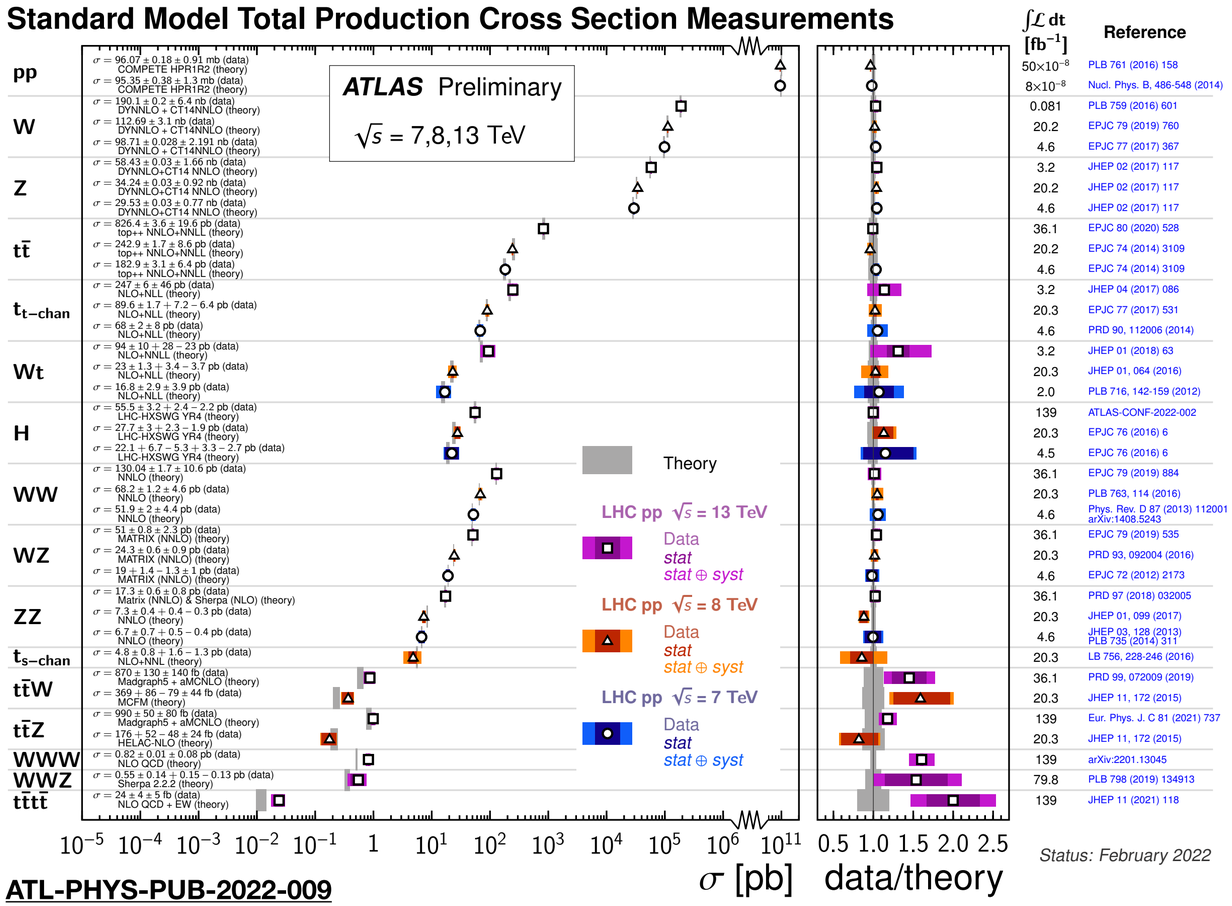
High Energy Resummation for Higgs-plus-Jet(s) Production

Jennifer Smillie

Higgs Maxwell Meeting, Feb 2023

Photo Credit: Kinrannoch Photography

LHC Summary So Far…

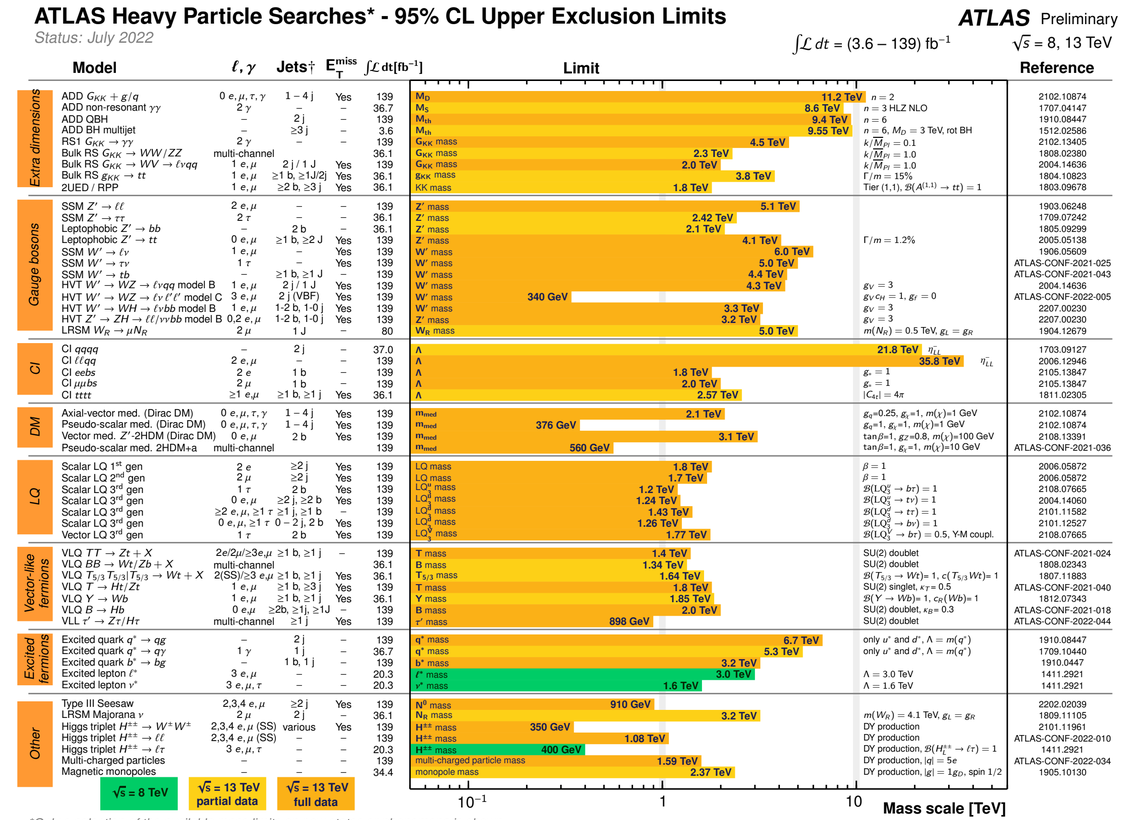


$\int \mathcal{L}\,dt$ [fb^{-1}]	Reference
50×10^{-8}	PLB 761 (2016) 158
8×10^{-8}	Nucl. Phys. B, 486-548 (2014)
0.081	PLB 759 (2016) 601
20.2	EPJC 79 (2019) 760
4.6	EPJC 77 (2017) 367
3.2	JHEP 02 (2017) 117
20.2	JHEP 02 (2017) 117
4.6	JHEP 02 (2017) 117
36.1	EPJC 80 (2020) 528
20.2	EPJC 74 (2014) 3109
4.6	EPJC 74 (2014) 3109
3.2	JHEP 04 (2017) 086
20.3	EPJC 77 (2017) 531
4.6	PRD 90, 112006 (2014)
3.2	JHEP 01 (2018) 63
20.3	JHEP 01, 064 (2016)
2.0	PLB 716, 142-159 (2012)
139	ATLAS-CONF-2022-002
20.3	EPJC 76 (2016) 6
4.5	EPJC 76 (2016) 6
36.1	EPJC 79 (2019) 884
20.3	PLB 763, 114 (2016)
4.6	Phys. Rev. D 87 (2013) 112001 arXiv:1408.5243
36.1	EPJC 79 (2019) 535
20.3	PRD 93, 092004 (2016)
4.6	EPJC 72 (2012) 2173
36.1	PRD 97 (2018) 032005
20.3	JHEP 01, 099 (2017)
4.6	JHEP 03, 128 (2013) PLB 735 (2014) 311
20.3	LB 756, 228-246 (2016)
36.1	PRD 99, 072009 (2019)
20.3	JHEP 11, 172 (2015)
139	Eur. Phys. J. C 81 (2021) 737
20.3	JHEP 11, 172 (2015)
139	arXiv:2201.13045
79.8	PLB 798 (2019) 134913
139	JHEP 11 (2021) 118

Status: February 2022

ATL-PHYS-PUB-2022-009

New physics searches have generated many exclusion limits (huge range of models, very high limits)



*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

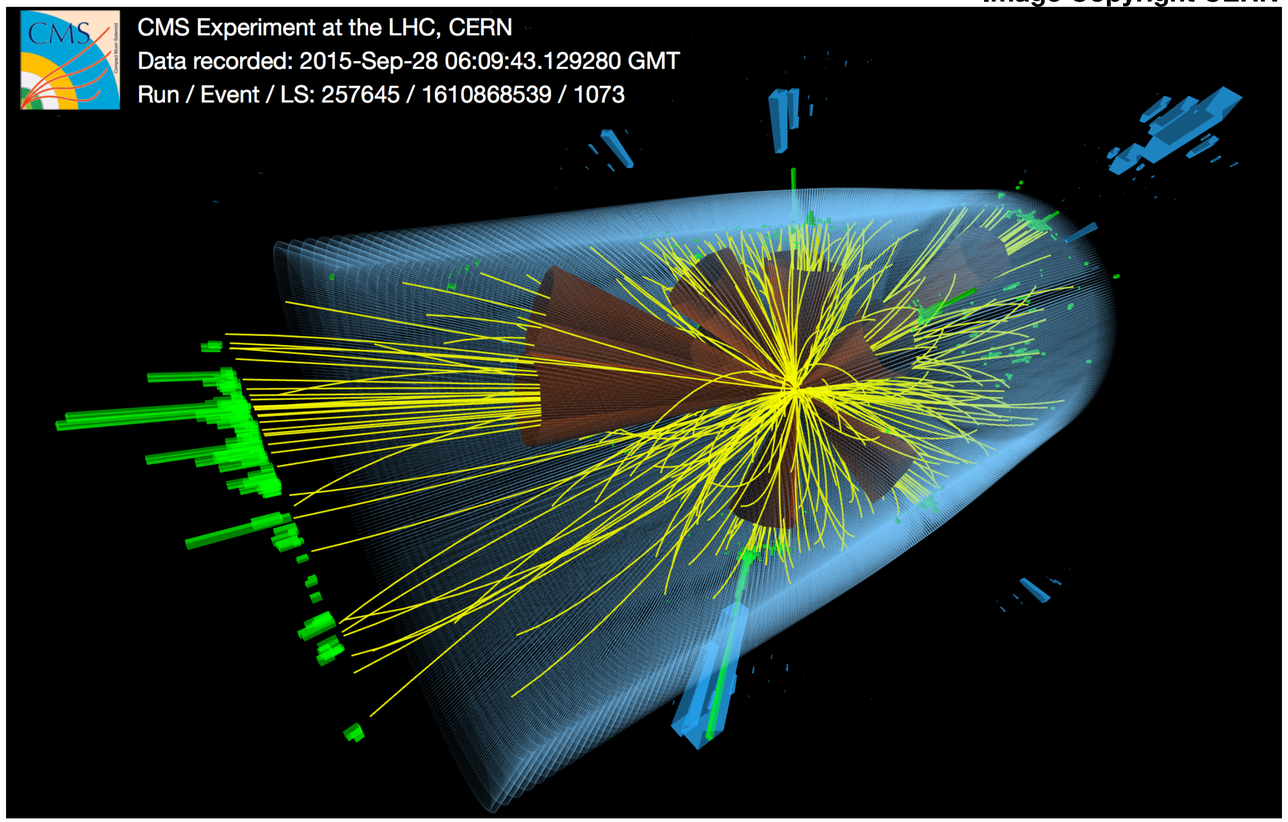
ATL-PHYS-PUB-2022-034

- Phenomenal agreement with theory so far
- Very sophisticated calculations, e.g. $t\bar{t}$ at NNLO+NNLL
  Czakon, Mitov arXiv:1112.5675

