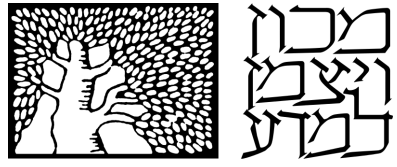
Stealthy new strong interactions

Emmanuel Stamou

in collaboration with J. Brod, J. Drobnak, A. L. Kagan and J. Zupan

Weizmann Institute of Science



Flasy 2014 @ University of Sussex

June 21, 2014

UnMotivational remarks

Yes, we have not discovered NP yet.

But:

- LHC is a hadron machine ➜ environment with large background
- many NP searches (have to) rely on leptonic final states or MET
- LHC13 starts next year

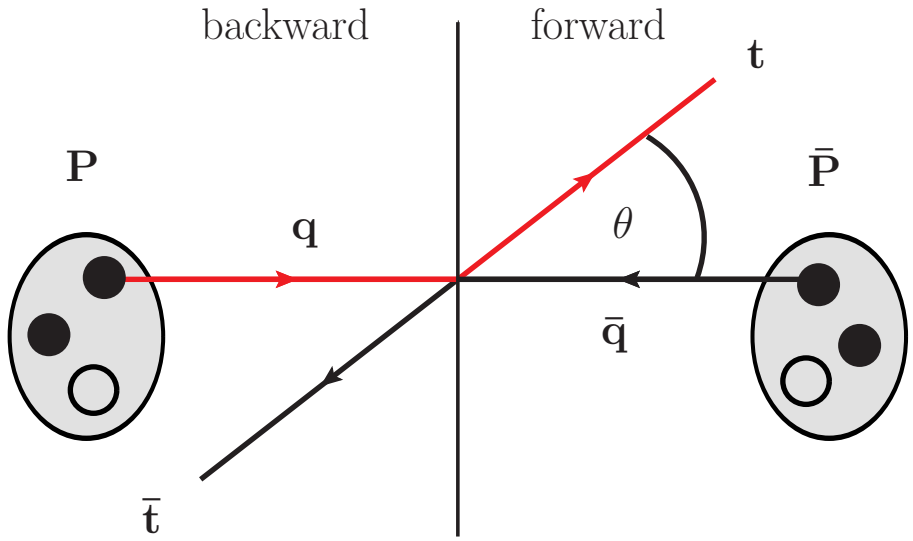
Questions:

- Is it possible that we missed some NP?
- Can it have $\mathcal{O}(1)$ couplings to the SM?
- Could the $A_{\rm FB}$ be a first manifestation?

Outline

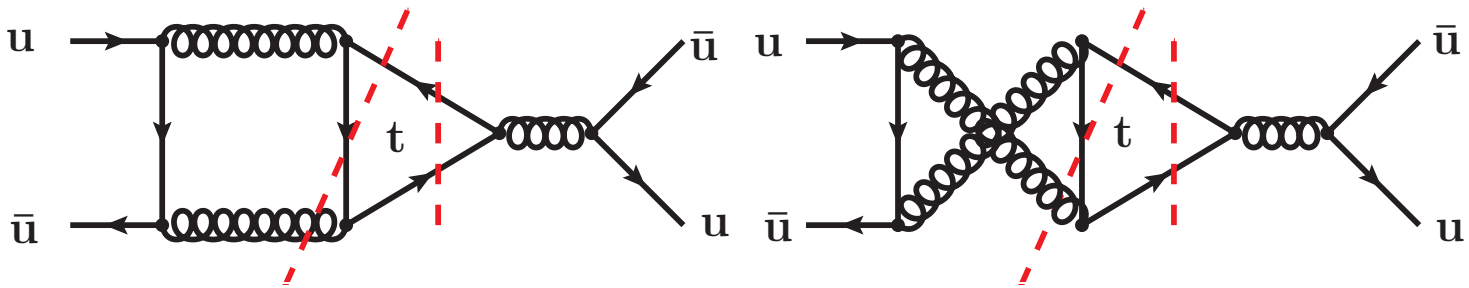
- $A_{\rm FB}$ present situation
- What we know from toy-models.
- UV-complete strong-interaction realisation
- Phenomenology at Tevatron and LHC.

Top-quark forward-backward asymmetry



CDF/D0 ➜ more tops in forward direction

QCD ➜ $A_{\mathrm{FB}} = 0$ at tree level,
$A_{\mathrm{FB}} > 0$ at NLO from real and virtual gluons

