Possible strategy for $\alpha_s(m_Z)$ extraction using secondary Lund jet planes

(based on *preliminary* work)

Cristian Baldenegro (Sapienza)

αS(mZ)-2024 workshop, Trento, Feb 5th-9th

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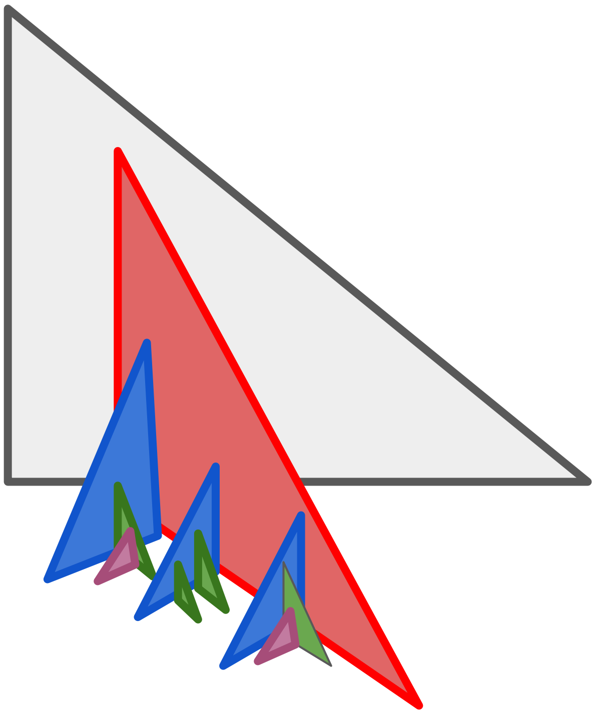


Thanks to Jacob March for early contributions
& to Alba Soto, Gregory Soyez, Leticia Cunqueiro, Matt Nguyen for their feedback

This talk (jet substructure):

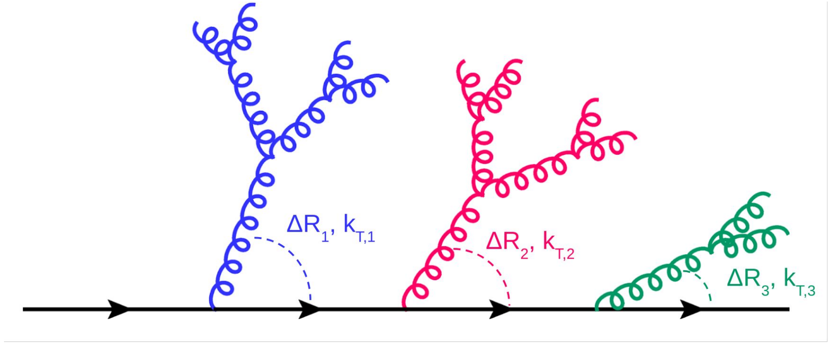
- Introducing the Lund jet plane & the “primary” Lund jet plane

- Quick recap of quark/gluon jet fraction issue at hadron colliders

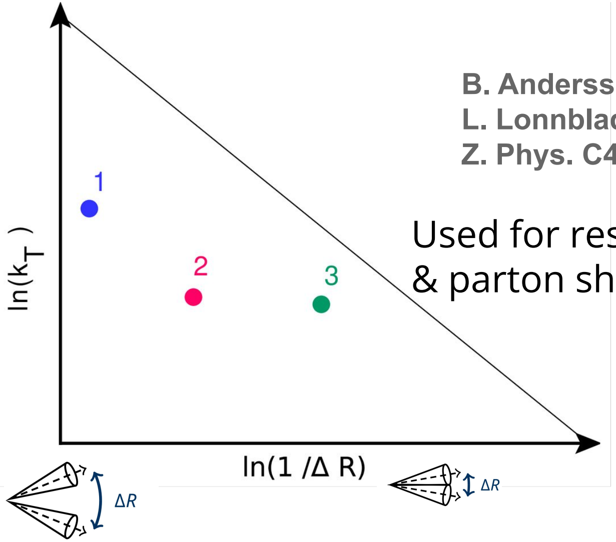
- “Secondary” Lund jet planes

- Average Lund multiplicity of the secondary Lund jet plane
  for a possible $\alpha_S(m_Z)$ extraction

The Lund plane: 2D phase-space of QCD branchings



k_T : relative transverse momentum of emission
ΔR: angular opening of emission and core



B. Andersson, G. Gustafson, L. Lonnblad, and U. Pettersson, Z. Phys. C43 (1989) 625

Used for resummation & parton showers

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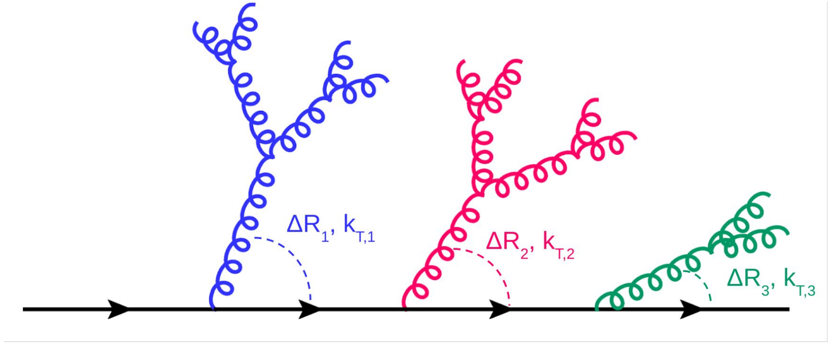

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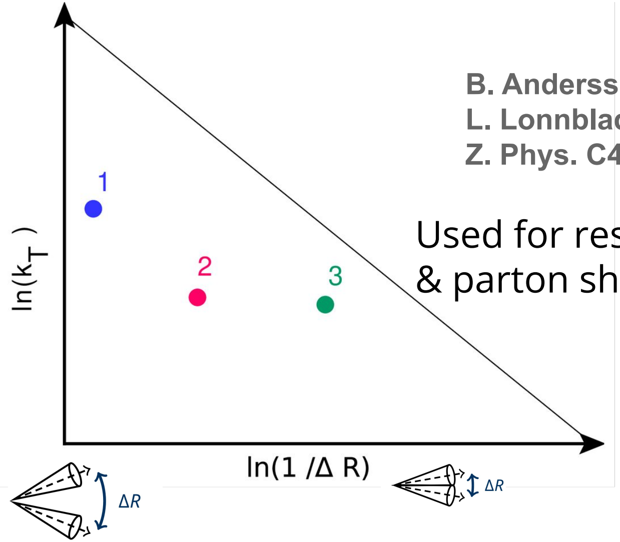

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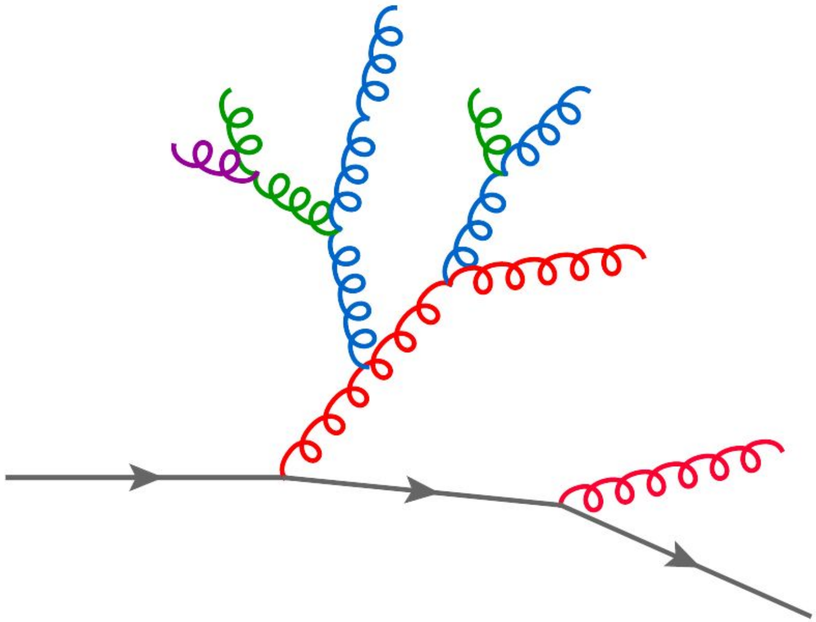
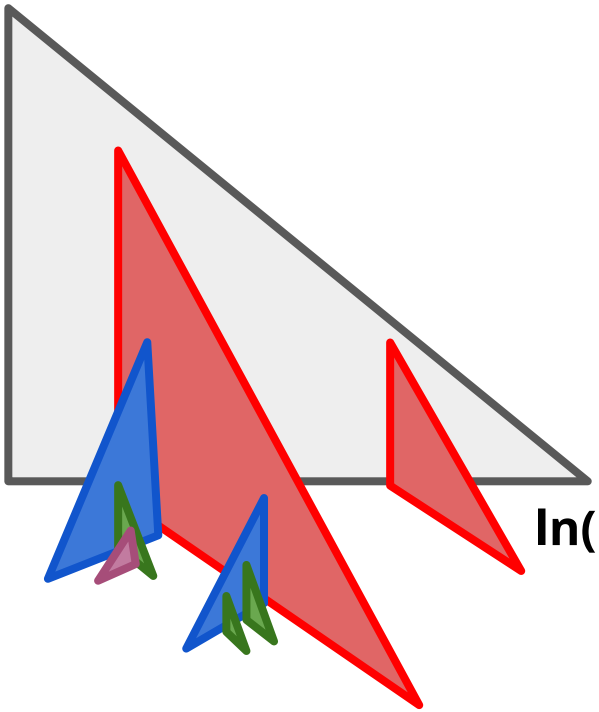
Used for resummation & parton showers

In soft & collinear limit of QCD, emissions fill the double-logarithmic plane of k_T and ΔR uniformly

$$\mathcal{P} \propto \alpha_\mathrm{s} \frac{\mathrm{d}k_\mathrm{T}}{k_\mathrm{T}} \frac{\mathrm{d}\Delta R}{\Delta R} = \alpha_\mathrm{s} \mathrm{d}\ln(k_\mathrm{T}) \mathrm{d}\ln(\Delta R)$$ ← **approximate self-similarity of QCD**

Each QCD emission spans its own Lund plane





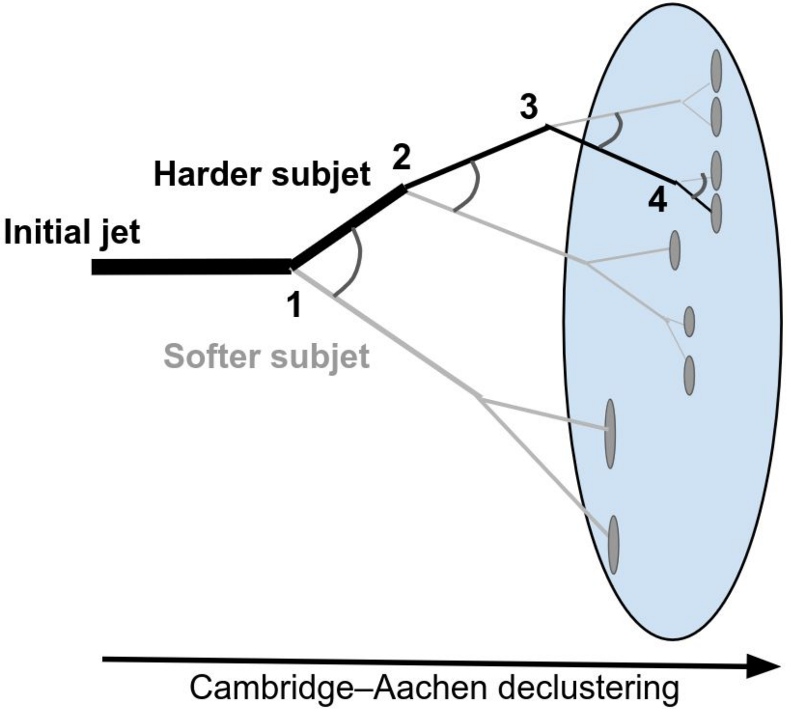
Emissions in **red** are the **"primary" emissions**

Emissions in **blue** are **"secondary" emissions**

Other colors are "subsidiary" emissions

Promotion to a practical tool: the primary Lund jet plane

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



1. A given jet is reclustered with the Cambridge/Aachen algorithm (pairwise clustering by proximity in rapidity-azimuth)

2. Follow Cambridge/Aachen clustering history in reverse, **along the <u>hardest</u> branch (hence "primary")**

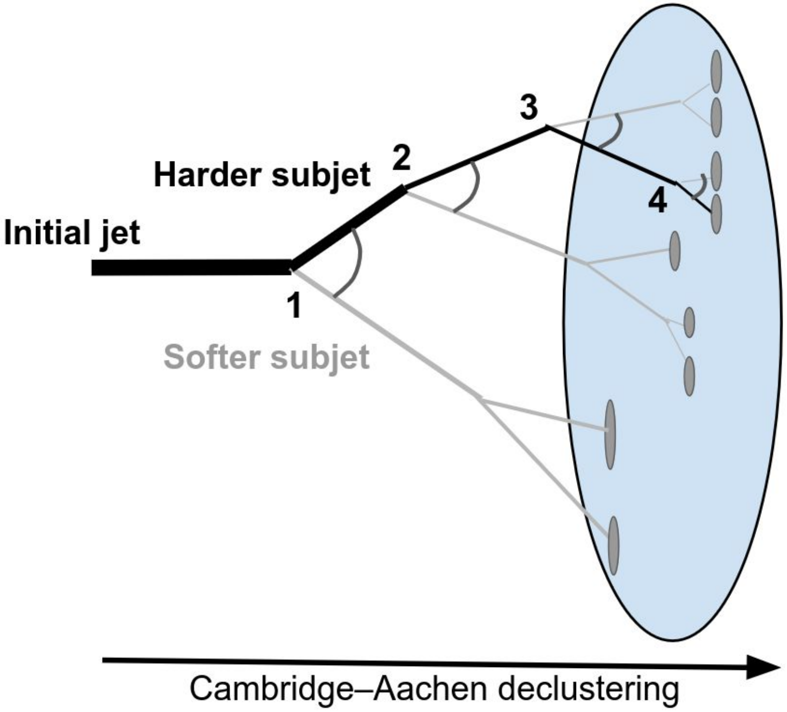
3. k_T and ΔR coordinates registered at each step

