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מכון טכנולוגי
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TECHNION
Israel Institute
of Technology

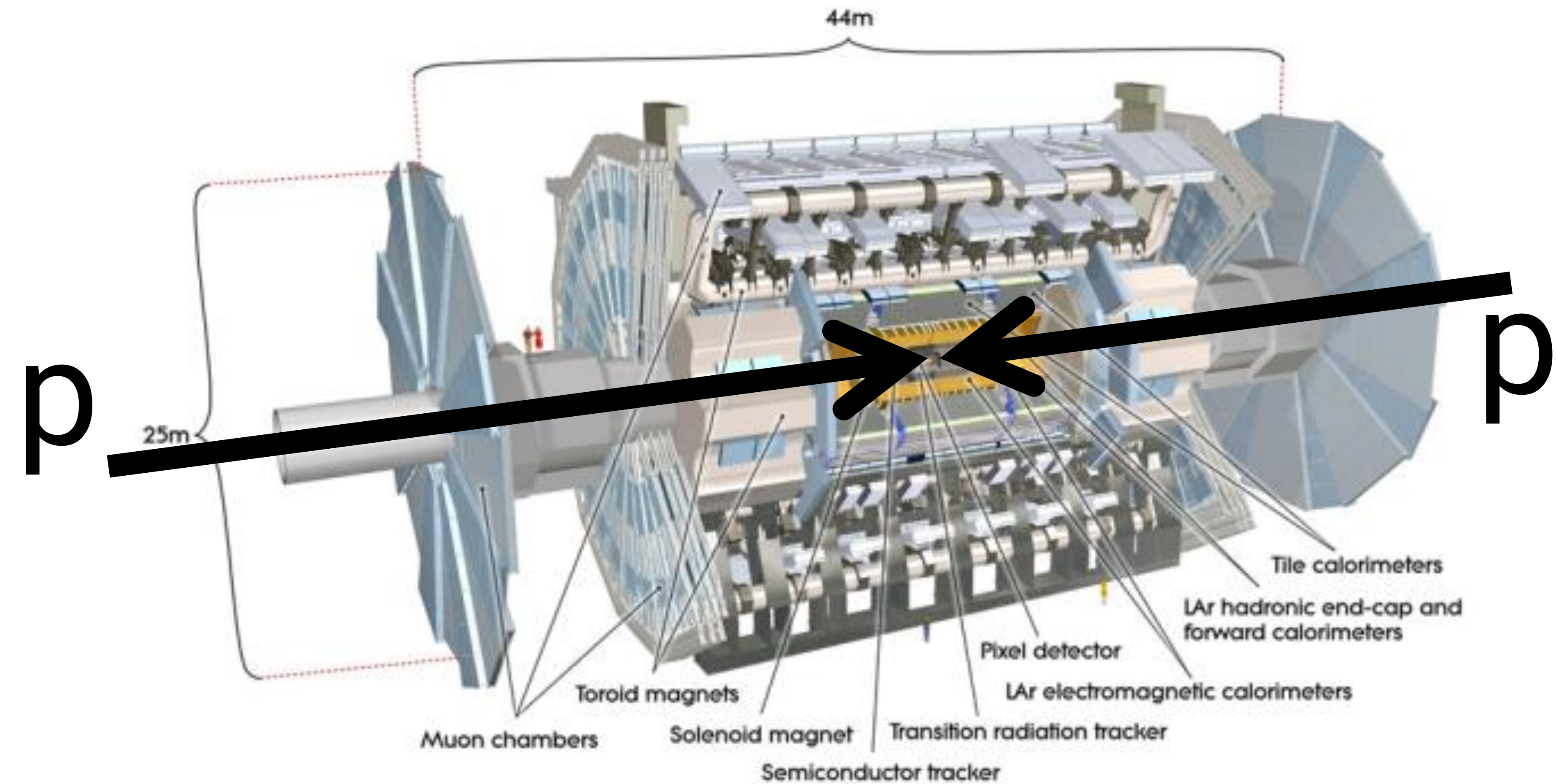
c-tagging for new physics at the LHC

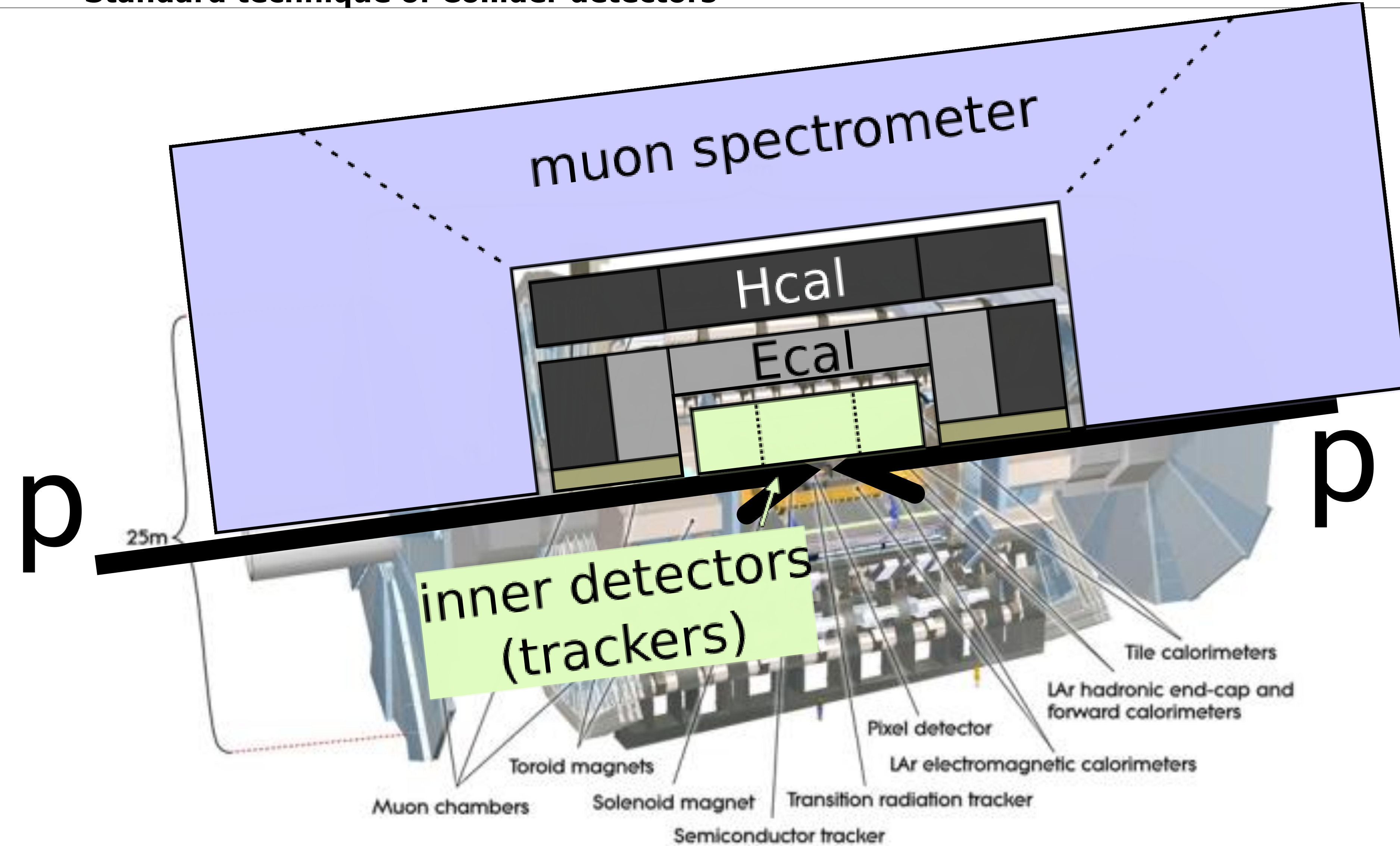
Sho IWAMOTO（岩本　祥）

25 Oct. 2017
Workshop on beyond standard model and the early universe
@ Tohoku University

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

(and discussion with Jonathan Shlomi @ Weizmann/ATLAS)


44m
25m
p
p
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker



muon spectrometer
Hcal
Ecal
p
p
inner detectors
(trackers)
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
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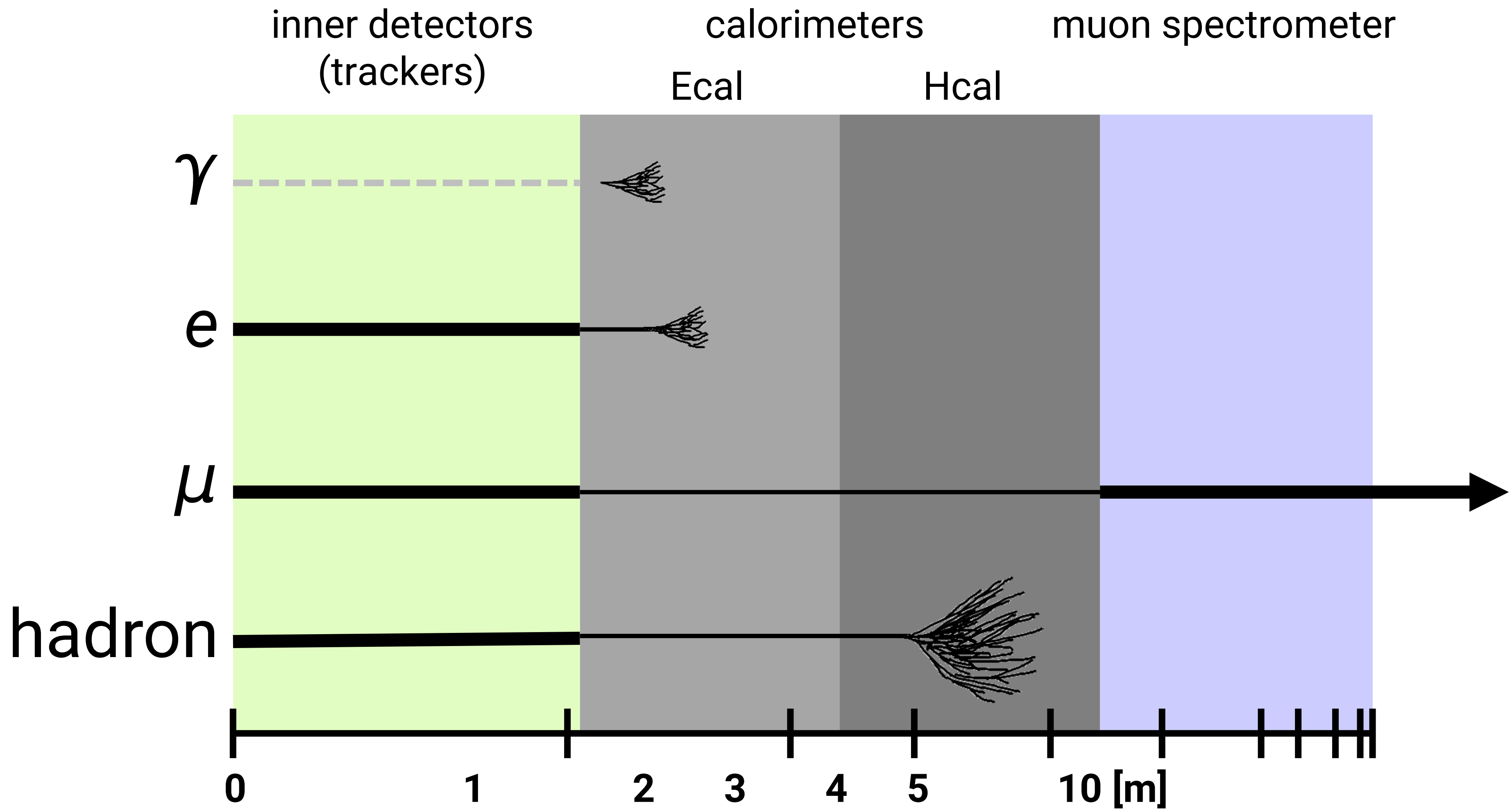

- τ-lepton? ⟶ τ-tagging
- which quark? or gluon? ⟶ quark-flavor tagging

1. **Quark-flavor tagging**
   - *b*-tagging
   - *c*-tagging
2. **Applications to BSM:
   SUSY model discrimination**
   - Motivation + Scope
   - Charm fraction
   - Results & discussion on uncertainty

1. Quark-flavor tagging

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- Quarks → form hadrons ("hadronize") → decay

time scale: $\Lambda_{\mathrm{QCD}}^{-1} \sim (200\,\mathrm{MeV})^{-1} \simeq 1\,\mathrm{fm}$

time scale: various

- u, d, s → light hadrons $(\pi^{\pm}, \pi^{0}, K^{\pm}, K_{\mathrm{S}}, K_{\mathrm{L}}, p, \ldots)$
- c → charm hadrons $(D^{\pm}, D^{0}, \Lambda_c^{+}, \ldots)$
- b → bottom hadrons $(B^{\pm}, B^{0}, \ldots)$

flavor tagging = to differentiate these hadrons

- t decays to $b+W$

  $(\Gamma(t \to bW) = 1.5\,\mathrm{GeV} > \Lambda_{\mathrm{QCD}})$

$$(\pi^{\pm}, \pi^{0}, K^{\pm}, K_{S}, K_{L}, p, \ldots)$$

8 10^{-8} 4 0.03 15 [m]

$$(D^{\pm}, D^{0}, \Lambda_{c}^{+}, \ldots)$$

0.3 0.1 0.06 [mm]

$$(B^{\pm}, B^{0}, \ldots)$$

0.5 0.5 [mm]

x Lorentz boost ($\gamma \sim 100$)

flavor tagging = to detect decays @ 1−10 cm

Note:
ATLAS installed a new layer
"insertable b-layer" @ 3.3cm at the beginning of Run 2.

1. Quark-flavor tagging

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- impact parameter (IP3D, IP2D)
- secondary vertex (SV)
- soft lepton detection

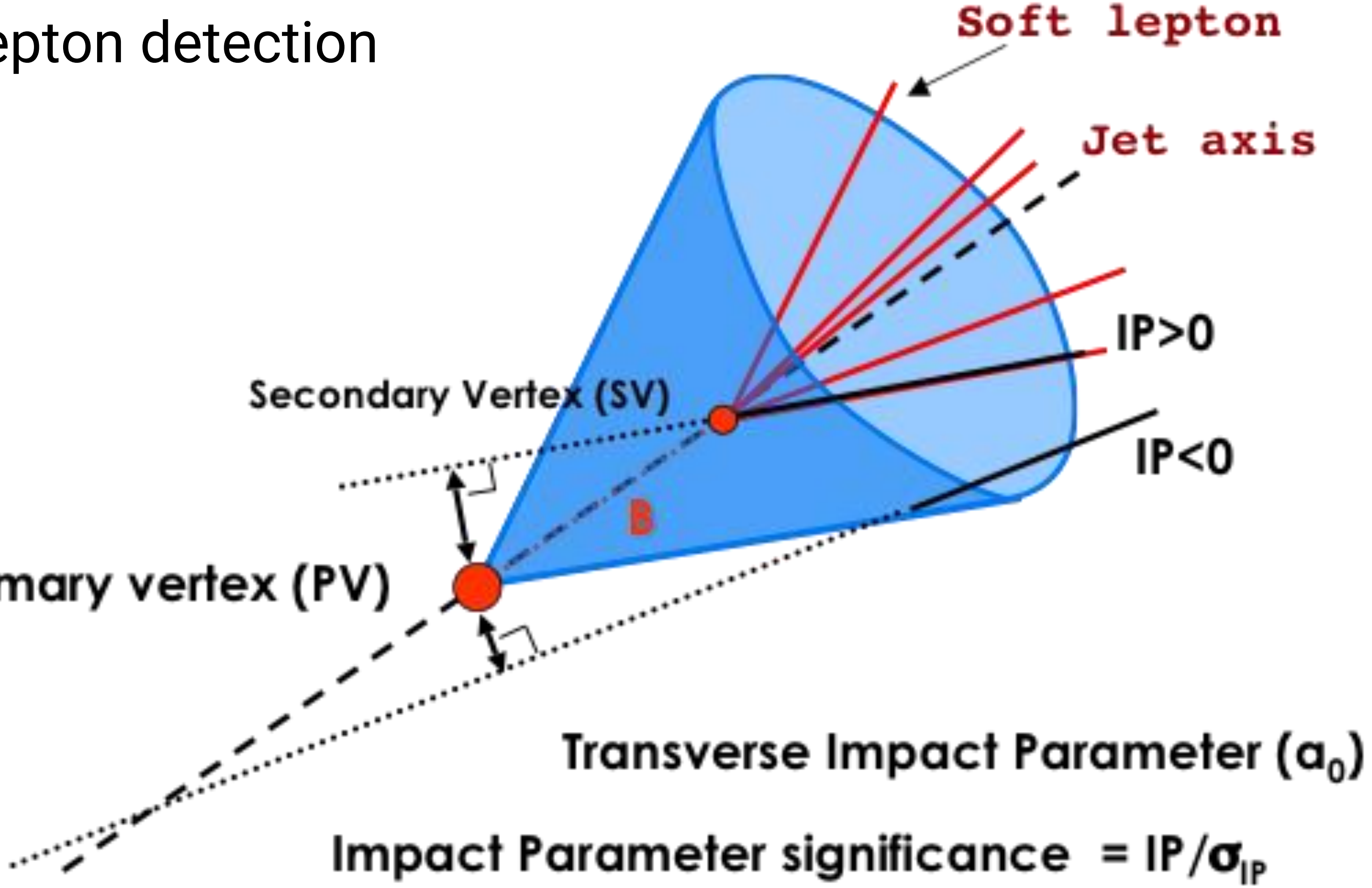
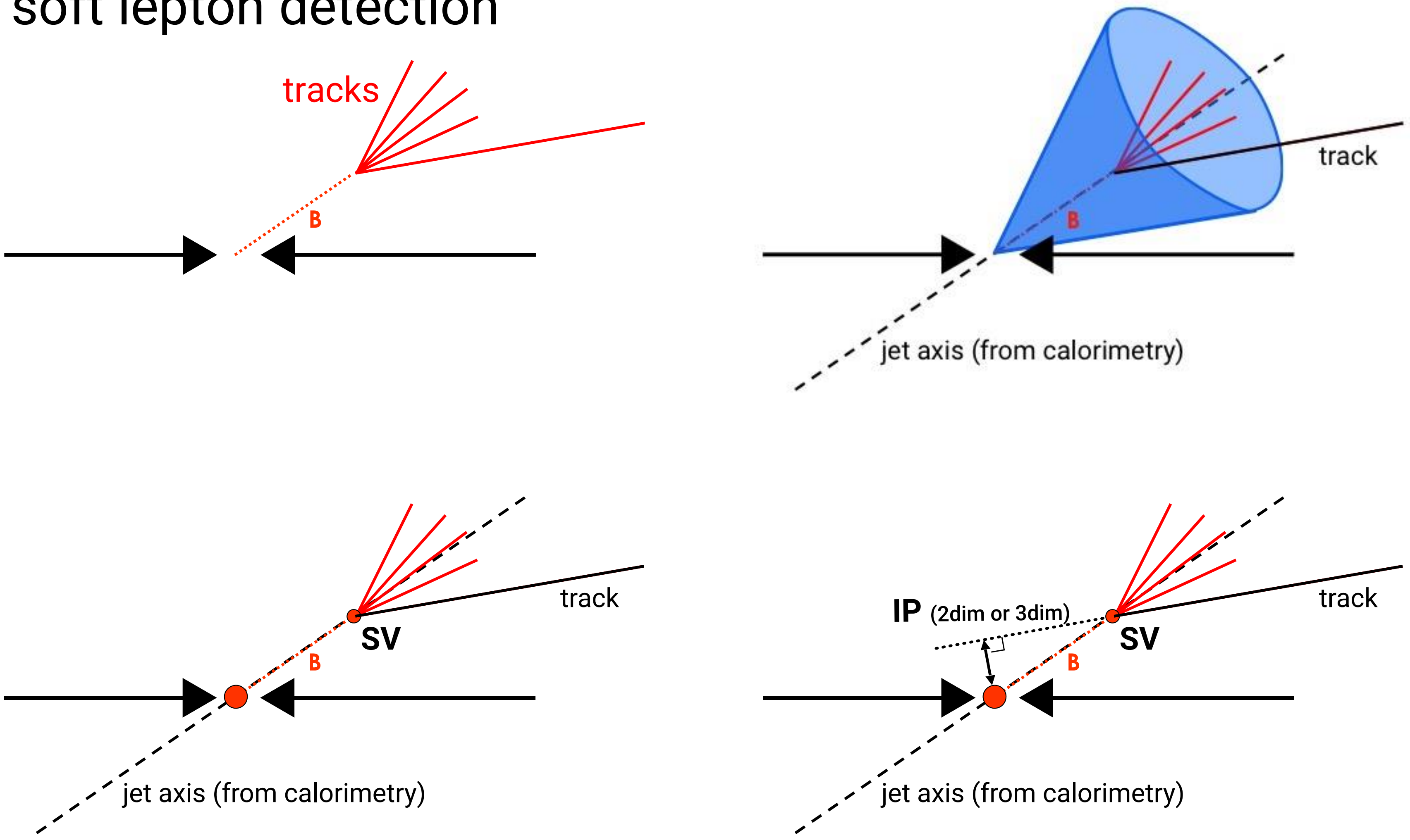


Figure from Lorenzo Feligioni’s talk slides
(but not sure who made this figure)