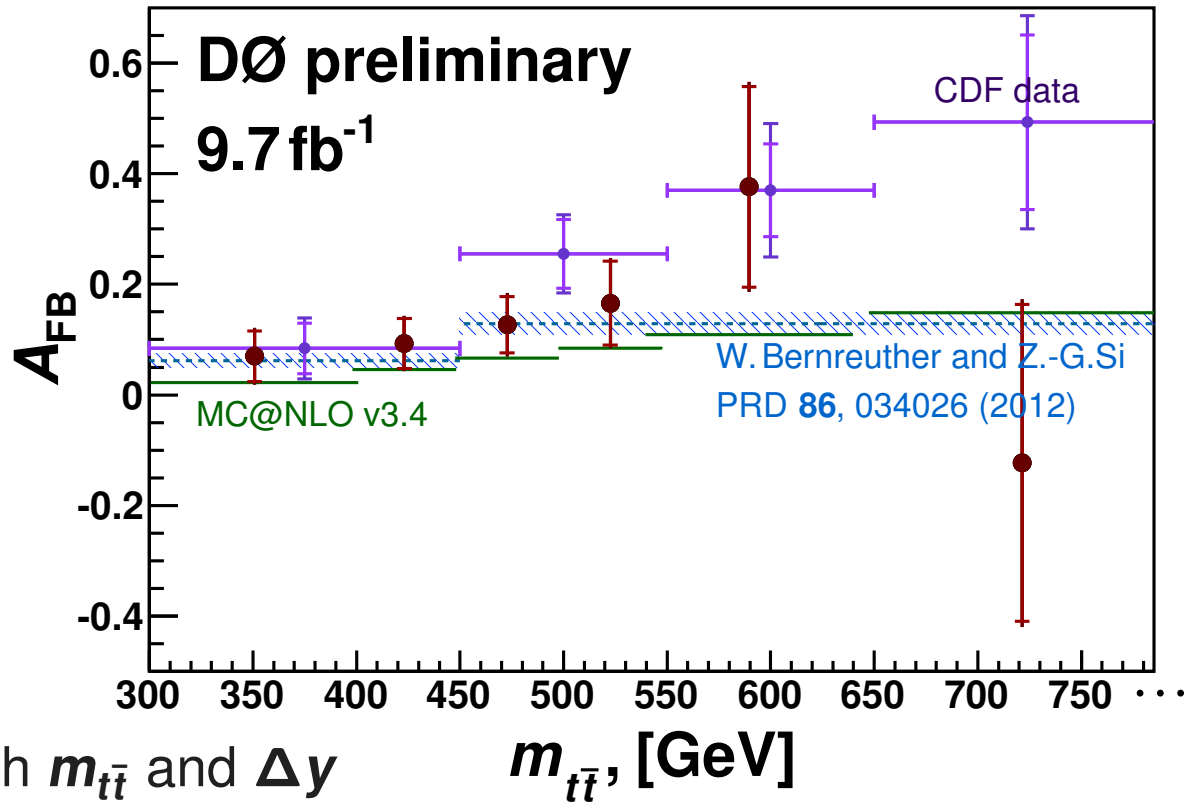


Tevatron: top-quark forward-backward asymmetry

$A_{FB}^{inc,CDF} = (16.4 \pm 4.7)\%$ [CDF, arXiv:1211.1003]

$A_{FB}^{inc,D0} = (10.6 \pm 3.0)\%$ [D0, arXiv:1405.0421]

$A_{FB}^{inc,average} = (12.3 \pm 2.5)\%$ $A_{FB}^{inc,SM} = (8.8 \pm 0.6)\%$



➜ **rise** with $m_{t\bar{t}}$ and Δy

➜ middle bins still give $\approx 3\sigma$ tension

➜ D0 has large errors in high bins

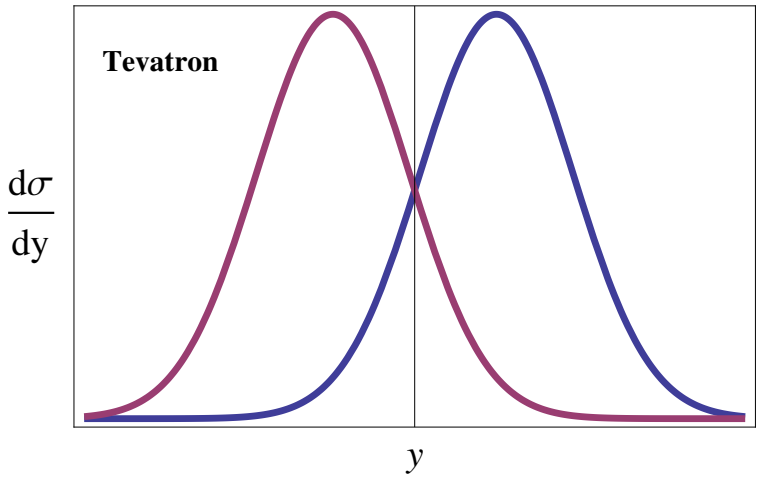
❶ requirement on NP

LHC: top-quark charge asymmetry

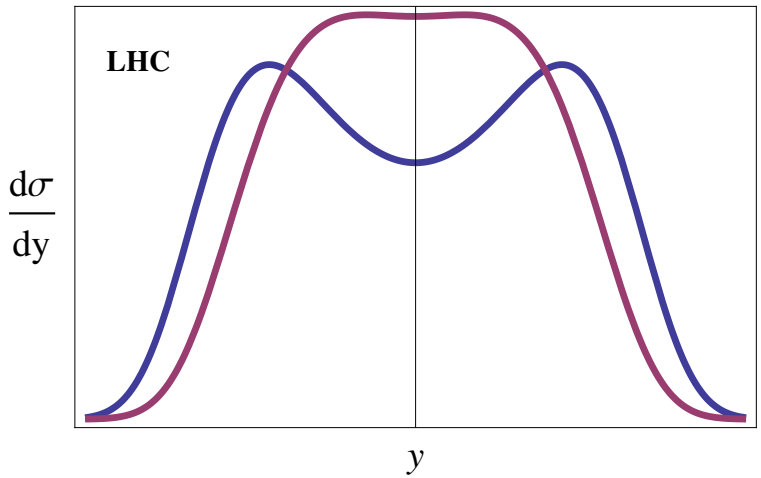
@LHC initial state is symmetric ➜ no A_{FB}. Instead

$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}$$

A_{FB} @ Tevatron



A_C @ LHC



Purple: anti-top distribution Blue: top distribution [Ahrens et al., 12]

Good agreement with SM:

$A_C(7\text{TeV}) = (1.0 \pm 0.8)\%$ [ATLAS, CMS] $A_C^{\text{SM}}(7\text{TeV}) = (1.23 \pm 0.05)\%$

$A_C(8\text{TeV}) = (0.5 \pm 0.9)\%$ [CMS] $A_C^{\text{SM}}(8\text{TeV}) = (1.11 \pm 0.04)\%$

[Bernreuther, Si; 12]

❷ requirement on NP

A_{FB} and NP

- A_{FB} comes from **interference** with SM

[Grinstein et al.; 11]

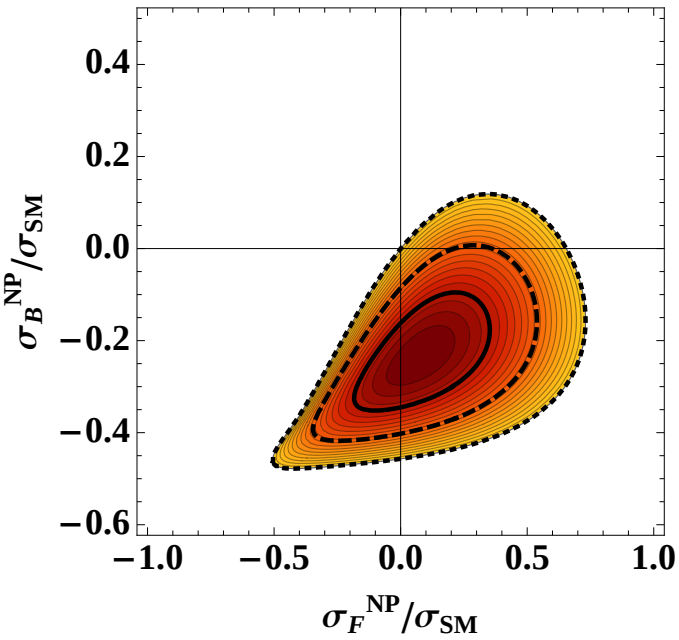
➜ Favoured scenarios:

s-channel: colour-octet vector with axial couplings

(heavy axigluon)

t-channel: colour-singlet or coloured resonances

(flavoured gauge bosons, flavoured resonances?)



