Framing energetic top-quark pair production at the LHC

Michigan State University High Energy Physics Seminar, 23 March 2021

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University of Oxford

with Fabrizio Caola, Frederic Dreyer and Ross McDonald, arXiv:2101.06068

UNIVERSITY OF OXFORD

THE ROYAL SOCIETY

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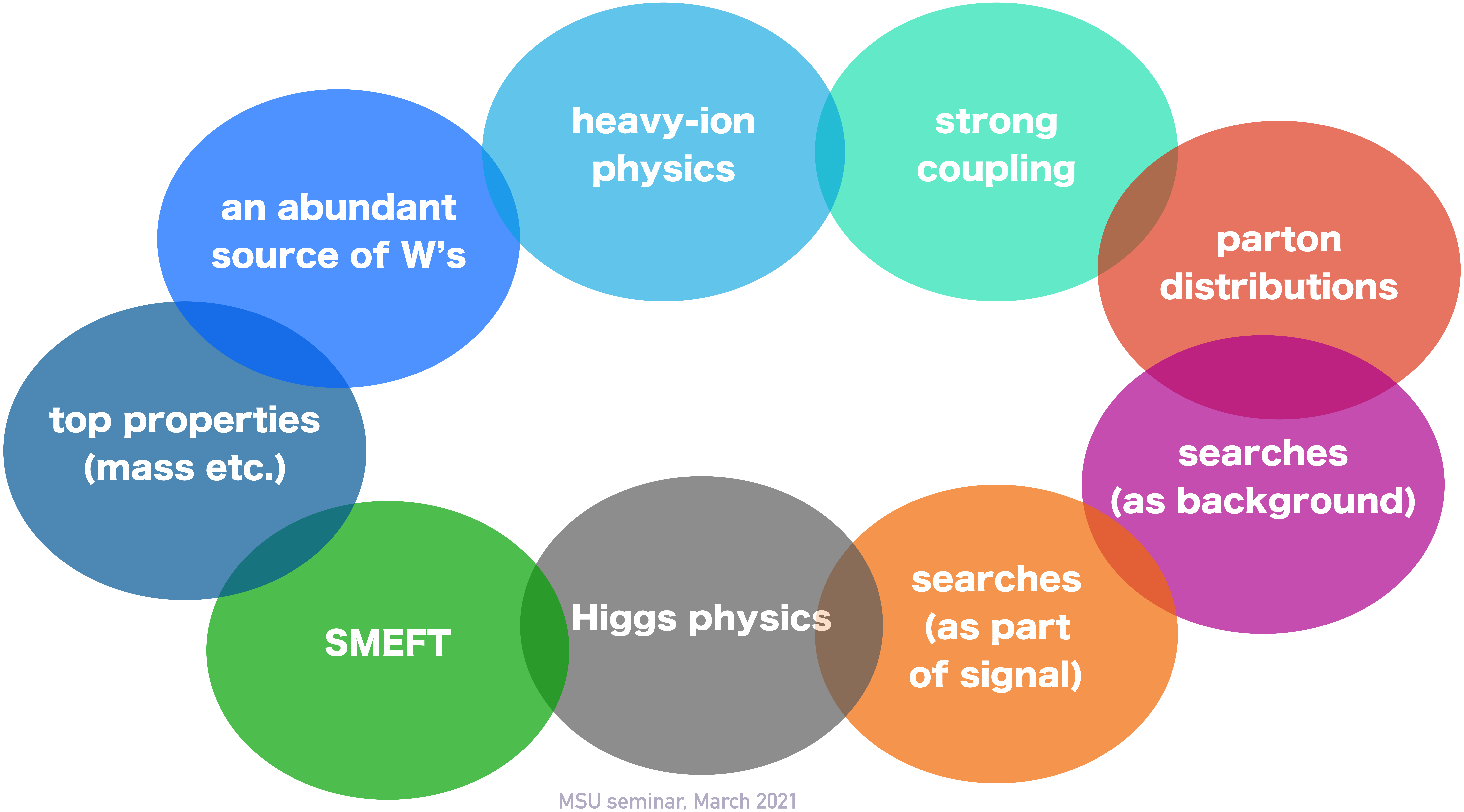
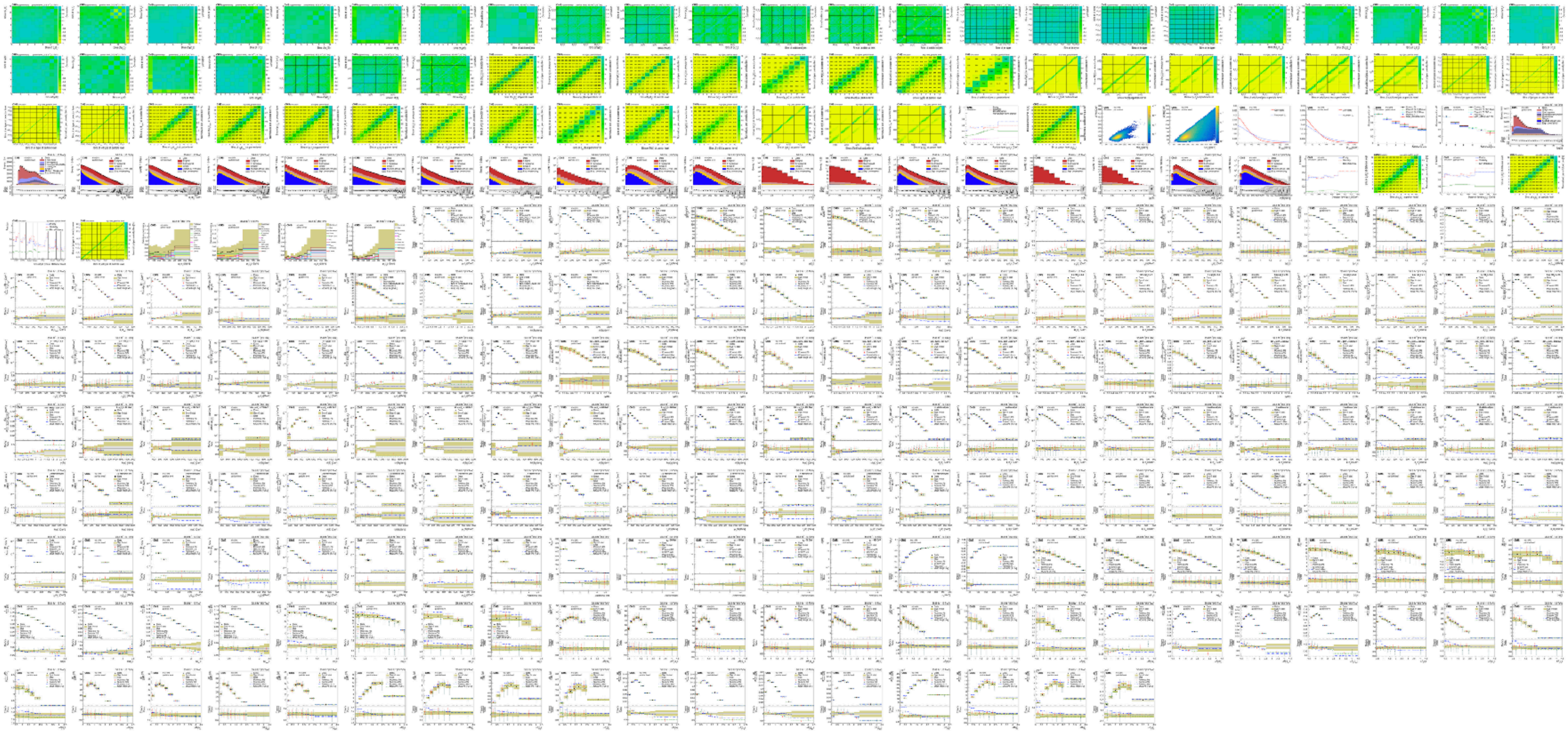
Tops: huge range of physics topics

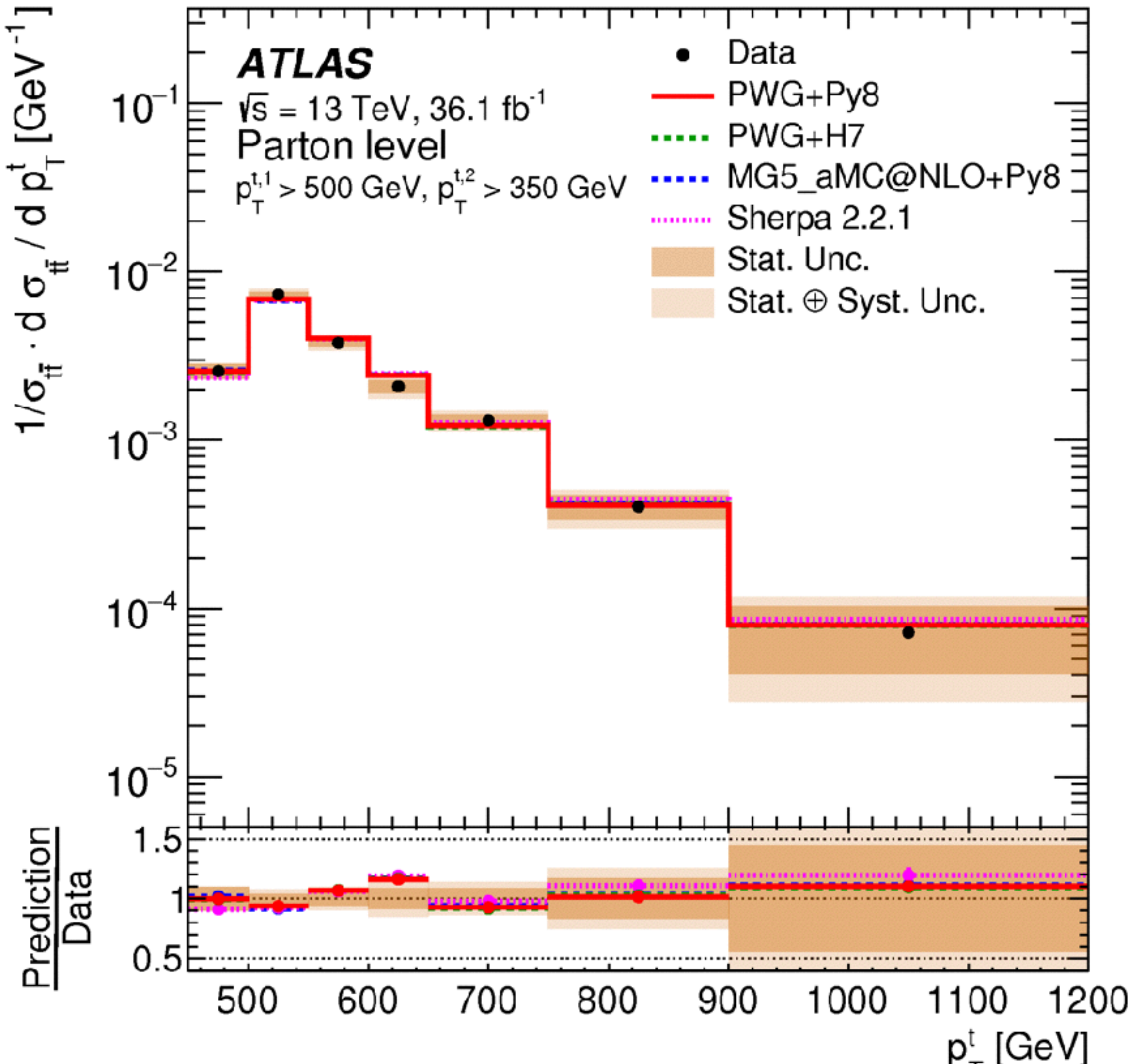


A rich environment: CMS 1803.08856 ($t\bar{t} \to \ell$+jets) has 270 plots!

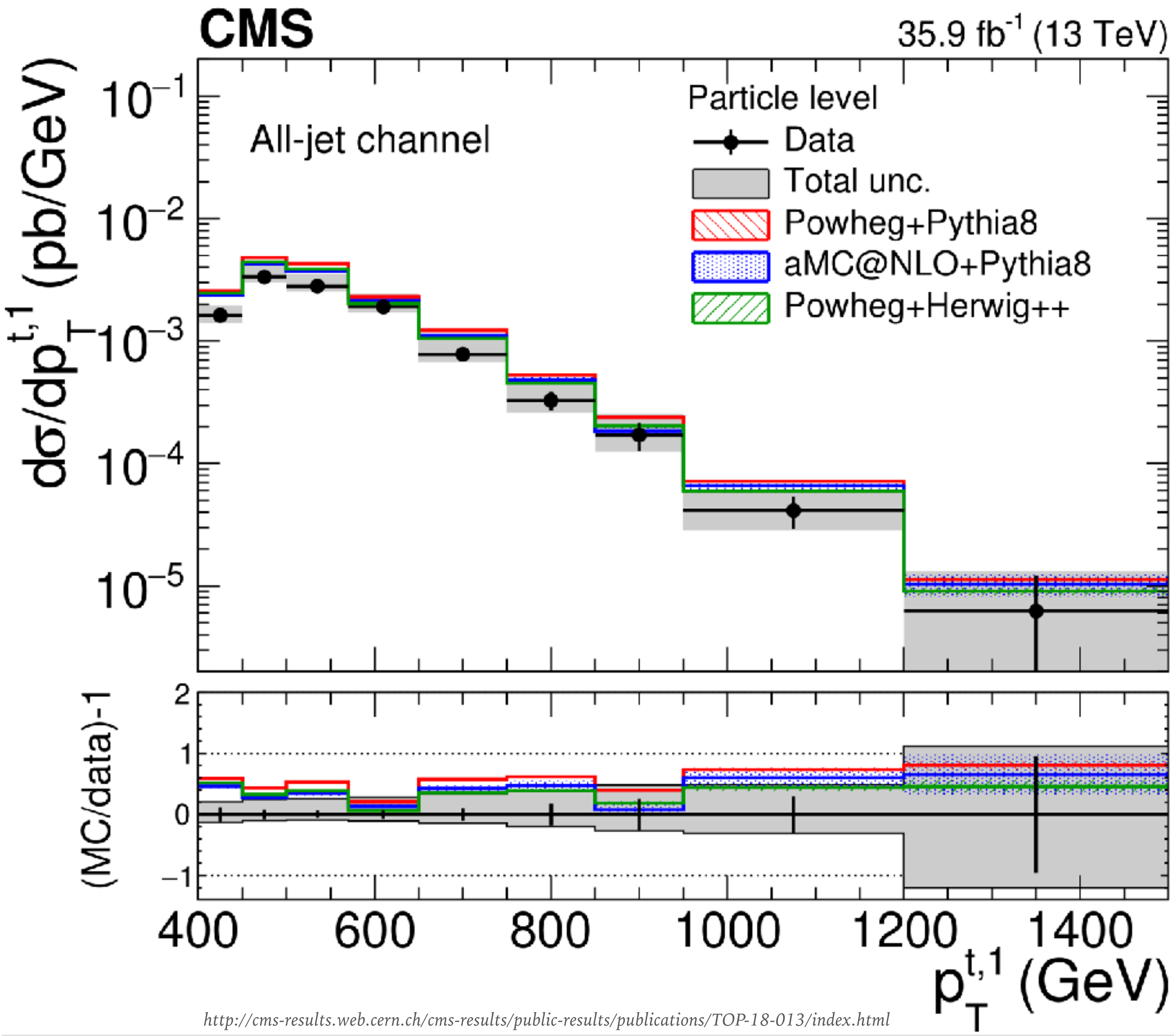


A rich environment: ATLAS 1908.07305 ($t\bar{t} \to \ell$+jets) has 368 plots!

LHC is probing large transverse momenta: 15% stat. precision at 800–900 GeV

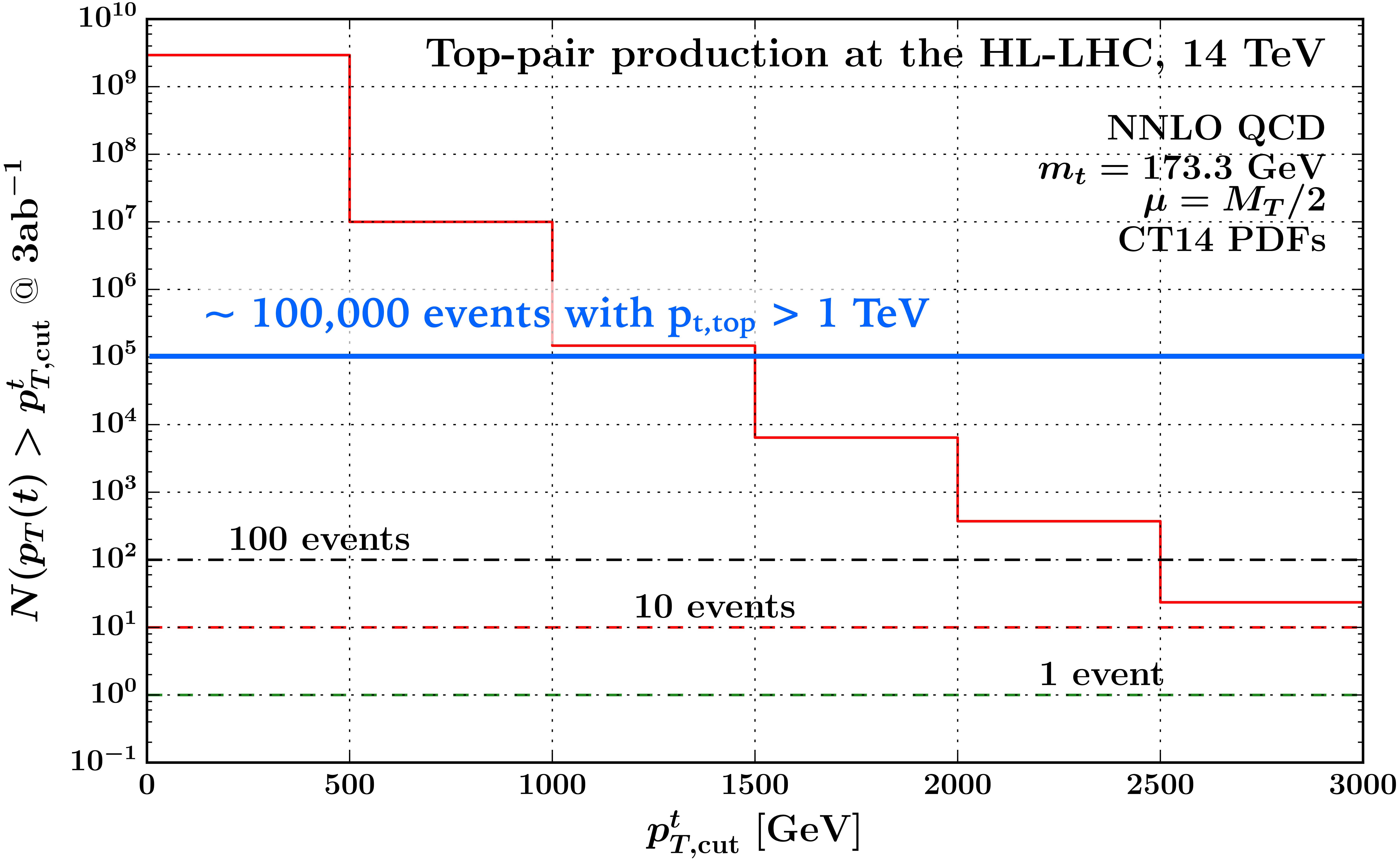


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2016-09/



http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP-18-013/index.html

Much more to come at HL-LHC



SM @ HL-LHC & HE-LHC
1902.04070

This talk

1. Remind ourselves of what energetic top-pair production looks like at leading order (many results are trivial, but useful to keep in mind)
2. Examine what changes at NLO
3. Implications for LHC cross sections
4. Where is this knowledge useful?
5. Outlook

Overall aim

provide a scaffolding for thinking about energetic top-pair production

1. Basics @ LO

What do we mean by “energetic”? Many variables can be used to measure event hardness

Hardness variable	explanation
$p_T^{\text{top,had}}$	transverse momentum of hadronic top candidate
$p_T^{\text{top,lep}}$	transverse momentum of leptonic top candidate
$p_T^{\text{top,max}}$	p_T of the top (anti-)quark with larger $m_T^2 = p_T^2 + m^2$
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$p_T^{\text{top,avg}}$	$\frac{1}{2}(p_T^{\text{top,had}} + p_T^{\text{top,lep}})$
$\frac{1}{2}H_T^{t\bar{t}}$	with $H_T^{t\bar{t}} = m_T^{\text{top,had}} + m_T^{\text{top,lep}}$
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$m_T^{J,\text{avg}}$	average m_T of the two highest m_T large-R jets (J_1, J_2)
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LO distributions @ large p_T

Limit of $p_T^{\text{top}} \gg m_{\text{top}}$

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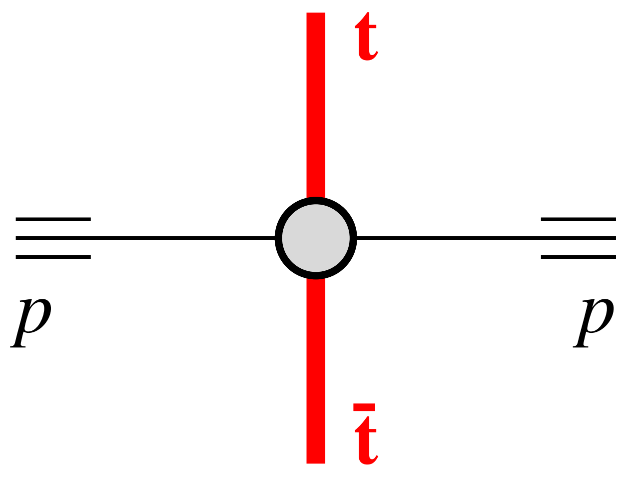
identical @ LO



$$\frac{d\sigma}{dp_{T,t}^2} = \frac{\alpha_s^2 \pi}{4p_{T,t}^4}\left[c_{gg}\mathcal{L}_{gg}(4p_{T,t}^2/s) + c_{q\bar{q}}\mathcal{L}_{q\bar{q}}(4p_{T,t}^2/s)\right]$$

LO, high-p_T cross section

$c_{gg} \simeq c_{q\bar{q}} \simeq 0.1$ at $p_{T,t} \sim 1$ TeV: coefficients that depend weakly on the slope of the PDFs

$\mathscr{L}_{gg}$ and $\mathscr{L}_{q\bar{q}}$: partonic luminosities, comparable for $p_{T,t} \sim 1$ TeV

LO distributions @ large p_T

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$m_T^{J,\text{avg}}$	average m_T of the two highest m_T large-R jets (J_1, J_2)

identical @ LO & high p_T

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unlike all others @LO

LO distributions @ large $m_{t\bar{t}}$

Limit of $m_{t\bar{t}} \gg m_{\text{top}}$

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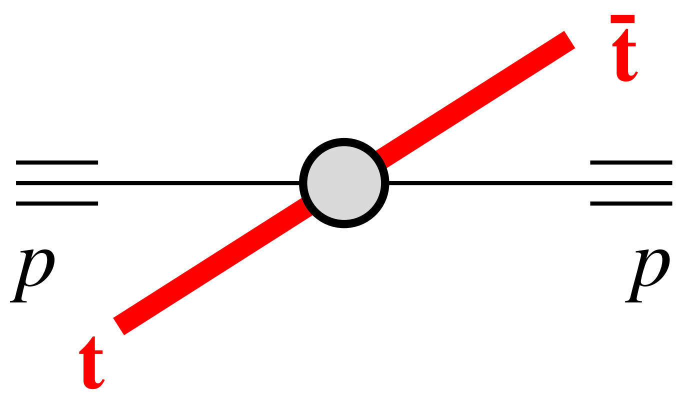
$\frac{1}{2}m^{t\bar{t}}$	half invariant mass of $p^{t\bar{t}} = p^{\text{top,had}} + p^{\text{top,lep}}$

