Boosting BSM Higgs discovery with jet substructure

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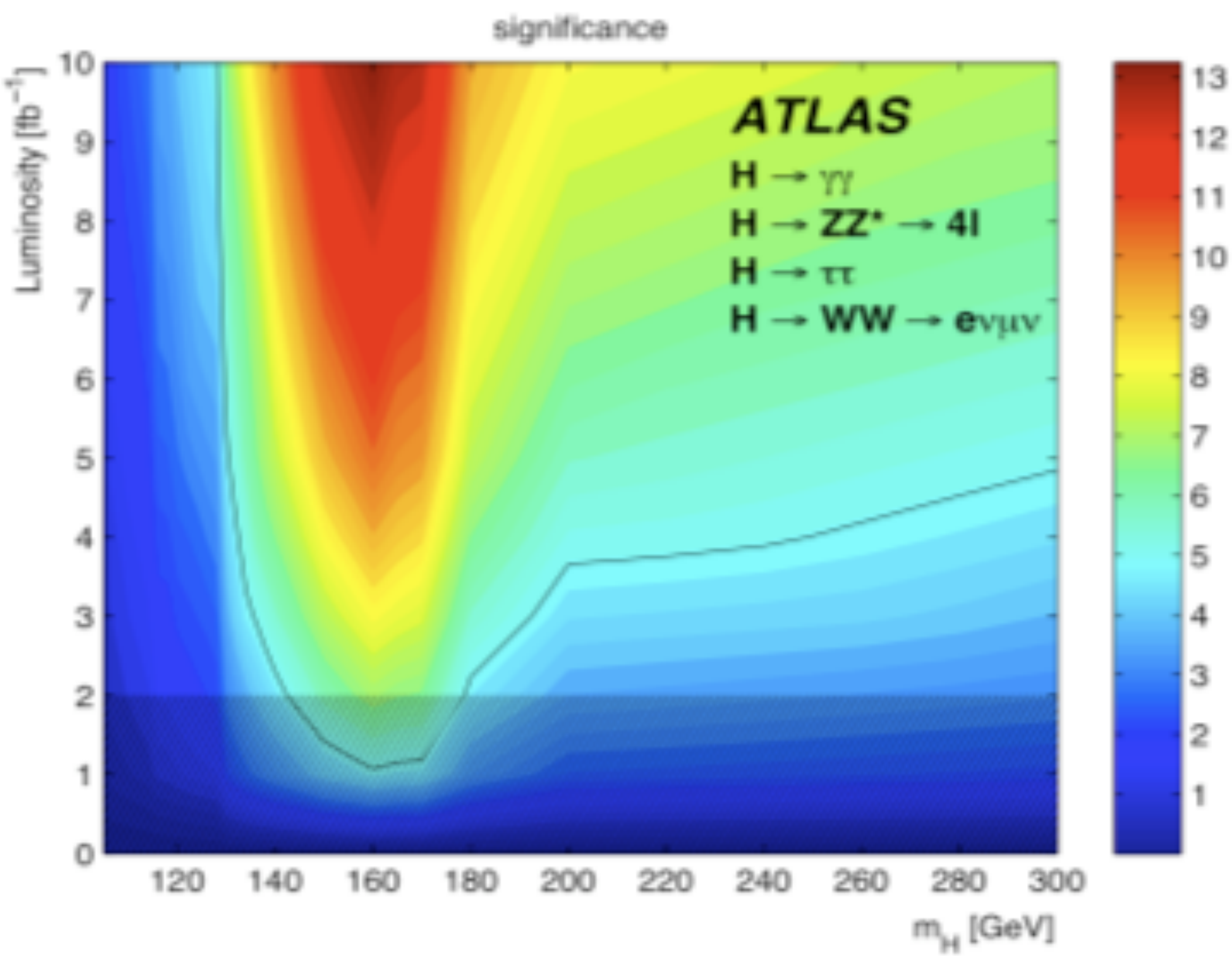
Fermilab

Despite large LHC cross sections...

a light Higgs $m_h \sim 115 - 130$ GeV, which decays primarily

$$h \to \bar{b}b \sim 80\%$$



will be difficult to find

most sensitive channel is

$$h \to \gamma\gamma + \text{jets}$$

$S/\sqrt{B} \sim 2.5$ for $\mathcal{L} = 10\ \text{fb}^{-1}$

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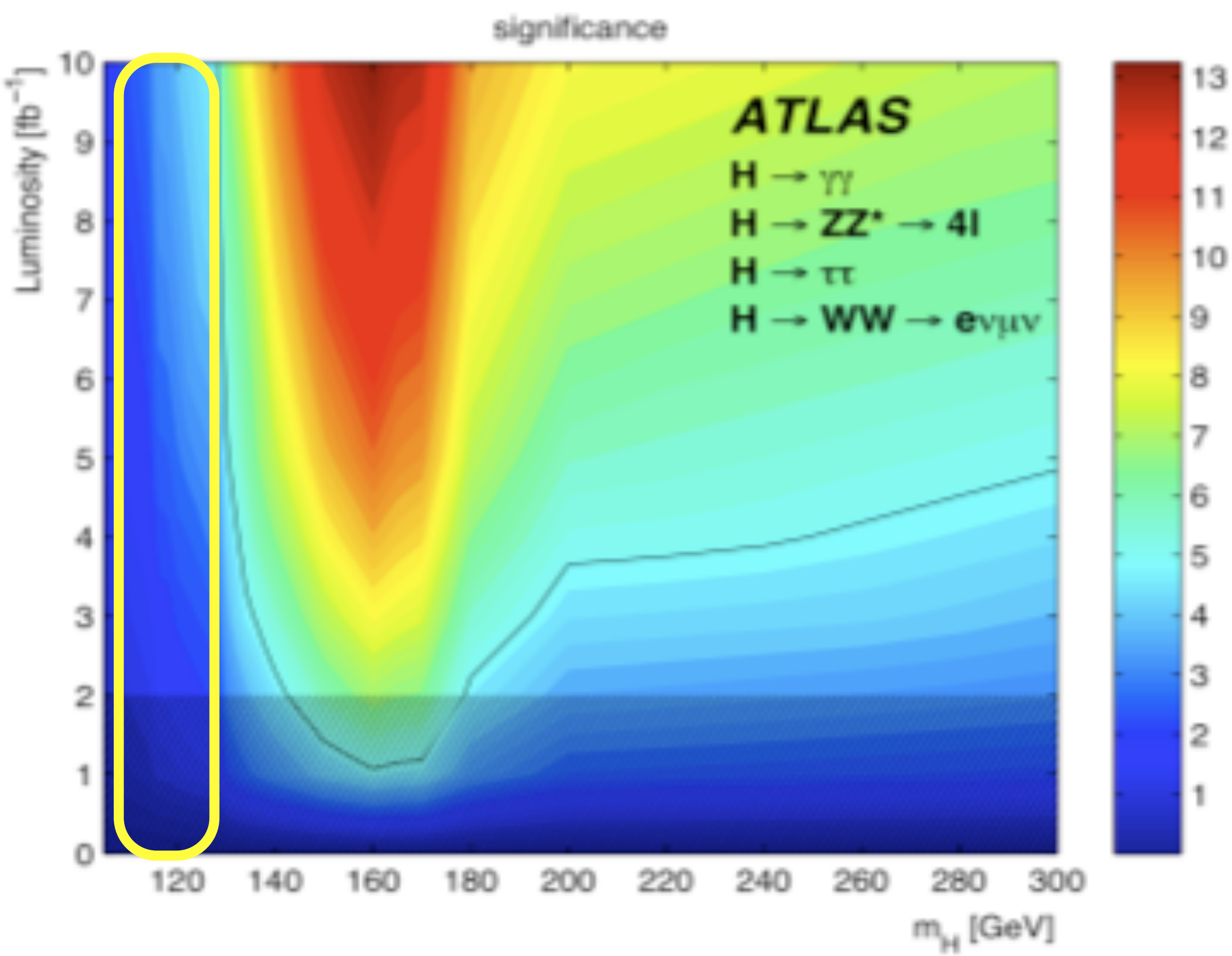

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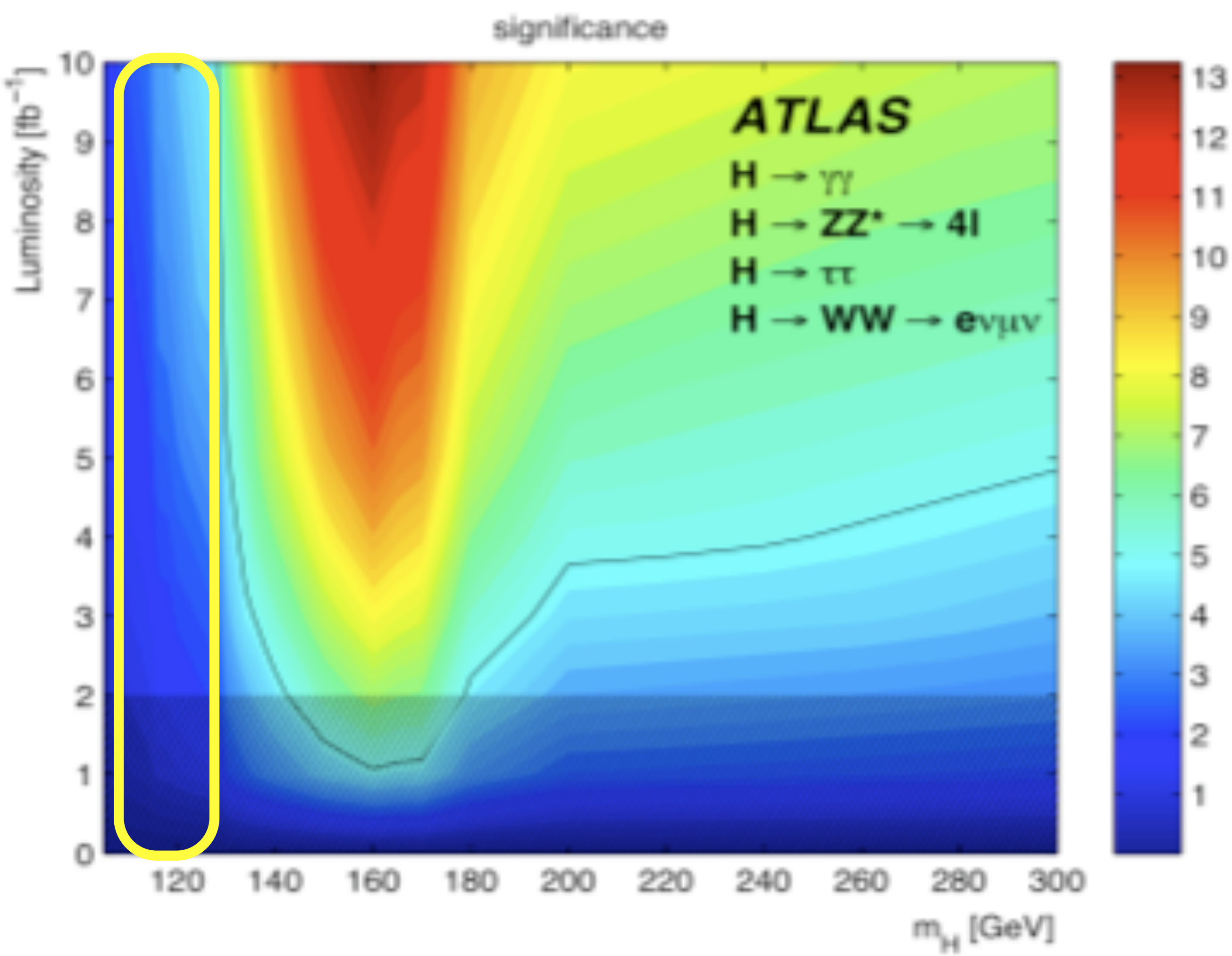

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$S/\sqrt{B} \sim 2.5$ for $\mathcal{L} = 10\ \text{fb}^{-1}$

$hW(\ell\nu)/hZ(\ell\ell, \nu\nu)$

$h \to \tau\tau$

also contribute,
but smaller

Recently, a new technique for light Higgses

(Butterworth, Davison, Rubin, Salam '08)

