QCD precision measurements at the LHC

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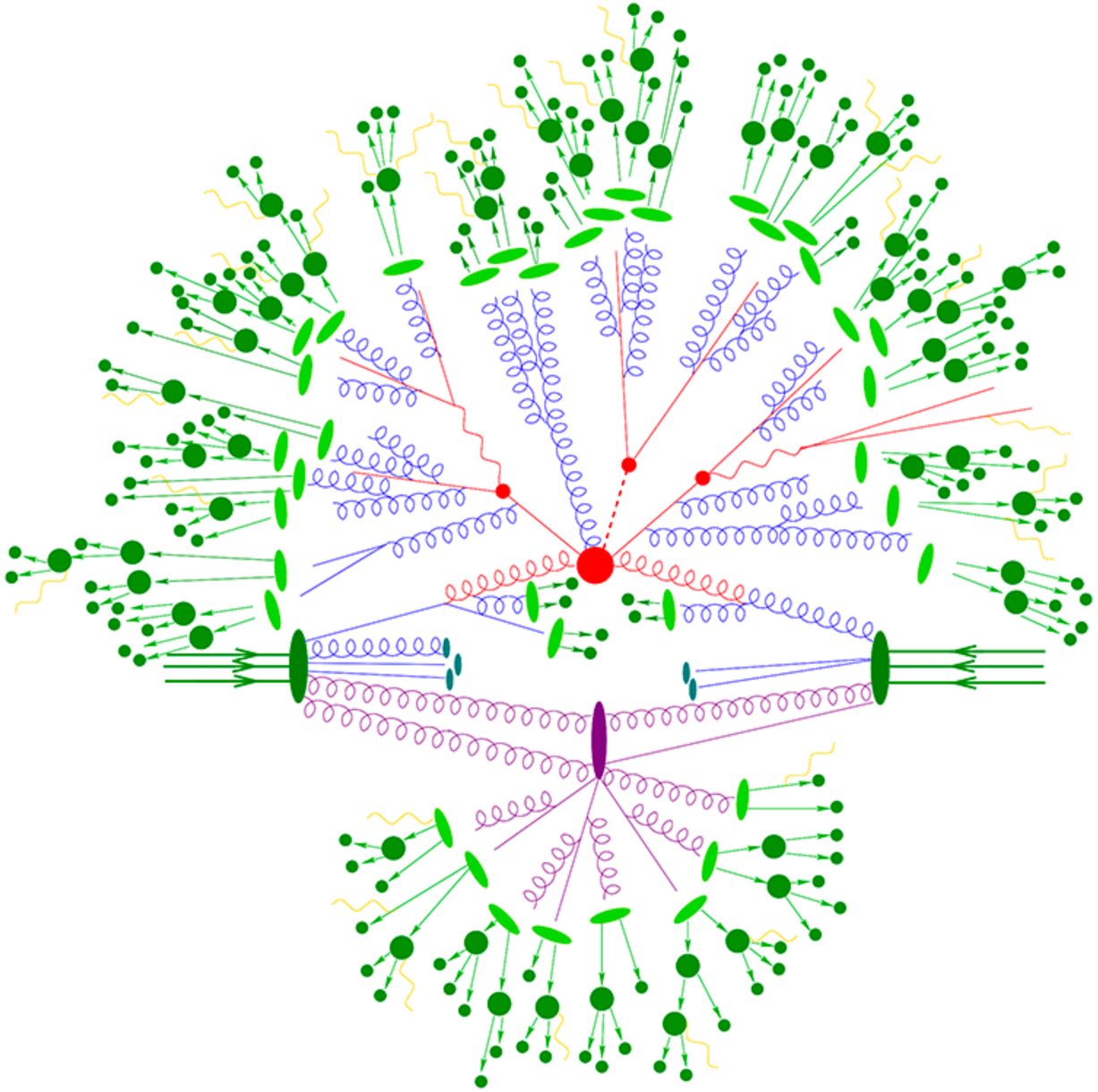
Hadron Collision

Hard Scattering

Parton Shower

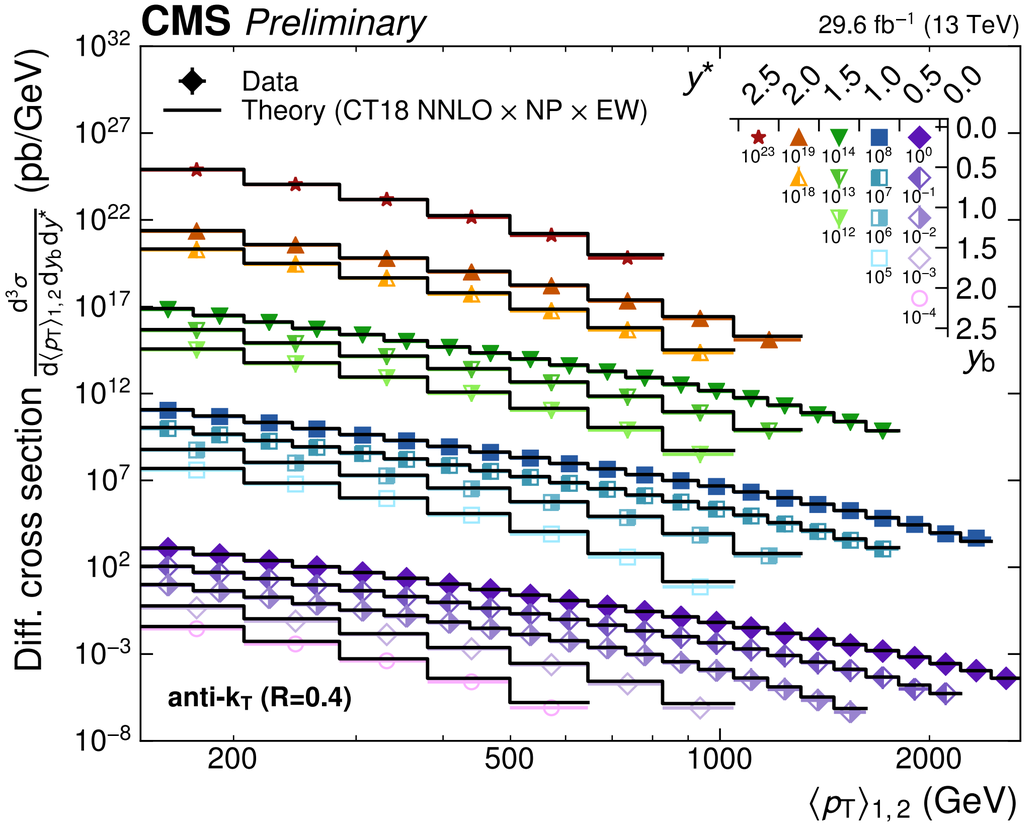
Hadronization

MPI



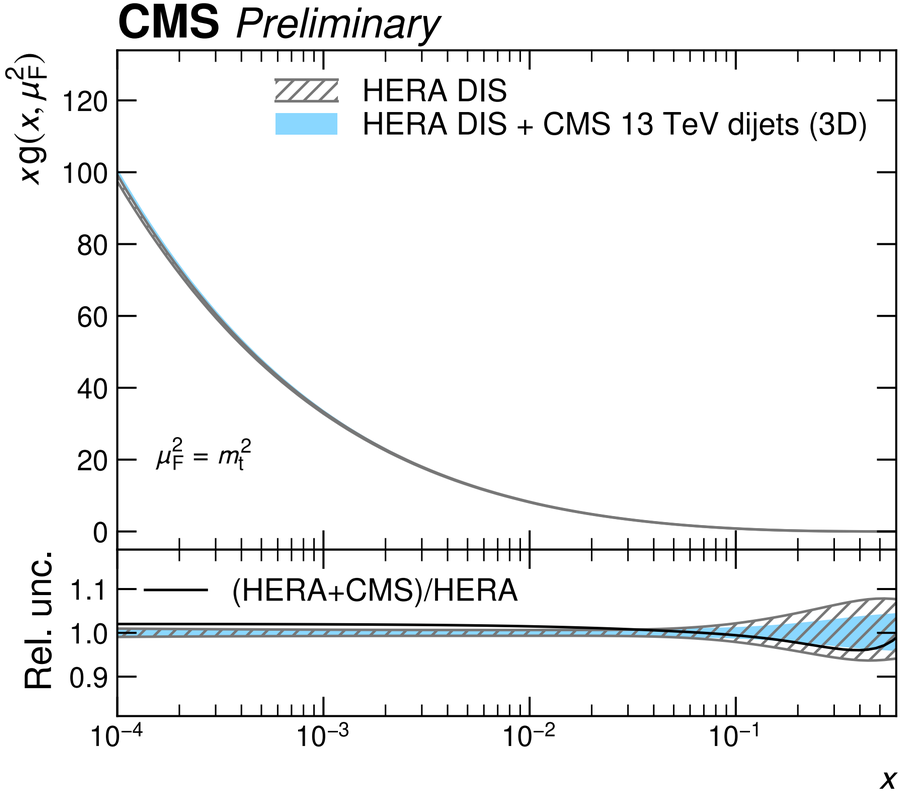
Using jets as proxies

Di-jet multi-differential cross section Compared to NNLO predictions, 10^{-4} - 10^{23}

