Challenges and future scenarios for High Energy Physics

International Centre for Theoretical Physics

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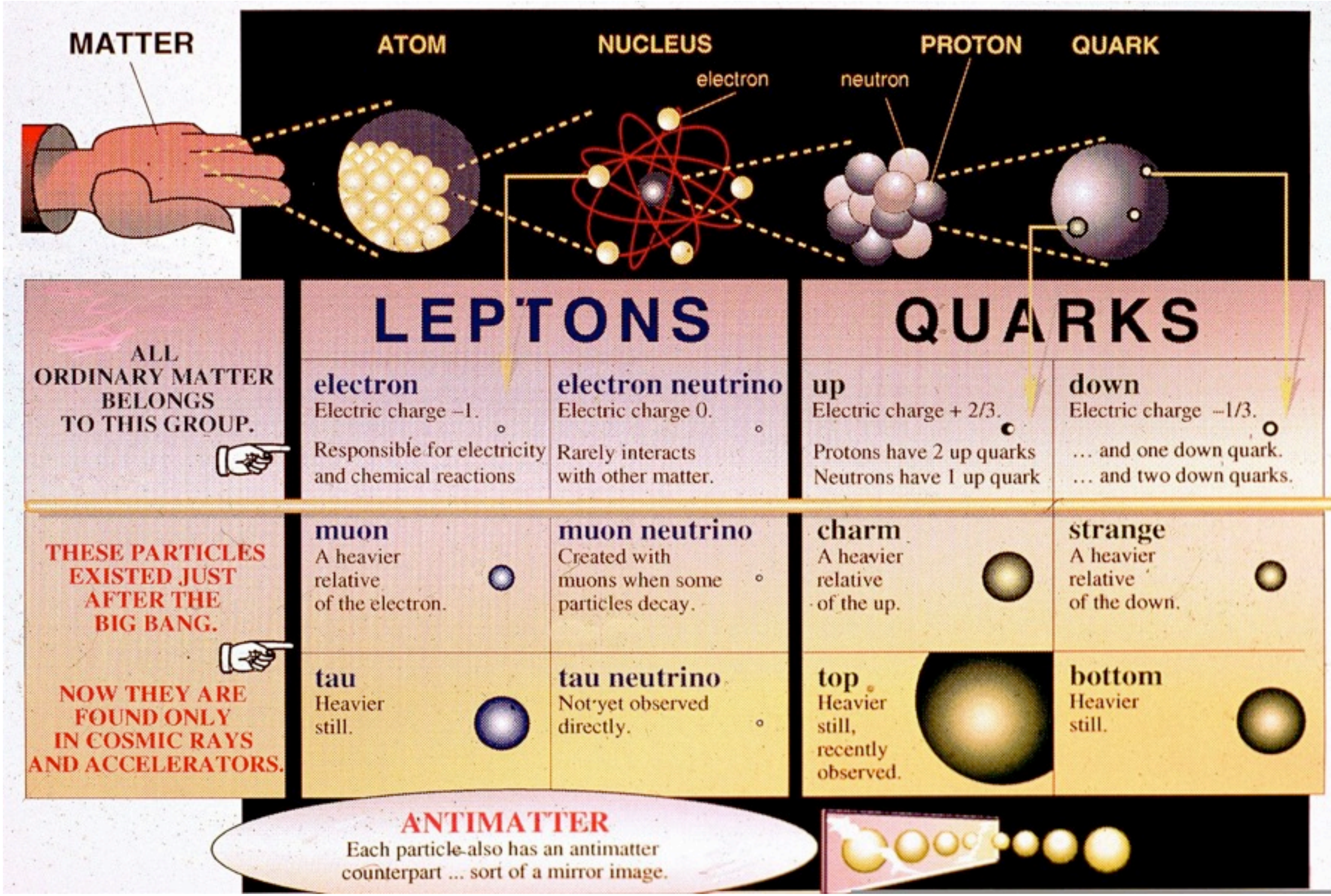
The Standard Model of particle physics



Status of the Standard Model

- **< 1973: theoretical foundations of the SM**
    - renormalizability of SU(2)xU(1) with Higgs mechanism for EWSB
    - asymptotic freedom, QCD as gauge theory of strong interactions
    - KM description of CP violation
- **Followed by 40 years of consolidation:**
    - **experimental** verification, via **discovery** of
        - **Fermions**: charm, tau, bottom, top (all discovered in the USA)
        - **Bosons**: gluon, W and Z, **Higgs** (all discovered in Europe)
    - **technical theoretical advances** (higher-order calculations, lattice QCD, ...)
    - **experimental** consolidation, via precision **measurement** of
        - EW radiative corrections
        - running of α_S
        - CKM parameters, ...
- **Remains to be verified:**
    - ***mechanism at the origin of particles' masses: is the Higgs boson dynamics what prescribed by the SM, or are there other phenomena at work?***

On particles' masses

For a composite system the mass is obtained by solving the dynamics of the bound state ⇒ $\mathbf{m=\langle E\rangle/c^2}$ with $\mathbf{\langle E\rangle=\langle T+U\rangle}$

Example: the proton mass. Dynamics of quarks and gluons inside the proton (they have negligible masses) ⇒ m_p = 938 MeV

But what about elementary particles? Elementary ⇒ no internal dynamics

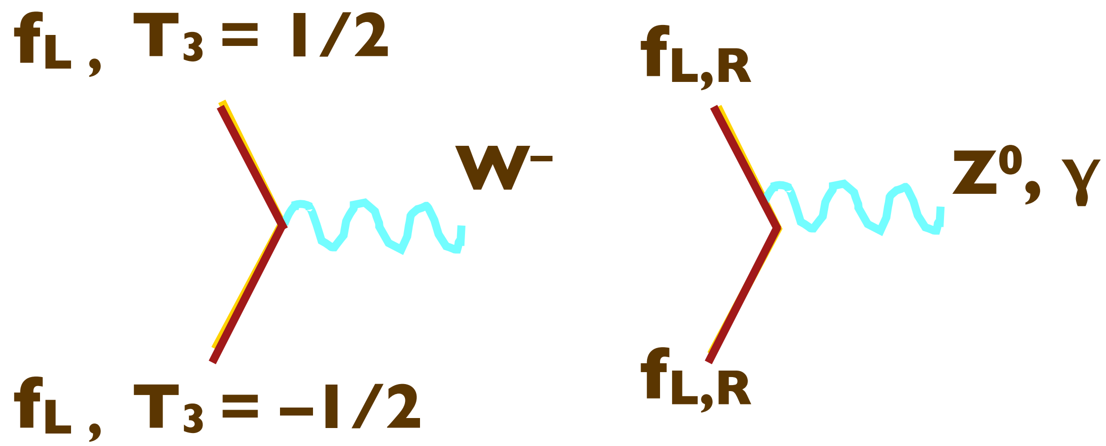
Need to develop a new framework within which to understand the origin and value of, for example, the electron mass

However:

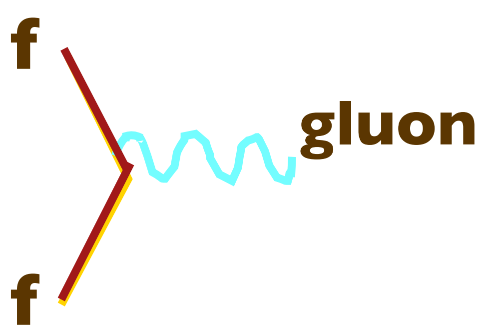
- Why do we need a mechanism to accommodate the masses of elementary particles?
- How about just assigning mass values as parameters?

In other words:
WHY are particle physicists so *obsessed* with the problem of particles' masses?

$SU(2)_L \otimes U(1)$



SU(3)

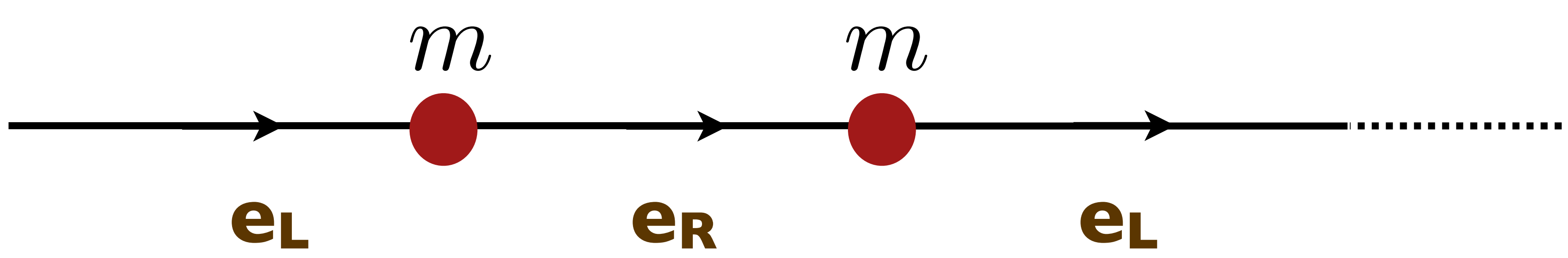


L-chirality	R-chirality
$\begin{pmatrix} u_{2/3} \\ d_{-1/3} \end{pmatrix}_L^{i=1,2,3}$	$u^i{}_R\,,\ \ d^i{}_R$
$\begin{pmatrix} \nu \\ e^- \end{pmatrix}_L$	$e^-{}_R$

+ 2 more "families" differing from the 1st one only in the mass of their elements

Parity asymmetry and mass for spin-1/2 particles

$$H \propto i\overline{\psi_L}\,\partial\cdot\gamma\,\psi_L + i\overline{\psi_R}\,\partial\cdot\gamma\,\psi_R + m\,\overline{\psi_L}\,\psi_R$$



For a massive particle, chirality does not commute with the Hamiltonian, so it cannot be conserved

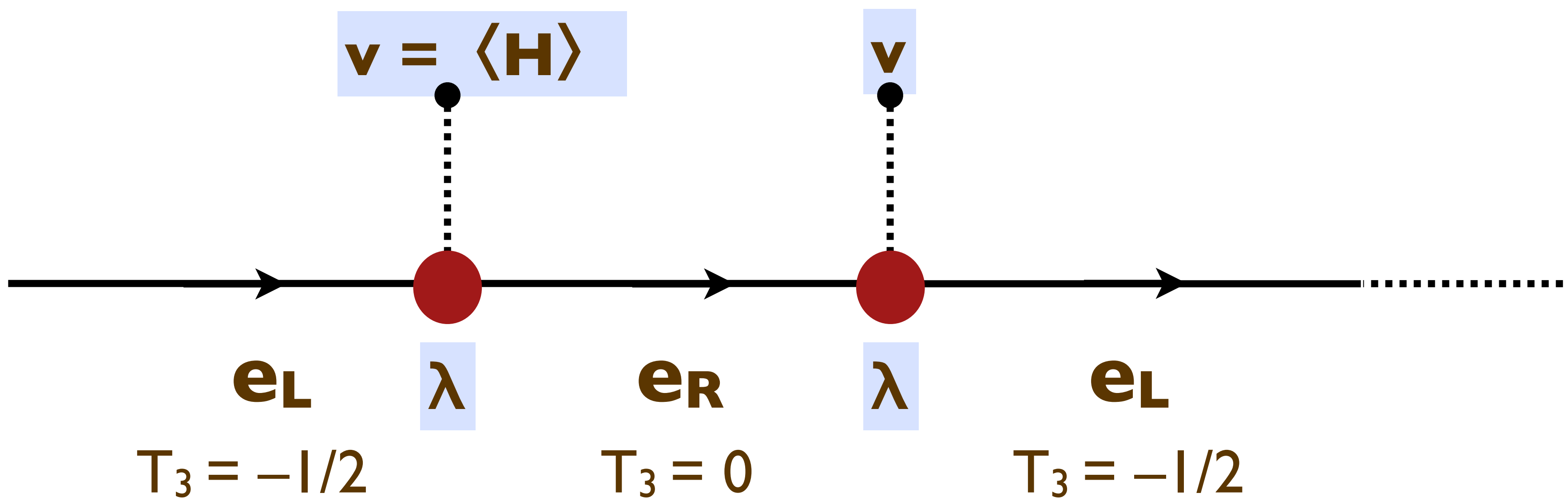
Chirality eigenstates cannot be Hamiltonian (physical) eigenstates

Nothing wrong with that in principle .... but chirality cannot be associated to a conserved charge!

The symmetry associated with the conservation of the weak charge must therefore be broken for leptons and quarks to have a mass

The SM solution ....

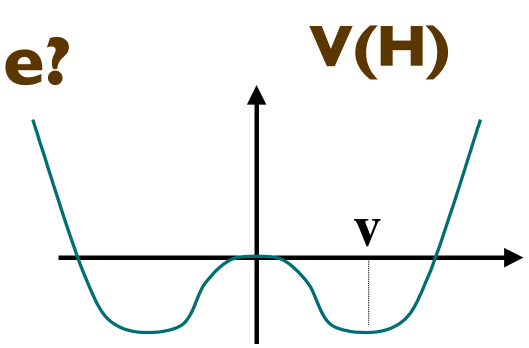
Time evolution of a massive particle:



The transition between L and R states, and the absorption of the changes in weak charge, are ensured by the interaction with a background scalar field, **H**. Its "vacuum density" provides an infinite reservoir of weak charge.

The number "**v**" is the expectation value of the so-called **Higgs field**.
The quantity "**λ**" is characteristic of the particle interacting with the Higgs field.
It can easily be shown that **this interaction leads to a mass m** $\propto$ **λ v**

Why should the field H develop a non-zero background value?



⇒ *Englert–Brout–Higgs–Guralnik–Hagen–Kibble mechanism*

What assigns to the various fermions the value of λ corresponding to their mass? Why λ[muon]≠ λ[electron]?

⇒ *???*

Why is it difficult to study the Higgs ?

Like any other medium, the Higgs continuum background can be perturbed. Similarly to what happens if we bang on a table, creating sound waves, if we "bang" on the Higgs background we can stimulate "Higgs waves", i.e. what we call the Higgs boson ...

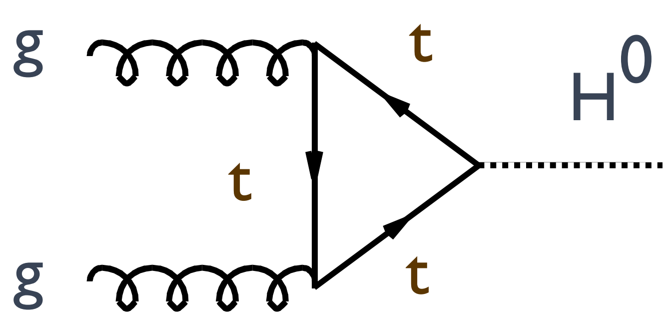
This requires not just energy (enough to create the H), but a large-mass probe (the H couples to mass, not to energy!)

Thus we typically need not just the energy required to produce the H, but also the energy required to produce the heavy particles that will stimulate its emission ...

- ☐ low rates, complex final states, large backgrounds, ...

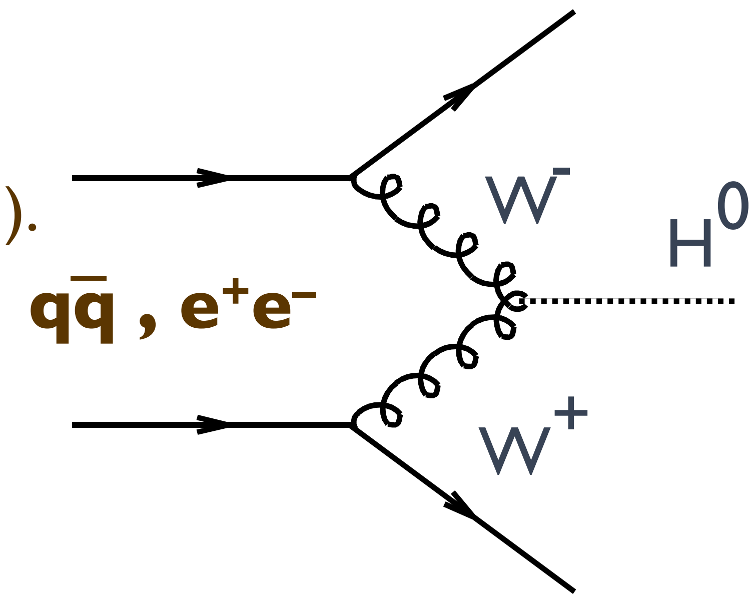
* Higgs particles are thus a bit like phonons ...

