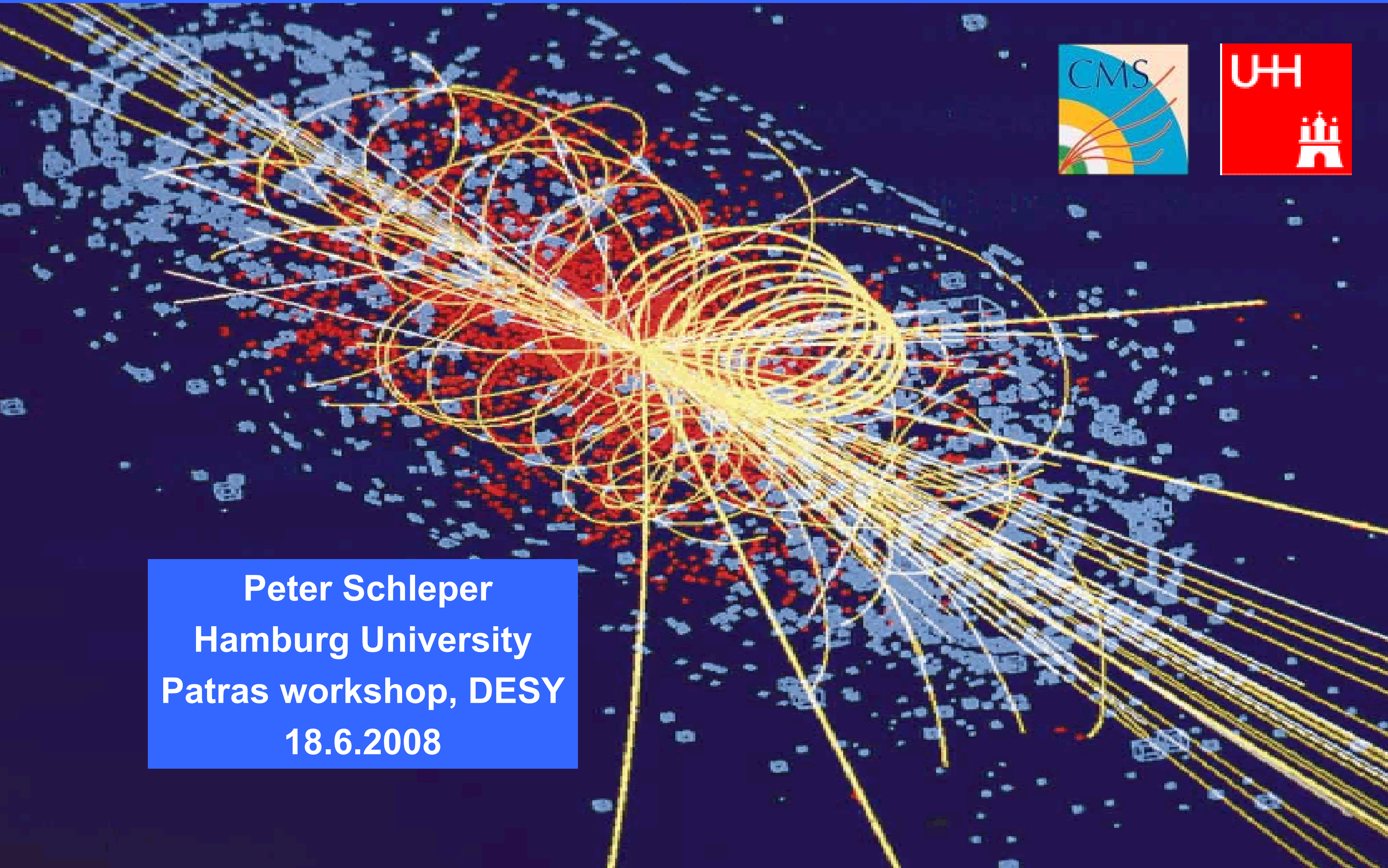
Accelerator based searches



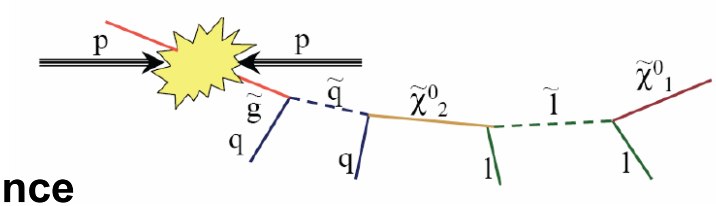
Peter Schleper
Hamburg University

Patras workshop, DESY
18.6.2008

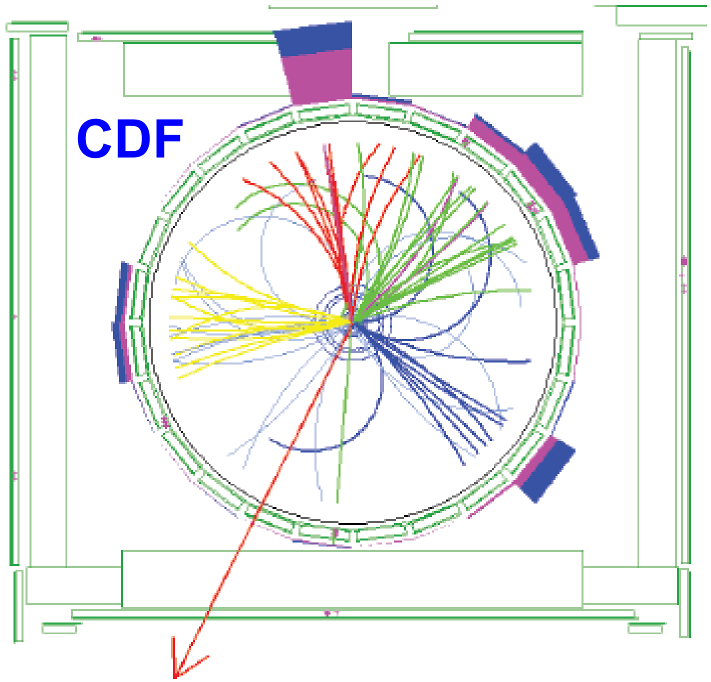
Introduction

Neutral, (very) weakly interacting particles → candidates for dark matter (DM)

DM candidates @ accelerators:



- If stable: invisible within detectors, like ν
- If produced together with SM particles:
  detectable as missing momentum in 4-momentum balance
- If produced together with other new particles: detectable as invisible decay product
  → requires mass gap
  → the hope: simultaneous discovery of DM particle and annihilation partners
  → a new sector in particle physics, e.g. Supersymmetry



- high energy → production of very heavy particles
- rich kinematic information in single interactions
  of (most) final state quanta
- detailed investigations possible (at least in principle)
  of rates, masses, decays, (spin)
- small number of colliding particles
  → requires not too small coupling

→ here: will concentrate on Supersymmetry

Accelerators

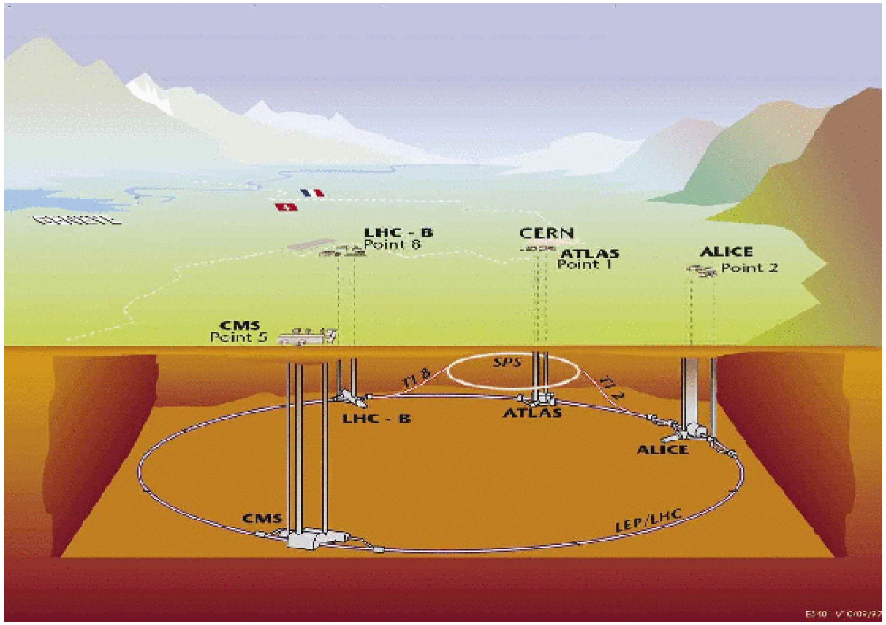
LEP: e+e- @ 209 GeV (finished)

- $M_{chargino}$ > 103.5 GeV, $M_{sleptons}$ > 100GeV,
- M_h > 114.5 GeV (if Higgs is SM-like)

HERA: ep @ 318 GeV (finished)

- only for R-parity violating SUSY → spoils DM candidates

LHC



Tevatron: pp @ 2 TeV (2009/10) CDF, D0

- Highest energy accelerator currently
- news on squarks, gluinos and charginos from $2 fb^{-1}$ (aim: $8 fb^{-1}$)

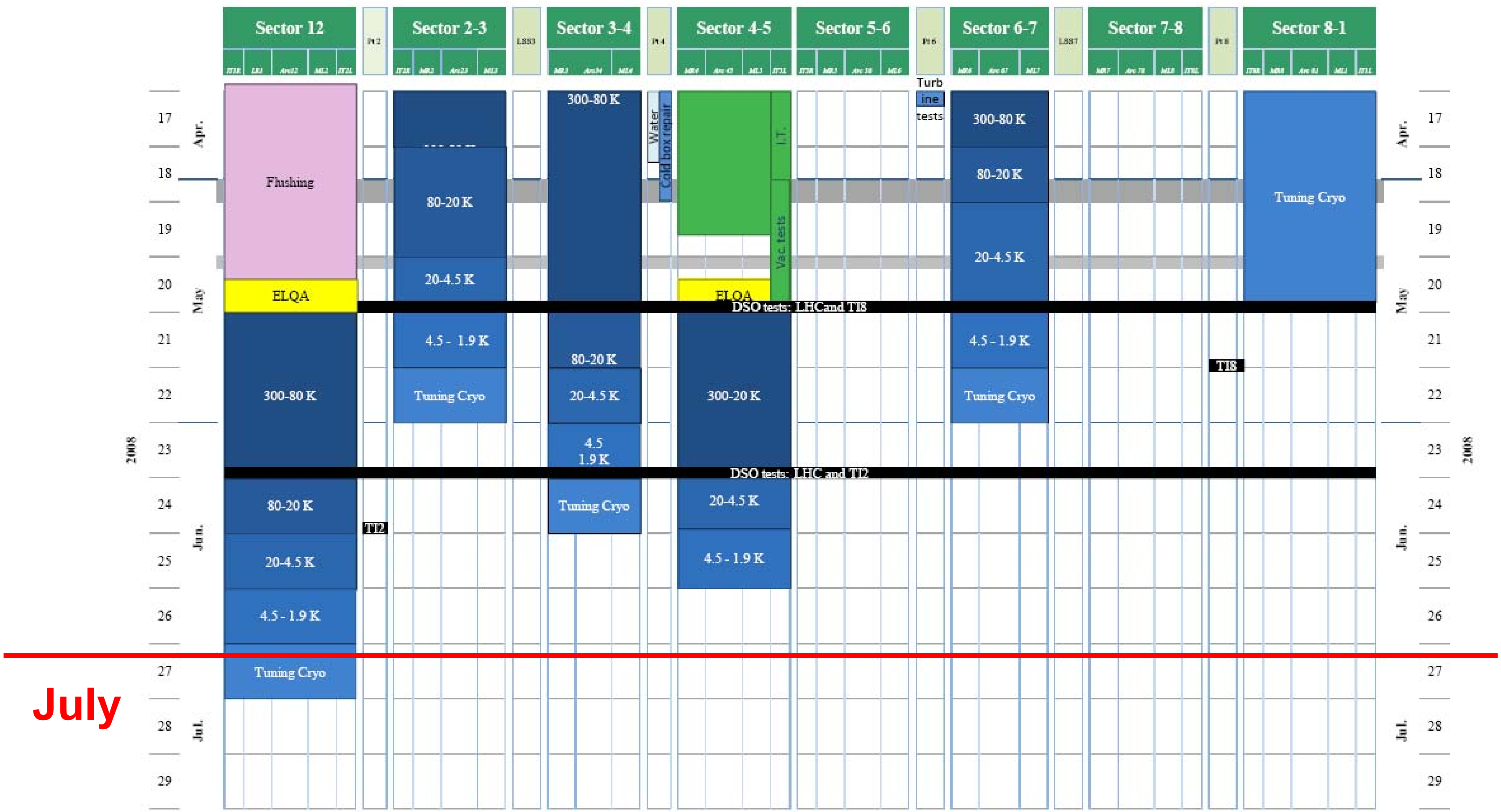
LHC: pp @ 14 TeV (July) ATLAS, CMS

- The machine to explore the TeV scale

ILC: e+e- @ 500 … 1000 GeV (not decided)