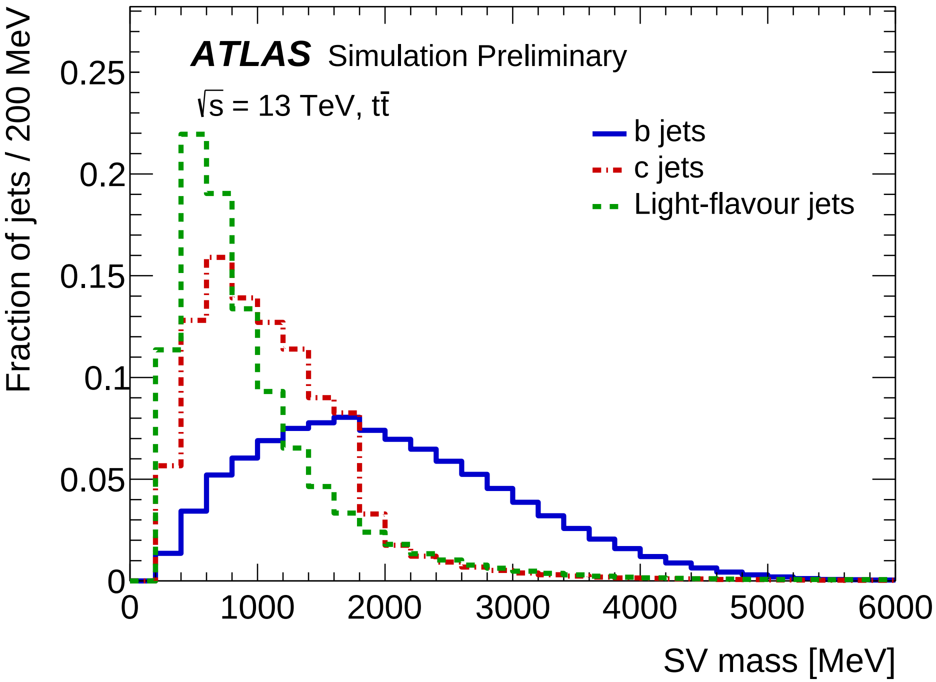
- impact parameter (IP3D, IP2D)
- secondary vertex (SV)
- soft lepton detection

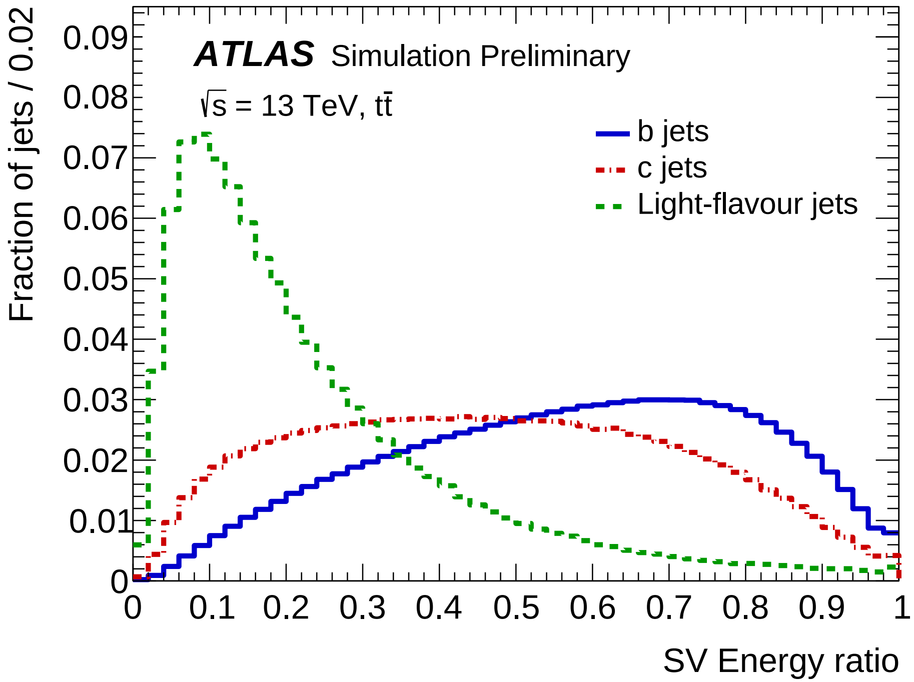


- impact parameter (IP3D, IP2D)
- secondary vertex (SV)
- soft lepton detection
- "JetFitter" … to reconstruct the whole decay chain

$$\bar{B}^0 \rightarrow \pi^+\pi^-\pi^+\pi^- D^0$$
$$\hookrightarrow \pi^+\pi^-\pi^+K^- \quad \text{etc…}$$

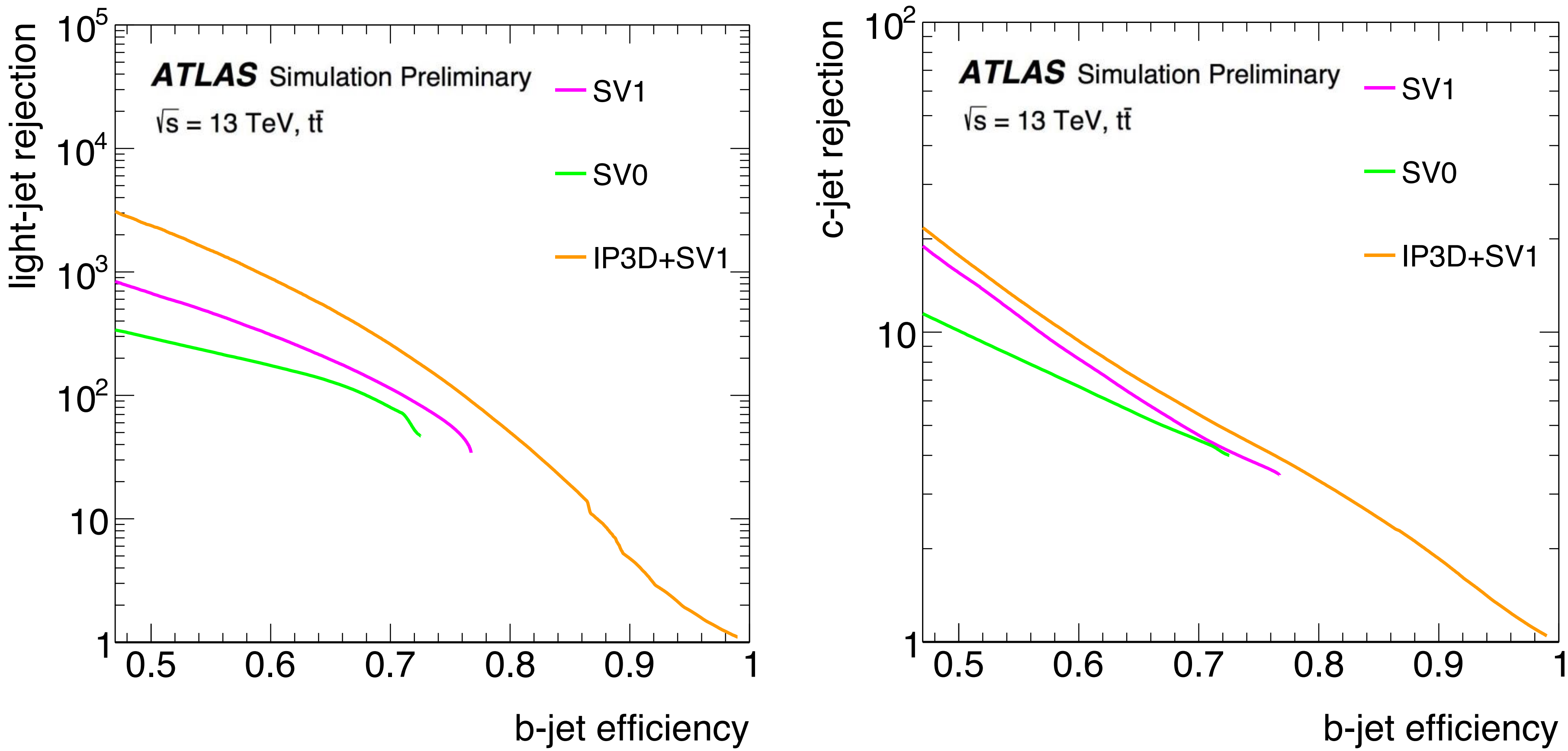
- secondary vertex (SV) : ATLAS simulation for 13 TeV (ttbar)





charm-jet = between *b*-jet and light-jet

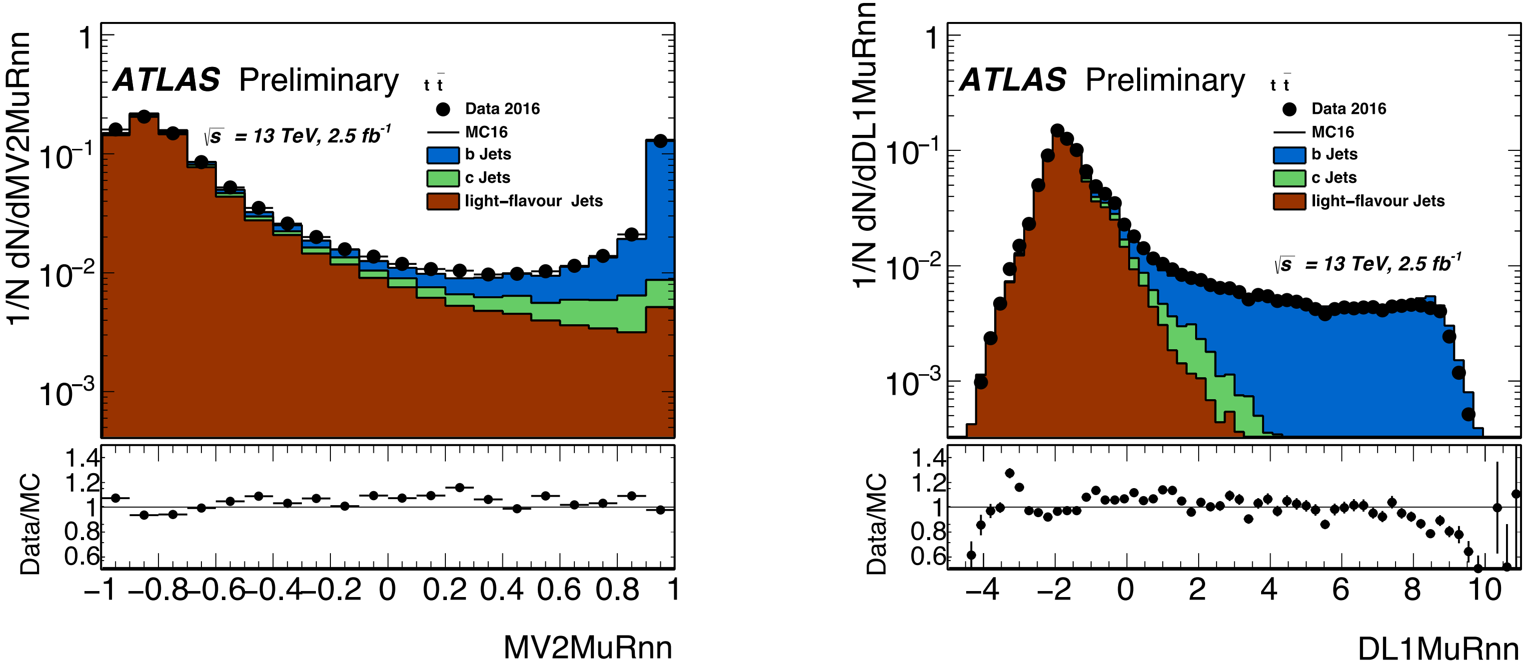
■ secondary vertex (SV) : ATLAS simulation for 13 TeV (ttbar)



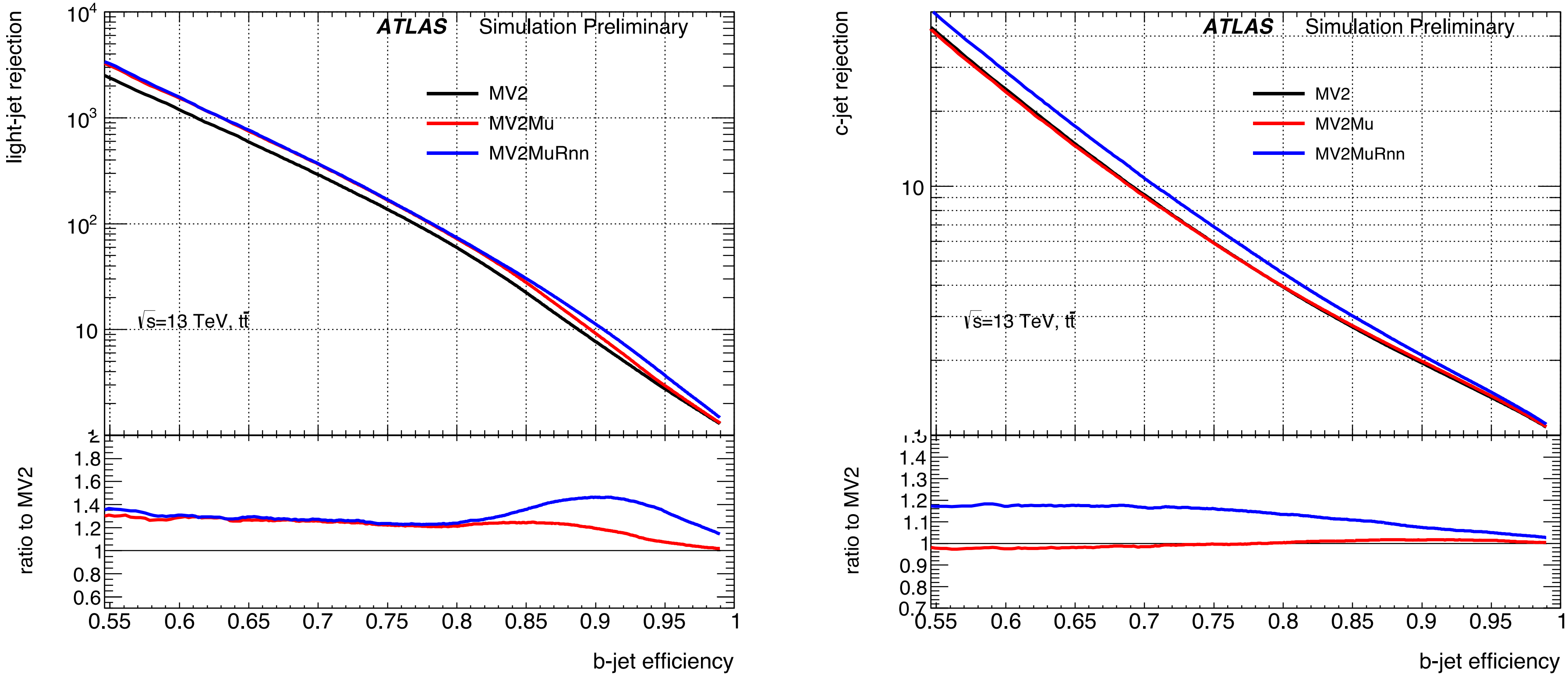
charm-jet = between *b*-jet and light-jet

- tracker-based: IP3D + RNNIP [recurrent neural network]
- vertex-based: SV, JetFitter
- lepton-based: soft muon tagger

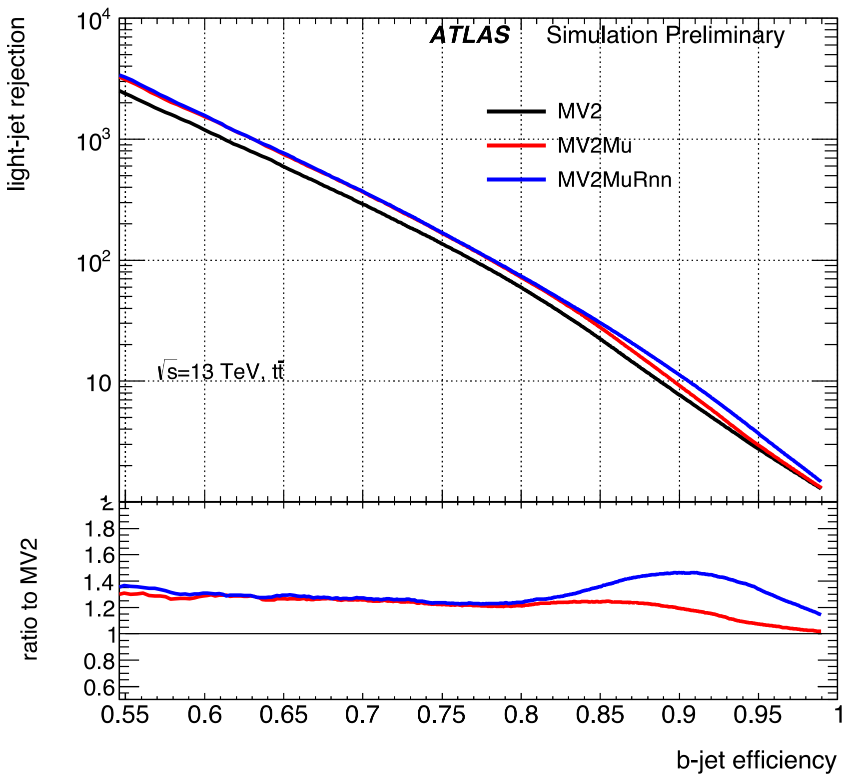
➢ boosted decision tree (MV2)
➢ deep learning (DL1)

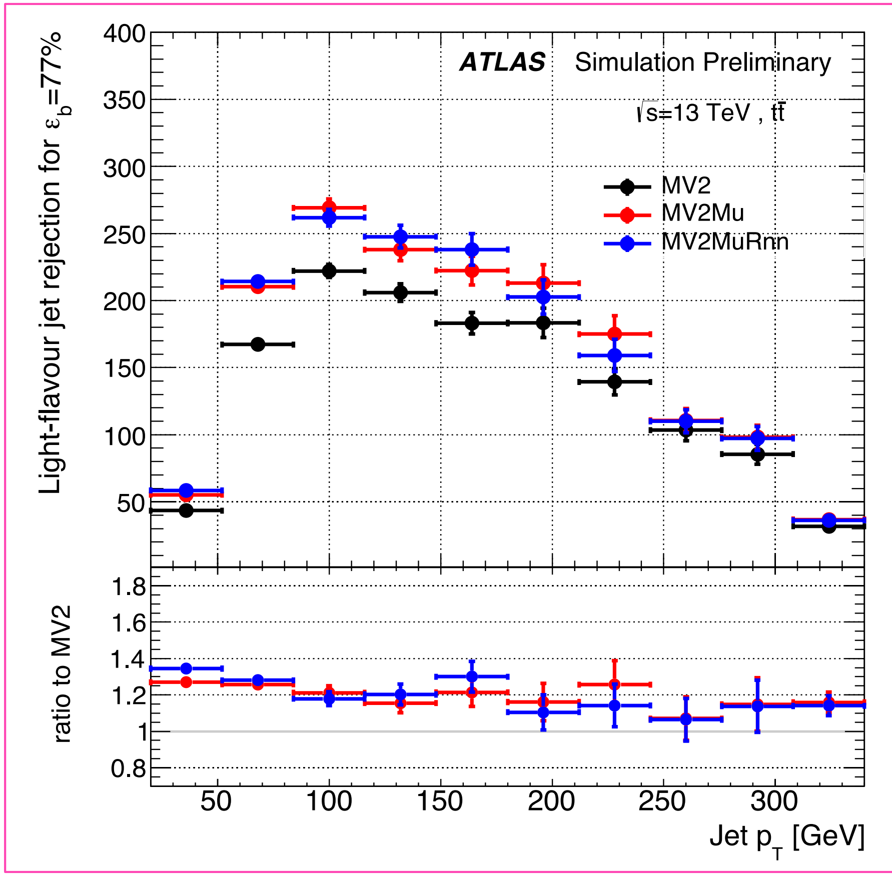


- RNN analyzes correlation between IPs of multiple tracks. Light rejection x2, c rejection x1.2, compared to IP3D.