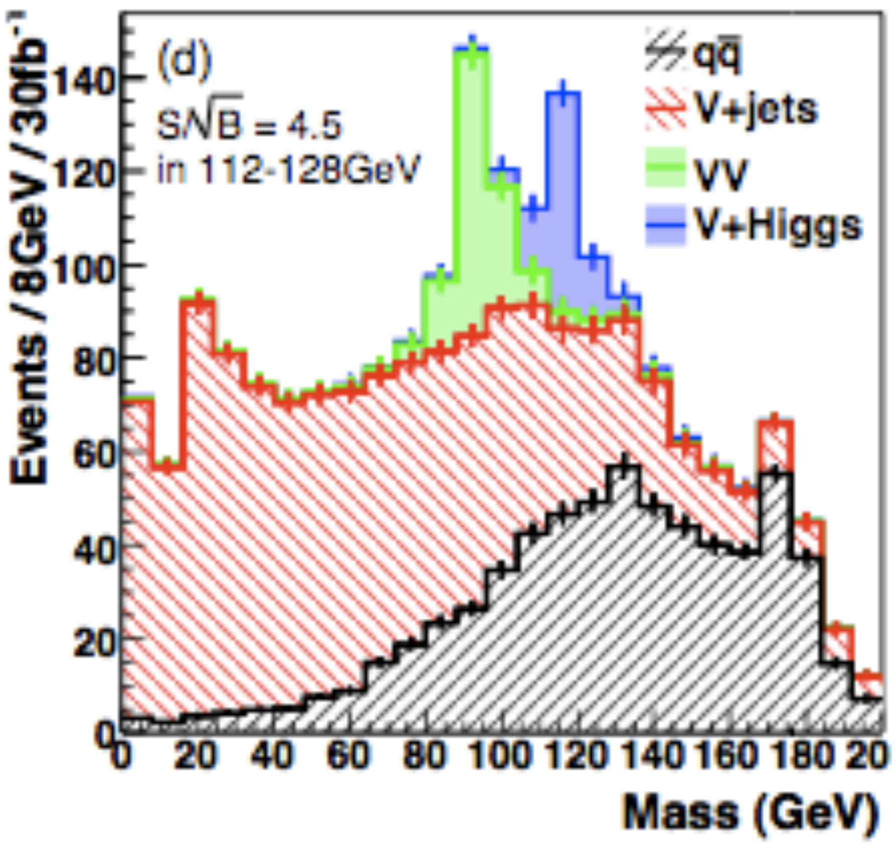
In associated production of Higgs + Z,W: $W(\ell\nu)/Z(\ell\ell) + h(\bar{b}b)$

significance ~ 4.5 for $\mathcal{L} = 30 \text{ fb}^{-1}$ $\left(\sim 2.6 \text{ for } \mathcal{L} = 10 \text{ fb}^{-1}\right)$

obtained by focusing on
boosted Higgses, $p_{T,h} > 200$ GeV

and looking for jet substructure

a boosted $h \to b\bar{b}$
appears in the detector
as a single 'fat' jet



(See Tilman's talk)

Boosted Higgses

interesting new approach

BUT a bit limited in SM

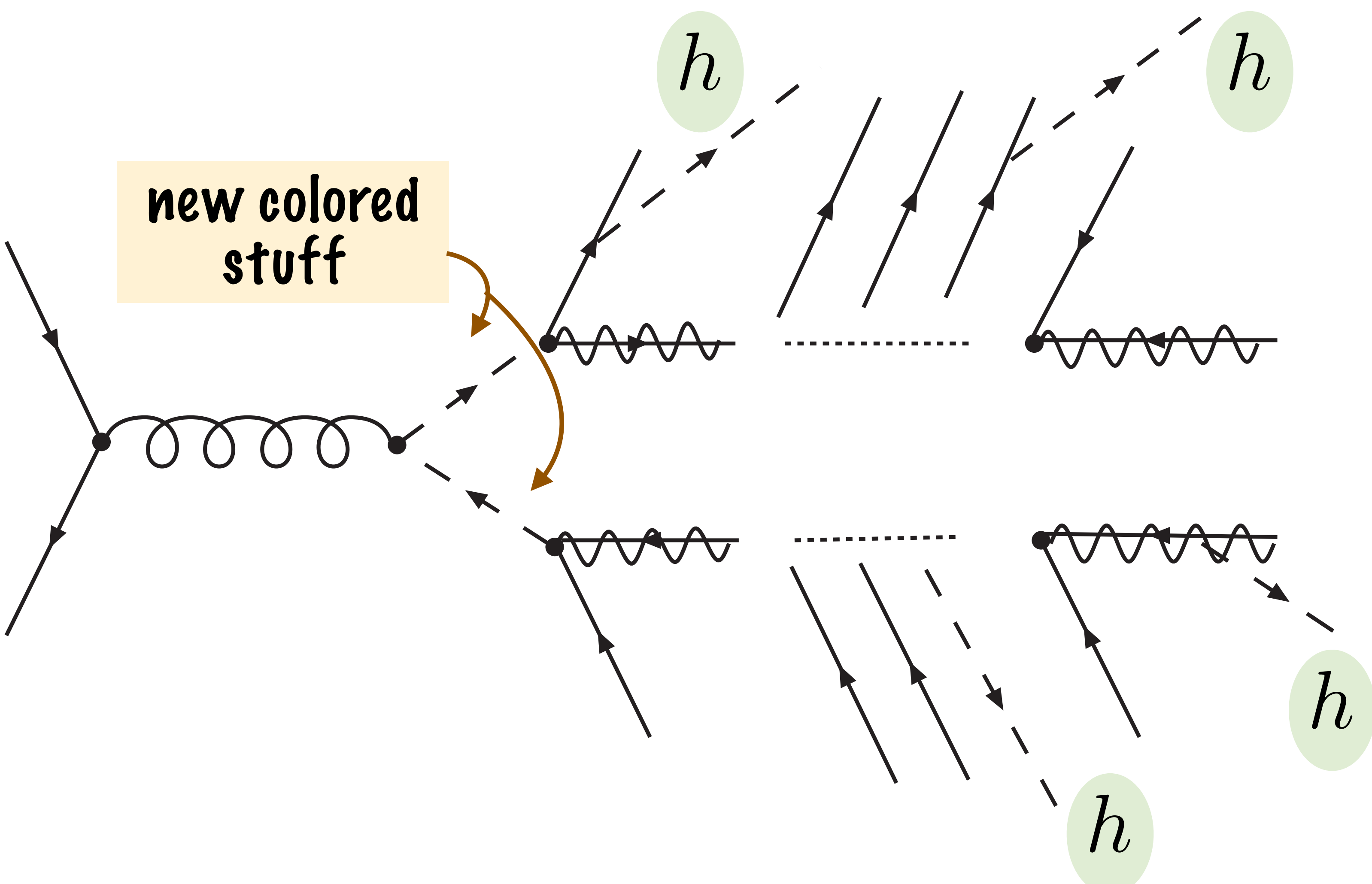
* boosted Higgs are rare in the SM: $\sim 5\%$ in $H + W/Z$

* need to trigger & suppress SM backgrounds: limited to W/Z leptonic decay modes

What about jet substructure analysis + BSM?

Higgs from BSM

BSM particles can decay to Higgses



= a new source of Higgses

initial (colored) states are **heavy** $(\sim \text{TeV})$

while Higgs can be light

higher fraction of boosted Higgses

Higgs from BSM

If BSM contains new colored states, production at LHC is easily in the $\sim$ few pb range

comparable to or greater than SM EW Higgs production

BSM production often comes with new, effective handles for suppressing SM backgrounds

$$\not{E}_T, \mathrm{high} - p_T \text{ jets}, \ell, \gamma, H_T, \cdots$$

Higgses from BSM have all of the important ingredients for a successful substructure analysis

the plan:

Jet Substructure Techniques + BSM = **an opportunity for light Higgs discovery**

1. Pick a new physics scenario with gives us a source of boosted Higgses

2. Use substructure techniques in these scenarios to combat backgrounds, both from the SM and from new physics

3. Adapt substructure to work in hectic, crowded BSM environments

example boosted Higgs source: SUSY

Though our techniques apply to a wide array of BSM scenarios, we'll look at SUSY

why SUSY?

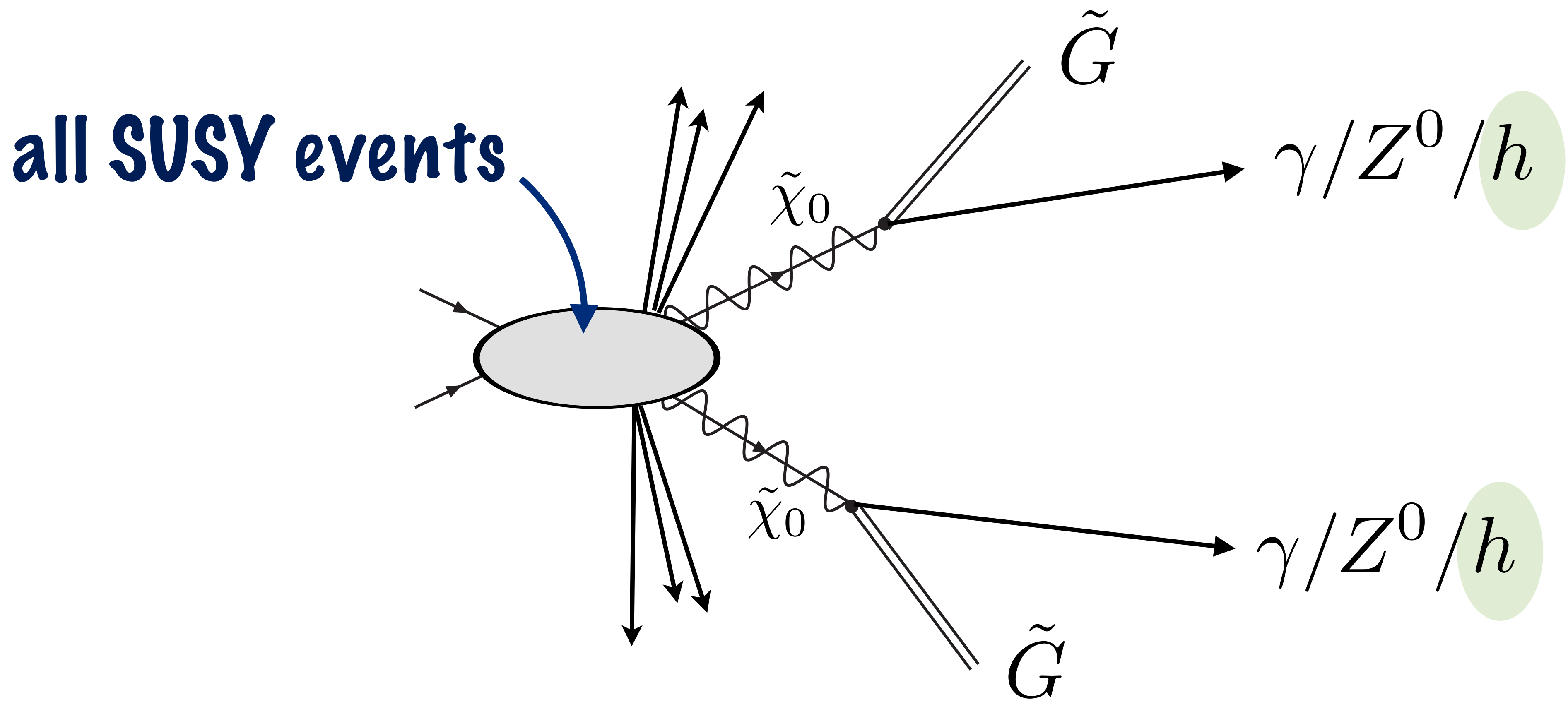
- MSSM Higgs has to be light $m_h \lesssim 130\ \mathrm{GeV}$, decays dominantly to $b\bar{b}$
- it has new colored particles (squarks, gluinos), which can be produced with large cross sections
- all events include $\not{E}_T$
- Higgs via various decays:

$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + h \qquad \tilde{t}_{L,R} \to \tilde{t}_{R,L} + h$$

$$\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm + h \qquad \tilde{\chi}_1^0 \to \tilde{G} + h$$

Neutralino Decays to Gravitinos

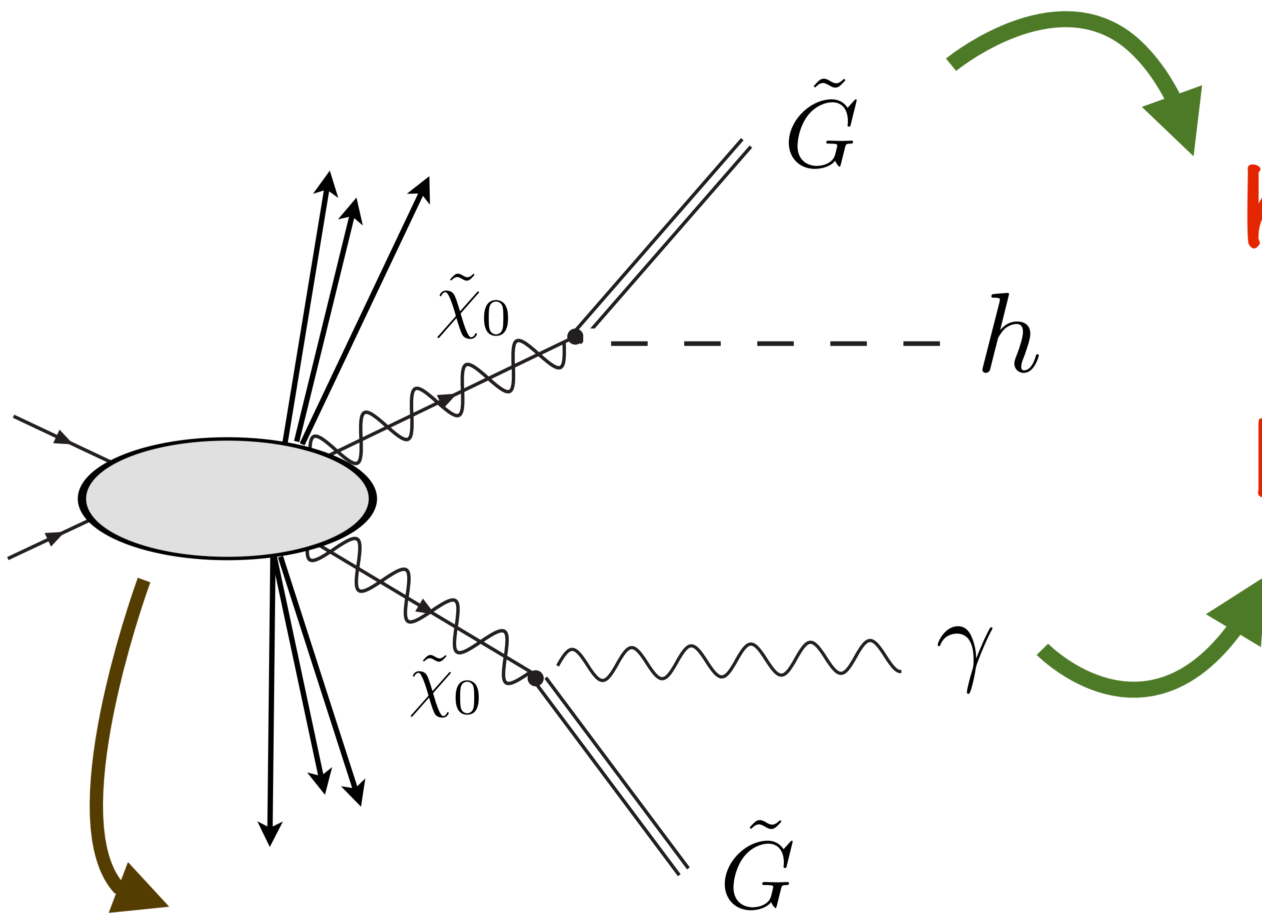
- happens when the scale of SUSY breaking is low (GMSB)
- decays of neutralinos governed by $M_1, M_2, \mu, \tan\beta$
- can get appreciable BR to Higgses when the lightest neutralino is primarily Higgsino $|\mu| \ll M_1, M_2$ (Matchev, Thomas '99 Meade, Reece, Shih '09)



