Supersymmetry: Lecture 3
superpartners in action

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Technion

gauge bosons (s=1) **+ gauginos (s=1/2)**

photon **+ photino**

gluon **+ gluinos**

W **+ wino** Z + **zino**

fermions **+ sfermions (scalars)**

quark **+ squark**

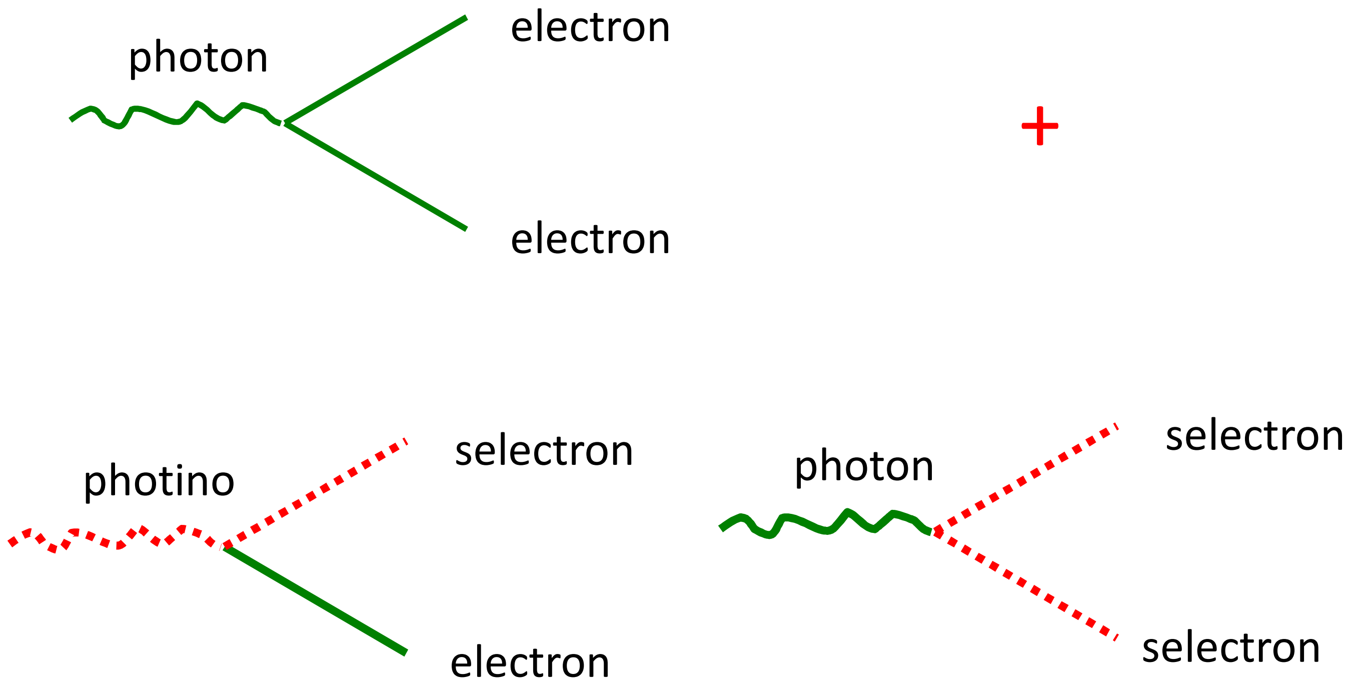
electron **+ selectron** ..

neutrino **+ sneutrino**

2x(Higgs (s=0) **+ Higgsino (s=1/2)**) each superpartner: same charges as SM particle

→ GAUGE + YUKAWA INTERACTIONS
COMPLETELY DICTATED

by SUSY + SM



superpartners appear in pairs

R-parity: SM fields = even superpartners=odd

the only freedom is in:

spectrum (determined by soft terms)

[+ interactions:

- are there R-parity breaking couplings or not?
- are gaugino-scalar-fermion couplings flavor diagonal or not?]

spectrum (soft terms): many possibilities
(depend on the mediation of SUSY breaking)

so: **don`t listen to theorists …**

.. if they tell you they know what the superpartner masses are

where can we observe superpartners?

- virtual corrections:
  electric and magnetic dipole moments
  flavor violating processes
  widths of known particles

- direct production: LHC

virtual corrections:

most relevant for LHC searches:

flavor violating processes: eg

$$K^0 - \bar{K}^0$$

$$b \to s\gamma$$

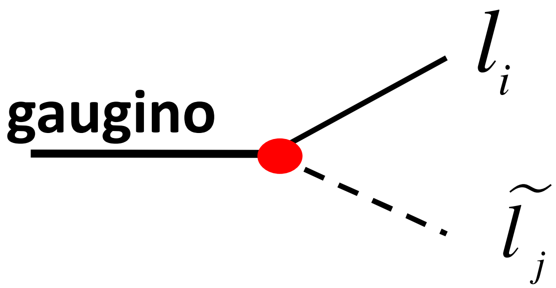
$$\mu \to e\gamma \ldots$$

let's talk about sleptons (easier)

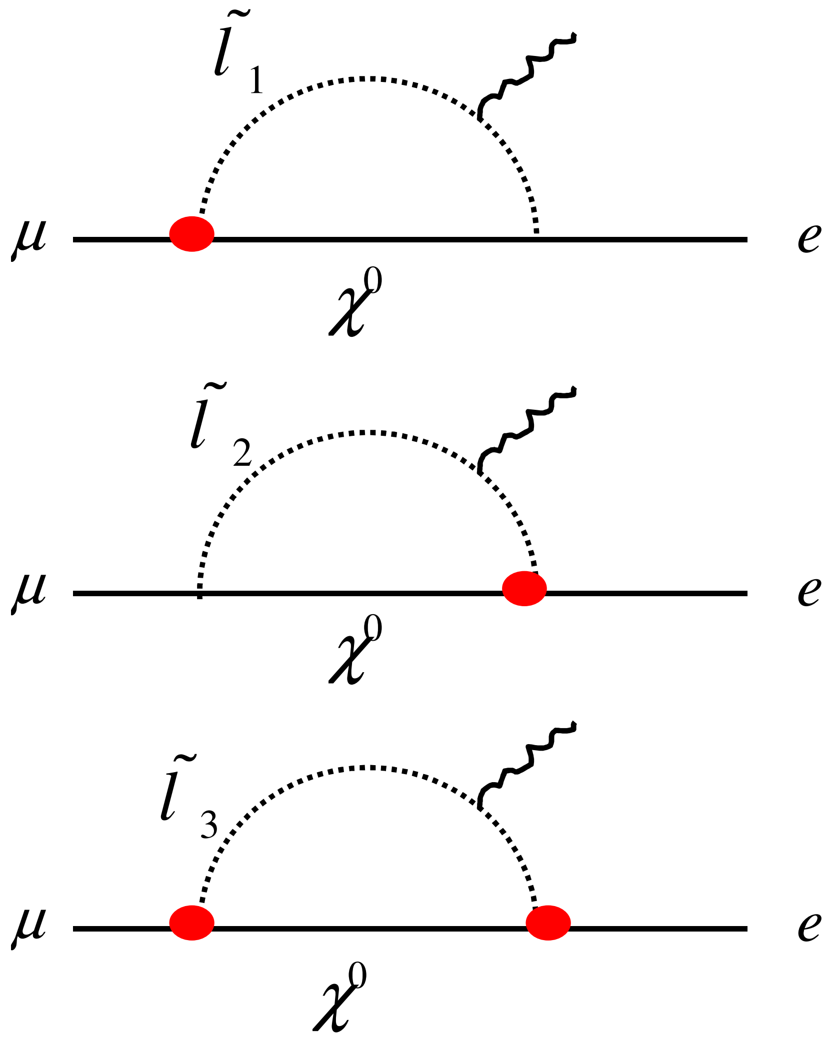
relevant parameters:

eg R-sleptons: $\tilde{l}_1, \,..\,, \tilde{l}_3$

- 3 masses: m_1, m_2, m_3
- mixings:



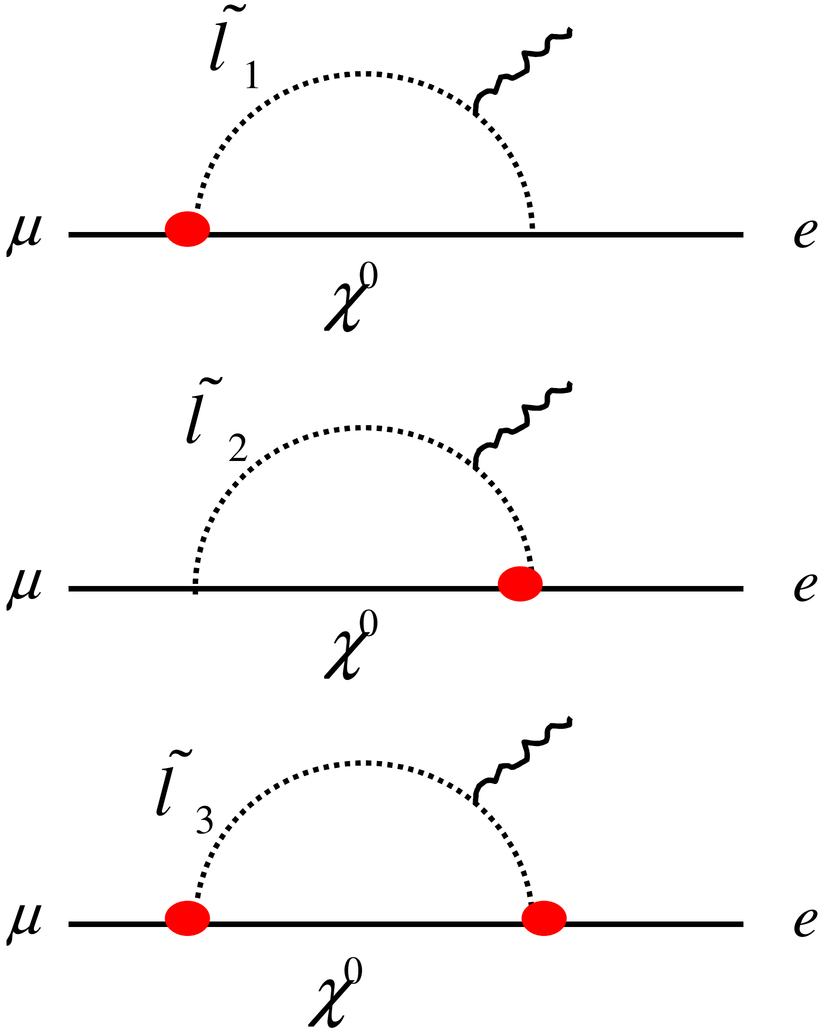
$\propto \; K_{ij} \quad i \neq j$



$$< 5.7 \cdot 10^{-13} \quad \text{(MEG)}$$

essentially constrains:

$$\delta_{ij} = \frac{\Delta m^2_{ij} \; K_{ij}}{m^2}$$



$$< 5.7 \cdot 10^{-13} \quad \text{(MEG)}$$

essentially constrains:

$$\delta_{ij} = \frac{\Delta m_{ij}^2 \; K_{ij}}{m^2}$$

$$K_{ij} \to 0 \quad Br \to 0$$

$$\Delta m_{ij}^2 \to 0 : \; K^*_{1j} K_{2j} = 0 \quad \text{(super-GIM)} \quad Br \to 0$$

