Supersymmetry and dark matter search: prospects and challenges

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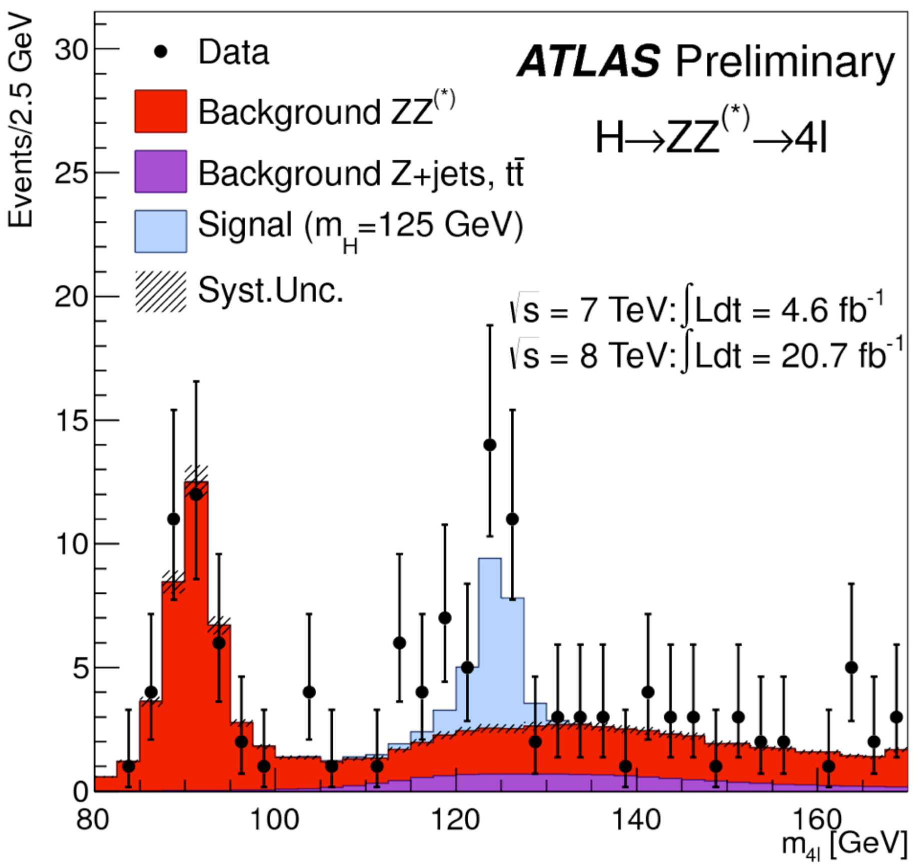
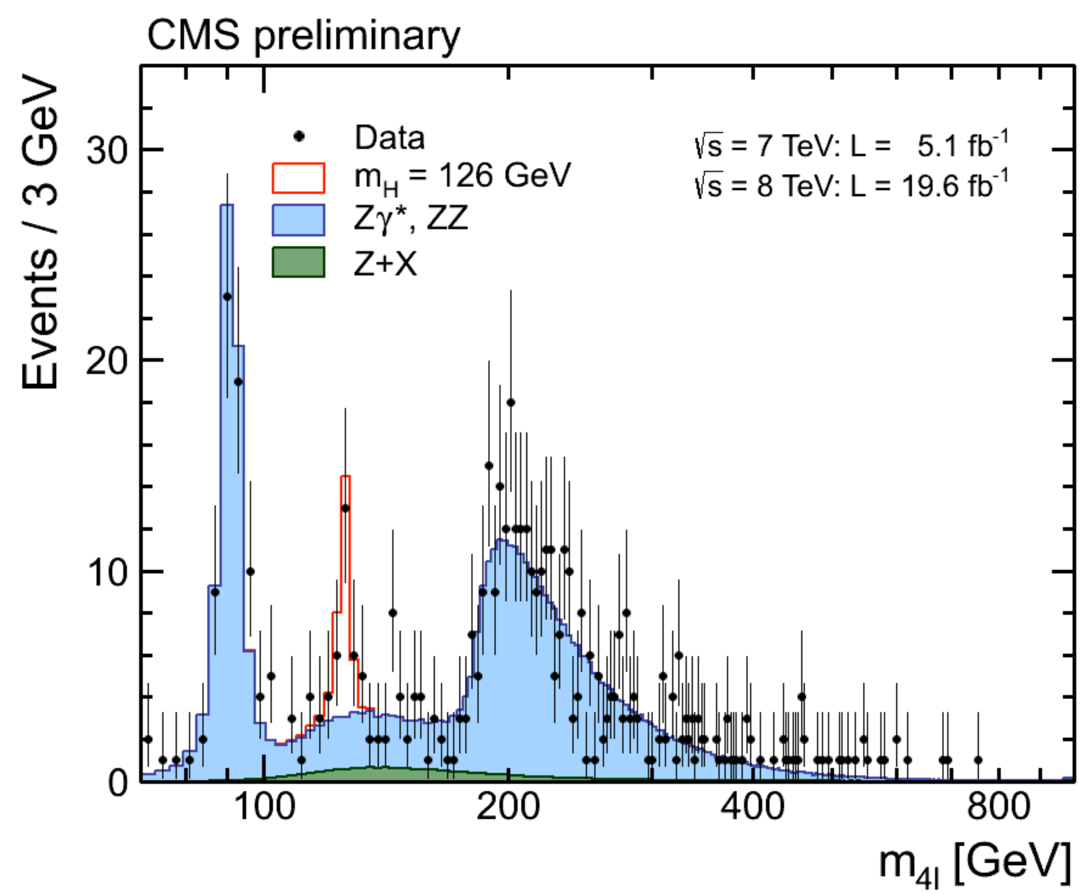
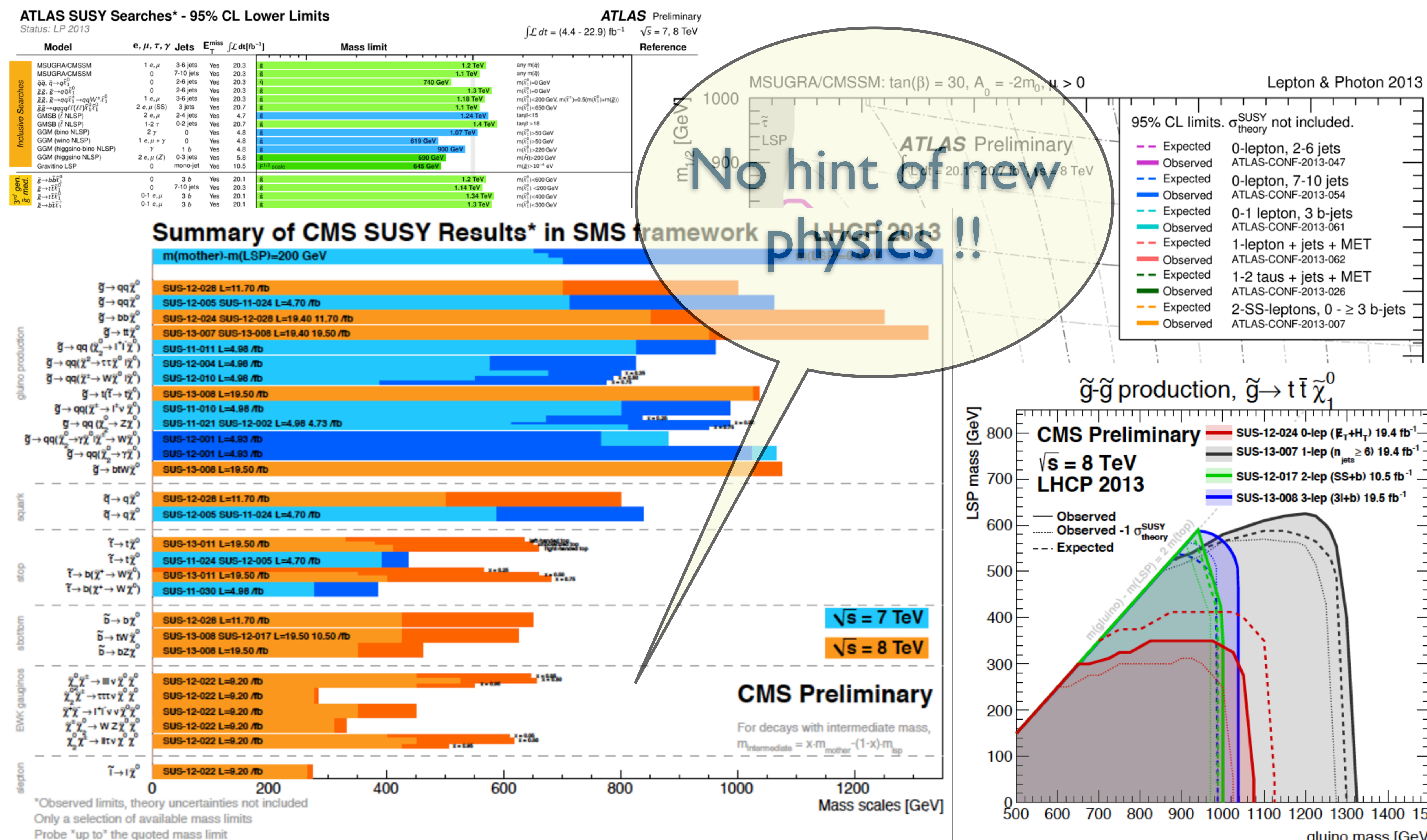
Observation of a new boson with mass ~125-126 GeV



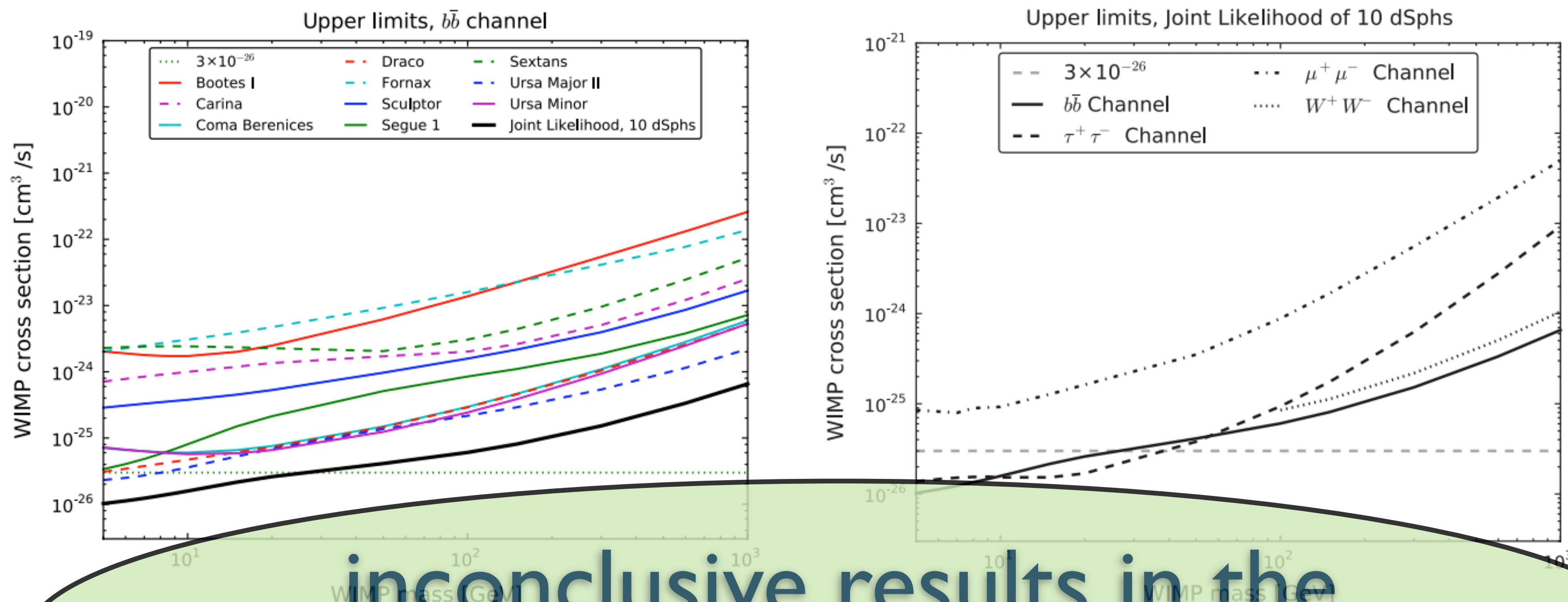


Properties: roughly consistent with Standard Model Higgs boson

New physics search: Large Hadron Collider



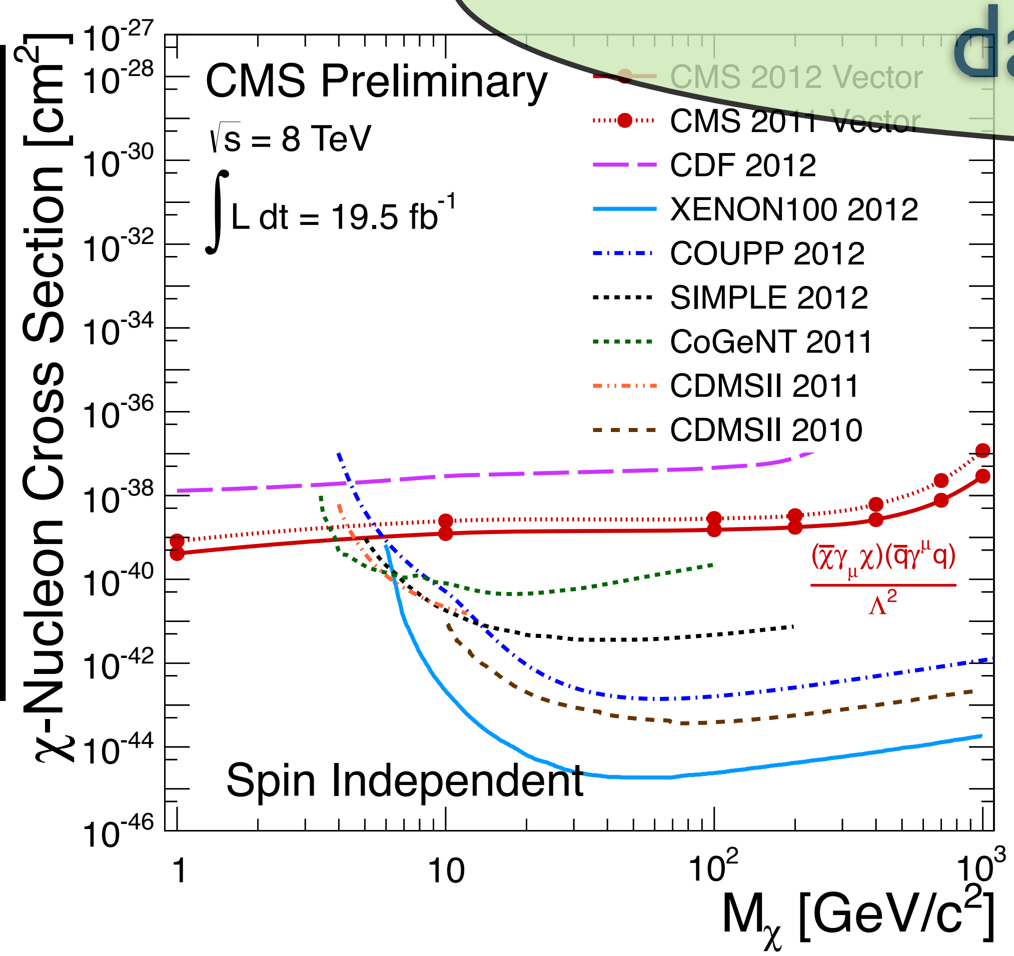
New physics search: dark matter

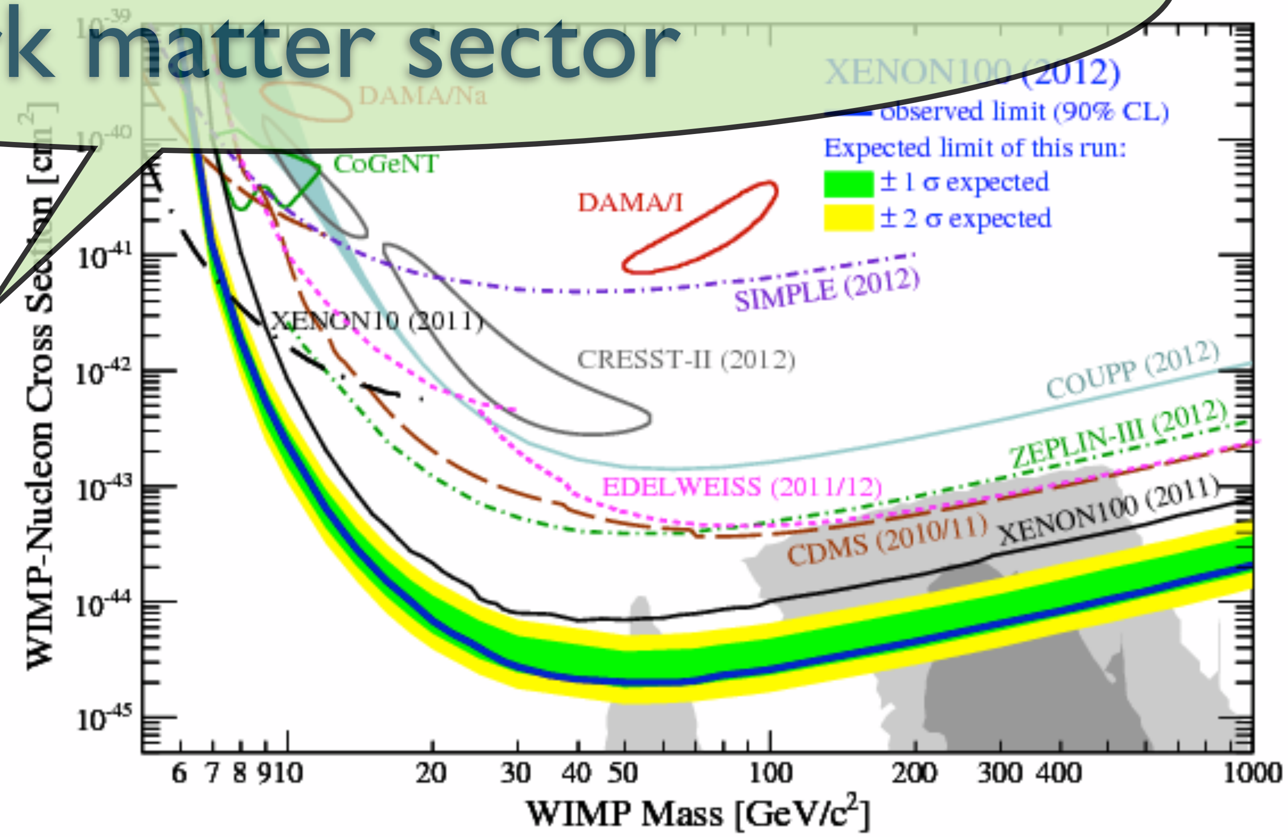


FERMI-LAT

inconclusive results in the dark matter sector

CMS





XENON- 100

Standard Model vs new physics

Standard Model should not be the ultimate theory

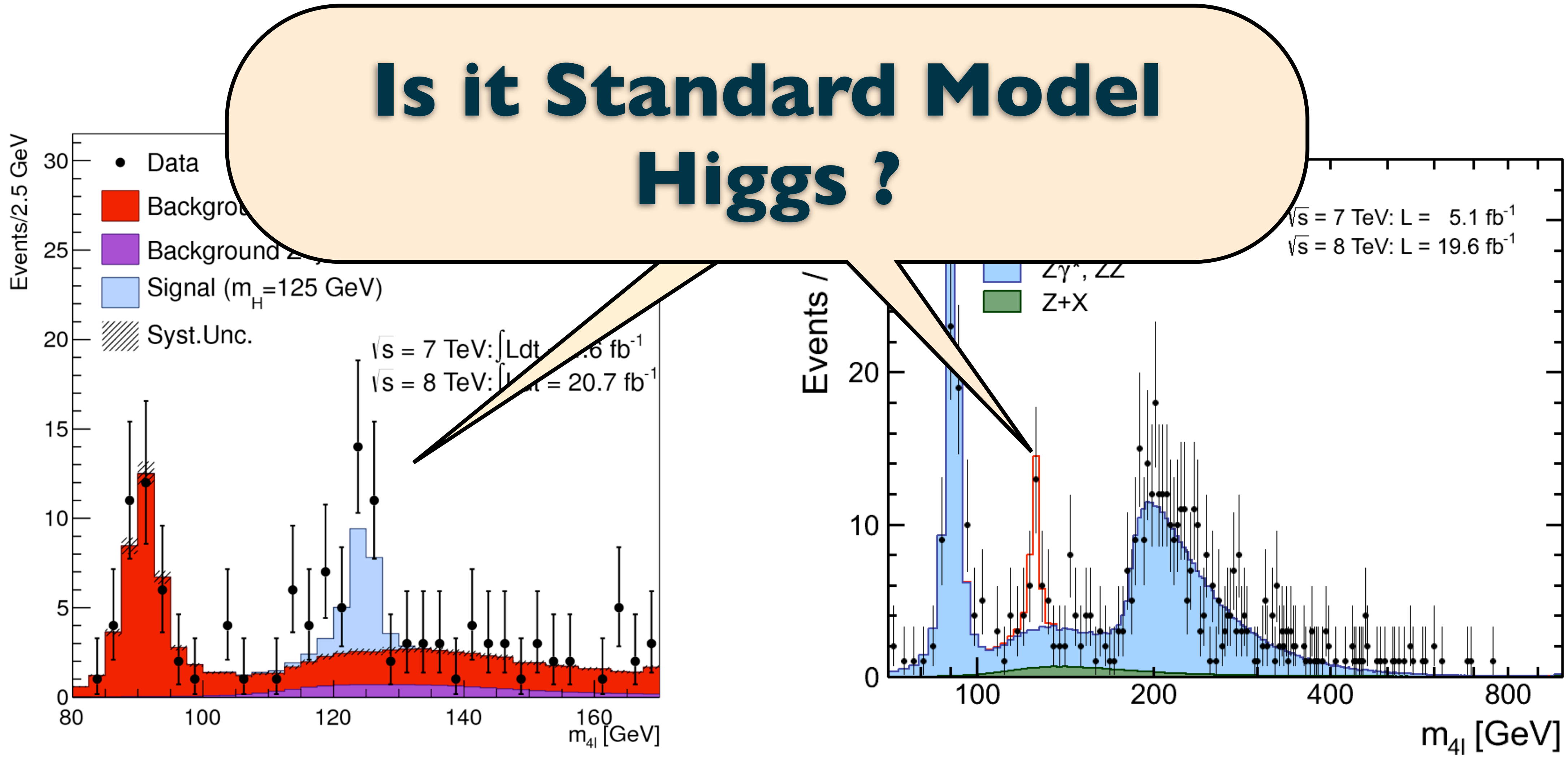
Experimental facts

1. Baryon Asymmetry of the Universe
2. Dark matter (and dark energy?)
3. Neutrino mass

Theoretical issues

1. Flavour structure
2. Hierarchy problem
3. Gauge coupling unification

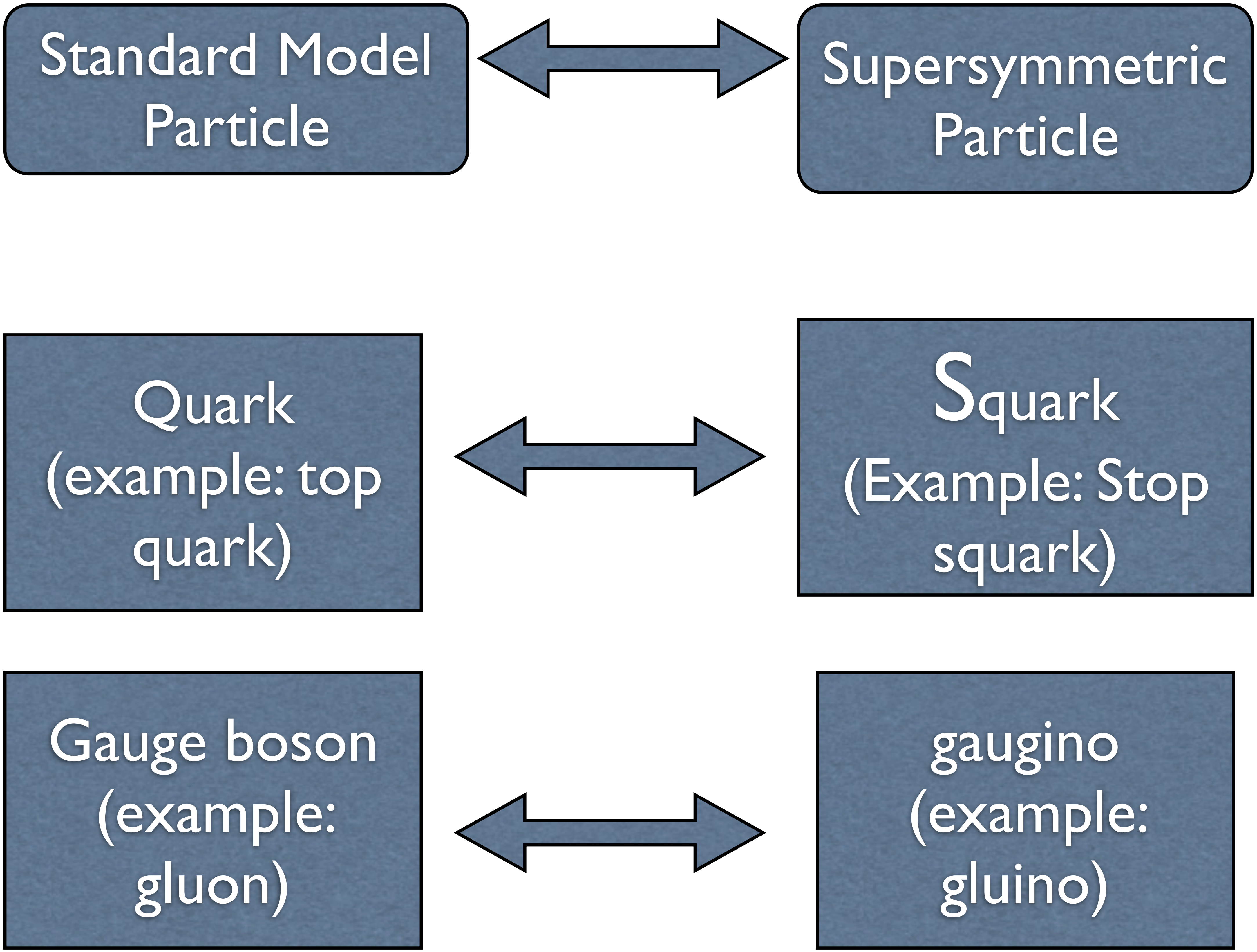
Observation of a new boson with mass ~125-126 GeV



What kind of new physics models are consistent with present LHC data ?