this will be our test source of Higgses

Why start with $\tilde{\chi}_1^0 \rightarrow \tilde{G} + h$?

- The mixed decay $\tilde{\chi}^0\tilde{\chi}^0 \rightarrow h + \gamma + \not{E}_T$ has a smaller rate, but many advantages



hard, isolated photon plus large $\not{E}_T$ kills off much of the SM background

heavier, colored sparticles control LHC production

- simplest BSM scenario we could think of to test jet substructure techniques on

Remember

* We focus on the subset of new physics events with boosted characteristics

specifically, demand one or more 'fat' jets: $p_{T,j} > 200\ \text{GeV}$

this limits the kinematic regime, costing us events, but we greatly reduce BSM combinatorial background

* Our goal is to discover the Higgs, not the new physics!

* also, going to high-p_T ⟶ better detector resolution:

ex., for jets: $$\left(\frac{\delta E}{E}\right)_{\text{jets}} \cong \frac{0.6}{\sqrt{E/\text{GeV}}} + 0.03$$ (ATLAS TDR, cone jets.)

so boosted analysis are also cleaner

Jet Substructure + BSM: Follow Butterworth et al

0802.2470

1. cluster particles into jets, $R = 1.2$

2. for each fat jet, undo clustering step by step, looking for mass drop and even splitting of energy between daughter jets

..if conditions met, stop undoing jets, record ΔR_{sub}

3. Resolve the fat jet into subjets at the scale $\cong \Delta R_{subs}/2$
subjets contain perturbative, angle-ordered radiation

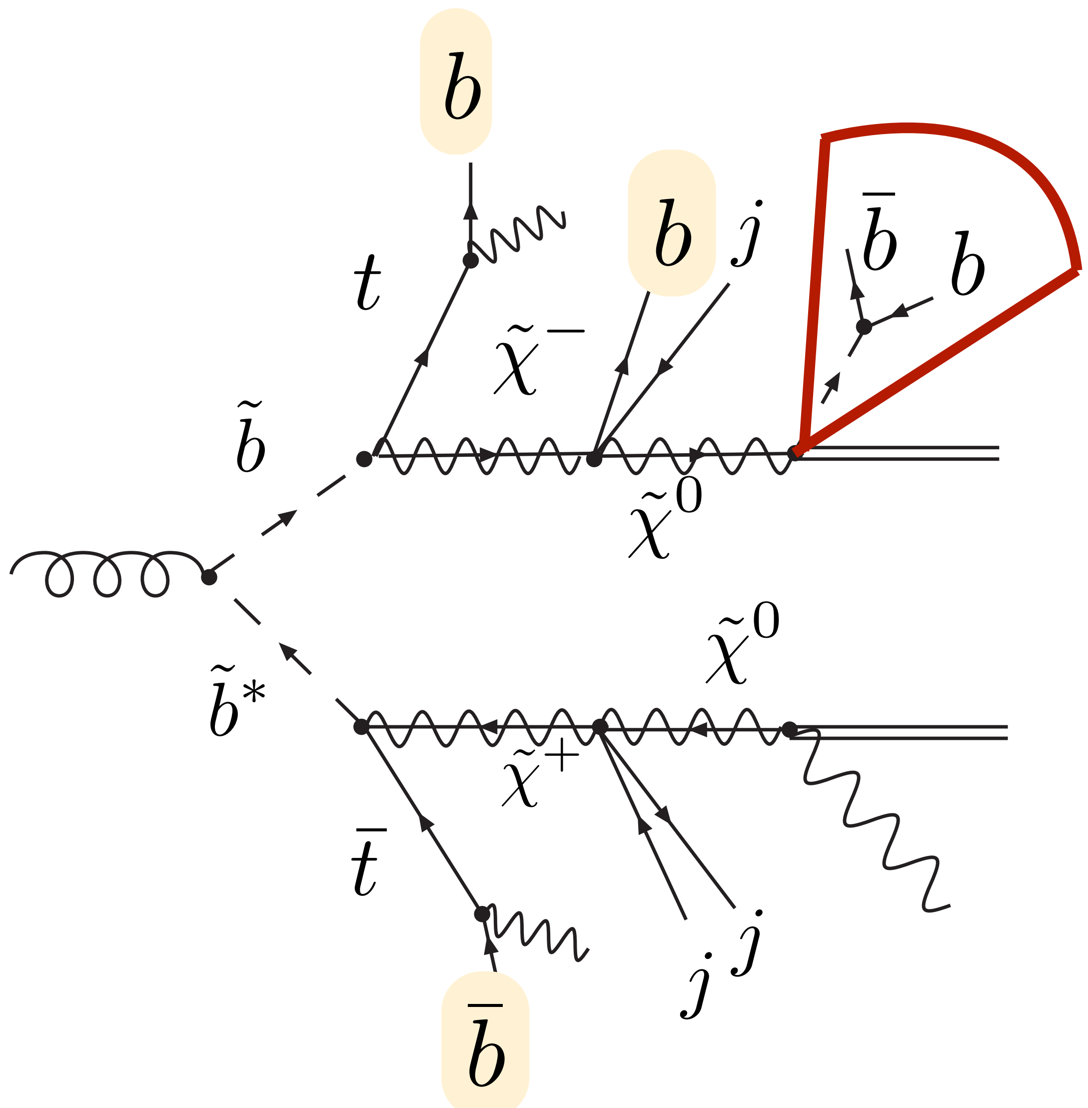
4. if two of the three hardest subjets are tagged as b-jets

→ candidate Higgs jet ←

Improved jet substructure

The large number of b quarks, especially when 3rd generation squarks are important in SUSY production, becomes a problem (similar to tth in SM)

(Plehn, Salam, Spannowsky '09)



extra b's can end up in the 'higgs jet' disrupting the substructure algorithm

identifying a pair of heavy particles is no longer enough

Improved jet substructure

- add another handle: p_T similarity

rather than stop at a mass drop, calculate

$$S_i = \frac{\min(p^2_{T_{j_1}}, p^2_{T_{j_2}})}{(p_{T_{j1}} + p_{T_{j_2}})^2} \Delta R_{j_1 j_2}$$

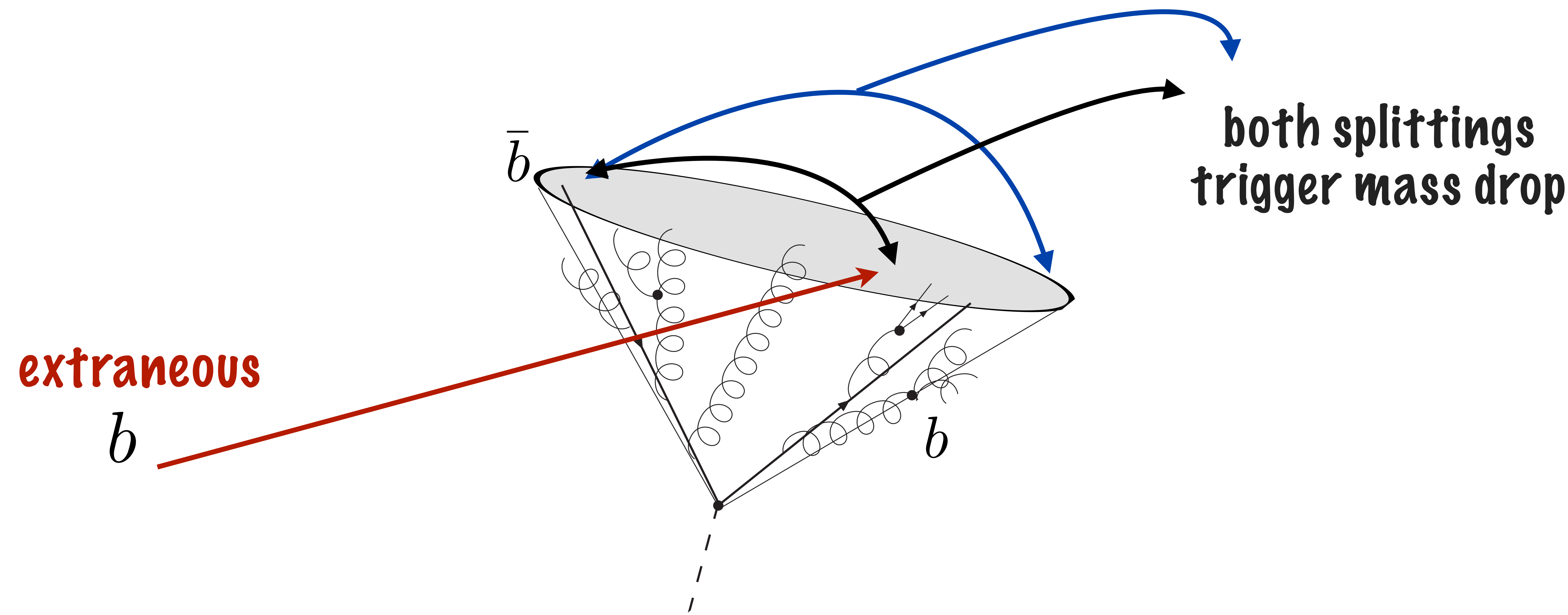
and continue undoing the original jet

at each subsequent mass drop, record S_i

(Kribs, AM, Roy, Spannowsky)

Improved jet substructure

- Identify the splitting with maximum S_i and two daughter b-jets as the Higgs candidate



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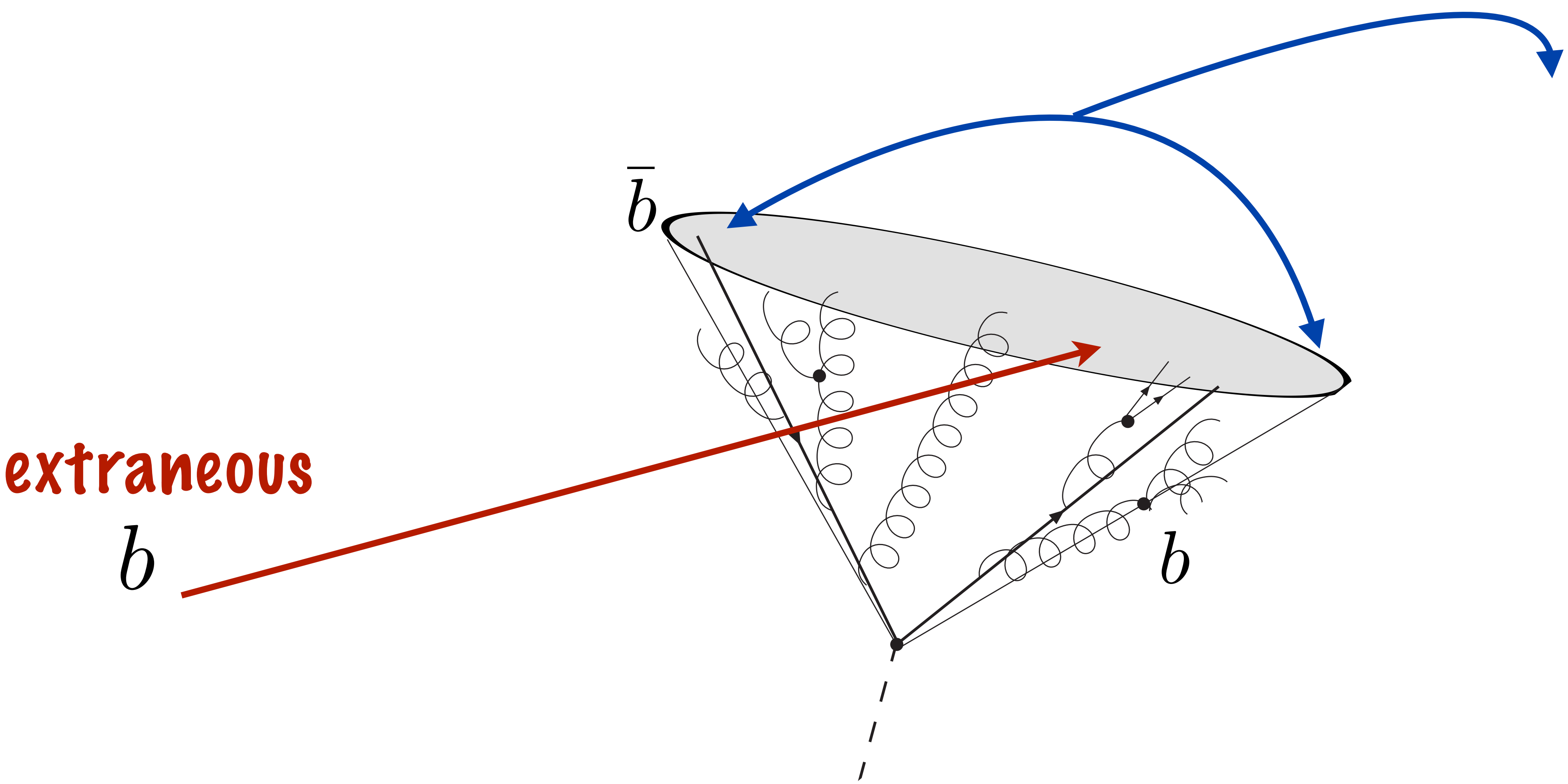

