הטכניון
מכון טכנולוגי לישראל
TECHNION
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Possible use of c-tag in SUSY phenomenology

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“EXPM-THEO cross-talk on charm-tagging”
in Israel Joint Particle Physics Meeting

Sho Iwamoto, Gabriel Lee, Yael Shadmi, Yaniv Weiss [1703.05748]

Applications of *c*-tagging:

- to measure $\mathrm{Br}(h \to c\bar{c})$ Perez, Soreq, Stamou, Tobioka [1505.06689]
- charm squark $(pp \to \tilde{c}\tilde{c}^*)$ ATLAS [1501.01325] (cf. Mahbubani, Papucci, Perez, Ruderman, Weiler [1212.3328])
- compressed top squark $(pp \to \tilde{t}\tilde{t}^*, \quad \tilde{t} \to c + \not{E}_\mathrm{T})$ ATLAS [1407.0608], CMS [CMS-PAS-SUS-13-009]
- FCNC / t−c mixing (e.g. "flavored naturalness" Blanke, Giudice, Paradisi, Perez, Zupan [1302.7232])

- to measure squark flavor

$$\begin{cases} pp \to \tilde{u}\tilde{u}^* \to u\bar{u} + \not{E}_\mathrm{T} \\ pp \to \tilde{c}\tilde{c}^* \to c\bar{c} + \not{E}_\mathrm{T} \\ pp \to \tilde{u}\tilde{c}^* \to u\bar{c} + \not{E}_\mathrm{T} \quad (??) \end{cases}$$

SUSY (squark) discovery

→ *c*-tagging: which squarks are produced?

⇩

SUSY flavor violation?

- squark mass differences
- squark mixing (beyond this work)

- to measure squark flavor

$$\begin{cases} pp \to \tilde{u}\tilde{u}^* \to u\bar{u} + \not{E}_T \\ pp \to \tilde{c}\tilde{c}^* \to c\bar{c} + \not{E}_T \\ pp \to \tilde{u}\tilde{c}^* \to u\bar{c} + \not{E}_T \quad (??) \end{cases}$$

- We have discovered SUSY in **2*j*+MET channel**.

$$pp \to \widetilde{q}\widetilde{q}^* \to (q\widetilde{\chi}_1^0)(\bar{q}\widetilde{\chi}_1^0) = 2j + \not{E}_{\mathrm{T}}$$

(This simplest decay chain is assumed.)

- Gluino $\widetilde{g}$ is heavier; no direct production.

- stop and sbottom $\widetilde{t}, \widetilde{b}$ are not considered either.

$$pp \to \widetilde{q}\widetilde{q}^* \to q\bar{q} + \not{E}_{\mathrm{T}};$$

$$\widetilde{q} = \textbf{some of } \widetilde{u}_{\mathrm{L,R}}, \widetilde{d}_{\mathrm{L,R}}, \widetilde{s}_{\mathrm{L,R}}, \widetilde{c}_{\mathrm{L,R}}.$$

- $N_{\tilde{q}} = 2$: $\tilde{u}_R$, $\tilde{c}_R$
- $N_{\tilde{q}} = 4$: $\tilde{u}_R$, $\tilde{c}_R$, $\tilde{d}_R$, $\tilde{s}_R$
- $N_{\tilde{q}} = 8$: all the 8 squarks

} are light and degenerate.
(having a same mass)
$m_{\tilde{q}}$

Other squarks are decoupled.

* underlying scenario: "flavored gauge mediation"
→ Gabriel Lee's talk here (WIS) on Apr 4.
Ierushalmi, SI, Lee, Nepomnyashy, Shadmi [1603.02637]

$$pp \to \tilde{q}\tilde{q}^* \to q\bar{q} + \not{E}_{\mathrm{T}};$$
$$\tilde{q} = \textbf{some of } \tilde{u}_{\mathrm{L,R}}, \tilde{d}_{\mathrm{L,R}}, \tilde{s}_{\mathrm{L,R}}, \tilde{c}_{\mathrm{L,R}}.$$

- number of events → crosssection $\sigma = \sigma(m_{\tilde{q}}, m_{\tilde{g}}, N_{\tilde{q}})$

- mT2 analysis $m_{\rm T2} \leq m_{\rm T2}^{\rm endpoint}(m_{\tilde{q}}, m_{\rm LSP})$

$$\left(\approx \frac{m_{\tilde{q}}^2 - m_{\rm LSP}^2}{m_{\tilde{q}}}\right)$$

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4 parameters v.s. 2 measurements

✓ Even if we assume the traditional SUSY ($N_{\tilde{q}}$ = 8), one parameter (esp. $m_{\tilde{g}}$) remains unknown.

→ **"charm fraction"** as another measurement.

1. **Introduction**
2. **Two detours**
   - Gluino mass?
   - LHC bounds and future
3. **"Charm fraction"**

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- Gluino mass?
- LHC bounds and future

3. “Charm fraction”