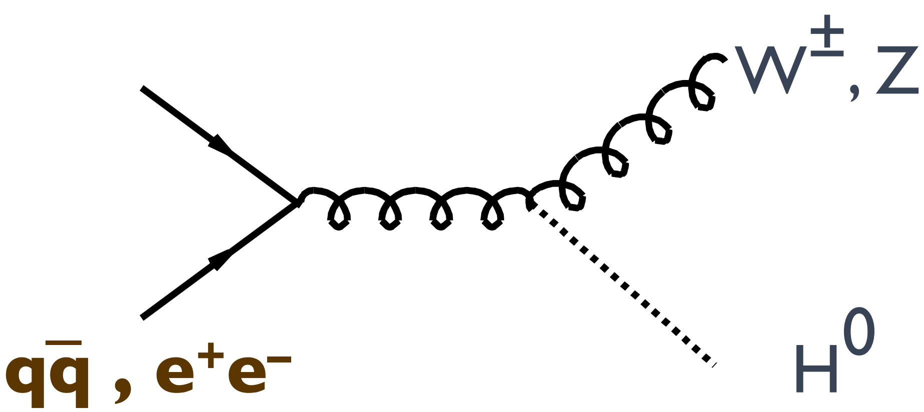
Four main production mechanisms



Gluon-gluon fusion (NNLO):
- Largest rate for all m(H).
- Proportional to the top Yukawa coupling, y_t
- gg initial state

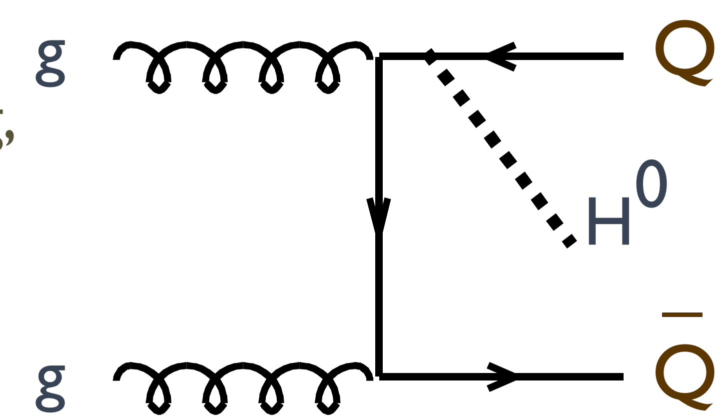
Vector-boson (W or Z) fusion (NLO):
- Second largest, and increasing rate at large m(H).
- Proportional to the Higgs EW charge
- mostly ud initial state



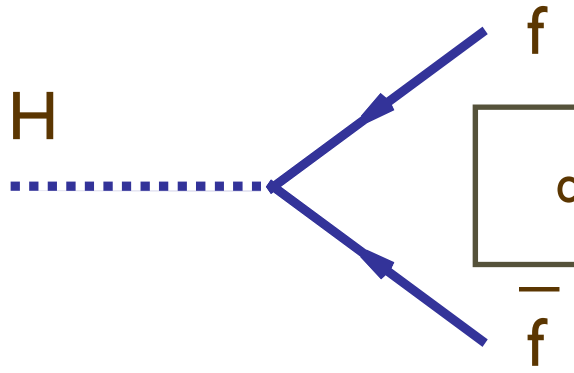


W(Z)-strahlung (NNLO):
- Same couplings as in VB fusion
- Different partonic luminosity

ttH/bbH associate production (NLO):
- Proportional to the heavy quark Yukawa coupling, y_Q, dominated by ttH
- Same partonic luminosity as in gg-fusion, except for different x-range

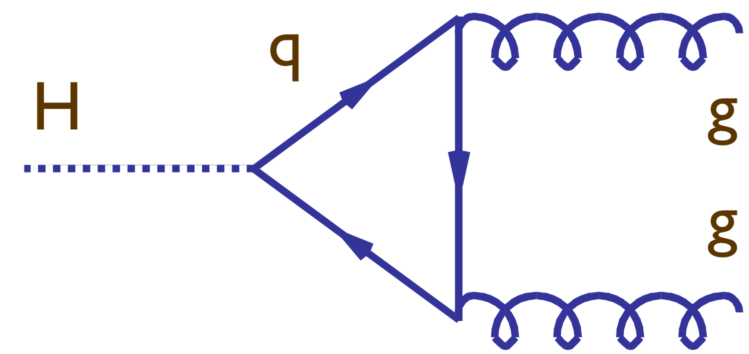


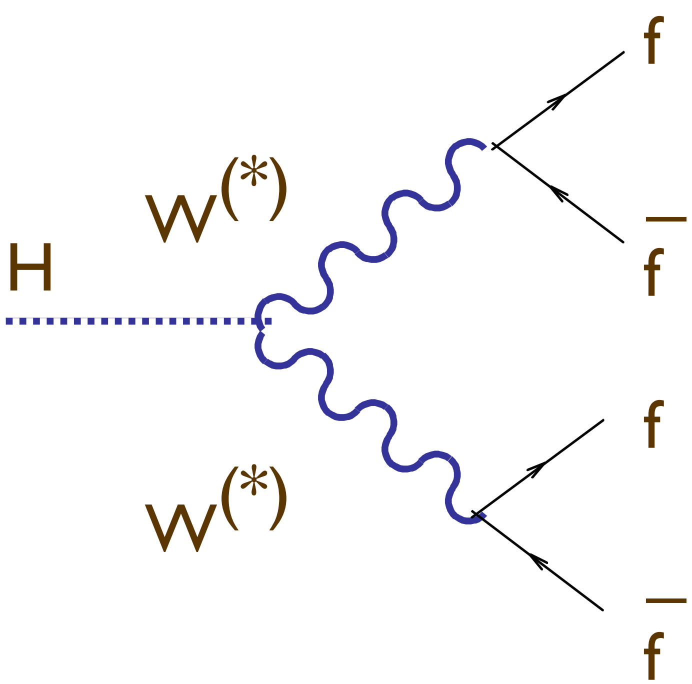
Higgs decays



$\propto m_f^2$ (evaluated at m_H, including QCD running effects)

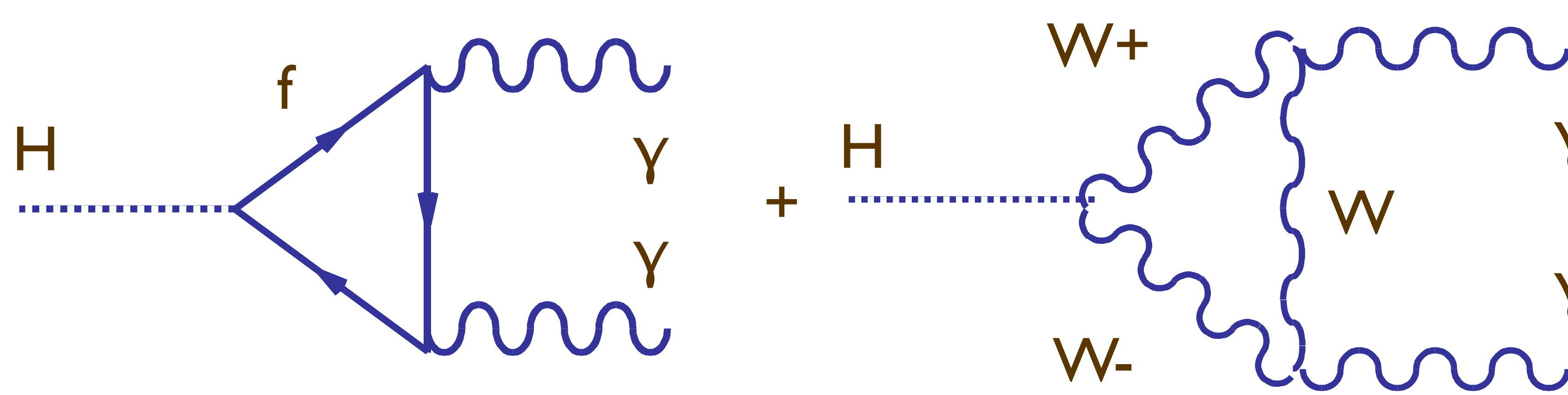
$\propto m_f^2$ (dominated by top-quark loops)



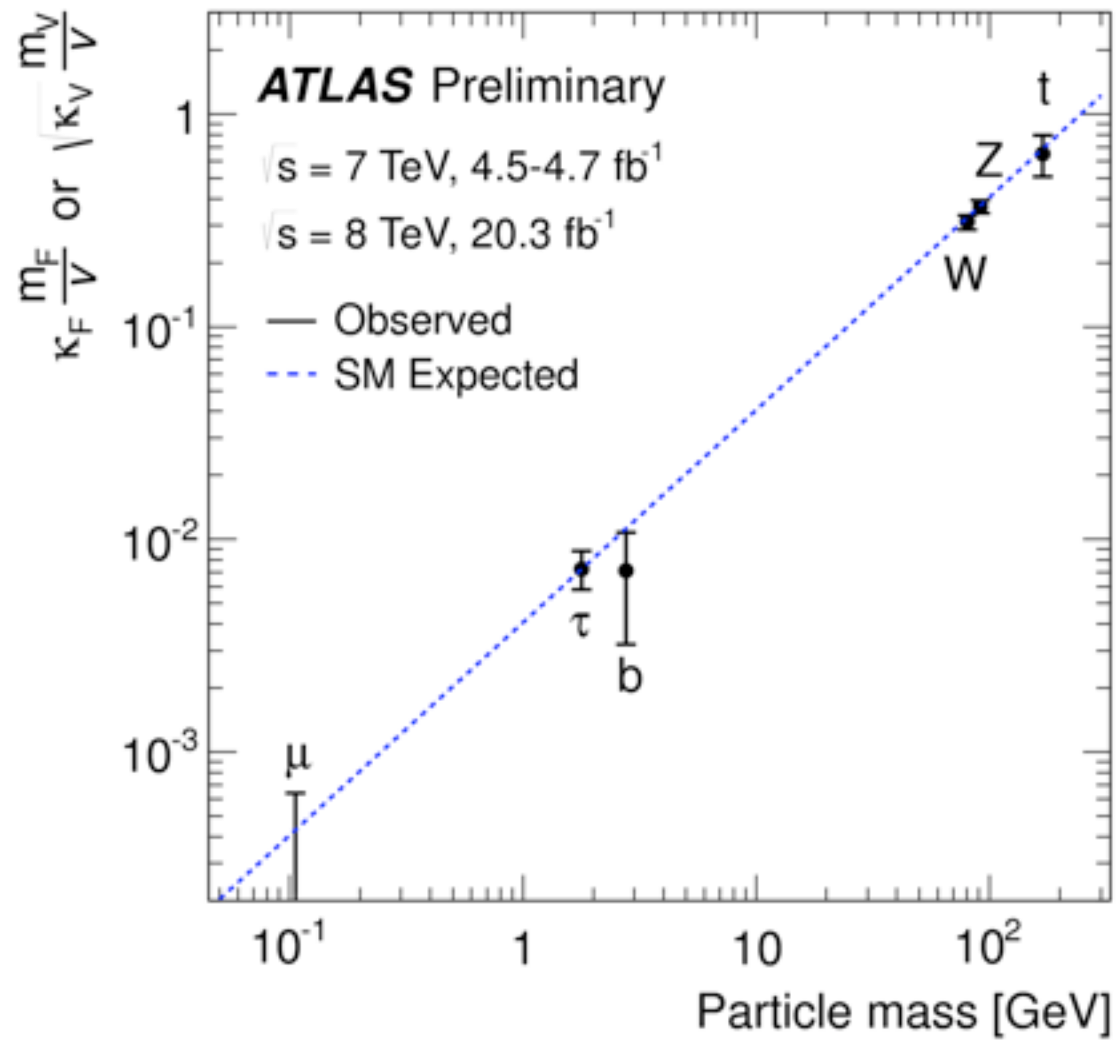


$\propto \alpha_W$ (sharp thereshold at m_H=2m_W , but large BR even down to 125 GeV). Similar processes with W↔Z.

Dominated by the EW couplings, only minor contribution from top loop m ⇒ correlated to H→WW



So far, so good ....



Note on "the mass of the Universe"

- proton's mass arises from QCD dynamics, not from the mass of its constituent quarks. Half of it is kinetic energy of the tightly bound relativisitic quarks, the other half is binding energy ($M=Ec^2$, $E=K+U$, virial theorem....)

- the mass of particles composing Dark Matter does not need to arise from the coupling with the Higgs. E.g. in Supersymmetry models it could mostly come from the breaking of supersymmetry, nothing to do with the Higgs or EWSB

What's to be learned from the Higgs, now that's been found?

The Higgs boson is directly connected to several key questions:

- What's the real origin of the Higgs potential, which breaks EW symmetry?
  - underlying strong dynamics? composite Higgs?
  - RG evolution from GUT scales, changing sign to quadratic term in V(H)?
  - Are there other Higgs-like states (e.g. $H^{\pm}$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?

- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?
  - does the PT wash out possible pre-existing baryon asymmetry?

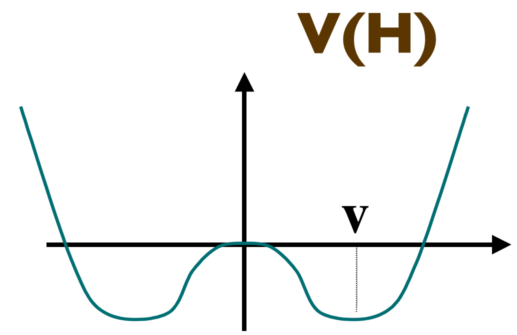
- Is there a relation between Higgs, EWSB, baryogenesis and Dark Matter?

- The hierarchy problem: what protects the smallness of m_H / $m_{Plank,GUT,...}$?

Higgs selfcouplings

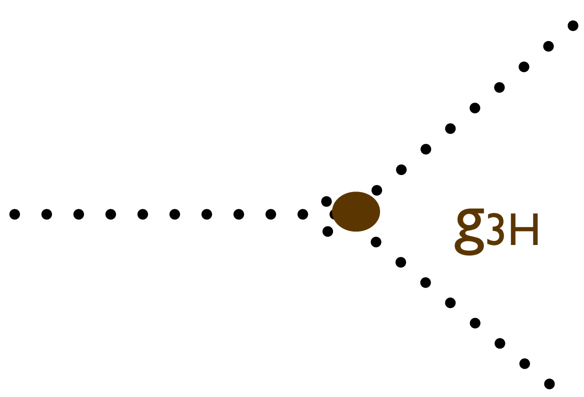
The Higgs sector is defined in the SM by two parameters, **μ** and **λ**:

$$V_{SM}(H) = -\mu^2 \, |H|^2 + \lambda \, |H|^4$$

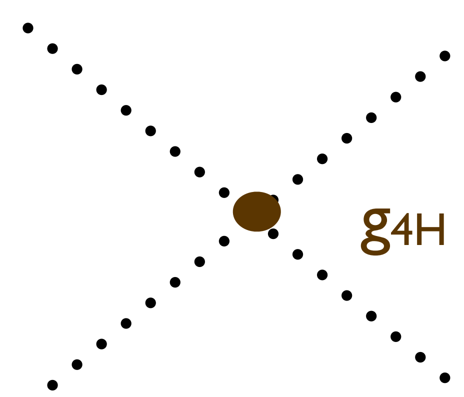


$$\frac{\partial V_{SM}(H)}{\partial H}|_{H=v} = 0 \quad \text{and} \quad m_H^2 = \frac{\partial^2 V_{SM}(H)}{\partial H \partial H^*}|_{H=v} \quad \Rightarrow \quad \begin{array}{rcl} \mu & = & m_H \\ \lambda & = & \frac{m_H^2}{2v^2} \end{array}$$

These relations uniquely determine the strength of Higgs selfcouplings in terms of m_H



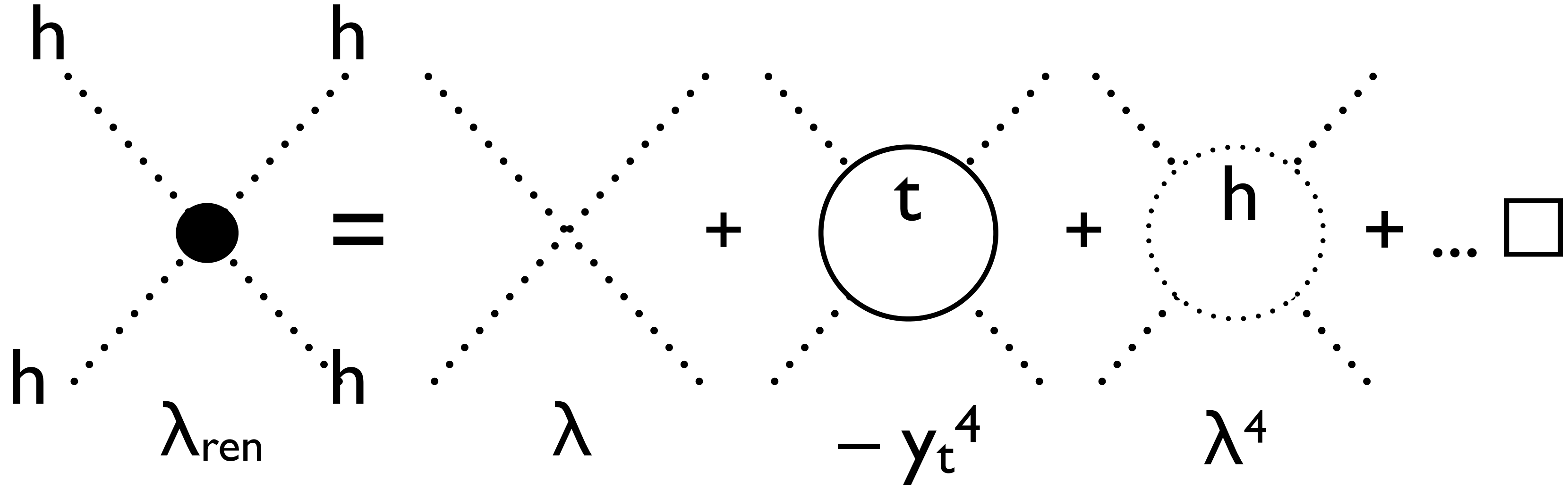
$g_{3H} \Rightarrow 6\lambda \, v = \frac{3m_H^2}{v}$ ~O(m_{top})



$g_{4H} \Rightarrow 6\lambda = \frac{3m_H^2}{v^2}$ ~O(1)

Testing these relations is therefore an important test of the SM nature of the Higgs mechanism