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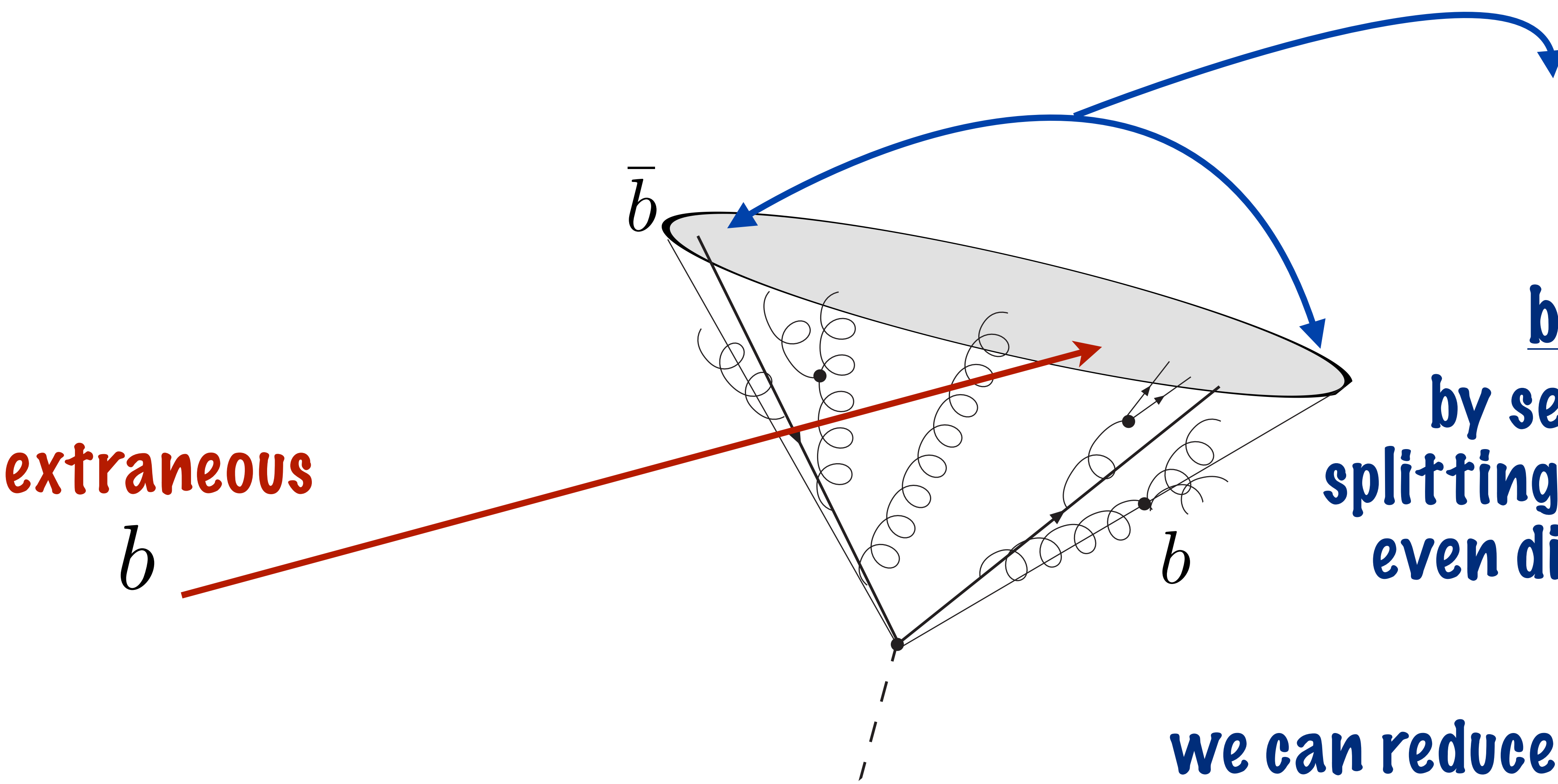


but

by selecting the splitting with the more even distribution of subjet p_T

we can reduce contamination

Improved Jet Substructure + BSM:

1. cluster particles into jets, $R = 1.2$

2. for each fat jet, undo clustering step by step, looking for mass drop and even splitting of energy between daughters.

   If conditions met, record $\Delta R_{sub,i}$ and S_i. Keep unclustering until no more parent jets

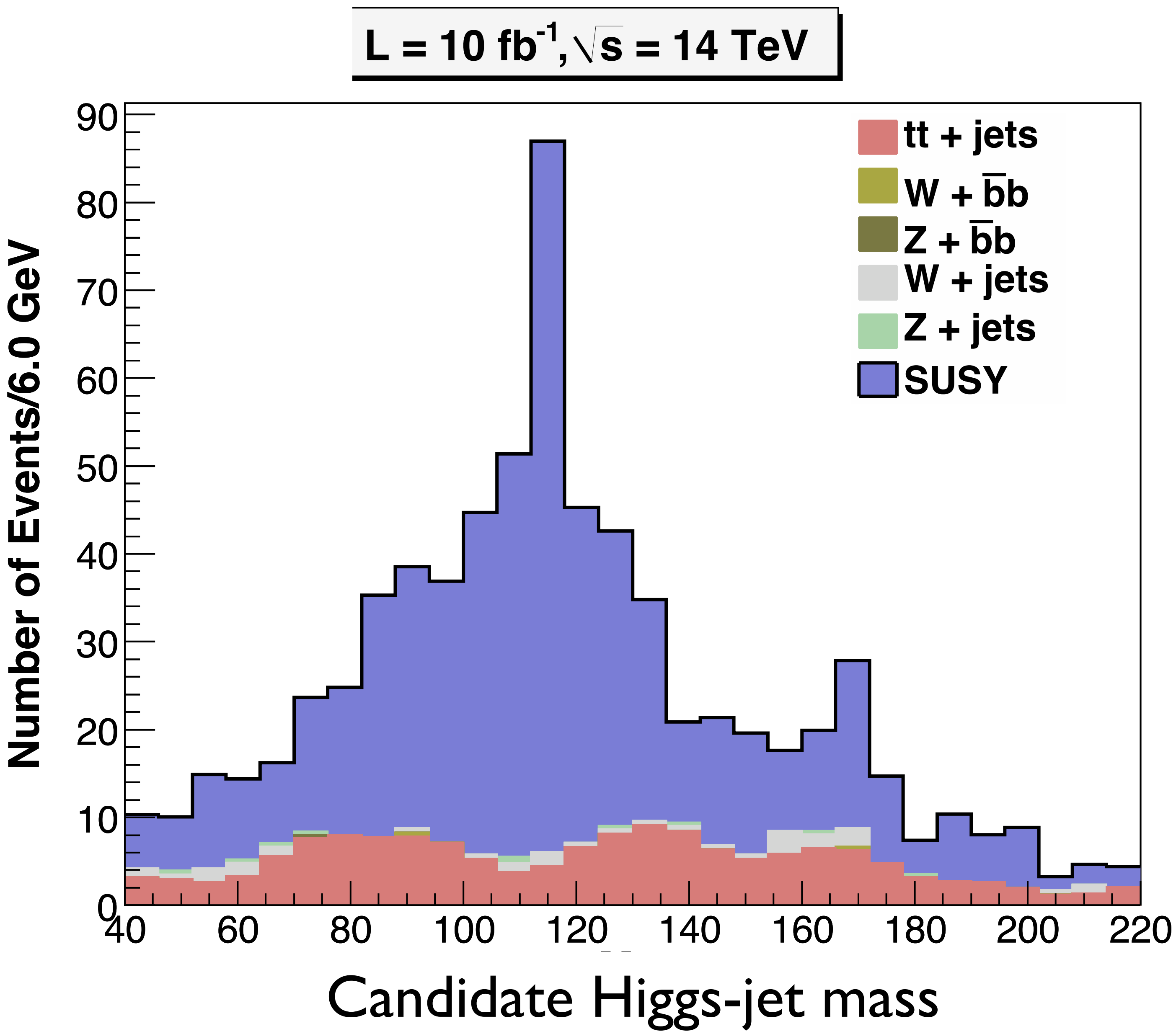
3. Determine which splitting n has most even p_T splitting

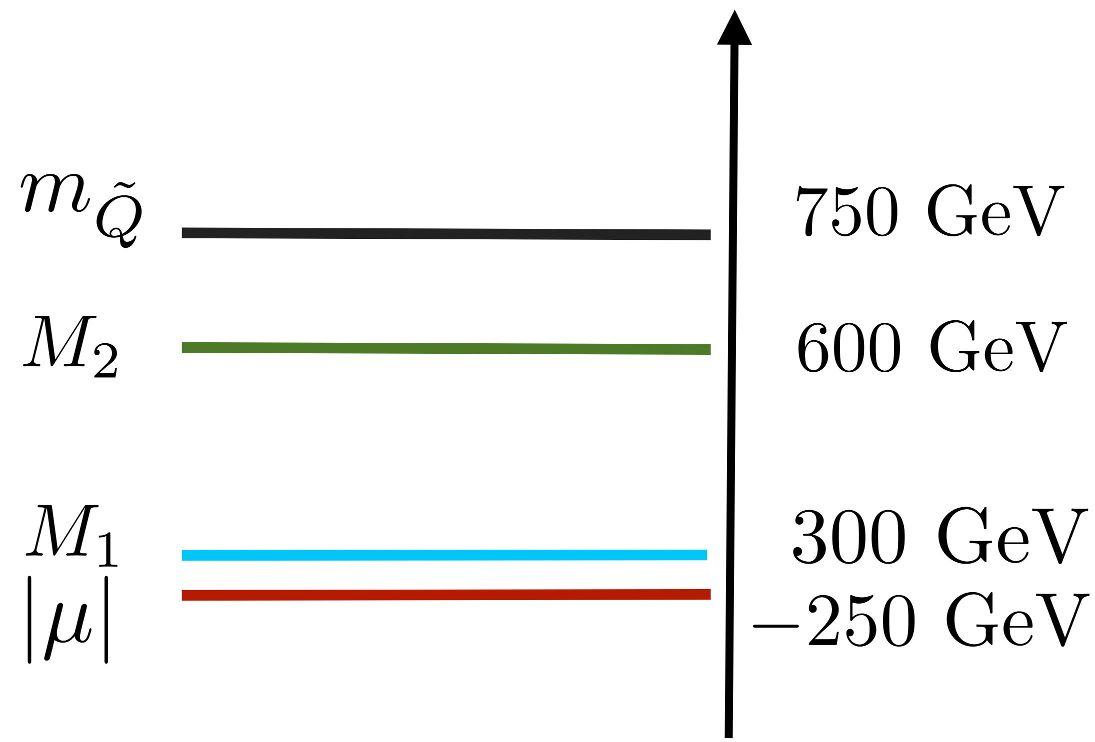
4. Resolve the fat jet into subjets at the scale $\cong \Delta R_{sub,n}/2$

5. if two of the three hardest subjets are tagged as b-jets

→ candidate Higgs jet ←

Results: Point #1





$BR(\tilde{\chi}^0 \to \tilde{G} + \gamma)$	$\sim$	43%
$BR(\tilde{\chi}^0 \to \tilde{G} + Z^0)$	$\sim$	29%
$BR(\tilde{\chi}^0 \to \tilde{G} + h)$	$\sim$	28%

light squarks dominate SUSY production

cuts:

substructure + $\not{E}_T > 100$ GeV, $p_{T\gamma} > 80$ GeV

boosted fraction $\sim 38\%$

Results: Details

Background: ALPGEN ⟶ PYTHIA6.4

Signal: SUSPECT2 ⟶ PYTHIA6.4

underlying event: ATLAS tune

- All final-state hadrons grouped into cells of size $(\Delta\eta \times \Delta\phi) = (0.1 \times 0.1)$
- Each cell is rescaled to be massless