Suppressing SUSY Flavor Violation

3 obvious approaches:
(or combination)

$$\delta_{ij} = \frac{\Delta m_{ij}^2 \, K_{ij}}{m^2}$$

small mass splittings
→ **degeneracy**

Suppressing SUSY Flavor Violation

3 obvious approaches:
(or combination)

$$\delta_{ij} = \frac{\Delta m^2_{ij} \; K_{ij}}{m^2}$$

small mixings:
→ **alignment**
slepton mass matrix "aligned" with lepton mass matrix: approximately diagonal together

Suppressing SUSY Flavor Violation

3 obvious approaches: (or combination)

$$\delta_{ij} = \frac{\Delta m_{ij}^2 \; K_{ij}}{m^2}$$

3. increase masses: taken care of by ATLAS and CMS ..

Suppressing SUSY Flavor Violation

3 obvious approaches:
(or combination)

$$\delta_{ij} = \frac{\Delta m^2_{ij} \; K_{ij}}{m^2}$$

there are viable models of each type

3. increase masses:
taken care of by ATLAS and CMS ..

LHC SEARCHES

supersymmetry is NOT a single model so:

rather than a **model based** approach

use a **signature based** approach

(both CMS and ATLAS!)

the only freedom is in:

spectrum (determined by soft terms)

[+ interactions:

– are there R-parity breaking couplings or not?
– are gaugino-scalar-fermion couplings flavor diagonal or not?]

general considerations: **interactions:**

R-parity conservation

- production: superpartners produced in **pairs**
- decay: superpartner → superpartner + SM
- the lightest superpartner (LSP) is stable

R-parity violating coupling(s) (RPV):

- production: single superpartner (resonant) production is possible

- decay: a superpartner can decay to SM (jets, leptons)

(see below)

R-parity violating coupling(s) (RPV): if small:

- production: single superpartner (resonant) production is possible

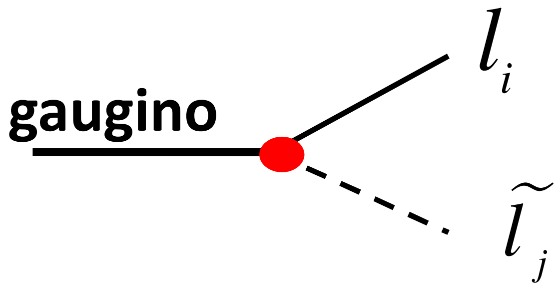
  competitive with gauge couplings because of kinematics

- decay: a superpartner can decay to SM (jets, leptons)

  only the LSP decays via the RPV coupling

general considerations: **interactions:**

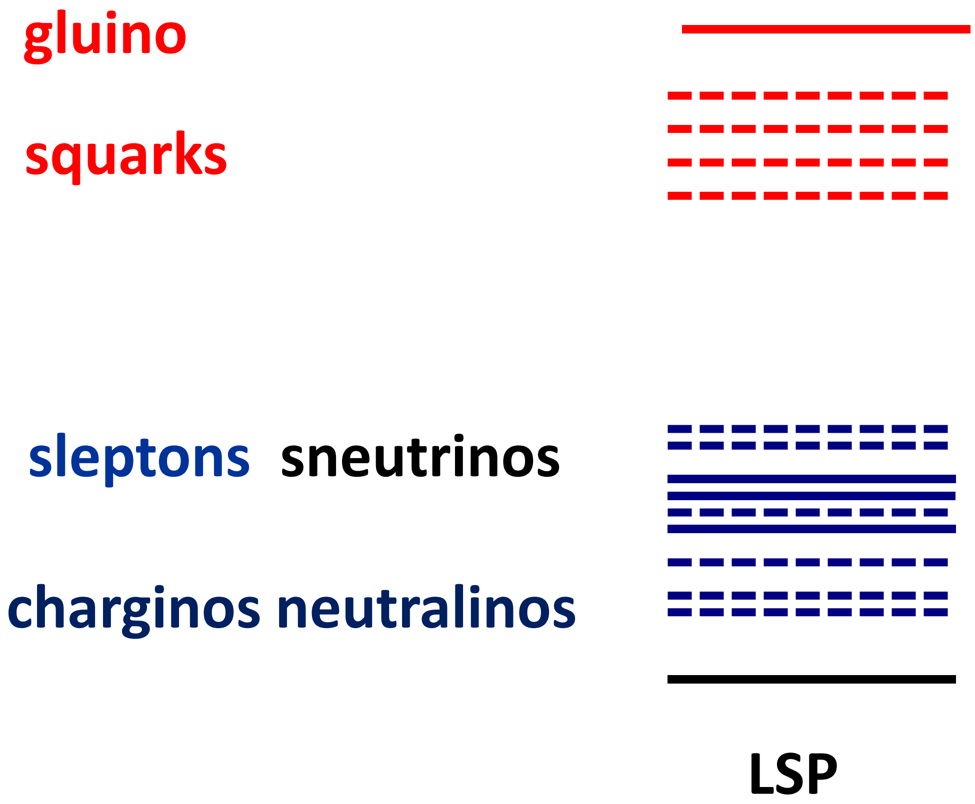
flavor mixing



$\propto K_{ij} \quad i \neq j$

mainly affects decay

general considerations: **spectrum:**



colored vs non-colored:

generically:

colored heavier
(factor of few-10)

(* don't know
squark vs gluino ??

sleptons vs neutralinos??)

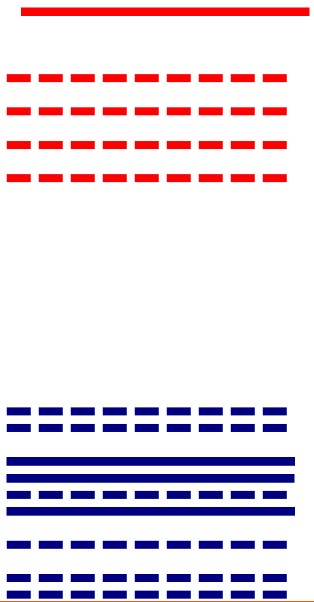
general considerations: **spectrum:**

gluino

squarks

sleptons **sneutrinos**

charginos neutralinos



colored vs non-colored:

generically:

colored heavier
(factor of few-10)

expect: squark gluino production dominates

general considerations: **spectrum:**

gluino

squarks

sleptons **sneutrinos**

charginos neutralinos

LSP

colored vs non-colored:

if larger hierarchy
(colored masses go up)
EWK production
more important
(slepton, neutralino,
chargino
production)

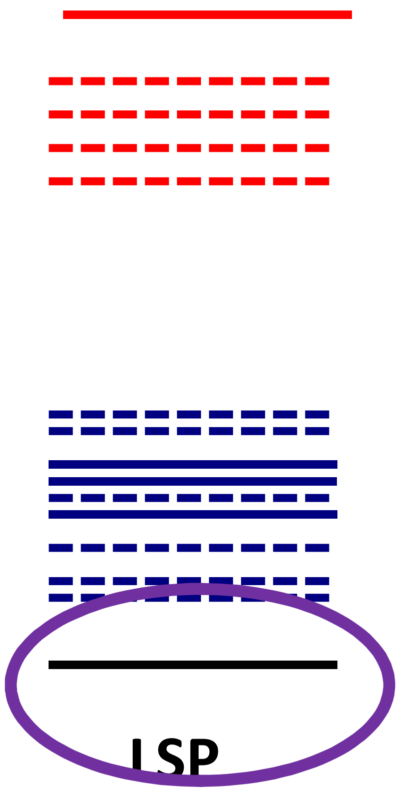
general considerations: **spectrum:**

gluino

squarks

sleptons sneutrinos

charginos neutralinos



identity of LSP

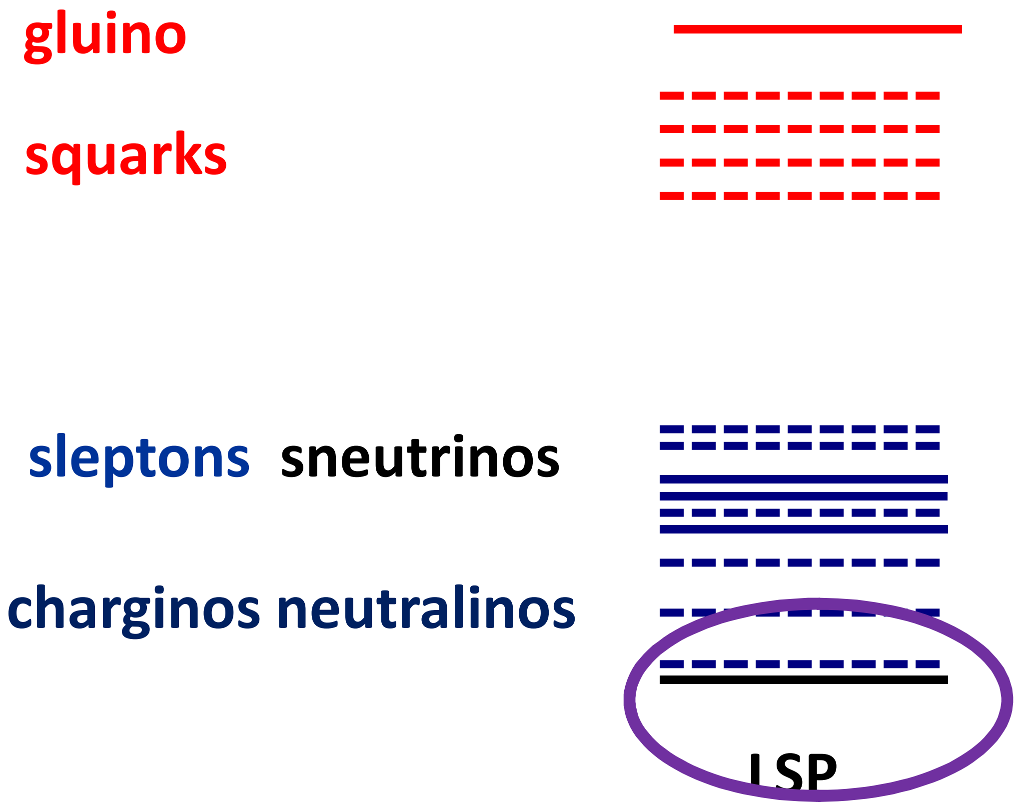
neutral or charged?