(meta)Stability of the Higgs potential

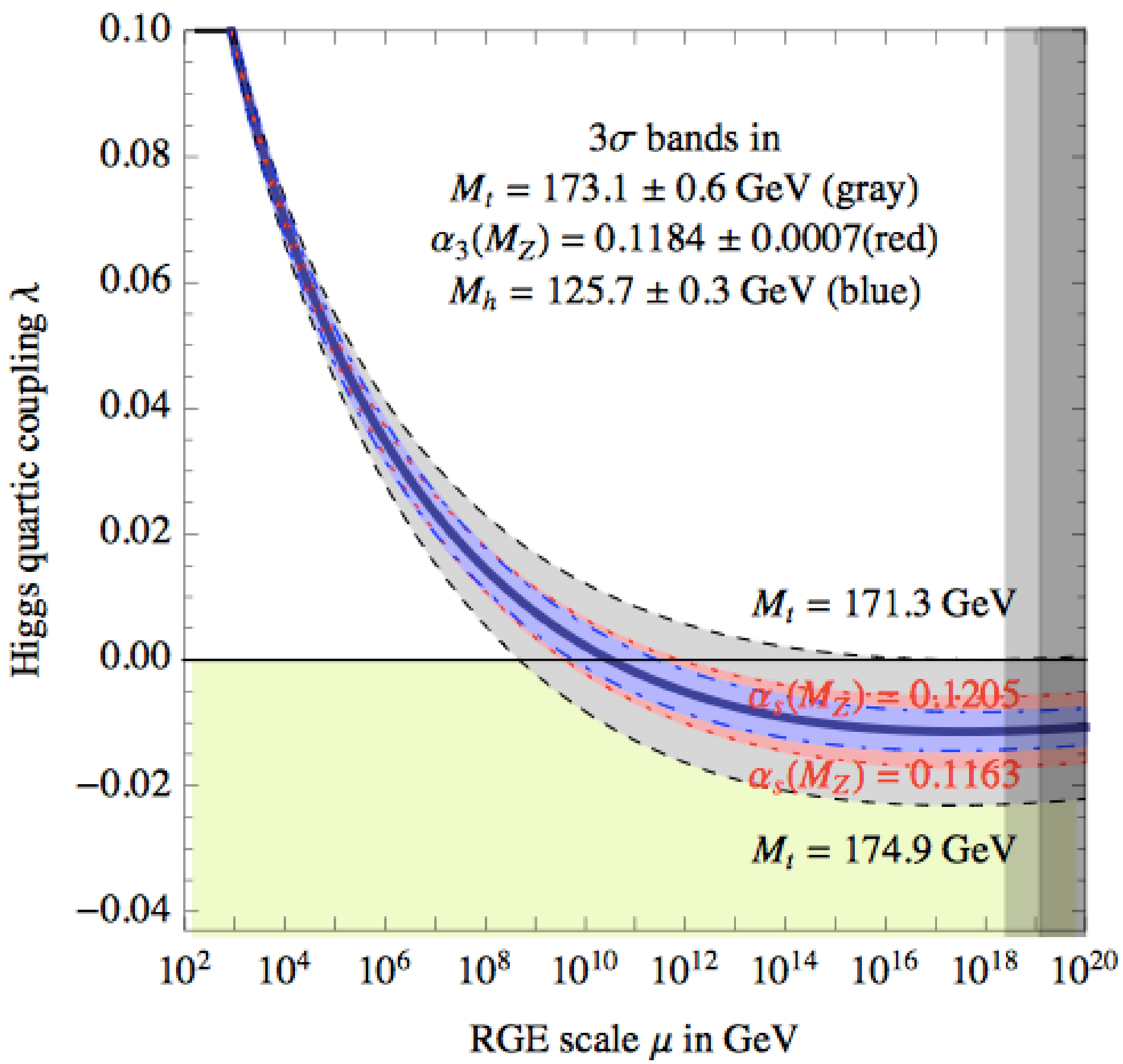


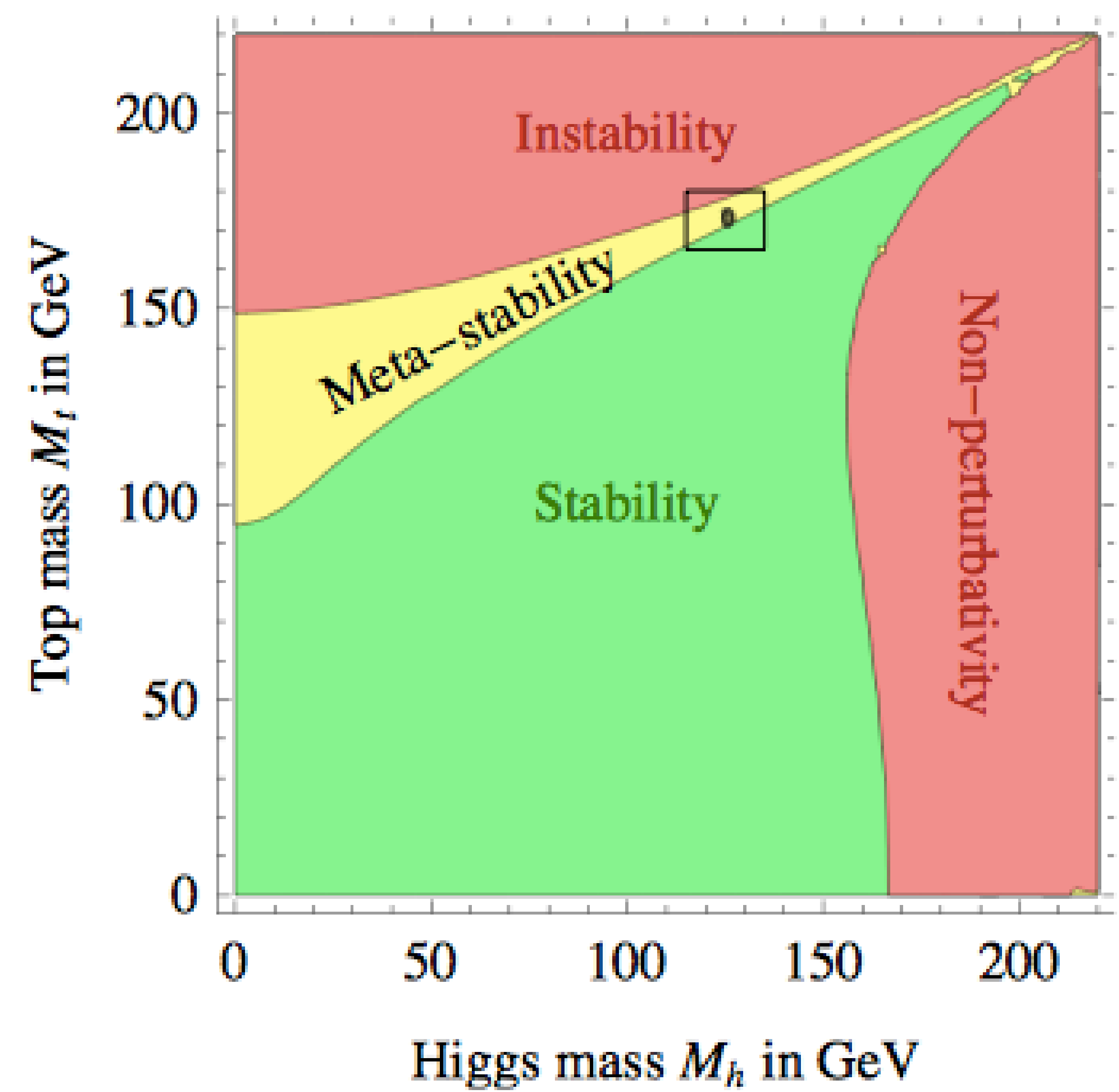
$$\frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4$$

$$\propto a\, m_H^4 - b\, m_t^4$$

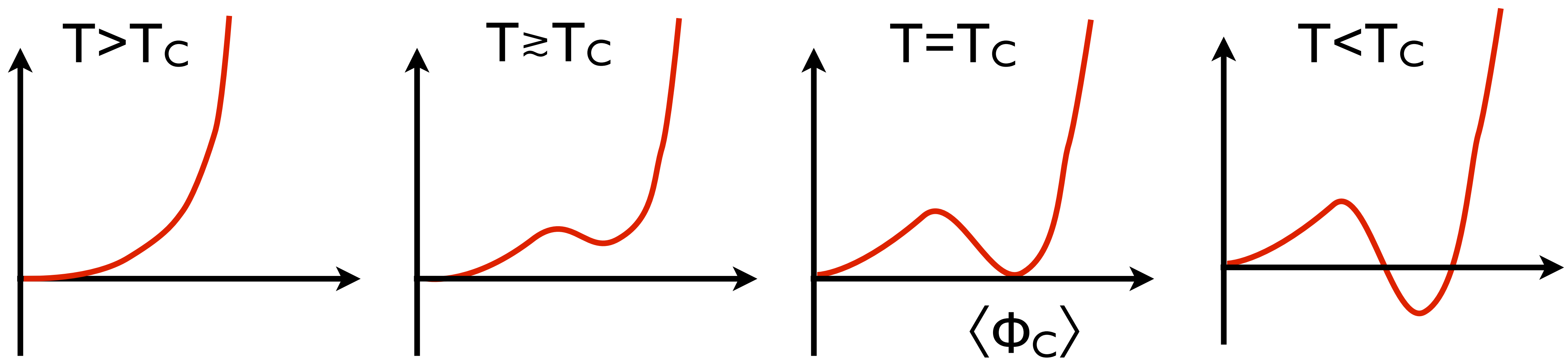
Higgs selfcoupling and coupling to the top are the key elements to define the stability of the Higgs potential

Degrassi et al, http://arxiv.org/pdf/1205.6497





The nature of the EW phase transition



Strong 1st order phase transition ⇒ $\langle \Phi_C \rangle > T_C$

In the SM this requires $m_H \lesssim 80$ GeV ⇒ new physics, coupling to the Higgs and effective at scales O(TeV), must modify the Higgs potential to make this possible

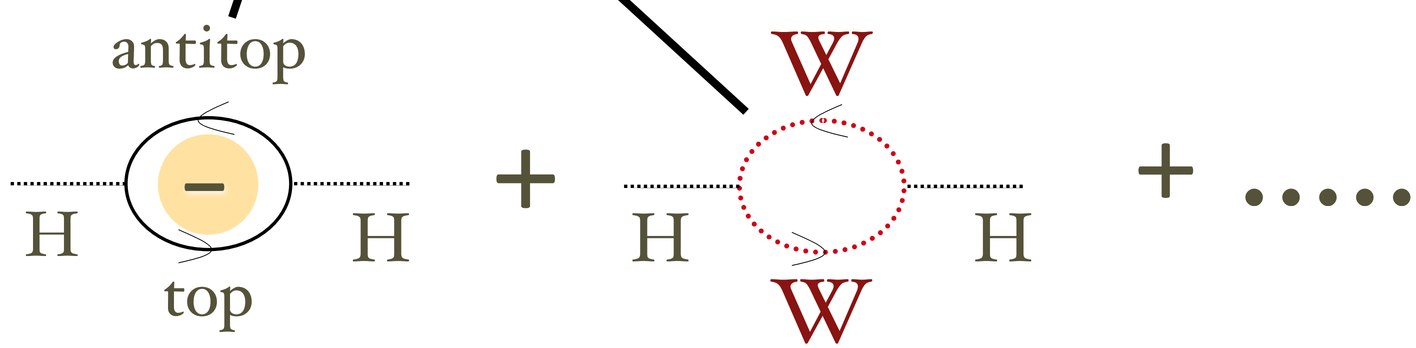
Understanding the role of the EWPT in the evolution or generation of the baryon asymmetry of the Universe is a key target for future accelerators

- Experimental probes:
  - study of triple-Higgs couplings (... and quadruple, etc)
  - search for components of an extended Higgs sector (e.g. 2HDM, extra singlets, ...)
  - search for new sources of CP violation, originating from (or affecting) Higgs interactions

H, the hierarchy problem, and physics beyond the SM

Calculating the radiative corrections to the Higgs mass in the SM poses an intriguing puzzle:

$$m_H^2 = m_0^2 - \frac{6G_F}{\sqrt{2}\pi^2}\left(m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2\right)\Lambda^2 \sim m_0^2 - (125\,\mathrm{GeV})^2\left(\frac{\Lambda}{400\mathrm{GeV}}\right)^2$$



Λ= scale up to which the SM is valid

renormalizability =>

$$m_H^2(v) \sim m_H^2(\Lambda) - (\Lambda^2 - v^2) \quad , \quad v = \langle H \rangle \sim 250\mathrm{GeV}$$

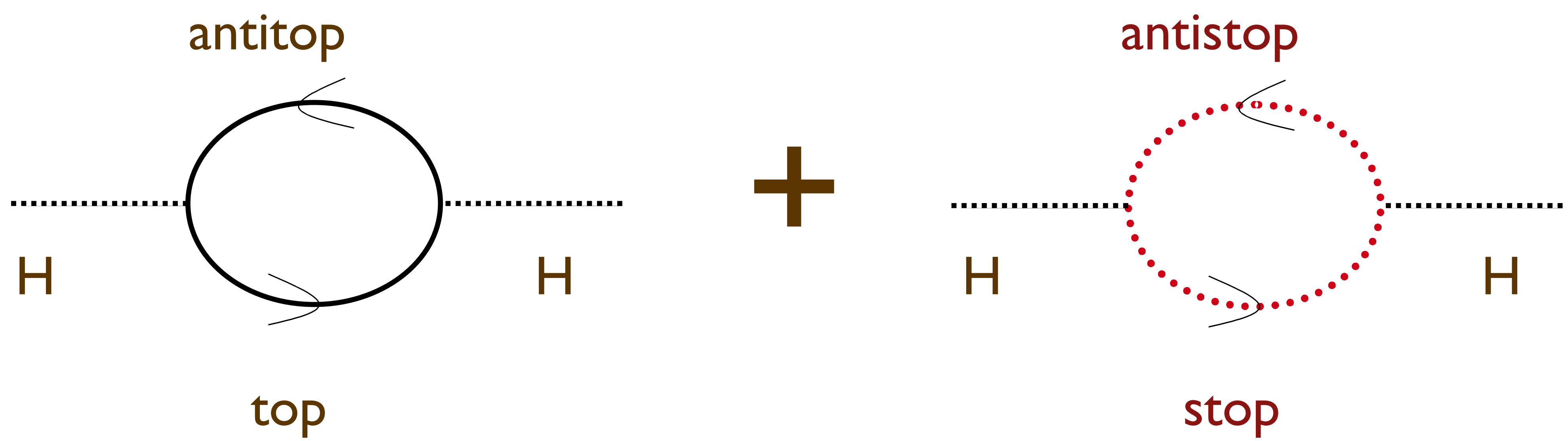
Assuming Λ can extend up to the highest energy beyond which quantum gravity will enter the game, 10^{19} GeV, keeping m_H below 1 TeV requires a fine tuning among the different terms at a level of 10^{-34}:

$$\frac{m_H^2(\Lambda) - \Lambda^2}{\Lambda^2} \sim \frac{v^2}{\Lambda^2} = O(10^{-34}) \text{ if } \Lambda \sim M_{Planck}$$

extremely **unnatural** if it is to be an accident !!

hierarchy, or **fine tuning,** problem

Higgs self-energy, Susy fix



(I)

$$\Delta m_H^2 \propto \ G_F\, m_t^4 \log(m_t/m_{stop})$$

stability of the natural scale of the Higgs mass restored!

$$m_H \leq M_Z + \text{ radiative corrections } (\propto \log(m_t/m_{stop}) \leq 135 \text{ GeV}$$

More in general ....

Tie the Higgs mass to some symmetry which protects it against quadratic divergencies

Supersymmetry — **H (scalar) ↔ fermion**

Gauge symmetry — **H (scalar) ↔ 5th component of a gauge bosons in 5 dimensions or more**

=> extra dimensional theories

Global symmetry — **$H \to H + a \;\Rightarrow\; L(H)=L(\partial H)$**

=> Little Higgs theories, Technicolor
H=pseudo-goldstone boson

The manifestations of these new symmetries (e.g. new particles, new interactions) cannot be too far from the TeV scale, in order to solve the Higgs fine tuning issue in a **natural** way

Status of BSM

- Until few yrs ago, we had a benchmark model, MSSM, expected to deliver the following:
  - low-mass Higgs h^0, no heavier than ~130 GeV
  - ~TeV scale squarks and gluinos, to be seen rapidly at the LHC
    - $\Rightarrow$ solution to the naturalness problem
  - extra Higgses (A^0 /H^0 /$H^\pm$) observed at the LHC
  - candidate for DM, confirmed by direct detection
  - interesting flavour phenomenology
    - explanation of $(g-2)_\mu$
    - sizable deviations from SM in $B(B_S \to \mu^+ \mu^-)$
    - $\mu \to e\gamma$ observed at MEG, consistent with SUSY neutrino masses induced at the GUT scale
    - CPV in the Higgs or squark/gluino sector, to explain BAU
    - electric dipole moments (e, n) measured, consistent with previous point

- Given our knowledge 4-5 yrs back, all of this could have happened by now.
- Even models alternative to SUSY (extra dim, little Higgs, SILH, ...) had the potential of matching the "natural" predisposition of SUSY to solve problems and to provide rich phenomenological consequences across the fields (LHC, flavour, astro/cosmo)
- **None of the above happened.**
- Thus a radical change in attitude in BSM model building is taking place, focusing on schemes that address individual issues or anomalies, leaving for later the understanding of the "grand picture"
- The above scenario may still happen, with a few-year delay, perhaps stretching a bit the "naturalness".
- This expectation is still high, and well justified

NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS CHIRAL SYMMETRY BREAKING

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Naturalness is not a recent "fashion": it's an original sin of the SM itself ... See e.g.