- t-channel mediator ≈ 150 GeV

➜ A_{FB} rises with $m_{t\bar{t}}$

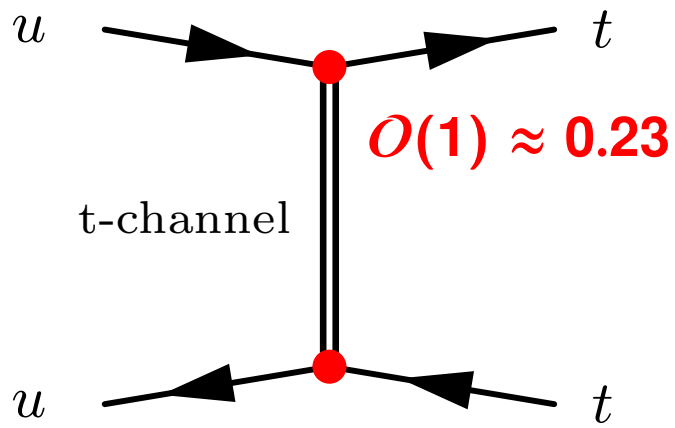
[Jung et al.; 09]

➜ compatible with diff. $t\bar{t}$ x-section

[Gresham et al.; 11]

➜ $O(1)$ $\bar{t}_R \not{u}_R$ couplings from flavour-symmetric sector favoured

[Grinstein et al.; 11]



❸ requirement on NP

Recapitulation / challenges / solutions

uv complete model with t-channel solution for the A_{FB}

- A_{FB} increasing with $m_{t\bar{t}}$ / Δy
  - ➜ $M_{med} \approx$ **150 GeV** with $\mathcal{O}(1)$ **couplings** to *t*-*u*
- A_C compatible with SM
  - ➜ possible through associate production of med. if
    $$\mathbf{BR(mediator} \rightarrow t\bar{u}\mathbf{)} \approx \mathbf{20\%}$$ [Drobnak et al.; 12]
  - ➜ need another dominant decay channel
- compatible with differential $t\bar{t}$ spectra
- compatible with same-sign, single top searches & FCNCs
  - ➜ flavour-symmetric sector
- not yet discovered at LHC

a new stealth strongly-coupled sector can naturally have such resonances

Strong interaction realisation

Idea:

❶ **confinement** of **new** asymptotically-free $\boldsymbol{SU(N)_{\mathrm{HC}}}$

(around 200 GeV)

❷ **breaking of chiral symmetry** of new HC quarks

(just like QCD)

❸ HC quarks form colour/HC singlet **bound states**

(π_{HC}, ρ_{HC}, K^*_{HC}, $a_{1\mathrm{HC}}$, ...)

❹ $O(1)$ couplings **only** to right-handed up-type quarks

(due to hypercharge assignment, couplings through partial compositeness)

❺ $U(2)_{u_R}$ symmetry protects from dangerous FCNCs

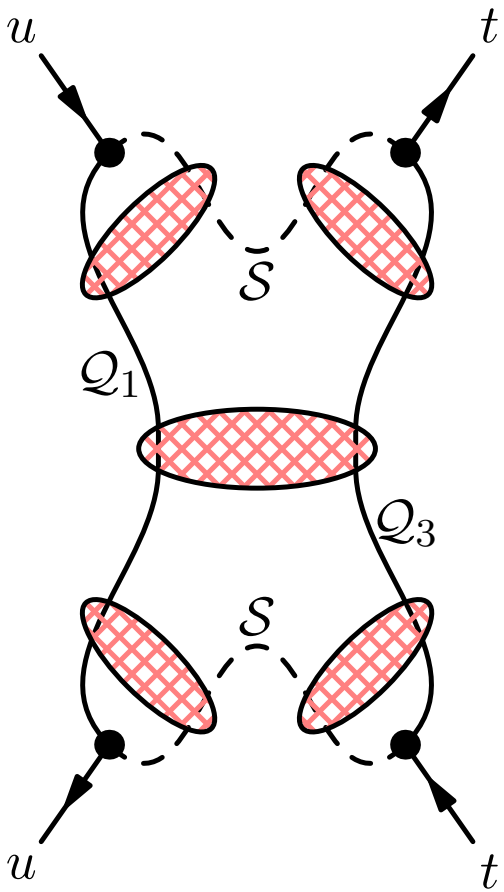
(just 5 new parameters)

❻ A_{FB} from resonances in the t-channel

(mediator has naturally a dominant decay channel other than $t\bar{u}$)

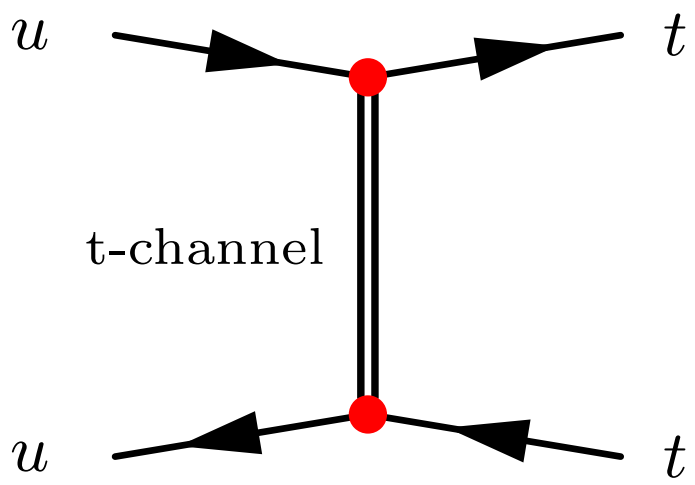
How it works

UV picture



=

IR picture



The model

- under $SU(3)_{\rm HC} \times SU(3)_c \times SU(2)_L \times U(1)_Y$

$$Q_{Li,Ri}(3,\ 1,\ 1,\ 0) \qquad \mathcal{S}(\bar{3},\ 3,\ 1,\ 2/3)$$

$$\mathcal{L}_{\rm NP} \supset m_{Q_{ij}}\,\bar{Q}_i Q_j + m_{\mathcal{S}}^2 |\mathcal{S}|^2 + \left(h_{ij}\,\bar{u}_{Ri}\,Q_{Lj}\,\mathcal{S} + h.c.\right)$$