(usually:
neutralino or slepton)

missing energy or
something else

main distinguishing feature of SUSY

general considerations: **spectrum:**



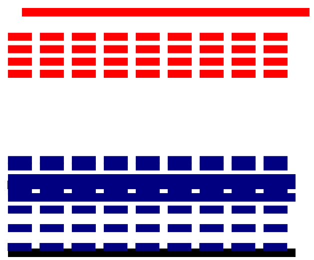
small mass differences

soft decay products
long lifetimes

general considerations: **spectrum:**

gluino

squarks



LSP

sleptons sneutrinos

charginos neutralinos

extreme case:
squished spectrum

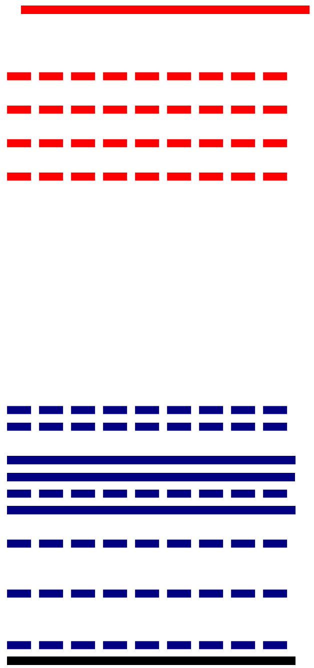
soft decay products

little missing energy

general considerations: **spectrum:**

gluino

squarks



<u>flavor dependent or not?</u>

up squark=charm squark?

d squark= s squark?

sleptons **sneutrinos**

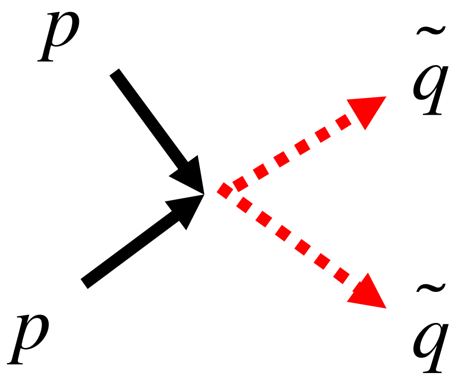
charginos neutralinos

LSP

smuon=selectron?

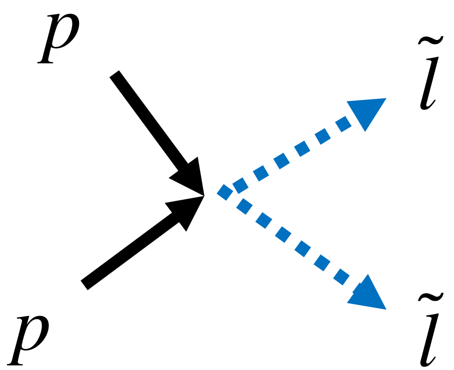
production: colored vs EWK

strong:



squark pair
or squark gluino
or gluino gluino

EWK:

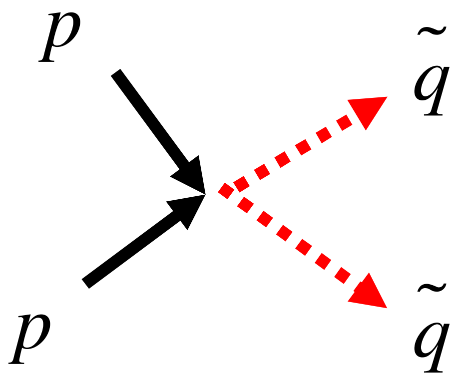


slepton pair
chargino pair …

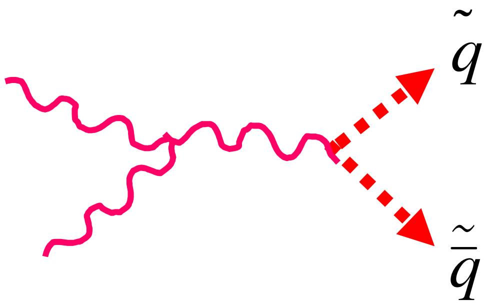
relative importance depends on colored masses vs EWK masses

production: flavor dependence

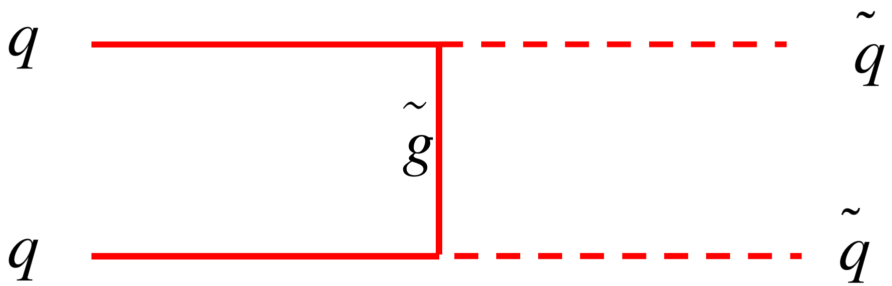
strong:



squark pair
or squark gluino
or gluino gluino



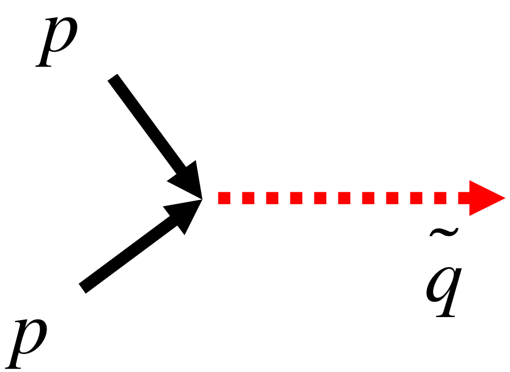
some channels flavor blind:
eg: gg to squark anti-squark



some channels
flavor sensitive
larger for
u-squark, d-squark

production: with R-parity violating coupling

in principle

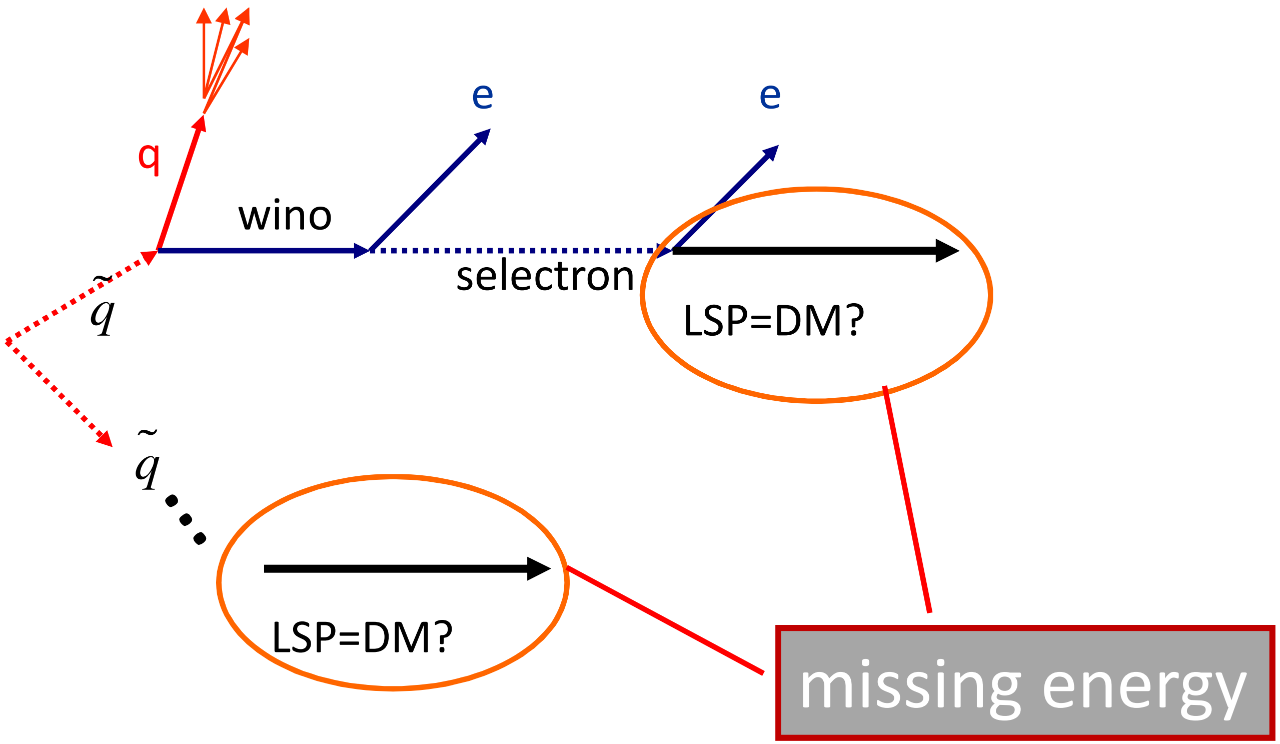


single squark
or slepton

coupling may be small but kinematics can win

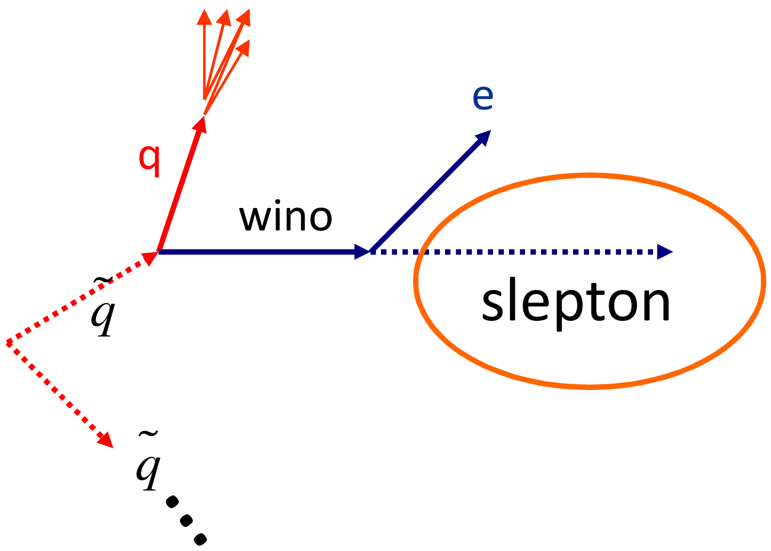
decay: (with no RPV coupling)

LSP = neutralino



decay: (with no RPV coupling)

LSP = slepton (stau?)



