Citius, altius, fortius

Top precision physics at the frontier

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HL-LHC will bring a 20 x enhancement in the luminosity, lots of more tops

FCC would bring many many more tops even!

Spoiler: at LHC we are often dominated by systematics. More statistics often do not help.

Where can these machines bring additional precision?

- Go to rare processes. Example: $t \to c\, H, H \to \gamma\gamma$

  → well explored, experiments already doing it

- Go fully differential, ex. $t \to W\, b \to l\, \nu\, b$ 4-D distributions

  → underway, 3-D done in ATLAS

- Go to high E

  → I'll outline some proposals with their potential problems

The bottom line

The effect of non-standard interactions of dimension higher than 4 grows with energy `*E*´ of final state particles

∂_ν in $\sigma^{\mu\nu}$ terms, no propagator in 4-fermion terms…

On the other hand, SM cross sections decrease with *E*.

And PDFs decrease with E.

Overall, going to high *E* enhances the potential effect of non-standard interactions. There is a balance between this enhancement and the larger uncertainties (systematic & statistical), larger backgrounds, etc.

See also: Farina et al. 1609.01857

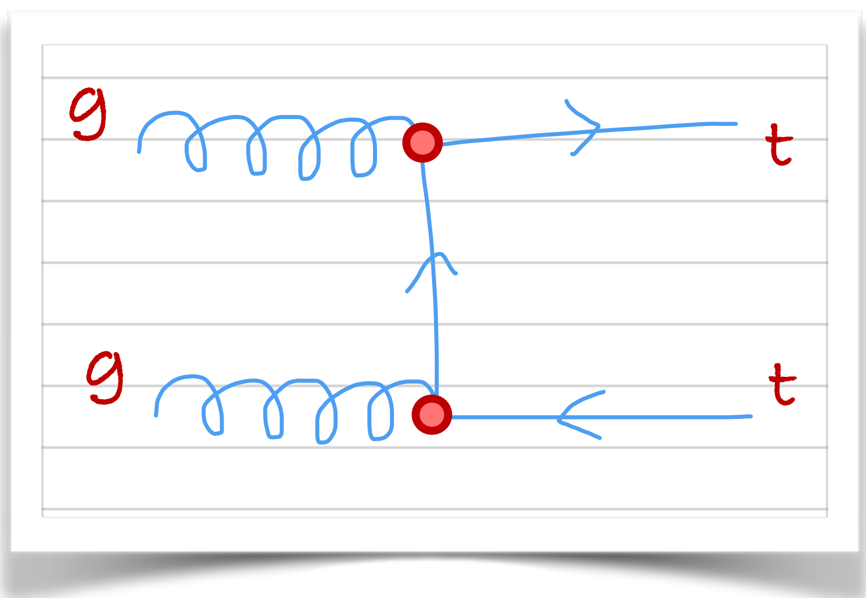
Example 1

pp → *tt* with top chromomagnetic / chromoelectric dipole moments

$$\mathcal{L}_{\rm tg} = -g_s \bar{t}\gamma^\mu \frac{\lambda_a}{2} t\, G^a_\mu + \frac{g_s}{m_t} \bar{t}\sigma^{\mu\nu}(d_V + i d_A \gamma_5)\frac{\lambda_a}{2} t\, G^a_{\mu\nu}$$

Well-known strategy: measure total cross section and set limits

Hioki and Ohkuma, 0910.3049, 1011.2655, 1306.5387



Two insertions of anomalous coupling

→ up to quartic anomalous terms in cross sections

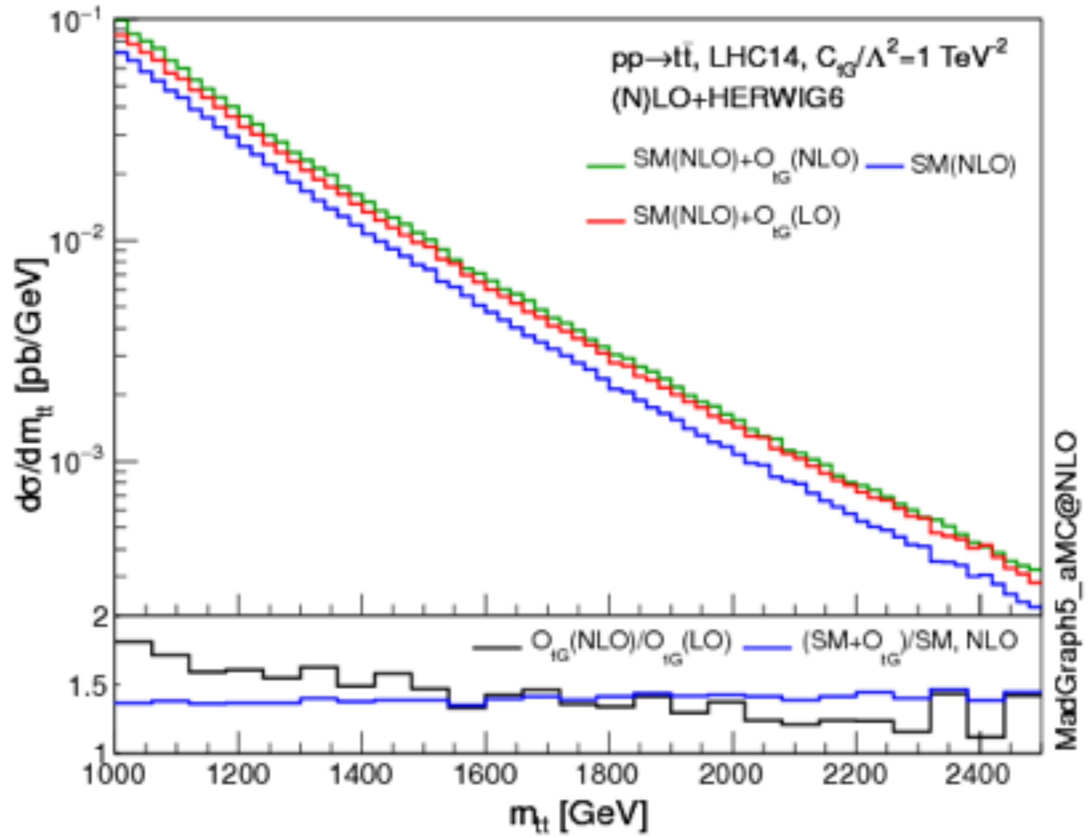
quadratic terms dominate at high *E*, anyway

I will not comment any more about the consistency of keeping quadratic terms. That discussion is boring old.

JAAS 1008.3225
JAAS et al. 1406.1798
Contino et al. 1604.06444

Note that at linear order in d_V, the shape of m_{tt} distribution is not changed by introducing the CMDM

Buarque Franzosi & Zhang , 1503.08841



Limits from total σ [$d_A = 0$], using fixed factorisation / renormalisation scale $Q = m_t$ for computations †

$$-0.0123 \leq d_V \leq 0.0099 \text{ (LO)}$$

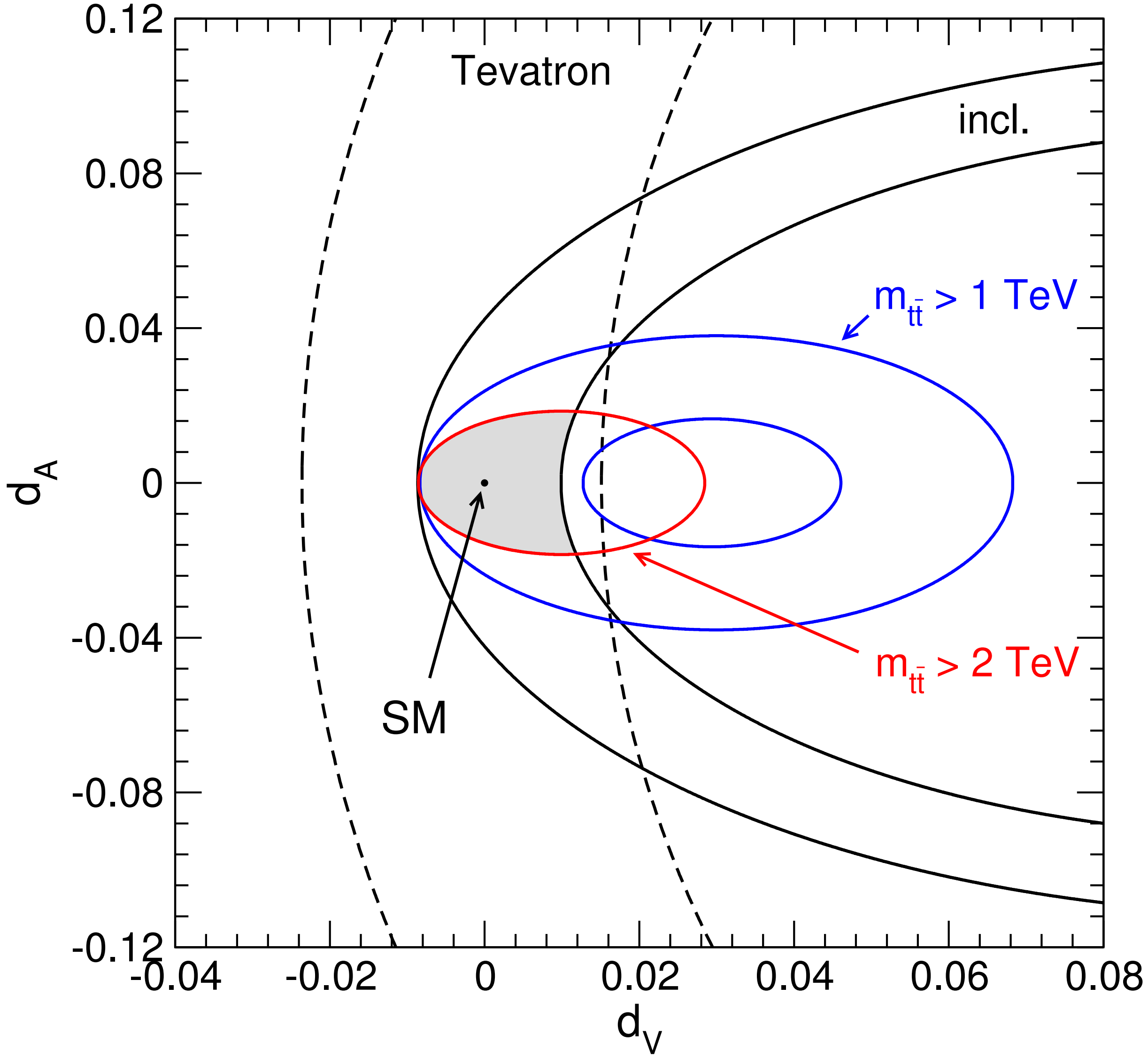
$$-0.0090 \leq d_V \leq 0.0096 \text{ (NLO)}$$

† Dynamical scale choices give different results, see later

Higher-order terms give enhancement at the tail

Simplest analysis taking top tagging efficiencies from CMS benchmark points

JAAS, Fuks, Mangano 1412.6654



Annulus shapes due to large cancellations between d_V and d_A [cubic terms]

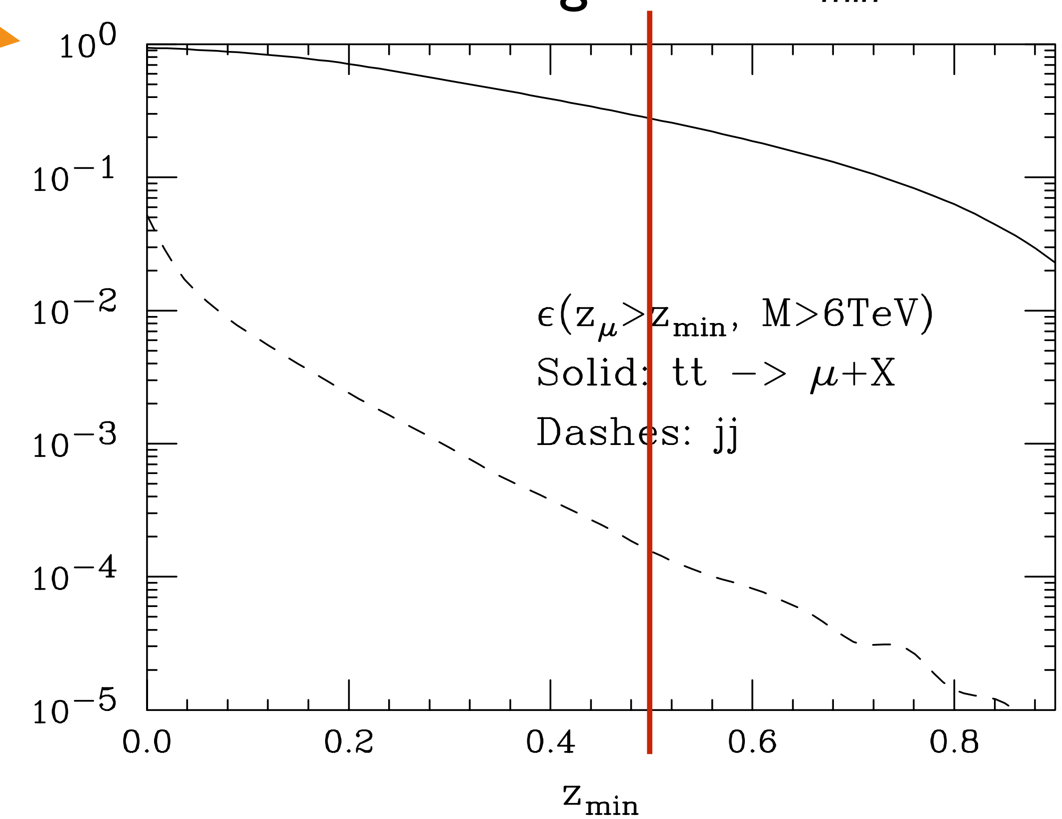
At higher m_{tt}, these cancellations disappear.