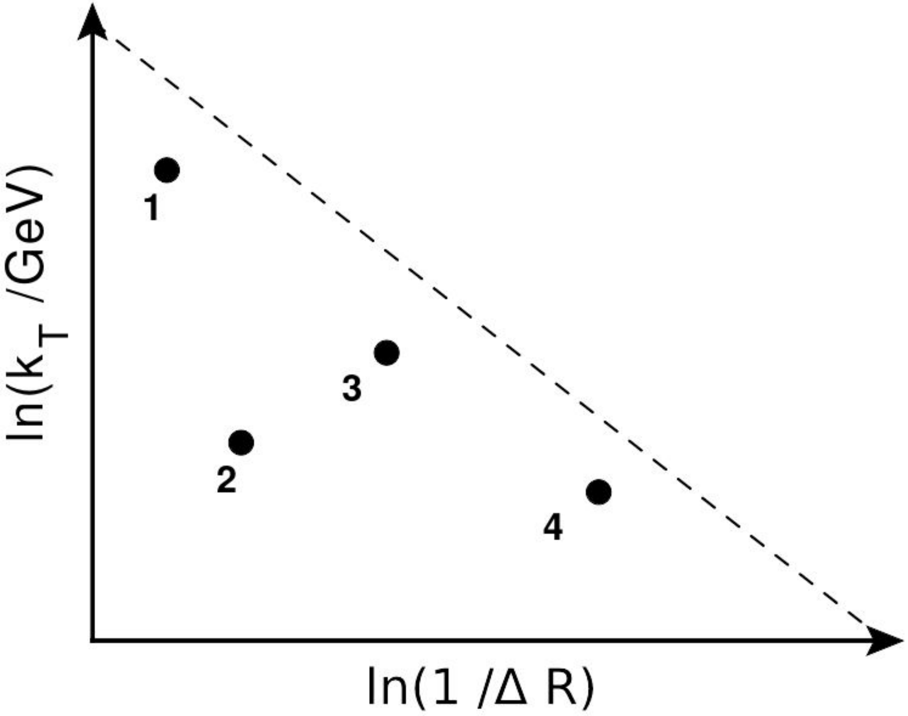
$$\Delta R = \sqrt{(y^{\rm softer} - y^{\rm harder})^2 + (\phi^{\rm softer} - \phi^{\rm harder})^2}$$

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

4. Done until the harder branch has a single constituent

A given jet is represented as a series of points in the Lund *jet* plane





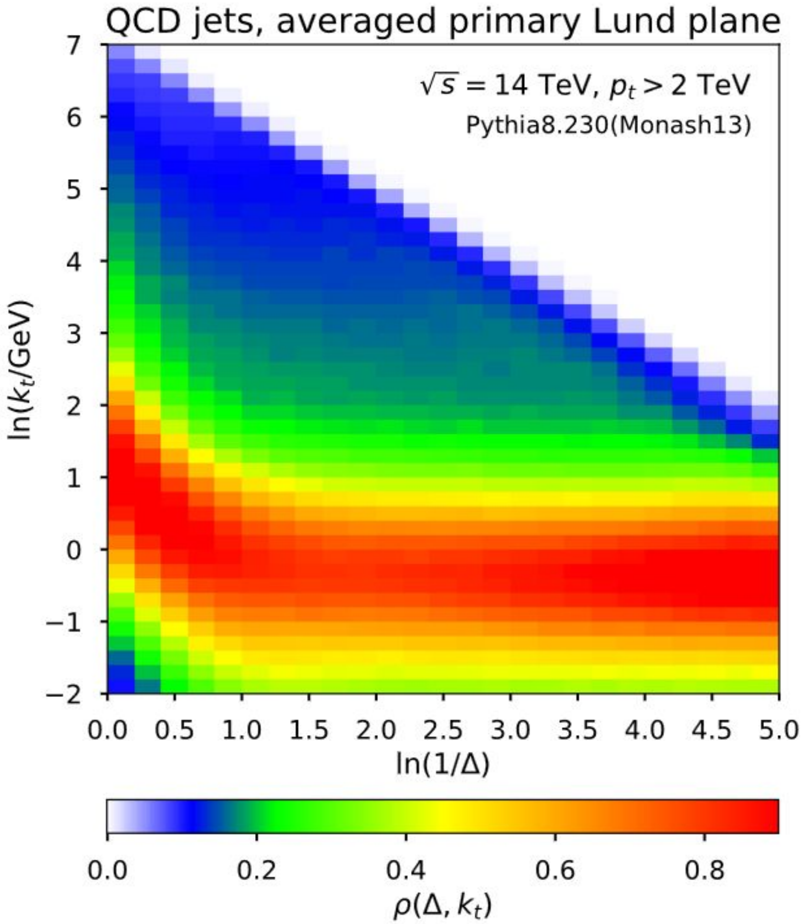
Define the *jet-averaged* number of emissions,
the primary Lund jet plane density

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

At leading order, it's "sculpted" by the running of $\alpha_S(k_T)$

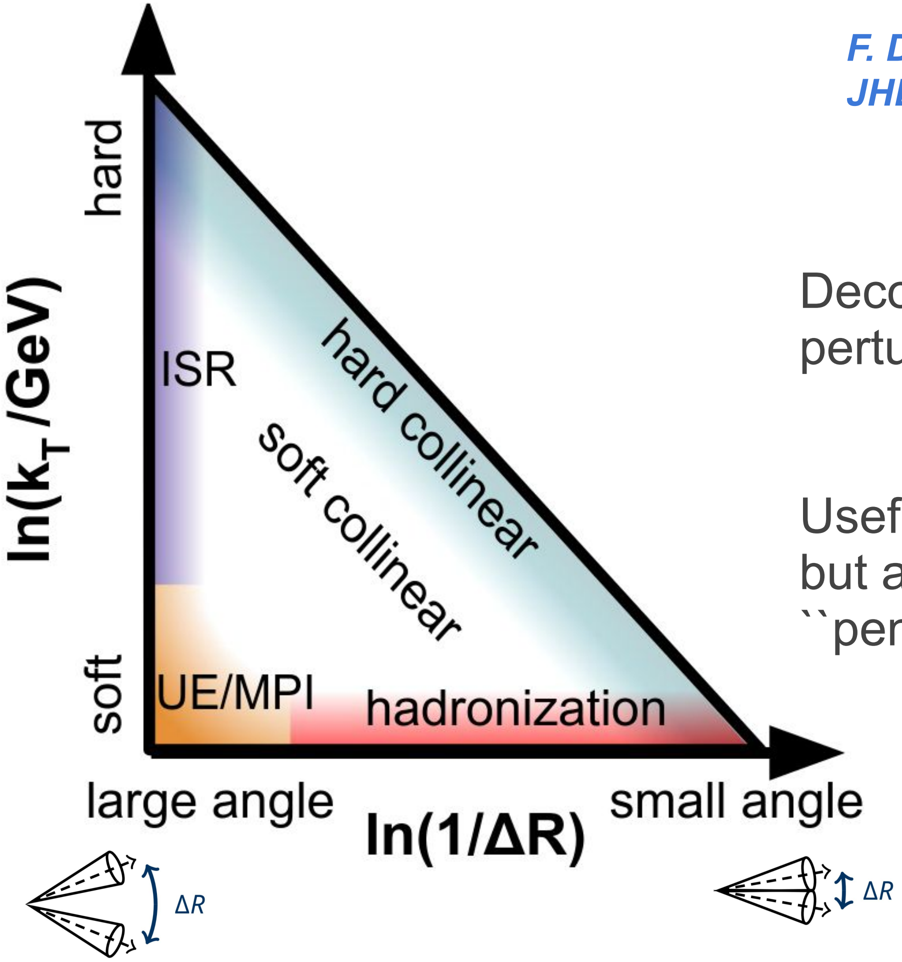
$$\rho(k_\mathrm{T}, \Delta R)_\mathrm{LO} \approx \frac{2}{\pi} C_\mathrm{R}^\mathrm{eff} \alpha_\mathrm{S}(k_\mathrm{T})$$

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

Physical mechanisms are ``factorized'' in the Lund jet plane

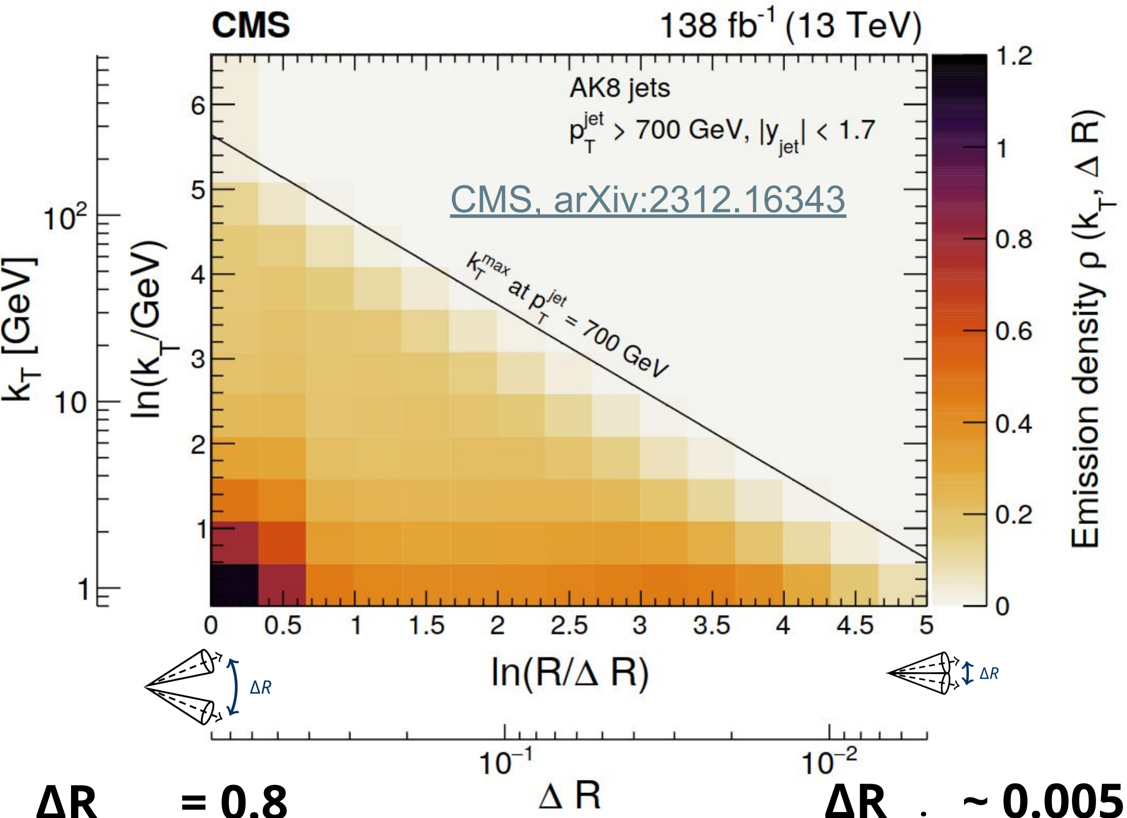


F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064

Decoupling of nonperturbative and perturbative contributions

Useful for MC tuning,
but also for comparison with
``pen-and-paper'' theory

measured primary Lund jet plane densities



ΔR_{max} = 0.8 **ΔR_{min} ~ 0.005**

Also measured by ATLAS [PRL 124, 222002 (2020)], & [ALICE-PUBLIC-2021-002]

CMS measurement setup (13 TeV):

