

# High Energy Resummation for Jet Processes at the LHC



Jennifer Smillie

Higgs Centre, University of Edinburgh

DESY Seminar Nov 2022



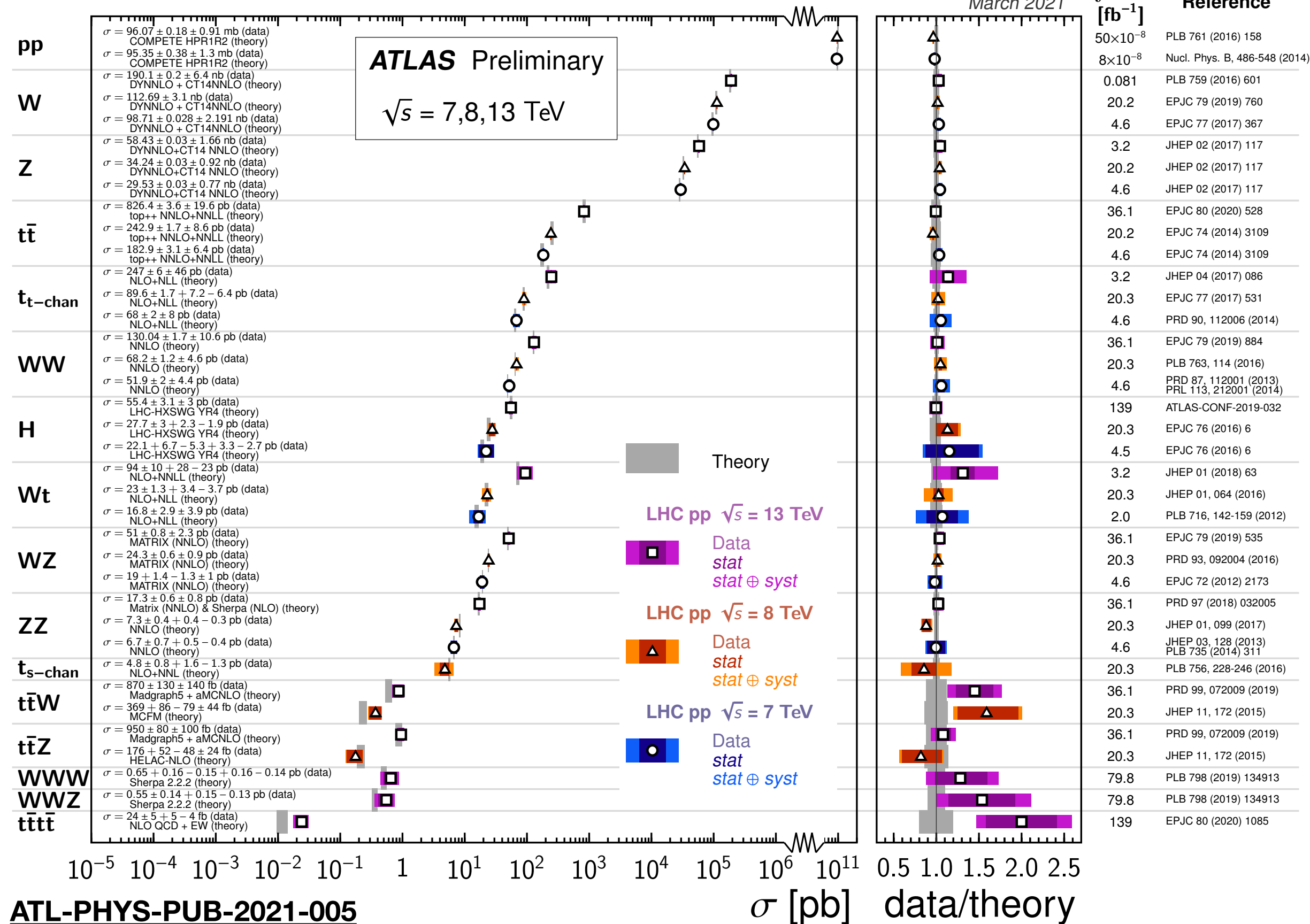
European Research Council  
Established by the European Commission







## Standard Model Total Production Cross Section Measurements



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

ATLAS Preliminary  
 $\int \mathcal{L} dt = (3.6 - 139)$  fb<sup>-1</sup>  
 $\sqrt{s} = 8, 13$  TeV

Model	$\ell, \gamma$	Jets $\dagger$	$E_{\text{miss}}^{\text{stat}}$	$\int \mathcal{L} dt$ [fb <sup>-1</sup> ]	Limit	Reference
<b>Extra dimensions</b>	ADD $G_{KK} + g/q$	0 $e, \mu, \tau, \gamma$	1-4 j	Yes	139	$M_0$ 11.2 TeV, $n=2$
	ADD non-resonant $\gamma\gamma$	2 $\gamma$	-	-	36.7	$M_s$ 8.6 TeV, $n=3$ HLZ NLO
	ADD QBH	-	2 j	-	37.0	$M_{\text{bh}}$ 8.9 TeV, $n=6$
	ADD BH multijet	-	$\geq 3 j$	-	3.6	$M_{\text{bh}}$ 9.55 TeV, $n=6, M_{\text{D}} = 3$ TeV, rot BH
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 $\gamma$	-	-	139	$G_{KK}$ mass 4.5 TeV, $k/M_{\text{Pl}} = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK}$ mass 2.3 TeV, $k/M_{\text{Pl}} = 1.0$
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu qq$	1 $e, \mu$	2 j / 1 J	Yes	139	$G_{KK}$ mass 2.0 TeV, $k/M_{\text{Pl}} = 1.0$
	Bulk RS $G_{KK} \rightarrow t\bar{t}$	1 $e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	$G_{KK}$ mass 3.8 TeV, $\Gamma/m = 15\%$
	2UED / RPP	1 $e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV, Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow t\bar{t}) = 1$
<b>Gauge bosons</b>	SSM $Z' \rightarrow \ell\bar{\ell}$	2 $e, \mu$	-	-	139	$Z'$ mass 5.1 TeV
	SSM $Z' \rightarrow \tau\bar{\tau}$	2 $\tau$	-	-	36.1	$Z'$ mass 2.42 TeV
	Leptophobic $Z' \rightarrow b\bar{b}$	-	2 b	-	36.1	$Z'$ mass 2.1 TeV
	Leptophobic $Z' \rightarrow t\bar{t}$	0 $e, \mu, \tau, \gamma$	$\geq 1 b, \geq 2 J$	Yes	139	$Z'$ mass 4.1 TeV, $\Gamma/m = 1.2\%$
	SSM $W' \rightarrow \ell\nu$	1 $e, \mu, \tau$	-	-	139	$W'$ mass 6.0 TeV
	SSM $W' \rightarrow \nu\bar{\nu}$	1 $\tau$	-	-	36.1	$W'$ mass 3.7 TeV
	HVT $W' \rightarrow WZ \rightarrow \ell\nu qq$ model B	1 $e, \mu$	2 j / 1 J	Yes	139	$W'$ mass 4.3 TeV
	HVT $Z' \rightarrow ZH$ model B	0-2 $e, \mu$	1-2 b	Yes	139	$Z'$ mass 3.2 TeV
	HVT $W' \rightarrow WH$ model B	0 $e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	$W'$ mass 3.2 TeV
	LRSM $W_R \rightarrow tb$	multi-channel	-	-	36.1	$W_R$ mass 3.25 TeV
	LRSM $W_R \rightarrow \mu N_R$	2 $\mu$	1 J	-	80	$W_R$ mass 5.0 TeV, $m(N_R) = 0.5$ TeV, $g_L = g_R$
<b>CI</b>	Cl $qqqq$	-	2 j	-	37.0	$\Lambda$ 21.8 TeV, $\eta_{LL}$
	Cl $\ell\ell qq$	2 $e, \mu$	-	-	139	$\Lambda$ 35.8 TeV, $\eta_{LL}$
	Cl $e\bar{e}bb$	2 $e, \mu$	1 b	-	139	$\Lambda$ 1.8 TeV, $g_s = 1$
	Cl $\mu\mu bb$	2 $\mu$	1 b	-	139	$\Lambda$ 2.0 TeV, $g_s = 1$
	Cl $t\bar{t}bb$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$\Lambda$ 2.57 TeV, $ C_{t1}  = 4\pi$
<b>DM</b>	Axial-vector med. (Dirac DM)	0 $e, \mu, \tau, \gamma$	1-4 j	Yes	139	$m_{\text{med}}$ 2.1 TeV, $g_s = 0.25, g_1 = 1, m(\chi) = 1$ GeV
	Pseudo-scalar med. (Dirac DM)	0 $e, \mu, \tau, \gamma$	1-4 j	Yes	139	$m_{\text{med}}$ 376 GeV, $g_s = 1, g_1 = 1, m(\chi) = 1$ GeV
	Vector med. $Z'$ -2HDM (Dirac DM)	0 $e, \mu$	2 b	Yes	139	$m_{\text{med}}$ 3.1 TeV, $\tan\beta = 1, g_s = 0.8, m(\chi) = 100$ GeV
	Pseudo-scalar med. 2HDM-a	0 $e, \mu$	2 b	Yes	139	$m_{\text{med}}$ 520 GeV, $\tan\beta = 1, g_s = 1, m(\chi) = 10$ GeV
	Scalar reson. $\phi \rightarrow t\bar{t}$ (Dirac DM)	0-1 $e, \mu$	1 b, 0-1 J	Yes	36.1	$m_{\text{med}}$ 3.4 TeV, $y = 0.4, A = 0.2, m(\chi) = 10$ GeV
<b>LQ</b>	Scalar LQ 1 <sup>st</sup> gen	2 $e$	$\geq 2 j$	Yes	139	LQ mass 1.8 TeV, $\beta = 1$
	Scalar LQ 2 <sup>nd</sup> gen	2 $\mu$	$\geq 2 j$	Yes	139	LQ mass 1.7 TeV, $\beta = 1$
	Scalar LQ 3 <sup>rd</sup> gen	1 $\tau$	2 b	Yes	139	$LQ_3^+$ mass 1.2 TeV, $\mathcal{B}(LQ_3^+ \rightarrow b\tau) = 1$
	Scalar LQ 3 <sup>rd</sup> gen	0 $e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	$LQ_3^+$ mass 1.24 TeV, $\mathcal{B}(LQ_3^+ \rightarrow \nu\tau) = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$\geq 2e, \mu, \geq 1\tau, \geq 1j, \geq 1b$	-	-	139	$LQ_3^+$ mass 1.43 TeV, $\mathcal{B}(LQ_3^+ \rightarrow \tau\nu) = 1$
	Scalar LQ 3 <sup>rd</sup> gen	0 $e, \mu, \geq 1\tau$	0-2 j, 2 b	Yes	139	$LQ_3^+$ mass 1.26 TeV, $\mathcal{B}(LQ_3^+ \rightarrow b\nu) = 1$
<b>Heavy quarks</b>	VLQ $T\bar{T} \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1	T mass 1.37 TeV, SU(2) doublet
	VLQ $B\bar{B} \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV, SU(2) doublet
	VLQ $T_{5/3}^+ T_{5/3}^- \rightarrow Wt + X$	2(SS) $\geq 3 e, \mu, \geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV, $\mathcal{B}(T_{5/3}^+ \rightarrow Wt) = 1, c(T_{5/3}^+ Wt) = 1$	
	VLQ $Y \rightarrow Wb + X$	1 $e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV, $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$
	VLQ $B \rightarrow Hb + X$	0 $e, \mu$	$\geq 2 b, \geq 1 j$	Yes	79.8	B mass 1.21 TeV, singlet, $\kappa_B = 0.5$
	VLQ $QQ \rightarrow WqWq$	1 $e, \mu$	$\geq 4 j$	Yes	20.3	Q mass 690 GeV
<b>Excited fermions</b>	Excited quark $q^* \rightarrow qg$	-	2 j	-	139	$q^*$ mass 6.7 TeV, only $u^*$ and $d^*$ , $\Lambda = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	1 $\gamma$	1 j	-	36.7	$q^*$ mass 5.3 TeV, only $u^*$ and $d^*$ , $\Lambda = m(q^*)$
	Excited quark $b^* \rightarrow b\gamma$	-	1 b, 1 j	-	36.1	$b^*$ mass 2.6 TeV
	Excited lepton $\ell^*$	3 $e, \mu$	-	-	20.3	$\ell^*$ mass 3.0 TeV, $\Lambda = 3.0$ TeV
	Excited lepton $\nu^*$	3 $e, \mu, \tau$	-	-	20.3	$\nu^*$ mass 1.6 TeV, $\Lambda = 1.6$ TeV
<b>Other</b>	Type III Seesaw	1 $e, \mu$	$\geq 2 j$	Yes	139	$N^0$ mass 790 GeV
	LRSM Majorana $\nu$	2 $\mu$	2 j	-	36.1	$N_R$ mass 3.2 TeV
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\bar{\ell}$	2,3,4 $e, \mu$ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 870 GeV
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 $e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV
	Multi-charged particles	-	-	-	36.1	multi-charged particle mass 1.22 TeV
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 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).

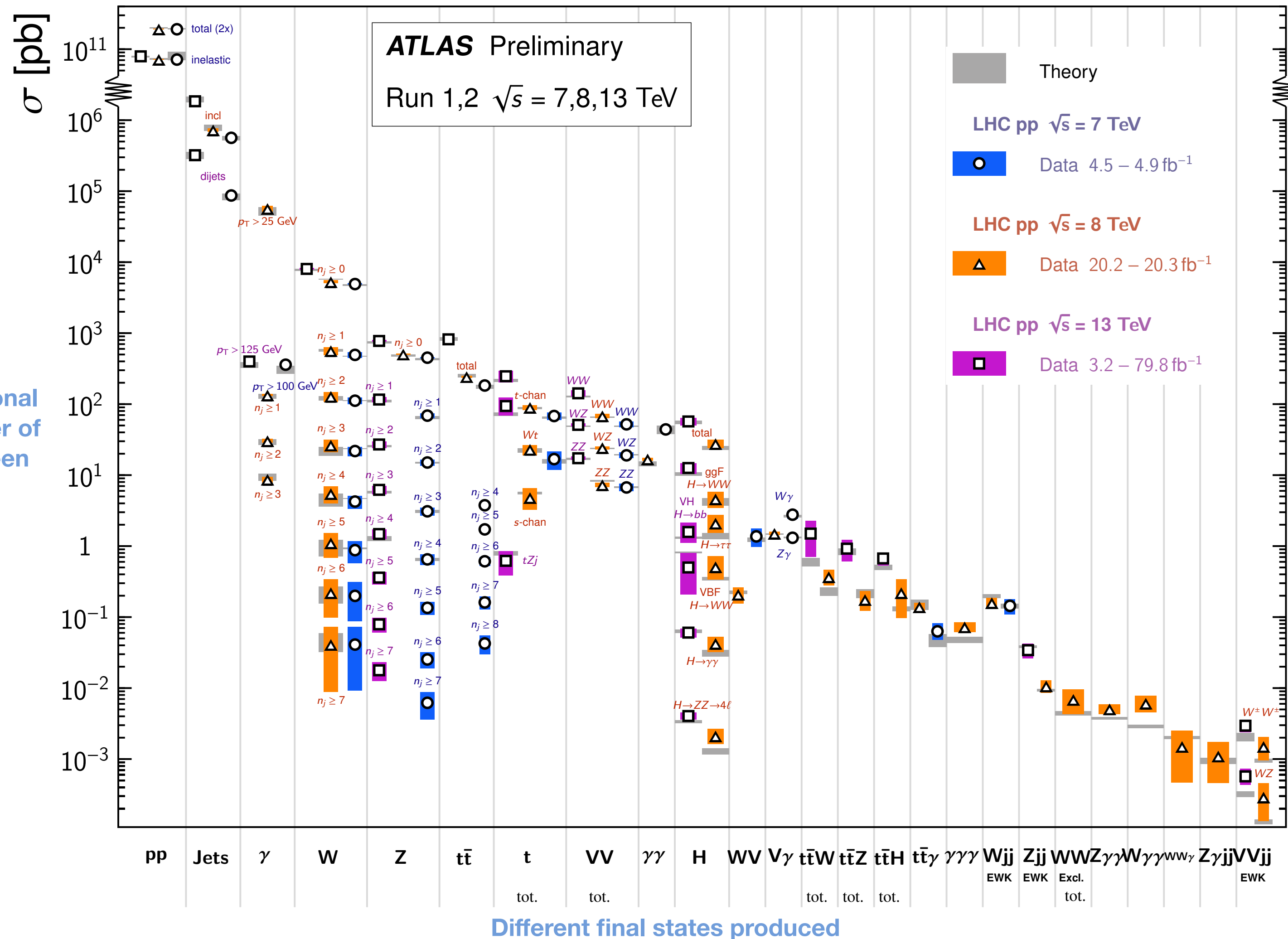
- Phenomenal agreement with theory so far
- Very sophisticated calculations, e.g.  $t\bar{t}$  at NNLO+NNLL  
Czakon, Mitov arXiv:1112.5675

ATL-PHYS-PUB-2021-009



## Standard Model Production Cross Section Measurements

Status: July 2018

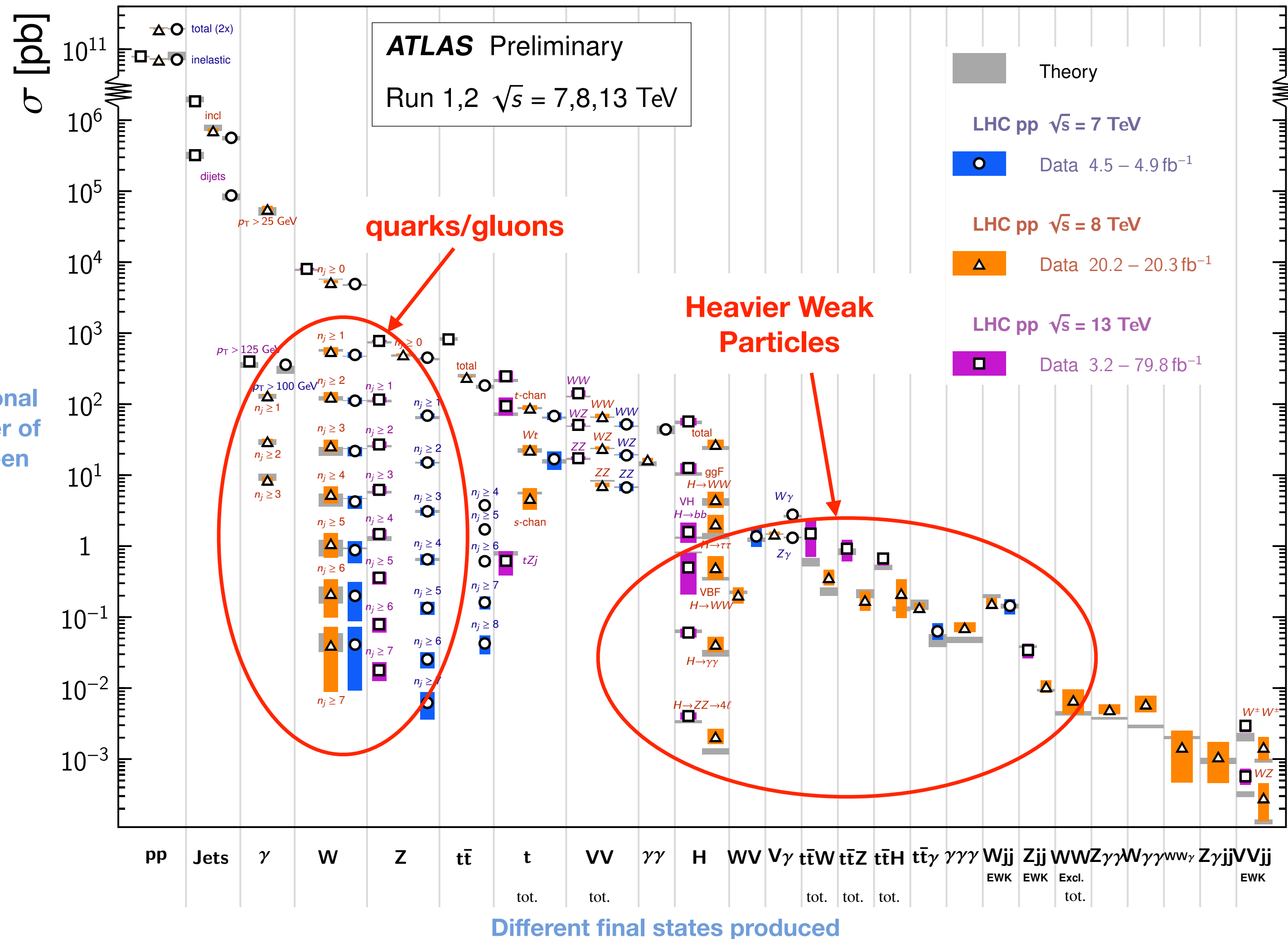


- Many more quarks and gluons than anything else!
- Need to understand these to detect anything else
- Actually quarks/gluons at these energies are new too