- chiral-symmetry breaking from **HC quark** condensate

  (copy of QCD)

- coupling to SM through colour-triplet **HC-antitriplet scalar** $\mathcal{S}$

  ("analogous" to QED in QCD)

- $\langle \mathcal{S}Q \rangle$ has charge of up-type quarks (u')

  ➜up-type quarks rendered partial composite

  ➜large mixing with 3rd generation

- $U(2)_{u_R}$ flavour symmetry ala MFV

  ➜ $m_{Q_{ij}} = diag(m_1, m_1, m_3)$ and $h_{ij} = diag(h_1, h_1, h_3)$

A viable benchmark

How do we get the **IR** spectrum/couplings from the **UV** parameters?

QCD as prototype

- pheno. quark model to fit meson masses from quark masses [Cheng, Shrock; 11]
- naive rescaling from $\Lambda_{\rm QCD}$ up to $\Lambda_{\rm HC}$ (e.g. $M_{\rho_{\rm QCD}}/M_{\rho_{\rm HC}} = f_{\rho_{\rm QCD}}/f_{\rho_{\rm HC}}$)
- vector-meson dominance for estimating strong couplings

We then perform a χ^2 fit including $A_{\rm FB}$, $A_{\rm C}$ and $\sigma_{t\bar{t}}$:

$\Lambda_{\chi{\rm HC}} \approx 180$ GeV	$\equiv$	$\Lambda_{\chi{\rm QCD}} \approx 700$ MeV
Q_1 [3GeV], Q_2 [3GeV], Q_3 [20GeV] of HC	$\equiv$	u, d, s of QCD
S [500GeV] of HC $> \Lambda_{\chi{\rm HC}}$	$\equiv$	c of QCD

IR spectrum

octet of (pseudo)-Nambu Goldstone bosons $\langle Q_i Q_j \rangle$

$\pi_{\rm HC}$ [60 GeV], $K_{\rm HC}$ [140 GeV], $\eta_{\rm HC}$ [161 GeV]

(neglect η-η' mixing)

nonet of vectors $\langle Q_i Q_j \rangle$

$\rho_{\rm HC}$ [177 GeV], $K^*_{\rm HC}$ [210 GeV], $\Omega_{\rm HC}$ [180 GeV], $\Phi_{\rm HC}$ [240 GeV]

($K^*_{\rm HC}$ main contribution to $A_{\rm FB}$ because $\Omega_{\rm HC}$ $\Phi_{\rm HC}$ ideally mixed)

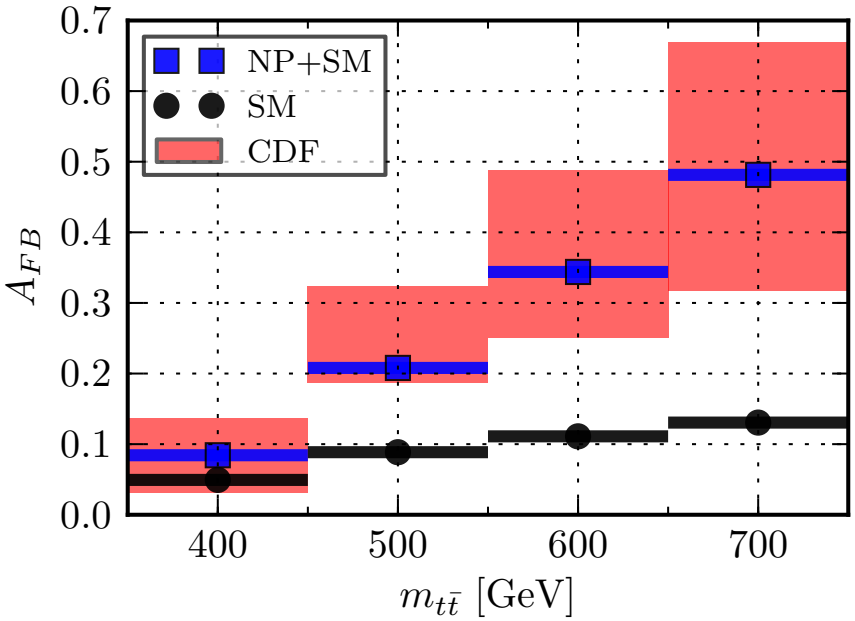
would-be *u'*s $\langle Q_i \mathcal{S} \rangle$

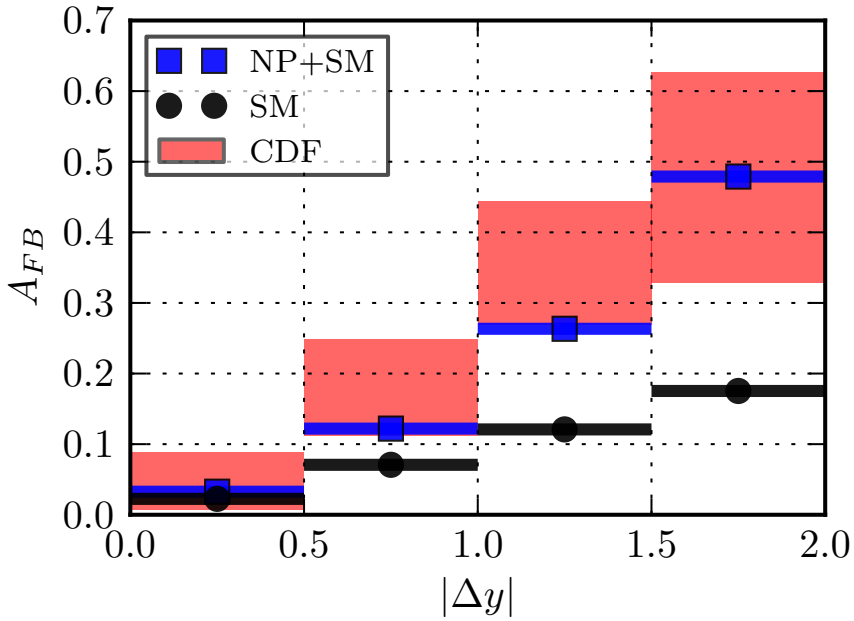
similar to top in SM: $\mathcal{S}$ decays before forming $\langle Q_i \mathcal{S} \rangle$

$\Gamma(\mathcal{S} \to u_j \overline{Q}_j) \propto m_{\mathcal{S}} |h_i|^2 \approx 240$ GeV

This benchmark has $h_1 \approx 2$ and $h_3 \approx 4$. Problem? Low Landau pole? Is the QCD breaking pattern disturbed? Currently looking into this.