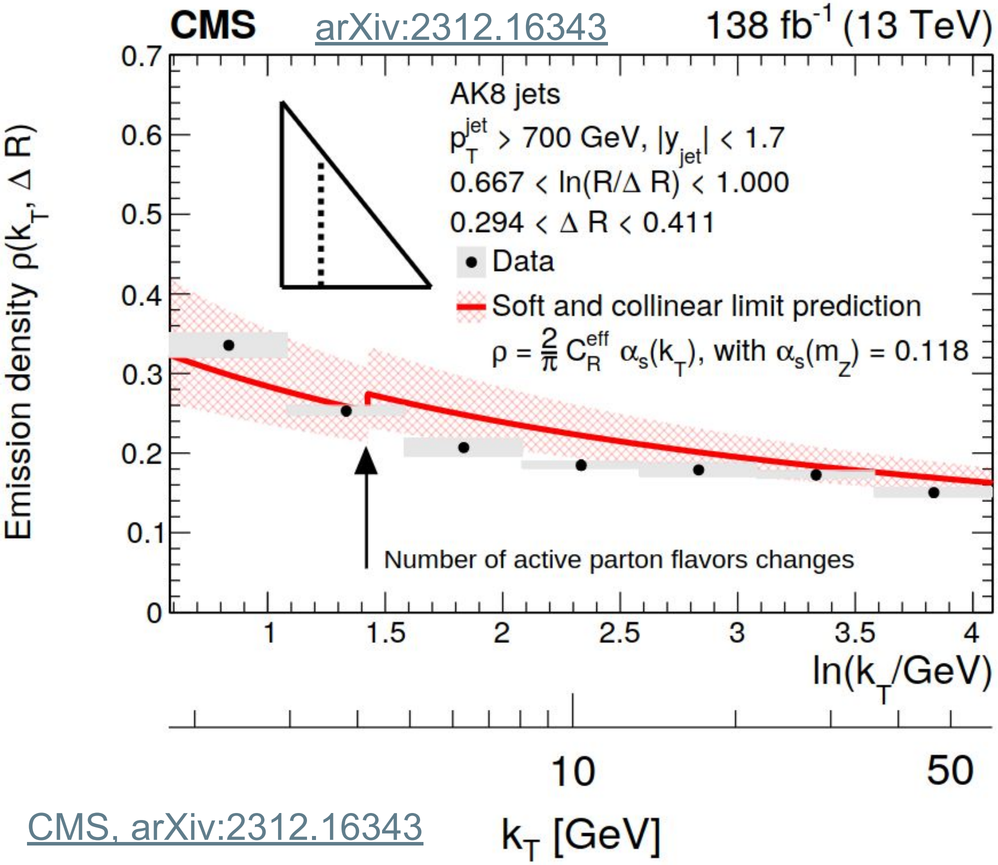
- Inclusive jet selection:
  p_T^{jet} > 700 GeV, $|y^{jet}|$ < 1.7,

  anti-k_T with R = 0.4 (or R = 0.8)

- charged-particles for jet substructure

Approximately flat for hard&collinear emissions due to running $\alpha_S(k_T) \sim 1/\ln(k_T/\Lambda_{QCD})$

Comparison to pocket-formula predictions



CMS, arXiv:2312.16343

Recall LO pocket formula for Lund density:

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

Running $\alpha_S(k_T)$ from few GeV to ~60 GeV qualitatively describes the data

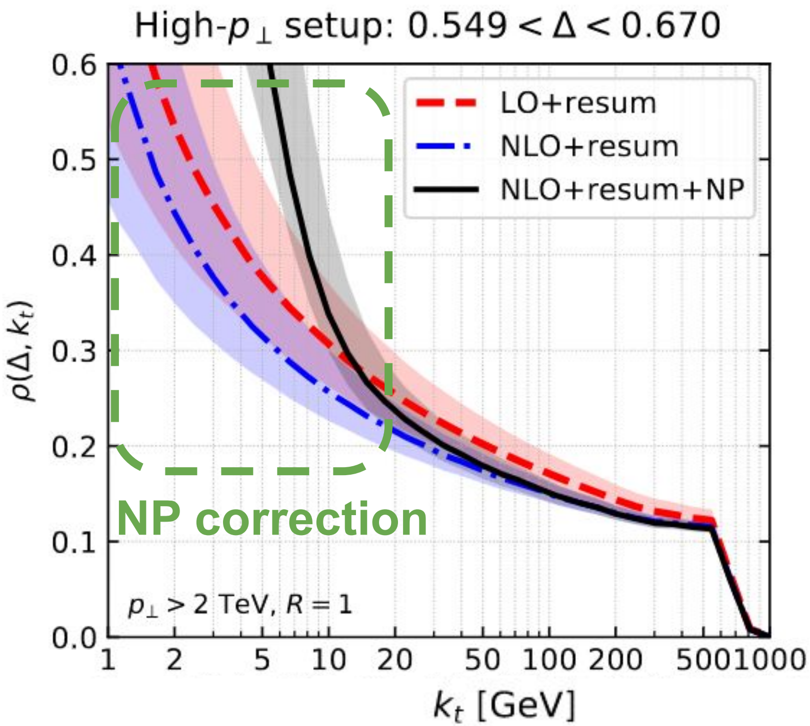
Quark/gluon fractions from PYTHIA8:

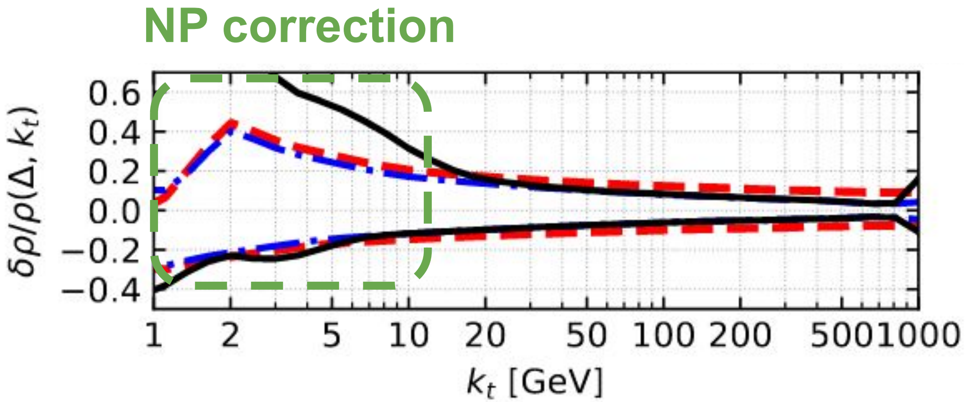
$$C_R^{eff} = f_q C_F + f_g C_A \sim 2$$

$f_q = 0.59,\ f_g = 0.41$

Analytical calculation (NLO+NLL+NP)

Lifson, Salam, Soyez JHEP 10 (2020) 170





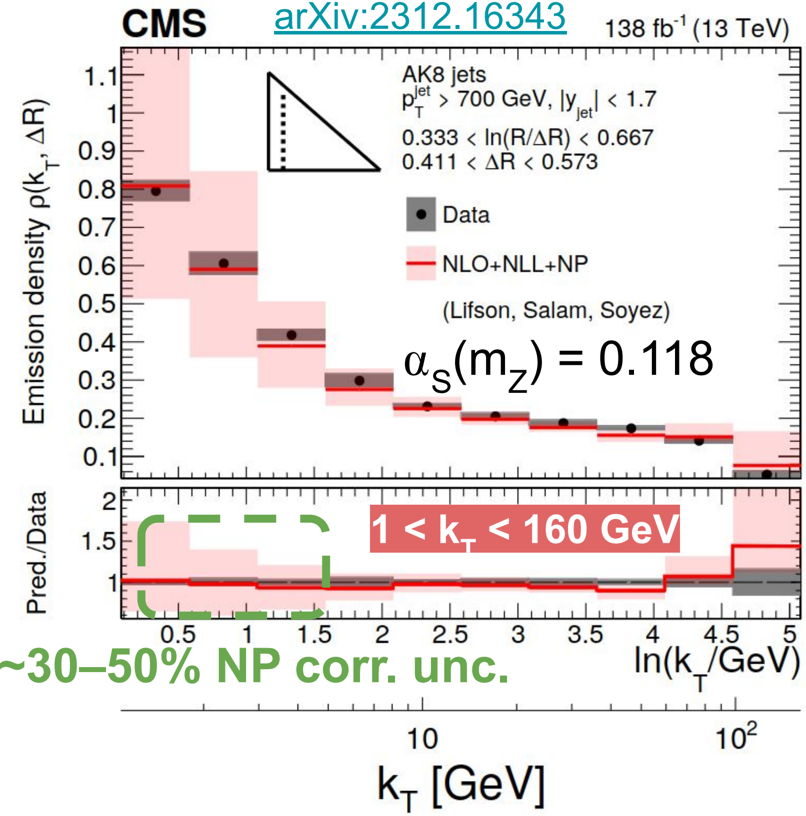
Uncertainties dominated by NP corrections at low k_T ~ 1 GeV (20–40%)

Dominated by pQCD uncertainties for high $k_T \gg 1$ GeV (5–10%)

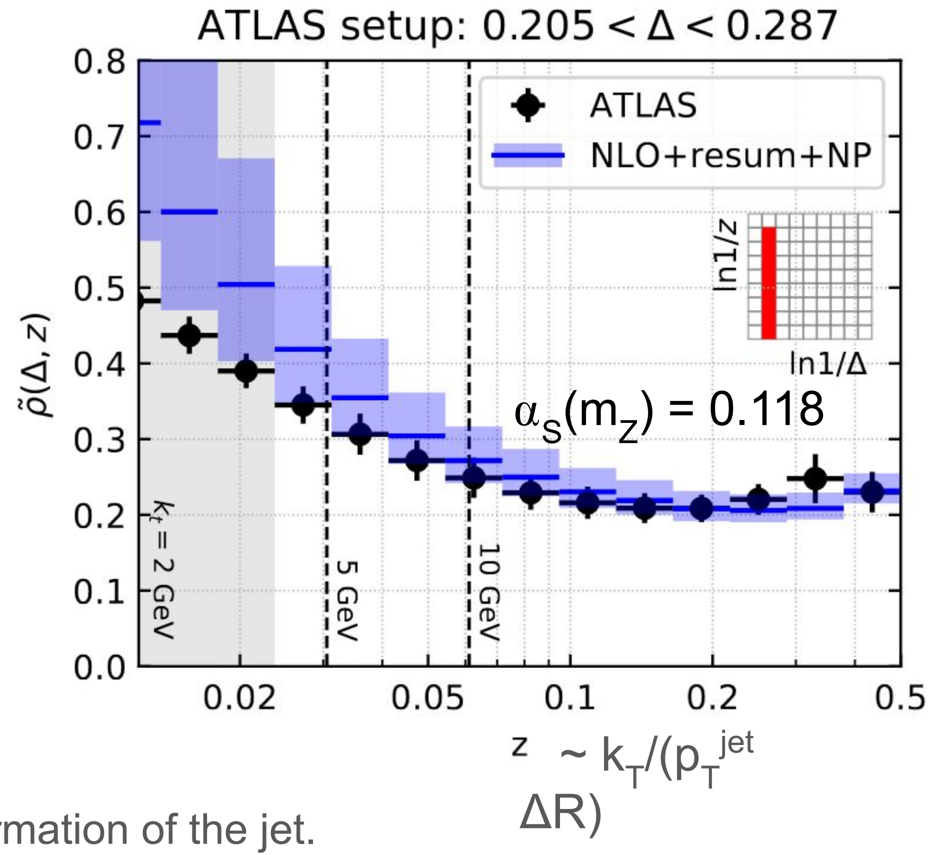
Resummation of full set of single-logarithms at NLL, two-loop beta function

Theory (NLO+NLL+NP) *versus* LHC data

arXiv:2312.16343



Lifson, Salam, Soyez JHEP 10 (2020) 170



First-principles understanding of the formation of the jet.

Could we use primary Lund jet plane data to extract $\alpha_S(m_Z)$?

Quark/gluon jet fraction issue

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

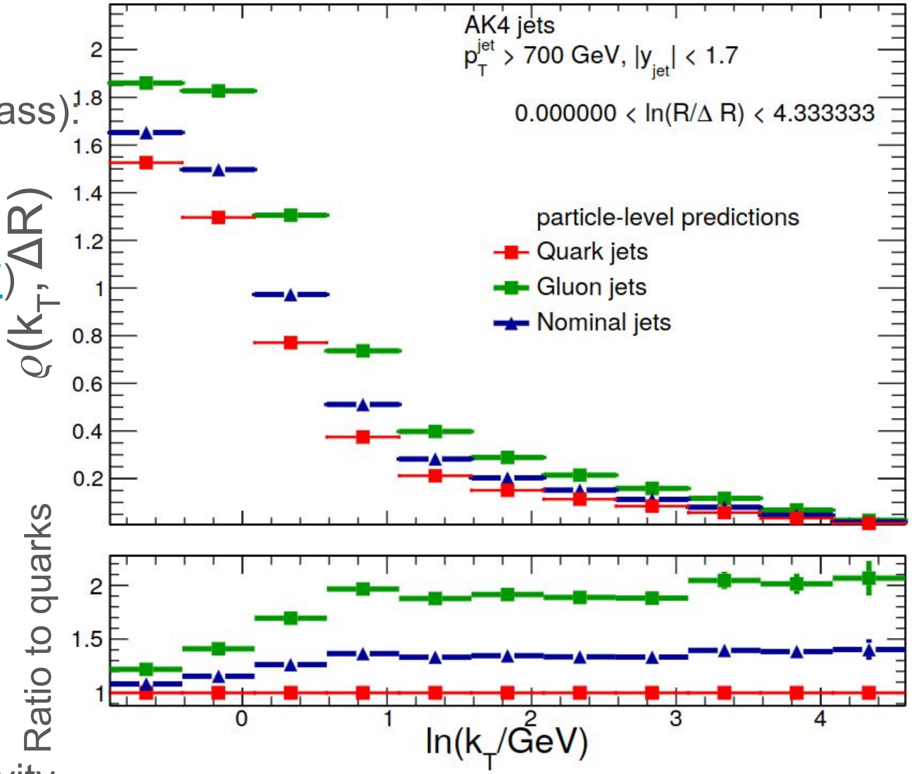
Different strategies have be adopted (w/ soft-drop mass):

- 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)

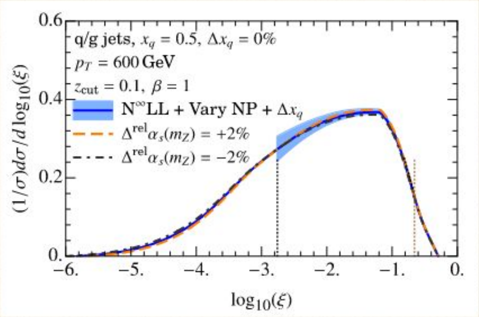
- Design observables with reduced q/g fraction sensitivity
  (cf Meng Xiao's talk on energy correlators, $\delta\alpha_S/\alpha_S$~4%)



Slide by Simone Marzani at alphaS-2022 workshop

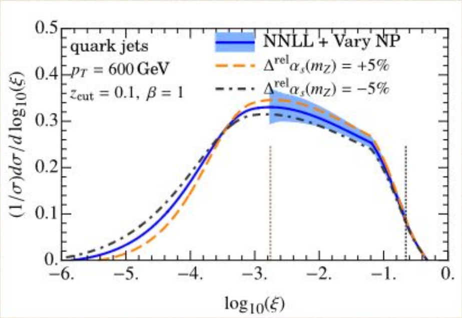
HOW WELL CAN WE DO?

