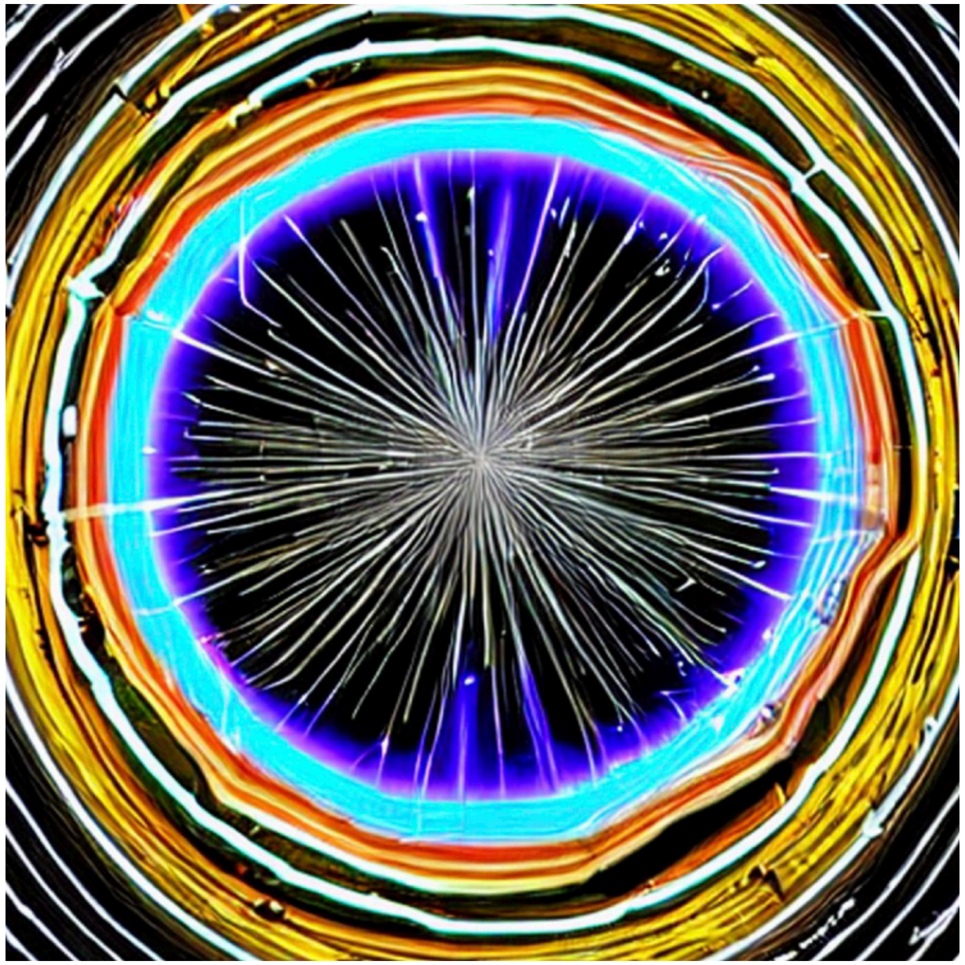
New Ideas in Jet Clustering

Roman Kogler
DESY

JetMET Workshop Brussels
May 16, 2023

Overview

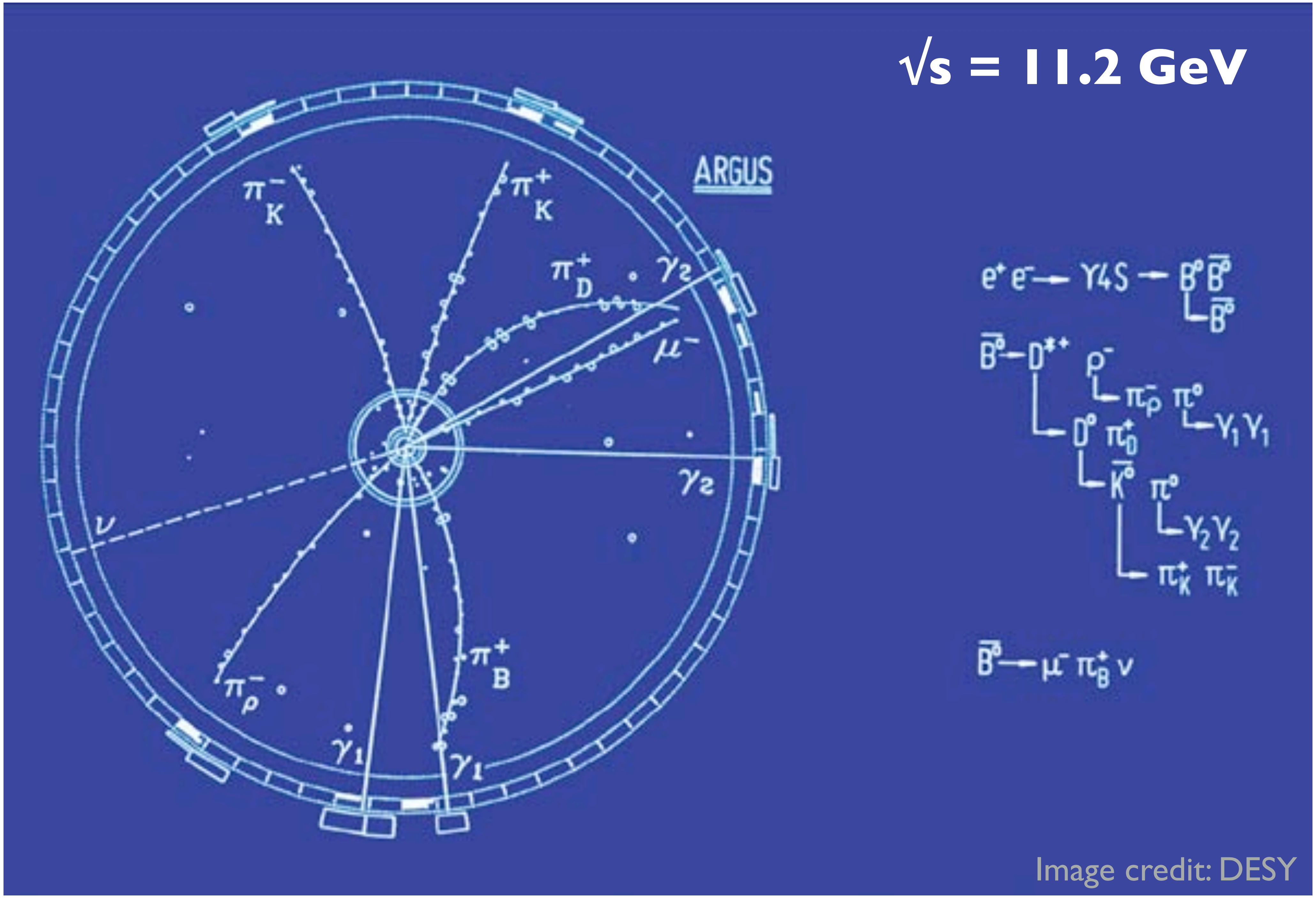
- Introduction
- Quark and Gluon Jets
- Exclusive Clustering
- Variable R Jets
- Scale Invariant Jet Clustering



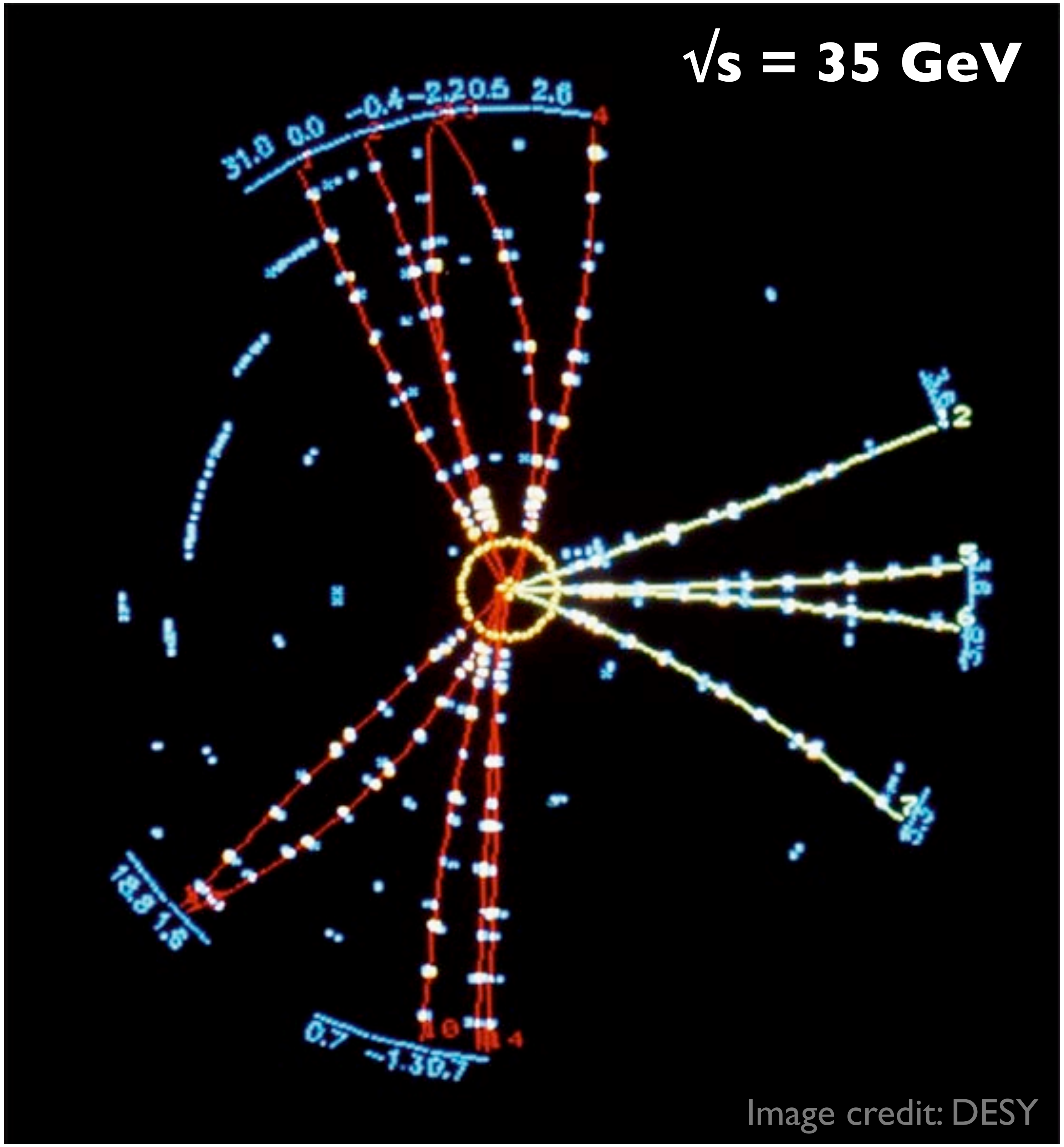
picsart.com

I will not cover machine learning techniques.

ARGUS at DORIS, 1987



TASSO at PETRA, 1979



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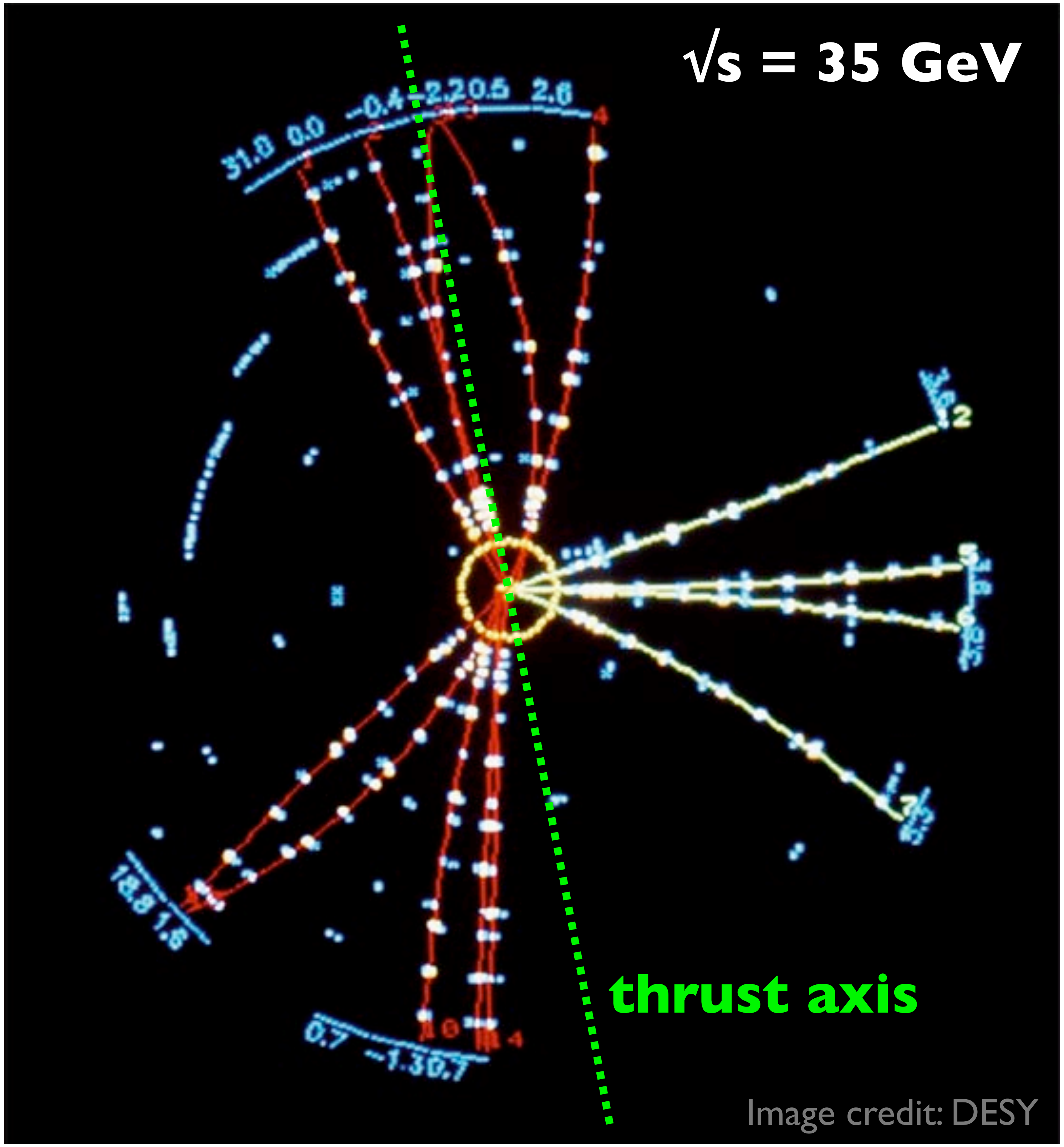
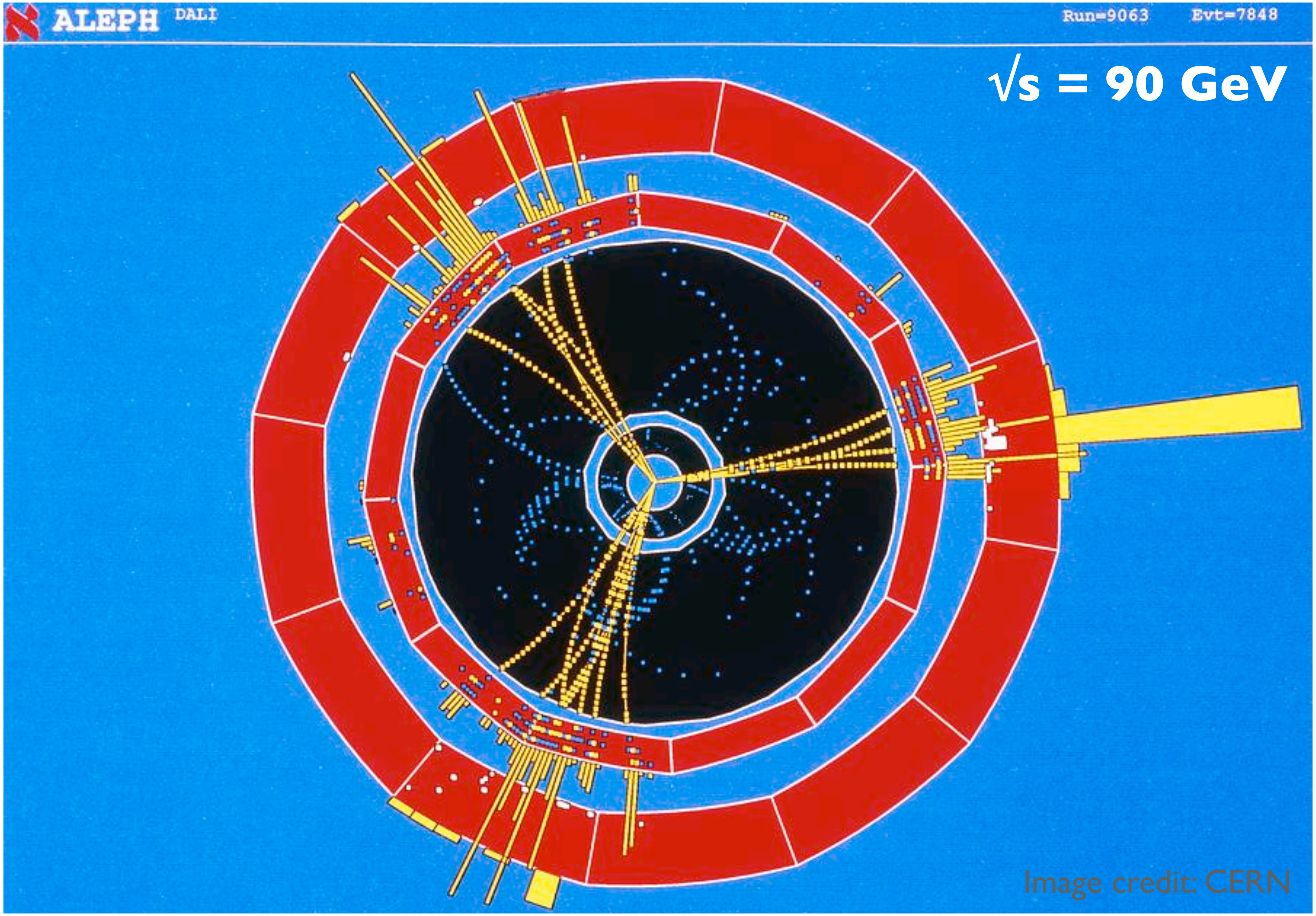
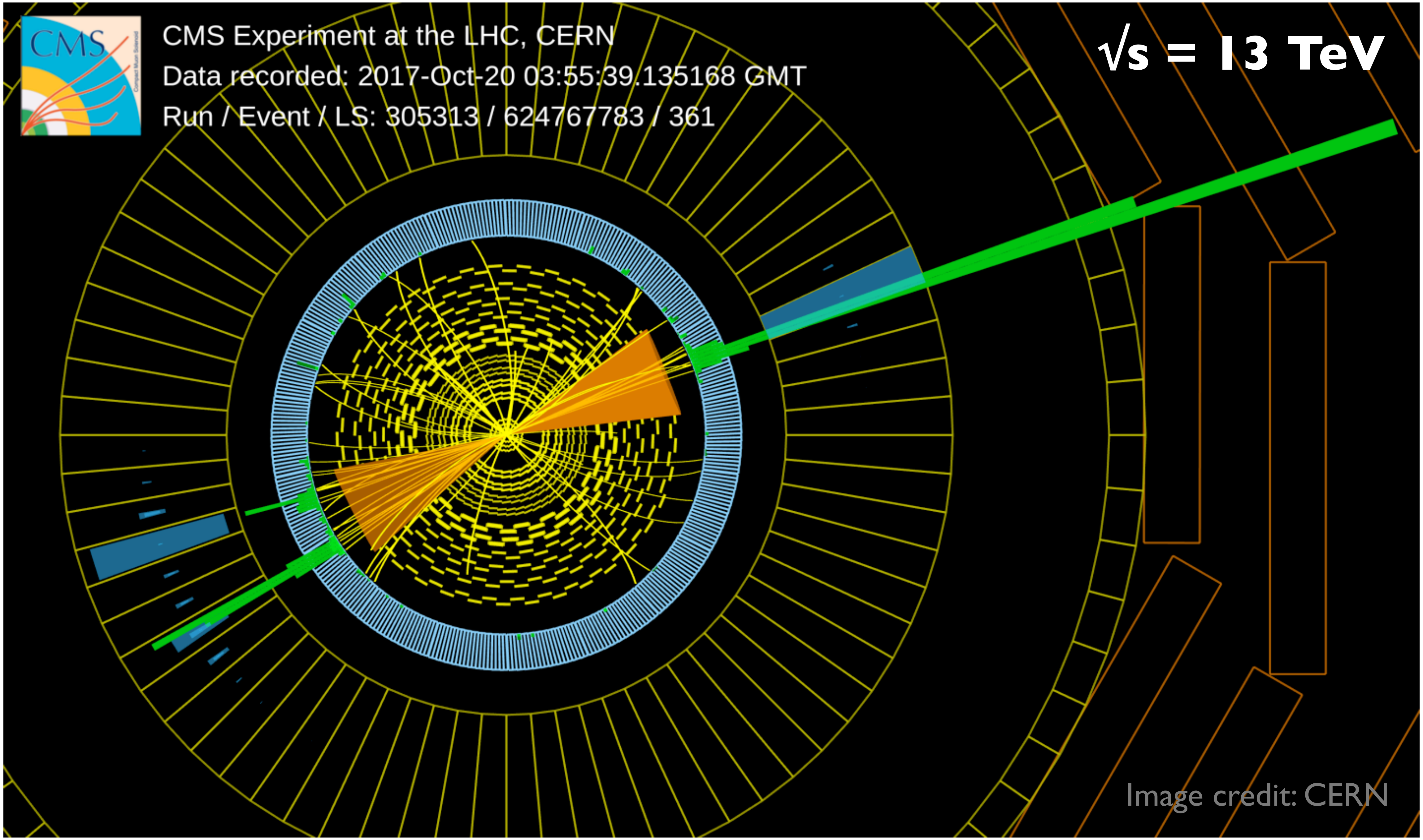