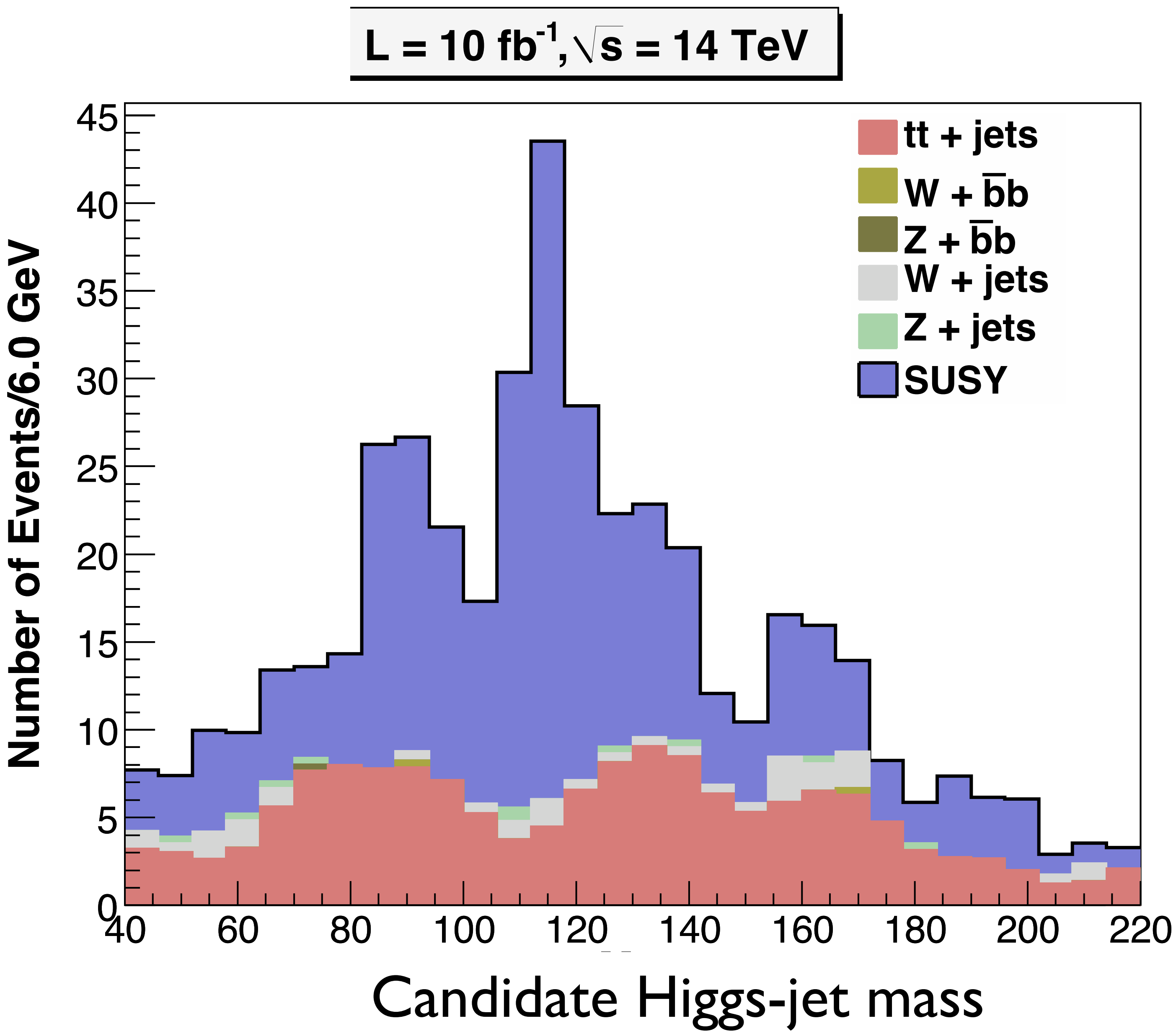
this models detector response (Thaler, Wang '08)

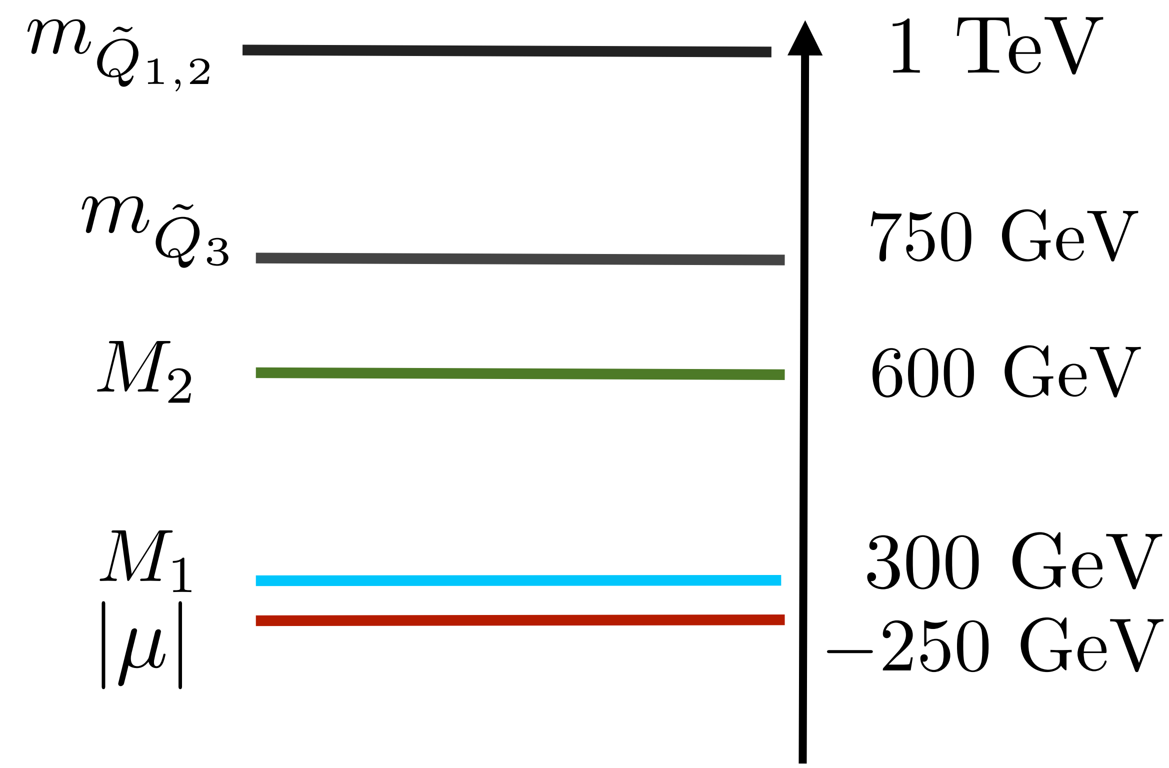
jet gymnastics performed using FastJet

b-tagging: 60% efficiency, 2% fake rate

jet-photon fake rate: $.1\%$

Results: Point #2





same ino spectrum as previous, but light squarks now 1 TeV

3rd generation squarks and gluinos play a bigger role in SUSY production, more b/t quarks in the events

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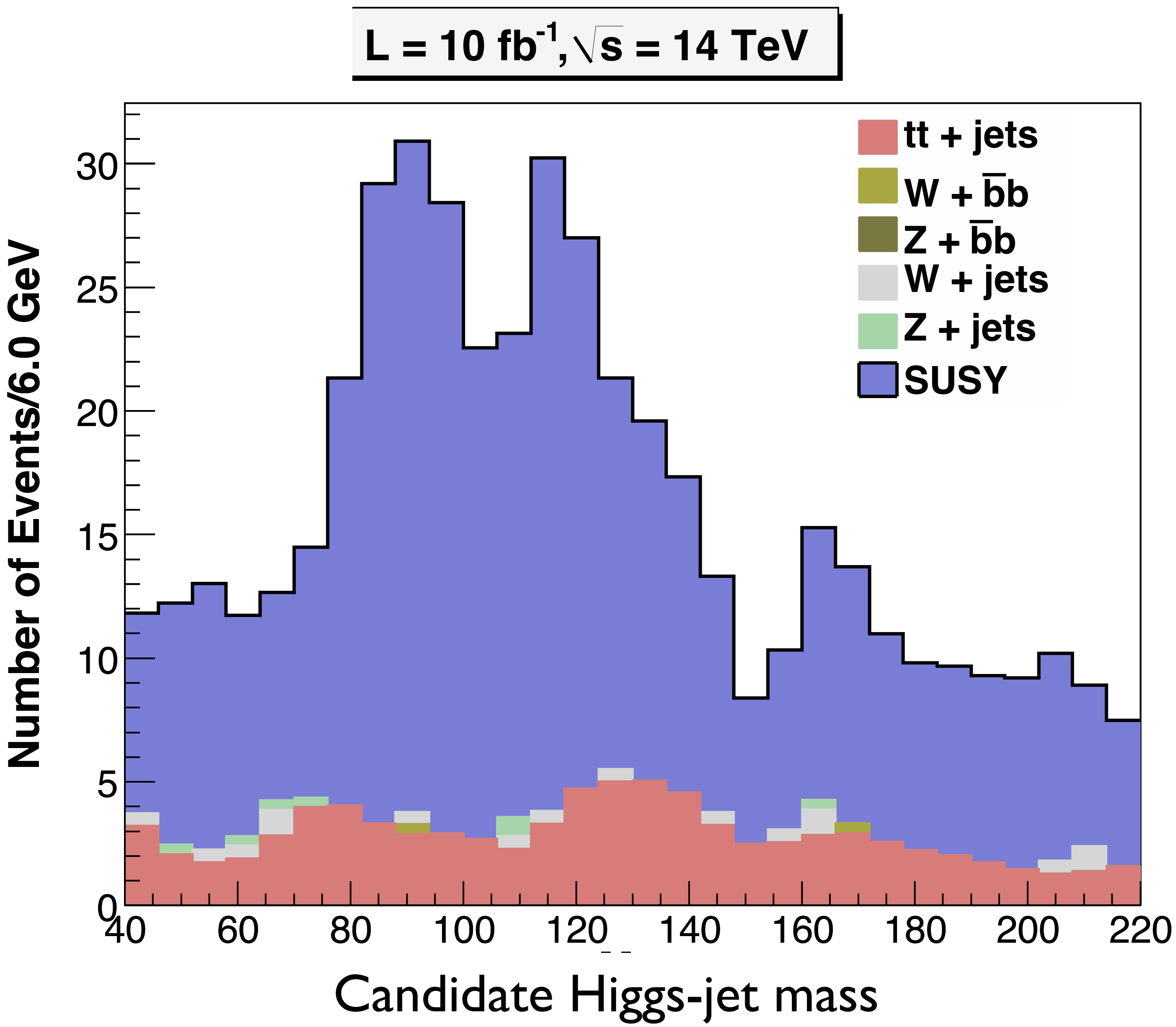
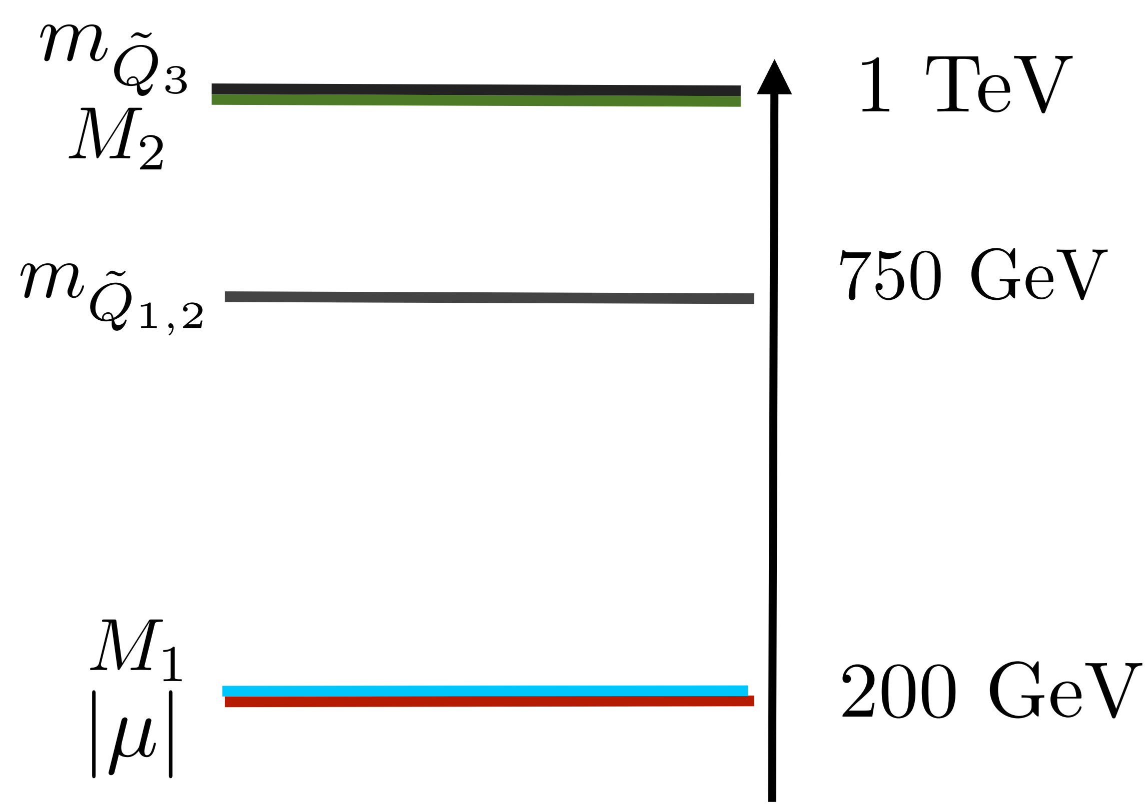
Results: Point #3



