High-purity gluon jet showers using secondary Lund jet planes

[*work in progress results*]

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BOOST 2024 @ Genoa, Italy
July 29th–August 2nd

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UNIVERSITÀ DI ROMA

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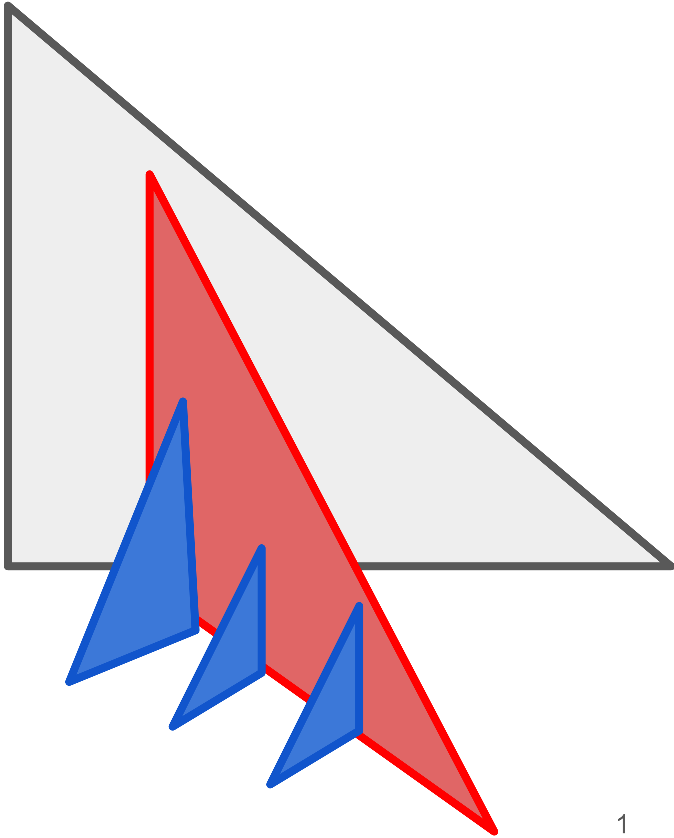
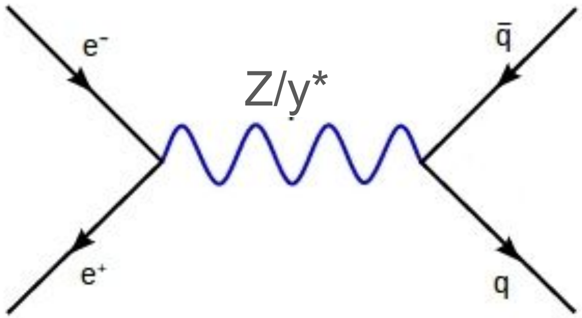


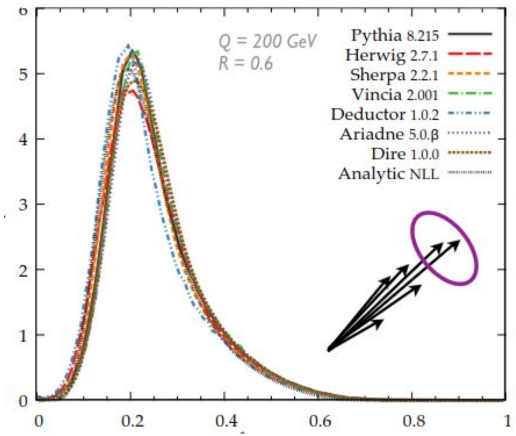
Some context:

``Quark jet showers strongly constrained at LEP, gluon jet showers not as much''

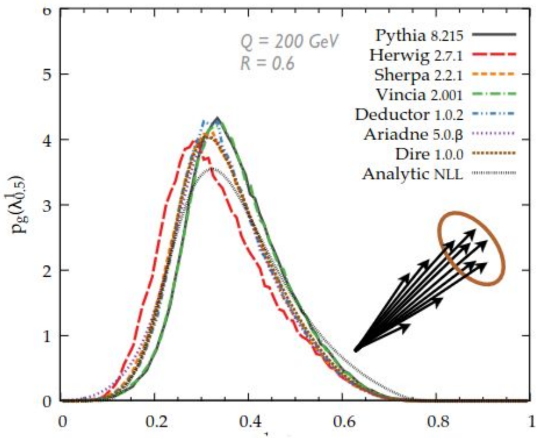
Les Houches studies,
JHEP 1707 (2017) 091



$e^+e^- \to$ quarks ($C_F = 4/3$) *vs.* $e^+e^- \to$ gluons ($C_A = 3$)



$$\text{LHA} = \sum_i z_i \sqrt{\theta_i}$$



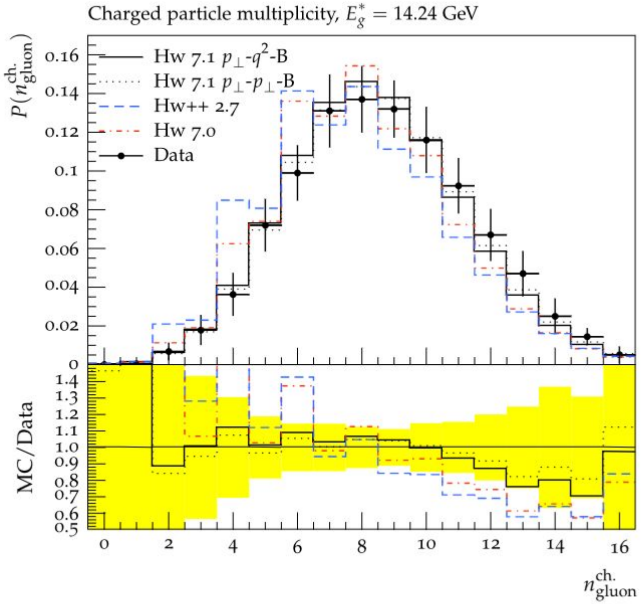
$$\text{LHA} = \sum_i z_i \sqrt{\theta_i}$$

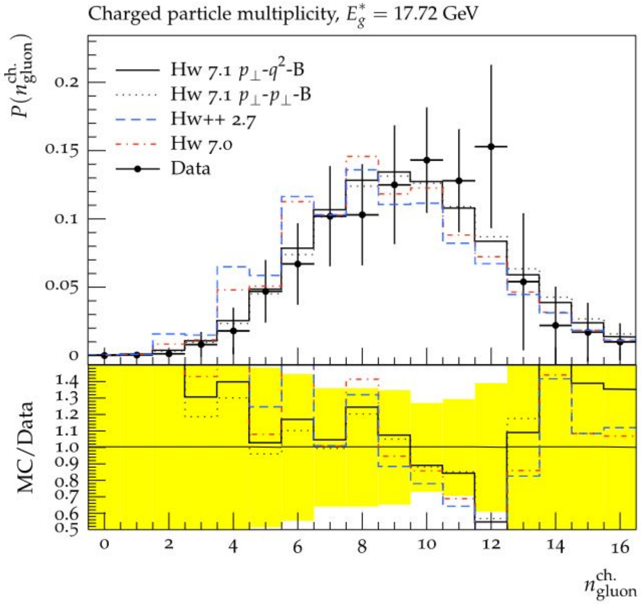
Smaller spread among quark jet
LEP constraints

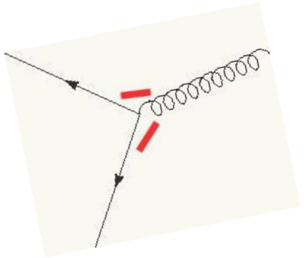
Larger spread for gluon jets
no LEP constraints!

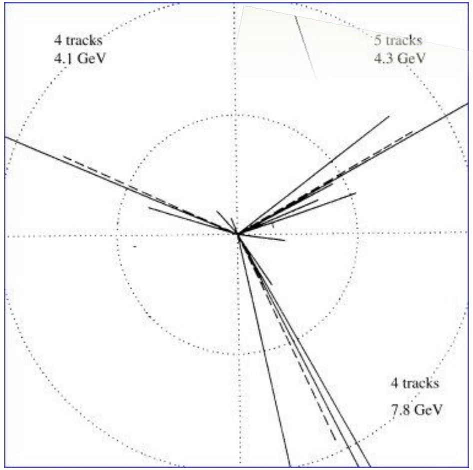
Gluon-rich jet samples at LEP ($e^+e^- \to b\bar{b}g$)

Data used in Herwig7.2 tuning (post Les Houches 2015)





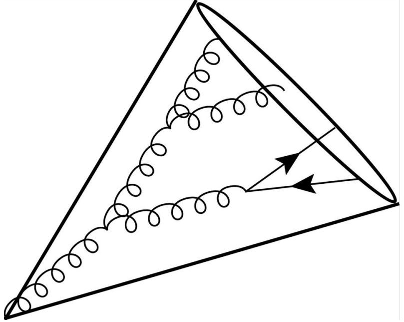




n^{ch} of soft gluon jets (E_T~14–18 GeV), uncertainties of ~30–40%

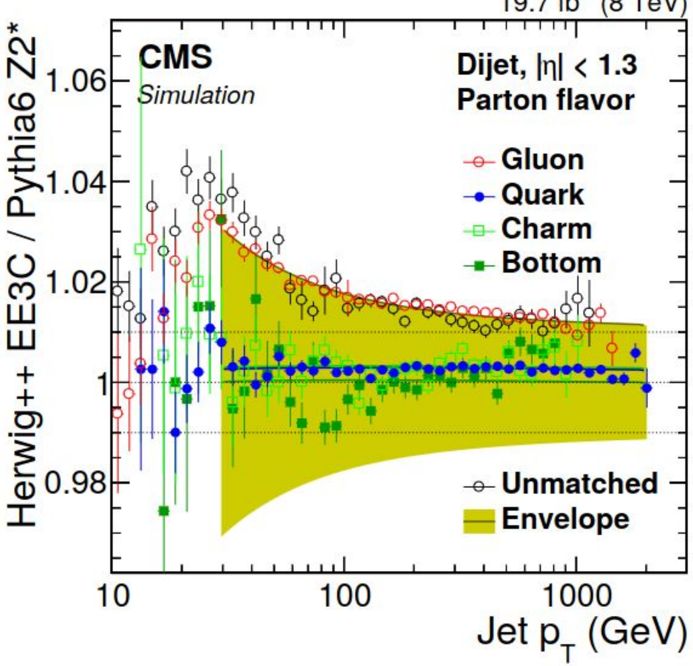
Otherwise, no other ``pure'' gluon jet samples available for MC tuning

Why gluon jet radiation?



