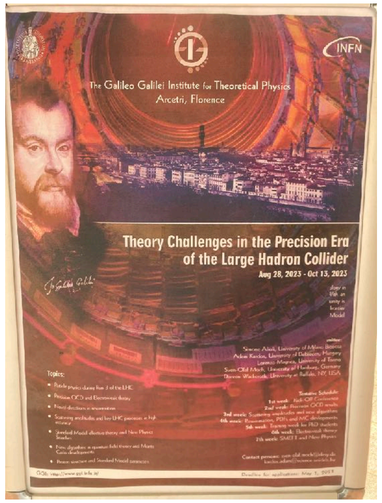
High Energy Resummation for Jet Processes at the LHC



Jennifer Smillie
Higgs Centre for Theoretical Physics

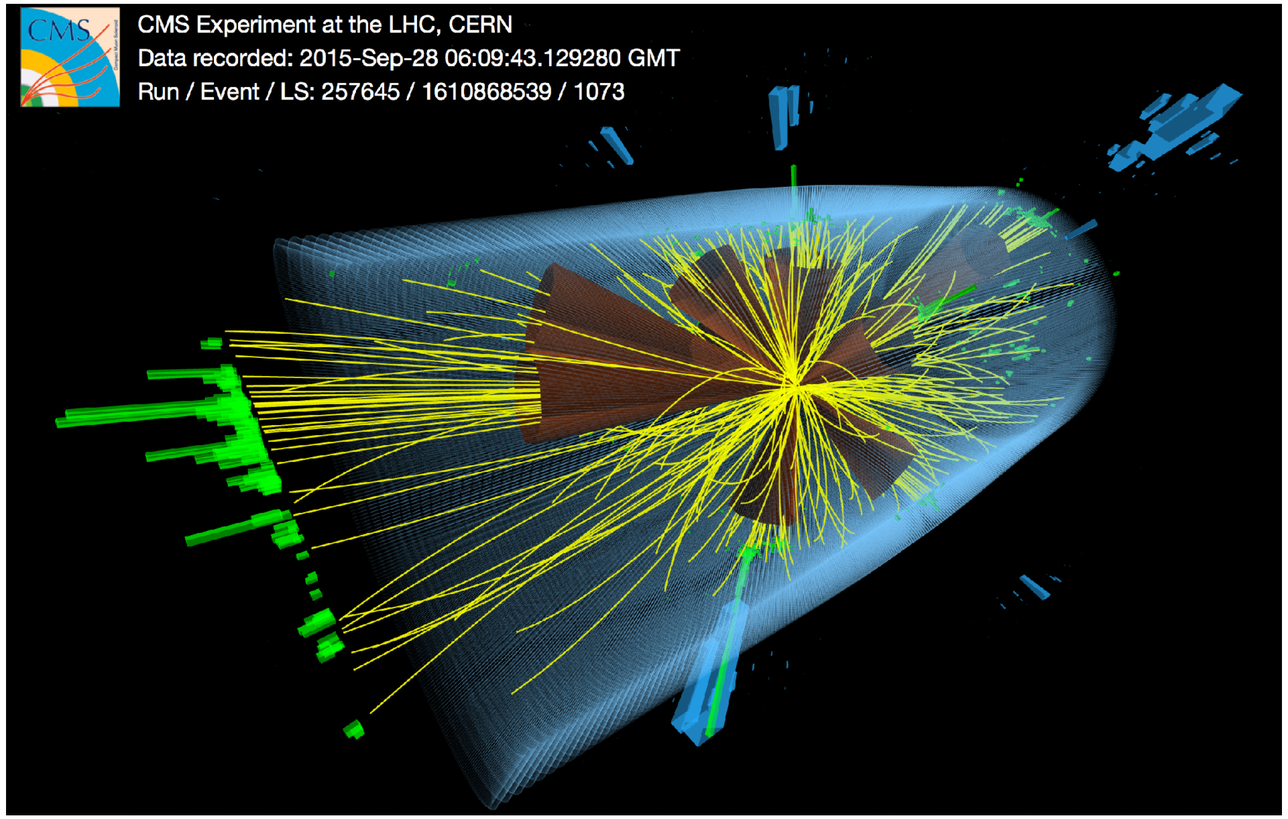
Theory Challenges in the Precision Era of the Large Hadron Collider

Galileo Galilei Institute — August 2023

European Research Council

One Example

12 jets with p_T > **50 GeV** at CMS (13 TeV)



Many colour-charged, hard particles with p_T, s_{ij}, $\hat{s}$

Large logs in s_{ij}/p_T^2 damage convergence of pert. expansion

High Energy Resummation

Inclusive 2-jet partonic cross section given by $\int d\mathrm{PS}_2\, |\mathrm{M}_{2j+}|^2$, with

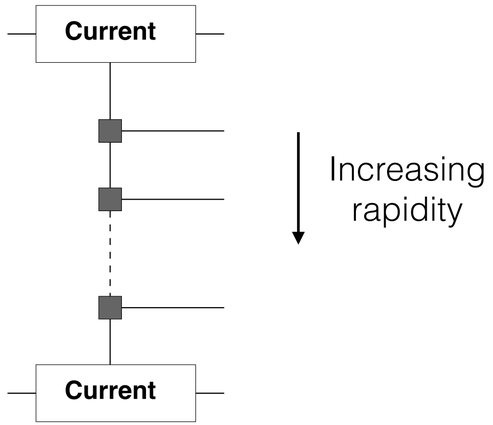
$$
\begin{aligned}
|\mathrm{M}_{2j+}|^2 \;=\;& \alpha_s^2 \left(a_2(s^2/t^2) + b_2\right) \\
&+ \alpha_s^3 \left(a_3(s^2/t^2)\log(s/t) + b_3(s^2/t^2) + c_3\right) \\
&+ \alpha_s^4 \left(a_4(s^2/t^2)\log^2(s/t) + b_4(s^2/t^2)\log(s/t) + \ldots\right) \\
&+ \ldots
\end{aligned}
$$

- Logs arise from integrals over loop momenta in virtuals and from integrals over reals
- Our description = **LO + LL + …**
- Considering large values of x , no $\log\left(\frac{1}{x}\right)$

High Energy Limit

Calculate leading terms from amplitudes in the High Energy limit: $s_{ij} \to \infty$, $|p_{Ti}|$ finite

See Einan Gardi's talk (Tues)



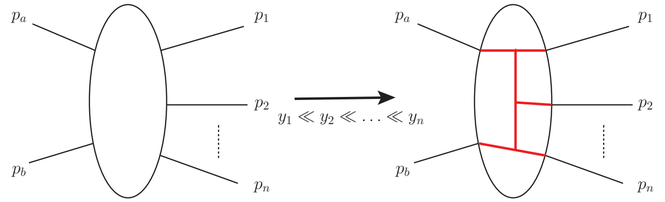
Local pieces, independent of the rest of the process (real + virtual)

Can use this simpler structure to make an efficient event generator for arbitrary numbers of quarks/gluons.