Supersymmetry

Supersymmetry (SUSY)



Supersymmetry (SUSY)

SM Particle ⟷ SUSY Particle

particles	SUSY particles	
quark (1/2)	squark (0)	$\tilde{q}$
lepton (1/2)	slepton (0)	$\tilde{l}$
gauge boson (1)	gaugino (1/2)	$\tilde{W}^{\pm}, \tilde{W}^{0}, \tilde{B}$ ..
Higgs (0)	higgsino (1/2)	$\tilde{H}_u, \tilde{H}_d$
graviton (2)	gravitino (3/2)	$\tilde{g}_{3/2}$

One of the most attractive new physics option

(dark matter , gauge coupling unification, hierarchy problem may be explained)

Broken symmetry (otherwise electron mass= Selectron mass= 0.5 MeV.. excluded.. no such particle observed)

many breaking mechanisms

more than 100 parameters in the low energy description

Supersymmetry

λ → Higgs self coupling is not a free parameter, determined by gauge couplings(tree level)

Tree level mass $M_H \leq M_Z$

Supersymmetry

λ ➡ Higgs self coupling is not a free parameter, determined by gauge couplings(tree level)

Tree level mass $M_H \leq M_Z$

Higher order correction

No quadratic divergence

dominant contribution from Stop squarks (superpartner of top quark)

$$m_h^2 \simeq M_Z^2 + \frac{3m_t^4}{4\pi^2 v^2}\left[\log\left(\frac{M_{SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12M_{SUSY}^2}\right)\right]$$

$M_{SUSY}^2 \rightarrow$ averaged stop squared mass $X_t = A_t - \mu/\tan\beta \rightarrow$ stop mixing parameter

Higgs boson and Supersymmetry

Is 125 GeV Higgs too heavy for SUSY ?

Option 1 : Heavy stop squarks

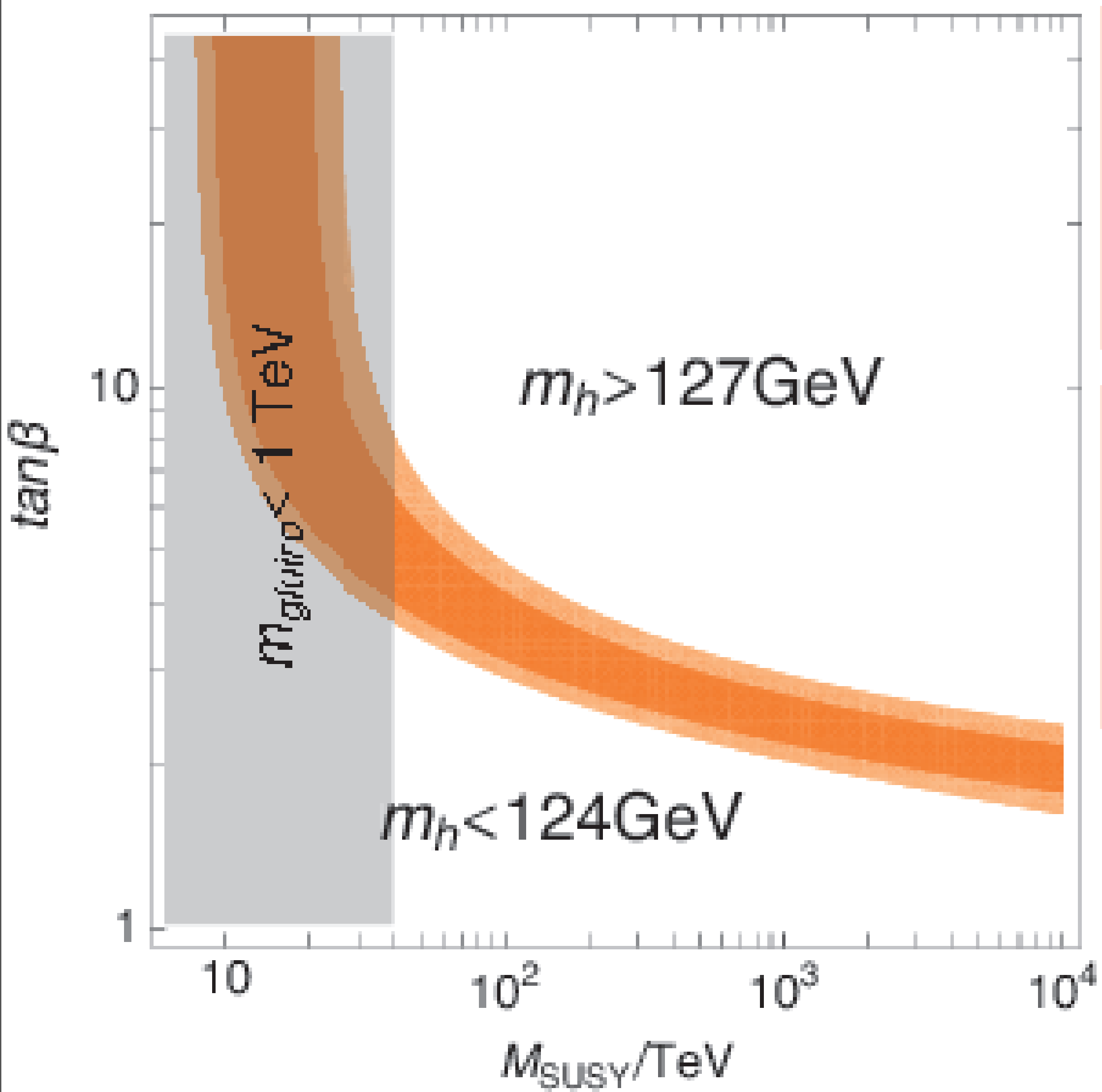
Higgs mass depends on stop masses : log sensitivity

Assume all squarks are heavy

Option I : Heavy stop squarks

Higgs mass depends on stop masses : log sensitivity

Assume all squarks are heavy



Required stop mass ~ a few TeV to hundreds of TeV !
Impossible to observe at LHC

Does it mean that other SUSY particles are also hundreds of TeV range ?

Fig: BB, B. Feldstein, M. Ibe, S. Matsumoto,T. Yanagida, PRD 2012

Option 1 : Heavy stop squarks

Higgs mass depends on stop masses : log sensitivity

Assume all squarks are heavy

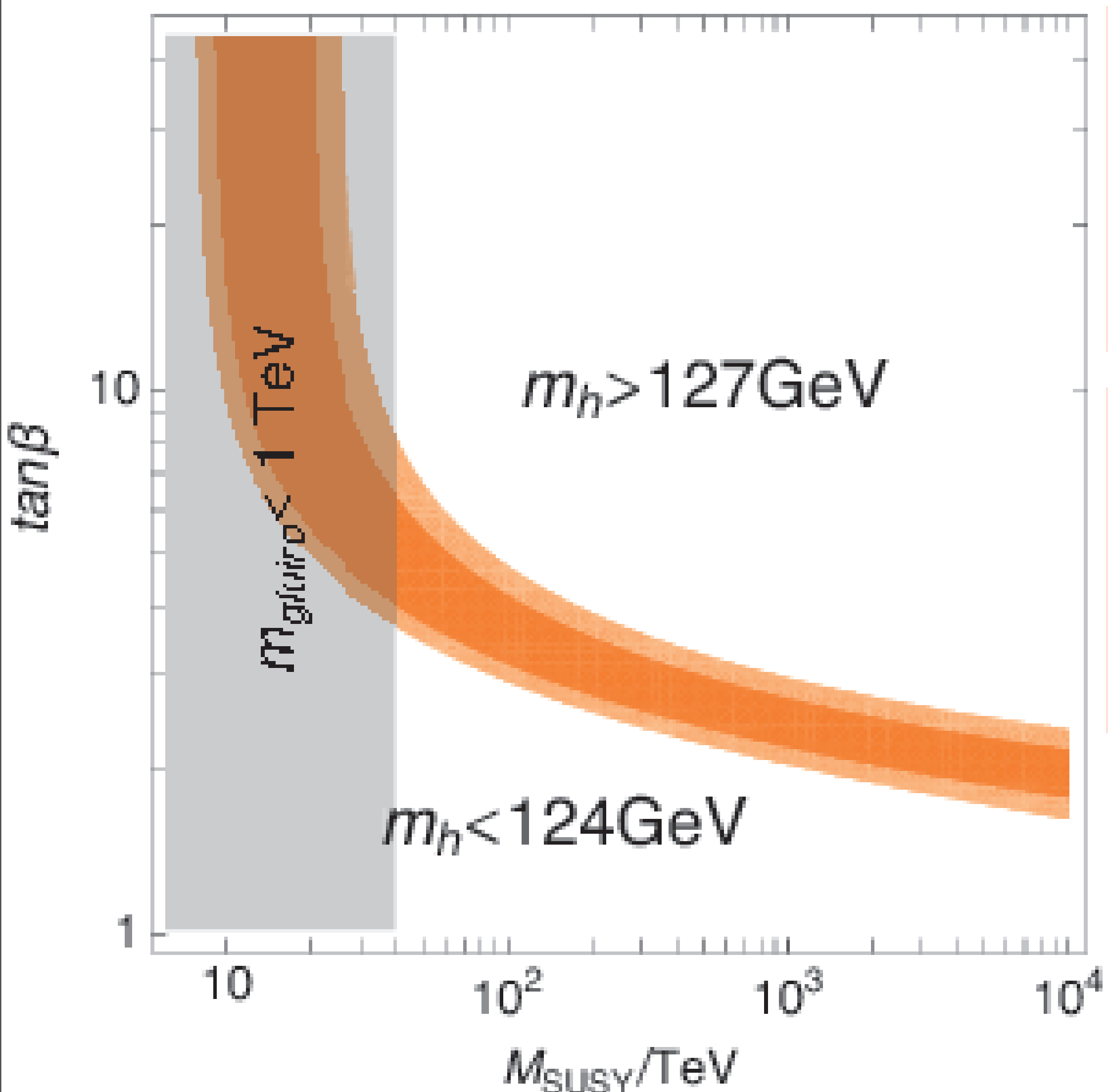


Fig: BB, B. Feldstein, M. Ibe, S. Matsumoto,T. Yanagida, PRD 2012

Required stop mass ~ a few TeV to hundreds of TeV !
Impossible to observe at LHC

Does it mean that other SUSY particle ... ds of TeV

Verification ??
very difficult

Chance to observe sparticles other than stop squarks at the LHC

Option II : Large stop squark mixing

Increase X_t parameter

Very large X_t value does not help

Optimal value: $$X_{t_{(OPT)}} = \sqrt{6} M_{\tilde{t}}$$

X_t appears in the off diagonal component of stop squark mixing matrix

Large X_t $\longrightarrow$ large stop squark mixing

Measurement of stop mixing matrix is very important

Many works in this direction..

Shelton,
Perelstein,
Krohn,
BB, Mandal, Nojiri,
Belenger et.al.,

Option II : Large stop squark mixing

Increase X_t parameter

Very large X_t value does not help

Optimal value: $X_{t_{(OPT)}} = \sqrt{6}$

Verification ??
Not always possible

X_t appears in the off diagon
stop squark mixing matrix

Large X_t $\longrightarrow$ large st quark mixing

Measurement of stop mi matrix is very important

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Option III: Add new particles/interactions

Add $\lambda S H_u H_d$ S= gauge singlet scalar

New contribution in tree level Higgs mass $\lambda v \sin 2\beta$

Two additional scalars very complicated Higgs phenomenology

large contribution for small $\tan\beta$
small loop correction from stop is sufficient for 125 GeV Higgs

Observations of more than 2 neutral Higgs bosons are required for verification

Option IV : Observed Higgs boson is not the lightest Supersymmetric Higgs boson

In MSSM 2 CP even Higgs bosons h1 and h2

Mh2 ~ 125-126 GeV and Mh1 < 125 GeV possible

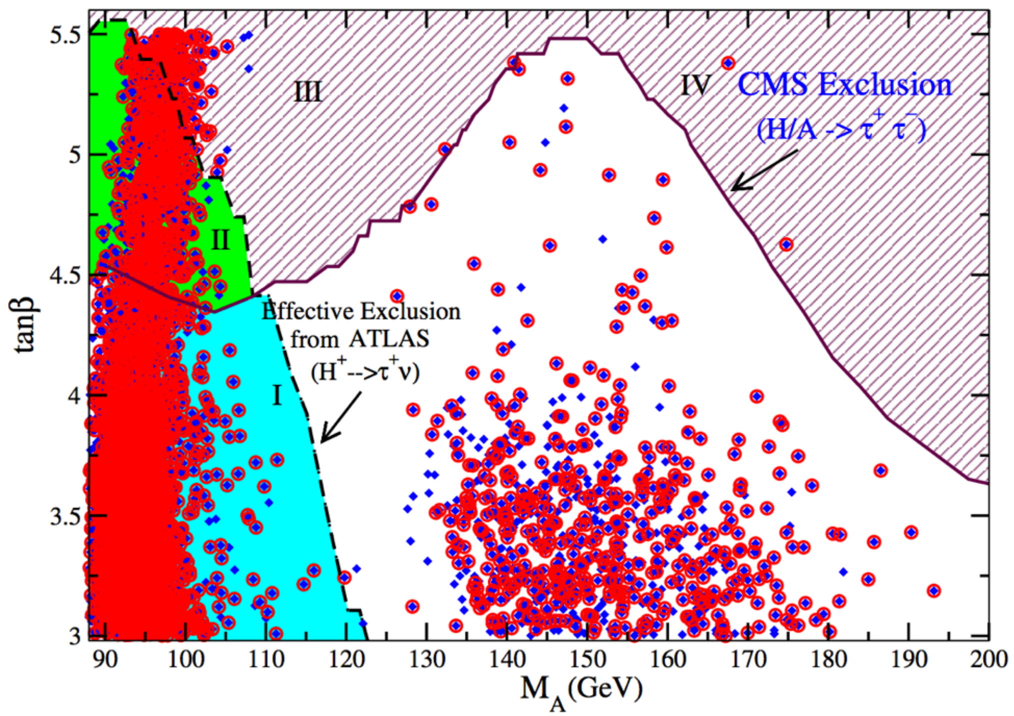
LEP experiment observed excess around 98 GeV

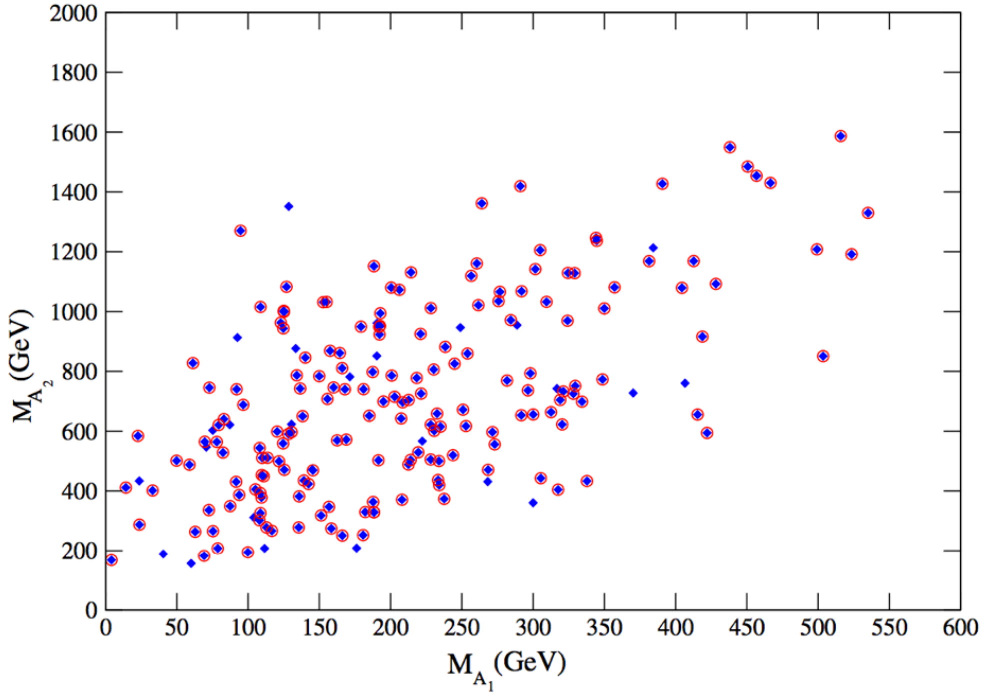
Is this h1 ??

Drees,
Asano et.al. ,
Christensen et.al.,
Ellawanger et.al.,
Djouadi.........

98 GeV Higgs MSSM vs NMSSM

This possibility is still allowed both in MSSM AND NMSSM





MSSM

NMSSM

BB, M. Chakraborti, A. Chakraborty, U. Chattopadhyay, D. Das, D. Ghosh, PRD 2013

Model independent discovery of 98 GeV Higgs is not possible at the LHC

Proposed International Linear Collider can discover lighter Higgs boson easily

Various Supersymmetric models are consistent with present Higgs data

Light SUSY particles are not disallowed by Higgs data

What is the status of supersymmetry direct search at the LHC ?