Top tagging at high *E*

Boosted tops give fat jets, so we have a *dijet* signature where top jets have

- leptons
- *b* quark subjets
- some jet substructure
- large groomed mass
- …

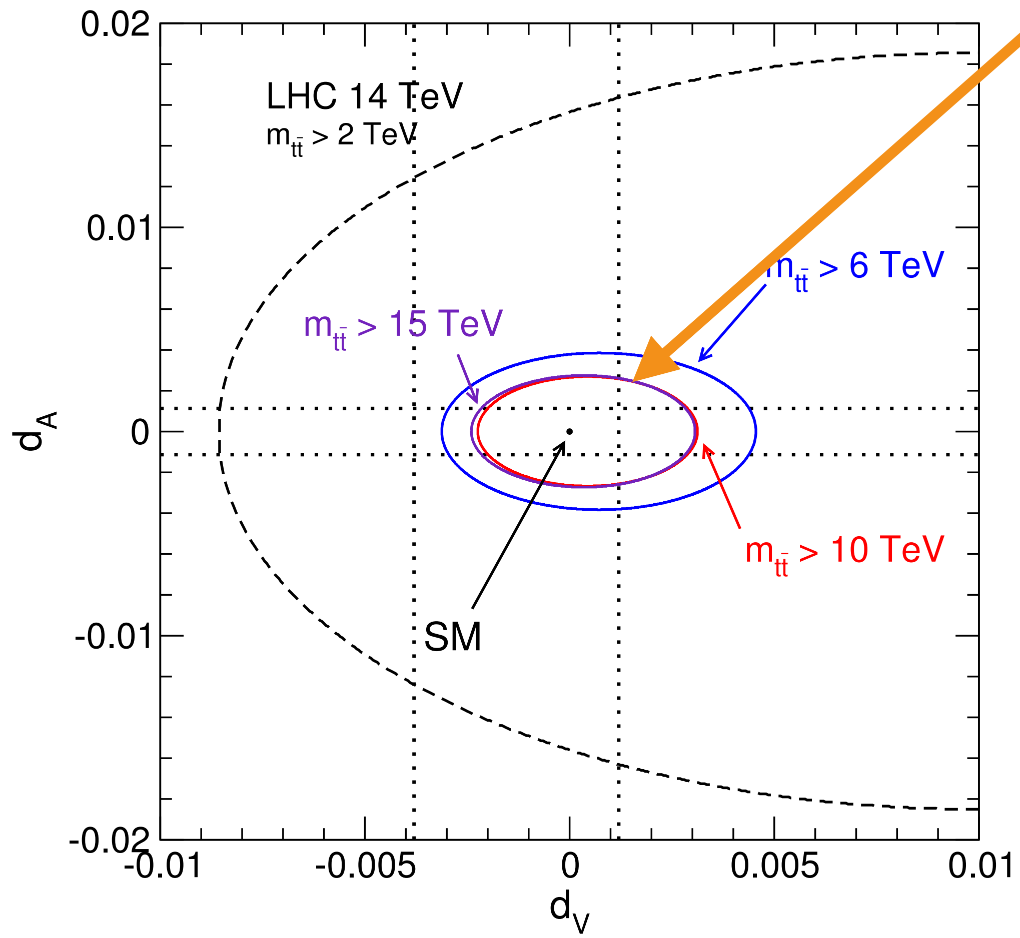
eff for having a lepton with p_T fraction `z´ larger than z_{min}

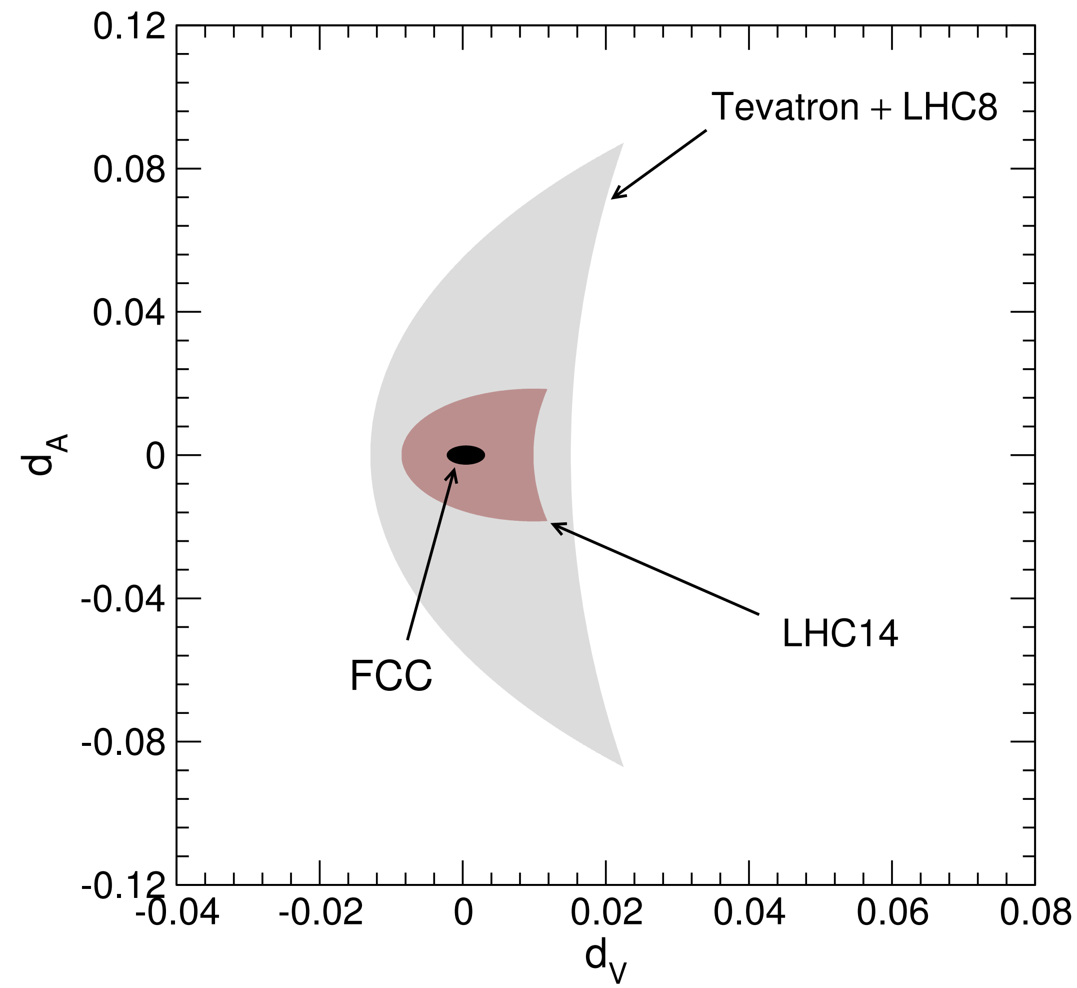


These features can be exploited to distinguish top jets from QCD jets. The dijet background is huge at high *E*, as it can be initiated by two valence quarks

Prospects for FCC with 100 TeV, 10 ab^{-1}

Sensitivity saturates at some point because of small statistics



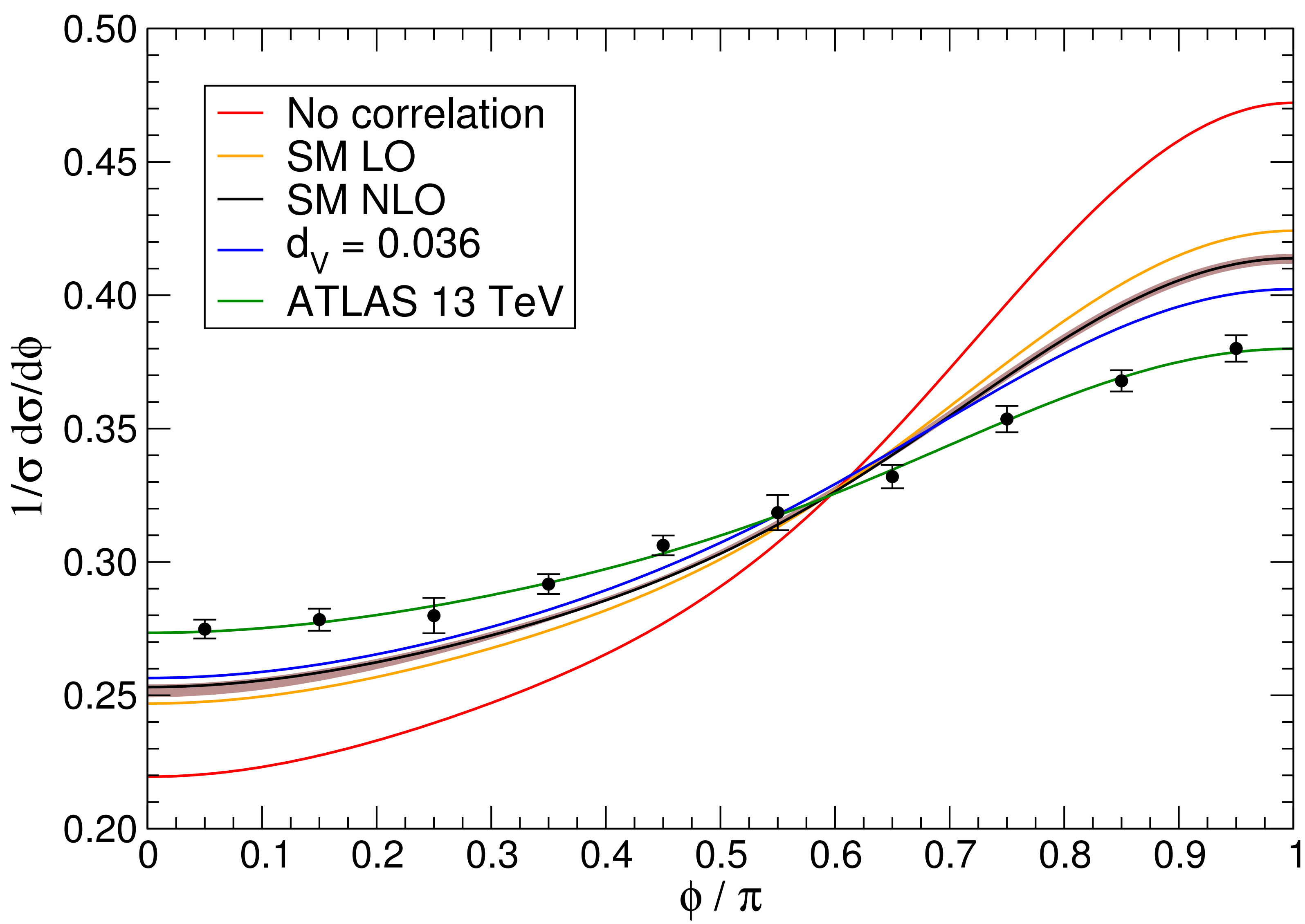


Note that effective operator approximation remains valid at this energy scale

Side note…

Top CMDM raises particular interest because it is among the few new physics that can increase the effective tt spin correlation… but not enough so as to explain the ATLAS measurement

JAAS 1806.07438



A top CMDM of the size $d_V = 0.036$ is in conflict with previously quoted limits, but what happens if one uses different scales Q?

