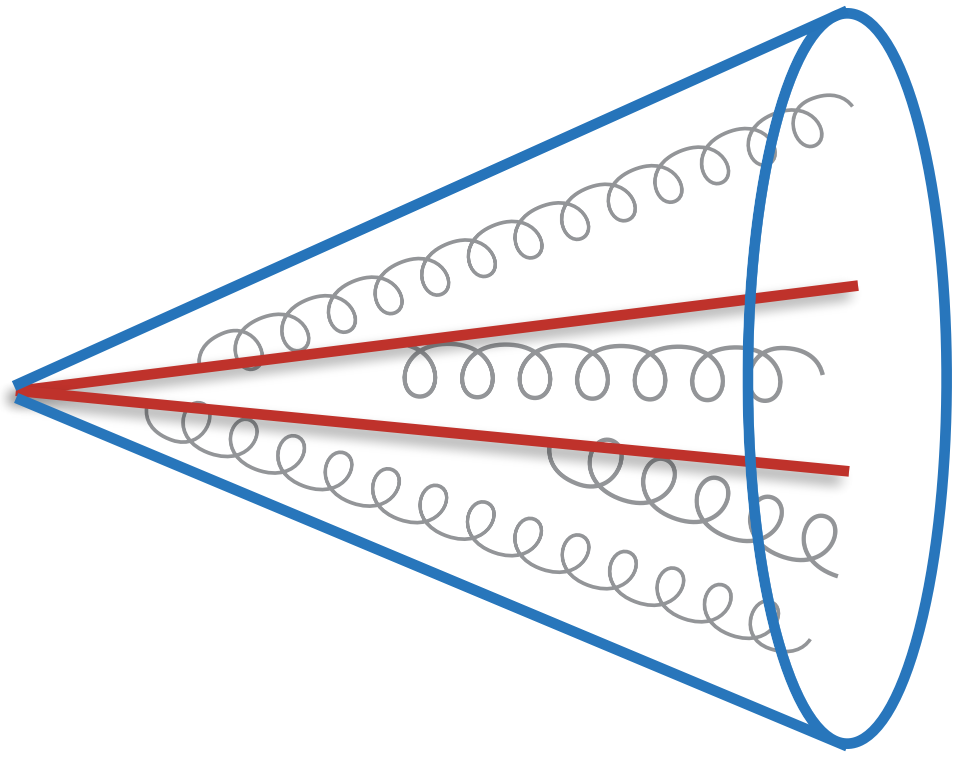
UNRAVELLING THE INNER STRUCTURE OF JETS WITH DYNAMICAL GROOMING



Alba Soto-Ontoso

+ Yacine Mehtar-Tani and Konrad Tywoniuk

LIP Seminar

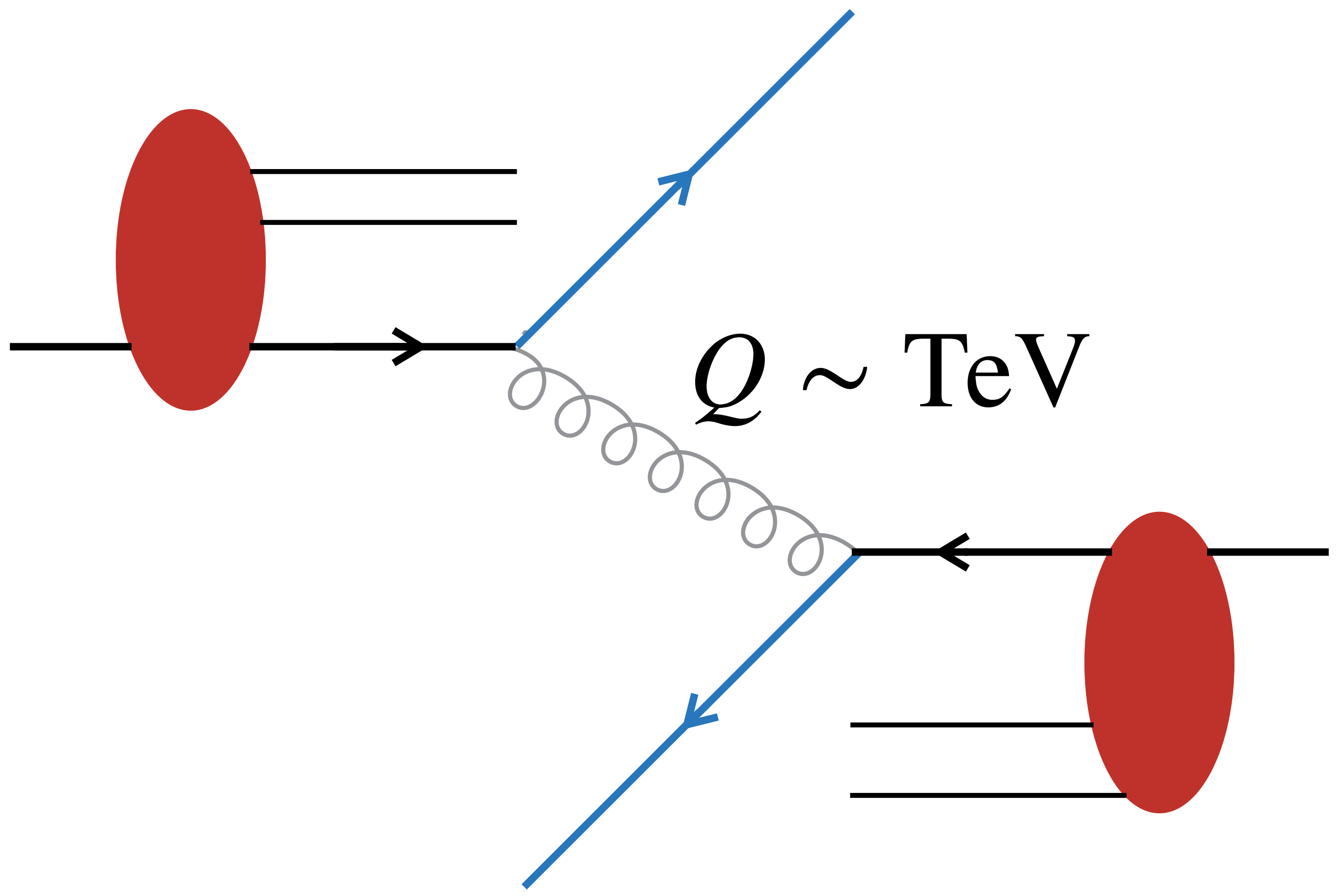
Remote, 30th July, 2020

BROOKHAVEN NATIONAL LABORATORY

Center for Frontiers in Nuclear Science

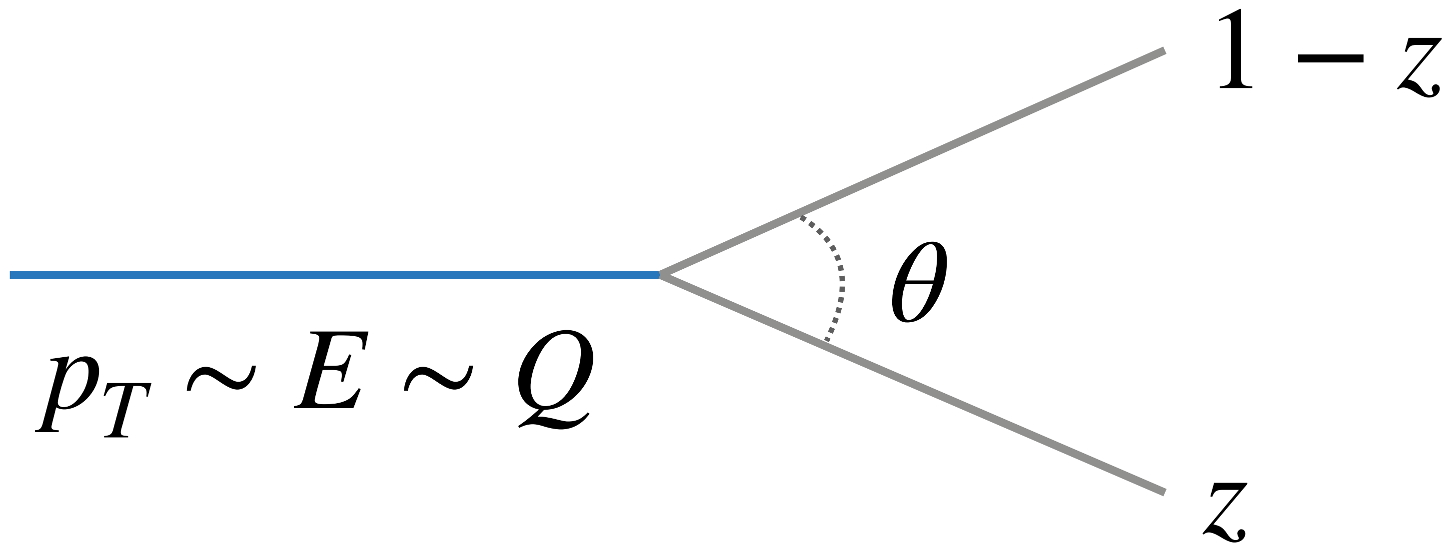
From quarks and gluons to QCD jets

2→2 hard scattering at LHC



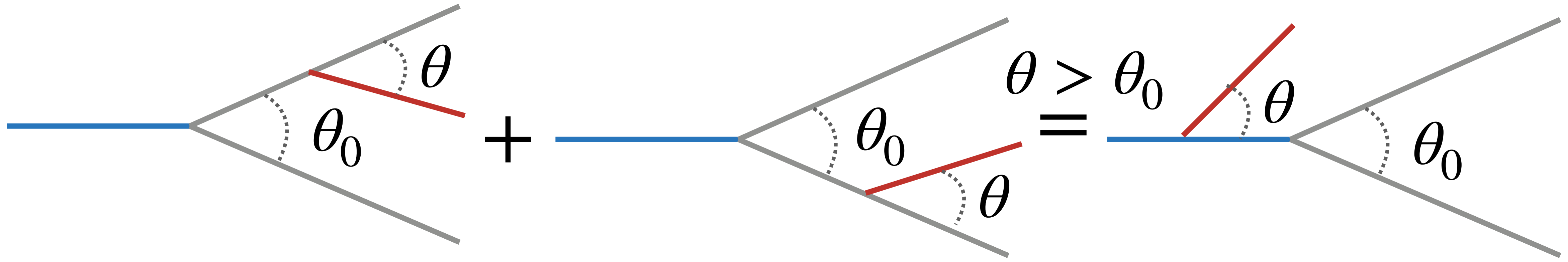
- Calculable in pQCD (NNLO for dijets)
- To be convolved with PDFs

Parton branching



$$d\Pi_{a\to bc} = \frac{\alpha_s}{\pi}\frac{d\theta}{\theta}P_{a\to bc}(z) \approx \frac{\alpha_s C_R}{\pi}\frac{dz}{z}\frac{d\theta}{\theta}$$

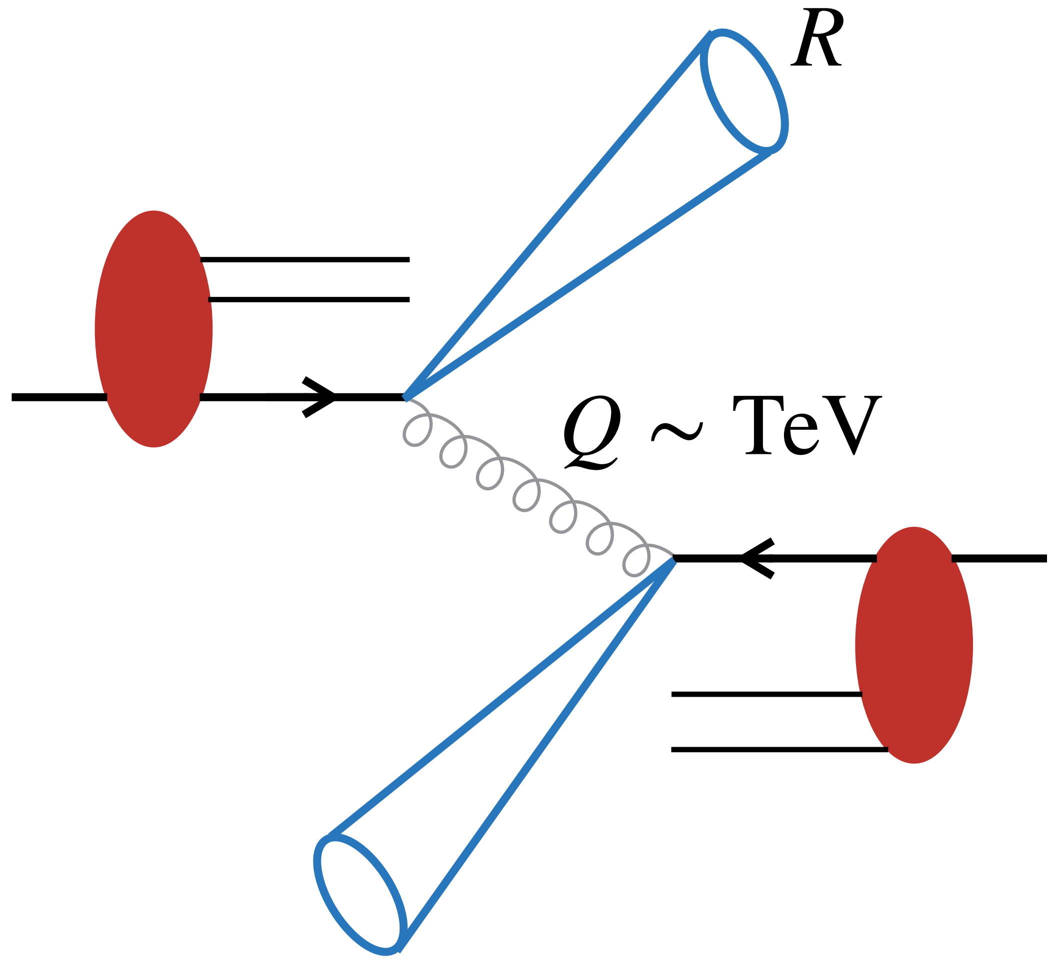
- Self-similar subsequent emissions
- Angular ordering as due to color coherence



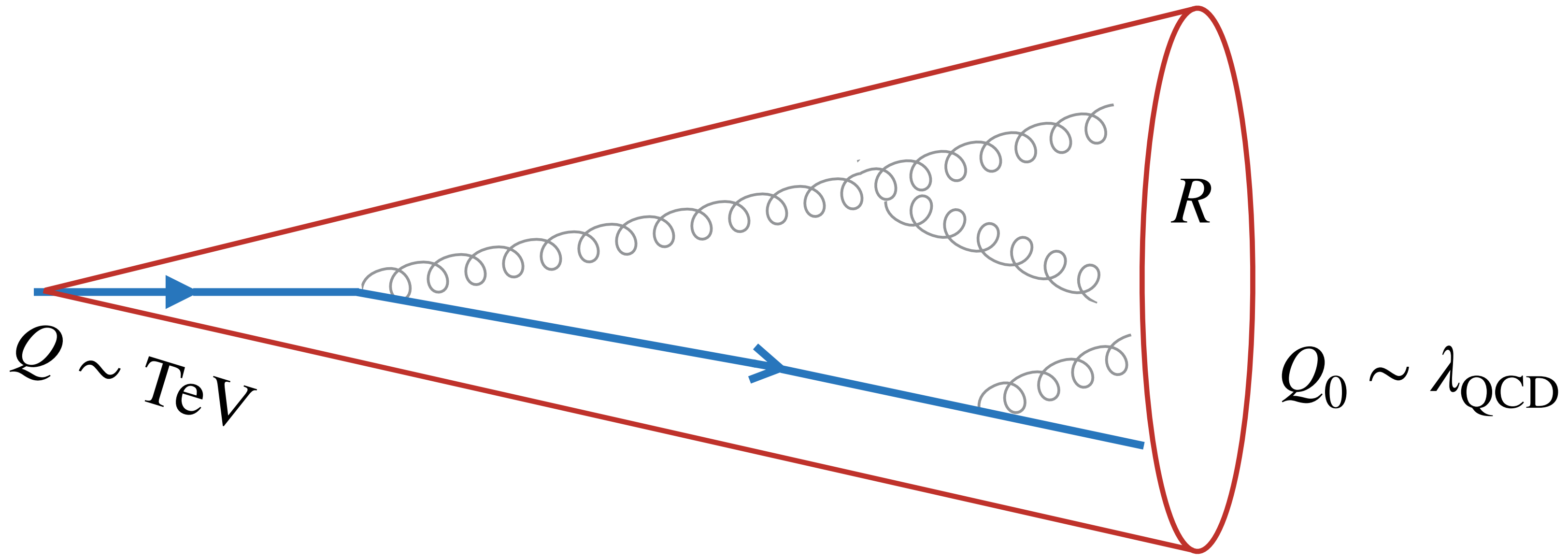
[Dokshitzer, Mueller et al '91]

QCD jets: theory and experiment

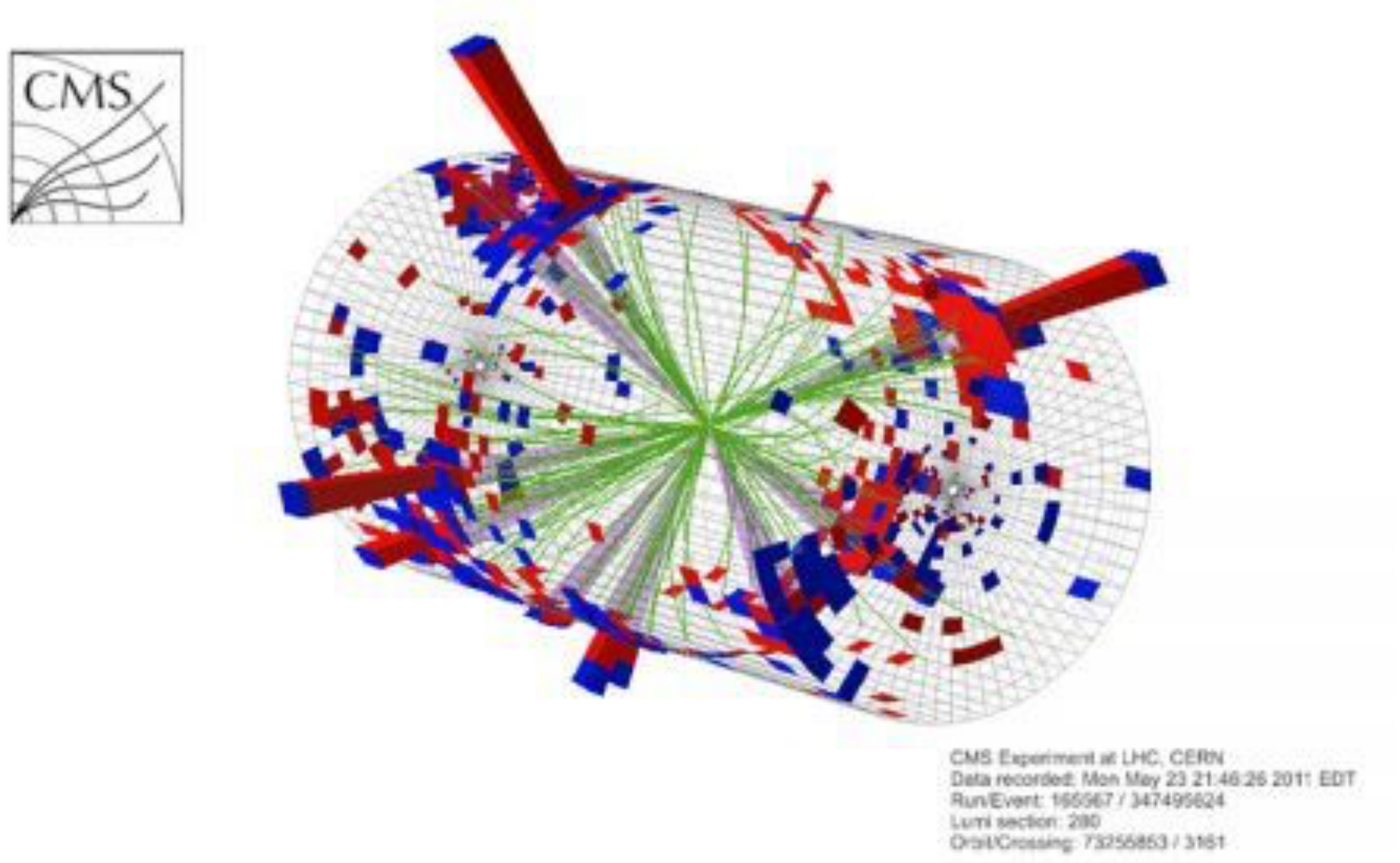
Theoretically: fragmentation of a highly energetic parton [Sterman, Weinberg '77]

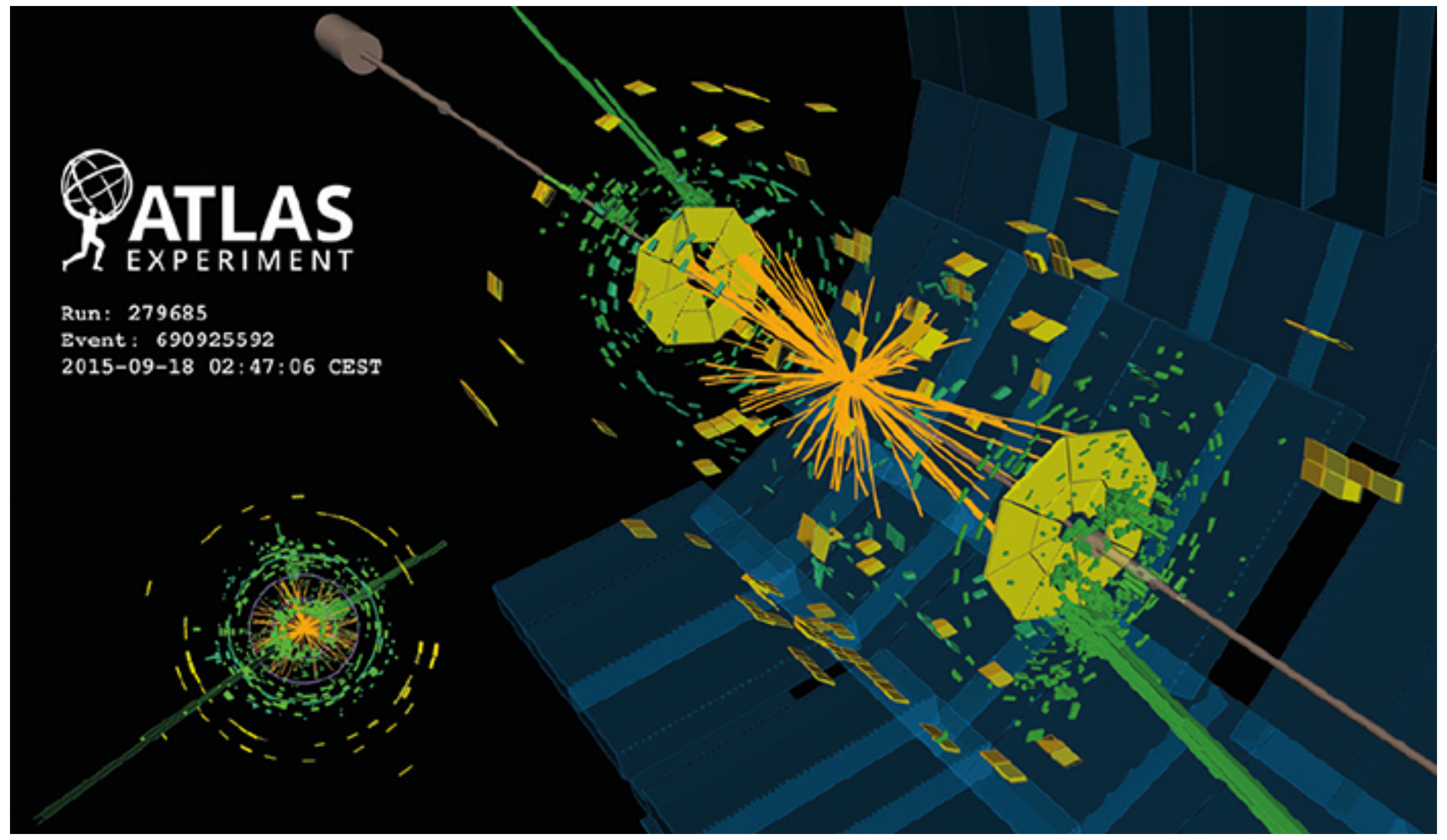


with



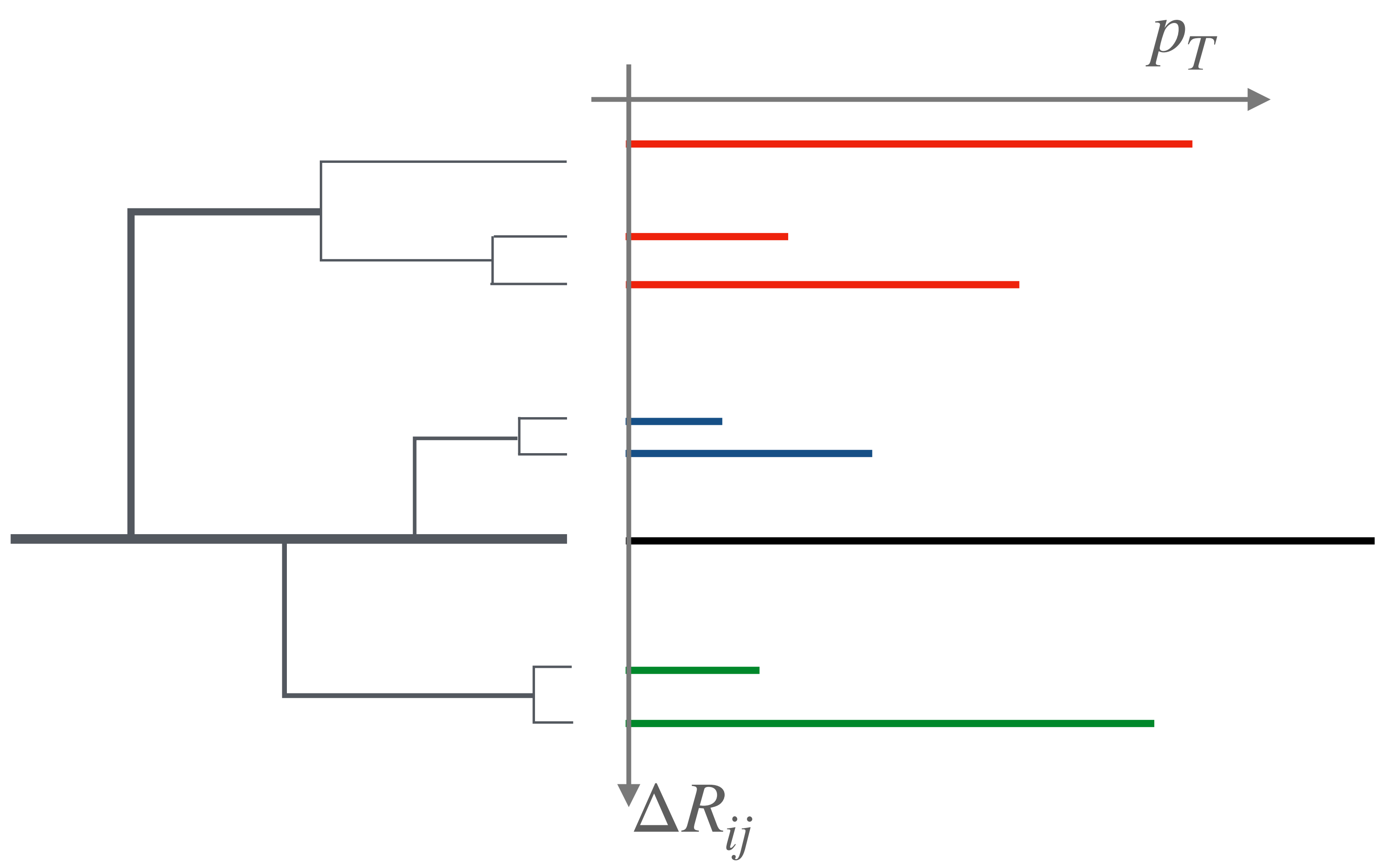
Experimentally: collimated stream of particle tracks/energy deposition in calorimeter





Jet reconstruction: clustering algorithms

Provide an operational definition of a jet to enable theory-to-data comparisons



Invert QCD branching process through pairwise clustering of particles that minimize

$$d_{ij} = \min(p_{\mathrm{T},i}^{2\alpha}, p_{\mathrm{T},j}^{2\alpha})\Delta R_{ij}^2/R^2$$

Cambridge/Aachen (C/A)

- Only angular measure ($\alpha = 0$)
- Ideal for substructure measurements

[Dokshitzer et al '97]

k_T algorithm

- k_T weighted metric ($\alpha = 1$)
- Sensitive to soft activity

[Catani et al '93, Ellis, Sopper '93]

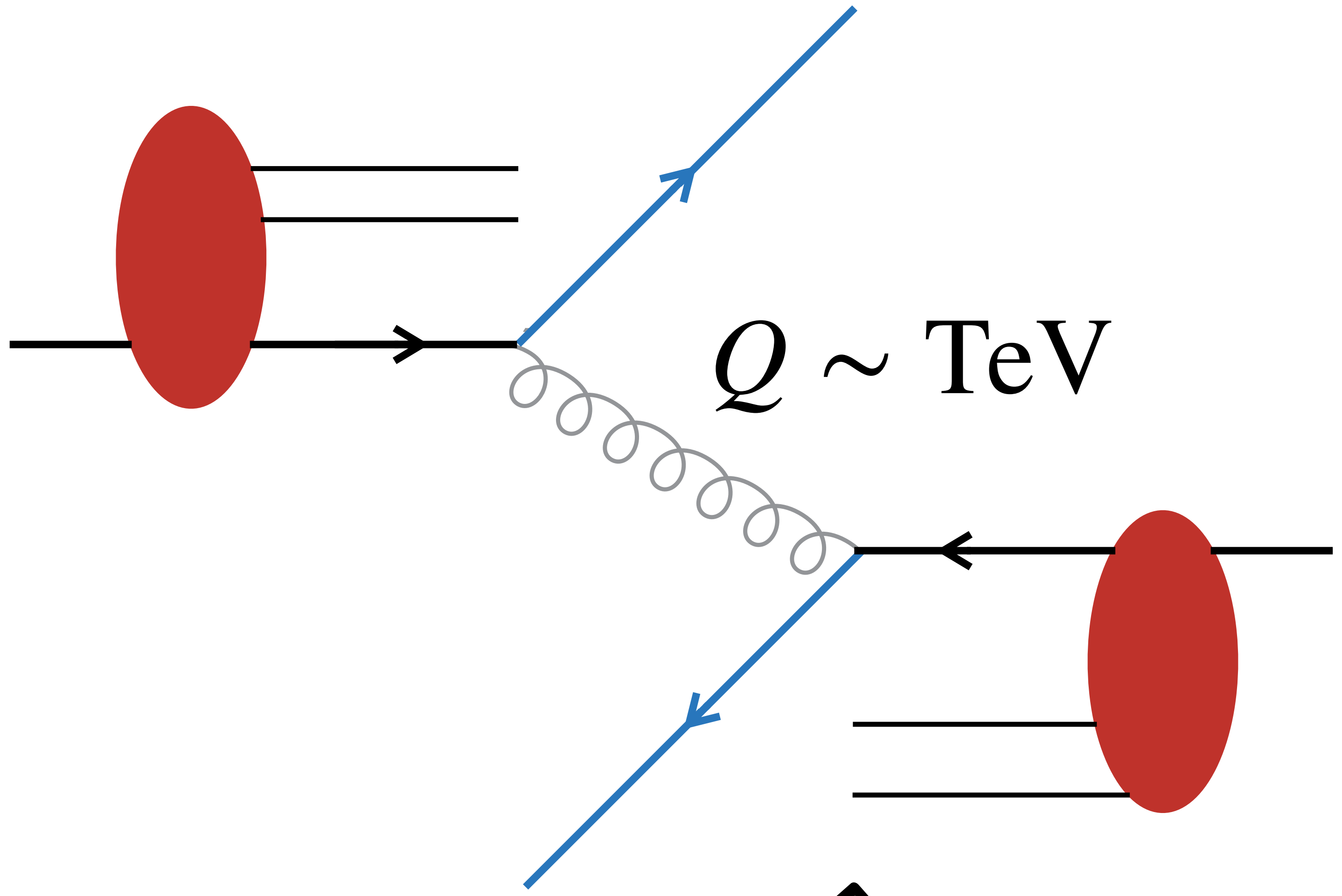
anti-k_T algorithm

- anti-k_T weighted metric ($\alpha = -1$)
- Resilient to soft activity, ideal for identifying candidate jets

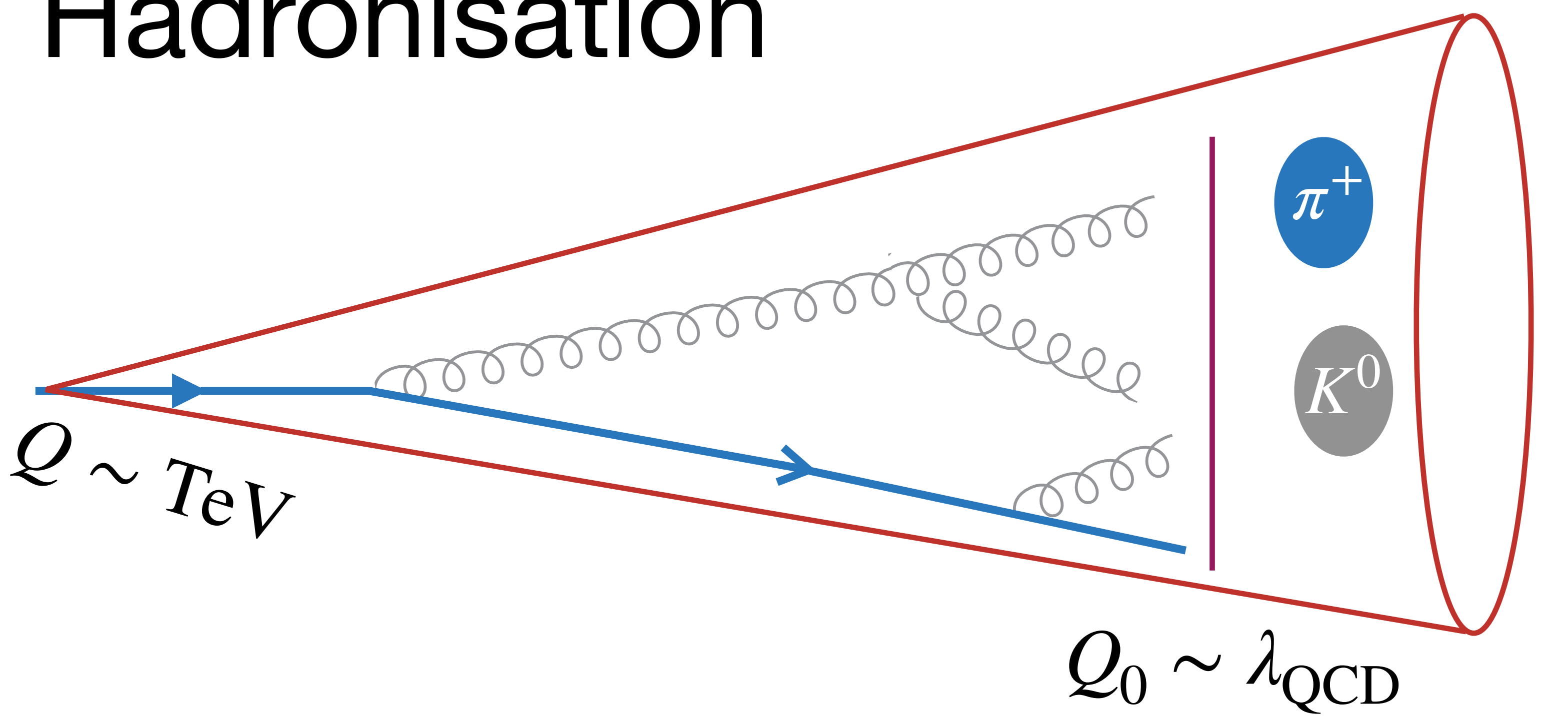
[Cacciari, Salam, Soyez '08]

