CAPTURING SOFT PARTICLES @ LHC FOR STUDIES OF DEGENERATED SUSY SPECTRA

Myeonghun Park

APCTP
Asia **P**acific **C**enter for **T**heoretical **P**hysics

LHC Targets

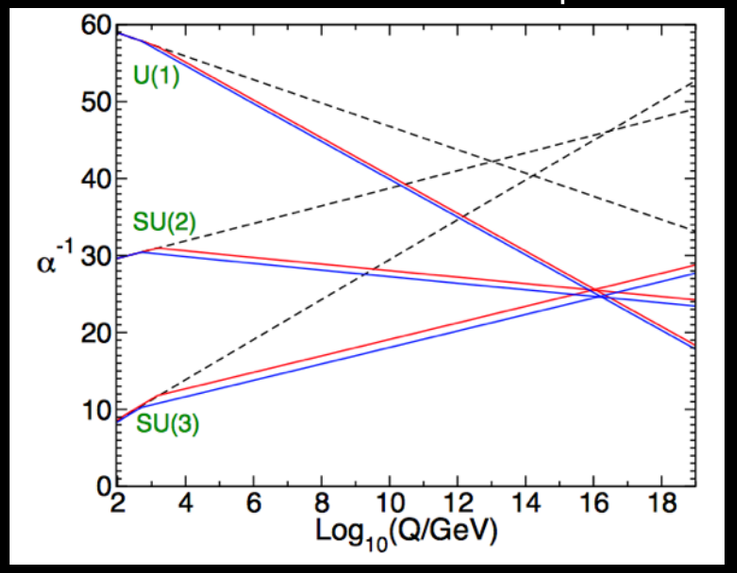
- In 1977, B. Lee, C. Quigg and H.B. Thacker estimated the upper bound of Higgs mass.

$$M_H \leq \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{\frac{1}{2}} \simeq 1\,\mathrm{TeV}$$

- Supersymmetry models.

$$m_H^2 \simeq m^2 + \frac{c}{16\pi^2}\Lambda^2$$

SUSY primer



Gauge unification with **SUSY~TeV**

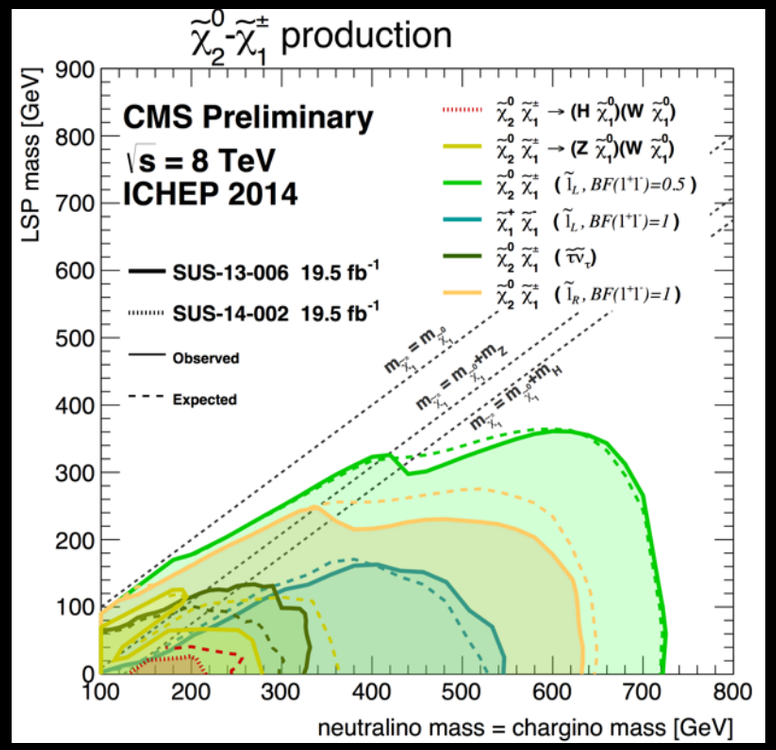
- Question for the (**F**uture) **C**ollider experiments:

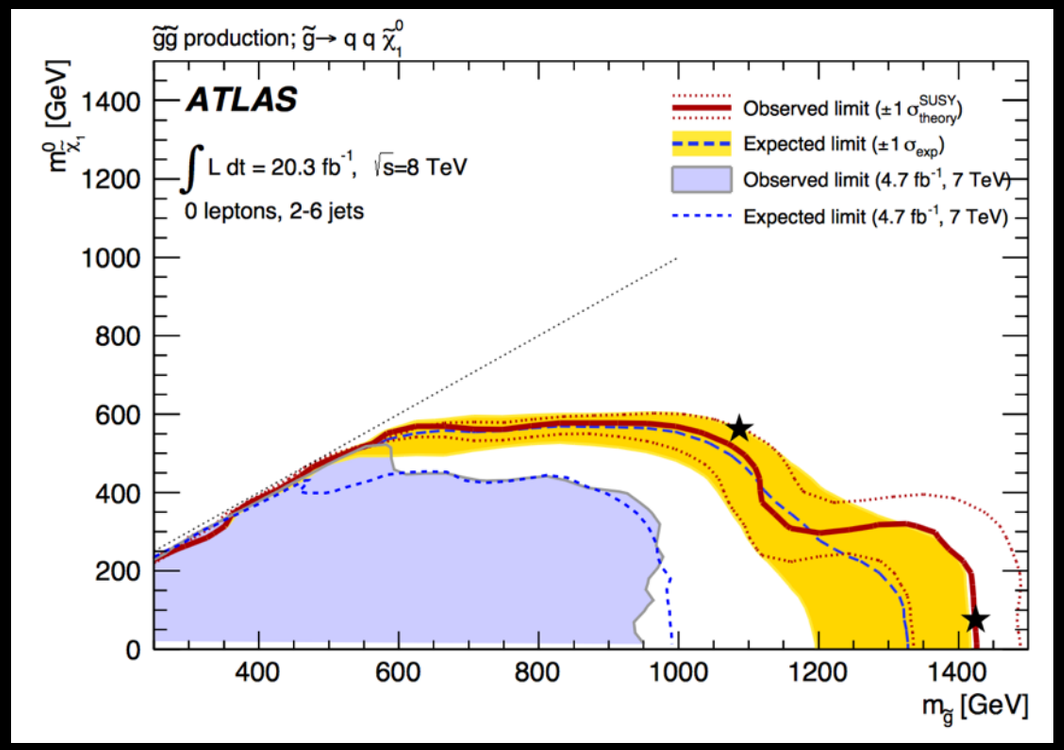
  Can LHC (FC) **reach** the relevant Energy scale for BSM discovery ?

- Question for theorists:

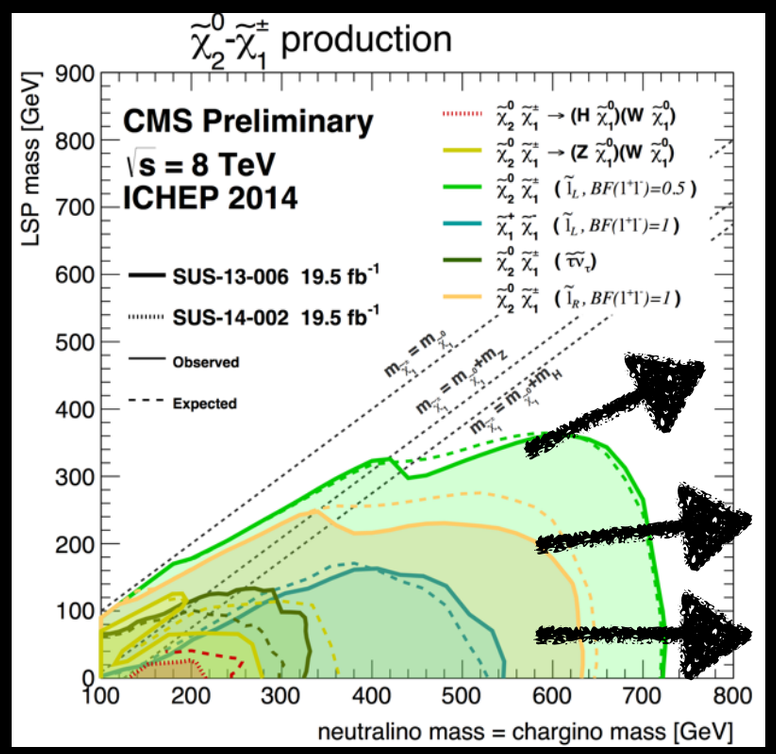
  Can we **estimate** the Energy scale of BSM ?

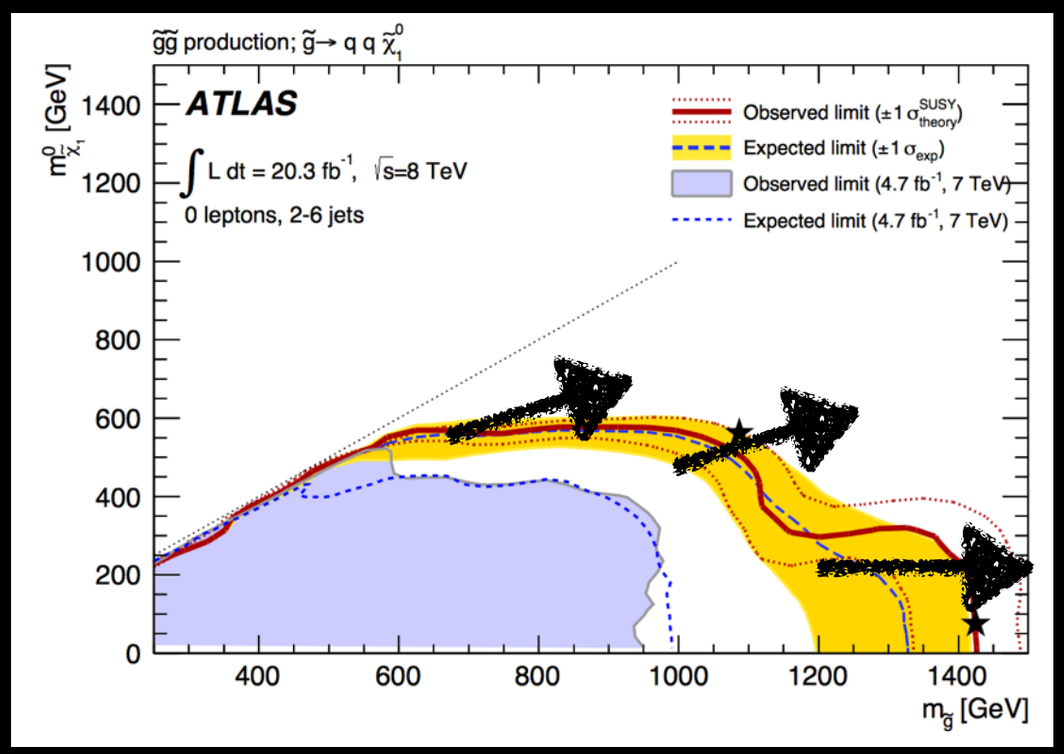
LHC Run 1 situation





LHC pushes limits…

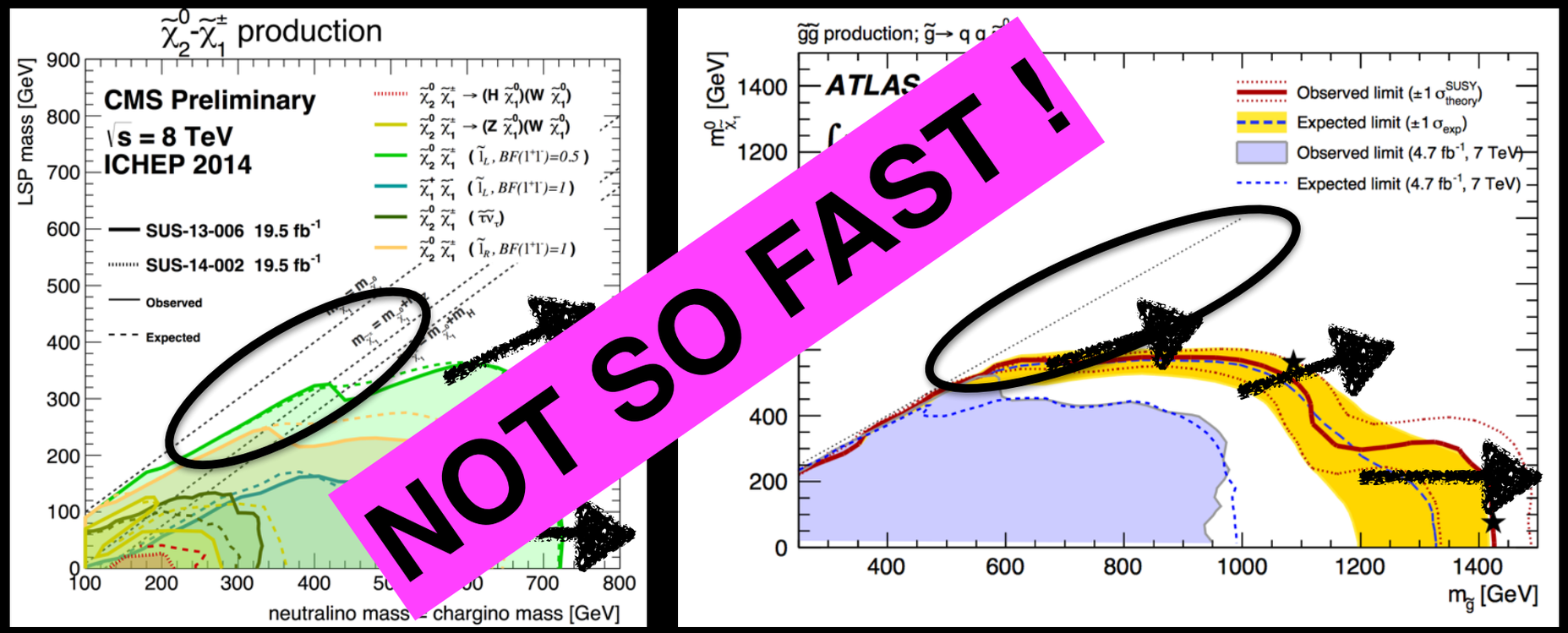




~ O(1) TeV SUSY [BSM] models are ruled out completely?