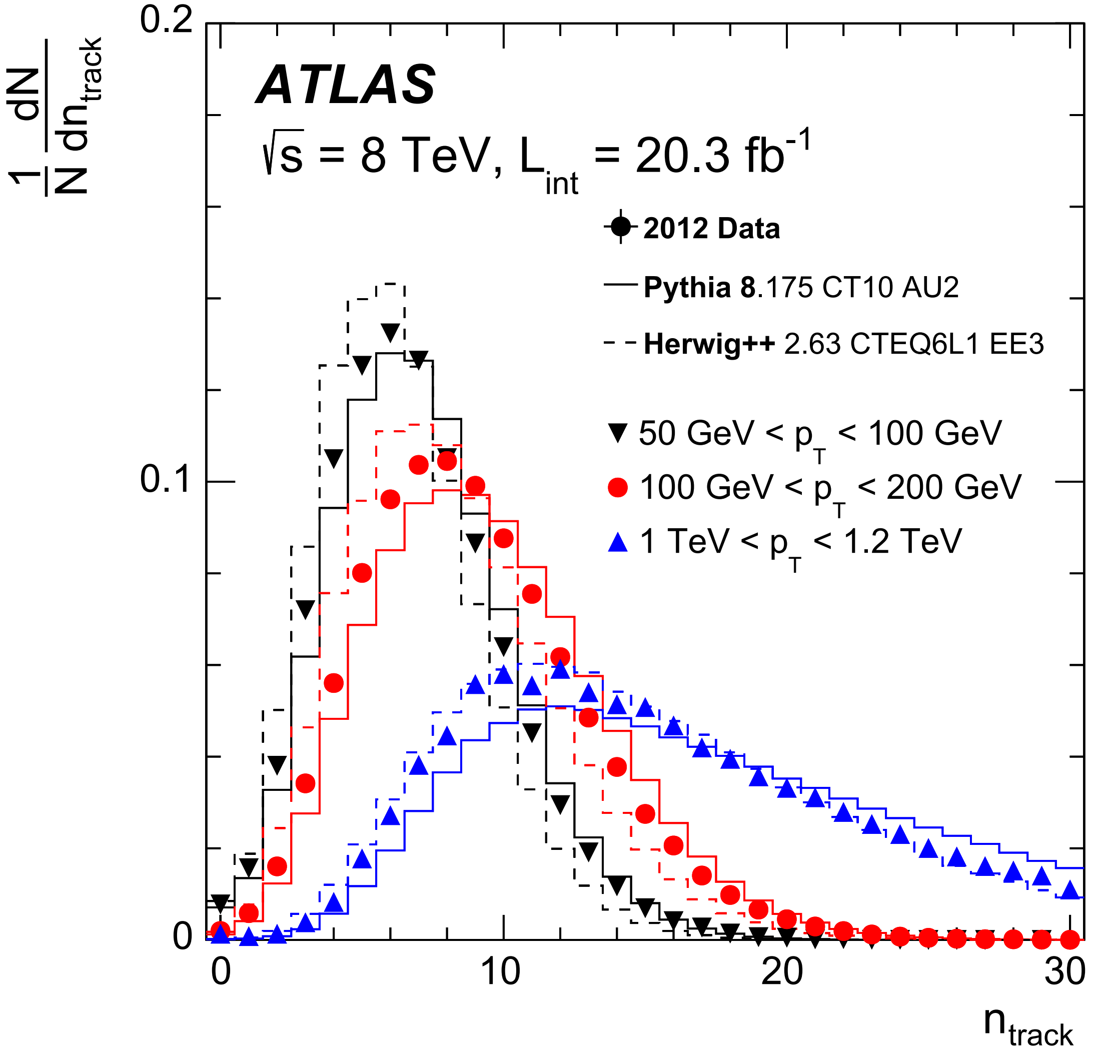
ALEPH at LEP, 1992



CMS at LHC, 2017



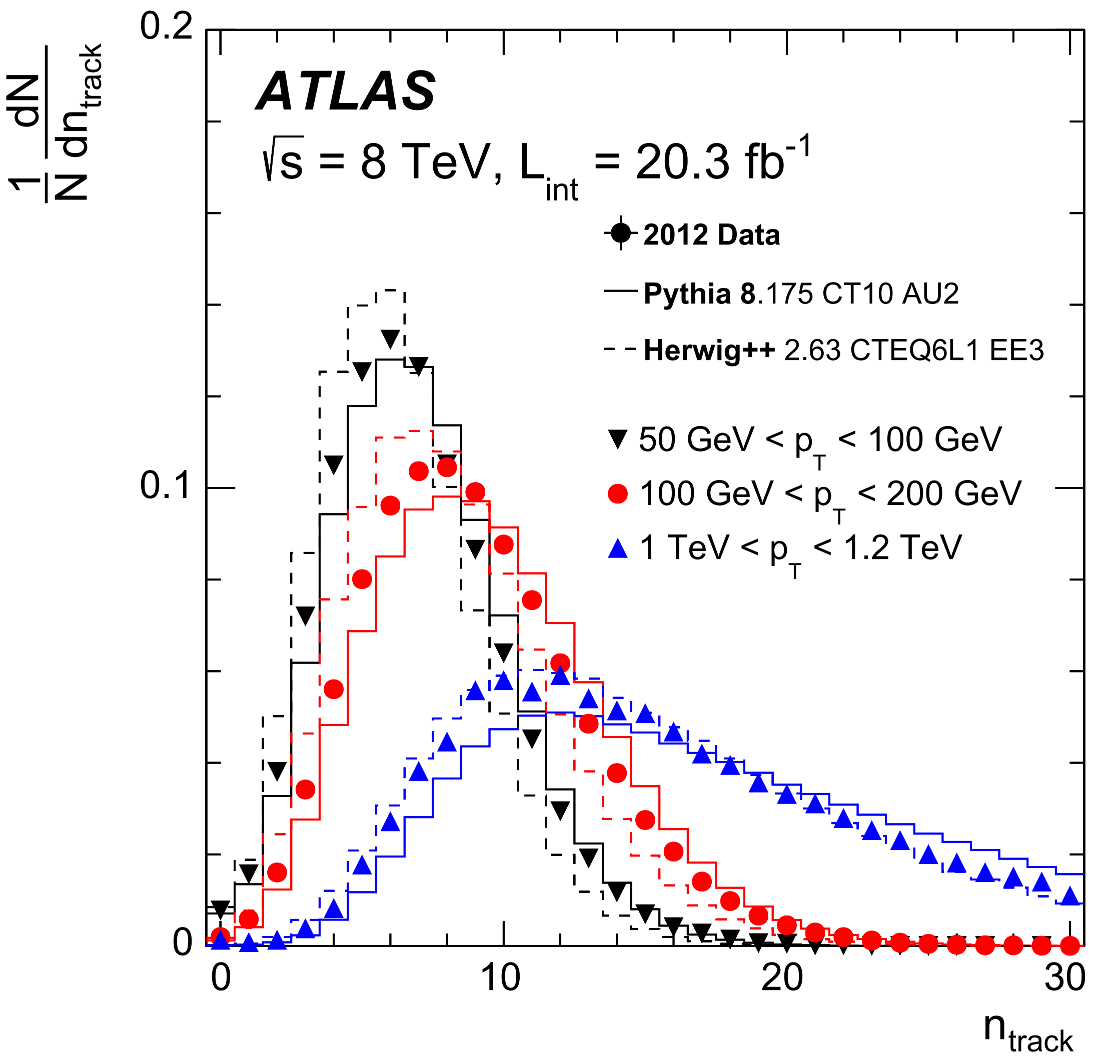
Charged Particles in Jets

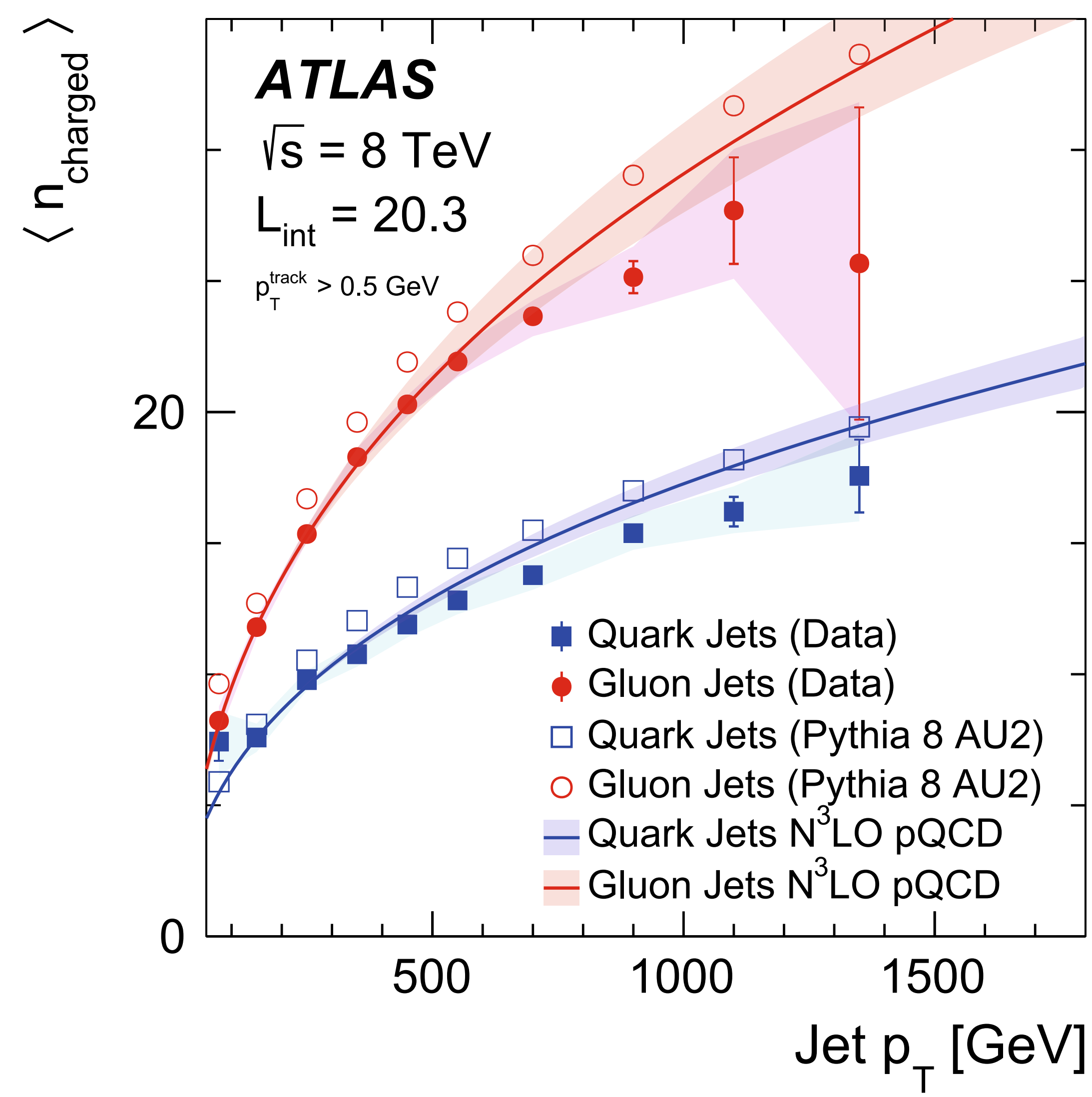


- Approximate particle content in a jet: $\pi^+ : \pi^- : \pi^0 = 1 : 1 : 1$ (+10% Kaons, Protons…)

[ATLAS, EPJC 76, 322 (2016)]

Charged Particles in Jets





- Approximate particle content in a jet: $\pi^+ : \pi^- : \pi^0 = 1 : 1 : 1$ (+10% Kaons, Protons…)
- Gluon jets have higher multiplicity (colour factor C_A compared to C_F)

[ATLAS, EPJC 76, 322 (2016)]

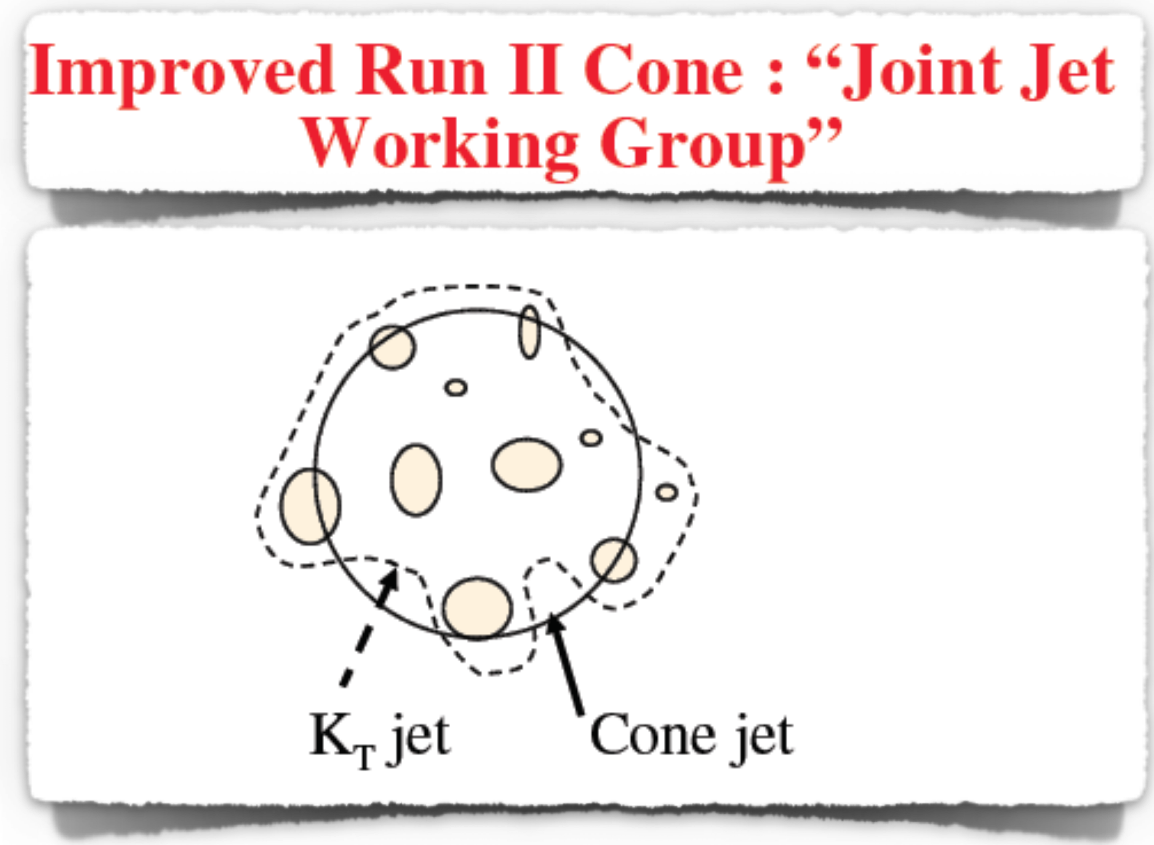
Jet Algorithms

The whole world is using anti-k_T jets, right?

Jet Algorithms

The whole world is using anti-k_T jets, right?

