

Why does 1 fm of plasma leave a jet alone?

Virtuality and the onset of jet quenching

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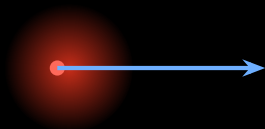
Quark, in a virtual state

$Q \gg \mu_D$, the medium
cannot resolve her yet

APS Division of Nuclear Physics
Fall Meeting, October 2026
Philadelphia, PA

O+O versus p+Pb, a puzzle?

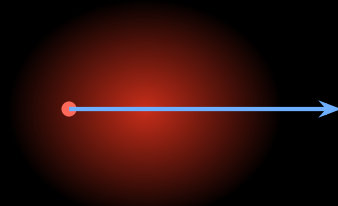
p+Pb



~ 1 fm

no quenching

O+O



$\sim 2-3$ fm

quenching

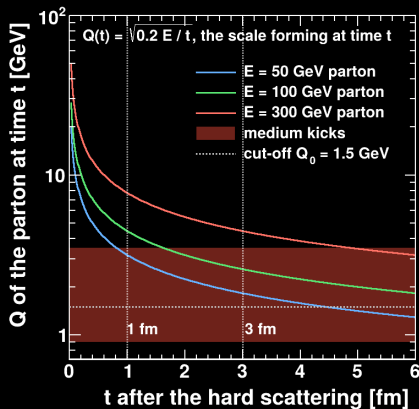
A factor of 2–3 in size, from nothing to something

Is the jet too virtual to notice the medium?

...This effect is due to the collinear splitting in pQCD, which reduces the parton energy only gradually and thus leads to an increase in time dilation as the virtuality drops. This means that the very energetic parton hardly notices the medium for the first 3–4 fm of its path length.

B. Müller, Nucl. Phys. A 855 (2011) 74

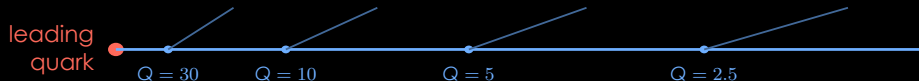
Can we test this in a full Monte Carlo?



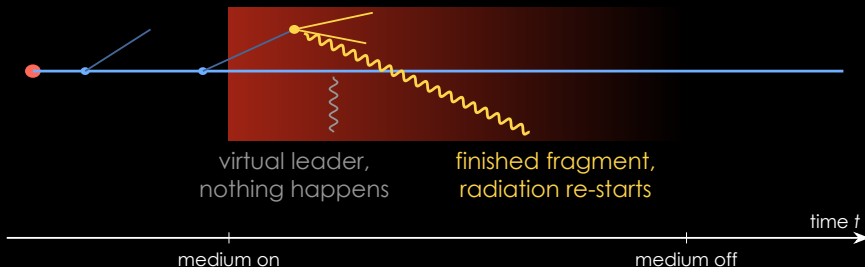
Curves show JEWEL's own formation-time rule $\tau = 0.2 E / Q^2$ (illustration). In full JEWEL runs the leading parton's last splitting comes at $\langle t \rangle = 1.0\text{--}1.4$ fm (3 fm brick, 50–400 GeV), and it is still virtual at its first kick 84% of the time at 1 fm. Müller's estimate uses $Q^2 = Q_{\text{vac}}^2 + \int \hat{q} dt$.

What can a medium kick do in JEWEL?