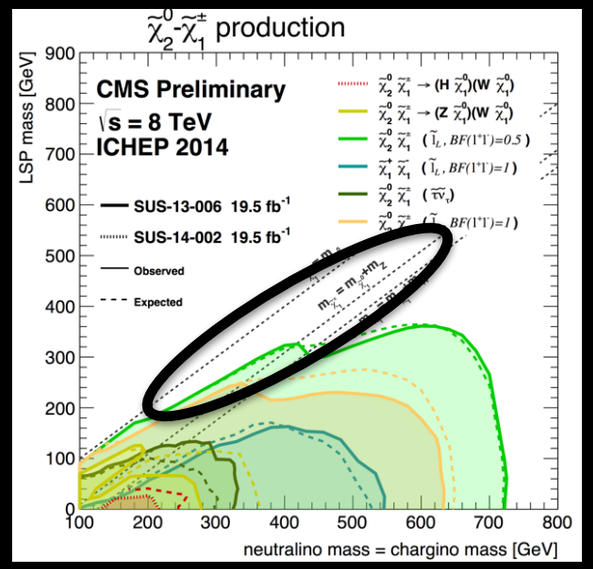
- LHC is approaching to its available energy limit !

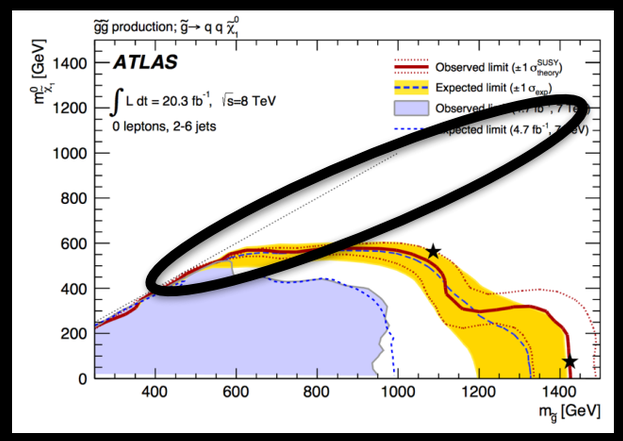
LHC pushes limits…



- Analyses become less sensitive in “degenerated” spectra.

Degenerated Spectrum

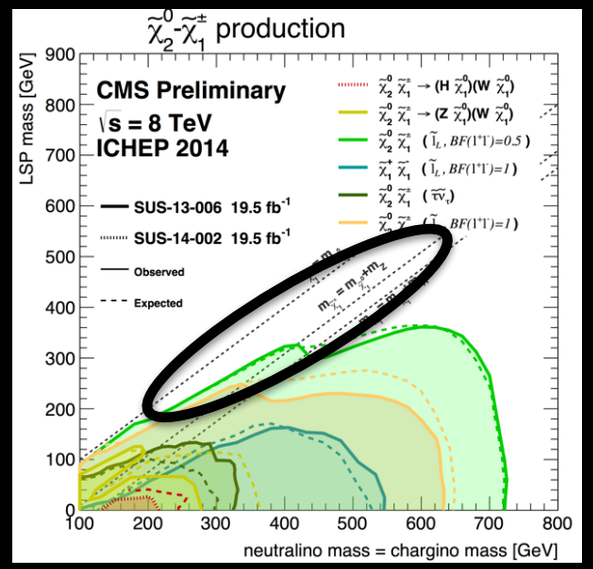


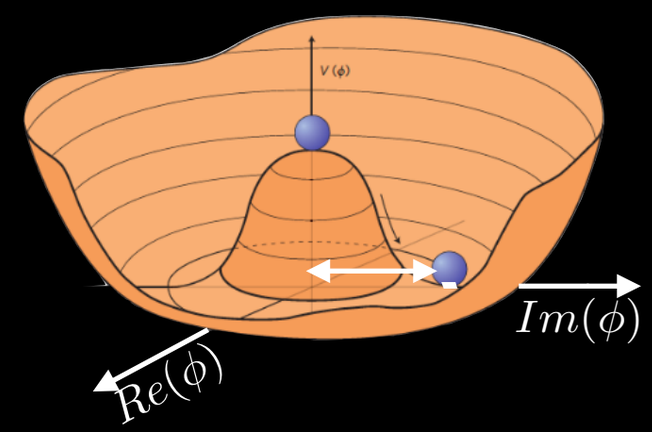


- It may looks like “left-over” points.

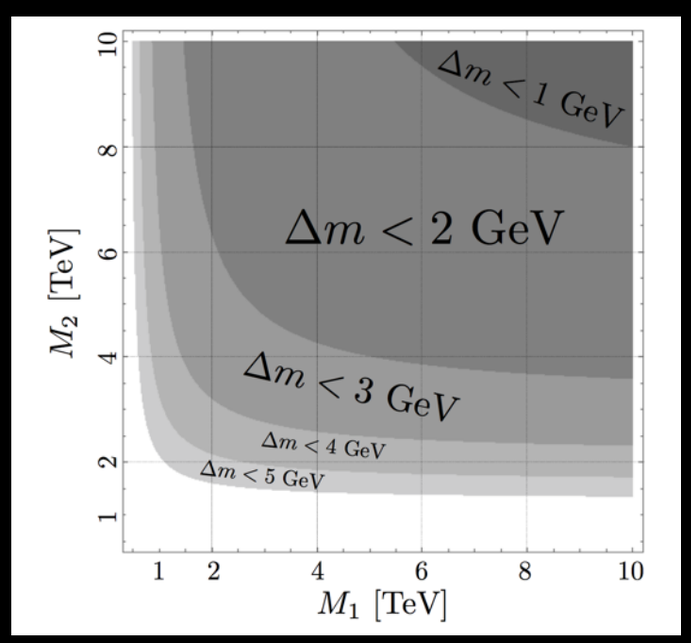
Minimal SUSY

- With a Higgs, the **most** important particles in Supersymmetric models,





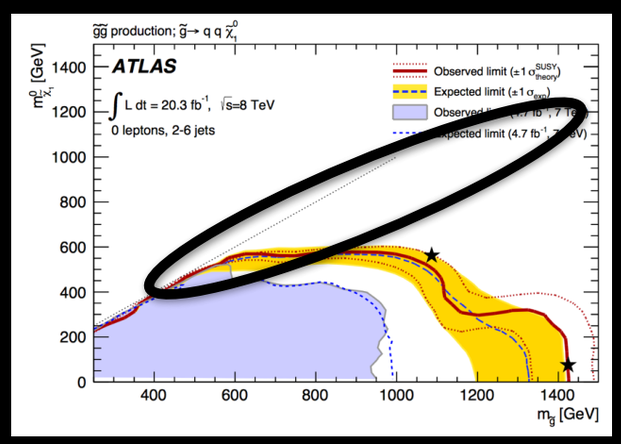
$$\frac{M_Z^2}{2} = -\mu + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$



$$\begin{pmatrix} M_1 & 0 & -m_W \tan\theta_W \cos\beta & m_W \tan\theta_W \sin\beta \\ & M_2 & m_W \cos\beta & -m_W \sin\beta \\ -m_W \tan\theta_W \cos\beta & m_W \cos\beta & 0 & -\mu \\ m_W \tan\theta_W \sin\beta & -m_W \sin\beta & -\mu & 0 \end{pmatrix}$$

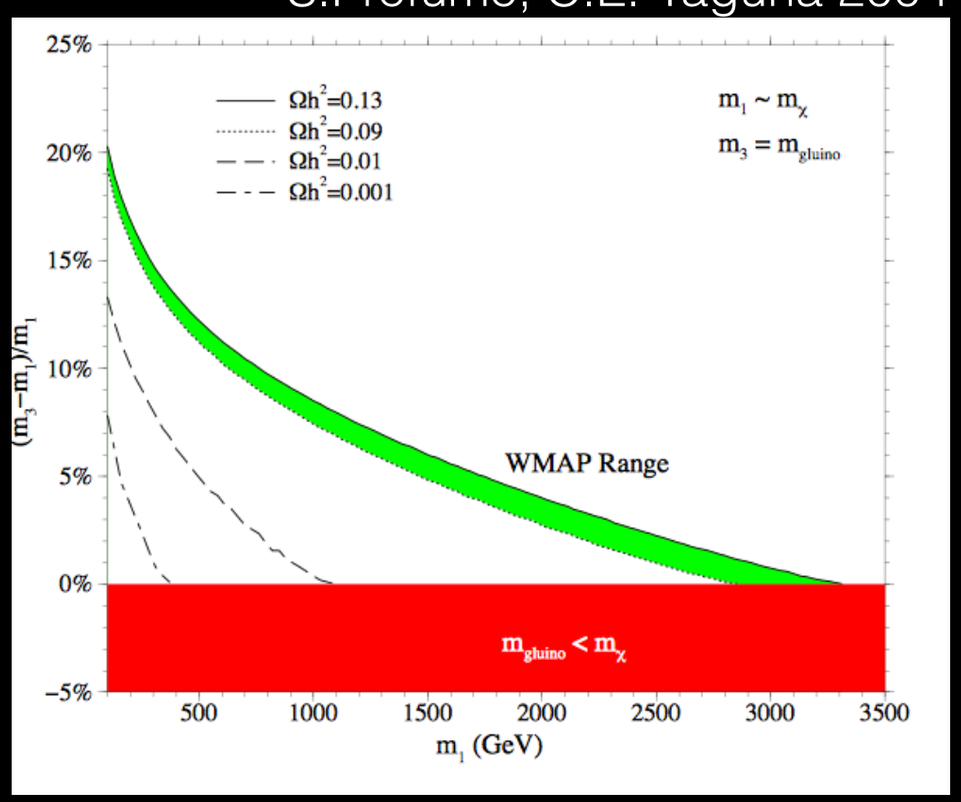
$$\Delta m \equiv m_{\chi_2^0} - m_{\chi_1^0} \approx \frac{m_W^2}{M_2} + \frac{m_W^2 \tan^2\theta_W}{M_1}$$

Dark matter within LHC reach

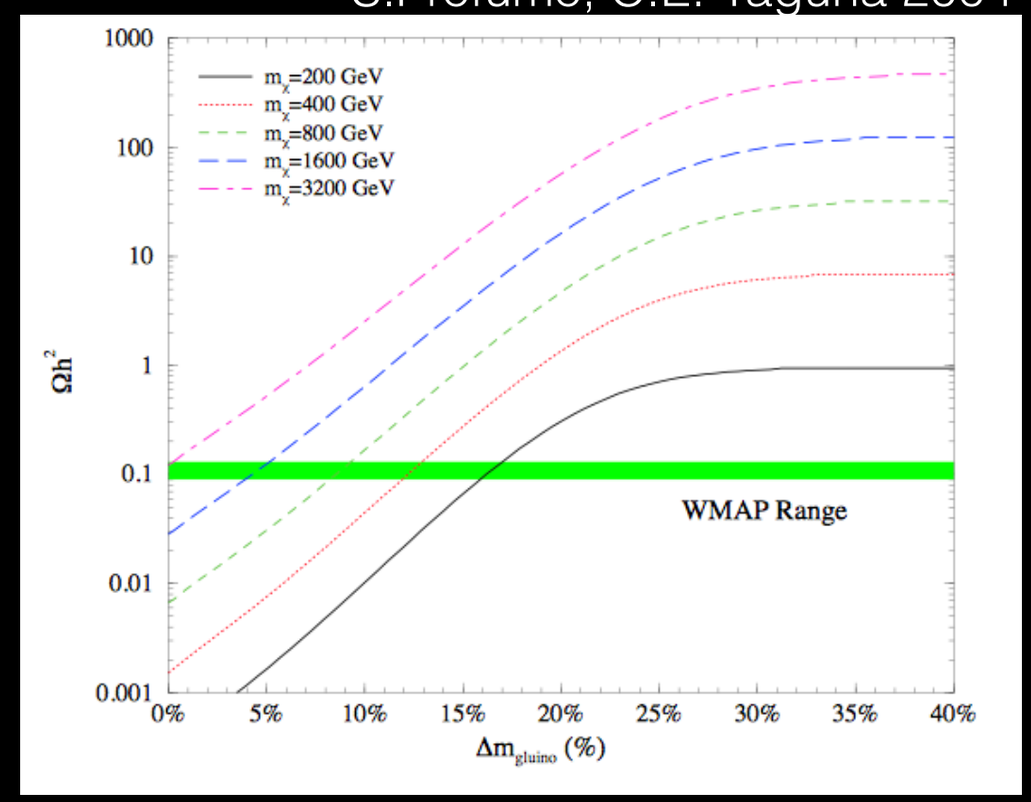


- Light Dark matter candidate (Bino LSP) with proper relic density !