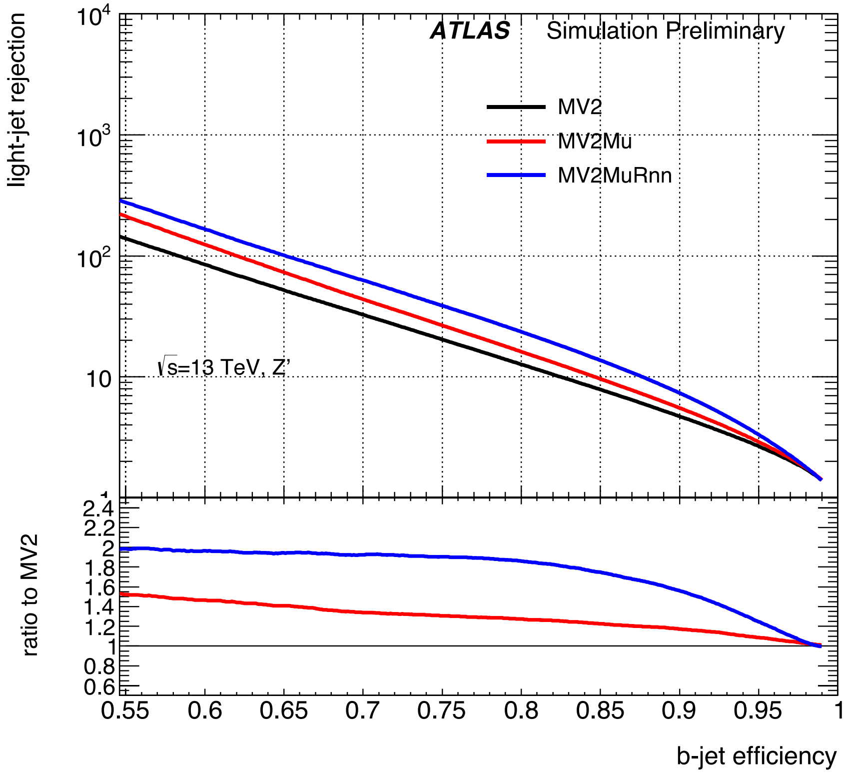
ϵ_b = 77% $\Rightarrow (\epsilon_l, \epsilon_c)$ = (1%, 16%) for $t\bar{t}$-sample

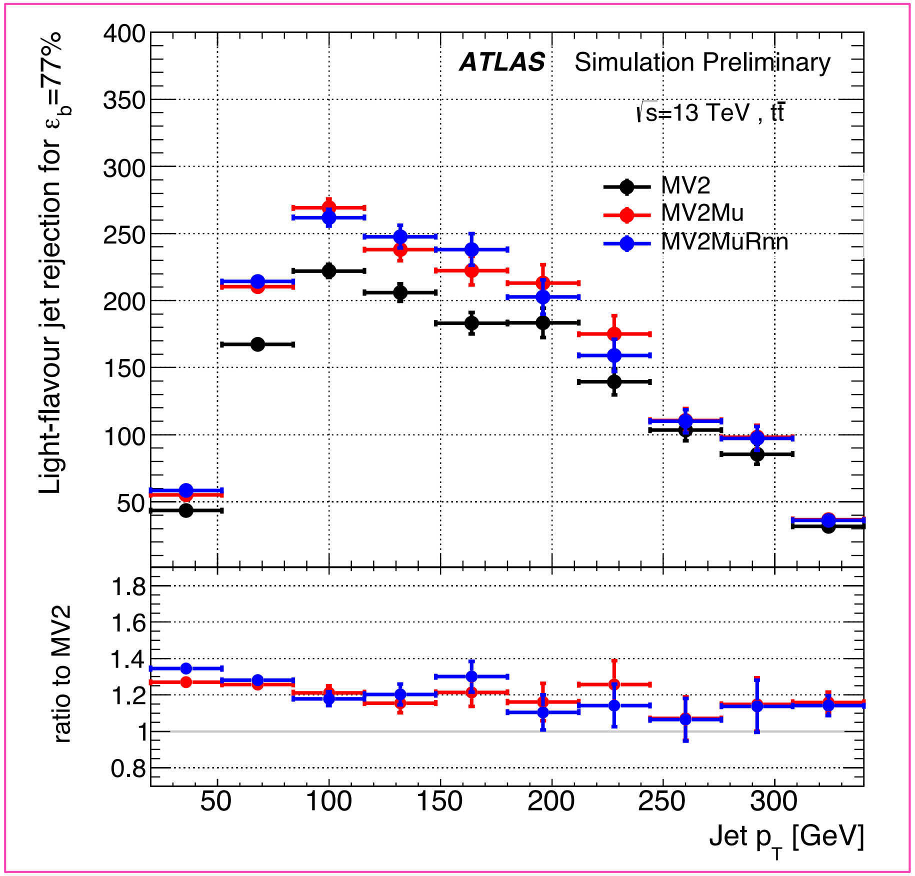




$\epsilon_b = 77\% \Rightarrow (\epsilon_l, \epsilon_c) = (1\%, 16\%)$ for $t\bar{t}$-sample

with significant p_T dependence

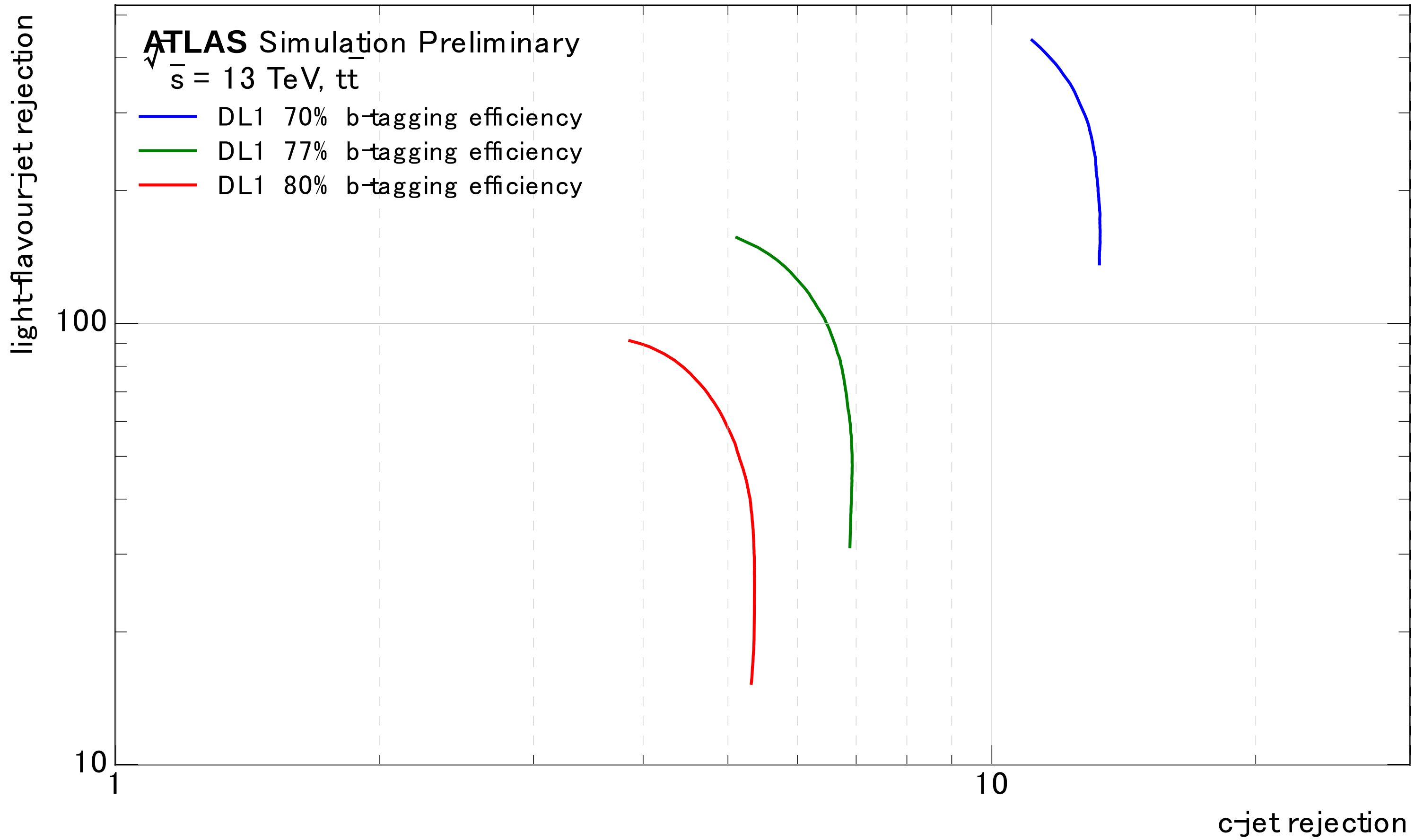




$$\epsilon_b = 77\% \Rightarrow (\epsilon_l, \epsilon_c) = (1\%, 16\%) \quad \text{for } t\bar{t}\text{-sample}$$

$$(\epsilon_l, \epsilon_c) = (3\%, 30\%) \quad \text{for 4 TeV } Z'\text{-sample}$$

with significant p_T dependence



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with significant p_T dependence

(MV ~ DL)

* “DL1 does provide specific advantages in terms of possible future R&D.”

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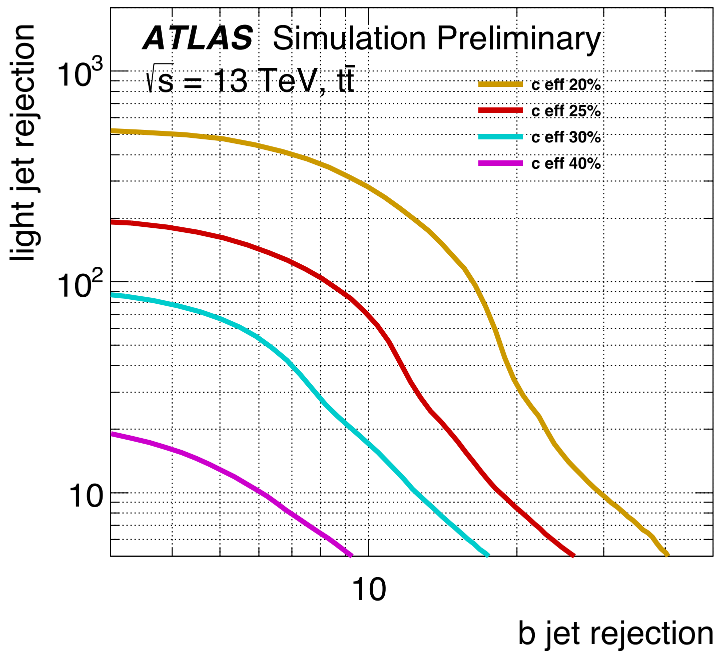
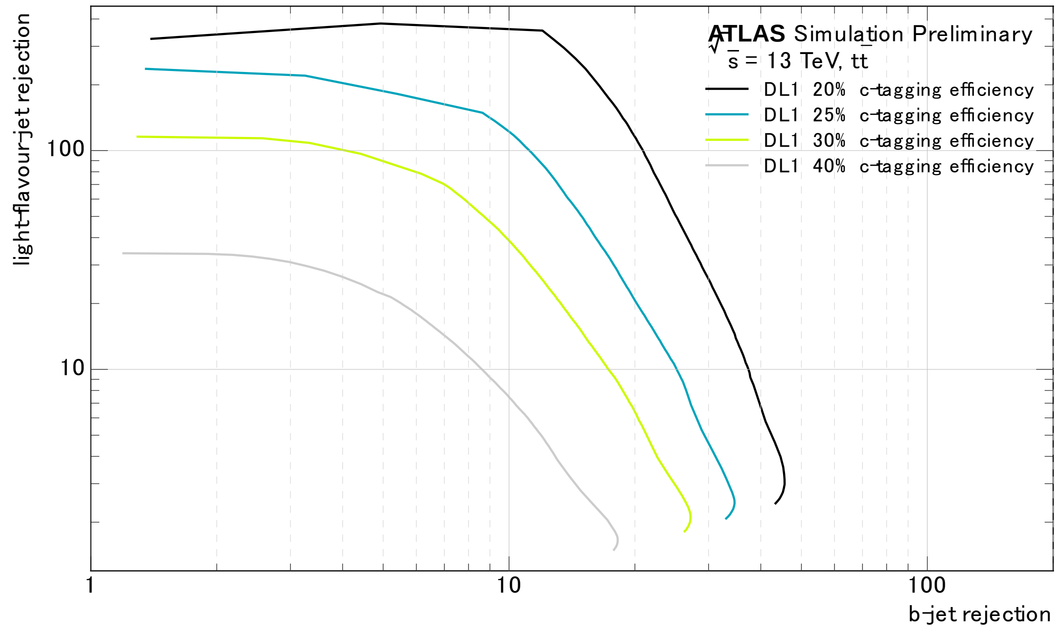
- “JetFitter” … to reconstruct the whole decay chain

$$\bar{B}^0 \to \pi^+\pi^-\pi^+\pi^- D^0$$
$$\hookrightarrow \pi^+\pi^-\pi^+K^-$$

$$D^0 \to \pi^+\pi^-\pi^+K^- \text{ etc...}$$

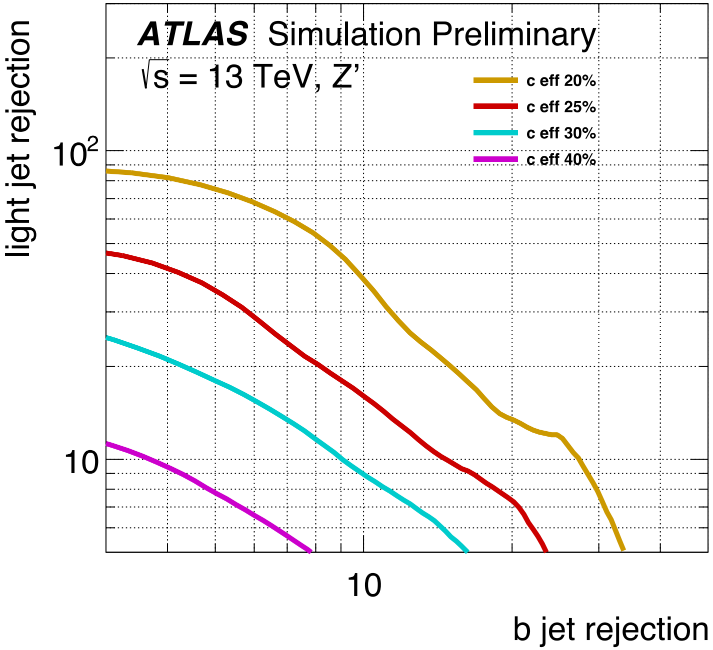
- decay products:
  - smaller multiplicity
  - larger energy & rapidity





$$(\epsilon_c; \epsilon_l, \epsilon_b) = (25\%; 1.4\%, 10\%) \quad \text{for } t\bar{t}\text{-sample (MV)}$$

$$(25\%; 0.8\%, 10\%) \quad \text{for } t\bar{t}\text{-sample (DL)}$$



$$
\begin{aligned}
(\epsilon_c;\epsilon_l,\epsilon_b) = (25\%; 1.4\%, 10\%) &\quad \text{for } t\bar{t}\text{-sample (MV)} \\
(25\%; 0.8\%, 10\%) &\quad \text{for } t\bar{t}\text{-sample (DL)} \\
(25\%; 2.8\%, 20\%) &\quad \text{for 4 TeV } Z'\text{-sample (MV)}
\end{aligned}
$$

- High-Luminosity LHC (2025−): **14 TeV, 3000/fb** in 20 years
  - a new tracker for ATLAS
  - more statistics → smaller systematic uncertainty
  - 200 collisions together with “interesting” collision (pile-up)
    - optimistic results obtained: similar tracker performance
  - R&D in machine learning?

- effect to *c*-tag?
  - “A bit too early to know“

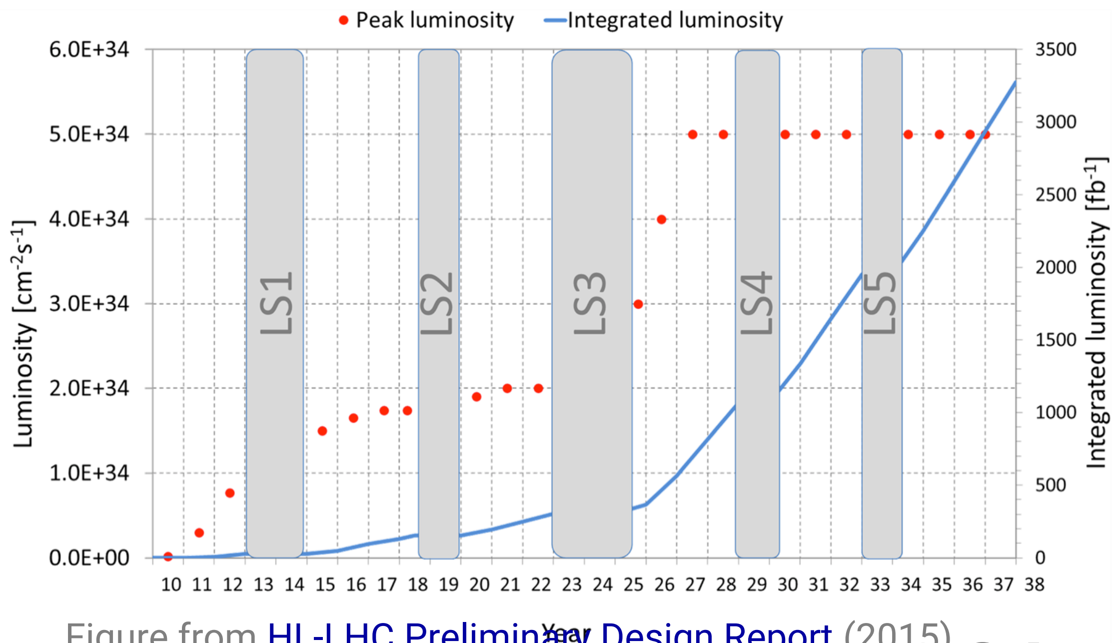


Figure from HL-LHC Preliminary Design Report (2015)

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- Higgs
  - to measure $\mathrm{Br}(h \to c\bar{c})$ Perez, Soreq, Stamou, Tobioka [1505.06689]
- SM flavor
  - FCNC / t−c mixing (e.g. "flavored naturalness" Blanke, Giudice, Paradisi, Perez, Zupan [1302.7232])
- SUSY
  - 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 [1707.07274]
  - to measure squark flavor

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

- ASSUME:
  - SUSY is discovered at the HL-LHC, $pp \to \text{2-jet} + \not{E}_T$.

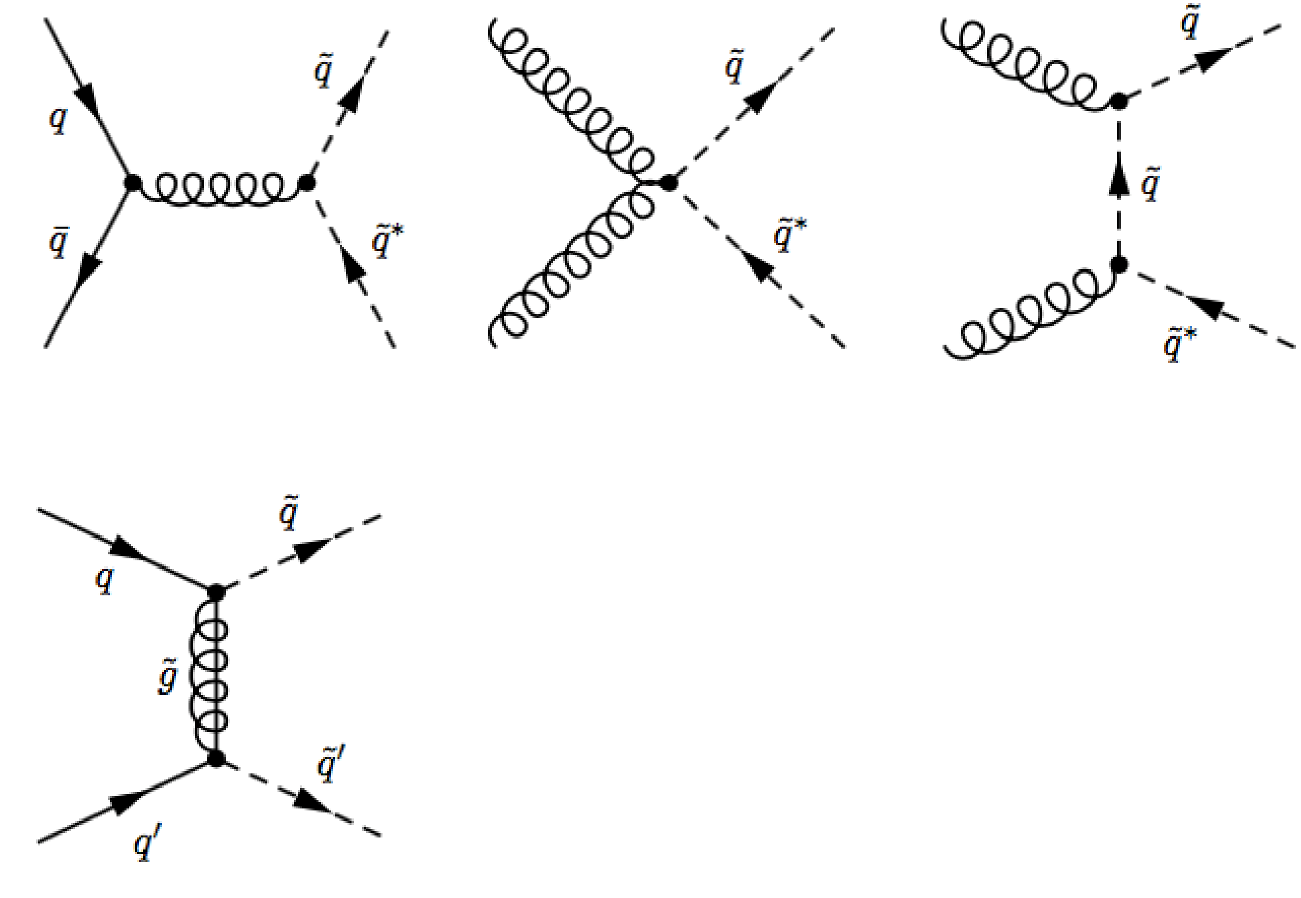
    = squark discovery ($pp \to \tilde{q}\tilde{q}^* \to qq + \text{LSPs}$)
- WONDER:
  - where is the gluino?
  - {how many / which} squarks are found?

SUSY model discrimination with *c*-tagger.