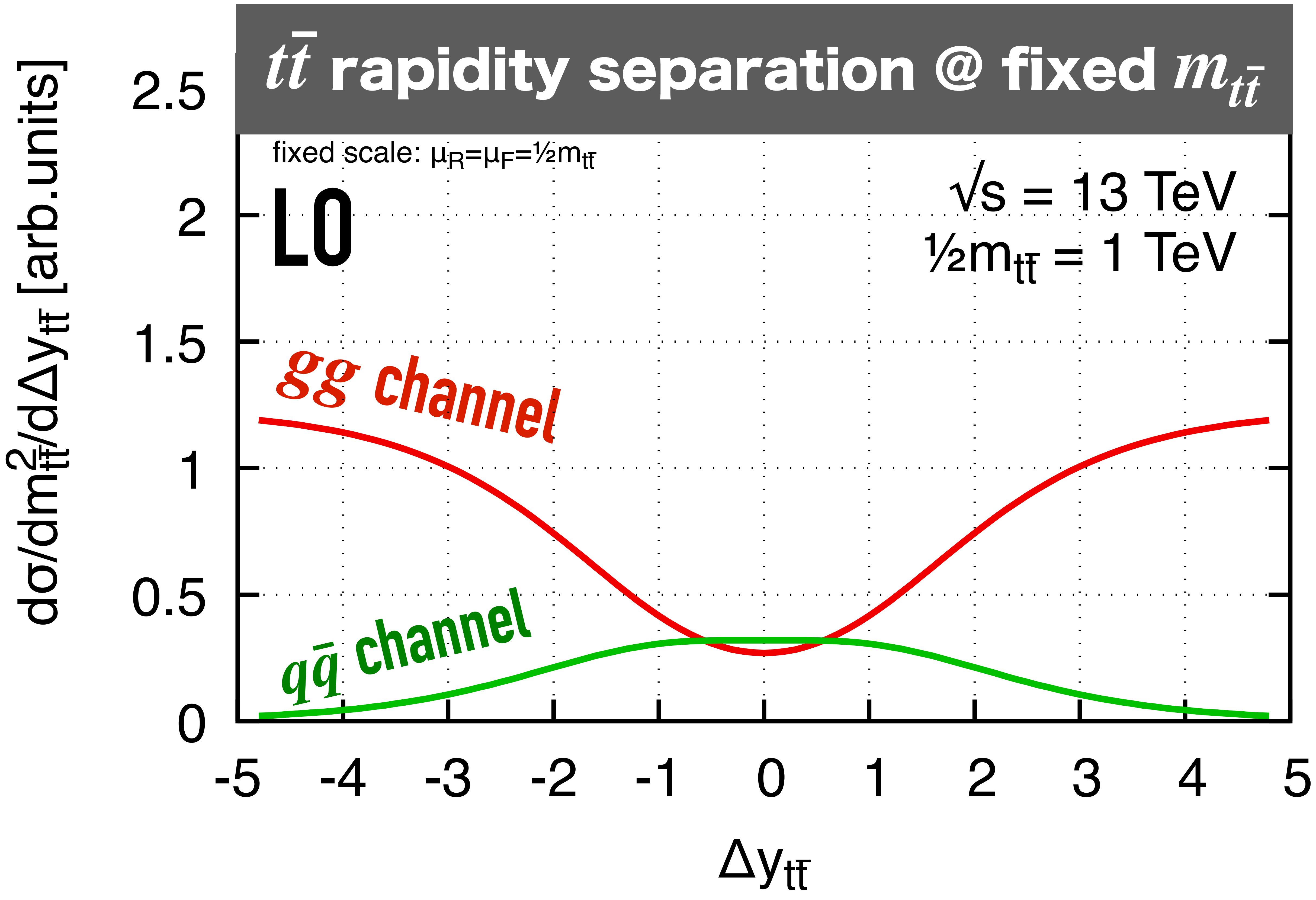


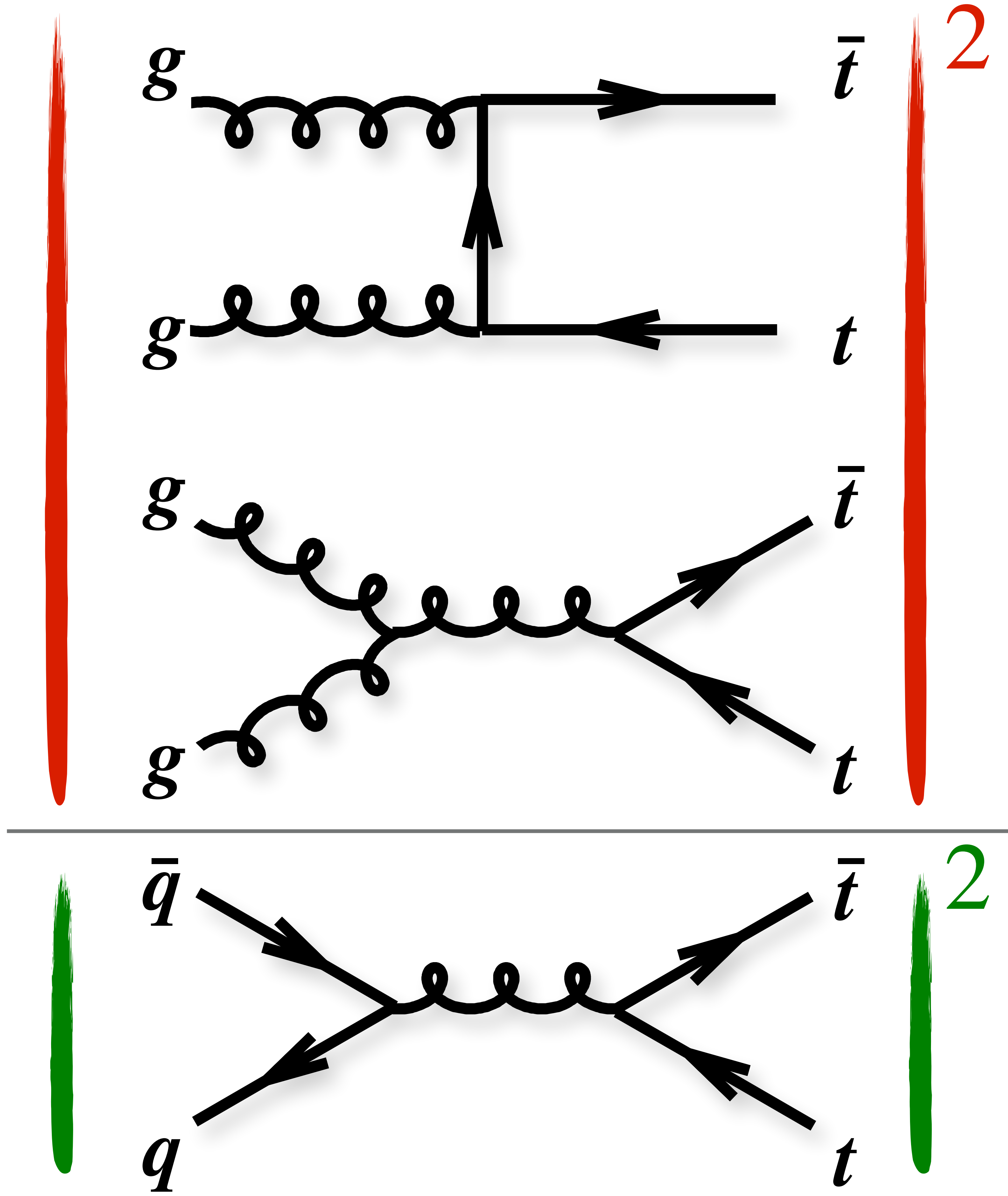
$$\frac{d\sigma}{dm^2_{t\bar{t}}} = \frac{\alpha_s^2 \pi}{m^4_{t\bar{t}}} \left[\left(\frac{1}{3} \ln \frac{m^2_{t\bar{t}}}{m^2_{\text{top}}} - \frac{7}{12} \right) \mathcal{L}_{gg}(m^2_{t\bar{t}}/s) + \frac{8}{27} \mathcal{L}_{q\bar{q}}(m^2_{t\bar{t}}/s) \right]$$

log-enhanced

unlike all others @LO

$\log(m_{tt}/m_t)$ in glue-glue channel comes from enhancement at large rapidity separations





Limit of $m_{t\bar{t}} \gg m_{top}$

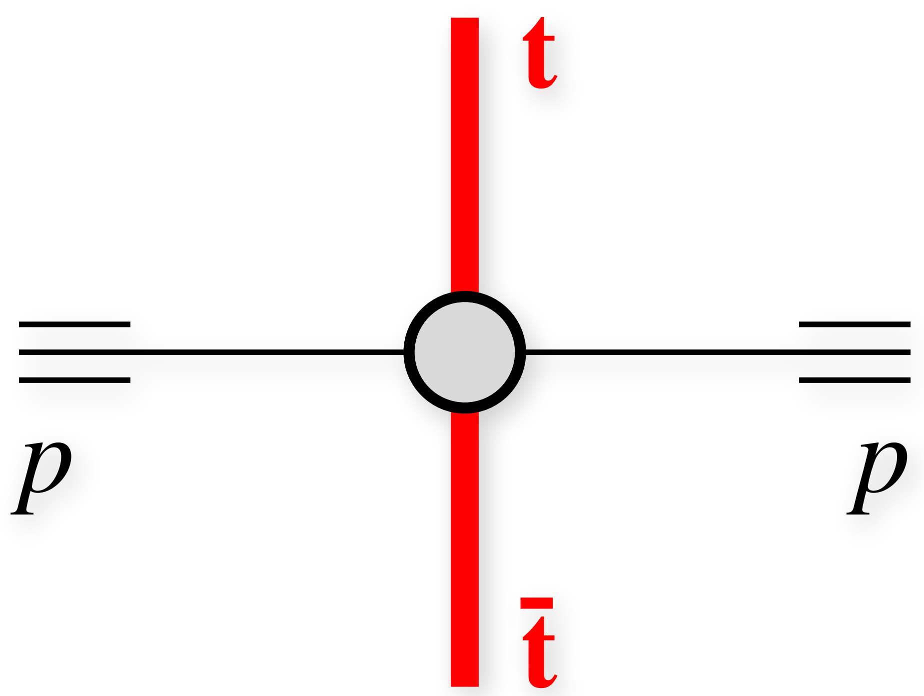
$$= \frac{1}{6}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}} - \frac{3}{8}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$$

$$= \frac{4}{9}\frac{\hat{t}^2}{\hat{s}^2+\hat{u}^2}$$

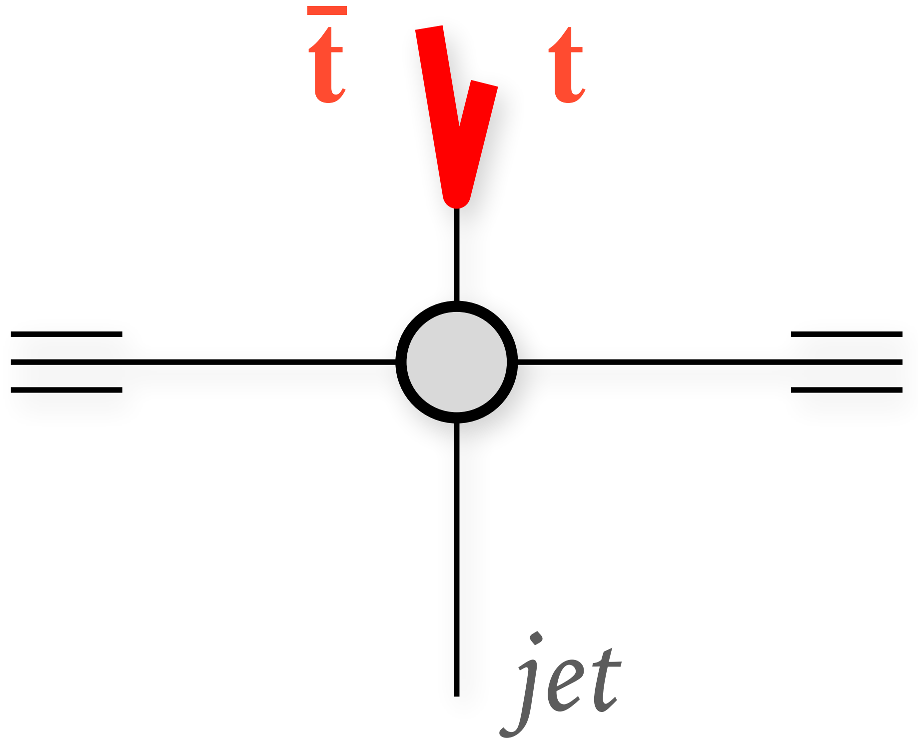
For $\hat{s}, \hat{u} \gg \hat{t}$ (i.e. large $\Delta y_{t\bar{t}}$), gg→$t\bar{t}$ t-channel top-quark exchange flat because of $1/\hat{t}$.

Distribution extends out to the kinematic limit $\Delta y_{t\bar{t}}^{\max} \simeq 2\ln m_{t\bar{t}}/m_{top}$

$t\bar{t}$ or jet transverse momentum



At α_s^2, p_T of the $t\bar{t}$ system is zero and there are no jets



At α_s^3, p_T of the $t\bar{t}$ system = p_T of the jet

$p_T^{t\bar{t}}$	transverse component of $p^{t\bar{t}}$
$p_T^{j_{\not t},1}$	transverse momentum of the leading small-R non-top jet

start only from α_s^3 [NLO]

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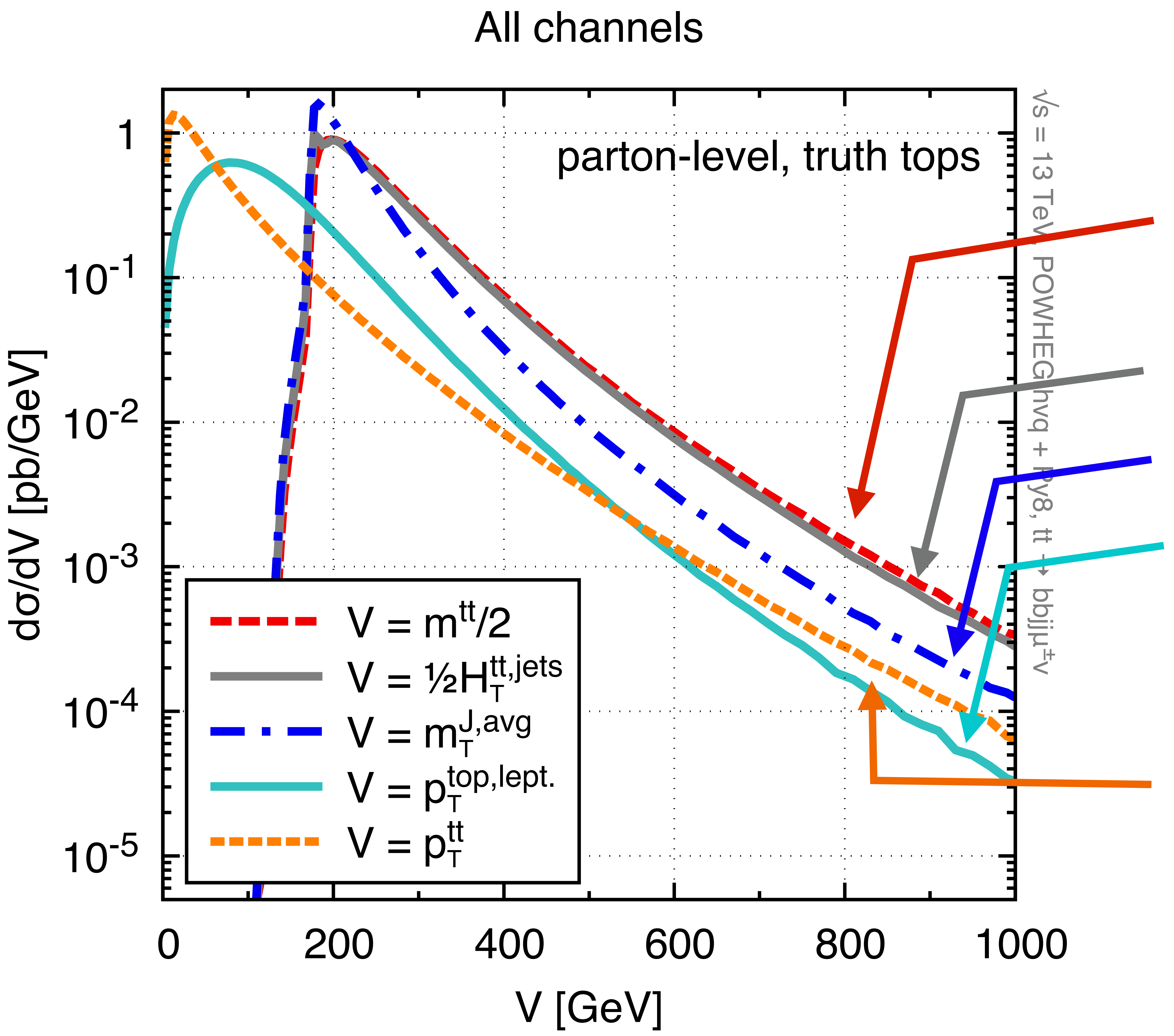
identical @ LO & high p_T

unlike all others @LO

start only from α_s^3 [NLO]

Compare LO expectations to POWHEG+Pythia8 NLO results



LO expectation

$\frac{1}{2}m^{t\bar{t}}$ should be enhanced by $\ln m^{t\bar{t}}/m_{\text{top}}$

$\frac{1}{2}H_T^{t\bar{t},\text{jets}}$, $m_T^{J,\text{avg}}$, $p_T^{\text{top,lept.}}$ should all be similar & smaller

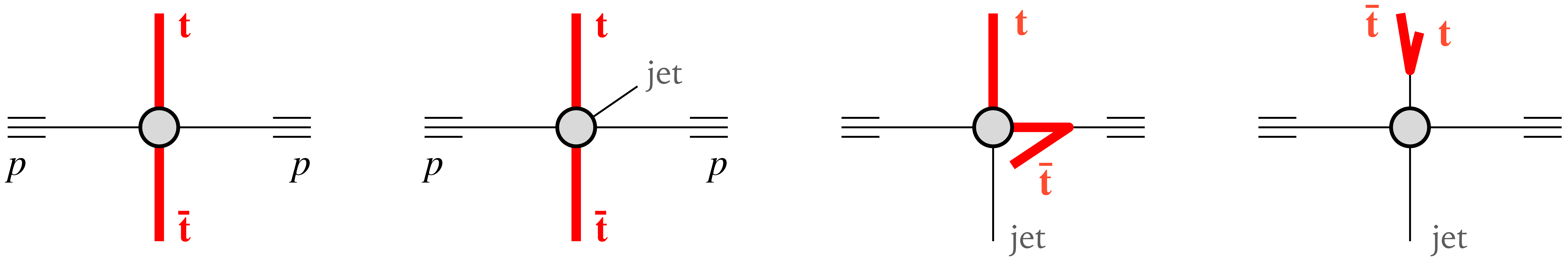
$p_T^{t\bar{t}} \simeq p_T^{j_{\ell,1}}$ should be suppressed

That is not what you see "out of the box"

2. Beyond LO

Topologies at LO and NLO

flavour creation | **flavour creation + jet** | **flavour excitation** | **gluon splitting**

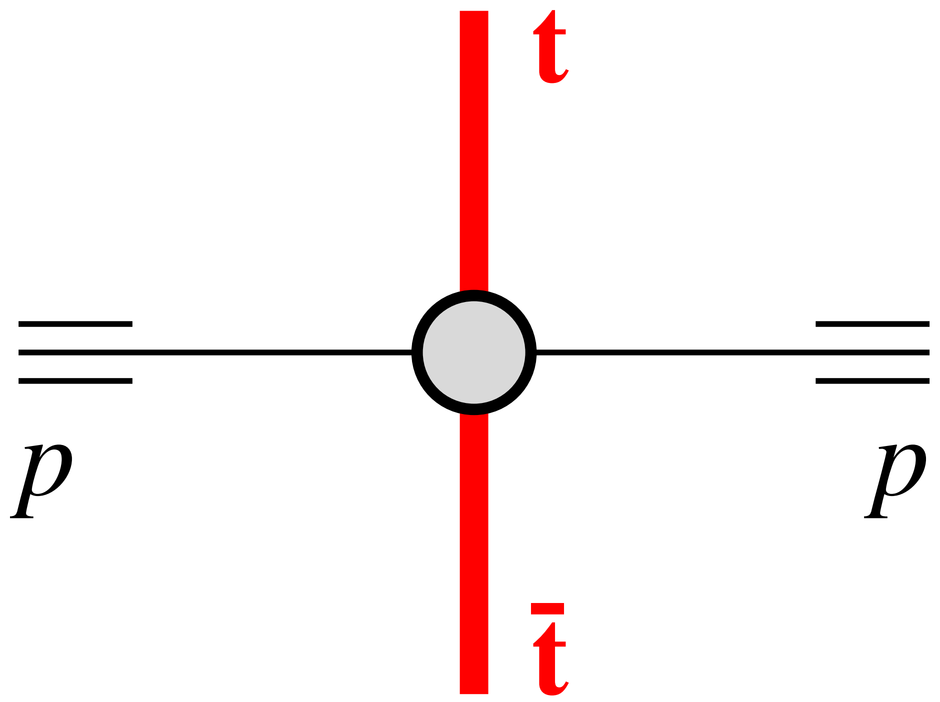


LO (α_s^2) | NLO (α_s^3) | NLO (α_s^3) | NLO (α_s^3)

$\alpha_s(1\,\text{TeV}) \simeq 0.09$ — so expect NLO topologies to be 10% correction
(but we know that QCD@LHC is never that simple…)

Consider $p_T = 1$ TeV, 90º scattering ($\hat{t} = \hat{u} = -\hat{s}/2$)

flavour creation



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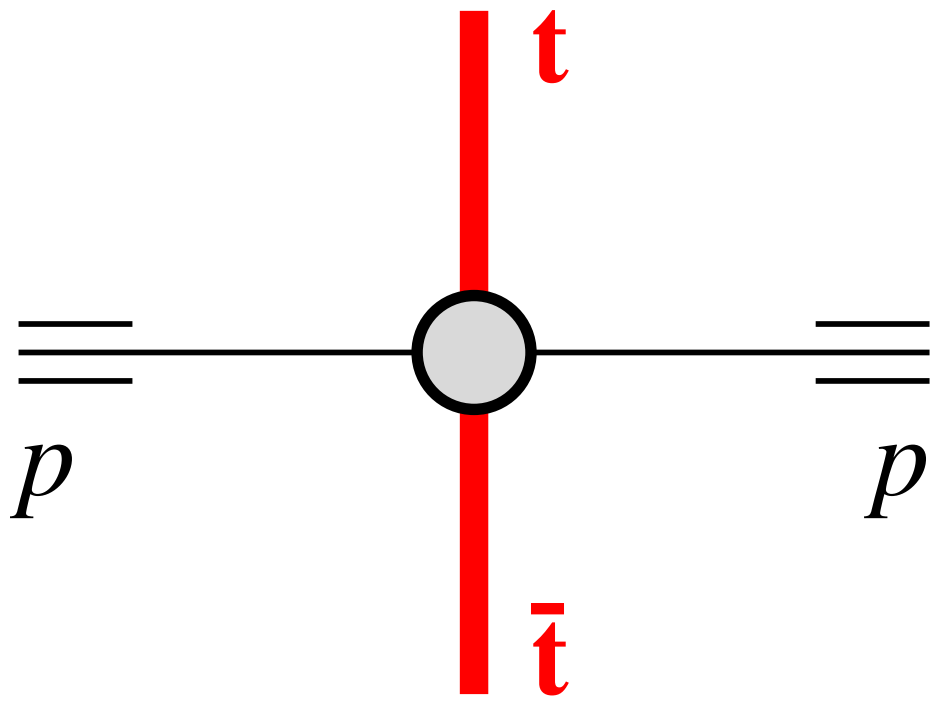

$$\sum_i \mathscr{L}_{q_i\bar{q}_i} \simeq 0.13$$

$$\times |\mathscr{M}_{q\bar{q}\to t\bar{t}}|^2 = g_s^4 \frac{C_F}{N_C} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2} = g_s^4 \frac{C_F}{N_C} \cdot \frac{1}{2}$$

$$\simeq g_s^4 \cdot 0.028$$

Consider $p_T = 1$ TeV, 90° scattering ($\hat{t} = \hat{u} = -\hat{s}/2$)

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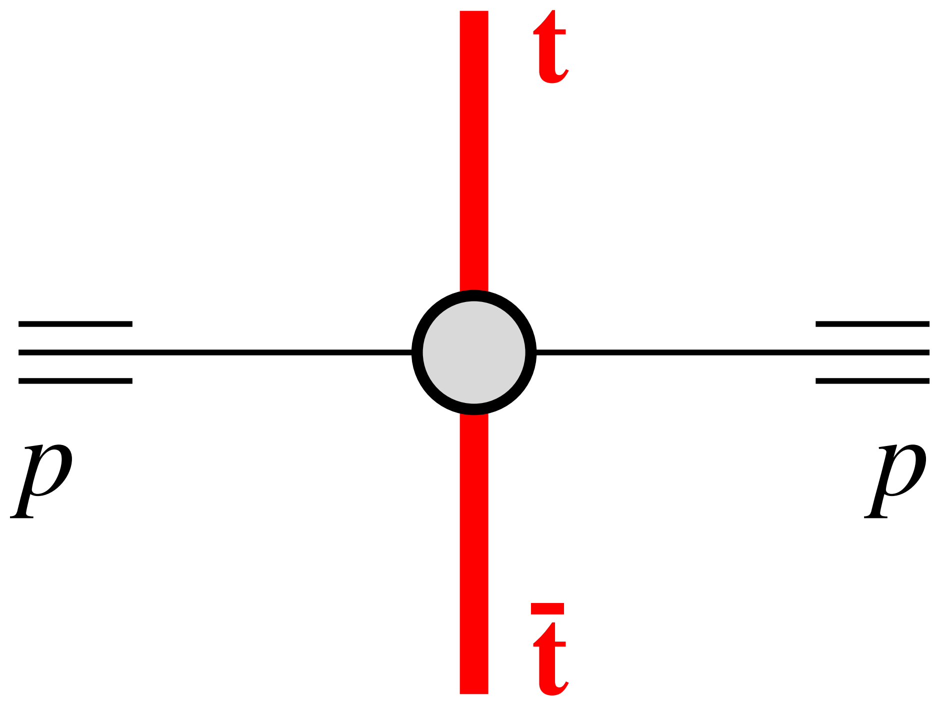
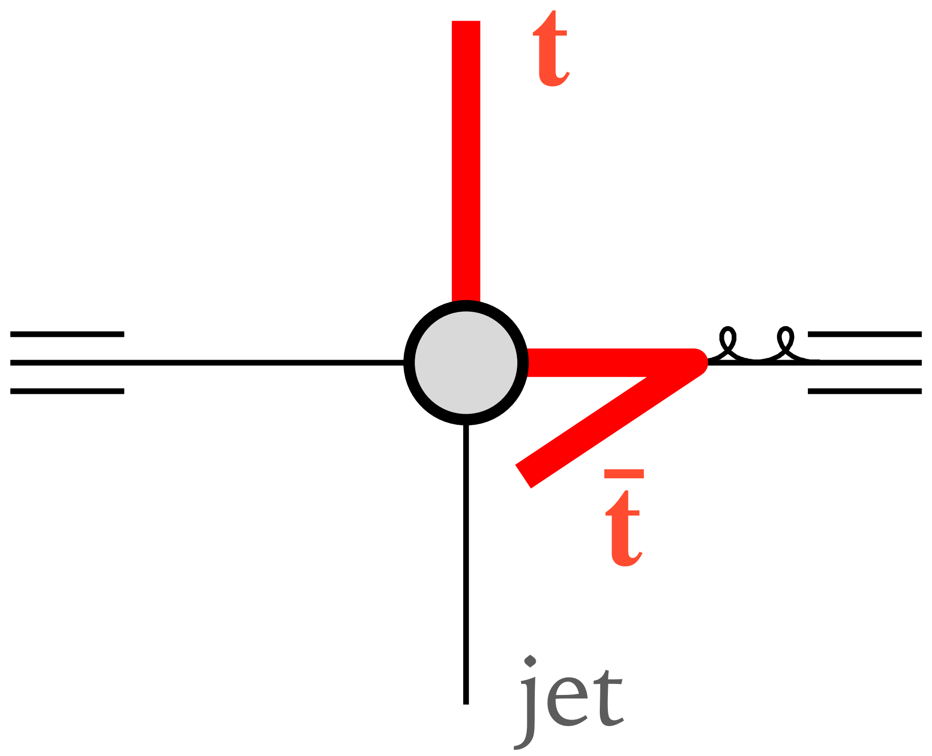


flavour excitation



Use a 6-flavour PDF scheme to estimate quark-top parton luminosity

(includes a power of α_s)

$$\sum_i \mathscr{L}_{q_i\bar{q}_i} \simeq 0.13$$

$$\times |\mathscr{M}_{q\bar{q}\to t\bar{t}}|^2 = g_s^4 \frac{C_F}{N_C} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2} = g_s^4 \frac{C_F}{N_C} \cdot \frac{1}{2}$$

$$\simeq g_s^4 \cdot 0.028$$

$$\mathscr{L}_{\Sigma t} + \mathscr{L}_{\Sigma\bar{t}} \simeq 0.0170 \quad \left[\Sigma \equiv \sum_i (q_i + \bar{q}_i)\right]$$

$$\times |\mathscr{M}_{qt\to qt}|^2 = g_s^4 \frac{C_F}{N_C} \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} = g_s^4 \frac{C_F}{N_C} \cdot 5$$

$$\simeq g_s^4 \cdot 0.038$$

Consider $p_T = 1$ TeV, 90° scattering ($\hat{t} = \hat{u} = -\hat{s}/2$)