vacuum, splittings in decreasing Q

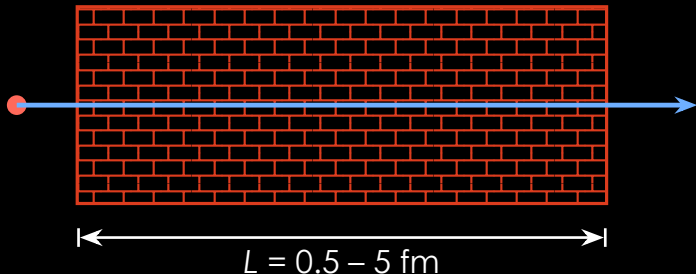


medium, only a kick harder than Q counts



The tool, a brick of plasma

$T = 0.2 - 0.4 \text{ GeV, static}$

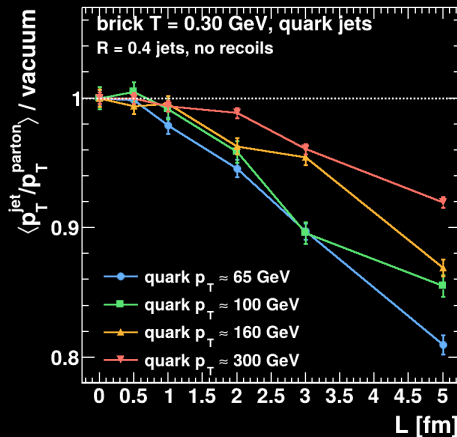


$$x = \frac{p_T^{\text{jet}}}{p_T^{\text{parton}}}$$

medium / vacuum

Two knobs, **length** and **temperature**

Is the first fermi invisible?



100 GeV quark jets

1 fm

almost nothing removed

3 fm

a clear loss

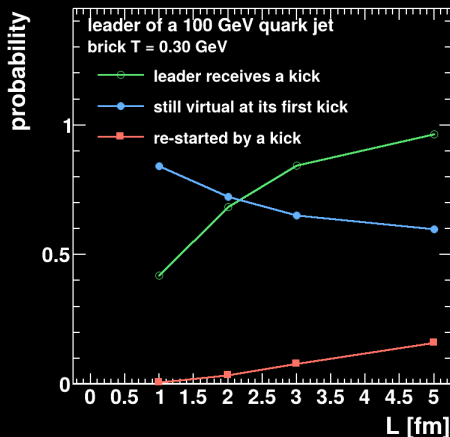
Nearly invisible

3× length, 10× loss

JEWEL 2.6.0 with a static brick (medium-brick.f), $T = 0.30$ GeV unless noted; p+p 5.02 TeV dijets, CT14nlo, default $Q_0 = 1.5$ GeV and Debye mass $\mu_D \simeq 3T$, recoils off, anti- k_T $R = 0.4$, $|\eta| < 0.7$.

Why? The leading parton is still virtual

at 1 fm



kicked

the leader does get kicks

still virtual

when first kicked

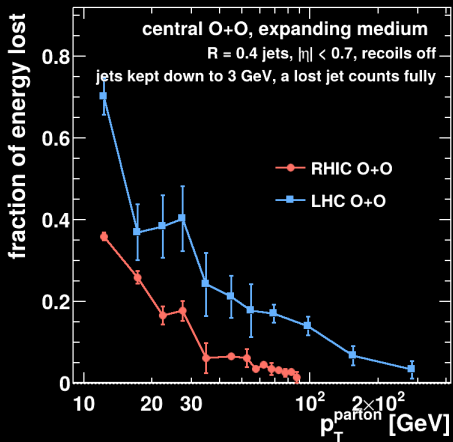
almost never

re-started by a kick

3 fm loss is mostly
finished fragments,
not the leading quark

JEWEL 2.6.0 with a static brick (medium-brick.f), $T = 0.30$ GeV unless noted; p+p 5.02 TeV dijets, CT14nlo, default $Q_0 = 1.5$ GeV and Debye mass $\mu_D \simeq 3T$, recoils off, anti- k_T , $R = 0.4$, $|\eta| < 0.7$. Leading parton followed through the event record (harder daughter at each splitting), 80–120 GeV quarks.

O+O, how much energy do jets lose?