NLO SM

total transverse mass

$$\sigma\ (\text{pb}) = 182 + 1950 d_V + 12600 d_V^2 \qquad [Q]$$

$$\sigma\ (\text{pb}) = 157 + 1670 d_V + 10600 d_V^2 \qquad [Q \times 2]$$

$$\sigma\ (\text{pb}) = 211 + 2250 d_V + 14700 d_V^2 \qquad [Q/2]$$

to be compared with $\sigma_{exp} = 241.5 \pm 1.4 \pm 5.7 \pm 6.2$ pb

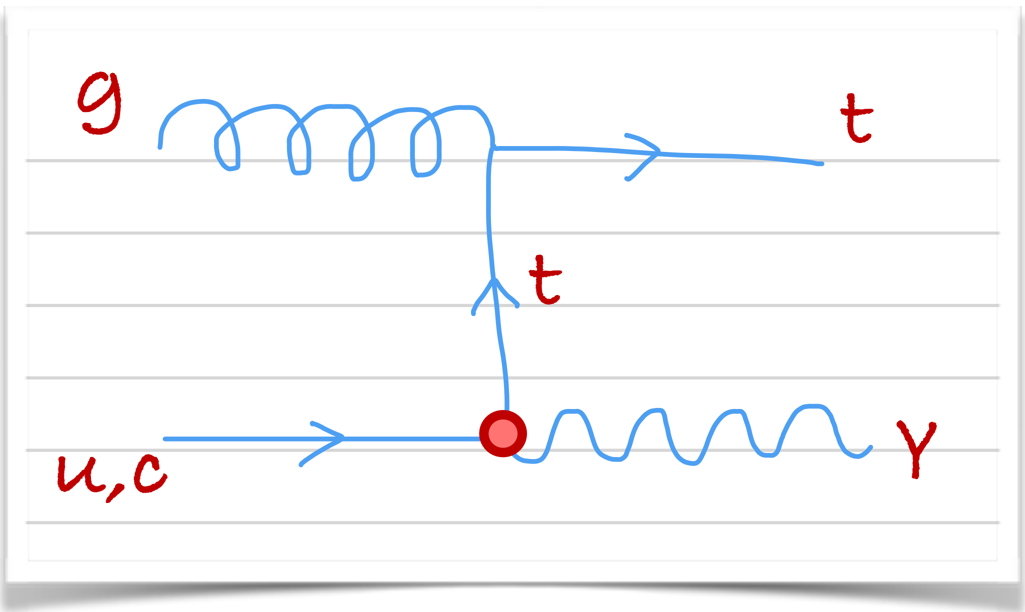
→ $0.006 \leq d_V \leq 0.046$ at 2σ level
if we allow for scale variation

NNLO corrections missing… Happy to discuss this at the next break!

Example II

Single γ*t* (or *Zt*) FCNC top production

$$\mathcal{L}_{\gamma t} = -e\bar{q}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\,(\lambda^L_{qt}P_L + \lambda^R_{qt}P_R)\,t\,A_\mu + {+\mathrm{H.c.}}$$



Enhancement of the single production (vs bkg) at high p_T known from old

del Aguila, JAAS, hep-ph/9909222

Top FCNC decays do not have such enhancement because *q* is small: top on-shell

The sensitivity of top FCNC decays $t \to q\gamma$ / qZ saturates because of background uncertainty, and higher statistics bring little (or no) benefit

ATL-PHYS-PUB-2016-019

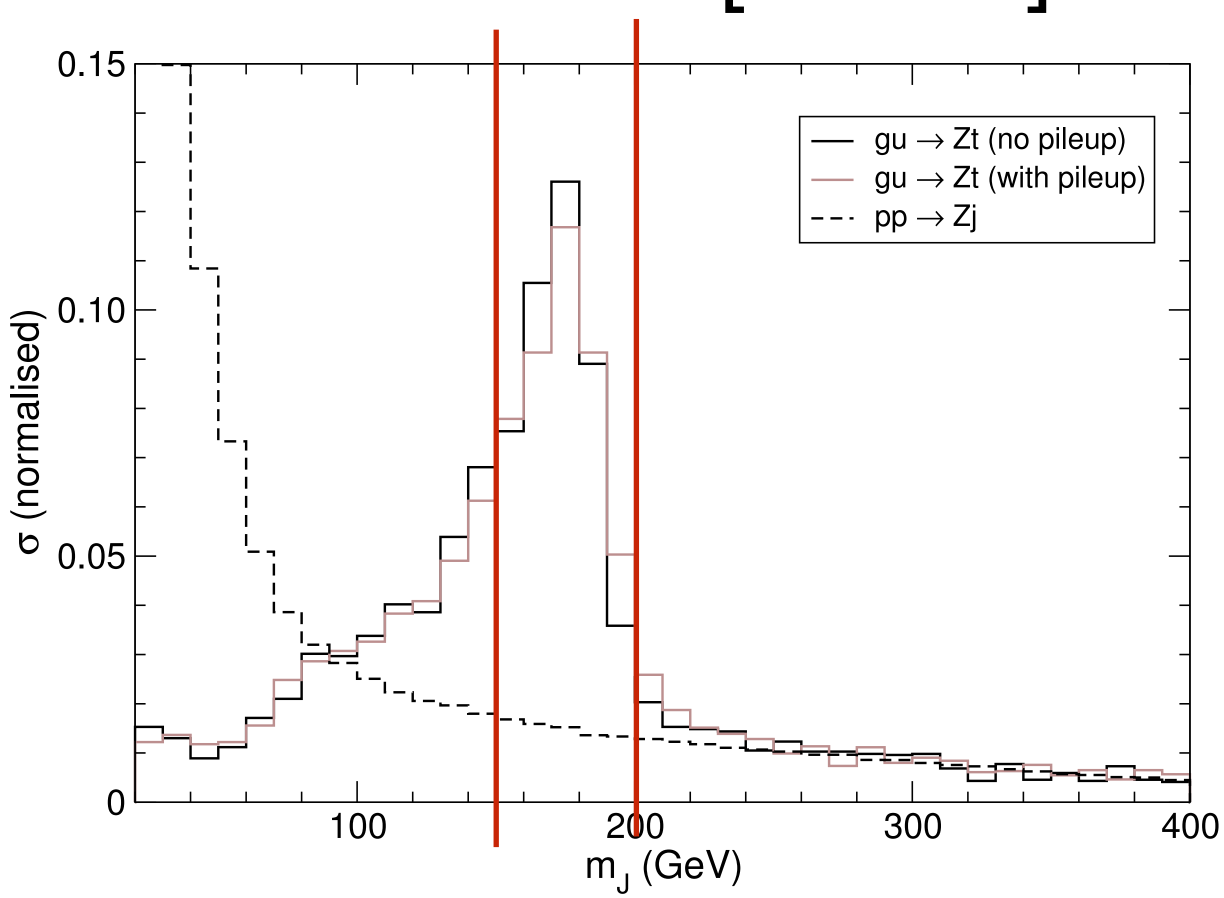
γt / Zt at high E

Main background is γj / Zj but also γWj / ZWj has to be suppressed

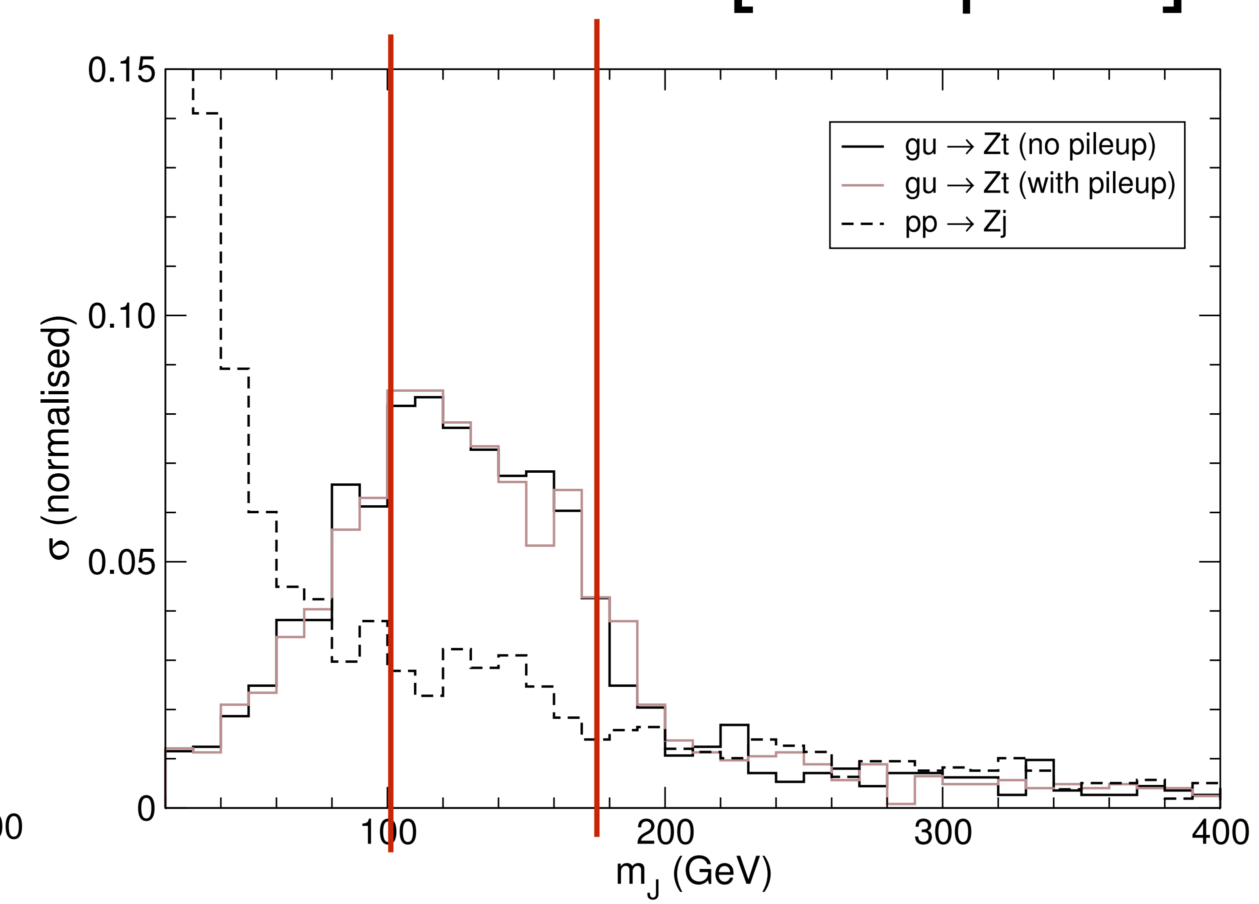
Z decay products are collimated but this is not a problem.

Simple and robust analysis: define \`semileptonic´ tops if jets have a lepton with $z \geq 0.1$ within $\Delta R \leq 0.3$, \`hadronic´ tops otherwise.

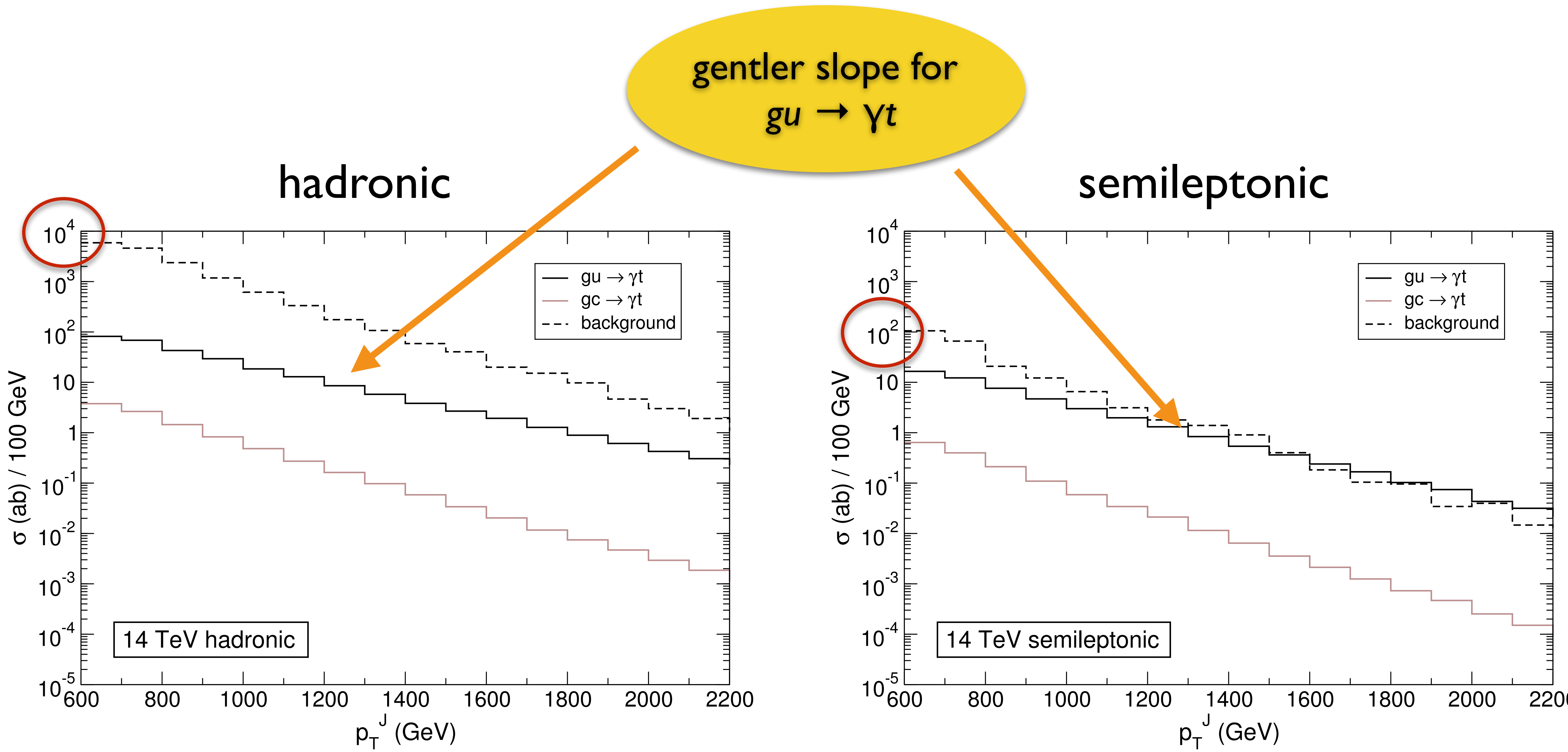
Trimmed mass [hadronic]