Possibilities

Low scale SUSY is not realized in nature

Low energy theory → Standard Model

SUSY particles are heavier than current limit

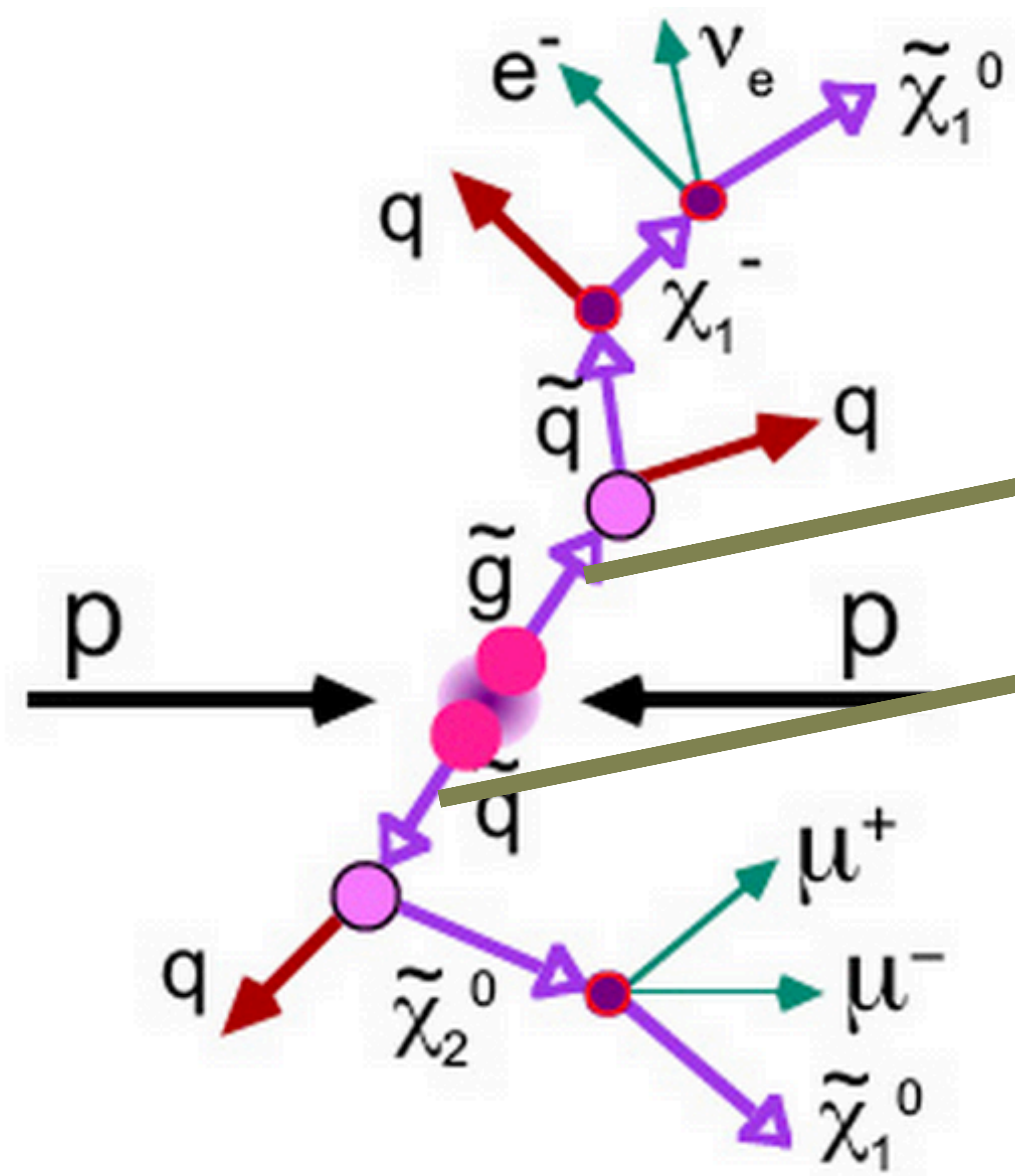
small production cross section → Observation in near future

Light SUSY particles are present and search channels are not very sensitive

large signal cs and background is also high → Observation in near future

Supersymmetry search

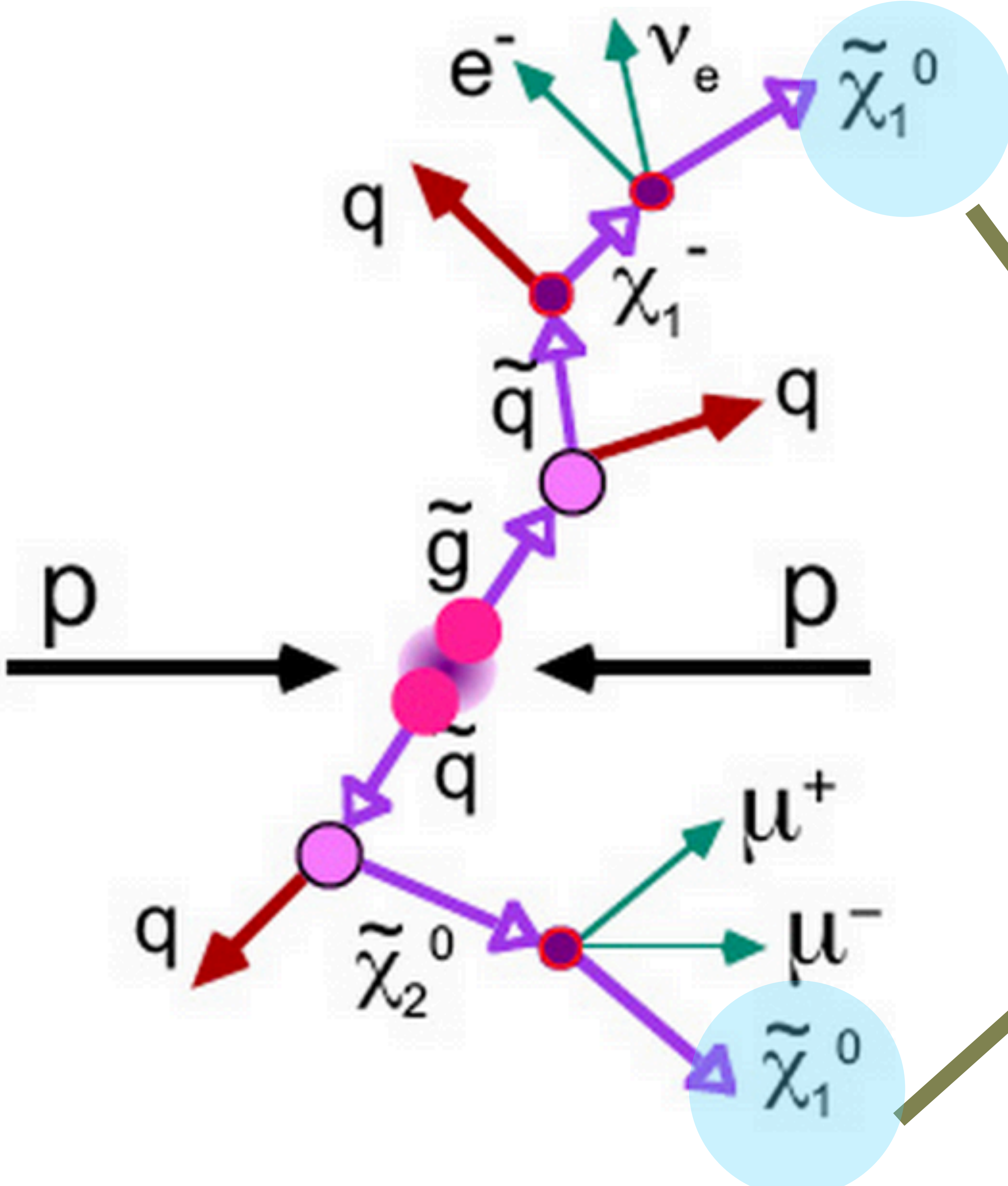
R- parity conserved



Pair production of SUSY particles

Supersymmetry search

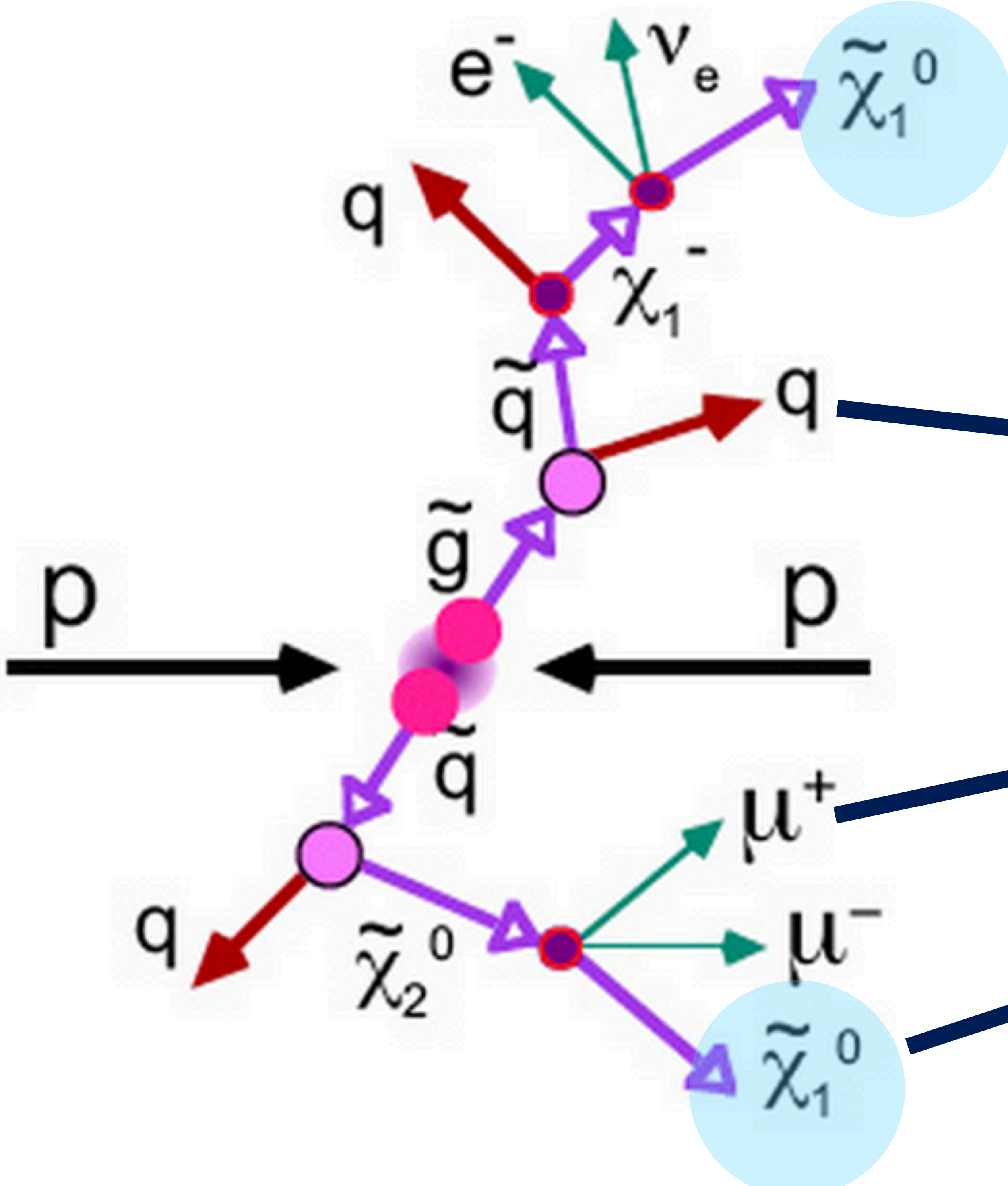
R- parity conserved



Lightest SUSY particle is stable (dark matter candidate)
Missing transverse energy

Supersymmetry search

R- parity conserved



Final state

Jets

+

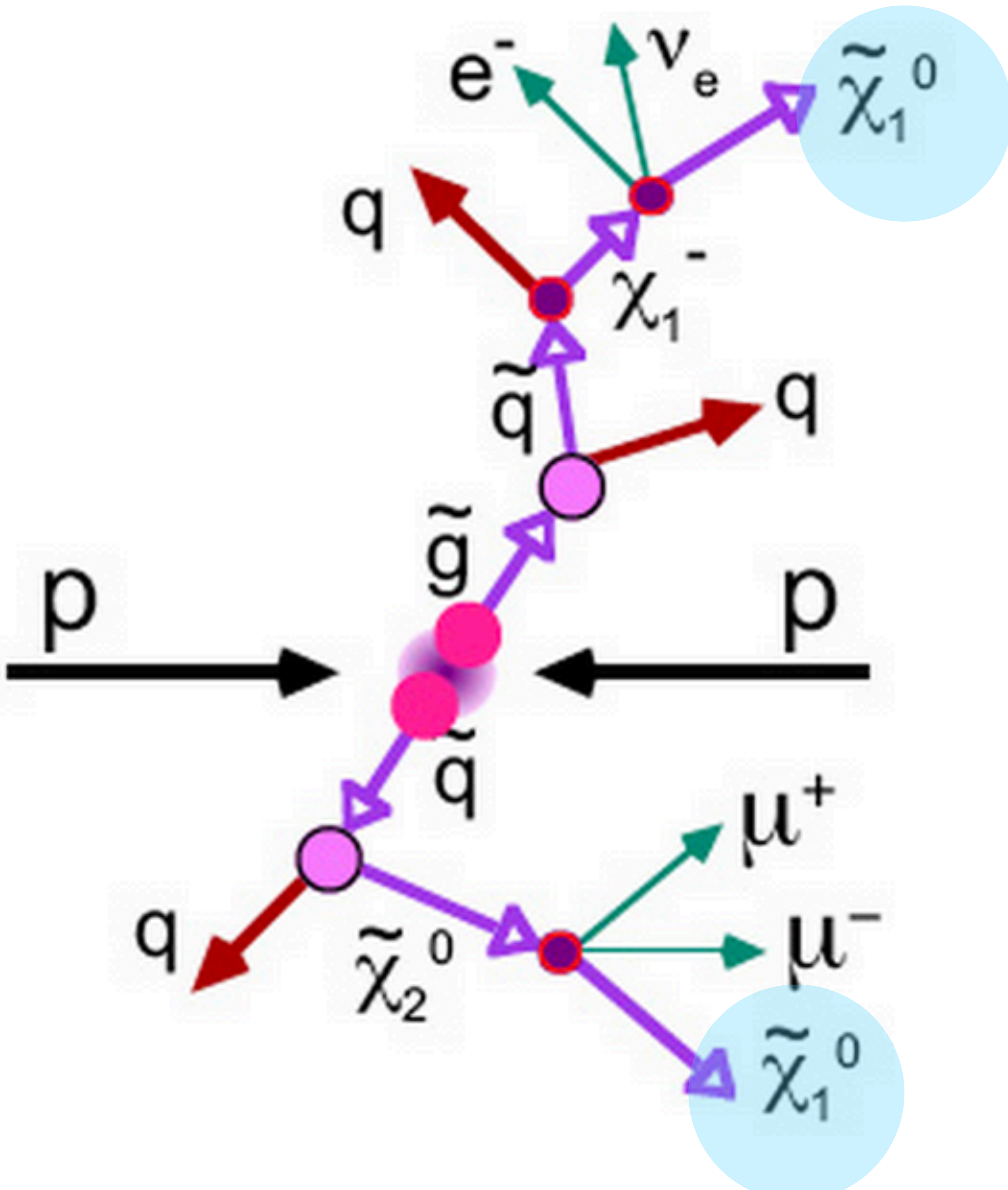
leptons

+

missing transverse energy

Supersymmetry search

R- parity conserved



A particular event

3 jets + 2 muons
+ 1 electron

Calculate missing
transverse energy

Search variables for Large Hadron Collider (LHC)

Missing transverse momentum(MET)

$$\not{p}_T = \sqrt{(-p_x)^2 + (-p_y)^2}$$

p_x, p_y → x and y component of visible momentum

Expectation :

SM: neutrino is the only source of missing energy

SUSY: Massive invisible particle → High $\not{p}_T$

Effective mass (MEFF):

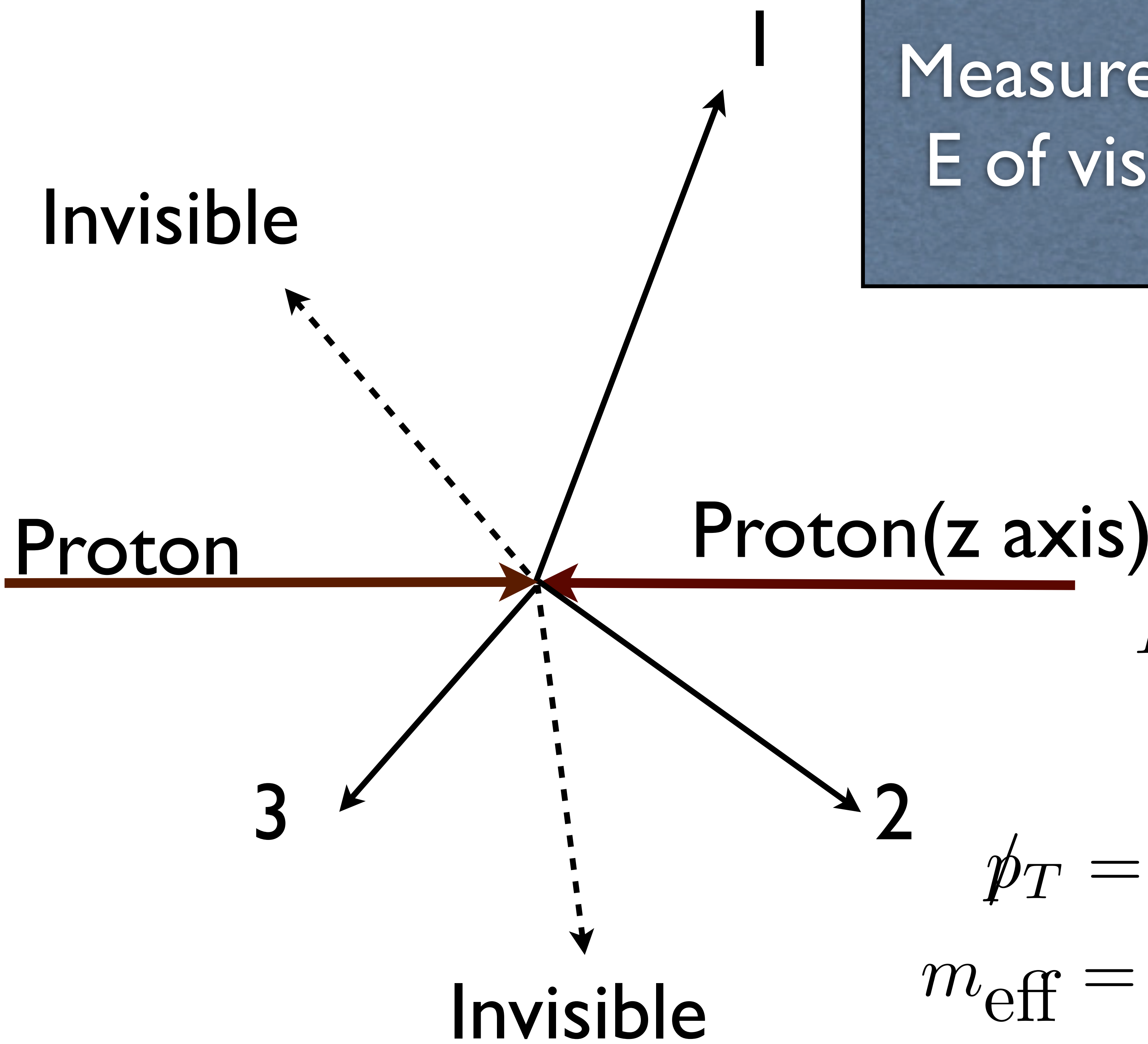
$$m_{\text{eff}} = \not{p}_T + \sum_{jets} p_T + \sum_{leptons} p_T$$

Expectation : It reflects the mass scale of the event

SUSY particles are much heavier than SM

SUSY Effective Mass distribution is much harder than SM

MET and MEFF



Measurement of p_x,p_y,p_z, E of visible particle possible

$$P_X = p_{x_1} + p_{x_2} + p_{x_3}$$

$$P_Y = p_{y_1} + p_{y_2} + p_{y_3}$$

$$\not{p}_T = \sqrt{(-P_X)^2 + (-P_Y)^2}$$

$$m_{\text{eff}} = \not{p}_T + p_{T_1} + p_{T_2} + p_{T_3}$$

$$p_T = \sqrt{p_x^2 + p_y^2}$$

SUSY Searches (CMS and ATLAS)

SUSY Search heavily depends on m_{eff} and $\not{p}_T$

CMSSM , 8 TeV LHC $m_{\tilde{g}} = m_{\tilde{q}} = 1.7\ \text{TeV}$ **ATLAS-CONF-2013-047**

looks very strong

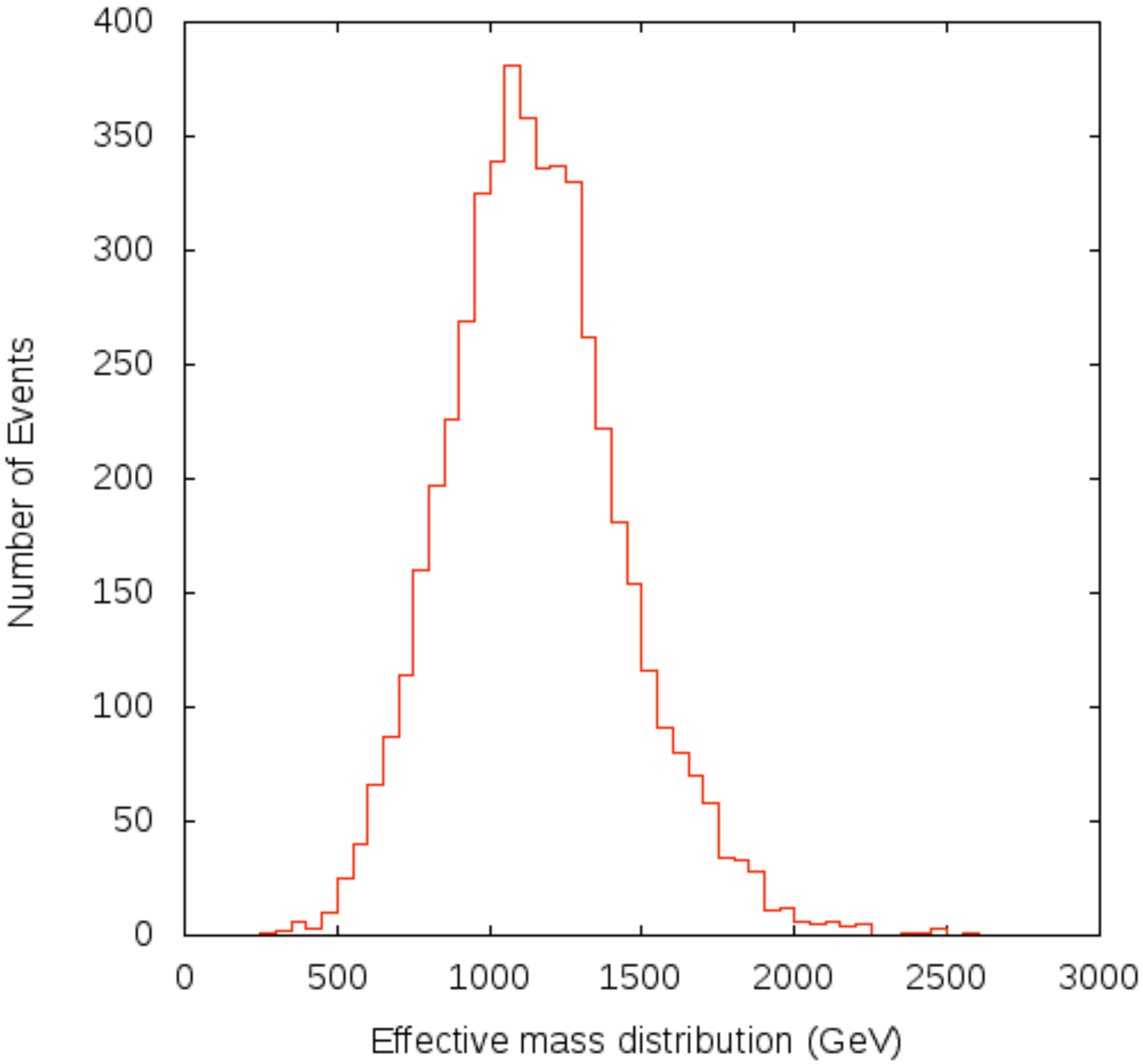
Is low scale SUSY ruled out ?