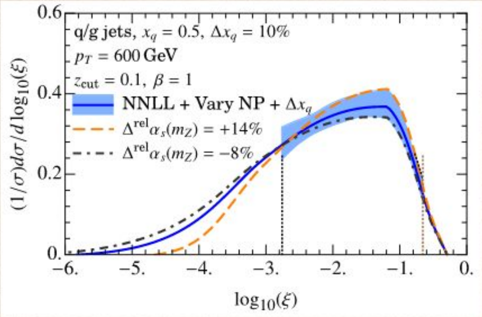
- work in progress to consider α_s sensitivity using state-of-the-art calculations



varying only the 6 non-pert parameters

including NNLL variations



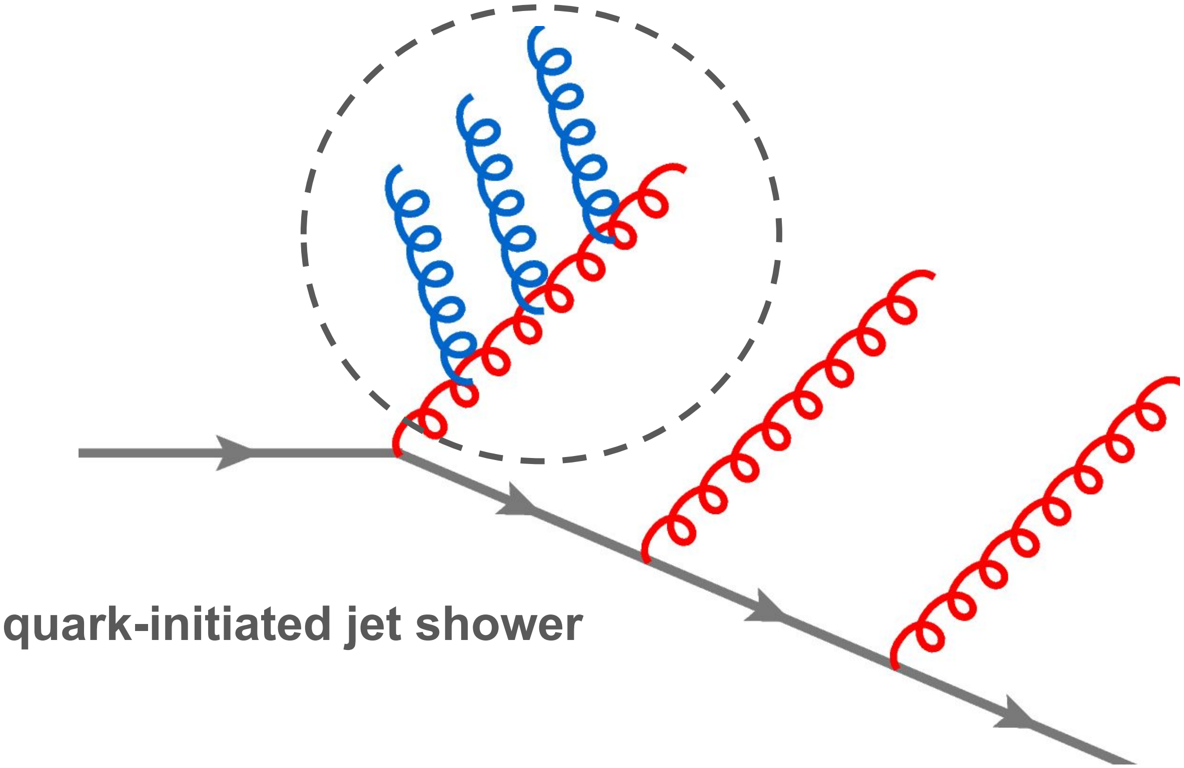


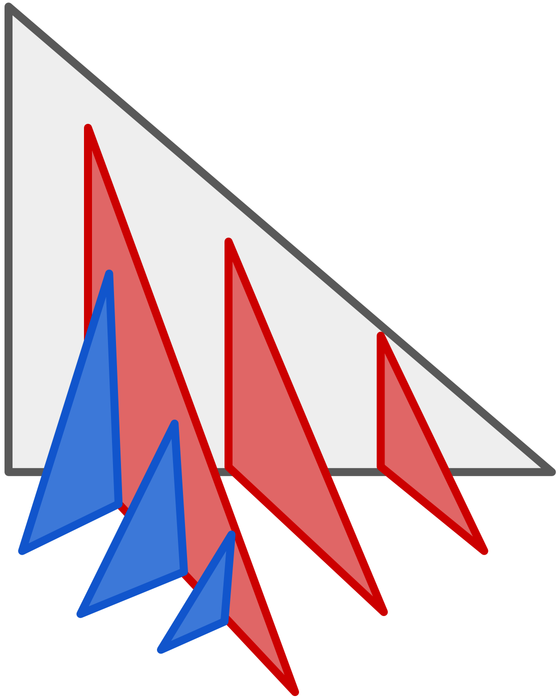
including 10% q/g fraction uncertainty

- without fitting for non-perturbative parameters, one gets 2% uncertainty
- perturbative and non perturbative uncertainties total to 5%
- this increases to 15% when considering quark/gluon mixtures

Hannesdottir, Pathak, Schwartz, Stewart (in preparation)

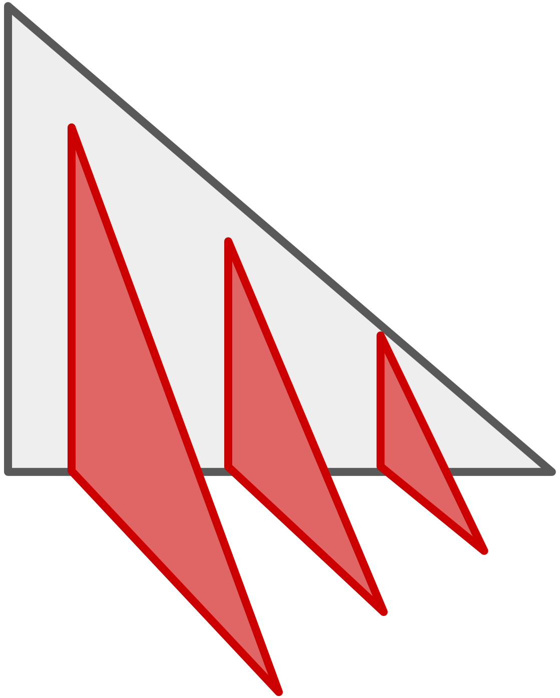
Secondary Lund planes





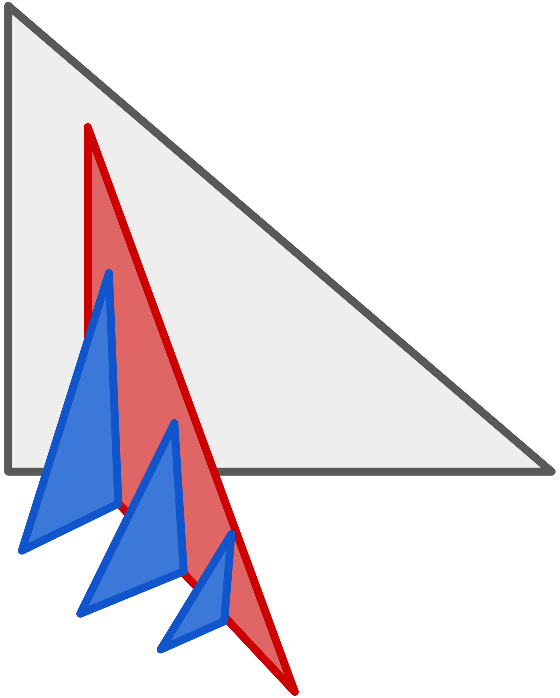
Primary Lund plane density

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



***Secondary* Lund jet plane density**

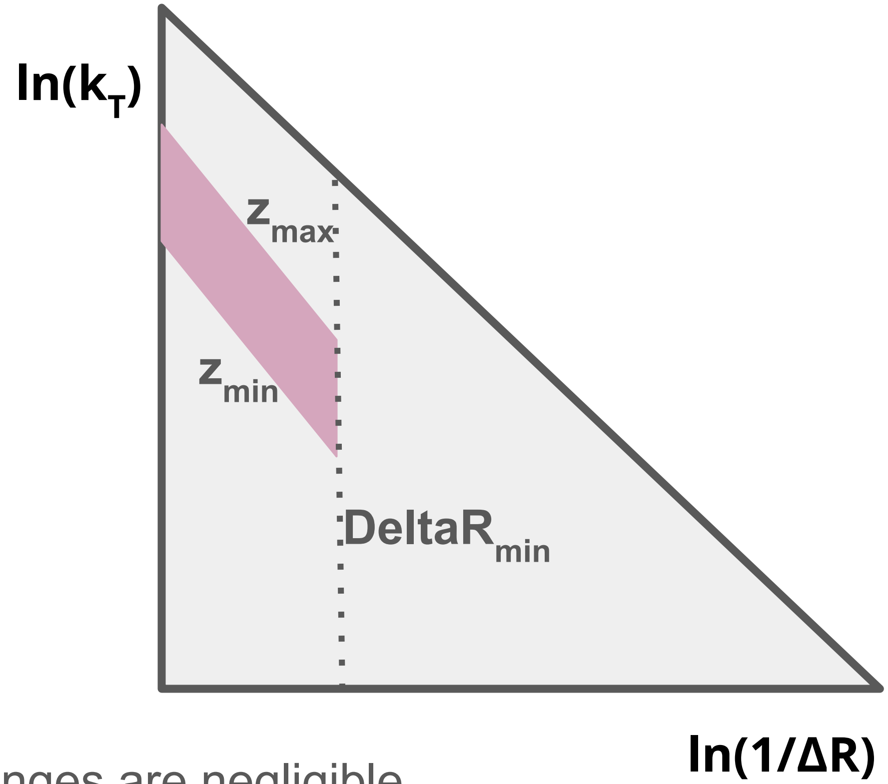
If **primary emission** is chosen judiciously, can obtain gluon-rich jet sample



Which primary emission should be selected?

Collinear:
Emission should be collinear, but
at sufficiently large angles for phase space
(e.g., ΔR_{min} ~ ½ R , ΔR_{max} < R)

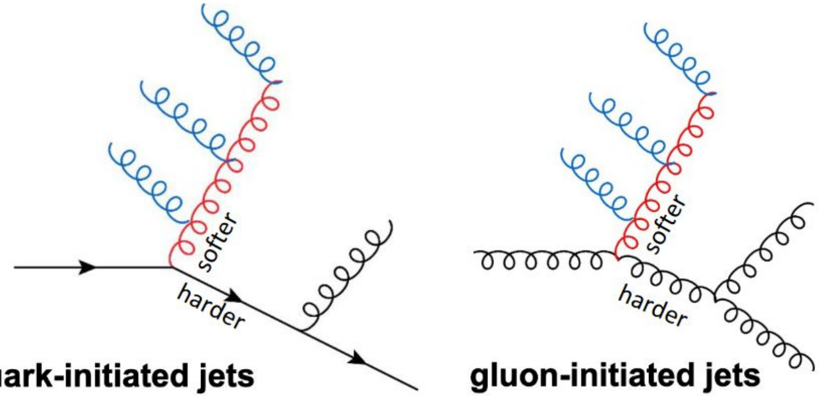
Soft (exploit 1/z pole):
Asymmetric momentum balance,
$z = p_{T,soft}/(p_{T,soft}+p_{T,hard})$ (e.g., 0.2 < z < 0.25)

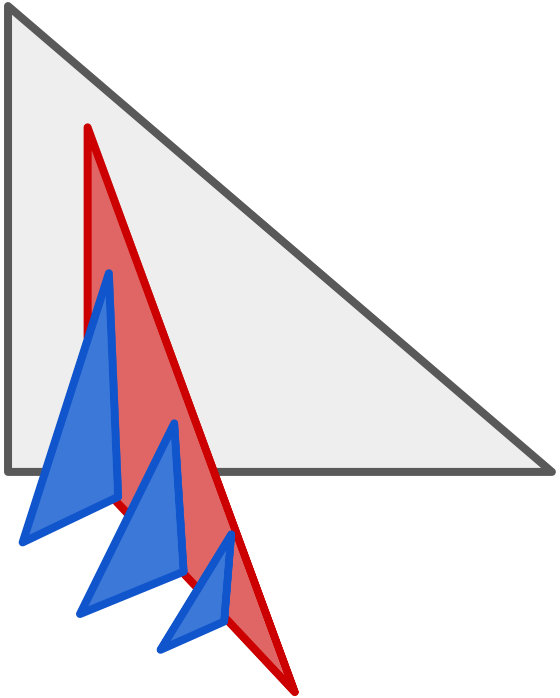


Phase-space region where parton flavor changes are negligible
(e.g., q→qg, g→qqbar, which would make secondary LJPs quark-like)

