Boosting SM and MSSM Higgs searches with Jet Substructure

Adam Martin (aomartin@fnal.gov)

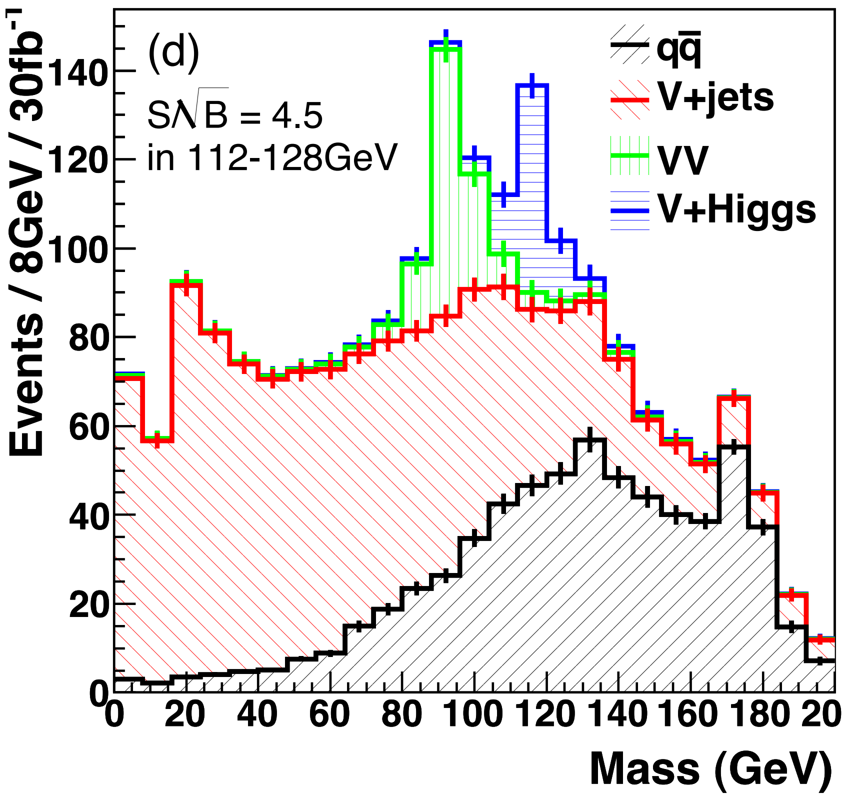
based on work with G. Kribs, T. Roy and M. Spannowsky (U. Oregon) arxiv: 0912.4731, 1006.1656

IPMU, Sept. 9th, 2010

Fermilab

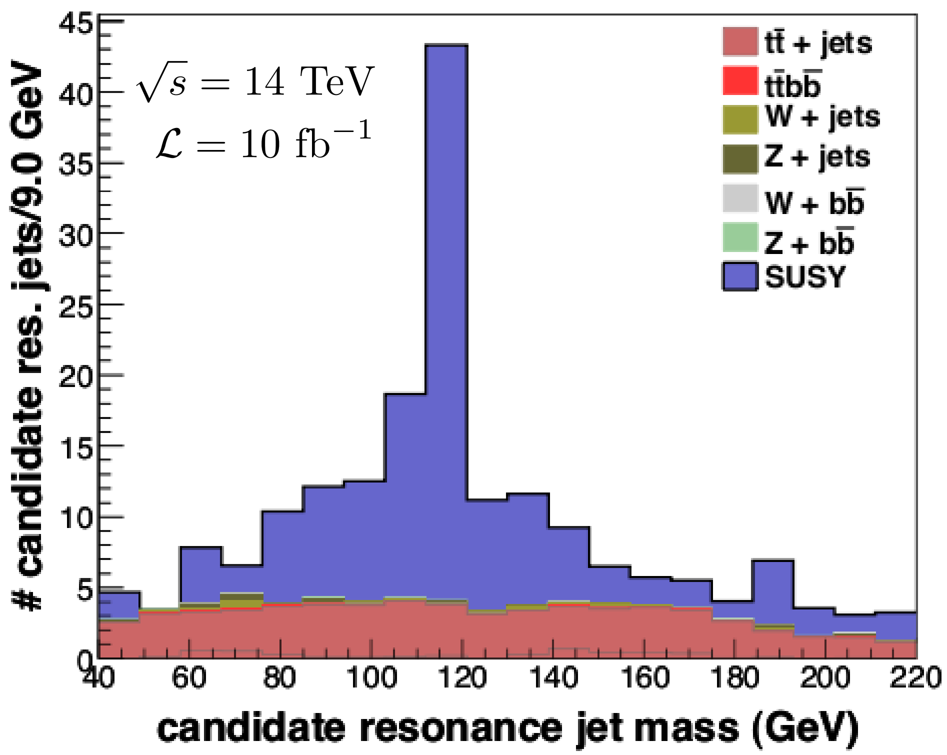
Punchline

A new method (BDRS), using "jet substructure", demonstrates discovery of h -> b,bbar at the LHC for light Higgs masses (S ≈ 4 for 30 fb^{-1})



We find that light MSSM Higgses are ideally suited to these techniques:

this opens up a new way to look for h (& H,H^{+-},A): Higgses from the decays of heavy sparticles



Could be first h discovery mode (before h -> $\gamma\gamma$, h -> $\tau\tau$) !!

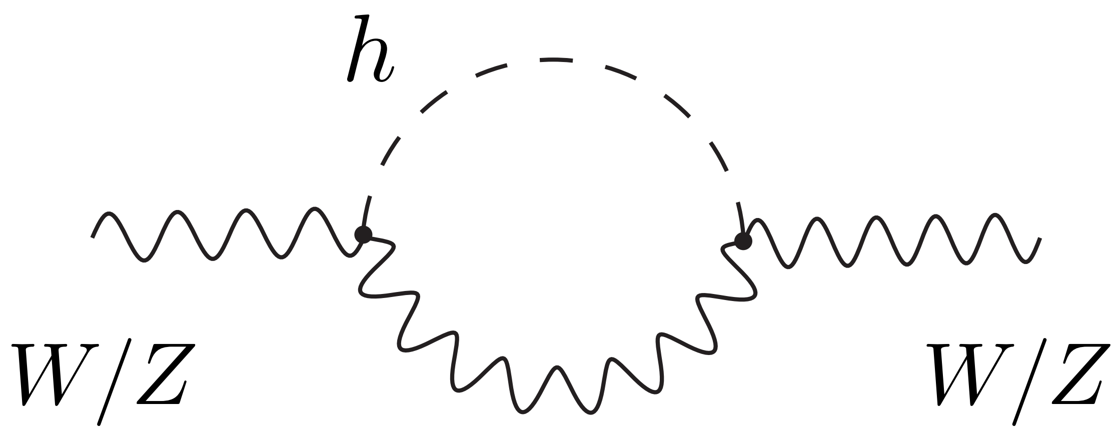
Outline

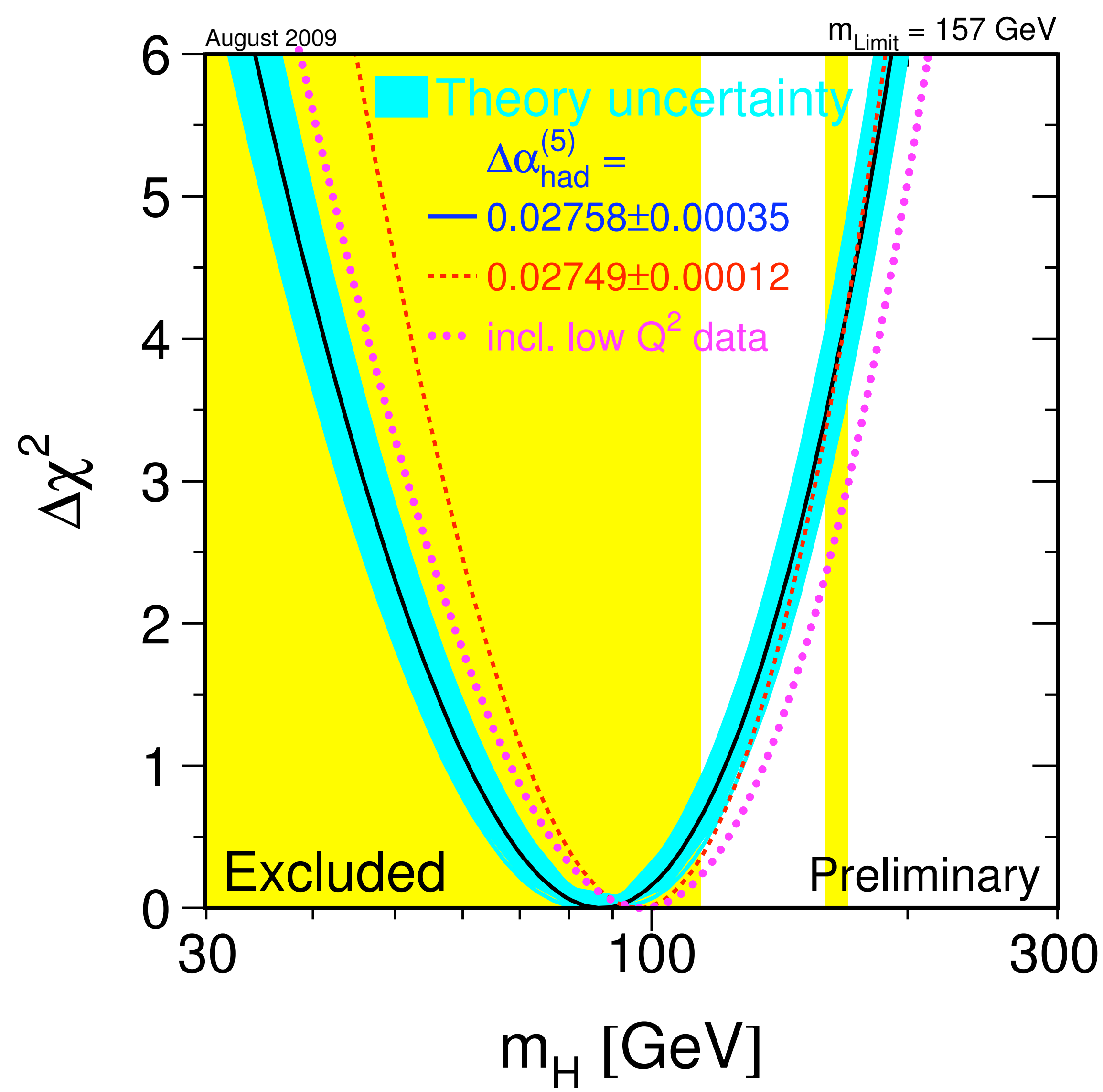
- Higgs in the SM
- A new handle on h->b bbar
- jets and jet-substructure
- Boosted MSSM Higgses
- Substructure for SUSY

Higgs in the SM

Where is the Higgs?

dependence on Higgs mass enters via virtual electroweak effects





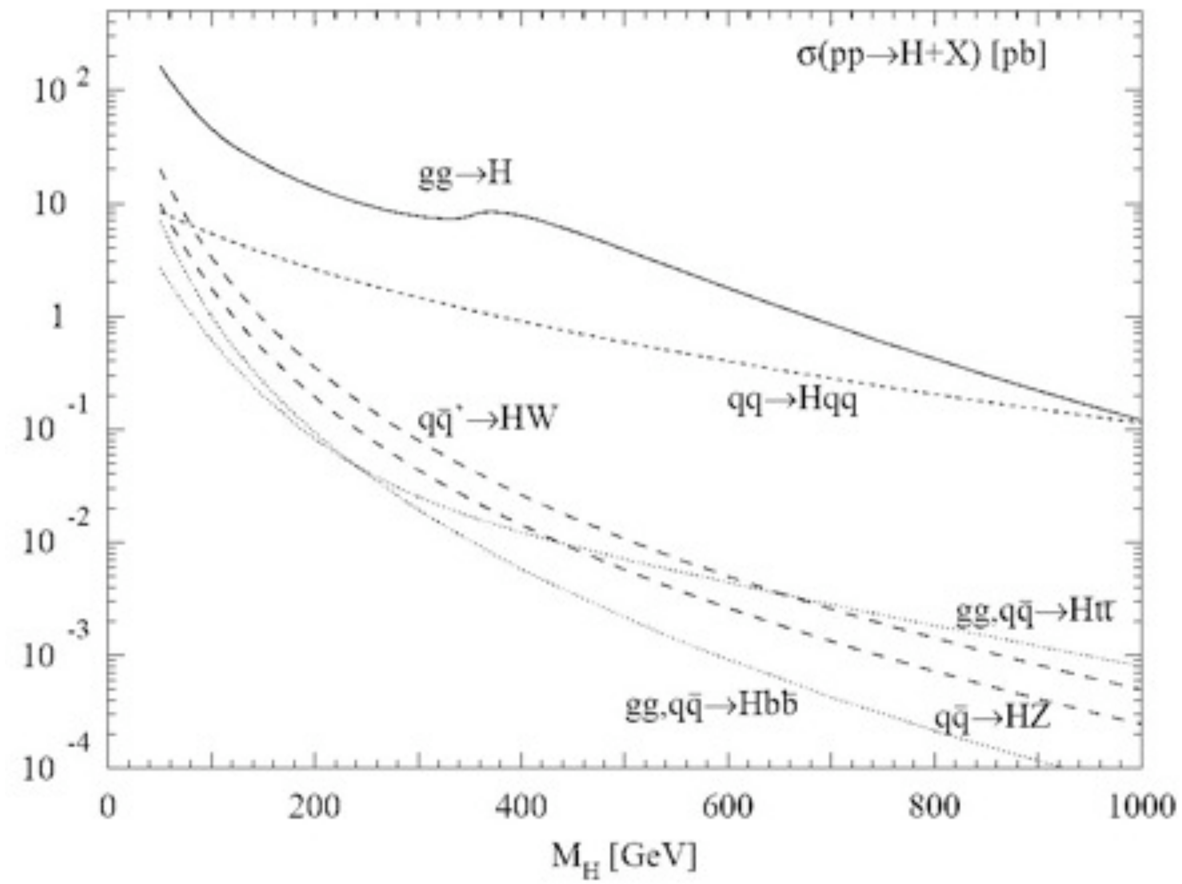
Precise measurements of EW observables indirectly bound m_H

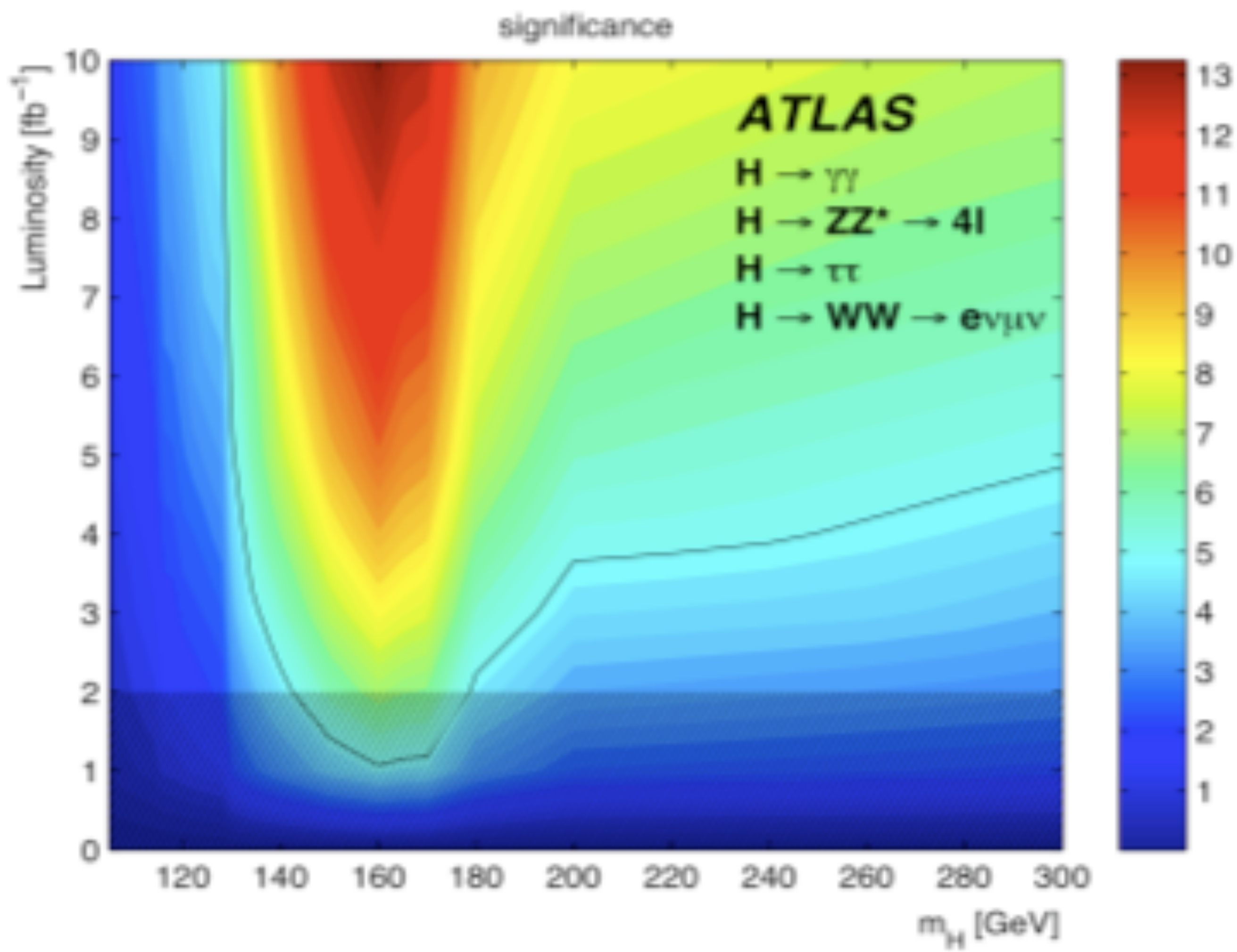
suggest that the Higgs is light

Unfortunately

BUT, although easy to produce at the LHC,

light Higgses are difficult to find





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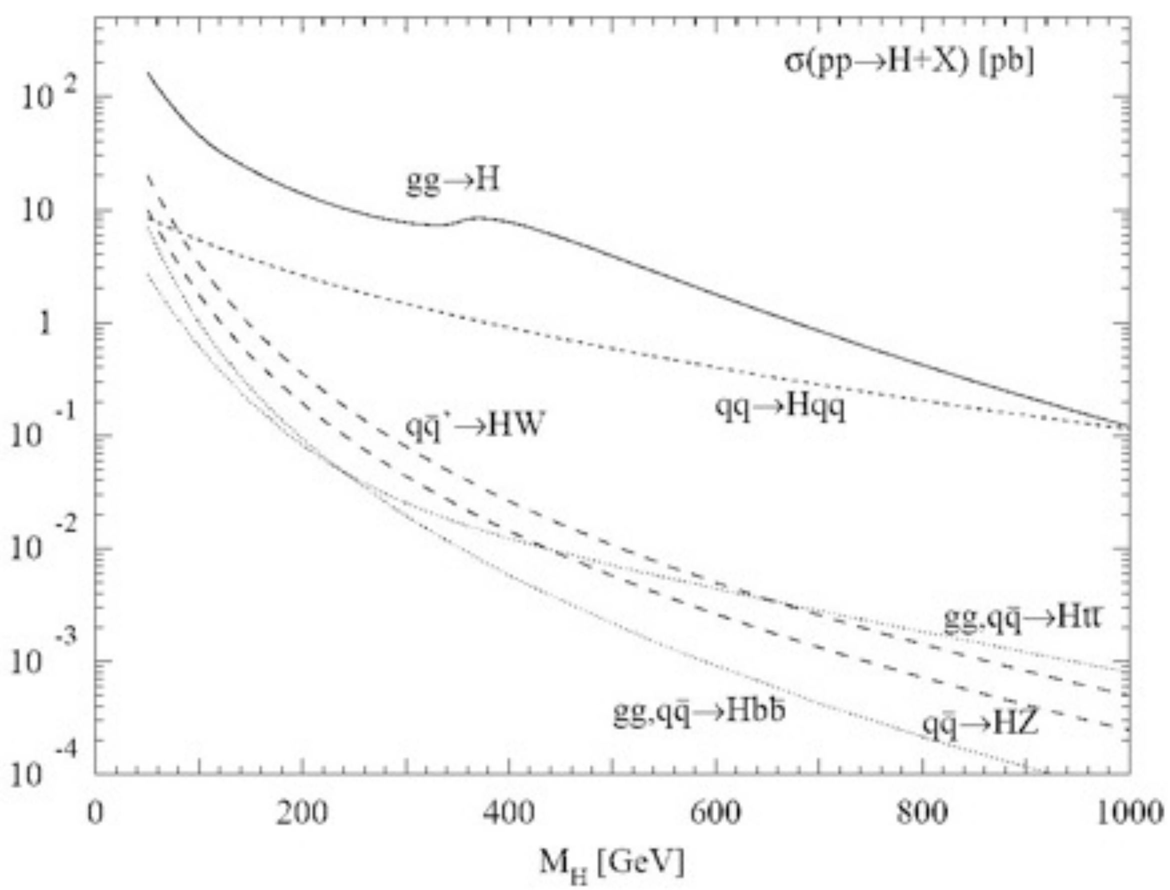

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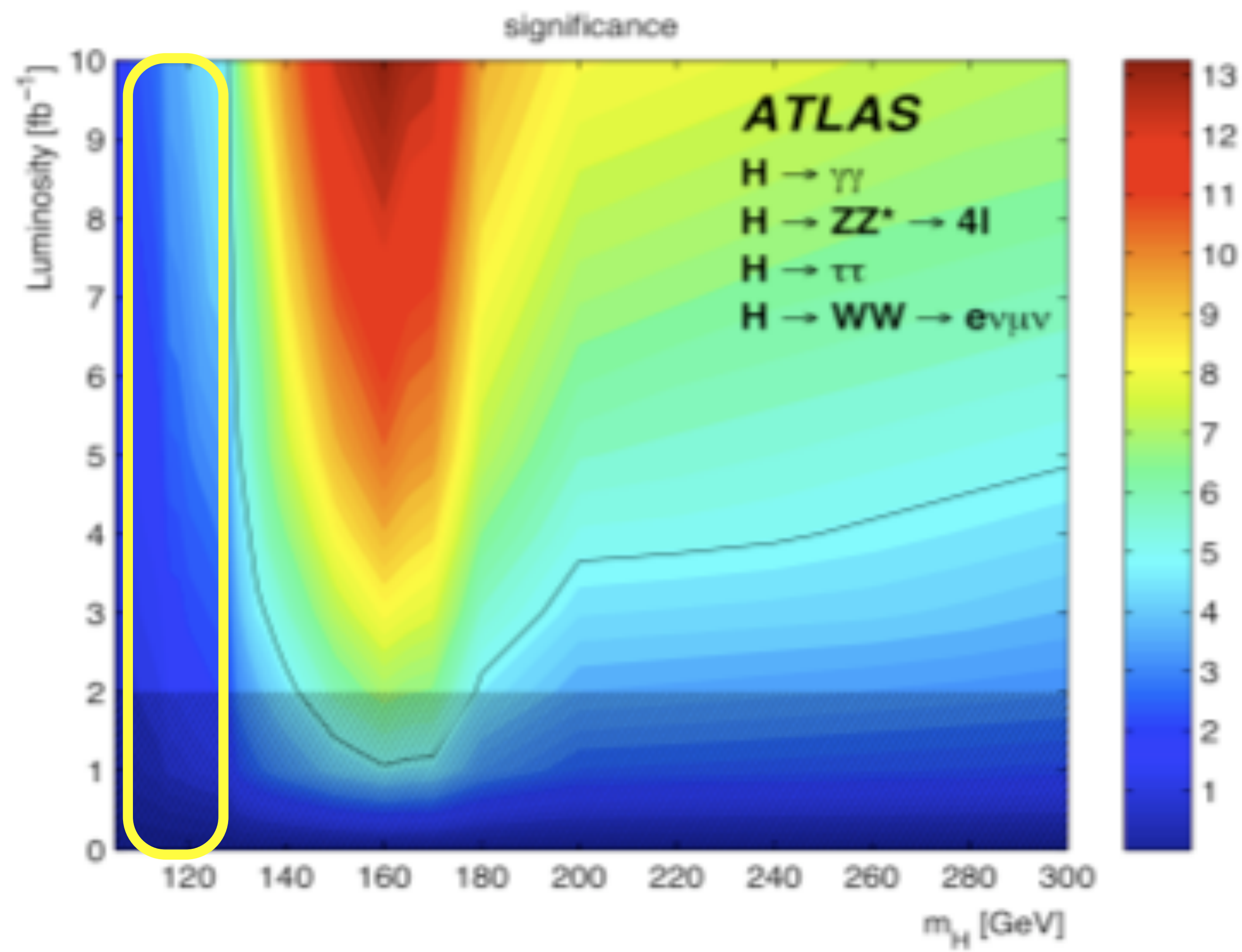
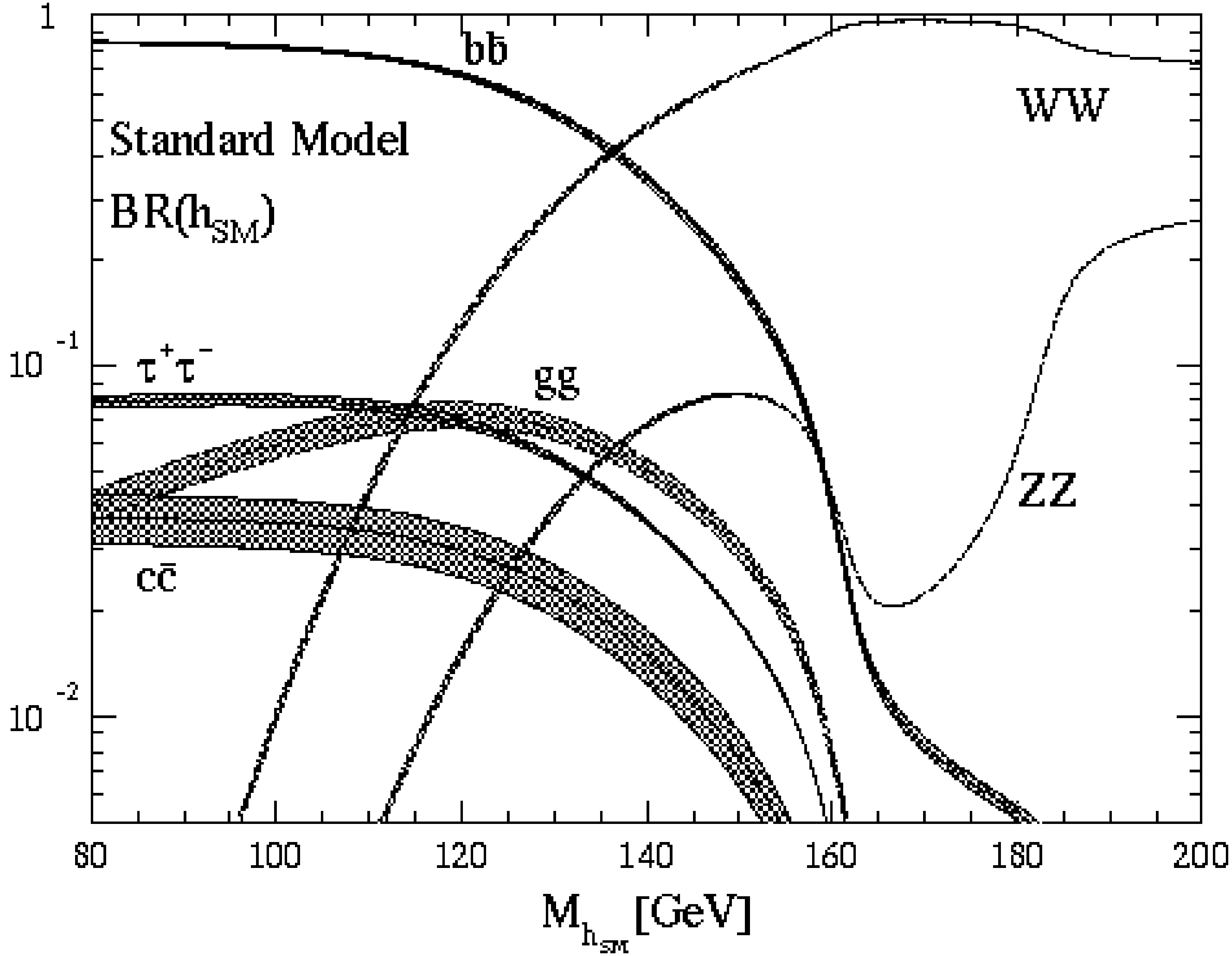
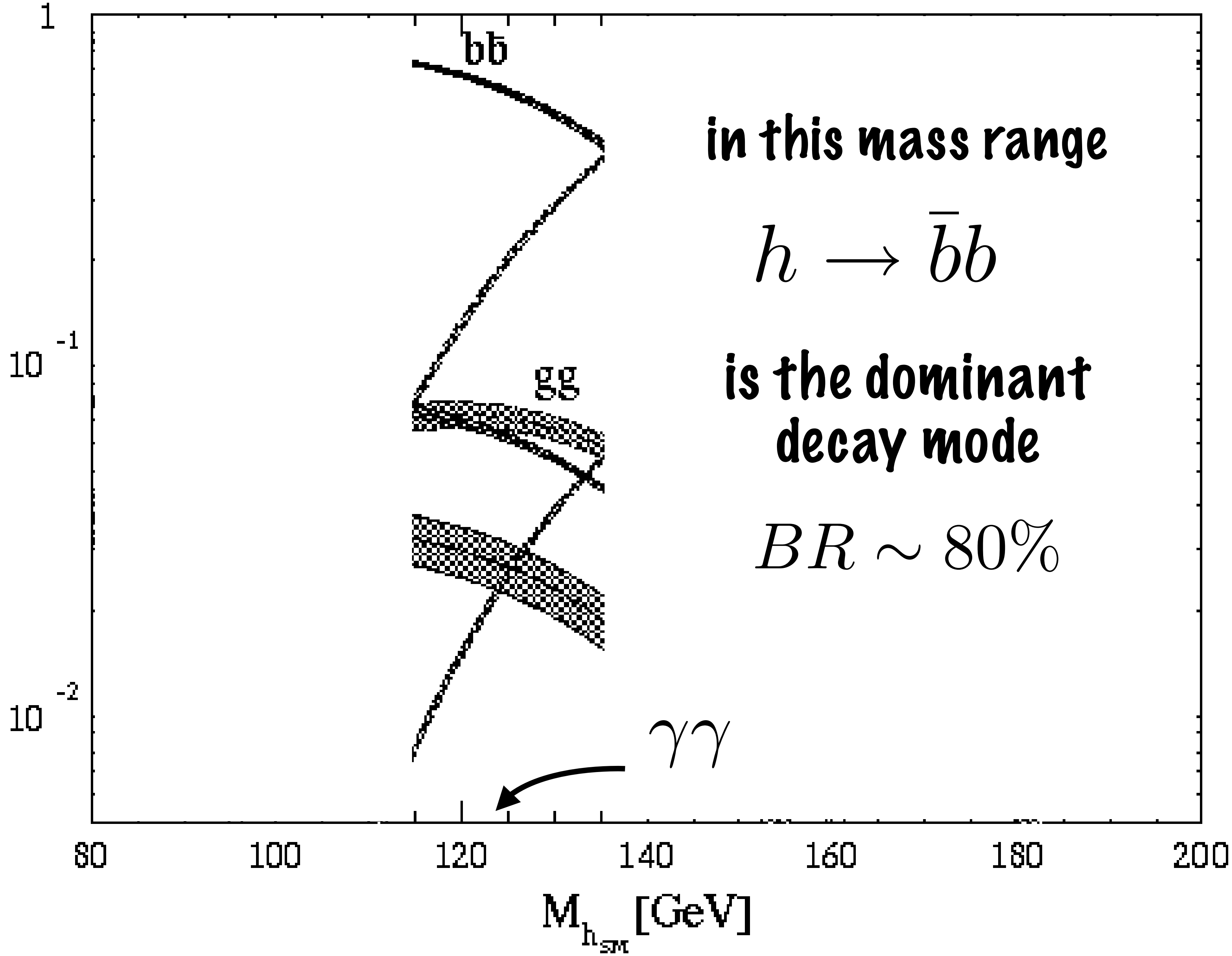


Branching Ratios of SM Higgs



HDECAY

Branching Ratios of SM Higgs



in this mass range

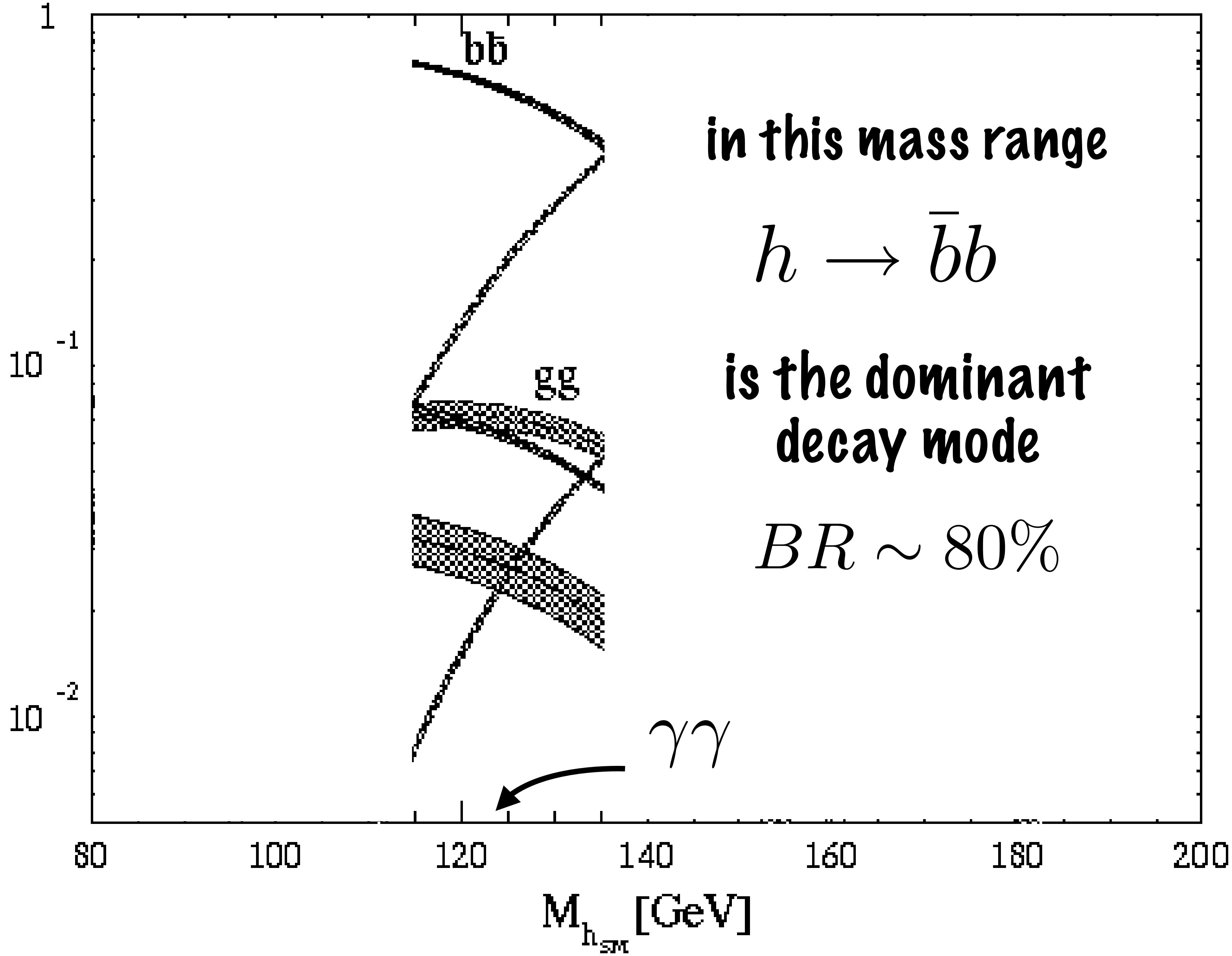
$$h \to \bar{b}b$$

is the dominant decay mode

$$BR \sim 80\%$$

HDECAY

Branching Ratios of SM Higgs



$\gamma\gamma$

in this mass range

$$h \to \bar{b}b$$

is the dominant decay mode

$$BR \sim 80\%$$

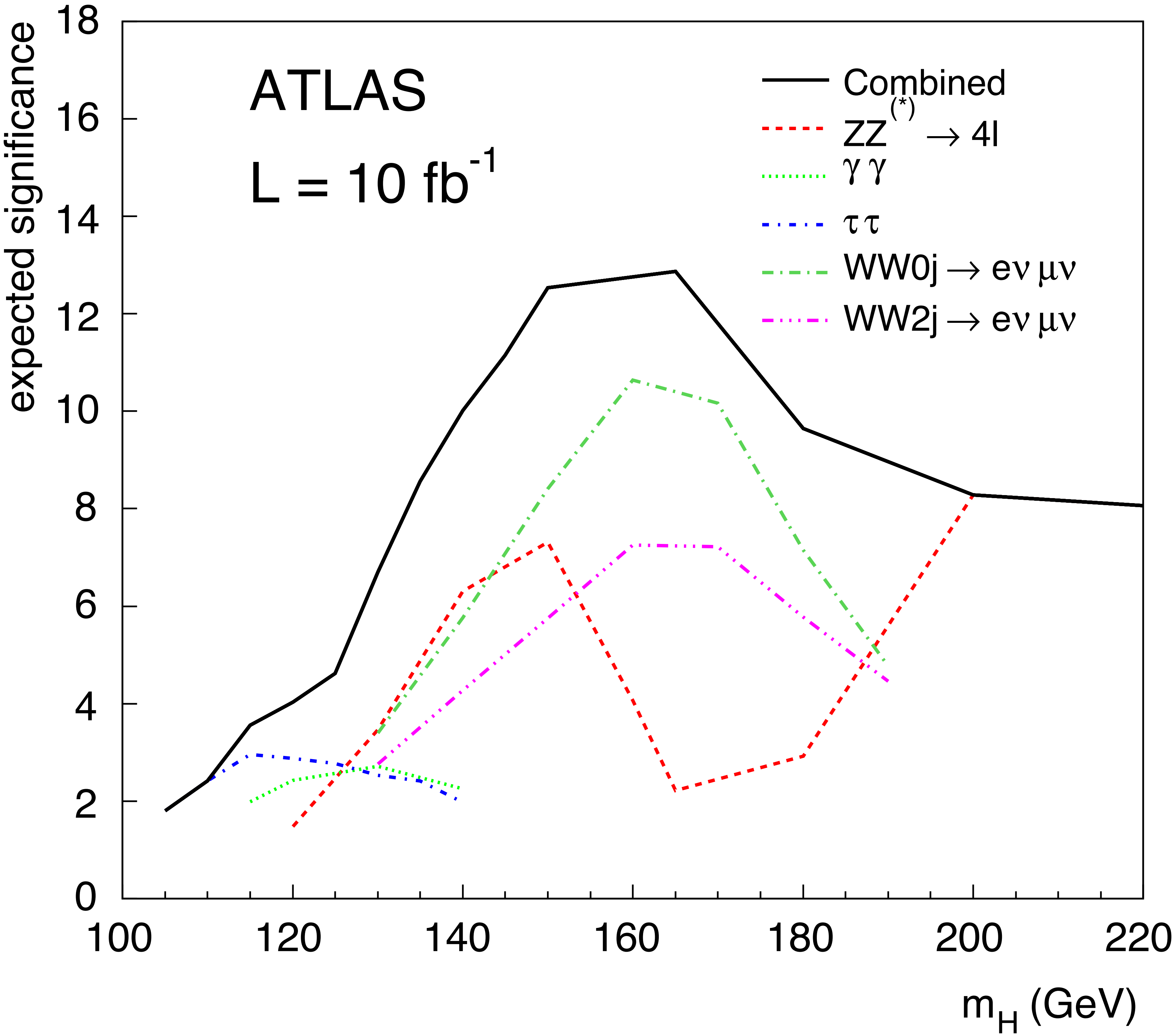
but the backgrounds in

$\bar{b}b$

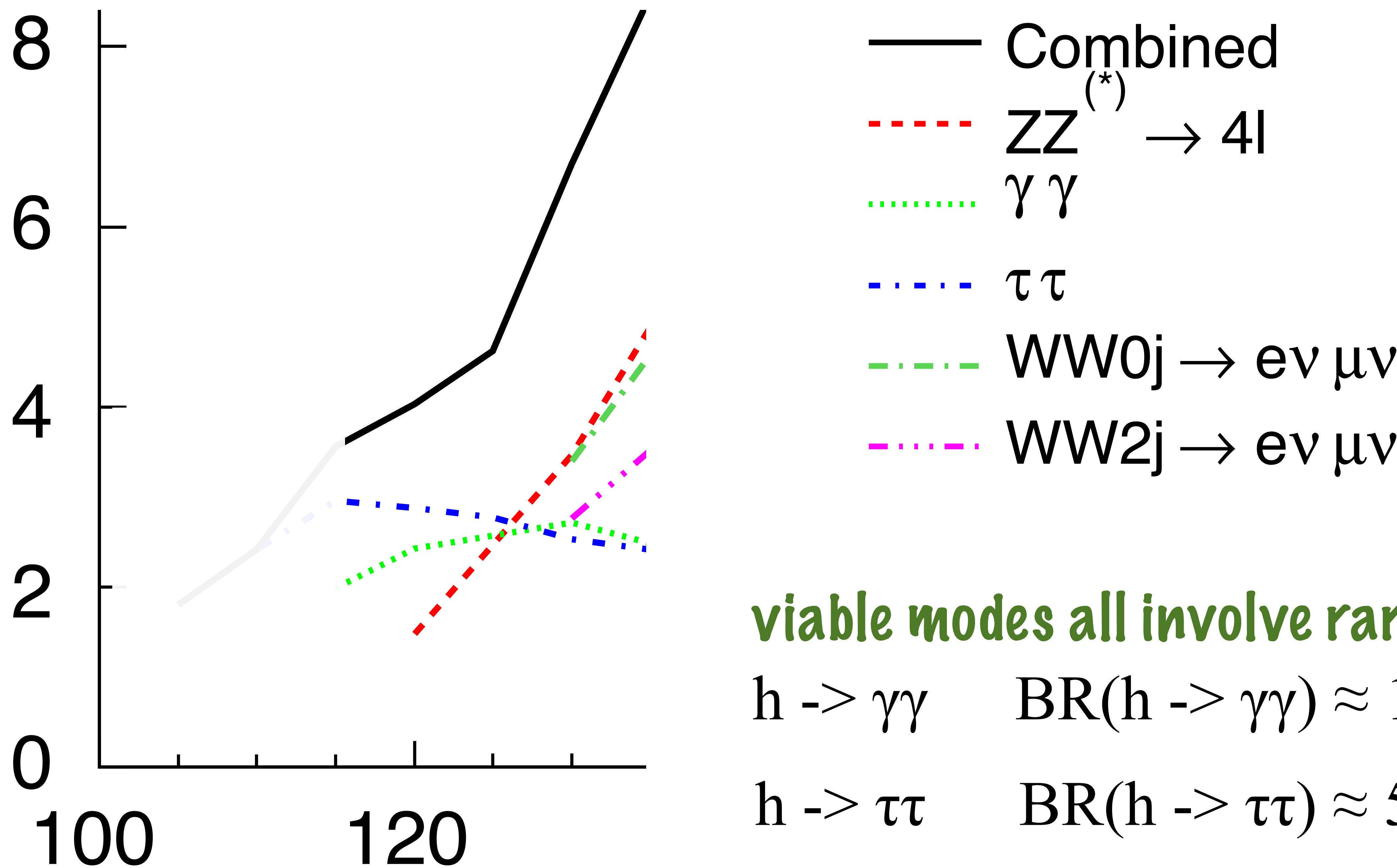
are way too high!