Understand the assumptions behind this bound

Assumption I: R parity conservation (missing energy)

Assumption II: a particular mass hierarchy (wide mass gap between squark gluino and lightest neutralino)

Effective Mass (Parton level)

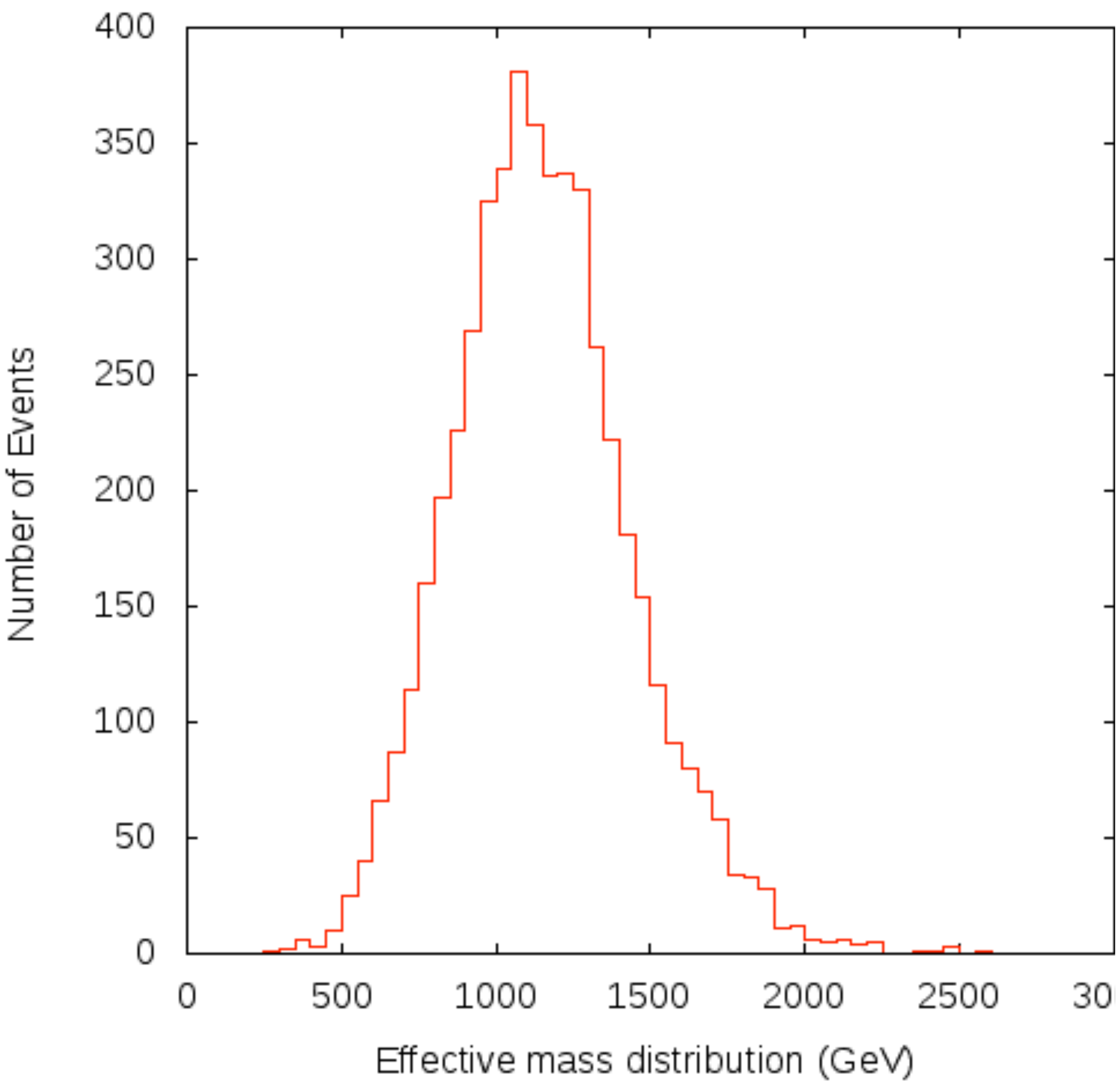


$M_{\tilde{g}} = 1 \text{ TeV} \quad M_{\tilde{\chi}_1^0} = 100 \text{ GeV}$

gluino pair production
and
gluino decay to lightest neutralino

High effective mass for signal
Effective mass peaks at low value for background
(Separation of signal and background very easy)

Effective Mass (Parton level)



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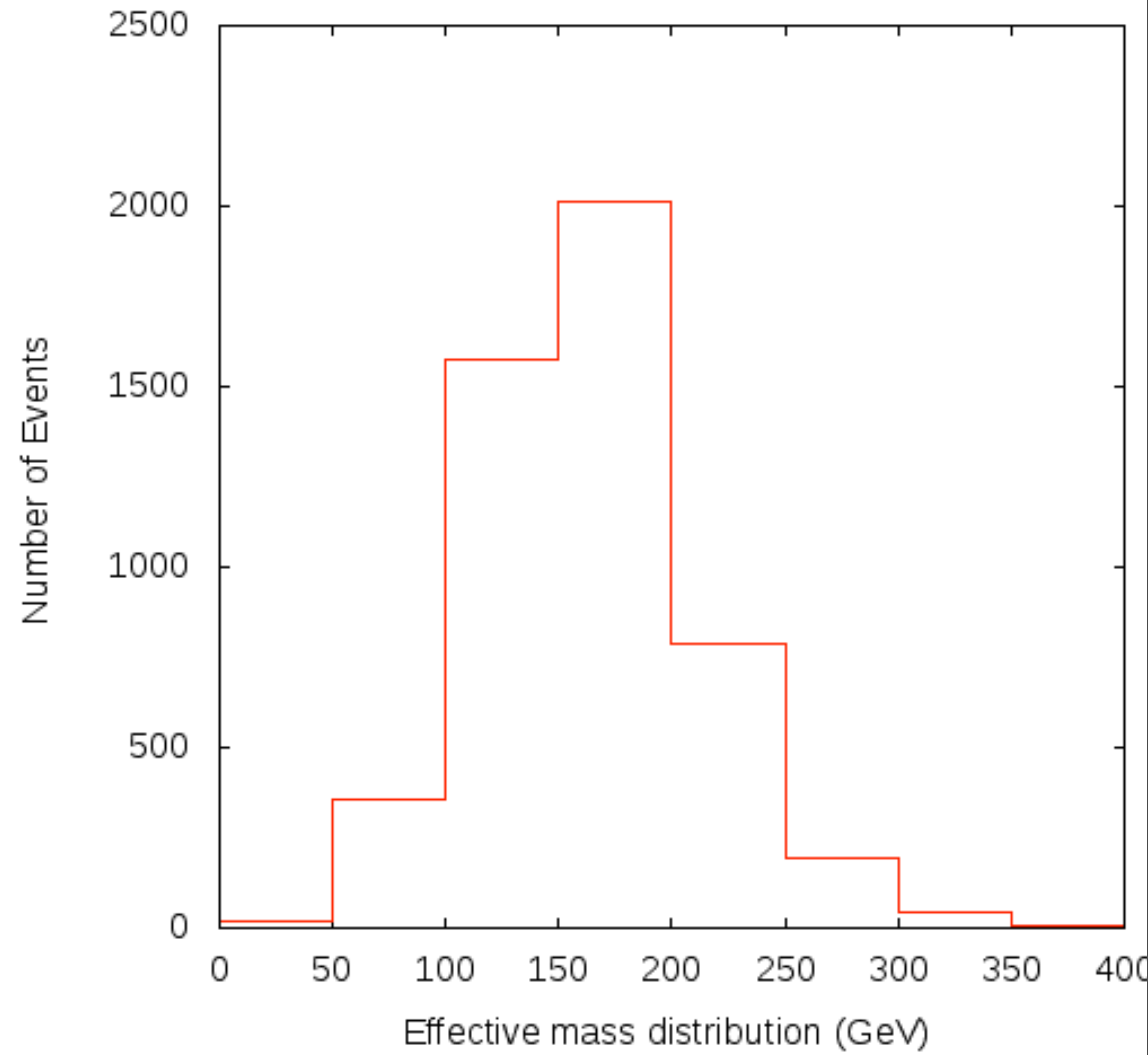
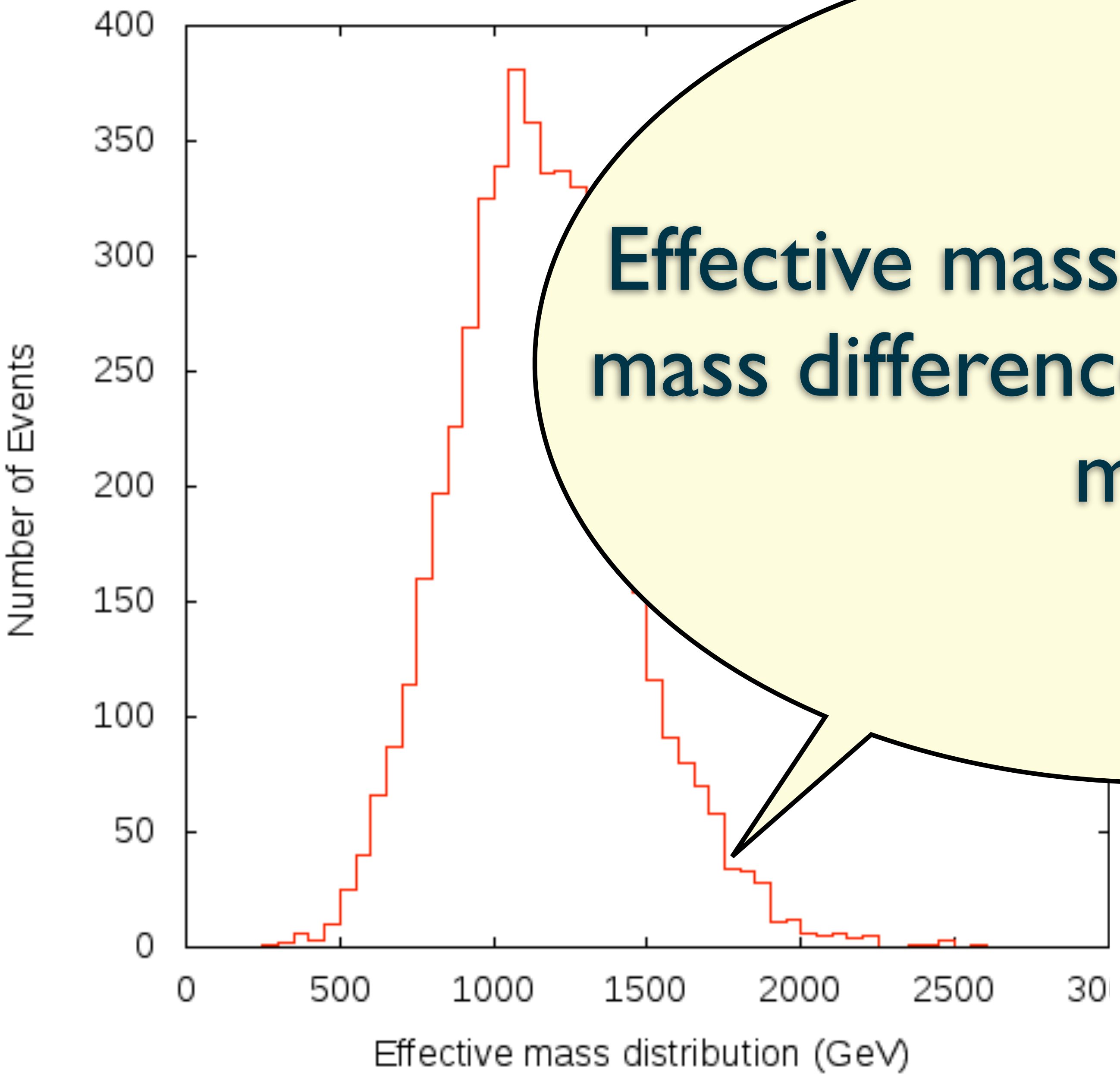
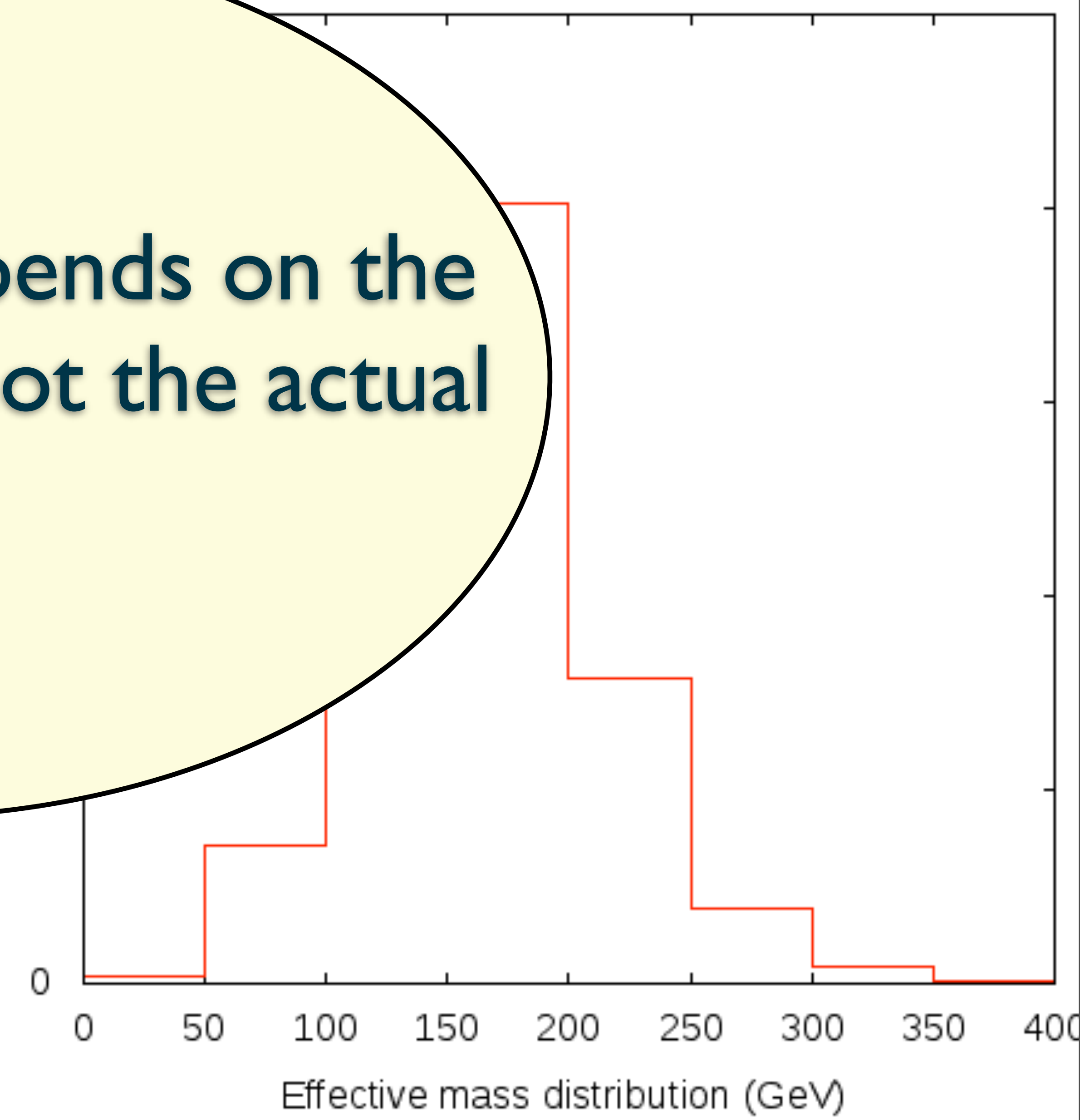


$$M_{\tilde{g}} = 1 \text{ TeV} \quad M_{\tilde{\chi}_1^0} = 900 \text{ GeV}$$

Effective Mass (Parton level)



Effective mass depends on the mass difference , not the actual mass



$M_{\tilde{g}} = 1\ \text{TeV} \quad M_{\tilde{\chi}^0} = 100\ \text{GeV}$

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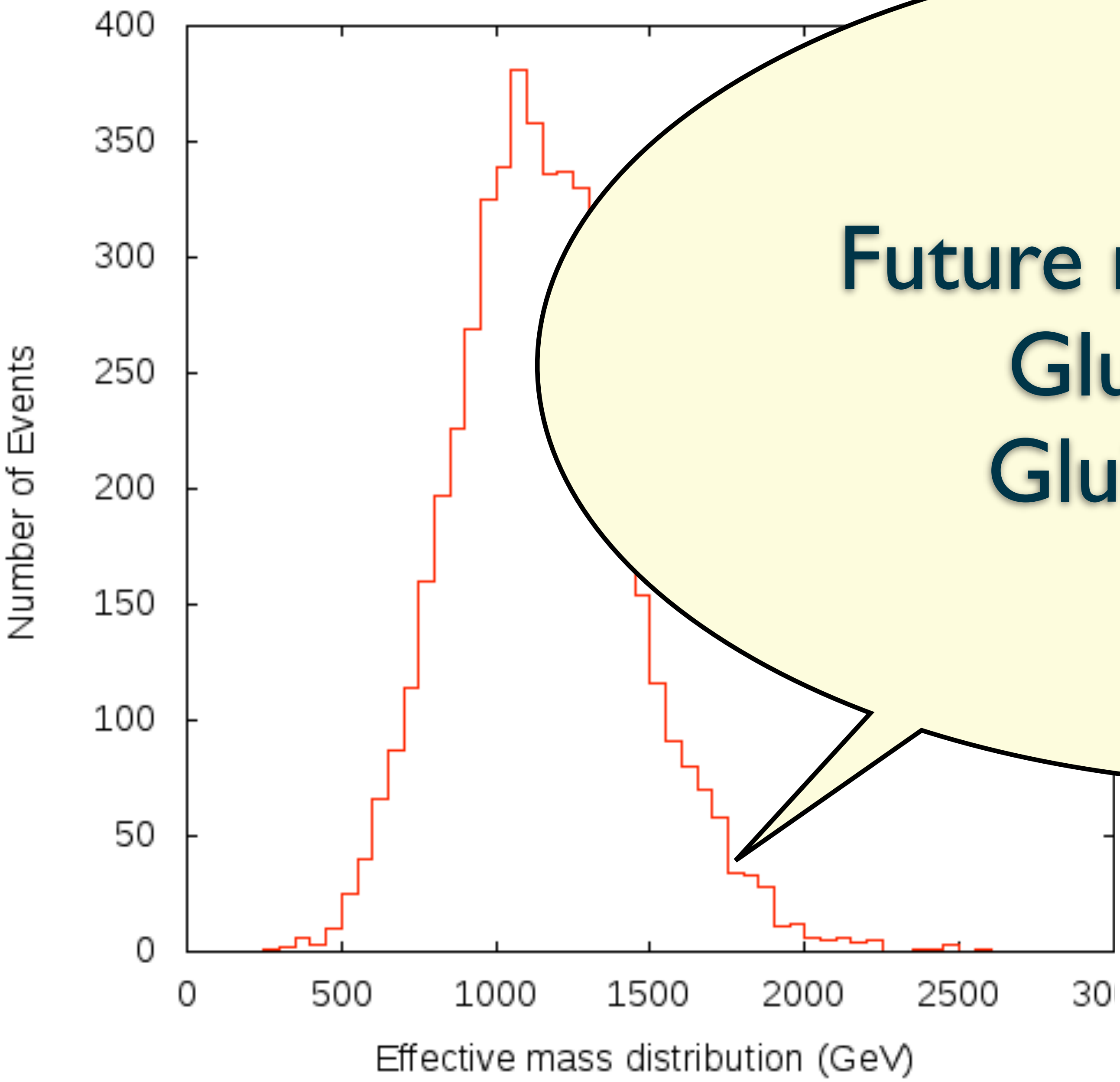
For compressed Supersymmetry the bound is drastically reduced compared to normal case

Effective Mass (Parton level)



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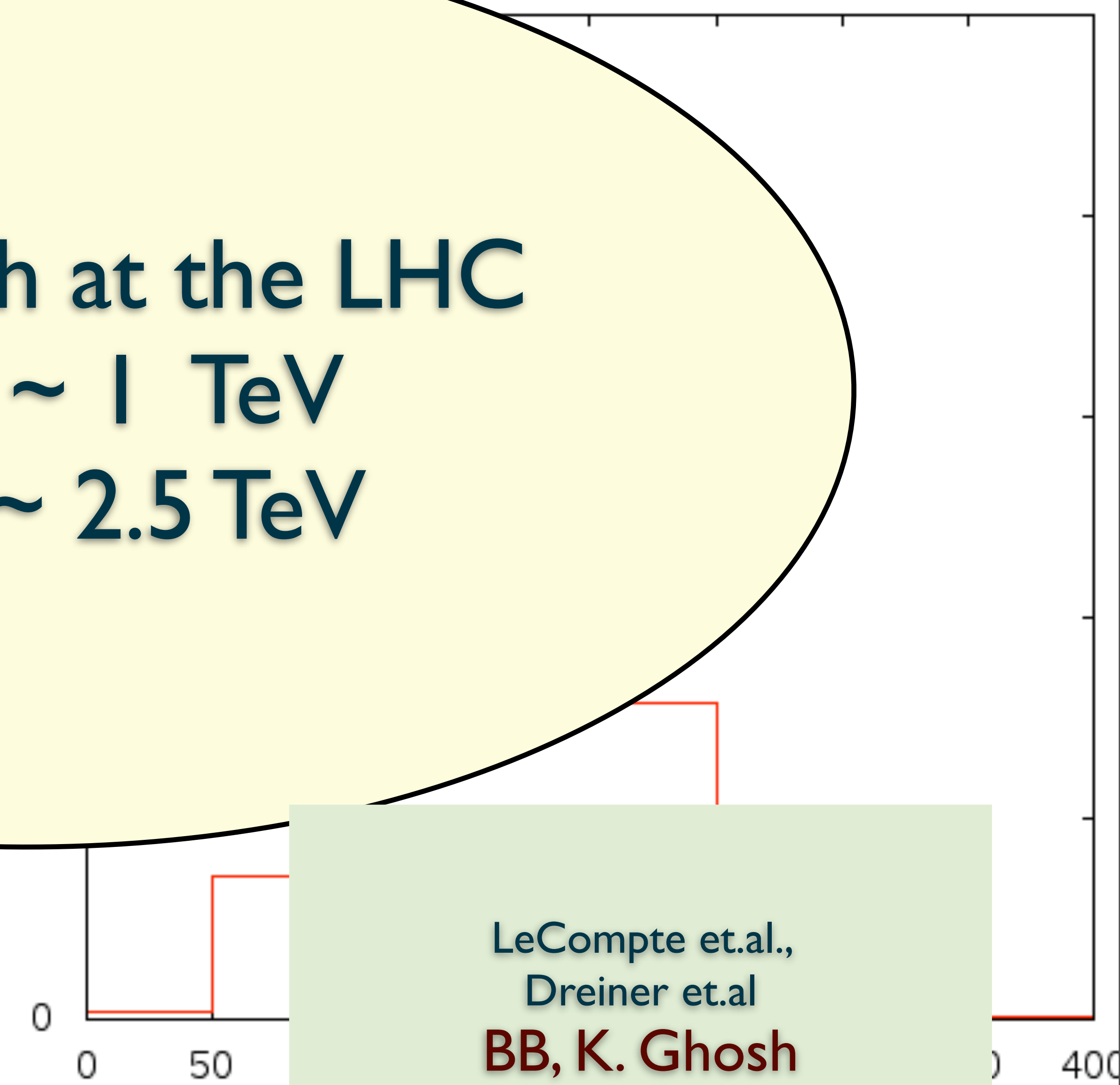