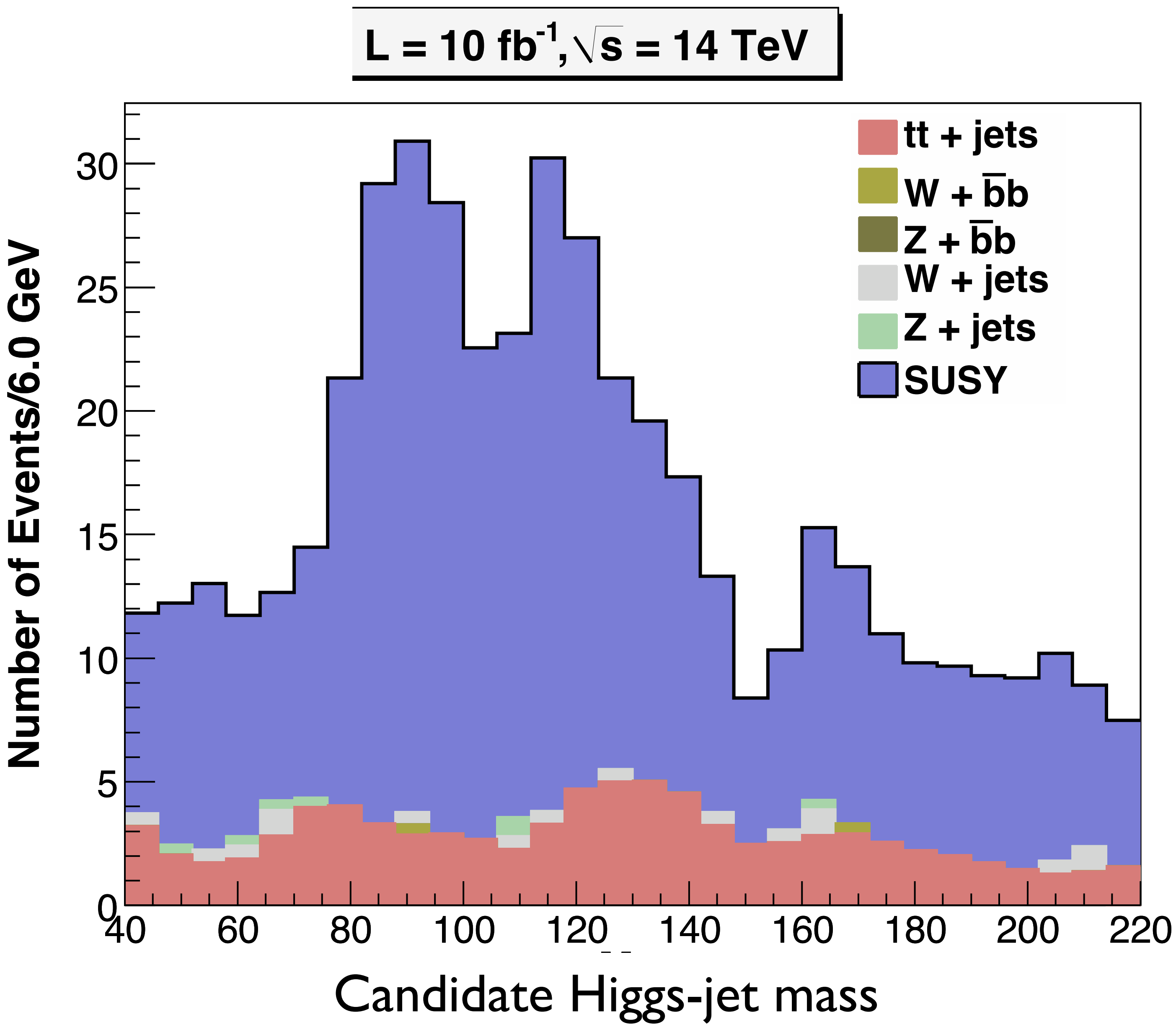


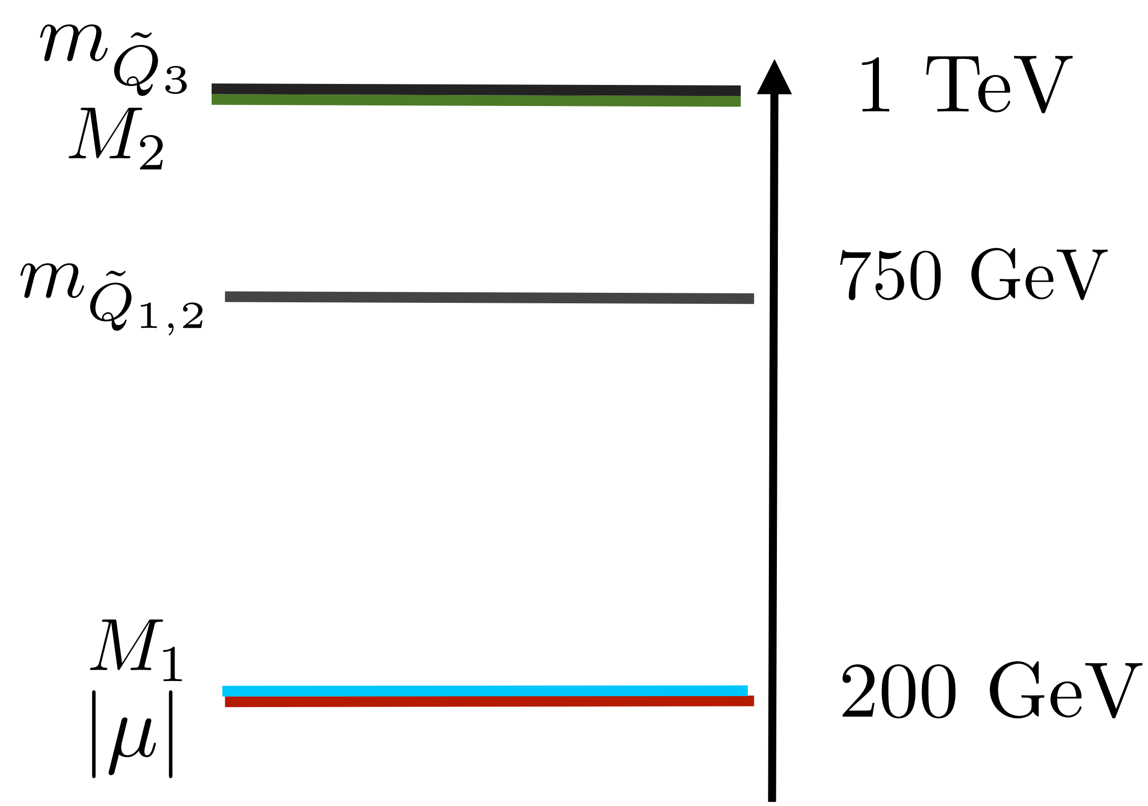
much trickier region of parameter space

$$\mathrm{BR}(\tilde{\chi}^0 \to \gamma + \tilde{G}) \sim 82.6\%$$
$$\mathrm{BR}(\tilde{\chi}^0 \to Z + \tilde{G}) \sim 16\%$$
$$\mathrm{BR}(\tilde{\chi}^0 \to h + \tilde{G}) \sim 1.3\%$$

boosted fraction $\sim 47\%$

Results: Point #3





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Comments

We've used SUSY with gravitino LSP as an example source of Higgses from BSM, but the technique is by no means limited this

Ingredients:

- new, heavy particles who's decays include Higgses
- some handle to suppress SM backgrounds (high-p_T particles, $\not{E}_T$)

ex.) SUSY w/ $\tilde{\chi}_0$ LSP
UED
Little Higgs
4th Generation
...

* cleanliness of substructure analysis

better extraction of underlying parameters

Conclusions

Light Higgses are hard to find at the LHC ...

- BSM particles offer a new source of Higgses at the LHC, especially boosted Higgses
- The rate is smaller, but BSM often comes with handles to suppress SM backgrounds
- Using jet substructure analysis to fight combinatorial BSM backgrounds, result is new channels to discover $h \to \bar{b}b$

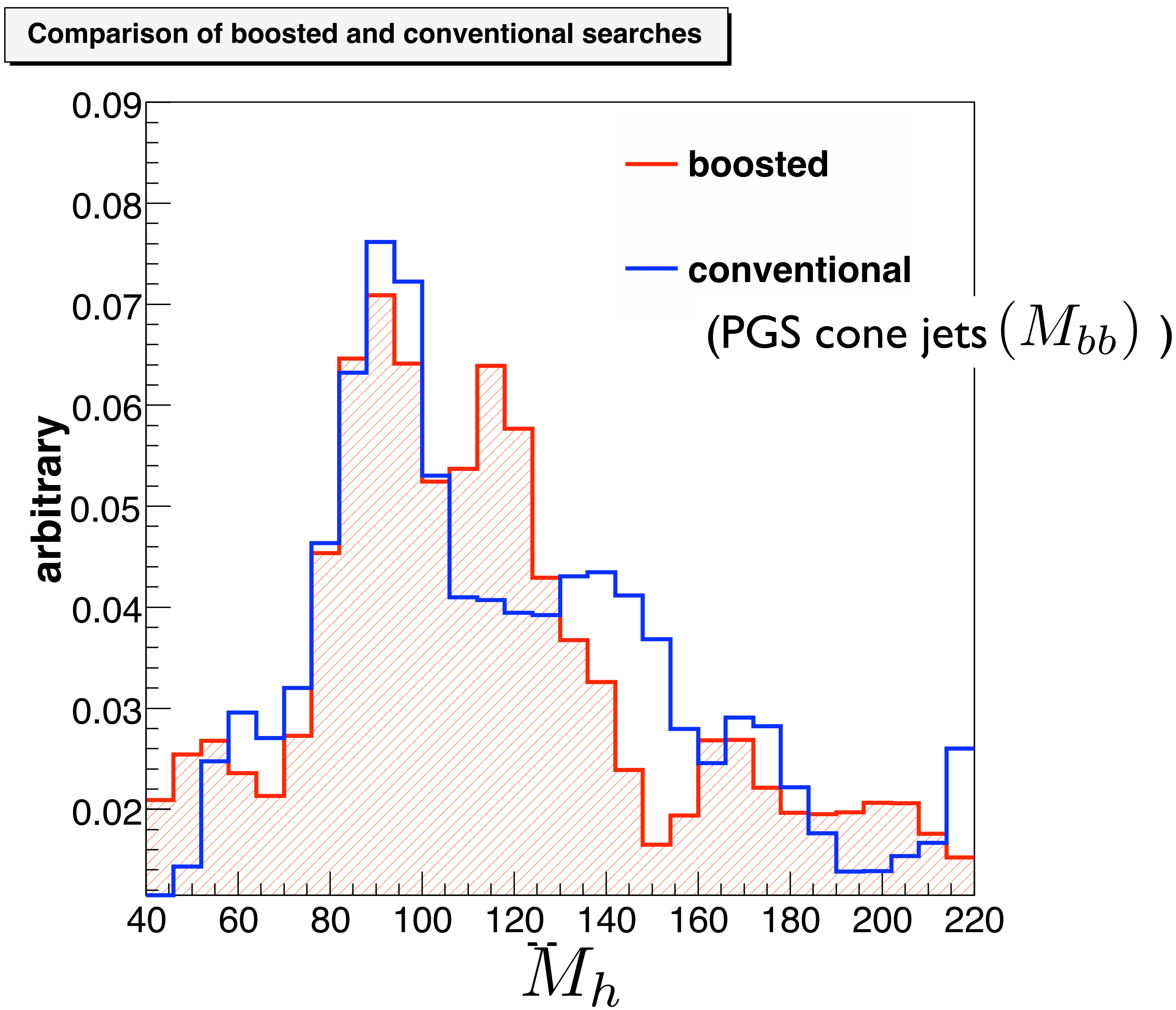
  improved substructure extends this to 'b-rich' environments

- Complementary to conventional Higgs searches, smaller jet-resolution effects
- These new Higgs discovery channels can easily be as significant (or more so !) than conventional $h \to \gamma\gamma$

Backup Slides

Results: Point #3

boosted analysis finds the Higgs peak even where conventional analysis fails completely or leads to confusing features

