NON-CONVENTIONAL OBJECTS FOR COLLIDER PHENOMENOLOGY:

JET-LIKE OBJECTS AND THEIR APPLICATIONS

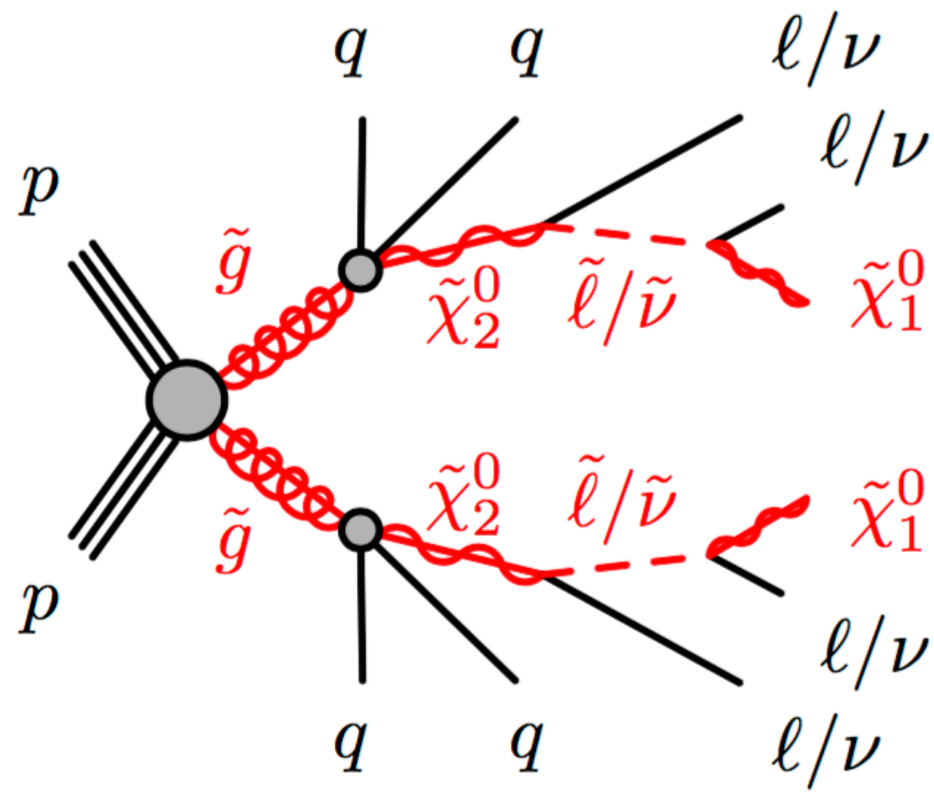
Myeonghun Park

Center for Theoretical Physics of the Universe

ibs 기초과학연구원
Institute for Basic Science

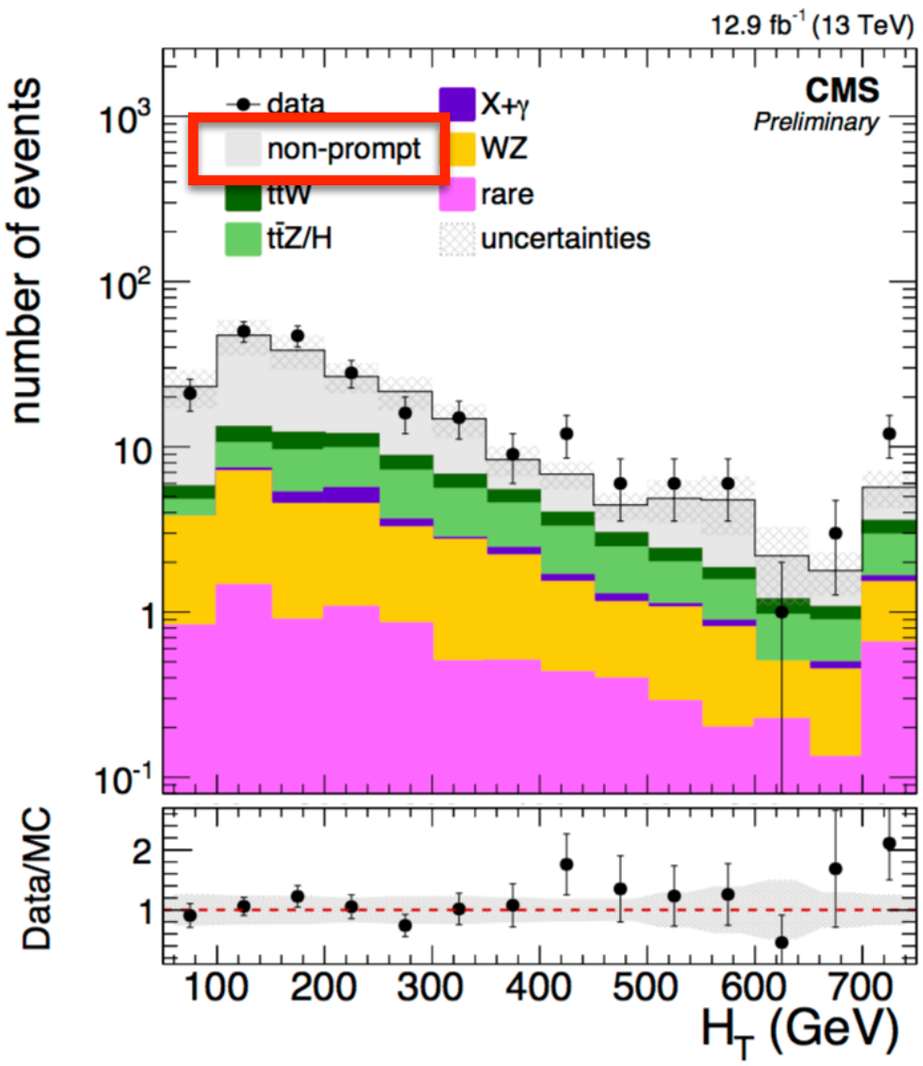
Charting the Unknown: interpreting LHC data from the energy frontier

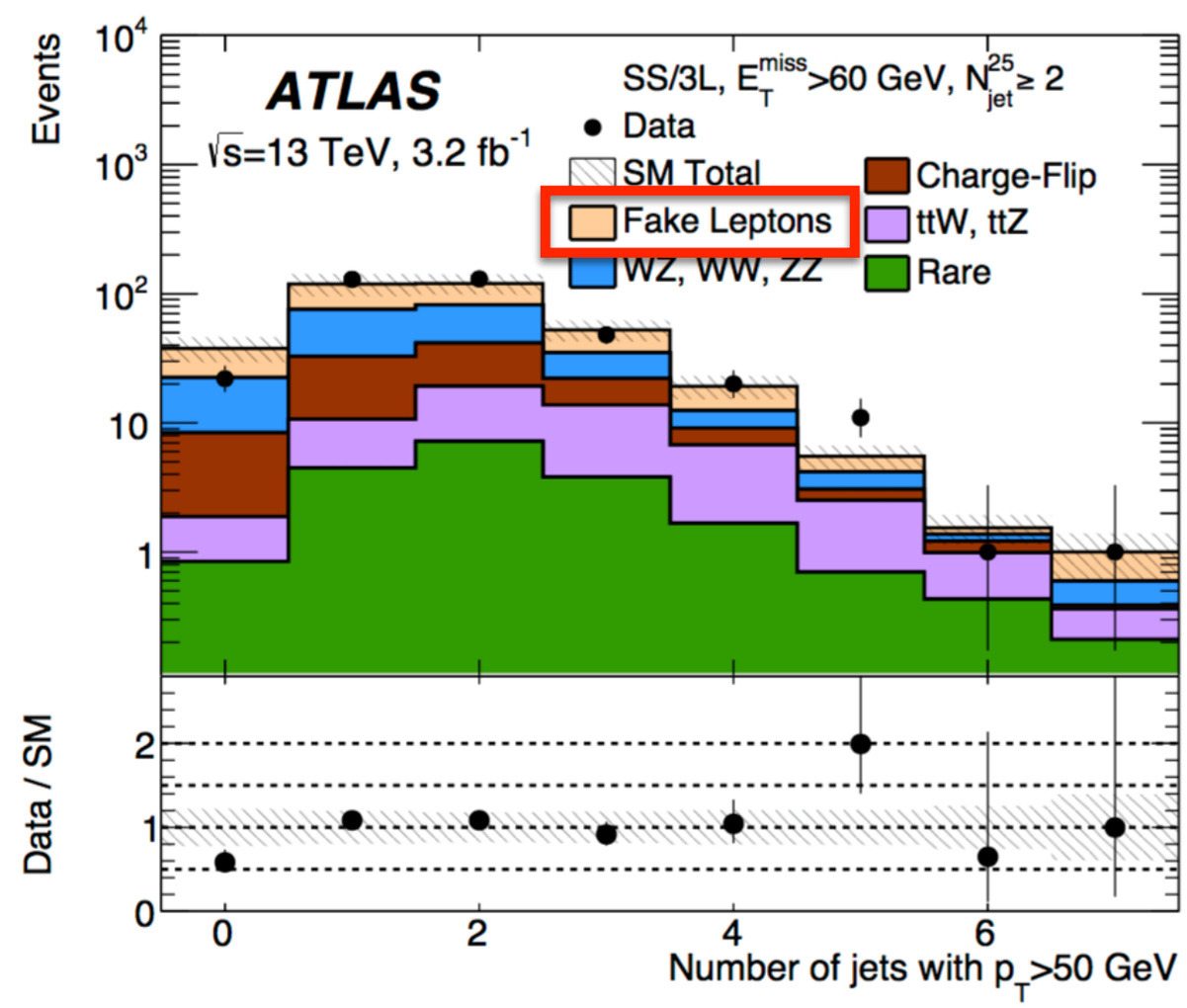
What we wanted to see



- “Famous” Golden channel (multi-leptons) in SUSY
- Not so many channels to provide MANY “prompt” leptons in SM

What bothers us





- "Non-prompt" (or fake) leptons from heavy flavor
- Di-lepton $t\bar{t}$ channels (one fake from B-jet)

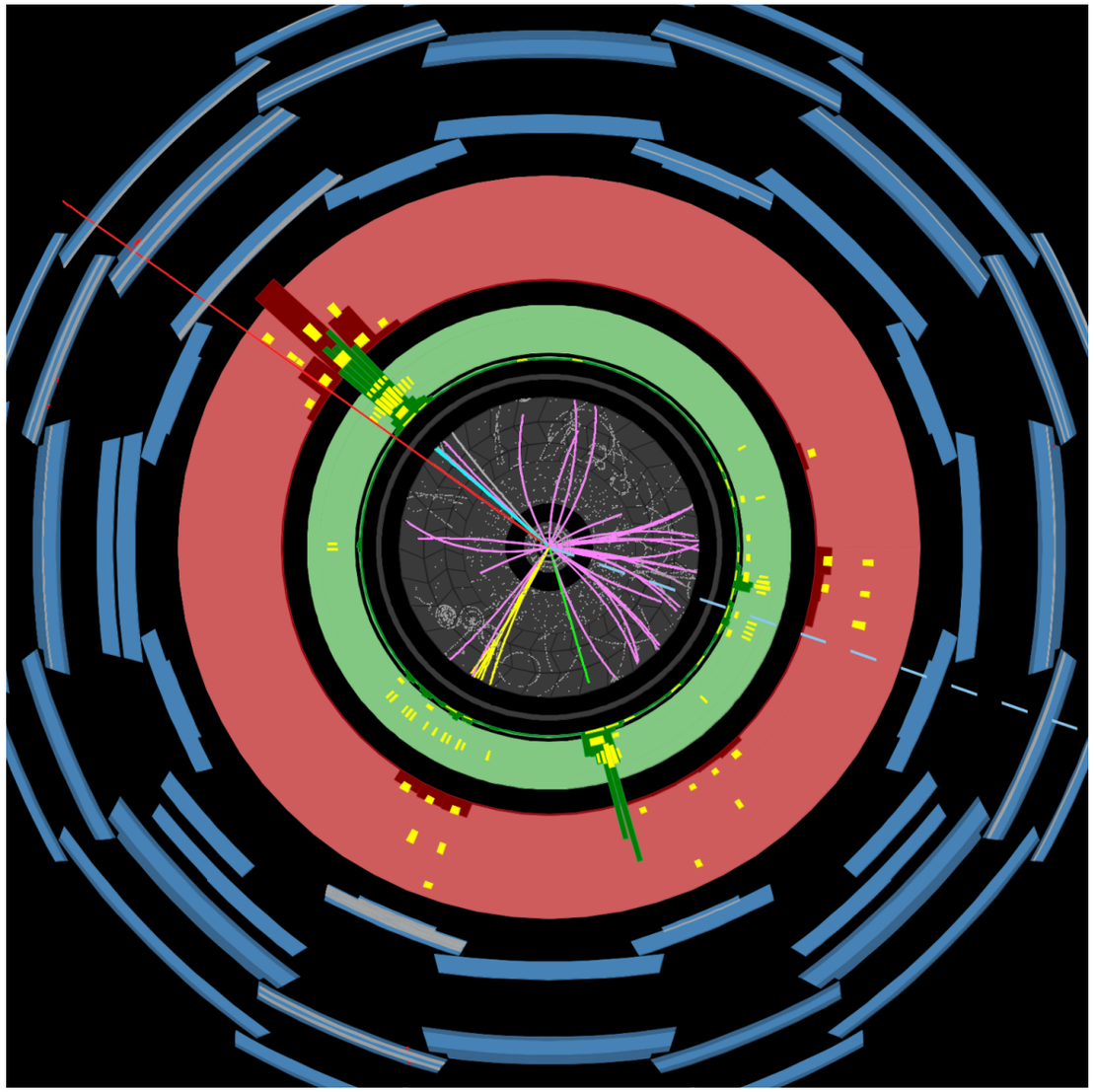
Conservative identification

Easy

Difficult

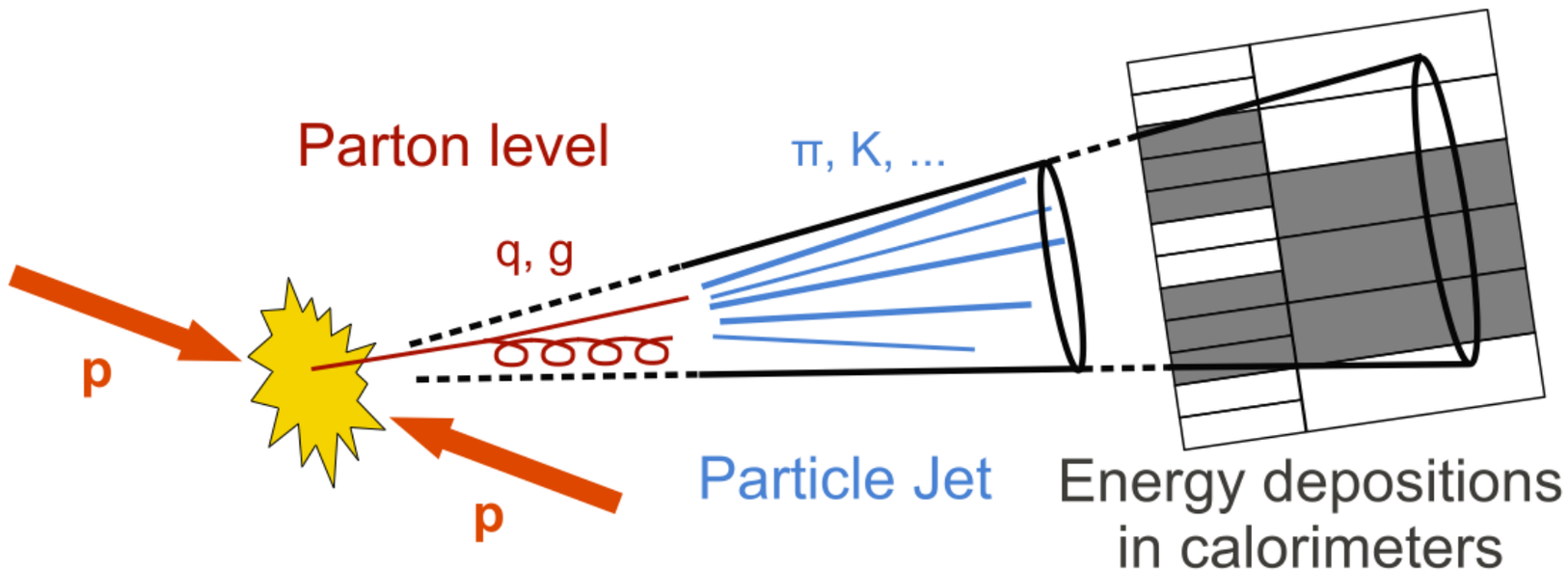
- The basic objects:
  1. Muon
  2. electron / photon
  3. Jet
  4. Heavy flavor jet, Tau-lepton