$M_{\tilde{g}} =$

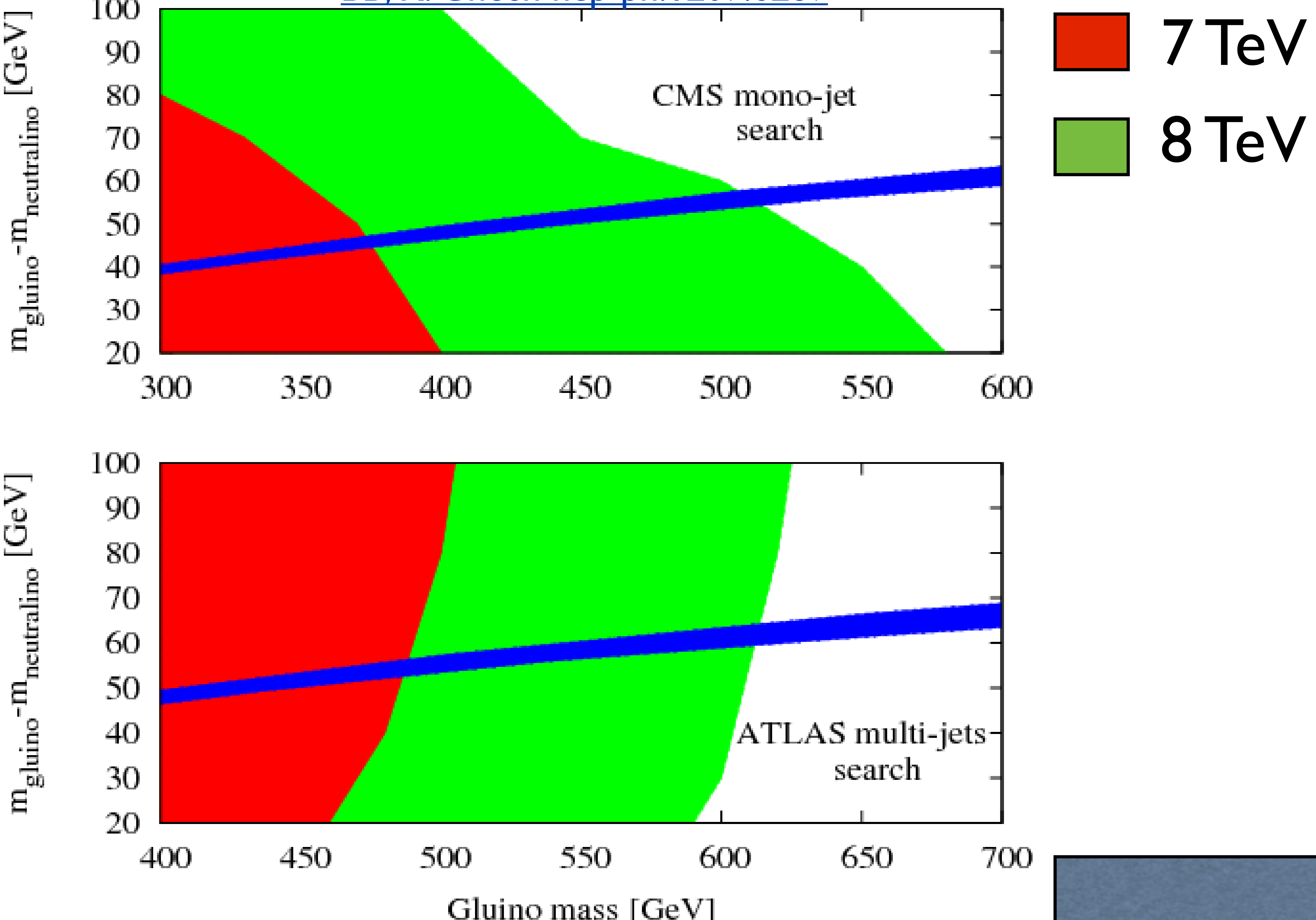
Future reach at the LHC
Gluino ~ 1 TeV
Gluino ~ 2.5 TeV

LeCompte et.al.,
Dreiner et.al
BB, K. Ghosh
BB, Chaudhuri, Ghosh, Poddar

For compressed Supersymmetry the bound is drastically reduced compared to normal case

7/8 TeV results

BB, K. Ghosh hep-ph:1207.6289



7/8 TeV bound on gluino ~ 500-600 GeV

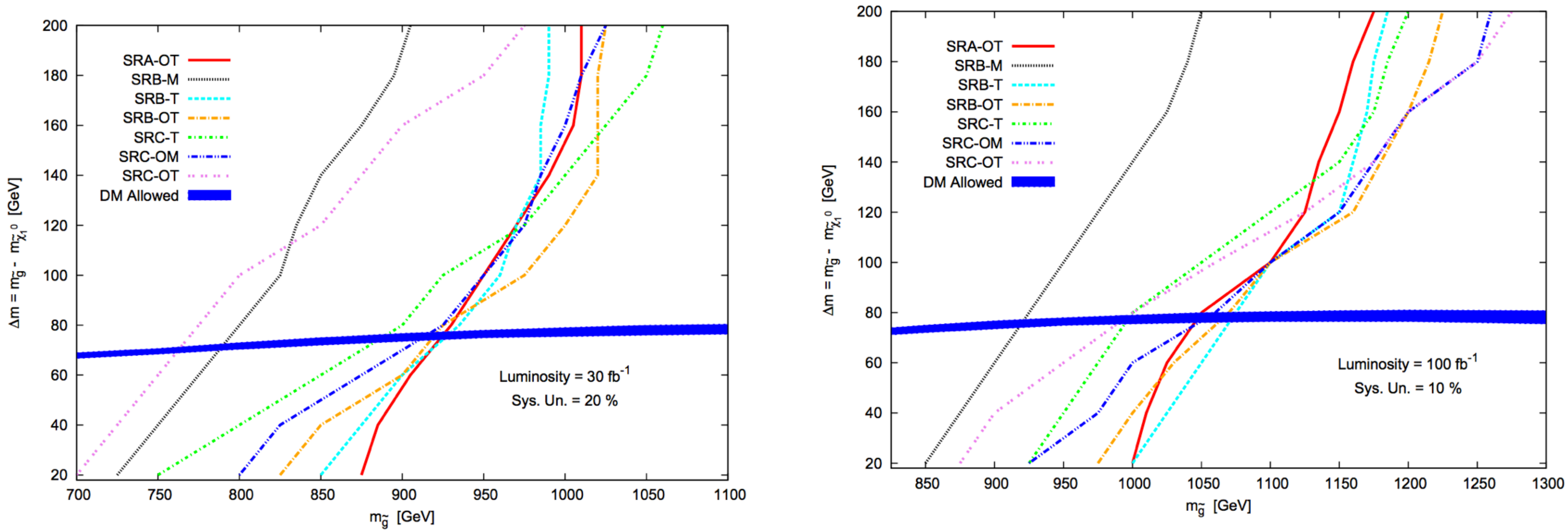
LeCompte et.al.,
Dreiner et.al
BB, K. Ghosh

14 TeV Cut flow

Cuts	Channel						
	SRA-OT (2j)	SRB-M (3j)	SRB-T (3j)	SRB-OT (3j)	SRC-T (4j)	SRC-OM (4j)	SRC-OT (6j)
$\not{E}_T$ [GeV] >	200	160	160	200	160	200	200
$P_T(j_1)$ [GeV] >	200	130	130	150	130	150	150
$P_T(j_2)$ [GeV] >	100	60	60	80	60	80	80
$P_T(j_3)$ [GeV] >	-	60	60	80	60	80	80
$P_T(j_4)$ [GeV] >	-	-	-	-	60	80	80
$\delta\phi(jet_i, \not{E}_T)_{min}$	0.4 (i=1,2)**	0.4 (i=1,2,3)	0.4 (i=1,2,3)	0.4 (i=1,2,3)	$0.4(i=[1,2,3])$ 0.2(P_T >40 GeV jets)		
$\not{E}_T/\ M_{eff}(N_j)$>	0.4	0.3	0.4	0.4	0.25	0.4	0.3
M_{eff}(incl.)[GeV] >	2400	1800	2200	2400	2200	2200	2400
$Z + jets$[fb]	4.0	18.4	3.9	1.8	2.8	0.66	0.9
$W + jets$[fb]	1.15	8.6	1.2	0.6	1.2	0.15	0.4
$t\bar{t} + jets$ [fb]	0.25	4.3	0.3	0.1	0.4	0.12	0.2
Total SM background[fb]	5.4	31.3	5.4	2.5	4.4	0.93	1.5
Upper limit on N_{BSM} at 95% CL Sys. Un.=20 %, $\mathcal{L}$=30fb^{-1}	59	381	68	35	57	17	23
Upper limit on N_{BSM} at 95% CL Sys. Un.=10 %, $\mathcal{L}$=100fb^{-1}	116	636	116	59	97	27	39

BB, Chaudhury, Ghosh, Poddar hep-ph: 1308:1526

LHC reach



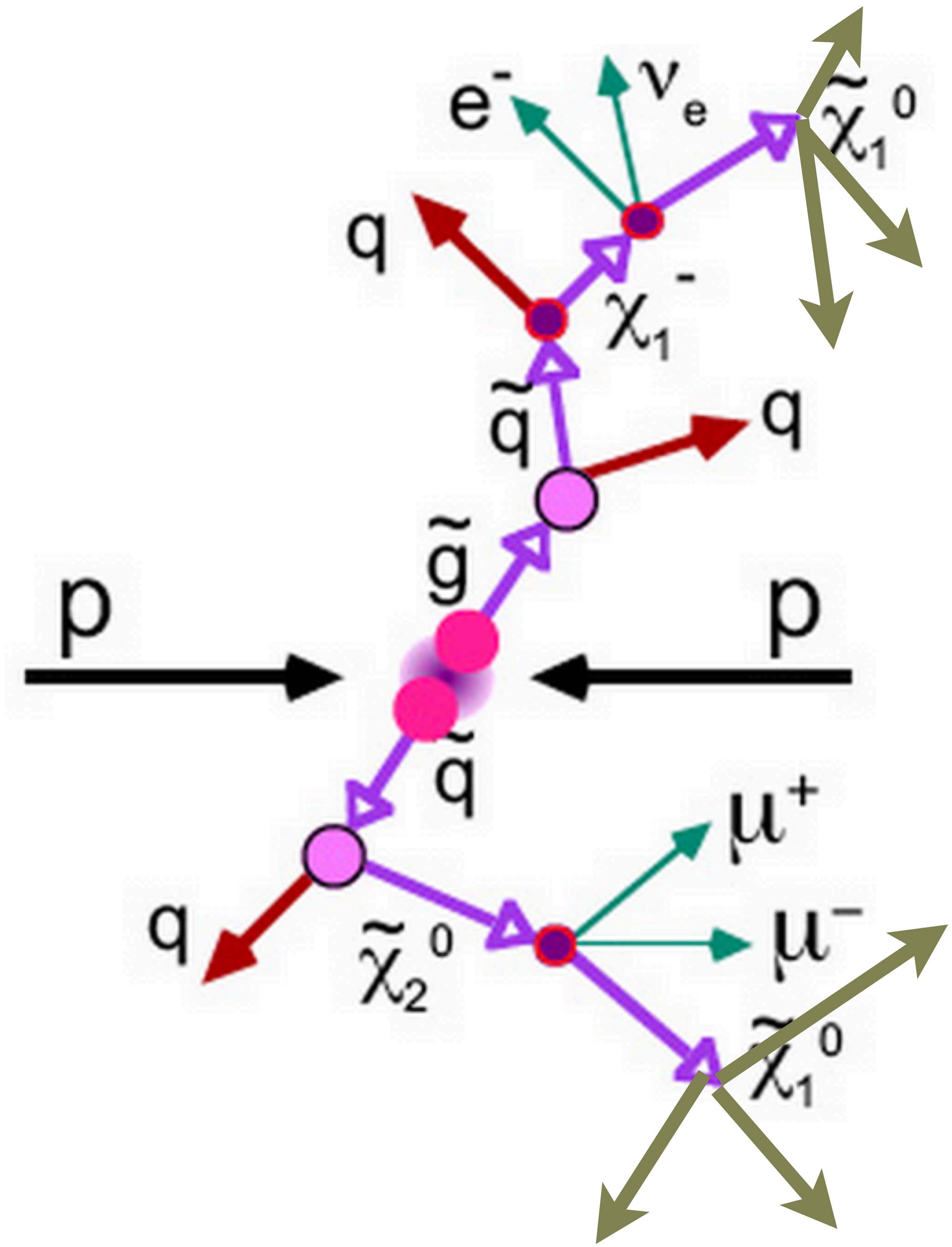
[BB, Chaudhury, Ghosh, Poddar hep-ph: 1308:1526](#)

Gluino mass
discovery limit ~ 725 GeV
Exclusion ~ 1.2 TeV

SUSY search

Two broad categories

R- parity violated

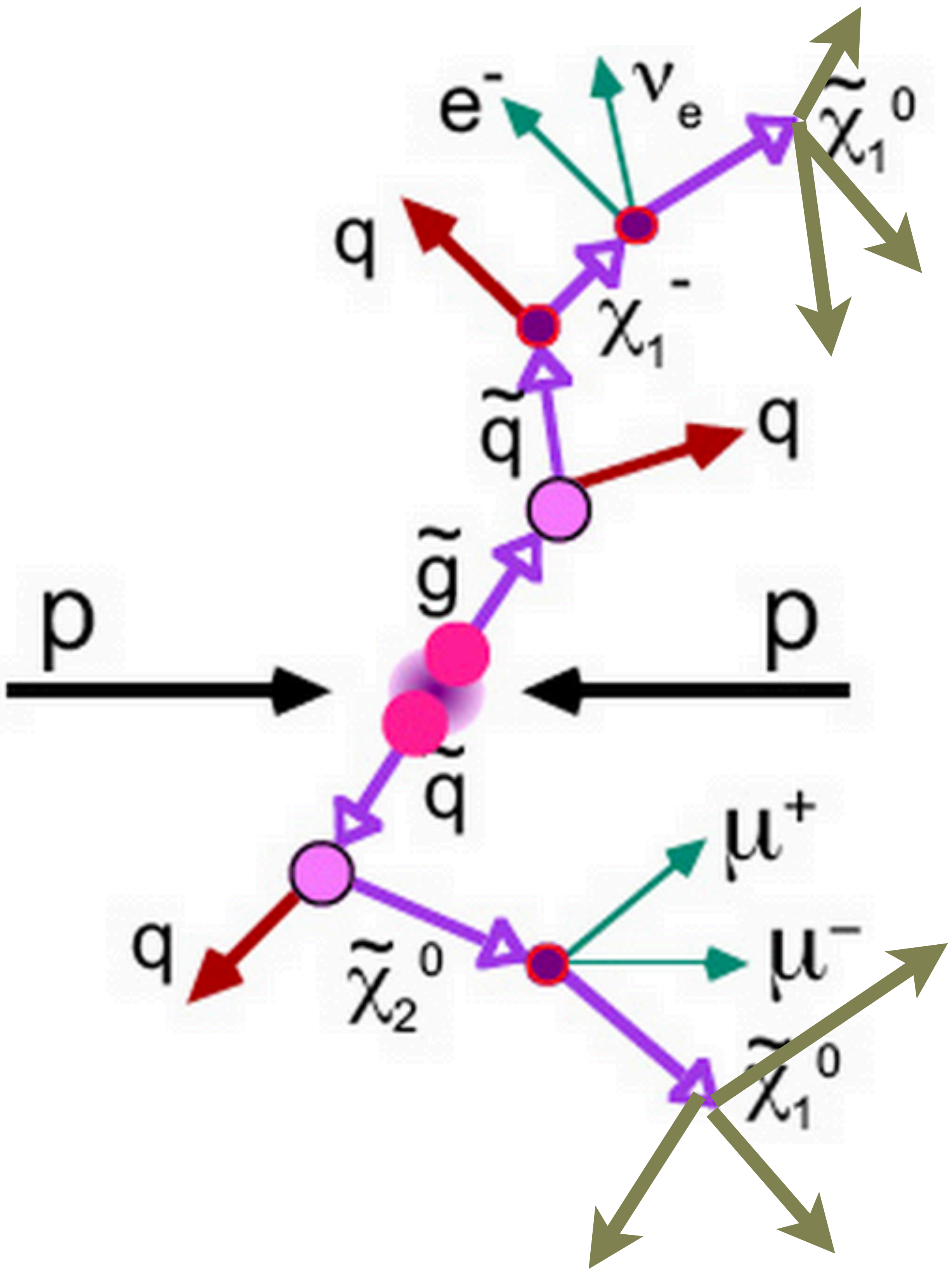


A typical SUSY event

SUSY search

Two broad categories

R- parity violated



Lightest SUSY particle is not stable

Small or no missing transverse energy

Relatively higher particle multiplicity

SUSY search

Two broad categories

R- parity violated

1. hard jets / leptons and particle multiplicity can be used for exclusion/discovery

2. Bound is comparable to the R-parity conserving case if leptons are present in the decay

3. If the decay mode does not contain leptons, bound may be weaker

LHC current bounds indicate that the new particles will possibly be heavy

Assumption: New particles will be produced at the 14 TeV LHC

The decay of new heavy particle to SM particles may give large Lorentz boost

Top quark production

$t \to bW$ ~ 100 % decay

$W \to \text{lepton}(e/\mu/\tau) + \text{neutrino}$

~33%

$W \to \text{quark} + \text{quark}$

~67%

Top quark production

$t \to bW$ ~ 100 % decay

$W \to \text{lepton}(e/\mu/\tau) + \text{neutrino}$ ~33%

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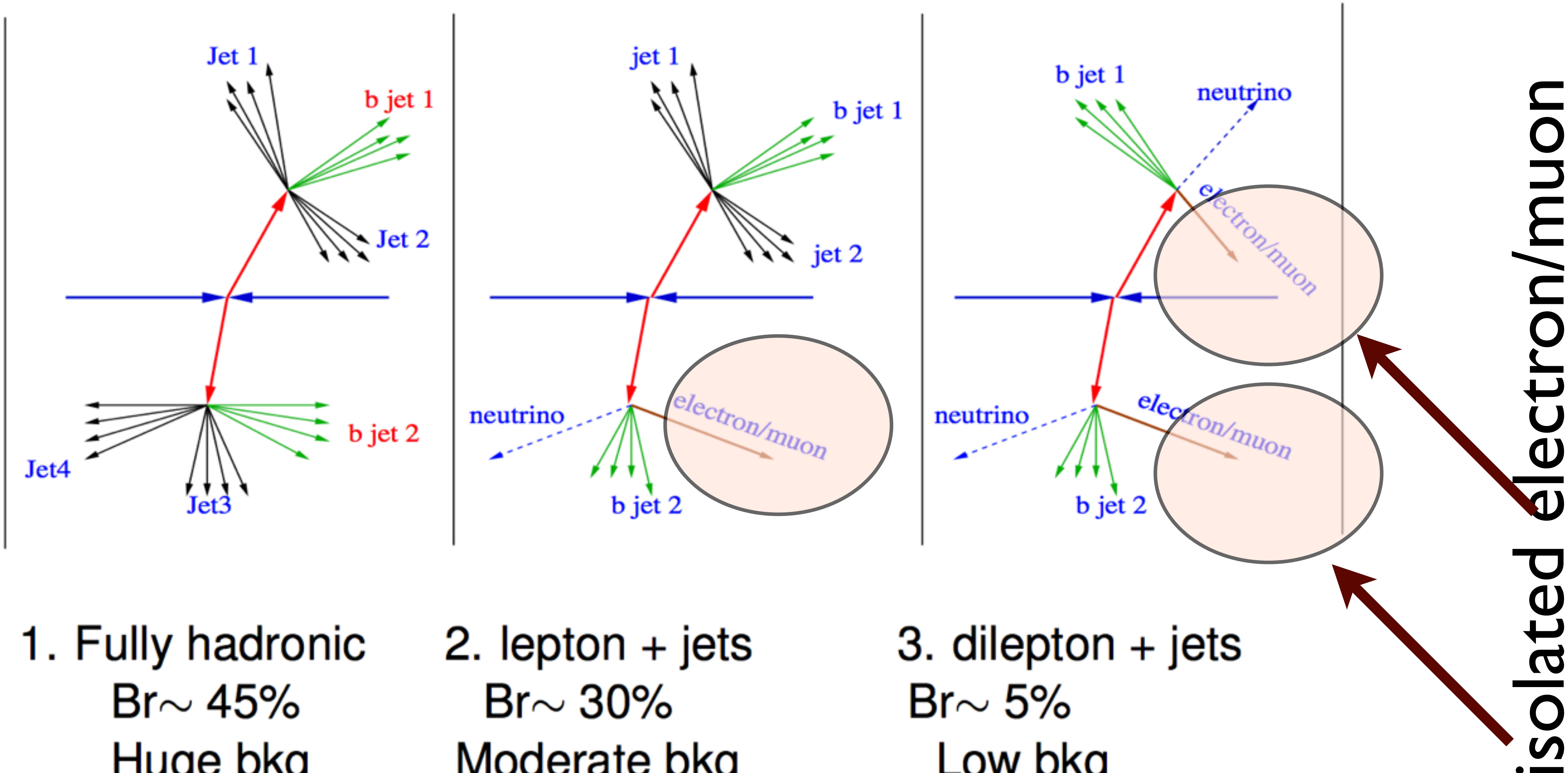
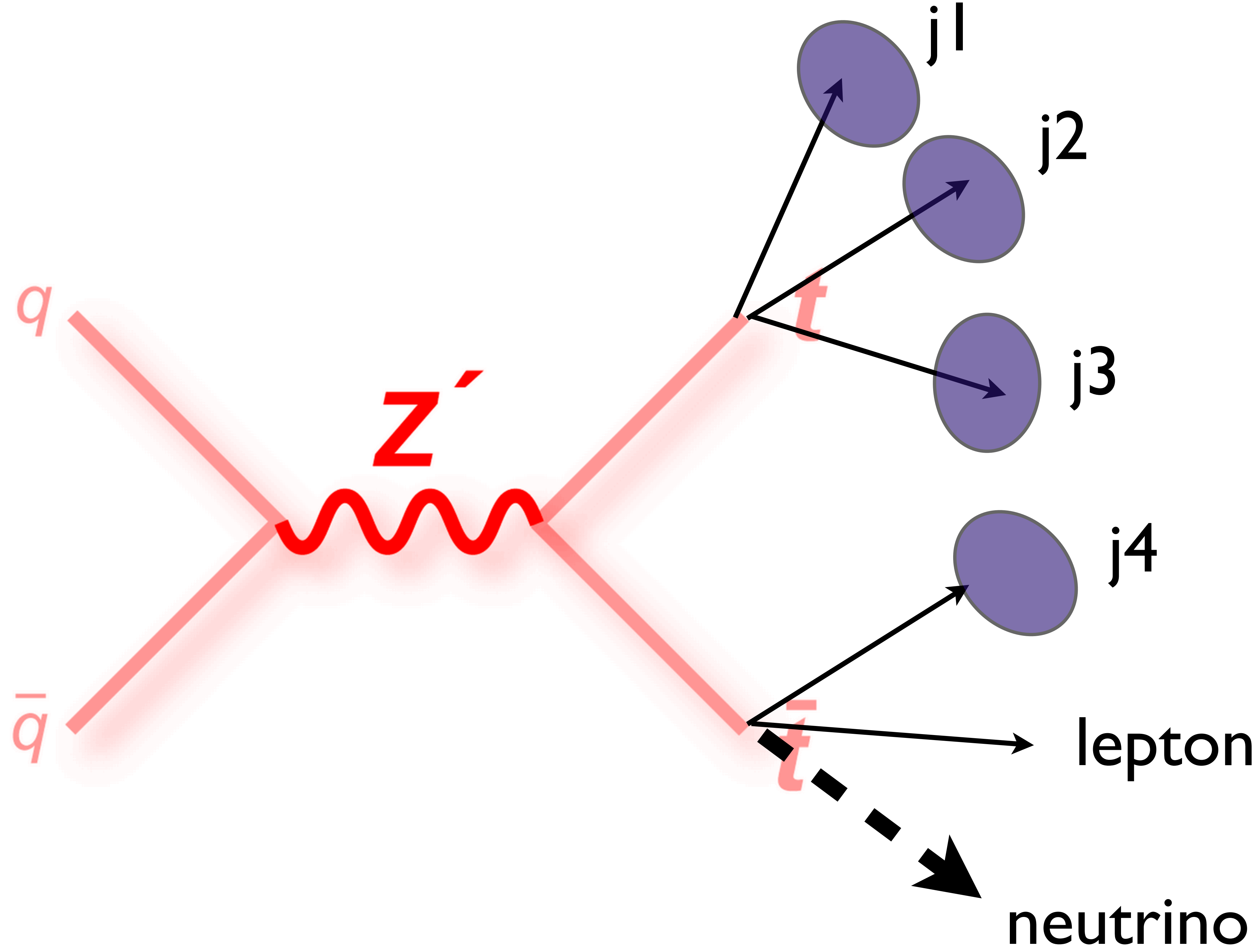


1. Fully hadronic
   Br~ 45%
   Huge bkg
2. lepton + jets
   Br~ 30%
   Moderate bkg
3. dilepton + jets
   Br~ 5%
   Low bkg