- Understand gluon radiation patterns
- Improve “vacuum” baseline for jet quenching MCs
- Reduce jet energy calibration uncertainties, **affects all jet measurements at the LHC** (e.g., **gluon jet response between Herwig7 vs Pythia8 in CMS*)**
- To reduce MC-biases in quark vs gluon discriminators

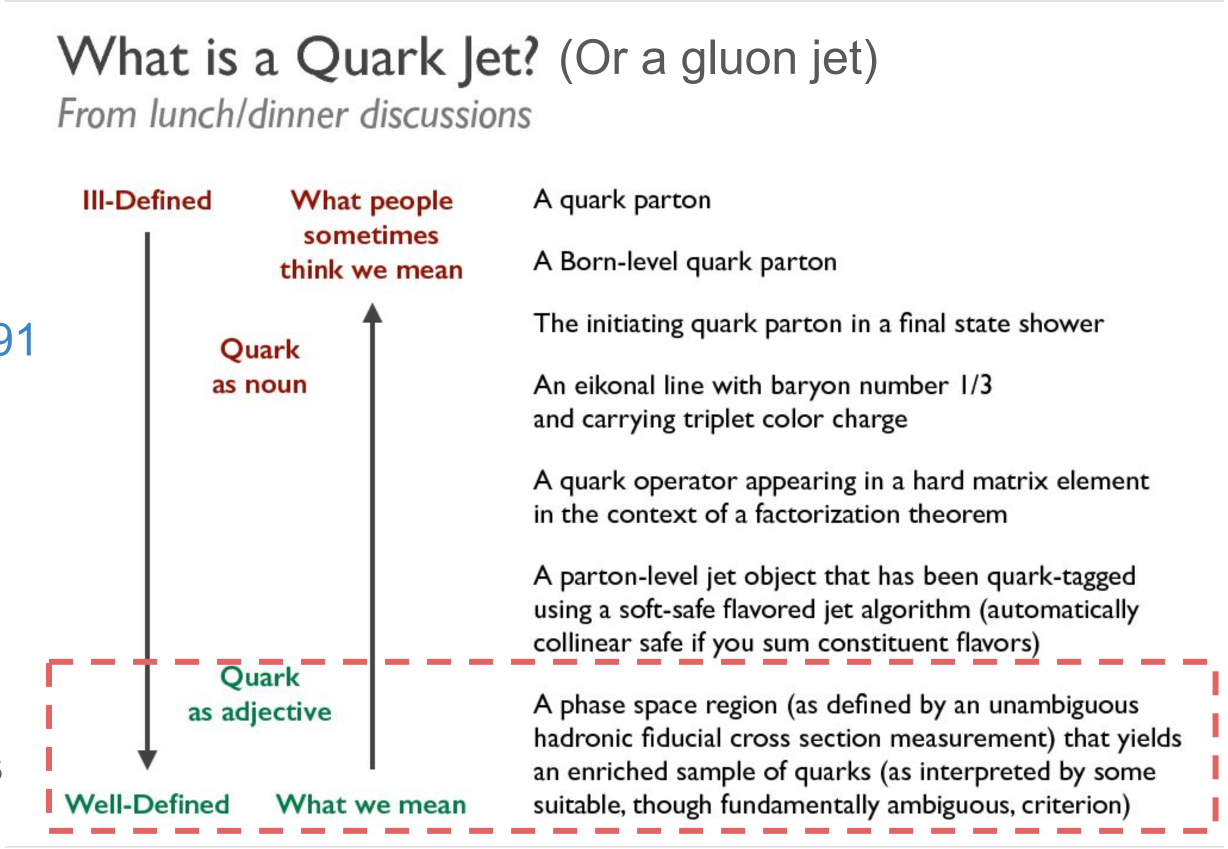
CMS, arXiv:1607.03663



Challenging to isolate gluon jets at a hadron collider

*ATLAS: **baryon&kaon fractions play a big role too**

Intrinsic ambiguity of parton flavor

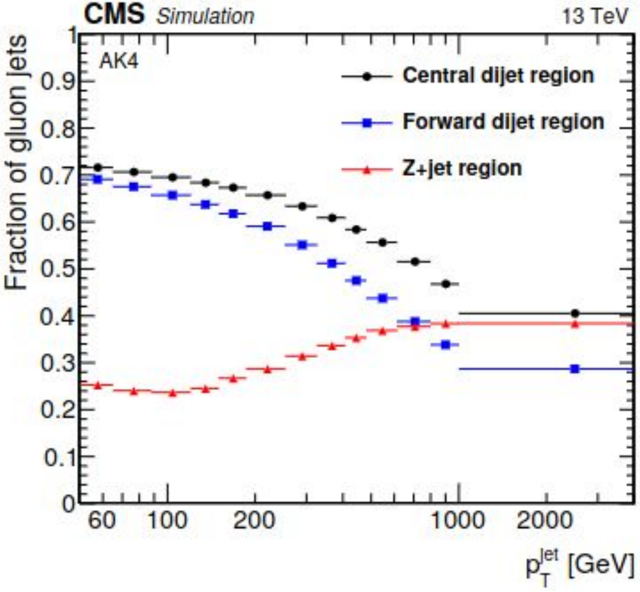


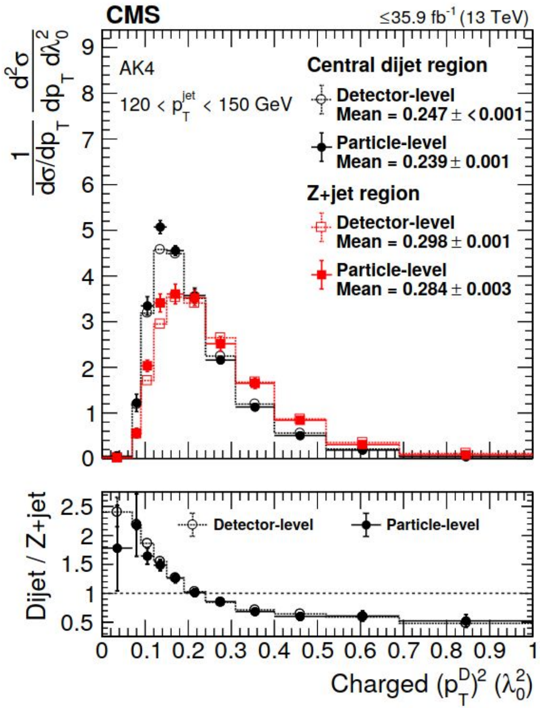
Les Houches 2015
JHEP 1707 (2017) 091

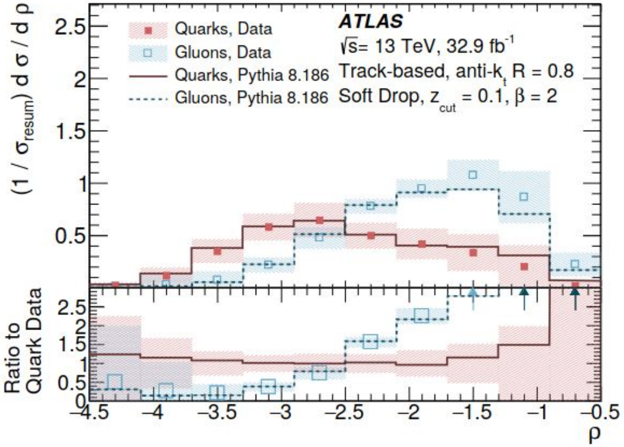
Hadron-level
phase space regions

Z+jet vs dijet

Central vs forward jets →Quark-like & gluon-like topic models







[CMS, JHEP 01 (2022) 188]

[ATLAS, PRD 101, 052007 (2020)]

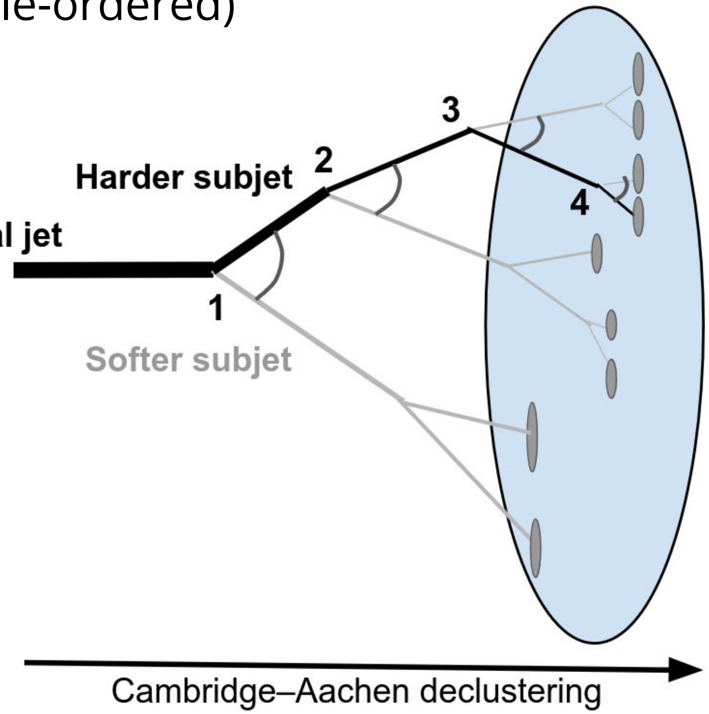
The primary Lund jet plane (quick recap)

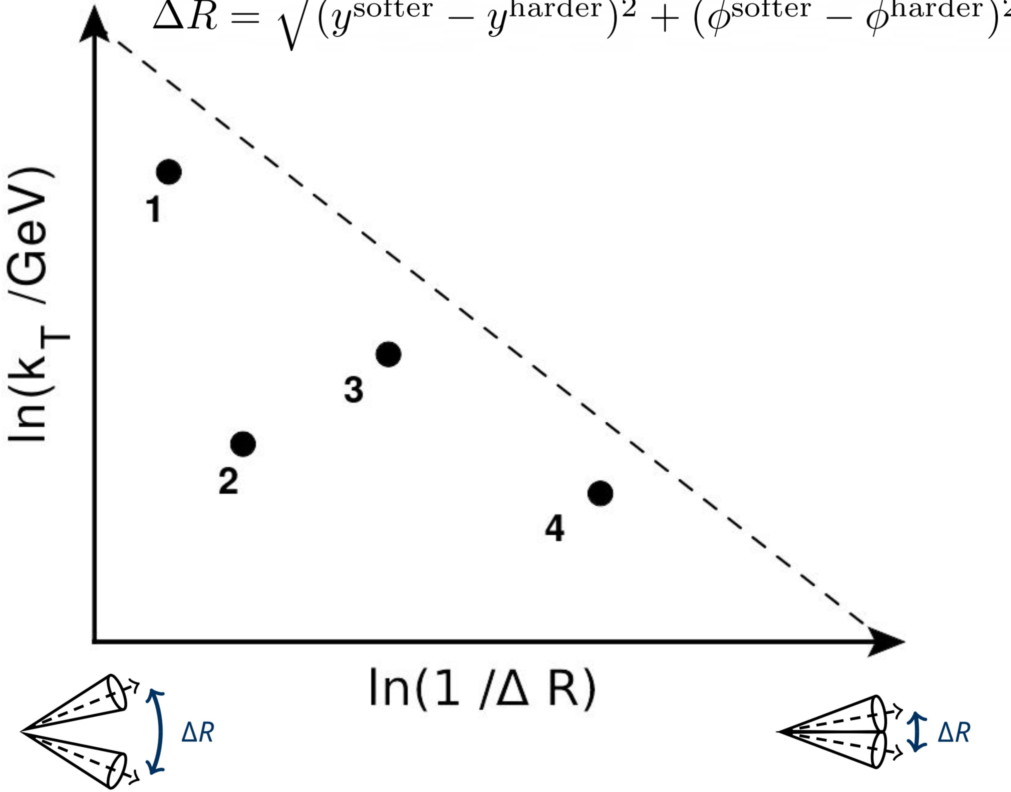
F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064