LSP = neutralino

- stable, neutral: good DM candidate (WIMP)
- LHC: transverse momentum imbalance:

  ``missing E_T"
- main handle against SM bgnds:
  - squark mass (or other mother particle) goes up:

    missing E_T goes up (LSP more boosted)
  - LSP mass goes up

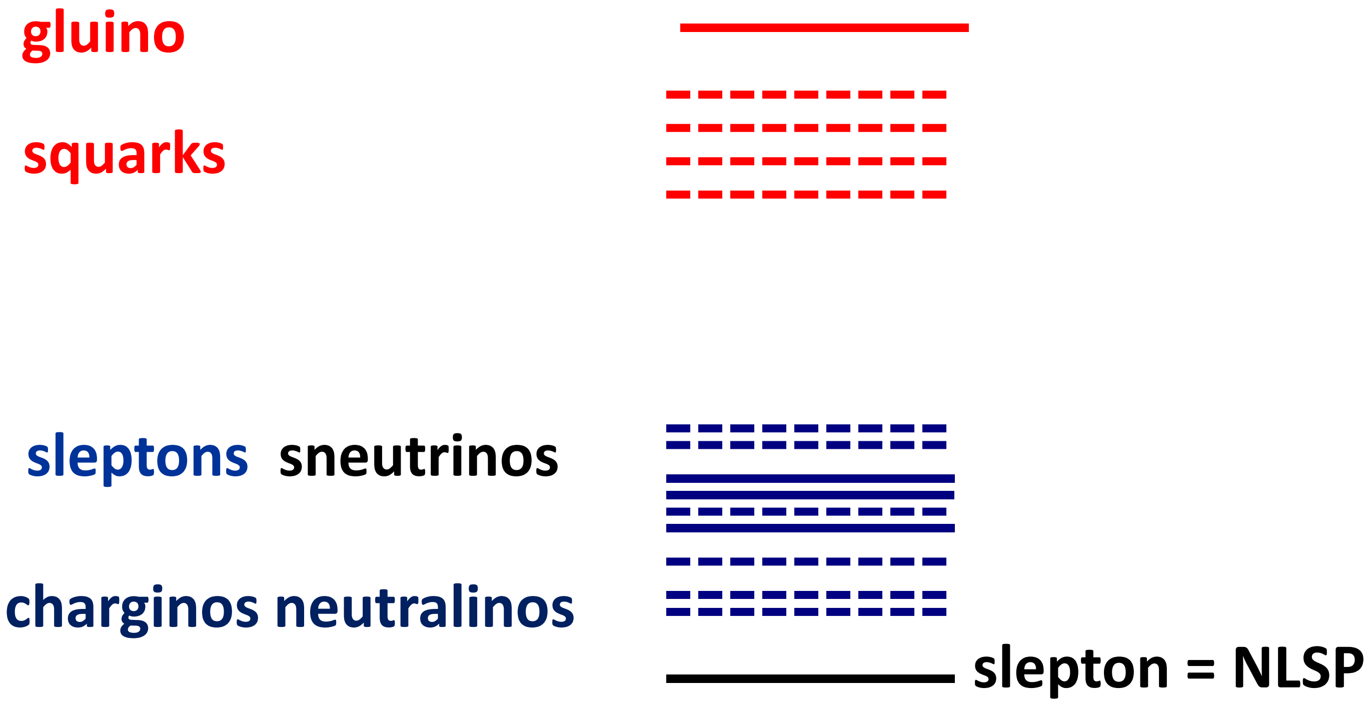
    missing E_T goes down (LSP less boosted)

efficiency goes down with mass difference

LSP = charged slepton

cosmology ?? ruled out if the slepton is stable

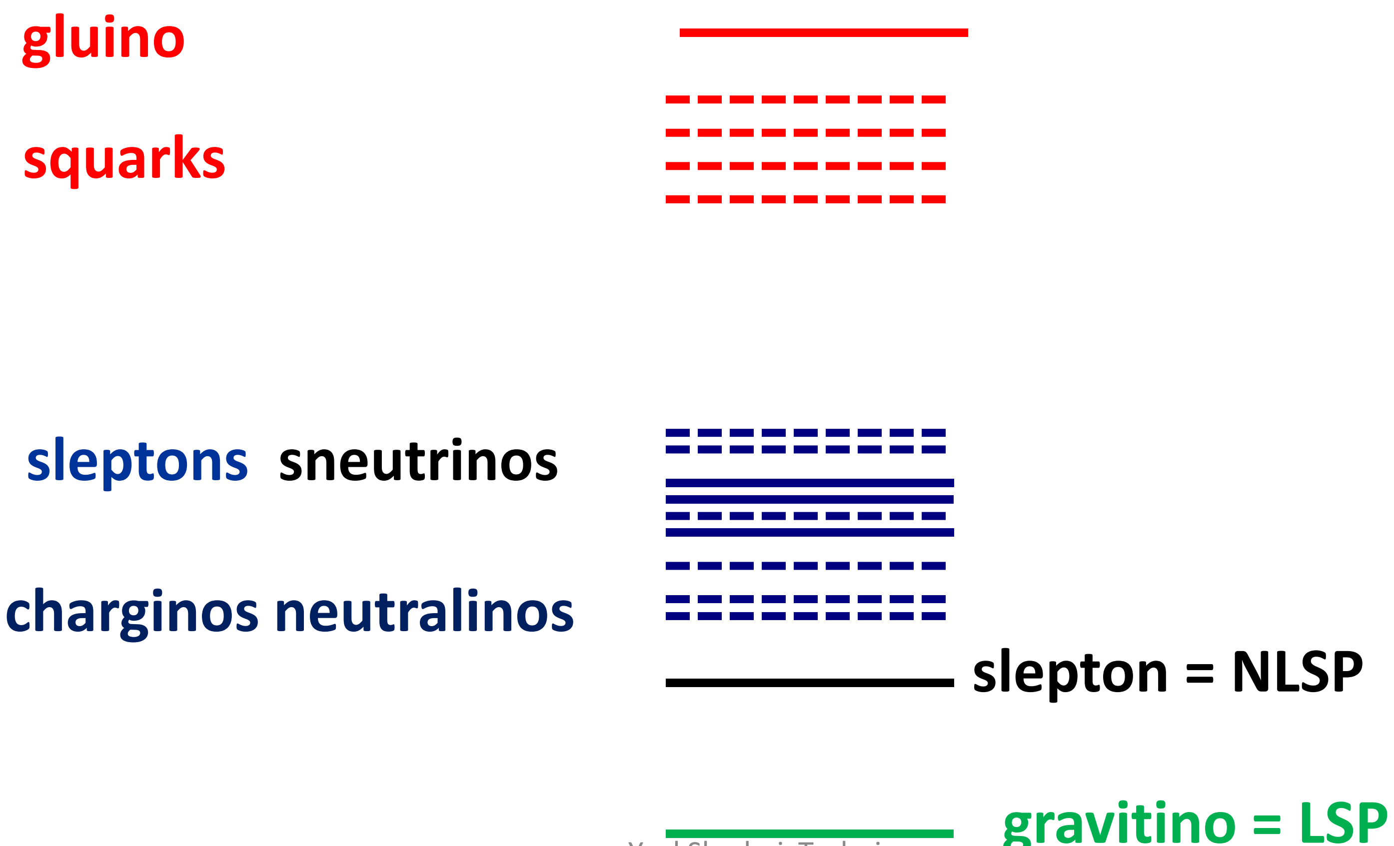
but it can be metastable:



LSP = charged slepton

cosmology ?? ruled out if the slepton is stable

but it can be metastable: **remember the gravitino?**



- lifetime only depends on
  SB scale (→ gravitino mass) and slepton mass
- a whole range
- in particular: slepton can exit detector:
  looks like a muon
- if it's seen: how do we know it's not a muon?
- but will it be seen?
- it`s slow: $\beta < 1$
  trigger? reconstruction? usually assume $\beta = 1$

{this is a good example of

a ``practical application” of thinking about SUSY (other BSM) models

you could say (should say?) we will have this amazing machine

why not look for long-lived charged particles

(regardless of any BSM) }

low beta: is it lost (forever..)?