HDECAY

ATLAS TDR 2009



ATLAS TDR 2009 (CMS is similar)



viable modes all involve rare decays

h -> γγ BR(h -> γγ) ≈ 1-2 x 10^{-3}

h -> ττ BR(h -> ττ) ≈ 5-7 x 10^{-2}

no way to use dominant h-> b bbar mode ..

or so we thought

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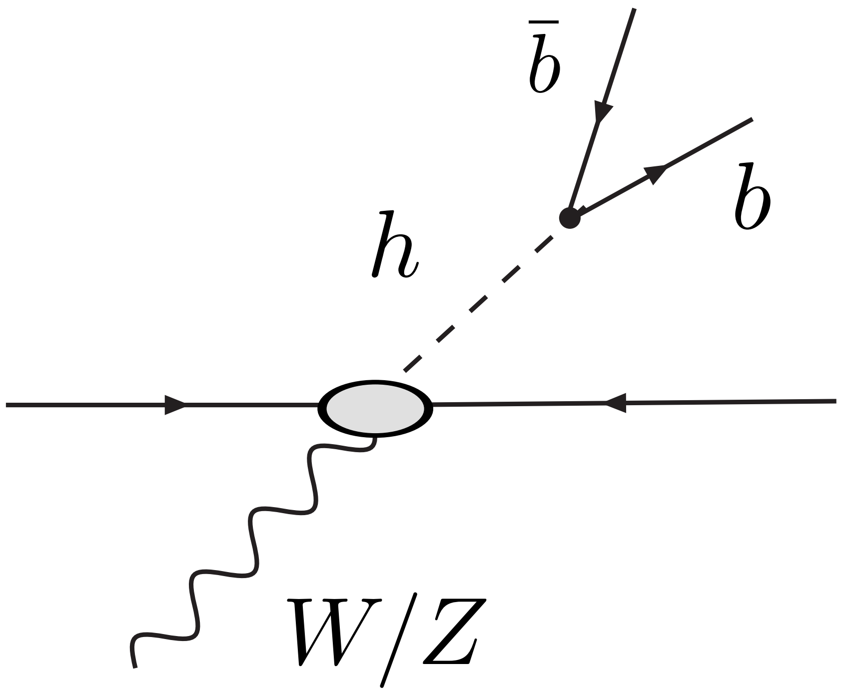
- Substructure for SUSY

Recently, a new technique for light Higgses

- proposed by BDRS = Butterworth, Davison, Rubin, Salam (0802.2470)
- considered associated Higgs production:

$$pp \longrightarrow W(\ell\nu)/Z(\ell\ell) + h(\bar{b}b)$$



find: significance ~ 4.5 for $\mathcal{L} = 30\ \mathrm{fb}^{-1}$

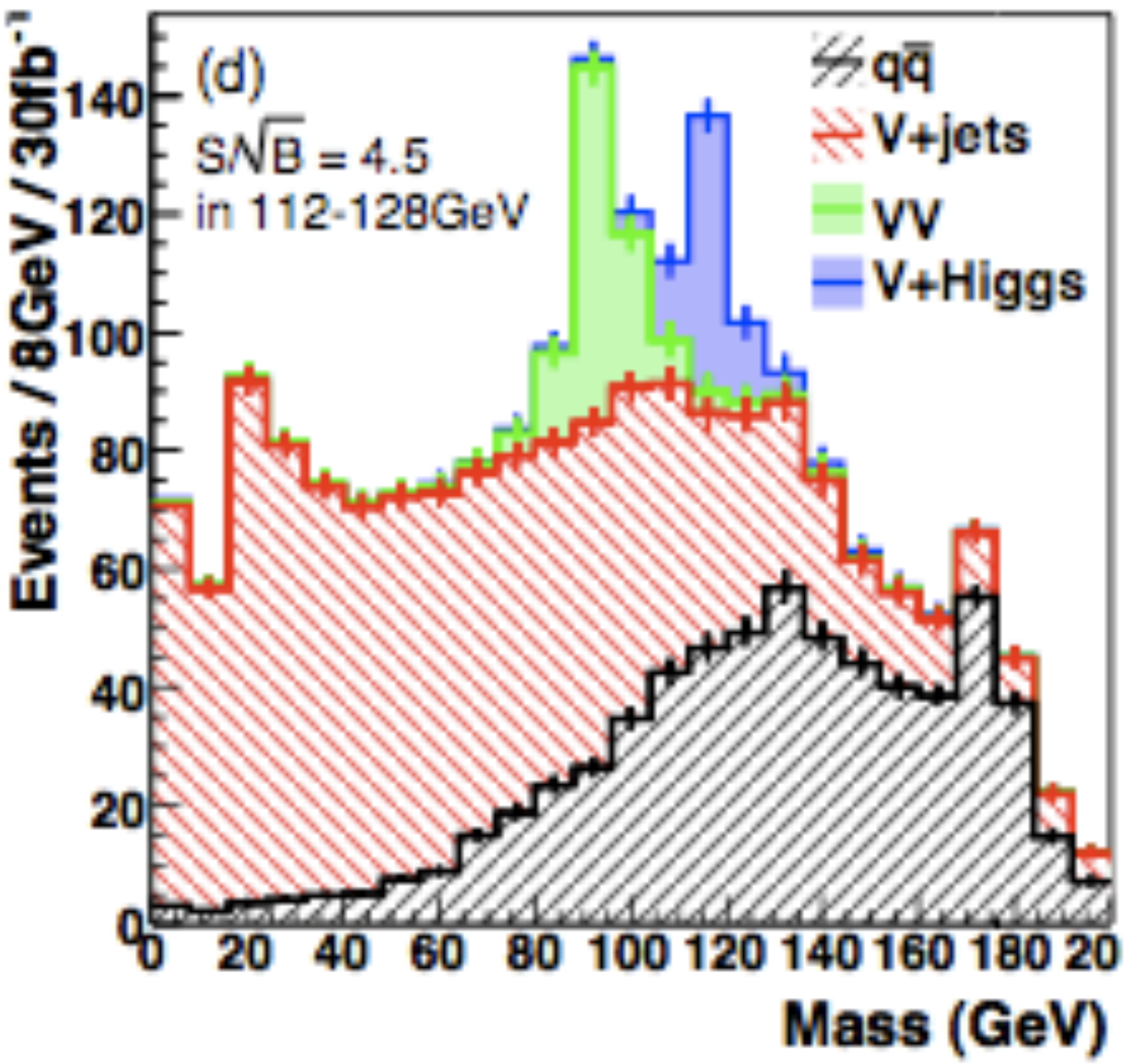
$$\left(\sim 2.6 \text{ for } \mathcal{L} = 10\ \mathrm{fb}^{-1}\right)$$

$\gtrsim$ 'conventional' channels!!

HOW? by focusing on boosted Higgses, $p_T > 200$ GeV

and using 'jet substructure' to differentiate signal from t tbar, W/Z + jets, etc. backgrounds

Recently, a new technique for light Higgses



(BDRS 0802.2470)

brings back a channel that had been thought extremely difficult at the LHC

allows measurement of y_b!

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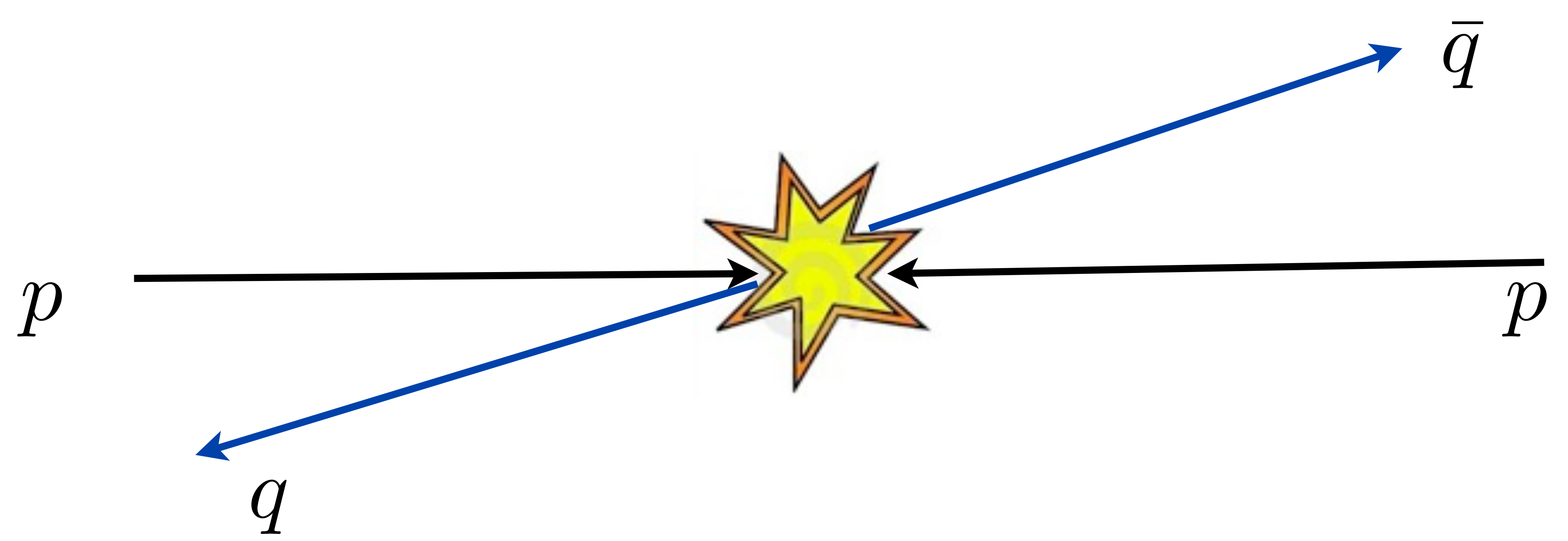
Jets at the LHC

There is a lot going on in jets at the LHC: Several scales

$$\sqrt{s} \gg M_W,\, M_Z,\, m_t,\, m_h \gg \Lambda_{QCD}$$

What's in a jet?

'theorist' picture: one hard parton = jet



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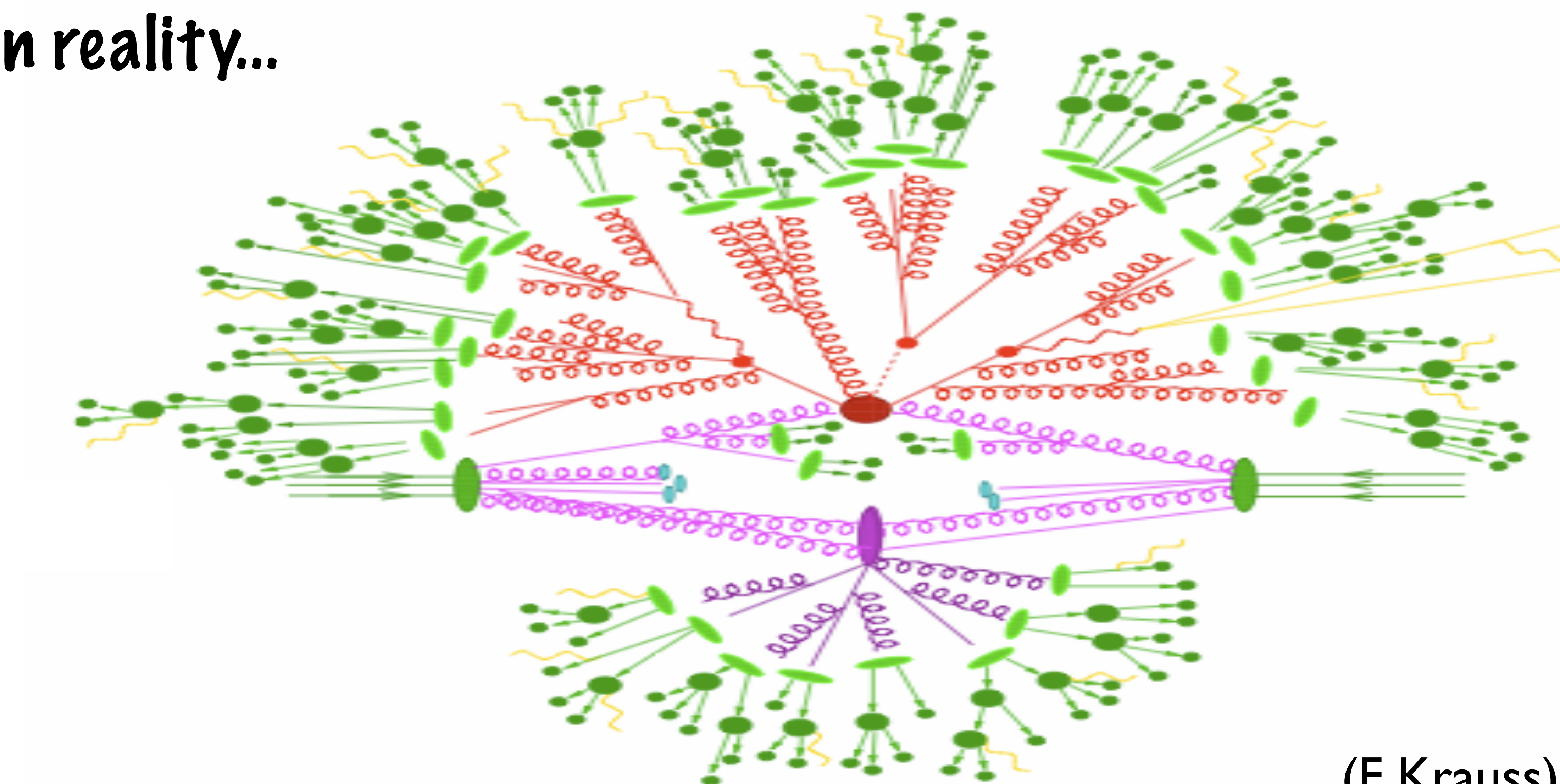
$$\sqrt{s} \gg M_W,\, M_Z,\, m_t,\, m_h \gg \Lambda_{QCD}$$

What's in a jet?

in reality...

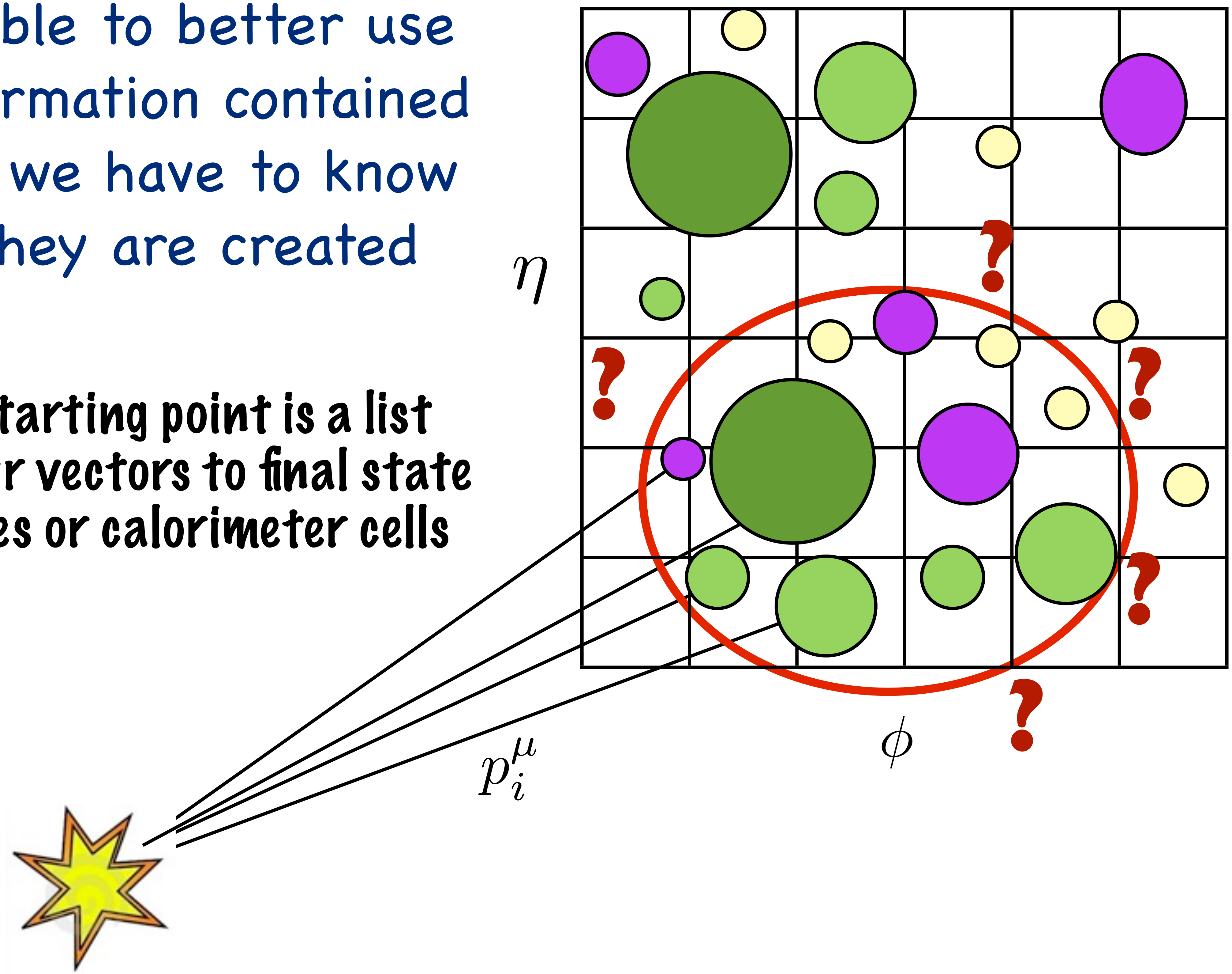


(F. Krauss)

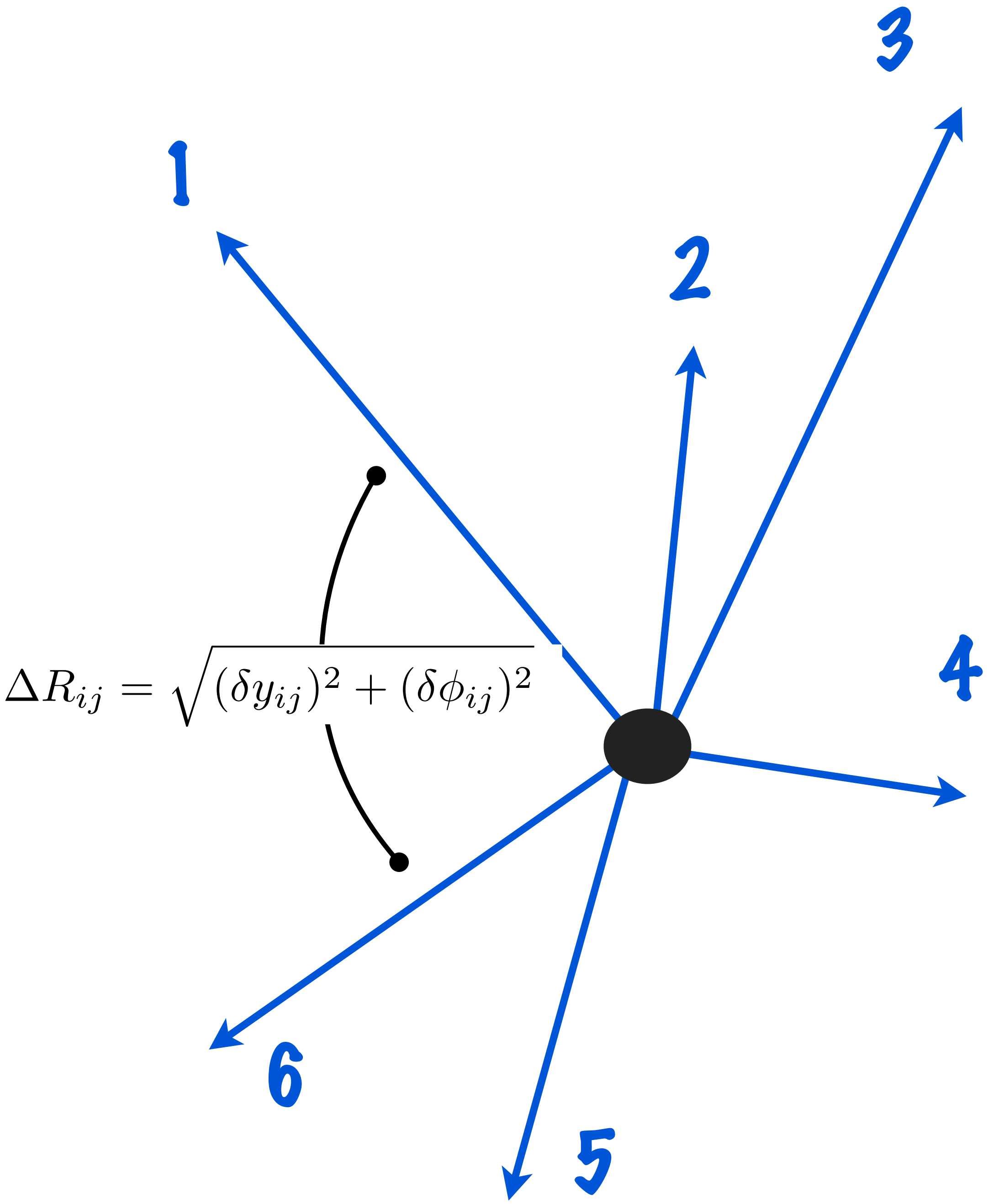
Jets at the LHC

to be able to better use the information contained in jets, we have to know how they are created

1.) the starting point is a list of four vectors to final state particles or calorimeter cells



Making and breaking jets



2.) from the list of final particles, calculate:

$$d_{ij} = \min(p_{Ti}^{2n},\, p_{Tj}^{2n})\, \frac{\Delta R_{ij}^2}{R^2}$$

jet `area'

$$d_i = p_{Ti}^{2n}$$

$$n = \begin{cases} n = 1 & k_T \\ n = 0 & \mathrm{C/A} \\ n = -1 & \text{anti-}k_T \end{cases}$$

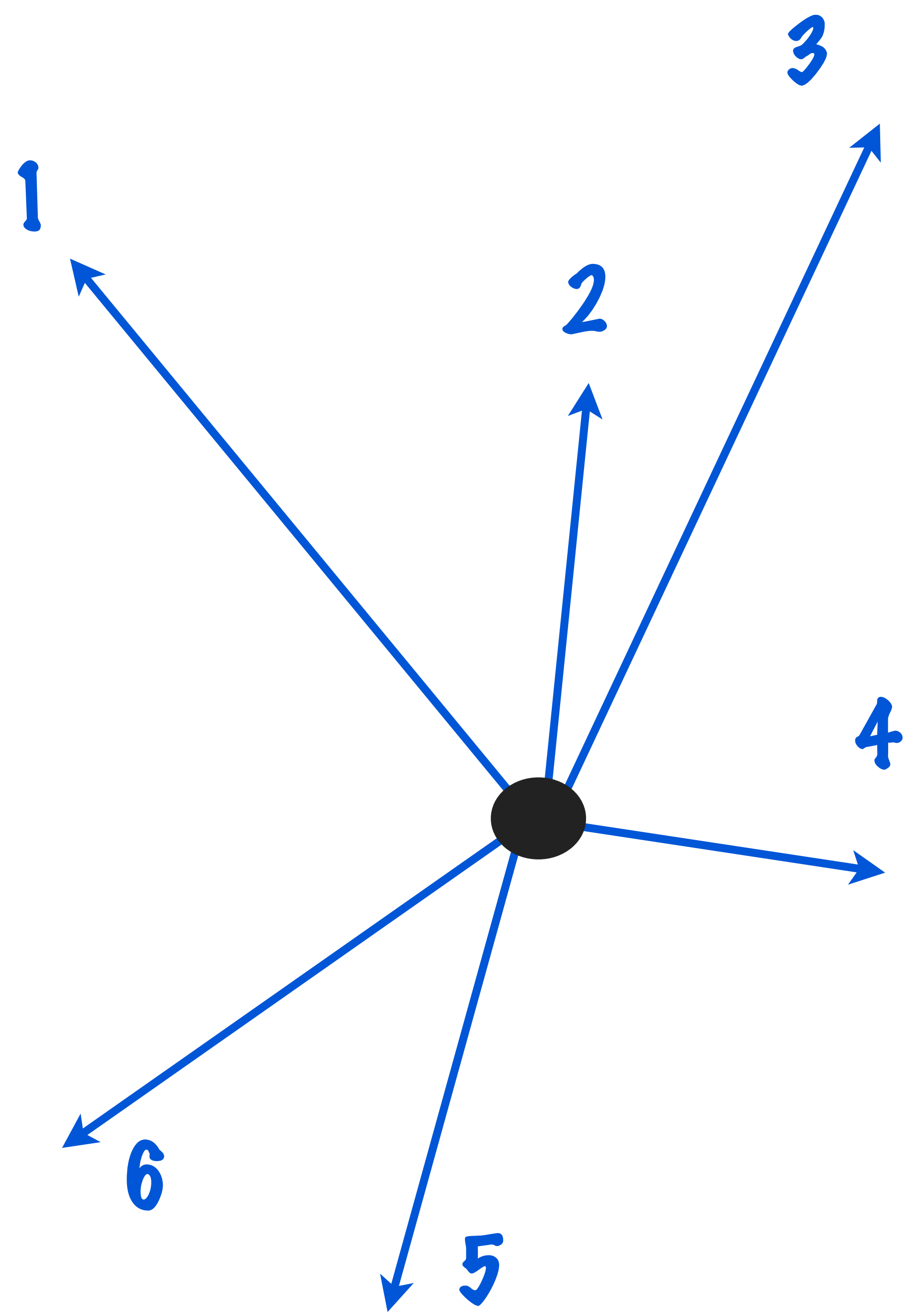
we use the C/A (angle ordered shower) throughout

more info? see talk by B. Tweedie at BOOST 2010

http://www.physics.ox.ac.uk/boost2010/index.asp

Making and breaking jets

find the minimum: $\min\left(d_{ij}, d_i\right)$

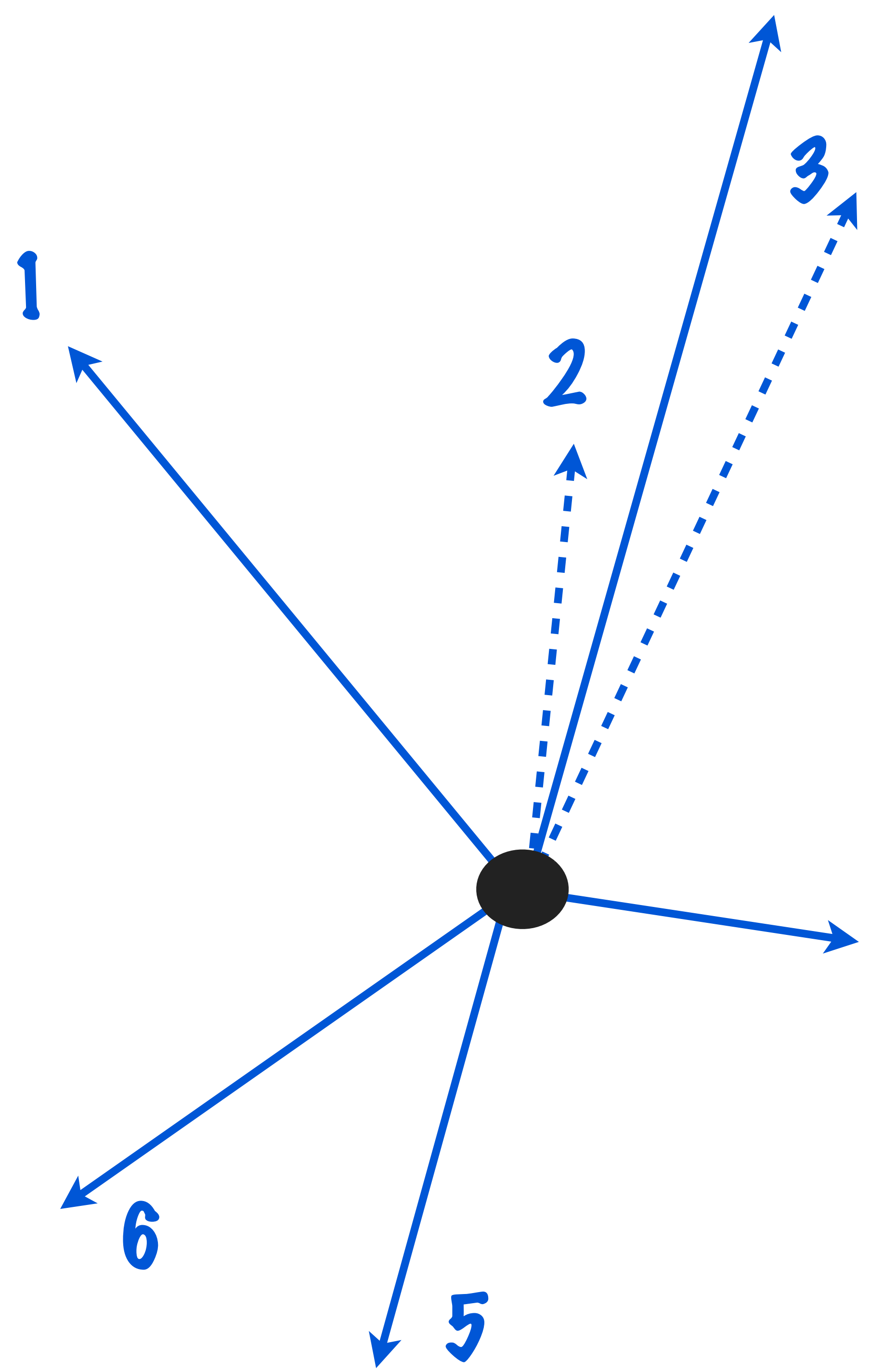


if min is one of the d_{ij}**,**
replace $\mathrm{particle}_j$ **and** $\mathrm{particle}_i$
with $\vec{k} = \vec{i} + \vec{j}$

and repeat...