Cambridge–Aachen reclustering to construct a tree of intrajet emissions (angle-ordered)

$$k_{\mathrm{T}} = p_{\mathrm{T}}^{\mathrm{softer}} \Delta R$$

$$\Delta R = \sqrt{(y^{\mathrm{softer}} - y^{\mathrm{harder}})^2 + (\phi^{\mathrm{softer}} - \phi^{\mathrm{harder}})^2}$$





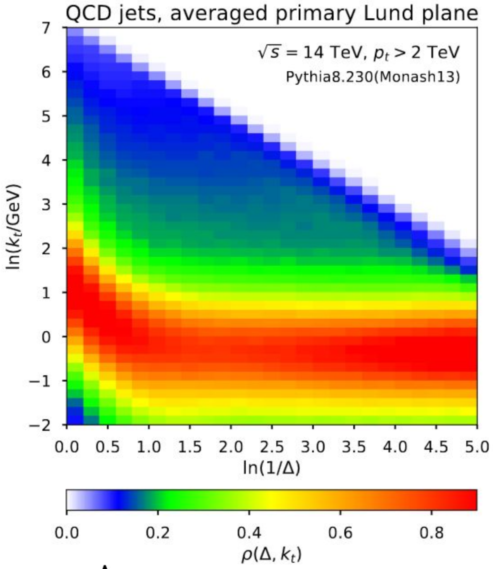
Define the *jet-averaged* number of emissions, **(primary Lund jet plane density)**

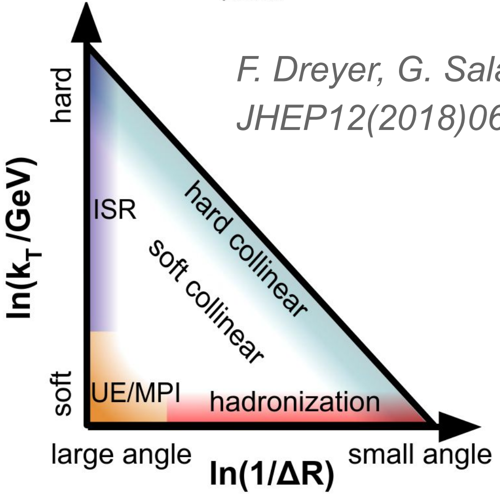
$$\rho(k_\mathrm{T}, \Delta R) \equiv \frac{1}{N_\mathrm{jets}} \frac{\mathrm{d}^2 N_\mathrm{emissions}}{\mathrm{d}\ln(k_\mathrm{T}/\mathrm{GeV})\mathrm{d}\ln(R/\Delta R)}$$

"sculpted" by the running of $\alpha_S(k_T)$ at LO

$$\rho(k_\mathrm{T}, \Delta R)_\mathrm{LO} \approx \frac{2}{\pi} C_\mathrm{R}^\mathrm{eff} \alpha_\mathrm{S}(k_\mathrm{T})$$

With $C_R = C_A = 3$ for g→gg or $C_F = 4/3$ for q→qg splittings





F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064

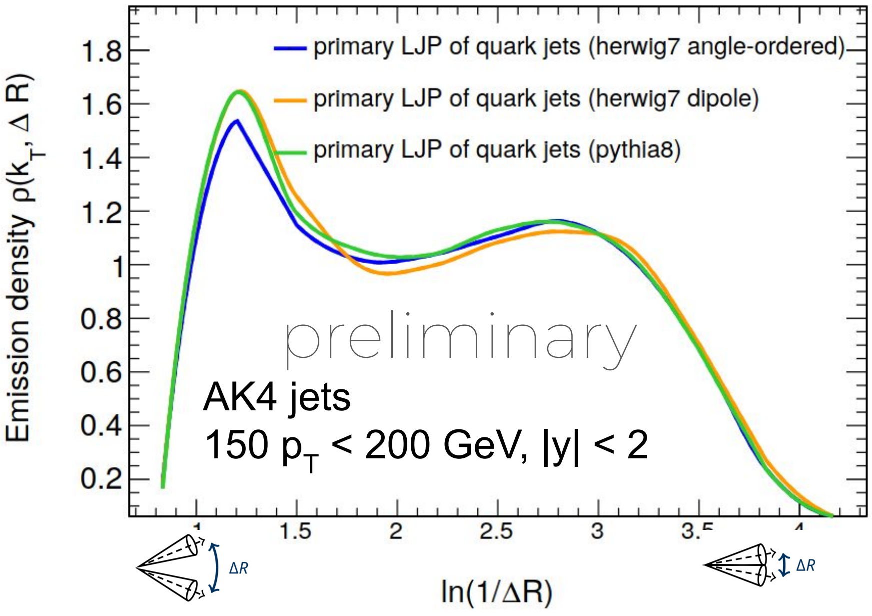
Ability of "factorizing" effects

Quarks vs gluon primary LJPs in pp collisions

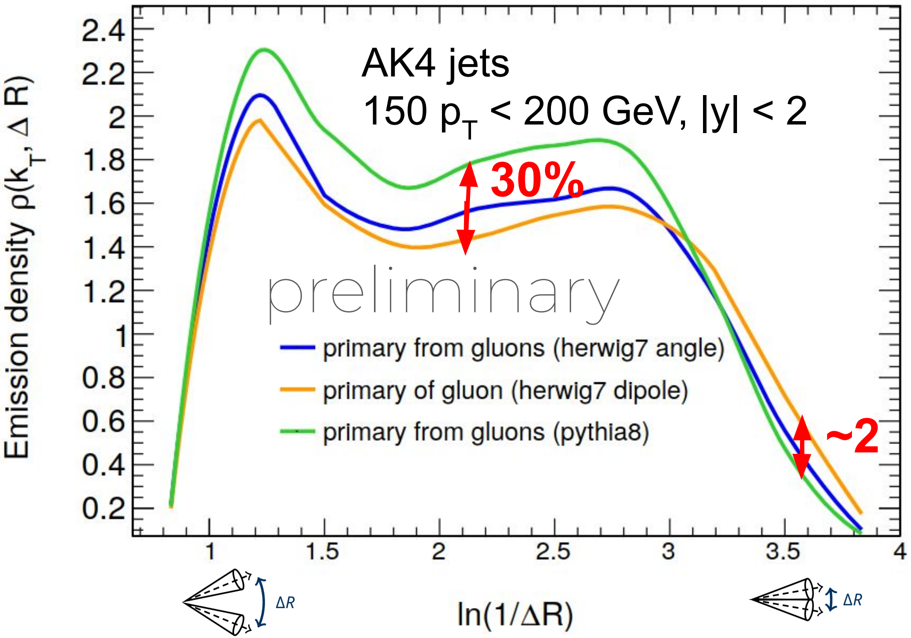
Hadron-level sim.

Same LJP slice at low k_T ~ 1 GeV

Quark jets (qq→qq)



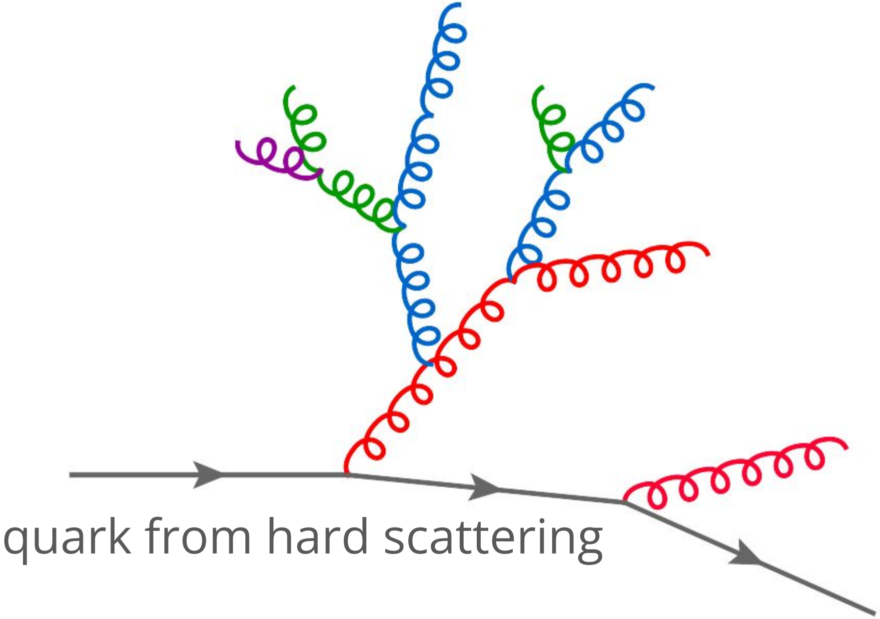
Gluon jets (gg→gg)

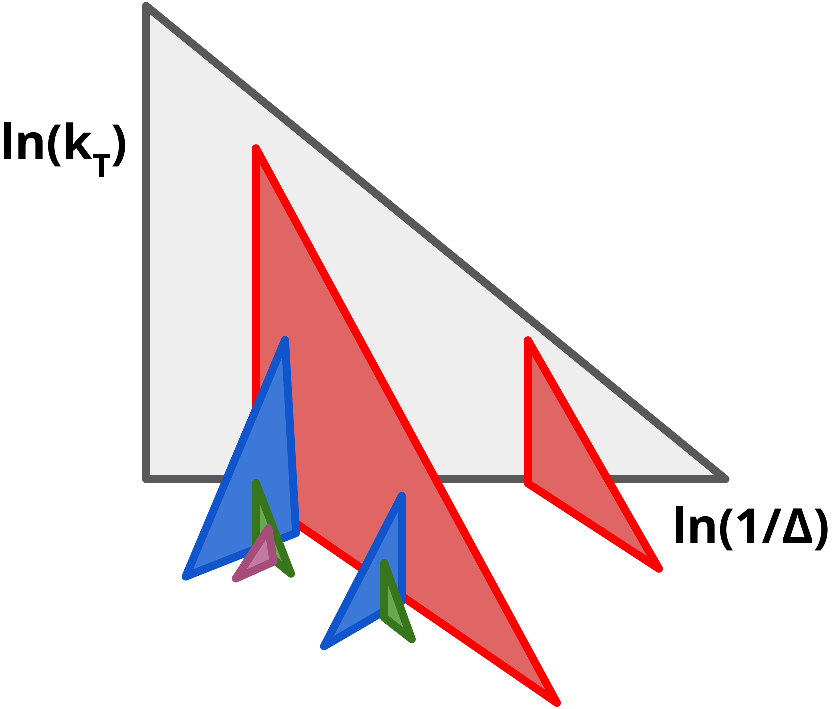


Spread of 1–5% (**LEP constraints**)

Much larger spread, up to 30% differences.
Not as constrained by LEP!

