High Energy Resummation for Jet Processes at the LHC



Jennifer Smillie Higgs Centre, University of Edinburgh **CERN TH Seminar Dec 2022**

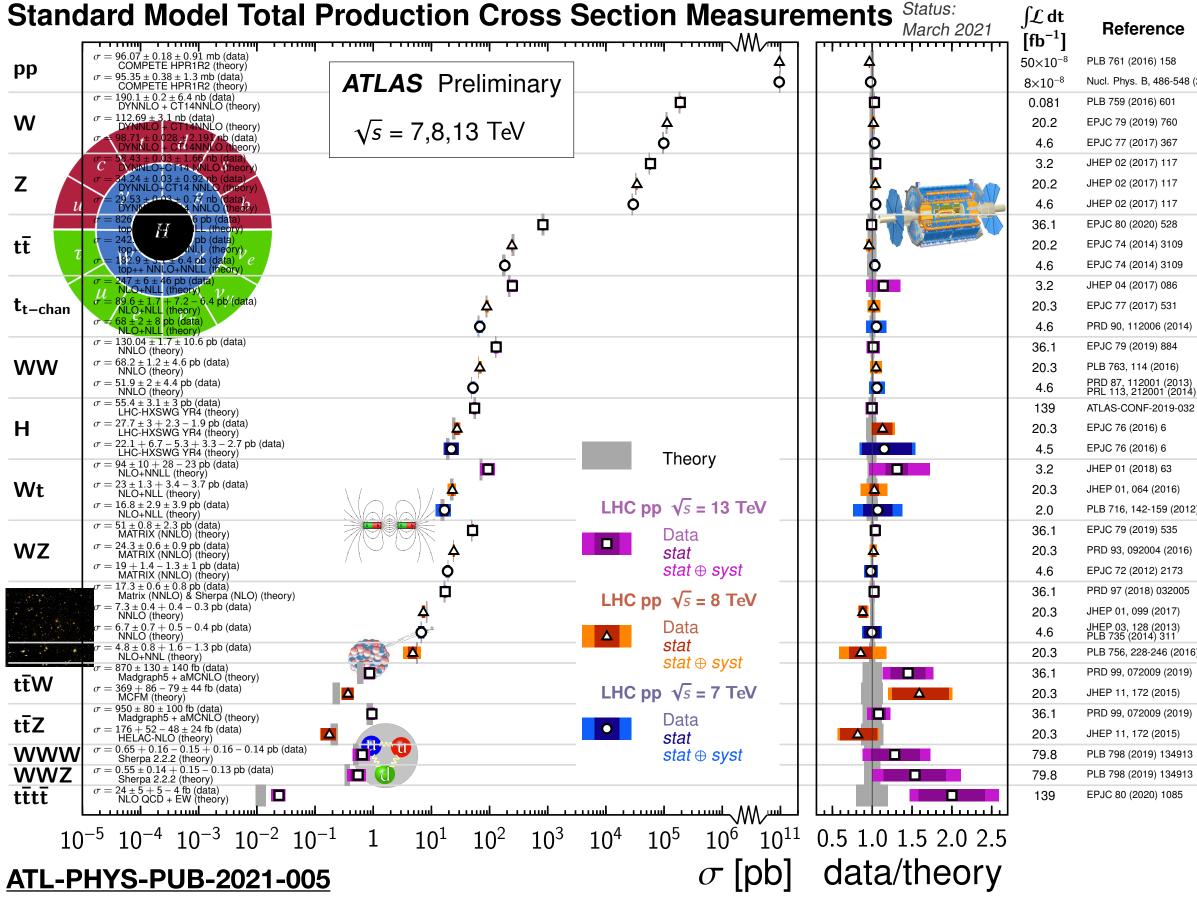


Photo Credit: Kinrannoch Photography









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

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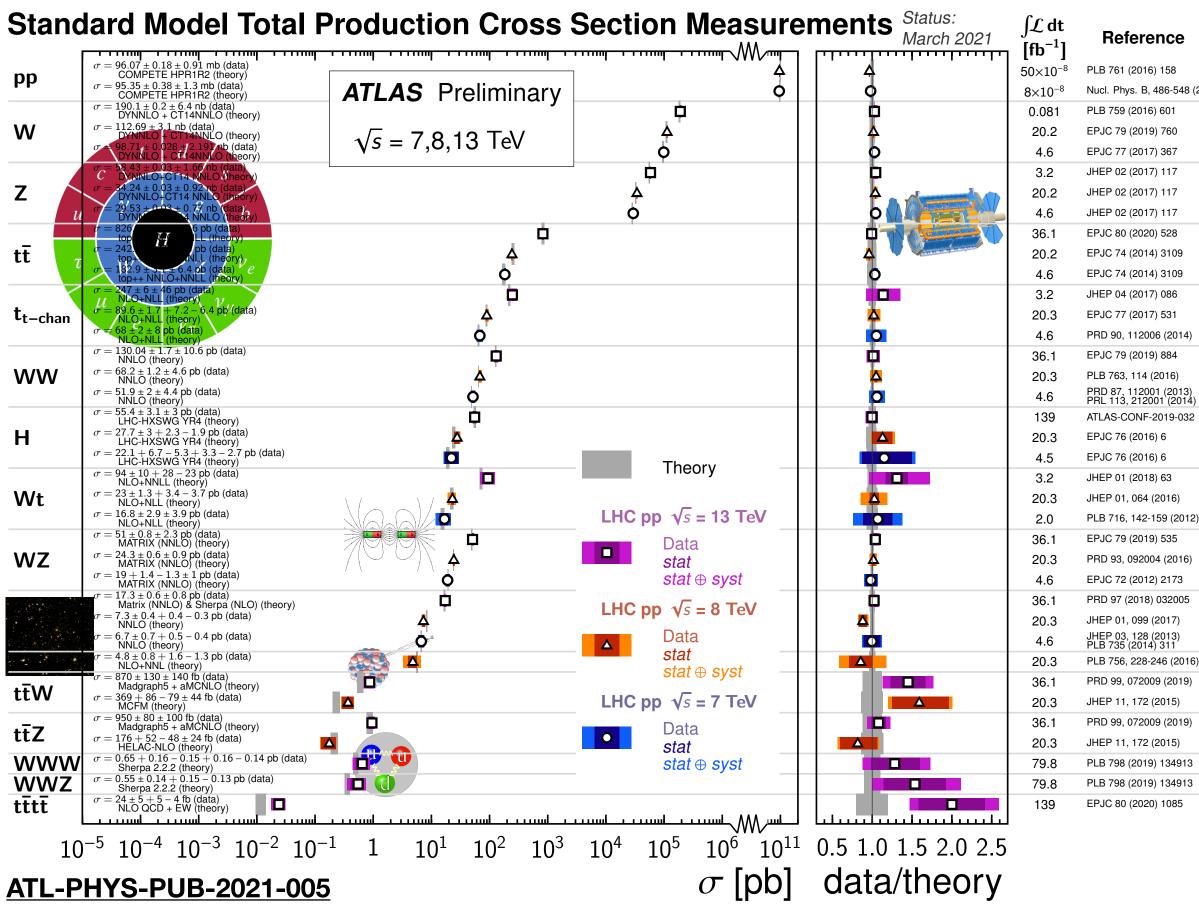


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Nucl. Phys. B. 486-548 (2014



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

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits Status: March 2021

 $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$ ℓ, γ Jets $\dagger E_{\tau}^{\text{miss}} \int \mathcal{L} dt [fb^{-1}]$ Model Limit ADD $G_{KK} + g/q$ $0 e, \mu, \tau, \gamma$ 1 – 4 j 139 **11.2 TeV** *n* = 2 ADD non-resonant $\gamma\gamma$ 2γ 36.7 8.6 TeV n = 3 HLZ NLO ADD QBH 2 j _ 37.0 **8.9 TeV** *n* = 6 **9.55 TeV** $n = 6, M_D = 3$ TeV, rot BH ADD BH multiie _ 3.6 ≥3 j RS1 $G_{KK} \rightarrow \gamma \gamma$ 2γ 139 4.5 TeV $k/\overline{M}_{Pl} = 0.1$ _ Bulk RS $G_{KK} \rightarrow WW/ZZ$ multi-channel 36.1 2.3 TeV $k/\overline{M}_{Pl} = 1.0$ Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell \nu a q$ 2j/1J 1 e,μ Yes 139 2.0 TeV $k/\overline{M}_{Pl} = 1.0$ 36.1 Bulk RS $g_{KK} \rightarrow tt$ $1 \ e, \mu \ge 1 \ b, \ge 1$ J/2j Yes $\Gamma/m = 15\%$ Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$ 2UED / RPP 1.8 TeV $1 e, \mu \ge 2 b, \ge 3 j$ Yes 36.1 SSM $Z' \rightarrow \ell \ell$ 2 e, µ 5.1 TeV 2.42 TeV SSM $Z' \rightarrow \tau \tau$ 2τ 36.1 36.1 139 139 2 b Leptophobic $Z' \rightarrow bb$ 2.1 TeV mass $\Gamma/m = 1.2\%$ Leptophobic $Z' \rightarrow tt$ 0 e,μ $\geq 1 \text{ b}, \geq 2 \text{ J}$ Yes 4.1 TeV ' mass SSM $W' \rightarrow \ell v$ $1 e, \mu$ 6.0 TeV Yes ' mass 3.7 TeV SSM $W' \rightarrow \tau v$ 36.1 1τ Yes 139 HVT $W' \rightarrow WZ \rightarrow \ell \nu q q$ model B 2j/1J $g_V = 3$ Yes Yes 1 e,μ 4.3 TeV 139 HVT $Z' \rightarrow ZH$ model B 0-2 e, µ 1-2 b 3.2 TeV $g_V = 3$ 139 3.2 TeV HVT $W' \rightarrow WH$ model B 0 e,μ $g_V = 3$ \geq 1 b, \geq 2 J LRSM $W_R \rightarrow tb$ multi-channe 36.1 3.25 TeV LRSM $W_R \rightarrow \mu N_R$ 2μ 1 J 80 $m(N_R) = 0.5 \text{ TeV}, g_L = g_R$ 5.0 Te CI gggc 2 j 37.0 **21.8 TeV** η_{LL} 35.8 TeV CI*ℓℓqq* 2 e, µ 139 139 CI eebs 2 e 1 b _ 1.8 TeV $g_* = 1$ Cl µµbs 2μ 139 1 b 2.0 TeV $g_* = 1$ 2.57 TeV $|C_{4t}| = 4\pi$ CI tttt ≥1 e,µ ≥1 b, ≥1 j Yes 36. Axial-vector med. (Dirac DM) 1 – 4 i g_q =0.25, g_{χ} =1, $m(\chi)$ =1 GeV 0 e, μ, τ, γ 139 2.1 TeV Pseudo-scalar med. (Dirac DM) 0 e, μ, τ, γ 1 – 4 i Yes 139 376 GeV $g_q=1, g_{\chi}=1, m(\chi)=1 \text{ GeV}$ Vector med. Z'-2HDM (Dirac DM) $0 e, \mu$ 2 b Yes 139 $\tan\beta=1, g_Z=0.8, m(\chi)=100 \text{ GeV}$ Pseudo-scalar med. 2HDM+a 139 0 e, µ 2 b Yes $\tan\beta=1, g_{\chi}=1, m(\chi)=10 \text{ GeV}$ 520 Ge\ Scalar reson. $\phi \rightarrow t_{\chi}$ (Dirac DM) 0-1 e, μ 1 b, 0-1 J 3 4 Te\ Yes 36.1 $y=0.4, \lambda=0.2, m(\chi)=10 \text{ GeV}$ 1.8 TeV Scalar LQ 1st ger $\beta = 1$ 139 139 Scalar LQ 2nd ger 2 μ $\beta = 1$ ≥ 2 j Yes 1.7 TeV 139 139 $\mathcal{B}(LO_2^u \to b\tau) = 1$ 1τ 2 b 1.2 TeV Scalar LQ 3rd ger Yes $0 e, \mu \ge 2 j, \ge 2 b$ Yes 1.24 TeV $\mathcal{B}(LQ_2^u \to tv) = 1$ Scalar LQ 3rd ger 139 139 $\geq 2e, \mu, \geq 1\tau \geq 1$ j, ≥ 1 b $\mathcal{B}(\mathrm{LO}_2^d \to t\tau) = 1$ Scalar LQ 3rd gen _ 1.43 TeV $0 e, \mu, \ge 1\tau \ 0 - 2 j, 2 b$ Yes 1.26 TeV $\mathcal{B}(\mathrm{LO}_{2}^{d} \to bv) = 1$ Scalar LQ 3rd gen VLQ $TT \rightarrow Ht/Zt/Wb + X$ 36. 1.37 TeV SU(2) doublet multi-channe 1.34 TeV $\mathsf{VLQ} \ BB \to Wt/Zb + X$ multi-channe 36.1 SU(2) doublet VLQ $T_{5/3} T_{5/3} | T_{5/3} \rightarrow$ $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) =$ 2(SS)/≥3 *e*,*µ* ≥1 b, ≥1 j 36.1 1.64 TeV Yes Yes 36.1 $\mathsf{VLQ} \ Y \to Wb + X$ $\geq 1 \text{ b}, \geq 1 \text{ j}$ $\mathcal{B}(Y \to Wb) = 1, c_R(Wb) = 1$ 1 e, µ 1.85 Te\ $\mathsf{VLQ} \ B \to Hb + X$ 0 e,µ 79.8 1.21 TeV singlet, $\kappa_B = 0.5$ VLQ $QQ \rightarrow WqWq$ 20.3 1 e,μ Excited quark $q^* \rightarrow qg$ 2 j 139 only u^* and d^* , $\Lambda = m(q^*)$ 6.7 TeV Excited quark $q^* \rightarrow q\gamma$ 1γ 36.7 only u^* and d^* , $\Lambda = m(q^*)$ -5.3 TeV Excited quark $b^* \rightarrow bg$ 1 b, 1 j _ 36.1 Excited lepton ℓ 3 e, µ 20.3 $\Lambda = 3.0 \text{ TeV}$ _ Excited lepton v 3 e,μ,τ 20.3 1.6 TeV $\Lambda=1.6~\text{TeV}$ Type III Seesaw 790 GeV 1 e, µ ≥ 2 j Yes 139 LRSM Maiorana y $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 2 μ 36.1 36.1 20.3 36.1 Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ 2,3,4 *e*, *µ* (SS) 870 GeV DY production Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ Multi-charged particles DY production, $\mathcal{B}(H_l^{\pm\pm} \rightarrow \ell \tau) = 1$ 3 e,μ,τ _ 1.22 TeV _ DY production, |q| = 5eMagnetic monopoles 2.37 TeV DY production, $|g| = 1g_D$, spin 1/234.4 √s = 13 TeV √s = 13 TeV <u>√s = 8 Te</u>' **10**⁻¹ 10 partial data full data 1 Mass scale [TeV]

