QCD considerations at 10 TeV pCM

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ECFA UK, September 2024

Introduction

Outline :

1. Logarithms can spoil the perturbative convergence
2. The effect of the high energy logarithm already at the LHC
3. Expectations and comparison to data

Fixed order QCD

Fixed order perturbative expansion of dijet observable R

$$R = r_0\alpha^2 + r_1\alpha_s^3 + r_2\alpha^4 + r_3\alpha^5 + r_4\alpha^6 + \cdots$$

Perturbative QCD works!

(fixed order for observables with large pt single scale)

Multi-Jet and Multi-Scale QCD: attempt to extend our understanding of perturbative QCD away from the study of total cross sections with one perturbative scale.

Excitement/Challenge: *not* just 5-10% effects!

Surprises may lurk round the corner

Discuss two recent measurements by ATLAS and their implications for predictions for future colliders

Resummation

Consider the **perturbative expansion** of an observable

$$R = r_0\alpha^2 + r_1\alpha_s^3 + r_2\alpha^4 + r_3\alpha^5 + r_4\alpha^6 + \cdots$$

Fixed order pert. QCD will calculate a fixed number of terms in this expansion. For multi-scale processes r_n may contain **large logarithms** so that $\alpha_s \ln(\cdots)$ is large.

$$R = \left(r_0^{LL} + r_0^{SL}\right)\alpha_s^2 + \left(r_1^{LL}\ln(\cdots) + r_1^{NLL} + r_1^{SL}\right)\alpha_s^3 + \cdot$$
$$= \alpha_s^2 \sum_{n=0} r_n^{LL}(\alpha_s \ln(\cdots))^n + \alpha_s^3 \sum_{n=1} r_n^{NLL}(\alpha_s \ln(\cdots))^{n-1} + \text{sub-leading terms}$$

Replace the perturbative parameter $\boldsymbol{\alpha_s}$ with $\boldsymbol{\alpha_s \ln(\cdots)}$. Useful if the terms can be **summed to all orders** in the perturbative expansion (LLA, NLLA).

The High Energy Logarithm

The High Energy Logarithm has as argument the hierarchy between the partonic centre of mass and the transverse jet momentum $\ln(\hat{s}/p_t^2) \sim \Delta y_{fb}$. This will dominate the behaviour of the perturbative corrections at large $\hat{s}/pt^2$.

Relevant for regions of large m_{jj} (VBF, VBS,...). Obviously even more important for higher energy colliders, but will here discuss recent results from LHC. Already clear effects in the relevant regions.

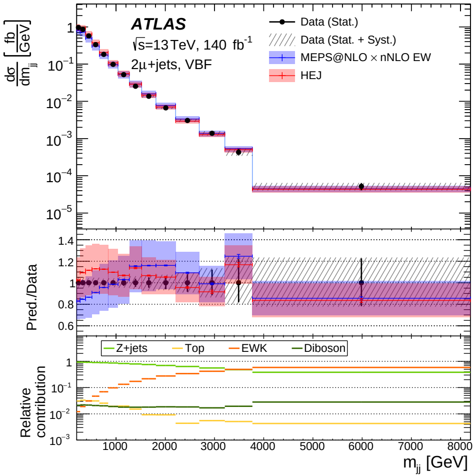
Two ATLAS studies:

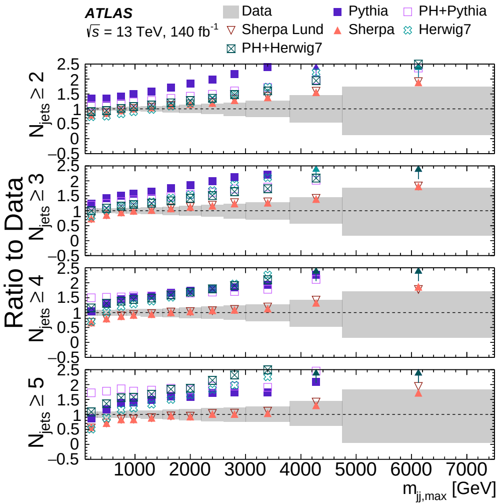
arxiv:2405.20206 $R_{32} = \sigma_{3j}/\sigma_{2j}$ studied vs. m_{jj}.

arxiv:2403.02793 Missing transverse momentum and jets.

Systematic deviations in $\log \hat{s}/p_t^2 \sim \Delta y$ for perturbative predictions not controlling the high energy logarithmic corrections.