A_{FB} and A_C





A_{FB}-A_C correlation naturally broken by associate K^*_{HC} production
(since K^*_{HC} not self-conjugate and BR($K^*_{HC} \to t\bar{u}_{HC} \approx 30\%$))

$A_C(7\ \text{TeV}) = 2.45\%$ (no associates) ➜ 1.37% (with associates)

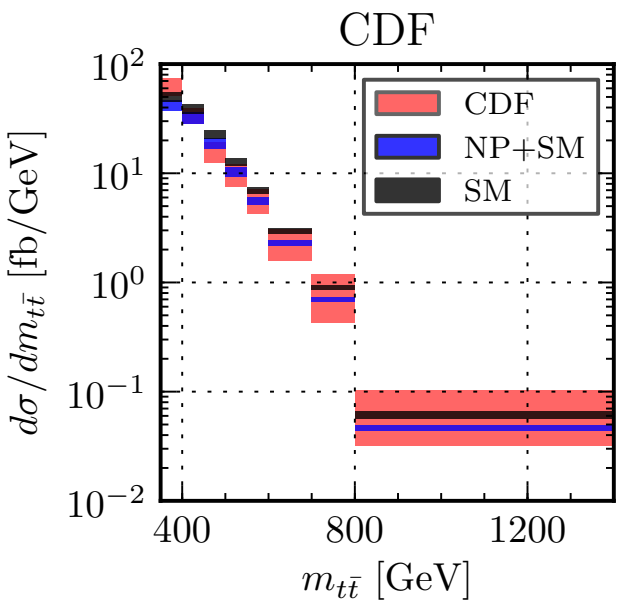
$A_C(7\ \text{TeV}) = (1.0 \pm 0.8)\%$ [ATLAS, CMS]

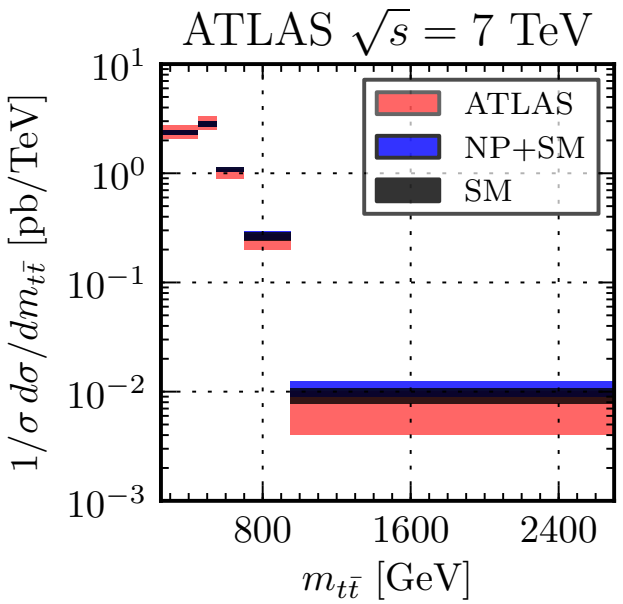
$A_C(8\ \text{TeV}) = 2.39\%$ (no associates) ➜ 1.35% (with associates)

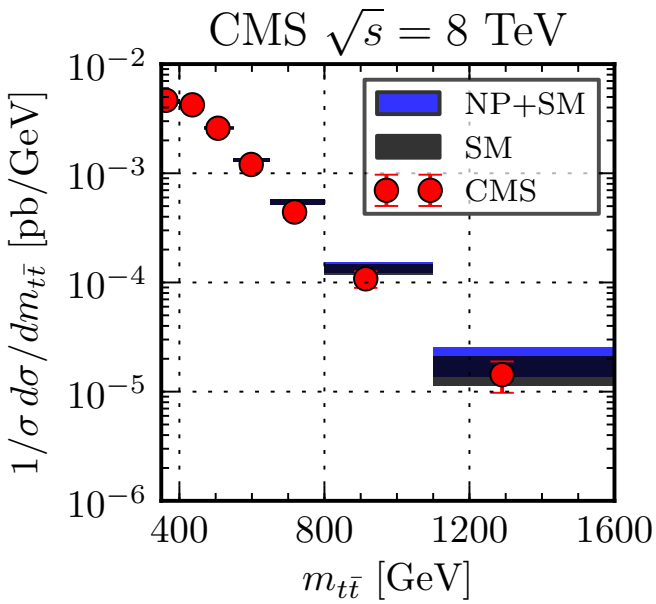
$A_C(8\ \text{TeV}) = (0.5 \pm 0.9)\%$ [ATLAS, CMS]

✓

Differential $t\bar{t}$ cross section at Tevatron and LHC

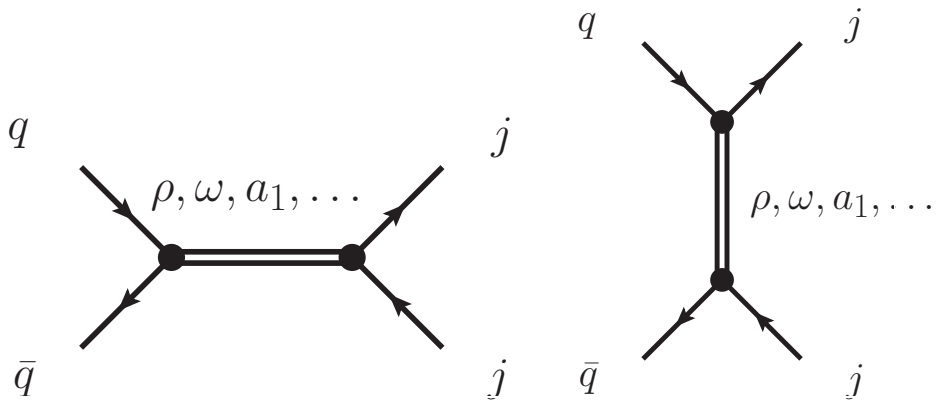


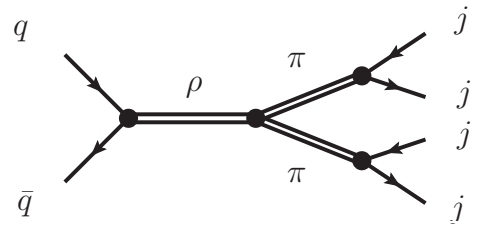




$\sigma_{t\bar{t}}$	SM + NP	experiment
Tevatron	6.38 ± 0.54 pb	7.50 ± 0.48 pb
LHC (7 TeV)	176 ± 15 pb	172.4 ± 8.5 pb
LHC (8 TeV)	251 ± 20 pb	234 ± 8 pb