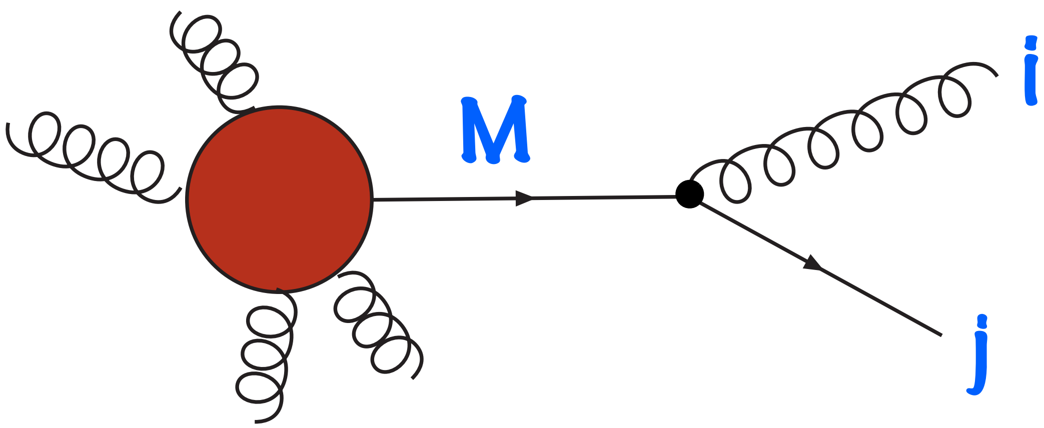


What does this accomplish?

for massless daughter particles:

$$\frac{\min(p_{T_i}^2, p_{T_j}^2)}{m_J^2}\Delta R_{ij}^2 \longrightarrow \frac{\min(z_i, z_i)}{\max(z_i, z_j)} \quad \begin{cases} z_i = E_i/E_{tot} \\ z_j = E_j/E_{tot} \end{cases}$$

... in soft, collinear limit

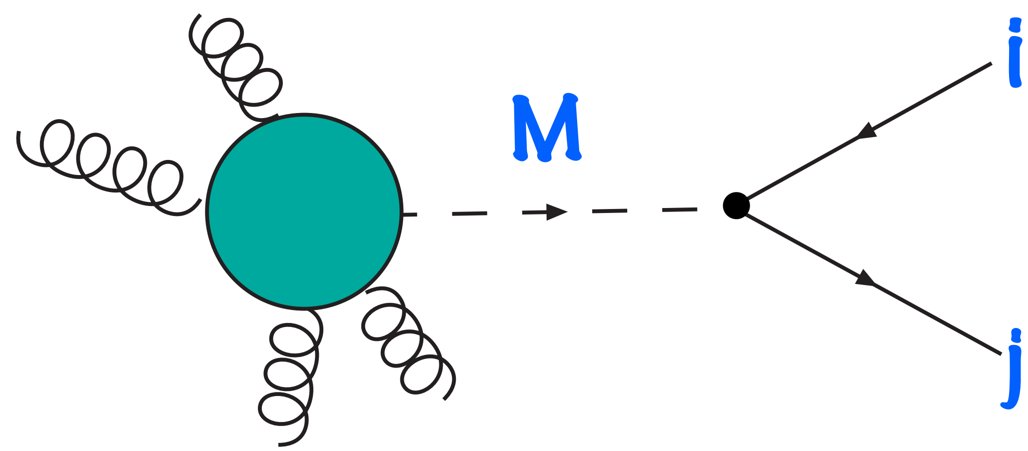


$$df_{M\to ij}^{QCD} \sim dQ_M^2 dz \frac{1}{Q_M^2} P_{M\to ij}(z)$$

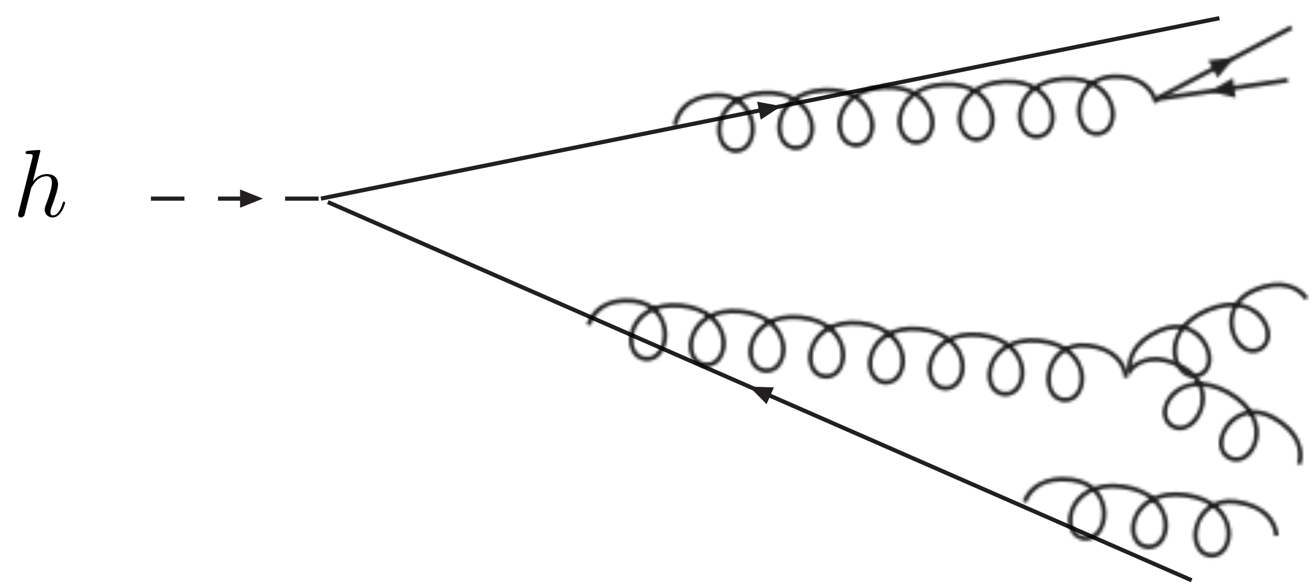
blows up as $z \longrightarrow 0$

$$df_{M\to ij}^{res} \sim dQ_M^2 dz \frac{\Gamma_{M\to ij}}{\Gamma_{M,tot}} \delta(Q_M^2 - m_{res}^2)$$

nonsingular in z



Jet Substructure: in pictures



subjets contain perturbative, angle-ordered radiation from $b/\bar{b}$

Diffuse radiation (underlying event) is filtered out

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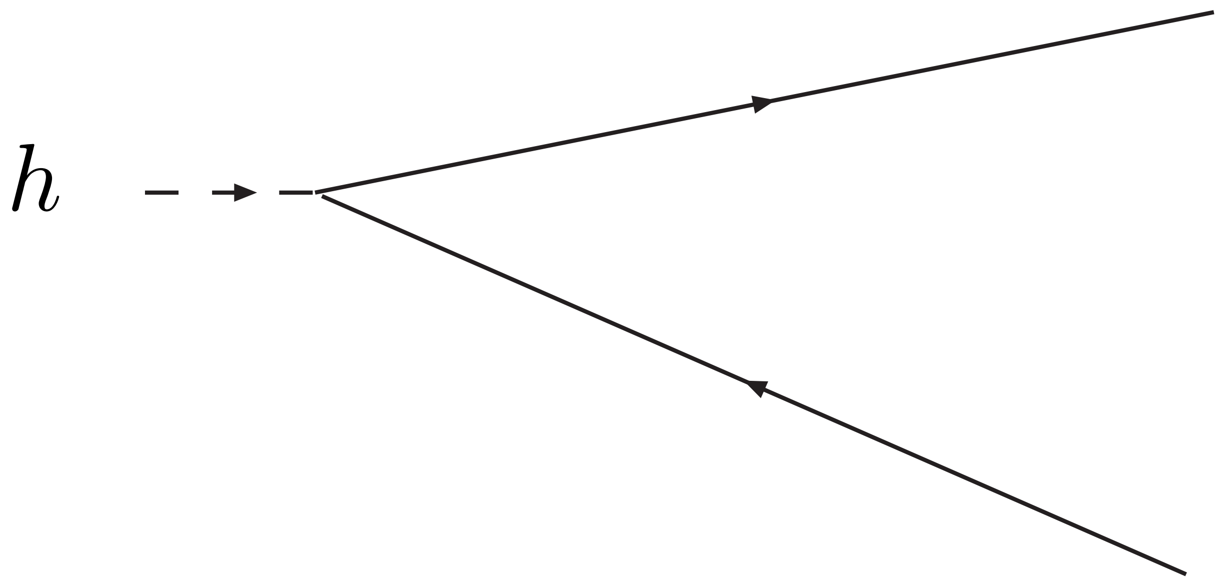

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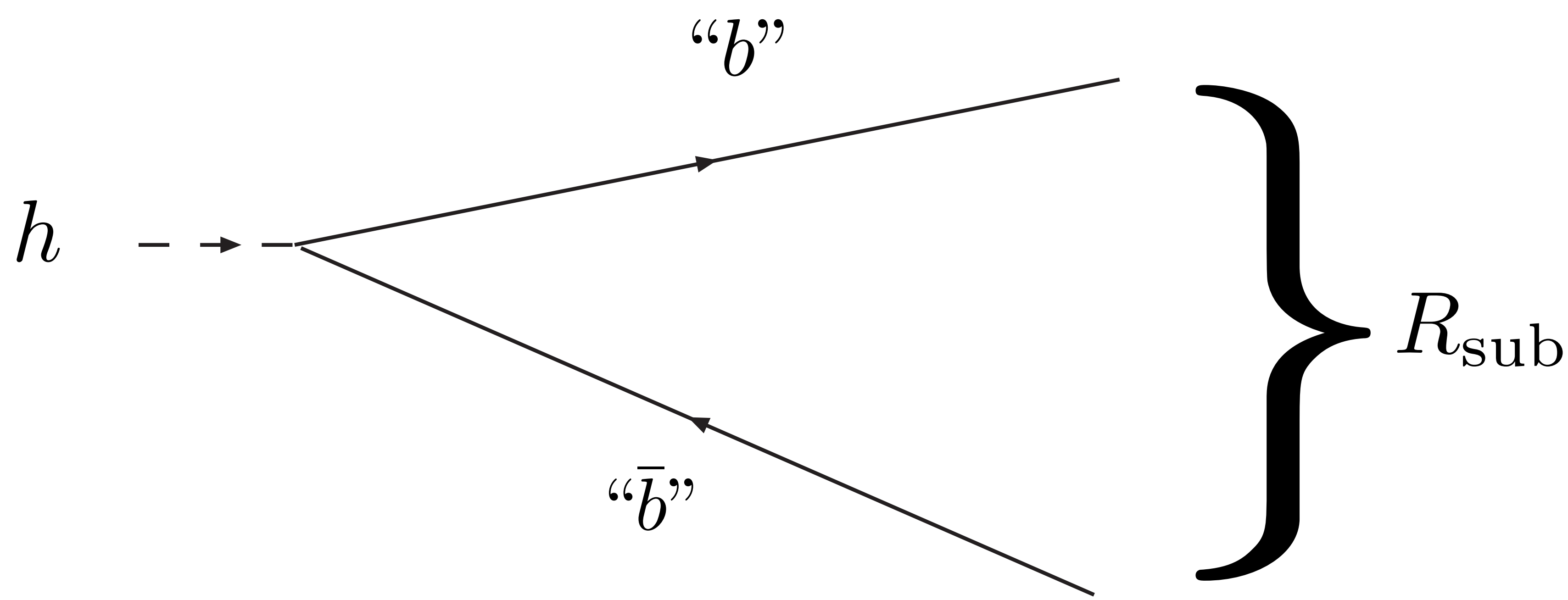

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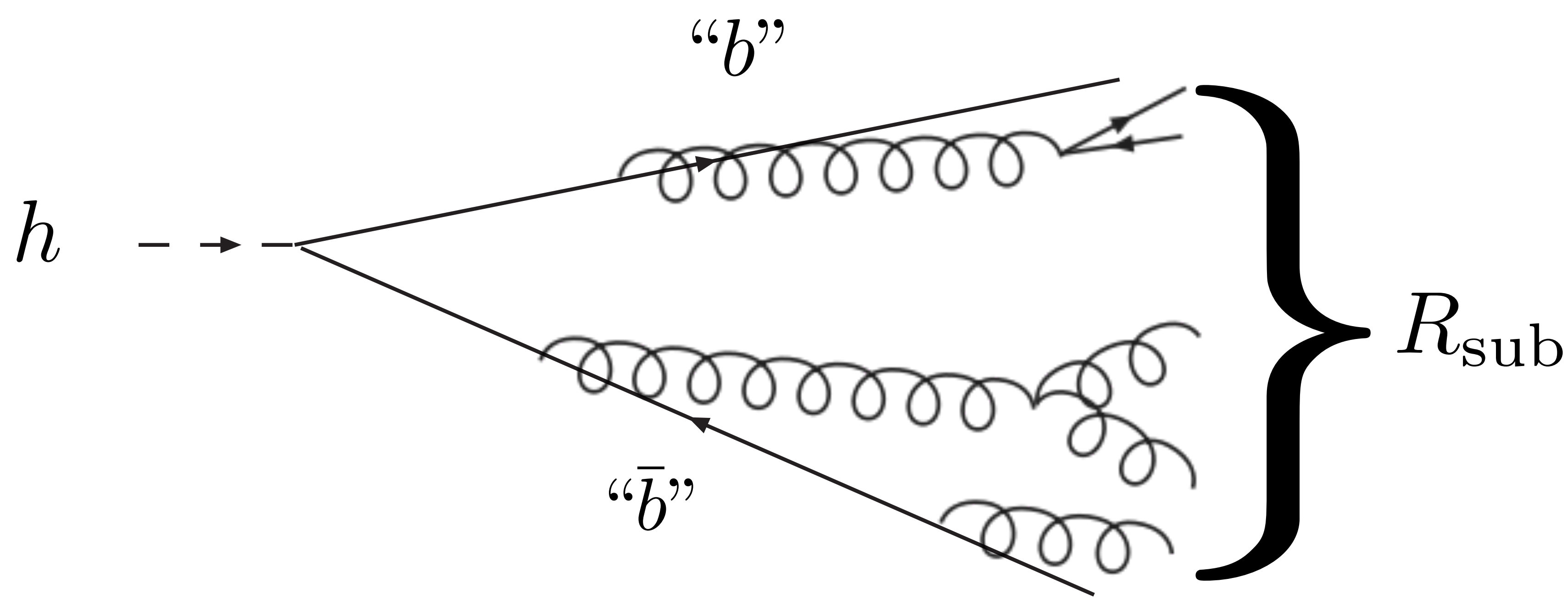