- to measure squark flavor

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

- Four QCD diagrams for $pp \rightarrow \widetilde{q}\widetilde{q}^*$



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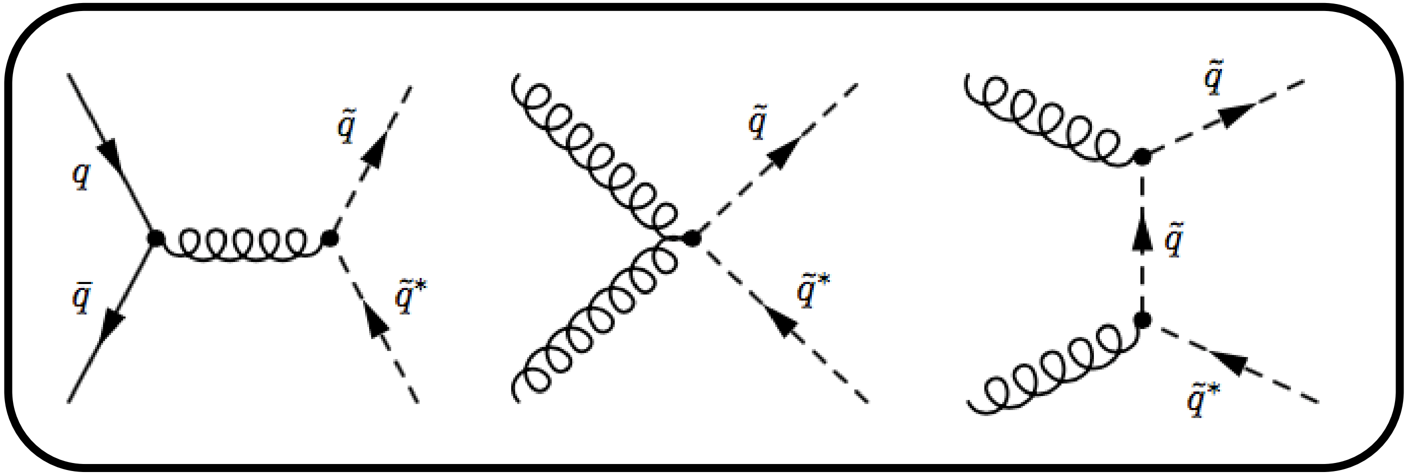
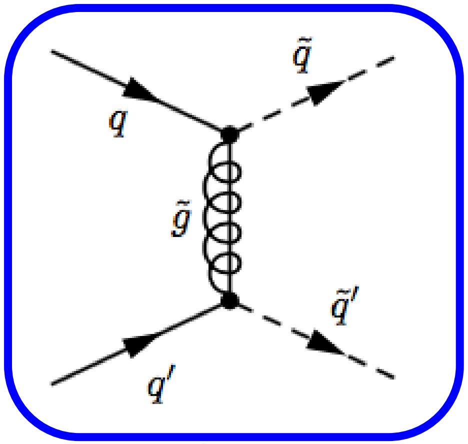




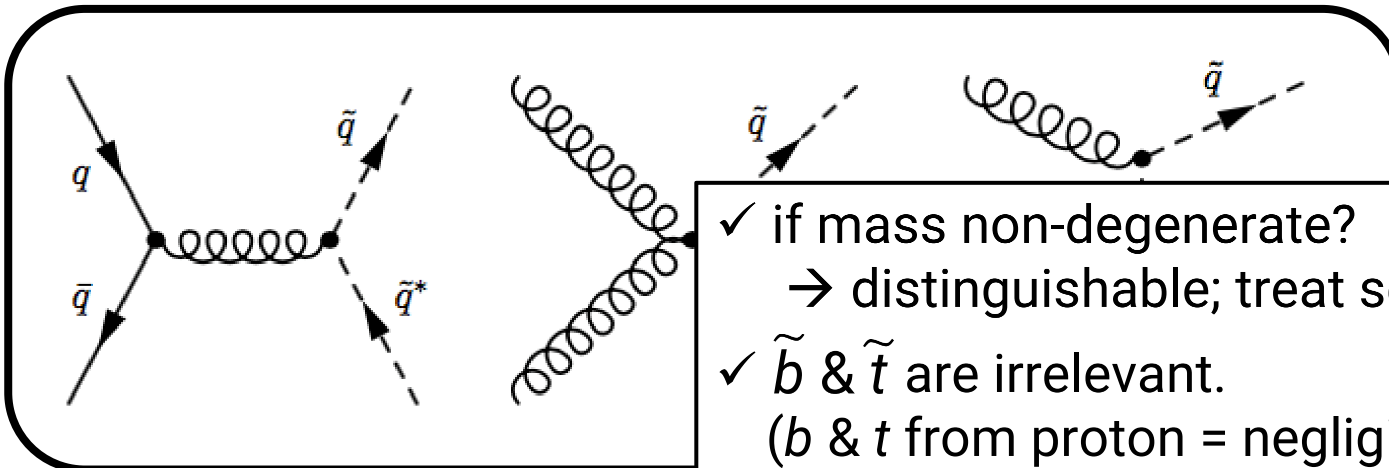
- no gluino.
- squark flavor democratic.

  $\tilde{u} = \tilde{c}$ if mass degenerate

- with gluino.
- squark flavor depends on initial parton.

  $\tilde{u} \gg \tilde{c}$ if mass degenerate

- Four QCD diagrams for $pp \to \tilde{q}\tilde{q}^*$



✓ if mass non-degenerate?
→ distinguishable; treat separately.

✓ $\tilde{b}$ & $\tilde{t}$ are irrelevant.
(b & t from proton = negligible)

- no gluino.
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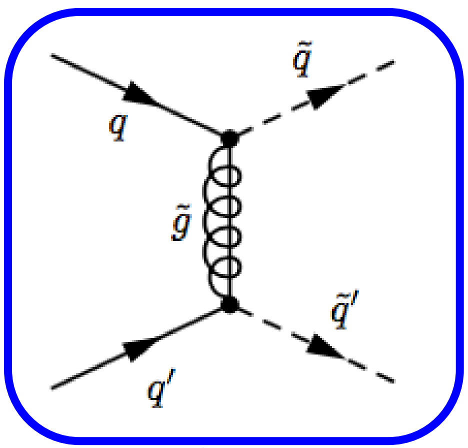

- with gluino.
- squark flavor depends on initial parton.

$\tilde{u} \gg \tilde{c}$ if mass degenerate

- some $\subset (\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c})$ are light (~TeV) and degenerate; $\tilde{B}$-LSP.

  ($pp \to$ 2-jet + $\not{E}_T$ realized)

  - others (incl. $\tilde{b}$ & $\tilde{t}$, $\tilde{W}$) are heavy (not produced).
  - three scenarios:
    - $N_{\tilde{q}} = 2$: $\tilde{u}_R$, $\tilde{c}_R$
    - $N_{\tilde{q}} = 4$: $\tilde{u}_R$, $\tilde{c}_R$, $\tilde{d}_R$, $\tilde{s}_R$
    - $N_{\tilde{q}} = 8$: all the 8 squarks

✓ if mass non-degenerate?
→ distinguishable; treat separately.
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(b & t from proton = negligible)

- No flavor violation. (confirmable from flavor expm?)
  - underlying scenario: "flavored gauge mediation"
    … flavor-viol. among $\tilde{q}_R$ is suppressed.

Ierushalmi, SI, Lee, Nepomnyashy, Shadmi [1603.02637]

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  ($pp \to$ 2-jet + $\not{E}_T$ realized)

  - others (incl. $\tilde{b}$ & $\tilde{t}$, $\tilde{W}$) are heavy (not produced).

    should be very heavy

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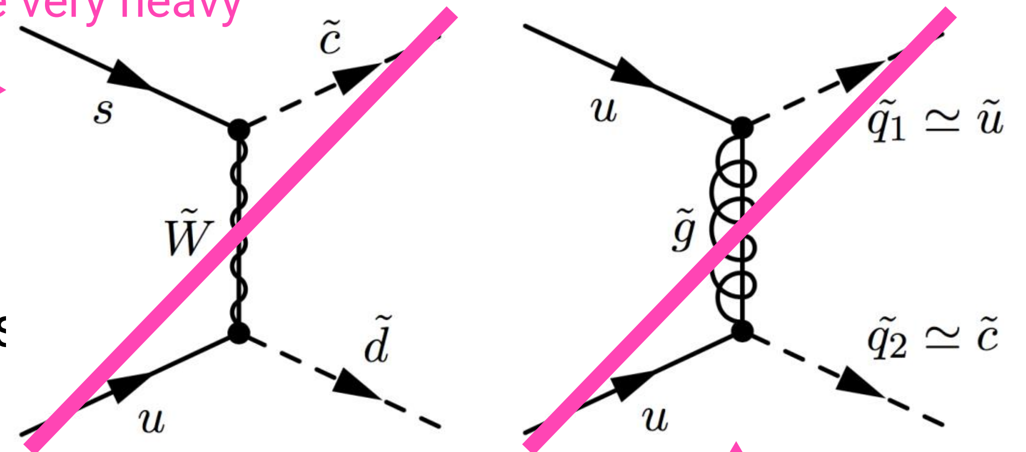

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* Investigation through c-tagging would be possible
if the tagger efficiency were super good… (or your idea is super good).

- Discrimination of the models in this scenario:

$$(N_{\widetilde{q}}, m_{\widetilde{q}}, m_{\mathrm{LSP}}, m_{\widetilde{g}})$$

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

} & $\widetilde{B}$-LSP are light and accessible.

- Discrimination of the models in this scenario:

$$(N_{\widetilde{q}}, m_{\widetilde{q}}, m_{\mathrm{LSP}}, m_{\widetilde{g}})$$

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

  - mT2 analysis $m_{\mathrm{T2}} \leq m_{\mathrm{T2}}^{\mathrm{endpoint}}(m_{\widetilde{q}}, m_{\mathrm{LSP}})$ $\left(\approx \frac{m_{\widetilde{q}}^2 - m_{\mathrm{LSP}}^2}{m_{\widetilde{q}}}\right)$

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- charm fraction $F_c := \dfrac{N(c\text{-tagged jet})}{N(\text{jet})}$ (among hardest 2 jets)

* We can also utilize “charm-jet deposition” $\{N_0^{\rm ev}, N_1^{\rm ev}, N_2^{\rm ev}\}$, where $N_n^{\rm ev}$ is the number of events with n c-jets.
Here we simply use Fc, which is $F_c = \dfrac{(N_1^{\rm ev}/2) + N_2^{\rm ev}}{N_0^{\rm ev} + N_1^{\rm ev} + N_2^{\rm ev}}$.

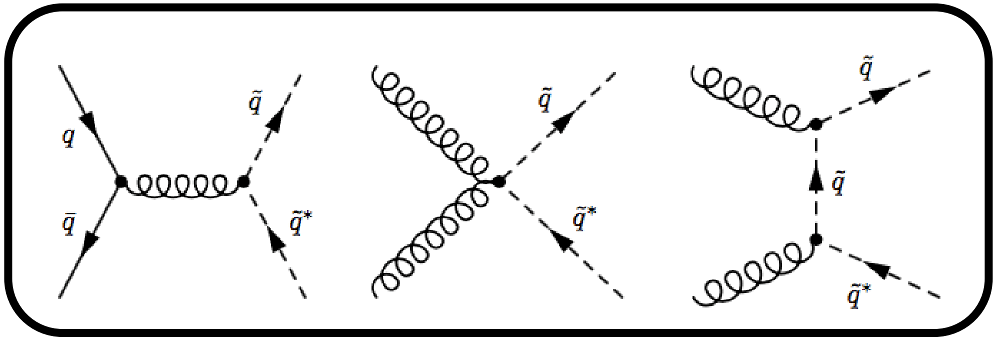
$$F_c := \frac{N\,(c\text{-tagged jet})}{N\,(\text{jet})}$$

(hardest 2 jets are considered; N(jet) = $2N$(event))

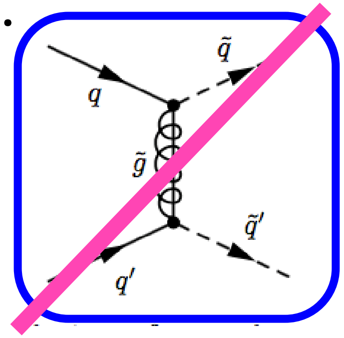
With

(no mistag, 100% efficiency)

- an "ideal" c-tagger
- no SM background,
- decoupled gluino



flavor-universal only.



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

- $N_{\tilde{q}} = 2$: $\tilde{u}_R$, $\tilde{c}_R$ → $\tilde{c}$ = 1/2
- $N_{\tilde{q}} = 4$: $\tilde{u}_R$, $\tilde{c}_R$, $\tilde{d}_R$, $\tilde{s}_R$ 1/4
- $N_{\tilde{q}} = 8$: all the 8 squarks 2/8

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

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

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→ in reality, "smeared" by

- tagger performance,
- SM background, and
- gluino contribution.

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• $N_{\tilde{q}} = 4$	: $\tilde{u}_R$, $\tilde{c}_R$, $\tilde{d}_R$, $\tilde{s}_R$	1/4
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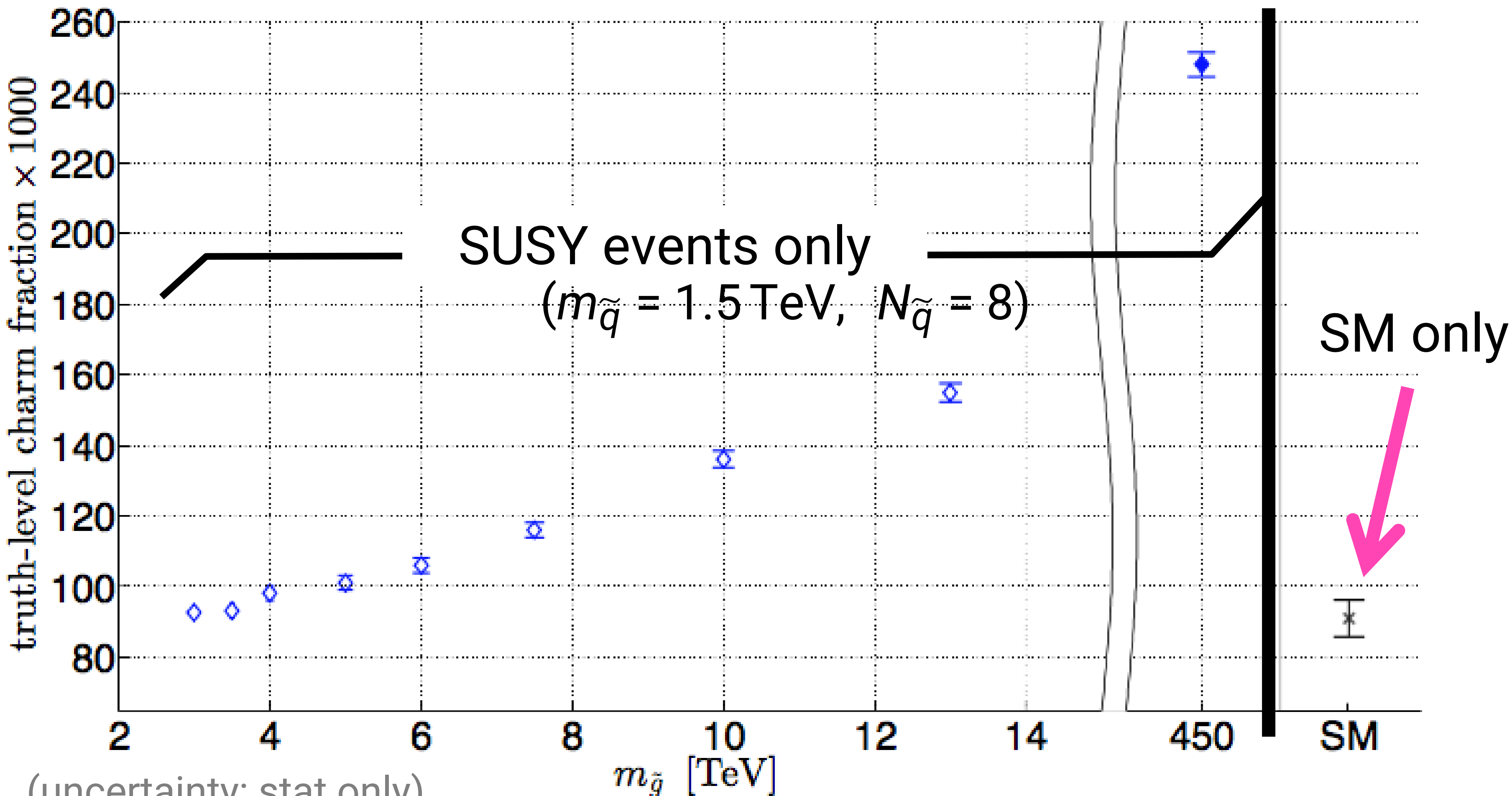
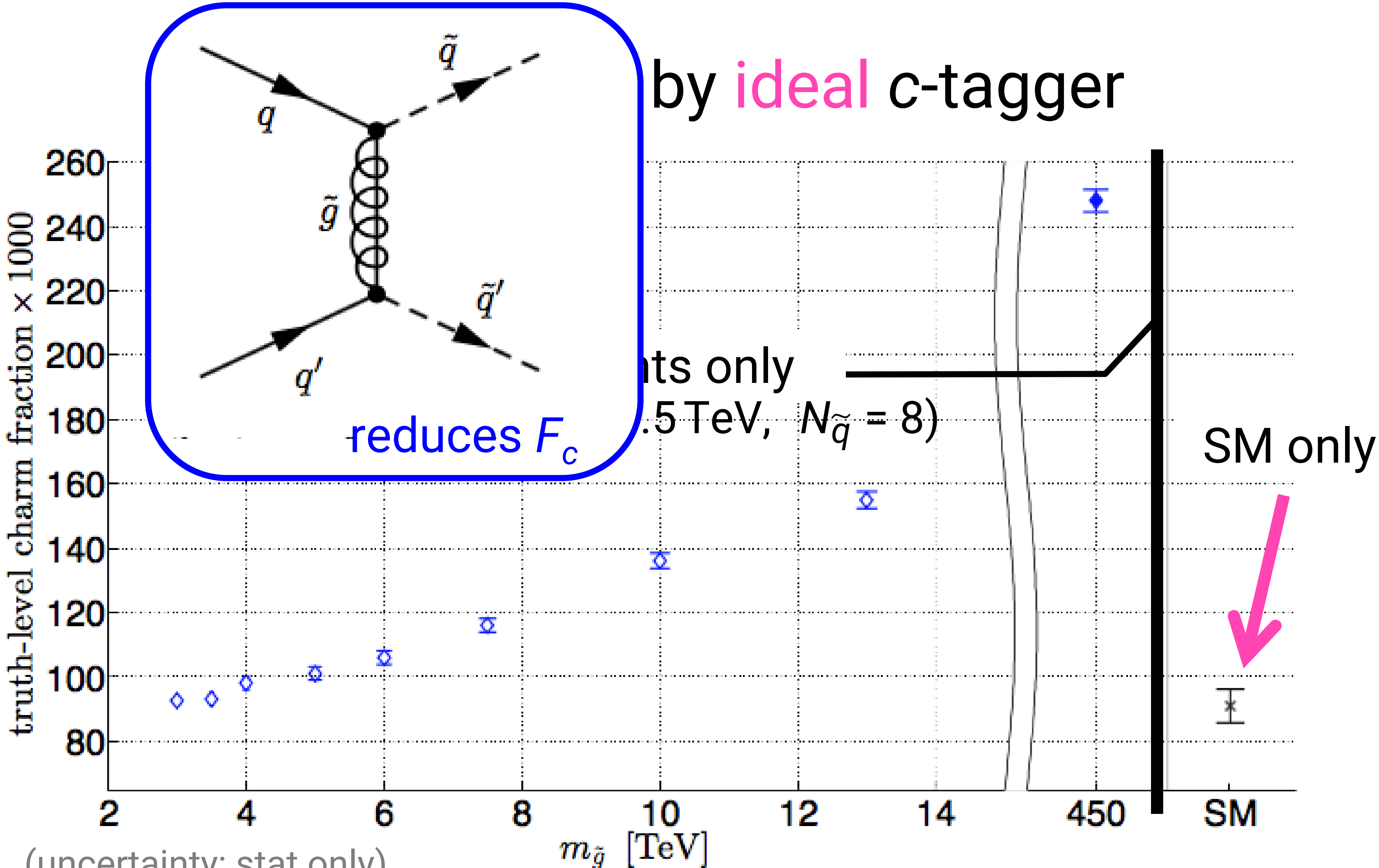
F_c measured by ideal c-tagger



(uncertainty: stat only)



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

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

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

→ in reality, "smeared" by

- tagger performance,
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- gluino contribution. ✓