Making and breaking jets

find the minimum: $\min\left(d_{ij}, d_i\right)$



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replace particle_j and particle_i
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Making and breaking jets

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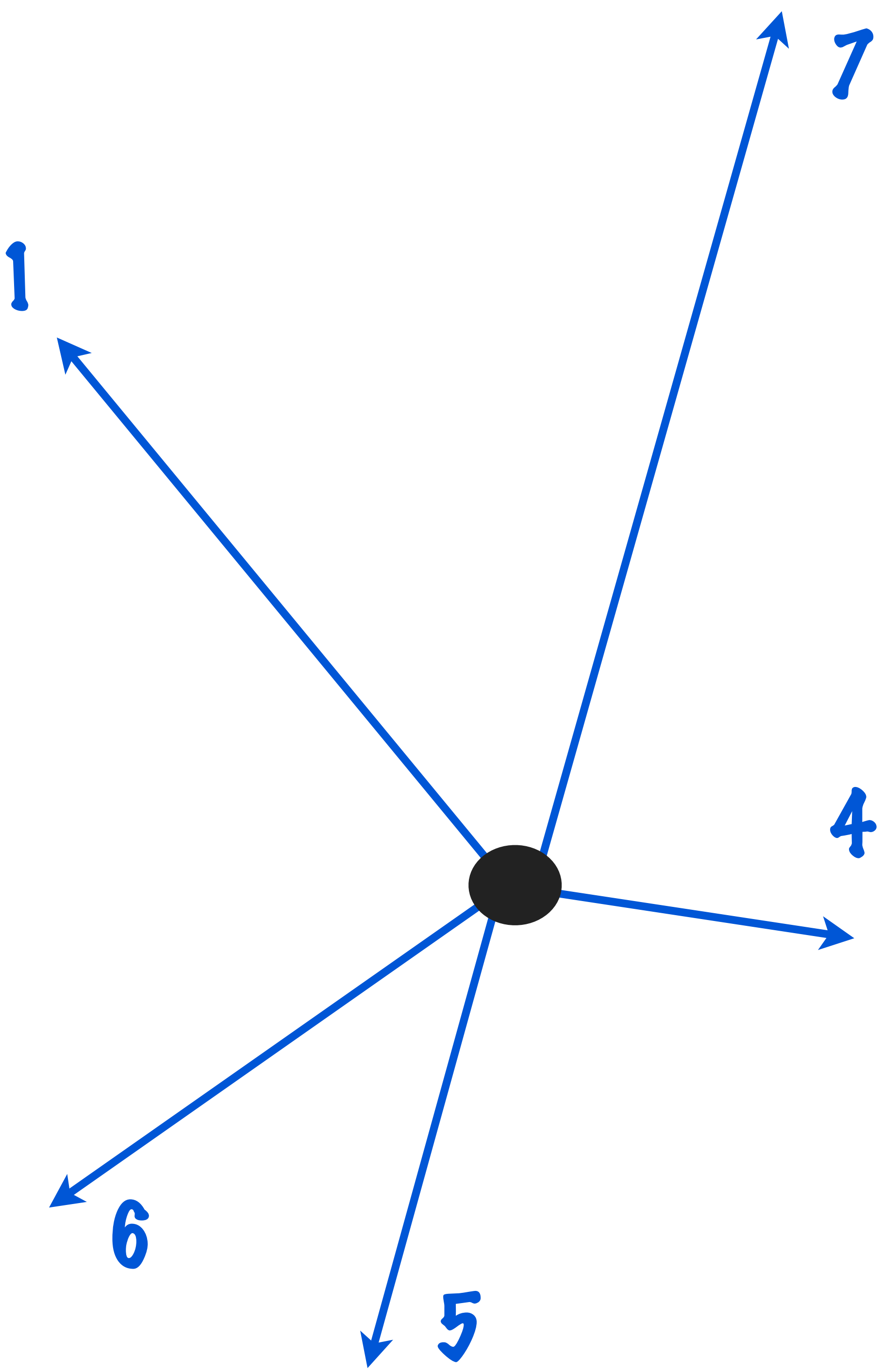

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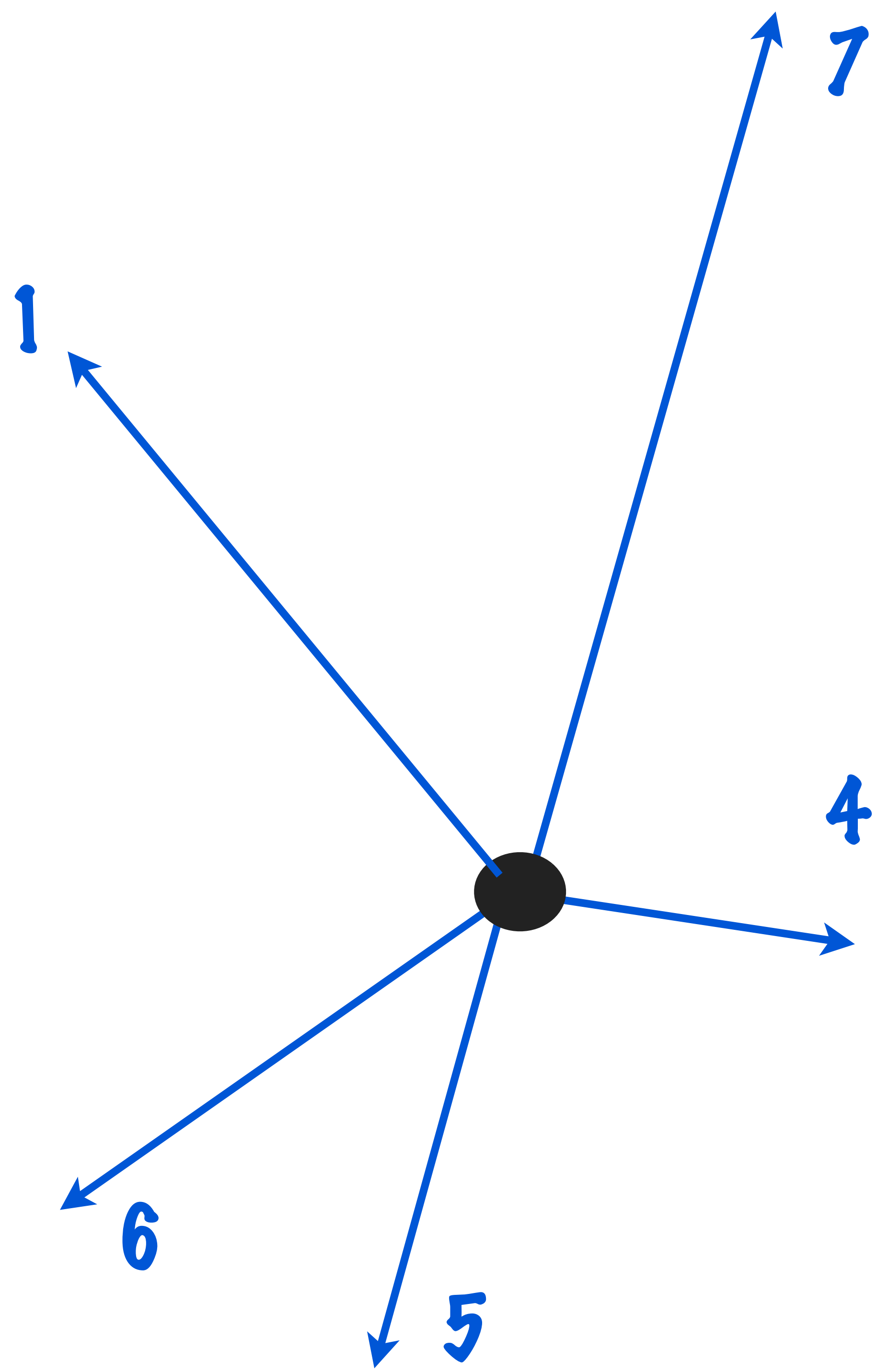
Making and breaking jets

if $\min(d_{ij}, d_i)$ is one of the d_i



promote $\mathrm{particle}_i$ to a jet,
and remove it from the list

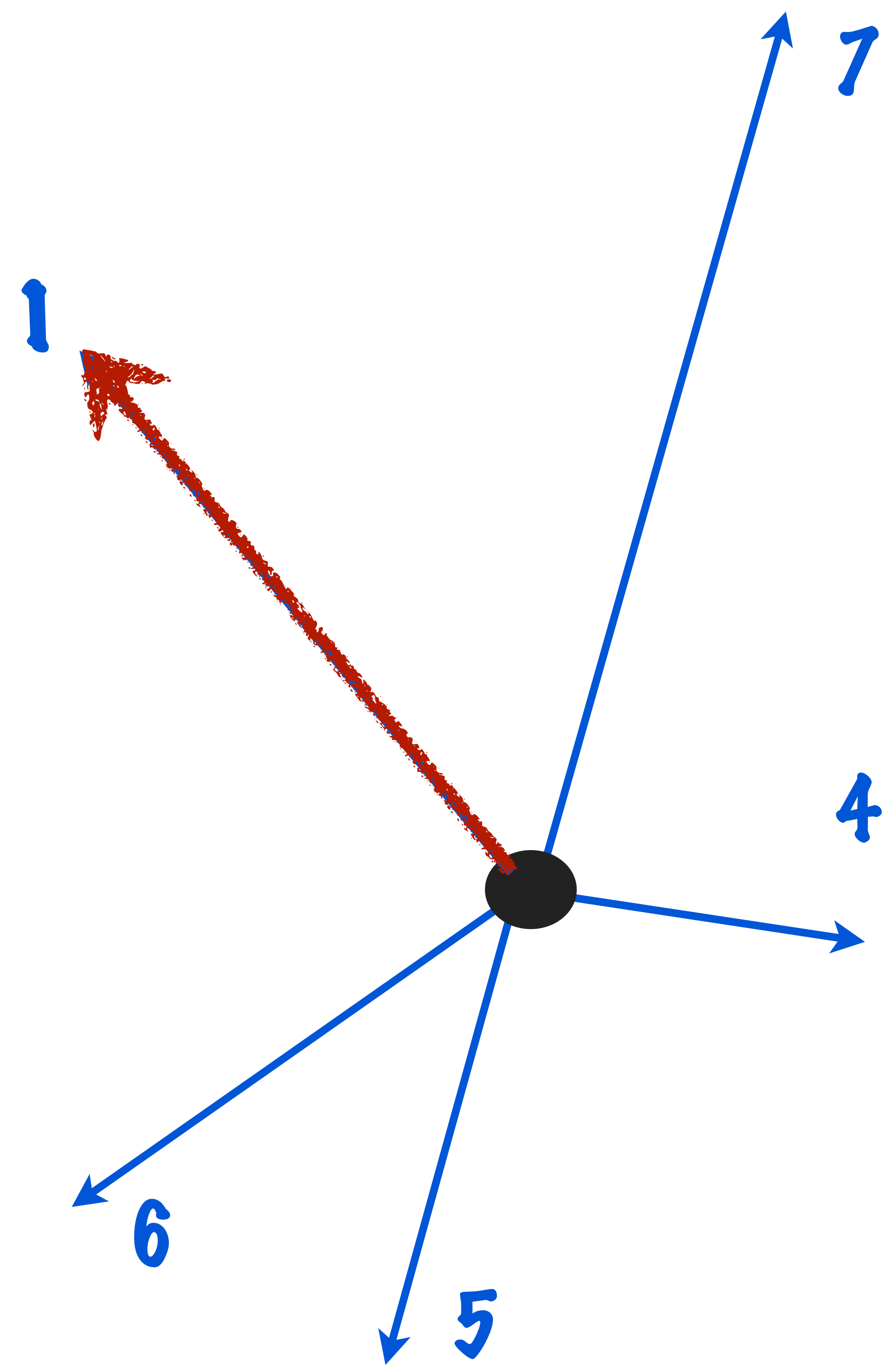
repeat the procedure until the list is empty

jet area = R controls when to stop combining objects (d_{ij})

'typically' R = 0.4 - 0.7

Making and breaking jets

if $\min\left(d_{ij}, d_i\right)$ is one of the d_i



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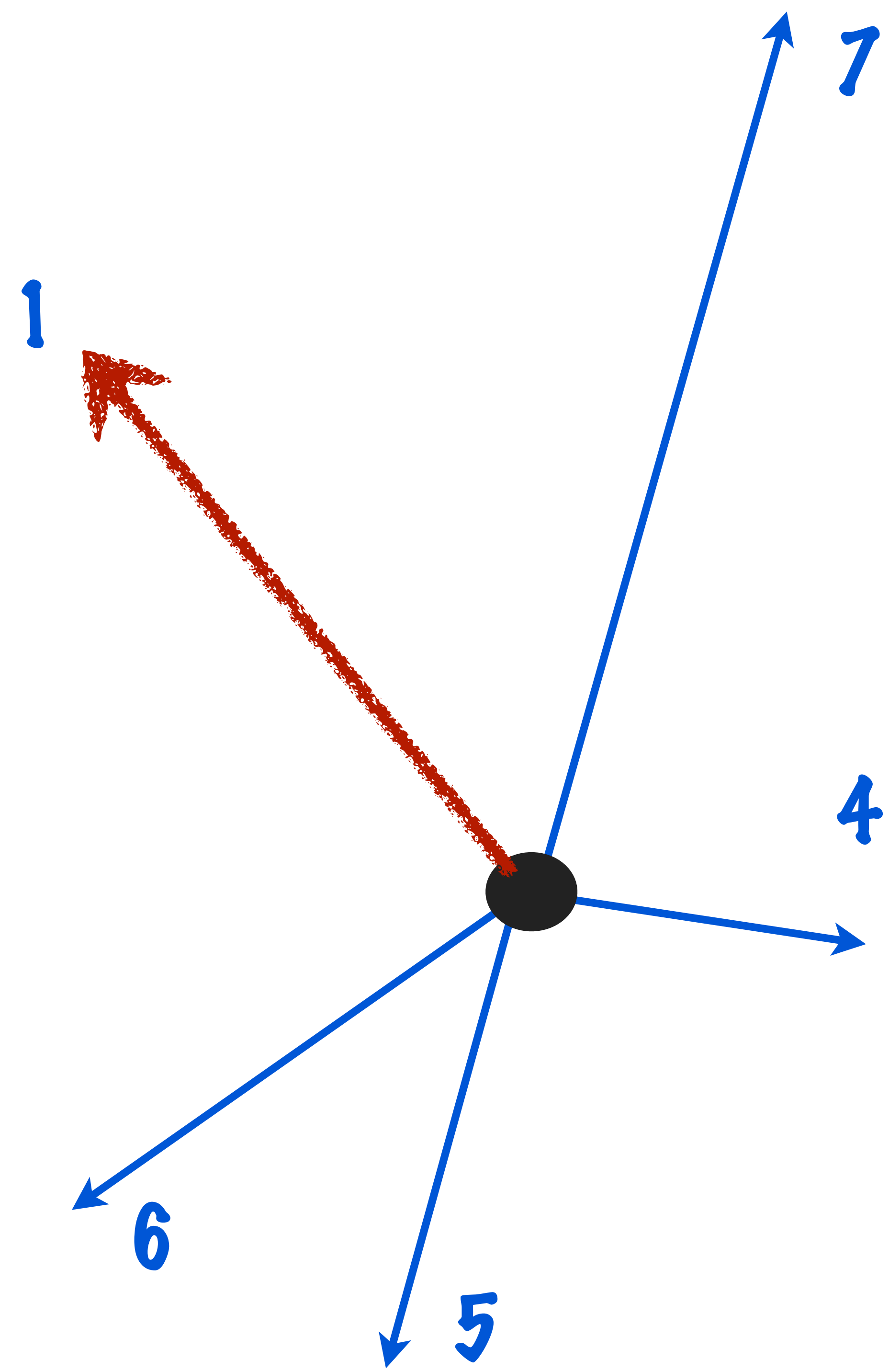

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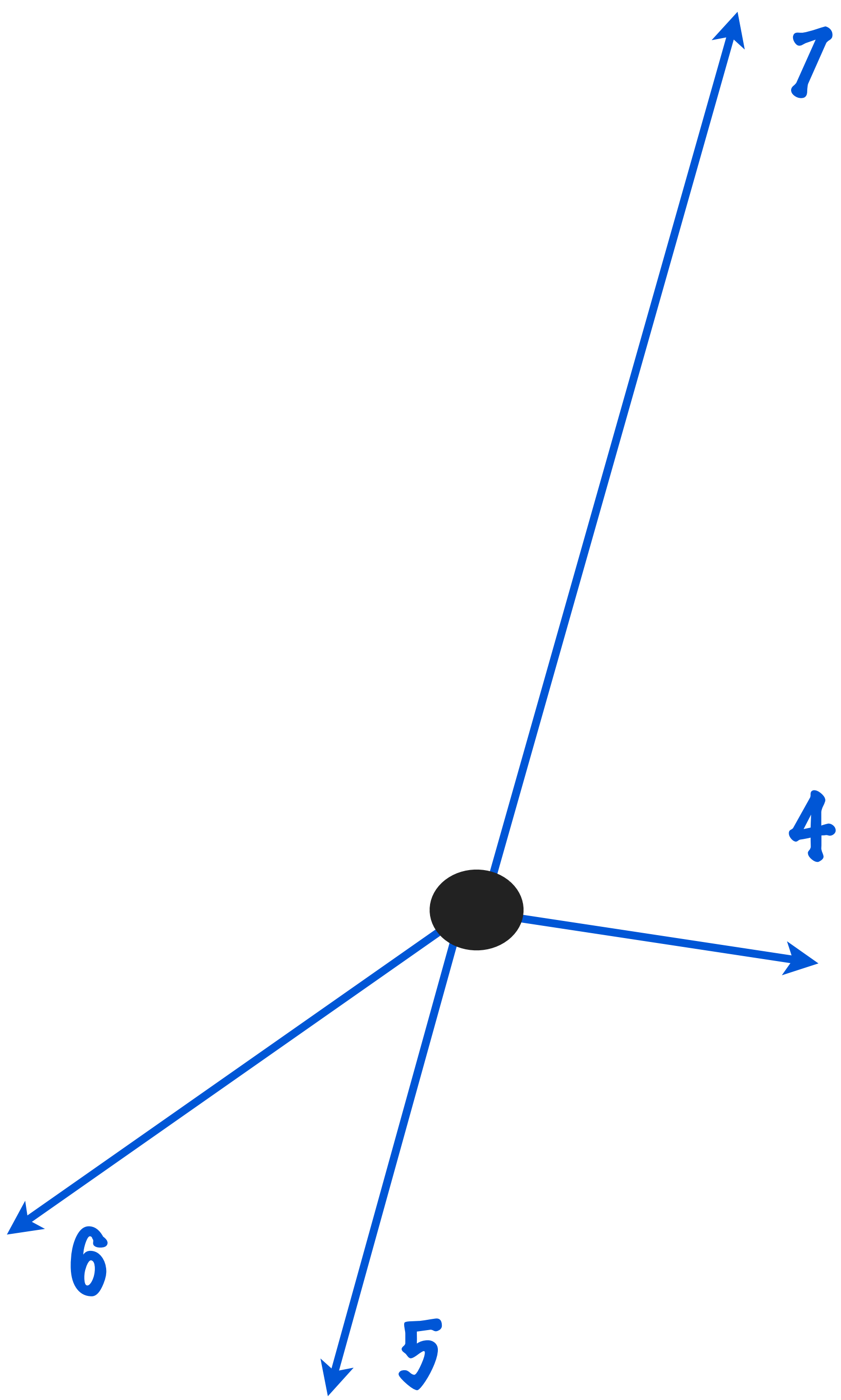

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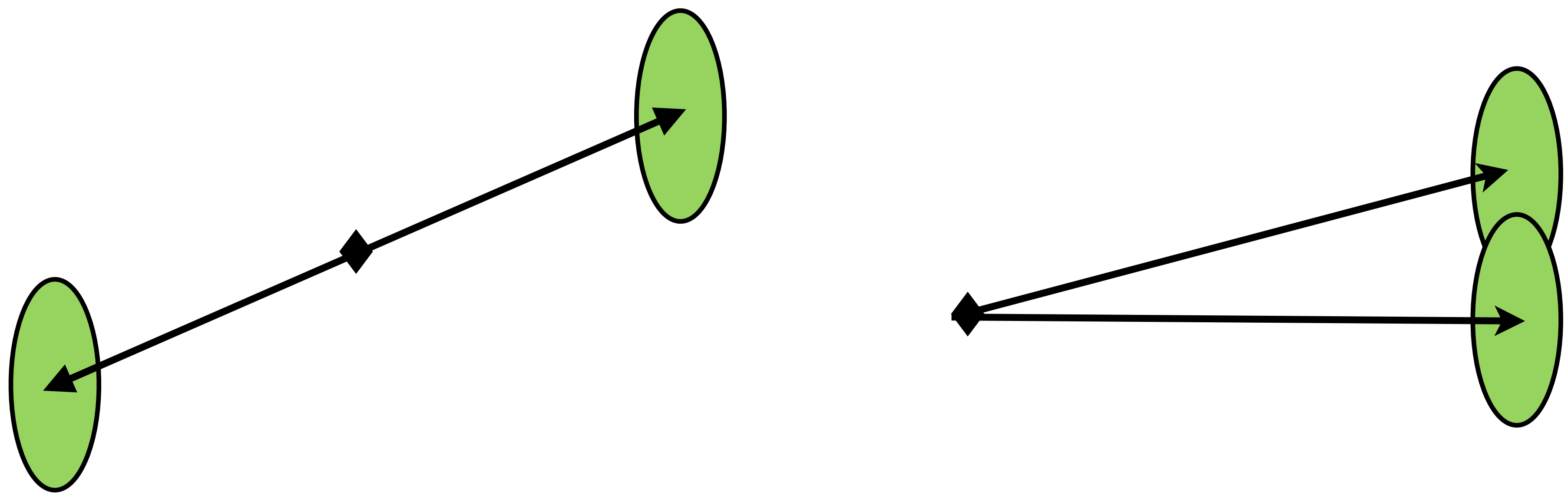
Jet substructure basics

when a heavy particle (Higgs) is boosted, its decay remnants get closer together in the detector



both decay products (and their associated radiation) can be captured by taking a larger jet cone -- resulting in a single 'fat-jet', R = 1.2 - 1.5

these 'resonance fat jets' have several distinct characteristics, which we can use to our advantage

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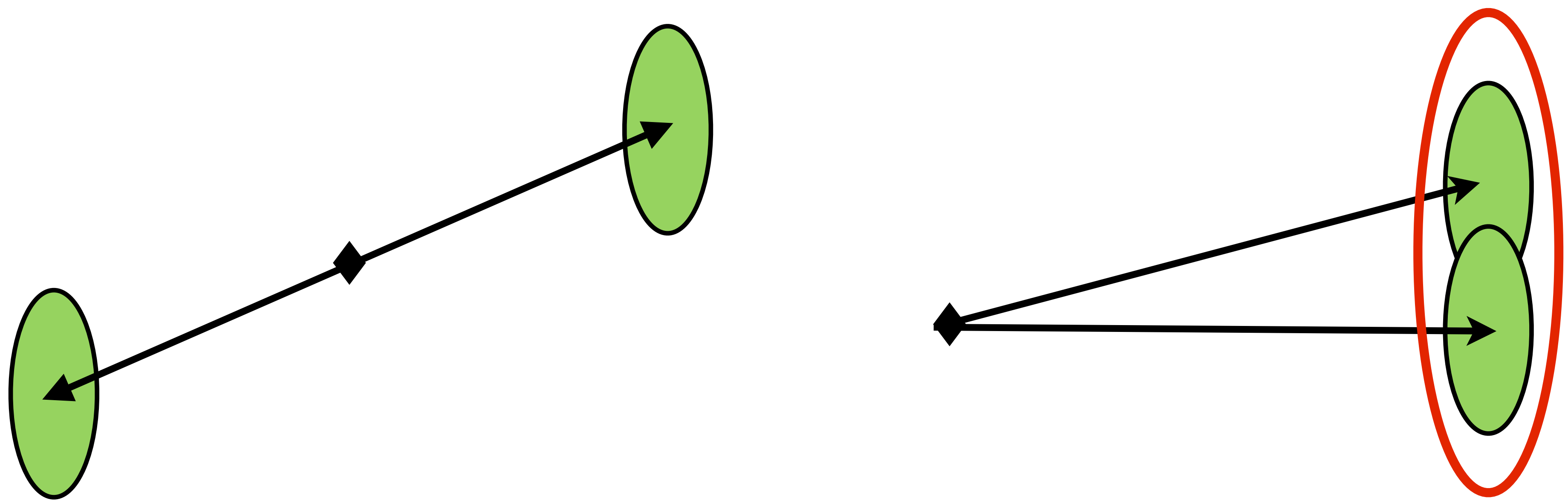

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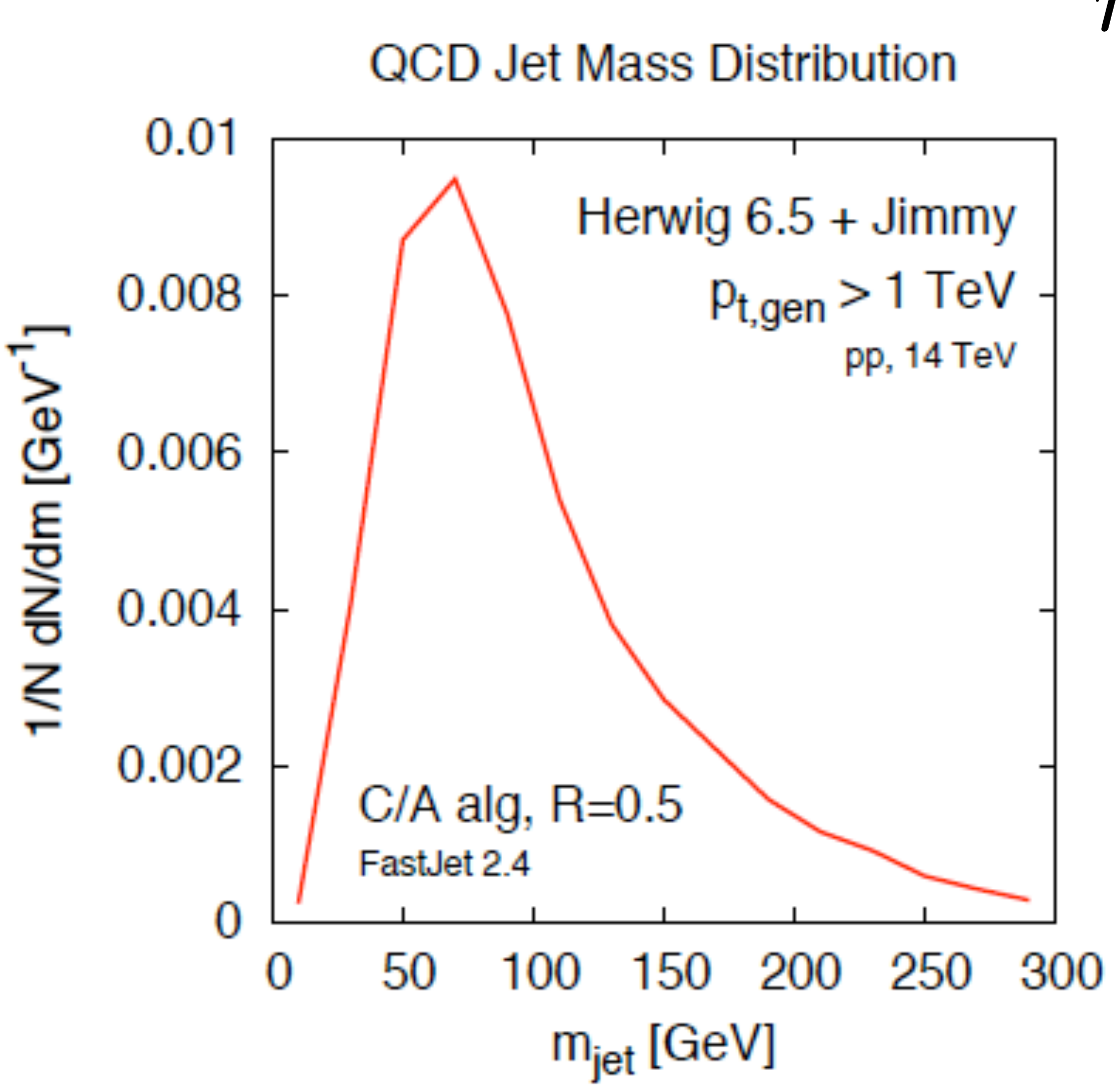
Jet substructure basics

1.) 'resonance fat jets' have high invariant mass

$$m_J \sim m_h$$



while we don't think of QCD jets as having high mass

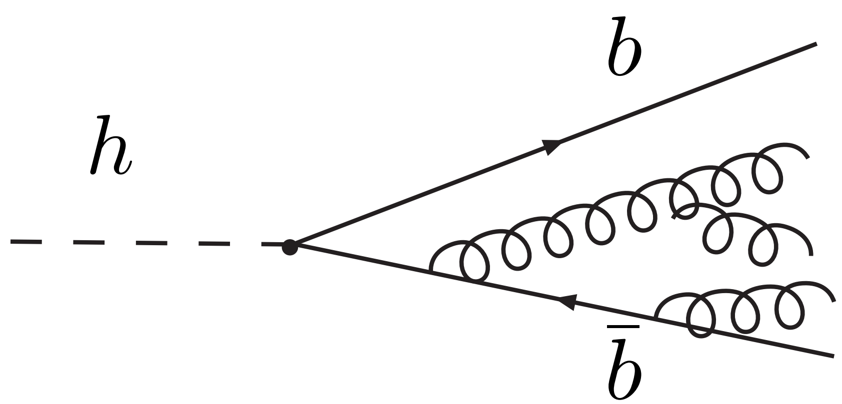
BUT there is a whole lot of QCD! tails extend to signal region

high jet-mass alone is not enough

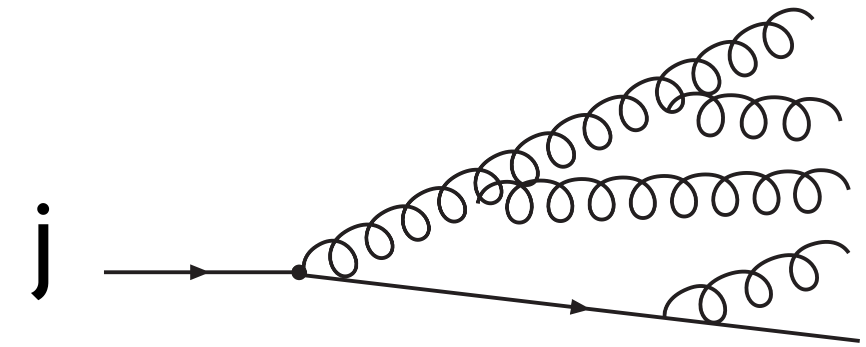
unlike boosted top, we want 2-body decay structure, and there is no longer a W among subjets

Jet substructure basics

2.) fat jets from resonance vs. QCD have very different origin



vs.

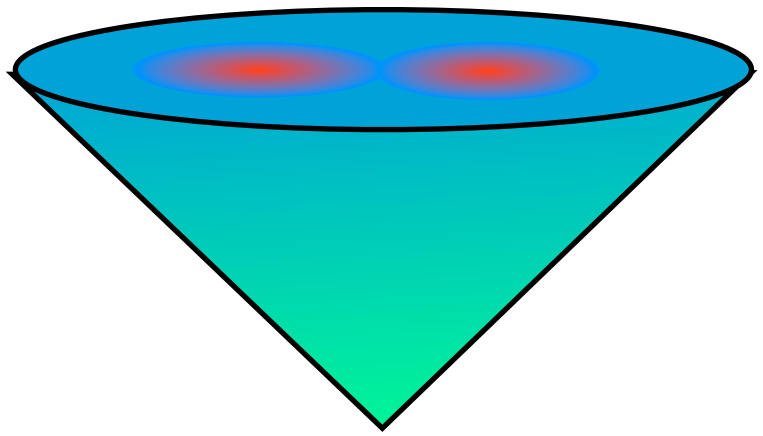


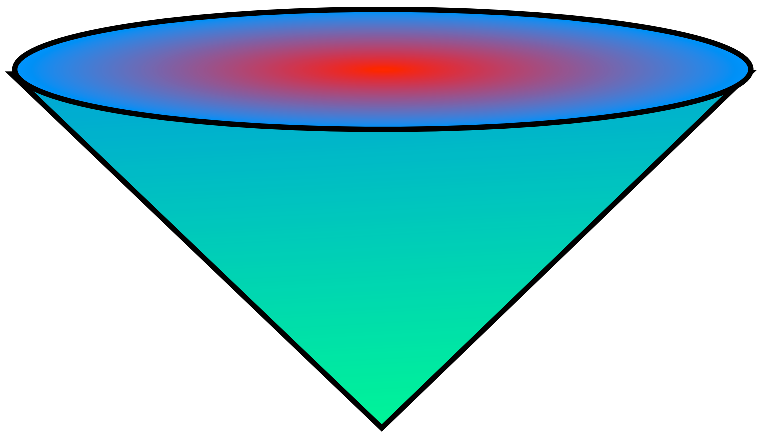
heavy particle decaying to two light particles

QCD radiation

expect two 'cores' of energy deposition within the jet

mainly gluon emission, dominated by soft, collinear emissisons

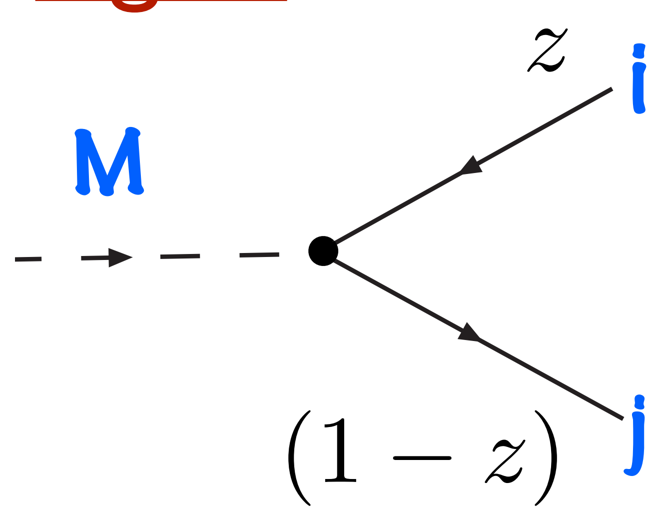




Mass drop & energy asymmetry

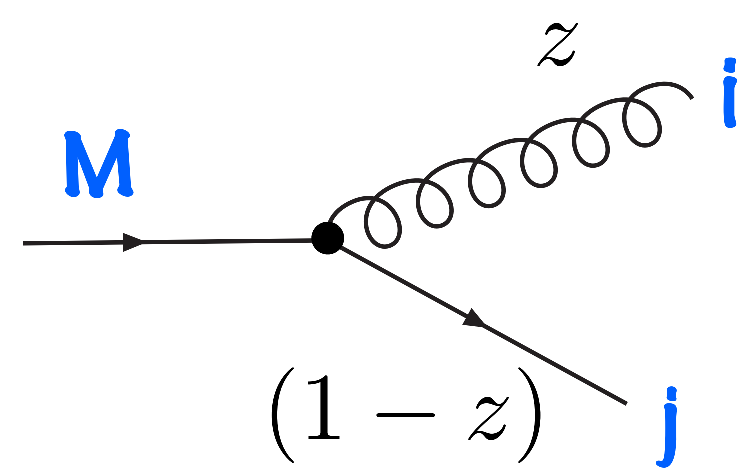
Jets are built from a series of 2 -> 1 mergings (k_T, C/A, anti-k_T)

Signal



$P_{1\to 2}(z) \propto$ independent of z

Background



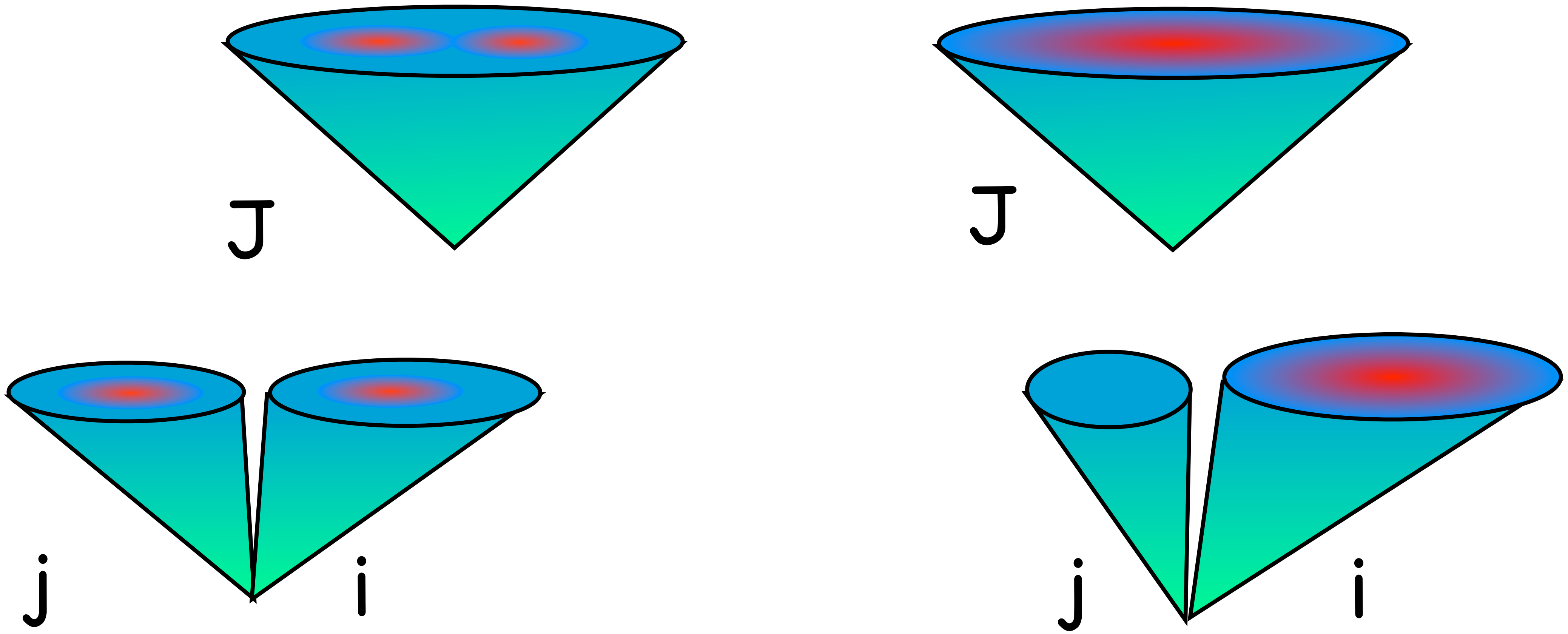
$P_{1\to 2}(z) \propto$ singular as z -> 0

energy is shared evenly in a heavy particle decay, while uneven sharing configurations dominate the background

cut on z removes background!