Powers of s_{ij} in the real matrix elements match powers of log in the inclusive matrix element.

Regge scaling dictates the scaling of the amplitude with s_{ij} for a given process:

$$\mathcal{M} \propto s_{12}^{\alpha_{12}} \dots s_{n-1,n}^{\alpha_{n-1,n}} \; f(\{p_{T,i}\})$$



where α_{ij} is the spin of that particle in effective t-channel

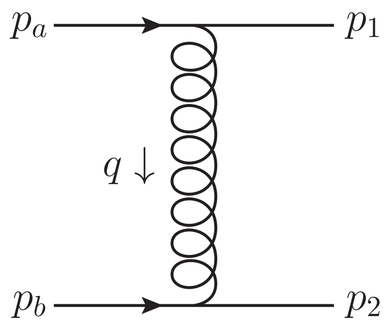
Brower, DeTar, Weis Phys Rept. 14:257, 1974

Not Quite the High Energy Limit

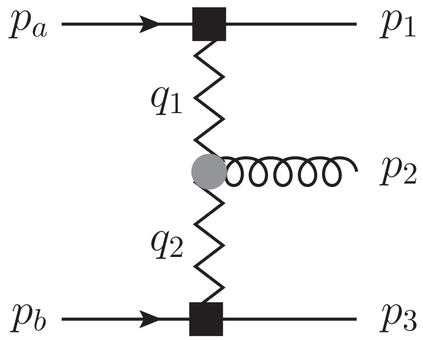
Kinematic parts (neglecting phases)

HEJ

HE



$$\frac{j^\mu(p_a,p_1)\cdot j_\mu(p_b,p_2)}{\hat{t}} \longrightarrow \frac{2\hat{s}}{|q_\perp|^2}$$



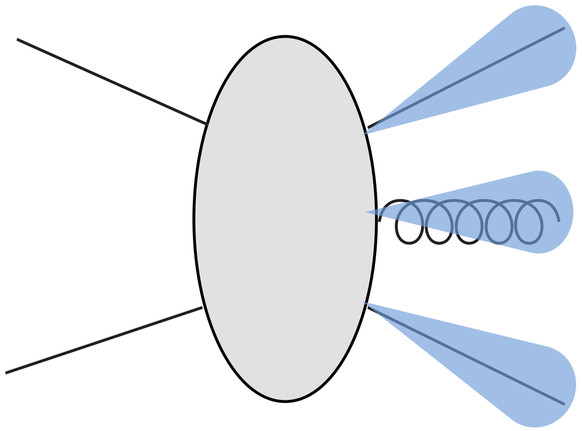
$$\varepsilon_\rho^* \frac{j^\mu(p_a,p_1)\cdot j_\mu(p_b,p_3)}{q_1^2 q_2^2}\times$$
$$\Big[-(q_1+q_2)^\rho$$
$$+\frac{p_a^\rho}{2}\left(\frac{q_1^2}{p_2.p_a}+\frac{p_2.p_b}{p_a.p_b}+\frac{p_2.p_3}{p_a.p_3}\right)+p_a\leftrightarrow p_1$$
$$-\frac{p_b^\rho}{2}\left(\frac{q_2^2}{p_2.p_b}+\frac{p_2.p_a}{p_a.p_b}+\frac{p_2.p_1}{p_b.p_1}\right)-p_b\leftrightarrow p_3\Big]$$
$$\longrightarrow \frac{2\hat{s}}{|q_{1\perp}|^2|q_{2\perp}|^2}\frac{q_{1\perp}^* q_{2\perp}}{\sqrt{2}p_{2\perp}}$$

or c.c.

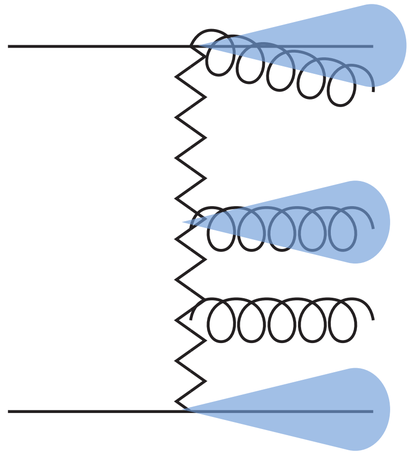
Matching to Fixed Order

Matching to fixed order event-by-event for each jet multiplicity:

- multiplicatively for matrix elements with LL or NLL description
- remaining configurations added



LO 3j event



Possible HEJ resummed event
with jet rapidities kept fixed

$$\text{Event weight} \sim \frac{|\mathcal{M}_{\text{LO}}|^2 |\mathcal{M}_{\text{HEJ}}|^2}{|\mathcal{M}_{\text{HEJ,LO}}|^2}$$

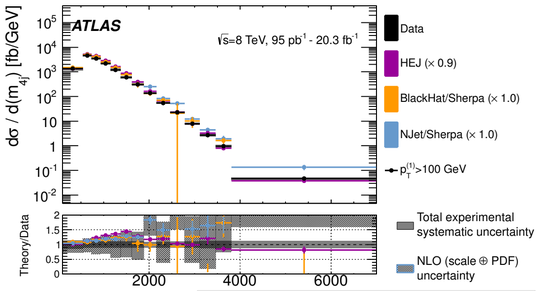
Modifications only to matrix elements, phase space exact and collinear factorisation of pdfs

“HEJ 2”