• $N_{\tilde{q}} = 2$: $\tilde{u}_R$, $\tilde{c}_R$		→ $\tilde{c}$ = 1/2
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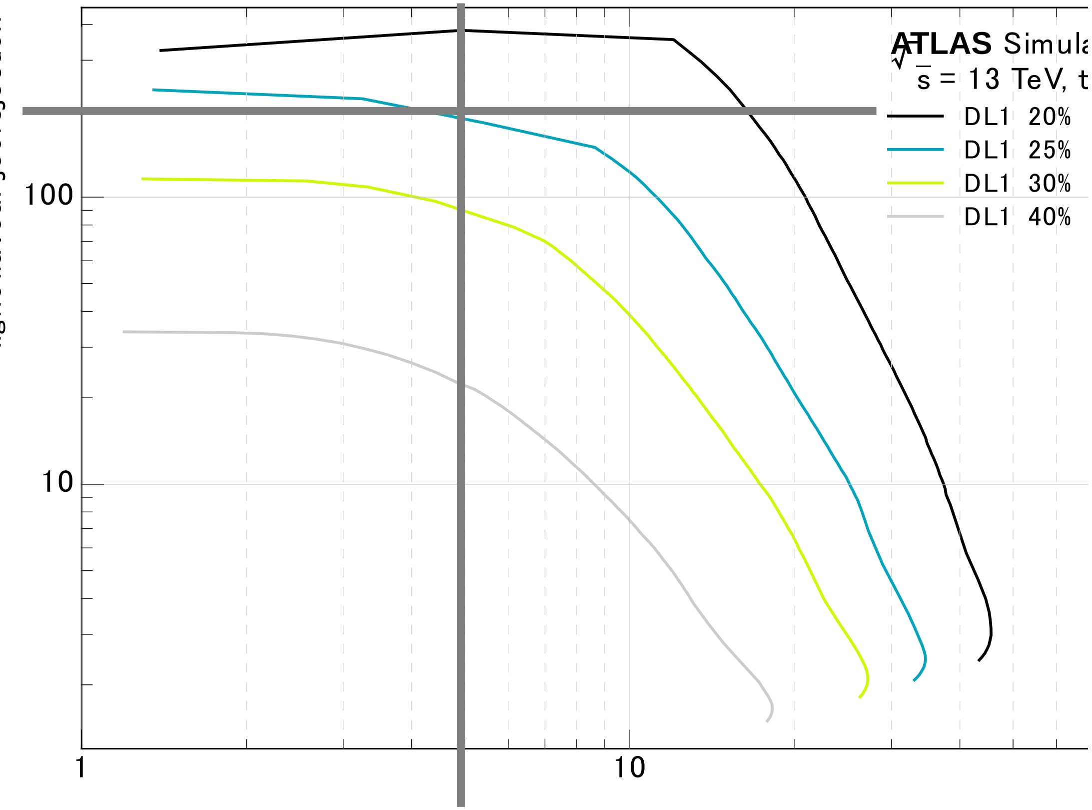
our benchmarks:

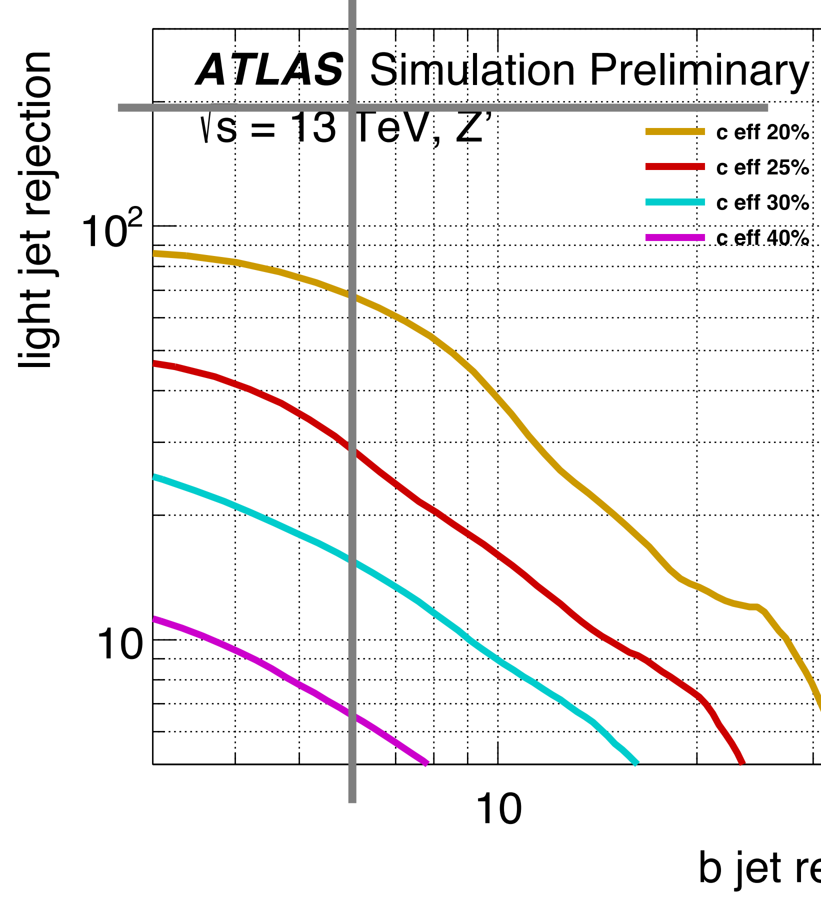
$$(\epsilon_c; \epsilon_b, \epsilon_l) = (50\%; 20\%, 0.5\%),$$
$$(30\%; 20\%, 0.5\%)$$

(universal over p_T, η)

Charm fraction



Deep learning, ttbar



MV2MuRnn, 4 TeV *Z'*

optimistic, but not "very".

our benchmarks:

$$(\epsilon_c; \epsilon_b, \epsilon_l) = (50\%; 20\%, 0.5\%),$$
$$(30\%; 20\%, 0.5\%)$$

(universal over p_T, η)

1. Quark-flavor tagging

- *b*-tagging
- *c*-tagging

2. Applications to BSM: SUSY model discrimination

- Motivation + Scope
- Charm fraction
- Results & discussion on uncertainty

We want to discriminate

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

with three "measurements":

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

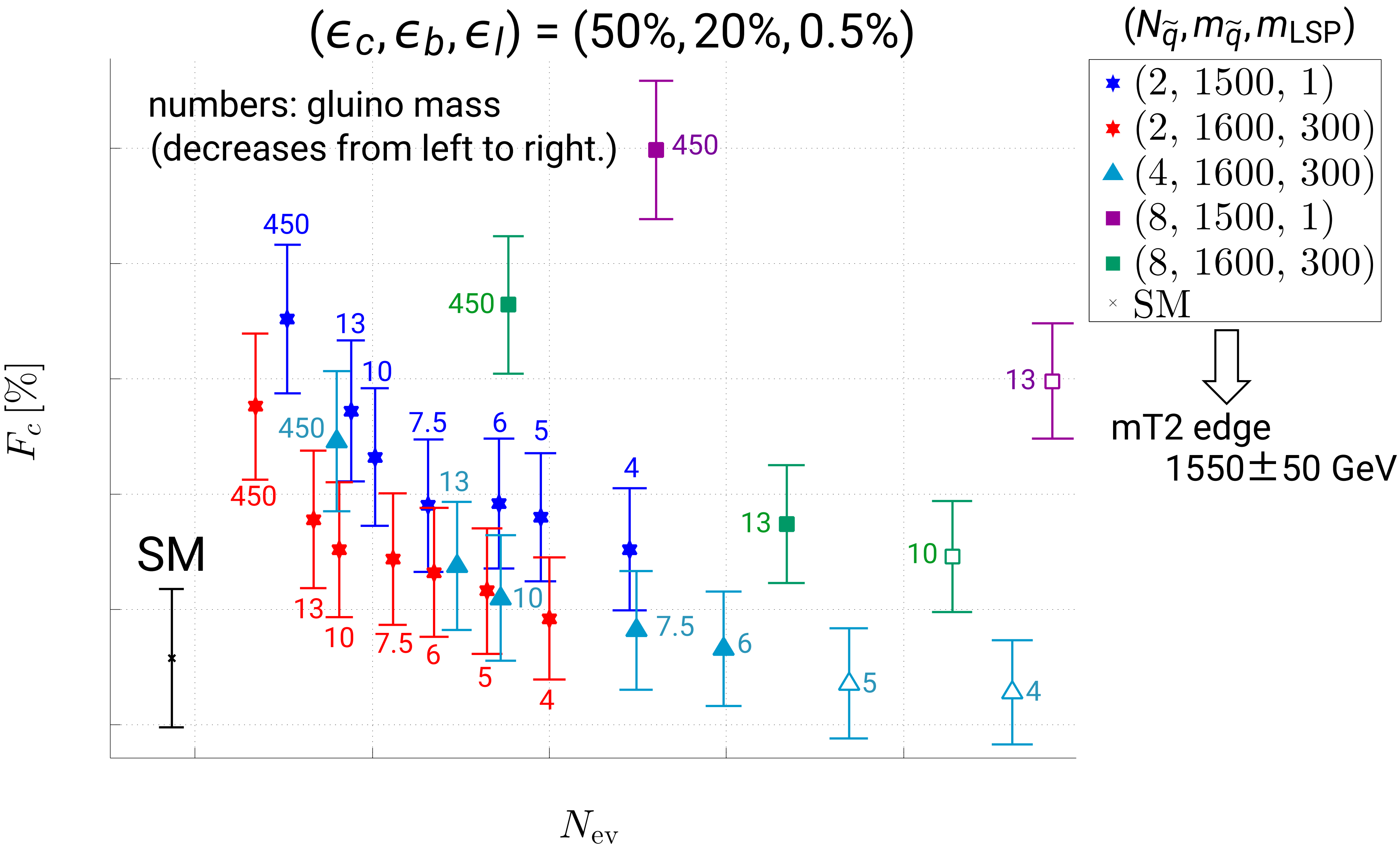
$$m_{\rm T2} \leq m_{\rm T2}^{\rm endpoint}(m_{\widetilde{q}}, m_{\rm LSP})$$

$$F_c = \frac{N_{c\text{-jets}}}{N_{\rm jets}} = F_c(m_{\widetilde{q}}, m_{\widetilde{g}}, N_{\widetilde{q}})$$

- ✓ larger for heavier $\widetilde{g}$
- ✓ typically SUSY > SM
- ➢ smeared by tagger

$(\epsilon_c; \epsilon_b, \epsilon_l)$ = (50%; 20%, 0.5%), (30%; 20%, 0.5%)

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

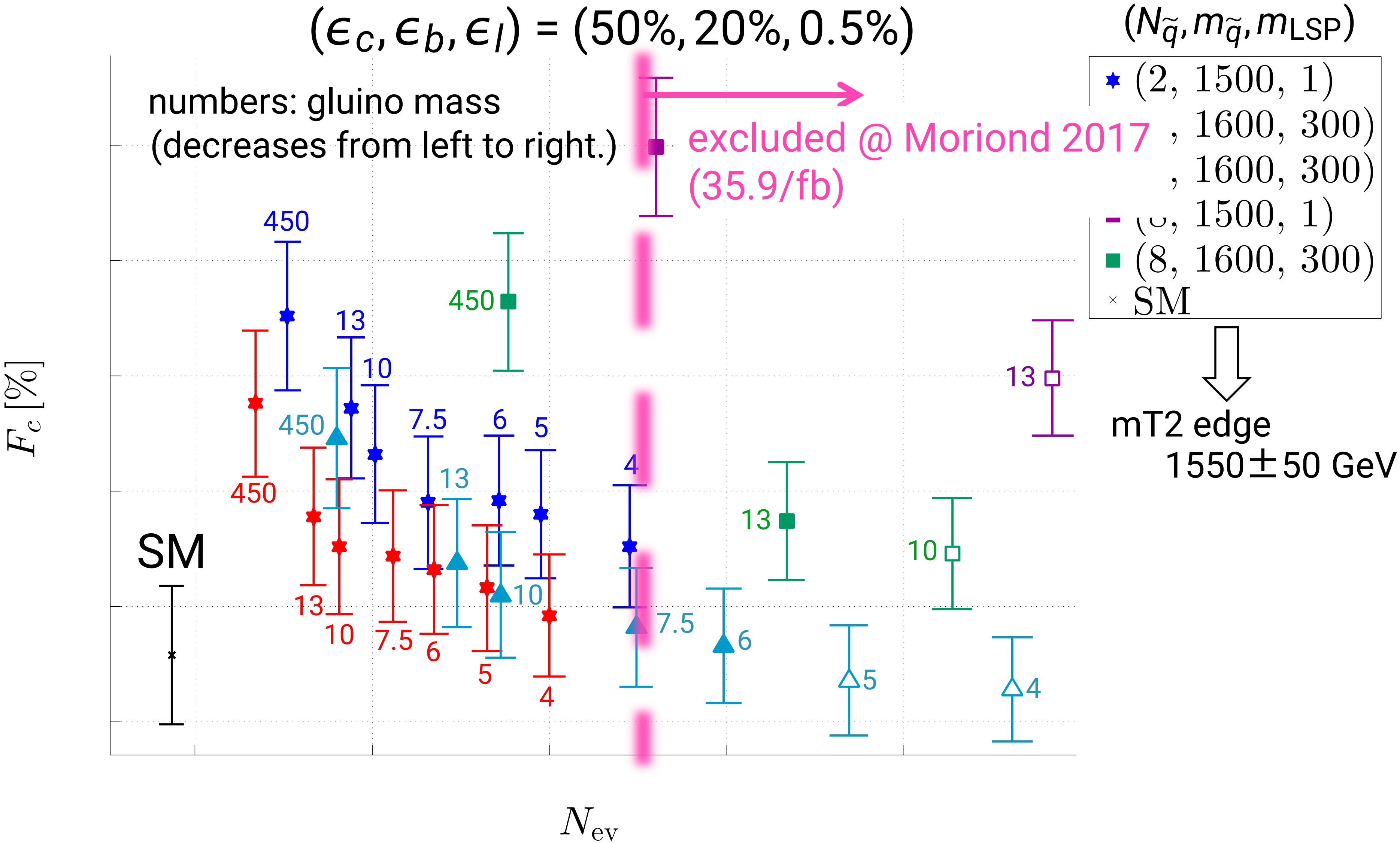


(uncertainty: stat only, *y*-axis only)

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

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



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

Analysis based on ATLAS HL-LHC (PHYS-PUB-2014-010; Meff-2j-3100).
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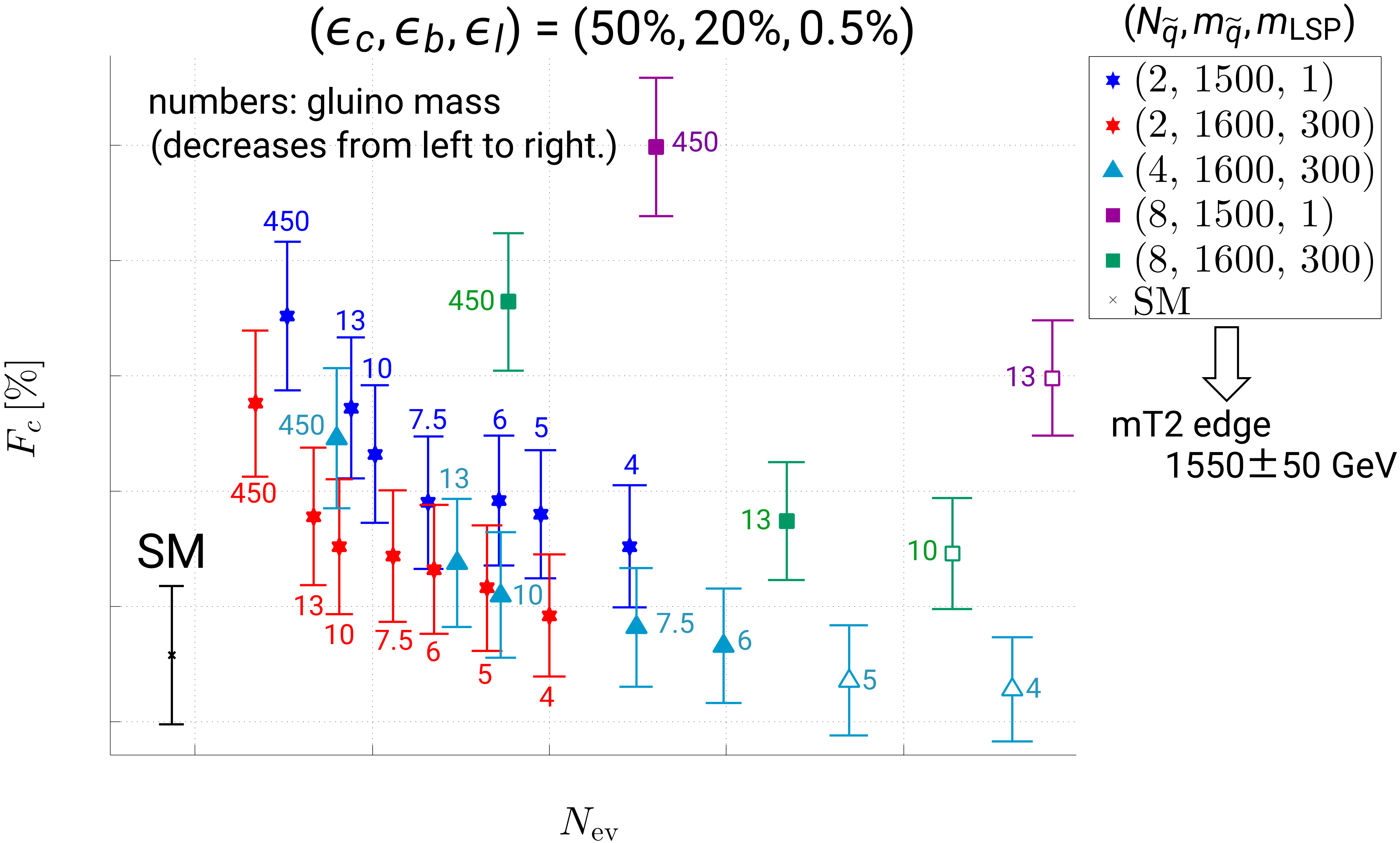
SUSY: prospino NLO SM: rescaling w.r.t. ATLAS simulation

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



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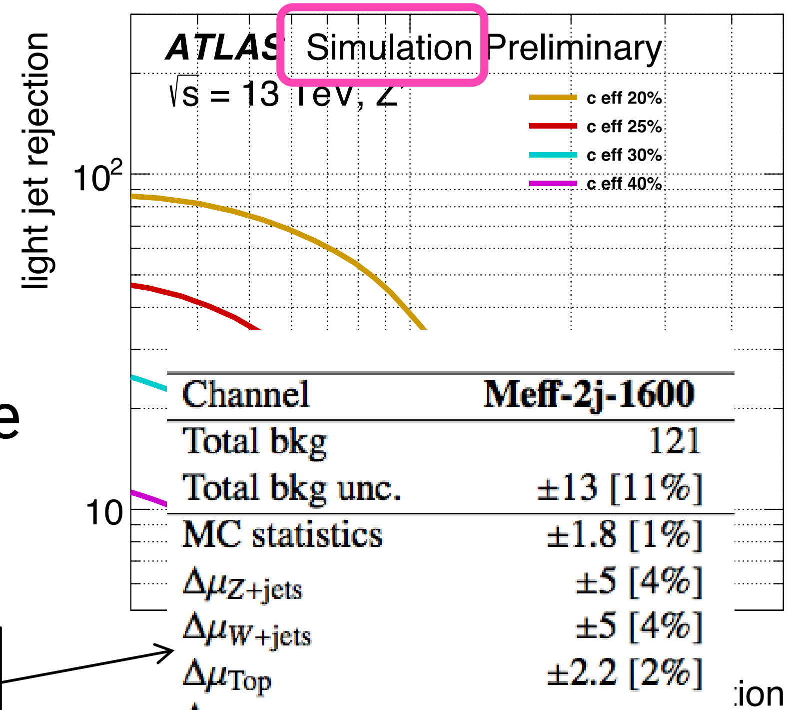
SUSY: prospino NLO SM: rescaling w.r.t. ATLAS simulation

- simulation ≠ data
  - → "commissioning" :
    compare against collider data.
    uncertain ← statistical uncertainty

- systematic uncertainties example



Channel	Meff-2j-1600
Total bkg	121
Total bkg unc.	±13 [11%]
MC statistics	±1.8 [1%]
$\Delta\mu_{Z+\text{jets}}$	±5 [4%]
$\Delta\mu_{W+\text{jets}}$	±5 [4%]
$\Delta\mu_{\text{Top}}$	±2.2 [2%]
$\Delta\mu_{\text{Multi-jet}}$	–
CRγ corr. factor	±4 [3%]
Theory Z	±9 [7%]
Theory W	±1.0 [1%]
Theory Top	±0.6 [0%]
Theory Diboson	±4 [3%]
Jet/MET	±1.8 [1%]
Multi-jet method	–

background number estimation
(stat. unc. + syst. unc. in control regions) → $\Delta\mu$ rows

background simulation model / scales → Theory rows

jet energy scale calibration,
jet energy resolution
missing energy modeling → Jet/MET

From ATLAS squark search (2j+MET)
[ATLAS-CONF-2016-078]

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

→ several syst. unc. cancelled.

but suffered from uncertainty on *c*-tagging.

➢ commissioning using ttbar sample is ongoing.