Each QCD emission spawns its own Lund plane



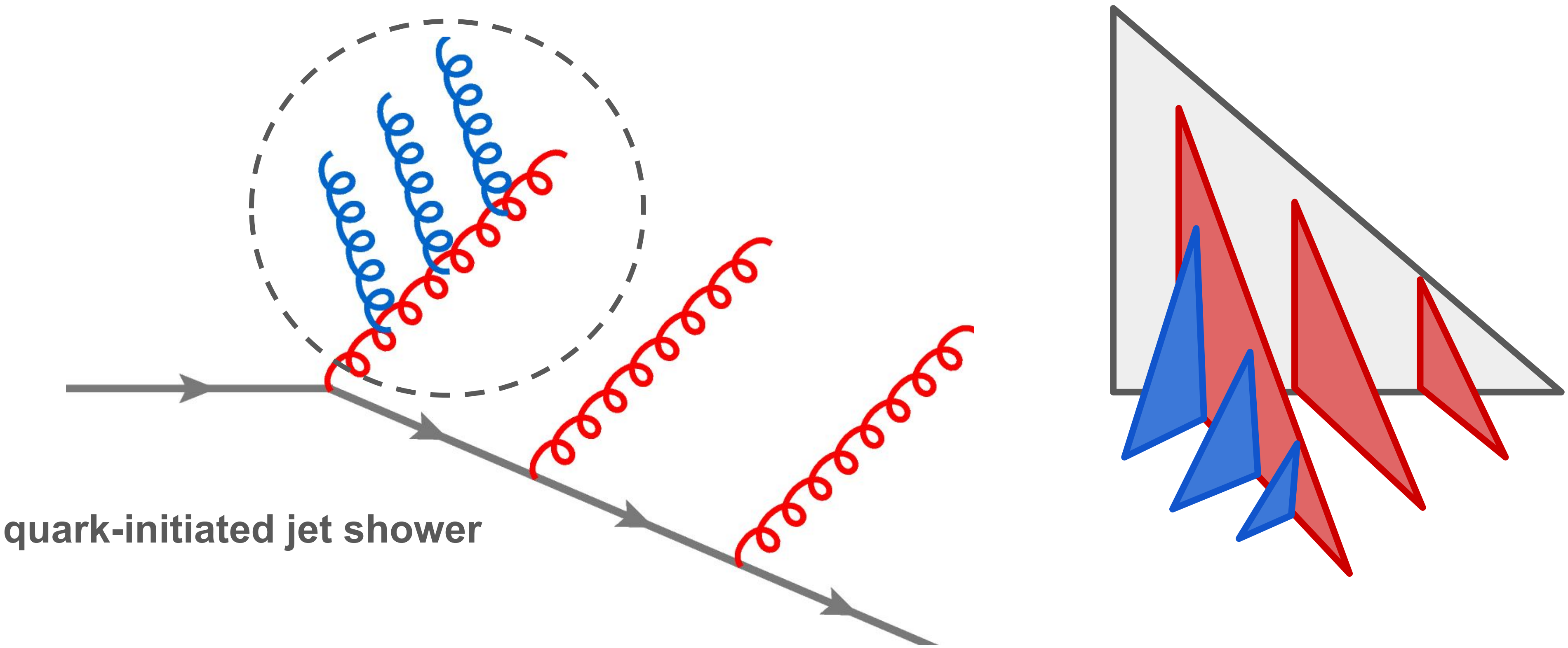


Emissions in **red** are the **“primary” emissions**

Emissions in **blue** are **“secondary” emissions**

Other colors represent “subsidiary” emissions

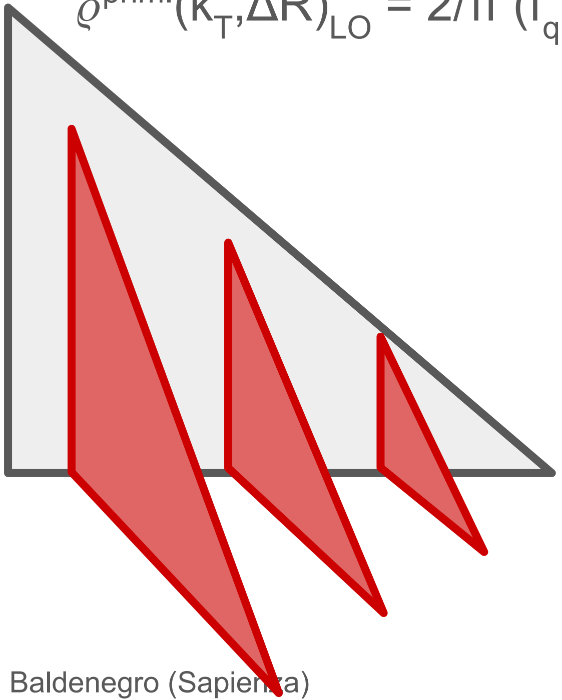
Secondary Lund planes for gluon radiation



Primary Lund plane

Average map for **mixture** of quark/gluon jets at high-p_T

$$\varrho^{prim.}(k_T,\Delta R)_{LO} = 2/\pi\ (f_q C_F + f_g C_A)\alpha_S(k_T)$$

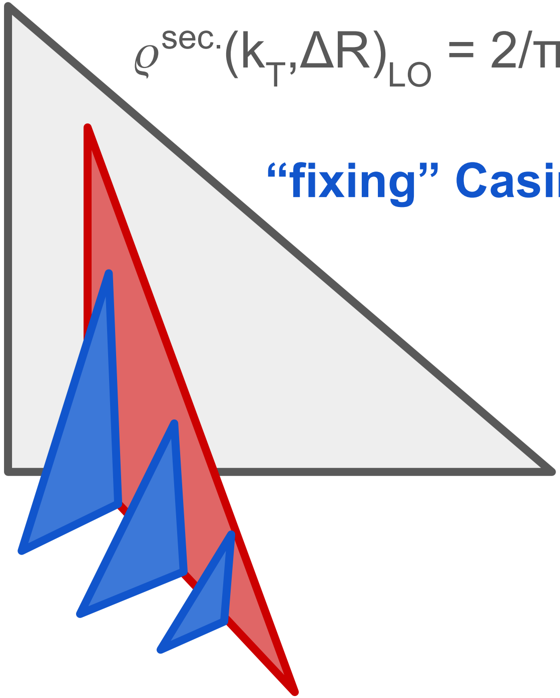


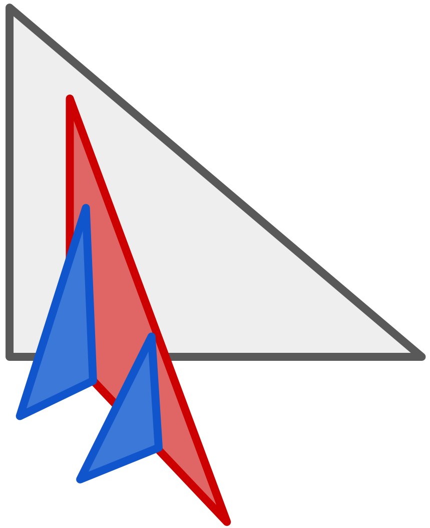
Secondary Lund jet plane

If **primary emission** is chosen judiciously, can obtain gluon-rich jet sample at a lower p_T