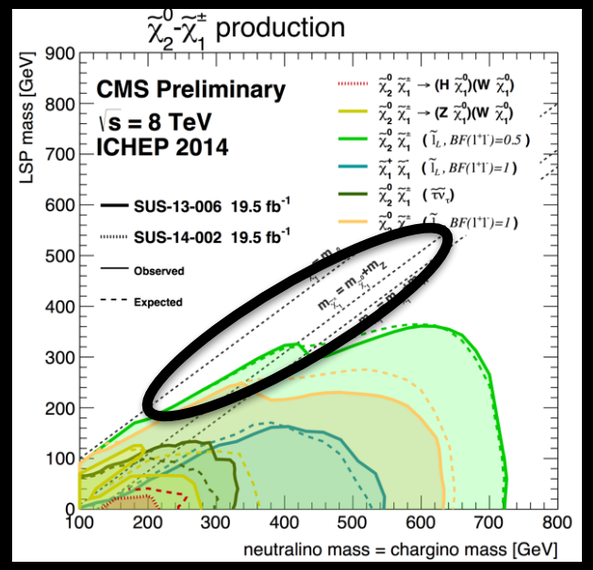
S.Profumo, C.E. Yaguna 2004

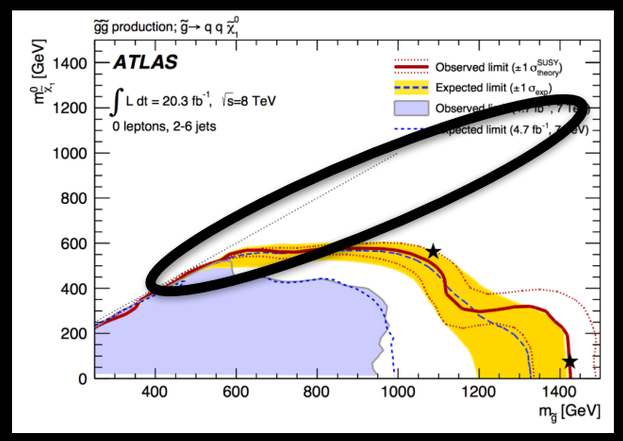


S.Profumo, C.E. Yaguna 2004



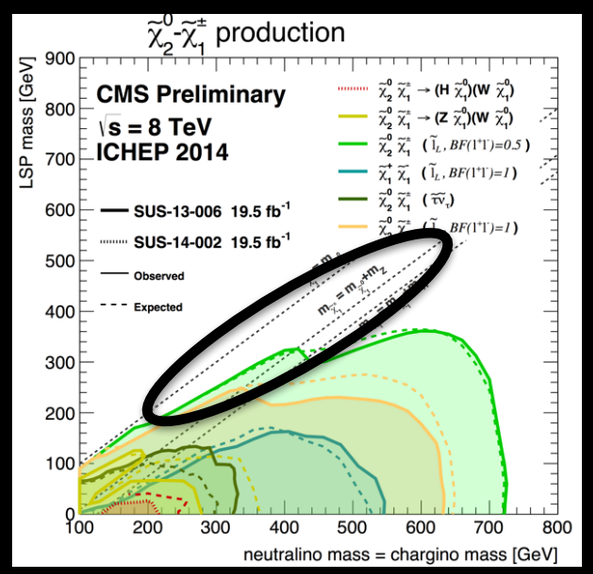
Degenerated Spectrum

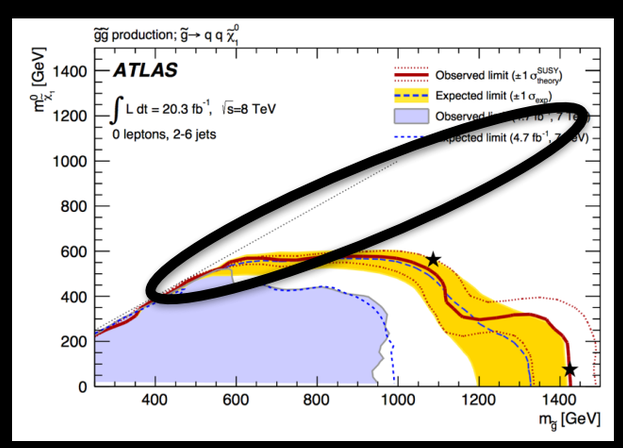




- Eventually (some) part of degenerated spectrum will be covered with increases in beam luminosity…

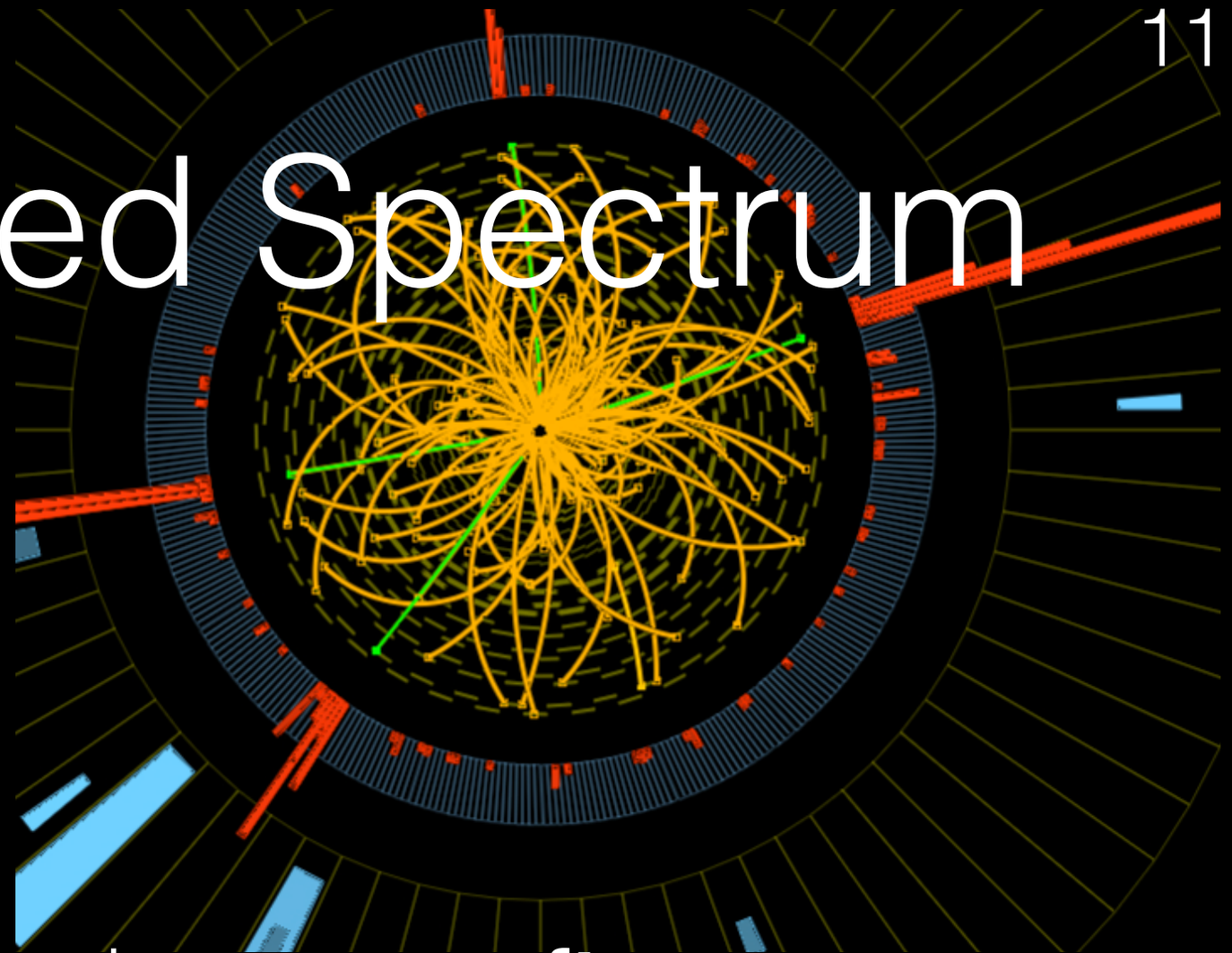
Degenerated Spectrum





- Current searching method is Tagging “Initial State Radiation (ISR) Jets” + Missing Energy

