ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

A search for heavy and long-lived staus in the LHCb detector at $\sqrt{s} = 7$ and 8 TeV

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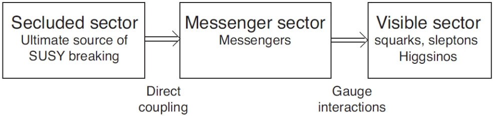
Outline

1.1. The minimal Gauge Mediated Supersymmetry Breaking (mGMSB)

- SUSY breaking in a secluded sector and transmitted to SM via messengers



- The mGMSB (arXiv:hep-ph/9801271v2 19 Apr 1999) is characterised by six fundamental parameters:

  Λ: the SUSY-breaking mass scale

  M_m: the messenger mass scale

  N_5: the number of messenger supermultiplets

  $\tan\beta$: ratio of the vacuum expectation values of the two Higgs fields

  $\mathrm{sgn}\mu = \pm$: sign of the Higgs mixing parameter

  C_{grav}: the scale factor of the gravitino coupling which controls the NLSP lifetime

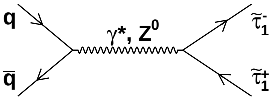
- The Lightest Supersymmetric Particle (LSP) is the gravitino,
  the Next to LSP can be a slepton.

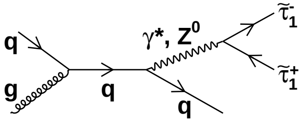
1.2. The staus

To get long-lived staus, SPS7 benchmark sets (arXiv:hep-ph/0202233v1 25 Feb 2002):

- $\Lambda \simeq 40 - 100$ TeV, $M_m = 2\Lambda$, $N_5 = 3$, $\tan\beta = 15$ and $\text{sgn}\mu = +1$.
- The $\tilde{\tau}$ lifetime is ~ 100 ns for $C_{grav} \sim 4000$.

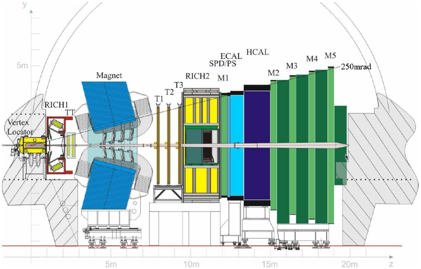
- Their mass is ≤ 1 TeV (John Ellis, hep-phy/0211168, 12 Nov 2002)
- They are charged (± 1), massive and can be long lived (i.e they do not decay inside the detector).
- Staus only have the electromagnetic interaction,
  $\Rightarrow$ they look like muons.
- We look for pairs produced in: $q + \bar{q} \rightarrow \tilde{\tau}_1^- + \tilde{\tau}_1^+$
  $\Rightarrow$ x-sections limits can be stated as function of the staus masses only





Outline

2.1. The LHCb detector



- Single forward spectrometer, $1.8 < \eta < 4.9$
- The LHCb detector is composed of:
  1. Tracking system: magnet, VErtex LOcator (VELO), Tracker Turecensis (TT) (Si strip),
     $T1 \div T3$ (straw drift tubes, Si strip sensors)
  2. PID system: Cherenkov detectors RICH1, RICH2, and the muon chambers (M1÷M5).
  3. Calorimeters (ECAL (SPD, PS, ECAL), HCAL).

2.2. Detecting massive stau pairs in LHCb

Characteristics of Drell-Yan produced stau pairs implies :

- Search for **pair candidates** looking like μ pairs.
- **Stau Cherenkov thresholds** is much higher than those of ordinary particles.
- Their energy depositions in calorimeters will be smaller than those of muons.
- Their energy deposition in Si detector will also be different.
- **Detection inefficiencies** due to staus low velocities as stau signals are delayed.

It is quite **difficult to use the LHCb data** to determine the inefficiency due to **delayed signals**
$\Rightarrow$ **Rely on Monte Carlo** in which timing info have been fully encoded.