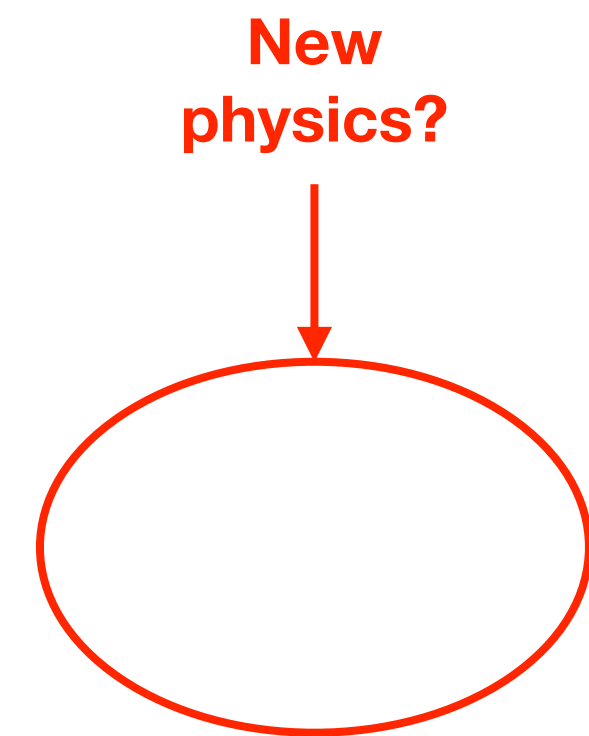


## Standard Model Production Cross Section Measurements

Status: July 2018



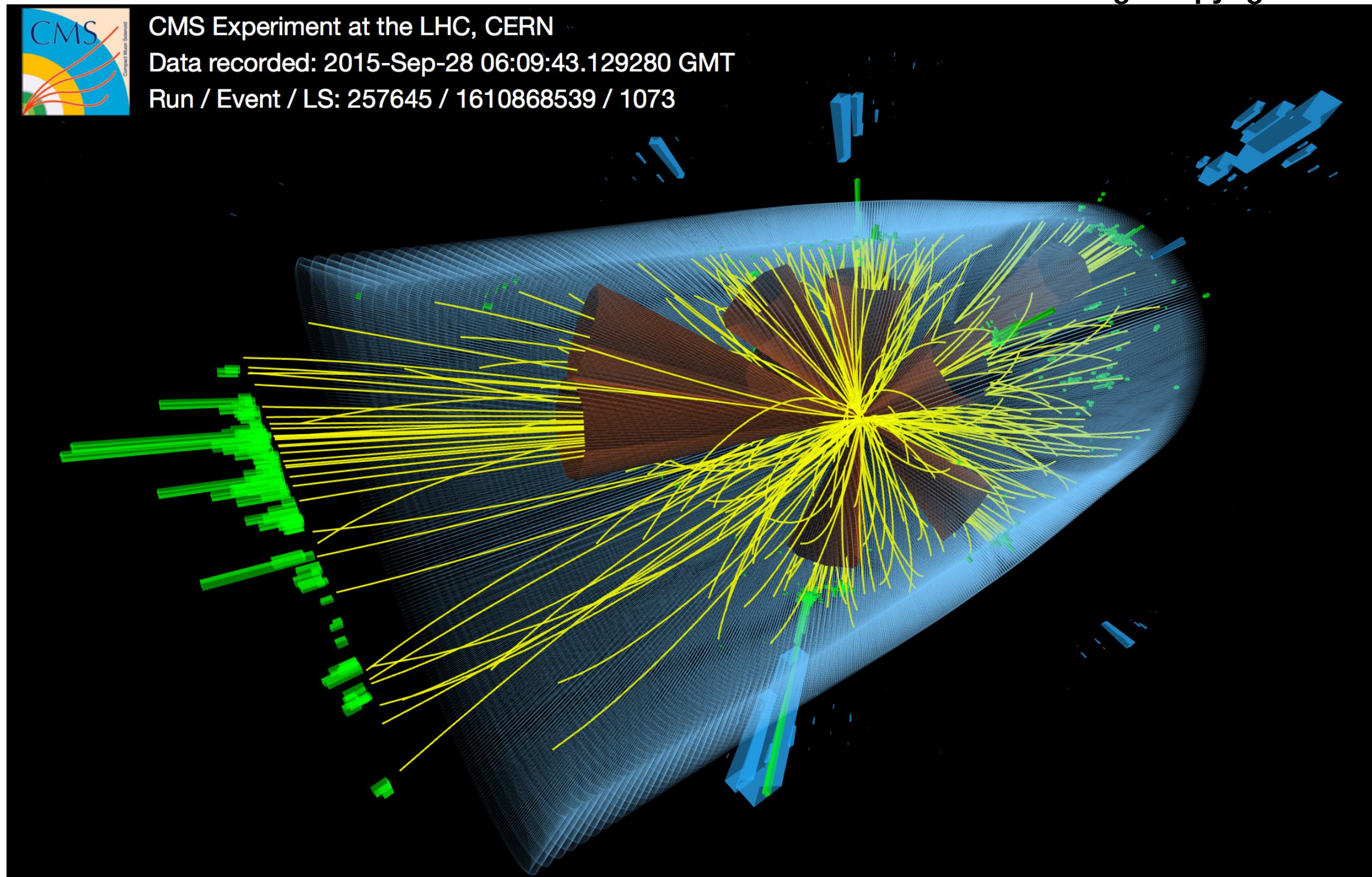
- Many more quarks and gluons than anything else!
- Need to understand these to detect anything else
- Actually quarks/gluons at these energies are new too





# A Challenge at High Centre of Mass

Image Copyright CERN



**12 jets** with  $p_T > 50 \text{ GeV}$   
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



# Which all-order?

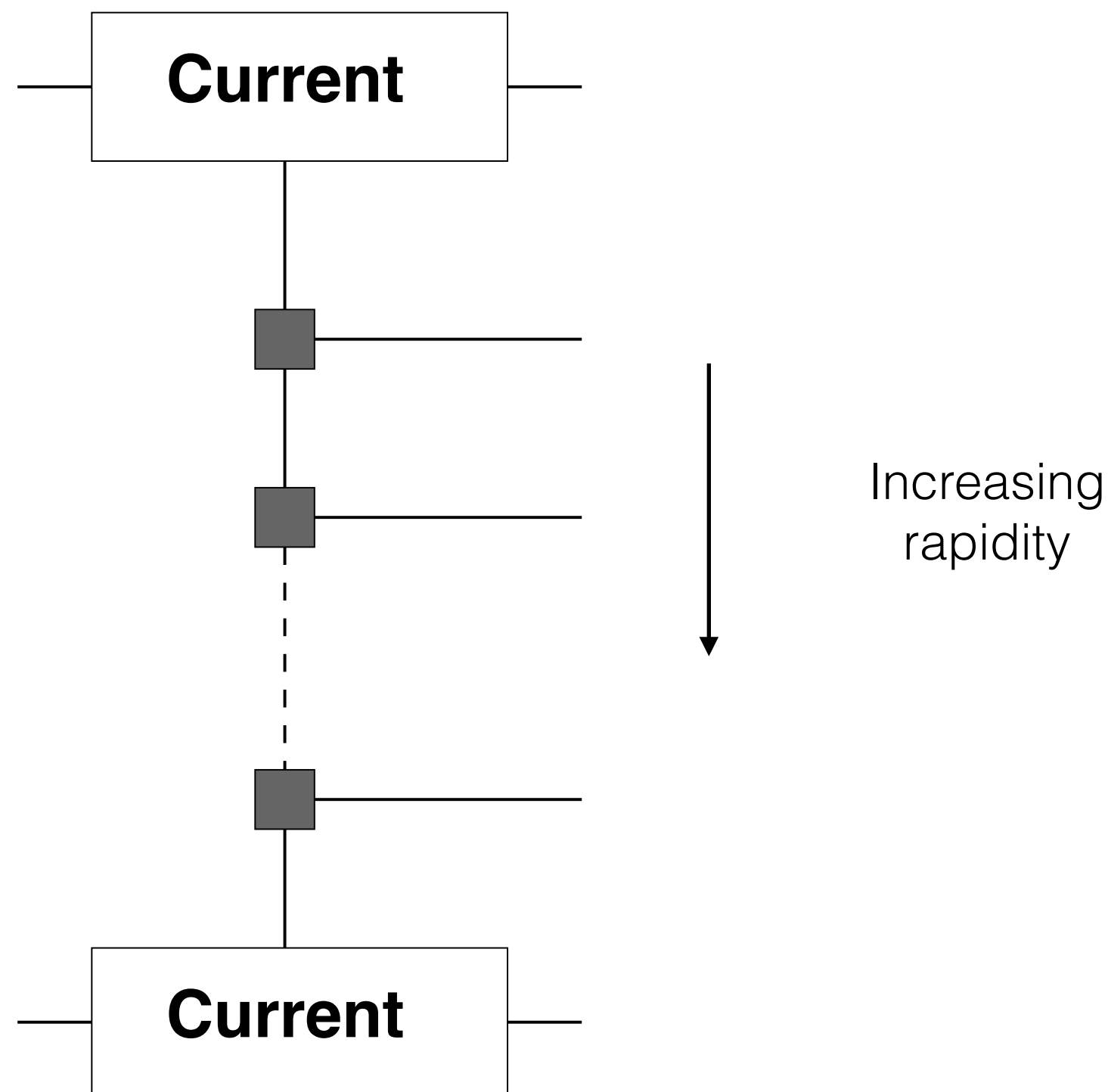
Inclusive 2-jet cross section given by  $\int d\text{PS}_2 |M_{2j+}|^2$ , with

$$\begin{aligned} |M_{2j+}|^2 = & \alpha_s^2 (a_2(s^2/t^2) + b_2) \\ & + \alpha_s^3 (a_3(s^2/t^2) \log(s/t) + b_3(s^2/t^2) + c_3) \\ & + \alpha_s^4 (a_4(s^2/t^2) \log^2(s/t) + b_4(s^2/t^2) \log(s/t) + \dots) \\ & + \dots \end{aligned}$$

- 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:  $s_{ij} \rightarrow \infty$ ,  $|p_{Ti}|$  finite



Local pieces, independent of the rest of the process

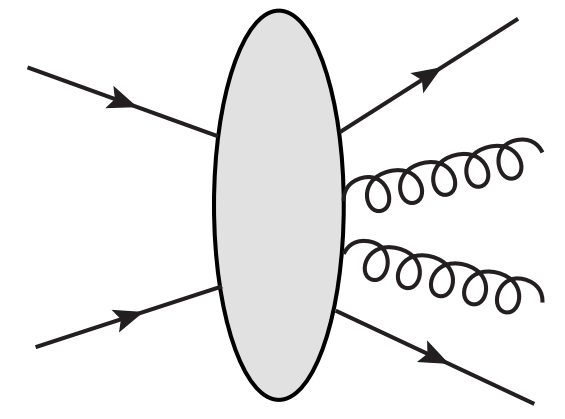
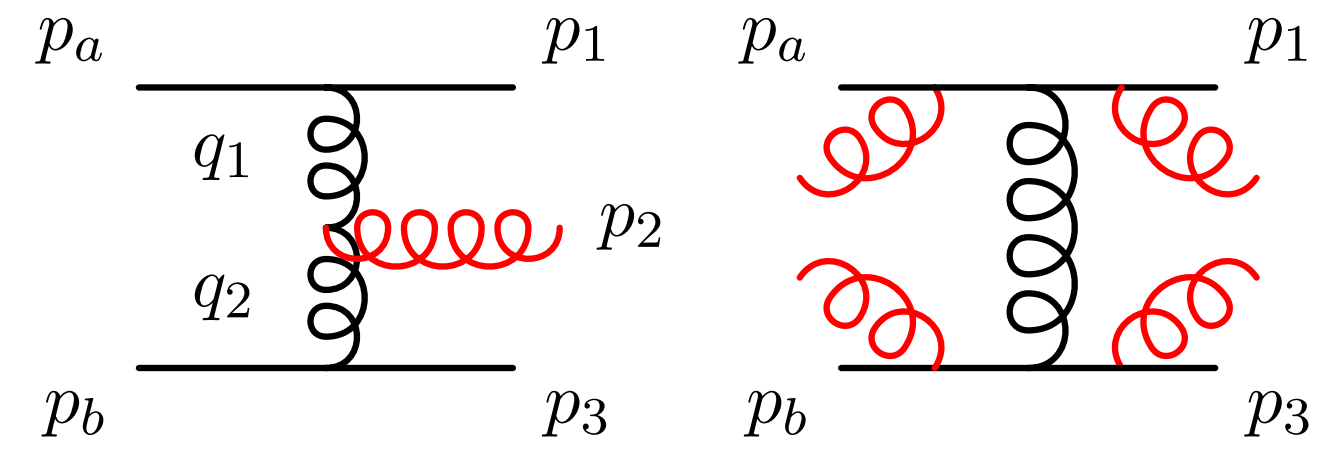
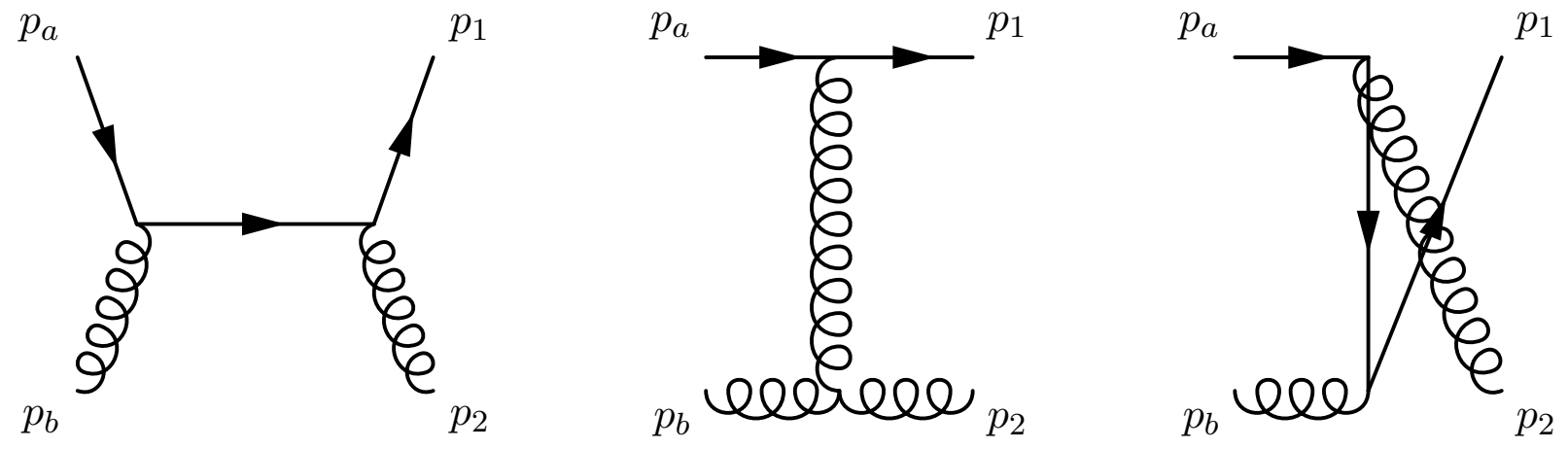
Applies to loop diagrams too, and generates leading logs in  $s_{ij}/p_T^2$

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

High Energy limit of amplitudes also very useful from theoretical point of view...

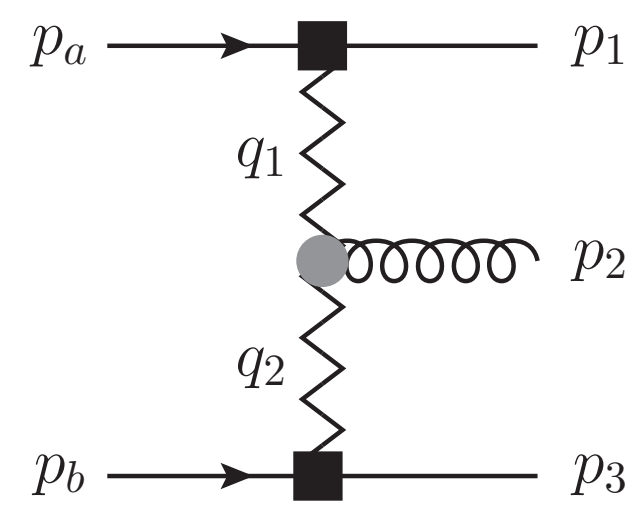


# Examples of the HE Limit



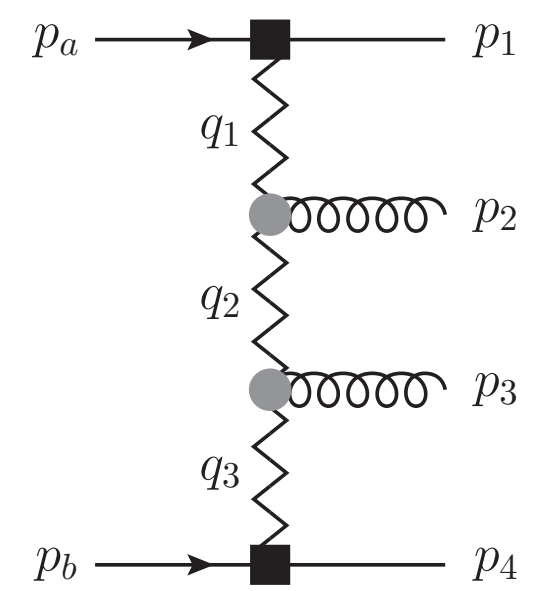
$$\mathcal{A}_{qQ \rightarrow qgQ} = g_s^3 C_g \varepsilon_\rho^* \frac{j^\mu(p_a, p_1) \cdot j_\mu(p_b, p_3)}{q_1^2 q_2^2} V^\rho(q_1, q_2)$$

$$V^\rho(q_1, q_2) = - (q_1 + q_2)^\rho + \frac{p_a^\rho}{2} \left( \frac{q_1^2}{p_2 \cdot p_a} + \frac{p_2 \cdot p_b}{p_a \cdot p_b} + \frac{p_2 \cdot p_3}{p_a \cdot p_3} \right) + p_a \leftrightarrow p_1 - \frac{p_b^\rho}{2} \left( \frac{q_2^2}{p_2 \cdot p_b} + \frac{p_2 \cdot p_a}{p_b \cdot p_a} + \frac{p_2 \cdot p_1}{p_b \cdot p_1} \right) - p_b \leftrightarrow p_3$$



$$\mathcal{A}_{qQ \rightarrow qggQ} = g_s^4 C_g C_{g'} \frac{j^\mu(p_a, p_1) \cdot j_\mu(p_b, p_4)}{q_1^2 q_2^2 q_3^2}$$

$$\times \varepsilon_\rho^* V^\rho(q_1, q_2) \times \varepsilon_\sigma^* V^\sigma(q_2, q_3)$$



• Exact result:

$$\frac{g_s^4 C_{CAM}}{6} \frac{|j^\mu(p_a, p_1) \cdot j_\mu(p_b, p_2)|^2}{\hat{t}^2}$$

with

$$C_{CAM} = \frac{1}{2} \left( C_A - \frac{1}{C_A} \right) \left( \frac{p_b^-}{p_2^-} + \frac{p_2^-}{p_b^-} \right) + \frac{1}{C_A}$$

• Only t-pole remains explicitly

• Same functions  $V^\rho(q_i, q_{i+1})$



# Main Equations

## Squared Matrix Element

$$\begin{aligned} \overline{|\mathcal{M}_{\text{HEJ}}^{\text{reg}}(\{p_i\})|^2} &= \frac{1}{4(N_C^2 - 1)} \|S_{f_1 f_2 \rightarrow f_1 f_2}\|^2 \\ &\cdot \left(g^2 K_{f_1} \frac{1}{t_1}\right) \cdot \left(g^2 K_{f_2} \frac{1}{t_{n-1}}\right) \\ &\cdot \prod_{i=1}^{n-2} \left(g^2 C_A \left(\frac{-1}{t_i t_{i+1}} V^\mu(q_i, q_{i+1}) V_\mu(q_i, q_{i+1}) - \frac{4}{\mathbf{p}_i^2} \theta(\mathbf{p}_i^2 < \lambda^2)\right)\right) \\ &\cdot \prod_{j=1}^{n-1} \exp[\omega^0(q_j, \lambda)(y_j - y_{j+1})], \end{aligned}$$

