Measurement of supersymmetry at a 1.4 TeV CLIC collider

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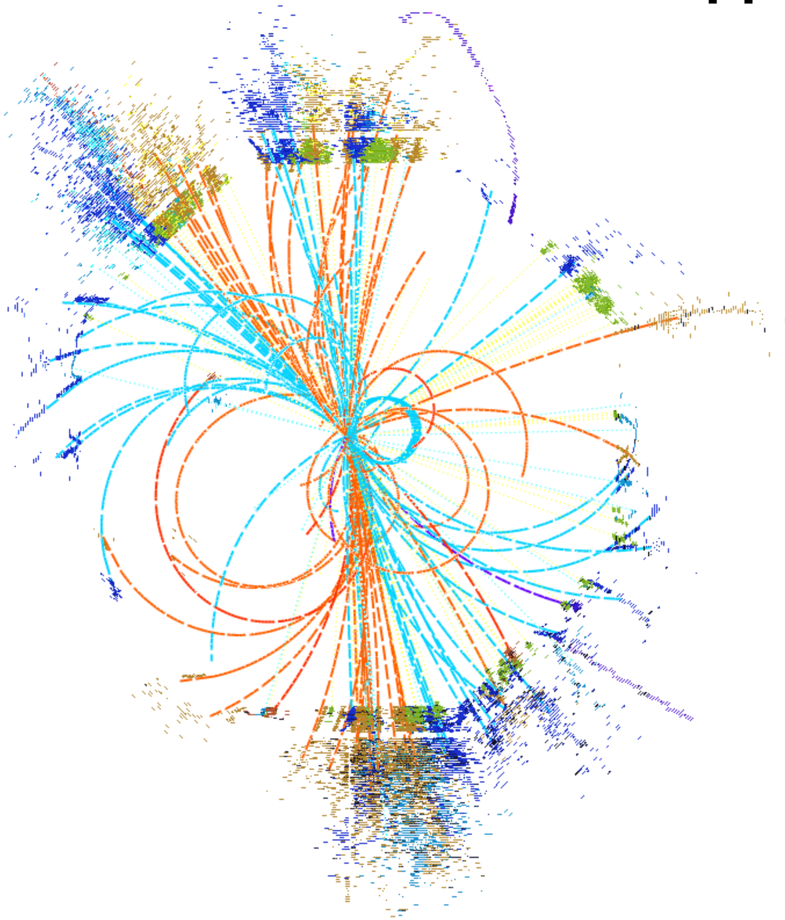
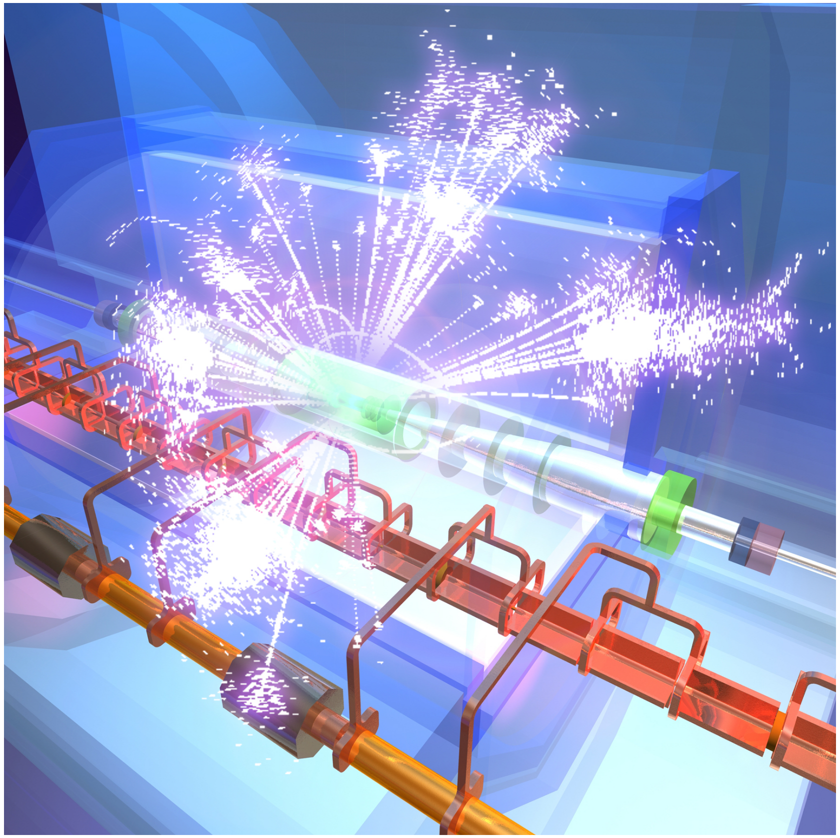




International Workshop on Future Linear Colliders, University of Texas at Arlington, 25/10/2012

Introduction

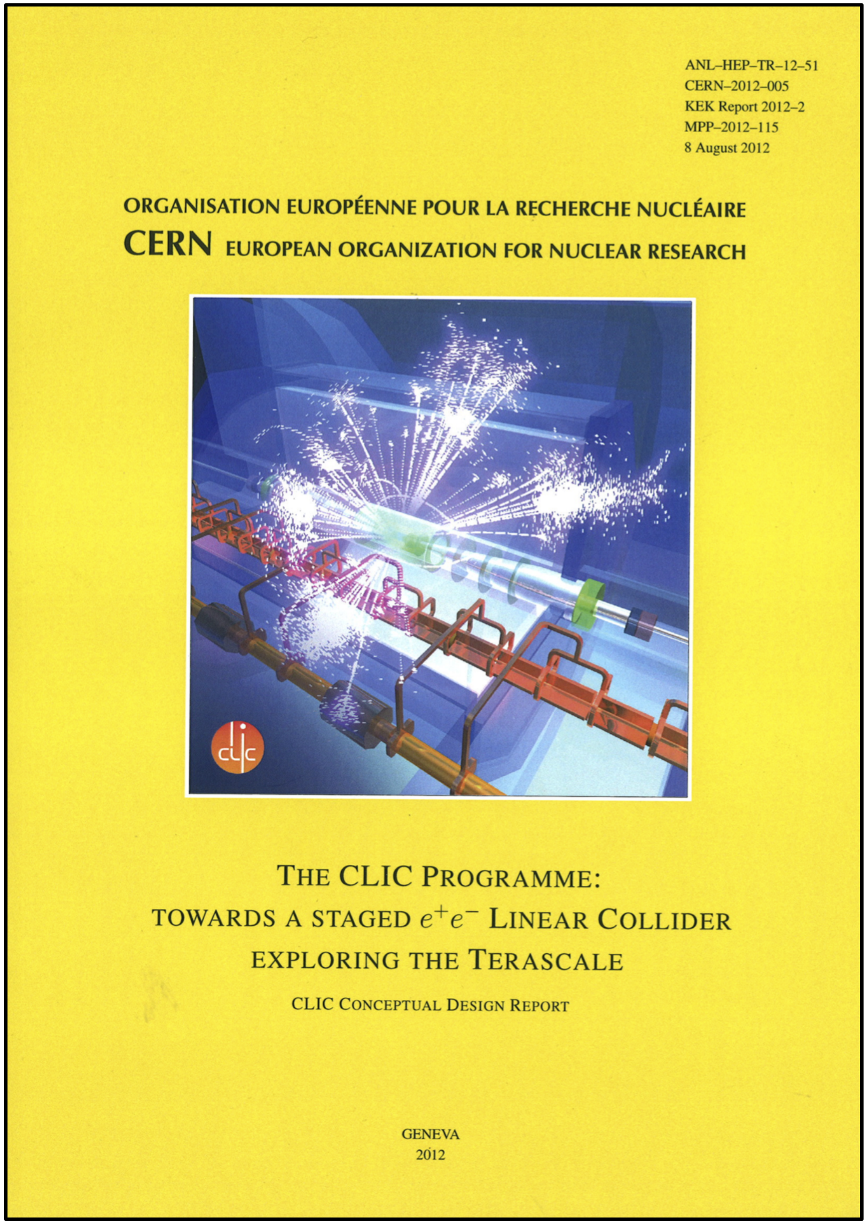
Introduction

- **Recently released CDR volume:** The CLIC Programme – Towards a staged e^+e^- Linear Collider exploring the Terascale

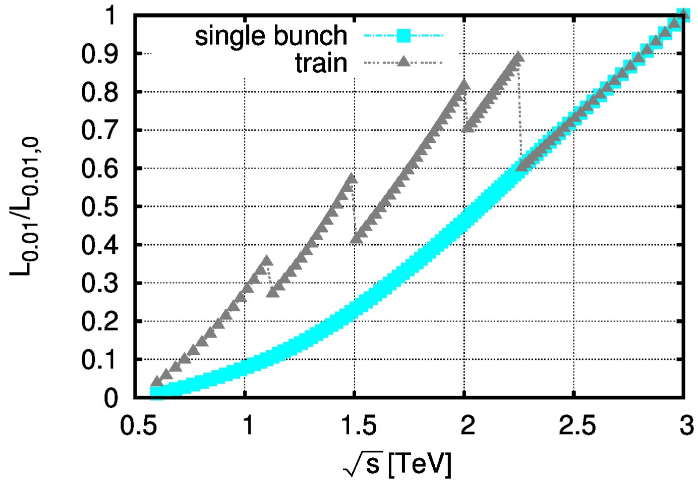
- Available online: arXiv:1209.2543

- Example scenarios are discussed where CLIC is built in three stages: 500 GeV, 1.4(1.5) TeV, 3 TeV

- All studies presented in the following were prepared for this document



Motivation for energy staging



Interesting physics (may) exist at various energies:

• **Few 100 GeV**:
Precision SM measurements: Higgs, top,...
• **Still unknown**:
Beyond Standard Model physics,
Potentially various thresholds from few 100 GeV to few TeV
→ Both require high luminosities!

