# **Accelerator based searches for Dark Matter**

Peter Schleper Hamburg University Patras workshop, DESY 18.6.2008



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# Introduction

### Neutral, (very) weakly interacting particles $\rightarrow$ candidates for dark matter (DM)

### DM candidates @ accelerators:

- If stable: invisible within detectors, like  $\boldsymbol{\nu}$
- If produced together with SM particles: detectable as missing momentum in 4-momentum balance



**CDF** 

- If produced together with other new particles: detectable as invisible decay product
   → requires mass gap
  - $\rightarrow$  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<sub>chargino</sub> > 103.5 GeV, M<sub>sleptons</sub> > 100GeV,
- M<sub>h</sub> > 114.5 GeV (if Higgs is SM-like)

### HERA: ep @ 318 GeV (finished)

only for R-parity violating SUSY → spoils DM candidates

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

- Highest energy accelerator currently
- news on squarks, gluinos and charginos from 2fb<sup>-1</sup> (aim: 8 fb<sup>-1</sup>)

### 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 Peter Schleper, Hamburg University



LHC

### LHC machine status cool down of accelerator segments



# LHC sectors cooled down by mid July commisioning of superconducting magnets, ...

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# **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 <sup>27</sup>
43 x 43	3.8 x 10 <sup>29</sup>
43 x 43	1.7 x 10 <sup>30</sup>
43 x 43	6.1 x 10 <sup>30</sup>
156 x 156	1.1 x 10 <sup>31</sup>
156 x 156	5.6 x10 <sup>31</sup>
156 x 156	1.1 x10 <sup>32</sup>

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### Time needed for ramp up of integrated luminosity

2009	2012	→upgrade to SLHC
 100 pb <sup>-1</sup>	100 fb <sup>-1</sup>	→ 1000 fb <sup>-1</sup>

# **P**<sub>T,miss</sub> reconstruction

### LHC detectors ATLAS & CMS

- hermiticity of detectors: no escaping particles (except v)
- losses close to beam pipe  $\rightarrow$  angular coverage of calorimeters up to  $\eta$ =2.5 ...5



- 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**<sub>T,miss</sub> reconstruction

#### Irreducible SM background:

 $\cdot Z \rightarrow vv$ ,  $W \rightarrow Iv$ ,  $t \rightarrow Wb \rightarrow Ivb$ ,  $b,c \rightarrow Ivq$ 

•measure bkg rates from data: e.g. measure  $Z \rightarrow \mu\mu$  to predict  $Z \rightarrow \nu\nu$ 

### **Experimental thresholds:**

Tevatron: P<sub>T,miss</sub> > 100 ..200 GeV LHC: low luminosity (2 \* 10<sup>31</sup> cm<sup>-2</sup> s<sup>-1</sup>)

**CMS** planning

- Trigger: P<sub>T,miss</sub> > 60 GeV & 1jet with P<sub>T,jet</sub> > 180 GeV or 2jets with P<sub>T,jet</sub> > 125 GeV or 3jets with P<sub>T,jet</sub> > 60GeV
- Analysis: P<sub>T,miss</sub> > 200 GeV & jets
   LHC: large luminosity
  - P<sub>T,miss</sub> > 200 ..600 GeV

### **ATLAS P<sub>T,miss</sub> resolution**



# **QCD** background

#### QCD jets $\rightarrow$ huge rates, large uncertainties

#### ETmiss dominated by jet resolution $\rightarrow$ reducible background

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



Squarks and gluinos: produced via strong processes
 → large, known cross-section



Charginos, neutralinos, sleptons: direct production via electroweak processes
 → much smaller rate (appear in squark and gluino decays)



 $\widetilde{q}\widetilde{q}, \widetilde{q}\widetilde{g}, \widetilde{g}\widetilde{g}$  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 +  $\chi_1^0$

$$\tilde{\mathbf{g}} \to \mathbf{q} \mathbf{q} \chi_1^{\mathbf{0}} \quad \tilde{\mathbf{q}} \to \mathbf{q} \chi_1^{\mathbf{0}}$$

- P P<sub>T,miss</sub> > 200 GeV for 2 jets > 100 GeV for 4 jets
- About 10 events seen /expected
   → no signal



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### **Tevatron results**



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# **Tevatron results**

#### Search for chargino-neutralino production

• decay in 3I + P<sub>T,miss</sub>



 $\rightarrow$  small SM bkg even

at low P<sub>T,miss</sub> > 20 GeV

- Data / SM = 7 / 6.4 events
- no signal

→ mSUGRA limit

M(χ̃\_1<sup>±</sup>)> 140 GeV

mSUGRA favourable since fairly large mass splitting in decay chain  $\rightarrow$  large P<sub>T</sub> leptons, large P<sub>T,miss</sub>



# **Tevatron – LHC comparison**



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# 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<sup>-4</sup>

Exploit kinematics to maximum extent: mass reconstruction method



# LHC SUSY analysis strategy

### 1) Inclusive analysis

#### Jets + ETmiss (+leptons)

- First evidence
- use Meff, ETmiss, #jets,I, event rate
  - 🔶 R<sub>P</sub>
  - 📫 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