The High Energy Jets (HEJ) framework is

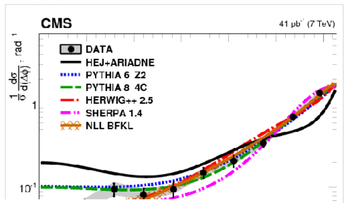
- exact for simple processes (2 to 2 (+X))
- accurate to leading logarithm in s/t
- constructed event-by-event
- takes LO samples as input

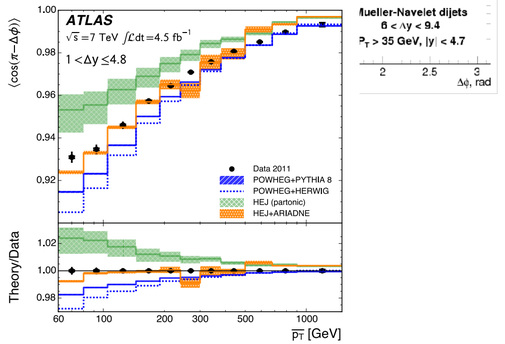
- gauge invariant in all phase space
- sufficiently fast for numerical integration (up to 30 gluons)



HEJ2 event generator: https://hej.hepforge.org

Andersen, Hapola, Heil, Maier & JMS arXiv:1902.08430





Extra colour-neutral bosons can be added without affecting the logarithmic accuracy

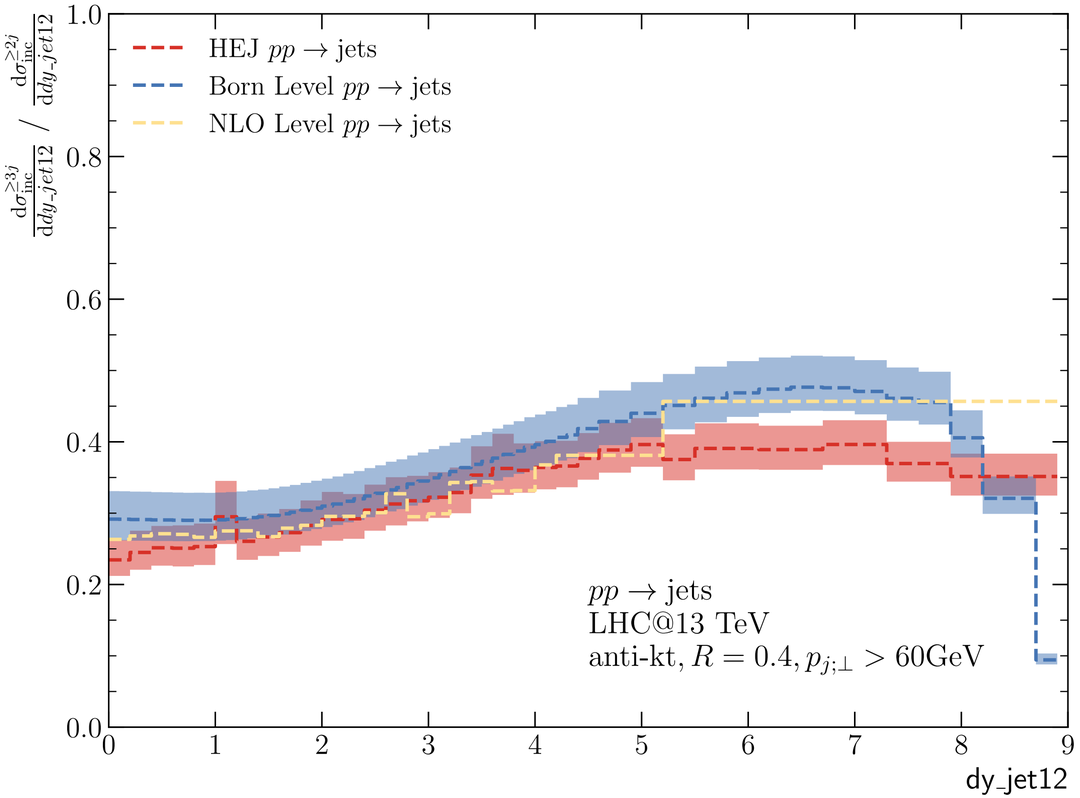
HEJ2.2 includes: $\geq 2j, H+ \geq 1j, W(\to \ell\nu)+ \geq 2j, Z/\gamma^*(\to \ell\bar{\ell})+ \geq 2j, W^{\pm}W^{\pm}+ \geq 2j$

Andersen, Ducloué, Elrick, Hassan, Maier, Paltrinieri, Papaefstathiou & JMS arXiv:2303.15778