Andersen & JMS arXiv:[0908.2786](https://arxiv.org/abs/0908.2786), [0910.5113](https://arxiv.org/abs/0910.5113)



# Main Equations

Squared Matrix Element

$$\begin{aligned}
 \overline{|\mathcal{M}_{\text{HEJ}}^{\text{reg}}(\{p_i\})|^2} = & \frac{1}{4(N_C^2 - 1)} \|S_{f_1 f_2 \rightarrow f_1 f_2}\|^2 \\
 & \cdot \left(g^2 K_{f_1} \frac{1}{t_1}\right) \cdot \left(g^2 K_{f_2} \frac{1}{t_{n-1}}\right) \\
 & \cdot \prod_{i=1}^{n-2} \left(g^2 C_A \left(\frac{1}{t_i t_{i+1}} V^\mu(q_i, q_{i+1}) V_\mu(q_i, q_{i+1}) - \frac{4}{\mathbf{p}_i^2} \theta(\mathbf{p}_i^2 < \lambda^2)\right)\right) \\
 & \cdot \prod_{j=1}^{n-1} \exp[\omega^0(q_j, \lambda)(y_j - y_{j+1})],
 \end{aligned}$$

Skeleton/Born Process

Resolved Real Emissions

Virtual + Unresolved Real (finite)

Andersen & JMS arXiv:0908.2786, 0910.5113

# Main Equations

Squared Matrix Element

$$\begin{aligned}
 |\mathcal{M}_{\text{HEJ}}^{\text{reg}}(\{p_i\})|^2 = & \frac{1}{4(N_C^2 - 1)} \|S_{f_1 f_2 \rightarrow f_1 f_2}\|^2 \\
 & \cdot \left(g^2 K_{f_1} \frac{1}{t_1}\right) \cdot \left(g^2 K_{f_2} \frac{1}{t_{n-1}}\right) \\
 & \cdot \prod_{i=1}^{n-2} \left(g^2 C_A \left(\frac{1}{t_i t_{i+1}} V^\mu(q_i, q_{i+1}) V_\mu(q_i, q_{i+1}) - \frac{4}{\mathbf{p}_i^2} \theta(\mathbf{p}_i^2 < \lambda^2)\right)\right) \\
 & \cdot \prod_{j=1}^{n-1} \exp[\omega^0(q_j, \lambda)(y_j - y_{j+1})],
 \end{aligned}$$

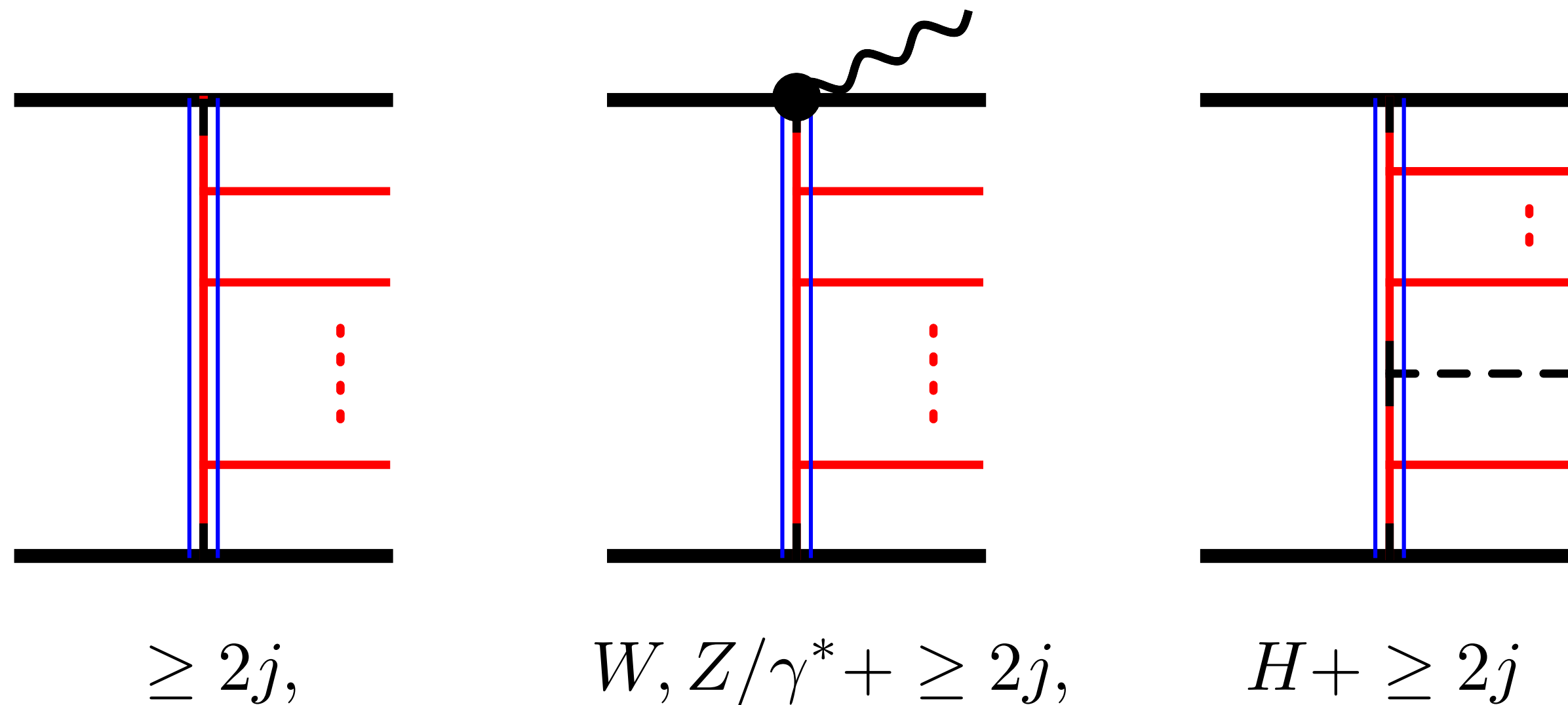
Skeleton/Born Process

Resolved Real Emissions

Virtual + Unresolved Real (finite)

Andersen & JMS arXiv:0908.2786, 0910.5113

Black = Skeleton/Born function  
Red = Range of resummation





# “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)

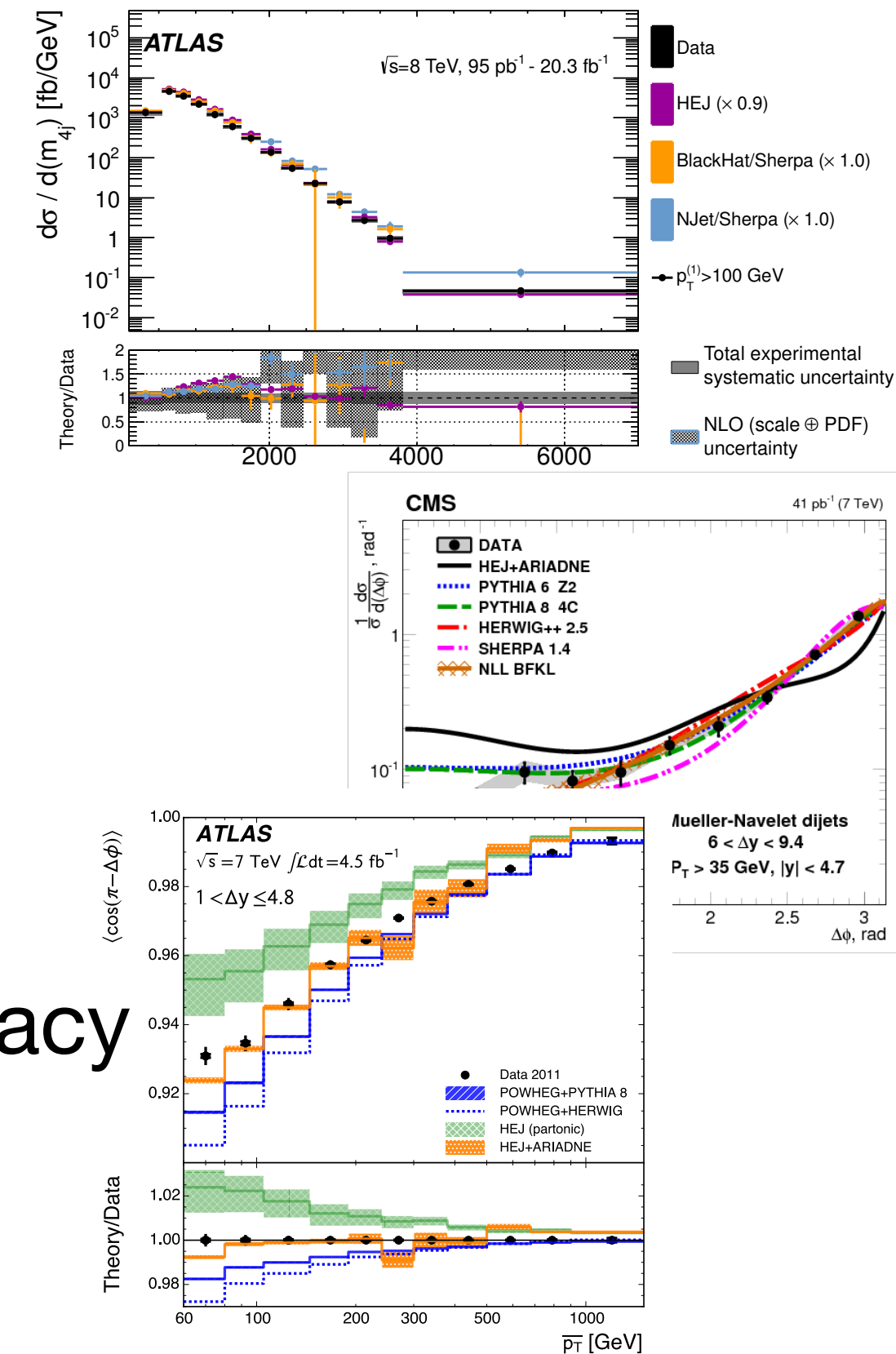
**HEJ2 event generator: <https://hej.hepforge.org>**

Andersen, Hapola, Heil, Maier & JMS [arXiv:1902.08430](https://arxiv.org/abs/1902.08430)

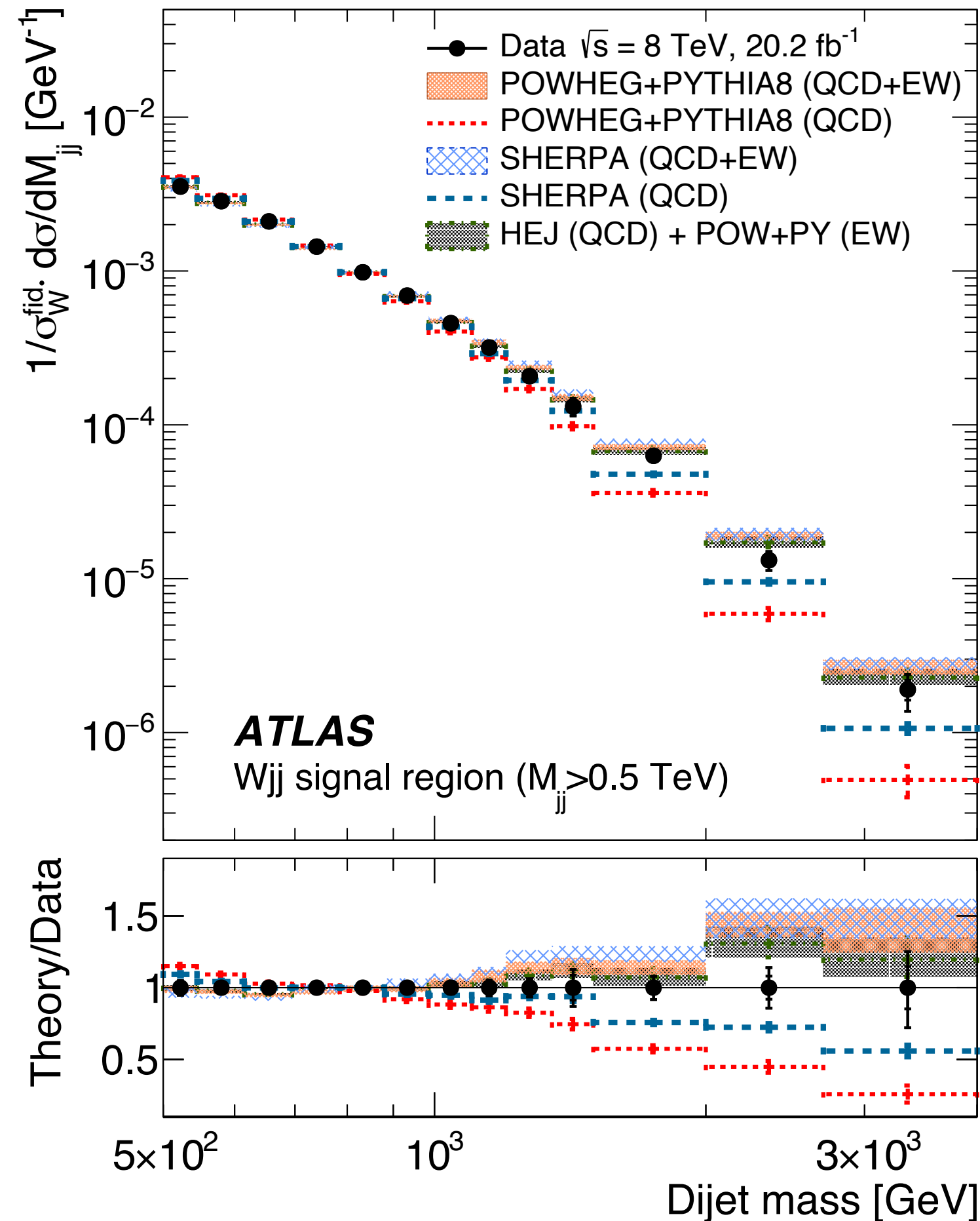
Extra colour-neutral bosons can be added without affecting the logarithmic accuracy

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

Andersen, Black, Brooks, Ducloué, Heil, Maier & JMS [arXiv:2110.15692](https://arxiv.org/abs/2110.15692)

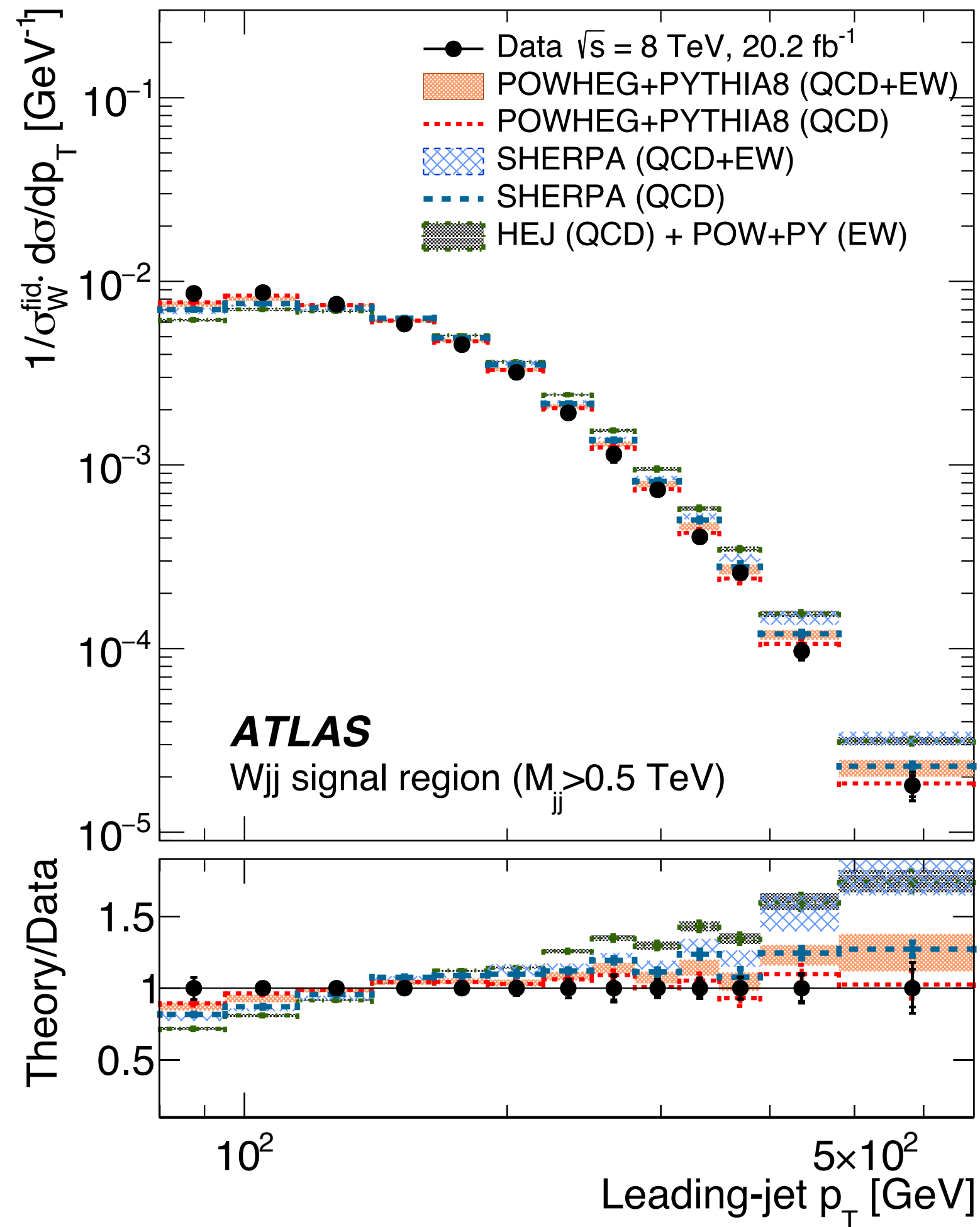


# 2017 ATLAS W+2j



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



- Different picture when plotted versus  $p_T$  as no systematic evolution in  $p_T$  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](https://arxiv.org/abs/1712.00178)  
 Andersen, Hassan, Jaskiewicz [arXiv:2210.06898](https://arxiv.org/abs/2210.06898)