- Before 2007
  - Durham/Jade (LEP)
  - Cambridge/Aachen (LEP)
  - k_T (HERA)
  - midpoint-cone (Tevatron)
- In 2008, the LHC was ready to ramp up to 14 TeV
  - ATLAS and CMS were eager to start with data taking using cone-type jet algorithms



[Mikołaj Ćwiok, Moriond QCD, 2007]

Jet Algorithms

- Catastrophic incident in Sep 2008
  - Magnet quench resulted in explosive Helium release
  - Repairs delayed the start by 14 months

[CDS, CERN 2008, 1185822]

Jet Algorithms

- Catastrophic incident in Sep 2008
  - Magnet quench resulted in explosive Helium release
  - Repairs delayed the start by 14 months
- At the same time, important ideas / breakthroughs

[CDS, CERN 2008, 1185822]

Dispelling the N^3 myth for the k_t jet-finder

Matteo Cacciari, Gavin P. Salam *

LPTHE, Universities of Paris VI and VII and CNRS, Paris, France

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The anti-k_t jet clustering algorithm

Matteo Cacciari and Gavin P. Salam

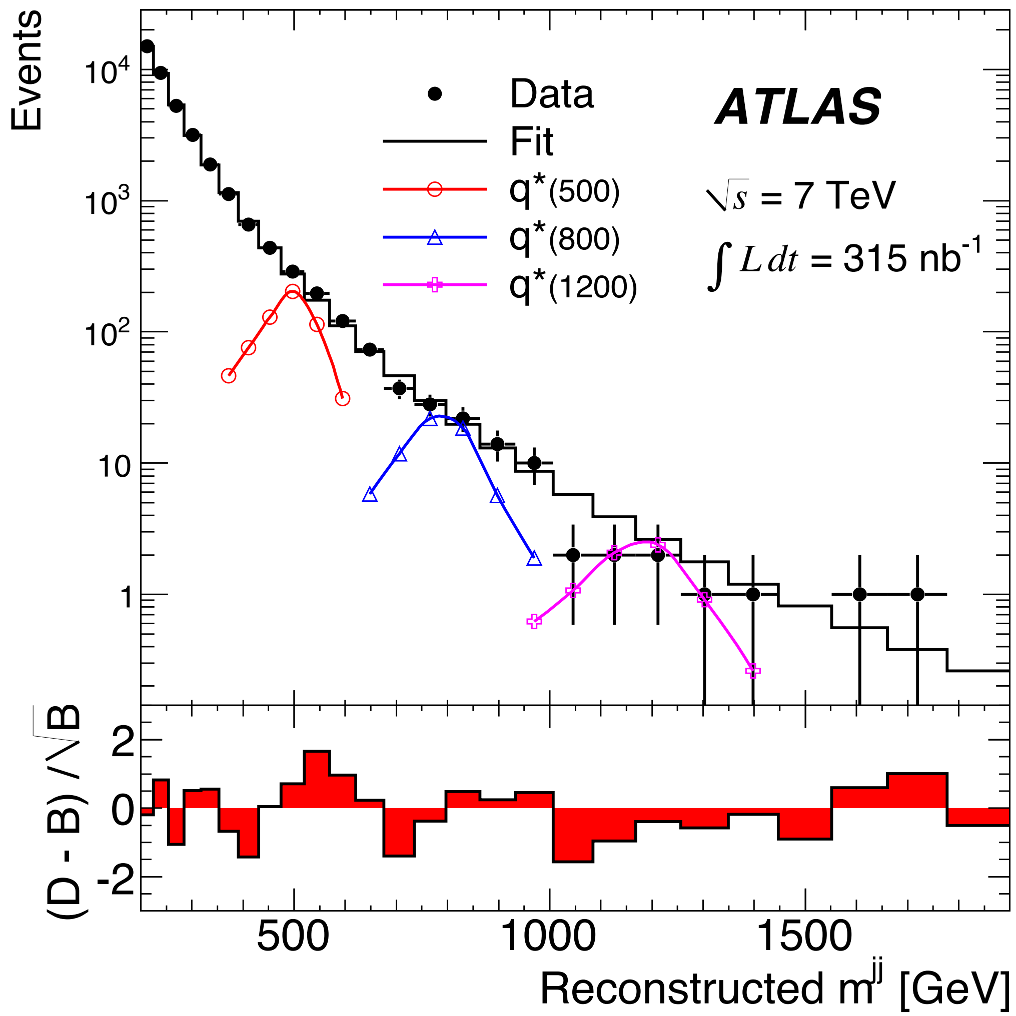
LPTHE, UPMC Université Paris 6,
Université Paris Diderot — Paris 7,
CNRS UMR 7589, Paris, France
E-mail: cacciari@lpthe.jussieu.fr, salam@lpthe.jussieu.fr

Gregory Soyez

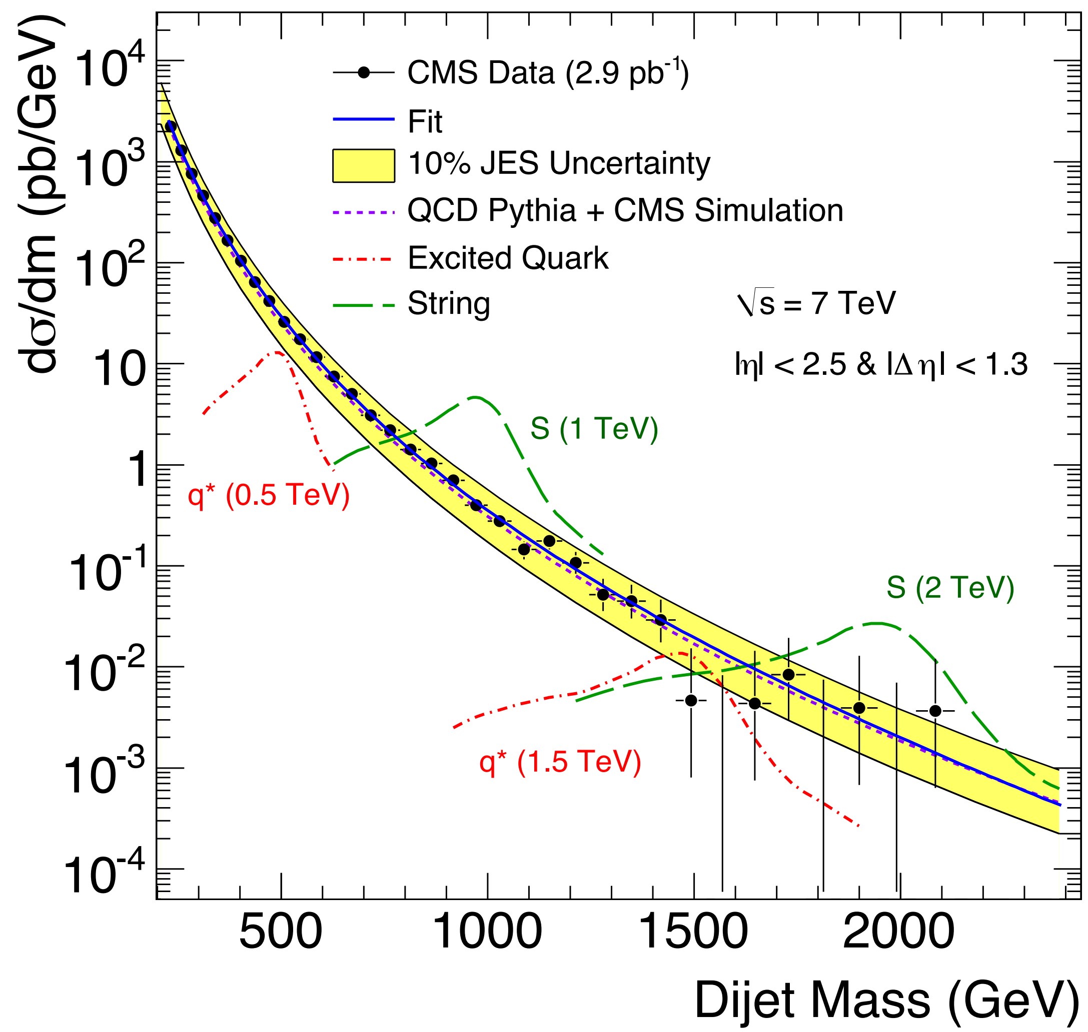
Brookhaven National Laboratory,
Upton, NY, U.S.A.
E-mail: gsoyez@quark.phy.bnl.gov

The Rest is History…

[ATLAS PRL 105, 161801]



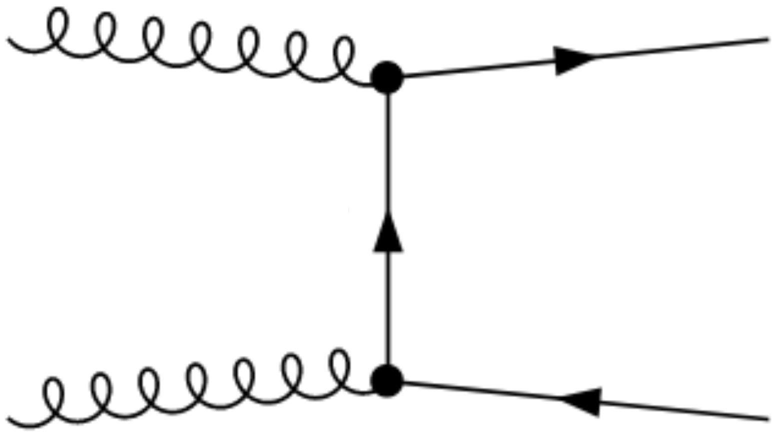
[CMS PRL 105, 211801]

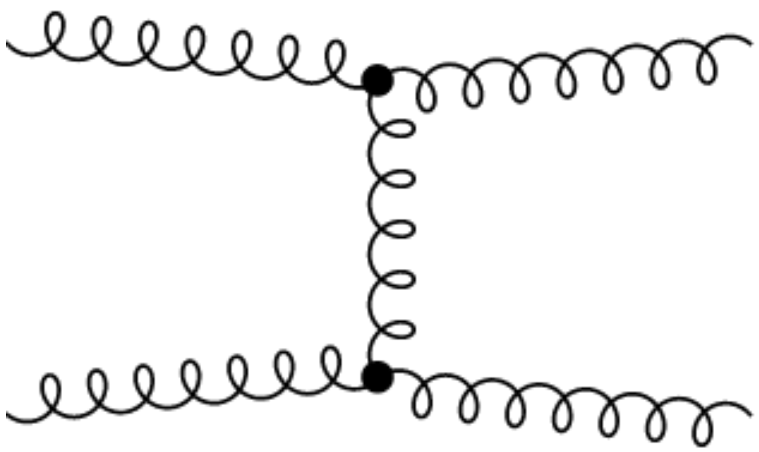


ATLAS dijet search using AK6 jets Sep. 2010

CMS dijet search using AK7 jets Oct. 2010

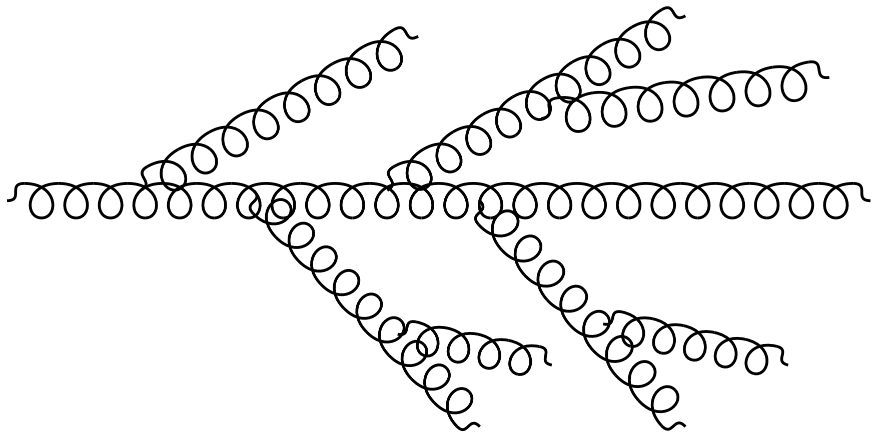
Quark and Gluon Jets





Corrections to Jet Observables

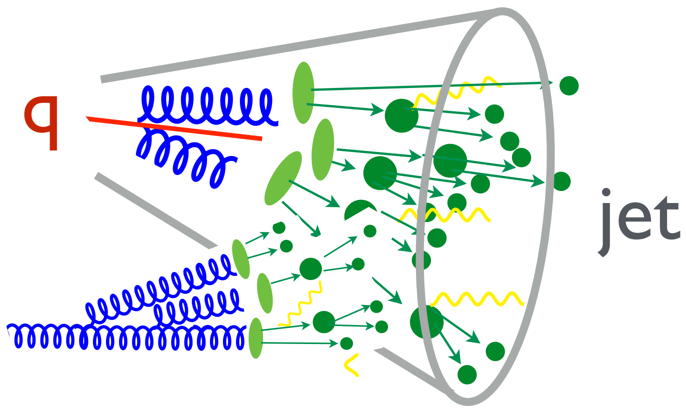
Perturbative effects



Lose E and p because of splittings

$$\frac{\langle \delta p_t \rangle_{\text{pert}}}{p_t} = \frac{\alpha_s}{\pi} L_i \ln R + \mathcal{O}(\alpha_s)$$

Non-perturbative effects

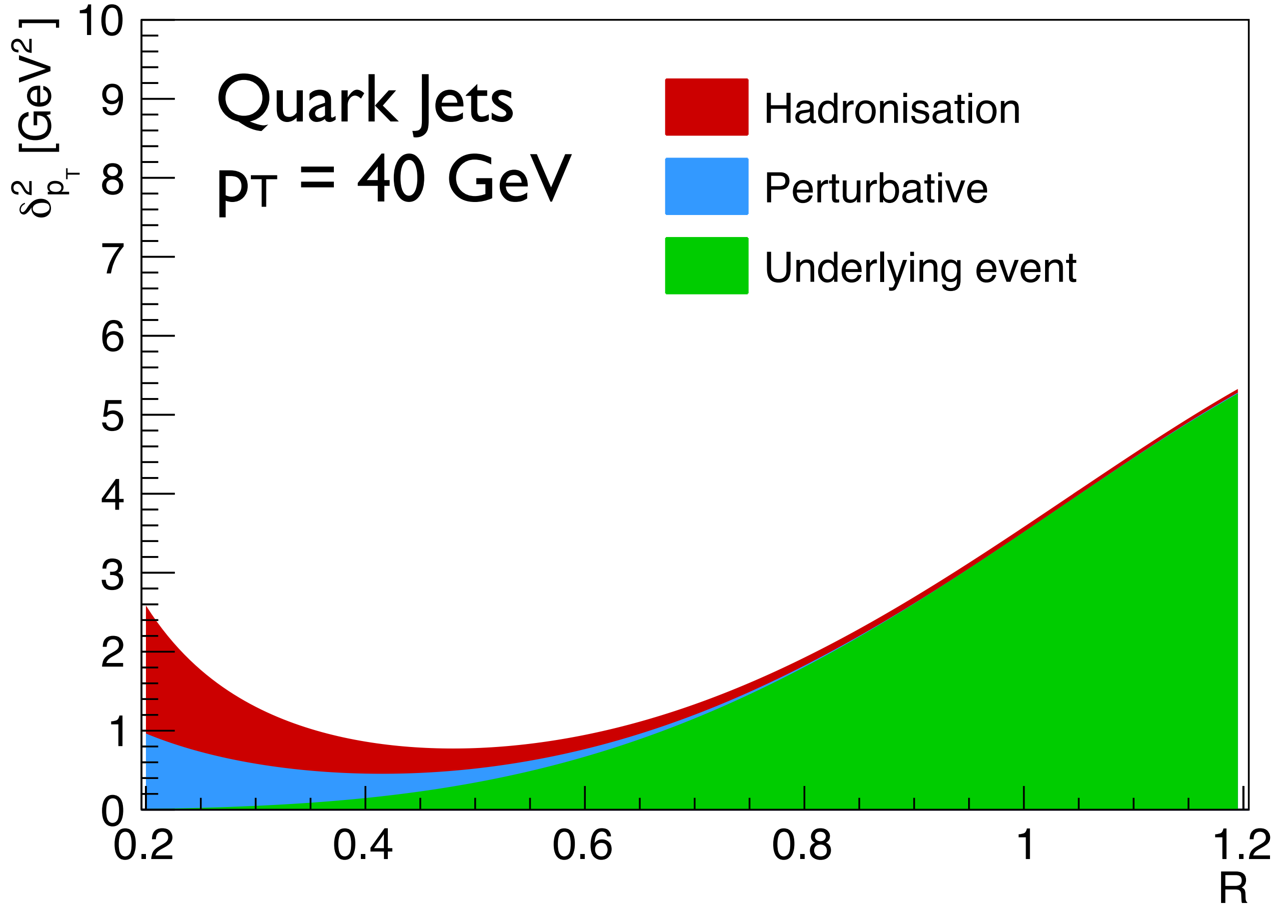


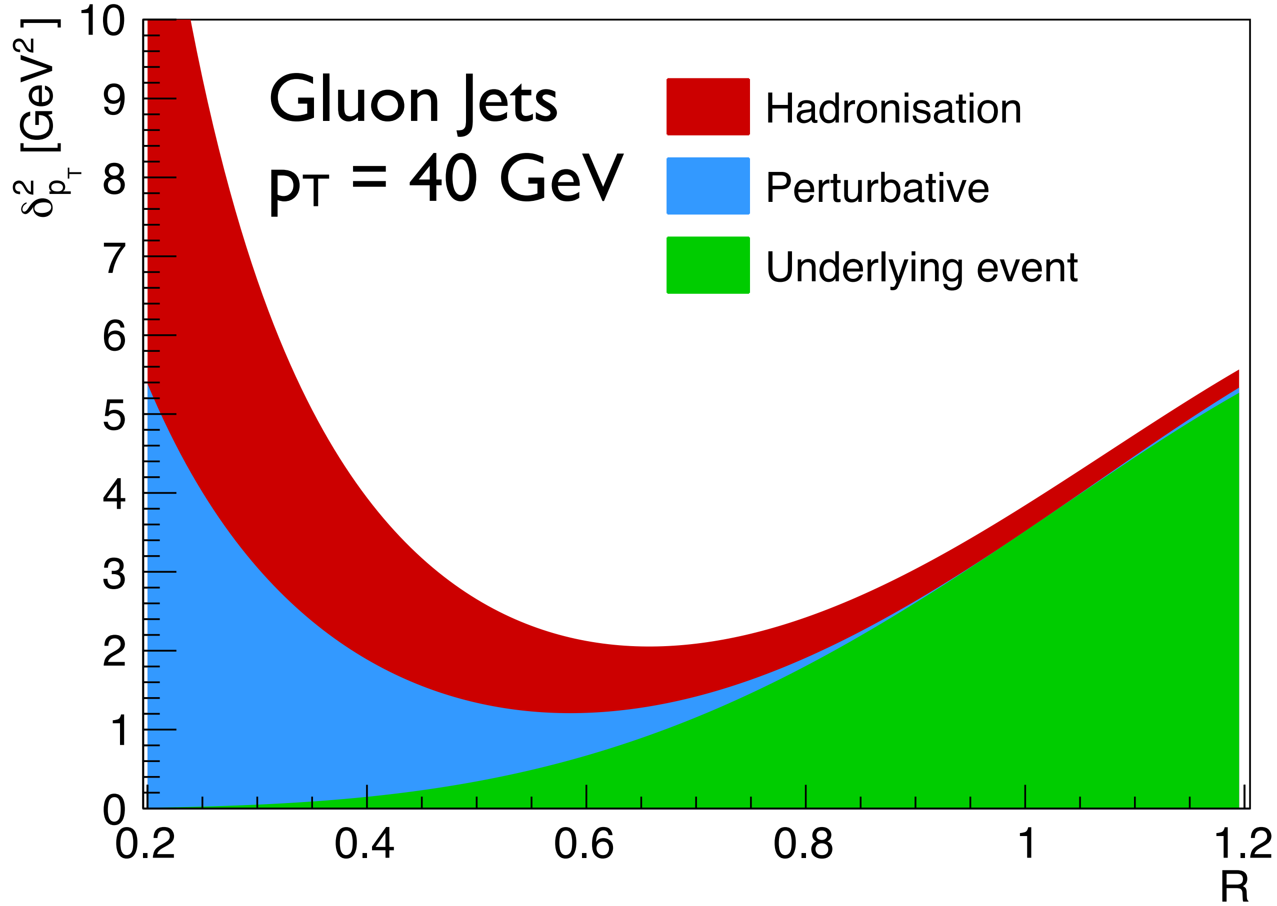
$$\langle \delta p_t \rangle_{\text{NP}} \sim -\frac{2C_F \Lambda}{\pi R}$$

$$\langle \delta p_t \rangle_{\text{UE}} \simeq \Lambda_{\text{UE}} R J_1(R) = \Lambda_{\text{UE}} \left(\frac{R^2}{2} - \frac{R^4}{8} + \dots \right)$$

[Salam, EPJC 67, 637 (2010)]

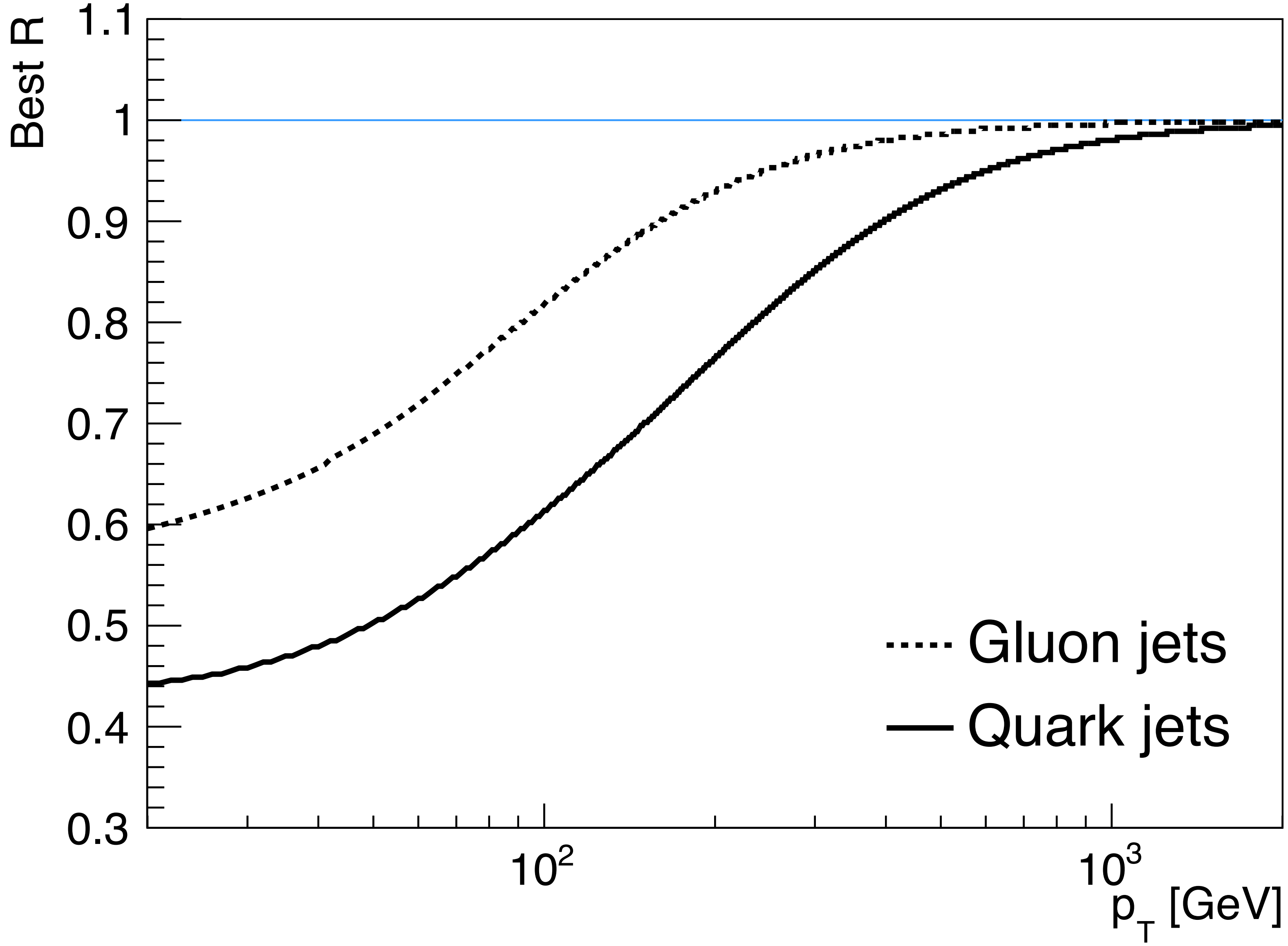
Uncertainties from Corrections





Smaller corrections for quark jets
Minimum at around R = 0.5 - 0.6

Is there an optimal R?