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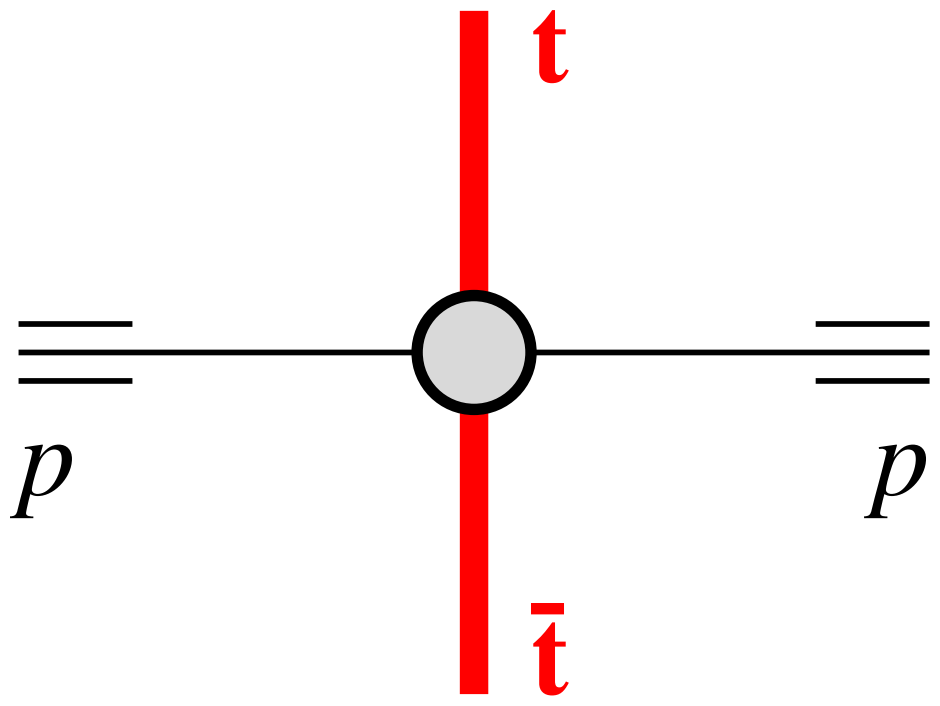

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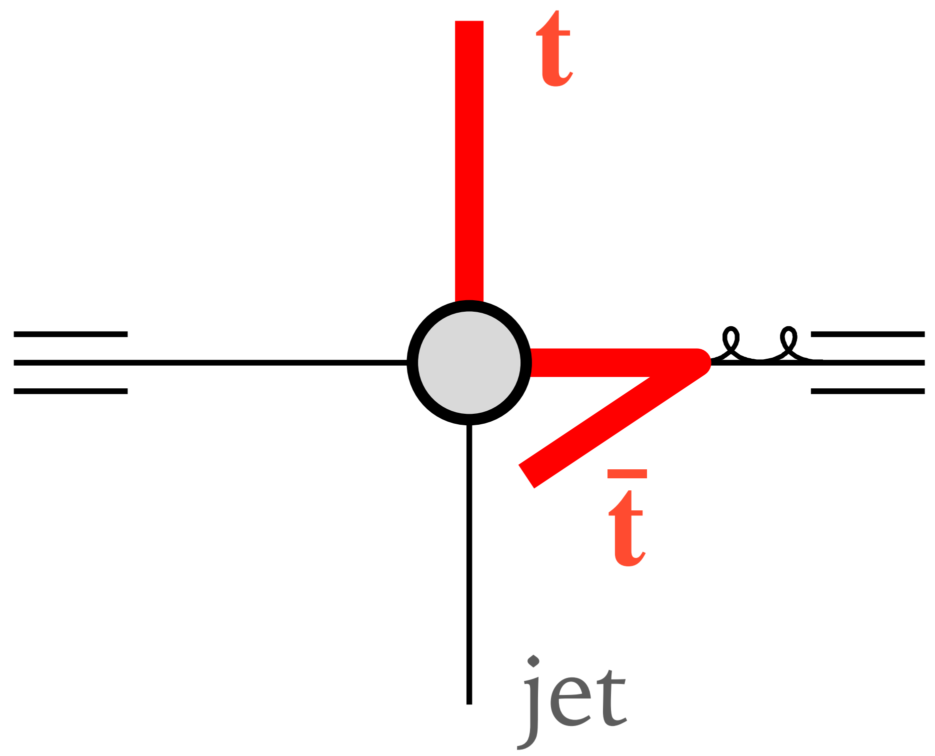

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$$\simeq g_s^4 \cdot 0.028$$

same order of magnitude

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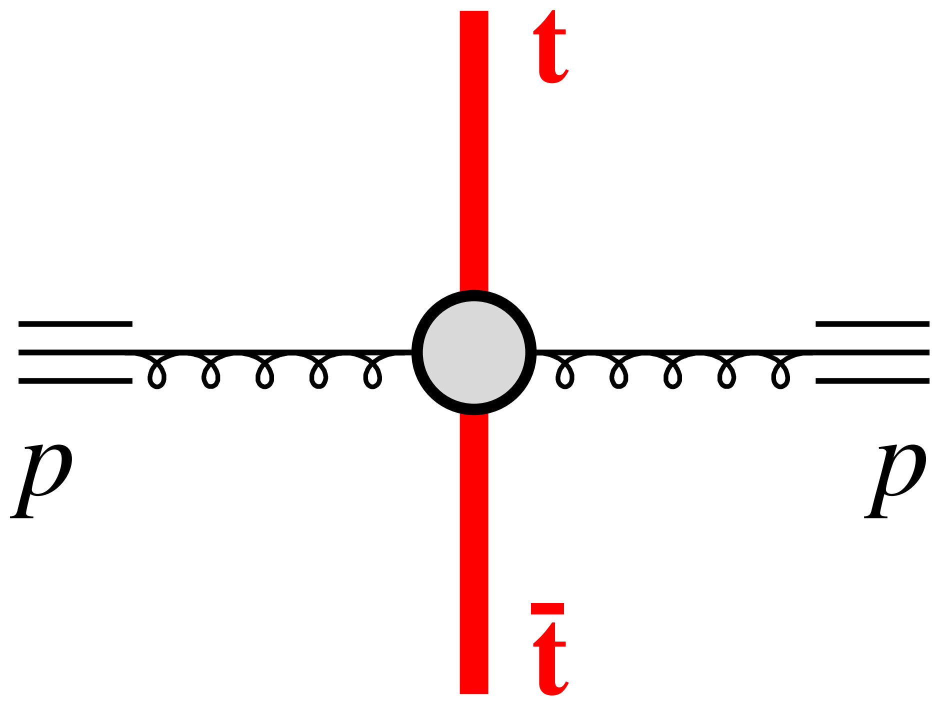

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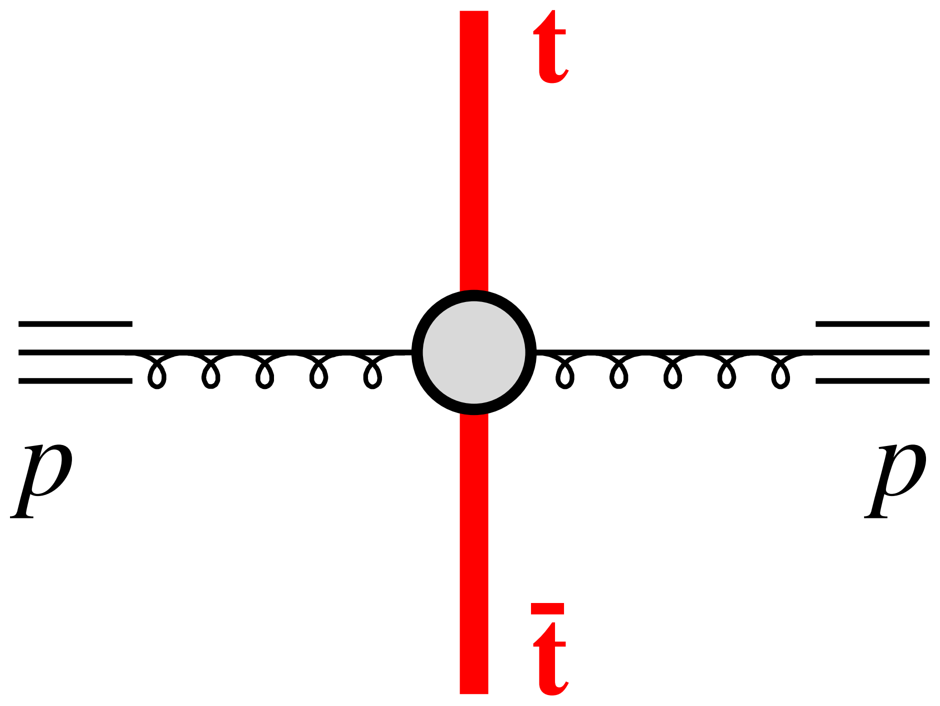

$\mathscr{L}_{gg} \simeq 0.16$

$\times |\mathscr{M}_{gg\to t\bar{t}}|^2 = g_s^4 \cdot \mathbf{0.15}$

$\simeq g_s^4 \cdot 0.024$

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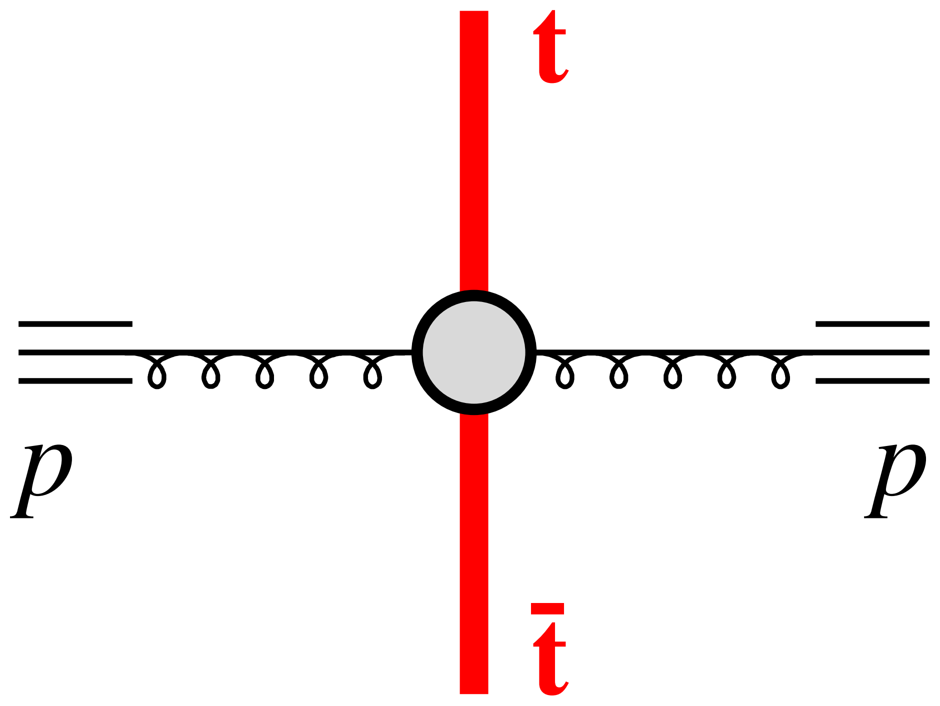
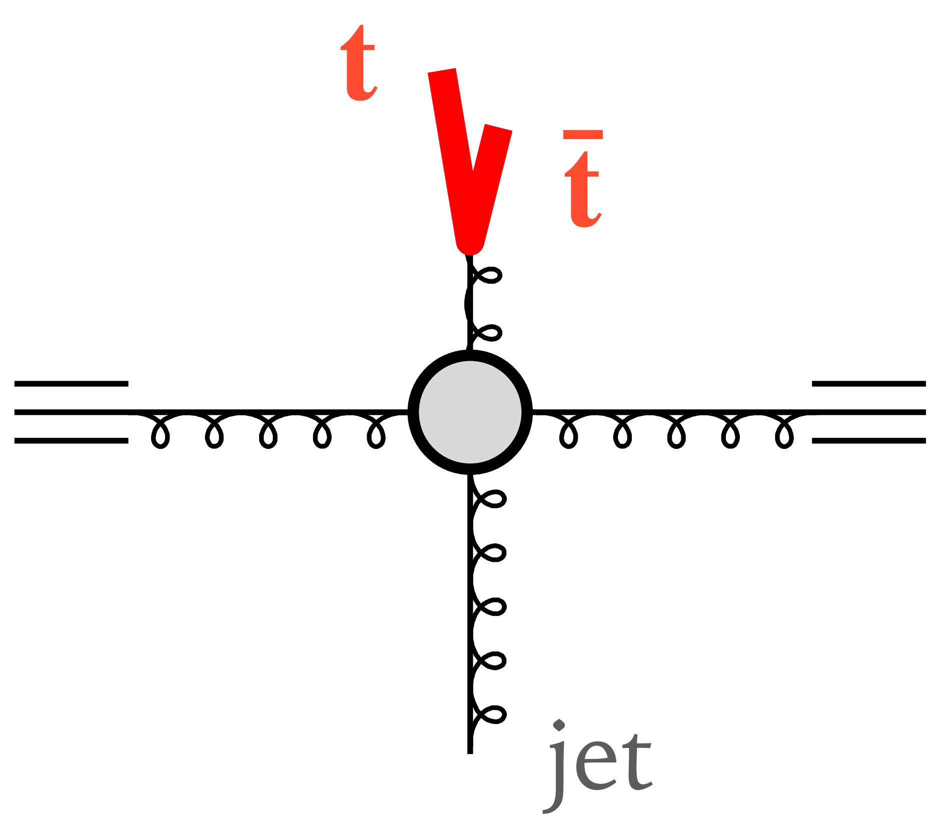


Use massive $g \to Q\bar{Q}$ splitting function to estimate $t\bar{t}$ content of a gluon jet (R=1)

(includes a power of α_s)

gluon splitting



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$\mathcal{L}_{gg} \simeq 0.16$

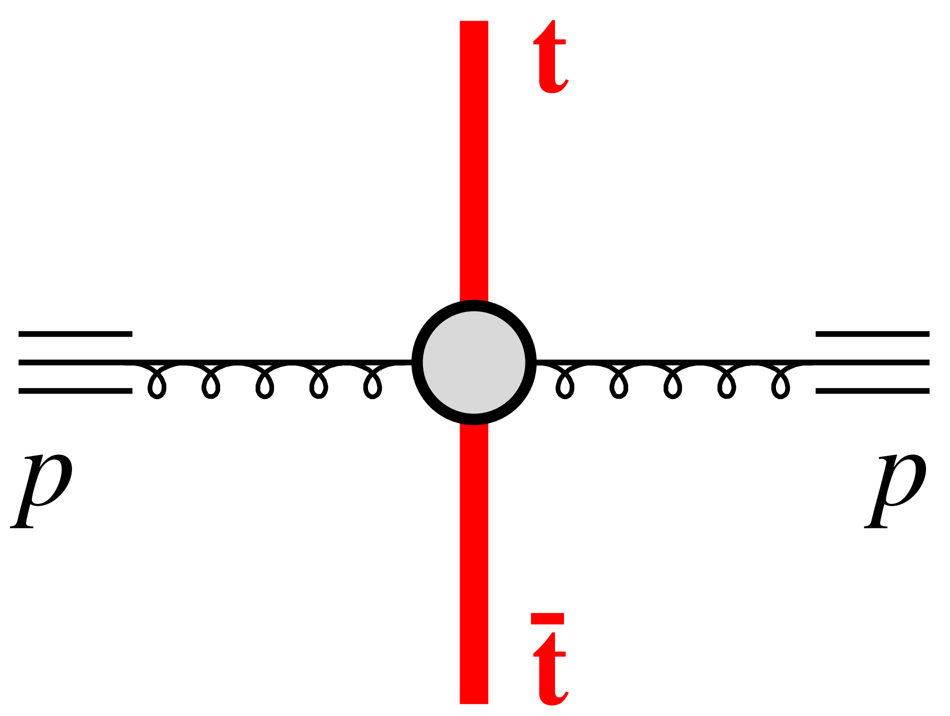
$\times |\mathcal{M}_{gg\to gg}|^2 = g_s^4 \cdot \mathbf{30.4}$

$\times \mathcal{P}_{g\to t\bar{t}} \simeq \mathbf{0.004}$

$\simeq g_s^4 \cdot 0.020$

Consider $p_T = 1$ TeV, 90° scattering ($\hat{t} = \hat{u} = -\hat{s}/2$)

flavour creation



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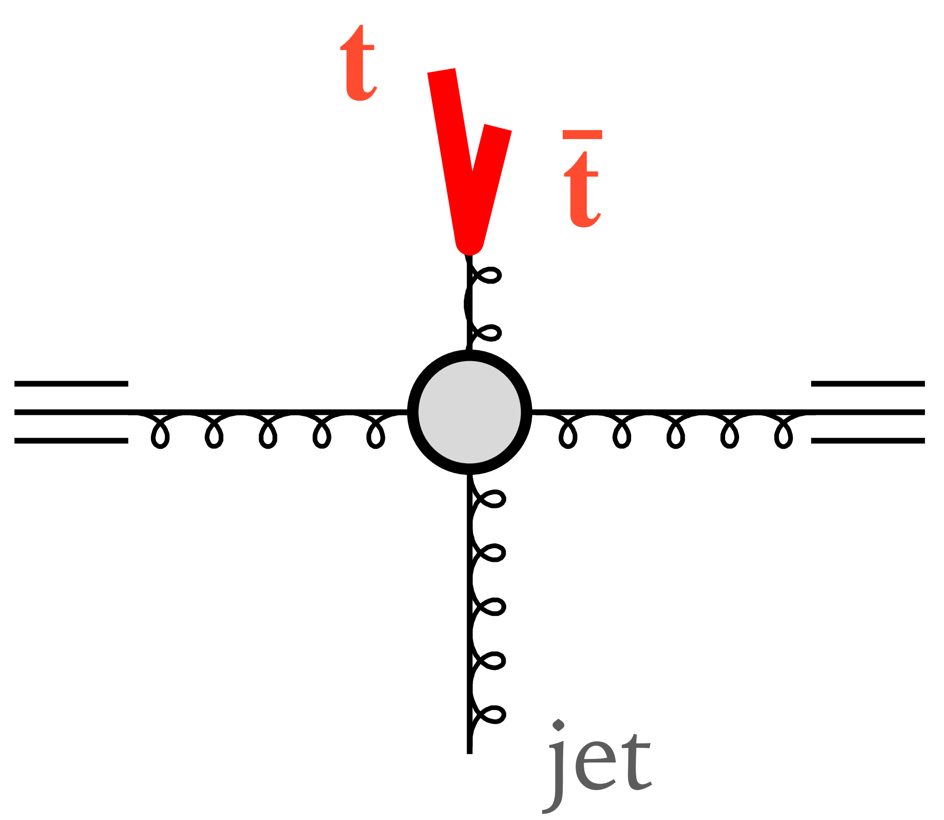

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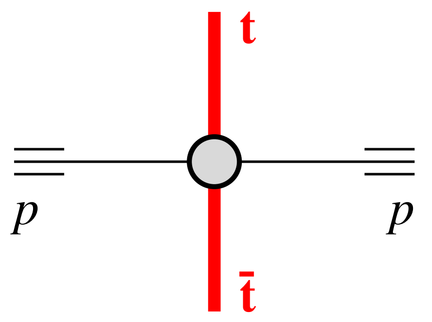
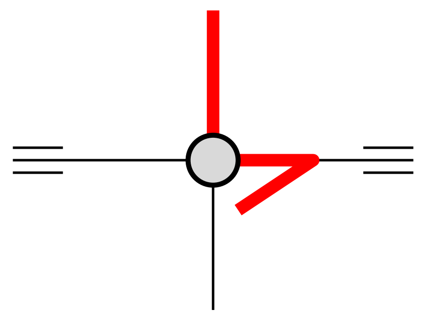
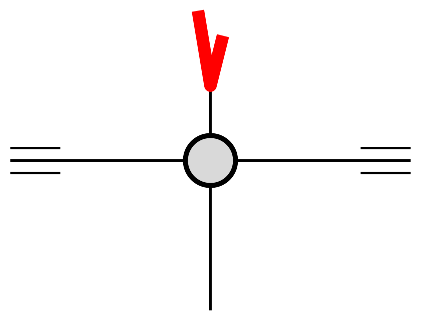
$\simeq g_s^4 \cdot 0.024$ **same order of magnitude** $\simeq g_s^4 \cdot 0.020$

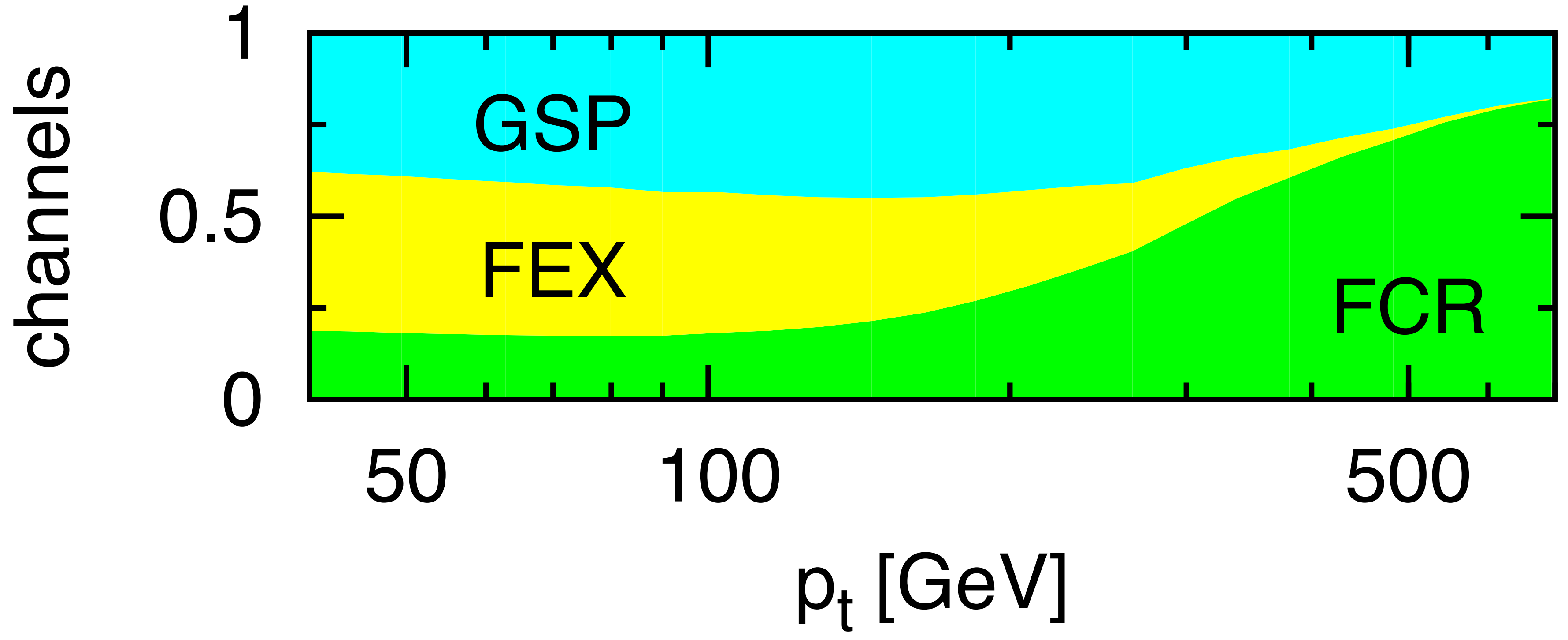
Consider $p_T = 1$ TeV, 90° scattering ($\hat{t} = \hat{u} = -\hat{s}/2$)

	topology	channel	$\|\mathrm{ME}\|^2$	luminosity	FS splitting	product
	FCR	$gg \to t\bar{t}$	0.15	0.16	1	0.024
		$q_i\bar{q}_i \to t\bar{t}$	0.22	0.13	1	0.028
	FEX	$tg \to tg$	6.11	0.0039	1	0.024
		$t\Sigma \to t\Sigma$	2.22	0.0170	1	0.038
	GSP	$gg \to gg(\to t\bar{t})$	30.4	0.16	$\mathcal{P}_{g\to t\bar{t}} \simeq 0.004$	0.020
		$g\Sigma \to g(\to t\bar{t})\Sigma$	6.11	1.22	$\mathcal{P}_{g\to t\bar{t}} \simeq 0.004$	0.031
		$q\bar{q} \to gg(\to t\bar{t})$	1.04	0.13	$\mathcal{P}_{g\to t\bar{t}} \simeq 0.004$	0.001

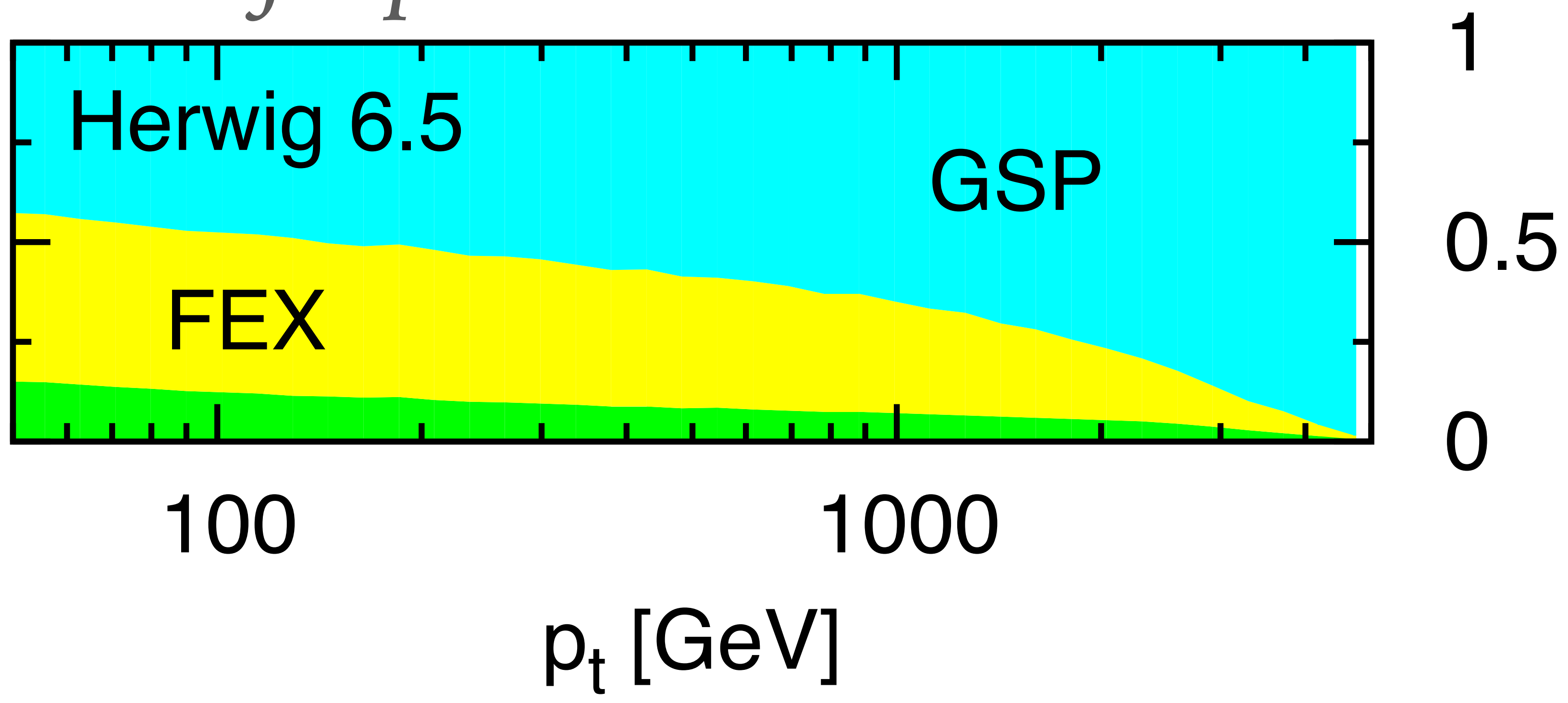
LO (FCR) and NLO (FEX,GSP) channels are all of same order of magnitude

Not the first time large FEX / GSP contributions are noticed, e.g.

