Framing energetic top-quark pair production at the LHC

LHC Top WG meeting, 19 May 2021

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Rudolf Peierls Centre for Theoretical Physics & Wadham College

with Frédéric Dreyer, Ross McDonald and Gavin Salam, arXiv:2101.06068

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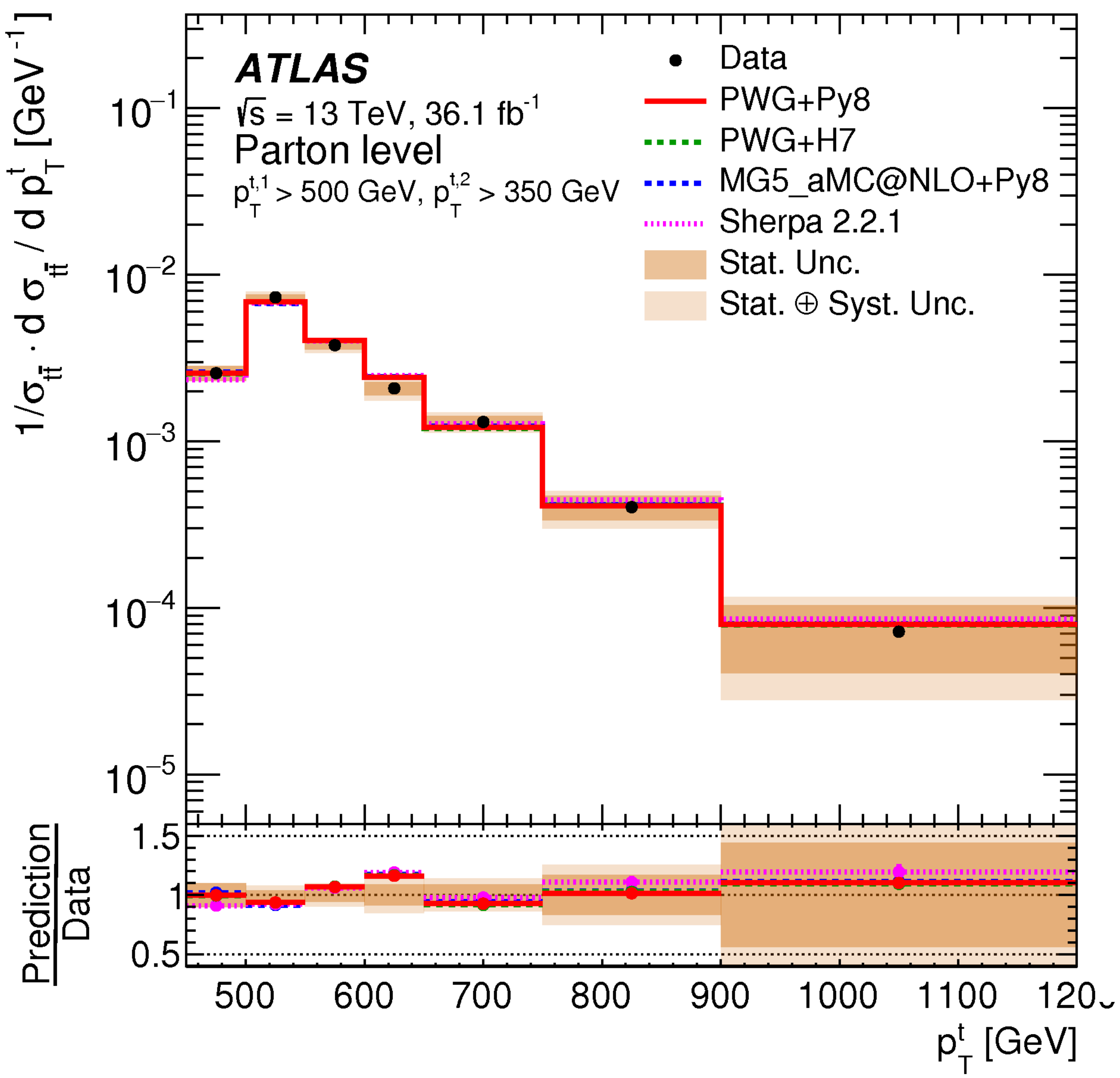
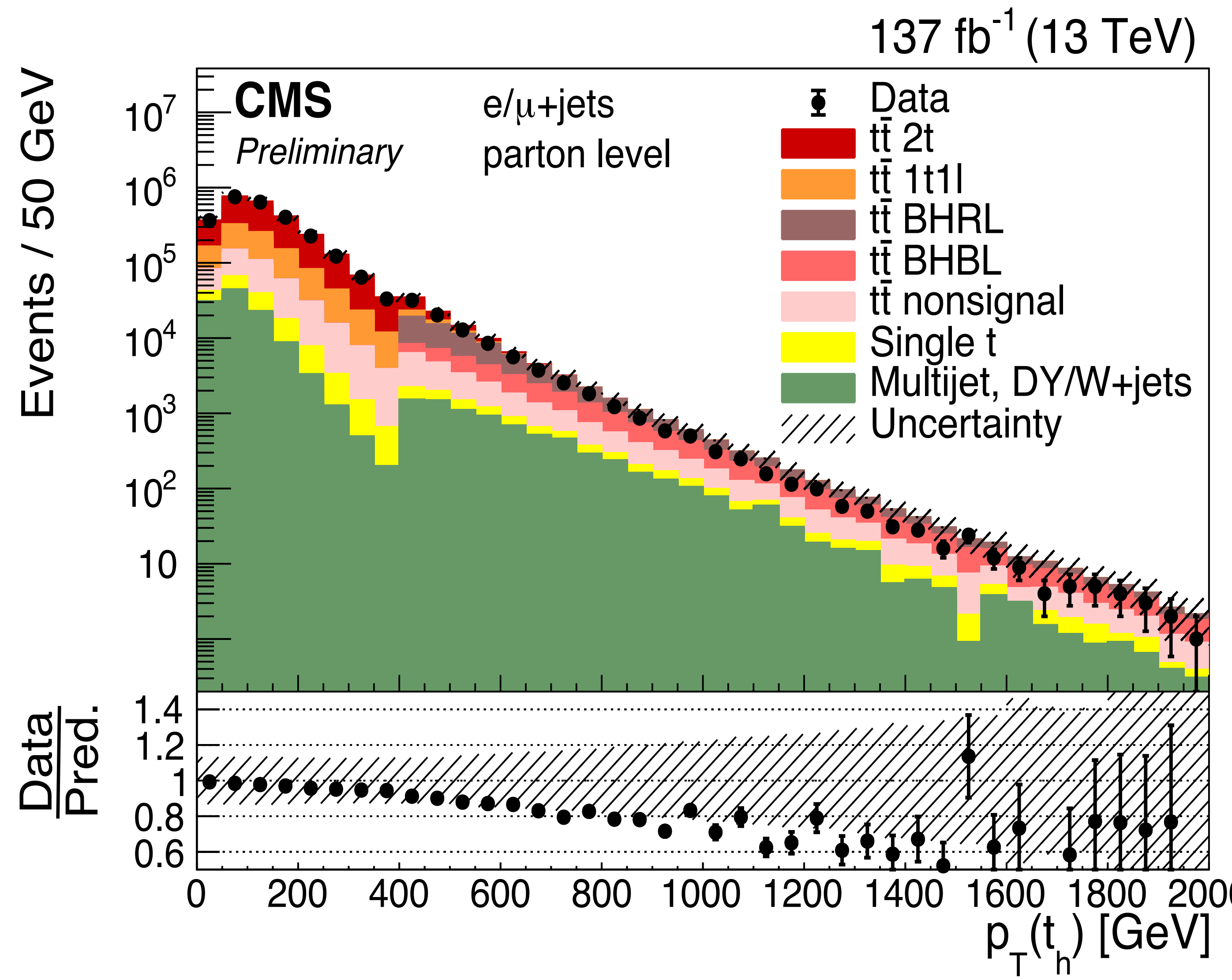
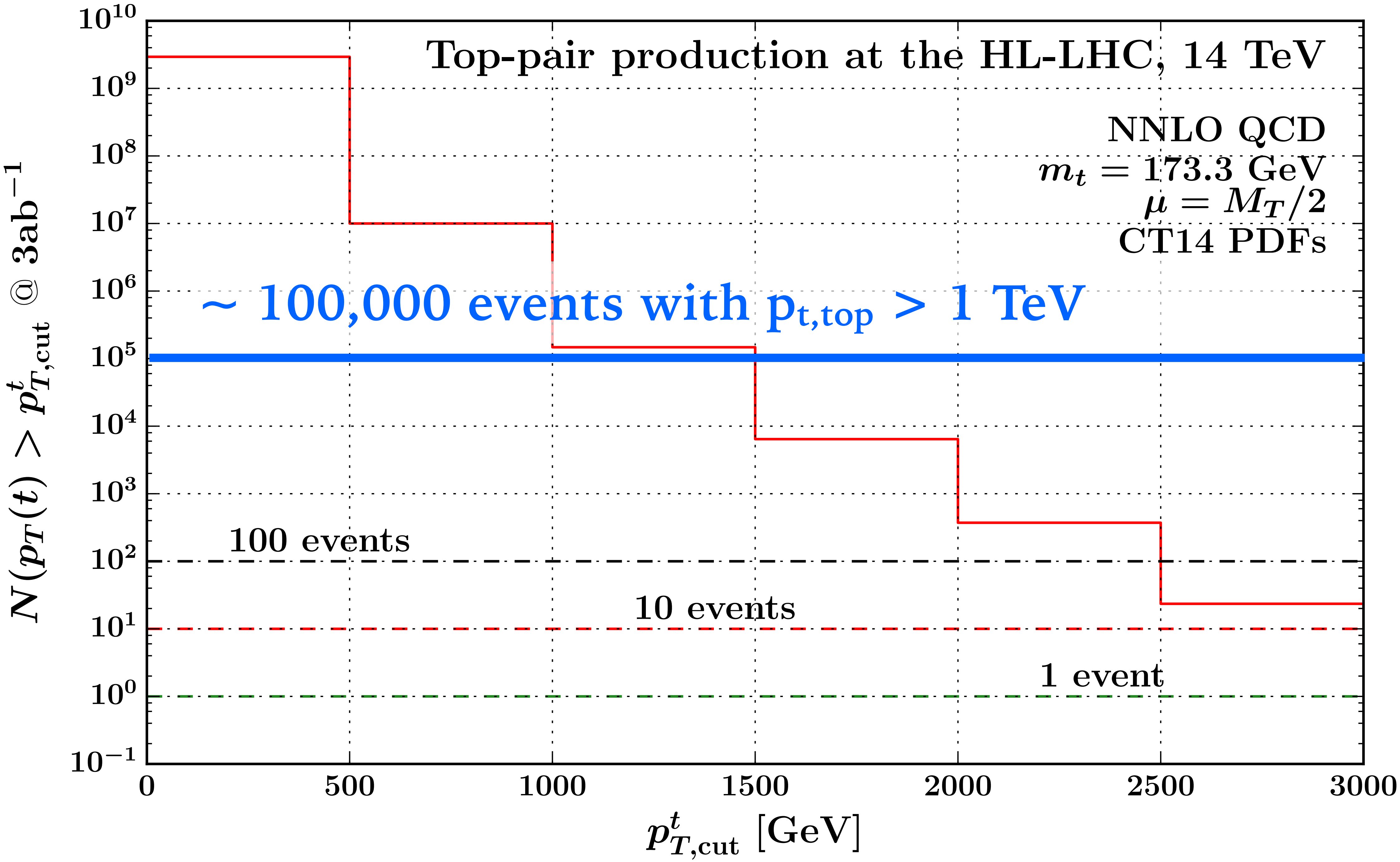
"Energetic tops": exploring the TeV region