*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-2021-009







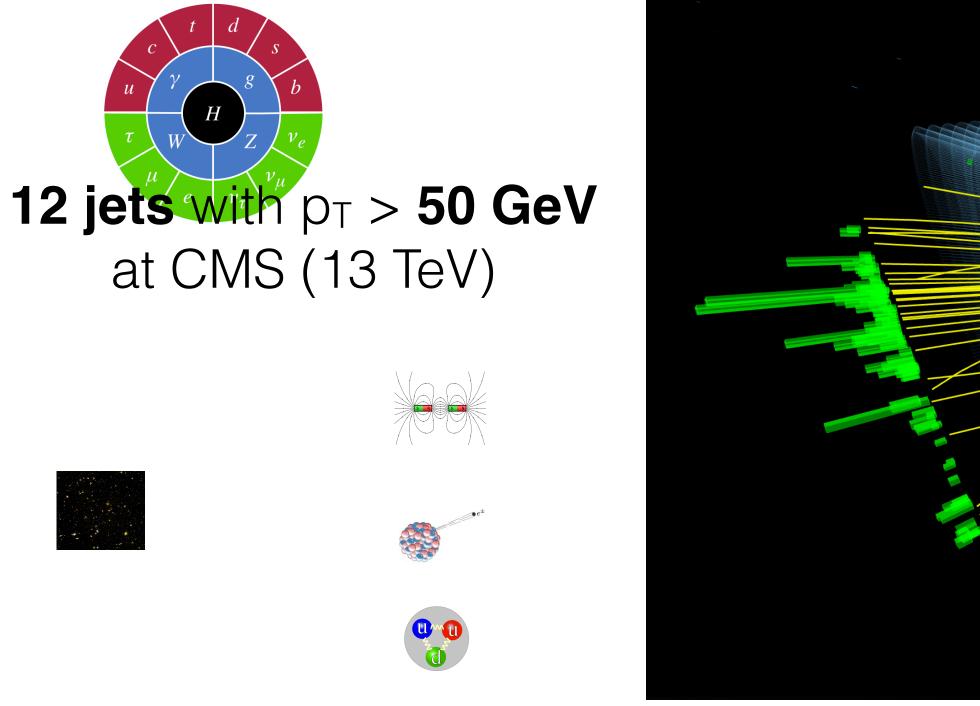
ATLAS Preliminary					
	\sqrt{s} = 8, 13 TeV Reference				
t BH	2102.10874 1707.04147 1703.09127 1512.02586 2102.13405 1808.02380				
tt) = 1	2004.14636 1804.10823 1803.09678				
= g _R	1903.06248 1709.07242 1805.09299 2005.05138 1906.05609 1801.06992 2004.14636 ATLAS-CONF-2020-043 2007.05293 1807.10473 1904.12679				
ν η _{LL}	1703.09127 2006.12946 ATLAS-CONF-2021-012 ATLAS-CONF-2021-012 1811.02305				
1 GeV eV =100 GeV 0 GeV) GeV	2102.10874 2102.10874 ATLAS-CONF-2021-006 ATLAS-CONF-2021-006 1812.09743				
	2006.05872 2006.05872 ATLAS-CONF-2021-008 2004.14060 2101.11582 2101.12527				
T _{5/3} Wt)= 1 Vb)= 1	1808.02343 1808.02343 1807.11883 1812.07343 ATLAS-CONF-2018-024 1509.04261				
(q^*) (q^*)	1910.08447 1709.10440 1805.09299 1411.2921 1411.2921				
$= g_R$ $\rightarrow \ell \tau) = 1$ $g_D, \text{ spin } 1/2$	20008.07949 1809.11105 1710.09748 1411.2921 1812.03673 1905.10130				







CMS Experiment at the LHC, CERN Data recorded: 2015-Sep-28 06:09:43.129280 GMT Run / Event / LS: 257645 / 1610868539 / 1073

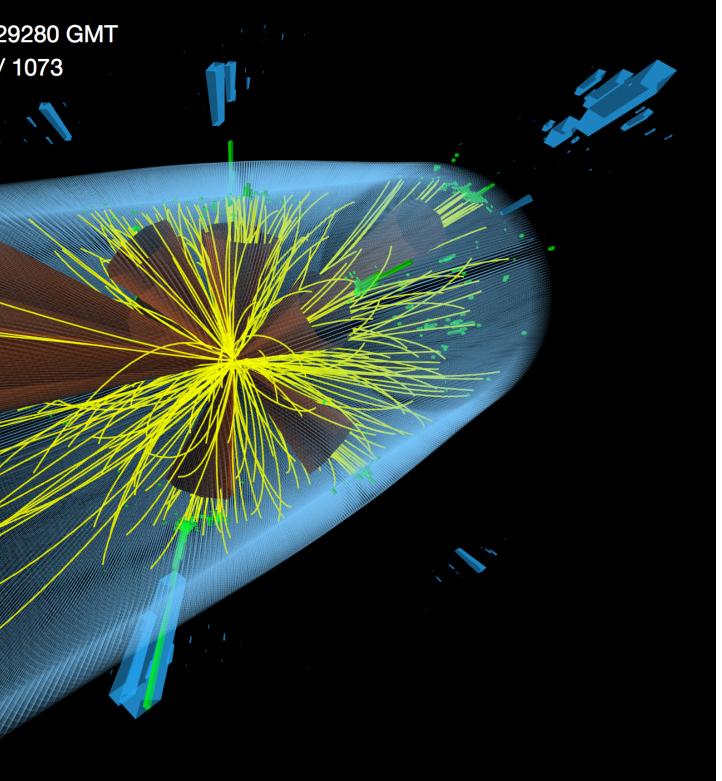


Many colour-charged, hard particles with p_T , s_{ij} , \hat{s} Large logs in s_{ij}/p_T^2 damage convergence of pert. expansion

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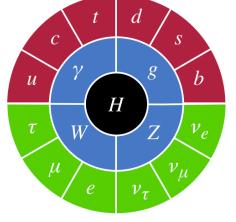
Image Copyright CERN

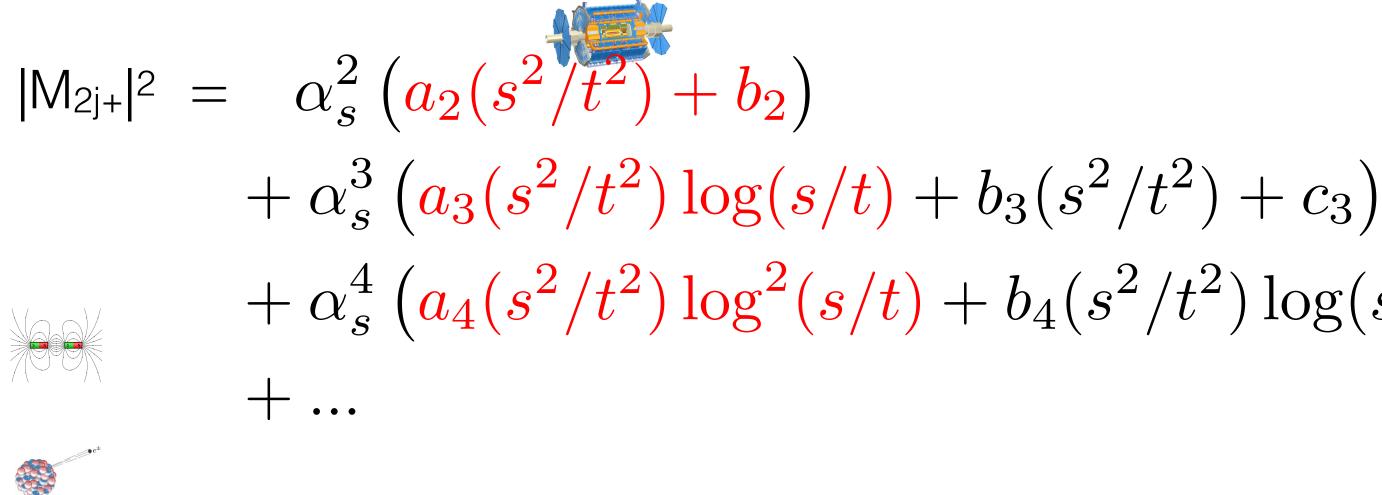






Inclusive 2-jet cross section given by $\int d\mathrm{PS}_2 \, |\mathsf{M}_{2j+}|^2$, with







- 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 + ...

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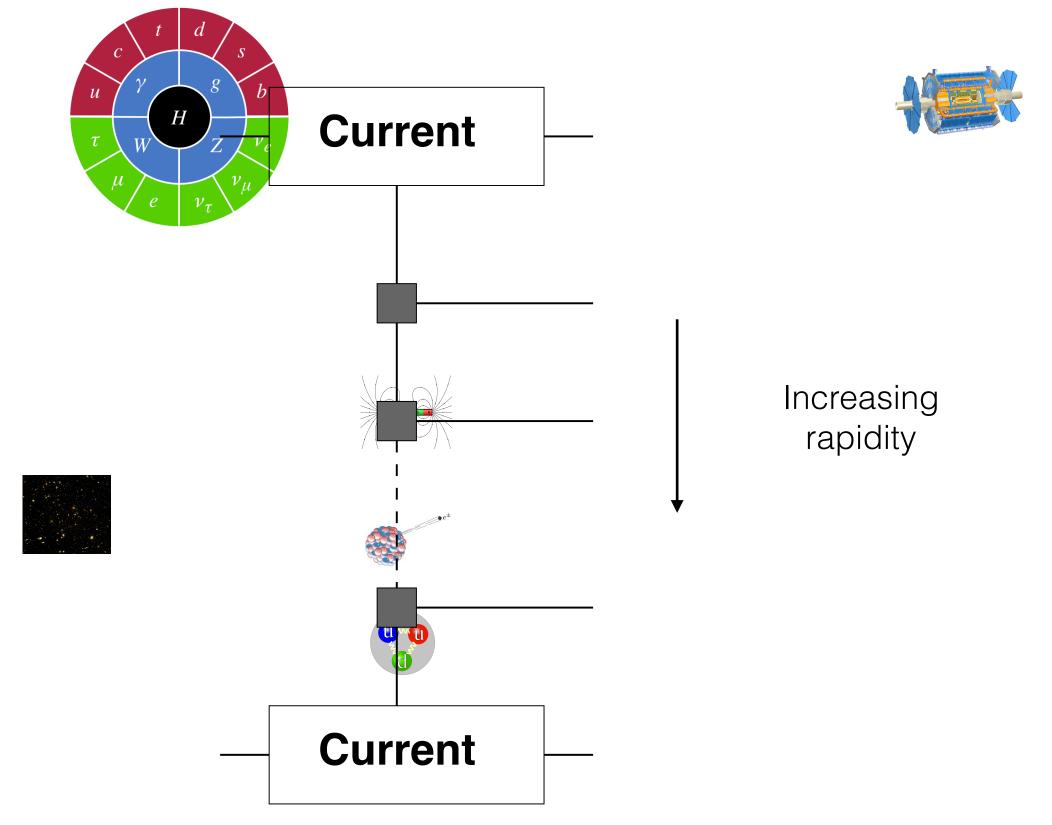


 $+ \alpha_s^4 \left(\frac{a_4(s^2/t^2) \log^2(s/t)}{s^2(s/t)} + b_4(s^2/t^2) \log(s/t) + \ldots \right)$





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

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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...

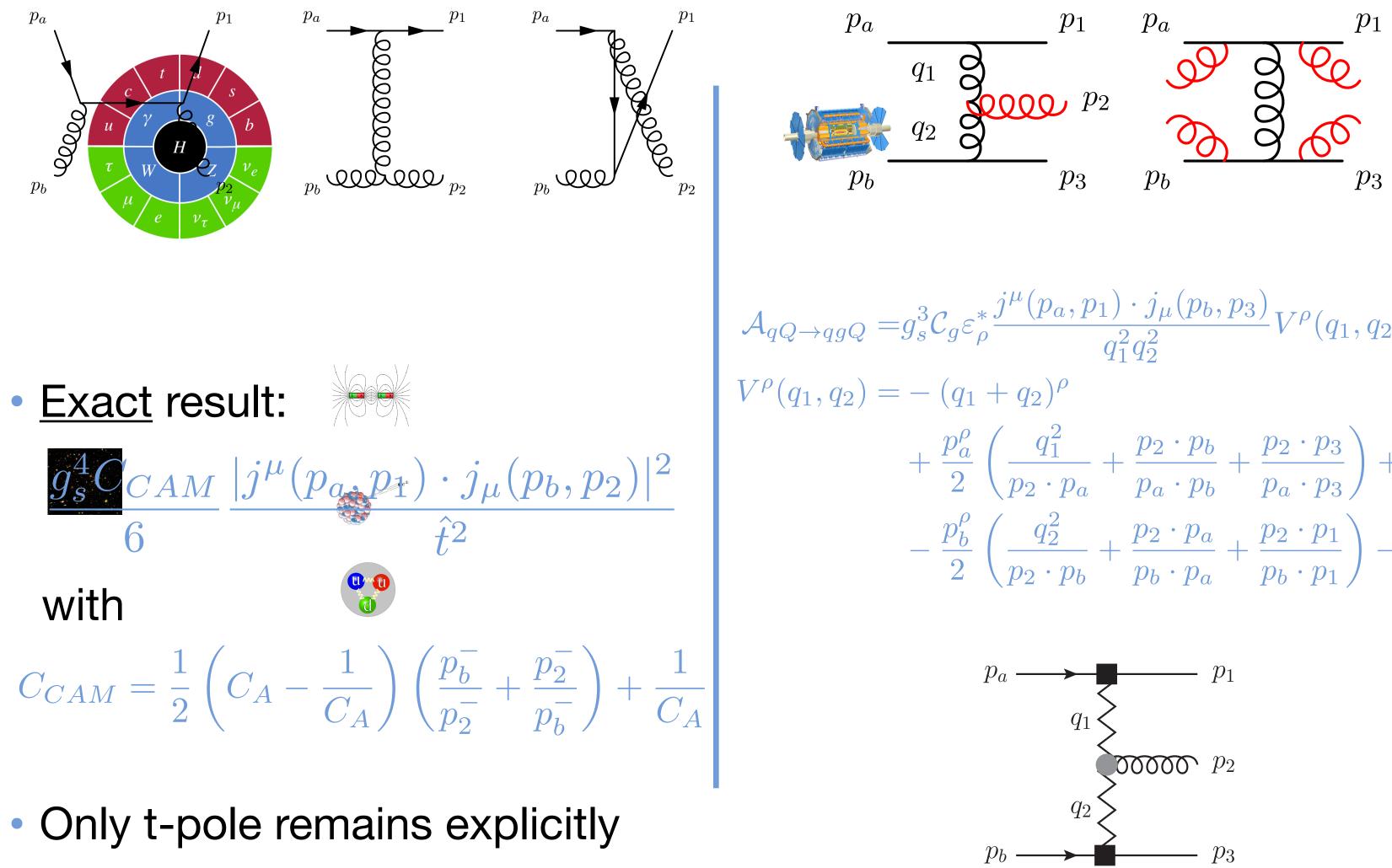








Examples of HE Limit



Only t-pole remains explicitly

Andersen & JMS arXiv:0908.2786, 0910.5113, Lipatov Sov. J. Nucl. Phys. 23:338-345, 1976

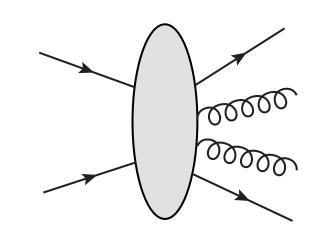
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$$\frac{(p_{a}, p_{1}) \cdot j_{\mu}(p_{b}, p_{3})}{q_{1}^{2}q_{2}^{2}}V^{\rho}(q_{1}, q_{2})$$

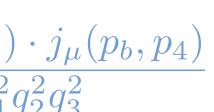
$$\frac{q_{2})^{\rho}}{(p_{2} \cdot p_{a})} + \frac{p_{2} \cdot p_{b}}{p_{a} \cdot p_{b}} + \frac{p_{2} \cdot p_{3}}{p_{a} \cdot p_{3}}\right) + p_{a} \leftrightarrow p_{1}$$