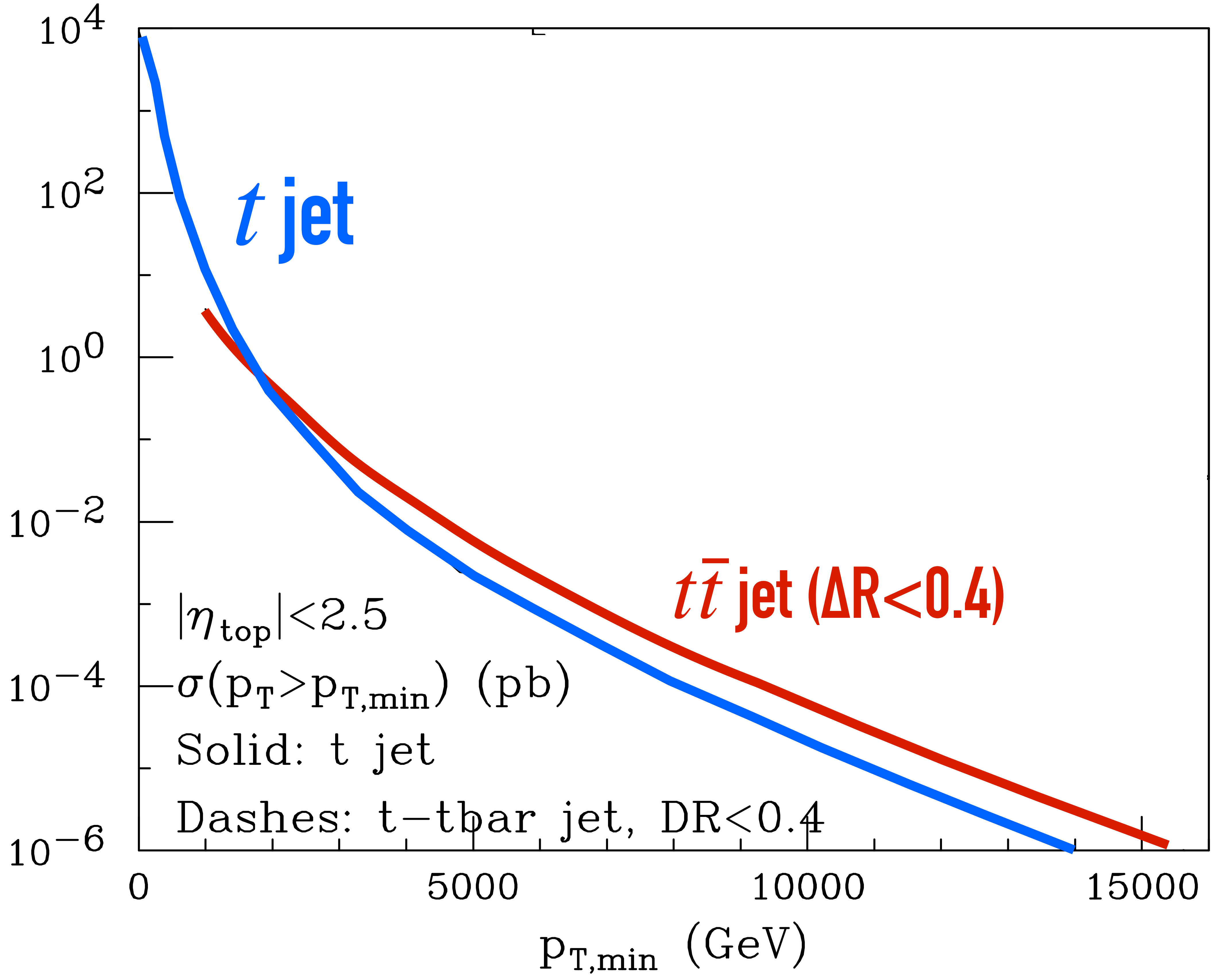
0704.2999, Banfi, GPS & Zanderighi
b-jet production at Tevatron



b-jet production at LHC



1607.01831, fig. 152, tops @ FCC-hh 100 TeV



In those cases, it seemed natural to ascribe large FEX/GSP to log p_T/m_Q enhancements

What we now understand is importance of $\times 10$ enhancements of t-channel ME^2 (e.g. $qt \to qt$) v. s-channel ME^2 (e.g. $q\bar{q} \to t\bar{t}$)

3. Implications for LHC cross sections

Interplay between hardness variable and channels

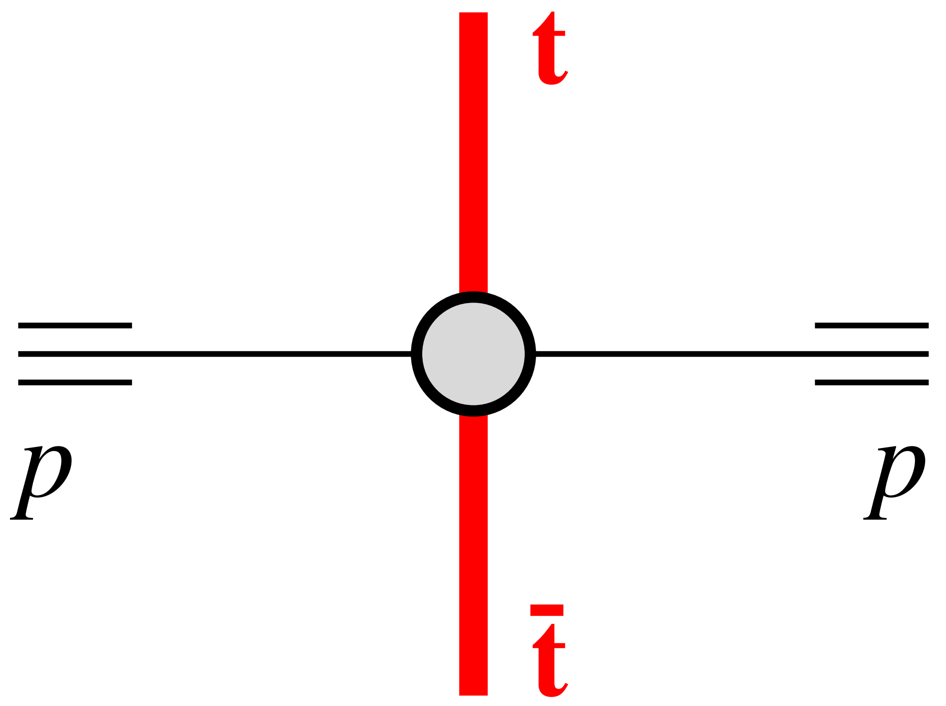
- LO (FCR) and NLO channels (FEX, GSP) were comparable when we chose similar underlying $2 \to 2$ scattering scales
- The question we'll ask is: for a given value of an observable, what is the underlying $p_T^{2\to2}$ scale.
- High-p_T cross section drops rapidly with increasing $2 \to 2$ scale ($p_T^{2\to2}$)

$$\sigma(p_T^{2\to2} > X) \sim X^{-p}, \qquad p \sim 7$$

Interplay between hardness variable and channels

$p_T^{\text{top,max}}$ — p_T of the top (anti-)quark with larger $m_T^2 = p_T^2 + m^2$

flavour creation



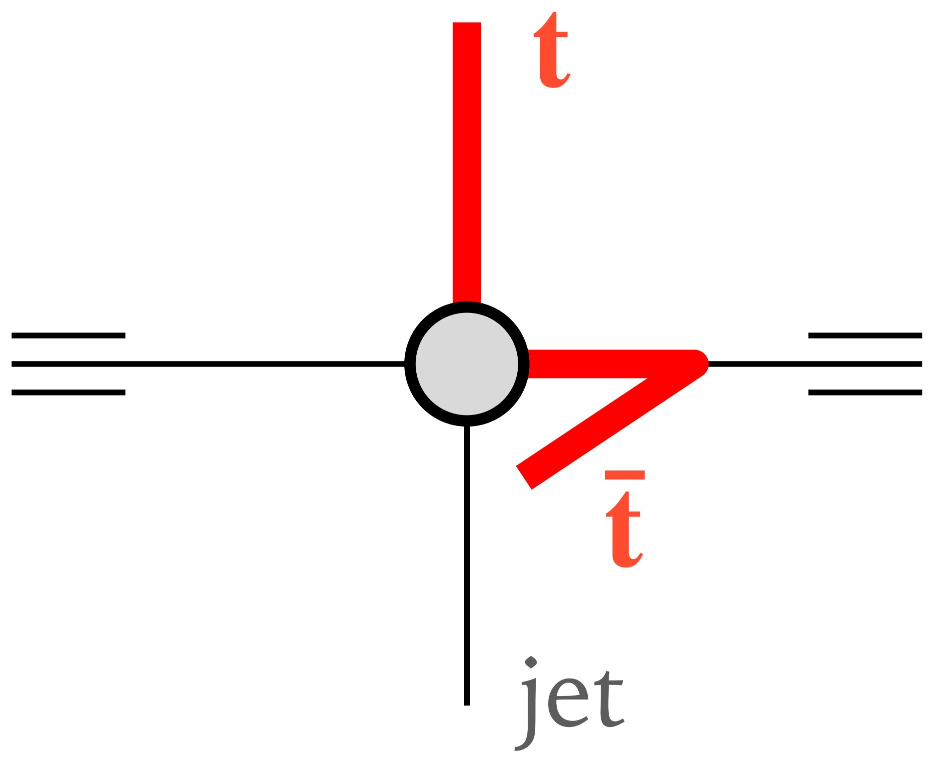
$p_T^{\text{top,max}} = 1\,\text{TeV}$

implies

$p_T^{2\to2} = 1\,\text{TeV}$

contributes fully

flavour excitation



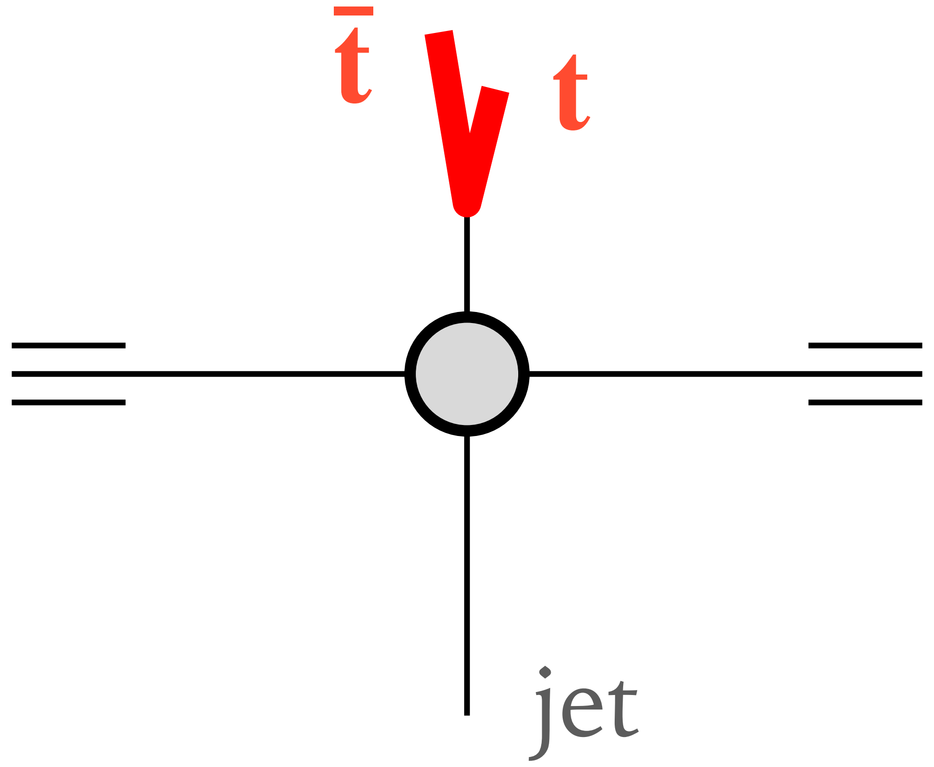
$p_T^{\text{top,max}} = 1\,\text{TeV}$

implies

$p_T^{2\to2} = 1\,\text{TeV}$

contributes fully

gluon splitting



$p_T^{\text{top,max}} = 1\,\text{TeV}$

implies

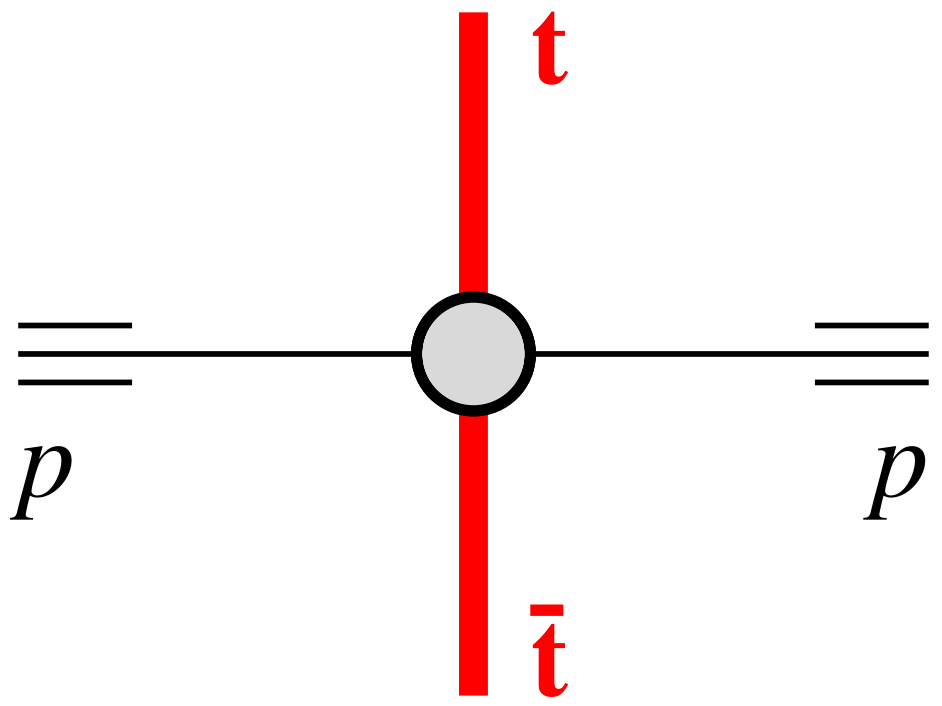
$p_T^{2\to2} \sim 1.5\,\text{TeV}$

σ suppressed by $(1/1.5)^7$

Interplay between hardness variable and channels

$p_T^{\text{top,min}}$ — p_T of the top (anti-)quark with smaller $m_T^2 = p_T^2 + m^2$

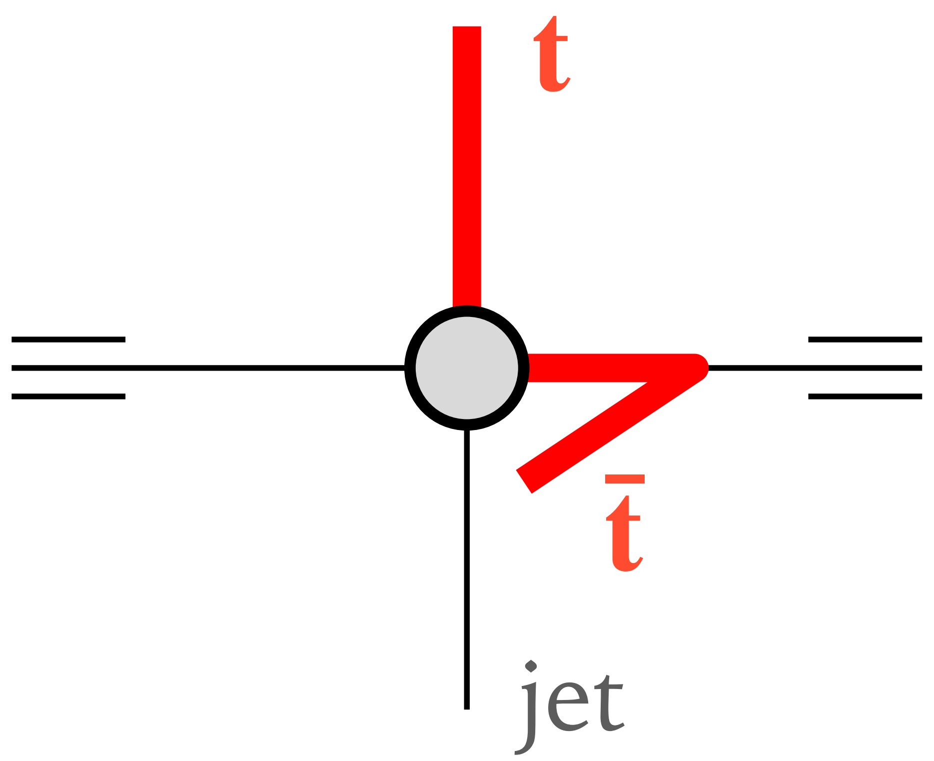
flavour creation



$p_T^{\text{top,min}} = 1\,\text{TeV}$
implies
$p_T^{2\to2} = 1\,\text{TeV}$

contributes fully

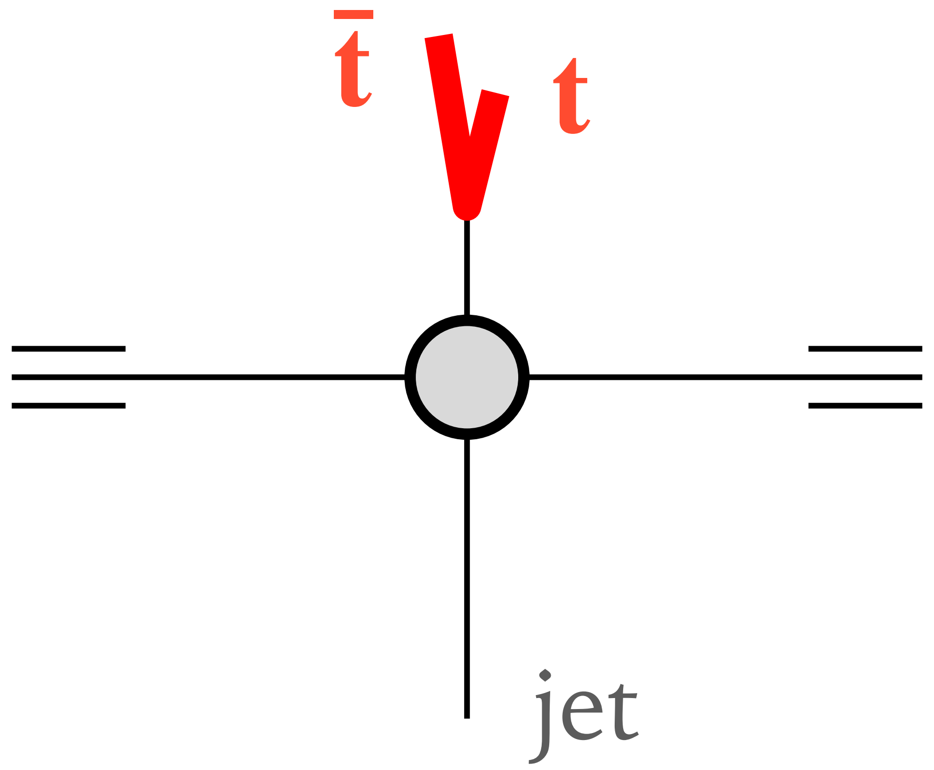
flavour excitation



$p_T^{\text{top,min}} = 1\,\text{TeV}$
implies
$p_T^{2\to2} \gtrsim 2\,\text{TeV}$

σ suppressed by $(1/2)^7$

gluon splitting

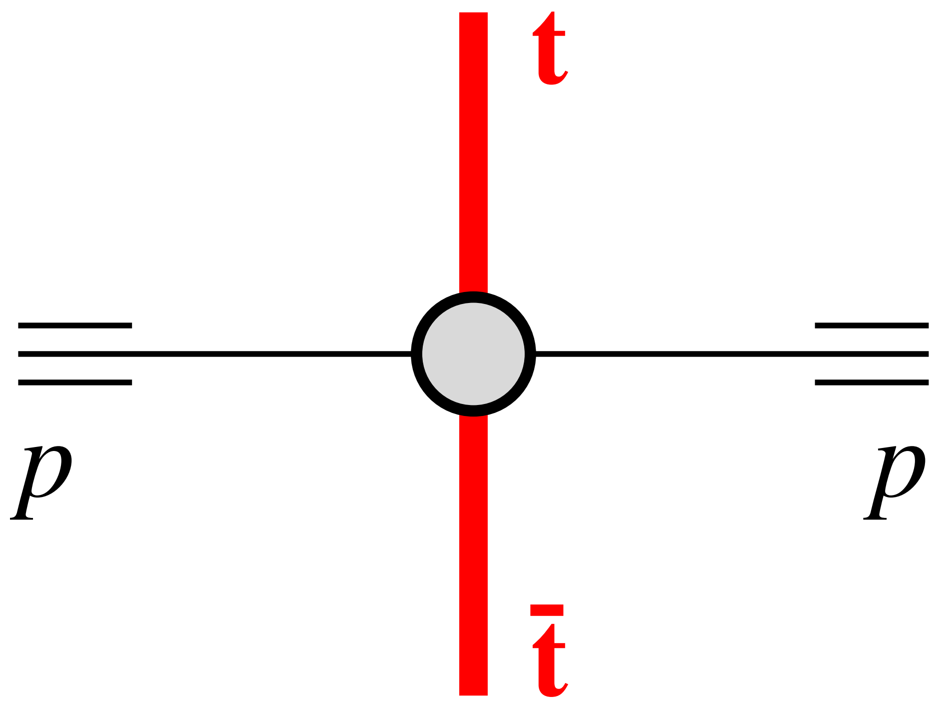
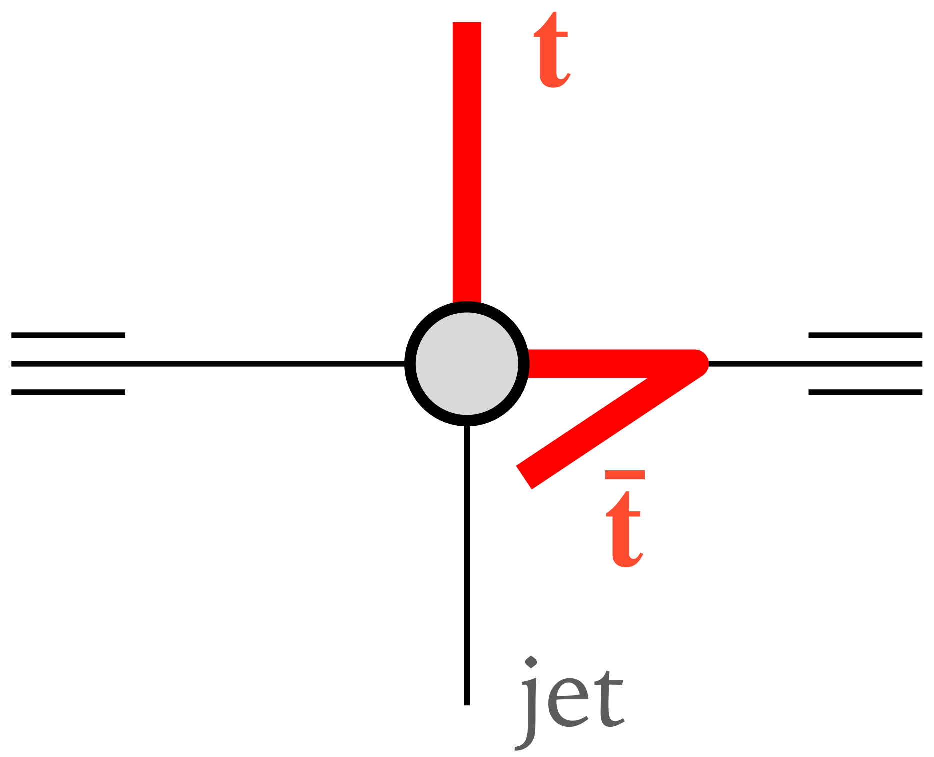
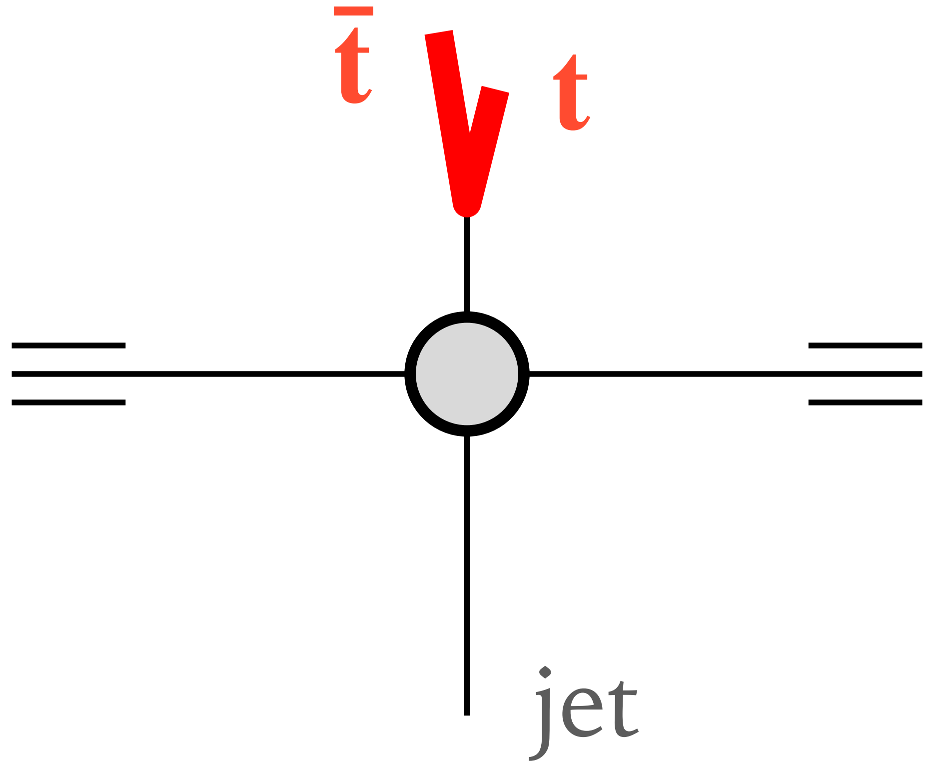