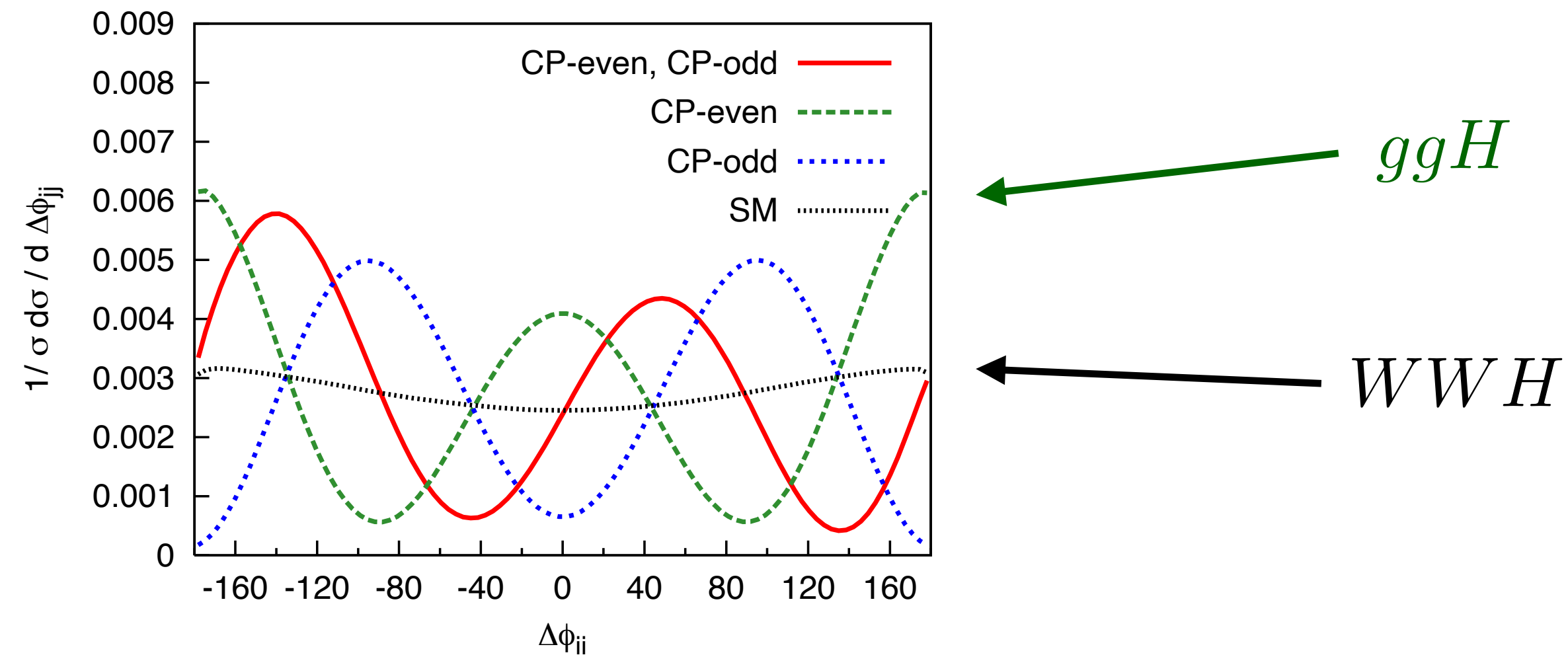


# Higgs + Dijets

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



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

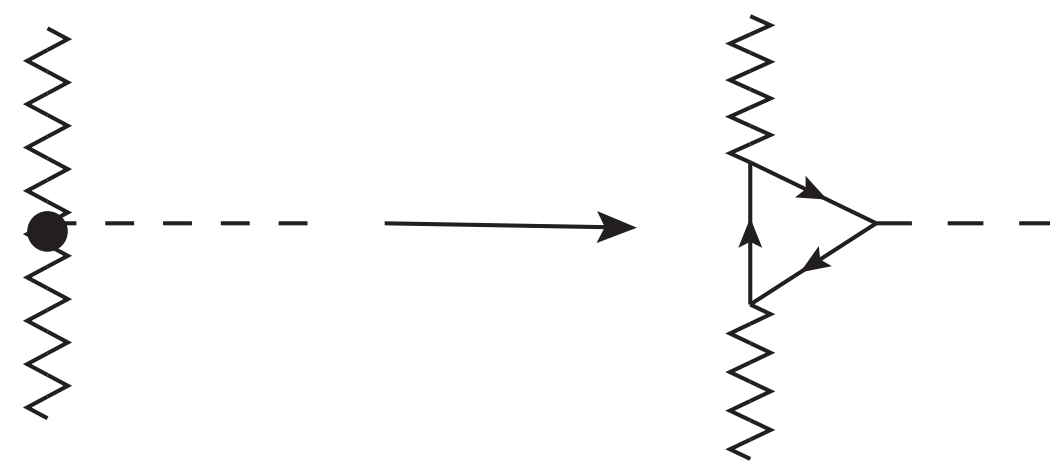
# Finite Quark Masses in H+2j

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

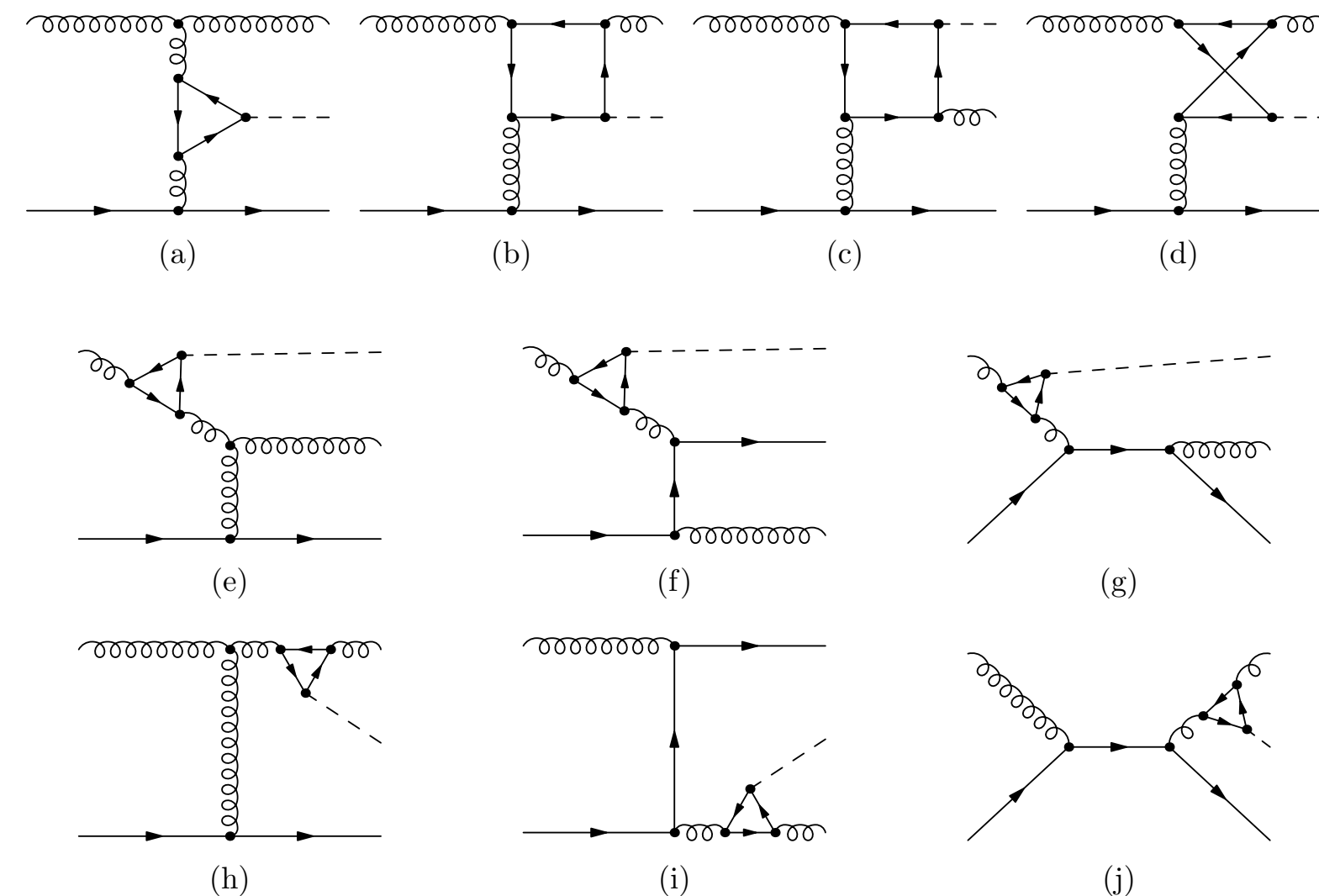
Del Duca et al [hep-ph/0105129](https://arxiv.org/abs/hep-ph/0105129), [hep-ph/0108030](https://arxiv.org/abs/hep-ph/0108030)  
 Greiner et al [arXiv:1608.01195](https://arxiv.org/abs/1608.01195)

In HEJ, factorised structure removes complexity from increasing number of jets

Del Duca, Kilgore, Oleari, Schmidt & Zeppenfeld [hep-ph/0301013](https://arxiv.org/abs/hep-ph/0301013)  
 Andersen, Cockburn, Heil, Maier & JMS [arXiv:1812.08072](https://arxiv.org/abs/1812.08072)



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



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](https://arxiv.org/abs/0811.4622); Cascioli, Maierhöfer, Pozzorini [arXiv:1111.5206](https://arxiv.org/abs/1111.5206)



Highest available =

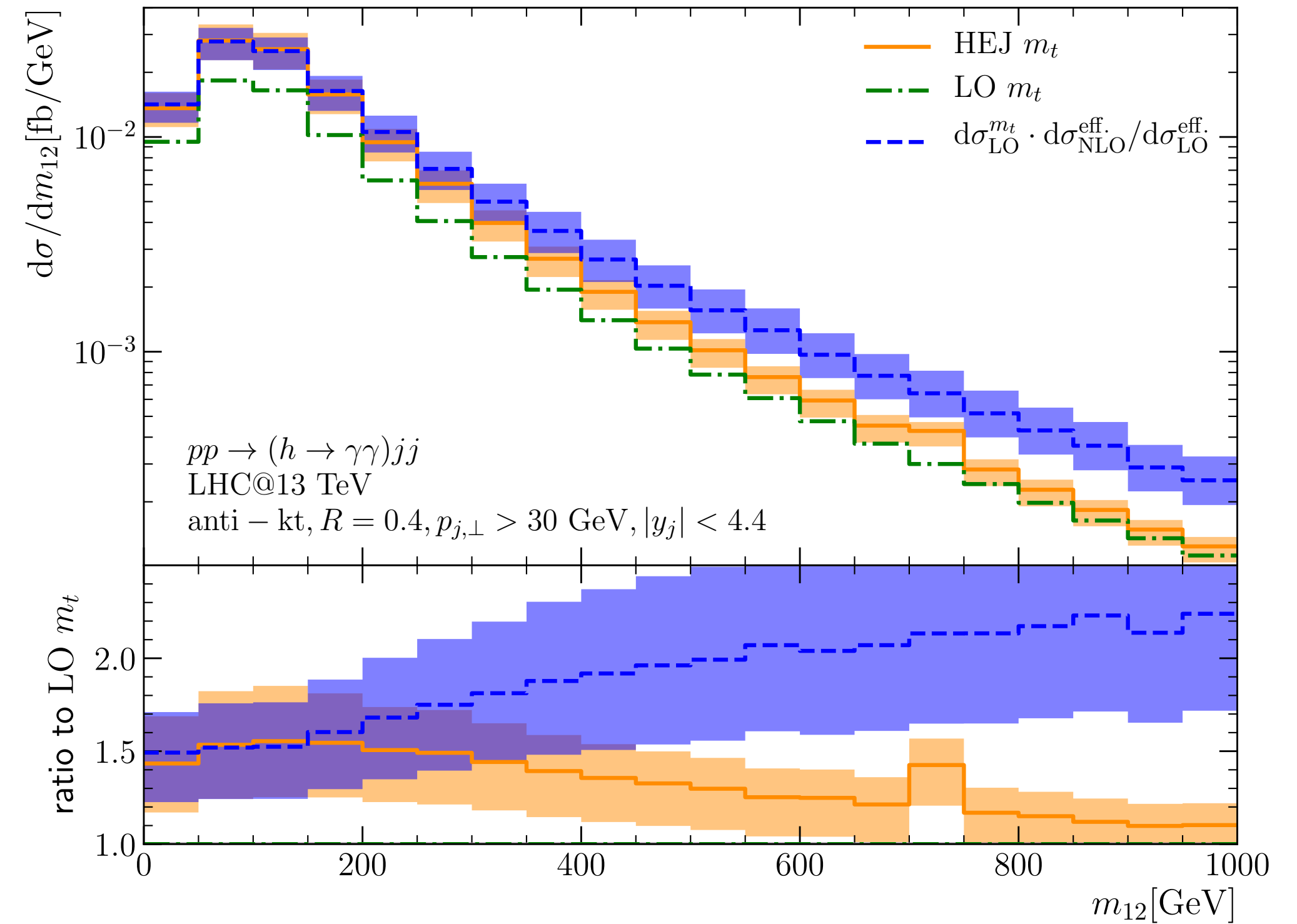
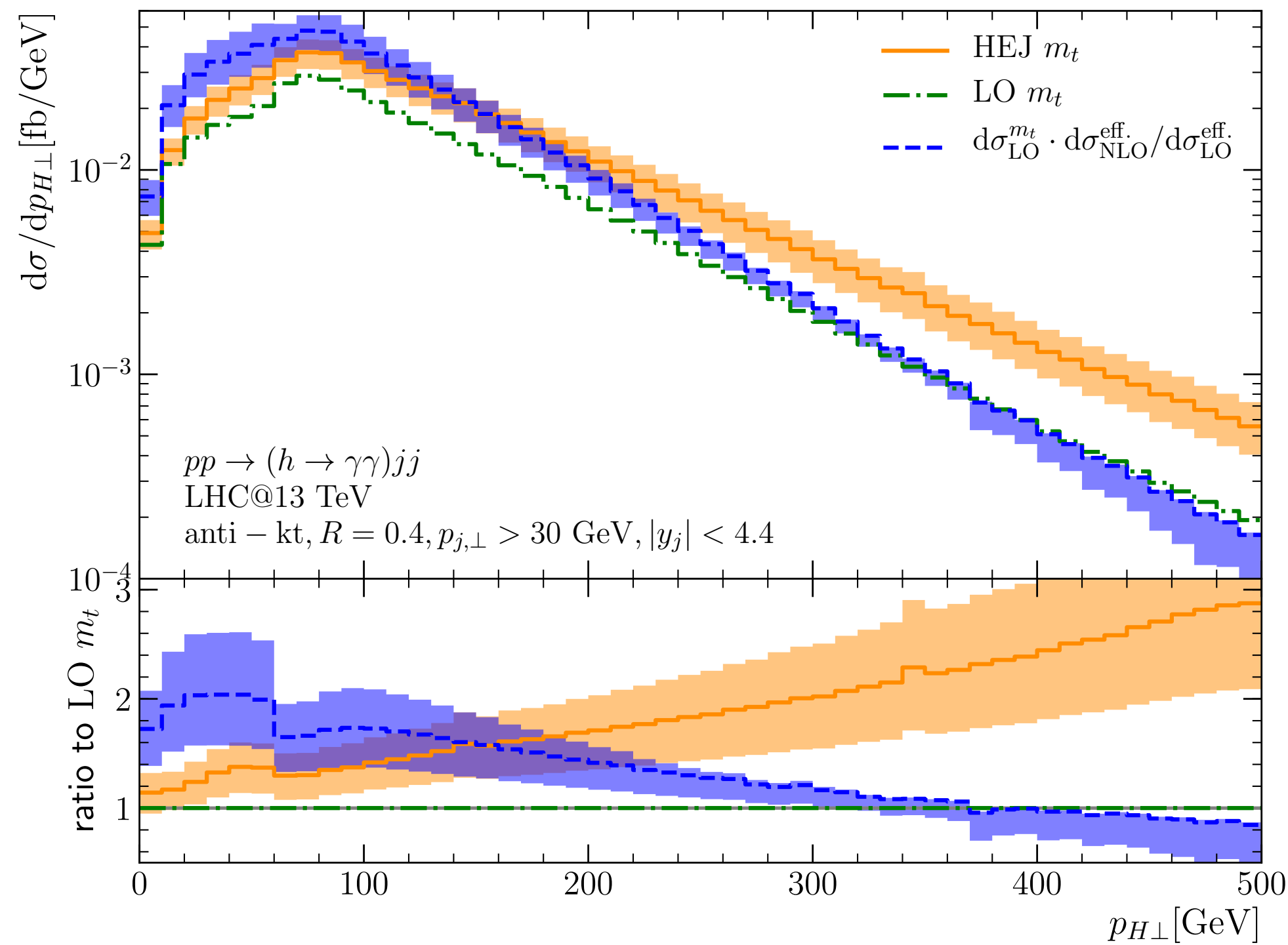
finite	$m_t$	$H + 2j$	at LO	( $3j$ results exist, but events not available)
infinite	$m_Q$	$H + 2j$	at NLO	
		$H + 5j$	at LO	

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



First probe the impact of higher orders in  $\alpha_s$

HEJ here temporarily without  $m_b$



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

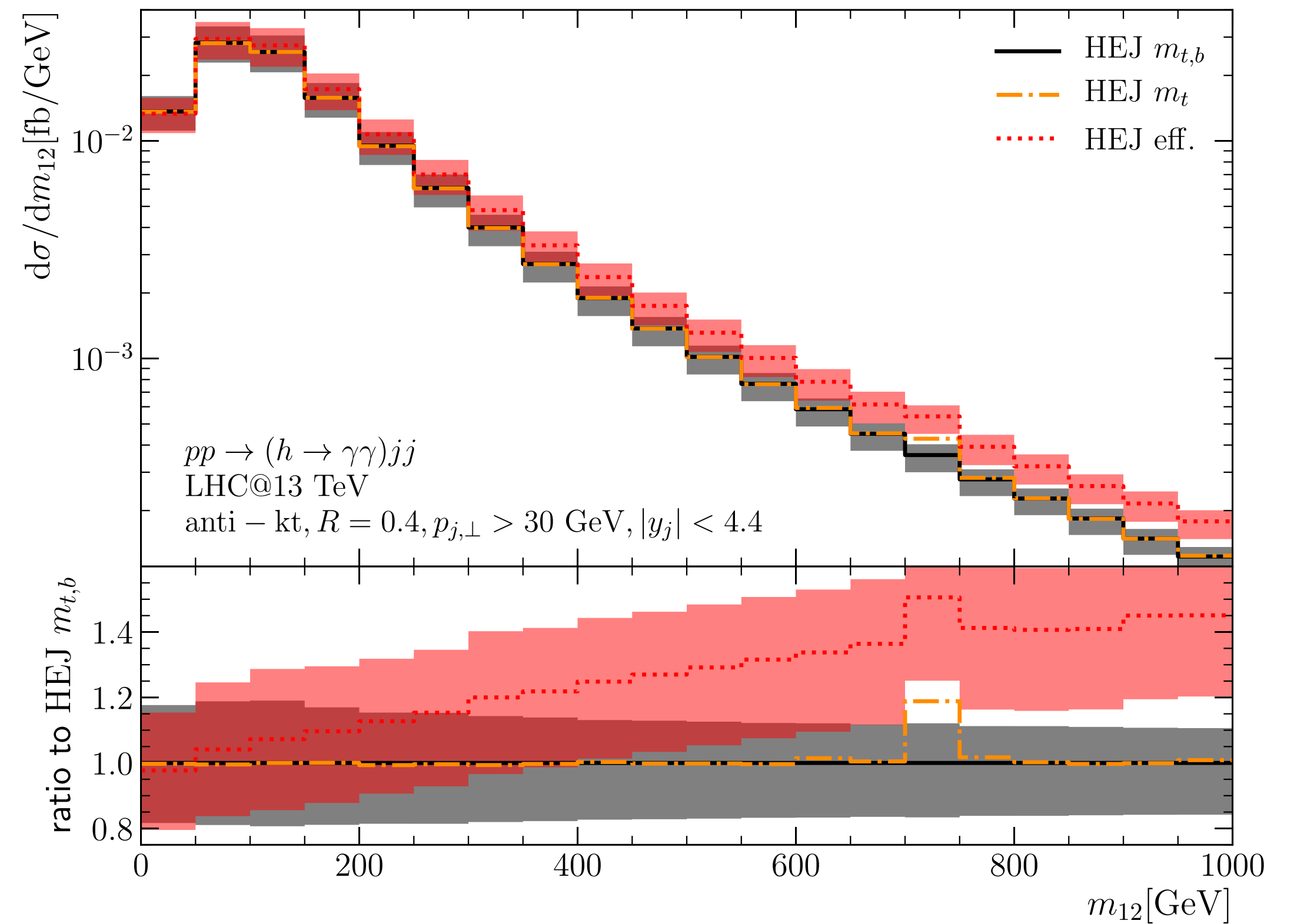
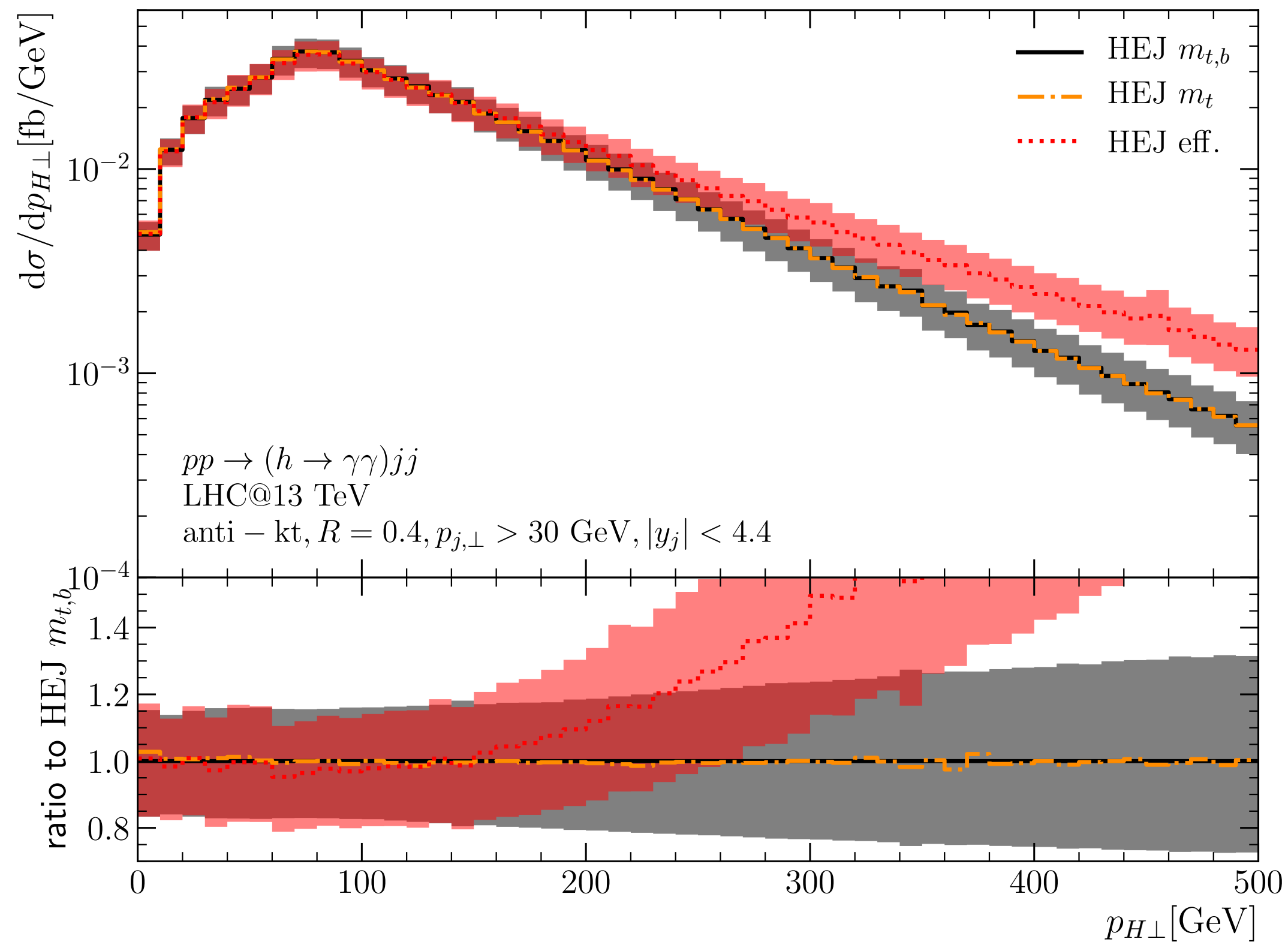
HEJ harder  $p_{H\perp}$  spectrum