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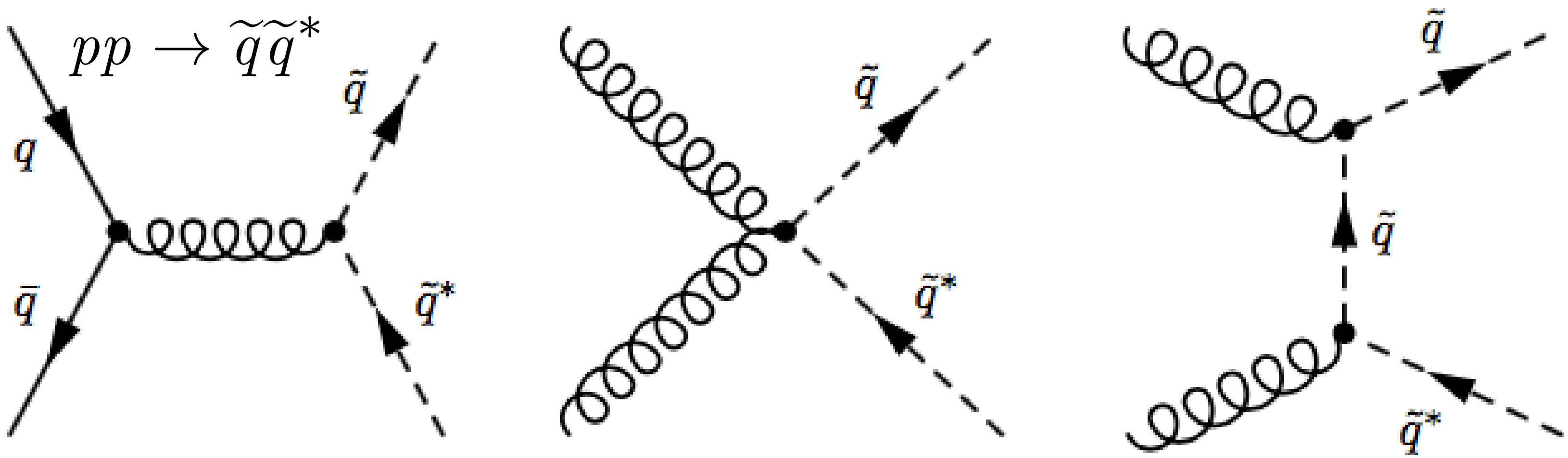
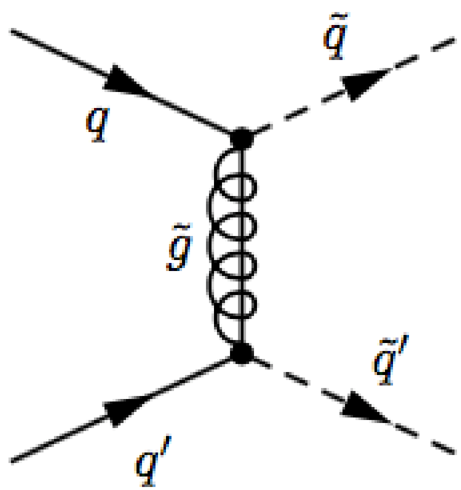
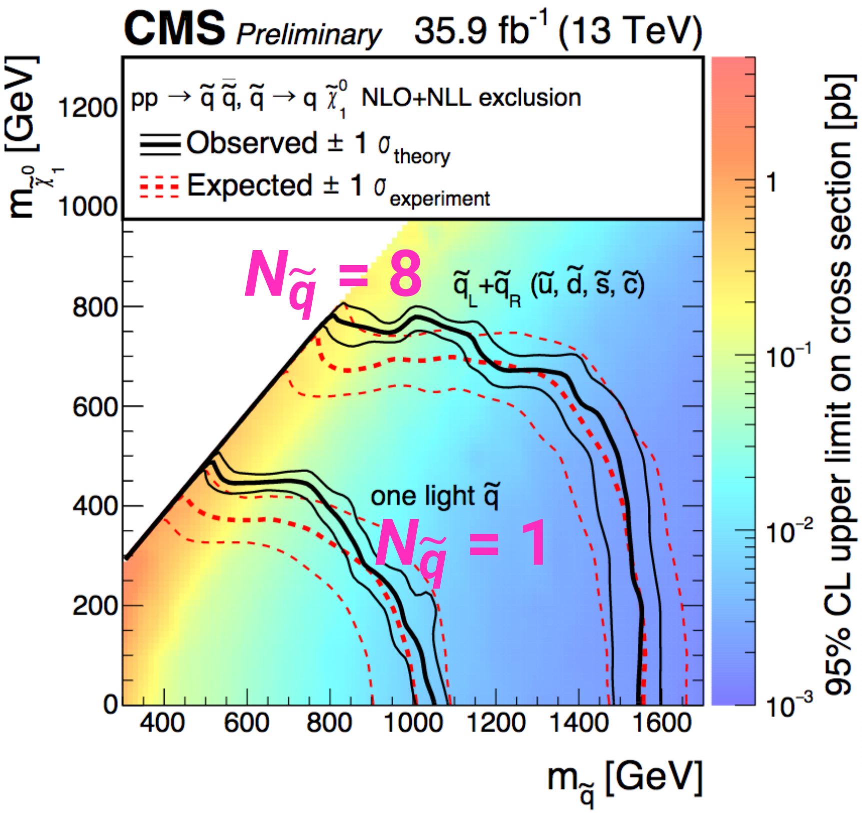
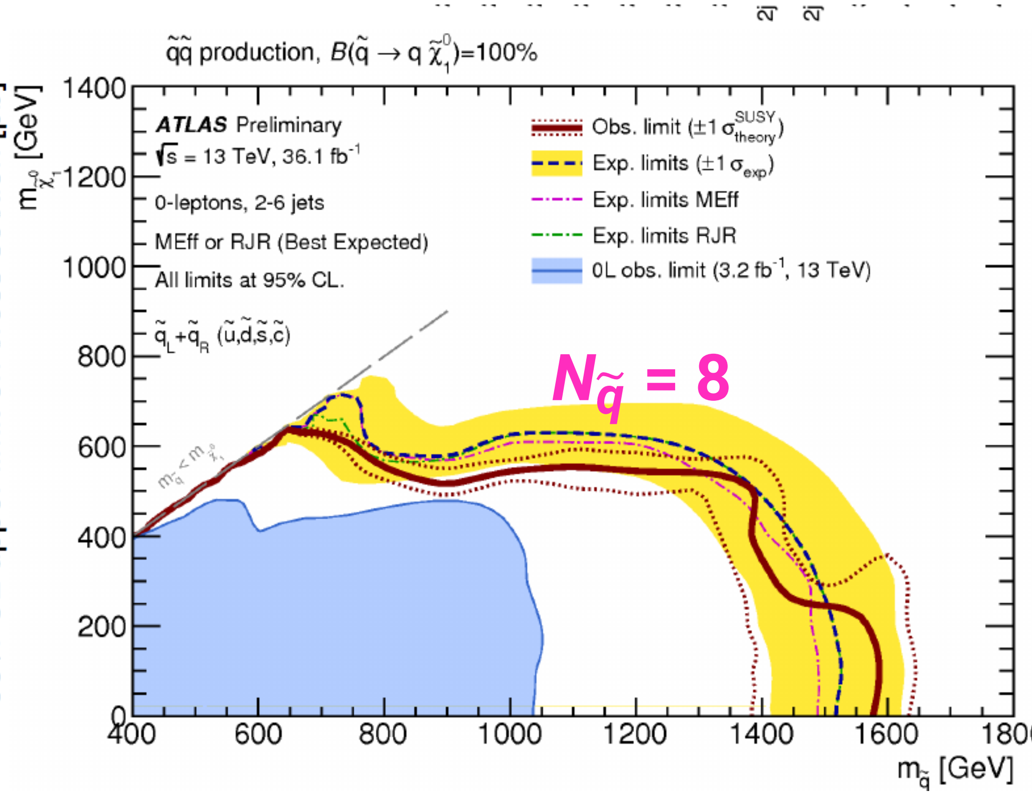
processes for $pp \to \tilde{q}\tilde{q}^*$