Jets environment at hadronic colliders

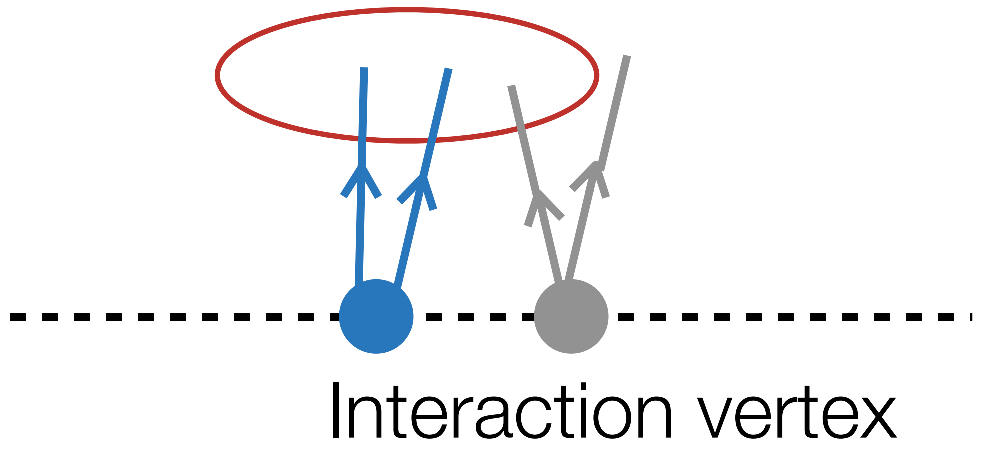
Not an isolated process…



- Hadronisation



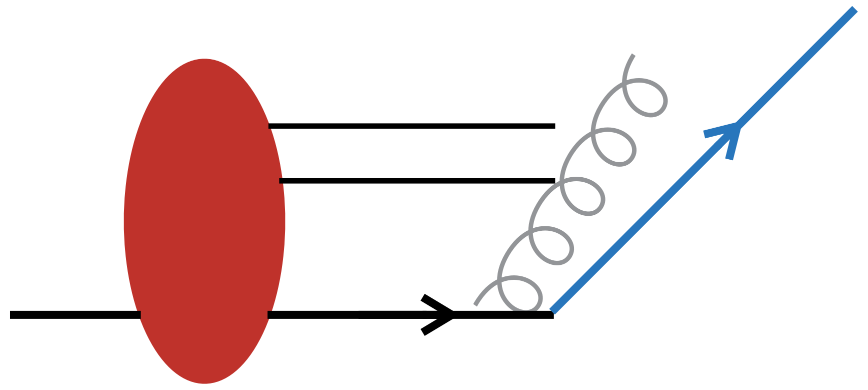
- Pileup

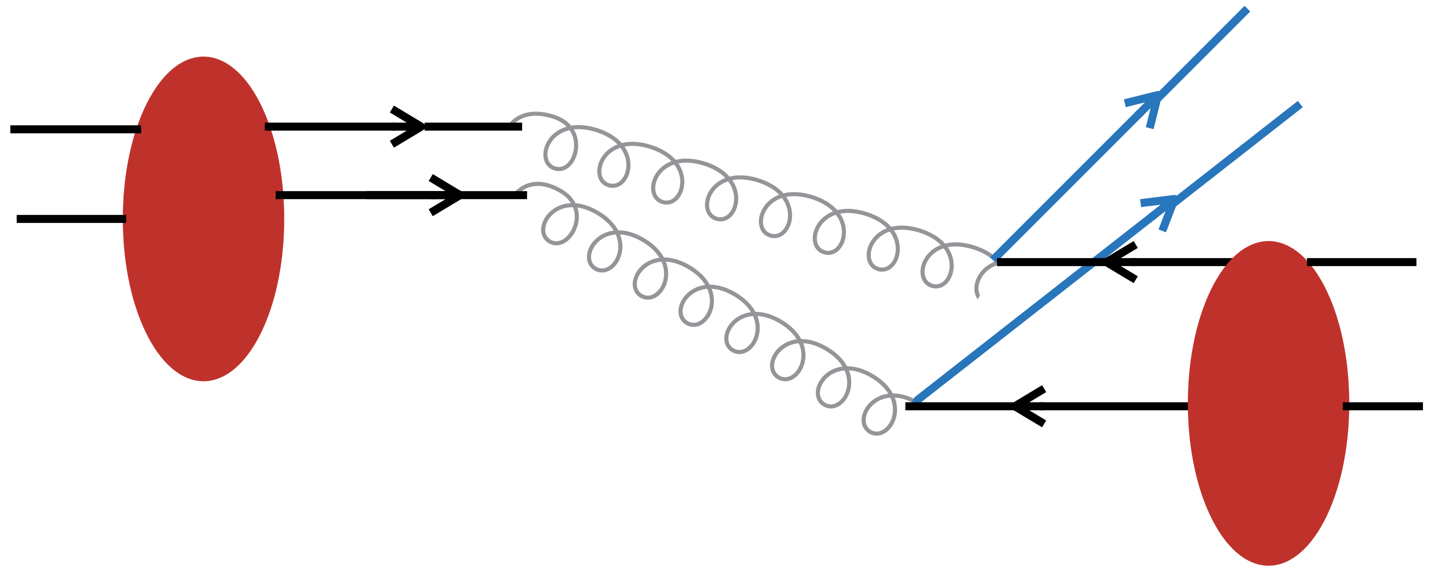


LHC: $\langle n_{\text{PU}} \rangle \sim 60$

HL-LHC: $\langle n_{\text{PU}} \rangle \sim 200$

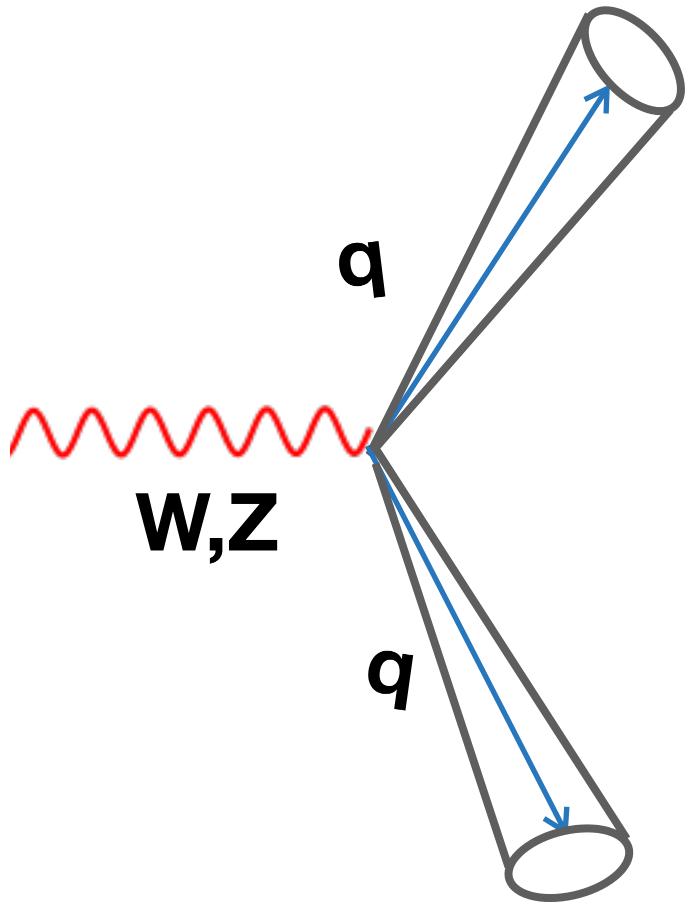
- Initial state radiation + Multi-parton interactions = underlying event





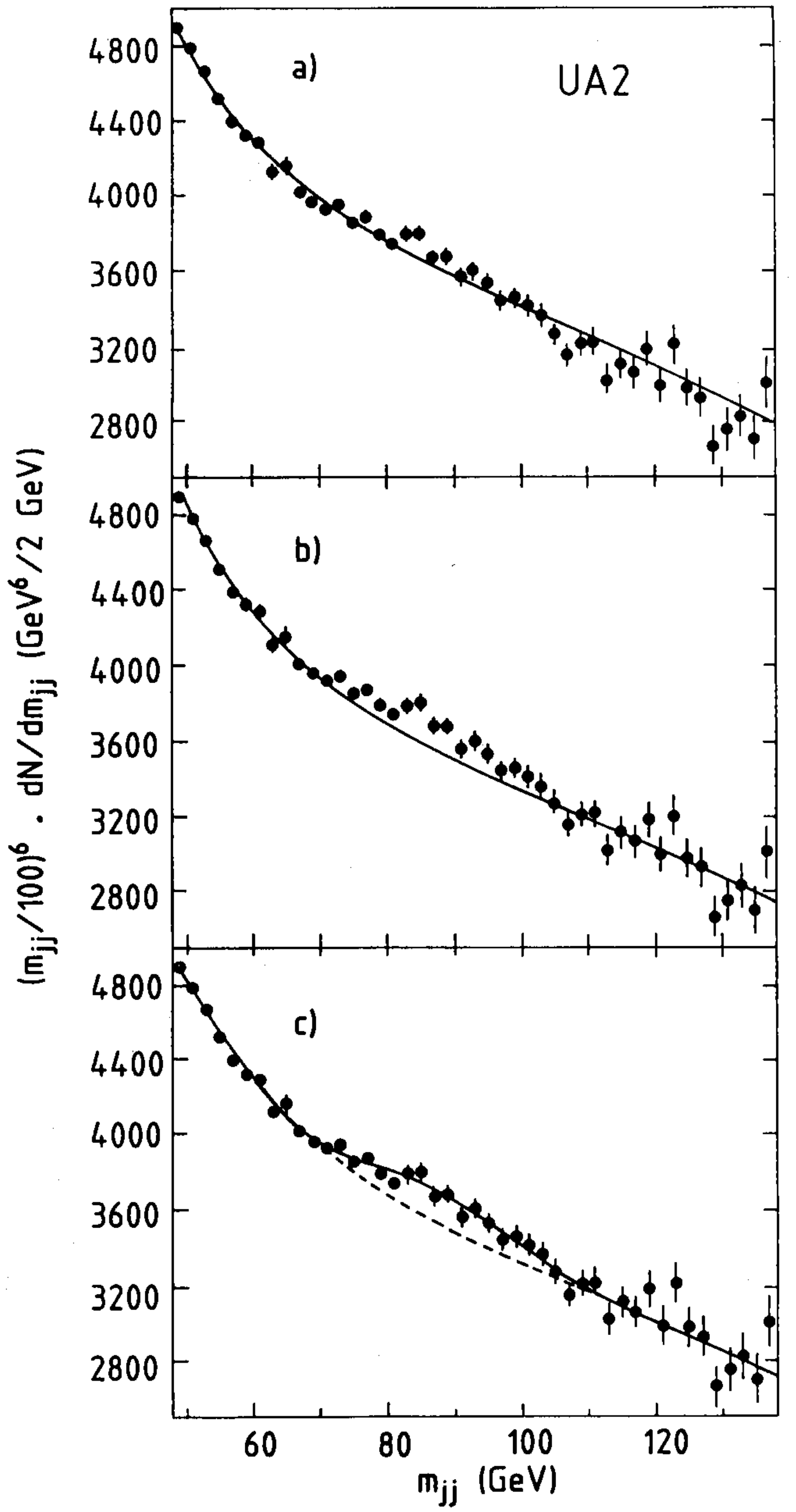
Jets as tools for particle searches

Standard search for particle X: look for bump in the dijet mass spectrum at M_X



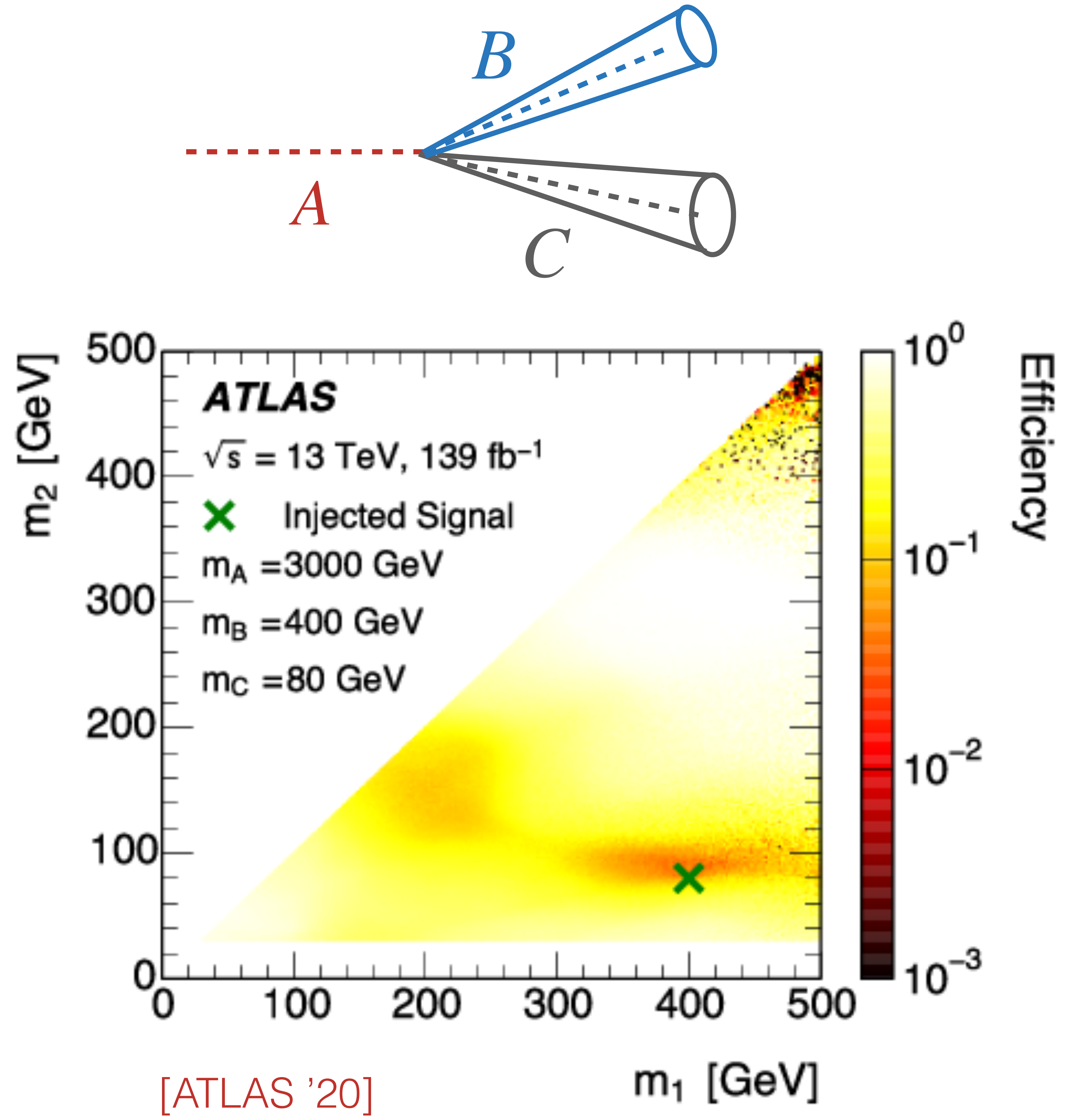
$p_T \sim M_X$

2 jets



[UA2'90]

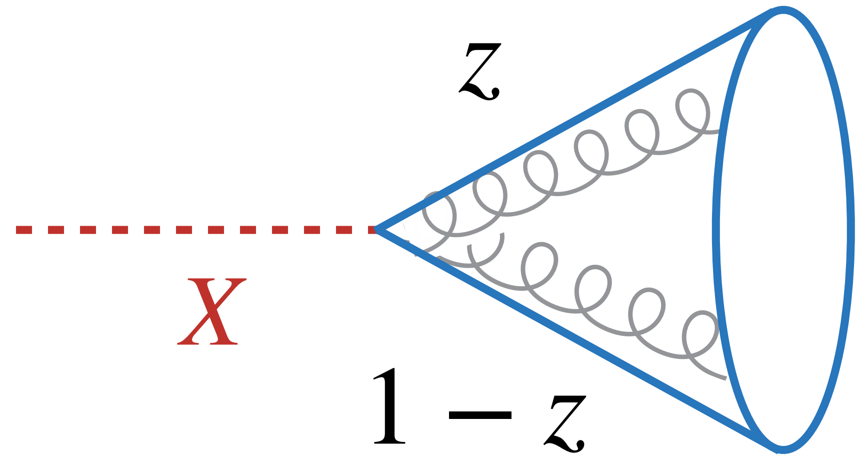
+30 years



Low efficiency ~ signal-like region

New particles at the EW scale

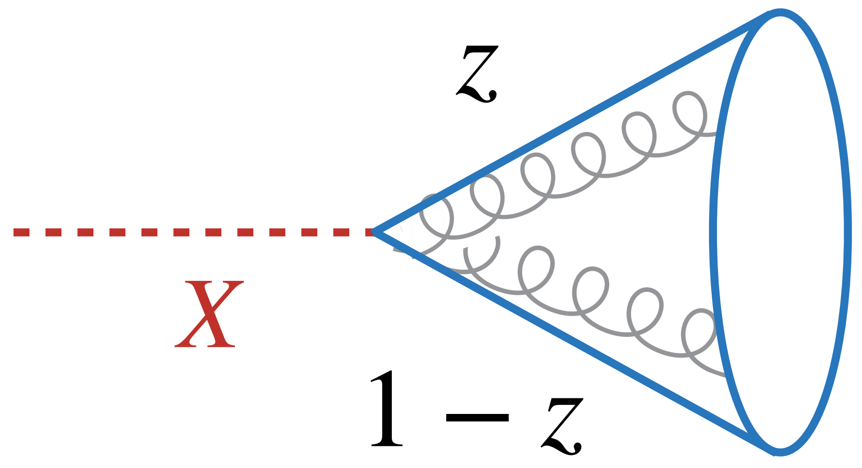
Boosted regime: LHC energies (10^4 GeV) >> electroweak scale (10^2 GeV)



$$\theta \approx \frac{1}{\sqrt{z(1-z)}} \frac{M_X}{p_{T,X}} \quad \text{with } p_{T,X} \gg M_X$$

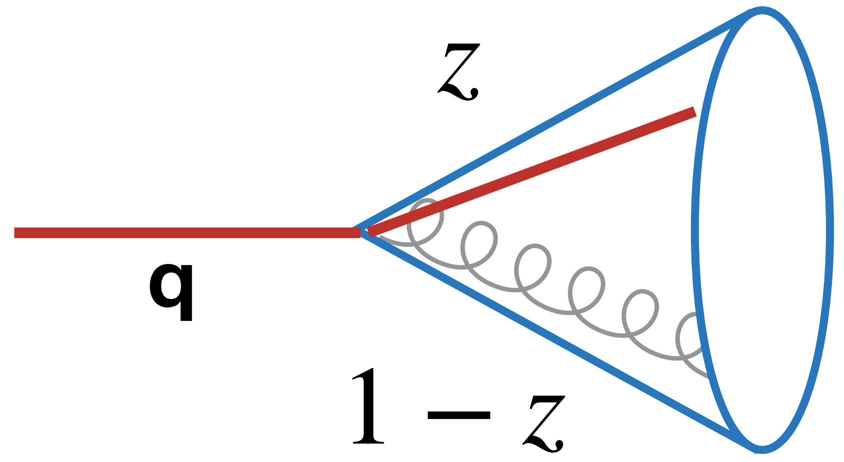
1 jet

Highly Lorentz-boosted resonances end up reconstructed as a single, large-R jet



Signal

vs

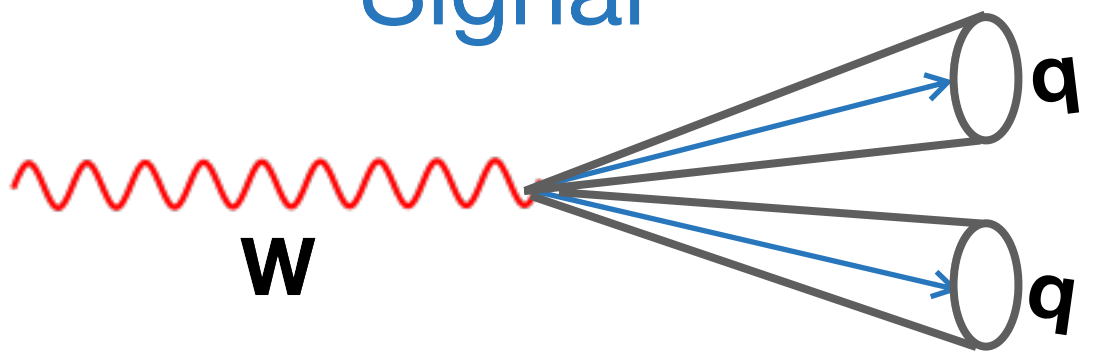


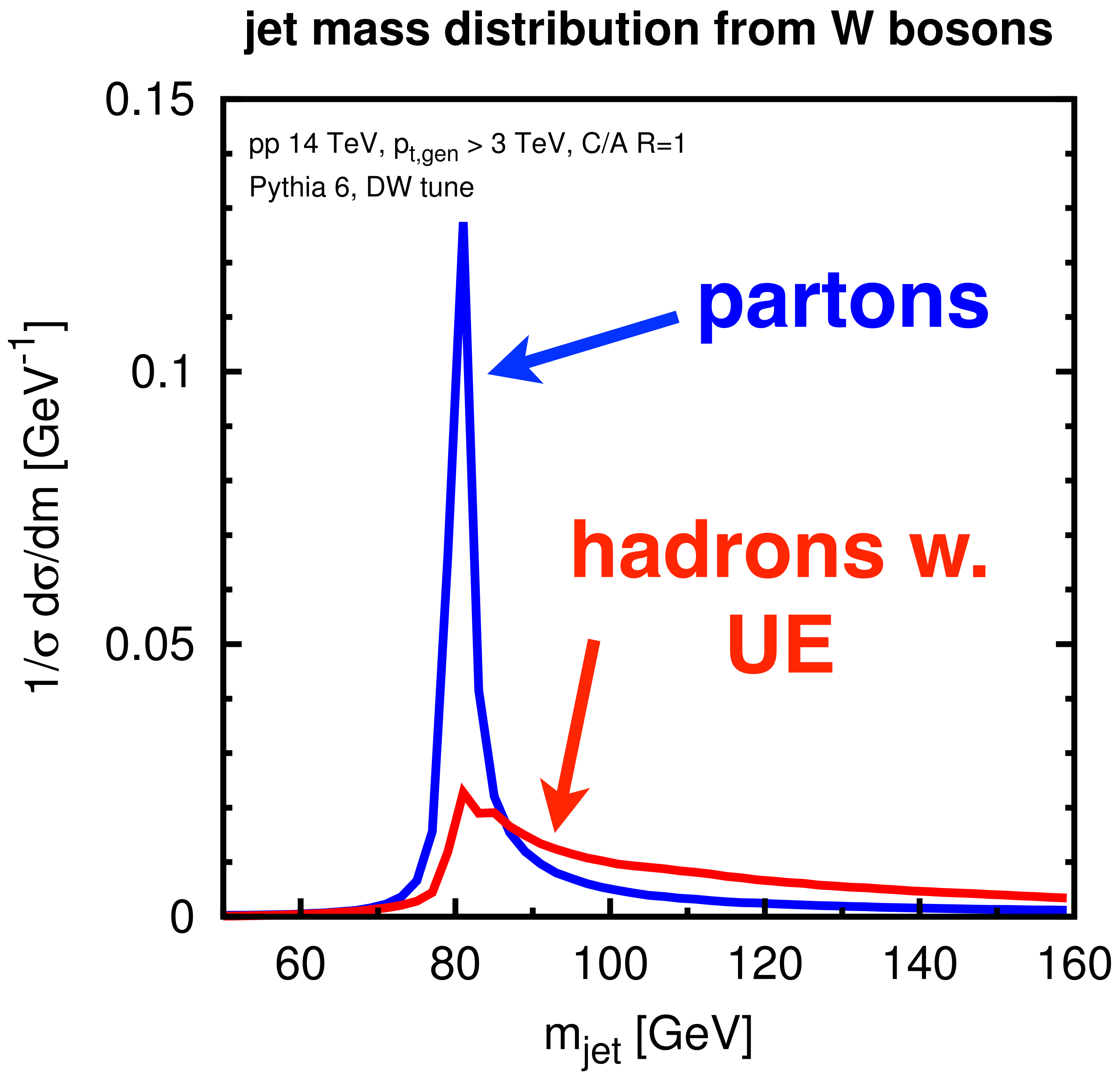
QCD background

How to distinguish signal jets from QCD background?

Jet mass discriminating power

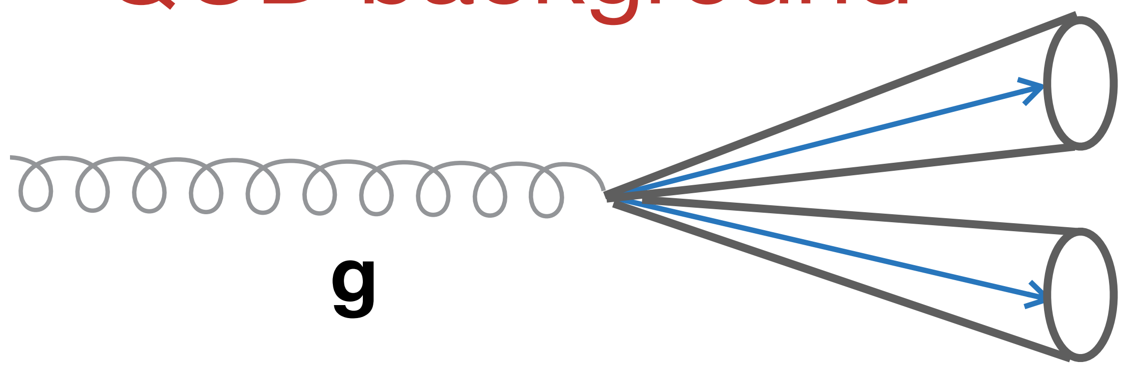
Signal

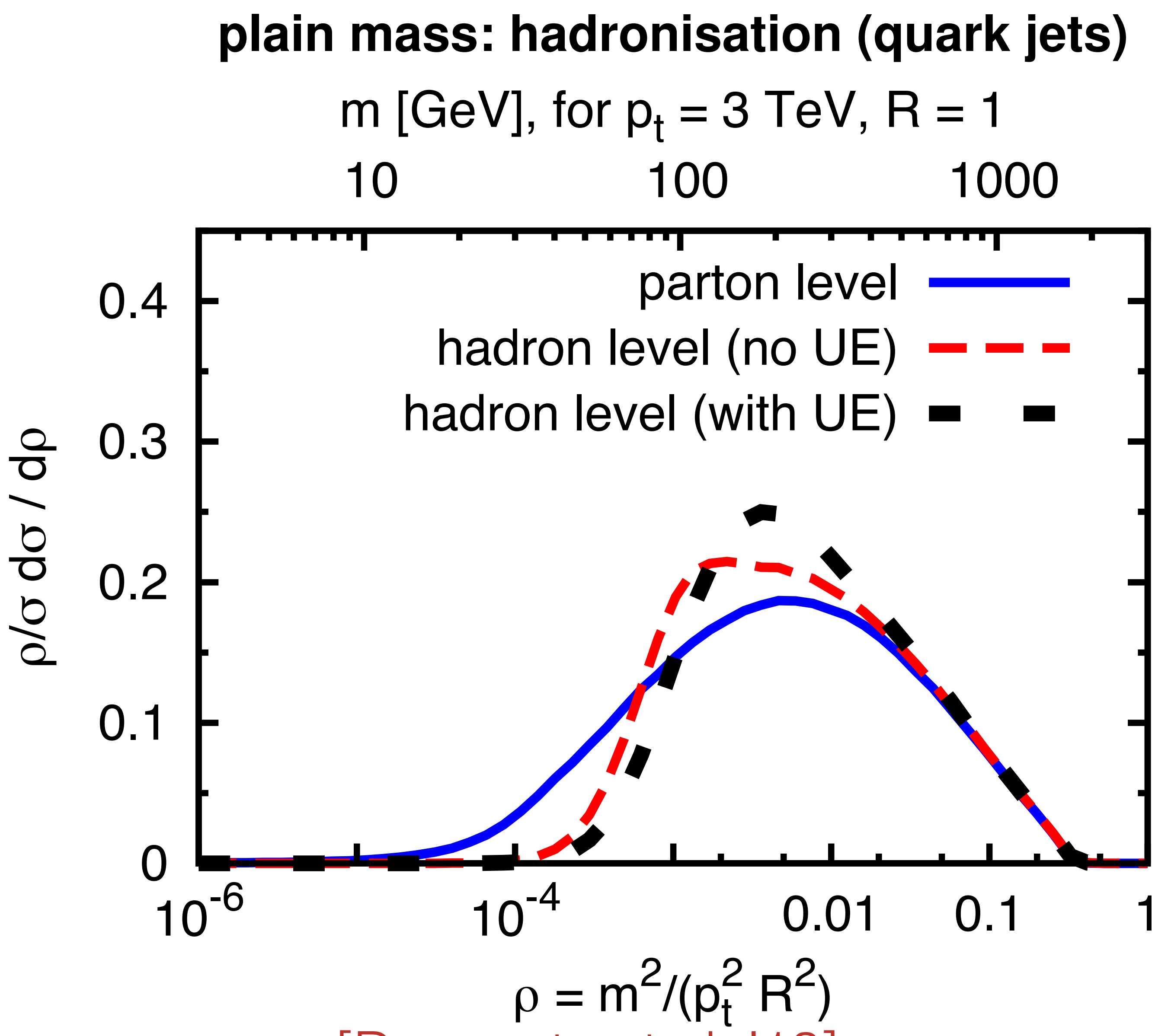




[Marzani BOOSTCamp'19]

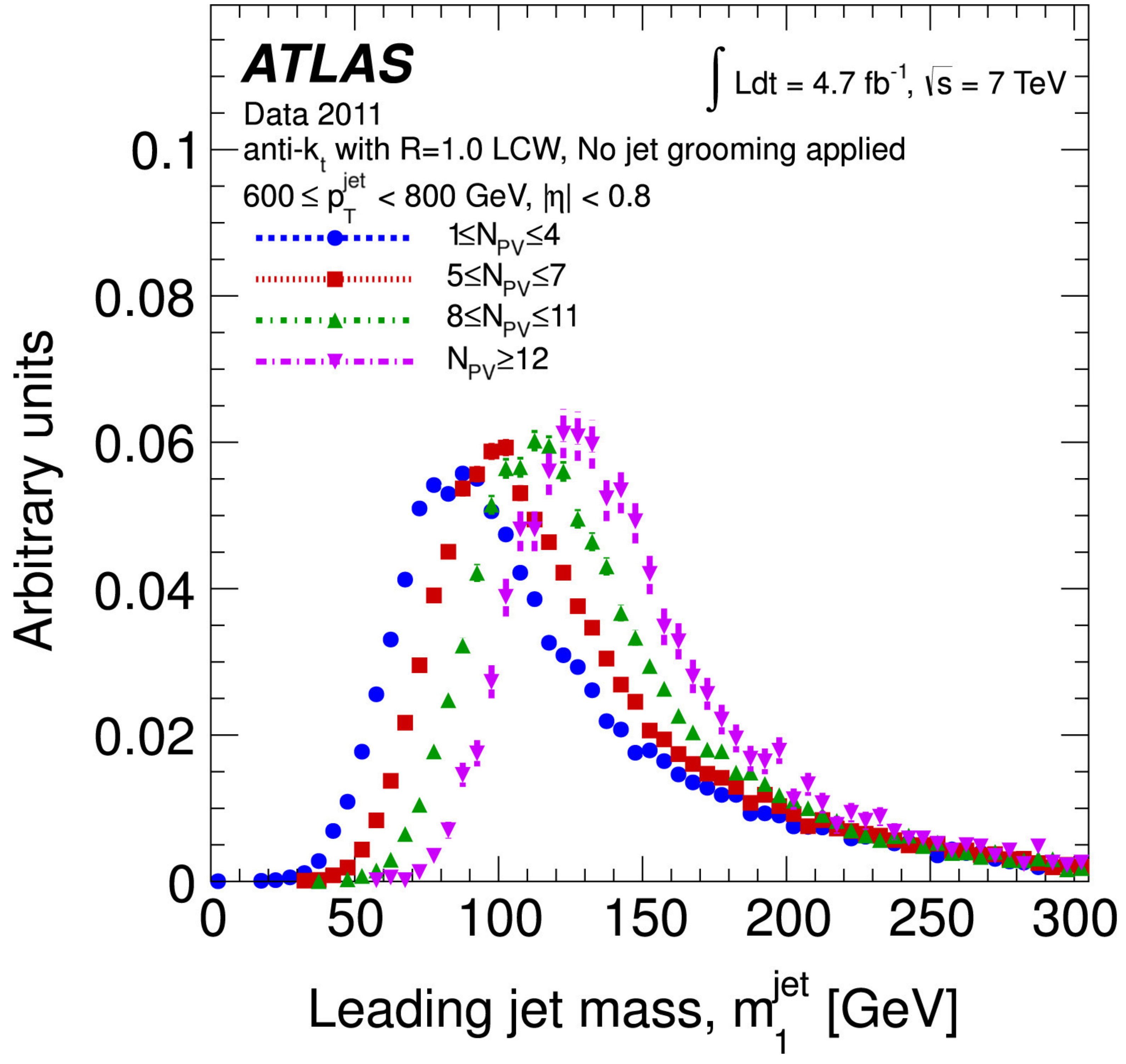
QCD background





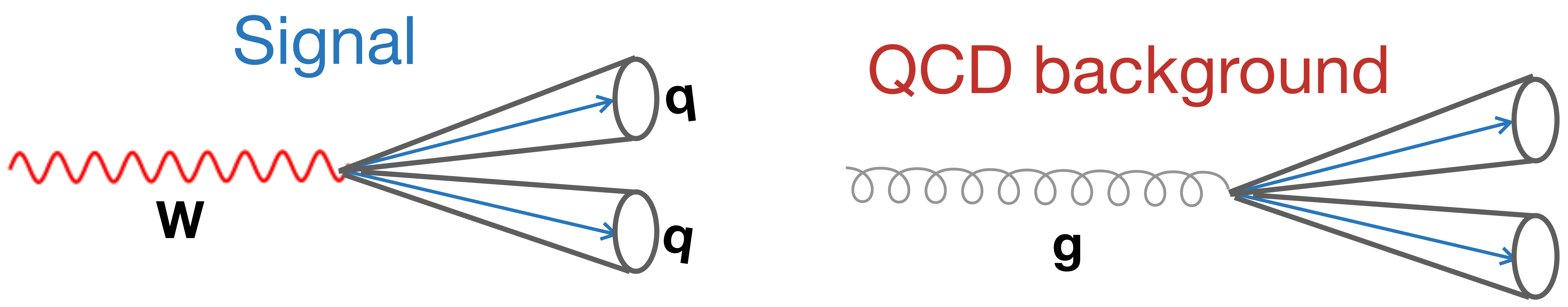
[Dasgupta et al. '13]