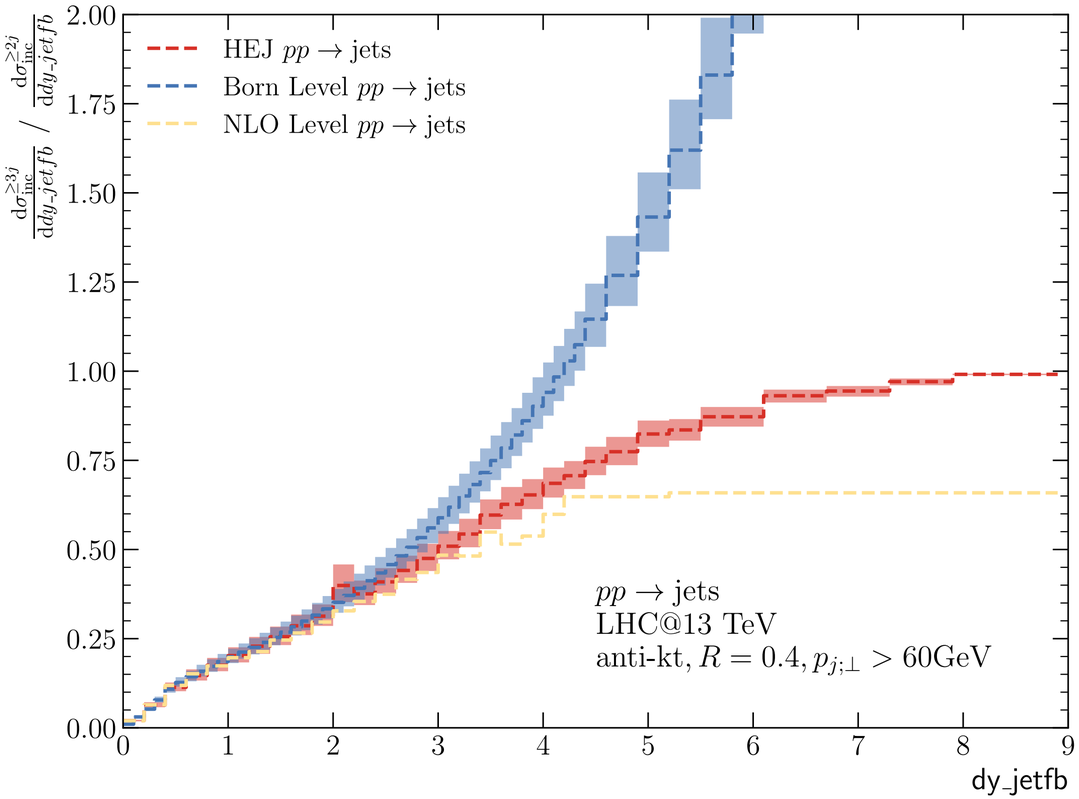
Inclusive 3-jet/2-jet Ratios

Comparison between resummed HEJ results and fixed order for forthcoming ATLAS study

Plots by C. Elrick



Similar, fairly flat vs Δy_{12}

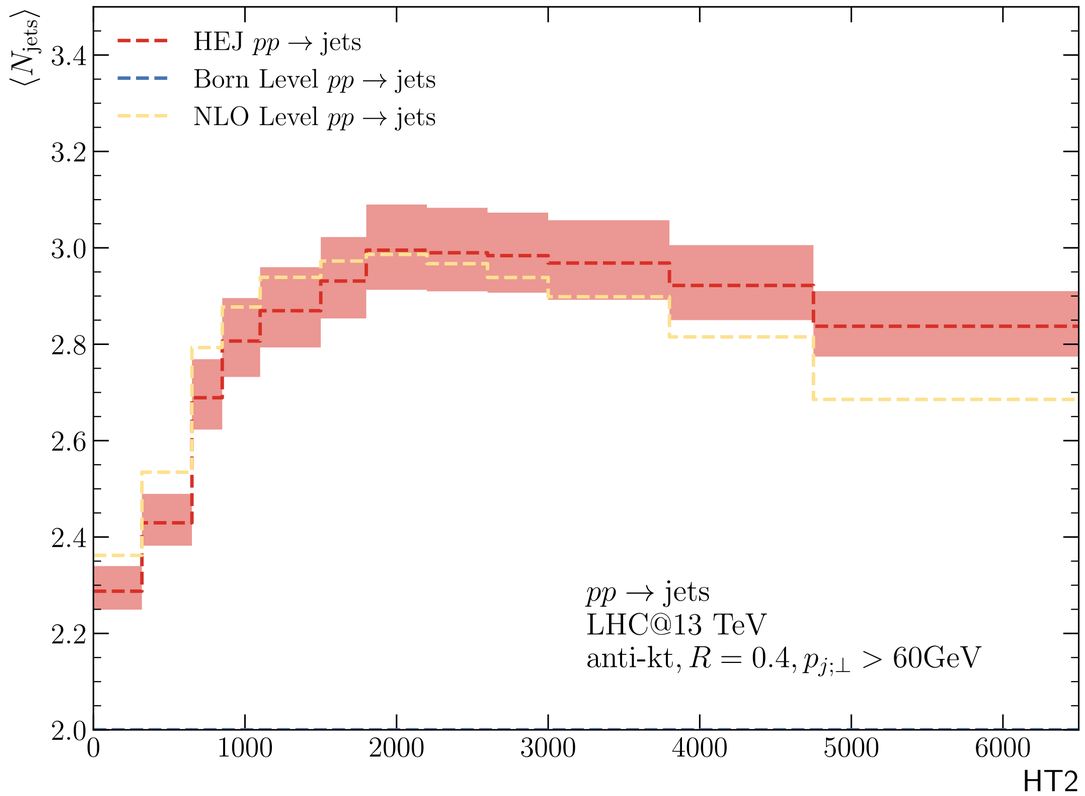


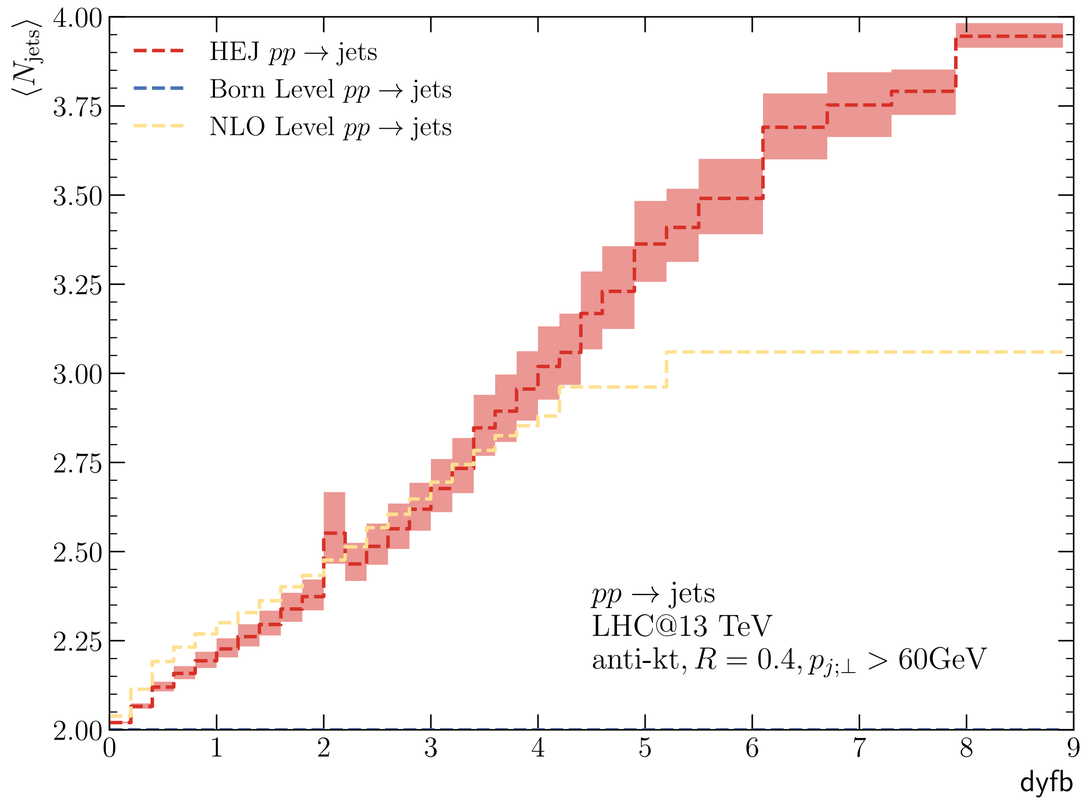
Larger differences vs

Example: Average Number of Jets

Comparison between resummed HEJ results and fixed order for forthcoming ATLAS study