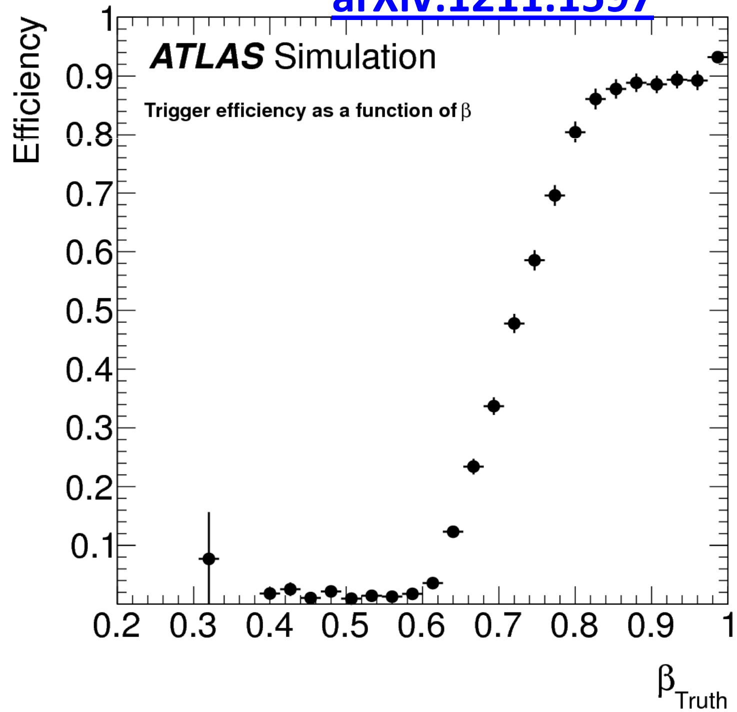
high beta: fake muon?

by now: good coverage in beta

muon detector (ATLAS) TOF

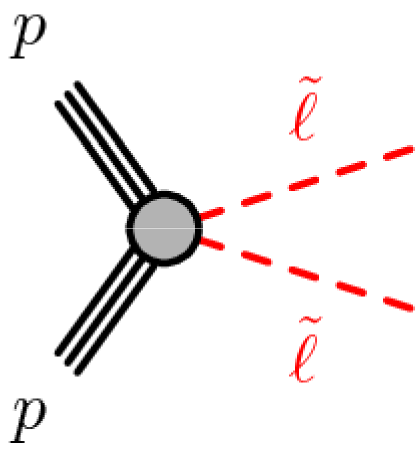
inner detector (CMS) dE/dx

arXiv:1211.1597

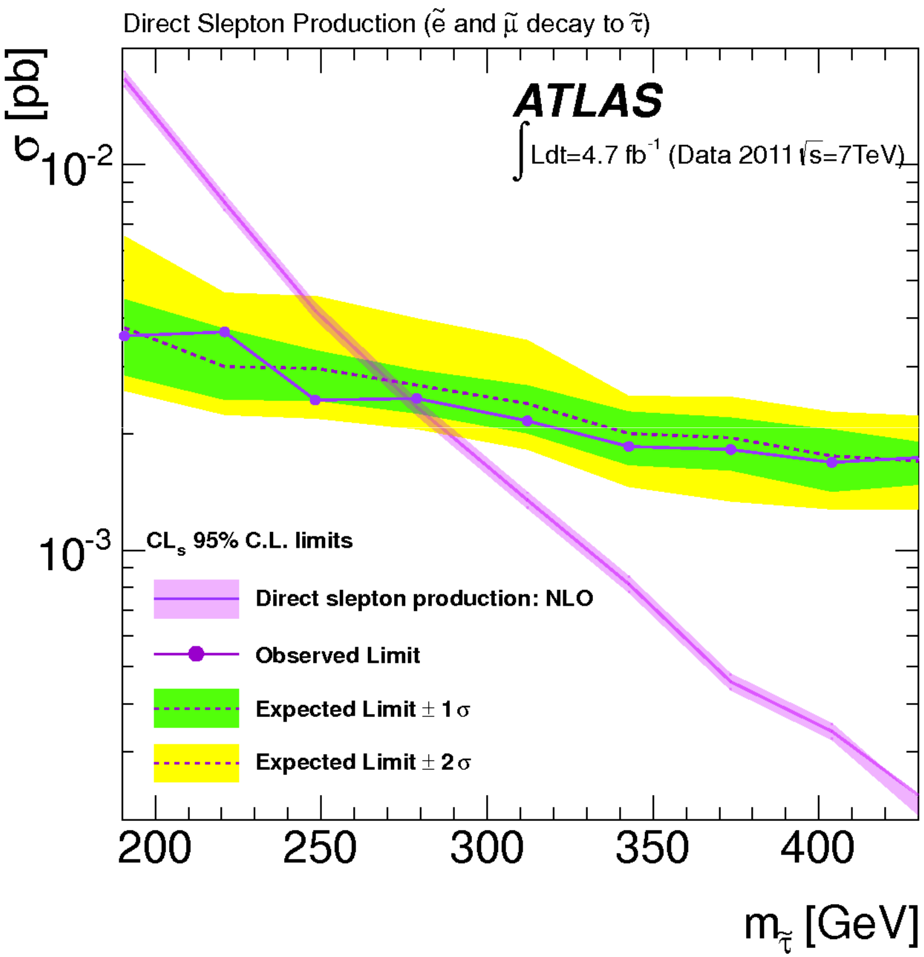


apply to the simplest process:

Drell-Yan slepton production



with ``zero SM bgnd"..



completely
model independent:
(almost)

any long-lived
scalar with charges
of slepton

(old result)

this is our first example of possible SUSY signatures

it’s the simplest: just DY production

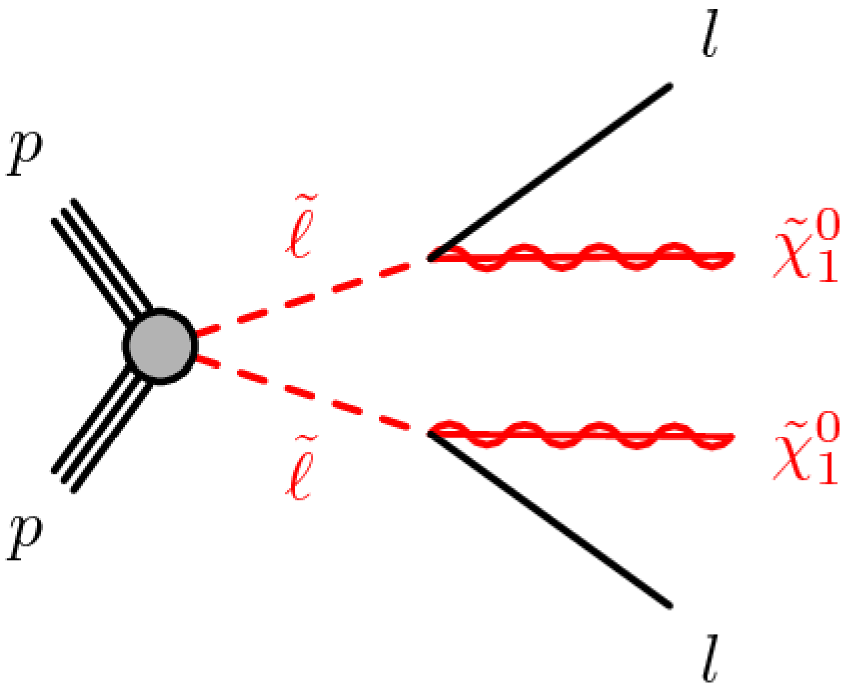
no SM bgnd **IF** you identify the long-lived slepton

let’s move to harder examples

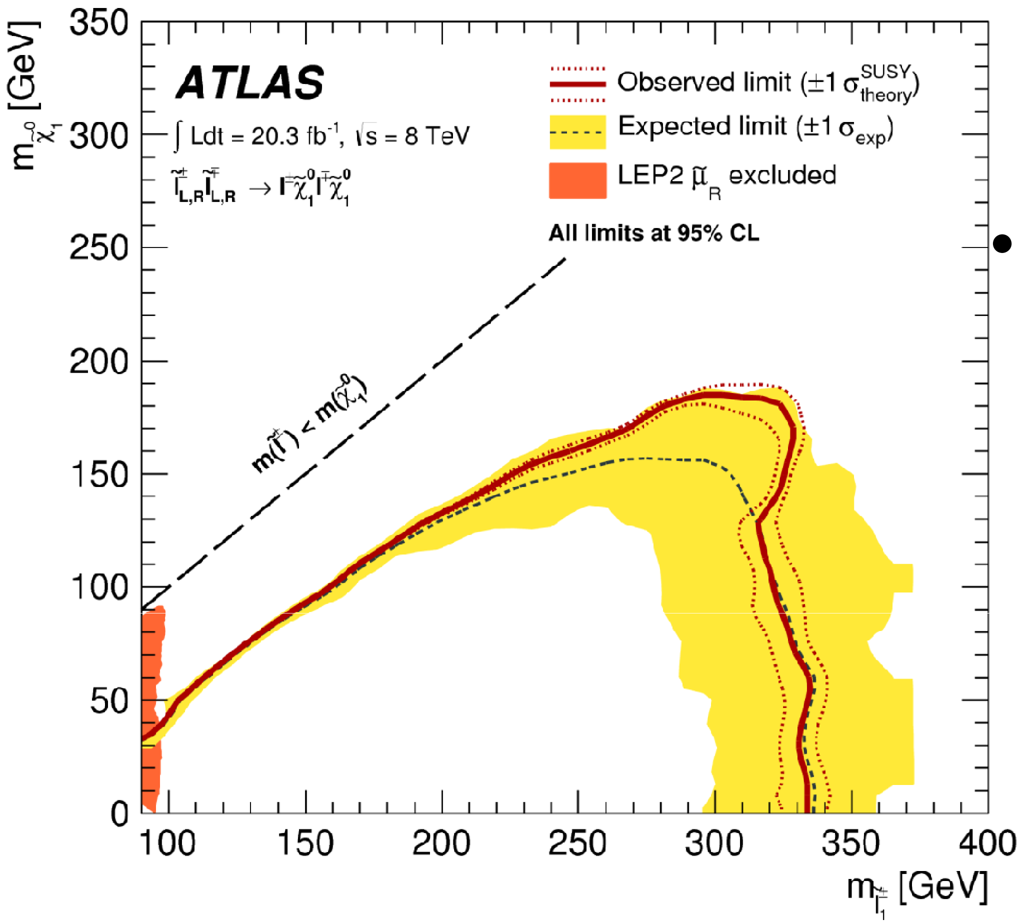
in the process:

- see how the different considerations we listed come into play
- learn about different handles for distnguishing signal from bgnd: **usually the main challenge**