- Significant fraction of events at the TeV scale
- p_t ~ 800-900 GV: 15-20% uncertainty

Energetic tops at the HL-LHC



[SM@HE-HL report, 1902.04070]

- Precise investigations of the TeV region possible at the HL-LHC

Main philosophy and outline

The ultimate goal:

provide a framework for thinking about energetic top-pair production

Mandatory feature:

this should be concrete, i.e. at implementable in actual experimental analysis (reconstruction…)

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Outline:

- Energetic top-pair production at LO&beyond
- Implications for LHC phenomenology: top-parton studies
- Why is this useful?
- Designing analysis strategies: reconstruction at hadron (particle) level

(In what follows: semileptonic $t\bar{t}$ decay for concreteness)

"Energetic" tops

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 $m_T^2 = p_T^2 + m^2$
$p_T^{\text{top,min}}$	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

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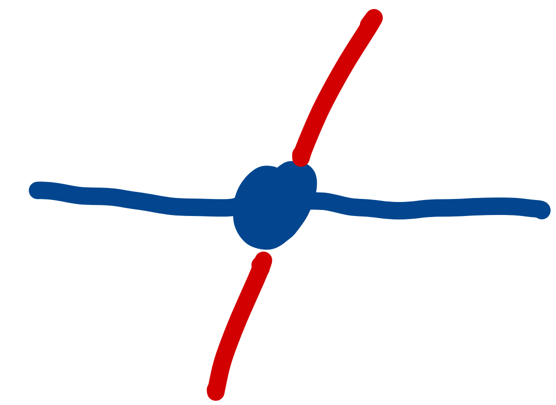
$p_T^{\mathrm{top,had}}$ $p_T^{\mathrm{top,lep}}$ $p_T^{\mathrm{top,max}}$ $p_T^{\mathrm{top,min}}$ $p_T^{\mathrm{top,avg}}$	Identical at LO 
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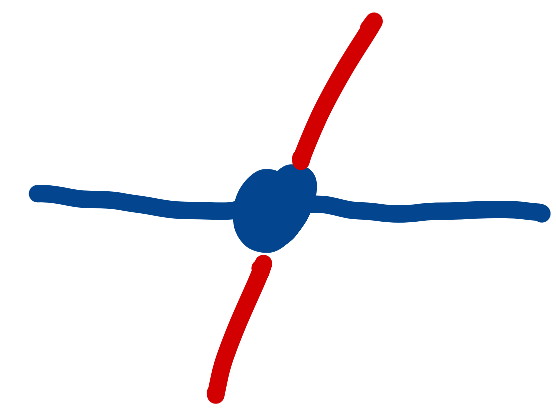
$p_T^{\mathrm{top,had}}$ $p_T^{\mathrm{top,lep}}$ $p_T^{\mathrm{top,max}}$ $p_T^{\mathrm{top,min}}$ $p_T^{\mathrm{top,avg}}$	Identical at LO & high p_t 
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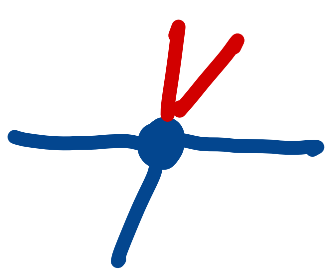
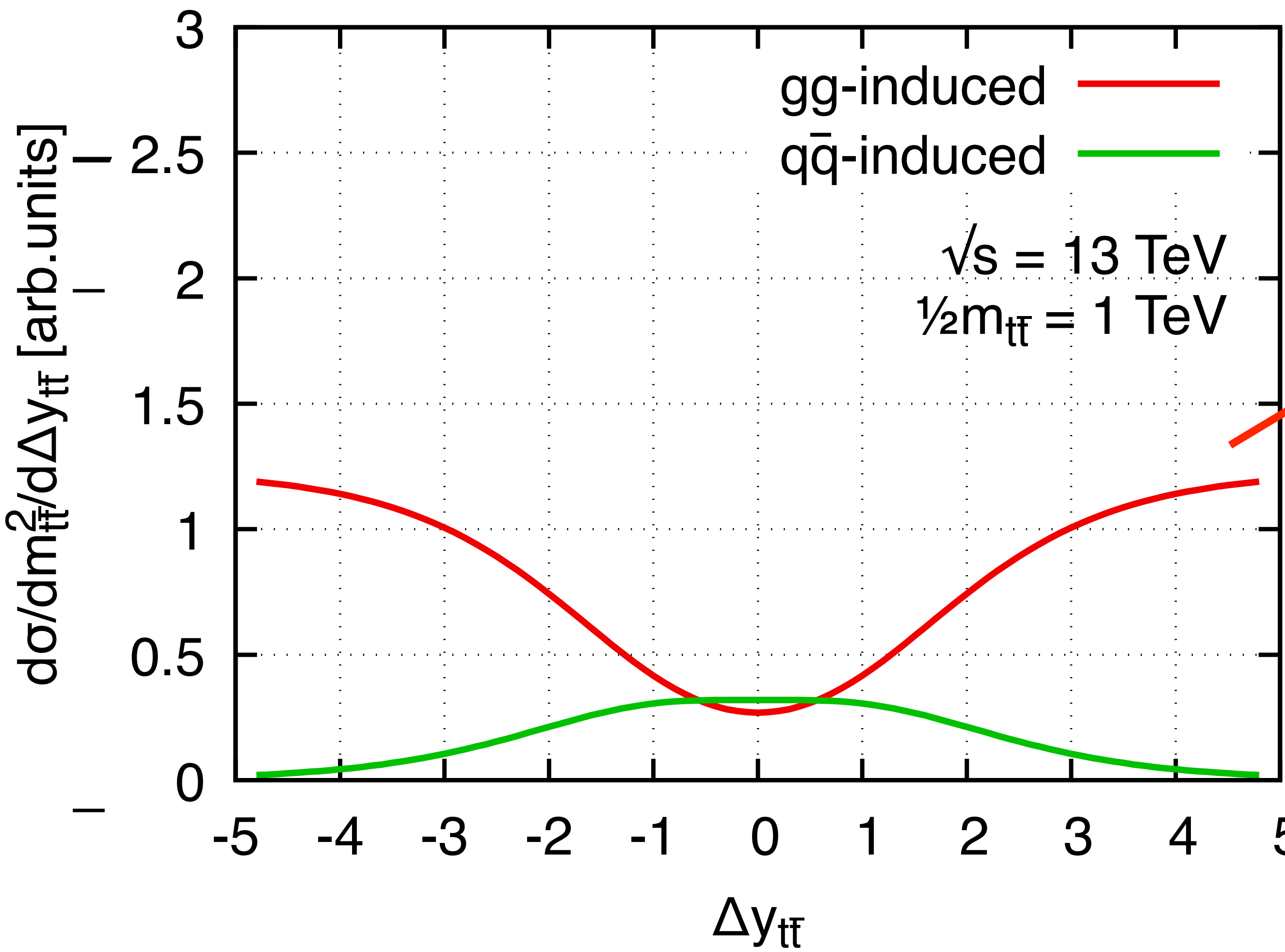
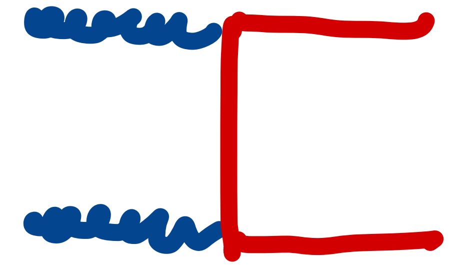
$p_T^{t\bar{t}}$ $p_T^{j_{\not{t}},1}$	α_s suppressed, starts at NLO



"Energetic" tops





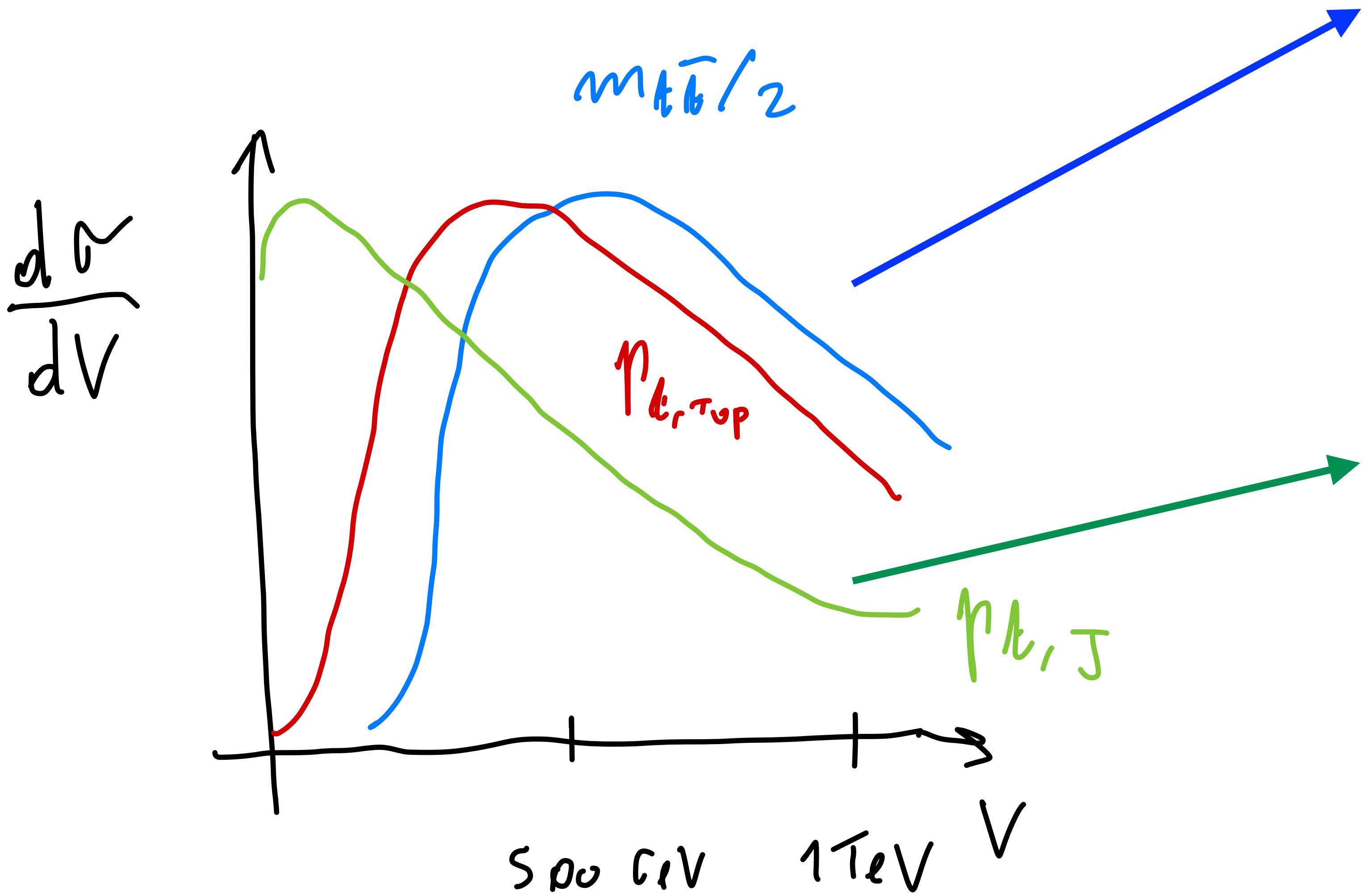
$$\Delta y_{t\bar{t}}^{\max} \approx 2 \ln m_{t\bar{t}} / m_{\mathrm{top}}$$