Mass drop & energy asymmetry

In practice, 'undo' the jets step by step : J -> i + j



Keep events where, at some stage: (Butterworth, et al '08)

1.) $m_i < \mu \, m_J$

2.) $\dfrac{\min(p_{T_i}^2, p_{T_j}^2)}{m_J^2} \Delta R_{ij}^2 > (y_{cut})^2$

Mass drop & energy asymmetry

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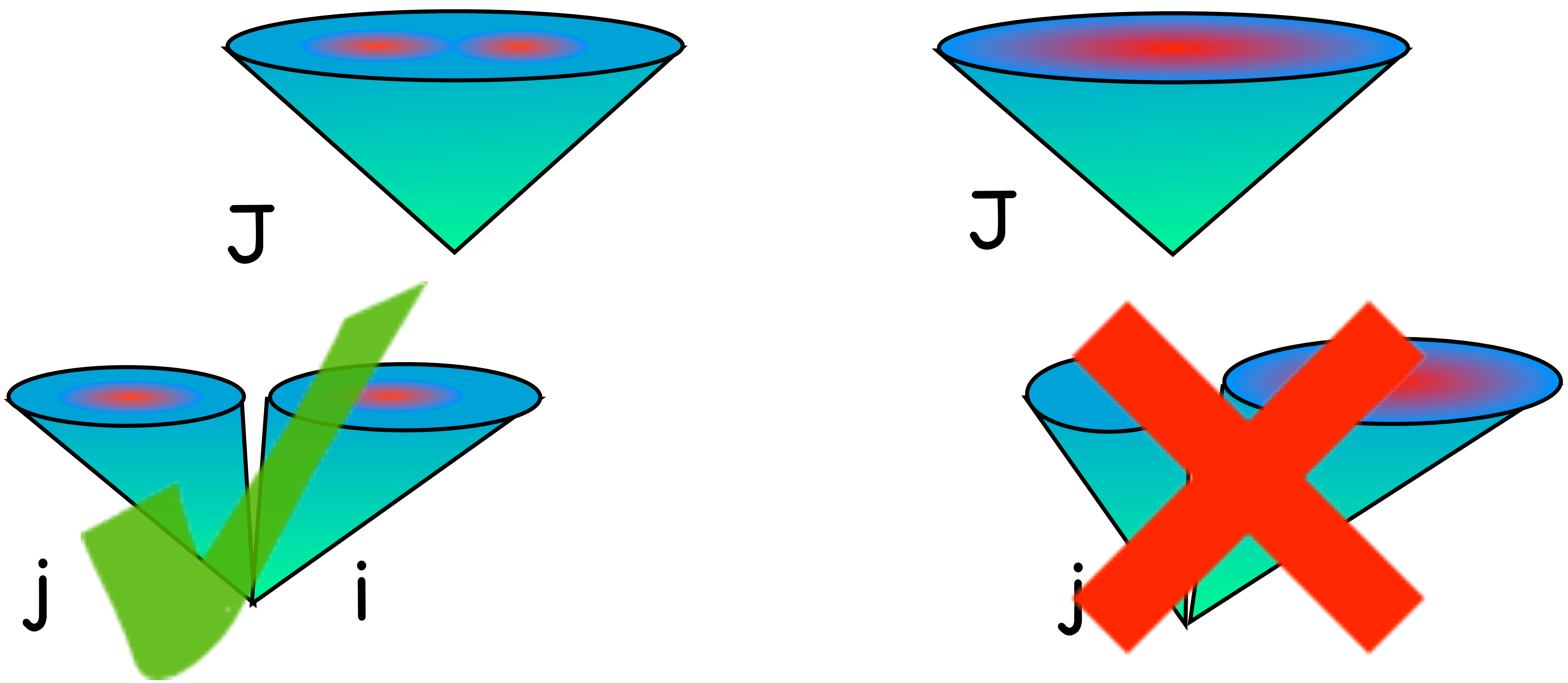

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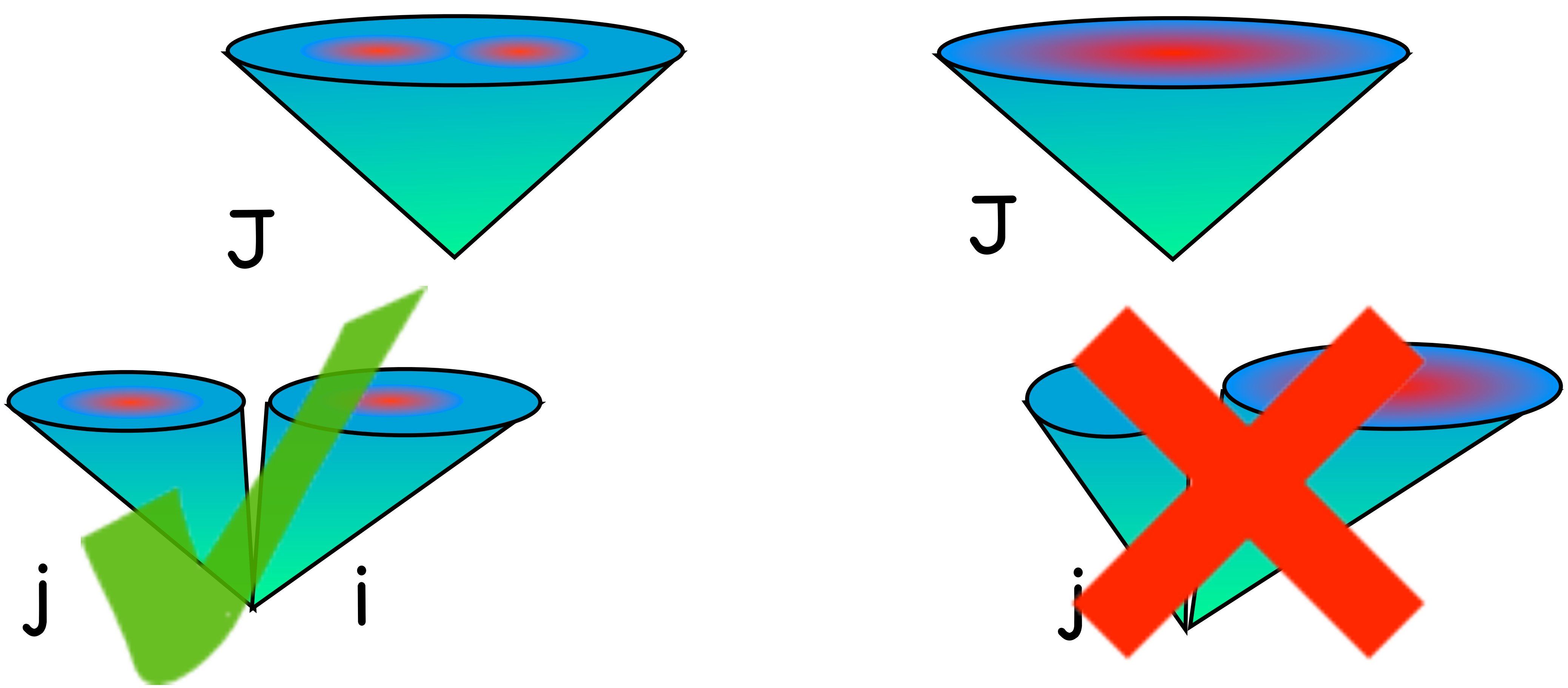

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2.) $\frac{\min(p_{T_i}^2, p_{T_j}^2)}{m_J^2} \Delta R_{ij}^2 > (y_{cut})^2$ $\quad \frac{\min(E_i, E_j)}{E_J} \equiv z$

Mass drop & energy asymmetry

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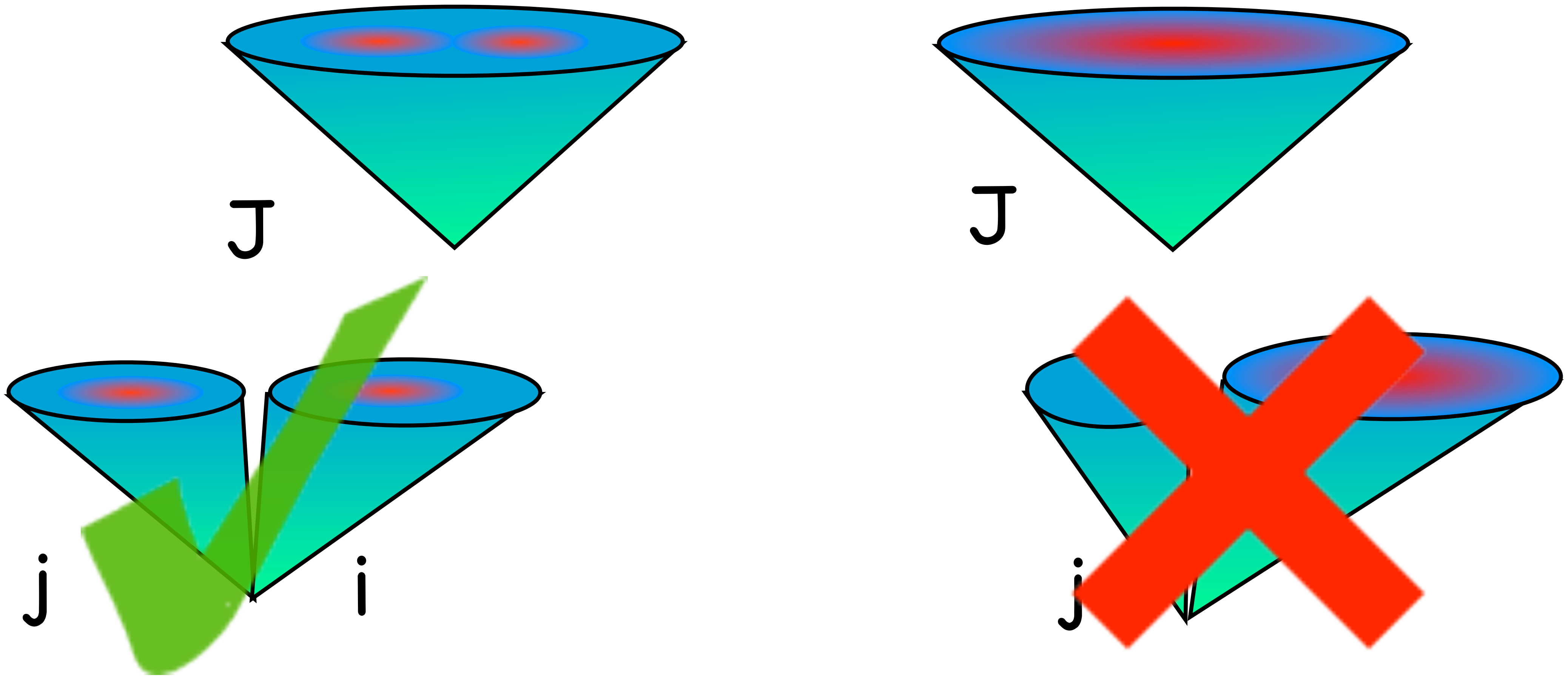


Keep events where, at some stage: (Butterworth, et al '08)

BDRS numbers

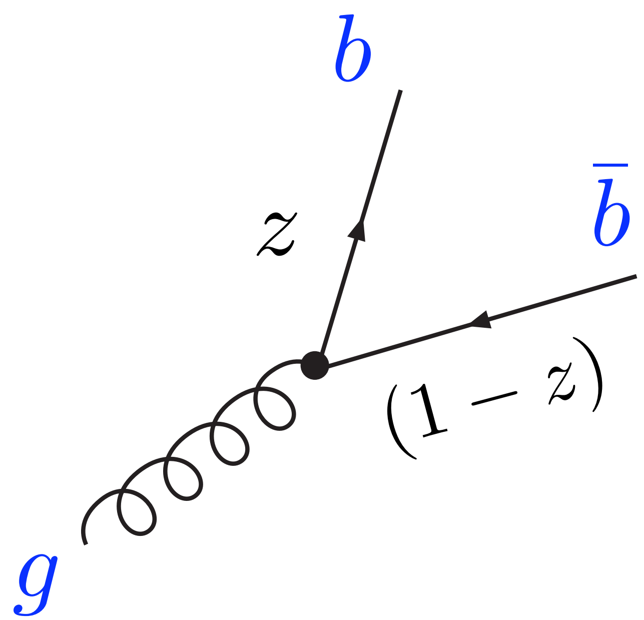
1.) $m_i < 0.68\, m_J$

2.) $\frac{\min(p_{T_i}^2, p_{T_j}^2)}{m_J^2} \Delta R_{ij}^2 > (0.3)^2$

$$\frac{\min\left(E_i, E_j\right)}{E_J} \equiv z$$

Mass drop & energy asymmetry

What about g-> b bbar ?



$P_{1\to 2}(z) \propto$ not singular in z

not removed by z-cut

BUT:

- because there is no singularity, g -> q qbar is a subleading process in the shower
- b bbar pairs will have low invariant mass, removed by looking at large jet mass

Filtering/Trimming/Pruning

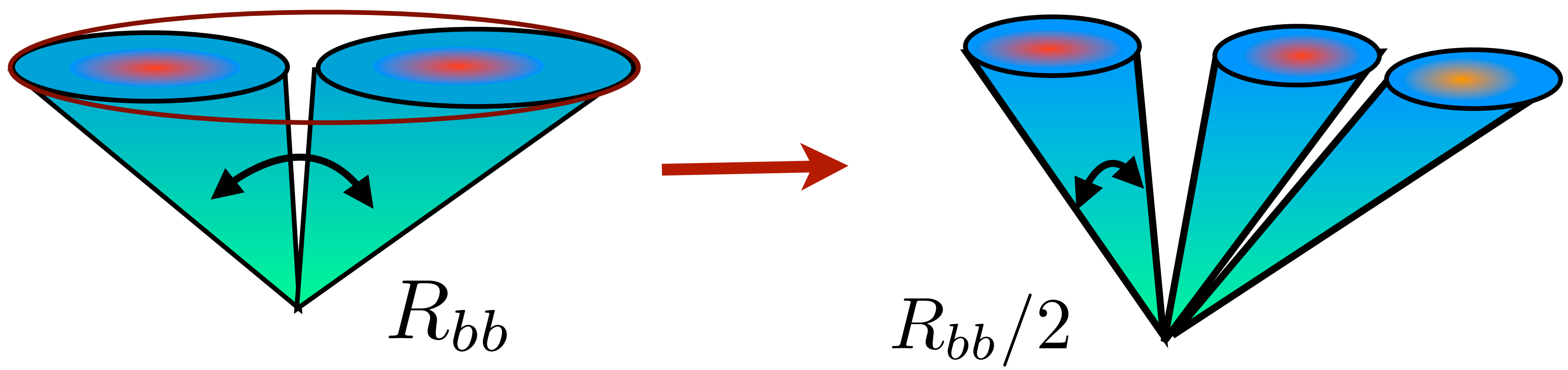
(Krohn et al 0912.1342) (Ellis et al 0912.0033)

the downside of a large cone is that it allows in a lot of energy unrelated to the resonance: UE and ISR

different techniques to try to subtract off the unwanted noise

Ex. Filtering

(Butterworth, et al '08)



refine jets on smaller scale, take only n_{filt} hardest

keeps perturbative, angle-ordered radiation, throws out the rest

not your 'garden-variety' jet tool !

Putting everything together

signal

R = 1.2, C/A

background

hard partons, FSR, ISR, UE

Putting everything together

signal R = 1.2, C/A background

hard partons, FSR, ISR, UE

undo jet clustering...

Putting everything together

signal

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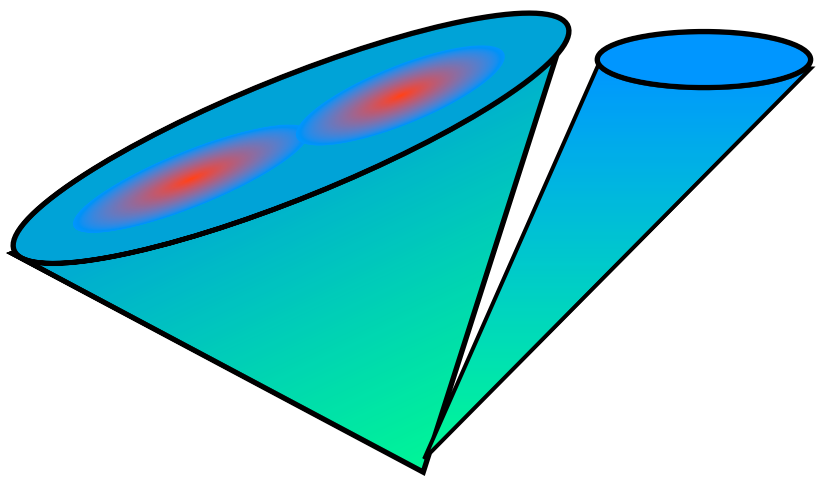

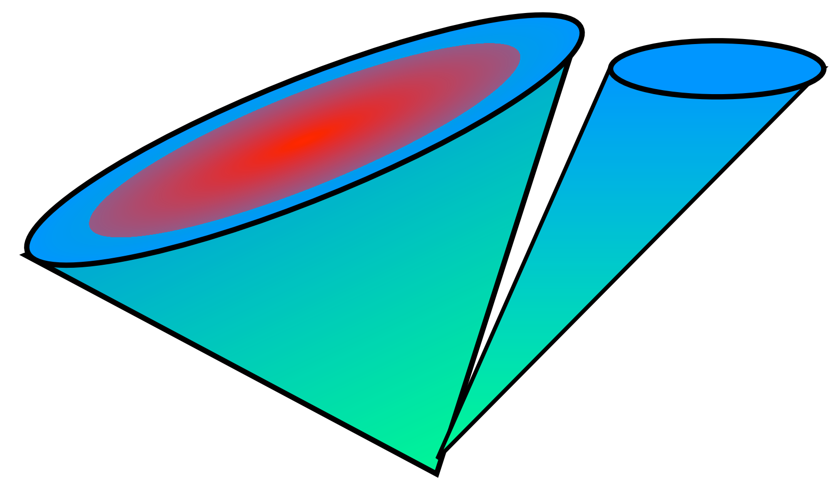

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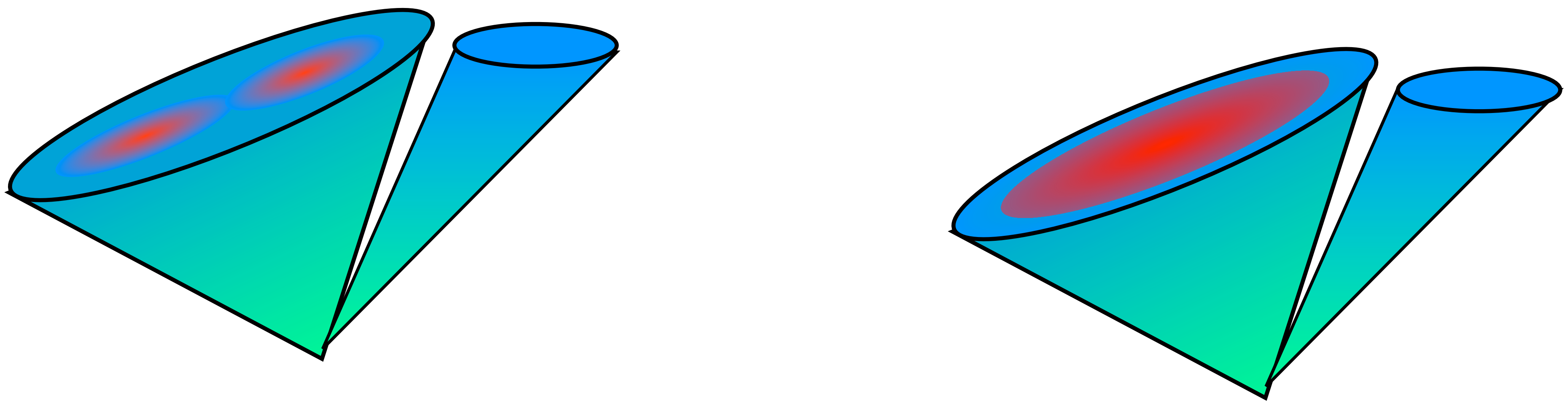

undo jet clustering...

if mass drop conditions **not satisfied**, throw away lighter daughter jet, continue

1.) $m_i < 0.68\, m_J$

2.) $$\frac{\min(p_{T_i}^2, p_{T_j}^2)}{m_J^2} \Delta R_{ij}^2 > (0.3)^2$$

Putting everything together

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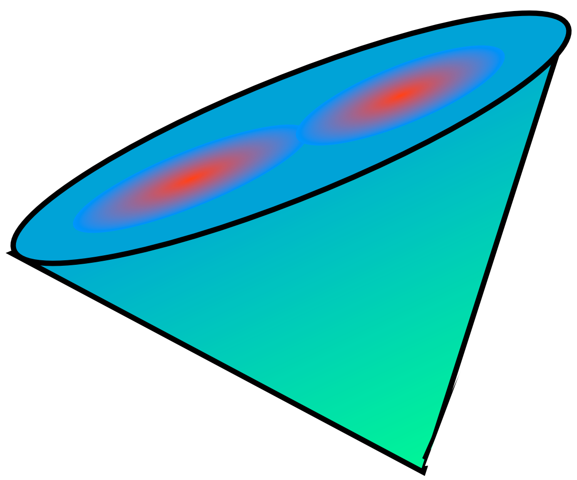

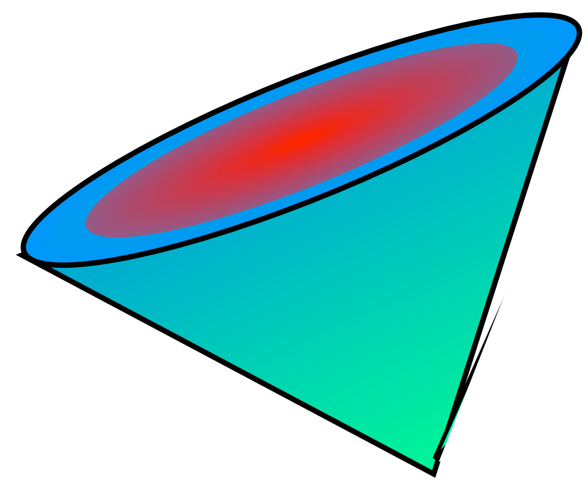

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Putting everything together

signal — R = 1.2, C/A — background

undo jet clustering...

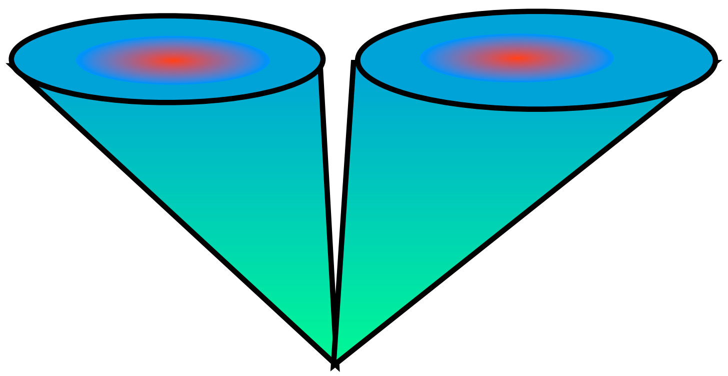
if mass drop conditions **not satisfied**, throw away lighter daughter jet, continue

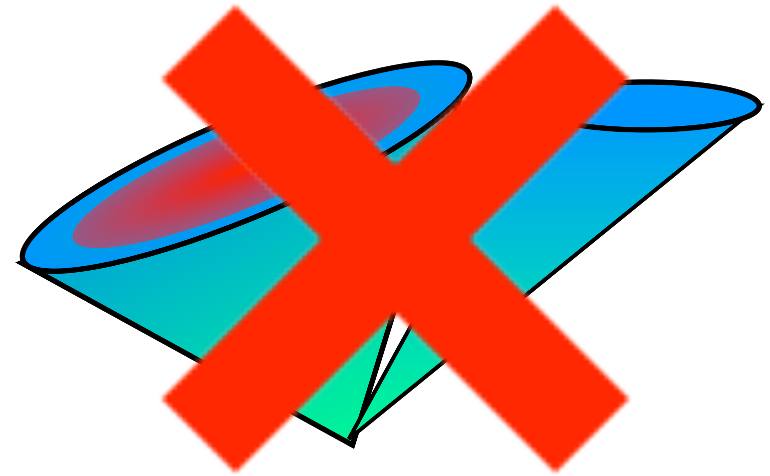
1.) $m_i < 0.68\, m_J$

2.) $\dfrac{\min(p_{T_i}^2, p_{T_j}^2)}{m_J^2} \Delta R_{ij}^2 > (0.3)^2$

Putting everything together

signal R = 1.2, C/A background



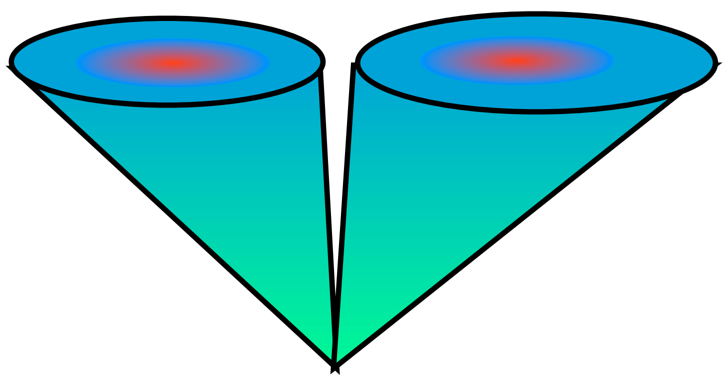


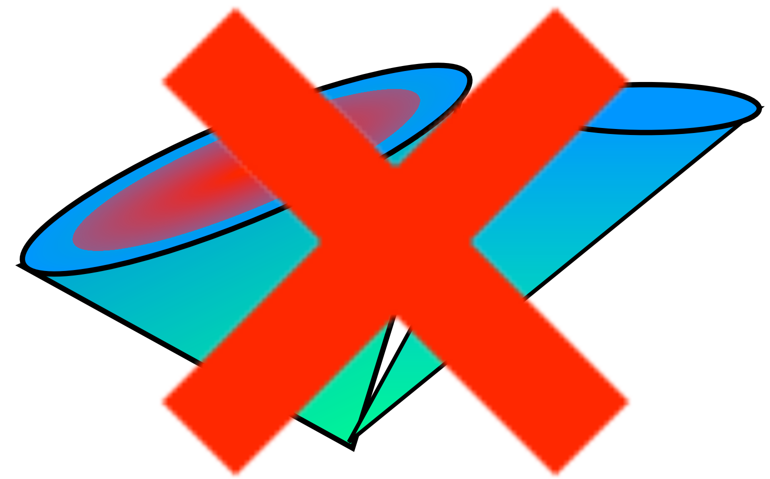
undo jet clustering...

at some stage, h->b bbar signal should pass mass-drop conditions, while QCD background will not

Putting everything together

signal R = 1.2, C/A background





undo jet clustering...

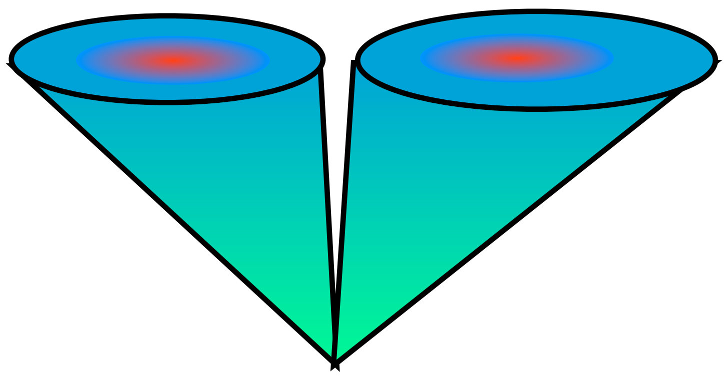
at some stage, h->b bbar signal should pass mass-drop conditions, while QCD background will not

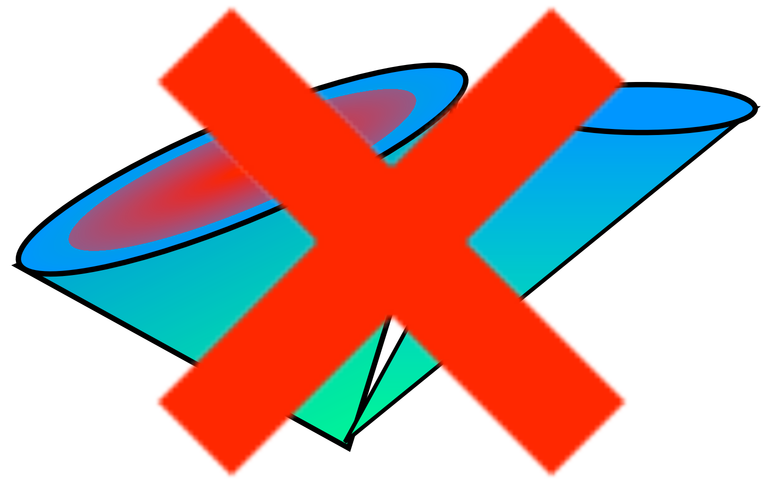
both b-tagged? if YES, then Filter

keep the hard partons, their perturbative radiation, throw away ISR/UE

Putting everything together

signal R = 1.2, C/A background





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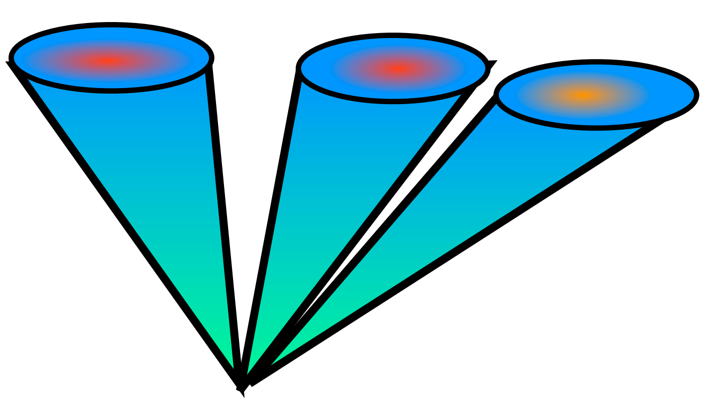

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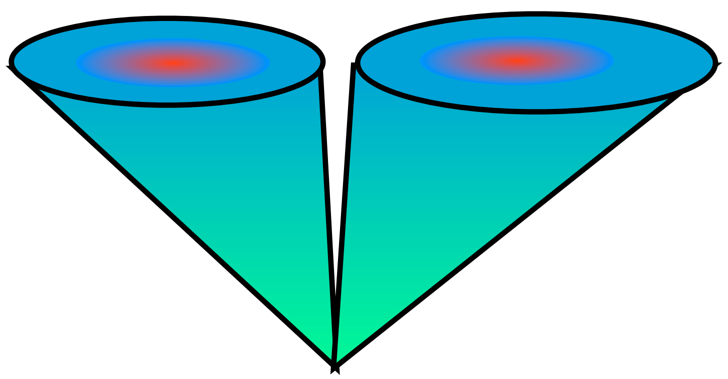

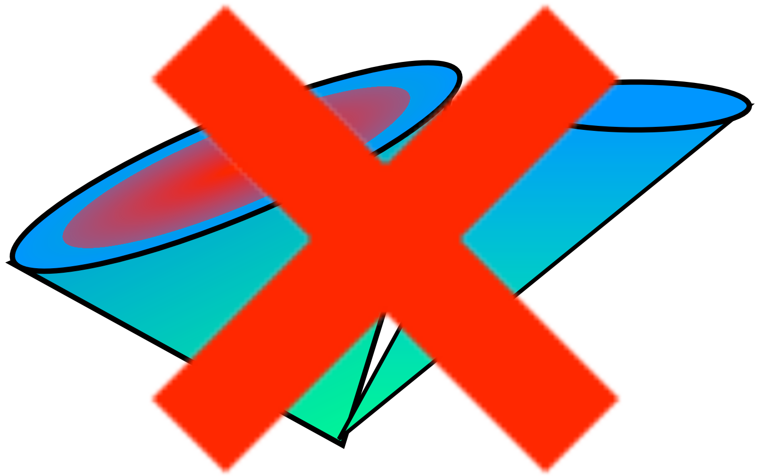

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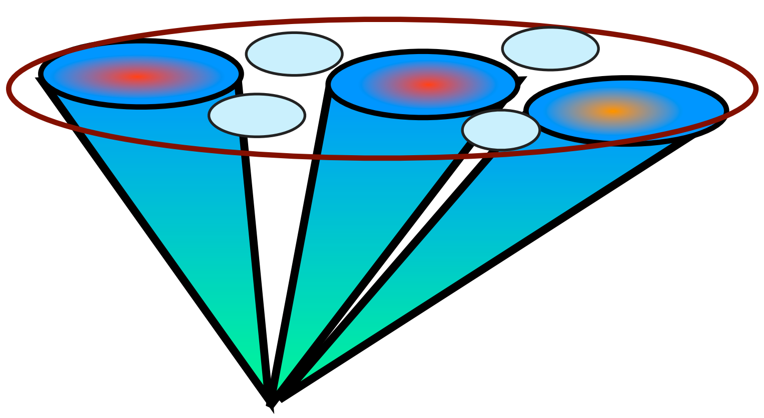


both b-tagged? if YES, then Filter

keep the hard partons, their perturbative radiation, throw away ISR/UE

Summarizing...

substructure analysis:

LOSE:

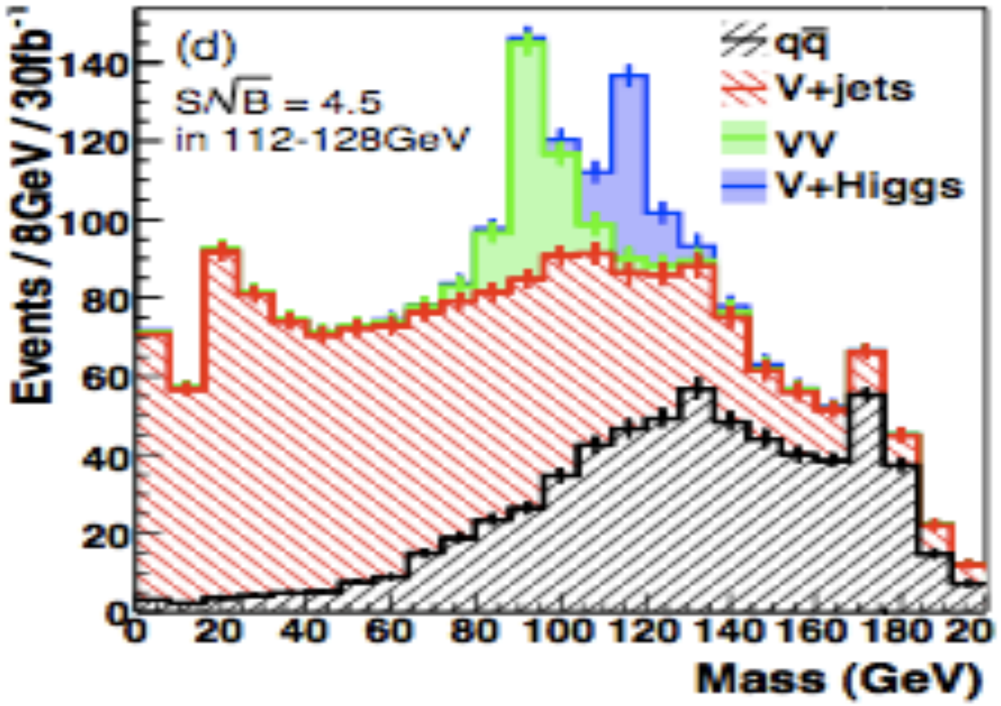
rate, as a significant boost (p_T > 200 GeV) is needed

GAIN:

1.) rejection over background through unique characteristics: high mass, structure

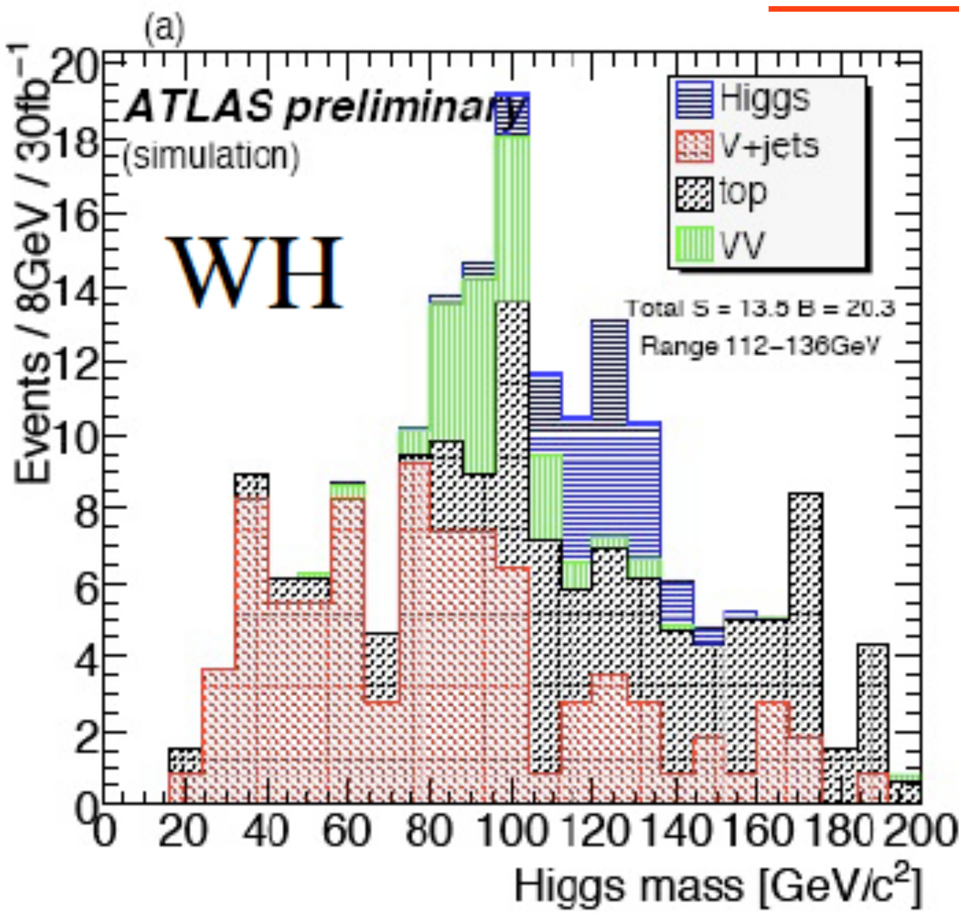
2.) resolution: combinatorics reduced, unwanted jet stuff (UE, ISR) rejected

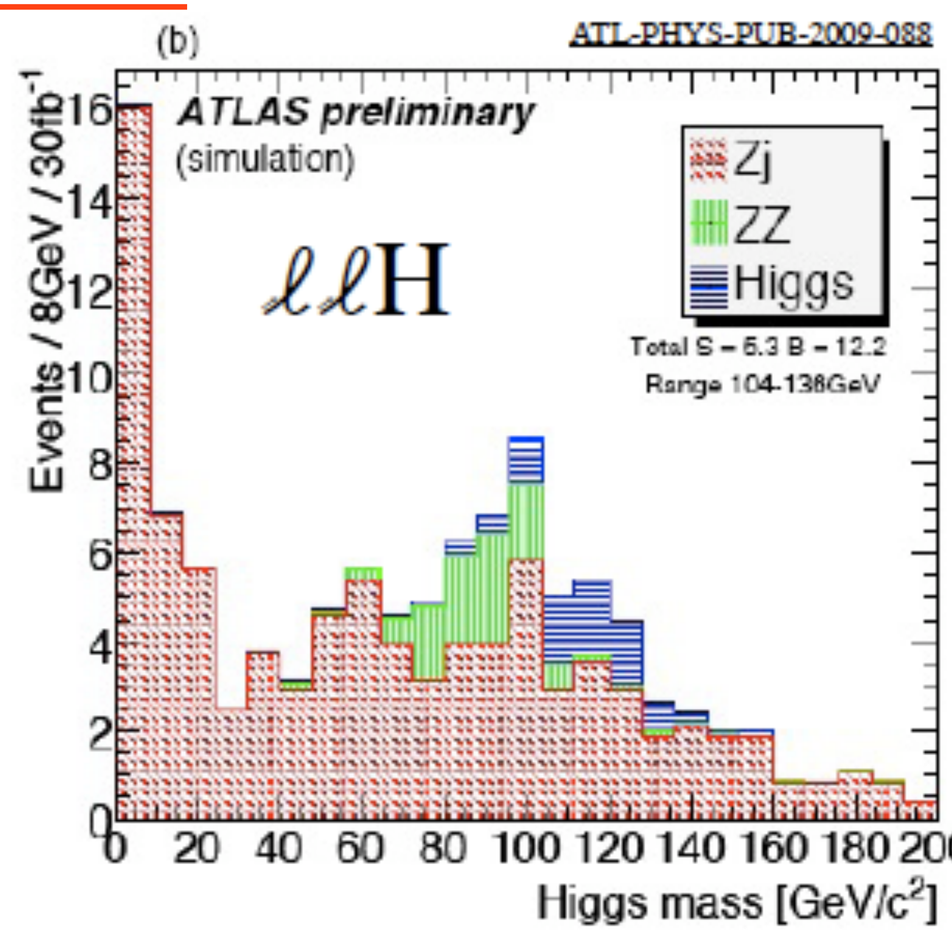
BDRS at ATLAS



- LHC 14 TeV; 30 fb^{-1}
- HERWIG/JIMMY cross-checked with PYTHIA with "ATLAS tune"
- 60% b-tag; 2% mistag
- no smearing