Plots by C. Elrick





Similar for $p_\perp$ observables

Similar for Δy_{fb} until limit of NLO

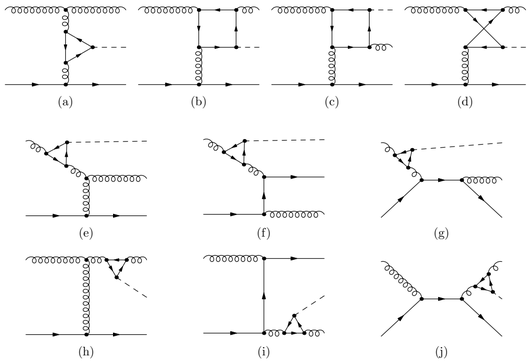
Application to Higgs VBF (QCD component)

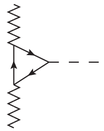
Fixed-order difficult because LO = 1-loop.
Don't even have LO results with full finite mass and loop effects for 4j+

Del Duca et al hep-ph/0105129, hep-ph/0108030
Greiner et al arXiv:1608.01195

In HE limit, factorised structure removes complexity from increasing number of jets

Del Duca, Kilgore, Oleari, Schmidt & Zeppenfeld hep-ph/0301013
Andersen, Cockburn, Heil, Maier & JMS arXiv:1812.08072





Only boxes and triangles for any *n*

Keeps all finite mass and loop propagator effects

Fixed-order matching performed to highest-available accuracy

Here use Sherpa and OpenLoops

Gleisberg et al arXiv:0811.4622; Cascioli, Maierhöfer, Pozzorini arXiv:1111.5206

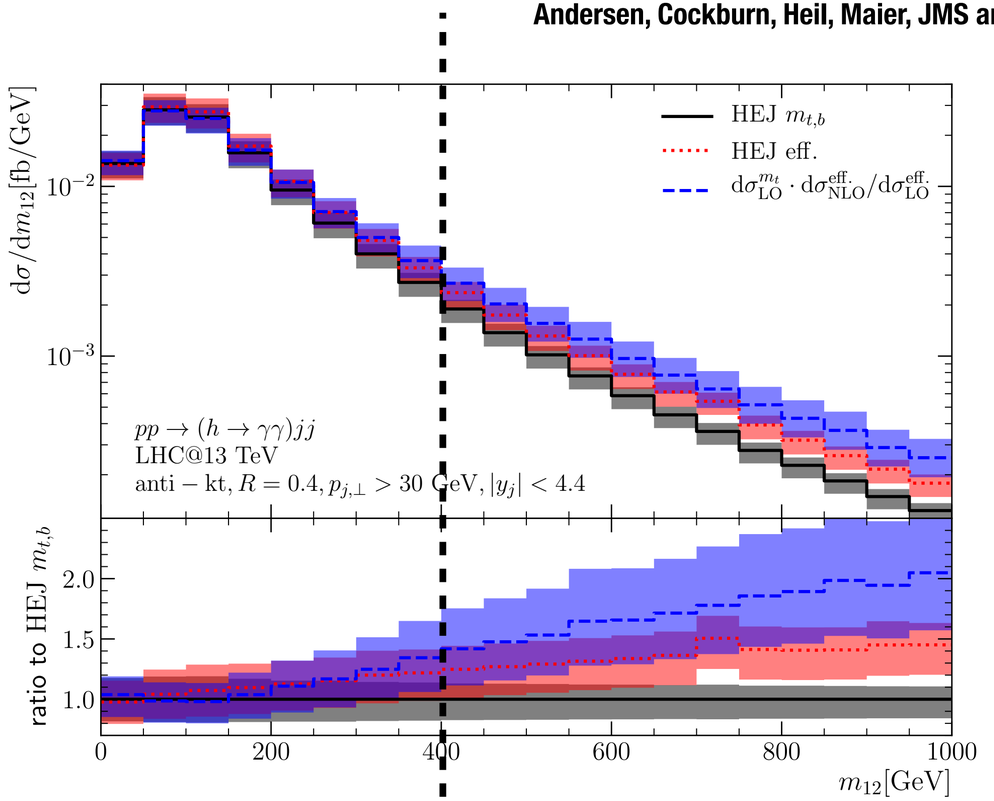
Application to Higgs VBF (QCD component)

Resummation alone reduces cross section at large values of m_{12}

Finite quark mass/loop effects reduce x-section in VBF cuts by *further* 11%

Prediction	xs after VBF cuts
Fixed order	9%
HEJ	4%

Andersen, Cockburn, Heil, Maier, JMS arXiv:1812.08072



Typical VBF cut

Similar impact on distributions in $pp \to W^{\pm}W^{\pm}jj$, also enhanced by exp. selections

