High-purity gluon jet showers using secondary Lund jet planes

[paper in preparation]

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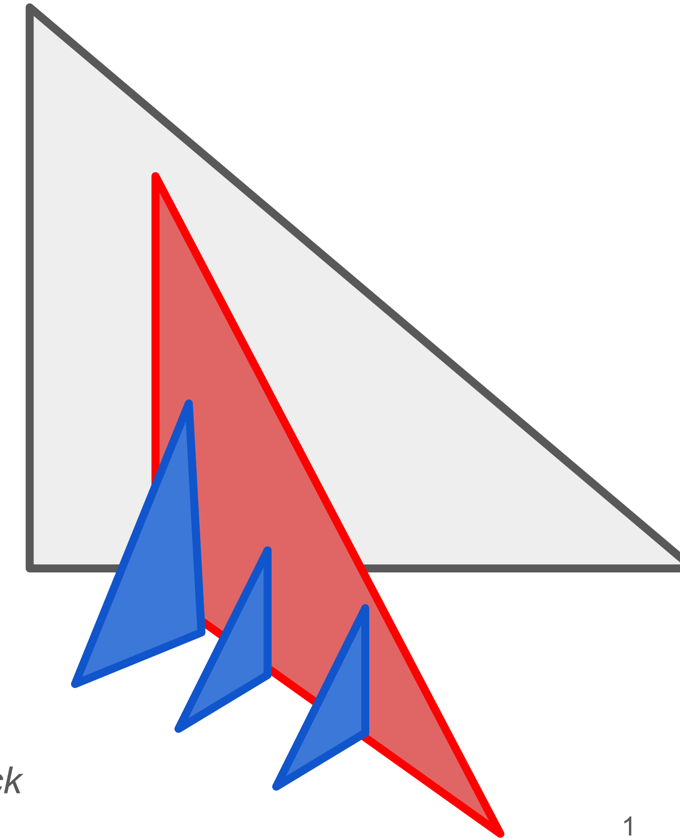
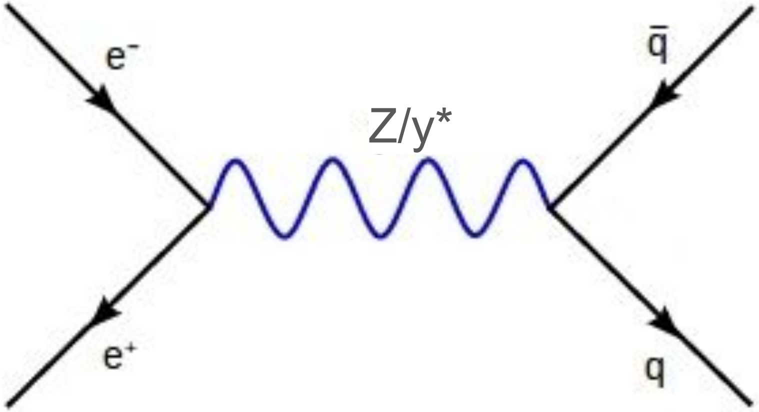
DIS 2024 @ Grenoble, France
April 8th–12th

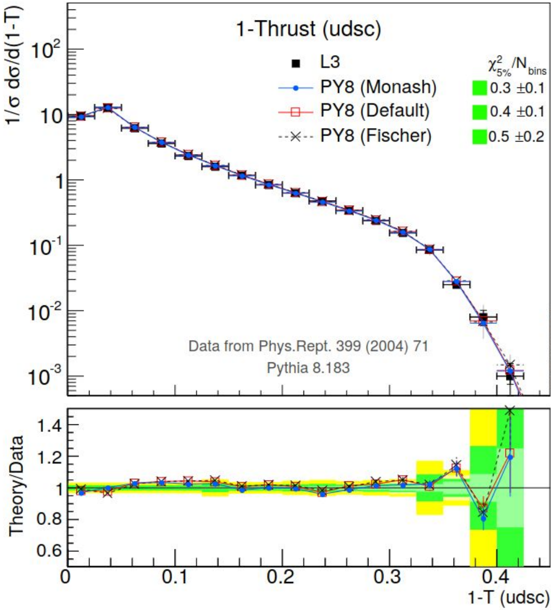


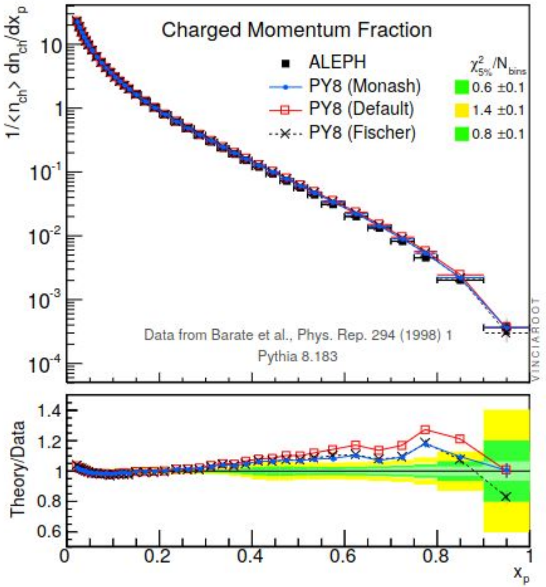
Thanks to Jacob March for early contributions
& Alba Soto, Gregory Soyez, Leticia Cunqueiro, Matt Nguyen for feedback

Particle physics lore:

“Quark showers are strongly constrained by LEP in $e^+e^- \rightarrow \gamma^*/Z^0 \rightarrow$ qqbar, **gluon showers not as much**”

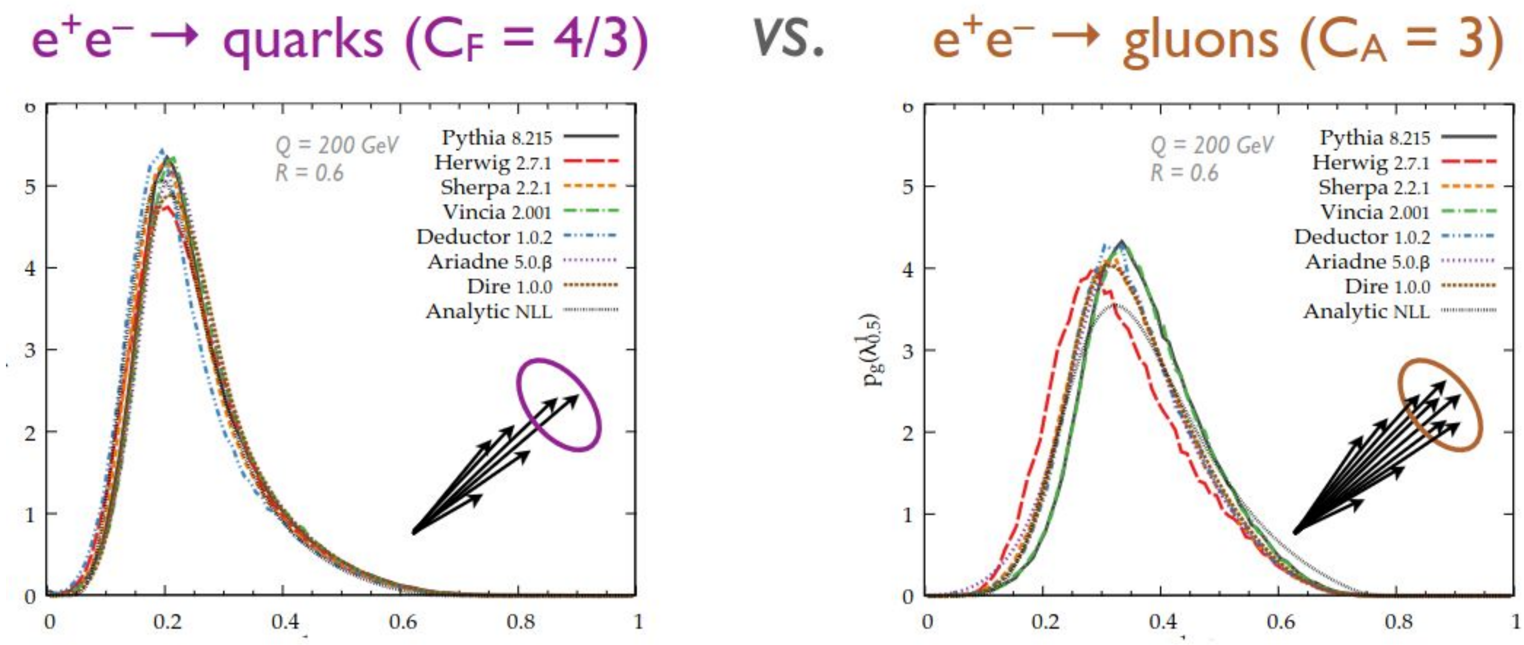






Example of LEP event shapes & frag. function use for tuning (Pythia8 monash tune)

Les Houches 2015 substructure studies



$1/p_{T,\,jet} \sum p_{T,i}\, \Delta R_{i,jet}$

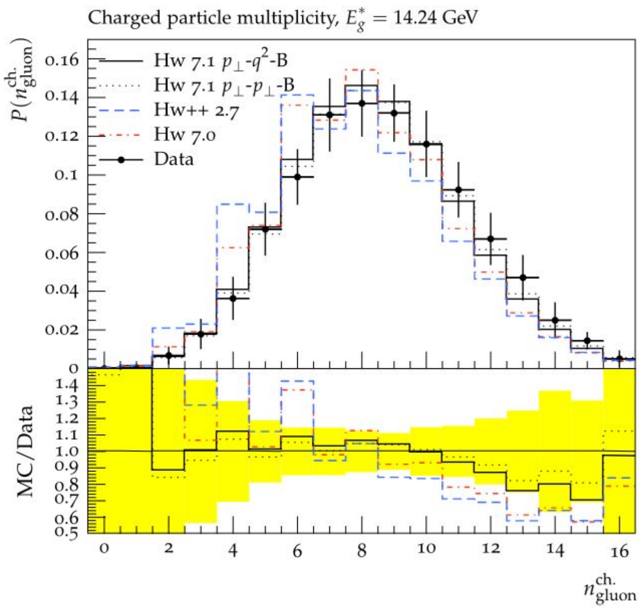
small spread

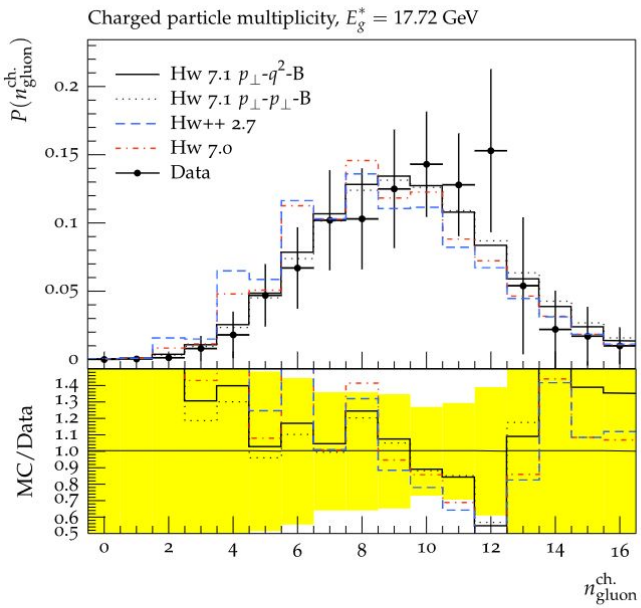
$1/p_{T,\,jet} \sum p_{T,i}\, \Delta R_{i,jet}$

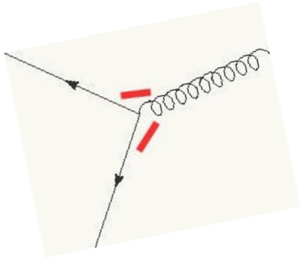
large spread

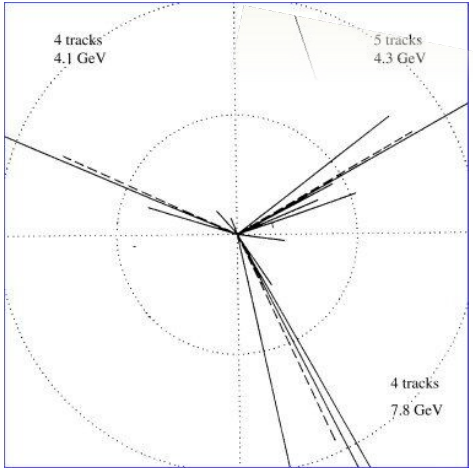
High-purity gluon jet samples at LEP ($e^+e^- \to bbg$)

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

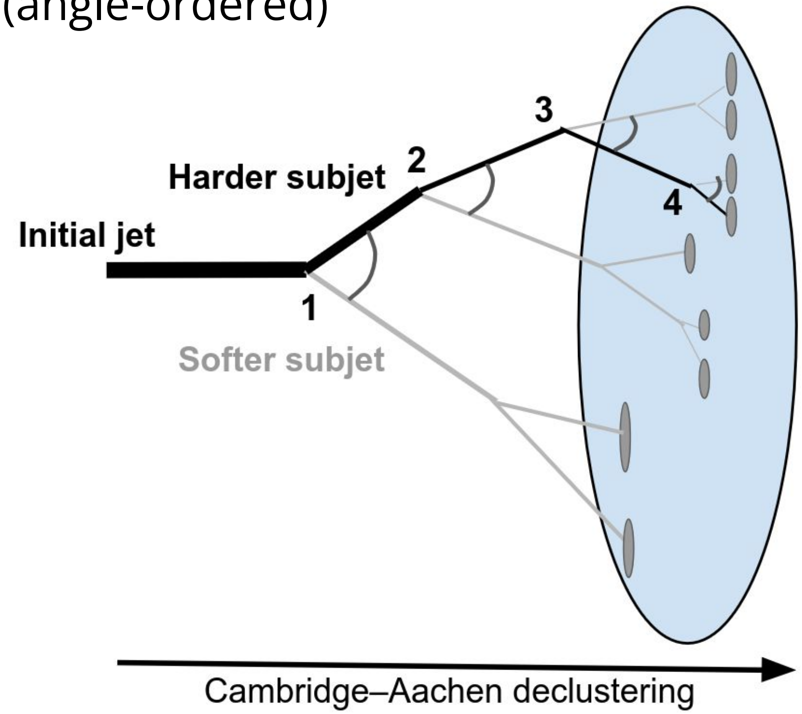
The Lund jet plane: 2D phase-space of 1→2 branchings in a jet

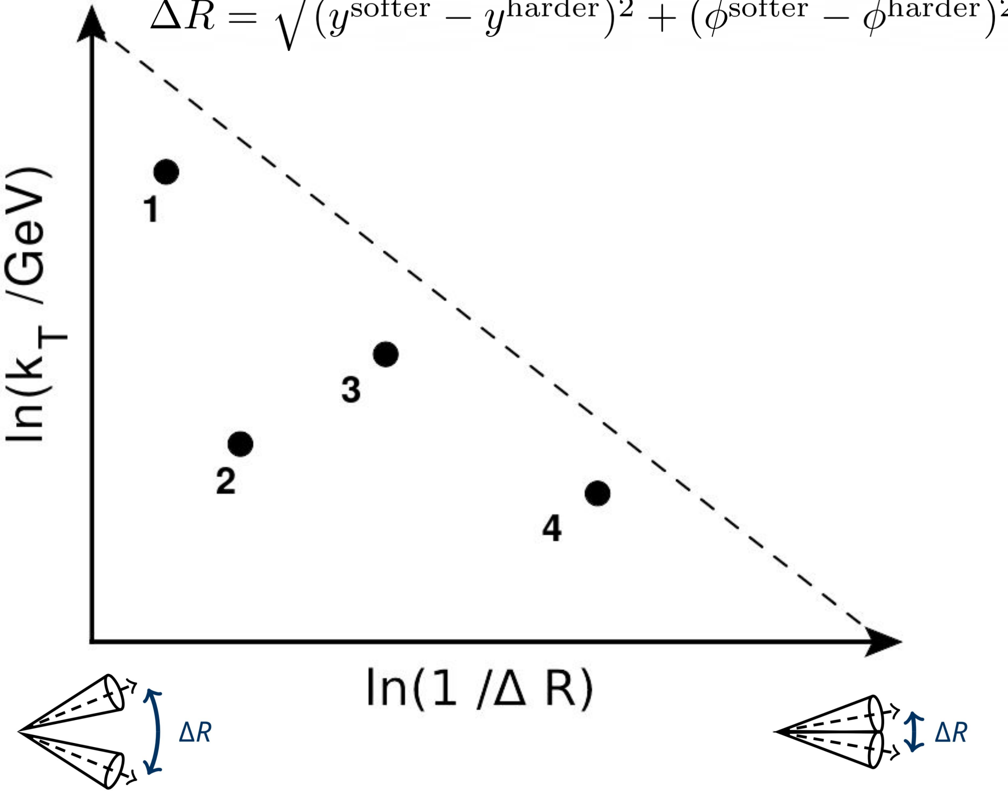
F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064

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

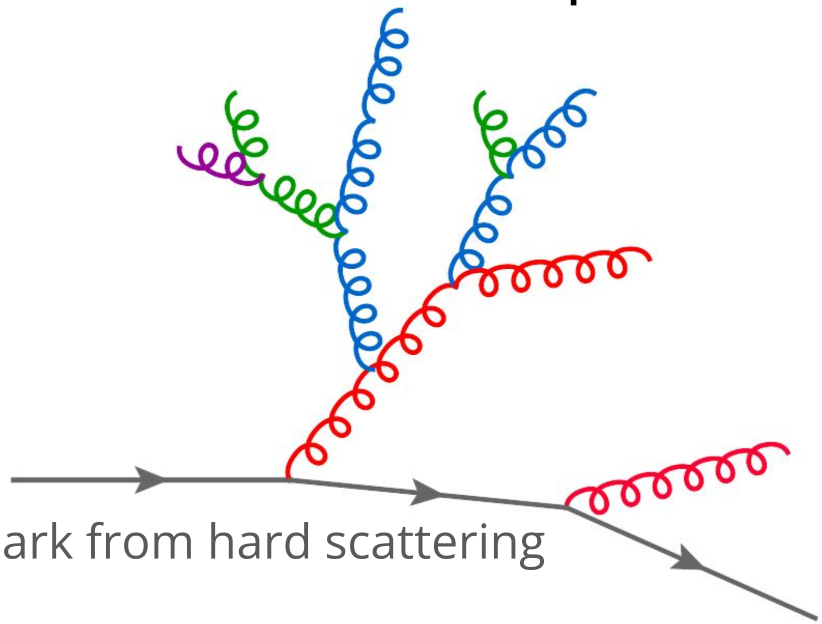
$$k_{\mathrm{T}} = p_{\mathrm{T}}^{\mathrm{softer}} \Delta R$$

