Physics with a 100 TeV pp collider

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- **Dark matter**
  - is TeV-scale dynamics (WIMPs) at the origin of Dark Matter ?

NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS CHIRAL SYMMETRY BREAKING

G. 't Hooft

Institute for Theoretical Fysics

Utrecht, The Netherlands

Naturalness is not a recent "fashion": it's an original sin of the SM itself, first identified by one of the fathers of the SM

Aug 1979. 23 pp.

NATO Adv.Study Inst.Ser.B Phys. 59 (1980) 135

As we will see, naturalness will put the severest restriction on the occurrence of scalar particles in renormalizable theories. In fact we conjecture that this is the reason why light, weakly interacting scalar particles are not seen.

Pursuing naturalness beyond 1000 GeV will require theories that are immensely complex compared with some of the grand unified schemes.

We're finally there, at 1 TeV, facing the fears about a light SM Higgs anticipated long ago

A remarkable attempt towards a natural theory was made by Dimopoulos and Susskind [2)]. These authors employ various kinds of confining gauge forces to obtain scalar bound states which may substitute the Higgs fields in the conventional schemes. In their model the observed fermions are still considered to be elementary.

Most likely a complete model of this kind has to be constructed step by step. One starts with the experimentally accessible aspects of the Glashow-Weinberg-Salam-Ward model. This model is natural if one restricts oneself to mass-energy scales below 1000 GeV. Beyond 1000 GeV one has to assume, as Dimopoulos and Susskind do, that the Higgs field is actually a fermion-antifermion composite field. Coupling this field to quarks and leptons in order to produce their mass, requires new scalar fields that cause naturalness to break down at 30 TeV or so.

- The observation of the Higgs where the SM predicted it would be, its SM-like properties, and the lack of BSM phenomena up to the TeV scale, make the naturalness issue as puzzling as ever
- Whether to keep believing in the MSSM or other specific BSM theories after LHC@8TeV is a matter of personal judgement. But the broad issue of naturalness will ultimately require an understanding.

➡ **The future of accelerator physics should be tailored to address this question**

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➥ Immense rates for phenomena in the sub-TeV mass range ⇒

increased precision w.r.t. LHC

➥ Access to very rare processes in the sub-TeV mass range ⇒

search for stealth phenomena, invisible at the LHC

Higgs physics

Higgs rates at high energy

NLO rates $\mathbf{R(E)} = \sigma(E\ \text{TeV})/\sigma(14\ \text{TeV})$

	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

In several cases, the gains in terms of "useful" rate are much bigger.
E.g. when we are interested in the large-invariant mass behaviour of the final states:
$\sigma(ttH, p_T^{top} > 500\ \text{GeV}) \Rightarrow R(100) = 250$

Task: explore new opportunities for measurements, to reduce systematics with independent/complementary kinematics, backgrounds, etc.etc.

Examples: how much can we reduce jet veto systematics by "measuring" jet rates/vetoes in "clean" channels like $H \to ZZ^*$? $H \to bb$ & $\tau\tau$ tagging ? .....

Additional Higgs bosons

⇒ commonly present in most SM extensions. E.g. at least 2 H doublets is mandatory in SUSY

⇒ implications for flavour, CPV, EW baryogenesis, ...

Difficult scenarios for searches at LHC:

- suppressed couplings to W/Z
- large masses

Problems addressed at 100 TeV thanks to higher rates, higher M reach

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E.g. 2HDM in SUSY

$m_h, m_H, m_A, m_{H^\pm}$ $\tan\beta \equiv \langle\Phi_2\rangle/\langle\Phi_1\rangle$

