Prospects of Discovering a New Massless Neutral Gauge Boson at the ILC

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In the Standard Model based on the $U_Y(1) \times SU_L(2) \times SU_C(3)$ gauge symmetry,

➔ **12 gauge bosons**

- 3 electroweak bosons W^{+-} and Z^0,
- 8 massless gluons
- and well known photon γ

It is possible to introduce new gauge fields into the SM
consistent with basic principia of gauge invariance.

One example of such an extension consists of introducing a new field $U_P(1)$ which mixes with the SM field $U_Y(1)$ in a manner that new particles come into the game

This mechanism provides an elegant way of introducing

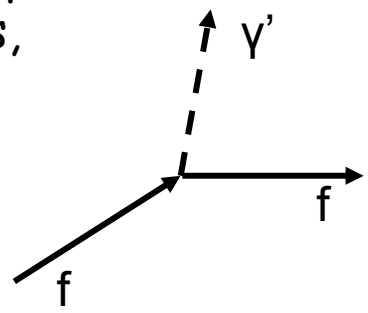
➔ - millicharged particles

- the two U(1) fields can mix such that one linear combination appears as the ordinary photon γ and the other as a massless spin-1 neutral particle, the 'paraphoton' γ'

Based on the effective Lagrangian for the interaction of this new particle with the SM fermions by considering higher dimensional operators, the Feynman rules for fermion-fermion-γ' vertices are proportional to

(Bogdan Dobrescu)

$$\propto C_f \frac{m_f}{M^2}$$



with C_f - dimensioness coupling strength, with f = u, d, e
m_f - mass of fermion
M - mass scale where the operators are generated
→ for large M, strong suppression of paraphoton interactions with SM fermions due to $1/M^2$

The coefficients **C_f are unknown**, but some **phenomenological constraints** exist:

- e.g. the μ-μ-γ' coupling $M/\sqrt{c_\mu} \geq 1.5$ TeV from expansion rate of universe and of possible paraphoton annihilation to muon pairs, with c_μ related to C_μ via $c_f = C_f * v_h / (\sqrt{2} m_f)$, with v_h the vacuum expectation value of the Higgs field
- $M/\sqrt{c_e} \geq 3.2$ (1.8) TeV from core of red giant stars
- $M/\sqrt{c_N} \geq 7$ TeV from neutrino signal of the supernova 1987 A

phenomenological bounds !

➔

- a massless neutral gauge boson may exist,
- it has non-zero but very small couplings to ordinary matter,
- so far, (rather weak) phenomenological bounds make it worthwhile to search for this photon-like state
- according to Feynman rules, γ′ coupling prop. to the fermion mass
  → favours coupling to the top quark !
- no bounds on c_t exist, search for γ′ at the next generation of colliders; since M might be very large
  → at least limits on $M/\sqrt{c_t}$ can be derived

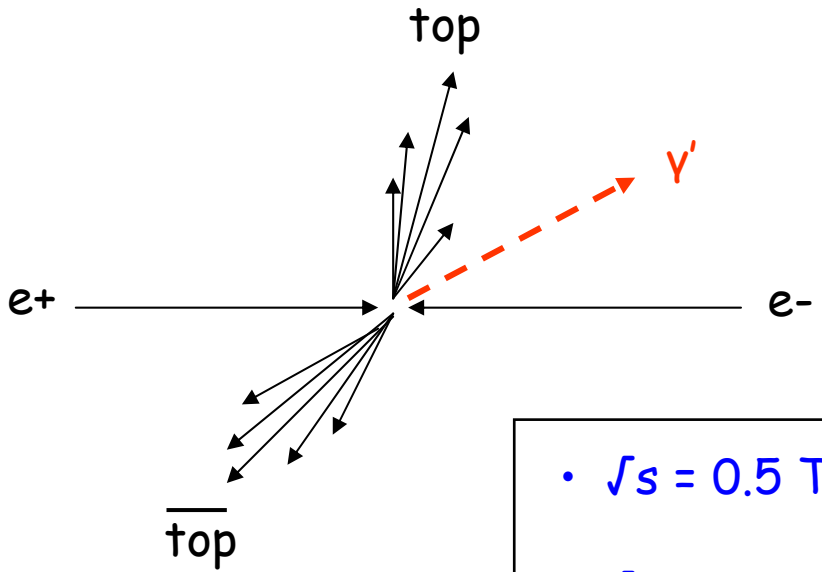
At the **LHC**, huge t t-bar (+jets) backgrounds
➔ (probably) precludes a sensitive search for γ′.