HEJ much steeper drop with  $m_{12}$

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

Now probe the impact of quark masses

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

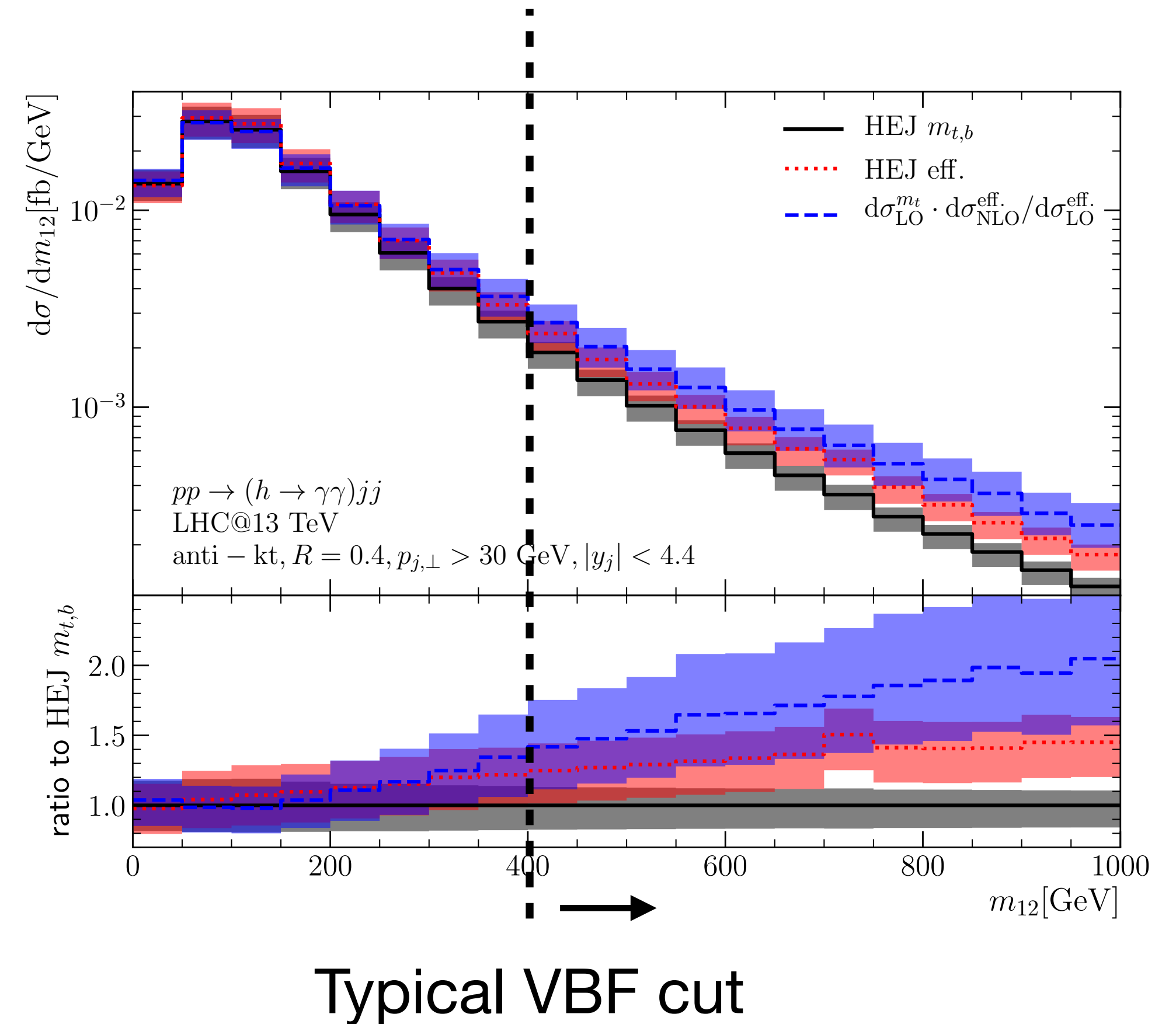


- Importance of finite quark mass increases with  $p_{H\perp}$
- Relatively small impact of  $m_b$ , finite  $m_t$  lowers predictions at large  $m_{12}$
- Therefore finite quark mass effects make VBF cuts more effective

# 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%



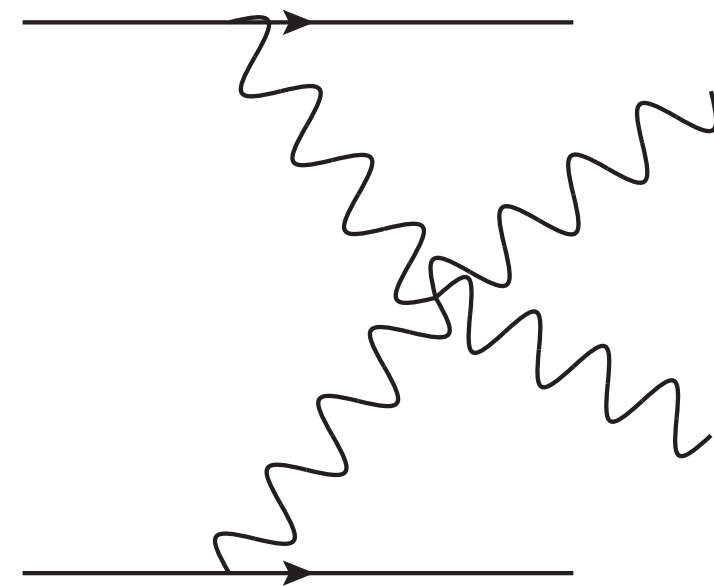


# Vector Boson Scattering

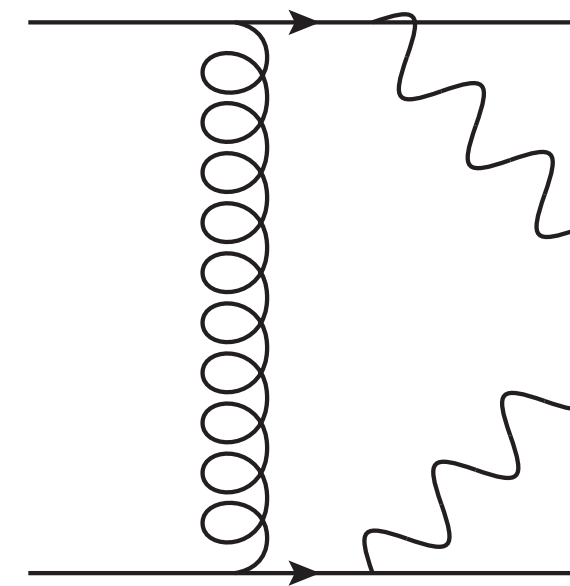
Vector Boson Scattering (VBS) sensitive probe of EWSB

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

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



$$QCD = O(\alpha_W^2 \alpha_s^2)$$

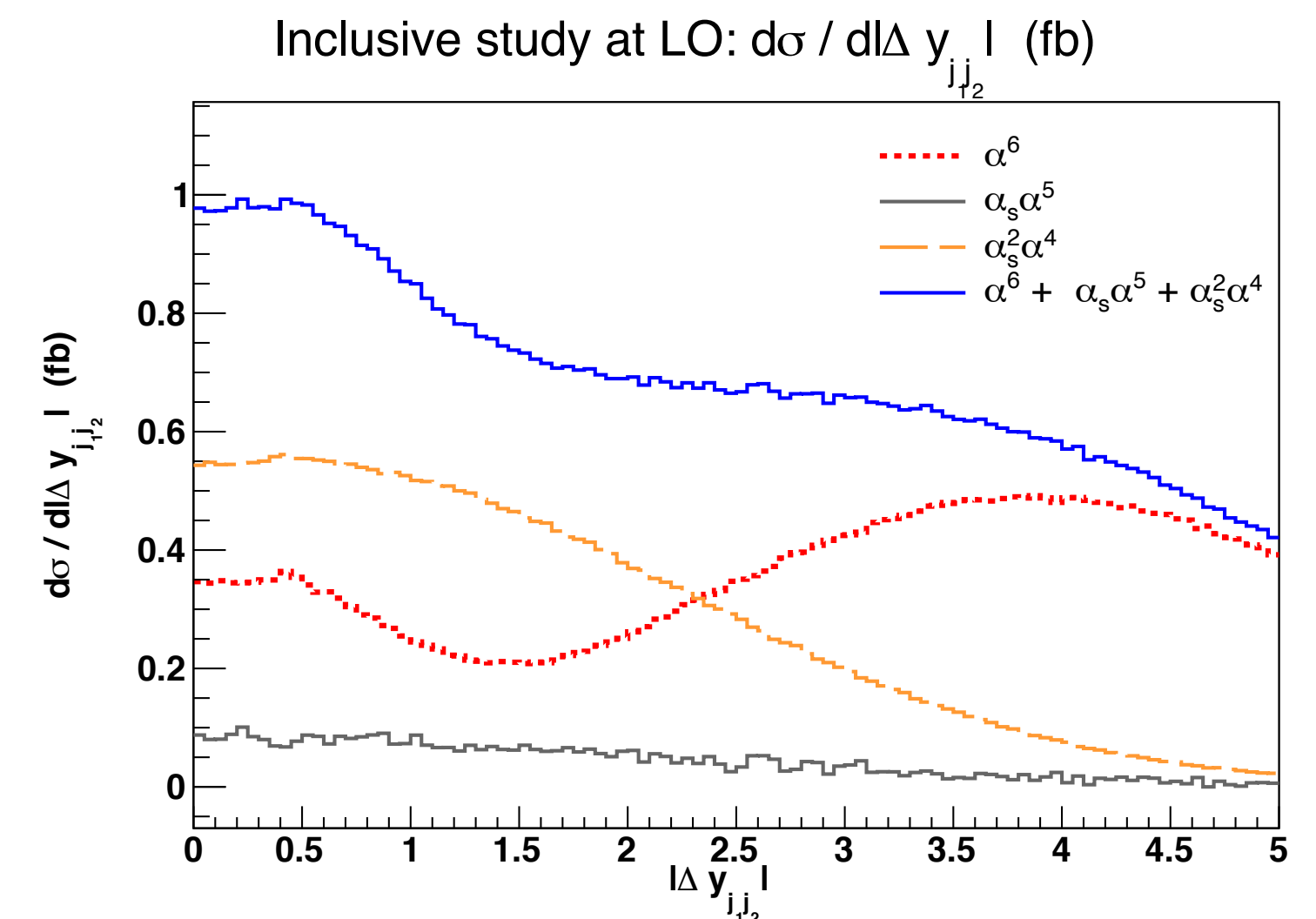


New in HEJ 2.2!

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  $pp \rightarrow Hjj$

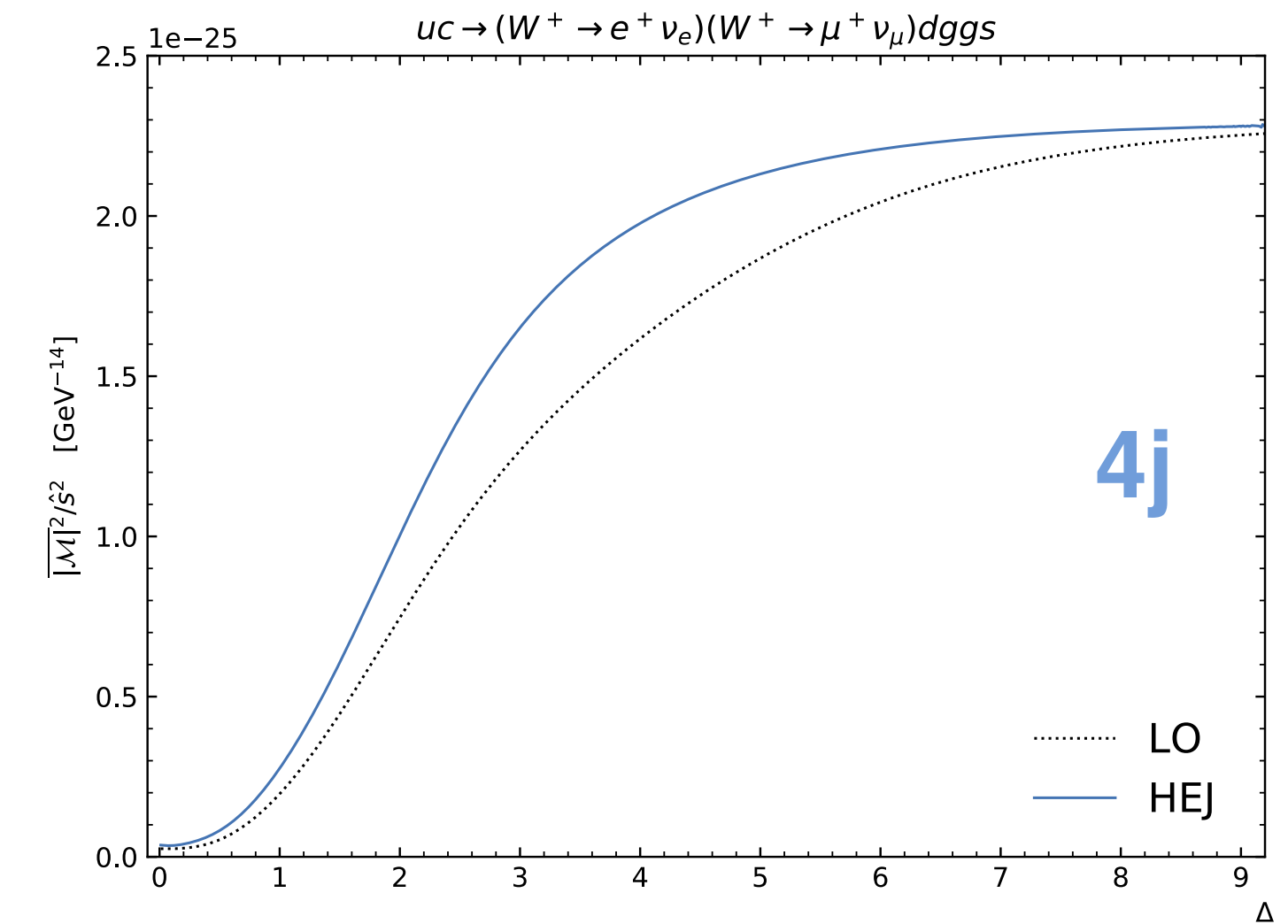
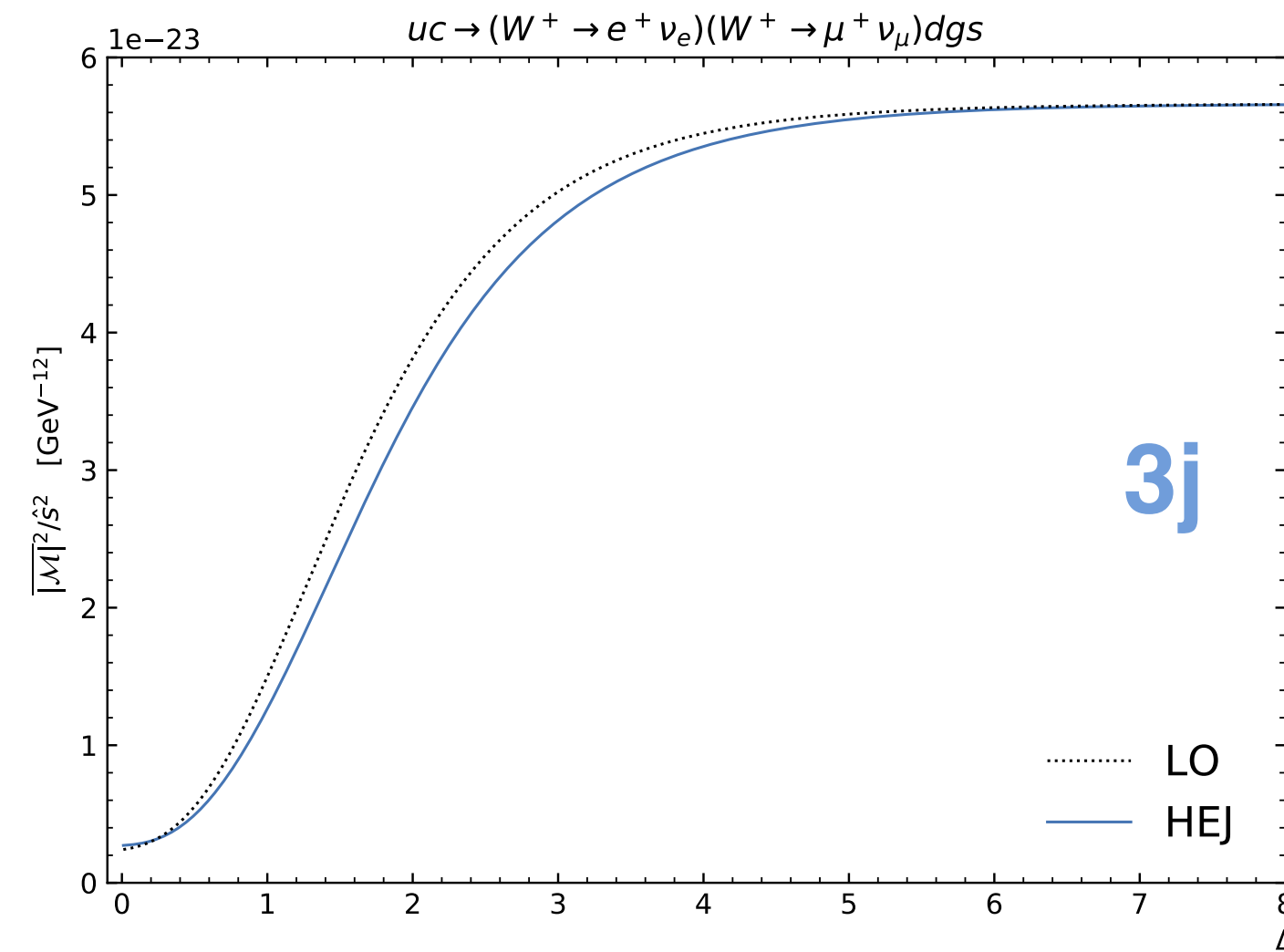