$$\frac{d\sigma}{dm_{t\bar{t}}^2} = \frac{\alpha_s^2 \pi}{m_{t\bar{t}}^4} \left[\left(\frac{1}{3} \ln \frac{m_{t\bar{t}}^2}{m_t^2} - \frac{7}{12} \right) \mathcal{L}_{gg} + \frac{8}{27} \mathcal{L}_{q\bar{q}} \right]$$

$\frac{1}{2} m^{t\bar{t}}$ | Very delicate observable at high scales

- Logarithmic enhancement (theoretically delicate beyond LO)
- Contributions from large-y, low-p_t tops (issue for boosted reco...)
- Plus: gluon/quark separation

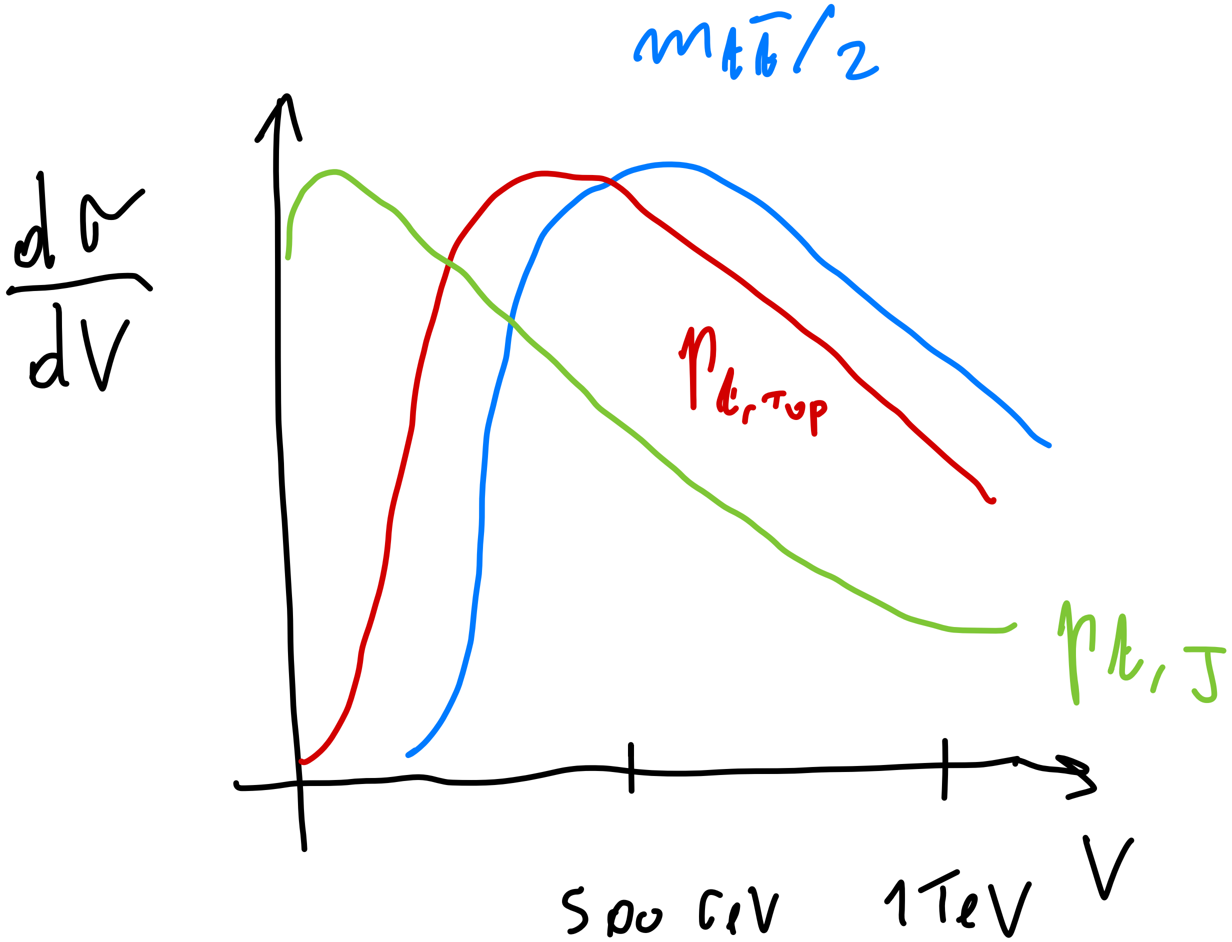
"Energetic" tops: expectations vs reality