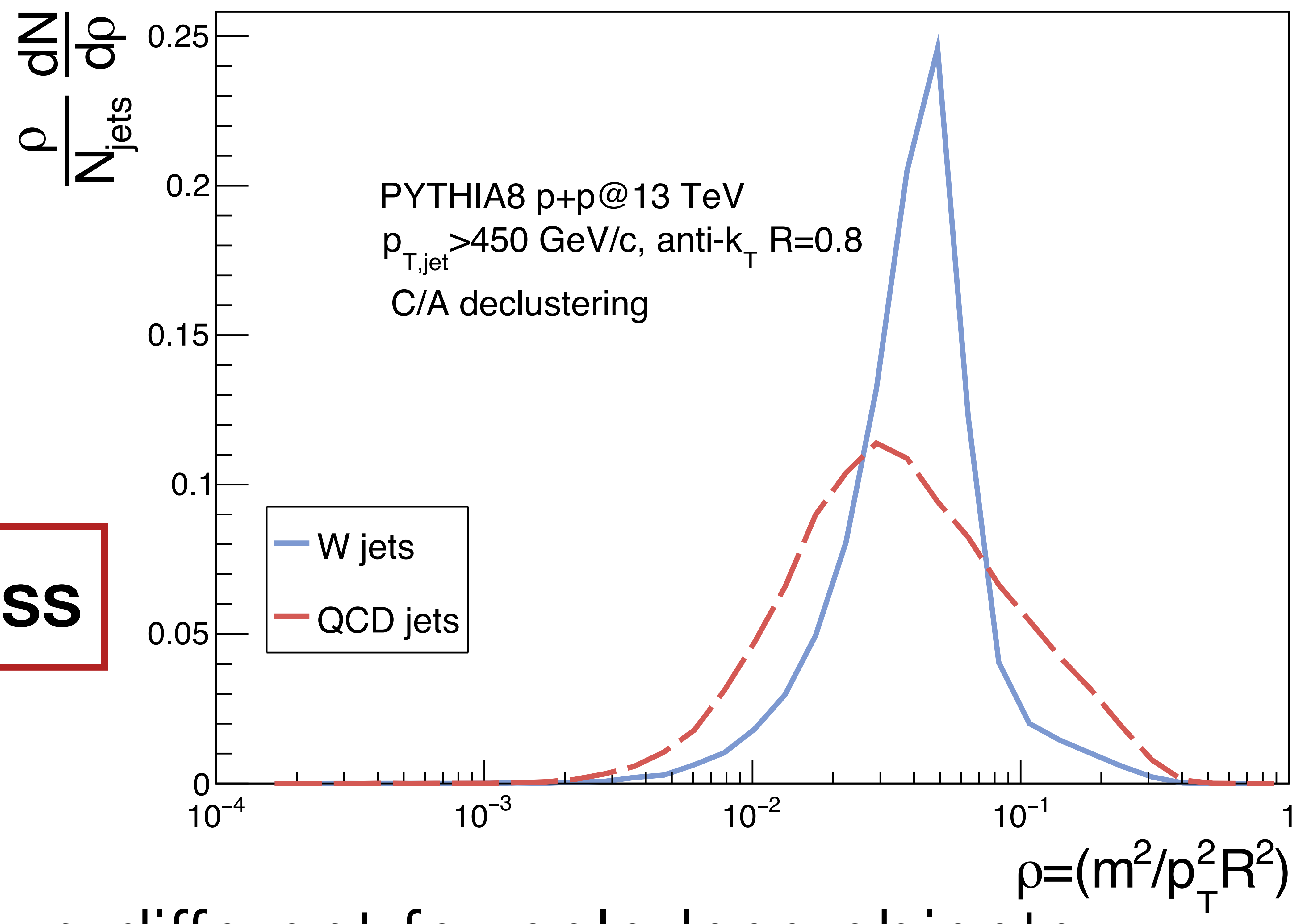
[ATLAS '15]



Jet mass is highly sensitive to non-perturbative contributions

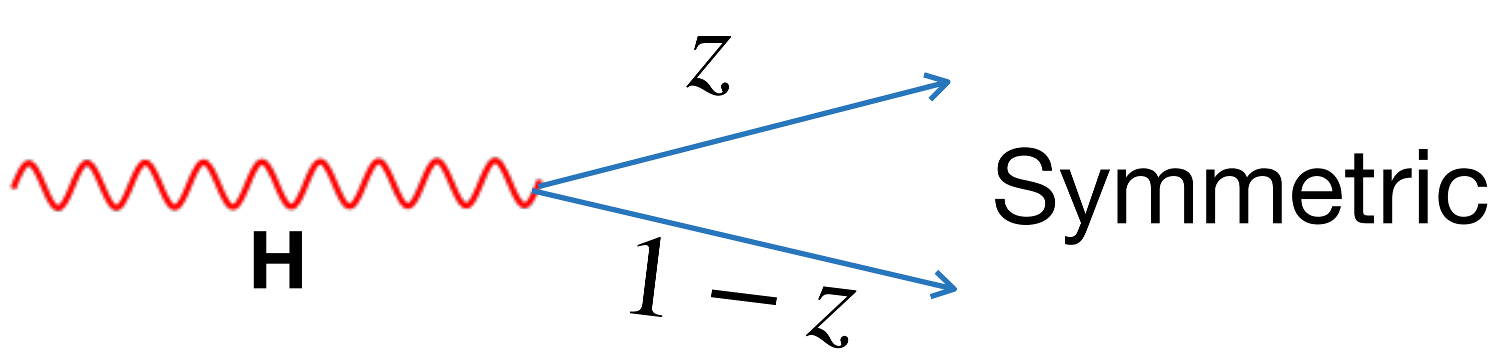
Beyond the jet mass: identifying boosted objects

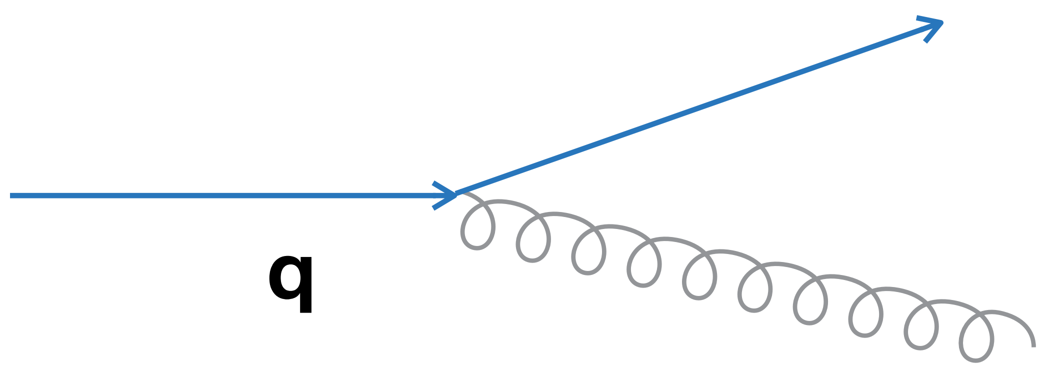




Not enough to put a cut on the *plain* jet mass

- **Exploit jet substructure:** e.g. radiation pattern different for colorless objects



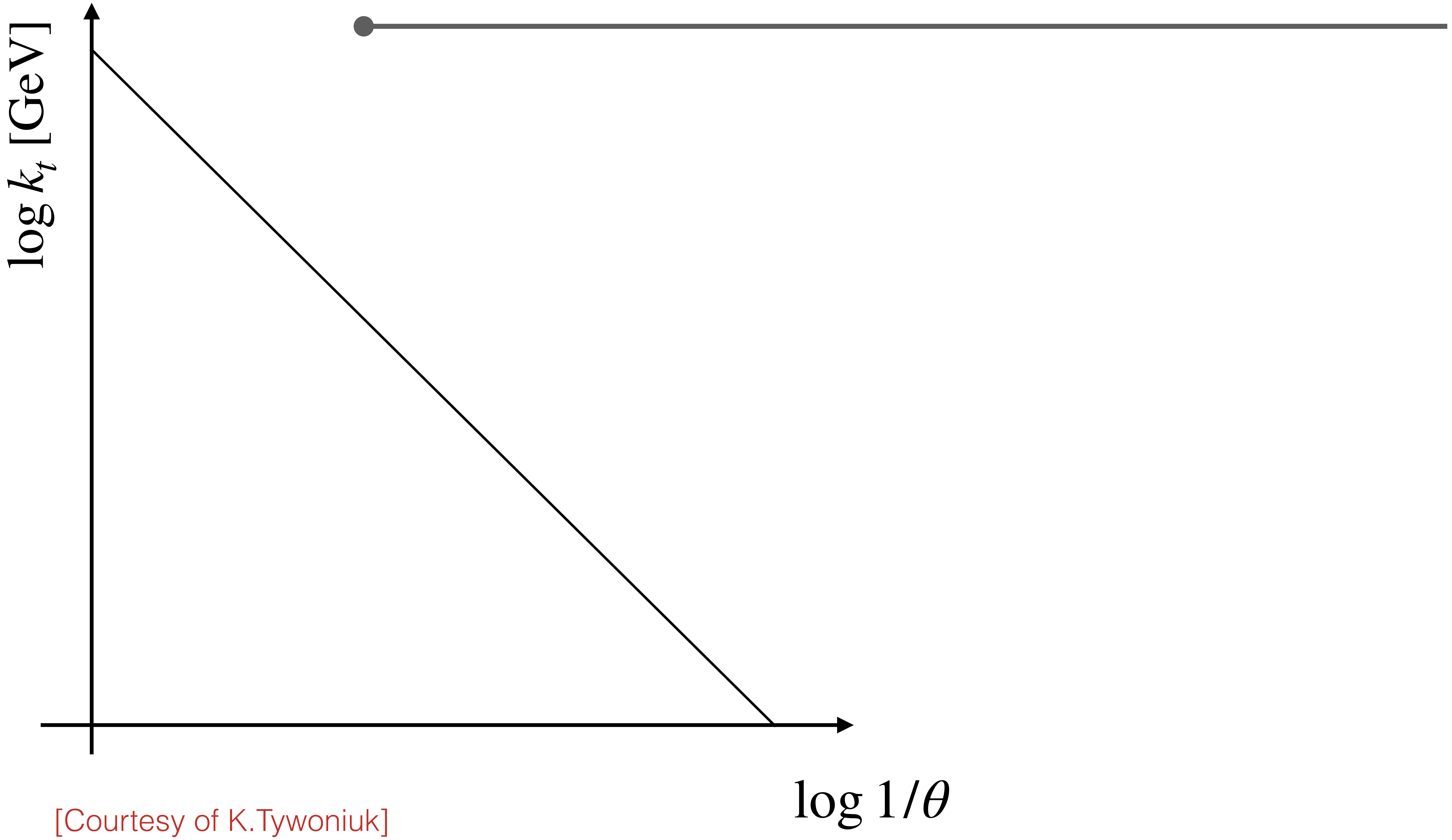


- **Grooming techniques:** remove soft, wide-angle radiation from the reconstructed jet
- **Machine learning** [Dreyer, Salam, Soyez'18]

Space-time picture of a jet: Lund plane representation

[Andersson, Gustafson, Lönnblad, Pettersson ’89]

$$t_{\mathrm{f}} = \frac{2z(1-z)p_T}{k_t^2}$$



[Courtesy of K.Tywoniuk]

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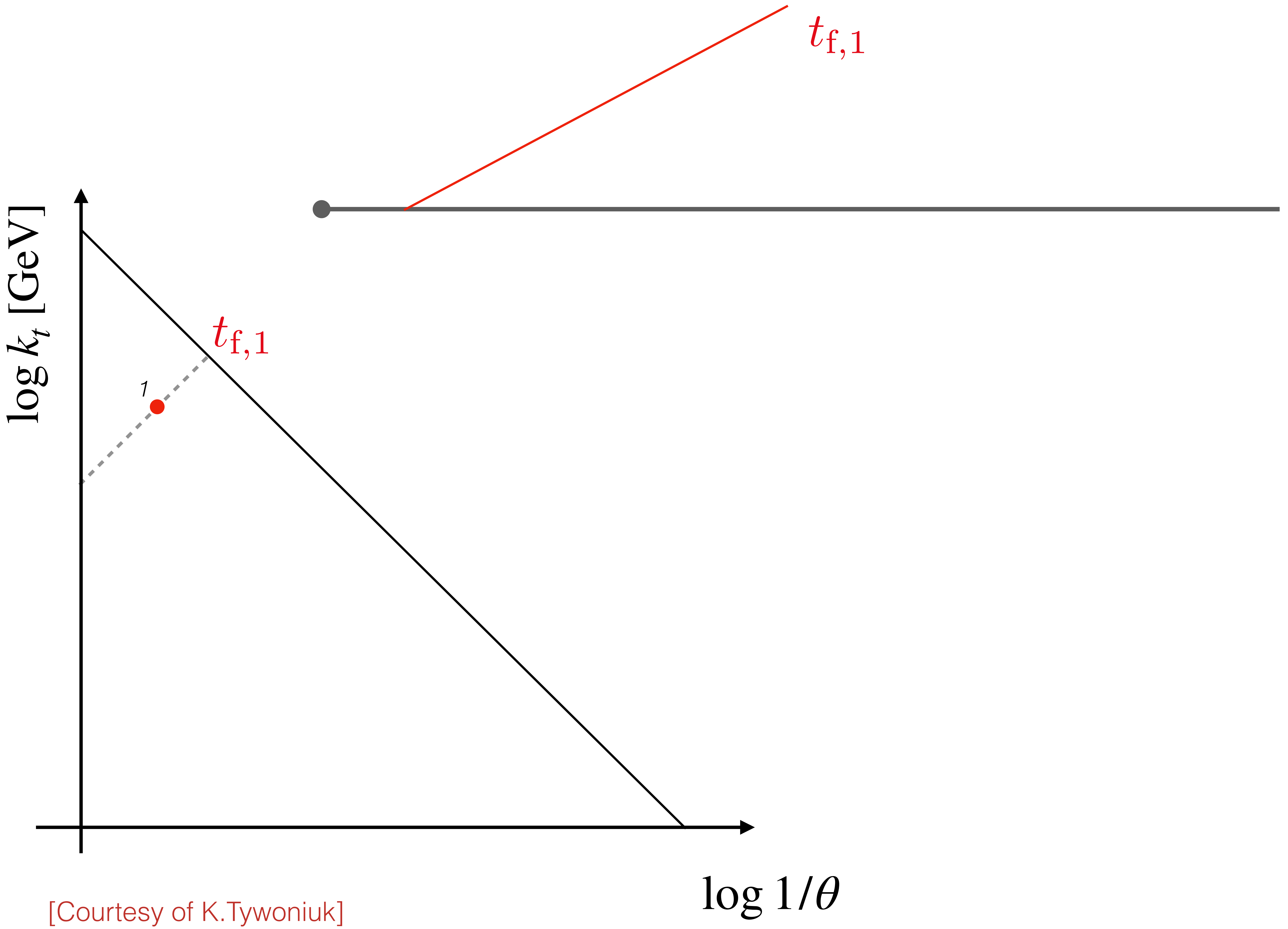

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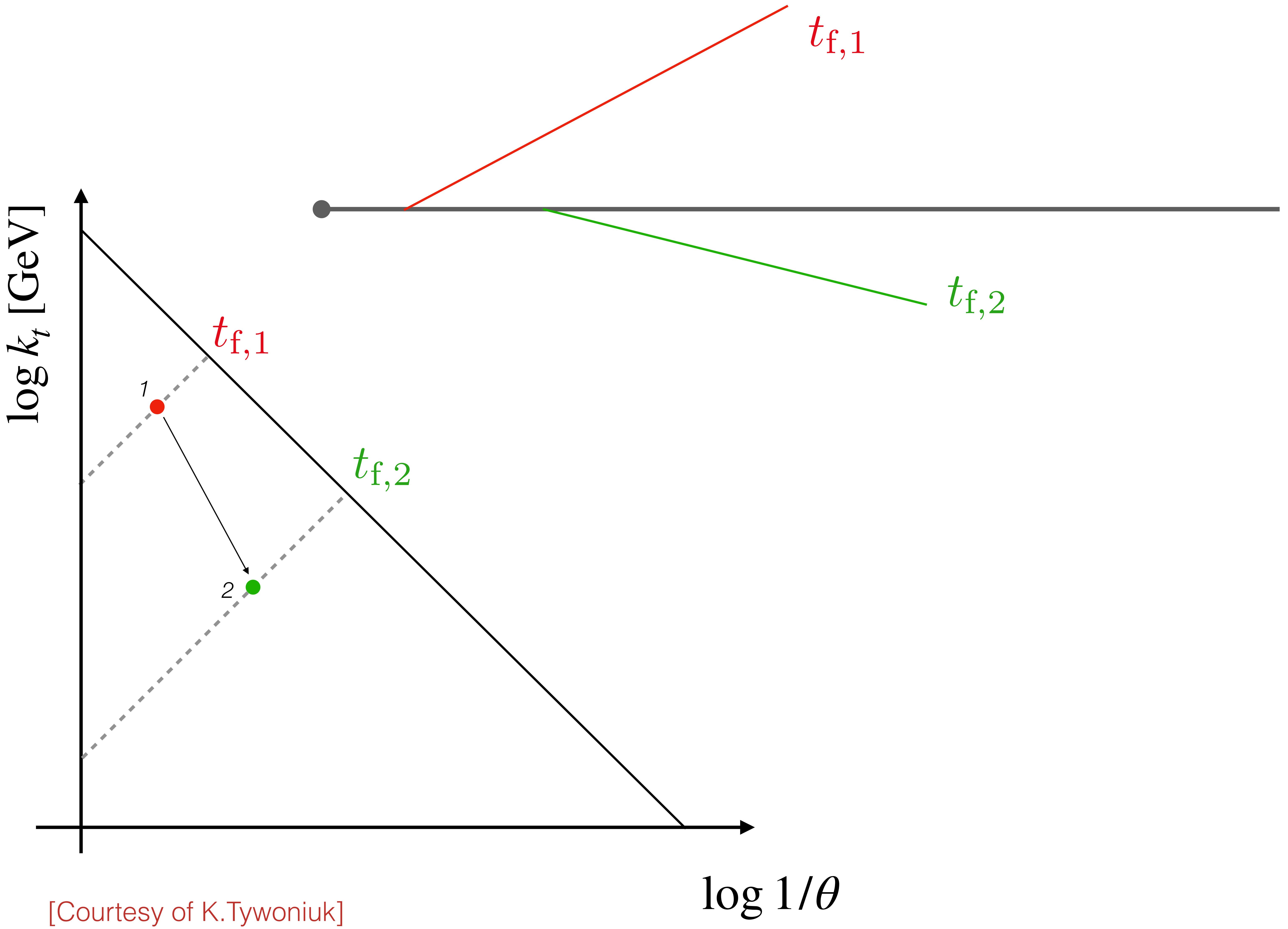

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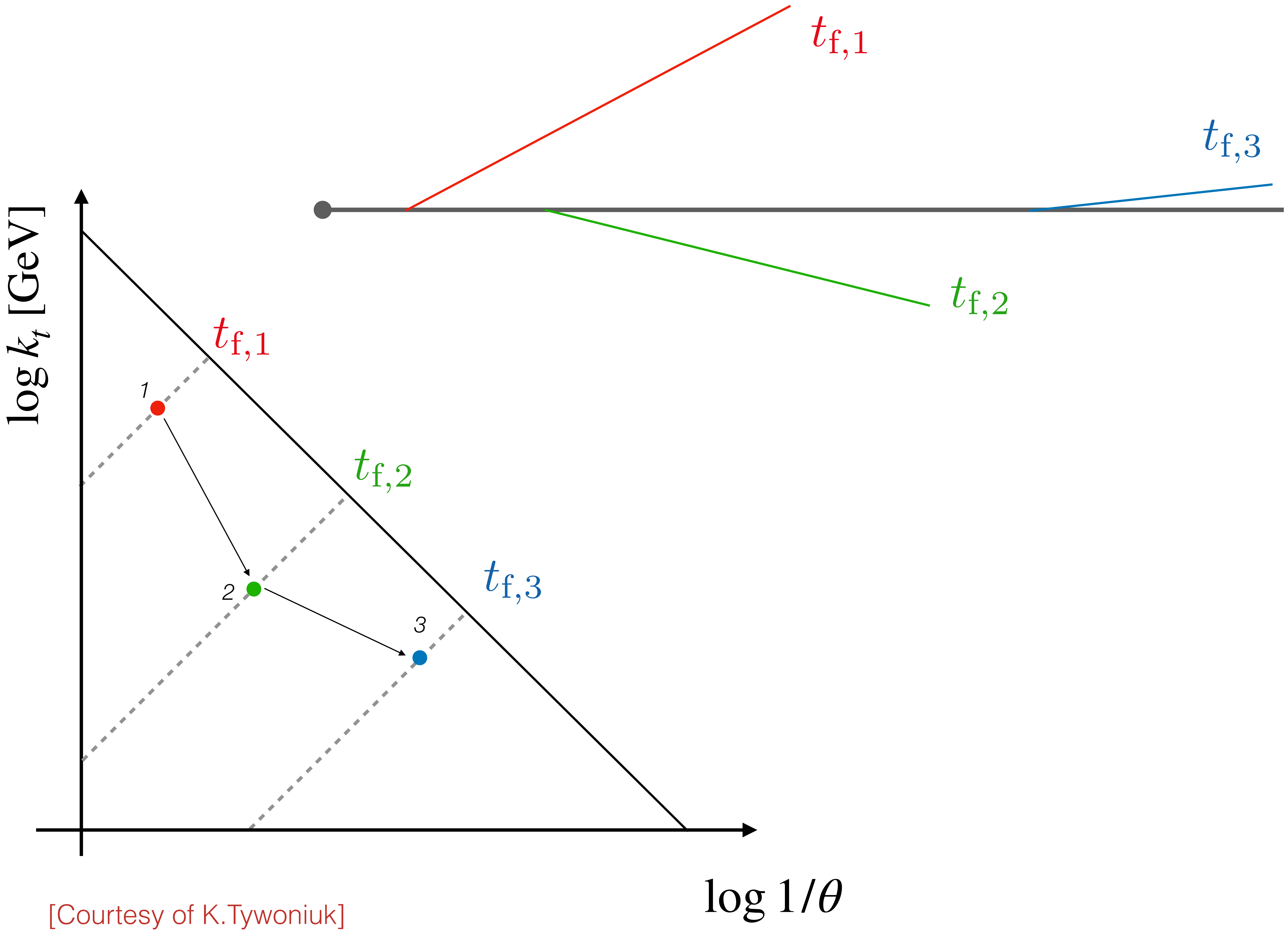

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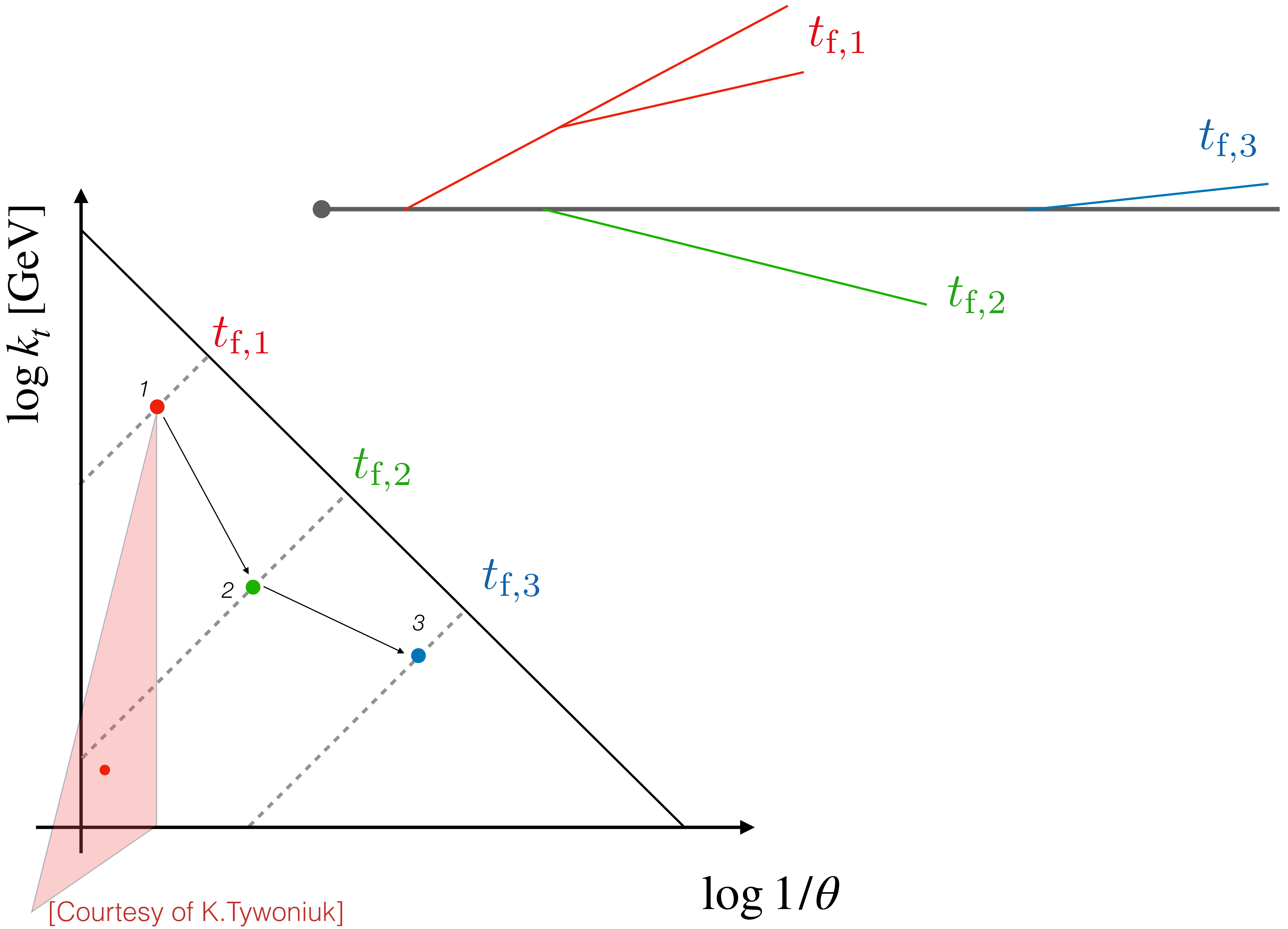

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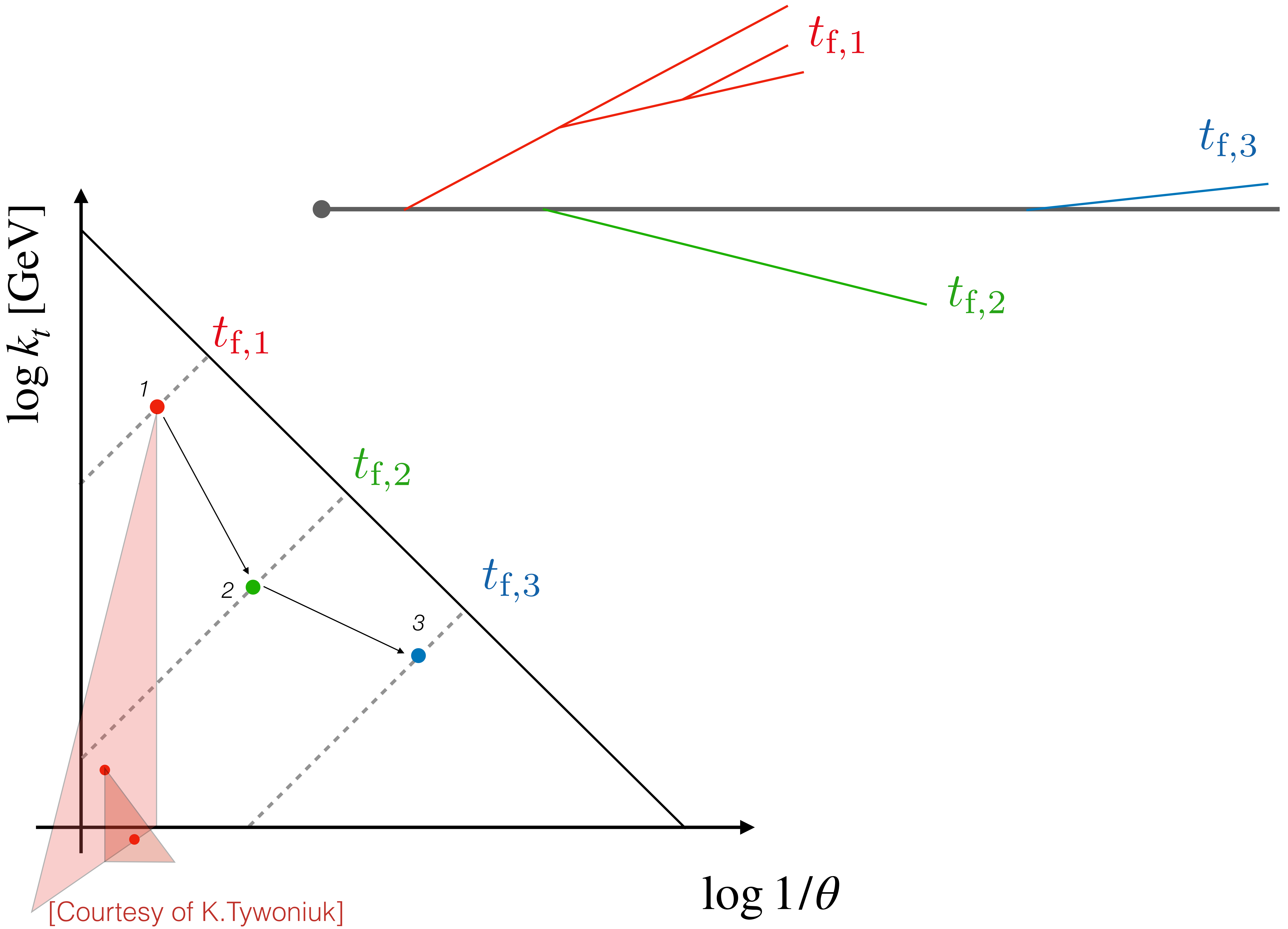

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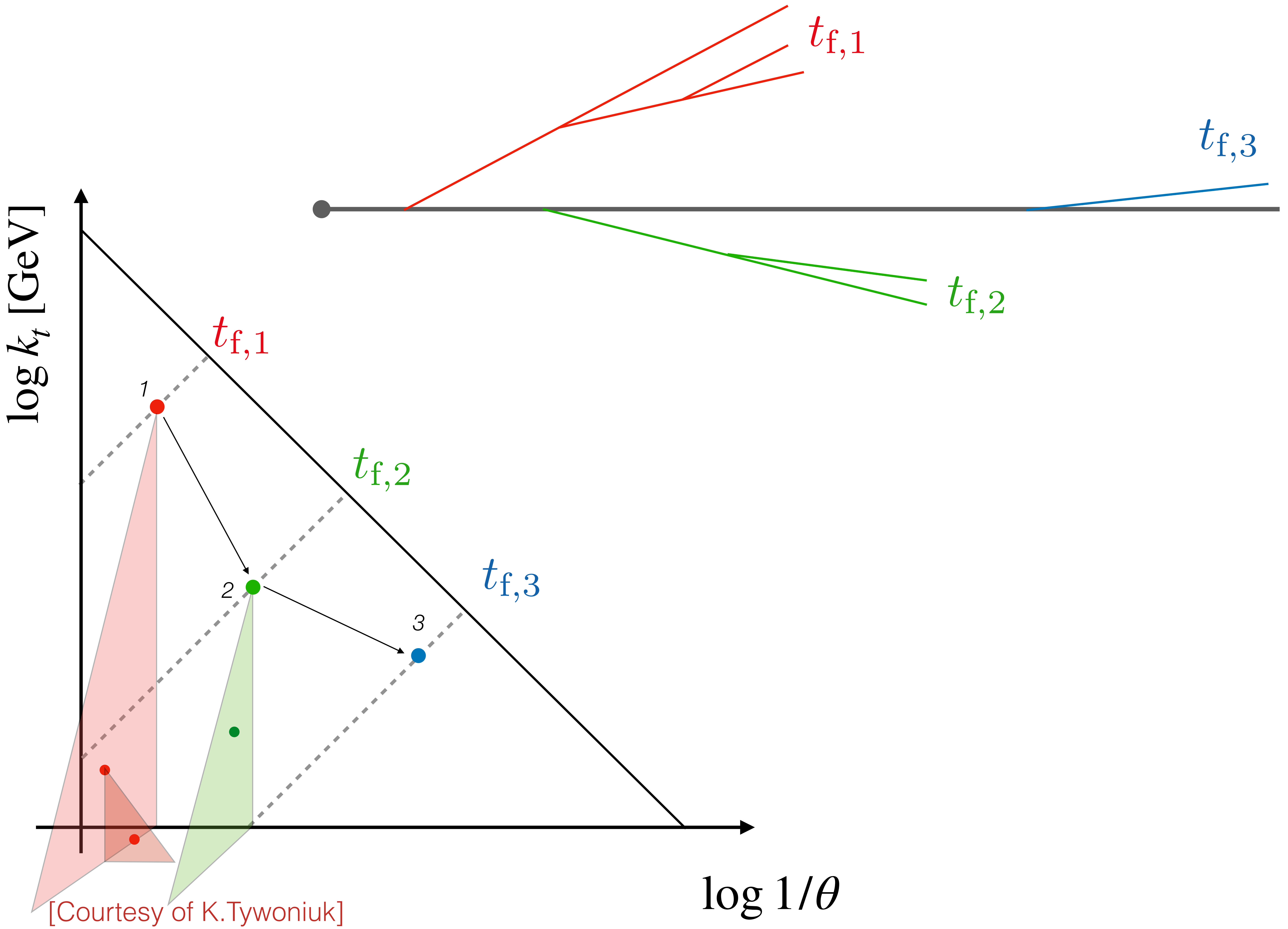

