Back to the future: beyond the LHC

Rencontres de Physique de la Vallée d'Aoste
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Contents

- The landscape at the TeV scale, after run 1of the LHC
- CERN's design study for Future Circular Colliders
- Beyond the TeV scale: physics opportunities for pp collisions @ 100 TeV

The landscape at the TeV scale

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

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, ...)**

Naturalness

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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  - compressed spectra: low MET, low ET, long lifetime heavy particles, ...
  - RPV
  - ....

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- Naturalness is an ill guided principle ⇒ Anthropic principle

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, $H^{\pm}$**

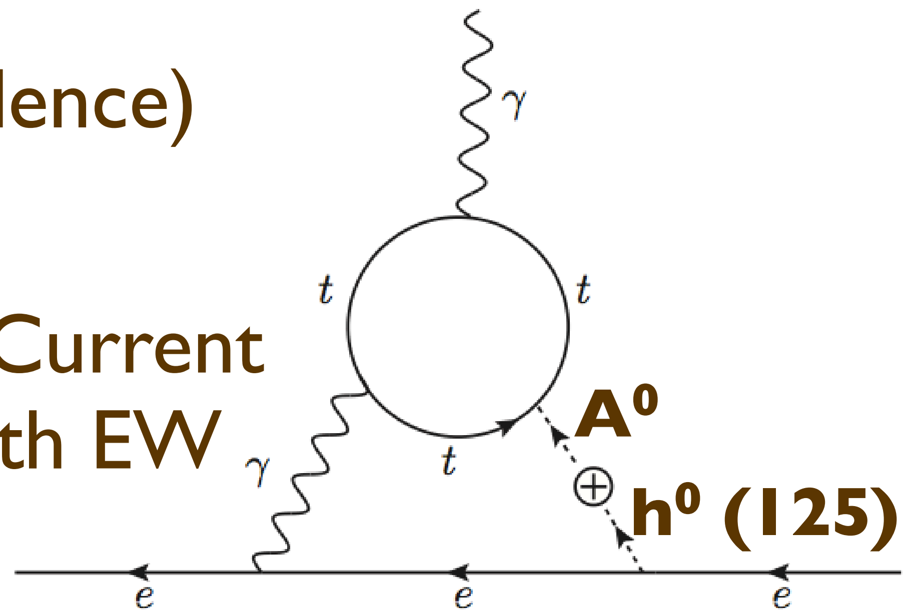
CP=1 CP=1 CP= –1

⇒ 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

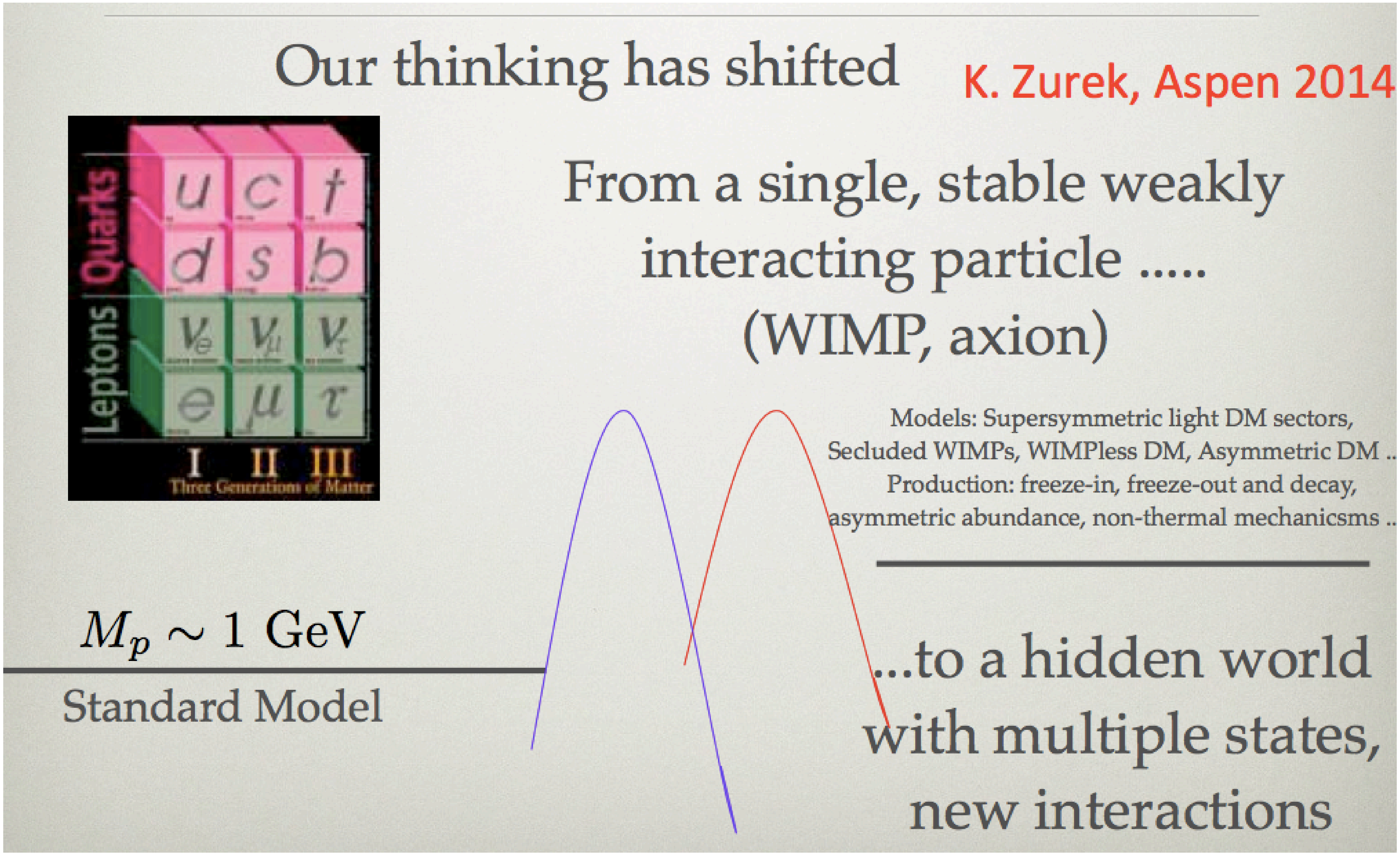
⇒ mixing of different CP states, even at few % level, is sufficient to induce enough CPV