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 more puzzling than 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***.
- Naturalness remains a guiding principle to drive the search of new phenomena at the LHC

Possible reasons for the lack of signals ...

- BSM particles are already being created at the LHC, but are hiding well:
  - compressed spectra: low MET, low ET, long lifetime heavy particles, ...
  - RPV
  - ....

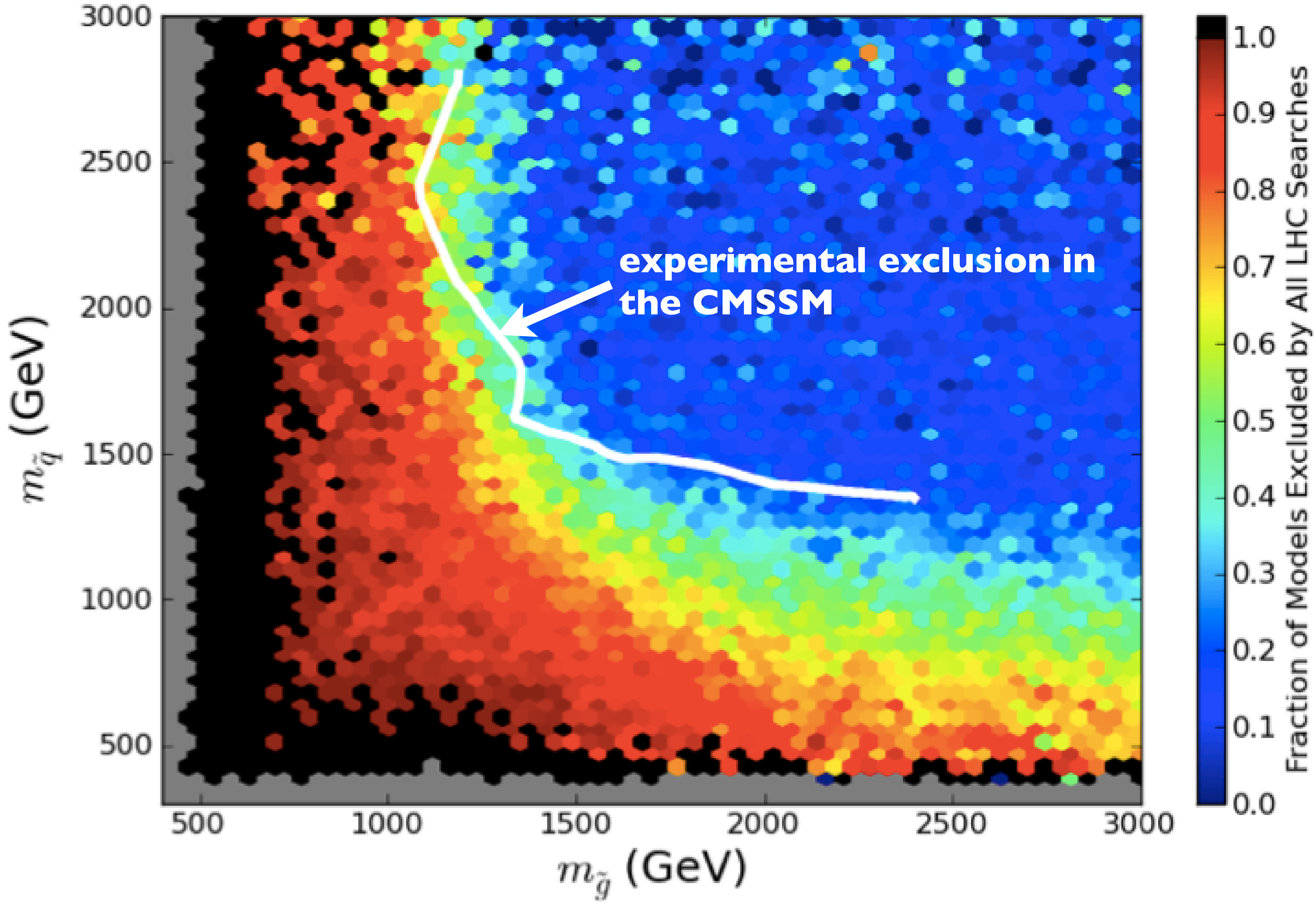
- BSM is less "conventional", fine-tuning or direct search constraints less tight
  - NMSSM
  - non-degenerate squarks
  - ....

- The scale at which naturalness is restored is higher than the TeV: acceptable, but becoming less and less "natural" as the scale grows ....

- Naturalness is an ill guided principle ⇒ Anthropic principle

Example of ways out: explore less constrained SUSY models

Fraction of excluded models in the pMSSM (19 parameters MSSM)



Rizzo et al, arXiv:1211.1981

Anomalies left over from run 1, some examples

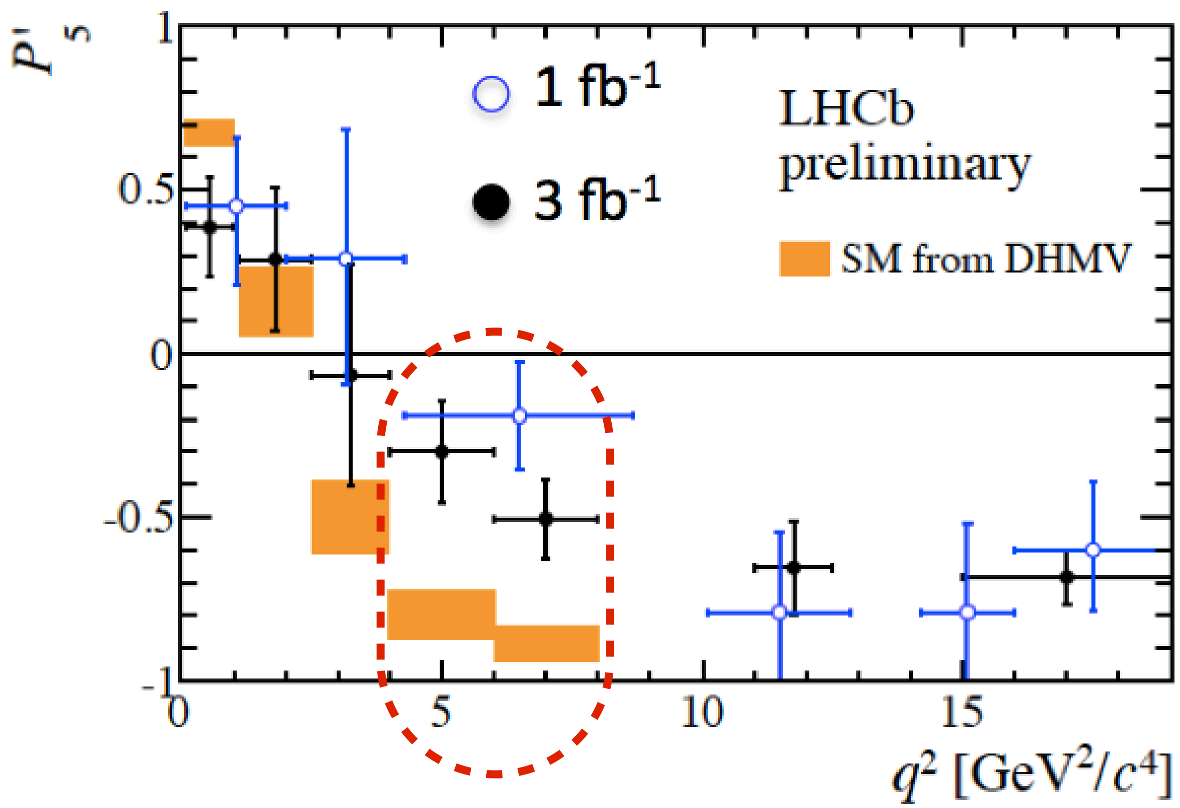
$$\mathrm{Br}[h \to \mu\tau] = \left(0.89^{+0.40}_{-0.37}\right)\%$$

CMS-PAS-HIG-14-005

stat **syst**

$$R(K) = \frac{B \to K\mu^+\mu^-}{B \to Ke^+e^-} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

LHCb, arXiv:1406.6482



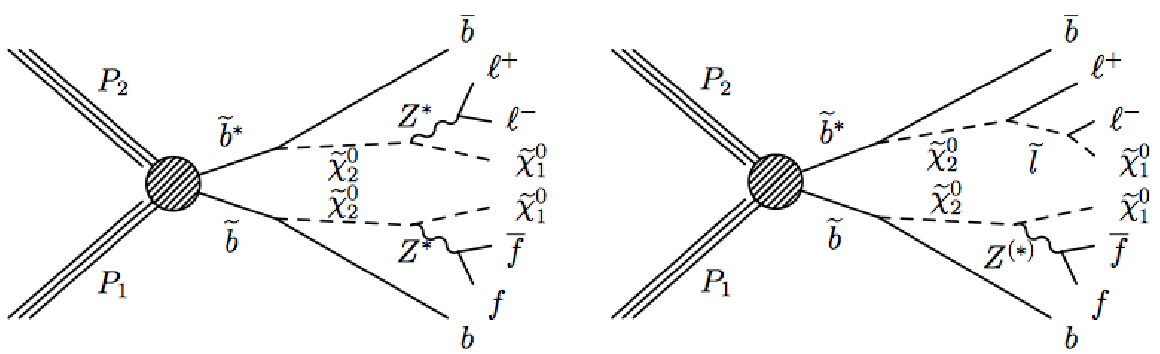
•$B \to K_* \mu^+\mu^-$ anomaly

LHCb, arXiv:1308.1707 and
3fb^{-1} update LHCb−CONF−2015−002

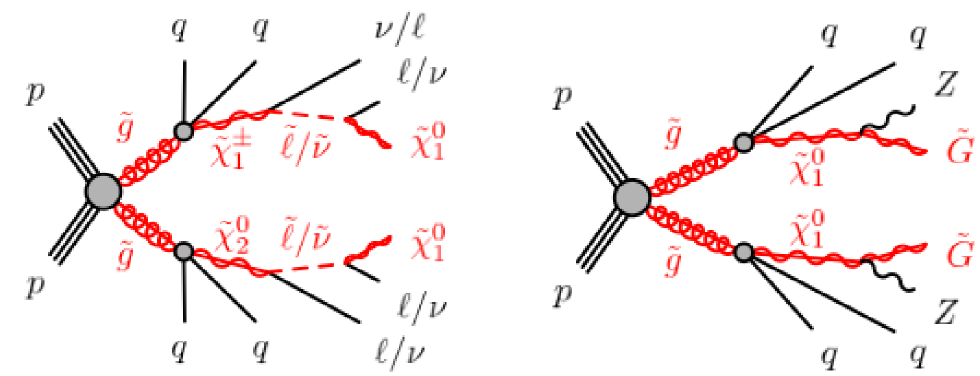
For possible interpretation within a single BSM model
see e.g. Crivellin, D'Ambrosio, Heeck, arXiv:1501.00993 (2HDM w. gauged L_μ–L_τ)

Anomalies left over from run 1, some examples

Dileptons + jets + MET (SUSY searches)



CMS, http://arxiv.org/abs/1502.06031



ATLAS, http://arxiv.org/abs/1503.03290

$N_{jets\ (p_T>40\ GeV)} \geq 2$, $E_T^{miss} > 150$ GeV
or
$N_{jets\ (p_T>40\ GeV)} \geq 3$, $E_T^{miss} > 100$ GeV

low mass: m_{ll} = (20–70) GeV
On-Z: m_{ll} = (81–101) GeV

$N_{jets\ (p_T>35\ GeV)} \geq 2$, $E_T^{miss} > 225$ GeV
$H_T > 600$ GeV

On-Z: m_{ll} = (81–101) GeV

Anomalies left over from run 1, some examples

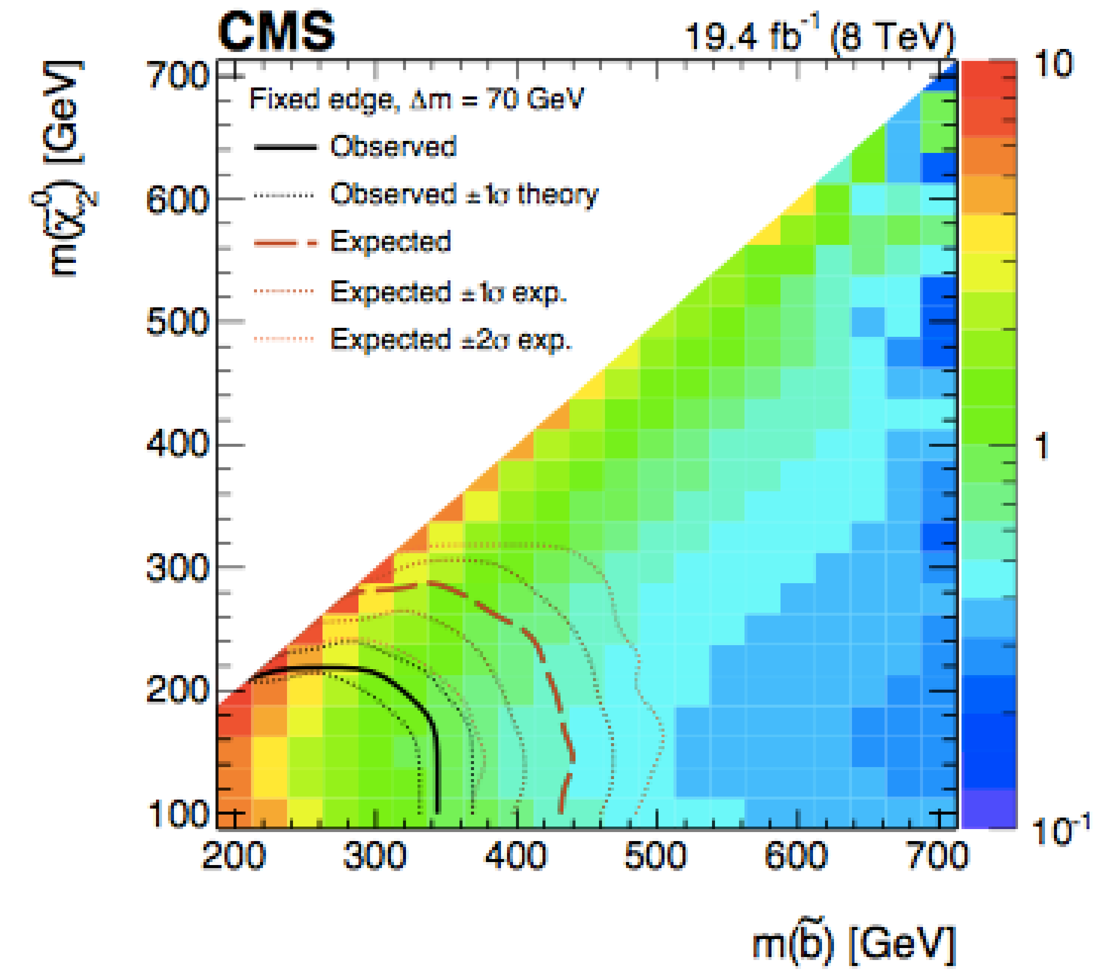
CMS, http://arxiv.org/abs/1502.06031

	Low-mass		On-Z	
	Central	Forward	Central	Forward
Observed	860	163	487	170
Flavor-symmetric	$722 \pm 27 \pm 29$	$155 \pm 13 \pm 10$	$355 \pm 19 \pm 14$	$131 \pm 12 \pm 8$
Drell–Yan	8.2 ± 2.6	2.5 ± 1.0	116 ± 21	42 ± 9
Total estimated	730 ± 40	158 ± 16	471 ± 32	173 ± 17
Observed−estimated	130^{+48}_{-49}	5^{+20}_{-20}	16^{+37}_{-38}	-3^{+20}_{-21}
Significance	$2.6\,\sigma$	$0.3\,\sigma$	$0.4\,\sigma$	$<0.1\,\sigma$