- precision TeV scale physics

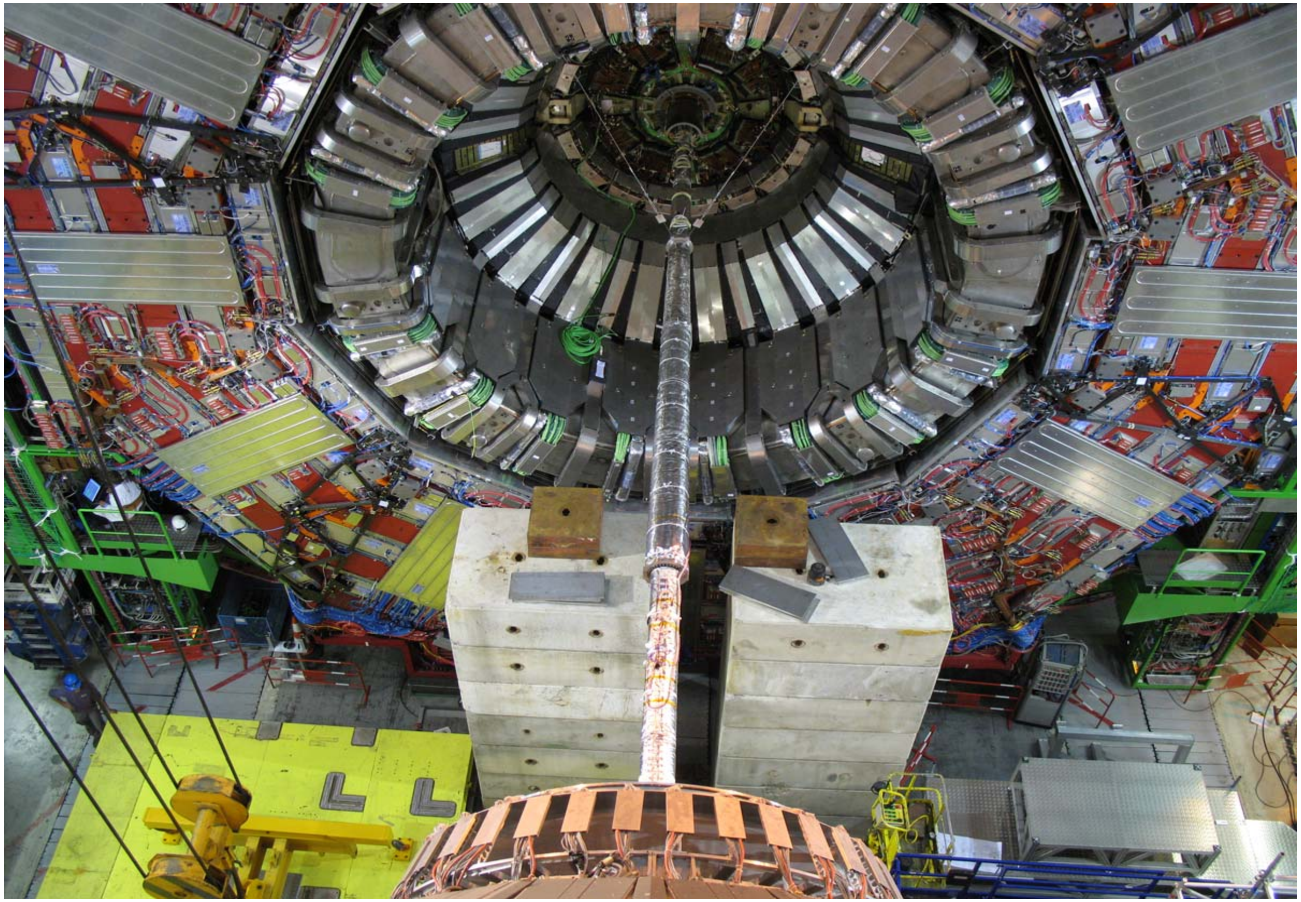
LHC machine status
cool down of accelerator segments



LHC sectors cooled down by mid July

commisioning of superconducting magnets, ...

LHC Experiments and Luminosity



ATLAS, CMS should close 2008, mid July

+ 10 days: first beam

+ 2 month: collisions at 10 TeV

21. Oct: LHC inauguration

Winter shutdown

2009: full energy (14TeV)

Bunches	Luminosity
1 x 1	10^{27}
43 x 43	3.8×10^{29}
43 x 43	1.7×10^{30}
43 x 43	6.1×10^{30}
156 x 156	1.1×10^{31}
156 x 156	5.6×10^{31}
156 x 156	1.1×10^{32}

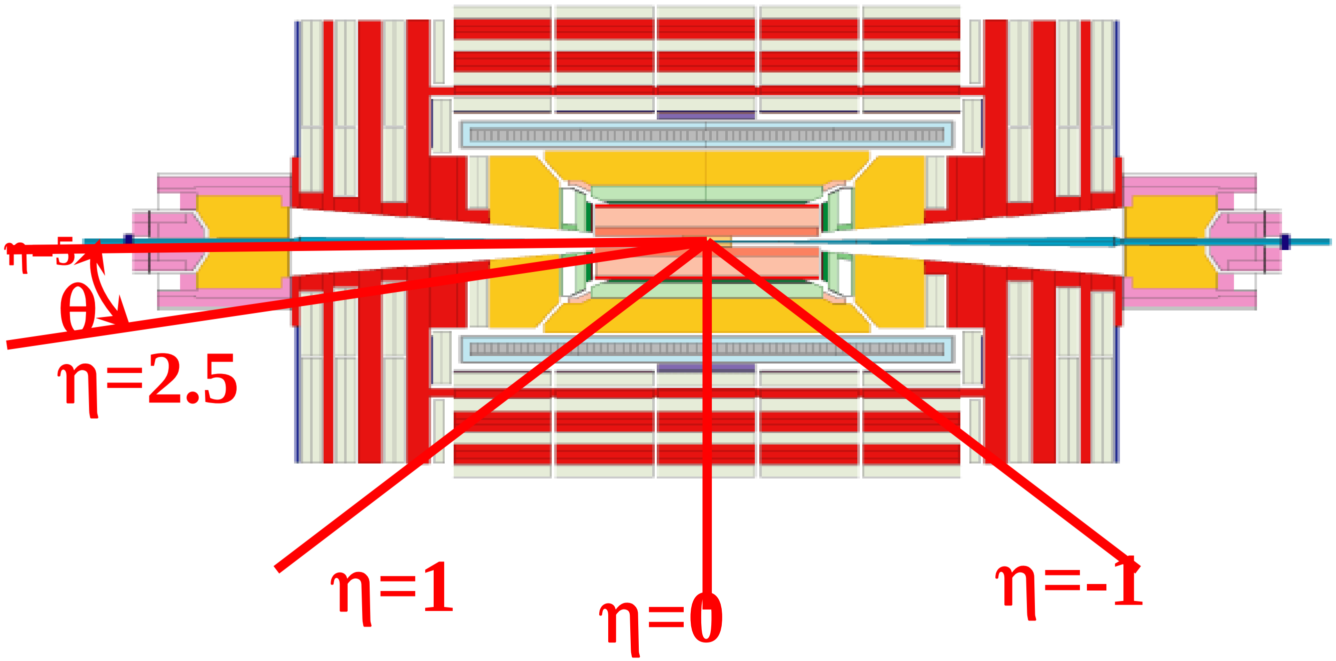
Time needed for ramp up of integrated luminosity

	2009	2012	→ upgrade to SLHC
...	100 pb^{-1}	... 100 fb^{-1}	→ 1000 fb^{-1}

$P_{T,miss}$ reconstruction

LHC detectors ATLAS & CMS

- hermiticity of detectors: no escaping particles (except ν)
- losses close to beam pipe → angular coverage of calorimeters up to η=2.5 …5



Large η calorimeters: difficult to calibrate

- tails in jet energy resolution: punch through (leakage of hadronic showers)
- cosmics, beam related background
- pile-up from other events of same/previous/following bunches

$P_{T,miss}$ reconstruction

Irreducible SM background:

- $Z \rightarrow \nu\nu$, $W \rightarrow l\nu$, $t \rightarrow Wb \rightarrow l\nu b$, $b,c \rightarrow l\nu q$
- measure bkg rates from data: e.g. measure $Z \rightarrow \mu\mu$ to predict $Z \rightarrow \nu\nu$

Experimental thresholds:

Tevatron: $P_{T,miss}$ > 100 ..200 GeV

LHC: low luminosity (2 * 10^{31} cm^{-2} s^{-1})

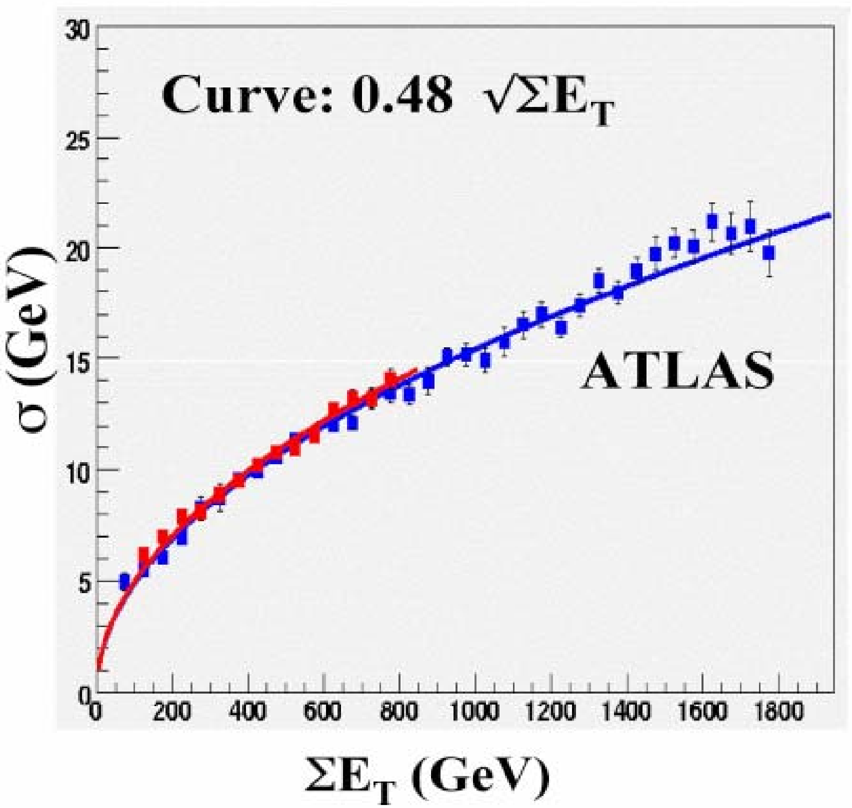
CMS planning

- Trigger: $P_{T,miss}$ > 60 GeV &
  1jet with $P_{T,jet}$ > 180 GeV or
  2jets with $P_{T,jet}$ > 125 GeV or
  3jets with $P_{T,jet}$ > 60GeV
- Analysis: $P_{T,miss}$ > 200 GeV & jets

LHC: large luminosity

- $P_{T,miss}$ > 200 ..600 GeV

ATLAS $P_{T,miss}$ resolution



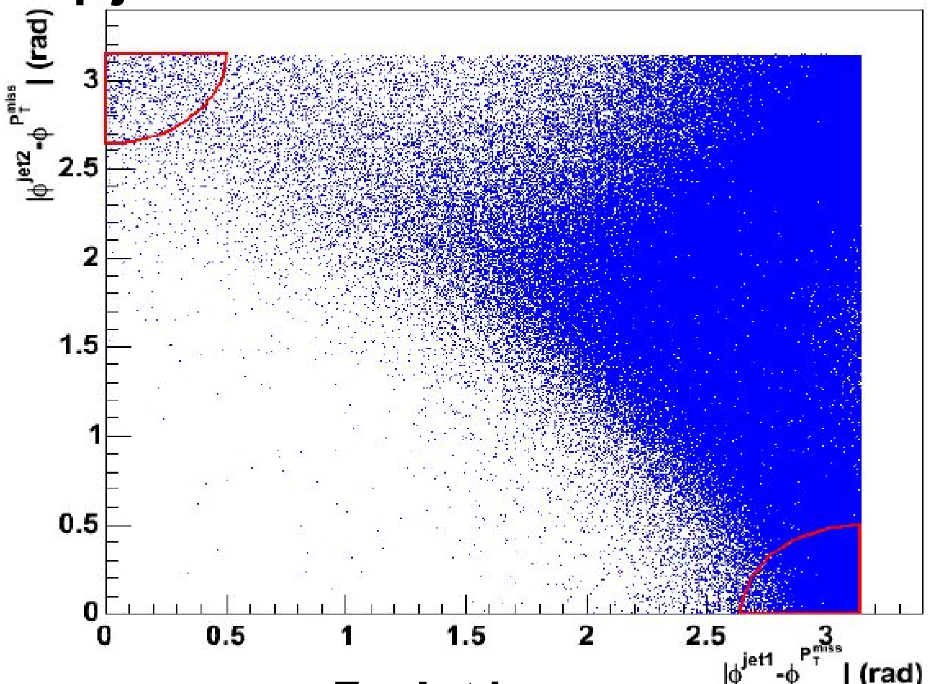
QCD background

QCD jets → huge rates, large uncertainties

ETmiss dominated by jet resolution → reducible background

- Cut on PTmiss direction w.r.t. jet direction
- Use remainder to estimate Bkg. from data

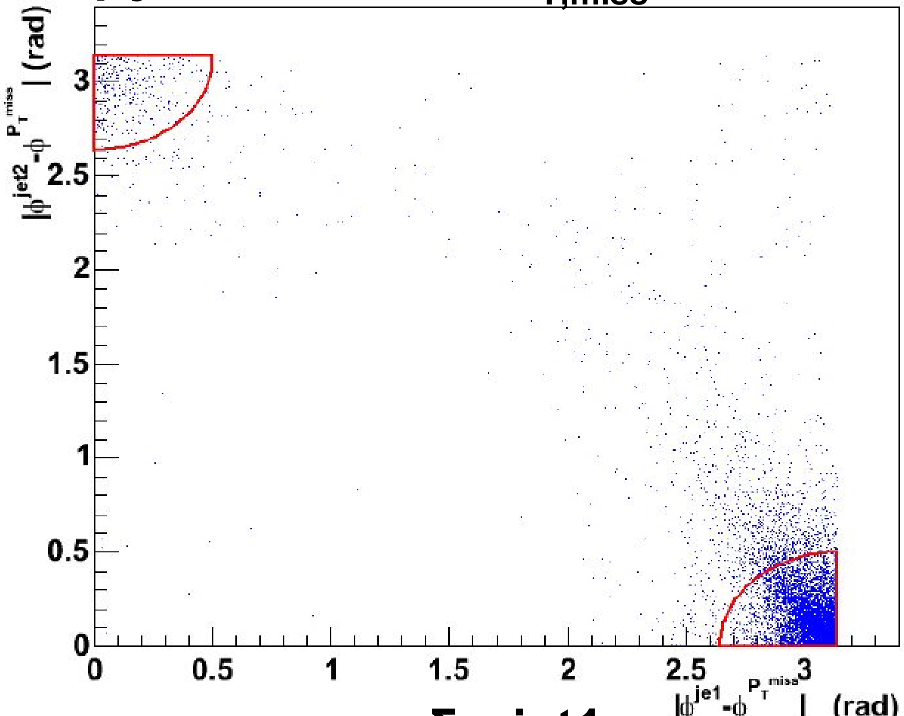
δφ jet2 SUSY simulation



δφ jet1

QCD simulation

δφ jet2 $P_{T,miss} > 200$ GeV

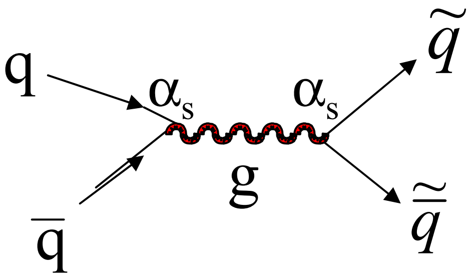


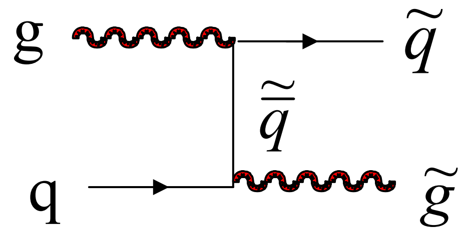
δφ jet1

Sparticle production at Tevatron and LHC

- **Squarks and gluinos:** produced via strong processes

→ large, known cross-section



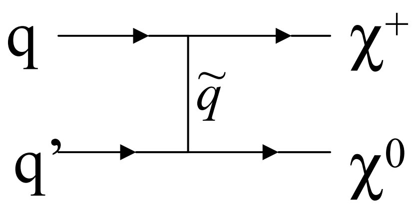


LHC

M (GeV)	*σ (pb)*	*Evts/yr*
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3