Compromise between statistics and background

lepton+jets channel $\Longleftrightarrow$ Golden channel for analysis

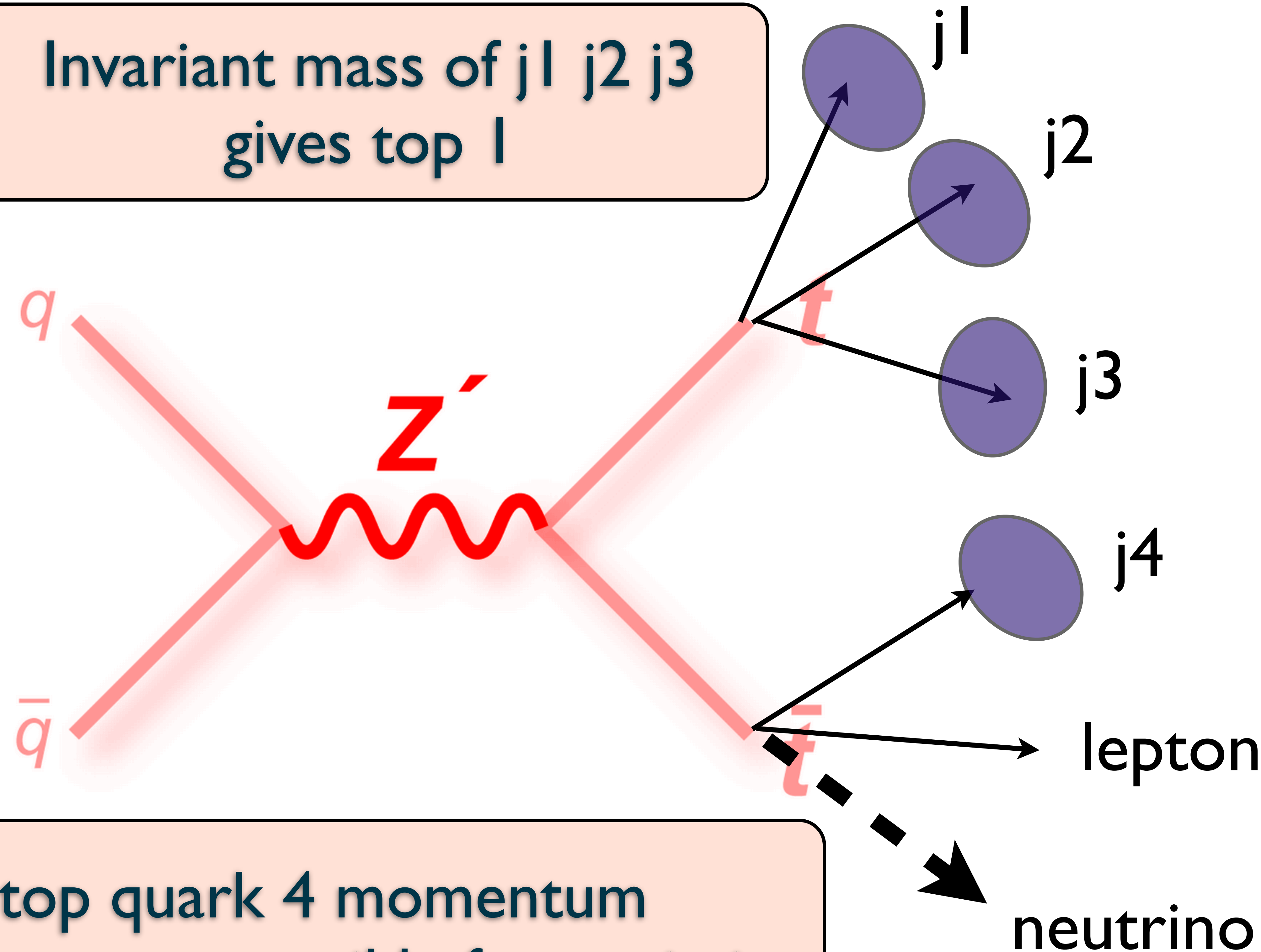
Technical Difficulty : Example : I



Technical Difficulty : Example : 1

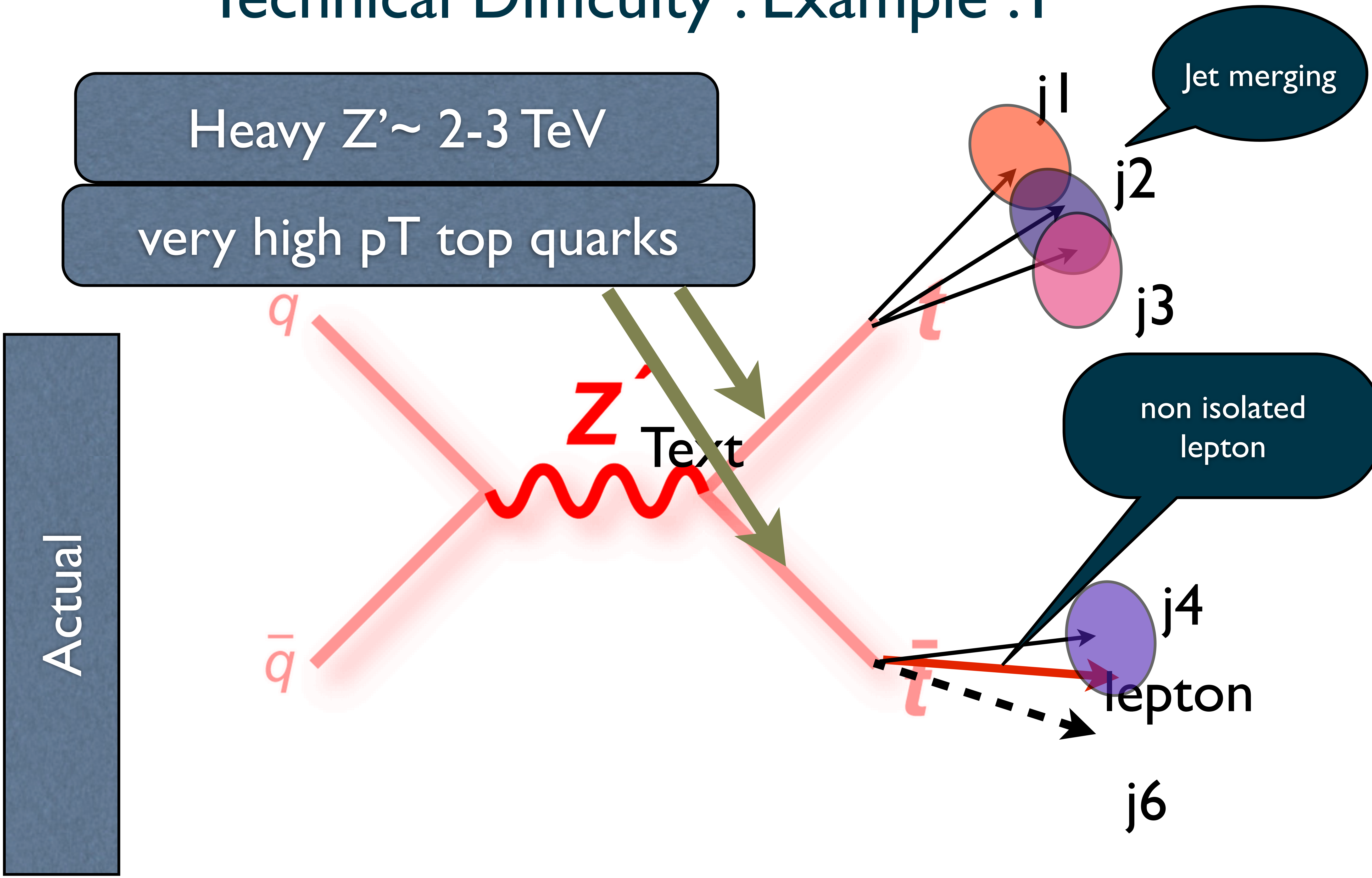
Expectation

Invariant mass of j1 j2 j3 gives top 1



top quark 4 momentum measurement possible from missing transverse energy, lepton and jet

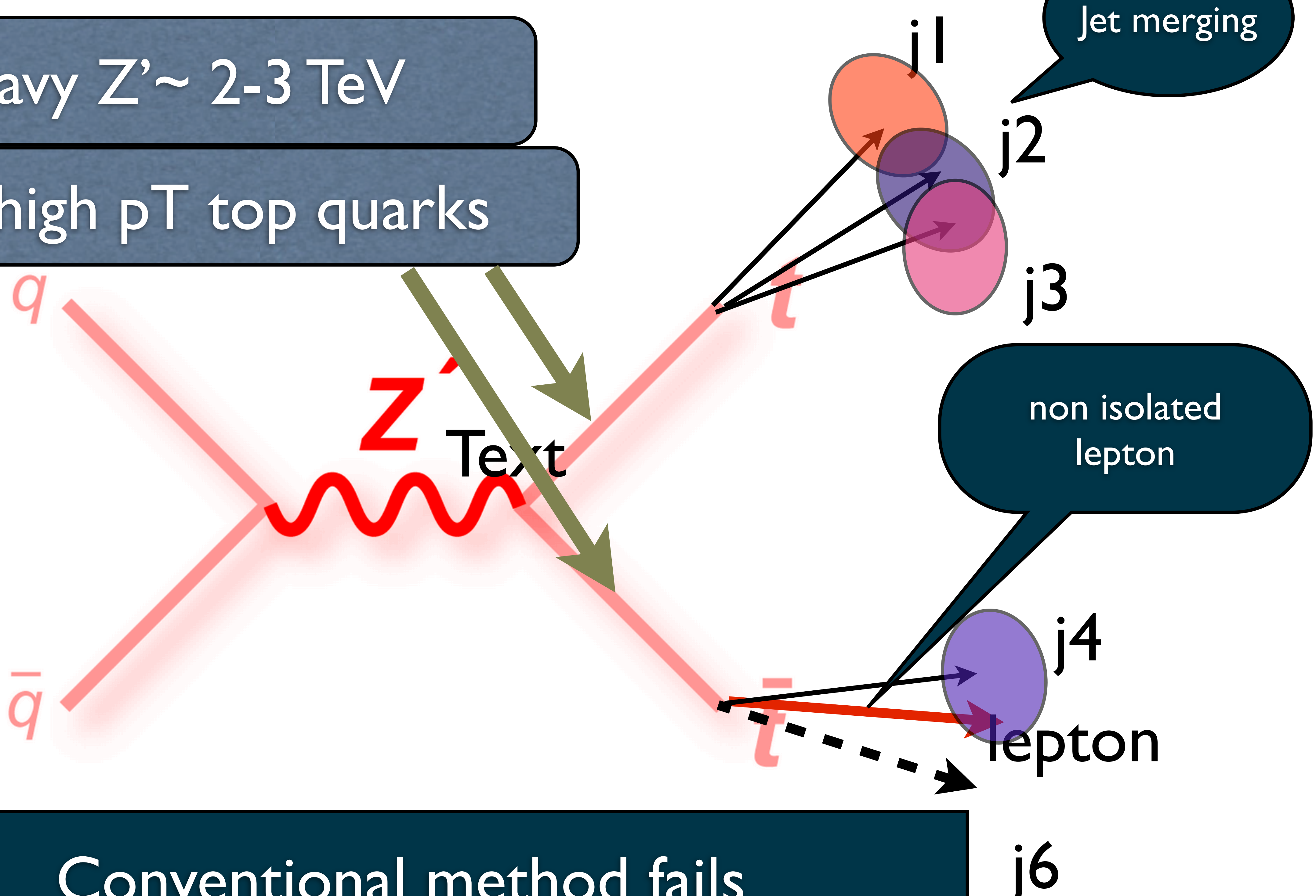
Technical Difficulty : Example : I



Technical Difficulty : Example : I

Heavy Z'~ 2-3 TeV

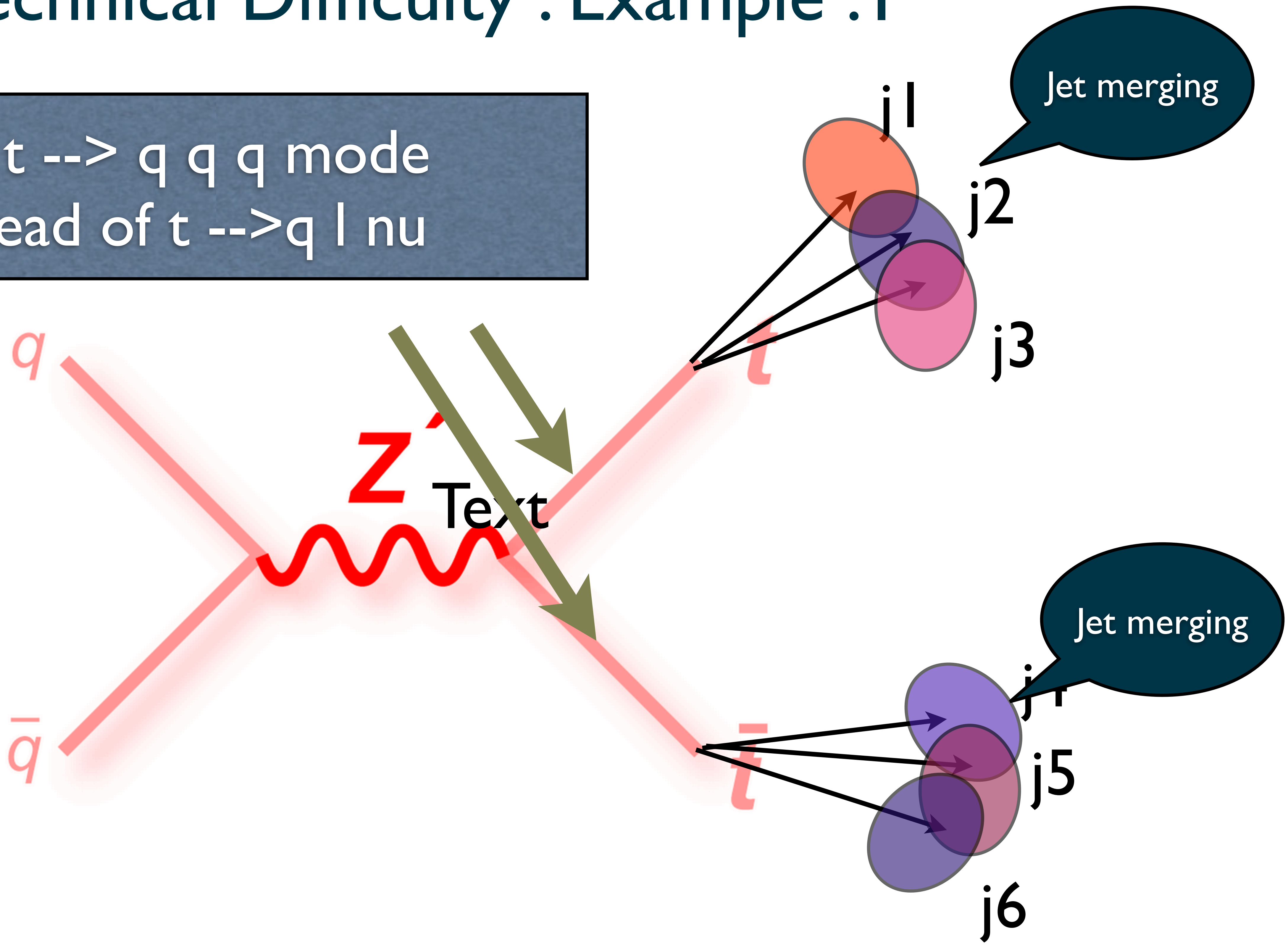
very high pT top quarks



Conventional method fails

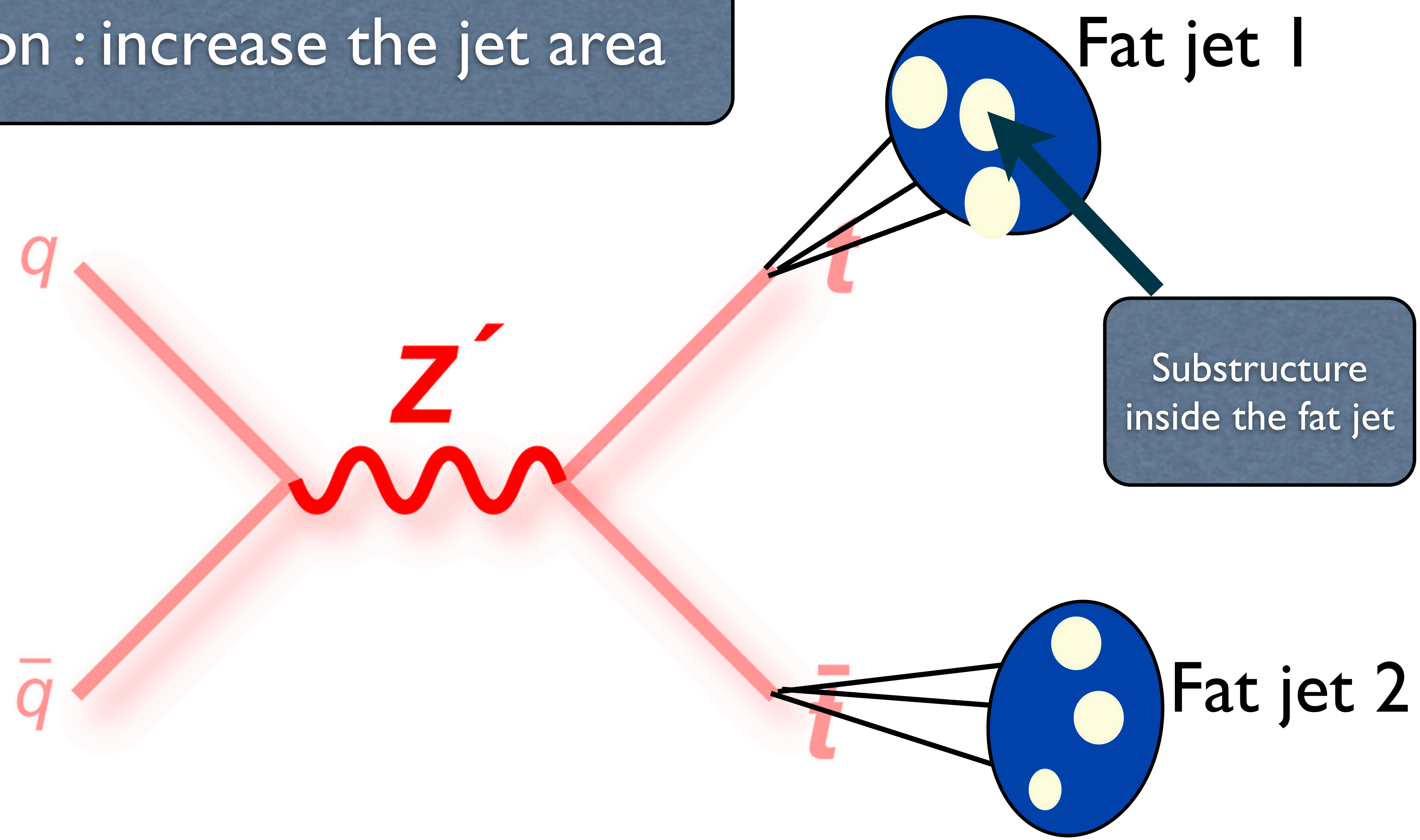
Technical Difficulty : Example : I

use t --> q q q mode
instead of t -->q l nu



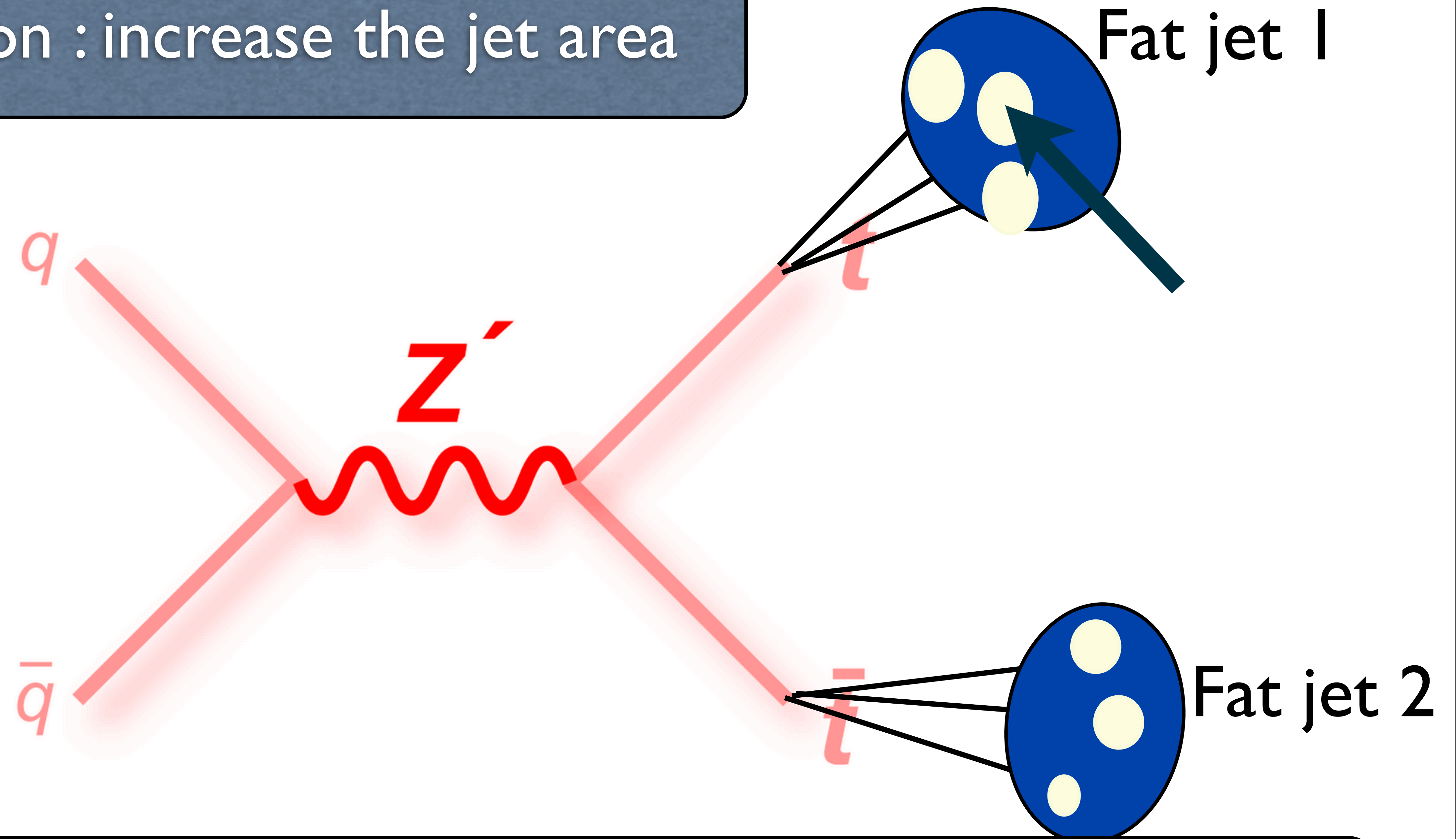
Technical Difficulty : Example : I

Solution : increase the jet area



Technical Difficulty : Example : I

Solution : increase the jet area

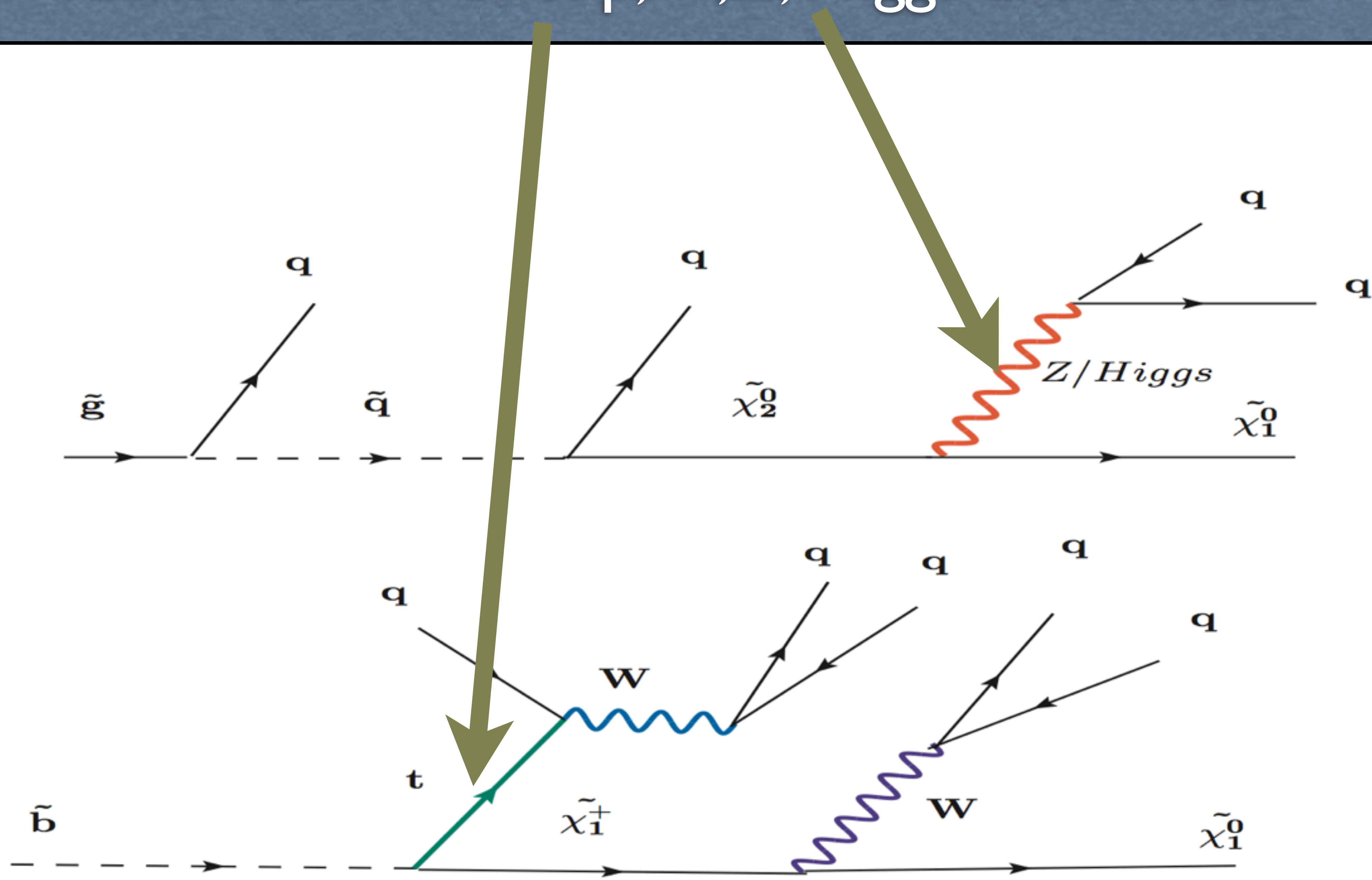


In reality, there are many technical challenges... multiple interaction, pile up, QCD mistagging...