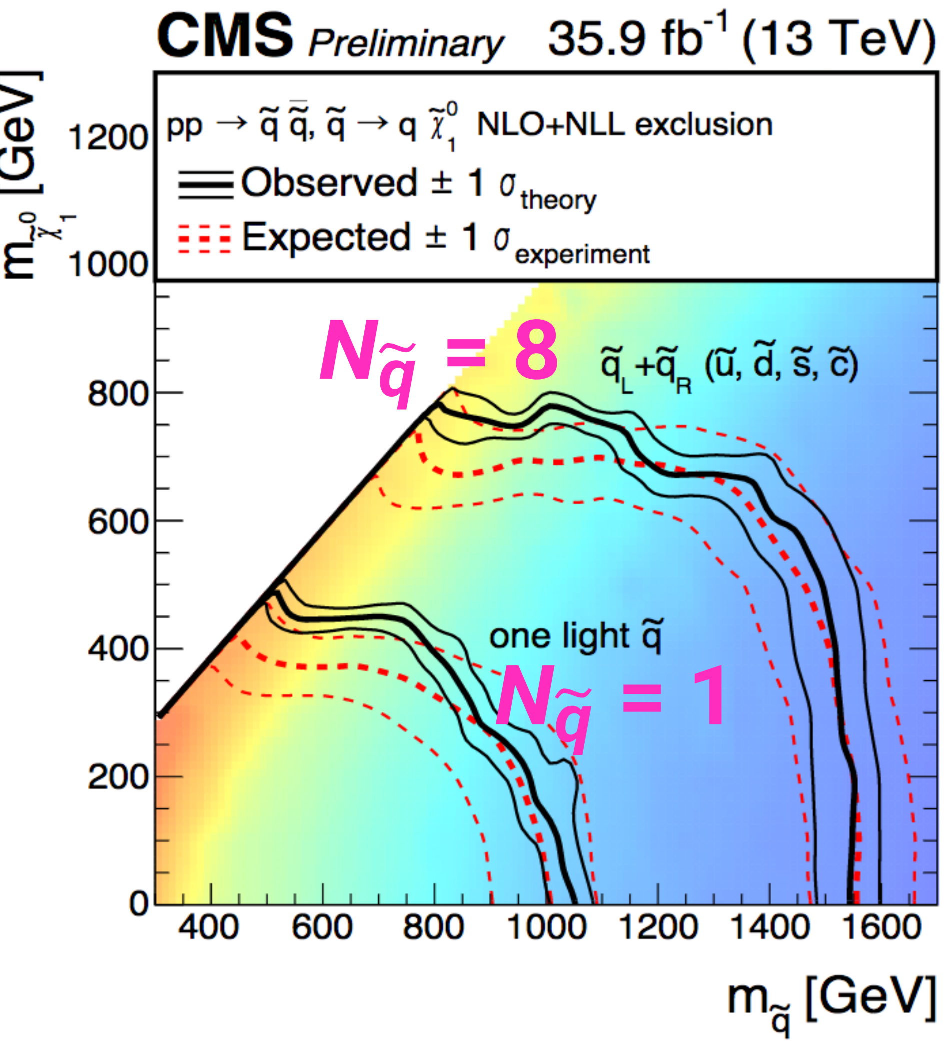
smaller $m_{\tilde{g}}$ ⇒ larger σ (or N_{ev})