fraction of parton energy
lost from the jet

both

fraction lost shrinks with
energy

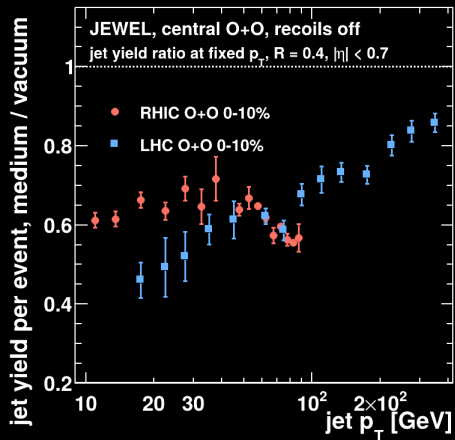
LHC medium

takes more at the same p_T

a parton whose jet is lost counts fully

JEWEL 2.6.0, medium-simple (Woods-Saxon $A = 16$, Bjorken cooling), 0–10%. LHC 5.36 TeV with $T_f = 0.455$ GeV at $\tau_f = 0.4$ fm, RHIC 200 GeV with $T_f = 0.264$ GeV at $\tau_f = 0.8$ fm (both entropy-scaled from the Pb+Pb / Au+Au tunes). CT14nlo, no nPDF, recoils off, anti- k_T , $R = 0.4$, $|\eta| < 0.7$. Fraction lost = $1 - (\text{sum of } x = p_T^{\text{jet}}/p_T^{\text{parton}} \text{ over leading jets matched to the hard parton, per generated event, medium / vacuum})$, quarks and gluons together. Jets kept down to 3 GeV, so a parton that loses its jet counts as $x = 0$. Samples are RHIC $\bar{p}_T > 7$ GeV (100k events), > 35 GeV (60k), and $> 55, 70, 80$ GeV (80k each, each used only above its threshold), LHC $\bar{p}_T > 10$ GeV (80k) and > 40 GeV (120k), and matching vacuum runs.

Prediction, what shape is the O+O jet R_{AA} ?



RHIC flat
to ~ 45 GeV, then drops

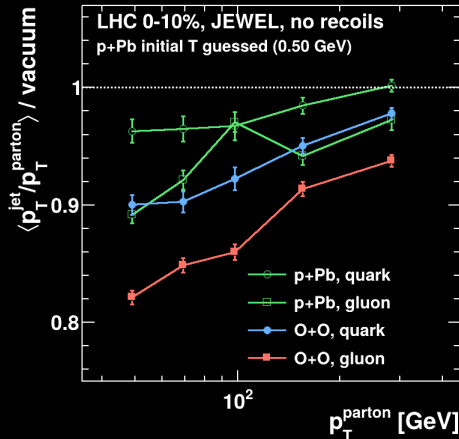
LHC rises
with jet p_T

absolute level set by the assumed
initial T , the shape is the prediction

data in extra slides
SPHENIX jets, [J. Park, HP2026 plenary](#)
CMS charged hadrons

JEWEL 2.6.0, medium-simple (Woods-Saxon $A = 16$, Bjorken cooling), 0-10%. LHC 5.36 TeV with $T_i = 0.455$ GeV at $\tau_i = 0.4$ fm, RHIC 200 GeV with $T_i = 0.264$ GeV at $\tau_i = 0.8$ fm (both entropy-scaled from the Pb+Pb / Au+Au tunes). CT14nlo, no nPDF, recoils off, anti- k_T , $R = 0.4$, $|\eta| < 0.7$. Jet yield per event, medium / vacuum. Samples as on the previous slide.

Central p+Pb in JEWEL?



a third
of the O+O quark-jet loss

geometry
extra uncertainty from the
proton's size and shape

initial $T = 0.50$ GeV is a guess,
data near unity constrain it

JEWEL 2.6.0 with medium-pA.f (Gaussian proton, width 0.5 fm, against the Pb thickness), p+Pb 5.02 TeV 0-10%, $T_i = 0.50$ GeV at $\tau_i = 0.4$ fm. O+O as on the O+O slides. CT14nlo, no nPDF, recoils off.

Summary

Why does 1 fm of plasma leave a jet alone? Tested in JEWEL

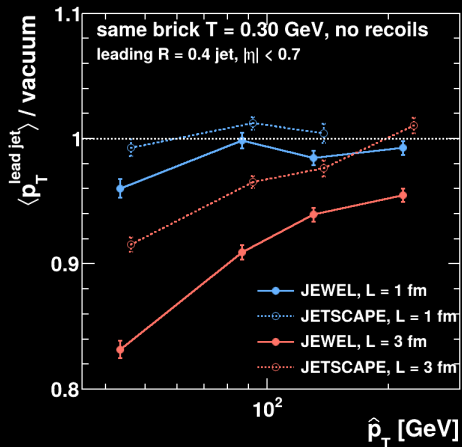
- The first fermi is nearly invisible, the jet is still too virtual for the medium to resolve

almost nothing at 1 fm, a clear loss by 3 fm

- Energy protects, higher- p_T jets stay virtual longer, and JEWEL and JETSCAPE agree
- In O+O the fraction of energy lost shrinks with jet energy at both RHIC and the LHC. Jet R_{AA} is flat at RHIC to ~ 45 GeV and then drops, and rises at the LHC