A Challenge at High Centre of Mass

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

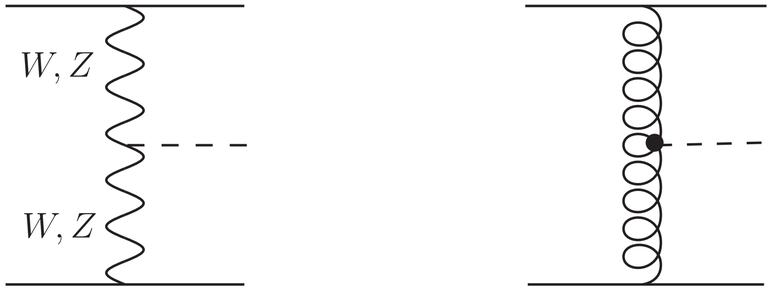
Image Copyright CERN



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

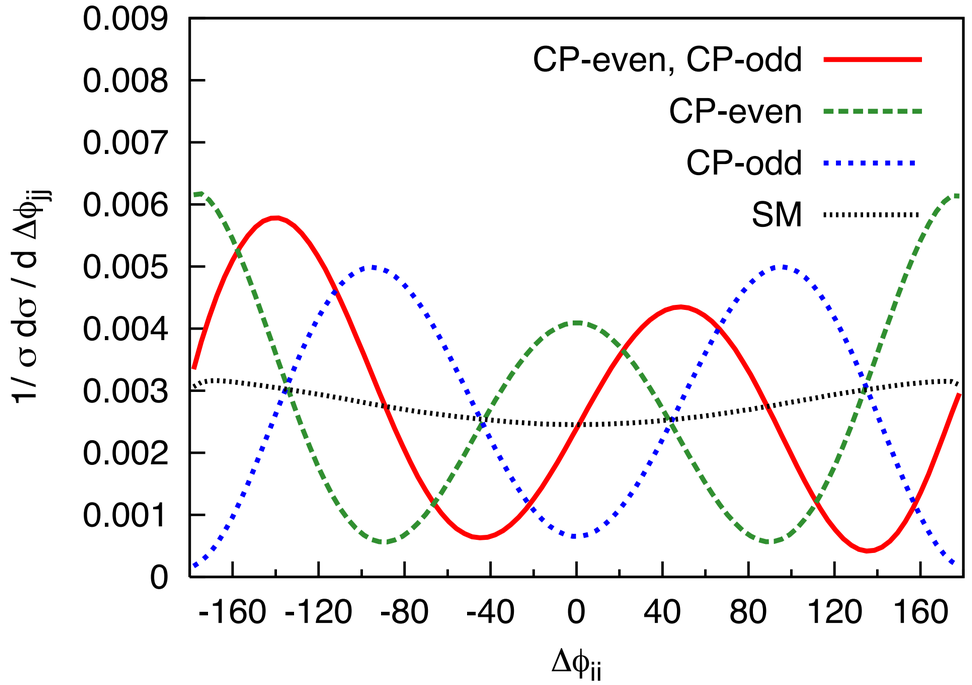
Higgs + Dijets



Higgs boson looks like SM so far, but critical to check CP structure of couplings to bosons

Azimuthal angle between the dijets is sensitive to this

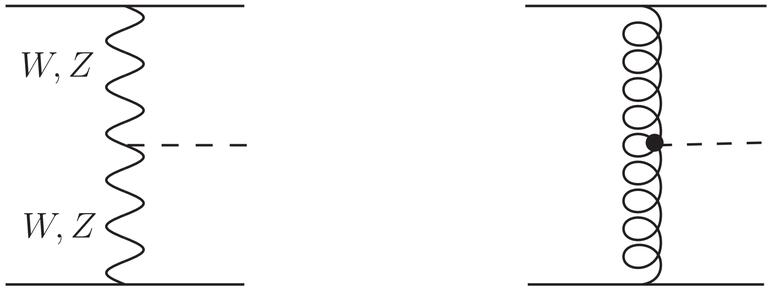
Figy et al **hep-ph/0609075**



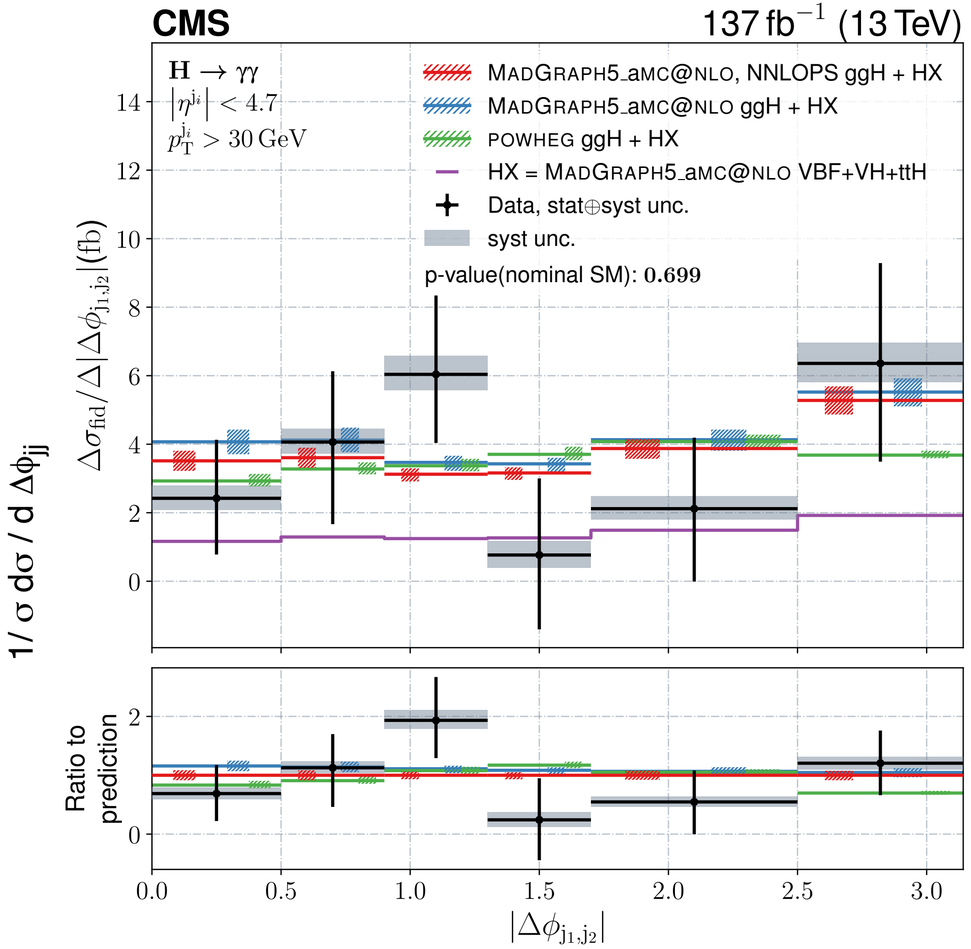
ggH

WWH

Higgs + Dijets



...critical to check CP



ggH

WWH

Azimuthal angle between the dijets is sensitive to this

Figy et al hep-ph/0609075

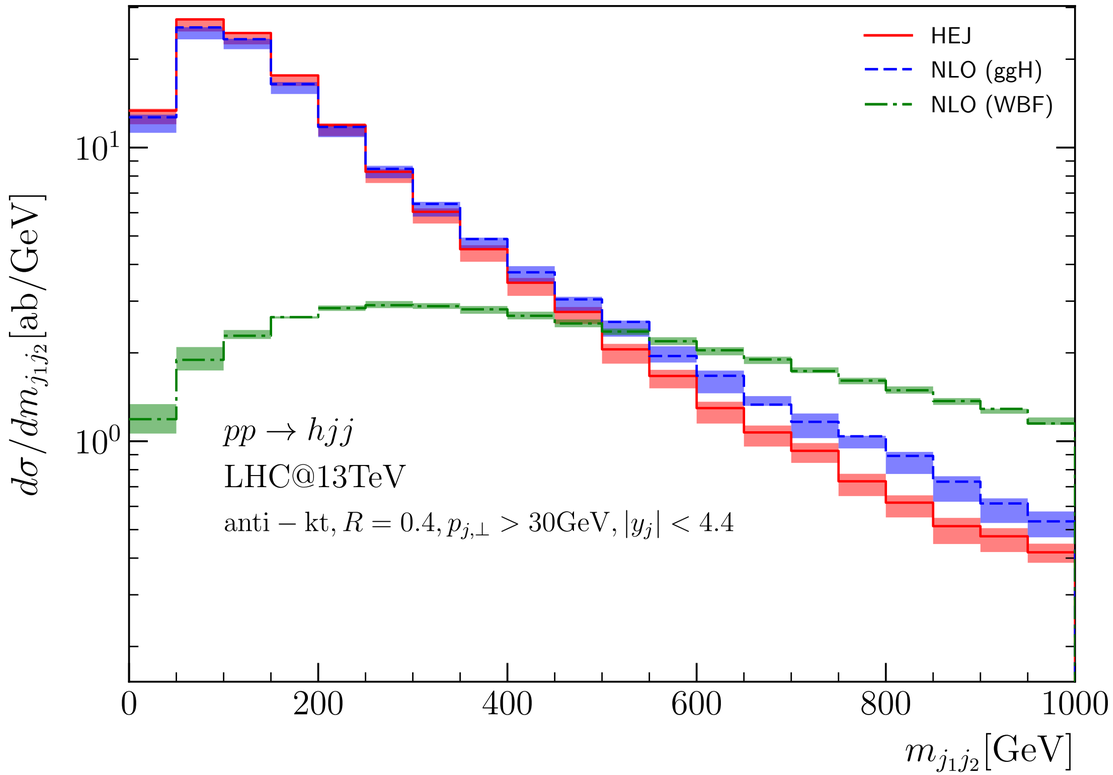
CMS arXiv:2208.12279

Higgs + Dijets

Use distinctive event shape to separate channels with “VBF cuts”

e.g. $\Delta y_{jj} > 2.8,\ m_{jj} > 400\ \text{GeV}$

BUT this precisely enhances higher orders in pert. expansion



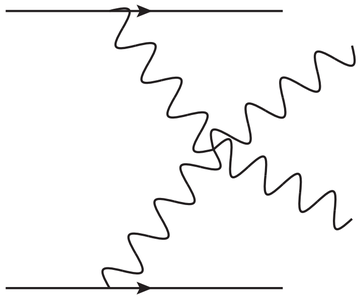
Andersen, Heil, Maier & JMS, in arXiv:1803.07977