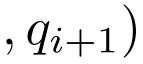
$$\frac{q_{2}^{2}}{(p_{2} \cdot p_{b})} + \frac{p_{2} \cdot p_{a}}{p_{b} \cdot p_{a}} + \frac{p_{2} \cdot p_{1}}{p_{b} \cdot p_{1}}\right) - p_{b} \leftrightarrow p_{3}$$



$$\mathcal{A}_{qQ \to qggQ} = g_s^4 \mathcal{C}_g \mathcal{C}_{g'} \frac{j^{\mu}(p_a, p_1) \cdot j}{q_1^2 q_2^2 q_2^2}$$
$$\times \varepsilon_{\rho}^* V^{\rho}(q_1, q_2)$$
$$\times \varepsilon_{\sigma}^* V^{\sigma}(q_2, q_3)$$

• <u>Same</u> functions $V^{\rho}(q_i, q_{i+1})$ p_3 p_b — $- p_4$

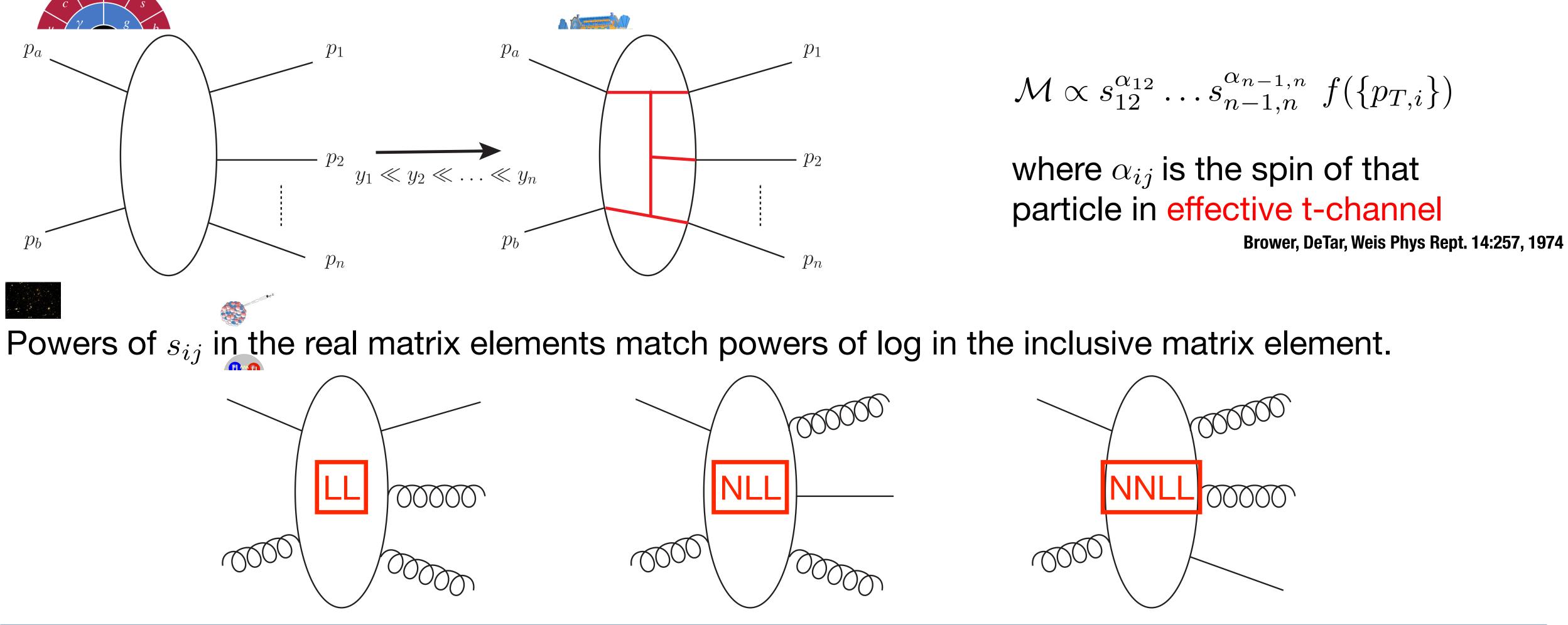








Regge scaling dictates the scaling of the amplitude with s_{ij} for a given process



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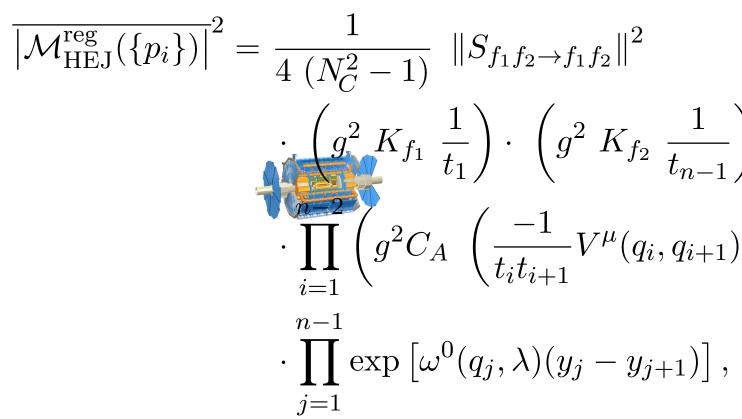


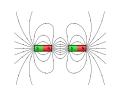












uared Matrix

Element







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$$_{2 \to f_1 f_2} \|^2$$

$$\left(g^2 K_{f_2} \frac{1}{t_{n-1}}\right)$$

$$\frac{-1}{q_{i+1}} V^{\mu}(q_i, q_{i+1}) V_{\mu}(q_i, q_{i+1}) - \frac{4}{\mathbf{p}_i^2} \theta\left(\mathbf{p}_i^2 < \lambda^2\right) \right)$$

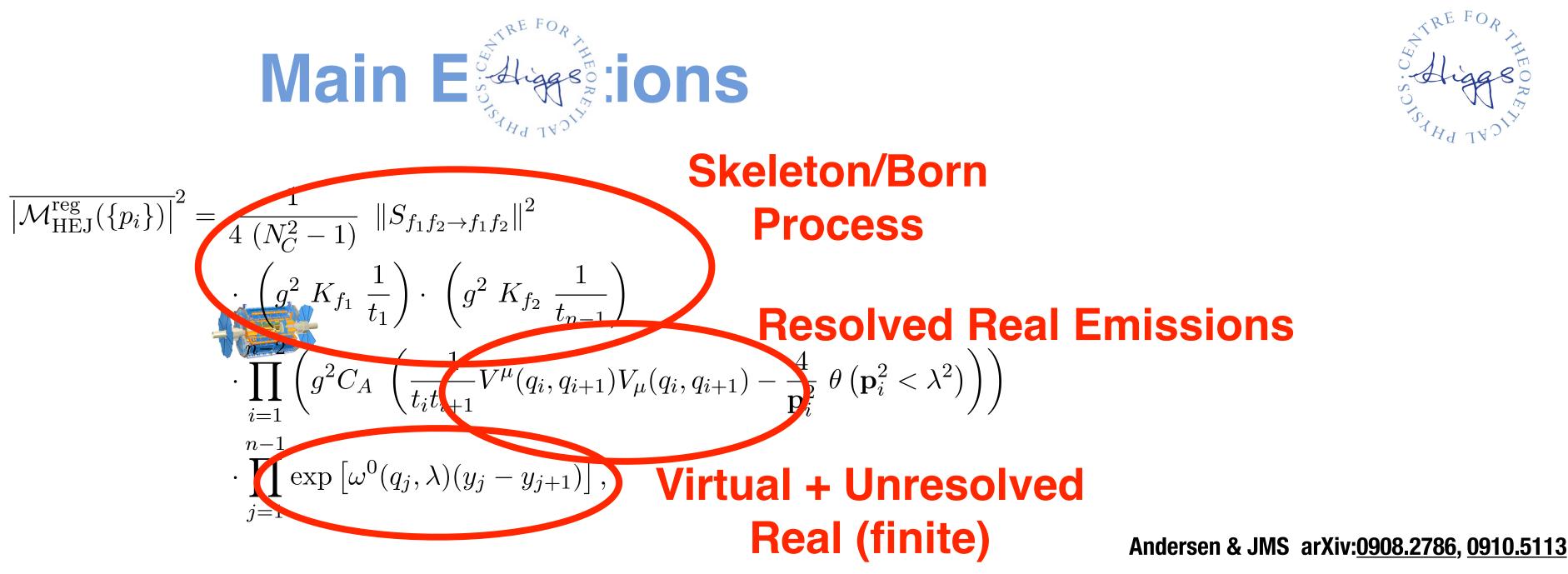
Andersen & JMS arXiv:0908.2786, 0910.5113

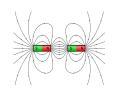












Jared Matrix

Element





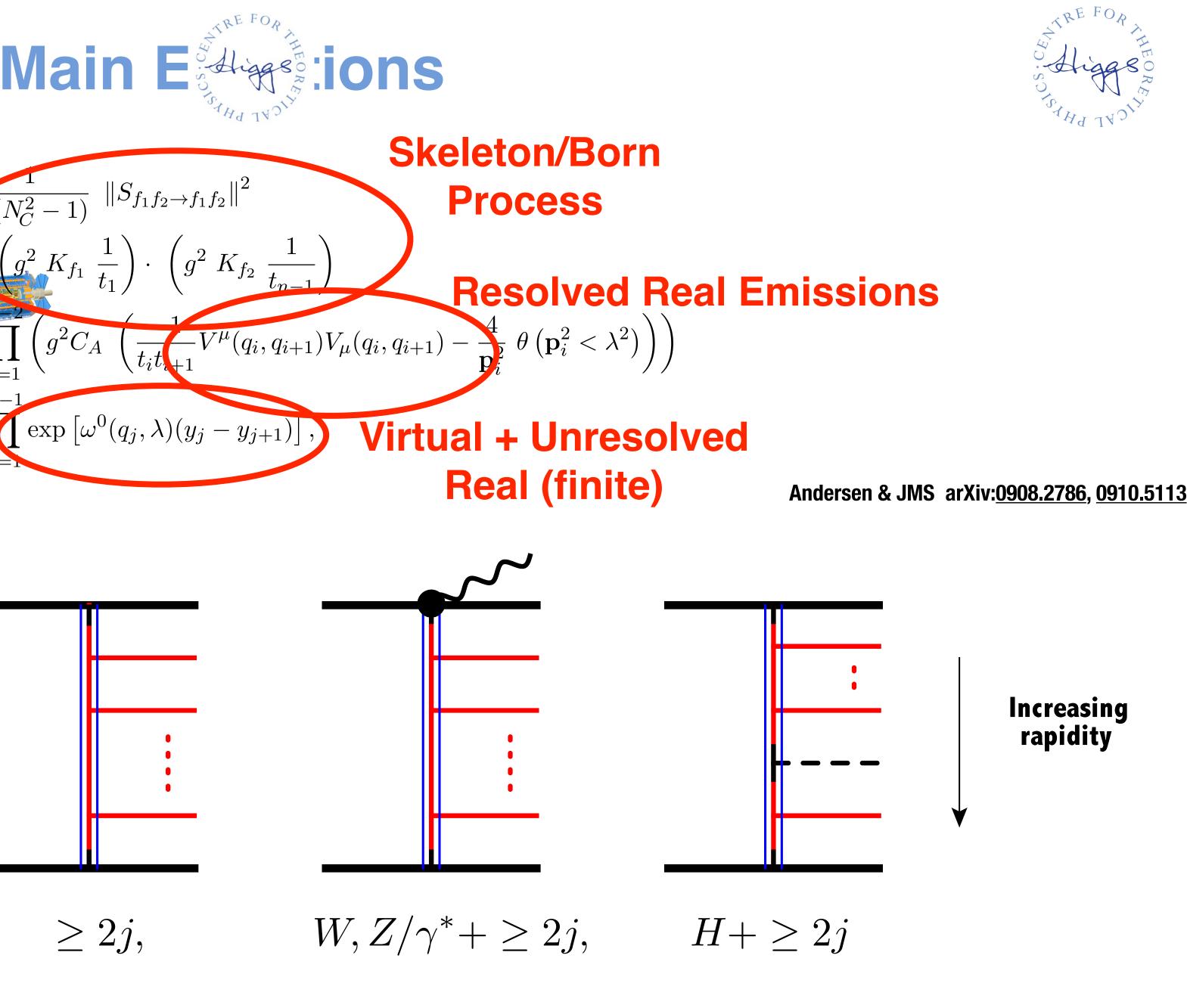


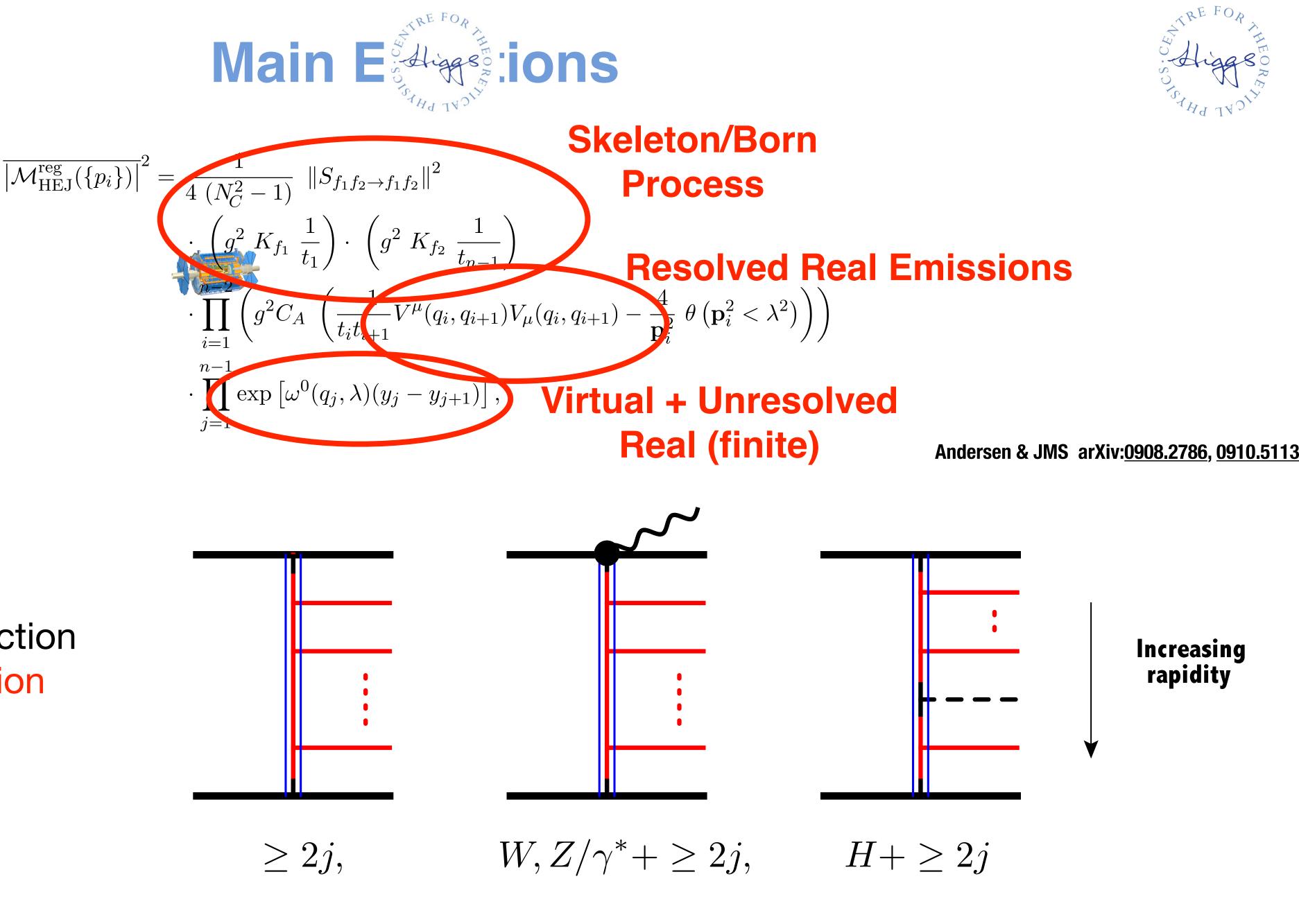
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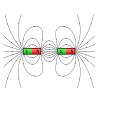