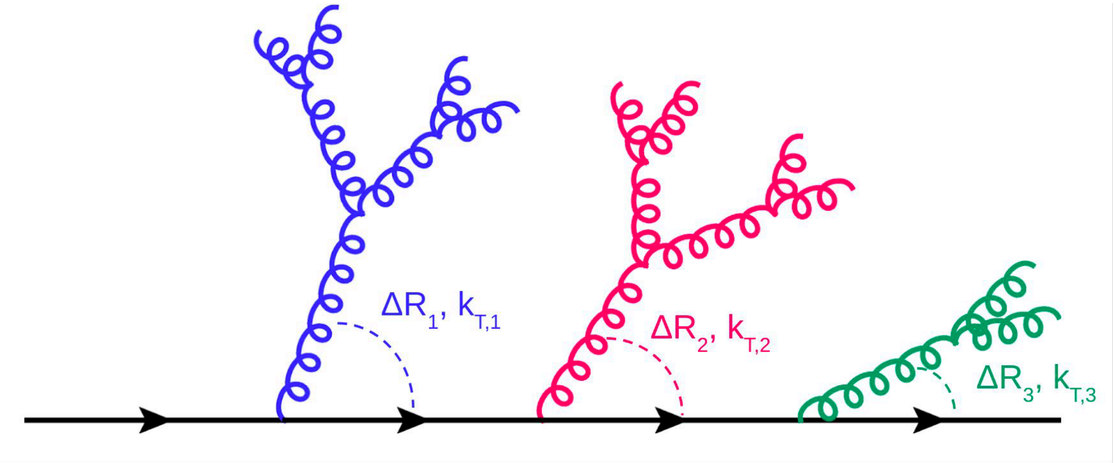


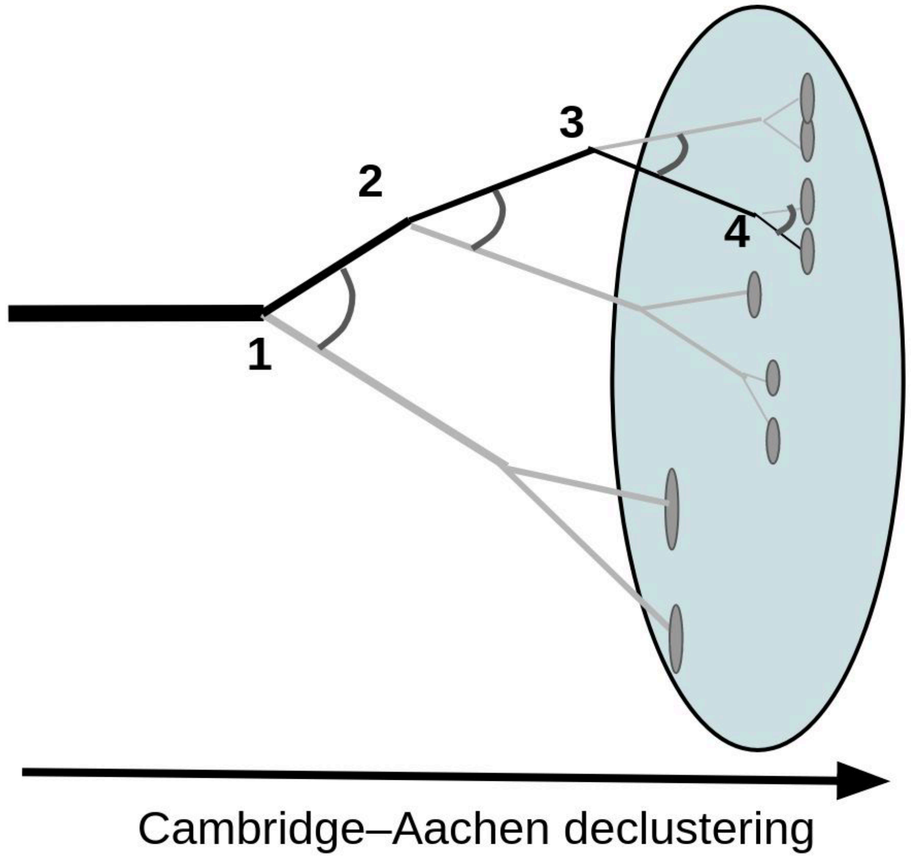
CMS-PAS-SMP-21-008

Constraints on gluon PDF



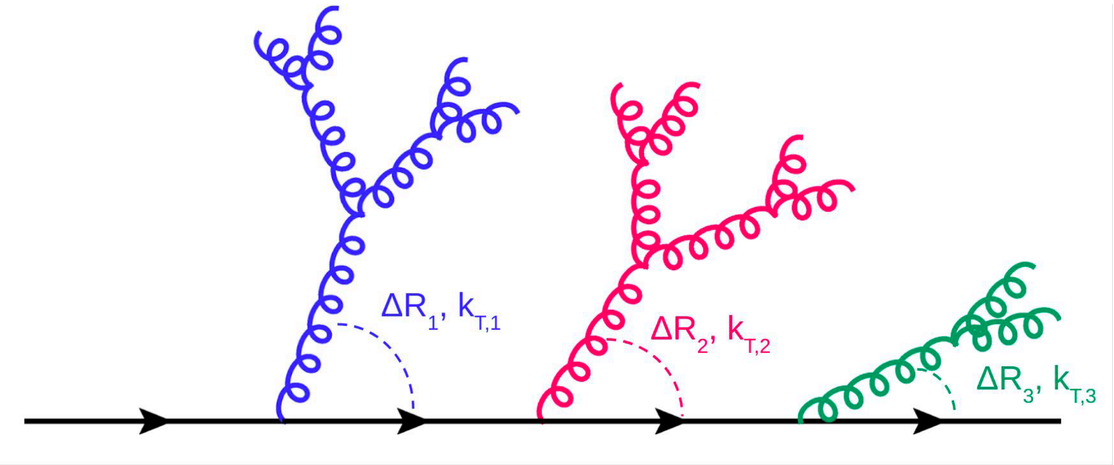
Parton shower and jet substructure

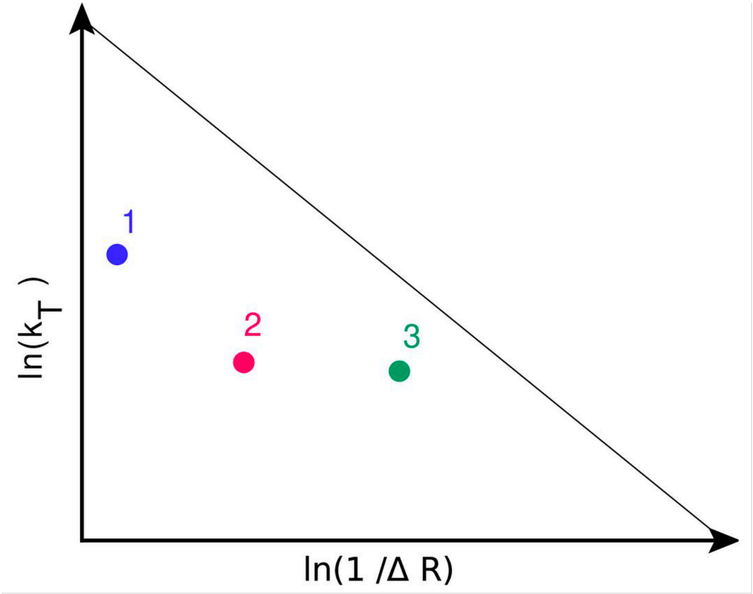




Angular-ordered

Lund plane





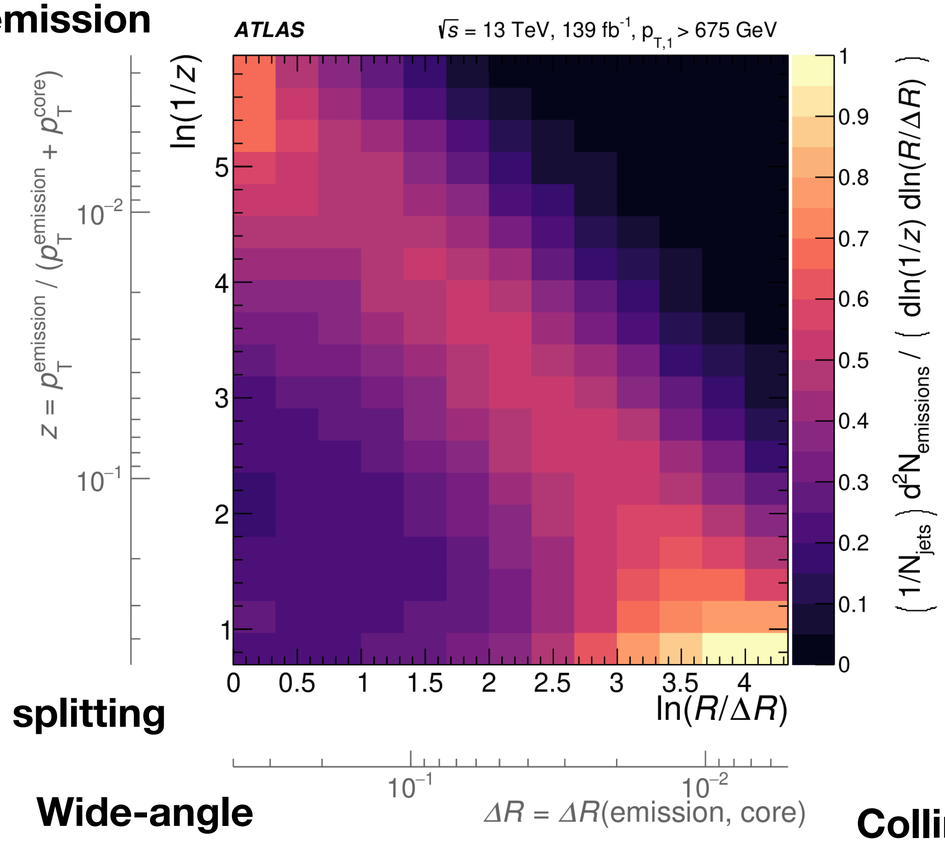
B. Andersson, G. Gustafson, L. Lonnblad, and U. Pettersson, Z. Phys. C43 (1989) 625