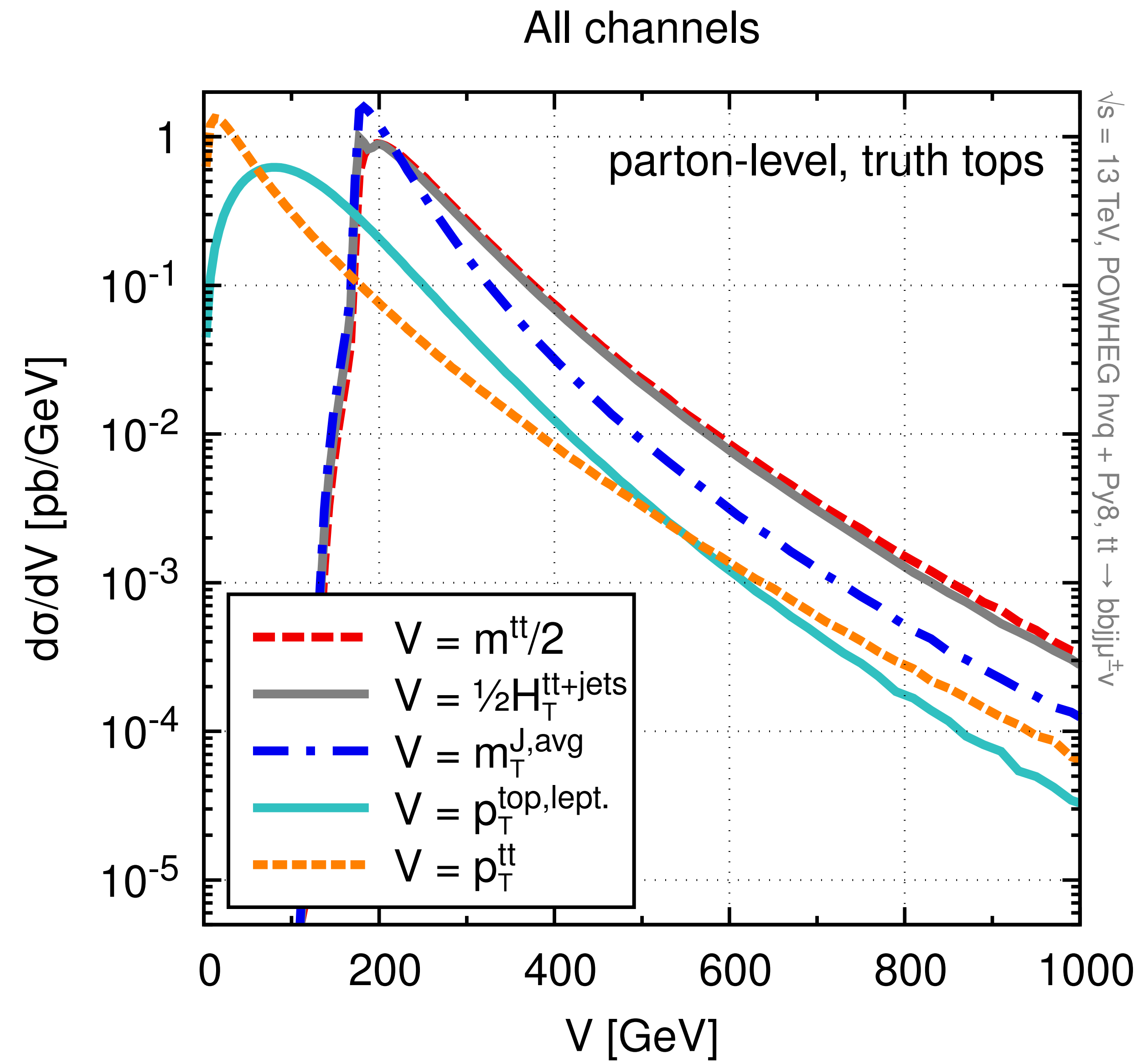
Log-enhanced

α_s suppressed

``Energetic” tops: expectations vs reality



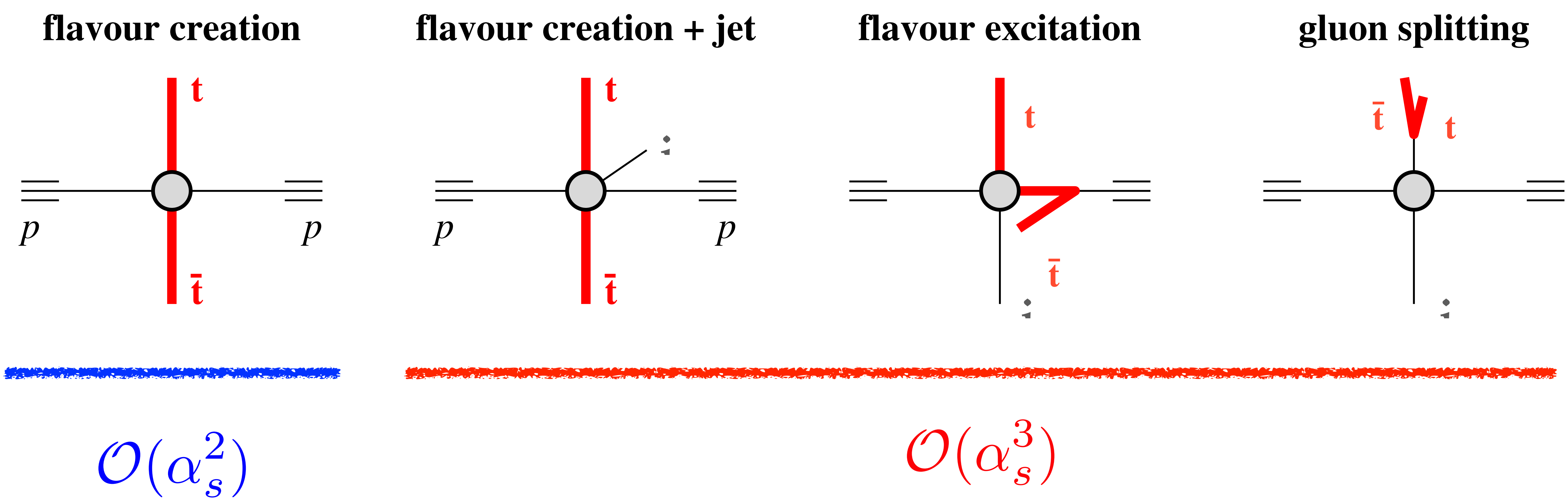
vs



[POWHEG NLO + Pythia8, see backup for full setup]

- ``LO” expectations do not borne out:
- E.g.: $m_{tt}/2$ > $H_t^{tt,jets}/2$ ~ $p_t^{top,lept}$ > p_t^{tt} [expectation] vs
  $m_{tt}/2$ ~ $H_t^{tt,jets}/2$ > p_t^{tt} > $p_t^{top,lept}$ [reality]

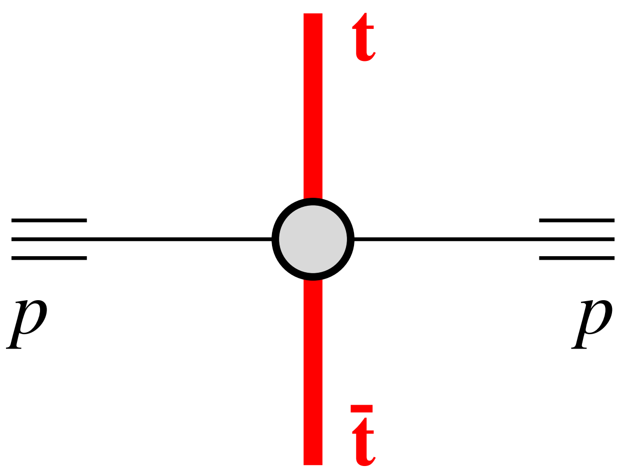
Understending energetic tops: 1-topologies

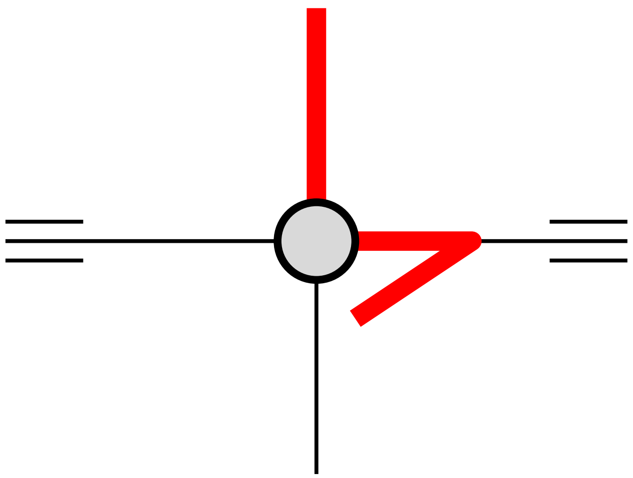


- ``NLO"-topologies suppressed by α_s(1 TeV) ~ 0.09
- $\ln(p_t/m_t)$ ~ 2, not large enough to compensate for α_s
- However, <u>underlying 2→2 scattering very different</u>

FCR vs FEX at high p_t

Consider high-p_t 2→2 scattering, i.e. p_t = 1TeV, $\theta=\pi/2$





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

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

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

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

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

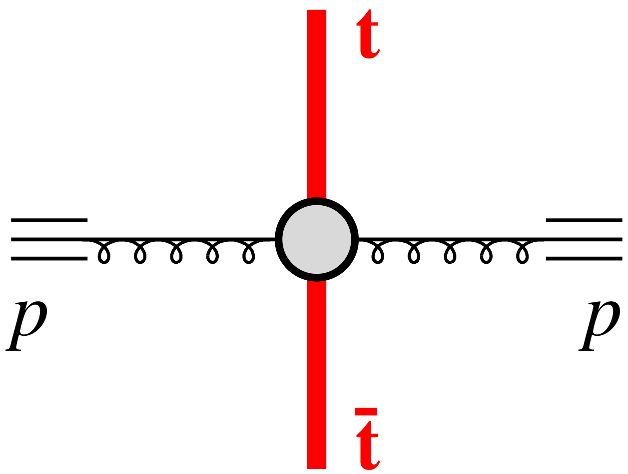
$$\simeq g_s^4 \cdot 0.038$$

Comparable results, t-channel exchange compensates for α_s

FCR vs GSP at high p_t

Consider high-p_t 2→2 scattering, i.e. p_t = 1TeV, θ=π/2

flavour creation

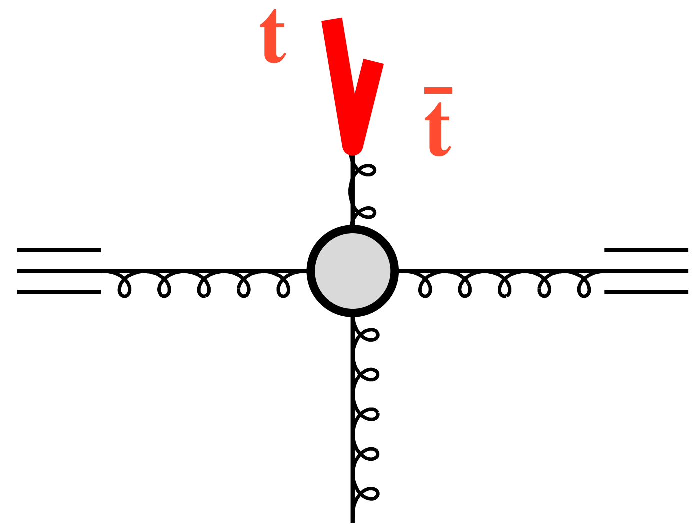


$$\mathscr{L}_{gg} \simeq 0.16$$

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

$$\simeq g_s^4 \cdot 0.024$$

gluon splitting



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

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

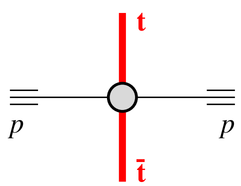
$$\times \mathscr{P}_{g\to t\bar{t}} \simeq \mathbf{0.004}$$

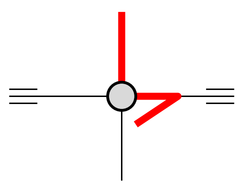
$$\simeq g_s^4 \cdot 0.020$$

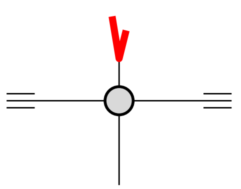
Again, ME enhancement compensates for α_s

FCR vs GSP at high p_t

Consider high-p_t 2→2 scattering, i.e. p_t = 1TeV, $\theta=\pi/2$







topology	channel	$\|ME\|^2$	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

- At high-p_t no ``perturbative” hierarchy, all topologies contribute equally
- Similar effects observed for b-production at the Tevatron [Banfi, Salam, Zanderighi 07]
- LHC: crucial role of t-channel enhancements (logs are not large)

Topologies vs observables: general principles

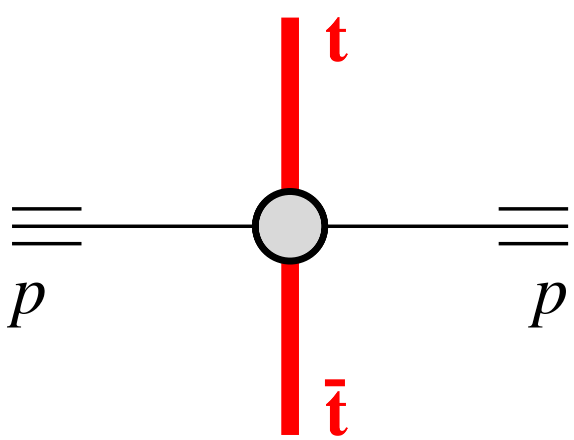
- For similar underlying 2 → 2 configurations: FCS ~ FEX ~ GSP
- However: different observables probe different underlying 2 → 2 configurations
- 2 → 2 cross section decreases very fast, $\sigma(p_t^{2\to2} > X) \sim 1/X^7$
- Small changes in X lead to large changes in σ