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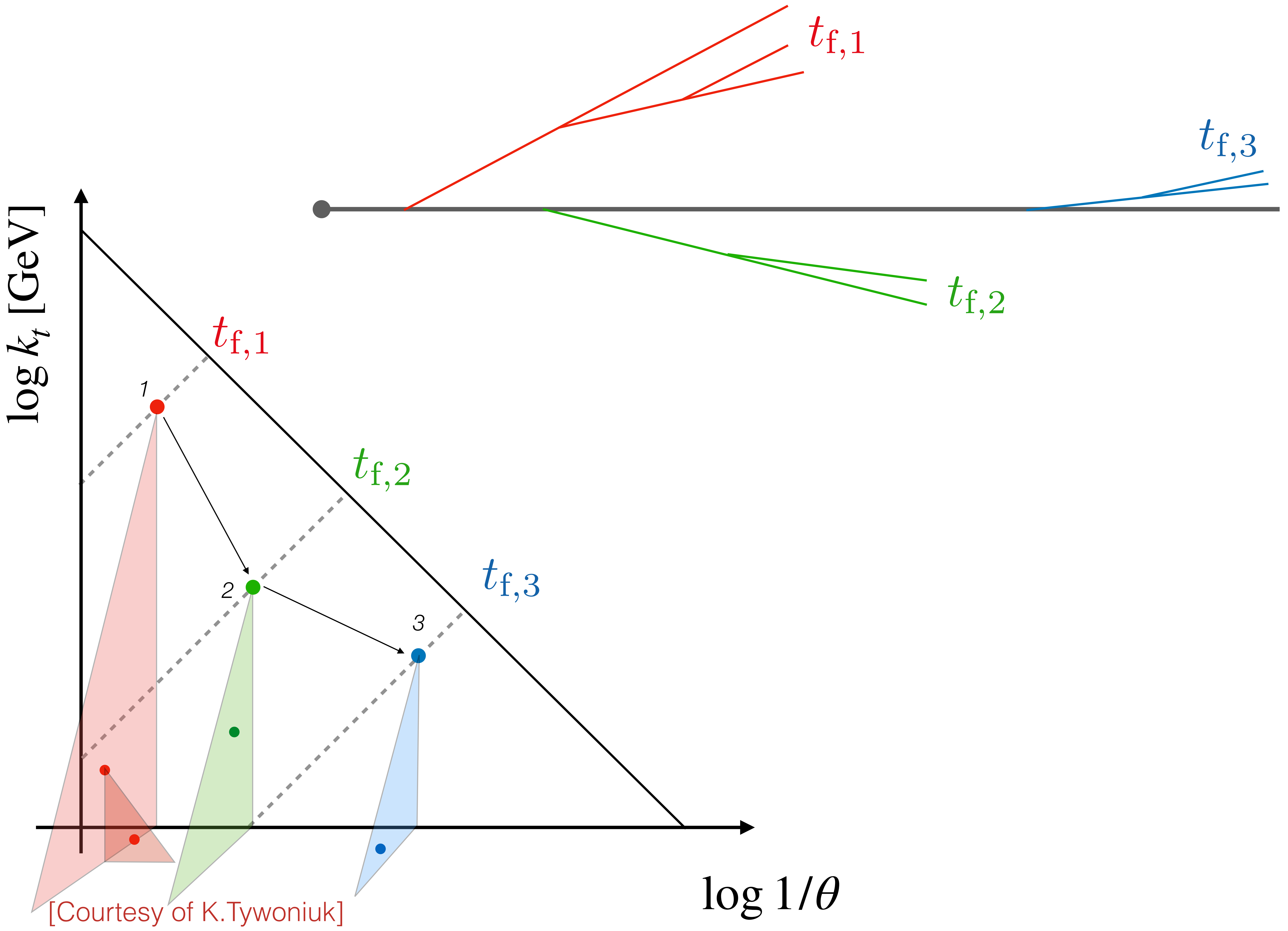

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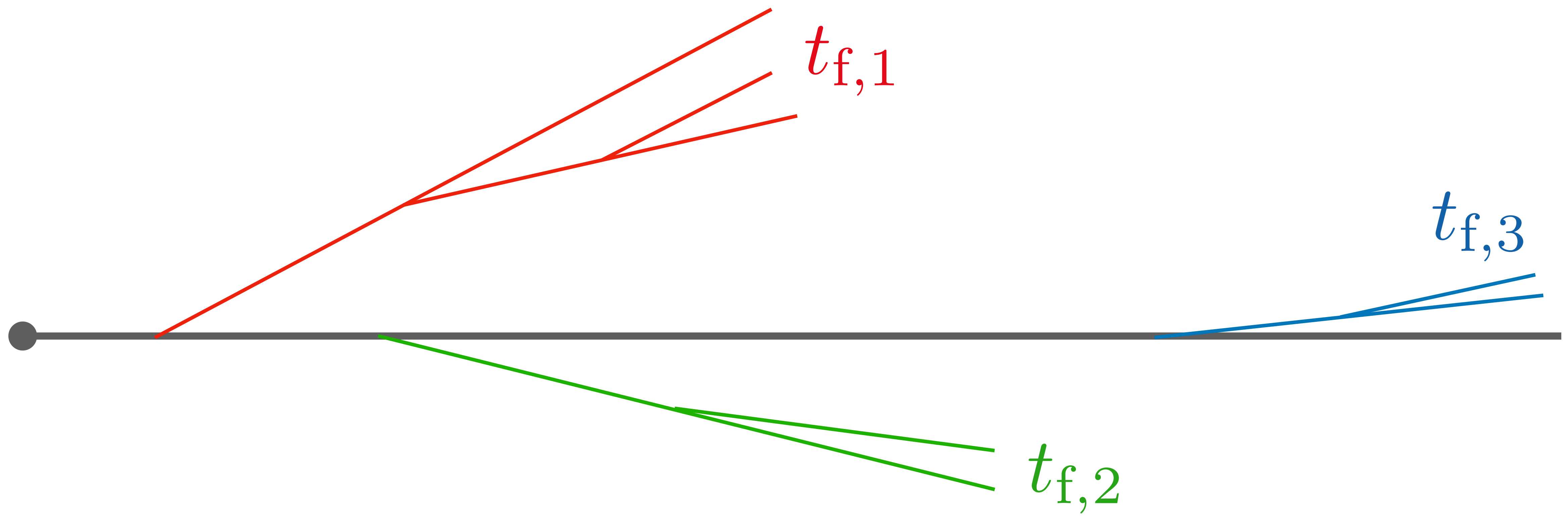

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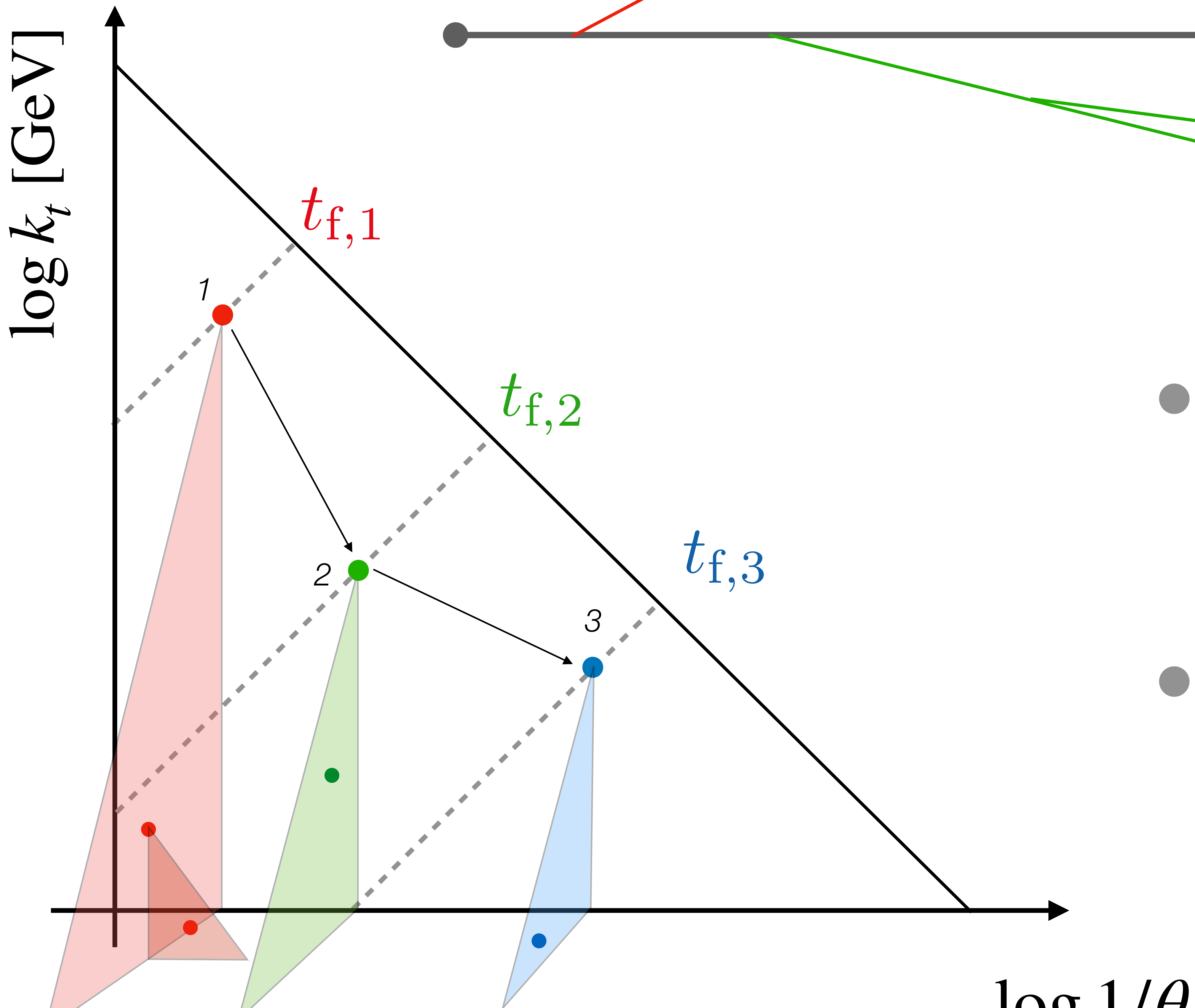


[Courtesy of K.Tywoniuk]

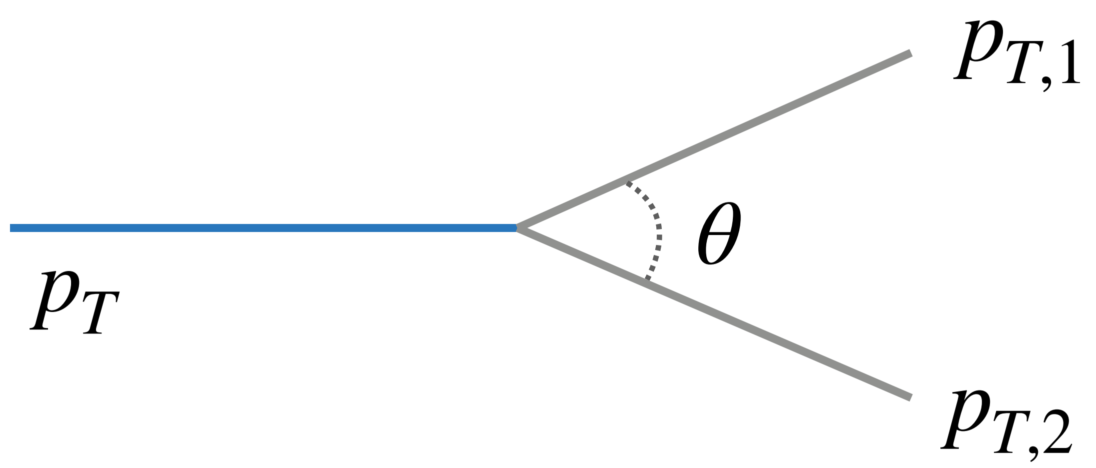
- **Lund diagram** (primary emission plane)
  - secondary branchings located on independent "leaves"
- Accessed in experimental data using jet reconstruction (C/A algorithm)

Primary Lund Plane: MC and data

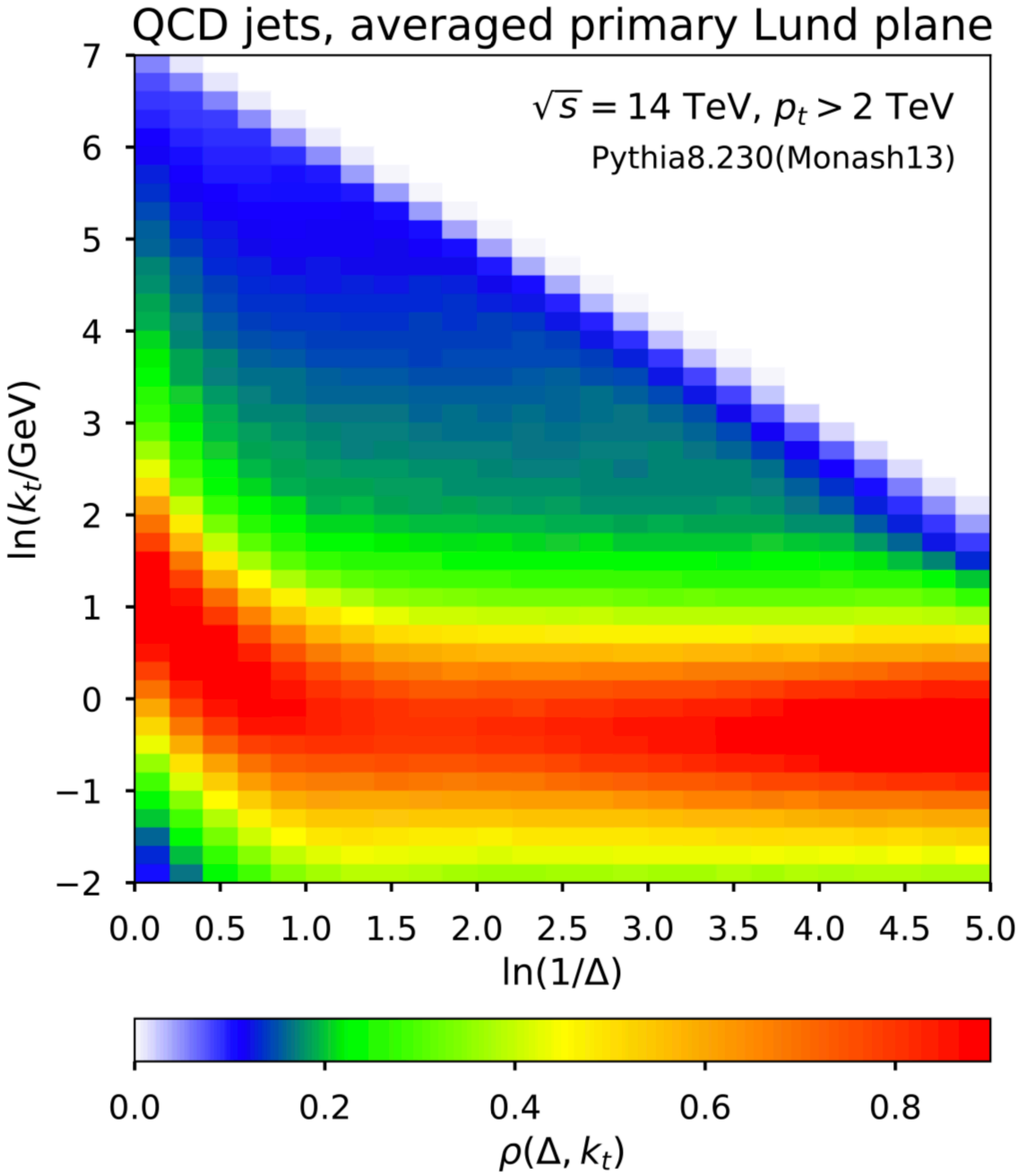
1) (Re)-cluster with C/A

2) Un-do last clustering step. Store $z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}, \theta$

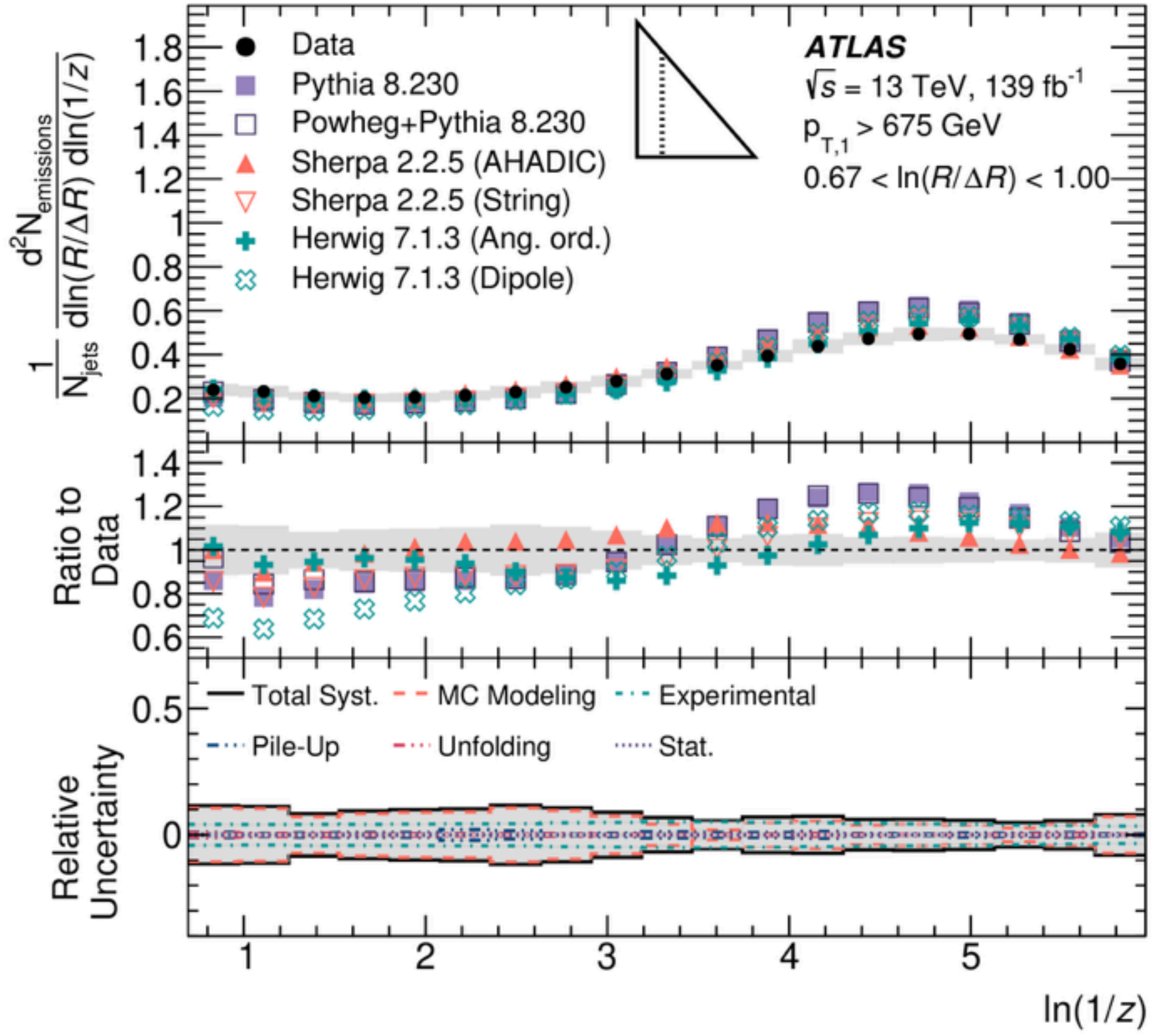
3) Repeat (2) following the hardest branch



[Dreyer, Salam, Soyez'18]



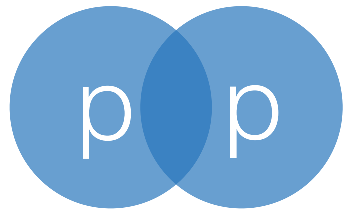
$$\rho \overset{\text{LL}}{\approx} \frac{\alpha_s C_R}{\pi} \frac{dz}{z} \frac{d\theta}{\theta}$$



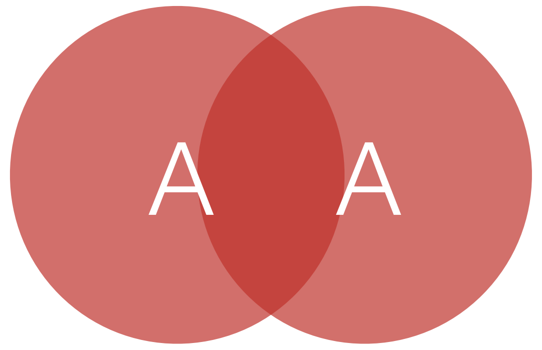
[ATLAS'20]

Why grooming?

Remove soft, wide-angle radiation from the reconstructed jet



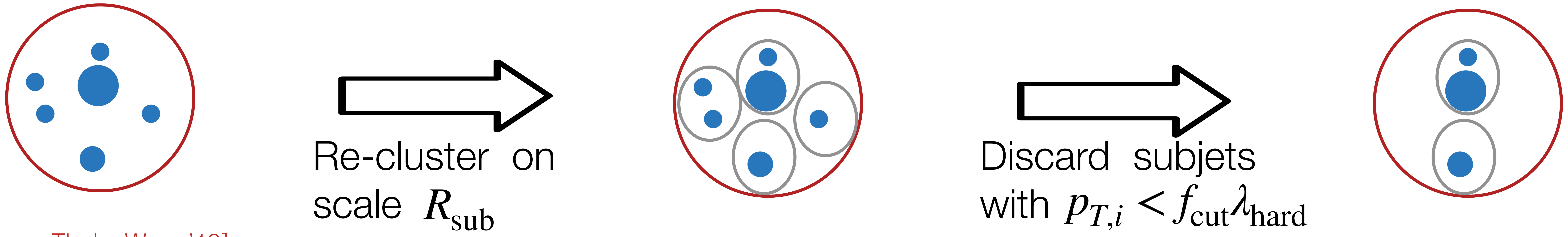
- Mitigate impact of:
  - Hadronization
  - Multi-parton interactions
  - Pileup
- Physics goals:
  - Enhance sensitivity to BSM searches
  - Constrain Monte Carlo generators



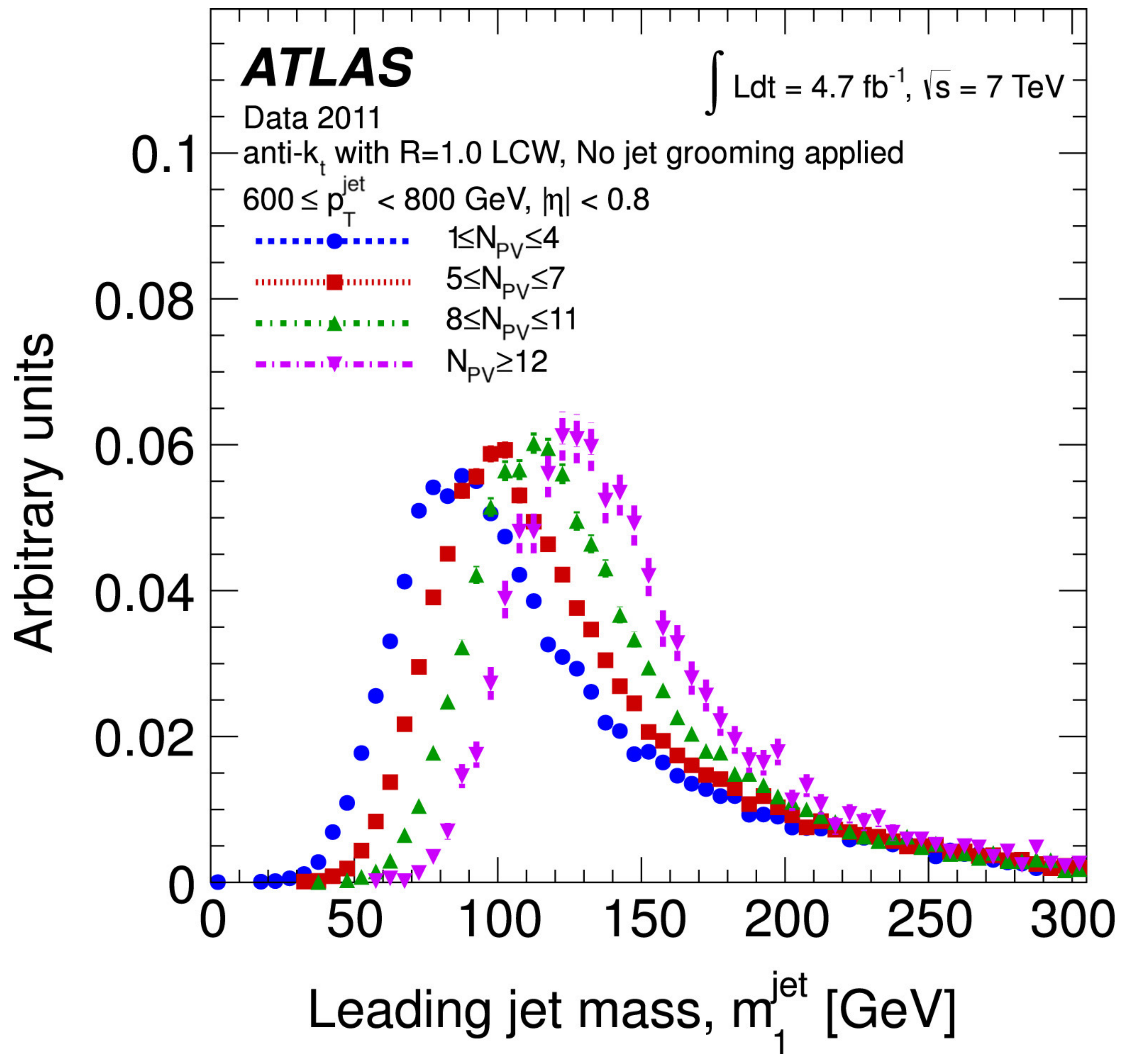
- Minimize sensitivity to:
  - Non-perturbative p+p effects
  - Thermal background
- Physics goals:
  - QGP effect on splitting function
  - Identify QGP angular resolution
  - Pin-down medium response

Enable theory-to-data comparisons without the need of a Monte Carlo

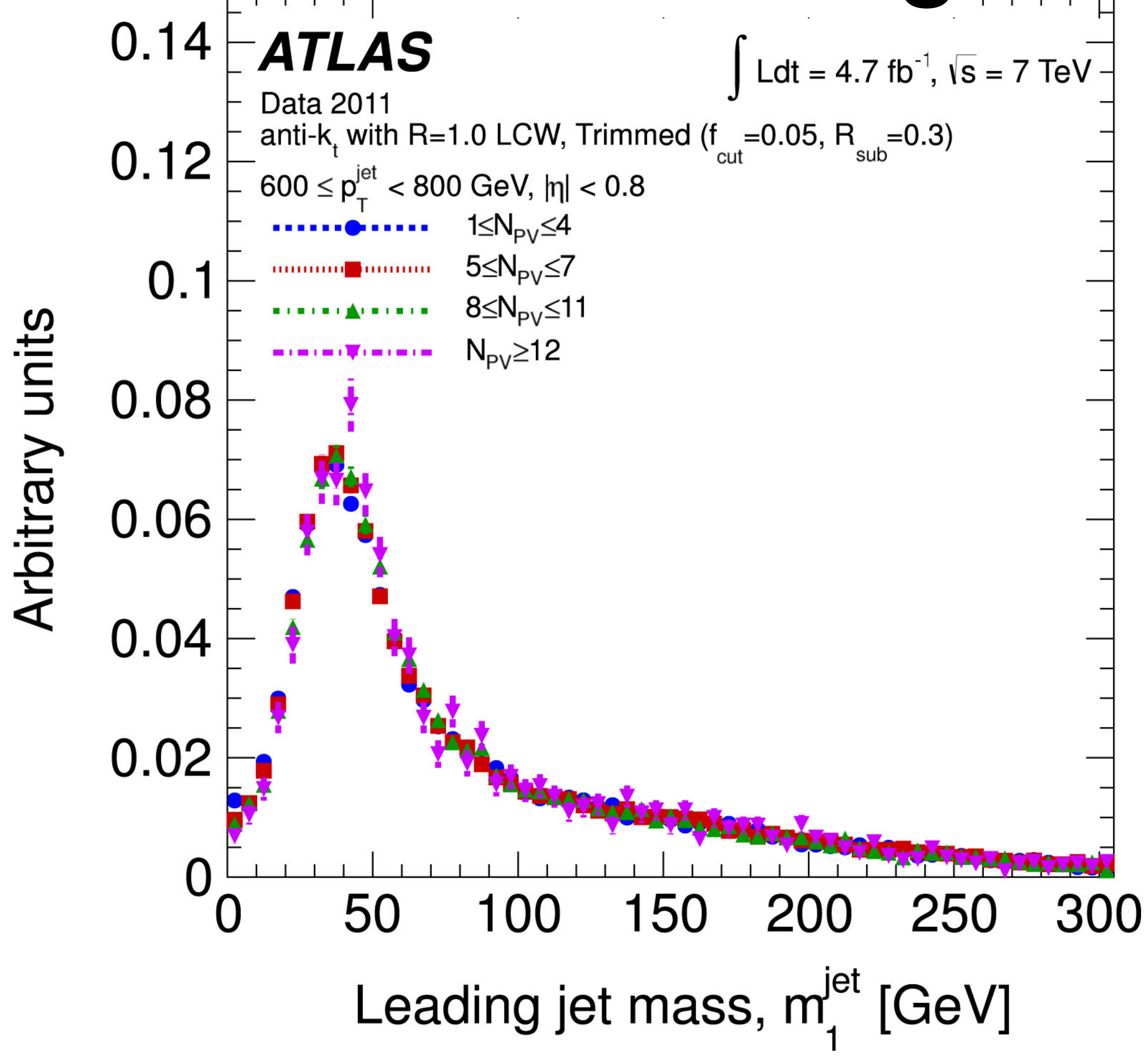
State-of-the-art grooming techniques: Trimming



[Khron,Thaler,Wang'10]



w/ Trimming

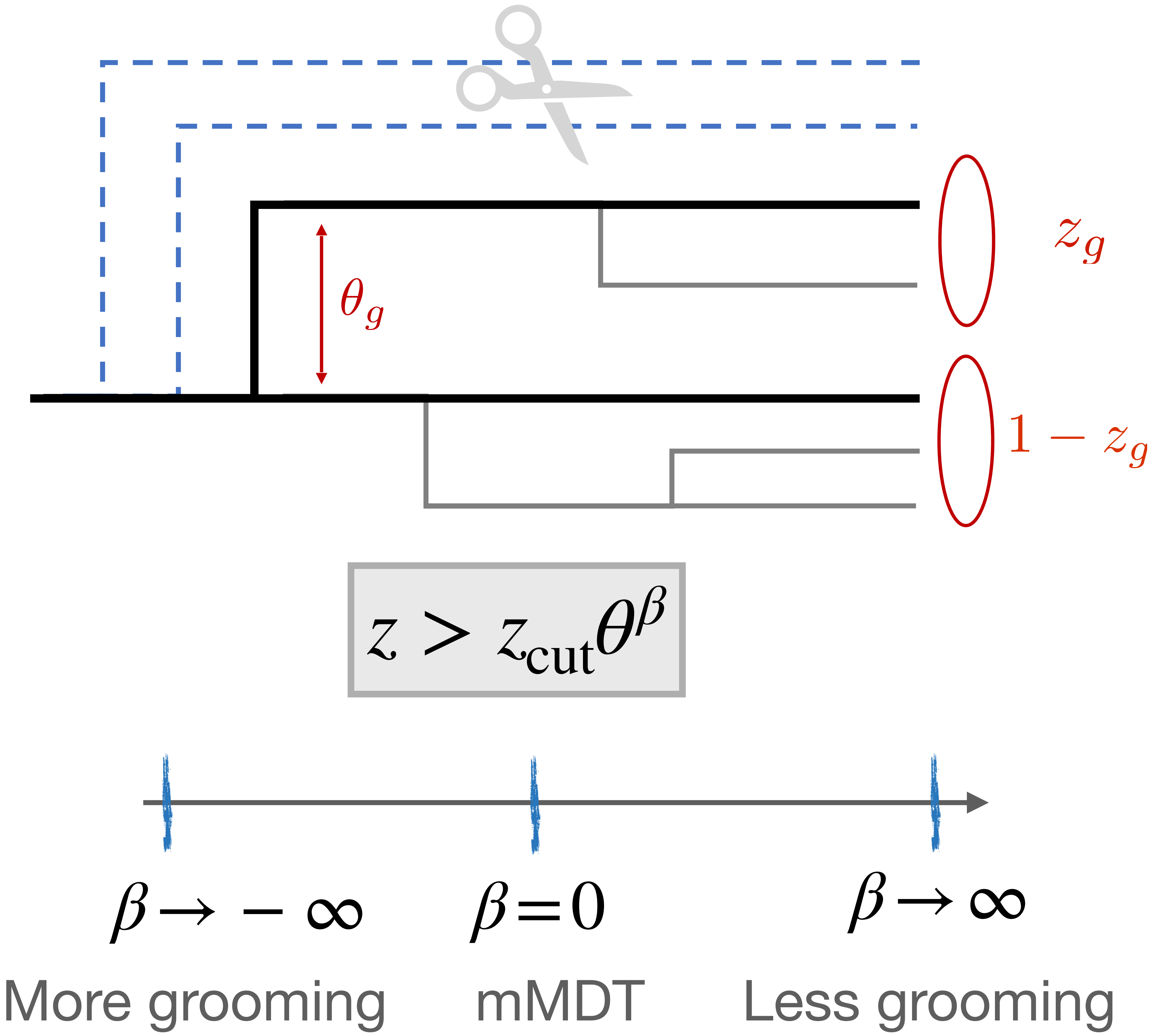


State-of-the-art grooming techniques: SoftDrop

Given a C/A reclustered jet, i.e. angular ordered tree:

SoftDrop (SD)

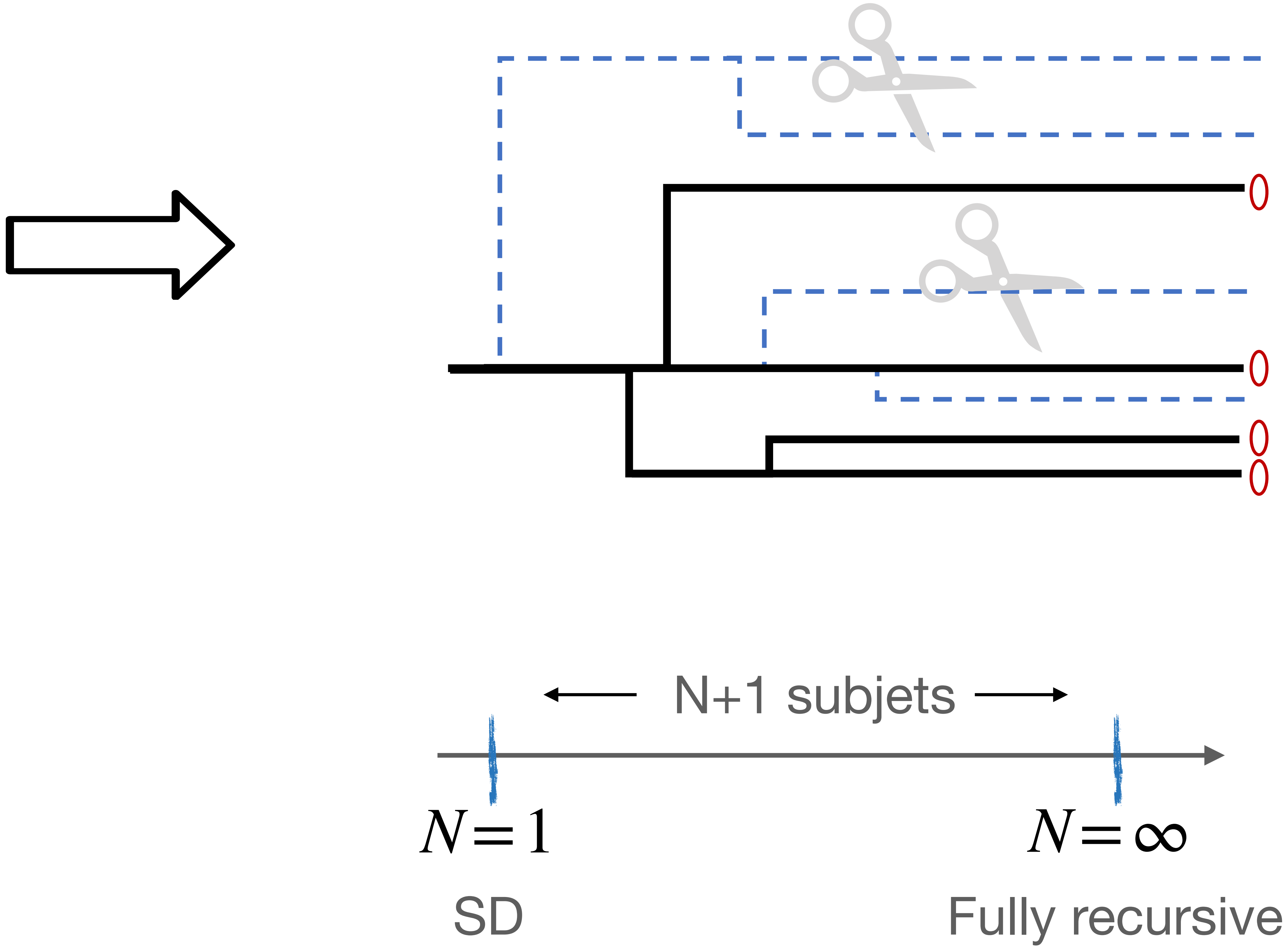
[Larkorski et al. JHEP'14]



[Butterworth et al.PRL'08]

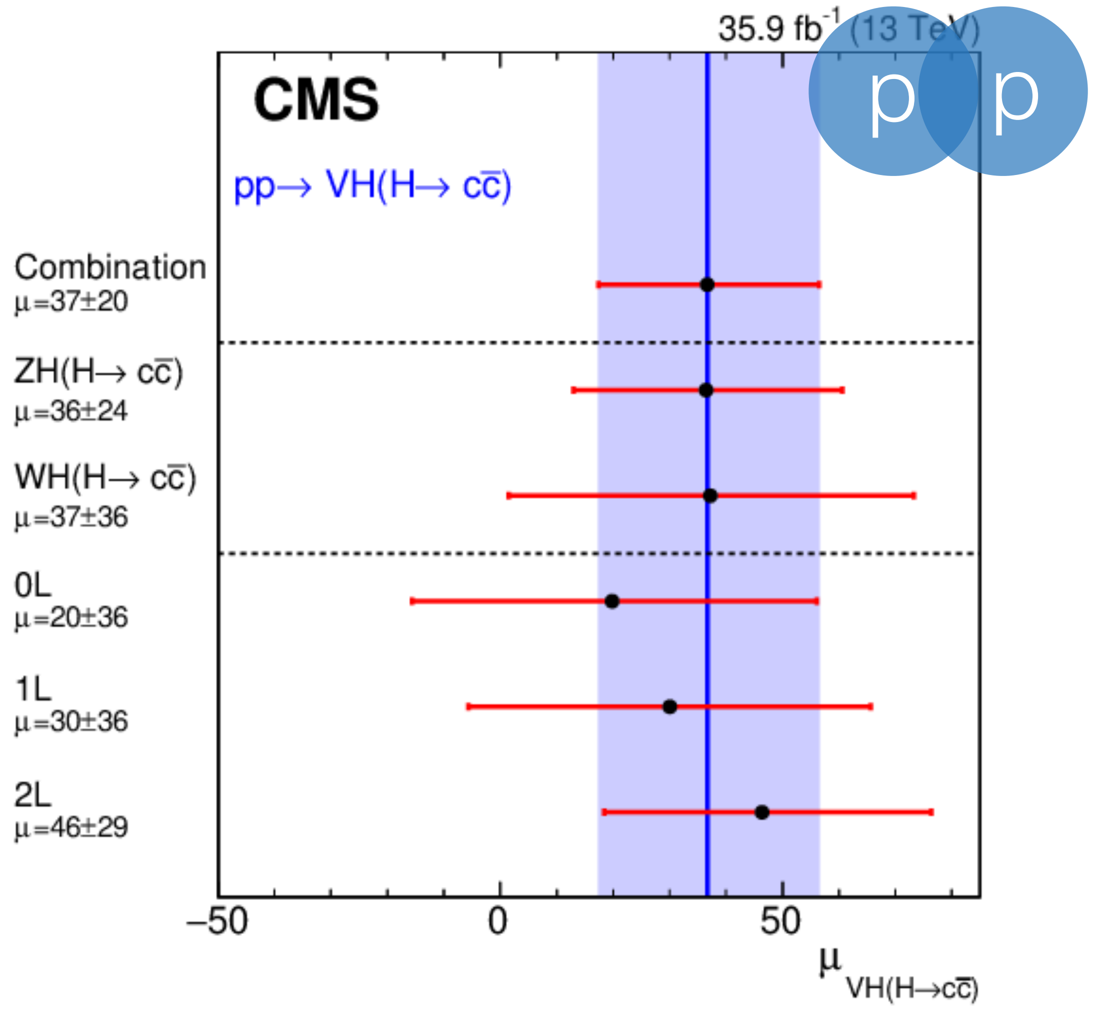
Recursive SoftDrop (RSDN)

[Dreyer et al. JHEP'18]

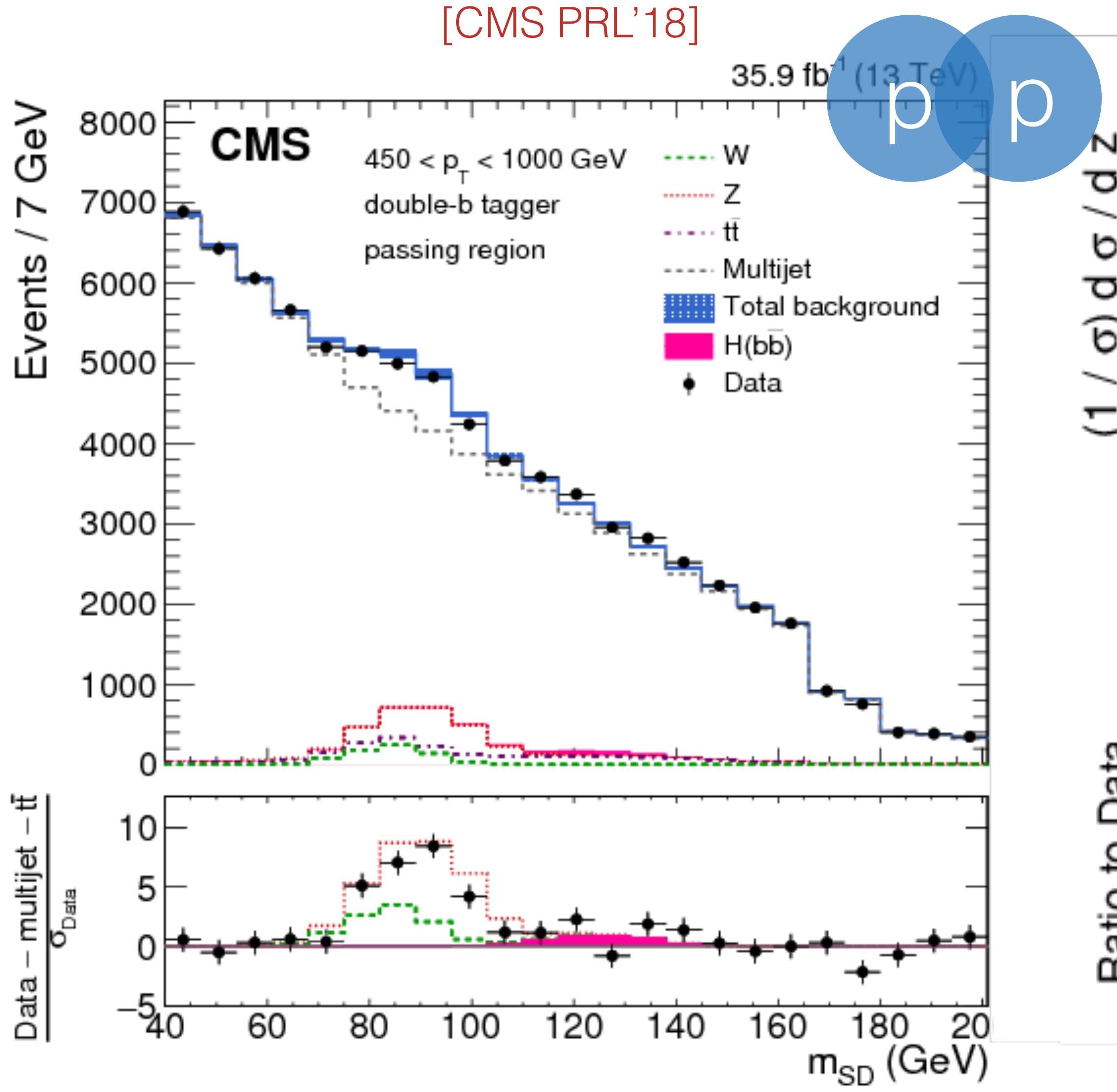


SoftDrop at work: from RHIC to LHC

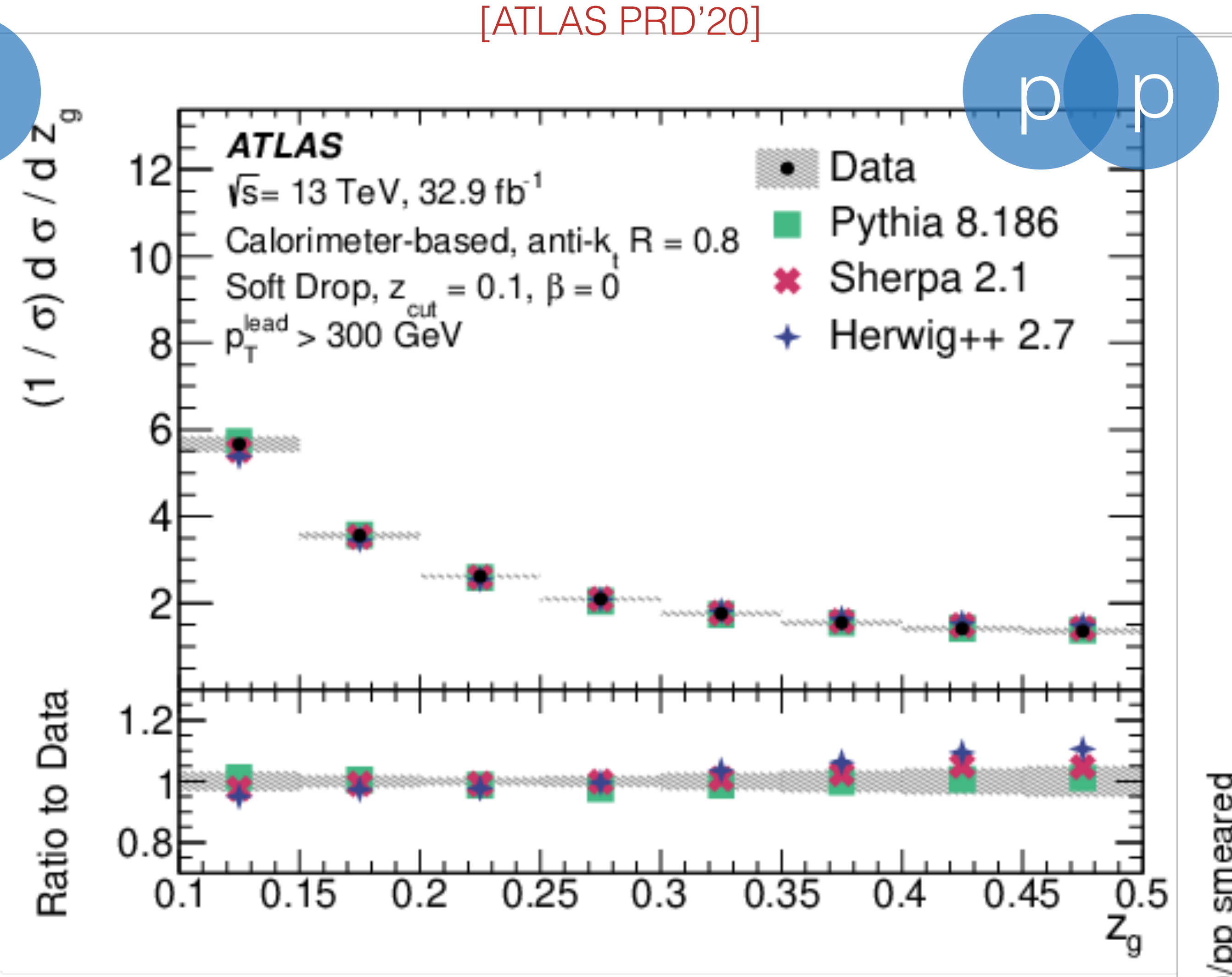
[CMS JHEP.20]



[CMS PRL'18]



[ATLAS PRD'20]



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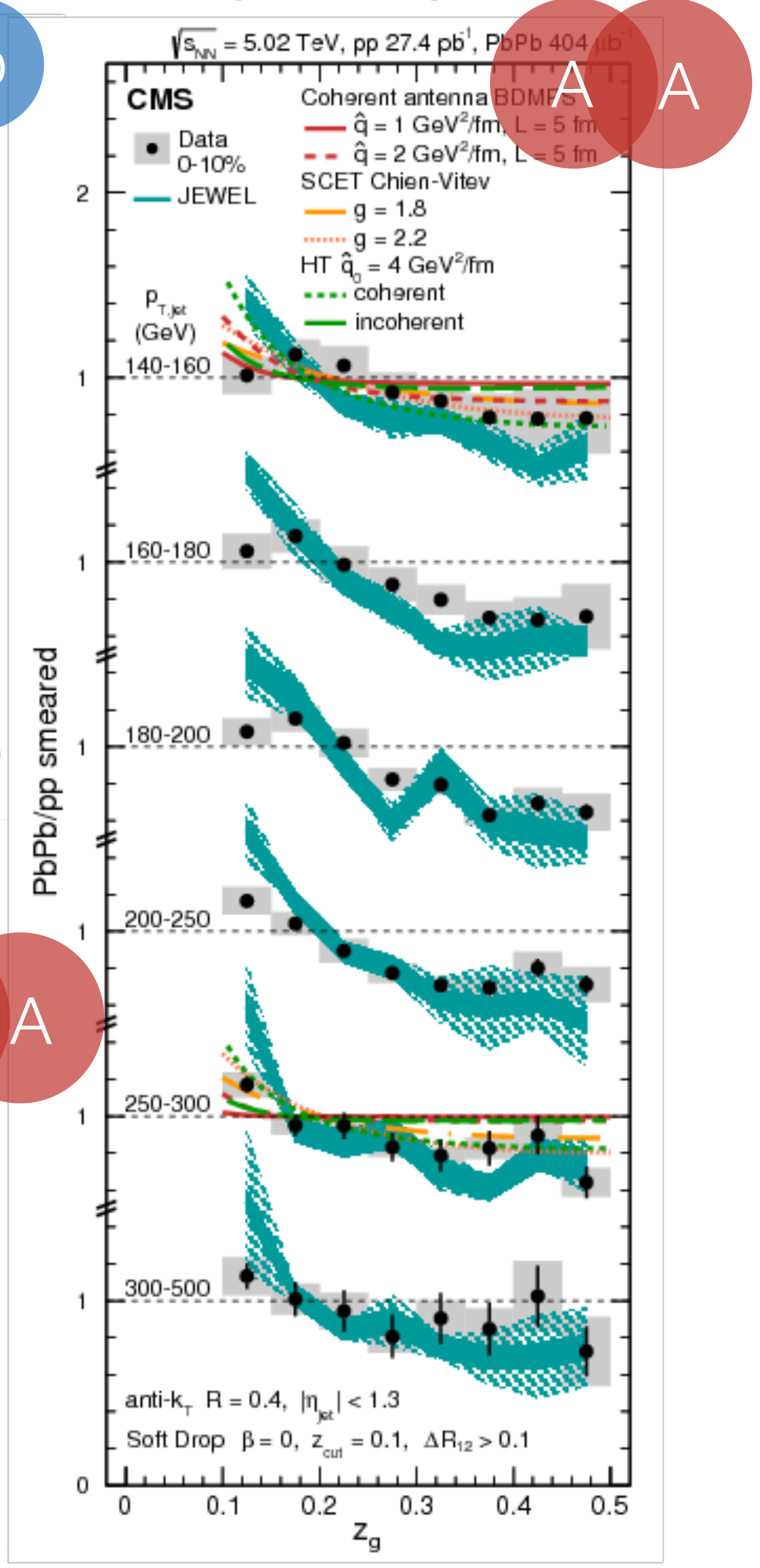
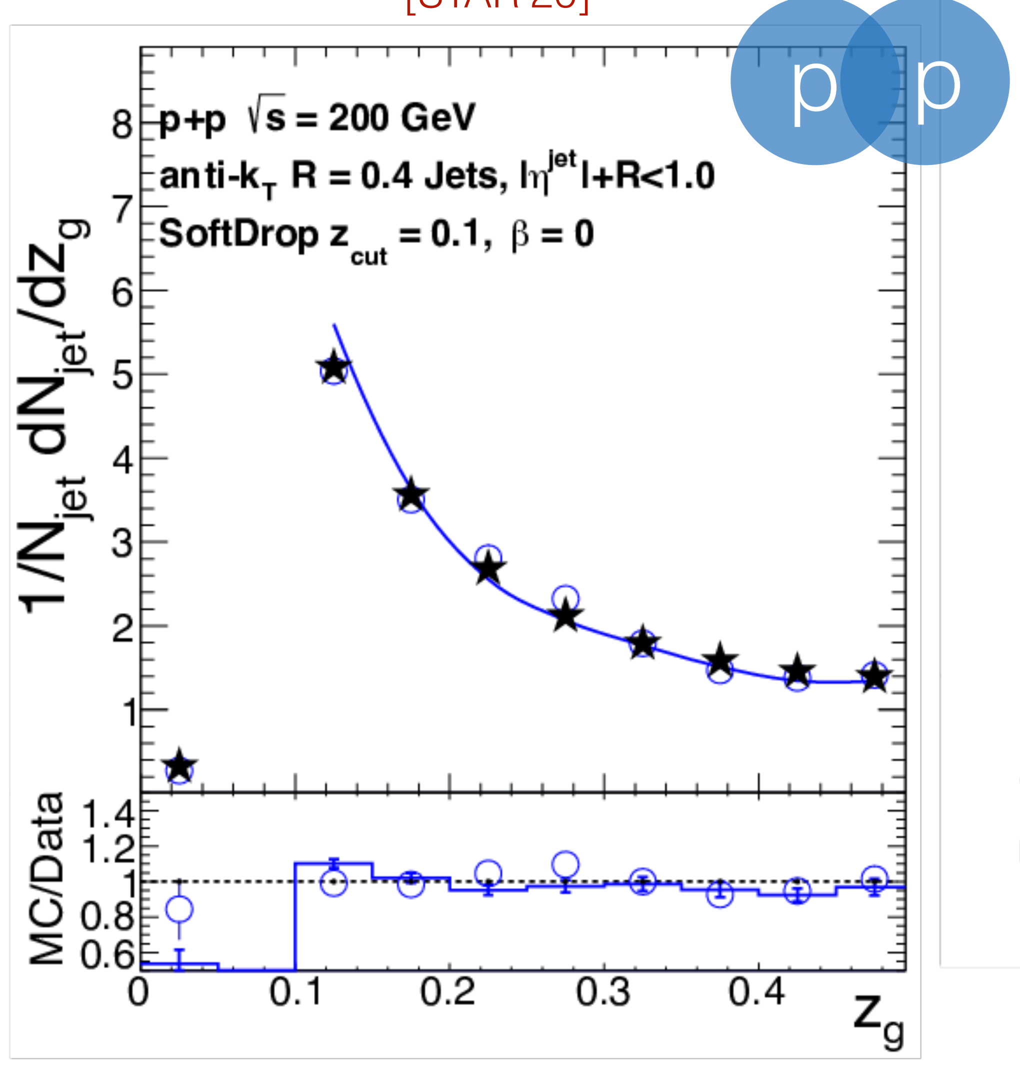
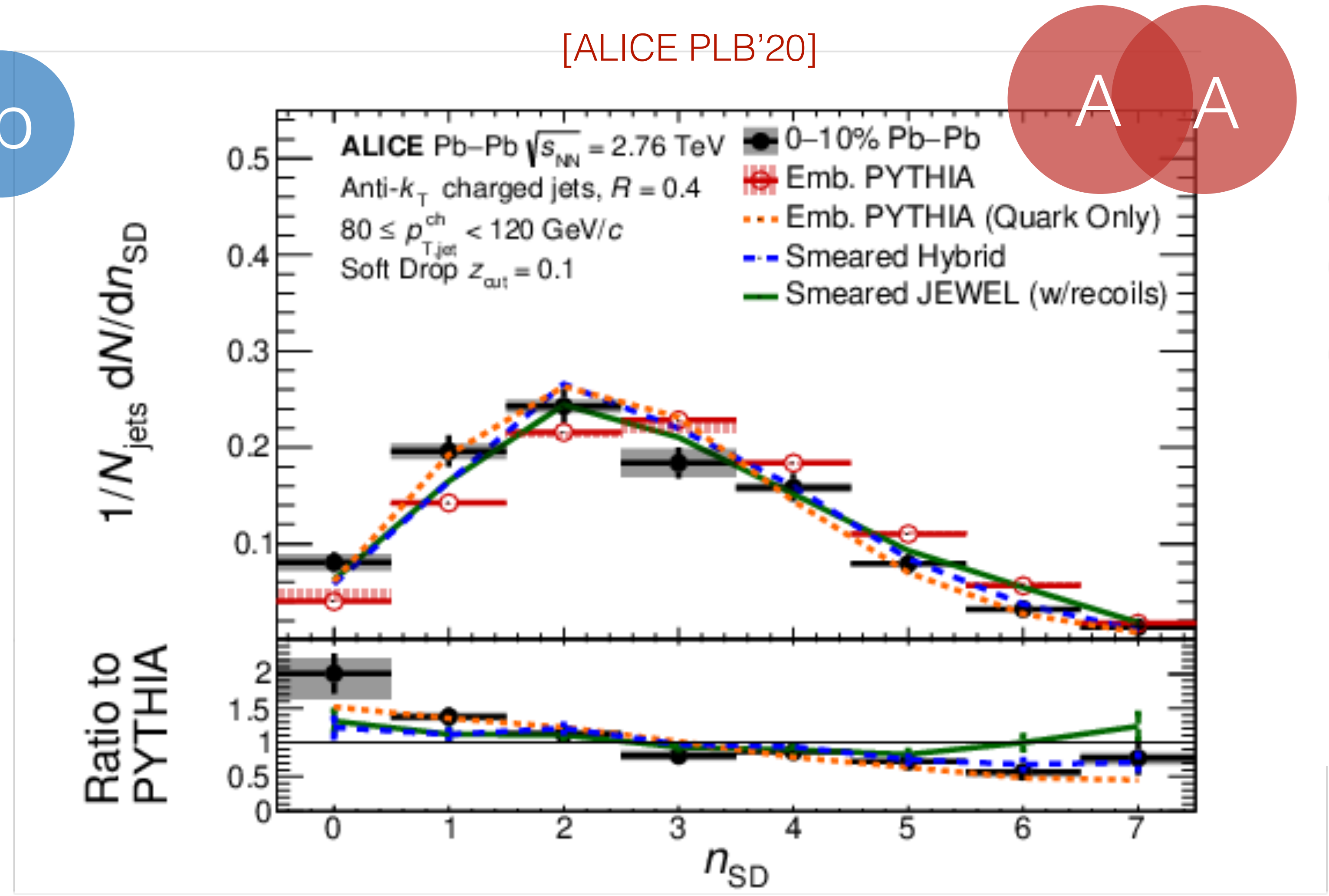


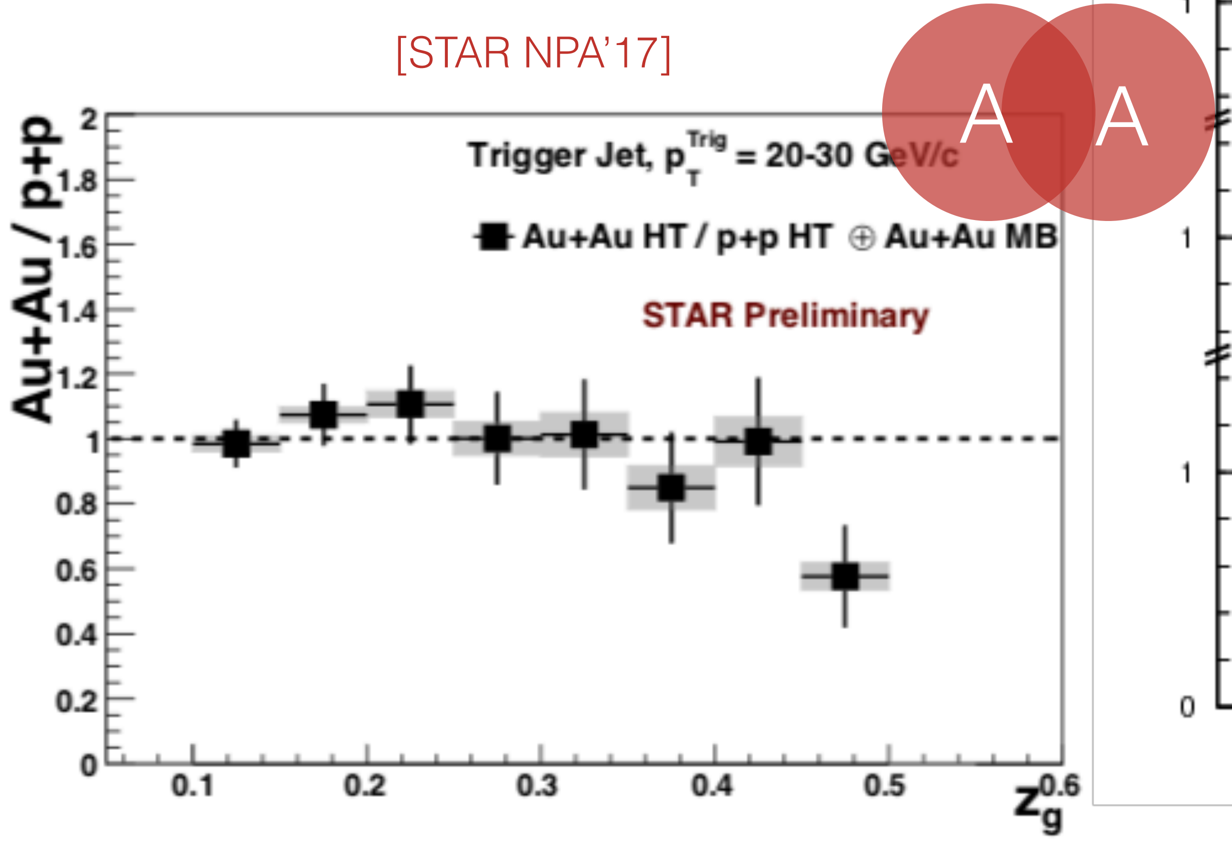
[STAR'20]



[ALICE PLB'20]



[STAR NPA'17]



+ lots of pQCD calculations

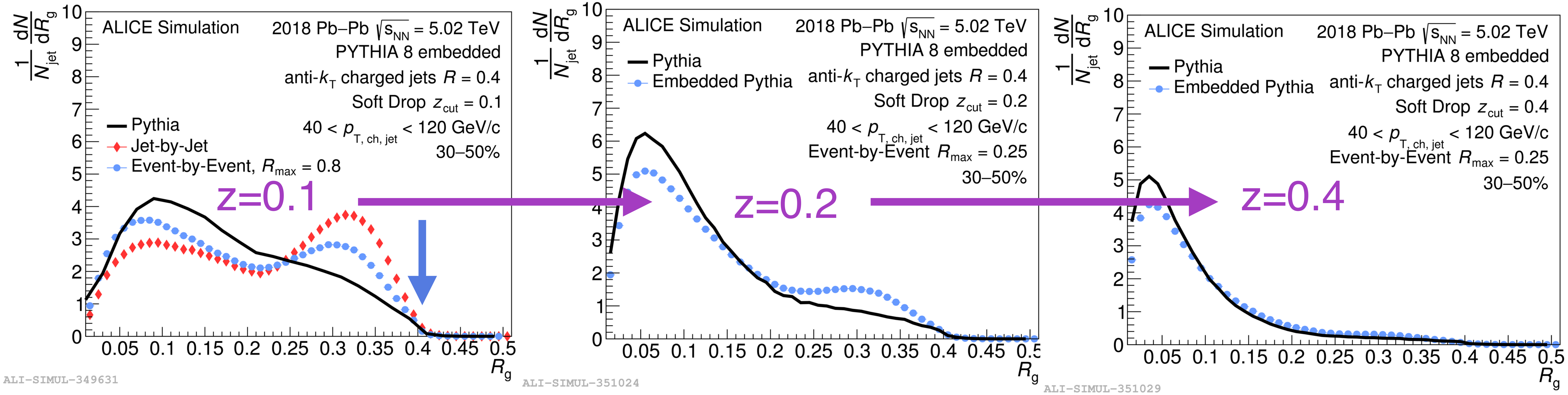
SoftDrop condition: free parameters

$$z > z_{\text{cut}}\theta^{\beta}$$

Theoretically: flexibility to select splittings from different kinematic regions

Experimentally: no optimal $(z_{\text{cut}}, \beta, N)$-values a priori. Tuned on an observable basis with Monte-Carlo, e.g. :

[Laura Havener talk at LHCP'20]



Dynamical grooming

Code: github/aontoso/JetToyHI [PRD 101 (2020) 3, 034004]

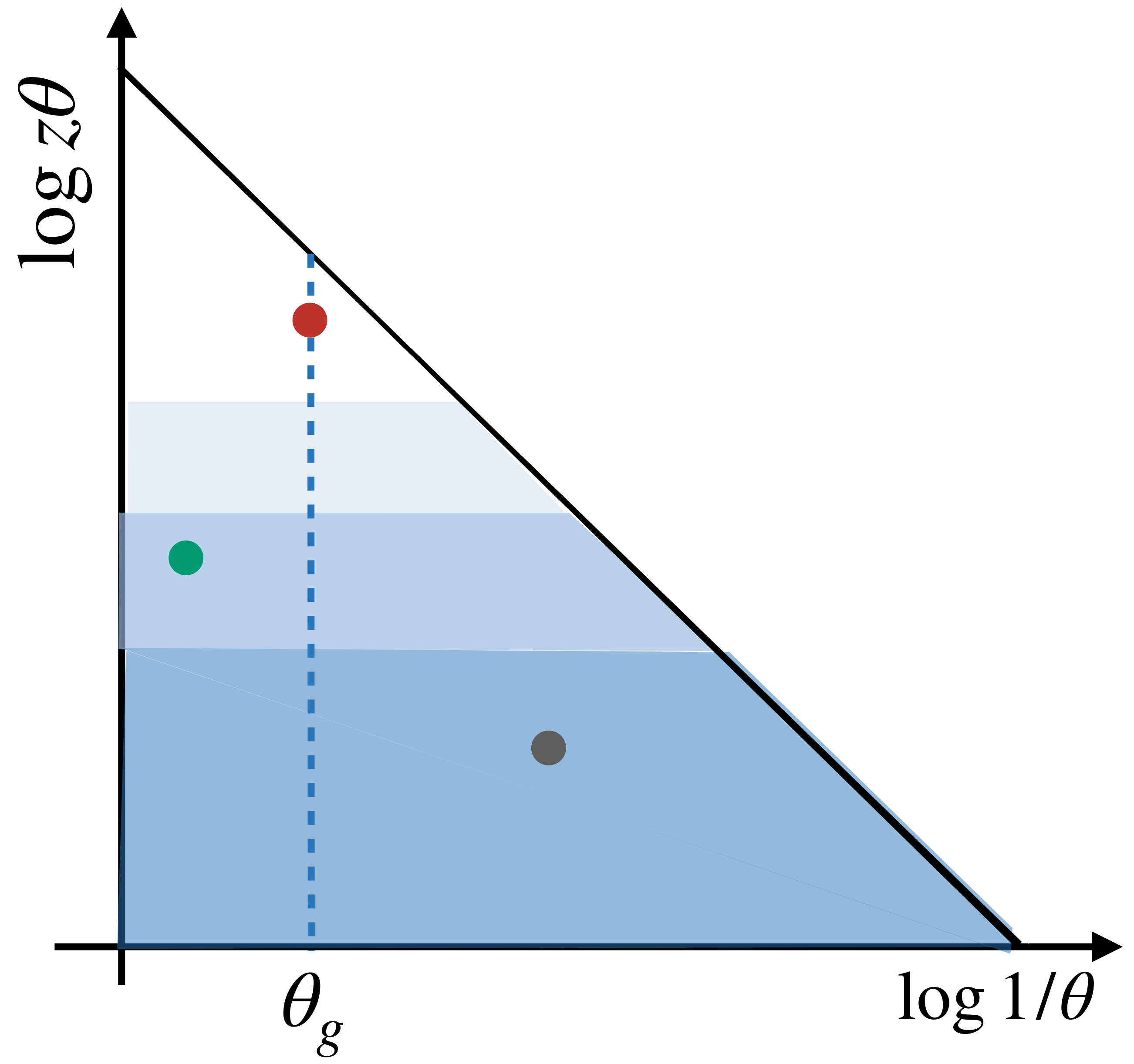
1) Find **hardest** branch in the C/A sequence, i.e.