Lund plane

PRL 124 (2020) 222002

CMS-PAS-SMP-22-007

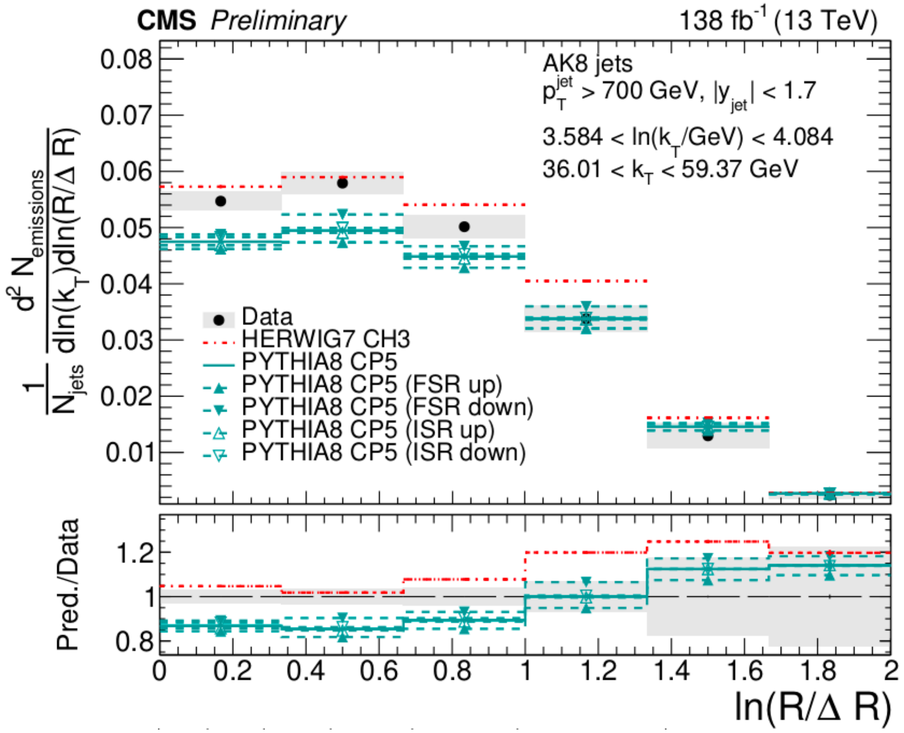
Soft-emission



Even splitting

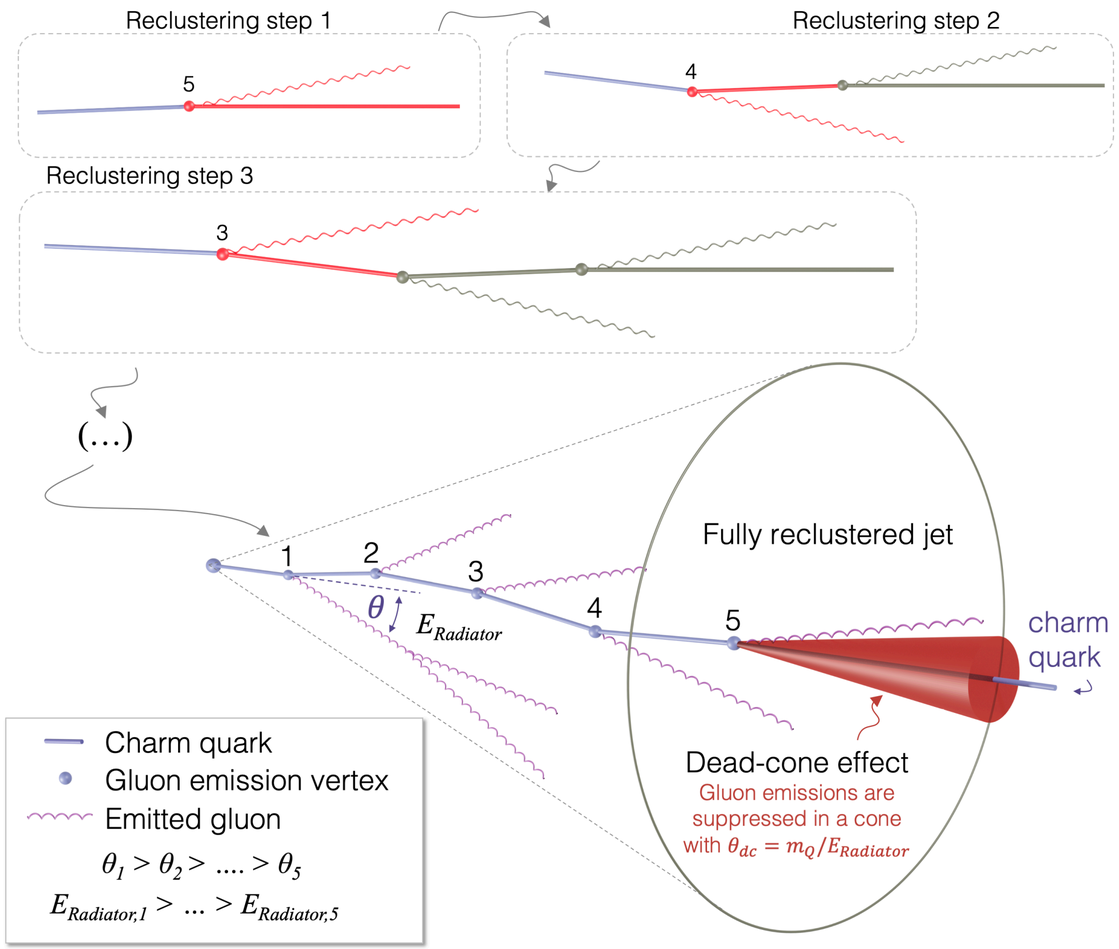
Wide-angle

Collinear

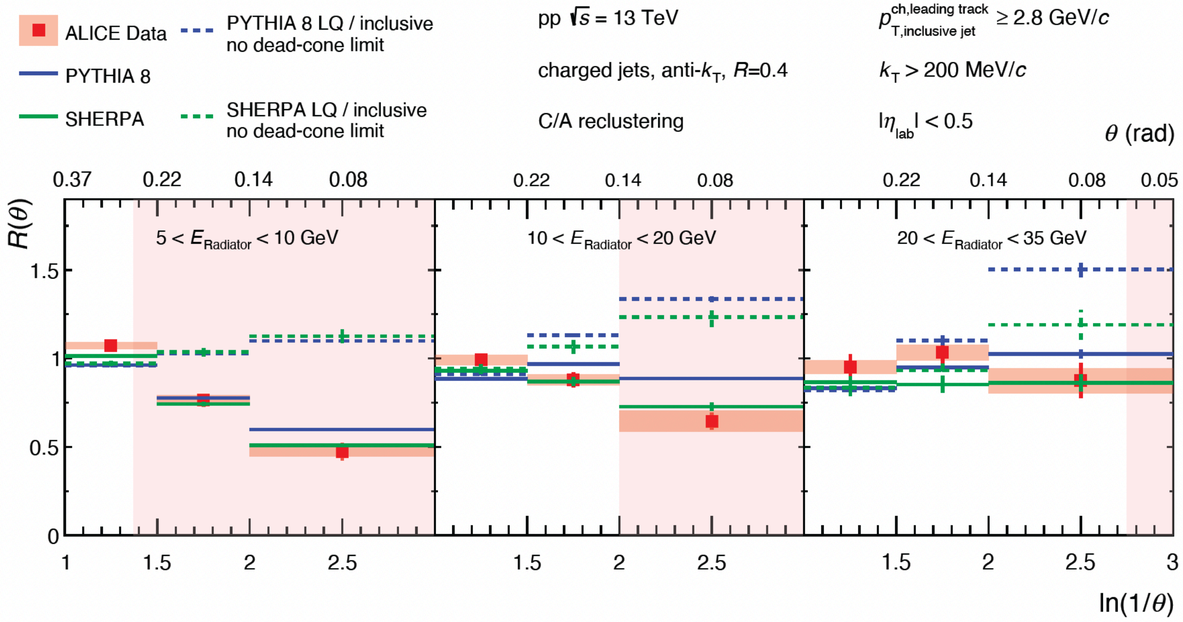


$$\frac{1}{N_{\text{jets}}}\frac{d^2N_{\text{emissions}}}{d\ln(1/z)d\ln(R/\Delta R)} \propto \text{constant},$$

Dead-cone effect

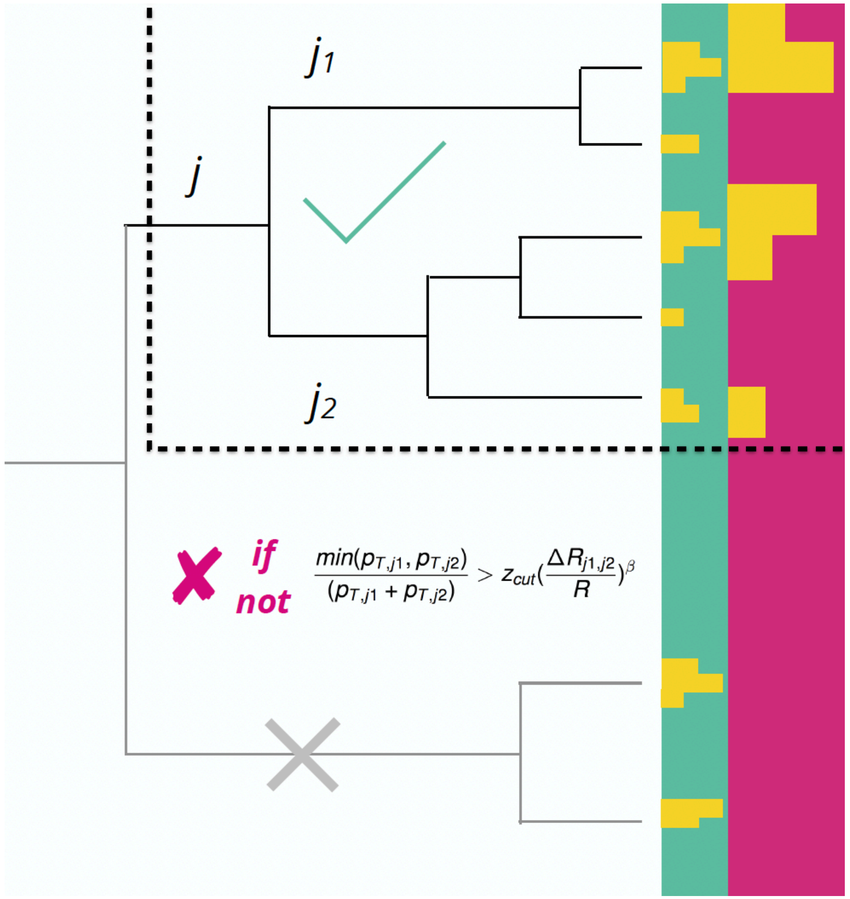


Nature 605, 7910 (2022): 440-446



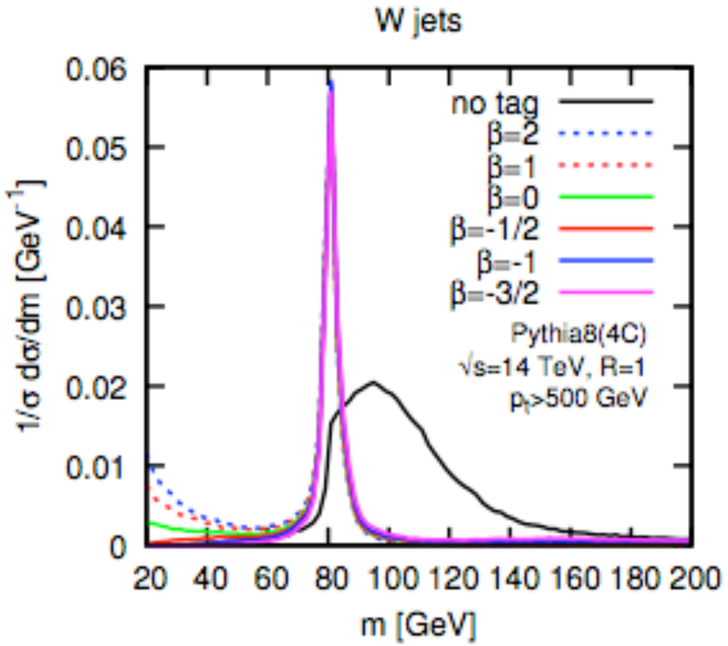
Jet grooming: soft-drop

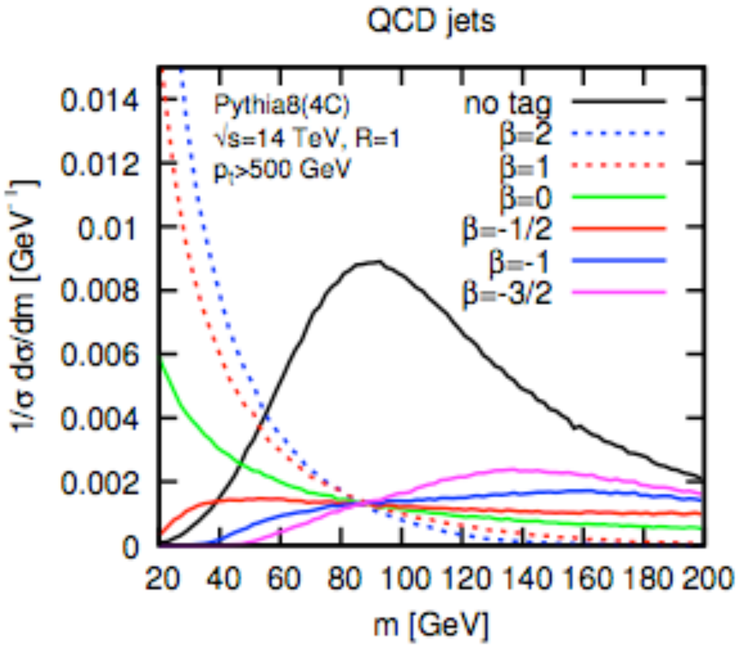
Remove soft and wide-angle radiation



MLB (CERN) — Jet reconstruction in ATLAS

Larkoski, Marzani, Soyez,Thaler, 2014

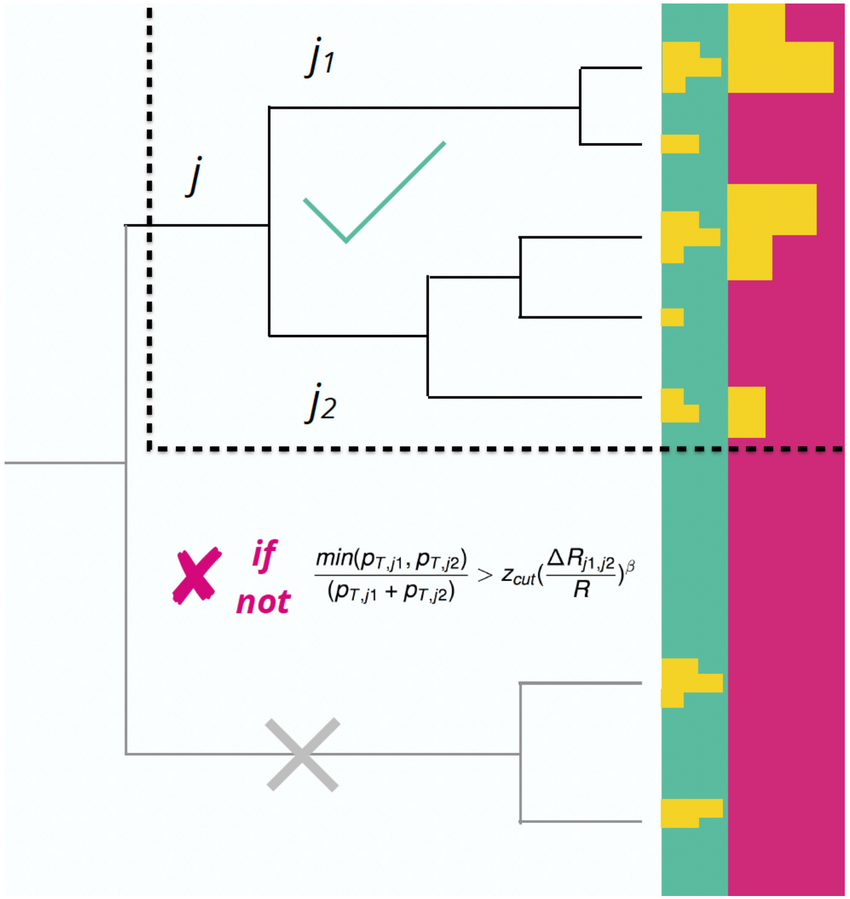




$$\frac{\min\left(p_{\mathrm{T},j_1}, p_{\mathrm{T},j_2}\right)}{p_{\mathrm{T},j_1} + p_{\mathrm{T},j_2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta},$$