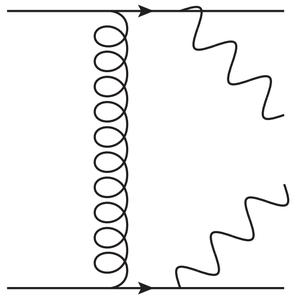
Vector Boson Scattering

Vector Boson Scattering (VBS) sensitive probe of EWSB

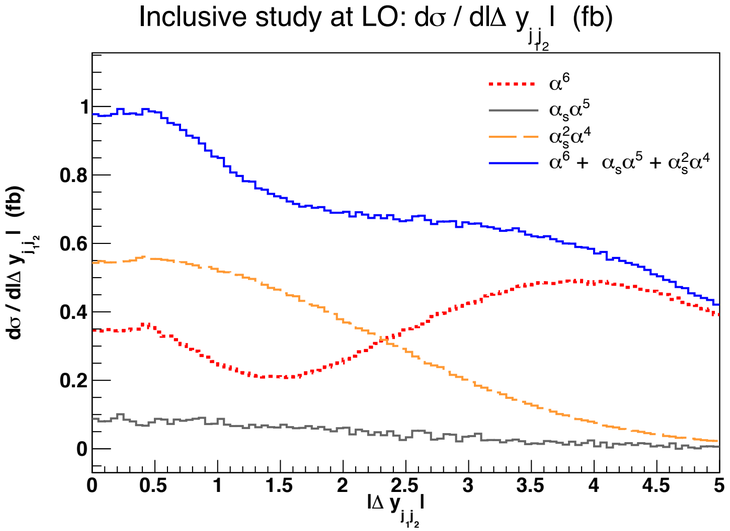
$pp \to W^+W^+jj$ proceeds through various diagrams including

$$\mathrm{EW} = O(\alpha_W^4)$$





$$\mathrm{QCD} = O(\alpha_W^2 \alpha_s^2)$$



Ballestrero et al arXiv:1803.07943

We would like to separate the EW and QCD channels, justified by assessing interference between the two to be small

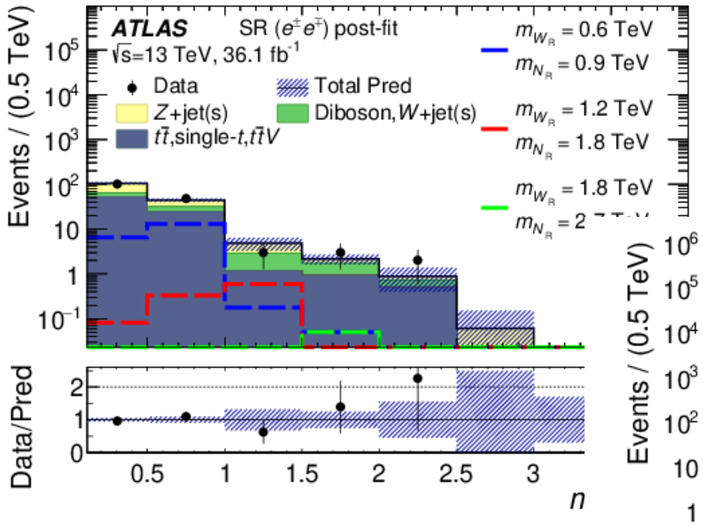
To isolate EW component, typically apply VBS cuts of large rapidity and/or large invariant mass on the jets.

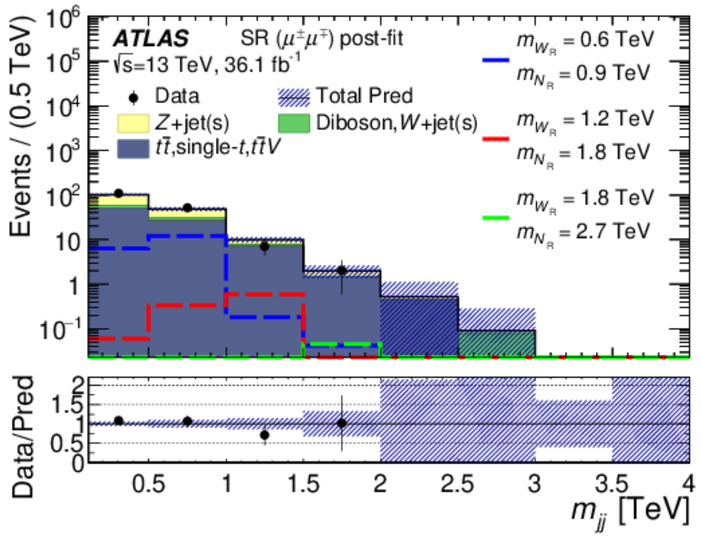
Very similar to $pp \to Hjj$

Exotics Searches

We want to exploit high centre-of-mass energy to search for new heavy particles at large invariant mass

e.g. a search for heavy right-handed neutrinos or right-handed Ws





ATLAS arXiv:1809.11105

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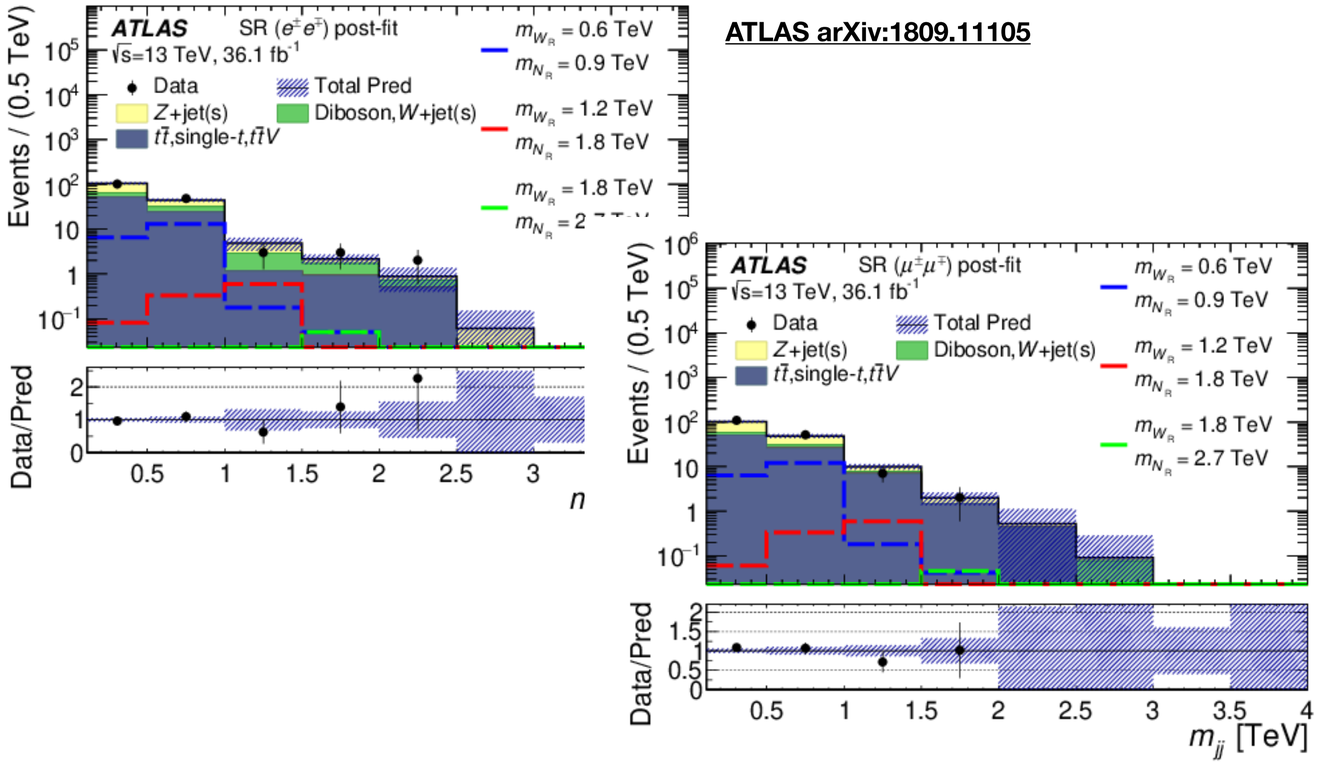
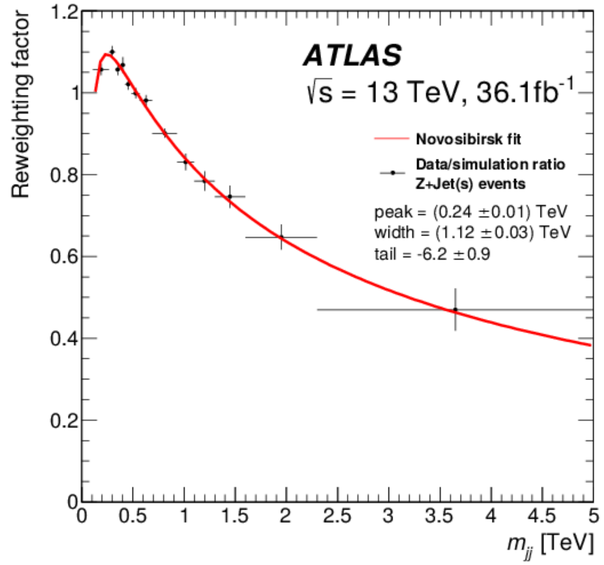


ATLAS arXiv:1809.11105



BUT needed to scale the MC background by this much

Which Logs in s/t?