- Require tight **isolation** criteria to remove “fake” objects

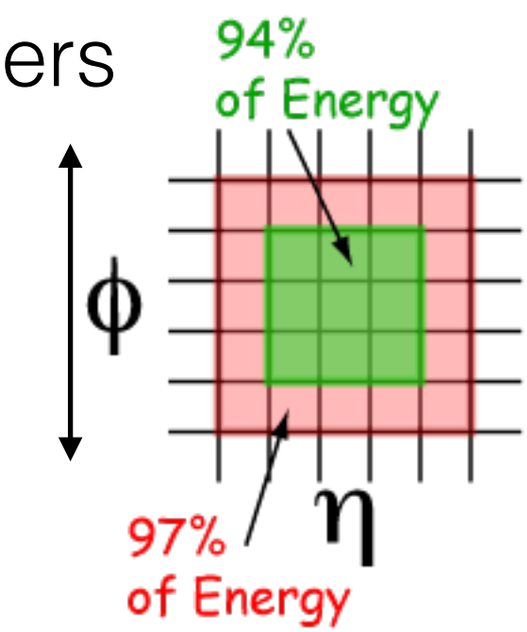


di-lepton $t\bar{t}$

Clustering “energy deposits”



- Collect energy deposits to capture particles from the initial parton
- Supercluster ECALs to capture energies from showers

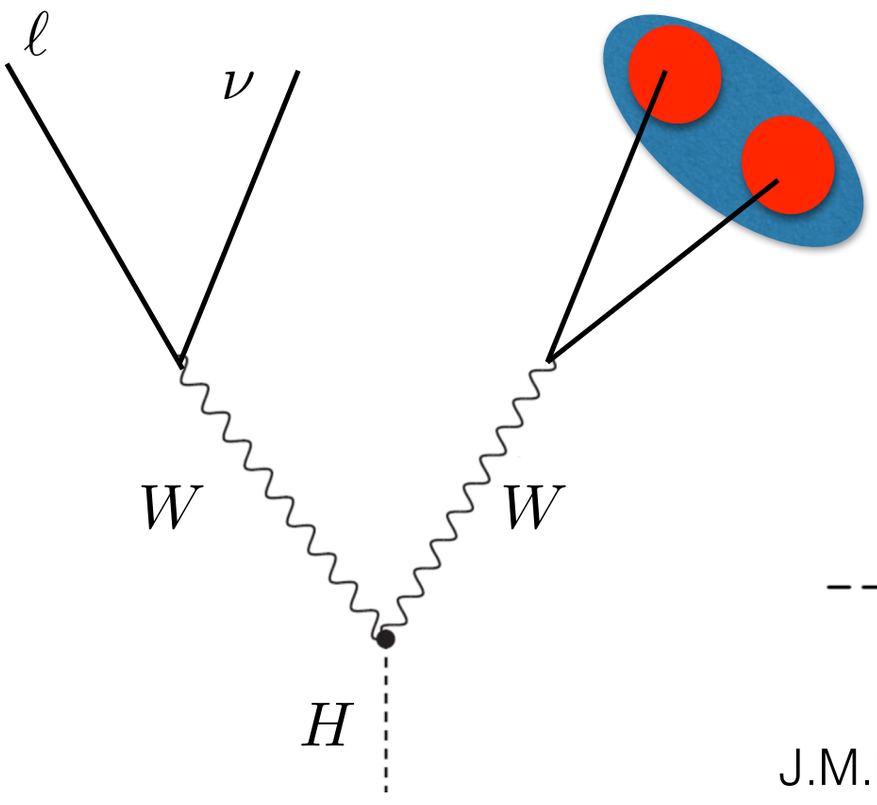


Generalized concept of “jet (**clustering**)” have been used!

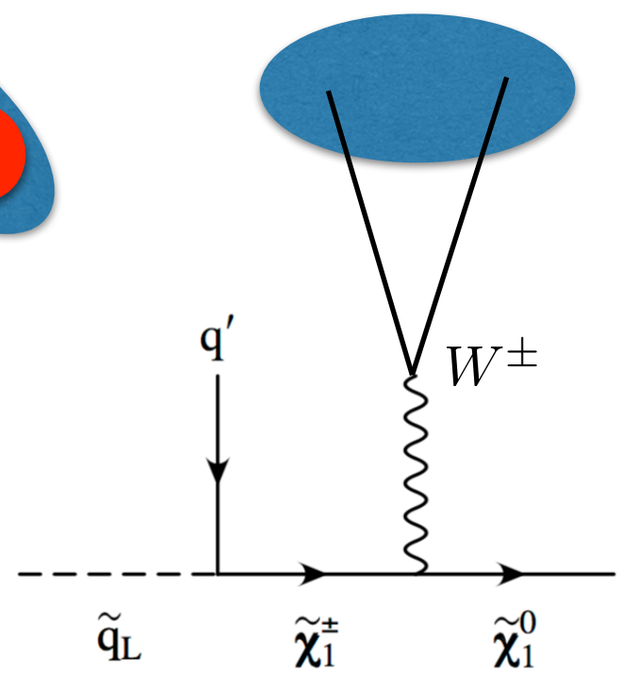
A Jet of jets

- Capture jets(quarks) from energetic [(highly) boosted] Top / W / Z / H

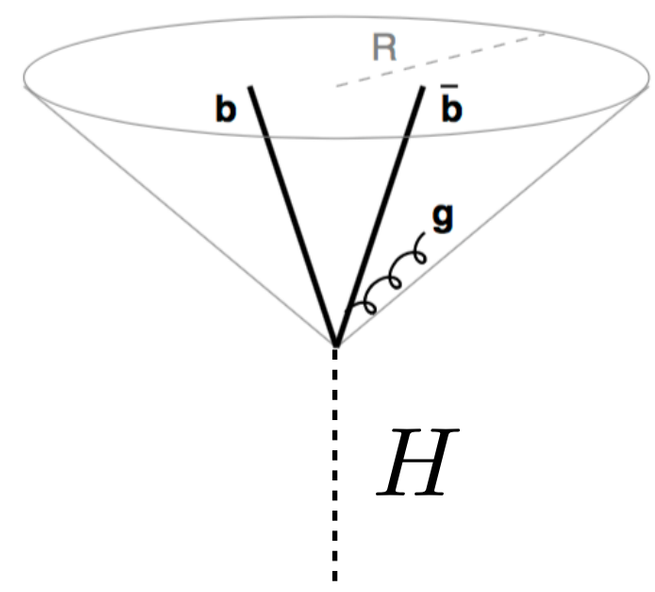
$$\Delta R \simeq \frac{2M_{(V/t/H)}}{P_{T(V/t/H)}}$$



M. Seymour (1994)



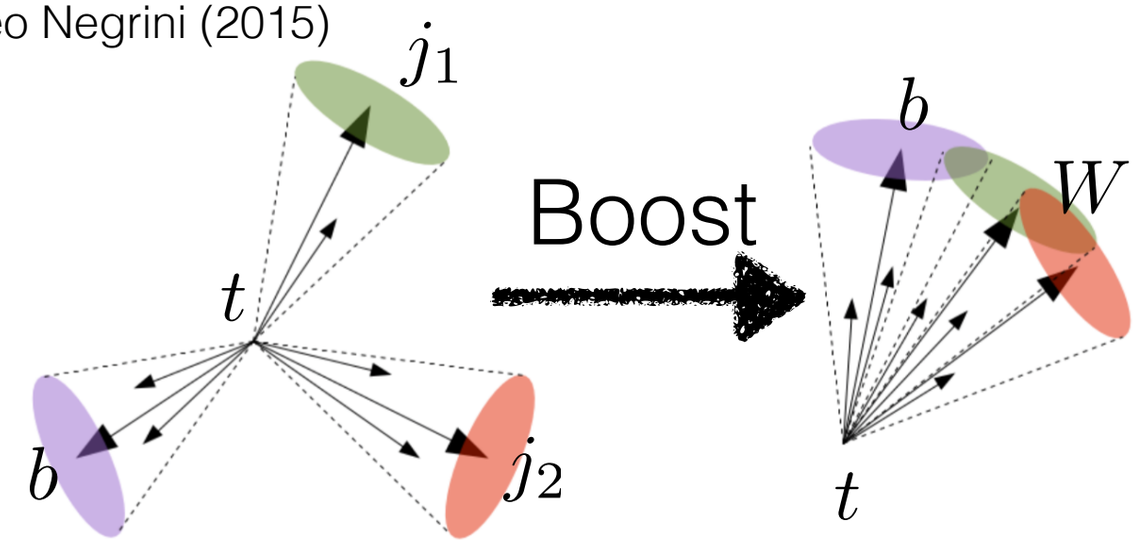
J.M.Butterworth, J. Ellis, A.R. Rakalv (2007)



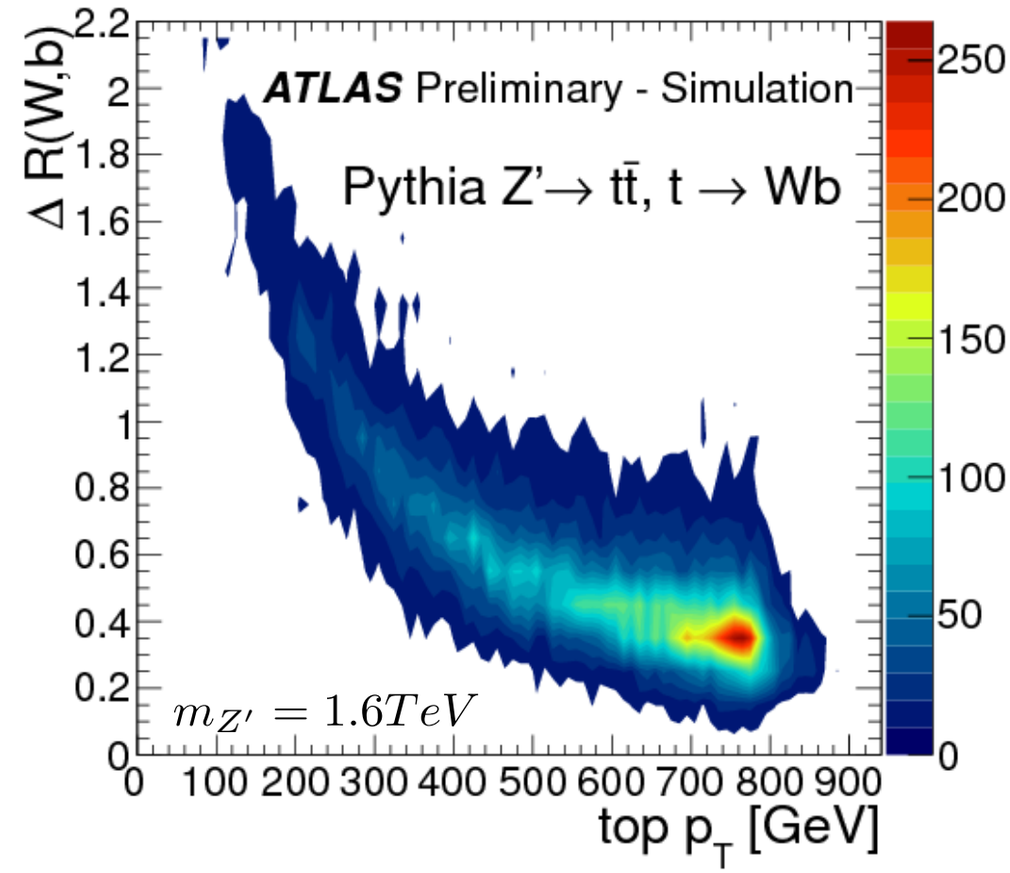
$pp \to V/H, (H \to b\bar{b})$

J.M.Butterworth, A.R. Davison, M. Rubin , G.P. Salam (2008)

Matteo Negrini (2015)



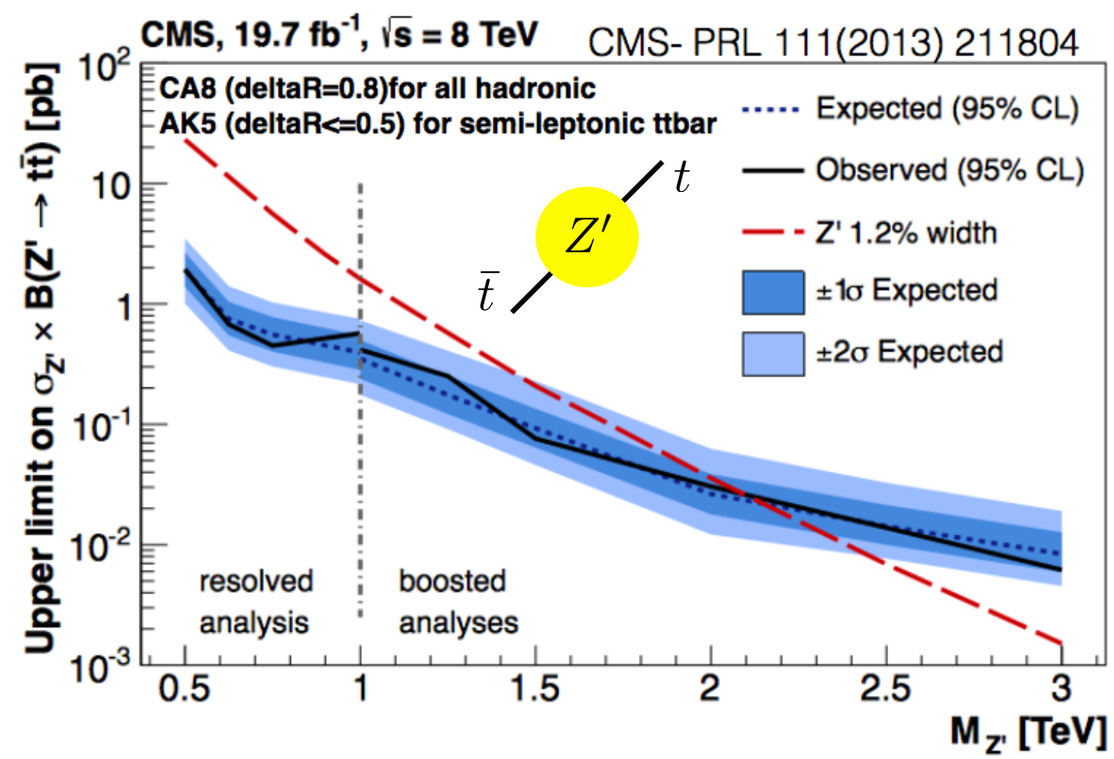
$t \to bW,\ (W \to j_1,\ j_2)$



$$\Delta R \simeq \frac{2M_{(V/t/H)}}{P_{T(V/t/H)}}$$

- J. Thaler, LT Wang (2008)
- D. Kaplan, K. Rehermann, M. D. Schwartz, B. Tweedie (2008)
- L.G.Almeida, SJ. Lee, G. Perez, I.Sung, J. Virzi (2008)
- MANY !