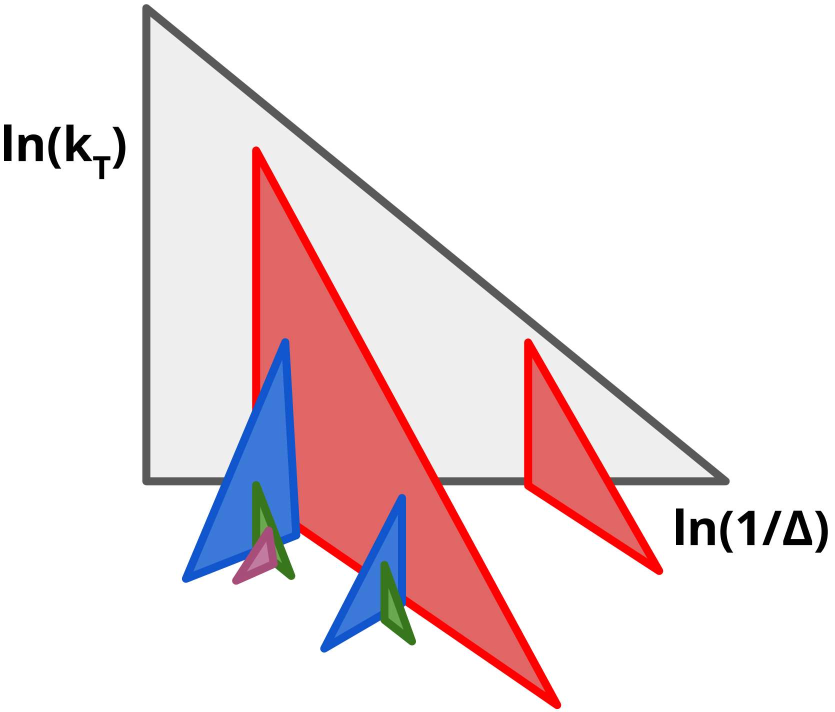
$$\Delta R = \sqrt{(y^{\mathrm{softer}} - y^{\mathrm{harder}})^2 + (\phi^{\mathrm{softer}} - \phi^{\mathrm{harder}})^2}$$





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

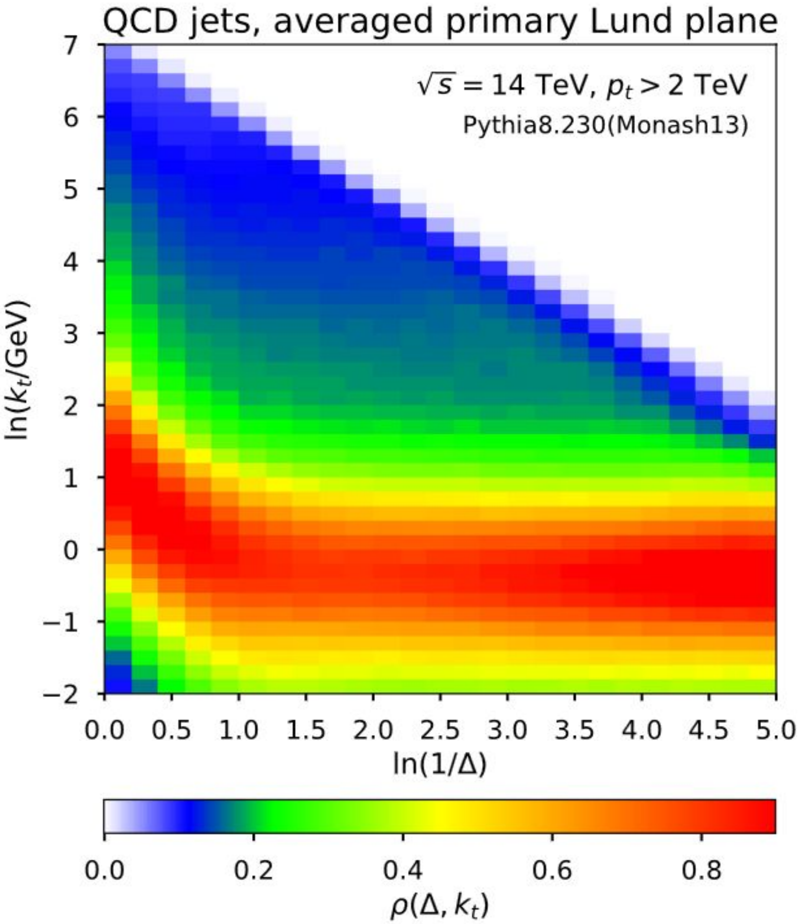
Define the *jet-averaged* number of emissions,
the primary Lund jet plane density

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

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

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

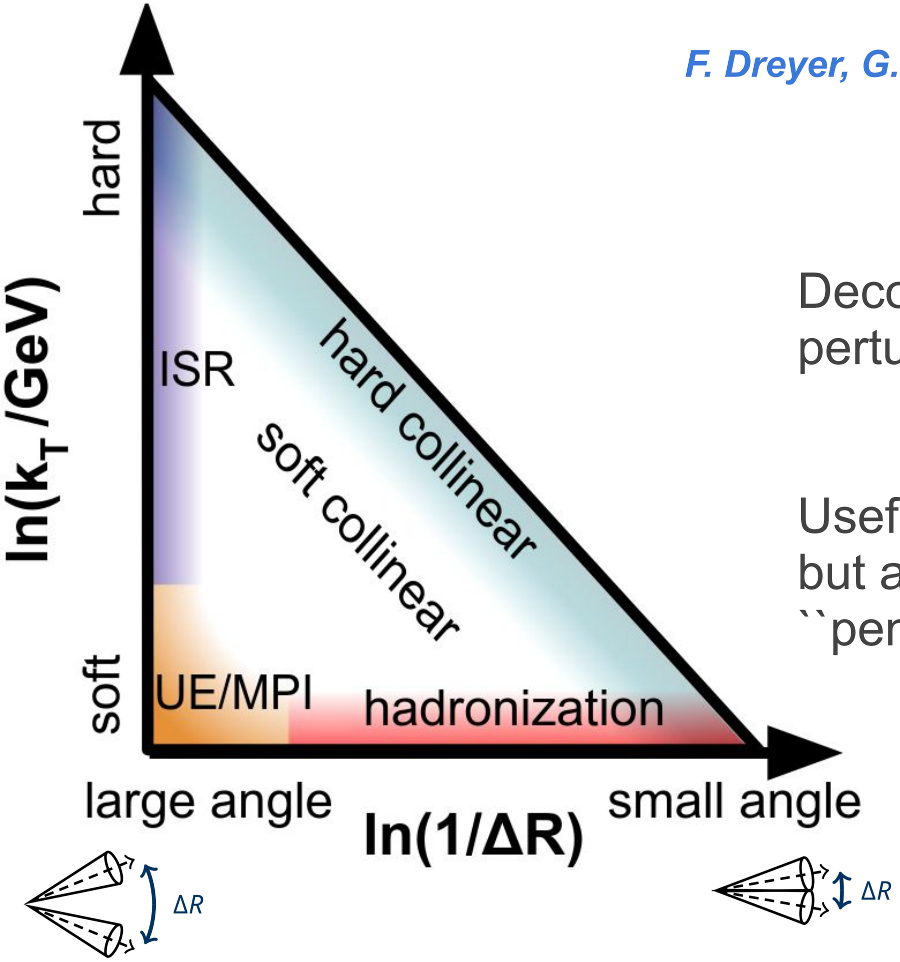
With $C_R = C_A = 3$ for g→gg or $C_F = 4/3$ for q→qg splittings



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

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

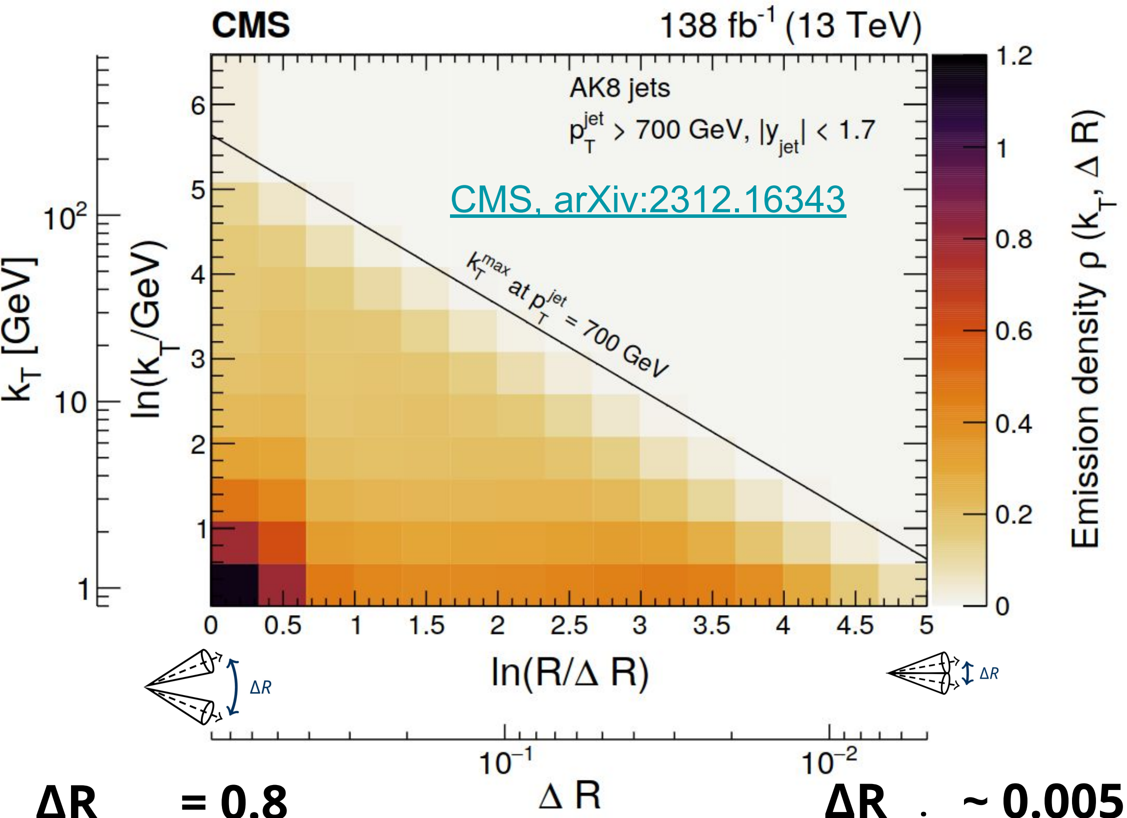
F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064



Decoupling of nonperturbative and perturbative contributions

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

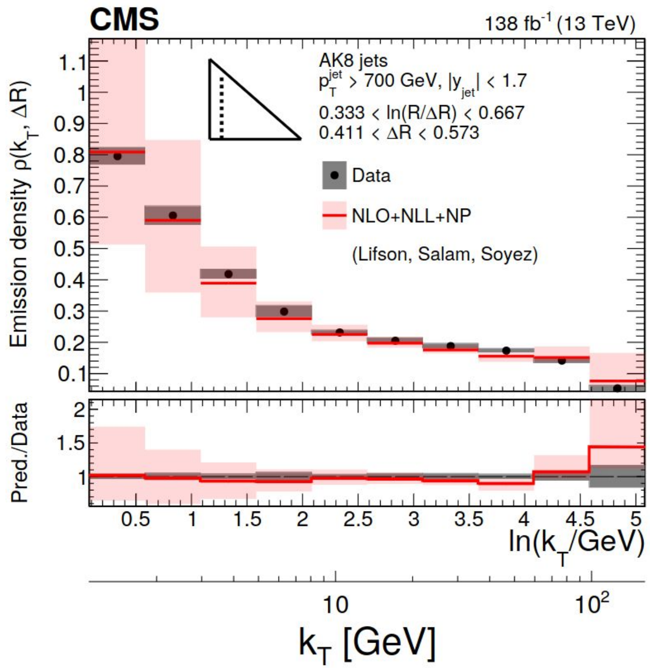
measured primary Lund jet plane densities



CMS, arXiv:2312.16343

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

Lifson, Salam, Soyez, arXiv:2007.06578



ΔR_{max} = 0.8

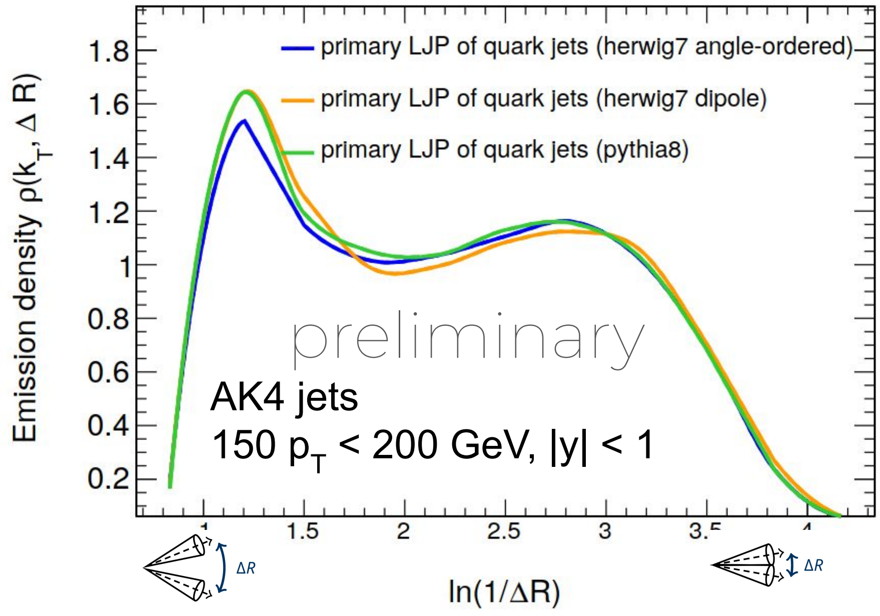
ΔR_{min} ~ 0.005

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

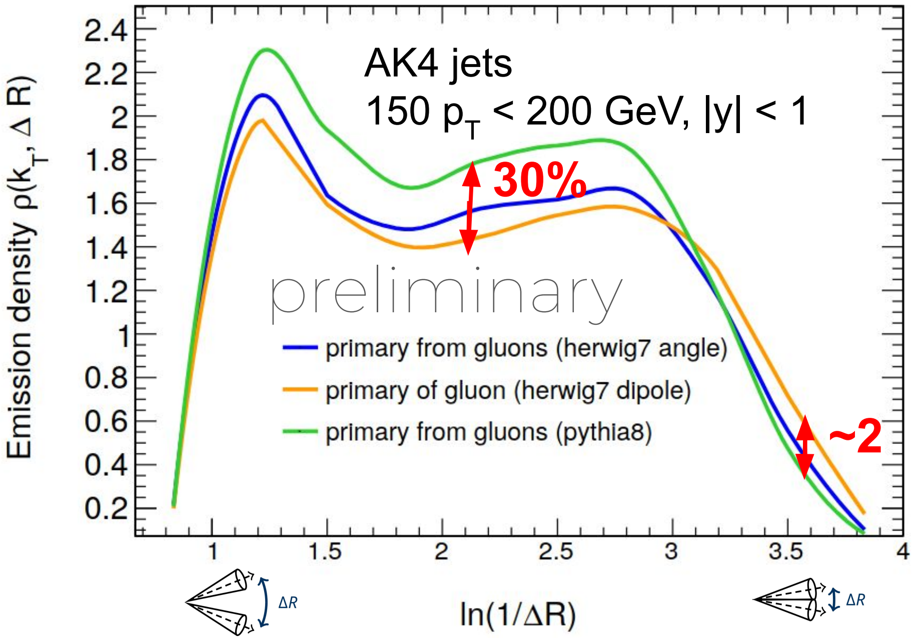
Quarks vs gluon primary LJPs in pp collisions

Same LJP slice at low k_T ~ 1–2 GeV

Quark jets (qq→qq)



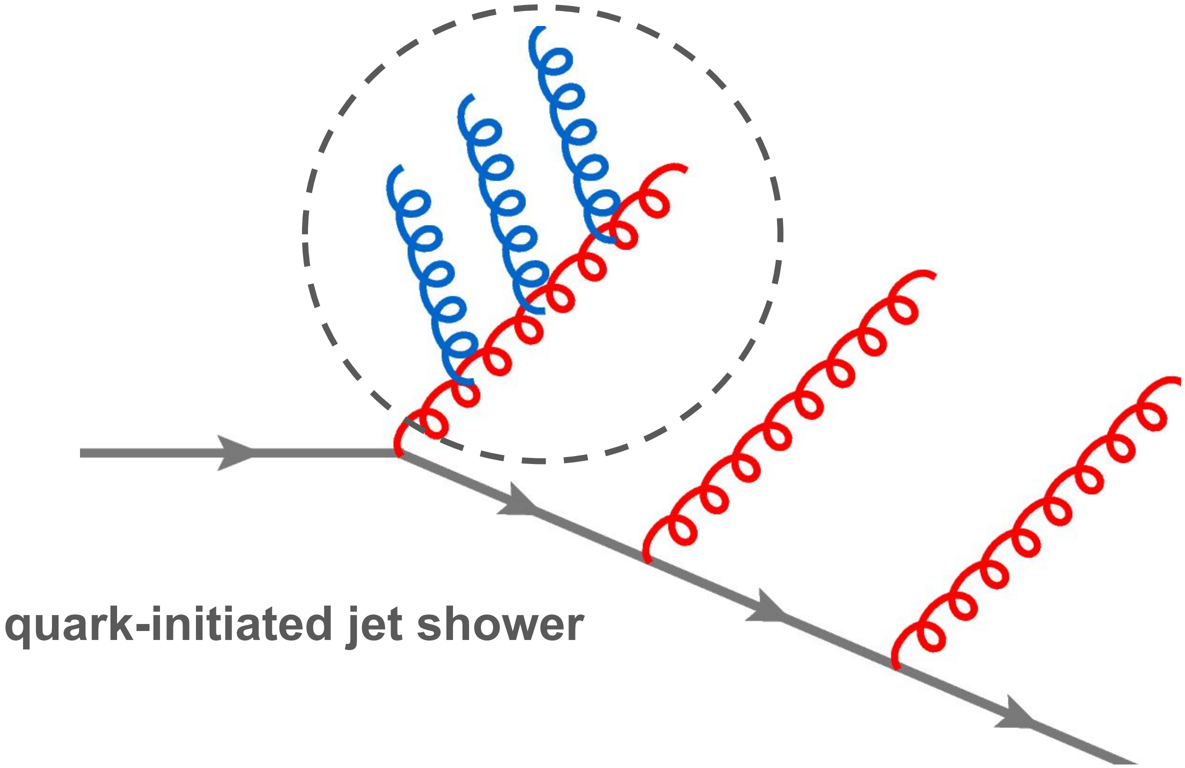
Gluon jets (gg→gg)