Drell-Yan slepton production: but LSP=neutralino

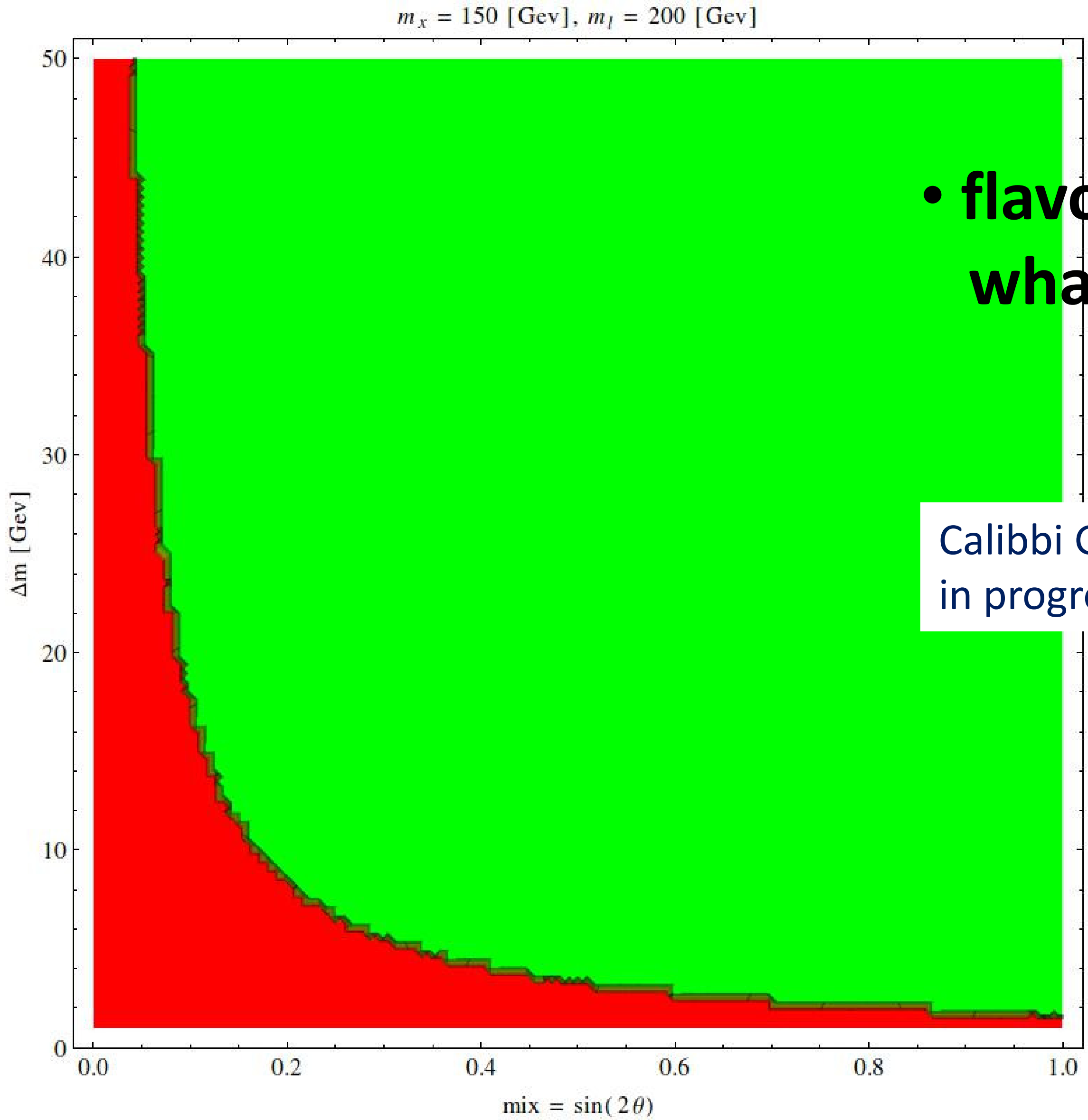


final state: opposite sign (OS) leptons + missing ET



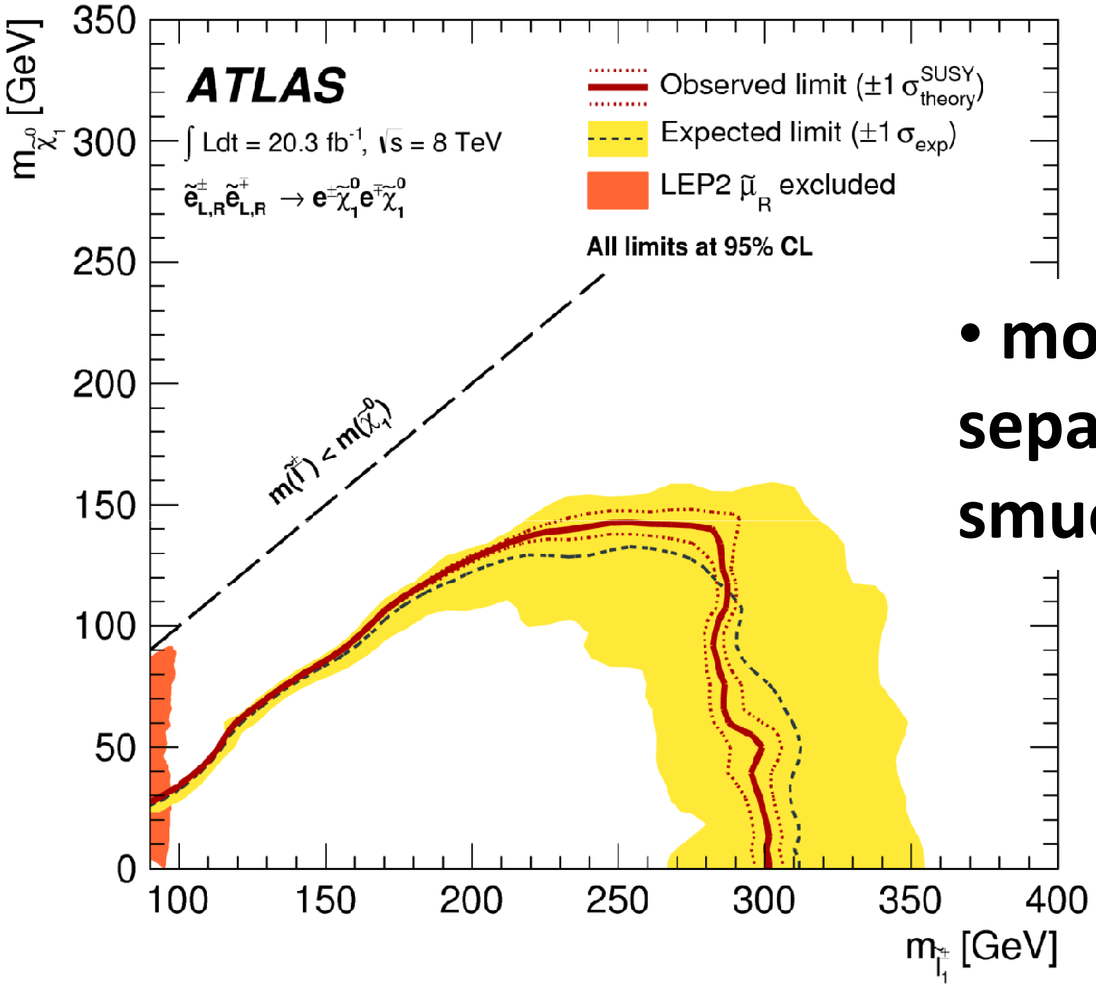
- **efficiency goes down with mass difference**

- **flavor: l=e, mu what if not degenerate?**



- **flavor: l=e, mu**
  what if not degenerate?

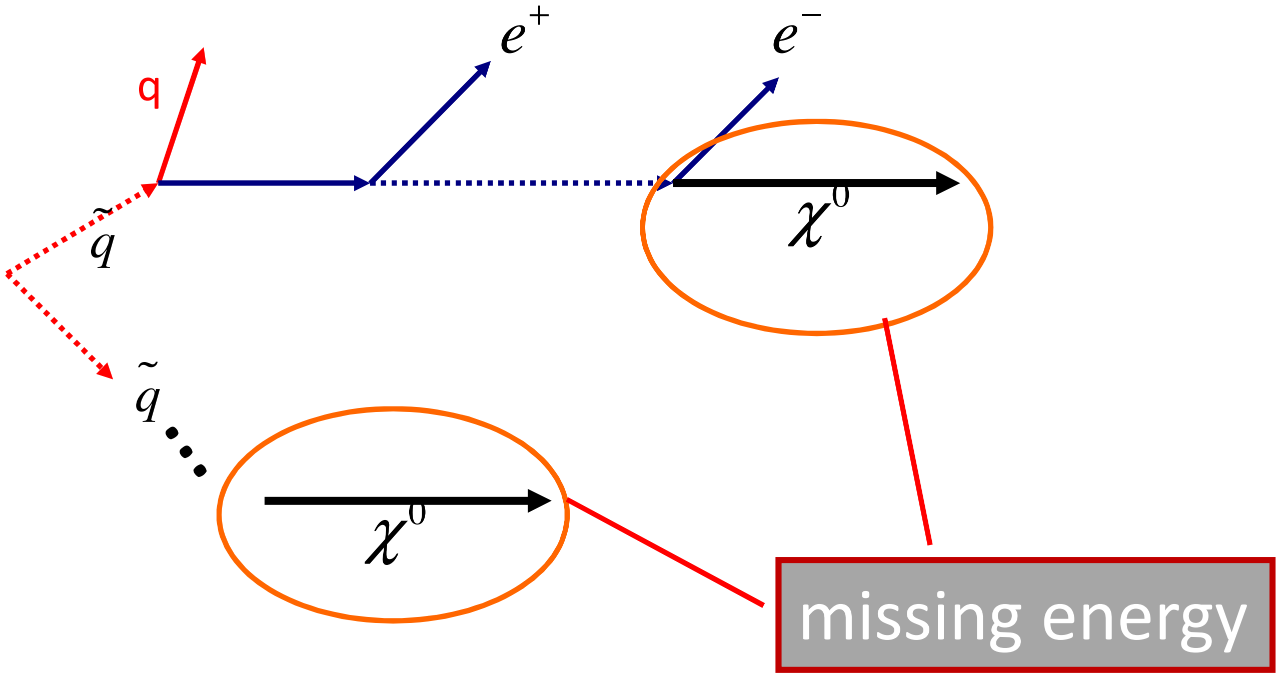
Calibbi Galon Masiero Paradisi YS
in progress



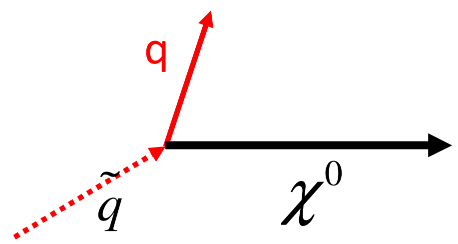
• **more info:**

separate info on selectron, smuon

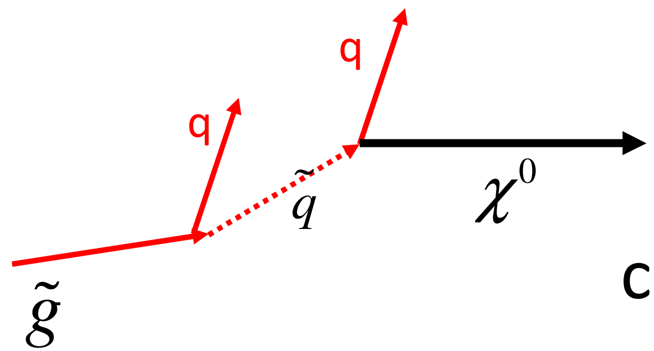
squark/gluino pair production (neutralino LSP)



or a shorter squark decay



gluino decay



costs another jet

squark/gluino pair production (neutralino LSP)