The **ILC** ideally suited to evaluate prospects of discovering (excluding) the γ′

$e^+ e^- \rightarrow t\,\bar{t}\,\gamma'$

Search strategy of the γ′ at ILC

➔ select a pair of acoplanar top quark jets with missing transverse energy E_T^{miss} carried away by the paraphoton



- $\sqrt{s}$ = 0.5 TeV with $\int Ldt$ = 500 fb^{-1}
- $\sqrt{s}$ = 1.0 TeV with $\int Ldt$ = 1000 fb^{-1}

All signal event simulations with **'coupling' $M/\sqrt{c_t}$ = 0.2 TeV**, resulting to reasonable number of events

➔ differentiation w.r.t. background

of t t-bar γ' events:

$M/\sqrt{c_t}$, TeV	√s = 0.5 TeV	√s = 1.0 TeV
0.1	90 000	680 000
0.2	5 700	42 500
0.3	1 100	8 200
0.5	40	1 100
1.0	10	70

all W's decay modes included

Event generation:
- **CompHEP** (extended to implement γ') → parton level; interfaced to PYTHIA
- **PYTHIA** (ISR / FSR; jet hadronisation, resonance decays); beamstrahlung
- **SIMDET** (detector response → energy flow objects)

Background:

other backgrounds are negligible after selection procedure

	√s = 0.5 TeV	√s = 1.0 TeV
t t-bar (γ)	276 675	200 310
t t-bar ν ν-bar	75	930

$M/\sqrt{c_t}$ < 0.1 TeV ?

- for such values, mixing between $U_Y(1)$ and $U_P(1)$ fields

  would lead to **millicharged particles with charges > 10^{-4}**

  ➔ which would be detected in various SM reactions

  contrary to experimental findings

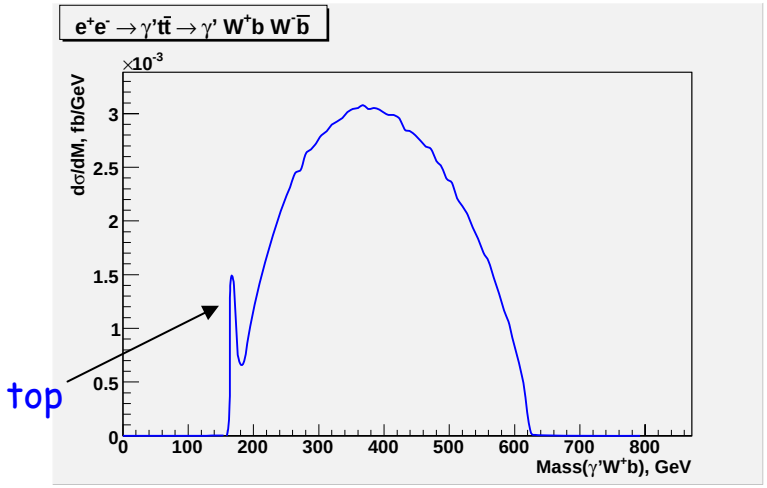
- eff. Lagrangian approach not valid

  for small (<~ 0.1 TeV) $M/\sqrt{c_t}$ values

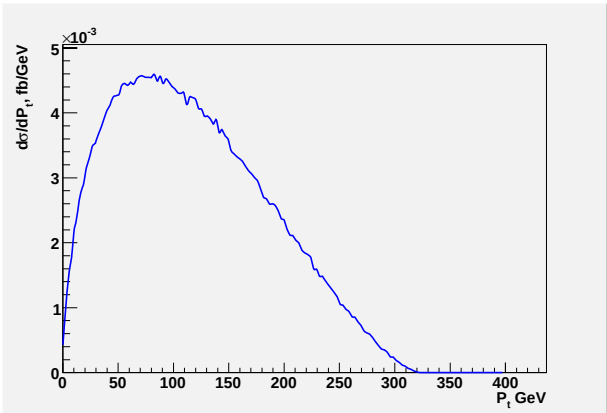
Few **properties of the signal** reaction relevant for selection procedure