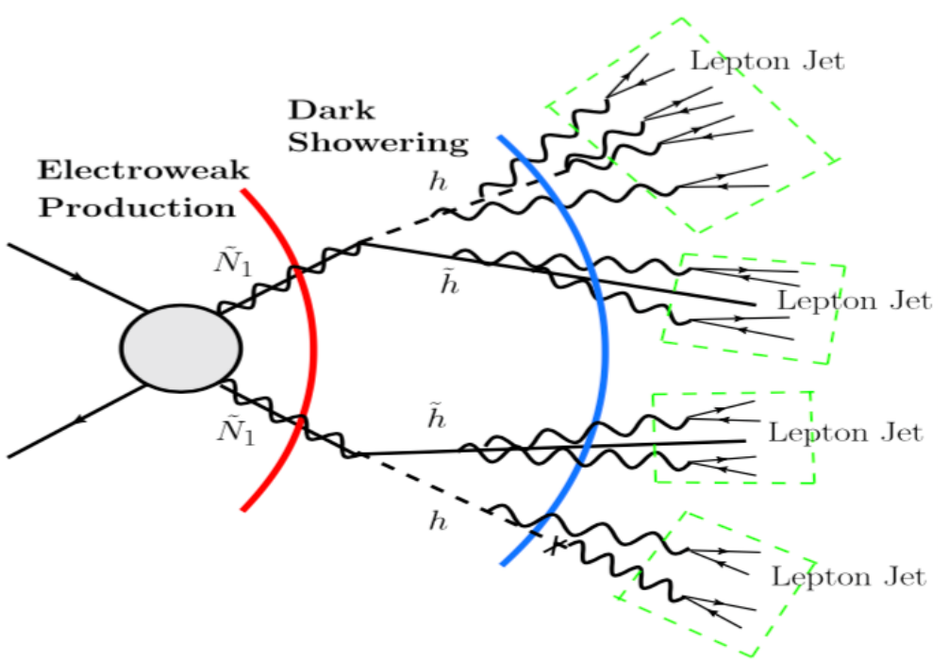
No combinatorics
v.s.
Rejecting QCD BKG



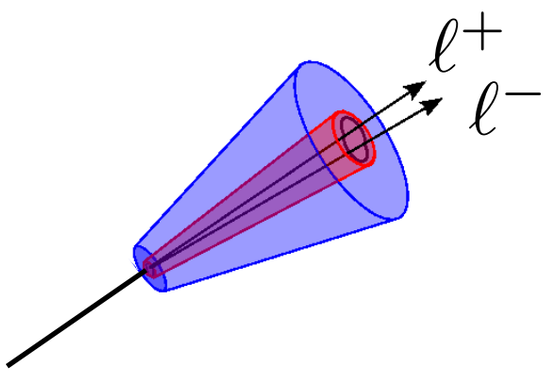
Scaling **down**

- When a "**light**" particle decays, $\Delta R \simeq \frac{2M}{P_T}$

Nima, N. Weiner (2008)
C Cheung, J.T. Ruderman, L.T. Wang, I. Yavin (2010)
A. Falkowski, J. T. Ruderman, T. Volansky, Jure Zupan (2010)
…



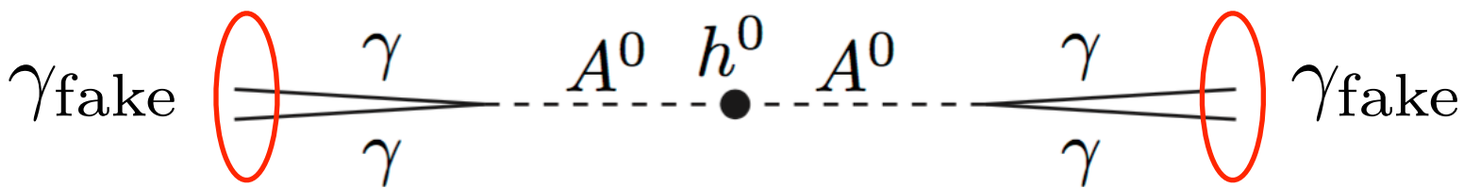
"Lepton-Jet"



1. Clustering relevant objects
2. Isolating from QCD junks

Scaling **down**

- Fake photon



B. A. Dobrescu, G. Landsberg, K.T. Matchev (2000)

- Separating photon-jet, photon and QCD-jet

S. D. Ellis, T. S. Roy, J. Scholtz (2012)

- Photon-jet got huge love-call from theorists recently :)

Extend clustering object

- Jet like objects from an **OFF-SHELL** particle.
- A lepton-jet from OFF-SHELL Z (Z^*)
- A fat-jet from OFF-SHELL Squark ($\tilde{q}^*$)

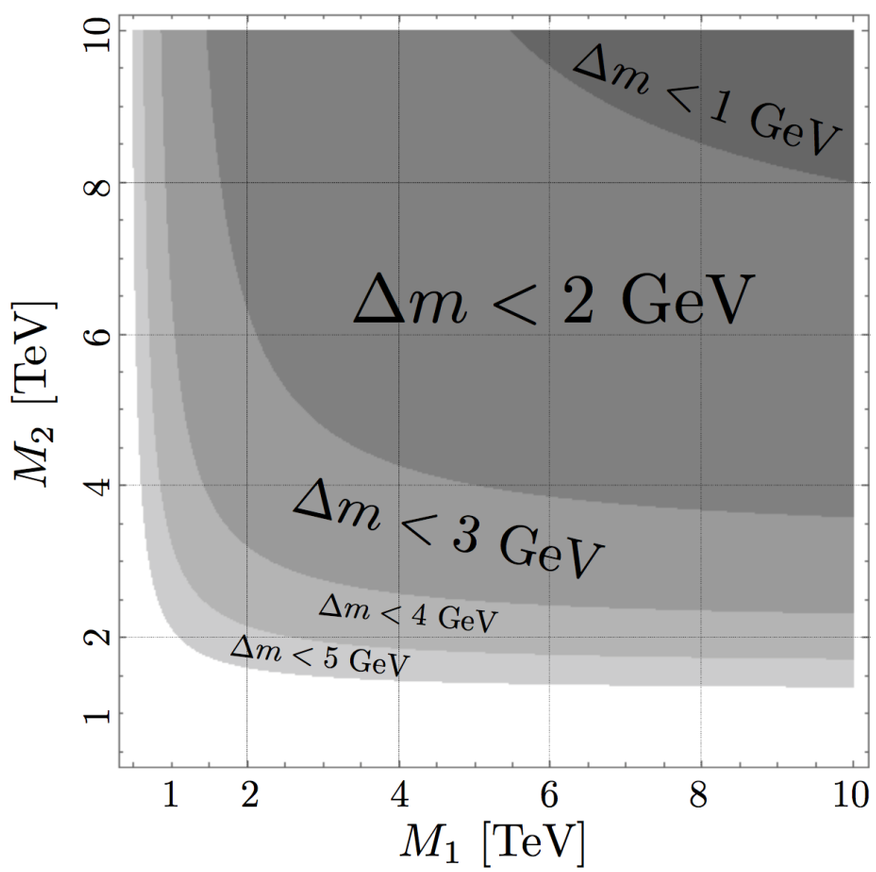
Degenerated Higginos

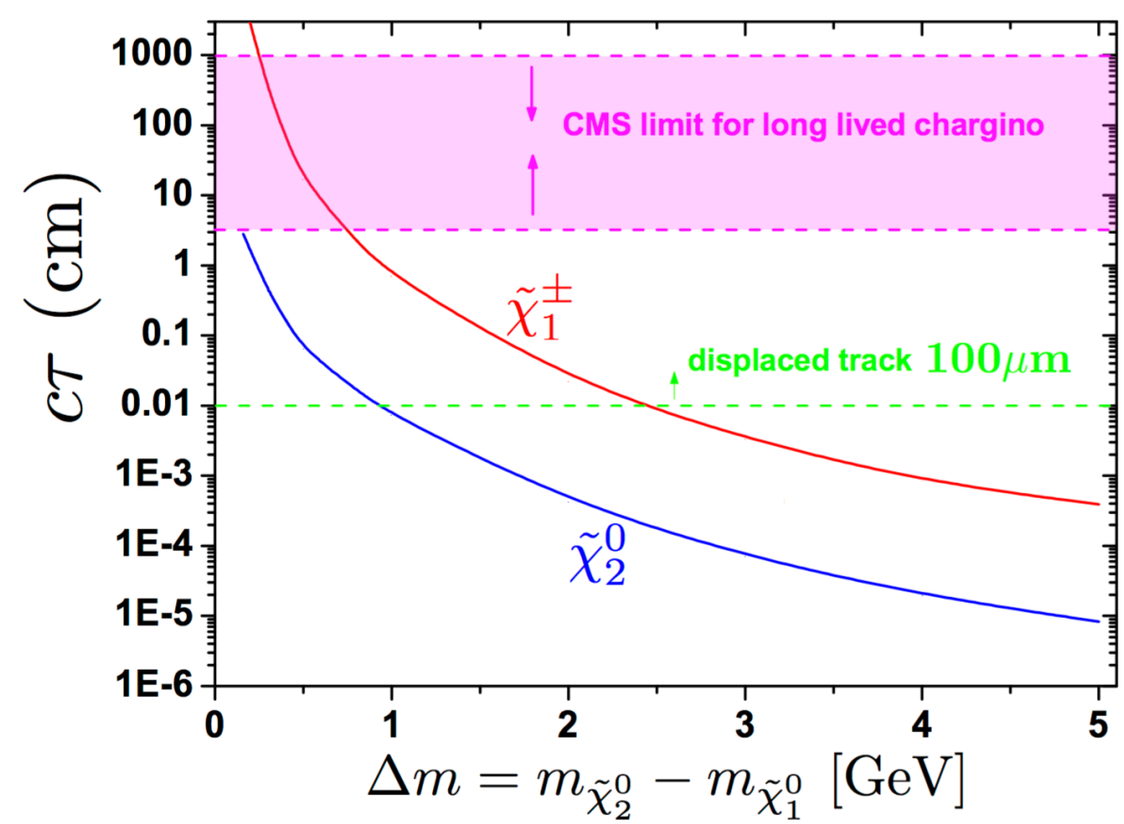
- In SUSY, EWSB

$$\frac{M_Z^2}{2} = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} \approx -\mu^2 - m_{H_u}^2$$

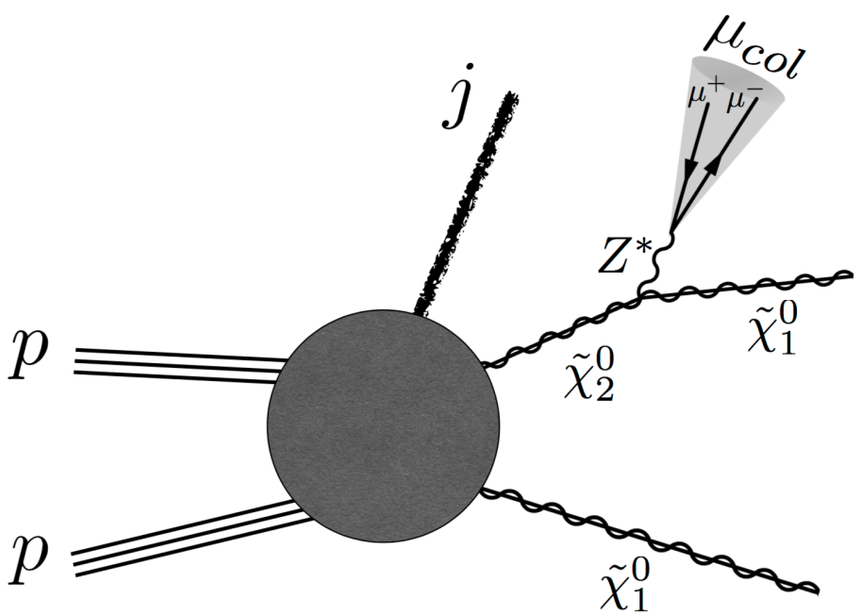
$$\Delta m \equiv m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx \frac{m_W^2}{M_2} + \frac{m_W^2 \tan^2\theta_W}{M_1}$$

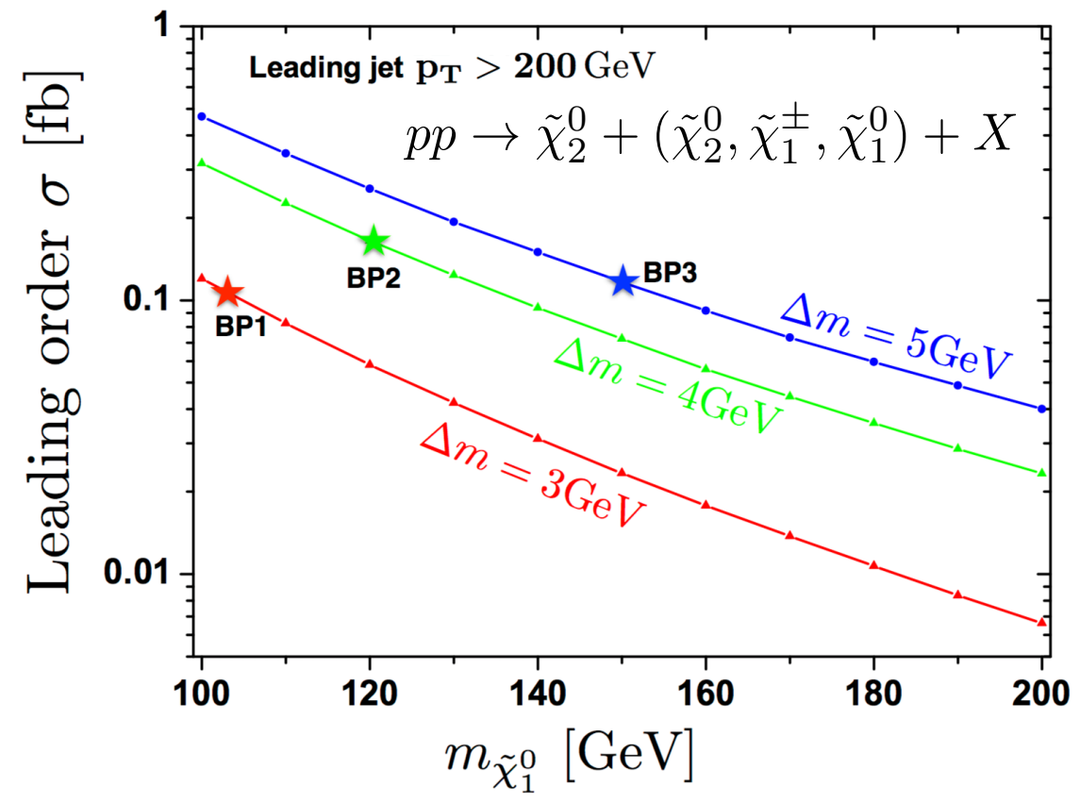
C. Han, D. Kim, S. Munir, **MP** (2015)