$$\varrho^{sec.}(k_T,\Delta R)_{LO} = 2/\pi\ \boxed{C_A\alpha_S(k_T)}$$

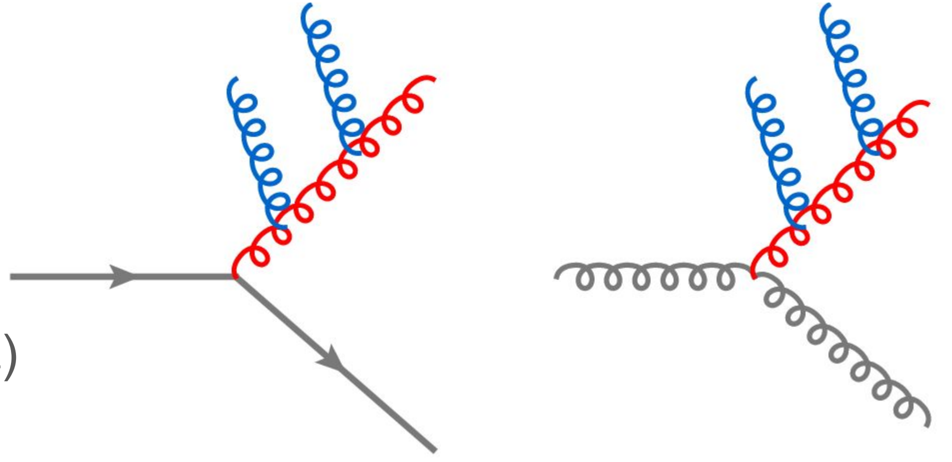
"fixing" Casimir factor





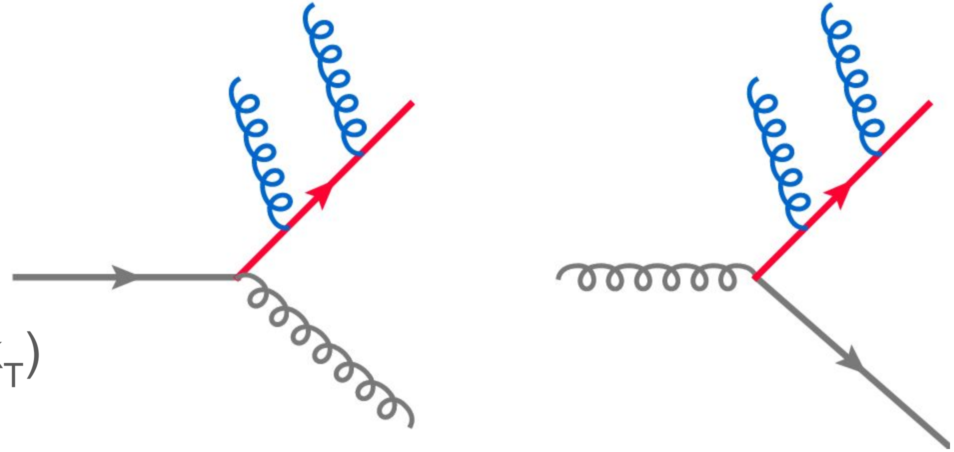
Gluon-dominated secondary Lund planes

$$\varrho^{\text{sec.}} \sim 2/\pi\, C_A\, \alpha_S(k_T)$$



Quark-dominated secondary Lund planes

$$\varrho^{\text{sec.}} \sim 2/\pi\, C_F\, \alpha_S(k_T)$$



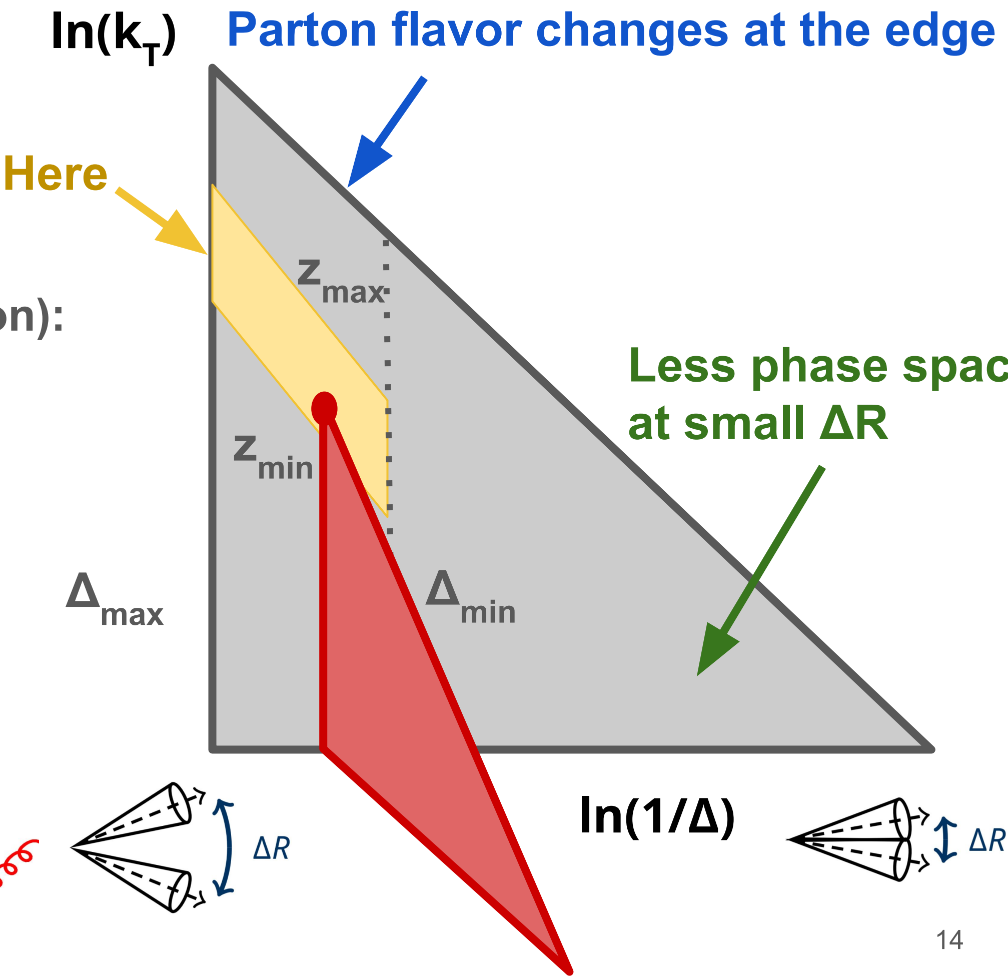
Which primary Lund emission?

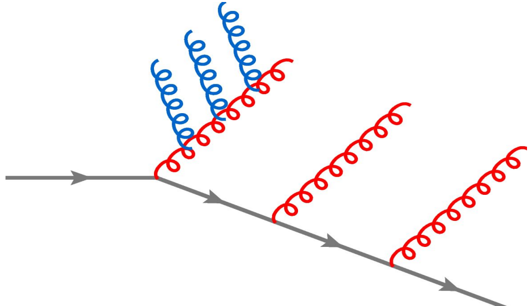
Collinear emission, but sufficiently large angles for phase space

(e.g., $\Delta R_{min} \sim ½ R$, $\Delta R_{max} \sim R$)

Soft emission (1/z pole of splitting function):
Asymmetric momentum balance,
$z = p_{T,soft}/(p_{T,soft}+p_{T,hard})$ (e.g., $0.2 < z < 0.25$)

Phase-space region where parton flavor changes are negligible

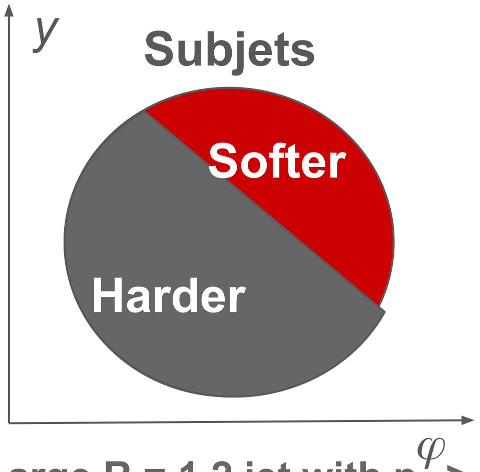




At least three setups (**picking** **leading (sub)jet**)

focus on this

1.SoftDrop-like (Cambridge/Achen tree)

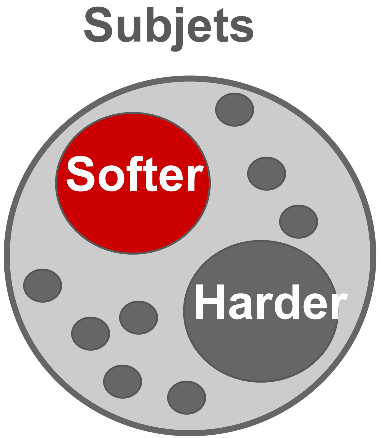


Large R = 1.2 jet with p_T > 1 TeV

SoftDrop emission with $R_g > 0.6$ && $0.1 < z_g < 0.3$

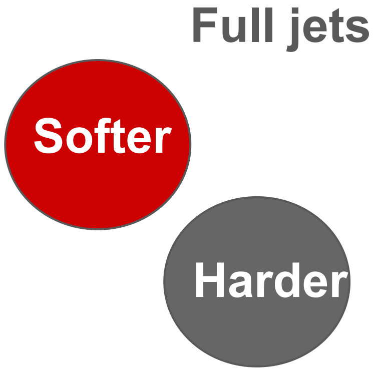
Clustering distortions at large angles

2. Trimming (R = 1.2 → R = 0.4)



Large R = 1.2 jet with p_T > 1 TeV →recluster w/ small R = 0.4

3. anti-k_T dijet selection (or multijet)



R = 0.4 jets, specific set of "collinear" dijets with asymmetric p_T

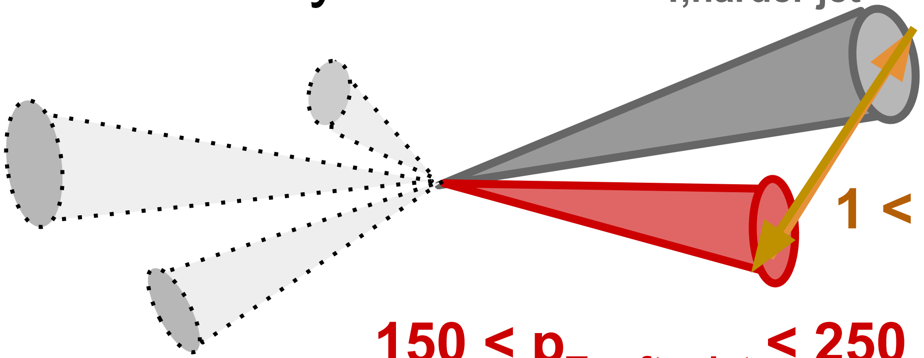
Experimentally simpler

Inclusive dijet selection

recoil jet radiation
treated inclusively

Quark/gluon mixture

$p_{T,\text{harder jet}} > 700$ GeV



$1 < \Delta R_{jj} < 1.2$

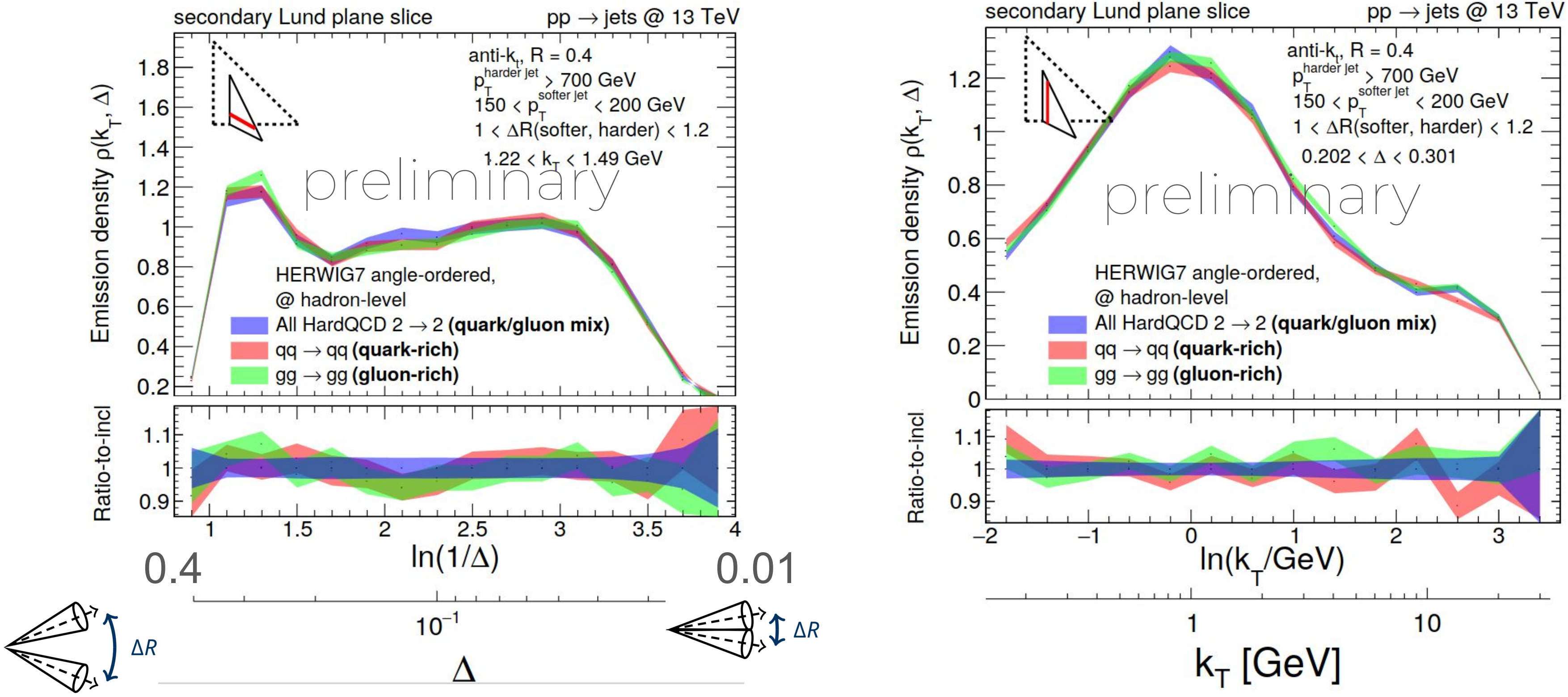
$150 < p_{T,\text{softer jet}} < 250$ GeV