One of the most active field of research in collider physics

Technical Difficulty : Example :2

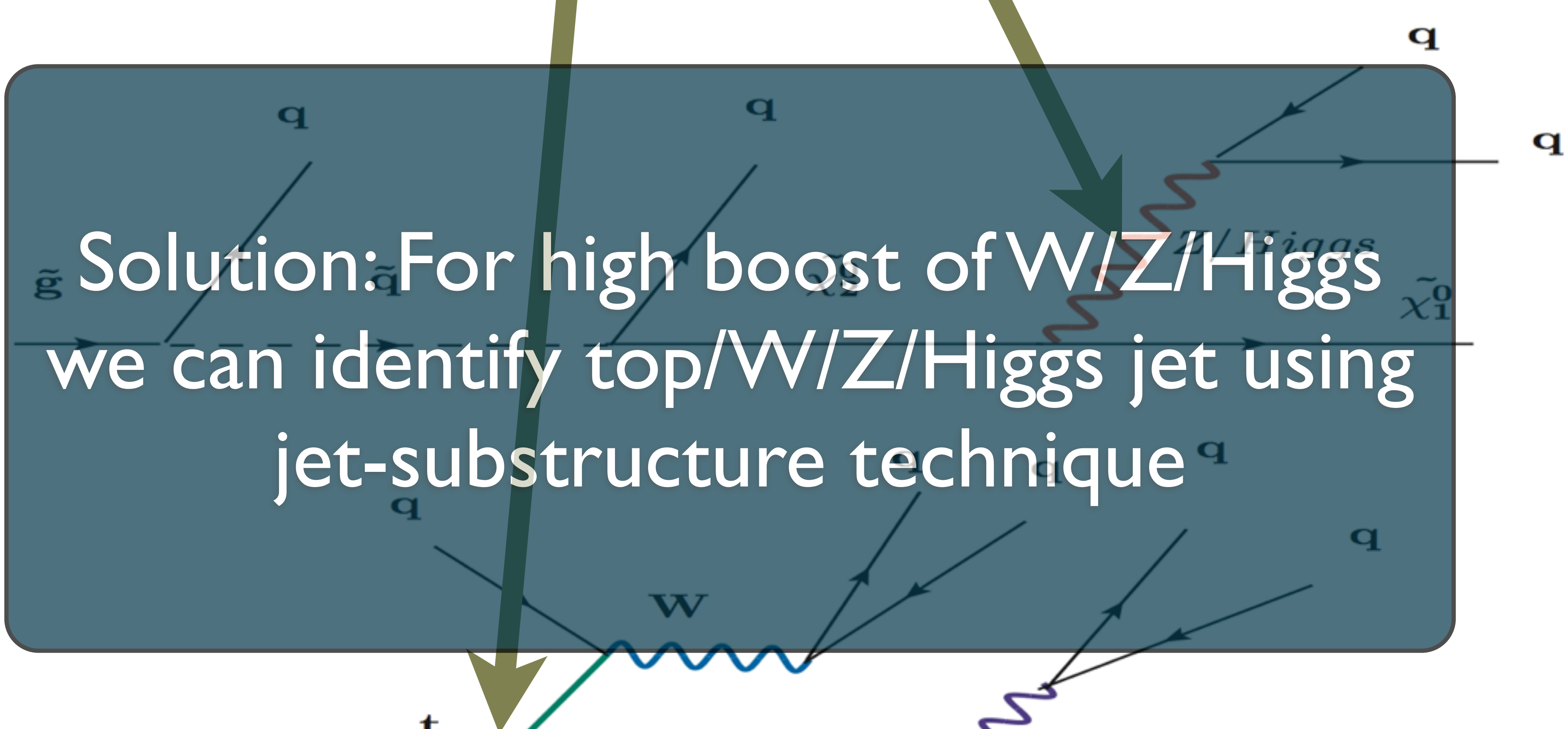
Identification of top, W, Z, Higgs are difficult



Long SUSY cascade

Technical Difficulty : Example :2

Identification of top,W,Z, Higgs are difficult



Solution: For high boost of W/Z/Higgs we can identify top/W/Z/Higgs jet using jet-substructure technique

Many applications : Very important for LHC 14 TeV run

Low mass supersymmetric particles are not excluded
(True for other new physics options)

Chance to observe at 14 TeV Large Hadron Collider
(New techniques may be required)

However, the current LHC bound may not be improved drastically

Is there any direction where we can expect many orders of magnitude improvement in near future?

Low mass SUSY particles are not excluded

More study is required to exclude/discover Supersymmetry / New physics

However, the current LHC bound may not be improved drastically

Dark matter

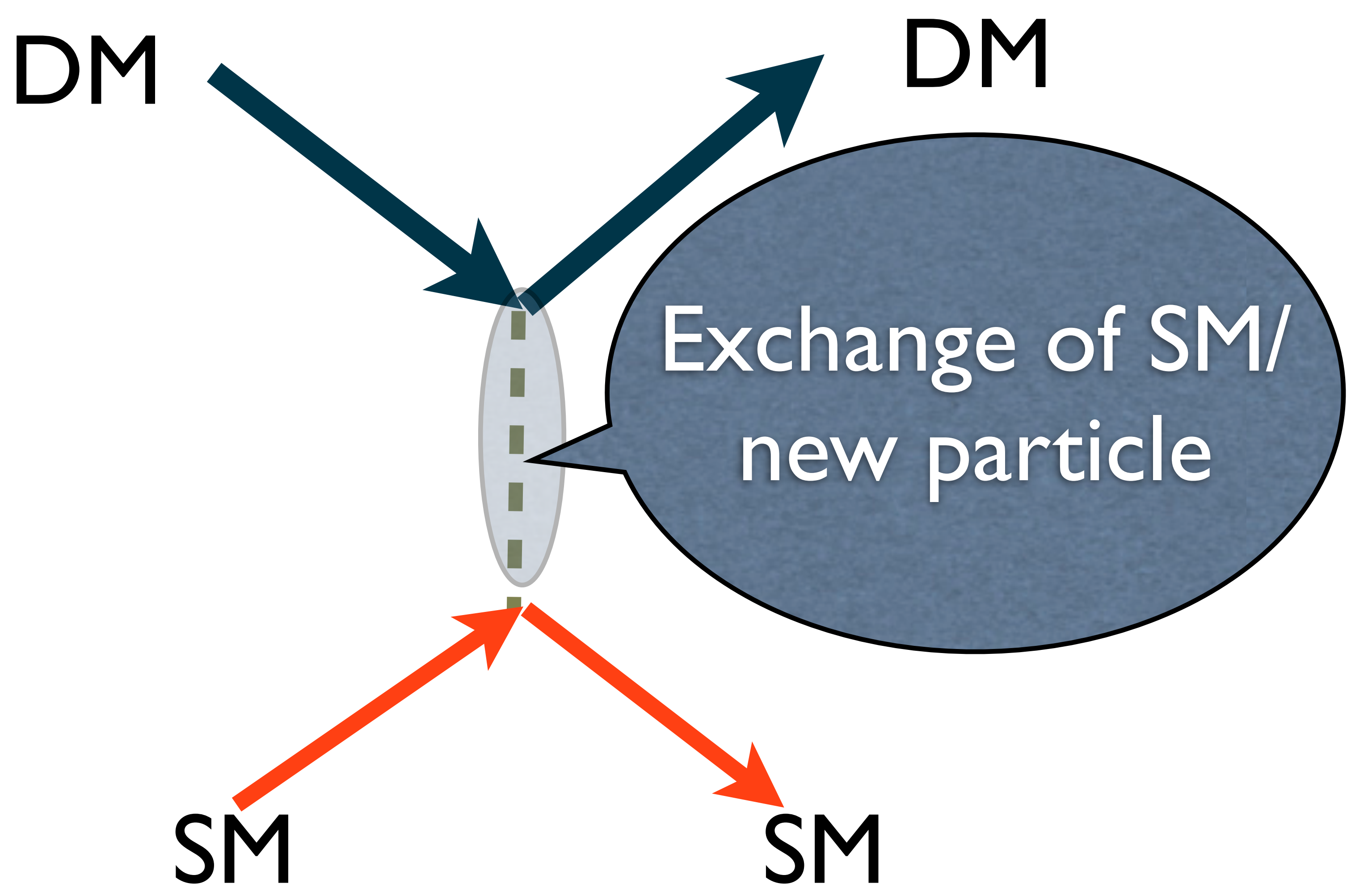
What we know

1. Many evidences
2. Weakly interacting

What we do not know

1. Mass ?
2. Charge ?
3. Interactions with SM particles?
4. Stable or unstable ?
5. Equal no of dark and anti dark matter ?

Detection of DM (direct detection)



Detection of DM (direct detection)

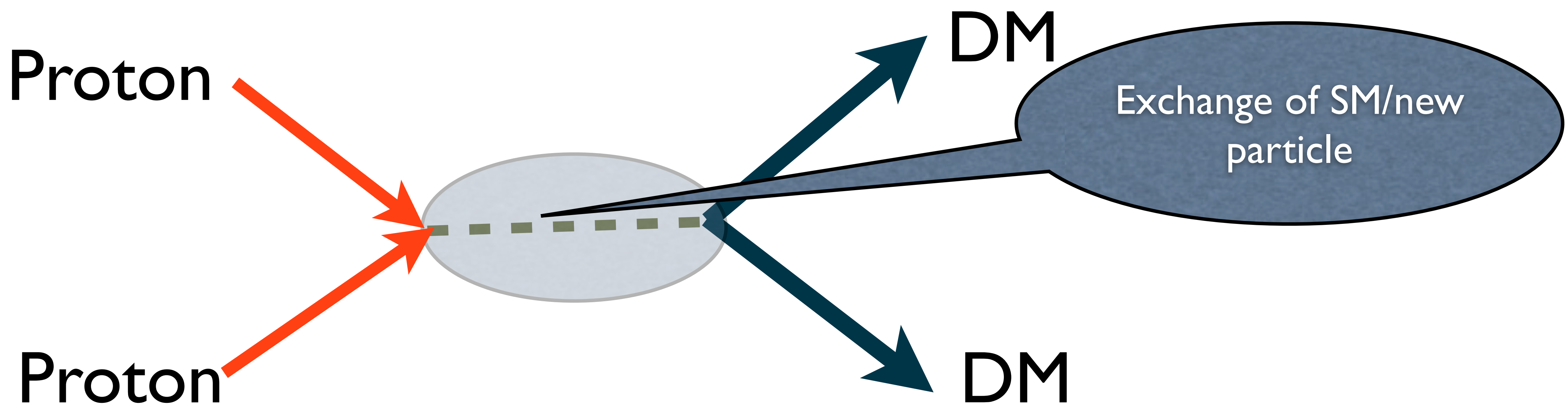
DM DM

1. Recoil of detector nuclei (Energy measurement)
2. Very effective for spin-independent interaction
3. Future limit can be improved by a factor of ~ 1000

For very light dark matter , recoil energy is very small

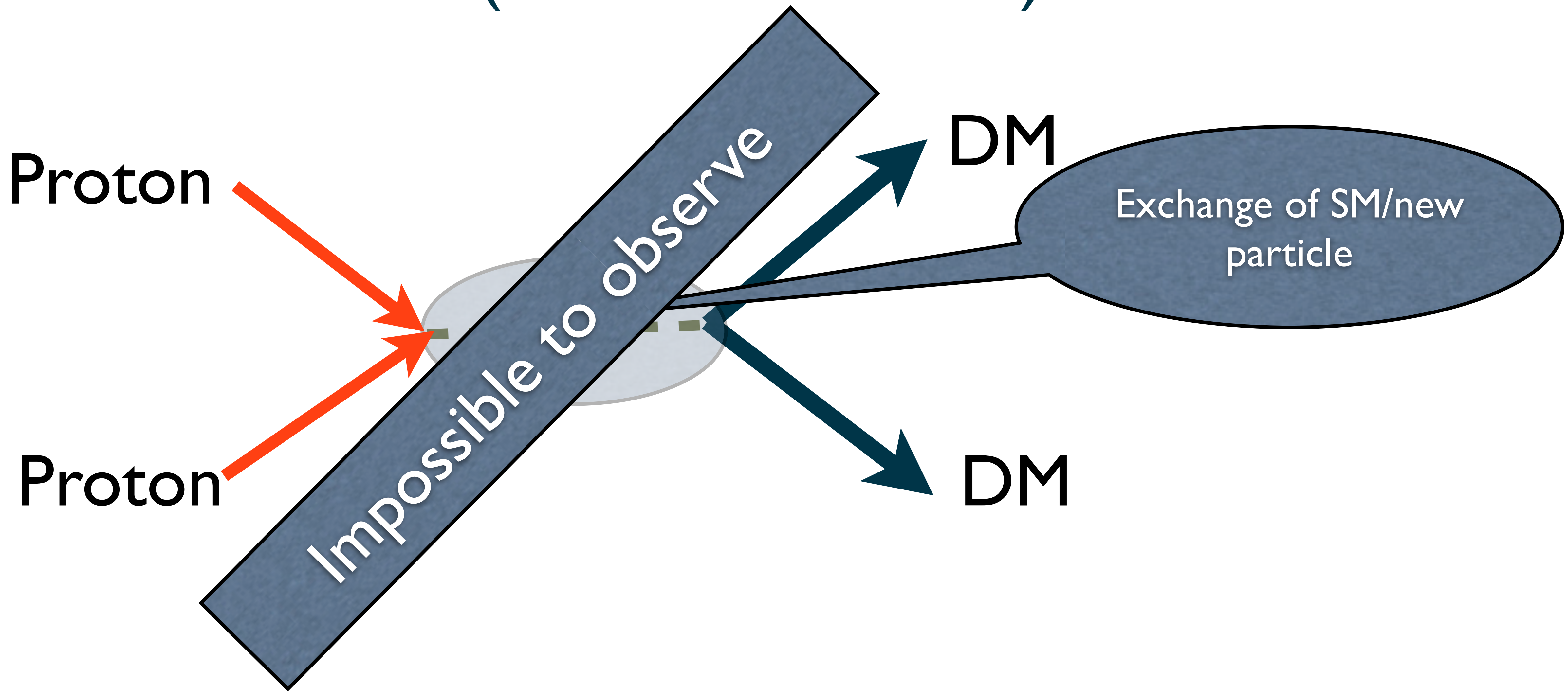
Not very effective

Detection of DM (Collider search)



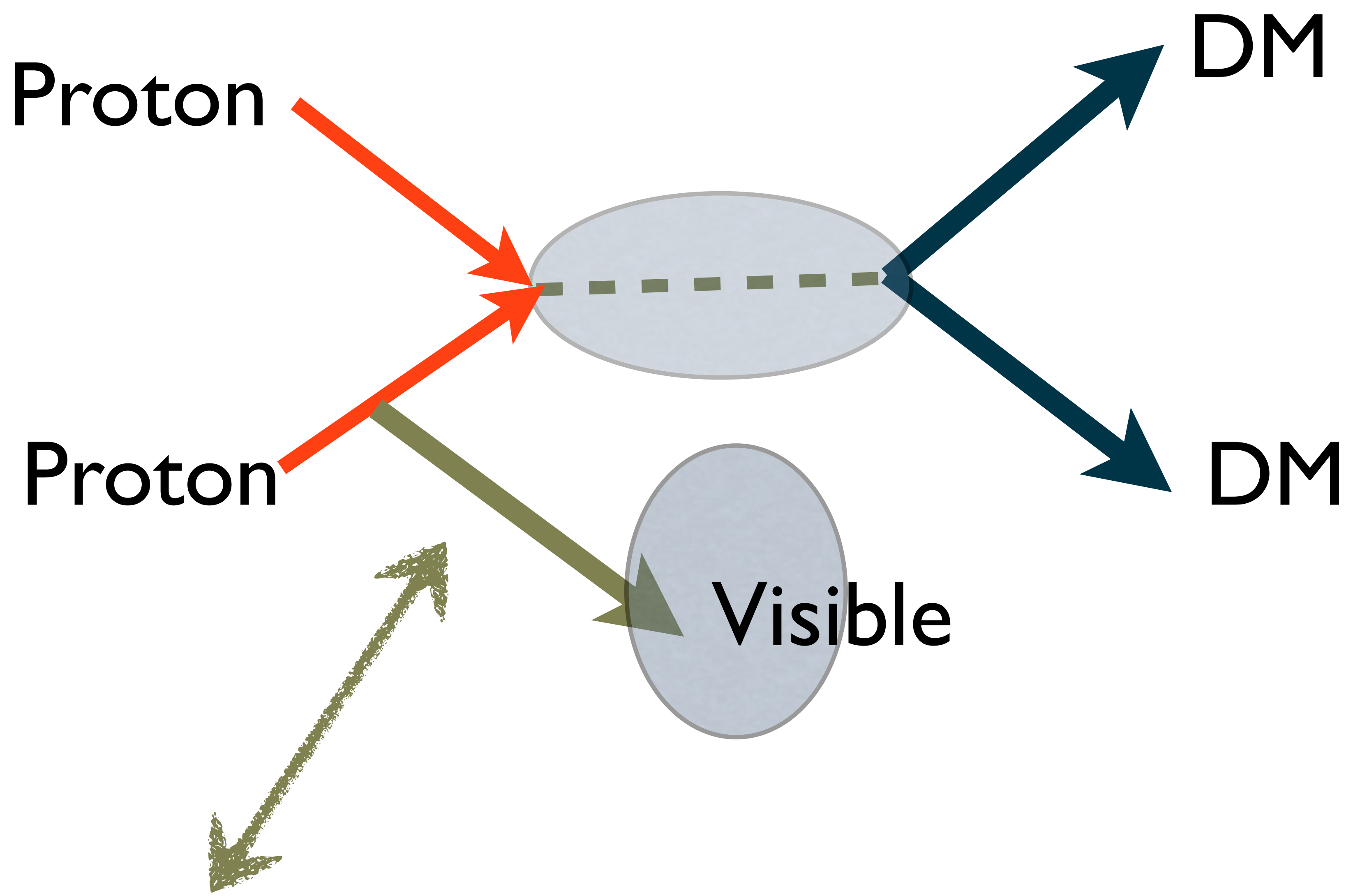
No missing transverse momentum : no trigger

Detection of DM (Collider search)



No missing transverse momentum : no trigger

Detection of DM (Collider search)



Photon, jets, gauge bosons ......

Detection of DM (Collider search)

DM

Signature : Mono-jet , Mono photon plus missing transverse energy

(Chance to see dark matter at the LHC)

radiation from internal leg

Photon, jets, gauge bosons ......