Outline

3.1. Signal and Background

Signal

Pairs of staus

$124 < m_{\tilde{\tau}} < 300$ GeV/c^2

Mass of pairs > 100 GeV/c^2

$\beta > 0.80$ (late arrival of $\tilde{\tau}$)

$m_{\tilde{\tau}}$ (GeV/c^2)	σ (fb) at $\sqrt{s} = 7$ TeV
124	$16.90\ ^{+5.0}_{-4.4}$
309	$0.34\ ^{+8.6}_{-6.0}$

(arXiv:hep-ph/9611232v1 5 Nov '96)
Uncertainty from PDF, energy scale and strong coupling

Background

Pairs of muons from $Z^0/\gamma^\star$

$M_{Z^0/\gamma^\star} > 100$ GeV/c^2

$P_T > 50$ GeV/c

	cross section (σ) (pb)
$\sqrt{s} = 7$ TeV	1.08 ± 0.10
$\sqrt{s} = 8$ TeV	1.36 ± 0.12

Uncertainty is from PDF and energy scale variation.

Strong reduction needed

Preselection of events:

- Good μ like tracks coming from primary vertex

Very efficient in rejecting $Z^0/\gamma^\star$ backgrounds and μ from heavy quark or τ decays. No "punch through" μ pair found.

3.2. Selection by Neural Network

Use a Neural Network (NN) to distinguish $\tilde{\tau}$ pairs from μ pairs.

Train the NN with MC variables.

- Energy deposition in VELO, ECAL and HCAL
- Response of the Cherenkov counters

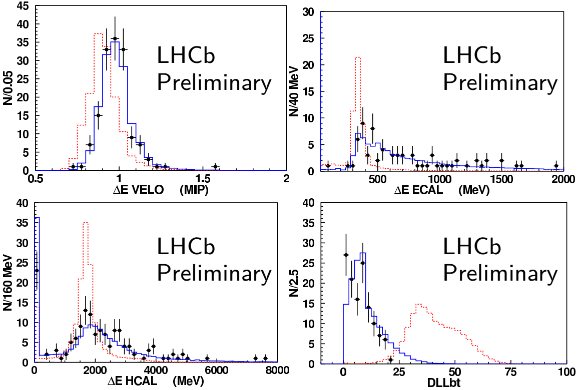
The statistics involved for training and testing, e.g. for 2011 MC :
Stau pairs : 156'000 pairs, Muon pairs : 238'000 pairs

Once the training is done, input preselected pairs into NN.

Calculate the product of the NN responses to the two tracks to form the **pair significance**.

3.3. Final selection by a Neural Network

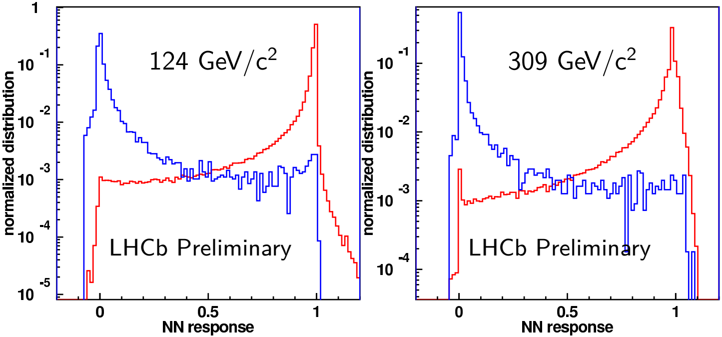
Four input variables to the NN (2012 preselected data)



The black dots with error bars are the 2012 data.
Red dashed is the expected shape from 124 GeV/c^2 staus (MC) and the blue histogram the background from muons from $Z^0/\gamma^\star$ decays (MC).
DLLbt is the **particle ID response** of the RICH counters.

3.4. Final selection by Neural Network

Response of the NN to MC individual tracks

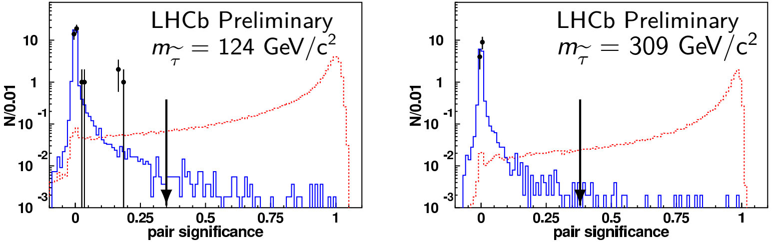


NN responses for MC muon tracks (blue) and MC stau tracks (red) for staus of 124 and 309 GeV/c^2.

