Boosting Top Partner Searches in Composite Higgs Models

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w/ Azatov(CERN), Salvarezza (Rome), Spannowsky (Durham) arXiv:1303.6601

Believe in Naturalness ?

Supersymmetry

Compositeness

Direct Search

"will take a minimalistic approach"
- ask minimal contents to maintain naturalness

→ **Natural SUSY (?)**
(natural) Compositeness

→ ***Top partners***

Indirect Search

EWPT
Higgs couplings measurements
Via $h + X$, $hh + X$ process etc
…

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→ ***Fermionic top partners***

Current situation is very peculiar !

Low mass top partner
-High cross section of pair production: QCD process, model-independent

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$$m_{TopPartner}^{Exp} \geq 700 \sim 800\ GeV$$

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No more improvement @LHC8 ?

$$\boxed{m_{TopPartner}^{Exp} \geq 700 \sim 800\ GeV}$$

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-High cross section of pair production: QCD process, model-independent

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This is the problem

High mass top partner
:Small cross section
Kinematics changes

$$m_{TopPartner}^{Exp} \geq 700 \sim 800\ GeV$$

Low mass top partner
-High cross section of pair production:
QCD process, model-independent

Current situation is very peculiar !

Boosted

$m_X \gg m_{EW}$

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:Small cross section

Kinematics changes

Single prod become important

Not Boosted

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-High cross section of pair production:
QCD process, model-independent

We are in a transition !

I. Improve signal eff.
:use kinematics, e.g. boost

II. Enhance signal rate:
:collect events from every single possible source

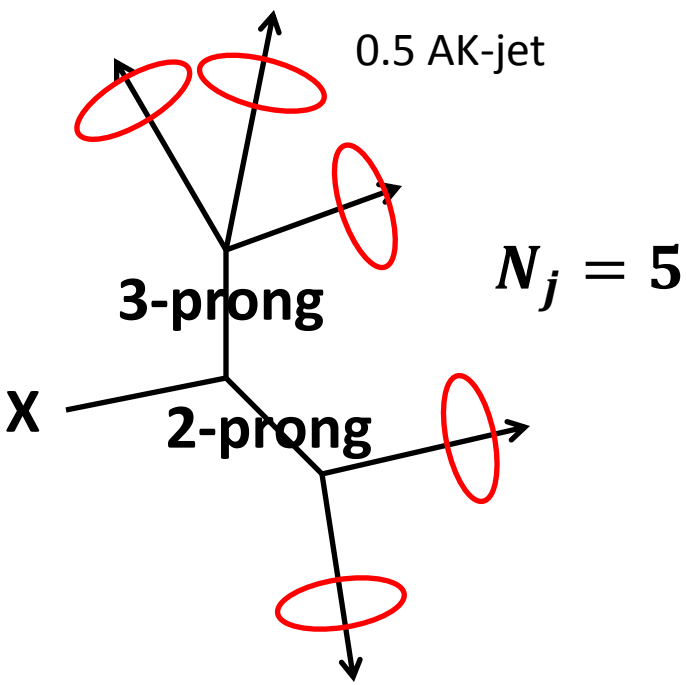
I. Increasing signal efficiency

What's the problem when things are boosted and how to overcome ?