EXTRA SLIDES

Does higher energy stay protected longer?



blue = 1 fm

red = 3 fm

solid JEWEL, dotted JETSCAPE

Both show **nothing at 1 fm**,
less loss at higher energy

JETSCAPE smaller, weaker
medium coupling

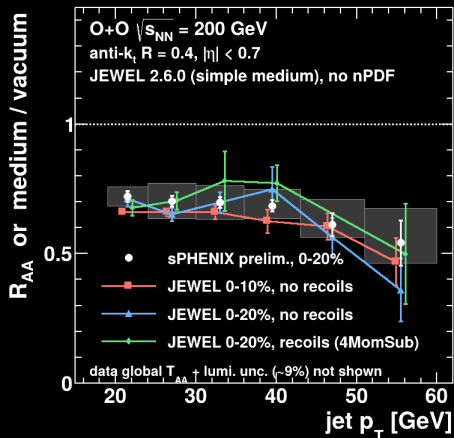
JETSCAPE $\alpha_s = 0.2-0.25$

JEWEL $\alpha_s \approx 0.5-0.9$ at the kick

JEWEL 2.6.0 with a static brick (`medium-brick.f`), $T = 0.30$ GeV unless noted; p+p 5.02 TeV dijets, CT14nlo, default $Q_0 = 1.5$ GeV and Debye mass $\mu_D \simeq 3T$, recoils off, anti- k_T $R = 0.4$, $|\eta| < 0.7$. Medium coupling. JEWEL evaluates $\alpha_s(|t| + \mu_D^2)$ at each kick (one loop, $\Lambda_{QCD} = 0.4$ GeV, $n_f = 3$, $\mu_D = 3T$), giving ≈ 0.86 for the softest kicks at $T = 0.3$ GeV and ≈ 0.5 at $|t| = 2$ GeV², and the elastic rate goes as α_s^2 . JETSCAPE defaults are MATTER HTL $\hat{q}$ with fixed $\alpha_s = 0.25$ and LBT $\alpha_s = 0.2$ with running switched on (`run_alpha = 1`). JEWEL's own 3 fm loss drops from 10% to 4% if its Debye mass is doubled. Recoils are dropped in both. JETSCAPE uses PYTHIA 8 hard scattering in $\hat{p}_T$ bins (5.02 TeV), MATTER above $Q_0 = 2$ GeV (`vir_factor 0.25`) + LBT below ($\alpha_s = 0.2$, running), the same static brick $T = 0.30$ GeV, no Bjorken expansion, recoils off, colorless hadronization, leading anti- k_T $R = 0.4$ jet, $|\eta| < 0.7$.

JETSCAPE 4.0.2, MATTER + LBT

O+O at RHIC versus sPHENIX preliminary jets



agree

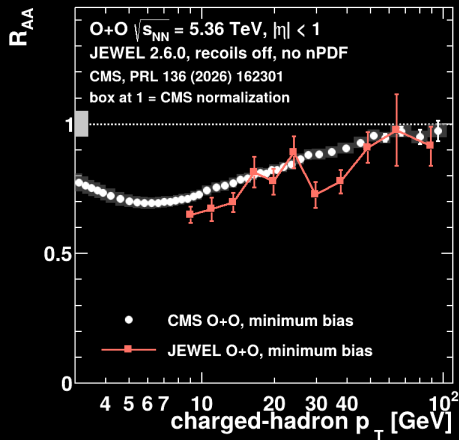
JEWEL 0–20%, with and without recoils, vs sPHENIX preliminary 0–20%

Values read from the vector figure. Global T_{AA} + luminosity uncertainty (~9%) not shown. JEWEL 2.6.0, medium-simple, O+O 200 GeV, $T_l = 0.264$ GeV at $\tau_l = 0.8$ fm, CT14nlo, no nPDF, medium / vacuum jet yield per event. 0–10% recoils off (150k events). 0–20% recoils off (50k events, run stopped at a hung event, vacuum matched channel by channel in isospin). 0–20% recoils on with 4MomSub (30k events, the 43–51 GeV bin, dominated by a single high-weight event, is not shown).