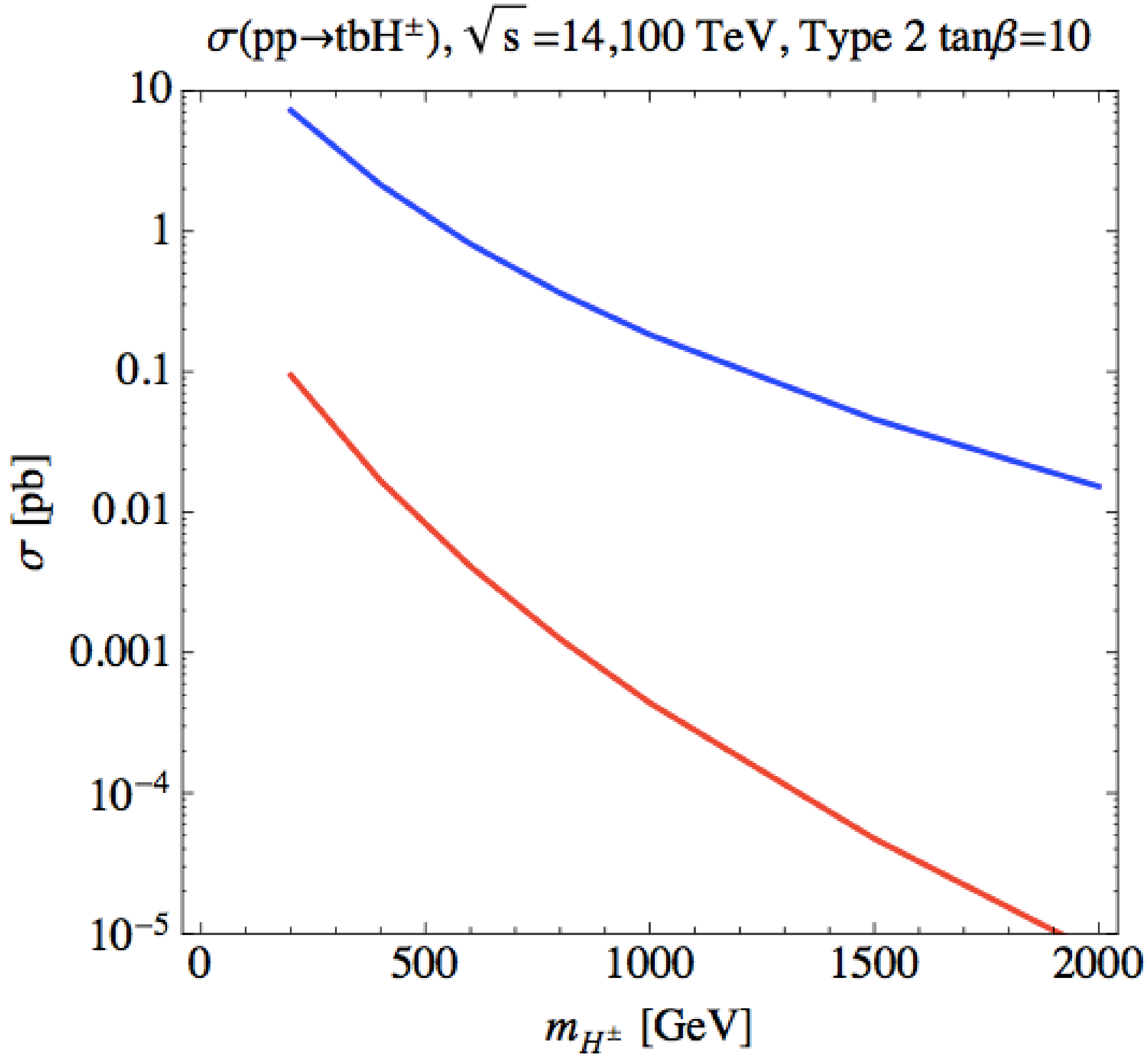
Fine tuning and naturalness: (N.Craig, BSM@100 Wshop)

$$\Delta \approx \sin^2(2\beta)\frac{m_H^2}{m_h^2}$$

$$\Delta(\tan\beta = 50) \leq 1 \rightarrow m_H \lesssim 3.1 \text{ TeV}$$

Extra H can be heavy, well above LHC reach, but cannot be arbitrarily heavy

Example: associated $H^{\pm}$ t b production



(N.Craig, BSM@100 Wshop)