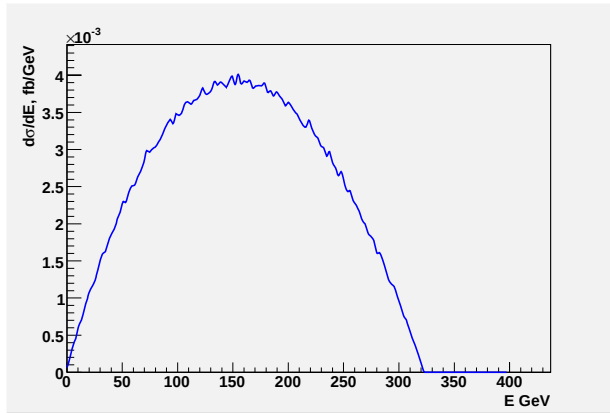
invariant mass of Wbγ'

➔ in most of events, the top which radiates the γ' is off-shell,
t → (W b) γ',
with M(Wb) = M_{top}



missing transverse momentum and missing energy (= trans.momentum / energy of paraphoton)





at 1 TeV

plus some other variables ➔ **selection procedure**

- Selection of only hadronic W decays, **W → q q-bar**,
  since leptonic decays **W → l ν** with neutrino(s) mimic γ' signal events

- jet finder selects 6- (7-) jet events from tt → (Wb) (Wb) → (qq)b (qq)b

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First attempt to select the signal –

consecutive cuts on kinematical variables

18 variables of 3 categories were considered:

- global event kinematics (aplanarity, thrust, missing energy, …)
- variables based on jet properties (θ-jet, …)
- variables based on jet correlations (angle between top quarks, …)