ATLAS STUDY

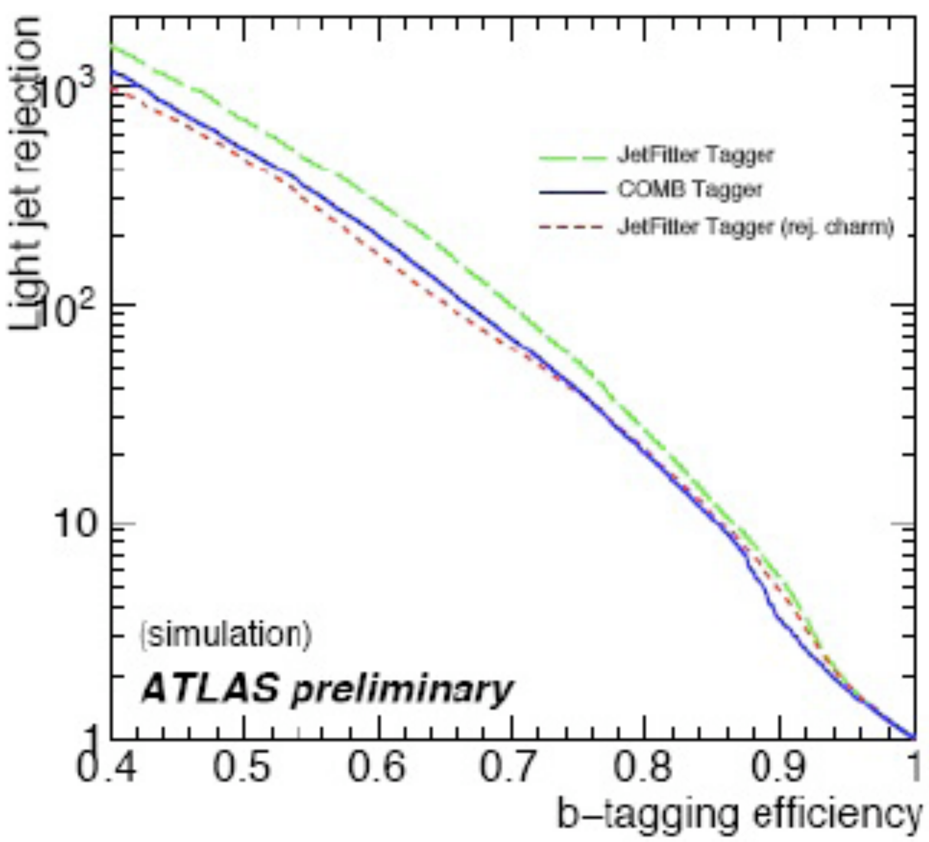


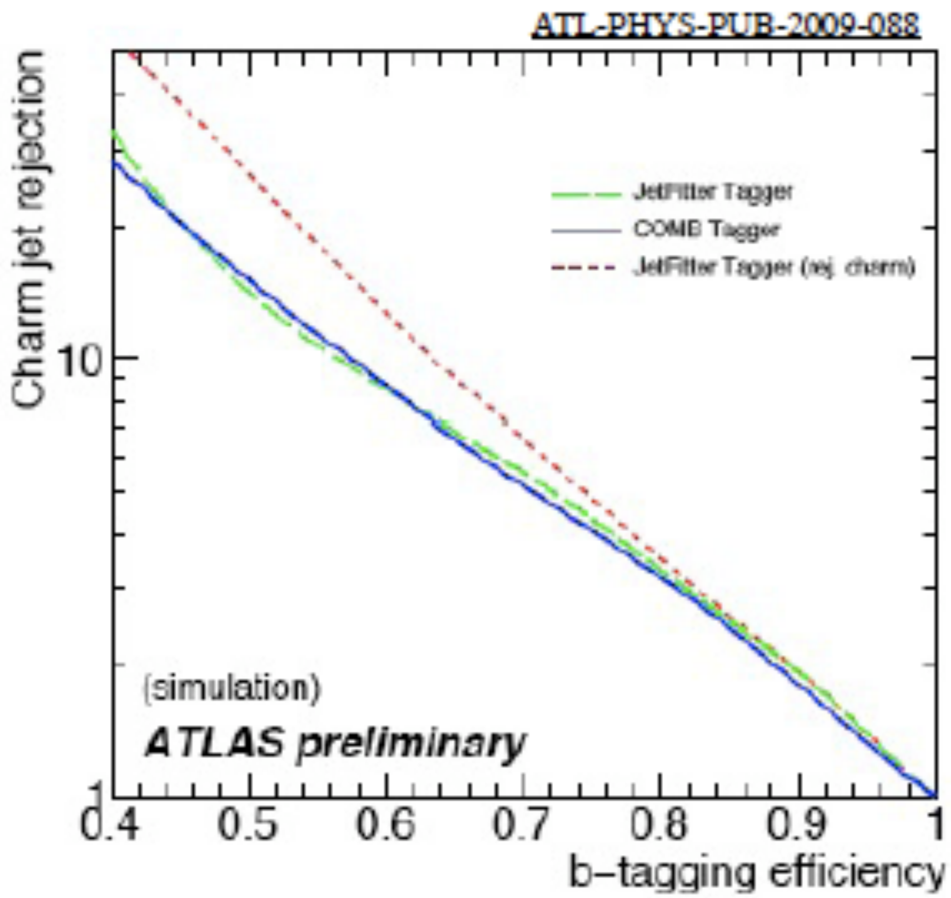


BDRS at ATLAS

ATLAS study: ~3.5σ at L = 30 fb^{-1}

b-tagging seems to work very will within jets with substructure





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:

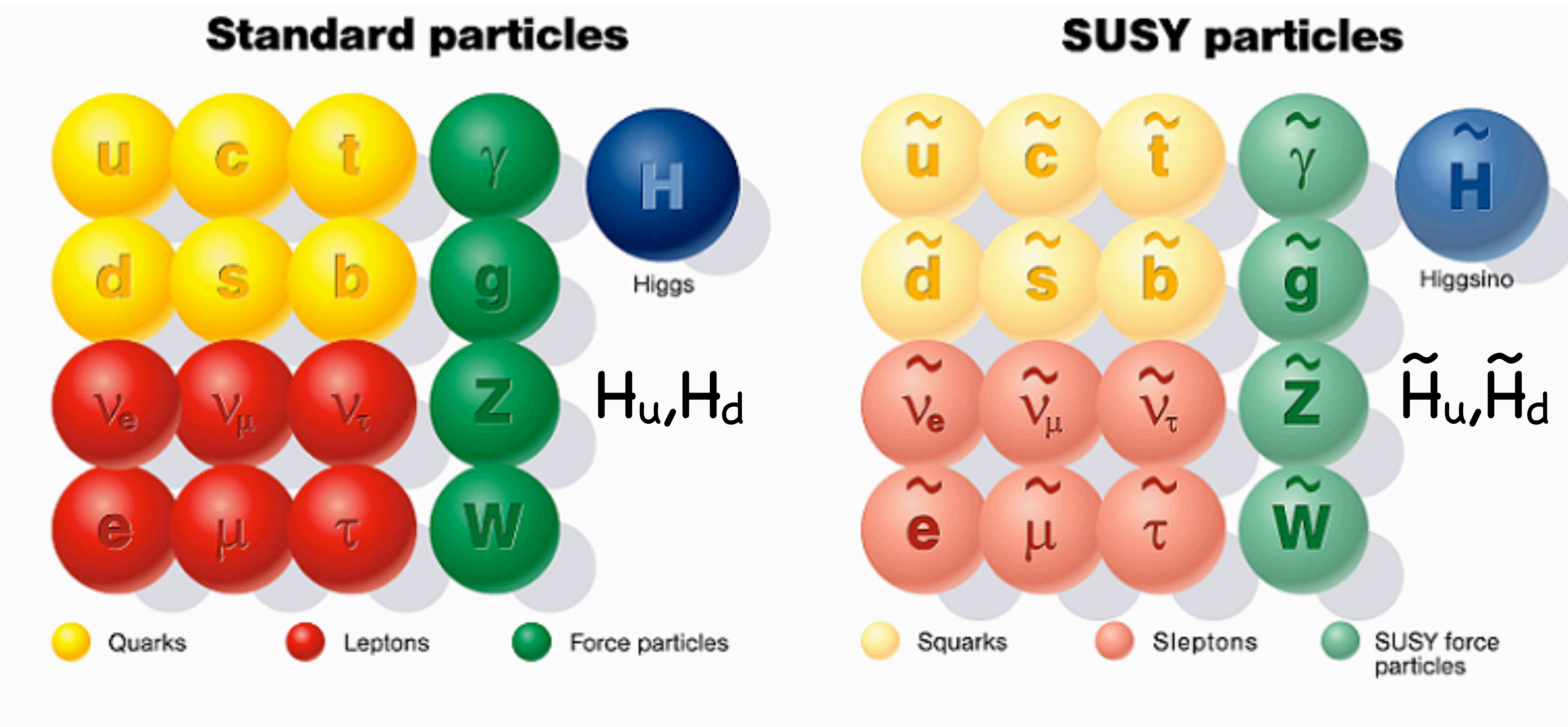
  limited to W/Z leptonic decay modes

What about BSM sources of boosted Higgses?

Outline

- Higgs in the SM
- A new handle on h->b bbar
- jets and jet-substructure
- **Boosted MSSM Higgses**
- Substructure for SUSY

For example: Weak Scale Supersymmetry



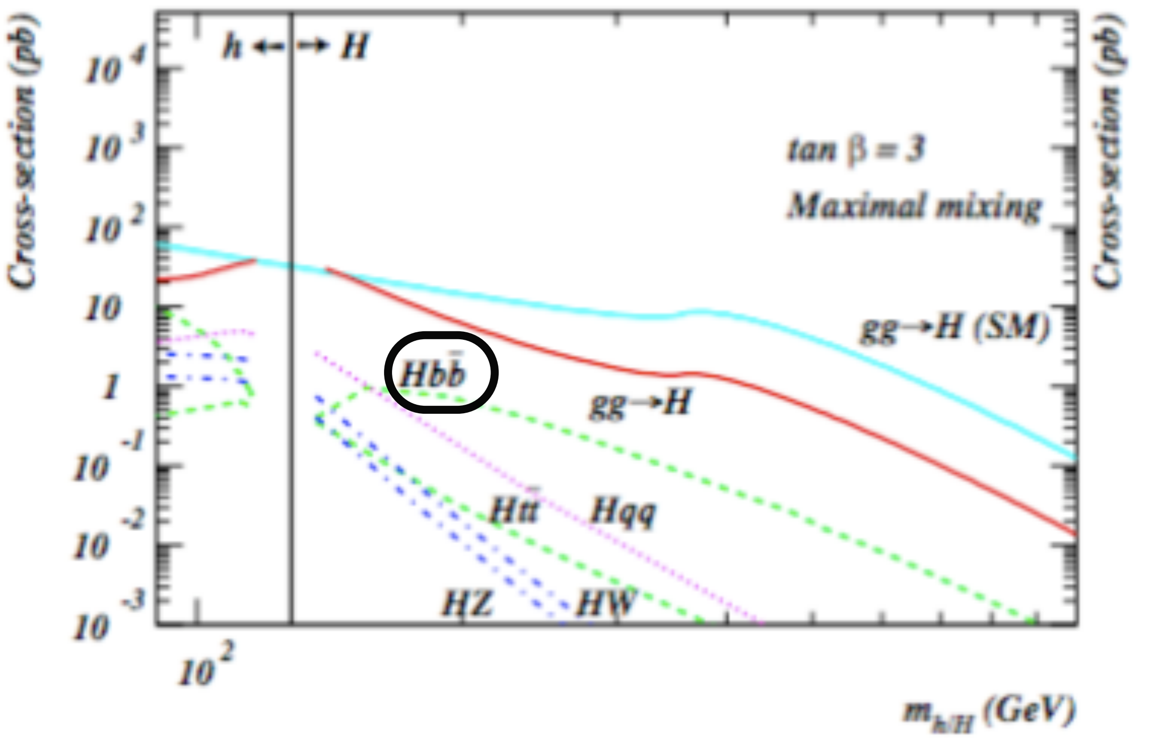
H_u, H_d

$\tilde{H}_u, \tilde{H}_d$

"Minimal Supersymmetric Standard Model (MSSM)"

Going beyond the SM... light Higgs still hard

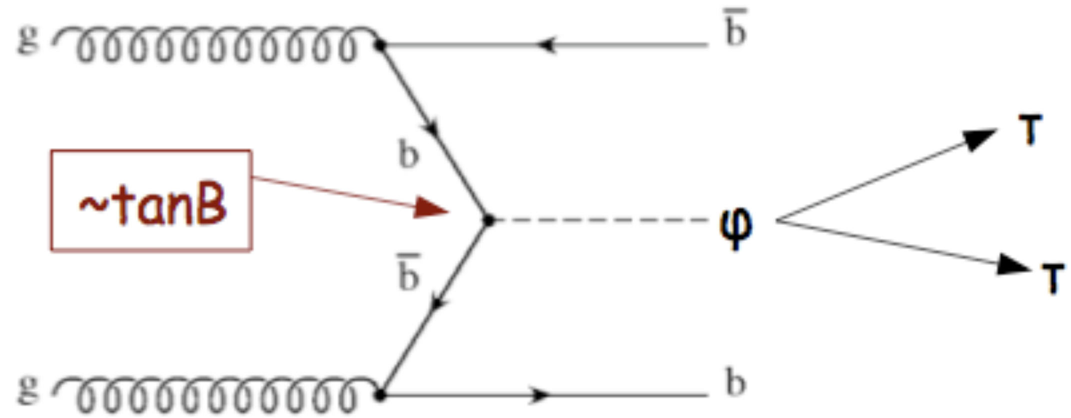
ex.) MSSM



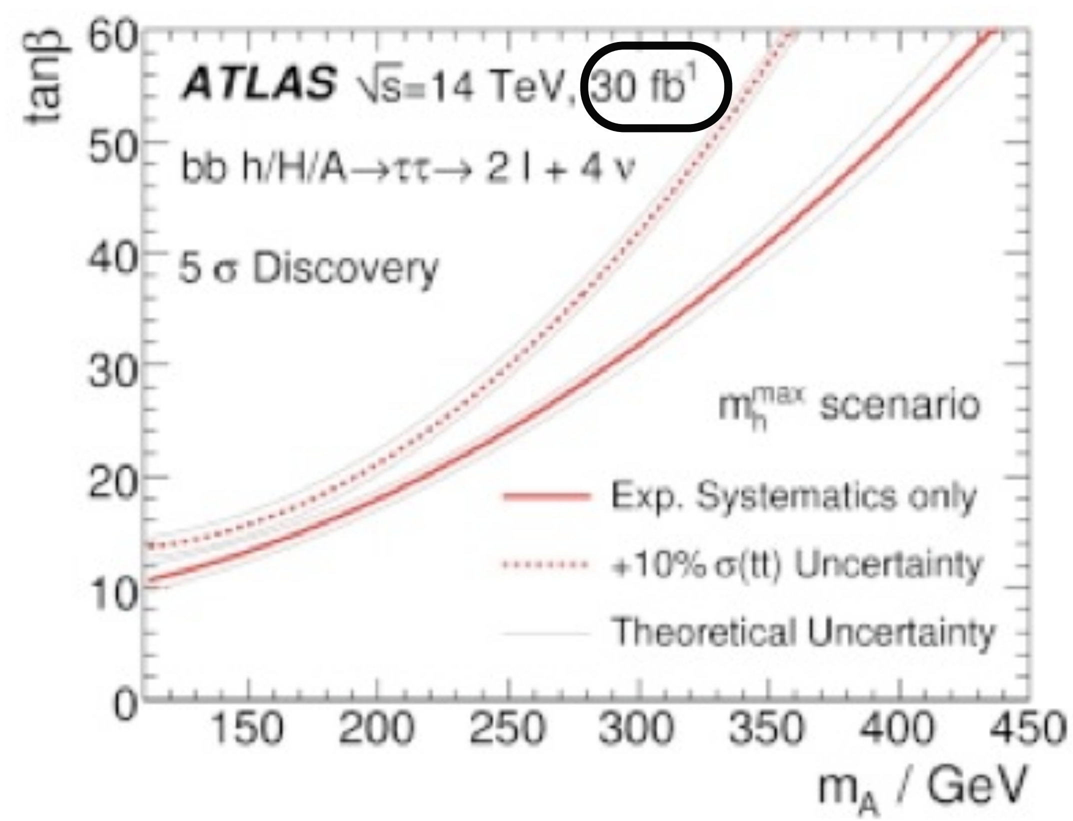
some enhancement, but only when m_A is small and $\tan\beta$ is large

flavor problems?

conventional MSSM light higgs search



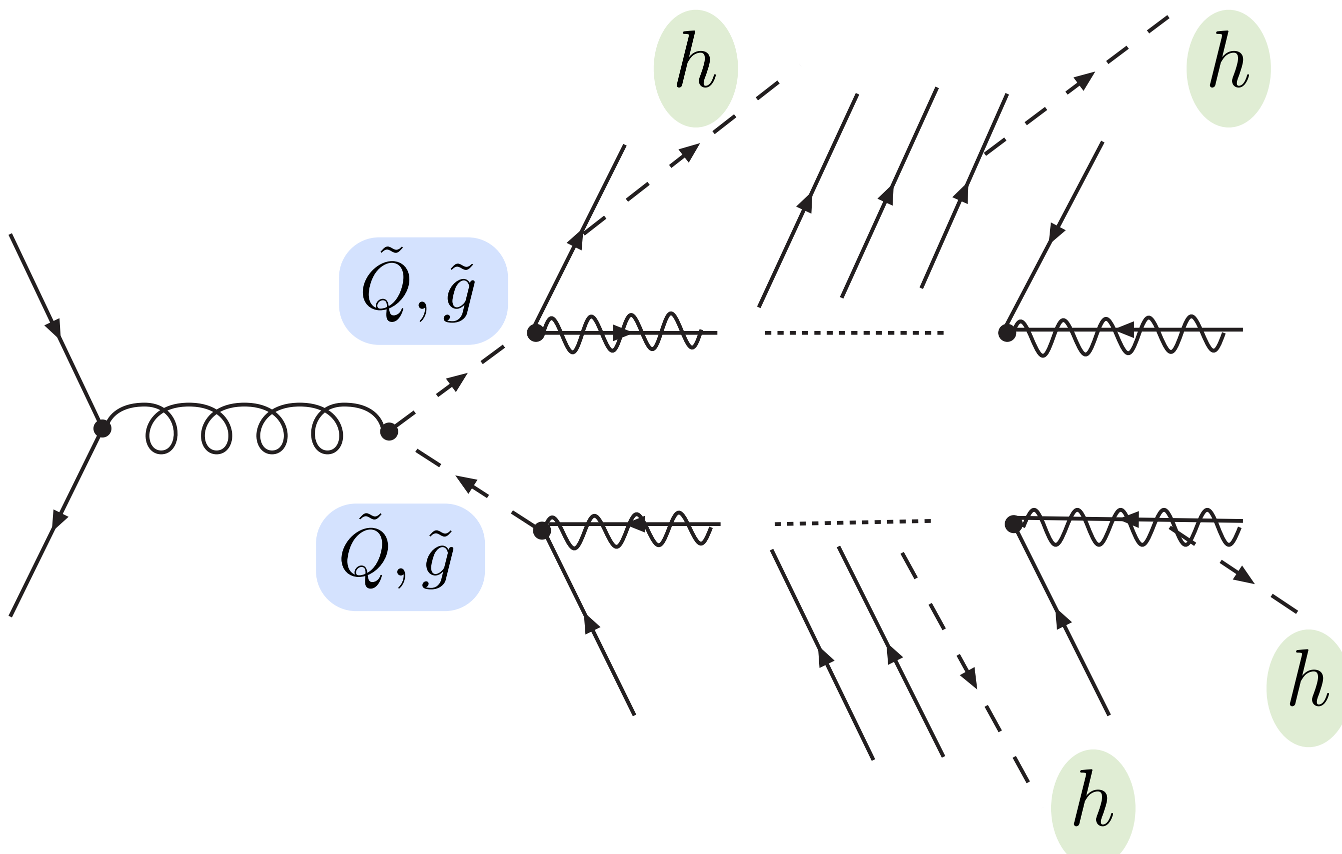
$bb\ h/H/A \to 2l + 4\nu$



Higgs in the MSSM

- MSSM Higgs has to be light $m_h \lesssim 130\ \mathrm{GeV}$, decays dominantly to $b\bar{b}$
- Squarks/gluinos carry color, so they have a large production cross section despite being heavy
- Sparticles cascade decay, decay products can include Higgses
- Sparticles are heavy --> light decay products (h!) tend to be boosted
- All events have MET --> powerful discriminator vs. SM backgrounds

MSSM Higgses from cascade decays

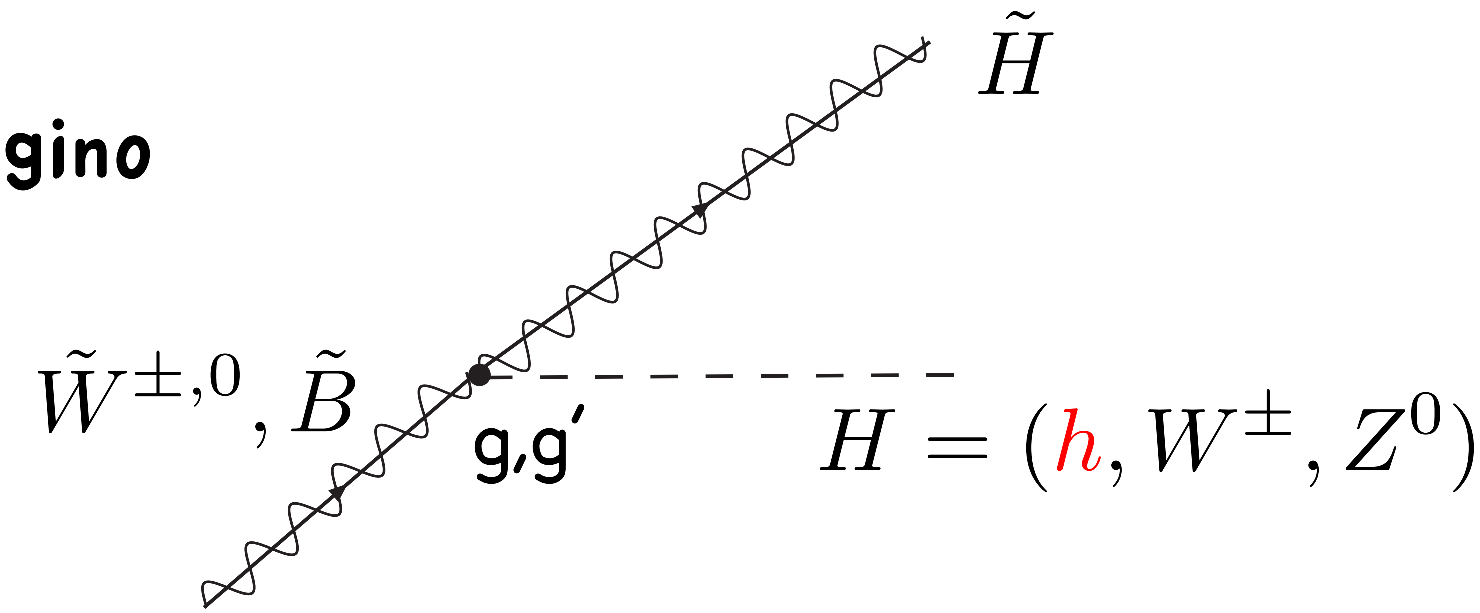


= a new source of boosted Higgses

are ideally suited for substructure analysis

MSSM + boosted Higgses

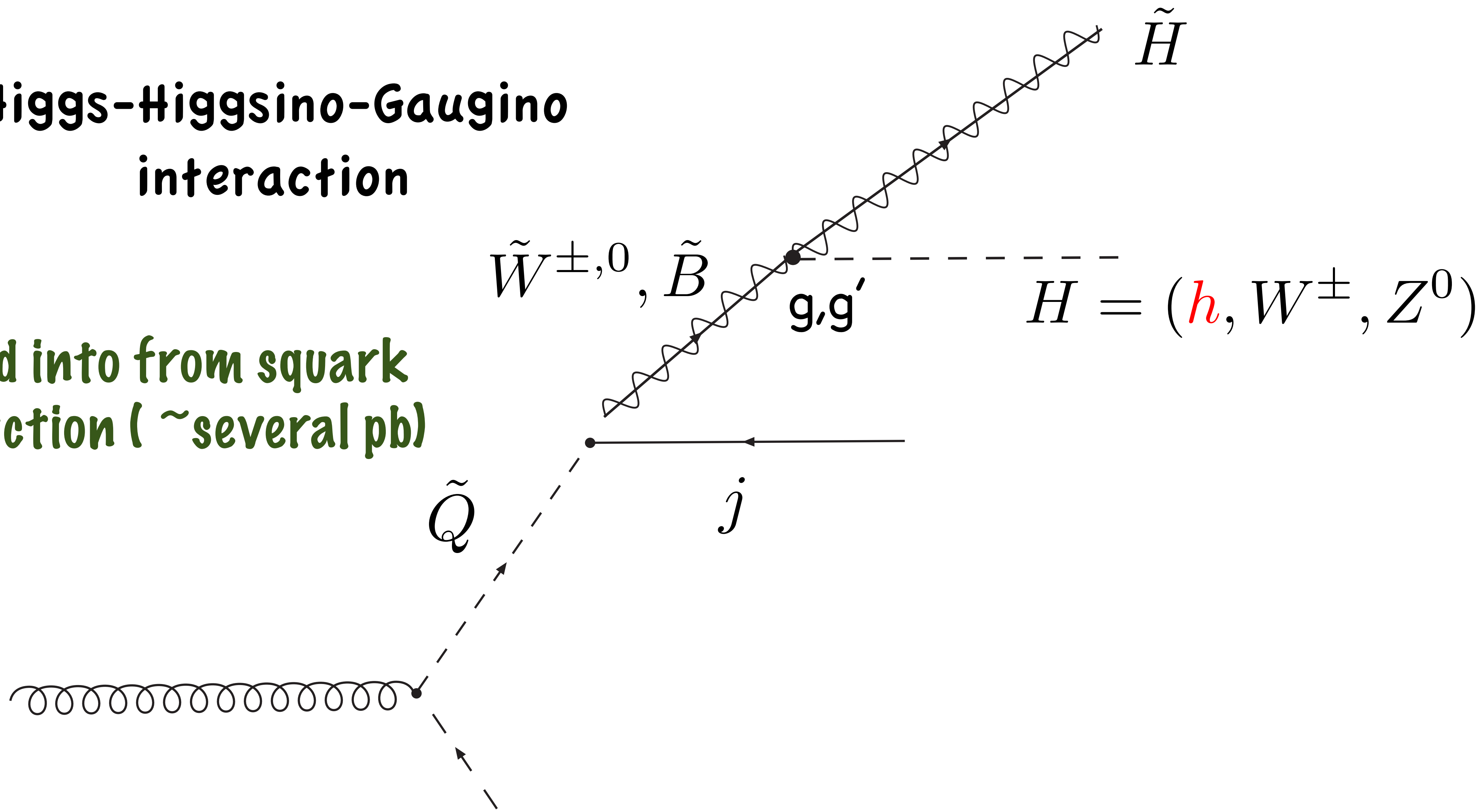
Higgs-Higgsino-Gaugino interaction



MSSM + boosted Higgses

Higgs-Higgsino-Gaugino
interaction

... fed into from squark
production (~several pb)



MSSM + boosted Higgses

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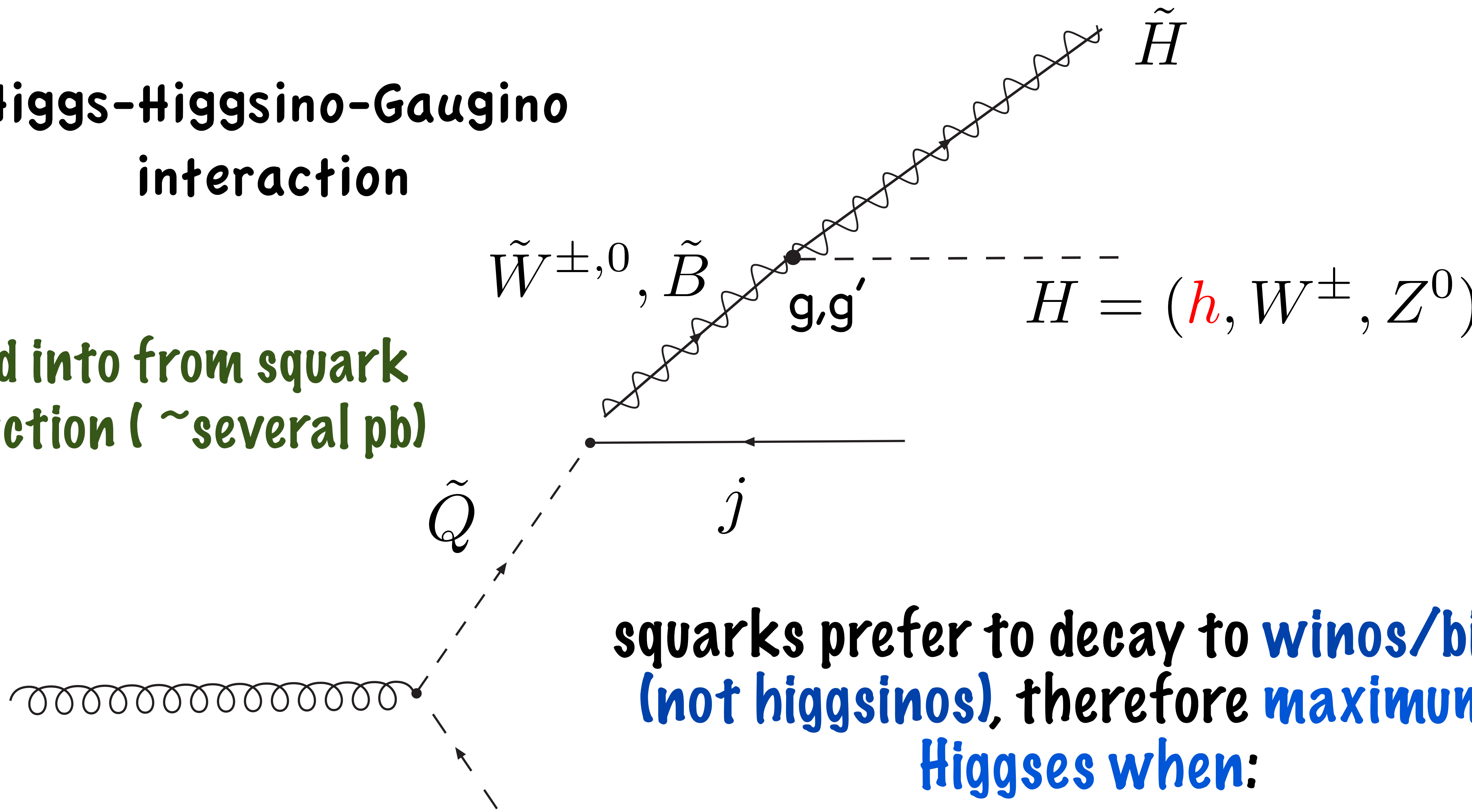

... fed into from squark production (~several pb)

squarks prefer to decay to winos/binos (not higgsinos), therefore maximum # Higgses when:

$$M_{\tilde{Q}} > M_2, M_1 > \mu$$

MSSM + boosted Higgses

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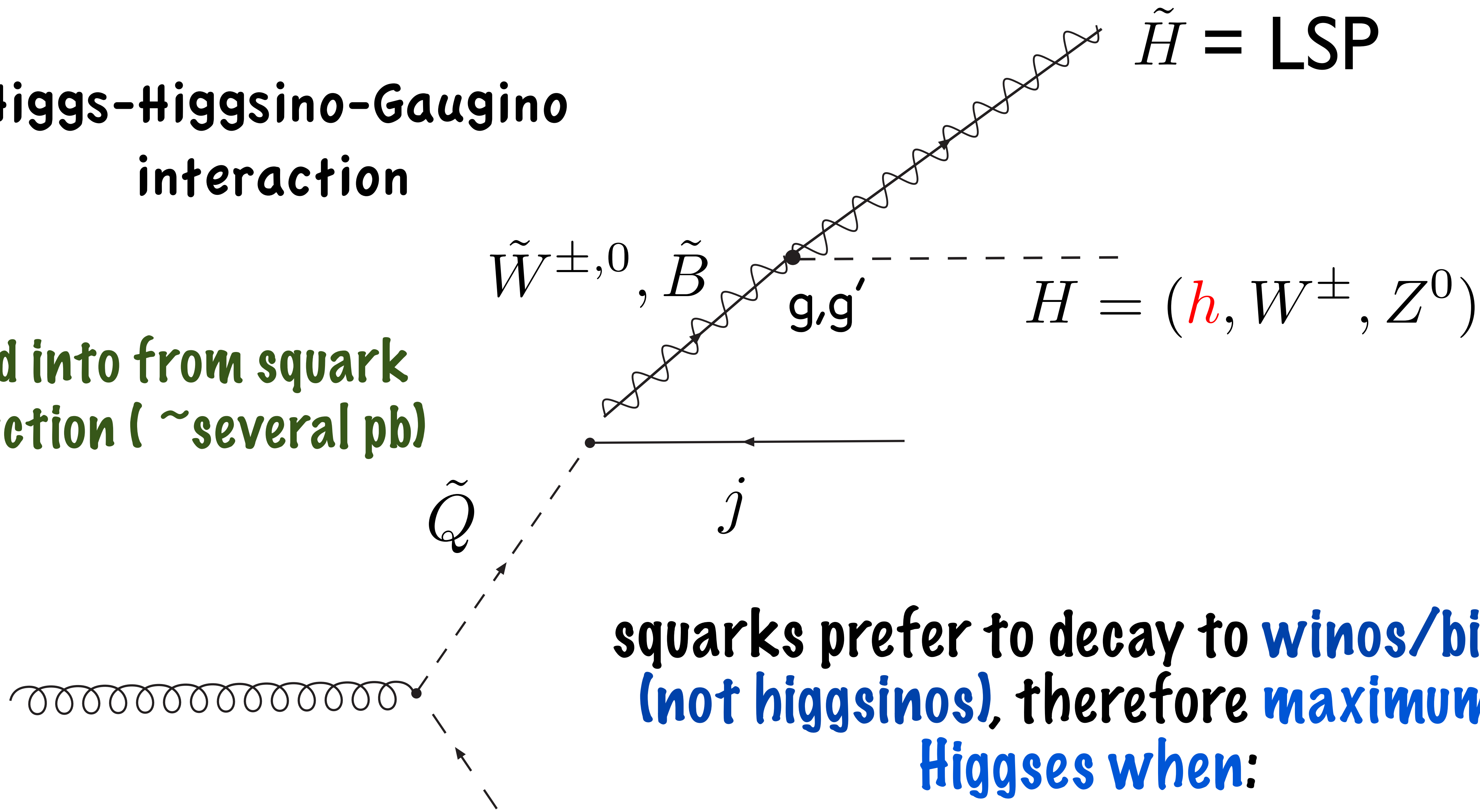