Generic features of very heavy H production/decay

Decoupling from W/Z ➡

- "narrow", since $\Gamma \propto m_H$ (cfr $\Gamma \propto m_H^3$ when decaying to W/Z)
- H/A → hh, tt dominate (boosted regime)

EW phase transition and BAU

- To generate and maintain a baryon asymmetry at the EWPT we need
  - a strong 1st order phase transition:
    - impossible in the SM if $m_H > 60$ GeV
    - requires modification of Higgs potential, via H interactions with new TeV states
  - sufficient CP violation
    - not enough through CKM
    - need non-CKM CPV in the quark, lepton or Higgs sectors
    - most examples engage TeV-scale particles (for ν's could be higher)

Example

2-Higgs double models **h^0 (125), H^0, A^0, $H^\pm$**

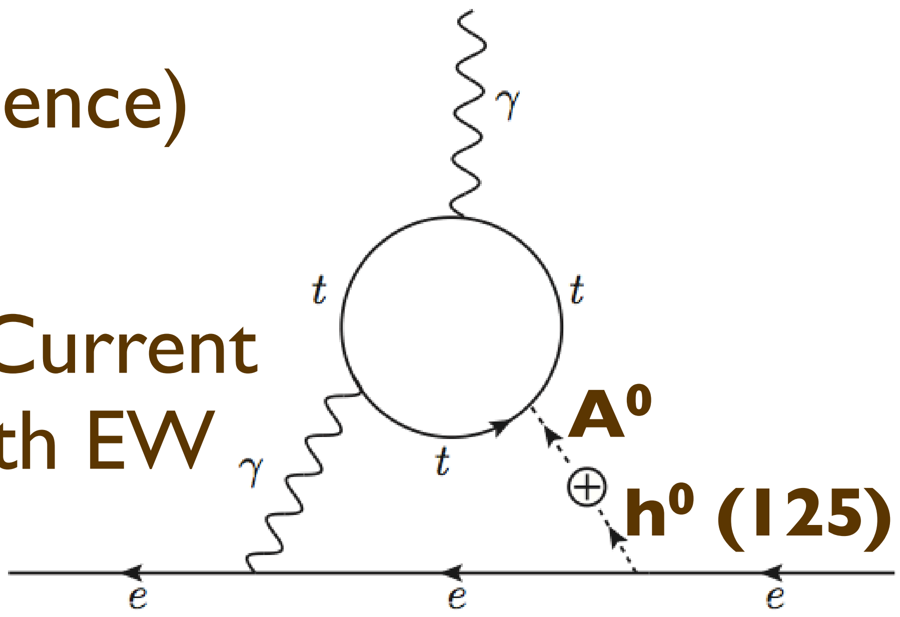
CP=1 CP=1 CP= –1

⇒ interactions among various H fields can create conditions for strong 1st order transition (Higgs vev(T_c) > T_c) - typically favours m(A^0) > 400 GeV

⇒ mixing of different CP states, even at few % level, is sufficient to induce enough CPV

Observables:

- additional Higgs states (direct or indirect evidence)
- h^0(125) not a CP eigenstate
- electric dipole moments (electron, neutron). Current EDM(e) close to range of CPV compatible with EW baryogenesis



Interesting questions

⇒ will there be no-lose scenarios ? E.g. for

- o MSSM 2HDM
- o 2HDM EW baryogenesis
- o ...