$$\kappa^{(a)} = \frac{1}{p_T} \max_{i \in \mathrm{C/A}} z_i(1 - z_i) p_{T,i} (\theta_i / R)^a$$

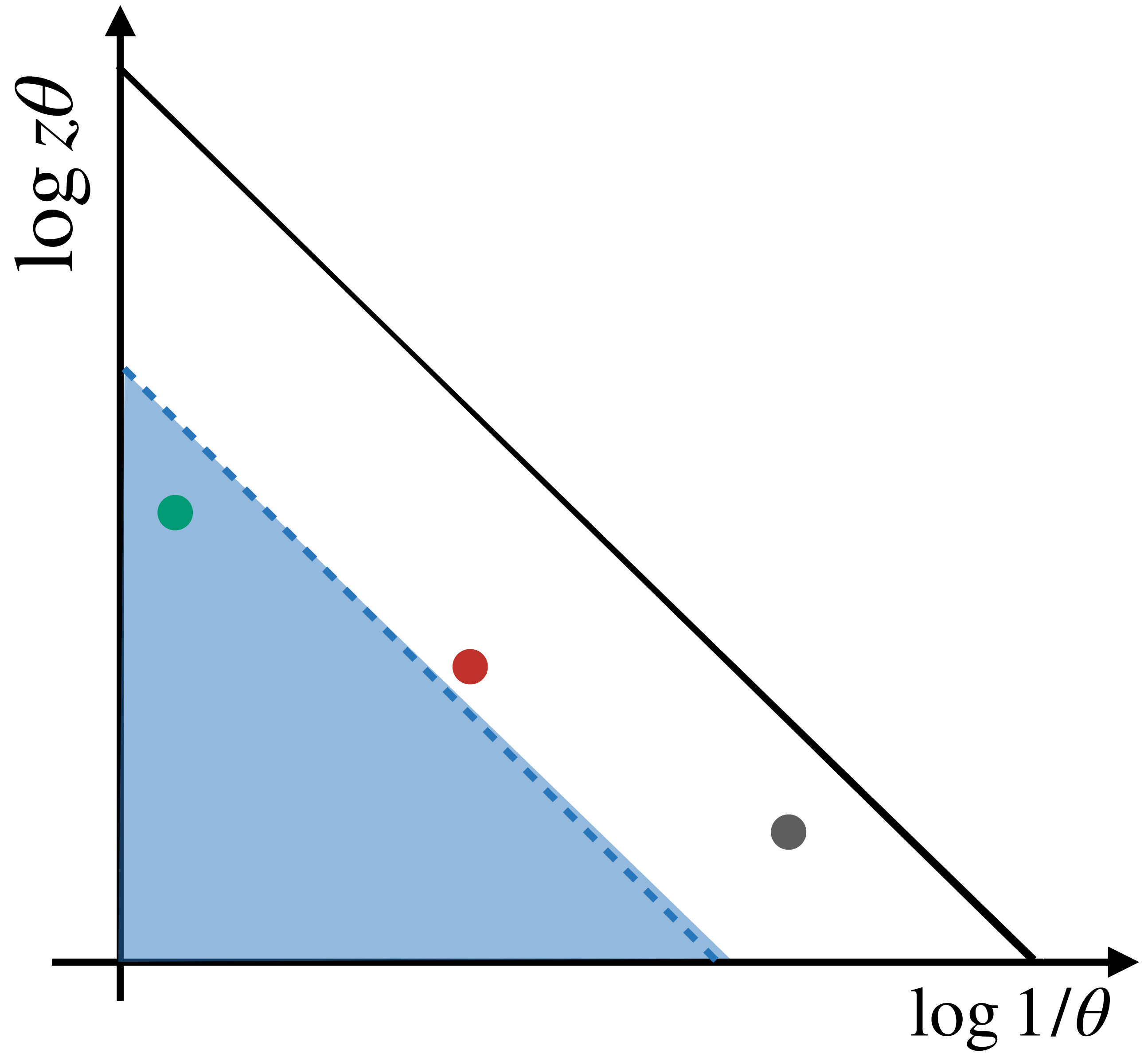
Physical interpretation: • a=2: TimeDrop • a=1: k_TDrop • a~0: zDrop

2) Drop all branches at larger angles, i.e. $\theta_i > \theta_g$

DyG:

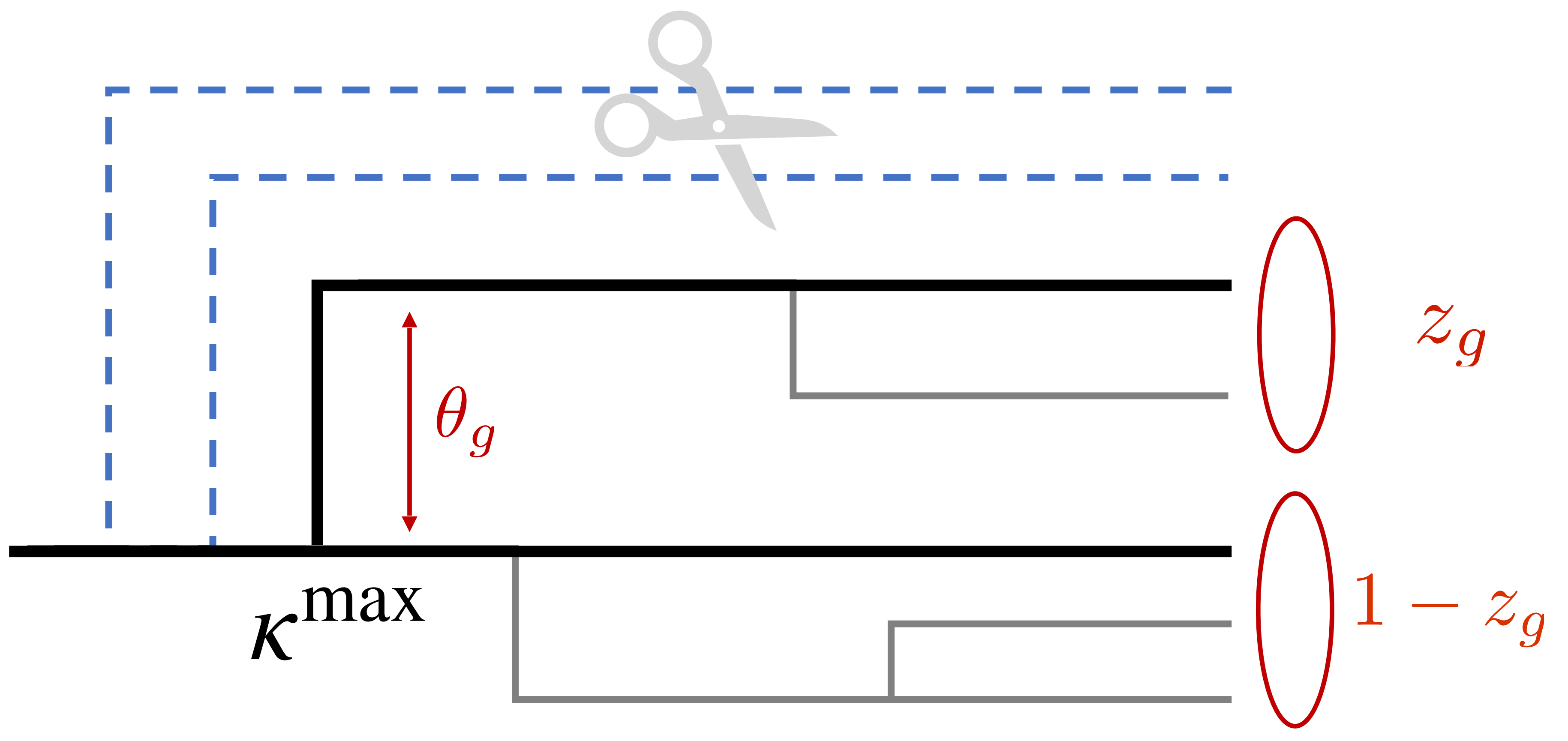


SD:

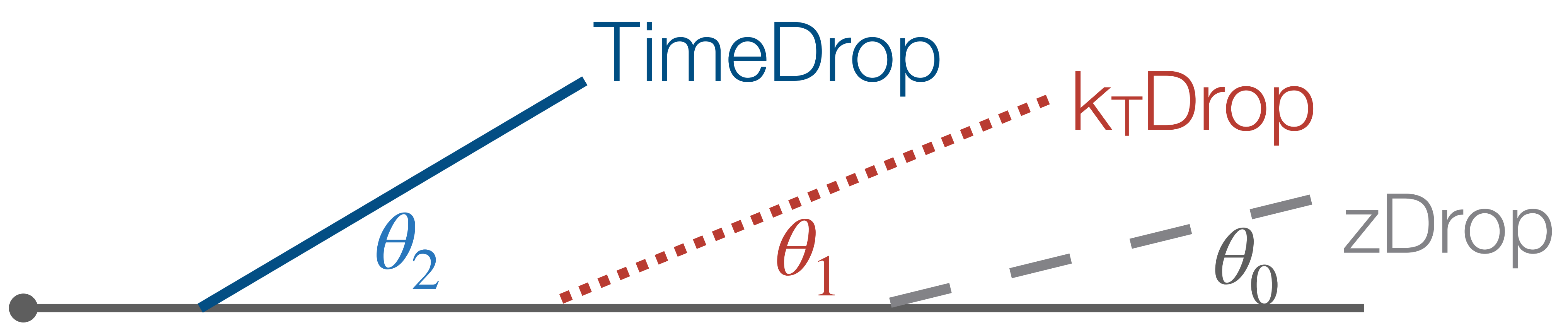


Remarks and physical interpretation of DyG

$$\kappa^{(a)} = \frac{1}{p_T} \max_{i \in \mathrm{C/A}} z_i(1 - z_i) p_{T,i} (\theta_i / R)^a$$



- Removing soft radiation sensitive to the total color charge of the jet
- Grooming condition auto-generated on a jet-by-jet basis
- More aggressive grooming with decreasing ***a*** (similar to β in SD)



$$\theta_2 > \theta_1 > \theta_0$$

Analytical framework of DyG

Building block: 2D phase space probability for the tagged DyG splitting

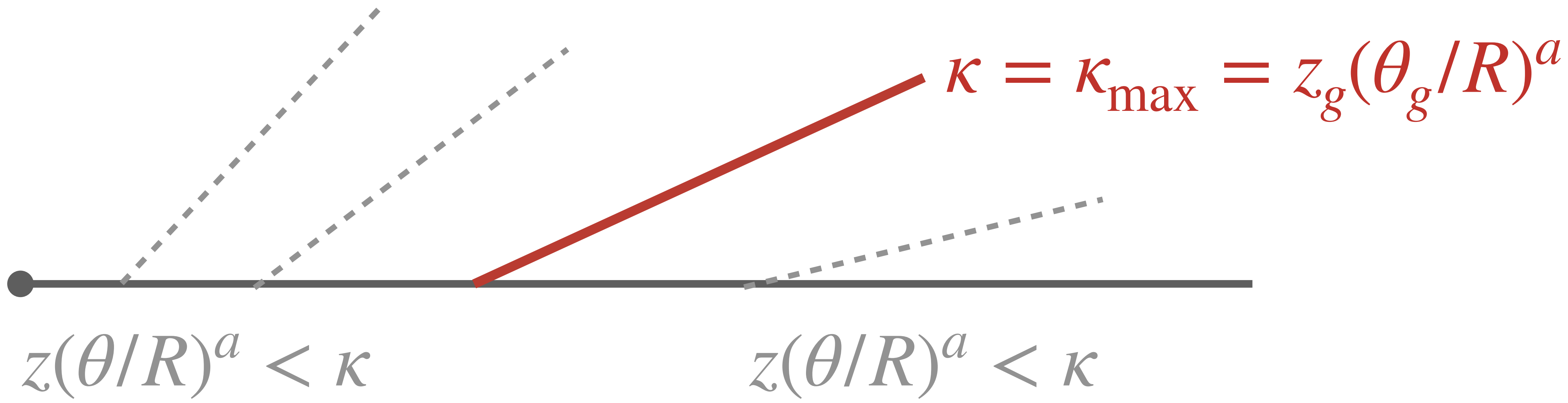
$$\mathscr{P}(z,\theta) = \frac{\alpha_s(k_t^2)}{\pi} P(z) \Delta(\kappa\,|\,a)$$

- Splitting function: probability to split given that all other splittings are softer
- Sudakov form factor: probability for no emission with $z(\theta/R)^a > \kappa$

$$\Delta(\kappa\,|\,a) = \exp\left[-\int_0^R \frac{\mathrm{d}\theta}{\theta}\int_0^1 \mathrm{d}z P(z) \times \Theta\left(z(1-z)(\theta/R)^a > \kappa\right)\right]$$

IRC safe for $a > 0$

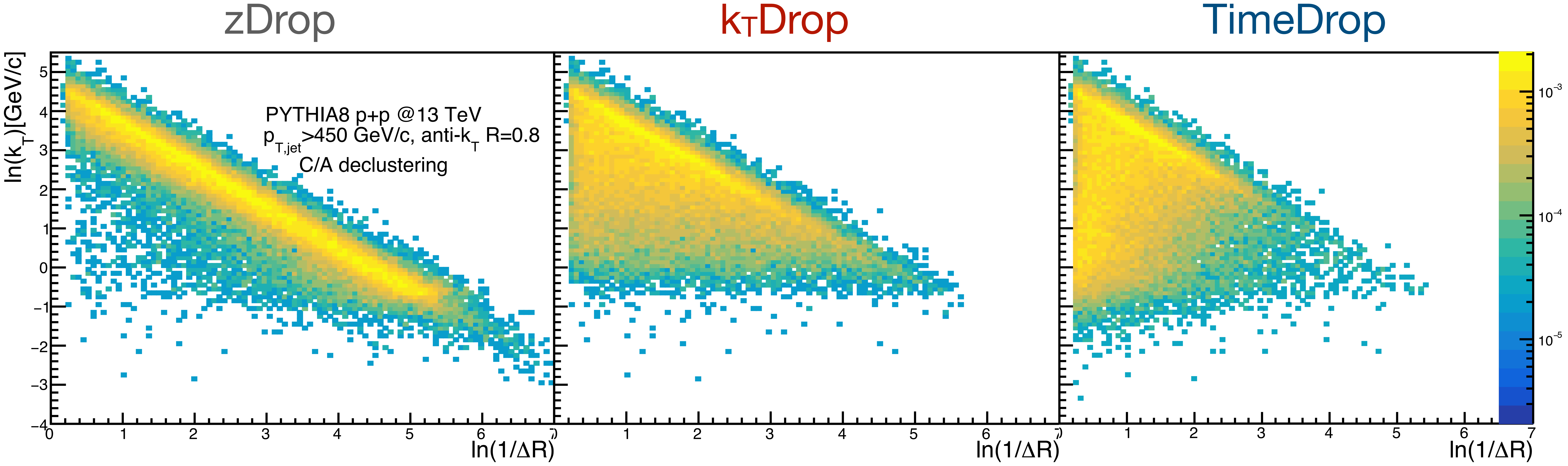
Vetoed showers
[Nason JHEP'04]



Lund planes for dynamically groomed QCD jets

PYTHIA 8,pp->dijet@13 TeV
HAD,UE::off

$$\mathscr{P}(z,\theta) = \frac{\alpha_s(k_t^2)}{\pi} P(z)\Delta(\kappa\,|\,a)$$



Dynamical cut when $\log^2(\kappa) \overset{\text{DLA}}{\sim} \log^2(z\theta^a) > a/\alpha_s$

z_g-distribution in DyG QCD jets

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}z} = \int_0^R \frac{\mathrm{d}\theta}{\theta}\mathscr{P}(z,\theta)$$

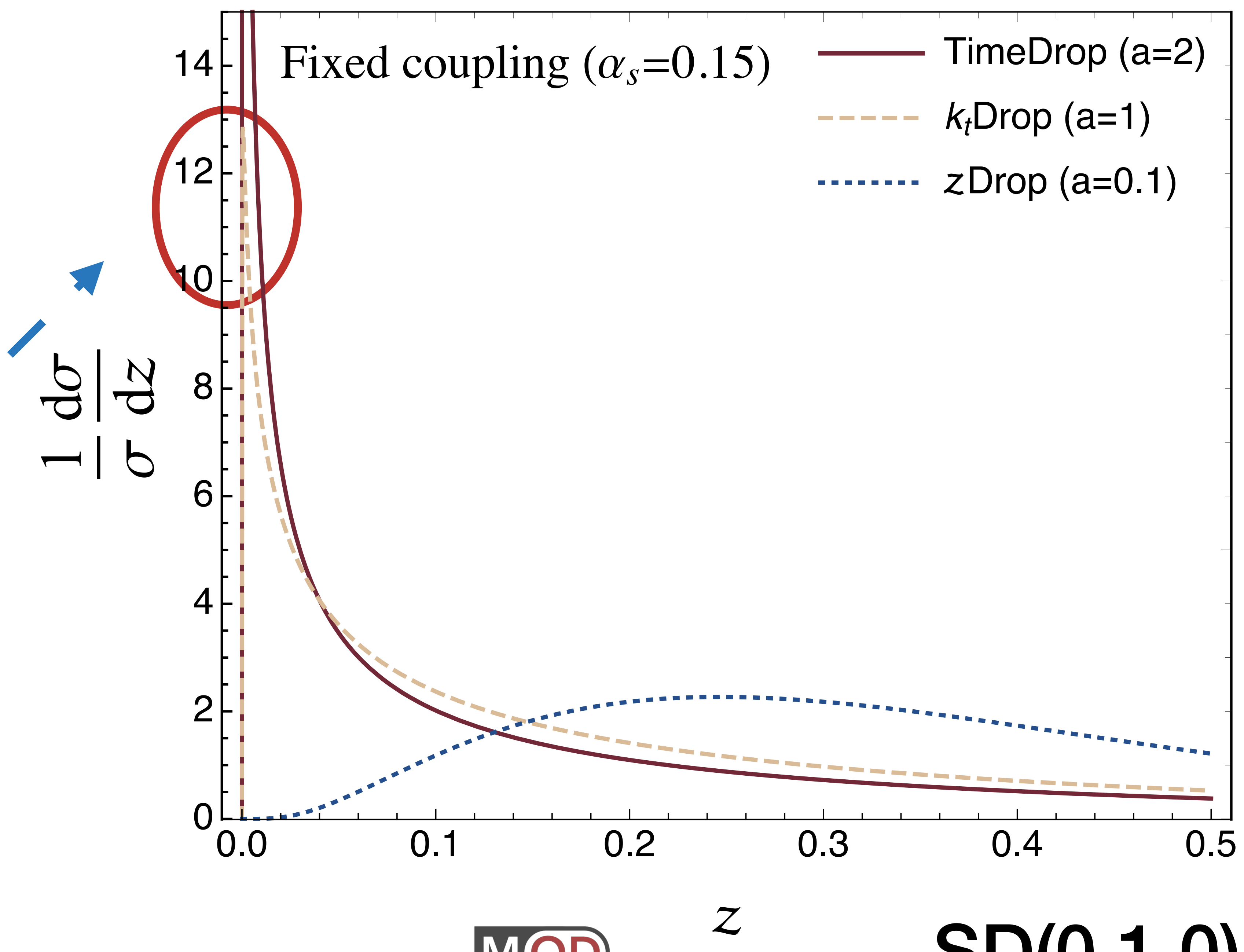
- Dynamical cut-off generated at

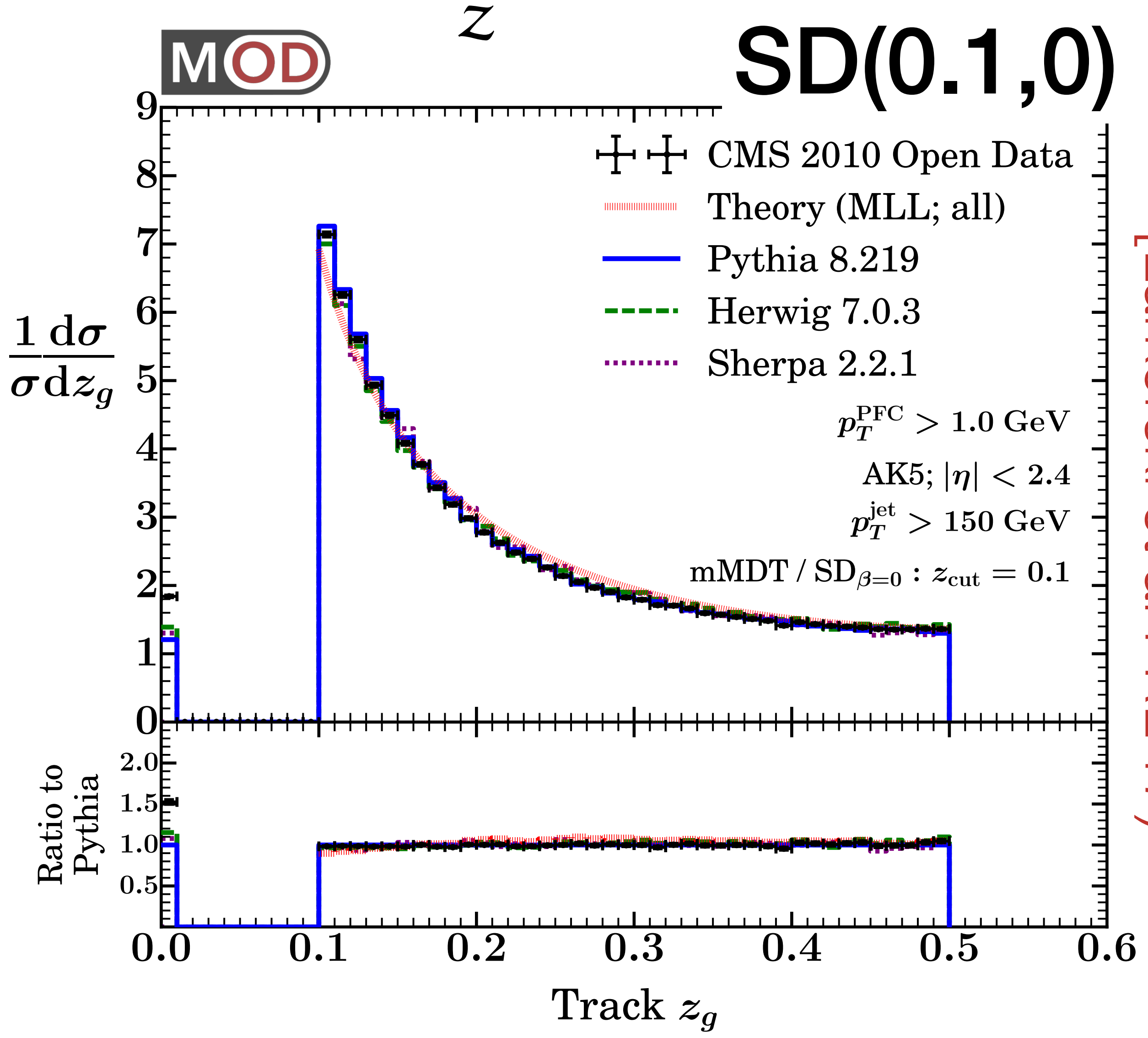
$$z_{\rm cut} \overset{\rm DLA}{\approx} \mathrm{e}^{-\sqrt{a/\bar{\alpha}}}$$

- For $z_{\rm cut} < z < 0.5$

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}z} \overset{\rm DLA}{\approx} P(z) \times \sqrt{\bar{\alpha}/a}$$

Possibility to measure $P(z)$ down to lower z



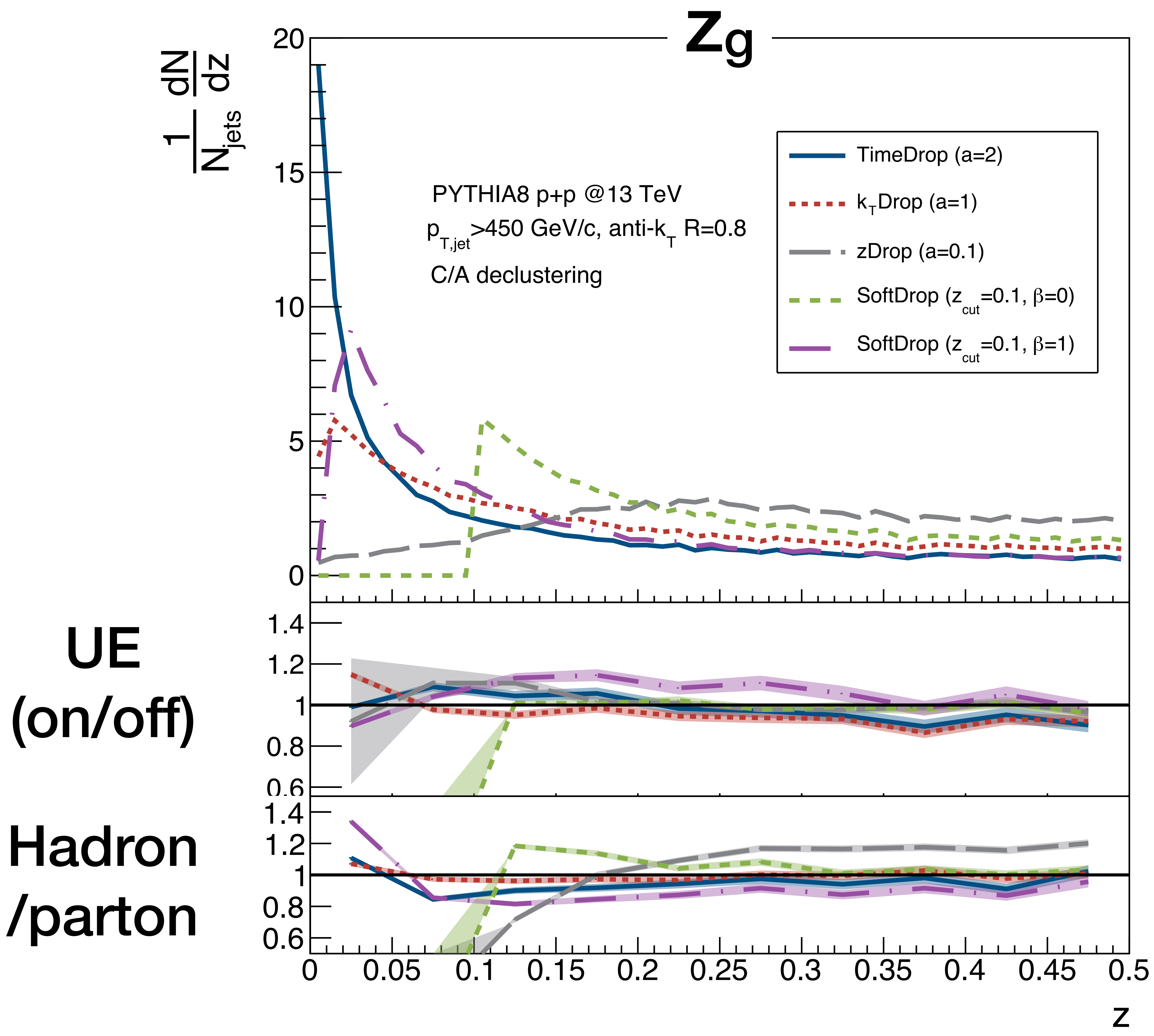


[Larkorski et al PRL'17]

Impact of UE* and hadronization in DyG-z_g (*UE==ISR and MPI)

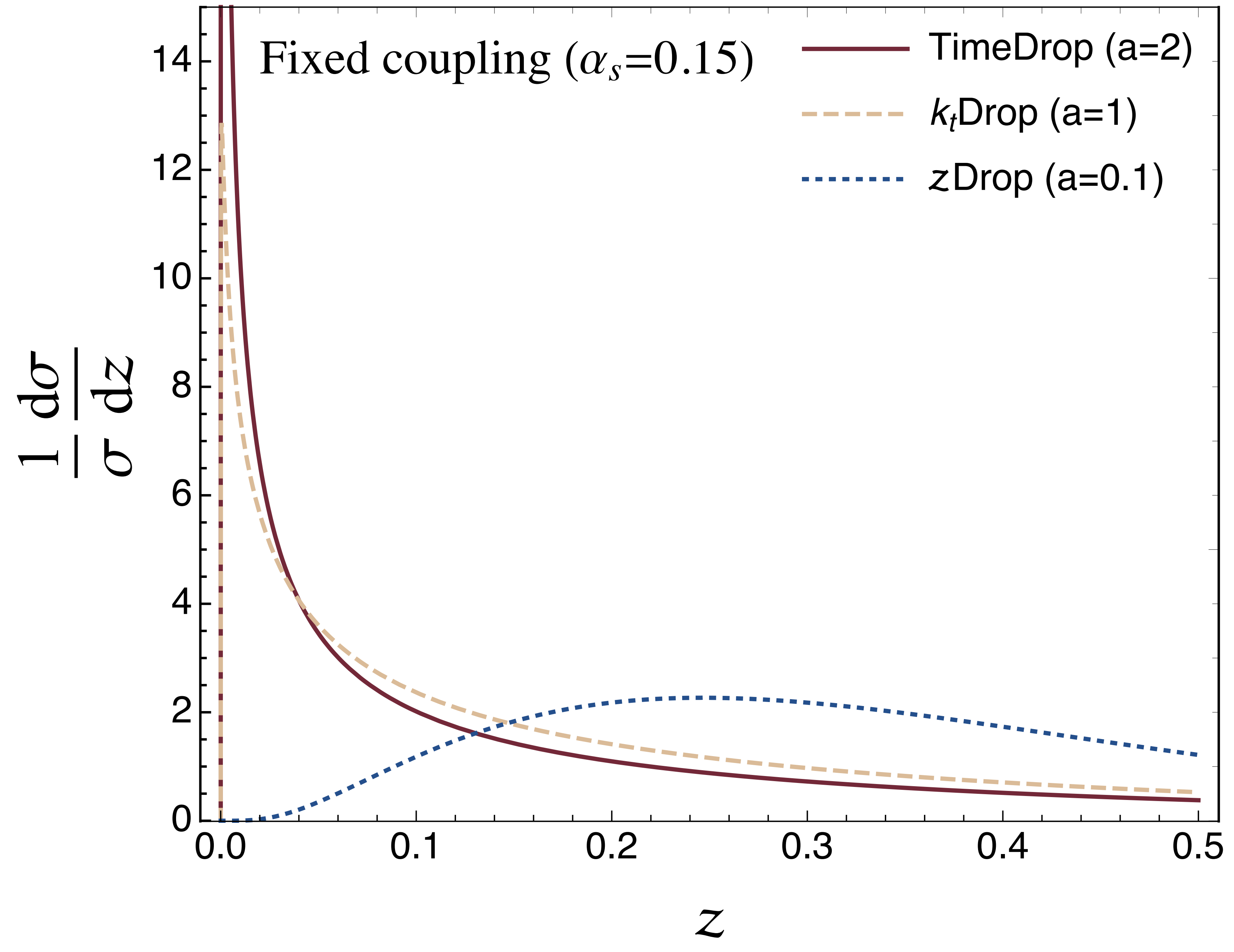
Comparison among:

- TimeDrop
- k_TDrop
- zDrop
- SD(0.1,0)
- SD(0.1,1)