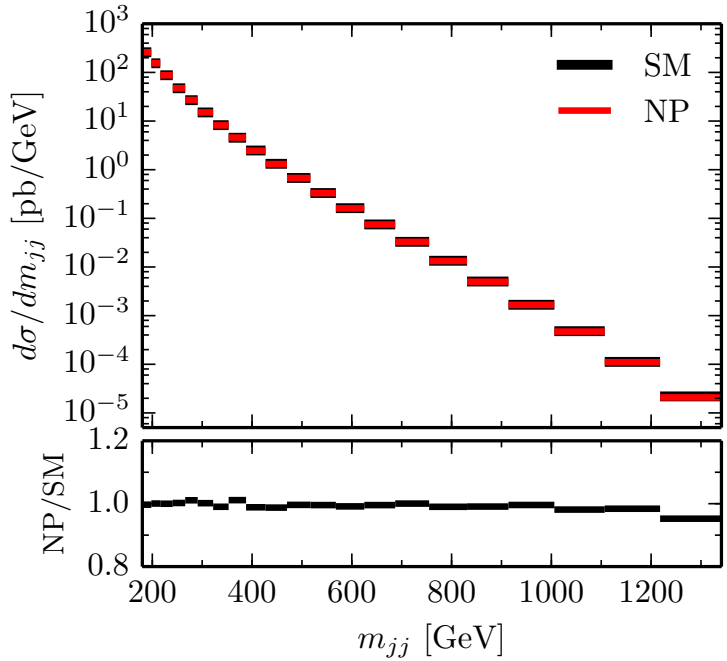
m_{jj} dijet spectra and dijet pairs constraints



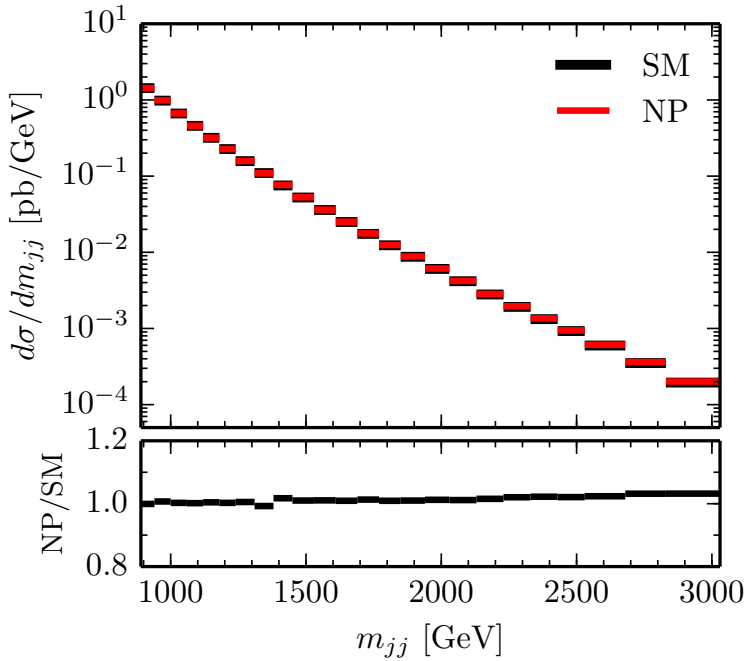


[CDF search, arxiv:1303.2699]