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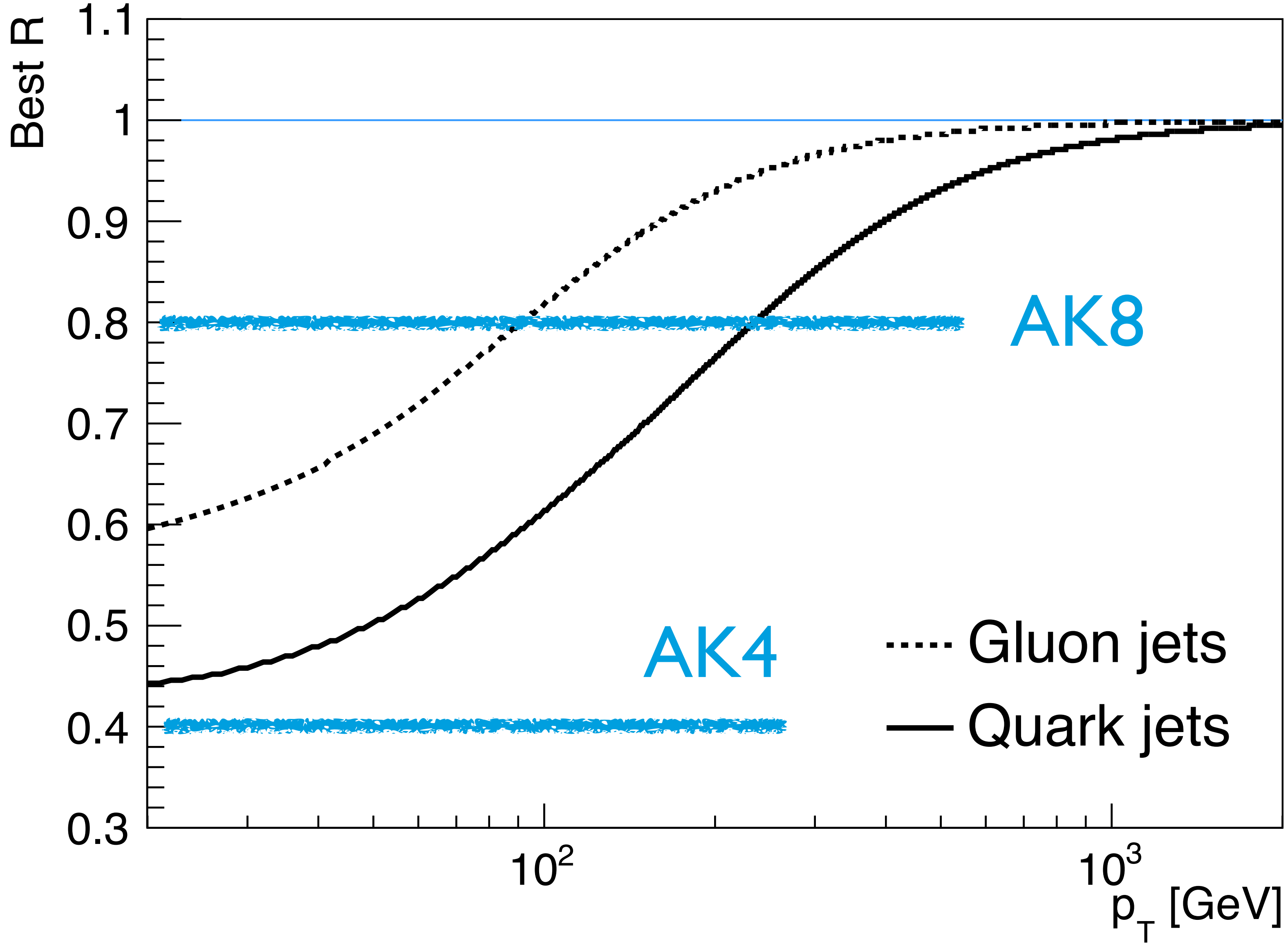
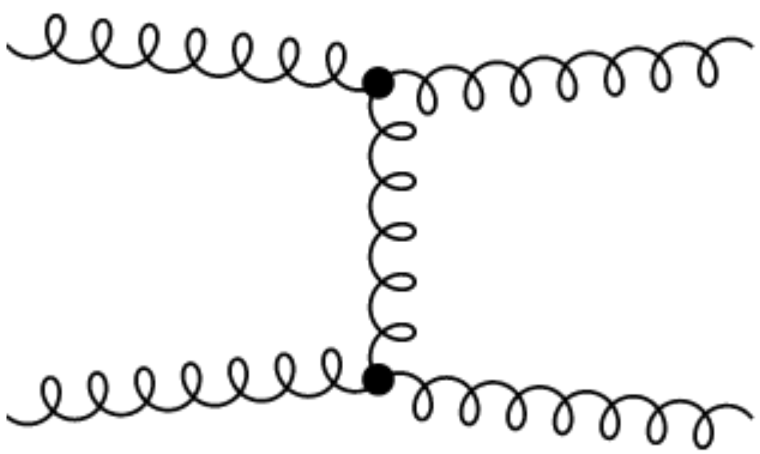


It depends…

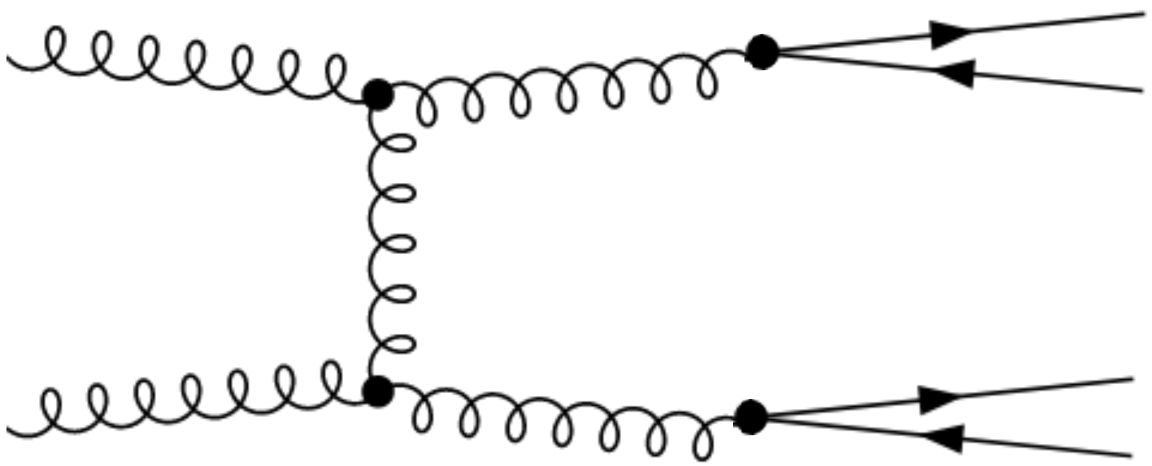
… on p_T and flavour

Defining Quark and Gluon Jets



Obviously two gluon jets…

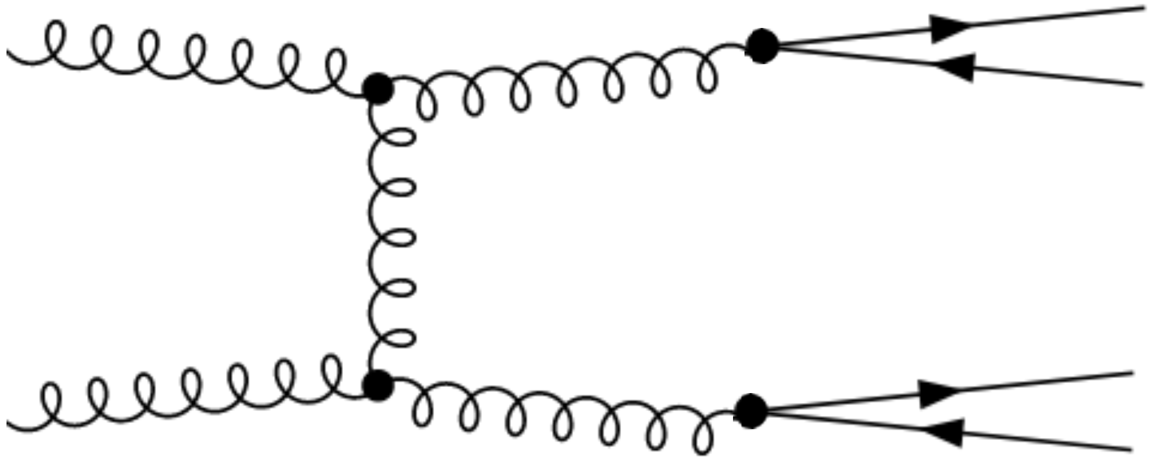
Defining Quark and Gluon Jets



Obviously two gluon jets…

… or not?!?

Defining Quark and Gluon Jets



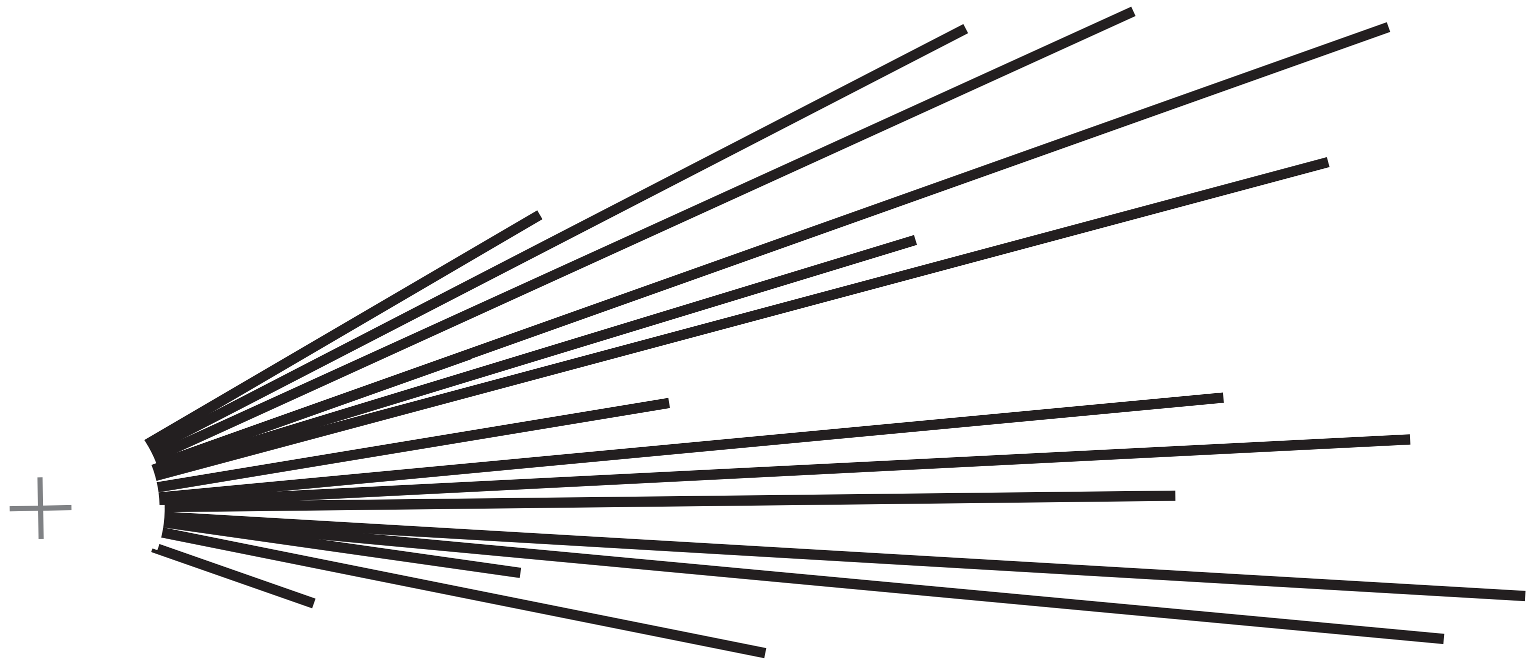
Obviously two gluon jets…

… or not?!?

- Parton flavour (from hard matrix element) is intrinsically flawed
- Physically meaningful definitions (not exhaustive)
  - N-Subjettiness [Larkoski, Metodiev, EPJC 10, 014 (2019)]
    - Possibility to unambiguously define quark jets ($\tau_N \rightarrow 0$)
    - Gluon jets always contaminated by quark jets, $(C_F/C_A)^{N_{emissions}}$
  - Flavour-k_T [Banfi, Salam, Zanderighi, EPJC 47, 113 (2006)]
  - Jet topics [Komiske, Metodiev, Thaler, JHEP 11 059 (2018)]
  - Fragmentation approach (WTA axis) [Caletti et al., JHEP 10 158 (2022)]

Jet substructure

- Remove unwanted / soft radiation from jets
- Aid the jet reconstruction and calibration
- Distinguish quark/gluon jets
- Tagging of fully merged W, Z, H and top jets



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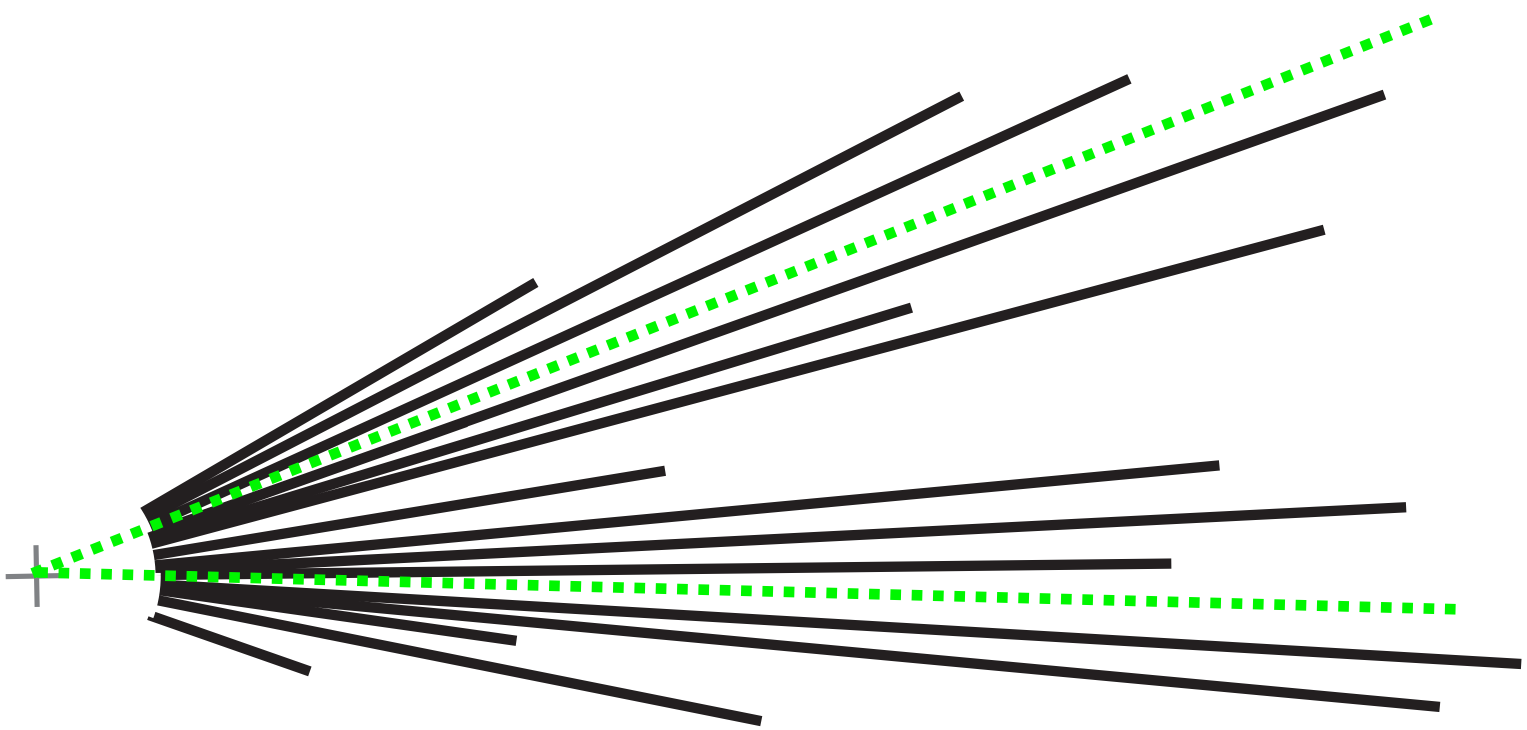
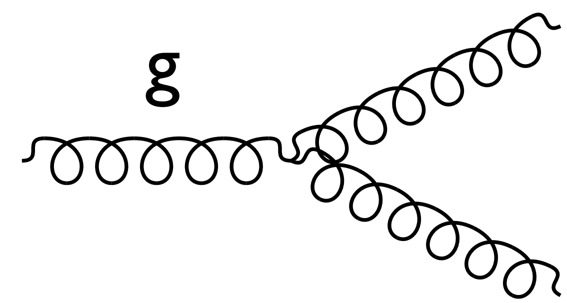
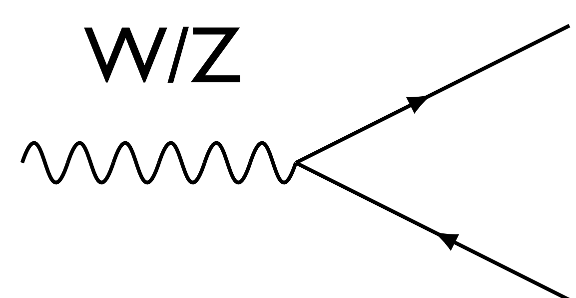