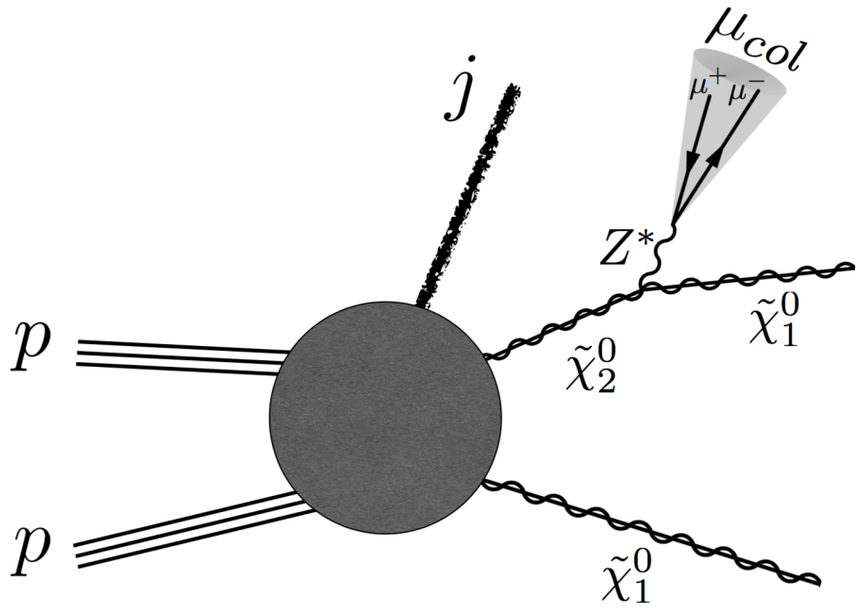


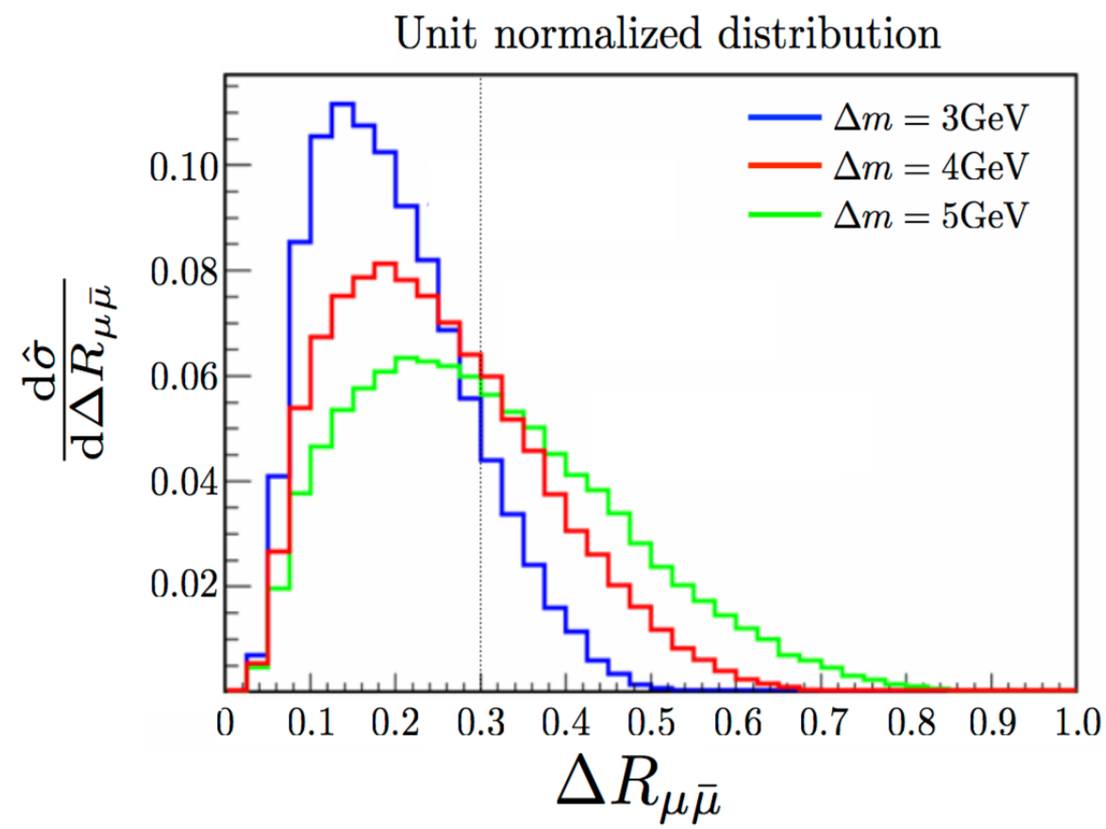
Degenerated Higginos





- Reduce a requirement for ISR PT.
- Once we tag a “particle”, we can impose more cuts.



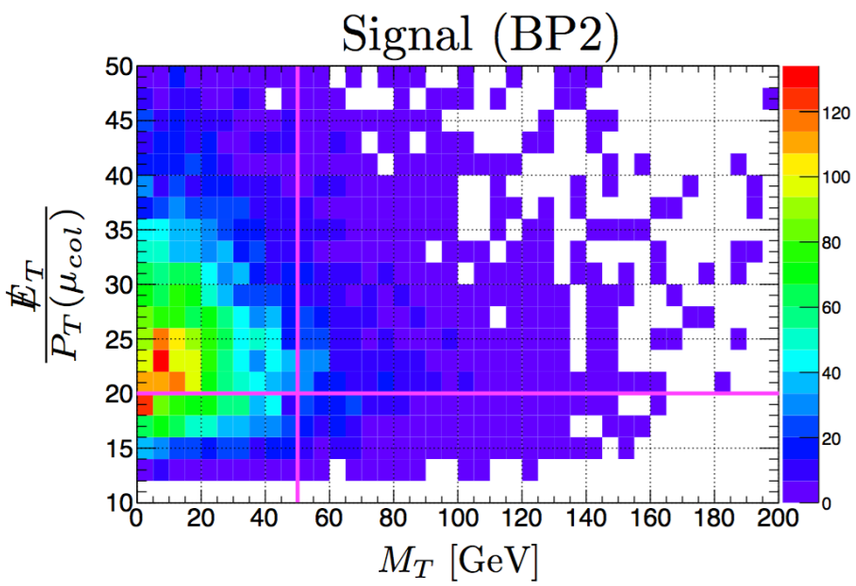


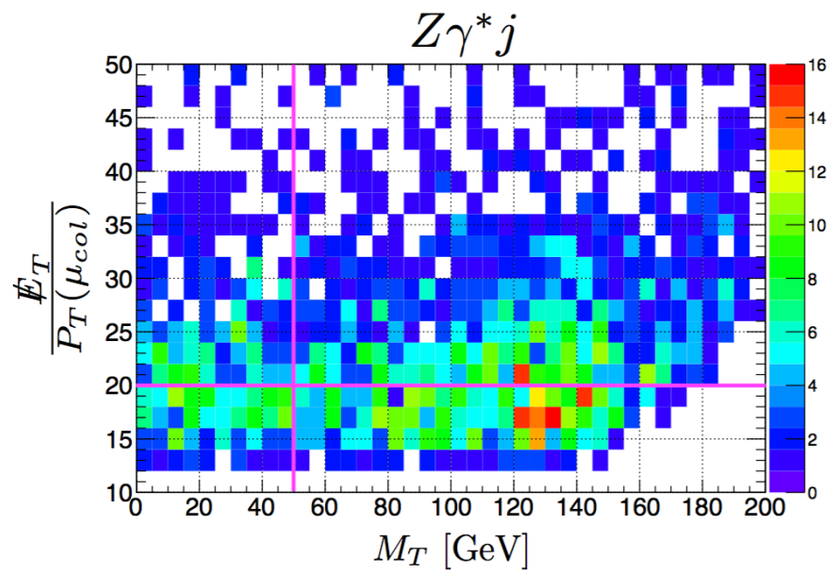
- "R = 0.3 is a conventional isolation cut"

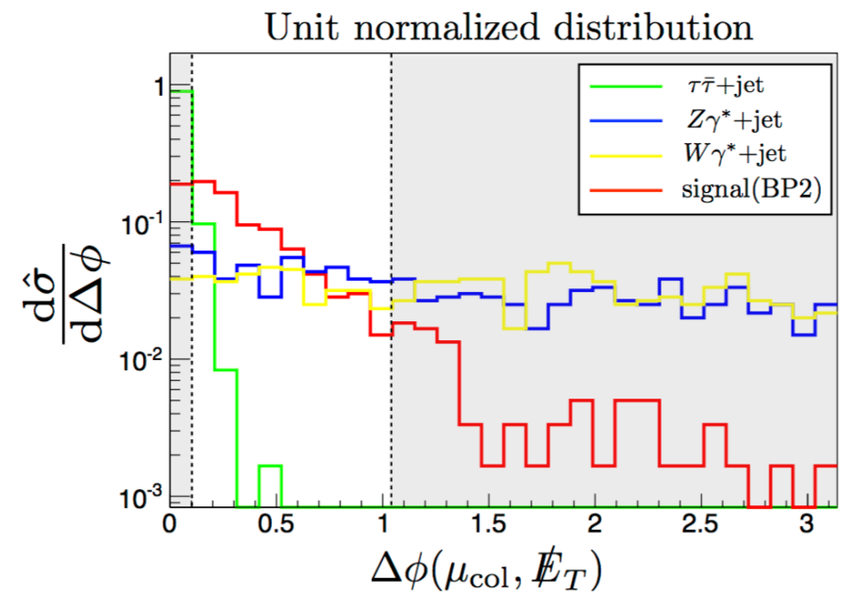
Major BKG:

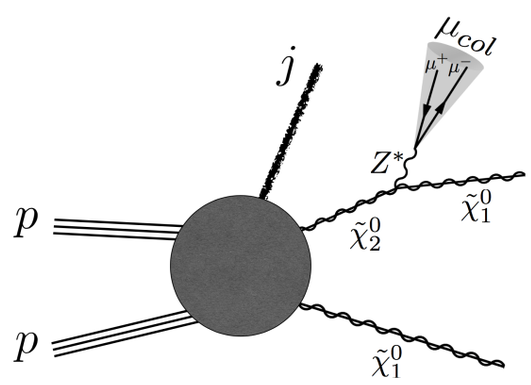
- $V + \gamma^* + jets$: A large $\not{E}_T$ results from the $W \to \ell\nu$ decay or the $Z \to \nu\nu$ decay and the two collinear muons originate from the virtual photon, γ^*. To reduce this background, we require $m_{\mu\bar{\mu}} > 1.0\,\text{GeV}$ and $\Delta R_{\mu\bar{\mu}} > 0.1$.
- $\tau\bar{\tau} + jets$: Each tau decays into a muon and a pair of neutrinos. Due to the large boost in the leading jet, these muons become highly collimated. The neutrinos produced
- $Vb\bar{b} + jets$ and $Zb + jets$: This background mimics our signal when the b-quarks decay into pairs of muons via double semileptonic decays. However, it is suppressed by 2×10^{-5}

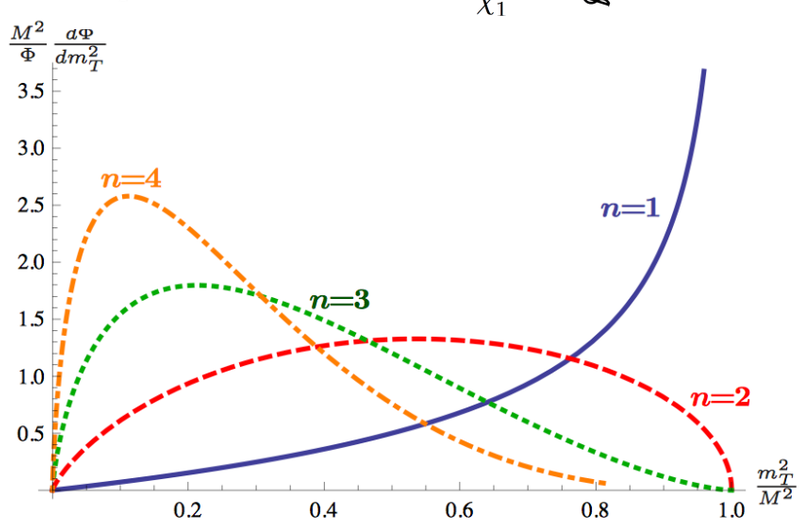
- Basic kinematic cuts to reduce Backgrounds











- Using a ratio of MET over PT(muon-jet). This represents a momentum flow of signals where most of energy goes into MET.

- The endpoint behavior of (transverse) mass variables are sensitive to the number of invisible particles.
  For **signals n=2**, while **BKG n=1**.

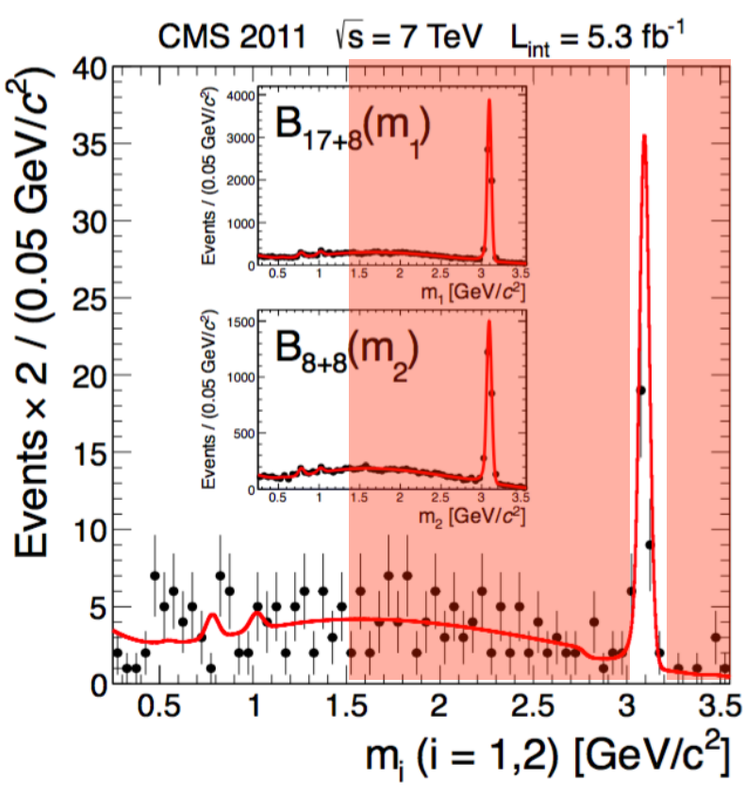
G. Giudice, B. Gripaios, R. Mahbubani (2011)

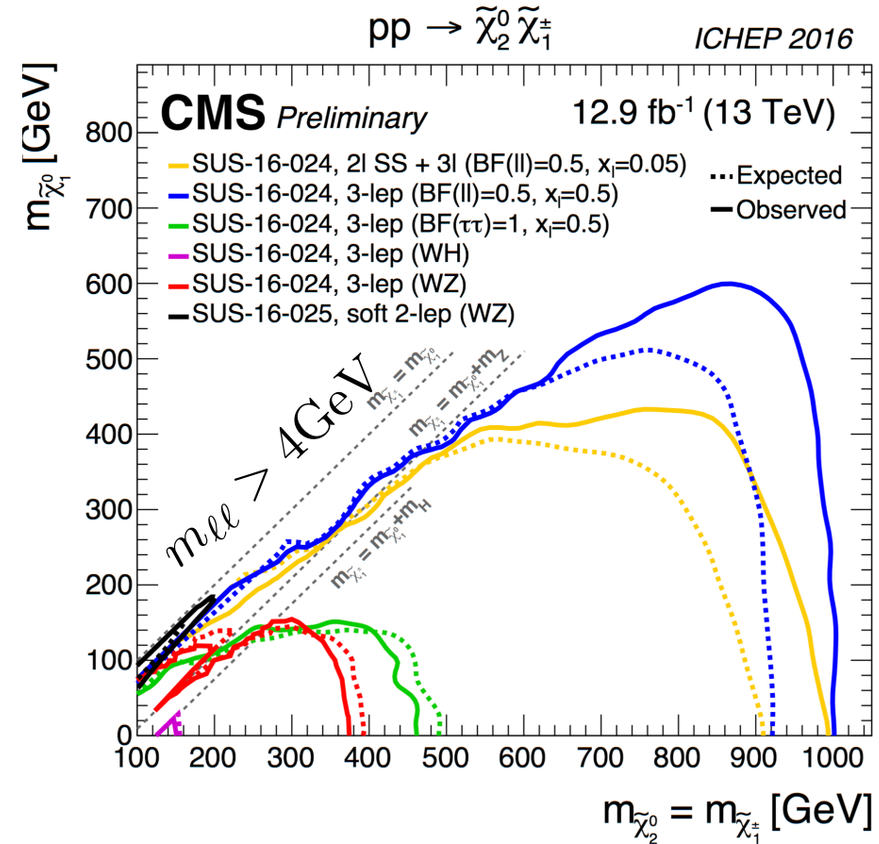
- For HL LHC (3000 inverse fb) of 14TeV collision,

Cuts	$W\gamma^* j$	$Z\gamma^* j$	$j\tau\tau$	Total BKG	BP1	BP2	BP3
Mono-jet	8.057	8.82	6.674	23.0	0.052	0.072	0.056
Basic $\mu_{\rm col}$	0.753	1.05	0.314	2.1	0.041	0.042	0.028
$\Delta\phi(\mu_{\rm col}, \not{E}_T)$	0.288	0.324	0.035	0.65	0.028	0.030	0.020
$m_{\mu_{\rm col}}$	0.106	0.118	0.024	0.248	0.017	0.023	0.015
M_T & $\frac{\not{E}_T}{p_T(\mu_{\rm col})}$	0.037	0.044	0.011	0.092	0.013	0.016	0.010
S/B					0.14	0.17	0.11
$S/\sqrt{B}\,(\sigma)$					2.4	2.9	1.85