E.g. traditional cut-and-count

E.g. Jet multiplicity has been one of power discriminants

$$\boldsymbol{m_X > m_{EW}}$$

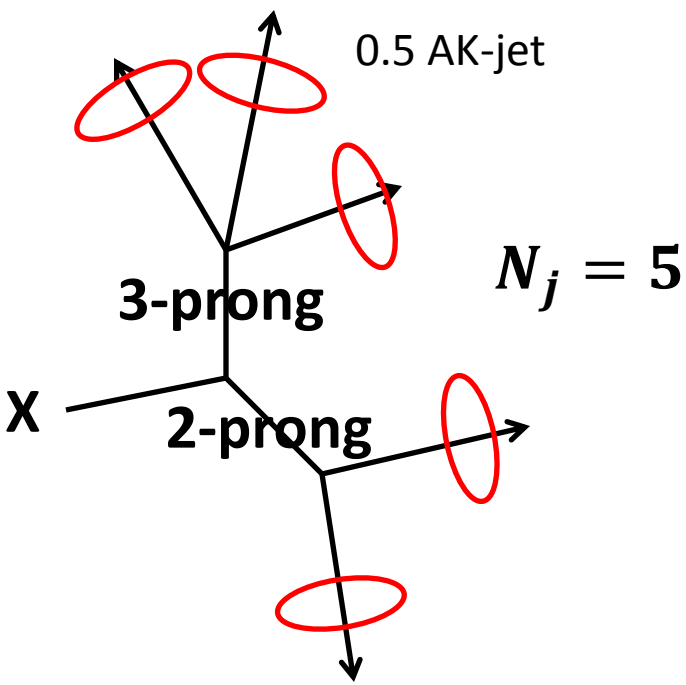


$$\boldsymbol{N_j = 5}$$

E.g. traditional cut-and-count

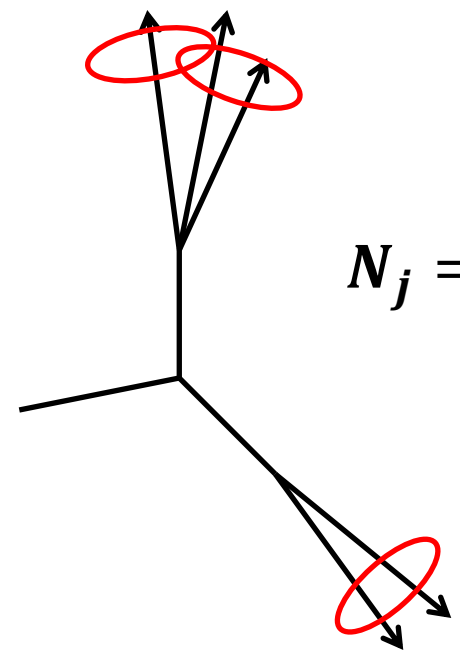
Jet multiplicity

$m_X > m_{EW}$



$N_j = 5$

$m_X \gg m_{EW}$

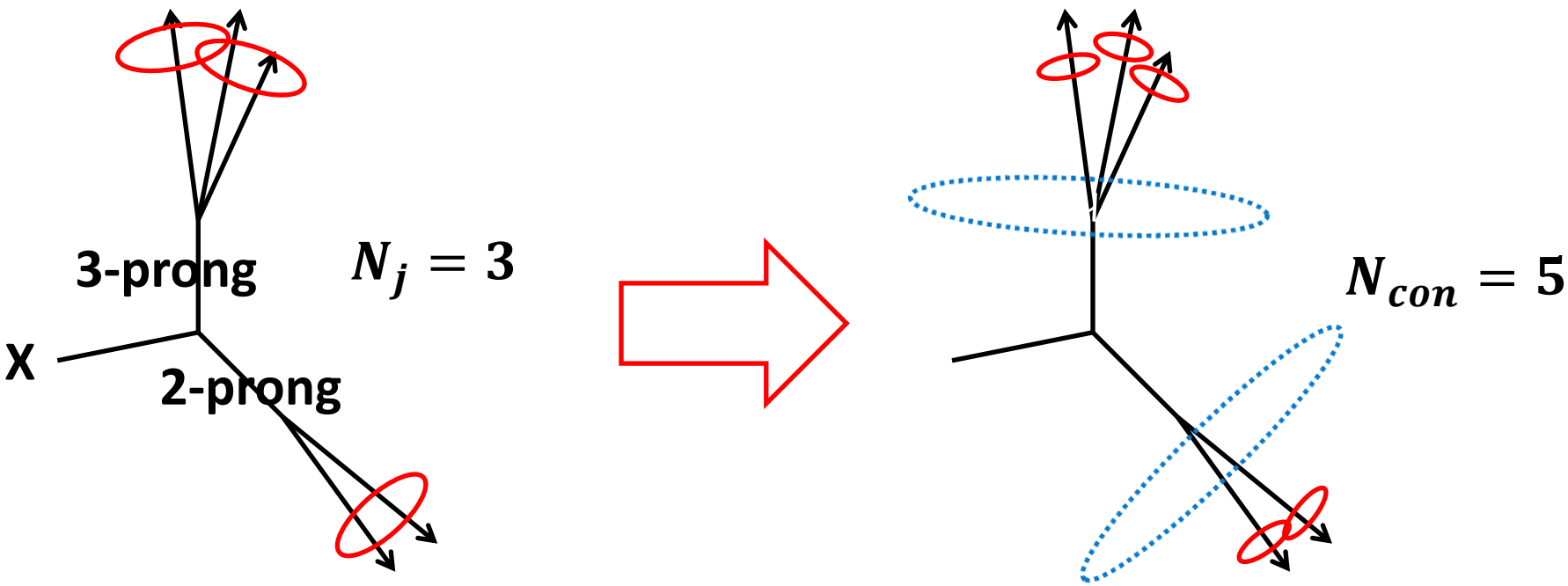


$N_j = 3$

Jet counting ceases to work!

Jet substructure

This is where jet-sub comes to us to help us!

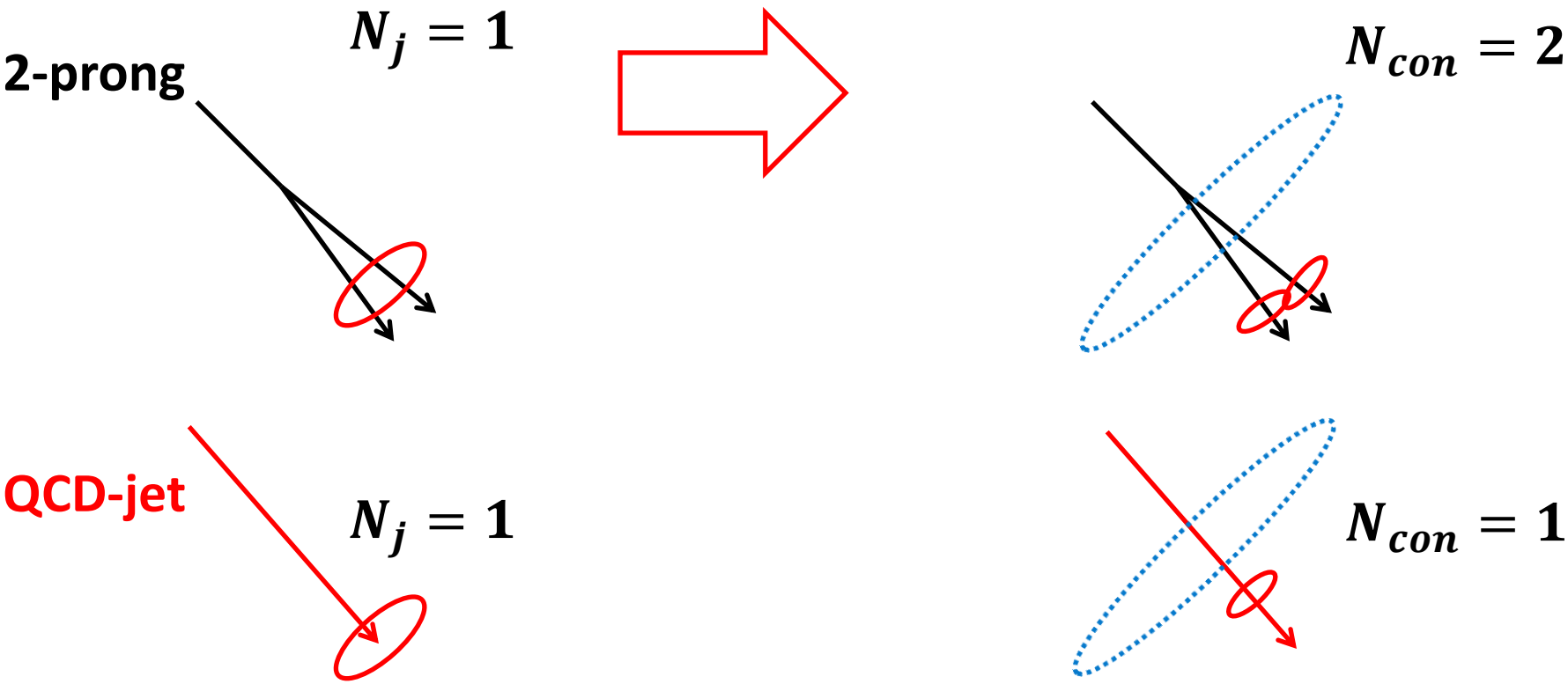


Jet substructure

Why this is important?

: we use jet multiplicity to discriminate the signal from backgrounds.

Eff. Is degraded when jet counting does not capture the correct physics



Jet substructure

Previous situation suggests us to count the number of constituents

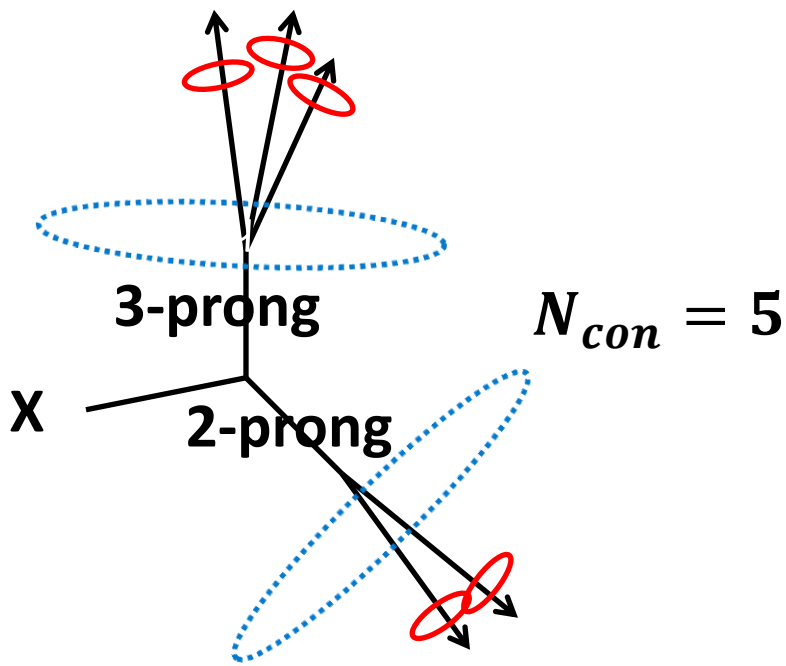
Number of "constituents"

$$N_{con} = \sum_{n} n \times N_{n-prong}$$

$$N_{1-prong} = traditional\ jet$$

$$N_{2-prong} = W, Z, h \rightarrow \bar{b}b\ taggers$$

$$N_{3-prong} = top\ taggers$$

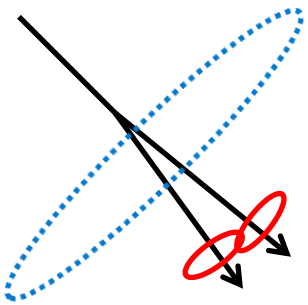


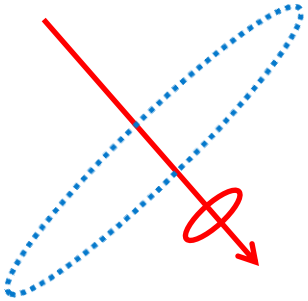
➡ Smooth interpolation from unboosted to boosted regime