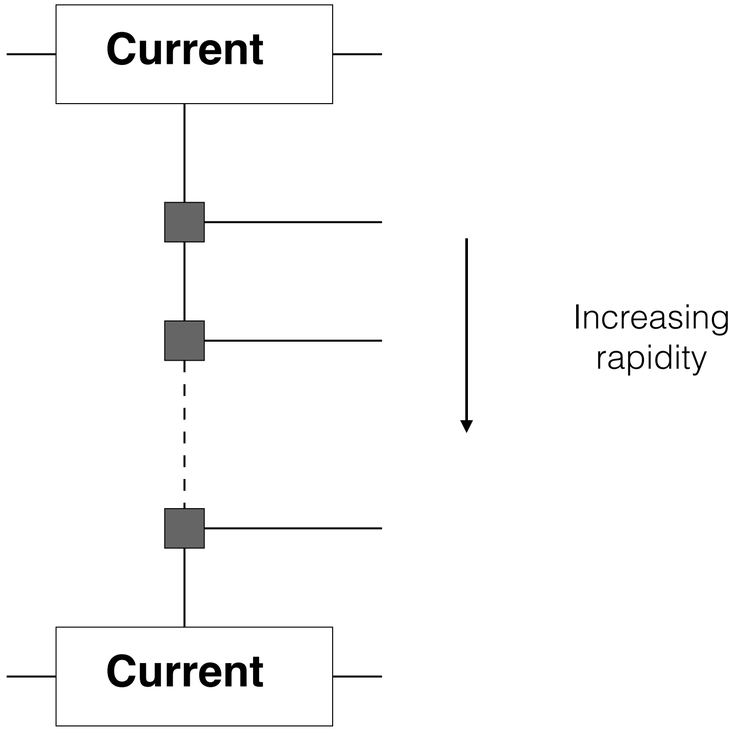
Inclusive 2-jet cross section given by $\int d\mathrm{PS}_2\ |\mathrm{M}_{2j+}|^2$, with

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

- LO = first line, NLO = first two lines
- Leading logs = the ‘a’-terms: $\alpha_s^{2+k}\log^k(s^2/t^2)$
- Logs arise from integrals over loop momenta in virtuals and from integrals over reals
- Our description = **LO + LL + …**

Amplitudes in the High Energy Limit

Fortunately, the matrix elements of these processes simplify in the High Energy limit: $s_{ij} \to \infty$, $|p_{Ti}|$ finite



Local pieces, independent of the rest of the process

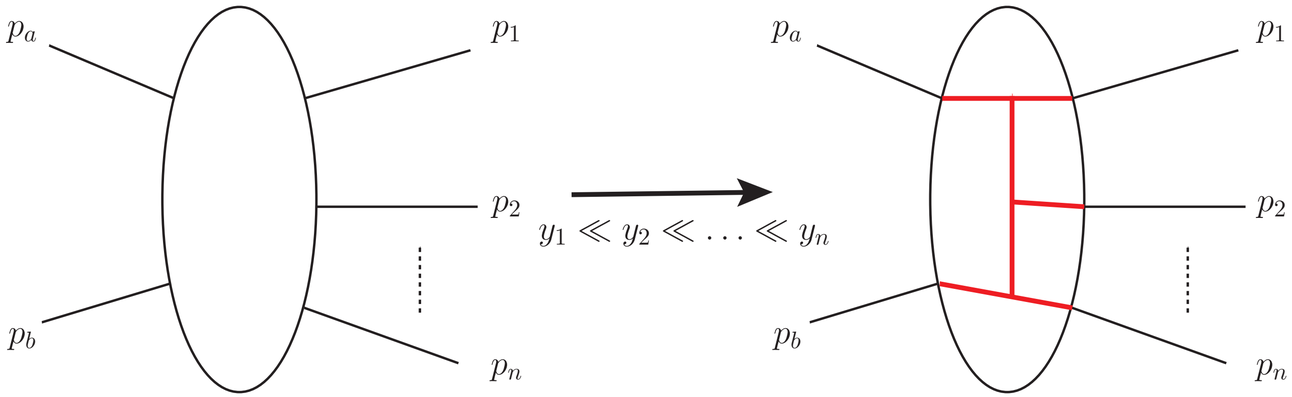
Applies to loop diagrams too, and generates leading logs in s_{ij}/p_T^2

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

High Energy limit of amplitudes also many theory applications…

Regge Scaling of Amplitudes

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

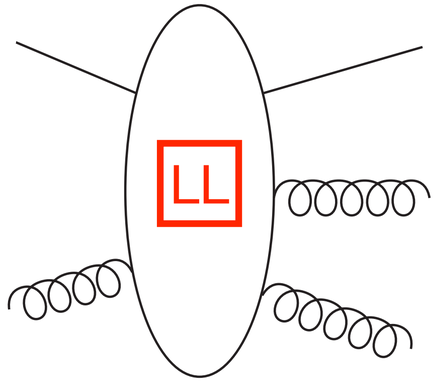


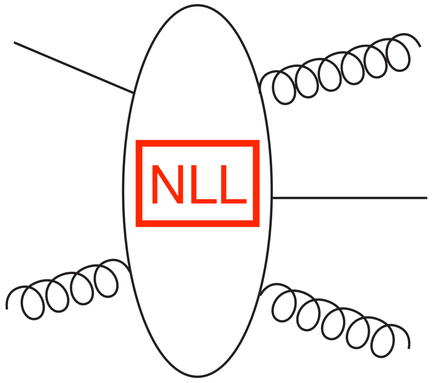
$$\mathcal{M} \propto s_{12}^{\alpha_{12}} \ldots s_{n-1,n}^{\alpha_{n-1,n}} \; f(\{p_{T,i}\})$$

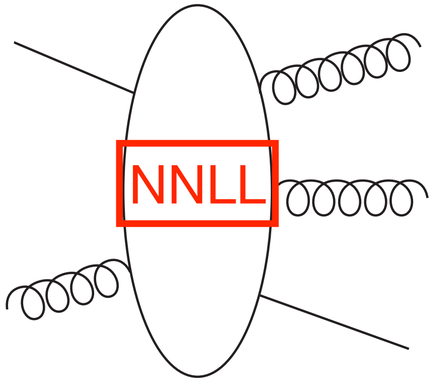
where α_{ij} is the spin of that particle in effective t-channel

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

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







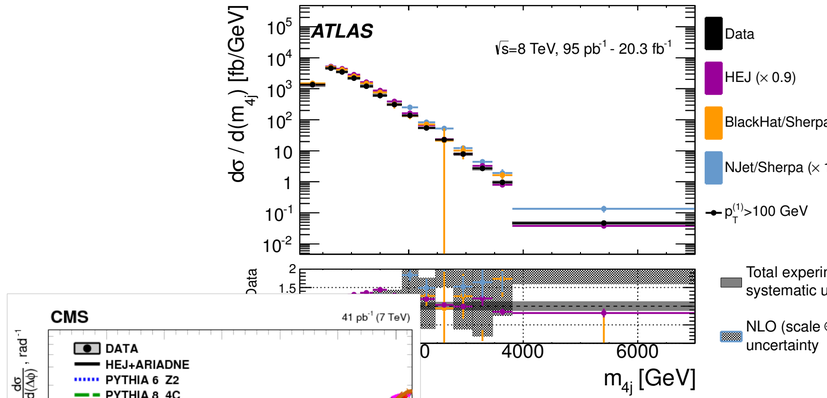
“HEJ 2”

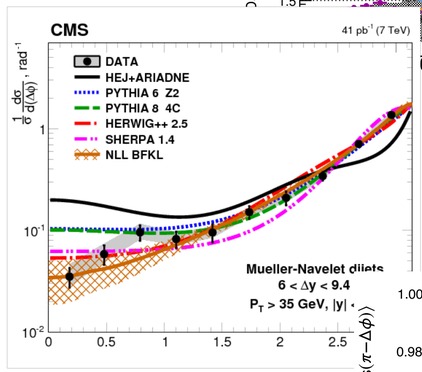
The High Energy Jets (HEJ) framework is

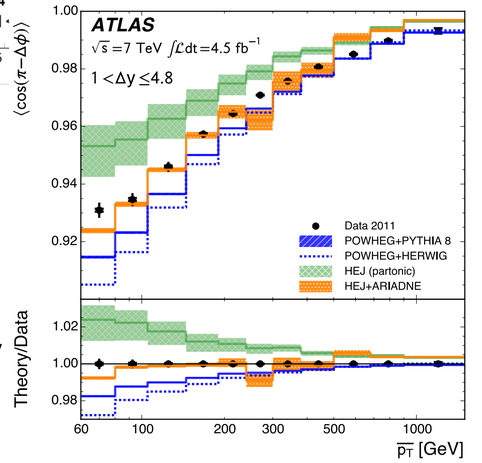
- exact for simple processes (2 to 2 (+X))
- accurate to leading logarithm in s/t
- constructed event-by-event
- sufficiently fast for numerical integration (up to 30 gluons)

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

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

Andersen, Black, Brooks, Ducloué, Heil, Maier & JMS arXiv:2110.15692

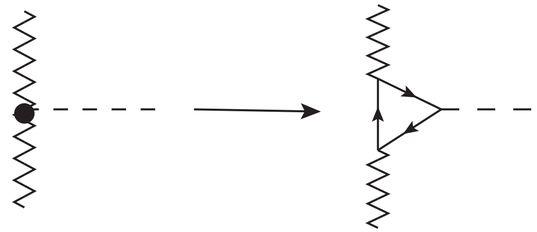
Finite Quark Masses in H+2j

Fixed-order stalled for full quark mass effects because LO = 1-loop.
LO results only for 2 and 3 jets (no NLO for 2j+)

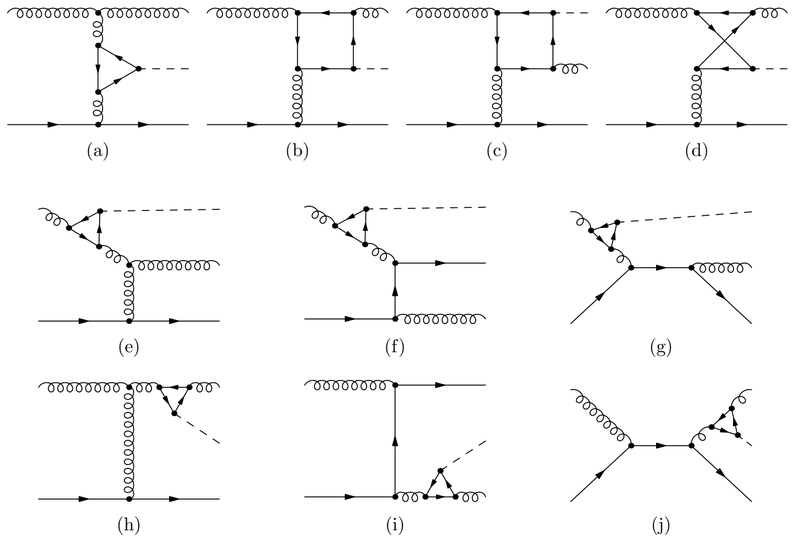
Del Duca et al hep-ph/0105129, hep-ph/0108030
Greiner et al arXiv:1608.01195

In HEJ, 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



Straight-forward
e.g. $qQ \to qHQ$



Outer Higgs more involved but calculated

Finite Quark Masses in HEJ

HEJ can include finite quark mass and loop propagator effects for *any* number of jets

Performed at amplitude level so we include mass effects from top quark, bottom quark *and* the interference between the two