Machine implementation:
• Significant luminosity penalty when running far below the nominal energy
• Possibility to start physics during construction phase for higher energies

In the following:
Potential of an intermediate energy stage at 1.4 TeV assuming L_{int} = 1.5 ab^{-1}
→ Attractive, because only one drive beam complex required

SUSY model for staged energy studies

Model parameters

$M_1 = 840$ GeV, $M_2 = 600$ GeV, $M_3 = 450$ GeV

$A_0 = -800$ GeV, $\tan\beta = 20$

$\mu = +902$ GeV , $m_{A^0,\mathrm{pole}} = 765$ GeV

$m_{\tilde{Q}_{1,2}} = m_{\tilde{u}_{1,2}} = m_{\tilde{d}_{1,2}} = 2000$ GeV

$m_{\tilde{Q}_3} = m_{\tilde{u}_3} = m_{\tilde{d}_3} = 900$ GeV

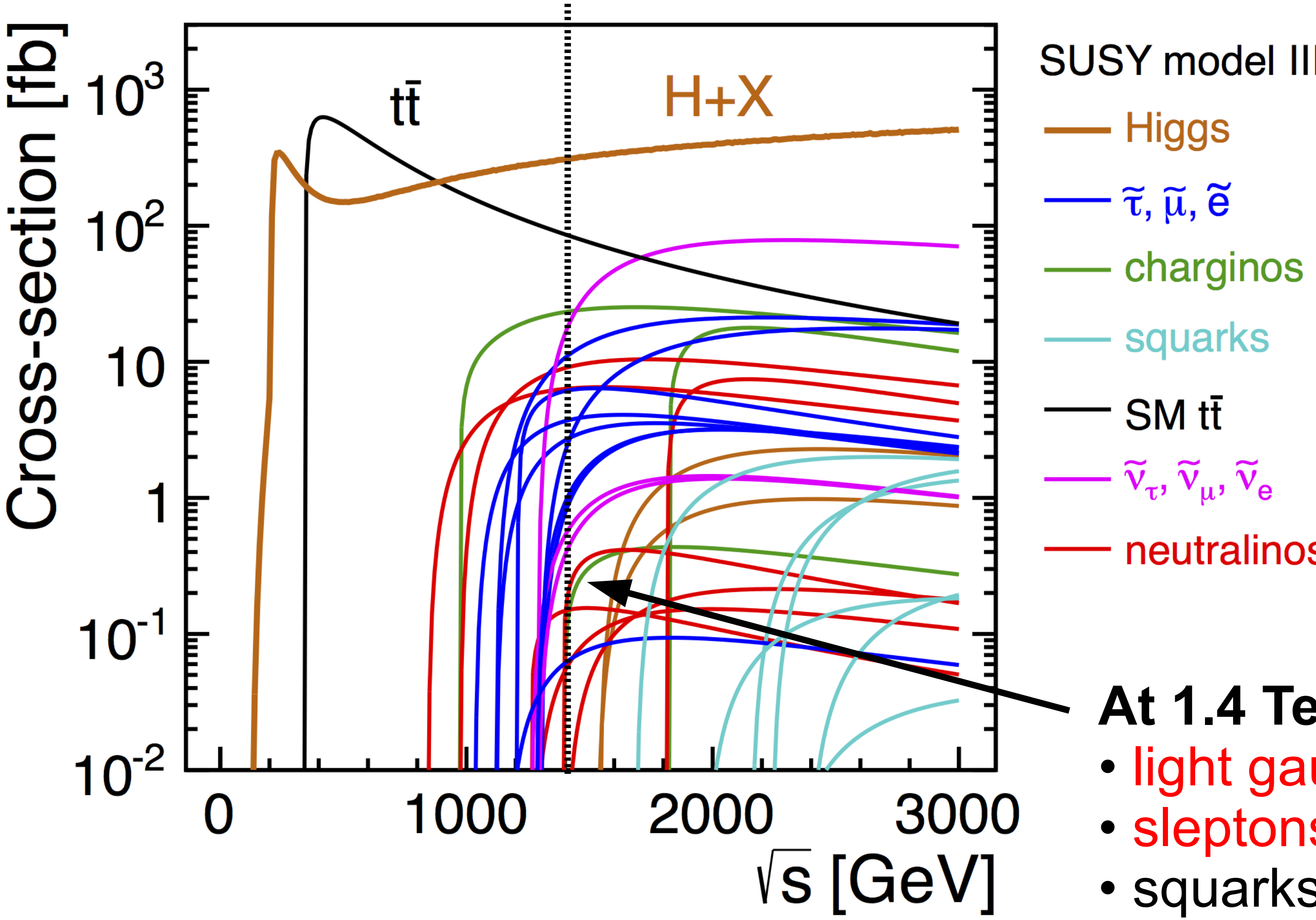
$m_{\tilde{L}_{1,2,3}} = m_{\tilde{e}_{1,2,3}} = 500$ GeV

Spectrum in GeV

Neutralinos ($\tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3, \tilde{\chi}^0_4$) =	357, 487, 904, 911
Charginos ($\tilde{\chi}^\pm_1, \tilde{\chi}^\pm_2$) =	487, 911
Sleptons ($\tilde{e}^-_R, \tilde{e}^-_L, \tilde{\nu}_e$) =	559, 650, 644
($\tilde{\tau}_1, \tilde{\tau}_2, \tilde{\nu}_\tau$) =	517, 642, 630
Gluino ($\tilde{g}$) =	1114
Squarks ($\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$) =	844, 1120, 1078, 1191
($\tilde{d}_R, \tilde{u}_R, \tilde{d}_L, \tilde{u}_L$) =	2167, 2181, 2197, 2196
Heavy Higgses (h, A^0, H^0, $H^\pm$)	118, 765, 765, 769

More details:
LCD-Note-2012-003

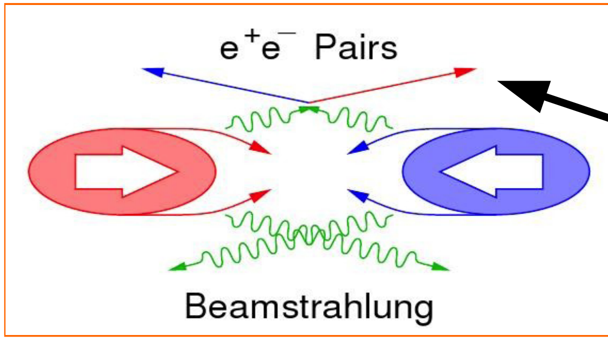
Cross sections



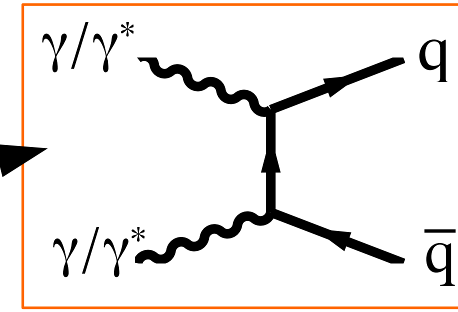
At 1.4 TeV:

- light gauginos
- sleptons
- squarks and charged Higgs too heavy

Experimental conditions



Beam-related backgrounds
- e^+e^- pairs
- $\gamma\gamma \rightarrow$ hadrons

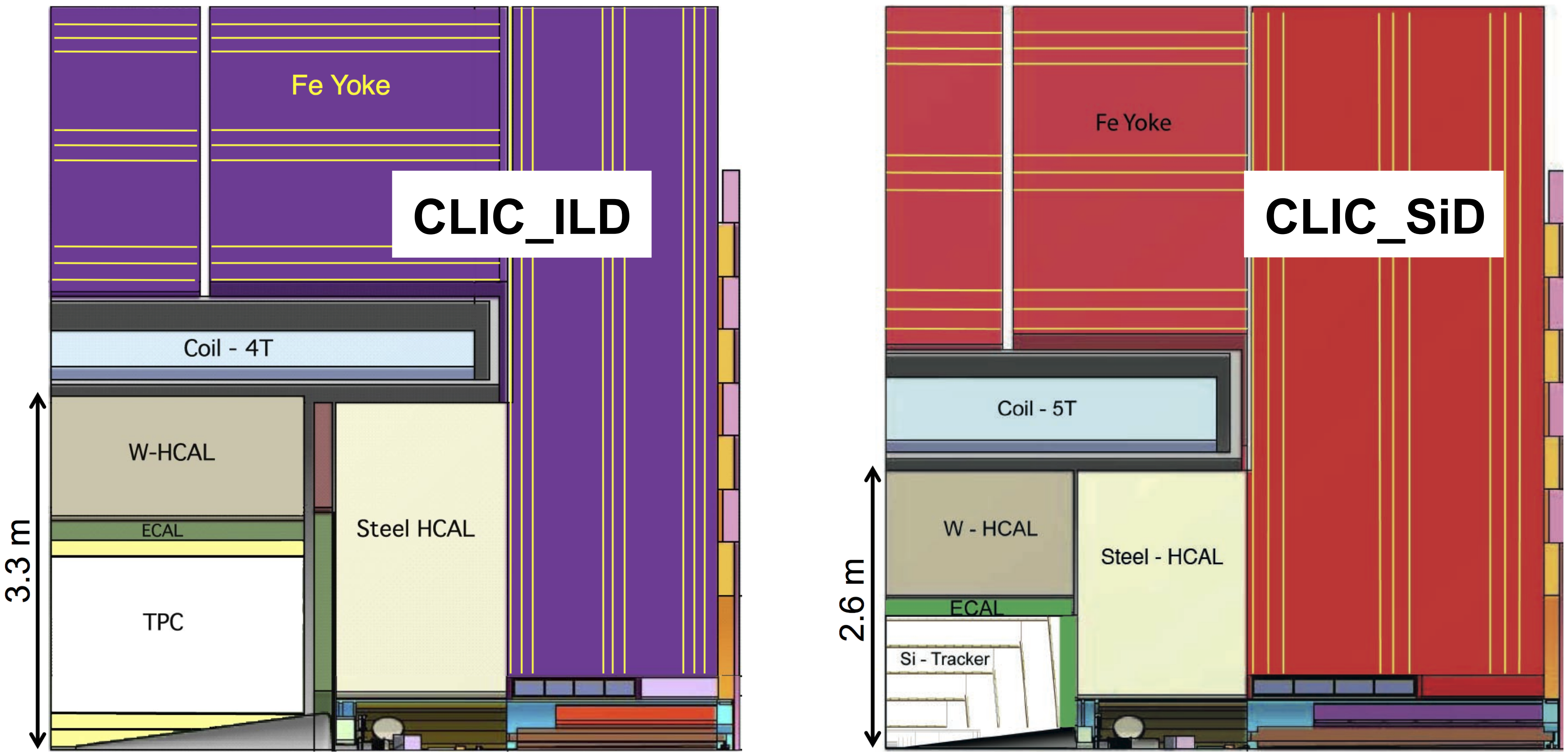


e^+e^- pairs: Detector design issue
(mostly very forward, high occupancies)
$\gamma\gamma \rightarrow$ hadrons:
- Main background in calorimeters and trackers $\rightarrow$ Impact on physics
- Overlay of physics events with pileup from 60 bunch crossings of $\gamma\gamma \rightarrow$ hadr. interactions in benchmark studies

$\sqrt{s}$ [GeV]	N($\gamma\gamma \rightarrow$ hadr.) / BX
350	0.05
500	0.3
1400	1.3
3000	3.2

- Backgrounds suppressed using combined cuts on cluster times and p_T
- Further reduction of the impact of the background is achieved using well-adapted jet finding strategies based on the LHC experience (FastJet)

CLIC detector concepts



Benchmark studies

1.) Gaugino pair production (LCD-Note-2012-006)
Final states: four jets and missing energy
Detector model: CLIC_SiD

2.) Stau pair production (LCD-Note-2012-009)
Final state: two tau leptons and missing energy
Detector model: CLIC_ILD

3.) First and second generation sleptons (LCD-Note-2012-012)
Final state: two electrons/muons, missing energy (and four jets)
Detector model: CLIC_ILD

→ Reconstruction for large variety of final states tested
→ Mostly different challenges compared to previous studies at 3 TeV

All studies were performed using full detector simulations!