Topologies vs observables: general principles

Example: $p_t^{\text{top, max}}$

If $p_t^{\text{top, max}} = 1$ TeV, then

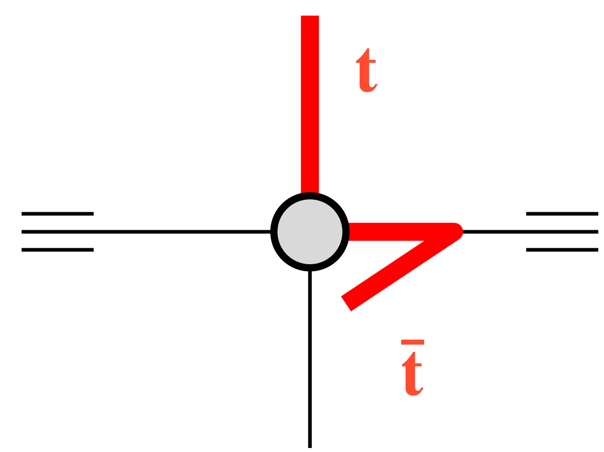
flavour creation



$p_t^{2\to2} = 1$ TeV

✔

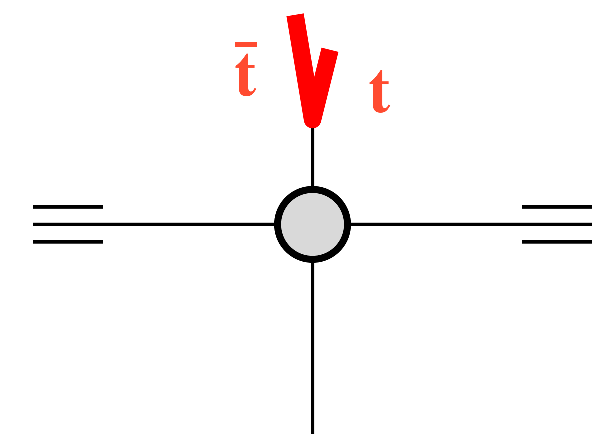
flavour excitation



$p_t^{2\to2} = 1$ TeV

✔

gluon splitting



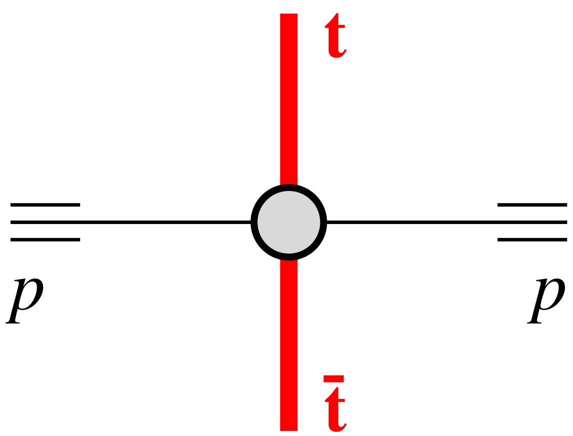
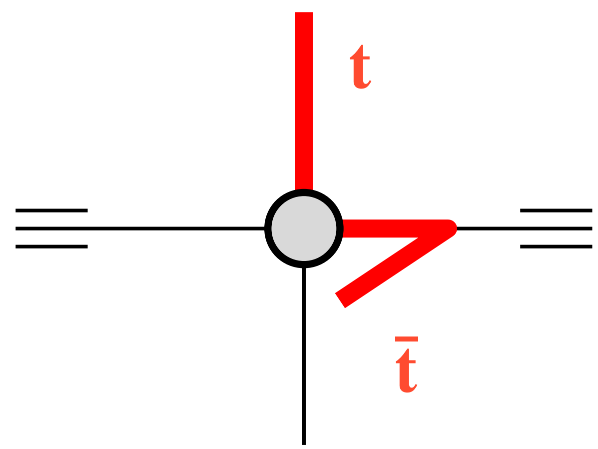
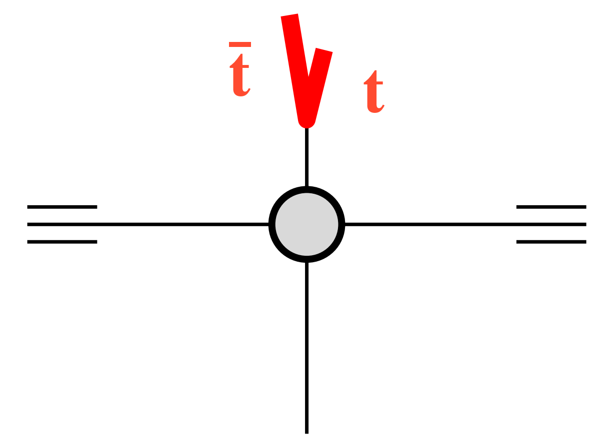
$p_t^{2\to2} \sim 1.5$ TeV

Suppressed by $(1/1.5)^7$

Topologies vs observables: general principles

Example: $p_t^{\text{top, min}}$

If $p_t^{\text{top, min}} = 1$ TeV, then

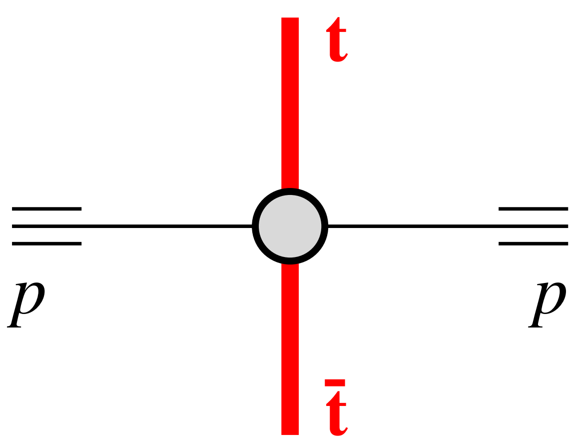
flavour creation	flavour excitation	gluon splitting
		
$p_t^{2\to2} = 1$ TeV	$p_t^{2\to2} \gtrsim 2$ TeV	$p_t^{2\to2} \gtrsim 2$ TeV
✔	Suppressed by $(1/2)^7$	Suppressed by $(1/2)^7$

Topologies vs observables: general principles

Example: $1/2\ H_t^{tt+jets} = 1/2\ (m_t^{top,had} + m_t^{top,lep} + \sum p_t^{jet})$

If $H_t^{tt+jets} = 1$ TeV, then

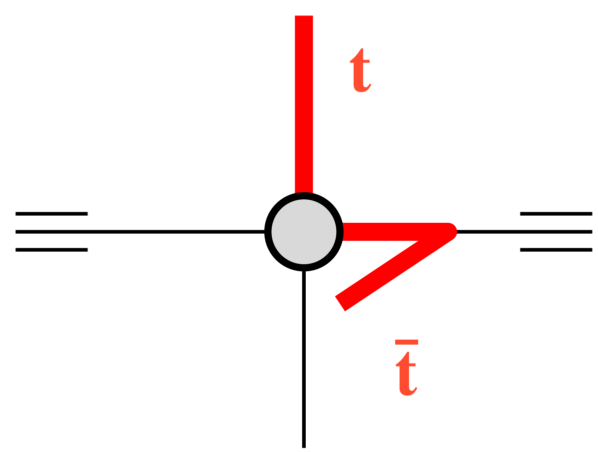
flavour creation



$p_t^{2\to 2} = 1$ TeV

✔

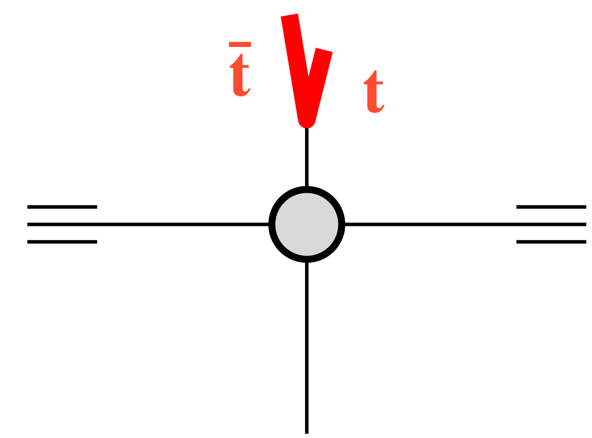
flavour excitation



$p_t^{2\to 2} \gtrsim 2$ TeV

✔

gluon splitting



$p_t^{2\to 2} \gtrsim 2$ TeV

✔

Democratic, all contribute

Topologies vs observables: general principles

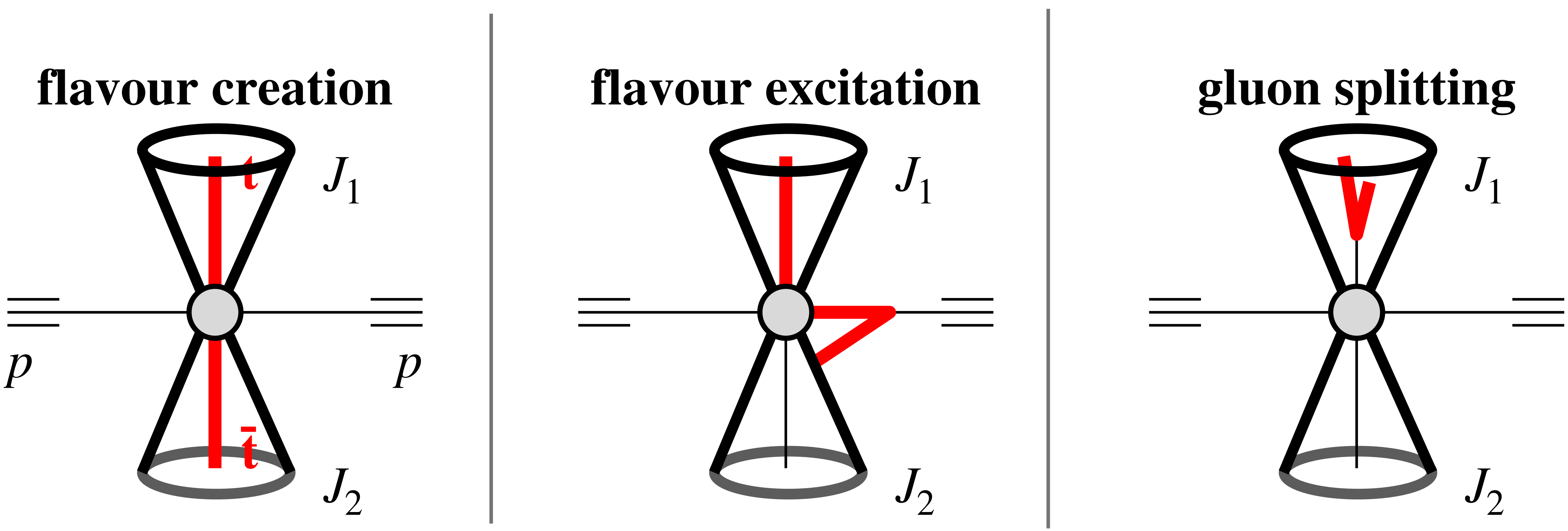
Easy to ``predict" which topologies will contribute