Based on the same simplified model as ours, but

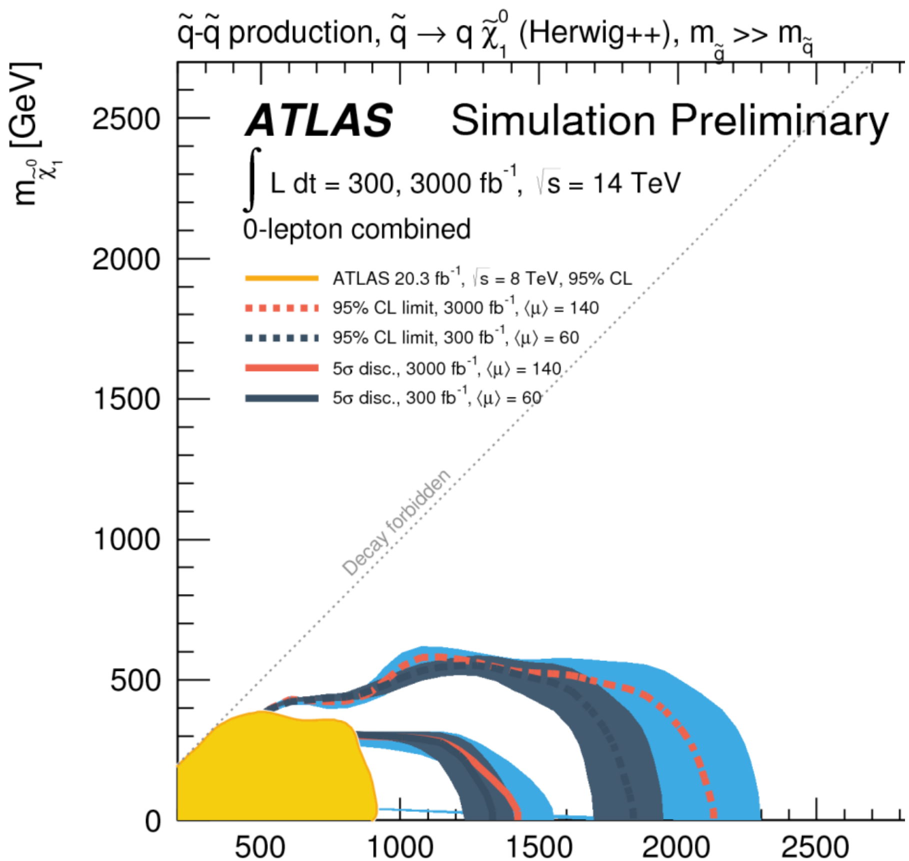
- $m_{\tilde{g}} = \infty$,
- $N_{\tilde{q}} = 1,\ 8$ (CMS), 8 (ATLAS).



13 TeV, 35.9 fb^{-1} :

for $m_{\tilde{g}} = \infty$ and $m_{LSP} = 0$,

- $N_{\tilde{q}} = 1$: $m_{\tilde{q}}$ < 1.05 TeV
- $N_{\tilde{q}} = 8$: < 1.55 TeV
- $N_{\tilde{q}} = 2$: $\lesssim$ 1.2 TeV
- $N_{\tilde{q}} = 4$: $\lesssim$ 1.35 TeV



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- $N_{\tilde{q}} = 1$: $m_{\tilde{q}} < 1.05$ TeV
- $N_{\tilde{q}} = 8$: < 1.55 TeV
- $N_{\tilde{q}} = 2$: $\lesssim 1.2$ TeV
- $N_{\tilde{q}} = 4$: $\lesssim 1.35$ TeV

14 TeV, 3000 fb^{-1} :

5σ disc. $m_{\tilde{q}} \lesssim 1.4$ TeV

2σ excl. $m_{\tilde{q}} \lesssim 2.2$ TeV

($N_{\tilde{q}} = 8$)

but they will do better....

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- $N_{\tilde{q}} = 2$: $\tilde{u}_R$, $\tilde{c}_R$
- $N_{\tilde{q}} = 4$: $\tilde{u}_R$, $\tilde{c}_R$, $\tilde{d}_R$, $\tilde{s}_R$
- $N_{\tilde{q}} = 8$: all the 8 squarks

$$F_c := \frac{N(\text{c-tagged jet})}{N(\text{jet})}$$

(Note: $N(\text{jet}) = 2N_{\text{ev}}$)

(no mistag, 100% efficiency)

With no SM background and with the "God's" *c*-tagger,

$F_c = (1/2, 1/4, 1/4)$ for $N_{\tilde{q}} = (2, 4, 8)$-scenarios.