Degenerated Spectrum

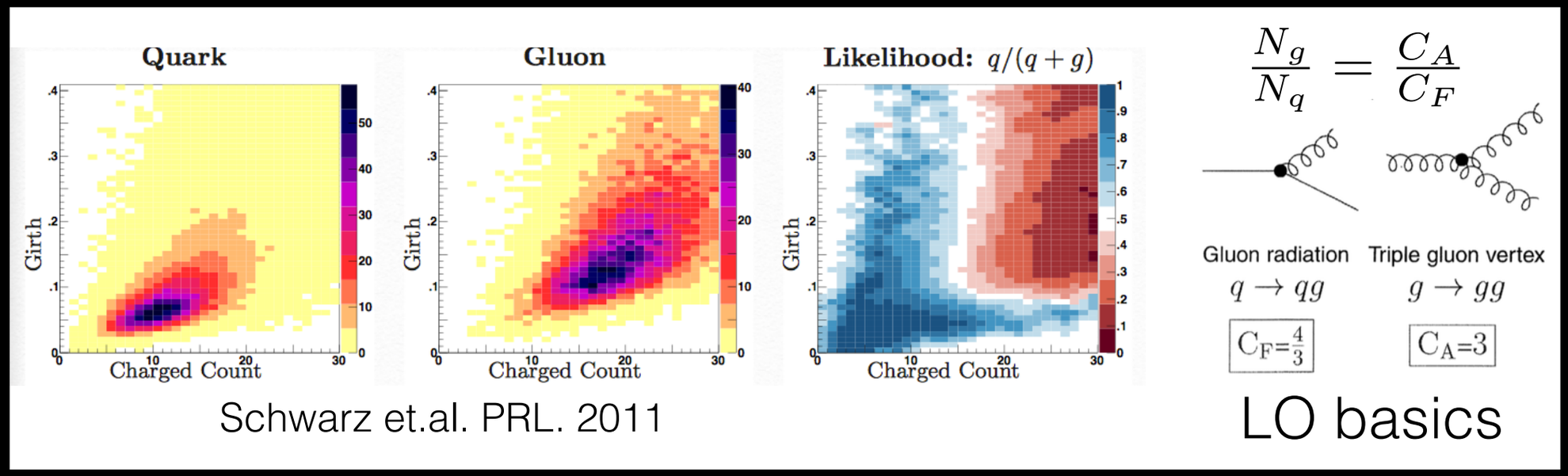


- Tagging ISR jets + MET

- 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

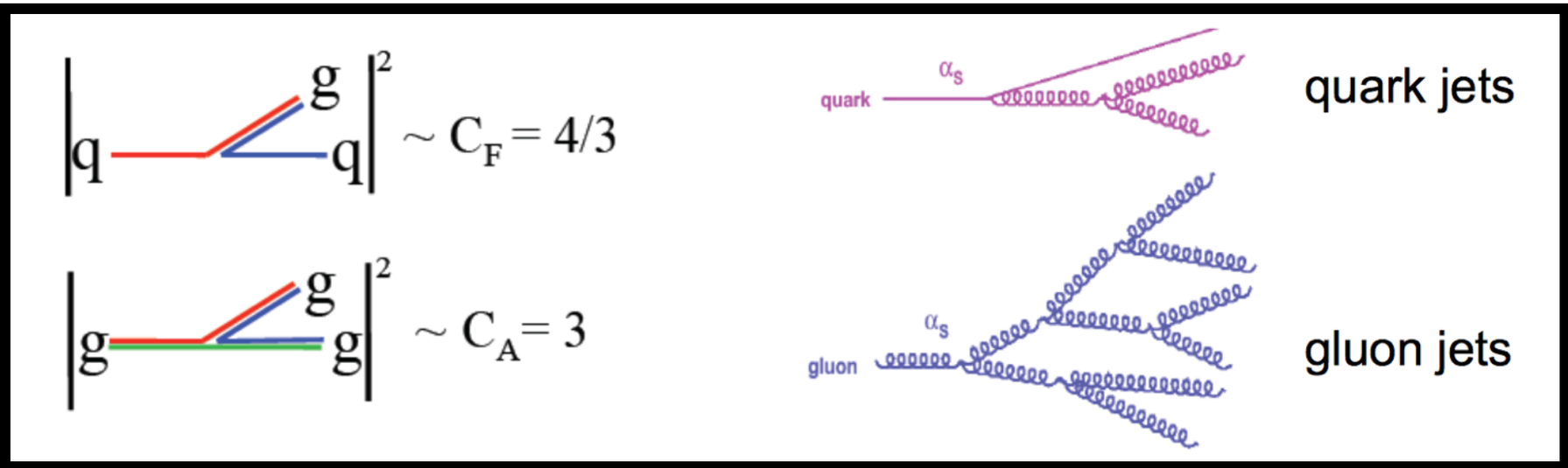
- Possibility to discriminate
  ISR jet (initially gluon) v. s. quark jets (in Z+jets)

- Tagging ISR over Standard Model backgrounds. (**g** v.s. **q**)



Schwarz et.al. PRL. 2011

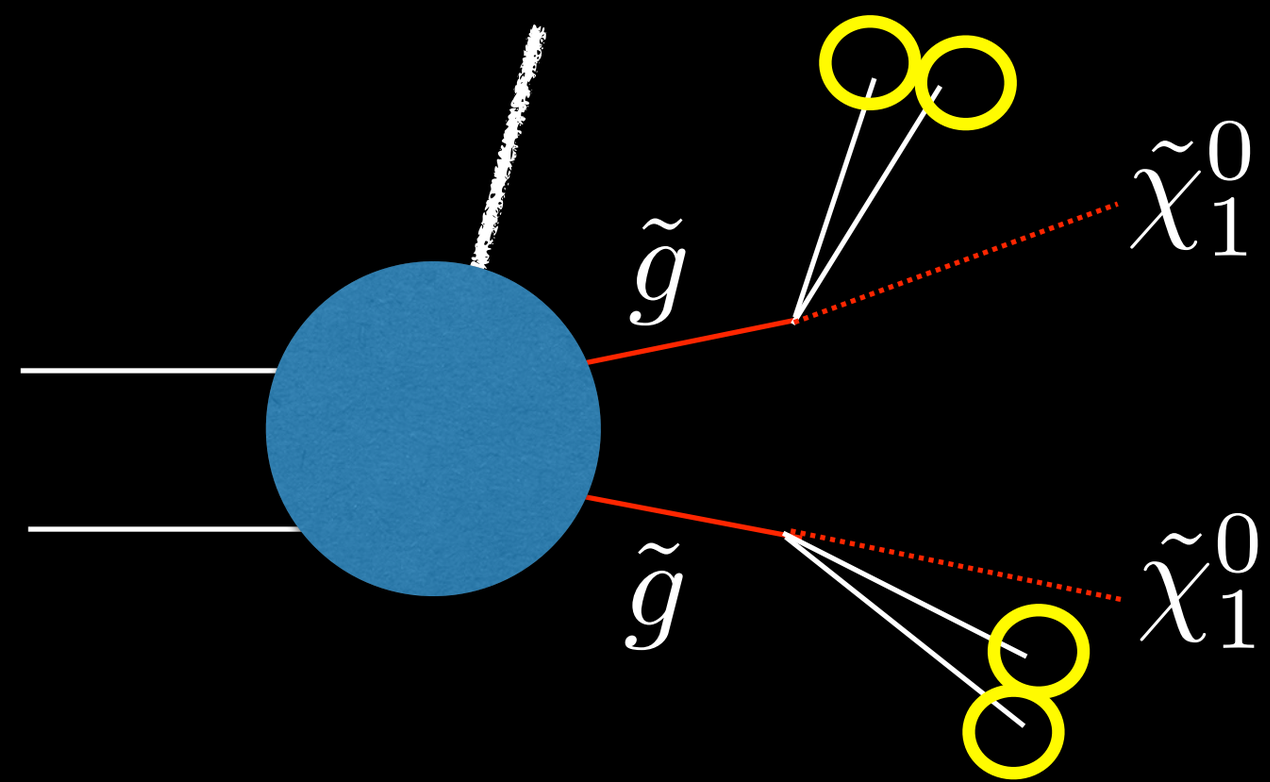
LO basics



g-initiated jet is “wider” compared to q-initiated jet

But Tagging ISR is **NOT ENOUGH!**
(Those analyses neglects the SUSY part!)

- Need to tag “Signals” from SUSY decay



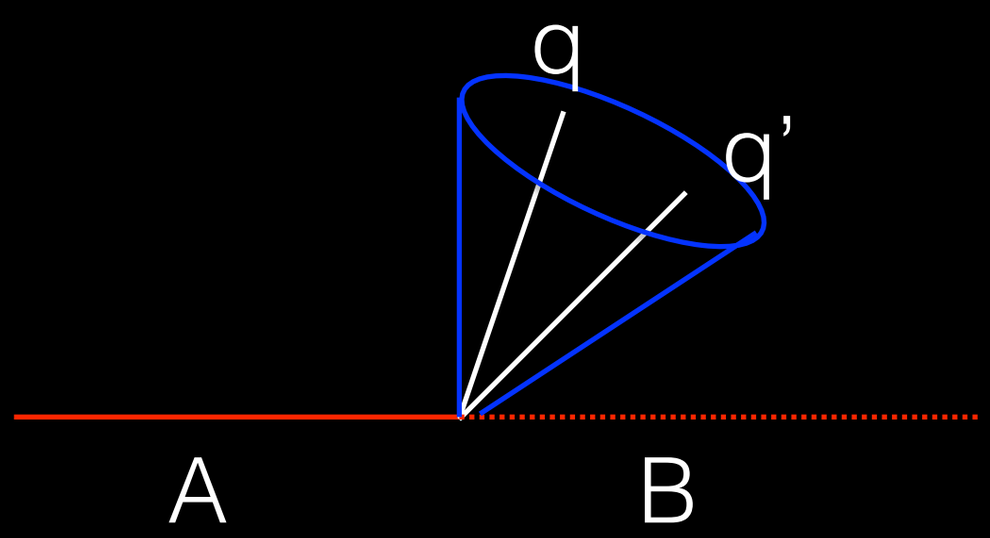
to understand **properties** of SUSY particles
(masses, spin and coupling structure)

- Tagging Soft jets coming from

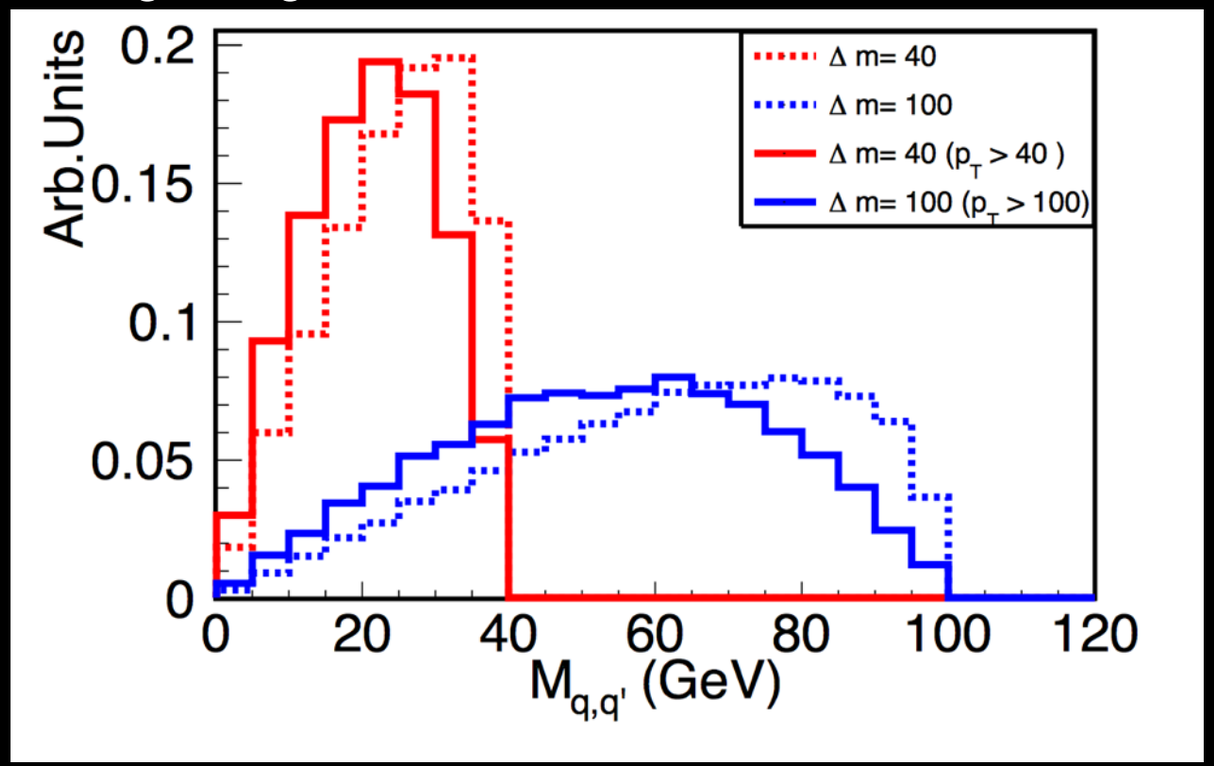
SUSY decay processes

based on Chengcheng Han, **MP**, arXiv1507.07729

Fat Jet



Chengcheng Han, MP 2015



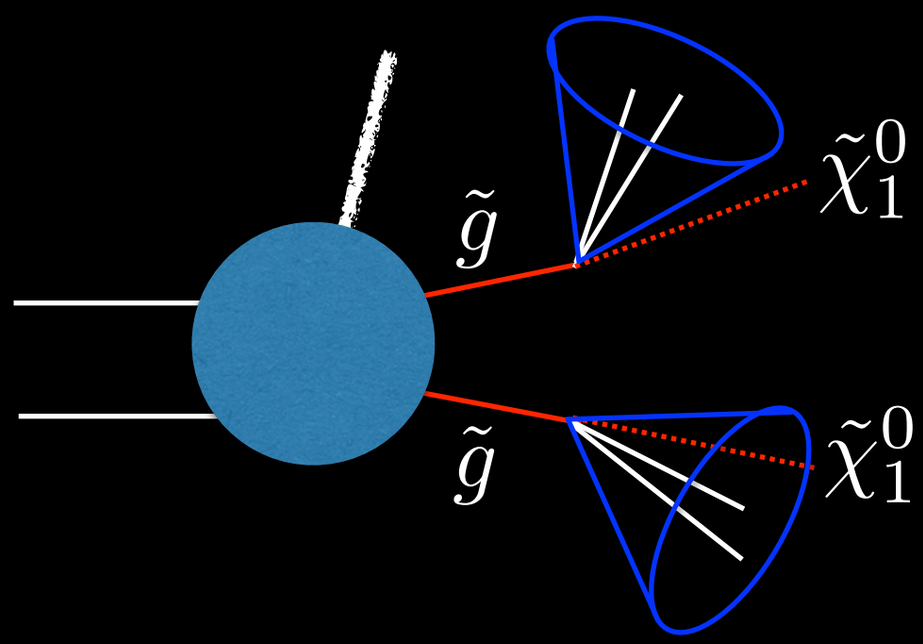
The peak of an 3-body invariant mass;

$$P_{qq'} = \left[\frac{m_A^2+m_B^2}{3}\left(2-\sqrt{1+\frac{12m_A^2m_B^2}{(m_A^2+m_B^2)^2}}\right)\right]^{\frac{1}{2}} \xrightarrow[\Delta m \ll m_A]{} \frac{\Delta m}{\sqrt{2}}$$