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

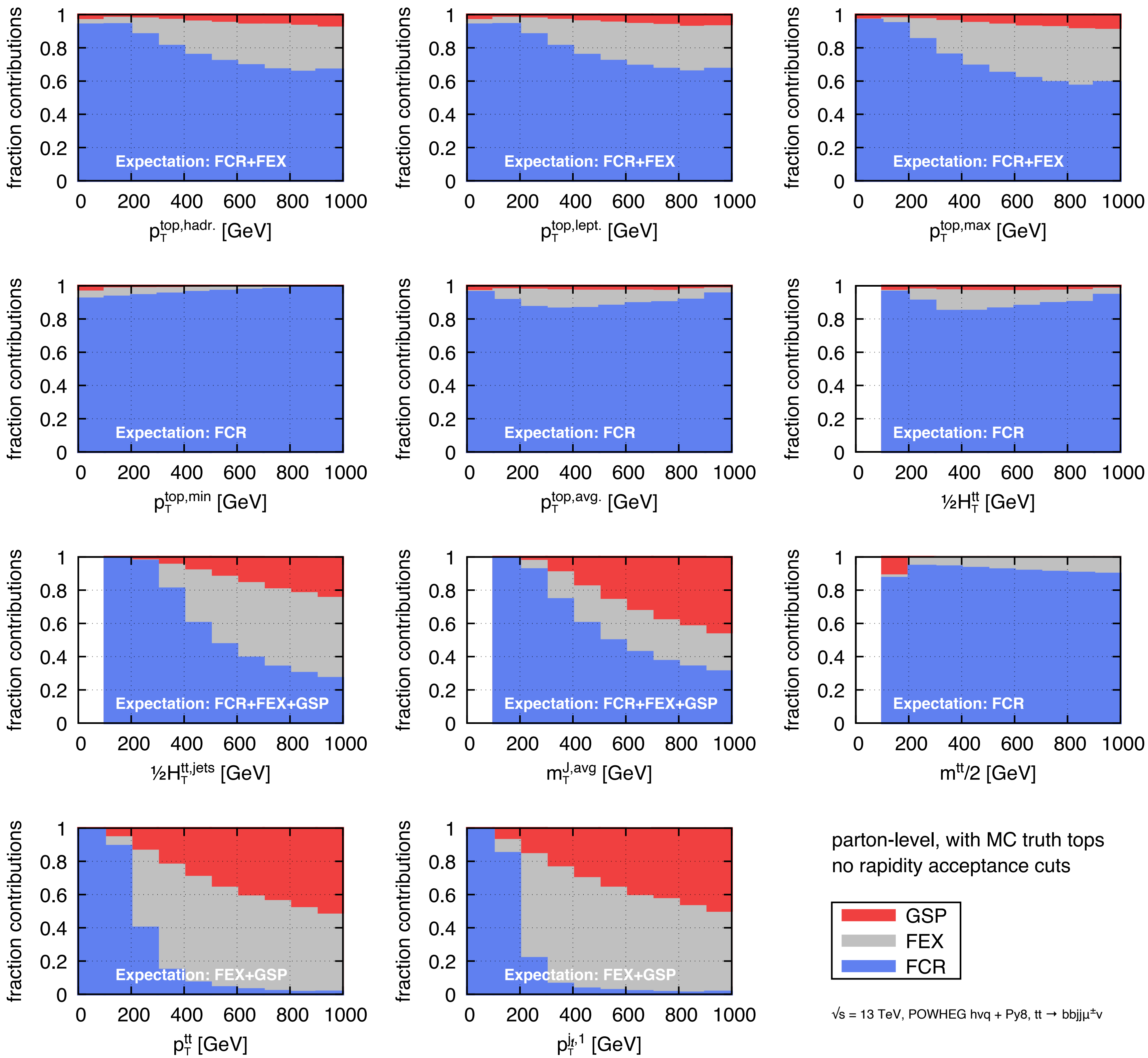
Topology definitions: parton level

1. Take top partons + aKT0.4 jets, and recluster them into R=1 (aKT) jets
2. Assign a topology according to the following

One top in J_1, one top in J_2	One top in either J_1 or J_2	J_1 or J_2 has two tops