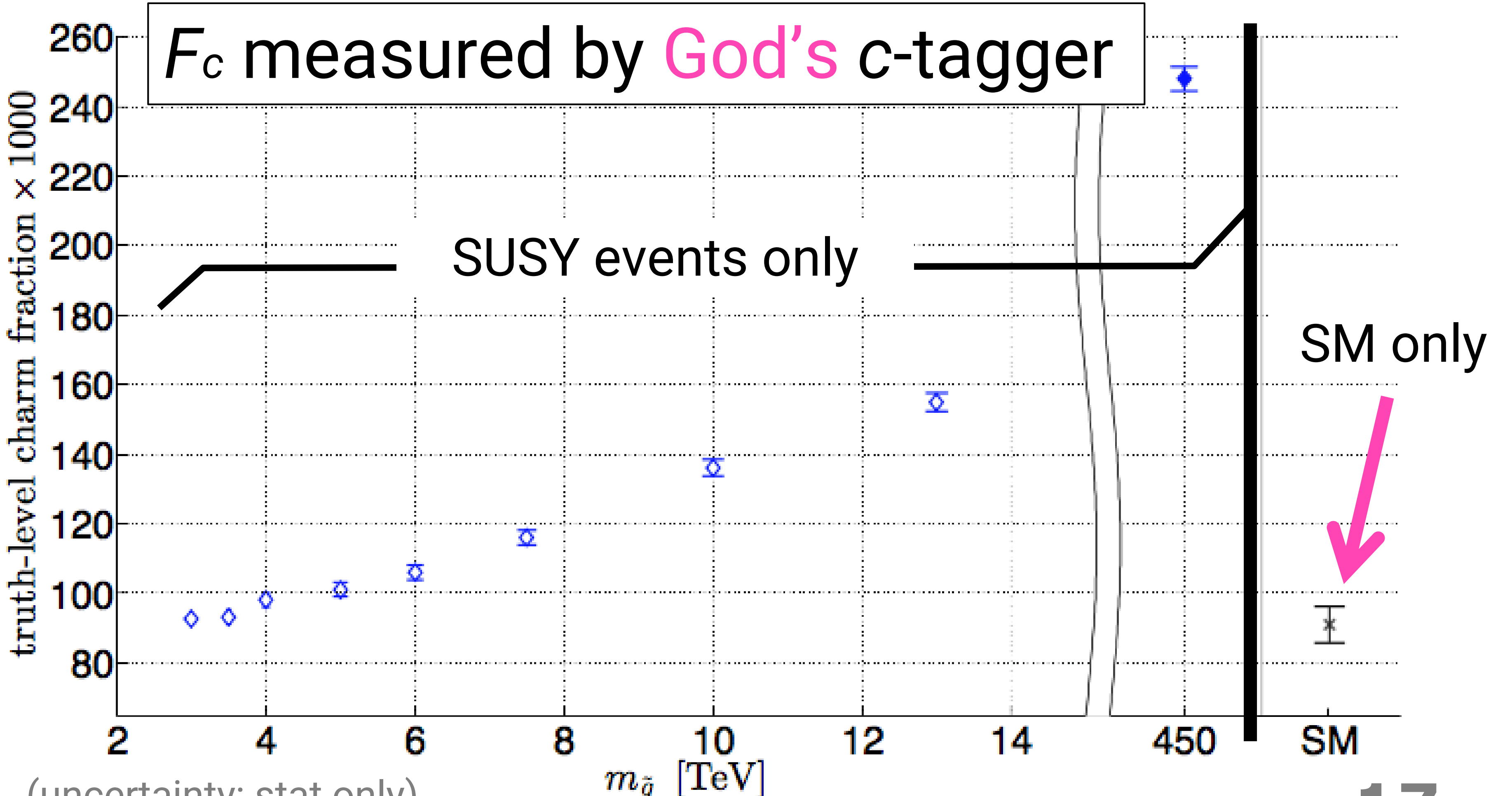
→ in reality, this ratio is smeared by

- tagger performance,
- SM background,
- and **gluino mass**.

$$F_c := \frac{N(\text{c-tagged jet})}{N(\text{jet})}$$

- $F_c(\text{SUSY}) > F_c(\text{SM})$
- larger $m_{\tilde{g}} \Rightarrow$ larger F_c

($m_{\tilde{q}}$ = 1.5 TeV, $N_{\tilde{q}}$ = 8)



(uncertainty: stat only)

$$F_c := \frac{N(\text{c-tagged jet})}{N(\text{jet})}$$

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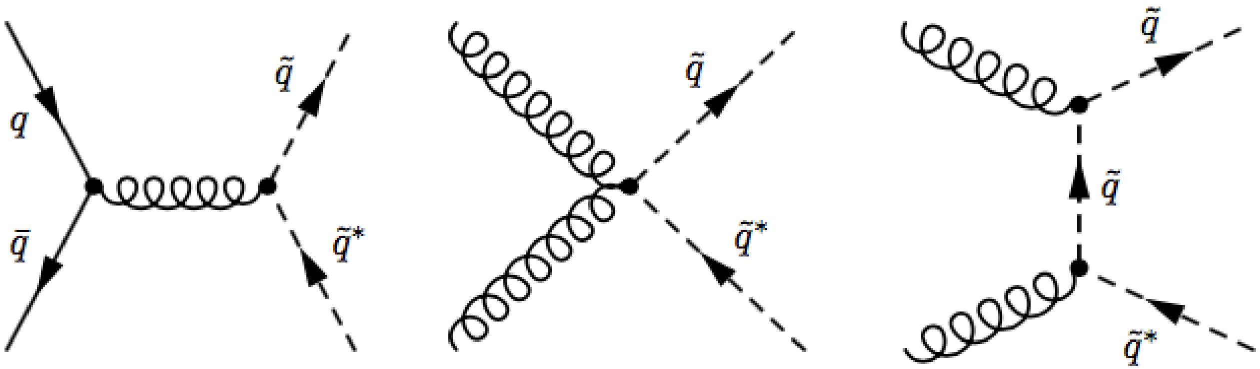
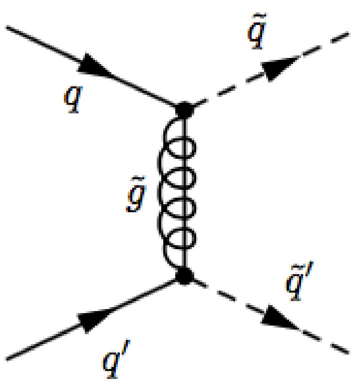