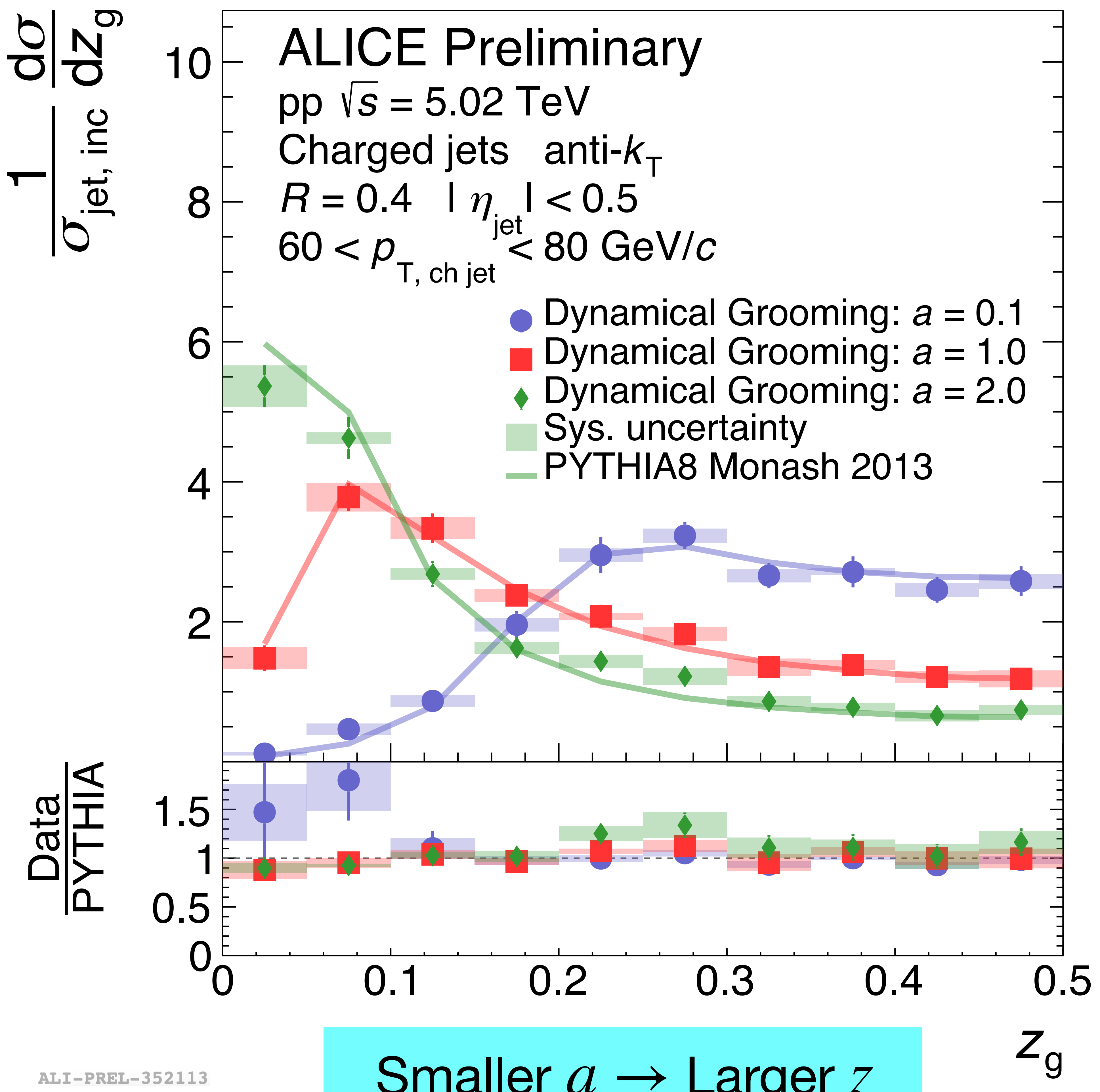


Overall similar behavior to SD. k_TDrop remarkably robust to hadronization

Measurement of z_g-distribution in DyG QCD jets



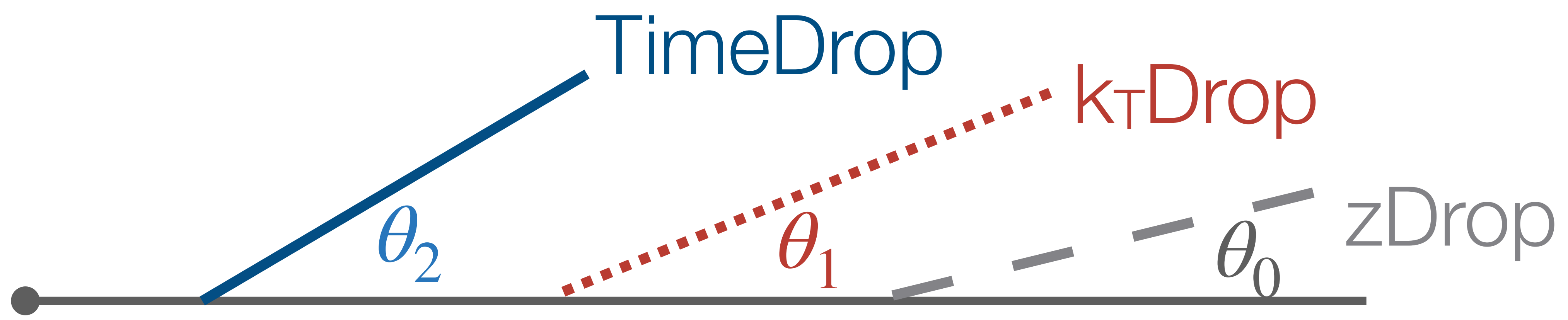
Qualitative agreement with data



[James Mulligan talk at HP'20]

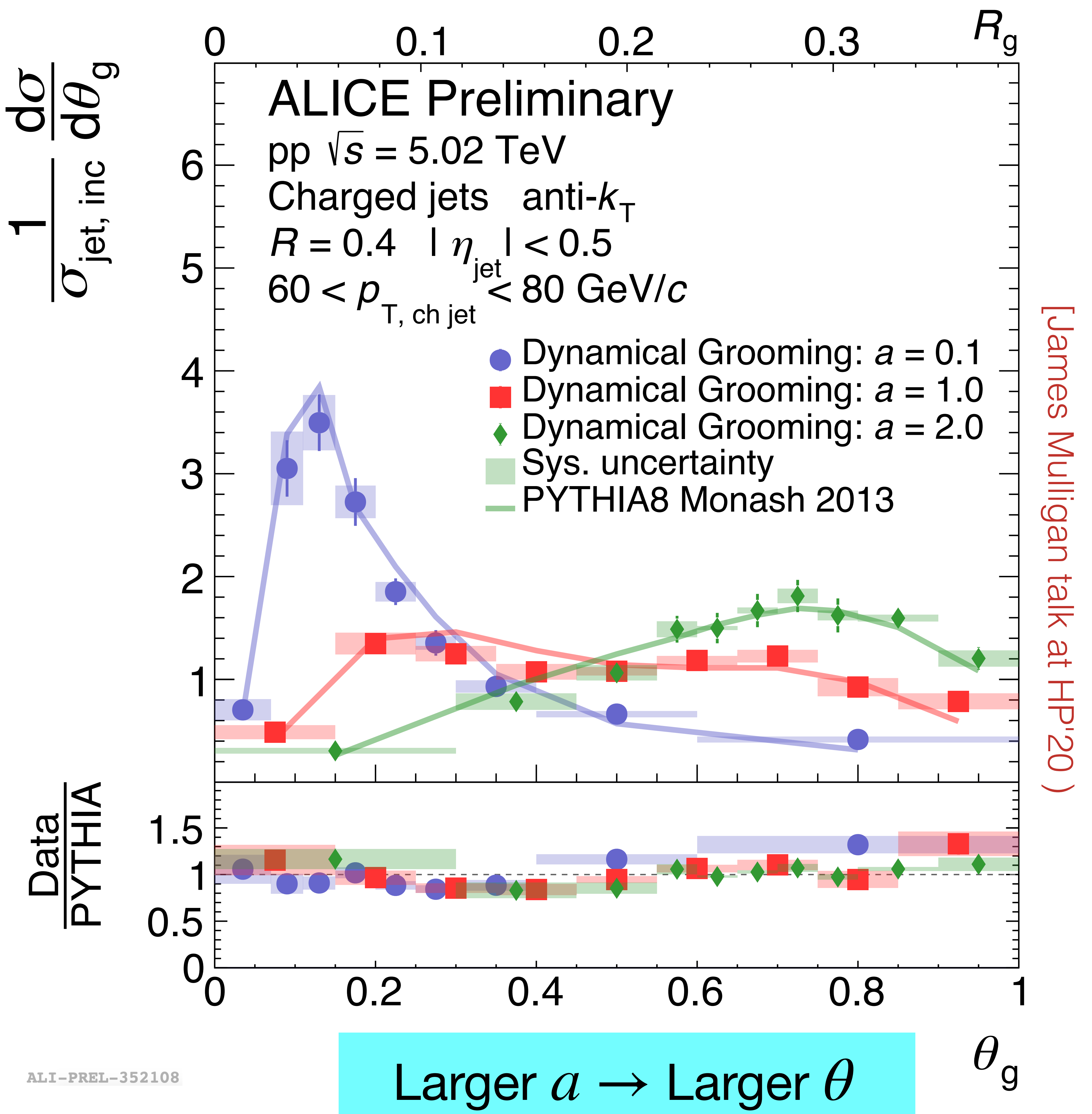
Smaller a → Larger z

Measurement of R_g-distribution in DyG QCD jets



$\theta_2 > \theta_1 > \theta_0$

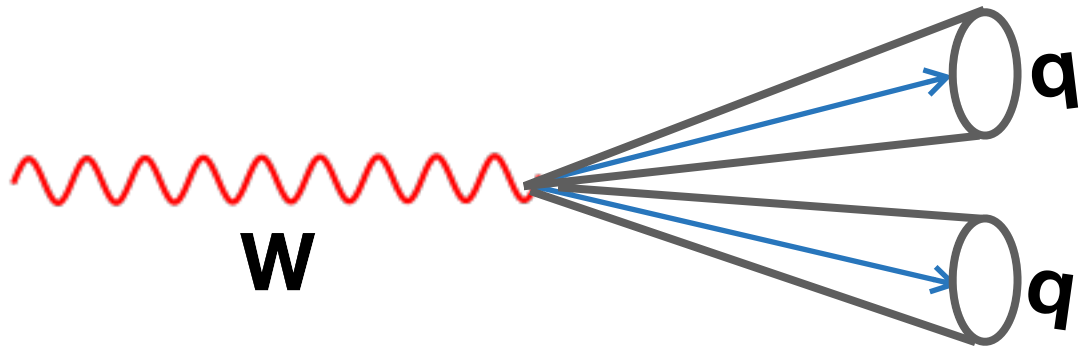
Qualitative agreement with data



Larger $a \rightarrow$ Larger θ

W tagging in the boosted regime

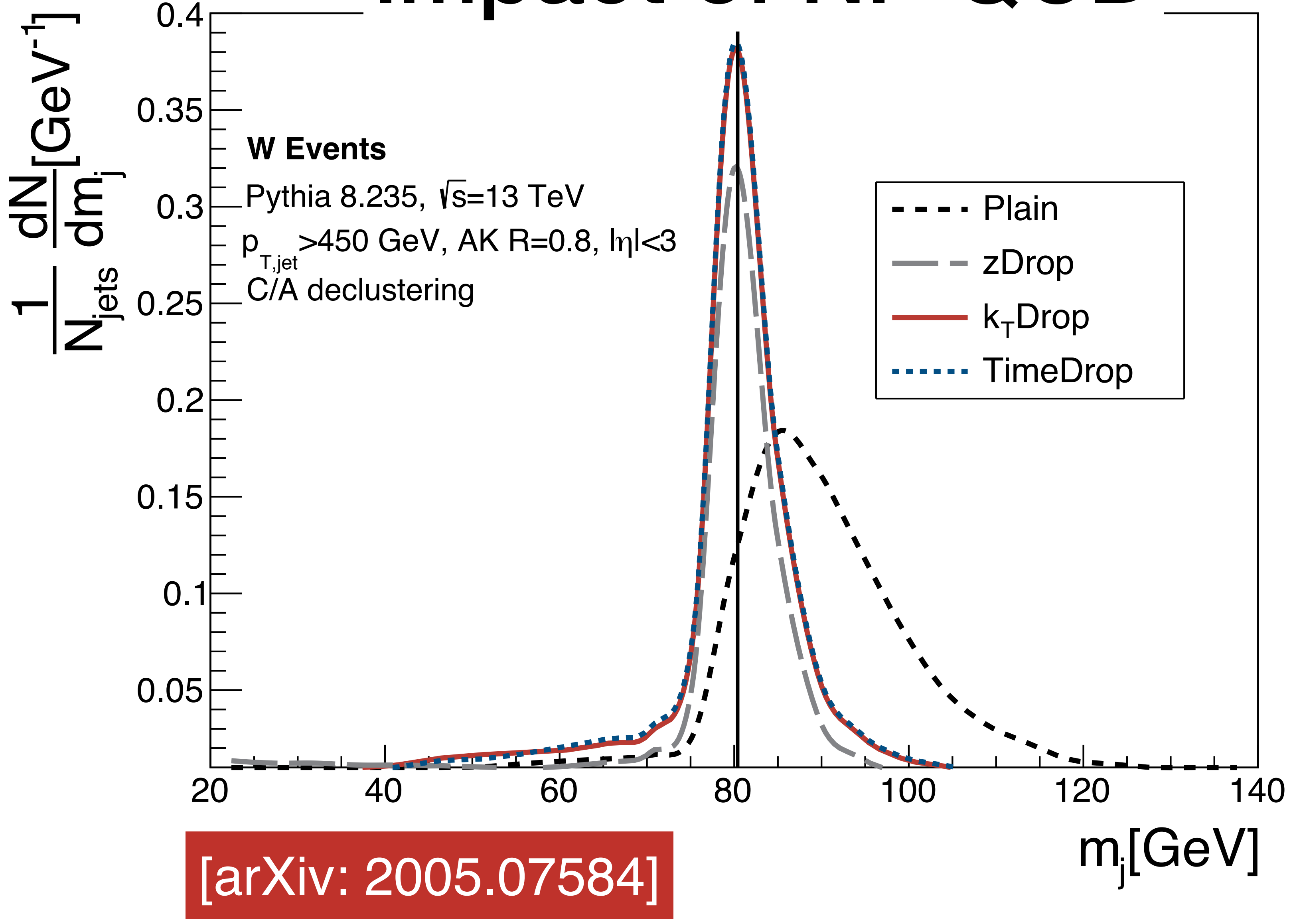
PYTHIA 8, pp->W; W->qq@ 13 TeV
+ n_{pu} minimum bias events + Constituent Subtraction

Topology: 

Comparison:
- TimeDrop
- k_TDrop
- zDrop
- SD(0.05,1)
- RSD_2(0.05,1)
- RSD_∞(0.05,1)

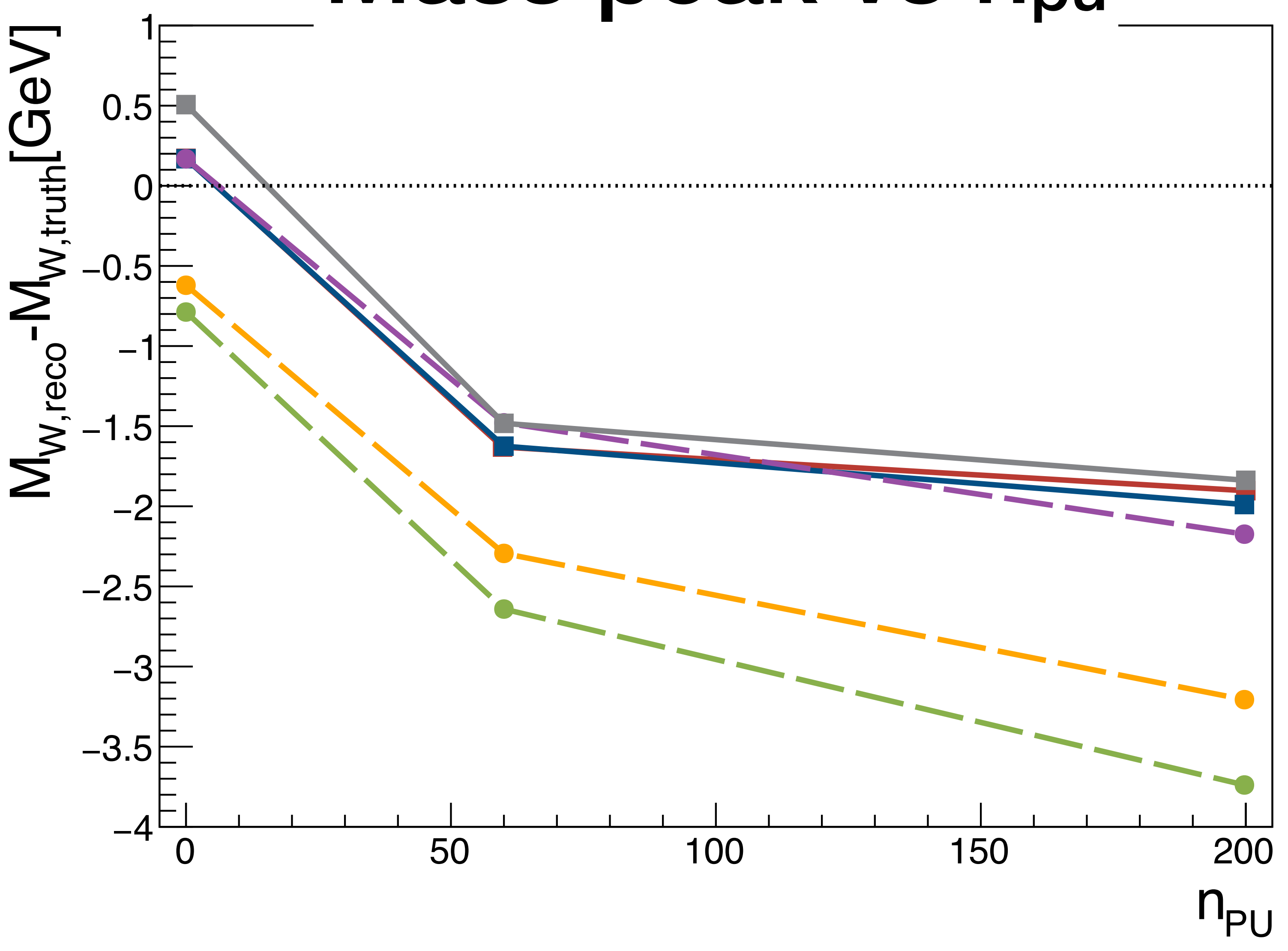
tuned by [Dreyer et al JHEP'20]

Impact of NP QCD

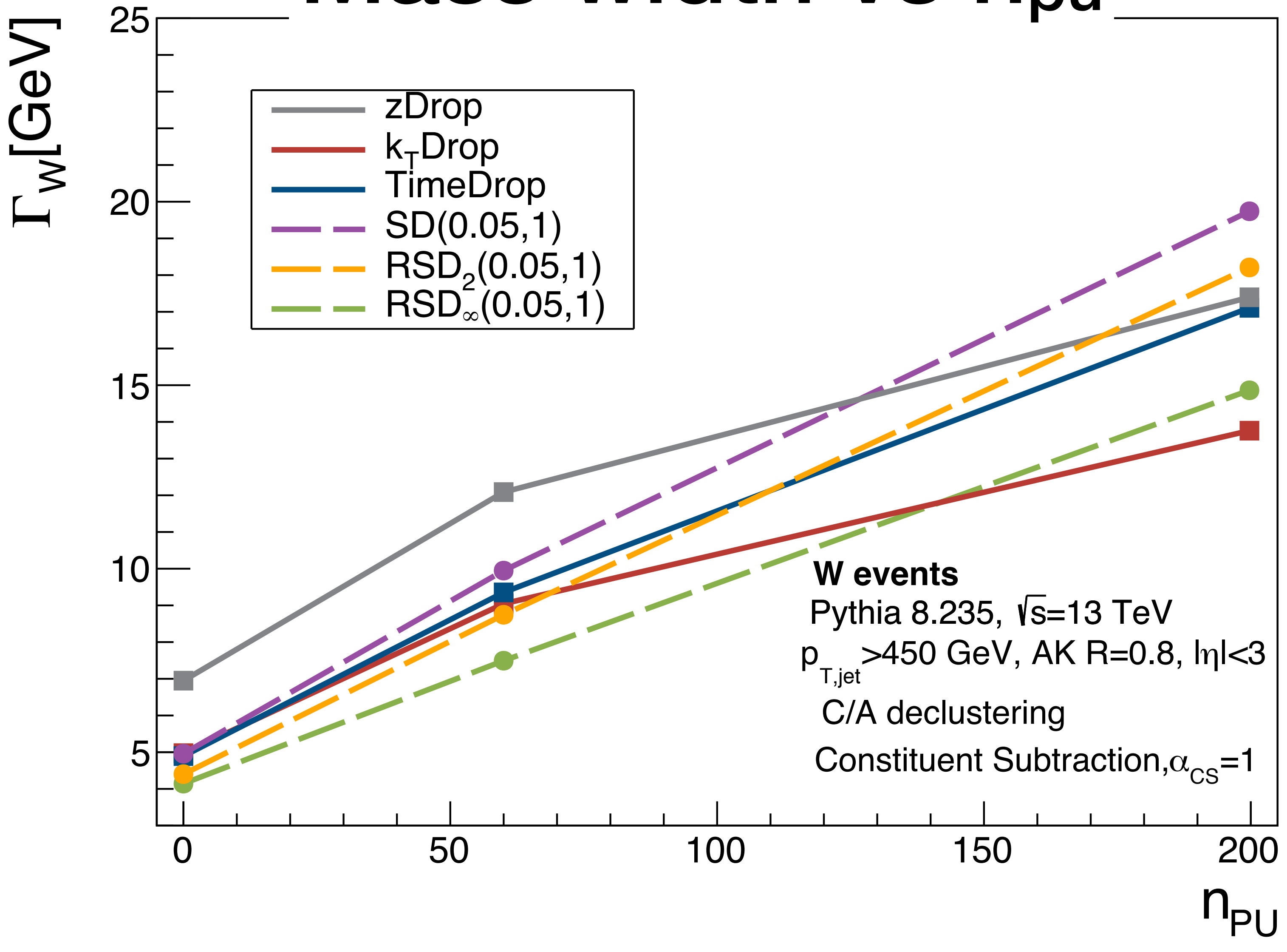


[arXiv: 2005.07584]

Mass peak vs n_{pu}



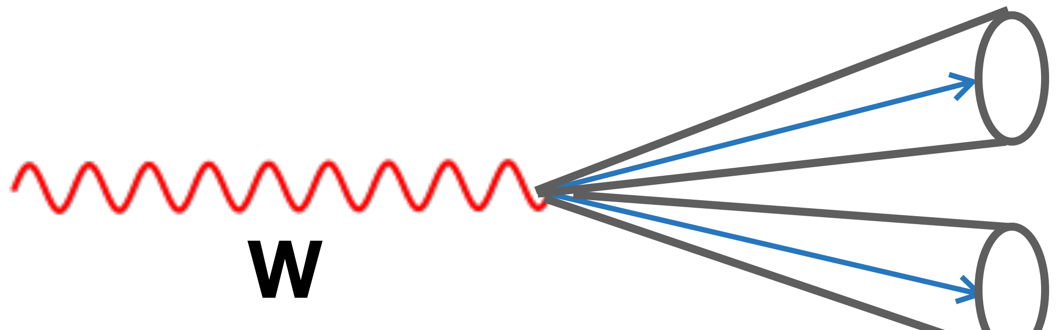
Mass width vs n_{pu}



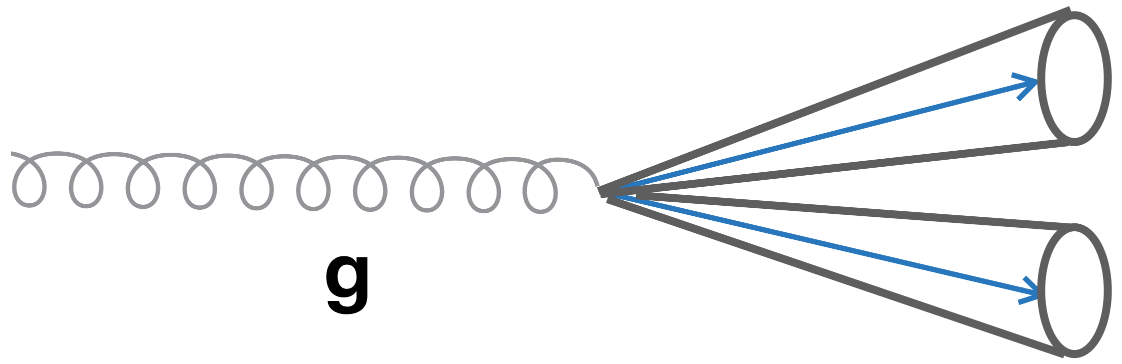
k_TDrop shows an enhanced resilience against background fluctuations

W tagging in the boosted regime

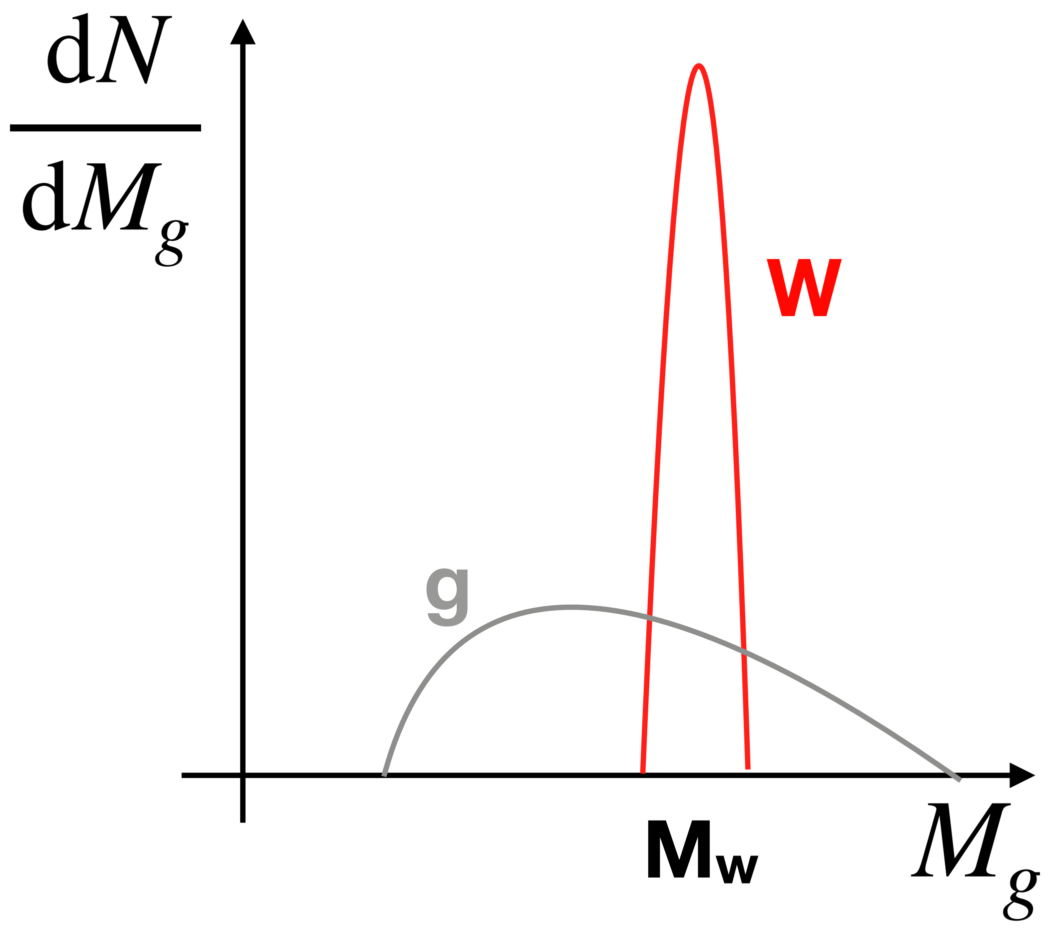
Tagging efficiency: how to distinguish a W jet from the abundant QCD background

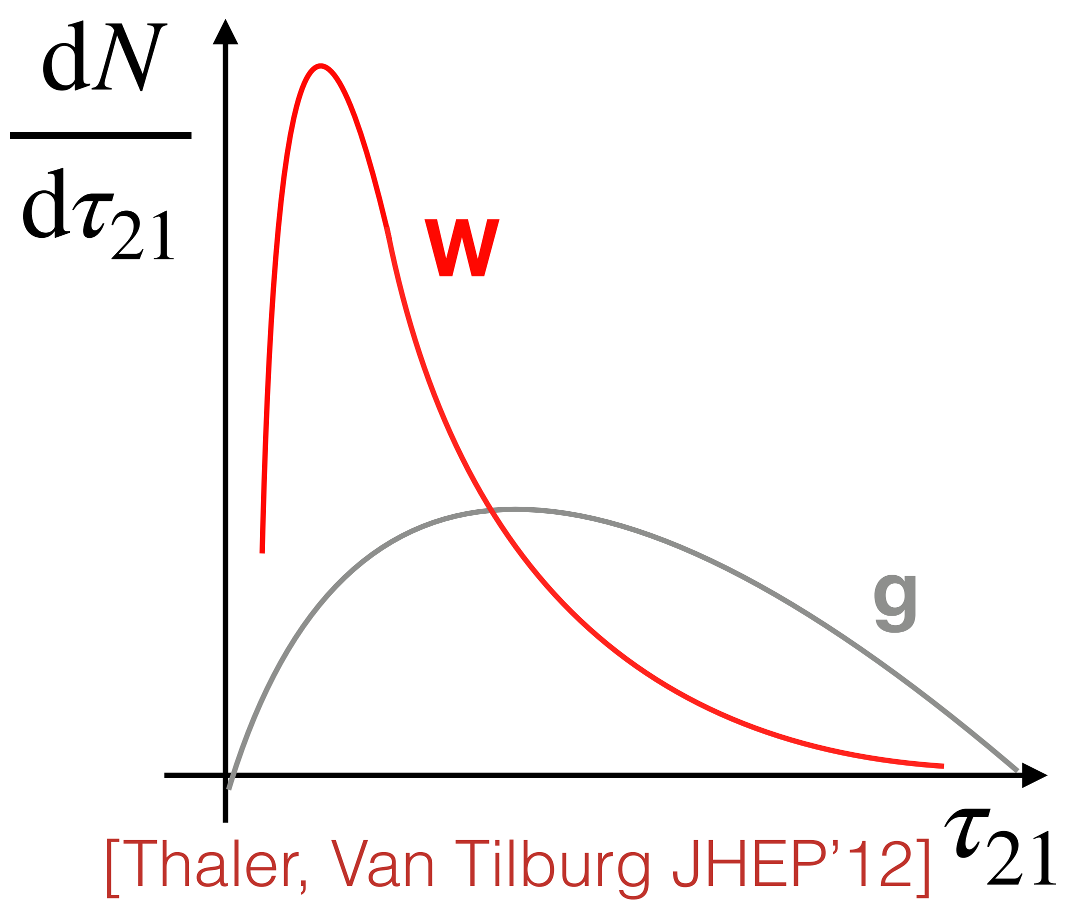


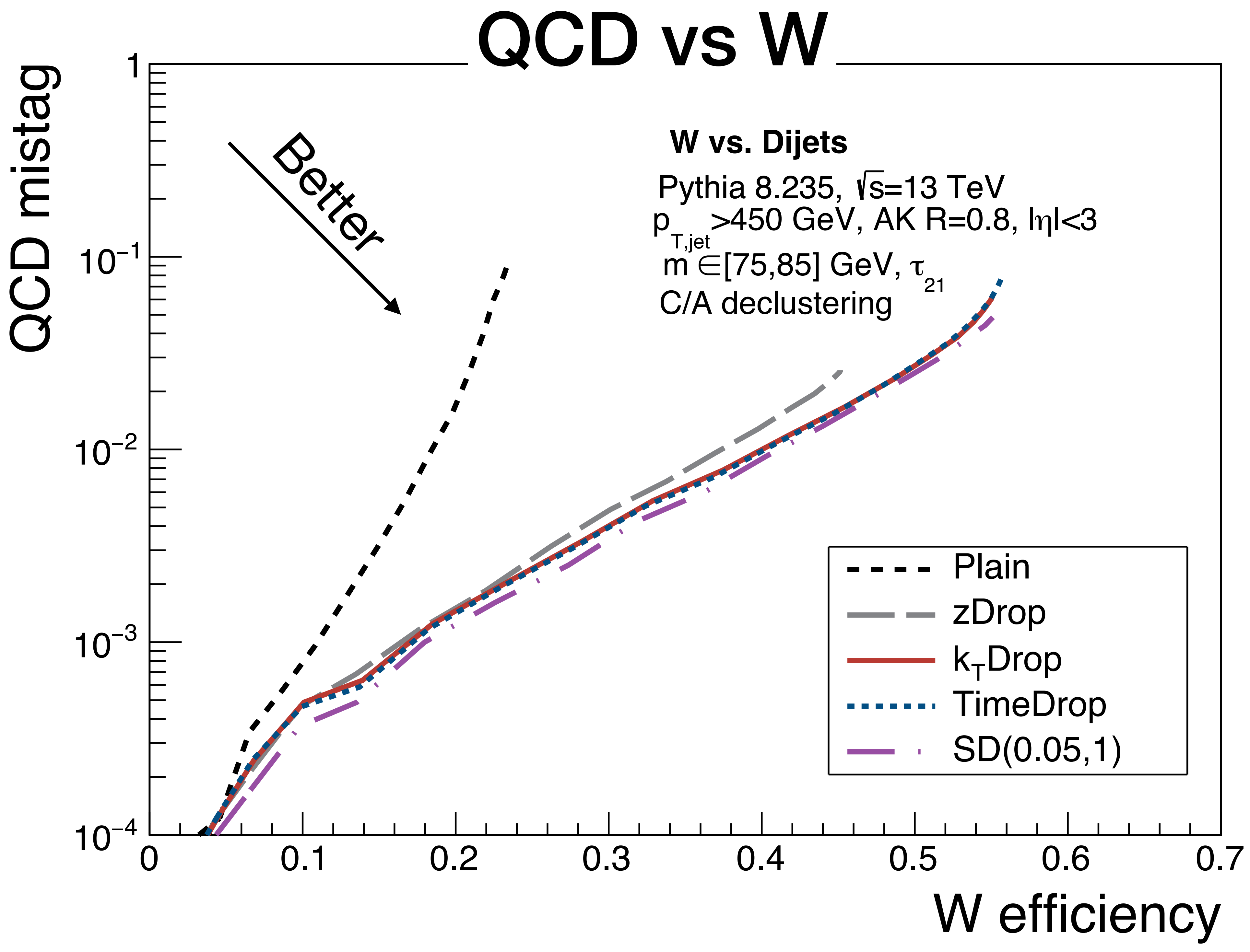
VS



Strategy: exploit differences on





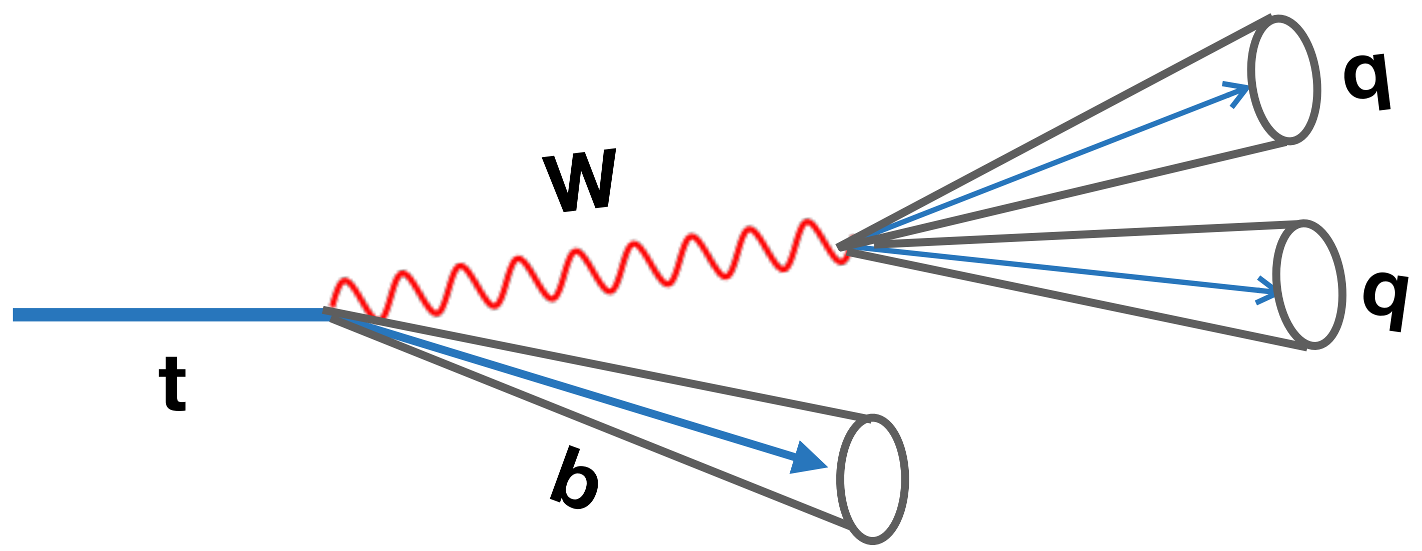


Out-of-the-box DyG delivers a comparable performance to SD

Top tagging in the boosted regime

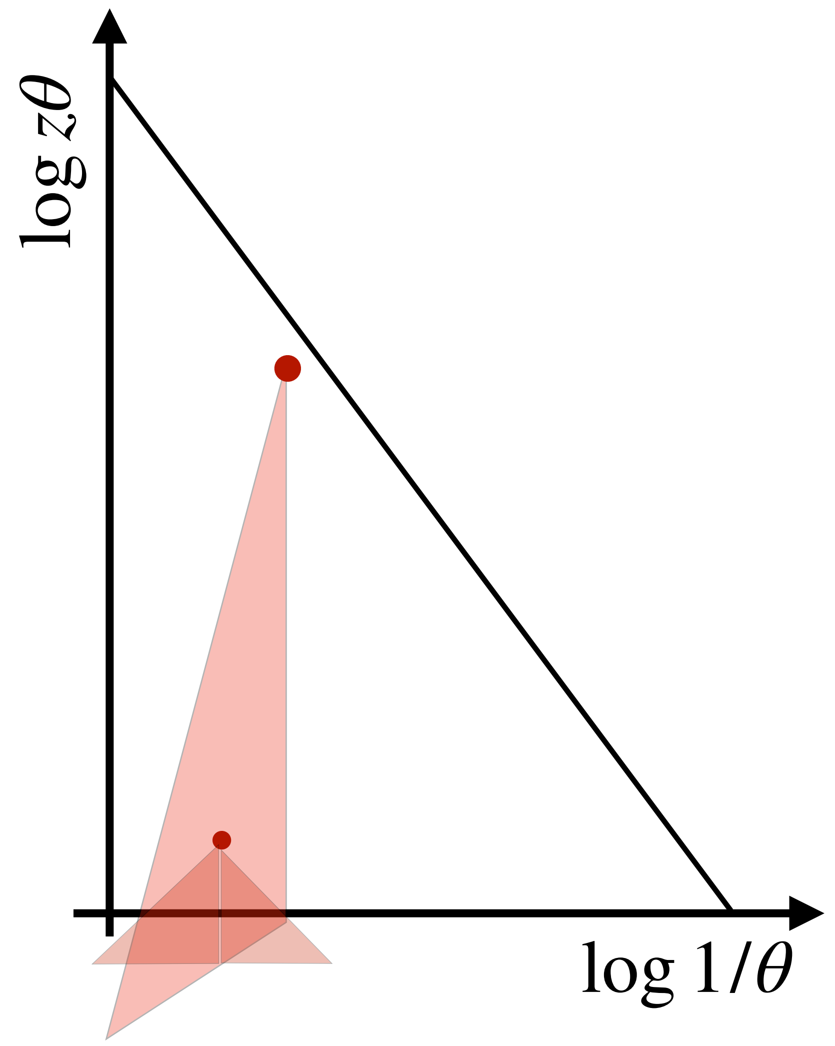
PYTHIA 8, pp->tt; t->Wb; W->qq @13 TeV
+n_{pu} minimum bias events +Constituent Subtraction