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

Highest available =

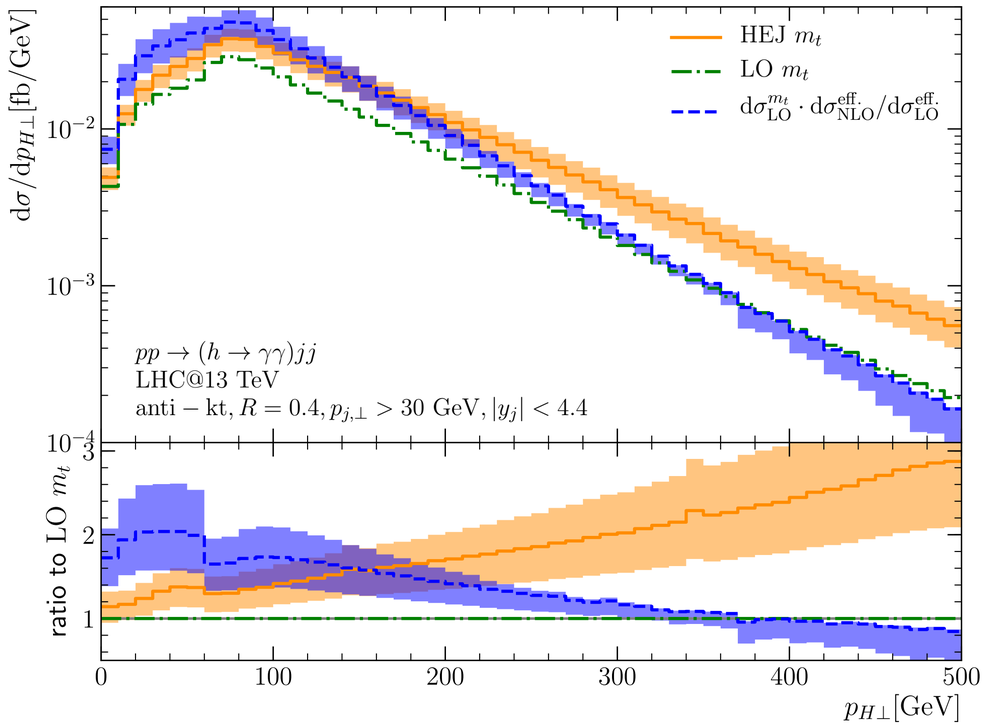
finite m_t	$H+2j$	at LO ($3j$ results exist, but events not available)
infinite m_Q	$H+2j$	at NLO
	$H+5j$	at LO

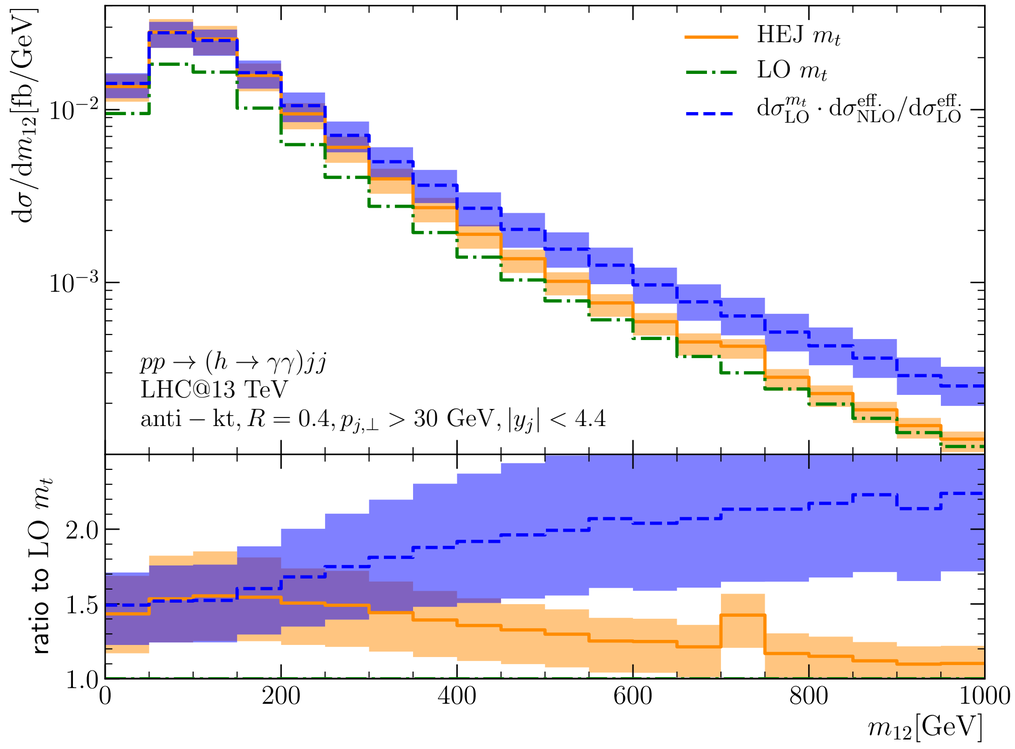
All predictions shown with $\mu_F = \mu_R = \max(m_H, m_{12})$ with indt variations by 1/2,2

Finite Quark Mass Results

First probe the impact of higher orders in α_s

HEJ here temporarily without m_b





NLO K-factors clearly not flat, very scale-dependent, all choices have problems

HEJ harder $p_{H\perp}$ spectrum

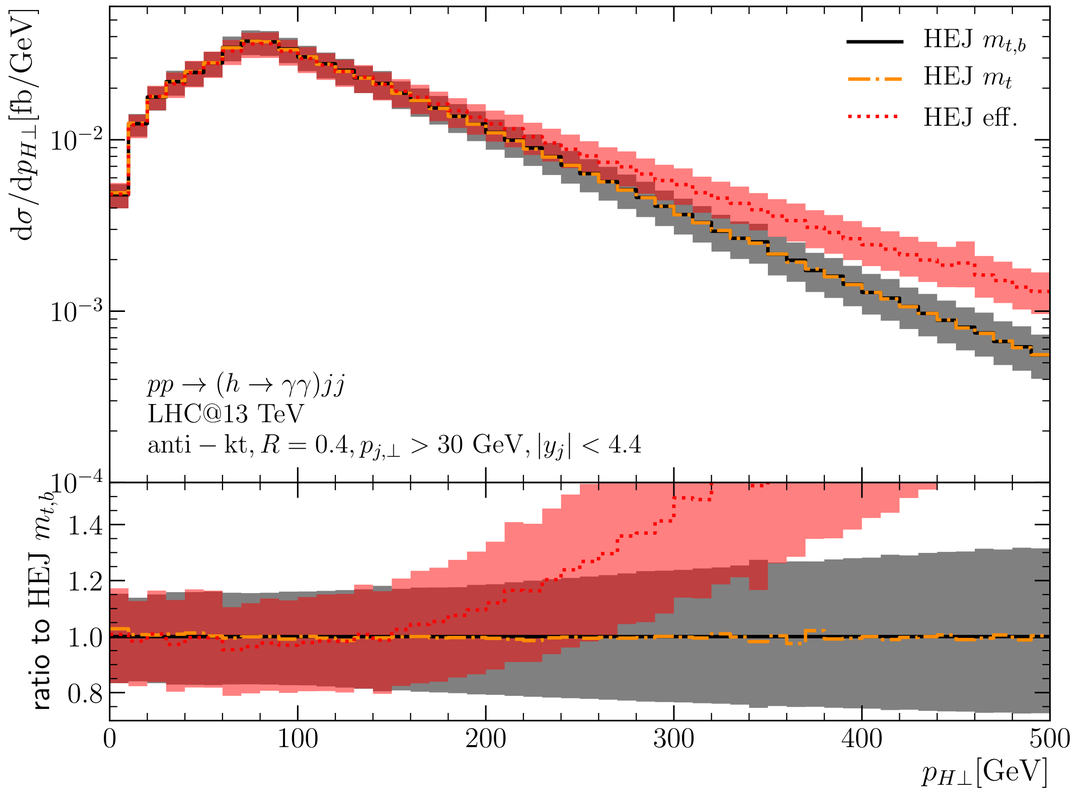
HEJ much steeper drop with m_{12}

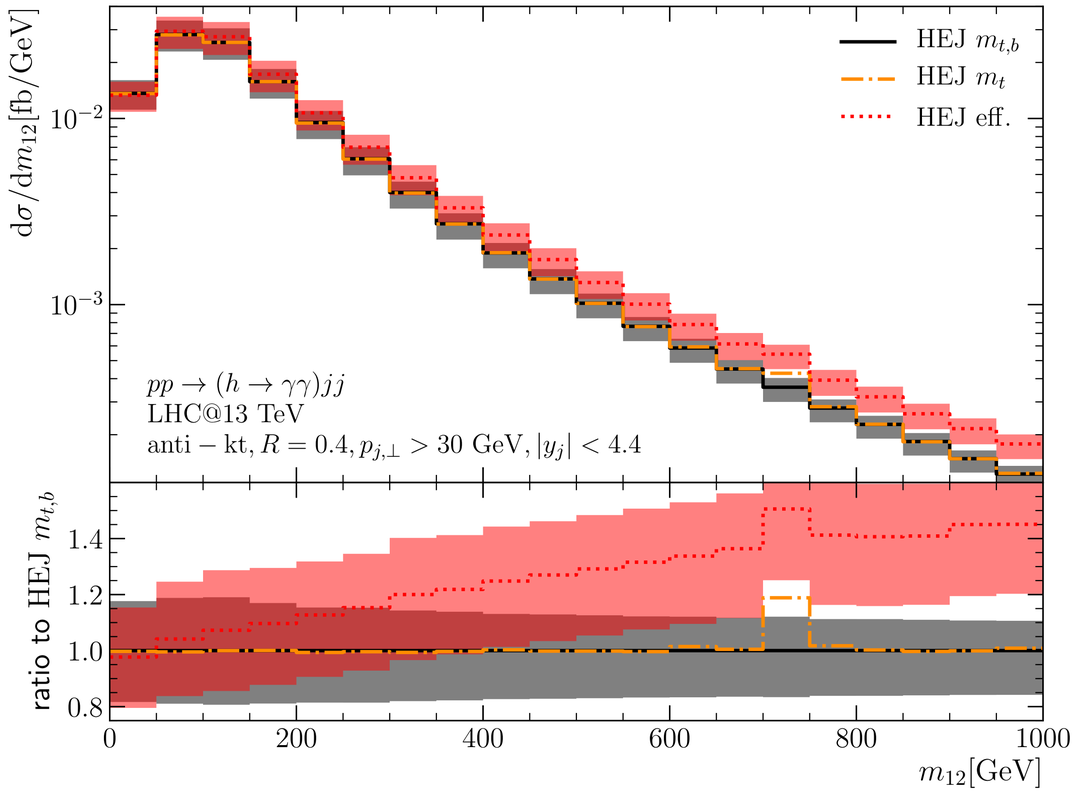
Andersen, Cockburn, Heil, Maier & JMS arXiv:1812.08072