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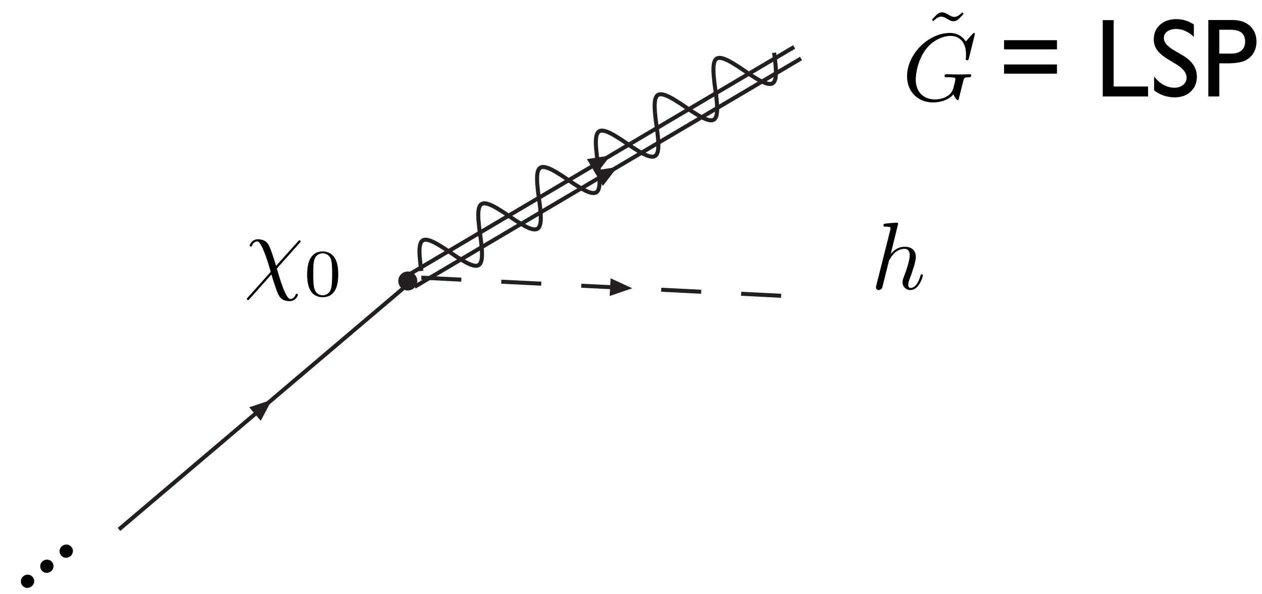
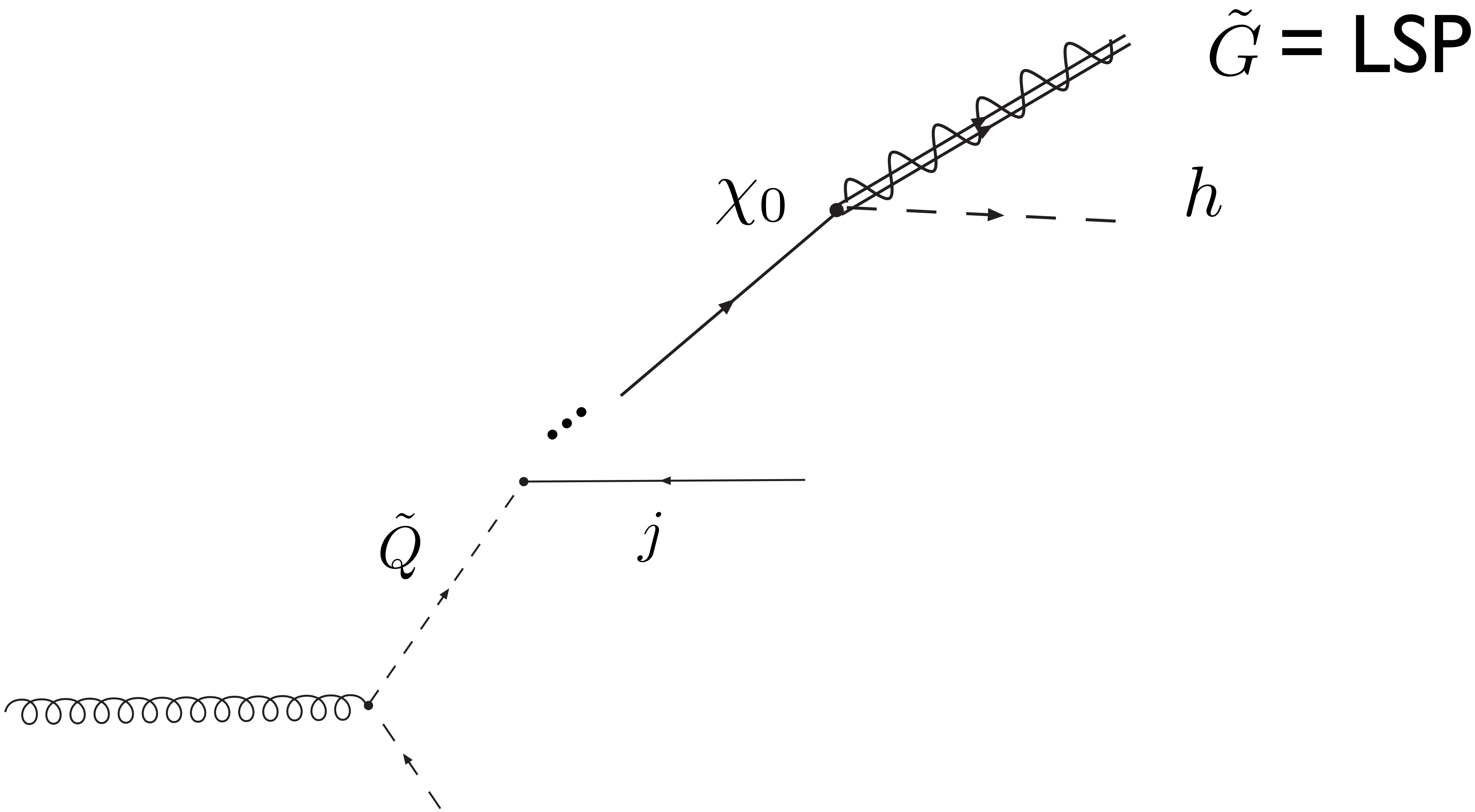
MSSM + boosted Higgses

2.) when the scale of SUSY-breaking is light (gmsb), gravitino is the LSP



MSSM + boosted Higgses

2.) **when the scale of SUSY-breaking is light (gmsb),**
gravitino is the LSP



MSSM + boosted Higgses

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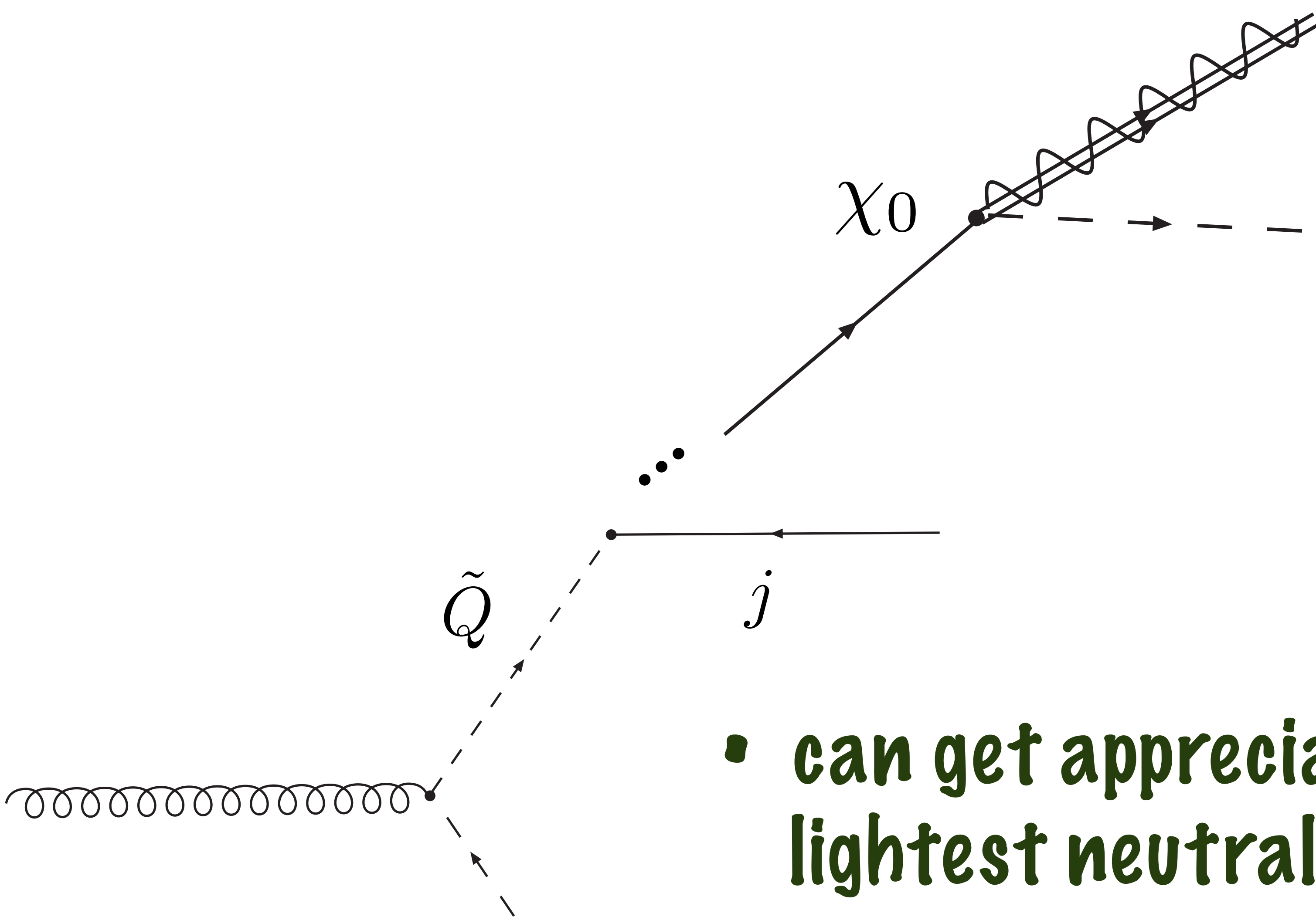


$\tilde{G}$ = LSP

$\chi_0 \rightarrow \gamma \,/\, Z \,/ h$

depending on $M_1, M_2, \mu, \tan\beta$

- 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)

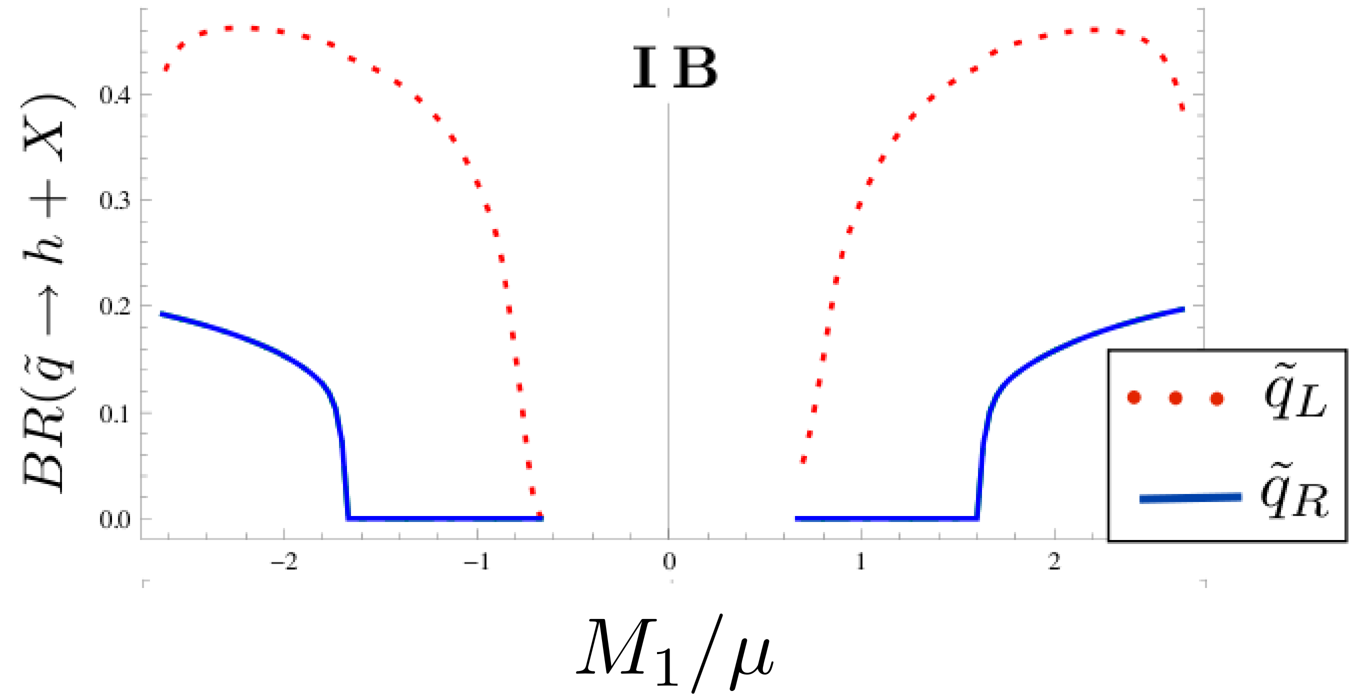
- Mixed decay mode $\chi_0\chi_0 \rightarrow h + \gamma + \not{E}_T + X$ is especially clean

MSSM + boosted Higgses

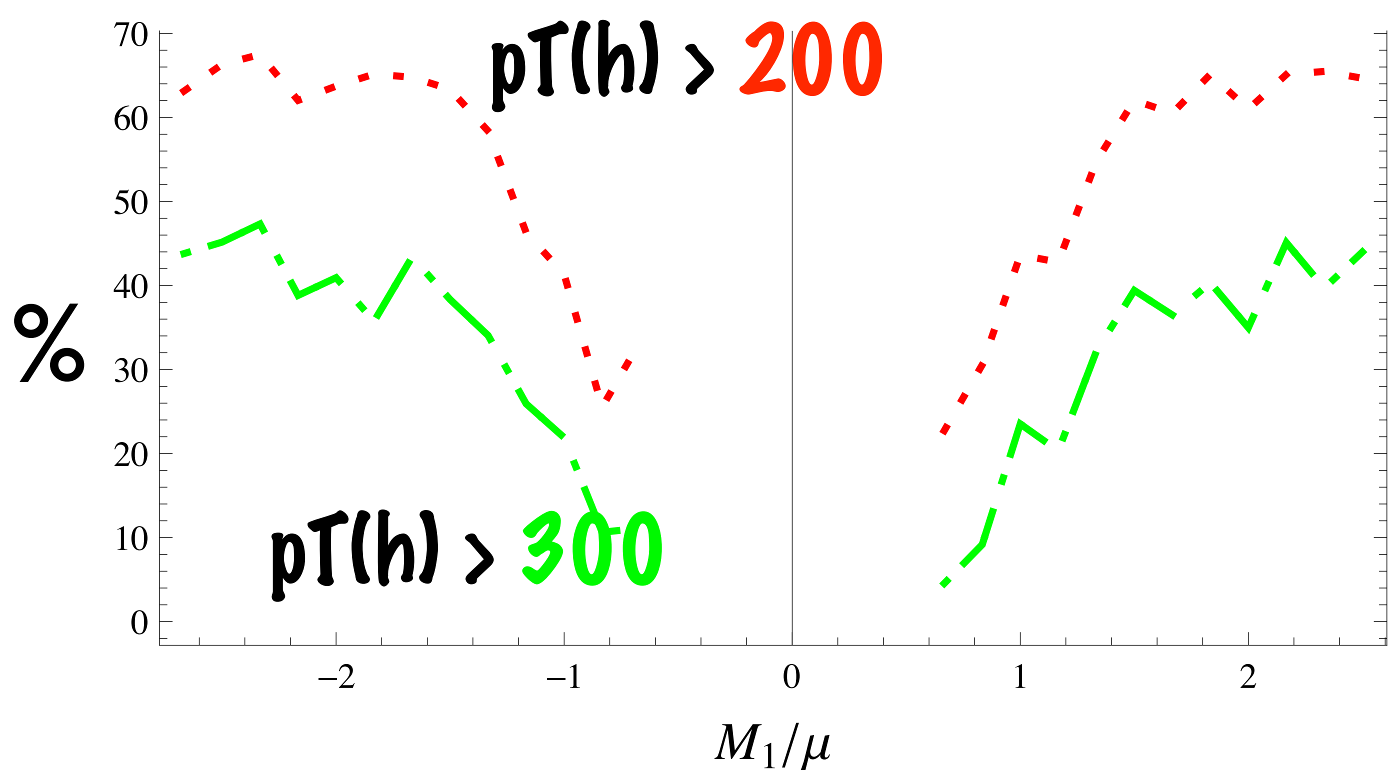
Branching ratios and boosted fraction: neutralino LSP

Ex.)

$$M_{\tilde{Q}} = 1 \text{ TeV}$$
$$\tan\beta = 10$$
$$\mu = 150 \text{ GeV}$$
$$M_{\tilde{L}} = 1 \text{ TeV}$$
$$M_2 = 2M_1, M_3 = 7M_1$$



Boosted Fraction

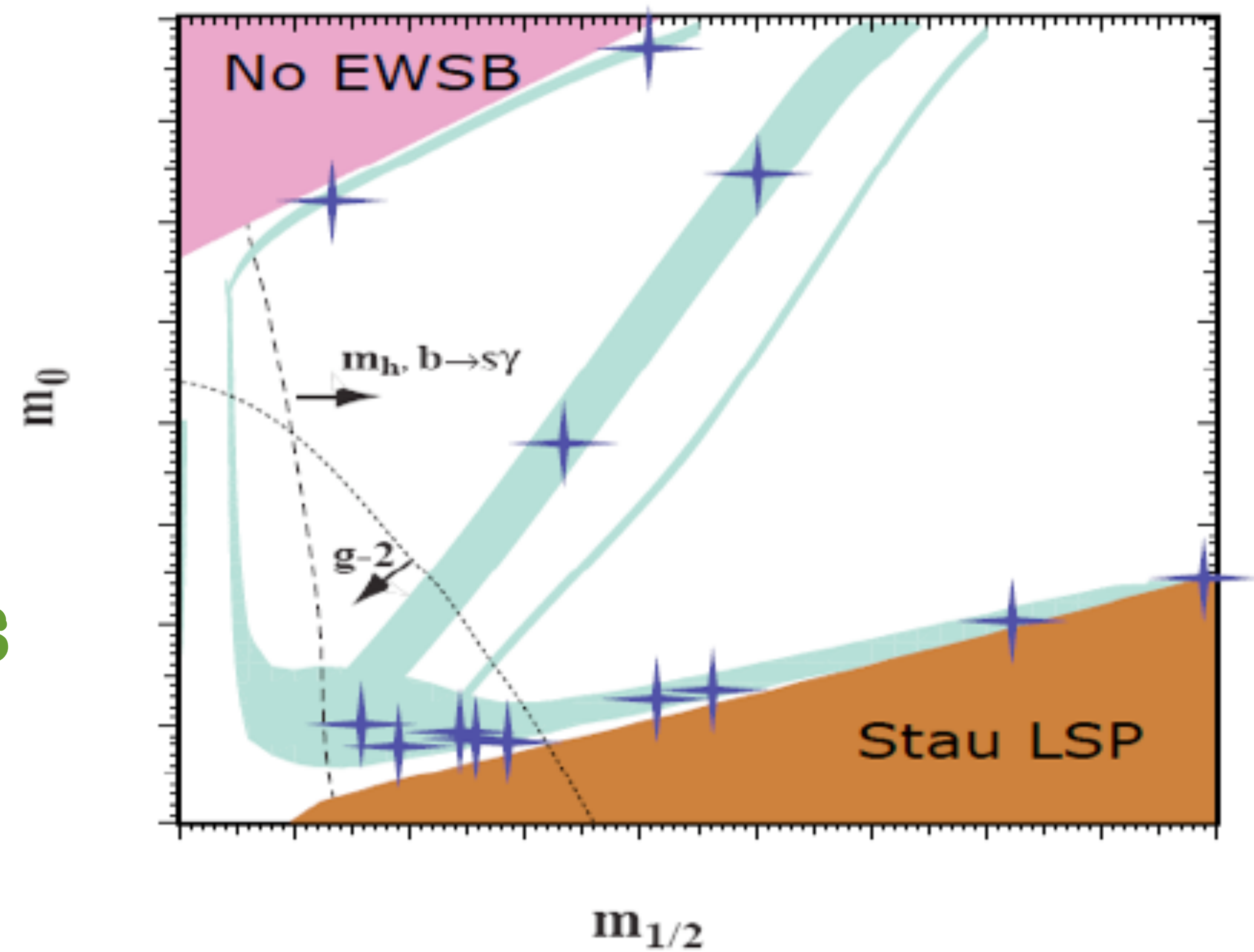


Hasn't cascade-Higgs been done before? Not really

1.) mSUGRA-ism --

Higgs BC + EWSB conditions generically give large μ

too few Higgses in cascades



forget mSUGRA, there is a much wider parameter space to explore!

Hasn't cascade-Higgs been done before? Not really

2.) light Higgsino LSP is not great for DM (< obs)

BUT, as long as we don't create $\Omega_{DM} > \Omega_{DM}^{obs}$

shouldn't be a constraint for Higgs discovery!

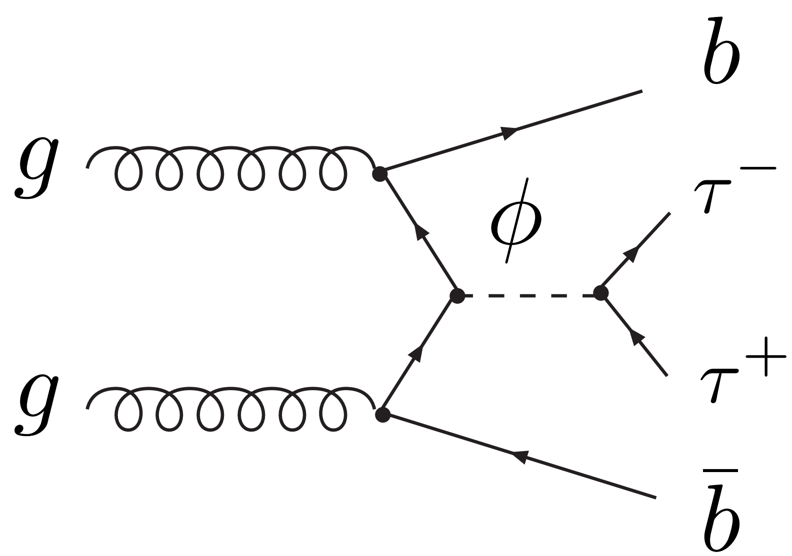
3.) Without boosted/substructure techniques, combinatorial background is **much** bigger --> degrades mass resolution

Outline

- Higgs in the SM
- A new handle on h->b bbar
- jets and jet-substructure
- Boosted MSSM Higgses
- Substructure for SUSY

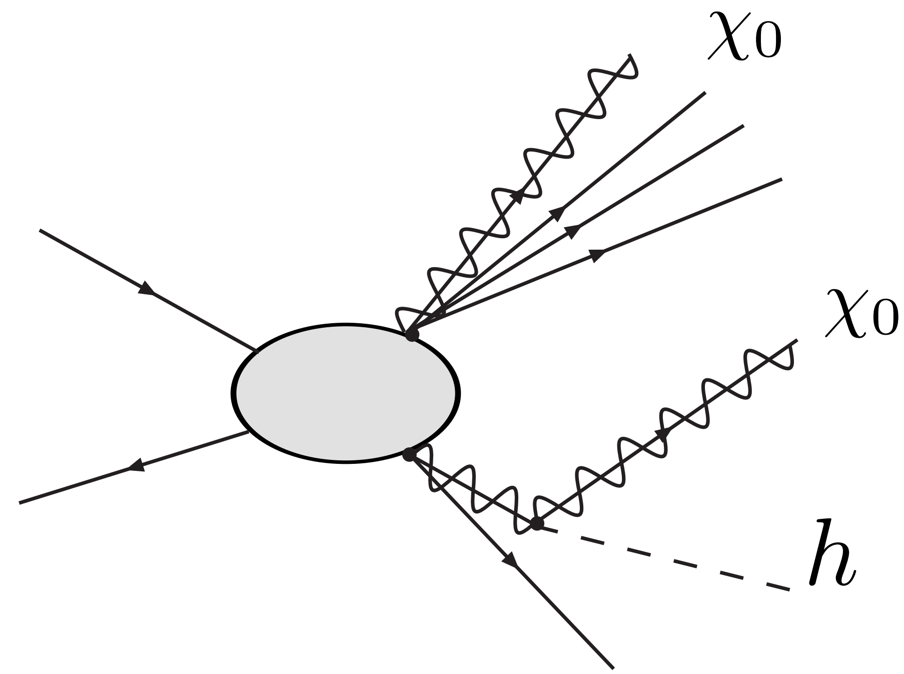
Higgses source comparison

how people usually look for the MSSM Higgs



- Higgs produced in association with SM particles
- smaller cross section (set by y_b)
- no (BSM) MET
- only SM backgrounds

how I want to look for the MSSM Higgs



- Higgses from sparticle decays
- Impose MET, H_T cuts to suppress SM background
- look for fat jets (C/A, R = 1.2)
- Look for substructure in remaining events -- suppresses combinatorial SUSY background & pulls out any Higgses

Remember

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

specifically, demand one or more 'fat' jets: $R = 1.2$ $p_{T,j} > 200\ \text{GeV}$

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

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

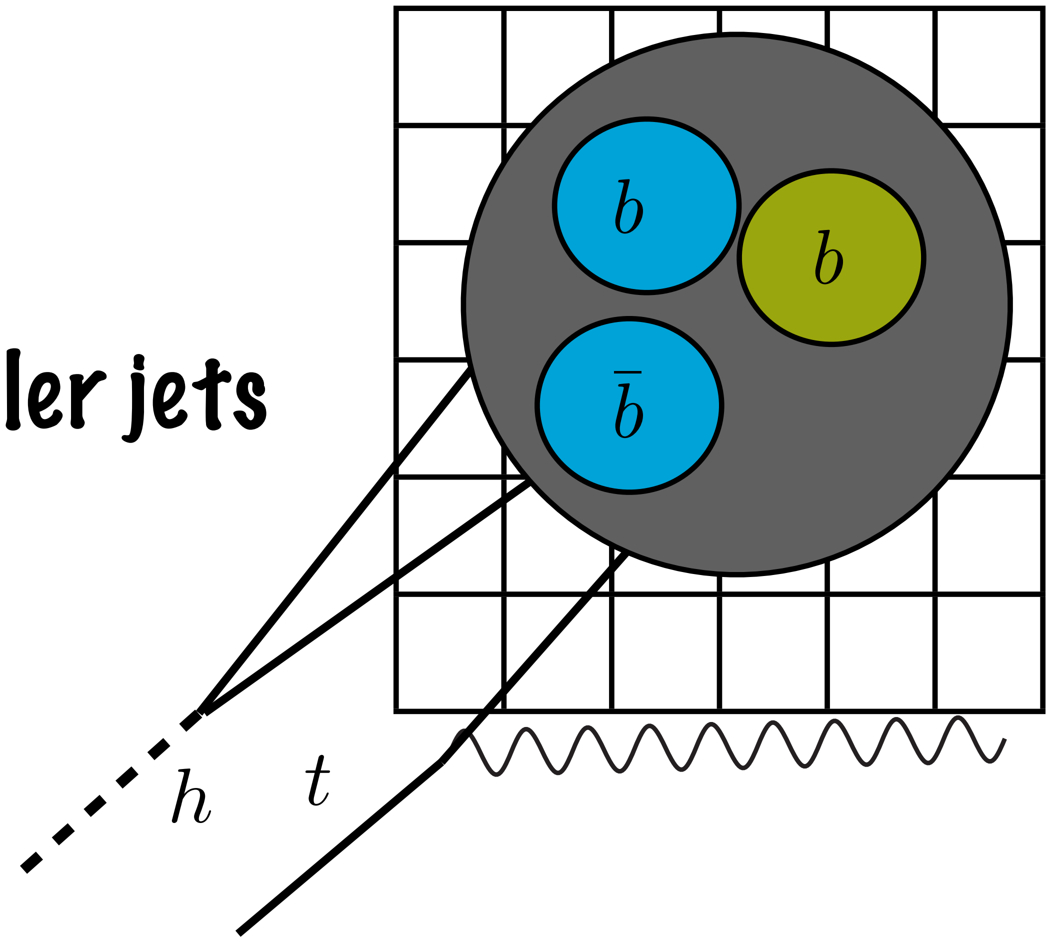
* also, going to high-p_T $\longrightarrow$ better detector resolution:

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

Substructure for SUSY

SUSY events are busy. Lots of extra high-p_T partons flying around from decays of $\tilde{q}/\chi^{\pm,0}/t$



We could:

1. Focus on higher boost = smaller jets

2. Adapt substructure routine

Substructure for SUSY

SUSY events are busy. Lots of extra high-p_T partons flying around from decays of $\tilde{q}/\chi^{\pm,0}/t$

Specifically:

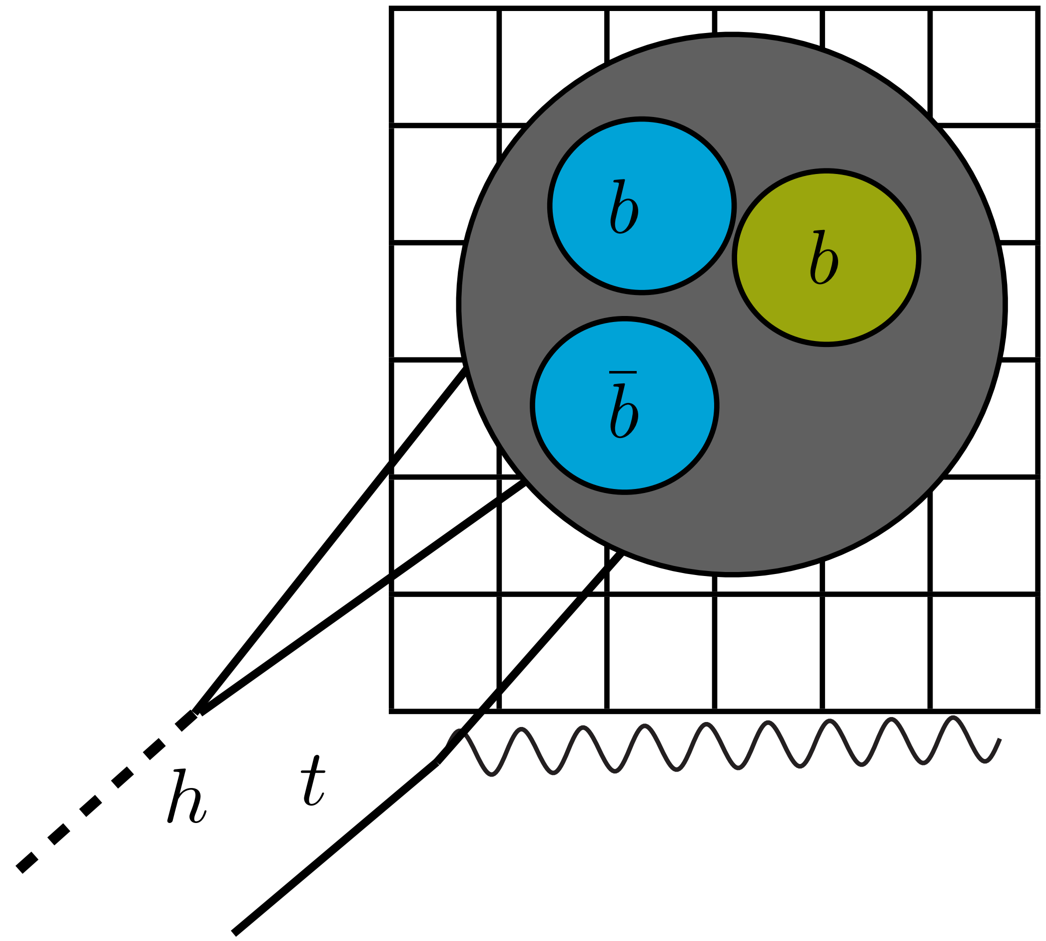
1. undo clustering: j -> j_1 + j_2

2a. if a mass drop (BDRS):

- keep j_2 = constituent
- j_1 -> j, goto 1.)

2b. otherwise, j_1 -> j, goto 1.

3. continue until $p_{T,j}$ < 30 GeV



take 2 b-tagged constituents with most similar p_T, filter

candidate higgs

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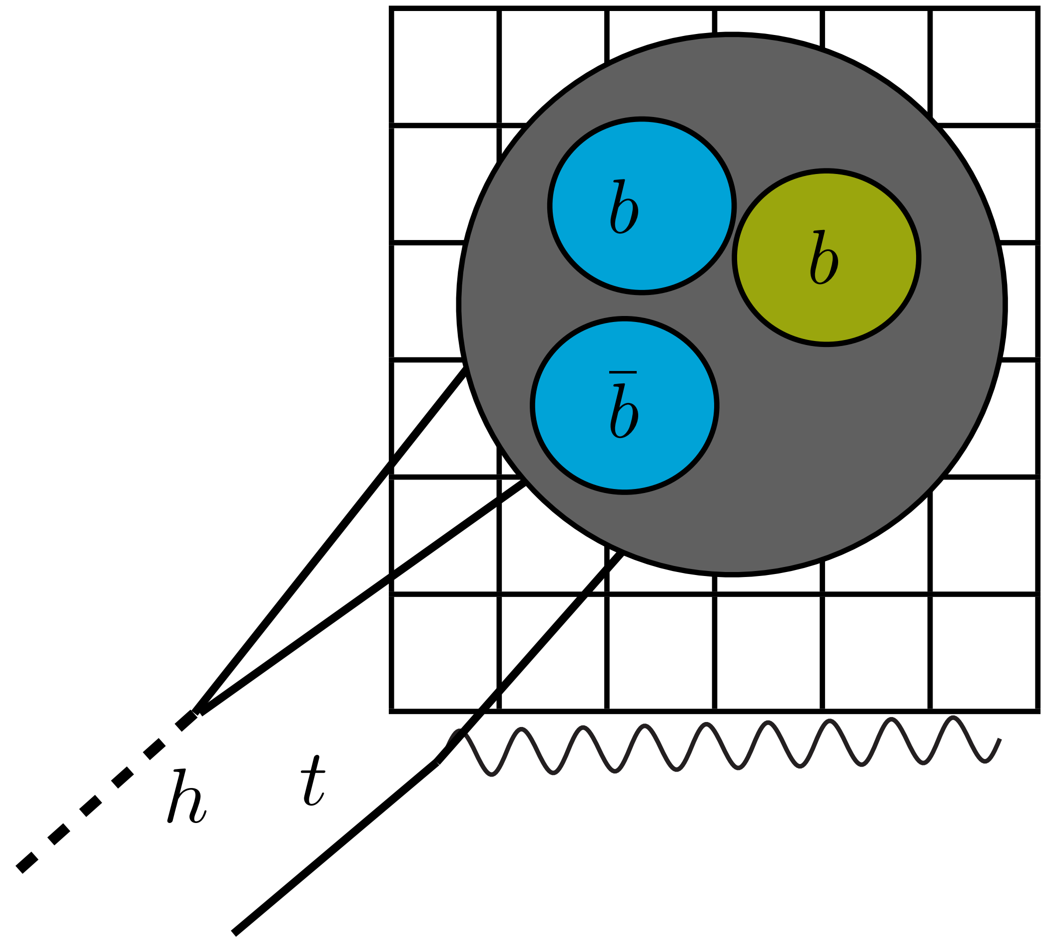
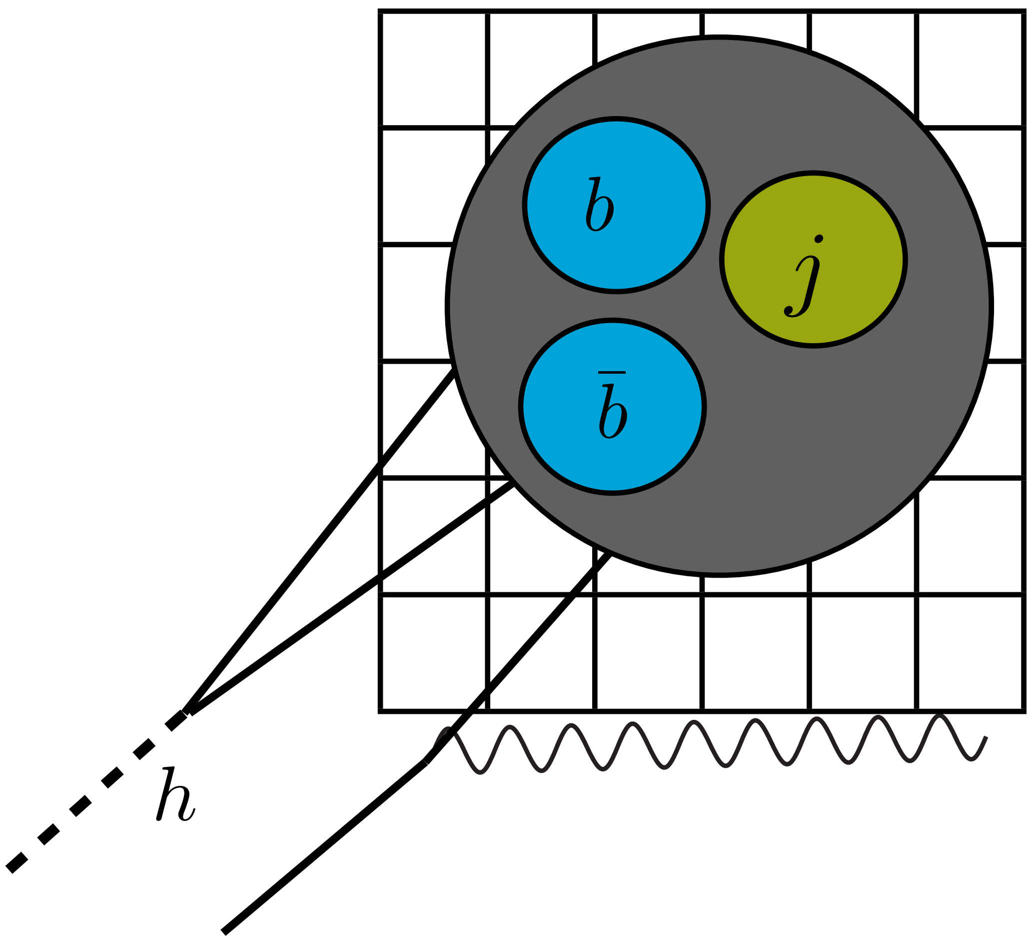


take 2 b-tagged constituents with most similar p_T, filter

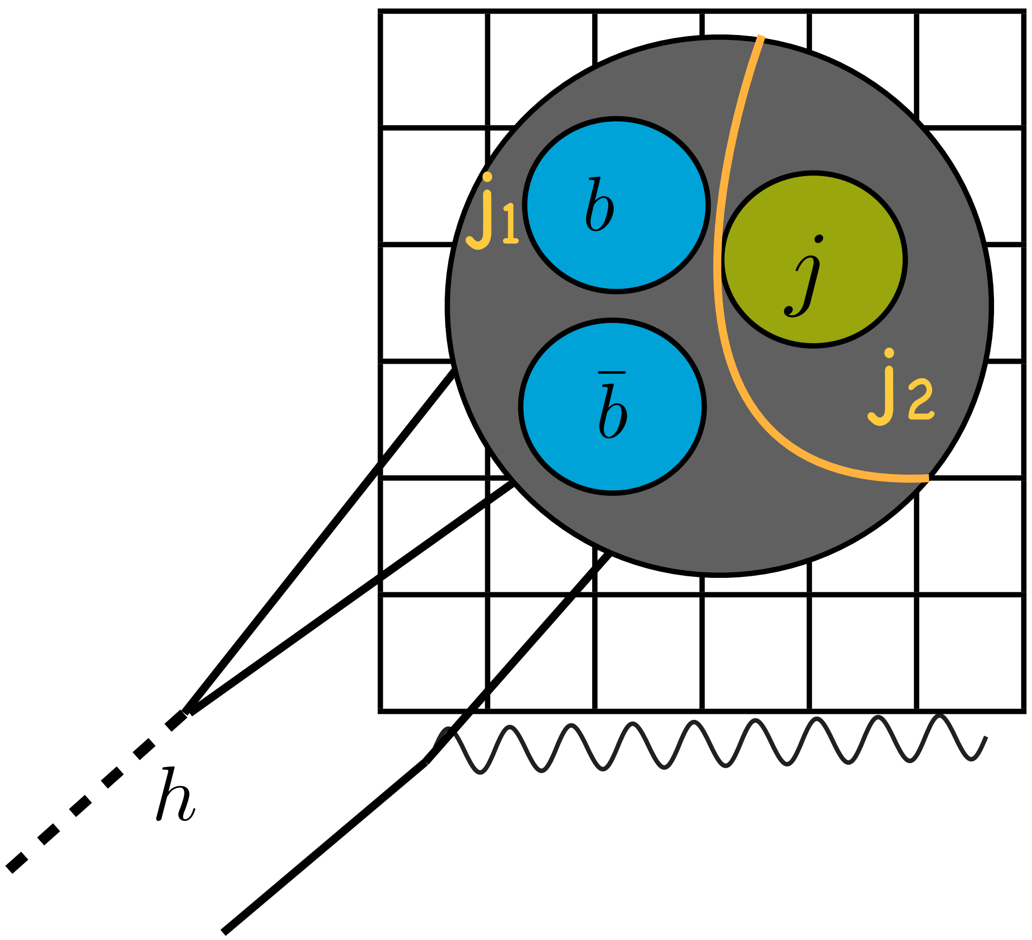
→ **candidate higgs**

similar method to t tbar h tagger (Plehn, Salam, Spannowsky '09)