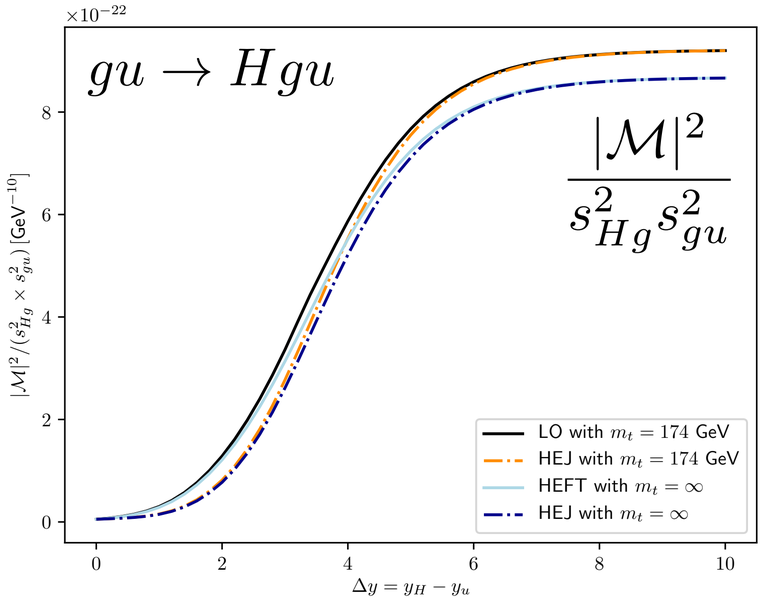
Andersen, Ducloué, Elrick, Nail, Maier, JMS arXiv:2107.06818

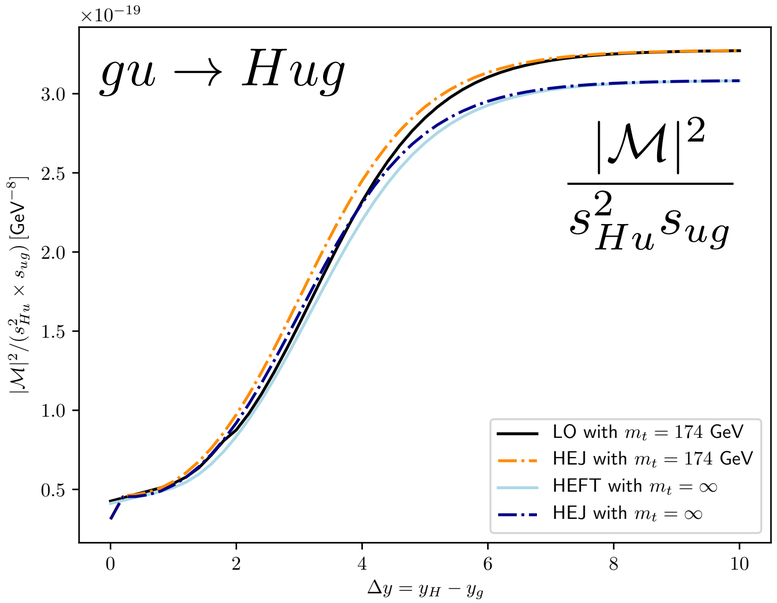
Higgs + 1j

HEJ has always resummed logarithms in the region between the outer jets in rapidity, hence always for processes with at least two jets

Observed in H+2j studies, that scaling with an intermediate Higgs boson was as in QCD

Andersen, Hapola, Maier, JMS arXiv:1706.01002





The same (Regge) scaling applies in the amplitude if the Higgs boson is external in rapidity

Hence can capture leading logs with the same method for H+1j

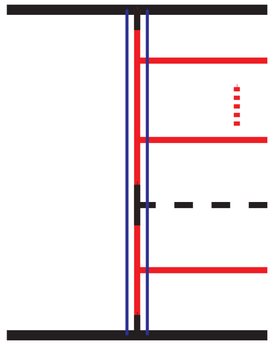
Andersen, Hassan, Maier, Paltrinieri, Papaefstathiou, JMS arXiv:2210.10671