Gaugino pair production

Gaugino pair production

Signal processes:

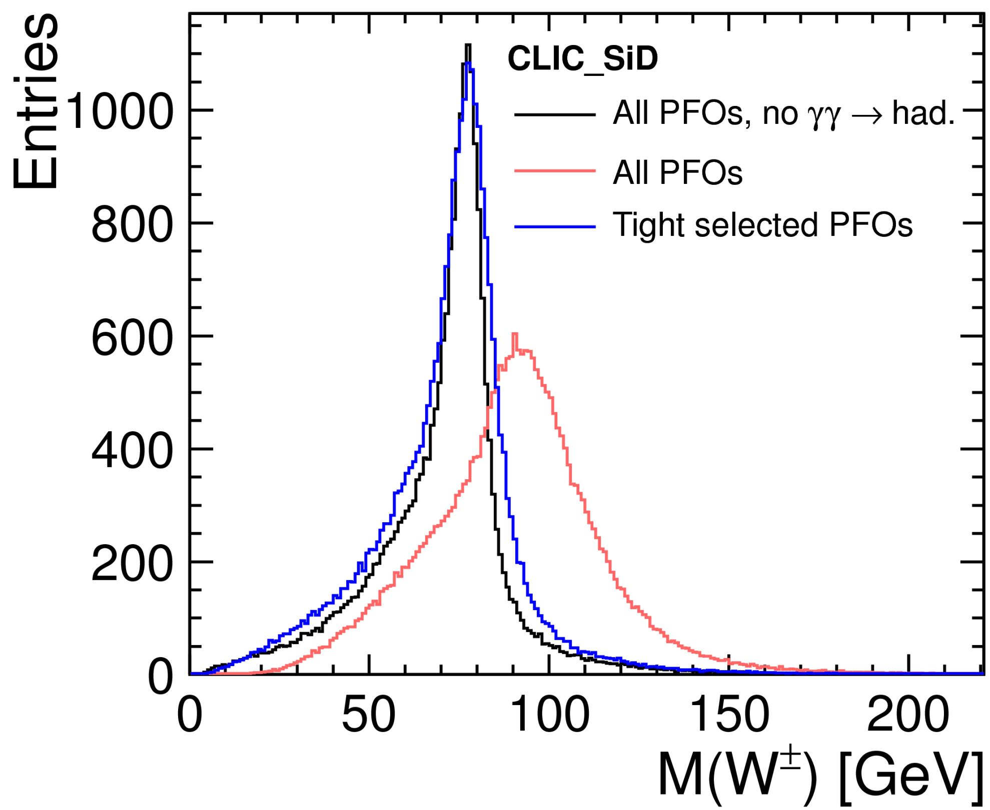
$$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow h(Z)h(Z)\tilde{\chi}_1^0\tilde{\chi}_1^0$$

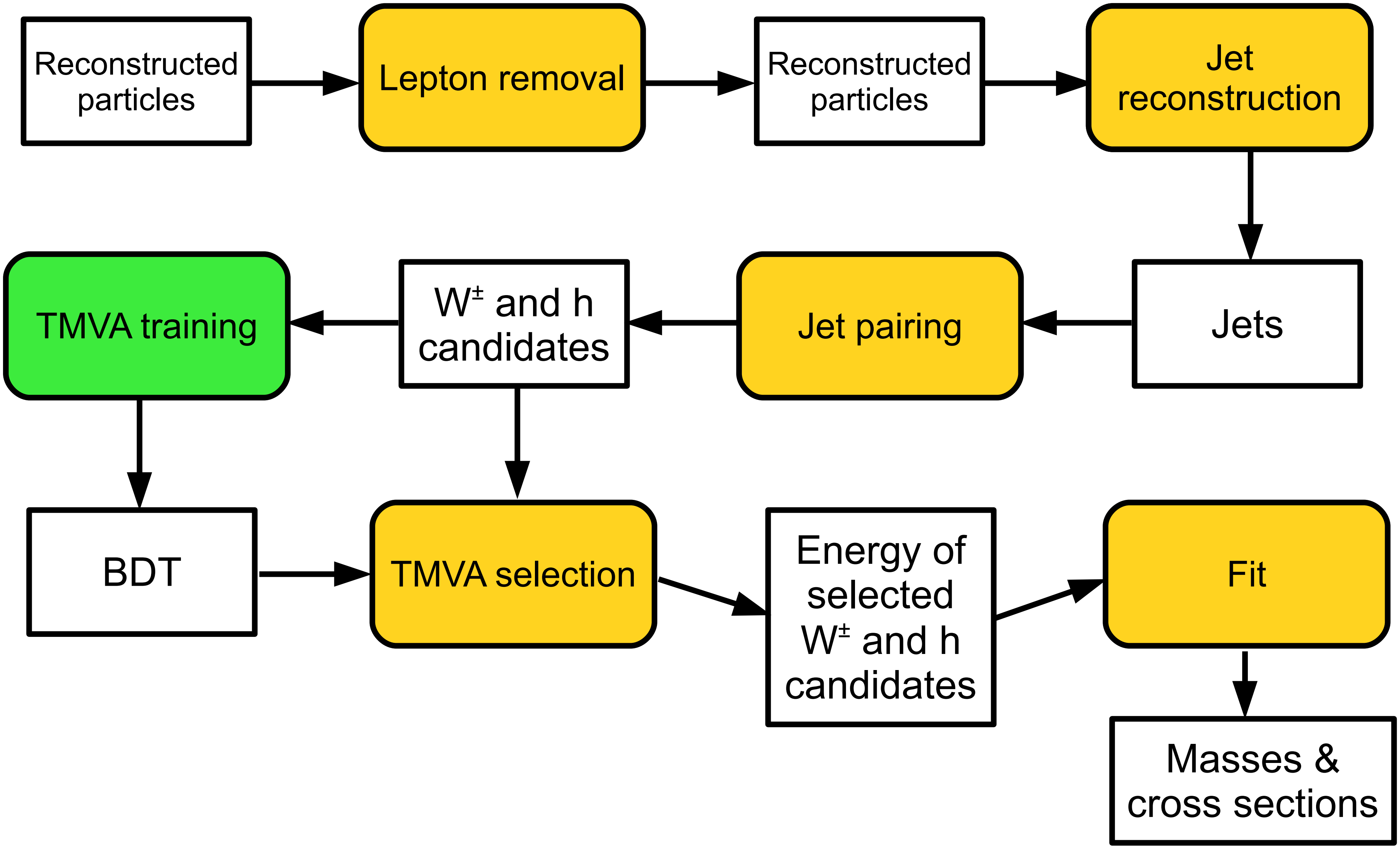
94.6% 5.1%

Hadronic $W^\pm$ and h decays
→ 4 jets and missing energy in the final states

Particular challenge:
Reconstruction of relatively low-energy jets in the presence of pileup from γγ → hadrons interactions



Analysis overview



Event selection

Pre-selection:

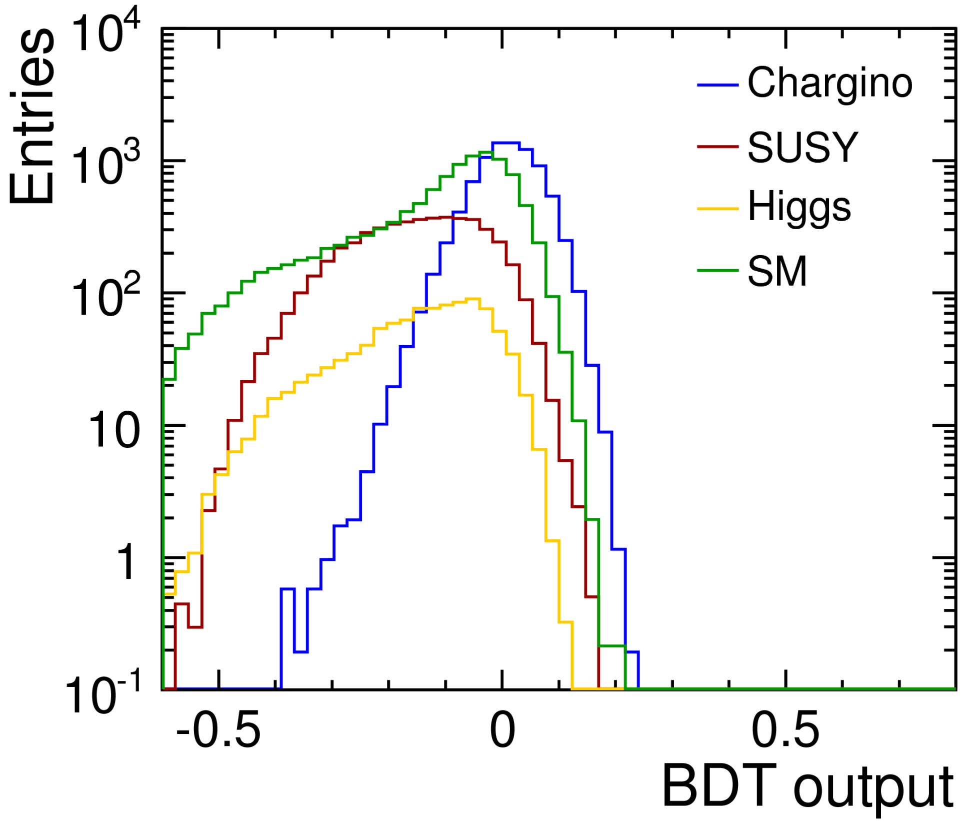
- $40 < M_{jj,1} < 160$ GeV and $40 < M_{jj,2} < 160$ GeV
- $|\cos\theta^{miss}| < 0.95$
- $|\cos\theta^{jj,1}| < 0.95$ and $|\cos\theta^{jj,2}| < 0.95$
- $p_T^{miss} < 250$ GeV
- $E^{vis} < 600$ GeV