Substructure for SUSY

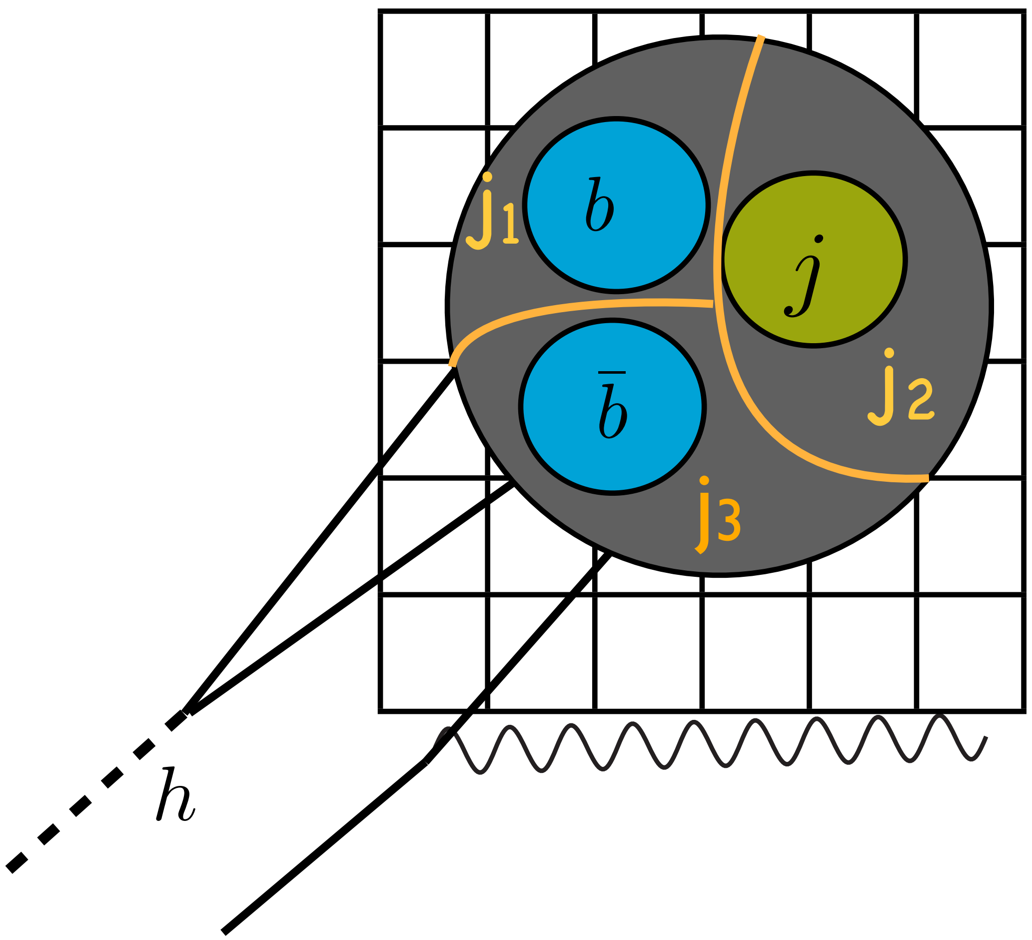


Substructure for SUSY



BDRS stops here

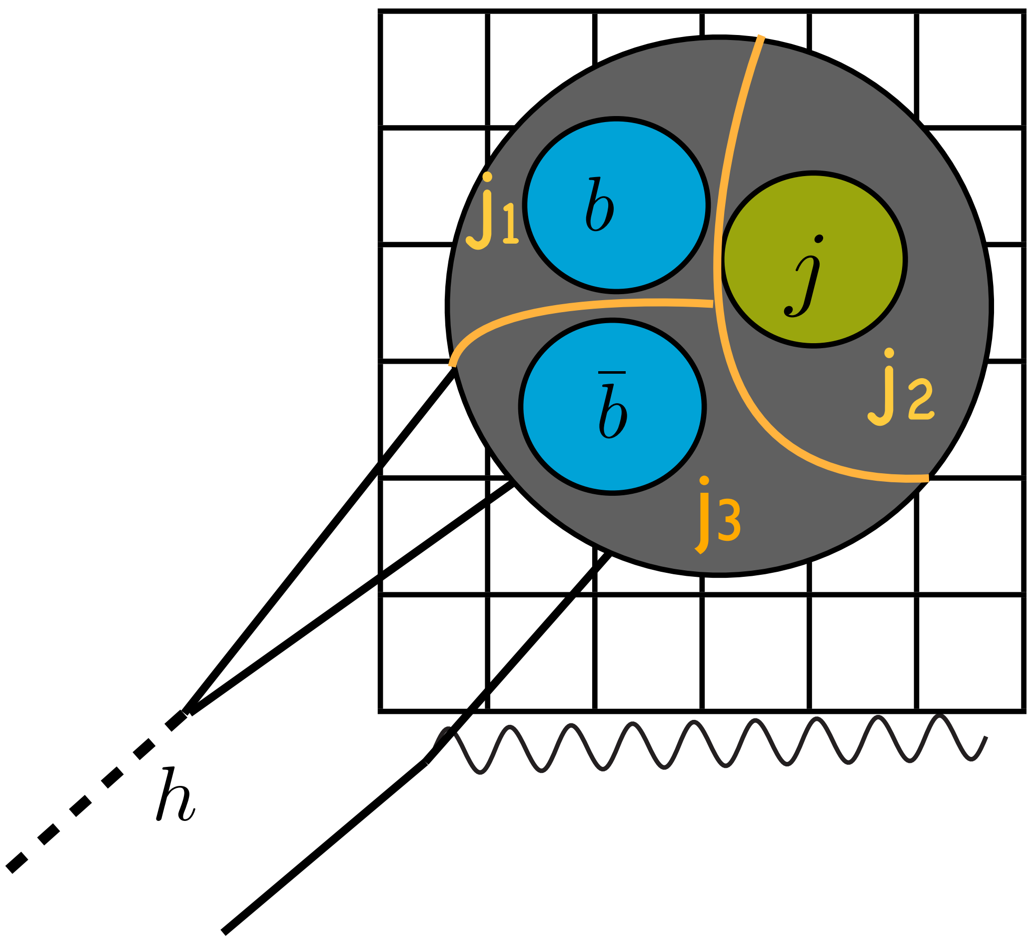
Substructure for SUSY



BDRS stops here

'similarity' method keeps going

Substructure for SUSY



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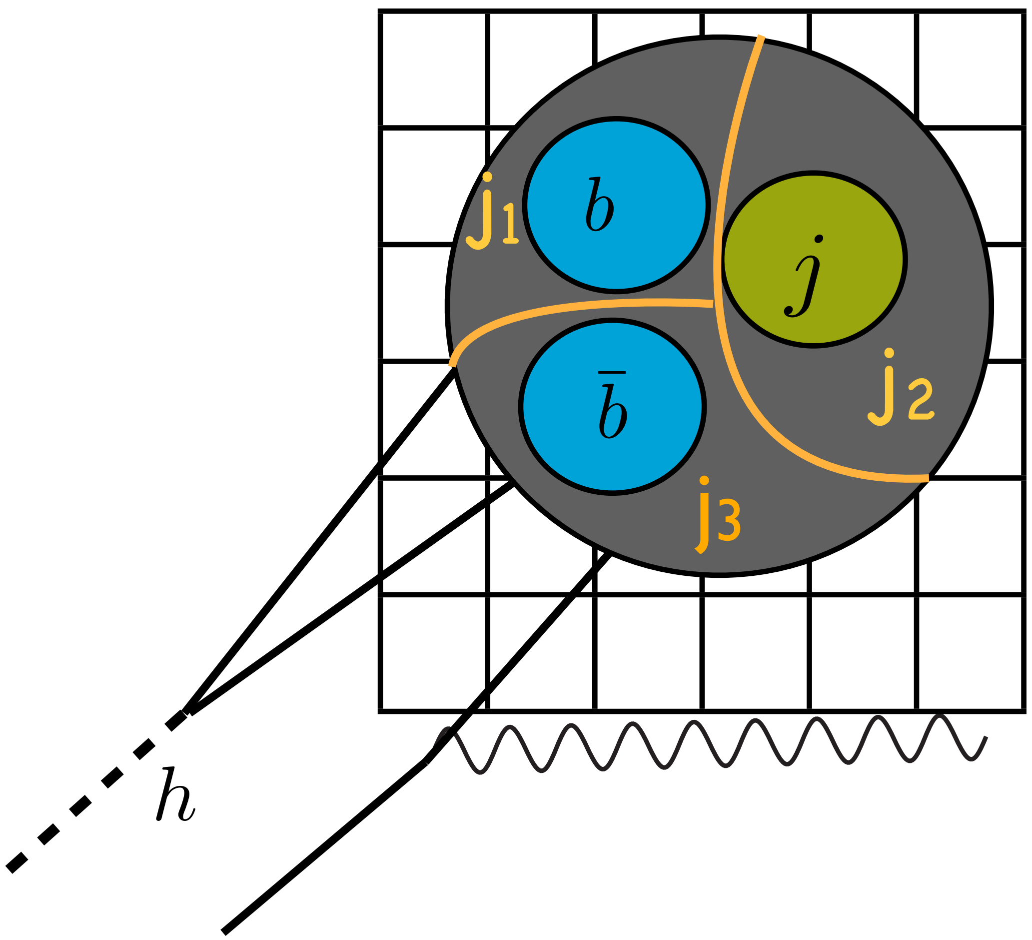
Higgs is spin-0 -> more symmetric decay products

Substructure for SUSY

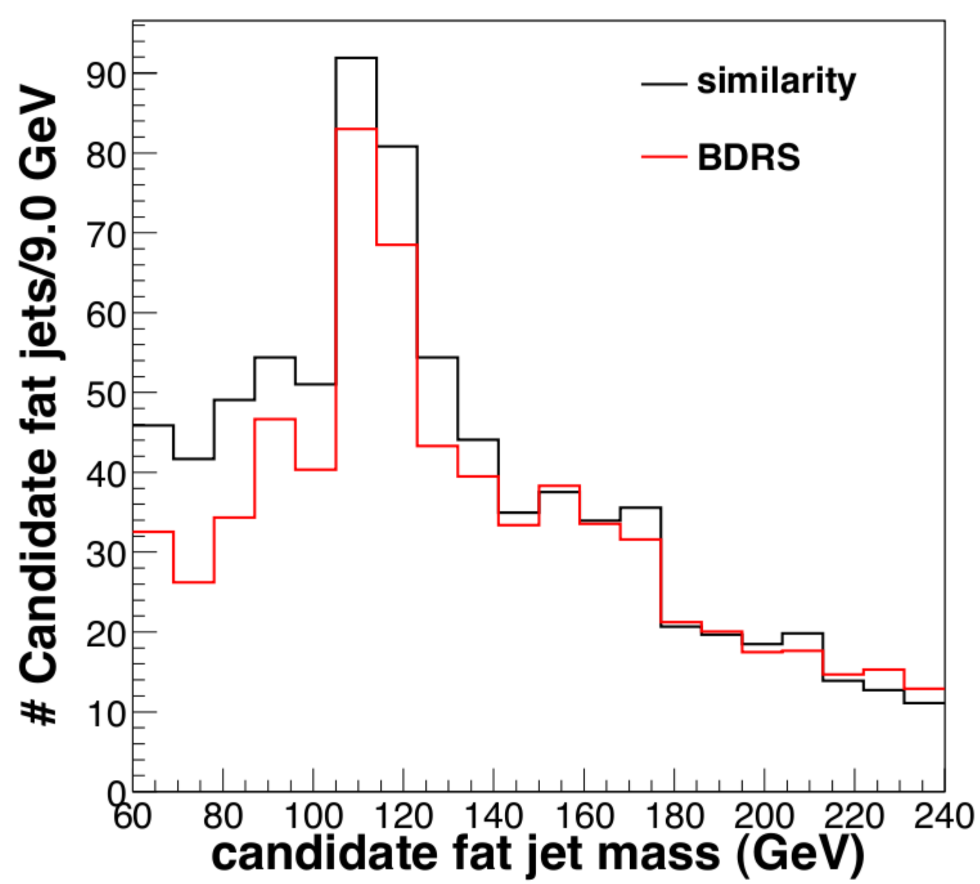


BDRS stops here

'similarity' method keeps going

Higgs is spin-0 -> more symmetric decay products

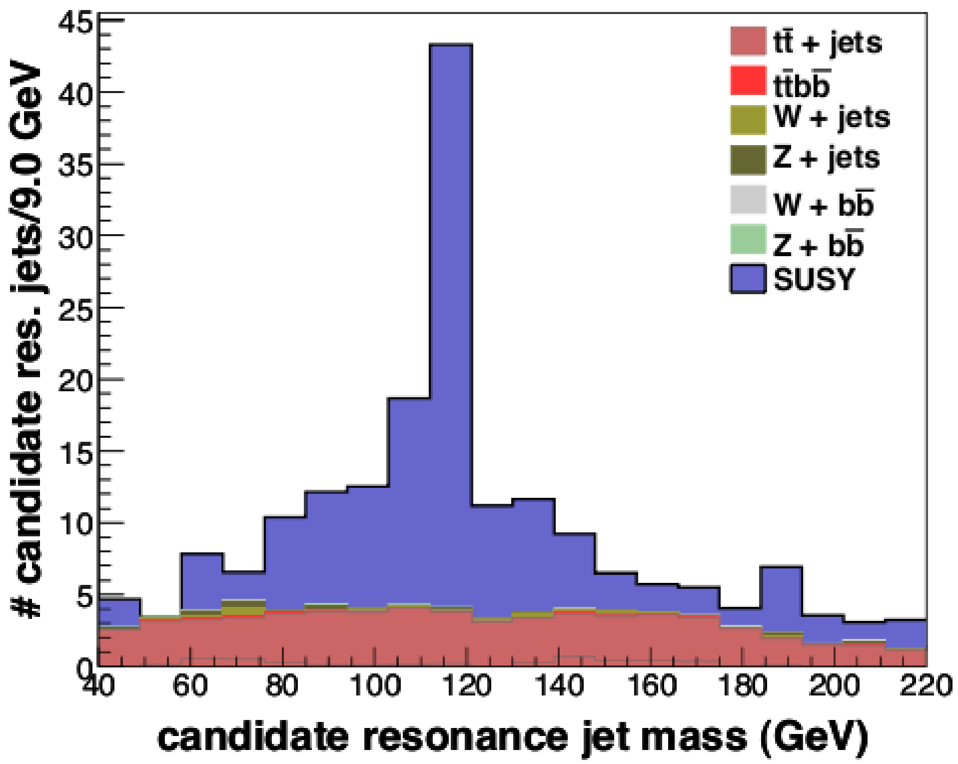
more efficient in busy environments

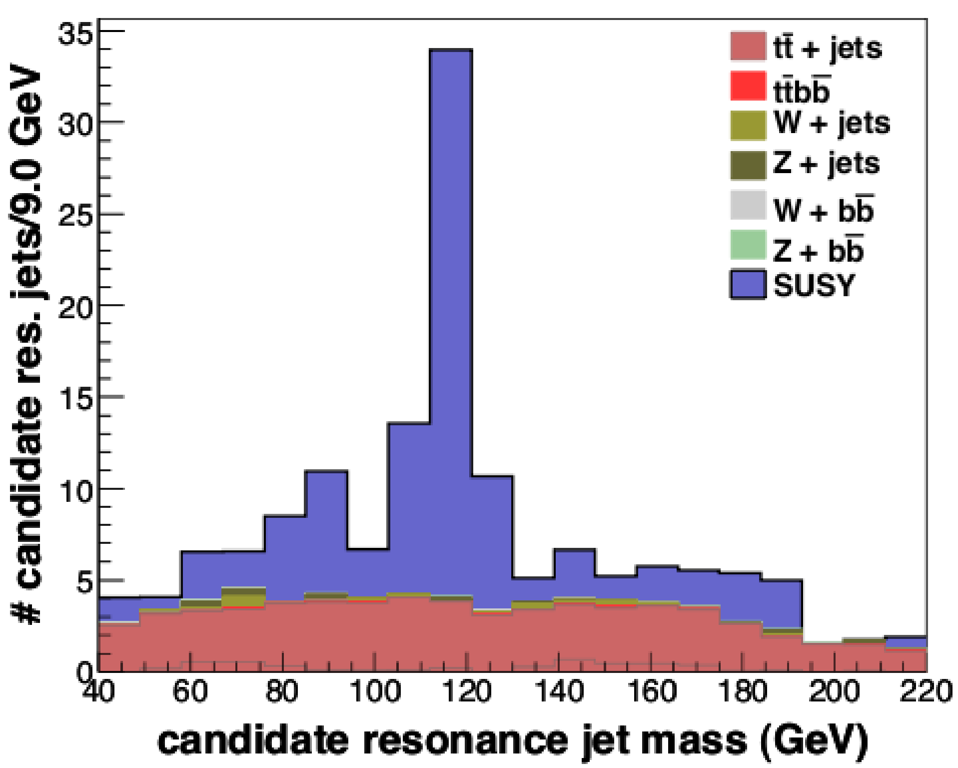


now, results..

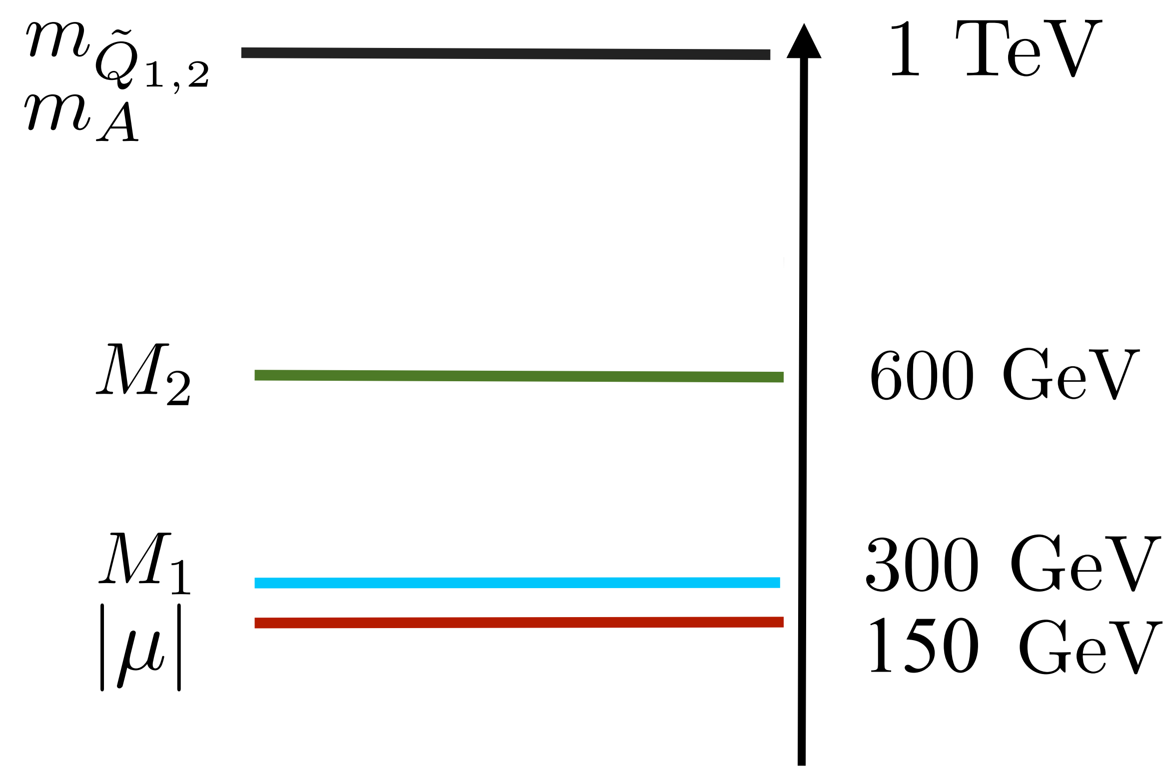
Neutralino LSP Results: #1

$L = 10\ \text{fb}^{-1}, \sqrt{s} = 14\ \text{TeV}$





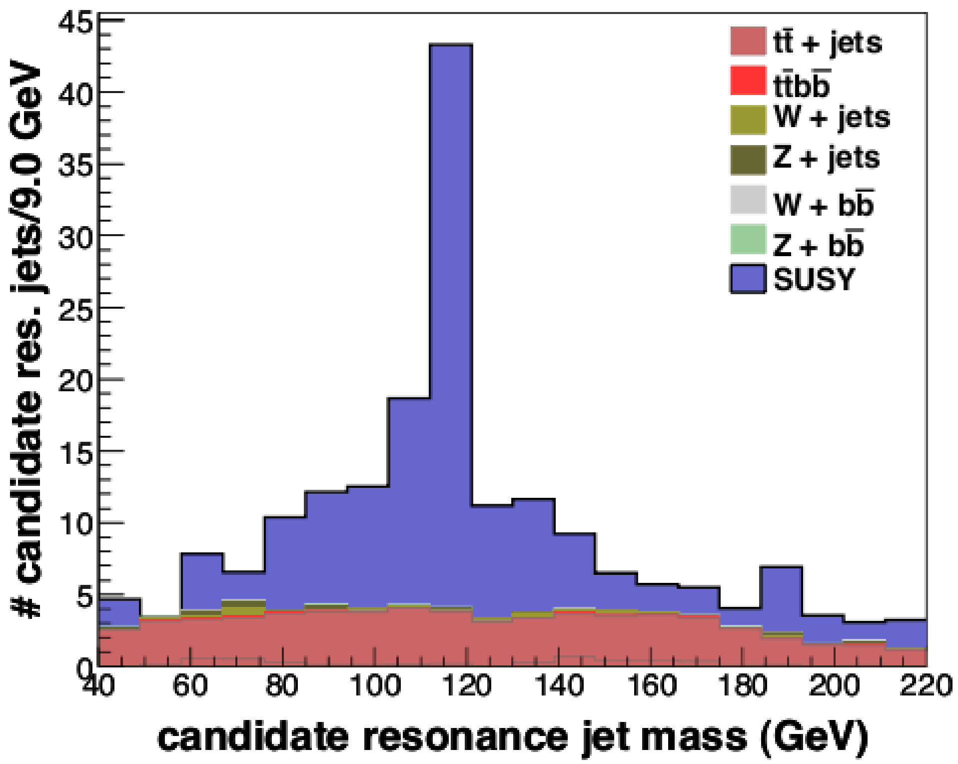
$$BR(\tilde{u}_L, \tilde{d}_L \to h + X) \sim 23\%$$
$$BR(\tilde{u}_R, \tilde{d}_R \to h + X) \sim 16\%$$

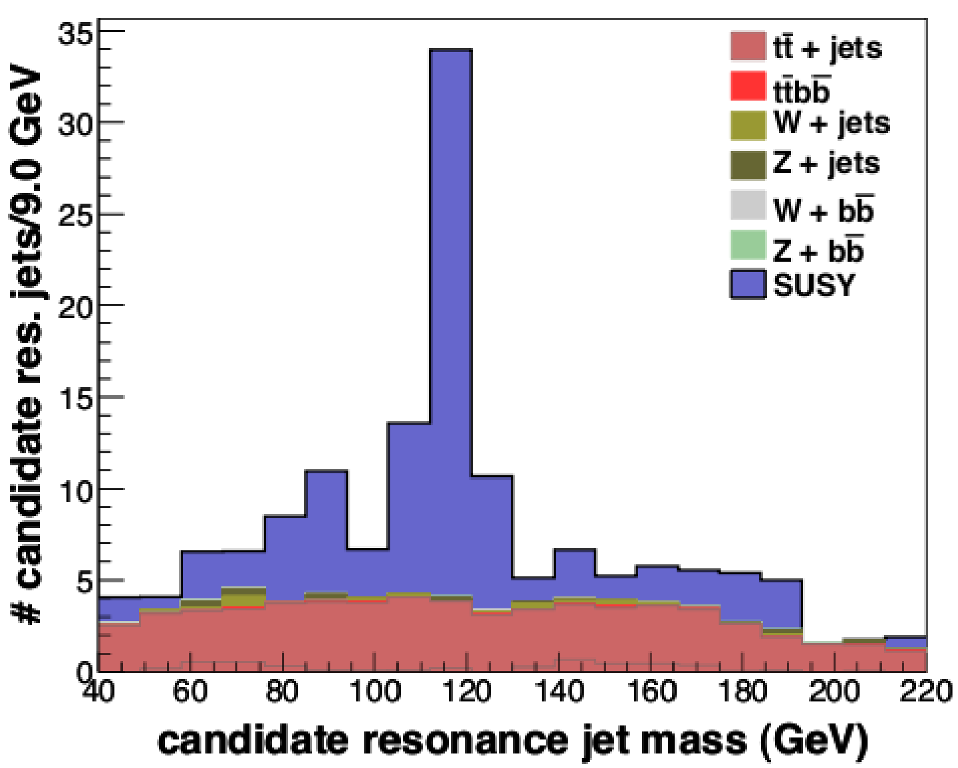


MET > 300 GeV, H_T > 1 TeV, 3+ jets, + substructure

Neutralino LSP Results: #1

$L = 10\ \mathrm{fb}^{-1}, \sqrt{s} = 14$ TeV





$$BR(\tilde{u}_L, \tilde{d}_L \to h + X) \sim 23\%$$
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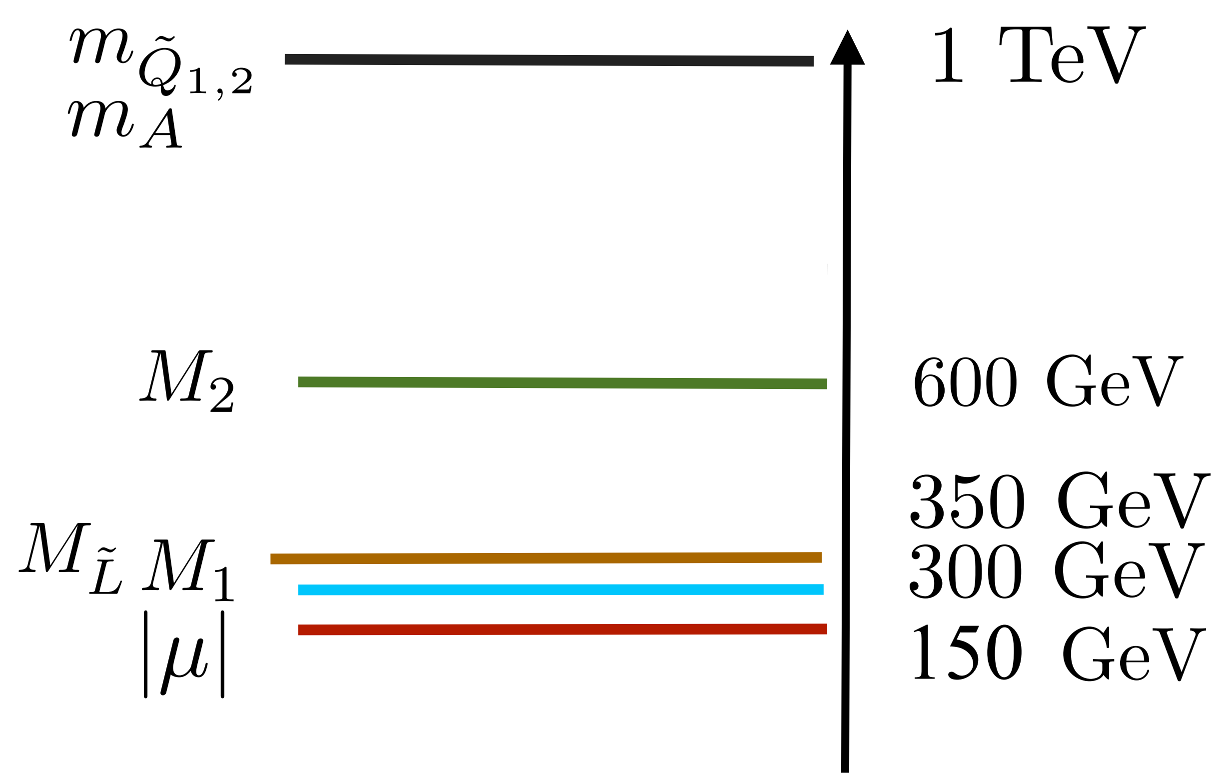


MET > 300 GeV, H_T > 1 TeV, 3+ jets, + substructure

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 (Thaler, Wang '08)

jet gymnastics performed using FastJet (hep-ph/0512210)

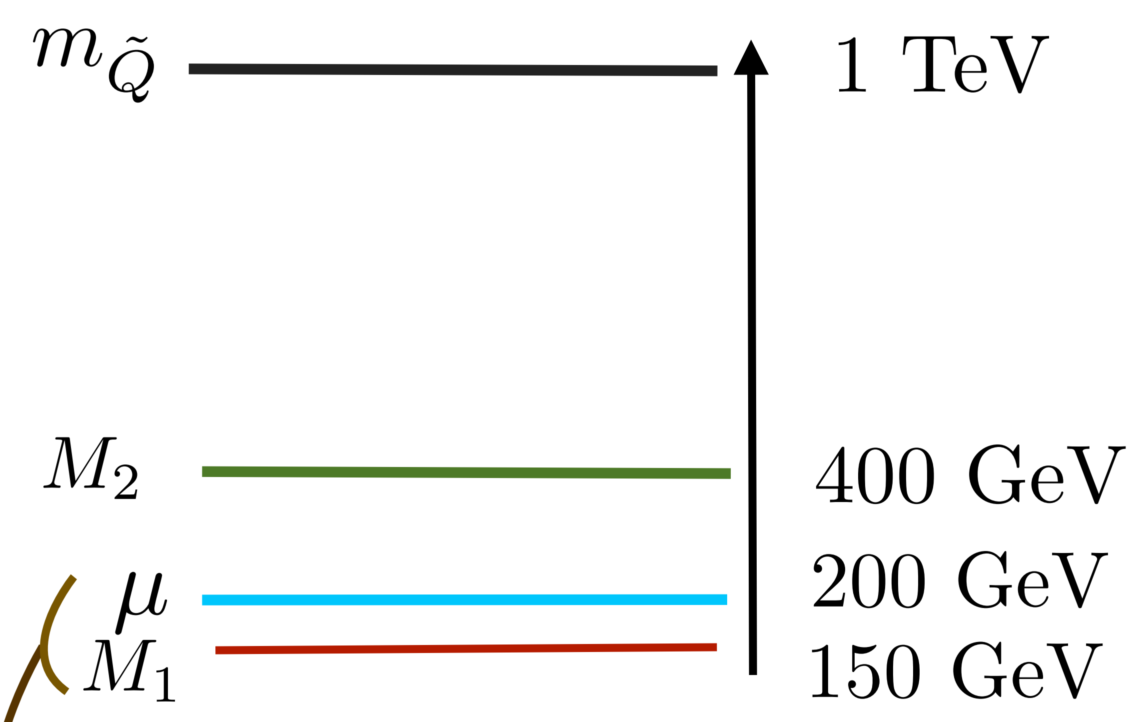
b-tagging: 60% efficiency, 2% fake rate

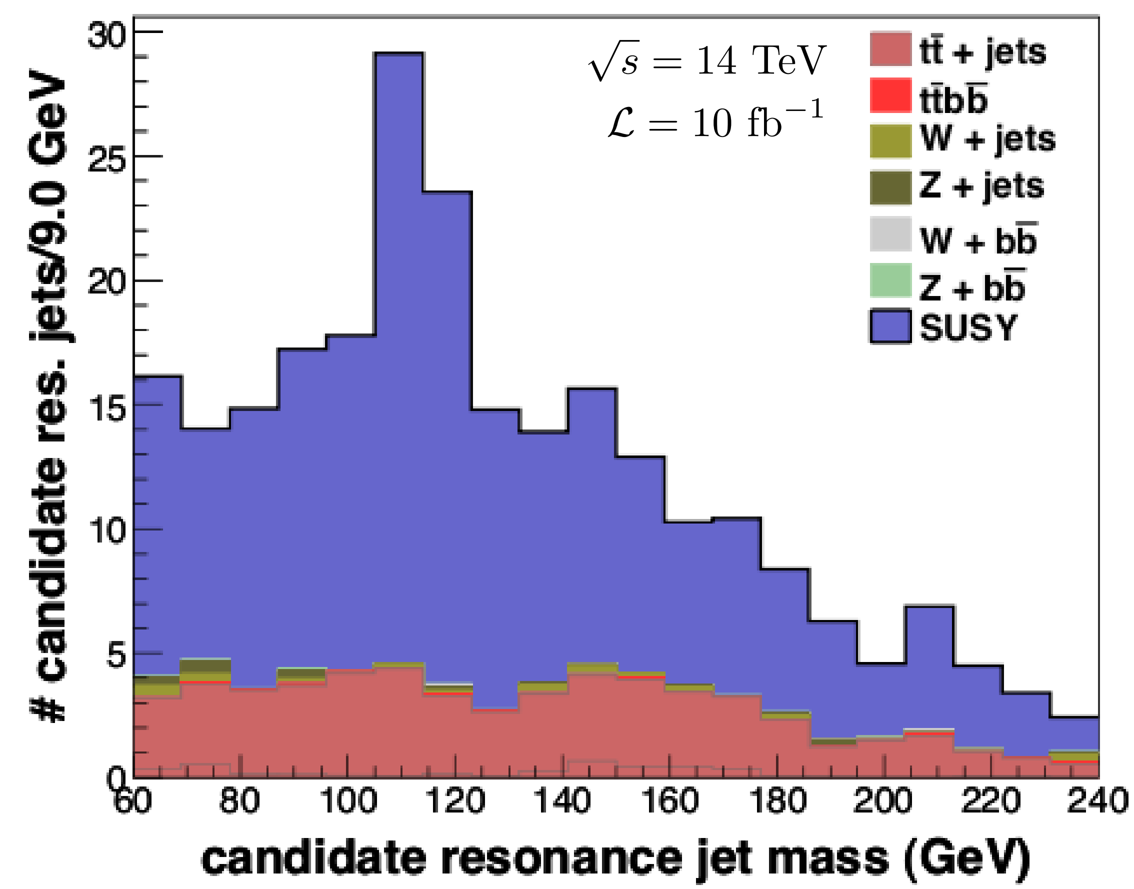
jet-photon fake rate: $.1\%$

"But I really liked SUSY Dark Matter..."