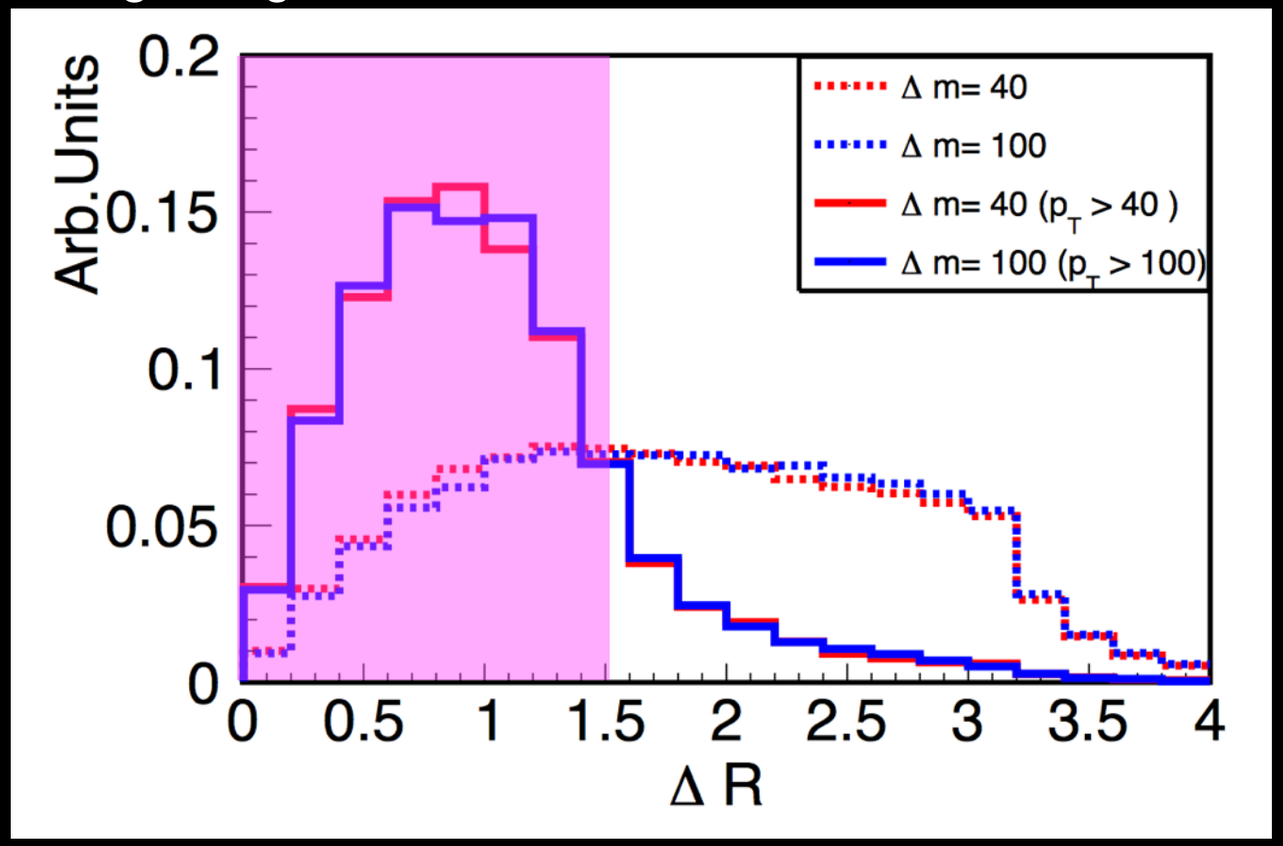
What will be the size of Fat Jet (FJ) ?

$$M_{qq'}^2 \simeq P_{T(q)}P_{T(q')}\Delta R^2 = z(1-z)P_{T(FJ)}^2\Delta R^2$$

Fat Jet



Chengcheng Han, MP 2015



$$\Delta R \simeq \frac{1}{\sqrt{z(1-z)}} \frac{M_{qq'}}{P_{T(FJ)}} \simeq 2 \frac{\Delta m}{\sqrt{2}} \frac{1}{\Delta m} = \sqrt{2}$$

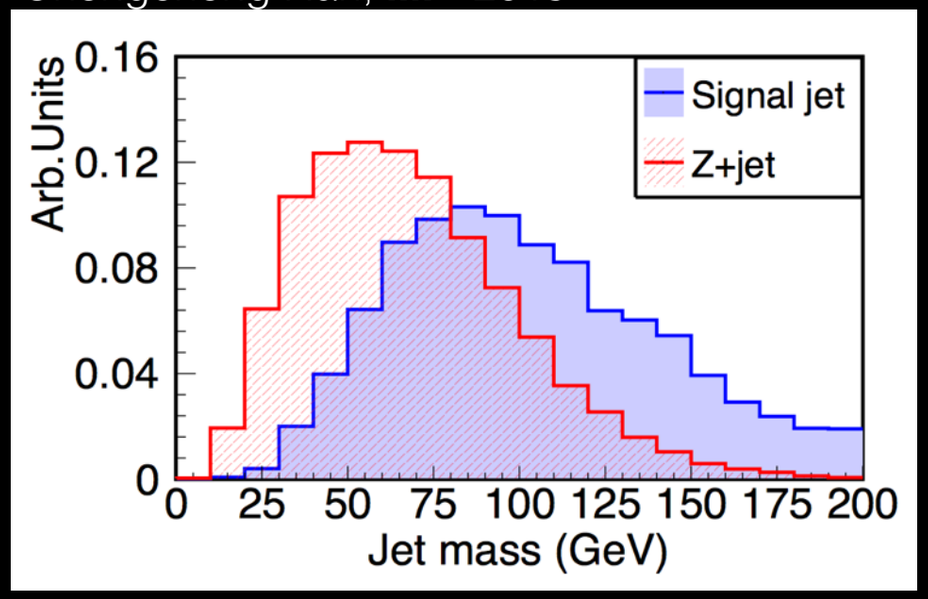
- Capturing soft jets with a “Fat” jet
  - Contamination from soft QCD activities
  - Need to distinguish signal fat-jet from QCD fat-jet

- Contamination from soft QCD activities can be removed by jet-grooming (Mass Drop Tagger)

QCD jets $< M_J^2 >_{\rm NLO} \simeq \bar{C}\left(\frac{P_J}{\sqrt{s}}\right)\alpha_s\left(\frac{P_J}{2}\right)P_J^2 R^2 \simeq (0.2 P_J R)^2$

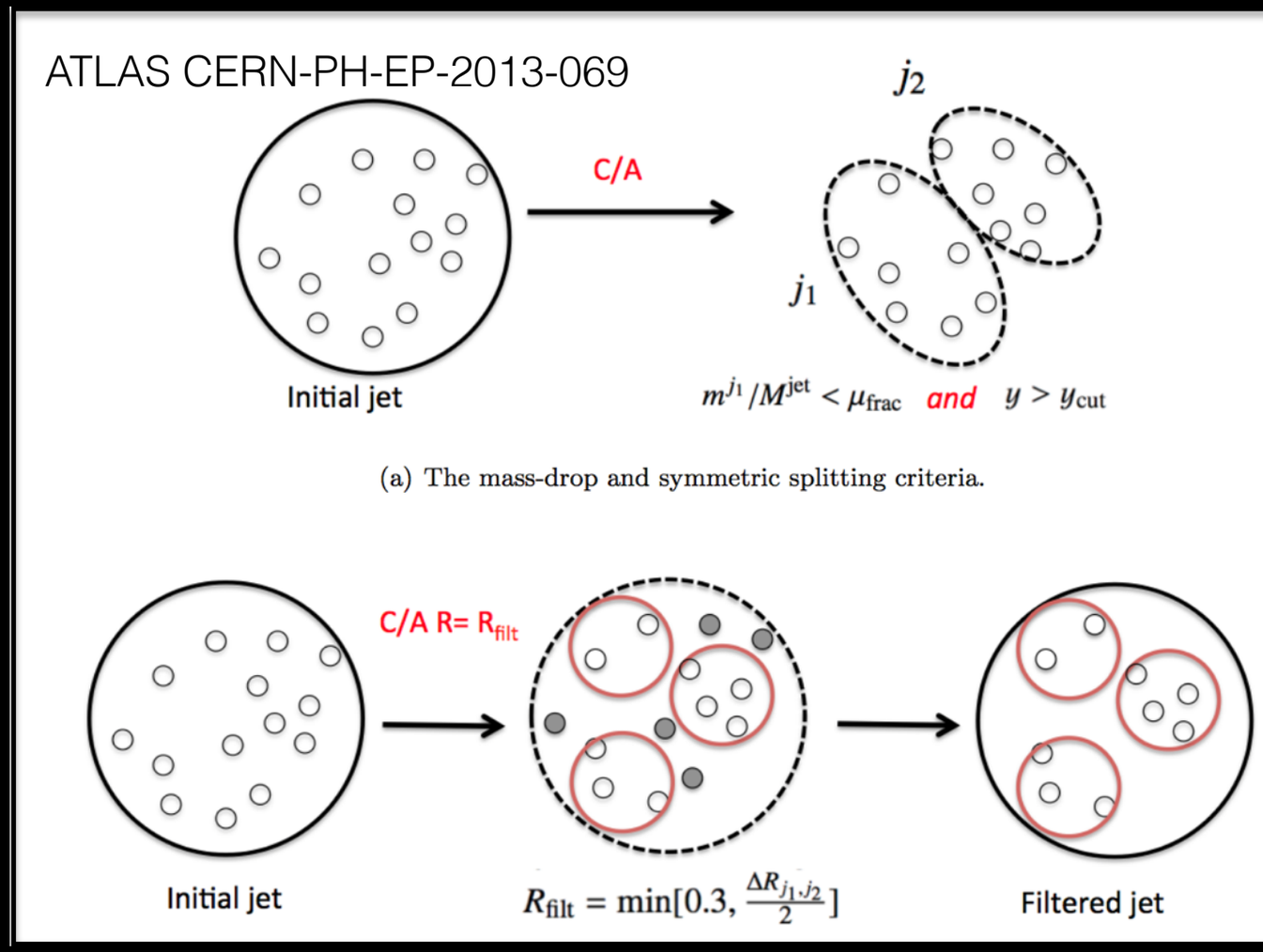
$$< M_J > \simeq 30\,GeV \ \text{with} P_J = 100\,GeV$$

Chengcheng Han, ***MP*** 2015



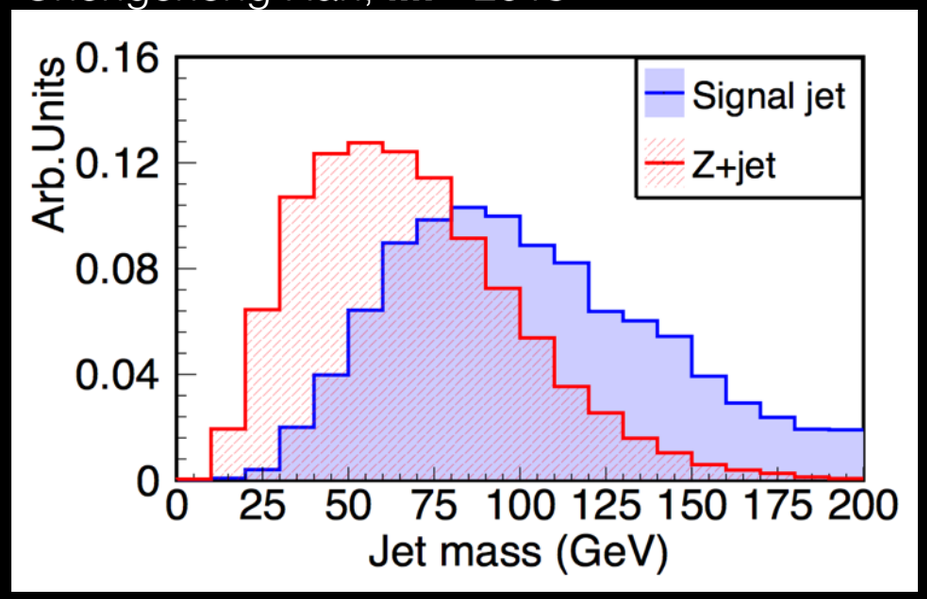
A cartoon to describe Mass Drop Tagger

ATLAS CERN-PH-EP-2013-069



(a) The mass-drop and symmetric splitting criteria.