⇒2.6 σ

... no signal on-peak

σ(350 GeV) ratio 13TeV/8TeV ~ 4.5

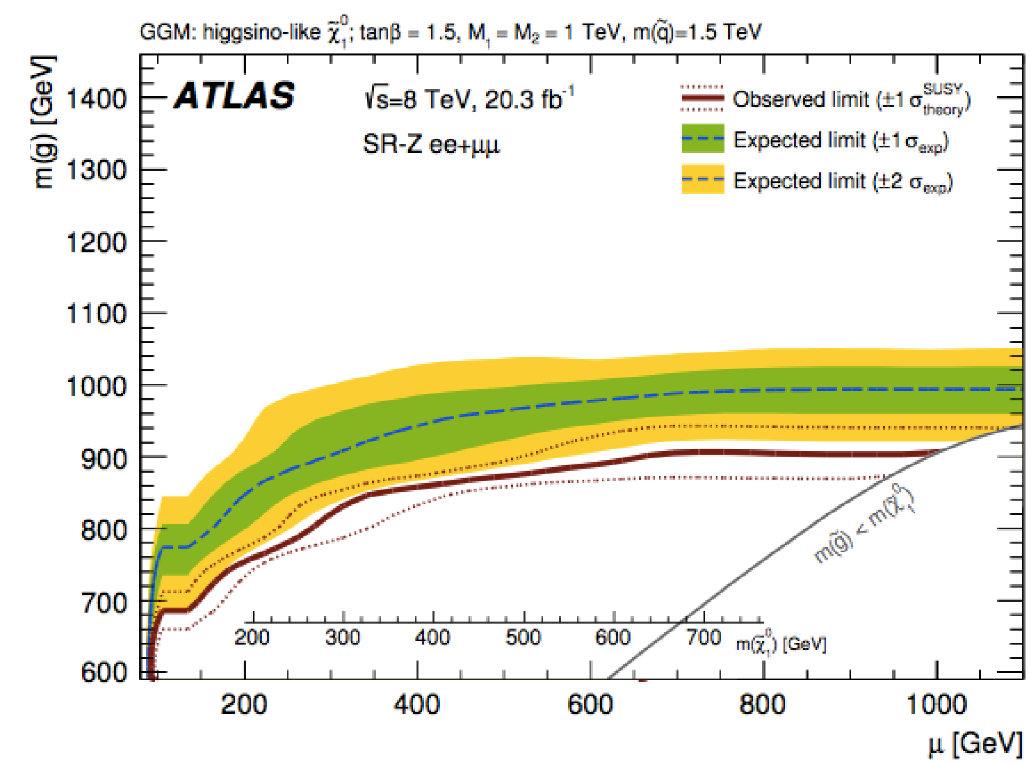


ATLAS, http://arxiv.org/abs/1503.03290

Channel	SR-Z *ee*		SR-Z *μμ*		SR-Z same-flavour combined
Observed events	16	**⇒3.0 σ**	13	**⇒1.6 σ**	29
Expected background events	4.2 ± 1.6		6.4 ± 2.2		10.6 ± 3.2
Flavour-symmetric backgrounds	2.8 ± 1.4		3.3 ± 1.6		6.0 ± 2.6
Z/γ^* + jets (jet-smearing)	0.05 ± 0.04		$0.02^{+0.03}_{-0.02}$		0.07 ± 0.05
Rare top	0.18 ± 0.06		0.17 ± 0.06		0.35 ± 0.12
WZ/*ZZ* diboson	1.2 ± 0.5		1.7 ± 0.6		2.9 ± 1.0
Fake leptons	$0.1^{+0.7}_{-0.1}$		$1.2^{+1.3}_{-1.2}$		$1.3^{+1.7}_{-1.3}$

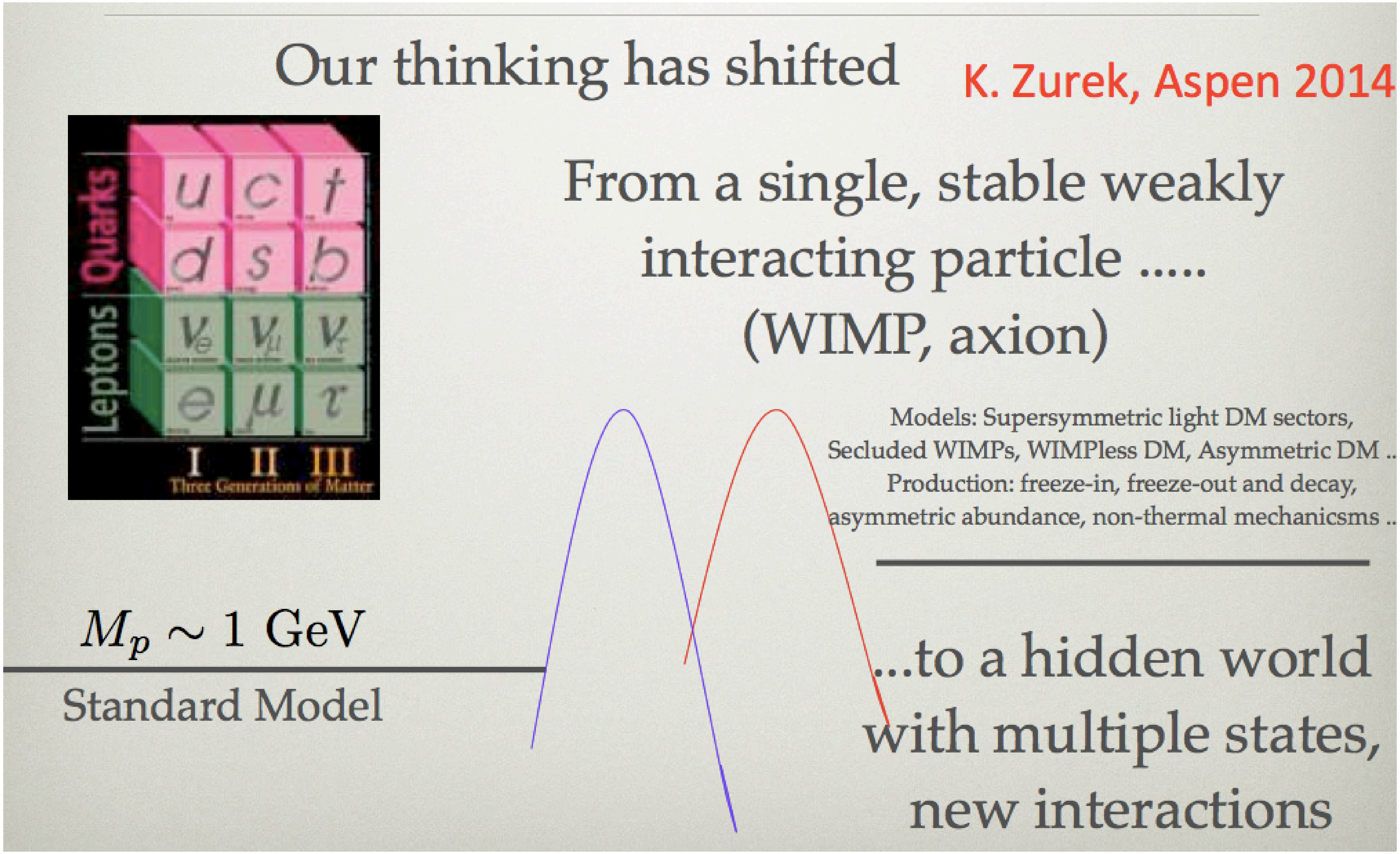
... but no signal off-peak

σ(800 GeV) ratio 13TeV/8TeV ~ 8.5



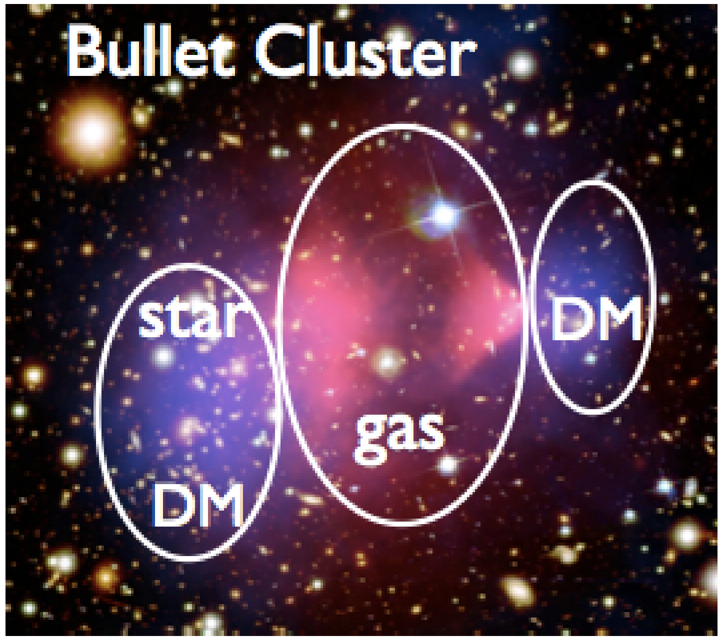
Already more than 10 TH interpretation papers on arXiv ....

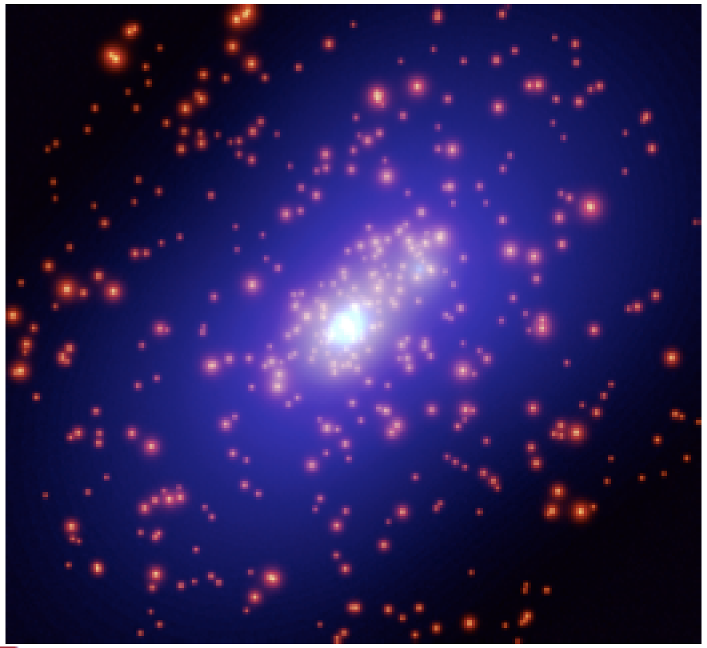
Dark Matter



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

Evidence building up for self-interacting DM





- A really large scattering cross section!

a nuclear-scale cross section

$\sigma \sim 1 cm^2 (m_\chi/g) \sim 2\times10^{-24} cm^2 (m_\chi/GeV)$

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

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"

How to move forward, towards finding the answer to key questions such as

- **What's the origin of Dark matter ?**
- **What's the origin of matter/antimatter asymmetry in the universe?**
- **What's the origin of neutrino masses?**
- **What determines the number and interactions of different families of quarks and leptons?**
- **...**

???

The “tools”

- Direct exploration of physics at the weak scale through high-energy colliders (linear/circular, ee/pp/ep/μμ)
- Quarks: flavour physics, EDM’s
- Neutrinos: CP violation, mass hierarchy and absolute scale, majorana nature
- Charged leptons: flavour violation, g–2, EDMs
- Axions, axion-like’s (ALPs), dark photons, ...

There is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can guarantee to find an answer to any of the questions above

$\Rightarrow$

- target broad and well justified scenarios
- consider the potential of given facilities to provide conclusive answers to relevant (*and answerable!*) questions
  - can we identify forms of *no-lose theorems ?*
- weigh the value of knowledge that will be acquired, no matter what, by a given facility (*the value of "measurements"*)

Most of the "big questions" touch directly on weak scale physics.

There are relevant, well defined questions, whose answer can be found exploring the TeV scale, and which can help guide the evaluation of the future exptl facilities. E.g.

- **Dark matter**
  - is TeV-scale dynamics (e.g. WIMPs) at the origin of Dark Matter ?
- **Baryogenesis**
  - did it arise at the cosmological EW phase transition ?
- **EW Symmetry Breaking**
  - what's the underlying dynamics? weakly interacting? strongly interacting ? other interactions, players at the weak scale besides the SM Higgs ?
- **Hierarchy problem**
  - "natural" solution, at the TeV scale?

The exploration of the high-energy frontier can provide conclusive answers to several of these questions

- **A complete study of the Higgs boson, of its interactions and of EWSB is a guaranteed deliverable of this programme ...**

- **... accompanied by an ambitious discovery potential, sensitive to possible manifestations of new physics at the TeV scale**

To address the scenarios raised by the question of "why don't we see new physics at the LHC" (i.e. (i) scale of new physics is too large, or (ii) signals are elusive), future facilities should guarantee

- *precision*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*

The known faces at the energy frontier are the linear e^+e^- colliders, namely ILC and CLIC

The new kids in town: **circular colliders**

Dec 2011 ***Latest LHC data corner the Higgs boson to within a small mass window in the 115-130 GeV range***

CERN-OPEN-2011-047
20 January 2012
Version 2.9
arXiv:1112.2518v1 [hep-ex]

A High Luminosity e^+e^- Collider in the LHC tunnel to study the Higgs Boson

Alain Blondel[1], Frank Zimmermann[2]
[1]DPNC, University of Geneva, Switzerland; [2]CERN, Geneva, Switzerland

Abstract: We consider the possibility of a 120x120 GeV e+e- ring collider in the LHC tunnel. A luminosity of $10^{34}/cm^2/s$ can be obtained with a luminosity life time of a few minutes. A high operation efficiency would require two machines: a low emittance collider storage ring and a separate accelerator injecting electrons and positrons into the storage ring to top up the beams every few minutes. A design inspired from the high luminosity b-factory design and from the LHeC design report is presented. Statistics of about $2x10^4$ HZ events per year per experiment can be collected for a Standard Higgs Boson mass of 115-130 GeV.

Summer 2012.

Higgs discovery => submissions to European Strategy Group Symposium

From the upgrade of the accelerator infrastructure in the LHC tunnel .....

LEP3 – Higgs factory in the LHC tunnel

Prepared by Frank Zimmermann, CERN, 9 April 2012; revised on 3 August 2012

CERN-ATS-2012-237

High Energy LHC
Document prepared for the European HEP strategy update

Oliver Brüning, Brennan Goddard, Michelangelo Mangano*, Steve Myers, Lucio Rossi, Ezio Todesco and Frank Zimmerman

CERN, Accelerator & Technology Sector
* CERN, Physics Department

..... to the development of more ambitious goals

EDMS Nr: 1233485
Group reference: CERN/GS-SE 27 July 2012

PRE-FEASIBILITY STUDY FOR AN 80KM TUNNEL PROJECT AT CERN

John Osborne (CERN), Caroline Waaijer (CERN), ARUP, GADZ

LEP3 and TLEP:

High luminosity e^+e^- circular colliders for precise Higgs and other measurements

Alain Blondel (University of Geneva), **John Ellis** (King's College London), **Patrick Janot** (CERN), **Mike Koratzinos** (University of Geneva), **Marco Zanetti** (MIT), **Frank Zimmermann** (CERN)

Fall 2012
The idea caught up …

Circular e+e- Higgs Factories

Convener: Dr. Daniel Schulte (CERN)

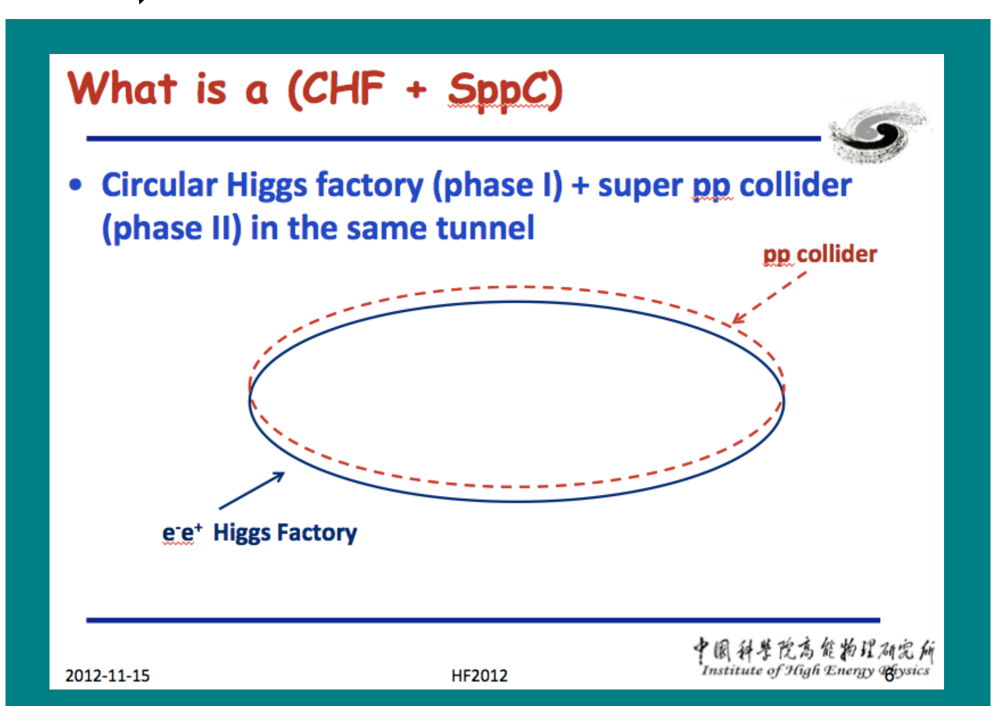
09:00 **LEP3 and TLEP** *25'*
Speaker: Dr. Frank Zimmermann (CERN)
Material: Slides