Ballestrero et al arXiv:1803.07943

# Vector Boson Scattering

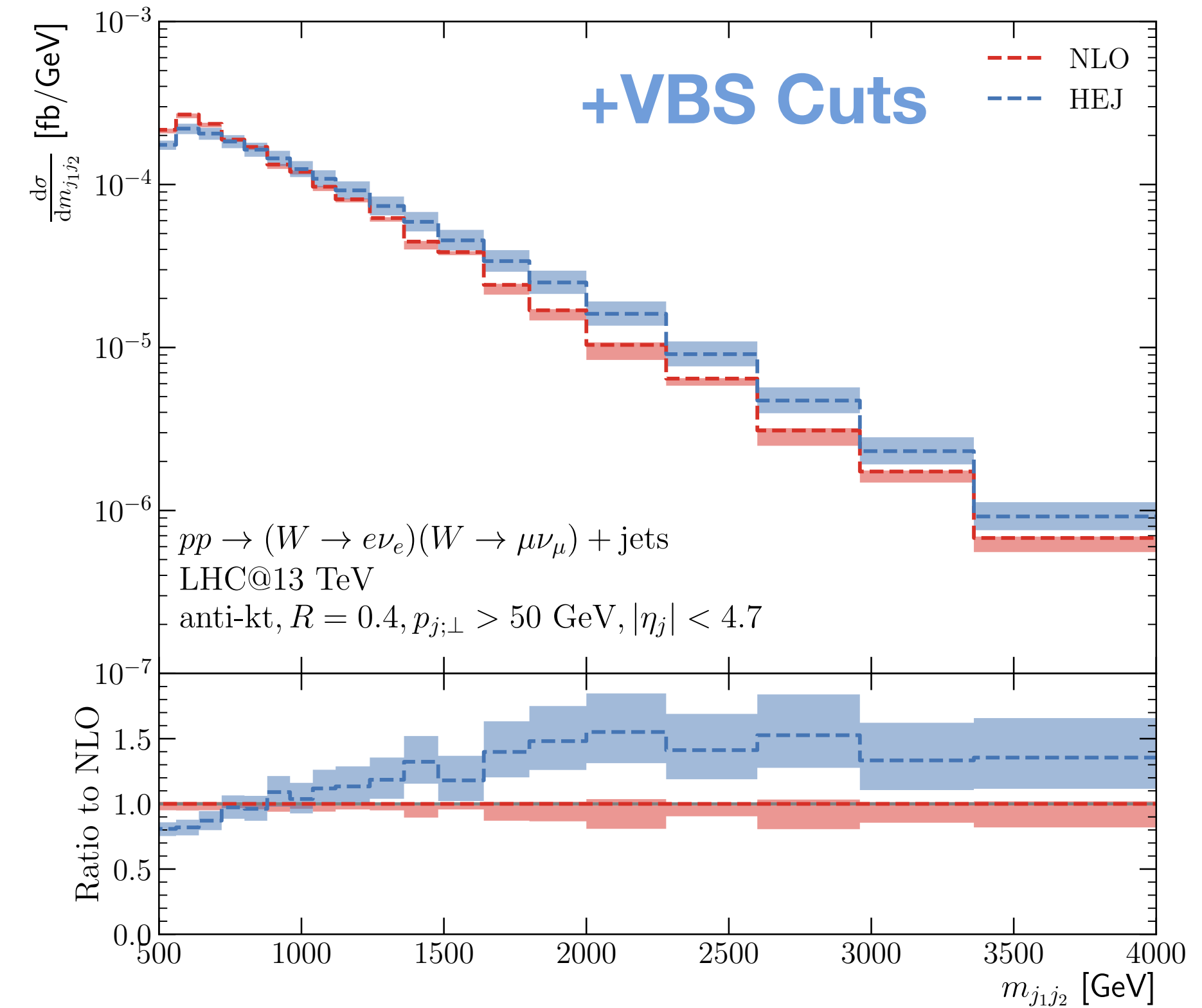
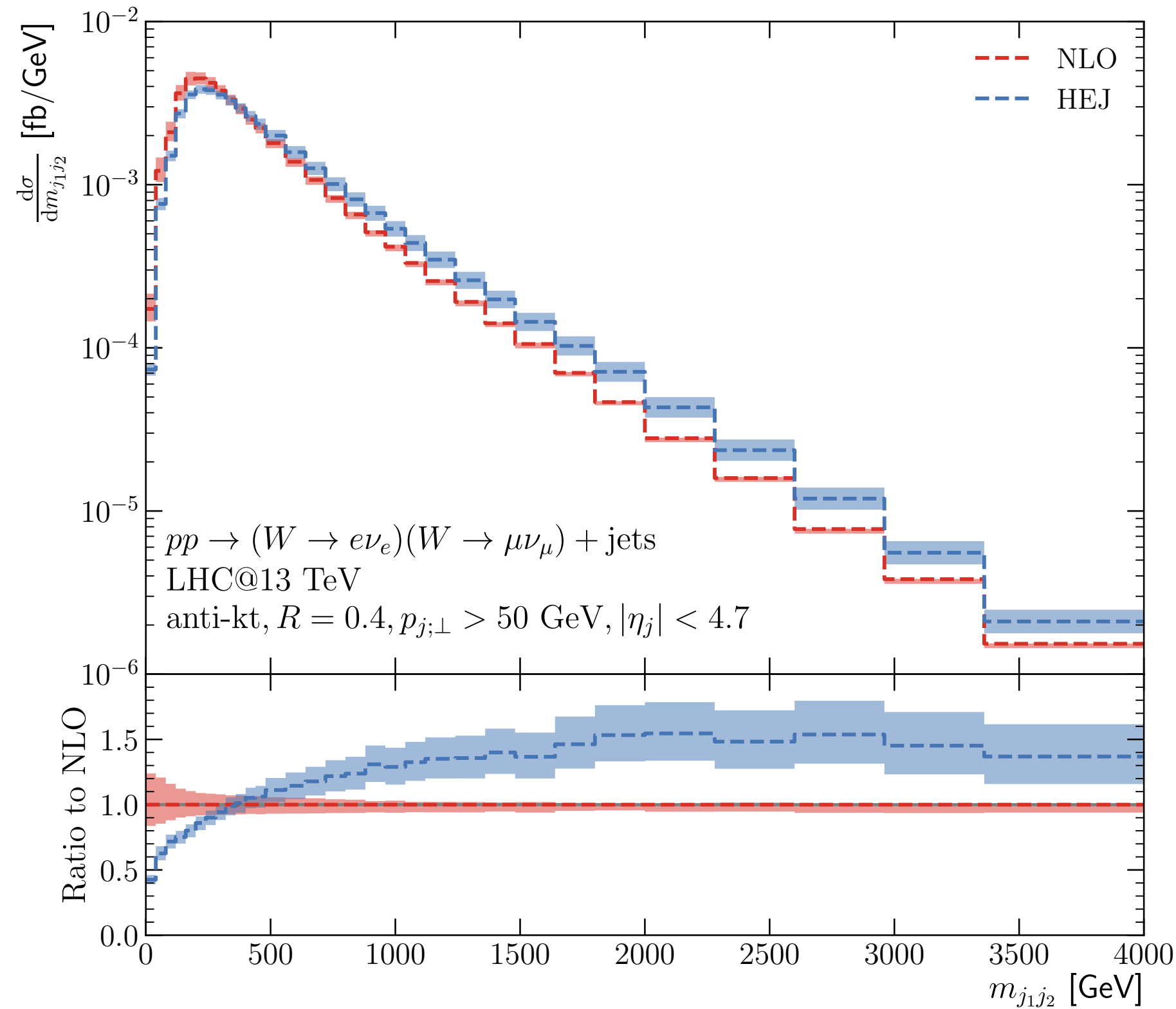
Now included in HEJ, where LL effects obtained by combining two single-W pieces

## PLUS interference



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

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

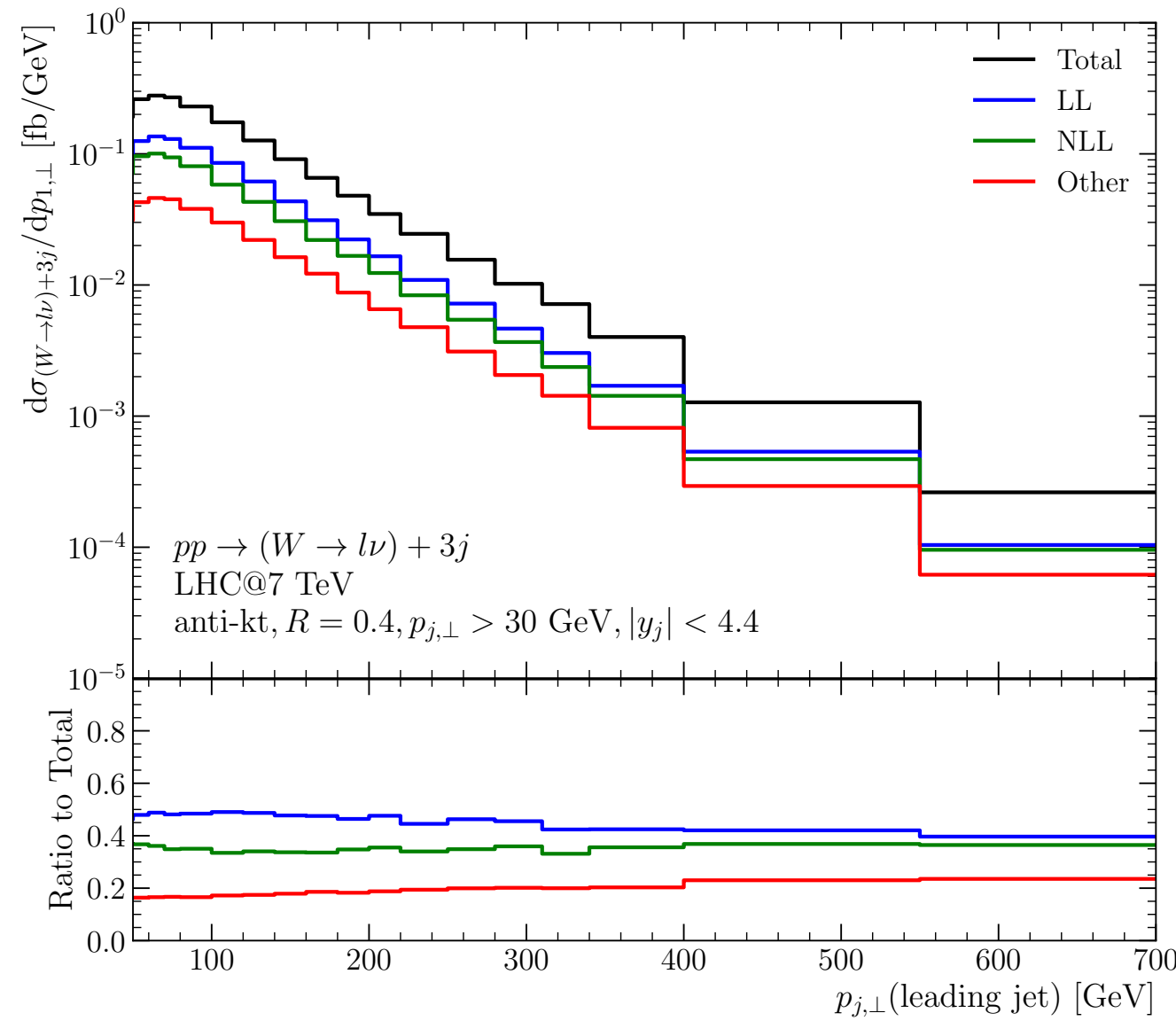


Shape of distributions changed by the all-order resummation

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

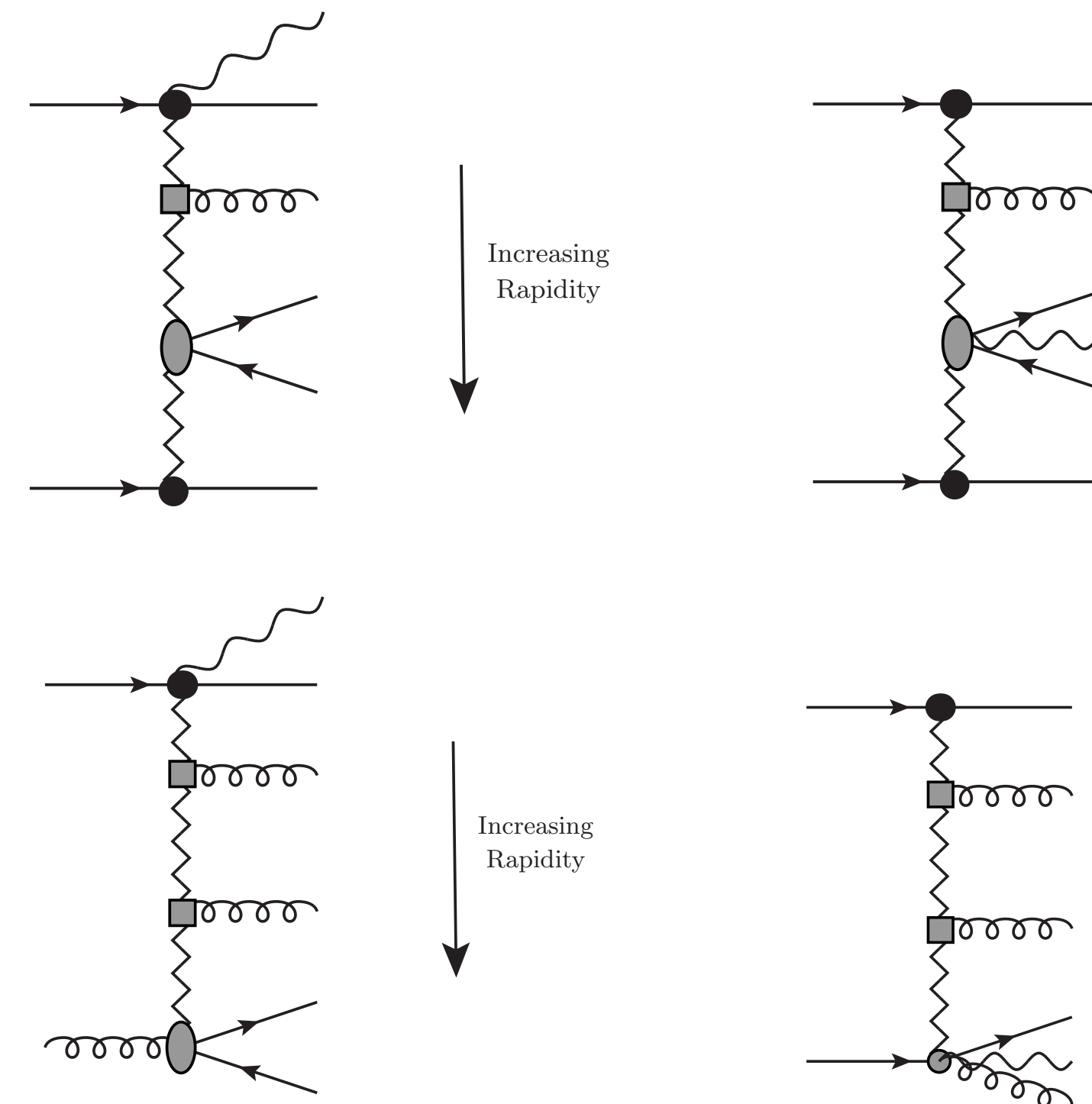


# Improvements at Large $p_T$ : NLL



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)



# Improvements at Large $p_T$ : NLO Matching

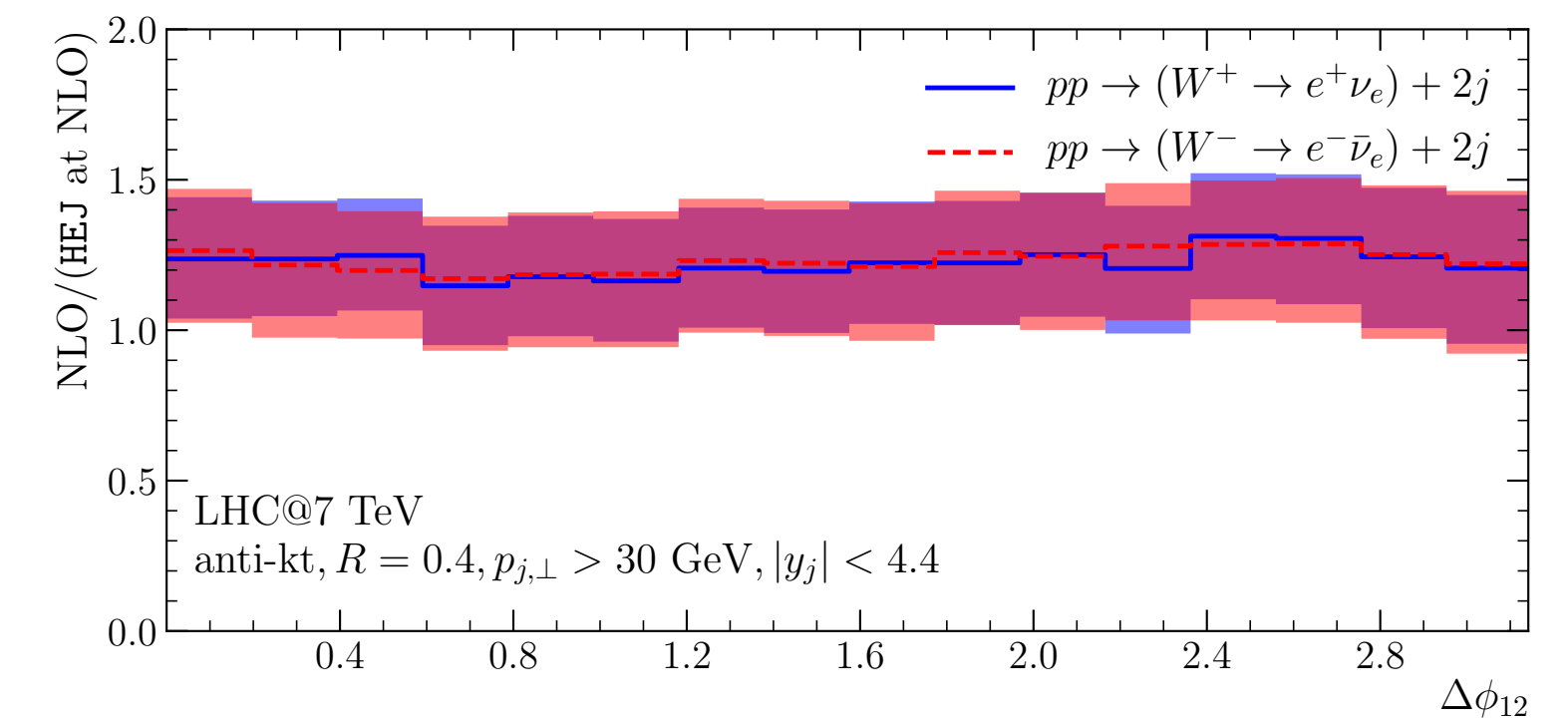
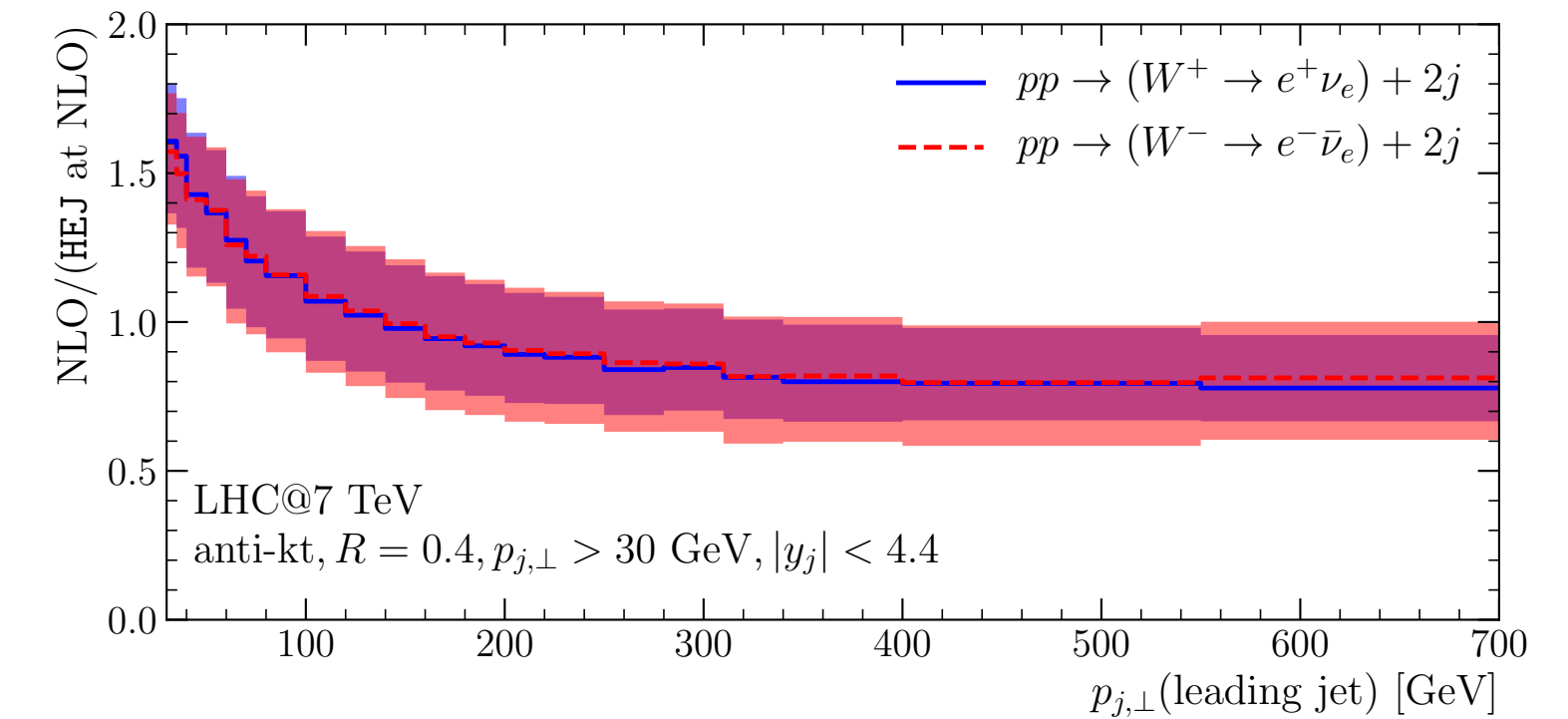
Not able yet to match to NLO event-by-event, but can do better than a k-factor by matching bin-by-bin