$\mathcal{O}(10^5–10^6)$ ``high-purity”
gluon-like jets w/ Run-2 stats

gluon-enriched

NB: baseline selection, can be fine-tuned

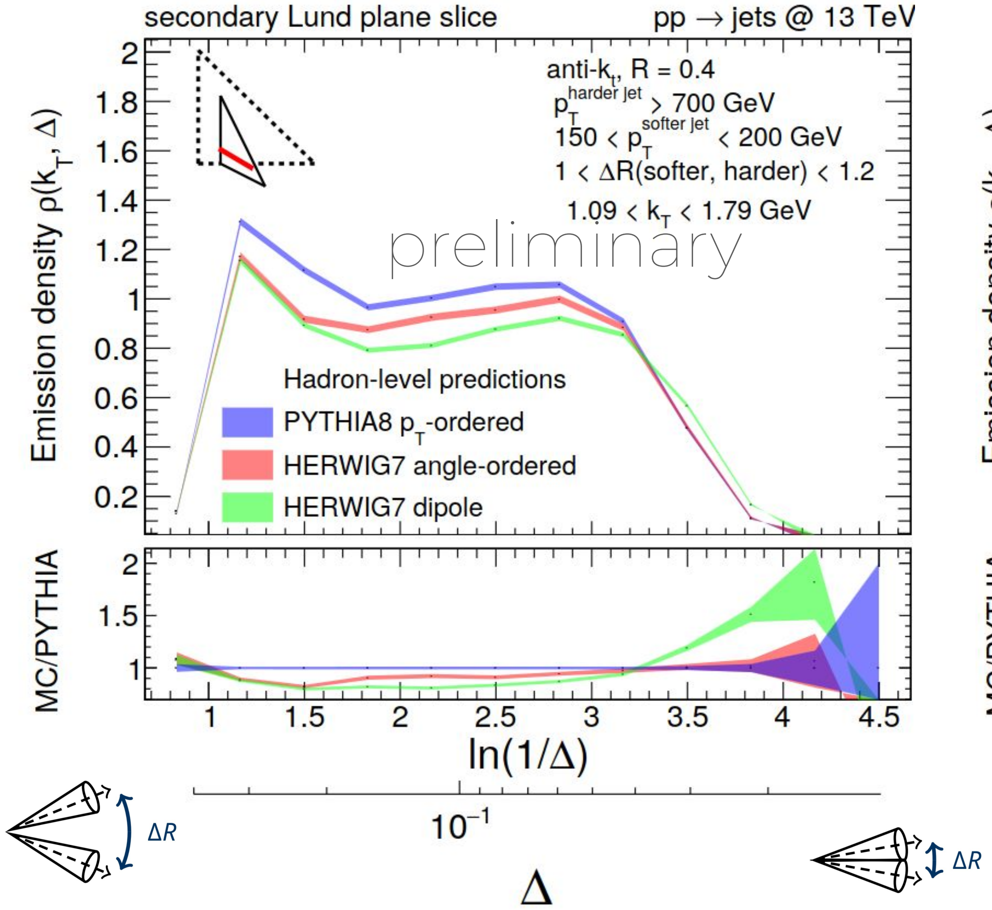
Process-independence, PDF-independence

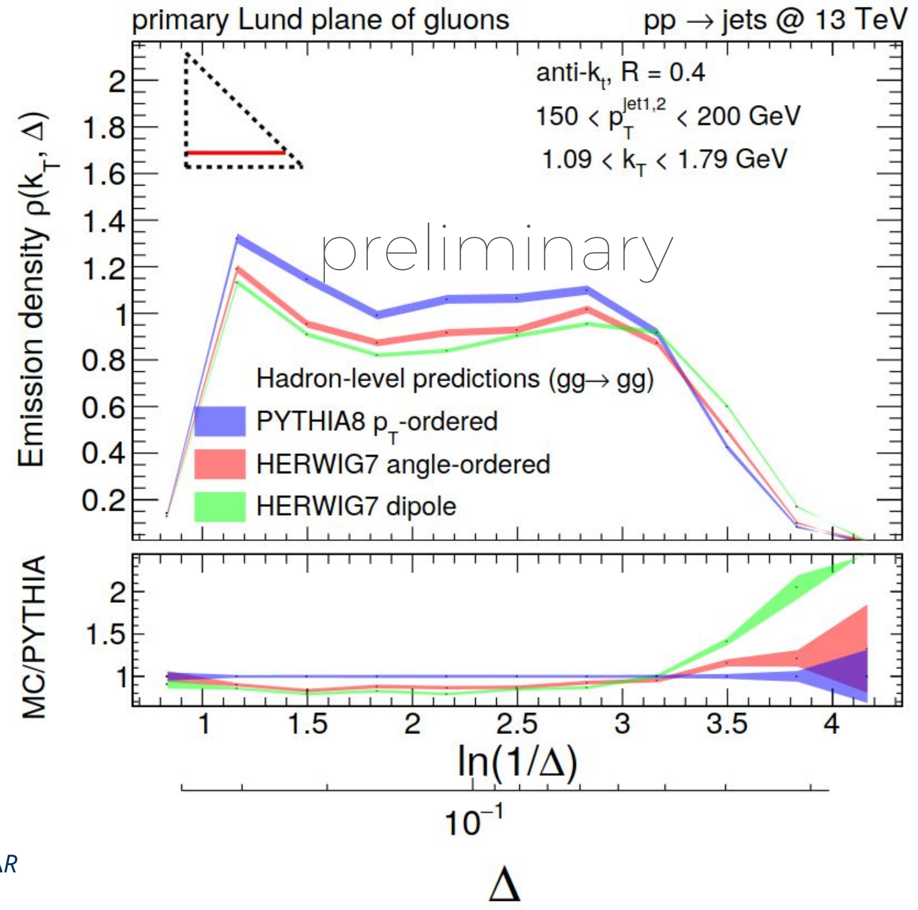


Similar results regardless of parton flavor of the hard scattering.
Can be checked in data w/ tight cuts on quark vs gluon taggers.

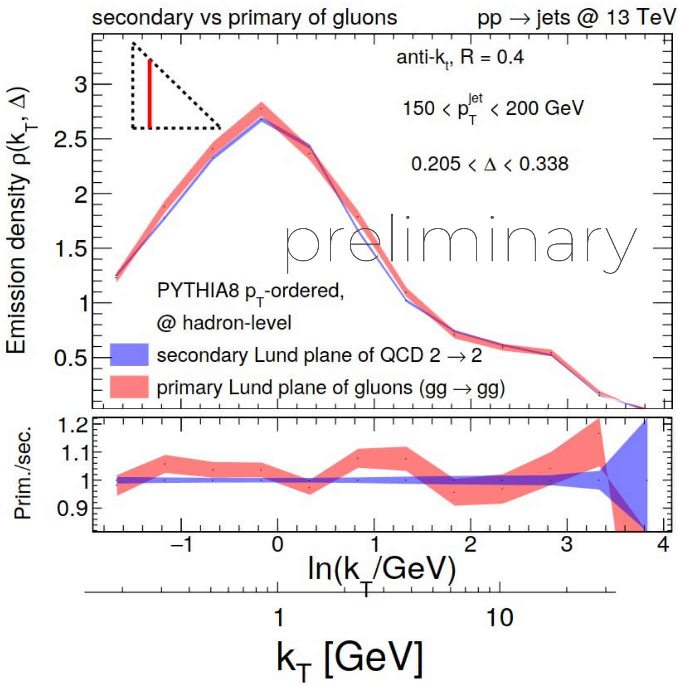
Model discrimination power:

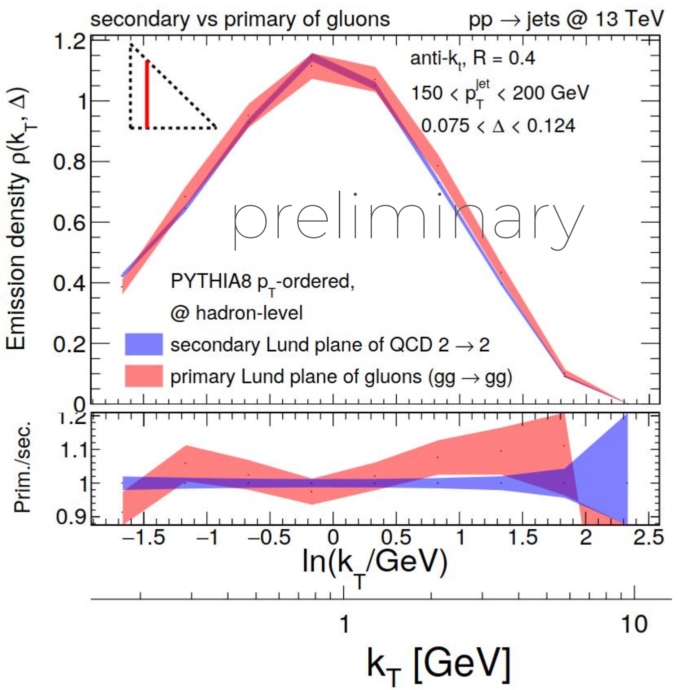
secondary Lund plane vs primary Lund plane of gluons (gg→gg)





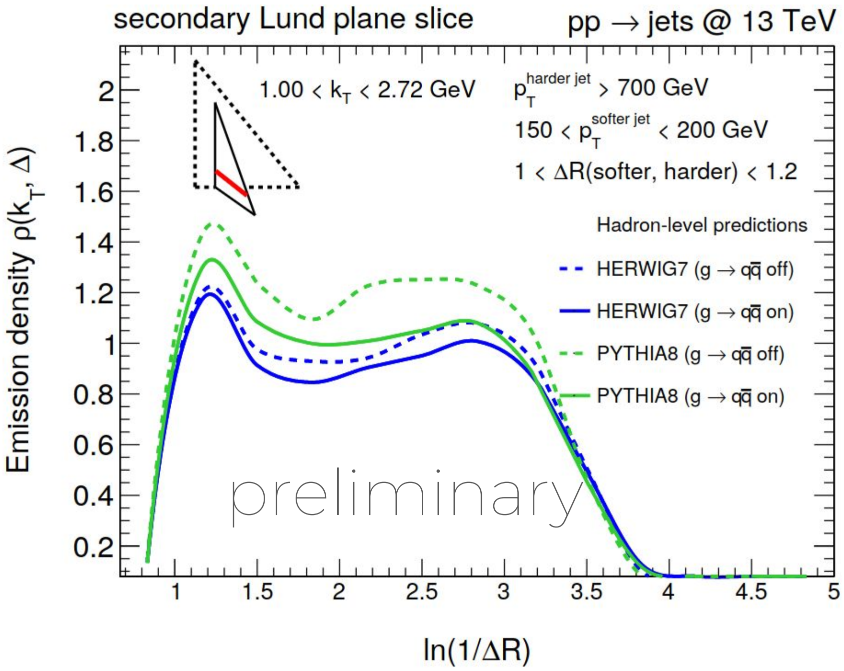
Secondary vs primary Lund jet plane of gluons (gg→gg)