Higgs + 1j

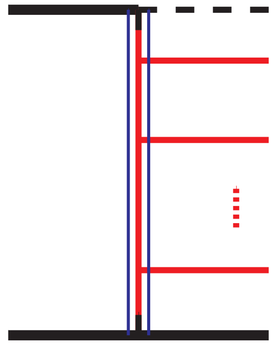
Black = Born/skeleton function

Red = Range of resummation

Previous 2jet+



Increasing rapidity

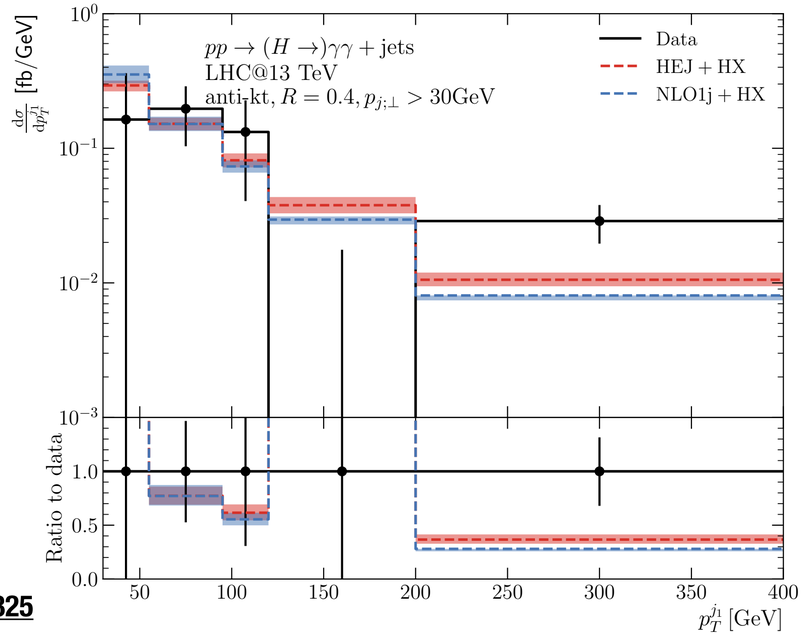


New 1jet+

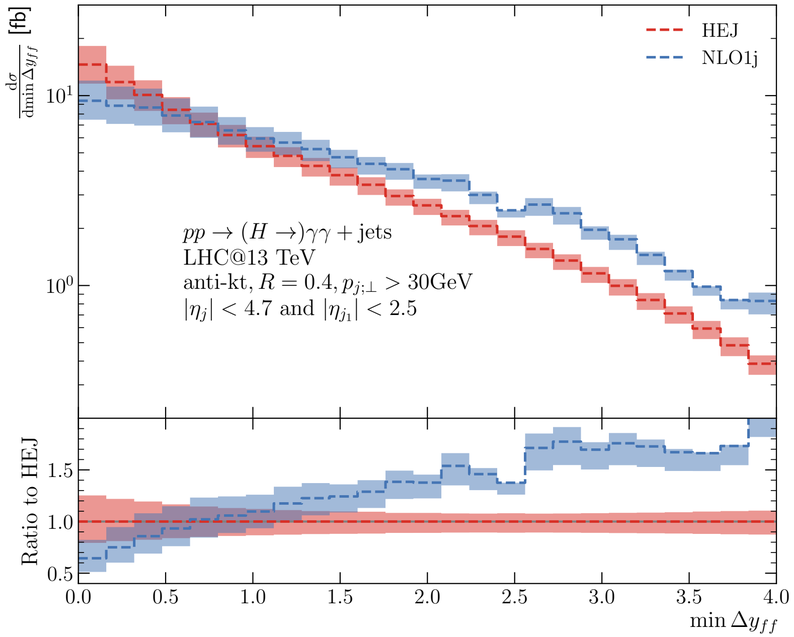
Similar effects on distributions

Andersen, Hassan, Maier, Paltrinieri, Papaefstathiou, JMS arXiv:2210.10671

"HX" adds VH, VH, …

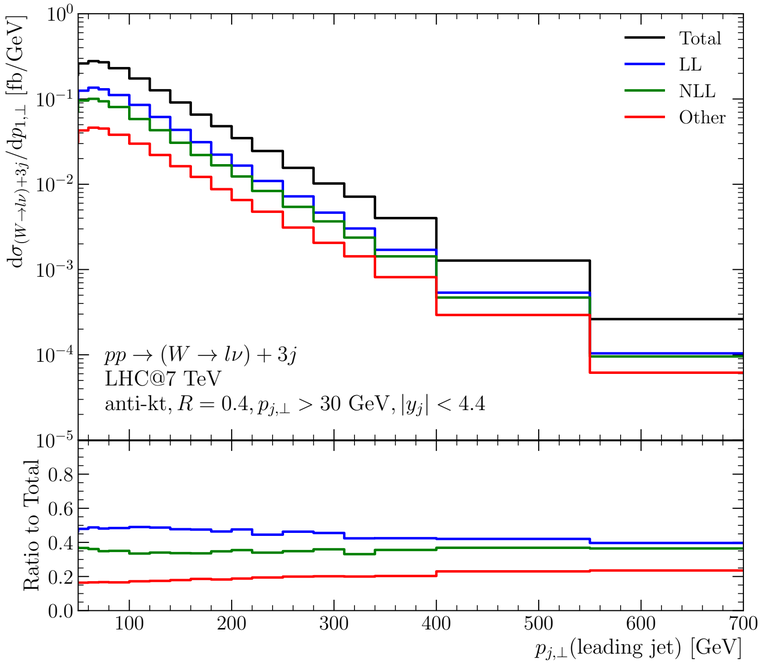


CMS data arXiv:1807.03825

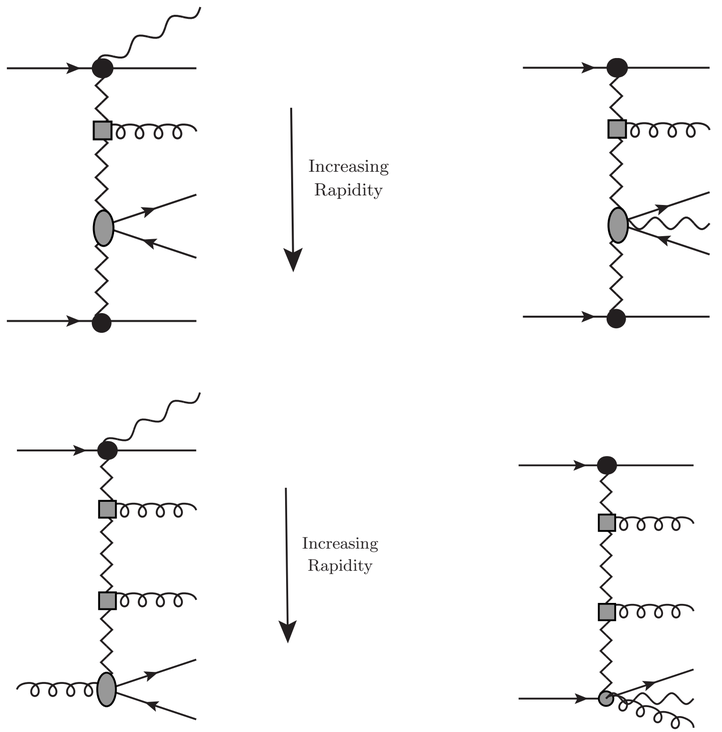


Suppression at large delta y

Improvements at Large p_T: NLL



Observed that particle channels which are formally next-to-leading log, contribute significantly at large p_T



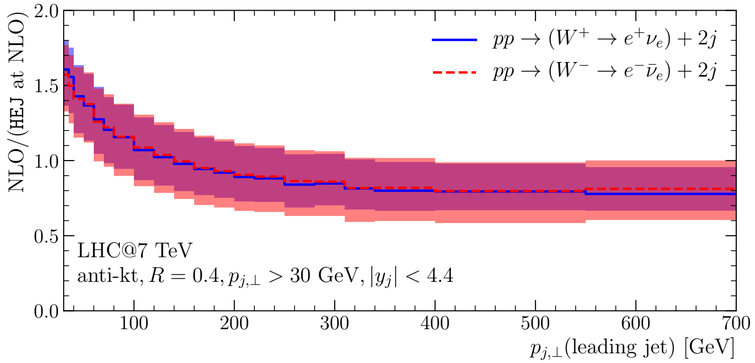
Can consistently apply resummation to all such channels (part of full NLL, and step towards it)

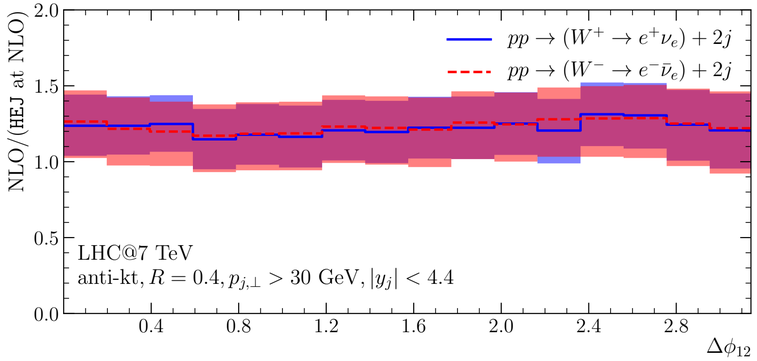
Andersen, Black, Brooks, Byrne, Maier, JMS arXiv:2012.10310

Improvements at Large p_T: NLO Matching

Not able yet to match to NLO event-by-event, but can do better than a k-factor by matching bin-by-bin

We derive predictions from HEJ, truncated to NLO and take the ratio to full NLO for each distribution.