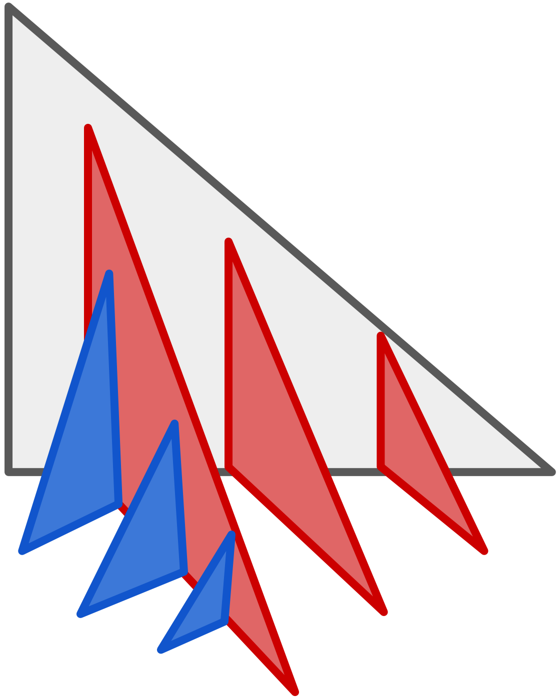


Spread of 1–5% (**LEP constraints**)

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

Secondary Lund planes for gluon radiation

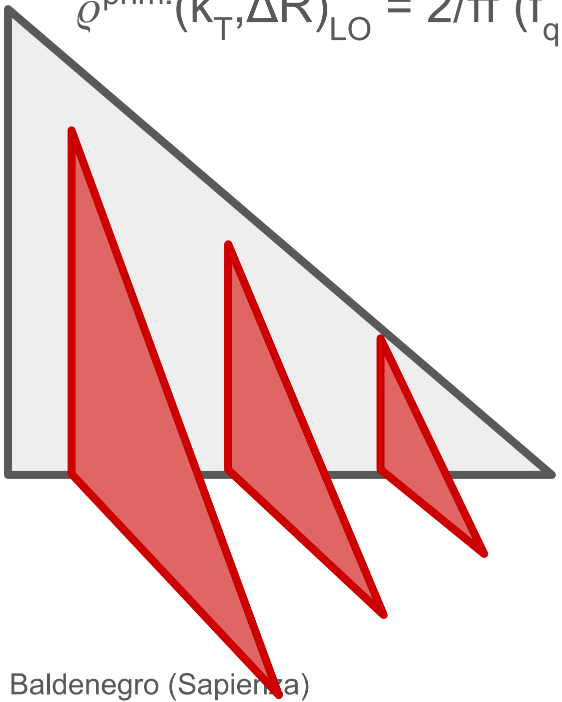




Primary Lund plane

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

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

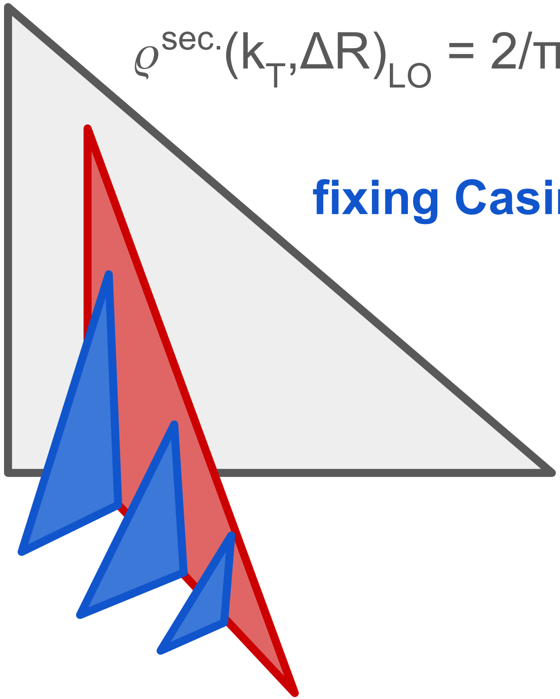


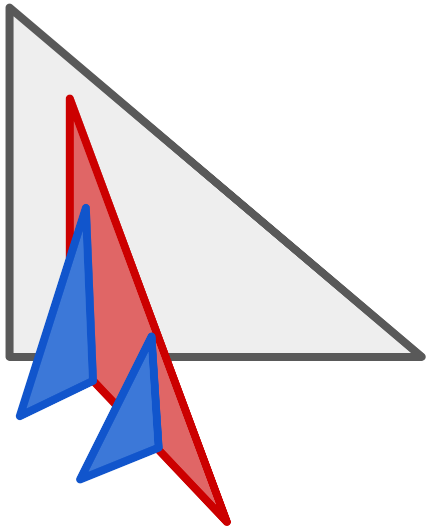
Secondary Lund jet plane

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

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

fixing Casimir factor!



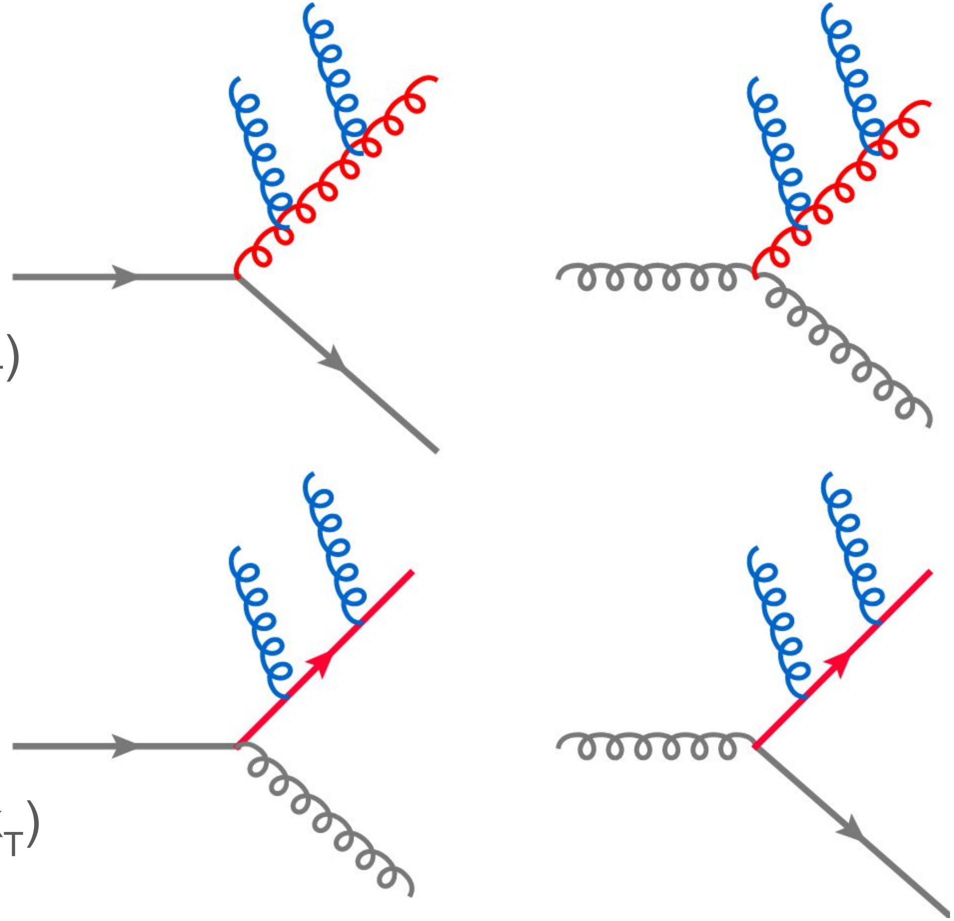


Gluon-dominated
secondary Lund planes

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

Quark-dominated
secondary Lund planes

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



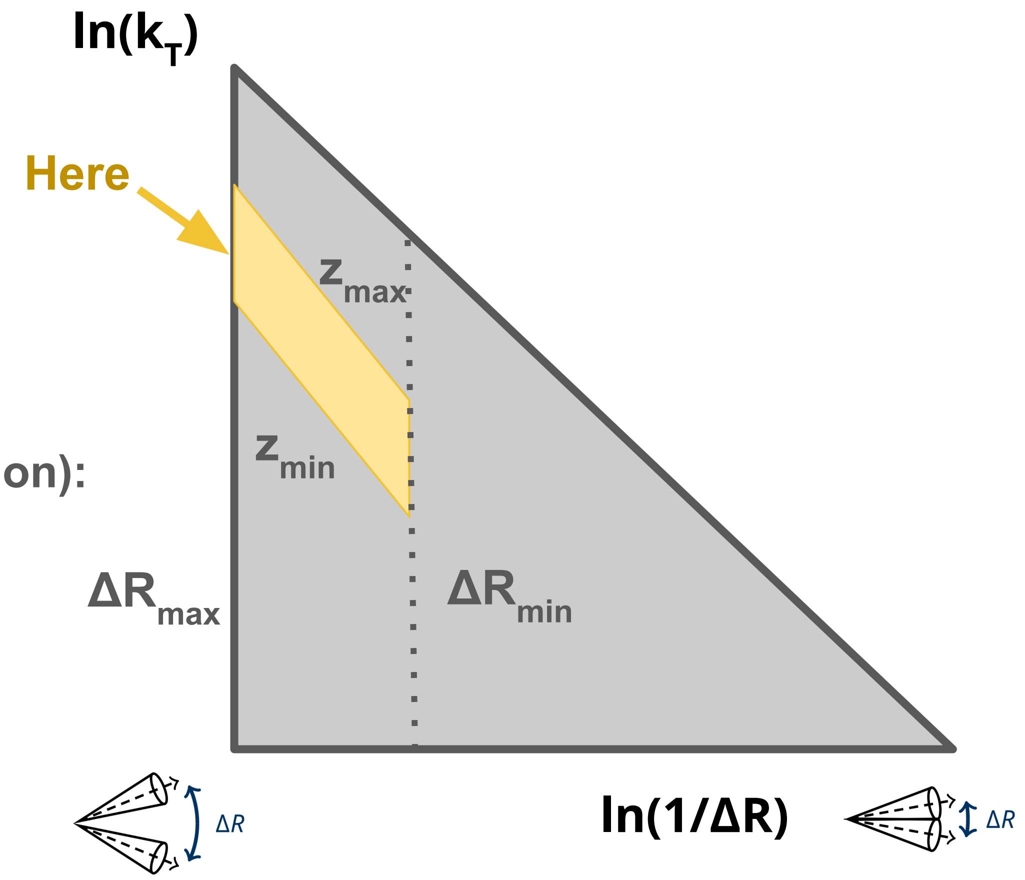
Which Lund primary emission?

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., $0.2 < z < 0.25$)

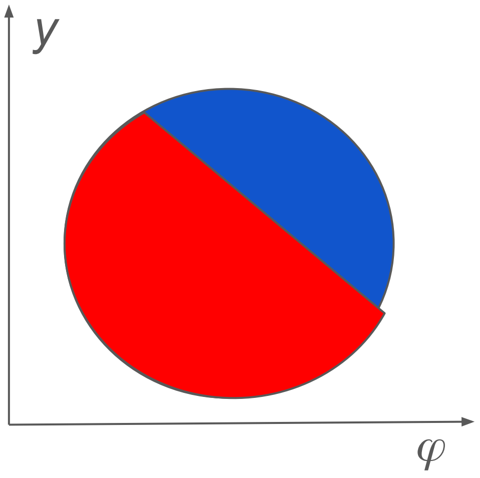
Phase-space region where parton flavor changes are negligible



At least three setups that work

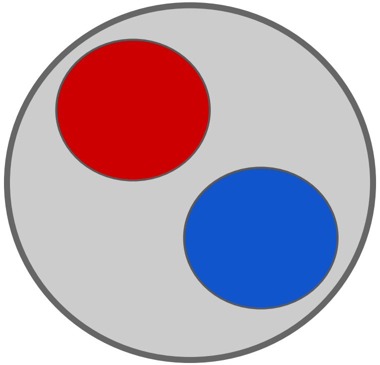
focus on this

1.SoftDrop-like (Cambridge/Achen tree)



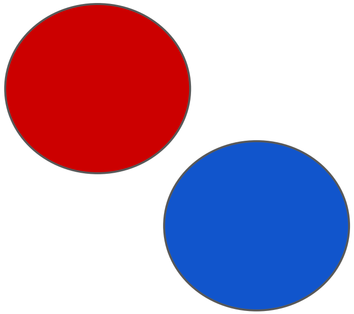
large R = 1.2 jet,
→find soft-drop emission with $R_g > 0.6$ & $0.2 < z_{cut} < 0.3$
(pick the subleading subjet)

2. Trimming (reclustering with smaller R)



large R = 1.2 jet
→recluster w/ small R = 0.4
(pick the subleading subjet)

3. anti-k_T dijet selection (or multijet)

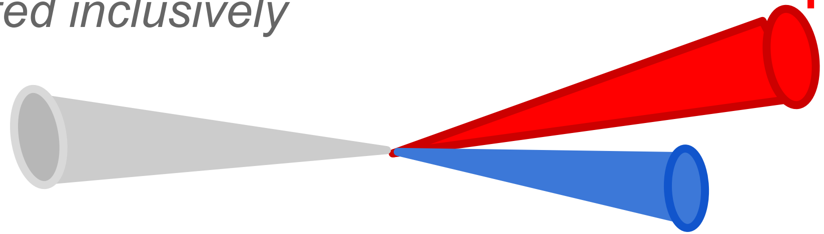


R = 0.4 jets, find all pairs of collinear jets with asymmetric p_T

anti-k_T R = 0.4 dijet selection

collinear topology + asymmetric p_T share

Other jets are treated inclusively



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

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

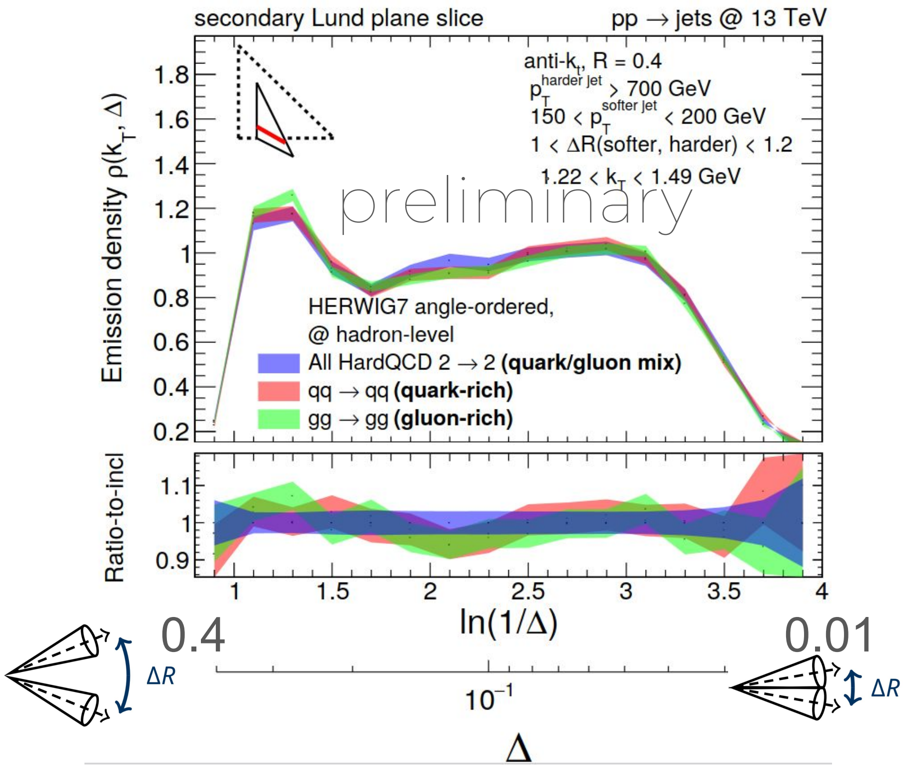
$150 < p_{T,softer} < 200$ GeV (enriched in gluon jets)

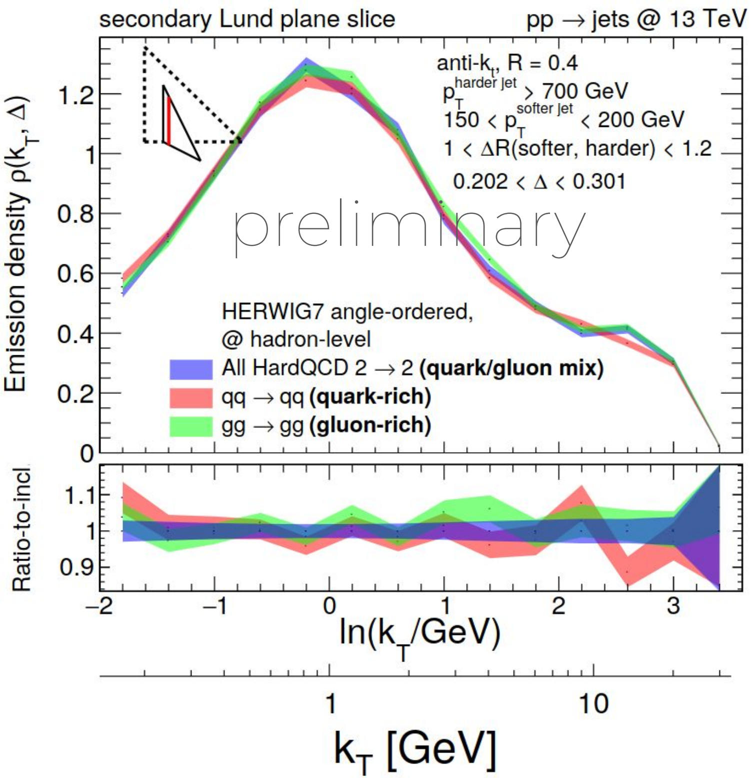
“inclusive” dijet selection (i.e., all jet pairs in the event contribute)

Unprescaled jet triggers $\mathcal{O}$(200k) ``high-purity” gluon jets in Run-2 or Run-3