Trimmed mass [semileptonic]



Signals (for $\lambda = 0.01$) and background as a function of the jet p_T [photon p_T cuts are equivalent]

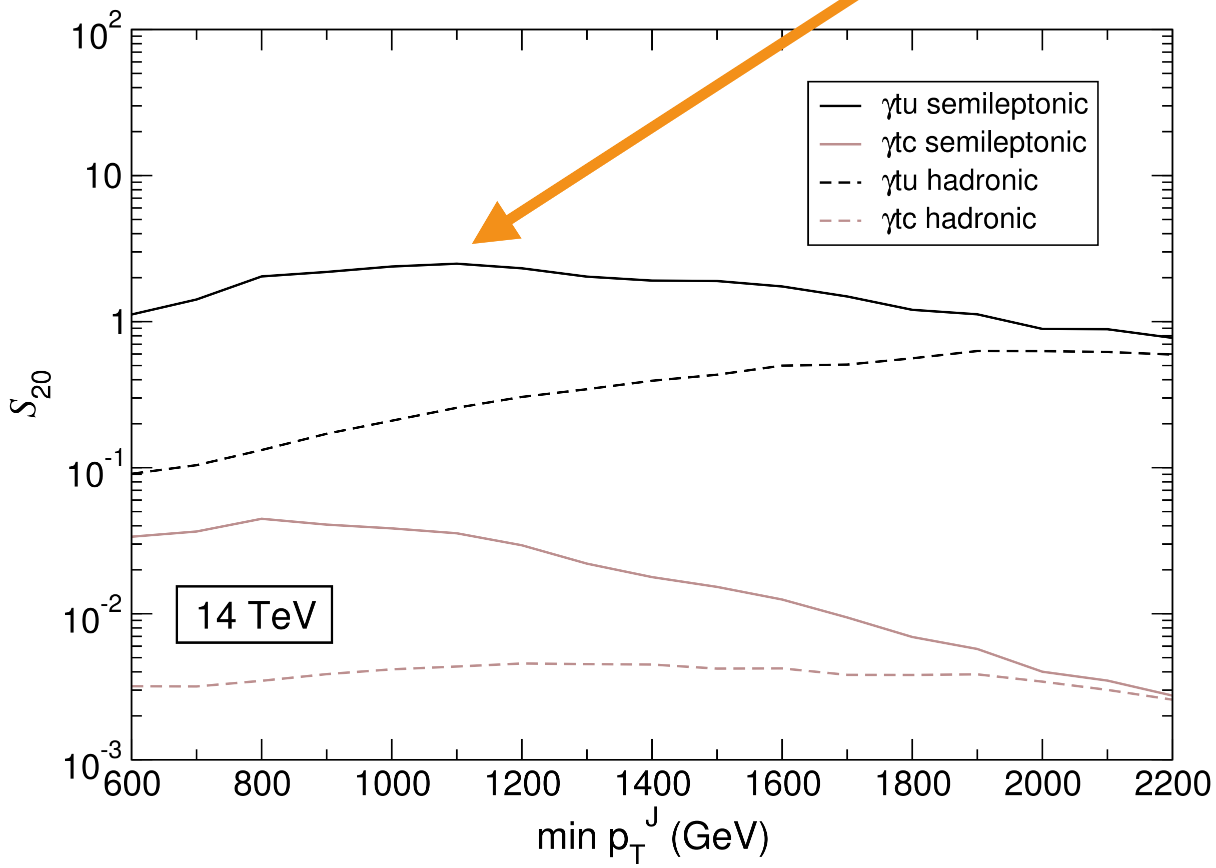


Asking for lepton reduces background by two orders of magnitude, 1/5 reduction of signal

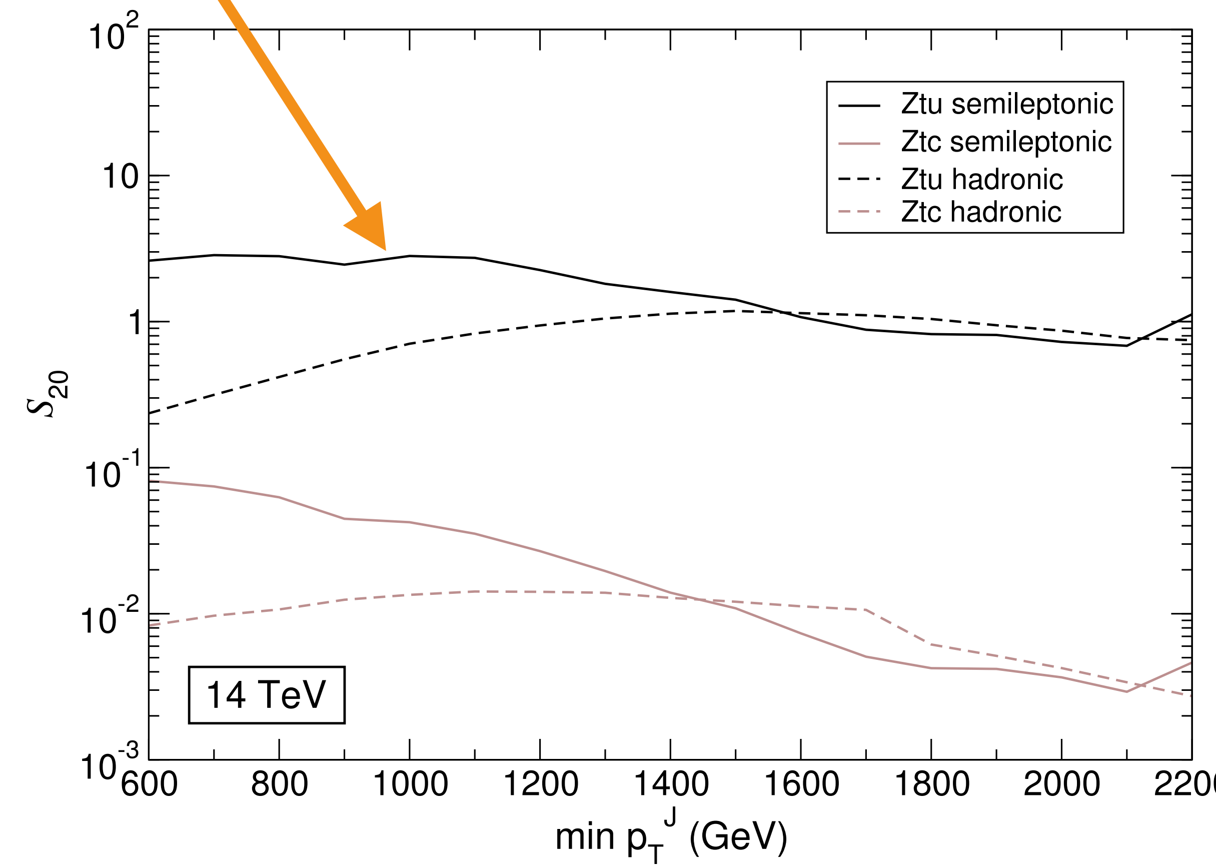
Signal significance as a function of minimum p_T cut [including 20% systematics]

reaches maximum

γt



Zt [$\sigma^{\mu\nu}$]