→ flavor universal

($\tilde{u} = \tilde{d} = \tilde{s} = \tilde{c}$ if degenerate)



gluino diagram

→ flavor non-universal

($\tilde{u} > \tilde{d} \gg \tilde{s} \gg \tilde{c}$ even degenerate)

(uncertainty: stat only)

Three "measurements" for 4 params.

$$N_{\rm ev} = N_{\rm ev}(m_{\widetilde{q}}, m_{\widetilde{g}}, N_{\widetilde{q}})$$

$$m_{\rm T2} \leq m_{\rm T2}^{\rm endpoint}(m_{\widetilde{q}}, m_{\rm LSP})$$

$$F_c = F_c(m_{\widetilde{q}}, m_{\widetilde{g}}, N_{\widetilde{q}})$$

- $N_{\widetilde{q}}$ = 2 : $\widetilde{u}_{\rm R}$, $\widetilde{c}_{\rm R}$
- $N_{\widetilde{q}}$ = 4 : $\widetilde{u}_{\rm R}$, $\widetilde{c}_{\rm R}$, $\widetilde{d}_{\rm R}$, $\widetilde{s}_{\rm R}$
- $N_{\widetilde{q}}$ = 8 : all the 8 squarks

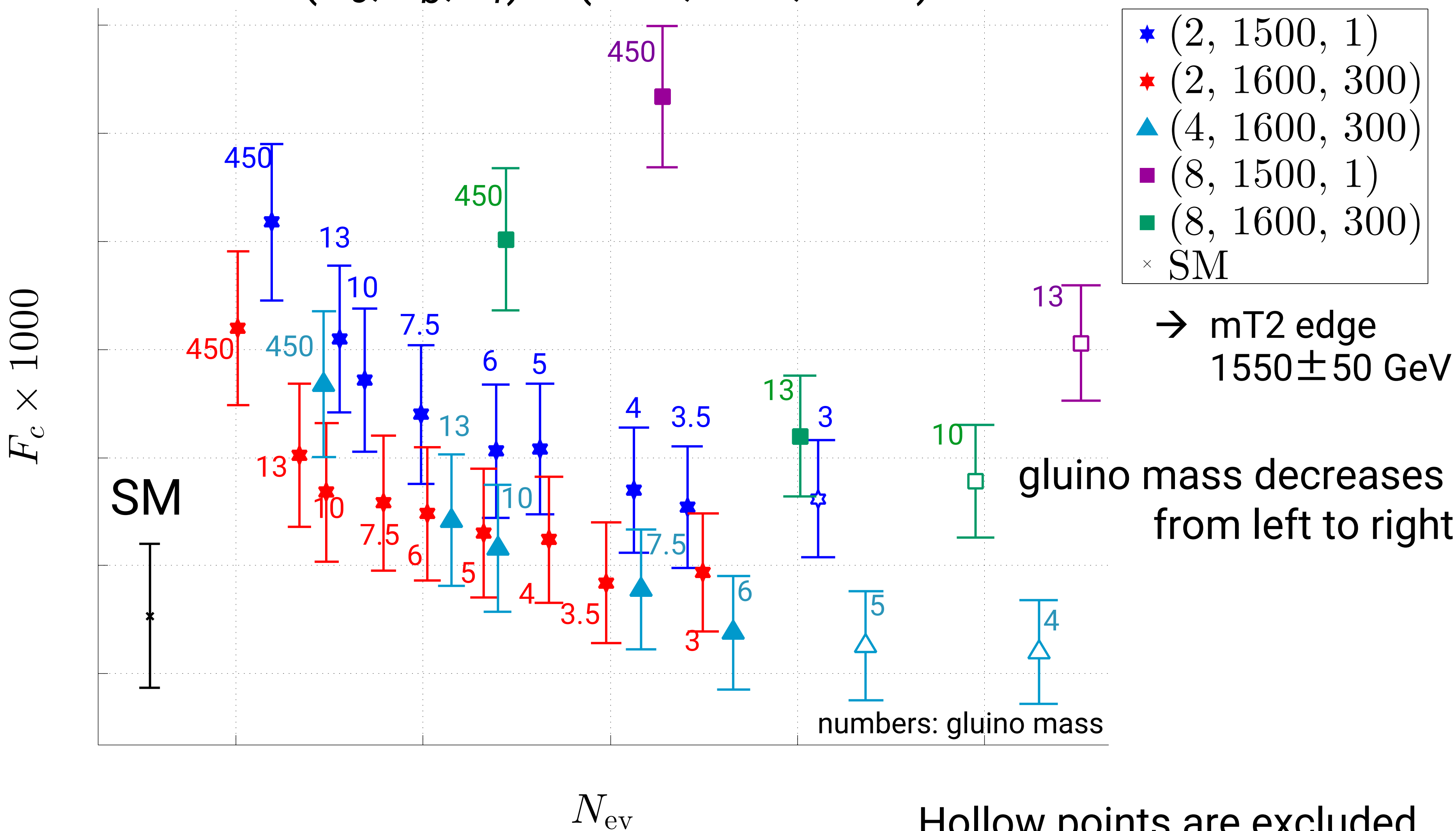
Gluino mass dependencies

- F_c(SUSY) > F_c(SM).
- larger $m_{\widetilde{g}}$ ⇒ larger F_c, smaller $N_{\rm ev}$.

We are not Gods.