- **Charginos, neutralinos, sleptons:** direct production via electroweak processes

→ much smaller rate (appear in squark and gluino decays)



LHC: $\sigma \approx$ pb for $m_\chi \approx$ 150 GeV

$$\tilde{q}\tilde{q}\,,\,\tilde{q}\tilde{g}\,,\,\tilde{g}\tilde{g}$$

production are <u>dominant</u> SUSY processes at LHC (if accessible)

Tevatron results

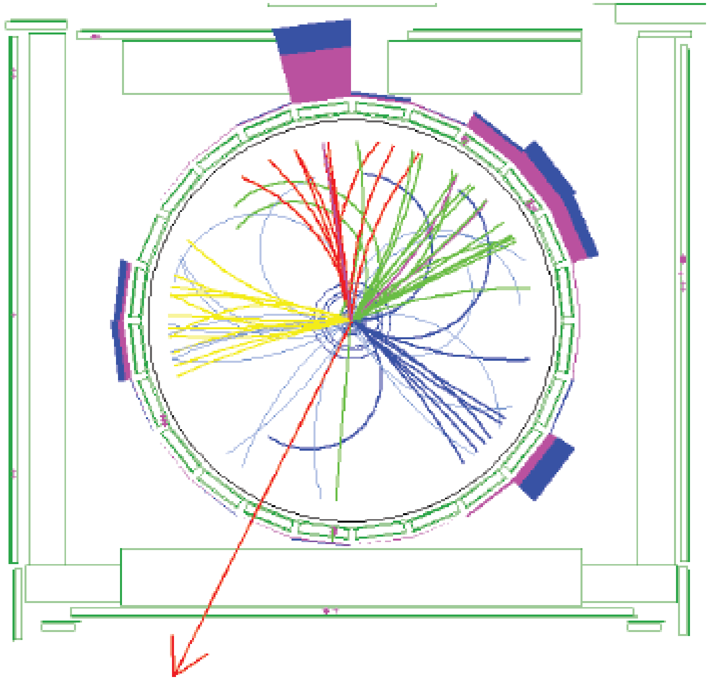
Search for gluinos-squarks

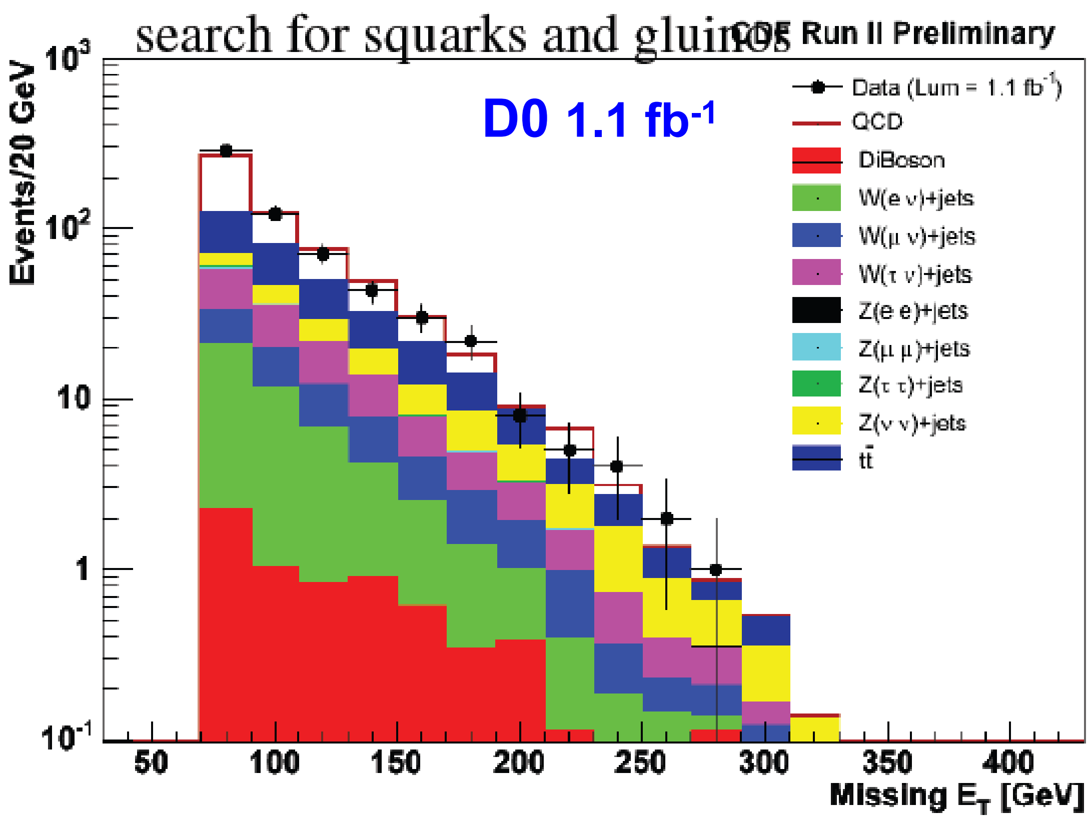
- High cross section for $\tilde{q}\tilde{q}, \; \tilde{q}\tilde{g}, \; \tilde{g}\tilde{g}$
- Decays to 2, 3 or 4 jets + χ_1^0

$$\tilde{g} \rightarrow qq\chi_1^0 \qquad \tilde{q} \rightarrow q\chi_1^0$$

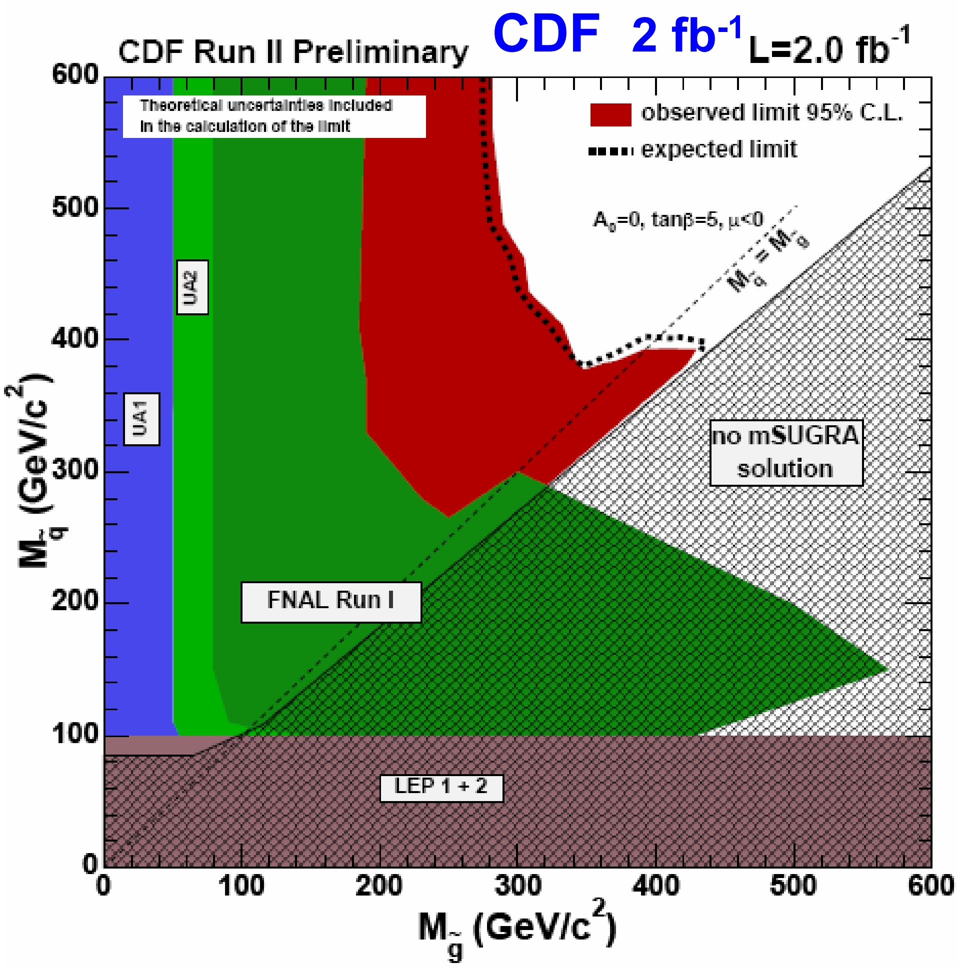
- $P_{T,miss}$ > 200 GeV for 2 jets
  > 100 GeV for 4 jets
- About 10 events seen /expected
  → no signal

CDF event with highest PT,miss





Tevatron results

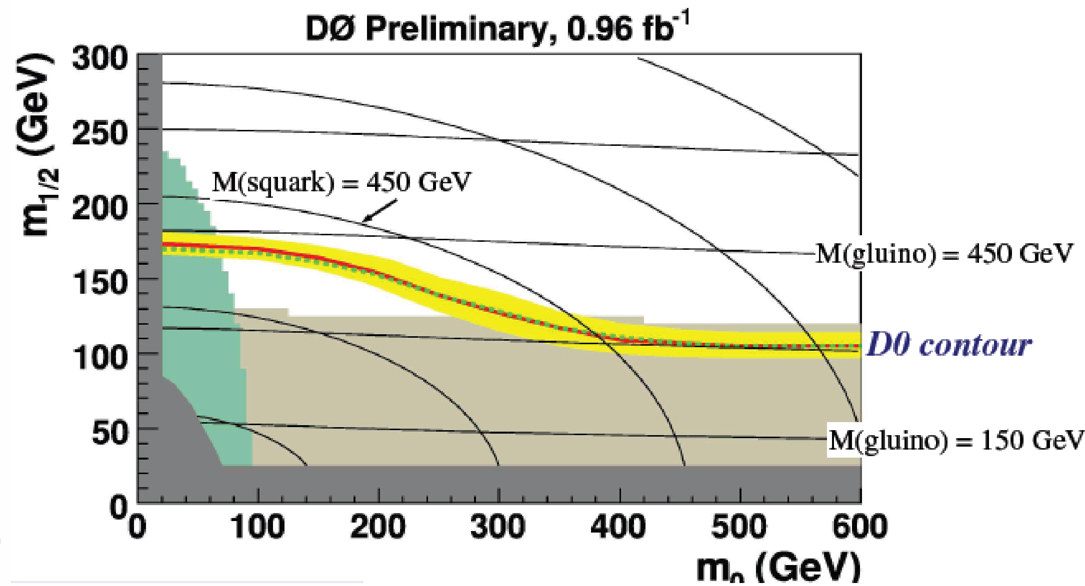


Search for gluinos-squarks

- **mSUGRA limit** for $\tilde{q}$ of 1.+2. generation

$$M_{\tilde{q}} > 400\mathrm{GeV}$$

$$M_{\tilde{g}} > 300\mathrm{GeV}$$



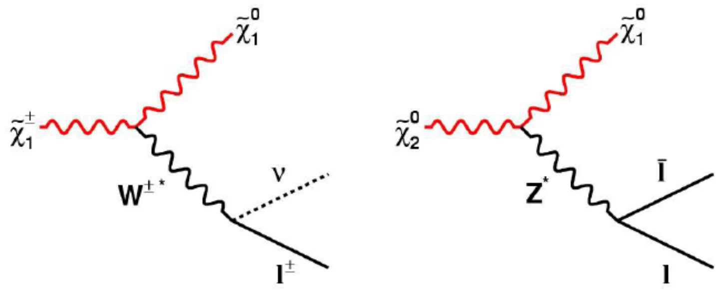
Light stop: $\tilde{t} \rightarrow c\chi_0^1$

→ $M_{\tilde{t}} < 149$ GeV for $M_{\chi_0^1} < 63$GeV **excluded**

Tevatron results

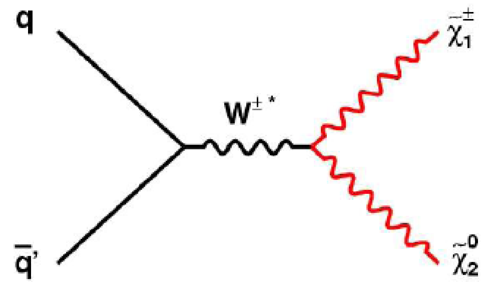
Search for chargino-neutralino production

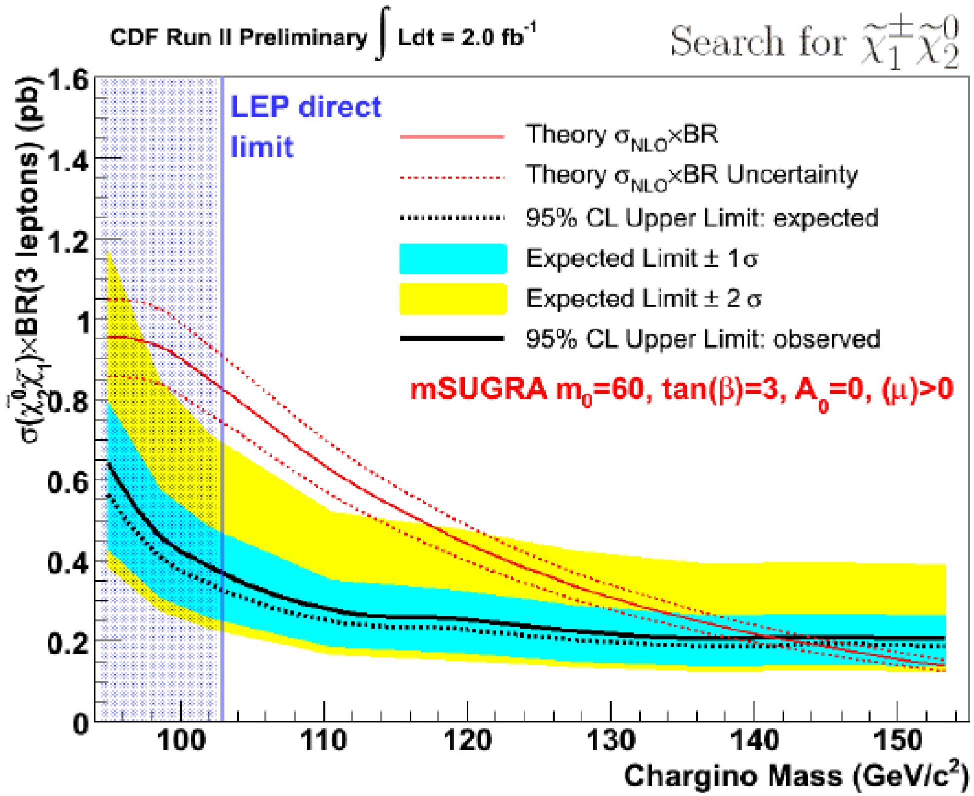
- decay in 3l + $P_{T,miss}$



→ small SM bkg even at low $P_{T,miss}$ > 20 GeV

- Data / SM = 7 / 6.4 events
- no signal
  → mSUGRA limit
  $M(\tilde{\chi}_1^{\pm})$ > 140 GeV