$Br\,(t \to u\gamma) \leq 1.8 \cdot 10^{-5}$

$Br\,(t \to c\gamma) \leq 6.1 \cdot 10^{-4}$

$Br\,(t \to uZ) \leq 4.1 \cdot 10^{-5}$

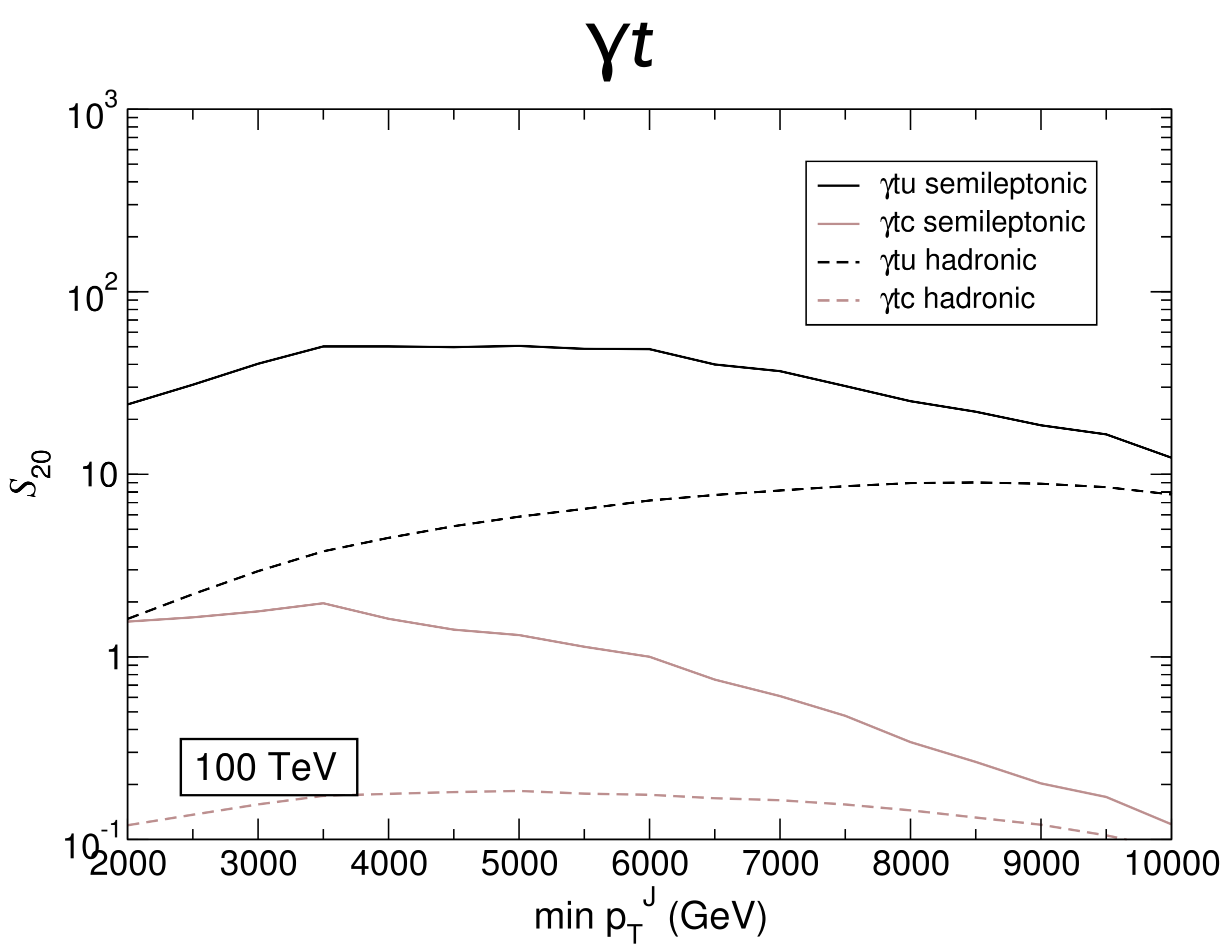
$Br\,(t \to cZ) \leq 1.6 \cdot 10^{-3}$

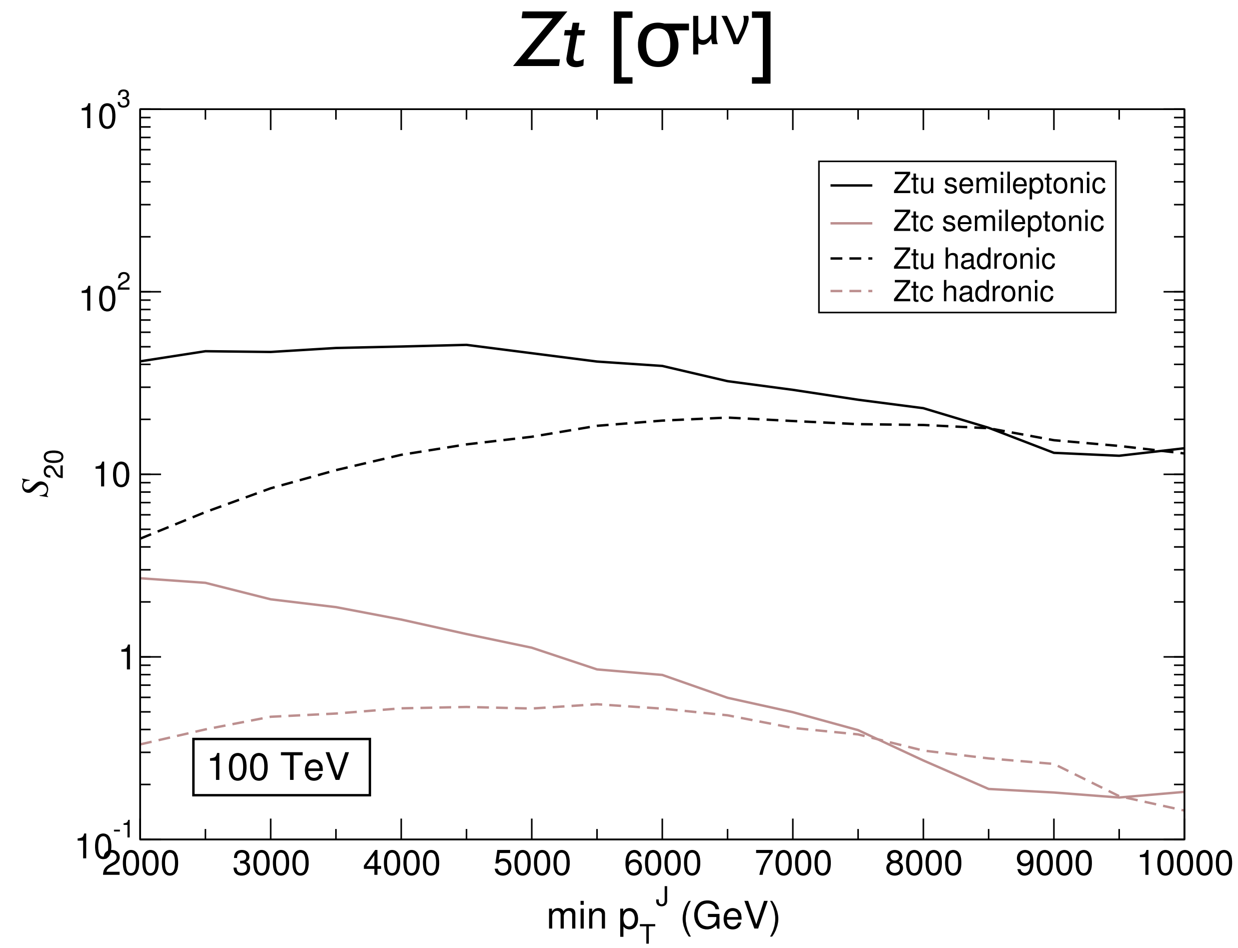
Comparison:

$Br\,(t \to uZ) \leq 1.3 \cdot 10^{-4}$

from *tt* decays

Sensitivity at FCC [including 20% systematics]





$$\mathrm{Br}\,(t \to u\gamma) \leq 9.1 \cdot 10^{-7}$$

$$\mathrm{Br}\,(t \to c\gamma) \leq 2.3 \cdot 10^{-5}$$

$$\mathrm{Br}\,(t \to uZ) \leq 2.7 \cdot 10^{-6}$$

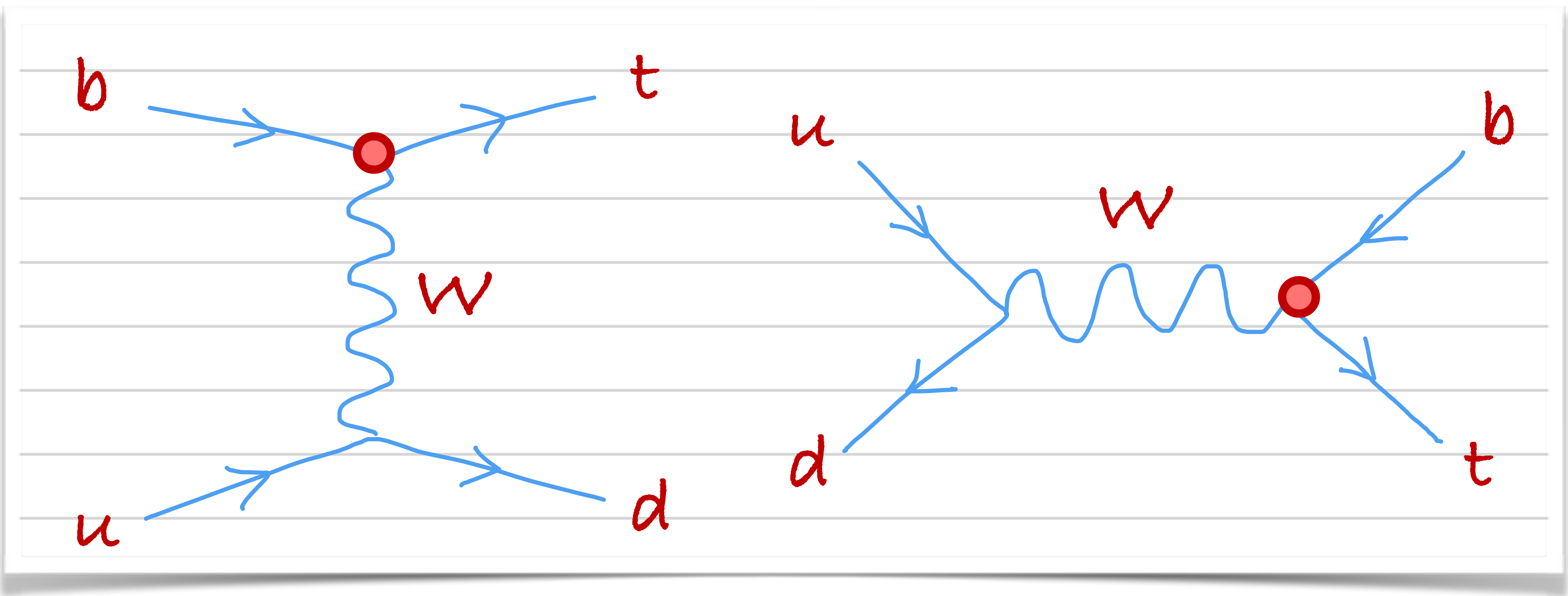
$$\mathrm{Br}\,(t \to cZ) \leq 5.0 \cdot 10^{-5}$$

Example III

Single top at high p_T

JAAS & Mangano, in preparation

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-} + \text{h.c.}\,,$$



Especially challenging since dijet and *tt* are both large backgrounds

Considering HL-LHC with 3 ab^{-1}

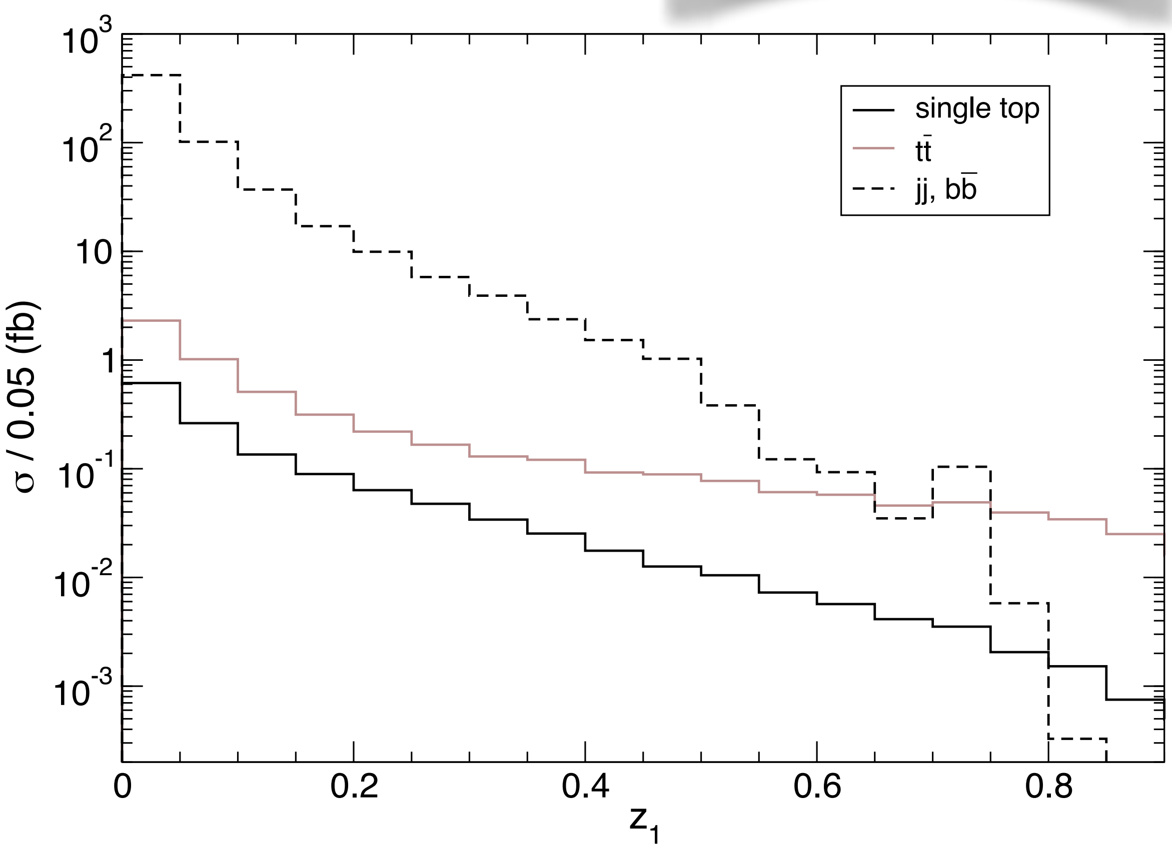
Baseline pre-selection

- one R=0.8 jet J [the one with largest mass] $|\eta| \leq 2.5$ with b-tagged subjet
- one R=0.4 jet j back-to-back with $|\eta| \leq 2.5$
  - not b-tagged / tj enriched
  - b-tagged / tb enriched
- $p_{T\,J} \geq 800$ GeV
- one lepton [the leading one if many] within $\Delta R \leq 0.5$ of J