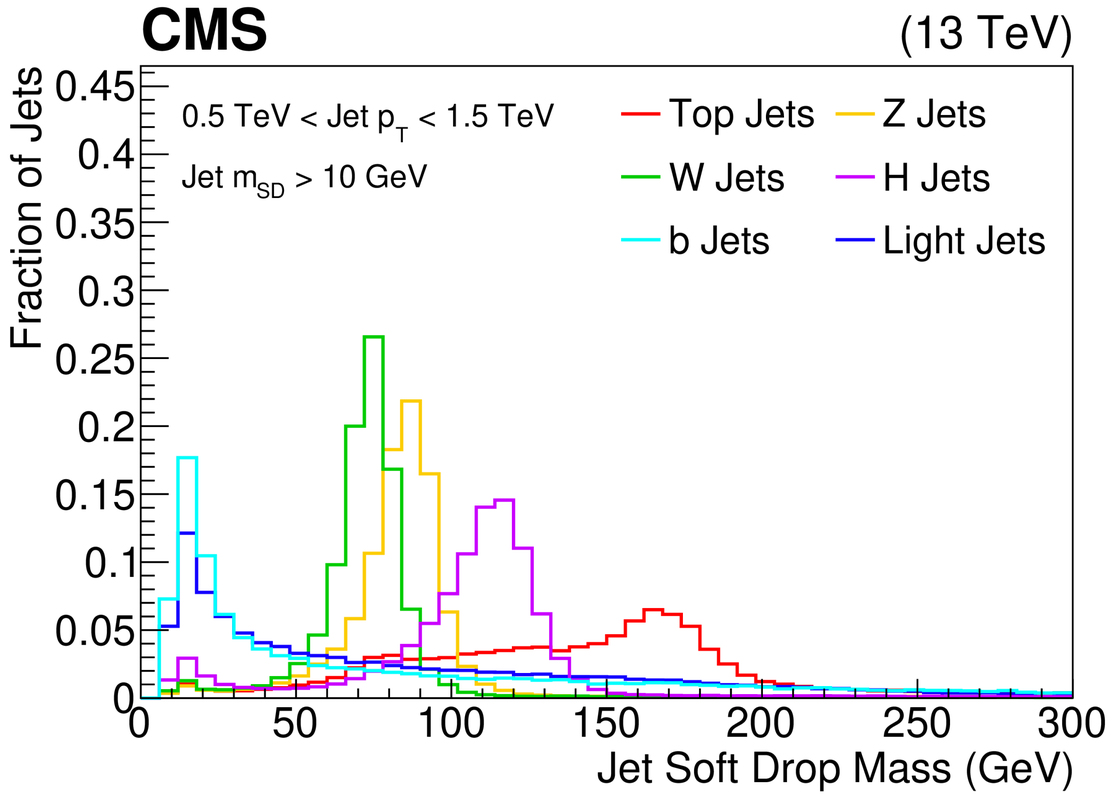
Jet grooming: soft-drop

Remove soft and wide-angle radiation



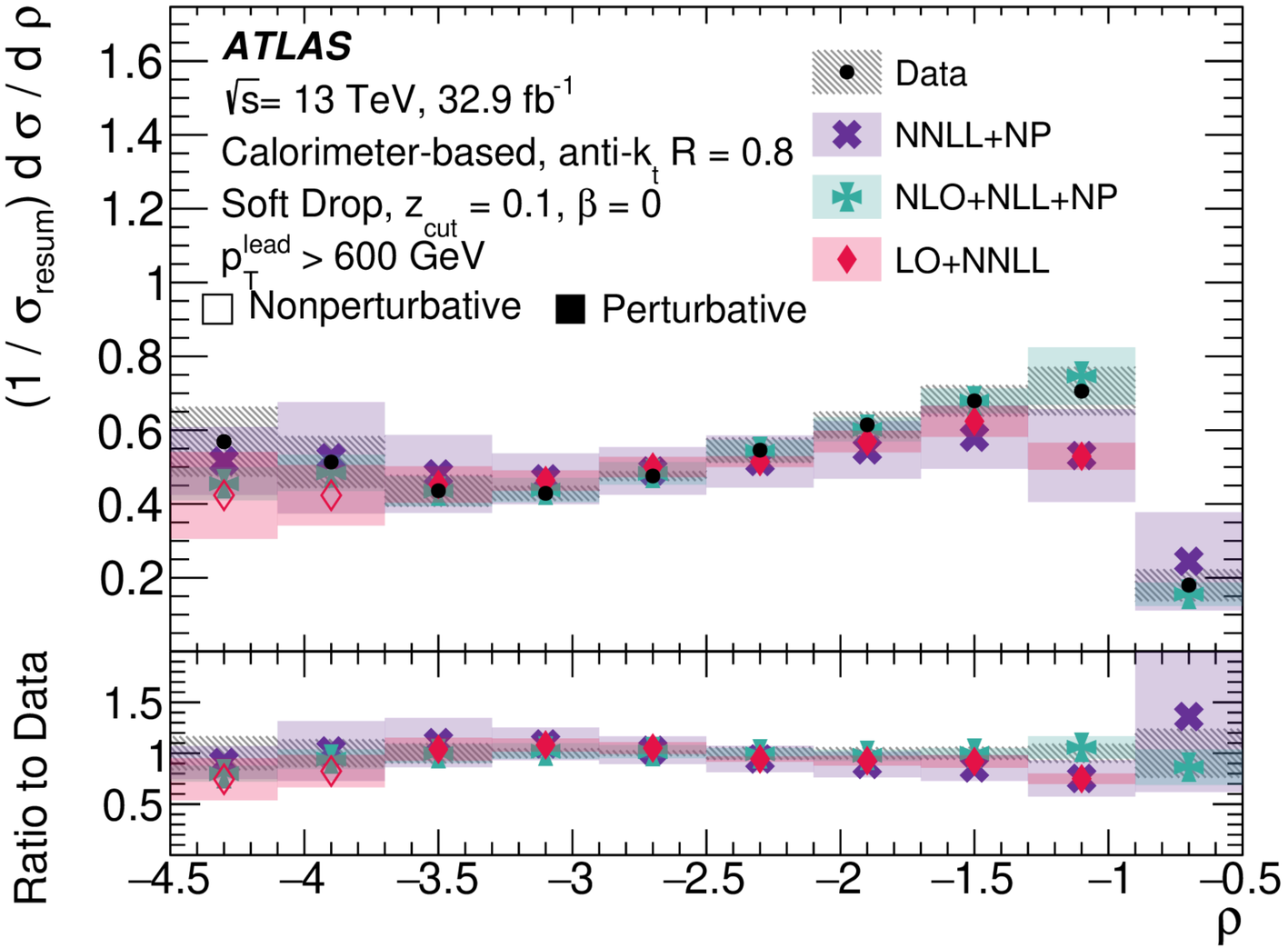
MLB (CERN) — Jet reconstruction in ATLAS