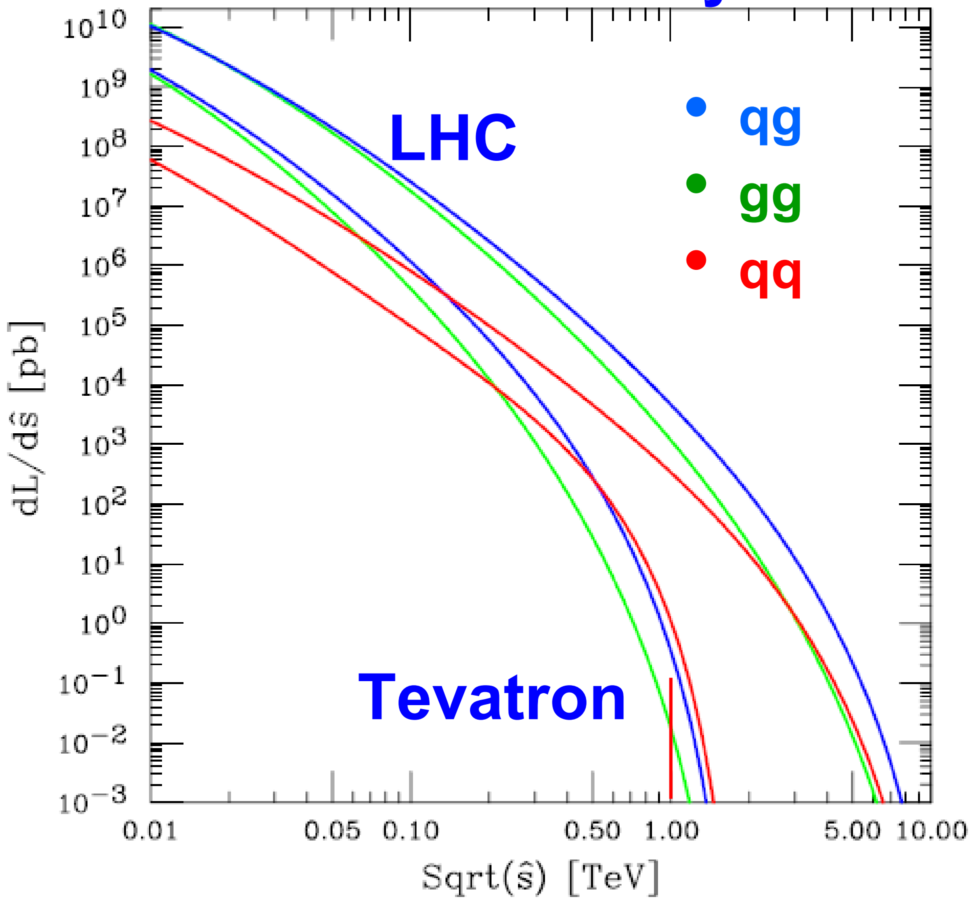




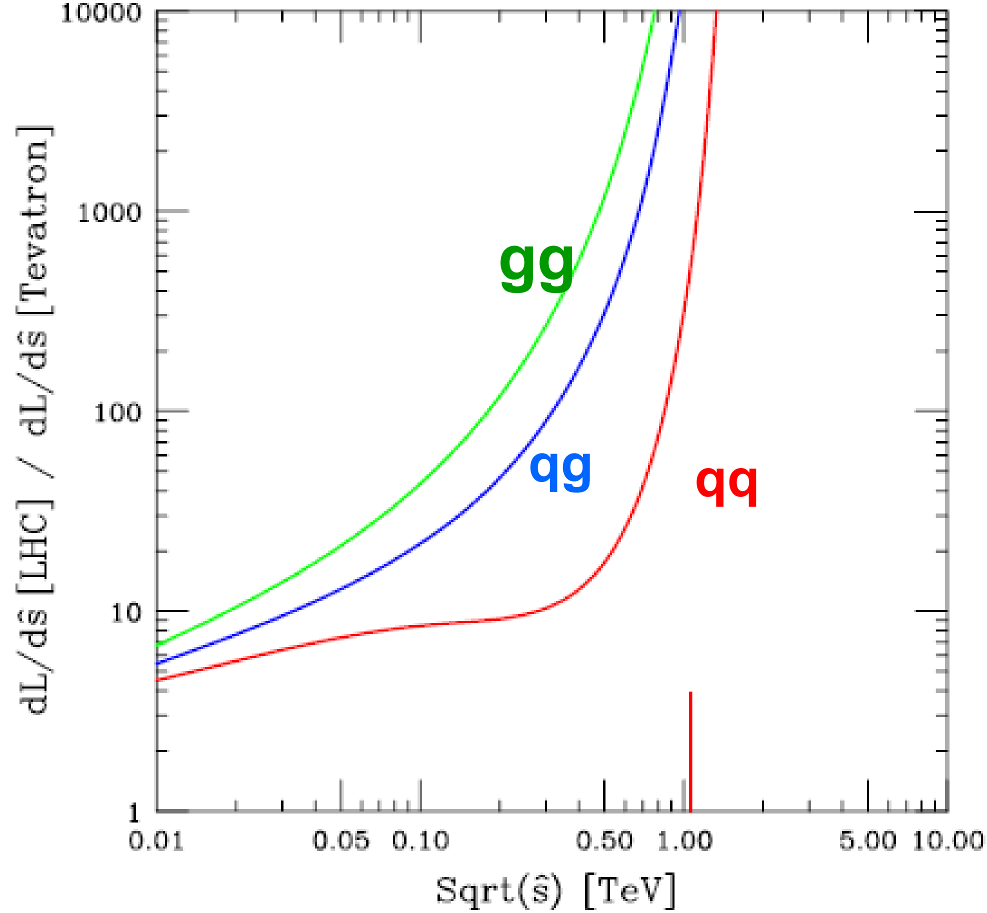
mSUGRA favourable since fairly large mass splitting in decay chain
→ large P_T leptons, large $P_{T,miss}$

Tevatron – LHC comparison

Parton Luminosity



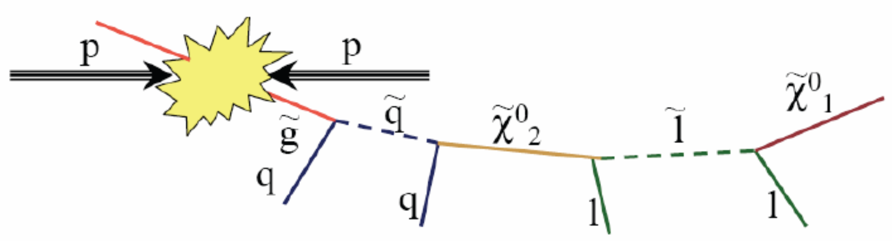
Ratio LHC / Tevatron:



LHC / Tevatron: factor 40 for gg→ H @ M_H= 120 GeV

factor 10000 for gg→ XX @ M_X= 0.5 TeV

LHC: signal and background

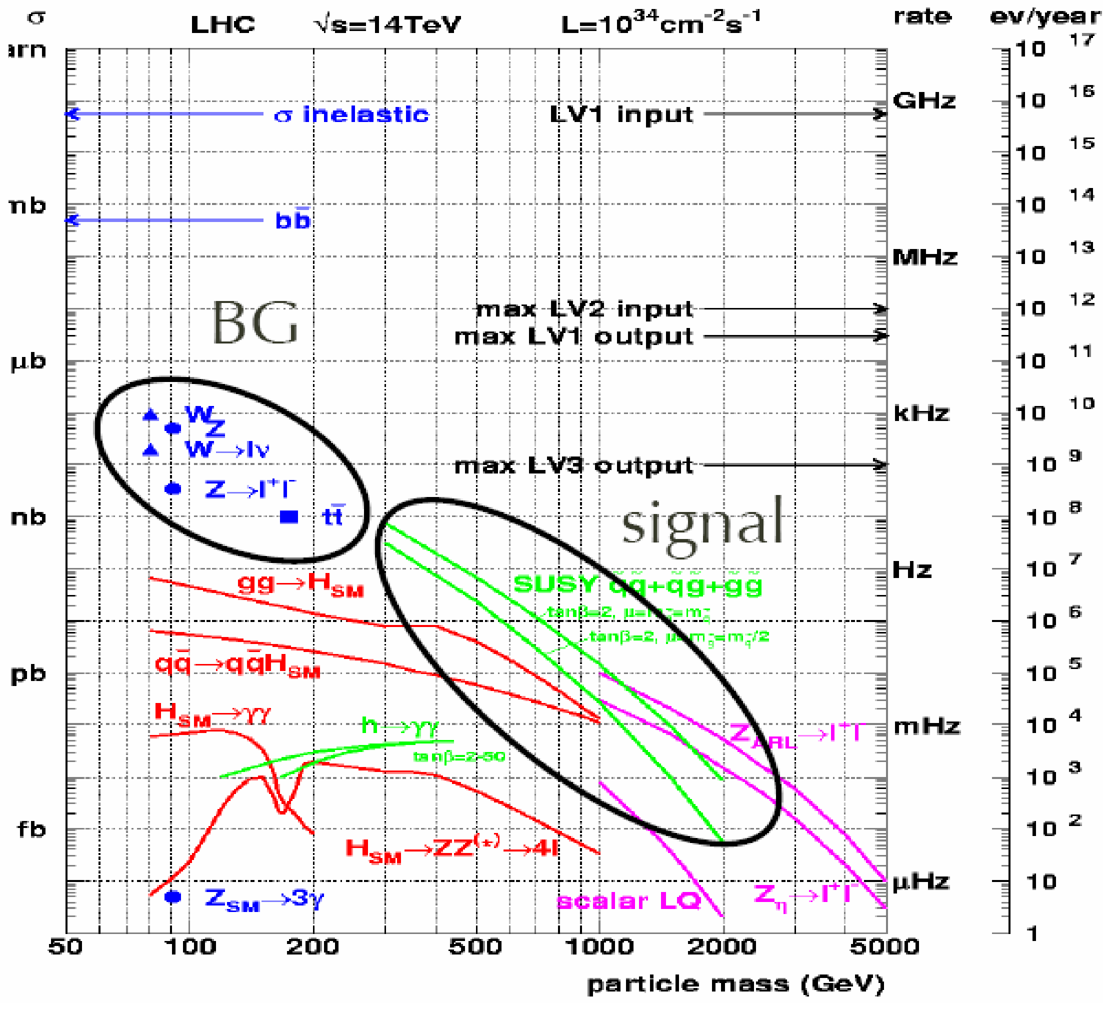


Dominant production of colored sparticles which will decay to leptons, jets + LSP

SUSY signal:
jets (and leptons) with large Pt
+ missing transverse energy
(typical e.g. for mSUGRA, GMSB)

BG from W, Z and tt production:
need strong rejection ~10^{-4}

Exploit kinematics to maximum extent:
mass reconstruction method



LHC SUSY analysis strategy

1) Inclusive analysis

- Jets + ETmiss (+leptons)
  - ➡ First evidence
  - ➡ use Meff, ETmiss, #jets,l, event rate
    - ➡ R_P
    - ➡ estimate squark+gluino mass,

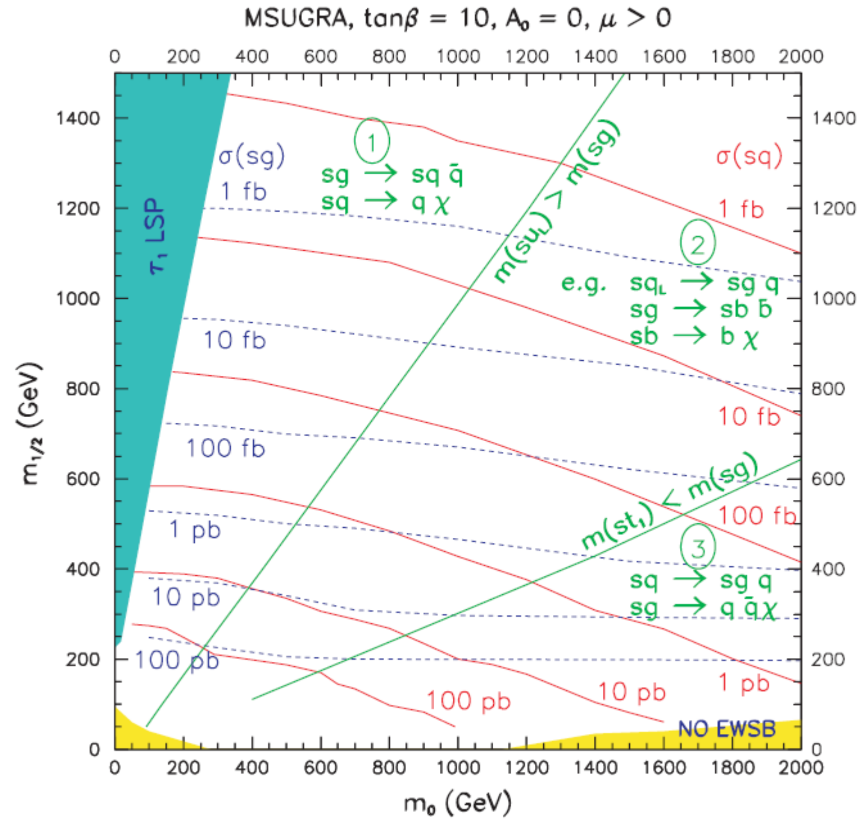
2) Exclusive analysis

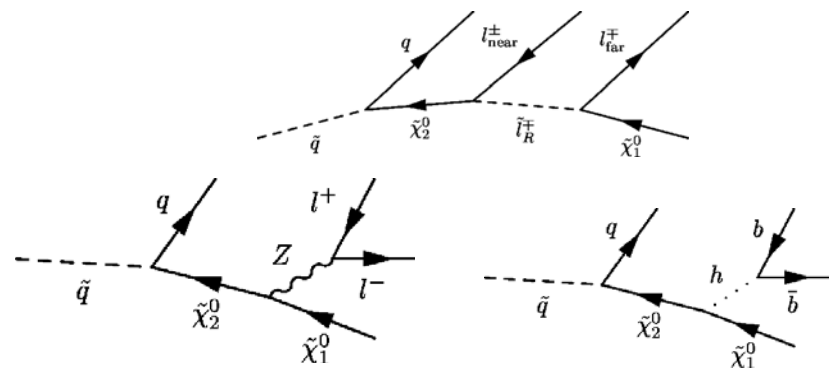
- check for e, mu, tau, gammas, Z0, W, top, higgs, heavy stable particles
  - ➡ kinematic analysis
  - ➡ estimate SUSY masses, BR

3) Higgs mass, SUSY higgs search

4) Check consistency with DM searches

➡ Is it SUSY ?