Finite Quark Mass Results

Now probe the impact of quark masses

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





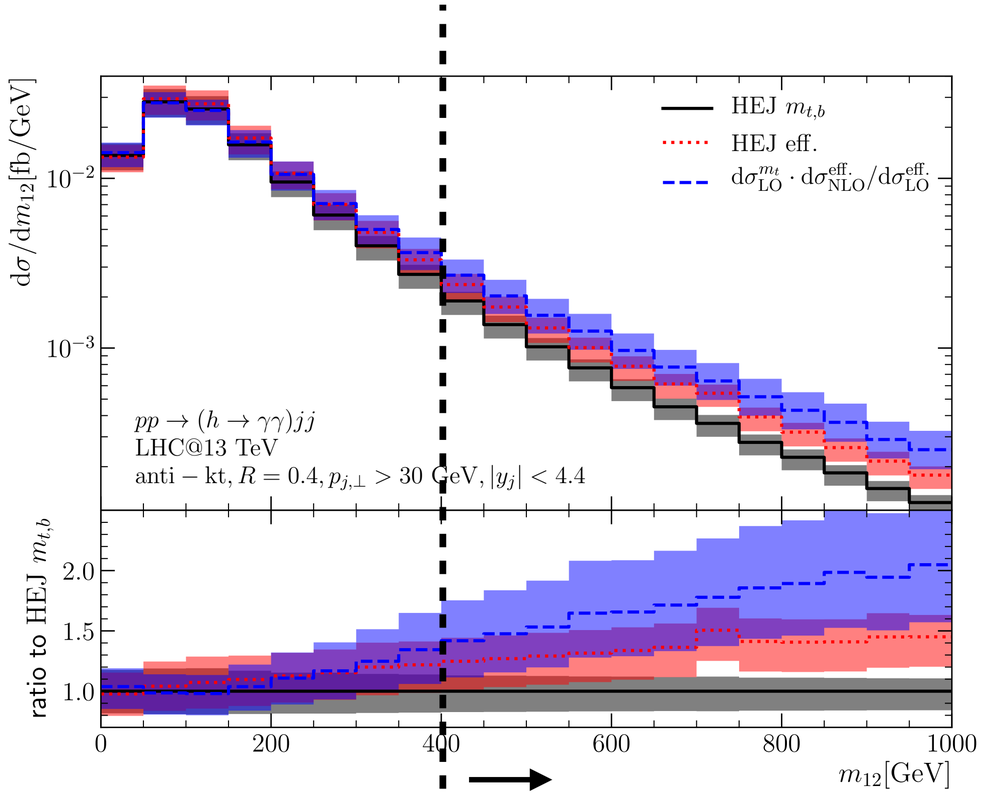
- Importance of finite quark mass increases with $p_{H\perp}$
- Relatively small impact of m_b, finite m_t lowers predictions at large m_{12}
- Therefore finite quark mass effects make VBF cuts more effective

Full HEJ Prediction vs “best” fixed-order

- 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%



Typical VBF cut

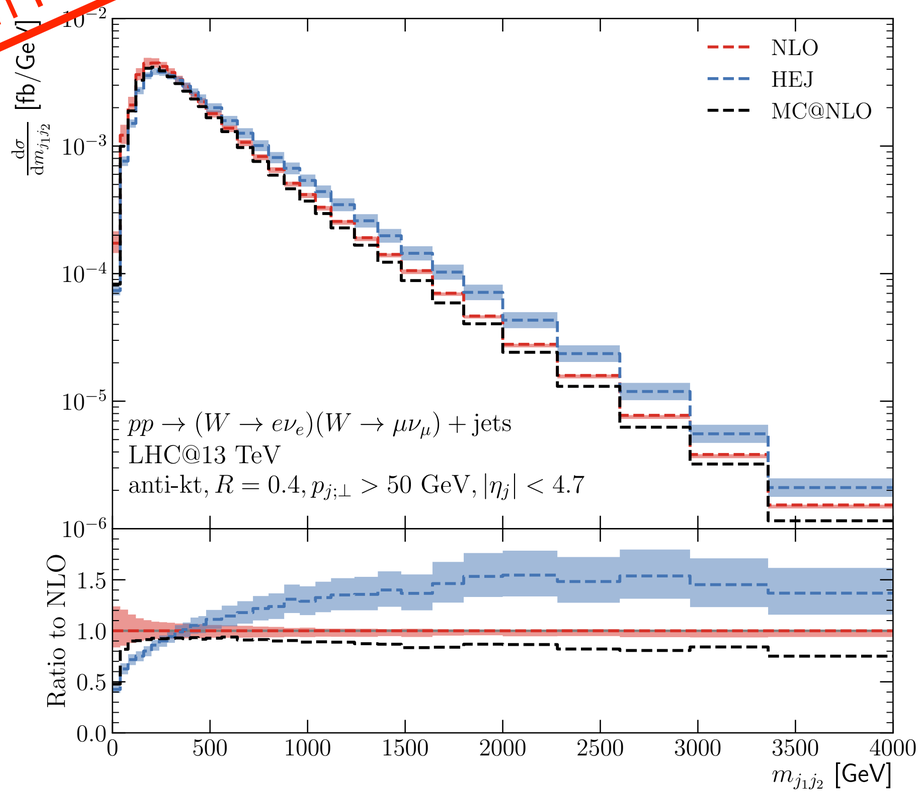
Andersen, Cockburn, Heil, Maier, JMS arXiv:1812.08072

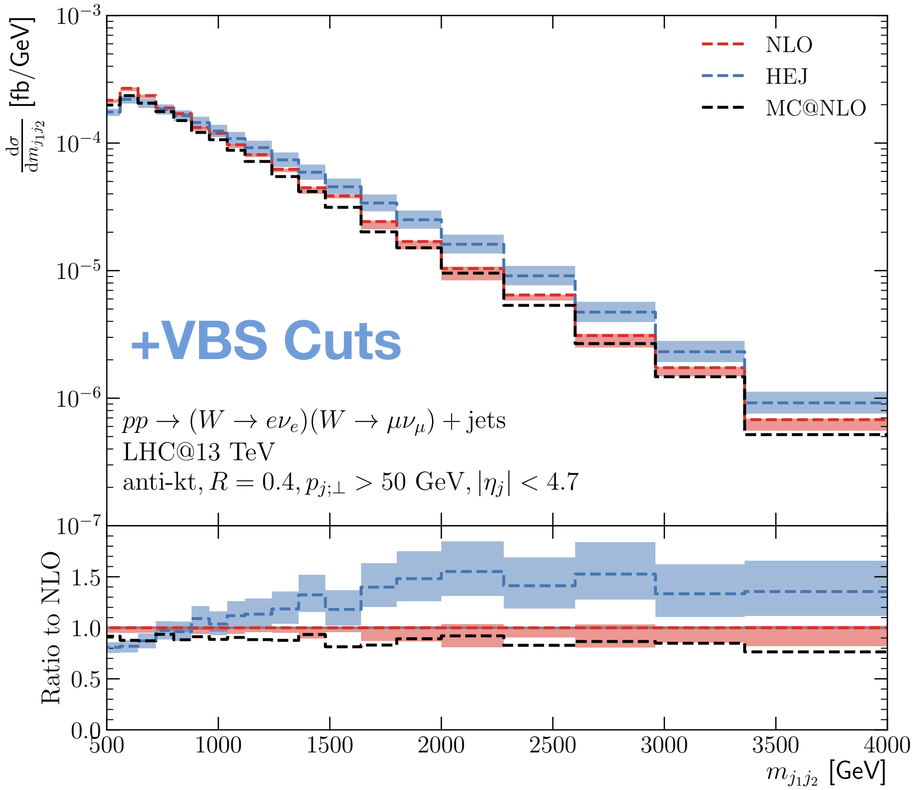
Vector Boson Scattering — Distributions

Impact on cross sections much reduced here (central scale choice) due to cancellation across phase space, not agreement throughout

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

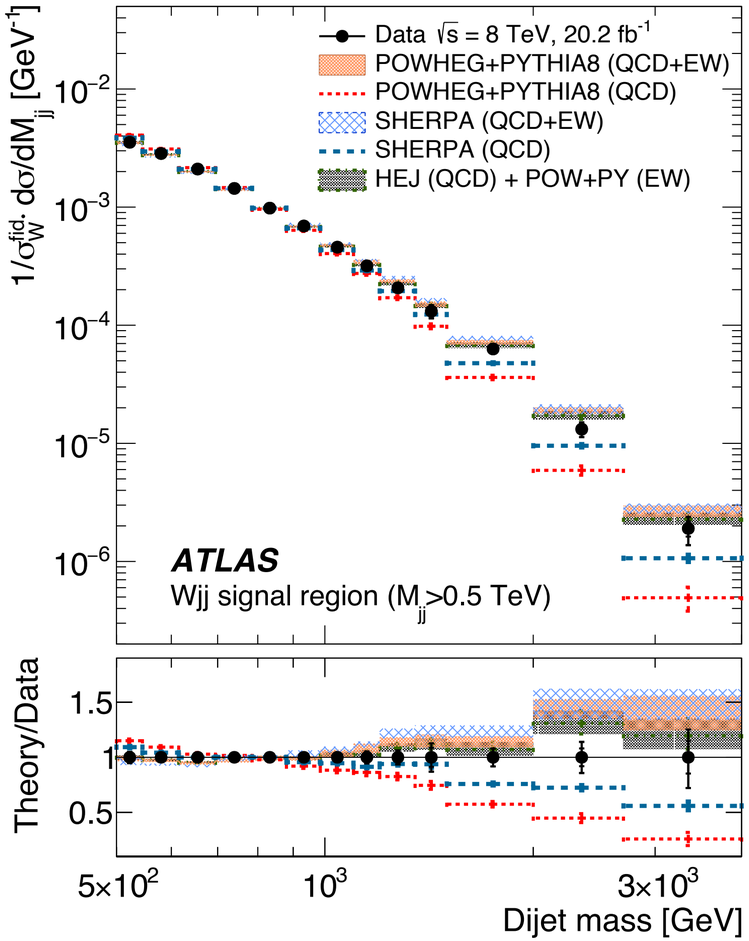
New in HEJ 2.2!





Shape of distributions significantly changed by the all-order resummation

2017 ATLAS W+2j



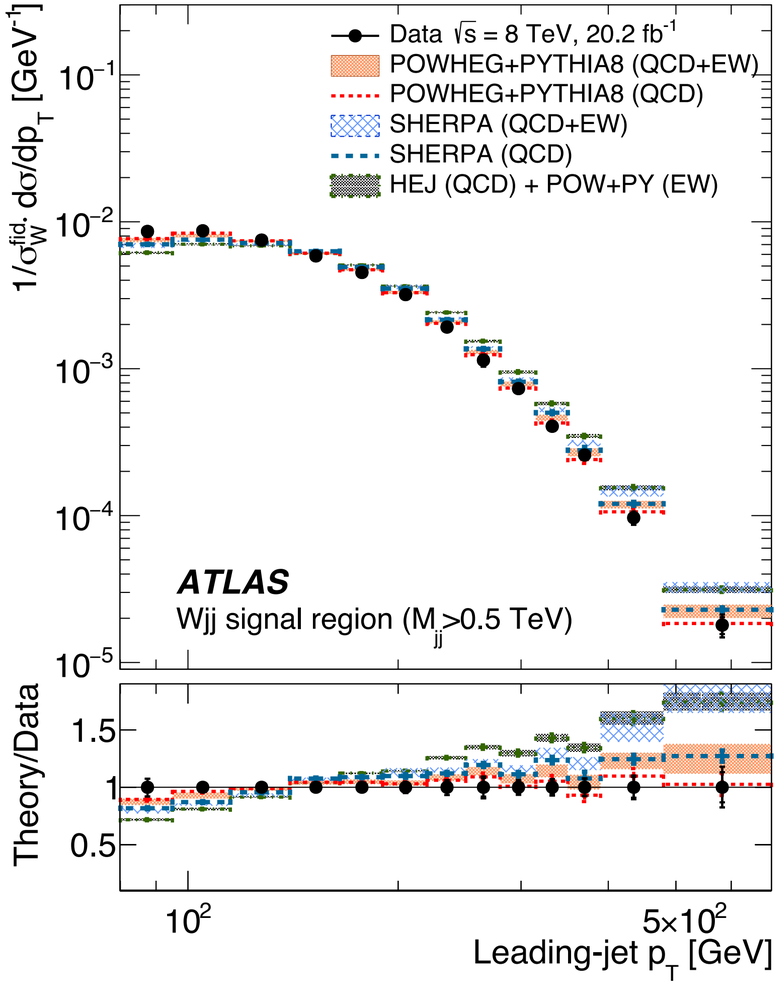
W+2j study to investigate separation of QCD/EW contributions compared to NLO+PS (Powheg/Sherpa) and HEJ+EW from Powheg