sPHENIX preliminary,
 SPH-CONF-JET-2026-02

J. Park, plenary talk
Hard Probes 2026

O+O at the LHC versus CMS charged hadrons



rise
reproduced

$9 \pm 2\%$

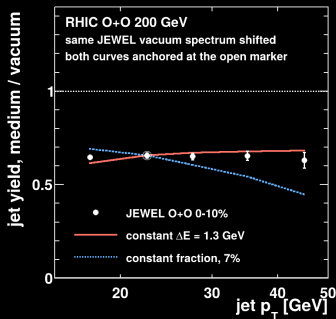
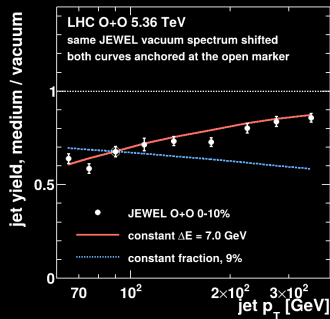
JEWEL below CMS, 8–43
GeV (CMS normalization
 $\pm 5\%$)

above 43 GeV they agree

HEPData ins3068407, minimum bias, $|\eta| < 1$. JEWEL 2.6.0, medium-simple, O+O 0–100%, $T_l = 0.455$ GeV at 0.4 fm, no nPDF, recoils off. Charged hadrons, medium / vacuum per event, six p_T slices combined with JEWEL's cross sections (200k vacuum, 40–120k O+O events each), impact parameters weighted by $T_{AB}(b)$. Errors statistical.

CMS, PRL 136 (2026) 162301

What shapes the O+O R_{AA} in p_T ?



slow ΔE

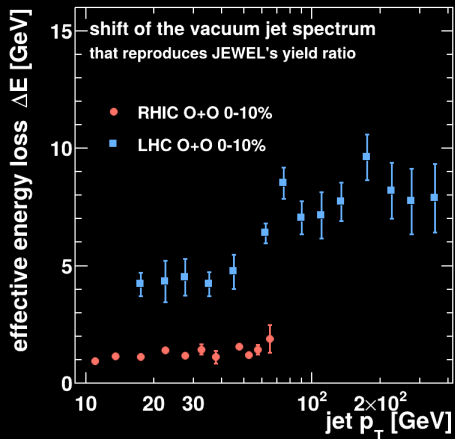
grows much more
slowly than the jet
energy

shape = spectrum

same 3 fm brick gives $\Delta E \approx 3$
GeV (RHIC jets) vs 10 GeV
(LHC jets)

Effective ΔE is the shift of JEWEL's own smooth vacuum jet spectrum that reproduces the medium / vacuum yield ratio in each bin (inclusive jets). Red is one constant ΔE , blue one constant fractional loss, both anchored to JEWEL at the open marker. Local power of the vacuum spectrum is LHC $n = 5.1 \rightarrow 6.6$ (80–400 GeV), RHIC $n = 7.2 \rightarrow 13$ (20–50 GeV). Effective ΔE in O+O is LHC 7–8 GeV (80–400 GeV), RHIC 1.3–1.6 GeV (20–50 GeV). Through the same 3 fm brick, LHC jets 9.5 $\rightarrow$ 11.6 GeV (80–400 GeV), RHIC jets 2.6 $\rightarrow$ 3.5 GeV (15–50 GeV), so the RHIC–LHC difference is mostly jet energy, not the medium. Within each range ΔE grows slowly. The effective shift also depends on the spectrum (steeper spectra favour less-quenched jets). The R_{AA} shape alone cannot isolate virtuality protection. In JEWEL it shows up in the path-length dependence. JEWEL O+O as on the O+O slides.