Jet substructure

Still there is a problem here

$N_{con} = 2$



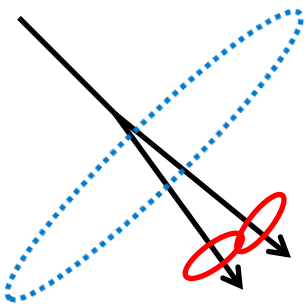


$N_{con} = 1$

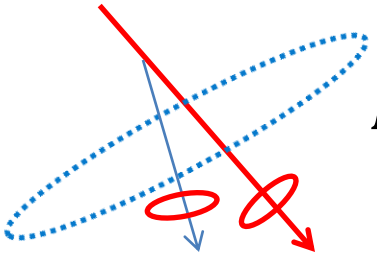
Jet substructure

Still there is a problem here

$N_{con} = 2$



*QCD-jet might increase multiplicity by hard emission, but this guy has to go through one more "hurdle", **Taggers***



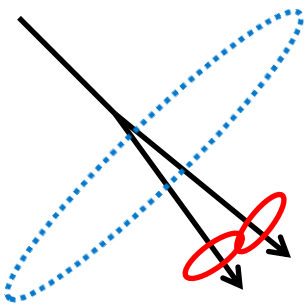
$N_{con} = 2$

Jet substructure

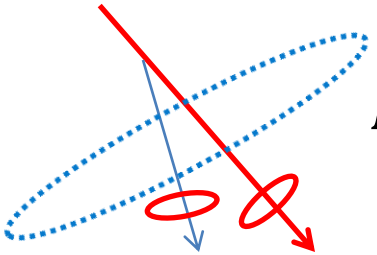
New counting variables arise !

$$N_{top}, N_W \ \ldots \ (\boldsymbol{or\ any\ combination})$$

$N_{con} = 2$



Taggers: *utilizes the internal kinematics and mass windows*



$N_{con} = 2$

Suggesting a new cut-and-count analysis

Boosted

(Jet substructure)

$H_T, N_{con}, N_{top}, N_W$ ...

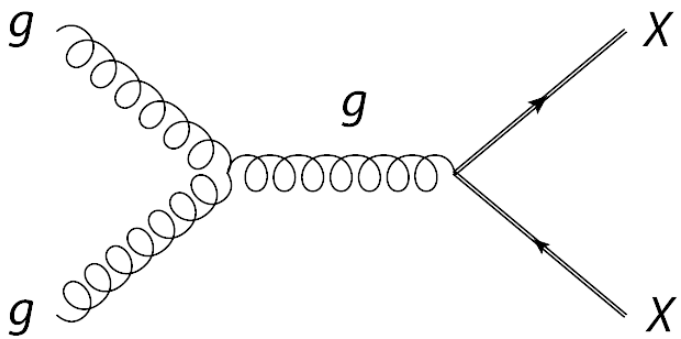
(*or any combination of these variables*)

Not Boosted

H_T, N_j ...

II. Increasing signal rates (for given backgrounds)

$$N_{total} =$$



$$= N_{pair}$$

II. Increasing signal rates (for given backgrounds)

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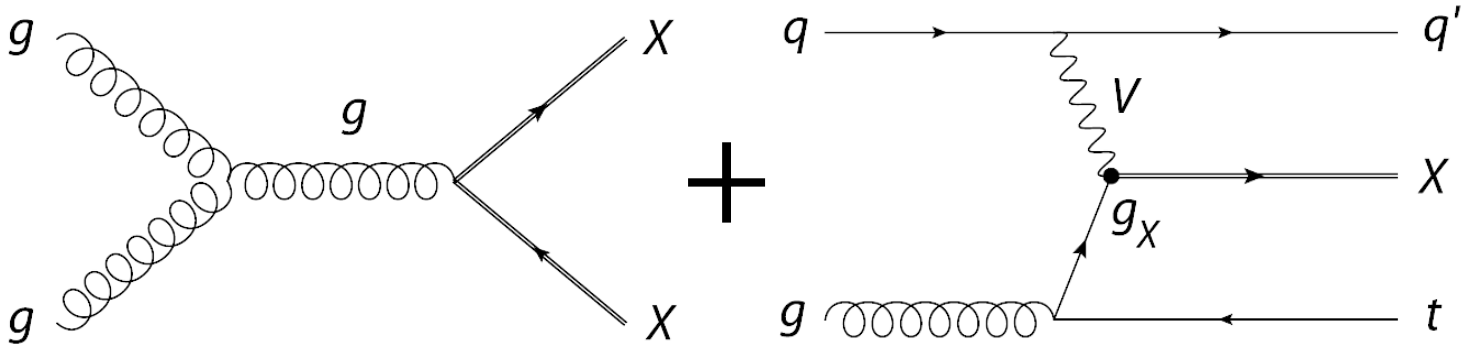

Correlate "processes"

$$= N_{pair} + g_X^2 \times N_{single}(g_X = 1)$$

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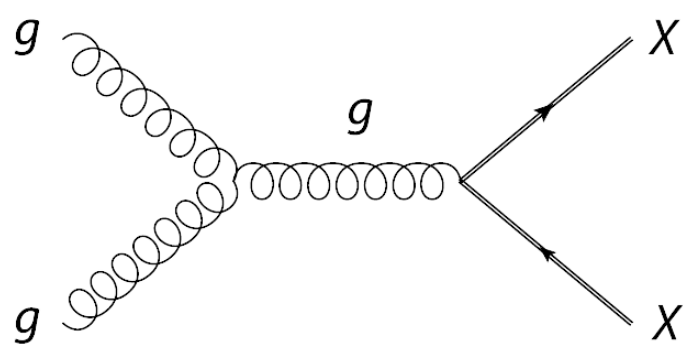
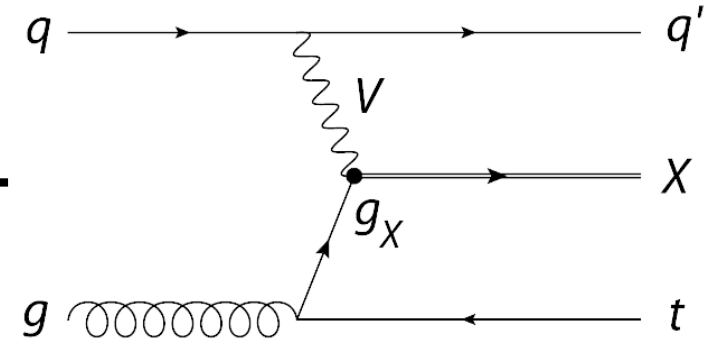
$$\sum_X \Bigg[$$



$$+$$



$$\Bigg]$$

Correlate "particles"