Choose **primary emission** is soft & collinear, i.e.,

$$z = p_{T,\text{emission}}/(p_{T,\text{emission}}+p_{T,\text{emitter}}) \ll 1/2$$

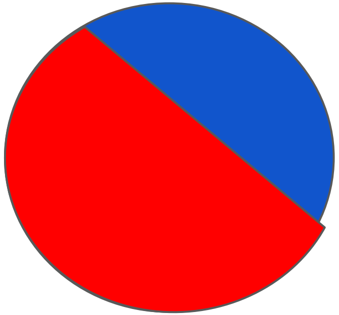




exploit infrared & collinear divergences

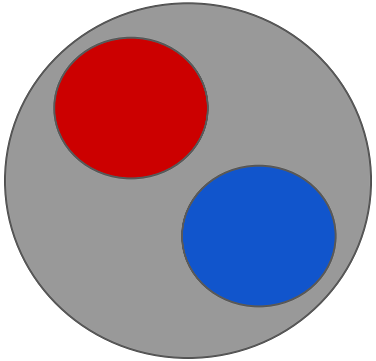
At least three setups

1.SoftDrop-like setup (Cambridge/Achen tree)



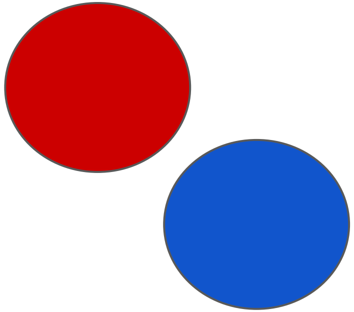
large R = 1.2 jet, undo clustering history

2. Trimming (reclustering with smaller R)



large R jet
→recluster w/ small R jets

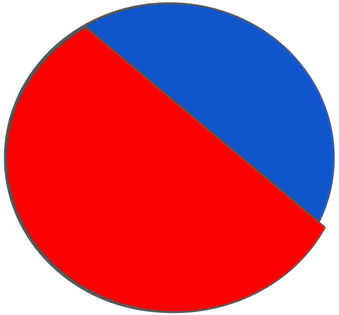
3. anti-k_T dijet selection (or multijet)



At least three setups

focus on this

1.SoftDrop-like setup
(Cambridge/Achen tree)



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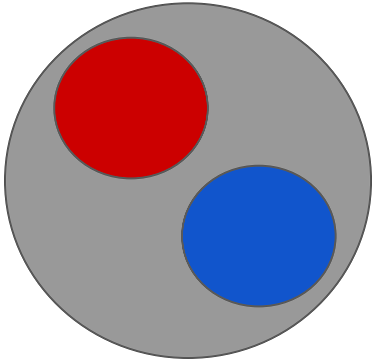

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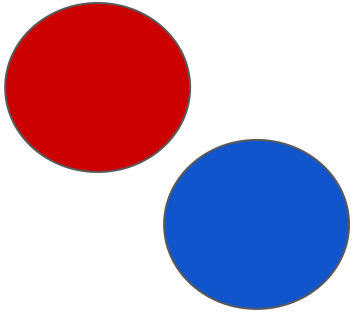
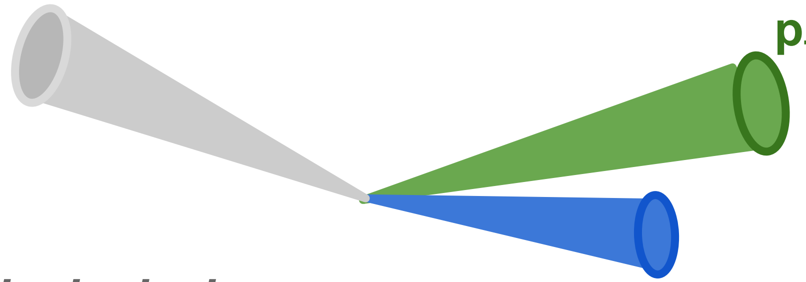


dijet selection (baseline, can be optimized)



$p_{T,jet1}$ > 700 GeV
(quark/gluon jet mixture)

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

$150 < p_{T,jet2} < 200$ GeV
(proxy for gluon-initiated jet)

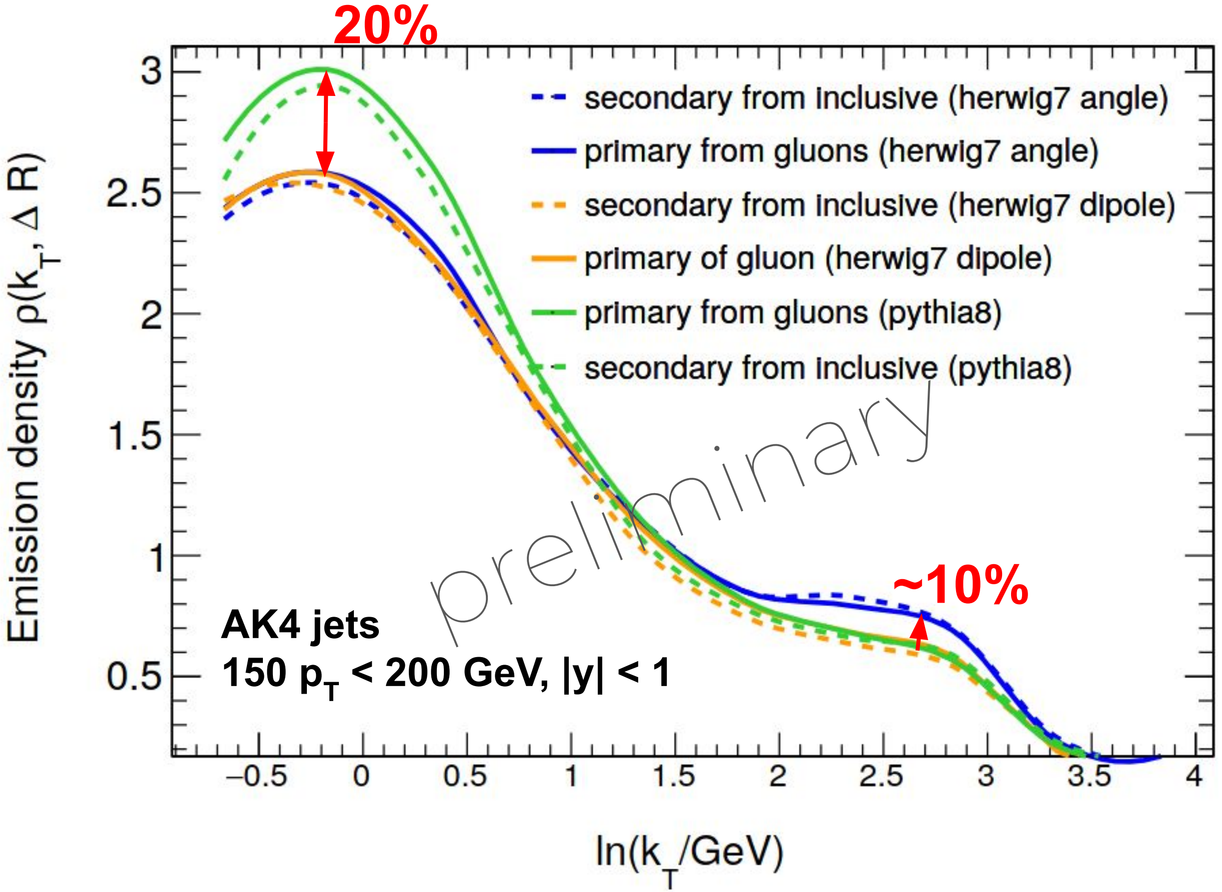
Treat recoiling jets inclusively (dijet+X)

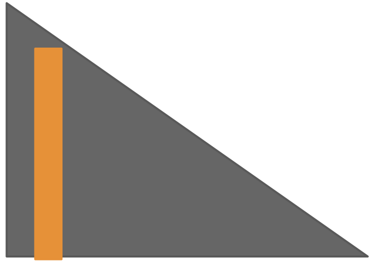
Two anti-k_T jets: harder with $p_{T,1}$ > 700 GeV,
softer with $150 < p_{T,2} < 200$ GeV
and $1 < \Delta R_{jj} < 1.2$ between the two

"inclusive" dijet selection (i.e., >= 1 pair per event)

Compute the substructure of the softer jet

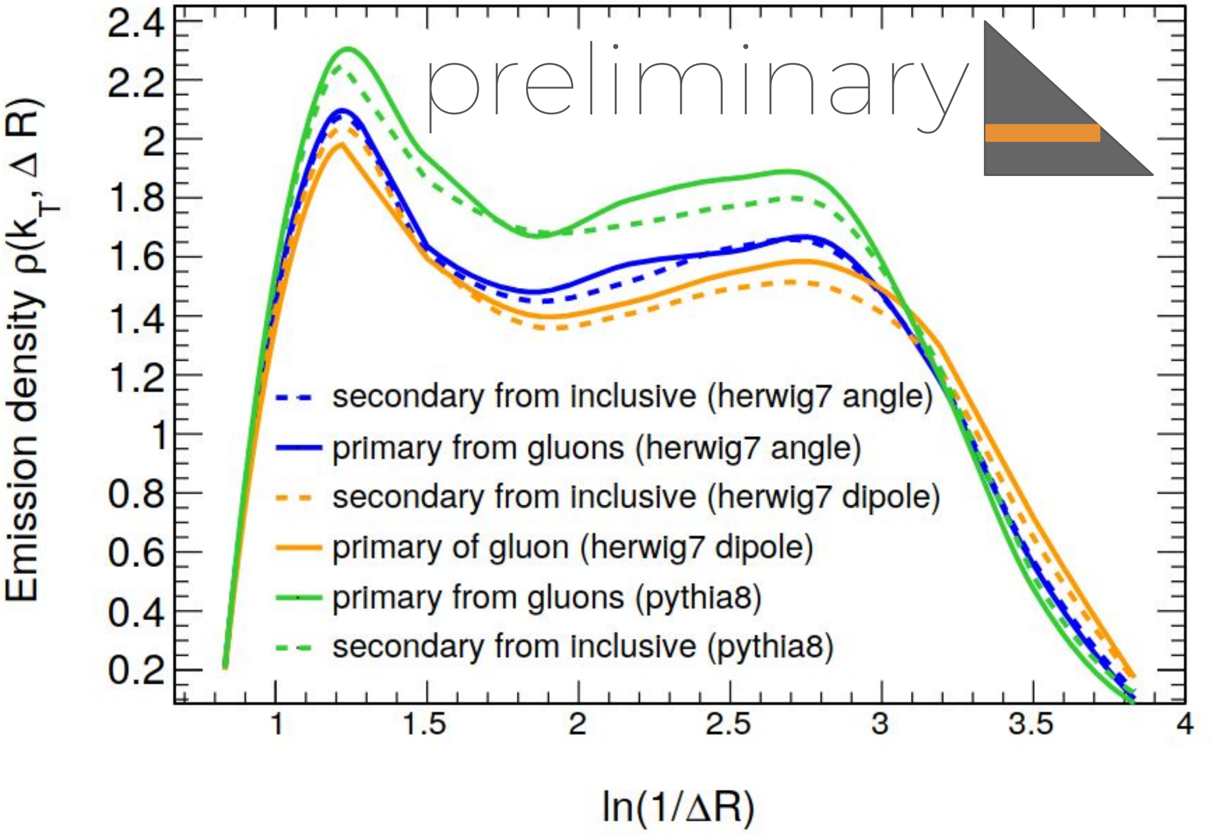
Similar model discrimination as with gluon primary LJPs (from gg→gg)



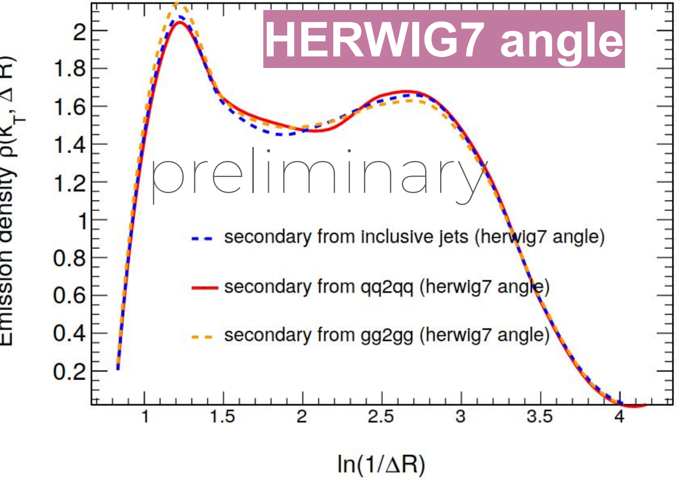


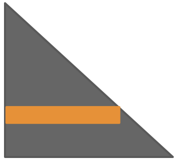
Similar model discrimination with gluon primary LJPs