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

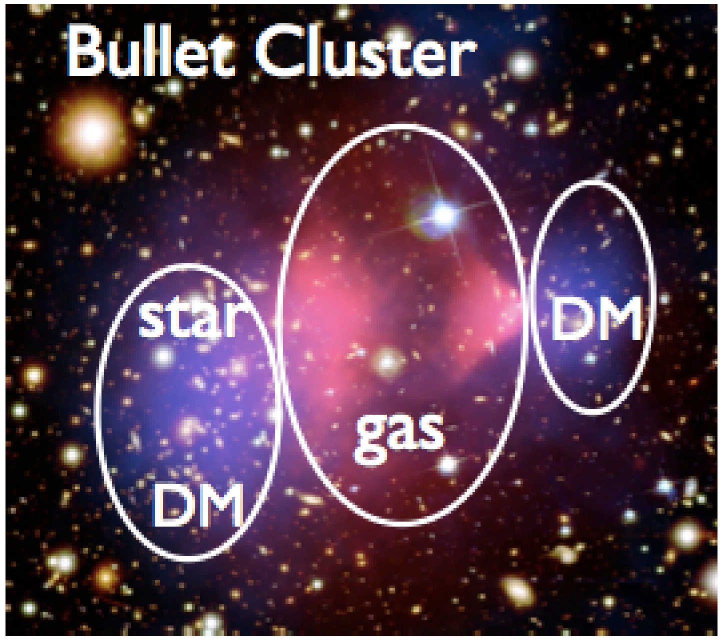


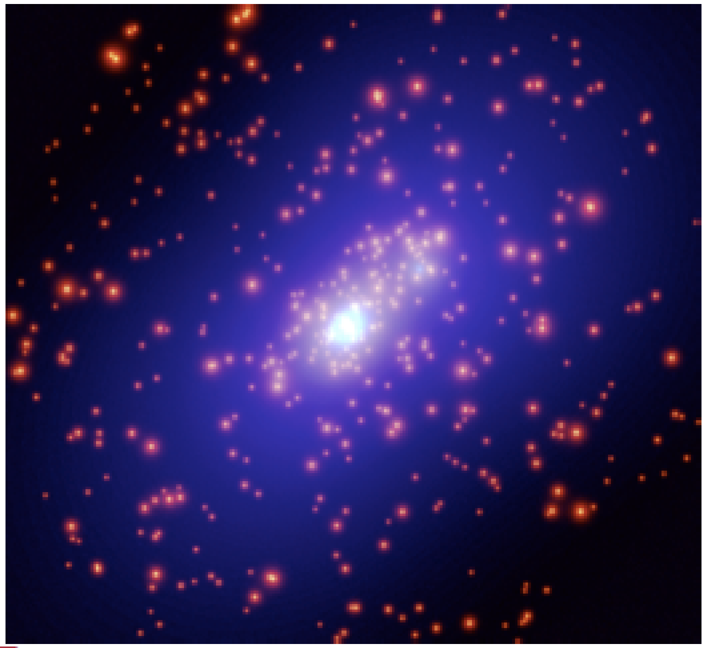
Dark Matter



ASPEN 2014: https://indico.cern.ch/event/276476/

Evidence building up for self-interacting DM





- A really large scaling cross section!

a nuclear-scale cross section

$\sigma \sim 1 cm^2 (m_X/g) \sim 2 \times 10^{-24} cm^2 (m_X/GeV)$

For a WIMP: $\sigma \sim 10^{-38} cm^2 (m_X/100 GeV)$

SIDM indicates a new mass scale

Hai-Bo Yu, ASPEN 2014:
https://indico.cern.ch/event/276476/

More in general, interest is growing in scenarios for EWSB with rich sectors of states only coupled to the SM particles via <u>weakly interacting</u> "portals"

(see e.g. R.Harnik, BSM@100 TeV workshop)

It is appealing to consider that they key to our puzzles lies in a tighter interplay between the DM sector, EWSB and “naturalness”.

This would be an intellectual revolution without precedents.

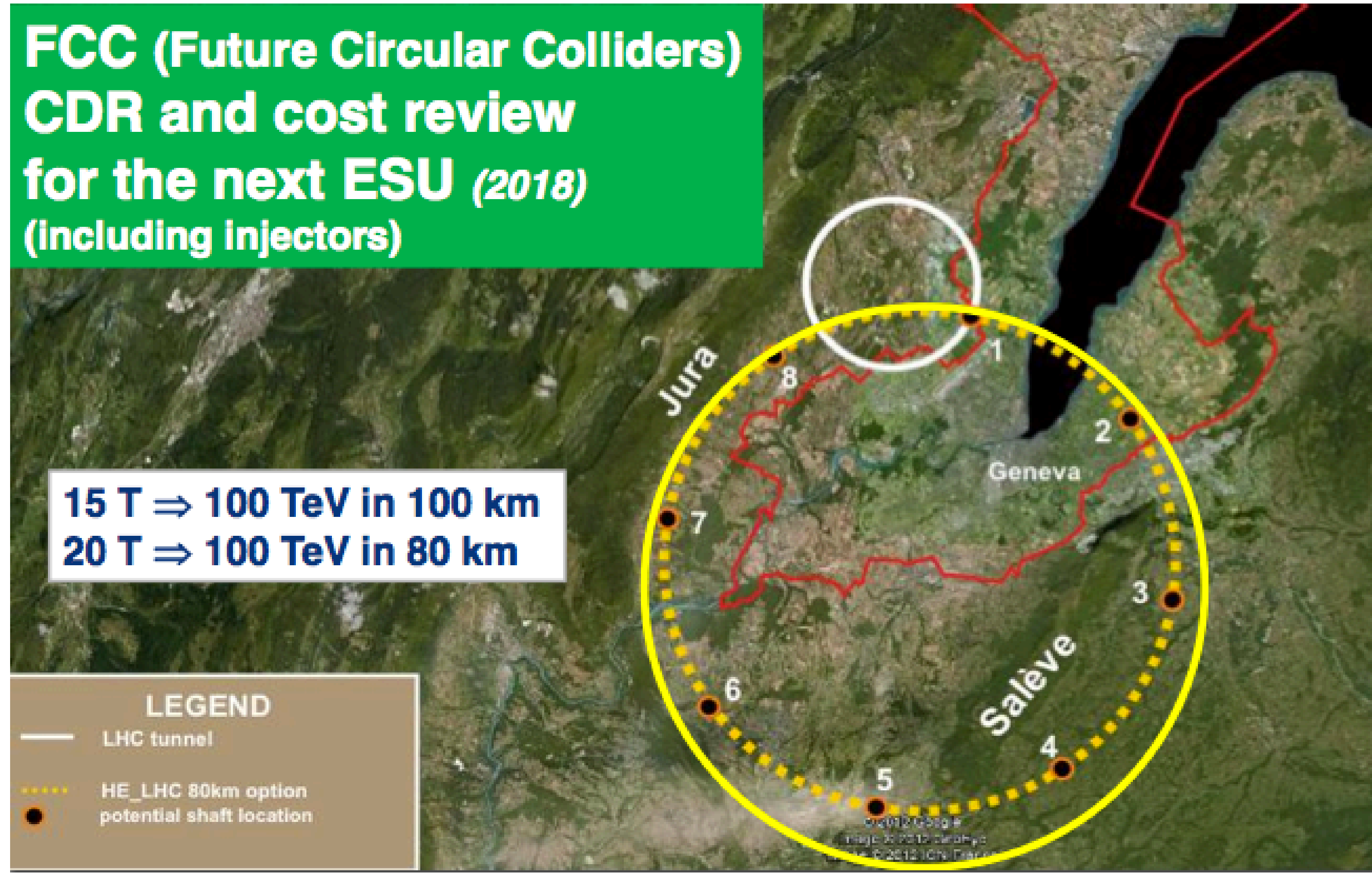
Uncovering or disproving a connection between DM and EWSB should remain a primary target of future programmes