Correlate "processes"

$$= \sum_X \left(N_{pair}^X + g_X^2 \times N_{single}^X(g_X = 1)\right)$$

Simplified Model

of the minimal composite Higgs, $SO(5)/SO(4)$

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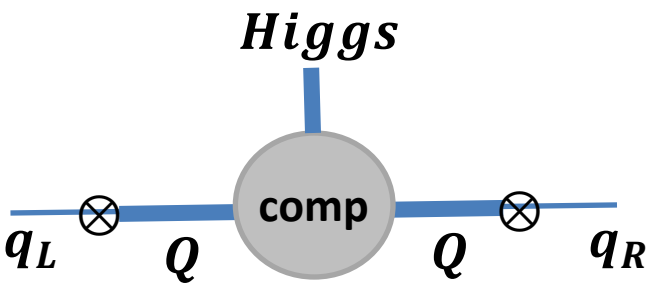
Partial compositeness



$$m_q = sin\varphi_{q_L}\, v\, Y_{comp}\, sin\varphi_{q_R}$$

Simplified Model
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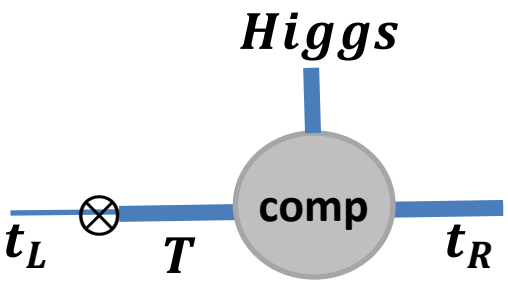
Partial compositeness

- **Fully composite RH top, partial composite LH top, bottom**



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Custodial symmetry protection

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Top partners in $\mathbf{4}_{2/3}$ of SO(4) (we do not include singlet top partner)

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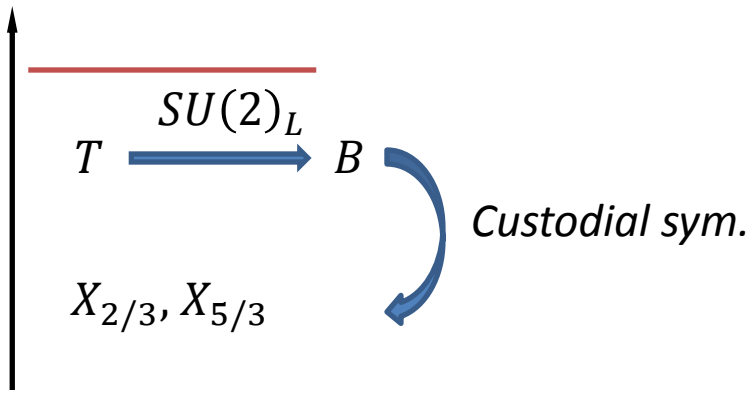

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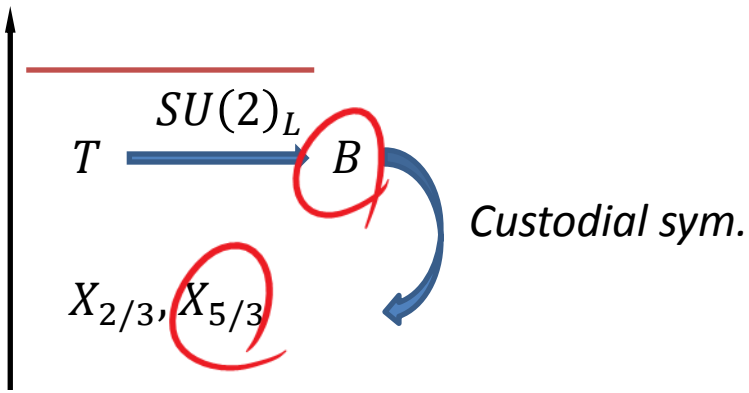


1. Target the lightest guy with unit branching fraction. Also use nearby top partner if it can jointly improve setting the limit, e.g. X5/3, B

2. Propagate the result from 1 to all the other top partners via mass relations among them

Simplified Model
of the minimal composite Higgs, $SO(5)/SO(4)$ (CCWZ)

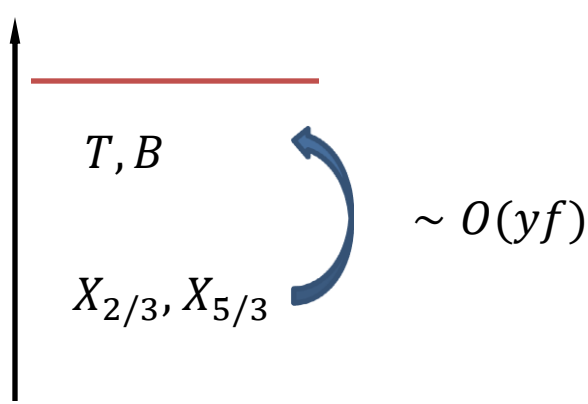
$$\mathcal{L} = \mathcal{L}_{\rm kin} - \bar{\Psi}\not{c}\Psi - M_\Psi \bar{\Psi}\Psi$$
$$+ i\, c_1 (\bar{\Psi}_R)_i \gamma^\mu d^i_\mu t_R + y\, f\, (\bar{Q}^{\mathbf{5}}_L)^I U_{I\,i} \Psi^i_R + y\, c_2\, f (\bar{Q}^{\mathbf{5}}_L)^I U_{I\,5} t_R + \text{h.c.}$$

arXiv:1211.5663
Simone, Matsedonskyi, Rattazzi, Wulzer

Main interaction for Single production

Elementary-composite mixing

$$g_X\, \bar{X} V t_R$$



e.g. $\boldsymbol{m_{X_{5/3}} = M_\Psi}$

$$\boldsymbol{m_B = \sqrt{m^2_{X_{5/3}} + (y\, f)^2}}$$

X5/3, B are very special

X5/3 : exotic charge of 5/3

It does not mix with other particles, the lightest top partner
It decays to tW with unit BR

B : bottom-like top partner

It dominantly decays to tW in our simplified model
B mass is not far from X5/3 for small *y f*

L + jets channel could be better than multilepton channel

Higher signal rates

, assuming “higher signal rates > cleaner backgrounds” (?)

Top partner search in CMS/ATLAS

There are two relevant searches, analyzing the full data set @ 8TeV. These two searches are also utilizing jet substructure

CMS: B2G-12-012 **($X_{5/3} \to tW$)**

$X_{5/3}$ top partner via (Inclusive) SSDL 770 GeV @95%CL

We will recast this analysis into our simplified model

CMS: B2G-12-015 **($T \to bW, tZ, tH$)**

has one lepton analysis (BDT: Boosted Decision Trees, uses jet sub.)