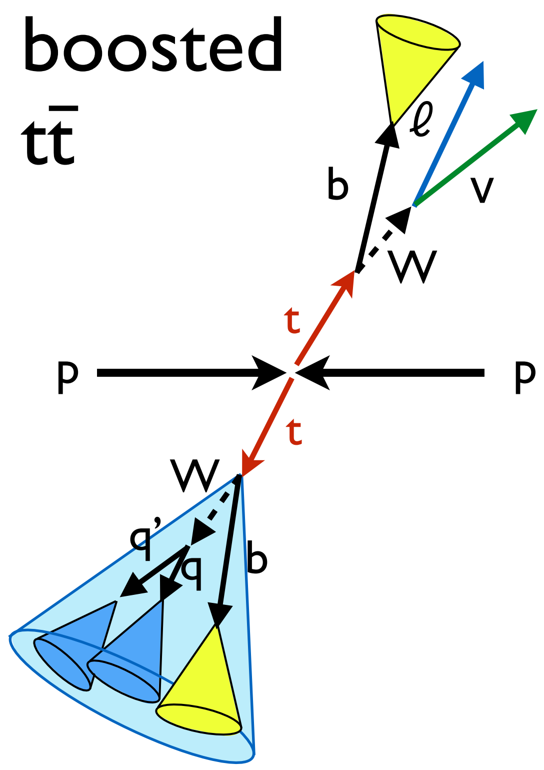


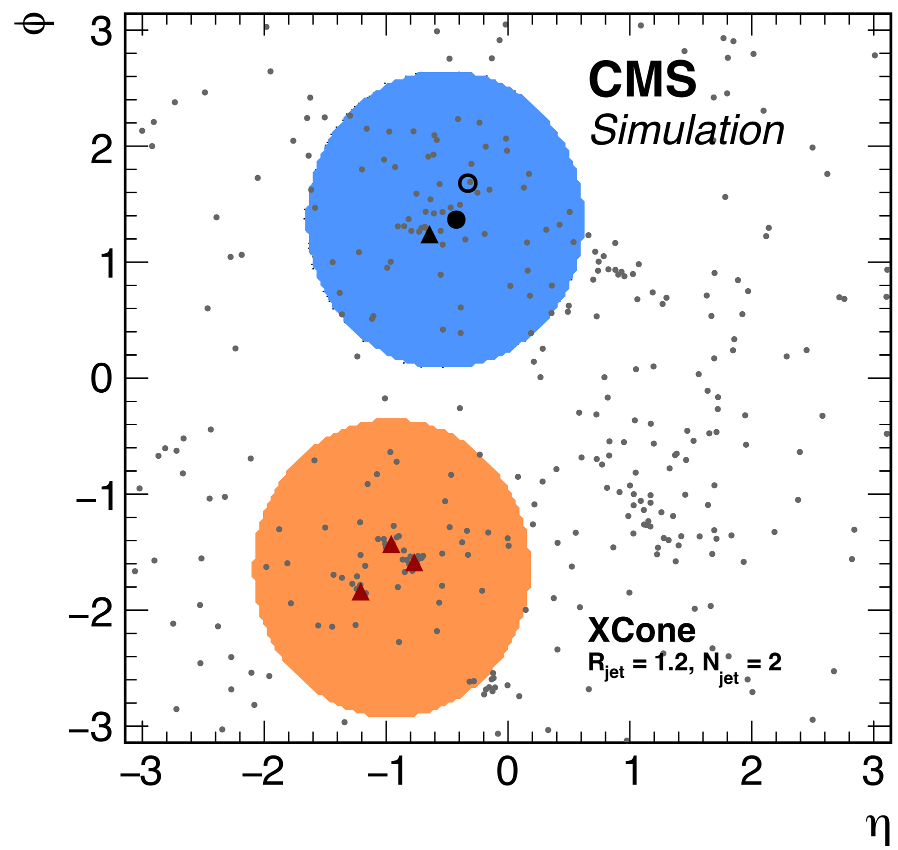


Exclusive Clustering

XCone

Use number of expected jets when event topology is known





- XCone assigns particles based on N-jettiness axes
- Natural transition resolved ↔ boosted

[Stewart et al., JHEP 11, 072 (2015)]

XCone

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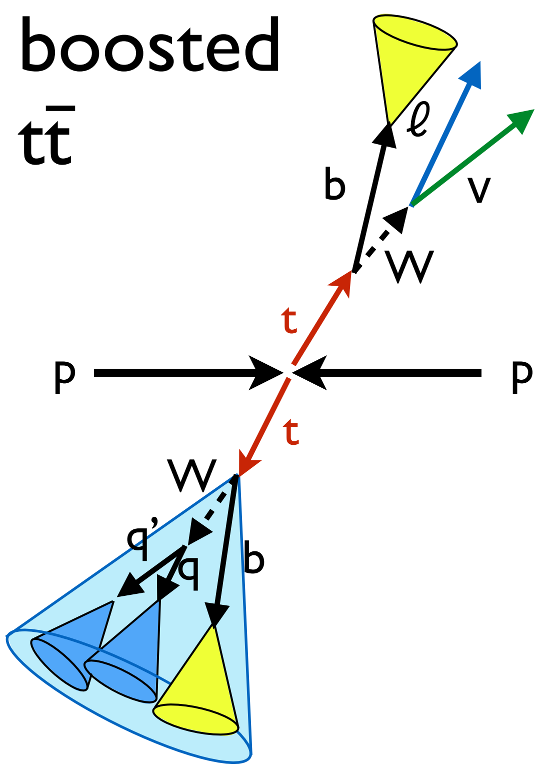

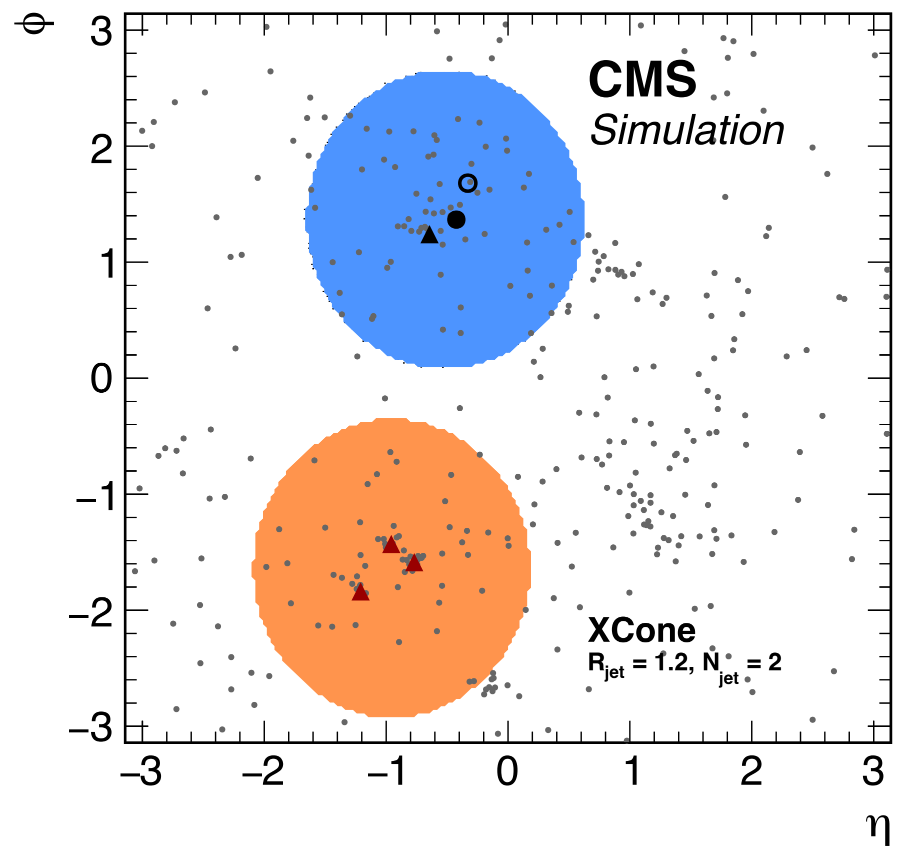

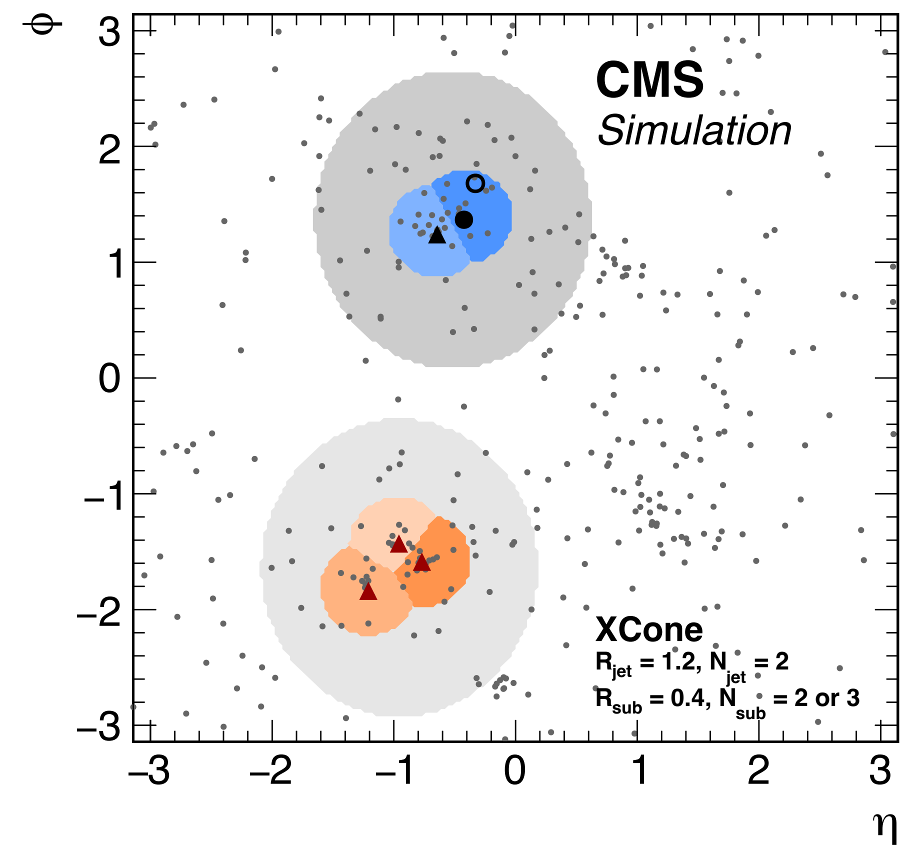

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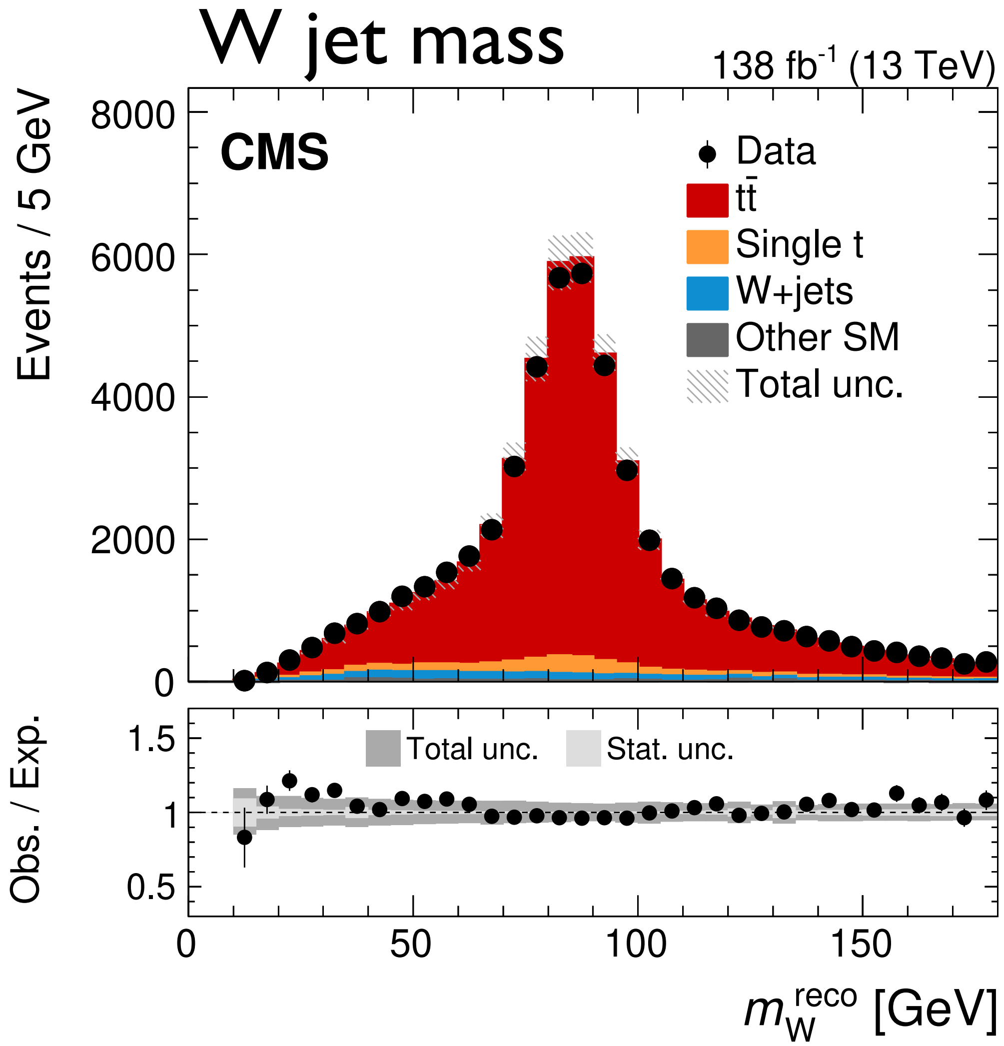
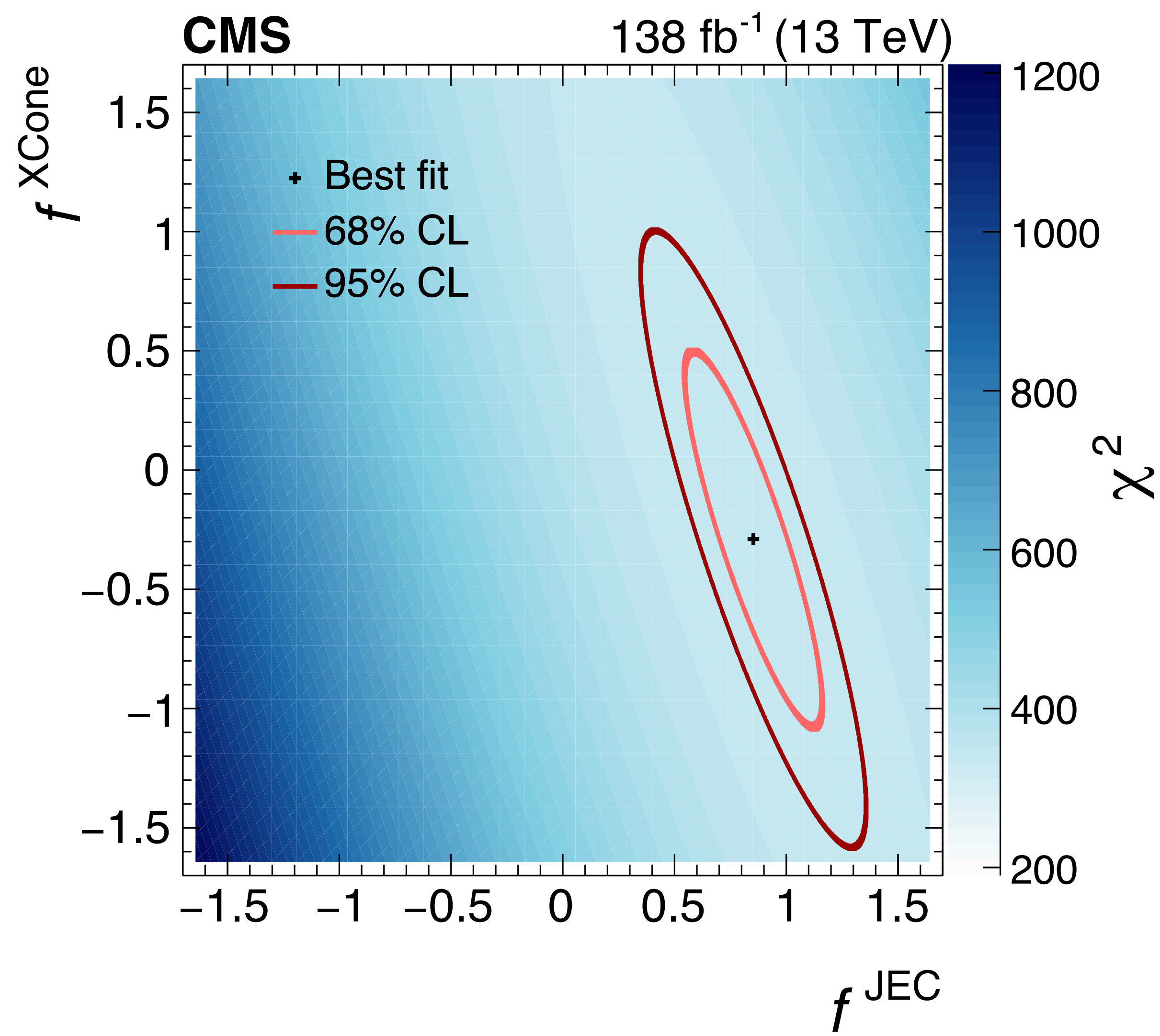
Measuring with XCone

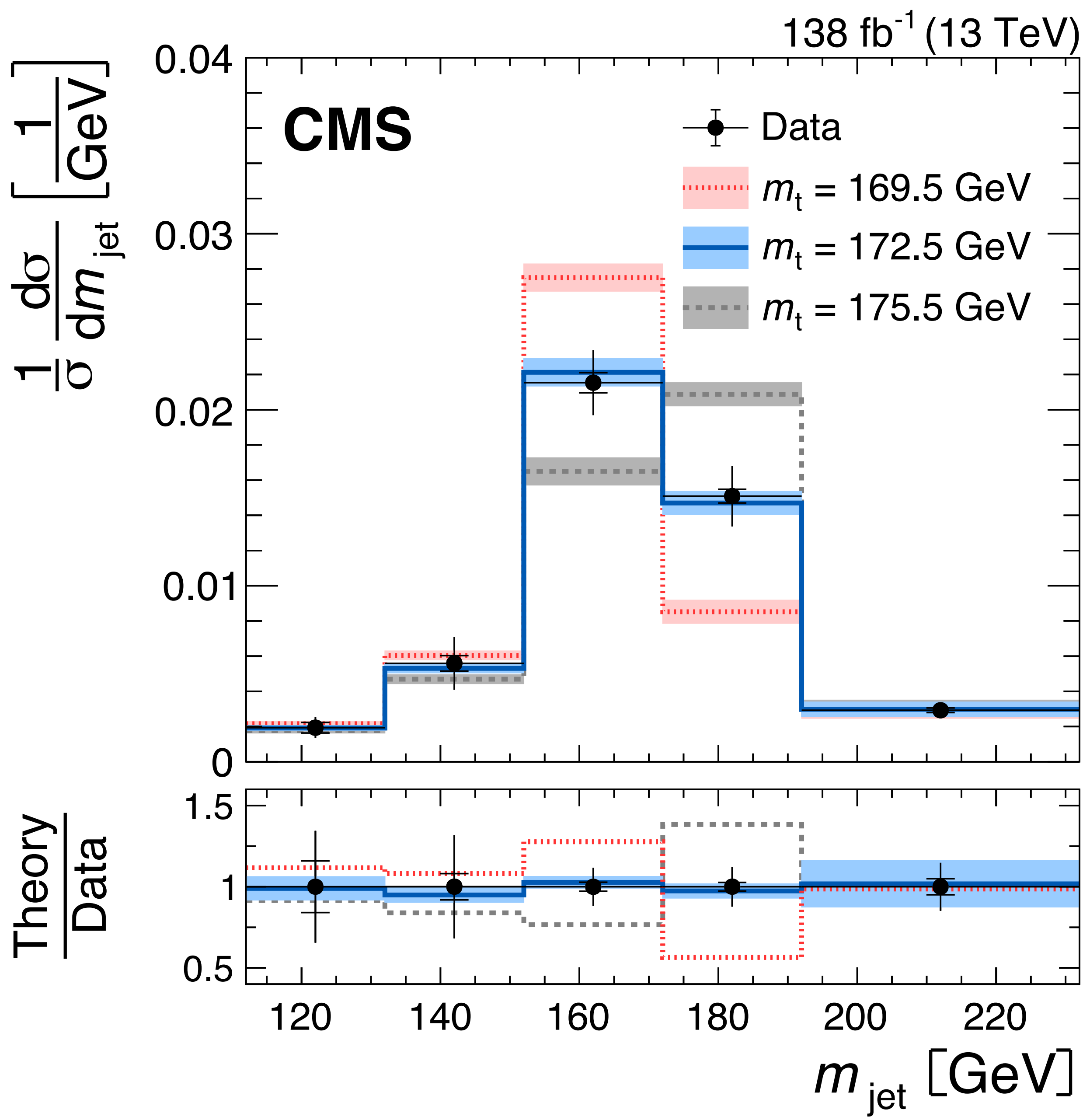




- Calibrate jet mass using "standard candle" M_W
- Excellent jet mass resolution of 6-8%