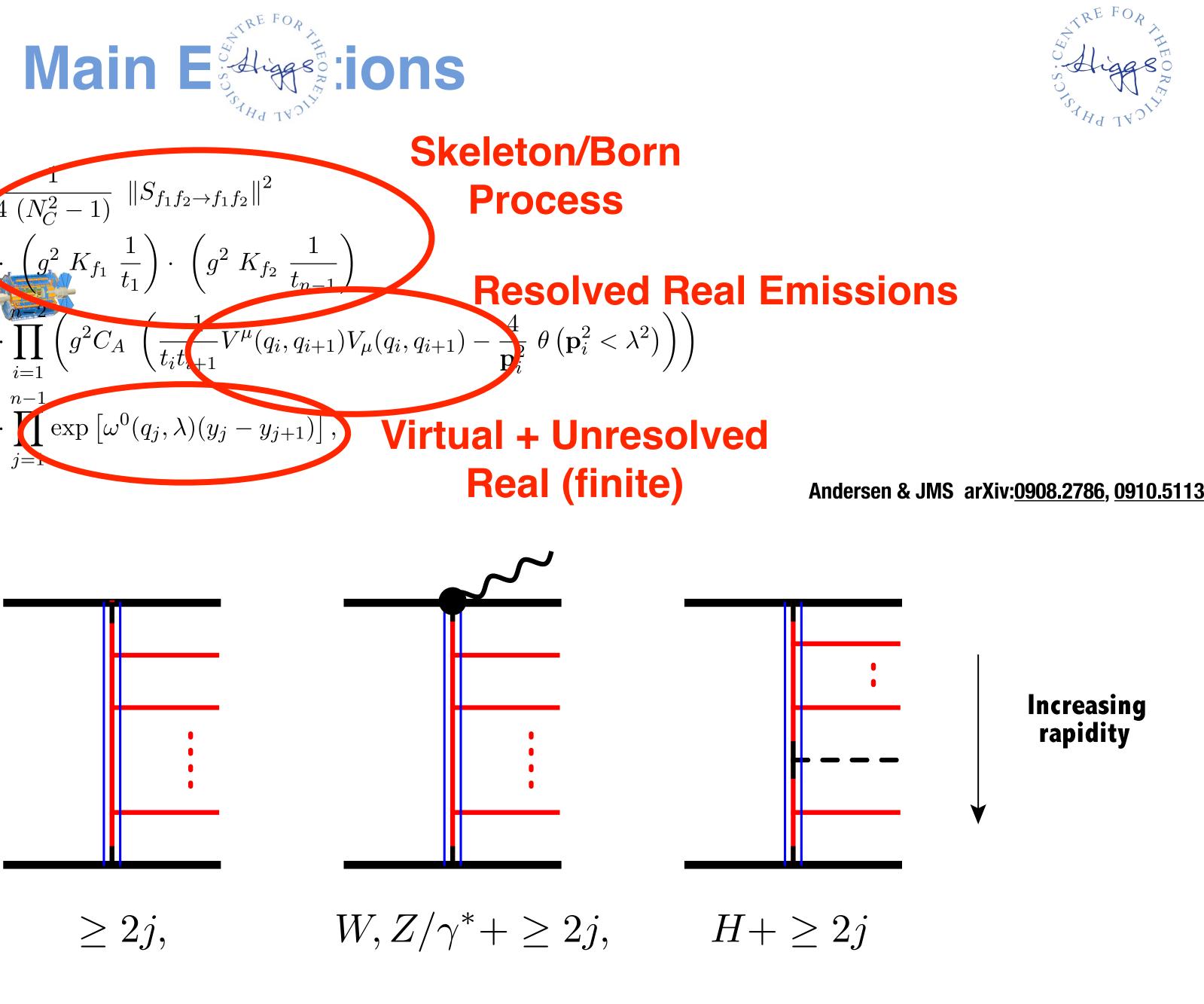
Jared Matrix

Element





Black = Skeleton/Born function Red = Range of resummation



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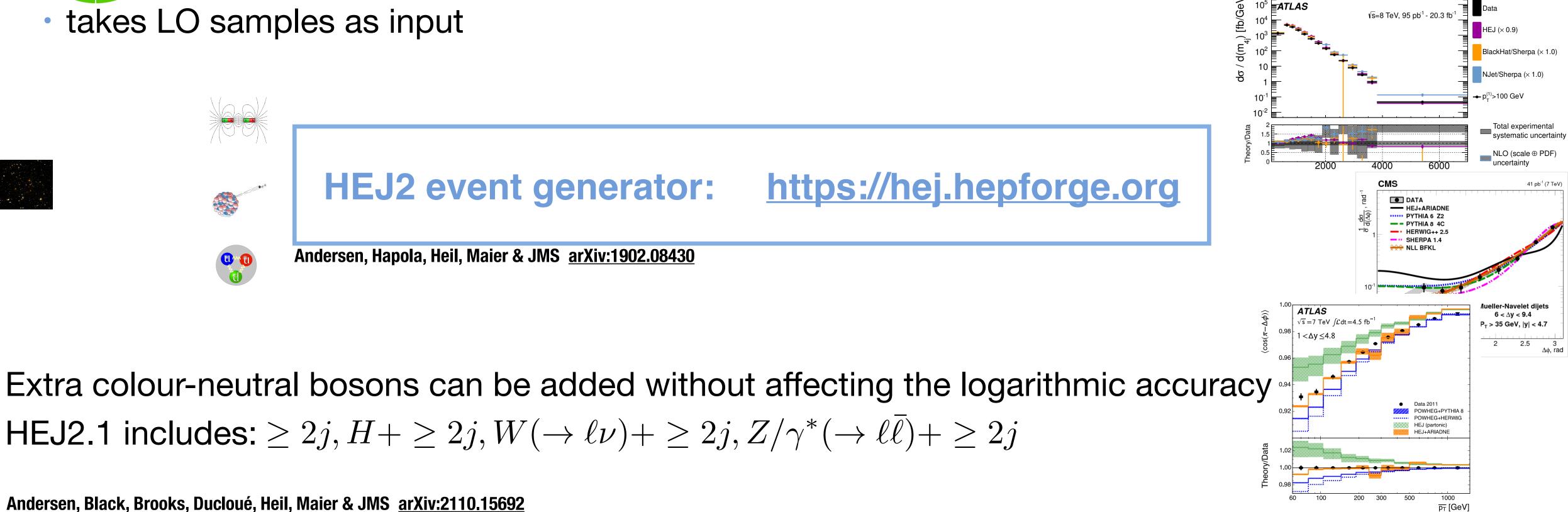




The High Energy Jets (HEJ) framework is

- exact for simple processes (2 to 2 (+X)) constructed event-by-event
- takes LO samples as input





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

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

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

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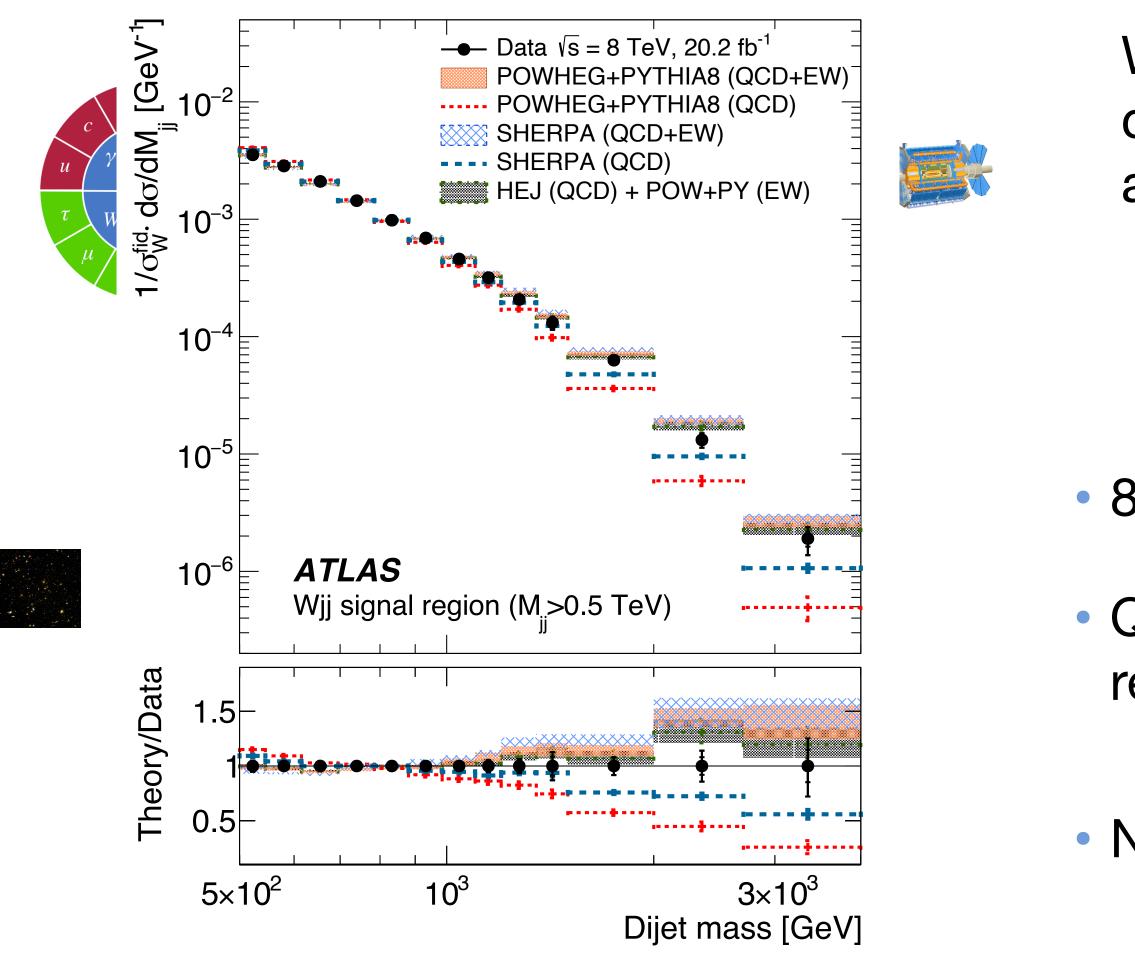
- gauge invariant in all phase space
- sufficiently fast for numerical integration (up) to 30 gluons)











ATLAS arXiv:<u>1703.04362</u>

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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

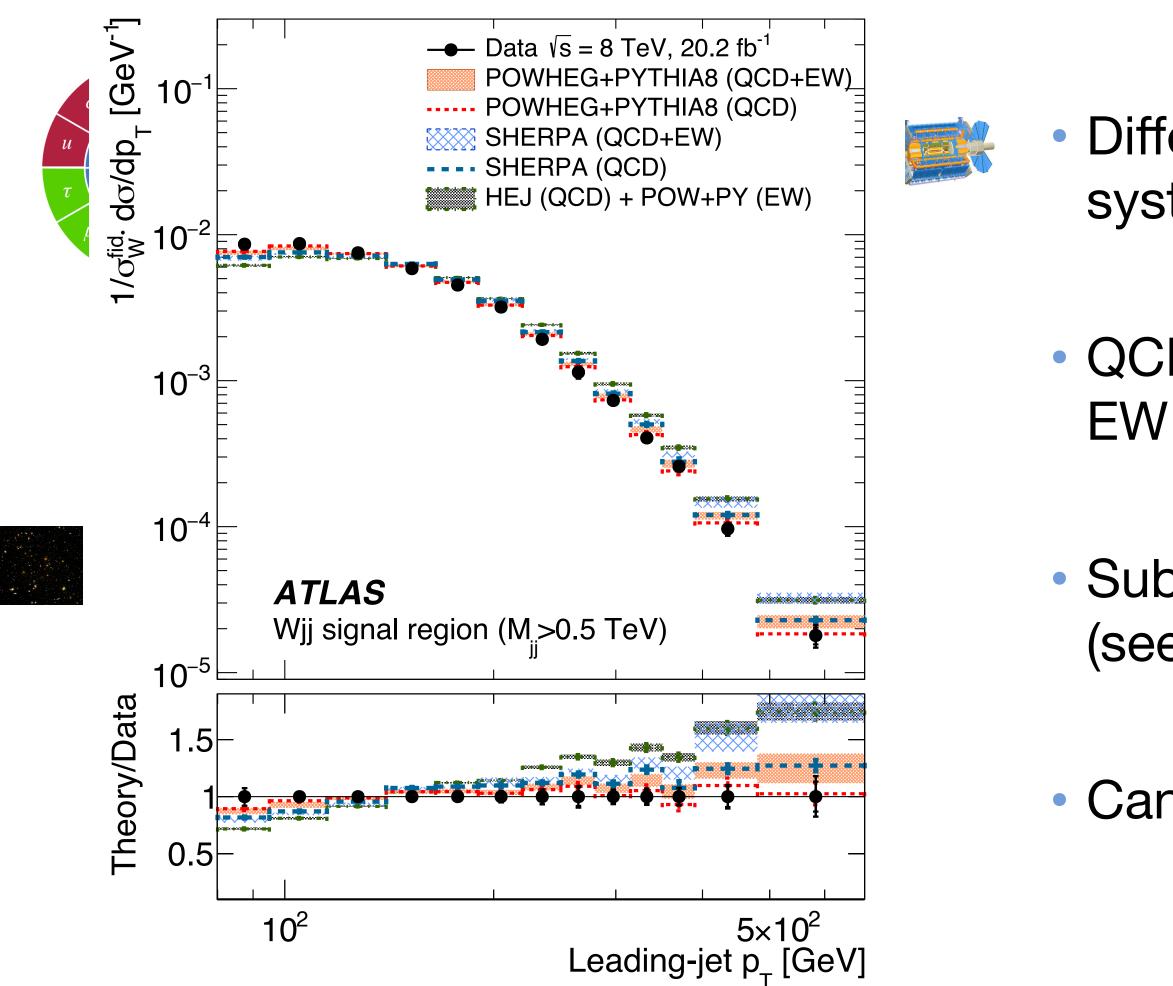












ATLAS arXiv:1703.04362

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- Different picture when plotted versus p_T as no systematic evolution in pT in HEJ.
- QCD contribution no longer suppressed compared to
- 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