tj enriched

$S/B = 2.2 \cdot 10^{-3}$

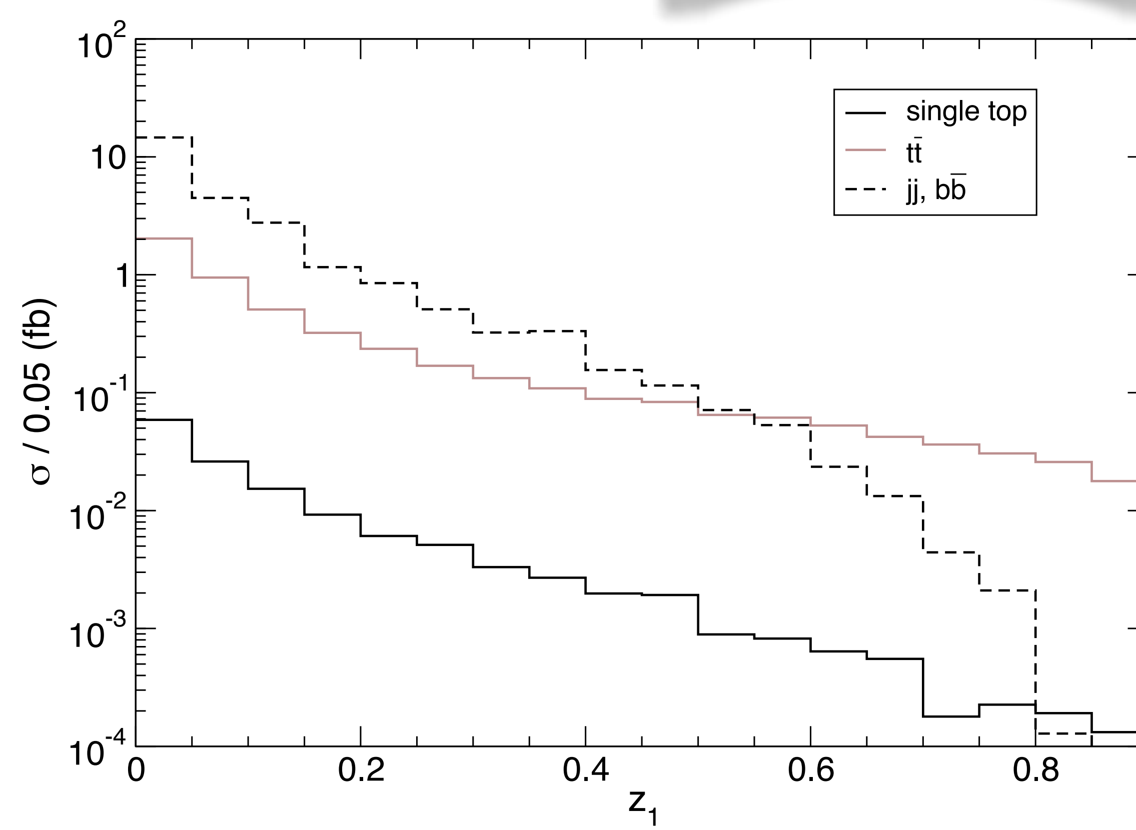
$S/\sqrt{B} = 3.0$



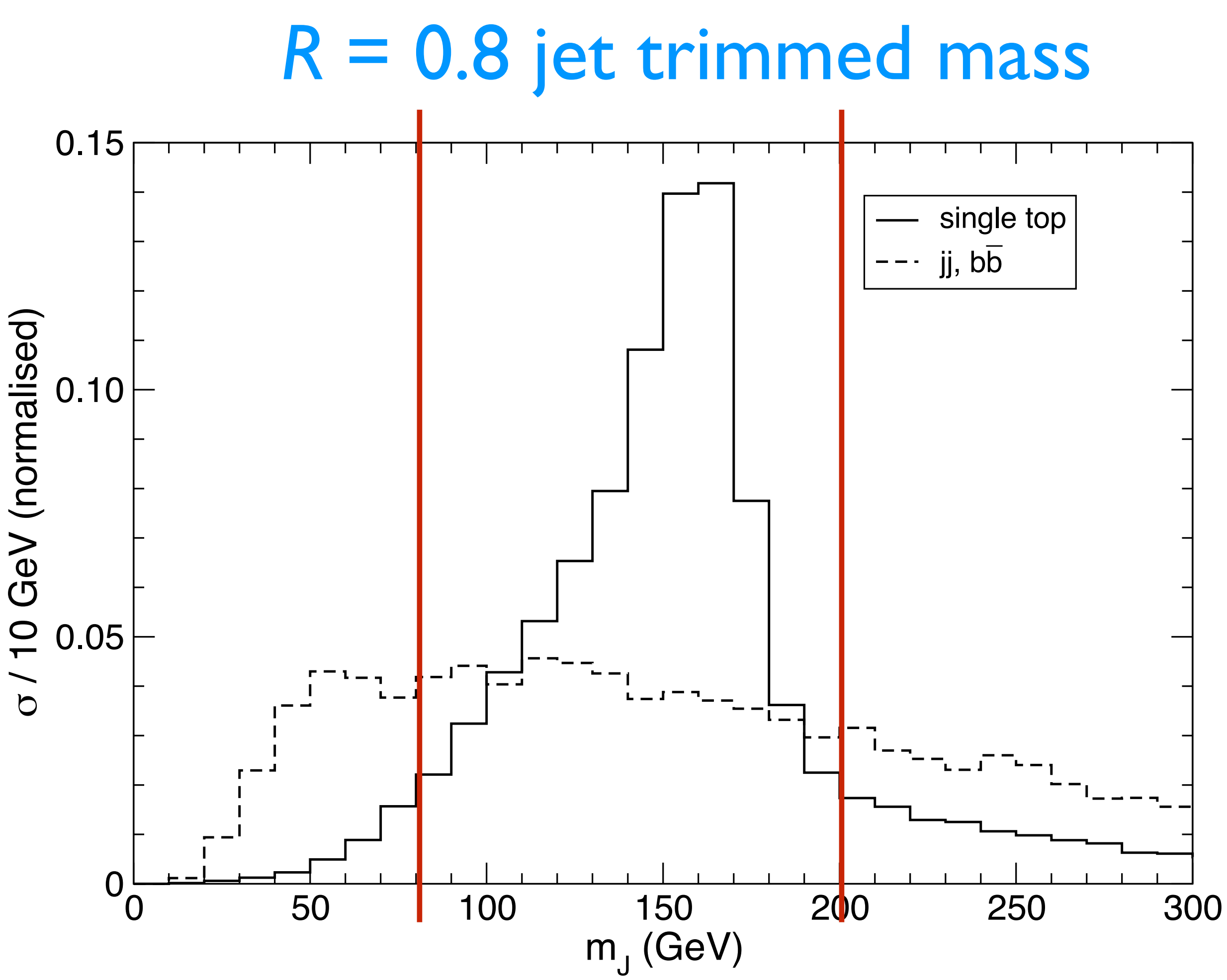
tb enriched

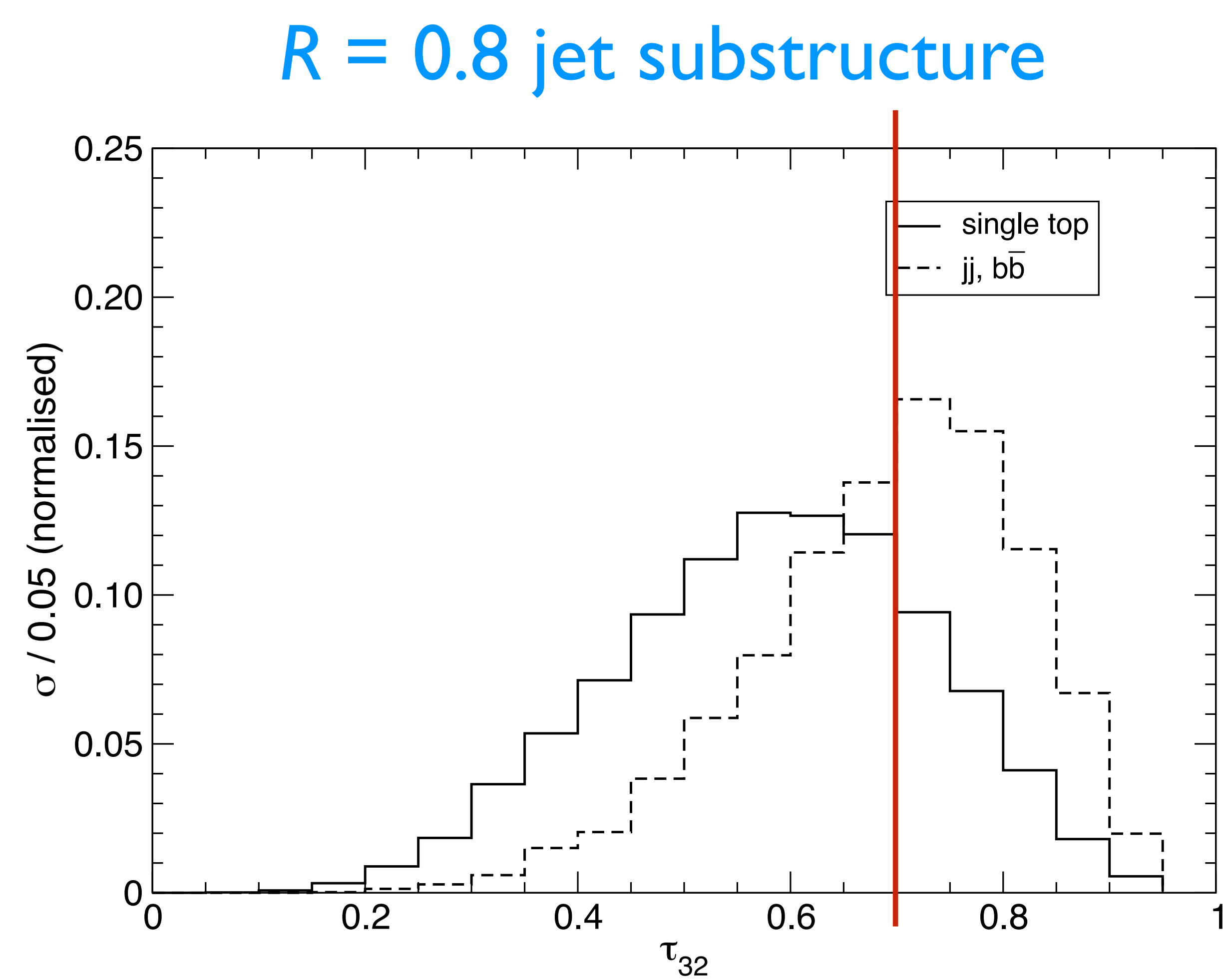
$S/B = 4.4 \cdot 10^{-3}$

$S/\sqrt{B} = 1.3$



Reduction of dijet background

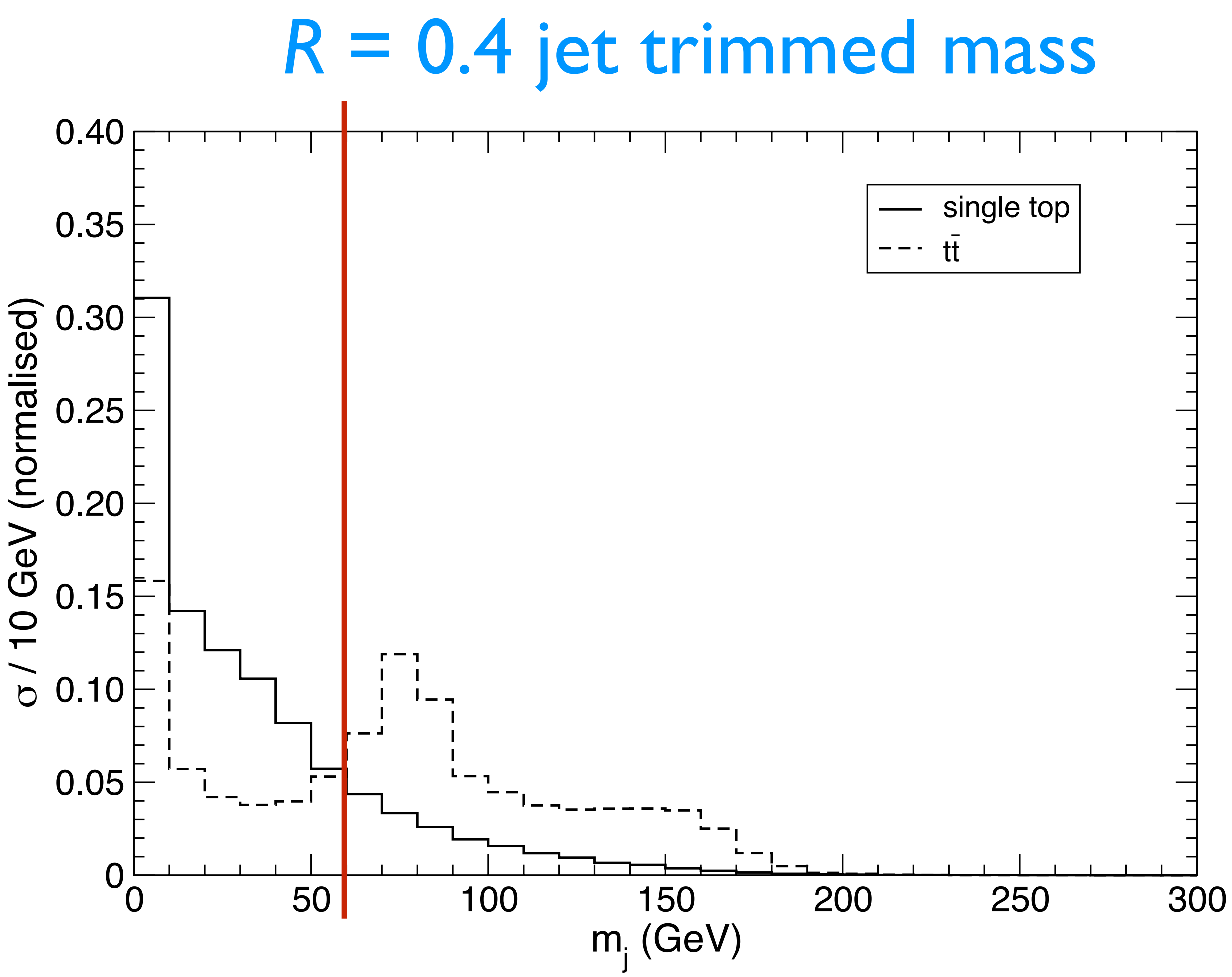


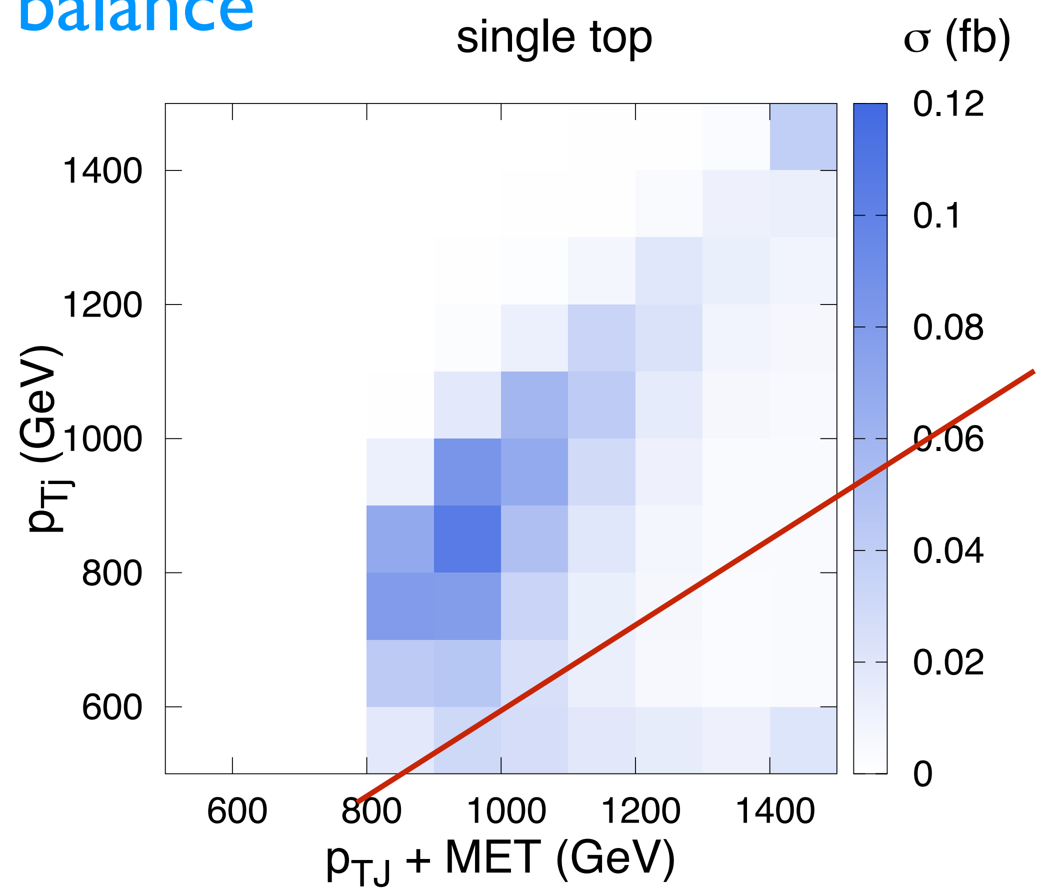


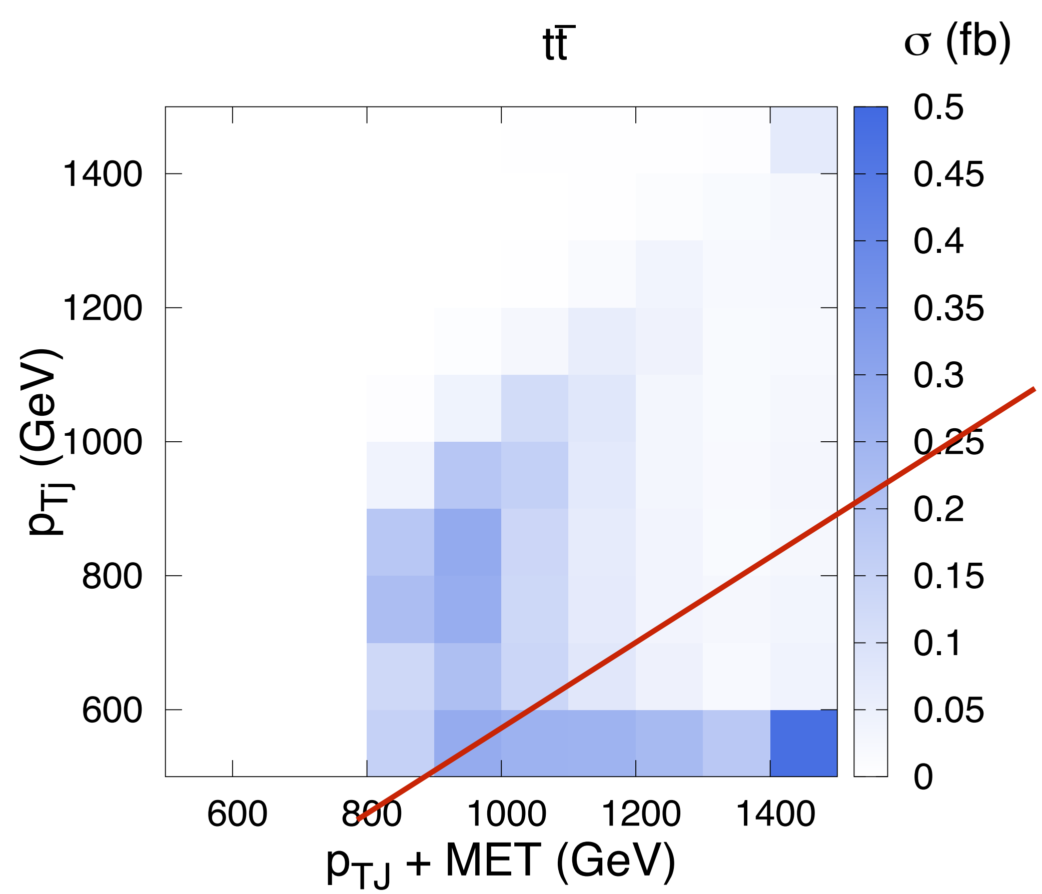
plus later cut on lepton momentum fraction z_l