$d\sigma/d\max(m_{jj})$



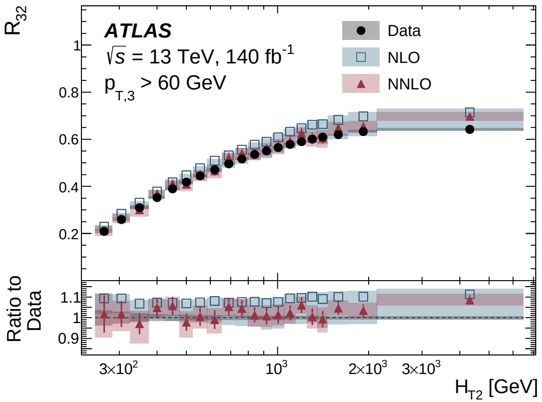


Systematic deviations in $\ln(m_{jj})$ for perturbative predictions not controlling the high energy logarithmic corrections.

R_{32} measurement

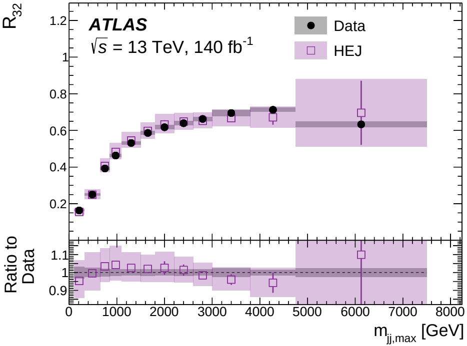
$R_{32} = \frac{\sigma_{3j}}{\sigma_{2j}}$ both measured vs. H_{T2}, m_{jj} and rapidity differences.
Simple cuts: Jets defined with anti-k_t, $R = 0.4$, $p_t > 60$GeV/c, $|y| < 4.4$.

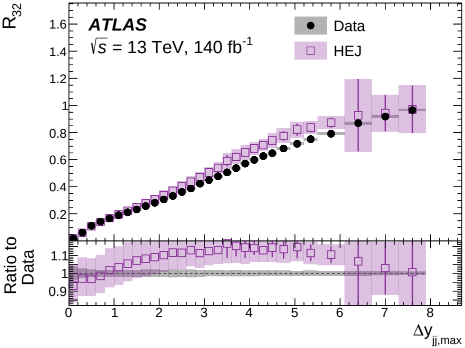
R_{32}



Plot from arxiv:2405.20206 (ATLAS).
Fixed order obtains reliable prediction vs. transverse momentum

R_{32}





Plots from arxiv:2405.20206 (ATLAS).
Data clearly has $R_{32} \sim \alpha_s \Delta y$. A leading logarithmic control should get the slope right (up to α_s corrections from NLL).

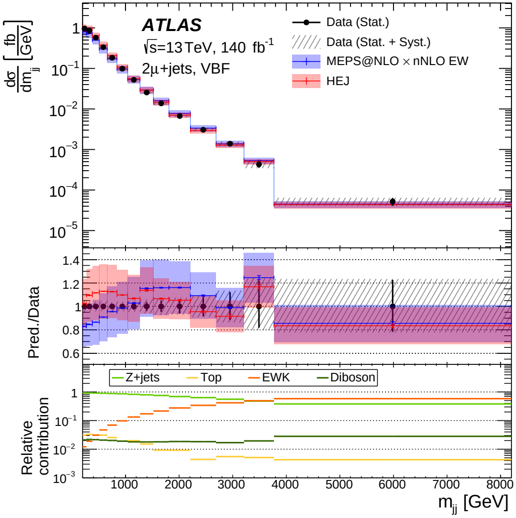
HEJ does indeed get the shape and slope right to within $\sim \alpha_s$ corrections.

Z plus jets

arxiv:2403.02793 ATLAS: Missing transverse momentum and jets.

Attribute	≥ 1 jet	VBF
$\Delta\phi$ (jet, $p_{\mathrm{T}}^{\mathrm{miss}}$)	> 0.4 for four leading p_{T} jets	
Hadronic τ-lepton	None with $p_{\mathrm{T}} > 20$ GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$	
Leading jet p_{T} [GeV]	> 120	> 80
Sub-leading jet p_{T} [GeV]	–	> 50
Leading jet $\lvert y\rvert$	< 2.4	< 4.4
Sub-leading jet $\lvert y\rvert$	–	< 4.4
Dijet invariant mass m_{jj} [GeV]	–	> 200
$\lvert\Delta y_{jj}\rvert$	–	> 1
In-gap jets	–	None with $p_{\mathrm{T}} > 30$ GeV

Z plus jets



Blue: State of the art prediction, but without high energy logarithms.
Red: High Energy Jets

arxiv:2403.02793 (ATLAS)

Where can this help the experimental programme

A better understanding/description of the radiation pattern (i.e. where the additional jets are radiated) will help in suppressing the “QCD” background in VBF/VBS studies.

Starts impacting other measurements already at the LHC

The high energy logarithms will be even more important at any future collider - need to start preparing the predictions now, but we need input form experiments to understand which directions to push first.