(fb)

- di-muon backgrounds from J/Ψ

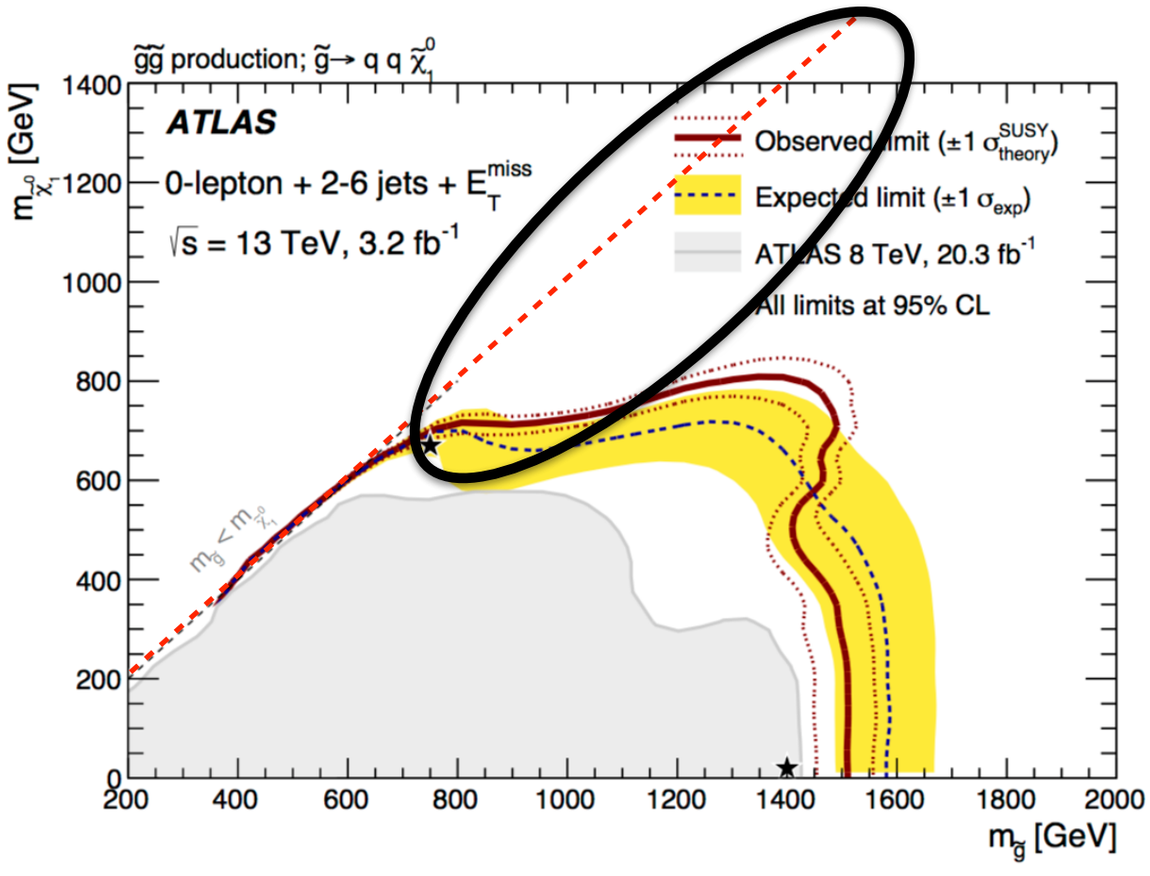


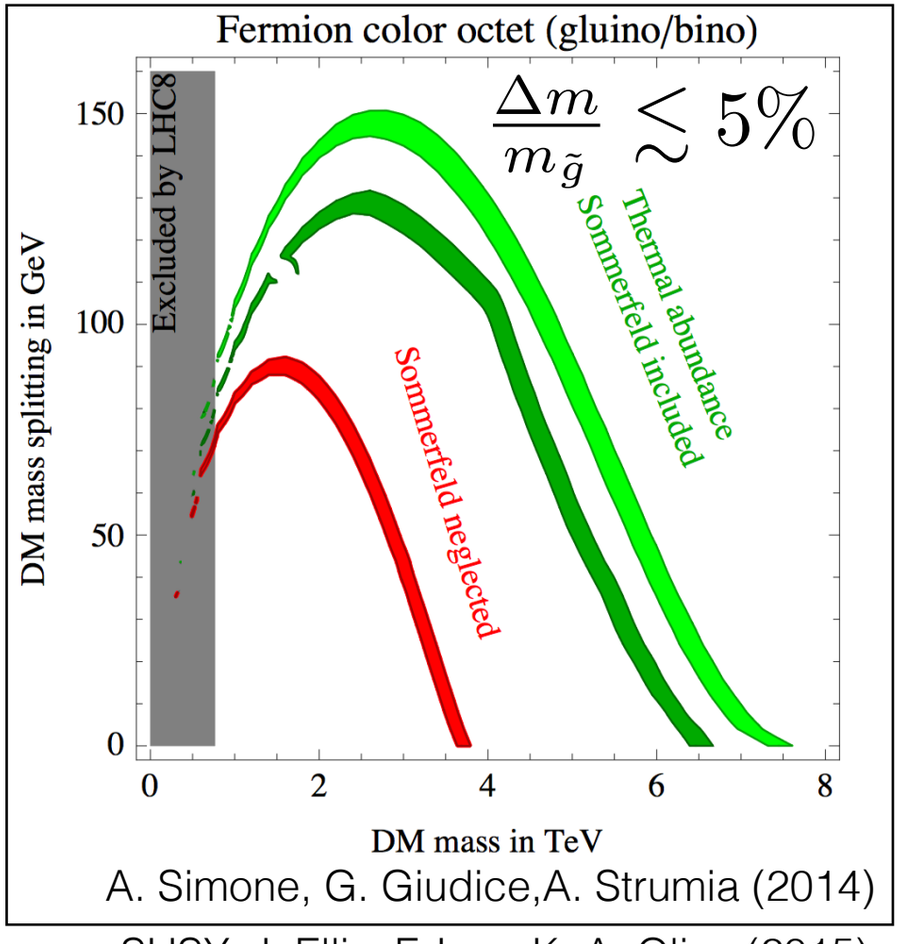


Color Octet - Color Singlet (Gluino - bino)

- When a colored particle is NLSP and $\Delta m \ll m_{\tilde{g}}$

the hadron colliders (LHC) may produce the colored particle, but the decaying products **would be too soft to tag**

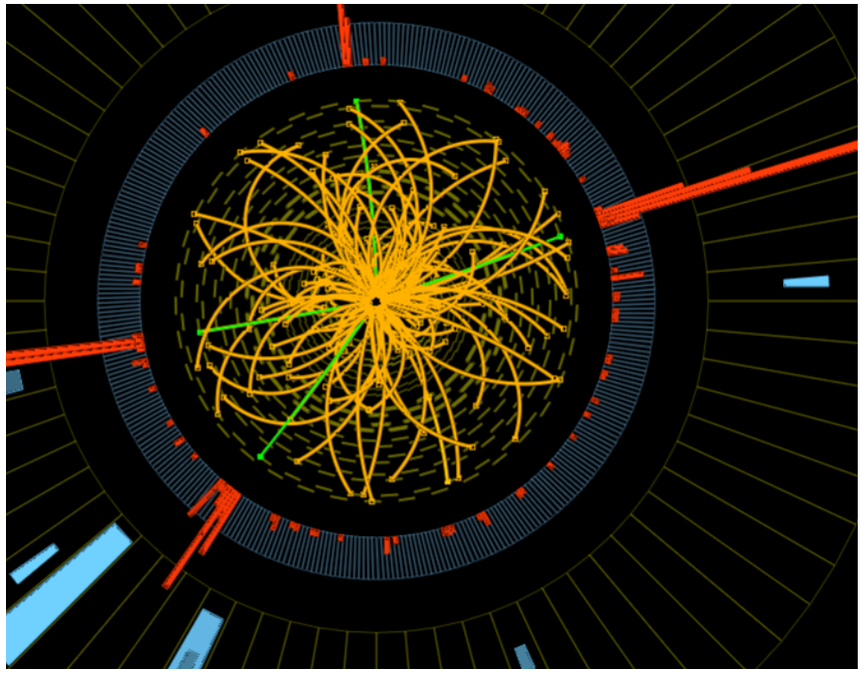




A. Simone, G. Giudice,A. Strumia (2014)

SUSY: J. Ellis, F. Luo, K. A. Olive (2015)

Too soft jets…



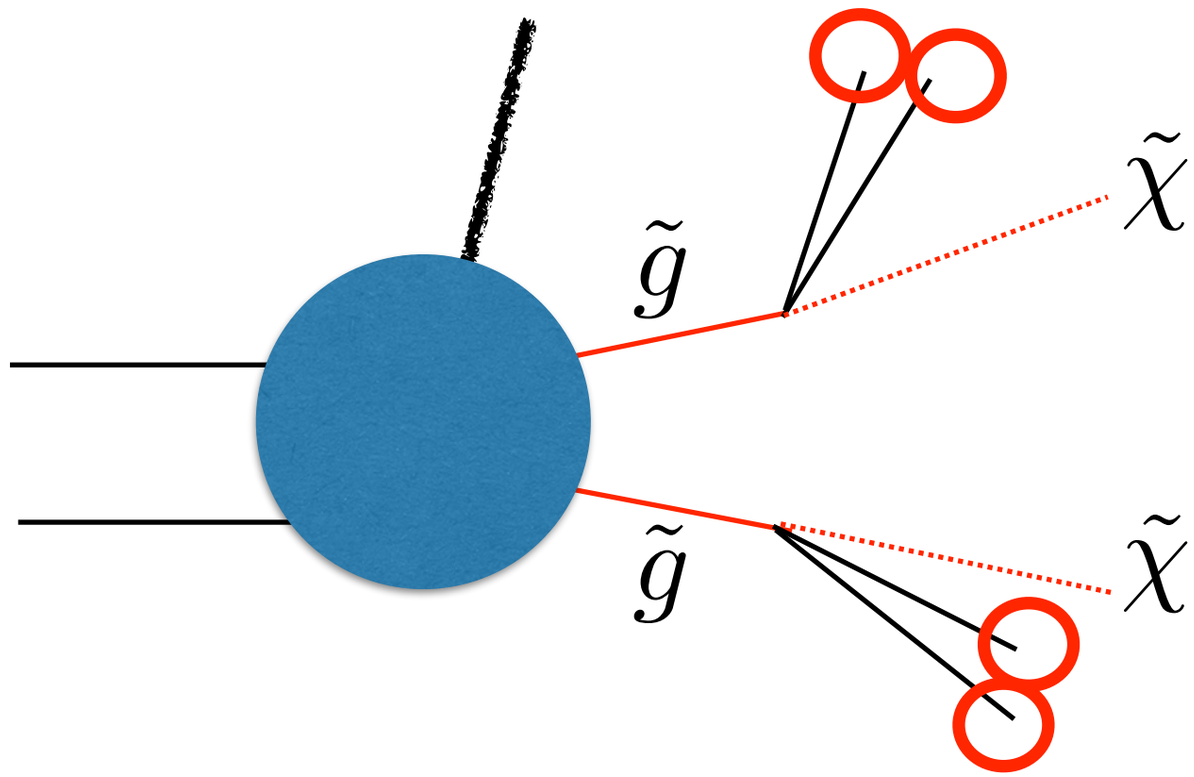
- Tagging ISR jets + MET

  - signals from SUSY decay become **soft**
  - PT of ISR gets **harder** with the mass scale of SUSY
  - Major BKG will be Z(to neutrinos)+jets

- Possibility to discriminate ISR jet (initially gluon) v. s. quark jets (in Z+jets)

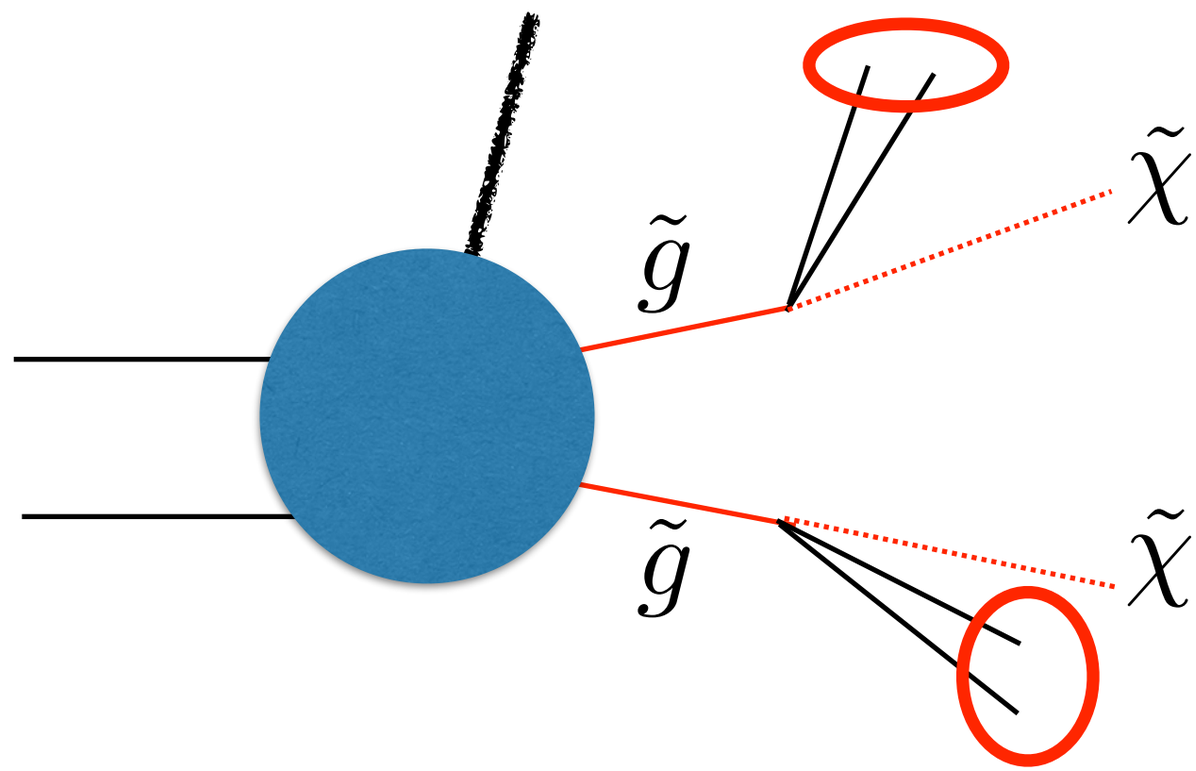
S. Mukhopadhyay, M. M. Nojiri, T.T. Yanagida (2014)

- Need to tag “Signals” from SUSY decay



to understand **properties** of SUSY particles
(masses, spin and coupling structure)

- Use a “Fat (Merged)”- Jet

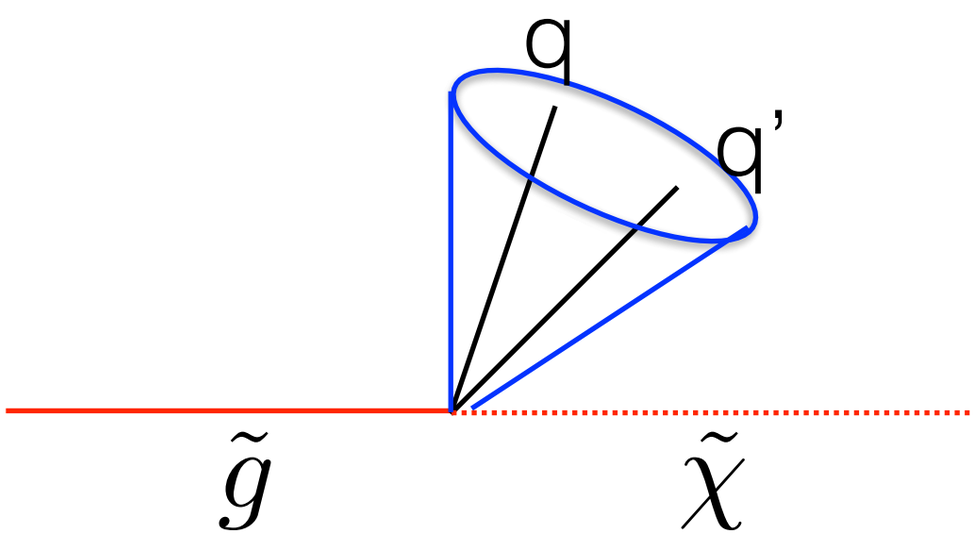


to enhance PT of jets

but maybe we need to have too large size?