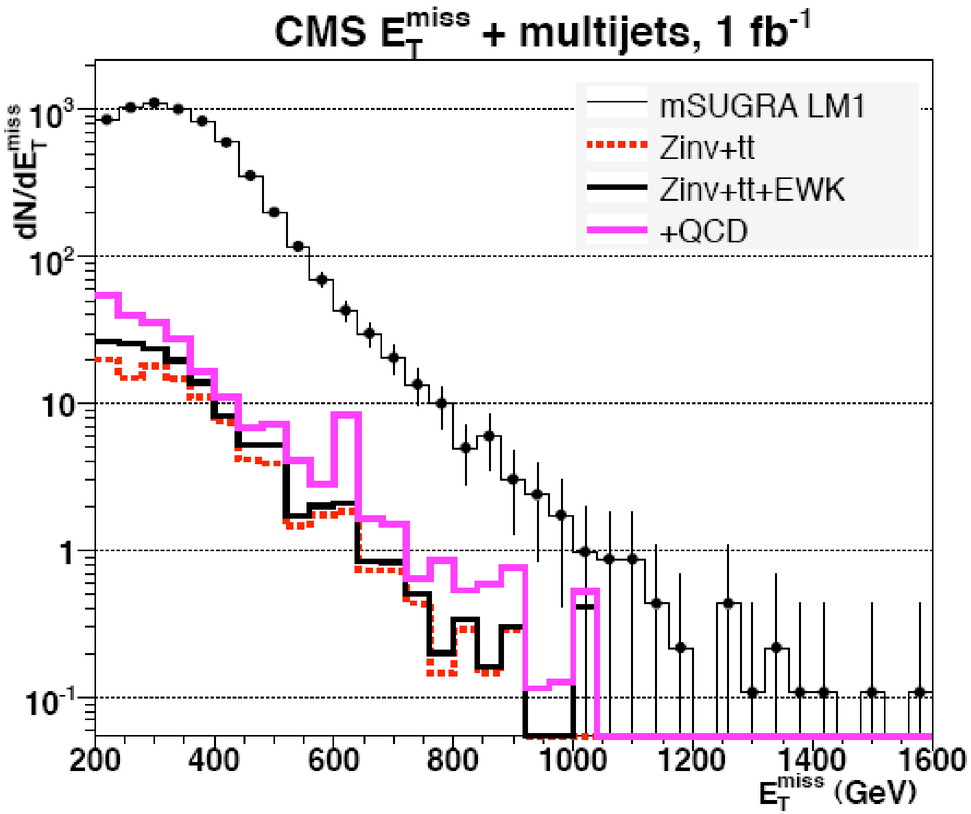


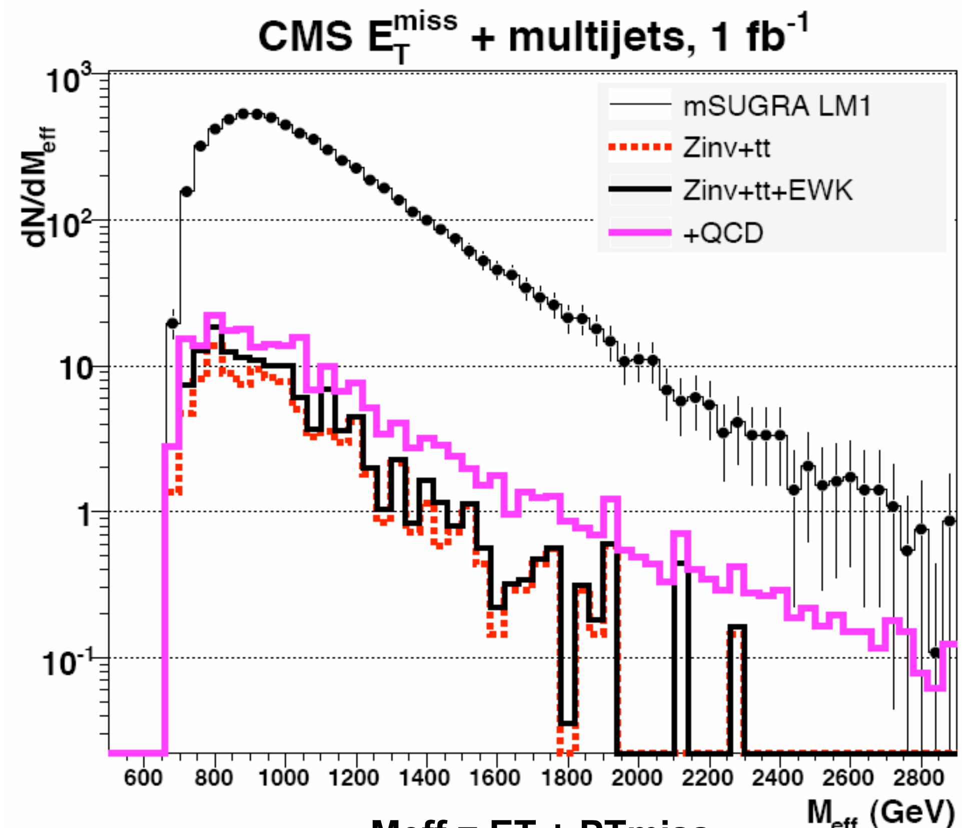


LHC Signal significance

e.g.: mSUGRA, low mass bulk region

Measure of total energy released in sparticle decay: ~ MSUSY



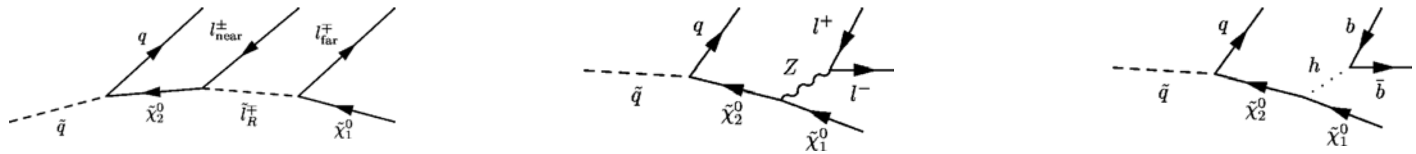


Meff = ET + PTmiss

High signal / background ratio

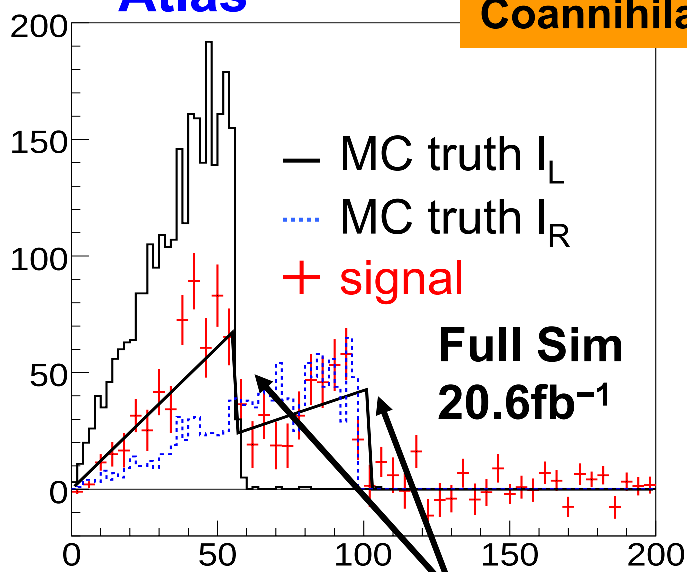
- **Background uncertainty not too important**
- **Discovery possible within ~ 1 year (if detector understood)**

LHC Di-lepton Endpoint analysis



Depending on point: different shape, number of edges, 2-body vs 3-body decay, …

Coannihilation

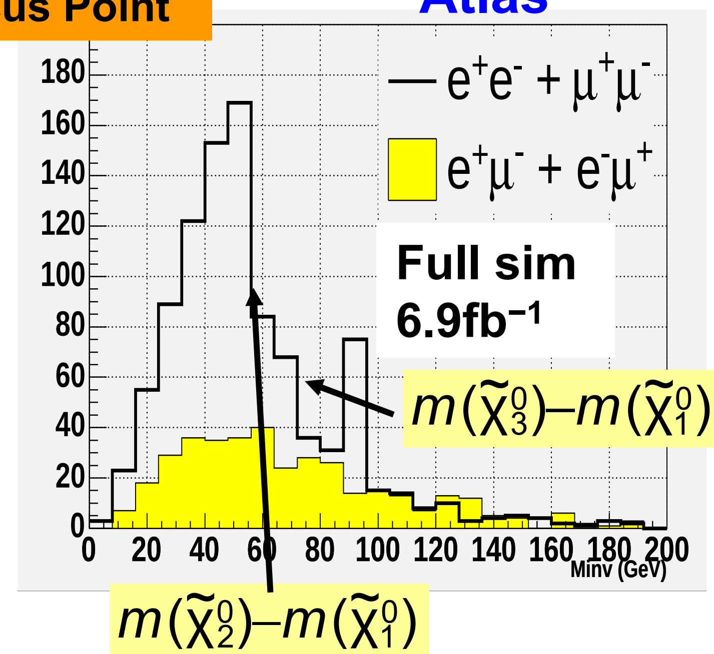


$m(\tilde{\chi}_2^0) > m(\tilde{l}_{L,R})$

→ **2 edges for left and right slepton**

- **small BR**
- **at least 1 lepton with small p_T**

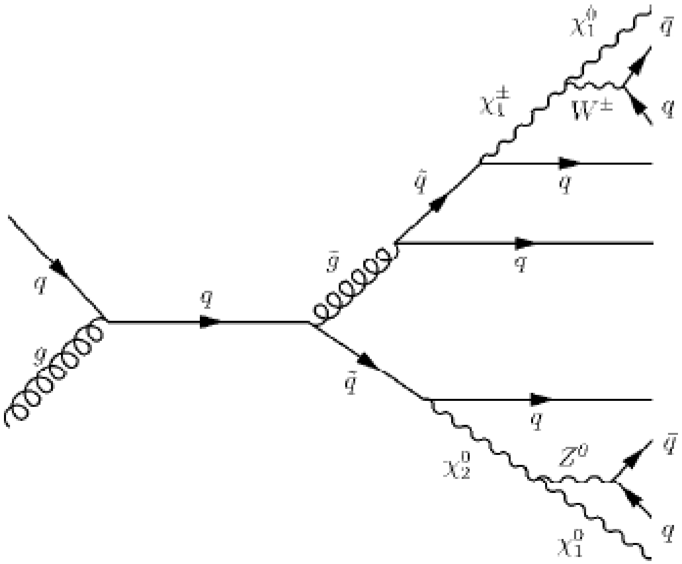
Focus Point



- **m_0 large, heavy scalars**
  → no sleptons in χ decays
- **direct 3-body decay:**

$$\tilde{\chi}_{2,3}^0 \rightarrow l^{\pm} l^{\mp} \tilde{\chi}_1^0$$

LHC hadronic cascade



If lepton branching too small

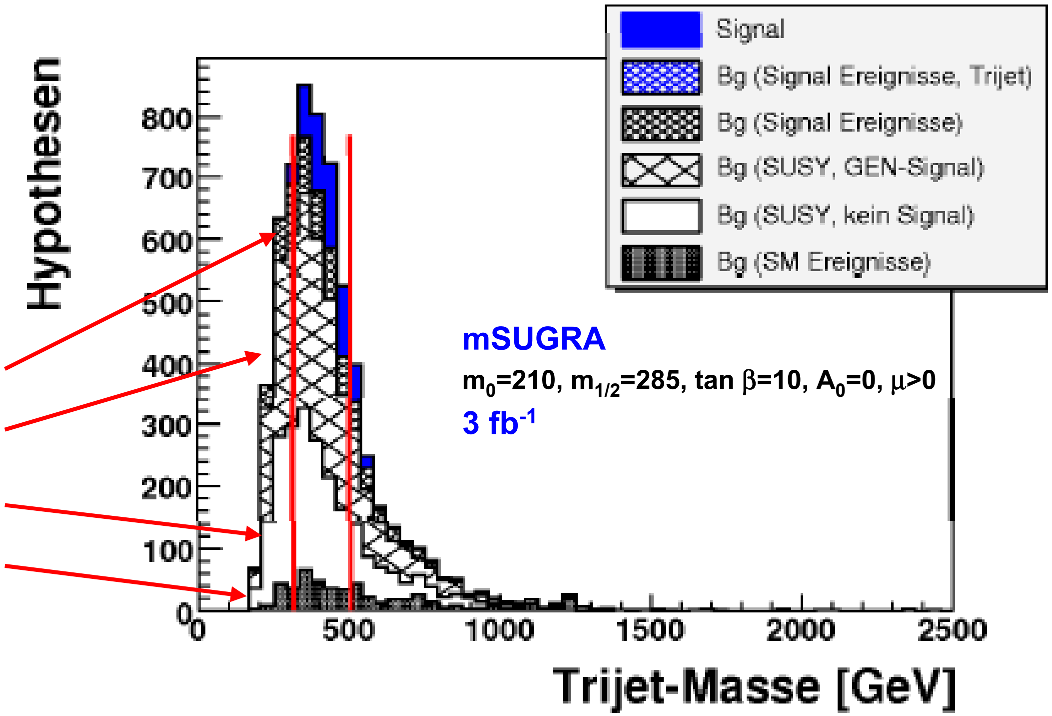
Kinematic analysis of fully hadronic decays ?