- 8 TeV data probing out to 3 TeV already
- QCD contribution decreases at large dijet mass, but remains significant
- NLO+PS slightly overshoot, and increasing

Similar for e.g. delta-y

ATLAS arXiv:1703.04362

2017 ATLAS W+2j

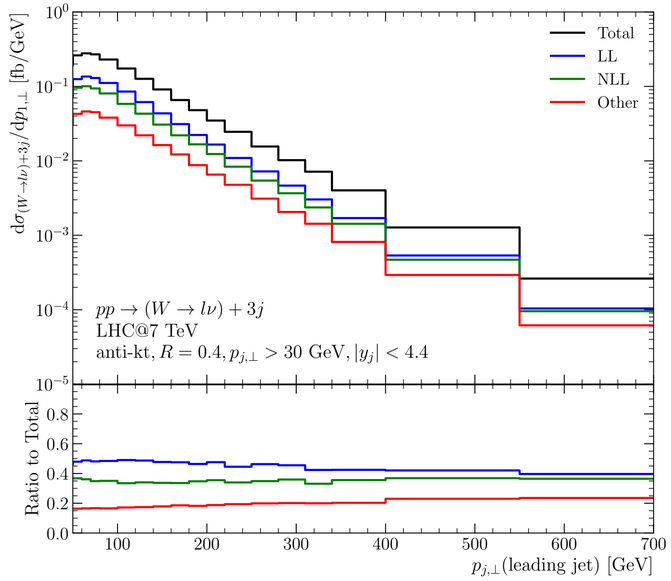


- Different picture when plotted versus p_T as no systematic evolution in pT in HEJ.
- QCD contribution no longer suppressed compared to EW
- Subleading corrections and NLO matching improve this (see later)
- Can also combine with a parton shower

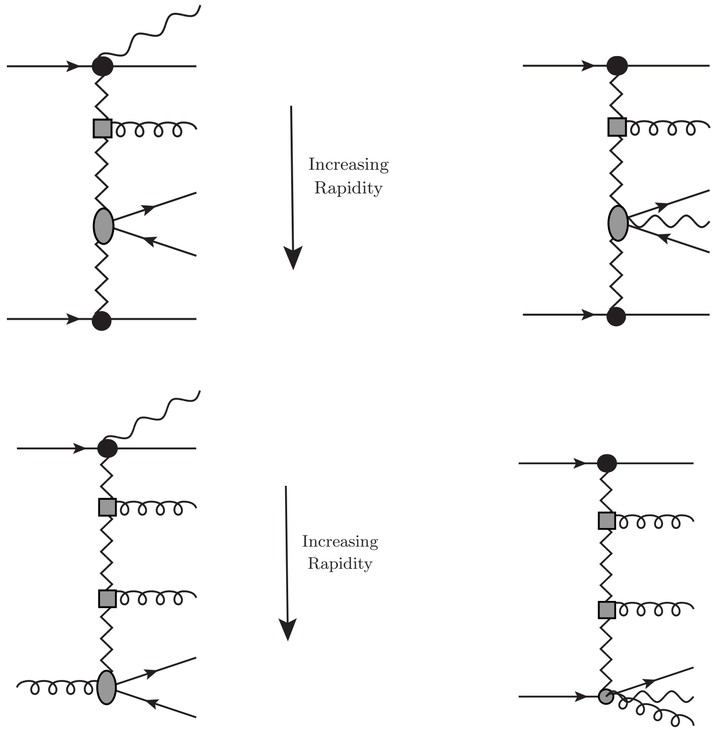
Andersen, Brooks & Lönnblad arXiv:1712.00178
Andersen, Hassan, Jaskiewicz arXiv:2210.06898

ATLAS arXiv:1703.04362

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

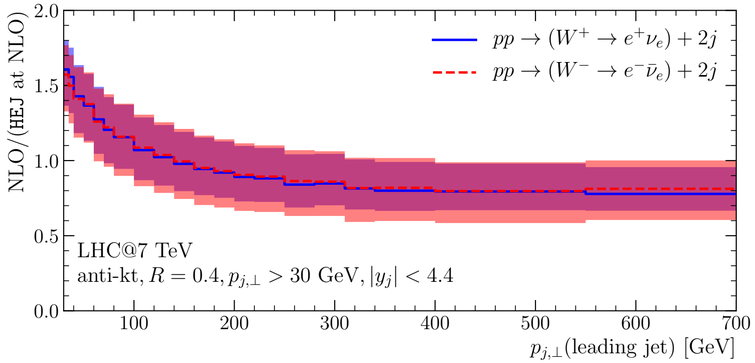
Improvements at Large p_T: NLO Matching

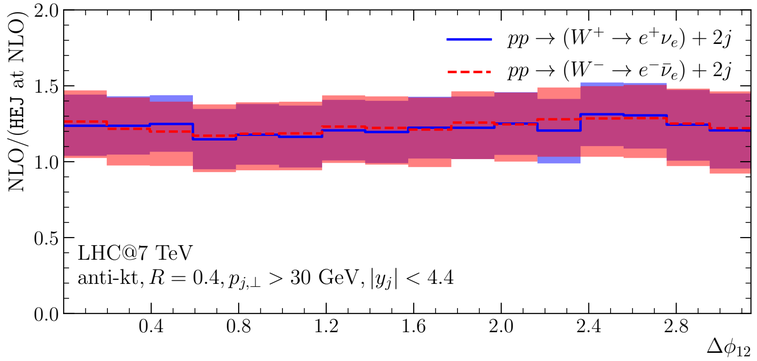
Not able yet to match to NLO event-by-event, but can do better than a k-factor by matching bin-by-bin

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

Final predictions are then given by

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

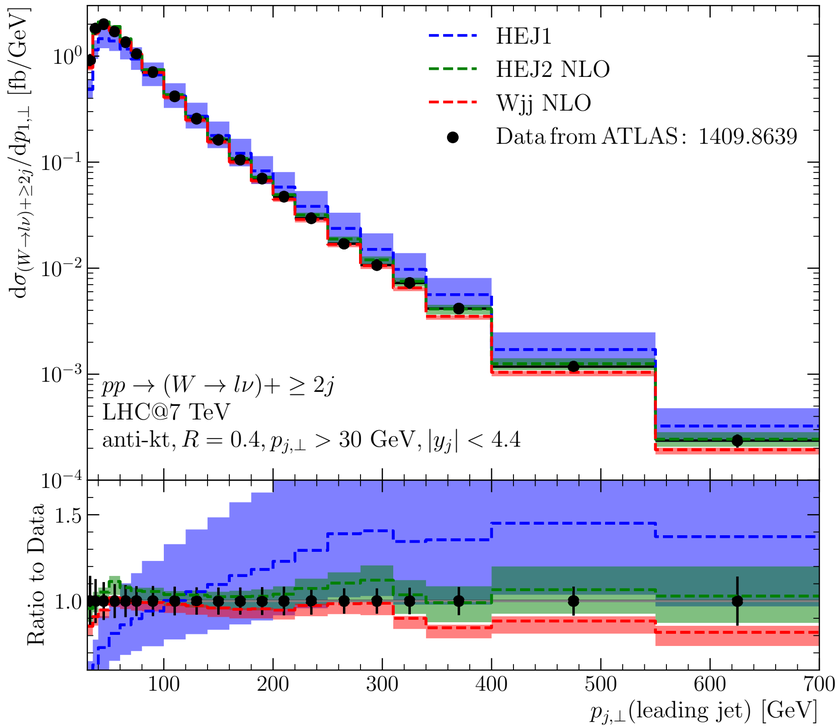


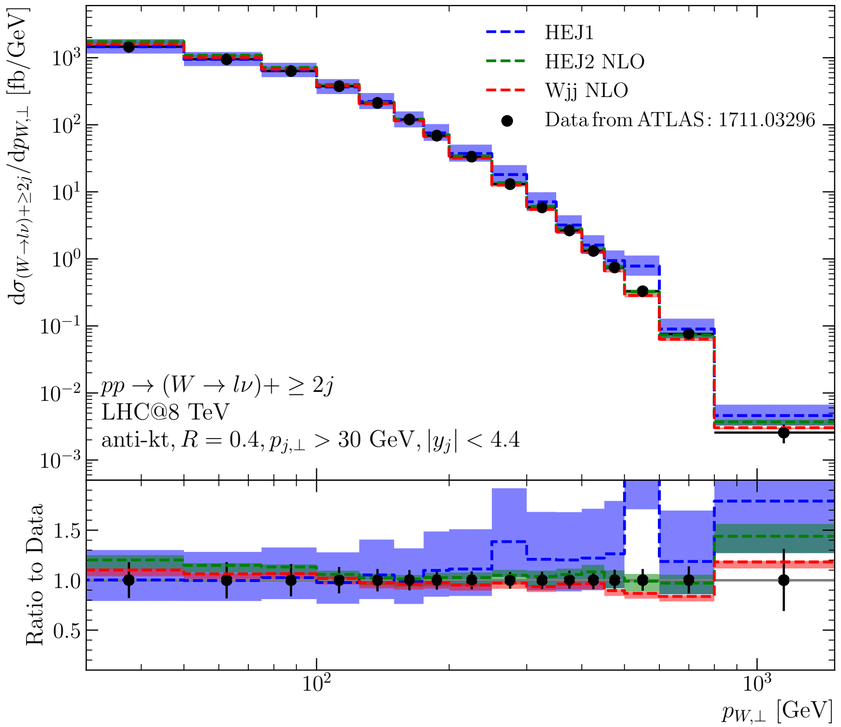


Can check by expansion that each bin is accurate to NLO+LL

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

Improved W-Plus-Dijets





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

- At large p_T values, require ≥ 4j events to obtain good agreement

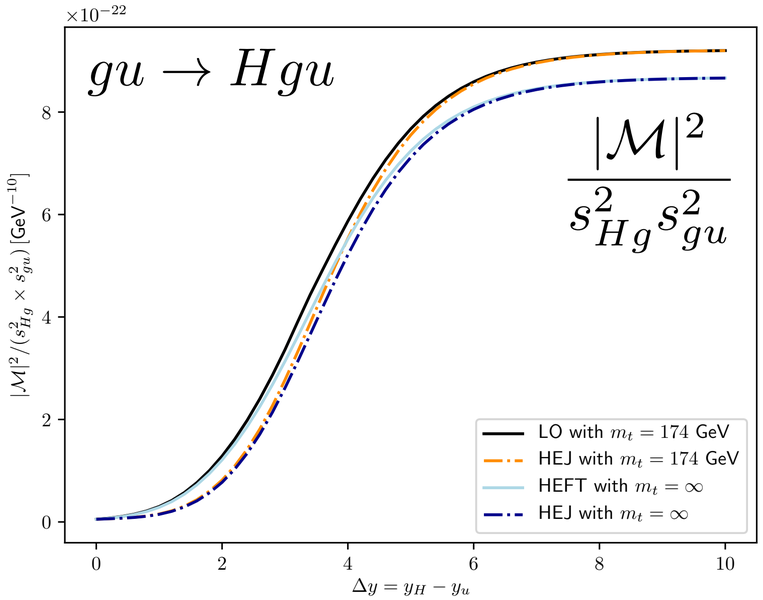
Andersen, Black, Brooks, Byrne, Maier, JMS arXiv:2012.10310