… "~~~10%"

↓

jet $p_{\mathrm{T}} \lesssim 400\,\mathrm{GeV}$

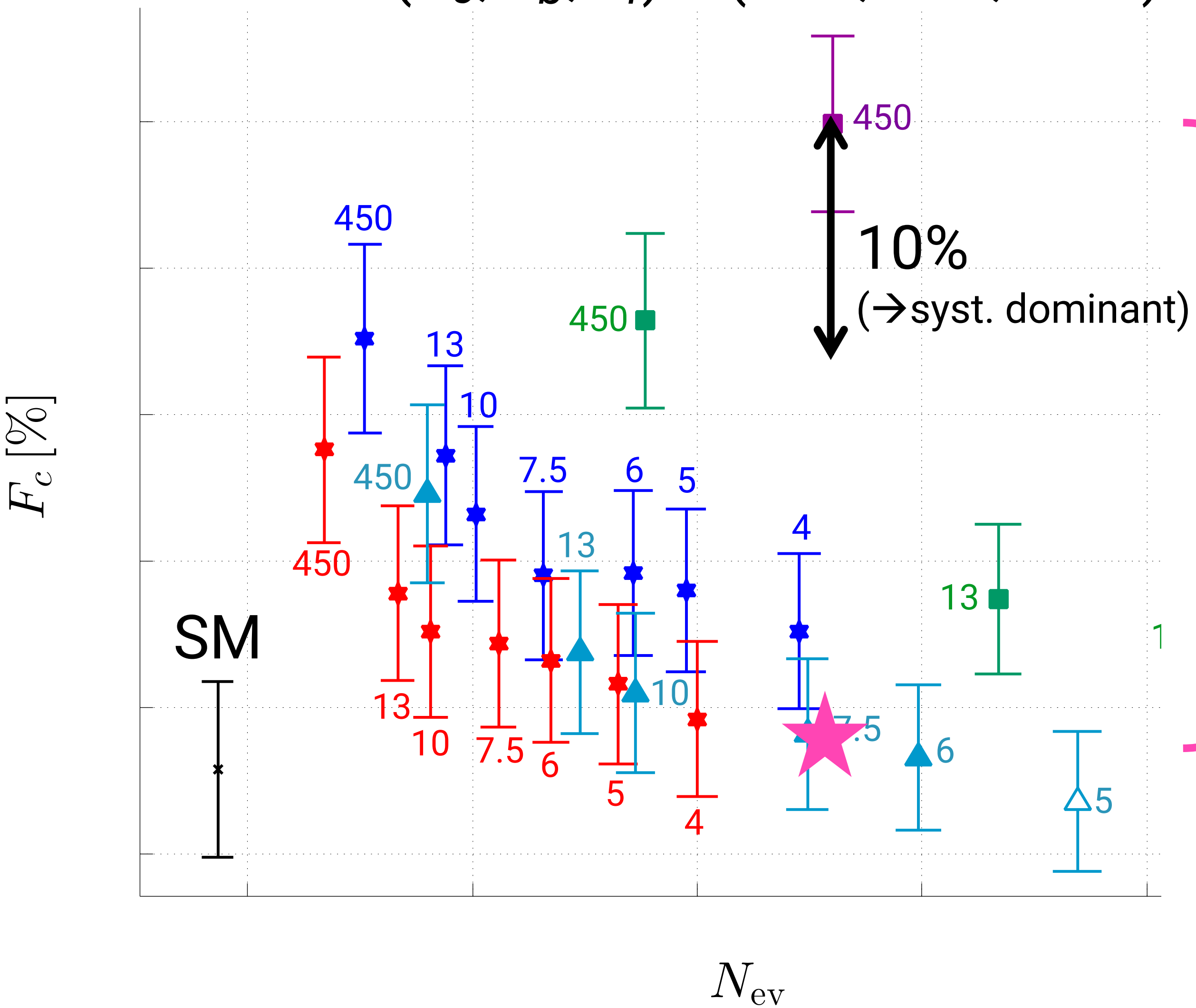
↓

No reliable estimate for our case.

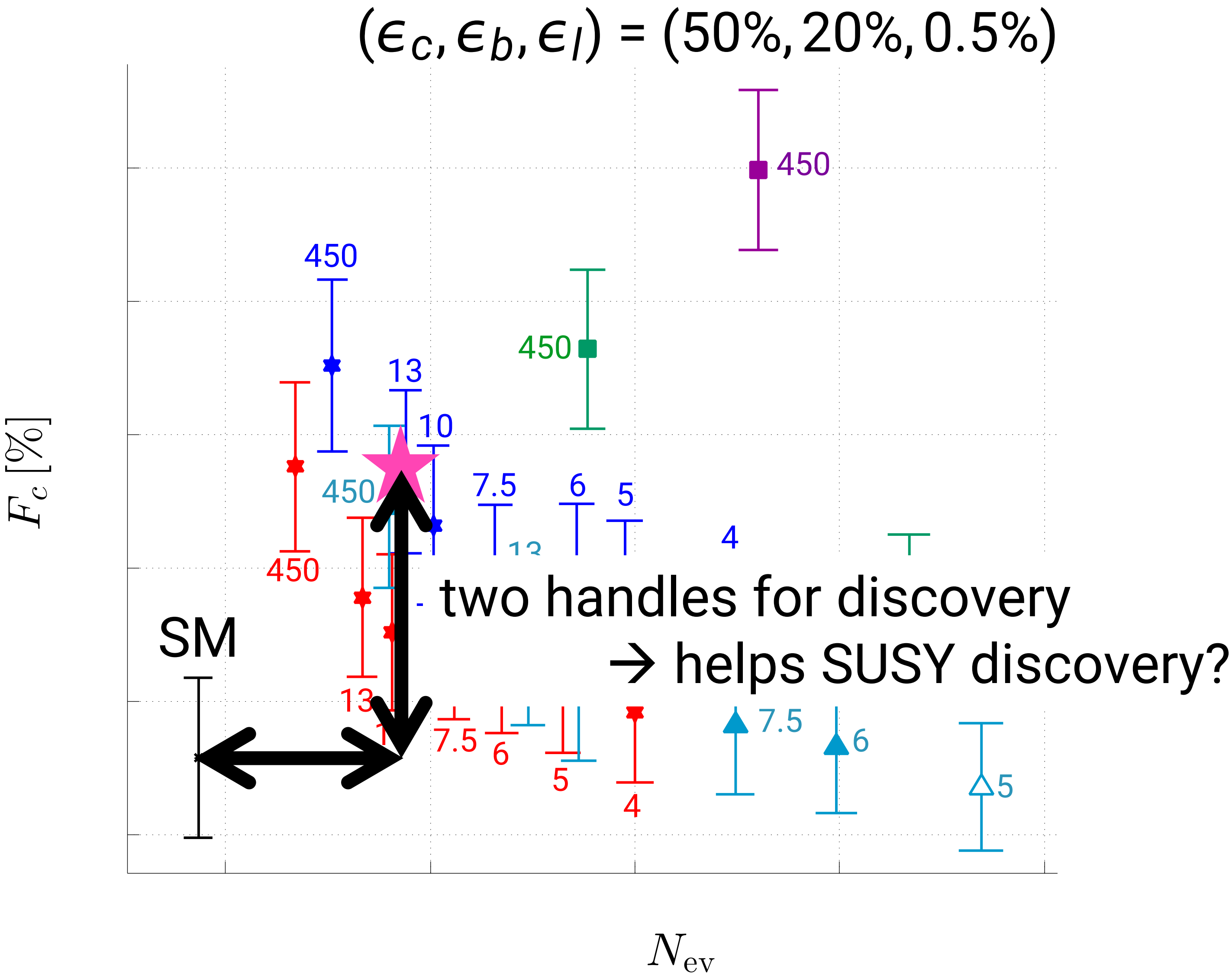
$F_c\,[\%]$

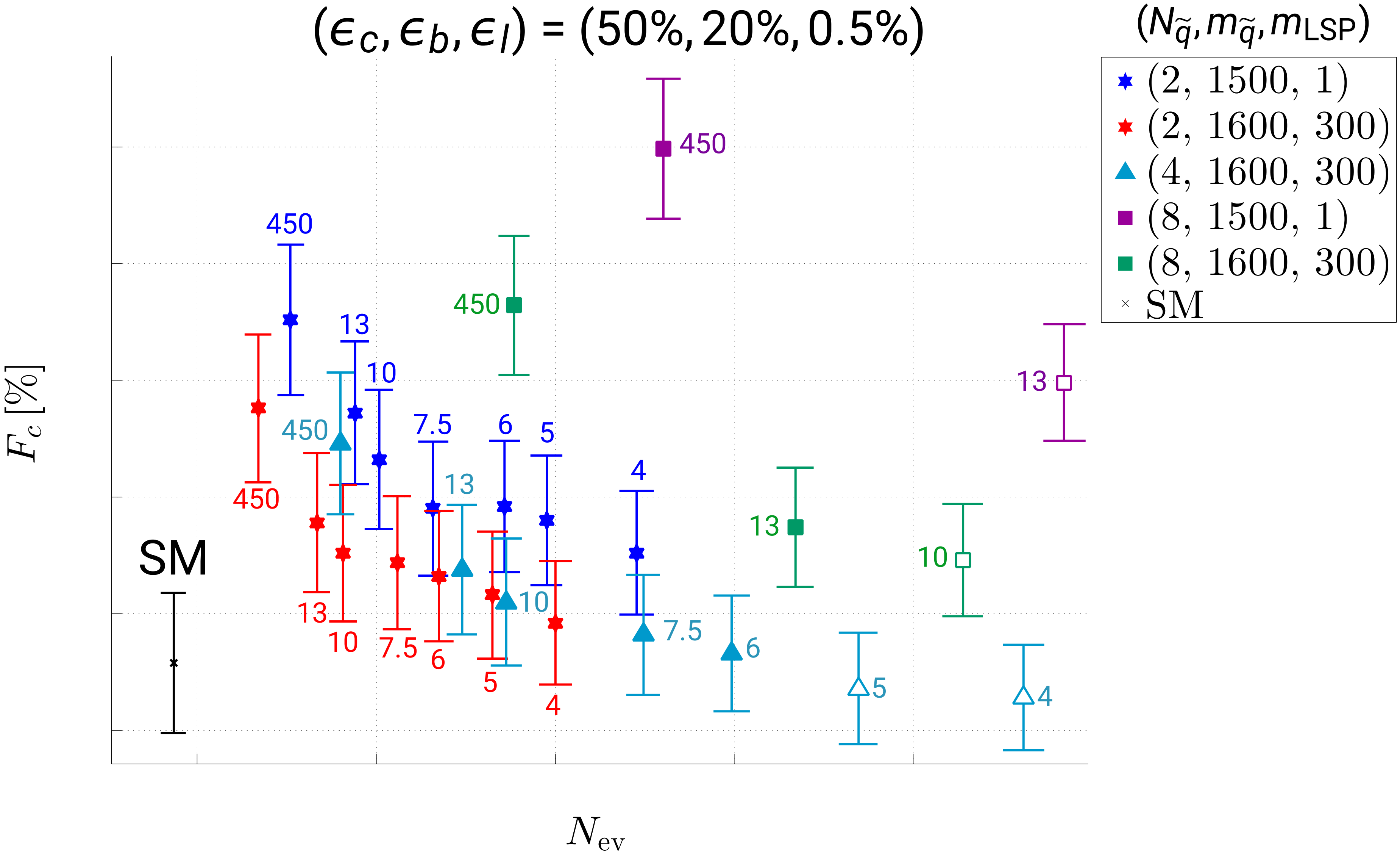
N_{ev}

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



2-3σ exclusion *may* be possible.


$(\epsilon_c, \epsilon_b, \epsilon_l) = (50\%, 20\%, 0.5\%)$
450
450
13
10
450
450
7.5
6
5
4
450
SM
13
7.5
6
5
4
7.5
6
5
two handles for discovery
→ helps SUSY discovery?
F_c [%]
$N_{\rm ev}$



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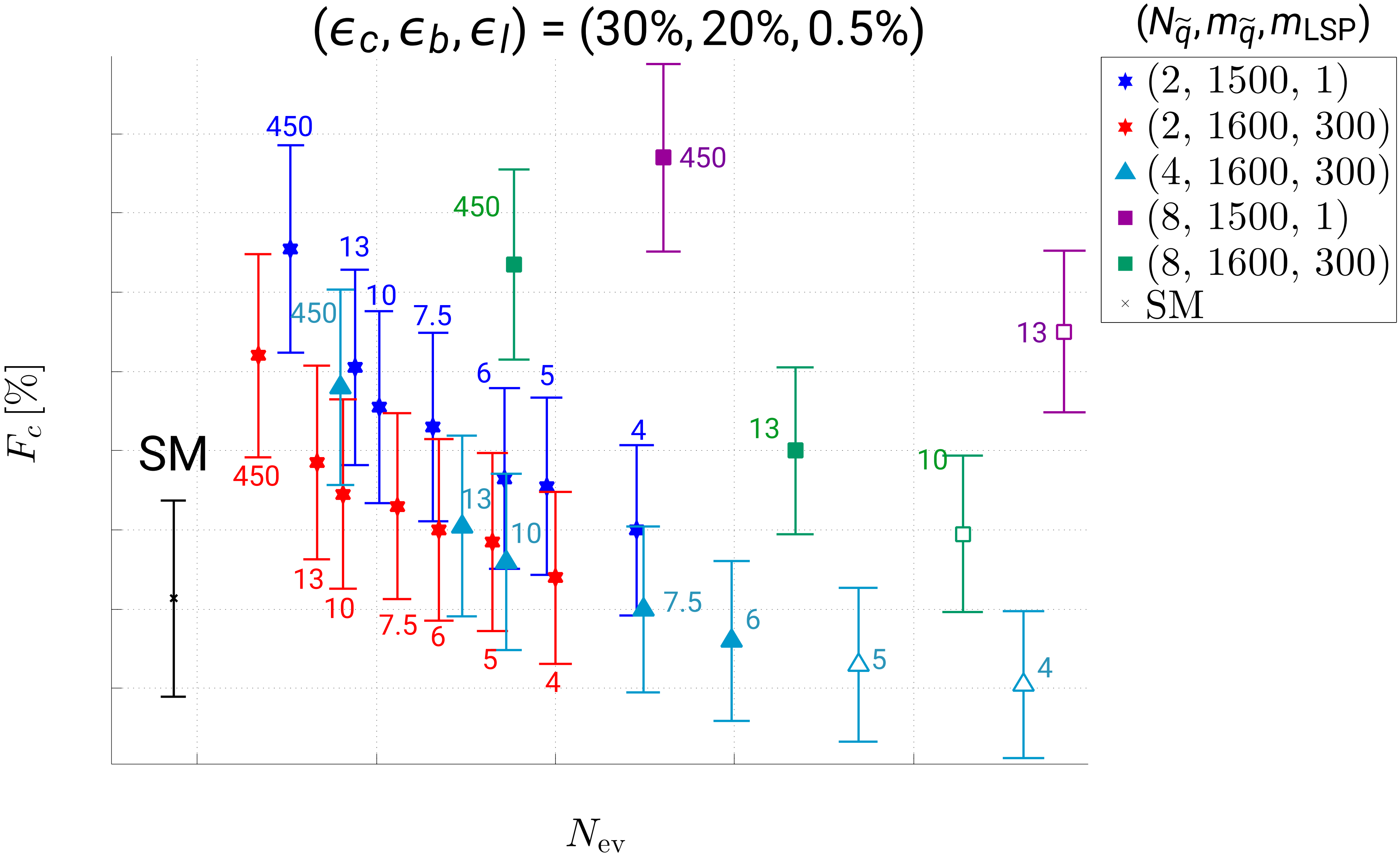

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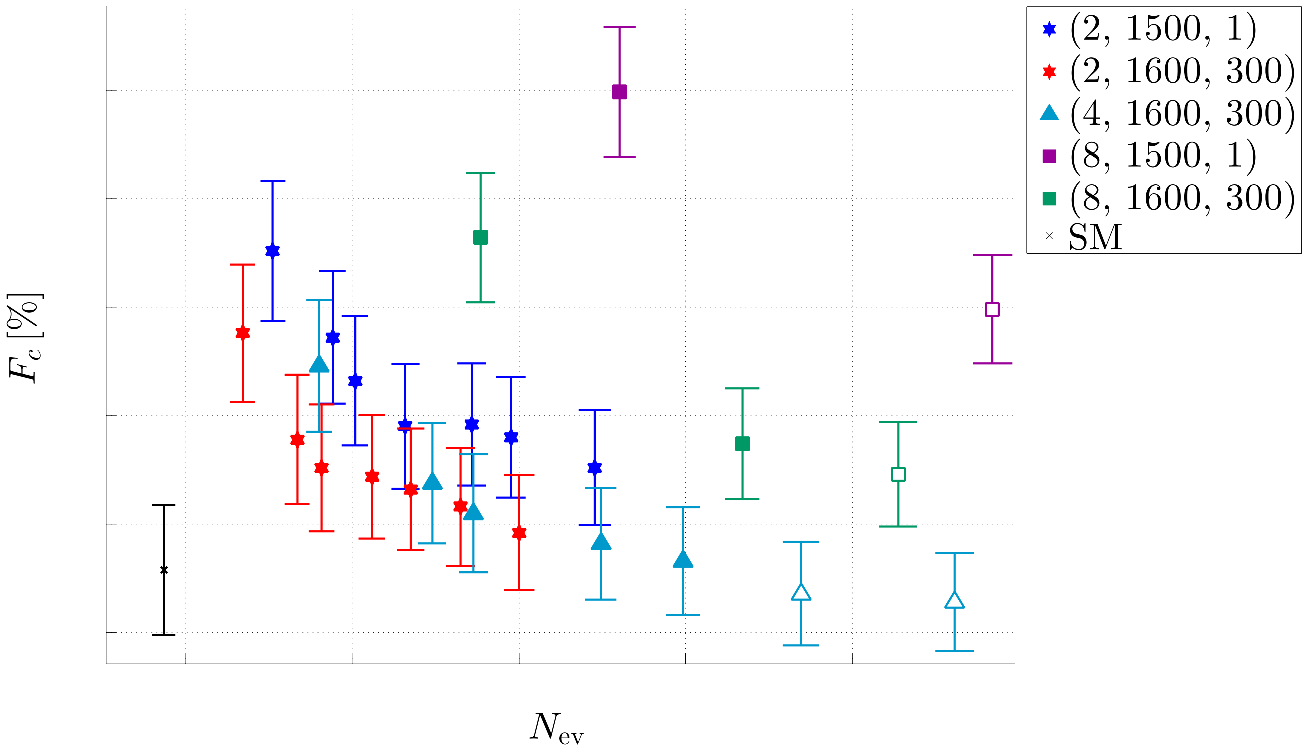
SUSY: prospino NLO SM: rescaling w.r.t. ATLAS simulation

- Flavor tagging @ LHC
  - crucial + rapidly developing (deep learning tagger @ Jul. 2017)
  - BSM application: “uncertainty”
- *charm*-tagging for SUSY model discrimination
  - interesting because { 1^{st} + 2^{nd} gen. are “expected” to be degenerate. / *c* in proton → indirect gluino mass meas.



1. Quark-flavor tagging

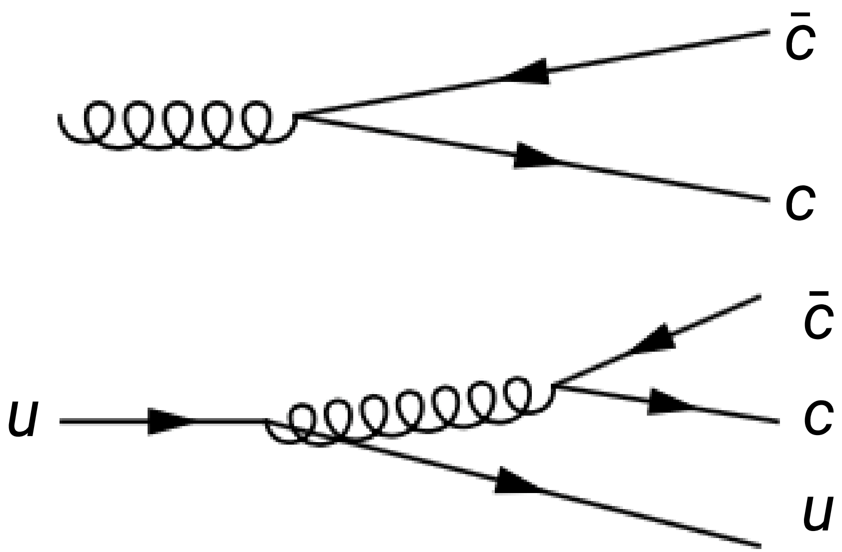
- *b*-tagging
- *c*-tagging

2. Applications to BSM: SUSY model discrimination

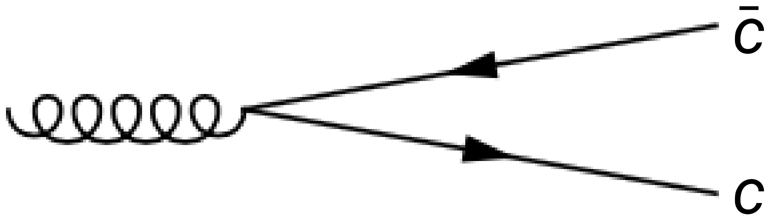
- Motivation + Scope
- Charm fraction
- Results & discussion on uncertainty
- one more subtlety in our analysis

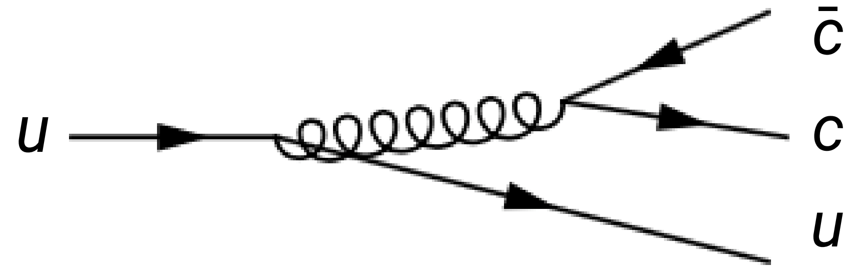
- Fast simulation for c-tagging?
  - impose $(\epsilon_c, \epsilon_b, \epsilon_l)$ on each jet.