Though we typically have too little DM

permitting $M_1 \lesssim \mu$, we can get consistent Ω_{DM}
without losing all our Higgses



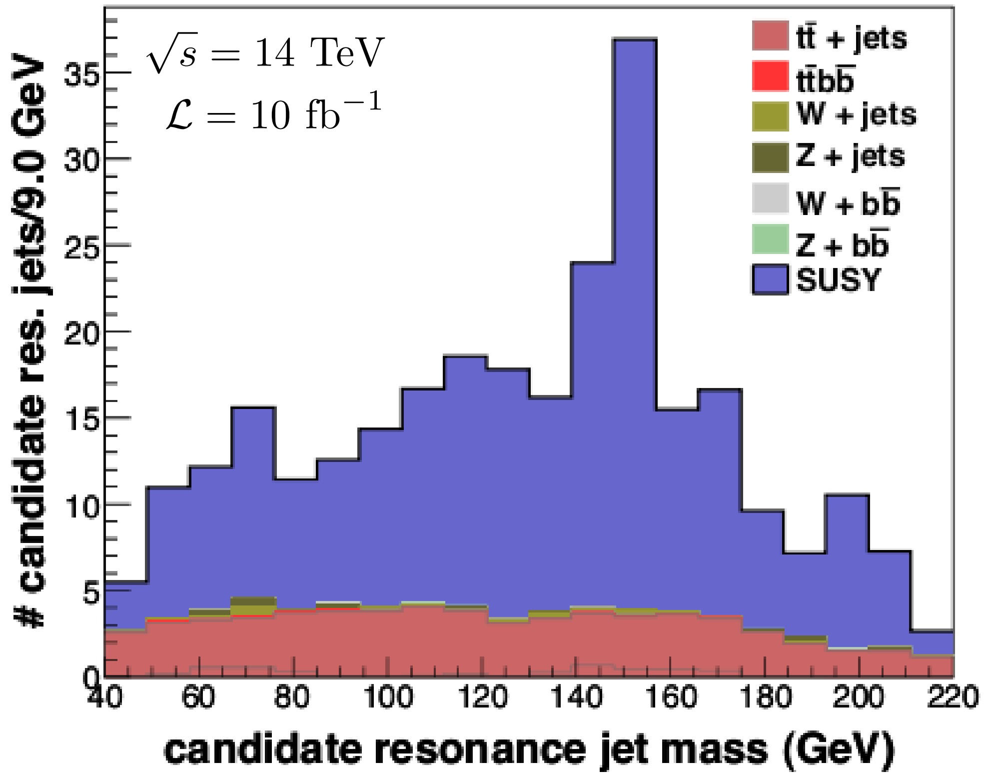


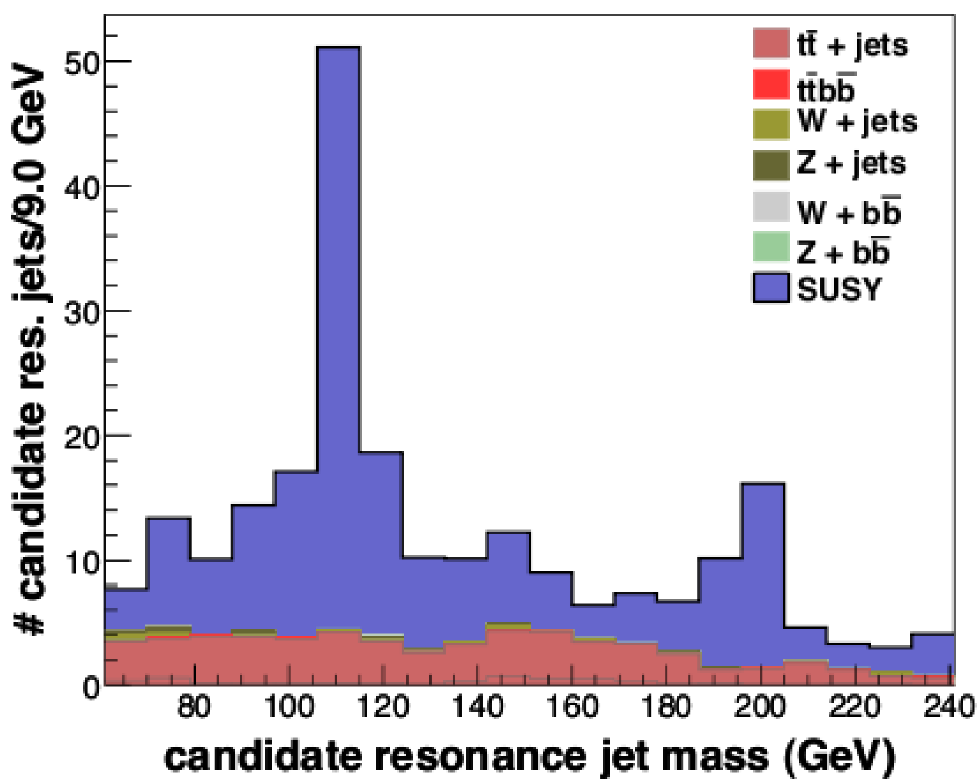
$M_1 \lesssim \mu$ shuts off bino -> Higgsino decays

shuts off RH squark to Higgs cascades, reducing the signal rate

Neutralino LSP Results: #2

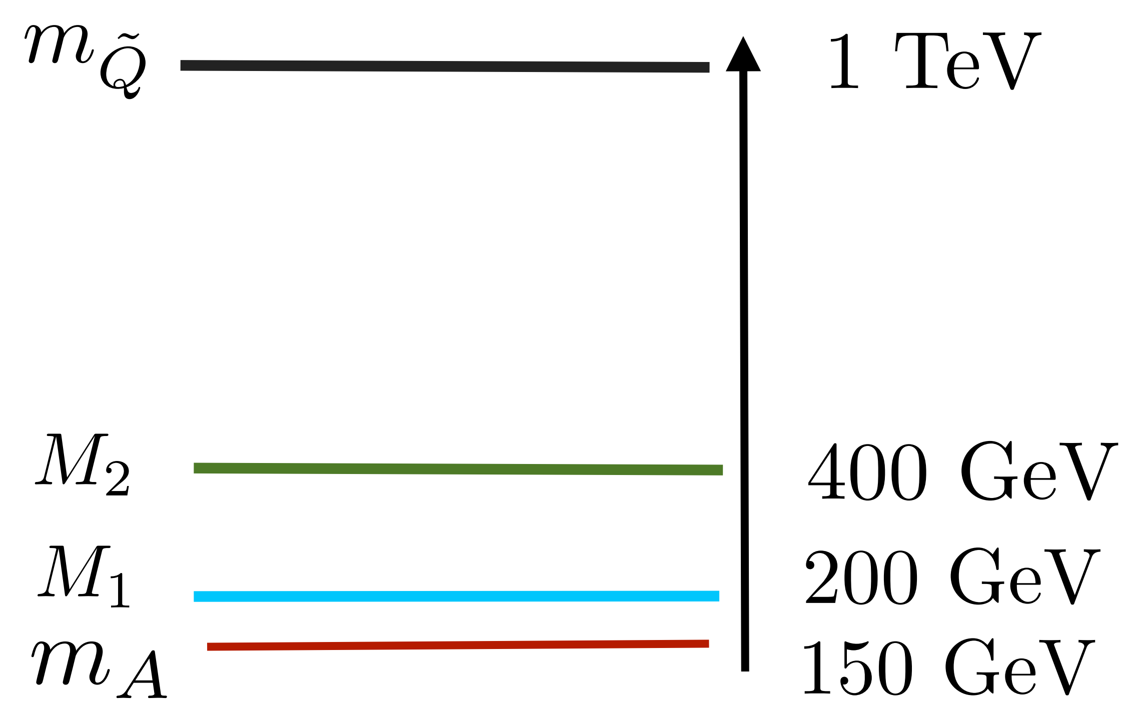
$\mu = -150\ \text{GeV},\ \tan\beta = 6.5$





$\mu = 200\ \text{GeV},\ \tan\beta = 5$

technique holds up at low m_A and $\tan\beta$, where traditional approaches have the most trouble

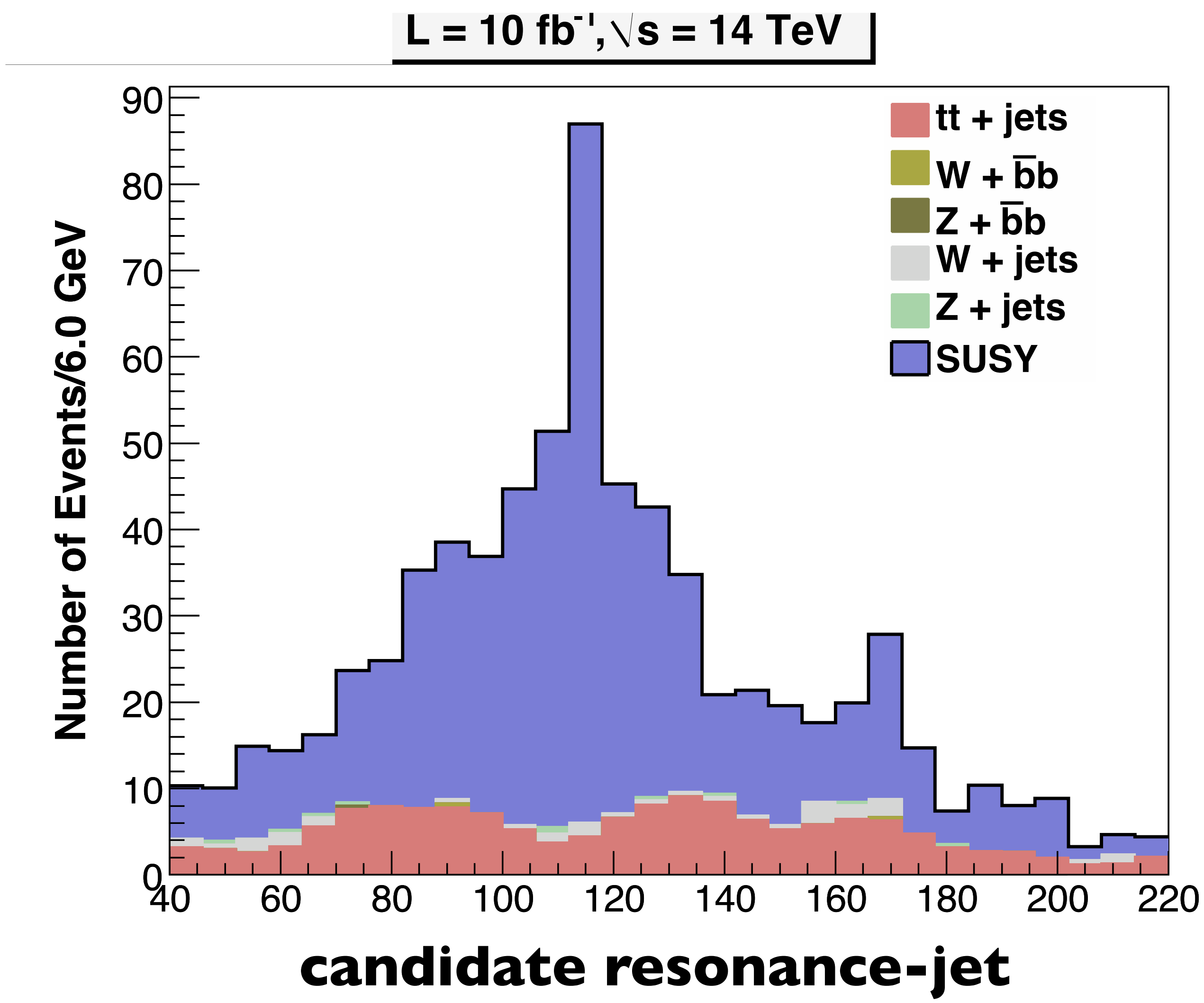


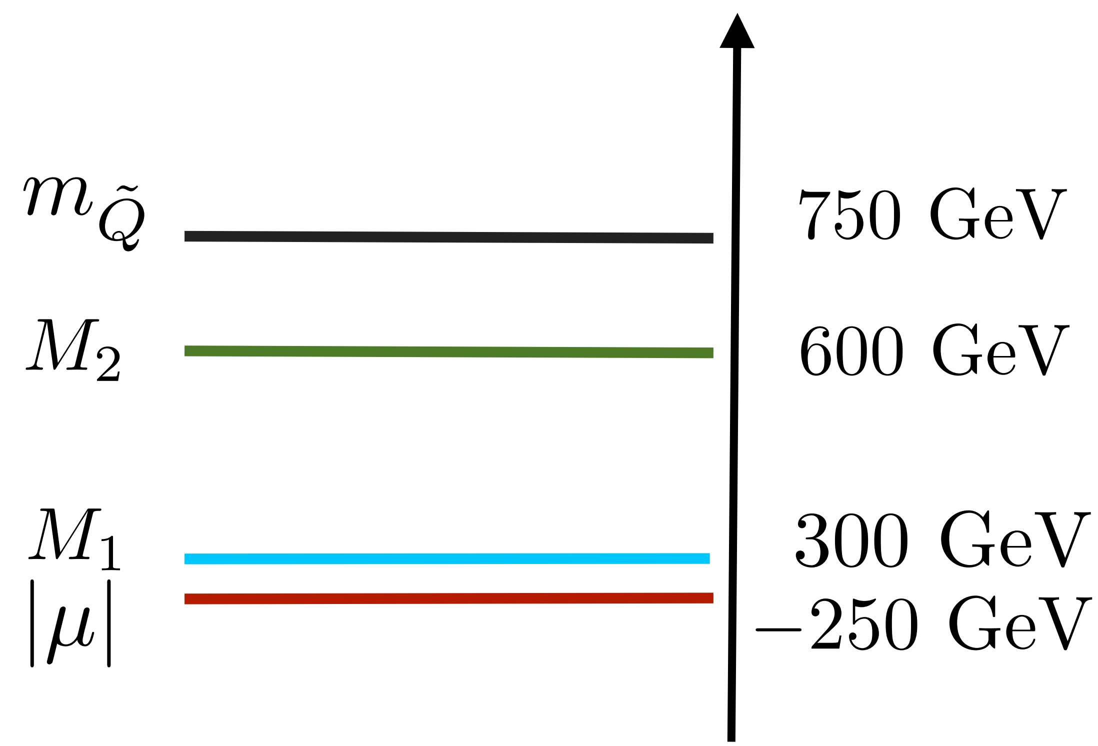
Can even discover heavier A,H states!

Gravitino LSP Results:

$$pp \to \text{SUSY} \to \chi_0\chi_0 \to h + \gamma + \not{E}_T + X$$

High-p_T photon makes things easier...
No need for large H_T, jet mult. cuts





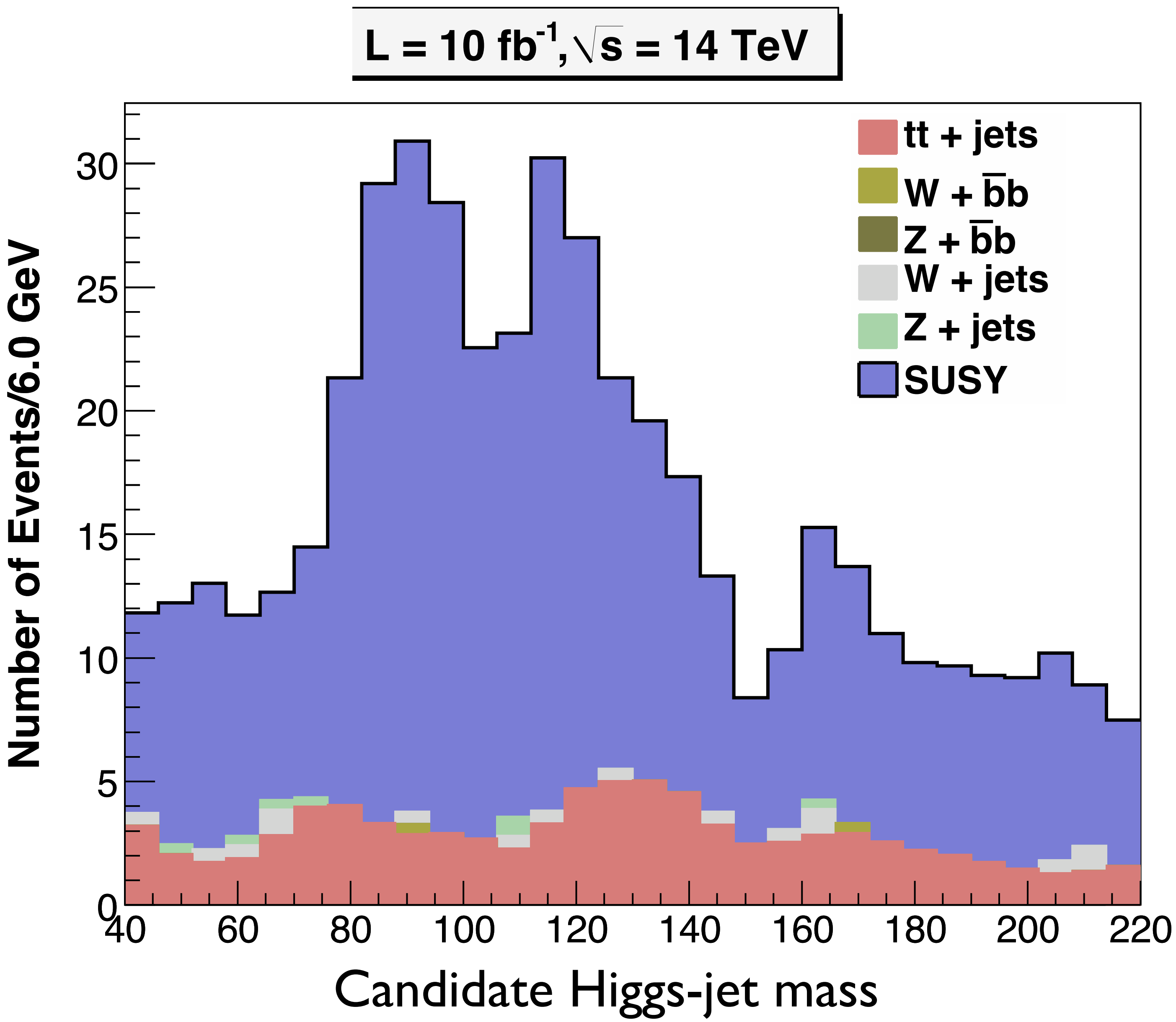
1 jet with substructure +

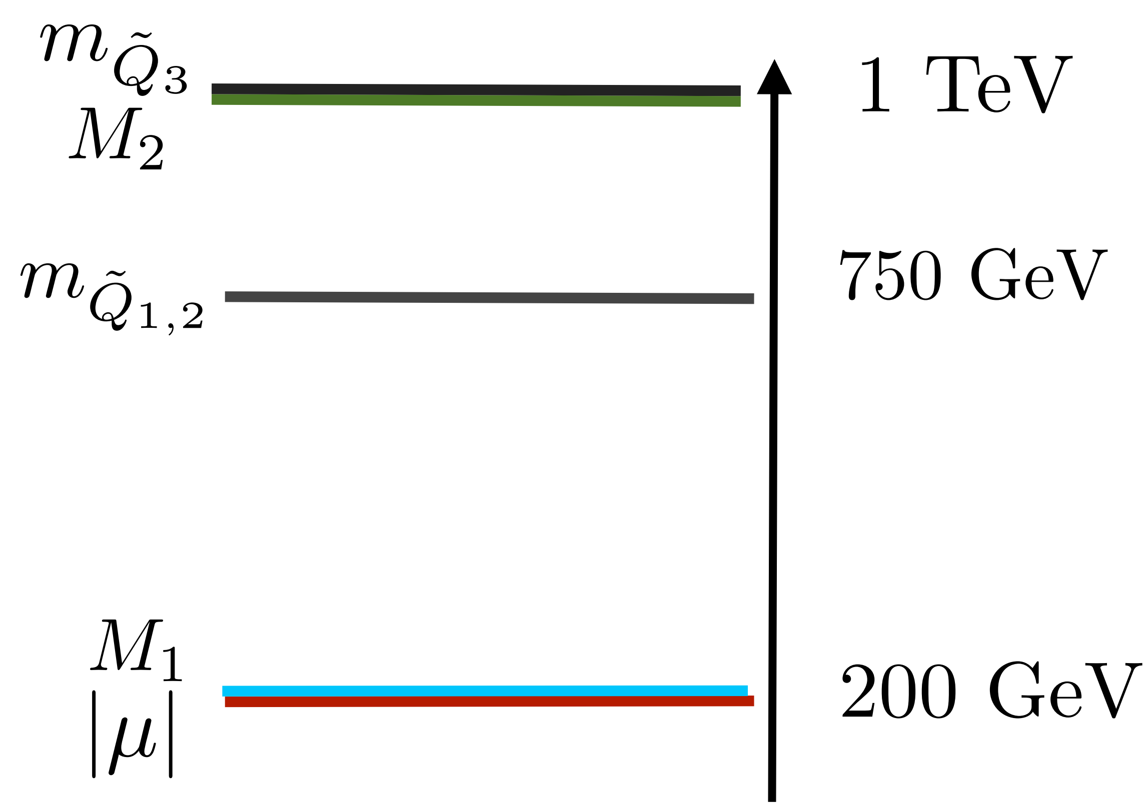
$$\not{E}_T > 100 \text{ GeV}$$

$$p_{T\gamma} > 80 \text{ GeV}$$

(0912.4731)

Gravitino LSP Results: Point #3





much trickier region of parameter space

boosted fraction $\sim 47\%$

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

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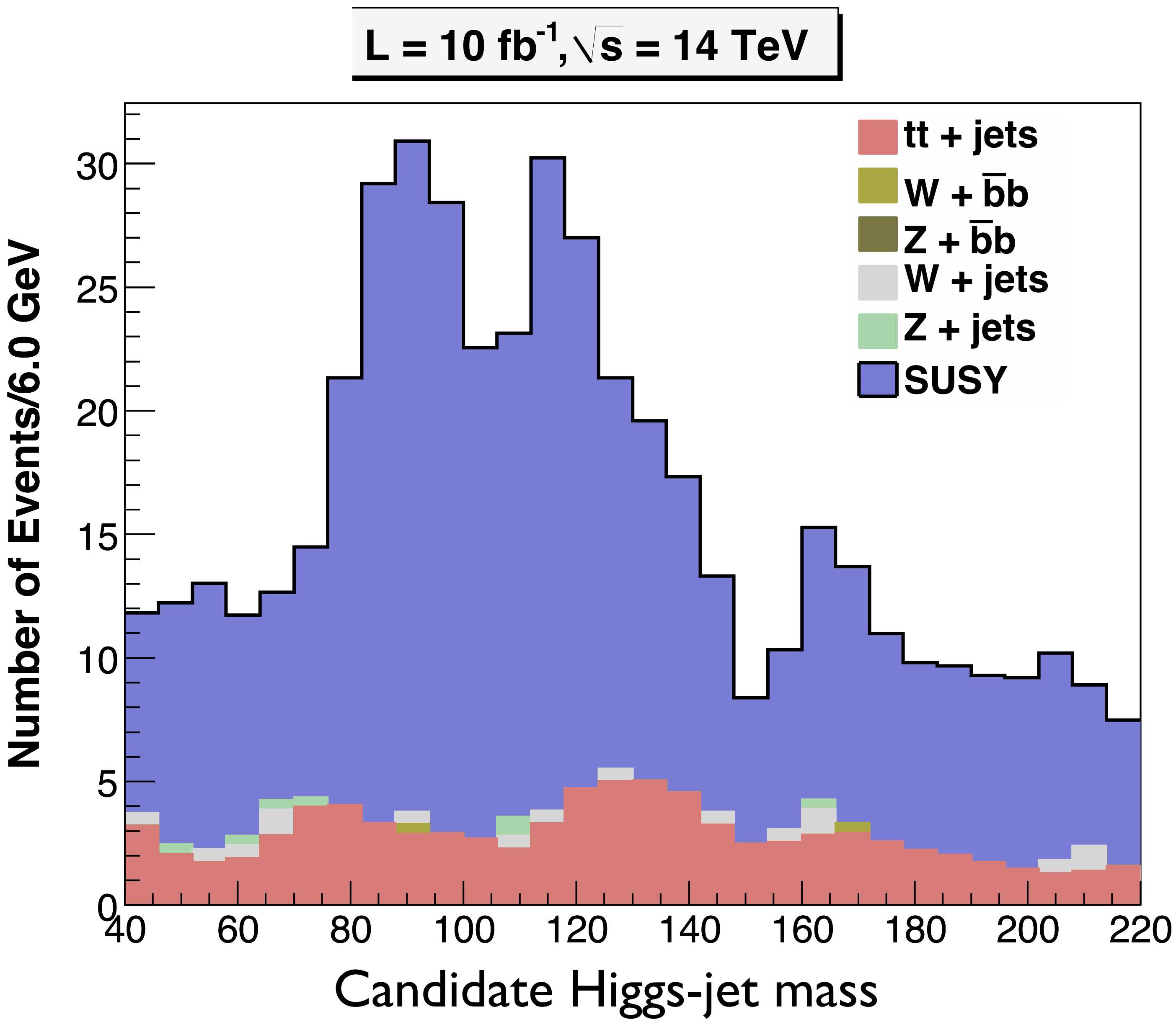

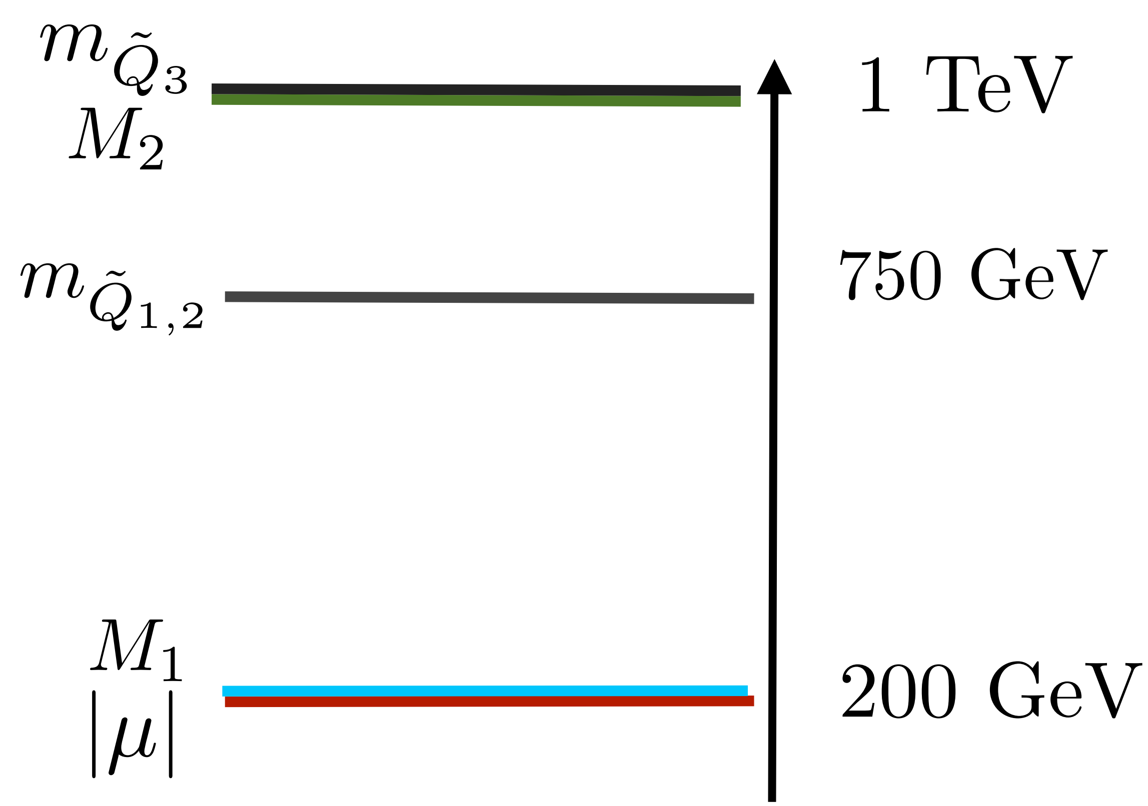

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MSSM Higgs Comments

We've used the MSSM as an example source of Higgses from BSM, but the technique is by no means limited to this

Ingredients:

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

* cleanliness of substructure analysis

better extraction of underlying parameters

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More exotic Higgses

Ex.) `Buried Higgs'

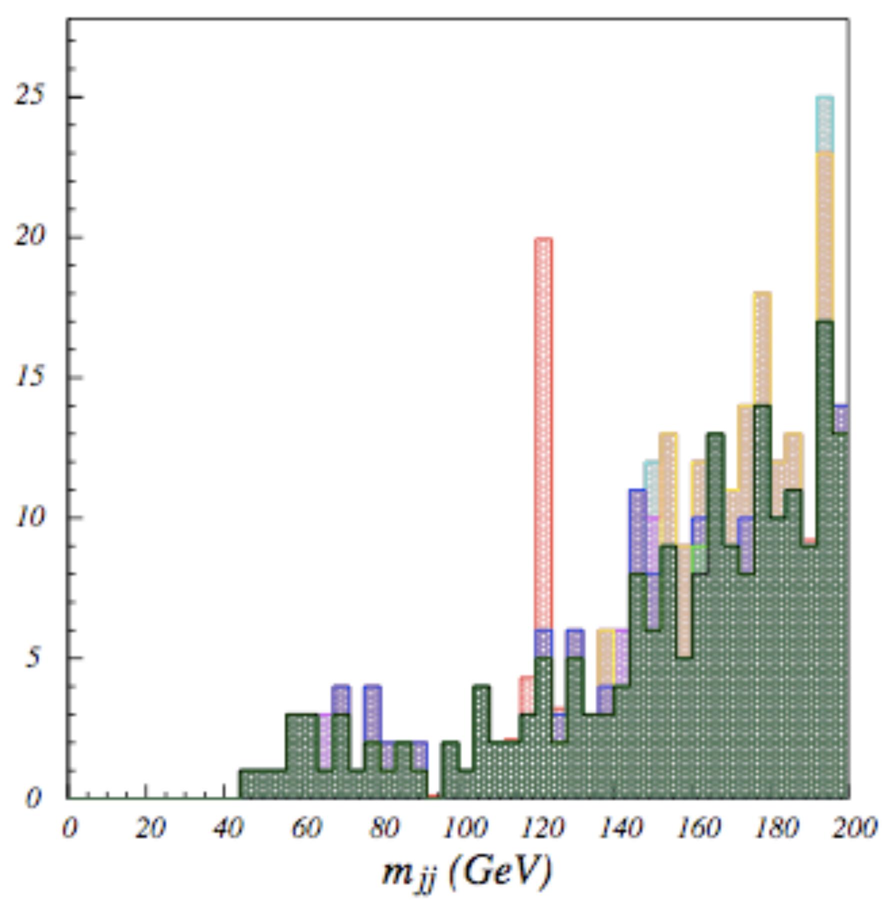
(Bellazini et al '09)

add in a new pseudoscalar η , can easily arrange for $h \to 2\eta$ to dominate: small m_η --> $h \to 2\eta \to 4g$!!

- η certainly boosted.
  2 light subjets of the same mass
- color singlet -> 2 color singlets
  distinct color flow

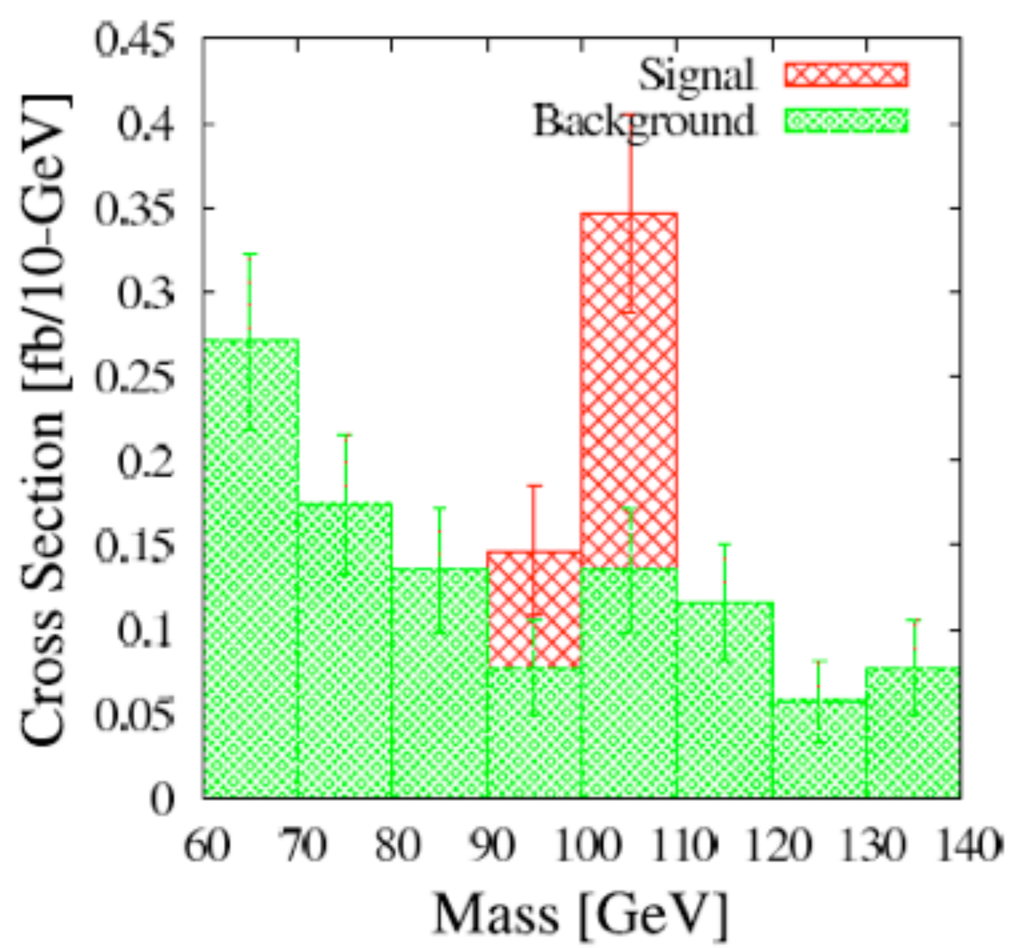
WH

Chen, Nojiri & Sreethawong '10



ttH

Falkowski et al '10



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tricky, but can be 'unburied' with substructure methods

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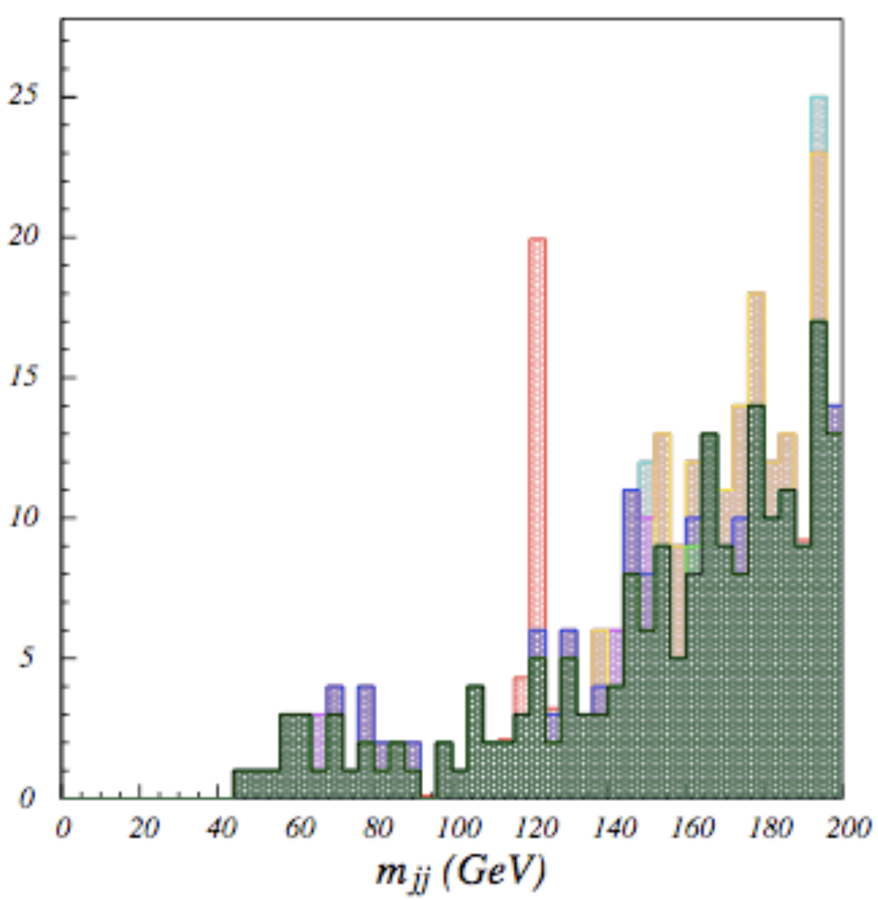

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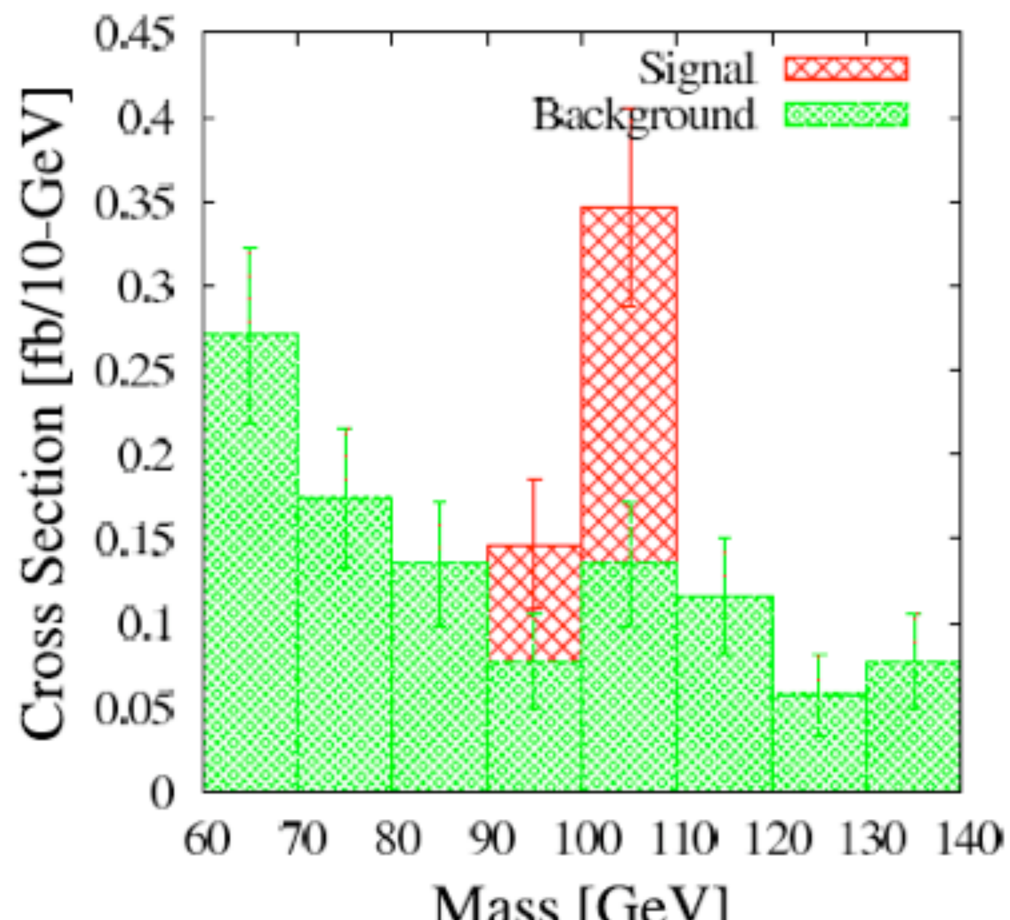

Conclusions

- Using jet substructure techniques, can find boosted $h \to \bar{b}b$

  brings back W/Z + h mode in SM

  can be extended to work in busy environments

- MSSM Higgs must be light, decays mainly to b-bbar

- Higgses from sparticle cascades have potentially large rate, high boost --> ideal for substructure

- For a wide range of SUSY parameters, cascade-Higgs discovery channels can easily be as significant (or more so) than conventional h -> γγ, h -> ττ (H/A discovery too!)