``Rivet-friendly” selection, makes it easier for data reinterpretation

Process-independence, PDF-independence

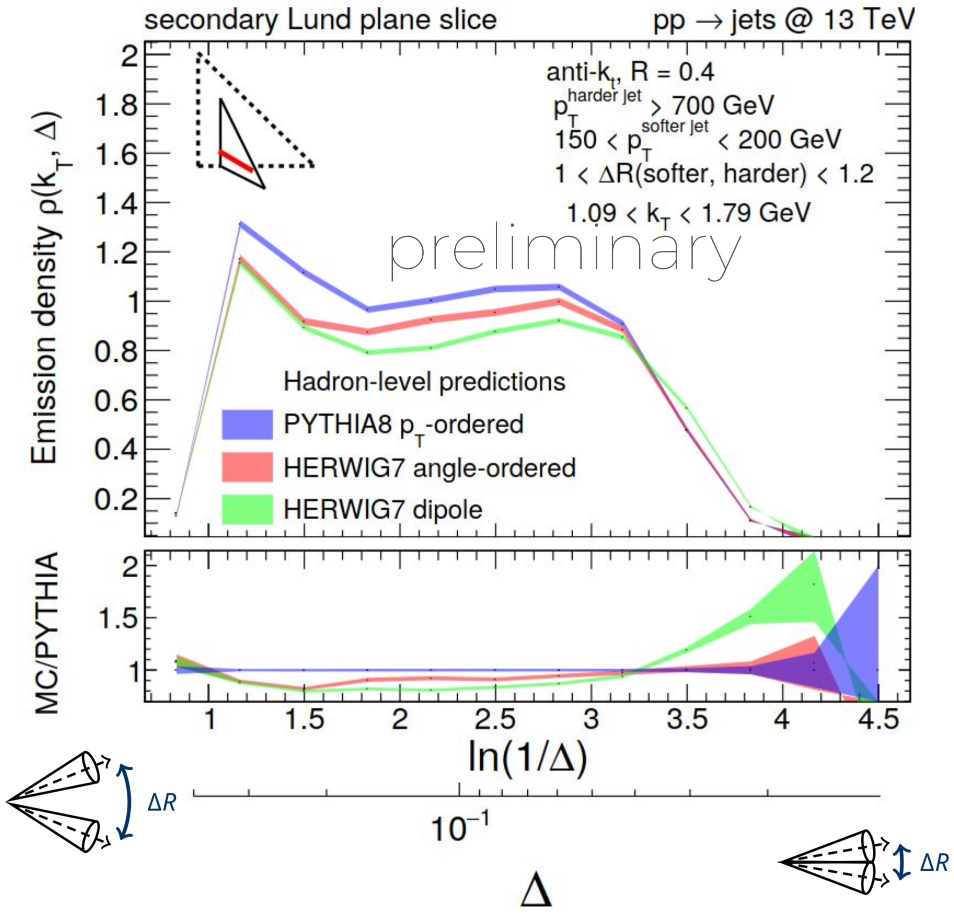


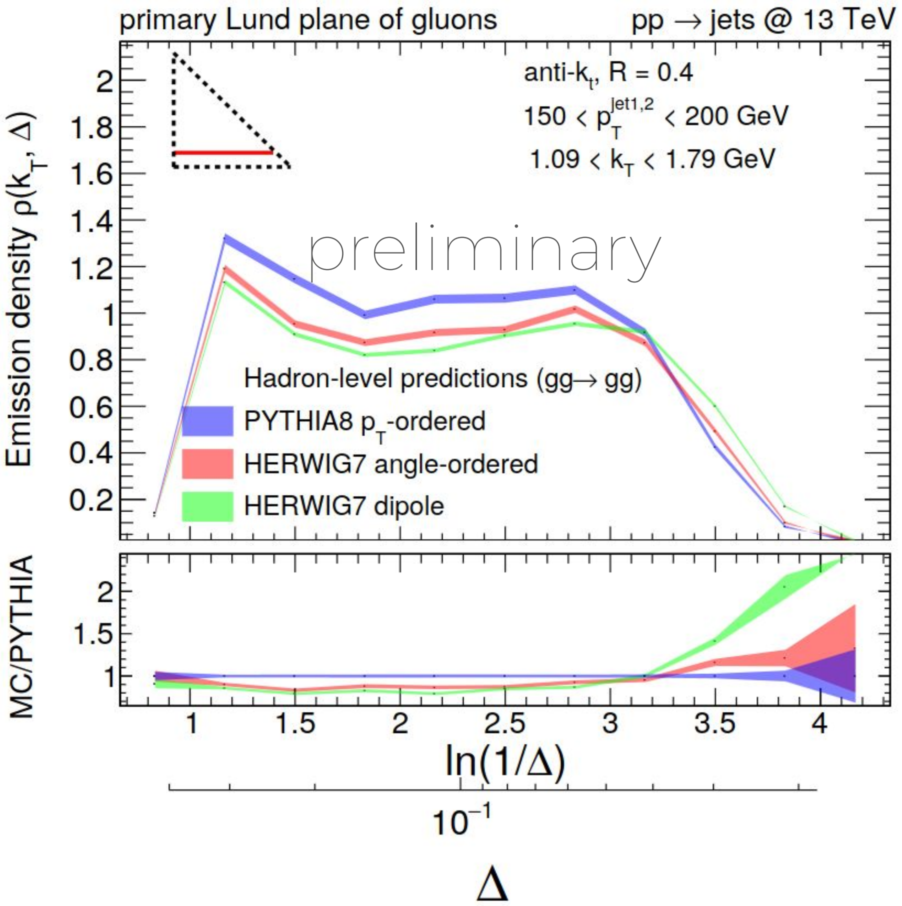


Same results regardless of parton flavor of the hard scattering!

(Observed also for PYTHIA8, HERWIG7 dipole shower)

Model constraining power vs hypothetical gluon primary LJP





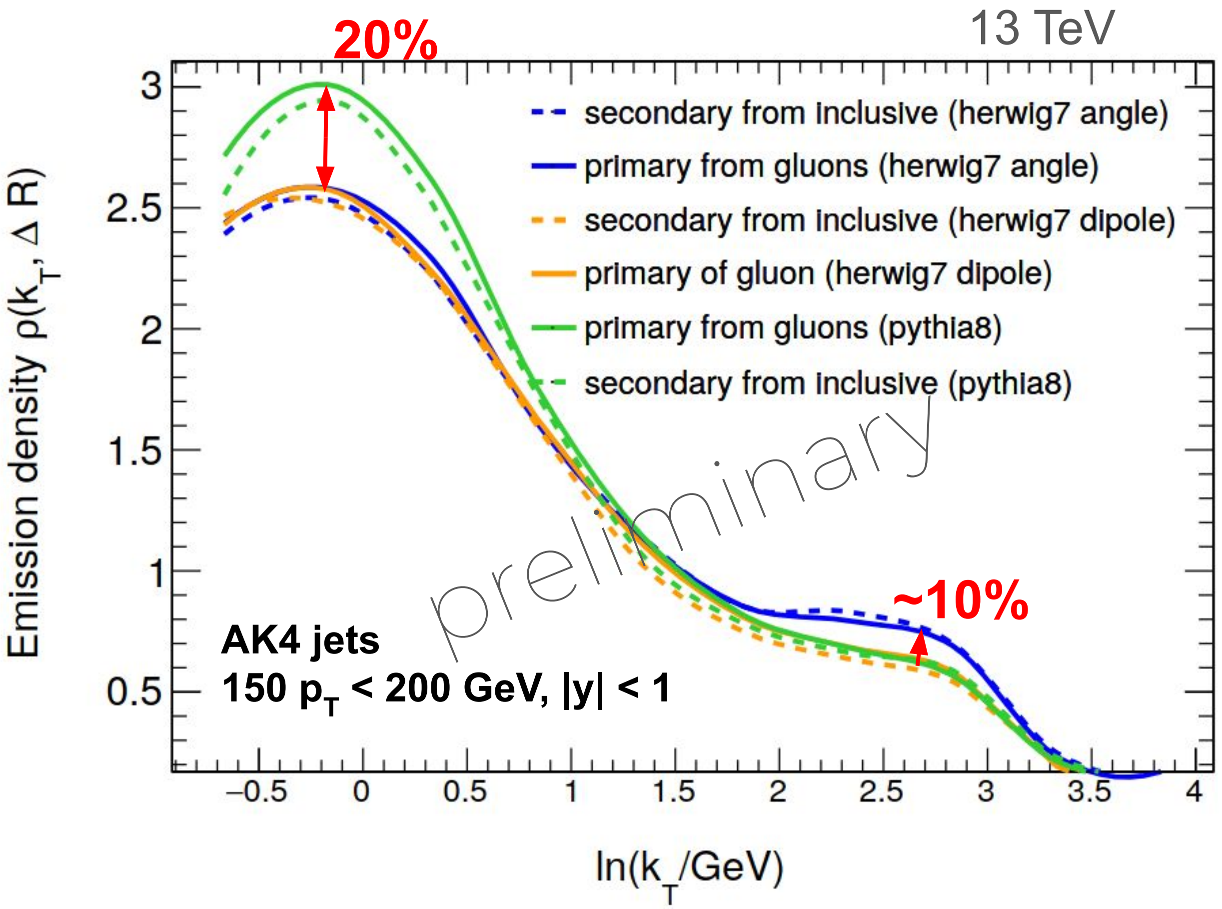
Summary

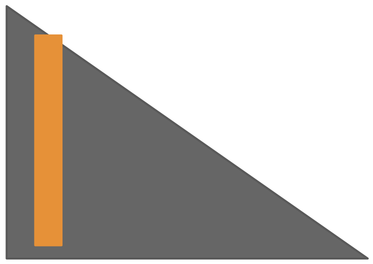
- Quark jet showers are strongly constrained at LEP;
  gluon jet showers much less so!

- Secondary Lund jet planes for high-purity gluon radiation at the LHC (resilient to quark/gluon jet composition)

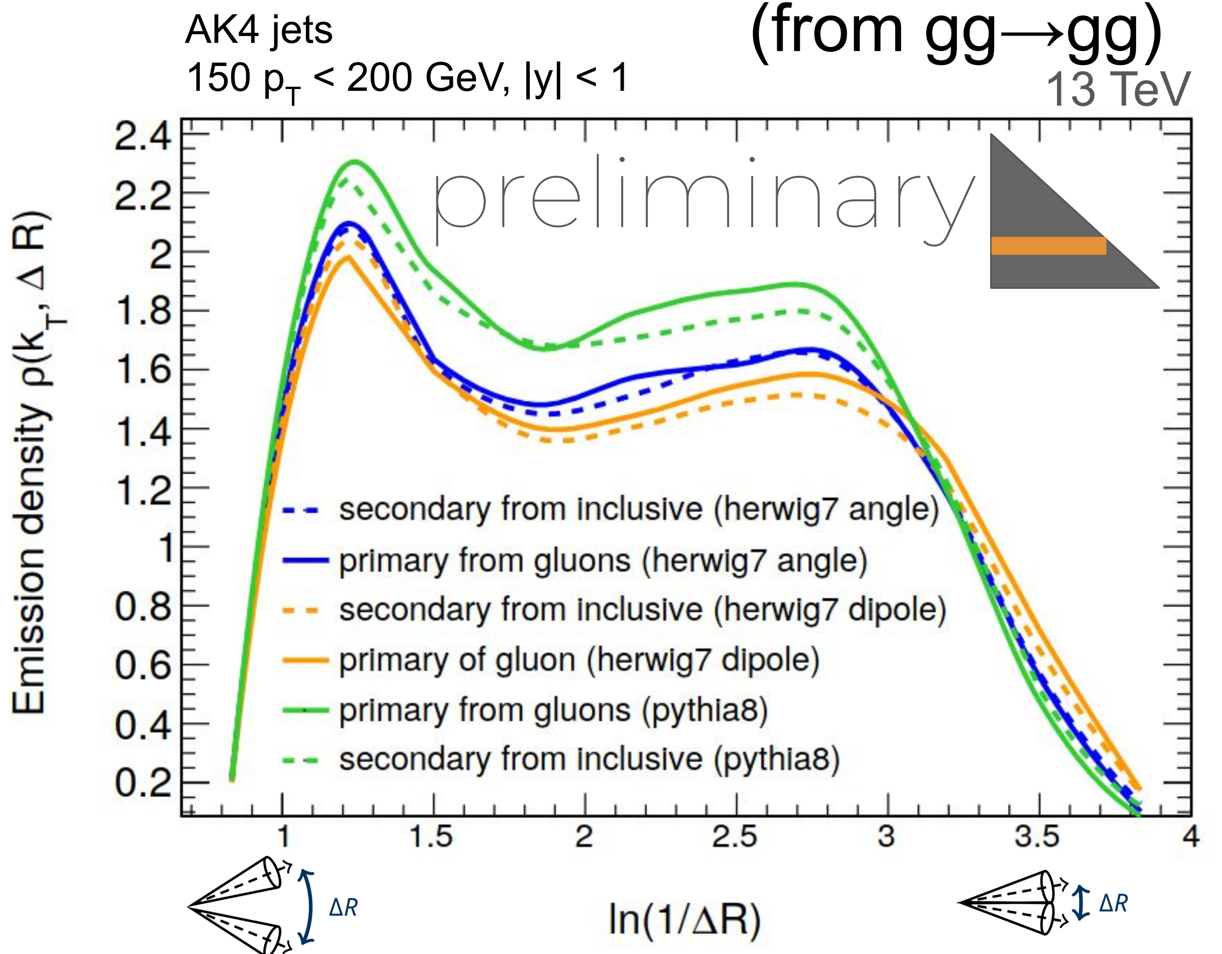
- Process-based enrichment, based on QCD infrared & collinear divergences backup

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





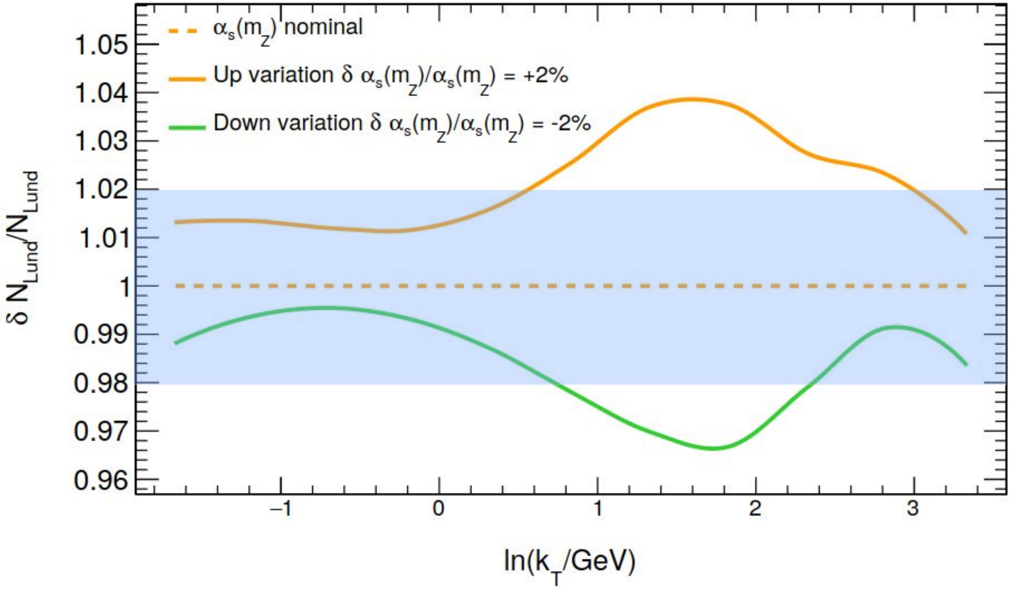
Similar model discrimination with gluon primary LJPs (from gg→gg)



Precision physics

Sensitivity to $\alpha_S^{MC}(m_Z)$ variations for intrajet multiplicity observable (more in backup)

Other jet substructure observables can be considered (e.g., groomed jet mass, energy-energy correlators)



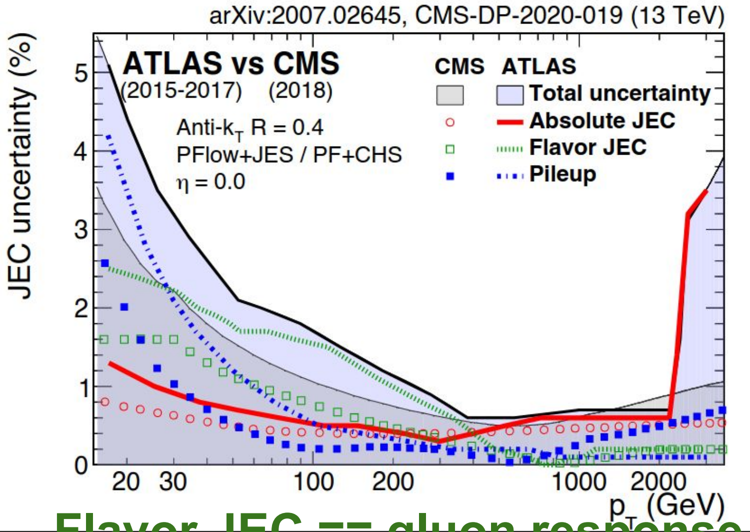
Strong resilience to PDF variations & quark/gluon fraction, potential path for α_S extraction using FSR at the LHC

Why gluon showers?

- Understanding of gluon radiation in detail.

- Gluon jet detector response uncertainties

- Quark vs gluon taggers (validation sample, tagging)



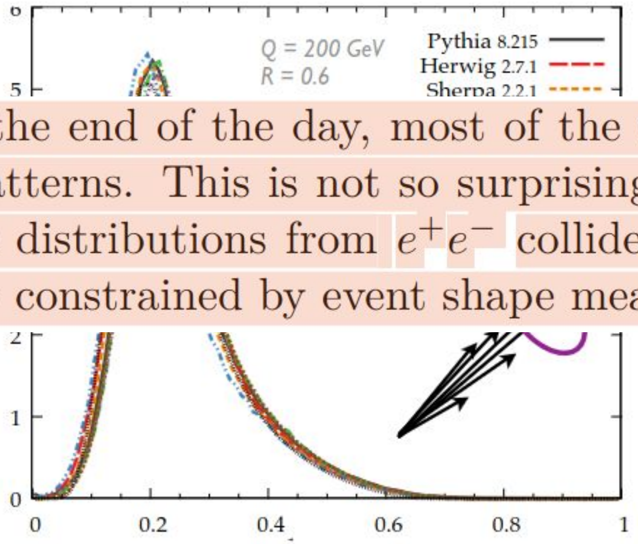
Flavor JEC == gluon response

- “Vacuum” parton showers typically used as baseline for gluon-jet quenching predictions for PbPb collisions

Les Houches 2015 substructure studies

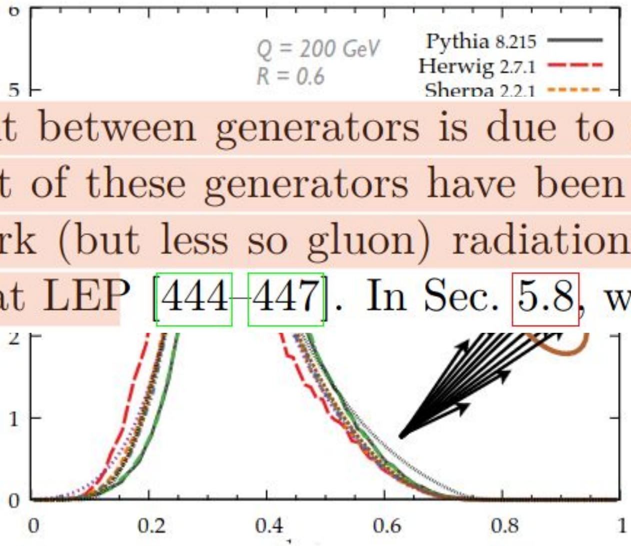
$e^+e^- \rightarrow$ quarks ($C_F = 4/3$) vs. $e^+e^- \rightarrow$ gluons ($C_A = 3$)

At the end of the day, most of the disagreement between generators is due to gluon radiation patterns. This is not so surprising, since most of these generators have been tuned to reproduce distributions from e^+e^- colliders, and quark (but less so gluon) radiation patterns are highly constrained by event shape measurements at LEP [444–447]. In Sec. 5.8, we suggest