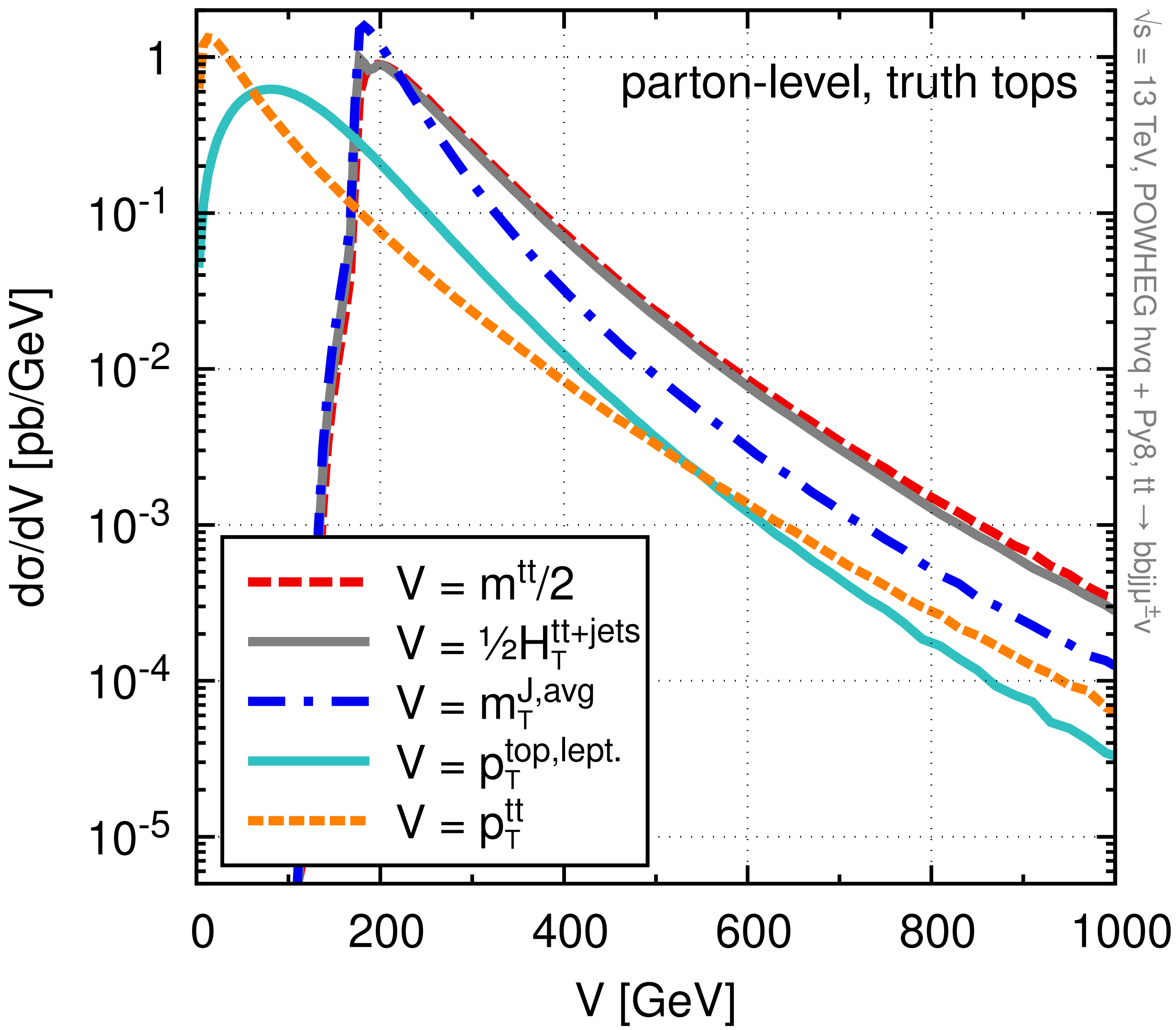
Topologies: validation



POWHEG+Pythia8 predictions in line with expectations

Back to expectation vs reality

Full



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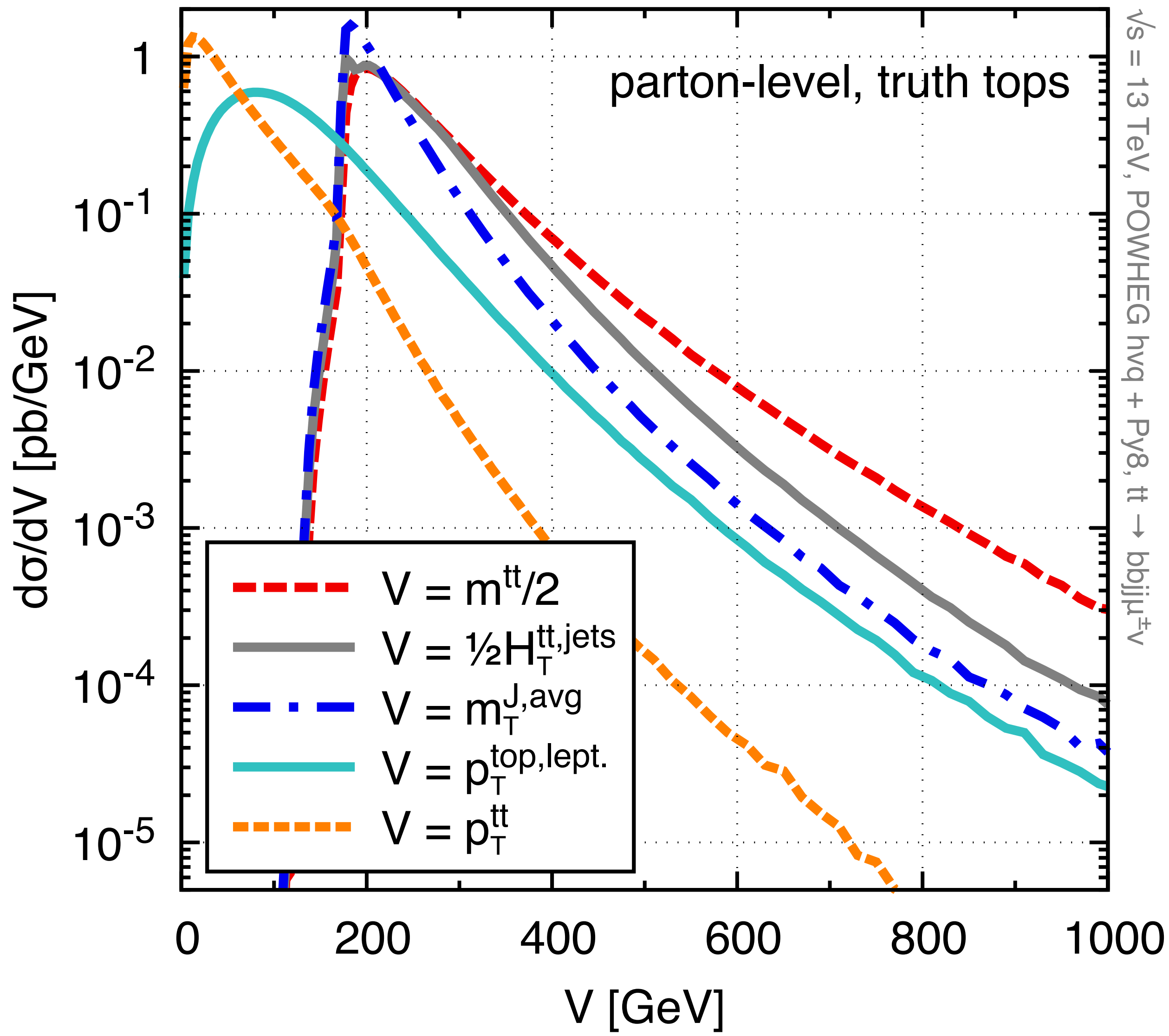
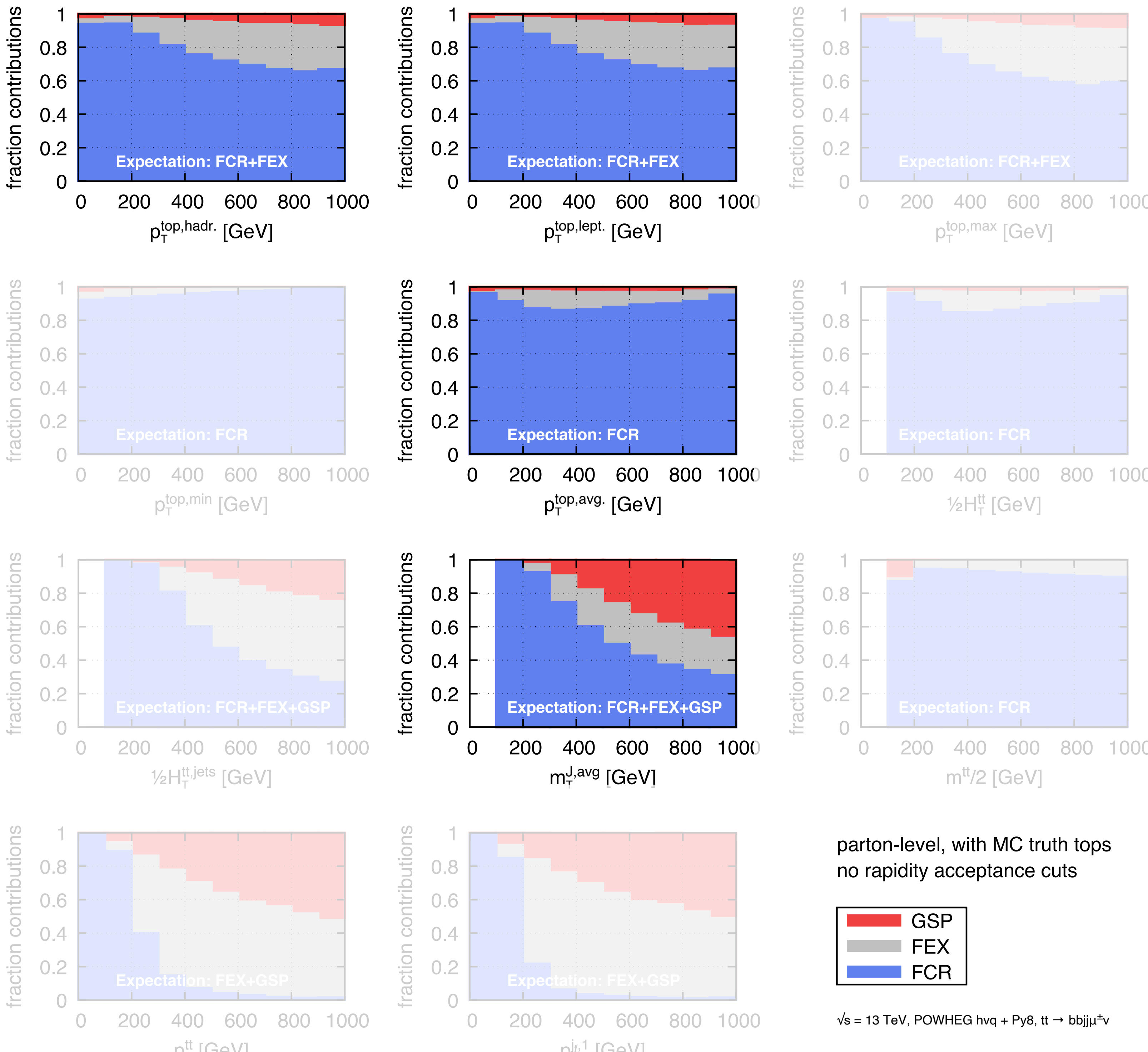


- ``LO" expectations $m_{tt}/2$ > $H_t^{tt,jets}/2$ ~ $p_t^{top,lept}$ > p_t^{tt} borne out in FCR
- Small differences between observables easy to understand

Applications: 1-highest precision

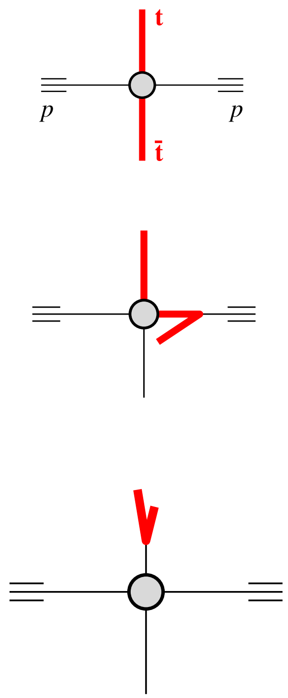


Select FCR-only

Moderate p_t: use ``safe'' observables ($p_t^{top,had/lep/avg}$, NOT $p_t^{top,max/min}$)

Very high p_t: use ``democratic'' $m_t^{jj,avg}$ to avoid logs

Applications: more general physics studies



topology	channel	$\|ME\|^2$	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

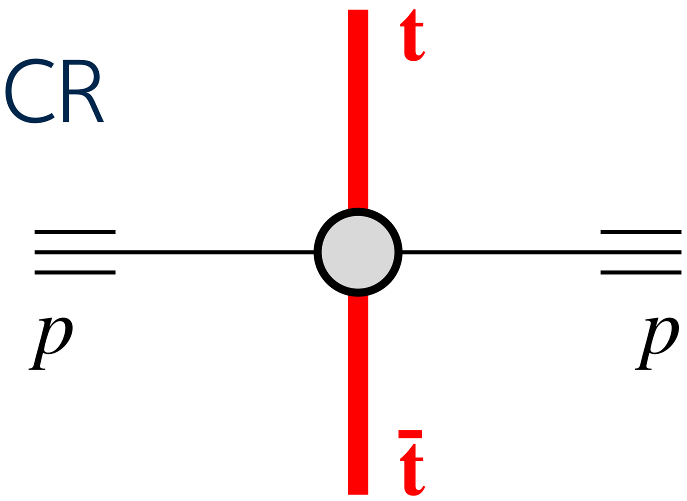
All topologies contribute similarly, but probe quite different structure

→ use to maximise information

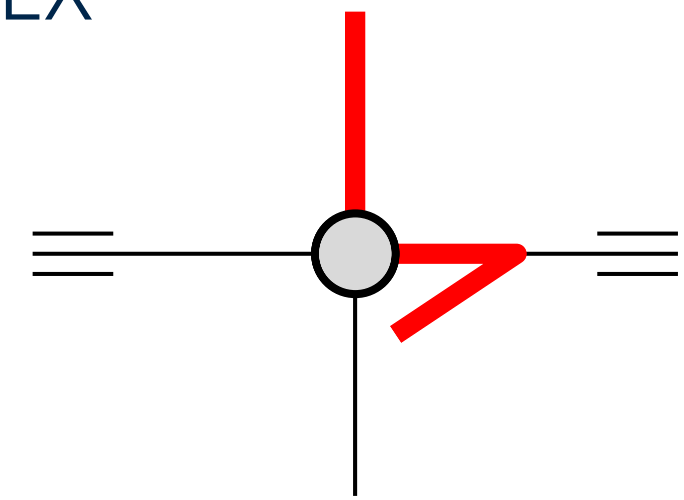
- FCR/FEX/GSP: sensitive to diferent EFT operators/BSM scenarios
- Sensitive to different PDFs/PDFs in different regions (e.g. FEX, g→tt probes gluon at larger-x)
- ...

Devising measurement strategies

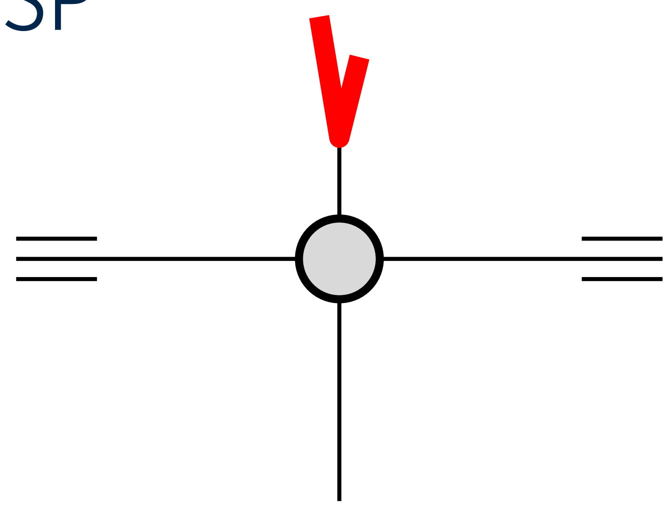
FCR



FEX



GSP

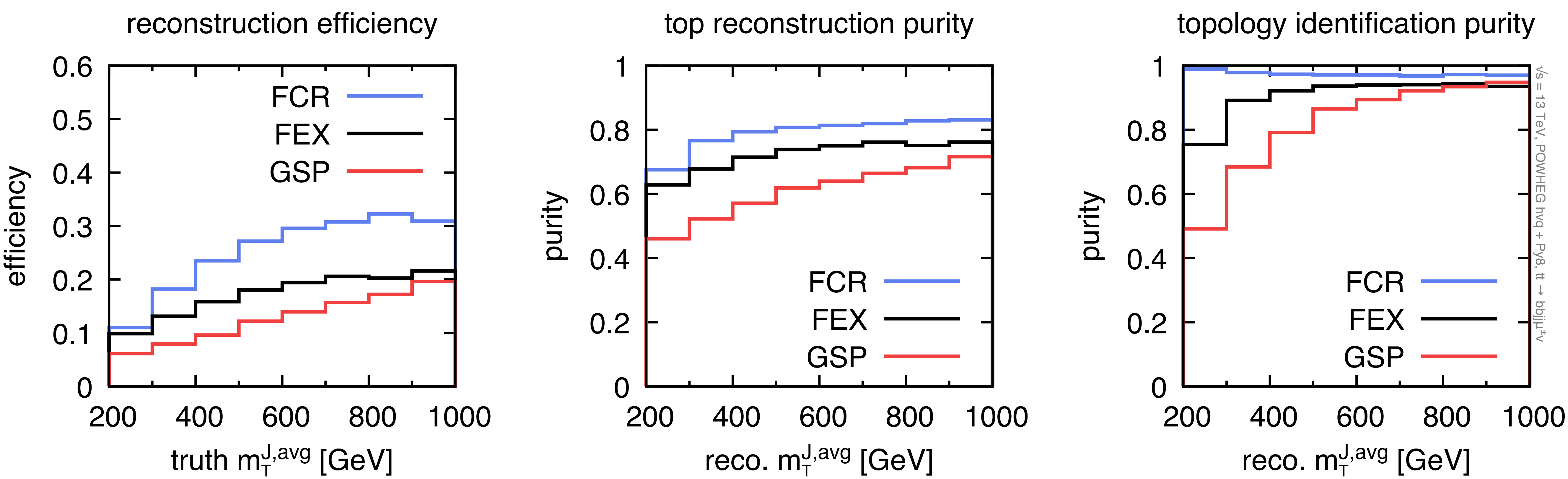


- Usual ``boosted or reconstructed strategy” only works for FCR
- FEX: one low and one high p_t top
- GSP: two tops in the same jet