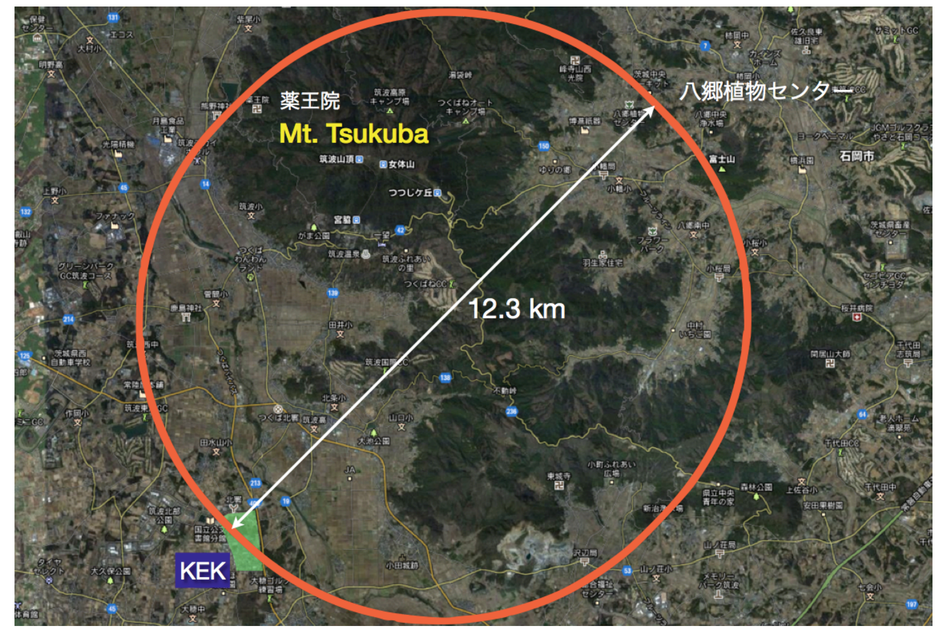
09:40 **SuperTristan** *15'*
Speaker: Dr. Katsunobu Oide (KEK)
Material: Slides

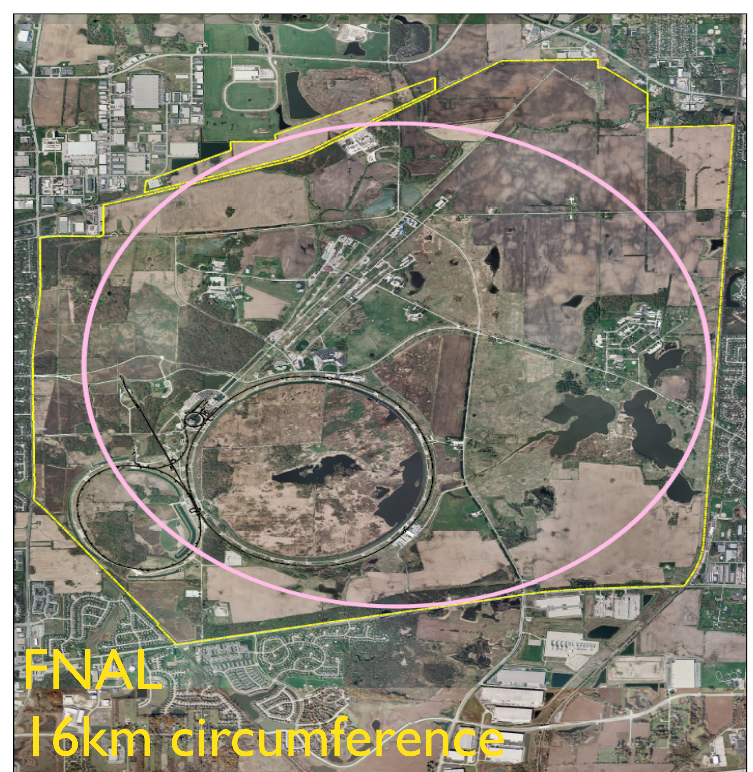
10:05 **Fermilab Site Filler** *15'*
Speaker: Dr. Tanaji Sen (Fermilab)
Material: Slides

10:30 **Coffee Break** *30'*

11:00 **IHEP Higgs Factory** *15'*
Speaker: Dr. Qing QIN (IHEP)
Material: Slides



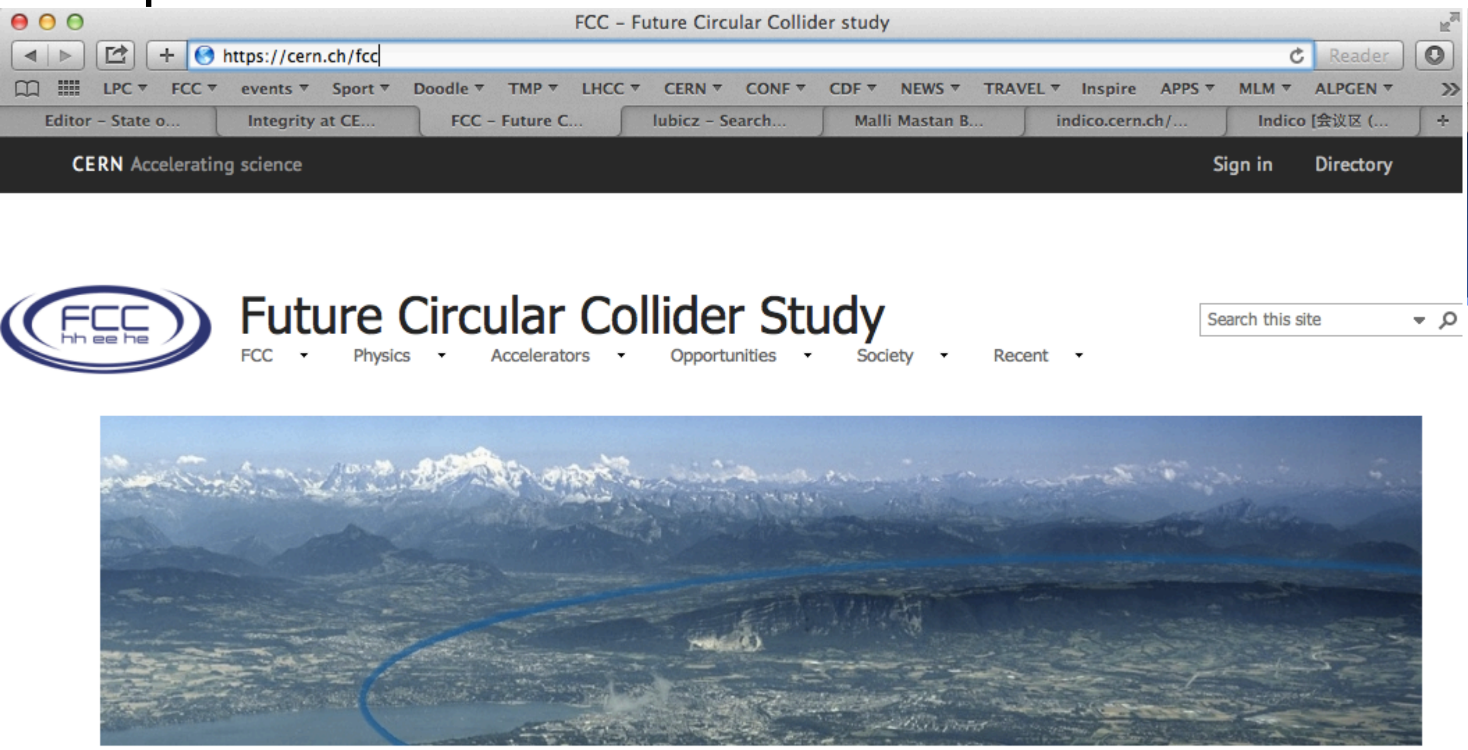




Final report:
http://www-bd.fnal.gov/icfabd/HF2012.pdf

… *and two efforts are formalized and develop into studies towards Conceptual Design Reports*

http://cern.ch/fcc



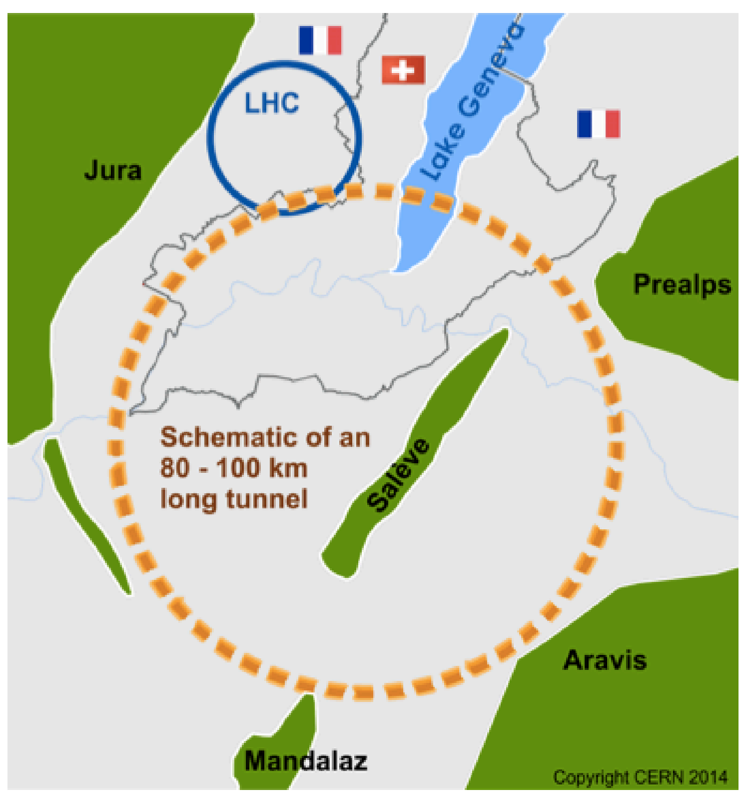
http://cepc.ihep.ac.cn

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)** → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km ~20 T ⇒ 100 TeV *pp* in 80 km

- ***e⁺e⁻* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area




Future Circular Collider Study Kickoff Meeting (12–15 February 2014)
indico.cern.ch/event/282344/
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12-15 February 2014
University of Geneva - UNI MAIL
Europe/Zurich timezone
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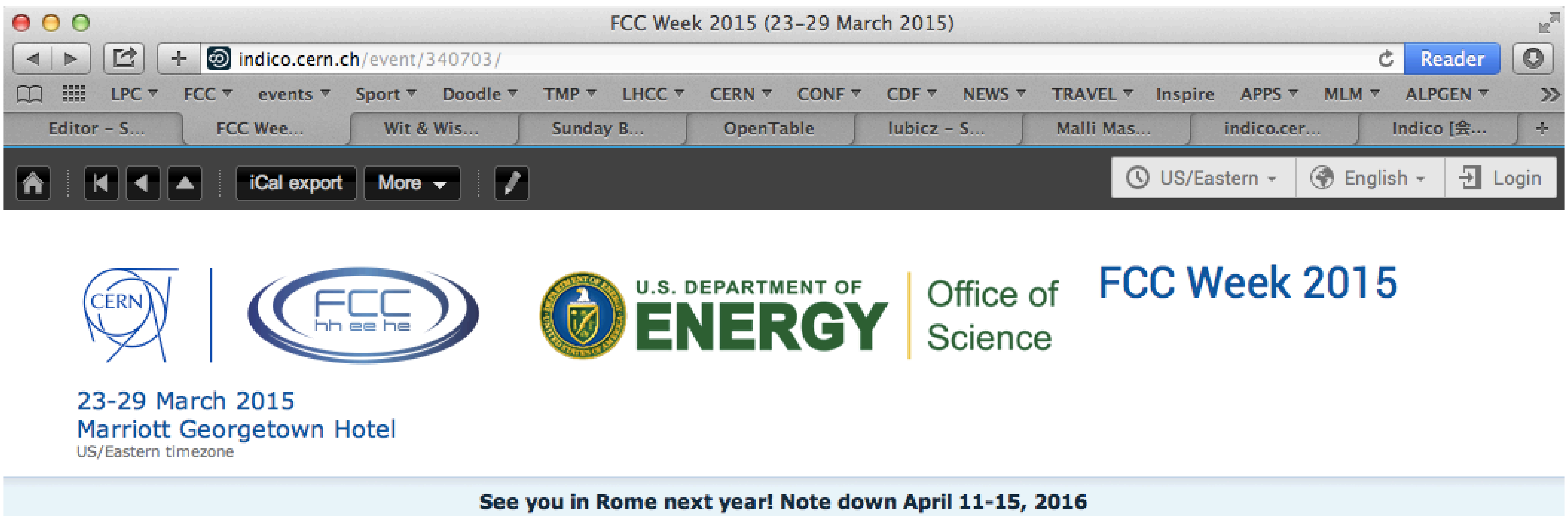
There is a live webcast for this event.
Future Circular Collider Study Kickoff Meeting


FCC Week 2015 (23–29 March 2015)
indico.cern.ch/event/340703/
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23-29 March 2015
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See you in Rome next year! Note down April 11-15, 2016


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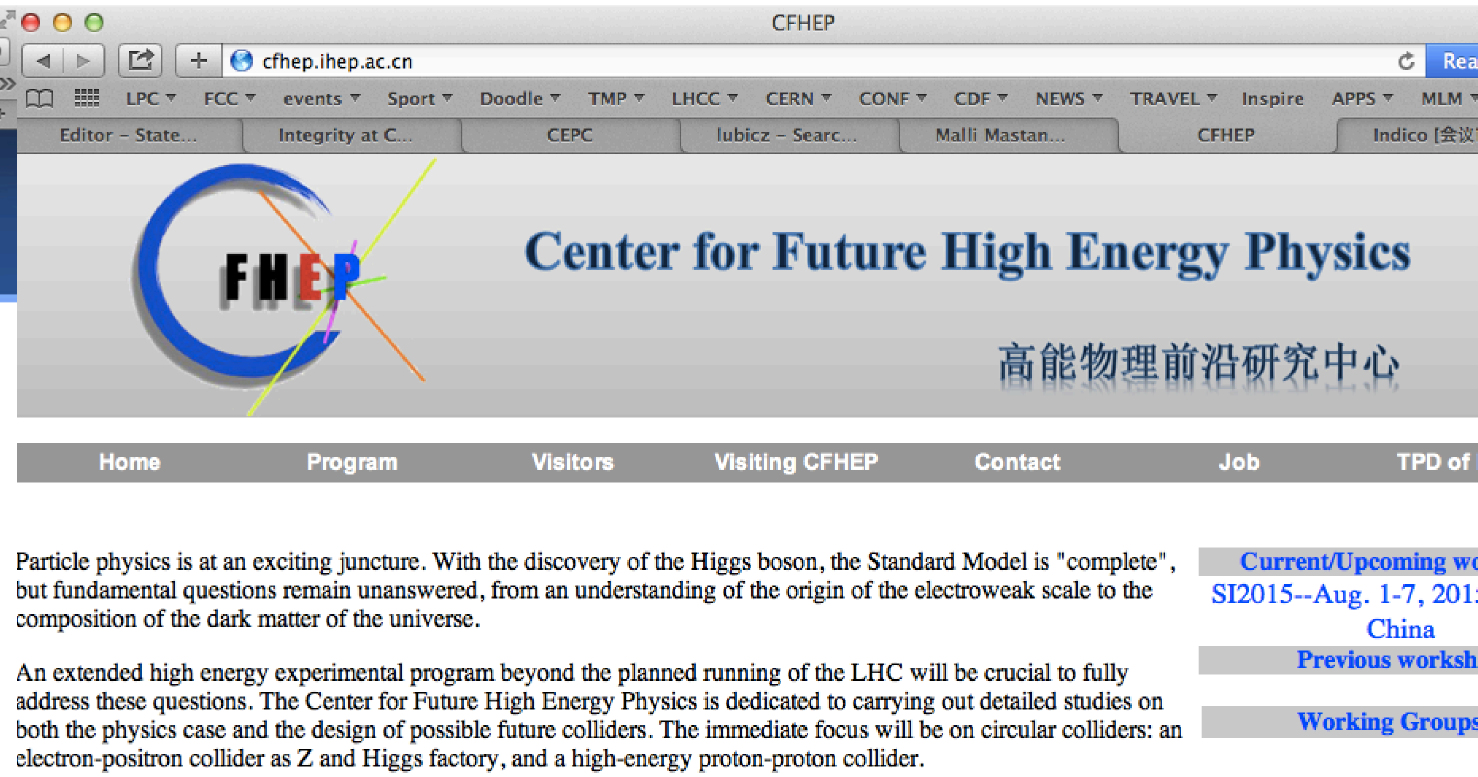
pre-CDR Author
Future High Energy Circular Colliders
The Standard Model (SM) of particle physics can describe the strong, weak and electromagnetic interactions under the framework of quantum gauge field theory. The theoretical predictions of SM are in excellent agreement with the past experimental measurements. Especially the 2013 Nobel Prize in physics was awarded to F. Englert and P. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".
CEPC preCDR volumes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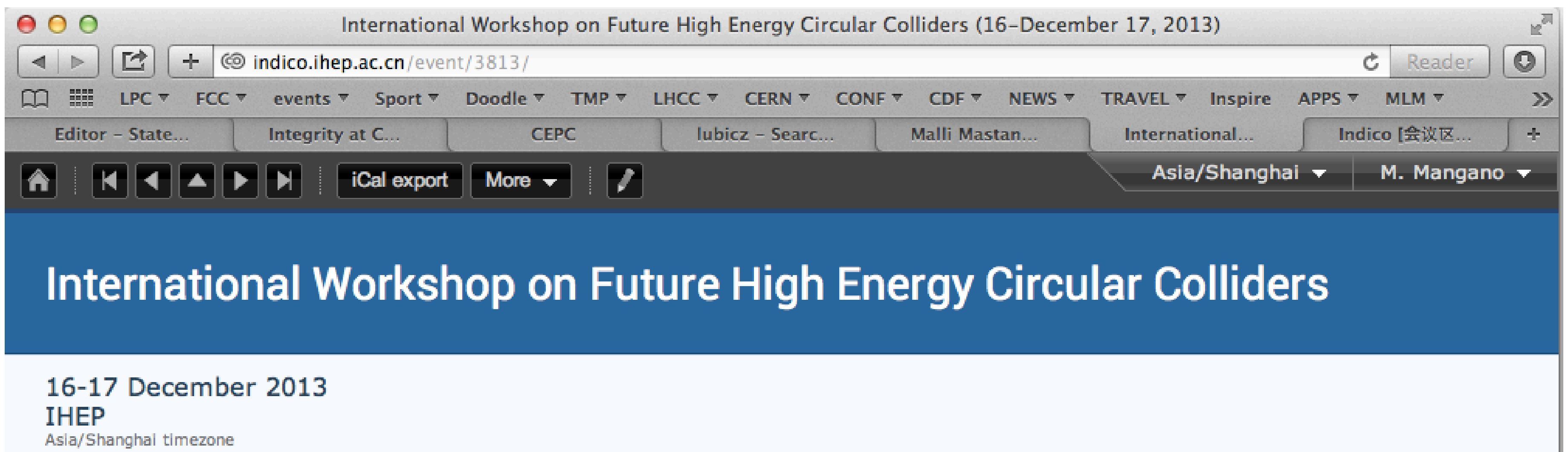
Particle physics is at an exciting juncture. With the discovery of the Higgs boson, the Standard Model is "complete", but fundamental questions remain unanswered, from an understanding of the origin of the electroweak scale to the composition of the dark matter of the universe.
An extended high energy experimental program beyond the planned running of the LHC will be crucial to fully address these questions. The Center for Future High Energy Physics is dedicated to carrying out detailed studies on both the physics case and the design of possible future colliders. The immediate focus will be on circular colliders: an electron-positron collider as Z and Higgs factory, and a high-energy proton-proton collider.
China