Remarks

- **Despite the relevance of these questions, and the conviction that they will find an answer, there is no guarantee that such answer will come soon.**
- **There is no absolute no-lose theorem in sight, pointing with absolute certainty to a given experimental facility**
- **The planning of future facilities may need to be driven by the exploratory spirit that characterized the golden age of particle physics.**
- **But the directions are clear:**
  - **higher precision studies (of Higgs sector, of EW interactions)**
  - **higher energy (push the search for “everyone else”)**

Design study for Future Circular Colliders

80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements
with possibility of e+-e- (TLEP) and p-e (VLHeC)



UNIVERSITÉ DE GENÈVE FCC

Future Circular Colliders Study Kickoff Meeting

12-15 February 2014
University of Geneva, Geneva
Europe/Zurich timezone

Search

Webcast: Please note that this event will be available live via the Webcast Service.

Future Circular Collider Kickoff Meeting

Machines and infrastructure conceptual designs	Technologies R&D activities Planning	Physics experiments detectors	
Infrastructure	High-field magnets	Hadron physics experiments interface, integration	MLM F.Gianotti A.Ball
Hadron collider conceptual design	Superconducting RF systems	$e^+ e^-$ coll. physics experiments interface, integration	J. Ellis P. Janot A. Blondel
Hadron injectors	Cryogenics	e^- - p physics and integration aspects	M. Klein
Lepton collider conceptual design	Specific technologies		
Safety, operation, energy management environmental aspects	Planning		

Target: conceptual design report (CDR) ready for the next Strategy Group assessment (~2018)

Parallel activities in the world

+ Fermilab wshop in August

Focus here on pp @ 100 TeV

- **Why 100 TeV ?**
  - Need for O(100 TeV) in the cards since the SSC days: fully explore EWSB, probing in particular unitarization of WW scattering at m(WW)> TeV, and explore dynamics well above EWSB
- **Prospects at 100 TeV ?**
  - Studied in the SSC years, in the framework of what was known at the time.
- **Why we need new studies of "the physics case" ?**
  - We learned many things since the SSC days.
  - Pinned down many unknowns: m_{top}, EWPT, CKM/CPV and FCNCs, m_H , DM, ν masses, gauge couplings (⇒unification ?), ...
  - Strongly constrained the options/room for new physics
  - Developed many new BSM scenarios ...... although with a focus on the implications for the LHC, ILC, CLIC, TLEP → no thoughts about 100 TeV !!

There is a strong motivation for a fresh look at the possible role of phenomena taking place at the 10 TeV scale

This process is starting now, a lot of work is required, and it premature to draw conclusions now

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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

FCC-hh physics activities documented on:

- o http://indico.cern.ch/categoryDisplay.py?categId=5258
- o https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

Mailing list exist (see e.g. header of any of the mtgs in the Indico category above) => register to be kept uptodate

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So far:

- 5 preparatory mtgs of the pp WG => *sample results presented in talks in the FCC-hh parallel sessions, Friday*
- 2 preparatory mtgs of the HI subgroup => *sample results presented in talks in the FCC-hh parallel sessions, Friday*
- "BSM opportunities at 100 TeV" Workshop:
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PLAN: prepare a report documenting the physics opportunities at 100 TeV, on the time scale of end-2015, ideally in cooperation with efforts in other regions

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- Identify new scenarios and opportunities specific to 100 TeV

In particular:

Focus on exposing what are the qualitative changes brought by the access to the 100 TeV region. Address obvious questions such as:

- if we haven't seen something by 14 Tev, why should it show up by 100 Tev?
- what are the origins and the motivations of mass scales in the range beyond the LHC, but within the reach of 100 TeV?
- what are the new rare processes that become interesting to explore with the increased statistics possible at 100 TeV?
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For phenomena that could already be probed at the LHC, which new observables and states that may open up for exploration at 100 TeV.
How do these interplay with other probes that could be available 30 years from now (e.g. from the cosmos, from an e+e– collider, etc)?

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Do not feel too constrained by assumed detector performance. We have no clue as to what the 100 Tev detectors will be like. Ideally the design of the detectors will adapt to the physics opportunities, so let's not bias ourselves early on with projected detector performance assumptions.

FHC: physics topics list => WG structure (preliminary)

FHC.1.1 Exploration of EW Symmetry Breaking (EWSB)

FHC.1.1.1 High-mass WW scattering, high mass HH production

FHC.1.1.2 Rare Higgs production/decays and precision studies of Higgs properties

FHC.1.1.3 Additional BSM Higgs bosons: discovery reach and precision physics programme

FHC.1.1.4 New handles on the study of non-SM EWSB dynamics (e.g. dynamical EWSB and composite H, etc)

FHC.1.2 Exploration of BSM phenomena

FHC.1.2.1 discovery reach for various scenarios (SUSY, new gauge interactions, new quark and leptons, compositeness, etc.)

FHC.1.2.2 Theoretical implications of discovery/non-discovery of various BSM scenarios, e.g. address questions such as:

- FHC.1.2.2.1 what remains of Supersymmetry if nothing is seen at the scales accessible at 100 TeV?
- FHC.1.2.2.2 which new opportunities open up at 100 TeV for the detection and study of dark matter?
- FHC.1.2.2.3 which new BSM frameworks, which are totally outside of the HL-LHC reach, become accessible/worth-discussing at 100 TeV ?

FHC.1.3 Continued exploration of SM particles
FHC.1.3.1 Physics of the top quark (rare decays, FCNC, anomalous couplings, ...)
FHC.1.3.2 Physics of the bottom quark (rare decays, CPV, ...)
FHC.1.3.2 Physics of the tau lepton (e.g. tau -> 3 mu, tau -> mu gamma and other LFV decays)
FHC.1.3.2 W/Z physics
FHC.1.3.3 QCD dynamics

FHC.1.4 Opportunities other than pp physics:
FHC.1.4.1 Heavy Ion Collisions
FHC.1.4.2 Fixed target experiments:
FHC.1.4.2.1 "Intensity frontier": kaon physics, mu2e conversions, beam dump experiments and searches for heavy photons, heavy neutrals, and other exotica...
FHC.1.4.2.2 Heavy Ion beams for fixed-target experiments

FHC.1.5 Theoretical tools for the study of 100 TeV collisions
FHC.1.5.1 PDFs
FHC.1.5.2 MC generators
FHC.1.5.3 N^nLO calculations
FHC.1.5.4 EW corrections

Few examples

Higgs physics

Higgs rates at high energy

NLO rates **R(E)** = σ(E TeV)/σ(14 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