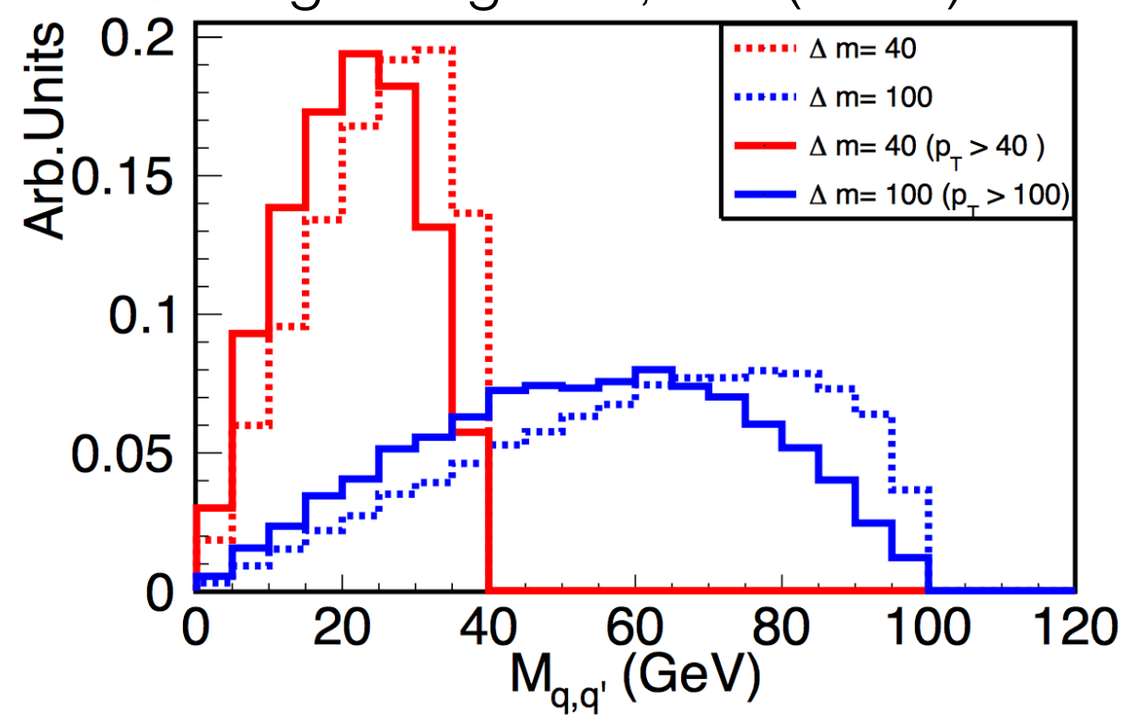
$$\Delta R = \frac{2M_{\mathrm{FJ}}}{P_{T(\mathrm{FJ})}} \gg 1$$

Shaping a phase-space



$$\Delta R \simeq \frac{2M_{\rm FJ}}{P_{T({\rm FJ})}}$$

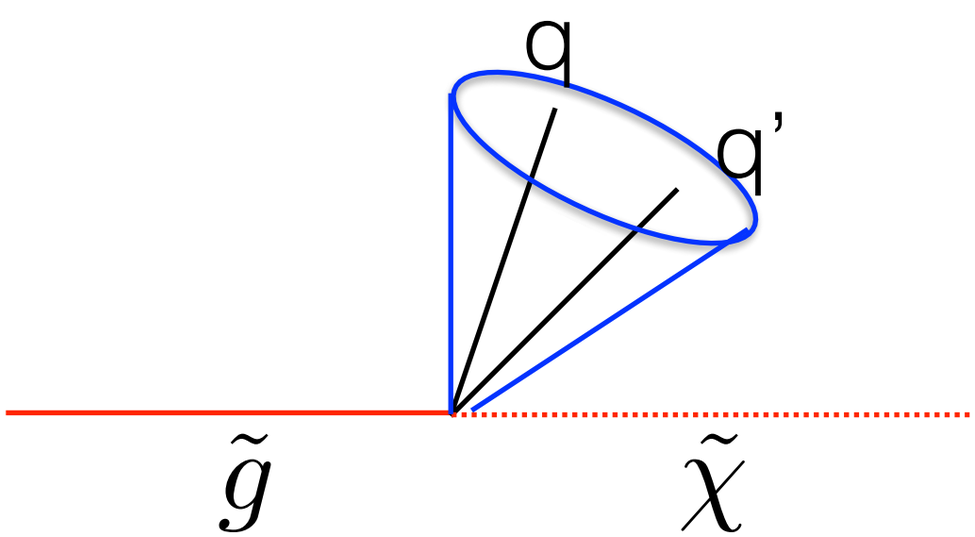
Chengcheng Han, **MP** (2016) PRD



- If we require a transverse momentum of fat-jet as $\mathcal{O}(m_{\rm FJ})$

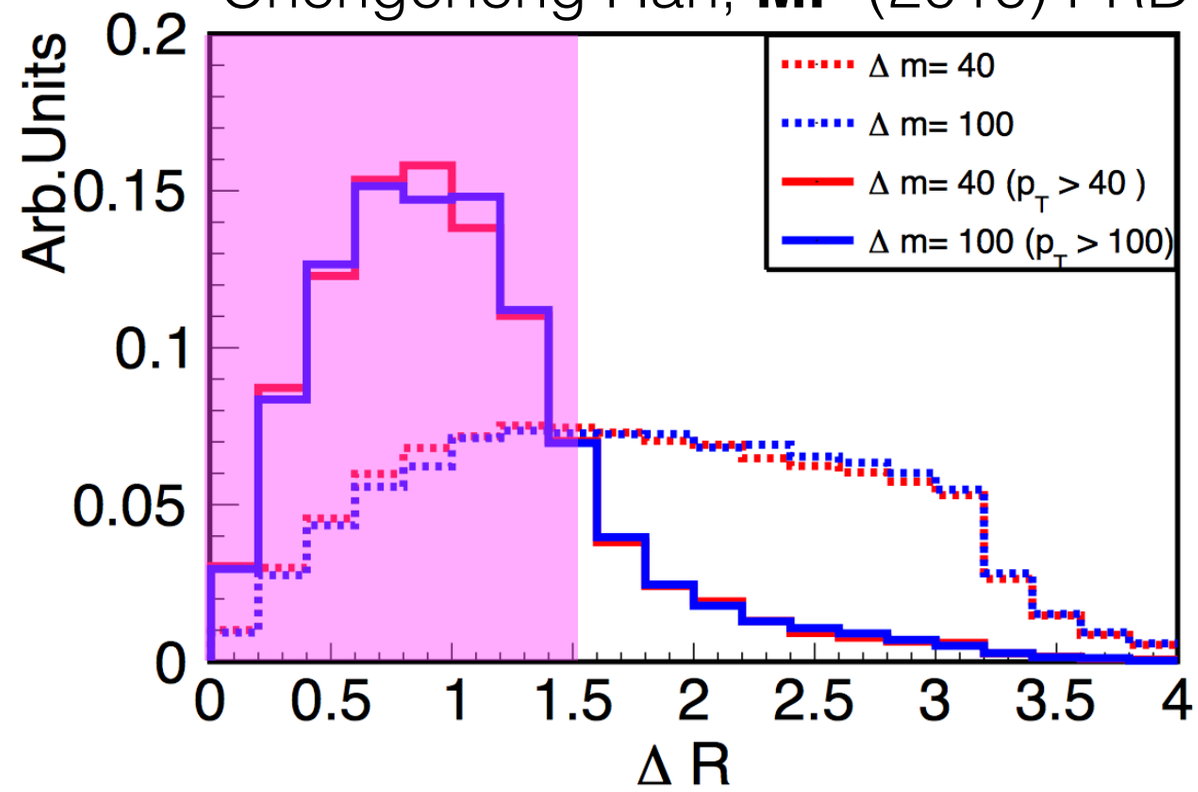
$$P_{qq'} = \left[\frac{m_{\tilde{g}}^2+m_{\tilde{\chi}}^2}{3}\left(2-\sqrt{1+\frac{12m_{\tilde{g}}^2 m_{\tilde{\chi}}^2}{(m_{\tilde{g}}^2+m_{\tilde{\chi}}^2)^2}}\right)\right]^{\frac{1}{2}} \xrightarrow[\Delta m \ll m_{\tilde{g}}]{} \frac{\Delta m}{\sqrt{2}},$$

Shaping a phase-space



$$\Delta R \simeq \frac{2M_{\rm FJ}}{P_{T({\rm FJ})}}$$

Chengcheng Han, **MP** (2016) PRD



- If we require a transverse momentum of fat-jet as $\mathcal{O}(m_{\rm FJ})$

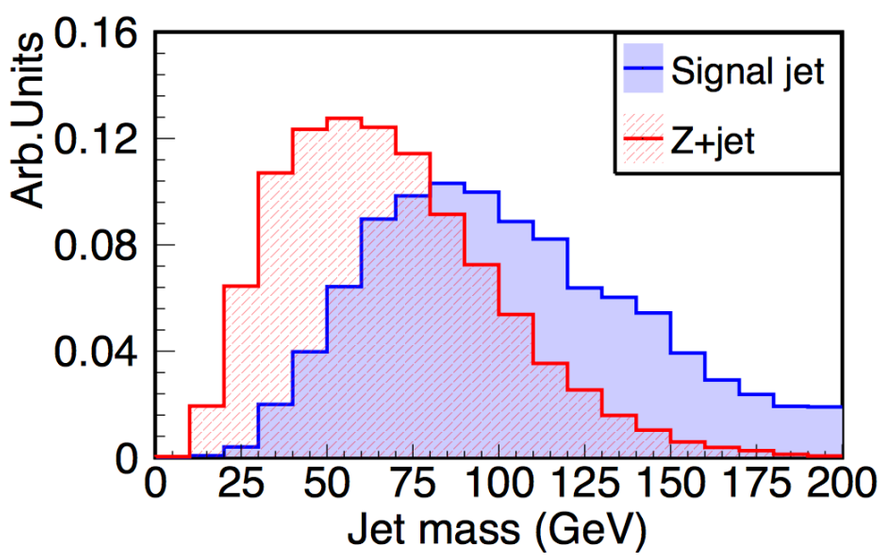
$$\Delta R \simeq \frac{2M_{\rm FJ}}{P_{T({\rm FJ})}} \simeq 2\frac{\Delta m}{\sqrt{2}}\frac{1}{\Delta m} \simeq 1.4$$

A price to use Fat-jet

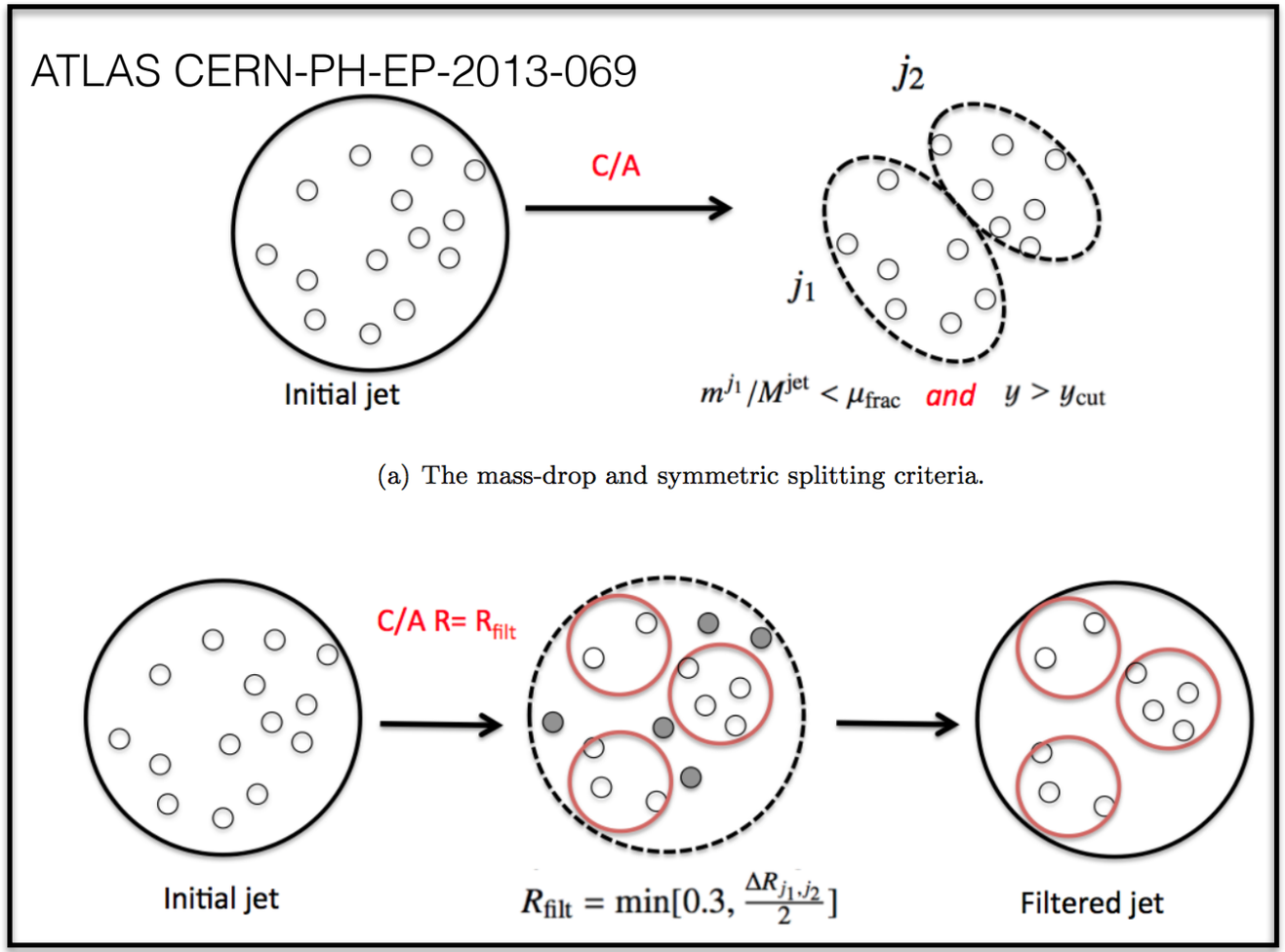
- Contaminations from soft QCD can be removed by jet-grooming methods.