[CMS, arXiv:2211.01456]

Top Quark Mass with XCone



- Top quark mass from unfolded cross section
  - Uncertainty of ~ 0.8 GeV

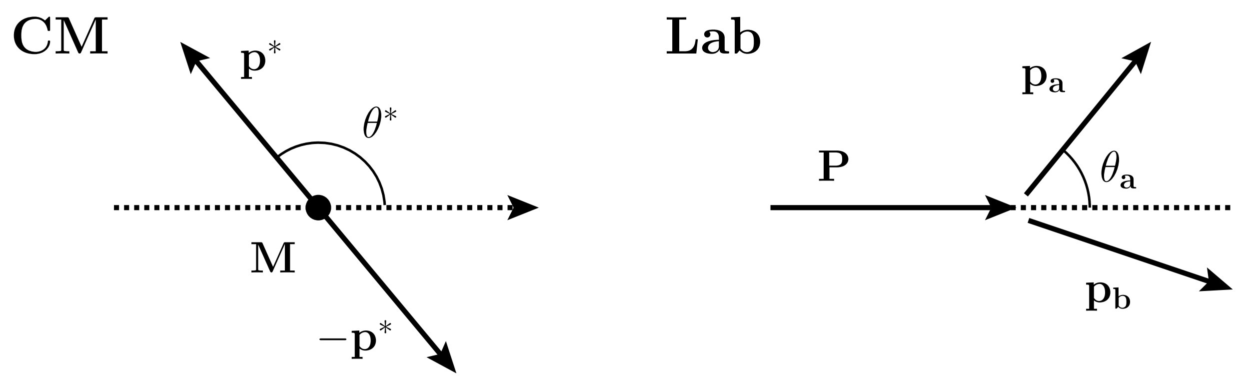
[CMS, arXiv:2211.01456]

Variable R Jets

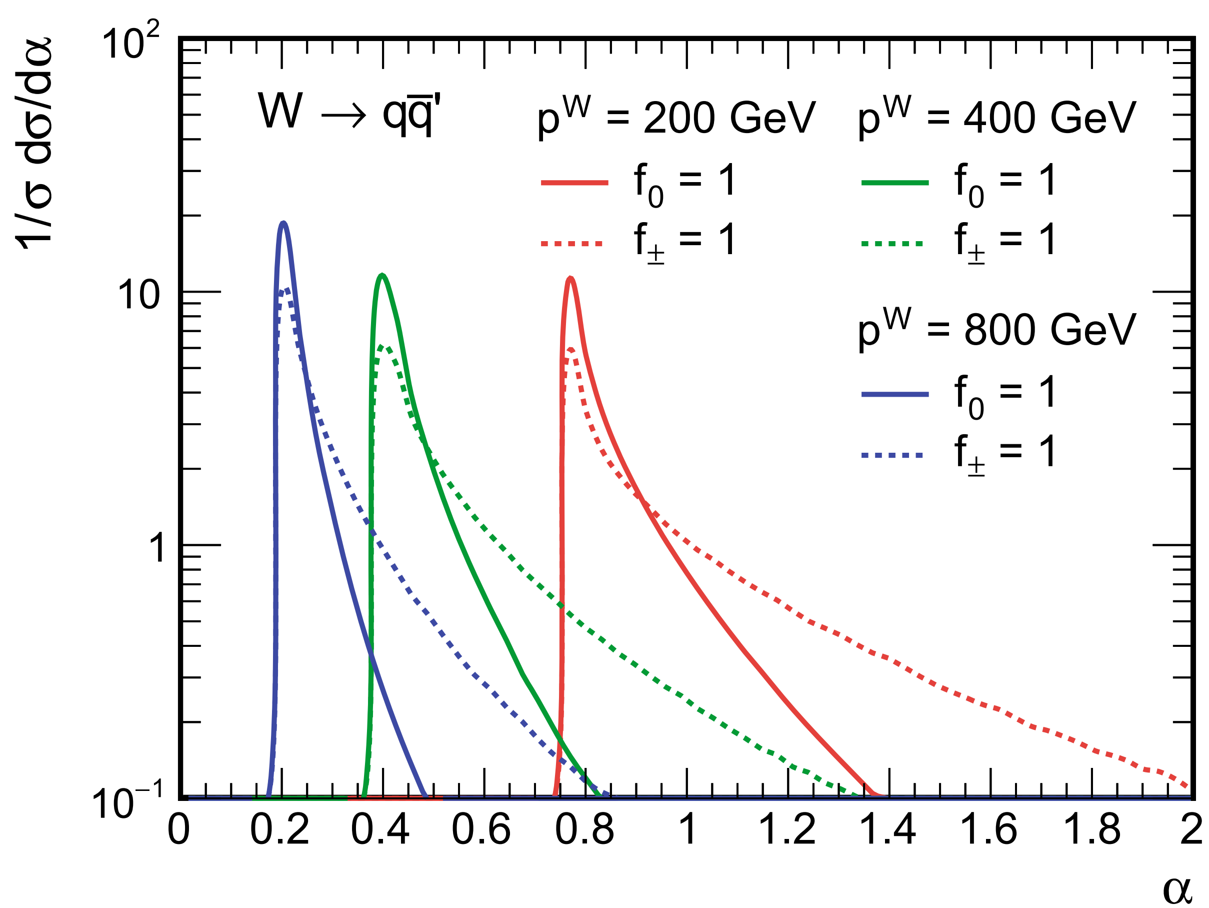
Particle Decays

W and Z bosons

$B_{W\to had} = 67.5\%$
$B_{Z\to had} = 69.2\%$



$$\frac{1}{\sigma}\frac{d\sigma}{d|\cos\theta^*|} = f_\pm \frac{3}{4}\left(1+|\cos\theta^*|^2\right) + f_0\frac{3}{2}|\sin\theta^*|^2$$



$$\alpha_{\min} \approx \frac{2M}{P}$$

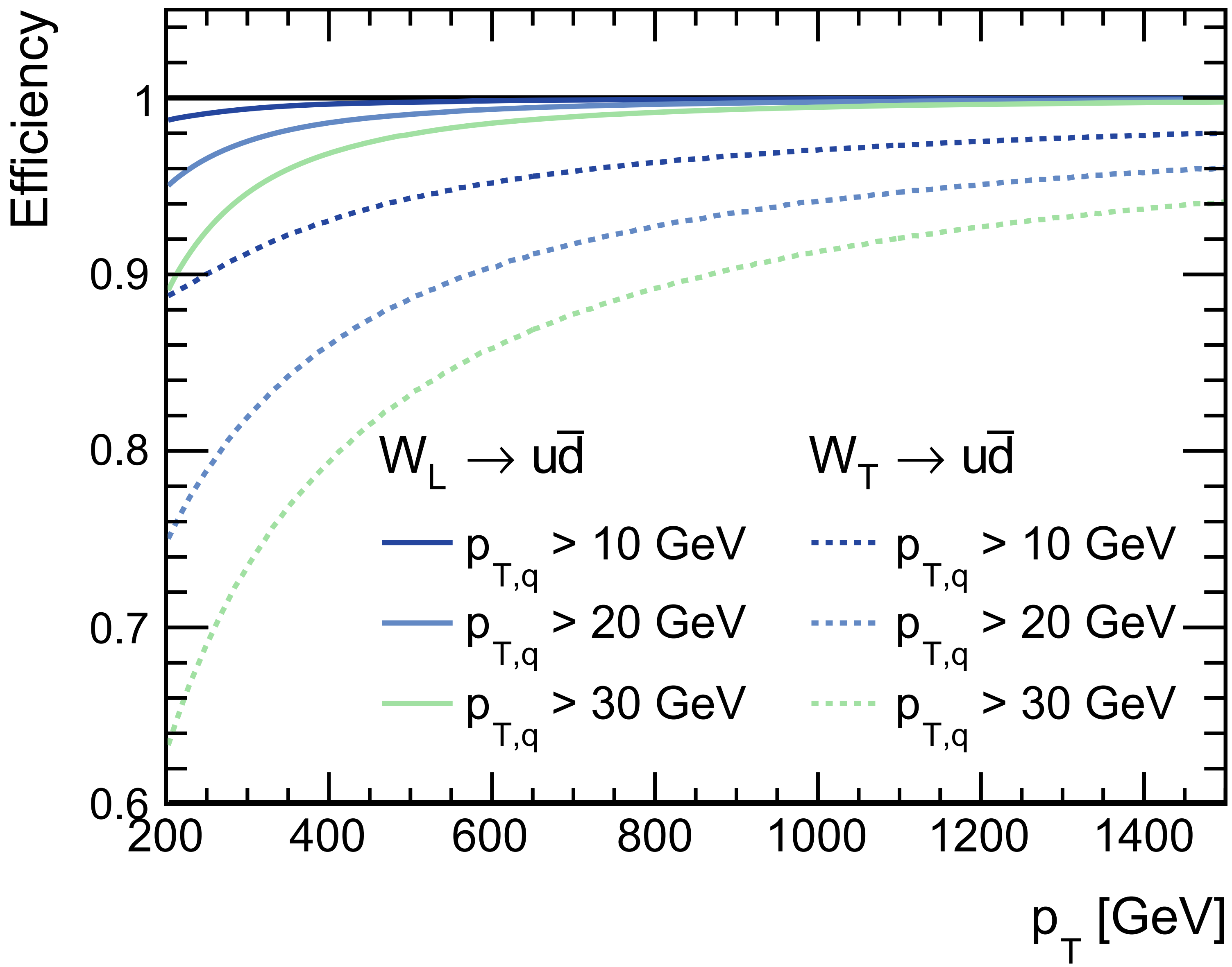
and consequently

$$\Delta R \approx \frac{2M}{P_T}$$

(holds for $P_T \gg M$)

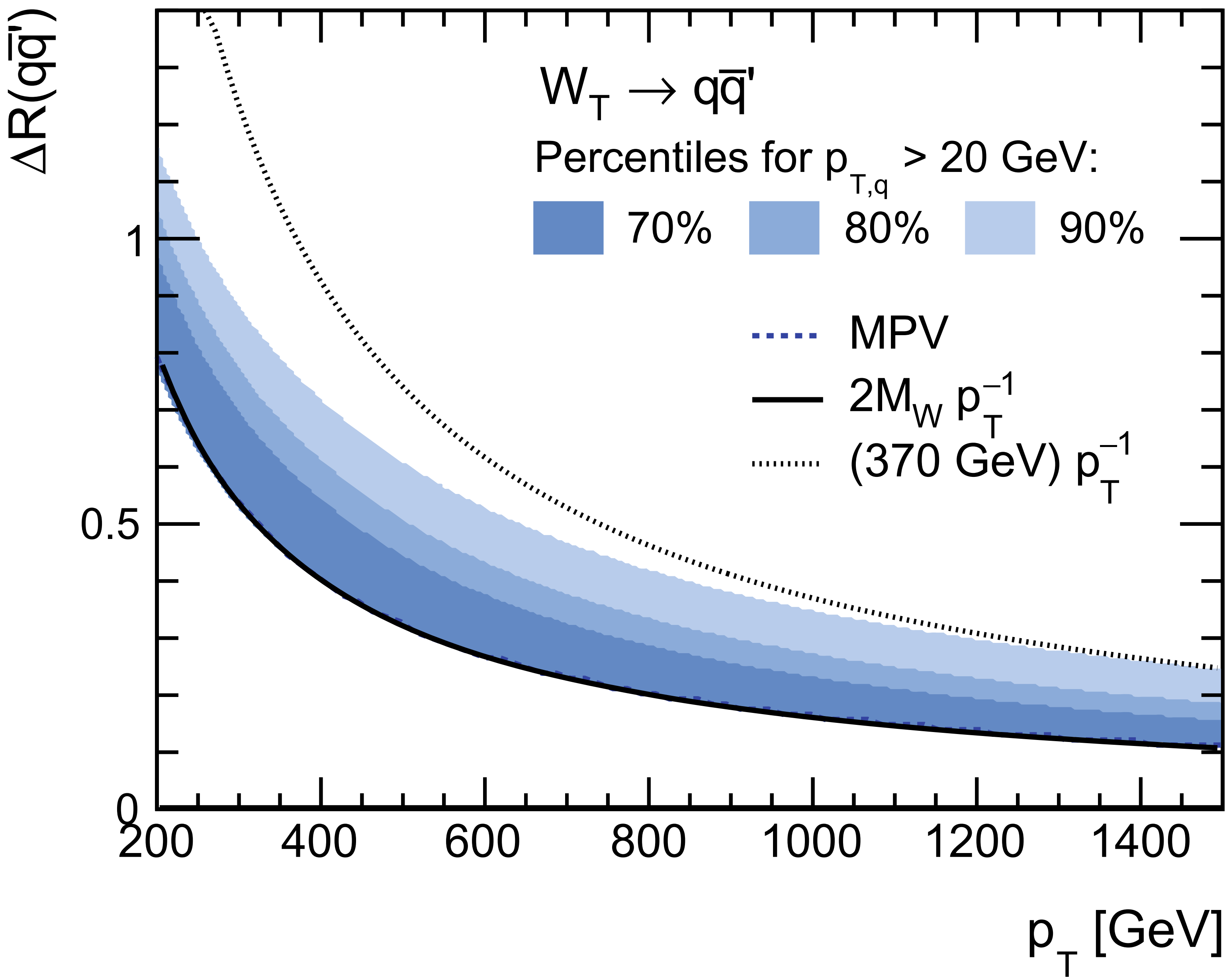
[RK, STMP 284 (2021)]

Quark (subjet) pT thresholds



[RK, STMP 284 (2021)]

Decay distance



- Similar picture for top quarks

[RK, STMP 284 (2021)]

Heavy Object Tagger with Variable R

[Lapsien, Haller, RK, EPJC 76, 600 (2016)]

One-pass clustering with integrated subjet finding

- Jet distance measures (with variable R)

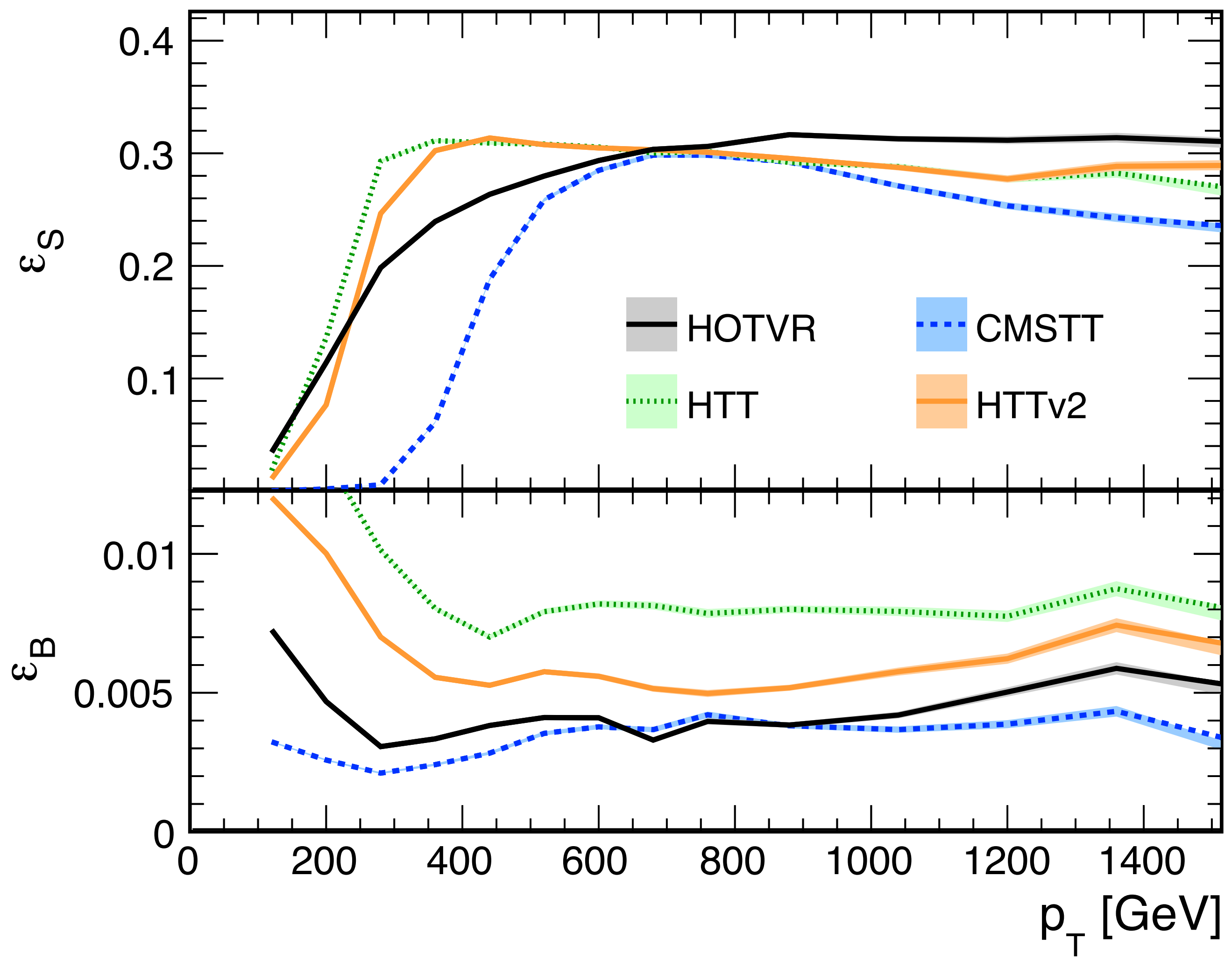
$$d_{ij} = \min[p_{T,i}^{2n}, p_{T,j}^{2n}]\Delta R_{ij}^2$$

$$d_{iB} = p_{T,i}^{2n} R_{\text{eff}}^2 \qquad R_{\text{eff}} = \frac{\rho}{p_T}$$

- Clustering veto at each step
  - mass jump veto
- Store objects i and j as subjets
- Used in tW resonance search

[CMS, JHEP 04, 048 (2022)]