CMS, B2G-18-005

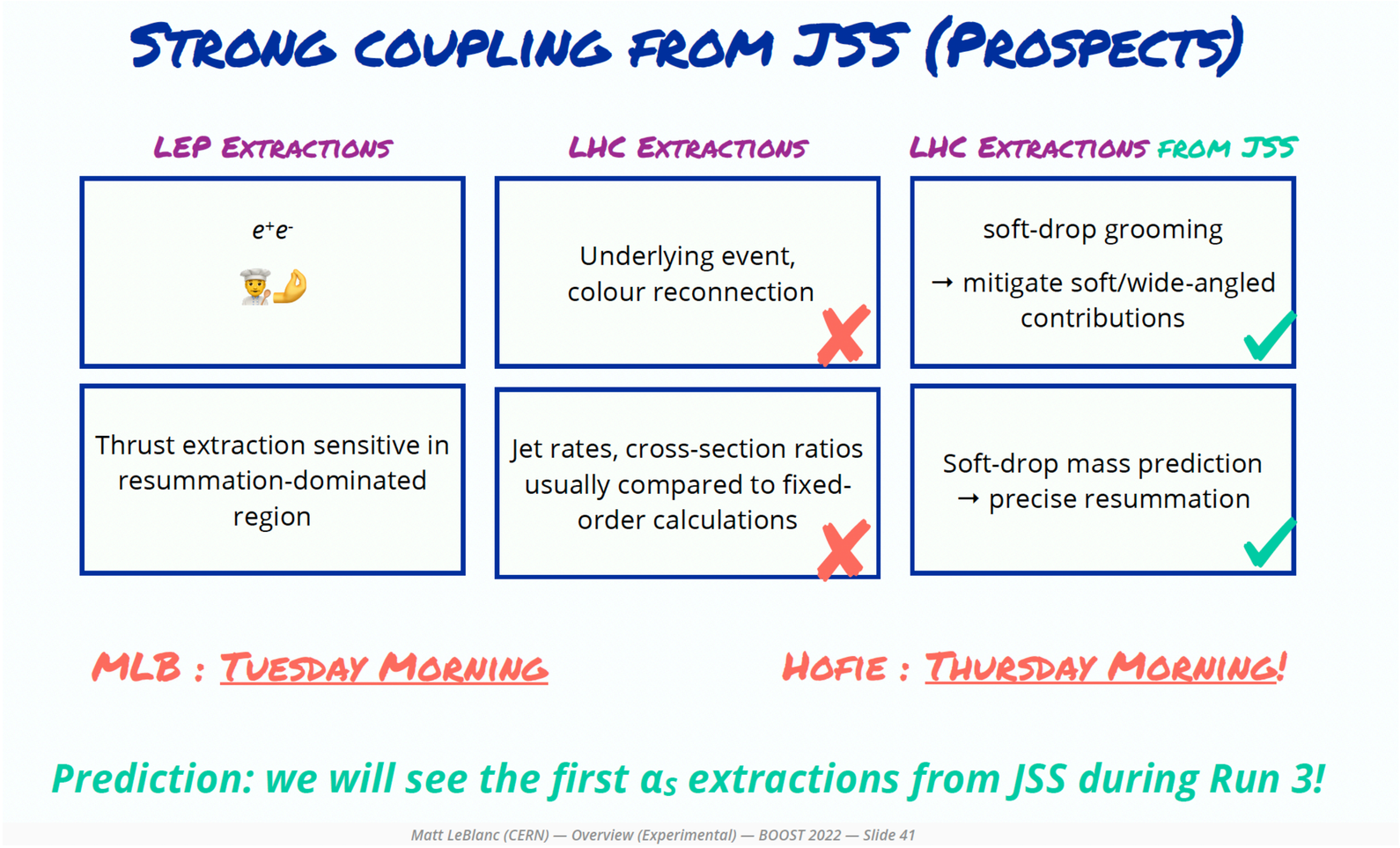


Soft-drop mass as taggers

Soft drop mass, high precision calculation

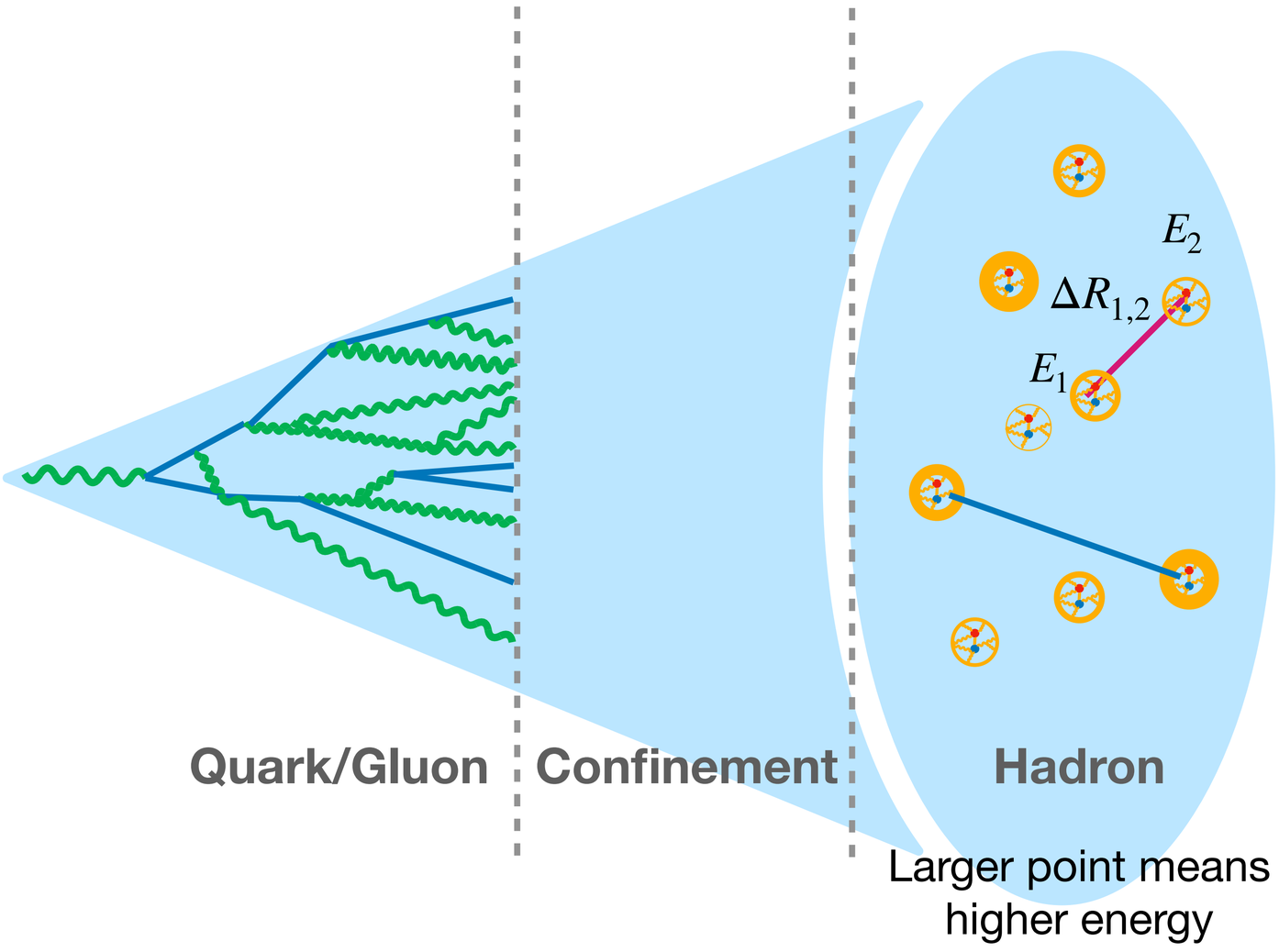


Soft drop and alphaS

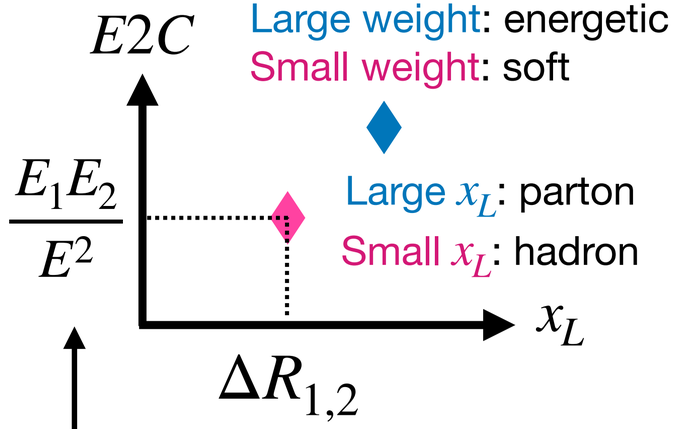


Leshouches2017, axXiv: 1803.07977, estimated precision on αS: 10%

Energy correlators: EnC



Larger point means higher energy



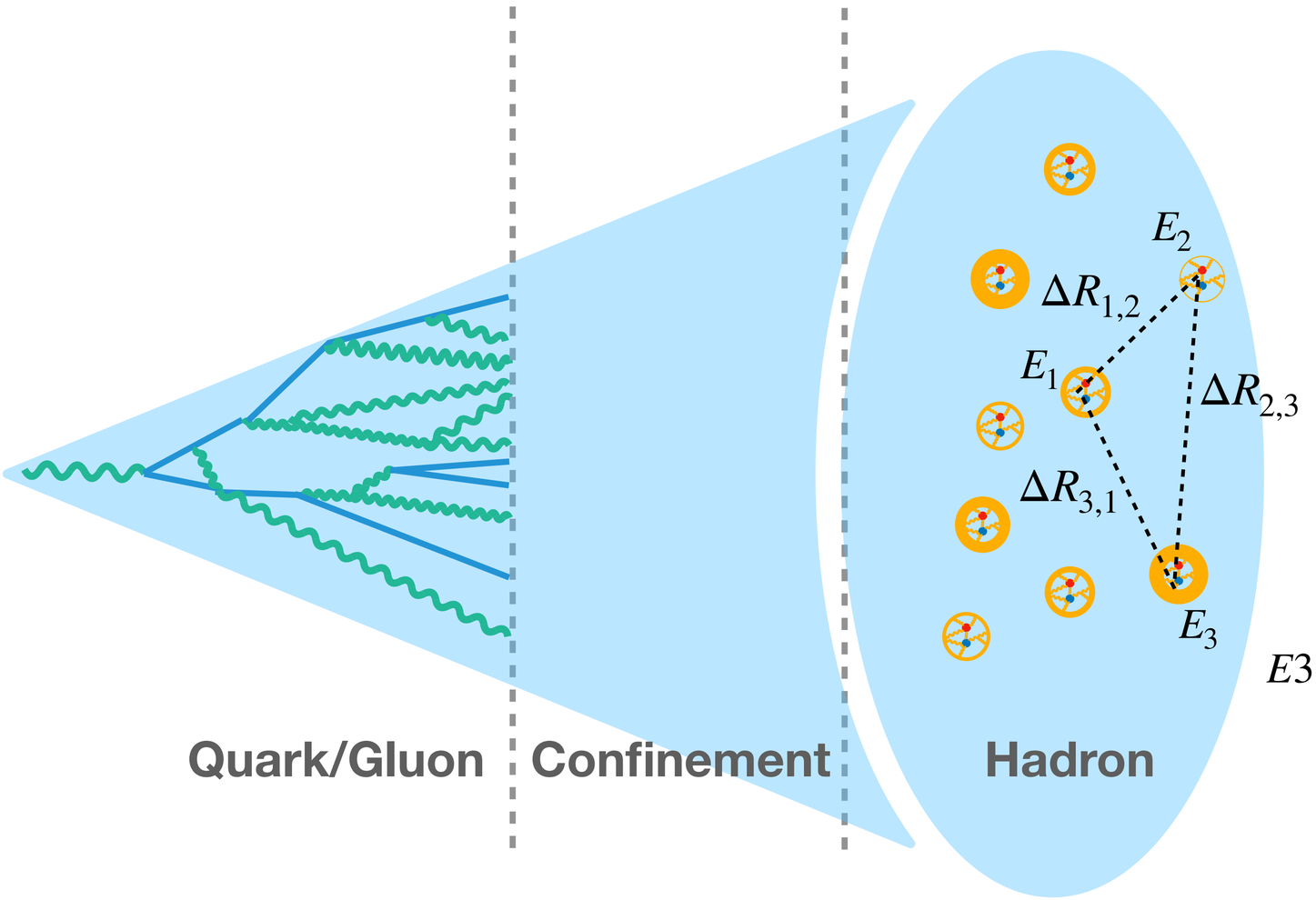
$$E2C = \frac{d\sigma^{[2]}}{dx_L} = \sum_{i,j}^{n} \int d\sigma \frac{E_i E_j}{E^2} \delta(x_L - \Delta R_{i,j})$$

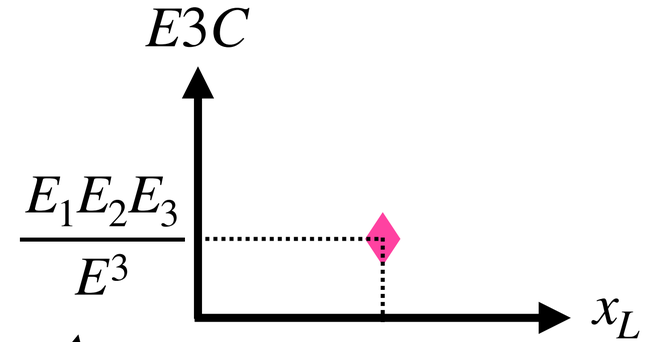
Chen, Moult, Zhang, and Zhu, *arXiv:2004.11381*

Lee, Meçaj, and Moult, *arXiv:2205.03414*

Chen, Gao, Li, Xu, Zhang, and Zhu, *arXiv:2307.07510*

Energy correlators: EnC





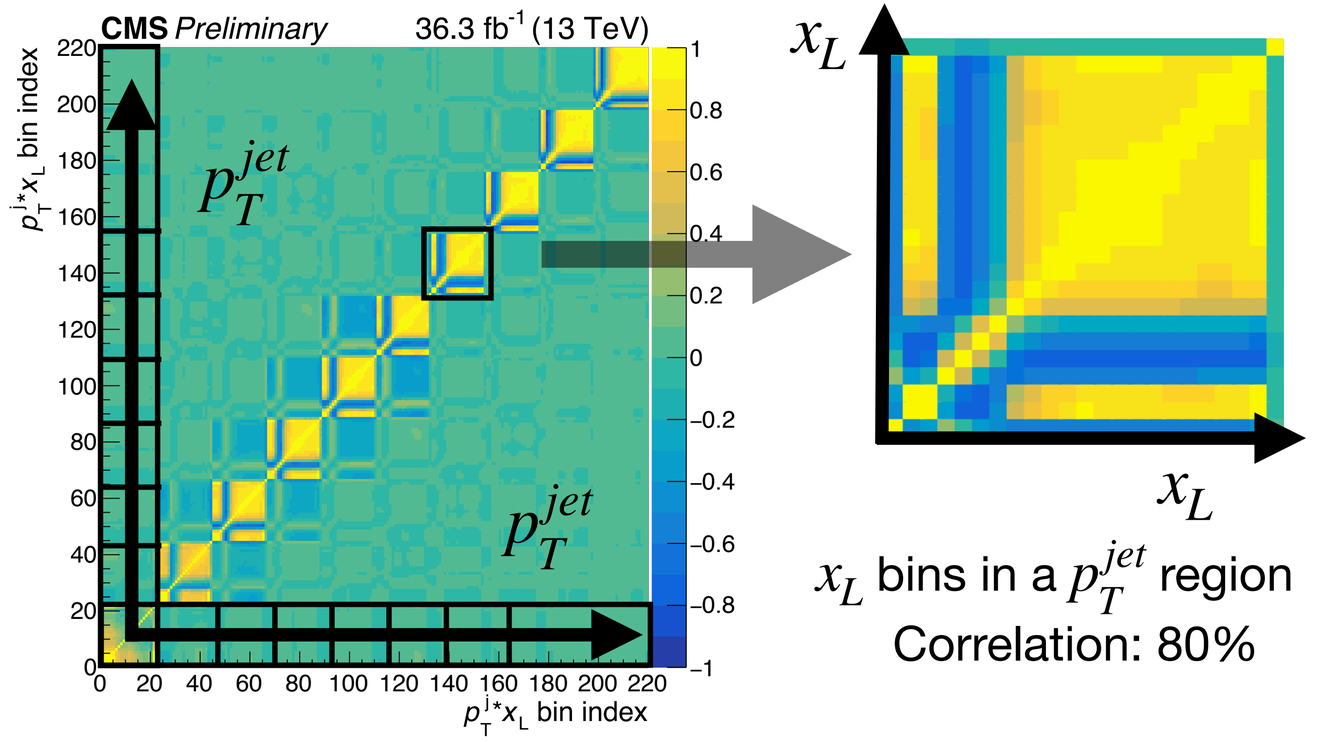
$$E3C = \frac{d\sigma^{[3]}}{dx_L} = \sum_{i,j,k}^{n} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - \max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k}))$$