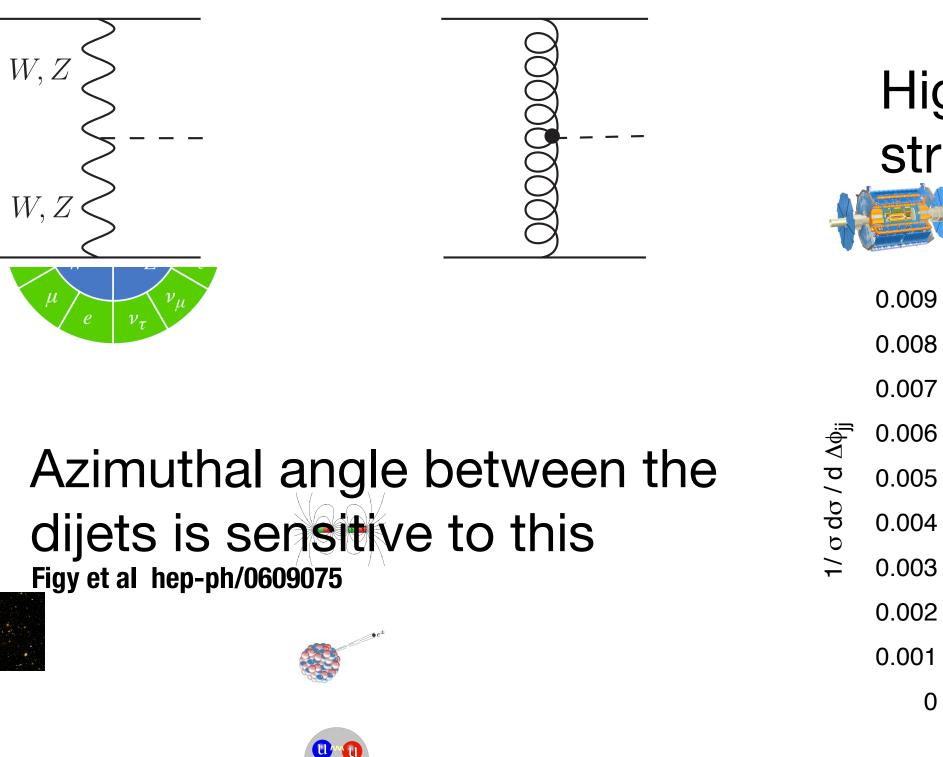












0.008 0.007 0.006 0.005 0.004 0.003 0.002 0.001 -160 -120

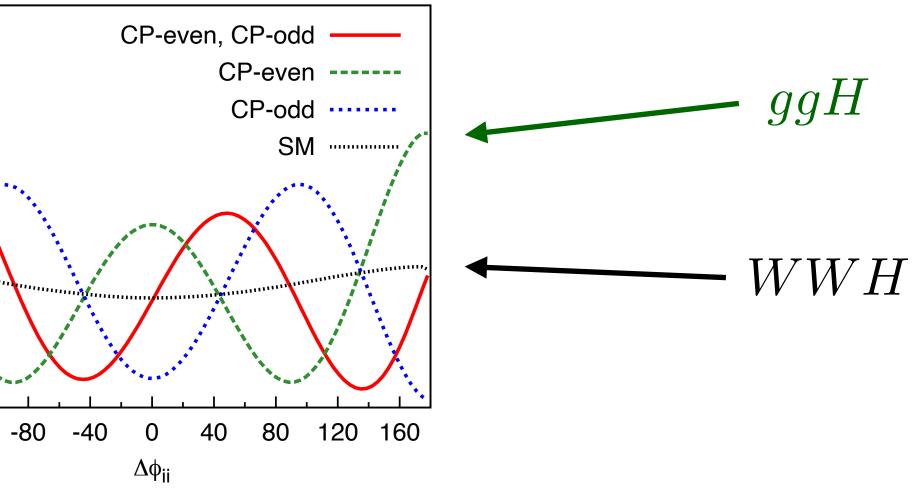
Use distinctive event shape to separate channels with "VBF cuts"

BUT this precisely enhances higher orders in pert. expansion

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

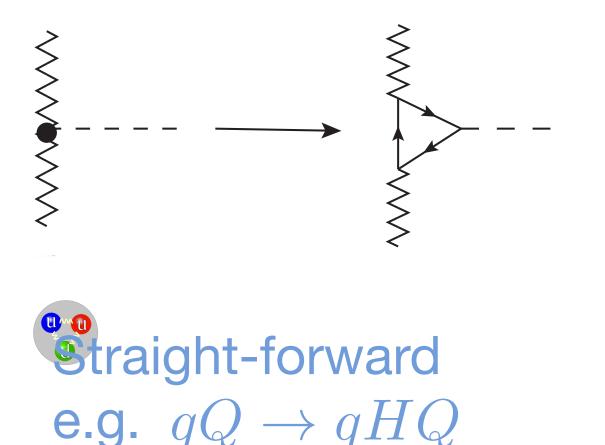


- e.g. $\Delta y_{jj} > 2.8, \ m_{jj} > 400 \text{ GeV}$





Fixed-order stalled for full quark mass effects because LO = 1-loop. LO results only for 2 and 3 jets (no NLO for 2j+) In HEJ, factorised structure removes complexity from increasing number of jets





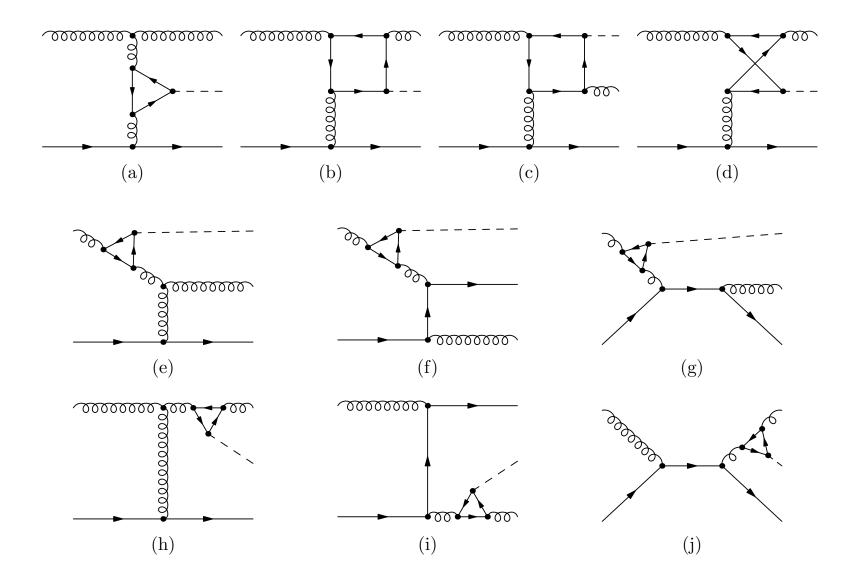
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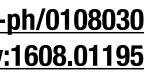
Del Duca et al <u>hep-ph/0105129</u>, <u>hep-ph/0108030</u> Greiner et al arXiv:1608.01195

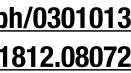
Del Duca, Kilgore, Oleari, Schmidt & Zeppenfeld <u>hep-ph/0301013</u> Andersen, Cockburn, Heil, Maier & JMS arXiv:1812.08072



Outer Higgs more involved but calculated











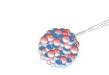
HEJ can include finite quark mass and loop propagator effects for <u>any</u> number of jets

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

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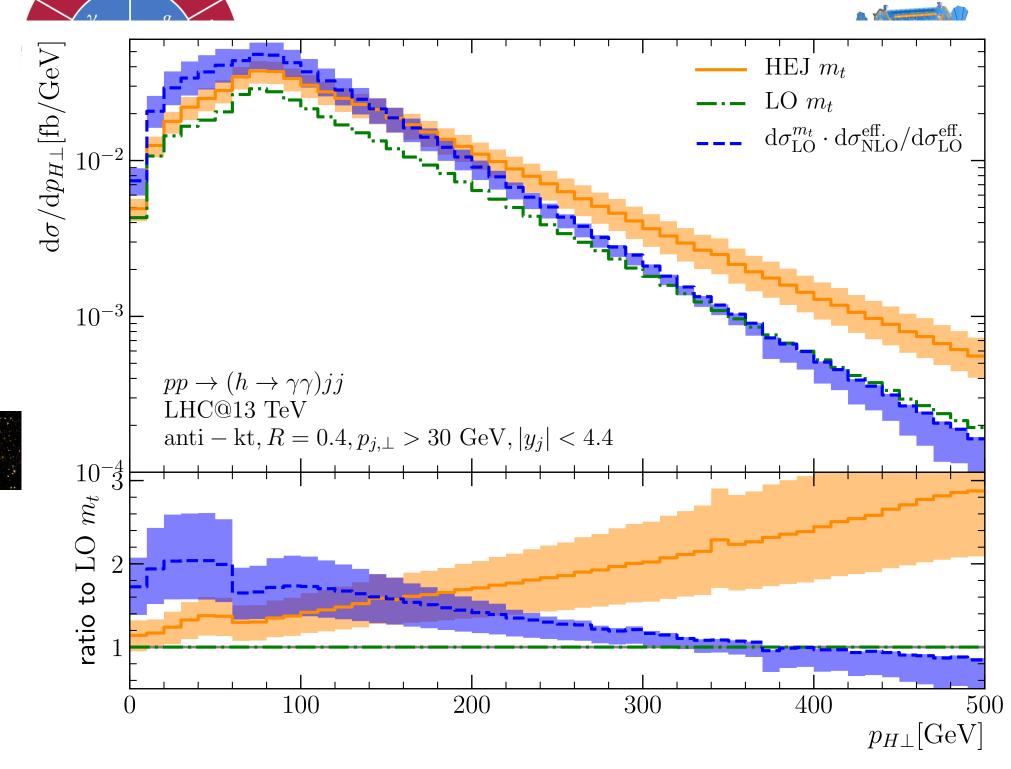






First probe the impact of higher orders in α_s

HEJ here temporarily without m_b



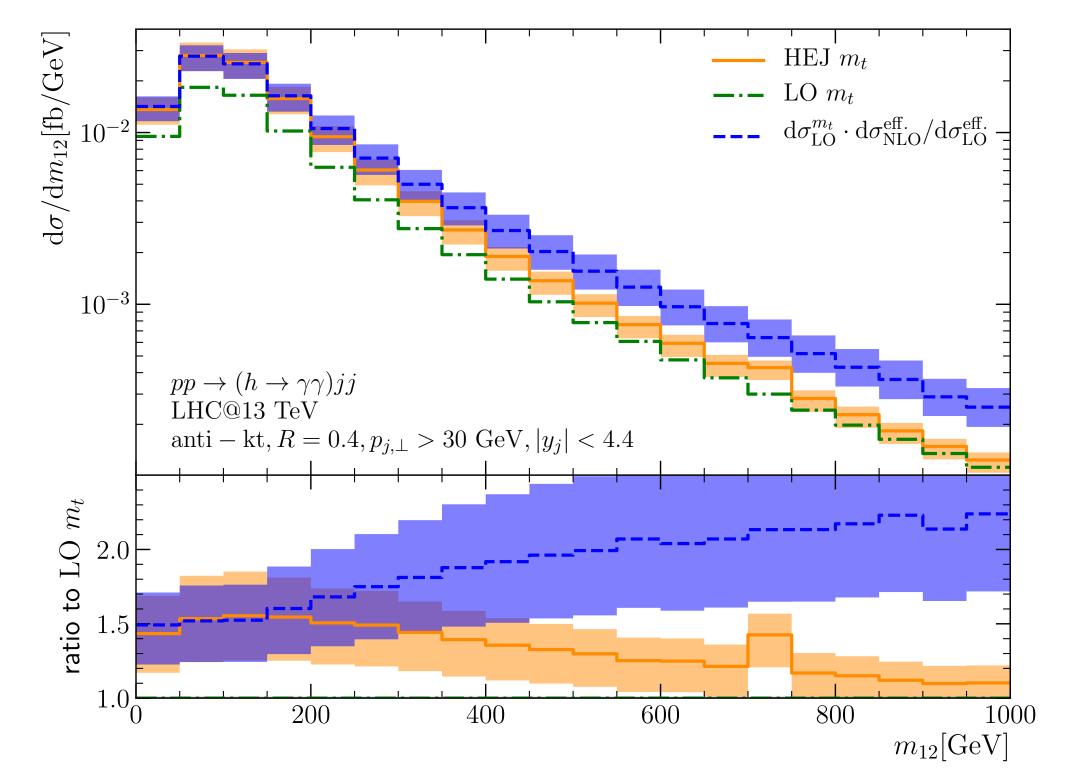
NLO K-factors clearly not flat, very scale-dependent, all choices have problems

HEJ harder $p_{H\perp}$ spectrum

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HEJ much steeper drop with m_{12} Andersen, Cockburn, Heil, Maier & JMS arXiv:1812.08072