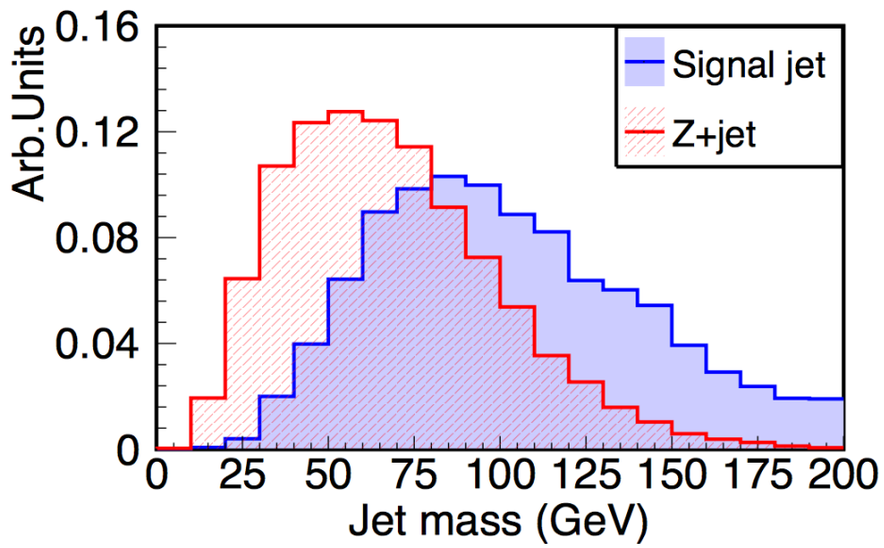
$$\sqrt{< M_J^2 >_{\rm NLO}} \approx 0.2 p_J R$$

$$< M_J > \simeq 30{\rm GeV} \text{ with } P_J = 100{\rm GeV}$$



A cartoon to describe Mass Drop



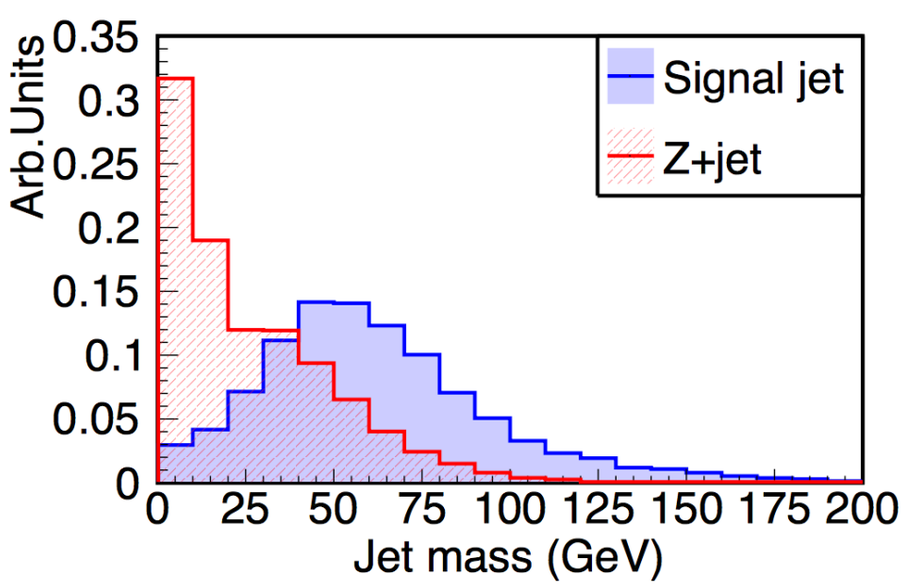


Sorting out QCD jet
by requiring a signal jet to satisfy

Symmetric condition:
same as BDRS Higgs tagger

1. $\frac{m_{j_1}}{m_{\mathrm{FJ}}} < \mu = 0.67$

2. $\left(\frac{\min(p^2_{Tj_1}, p^2_{Tj_2})}{m_j^2}\right) \Delta R^2_{(j_1,j_2)} > y_{\mathrm{cut}} = 0.09$



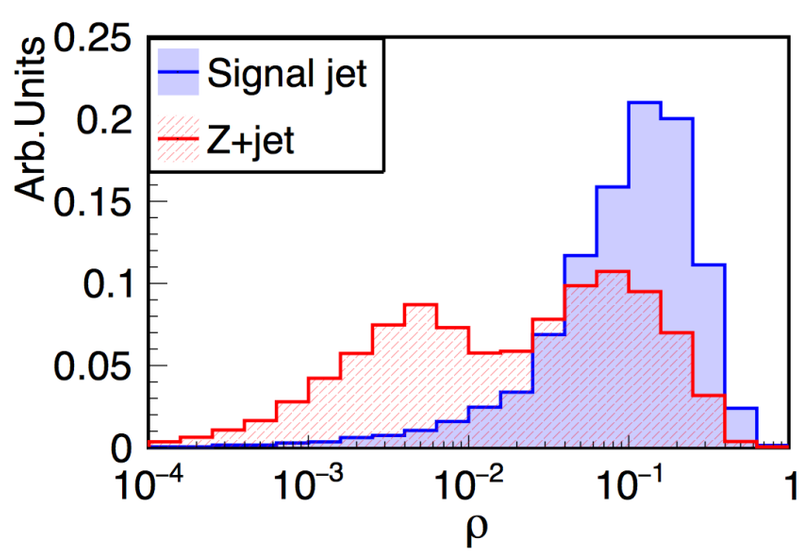
Jet substructure

- MDT helps to reconstruct Jet-mass.
  But, QCD always wins with cross-sections…

- Need to have another handle

$$\rho = \frac{m_{\mathrm{FJ}}^2}{p_{T\mathrm{FJ}}^2 R^2} \simeq z(1-z)\frac{R_{qq'}^2}{R^2} \sim 0.2$$

q-initiated jet: $\frac{\rho}{\sigma}\frac{d\sigma}{d\rho} = \frac{\alpha_s C_F}{\pi}\left[\Theta(\rho - y_{\mathrm{cut}})\ln\frac{1}{\rho} + \Theta(y_{\mathrm{cut}} - \rho)\ln\frac{1}{y_{\mathrm{cut}}} - \frac{3}{4}\right]$



BP $m_{\tilde{\chi}_1^0} = 600$	cuts	Signal (ϵ_{tag})	$Z+j$ (ϵ_{fake})
BP1	$10 < m_{\mathrm{FJ}} < 40$	0.75	0.55
$\Delta m = 40$	Additional $\rho > 0.1$ cut	0.40	0.18
BP2	$40 < m_{\mathrm{FJ}} < 100$	0.62	0.22
$\Delta m = 100$	Additional $\rho > 0.1$ cut	0.42	0.12

Prescreening with Fat Jet

(1) Find all the jets after C/A algorithm $p_T > \Delta m$ denoted by $j_1, j_2 ... j_n$. Each jet the pass MDT and calculate the ρ_{j_i}.

(2) Choose the jet who has the largest ρ, take this jet as the signal jet. $\rho > 0.1$

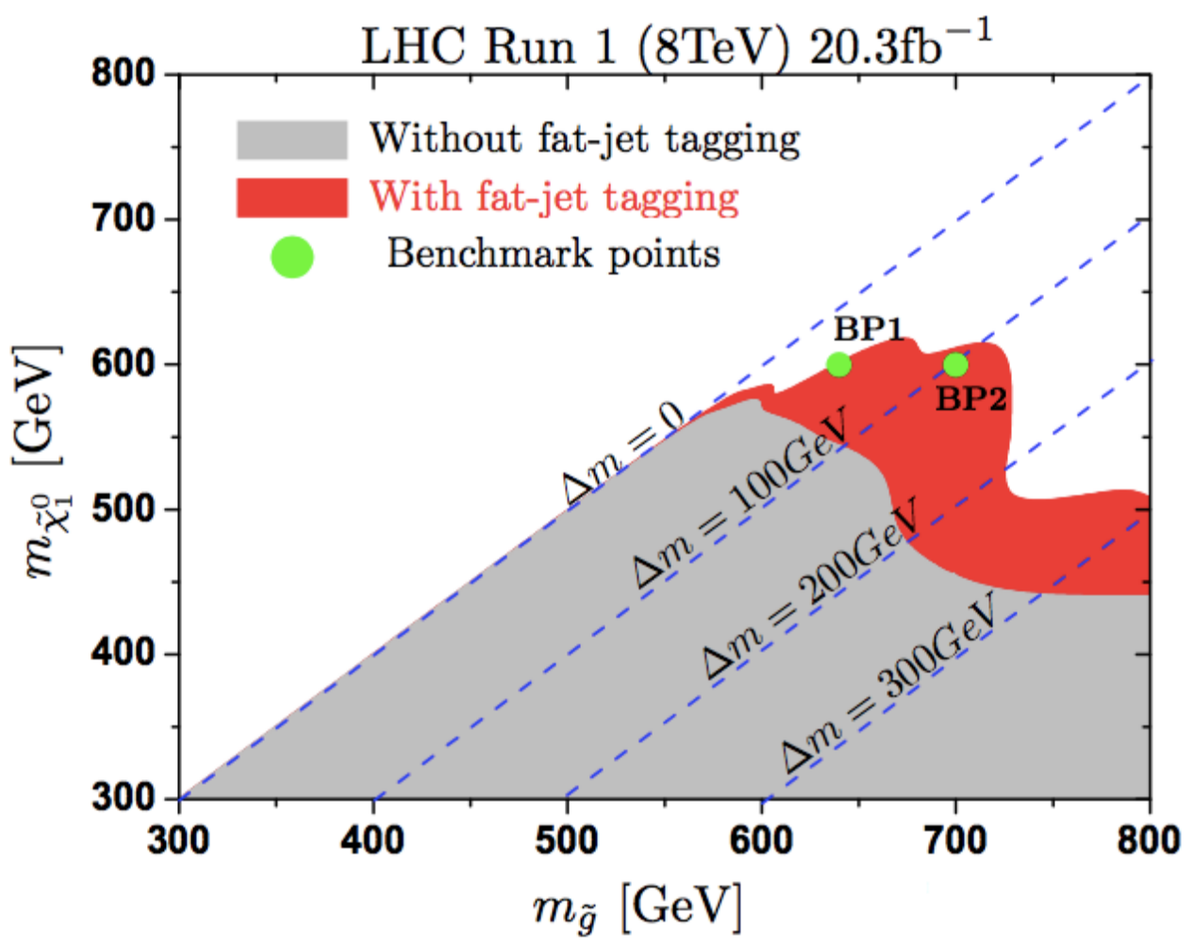
$$\frac{1}{4}\Delta m < m_{\rm FJ} < \Delta m \text{ for } \Delta m \geq 20\,\text{GeV}\,,$$

$$5\,\text{GeV} < m_{\rm FJ} < 20\,\text{GeV} \text{ for } \Delta m < 20\,\text{GeV}\,.$$

Re-cluster jets

ATLAS analysis

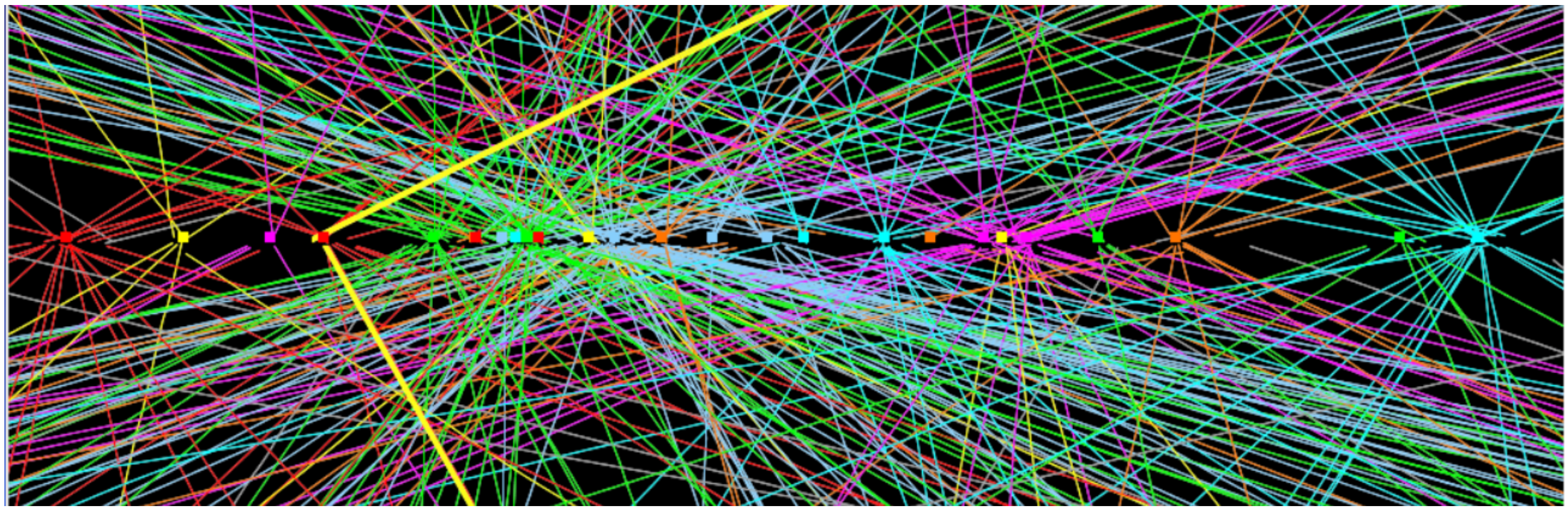
Signal region "2jm"	cuts
E_T^{miss} [GeV]	> 160
$p_T(j_1)$ [GeV]	> 130
$p_T(j_2)$ [GeV]	> 60
$\Delta\phi(jet_{1,2,(3)}, E_T^{miss})_{min}$	> 0.4
$E_T^{miss}/\sqrt{H_T}[\text{GeV}^{1/2}]$	> 15
$m_{eff}(incl.)$ [GeV]	> 1200

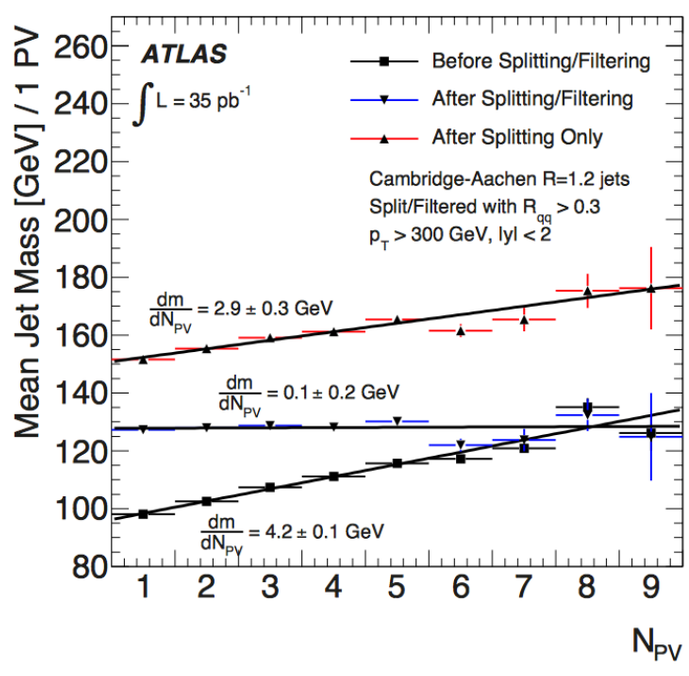


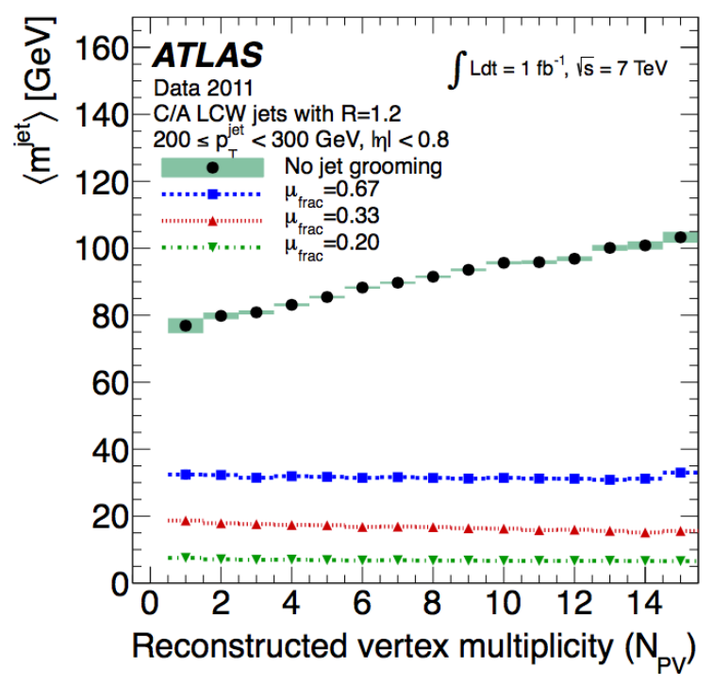
Very degenerated spectrum of $\Delta m \lesssim 20\text{GeV}$ is challenging

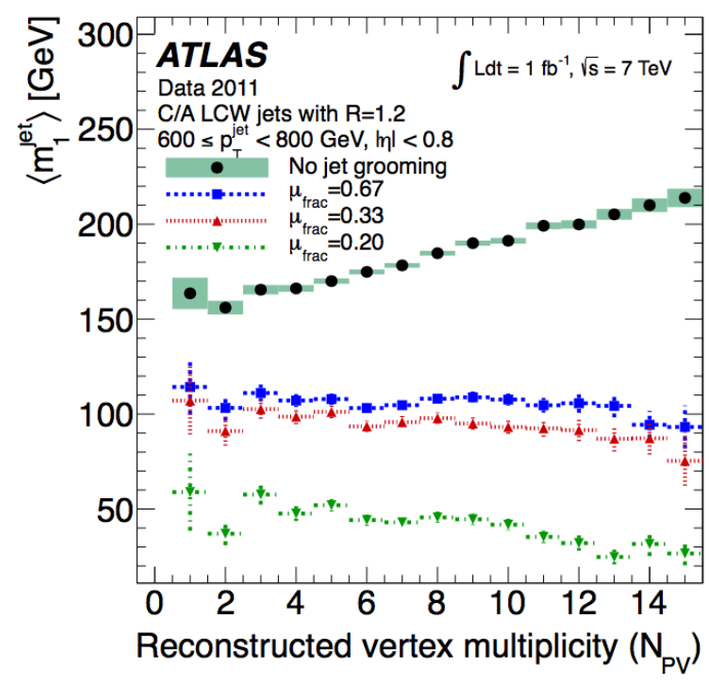
due to a jet qualification issue after pile-up removal.