Chengcheng Han, ***MP*** 2015



Selecting out QCD jet
by requiring a signal jet to satisfy

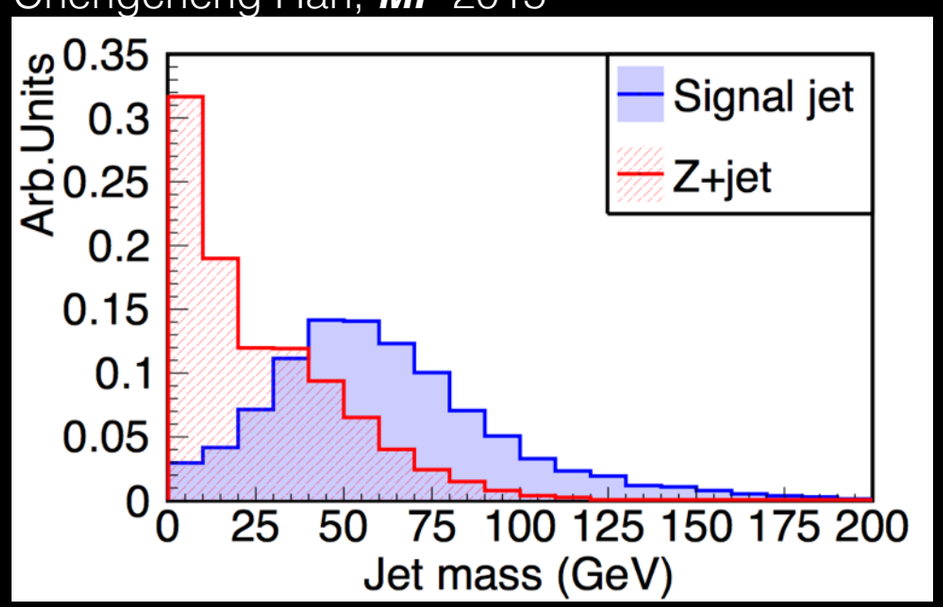
Symmetric condition

$$\frac{m_{j1}}{m_{FJ}} < \mu_{frac}, \quad \mu_{frac} = 0.67$$

MDT

$$\frac{\min[p^2_{T(j_1)}, p^2_{T(j_2)}]}{m^2_{FJ}} \times \Delta R^2 > y_{cut}, \quad y_{cut} = 0.09$$

Chengcheng Han, ***MP*** 2015



to maximize $\frac{S}{\sqrt{B}}$

by J. Butterworth et.al. hep-ph/0802.2470

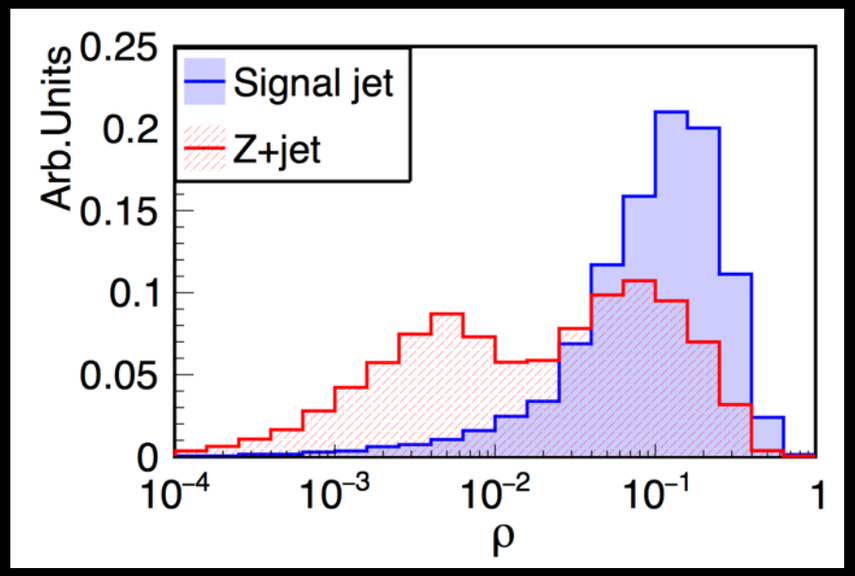
Jet substructure

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

- Need to have another handle

$$\rho \equiv \frac{M_J}{P_T^2 R^2} \simeq z(1-z)\frac{R_{qq'}^2}{R^2} \sim 0.2$$ for signal fat-jet

$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho} \propto \Theta(\rho - y_*)\ln\frac{1}{\rho} + \Theta(y_* - \rho)\ln\frac{1}{y_*} - \frac{3}{4}$$



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

Enhance Sensitivity

- Apply our method as prescreening on top of existing ATLAS analysis.

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.

cuts	Signal	Z+jet
40 GeV $< m_j <$ 100 GeV	0.686	0.246
$\rho > 0.1$ and 40 GeV $< m_j <$ 100 GeV	0.495	0.16

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
$E_T^{miss}/\sqrt{H_T}[\mathrm{GeV}^{1/2}]$	> 15
$m_{eff}(incl.)$ [GeV]	> 1200

Benchmark points:
1. Delta M = 100GeV
2. Delta M = 40 GeV
with M(LSP)=600GeV

Methods			Z+js	W+js	$t\bar{t}$+js	Total	BP1	σ	BP2	σ
ATLAS			430	216	47	693	74	1.34	57	1.03
With FJ	Δm	40	48	31	7	86	27	2.12	–	
		100	21	18	11	50	–		17	1.96

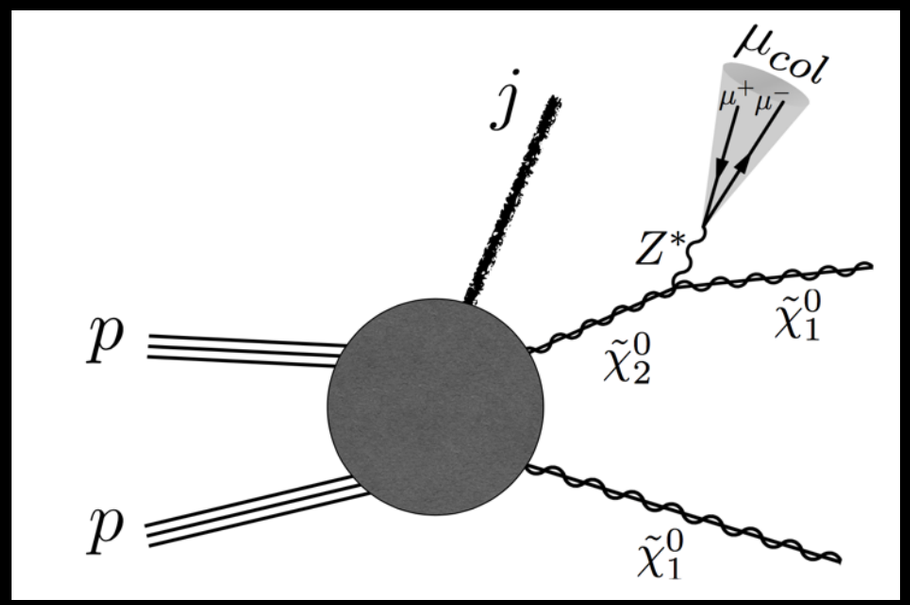
LHC 8TeV with 20.3 fb^(-1) luminosity [RUN1]