$p_T^{\text{top,min}} = 1\,\text{TeV}$
implies
$p_T^{2\to2} \gtrsim 2\,\text{TeV}$

σ suppressed by $(1/2)^7$

Interplay between hardness variable and channels

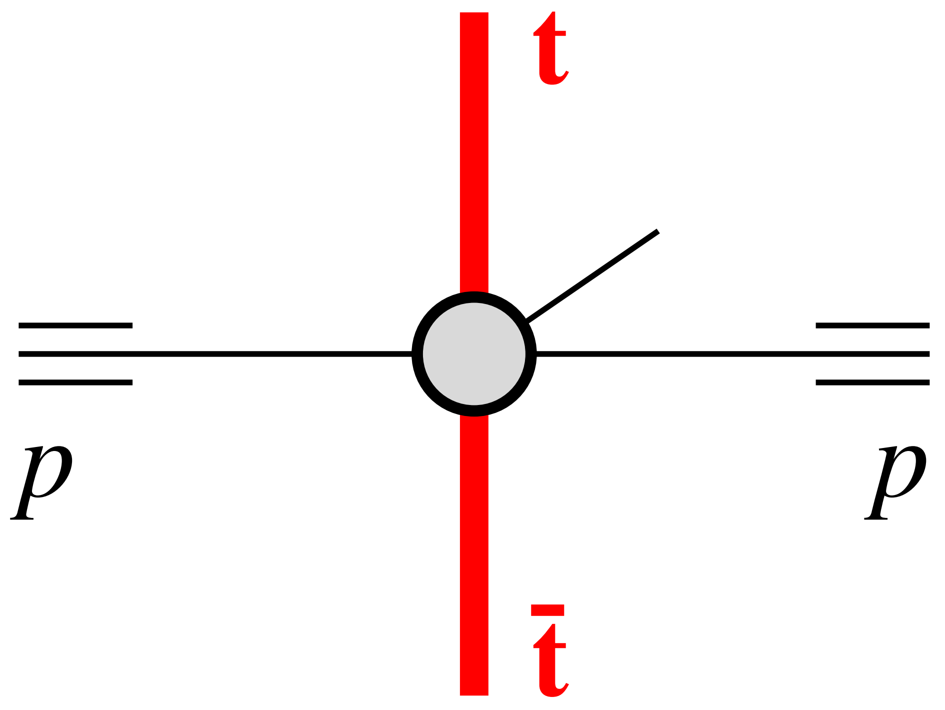
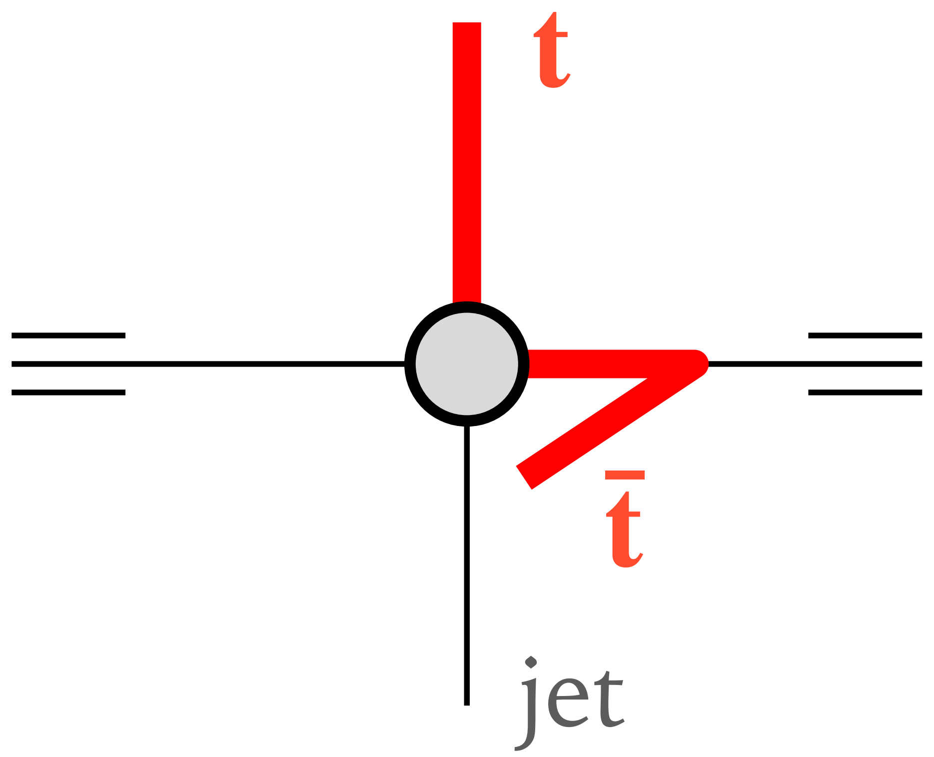
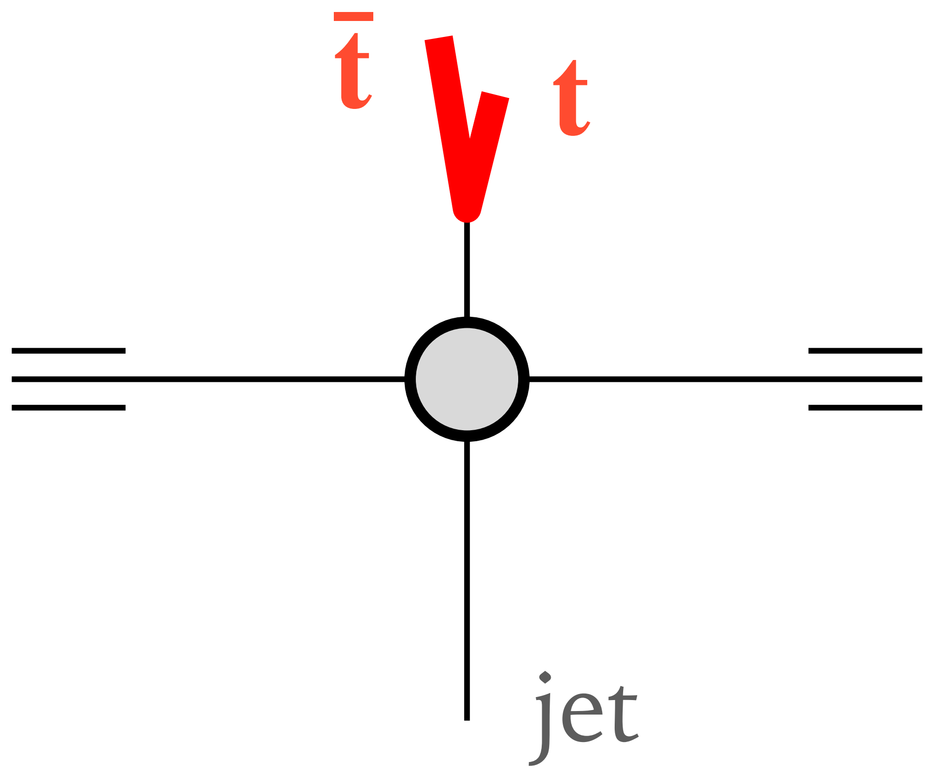
$\frac{1}{2} H_T^{t\bar{t}+\text{jets}}$ with $H_T^{t\bar{t}+\text{jets}} = m_T^{\text{top,had}} + m_T^{\text{top,lep}} + \sum_i p_T^{j_{\not{t}},i}$

flavour creation	**flavour excitation**	**gluon splitting**
		
$\frac{1}{2} H_T^{t\bar{t}+\text{jets}} = 1\,\text{TeV}$ implies $p_T^{2\to 2} = 1\,\text{TeV}$ contributes fully	$\frac{1}{2} H_T^{t\bar{t}+\text{jets}} = 1\,\text{TeV}$ implies $p_T^{2\to 2} = 1\,\text{TeV}$ contributes fully	$\frac{1}{2} H_T^{t\bar{t}+\text{jets}} = 1\,\text{TeV}$ implies $p_T^{2\to 2} = 1\,\text{TeV}$ contributes fully

A democratic hardness scale: doesn't care how p_T is shared between tops and jets

Interplay between hardness variable and channels

$p_T^{j_{\not{t},1}}$ transverse momentum of the leading small-R non-top jet

flavour creation + jet	flavour excitation	gluon splitting
		

flavour creation + jet	flavour excitation	gluon splitting
$p_T^{j_{\not{t},1}} = 1\,\text{TeV}$	$p_T^{j_{\not{t},1}} = 1\,\text{TeV}$	$p_T^{j_{\not{t},1}} = 1\,\text{TeV}$
implies	implies	implies
$p_T^{2\to2} \gtrsim 2\,\text{TeV}$	$p_T^{2\to2} = 1\,\text{TeV}$	$p_T^{2\to2} \sim 1\,\text{TeV}$
σ suppressed by $(1/2)^7$	contributes fully	contributes fully

Channels that dominate for each observable

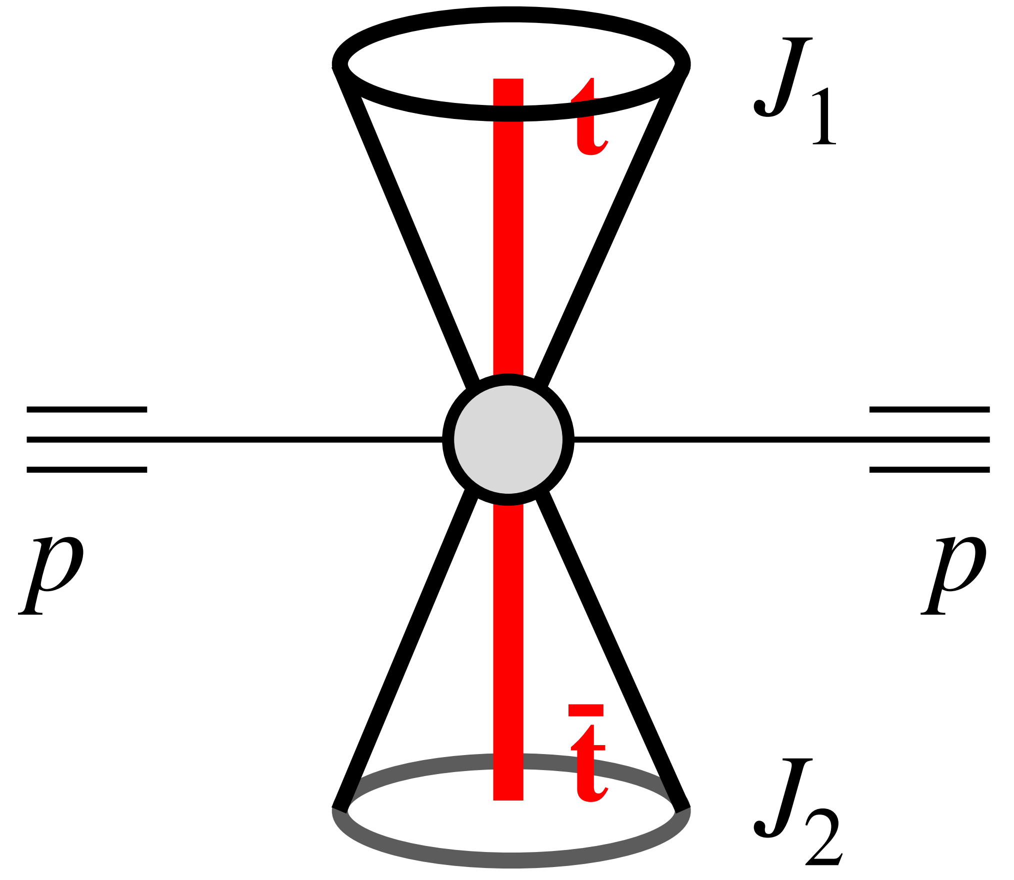
Hardness variable	explanation	FCR	FEX	GSP
$p_T^{\text{top,had}}$	transverse momentum of hadronic top candidate	✓	✓	
$p_T^{\text{top,lep}}$	transverse momentum of leptonic top candidate	✓	✓	
$p_T^{\text{top,max}}$	p_T of the top (anti-)quark with larger $m_T^2 = p_T^2 + m^2$	✓	✓	
$p_T^{\text{top,min}}$	p_T of the top (anti-)quark with smaller $m_T^2 = p_T^2 + m^2$	✓		
$p_T^{\text{top,avg}}$	$\frac{1}{2}(p_T^{\text{top,had}} + p_T^{\text{top,lep}})$	✓		
$\frac{1}{2}H_T^{t\bar{t}}$	with $H_T^{t\bar{t}} = m_T^{\text{top,had}} + m_T^{\text{top,lep}}$	✓		
$\frac{1}{2}H_T^{t\bar{t}+\text{jets}}$	with $H_T^{t\bar{t}+\text{jets}} = m_T^{\text{top,had}} + m_T^{\text{top,lep}} + \sum_i p_T^{j_{\not{t}},i}$	✓	✓	✓
$m_T^{J,\text{avg}}$	average m_T of the two highest m_T large-R jets (J_1, J_2)	✓	✓	✓
$\frac{1}{2}m^{t\bar{t}}$	half invariant mass of $p^{t\bar{t}} = p^{\text{top,had}} + p^{\text{top,lep}}$	✓		
$p_T^{t\bar{t}}$	transverse component of $p^{t\bar{t}}$		✓	✓
$p_T^{j_{\not{t}},1}$	transverse momentum of the leading small-R non-top jet		✓	✓

Basic analysis with top partons

- Take top-partons + normal R=0.4 jets, and cluster them using an R=1 jet algorithm*
  (gives large-R jets $J_1, J_2, \ldots$ in order of decreasing m_T)
- Identify event topology as follows

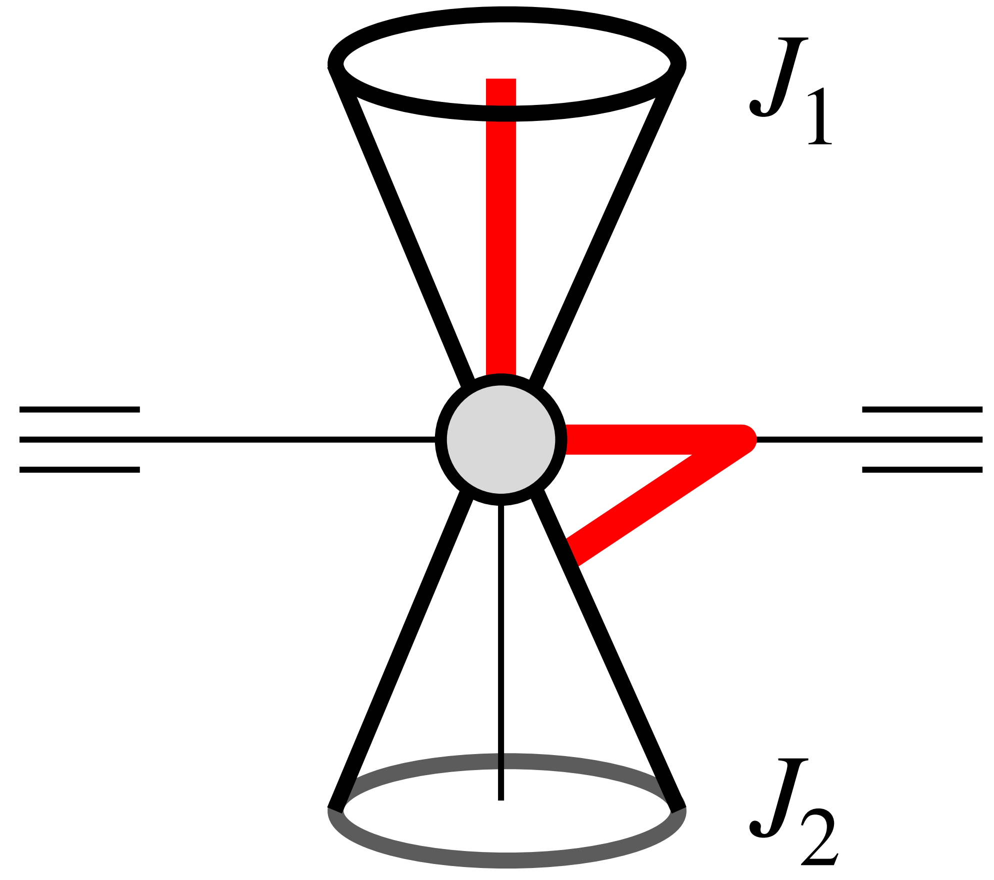
J_1 and J_2 each contain a top

flavour creation



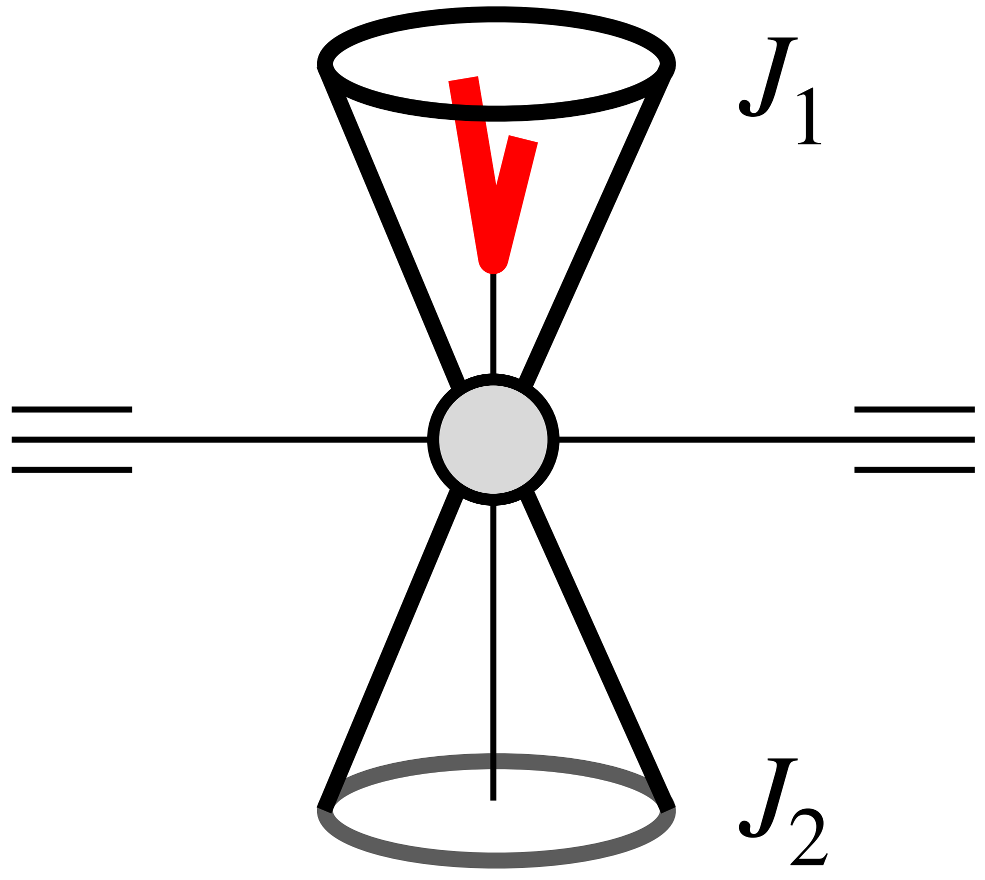
Just one of J_1 and J_2 contains a single top

flavour excitation



J_1 or J_2 contains two tops

gluon splitting



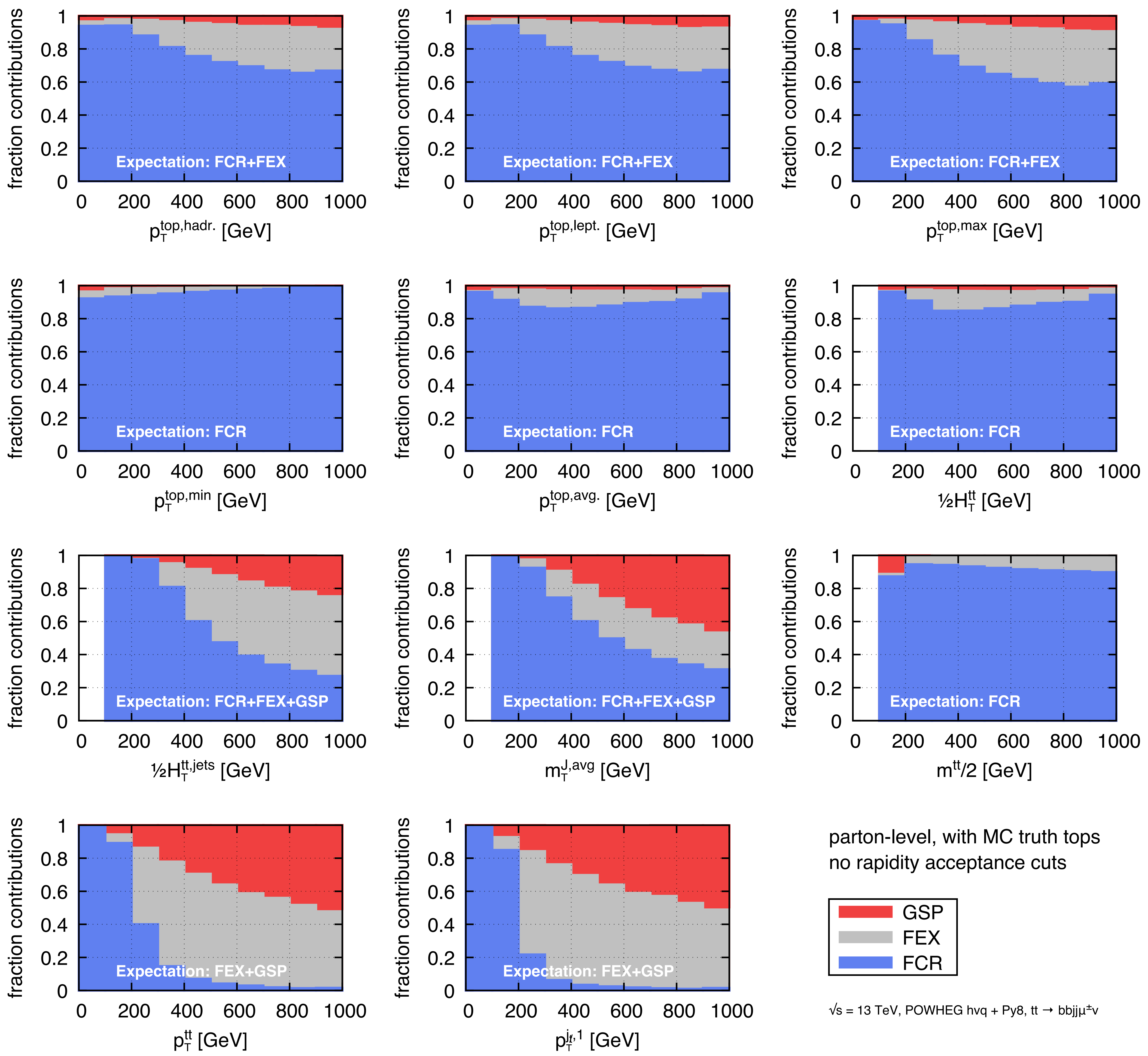
** one could use a flavour-safe jet algorithm, but we used anti-k_T to keep things simple*

Setup for testing

- 13 TeV pp collisions
- POWHEGBox v2, hvq process (NLO for $t\bar{t}$)
- PDF4LHC15_nnlo_mc PDF sets
- Showering with Pythia8, parton level
- Reconstruct jets with the FastJet and the anti-k_t algorithm,
  - $R = 0.4$ small-R jets, $p_{T,j} > 30\,\text{GeV}$, from non-top partons
  - then $R = 1$ jets with the small-R jets and top-parton as inputs
- Also: cross checks with POWHEGBox NLO $t\bar{t}j$ process (Alioli, Moch & Uwer 1110.5251), finding good agreement for the channels that start at α_s^3.