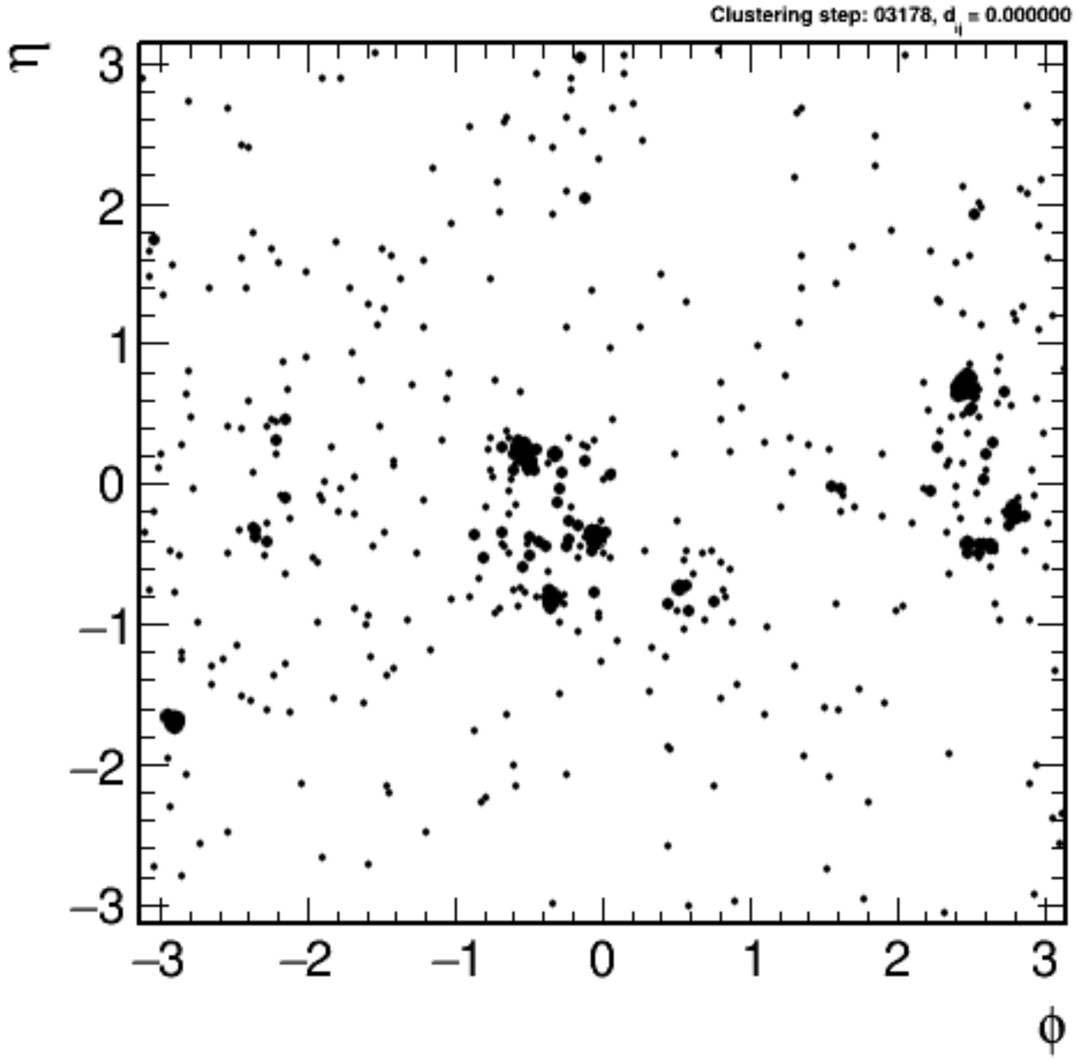
- Works beautifully, but can be improved



[RK, STMP 284 (2021)]

HOTVR with soft drop

- Use soft drop veto instead of mass jump
  - At each clustering step, test $\frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{\text{cut}} \left(\frac{\Delta R_{ij}}{R_{\text{eff}}} \right)^{\beta}$
  - Remove softer subjet if not fulfilled
  - Active area exactly 0, because ghosts get groomed
- Expand with mass-dependent R (work in progress)



[Albrecht, Benecke, RK, work in progress]

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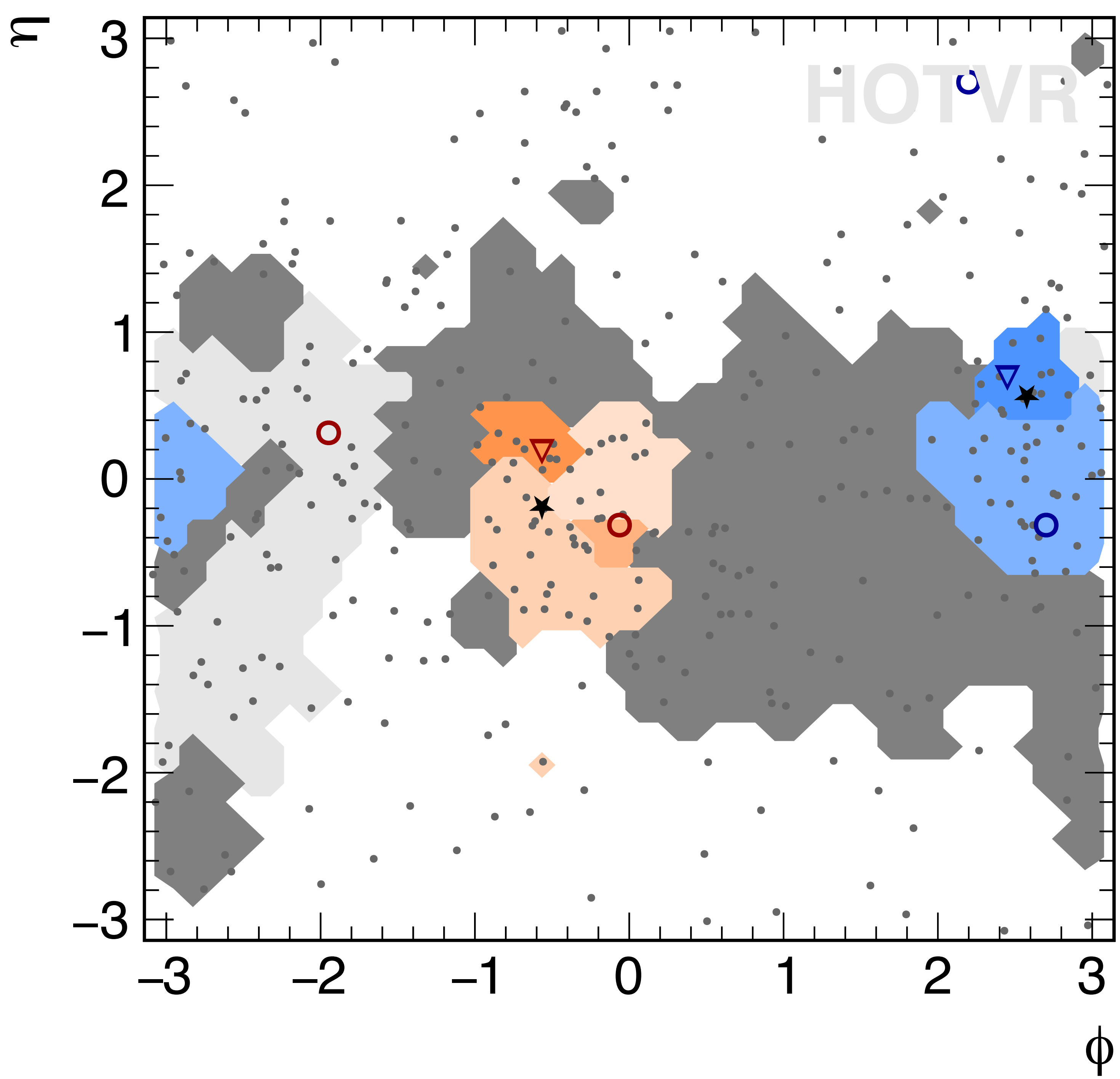
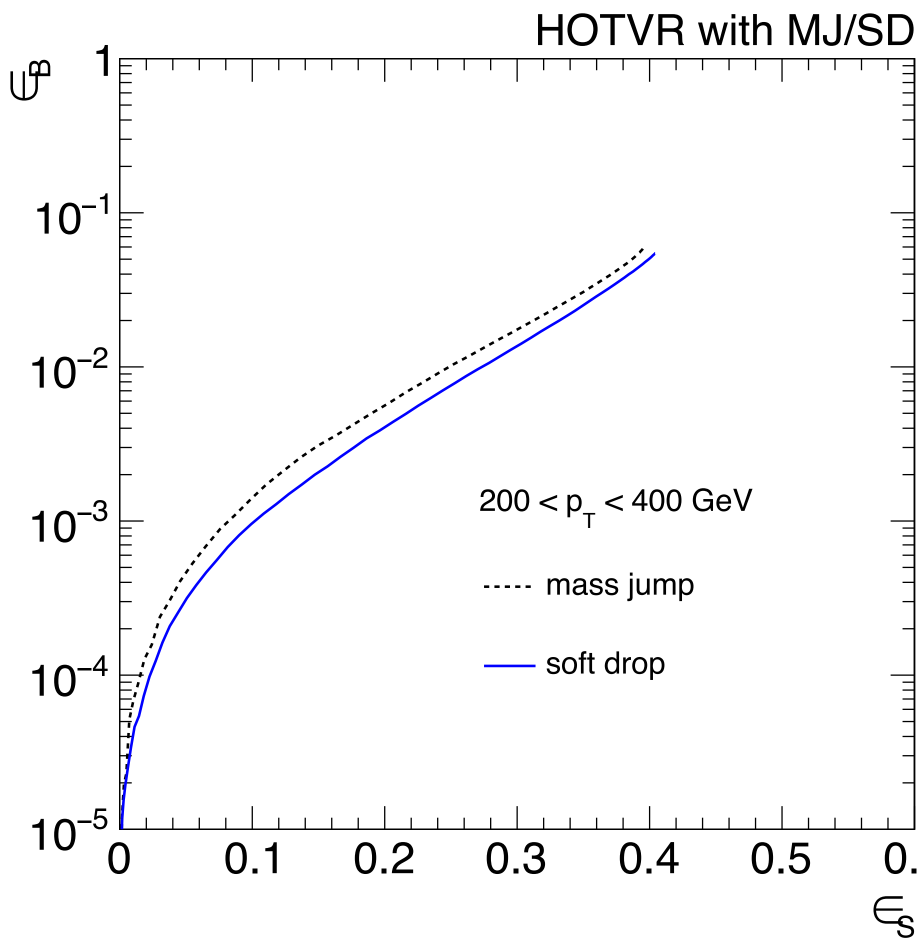
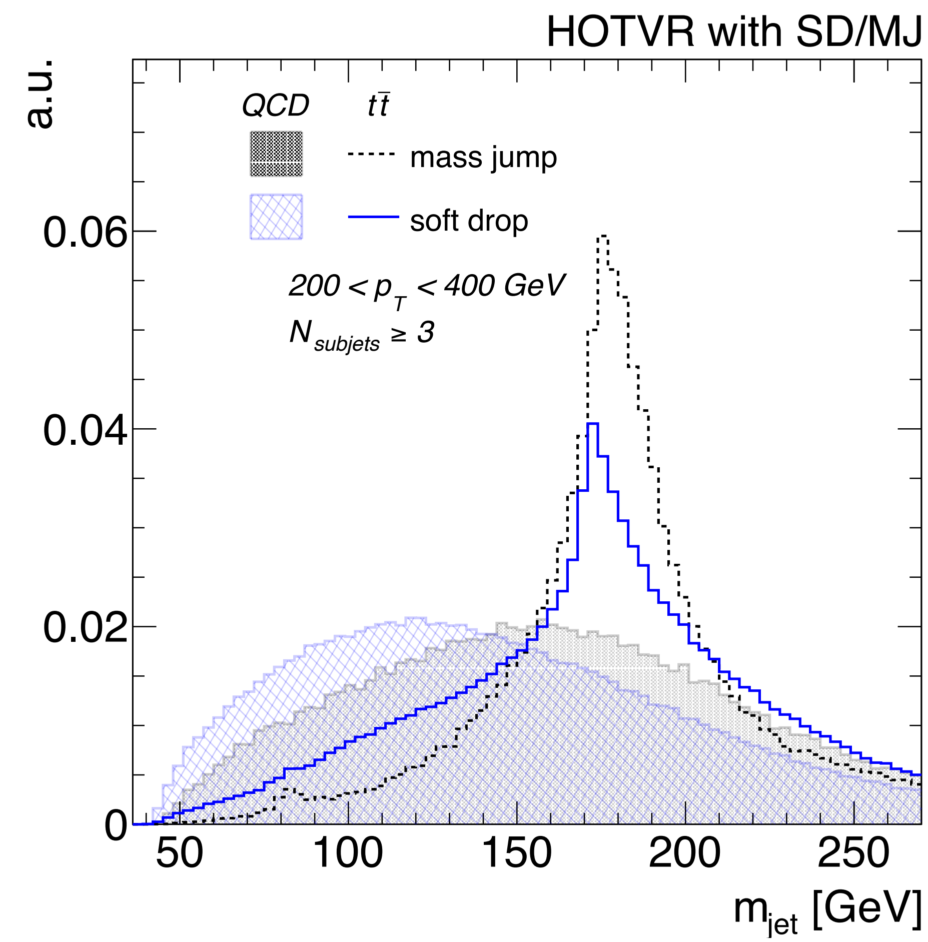


[Albrecht, Benecke, RK, work in progress]

HOTVR with soft drop





- Stronger grooming with soft drop
- No essential tagging information is lost with HOTVR-SD jets compared to plain Variable R jets
  - Better starting point for (ML) taggers

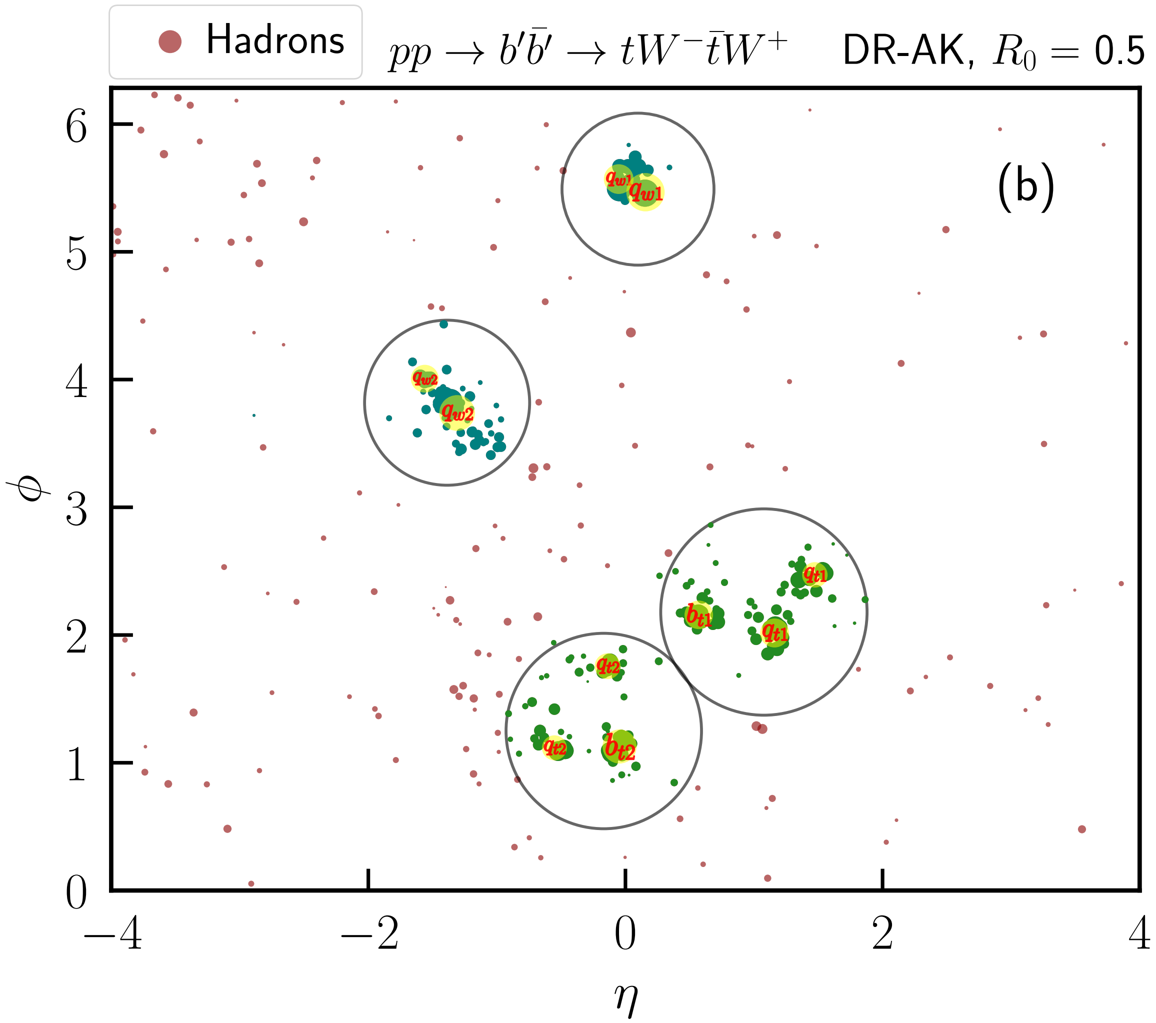
[Albrecht, Benecke, RK, work in progress]

Scale Invariant Jets

Other Variable-Size Jets

Local, dynamical R [Mukhopadhyaya, Samui, Singh, JHEP 2023, 19 (2023)]

$$R_{d_i} = R_0 + \sigma_i . \qquad \sigma_i^2 = \frac{\sum_{a<b} p_{T_a} p_{T_b} \Delta R_{ab}^2}{\sum_{a<b} p_{T_a} p_{T_b}} - \left(\frac{\sum_{a<b} p_{T_a} p_{T_b} \Delta R_{ab}}{\sum_{a<b} p_{T_a} p_{T_b}} \right)^2 ,$$



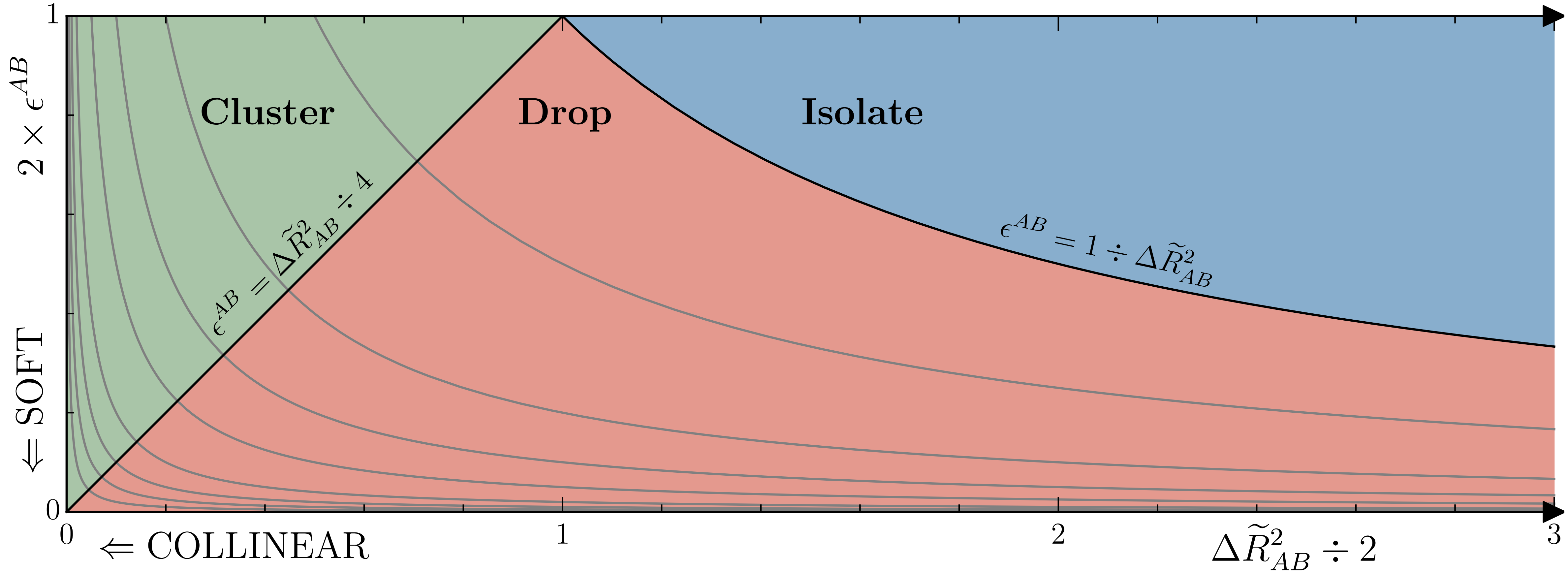
- Useful in searches with high p_T and multi-prong resonances
- Minimum R_0 needed, can not have jets smaller than that
- Adjustment of R_0 to analysis needs