Outline

4.1. Results : selection by the Neural Network

Number of candidates after the NN selection for the 2011 data set



Number N of candidates as a function of the pair significance for muon and stau pairs.
The left and right figures : stau masses of 124 and 309 GeV/c^2, respectively.
The black dots with error bars are the 2011 data set.
The red dashed histogram is the expected shape for 124 GeV/c^2 staus and the blue histogram the background.

The arrows show the **chosen cut : keep 95% of staus.**

4.2. Results

Expected numbers of stau and muon pairs in the signal region

$m_{\tilde{\tau}}$ (GeV/c^2)	$\mathcal{L} = 1.01$ fb^{-1}, 7 TeV		$\mathcal{L} = 2.1$ fb^{-1}, 8 TeV	
	muon pairs	stau pairs	muons pairs	stau pairs
124	0.0082 ± 0.0045	0.7534 ± 0.1379	0.0102 ± 0.0057	2.0298 ± 0.3605
309	0.0013 ± 0.0008	0.0026 ± 0.0005	0.0032 ± 0.0018	0.0090 ± 0.0017

Expected number of μ pairs close to zero,
$\widetilde{\tau}$ pairs almost zero except for the lowest mass hypothesis.

No event found !

4.3. Systematic uncertainties

Sources of systematic uncertainties

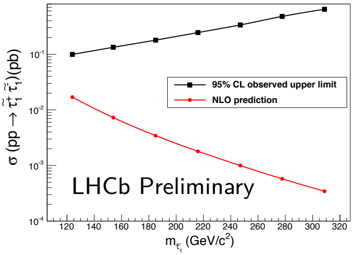
- **Luminosity** : 3.5% for 2011 and 1.2% for 2012
- **Preselection efficiency**
  - **Staus** : late arrival time : 2.2% to 3.7%, acceptance : 2%
  - **Muons** : trigger, hadron rejection cut, acceptance : 17%
- **Neural network** : due to dispersion of results from various detector calibrations
  - **Staus** : deviations of the efficiency less than 2%
  - **Muons** : few events survive $\Rightarrow$ large binomial errors, up to 50%

	2011		2012	
	staus	backg.	staus	backg.
Luminosity	3.5	3.5	1.2	1.2
Preselection	3.0–4.2	17.0	3.0–4.2	17.0
Neural Network	2.0	50.0	2.0	50.0
Total syst.	5.0–5.8	52.9	3.8–4.8	52.8

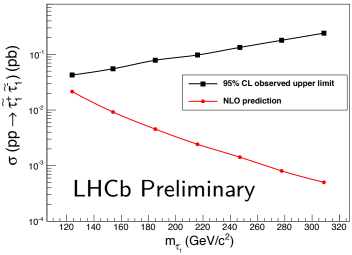
Systematic uncertainties (in %) for the stau pairs selection and on the background retention.

4.4. Upper limits on cross section of $\tilde{\tau}$ pair production

- Upper limits are calculated at 95% CL using the Feldman-Cousins approach for zero observed event, accounting for the expected number of background events and for the uncertainties on both signal and background.
- These are **upper limits for the Drell-Yan production of $\tilde{\tau}$ pairs.**



Upper limits at $\sqrt{s} = 7$ TeV



Upper limits at $\sqrt{s} = 8$ TeV

NLO calculations use *PROSPINO* program (arXiv:hep-ph/9611232v1 5 Nov 1996)

5. Conclusions and Outlook

- A search for heavy and long-lived staus in the LHCb detector at $\sqrt{s} = 7$ and 8 TeV has been performed for stau masses ranging from 124 to 309 GeV/c^2.

- The 2011 and 2012 data sets corresponding to the luminosities of 1 fb^{-1} and 2 fb^{-1} have been analyzed. No events have been observed.

- The upper limits on the cross section for stau pair production in *pp* collisions at $\sqrt{s} = 7$ and 8 TeV have been set.
We will try to combine the two periods.

- **Prospect:** The detection of heavy stable particles is limited by the trigger width; a trigger allowing an extra delay of ∼5 ns would allow to detect particles with β down to ~ 0.6 but this would require in addition an *ad hoc* modification of the tracking algorithm.