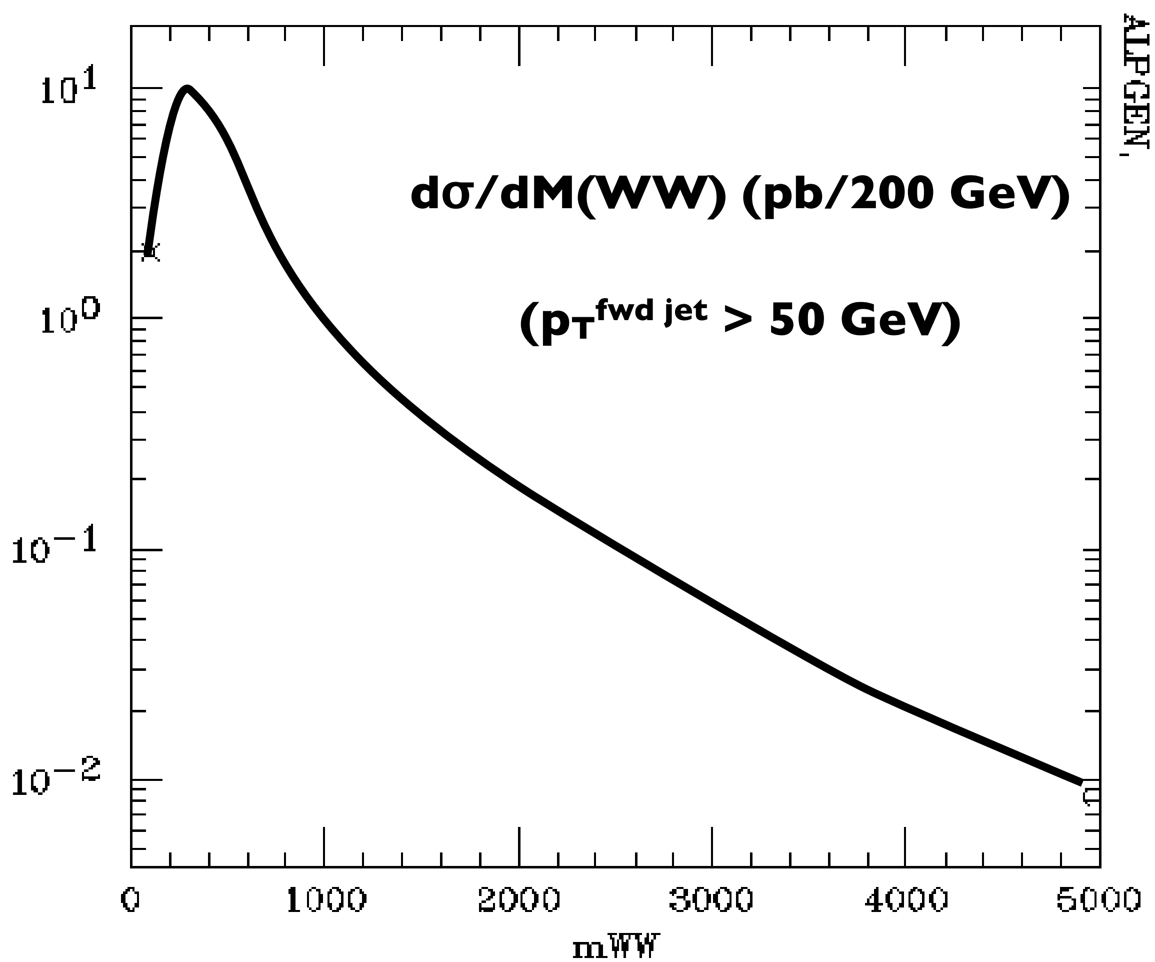
⇒ how will, in these scenarios, naturalness constraints from the stop/gluino sectors compare to those from the Higgs sector?