International Workshop on Future High Energy Circular Colliders (16–December 17, 2013)
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Asia/Shanghai
M. Mangano
International Workshop on Future High Energy Circular Colliders
16-17 December 2013
IHEP
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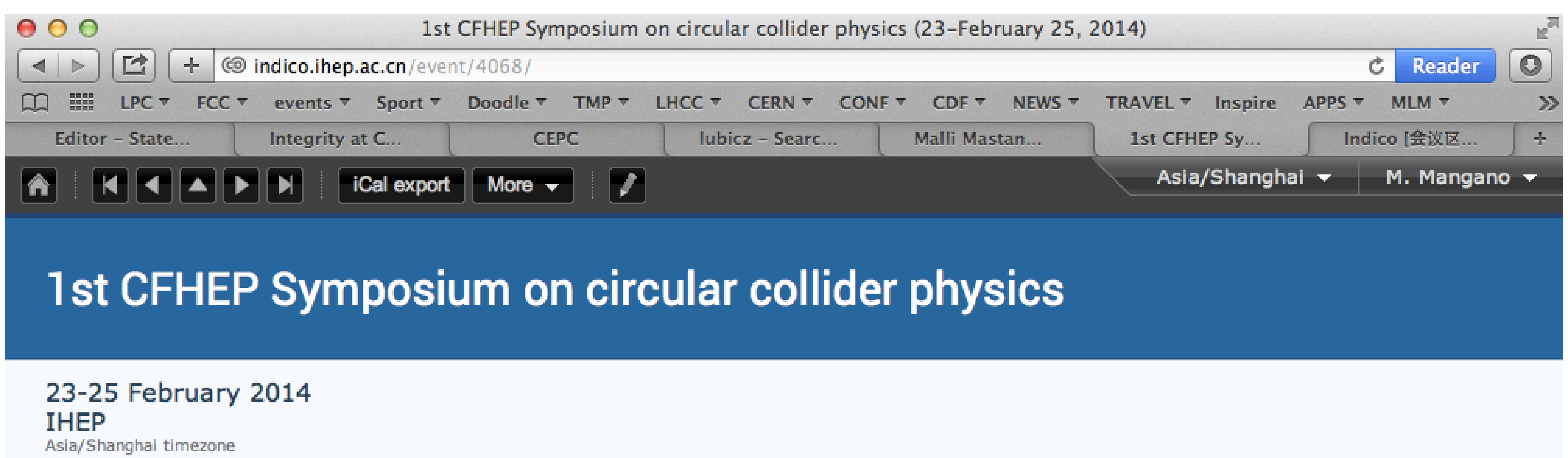
1st CFHEP Symposium on circular collider physics (23–February 25, 2014)
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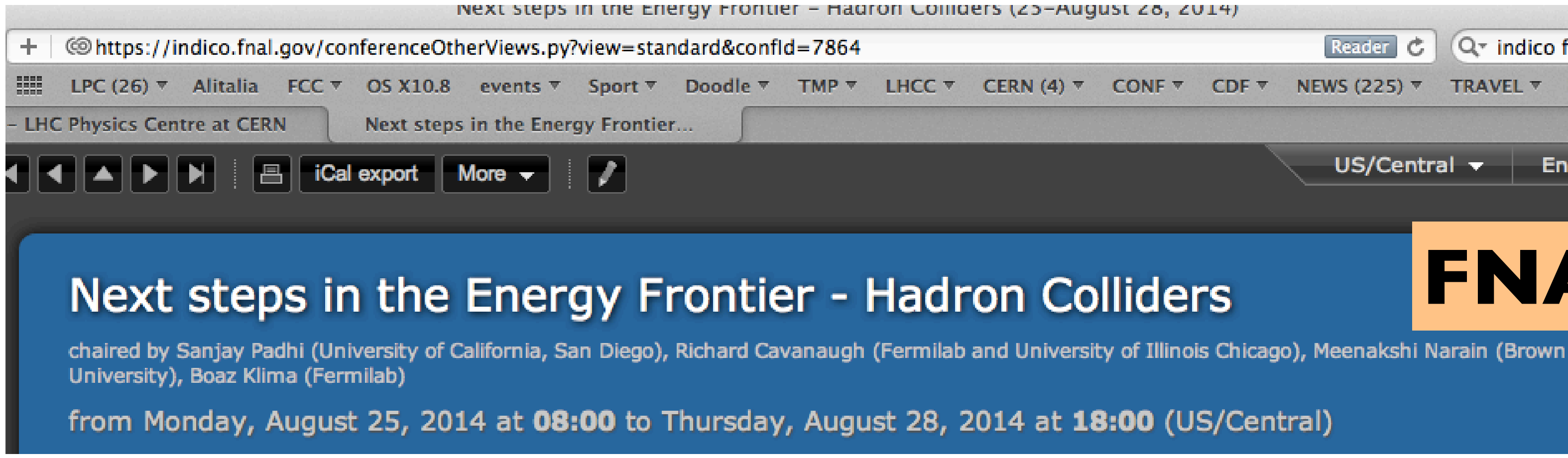
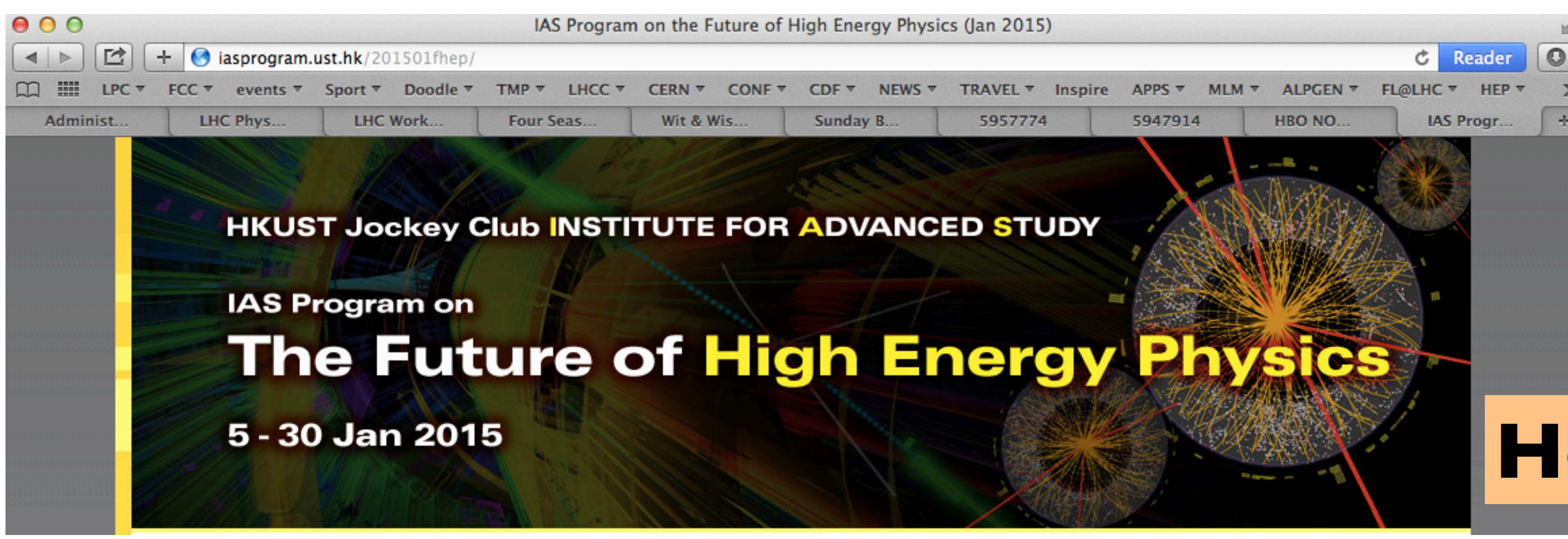
1st CFHEP Symposium on circular collider physics
23-25 February 2014
IHEP
Asia/Shanghai timezone

Physics workshops spontaneously organized all over the world document better than anything else the physics results, and the interest of the community ....

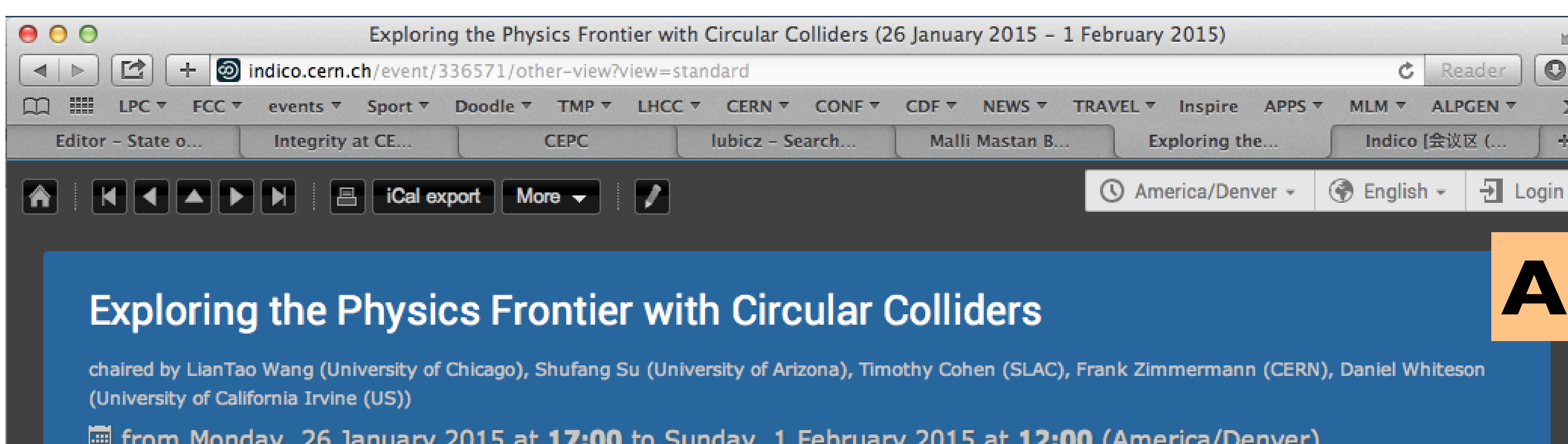
SLAC



FNAL



Hong Kong



Aspen

Key goals of a future circular collider complex

- Thorough **measurements** of the Higgs boson and its dynamics
- Significant extension, via direct and indirect probes, of the **search** for physics phenomena beyond the SM

Fulfilling these goals will also require dedicated attention to crucial ingredients, such as

- *the progress of theoretical calculations for precision physics*
- *the experimental data needed to improve the knowledge of fundamental inputs such as SM parameters, PDFs and to assess/reduce theoretical systematics*
  - *relevance of running e^+e^- at Z pole and tt threshold*
  - *relevance of ep programme*

- Maximal exploitation of the facility, e.g.
  - *physics with heavy ion collisions*
  - *physics with the injector complex*

Higgs couplings programme

- Precise measurement of main Higgs couplings:
  - W,Z bosons, 3rd generation fermions (⇒probe existence of BSM effective couplings, e.g. due to non-elementary nature of H, determine CP properties, etc.)
- Couplings to 2nd and 1st generation (⇒universality of Higgs mass-generation mechanism)
- Higgs selfcouplings (⇒probe Higgs potential, to test possible underlying structure of Higgs, deviations from "mexican hat", etc)
- Couplings to non-SM objects (e.g. invisible decays)
- non-SM couplings (e.g. forbidden decays)

Projections

g_{HXY}	FCC-ee
ZZ	0.16%
WW	0.85%
γ γ	1.7%
Zγ	
tt	
bb	0.88%
τ τ	0.94%
cc	1.0%
ss	
μμ	6.4%
uu,dd	
ee	
HH	
BR_{exo}	0.48%

model indep. fit of 240 GeV data

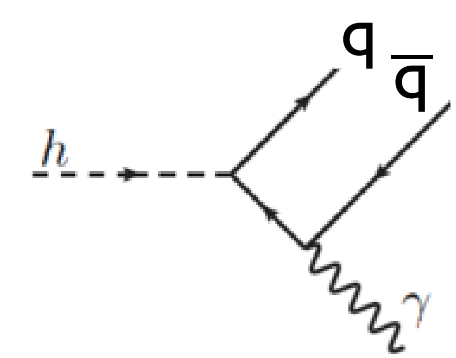
$H \to J/\Psi\,\gamma$ → y_c

$H \to \phi\,\gamma$ → y_s

50 evts

$H \to \rho\,\gamma$

$H \to \omega\,\gamma$ → y_u, y_d



$e^+e^- \to H$

L = 10 ab^{-1}

$\kappa_e < 2.2$ at 3σ

Projections

g_{HXY}	FCC-ee
ZZ	0.16%
WW	0.85%
γ γ	1.7%
Zγ	
tt	
bb	0.88%
τ τ	0.94%
cc	1.0%
ss	H→Vγ, in progr.
μμ	6.4%
uu,dd	H→Vγ, in progr.
ee	e^+e^-→H, in progr.
HH	
BR_{exo}	0.48%

model indep. fit of 240 GeV data

Projections

	σ	N / 10ab⁻¹
gg→H	740 pb	7.4 G
VBF	82 pb	0.8 G
WH	16 pb	160 M
ZH	11 pb	110 M
ttH	38 pb	380 M
gg→HH	1.4 pb	14 M

g_{HXY}	FCC-ee	FCC-hh	
ZZ	0.16%		
WW	0.85%		
γ γ	1.7%		
Zγ		1% ?	→ extrapolation from HL-LHC estimates
tt		1% ?	→ from ttH/ttZ
bb	0.88%		
τ τ	0.94%		
cc	1.0%		
ss	H→Vγ, in progr.		
μμ	6.4%	2% ?	→ extrapolation from HL-LHC estimates
uu,dd	H→Vγ, in progr.		
ee	e^+e^-→H, in progr.		
HH		5% ?	→ from HH → bb γγ
BR_{exo}	0.48%	$< 10^{-6}$?	→ for specific channels, like H→eμ, ...

FCC-hh ambitious but possible targets?