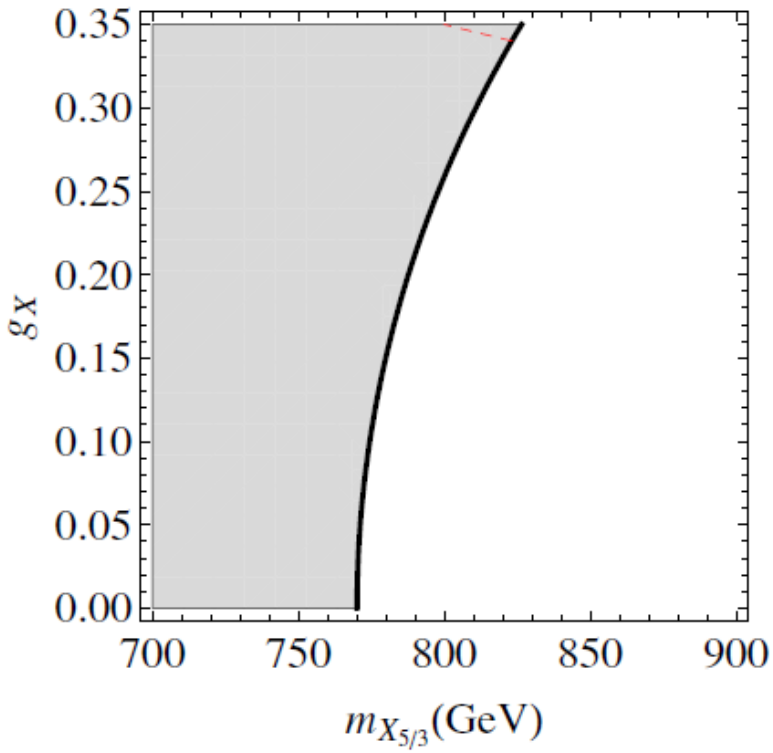
	Branching Fractions			expected	observed
Scenario	T→bW	T→tH	T→tZ	limit	limit
(0) Nominal	0.5	0.25	0.25	733 GeV	667 GeV
(1) Full tZ	0.0	0.0	1.0	689 GeV	644 GeV

Full tZ is applicable to tW (but with different BR). We will NOT recast this analysis

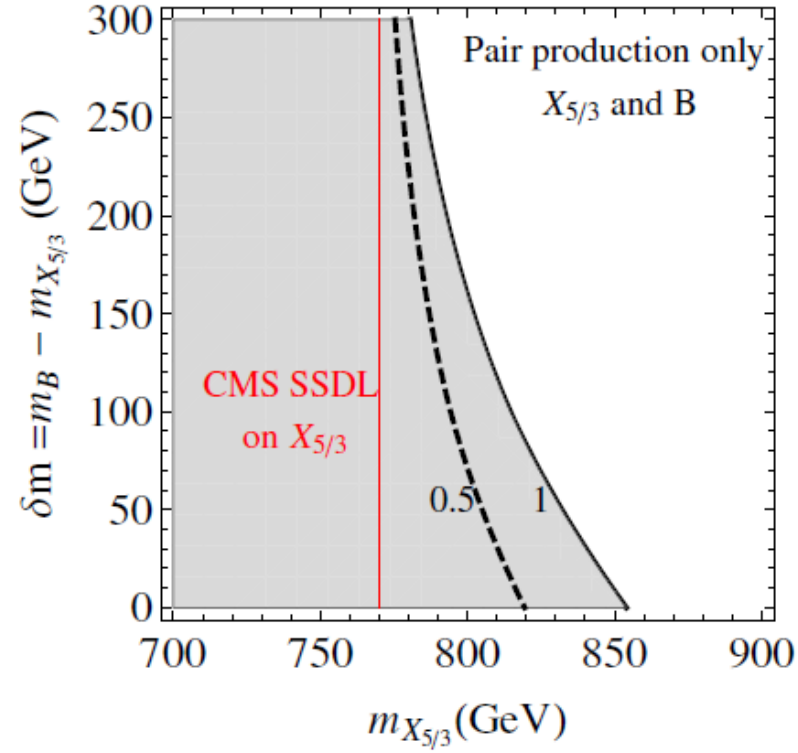
Our own one lepton analysis will cover this case

Recasting CMS SSDL

"process" correlation



"particles" correlation



$$N_{total} = N_{pair} + g_X^2 \times N_{single}(g_X = 1)$$

$$N_{total} = \sum_X N_{pair}^X$$

“Our” one lepton analysis

Cut & count Analysis

1. Lepton Isolation: less than 15% activity in 0.3 cone
2. Clustering event into R = 0.8 C/A jets
3. Run HEP Top-Tagger over all fat-jets (remove from the list: top-jets)
4. Run BDRS-type W-tagger over the remaining fat-jets (remove from the list: W-jets)
5. Re-cluster the remaining fat-jets into R = 0.5 anti-kT jets
6. Cut-and-count analysis with (HT, Ncon, Ntop, NW). HT= pT-sum of jets and lepton

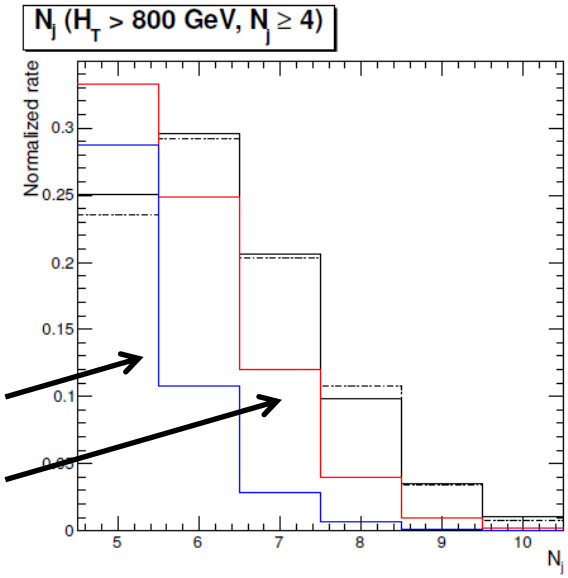
Top partner reconstruction

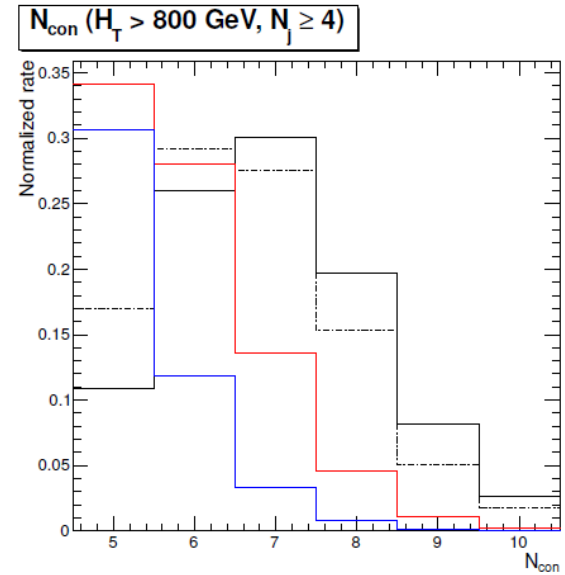
1. Search for top by pairing hadronic W-jet with nearby jet.
2. Search for leptonic top by pairing leptonic W with nearby jet
3. Take an invariant mass of top and W with the largest $\Delta\phi_{tW}$
4. Apply 20% of top partner mass window