Reduction of *tt* background

p_T balance





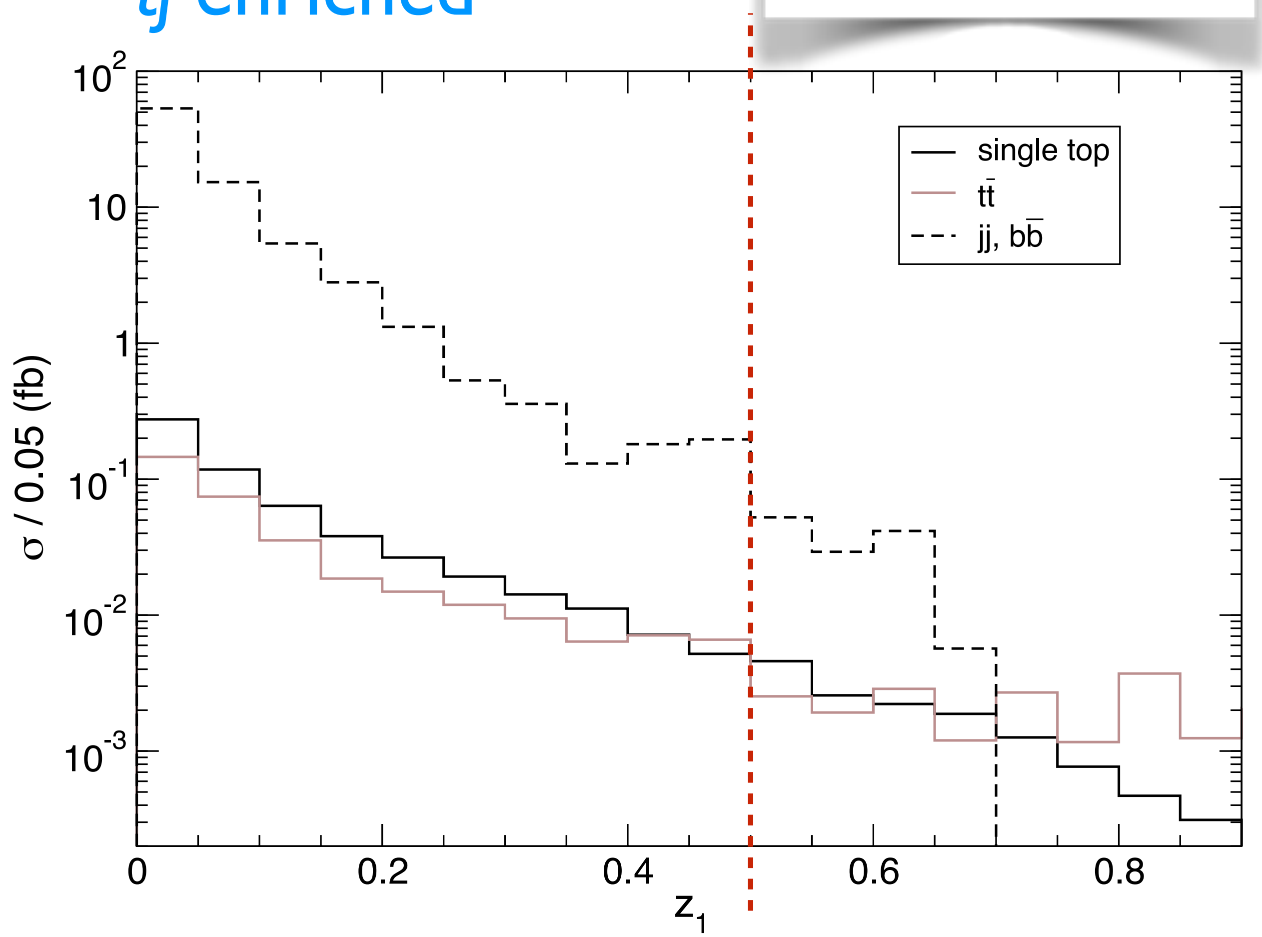


After these improvements…

tj enriched

$S/B = 7.4 \cdot 10^{-3}$

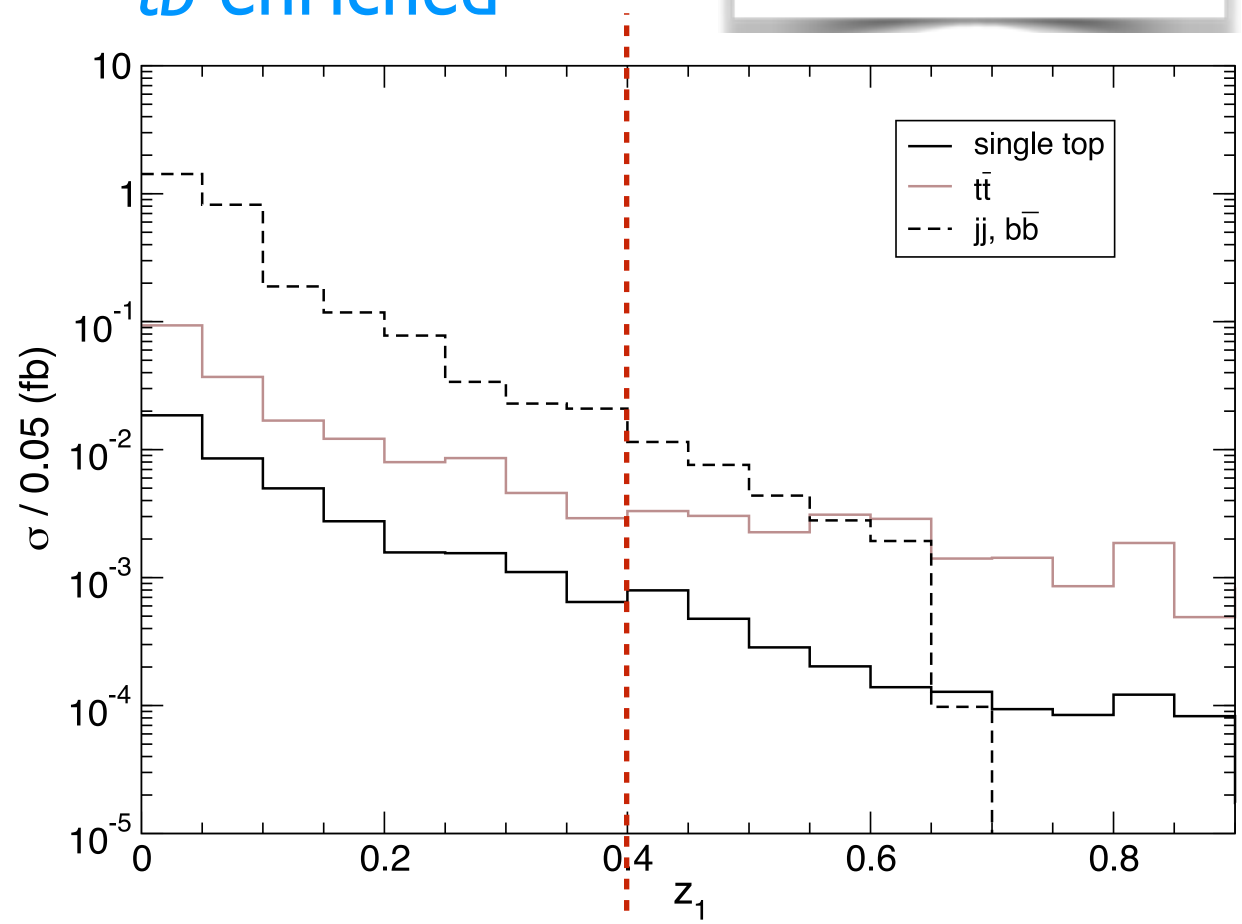
$S/\sqrt{B} = 3.6$



tb enriched

$S/B = 1.4 \cdot 10^{-2}$

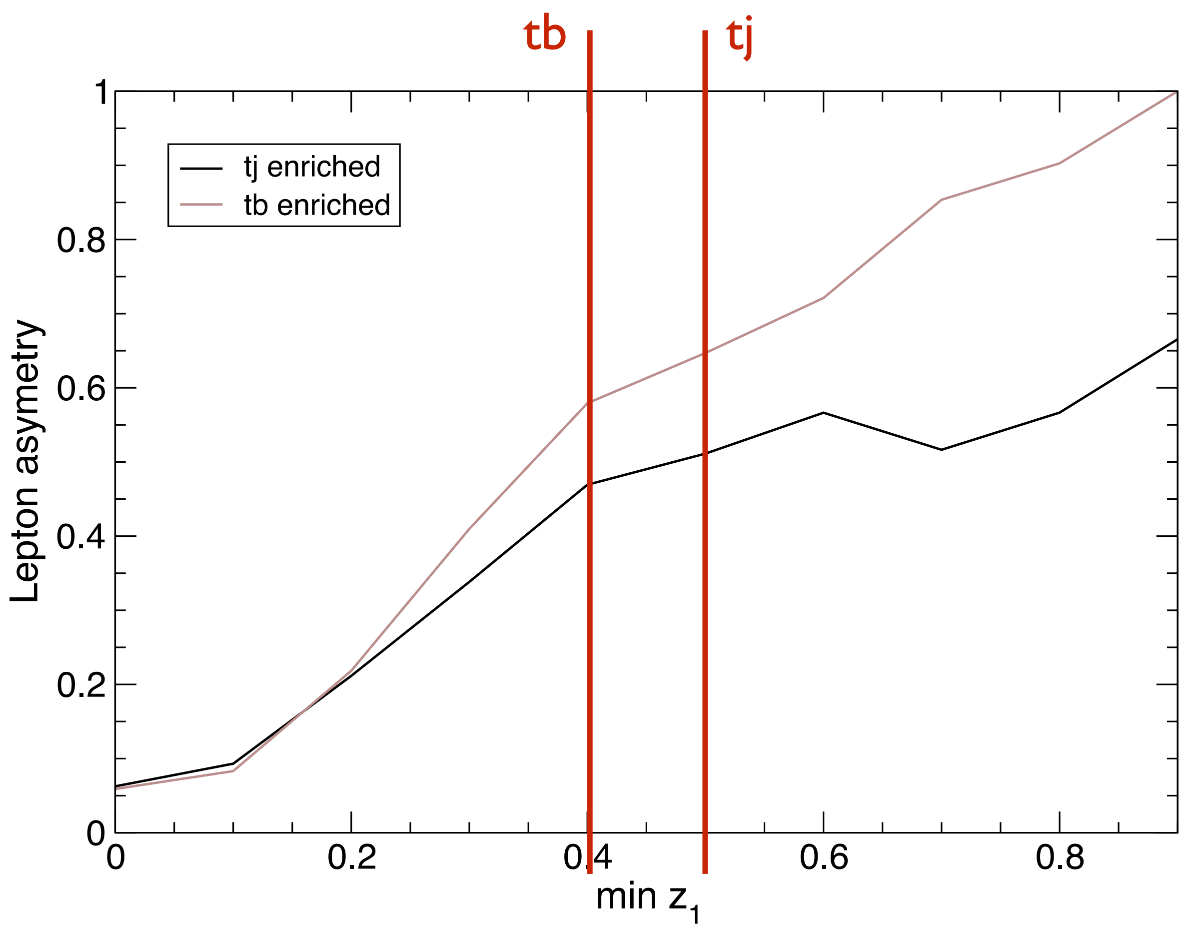
$S/\sqrt{B} = 1.3$



still can cut on z_1 to improve significance, but first need to address background systematic uncertainties

Signal has charge asymmetry: more l^+ than l^-. One can use the negative lepton sample [which includes signal too!] to normalise and get limits from the positive sample.

Doing this, the signal significance is $\sim \frac{S_+ - S_-}{\sqrt{B/2}}$ and large z_l is good to enhance the asymmetry



Significance for SM signal

tj enriched: 1.5σ

tb enriched: 0.5σ

Limits
$|g_L| \leq 0.041$ 95%CL
$|g_L| \leq 0.079$ 95%CL

would amount to 0.7% change in inclusive $R_{t\text{-}ch}$

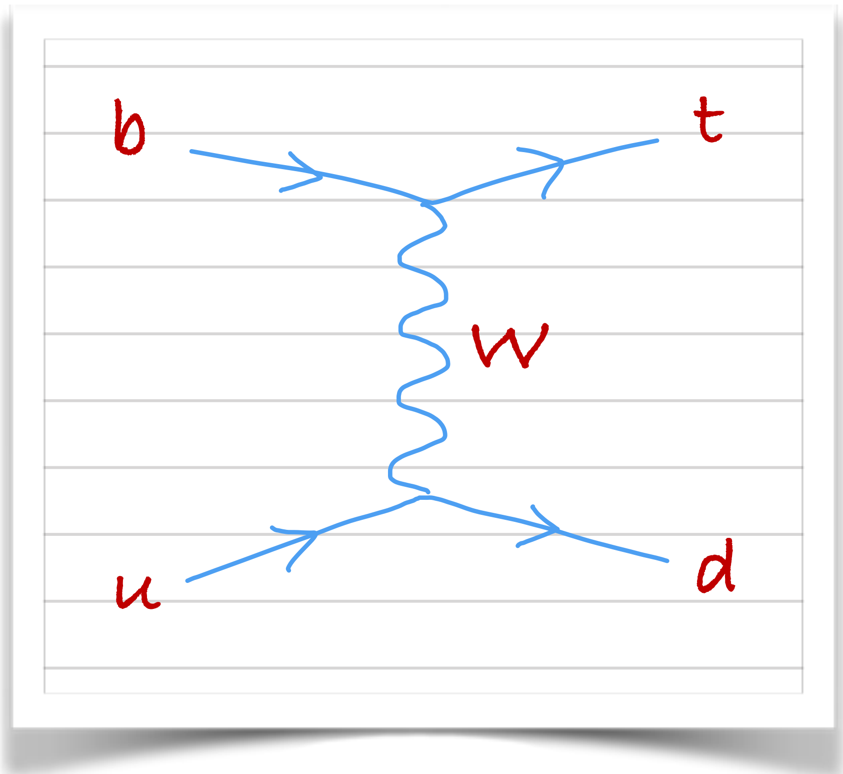
Comparison: $R_{t\text{-}ch}$ = 1.65 ± 0.02 (stat) ± 0.04 (syst) CMS 13 TeV

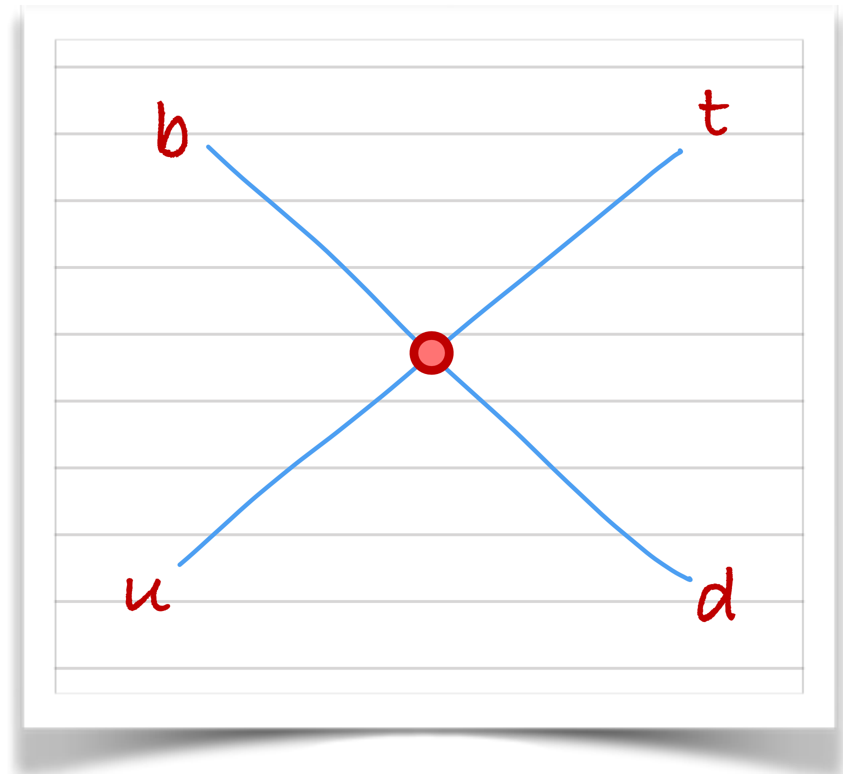