- ➢ tagger performance and systematic uncertainties
- ➢ SM background

$(\epsilon_c, \epsilon_b, \epsilon_l) = (50\%, 20\%, 0.5\%)$

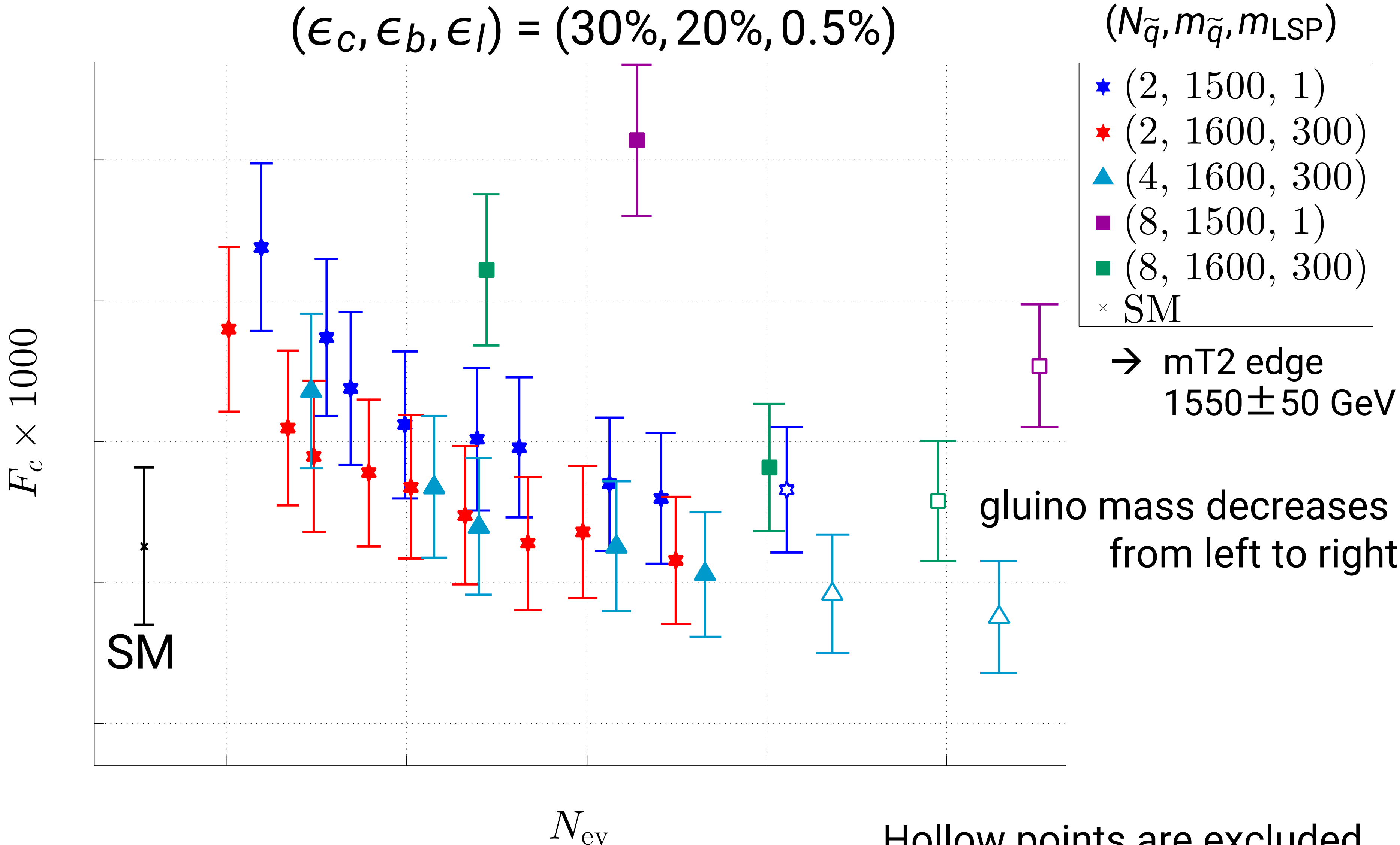


(uncertainty: stat only, *y*-axis only)

Hollow points are excluded
by 13TeV 13.3/fb data.

ATL-CONF-2016-078 (Meff-2j-2000)

Analysis based on ATLAS HL-LHC (PHYS-PUB-2014-010; Meff-2j-3100).
SUSY and SM by MG5+Pythia6/taoula+Delphes3.3.0 (default-CMS but dR=0.4).
SUSY: prospino NLO SM: rescaling w.r.t. ATLAS simulation