Fraction in each topology v. hardness scale

Fraction in each topology v. hardness scale

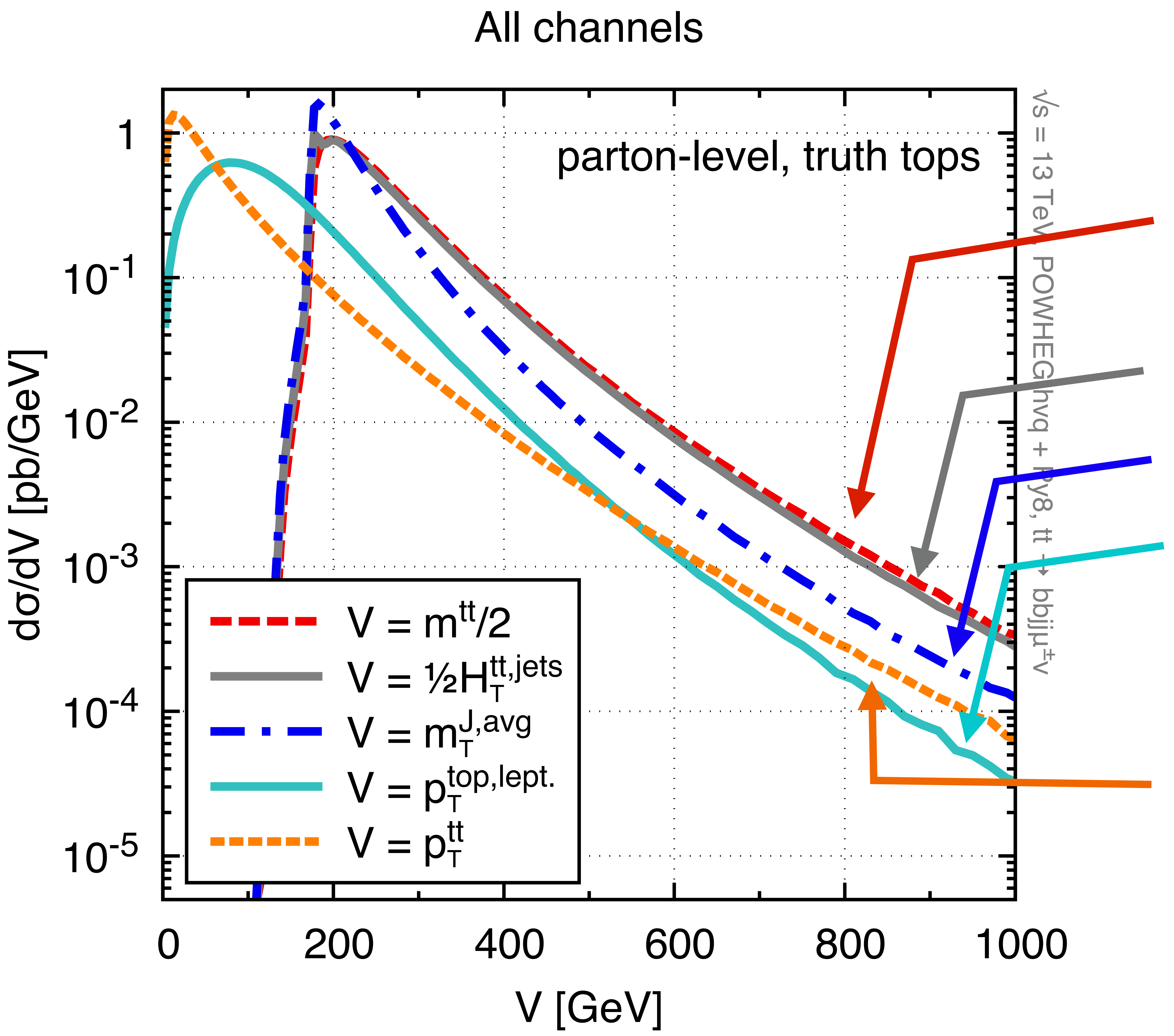


For each event hardness measure, POWHEG+Pythia show ~ same channel mixture as expected from our arguments

"Democratic" observables ($\frac{1}{2}H_T^{t\bar{t},\text{jets}}$, $m_T^{J,\text{avg}}$) show commensurate contributions from all 3 topologies

4. Where is this knowledge useful?

Compare LO expectations to POWHEG+Pythia8 NLO results



LO expectation

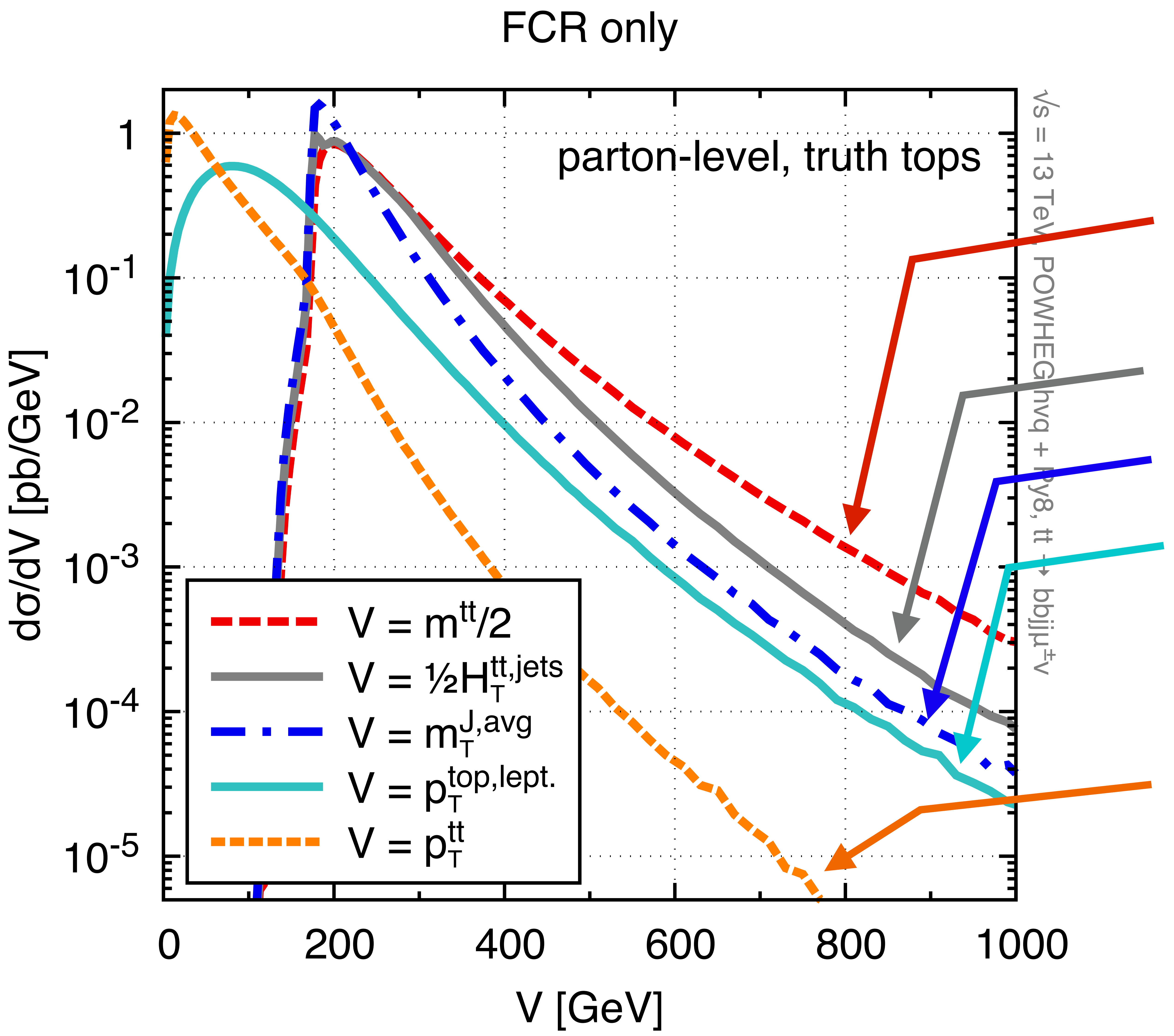
$\frac{1}{2}m^{t\bar{t}}$ should be enhanced by $\ln m^{t\bar{t}}/m_{\text{top}}$

$\frac{1}{2}H_T^{t\bar{t},\text{jets}}$, $m_T^{J,\text{avg}}$, $p_T^{\text{top,lept.}}$ should all be similar & smaller

$p_T^{t\bar{t}} \simeq p_T^{j_{\ell,1}}$ should be suppressed

That is not what you see "out of the box"

Compare LO expectations to POWHEG+Pythia8 NLO results



LO expectation

$\frac{1}{2}m^{t\bar{t}}$ should be enhanced by $\ln m^{t\bar{t}}/m_{\rm top}$

$\frac{1}{2}H_T^{t\bar{t},\rm jets}$

$m_T^{J,\rm avg}$

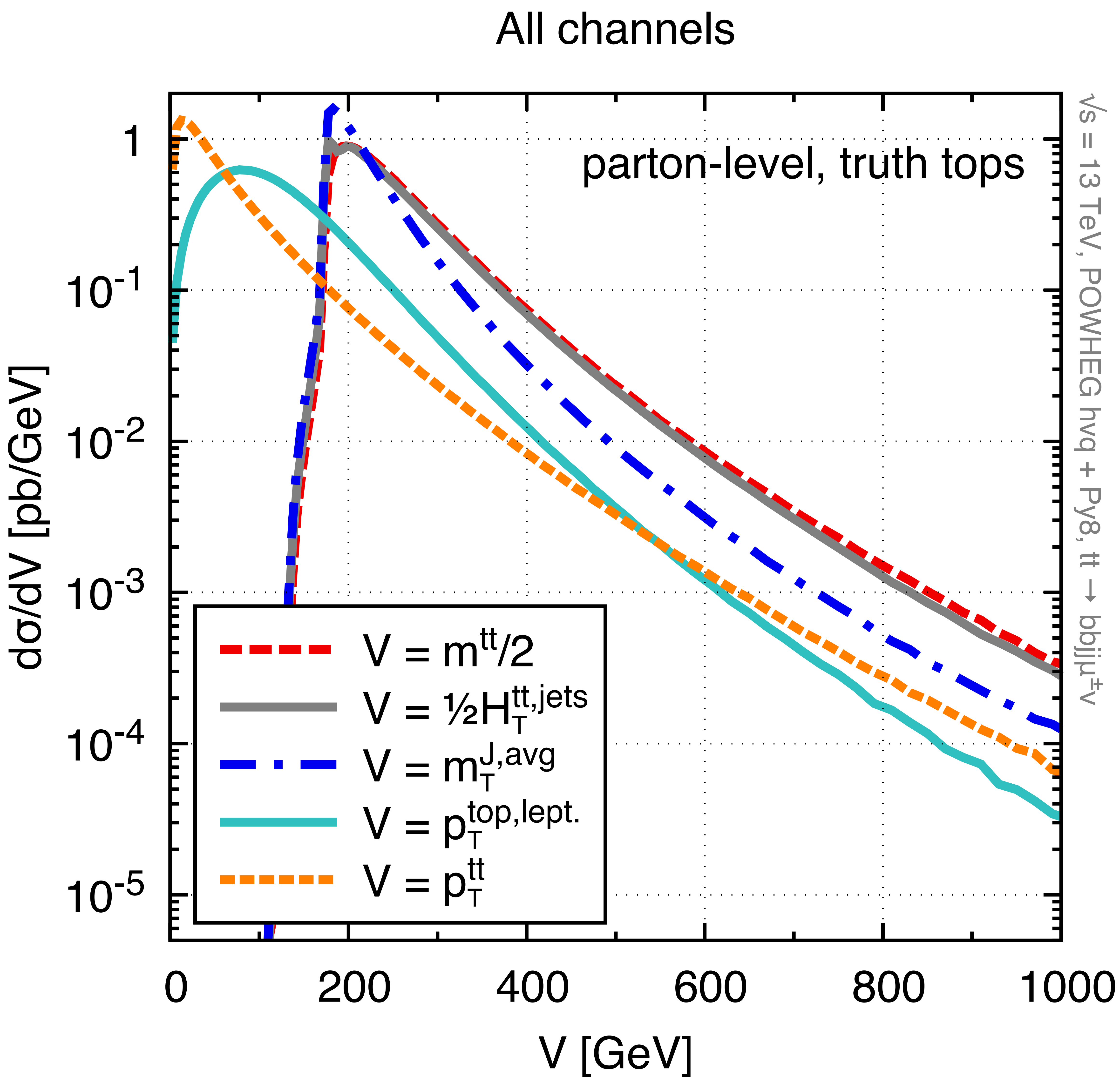
$p_T^{\rm top,lept.}$

should all be similar & smaller

$p_T^{t\bar{t}} \simeq p_T^{j_{t,1}}$ should be suppressed

Selecting just FCR, LO expectations are mostly confirmed

Making sense of what we see



LO expectation

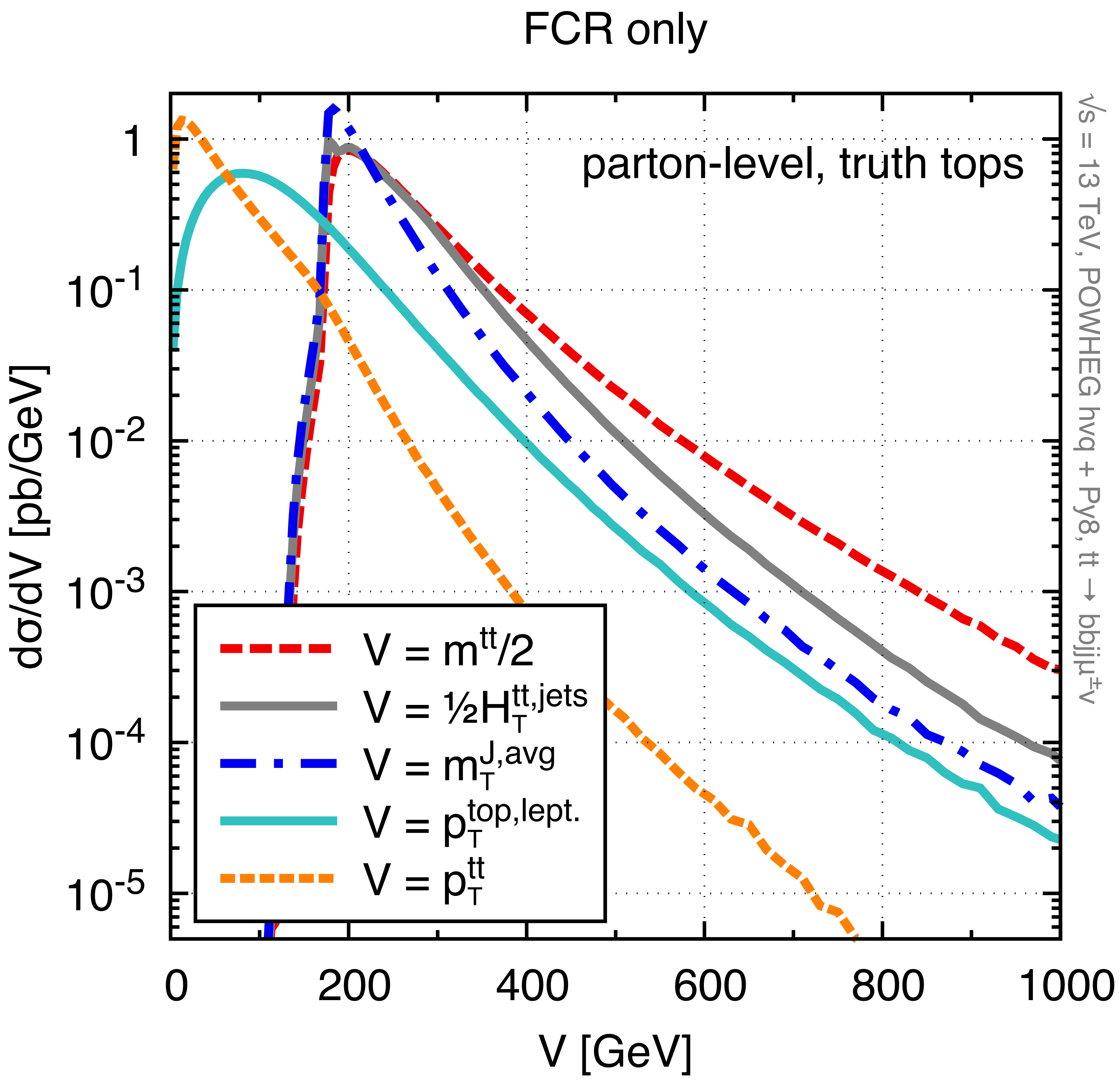
$\frac{1}{2}m^{t\bar{t}}$ should be enhanced by $\ln m^{t\bar{t}}/m_{\rm top}$

$\frac{1}{2}H_T^{t\bar{t},\rm jets}$, $m_T^{J,\rm avg}$, $p_T^{\rm top,lept.}$, etc. should all be similar

$p_T^{t\bar{t}} \simeq p_T^{j_{\ell,1}}$ should be suppressed

That is not what you see "out of the box"

Making sense of what we see



LO expectation

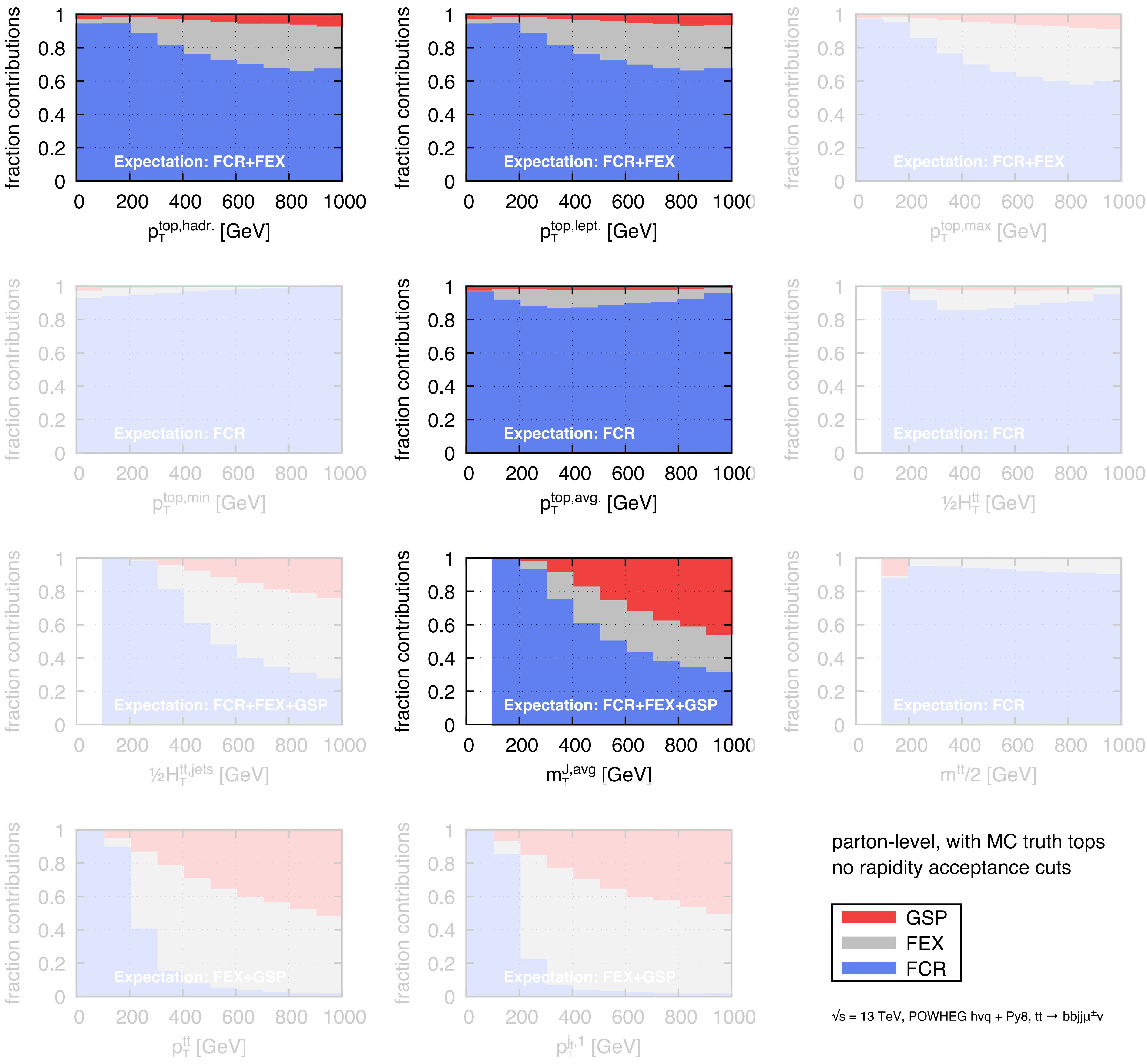
$\frac{1}{2}m^{t\bar{t}}$ should be enhanced by $\ln m^{t\bar{t}}/m_{\text{top}}$

$\frac{1}{2}H_T^{t\bar{t},\text{jets}}$, $m_T^{J,\text{avg}}$, $p_T^{\text{top,lept.}}$, etc. should all be similar

$p_T^{t\bar{t}} \simeq p_T^{j_{t,1}}$ should be suppressed

It is ~ what you see if you select just FCR topology

Highest precision top physics



Select only events classified as FCR

Study safest observables (never max or min)

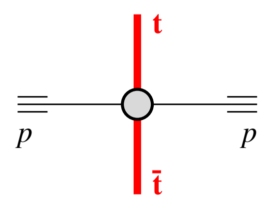
If scale is not too high:

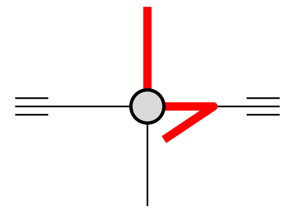
$p_T^{\text{top,lept.}}, p_T^{\text{top,hadr.}}, p_T^{\text{top,avg.}}$

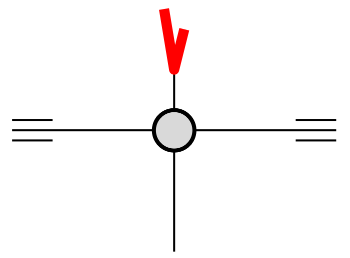
At highest scales, avoid top fragmentation logarithms ("FONLL" terms) with

$m_T^{J,\text{avg.}}$ or $p_T^{J,\text{avg.}}$

Exploiting all available information





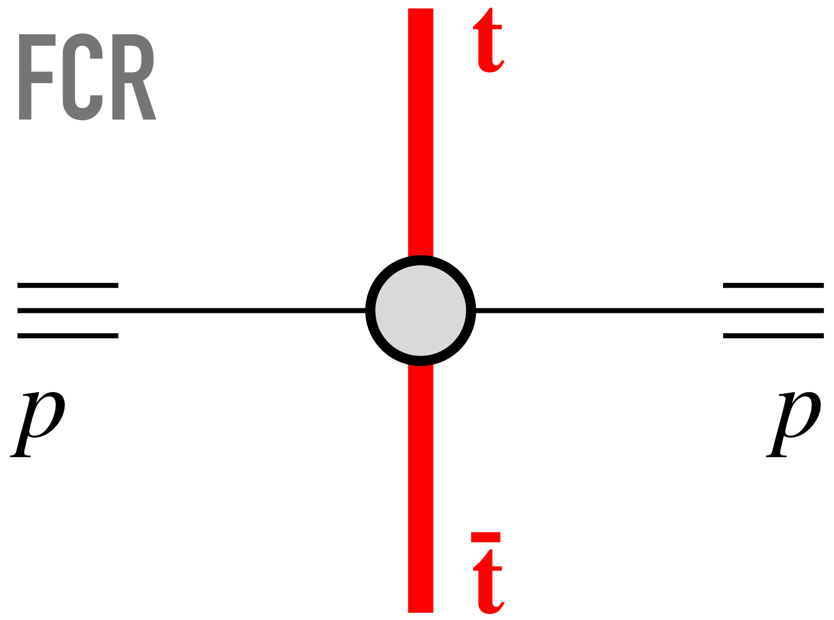


topology	channel	$\lvert\mathrm{ME}\rvert^2$	luminosity	FS splitting	product
FCR	$gg \to t\bar{t}$	0.15	0.16	1	0.024
	$q_i\bar{q}_i \to t\bar{t}$	0.22	0.13	1	0.028
FEX	$tg \to tg$	6.11	0.0039	1	0.024
	$t\Sigma \to t\Sigma$	2.22	0.0170	1	0.038
GSP	$gg \to gg(\to t\bar{t})$	30.4	0.16	$\mathcal{P}_{g\to t\bar{t}} \simeq 0.004$	0.020
	$g\Sigma \to g(\to t\bar{t})\Sigma$	6.11	1.22	$\mathcal{P}_{g\to t\bar{t}} \simeq 0.004$	0.031
	$q\bar{q} \to gg(\to t\bar{t})$	1.04	0.13	$\mathcal{P}_{g\to t\bar{t}} \simeq 0.004$	0.001

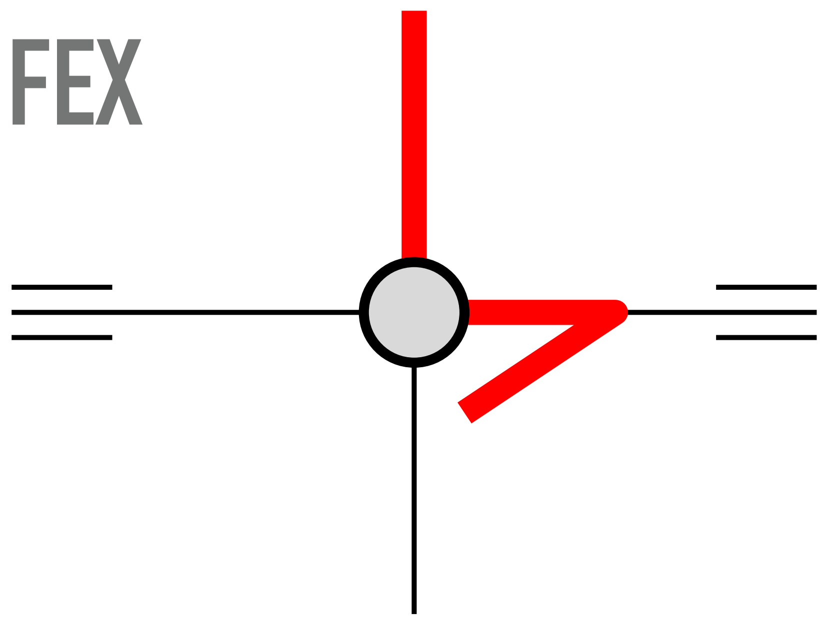
- For SM-EFT fits and searches, each topology may bring sensitivity to different operators, and/or kinematic regions
- Exploit different sensitivity to PDFs: e.g. FEX involves initial-state $g \to t\bar{t}$, which requires higher-x gluon than other processes at similar p_T
- Etc.