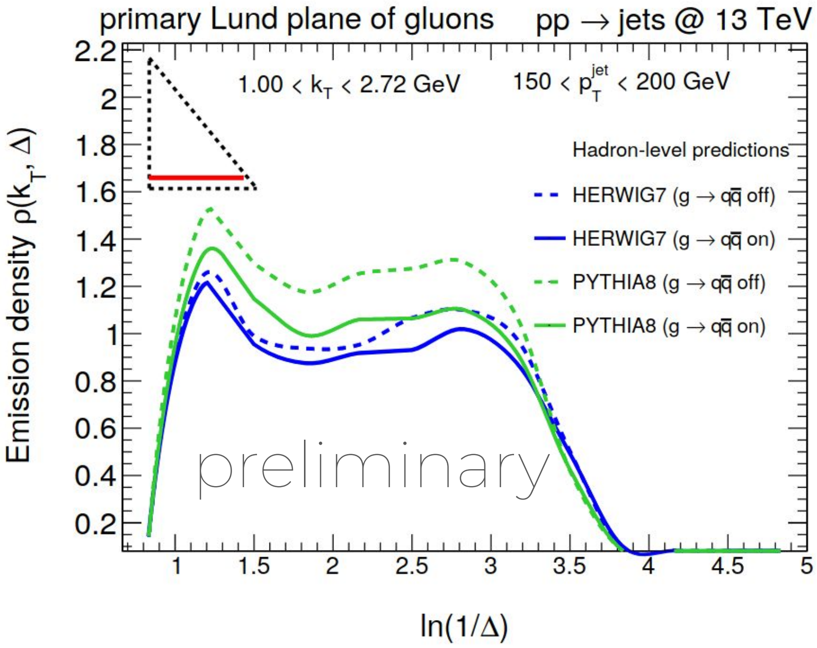




NB: reweighted p_T spectrum to remove jet p_T biases

Gluon splitting (g→qq on vs off)





Similar effects of g→qqbar on vs off in both secondary vs primary Lund plane of gluons

Summary

- Gluon-rich final state radiation using simple hadron-level cuts
  (“Rivet-friendly” for tuning)

- Resilient to flavor of partons in hard scattering
  (cf simulation studies using LO MC generators)

- Can be extended to other observables
  (dynamical k_T, groomed jet mass, angularities…)

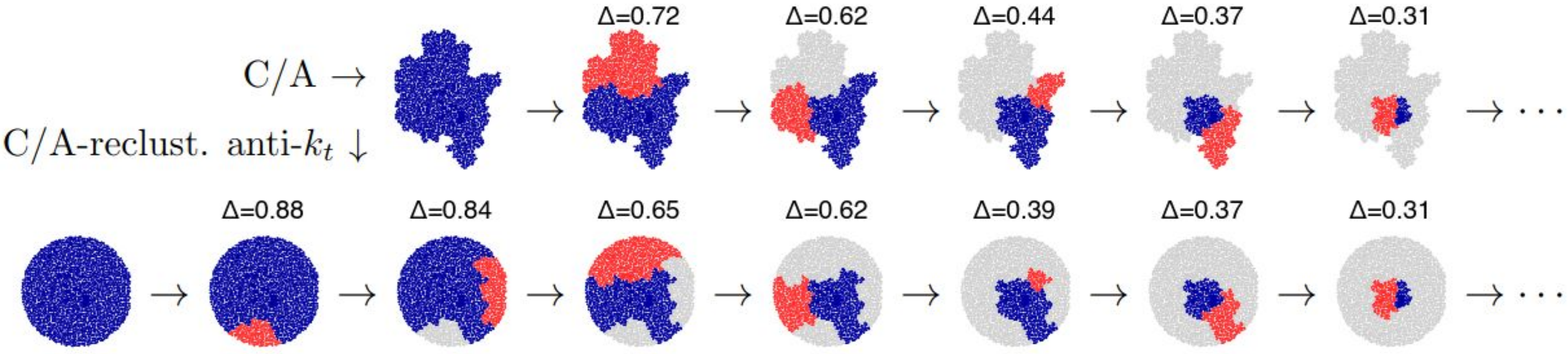
- Potential applications for precision physics
  (e.g., α_S with resilience to quark/gluon fraction)

  Would require a 2→3 fixed-order piece at lowest order
  (trade-off between q/g fraction vs order of pQCD)

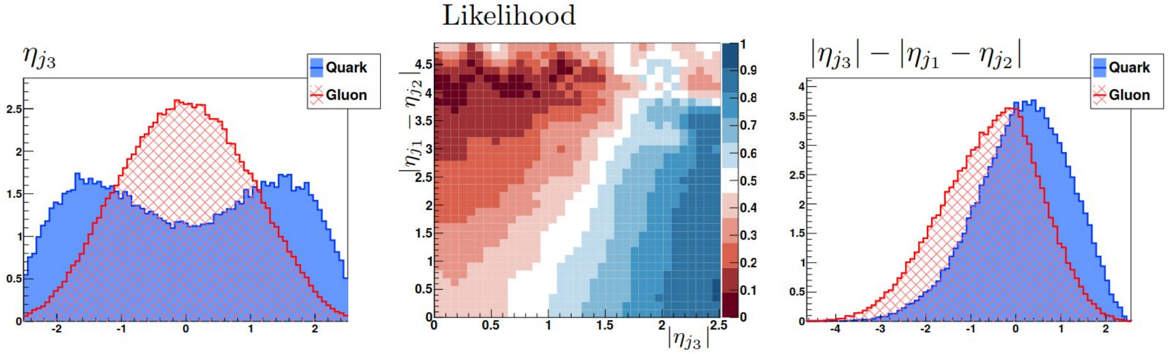
backup

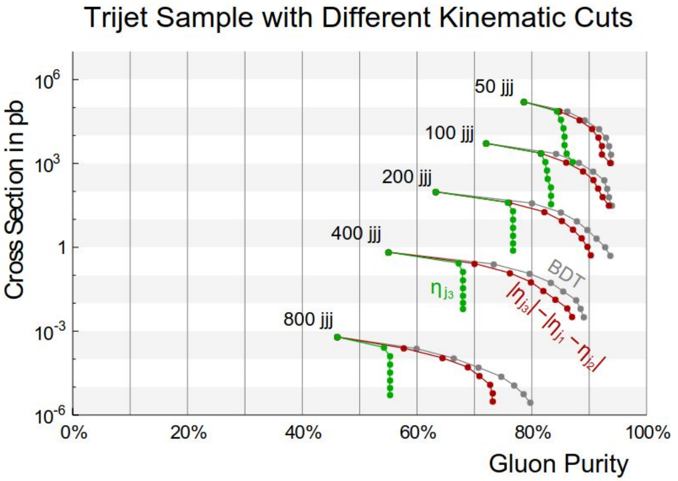
Distortions due to initial anti-k_T clustering

arXiv:1807.04758



Related proposal for gluon jet enrichment

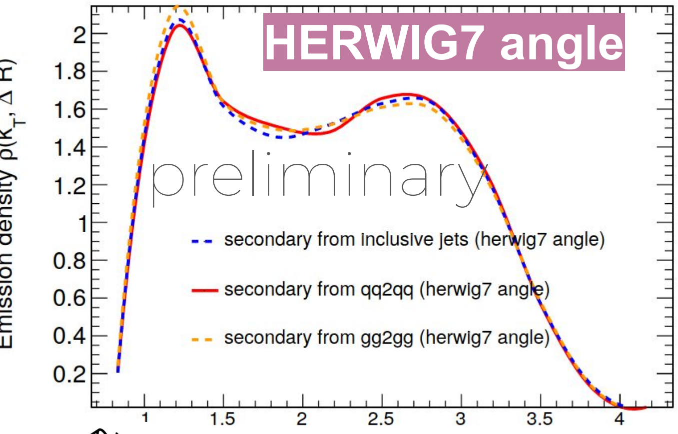


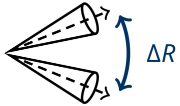


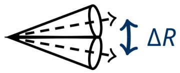
J. Gallicchio, M. D. Schwartz [arXiv.org/abs/1104.1175](https://arxiv.org/abs/1104.1175)

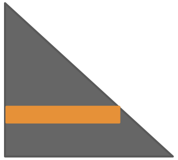
Rectangular cuts on based on BDT-training on trijet MC sample, using $|\eta_3|$-$|\eta_1 - \eta_2|$ & η_3 discriminant

Process- & PDF-independent observable

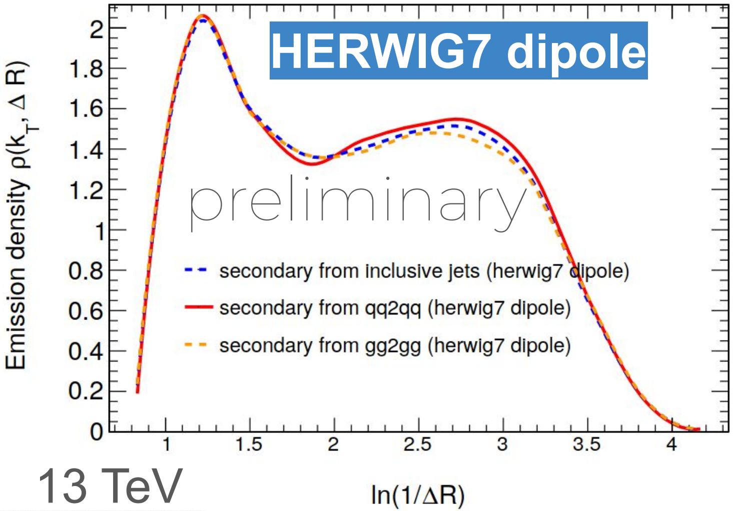


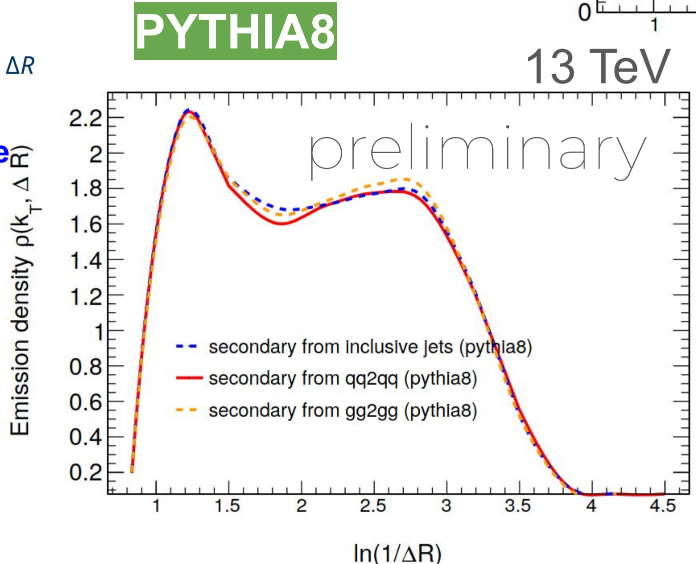






13 TeV





Secondary LJP from quark-gluon mixture (inclusive jets)