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

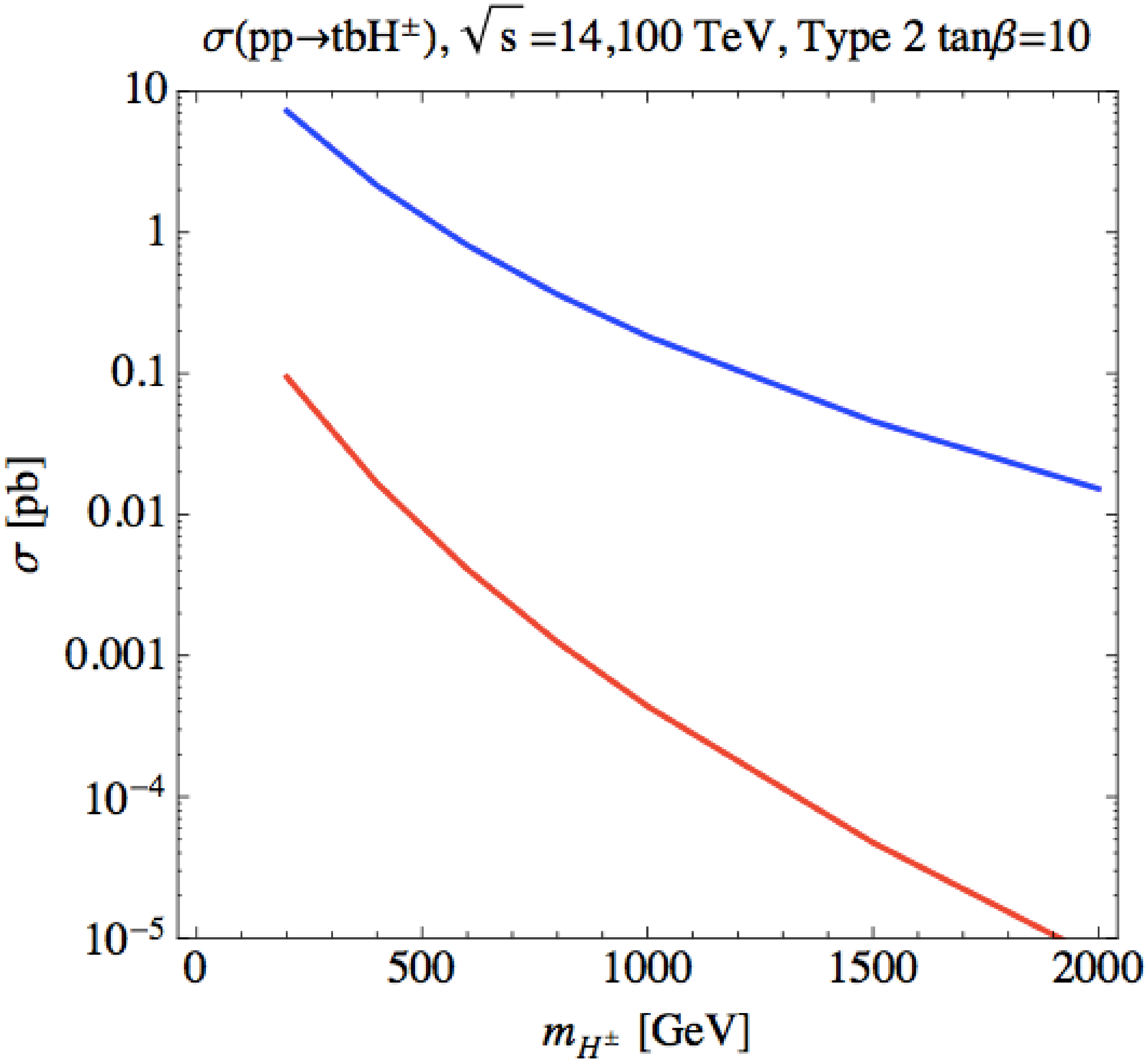
Fine tuning and naturalness: (N.Craig, BSM@100 Wshop)

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

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

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)

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.