Example IV

Beyond cross section: polarisation

t-channel single top production with four-fermion operators

JAAS, Degrande, Khatibi 1701.05900



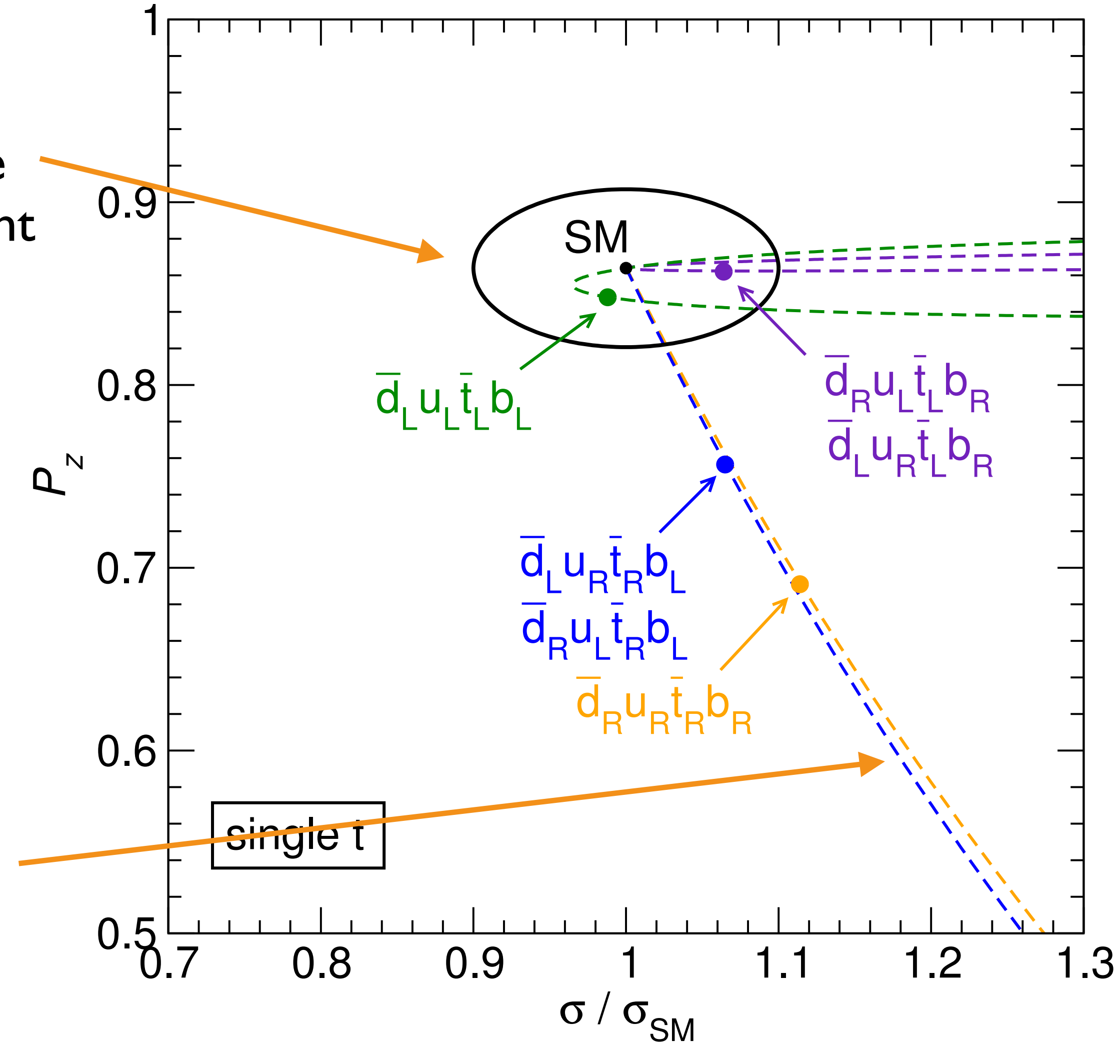


Expansion of cross section and polarisation

$$\sigma = A_0 + A_{\text{int}} \frac{C}{\Lambda^2} + A_2 \left(\frac{C}{\Lambda^2}\right)^2$$

$$P_z = \left[B_0 + B_{\text{int}} \frac{C}{\Lambda^2} + B_2 \left(\frac{C}{\Lambda^2}\right)^2 \right] / \sigma$$

Sensitivity of inclusive measurement



size of new physics effects

- Inclusive: A_2/A_0 = 0.11 TeV^4, B_2/B_0 = -0.11 TeV^4
- p_T (top) ≥ 200 GeV: A_2/A_0 = 2.1 TeV^4, B_2/B_0 = -2.6 TeV^4

Large enhancement of anomalous effects in polarisation too, but need dedicated sensitivity study!

Summary

It is well established

— though we still don't have measurements —

that anomalous interactions from dim-6 operators are better probed at high *E*, despite drawbacks:

- larger systematics
- smaller statistics
- non-resolved objects (tops, *Z*/*W* bosons, …)

I've given a lot of examples, it's your turn to make them real