Secondary LJP from quarks (qq→qq hard scattering)

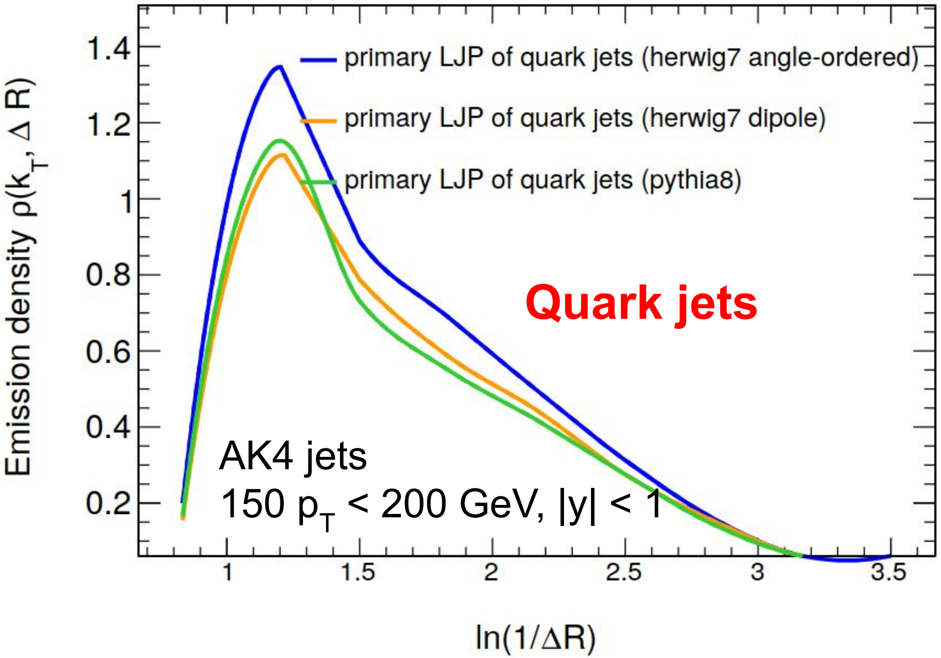
Secondary LJP from gluons (gg→gg hard scattering)

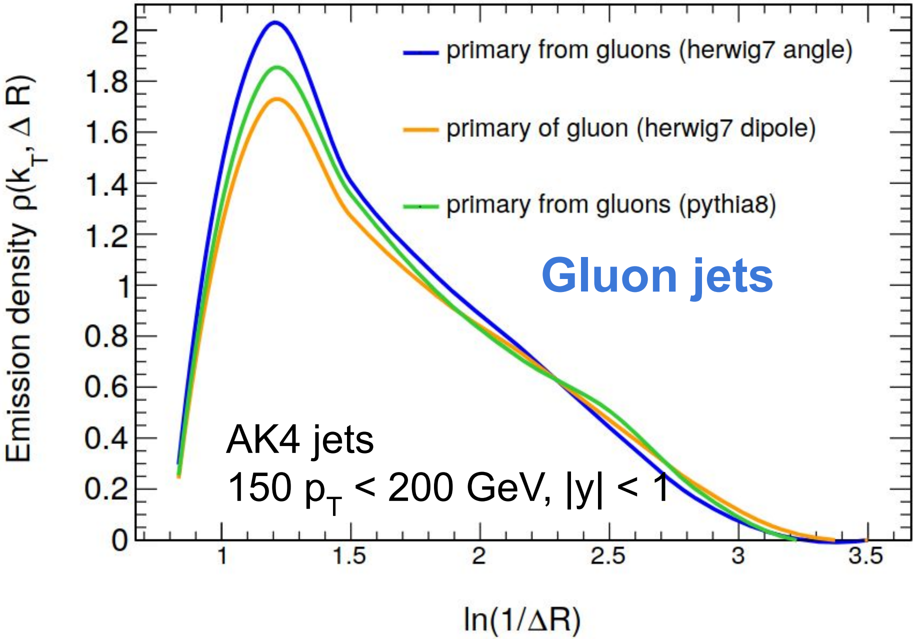
Differences negligible within expected sensitivity

Shape and normalization resilient to underlying q/g fraction

“Quark jets constrained by LEP” mostly accurate for low p_T jets cf reach of LEP

Differences in perturbative regime (k_T >~ 5 GeV) for quark and gluon jet showers

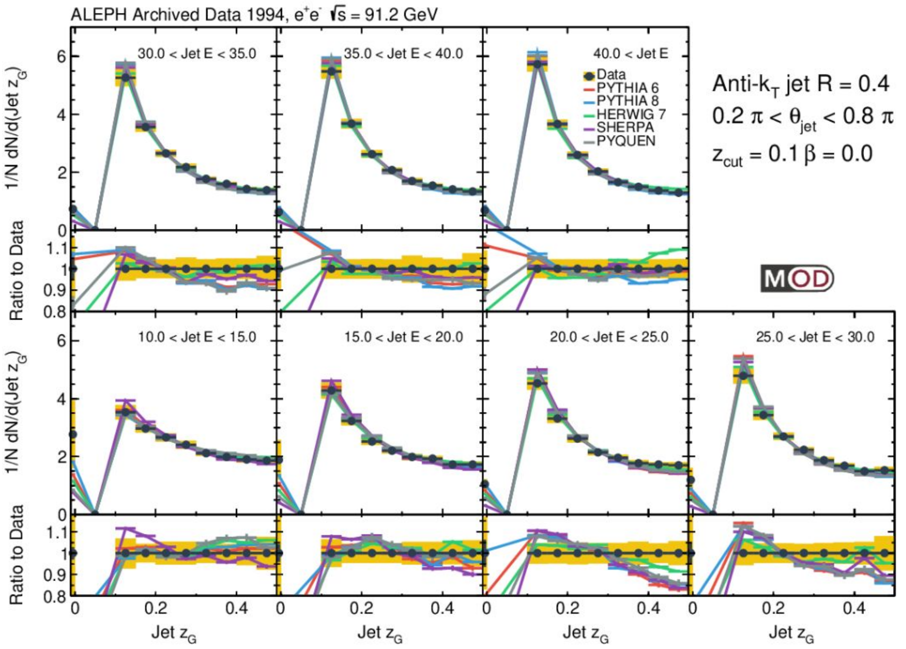




Herwig7 dipole usually closer to Pythia8 in the perturbative region

Herwig7 angle-ordered usually higher in perturbative region

"Quark jets constrained by LEP"

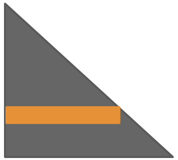


Data/MC differences with Lund-based observables. For example, soft-drop z_G with archived ALEPH data shows mismodeling for z_G~0.5 (upper edge of Lund plane).

LHC data valuable to clarify mismodeling (dijet, Z+jet, UPC jets…) for high-p_T quark jets

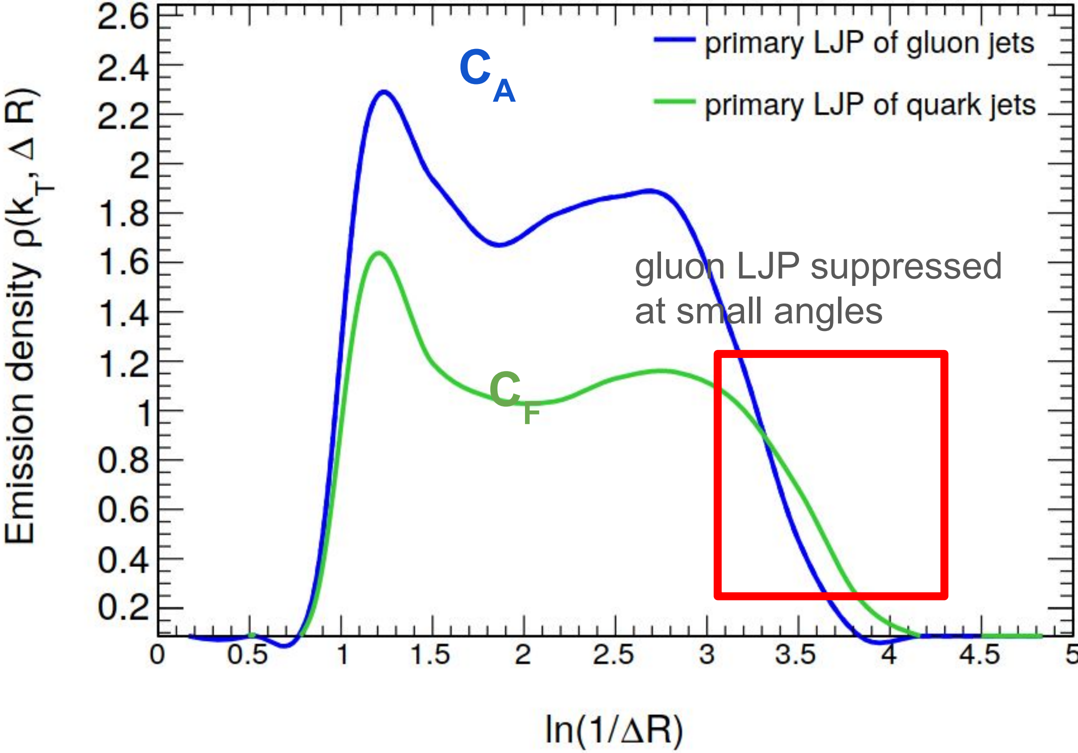
[Yi Chen et al arxiv.org/abs/2111.09914](arxiv.org/abs/2111.09914)

Quarks vs gluon Lund planes



Not ***just*** C_A/C_F scaling! Leading parton momentum loss in the Lund tree history, soft&collinear divergences, color reconnection effects, …

Gluon LJP is suppressed at small angles wrt quark LJP



Quark/gluon jet fraction issue

``α_S always paired with a color factor, $C_i\alpha_S$''

Different strategies have be adopted (w/ soft-drop mass):

- PDF uncertainties (H. S. Hannesdottir, A. Pathak, M. D. Schwartz, I. W. Stewart, arXiv:2210.04901 , Les Houches 2017)

- Fit $\alpha_S(m_Z)$ and quark/gluon fraction (Les Houches 2017)

- Statistically "demix" quark- and gluon-like samples (arXiv:2206.10642)

- Design observables with reduced q/g fraction sensitivity (cf Meng Xiao's talk on energy correlators, $\delta\alpha_S/\alpha_S$~4%)