$1/p_{T,\,jet} \sum p_{T,i}\, \Delta R_{i,jet}$

small spread

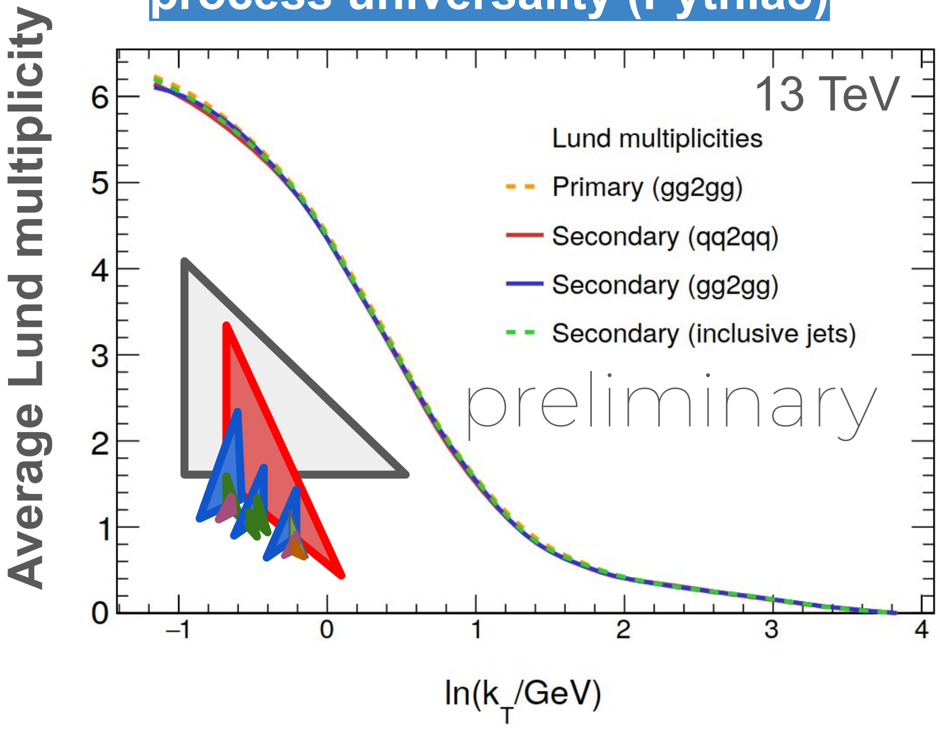


$1/p_{T,\,jet} \sum p_{T,i}\, \Delta R_{i,jet}$

large spread

average Lund multiplicity of gluons

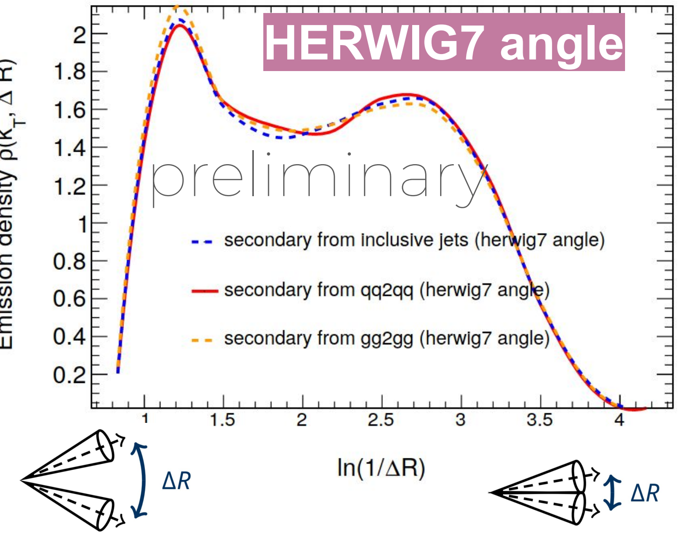
process universality (Pythia8)

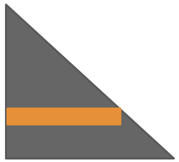


Robust to to quark/gluon fraction, (independent of hard-process&PDFs)

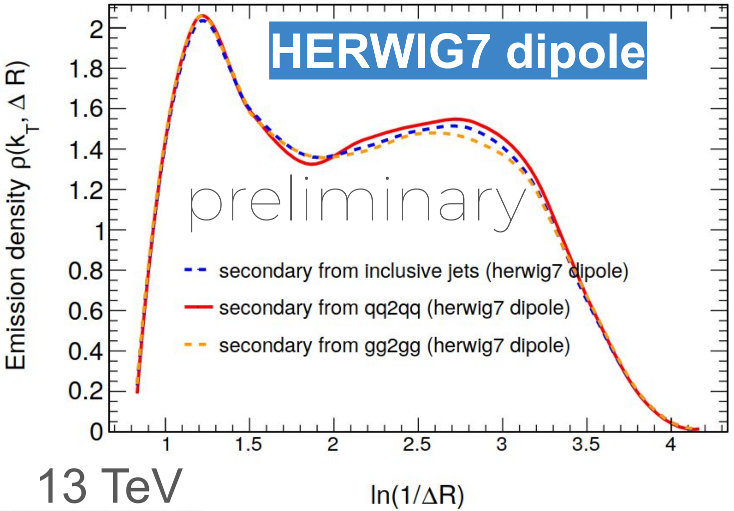
compatible with Lund multiplicity from **Born-level gluons**!

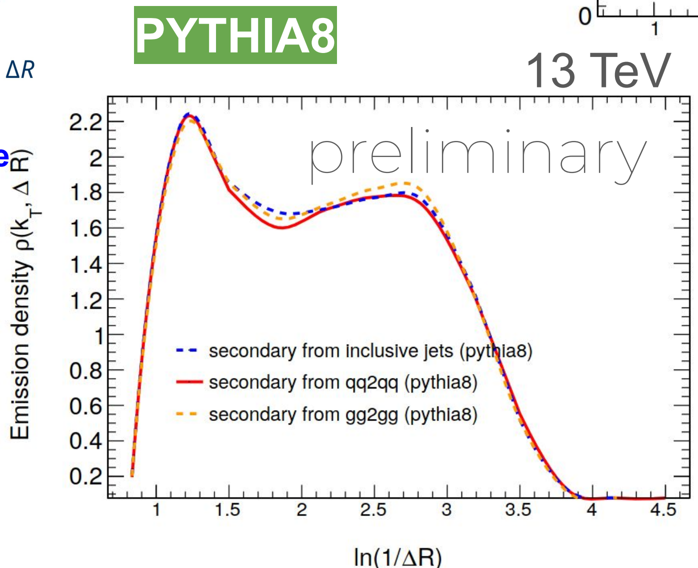
Process- & PDF-independent observable





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

Average Lund multiplicity

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

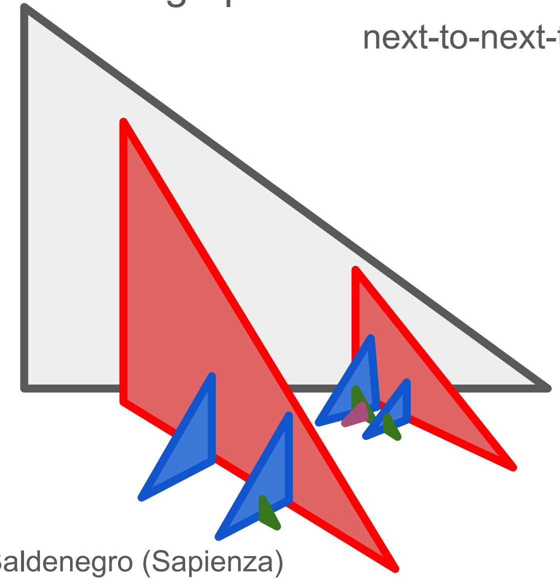
1. Undo the ***full*** Lund tree

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

3. Average over *all* jets in the sample

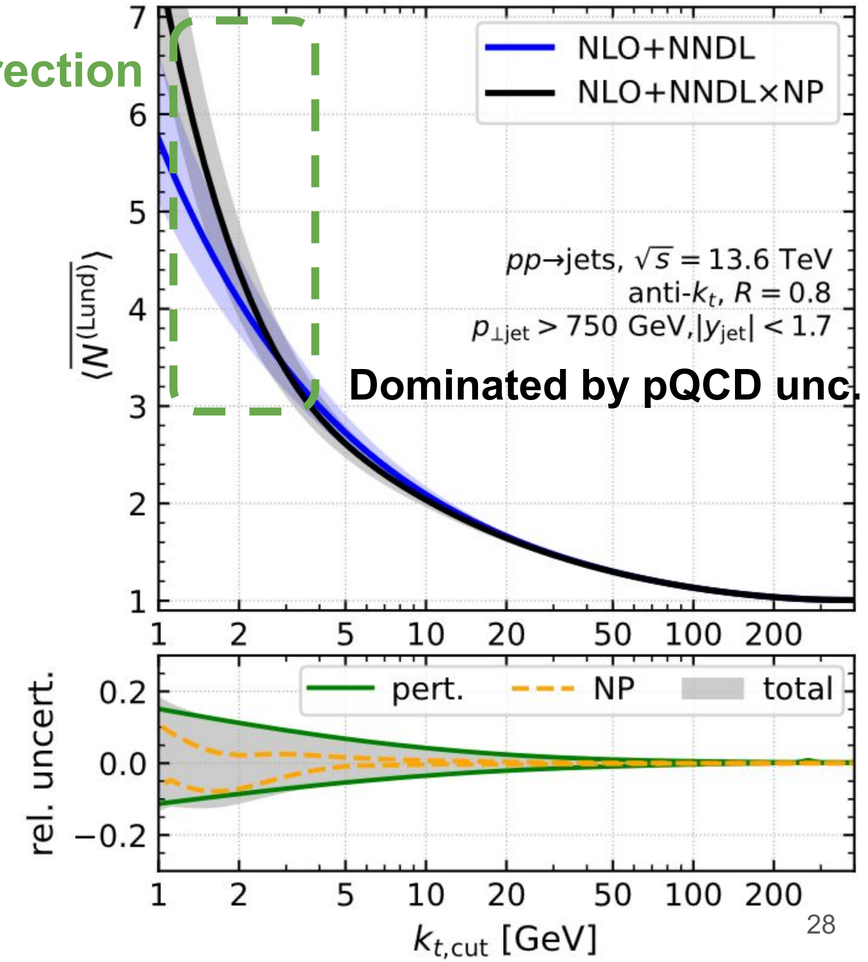
Amenable to high precision calculations (**NLO+NNDL**)

next-to-next-to-double logarithmic



5% NP correction

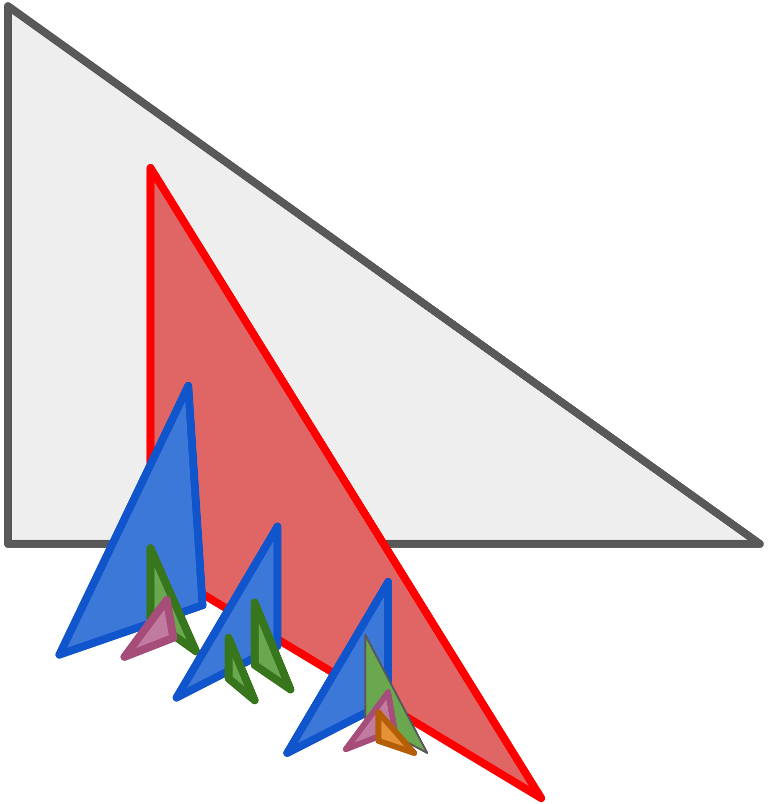
Dominated by pQCD unc.



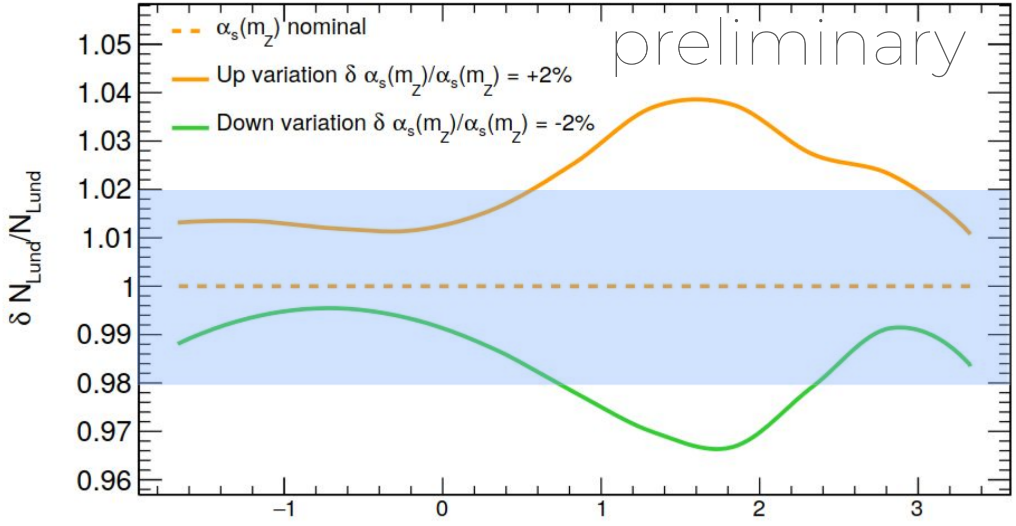
Average Lund multiplicity of the secondary Lund plane

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

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



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)

Ballpark expected experimental unc. of ~2%

Discussing with theorists about calculability (or other observables)

+- 2% shifts on $\alpha_s(m_Z)$ → O(3-4%) changes on Lund multiplicity for gluons

[nonlinear scaling with $\alpha_s(m_Z)$ due to cumulative # of g→gg splittings]

From Les Houches 2015

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

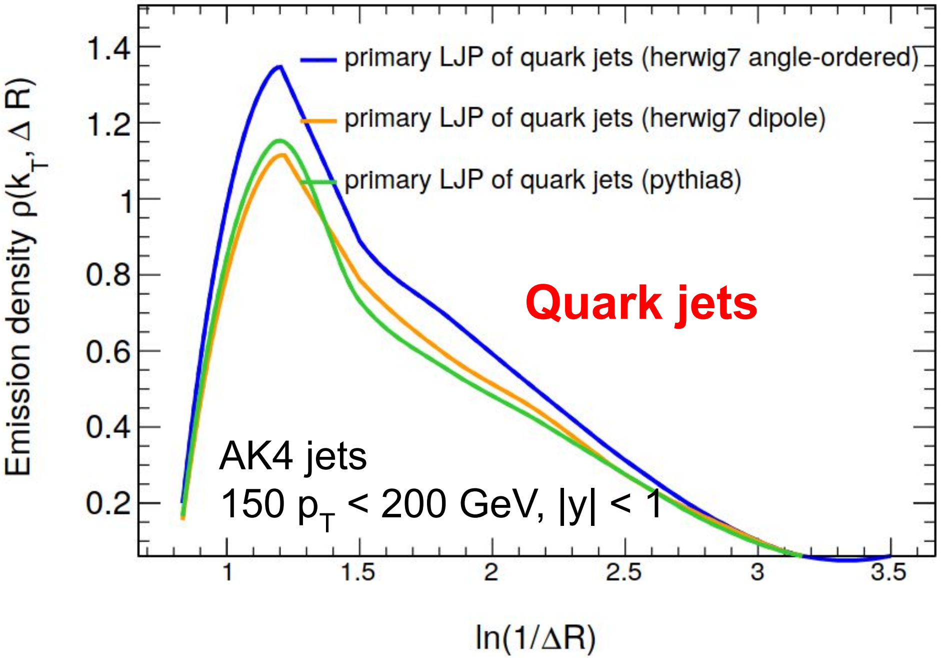
From lunch/dinner discussions

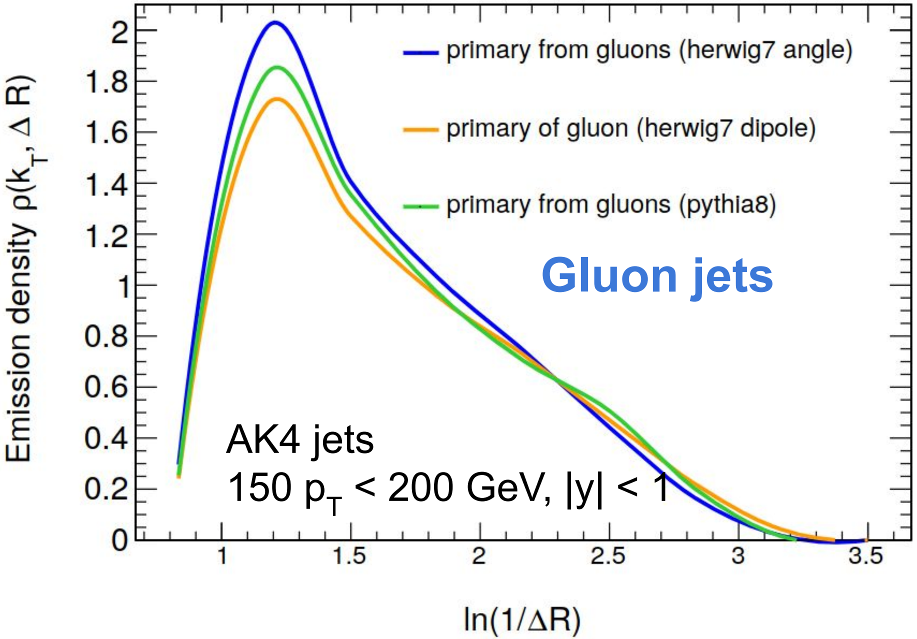
Ill-Defined ↓ Well-Defined	What people sometimes think we mean ↑ What we mean	
Quark as noun		A quark parton
		A Born-level quark parton
		The initiating quark parton in a final state shower
		An eikonal line with baryon number 1/3 and carrying triplet color charge
		A quark operator appearing in a hard 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

“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



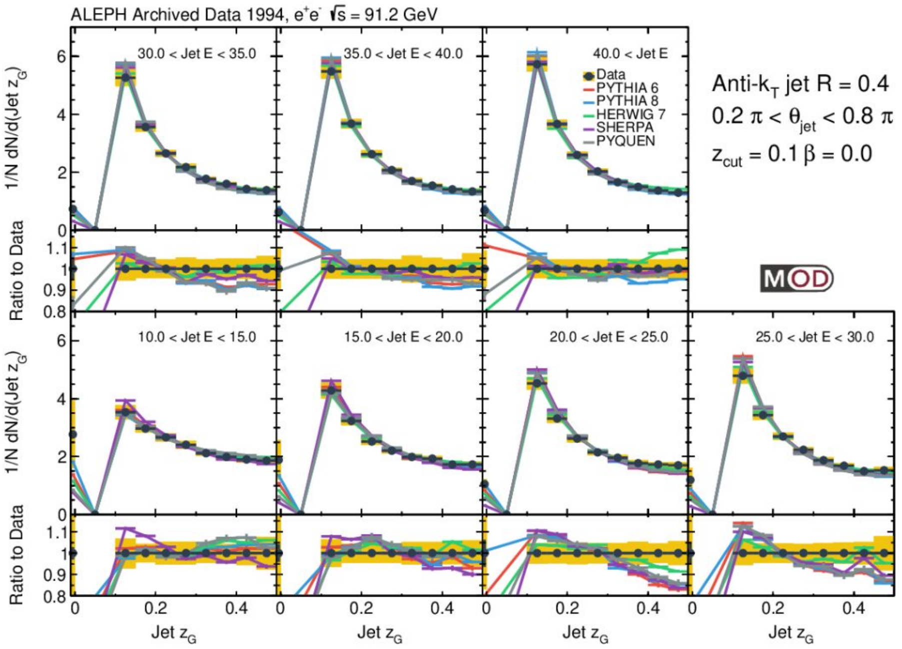


Herwig7 dipole usually closer to Pythia8 in the perturbative region

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).