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

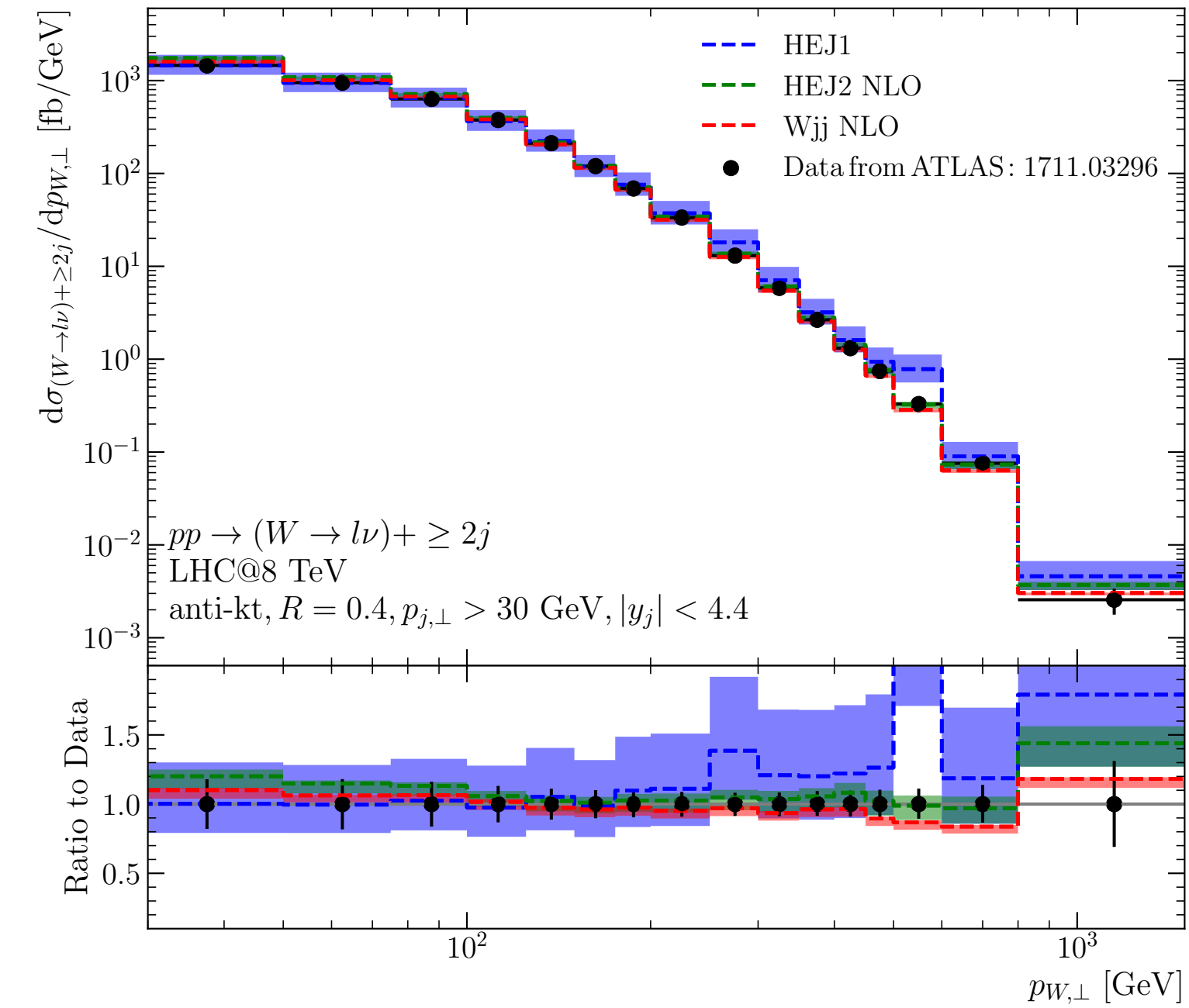
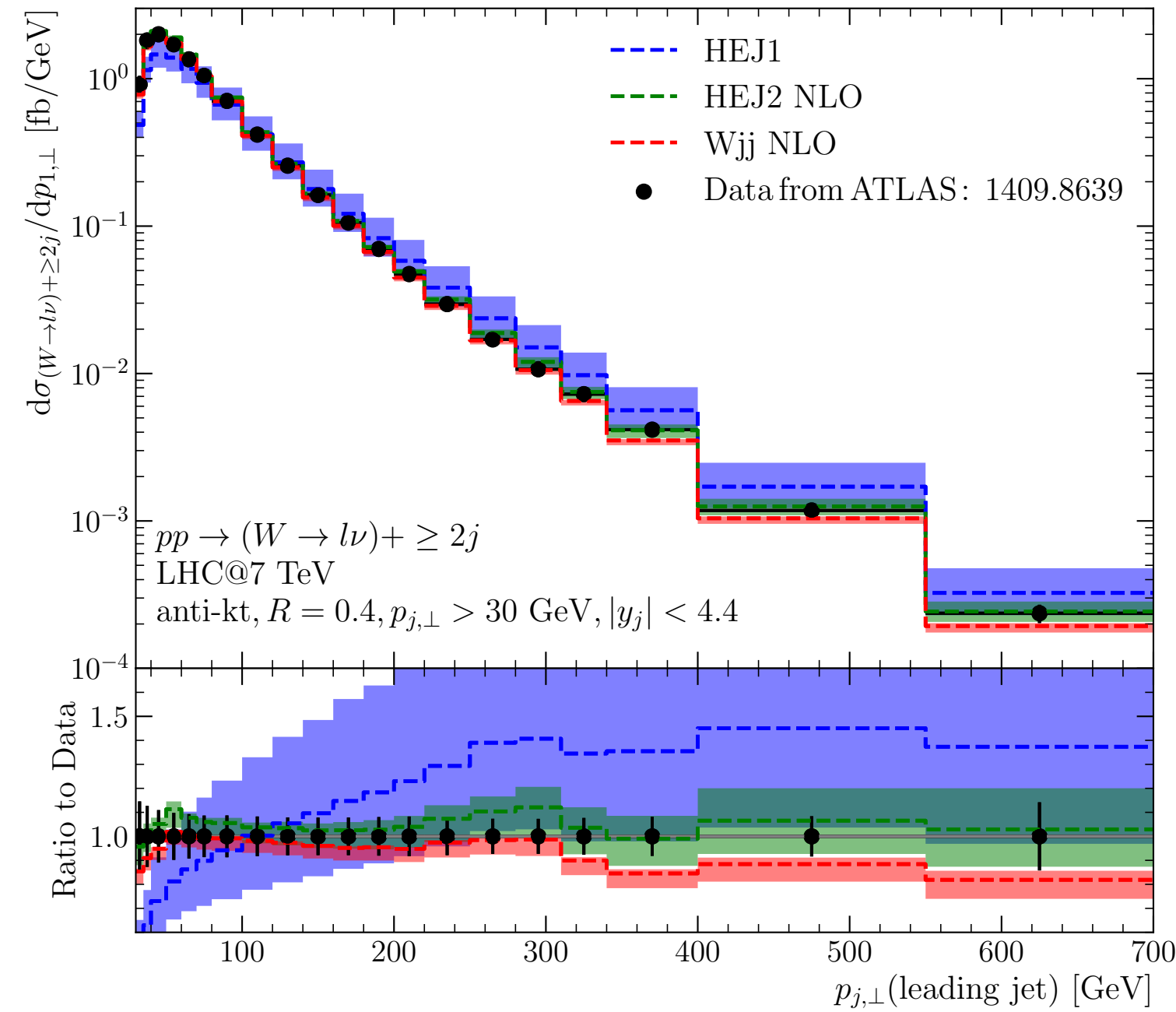
Final predictions are then given by

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

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



# Improved W-Plus-Dijets



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

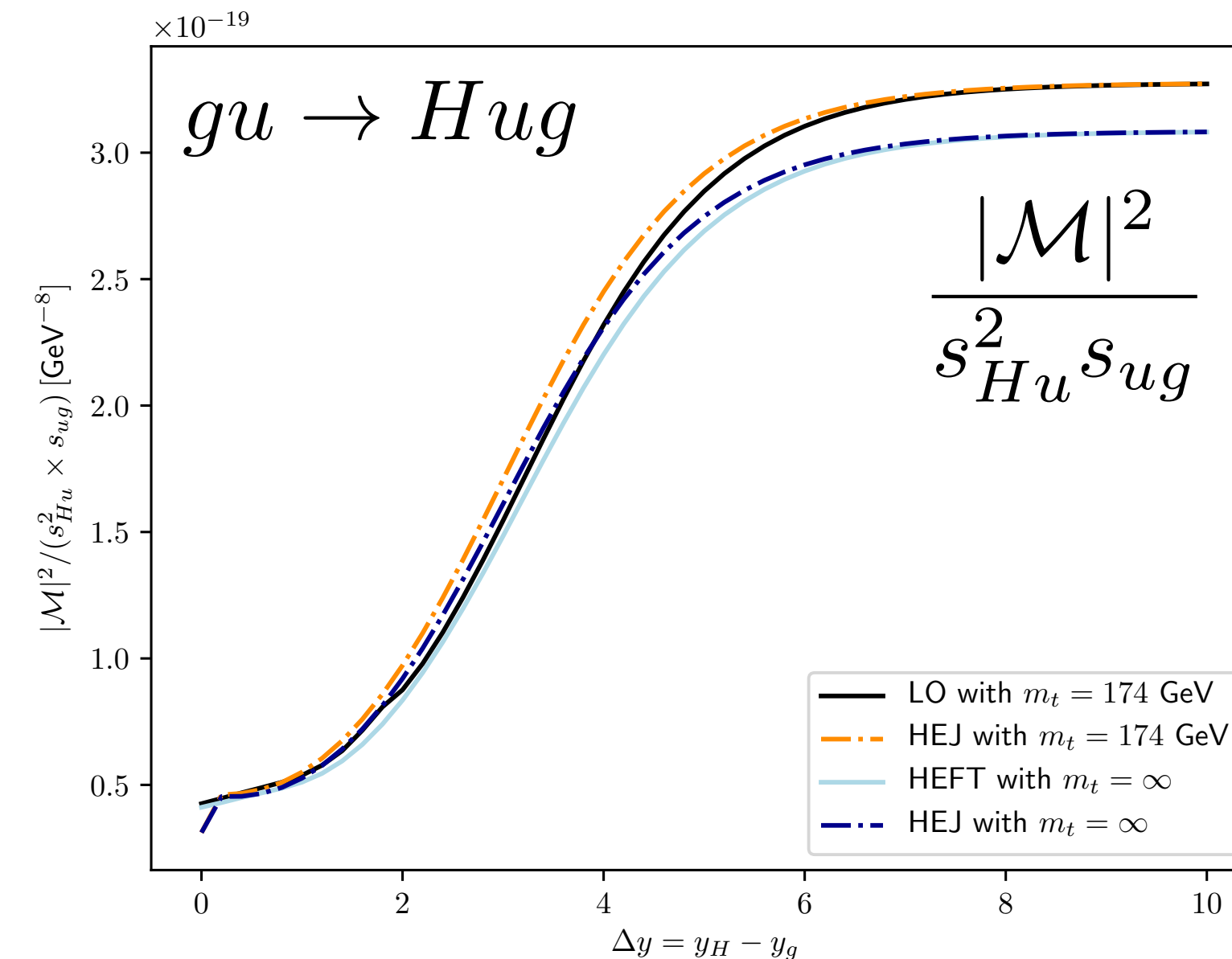
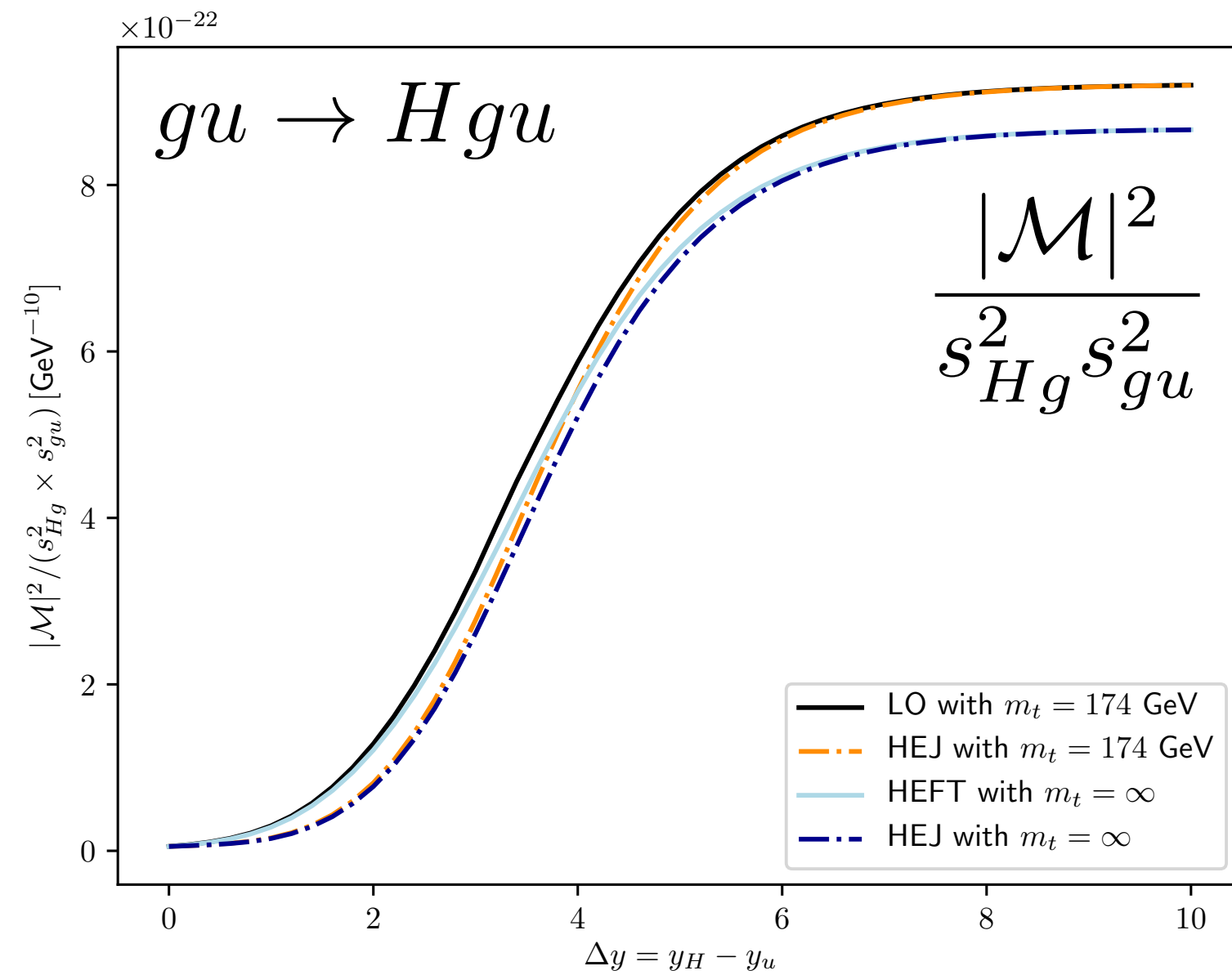
- At large  $p_T$  values, require  $\geq 4j$  events to obtain good agreement



# 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](https://arxiv.org/abs/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

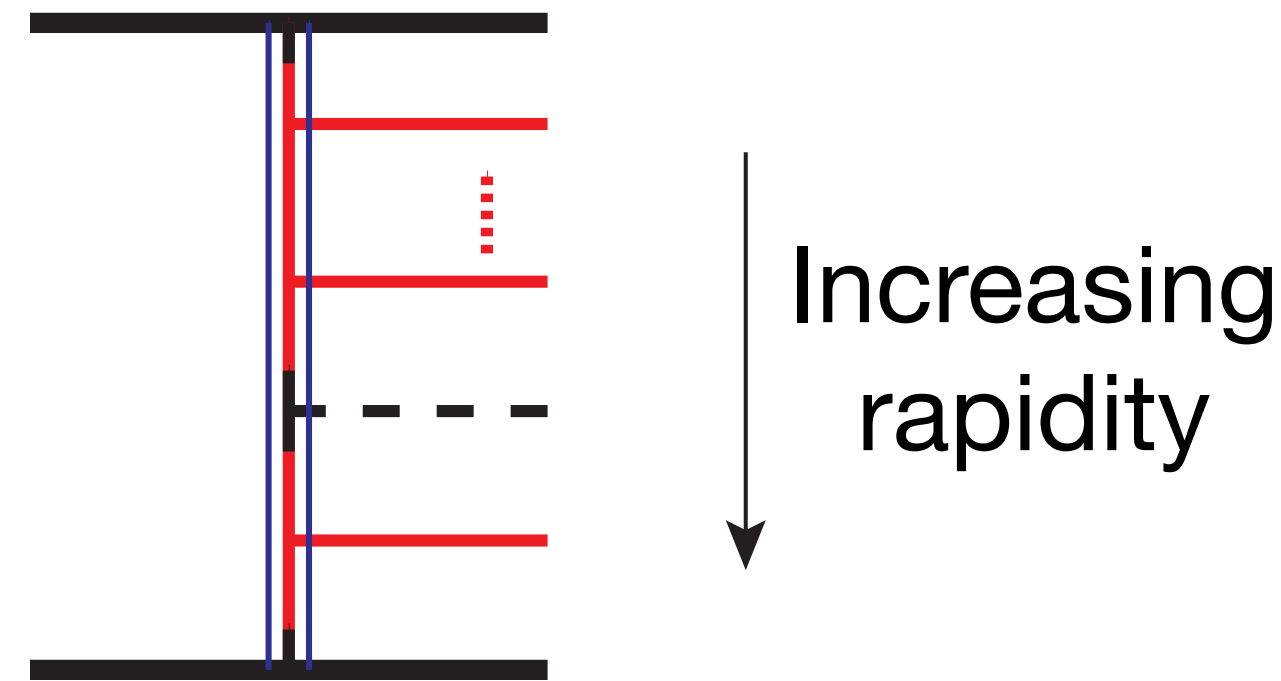
Andersen, Hassan, Maier, Paltrinieri, Papaefstathiou, JMS [arXiv:2210.10671](https://arxiv.org/abs/2210.10671)