    → how to define "truth jet flavor" in simulation?
- our naive method (we modified Delphes3)
  - a jet is "truth-level b-jet" if b-parton/hadron in jet,
  - else: "truth-level c-jet" if c-parton/hadron in jet, else "light-jet".
- subtlety:



→ "truth c" [incorrect!]



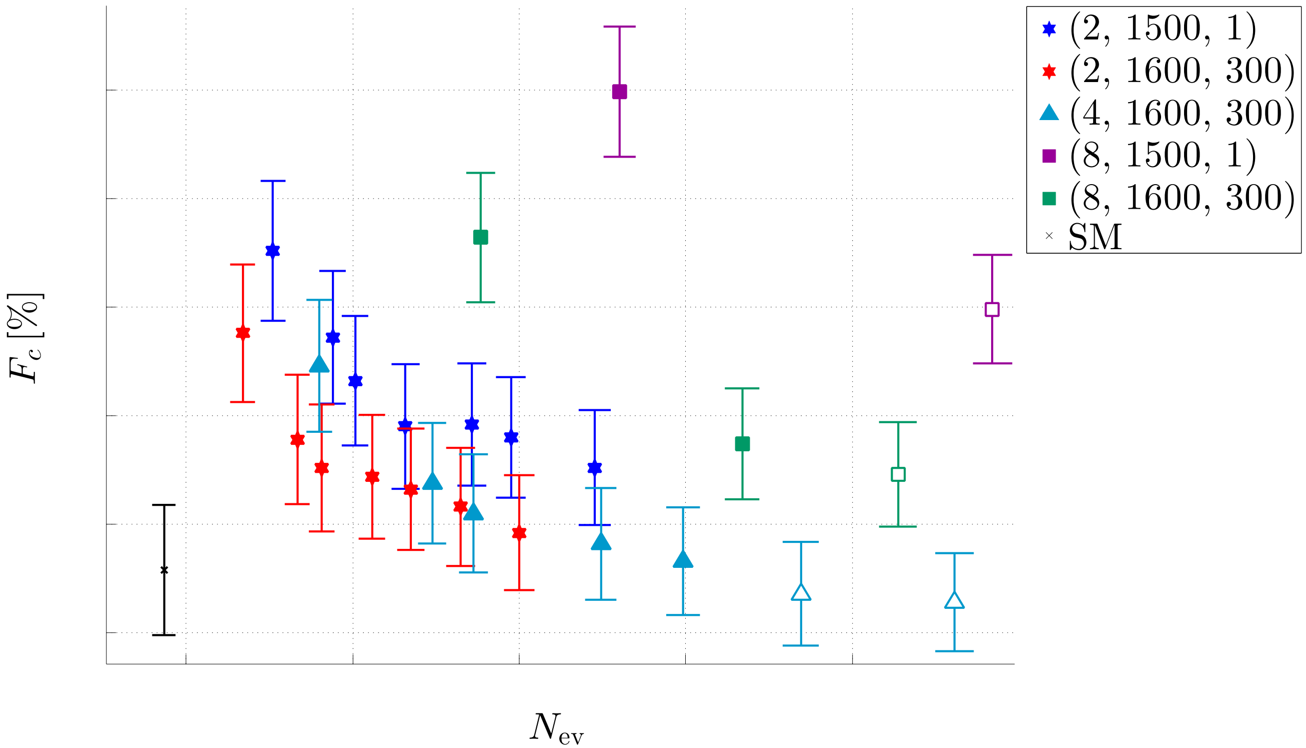


- big effect to SM
- smaller for squark process
- In our simulation:
  another syst. unc. on “SM”
- At experiment:
  calibrated in “commissioning”

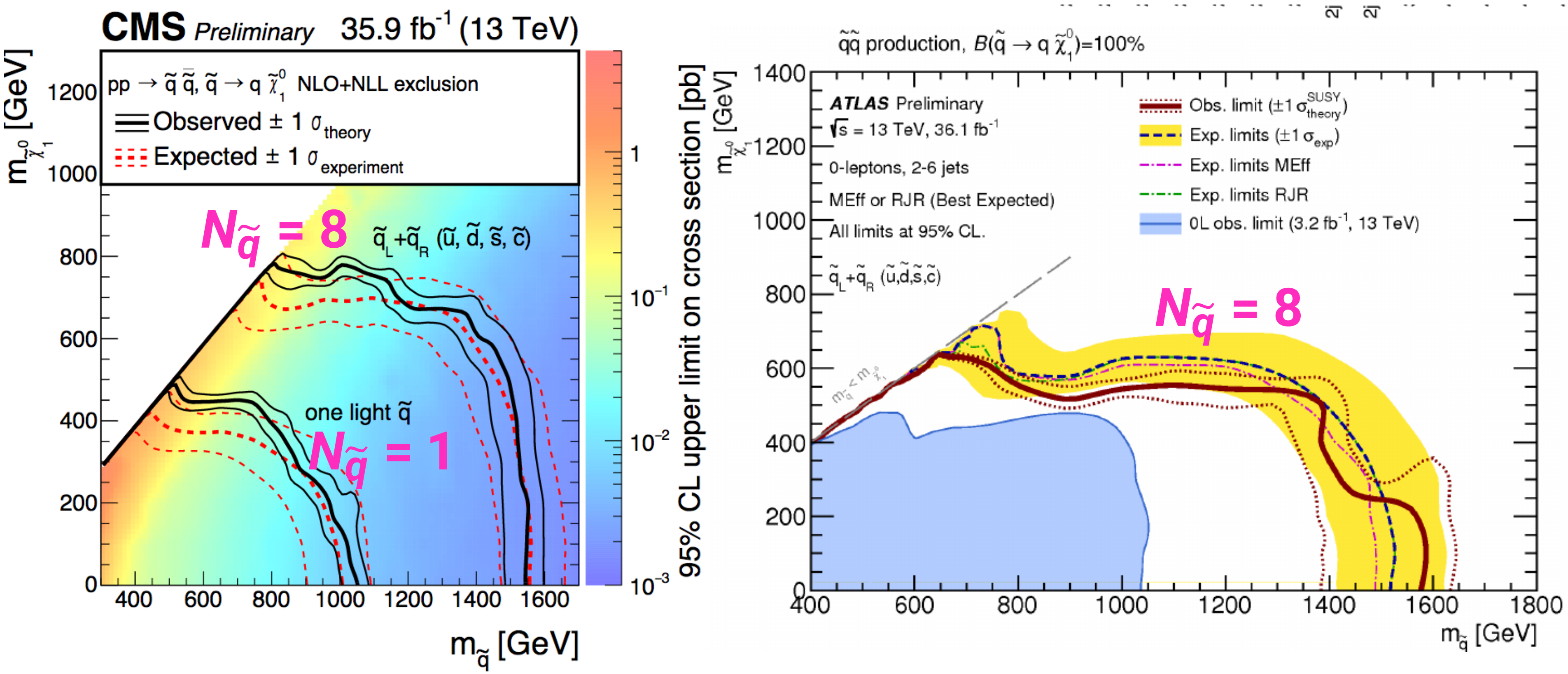
- also affects squark proc.
- negligible
  @ current precision
- careful stud required
  for future (higher precision)

ex) flavor violation in SUSY

- Flavor tagging @ LHC
  - crucial + rapidly developing (deep learning tagger @ Jul. 2017)
  - BSM application: "uncertainty"
- *charm*-tagging for SUSY model discrimination
  - interesting because { 1^{st} + 2^{nd} gen. are "expected" to be degenerate.
    c in proton → indirect gluino mass meas.

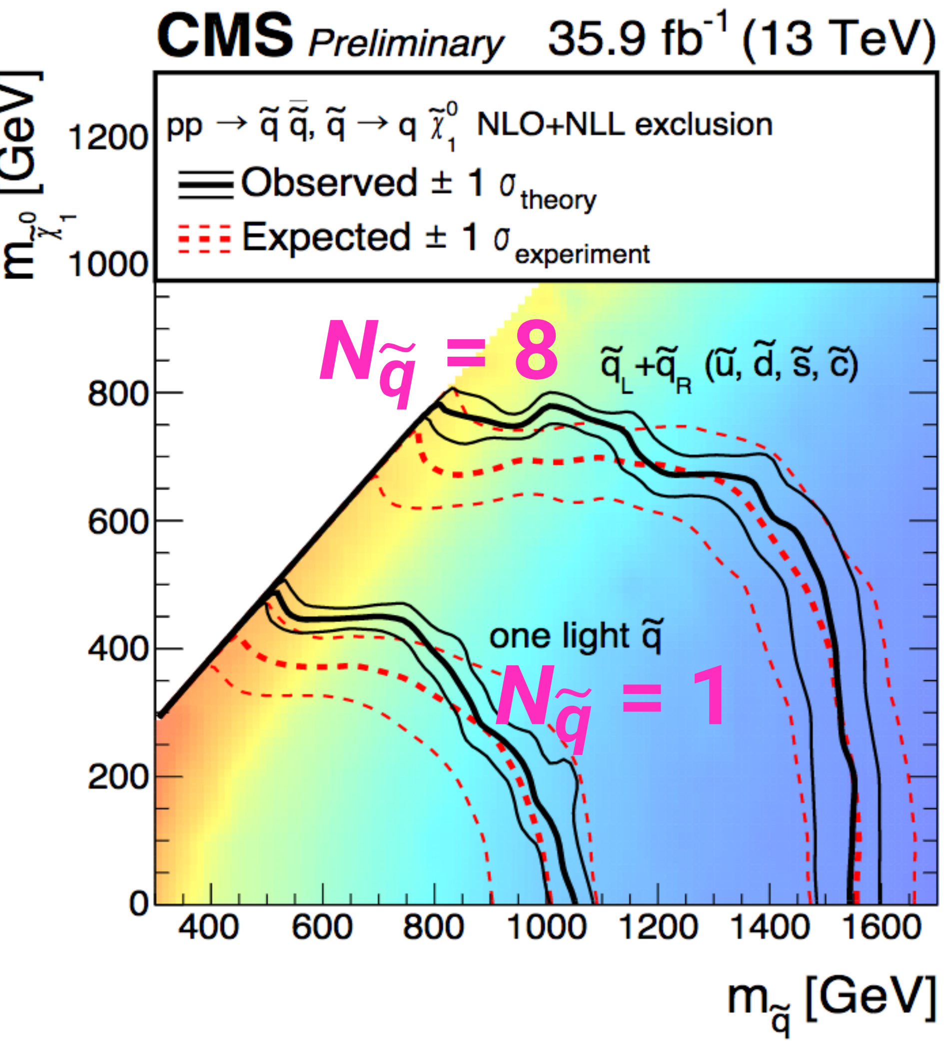


Moriond 2017 (squark)



Based on the same simplified model as ours, but

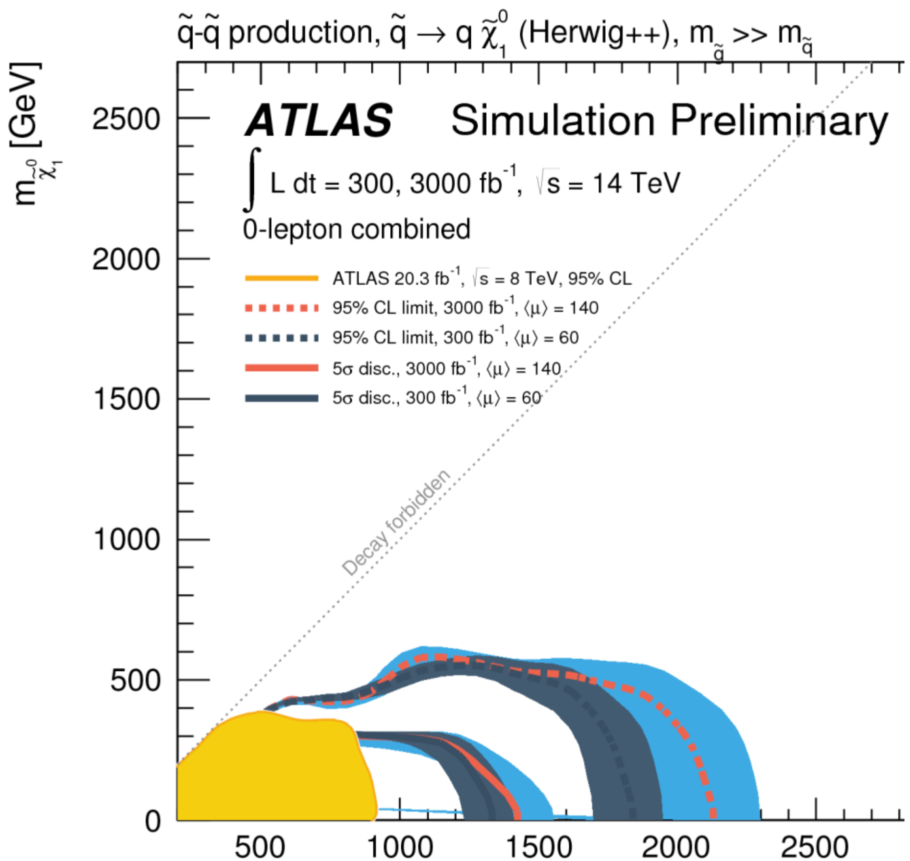
- $m_{\tilde{g}} = \infty$,
- $N_{\tilde{q}} = 1,\ 8$ (CMS), 8 (ATLAS).



$13\,\mathrm{TeV}, 35.9\,\mathrm{fb}^{-1}$:

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

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



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

14 TeV, 3000 fb^{-1} :

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

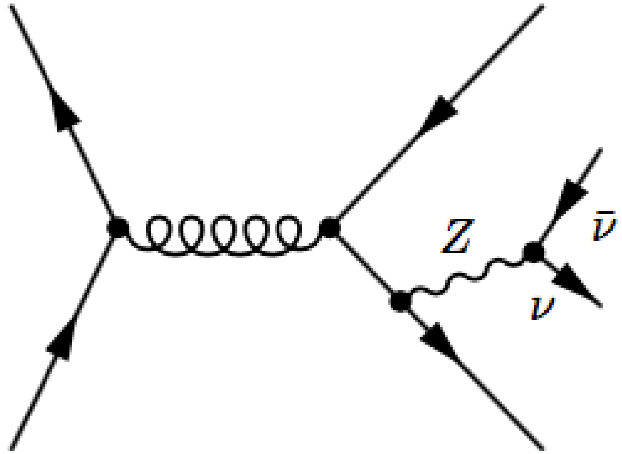
2σ excl. $m_{\tilde{q}} \lesssim 2.2$ TeV

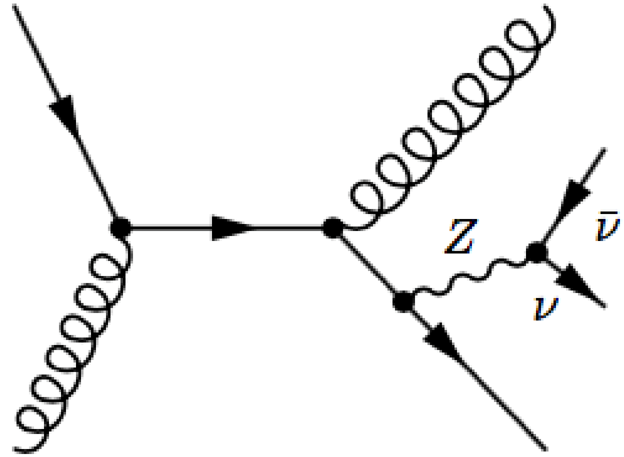
($N_{\tilde{q}} = 8$)

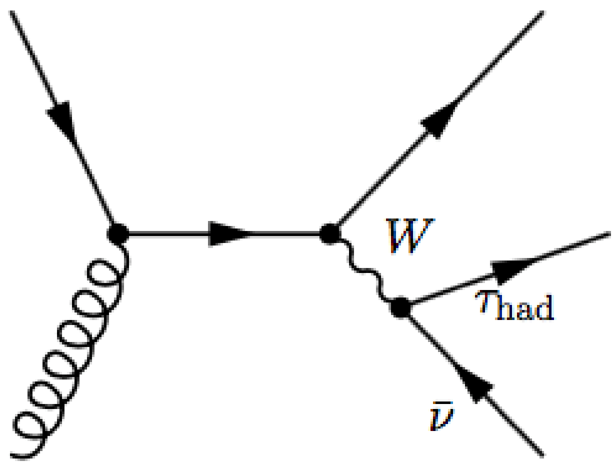
but they will do better....

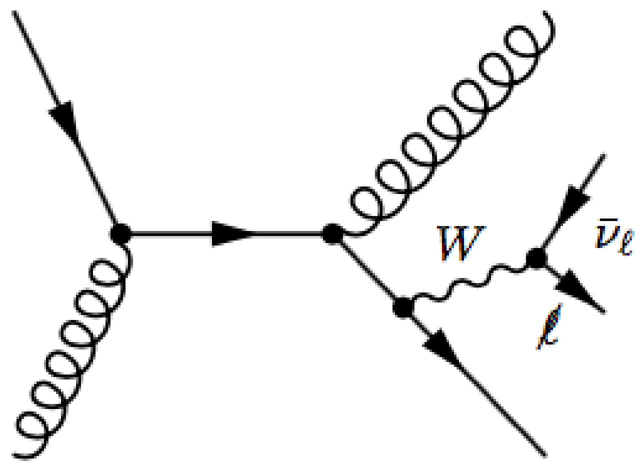
Details of simulation

Background simulation details









Signal samples are generated by MadGraph_aMC@NLO 5 [13] at LO, with the PDF set NNPDF2.3QED at LO with $\alpha_s = 0.13$ [14]. The baseline selections described in Table 3 are applied based on the missing transverse energy and jet p_T. Parton showering and hadronization are performed by Pythia 6.4 [15]. Tau decays are simulated by TAUOLA [16]. For detector simulation, Delphes 3.3.0 [17] is utilized with the default detector card, where the parameter of anti-k_T algorithm [18, 19] for jet clustering is replaced by $R = 0.4$ to match the ATLAS studies. Pile-up effects are not considered. These signal samples are rescaled by next-to-leading-order (NLO) K-factors, which are calculated by Prospino 2 [20][1]. We then apply the selection cuts for SR Meff-2j-2000 and, using the K-factors for 13 TeV collisions, and compare to the upper bound obtained by the ATLAS analysis [11] to determine whether the model point is excluded.

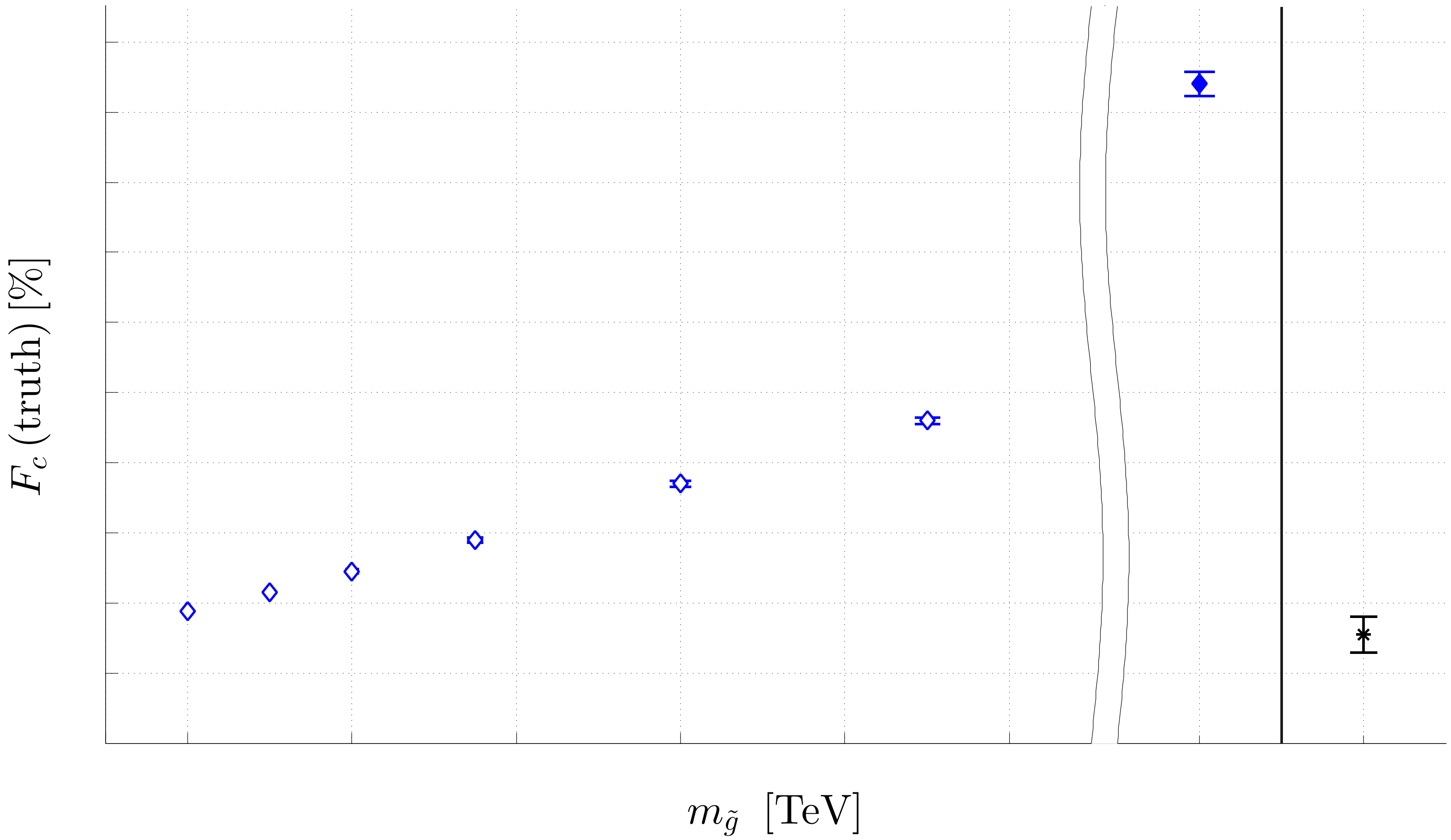
[1] Prospino does not handle non-degenerate squarks from the first two generations. However, the NLO correction is dominated by QCD contributions (light quarks and gluons) [21]. Therefore, additional heavy squarks only contribute at next-to-next-to-leading order and the Prospino K-factors are a good approximation even in this case. As previously mentioned, we only require mild hierarchies between the masses of the lightest and other squarks, so we will ignore leading-log corrections.