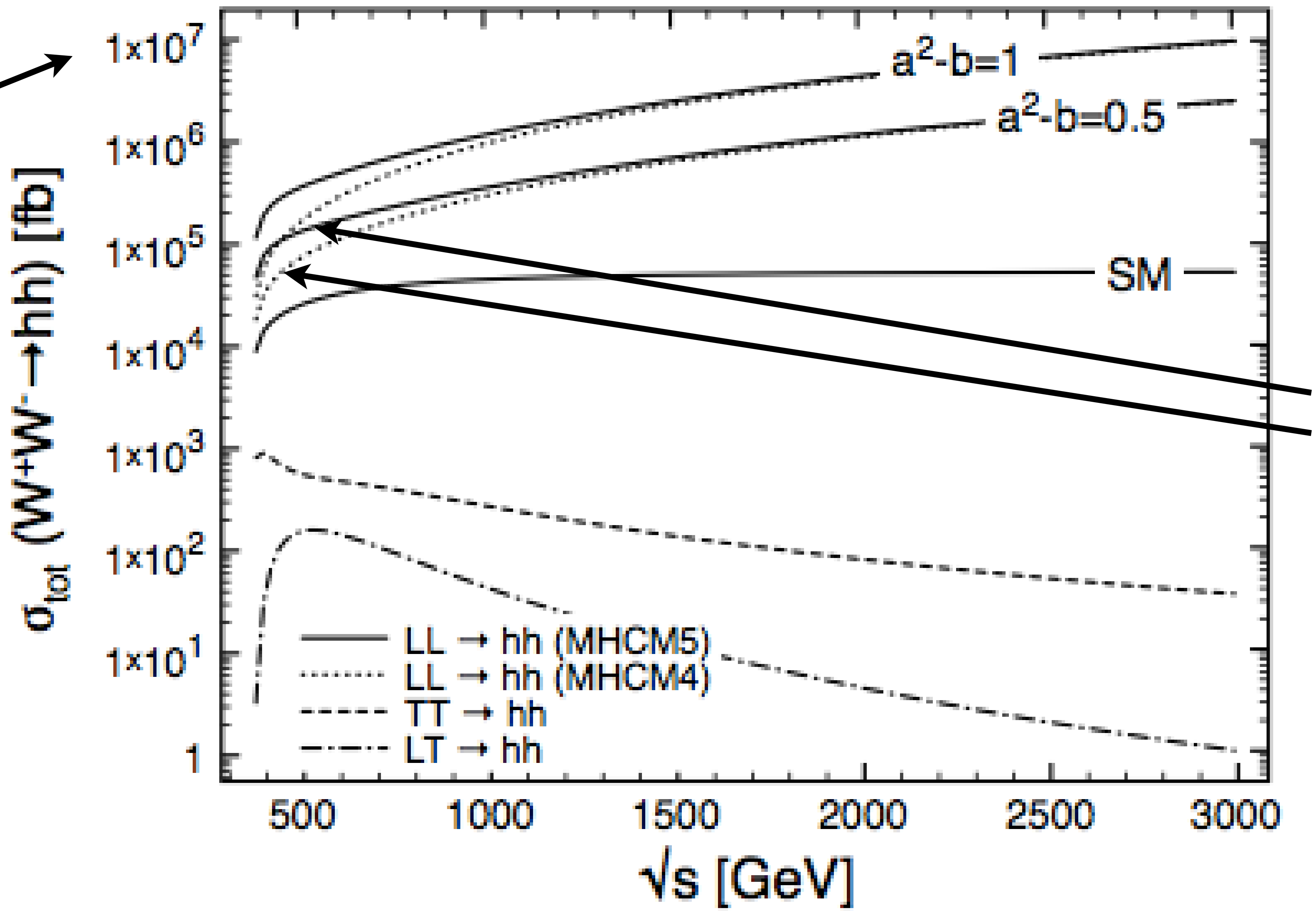
EW interactions at high energy

High-energy WW scattering

Example: WW→HH

R.Contino et al, arXiv:1002.1011v2

partonic cross sections

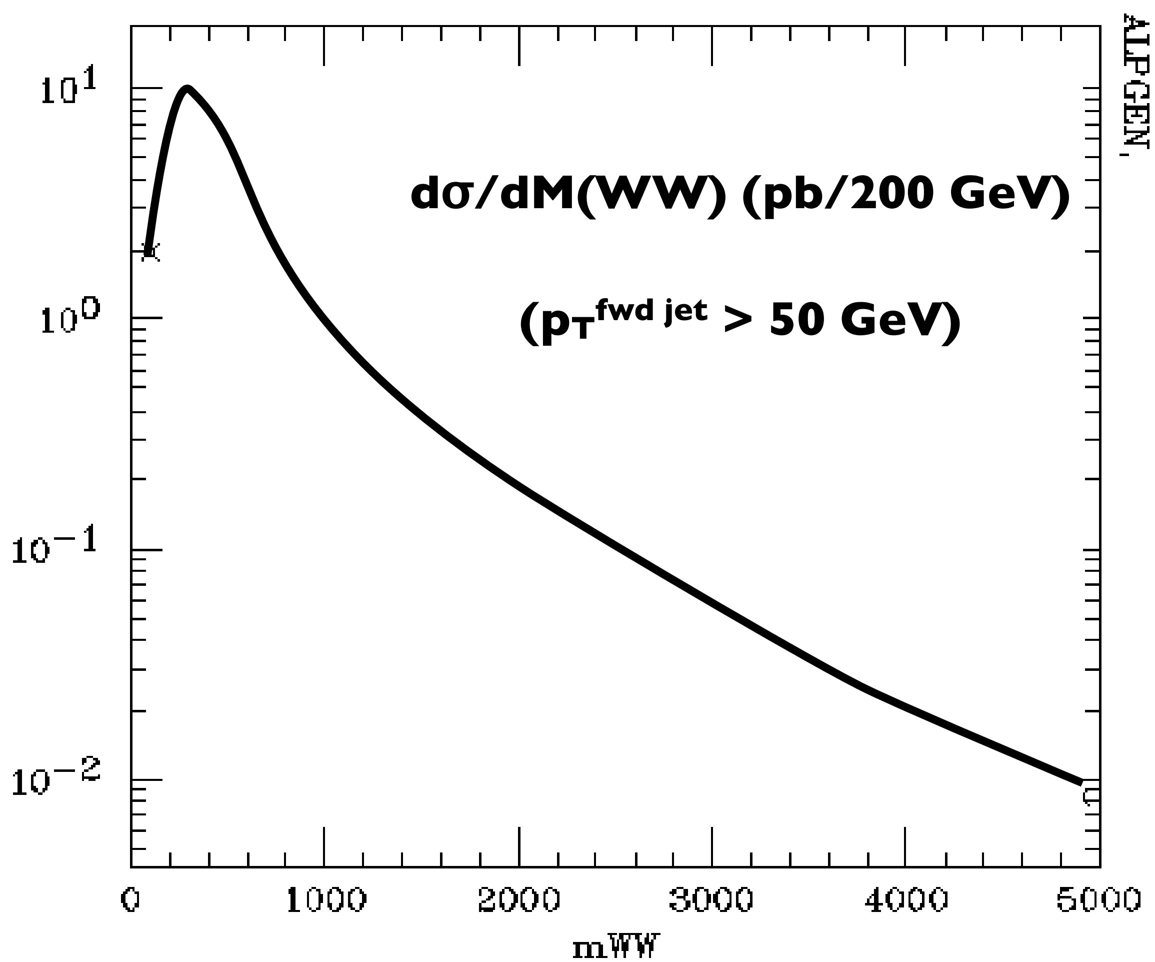


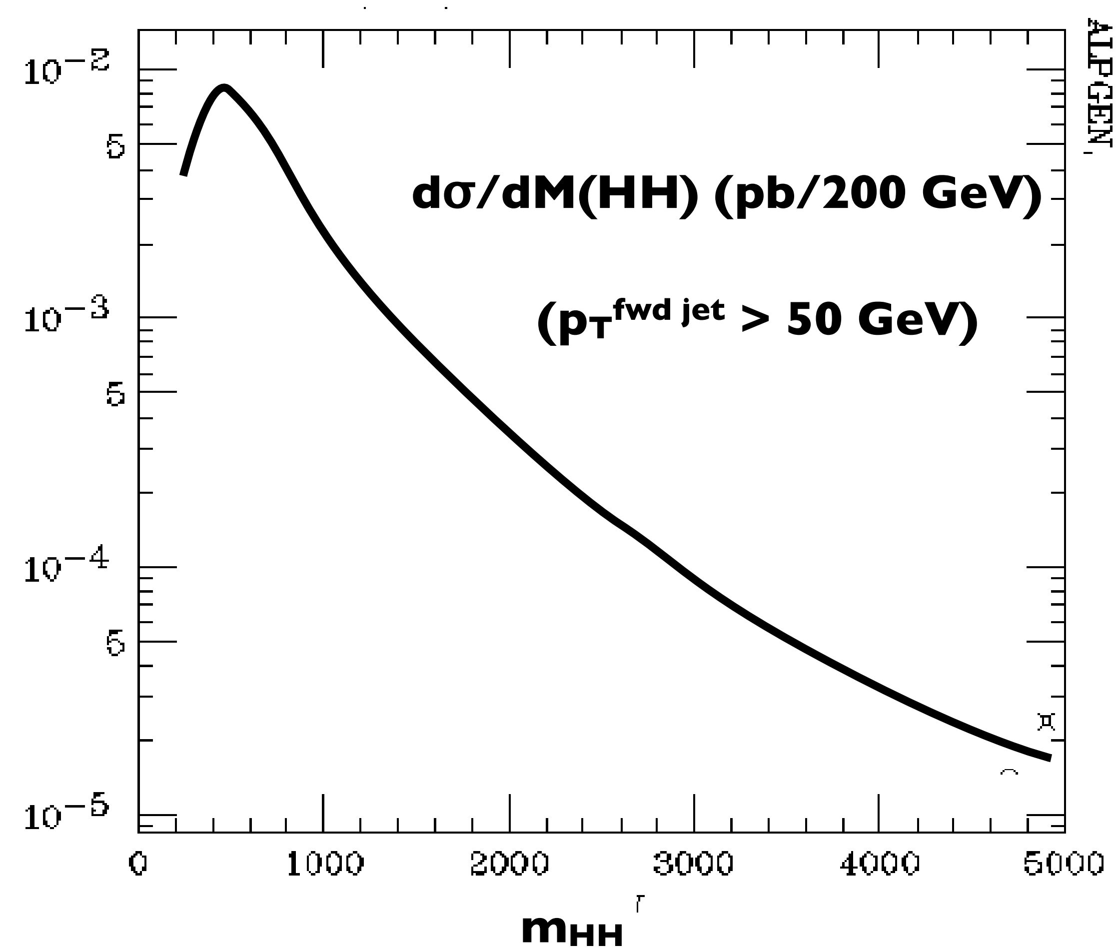
different anomalous HHH couplings:

invariant mass spectrum of HH discriminates among BSM models

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

Exploration of EW interactions at high energy via Multi-gauge boson production

At 100 TeV:

WW	**σ=770 pb**	(no BR included)
WWW	**σ=2 pb**	
WWZ	**σ=1.6 pb**	
WWWW	**σ=15 fb**	
WWWZ	**σ=20 fb**	
....		

Tasks:

- o determine experimental accept/eff's: how high can we go in multiplicity?
- o what can we learn on EW interactions at high energy from these studies?
- o which variables/correlations to consider?
- o can we use dijet decays at high pt(W) ?

WIMP DM search

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

<u>DM overclosure upper limits:</u>

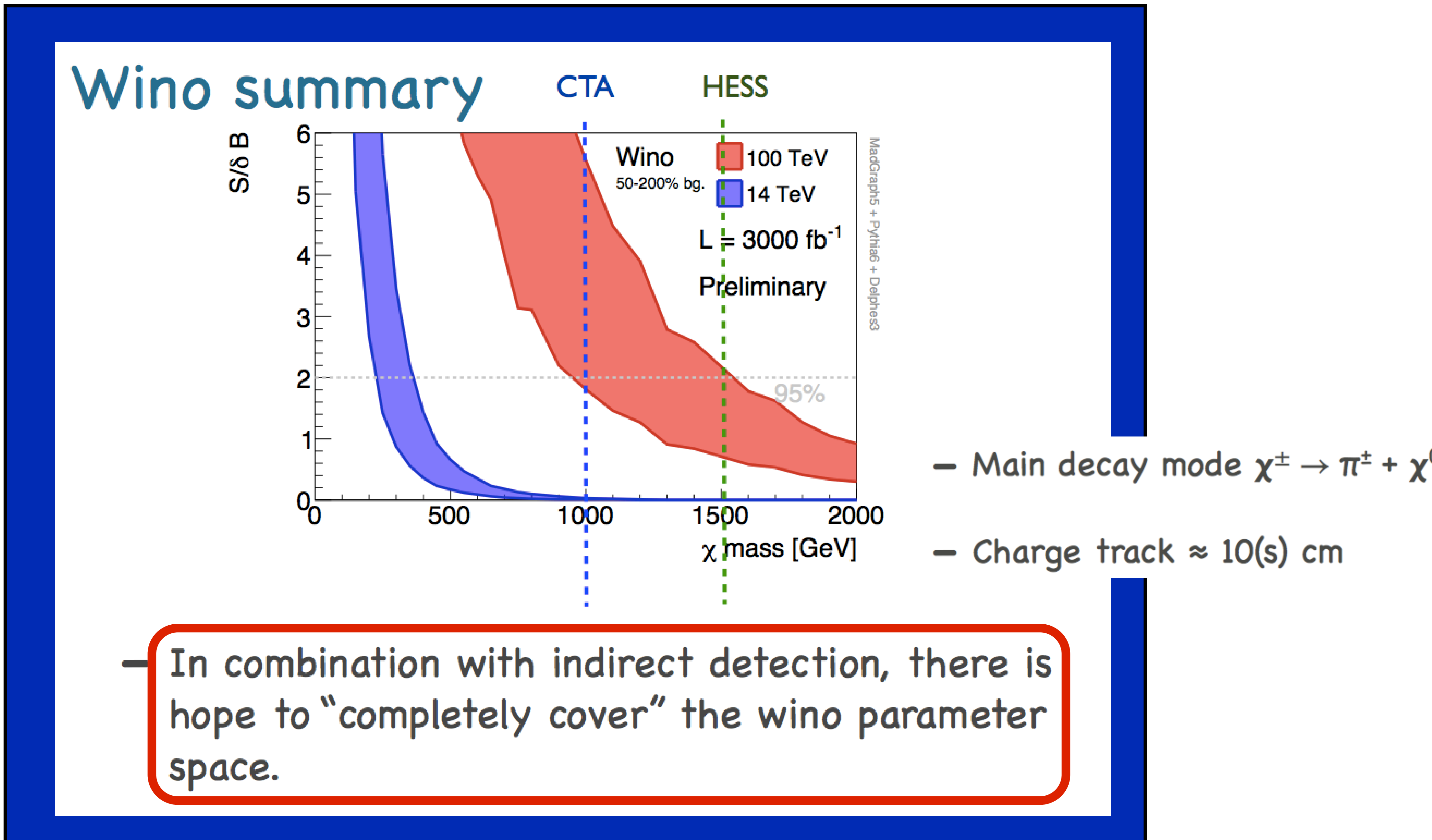
$M_{WIMP} < 1.8$ TeV $(g^2/0.3)$ $\Rightarrow$