Event selection:

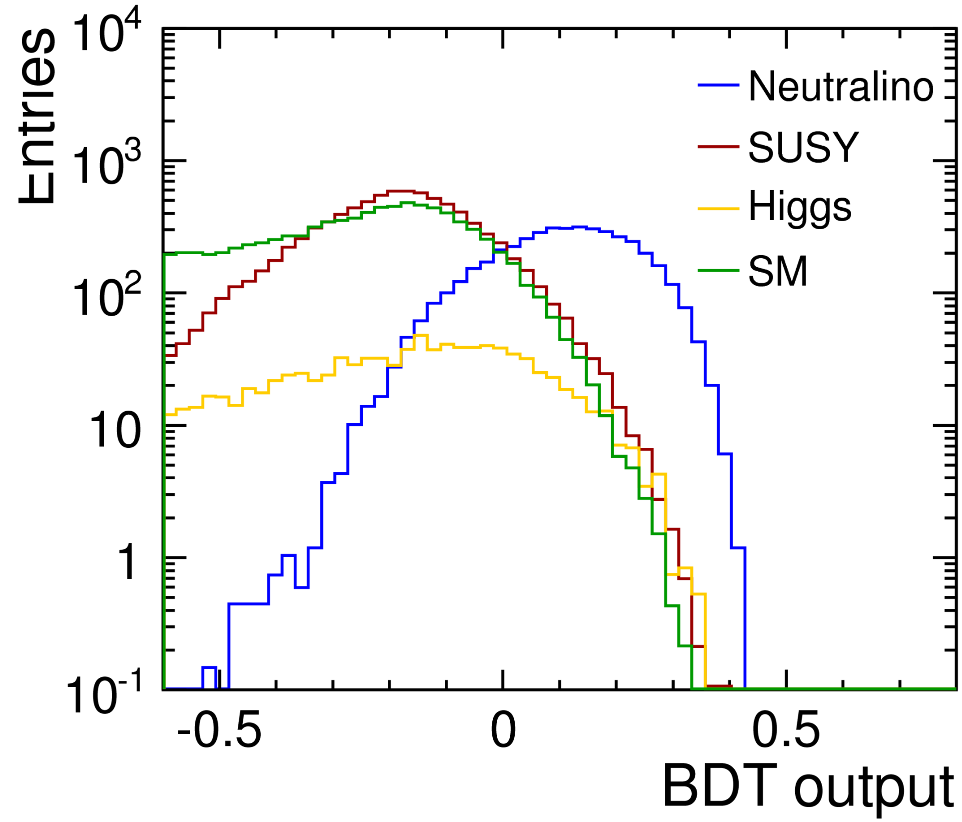
- Based on Boosted Decision Trees (BDTs) as implemented in TMVA
- The BDTs were trained using 17 variables describing kinematic properties of the reconstructed $W^{\pm}$ and h candidates as well as the event topology

BDT outputs

Chargino

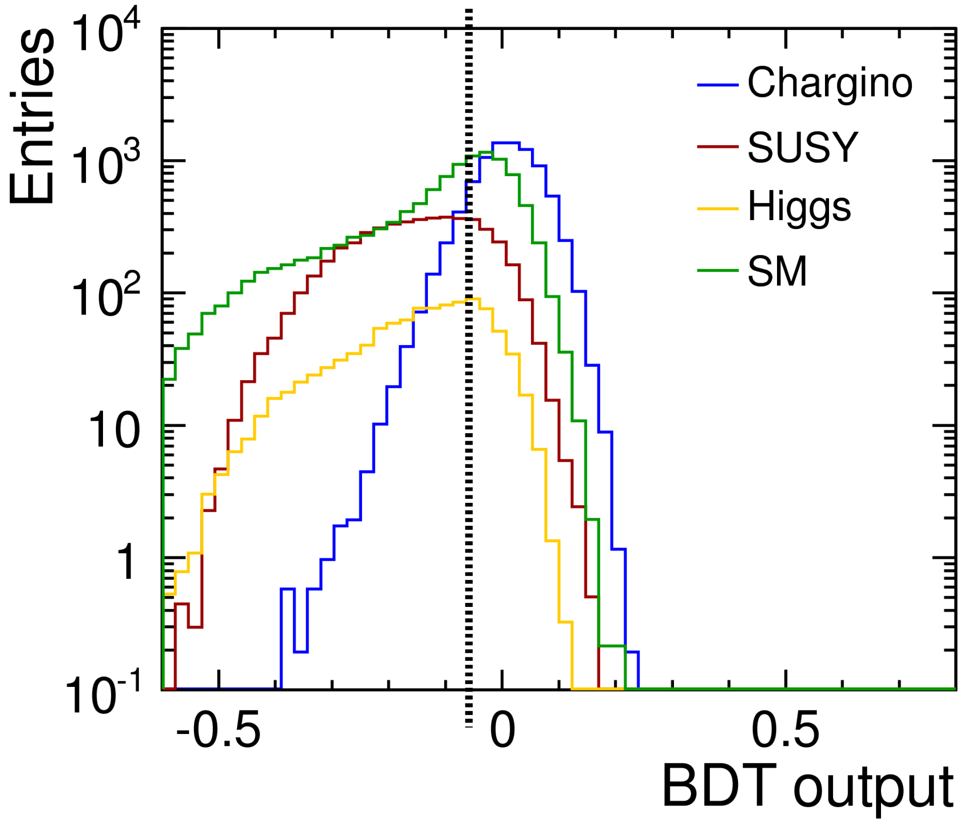


Neutralino

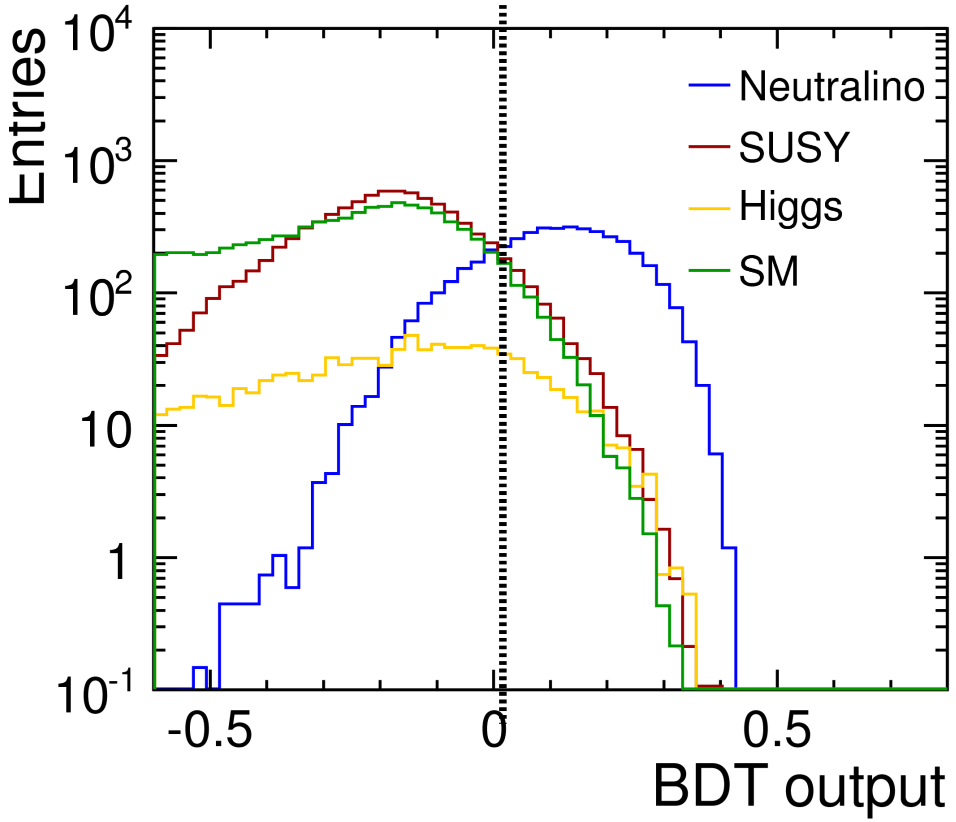


BDT outputs

Chargino



Neutralino

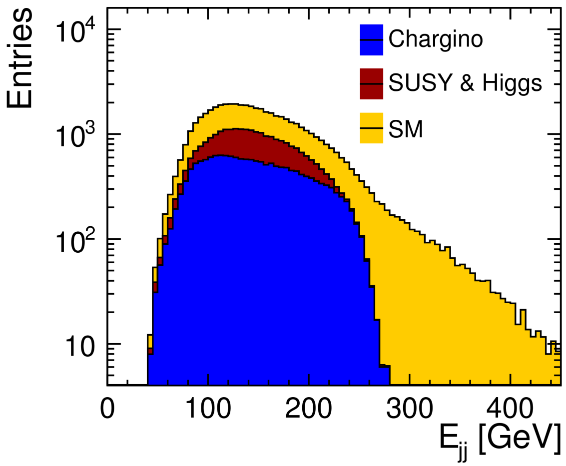


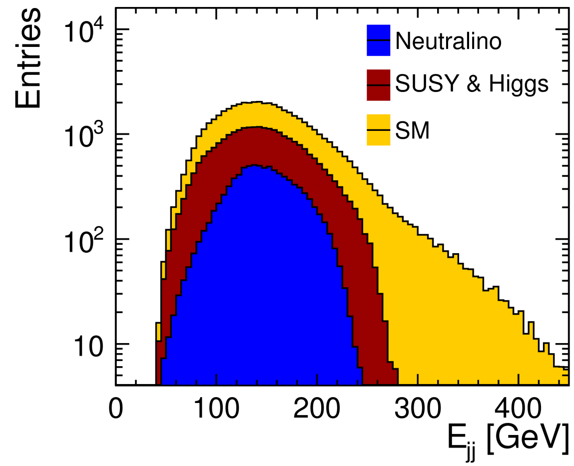
Cuts chosen to optimise S / (S+B)$^{1/2}$:

BDT output > -0.0677

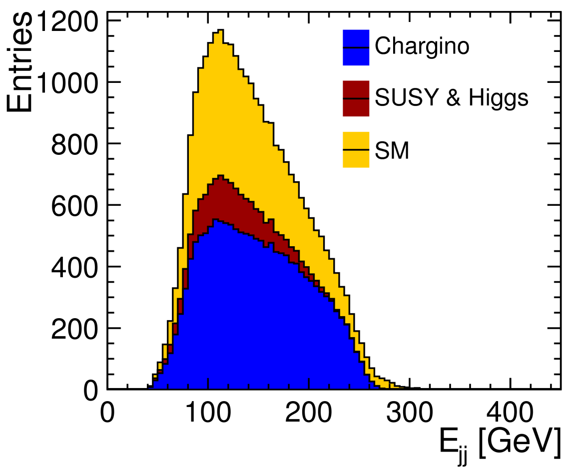
BDT output > 0.0158

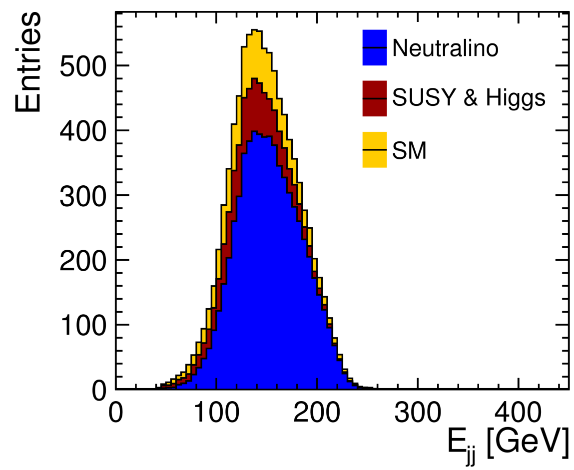
Energy spectra of $W^{\pm}$ and h candidates





Before cut on BDT output





After cut on BDT output

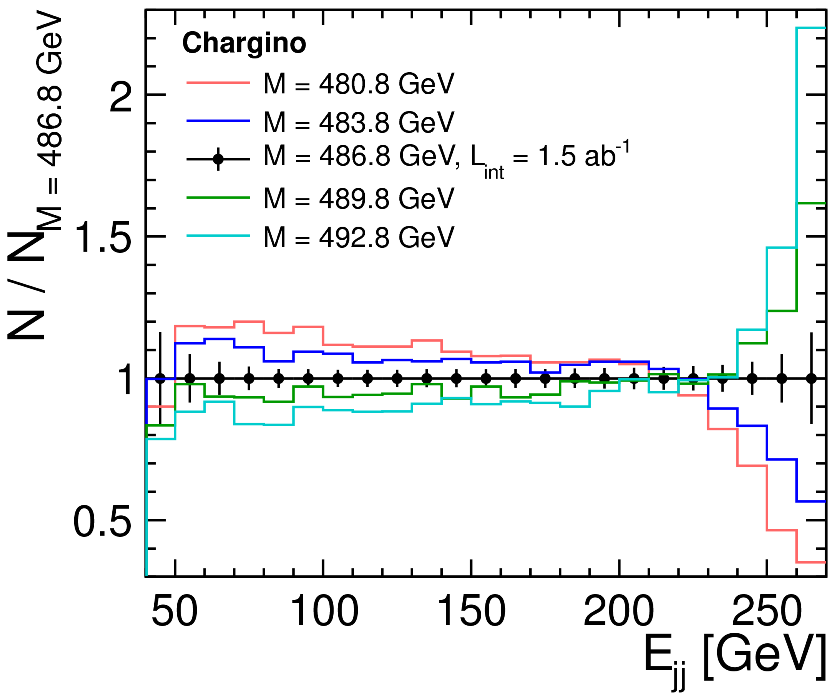
Pair production cross sections from counting selected events:

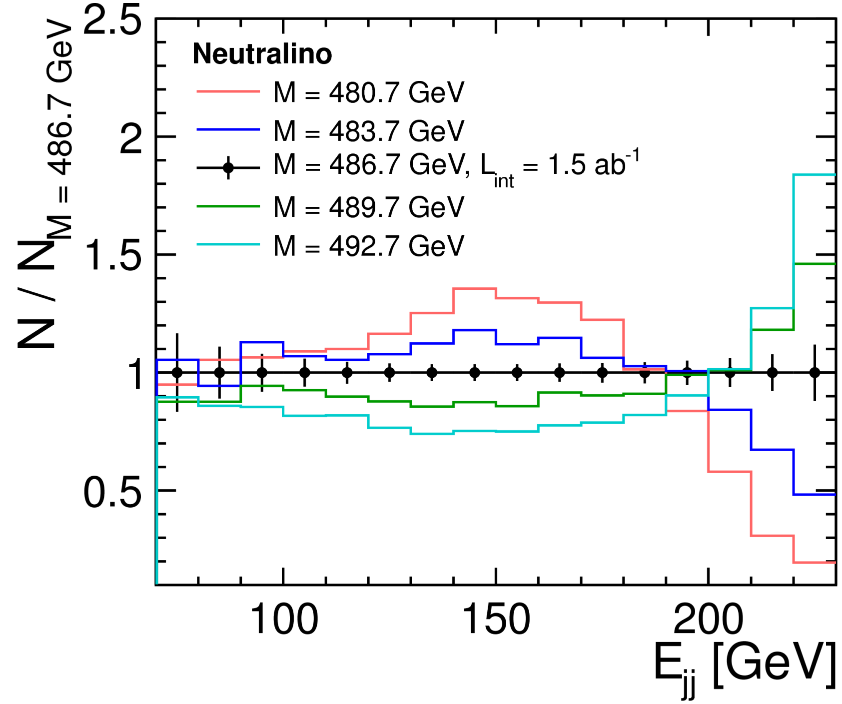
$$\boxed{\sigma(e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-) = 15.32 \pm 0.17 \text{ fb}}$$

$$\boxed{\sigma(e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0) = 5.40 \pm 0.08 \text{ fb}}$$

L_{int} **= 1.5 ab^{-1}**

Mass measurements





The reconstructed boson energy spectra are sensitive to the SUSY particle masses

L_{int} = 1.5 ab^{-1}

$$\boxed{M(\tilde{\chi}_1^+) = 487.4 \pm 0.8 \text{ GeV}}$$

$$\boxed{M(\tilde{\chi}_2^0) = 487.9 \pm 0.5 \text{ GeV}}$$

Systematic uncertainties

A detailed evaluation of the systematic uncertainties is impossible at this point. → Illustration of a few potentially dominating effects:

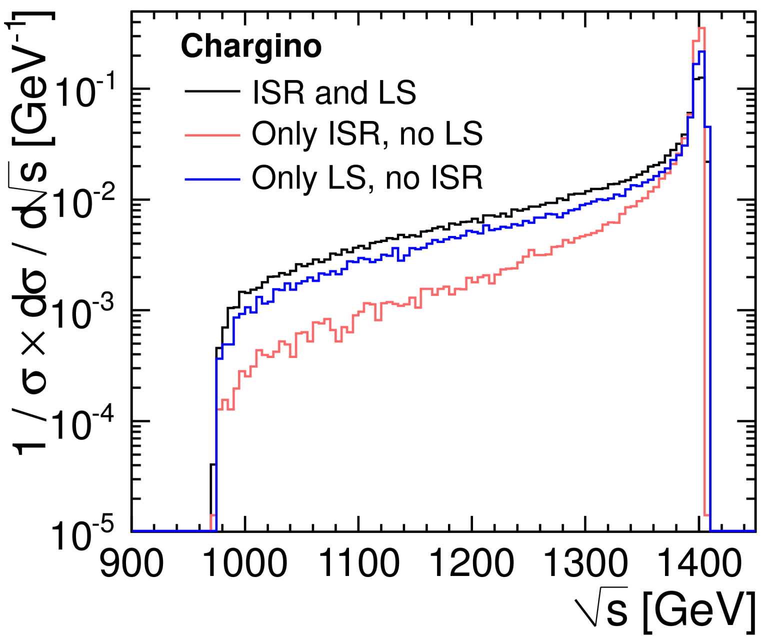
1.) Mass of the lightest neutralino: Impact on the reconstructed energy spectra. An uncertainty of 1% (from sleptons) translates to:

$$\Delta M(\tilde{\chi}_1^{+}) = \pm 1.4\ \mathrm{GeV}, \Delta M(\tilde{\chi}_2^{0}) = \pm 1.3\ \mathrm{GeV}$$

2.) Jet energy scale: A 1% uncertainty in the jet energy scale leads to:

$$\Delta M(\tilde{\chi}_1^{+}) =^{+2.8}_{-3.4}\ \mathrm{GeV}, \Delta M(\tilde{\chi}_2^{0}) =^{+1.1}_{-1.4}\ \mathrm{GeV}$$

3.) Luminosity spectrum (LS):
“Ad-hoc” variation: 1% of events moved from peaks to tails and vice versa for both beams.