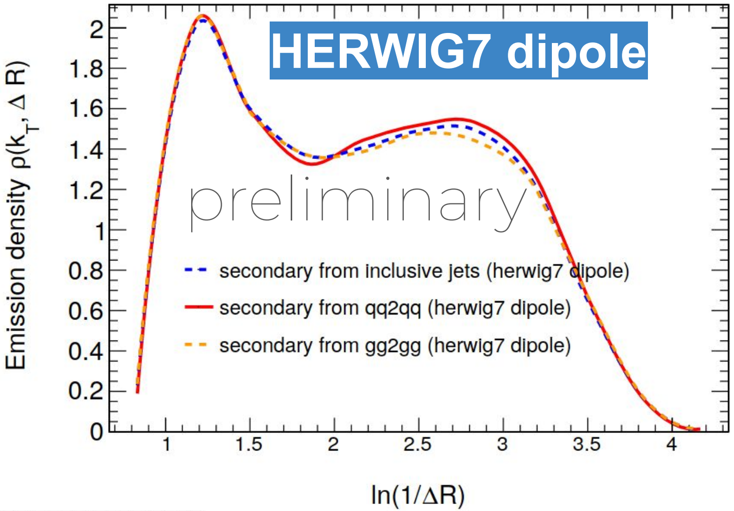
AK4 jets
150 p_T < 200 GeV, |y| < 1

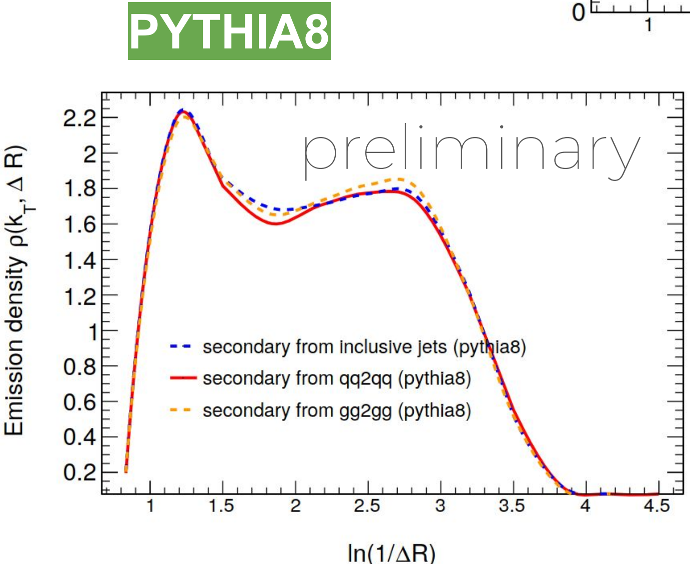


Process-independent Lund-plane densities









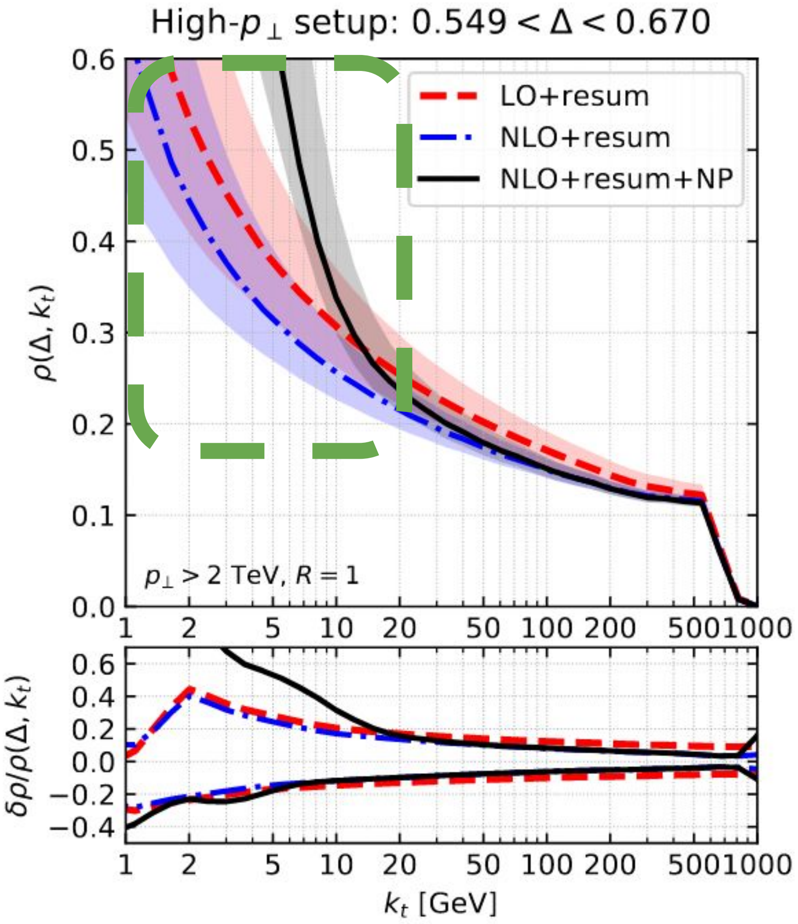
Secondary LJP from inclusive jets
Secondary LJP from quarks (qq→qq)
Secondary LJP from gluons (gg→gg)

Differences negligible within expected sensitivity

Shape and normalization resilient to underlying q/g fraction

Not very sensitive to quark/gluon fraction with secondary Lund jet plane densities

However, still limited by size of pQCD uncertainties (about 20% at $k_T \sim 5$ GeV), and NP corrections are large at low k_T



(a) large angles: $0.549 < \Delta < 0.670$

Average Lund multiplicity

[A. Soto-Ontoso, R. Medves, G. Soyez JHEP04(2023)104]

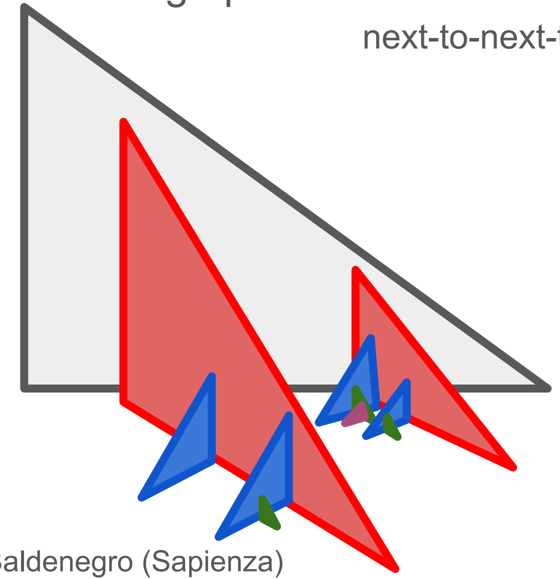
1. Undo the ***full*** Lund tree

2. Count # of emissions with $k_T > k_{T,cut}$

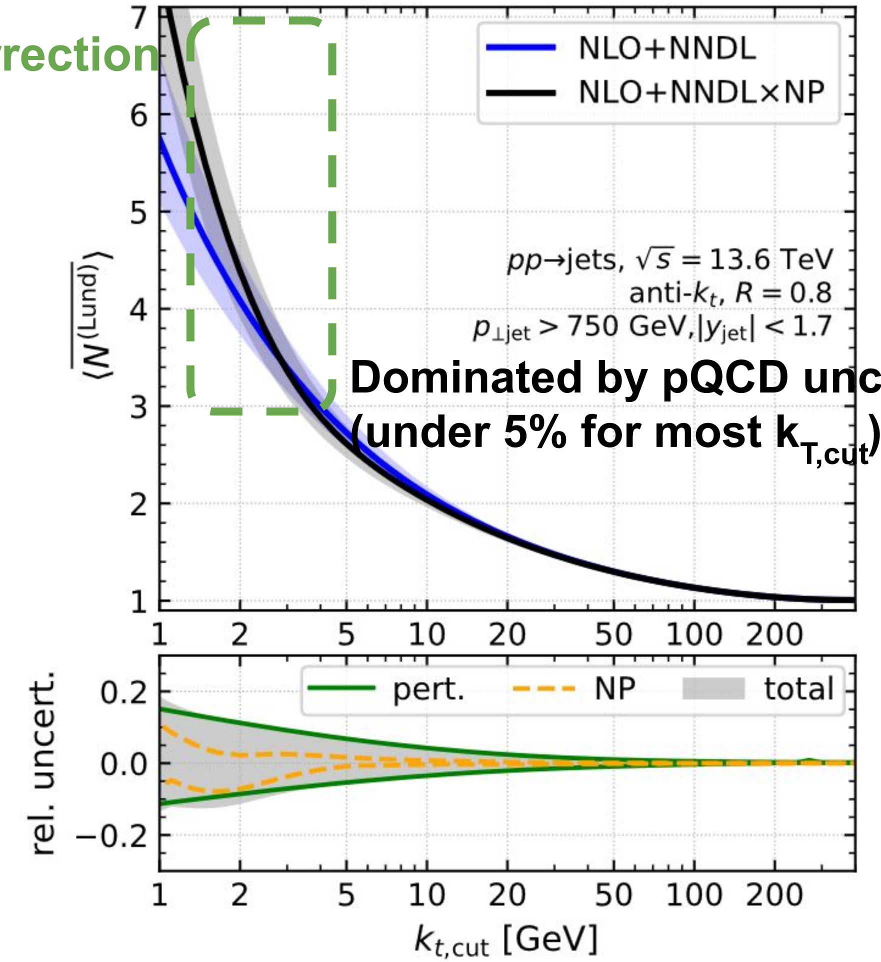
3. Average over *all* jets in the sample

Amenable to high precision calculations (**NLO+NNDL**)

next-to-next-to-double logarithmic

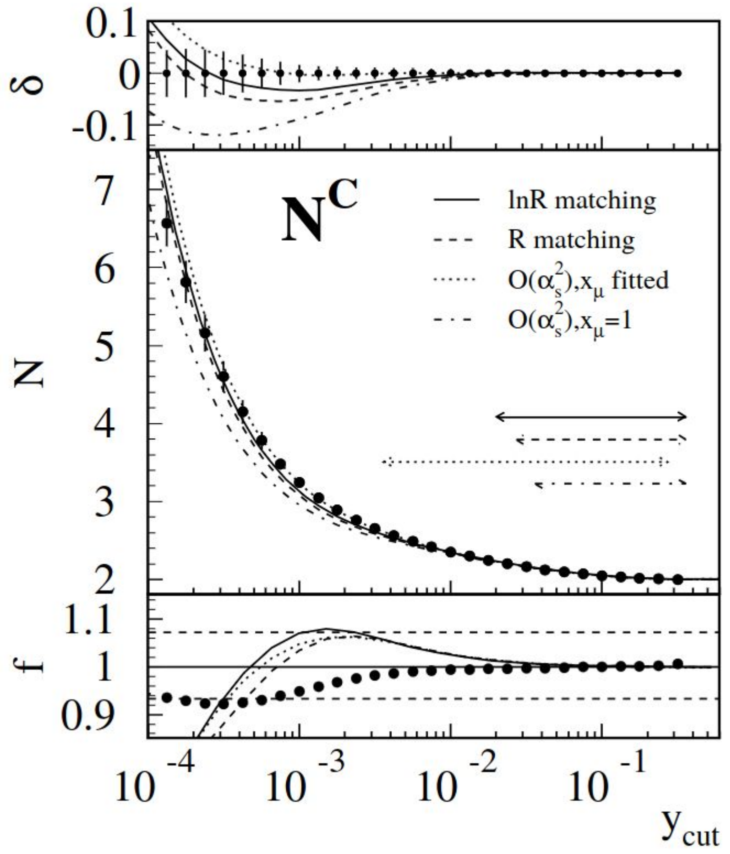


5% NP correction



Dominated by pQCD unc
(under 5% for most $k_{T,cut}$)