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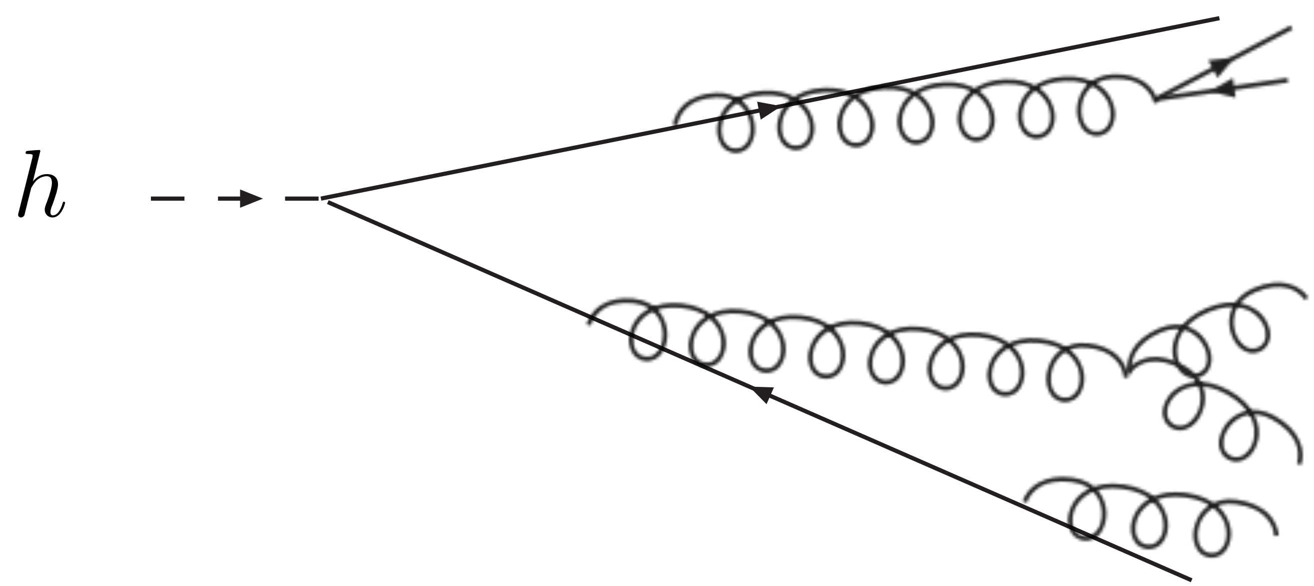

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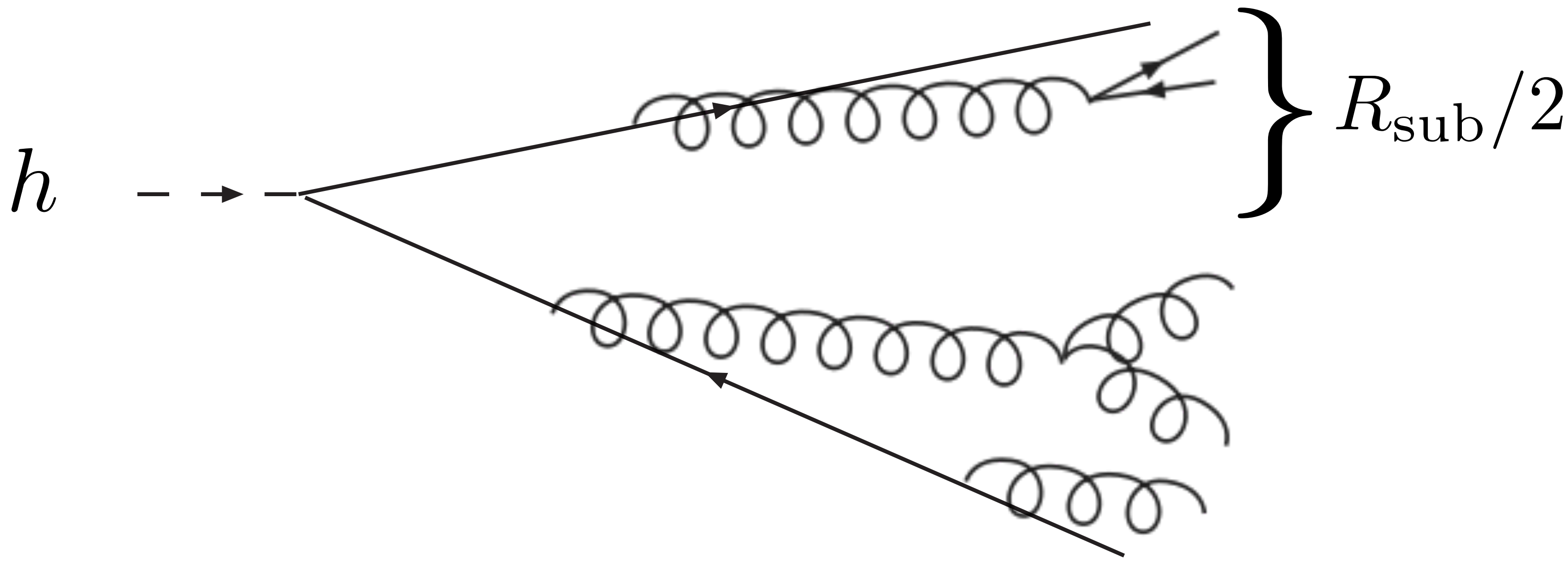

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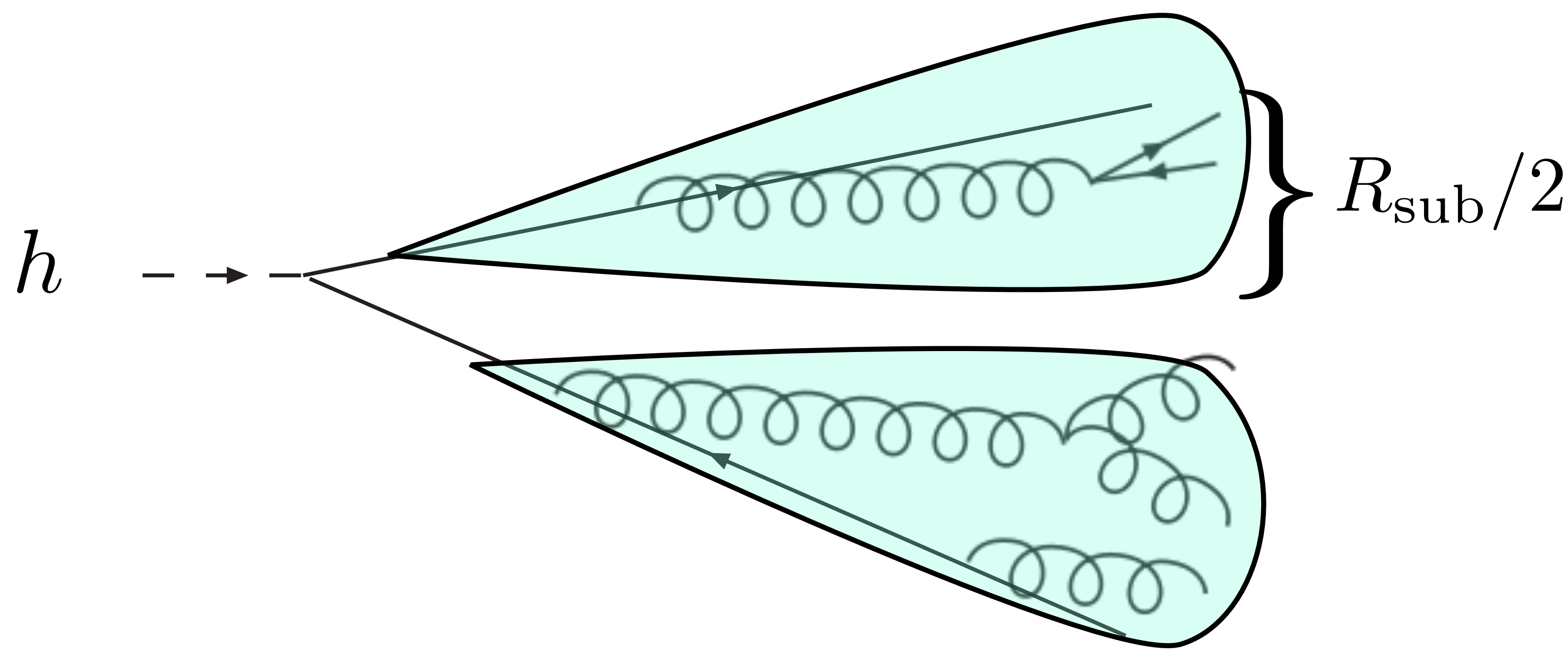

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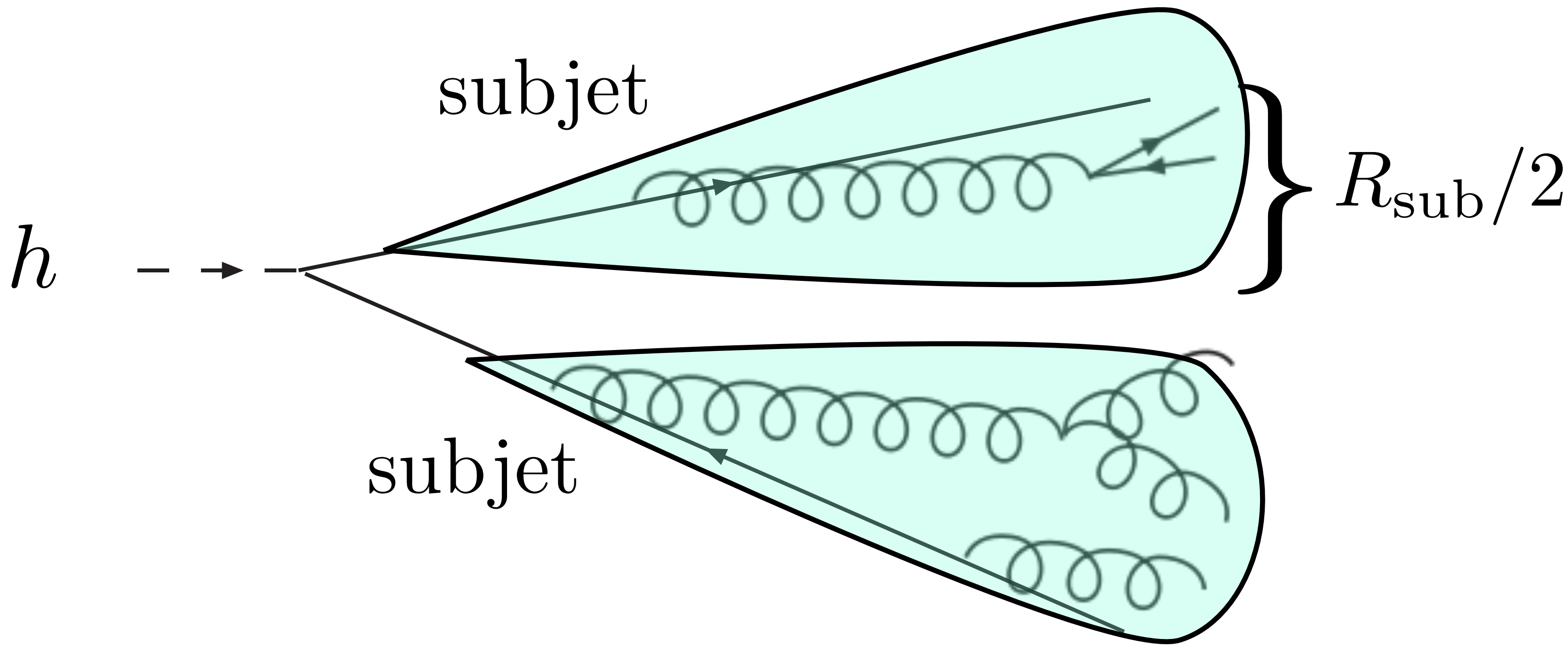

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