Designing measurement strategies

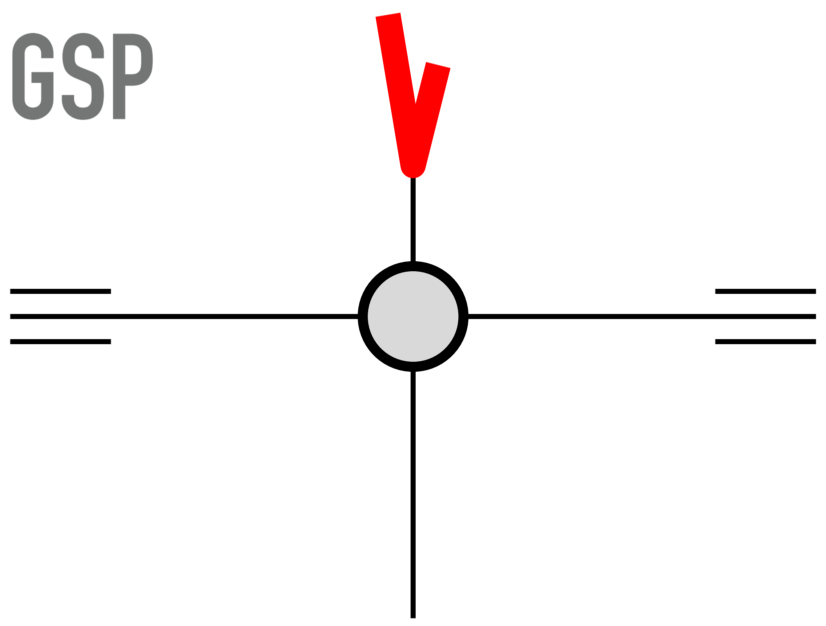
FCR



FEX



GSP



- Depending on p_T range, one normally carries out either a resolved analysis or a boosted analysis (one top inside a jet)
- That's fine for FCR
- But FEX has one high-p_T top, one lower-p_T top
- GSP has two tops within a single jet

Especially critical for parton-level experimental results (if analysis is insensitive FEX/GSP, but parton level cross-section has it, then "unfolding" is simply injecting MC info in place of missing data).

Our particle-level analysis

Algorithm 2 Event analysis algorithm at hadron (particle) level

Require: at least one lepton (we require it to have a transverse momentum of at least 25 GeV), missing transverse momentum and hadrons.

1: Cluster the hadronic part of the event with the anti-k_t algorithm with $R = 0.4$ and discard any jets below some p_t threshold, $p_{T,\min}$, as one would normally (we take $p_{T,\min} = 30$ GeV).

2: Optionally, e.g. if subject to finite detector acceptance, exclude jets and leptons with an absolute rapidity beyond some $y_{\max}$. The remaining set of jets is referred to as $\{j\}$ and the hadrons contained within that set of jets is $\{H\}$.

3: For each jet j, recluster its constituents with the exclusive longitudinally invariant ($R = 1$) k_t algorithm [61] with a suitable d_{cut} (we use $(20 \text{ GeV})^2$), thus mapping the $R = 0.4$ jets $\{j\}$ to a declustered set $\{j_d\}$. One applies b-tagging to the $\{j_d\}$ (sub)jets to aid with the subsequent top identification.

4: Use a resolved top-tagging approach to identify the hadronic and leptonic top-quark candidates from the lepton(s) and from the jets $\{j_d\}$ obtained in step 3. Here, we will adopt the algorithm outlined in Section 4.2.

5: Identify all particles from the set $\{H\}$ that do not belong to either of the top-quark candidates. Refer to this subset as $\{H_{\not t}\}$. Cluster the $\{H_{\not t}\}$ with the original jet definition (anti-k_t, $R = 0.4$) and apply a transverse momentum threshold $p_{T,\min}$ to obtain the set of non-top $R = 0.4$ jets, $\{j_{\not t}\}$, ordered in decreasing p_T.

6: Apply step 3 of Algorithm 1 using $\{j_{\not t}\}$ and the reconstructed top and anti-top candidates as the inputs.

Designed to work for resolved and (moderately) boosted top decays, including $g \to t\bar{t}$ within a jet

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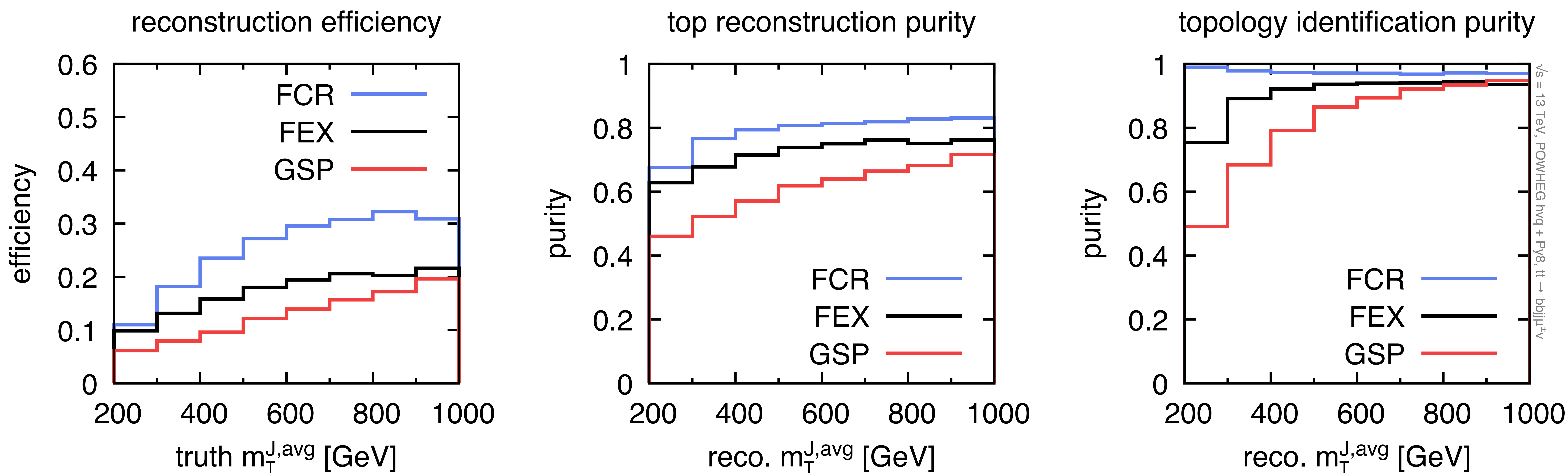
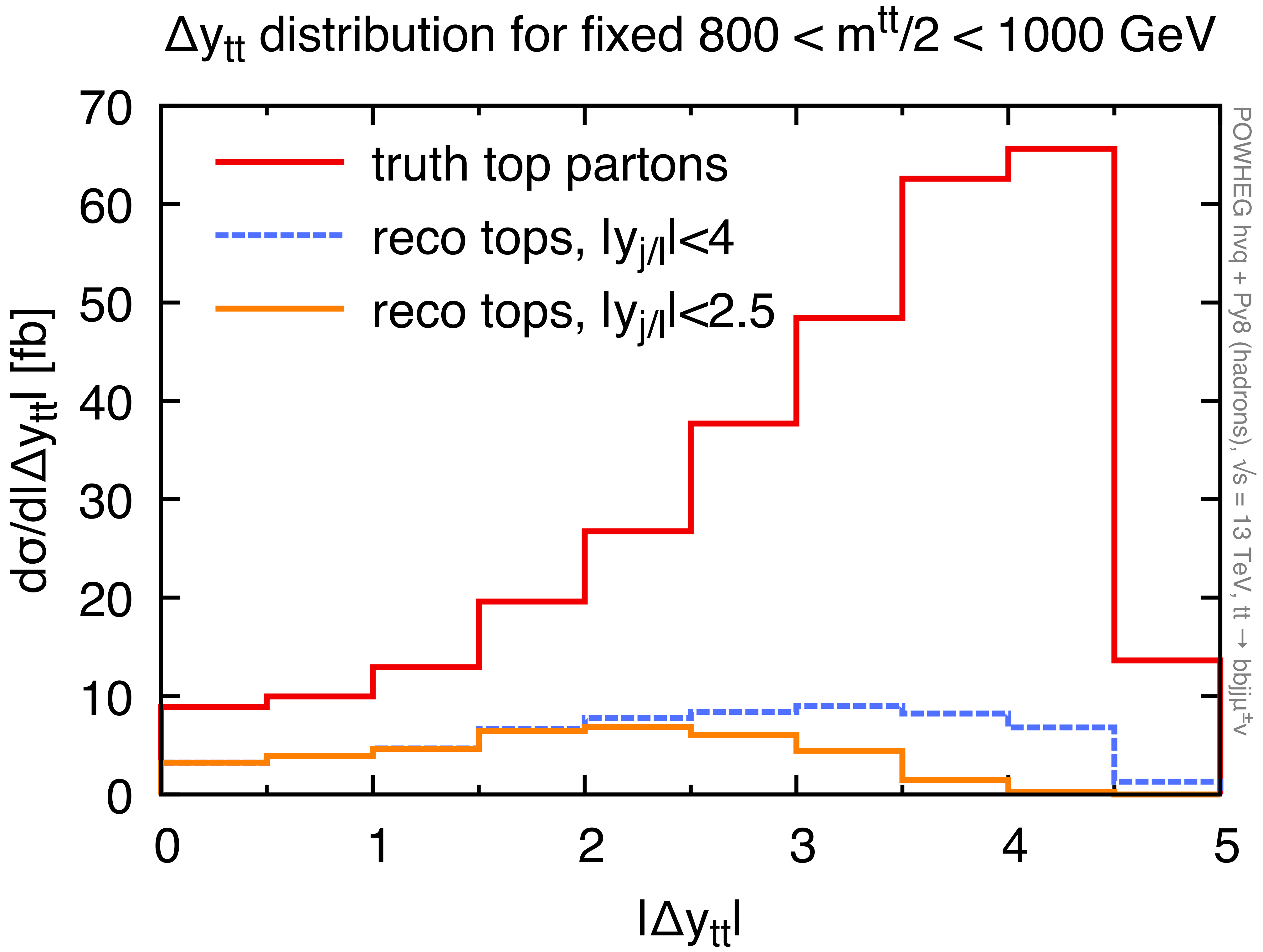
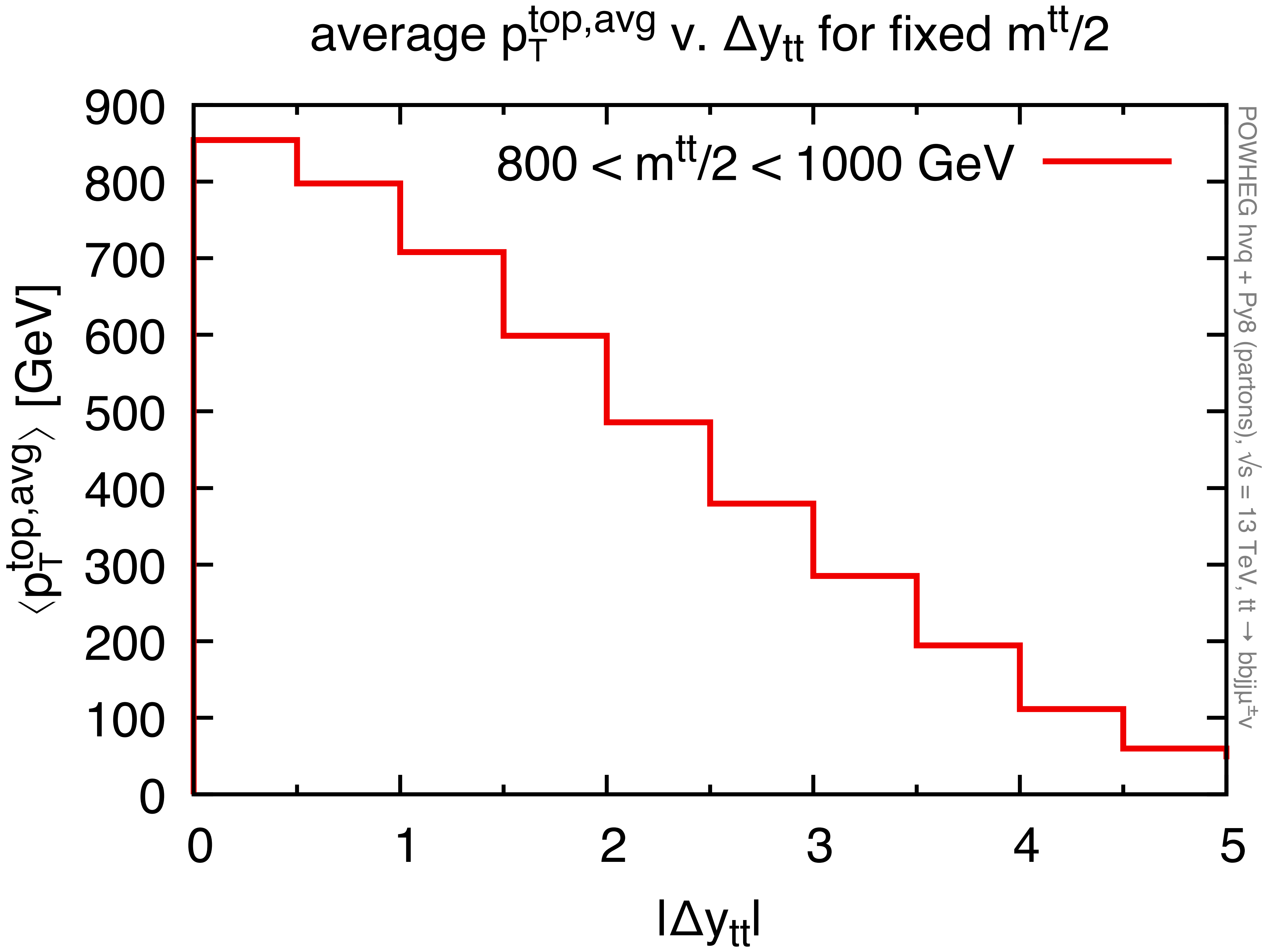
2: Optionally, e.g. if subject to finite detector acceptance, exclude jets and leptons with an absolute rapidity beyond some $y_{\max}$. The remaining set of jets is referred to as $\{j\}$

Designed to work for resolved and (moderately) boosted top decays, including $g \to t\bar{t}$ within a jet



Reconstructed tops and the $m_{t\bar{t}}$ distribution





- Events with large $m_{t\bar{t}}$ mostly have large $\Delta y_{t\bar{t}}$, and low p_T^{top}
- Integral over phase space gives large logs, e.g. $\alpha_s^{2+n} \ln^{2n-1} m_{t\bar{t}}/m_{\text{top}}$ (Kirschner & Lipatov '83)
- Large $\Delta y_{t\bar{t}}$ and low p_T^{top} hard to measure experimentally
- **It may make sense to measure $m_{t\bar{t}}$ with an additional condition such as $|\Delta y_{t\bar{t}}| < 2$**

5. Outlook & conclusions

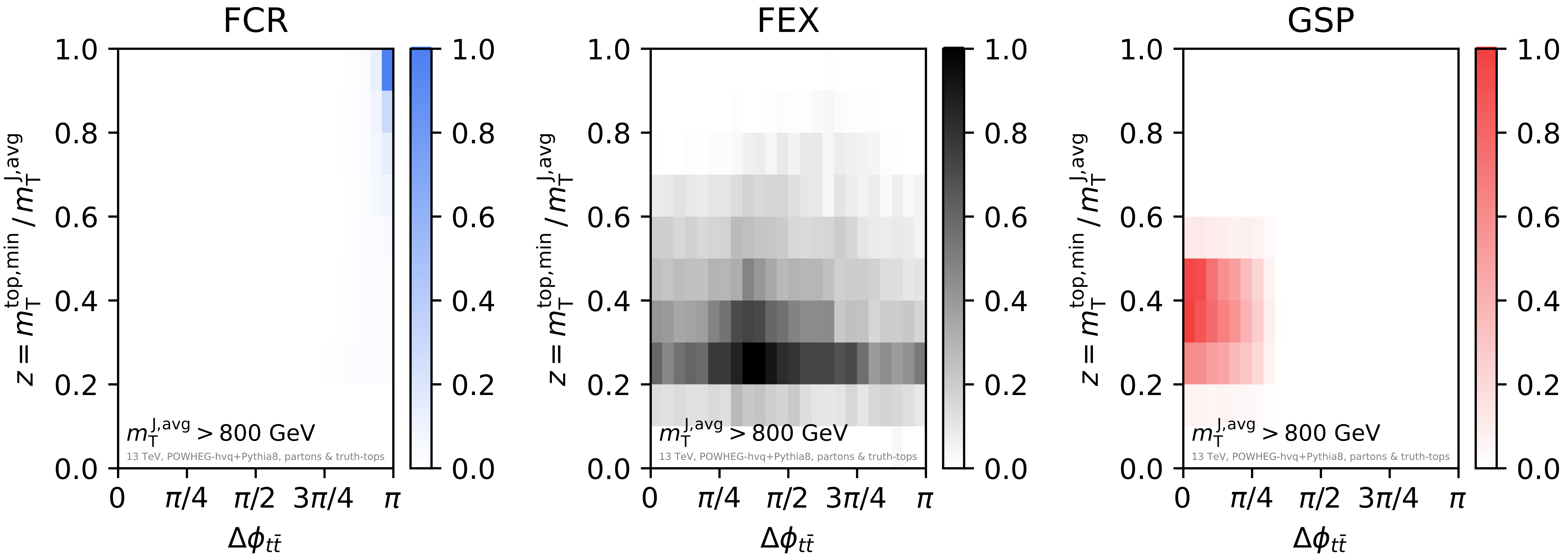
Core messages

- At large momentum transfer, NLO top-production topologies (FEX, GSP) are comparable to LO topology (FCR), because a much larger underlying $2 \to 2\ |\mathrm{ME}|^2$ (with t-channel gluons) ~ compensates for the extra factor of α_s
- Non-trivial interplay with choice of event hardness variable; NLO simulations calculations confirm simple picture of how this works
- Awareness of this is potentially important in a range of applications of $t\bar{t}$ physics (precision measurements, PDF fits, EFT fits, etc.)
- At parton level, a simple algorithms tells you the classification for any given event
- At particle level, design analyses to simultaneously be able to reconstructed high and low-p_T tops, and two tops in a single jet
- Beware of exp. & th. complications in $m_{t\bar{t}}$ distribution; maybe measure it with $\Delta y_{t\bar{t}}$ cut

Backup

more on topologies

More differential phase-space info on different topologies



$$g \longrightarrow t\bar{t}$$

Gluon to $t\bar{t}$ splitting within a jet of radius R

$$\mathcal{P}_{g\to t\bar{t}} = \frac{\alpha_s T_R}{2\pi}\frac{2}{3}\left(\ln\frac{p_{T,t}^2 R^2}{m_{\text{top}}^2} - \frac{23}{6}\right)$$

$p_T R \gg m_{\text{top}}$ and $R \ll 1$

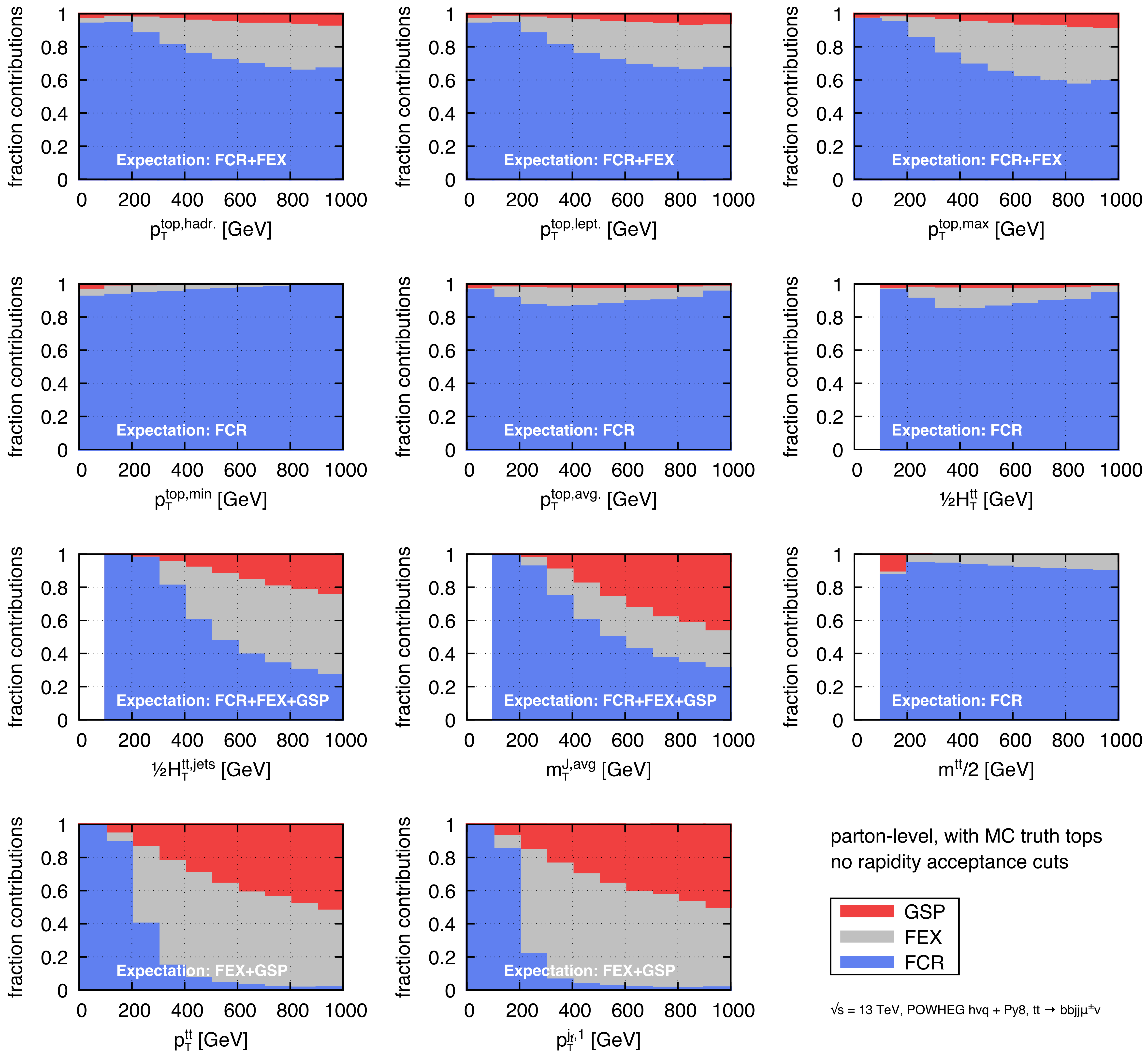
NB: is negative for $p_{T,t} = 1$ TeV, $R = 1$, i.e. not 1 TeV is not sufficiently asymptotic

$$\mathcal{P}_{g\to t\bar{t}} \simeq \frac{\alpha_s T_R}{2\pi}\frac{1}{3}\frac{\ln(1 + e^{4x-23/3} + e^{2x}/10)}{1 - 0.101e^{-(x-2.2)^2/2.3}}\,, \qquad x = \ln\frac{p_{T,t}R}{m_{\text{top}}}$$