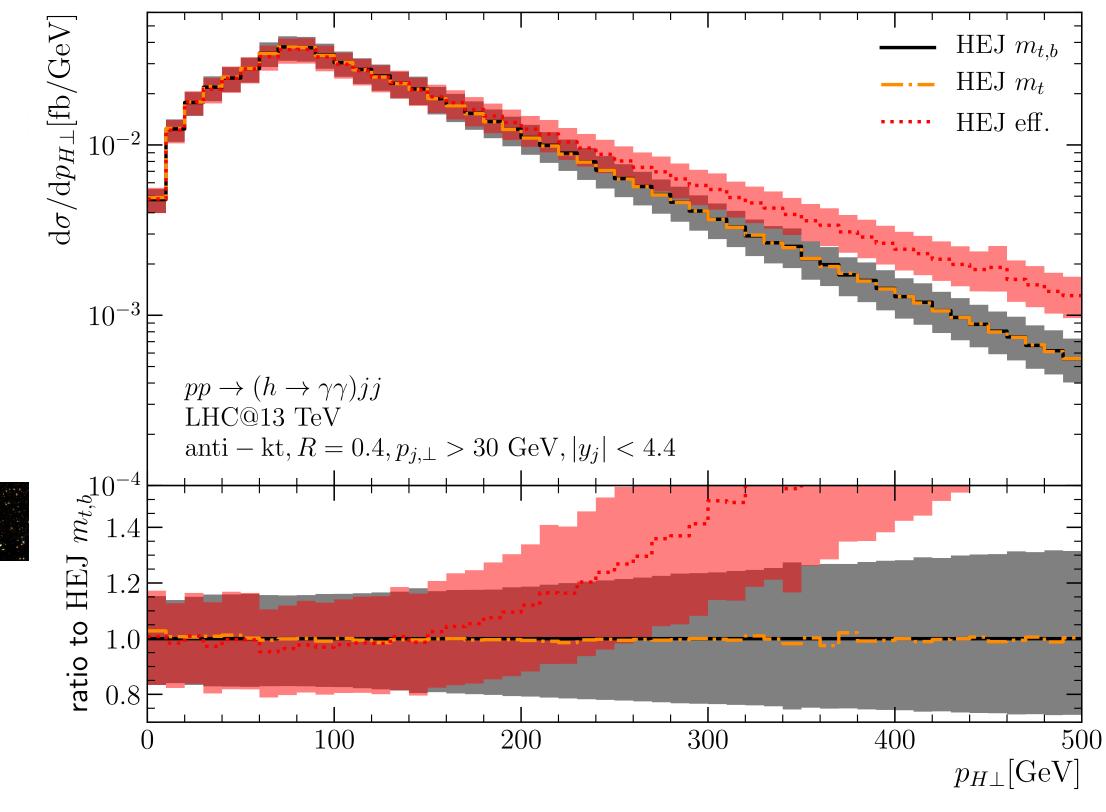








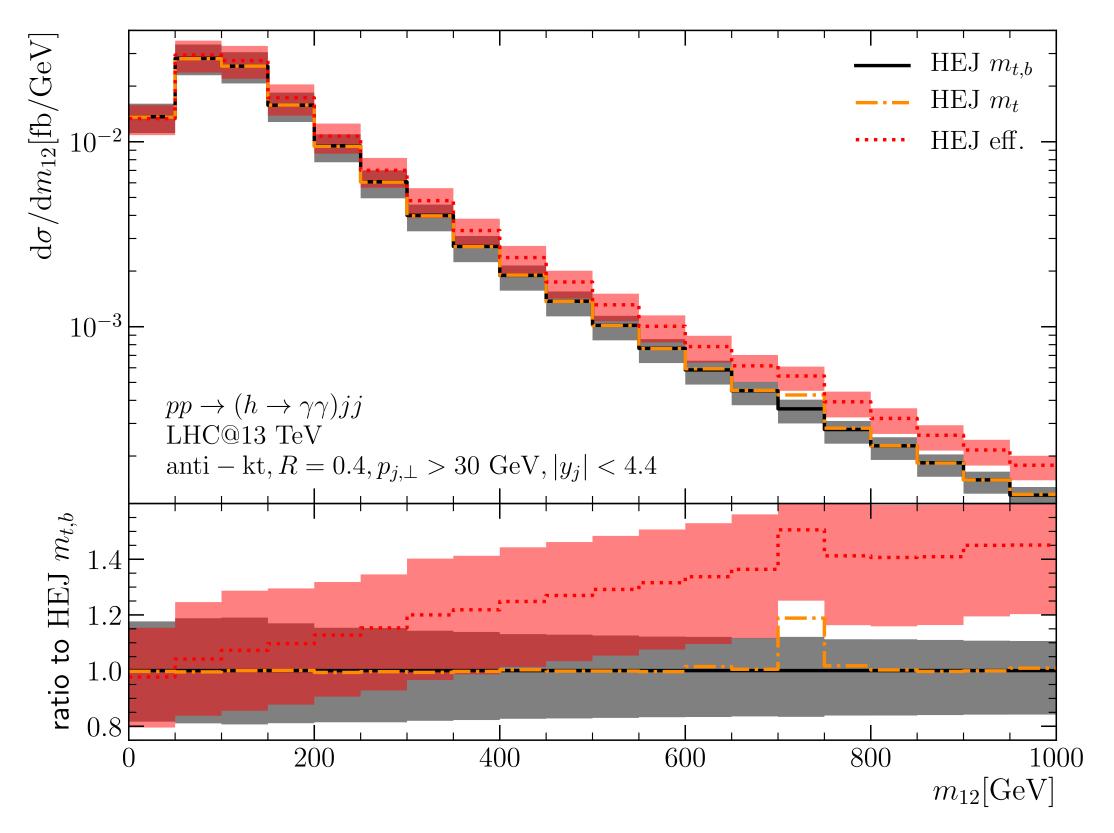
Now probe the impact of quark masses



- Importance of finite quark mass increases with $p_{H\perp}$



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

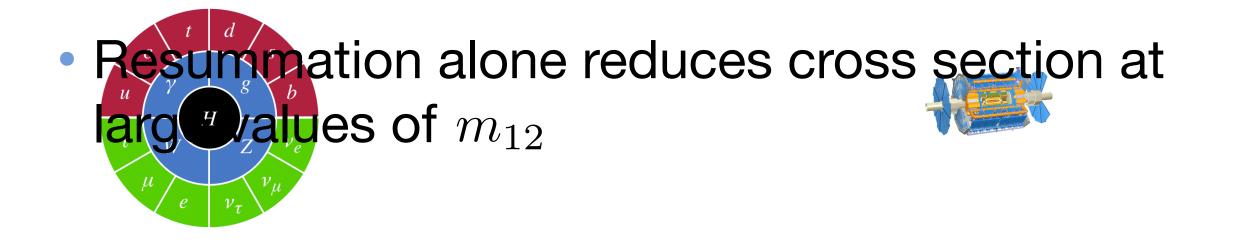


• Relatively small impact of m_b , finite m_t lowers predictions at large m_{12} Therefore finite quark mass effects make VBF cuts more effective



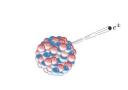






 Finite quark mass/loop effects reduce x-section in VBF cuts by *further* 11%



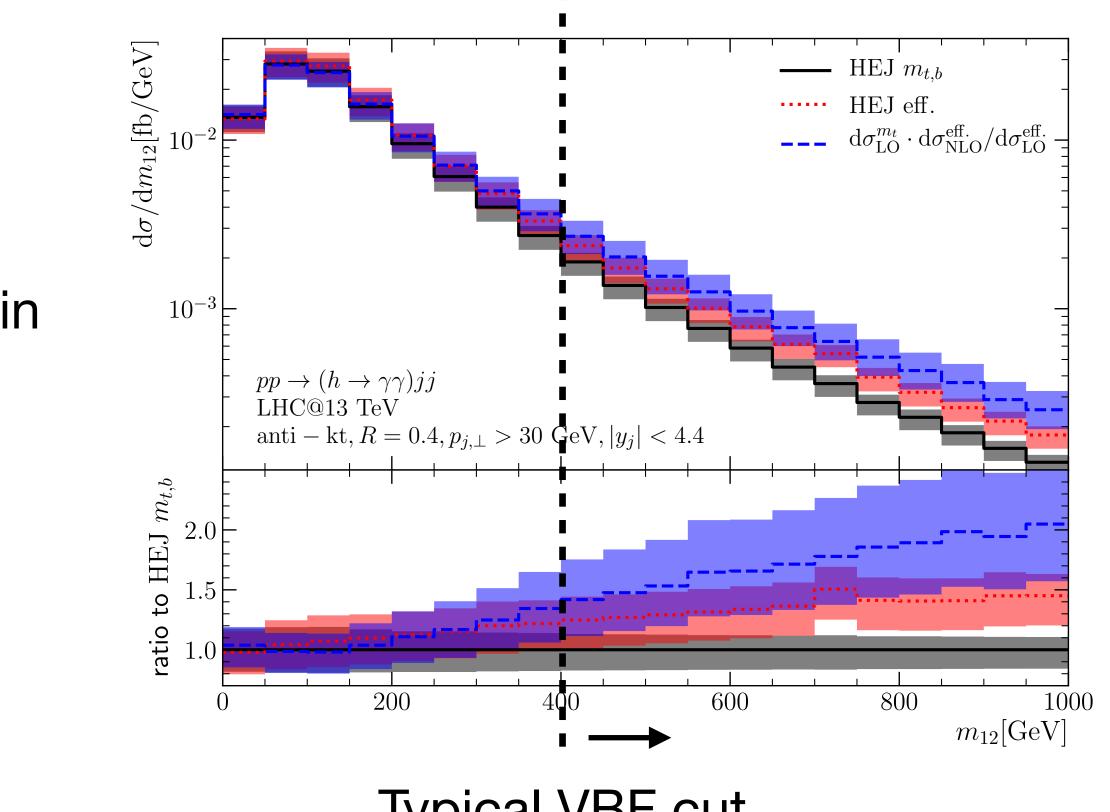


Prediction	xs after VBF cuts
Fixed order	9%
HEJ	4%

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Typical VBF cut

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



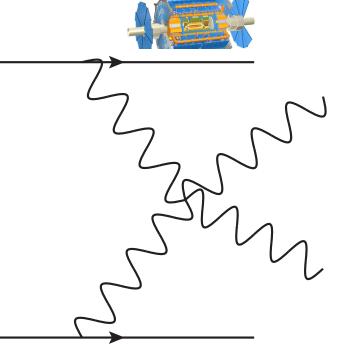




Vector Boson Scattering (VBS) sensitive probe of EWSB

 W^+jj proceeds through various diagrams including

```
EW = O(\alpha_W^4)
```



0.006

0.005

0.004

0.003

0.001

-0.001

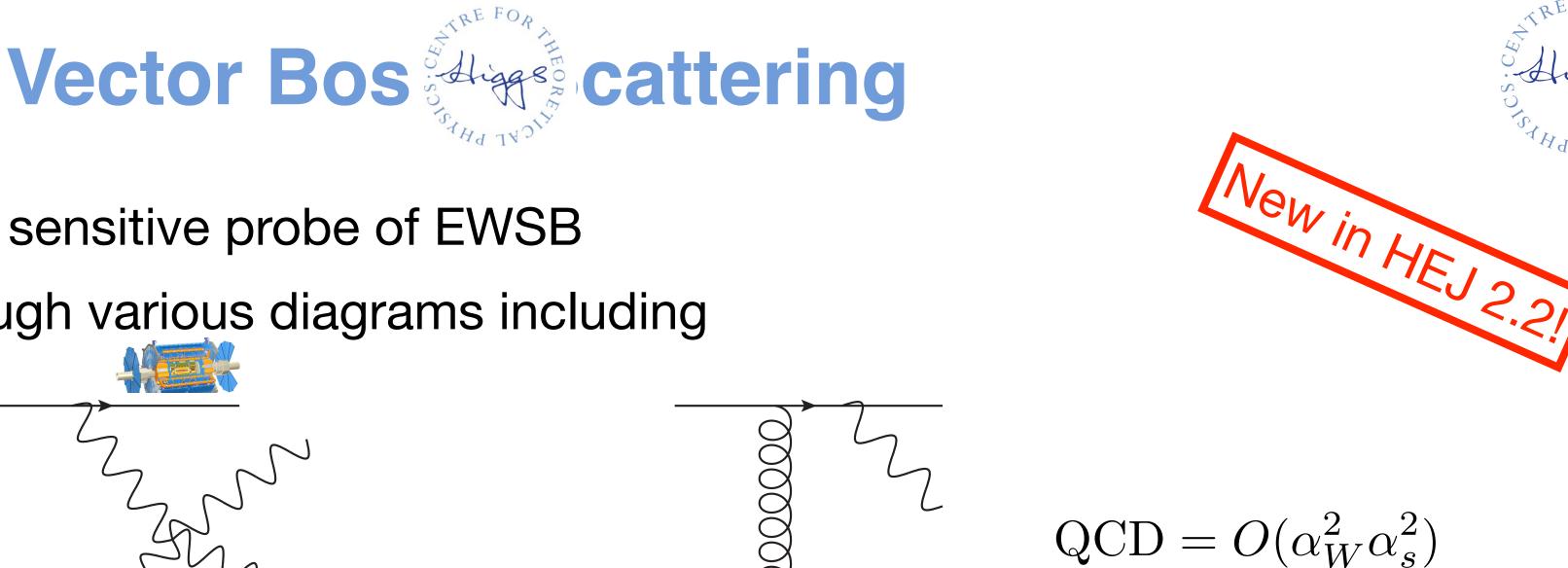
100

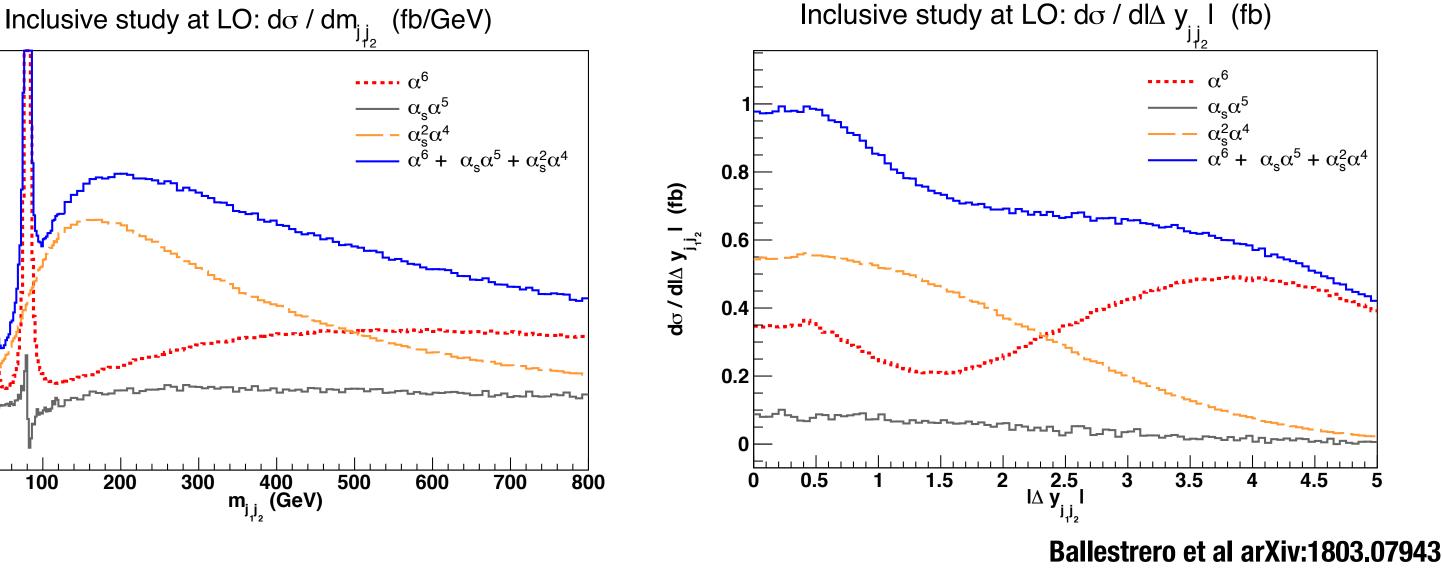
We would like to separate the EW and assessing interference between the tw ية¹ 0.002

To isolate EW component, typically ap and/or large invariant mass on the jets

Very similar to $pp \rightarrow Hjj$

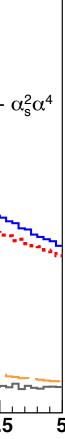
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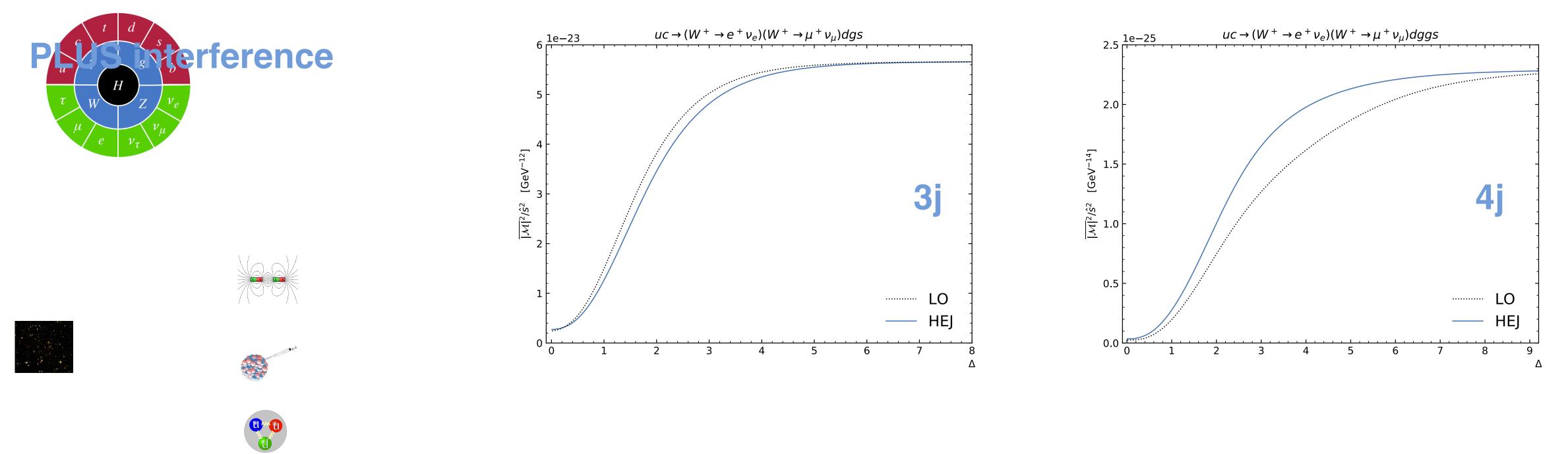








Now included in HEJ, where LL effects obtained by combining two single-W pieces



Impact on cross sections much reduced here (central scale choice)