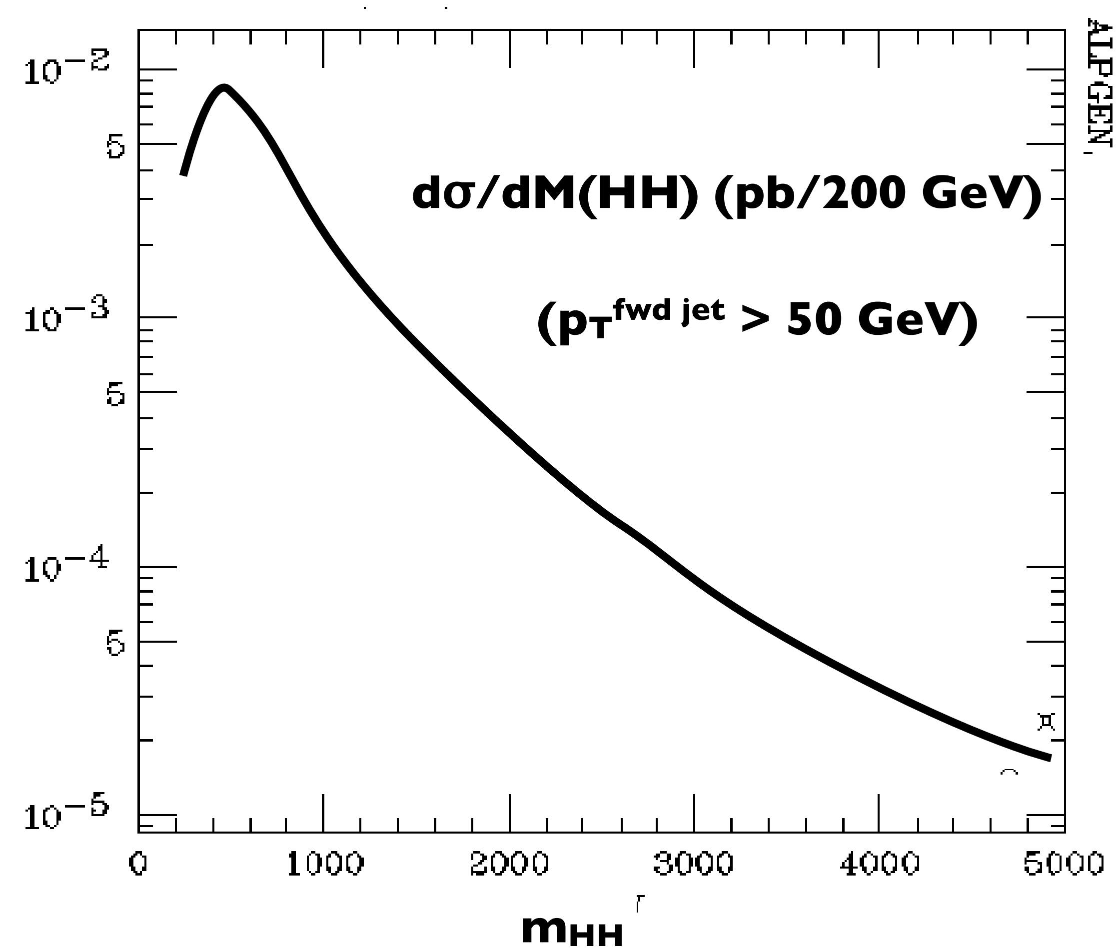
Studies of such questions and of discovery reach just starting.

EW interactions at high energy

EWSB probes: high mass WW/HH in VBF

SM rates at 100 TeV





100 fb with M(WW) > ~3 TeV

1 fb with M(HH) > ~2 TeV

WIMP DM search

Can a 100 TeV collider detect or rule out WIMP scenarios for DM ?

→ Liantao's presentation

Production and study of SM particles and processes

10 ab^{-1} at 100 TeV imply:

10^{10} Higgs bosons => 10^4 x today

⇒ precision measurements

⇒ rare decays, FCNC probes

($H \to e\mu$, $t \to cV$ ($V=Z, g, \gamma$), $t \to cH$, ...)