Scale Invariant Jets

- Optimal distance parameter R depends on energy scale of event
- Idea: a scale-invariant algorithm, independent of R

$$\delta_{AB} = \epsilon^{AB} \times \Delta\widetilde{R}^2_{AB} = \frac{\cosh \Delta y_{AB} - \xi^A \xi^B \cos \Delta\phi_{AB}}{\cosh \Delta u_{AB}}$$

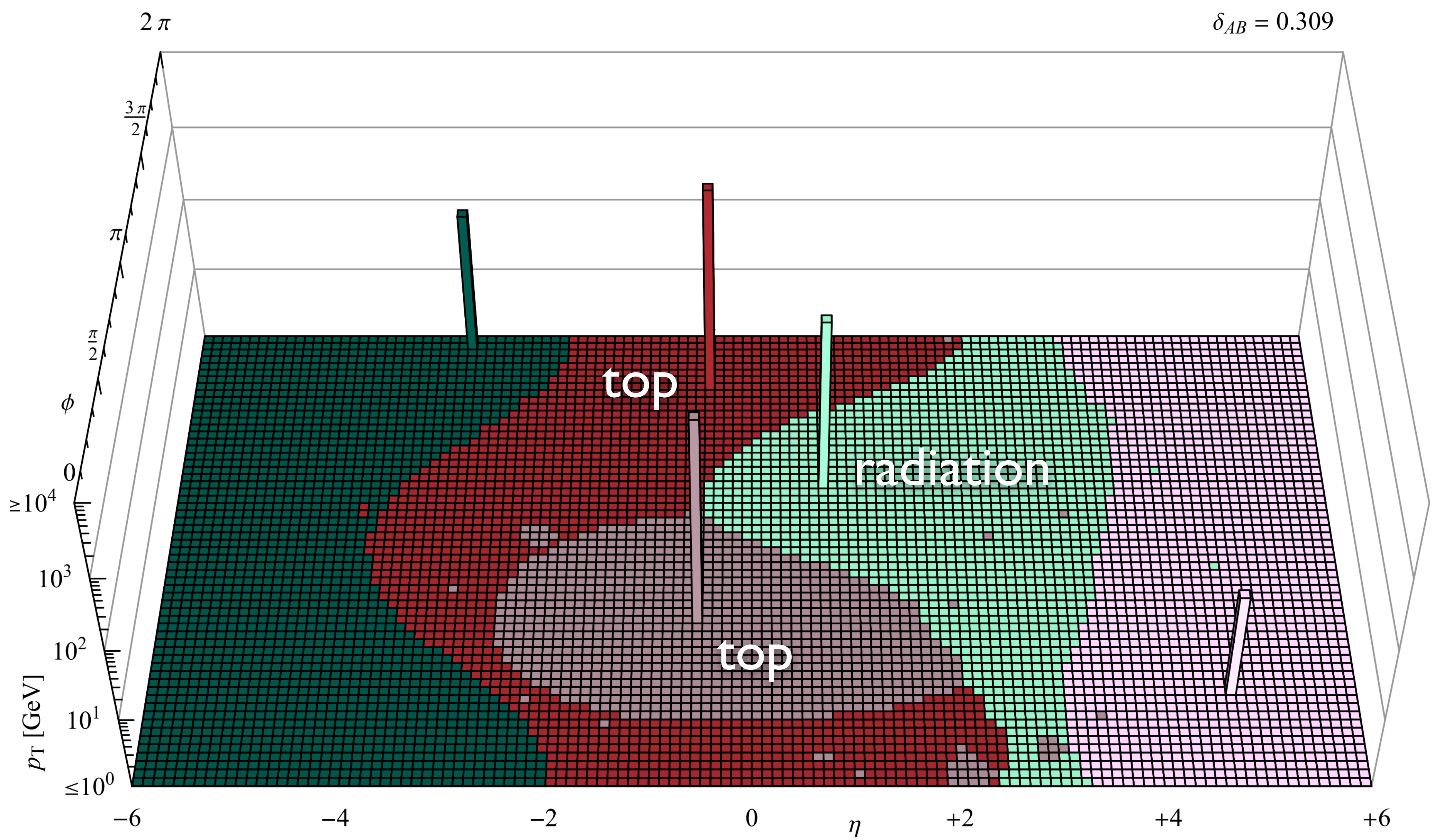
- Inherent soft-drop-like grooming in "Drop" region



[Larkoski, Rathjens, Veatch, Walker, arXiv:2302.08609]

Scale Invariant Jets

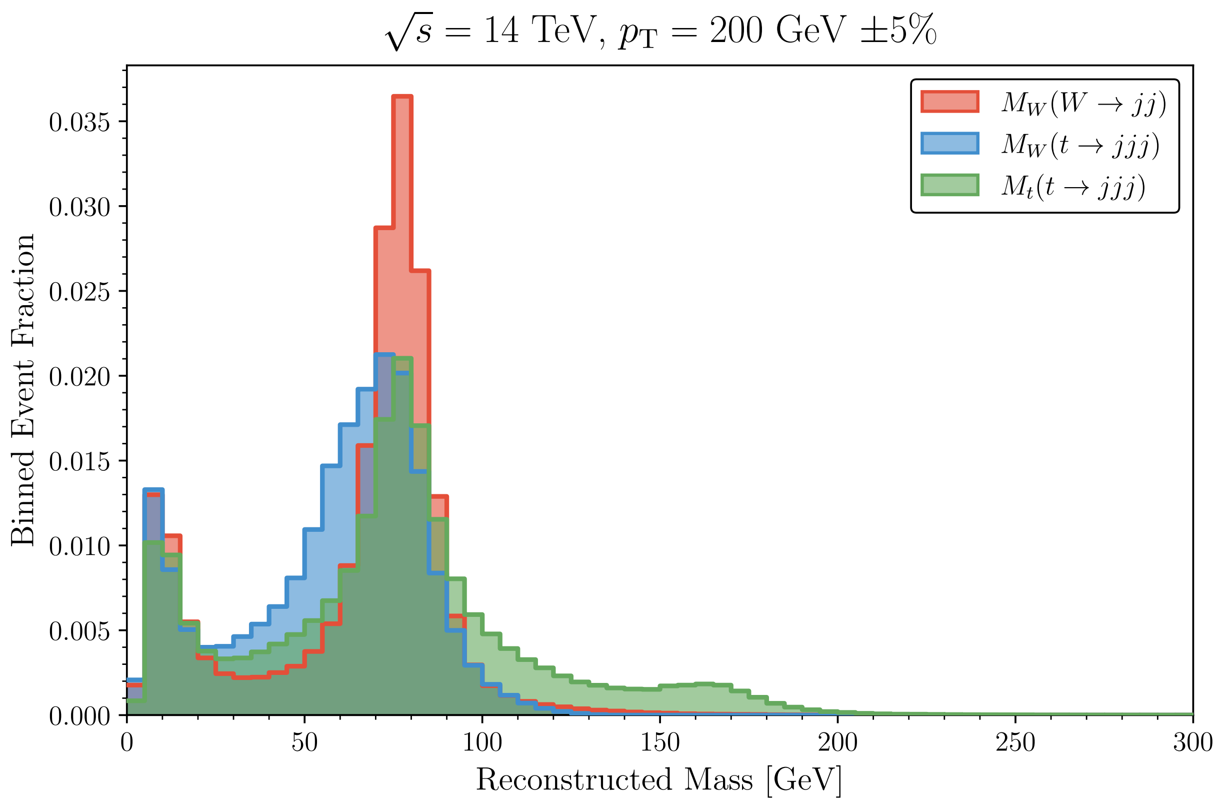
- If left running, the whole event will merge into one large jet
  - Large discontinuity in distance measure δ_{AB} in the last steps

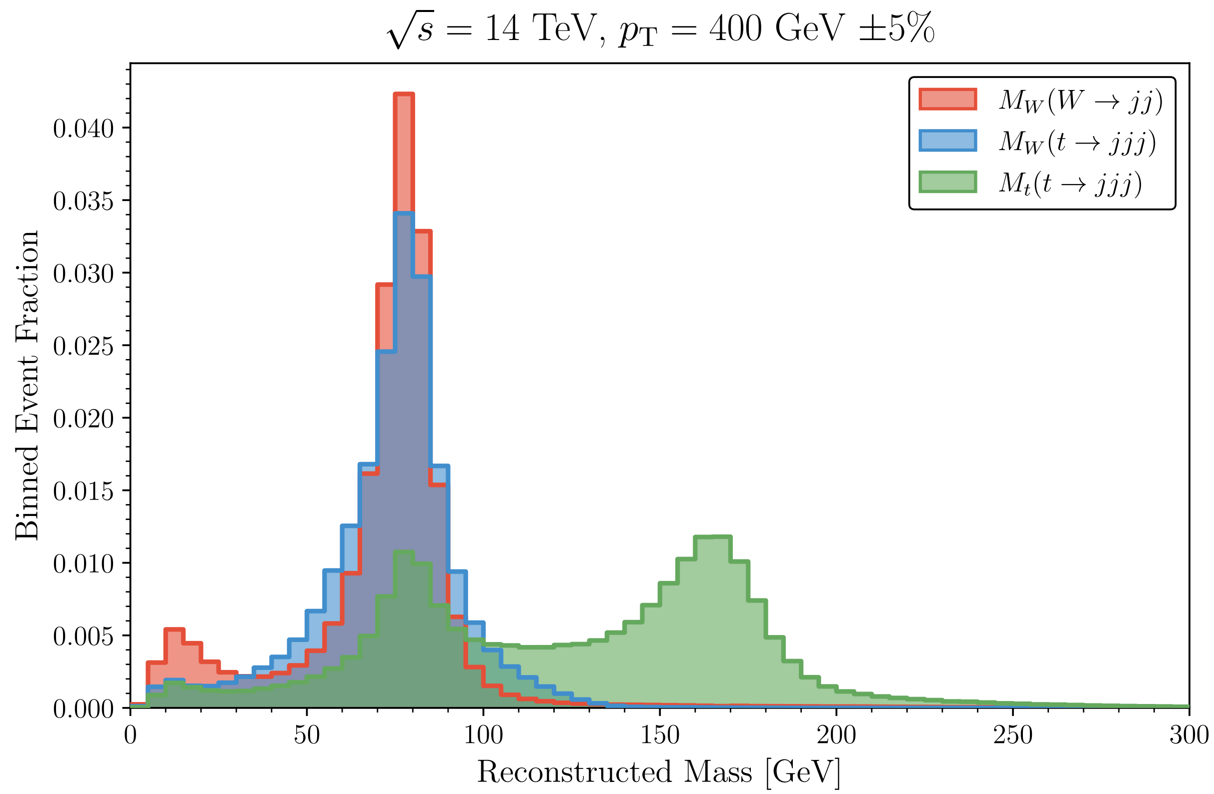


[Larkoski, Rathjens, Veatch, Walker, arXiv:2302.08609]

Scale Invariant Filtered Tree (SIFT)

Clustering history (N-subjet tree): Exclusive (sub)jet counts





[Larkoski, Rathjens, Veatch, Walker, arXiv:2302.08609]

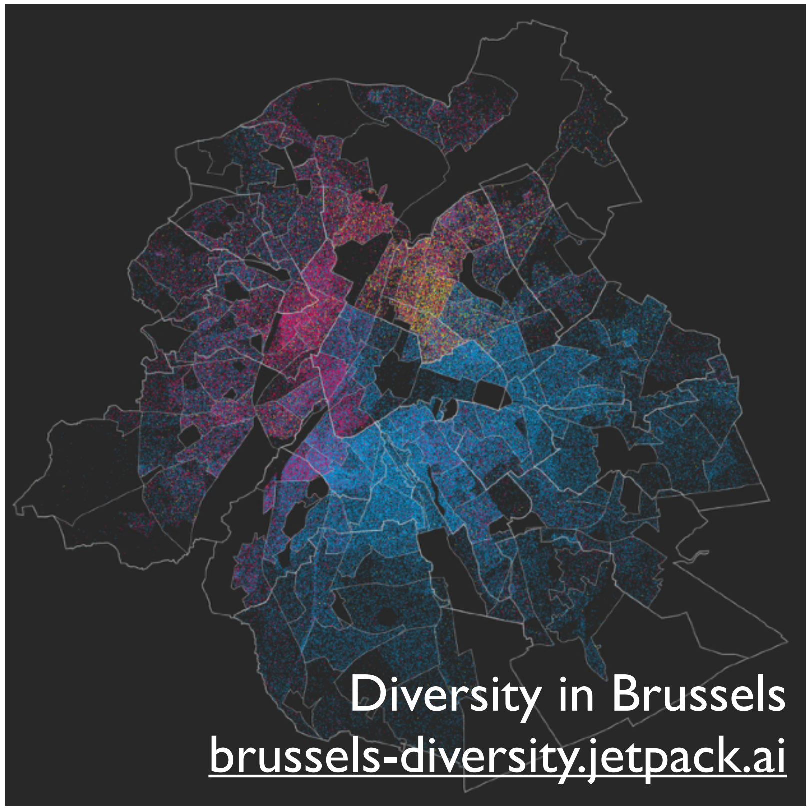
- Promising results over a large range of p_T
- Tagging results (obtained with BDT) better than for fixed-R jets

Comprehensive comparison of all algorithms needed

Summary

Last 10 years huge progress in jets and jet substructure

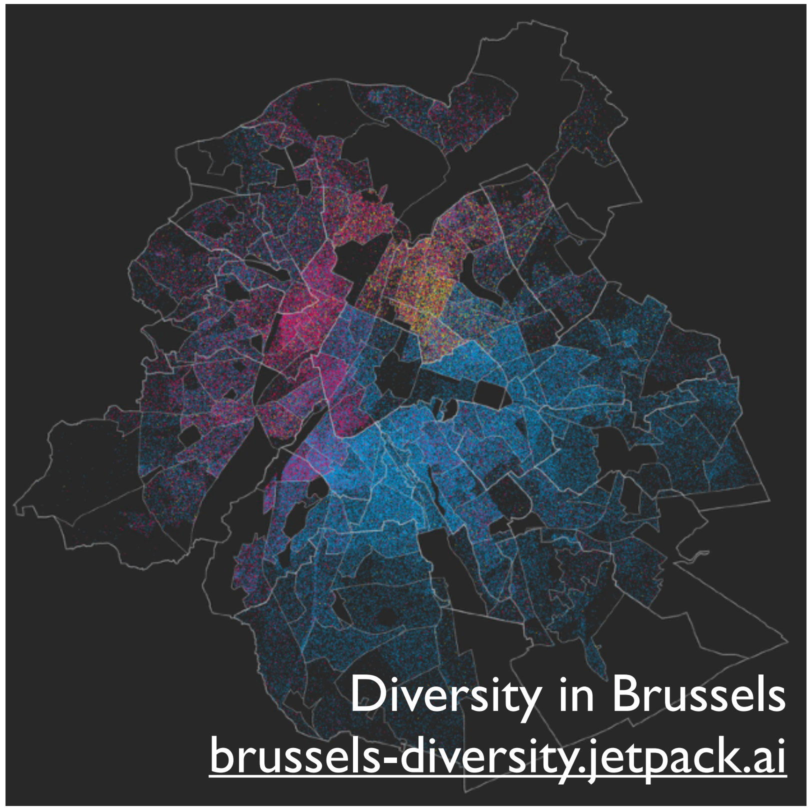
- Why are we still using AK4 for measurements and AK8 for tagging?
- Should be using:
  - Large jets (or R ~ p_T) for measurements
  - Decreasing jets R ~ $1/p_T$ for tagging
  - Unambiguous (IRC safe) definition of q/g jets



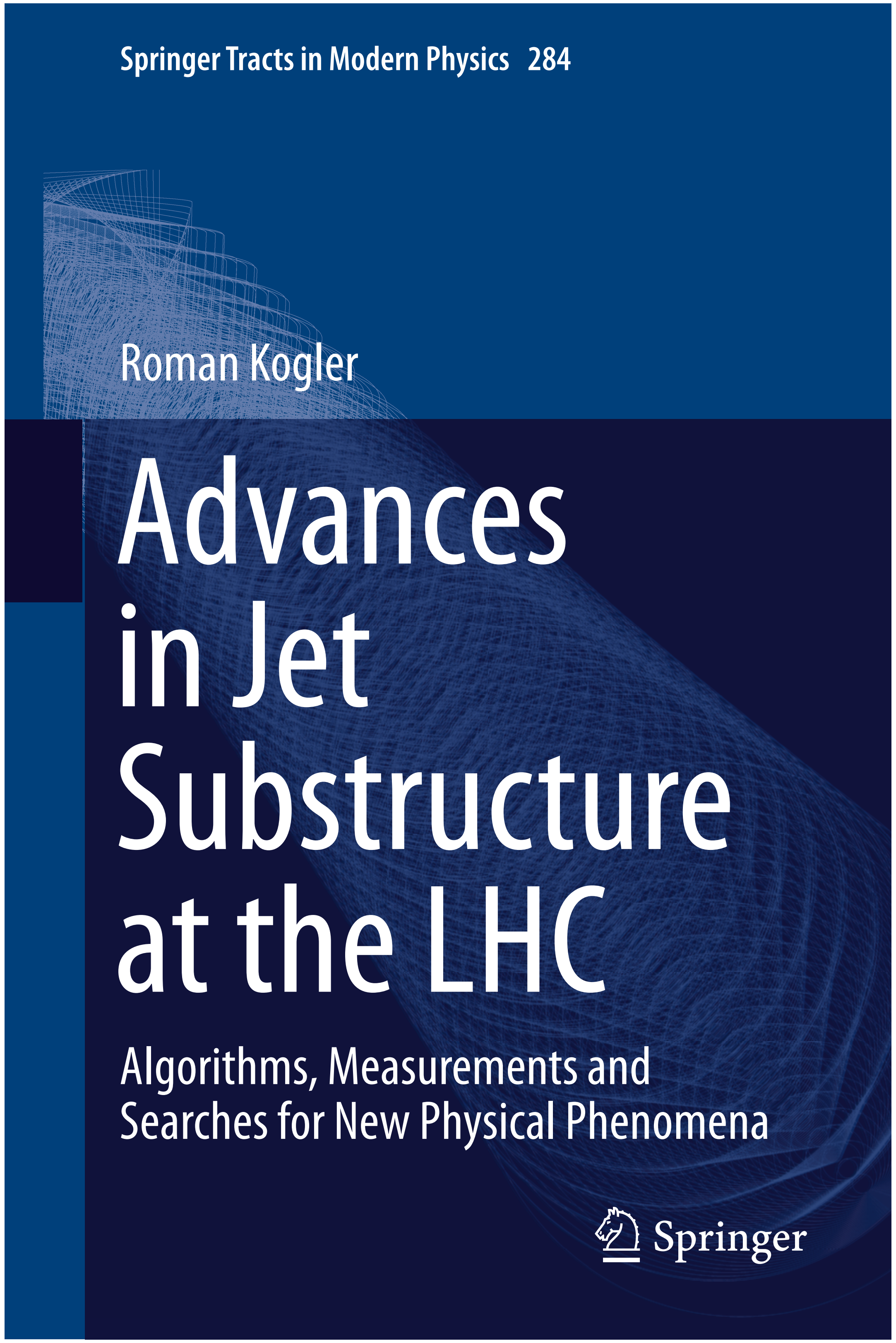
Summary

Last 10 years huge progress in jets and jet substructure

- Why are we still using AK4 for measurements and AK8 for tagging?
- Should be using:
  - Large jets (or R ~ p_T) for measurements
  - Decreasing jets R ~ $1/p_T$ for tagging
  - Unambiguous (IRC safe) definition of q/g jets



- We are all busy with Run 3 (and 2)
- Hopefully, no catastrophic incident is needed for the next consolidation of our jet usage
  - Preparation of HL-LHC: chance for new ideas
  - Be open for new techniques and strategies
  - Start with data formats, analyses will follow



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