Combinatorial background

Not complete reconstruction

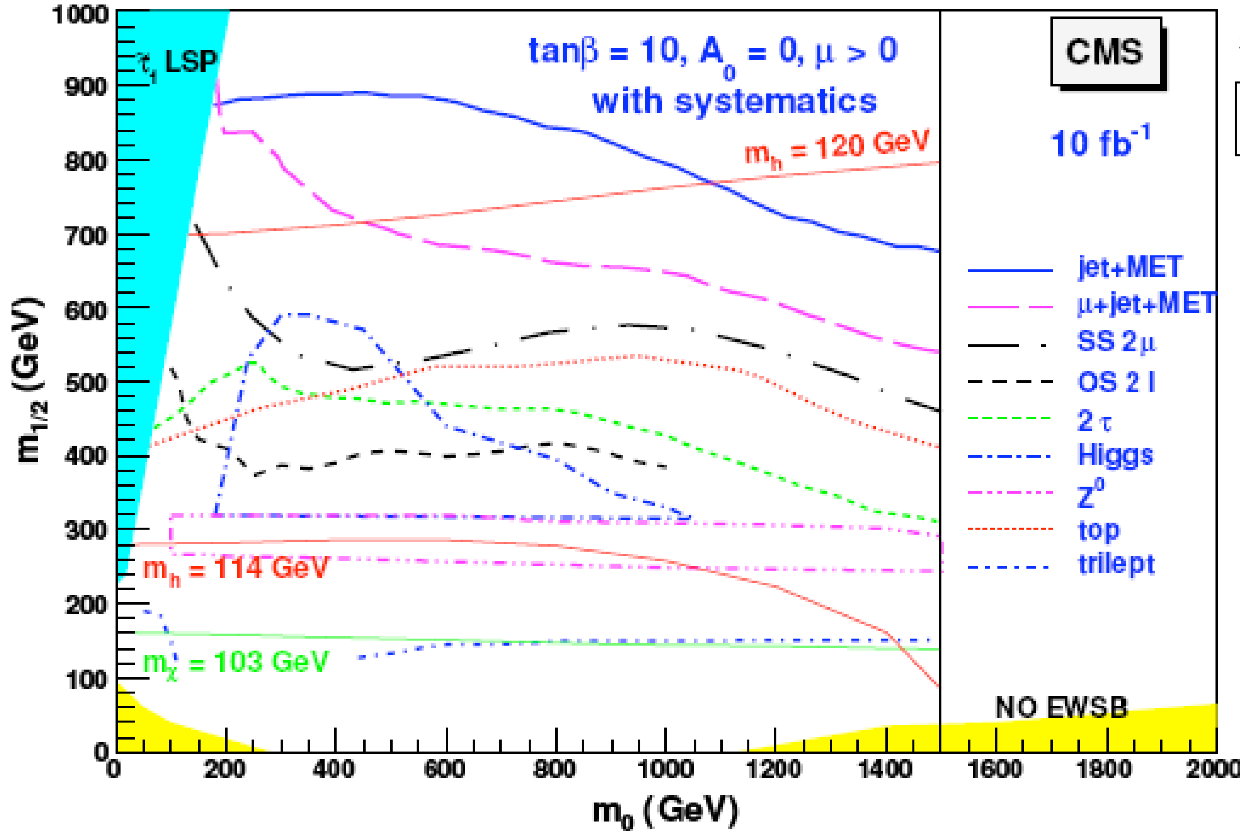
Different SUSY decay chains

SM background



- **Very difficult to extract masses etc.**

LHC SUSY discovery reach



similar for Atlas

Discovery reach for squarks/gluinos

Time	mass reach
1 month at 10^{33}	~ 1.3 TeV
1 year at 10^{33}	~ 1.8 TeV
1 year at 10^{34}	~ 2.5 TeV
ultimate (300 fb^{-1})	~ 2.5 - 3 TeV

- **Large discovery potential already in the first year (2009)**
- **Reach at full luminosity: ~ 2.5 ... 3 TeV for squark and gluino masses**
- **Combined data of many different final states possible (at not too large $m_{1/2}$)**
  - **Some interpretation possible in terms of fundamental SUSY parameters → DM predictions**
  - **Interpretation very model dependent !**

Meta-Stable Heavy Particles

SUSY: if LSP = Gravitino

Small coupling of produced new (s)particles to DM candidate

long lifetime of NLSP if Rp is conserved or very small

- **neutral NLSP = χ_1^0**
- **charged NLSP = $\tilde{\tau}_1$**

Charged NLSP Signature:

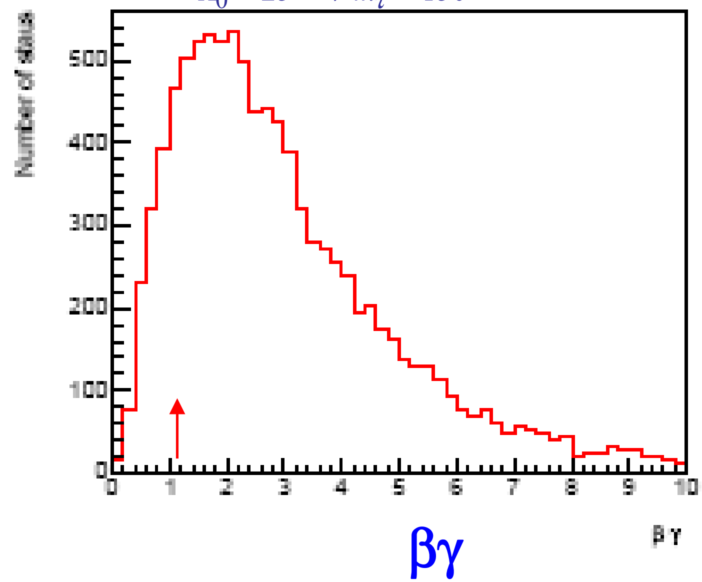
- **high mass particle, penetrating like a μ**
- **No $P_{T,miss}$**
- **energy limited by direct production cross sections or phase space from decays N^nLSP → NLSP**

  → velocity sometimes limited: $\beta\gamma < 1$

  → measure velocity and momentum in B-field → mass

hep-ph/0508198

Scenario ε with Gravitino LSP: $m_{1/2} = 440, m_0 = 20, \tan\beta = 15, \mu > 0, A_0 = 25 \Rightarrow m_{\tilde{\tau}} = 150$



Similar signatures from

- **Kaluza-Klein states in UED** $\tau_R^1, \bar{\tau}_R^1$
- **Split-Susy with large m_0: gluino (decay via virtual squark)**
- **Light stop:** $\tilde{t}_1 \to c\chi_1^0$

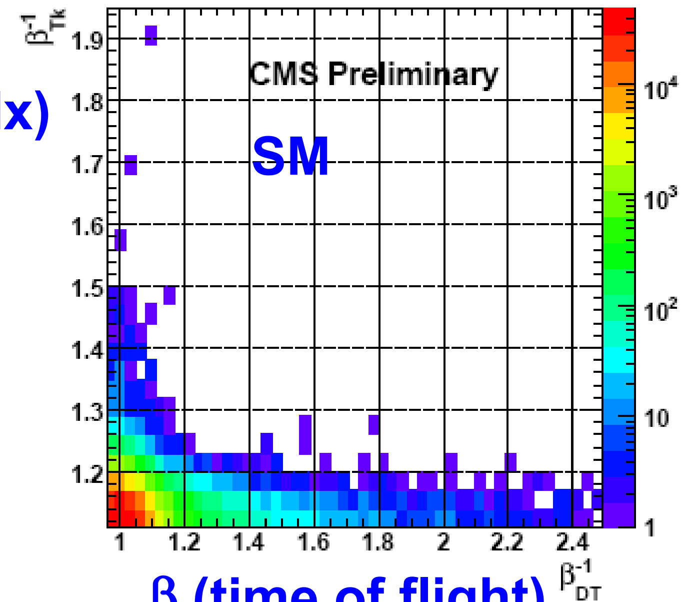
  R-hadrons with little hadronic energy loss in material

Meta-Stable Heavy Charged particles

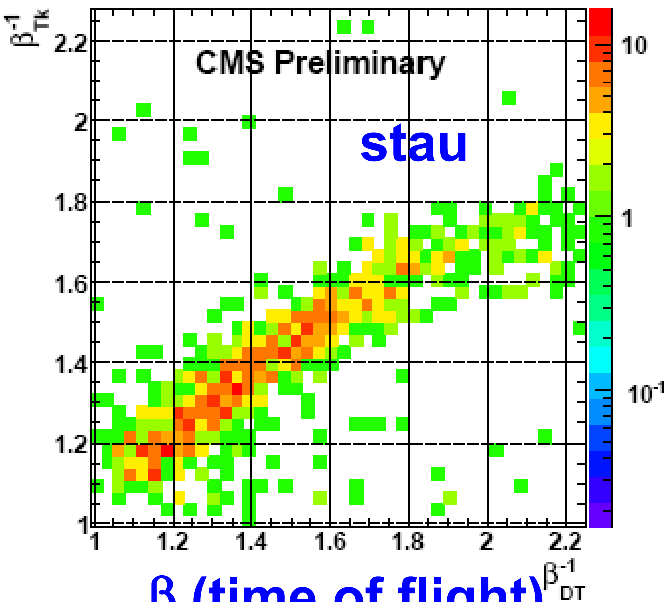
Experimentally:

- Measure momentum in tracking detectors
- if decay length $\beta\gamma c\tau$ > ~10m → decay outside detector, else measure decay length
  penetrating like a myon
- if velocity β < 0.9 → time of flight measurement in myon system or calor.
  → slower than myon of the same momentum
- if momentum / mass $\beta\gamma$ < 1 → dE/dx ionisation measurement:
  → stronger ionisation than a fast myon

β (dE/dx)



β (time of flight)

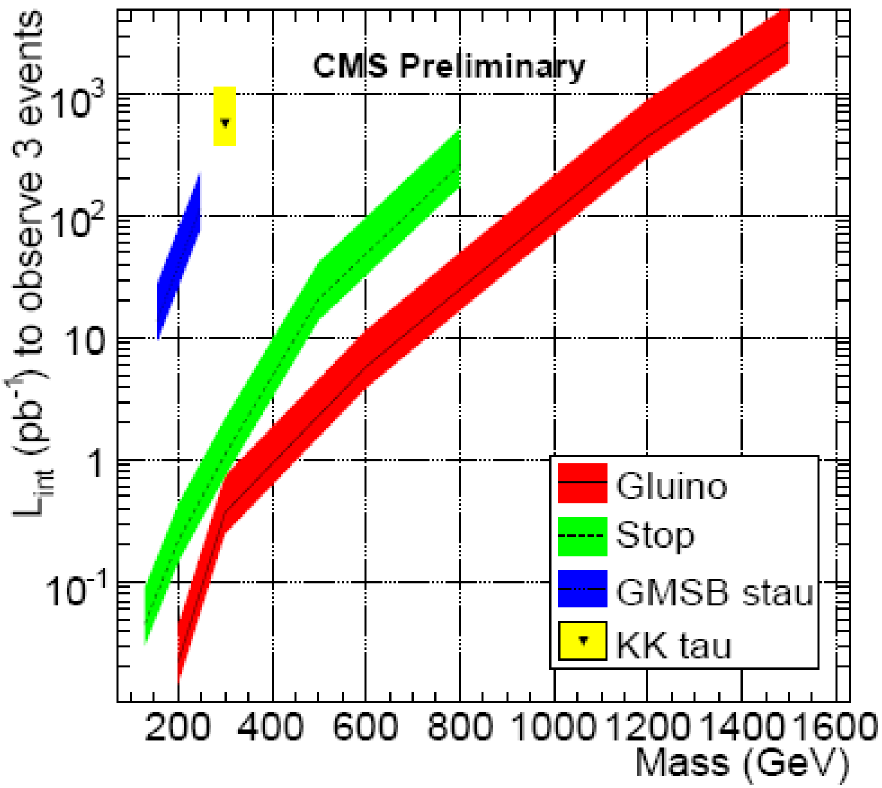


β (time of flight)

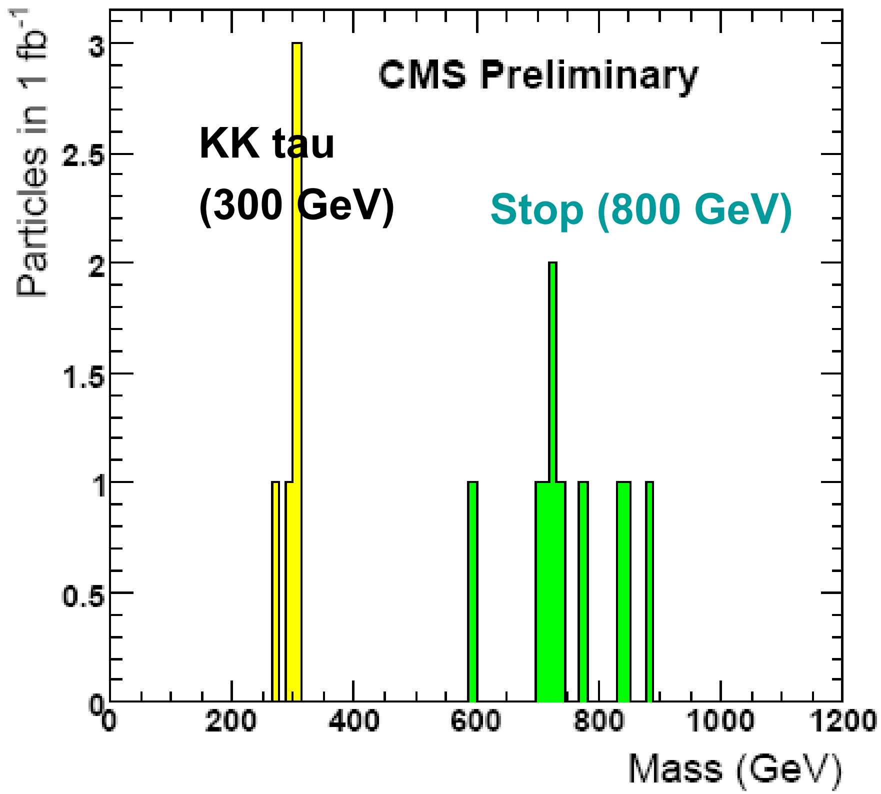
No SM background !