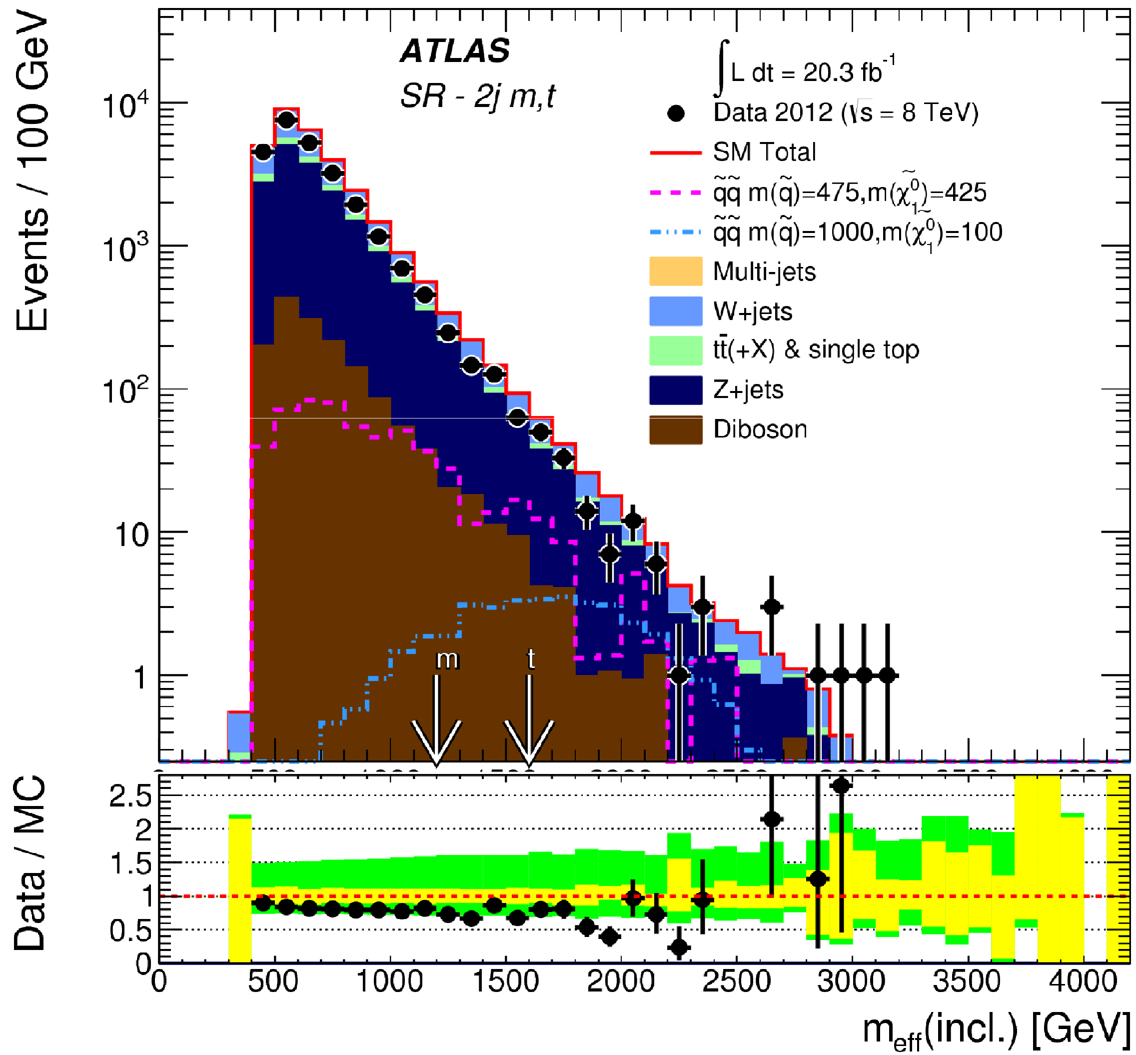
- missing ET + at least 2-4 jets
- missing ET: main tool in fighting SM bgnd
- more: pair production of heavy particles

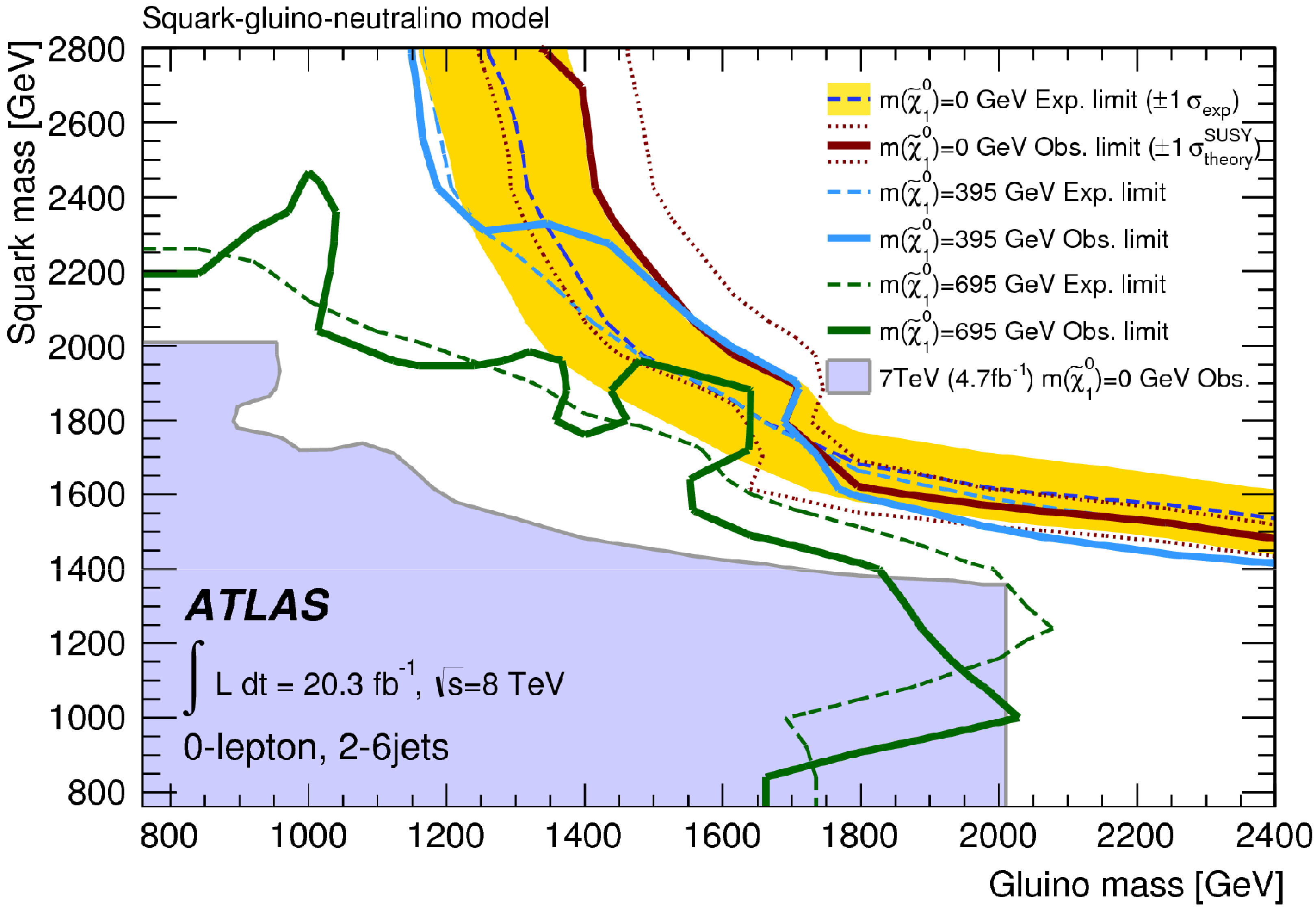
$$m_{eff} = |\vec{p}_T^{\,miss}| + \sum_{jets/vis} |\vec{p}_T^{\,i}| \qquad H_T = \sum_{jets} |\vec{p}_T^{\,i}|$$

- SM falls
- heavy particle production kicks in,
- then falls more slowly

Search for squarks and gluinos with the ATLAS detector in final states with jets and missing transverse momentum using $\sqrt{s} = 8$ TeV proton–proton collision data

signature based (simplified model)