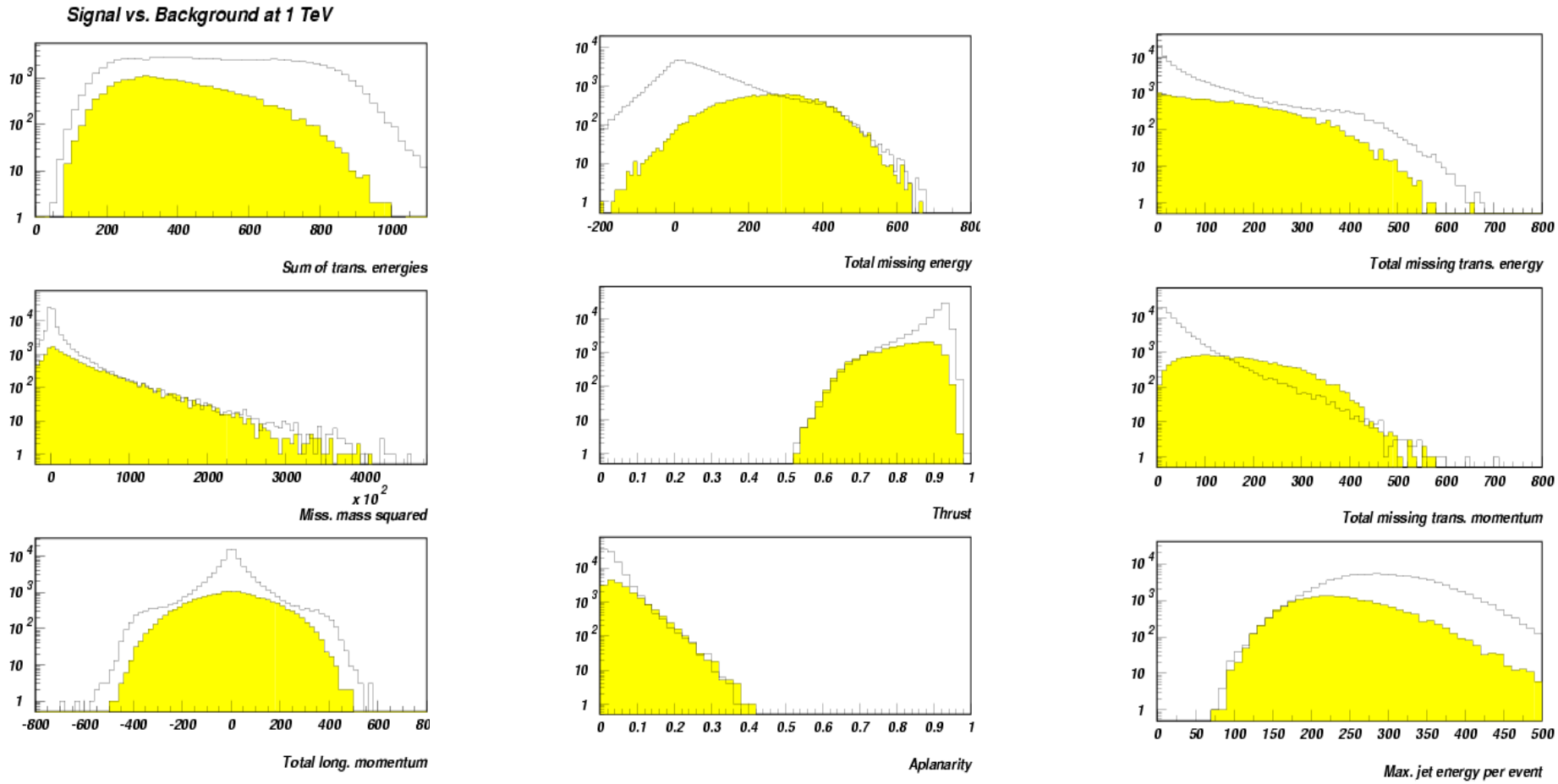
↷

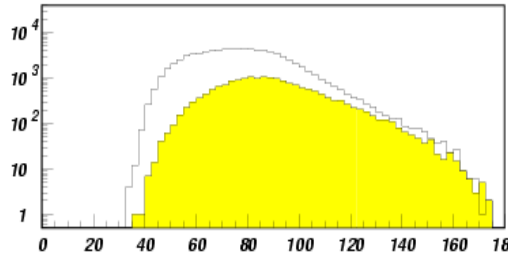
This method was found to be inefficient to select signal from large bkg,

mainly due to the failure of distinct properties between signal and bkg events

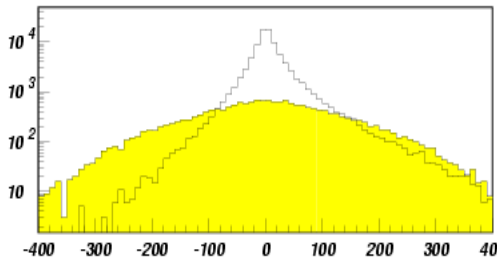
background events

signal events

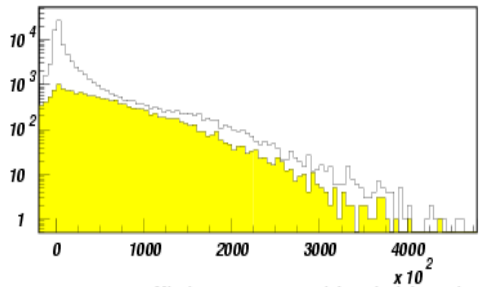




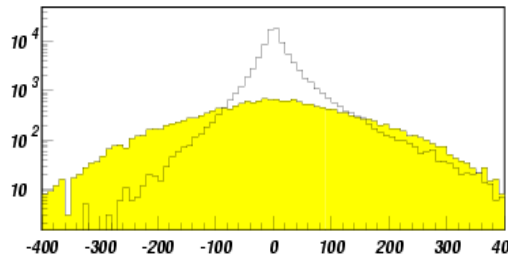
Max. angle between two jets in given hemisphere



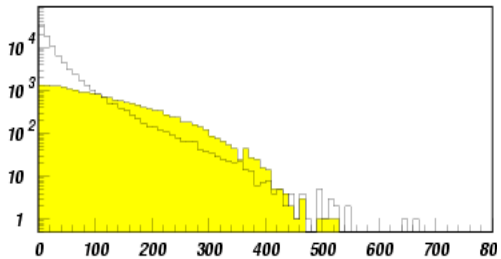
Missing z-momentum, from jet information