CDF @ Tevatron

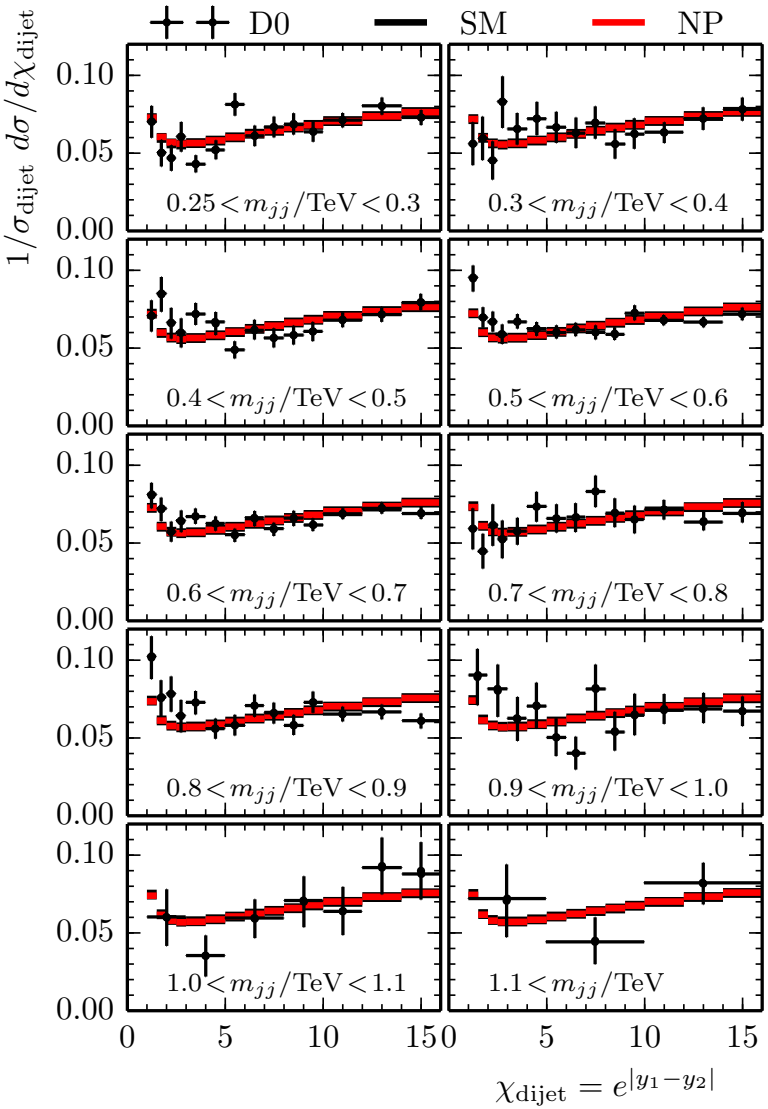


CMS @ LHC

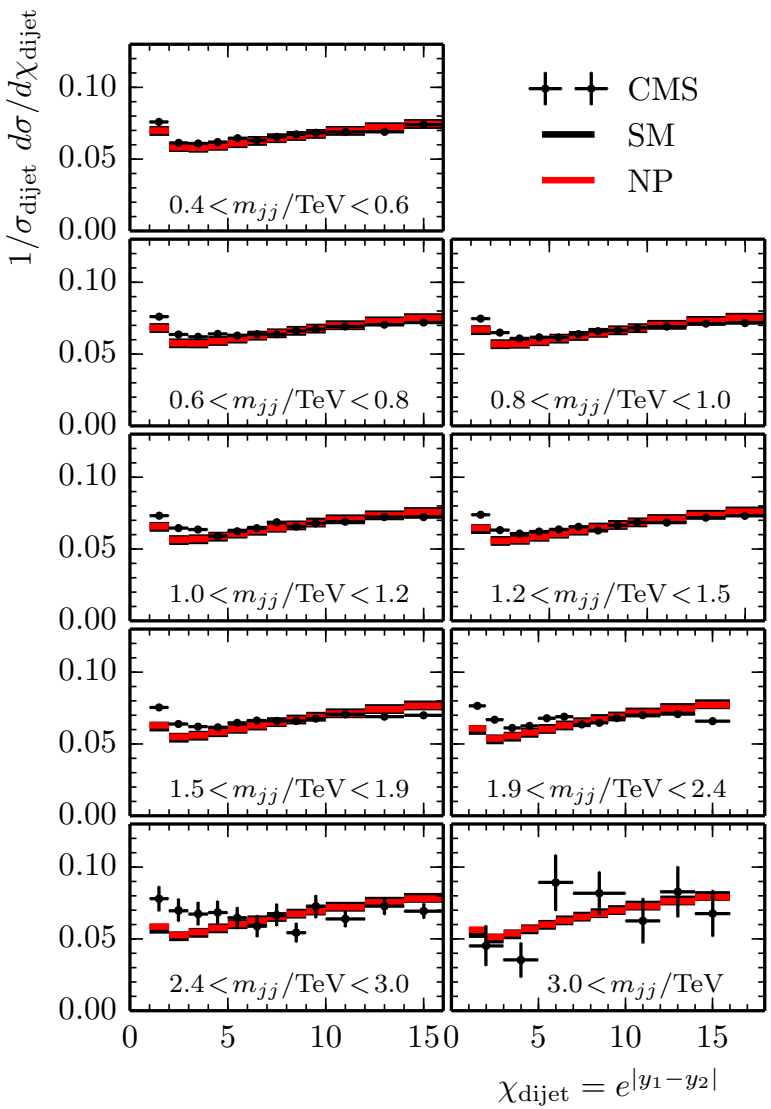


Dijet angular distributions

D0 @ Tevatron

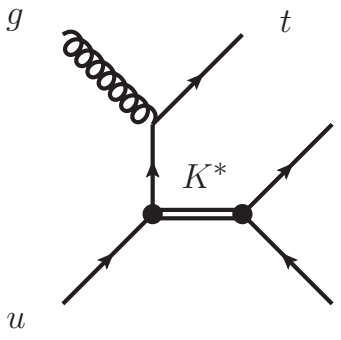


CMS @ LHC



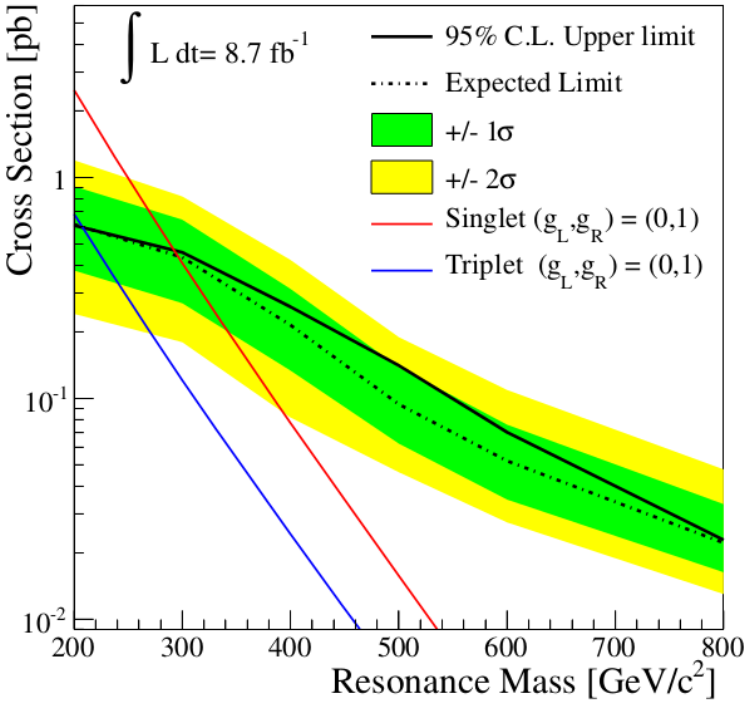
Top-jet resonance searches

$$\sigma_{K^* t} \times \mathrm{Br}_{K^* \to \bar{t} j} = 0.07\,\mathrm{pb}$$
$$\sigma_{K_1 t} \times \mathrm{Br}_{K_1 \to \bar{t} j} = 0.008\,\mathrm{pb}$$