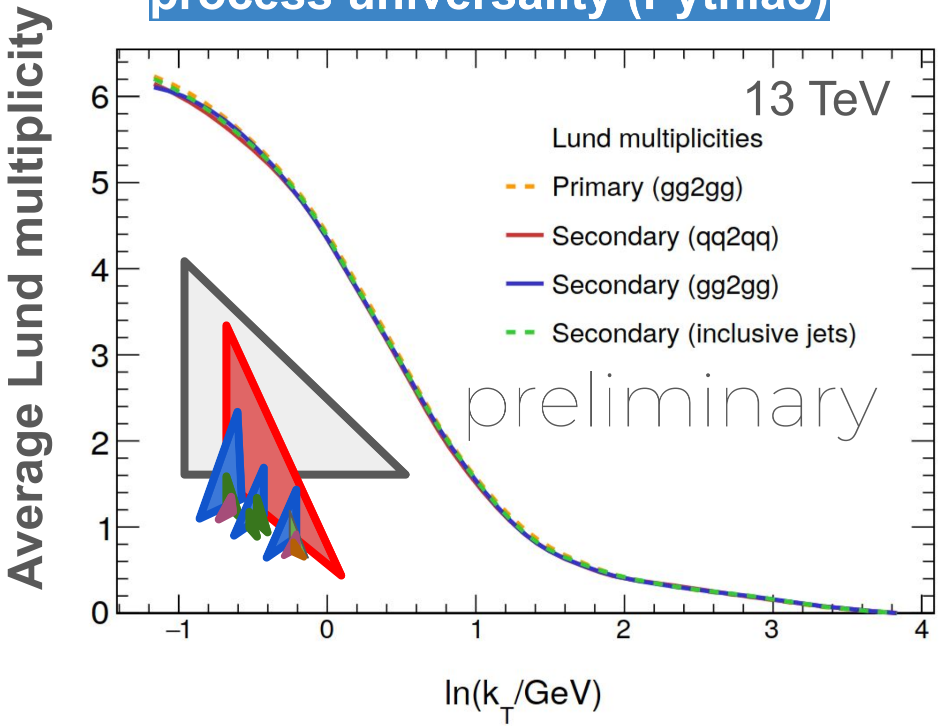


LHC data valuable to clarify mismodeling (dijet, Z+jet, UPC jets…) for high-p_T quark jets

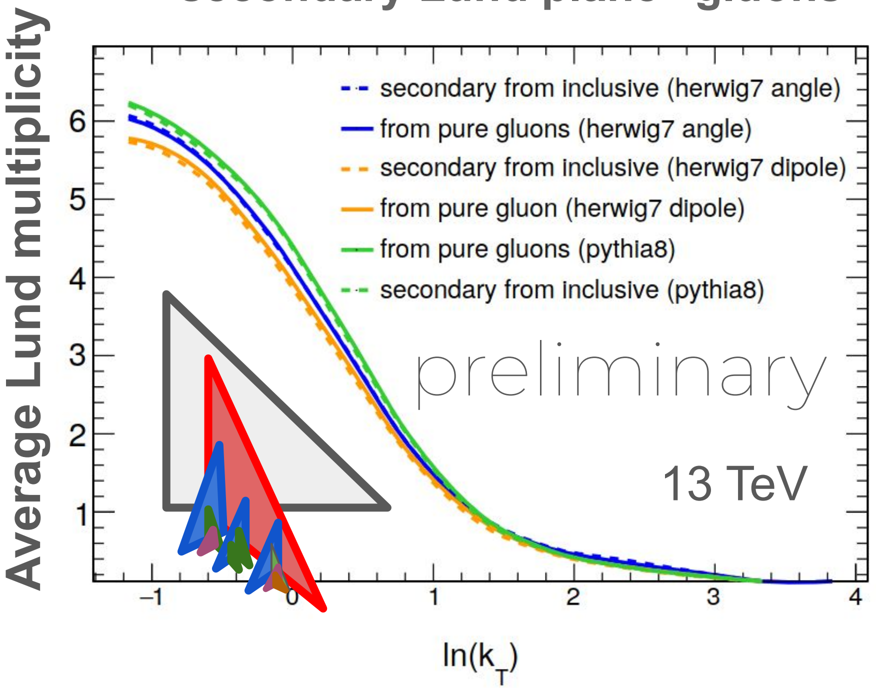
Yi Chen et al
arxiv.org/abs/2111.09914

average Lund multiplicity of gluons

process universality (Pythia8)



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

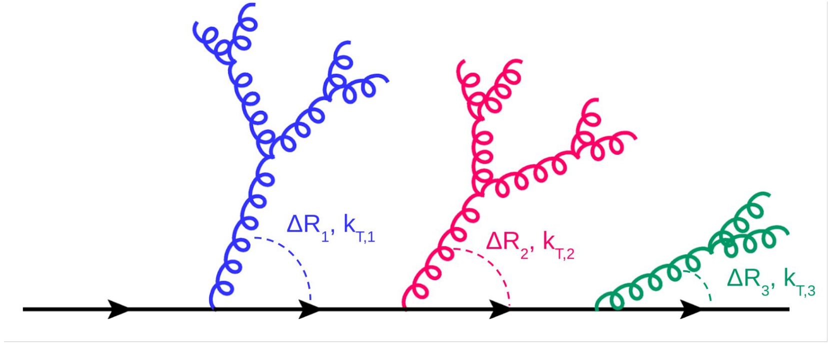


Robust to to q/g fraction & PDFs uncertainties

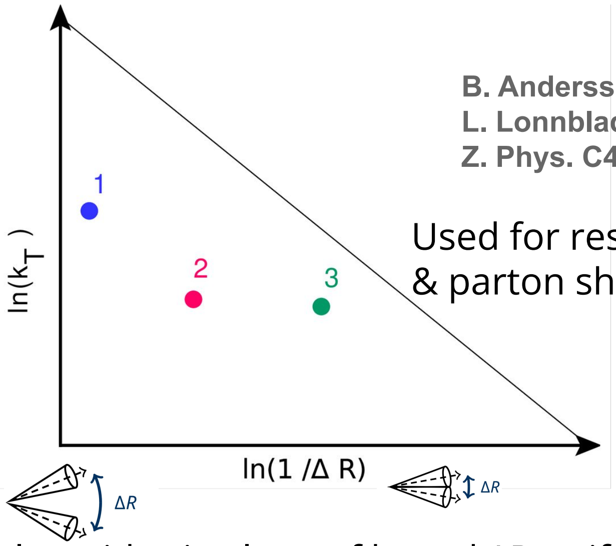
Solid lines: gg→gg primary
Dashed lines: incl. jets secondary

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

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

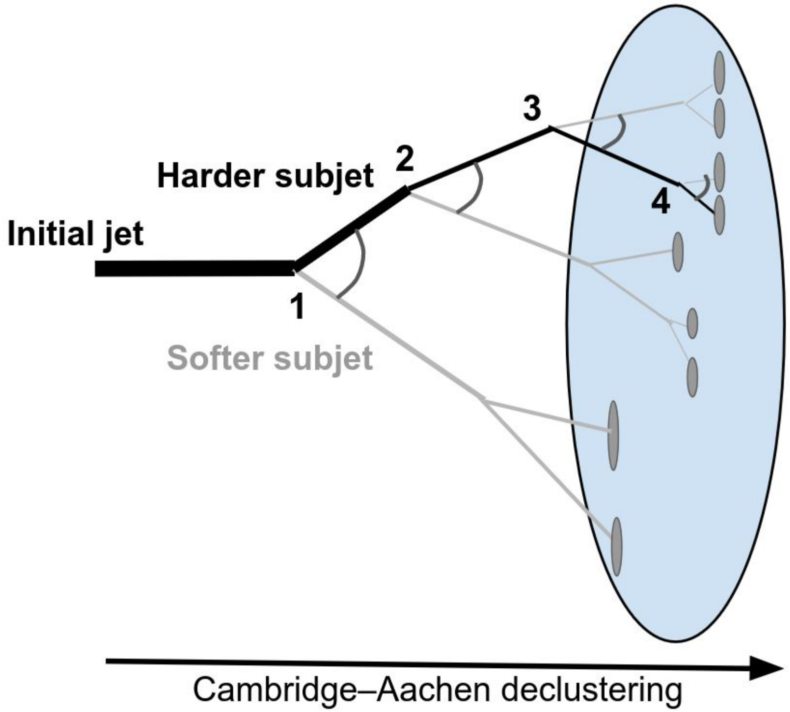
Used for resummation & parton showers

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

$$\mathcal{P} \propto \alpha_s \frac{dk_T}{k_T}\frac{d\Delta R}{\Delta R} = \alpha_s d\ln(k_T) d\ln(\Delta R)$$ ← **approximate self-similarity of QCD**

Promotion to a practical tool: the primary Lund jet plane

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



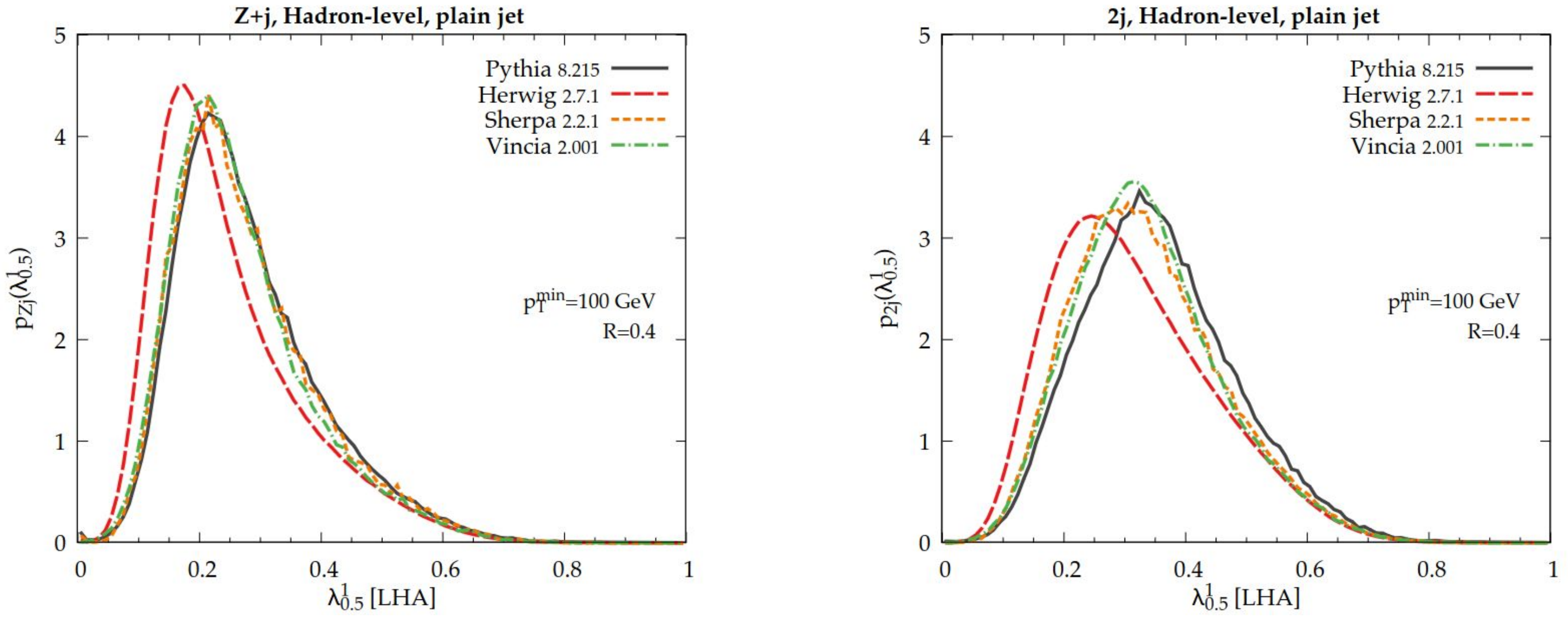
1. Recluster jet with Cambridge/Aachen algorithm (pairwise clustering by proximity in rapidity-azimuth)
2. Follow Cambridge/Aachen clustering history in reverse, **along the <u>hardest</u> branch (hence "primary")**
3. k_T and ΔR coordinates registered at each step

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

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

Differences carry over to the LHC (Z+jet vs dijet)

Quark-like (~70%) **Gluon-like (~70%)**

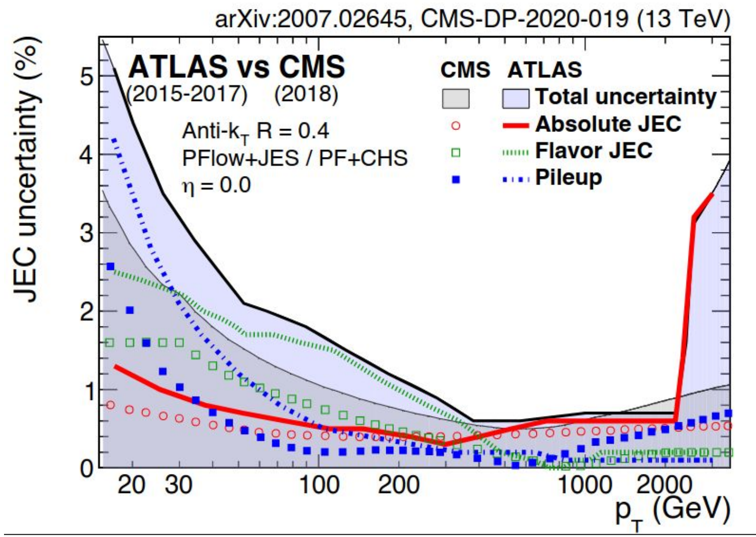


Motivated the SMP-20-011 measurement

Other applications within CMS

-Another handle to test quark vs gluon taggers

-Detector-level data/MC differences relevant for jet calibration (e.g., HCAL response, tracking, baryon fraction cf ATLAS findings)



Is it really that interesting?

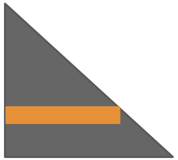
In soft&collinear limit, only difference between quarks and gluons due to color factors

$$\mathcal{P} \propto C_i \alpha_\mathrm{s} \frac{\mathrm{d}z}{z} \frac{\mathrm{d}\Delta}{\Delta}$$

$C_i = C_A$ *or* C_F

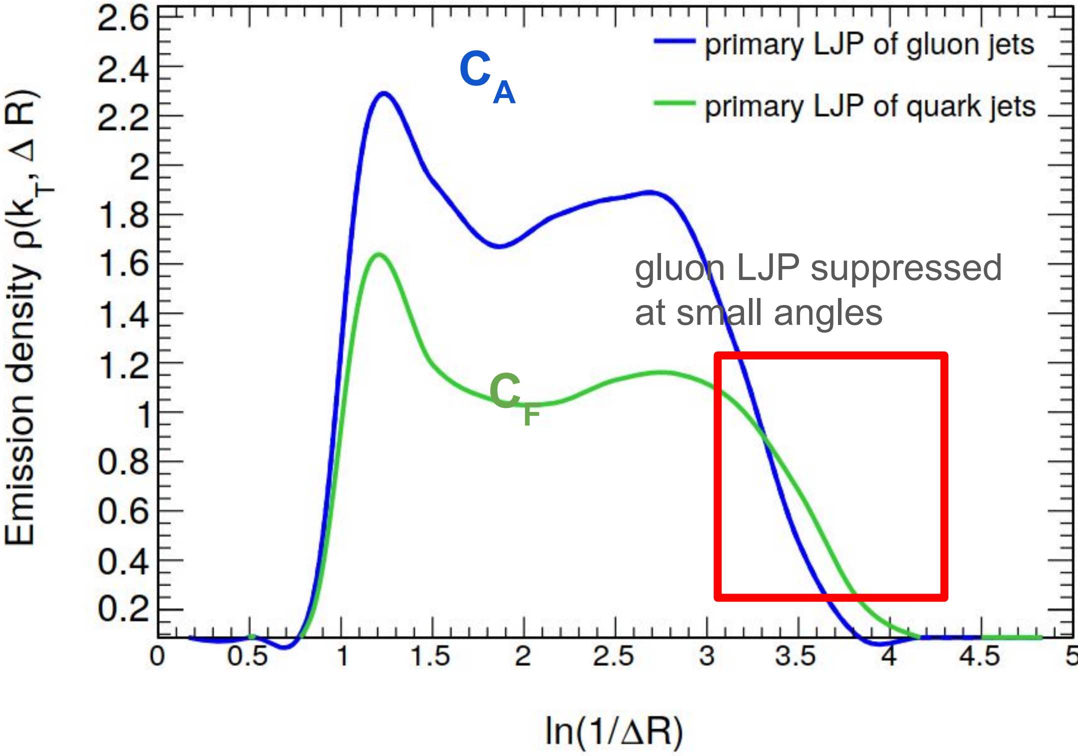
The ***interesting*** differences between quark and gluon fragmentation comes from corrections beyond naïve Casimir scaling (e.g., spin correlations, polarization effects, color reconnections, g→qqbar & g→ggg, …, NLO corrections to splitting functions, …)

Quarks vs gluon Lund planes



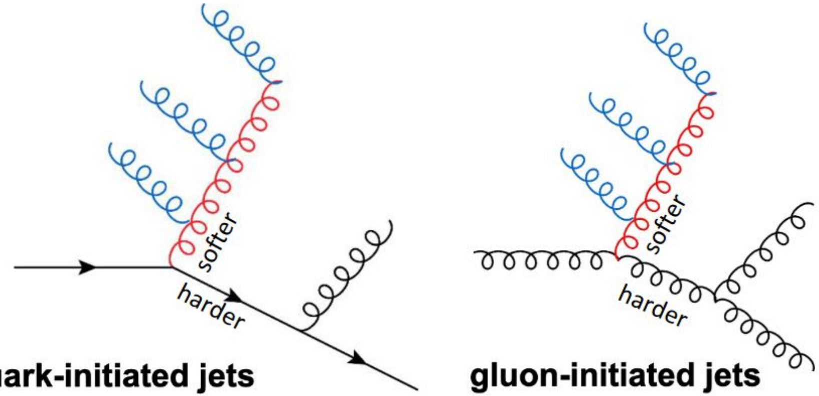
Not ***just*** C_A/C_F scaling! Leading partor momentum loss in the Lund tree histoı soft&collinear divergences, color reconnection effects, …