Effective energy loss, same jet p_T , two media



same jet p_T

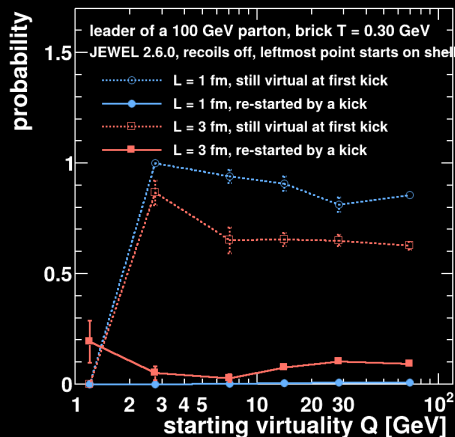
the LHC O+O medium
takes much more

within each

ΔE grows only slowly with
 p_T

Effective ΔE is the shift of JEWEL's own smooth vacuum jet spectrum (cubic fit in $\ln$ - $\ln$ over each sample's range) that reproduces the medium / vacuum yield ratio in each bin. Samples are RHIC $p_T > 7$ and > 35 GeV, LHC $p_T > 10$ and > 40 GeV. With the same 3 fm brick instead (extra slide before), RHIC and LHC jets differ by jet energy alone. JEWEL 2.6.0, medium-simple (Woods-Saxon $A = 16$, Bjorken cooling), 0-10%. LHC 5.36 TeV with $T_f = 0.455$ GeV at $\tau_f = 0.4$ fm, RHIC 200 GeV with $T_f = 0.264$ GeV at $\tau_f = 0.8$ fm (both entropy-scaled from the Pb+Pb / Au+Au tunes). CT14nlo, no nPDF, recoils off, anti- k_t , $R = 0.4$, $|\eta| < 0.7$.

How complete is the shield?

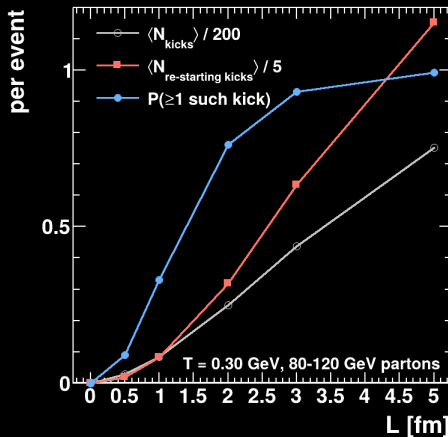


starting Q
hardly matters

84%
first resolved parton is a
finished fragment

JEWEL draws the starting virtuality from the Sudakov form factor between Q_0 and $\hat{p}_T$, so it is spread widely (100 GeV partons, 0.3% on shell, 1% at 1.5–5 GeV, 4% at 5–10, 18% at 10–20, 75% above 20 GeV). Only partons starting on shell are re-started noticeably more often (19% vs 9% at 3 fm, few events). Leader at 1 fm re-started 0.7% overall. Soft fragments ($E < 0.2 p_T^{\text{parton}}$) take 78% of first re-starting kicks at 1 fm and 77% at 3 fm (on shell 84%, 88%). JEWEL 2.6.0 with a static brick (medium-brick.f), T = 0.30 GeV unless noted; p+p 5.02 TeV dijets, CT14nlo, default $Q_0 = 1.5$ GeV and Debye mass $\mu_D \simeq 3T$, recoils off, anti- k_T R = 0.4, $|\eta| < 0.7$.

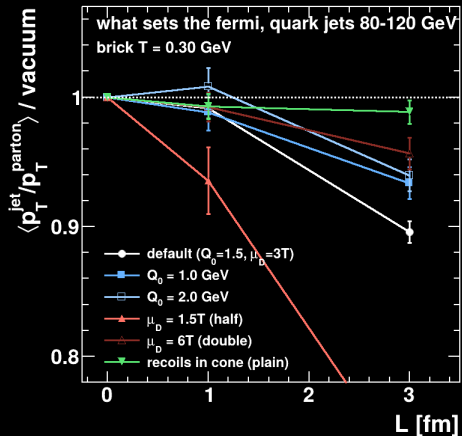
Kicks are there at 1 fm, resolution is not



many kicks
already at 1 fm

very few
change the shower

What sets the fermi?



μ_D

Debye mass is the biggest
lever at 3 fm

6–8%

3 fm loss with medium
response subtracted

JEWEL 2.6.0 with a static brick (medium-brick.f), T = 0.30 GeV unless noted; p+p 5.02 TeV dijets, CT14nlo, default $Q_0 = 1.5$ GeV and Debye mass $\mu_D \simeq 3T$, recoils off, anti- k_T , $R = 0.4$, $|\eta| < 0.7$. Variations are Debye mass $\times 0.5 / \times 2$ (MDSCALEFAC, the $\times 0.5$ runs are $\sim 50\times$ slower and were stopped at 1.2k / 3.9k events), $Q_0 = 1.0 / 2.0$ GeV, recoils on with 4MomSub or constituent subtraction.