CMS E<sup>miss</sup><sub>T</sub> + multijets, 1 fb<sup>-1</sup>



#### 10-10<sup>-1</sup> 10<sup>-1</sup> 200 400 800 1000 1200 1400 10 E<sup>miss</sup> (GeV) 600 1600 600 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 800 Meff = ET + PTmiss

mSUGRA LM1

Zinv+tt+EWK

Zinv+tt

+QCD

#### High signal / background ratio

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

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M<sub>eff</sub> (GeV)

# LHC Di-lepton Endpoint analysis







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



# LHC hadronic cascade



#### Very difficult to extract masses etc.

# LHC SUSY discovery reach



- 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<sub>1/2</sub>)
  - Some interpretation possible in terms of fundamental SUSY parameters → DM predictions
  - Interpretation very model dependent !

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# **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 =  $\chi_1^0$
- charged NLSP =  $\tilde{\tau}_1$

#### **Charged NLSP Signature:**

- high mass particle, penetrating like a μ
- No P<sub>T,miss</sub>
- energy limited by direct production cross sections or phase space from decays N<sup>n</sup>LSP → NLSP
  - $\rightarrow$  velocity sometimes limited:  $\beta\gamma < 1$
  - $\rightarrow$  measure velocity and momentum in B-field  $\rightarrow$  mass

#### Similar signatures from

- Kaluza-Klein states in UED  $au_R^1, au_R^1$
- Split-Susy with large m<sub>0</sub>: gluino (decay via virtual squark)
- Light stop:  $\tilde{t}_1 \rightarrow c \chi_1^0$ R-hadrons with little hadronic energy loss in material

#### hep-ph/0508198



# **Meta-Stable Heavy Charged particles**

#### **Experimentally:**

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

 $\rightarrow$  stronger ionisation than a fast myon





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

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# 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</li>
- 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



- $\rightarrow$  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

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### **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



# **SUSY bench mark points**



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### **Rare Processes and Cosmology**



### mSUGRA allowed regions

m<sub>1/2</sub> (TeV) 2 4 TeV 1.8 4 TeV  $m_{\alpha}^{-} = 3 \text{ TeV}$ 1.6  $m_g^- = 3 \text{ TeV}$ 1.4 1.2 2 TeV 1 2 TeV 0.8 0.6 1 TeV 1 TeV 0.4 0.2 0 2 3 4 5 1 m<sub>o</sub> (TeV) •  $0 < \Omega h^2 < 0.094$  Excluded •  $0.094 < \Omega h^2 < 0.129$ • LEP2

mSUGRA : tan $\beta$ =10, A<sub>0</sub>=0,  $\mu$ >0, m<sub>t</sub>=171.4 GeV

mSUGRA :  $A_0 = 0, \mu > 0, \tan\beta = 52, m_t = 171.4 \text{ GeV}$ 



# **Expectations for staus**

### $\widetilde{G} = \mathbf{LSP}, \ \widetilde{\tau} = \mathbf{NLSP}$

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

very long lifetime and decay length  $\Rightarrow \tilde{\tau}$  pairs from decay chains (trigger !)  $\Rightarrow \tilde{\tau}$  at central rapidity and  $P_{\tilde{\tau}} > 10 \text{ GeV}$  $\Rightarrow P_{\tilde{\tau}}/M_{\tilde{\tau}} = \beta_{\tilde{\tau}}\gamma_{\tilde{\tau}}$  partially below 1

#### $\widetilde{\tau}$ Signature :

charged track  $\Rightarrow$  momentum measurement

- A:most  $\tilde{\tau}$  with large  $\beta\gamma$ 
  - $\Rightarrow$  minimum ionisation in detector similar to a  $\mu$
- **B**: (small) fraction of  $\tilde{\tau}$  with low  $\beta$ 
  - $\Rightarrow$  high ionisation
  - $\Rightarrow$  time delay w.r.t. to  $\mu$  with same P
- C: tiny fraction of  $\tilde{\tau}$  with very low  $\beta$ 
  - $\Rightarrow \widetilde{\tau}$  will stop in detector
  - $\Rightarrow$  decay of  $\widetilde{\tau}$  much later

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DeRoeck, Ellis, Gianotti, Moortgat, Olive,Pape: hep-ph/0508198 Scenario ε with Gravitino LSP:



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# LHC Machine Status: Cooldown



# P<sub>T,miss</sub> Signatures

#### New weakly interacting particles A

- Stable or meta-stable
- Massive or light (~0 .... few 100 GeV)
- $\rightarrow$  neutral: invisible to experiments
- $\rightarrow$  charged:  $\mu$  –like particles  $\rightarrow$  no P<sub>T,miss</sub> signature

#### Production mechanisms @ colliders (pp):

- direct:  $pp \rightarrow A + A$
- associated:  $pp \rightarrow A + SM$ -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:  $pp \rightarrow A+A + p$ -remnants
- Associated: pp→ A + X + p-remnants
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