wino: m$\lesssim$3 TeV

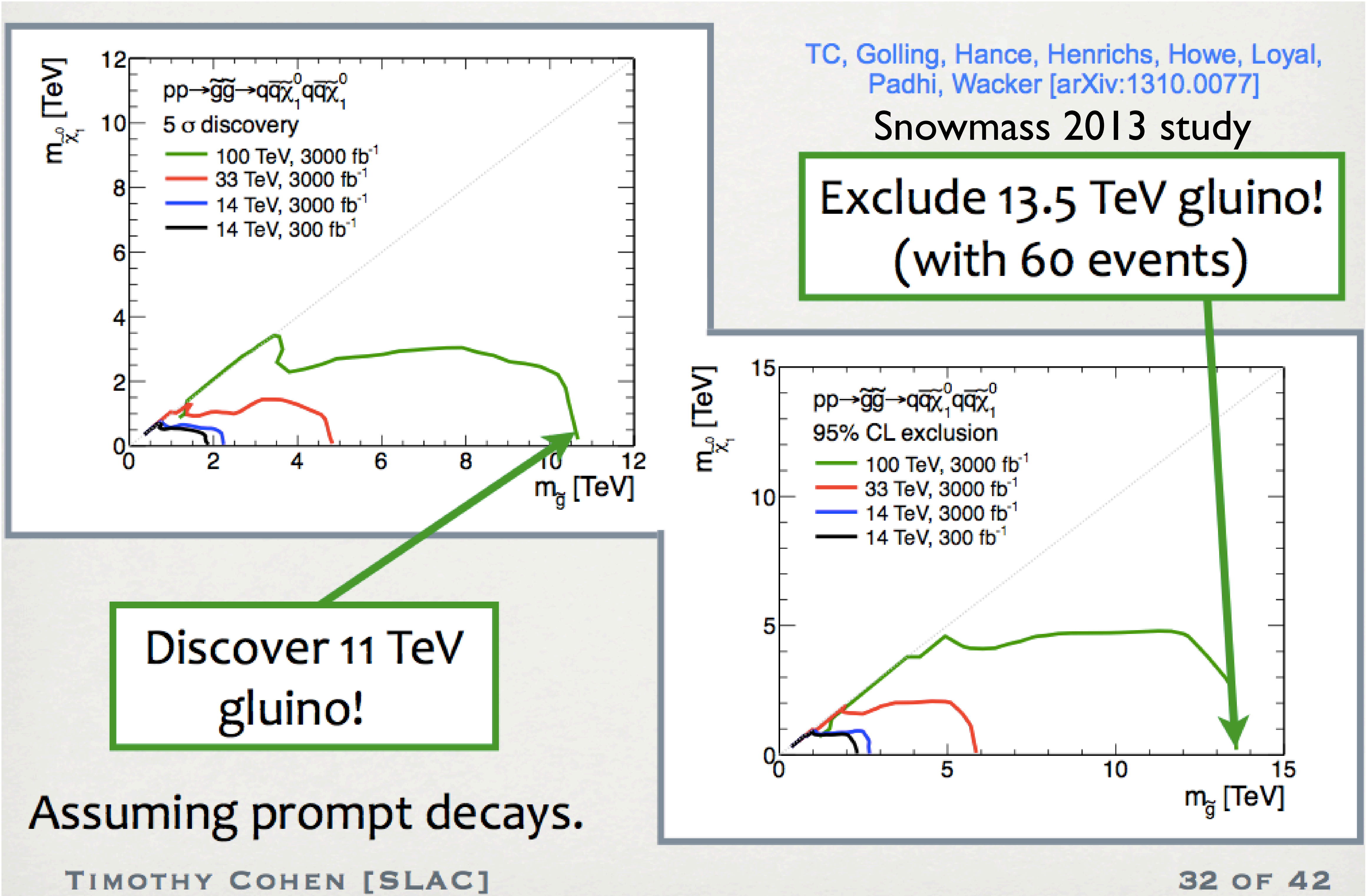
higgsino: m$\lesssim$1.1 TeV

In anomaly-mediated SUSY or split SUSY $\Rightarrow$

$m_{gluino} \lesssim$ 10 TeV



L.T.Wang, (see also P.Schwaller and T.Cohen) BSM@100 TeV Workshop



T.Cohen, BSM@100 TeV Workshop,
http://indico.cern.ch/event/284800/

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 <u>very</u> serious thinking:

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

W decays

- o W mass ??

- o SM rare decays -- Examples:

$W^\pm \to \pi^\pm \gamma$ $\quad$ $BR_{SM} \sim 10^{-9}$, CDF$\leq 6.4 \times 10^{-5}$

$W^\pm \to D_s^\pm \gamma$ $\quad$ $BR_{SM} \sim 10^{-9}$, CDF$\leq 1.2 \times 10^{-2}$

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

- o SM inclusive decays -- Examples:

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

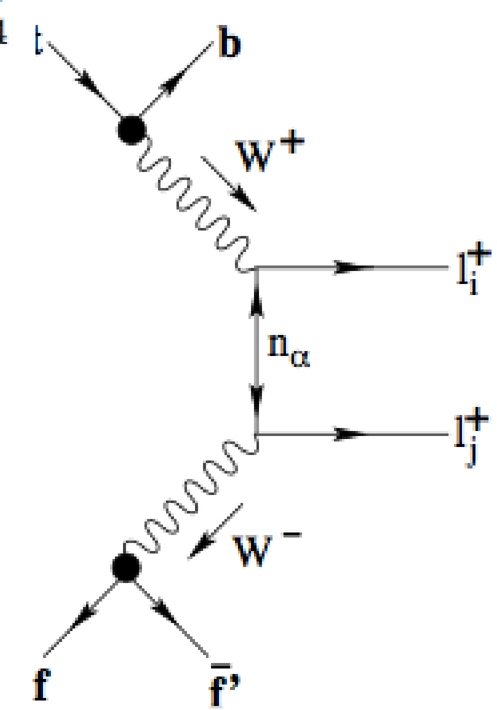
- o BSM decays -- Are there interesting channels to consider?