N_j vs N_{con}

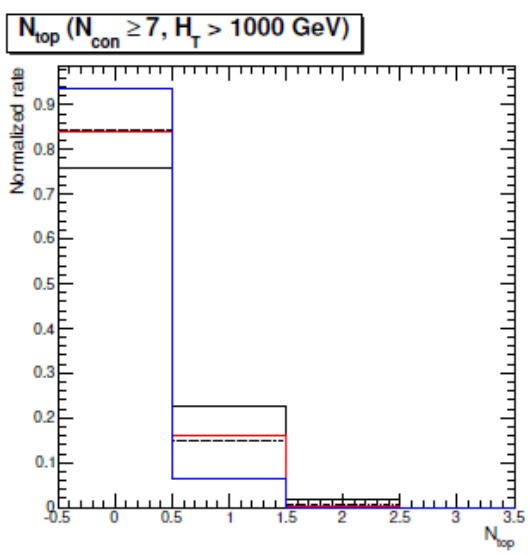
$w + jets$

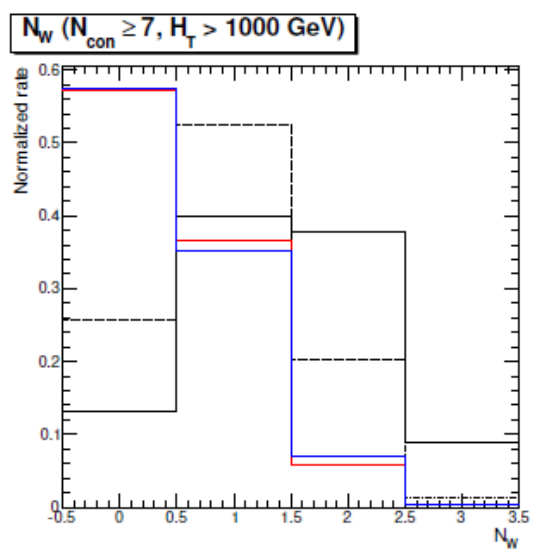
$\bar{t}t + jets$

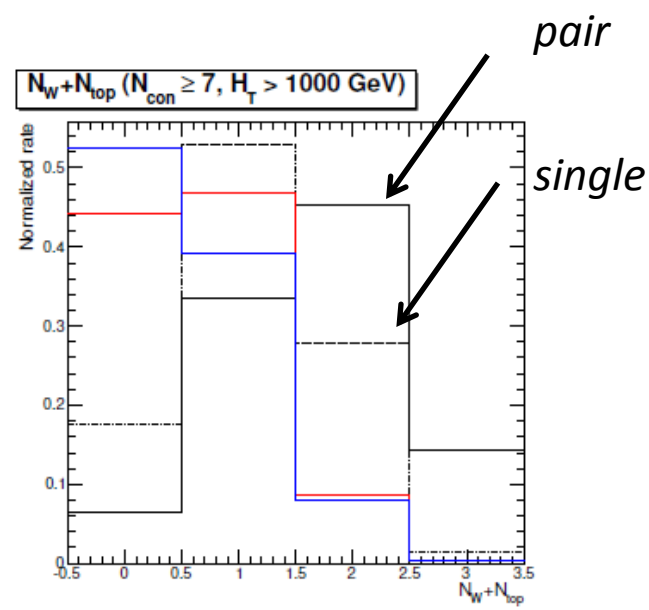




$N_{top}, N_W, N_{top} + N_W$

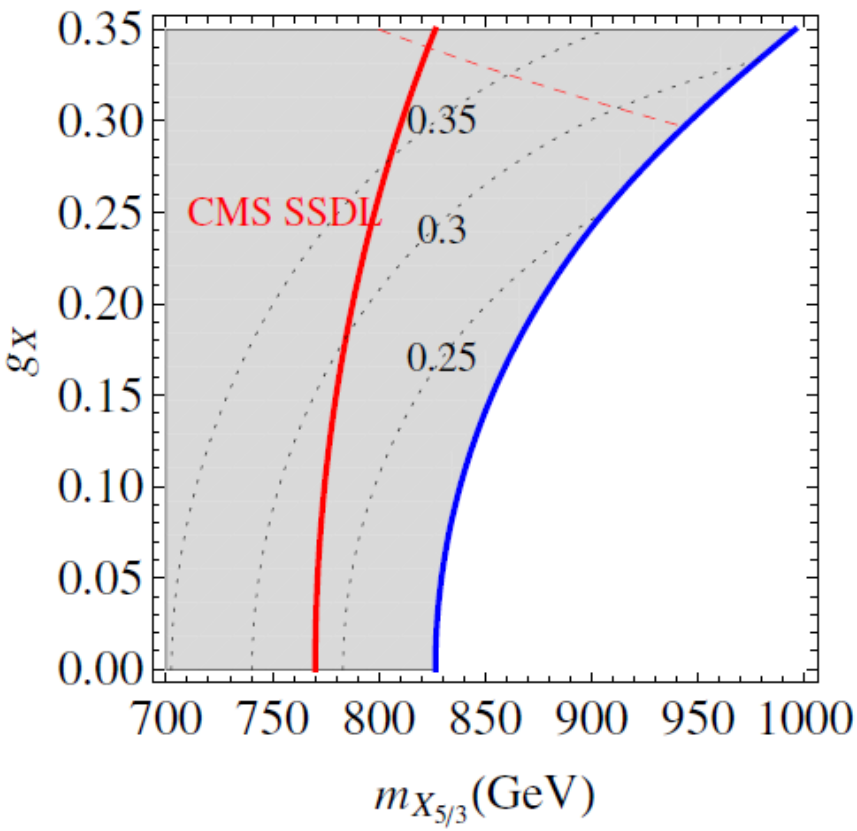


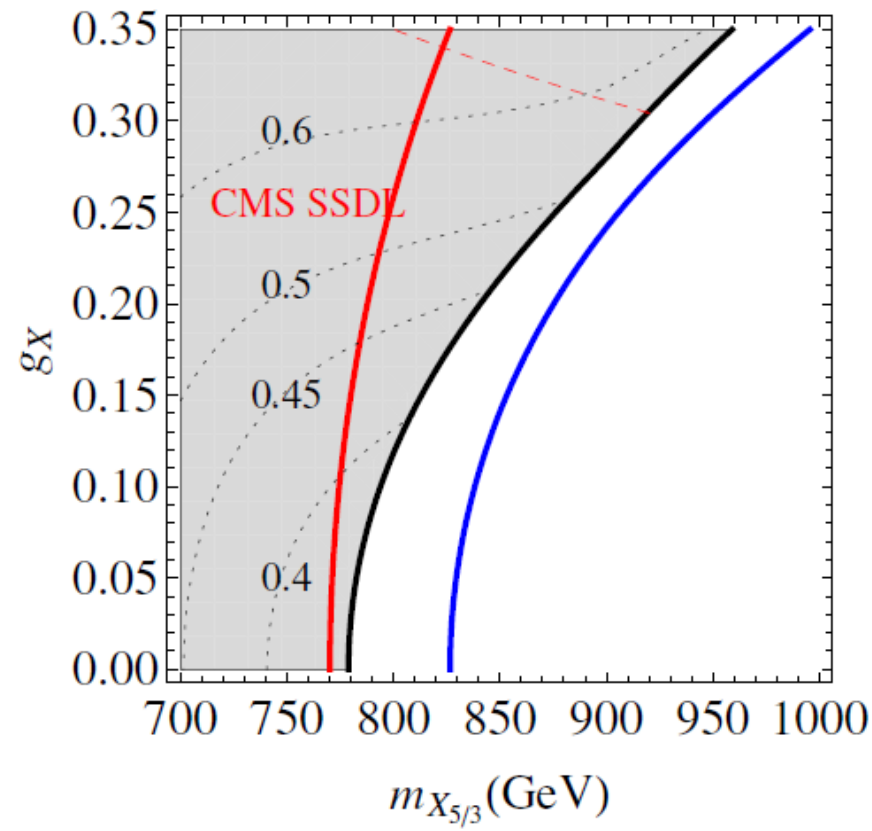




“process” correlation by cut-and-count

“process” correlation by cut-and-count and top partner mass reco.