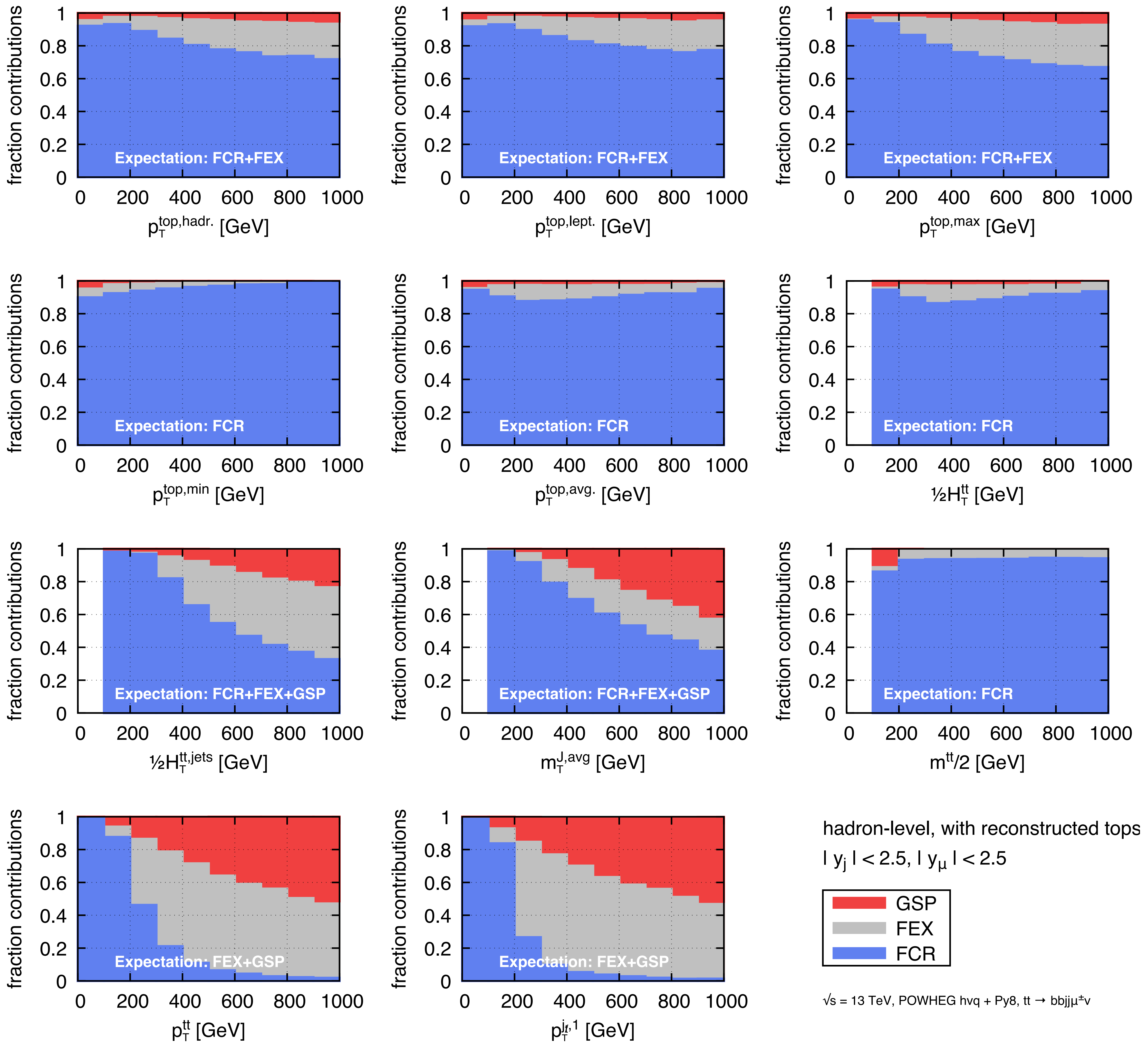
$p_T \gg m_{\text{top}}$ and $R \ll 1$

truth v. reconstructed tops

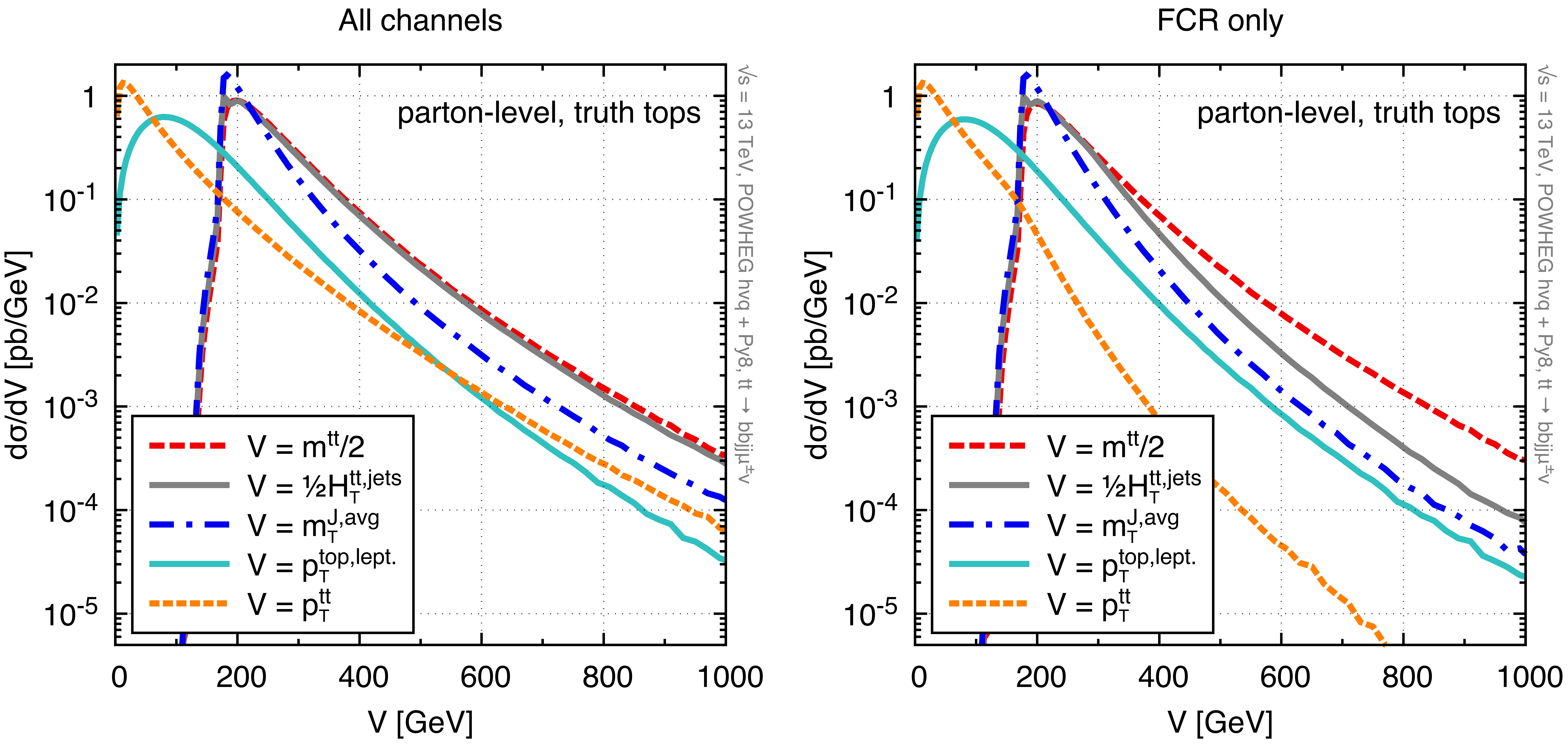
parton-level analysis



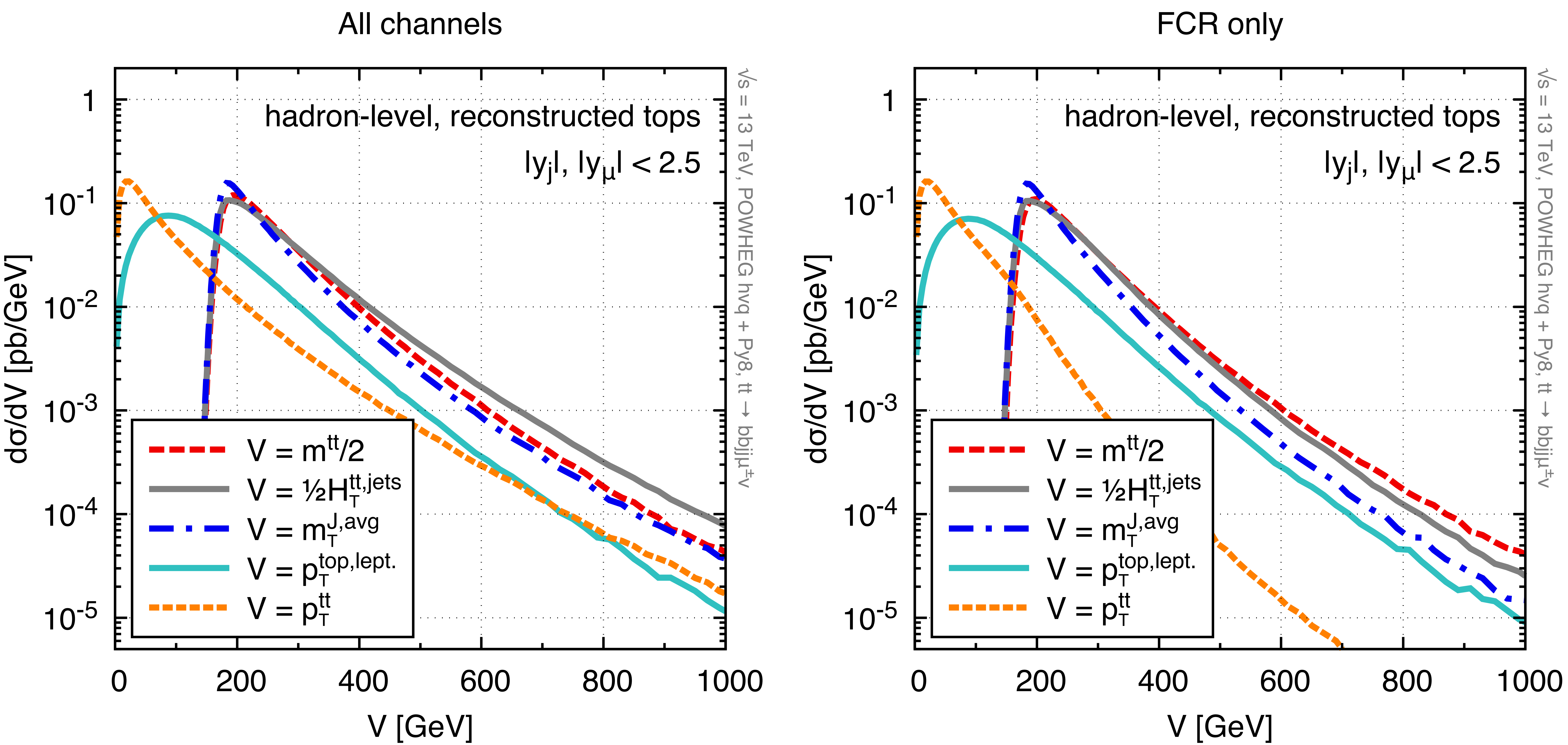
fiducial particle (hadron) level



Parton-level spectra

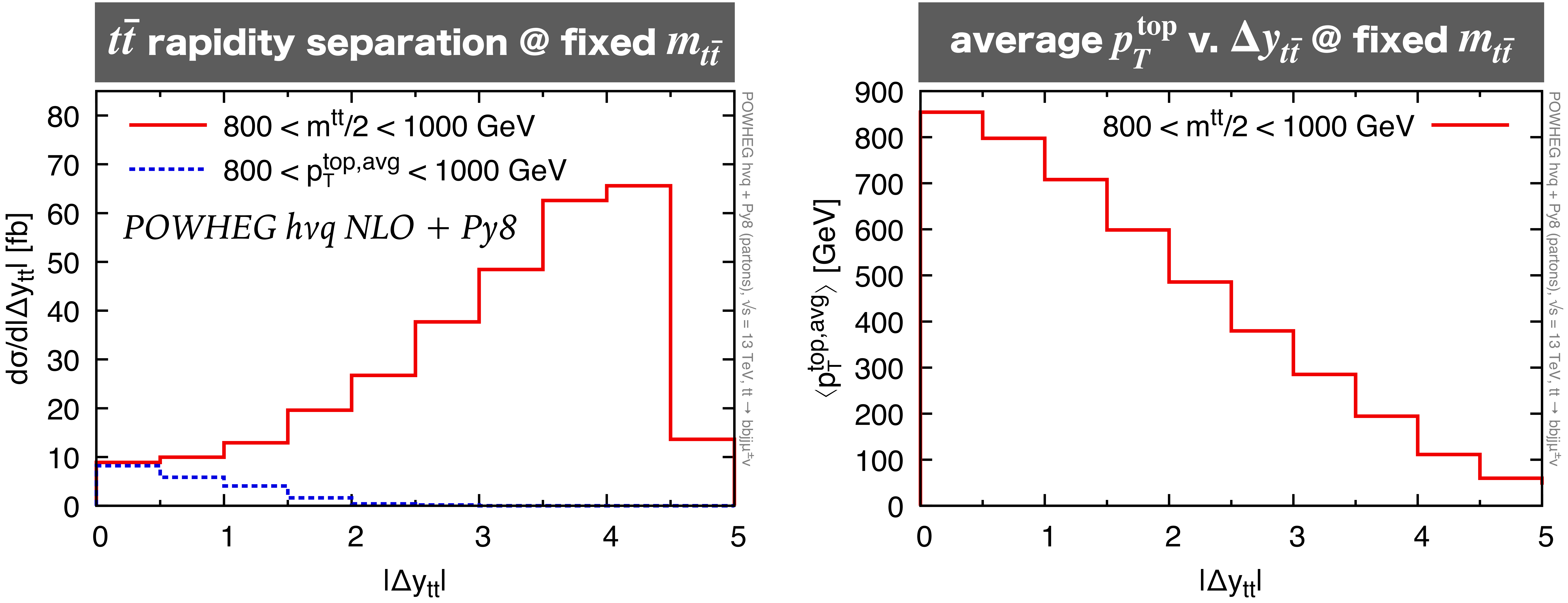


Fiducial particle (hadron) level spectra



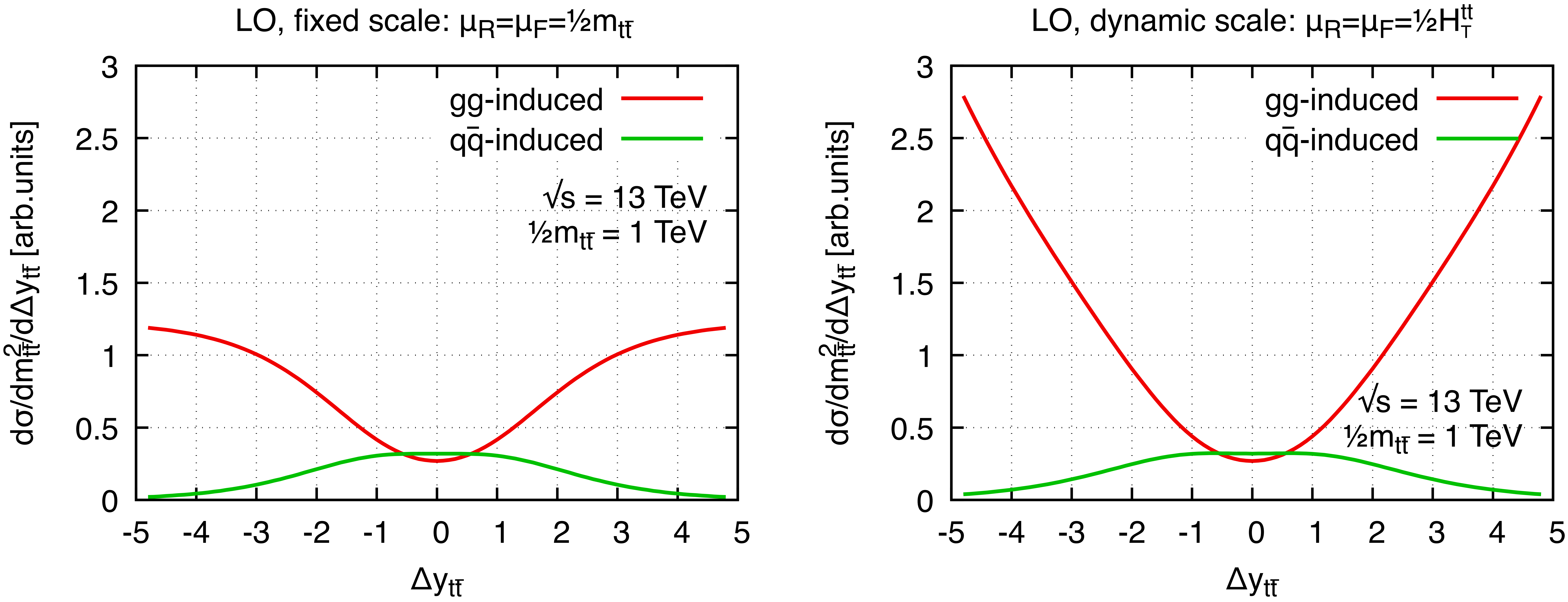
large $m_{t\bar{t}}$

Enhancement at large $\Delta y_{t\bar{t}}$ even stronger at NLO

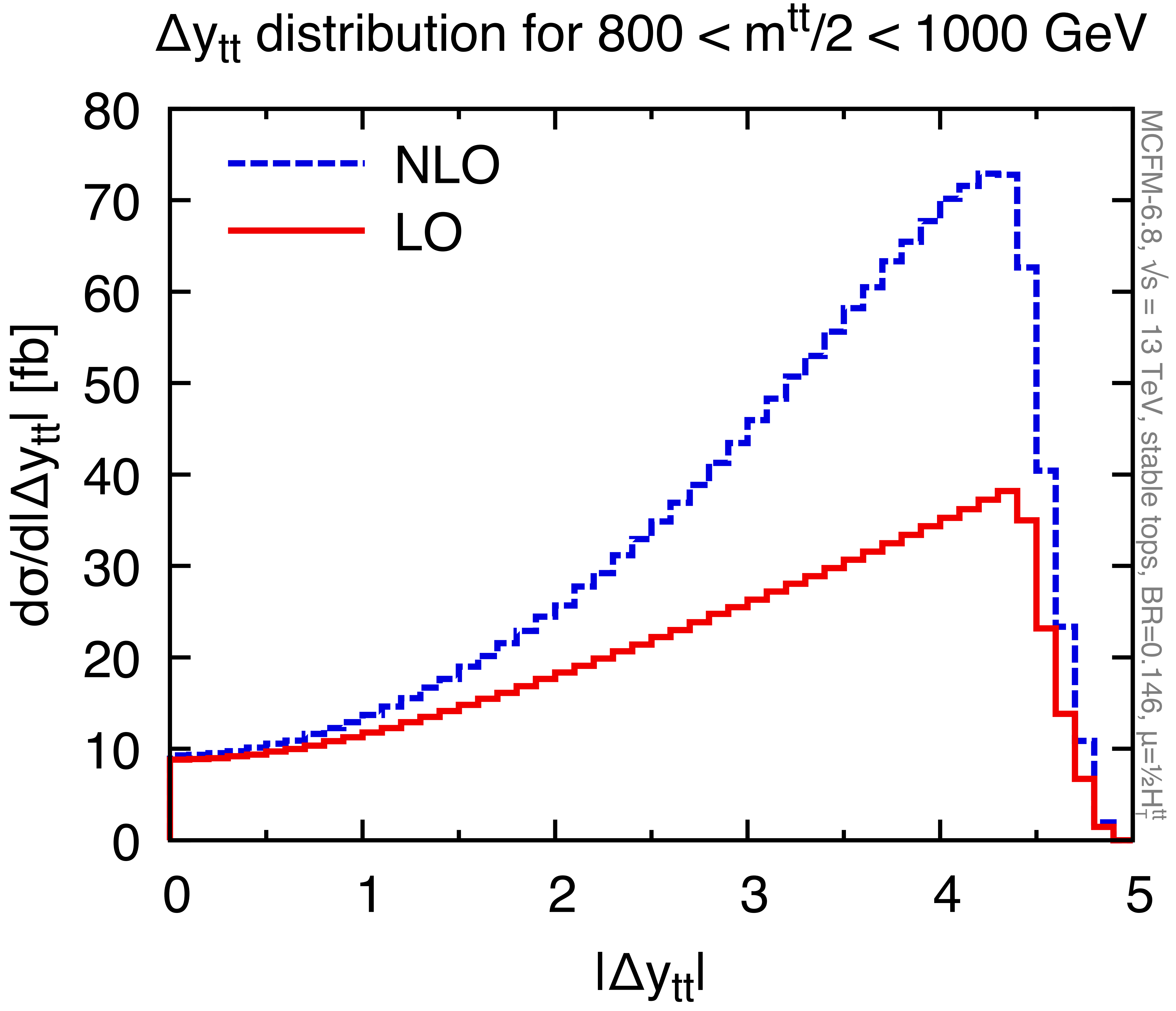


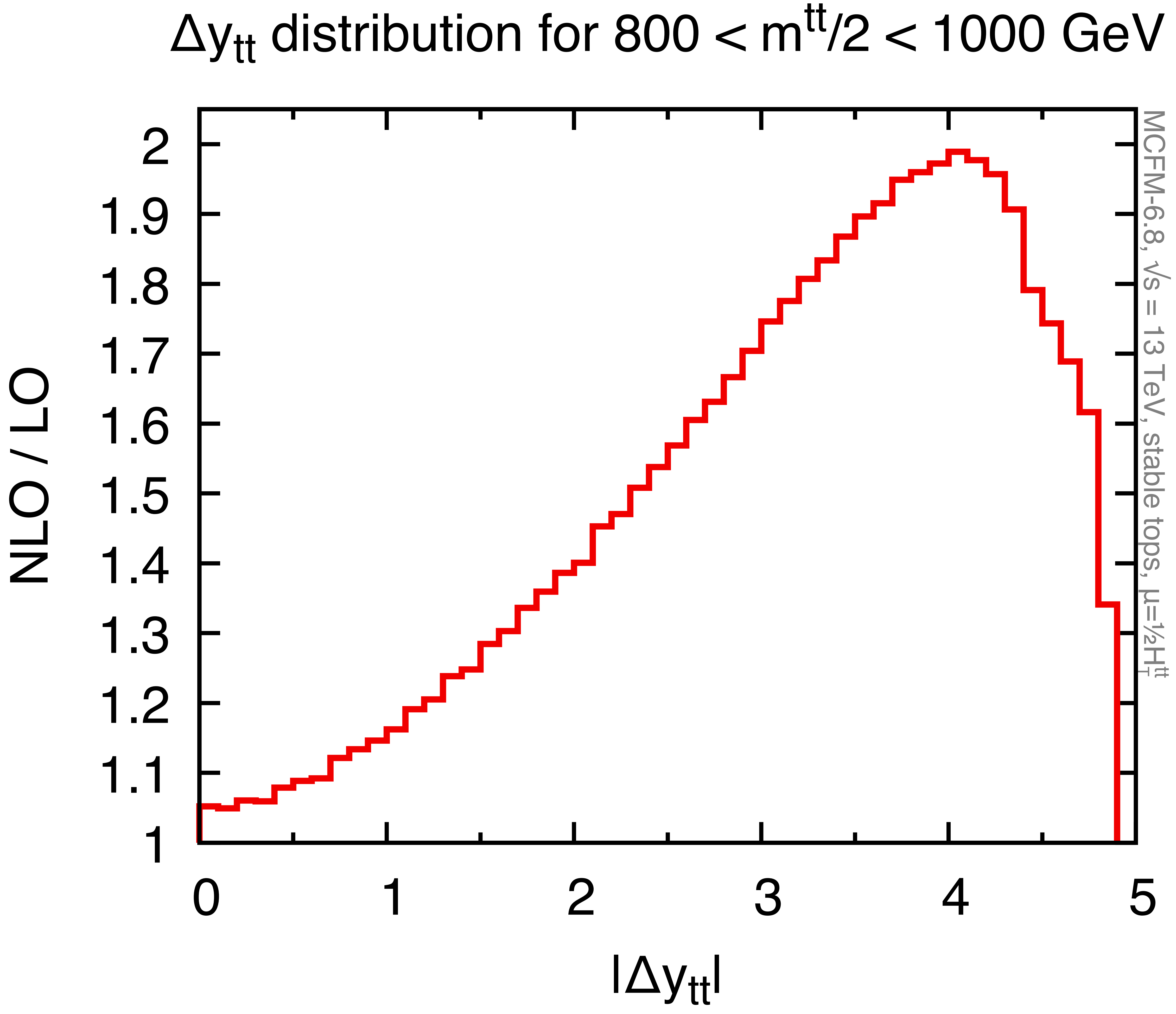
Large $m_{t\bar{t}}$ does not imply large p_T^{top}

LO for fixed m_{tt} – with fixed. v running scale

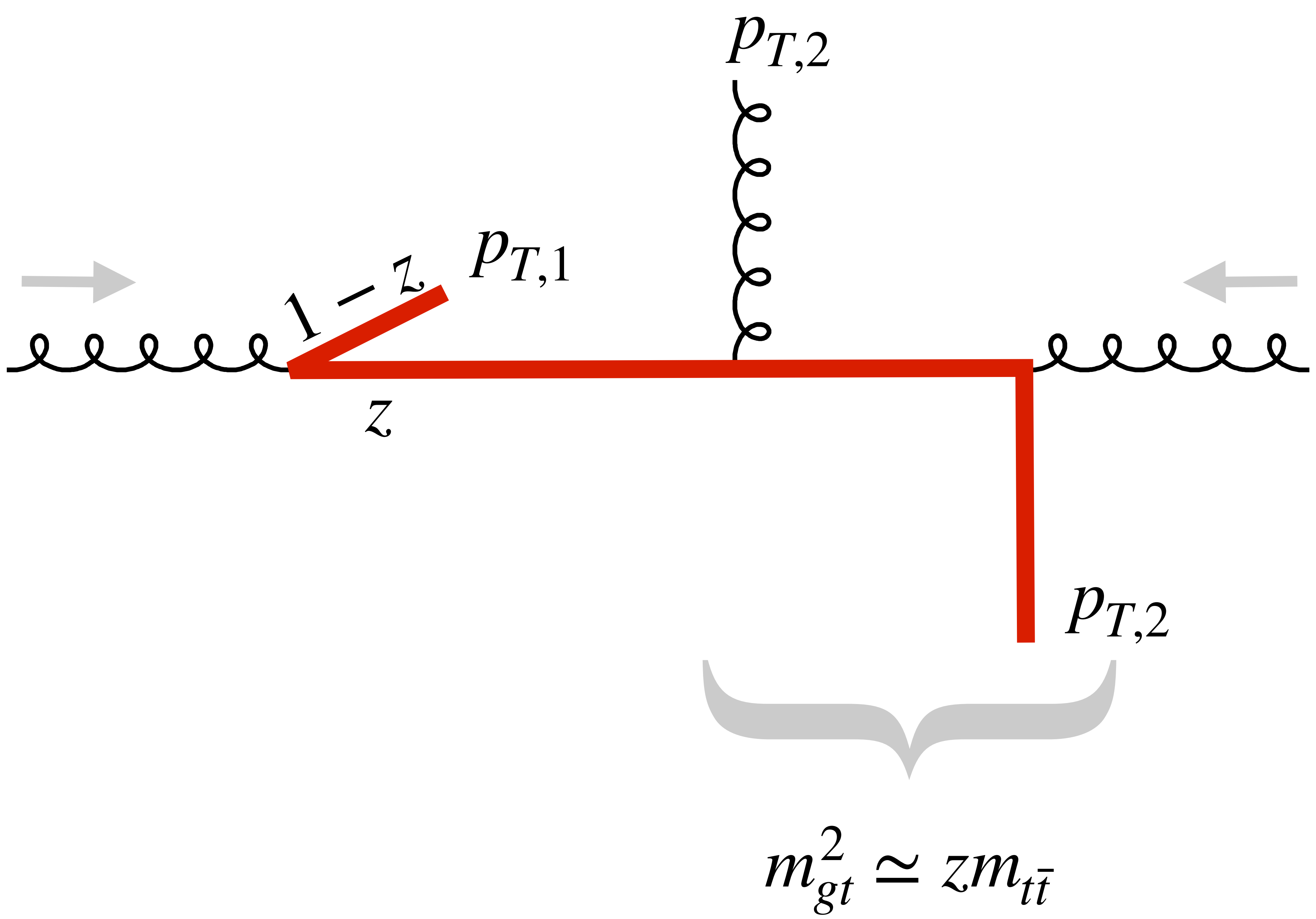


NLO v. LO for fixed m_{tt} bin [MCFM]





Kirschner–Lipatov double logs at NLO



$$\frac{d\sigma}{dm_{t\bar t}^2} = \int dz P_{tg}(z) \frac{dp_{t1}^2}{p_{t1}^2} \int dm_{tg}^2 \frac{d\sigma_{tg\to gt}^{t-\text{chan}}}{dm_{tg}^2} \delta(m_{t\bar t}^2 - m_{tg}^2/z)$$

$$= \int dz P_{tg}(z) \frac{dp_{t1}^2}{p_{t1}^2} z \left. \frac{d\sigma_{tg\to gt}^{t-\text{chan}}}{dm_{tg}^2} \right|_{m_{tg}^2 = z m_{t\bar t}^2}$$

$$\propto \int dz \alpha_s \frac{dp_{t1}^2}{p_{t1}^2} z \frac{\alpha_s^2 \ln m_{t\bar t}^2/p_{t1}^2}{(z m_{t\bar t}^2)^2}$$

$$\propto \frac{\alpha_s^2}{m_{t\bar t}^4} \ln^3 \frac{m_{t\bar t}^2}{m_{\text{top}}^2}$$

- They are present also in non-singlet splitting functions, and subleading corrections are quite large, so conceivably not relevant until beyond-LHC
- Beyond LHC, watch out also for 4-top ($\alpha_s^4/m_{t\bar t}^2 m_{\text{top}}^2$) and $b\bar b \to t\bar t$ (EW, $\alpha_{\text{EW}}^2/m_{t\bar t}^2 m_{\text{top}}^2$)