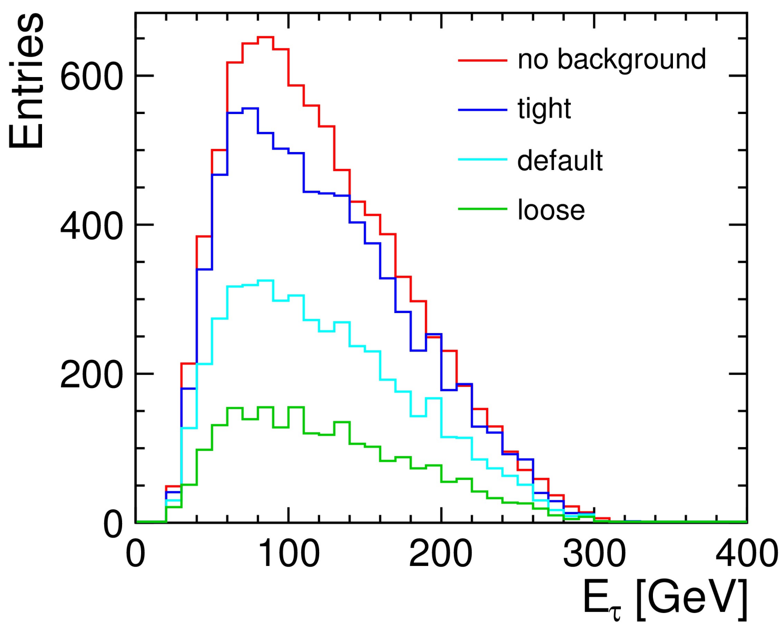
- Negligible impact on masses
- Change in cross sections similar to statistical uncertainties

Stau pair production

Stau pair production

Signal process:

$$e^+e^- \rightarrow \tilde{\tau}_1\tilde{\tau}_1 \rightarrow \tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$



Reconstruction of hadronic tau decys
→ TauFinder (LCD-Note-2010-009):
Seeded cone-based jet finding algorithm:

- Seed p_T: > 15 GeV
- τ candidate inv. Mass: < 2.5 GeV
- Search cone: 0.07 radian
- Isolation cone: 0.3 radian
- Energy in isolation cone: 2 GeV

- 60% efficiency for signal τ leptons, 0.6% fake rate for quark jets

- Rejection of pileup from γγ → hadrons interactions crucial

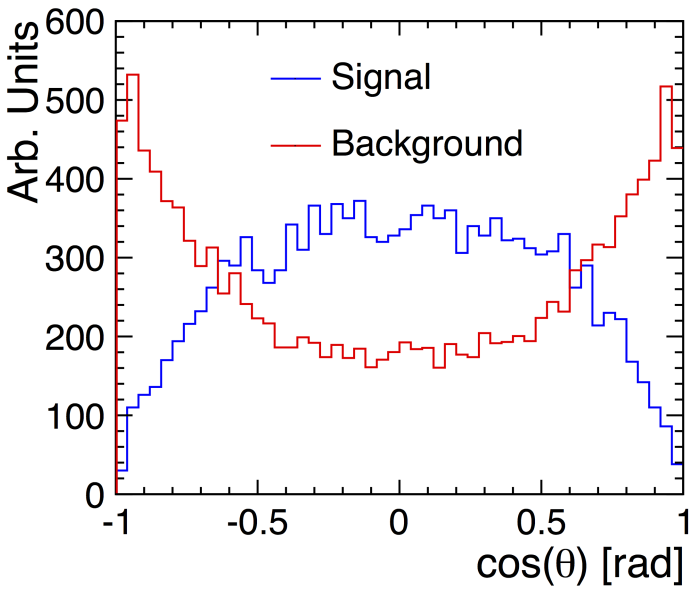
Event selection

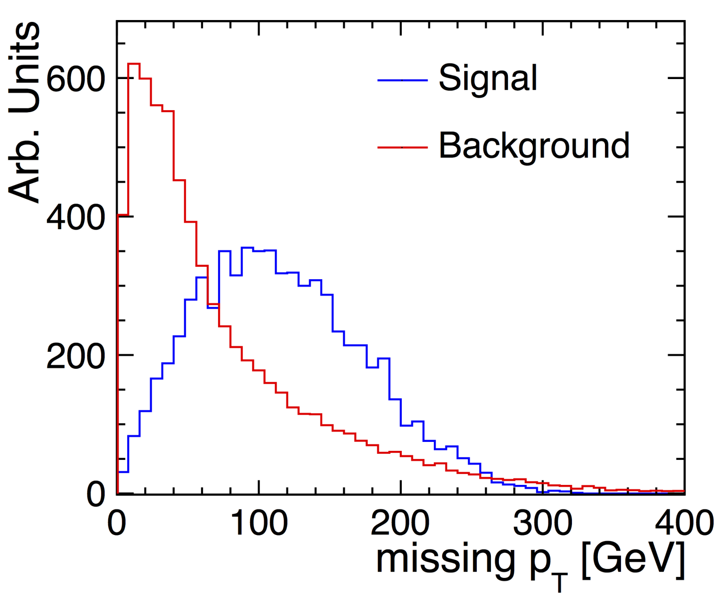
Pre-selection:

- 10° < Θ(τ) < 170°, p(τ) > 20 GeV for both τ's
- ΔΦ(τ, τ) < 178°
- Angle between tau candidates > 23°
- 40 < M(τ, τ) < 650 GeV

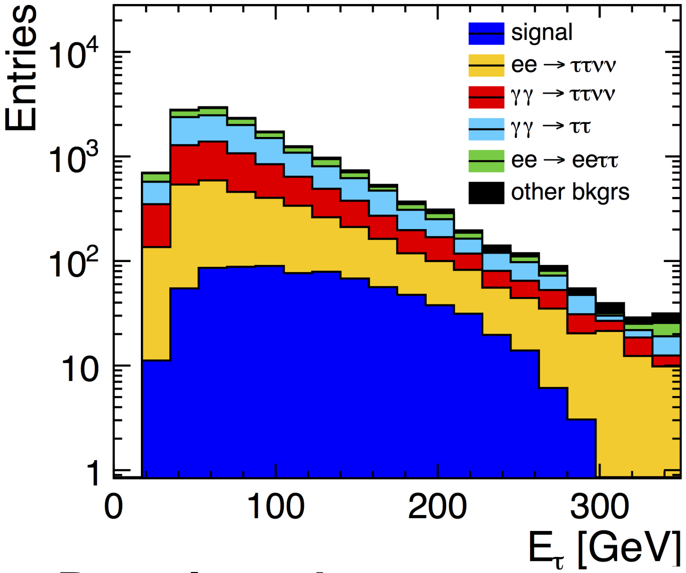
Event selection:

- Based on Boosted Decision Trees (BDTs) as implemented in TMVA using 16 input variables

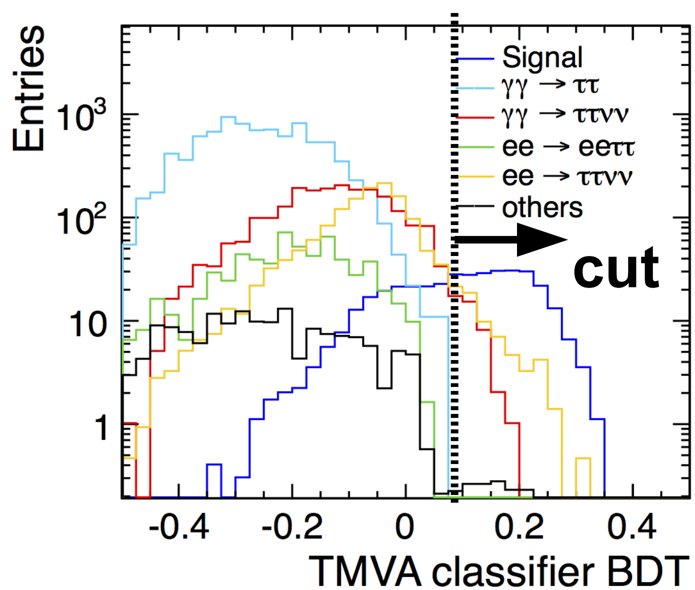


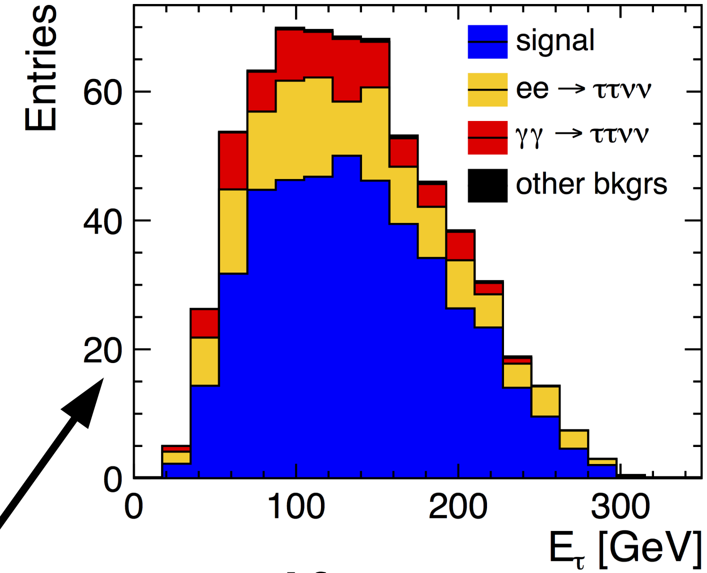


Boosted decision tree



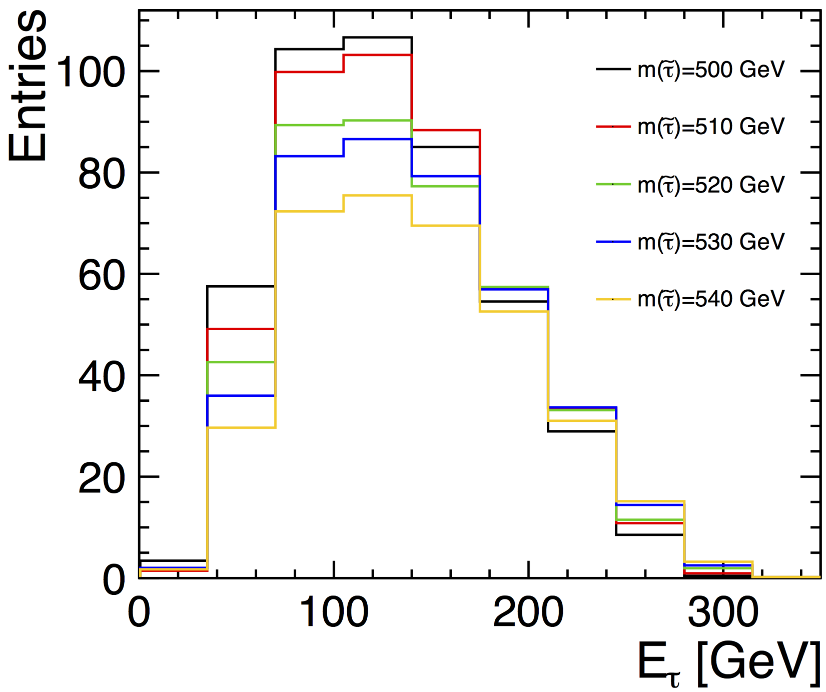
Preselected candidates





After cut on BDT output

Signal extraction and result



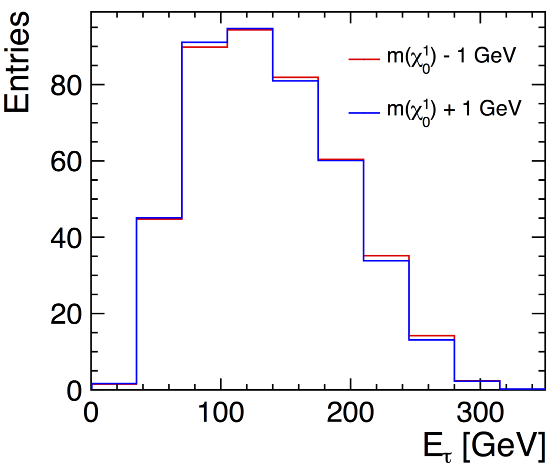
2D template fit to extract the mass and pair production cross section:

Parameter	Binning	Uncertainty
$M(\tilde{\tau}_1)$	10	10.2 GeV
	15	11.3 GeV
$\sigma(\tilde{\tau}_1\tilde{\tau}_1)$	10	8.1%
	15	7.5%

L_{int} = 1.5 ab^{-1}

$$M(\tilde{\tau}_1) = 517\ \text{GeV}$$

Dependence on the lightest neutralino mass marginal



First and second generation sleptons

First and second generation sleptons

Signal processes:

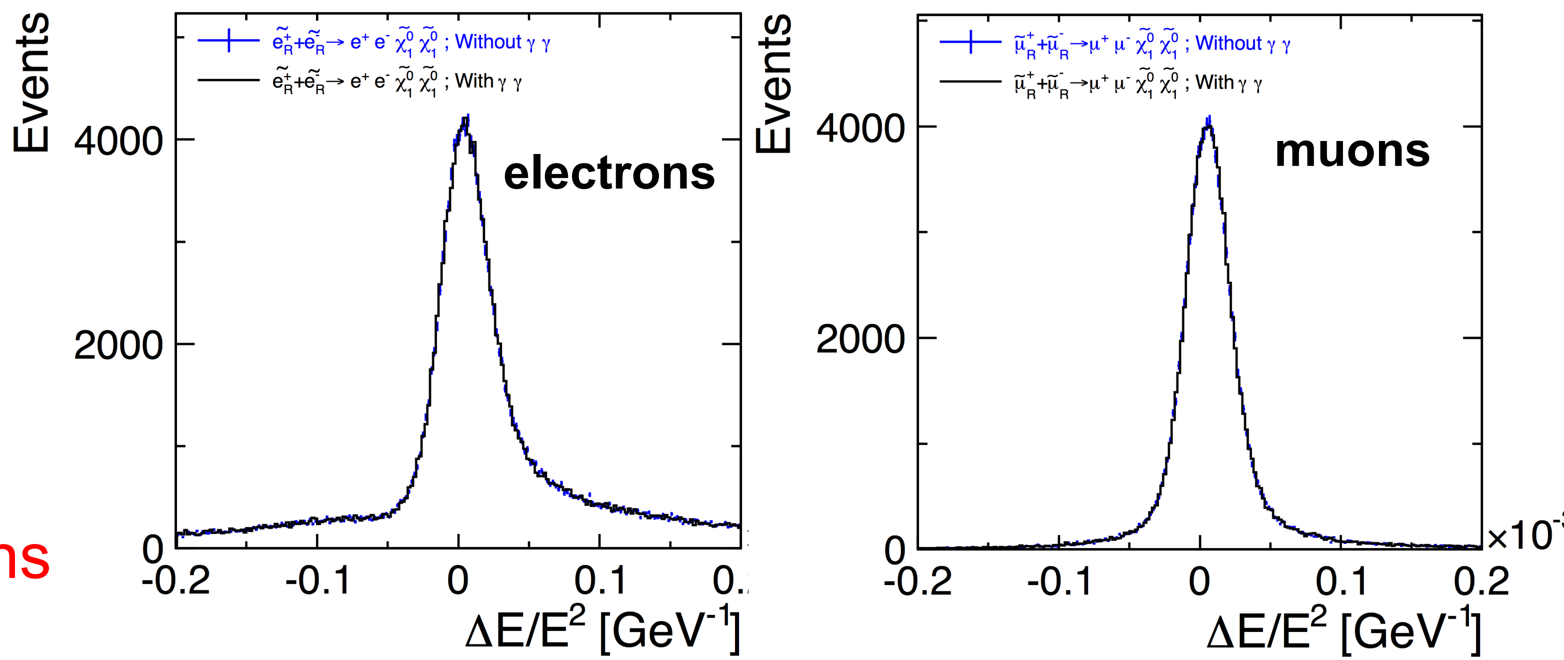
$$e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0 \qquad \text{BR} = 100\%$$

$$e^+e^- \to \tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0 \qquad \text{BR} = 100\%$$

$$e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e \to e^+e^-\tilde{\chi}_1^+\tilde{\chi}_1^- \to e^+e^-W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0 \qquad \text{BR} = 53\%$$

- Test of electron and muon reconstruction

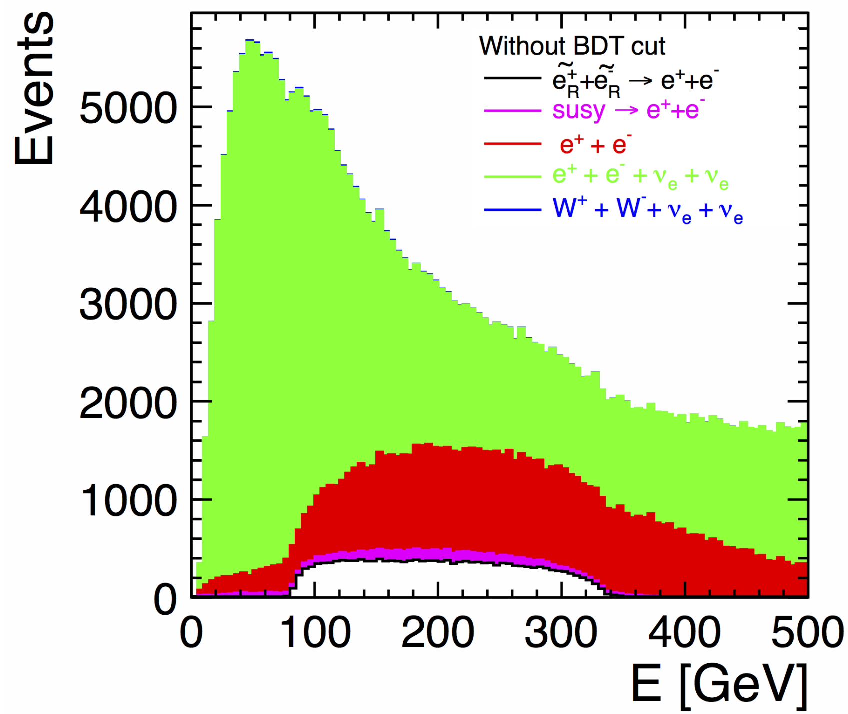
- Pileup from $\gamma\gamma \to$ hadrons has almost no impact on the energy resolutions



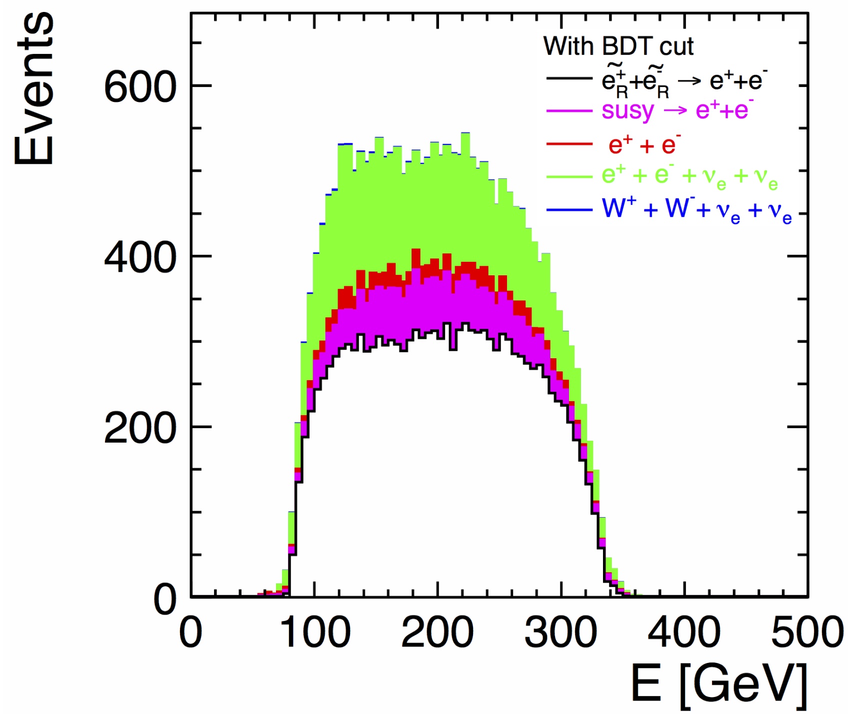
Event selection

Based on boosted decision trees using 9 variables describing the final state lepton system

Example: $e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^- \rightarrow e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$