⇒ CP violation

10^{12} top quarks => 5 10^4 x today

=> 10^{12} W bosons from top decays

=> 10^{12} b hadrons from top decays (particle/antiparticle tagged)

=> 10^{11} $t \to W \to$ taus ⇒ rare decays $\tau \to 3\mu$, $\mu\gamma$, CPV

=> few x10^{11} $t \to W \to$ charm hadrons

⇒ rare decays $D \to \mu^+\mu^-$, ..., CPV

The possibility of detectors dedicated to final states in the 0.1 - 1 TeV region deserves very serious thinking:

focus on Higgs, DM and weakly interacting new particles, top, W

W decays

- W mass ??
- SM rare decays -- Examples:

  $W^\pm \rightarrow \pi^\pm \gamma$ BR$_{SM} \sim 10^{-9}$, CDF$\leq 6.4 \times 10^{-5}$

  $W^\pm \rightarrow D_s^\pm \gamma$ BR$_{SM} \sim 10^{-9}$, CDF$\leq 1.2 \times 10^{-2}$

  What is the theoretical interest in measuring these rates? What else ?

- SM inclusive decays -- Examples:

  $R = BR_{had} / BR_{lept}$: what do we learn ? Achievable precision for CKM, α_S , ... ?

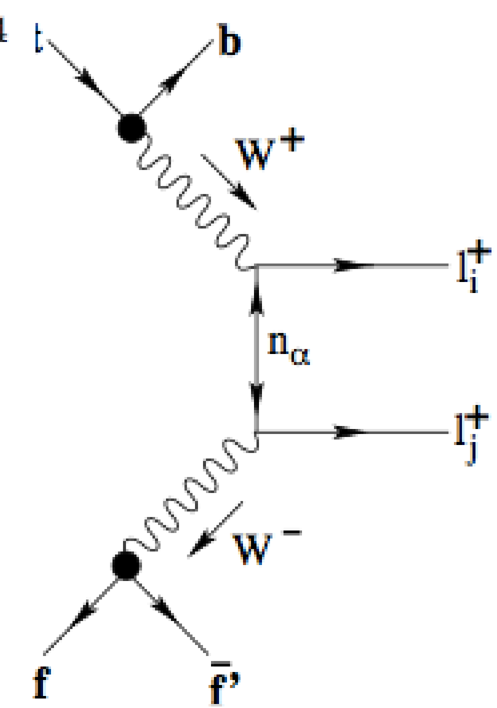
- BSM decays -- Are there interesting channels to consider?

-- Example

BNL-HET-06/9
OITS-784

Majorana neutrinos and lepton-number-violating signals in top-quark and W-boson rare decays

Shaouly Bar-Shalom[a,*] Nilendra G. Deshpande[b,†] Gad Eilam[a,‡] Jing Jiang[b,§] and Amarjit Soni[c,¶]



* Off-shell W/Z production above 10 TeV DY mass. E.g.

- measure the running of EW couplings, sensitive to new weakly-interacting particles, possibly hidden from direct discovery (⇒ Rudermann at BSM@100 TeV wshop)

- 10^4 pp → W^* → top+ bottom with M(tb) > 7 TeV

* QCD jets up to 25-30 TeV ⇒ running of α_S , ...

* SM violation of B+L via EW anomaly (not viable below 30 TeV) (⇒ Khoze and Ringwald at BSM@100 TeV wshop)

* Growth of heavy flavour densities inside proton (c, b and ultimately top) ⇒new opportunities for studies within and beyond the SM (⇒ Perez at BSM@100 TeV wshop)

* ....

Plenty of room for new ideas

Final Remarks

- **Our field has other open puzzles, associated e.g. to**
  - **neutrinos**
  - **flavour**
  - **axion**
  - **...**

- **These puzzles hint at scales that are typically much larger than O(TeV), even as large as the GUT scale**

- **The complete understanding of TeV-scale physics is necessary to put in perspective and properly interpret the information about those high scales that may come from indirect probes (neutrinos, p-decay, coupling unification, ...)**

- **A 100 TeV pp collider possibly provides the best probe of TeV-scale physics**