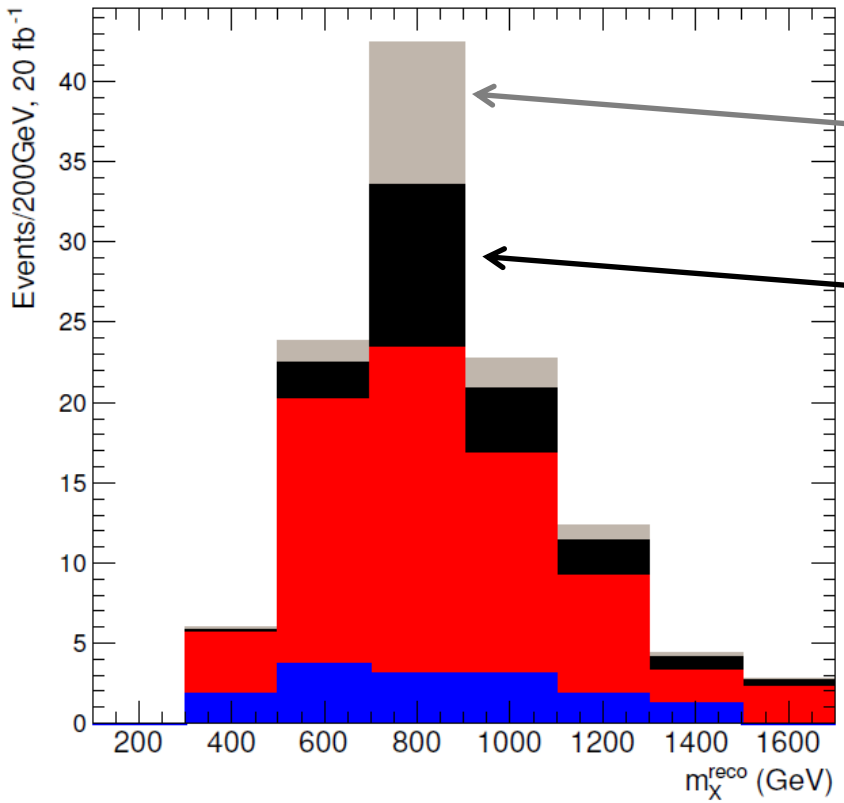




$N_{con} \geq 7, \quad H_T \geq \#$:To keep 90% of pair prod. signal after $N_{con} \geq 7$

$N_{top} + N_W \geq 2$:Insensitive to jet radius

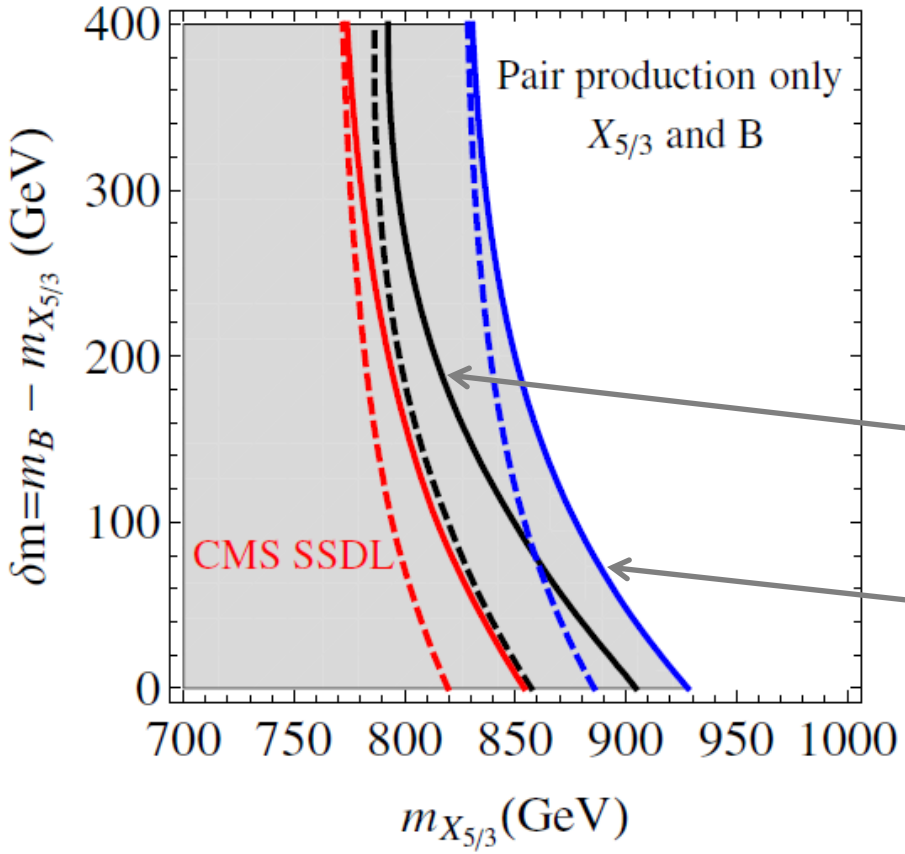
$1.2\, m_X \geq m_X^{reco} \geq 0.8\, m_X$



Single production with gX=0.32

Pair production

“particle” correlation



Cut & count + mass reconstruction In l+jets channel

Cut & count in l+jets channel

Recast the results into model-parameters of the simplified model

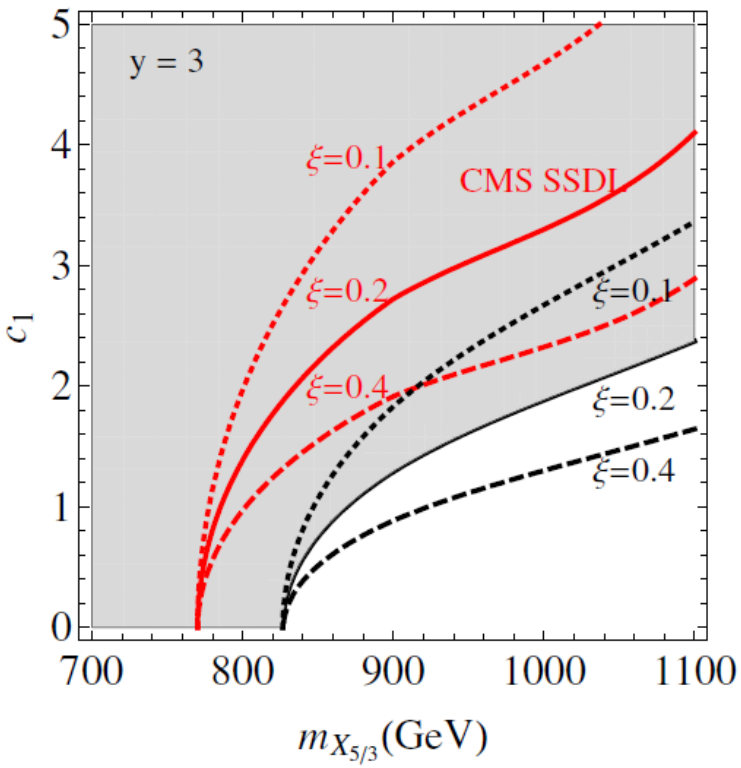
$$\sum_{X} (N_{pair}^{X} + g_X^2 \times N_{single}^{X}(g_X = 1))$$