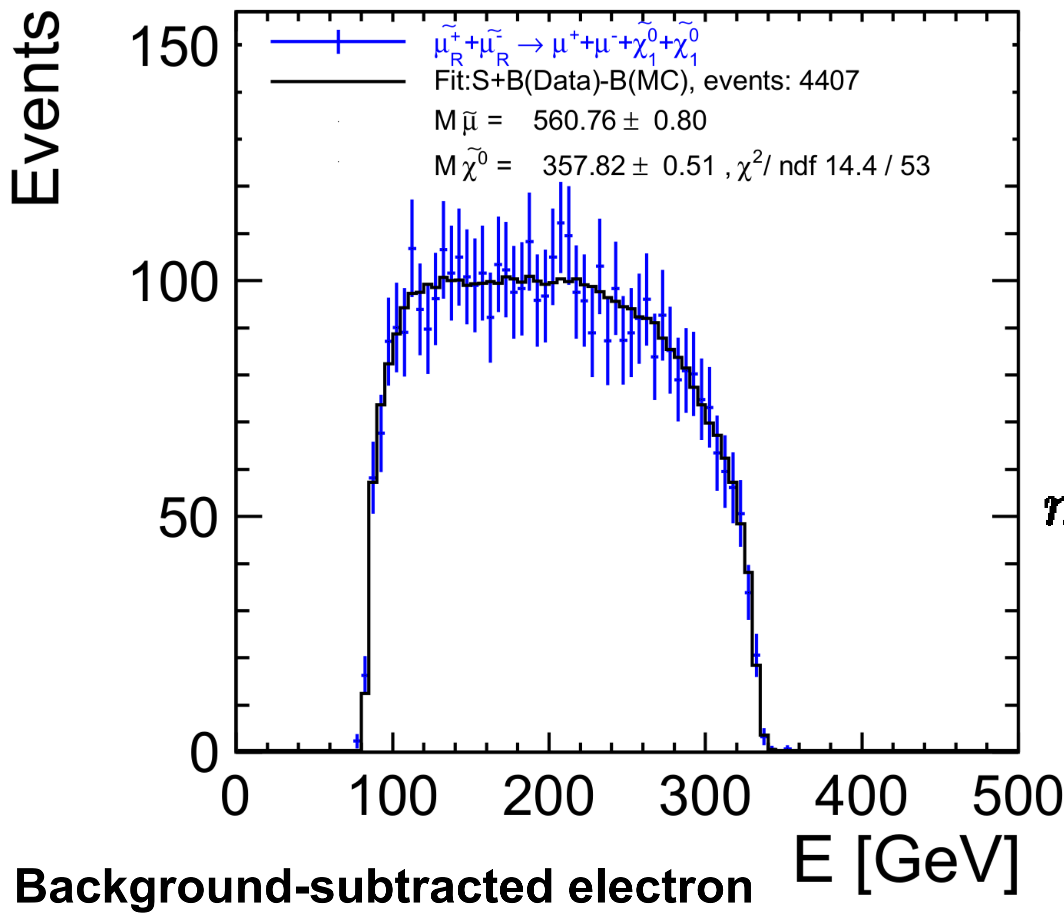
Before cut on BDT output



After cut on BDT output

Signal extraction

$$e^+e^- \to \tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$



Background-subtracted electron energy distribution

- The upper (E_H) and lower (E_L) edges of the electron energy distribution are sensitive to the SUSY particle masses:

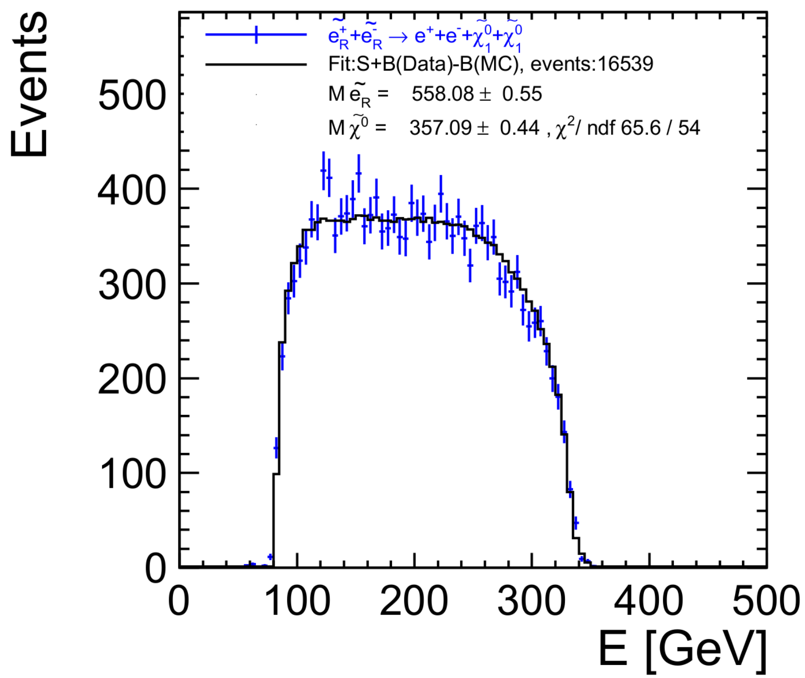
$$m(\tilde{e}_R^\pm) = \frac{\sqrt{s}}{2}\left(1 - \frac{(E_H - E_L)^2}{(E_H + E_L)^2}\right)^{1/2}$$

$$m(\tilde{\chi}_1^0) = m(\tilde{e}_R^\pm)\left(1 - \frac{2(E_H + E_L)}{\sqrt{s}}\right)^{1/2}$$

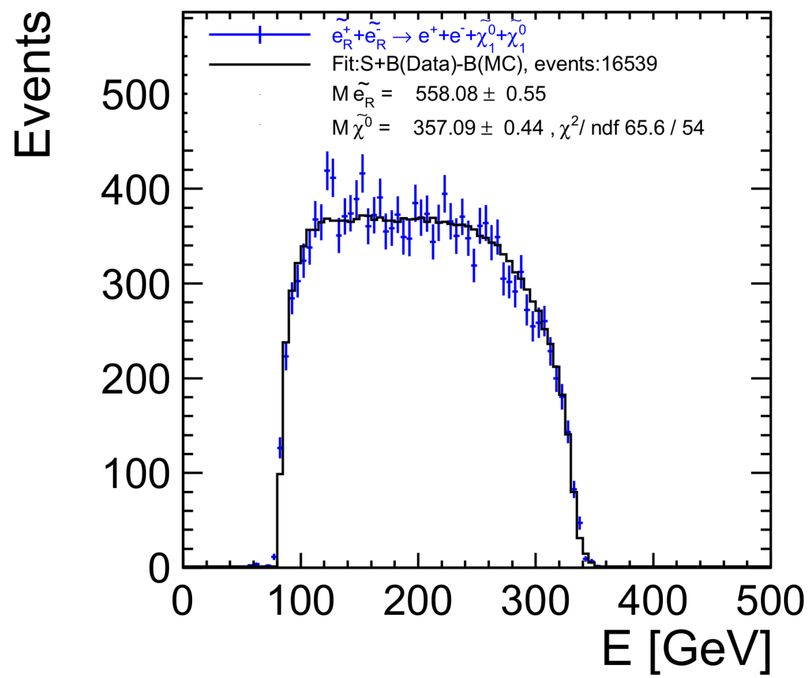
- The fit to extract these masses includes the ISR and beamstrahlung effects

Other final states and results

$$e^+e^- \to \tilde{\mu}^+_R\tilde{\mu}^-_R \to \mu^+\mu^-\tilde{\chi}^0_1\tilde{\chi}^0_1$$



$$e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e \to e^+e^-\tilde{\chi}^+_1\tilde{\chi}^-_1$$



Process	Decay Mode	σ fb	$m_{\tilde{\ell}}$ GeV	$m_{\tilde{\chi}^0_1}$ or $m_{\tilde{\chi}^\pm_1}$ GeV
$e^+e^- \to \tilde{\mu}^+_R\tilde{\mu}^-_R$	$\mu^+\mu^-\tilde{\chi}^0_1\tilde{\chi}^0_1$	1.11 ± 0.03	560.8 ± 0.8	357.8 ± 0.5
$e^+e^- \to \tilde{e}^+_R\tilde{e}^-_R$	$e^+e^-\tilde{\chi}^0_1\tilde{\chi}^0_1$	5.69 ± 0.06	558.1 ± 0.6	357.1 ± 0.5
$e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e$	$e^+e^-\tilde{\chi}^\pm_1\tilde{\chi}^\pm_1$	5.56 ± 0.20	644.3 ± 16.3	487.6 ± 13.3

L_{int} = 1.5 ab^{-1}

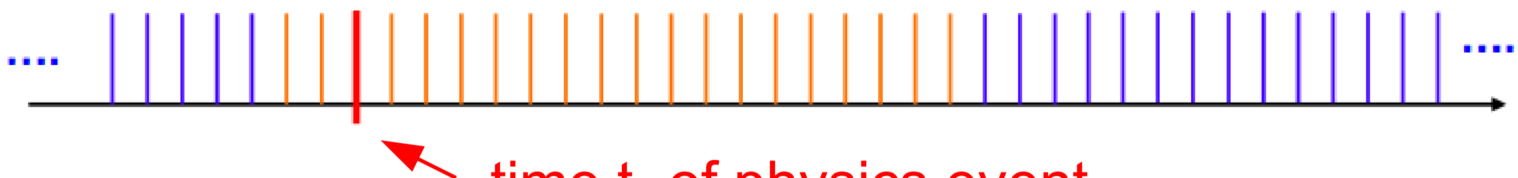
Instead of a summary

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Unit	Generator value	Stat. error
1.4	Sleptons production	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	σ	fb	1.11	2.7%
				$\tilde{\ell}$ mass	GeV	560.8	0.1%
				$\tilde{\chi}_1^0$ mass	GeV	357.8	0.1%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		σ	fb	5.7	1.1%
				$\tilde{\ell}$ mass	GeV	558.1	0.1%
				$\tilde{\chi}_1^0$ mass	GeV	357.1	0.1%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		σ	fb	5.6	3.6%
				$\tilde{\ell}$ mass	GeV	644.3	2.5%
				$\tilde{\chi}_1^\pm$ mass	GeV	487.6	2.7%
1.4	Stau production	$\tilde{\tau}_1^+\tilde{\tau}_1^- \to \tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\tau}_1$ mass	GeV	517	2.0%
				σ	fb	2.4	7.5%
1.4	Chargino production	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$	III	$\tilde{\chi}_1^\pm$ mass	GeV	487	0.2%
				σ	fb	15.3	1.3%
	Neutralino production	$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0 h/Z^0 \tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	GeV	487	0.1%
				σ	fb	5.4	1.2%

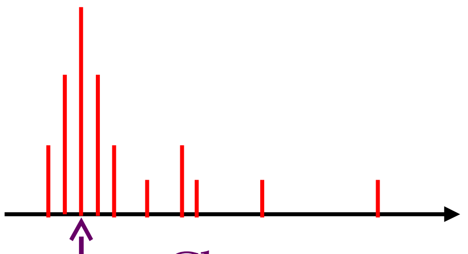
Backup slides

Background suppression

Triggerless readout of full bunch train:



time t_0 of physics event



Identify t_0 of physics event in offline event filter

• Define reconstruction window around t_0

• All hits and tracks in this window are passed to the reconstruction
→ Physics objects with precise p_T and cluster time information

→ Background rejection using combined timing & p_T cuts

• Further reduction of the impact of the background is achieved using well-adapted jet finding strategies based on the LHC experience (FastJet)