Thank you for your attention

Backup Slides

Other backgrounds

- Decays $Z^0/\gamma^\star -> \tau\tau$ where both taus decay leptonically to muons and neutrinos. This decay is estimated by MC to contribute 0.017 events into the event number selected by selection cuts for 1 fb^{-1} at 7 TeV collisions.
- Decays of the top quark pairs may contribute if both top quarks decay into muons via heavy mesons. This background may contribute 0.13 events into the event number selected by selection cuts for 1 fb^{-1} at 7 TeV collisions. This estimation is done using MC.
- Pions and kaons may be mis-identified as muons if they decay in flight or they have enough energy to escape the calorimeters and are identified as muons in the muon chambers. To estimate this background, same sign di-muons have been selected (*StrippingMuMuSSLine4*); no event has been found after the preselection cuts have been applied to this 1 fb^{-1} sample. Our onclusion : contribution from mis-ID muons is negligible.

Cross section

$m_{\tilde{\tau}}$ (GeV/c^2)	σ (fb) at $\sqrt{s} = 7$ TeV	σ (fb) at $\sqrt{s} = 8$ TeV
124	16.90 ± 0.07 (stat) $^{+5.0}_{-4.4}$ (syst)	$21.20 \pm 0.07\ ^{+3.8}_{-4.8}$
154	$7.19 \pm 0.07\ ^{+6.1}_{-4.6}$	$9.20 \pm 0.07\ ^{+5.6}_{-4.3}$
185	$3.44 \pm 0.07\ ^{+6.6}_{-4.9}$	$4.50 \pm 0.07\ ^{+5.9}_{-4.7}$
216	$1.79 \pm 0.07\ ^{+6.8}_{-5.3}$	$2.39 \pm 0.07\ ^{+6.7}_{-4.8}$
247	$1.0 \pm 0.07\ ^{+7.5}_{-5.8}$	$1.35 \pm 0.07\ ^{+7.1}_{-5.4}$
278	$0.57 \pm 0.07\ ^{+7.6}_{-6.2}$	$0.80 \pm 0.07\ ^{+7.0}_{-5.9}$
309	$0.34 \pm 0.07\ ^{+8.6}_{-6.0}$	$0.49 \pm 0.07\ ^{+7.9}_{-5.9}$

Cross sections for the stau pair production at NLO in pp collisions at $\sqrt{s} = 7$ and 8 TeV. The systematic uncertainties include the uncertainties on the PDF, the energy scale and the strong coupling.

	cross section (σ) (pb)
$\sqrt{s} = 7$ TeV	1.08 ± 0.10
$\sqrt{s} = 8$ TeV	1.36 ± 0.12

Cross section for $Z/\gamma^\star \to \mu^+\mu^-$ in pp collisions retricted to the domain $M_{Z/\gamma^\star} > 100$ GeV/c^2, $p_T^\mu > 50$ GeV/c, $1.9 < \eta_{\mu^\pm} < 4.9$.
Uncertainty is from PDF and energy scale variation.

Acceptance factors (A)

A is the ratio between the number of stau pairs entering into the LHCb detector's acceptance and the number of stau pairs generated in 4π.

$m_{\tilde{\tau}}$	124	154	185	216
7 TeV	8.91±0.02	6.92±0.02	5.53±0.02	4.49±0.01
8 TeV	10.12±0.03	8.10±0.02	6.52±0.02	5.40±0.02

$m_{\tilde{\tau}}$	247	278	309
7 TeV	3.65±0.01	3.05±0.01	2.56±0.01
8 TeV	4.47±0.01	3.76±0.01	3.2±0.01

Acceptance factors, A, (in %) for stau pairs at $\sqrt{s} = 7$ and 8 TeV, as a function of the stau mass (in Gev/c^2). The uncertainties are statistical.

Definition of the pair isolation I

We consider the asymmetry between the transverse momentum (P_T) of the considered track and the scalar sum (ΣP_T) of the transverse momenta of all charged particles in a cone surrounding this considered track.

$$I_{track} = \frac{P_T - \Sigma P_T}{P_T + \Sigma P_T} \tag{1}$$

Here, the cone is defined by:

$$R = \sqrt{(\eta_{track} - \eta_{particle})^2 + (\phi_{track} - \phi_{particle})^2} < 0.5 \tag{2}$$

where $(\eta_{track}, \phi_{track})$ are the coordinates of the considered track in spherical coordinates, $(\eta_{particle}, \phi_{particle})$ are the coordinates of any other charged particle. Then, the isolation of a pair can be defined:

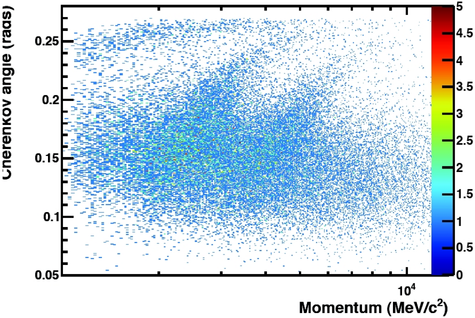
$$I = \sqrt{\frac{(I_{track1} - 1)^2 + (I_{track2} - 1)^2}{8}} \tag{3}$$

Pre-selection efficiencies

$m_{\tilde{\tau}}$	MC11		MC12	
	ϵ for stau pairs	ϵ for muon pairs	ϵ for stau pairs	ϵ for muon pairs
124	52.21 ± 0.06	22.74 ± 0.03	47.42 ± 0.05	21.12 ± 0.03
154	51.52 ± 0.06	21.84 ± 0.03	46.83 ± 0.05	20.55 ± 0.03
185	48.40 ± 0.06	21.84 ± 0.03	44.12 ± 0.05	20.55 ± 0.03
216	44.23 ± 0.06	19.66 ± 0.03	40.55 ± 0.05	19.04 ± 0.02
247	39.43 ± 0.06	17.05 ± 0.03	36.82 ± 0.05	17.10 ± 0.02
278	34.57 ± 0.06	17.05 ± 0.03	32.85 ± 0.05	17.10 ± 0.02
309	29.90 ± 0.06	11.28 ± 0.02	28.79 ± 0.05	12.24 ± 0.02

Pre-selection efficiency (ϵ in %) for muon and stau pairs for the two centre of mass energies. The errors are statistical. The first column gives the stau mass hypothesis considered in the event selection (in GeV/c^2).

Identification performance in the aerogel



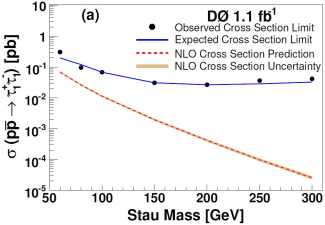
Cross section upper limits

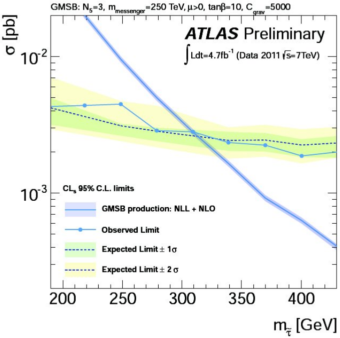
$m_{\tilde{\tau}}$ (GeV/c^2)	2011 ($\mathcal{L} = 1.01$ fb^{-1}, 7 TeV)		2012 ($\mathcal{L} = 2.1$ fb^{-1}, 8 TeV)	
	NLO cross-section	upper limit	NLO cross-section	upper limit
124	0.0169 $\pm$ 0.0008	0.0718	0.0212 $\pm$ 0.0008	0.0332
154	0.0072 $\pm$ 0.0004	0.0931	0.0092 $\pm$ 0.0005	0.0419
185	0.0034 $\pm$ 0.0002	0.1238	0.0045 $\pm$ 0.0003	0.0550
216	0.0018 $\pm$ 0.0001	0.1654	0.0024 $\pm$ 0.0001	0.0723
247	0.0010 $\pm$ 0.0001	0.2255	0.0014 $\pm$ 0.0001	0.0961
278	0.0006 $\pm$ 0.0001	0.3171	0.0008 $\pm$ 0.0001	0.1280
309	0.0003 $\pm$ 0.0001	0.4228	0.0005 $\pm$ 0.0001	0.1715

Cross-section (pb) for stau pair production as predicted by theory at NLO, and 95%CL upper limits from zero observed events in 2011 and 2012.

Comparison to the limits from D0 and ATLAS experimen

D0: Limits on the stau pair production.
ATLAS: Limits on the stau production.





	result from thesis	D0	ATLAS
Upper limits	highest	medium	lowest
$\sqrt{s}$ (TeV)	7	1.96	7
L (fb^{-1})	1	1.1	4.7
Geometry acceptance	$1.8 < \eta < 4.9$	$0 < \eta < 2$	full acceptance
Method	Feldman-Cousins	Bayesian limit	CL_s