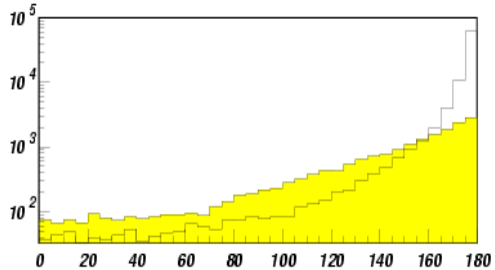
Missing energy squared, from jet information



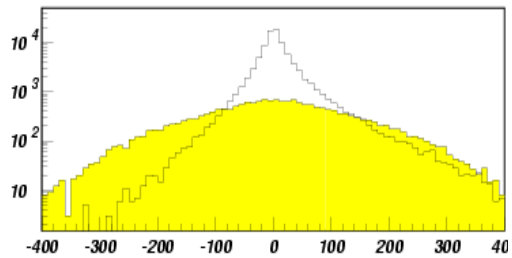
Missing x-momentum, from jet information



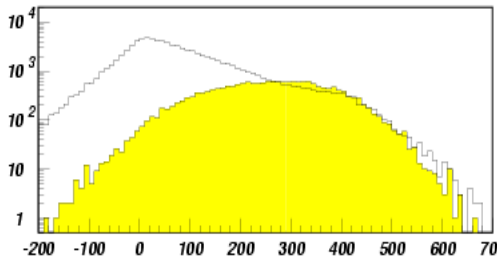
Missing trans. momentum, from jet information



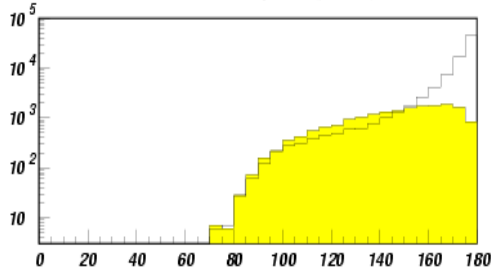
Coplanarity, from jet information



Missing y-momentum, from jet information



Missing trans. energy, from jet information



Angle between top/anti-top, from jet information

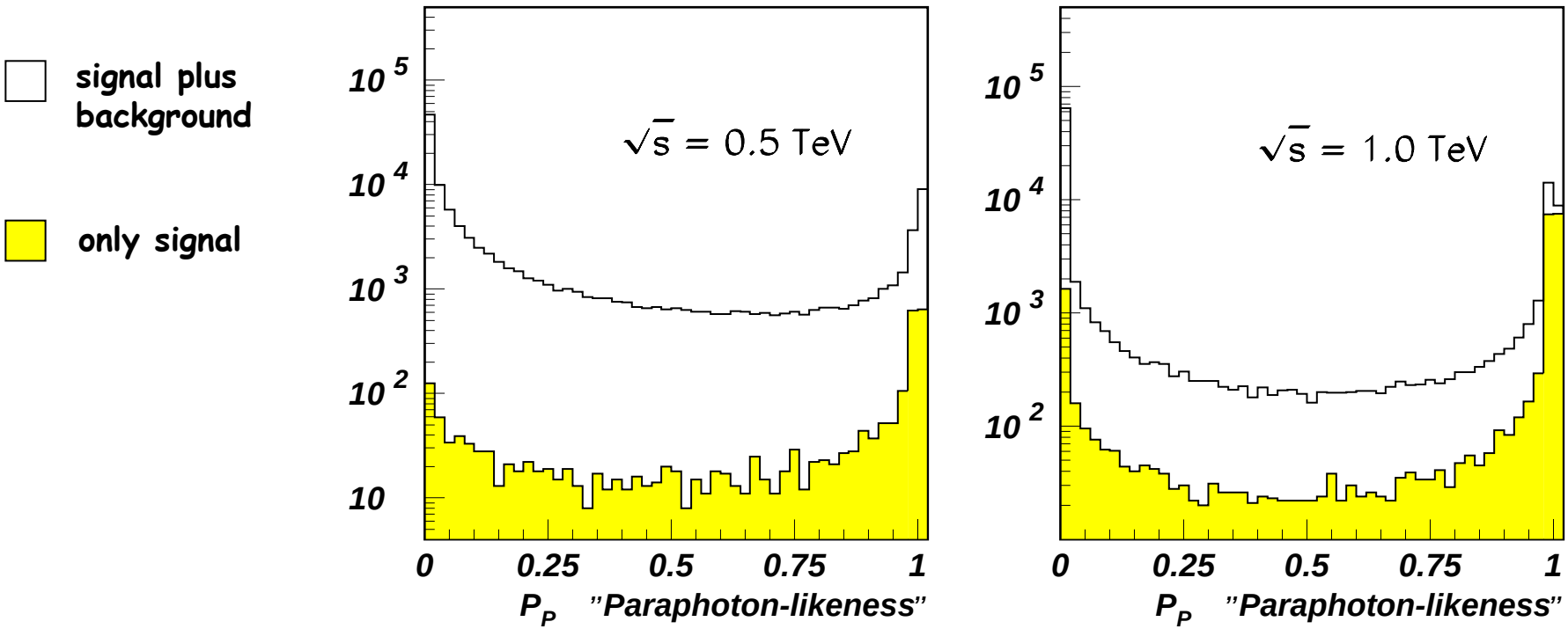
Thus, selection method was applied: **multivariate selection procedure**