-- Example

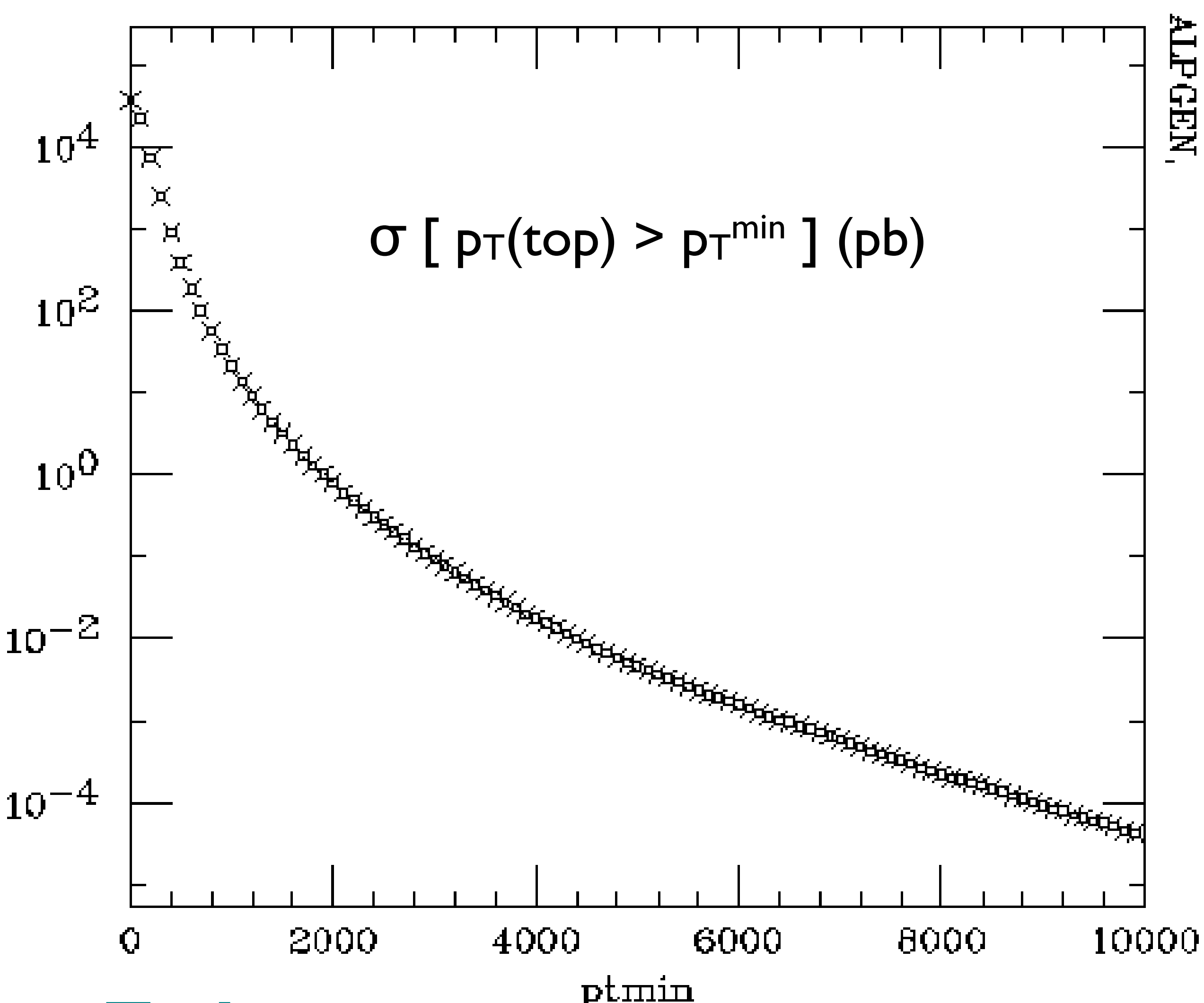
BNL-HET-06/9
OITS-784

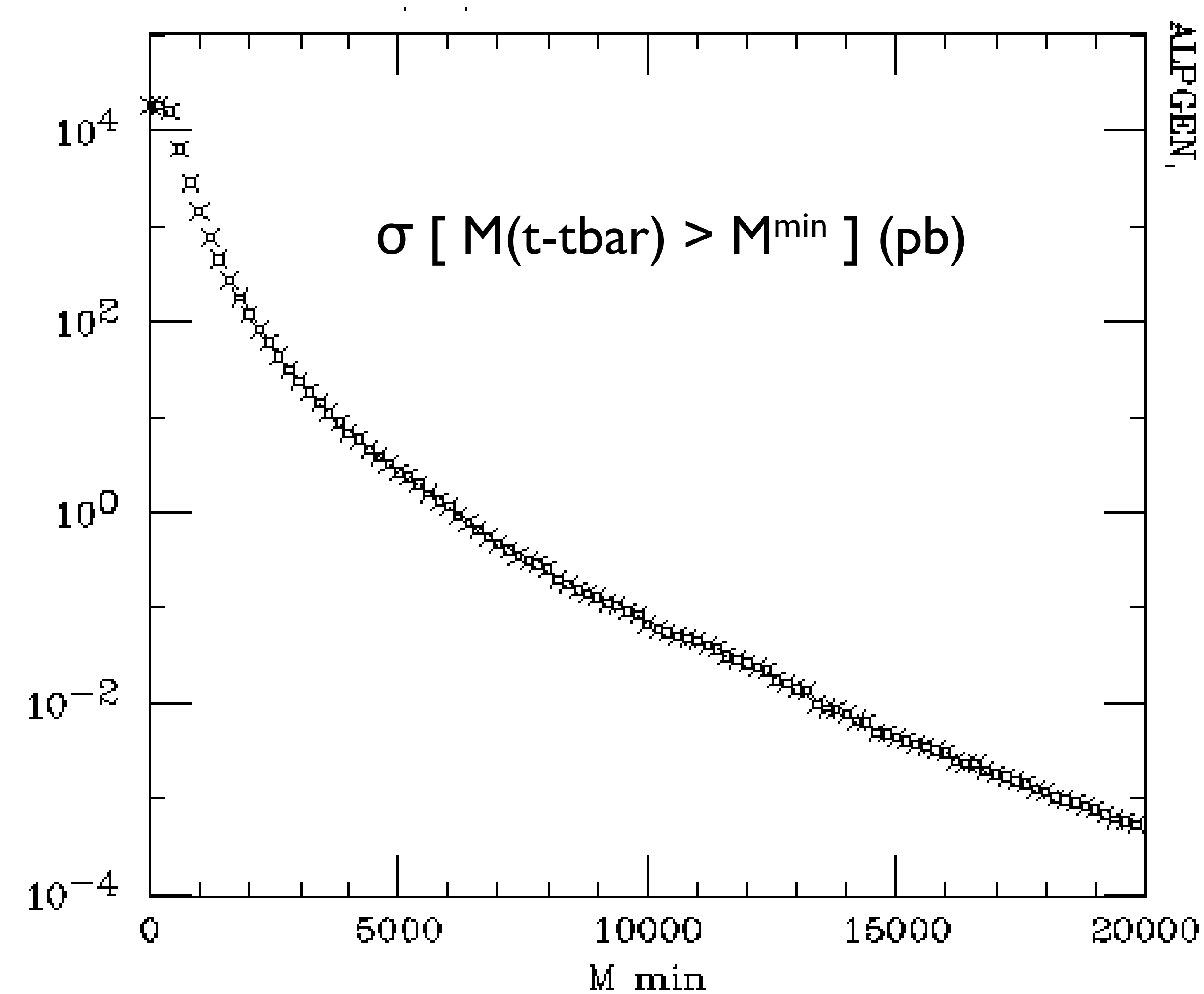
Majorana neutrinos and lepton-number-violating signals in top-quark and W-boson rare decays

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



Inclusive t-tbar production: distributions





Tasks:

o explore tagging of multi-TeV tops

o study mass resolution for resonance searches, define search potential (σ_{BSM} vs M_{BSM})

o explore opportunities for top coupling studies at large Q

Example: what can we learn from
10^4 pp → W* → top+ bottom with M(tb) > 7 TeV ?

Top decays and interactions

Rare decays: t $\rightarrow$W Z b, ...
FCNC probes: t$\rightarrow$cV (V=Z,g, γ), t$\rightarrow$cH
CP violation: spin/momentum correlations of decay products, ...

BSM@100:
Zupan (FCNC top int's)
Kamenik (CPV top int's)

Top as a tool for BSM searches

Tasks:

o quantitative exploration of measurement potential (statistics, systematics, dedicated detector/trigger requirements)

* 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

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- In either case, the LHC can meanwhile deliver a rich programme of measurements, from precision studies of Higgs and top properties, to QCD studies at extreme energies, to the search for very rare phenomena. Don't forget the Tevatron was about to deliver its biggest result, the Higgs discovery, over 25 years after start up !