If there are leptons (lepton= muon) that's the best signal@LHC

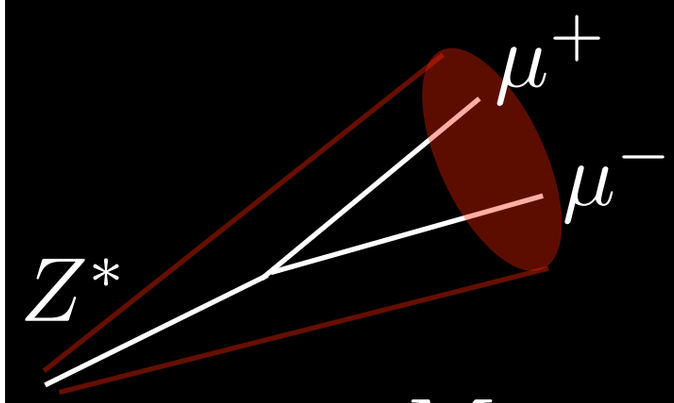
- Soft muons from SUSY decay,

based on Chengcheng Han, Shoaib Munir, Doyoun Kim, MP
JHEP1504(2015)132

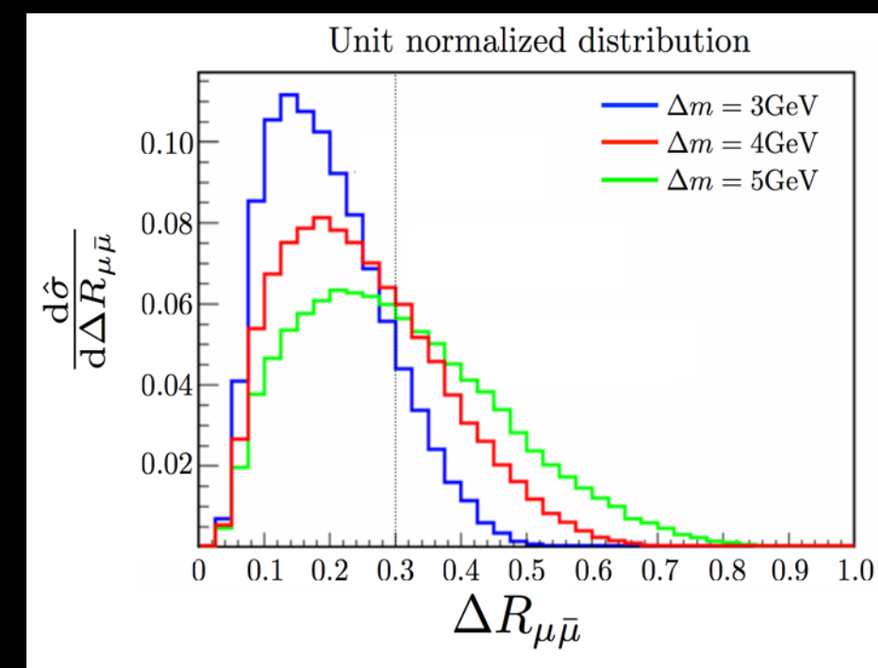
Enhance sensitivity



MP , PARC@APCTP, JHEP 2015



$$\Delta R \propto \frac{M}{P_T}$$



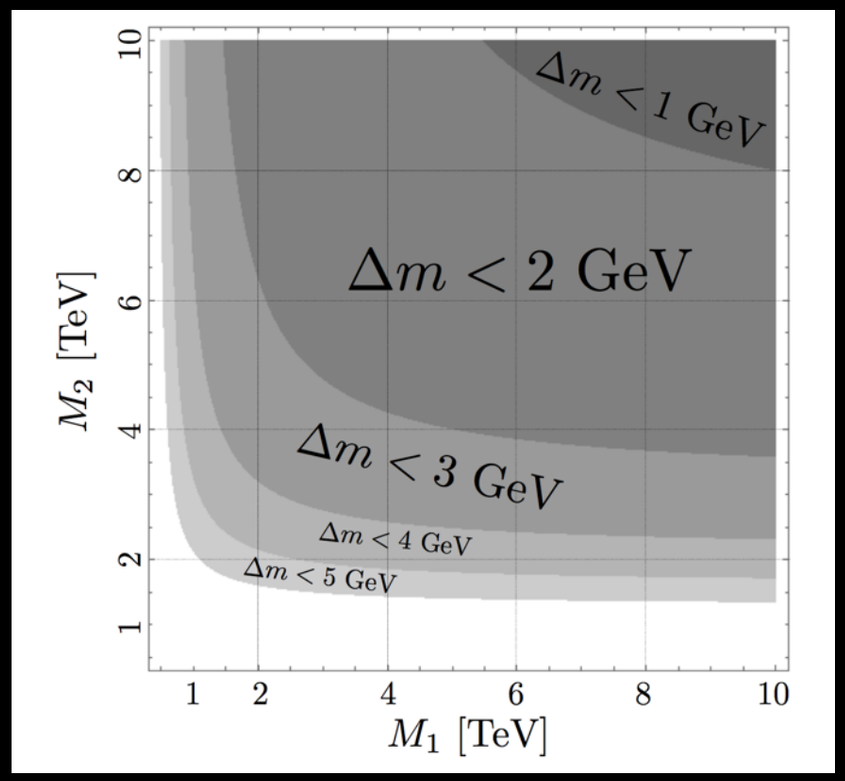
MP , PARC@APCTP, JHEP 2015

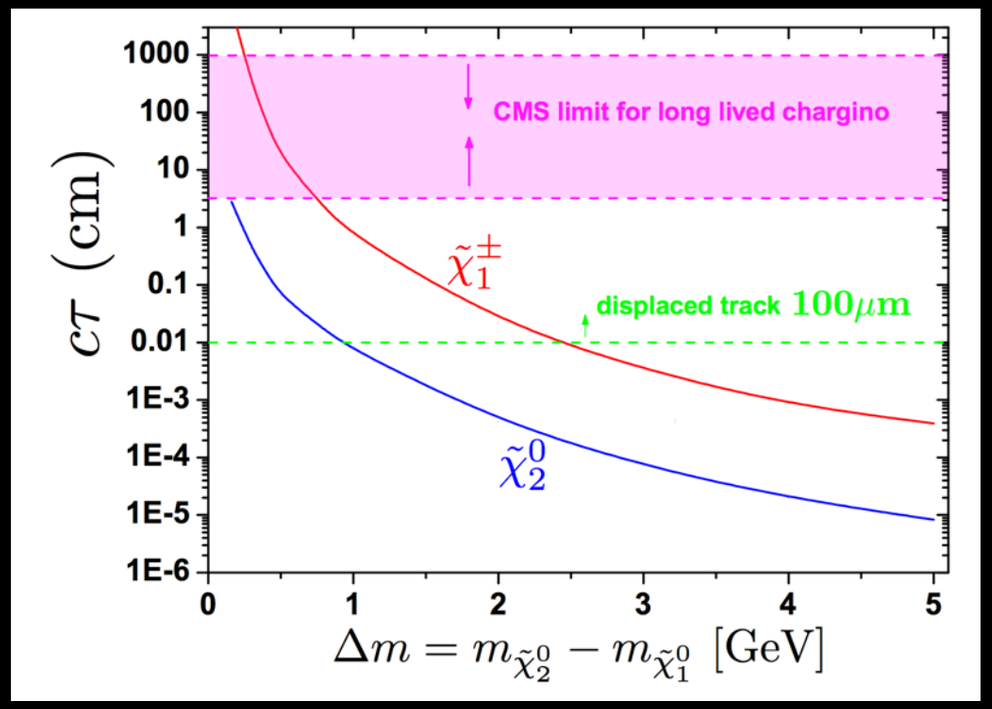
- Non-boosted “Light Object” inside a small cone
- We tag a “offshell Z boson” over Backgrounds.

- Based on the our previous discovery of the Higgs boson, we may think that will be one of the most important particle-contents in the Supersymmetric models

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

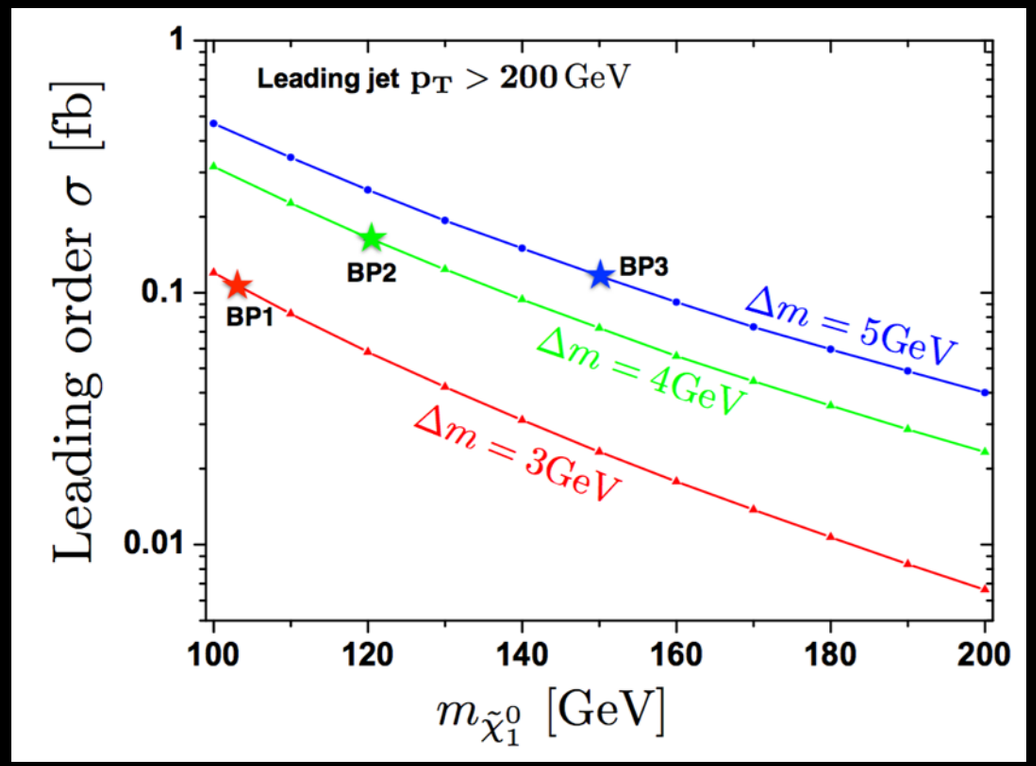
$$m_{\tilde{\chi}^\pm} - m_{\tilde{\chi}} \simeq \frac{\Delta m}{2}$$





Study point {3, 4, 5} GeV mass gaps.

Some detailed information on our analysis

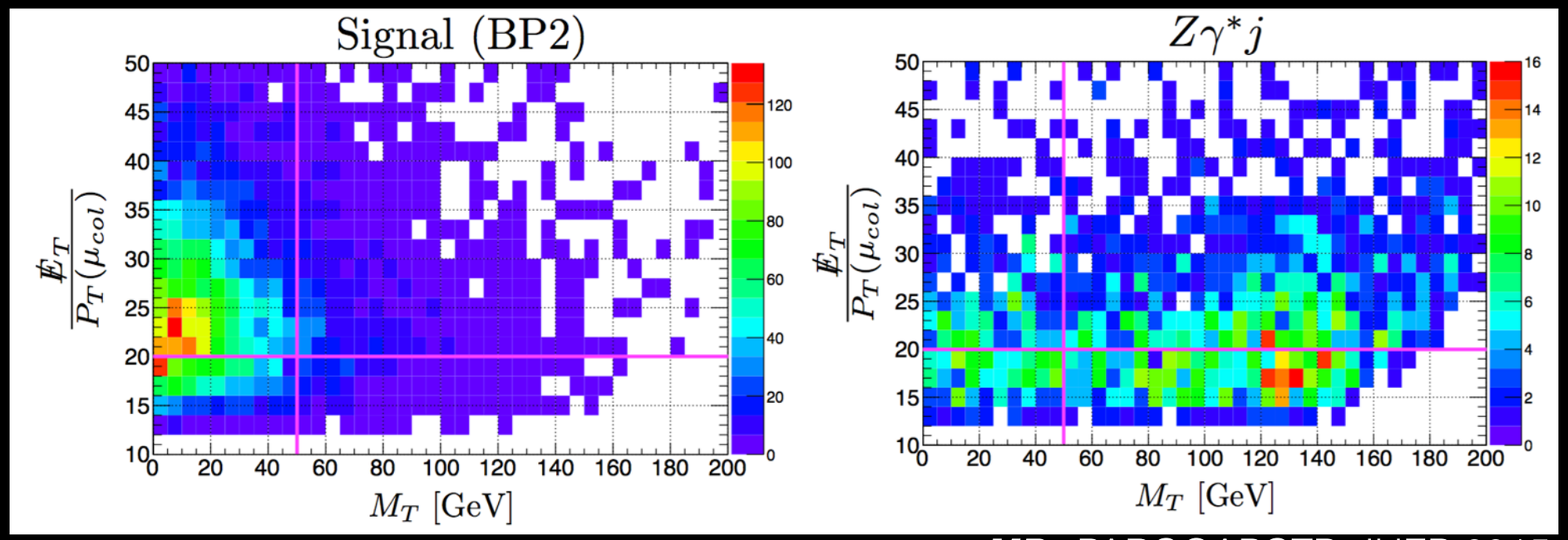


- With HL LHC (3000 Inverse fb), we will have O(100) events.

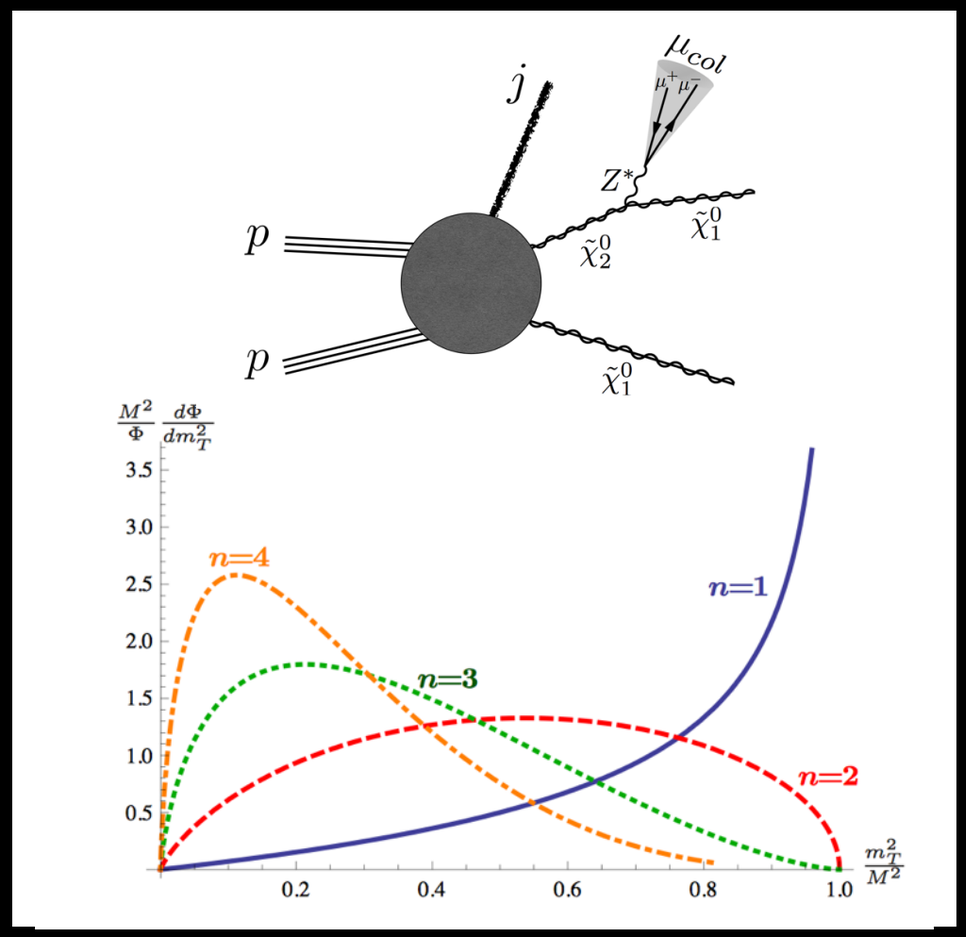
- Major Standard model backgrounds,

- $V + \gamma^* + jets$: 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



MP, PARC@APCTP, JHEP 2015



- 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.

With a Hope!