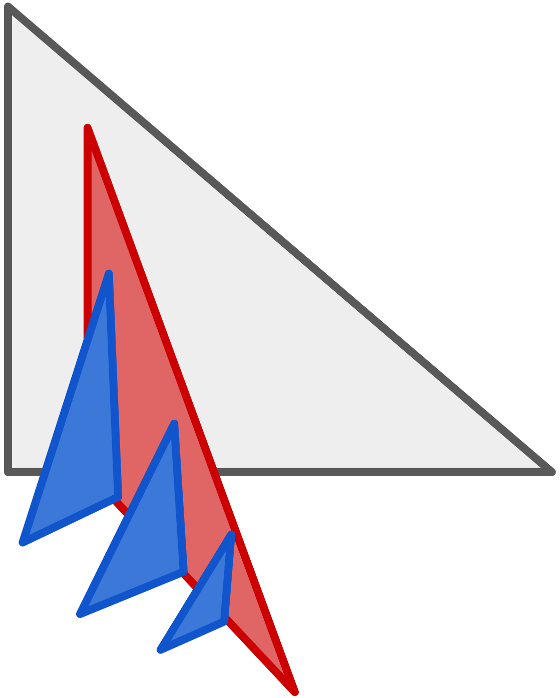
Gluon LJP is suppressed at small angles wrt quark LJP



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

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

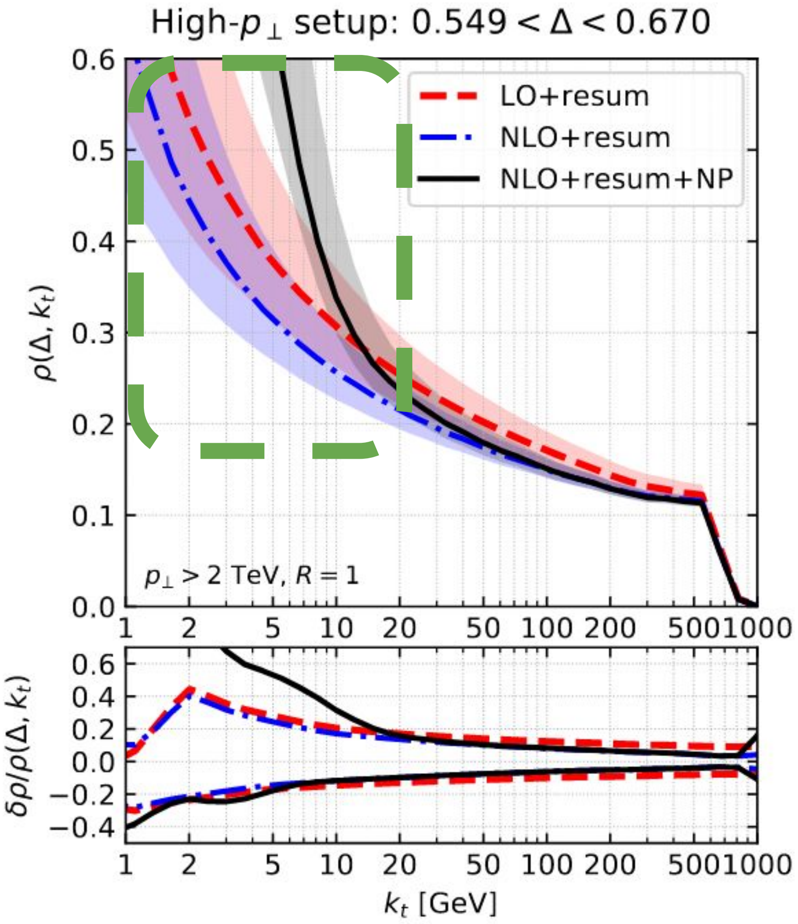




exploit infrared & collinear divergences

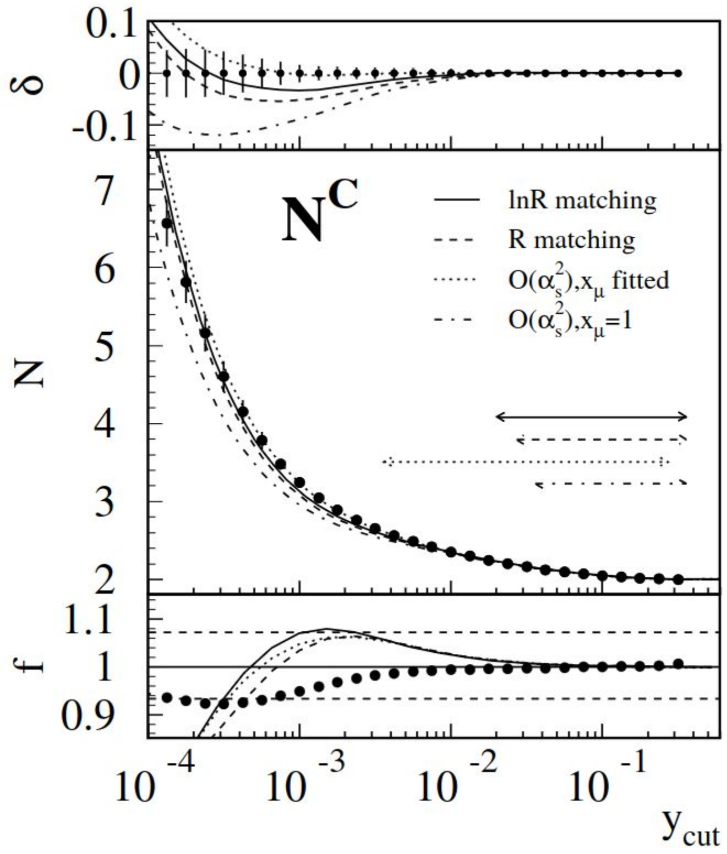
Not very sensitive to quark/gluon fraction with secondary Lund jet plane densities

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: $0.549 < \Delta < 0.670$

Similar jet multiplicity observable measured at LEP



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

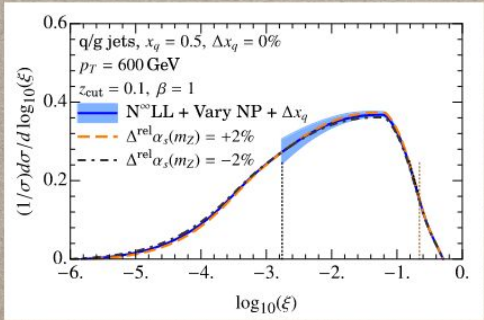
used for $\alpha_S(m_Z)$ extractions by [JADE&OPAL, EPJC 17:19-51 ,2000]

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

Slide by Simone Marzani at alphaS-2022 workshop

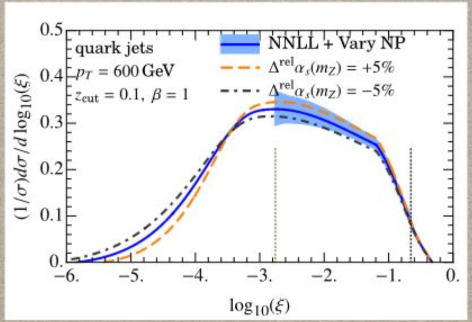
HOW WELL CAN WE DO?

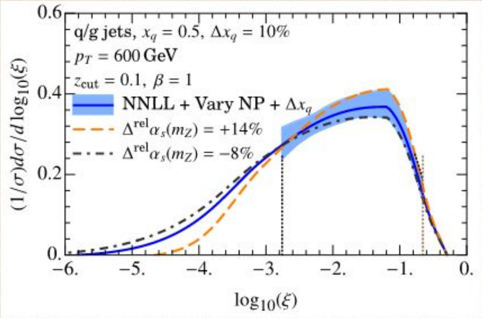
- work in progress to consider α_s sensitivity using state-of-the-art calculations



varying only the 6 non-pert parameters

including NNLL variations





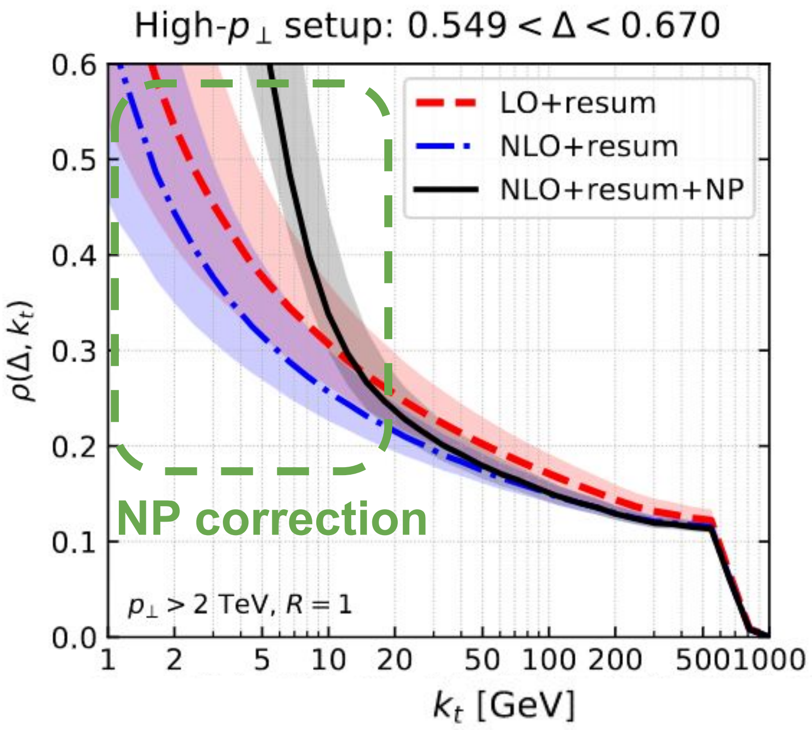
including 10% q/g fraction uncertainty

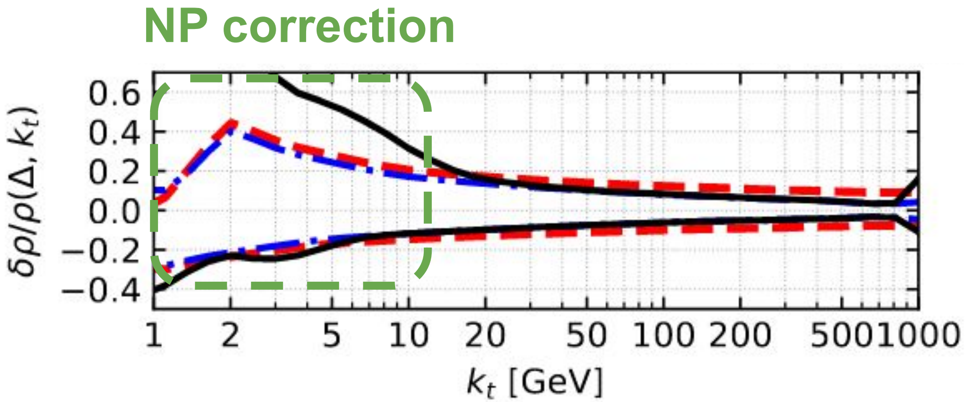
- without fitting for non-perturbative parameters, one gets 2% uncertainty
- perturbative and non perturbative uncertainties total to 5%
- this increases to 15% when considering quark/gluon mixtures

Hannesdottir, Pathak, Schwartz, Stewart (in preparation)

Analytical calculation (NLO+NLL+NP)

Lifson, Salam, Soyez JHEP 10 (2020) 170





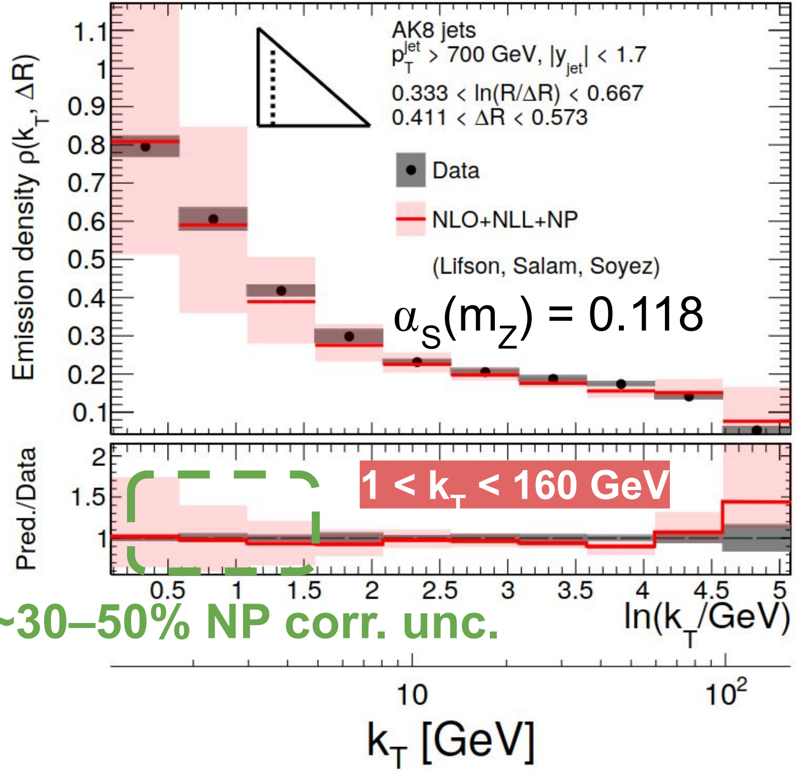
Uncertainties dominated by NP corrections at low k_T ~ 1 GeV (20–40%)

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

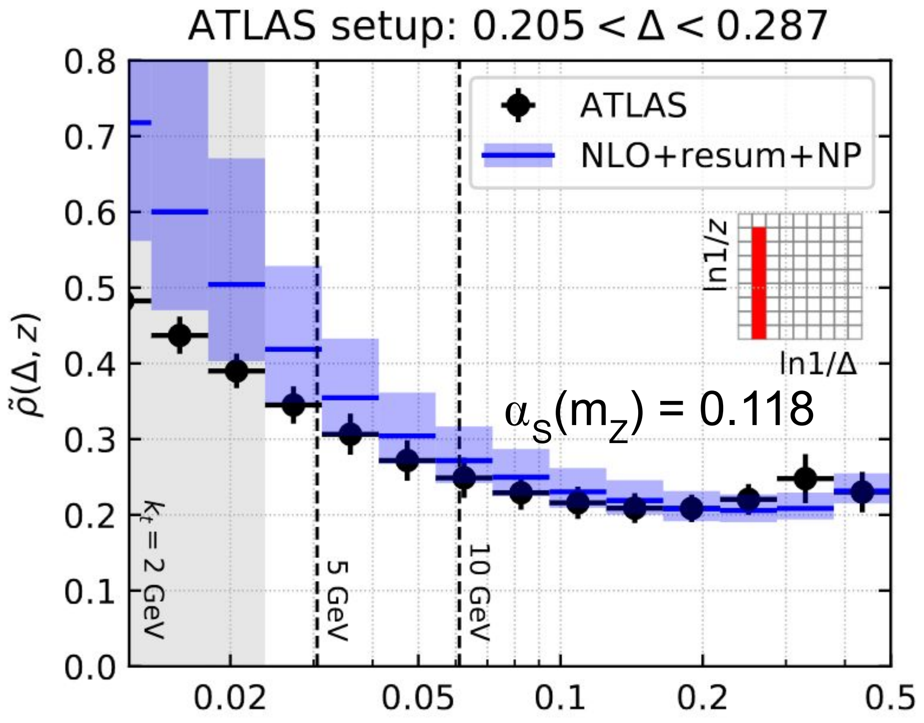
Theory (NLO+NLL+NP) *versus* LHC data

arXiv:2312.16343



~30–50% NP corr. unc.