		Meff-2j-2000	Meff-2j-3100	
		Signals	$Z+$jets	Signals
$\lvert\not{p}_T\rvert$ [GeV]	$>$	—	150	—
Leading jet p_T [GeV]	$>$	150	500	150
Subleading jet p_T [GeV]	$>$	—	60	—

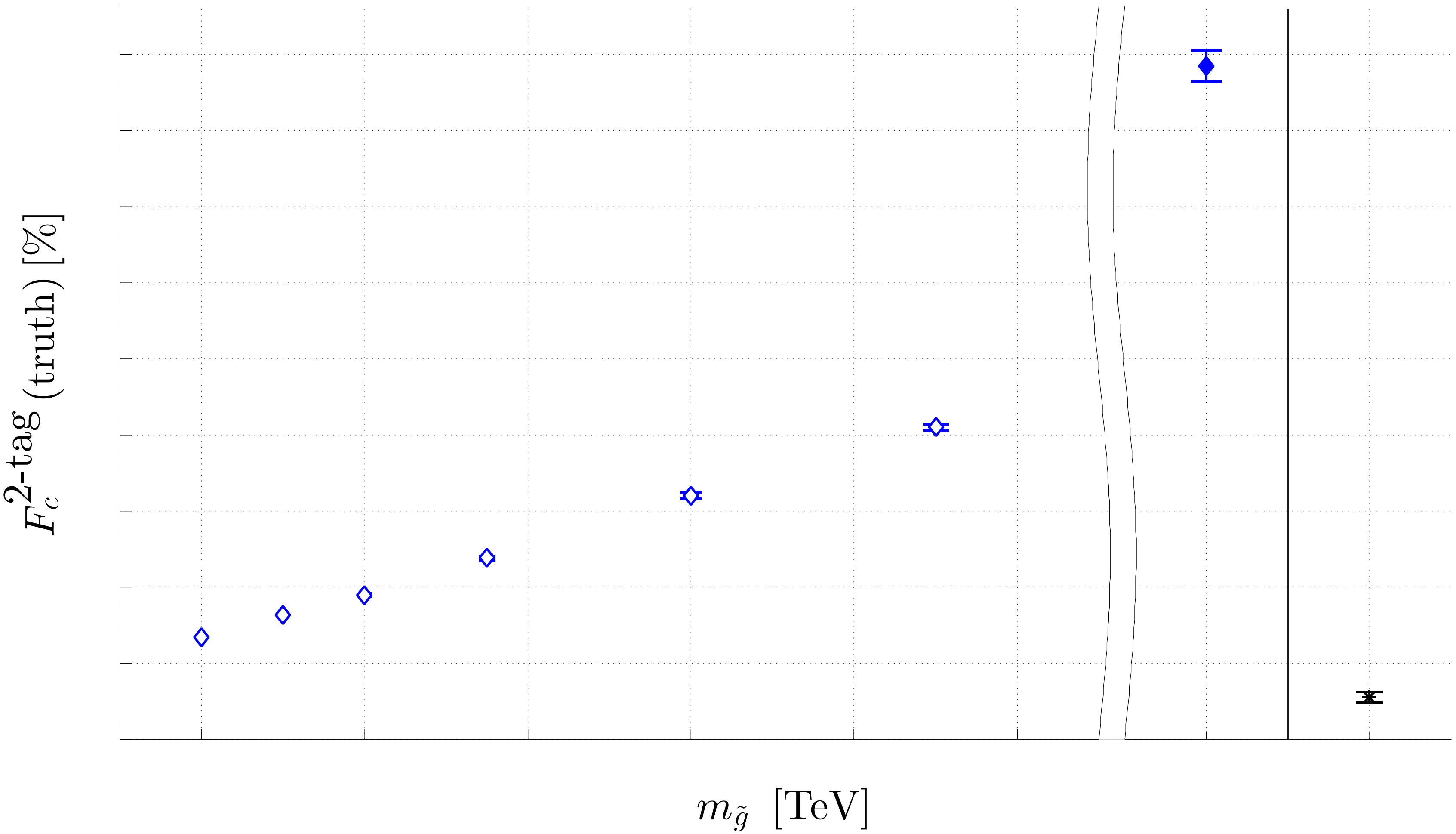
Table 2: Definitions of our signal regions. SR Meff-2j-2000 is from the ATLAS analysis based on $13.3\,\mathrm{fb}^{-1}$ data at the 13 TeV LHC [11], and Meff-2j-3100 is based on the HL-LHC study [10]. In Meff-2j-2000 (Meff-2j-3100), jets are required to satisfy $p_T > 50\,\mathrm{GeV}$ and $|\eta| < 2.8$ ($p_T > 20\,\mathrm{GeV}$ 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
$\|\eta(j_1, j_2)\|$	<	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

Event-based approach



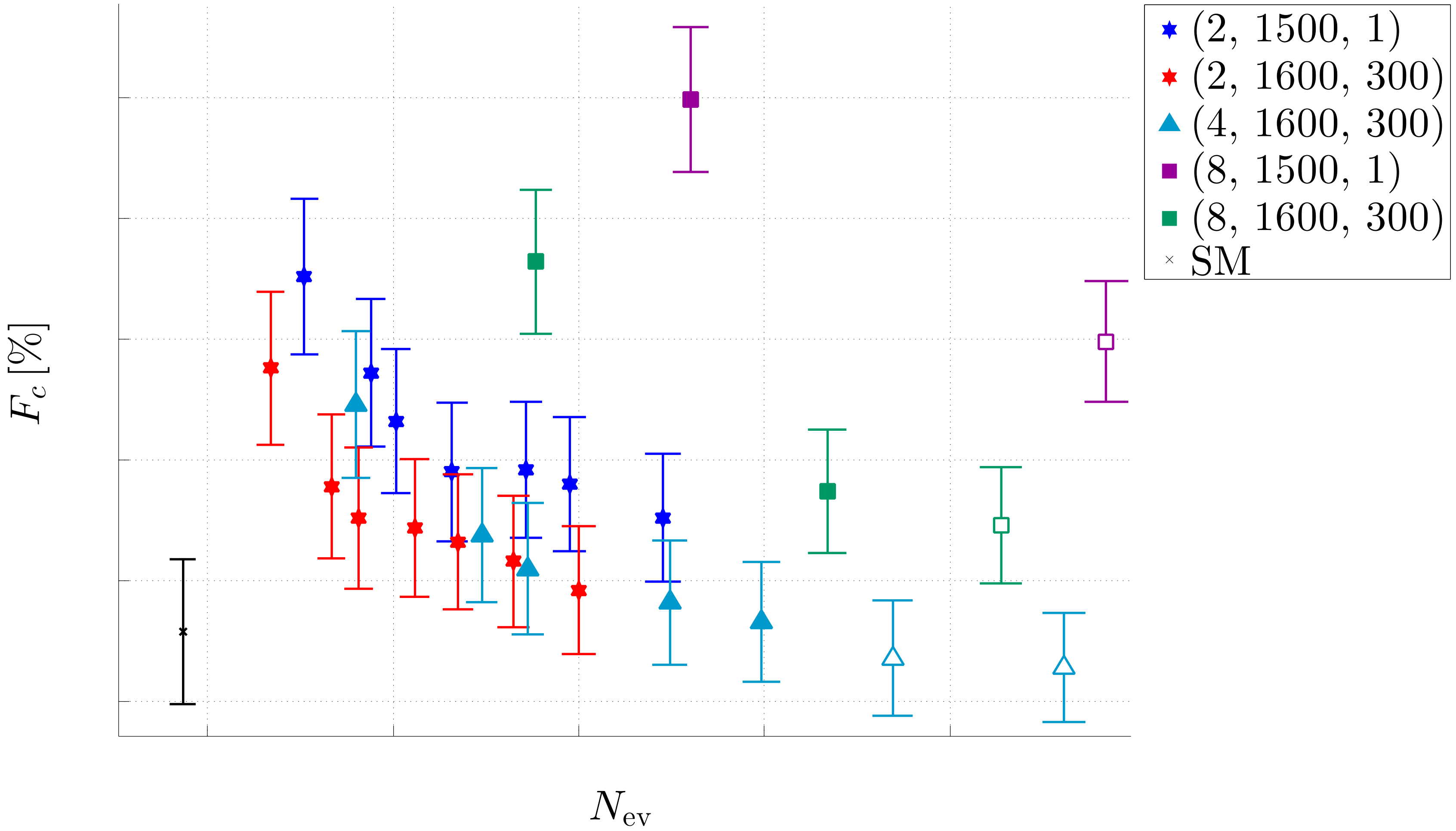
1.5TeV 8-squark; MC unc. only



1.5TeV 8-squark; MC unc. only

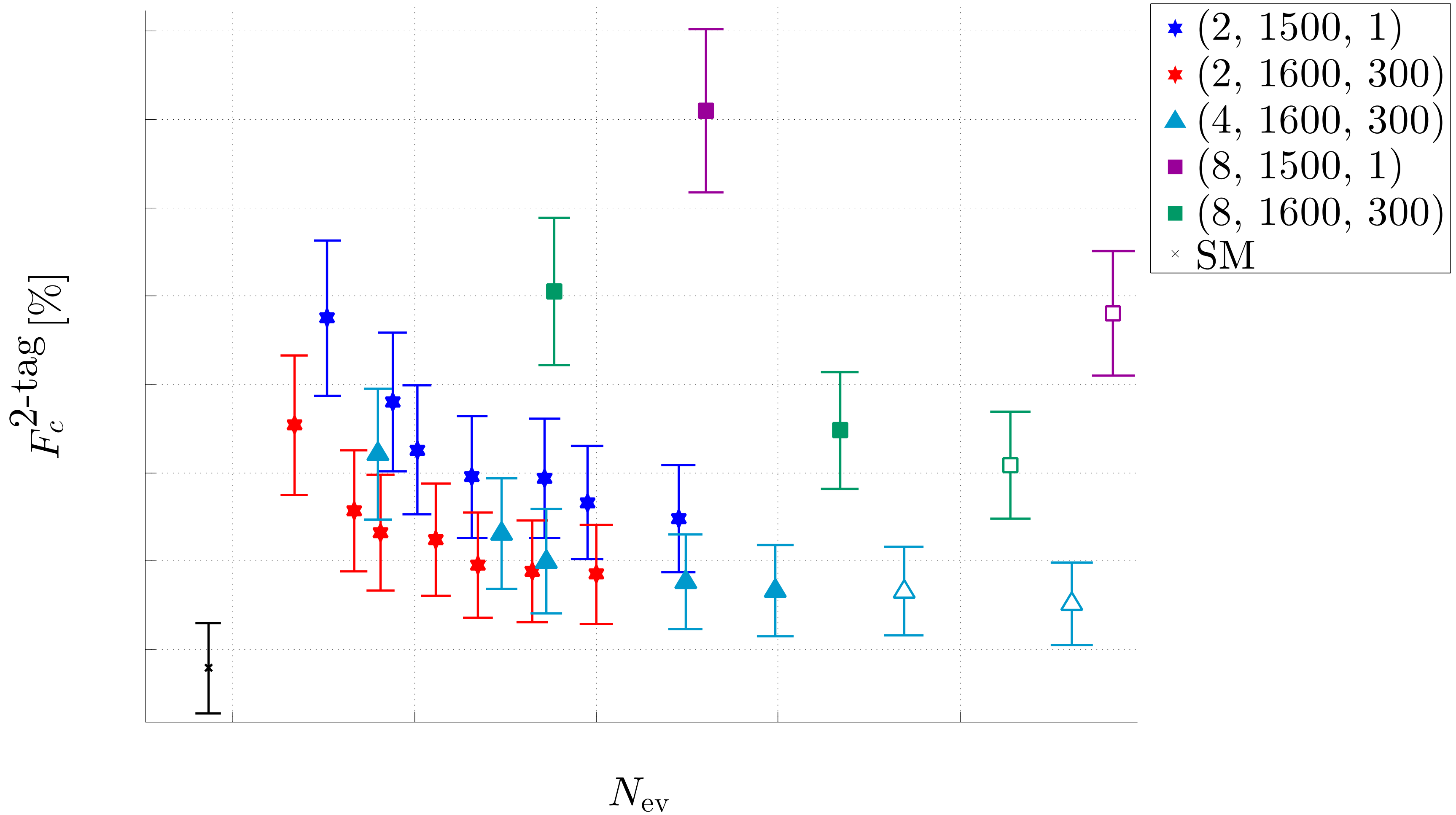
$F_c \equiv \frac{N_c}{2N_{\text{ev}}}$

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



(uncertainty: stat only, y-axis only)

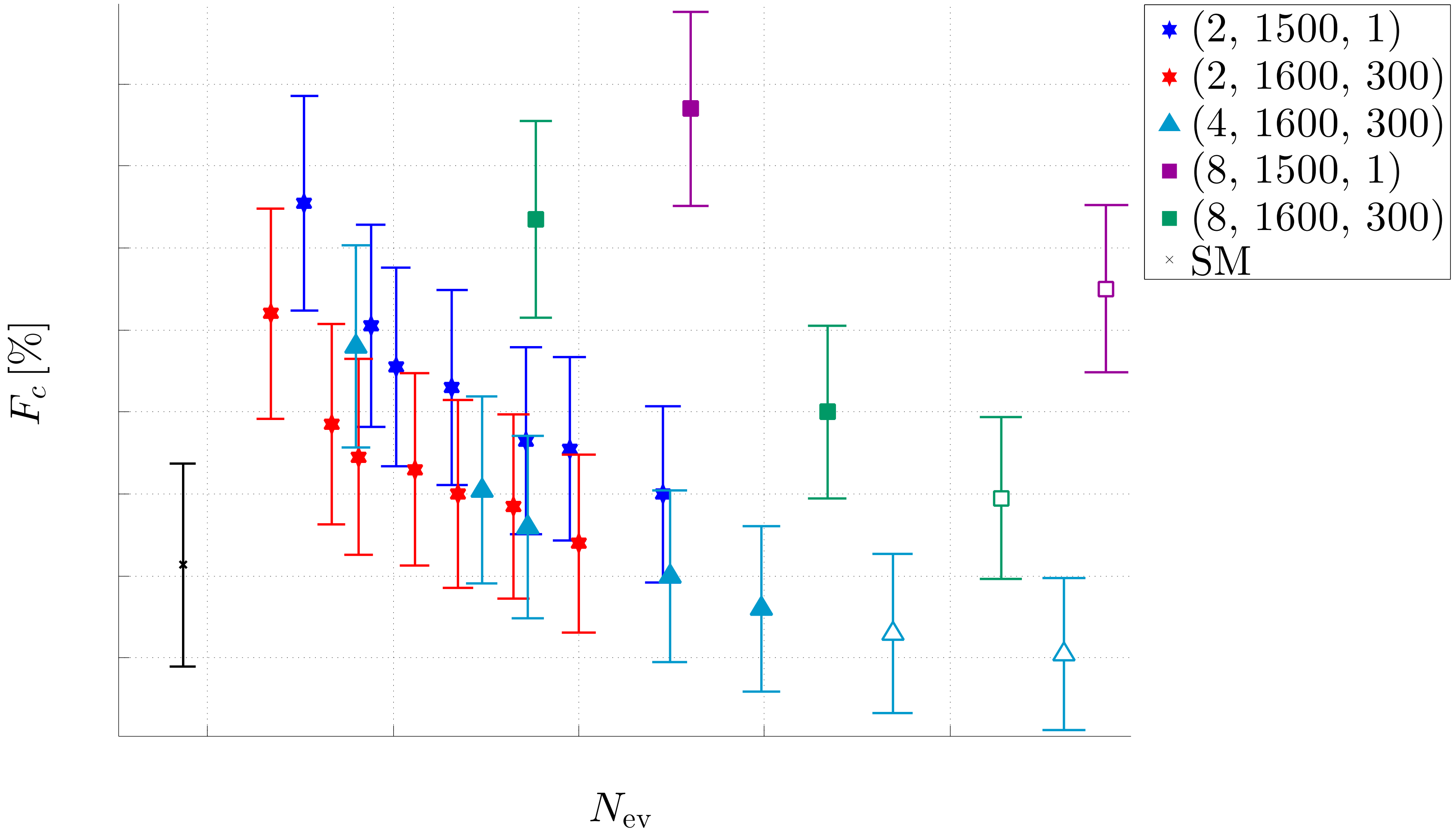
$$F_c^{\text{2-tag}} \equiv \frac{N^{\text{2-tag}}}{N_{\text{ev}}} \quad (\epsilon_c, \epsilon_b, \epsilon_l) = (50\%, 20\%, 0.5\%)$$



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

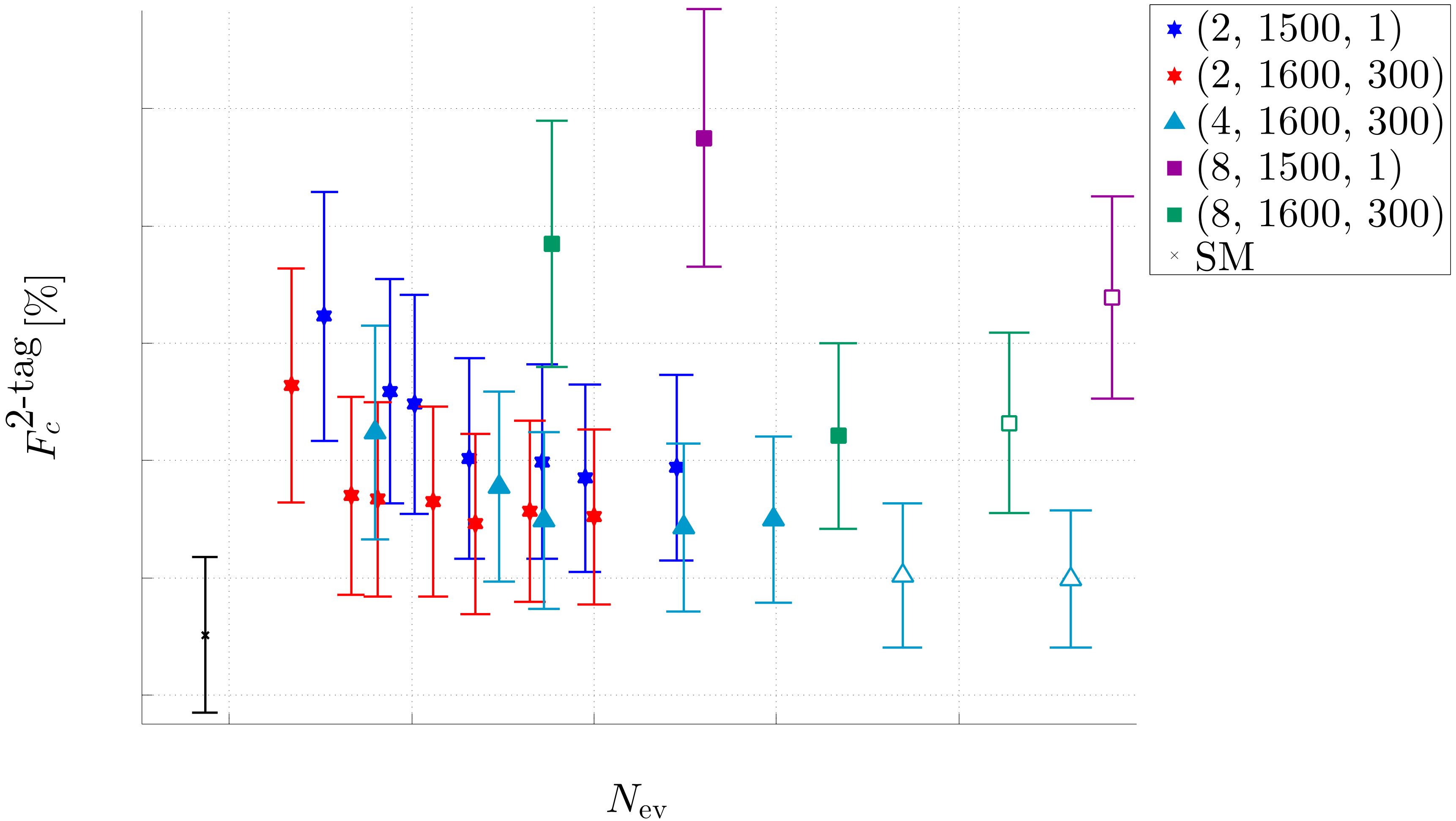
$$F_c \equiv \frac{N_c}{2N_{\rm ev}}$$

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



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

$$F_c^{2\text{-tag}} \equiv \frac{N^{2\text{-tag}}}{N_{\text{ev}}}$$ $(\epsilon_c, \epsilon_b, \epsilon_l) = (30\%, 20\%, 0.5\%)$



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