Cross Section (fb)	without VBS cuts, $\sigma_{\rm incl}$	with VBS cuts, $\sigma_{\rm VBS}$	$\sigma_{ m VBS}/\sigma_{ m incl}$
HEJ2 W^+W^+	1.428 ± 0.002	0.1219 ± 0.0004	0.0854 ± 0.0003
NLO W^+W^+	1.41 ± 0.05	0.12 ± 0.07	0.08 ± 0.02
HEJ2 W^-W^-	0.6586 ± 0.0003	0.0402 ± 0.0001	0.0610 ± 0.0002
NLO W^-W^-	0.68 ± 0.02	0.04 ± 0.01	0.06 ± 0.02

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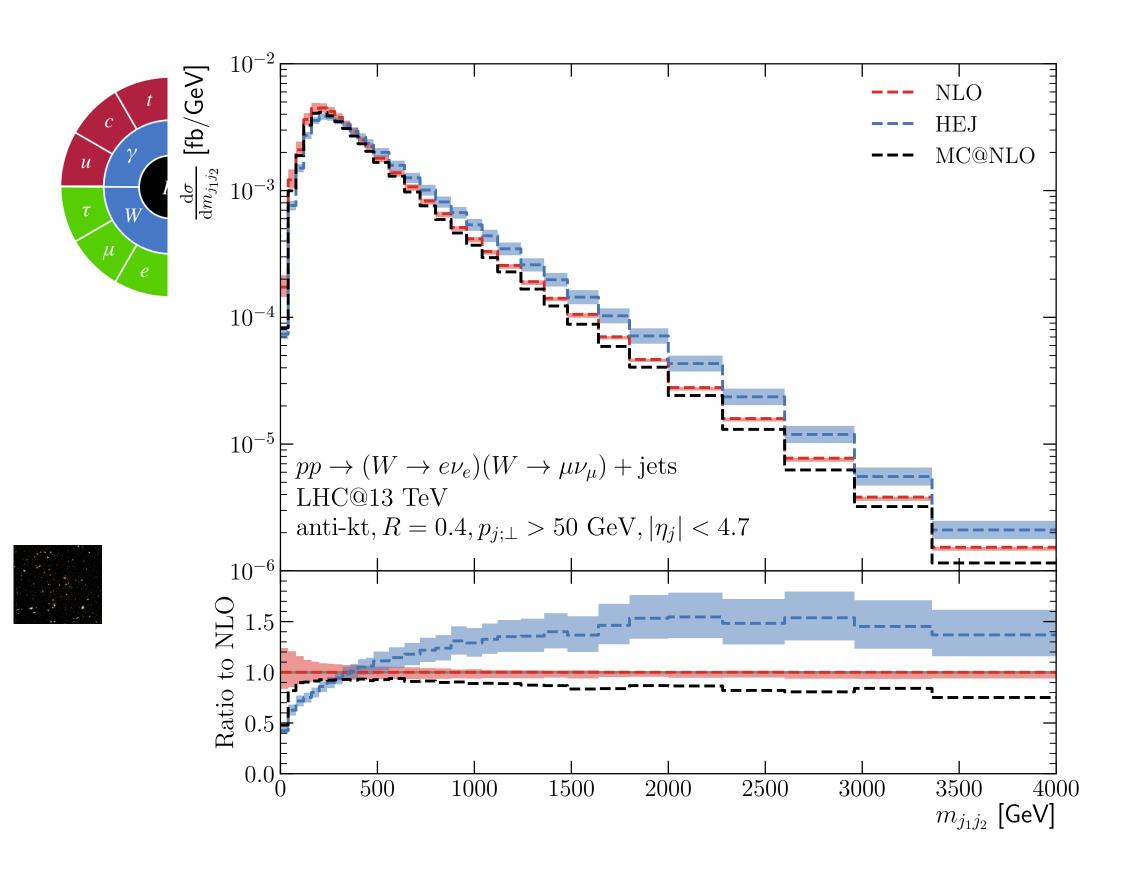


Andersen, Ducloué, Elrick, Nail, Maier, JMS arXiv:2107.06818







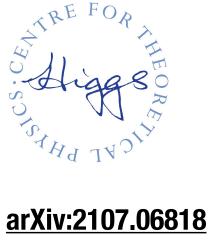


Shape of distributions changed by the all-order resummation

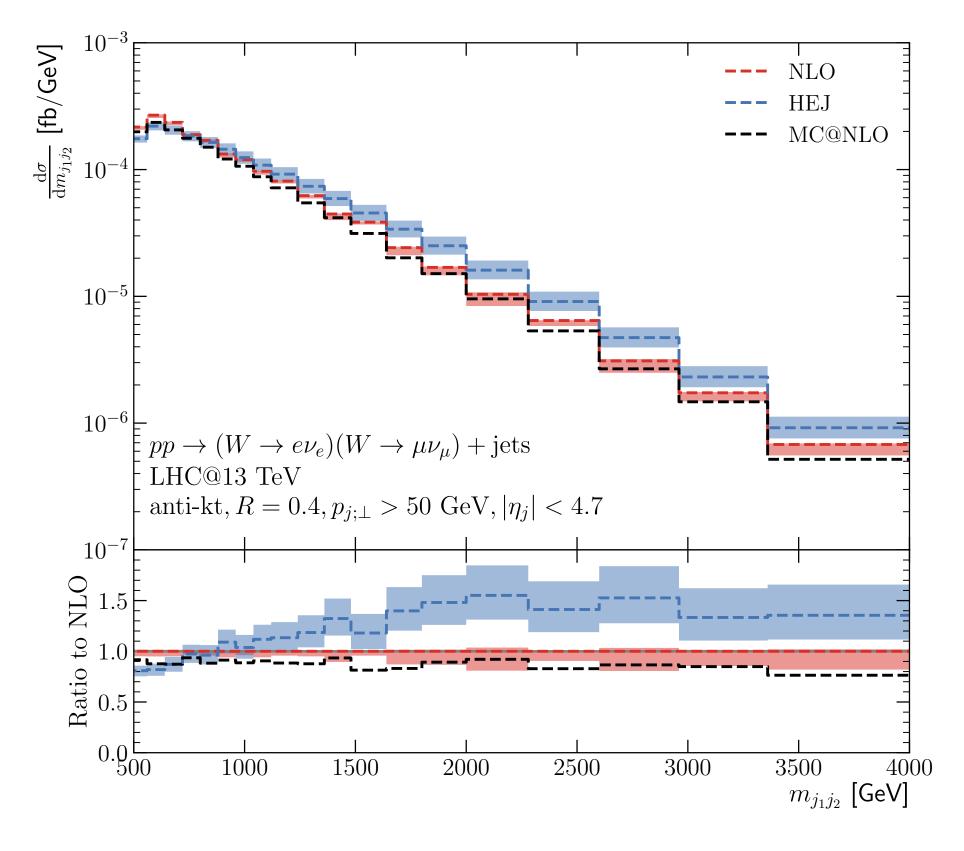
Agreement of total cross sections is a cancellation across phase space, not agreement throughout

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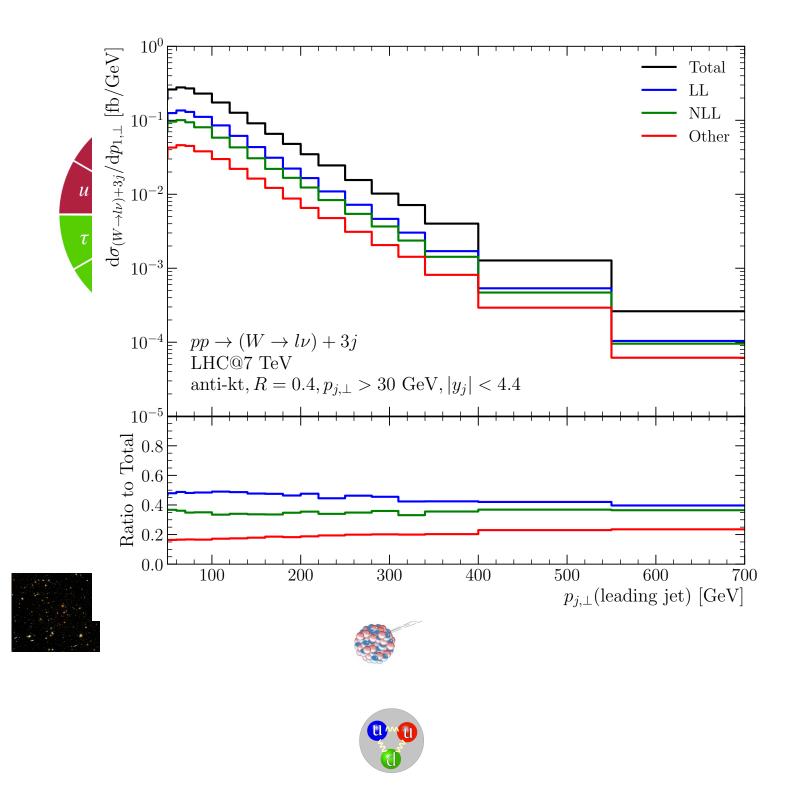


Andersen, Ducloué, Elrick, Nail, Maier, JMS arXiv:2107.06818











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

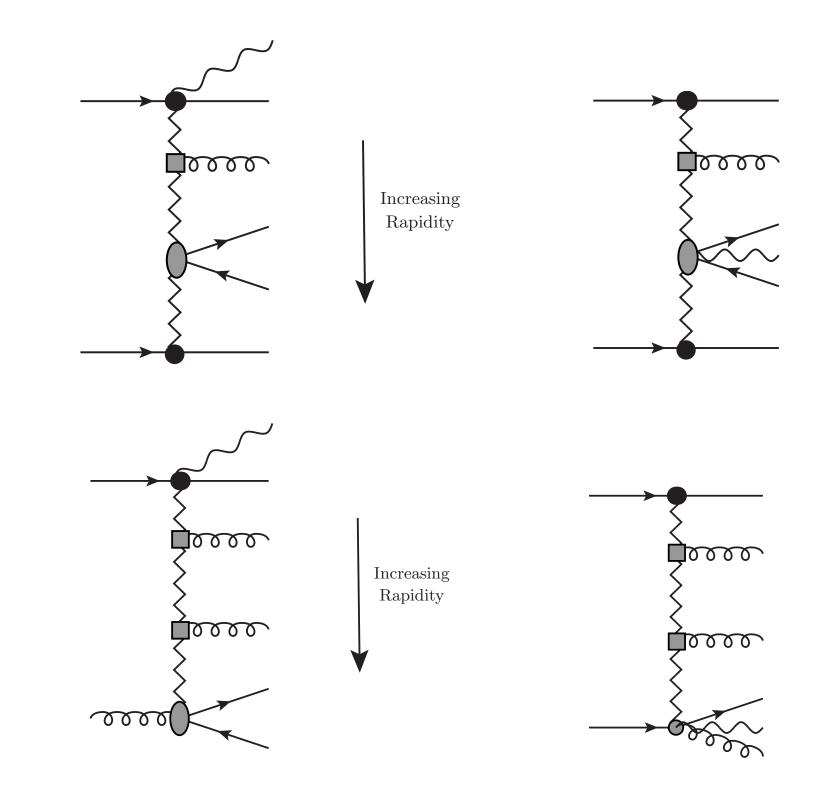
Andersen, Black, Brooks, Byrne, Maier, JMS arXiv:2012.10310

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

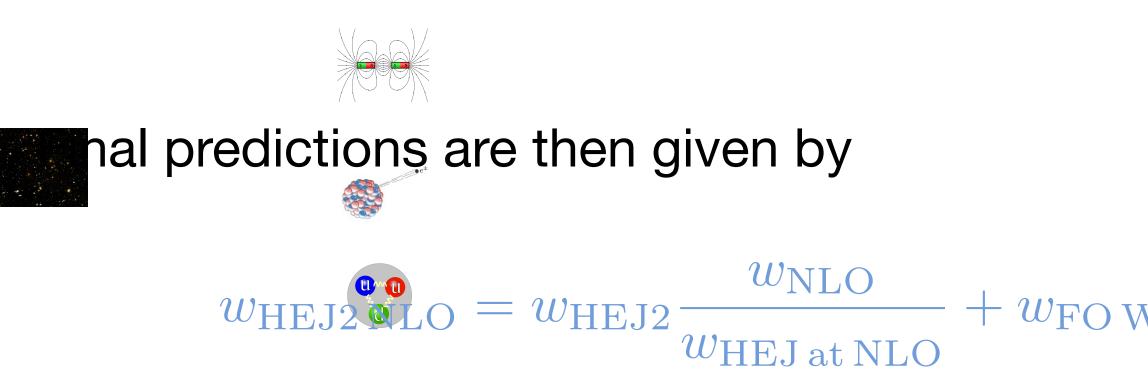






NLO) at $\rightarrow (W^- \rightarrow e^- \bar{\nu}_e) + 1$ NLO/(HEJ $0.5 \vdash$ LHC@7 TeV anti-kt, $R = 0.4, p_{j,\perp} > 30 \text{ GeV}, |y_j| < 4.4$ 100 200400 500600 700 $p_{j,\perp}$ (leading jet) [GeV] NLO) $\rightarrow e^{+}\nu_{e}$) $pp \rightarrow (W^- \rightarrow e^- \bar{\nu}_e)$ at 1 NLO/(HEJ nal predictions are then given by $0.5 \vdash$ - LHC@7 TeV $w_{\text{HEJ2}} = w_{\text{HEJ2}} = w_{\text{HEJ2}}$ anti-kt, $R = 0.4, p_{j,\perp} > 30 \text{ GeV}, |y_j| < 4.4$ $+ w_{\rm FOW+\geq 4j}$ 1.20.4 0.82.02.42.8 $w_{
m HEJ\,at\,NLO}$ $\Delta \phi_{12}$

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.