Similar jet multiplicity observable measured at LEP



$\sim k_{T,cut}/Q$

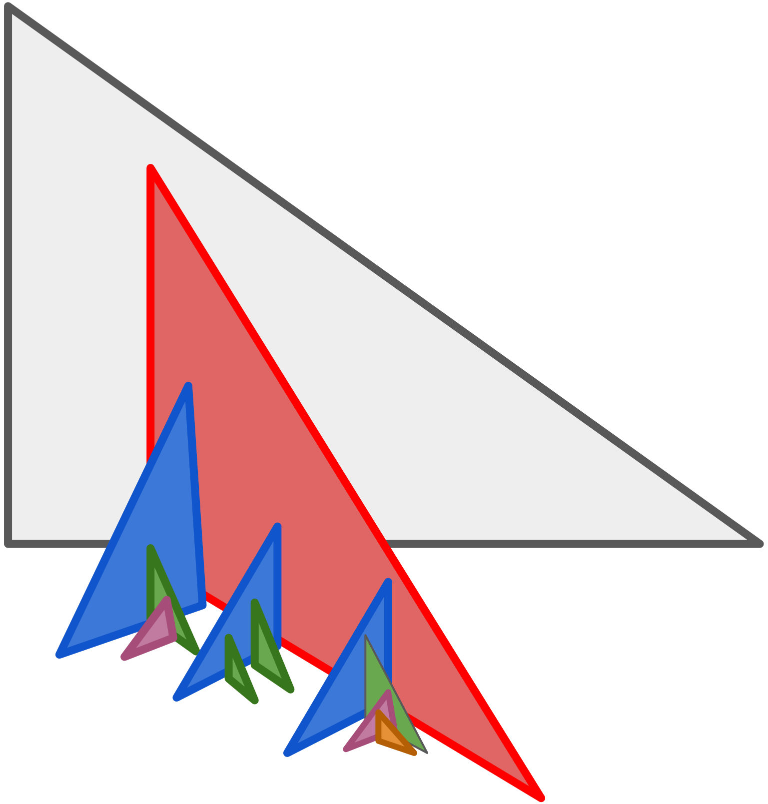
used for $\alpha_s(m_Z)$ extractions by [JADE&OPAL, EPJC 17:19-51 ,2000]

$$\alpha_s(M_{Z^0}) = 0.1187^{+0.0034}_{-0.0019}.$$

Average Lund multiplicity of the secondary Lund plane

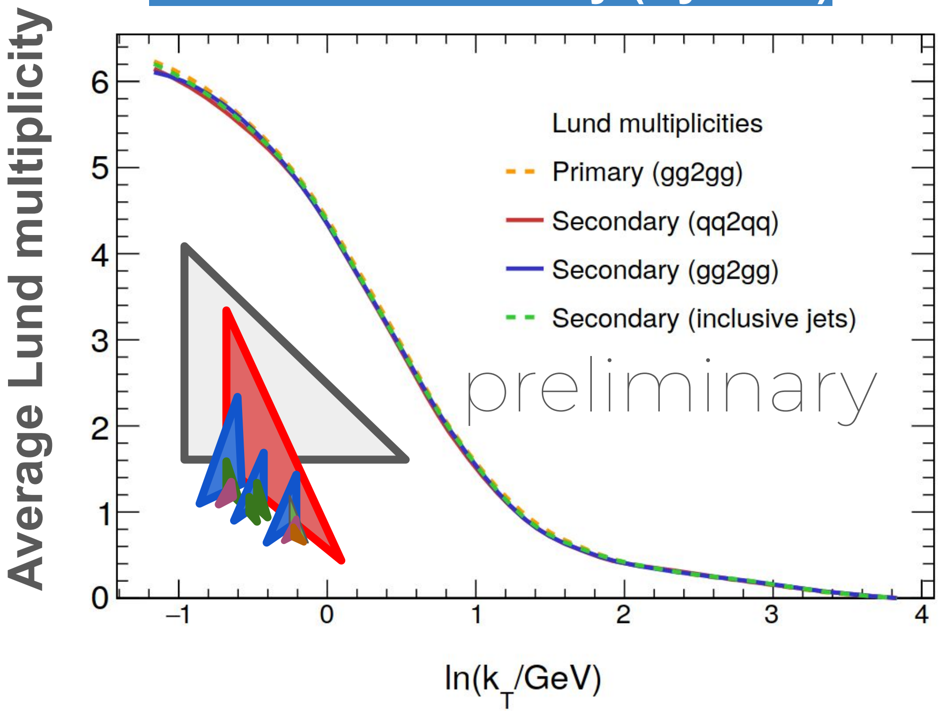
Decluster the full Lund tree of the ***primary emission***

Use as proxy for average Lund multiplicity of gluon-initiated jets



average Lund multiplicity of gluons

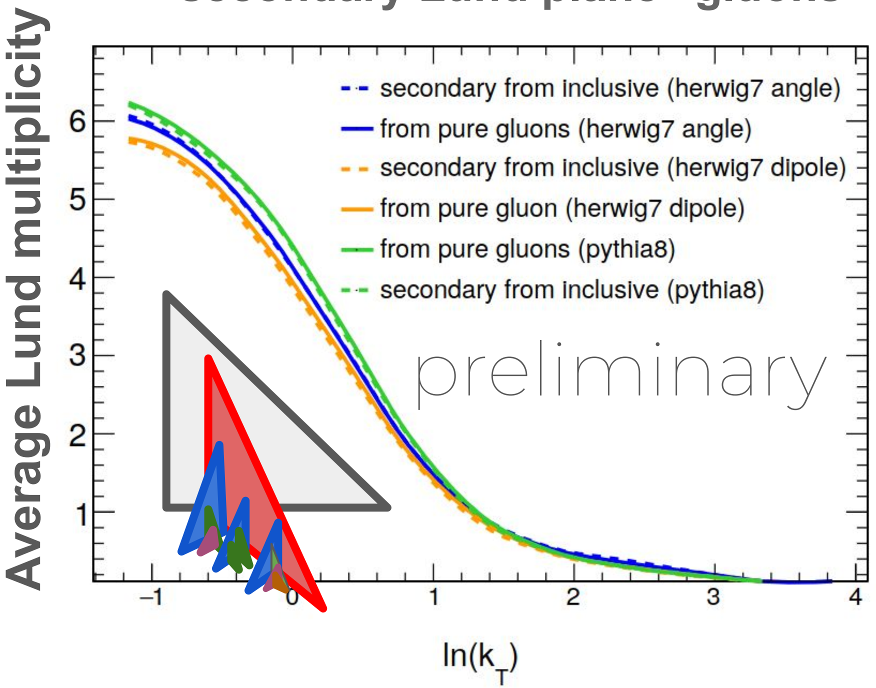
Process universality (Pythia8)



Robust to to q/g fraction & PDFs uncertainties

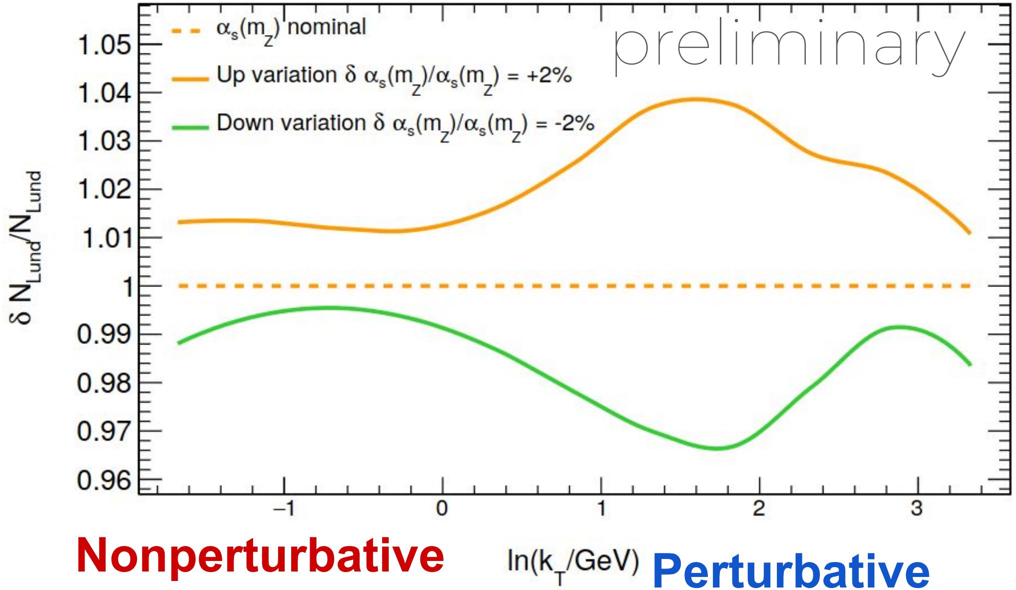
coincides with Lund multiplicity from **Born-level gluons**!

MC comparison of pure gluons vs "secondary Lund plane" gluons



Solid lines: gg→gg primary
Dashed lines: incl. jets secondary

Sensitivity to $\alpha_S^{MC}(m_Z)$ variations (NB: used PYTHIA8 for proof of concept)



Nonperturbative (k_T << 1 GeV)

Perturbative (k_T >> 1 GeV)

+- 2% shifts on $\alpha_S(m_Z)$ results in O(3-4%) changes on Lund multiplicity for gluons

[does not scale linearly with $\alpha_S(m_Z)$, "cumulative" g→gg splittings]

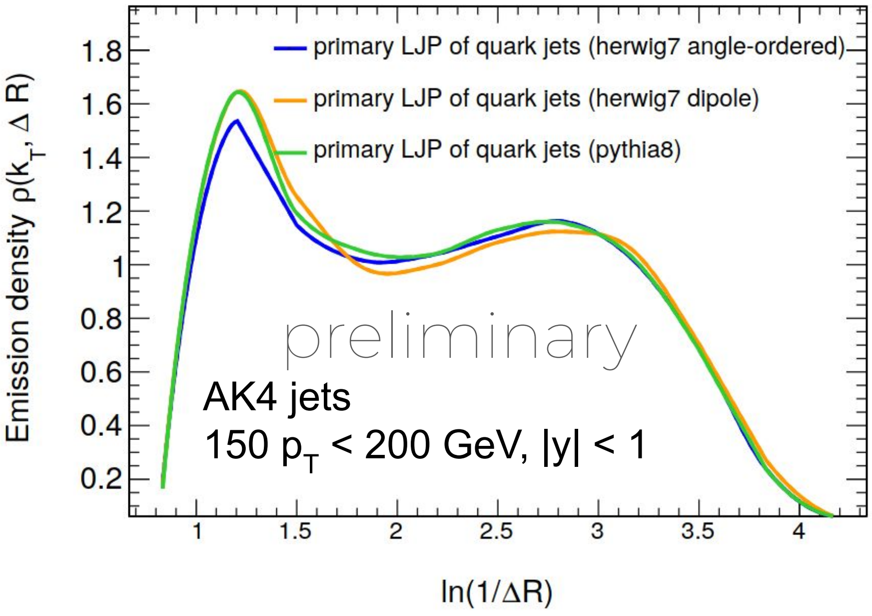
Summary

- Lund jet plane used to explore the radiation pattern of jets, used to test parton showers & resummation
- **Secondary Lund jet planes** for gluon-rich radiation, large reduction on quark/gluon jet fraction (PDF) sensitivity
- Average Lund multiplicity could be used for an $\alpha_S(m_Z)$ extraction, Nonperturbative & perturbative corrections are “factorized” in k_T
- Other substructure observables can be considered (e.g., soft-drop groomed mass, generalized angularities, dynamical k_T, …)