Insensitive to soft radiation

EnC: statistical correlations

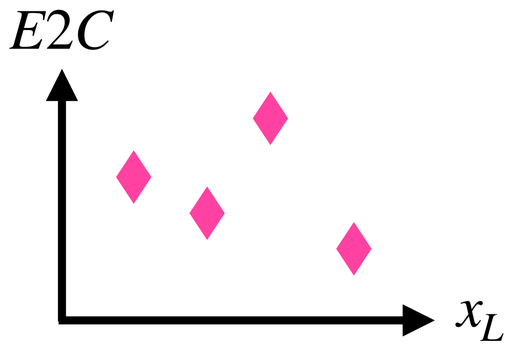
Multi entry distribution for every jet, statistical correlation important

E2C correlation matrix



x_L bins in a p_T^{jet} region

Correlation: 80%

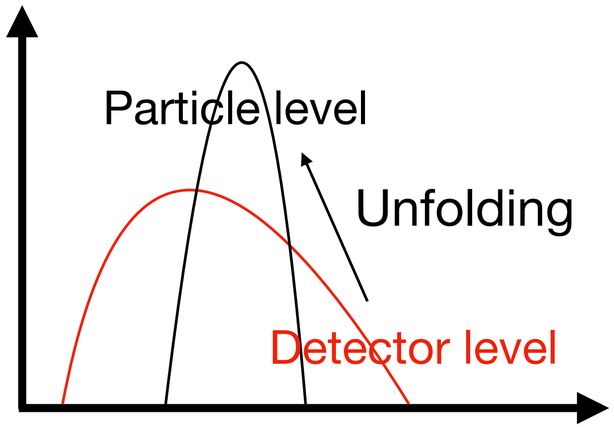


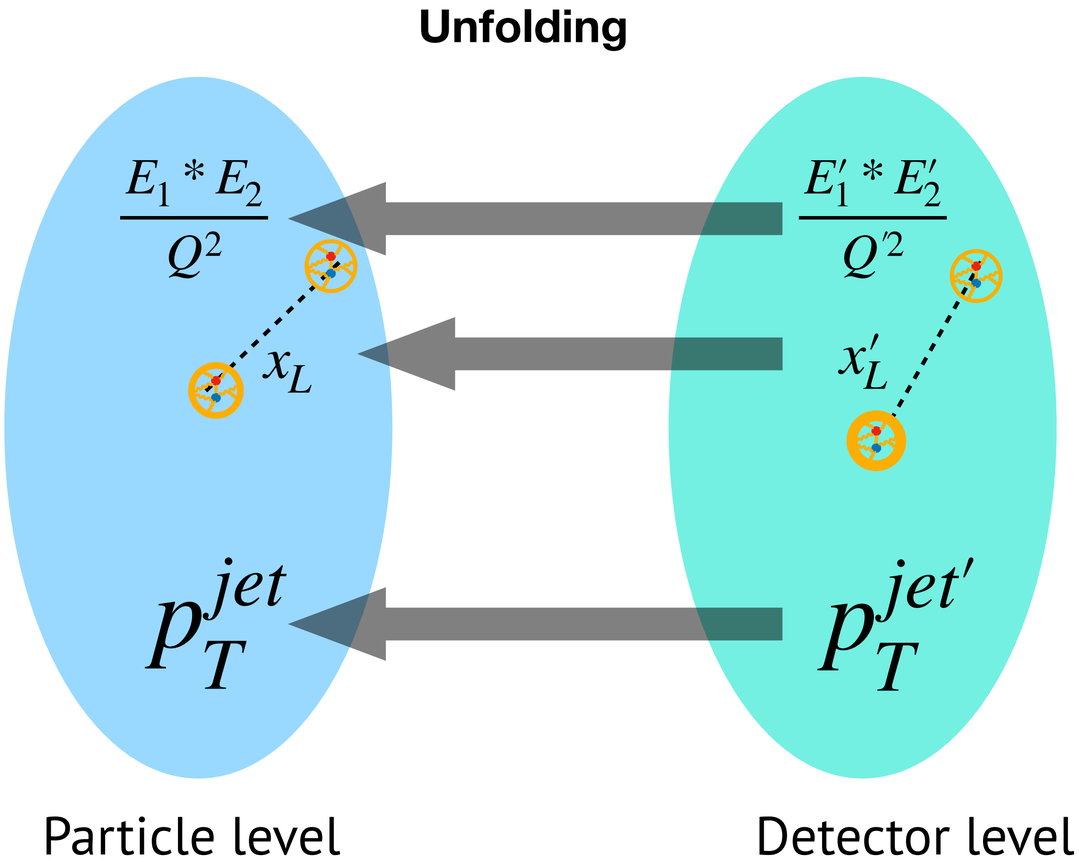
EnC: Constituent unfolding

Unfolding: detector level -> particle level

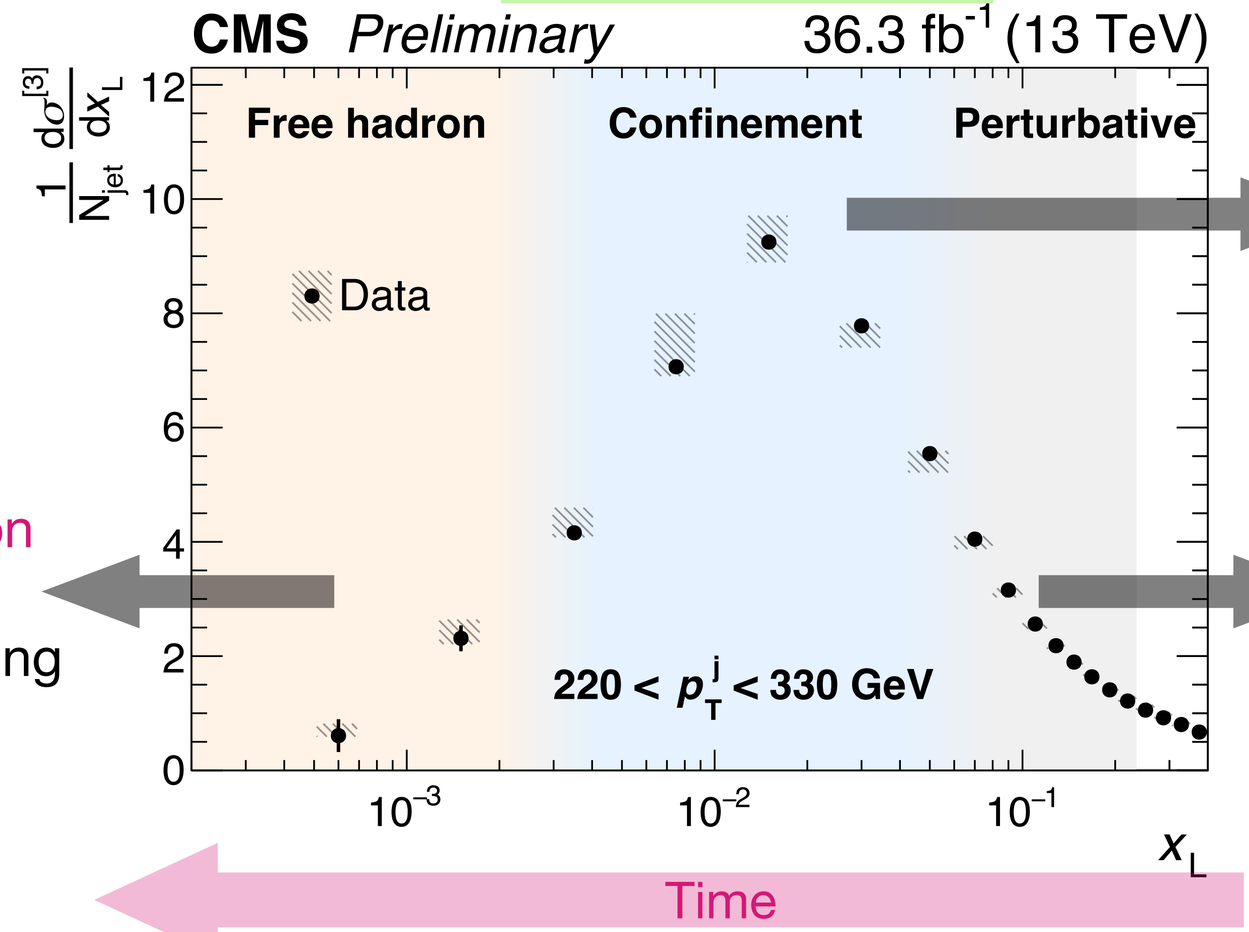
Unfold jet constituents instead of distribution:

- p_T^{jet}, x_L and energy weight, 3D unfolding
- $10 * 22 * 20 = 4400$ bins





E3C measurement



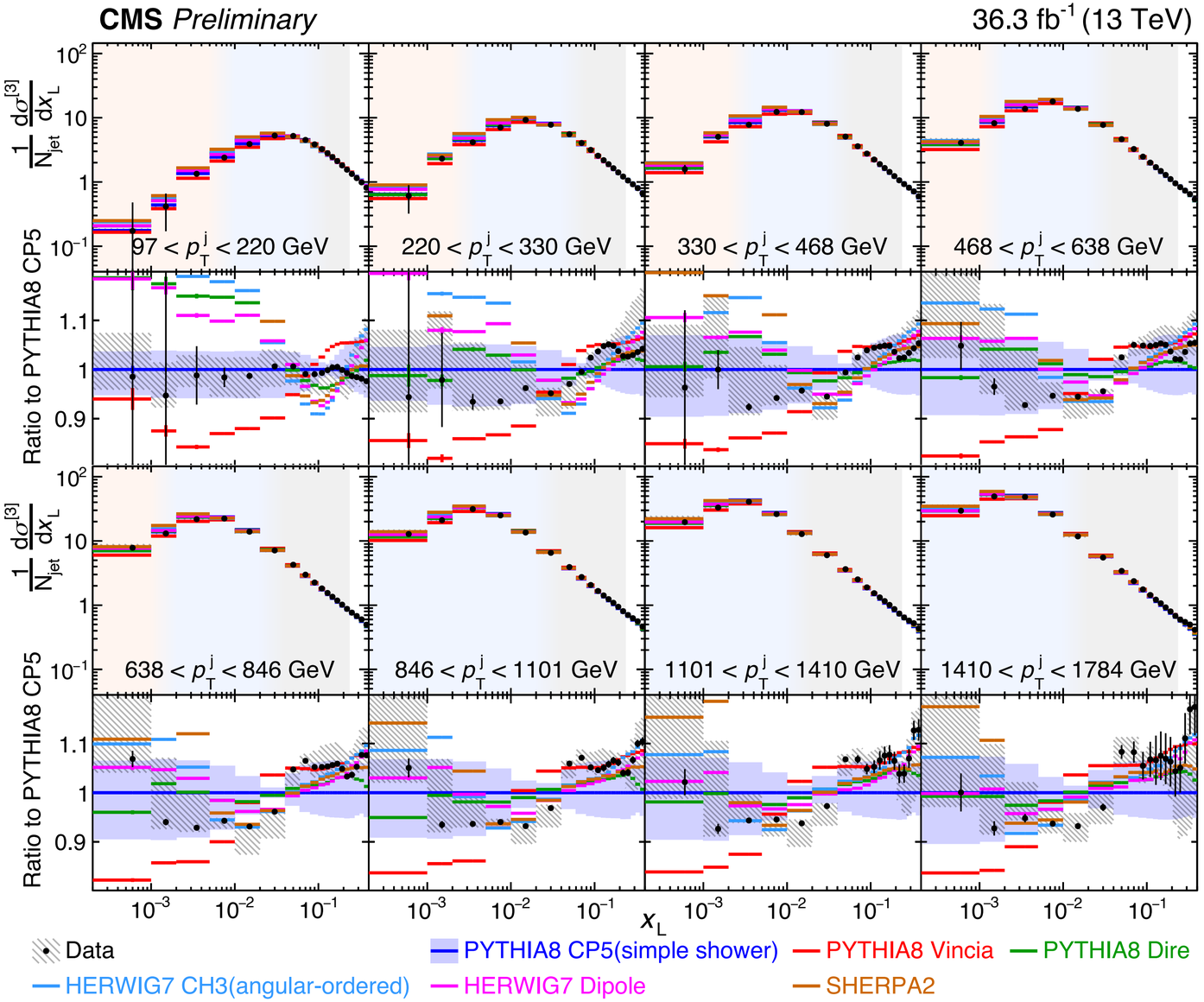
Phase transition
from parton to hadron

Non-interacting hadron
random distribution
integer power-law scaling

Interacting partons
non-integer scaling

CMS-PAS-SMP-22-015
https://cds.cern.ch/record/2866560

E3C in all pT regions

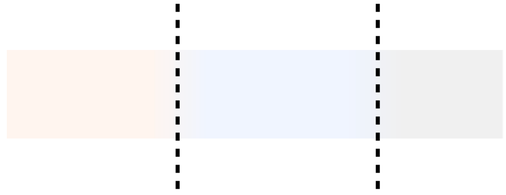


Boundary shift with jet pT

$$Q \propto x_L{}^{*} p_T^{jet}$$

$$p_T^{jet} \uparrow,\ x_L \downarrow$$

Boundary



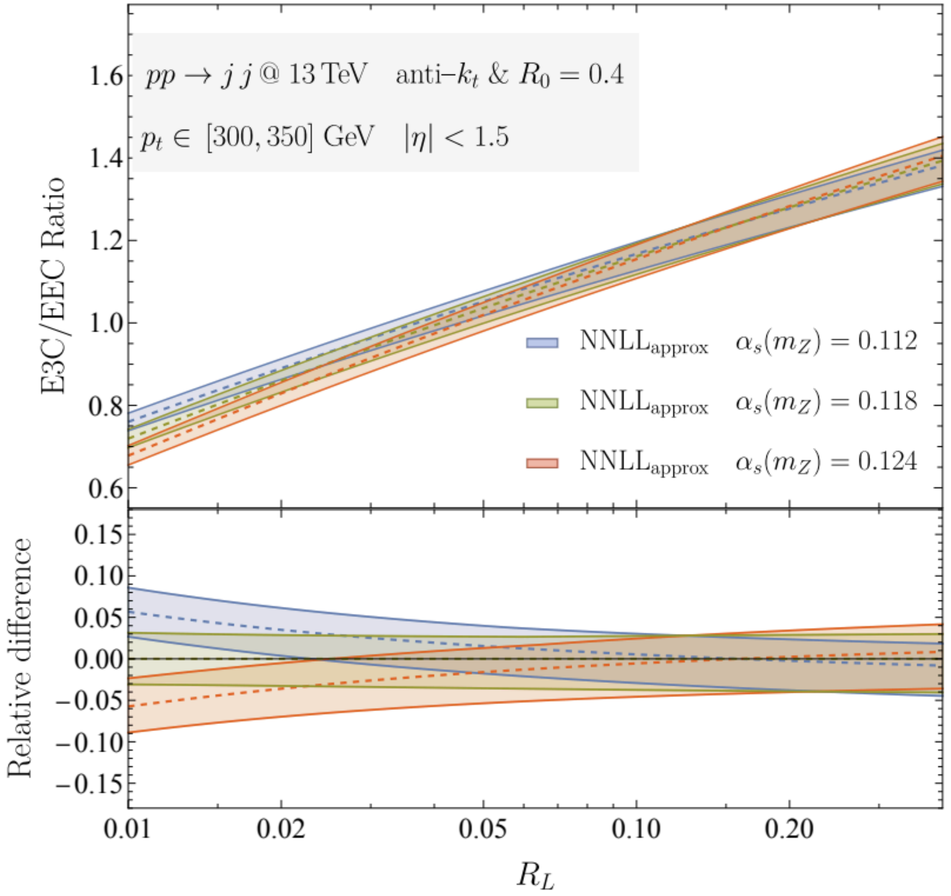
$$x_L \approx \frac{0.8}{p_T^{jet}} \qquad x_L \approx \frac{20}{p_T^{jet}}$$

E3C/E2C: a new way to extract α_S

Chen, Gao, Li, Xu, Zhang, and Zhu, *arXiv:2307.07510*

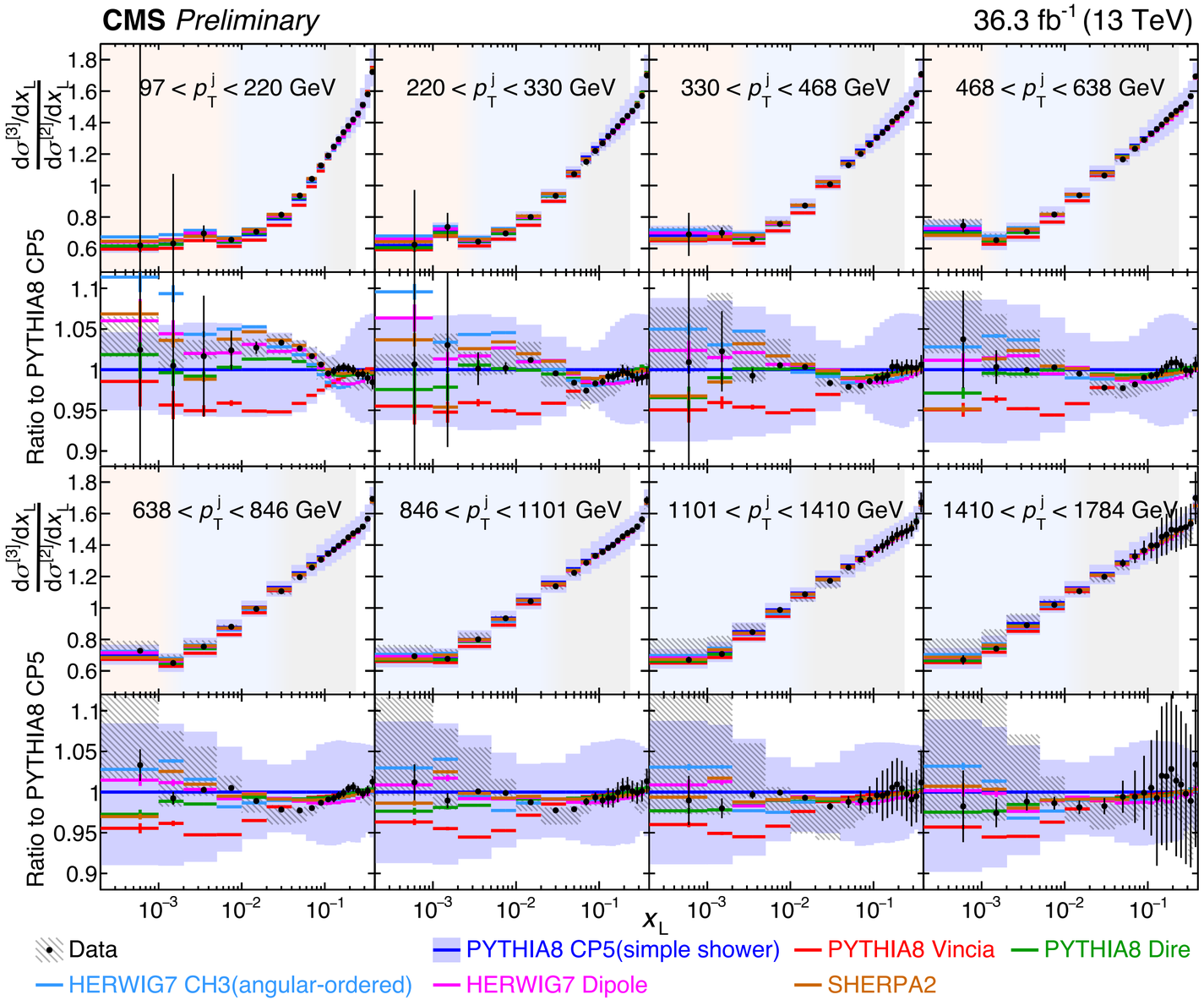
At LL, E3C/E2C is a linear function of α_s

$$\propto \alpha_S(Q)\ln x_L + O(\alpha_s^2)$$



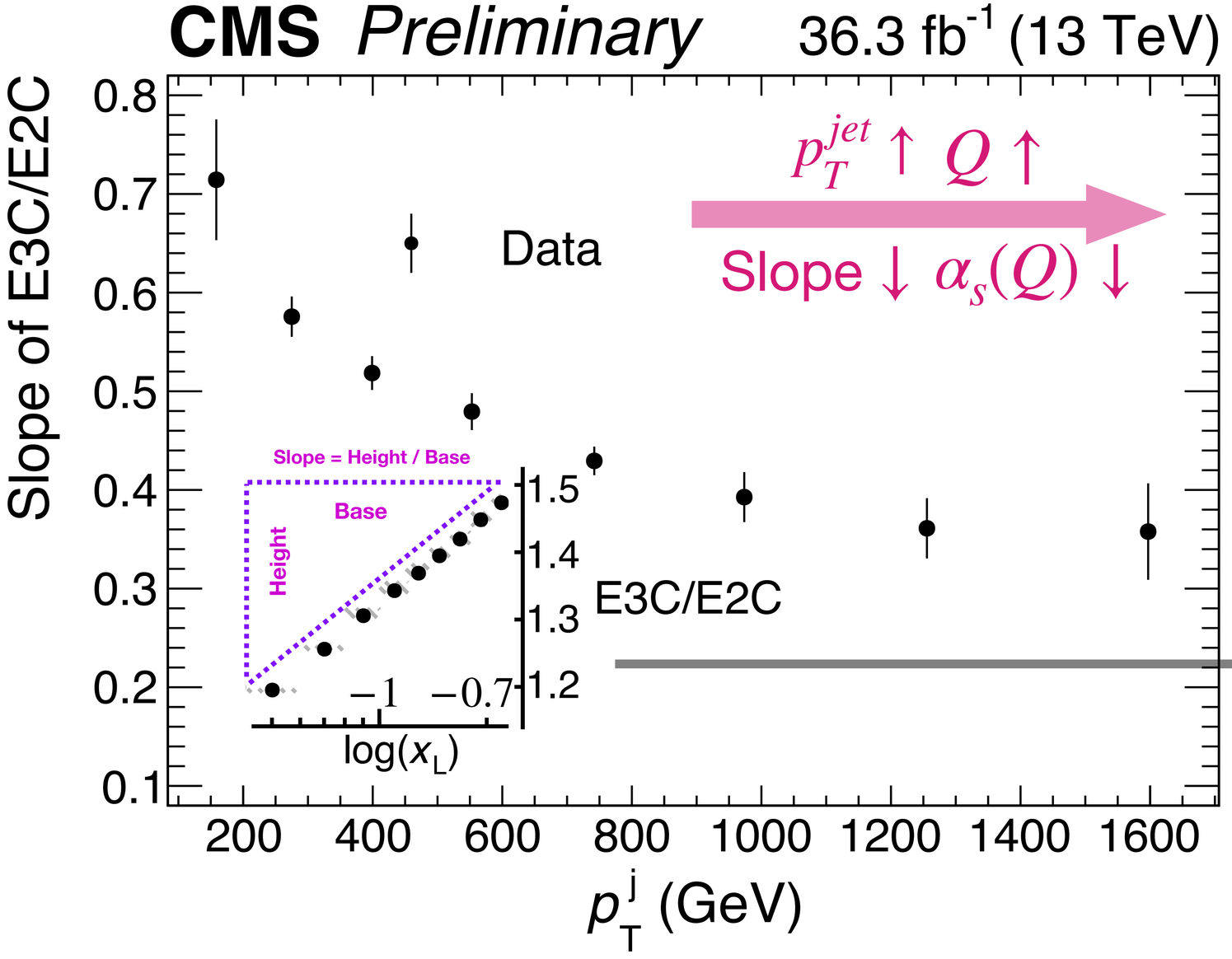
$\alpha_S(M_Z) \uparrow$ Slope $\uparrow$