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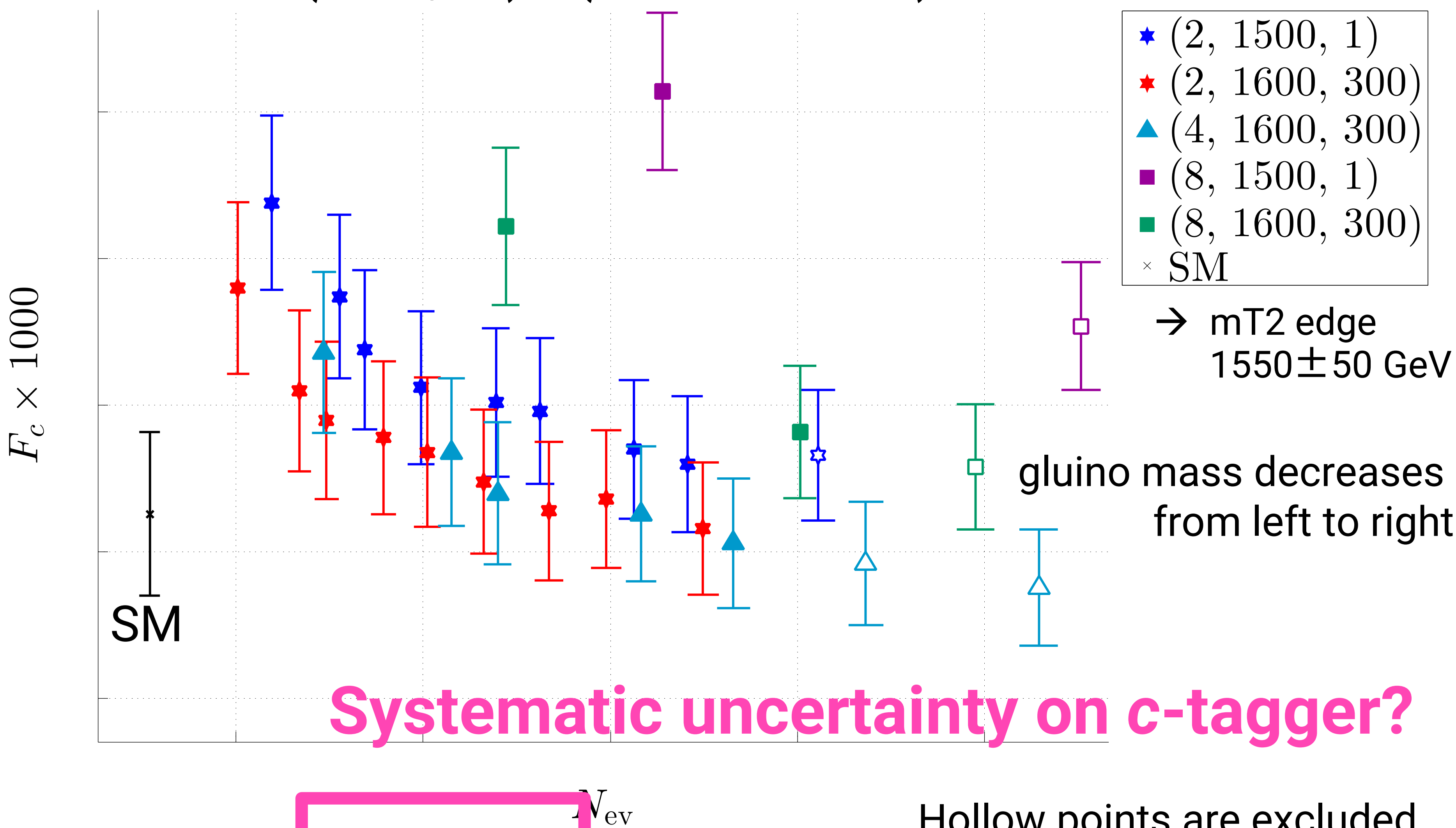
$(\epsilon_c, \epsilon_b, \epsilon_l) = (30\%, 20\%, 0.5\%)$



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- Simplified model for 2j+MET search (squark production):

$(m_{\tilde{g}}, m_{\tilde{q}}, m_{\text{LSP}}) + N_{\tilde{q}}$ v.s.

$$N_{\text{ev}} = N_{\text{ev}}(m_{\tilde{q}}, m_{\tilde{g}}, N_{\tilde{q}})$$

$$m_{\text{T2}} \leq m_{\text{T2}}^{\text{endpoint}}(m_{\tilde{q}}, m_{\text{LSP}})$$

$$F_c = F_c(m_{\tilde{q}}, m_{\tilde{g}}, N_{\tilde{q}})$$

New!

- F_c(SUSY) > F_c(SM)
- larger $m_{\tilde{g}}$ ⇒ smaller N_{ev}, larger F_c

- good discrimination ← very good understanding of *c*-tagger.
  - How to measure efficiency / mistag rates? (esp. for pT > top mass)?
  - developments of "AI" tagger?

- **c-tagging is important & lots of potential!**

Table 2: Definitions of our signal regions. SR Meff-2j-2000 is from the ATLAS analysis based on $13.3\,\mathrm{fb}^{-1}$ data at the 13 TeV LHC [11], and Meff-2j-3100 is based on the HL-LHC study [10]. In Meff-2j-2000 (Meff-2j-3100), jets are required to satisfy $p_T > 50\,\mathrm{GeV}$ and $|\eta| < 2.8$ ($p_T > 20\,\mathrm{GeV}$ and $|\eta| < 4.5$), and $\Delta\phi$ cuts are applied to all the jets with $p_T > 50\,\mathrm{GeV}$ ($p_T > 40\,\mathrm{GeV}$). H_T is the scalar sum of p_T of all the jets, and $m_{\mathrm{eff}}(\mathrm{incl.})$ is the sum of $\not{E}_T$ and H_T. Events are vetoed if electrons and/or muons with $p_T > 10\,\mathrm{GeV}$ are present.

		Meff-2j-2000	Meff-2j-3100
Number of jets, electrons, muons		$\geq 2, = 0, = 0$	
$\not{E}_T$ [GeV]	$>$	250	160
$p_T(j_1), p_T(j_2)$ [GeV]	$>$	250, 250	160, 60
$\lvert\eta(j_1, j_2)\rvert$	$<$	1.2	—
$\Delta\phi(j_{1,2,(3)}, \not{E}_T)_{\mathrm{min}}$	$>$	0.8	0.4
$\Delta\phi(j_{i>3}, \not{E}_T)_{\mathrm{min}}$	$>$	0.4	0.2
$\not{E}_T/\sqrt{H_T}$ [GeV$^{1/2}$]	$>$	20	15
$m_{\mathrm{eff}}(\mathrm{incl.})$ [GeV]	$>$	2000	3100