$$g_X = g_X\,(f, y, c_1, c_2, M_\Psi)$$

$$m_X = m_X\,(f, y, c_1, c_2, M_\Psi)$$

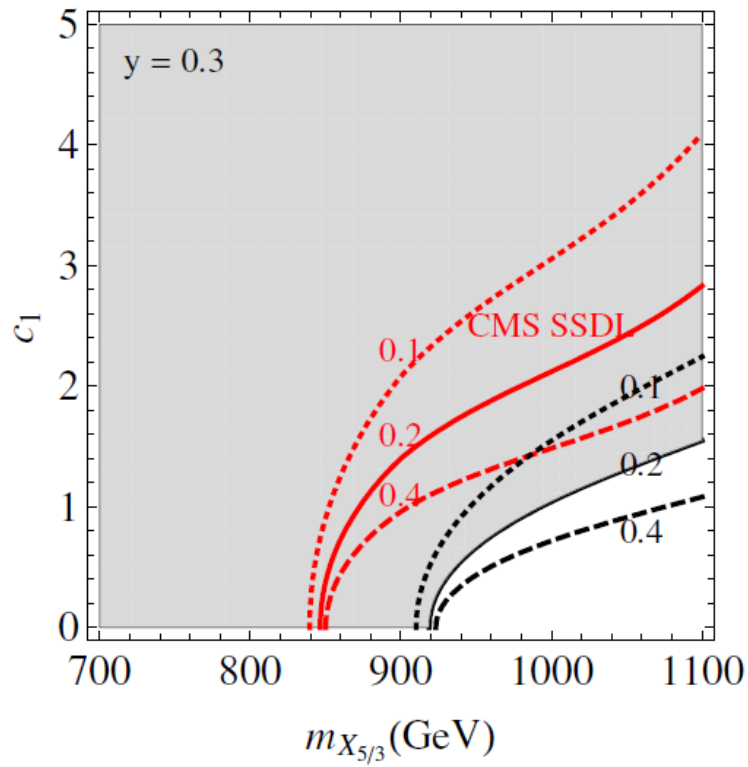
“process” correlation

$m_B \gg m_{5/3}$



“process + particle” correlation

$m_B \geq m_{5/3}$



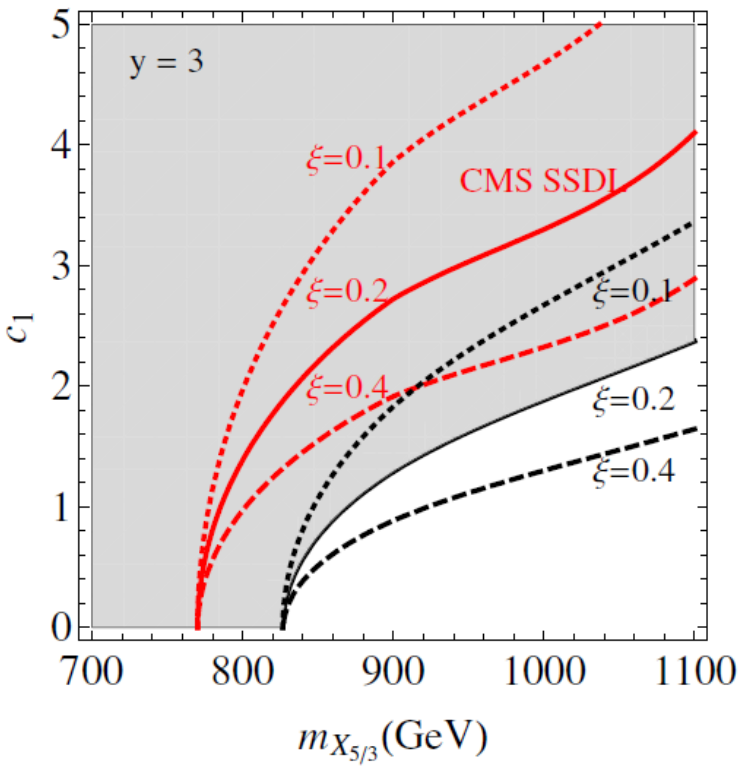
$\xi \equiv (v/f)^2$

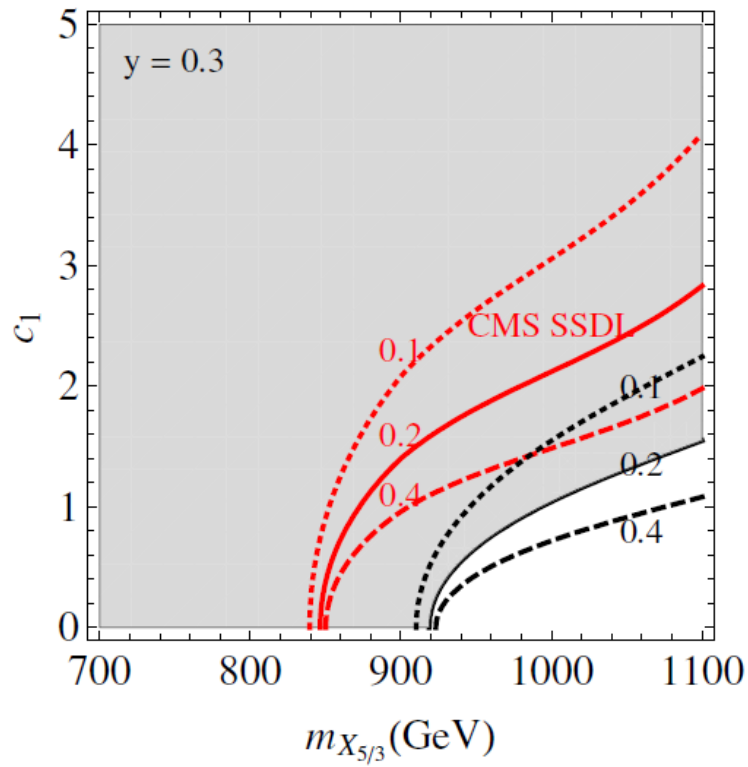
All other top partners in the same multiplet take benefit of X5/3 (and B)

Indirectly

$$m_B \gg m_{5/3}\ (= m_{2/3})$$

$$m_B \geq m_{5/3}\ (= m_{2/3})$$





$$\xi \equiv (v/f)^2$$

Indirectly

$$m_{B,T} > 1.5 - 2.5\ TeV$$

$$m_{B,T} > 930 - 940\ GeV$$

Summary

We are already in the boosted regime

Jet substructure may not be optional
: traditional cut-and-count analysis needs to change accordingly

Naturalness plus some reasonable assumptions defines structure of top partners

Use that model-dependent structure to boost top partner searches
: process correlation, particle correlation, mass relation among top partners etc.