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

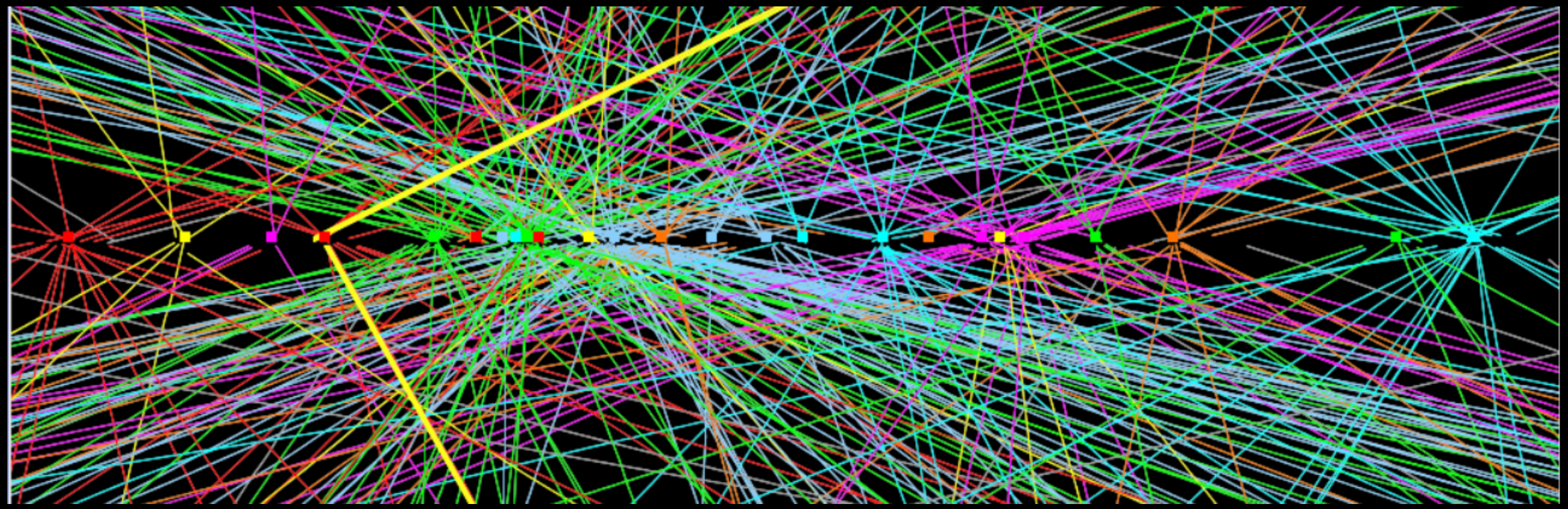
Cuts	$W\gamma^* j$	$Z\gamma^* j$	$j\tau\tau$	Total BKG	BP1	BP2	BP3
Mono-jet	8.057	8.82	6.674	23.0	0.052	0.072	0.056
Basic $\mu_{\rm col}$	0.753	1.05	0.314	2.1	0.041	0.042	0.028
$\Delta\phi(\mu_{\rm col}, \not{E}_T)$	0.288	0.324	0.035	0.65	0.028	0.030	0.020
$m_{\mu_{\rm col}}$	0.106	0.118	0.024	0.248	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

- We have a sensitivity to probe these non-trivial area.

- Please remember that cuts are not “very” optimized :)

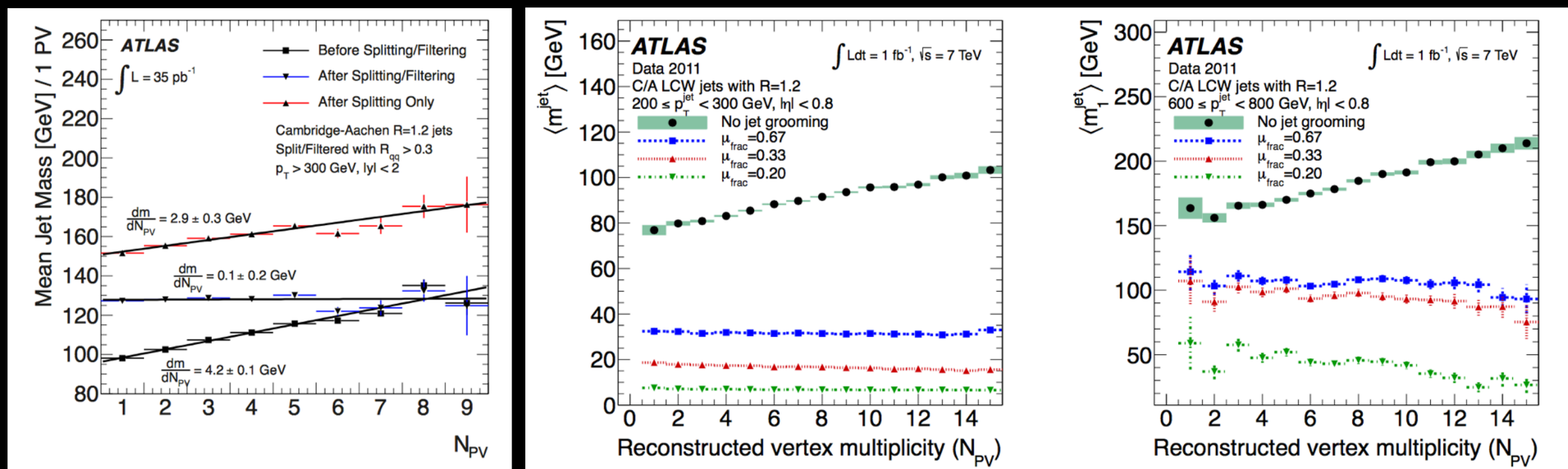
Difficulties…

- We illustrated how the LHC searches can get sensitivities in the degenerated spectrum.
  [at the level of “theorists’ analysis”]

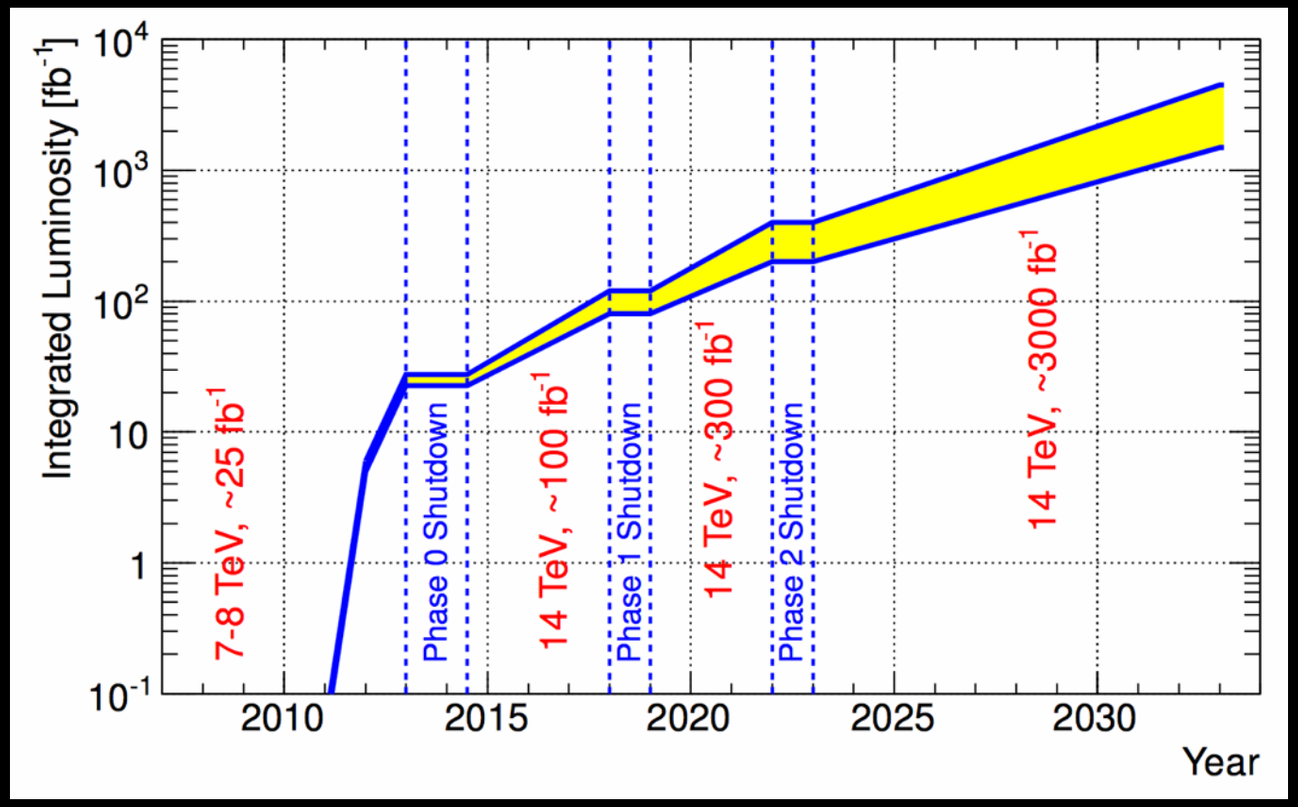


Difficulties…

- We illustrated how the LHC searches can get sensitivities in the degenerated spectrum.
  [at the level of “theorists’ analysis”]



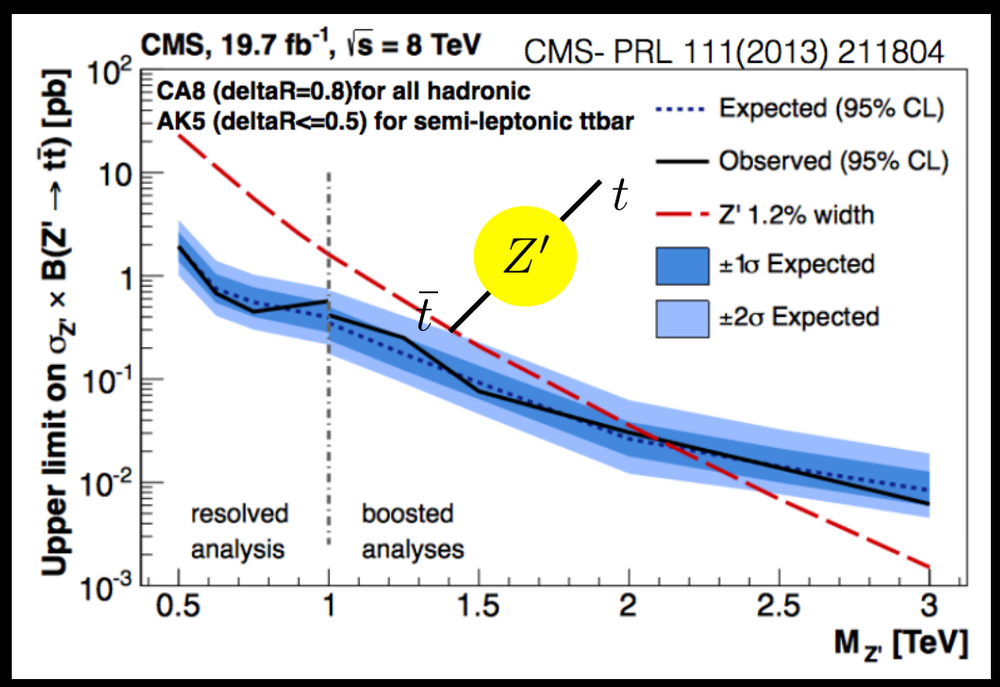
PT > O(50) GeV will be safe..but need to be confirmed experimentally.

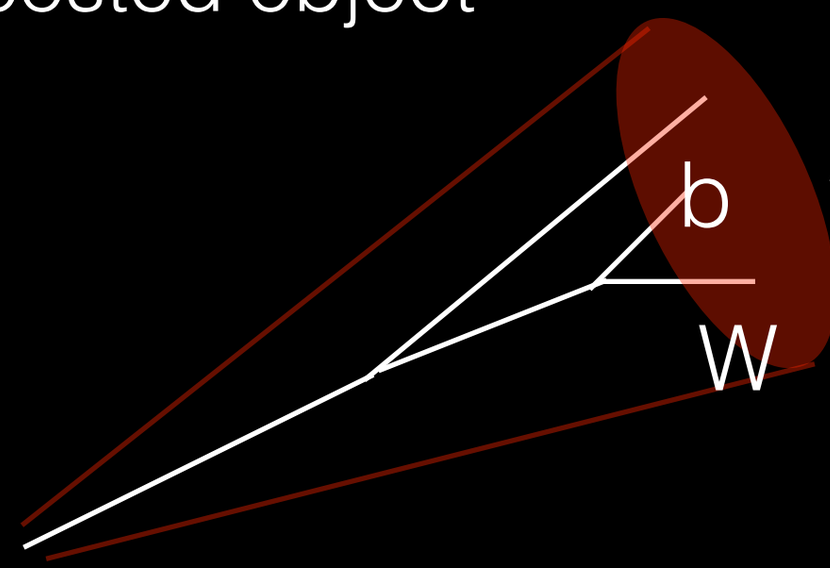


Situation will get worse @ HL LHC

Summary

- Using a Fat-jet in degenerated spectrum got motivation from
  1. Tagging a dark photon
  2. Tagging particles from Boosted object





$$\Delta R \propto \frac{M}{P_T}$$

Top-quark jet tagging

- Need to invest on O(50) - O(100) GeV PT jets

- Capturing soft signatures at colliders are another venue for searches of a new physics
- There have been developments in jet substructures for boosted objects.
- We can also adapt similar concept for the degenerated spectra.
- Tagging Soft particles with Fat jet provides a way to add more **sophisticated** analyses & **measure** properties of BSM particles !