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

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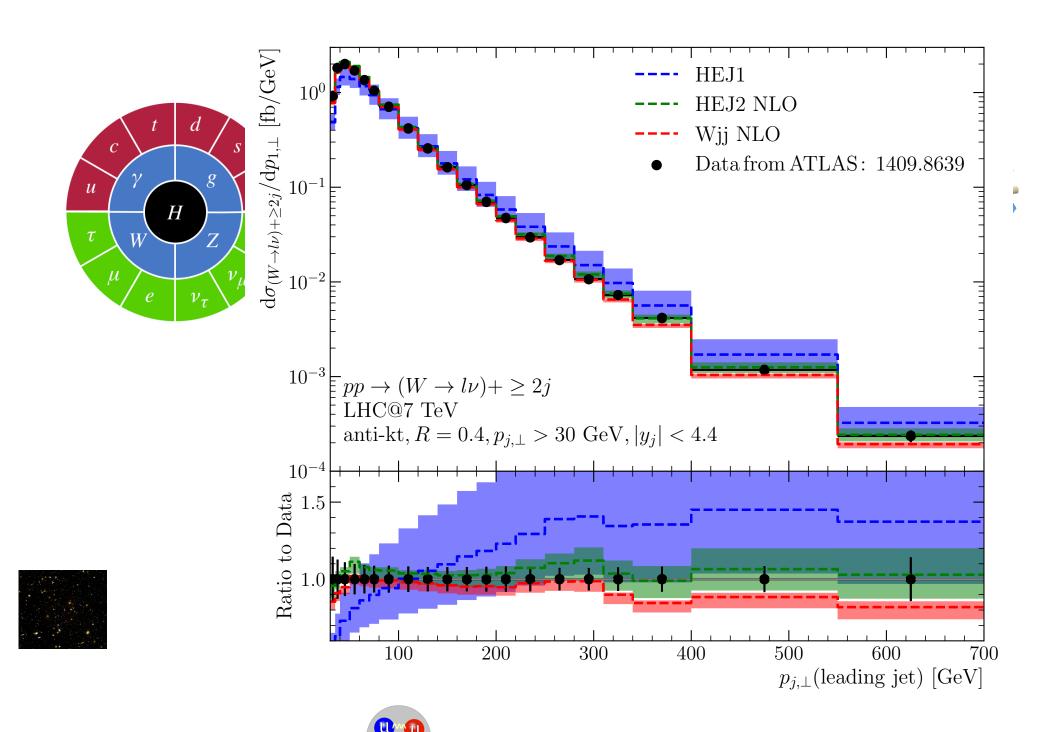


Andersen, Black, Brooks, Byrne, Maier, JMS arXiv:2012.10310



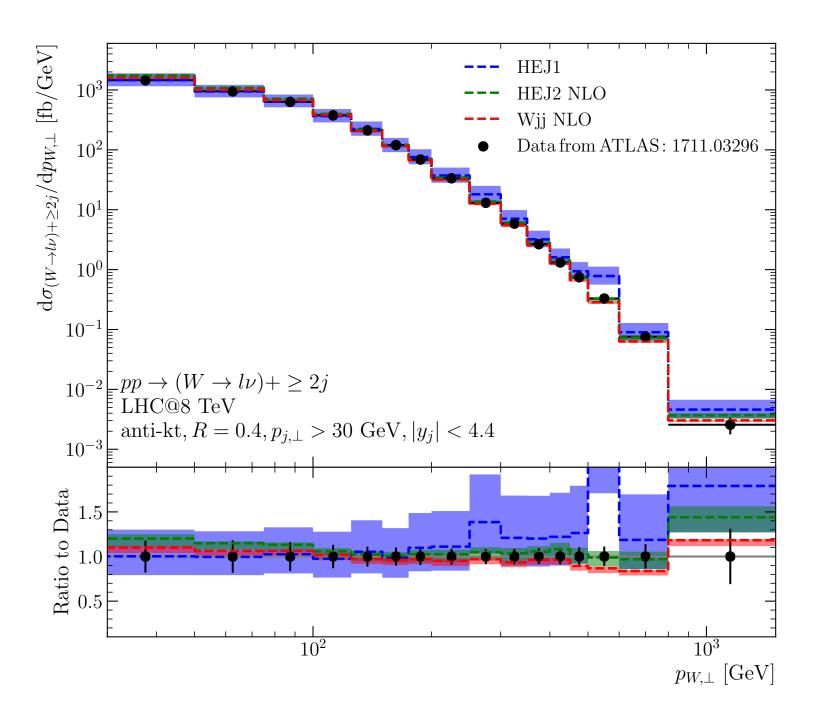






- HEJ2 NLO prediction lies between the previous two
- Scale variation reduced larger than NLO due to higher multiplicities





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

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

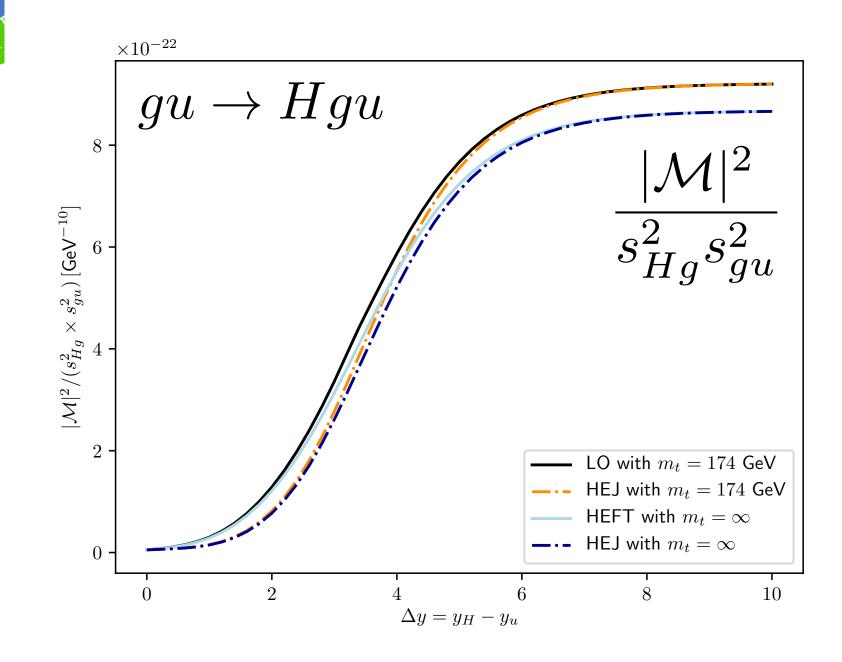






Higgs +

- processes with at least two jets
 - prived in H+2j studies, that scaling with an intermediate Higgs boson was as in QCD



- 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

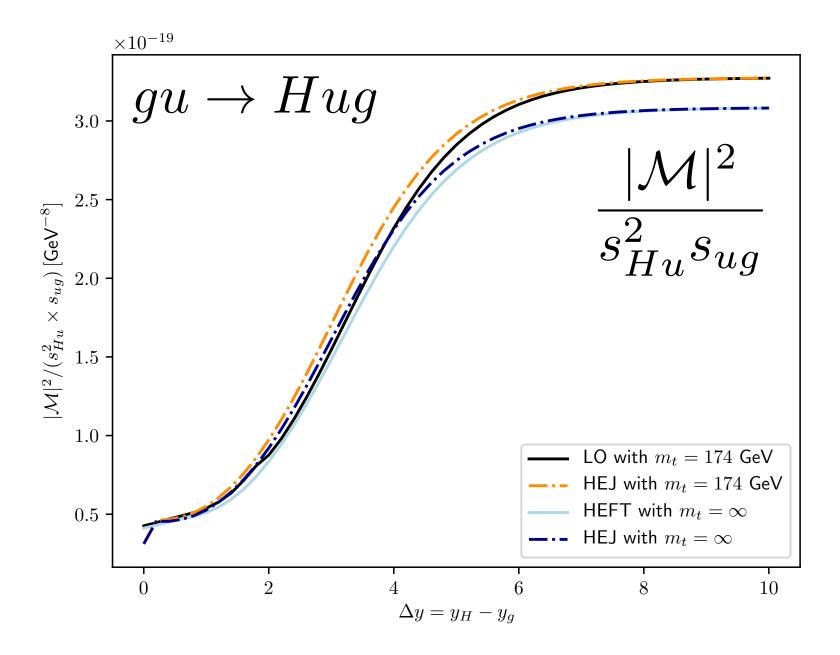
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HEJ has always resummed logarithms in the region between the outer jets in rapidity, hence always for

Andersen, Hapola, Maier, JMS arXiv:1706.01002

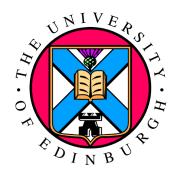


Andersen, Hassan, Maier, Paltrinieri, Papaefstathiou, JMS arXiv:2210.10671



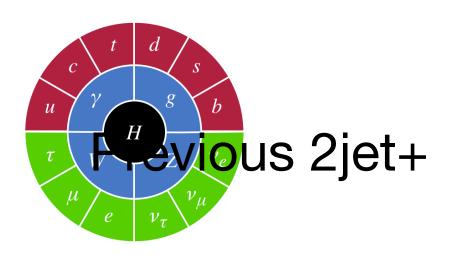




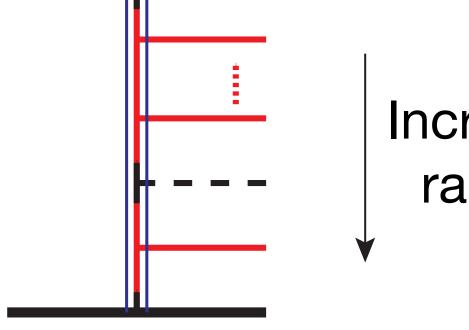




Black = Born/skeleton function



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Similar effects on distributions

 $rac{\mathrm{d}\sigma}{\mathrm{d}p_T^{j_1}}$ [fb/GeV] Data $pp \to (H \to)\gamma\gamma + \text{jets}$ **---** HEJ LHC@13 TeV --- NLO1j anti-kt, $R = 0.4, p_{j;\perp} > 30 \text{GeV}$ $|\eta_j| < 4.7$ and $|\eta_{j_1}| < 2.5$ Data includes "HX" not in HEJ or NLO 10^{-} data 1.0 Ratio to .0 ------0.0100 150200 300 50250350 400 CMS data arXiv:1807.03825 $p_T^{j_1}\left[\mathrm{GeV}
ight]$



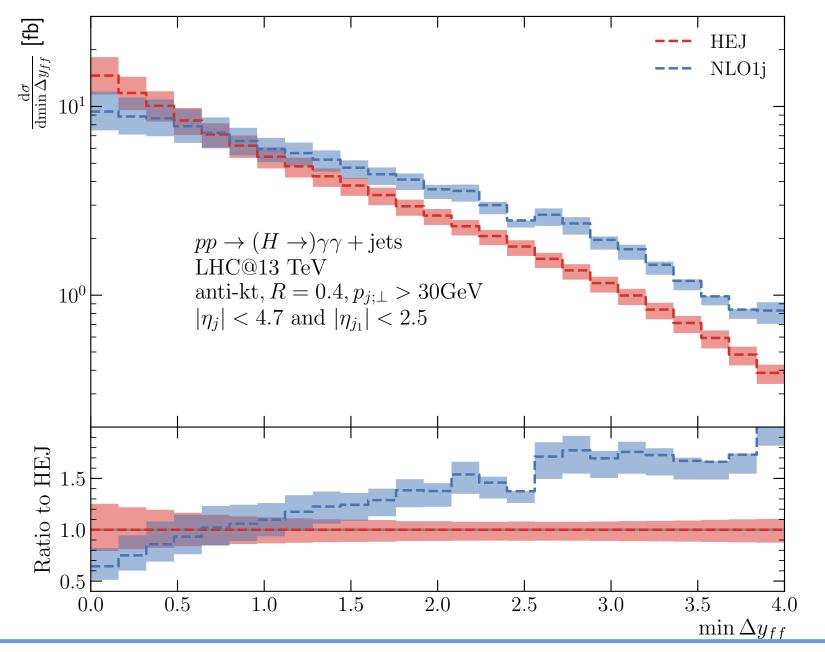


Red = Range of resummation

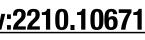
Increasing rapidity

New 1jet+

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





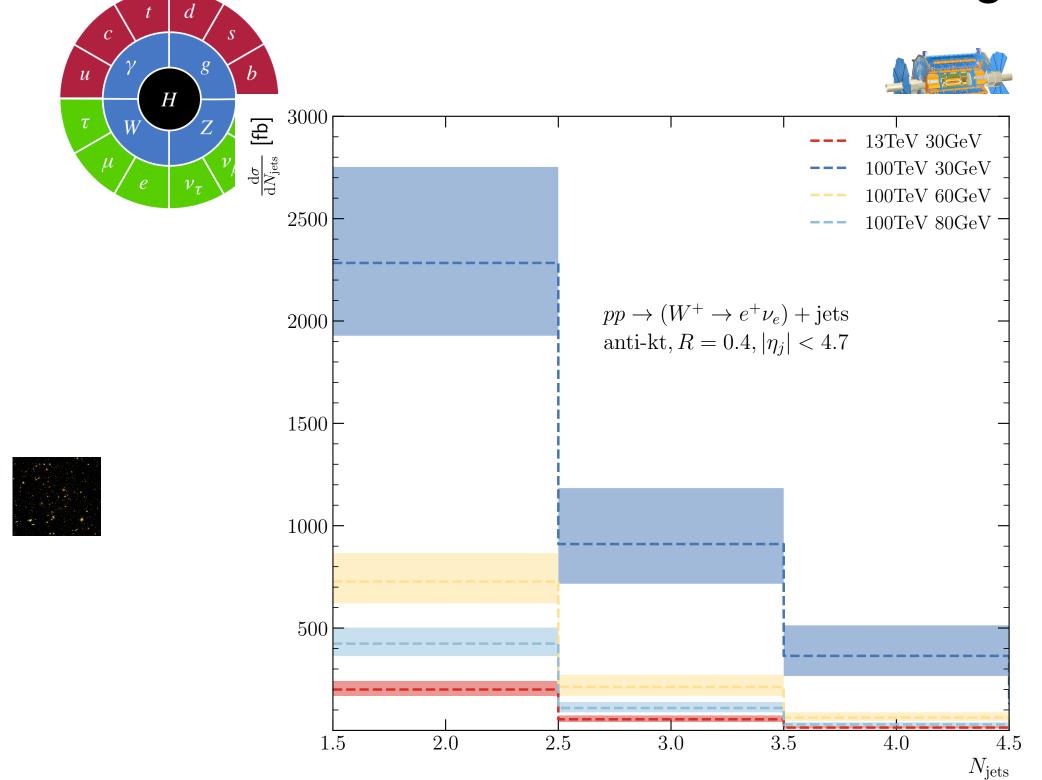








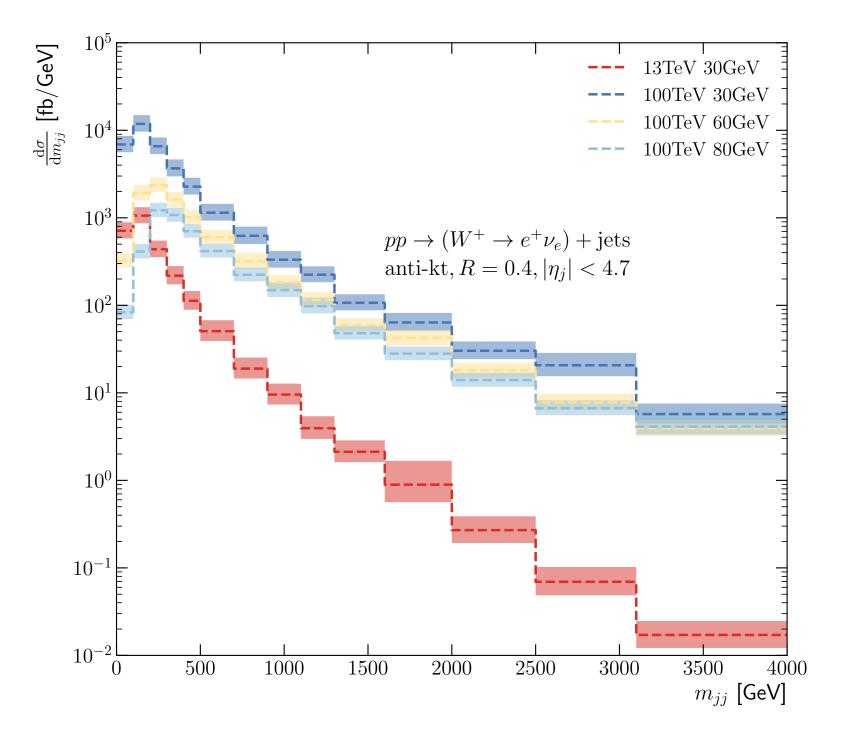
What about a 100 TeV collider? Even larger centre-of-mass energy will give even larger logs!



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

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Plots: Conor Elrick Jenni Smillie





Gurrent and future data demand higher precision predictions Energy Jets allows the description of high energy logs in a *ly* flexible framework

 High Energy Jets provides alternative way to include finite quark mass effects



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Recent improvements improve the description of data away from the strict limit

Ongoing work to increase accuracy to full NLL and to full NLO

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