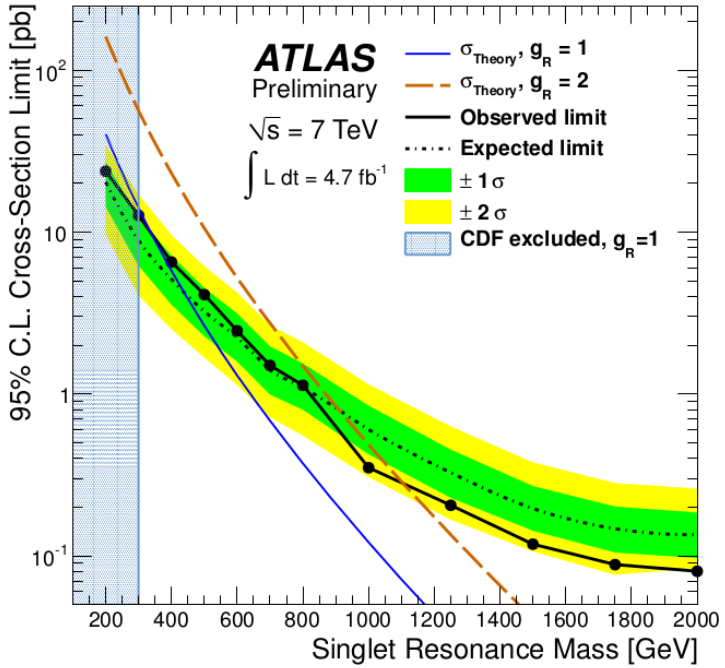


$$\sigma_{K^* t} \times \mathrm{Br}_{K^* \to \bar{t} j} = 4.4\,\mathrm{pb}$$
$$\sigma_{K_1 t} \times \mathrm{Br}_{K_1 \to \bar{t} j} = 0.8\,\mathrm{pb}$$

CDF [1203.3894]



ATLAS [CONF-2012-096]



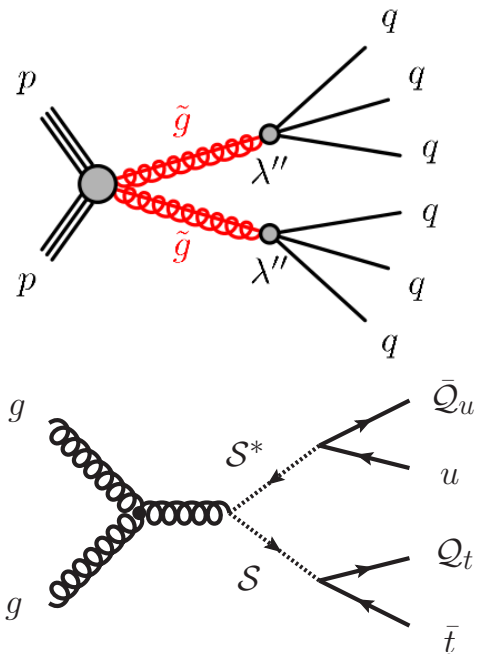
➜Possible signal at LHC13.

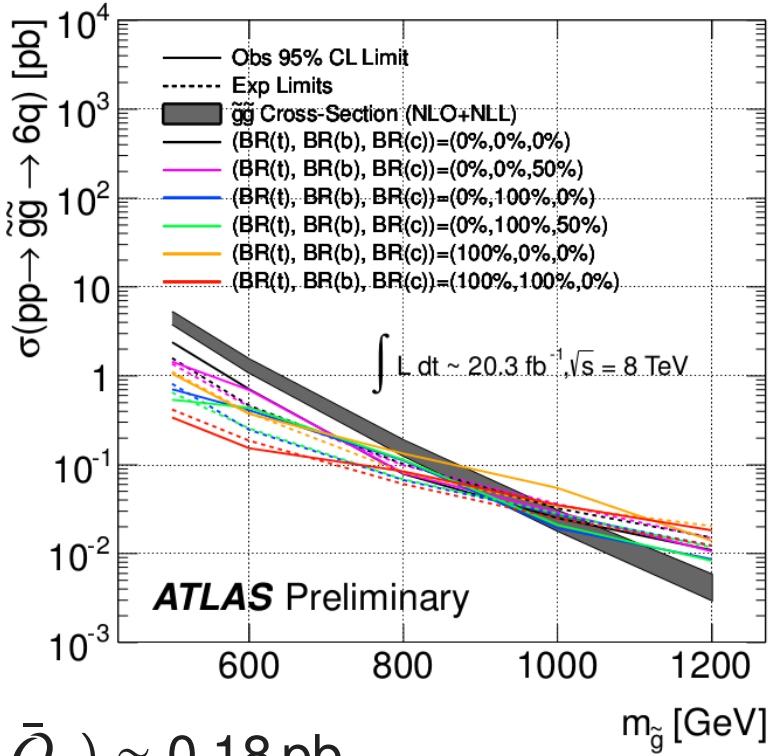
$\mathcal{S}$ production and multi-jet searches

- ATLAS searches for multi-jets from gluinos with RPV decays.

[ATLAS-CONF-2013-091]

- $\mathcal{S}$ also decays to high multiplicity jets.





$$\sigma(pp \to \mathcal{S}\mathcal{S}^* \to q\bar{q}Q_q\bar{Q}_q) \approx 0.18\,\text{pb}$$

$$\sigma(pp \to \mathcal{S}\mathcal{S}^* \to q\bar{t}\bar{Q}_qQ_t + \bar{q}tQ_q\bar{Q}_t) \approx 0.6\,\text{pb}$$

$$\sigma(pp \to \mathcal{S}\mathcal{S}^* \to t\bar{t}Q_t\bar{Q}_t) \approx 0.6\,\text{pb}$$

✓

➜Another possible signal at LHC13

Conclusions

- We constructed a **uv-complete model** with many **low-mass resonances** from a new strongly interacting sector.

  ➜ natural (does not address the hierarchy problem)
  ➜ $\mathcal{O}(1)$ couplings to up-type quarks

- It is **stealth** @ LHC

  ➜ multi-jet final state
  ➜ no MET, no leptonic final states
  ➜ can give **large** $A_{\rm FB}$

- Good prospects for discovery at LHC13 and is a proof of principle for what we may have missed.

LHC results...

[Avelino Vicentes talk]

Backup

Associated K production

- Recall $M_K = 143\,\text{GeV}$
  - Contribution to single top + W production?
    $\sigma_{tW} < 1.7\,\text{pb}$ (cf. $\sigma_{tW} = 16^{+5}_{-4}\,\text{pb}$ [CMS, arxiv:1209.3489])
  - Contribution to $\sigma_{t\bar{t}}$?
    $\sigma_{t\bar{t}} < 11\,\text{pb}$ (cf. $\sigma_{t\bar{t}} = 239 \pm 13\,\text{pb}$ [CMS, arxiv:1312.7582])
  - $\Rightarrow$ Contributions smaller than current exp. error