E3C/E2C



p_T^{jet} ↑ , Slope ↓

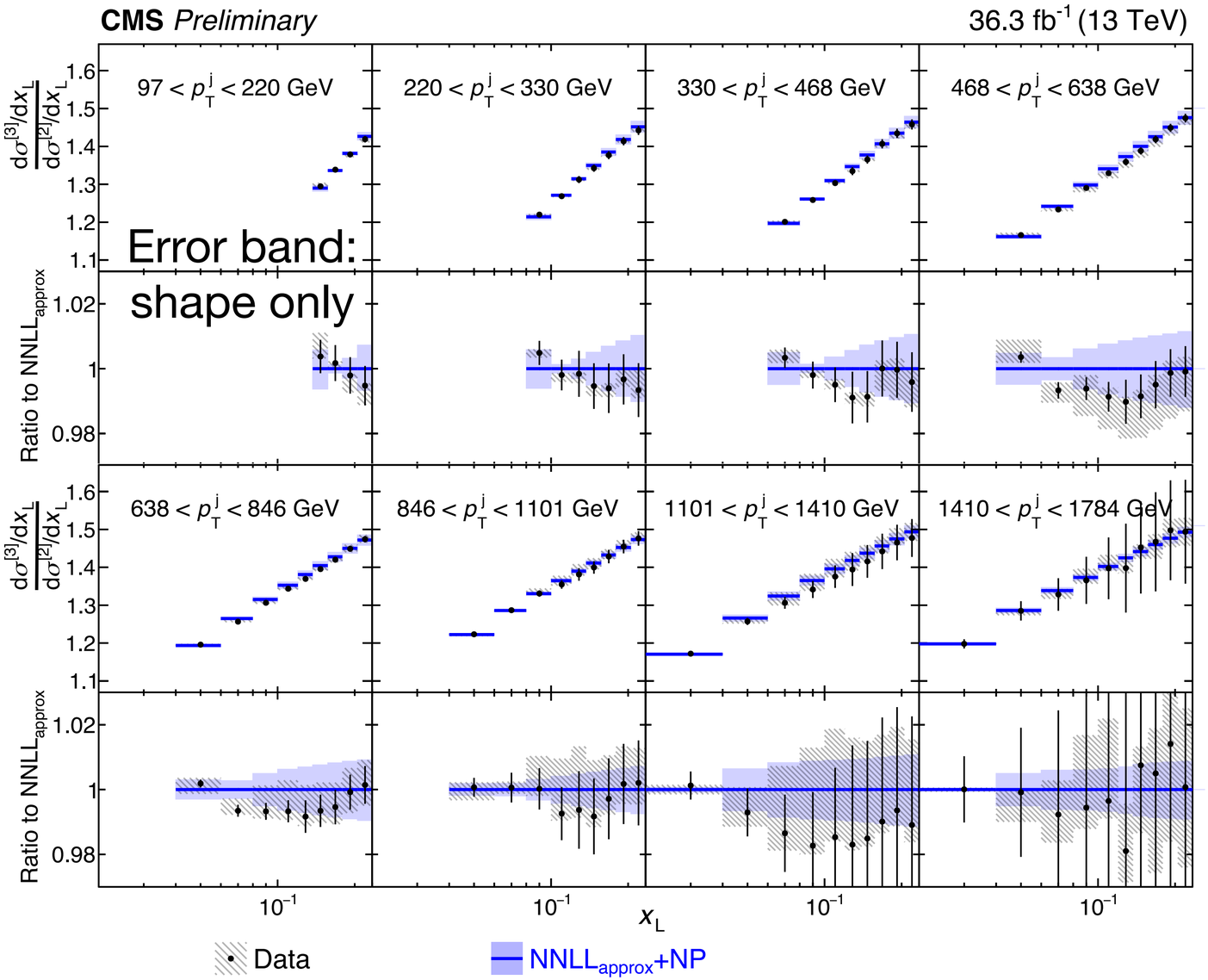
Direct observation of asymptotic freedom



$\propto \alpha_S(Q) \ln x_L + O(\alpha_s^2)$

Data point: slope fitted in a p_T^{jet} region

Unfolded E3C/E2C vs NNLL-approx



$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

$$= 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

major source

Covariance matrix

QCD scale of NNLLapprox

Neutral hadron energy scale

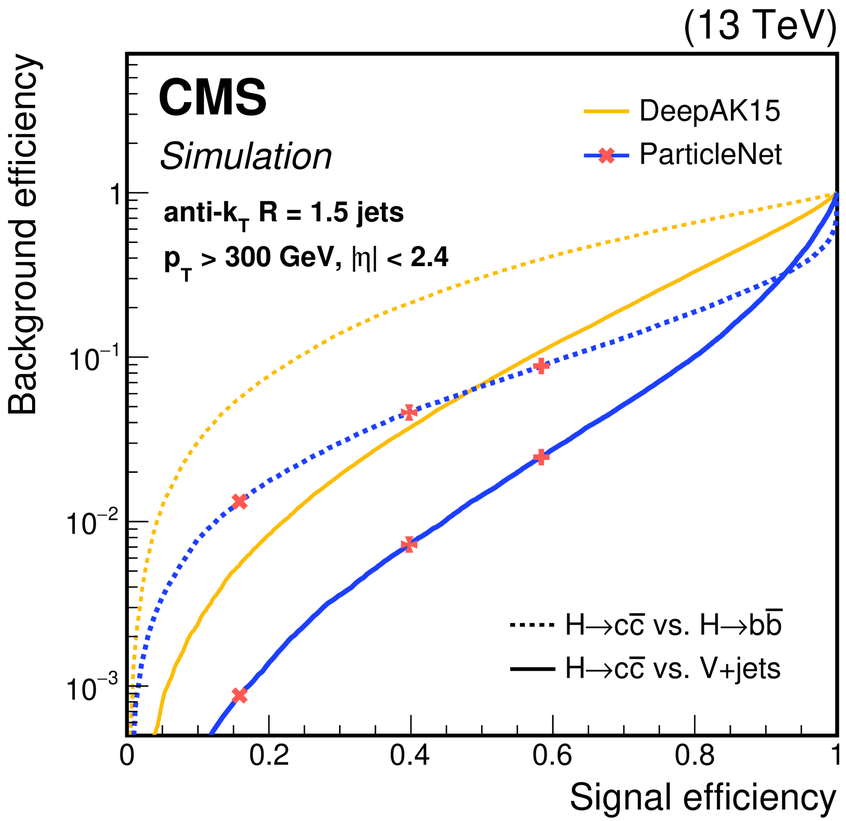
Uncertainty ~ 4%,
Most precise from jet substructure to date

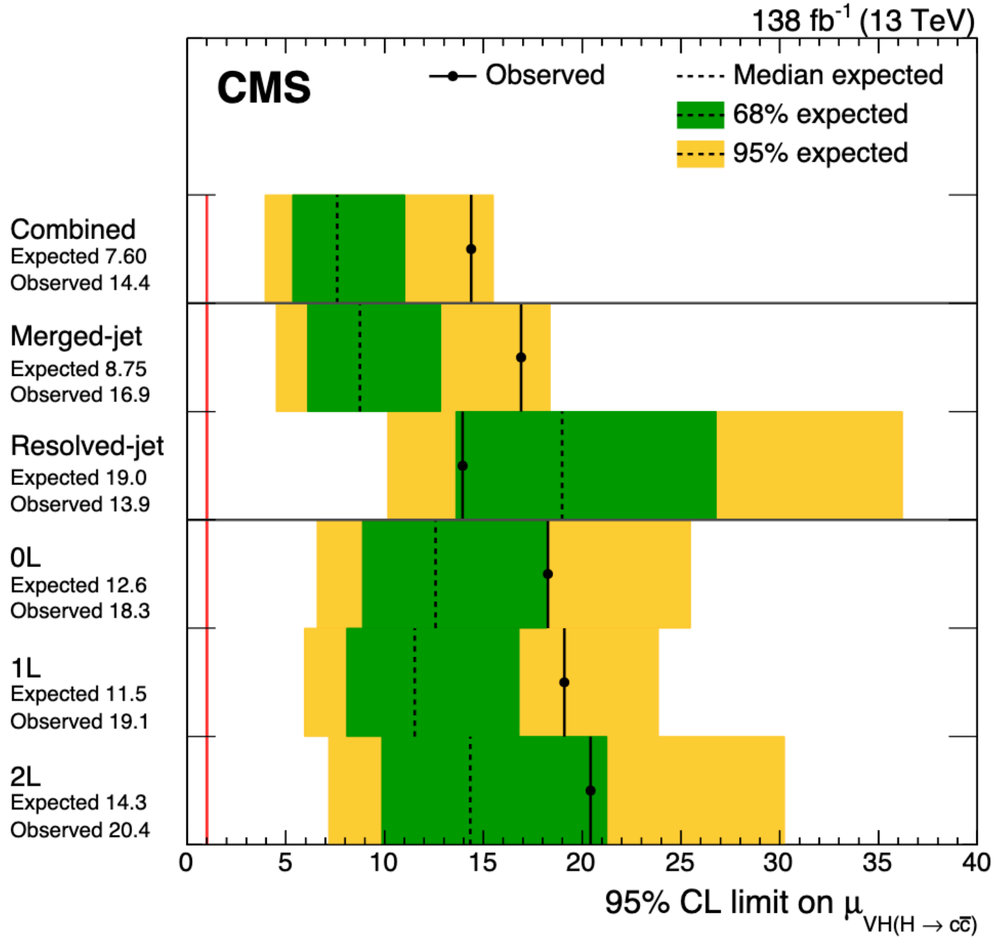
Summary

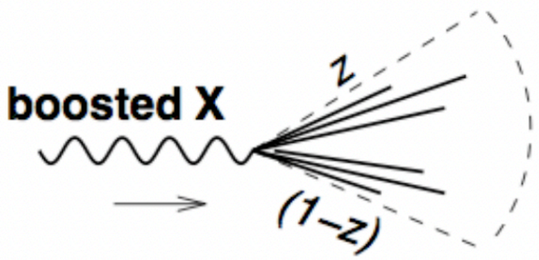
- Rich program in QCD precision measurement
- Jet substructure has become a powerful tool to understand QCD with high precision

Backup

http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-21-008/index.html







single jet

$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

Matteo Cacciari, FeynRules/MadGraph School