LHC potential for meta-stable heavy charged particles

Luminosity needed to observe 3 events



Mass reconstruction from P and β

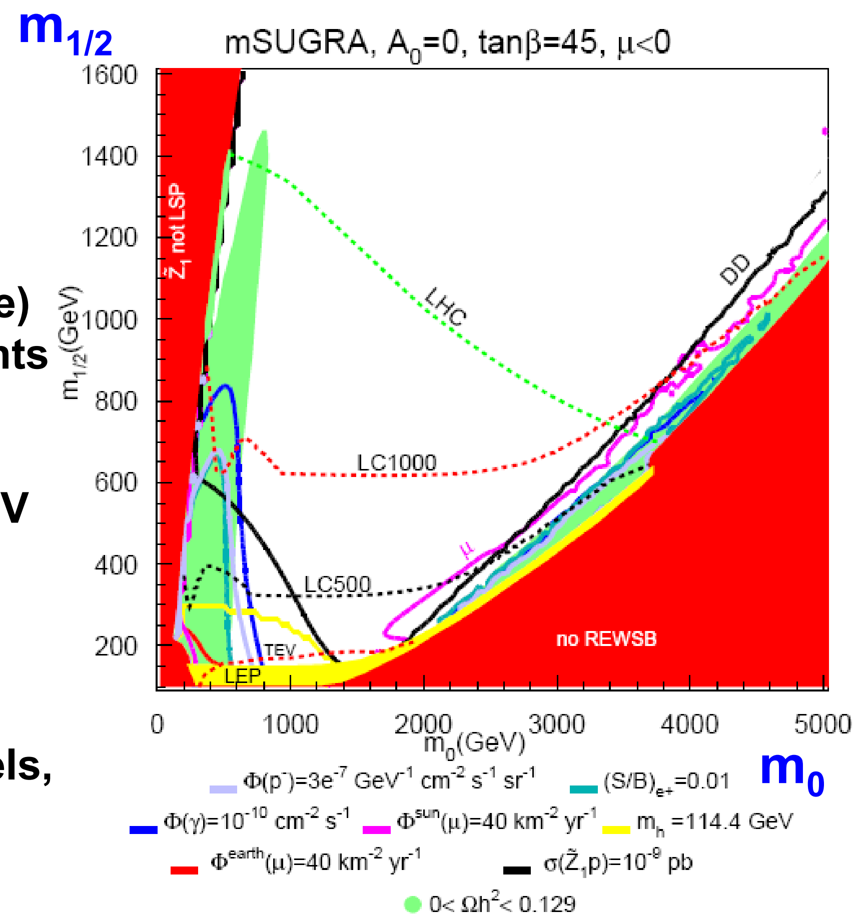


- window to very weakly interacting DM
- mass determination with very few events possible

Conclusion

Colliders:

- DM candidates are not detectable
- need to produce particles, which couple and decay into WIMPs + SM particles
- simultaneous discovery of DM particle and annihilation partners
- detailed investigations possible (at least in principle) of rates, masses, decays, (spin) in single experiments



LEP: higgs mass bound

Tevatron: squark > 400, gluino > 300, chargino > 140 GeV

LHC:

- squark, gluino < 3 TeV
- large potential to disentangle some parameters of the new physics
- however notoriously difficult regions in some models, e.g. small mass gaps between LSP and others
- heavy stable particles as a window to very weakly interacting DM

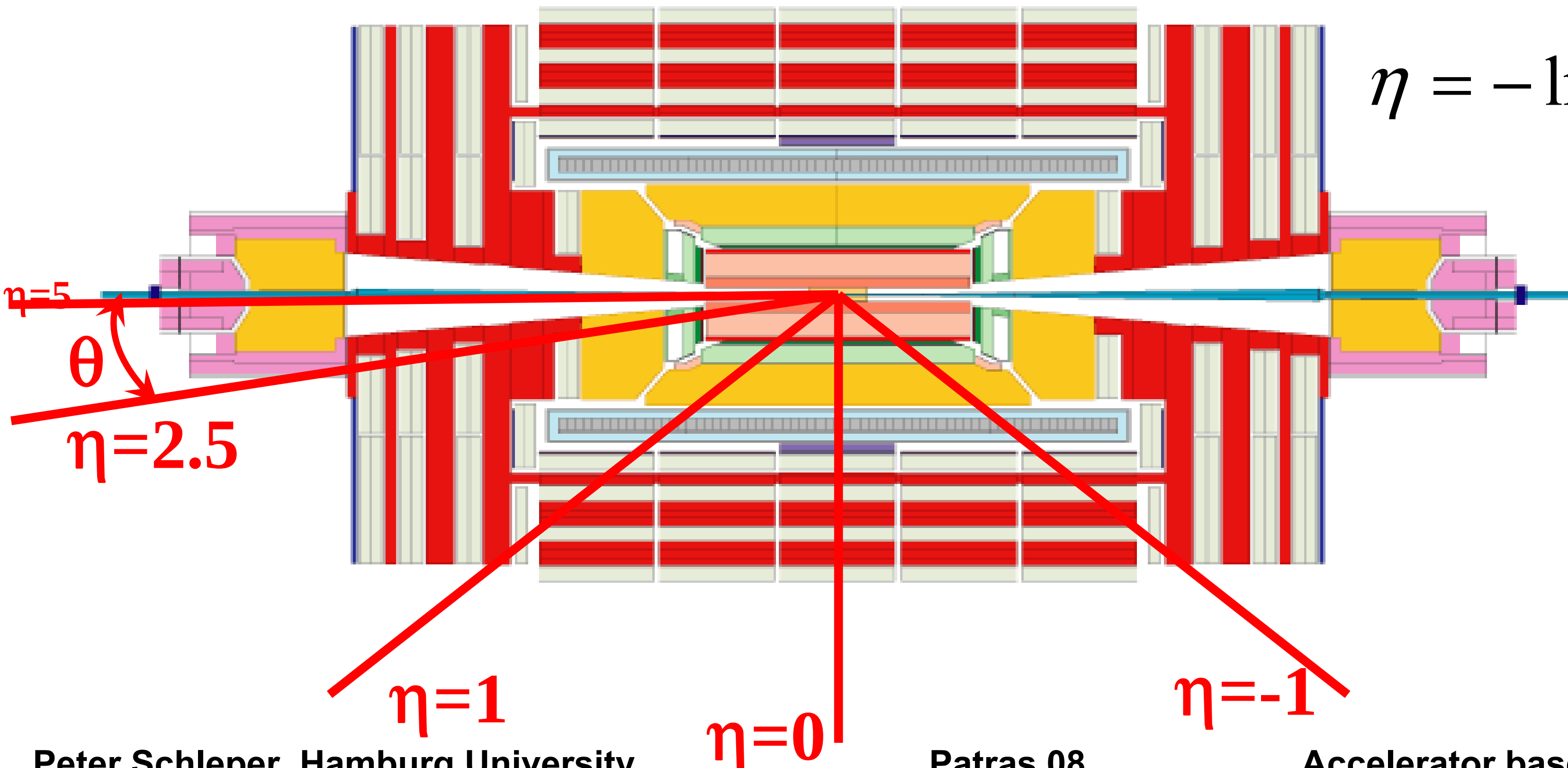
→ Needs DM searches and colliders to disentangle theoretical models

→ Observations at LHC, DD and ID will influence strongly the decision for new experiments, including a new linear collider

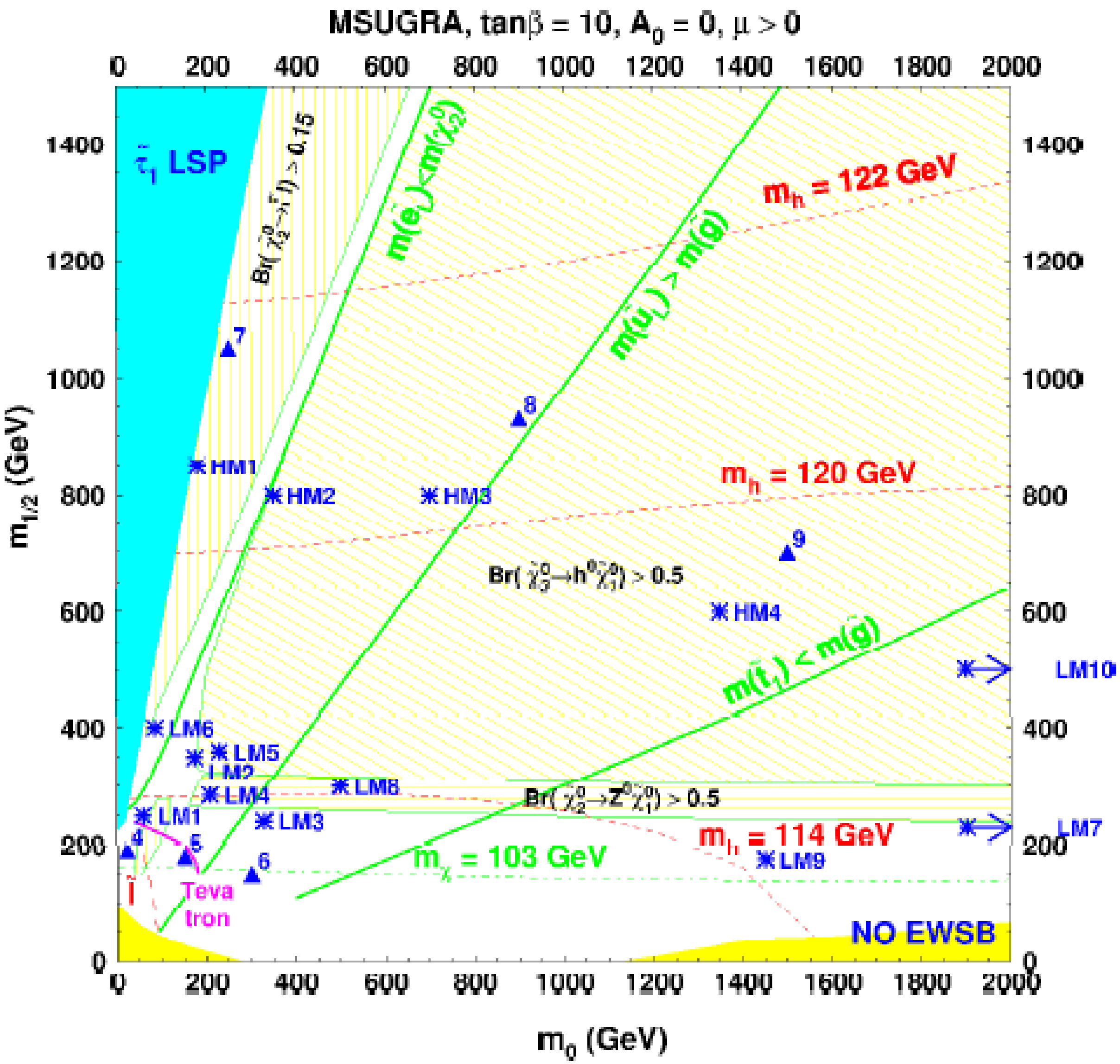
Detector Acceptance

Acceptance η	Central (Barrel)	Forward (Endcap)
Tracking	< 1.5	< 2.4
Elektrons	< 1.2	< 2.5
Hadrons	< 1.2	< 2.5 → 5
Myons	< 1.2	< 2.5