Pile- up issue









Need to look into PT ~ O(100) GeV

Boosted object

based on Chengcheng Han, M.M. Nojiri, MP (Phys.Lett. B760 (2016) 775-779)

- We assume that top-quarks ~ ON-shell when they are from a very heavy resonance.
  - Boosted Top-tagger (with top-quark mass window)

- What happen if there are non-negligible portion of top-quark from a heavy resonance being OFF-SHELL?

$\mathcal{L} \supset \frac{c_t}{\Lambda^2} G_\mu \left(\bar{Q}_L \tilde{H}\right) \gamma^\mu \left(\tilde{H}^\dagger Q_L\right)$ can induce unitarity violation

$$t(p_1) + G_\sigma(p_2) \to W^\mu(p_3) + b(p_4)$$

A new physics should arise before the cut-off.

Heavy Top-partner

- Spin 1 color octet G and vector-like top-partner T

$$\mathcal{L} \ni g_s G_\mu \bar{T}\gamma^\mu T - m_T \bar{T}T - (y\bar{Q}_L \tilde{H} T_R + y_t \bar{Q}_L \tilde{H} t_R + h.c.),$$

mixing $\begin{pmatrix} \bar{t}_L & \bar{T}_L \end{pmatrix} \begin{pmatrix} y_t \frac{v}{\sqrt{2}} & y\frac{v}{\sqrt{2}} \\ 0 & m_T \end{pmatrix} \begin{pmatrix} t_R \\ T_R \end{pmatrix}$

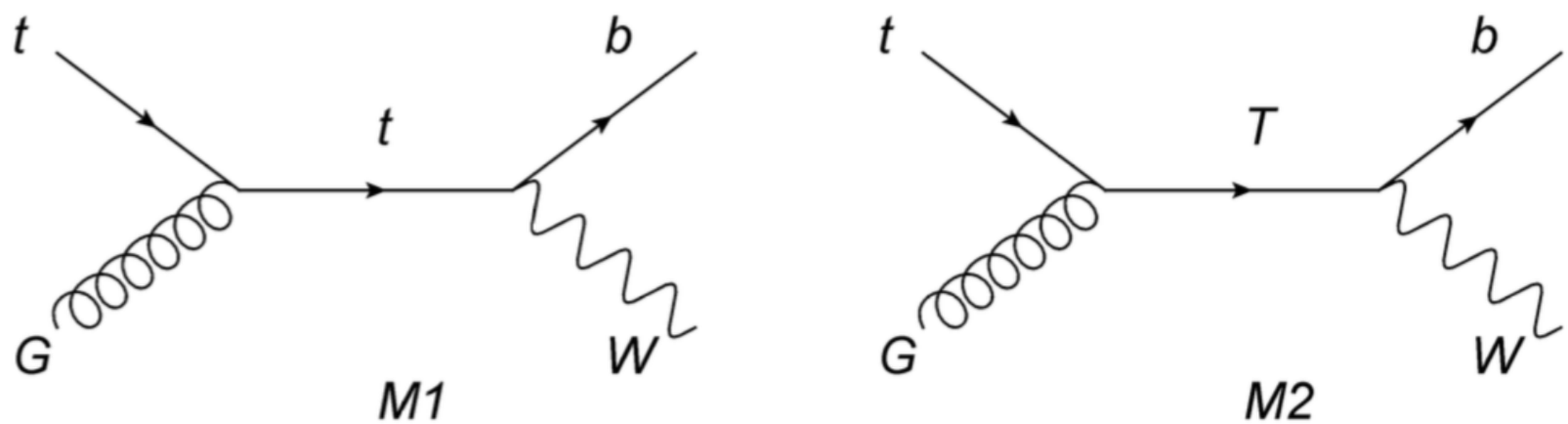
$$\begin{pmatrix} t'_{L,R} \\ T'_{L,R} \end{pmatrix} = \begin{pmatrix} \cos\theta_{L,R} & \sin\theta_{L,R} \\ -\sin\theta_{L,R} & \cos\theta_{L,R} \end{pmatrix} \begin{pmatrix} t_{L,R} \\ T_{L,R} \end{pmatrix}$$

$$\text{with } \sin\theta_L \sim \frac{yv}{\sqrt{2}m_T}, \quad \sin\theta_R \sim \frac{m_t}{m_T}\sin\theta_L$$

by integrating out a top-partner

$$\mathcal{L} \simeq \frac{c_t}{m_T^2} G_\mu (\bar{Q}_L \tilde{H})\gamma^\mu (\tilde{H}^\dagger Q_L)$$

Recovering Unitarity



$$t(p_1) + G_\sigma(p_2) \to W^\mu(p_3) + b(p_4)$$

There would be a cancelation between two diagrams

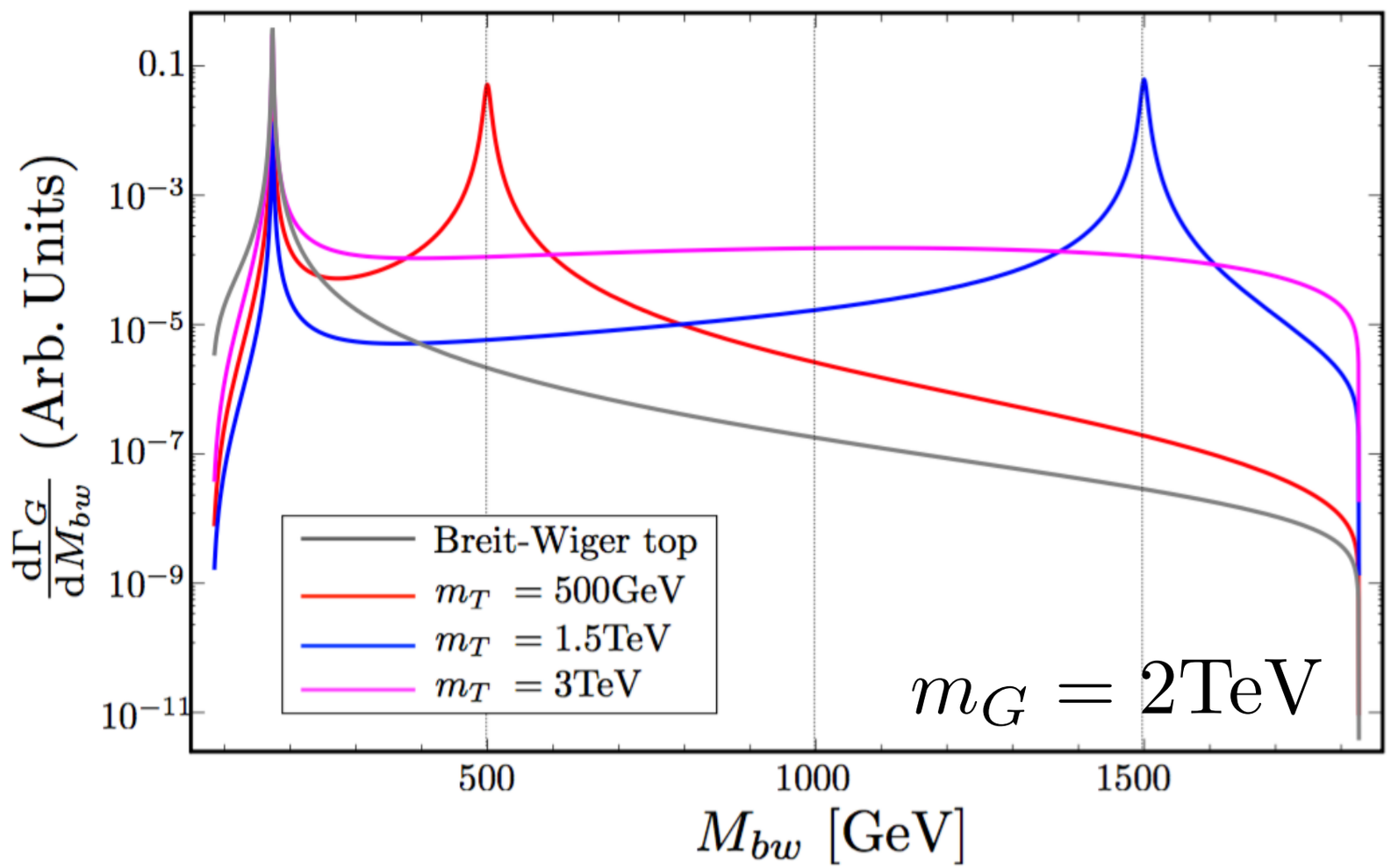
$$\mathcal{M}_1 \propto \sin^2\theta_L \cos\theta_L \bar{u}_b \frac{\not{p}_3}{m_w} P_L \frac{1}{\not{p}_1+\not{p}_2-m_t} \gamma_\sigma P_L u_t \epsilon_G^\sigma \propto \frac{\sin^2\theta_L \cos\theta_L}{m_w} \bar{u}_b P_R \left(\frac{m_t}{\not{p}_1+\not{p}_2-m_t} + 1\right) \gamma_\sigma P_L u_t \epsilon_G^\sigma$$

$$\mathcal{M}_2 \propto -\sin^2\theta_L \cos\theta_L \bar{u}_b \frac{\not{p}_3}{m_w} P_L \frac{1}{\not{p}_1+\not{p}_2-m_T} \gamma_\sigma P_L u_t \epsilon_G^\sigma \propto -\frac{\sin^2\theta_L \cos\theta_L}{m_w} \bar{u}_b P_R \left(\frac{m_T}{\not{p}_1+\not{p}_2-m_T} + 1\right) \gamma_\sigma P_L u_t \epsilon_G^\sigma$$

$$\mathcal{M} \propto \bar{u}_b P_R \left(\frac{m_t}{\not{p}_1+\not{p}_2-m_t} - \frac{m_T}{\not{p}_1+\not{p}_2-m_T}\right) \gamma_\sigma P_L u_t \epsilon_G^\sigma$$

Visible effects

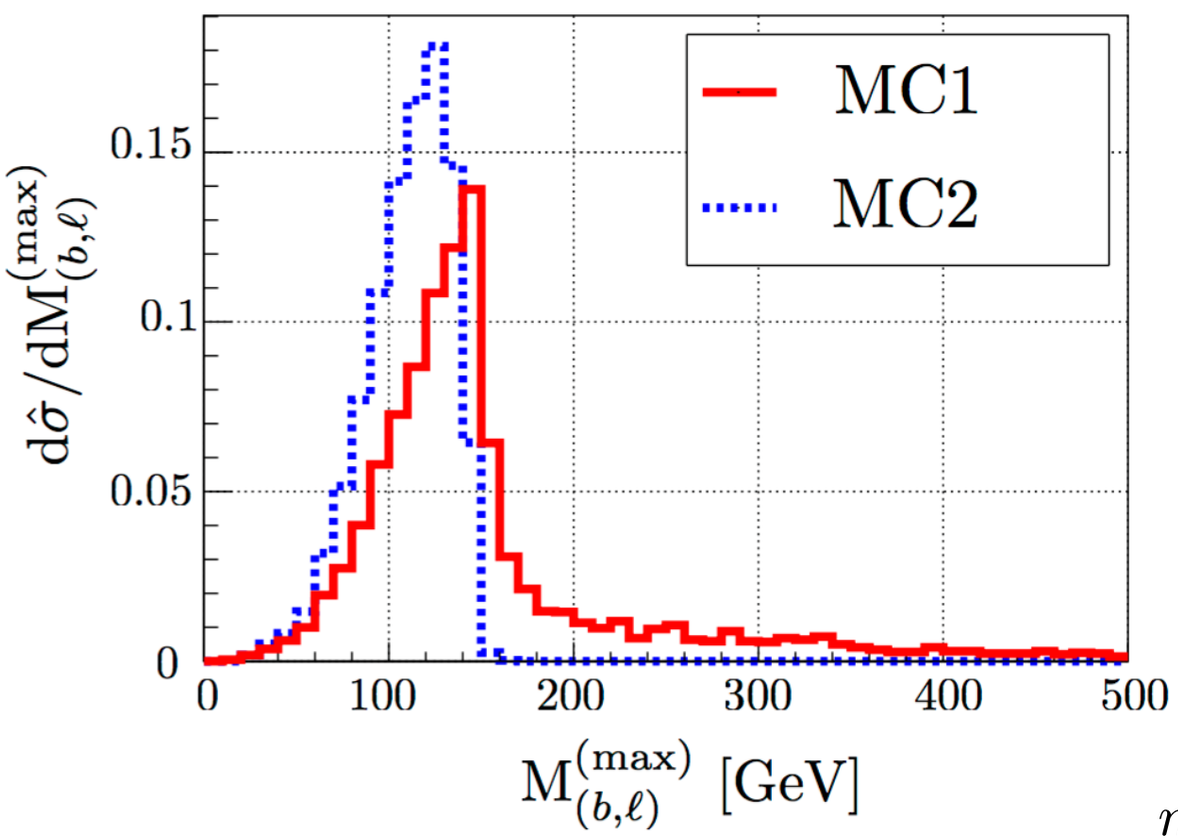
- From G decay, there would be a trace of a heavy top-partner in the invariant mass of (b,W)



Effects on collider phenomenology

- If we consider large $G \to t\bar{t}$ branch ratio,
  $pp \to GG$ would be dominant over single G production

  - Four top-quark channel with 4b+ 2l



Define a measure to check the "off-shellness"

$$M^{(max)}_{(b,\ell)} = \max_{i=1,2}\left(\min_{j=1,\cdots 4}\{m_{(b_j,\ell_i)}\}\right)$$

- MC1: $pp \to GG \to b\bar{b}b\bar{b}\ell^+\ell^-\nu\bar{\nu}jjjj$
- MC2: $pp \to GG \to t\bar{t}t\bar{t}$

$m_G = 1.8\text{TeV},\ m_T = 3.5\text{TeV}, y = 2.0\,(\sin\theta_L = 0.1)$

Effects on collider phenomenology

LHC 14TeV 3ab(-1)

(fb)

Analysis cut	MC1	MC2	$(t\bar{t}bW\bar{b}W)$	$(bW\bar{b}Wb\bar{b})$
P_T requirements ($p_T^{\ell,j} > 50\,\mathrm{GeV}$)	0.22	0.19	0.18	5.5
Heavy flavored jet tagging (one high P_T top and four b-jet)	0.051	0.050	0.0024	10^{-3}
$\mathrm{M}_{(b,\ell)}^{(\mathrm{max})} > 170\,\mathrm{GeV}$	0.012	0	10^{-4}	$< 10^{-4}$

- Top tagging / faking: 0.5 / 0.01
- -b tagging: 0.8

We will observe the trace of a Heavy top-partner as $\mathcal{O}(30)$

Summary

- Theorists have provided “Non-conventional” object to the collider experiments to check
  - Otherwise, we will miss the physics behind them.

- We propose to enlarge a concept of “Jet” to cluster off-shell particles.

- If we keep using the conventional concept (in tagging top-quark from a heavy resonance) we may miss some interesting thing!