Topology:



w/o angular ordering

$\theta_{qq} \not< \theta_{Wb}$

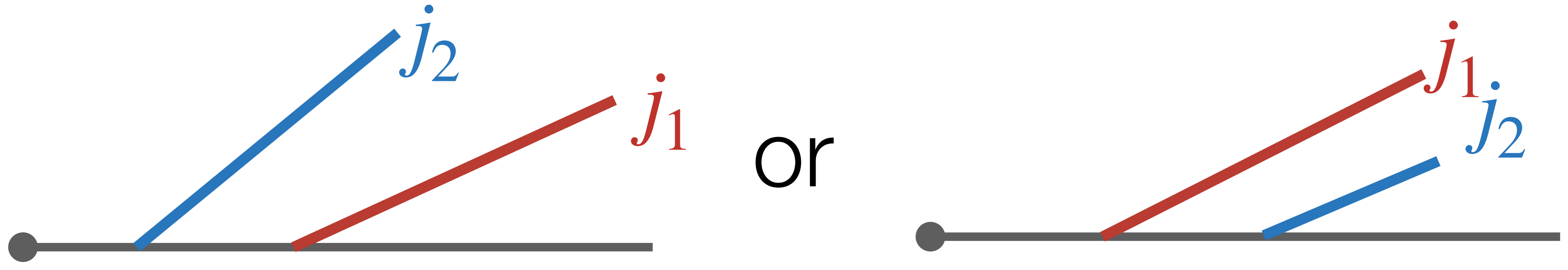


3-prong DyG: first step towards n-prong DyG

1) Find **hardest** branch: $j_1, \theta_{\text{leading}}$

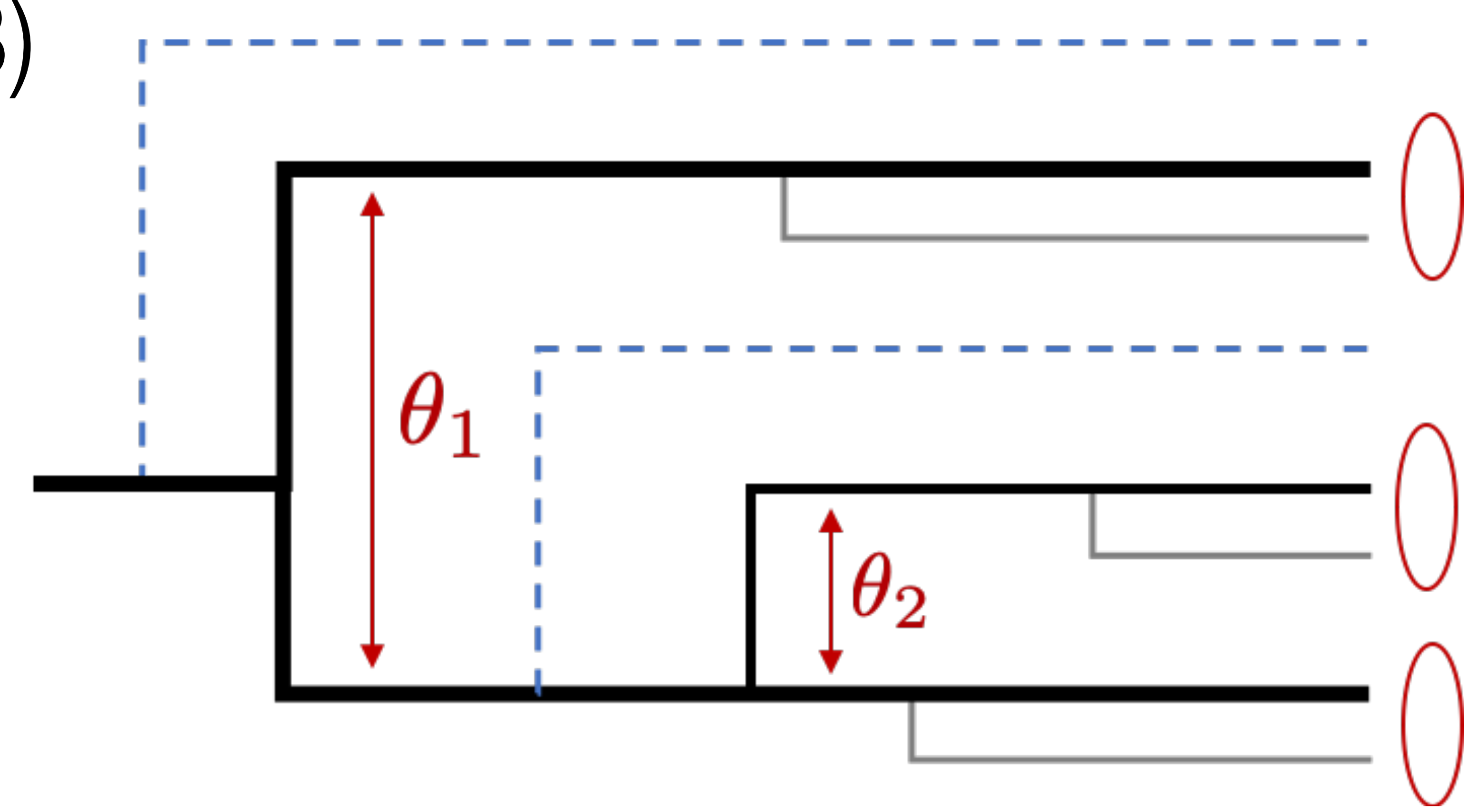
2) Look for the **next-to-hardest:** $j_2, \theta_{\text{sub-leading}}$

a) j_2 on primary Lund Plane of j_1



b) j_2 on secondary Lund Plane of j_1

3)



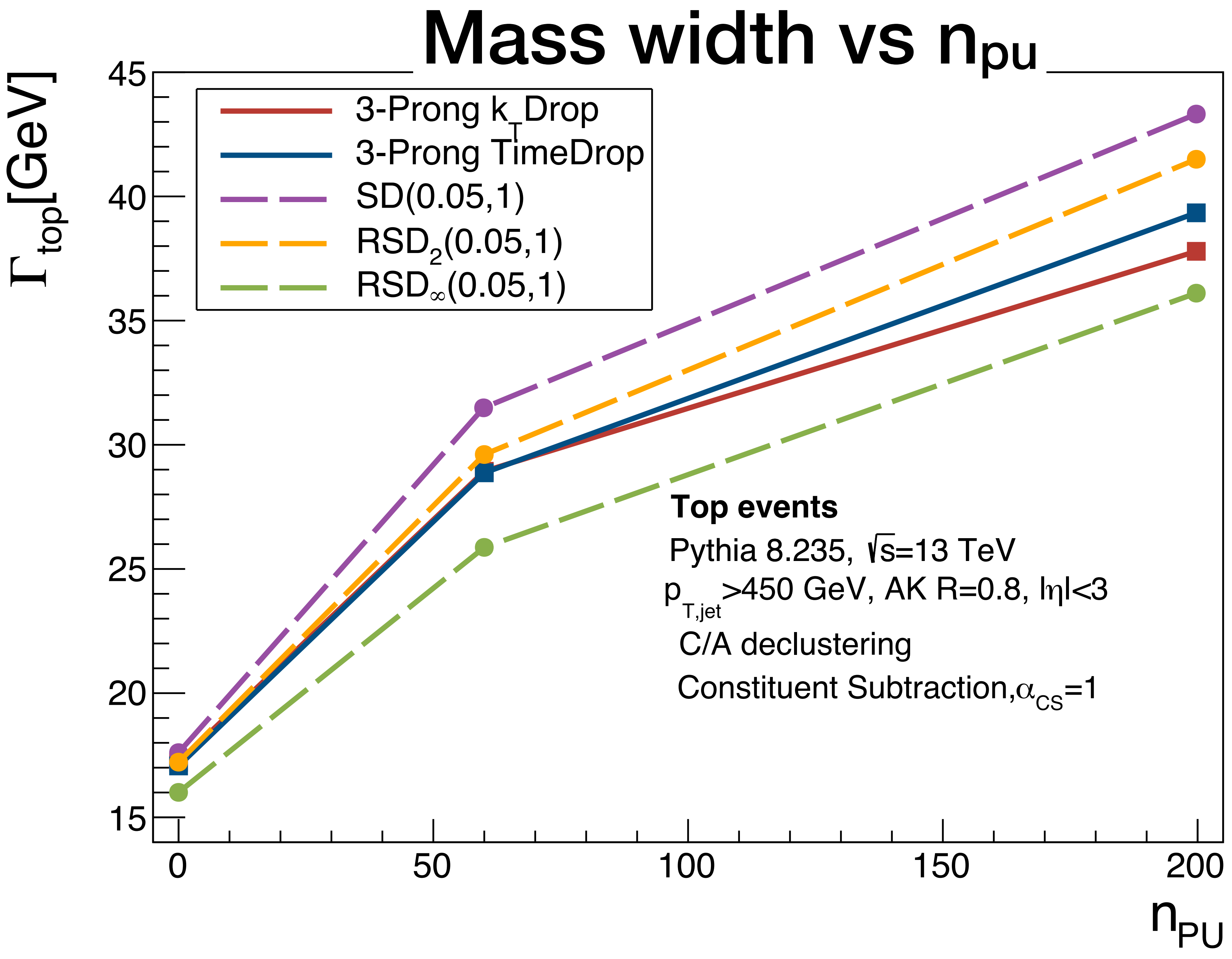
$$\theta_1 = \max(\theta_{\text{leading}}, \theta_{\text{sub-leading}})$$

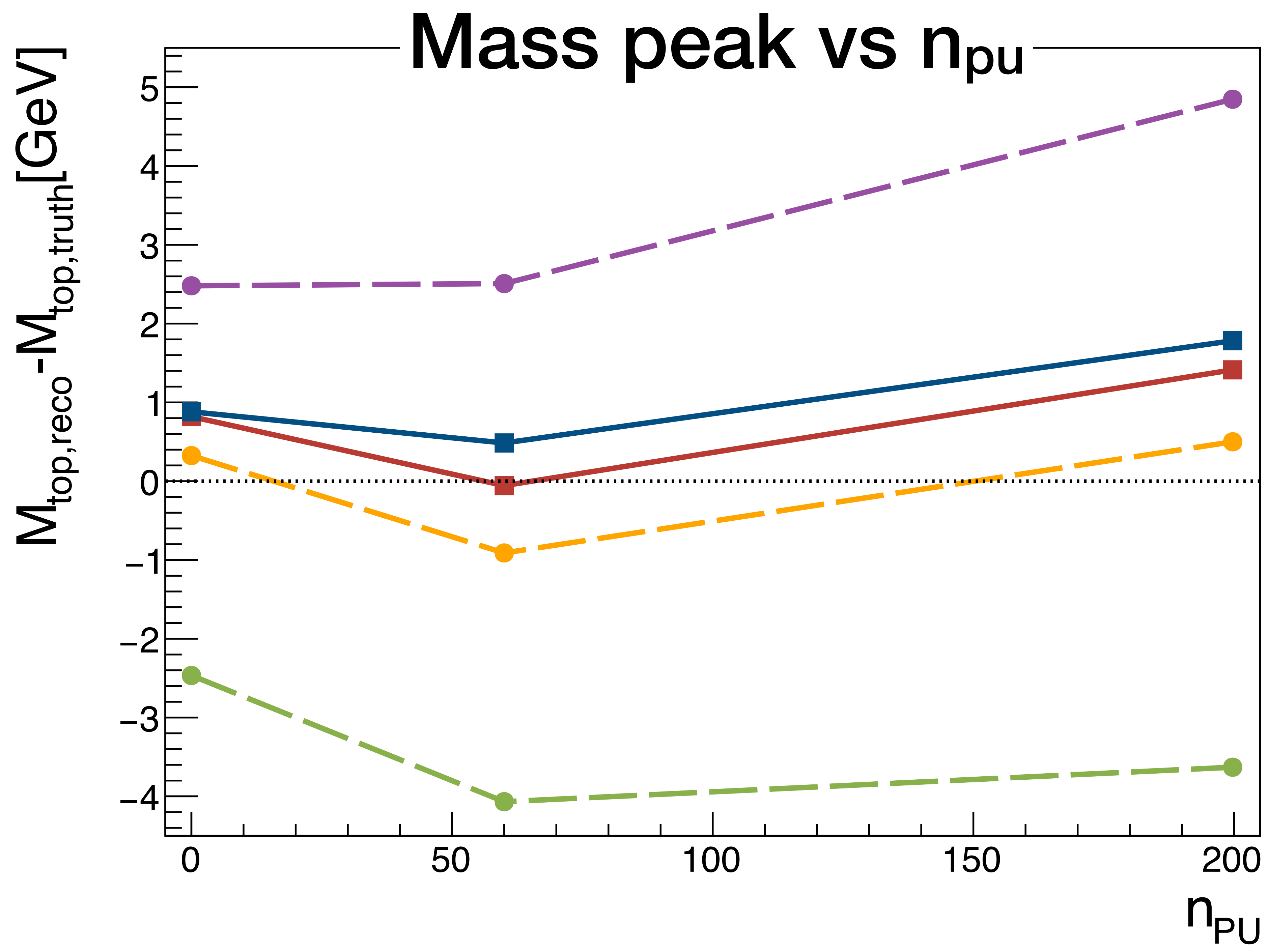
$$\theta_2 = \min(\theta_{\text{leading}}, \theta_{\text{sub-leading}})$$

Top tagging in the boosted regime

PYTHIA 8, pp->tt; t->Wb; W->qq @13 TeV
+n_{pu} minimum bias events +Constituent Subtraction

Comparison:
- TimeDrop
- k_TDrop
- SD(0.05,1)
- RSD_2(0.05,1)
- RSD_∞(0.05,1) tuned by [Dreyer et al JHEP'20]

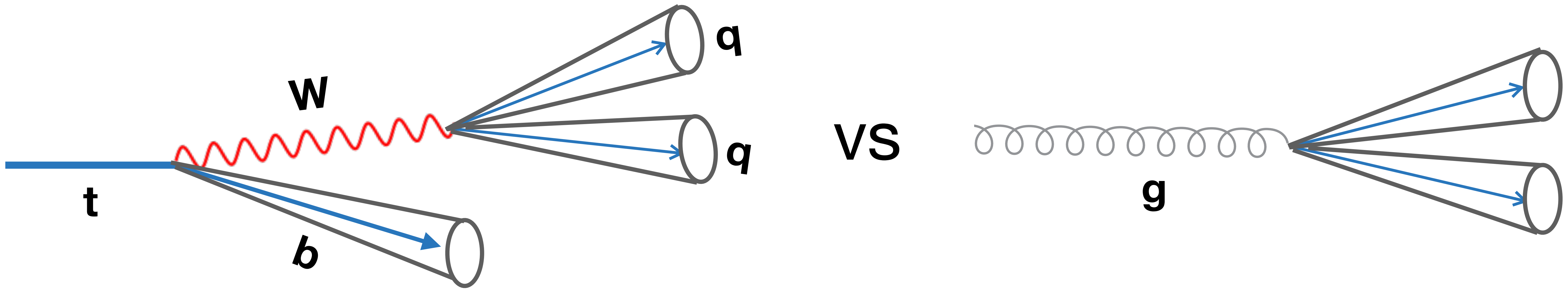




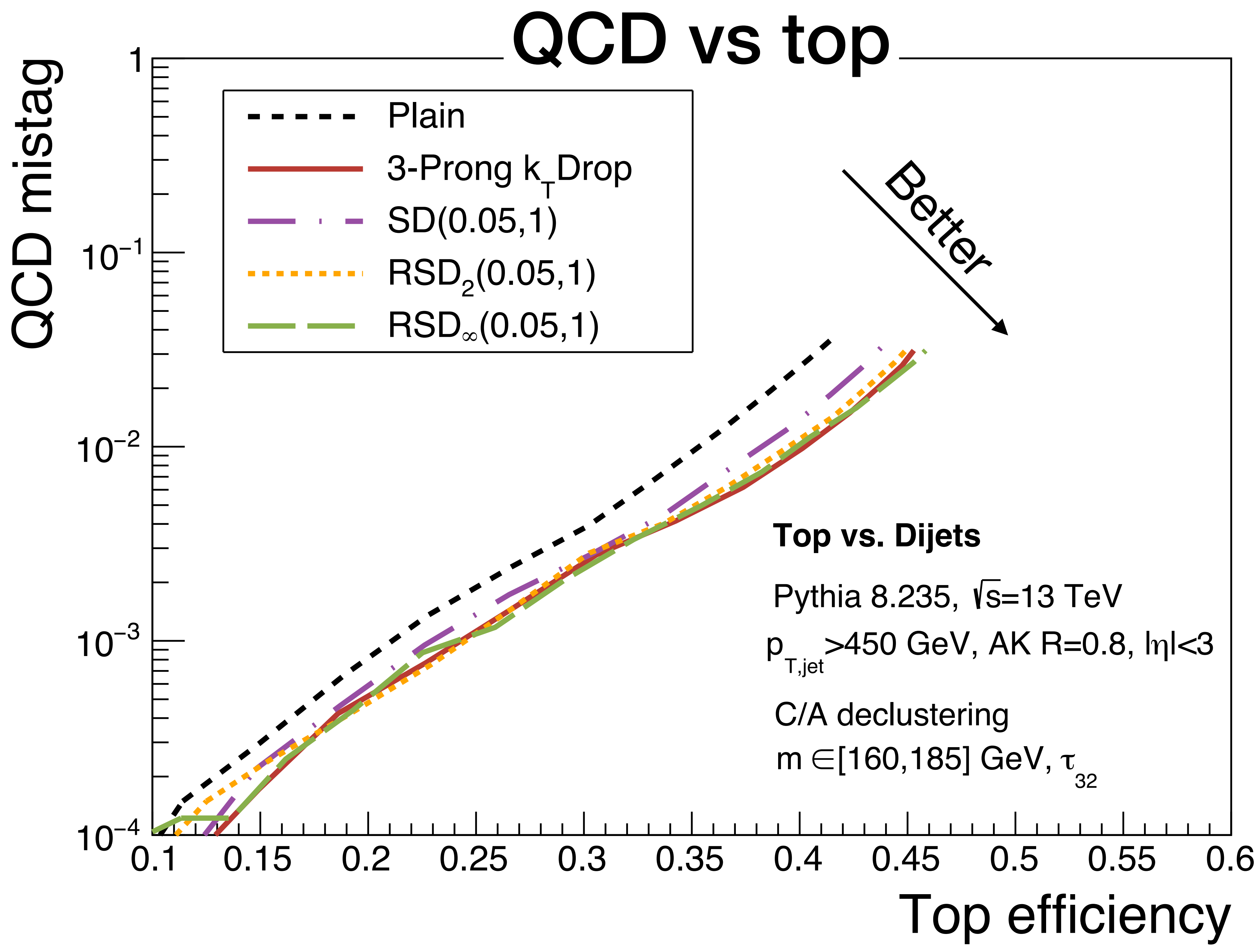
3-Prong DyG neat improvement with respect to traditional SoftDrop

Top tagging in the boosted regime

PYTHIA 8, pp->tt; t->Wb; W->qq @13 TeV
+n_{pu} minimum bias events +Constituent Subtraction



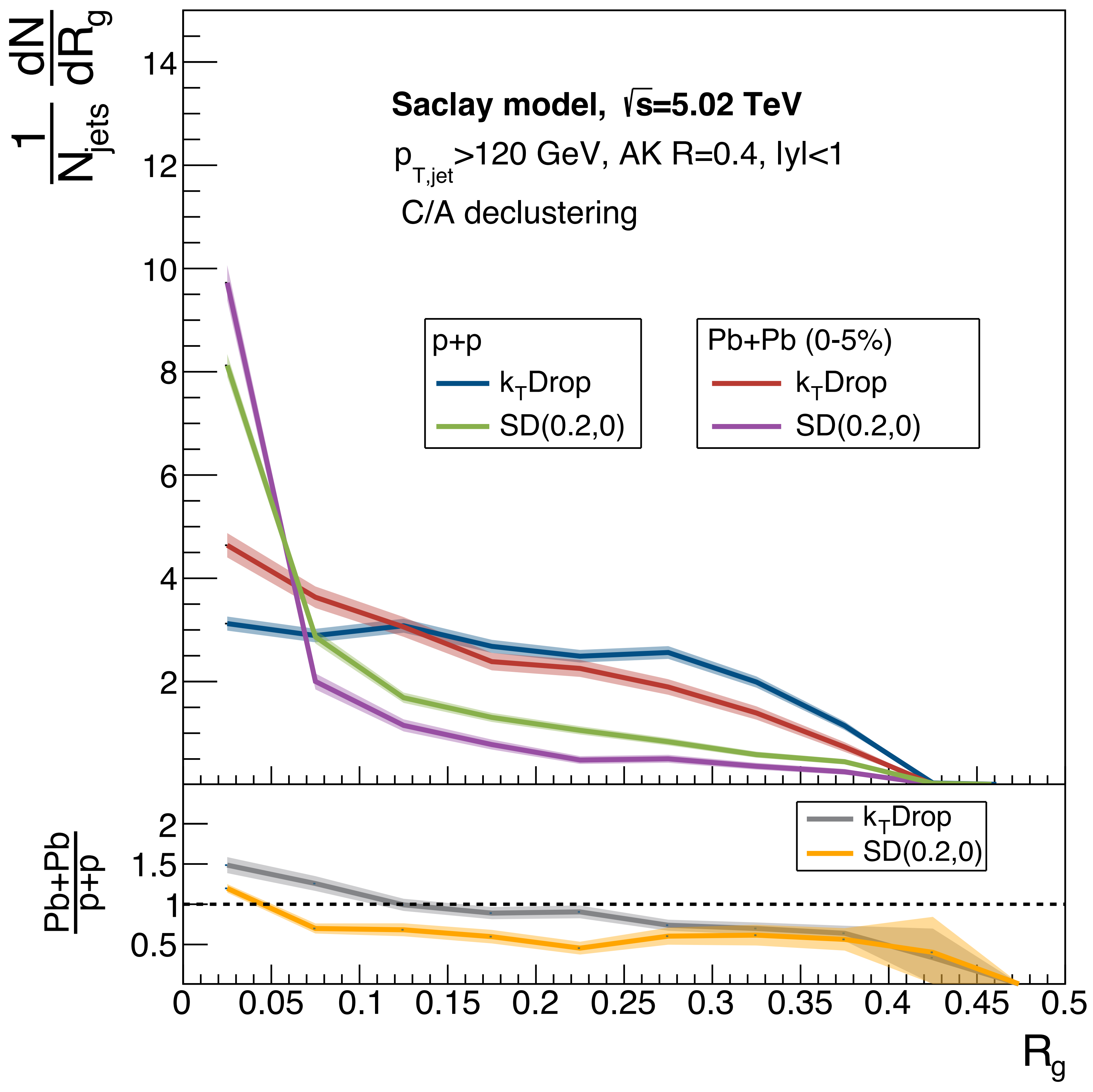
Comparable top tagging performance to (R)SD without the need to fine-tune

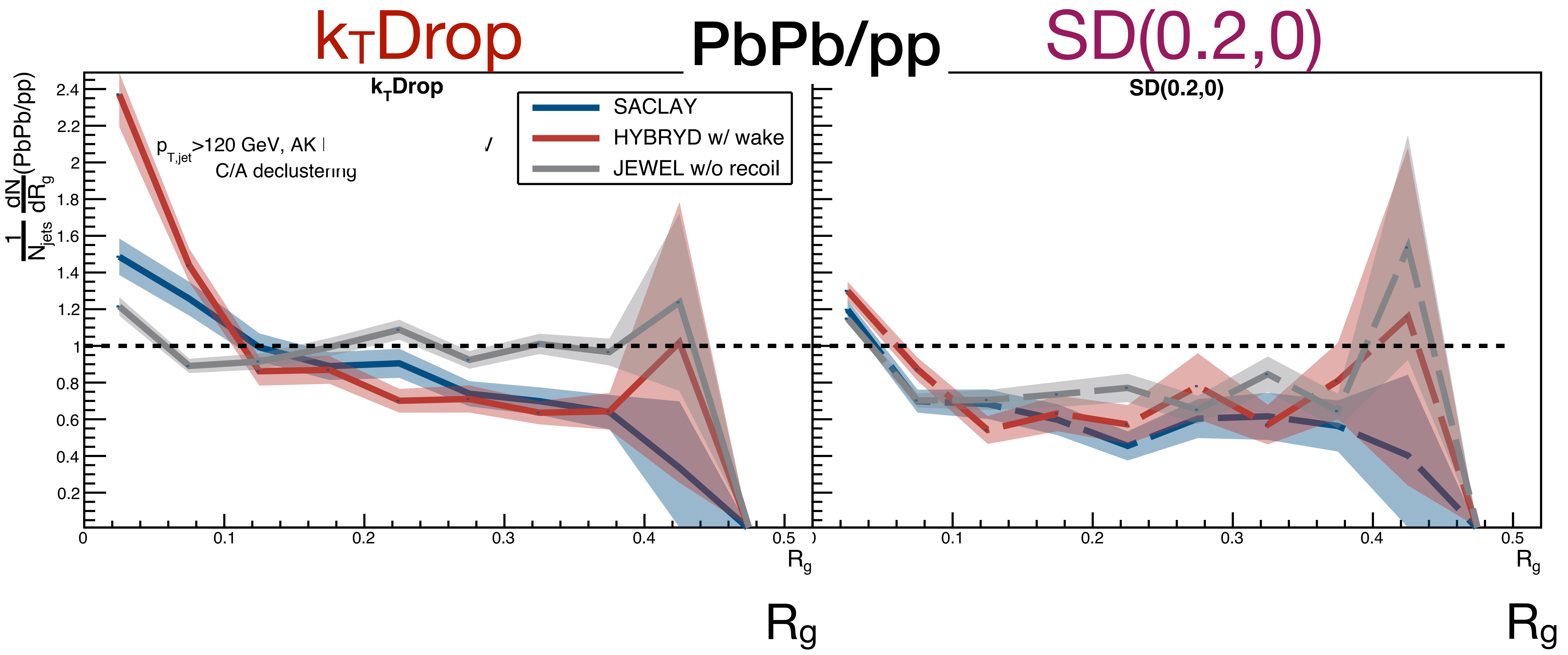


Sneak peek into heavy-ion collisions

ALICE-like set up
Samples: JetTools GitHub

Goal: asses discriminating power of the k_TDrop R_g-distribution compared to SD





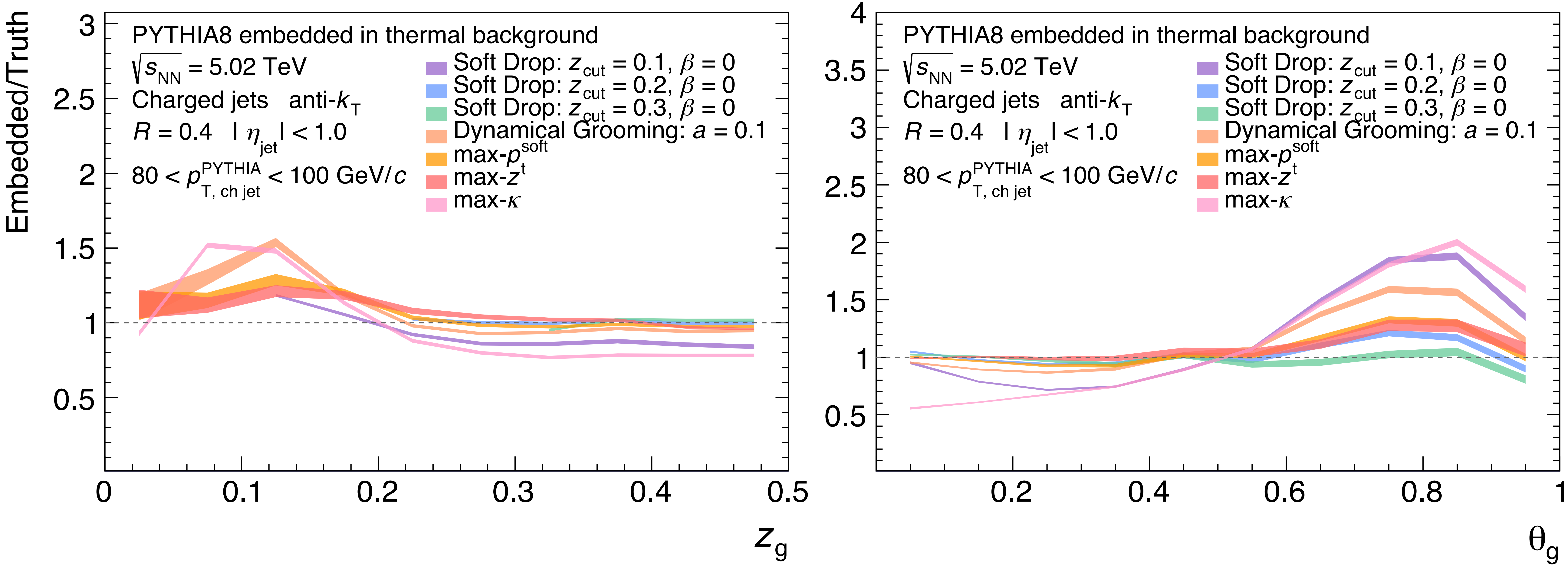
- Saclay: P. Caucal et al
- Hybrid w/wake: D. Pablos et al
- JEWEL w/o recoil: K. Zapp et al

Beware: thermal background not included.

Sneak peek into heavy-ion collisions

ALICE-like set up
Samples: JetTools GitHub

Dynamical grooming performance in a realistic environment [Mulligan, Ploskon arXiv:2006.01812]



Note 1: "max-z" is DyG with a=0 (IRC unsafe)

Note 2: The choice of a=0.1 as zDrop is arbitrary

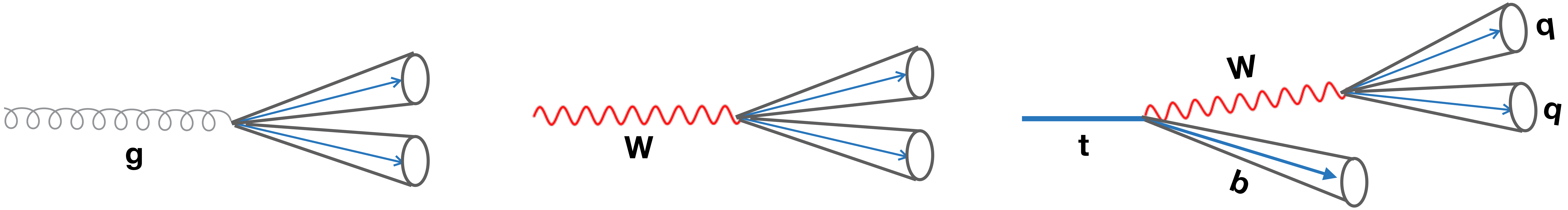
Take-home messages

Introduced **dynamical grooming** based on identifying the hardest splitting jet-by-jet

$$\kappa^{(a)} = \frac{1}{p_T} \max_{i \in \mathrm{C/A}} z_i(1 - z_i) p_{T,i} (\theta_i / R)^a$$

Properties:

- **Calculable:** IRC (IR and Collinear) safe for $a > 0$
- **Versatile:** successfully applied to different scenarios without fine-tuning



- **Resilient:** to underlying event, hadronization and pileup (thermal bkg in HIC?)

Ready to use: Code: github/aontoso/JetToyHI