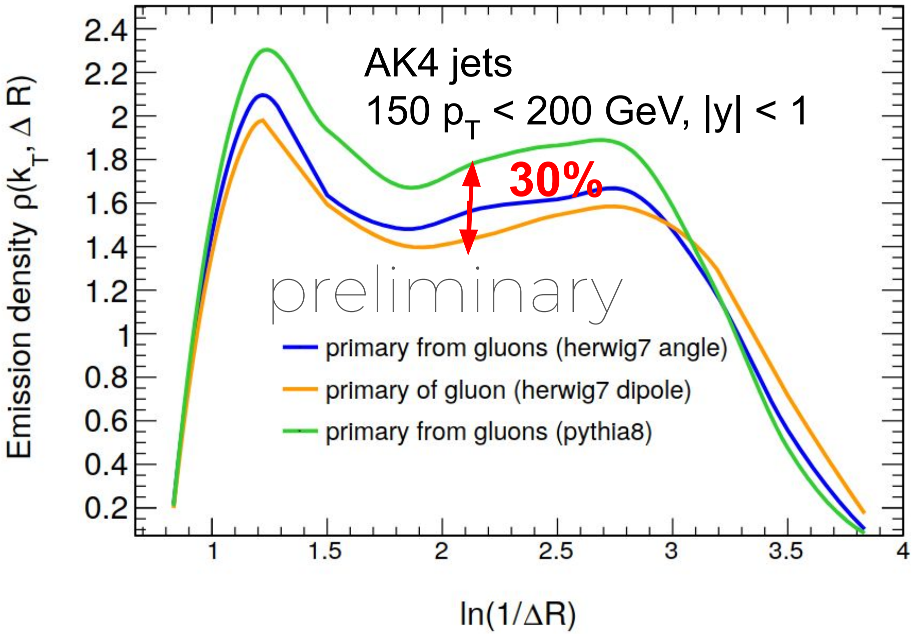
Quarks vs gluon primary LJPs at the LHC

Same Lund plane slice at low k_T ~ 1–2 GeV

Quark jets



Gluon jets

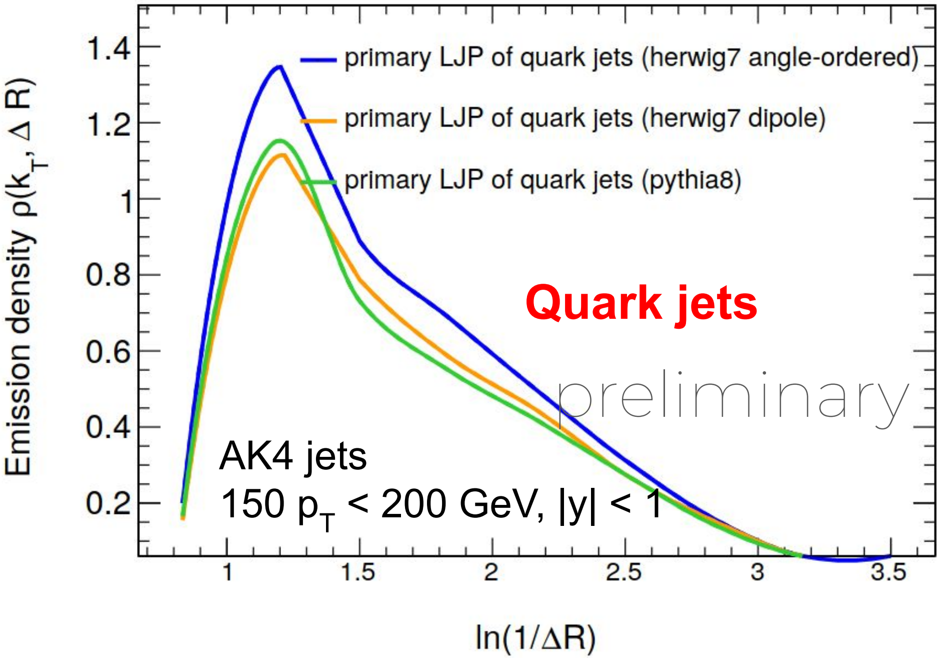


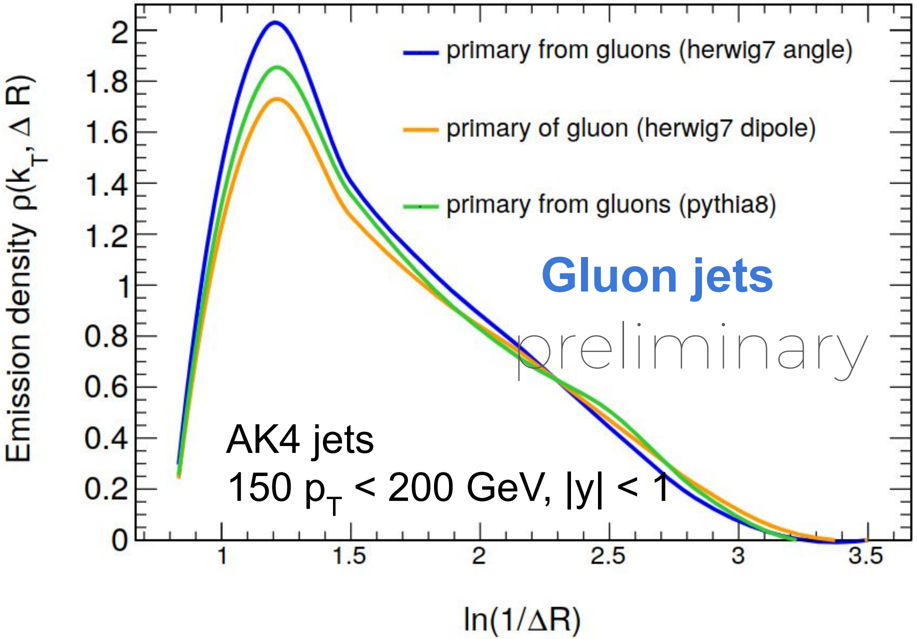
Spread of 1-5%, thx to LEP constraints

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

"Quark jets constrained by LEP" mostly accurate for low p_T jets (at LEP, $p_{T,max} = m_Z/2 \sim 45$ GeV)

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



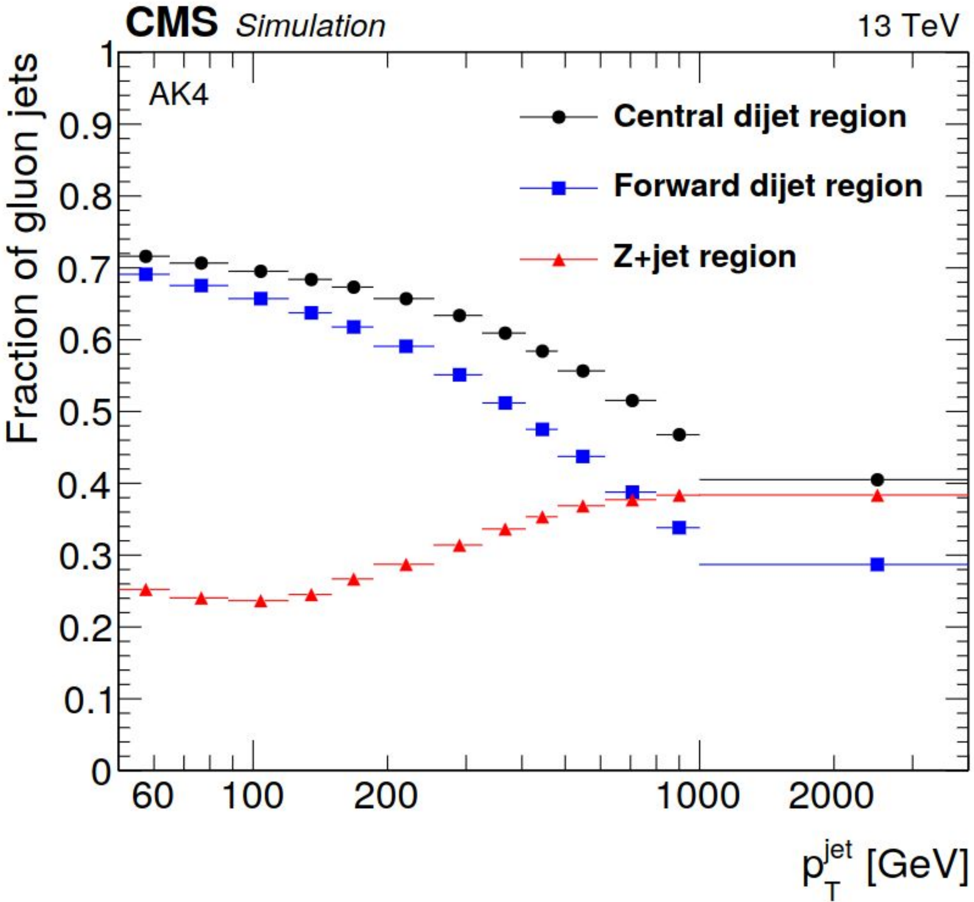


Herwig7 dipole usually closer to Pythia8 in the perturbative region

Herwig7 angle-ordered usually higher in perturbative region

Quark/gluon composition in Z+jet and dijet at the LHC

Up to ~70% gluons in dijet
Up to ~75% quarks in Z+jet



From Les Houches 2015

What is a Quark Jet? **(Or gluon jet)**

From lunch/dinner discussions

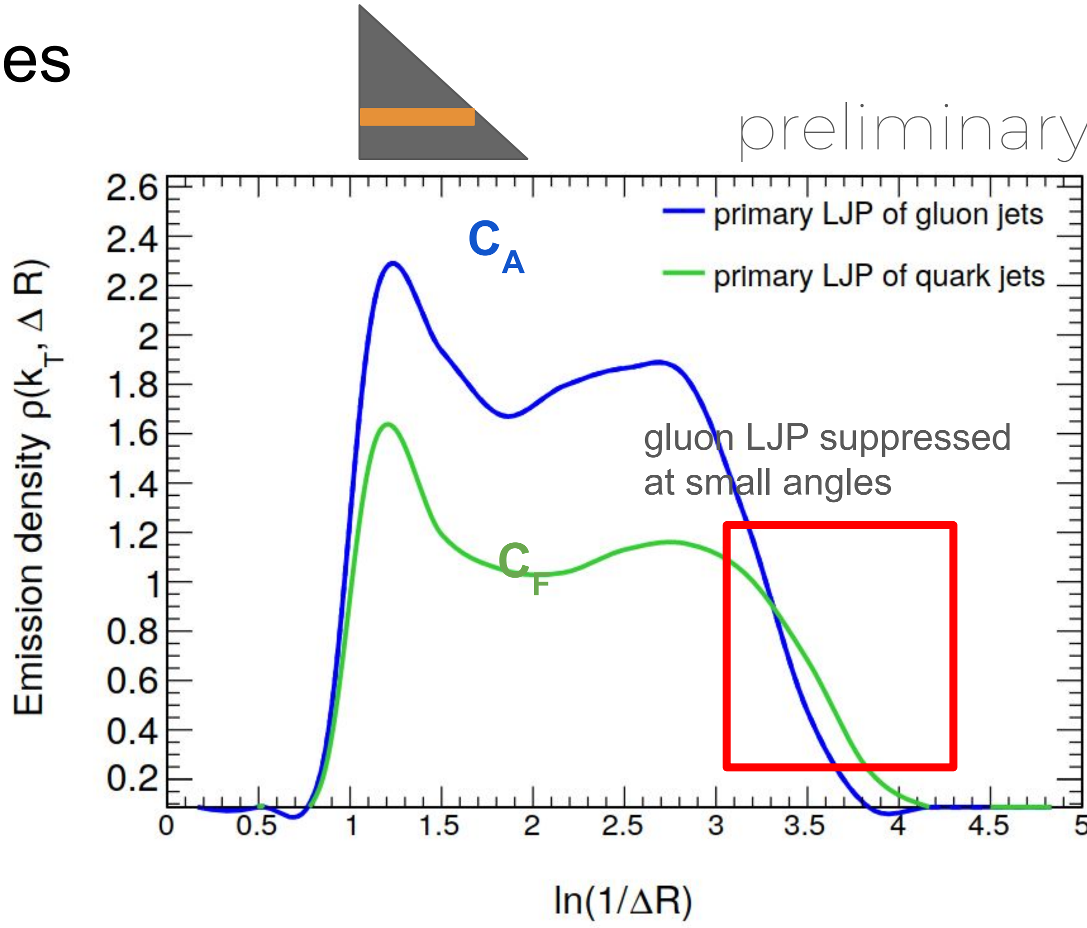
Ill-Defined → Well-Defined	What people sometimes think we mean ← What we mean	
Quark as noun		A quark parton
		A Born-level quark parton
		The initiating quark parton in a final state shower
		An eikonal line with baryon number 1/3 and carrying triplet color charge
		A quark operator appearing in a hard matrix element in the context of a factorization theorem
		A parton-level jet object that has been quark-tagged using a soft-safe flavored jet algorithm (automatically collinear safe if you sum constituent flavors)
Quark as adjective		A phase space region (as defined by an unambiguous hadronic fiducial cross section measurement) that yields an enriched sample of quarks (as interpreted by some suitable, though fundamentally ambiguous, criterion)

Operate here

Quarks vs gluon Lund planes

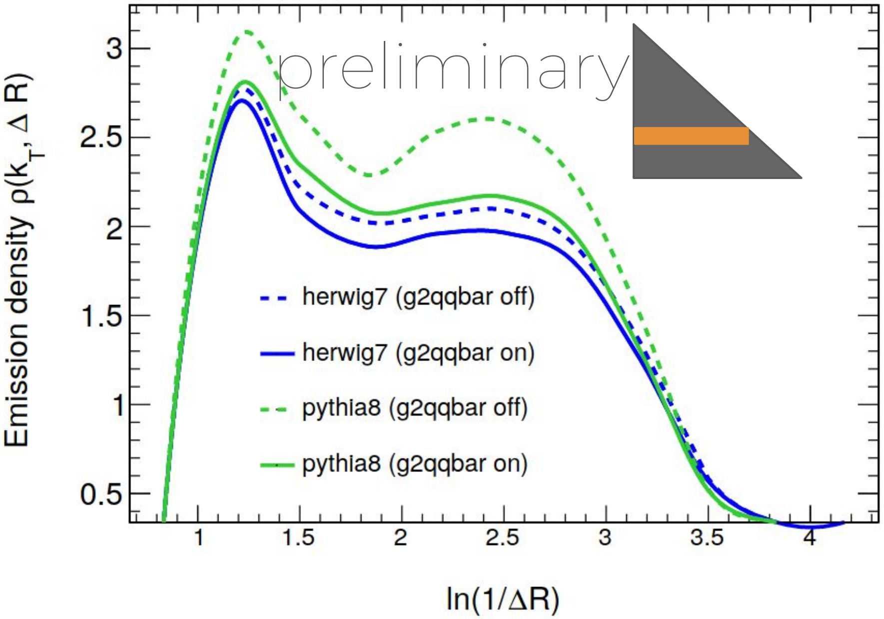
Not ***just*** C_A/C_F scaling! Leading partor momentum loss in the Lund tree histoi soft&collinear divergences, color reconnection effects, …

Gluon LJP is suppressed at small angles wrt quark LJP

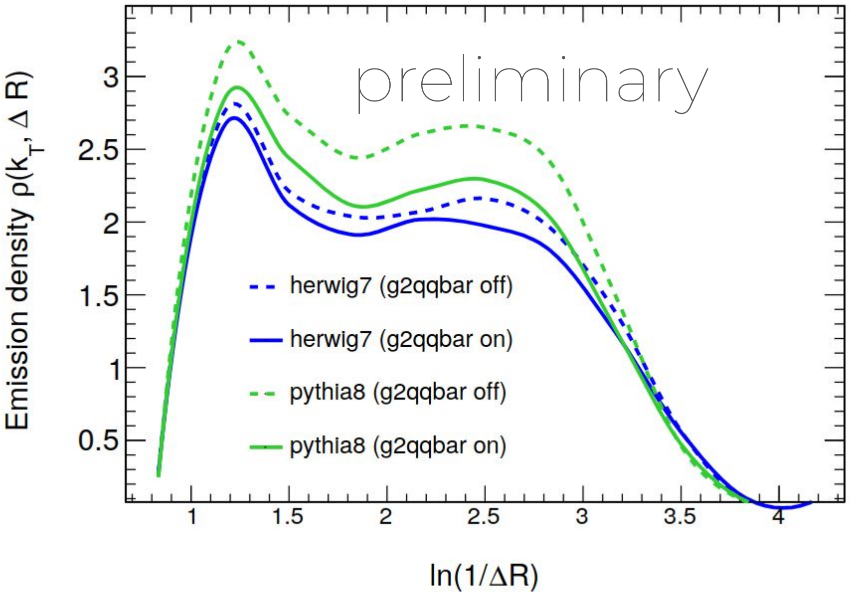


g→qq off / g →qq on check

Effect on secondary LJP



Effect on the gluon primary LJP



Turning off g→qq increases the density of emissions by a similar magnitude for **both** secondary LJP and *gluon* primary LJPs

More dramatic effect for pythia8 (~25%) than herwig7 (~5%)