# Higgs + 1j in HEJ

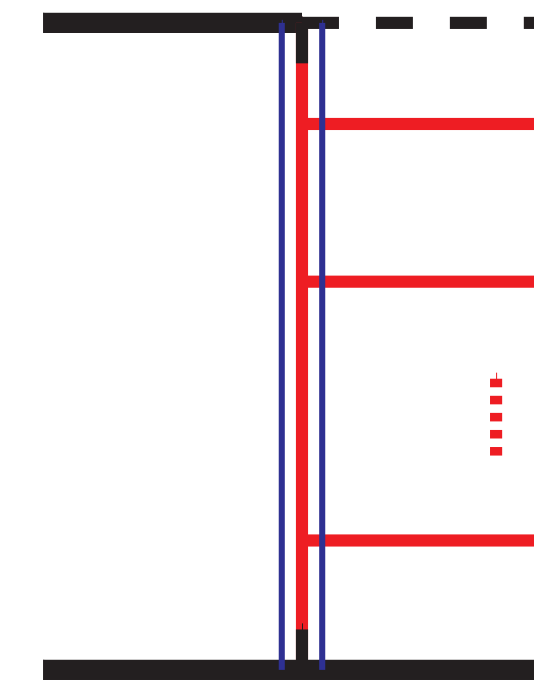
Black = Born/skeleton function

Red = Range of resummation

Previous 2jet



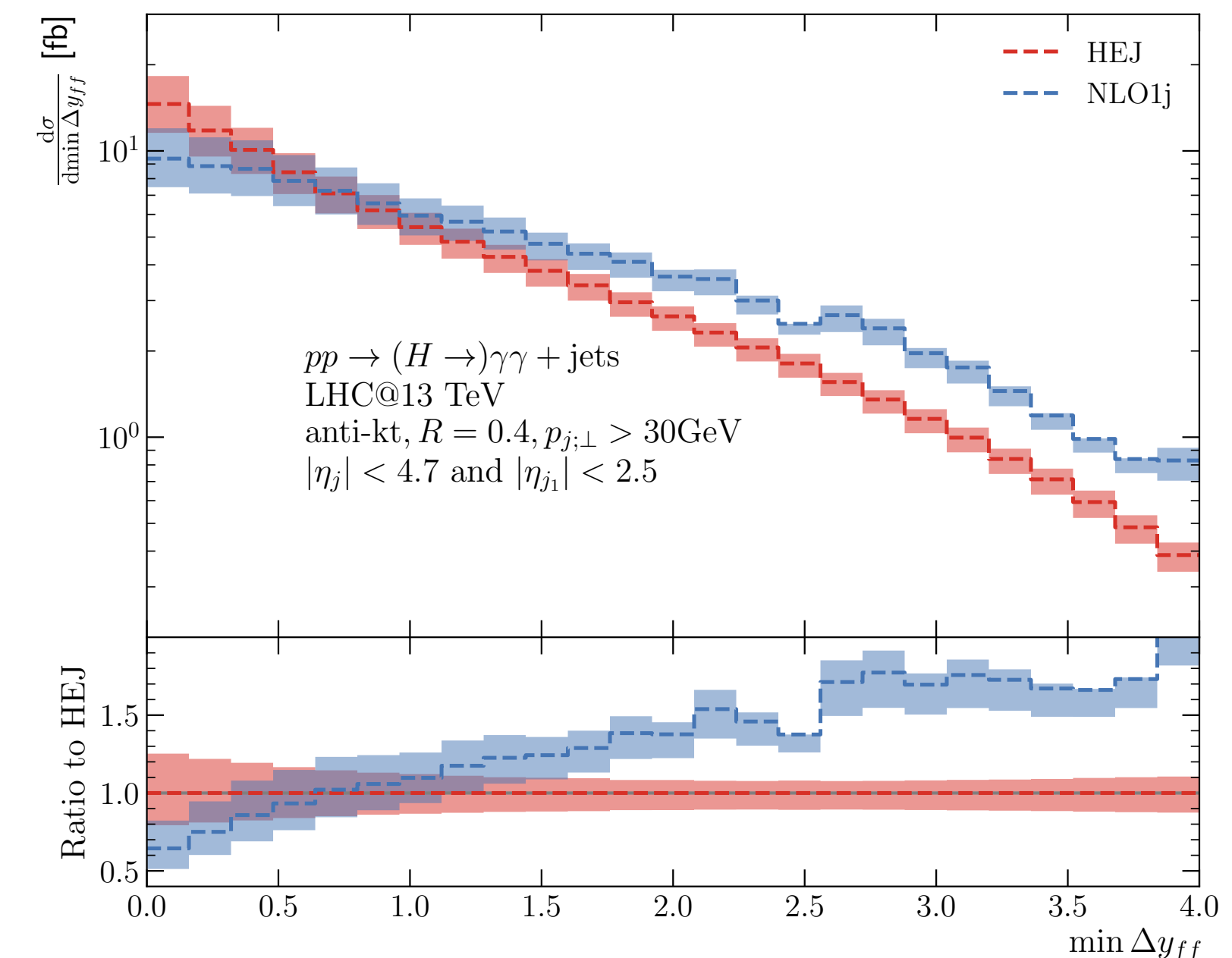
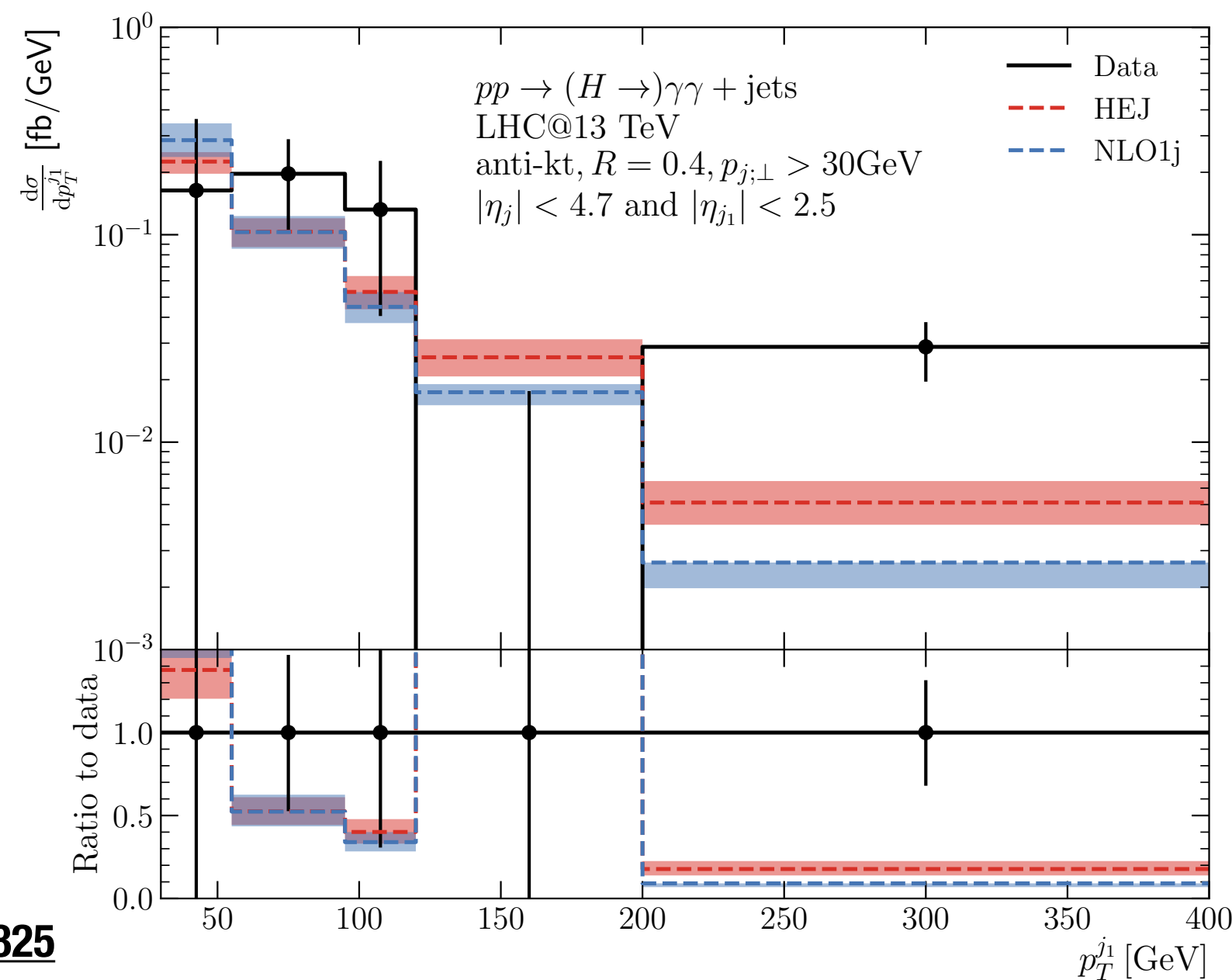
New 1jet



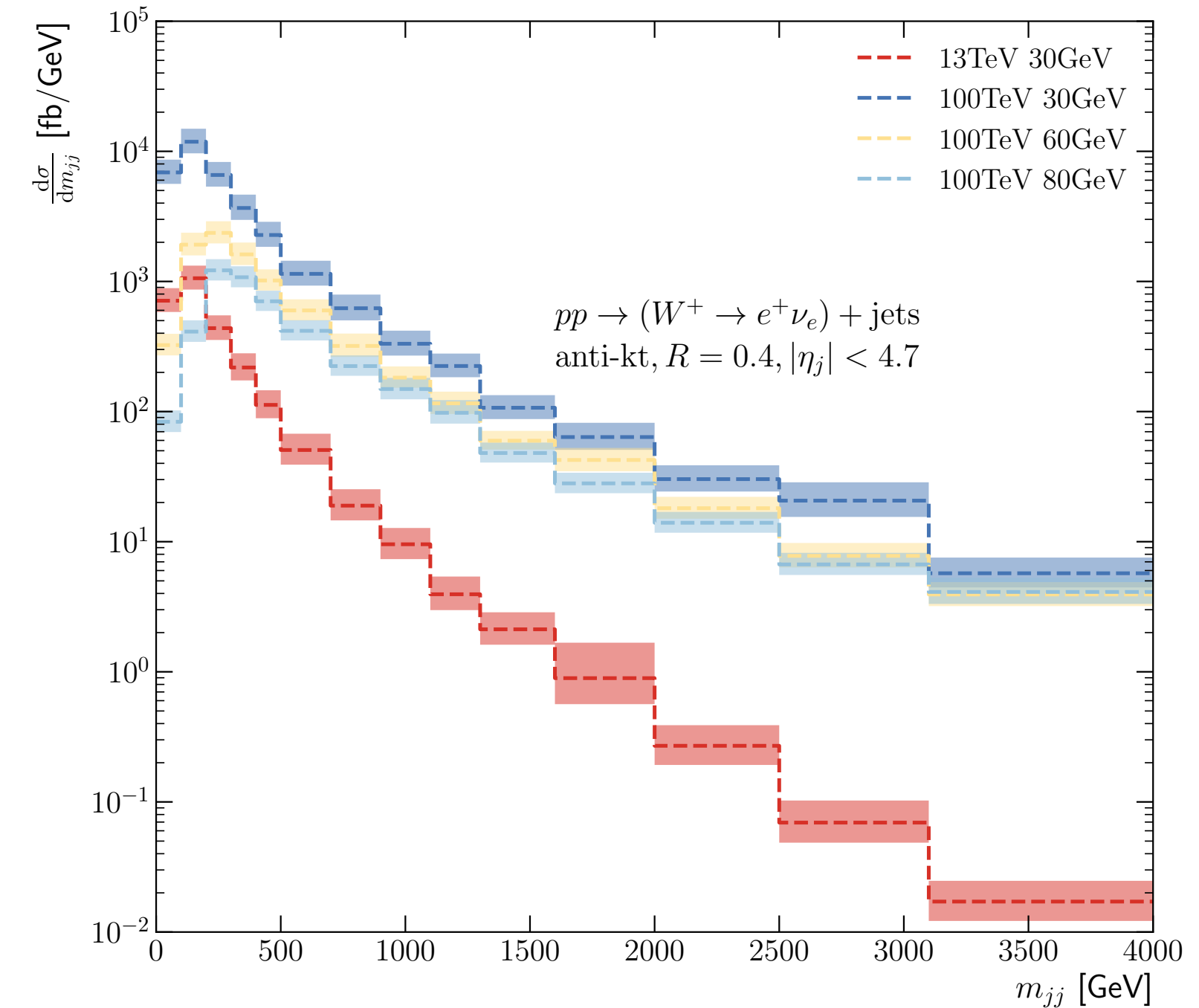
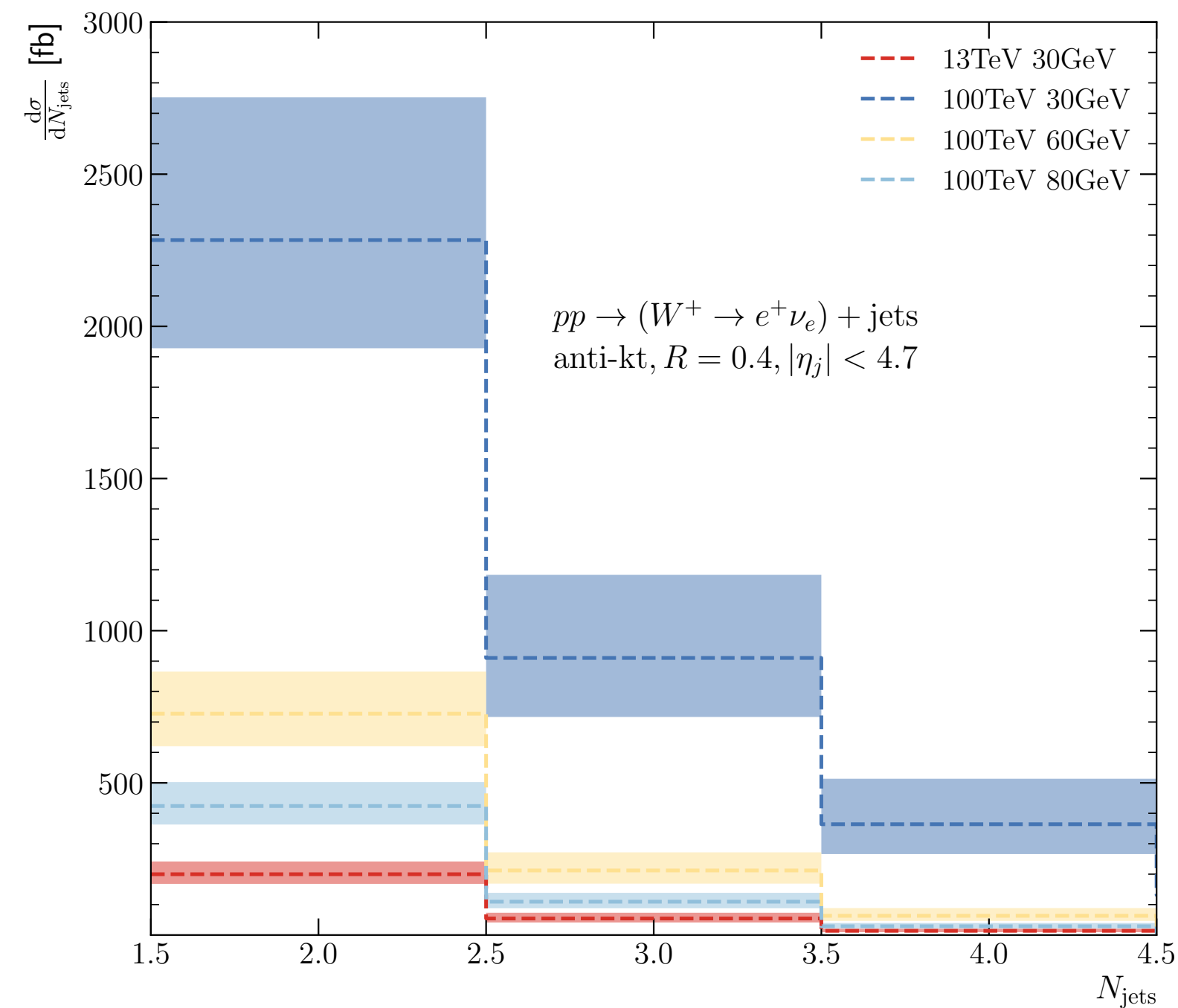
Similar effects on distributions

Andersen, Hassan, Maier, Paltrinieri, Papaefstathiou, JMS [arXiv:2210.10671](https://arxiv.org/abs/2210.10671)

Data includes "HX" not in HEJ or NLO



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

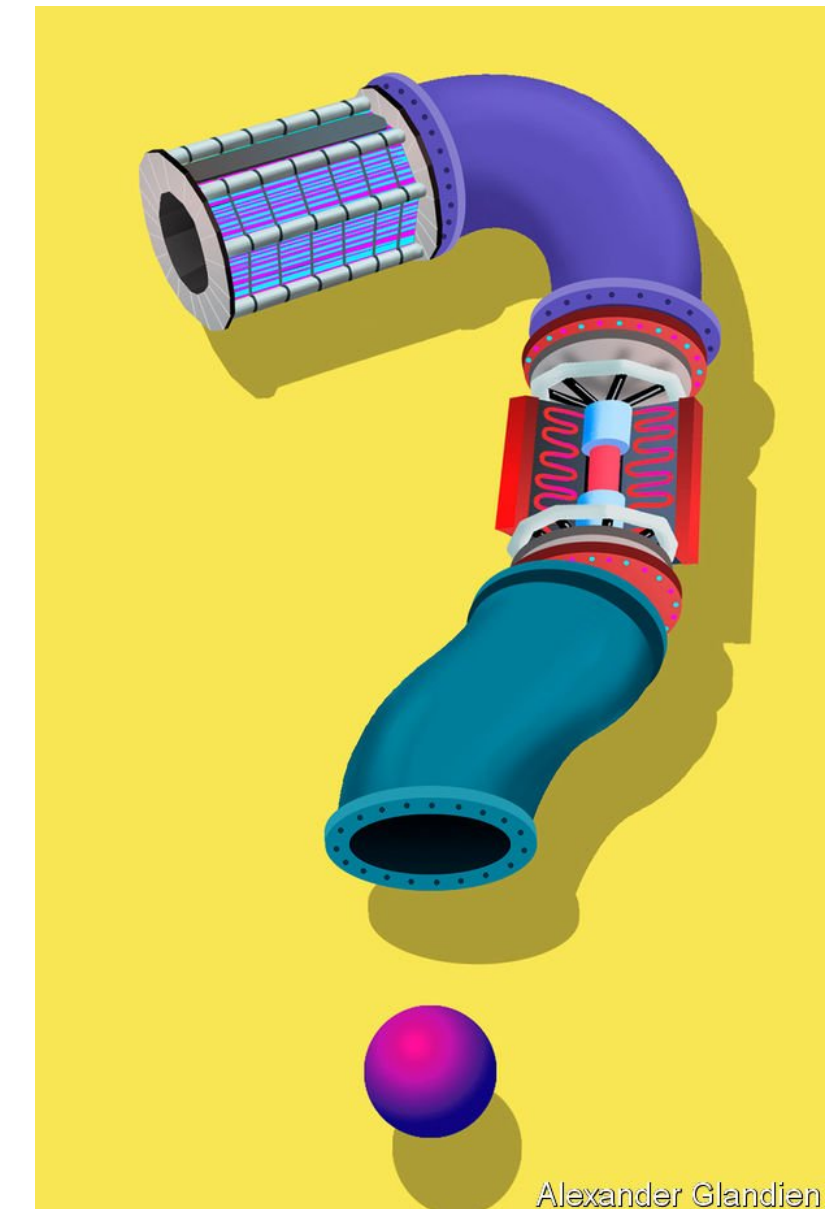


Higher pT cuts can control the jet rates, but impact of logs on distributions will be large



# Summary & Outlook

- Current and future data demand higher precision predictions
- 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>