Critical for unfolding to parton level (if analysis is not sensitive to FEX/GSP, unfolding purely based on MC, not data…)

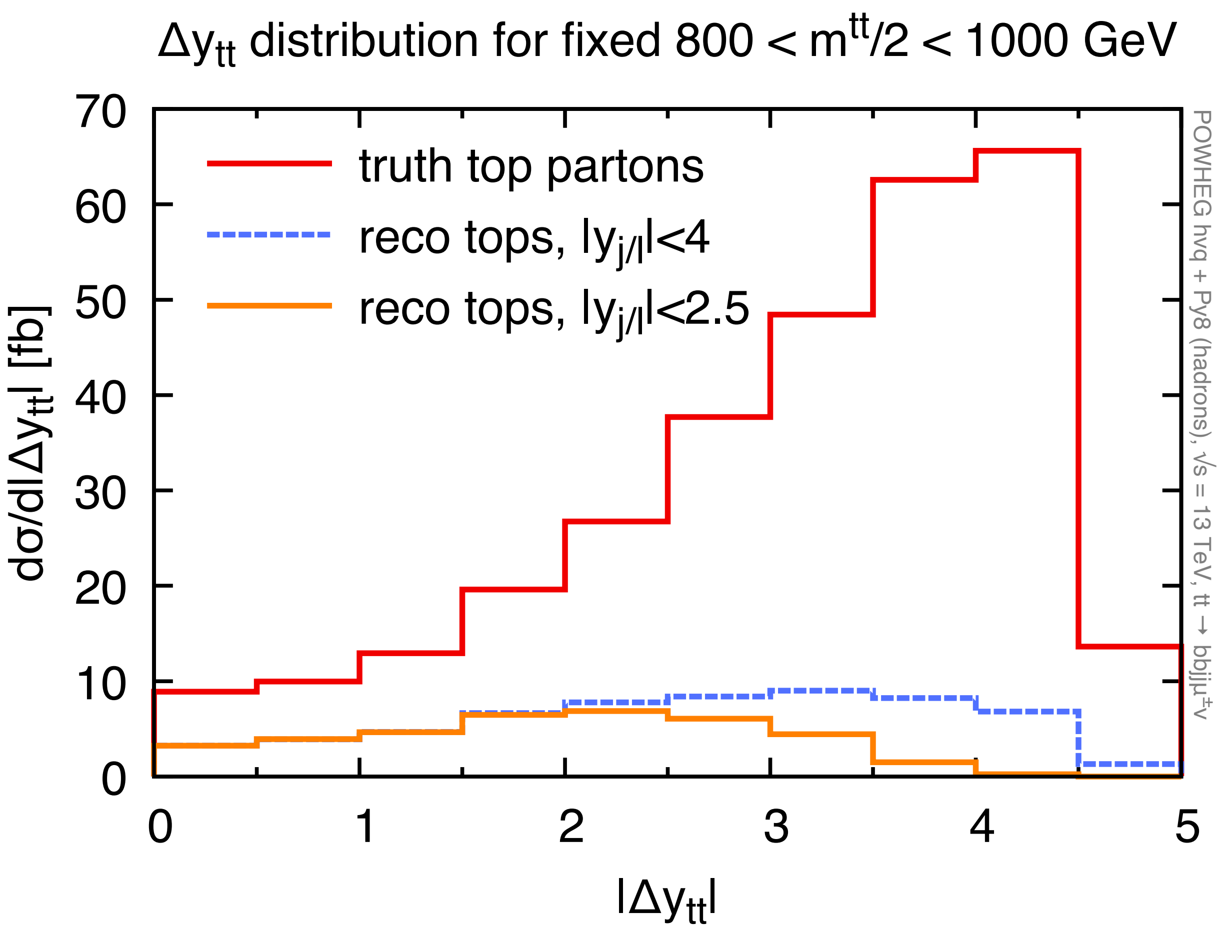
A realistic particle-level analysis

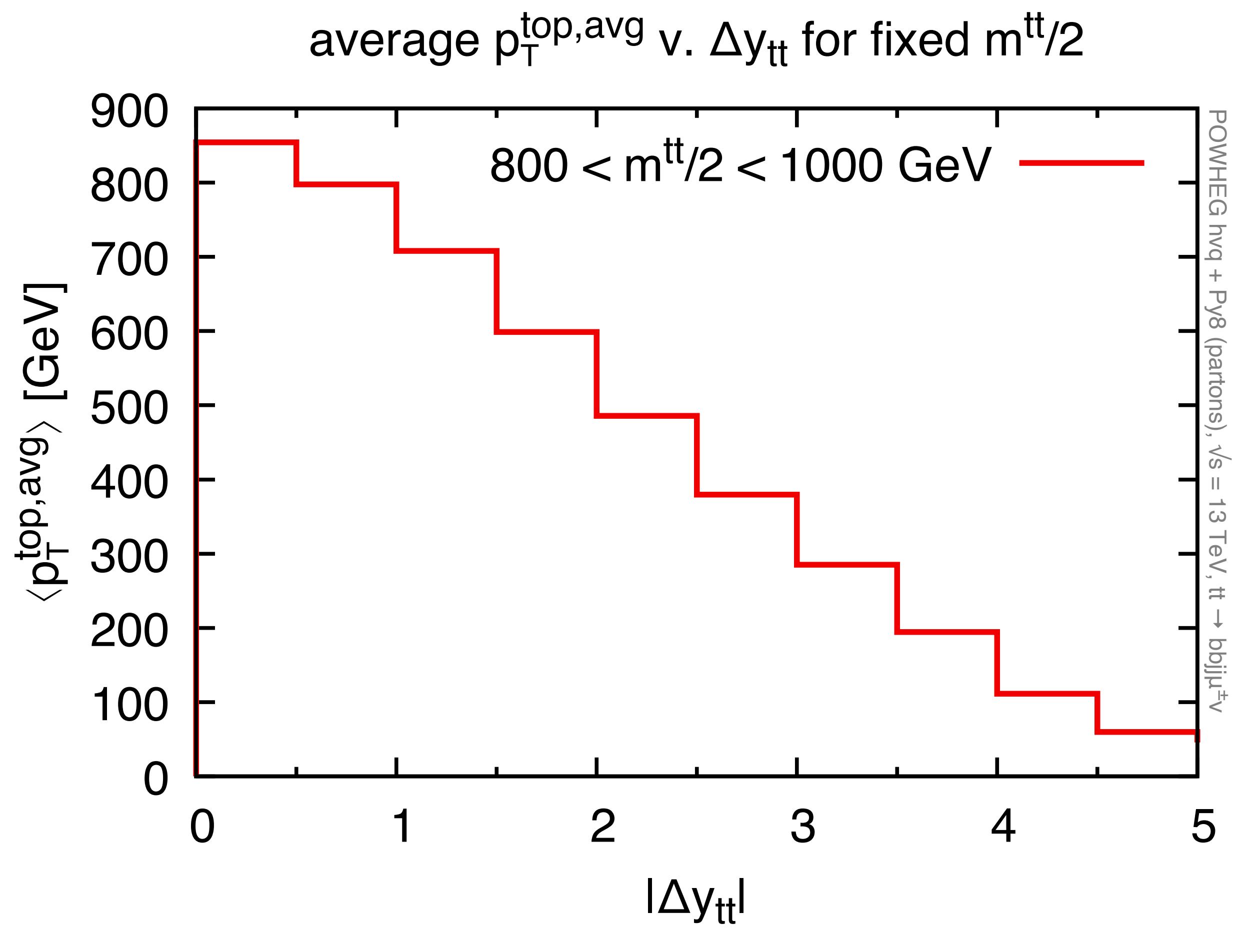
It is possible to design a realistic algorithm that works for both resolved and (moderately) boosted top decays (see backup slides for its precise definition)



- Algo behaviour is encouraging, both for efficiency and purity
- Our guiding principle: simplicity over optimisation (→ both simple to implement and improvable)

Back to the m_{tt} distribution





- Large contribution from low-p_t, large Δy → difficult to reconstruct
- Can lead to poorly controlled unfolding
- TH: a lot of source of (poorly controlled) potentially large corrections (q-induced BFKL…)
- If measuring m_{tt} at high scale: put a $|\Delta y < 2|$ cut
- Large enough to exploit features (e.g. gg vs qq), but safer

Conclusions

- At large scale, LO (FCR) and NLO (GSP/FEX) topologies give comparable contributions, due to t-channel matrix-element enhancements that compensate for α_s
- Non-trivial interplay between topologies and choice of observable. Different observables probe different underlying scattering
- Topology classification/extraction could help maximising info from top data (EFT, PDFs…)
- Simple parton level algorithm can classify topologies
- Interesting to develop algorithms that can deal with both resolved and boosted tops. Simple algo developed for our analysis, promising results
- Careful in TH-EXP comparisons e.g. for m_{tt}

Backup slides

Setup

- LHC13
- POWHEGBox v2, hvq (NLO for tt)
- PDF4LHC15_nnlo_mc
- Cross-checked using POWHEGBox NLO ttj that agreement on $O(\alpha_s^3)$ channels is reasonable

The particle-level algorithm

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, $p_{T,\mathrm{min}}$, as one would normally (we take $p_{T,\mathrm{min}} = 30$ 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 $(20\ \mathrm{GeV})^2$), 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 $p_{T,\mathrm{min}}$ 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.