Many variables (18) were considered simultaneously;

- for each event a probability, the **PARAPHOTON-LIKENESS**, was estimated

so that **background events** → $P_p \sim 0$

while **signal events** → $P_p \sim 1$



With $P_P > 0.98$ ➔ **efficient signal selection with small bkg !**

√s, TeV	signal events	bkg events	S/√B
0.5	1264	10310	12.4
1.0	14882	8116	165.2

Probability for bkg to fluctuate up to produce signal events

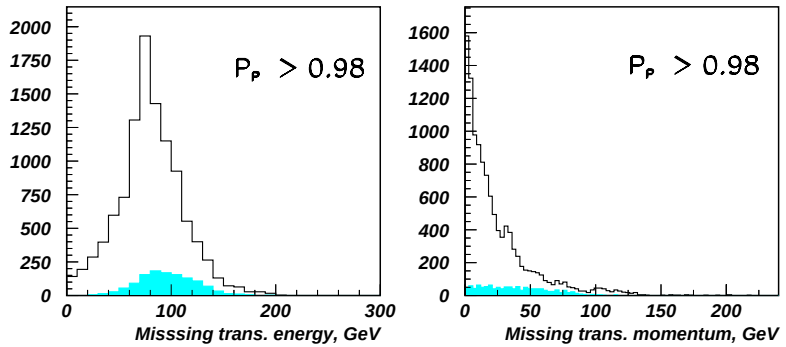
$0.5\ 10^{-12}$ at 0.5 TeV

$< 10^{-15}$ at 1.0 TeV

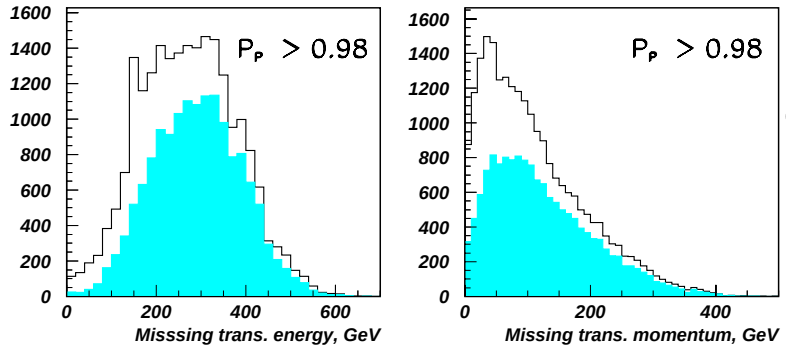
(assuming Gaussian distribution)

signal plus bkg

only signal



← 0.5 TeV



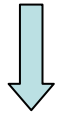
← 1.0 TeV

cut on the missing transverse momentum/ energy improves the signal/background ratio and provides an almost background-free event sample

e.g. miss. p_{trans} > 100 GeV

➔ what value of $M/\sqrt{c_t}$ is needed for a 5 σ effect ?

- at 0.5 TeV, the limit is $M/\sqrt{c_t} = 0.32$ TeV
- at 1.0 TeV, the limit is $M/\sqrt{c_t} = 0.61$ TeV



seems to be the most stringent limit accessible from the next generation of colliders