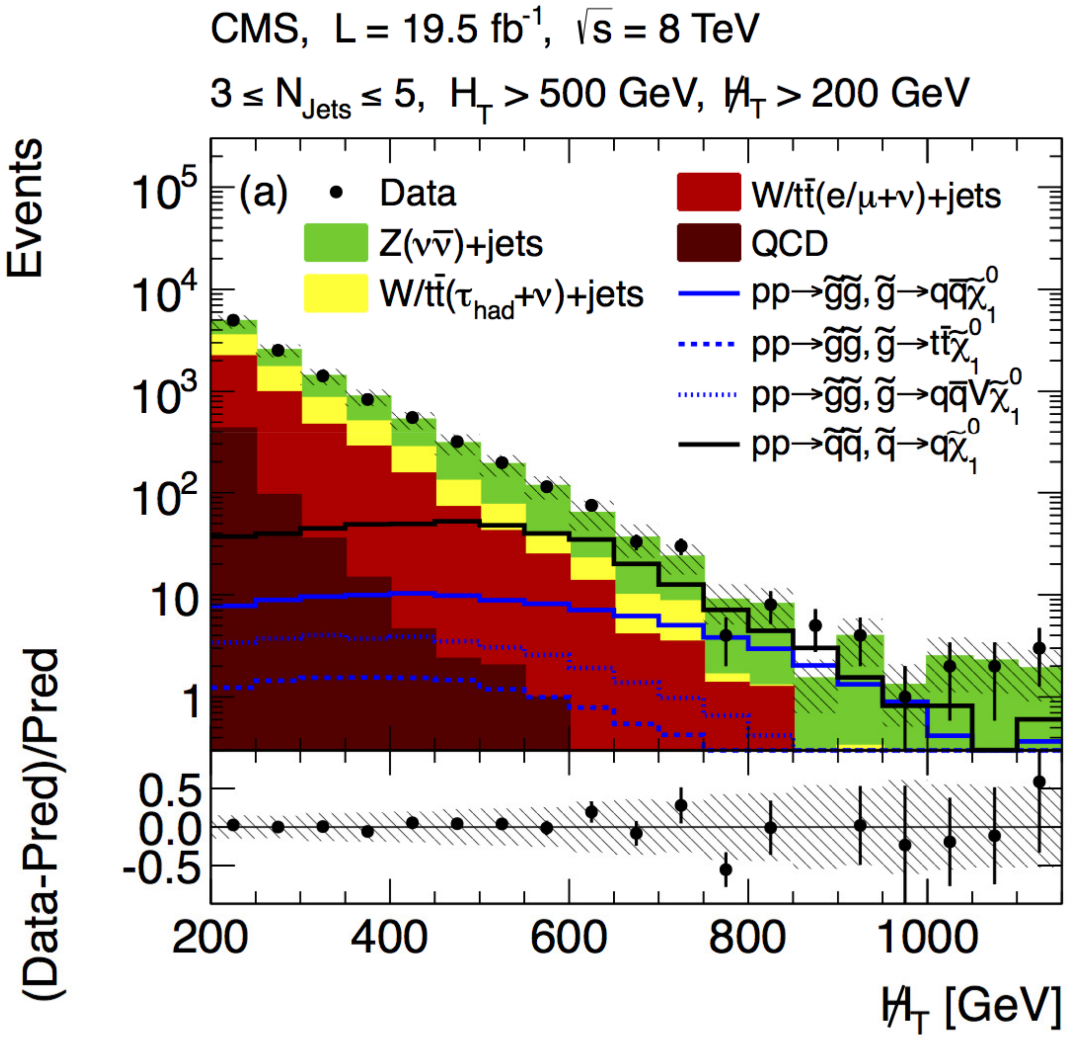


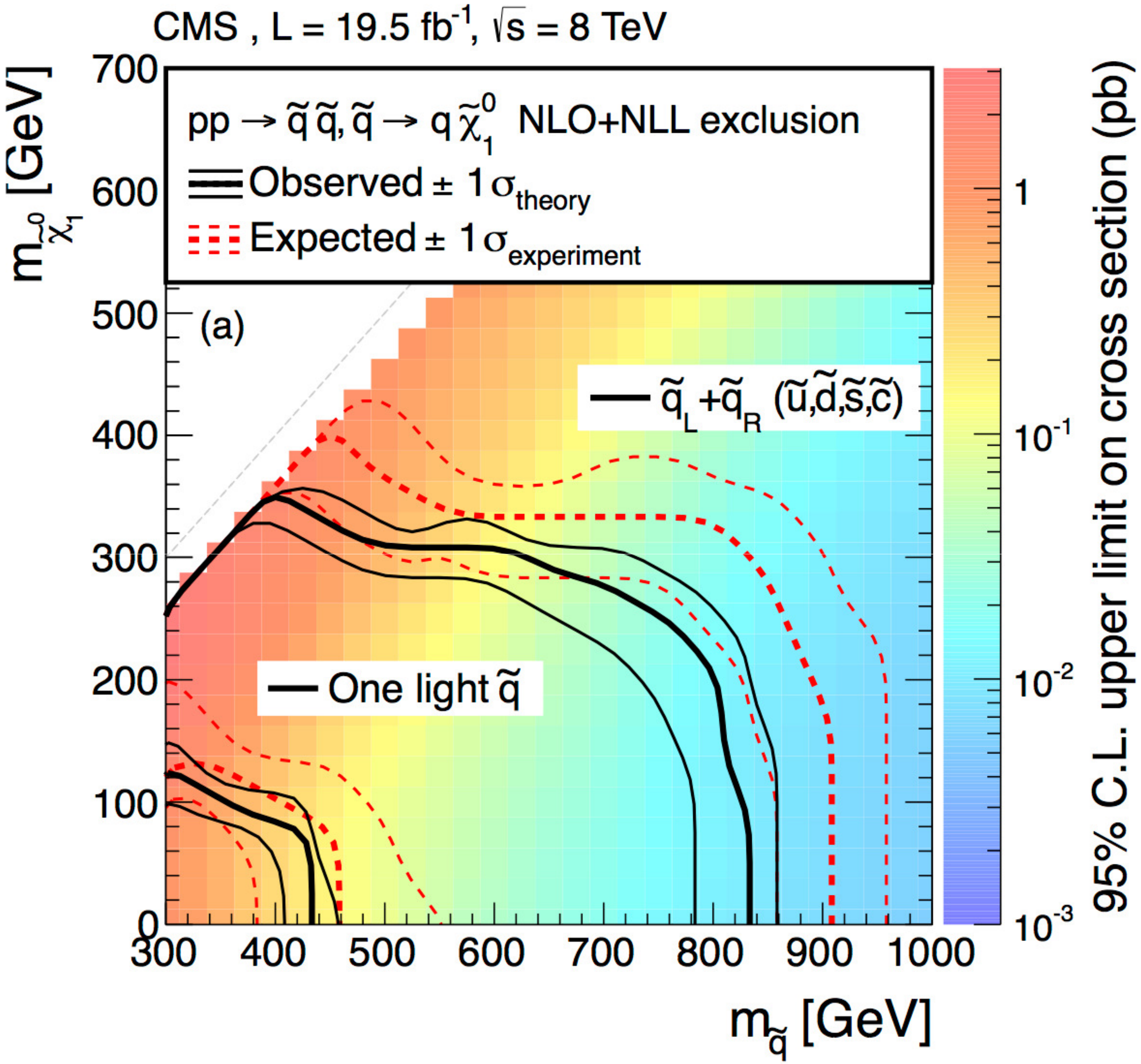
efficiency goes down with mass difference

Search for new physics in the multijet and missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration

signature based (simplified model)





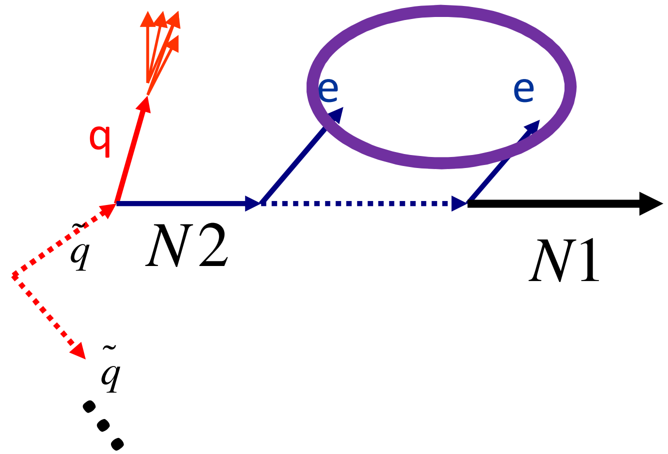
CMS , L = 19.5 fb^{-1}, $\sqrt{s}$ = 8 TeV
$pp \to \tilde{q}\tilde{q}, \tilde{q} \to q\tilde{\chi}^0_1$ NLO+NLL exclusion
Observed ± 1 σ_{theory}
Expected ± 1 $\sigma_{experiment}$
(a)
$\tilde{q}_L + \tilde{q}_R$ ($\tilde{u},\tilde{d},\tilde{s},\tilde{c}$)
One light $\tilde{q}$
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{q}}$ [GeV]
95% C.L. upper limit on cross section (pb)
700
600
500
400
300
200
100
0
300
400
500
600
700
800
900
1000
1
10^{-1}
10^{-2}
10^{-3}

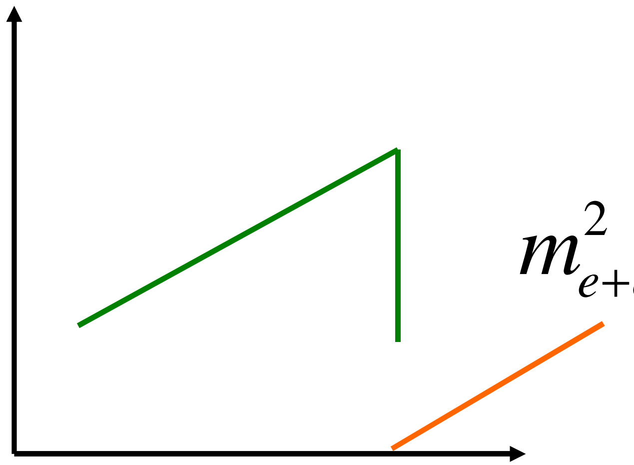
more sophisticated kinematic variables:

kinematic edges:

e+ e- from successive

2-body decays





$$m^2_{e+e-}\Big| \propto (m^2_{N2} - m^2_{\tilde{e}})(m^2_{\tilde{e}} - m^2_{N1})$$

signal is peaked whereas SM flat

event has to sides:

combinatorial bgnds

but there`s also an advantage:

``double" the number of kinematic variable

same number of unknowns (neutralino, slepton masses..)

construct variables that exploit this: M_{T2}

let`s go back and think about other things we mentioned:

flavor: production: squarks not necessarily degenerate

if gluino not very heavy: more sensitive to up, down

but efficiency drops with squark mass: light charm squarks hiding? (CMS plot: around 400 GeV)

flavor: decay: slepton mixing: not just e-e but also e-mu

flavor: top: the top is special:

theory:

- RGE: large top Yukawa: stop mass goes down

  stop usually lightest squark

- top: large contribution to quadratic divergence in Higgs mass

  to avoid fine tuning: OK if just the stop is around the weak scale (with other squarks heavy)

  ``natural supersymmetry”

this motivates dedicated stop searches

to conclude:

supersymmetry is a beautiful and powerful theoretical idea:

it`s an extension of space-time symmetry

it exchanges fermions and bosons

supersymmetric theories: only log divergences

(even when supersymmetry broken by mass splittings) supersymmetric extensions of the SM:

no quadratic divergence in Higgs mass: natural theory (already some fine-tuning since superpartners are heavy)

field content + gauge and Yukawa interactions dictated (by SM + supersymmetry)

supersymmetry-breaking terms can be generated through spontaneous supersymmetry breaking many different possibilities for the mediation

(often just a few parameters determine all the 100 or so supersymmetry-breaking terms in the MSSM)

→ a variety of LHC signatures

when you discover something in the coming run:

is it supersymmetry?