$$\eta = -\ln\left(\tan\left(\theta/2\right)\right)$$

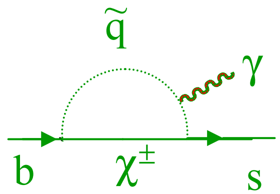


SUSY bench mark points



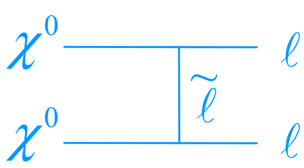
Rare Processes and Cosmology

- $B \rightarrow s\gamma$ excluded

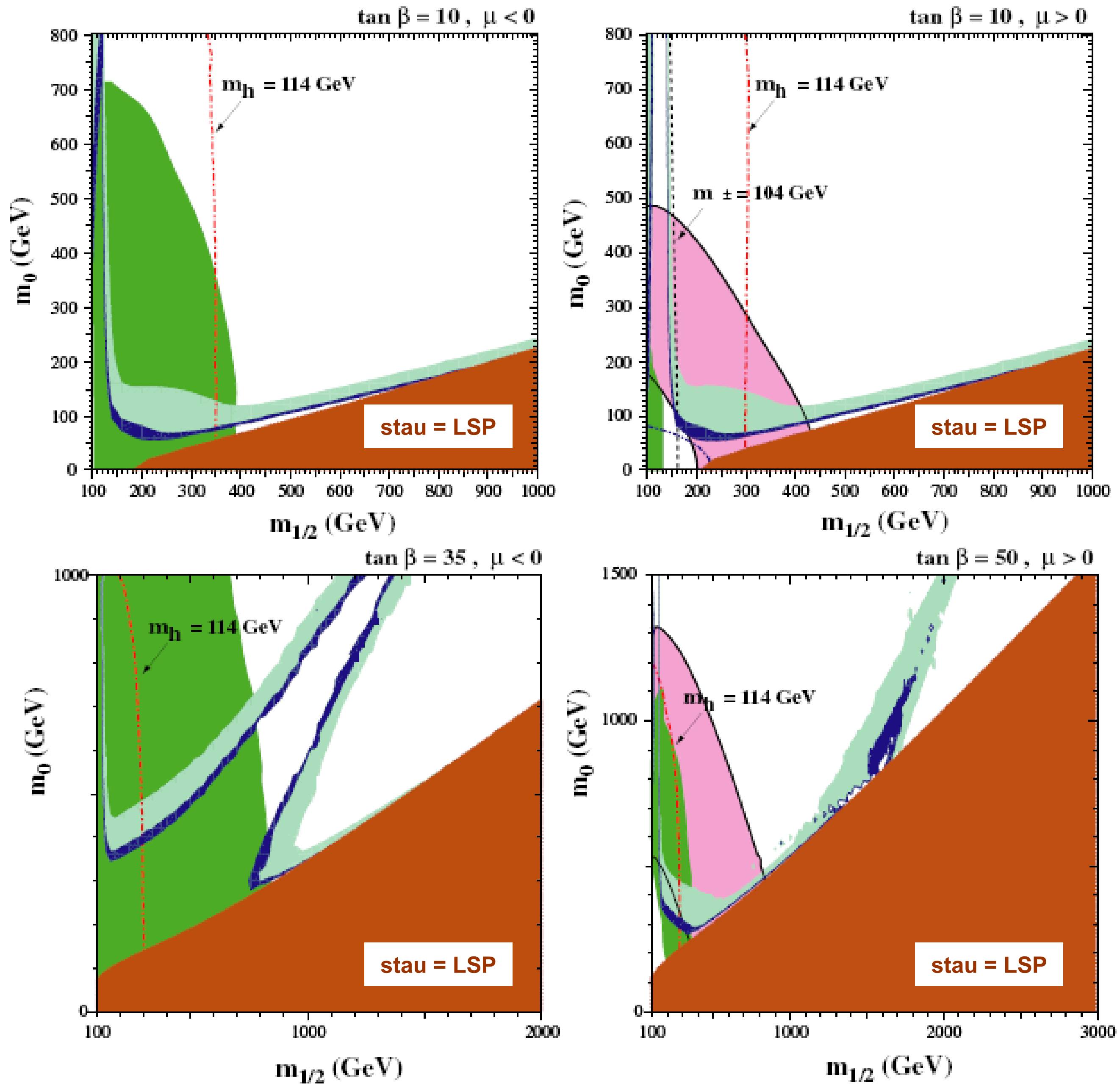


- g_{μ}-2 favoured

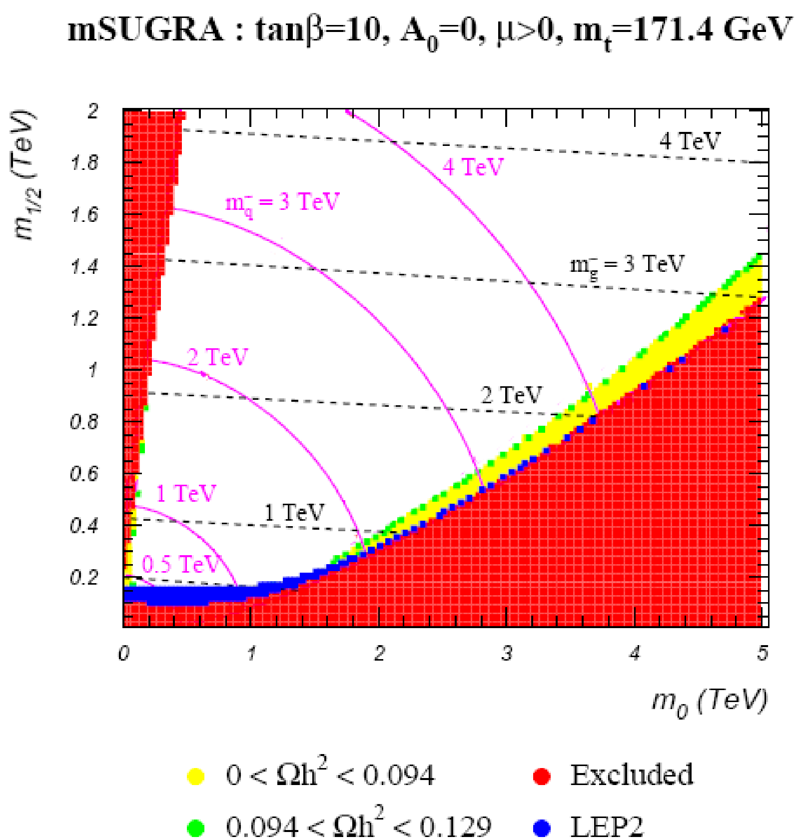
- Dark matter favoured

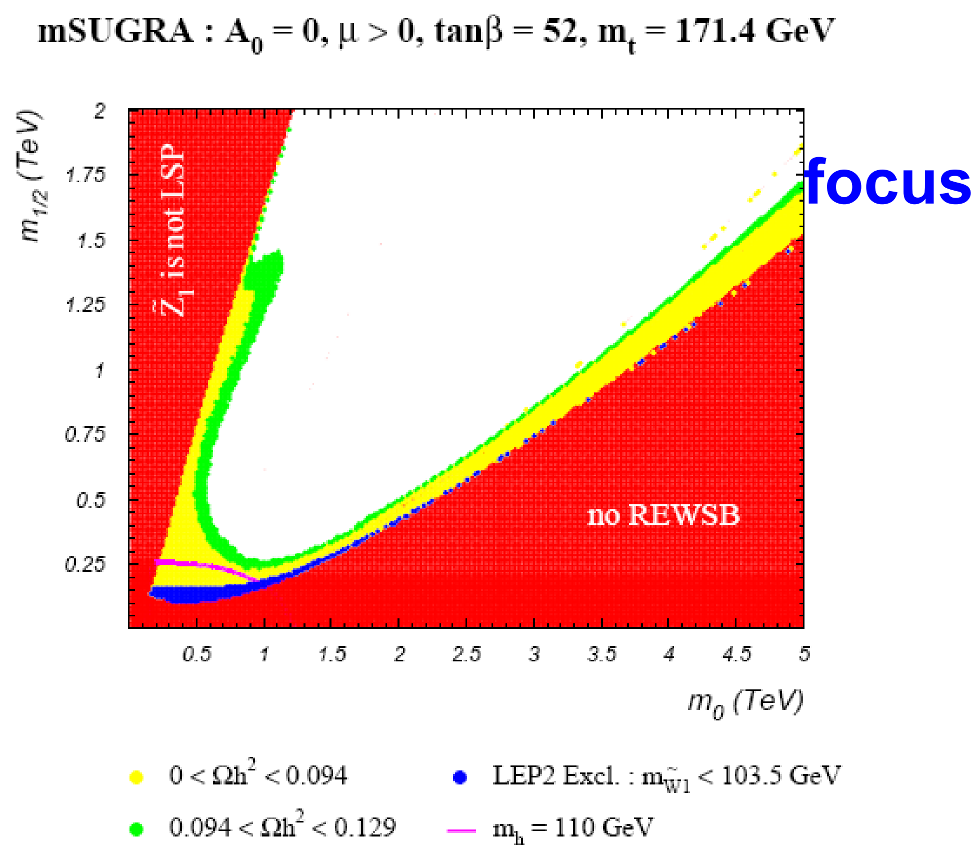


- m_{LSP} < 500 GeV



mSUGRA allowed regions





Expectations for staus

$\tilde{G}$ = **LSP**, $\tilde{\tau}$ = **NLSP**

$M(\tilde{\tau}_1) = 100...350$ **GeV**

very long lifetime and decay length

$\Rightarrow \tilde{\tau}$ **pairs from decay chains (trigger !)**

$\Rightarrow \tilde{\tau}$ **at central rapidity and** $P_{\tilde{\tau}} > 10$ **GeV**

$\Rightarrow P_{\tilde{\tau}}/M_{\tilde{\tau}} = \beta_{\tilde{\tau}}\gamma_{\tilde{\tau}}$ **partially below 1**

$\tilde{\tau}$ Signature:

charged track $\Rightarrow$ **momentum measurement**

A: most $\tilde{\tau}$ with large $\beta\gamma$

$\Rightarrow$ **minimum ionisation in detector similar to a μ**

B: (small) fraction of $\tilde{\tau}$ with low β

$\Rightarrow$ **high ionisation**

$\Rightarrow$ **time delay w.r.t. to μ with same P**

C: tiny fraction of $\tilde{\tau}$ with very low β

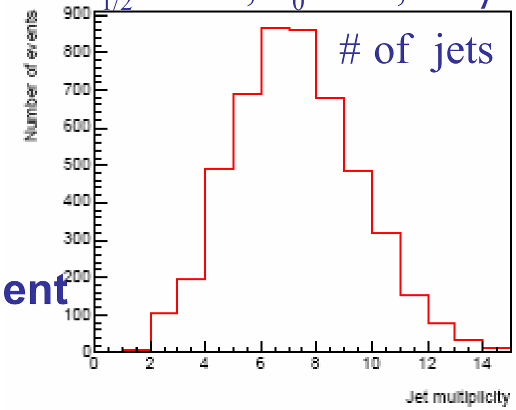
$\Rightarrow \tilde{\tau}$ **will stop in detector**

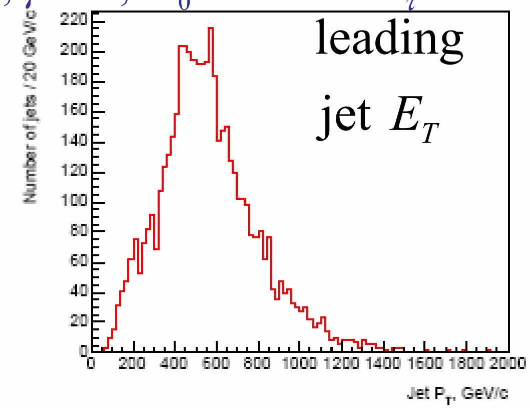
$\Rightarrow$ **decay of $\tilde{\tau}$ much later**

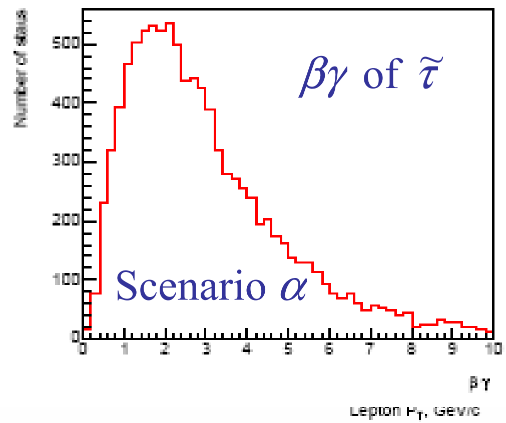
DeRoeck, Ellis, Gianotti, Moortgat, Olive, Pape: hep-ph/0508198

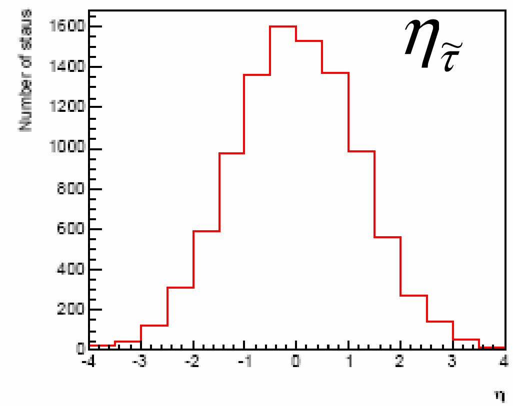
Scenario ε with Gravitino LSP:

$m_{1/2} = 440, m_0 = 20, \tan\beta = 15, \mu > 0, A_0 = 25 \Rightarrow m_{\tilde{\tau}} = 150$









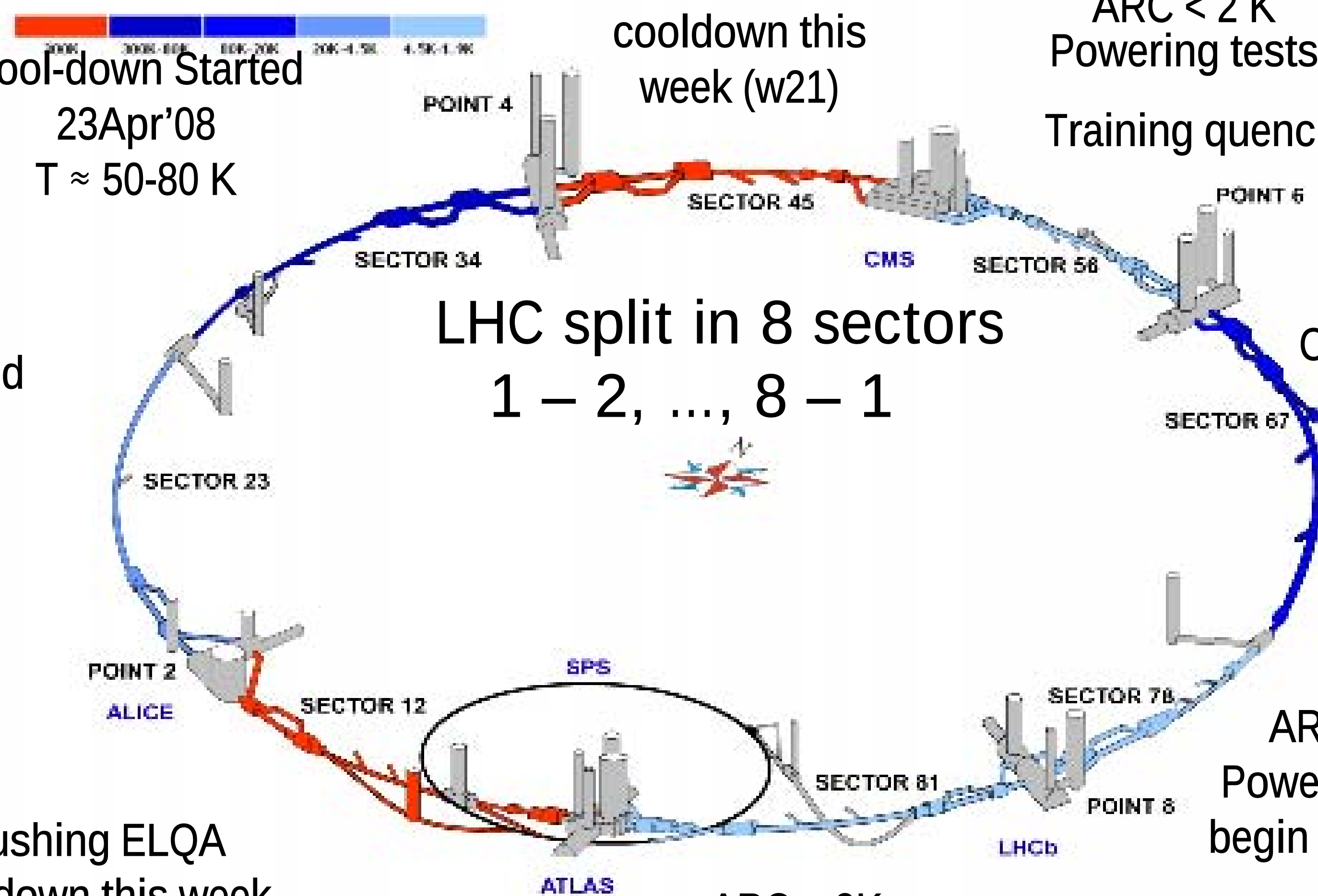
LHC Machine Status: Cooldown

Cool-down Started
23Apr'08
T ≈ 50-80 K

Start 2nd
cooldown this
week (w21)

ARC < 2 K
Powering tests

Training quenches



Cool-down Started
7Apr'08
T ≈ 4 K

LHC split in 8 sectors
1 – 2, ..., 8 – 1

Cool-down Started
31Mar08
T ≈ 20-40 K

ARC < 2K
Powering tests
begin on 13 May

Flushing ELQA
Cooldown this week

ARC < 2K
Powering tests
fullsteam w23

$P_{T,miss}$ Signatures

New weakly interacting particles A

- Stable or meta-stable
- Massive or light (~0 …. few 100 GeV)
- → neutral: invisible to experiments
- → charged: μ –like particles → no $P_{T,miss}$ signature

Production mechanisms @ colliders (pp):

- direct: pp → A + A
- associated: pp → A + SM-particles
- decays: pp → B + B → A + A + SM-particles

  production of heavier particles B with decay B→ A + SM-particles

  missing transverse momentum from A,A partially cancels

  B might be annihilation partner for A

Production mechanisms @ colliders:

- direct: pp → A+A + p-remnants
- Associated: pp→ A + X + p-remnants