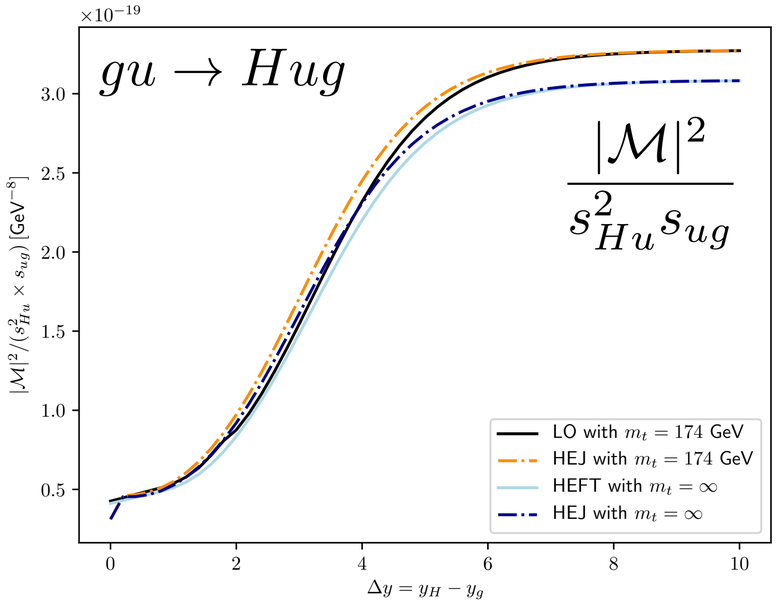
Higgs + 1j in HEJ

- 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 the same framework can be applied to H+1j

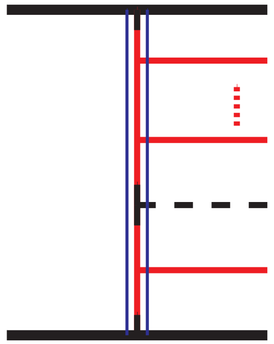
Andersen, Hassan, Maier, Paltrinieri, Papaefstathiou, JMS arXiv:2210.10671

Higgs + 1j in HEJ

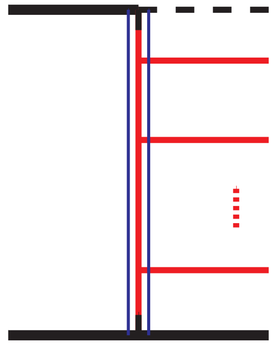
Black = Born/skeleton function

Red = Range of resummation

Previous 2jet+



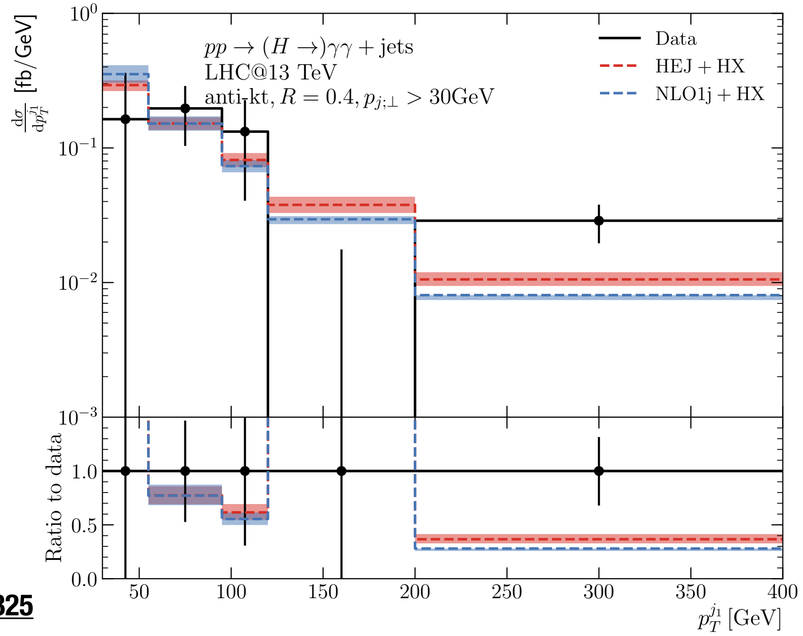
Increasing rapidity



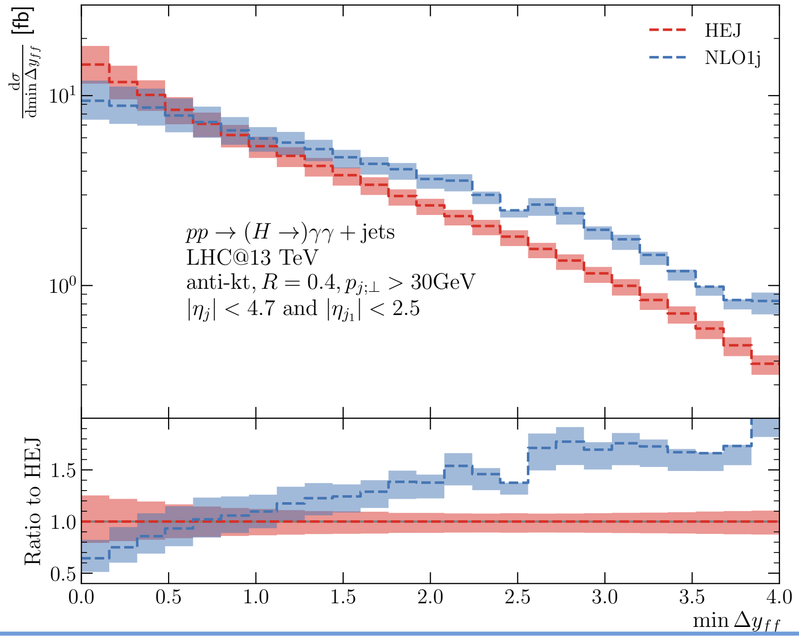
New 1jet+

Similar effects on distributions

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

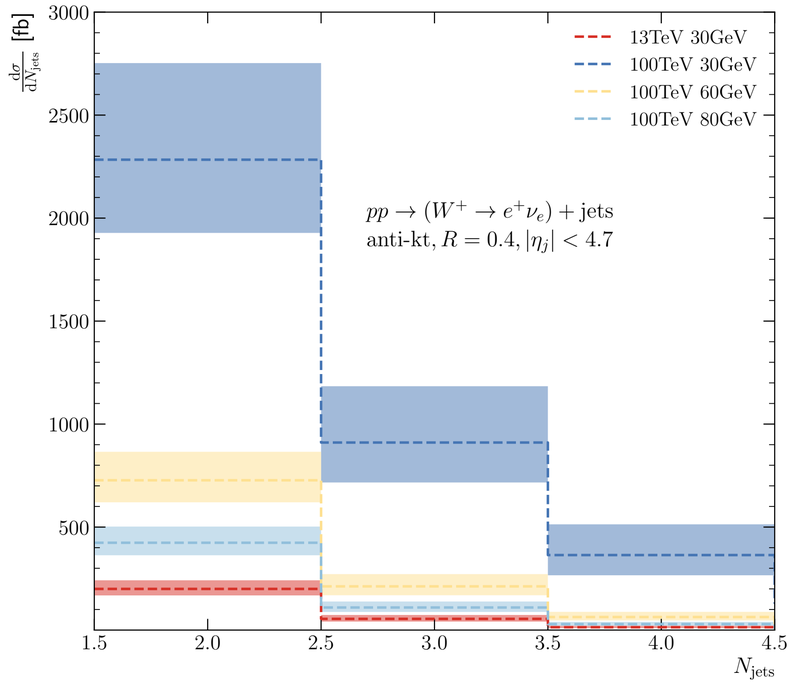


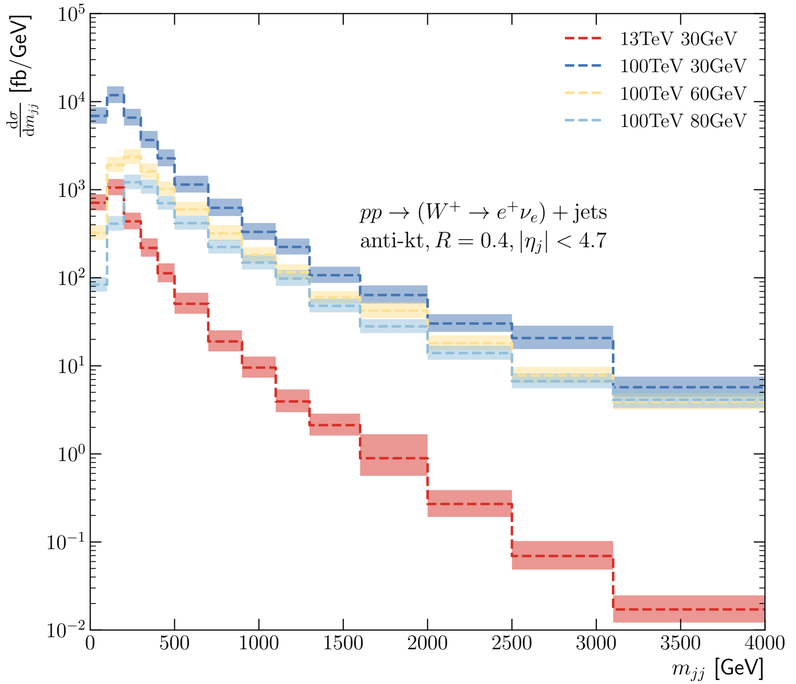
CMS data arXiv:1807.03825



Looking Forward

What about a 100 TeV collider? Even larger centre-of-mass energy will give even larger logs!



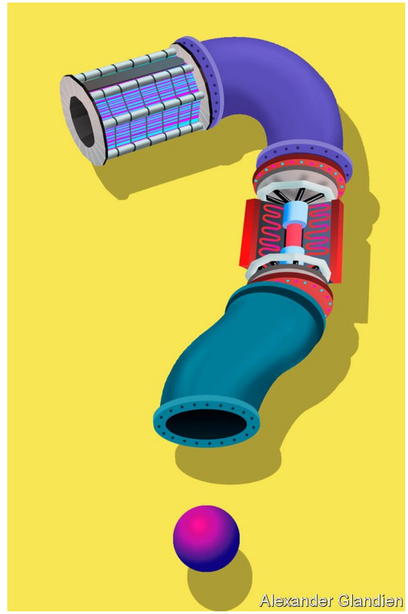


Higher pT cuts can control the jet rates, but impact of logs on shapes of distributions will be large

Plots: Conor Elrick

Summary & Outlook

- Current and future data demand higher precision predictions…
- … and demand calculation of new effects
- 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



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