Lifson, Salam, Soyez JHEP 10 (2020) 170



$z \sim k_T/(p_T^{jet} \Delta R)$

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)
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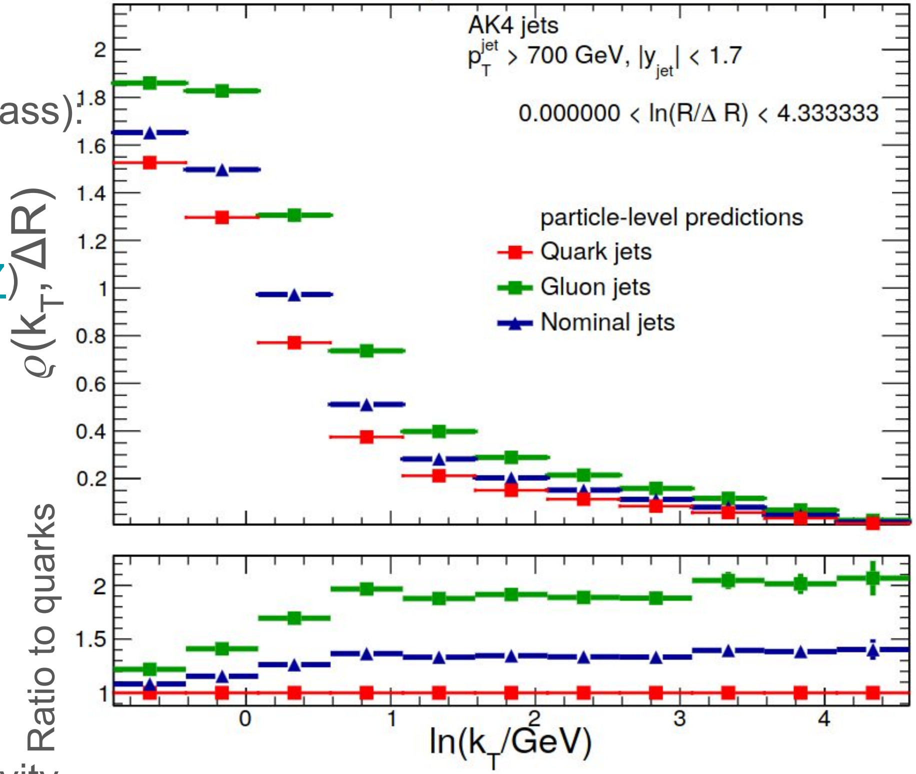
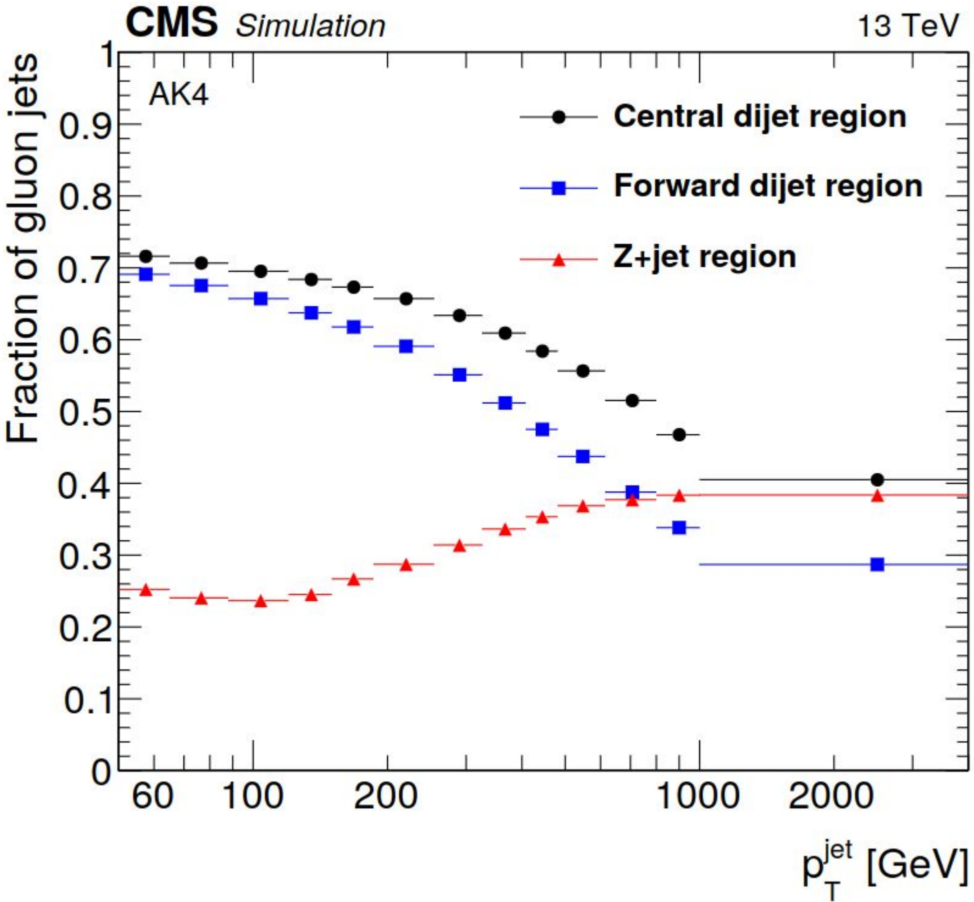
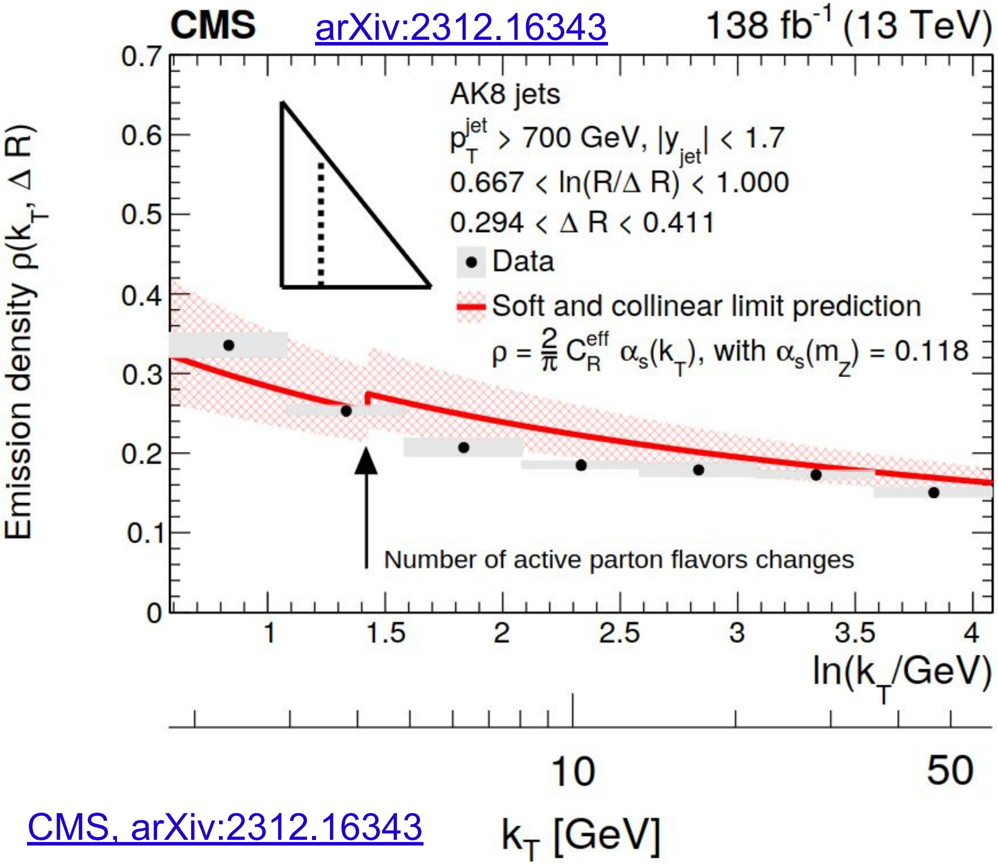


Quark/gluon composition in Z+jet and dijet at the LHC

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



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

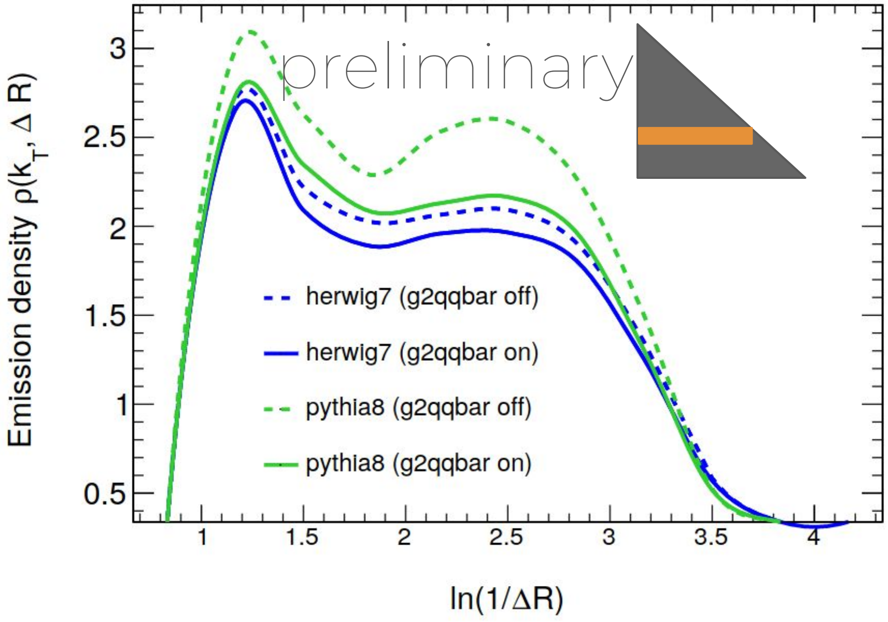
Quark/gluon fractions from PYTHIA8:

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

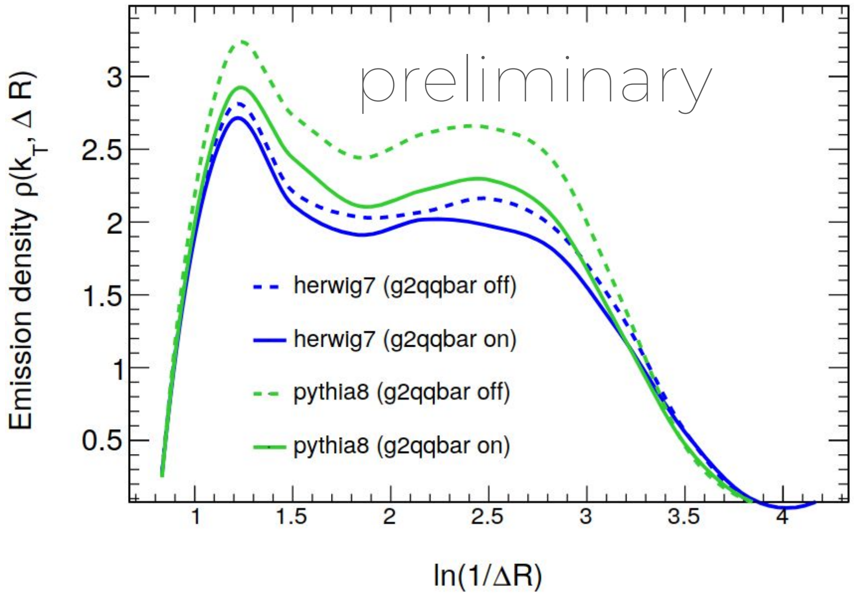
$f_q = 0.59$, $f_g = 0.41$

g→qq off / g →qq on check

Effect on secondary LJP



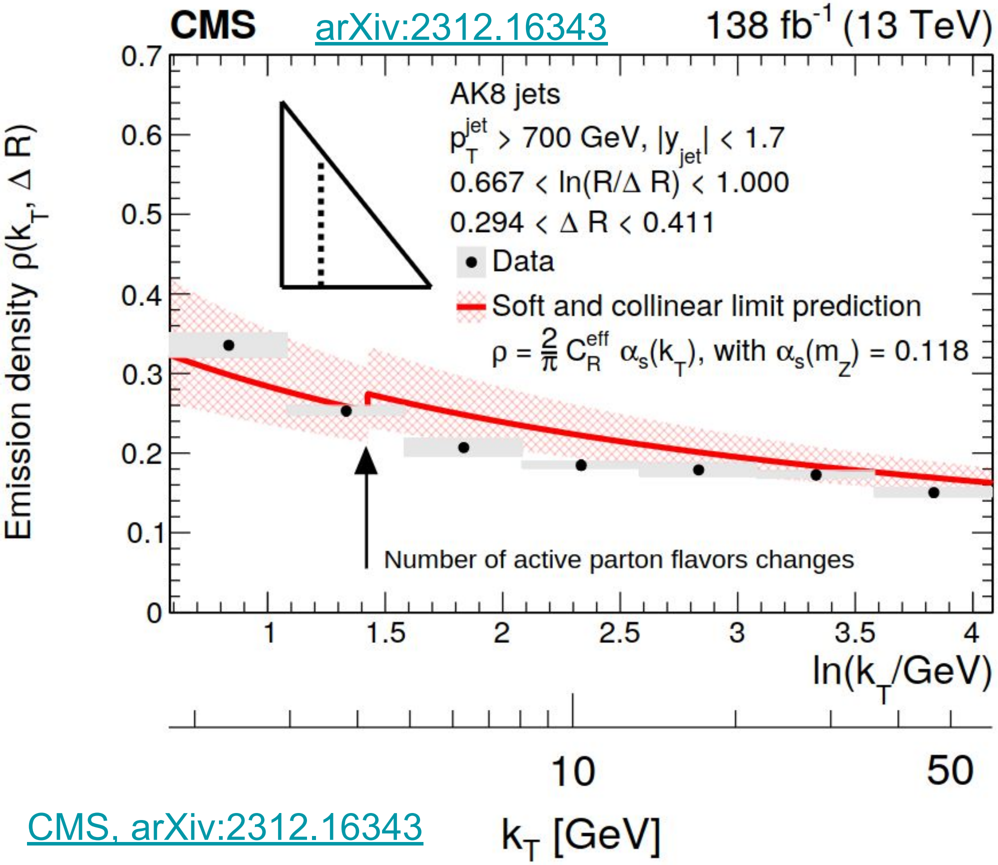
Effect on the gluon primary LJP



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%)

Comparison to pocket-formula predictions



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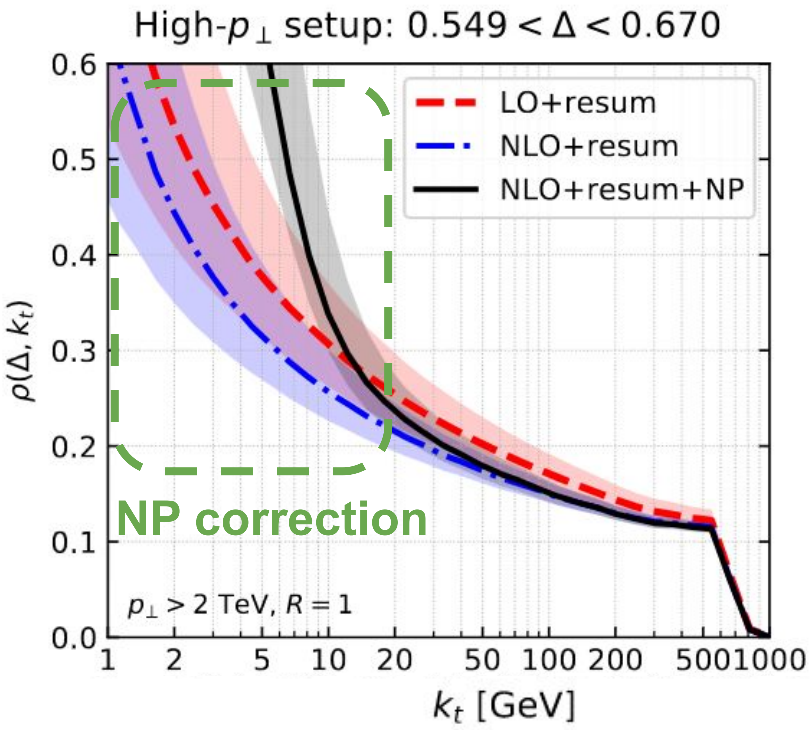

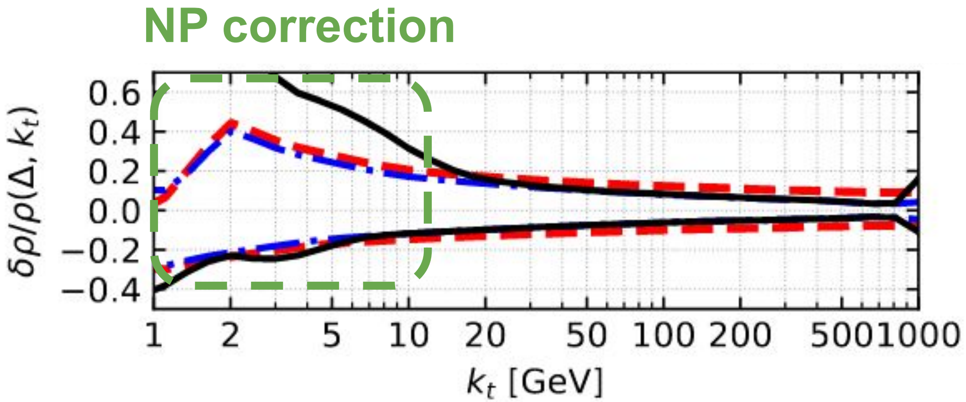

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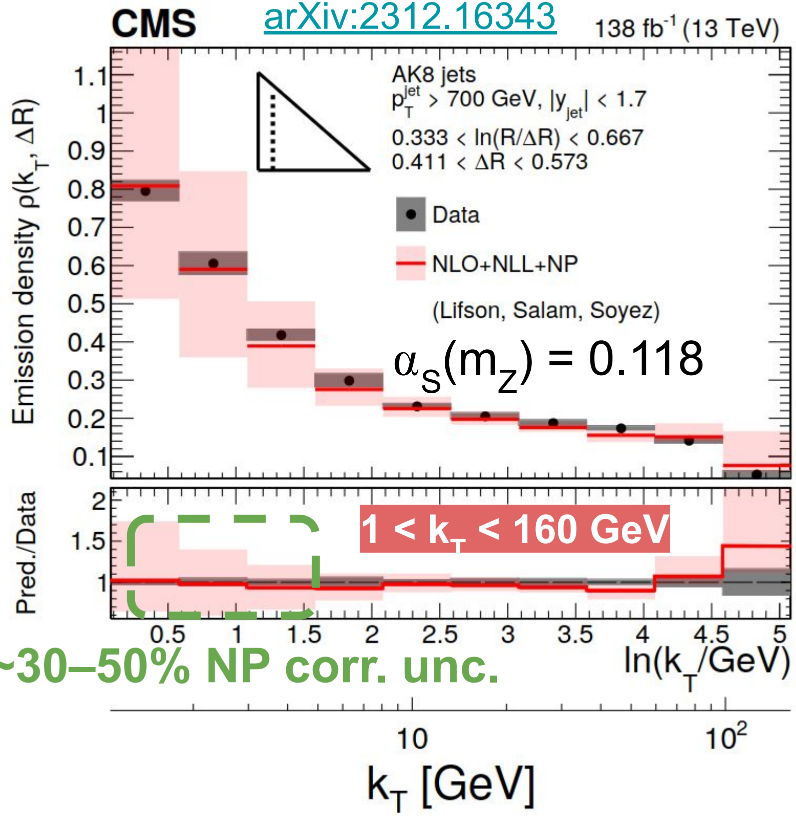

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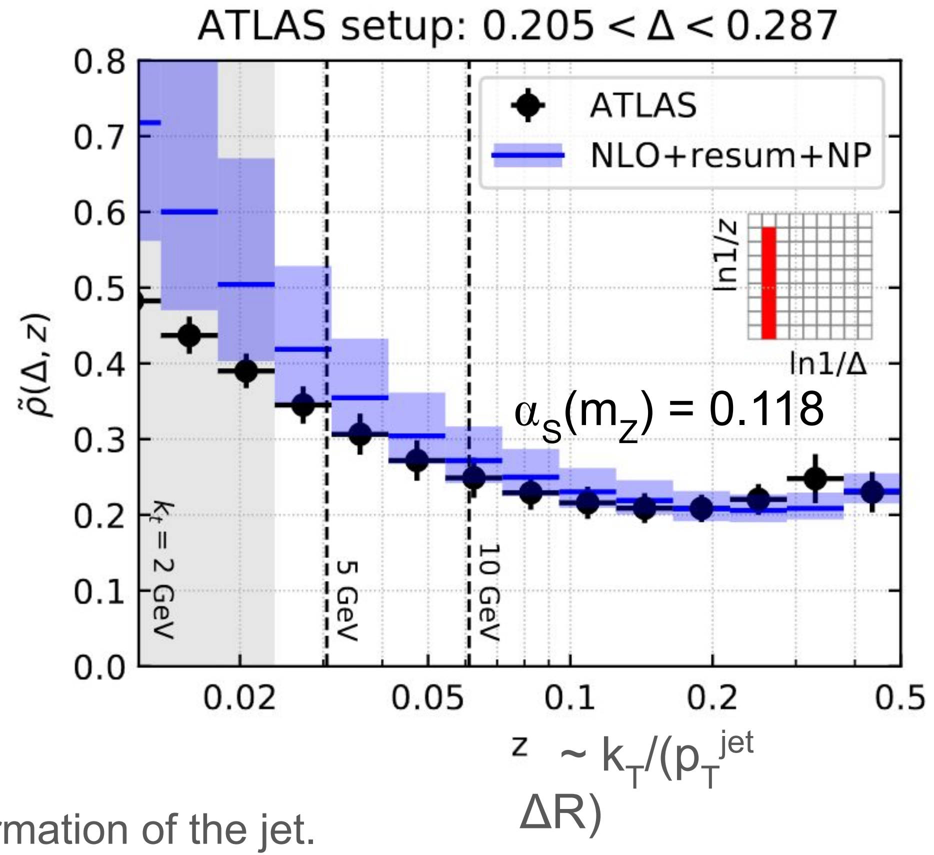

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