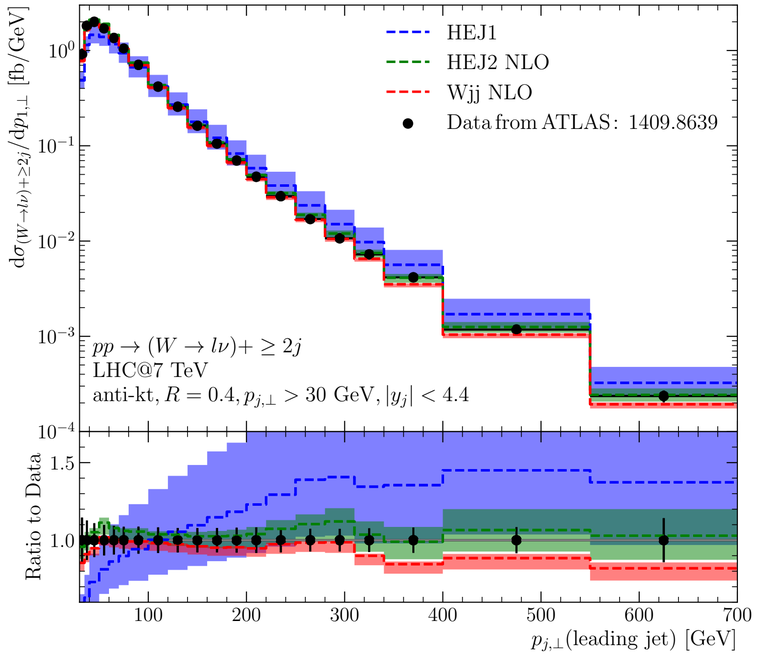
Final predictions are then given by

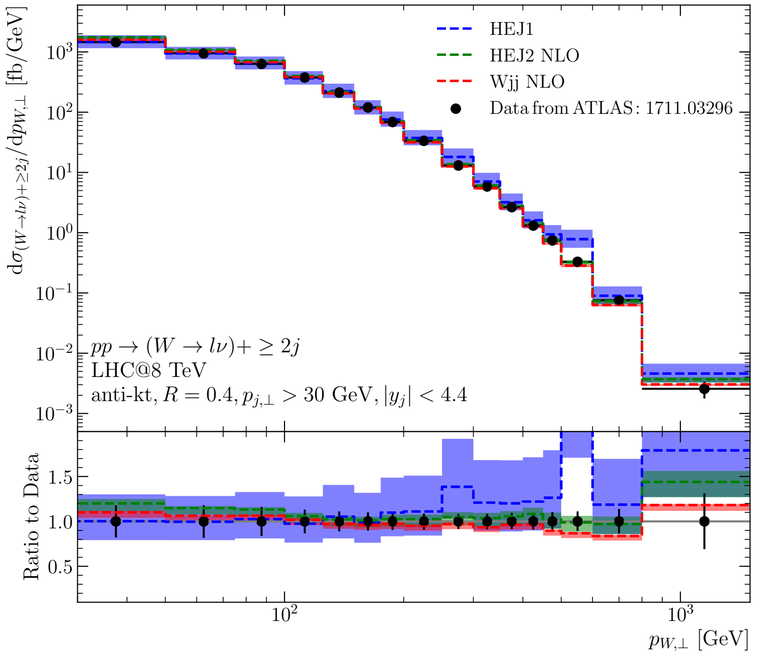
$$w_{\text{HEJ2 NLO}} = w_{\text{HEJ2}} \frac{w_{\text{NLO}}}{w_{\text{HEJ at NLO}}} + w_{\text{FO W+}\geq\text{4j}}$$

Can check by expansion that each bin is accurate to NLO+LL

Andersen, Black, Brooks, Byrne, Maier, JMS arXiv:2012.10310

Improvements at Large p_T: Wjj





- HEJ2 NLO prediction lies between the previous two
- Scale variation reduced — larger than NLO due to higher multiplicities

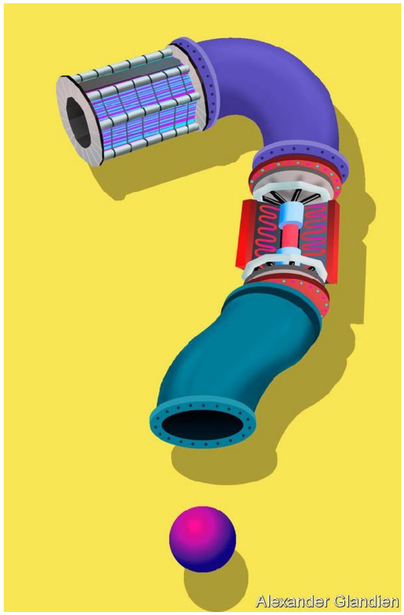
Andersen, Black, Brooks, Byrne, Maier, JMS arXiv:2012.10310

- At large p_T values, require ≥ 4j events to obtain good agreement
- See also progress merging with a parton shower

Andersen, Brooks & Lönnblad arXiv:1712.00178
Andersen, Hassan, Jaskiewicz arXiv:2210.06898

Summary & Outlook

- This is the “Precision Era of the Large Hadron Collider”
- High Energy Jets allows the description of high energy logs in a fully flexible framework
- High Energy Jets provides alternative way to include finite quark mass effects
- Recent improvements improve the description of data away from the strict limit
- Ongoing work to increase accuracy to full NLL and to full NLO



HEJ2 event generator: https://hej.hepforge.org