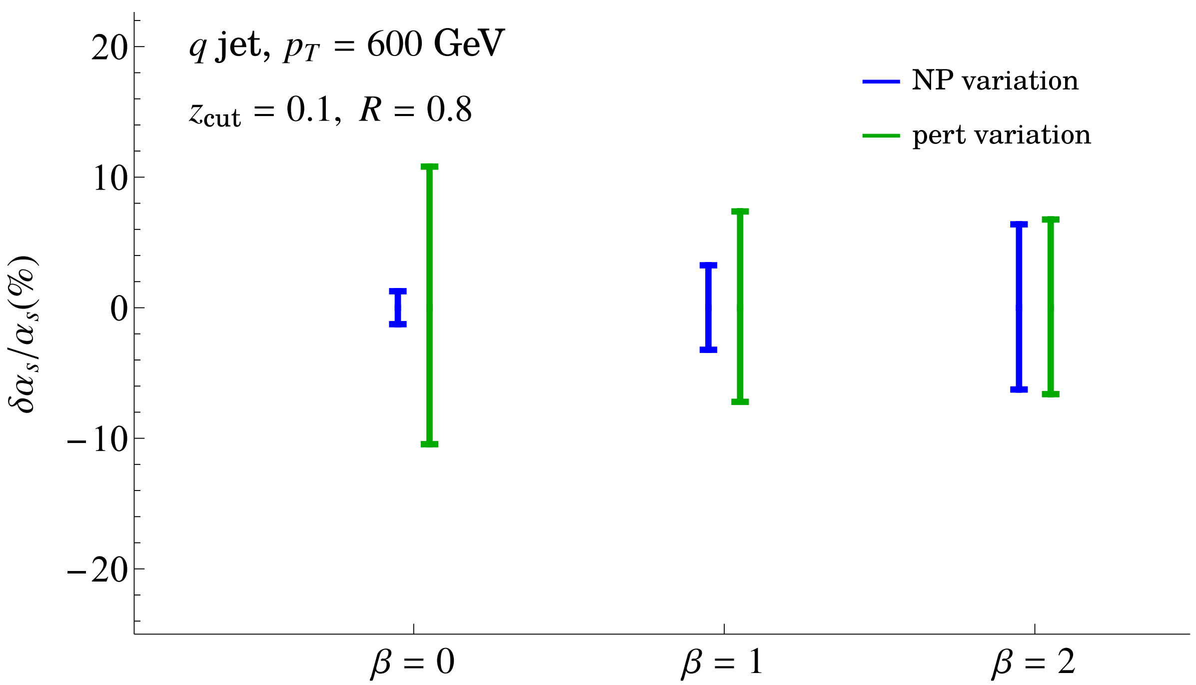
- transition region must be accurately modelled as it is likely to be important for fits

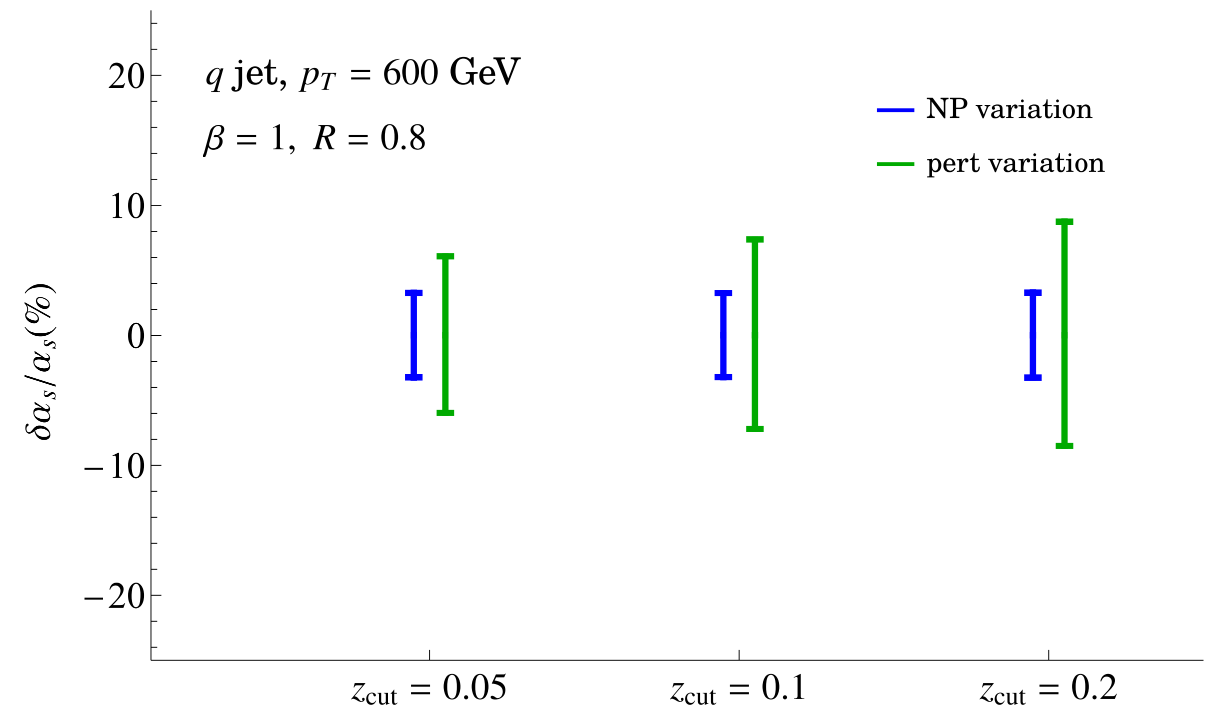
Benkendorfer, Larkoski (2021)

- 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 (to appear)

- 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*
[2]*National Taiwan University, Taipei 10617, Taiwan*
[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]
[1]*MPI für Physik, Föhringer Ring 6, 80805 München, Germany*

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.