Detection of DM (Collider search)

Advantage :

1. This method also important for very low mass dark matter (unlike direct detection)

2. Equally good for spin-dependent and spin-independent interactions

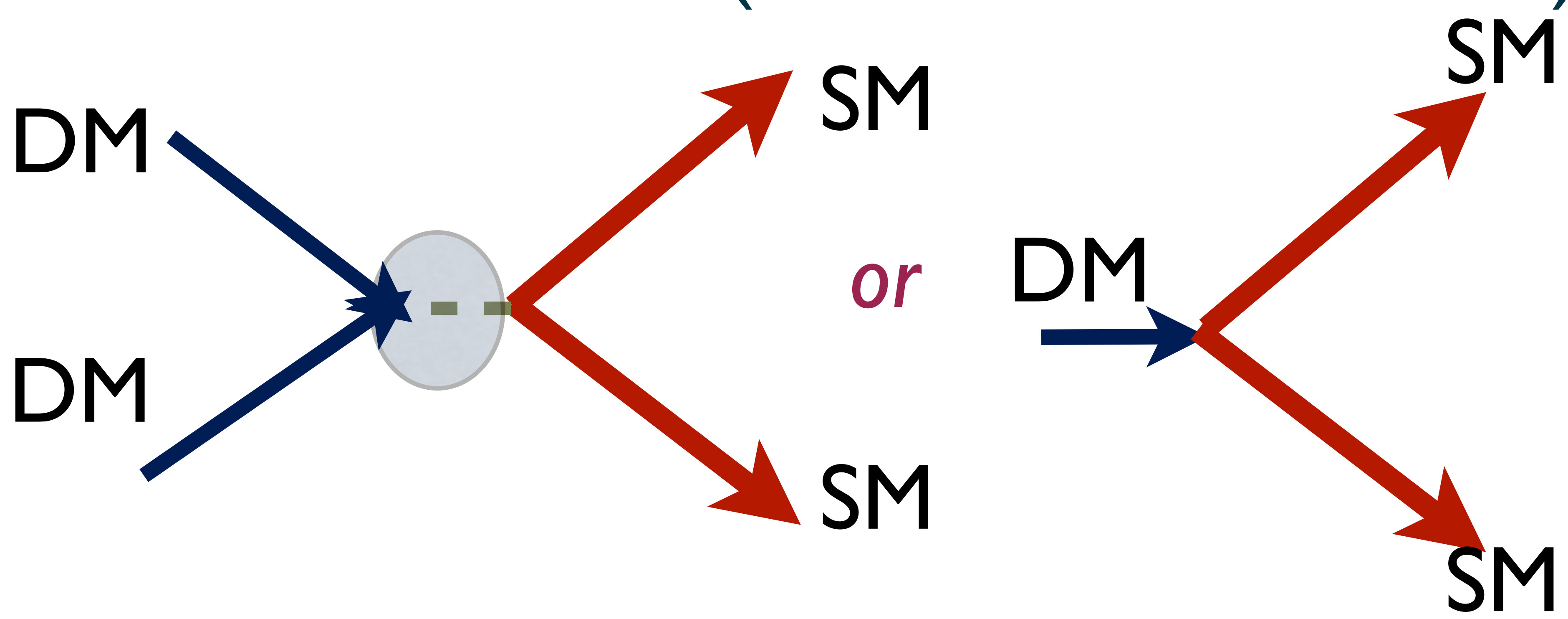
Disadvantage:

Need interaction with quark/gluon

Not much improvement in future

Interactions with top/bottom quark is difficult to probe even in future (BB, Choudhuri, Harigaya, Matsumoto, Nojiri, JHEP 13)

Detection of DM (Indirect Detection)



Gamma, neutrinos, positron, anti-proton..

Advantage : It may cover wide energy range (GeV to Tens of TeV)

Disadvantage : huge uncertainty in Astrophysical background

better than LHC ?

wino dark matter in High scale type of SUSY scenario

future bound from gamma ray telescopes using dwarf spheroidal galaxy data may be better than LHC (BB, Ibe, Ichikawa, Matsumoto.. in preparation)

Higgs dark matter portal

Coupling of dark and visible sectors is through Higgs

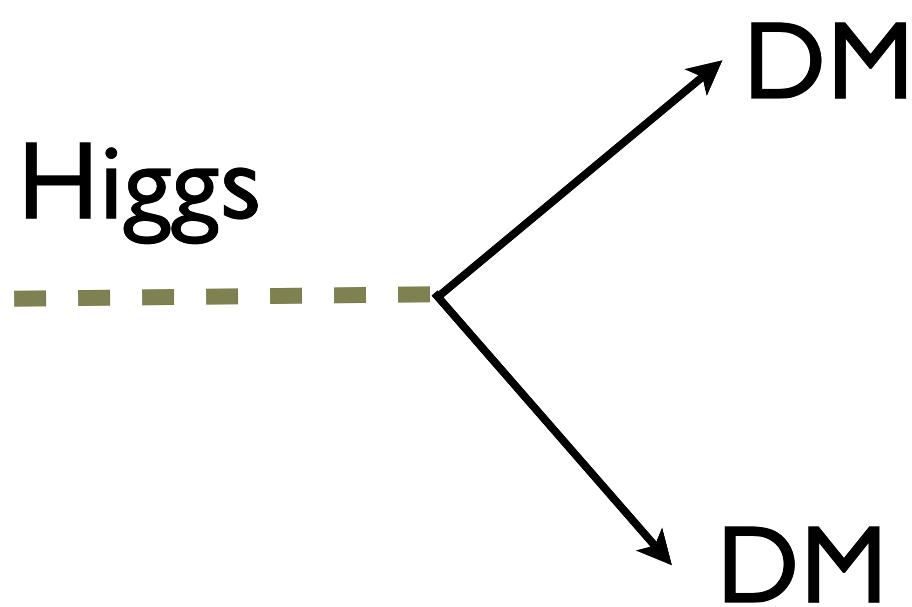
Scalar DM $\phi^\dagger_{\mathrm{DM}}\phi_{\mathrm{DM}}H^\dagger H$ renormalizable

Fermionic DM $\overline{\chi}_{\mathrm{DM}}\chi_{\mathrm{DM}}H^\dagger H$

Another Possibility: $\overline{\chi}_{\mathrm{DM}}\chi_{\mathrm{DM}}\phi$

ϕ and mixes with Higgs

Dark matter and Higgs boson



Invisible Higgs decay Possible ?

Br(H -> DM DM) ~ 20 % is still allowed

International Linear Collider can probe Br(H -> DM DM) up to 0.6% ...... very effective

Conclusion

- SUSY : many possibilities consistent with 125 GeV Higgs
- It is too early to think that SUSY is excluded
- Precise measurements of Higgs properties required (LHC, ILC ?)
- Dark matter bounds may be improved by orders of magnitude within a decade.

Thank you.

Extra Slides

Possibilities

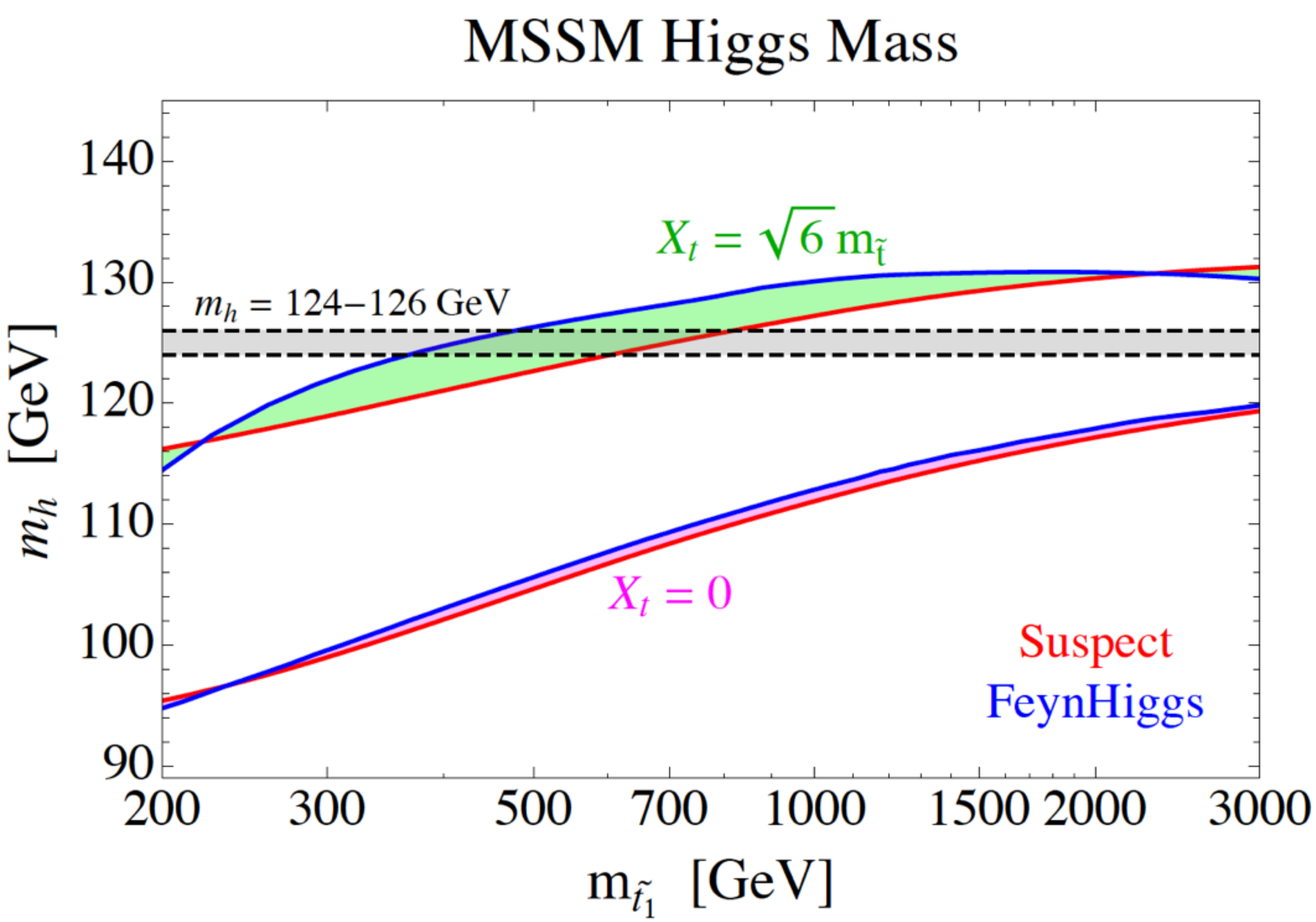
B. Large stop mixing

X_t

$$M^2 = \begin{pmatrix} M_L^2 + m_t^2 + \Delta_u & \sqrt{2} m_t \sin\beta (A_t - \mu \cot\beta) \\ \sqrt{2} m_t \sin\beta (A_t - \mu\cot\beta) & M_R^2 + m_t^2 + \Delta_{\bar{u}} \end{pmatrix},$$

arXiv:0811.1024

$$\Delta_u = \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right)\cos 2\beta\, m_Z^2\,, \qquad \Delta_{\bar{u}} = \frac{2}{3}\sin^2\theta_W \cos 2\beta\, m_Z^2\,.$$



arXiv:1112.2703

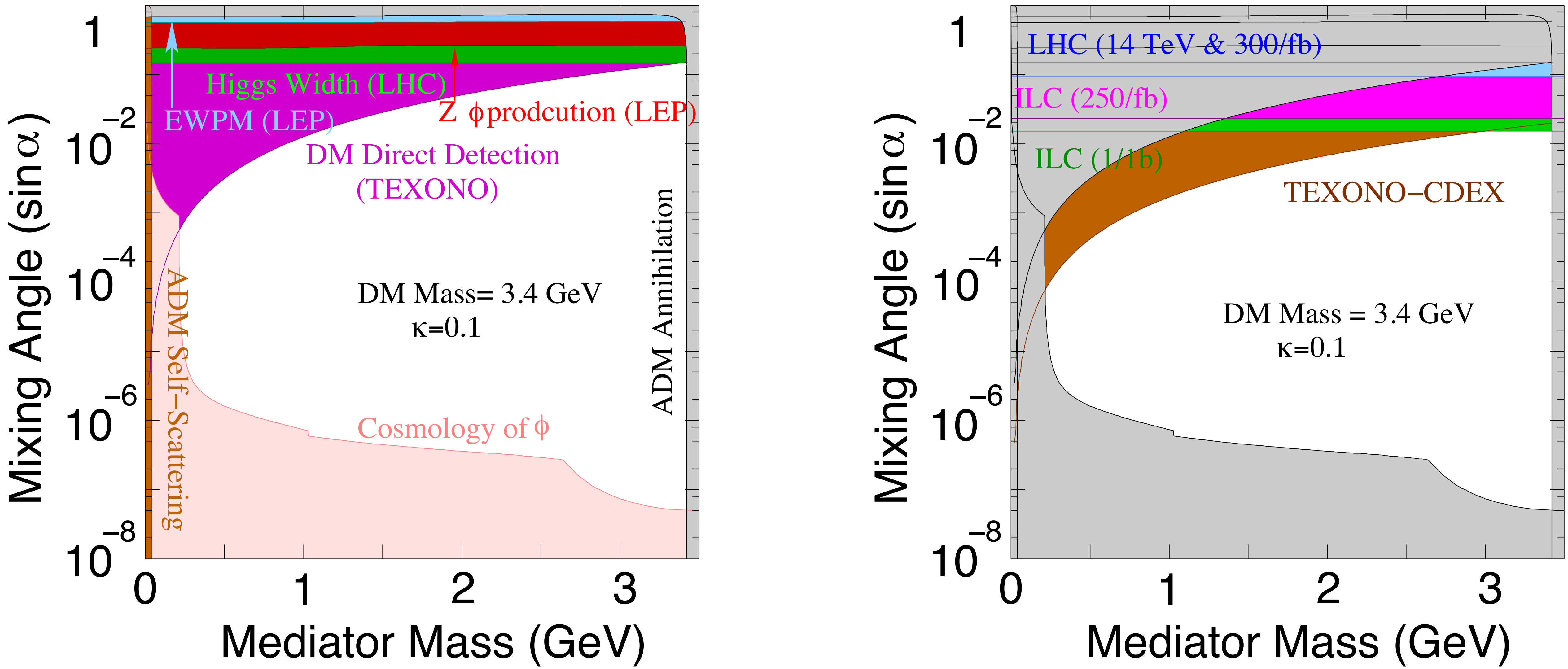
Light fermionic Asymmetric dark matter

$$\mathcal{L} = i\,\overline{\chi}(\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu\phi'\partial^\mu\phi' - m_{\phi'}^2\phi'^2) - \kappa\overline{\chi}\chi\phi' - V(H',\phi'),$$

$$V(H',\phi') = V(H')_{SM} + \lambda_1\phi'|H'|^2 + \lambda_2\phi'^2|H'|^2 + \lambda_3\phi'^3 + \lambda_4\phi'^4.$$

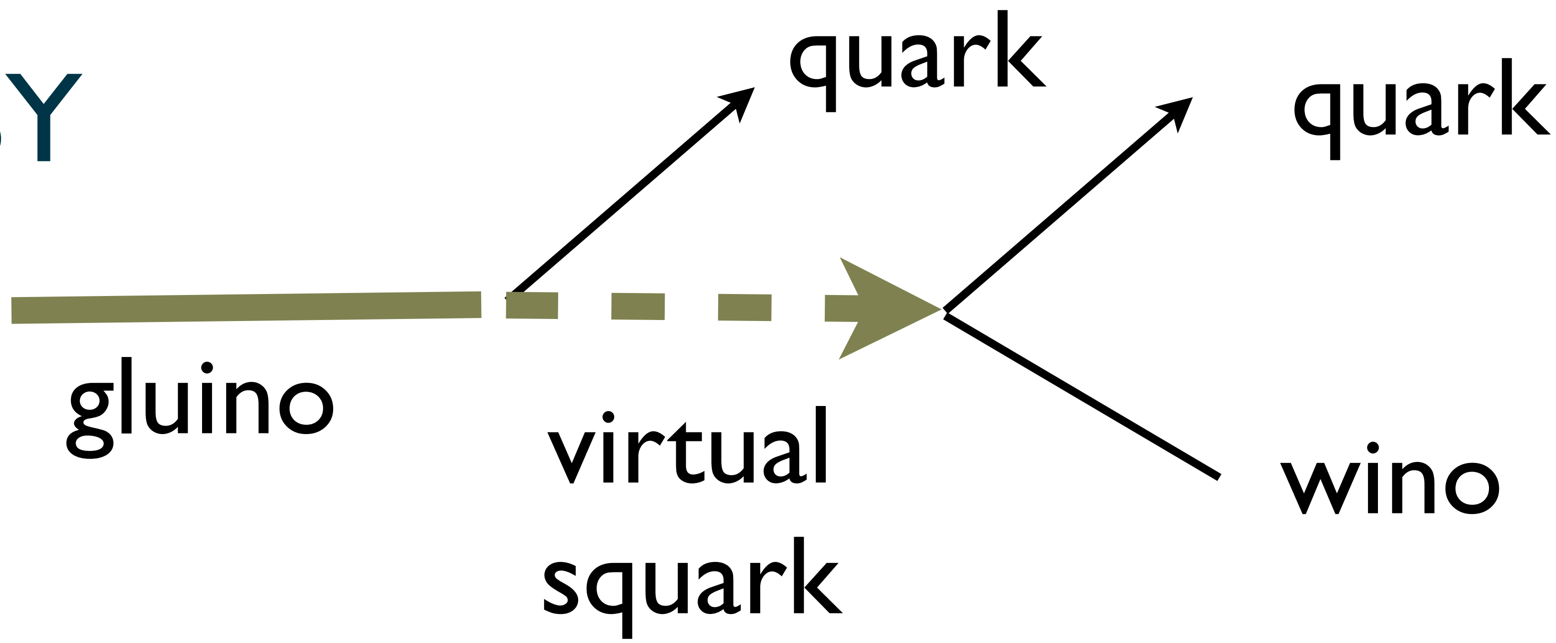
$$h = (\cos\alpha)\,h' - (\sin\alpha)\,\phi',$$

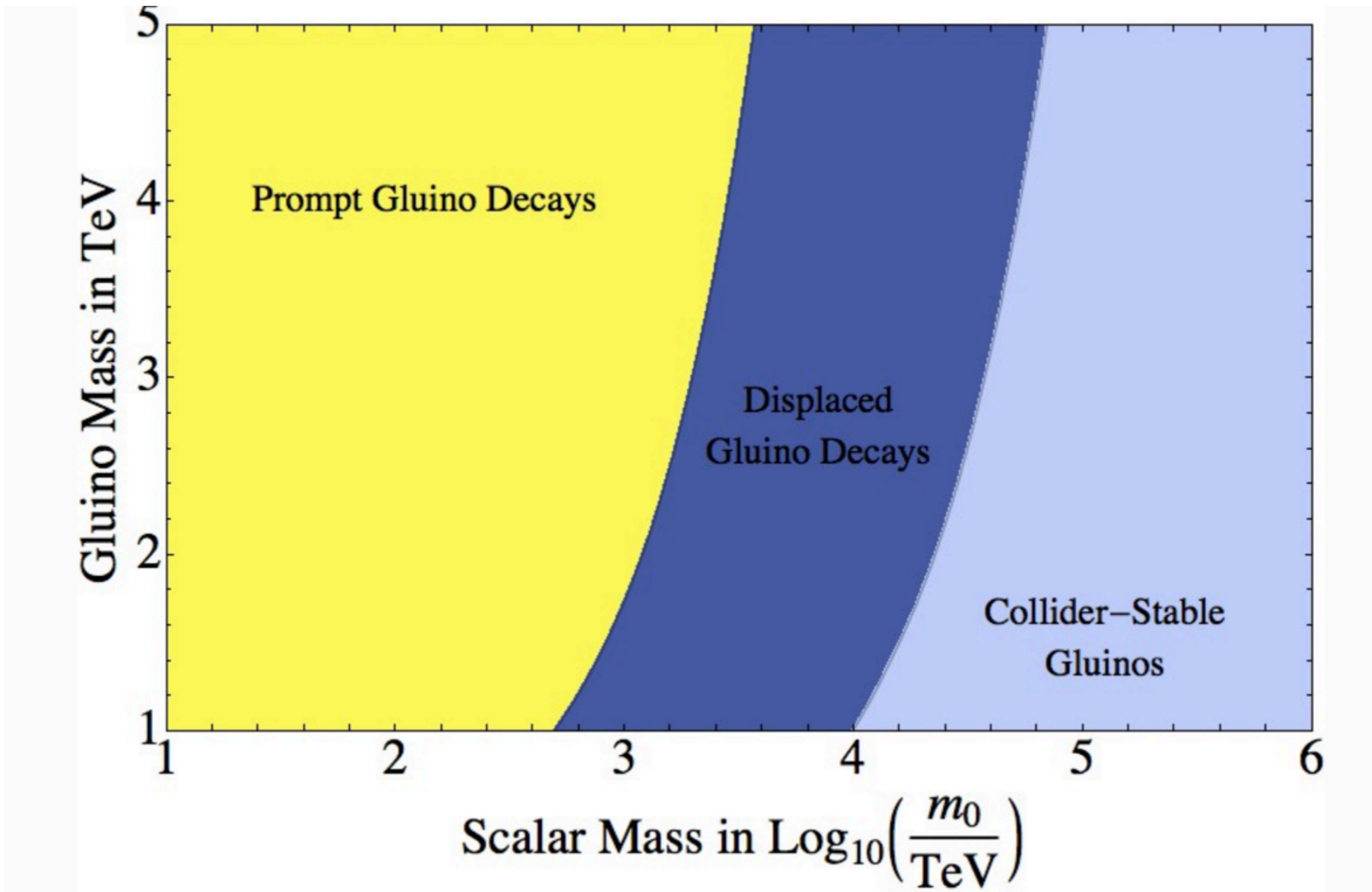
$$\phi = (\sin\alpha)\,h' + (\cos\alpha)\,\phi'.$$



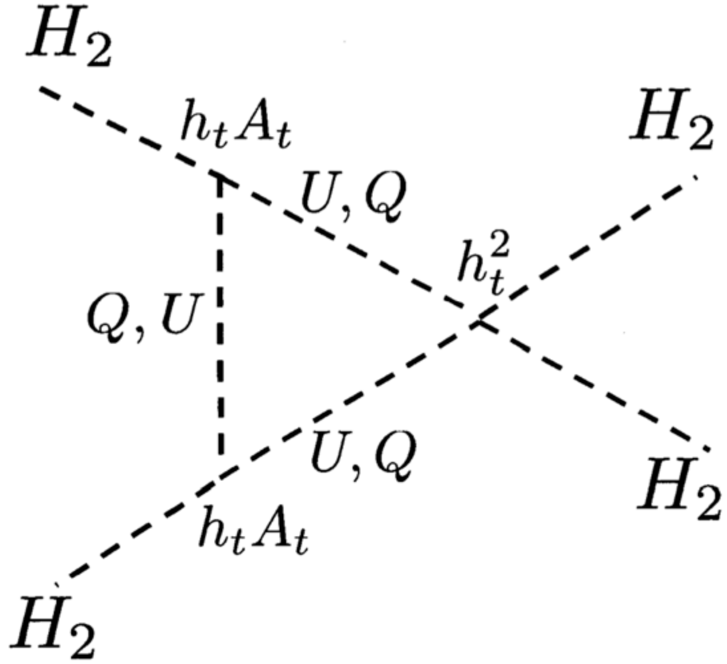
BB, Matsumoto, Mukhopadhyay, Nojiri, JHEP 2013

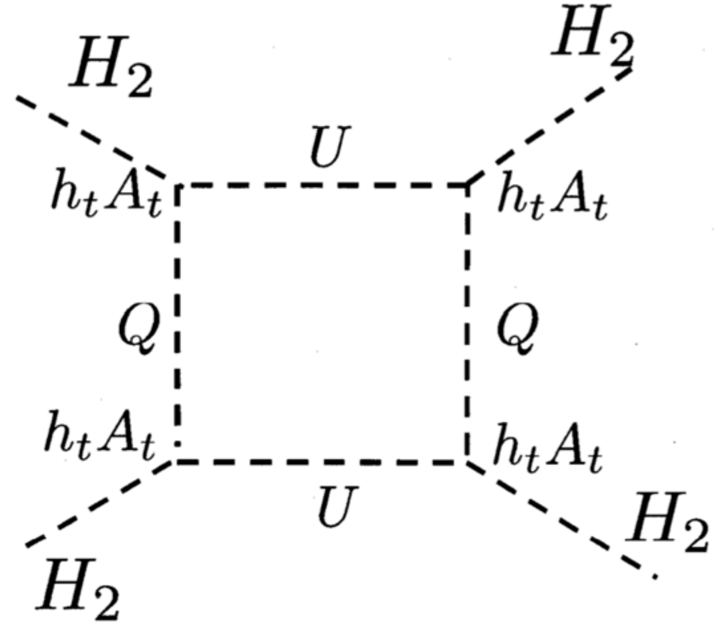
High Scale SUSY





arXiv:1210.0555





Top & Stop Contributions to the Higgs Quartic Coupling