@FCC-hh:

- ttH coupling:
  - 1% theoretical precision on y_{top} , from measurement of σ(ttH)/σ(ttZ) and using BR info from FCC-ee

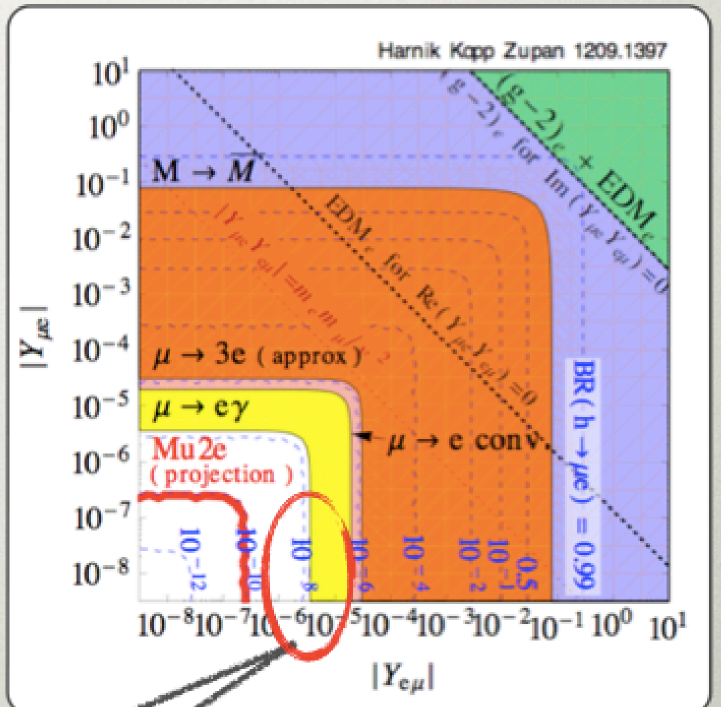
- H selfcoupling:

M.Son @ FCC week

$HH \rightarrow b\bar{b}\gamma\gamma$	Barr,Dolan,Englert,Lima, Spannowsky JHEP 1502 (2015) 016	Contino, Azatov, Panico, Son arXiv:1502.00539	He, Ren, Yao (follow-up of Snowmass study)
$FCC_{@100TeV}$ 3/ab	30~40%	30%	15%
$FCC_{@100TeV}$ 30/ab	10%	10%	5%
$S/\sqrt{B}$	8.4	15.2	16.5
Details	✓ λ_{HHH} modification only ✓ $c \rightarrow b$ & $j \rightarrow \gamma$ included ✓ Background systematics ○ $b\bar{b}\gamma\gamma$ not matched ✓ $m_{\gamma\gamma} = 125 \pm 1$ GeV	✓ Full EFT approach ○ No $c \rightarrow b$ & $j \rightarrow \gamma$ ✓ Marginalized ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 5$ GeV ✓ Jet $/W_{had}$ veto	✓ λ_{HHH} modification only ✓ $c \rightarrow b$ & $j \rightarrow \gamma$ included ○ No marginalization ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 3$ GeV

$h \to \mu e$

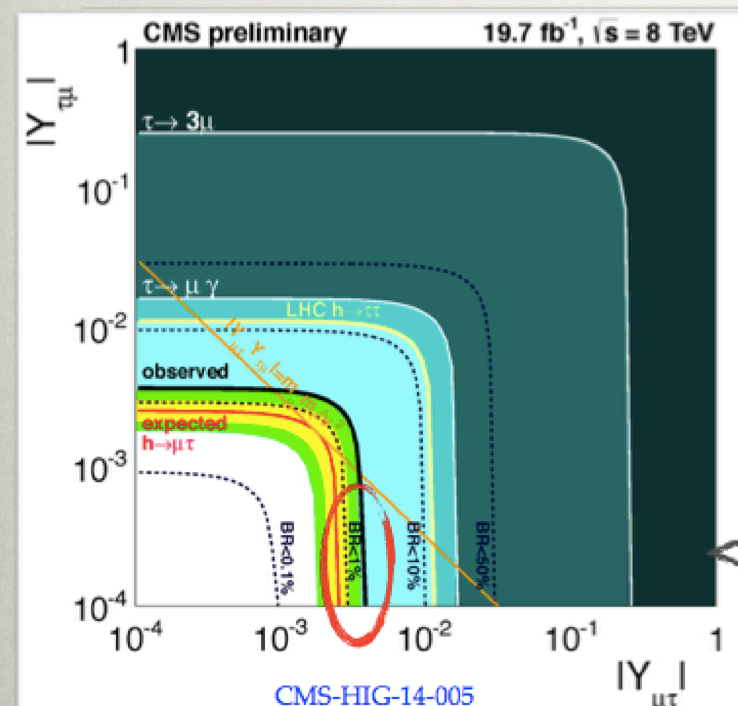
- indirect bounds better than LHC
- $h \to \mu e$ very clean channel



- what can one do with 10^9 Higgses @100TeV?

FCC week, Mar 26 2015, Washington DC

$h \to \tau\mu$



- right now: 2j channel statistics limited, 0j+1j not
- how about with $\sim 10^9$ *h?* ***LHC8*** $\Rightarrow$ ***100 TeV 3 ab^{-1}***
- assume same scaling for signal and bckg
  - *$Br \sim 10^{-2} \Rightarrow Br \sim 10^{-4}$*
  - *$\Lambda \sim 0.2$ TeV $\Rightarrow \Lambda \sim 2$TeV*
- if bckg free
  - *$Br \sim 10^{-2} \Rightarrow Br \sim 10^{-6}$*
  - *$\Lambda \sim 0.2$ TeV $\Rightarrow \Lambda \sim 20$TeV* ($Y_{\mu\tau} Y_{\tau\mu} = m_\mu m_\tau / \Lambda^2$)

BSM Higgs Sectors

D.Curtin @ FCC week

Big Picture Motivations

- Naturalness
  - SUSY
  - pGB
  - uncolored?
- Electroweak Phase Transition
  - Baryogenesis?
- Higgs Portal
  - Dark Matter?
  - *Generic BSM*

IR Models

- SM+S (mixed/unmixed)
- SM+fermions
- 2HDM
- 2HDM+S
- SILH
- ....

UV Completions & Rest of Theory

Observables at Current + Future Colliders

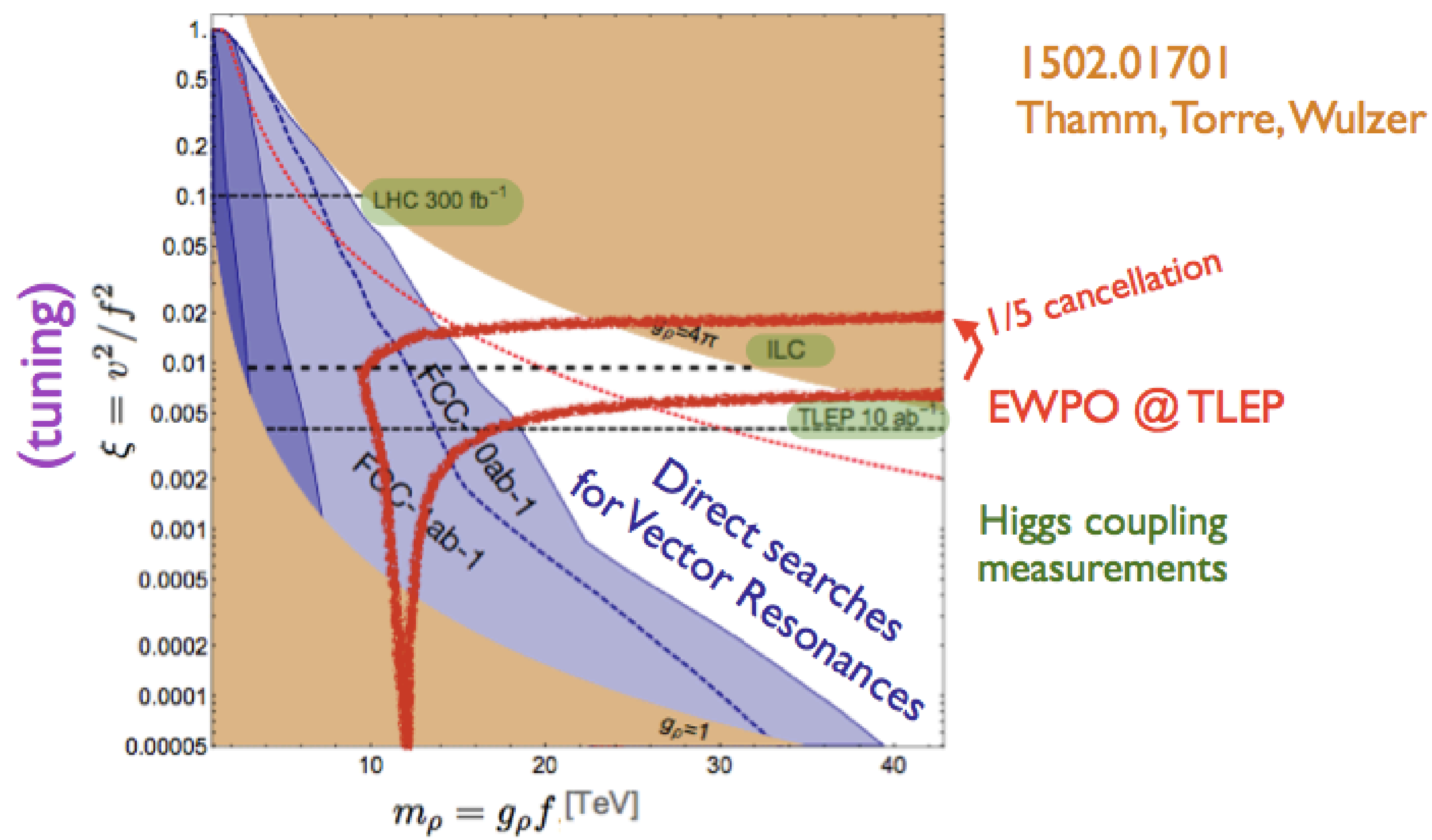
- producing extra higgs states (incl. superpartners)
- Exotic Higgs Decays
- Electroweak Precision Observables
- Higgs coupling measurements
- Higgs portal direct production of new states
- Higgs self coupling measurements
- Zh cross section measurements

Composite Higgs Models

D.Curtin @ FCC week

Want Lepton colliders to probe Higgs coupling deviations & EWPO

Want 100 TeV to produce vector resonances of strongly coupled sector (as well as top partners)



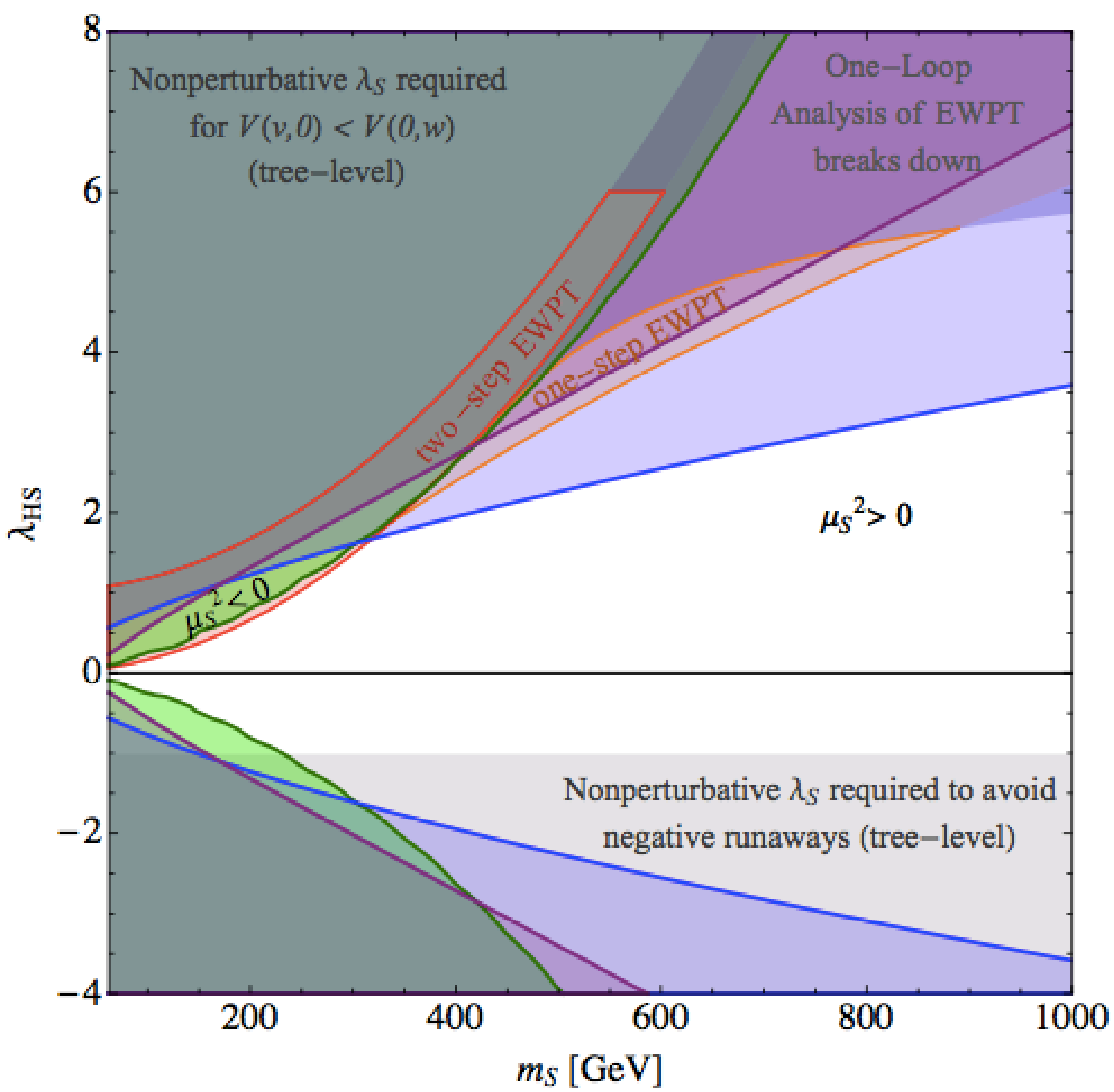
Interplay of EW precision tests (Tera-Z@FCC-ee), Higgs BR measurements (H@FCC-ee) and direct resonance searches (10-30 TeV, @ FCC-hh)

Minimal stealthy model for a strong EWPT

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4$$

D.Curtin @ FCC week

Unmixed SM+S. No exotic higgs decays, no higgs-singlet mixing, no EWPO, ...



Two regions with strong EWPT

Only Higgs Portal signatures:
- $h^* \to SS$ direct production
- Higgs cubic coupling
- σ(Zh) deviation (> 0.6% @ TLEP)

100 TeV collider could cover *entire* parameter space.

TLEP (super ILC) can cover *some* of parameter space.

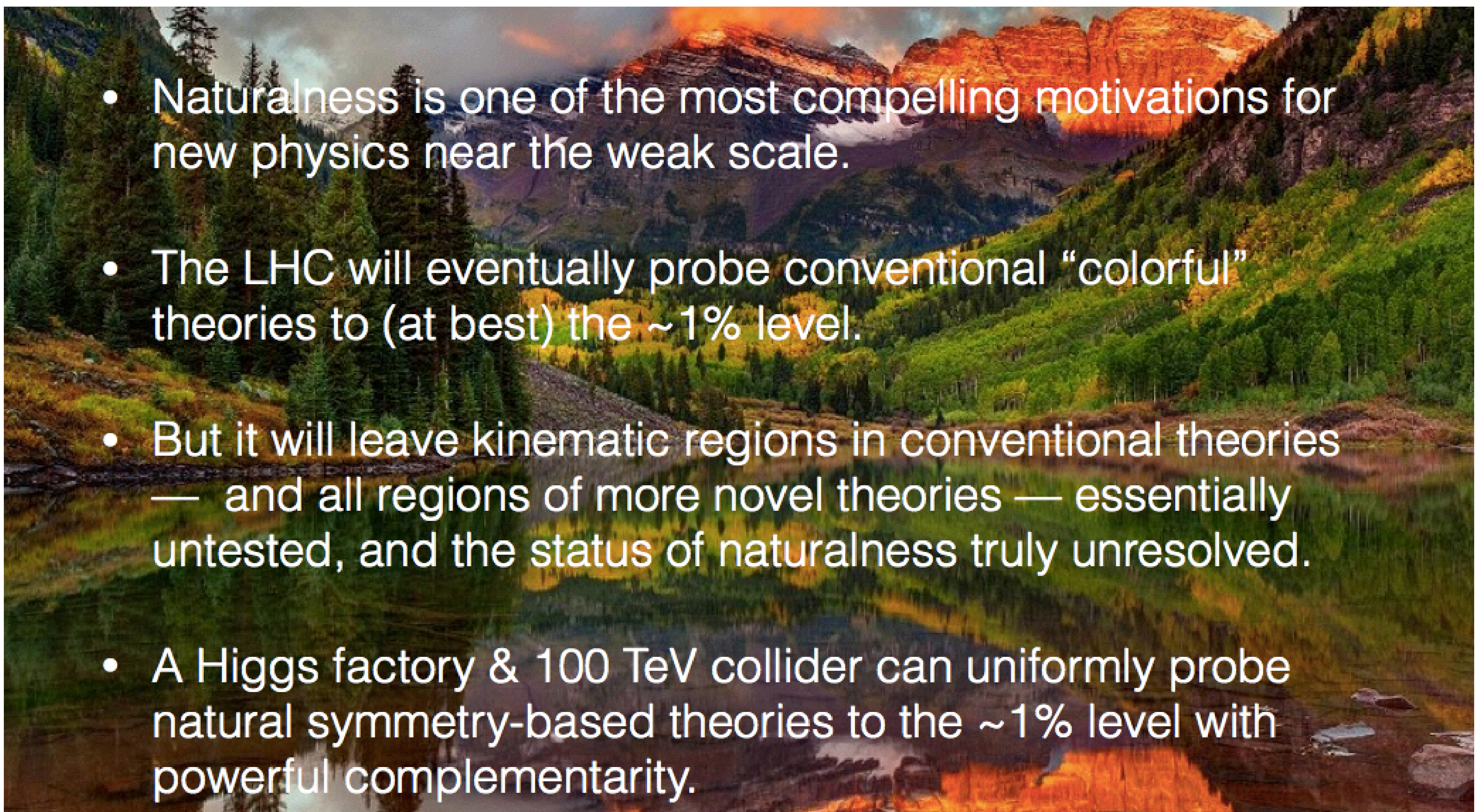
Potential complimentarily!

1409.0005 DC, Patrick Meade, Tien-Tien Yu

⇒ Appearance of first "**no-lose**" arguments for classes of compelling scenarios of new physics

Scenarios for new physics

- Guidelines for the future
  - Search for all that's searchable!
  - Don't necessarily try to tie together under a single interpretation all TH issues and exptl puzzles ....
  - .... but still make reference to established conceptual frameworks as guiding principles to steer the exploration!



N.Craig @ FCC week

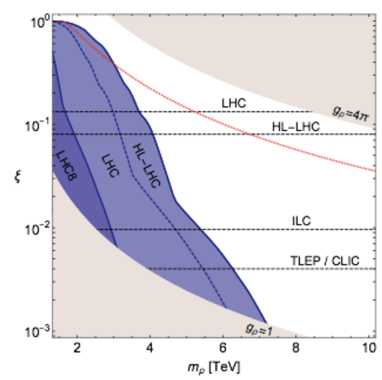
N.Craig

Colorful naturalness

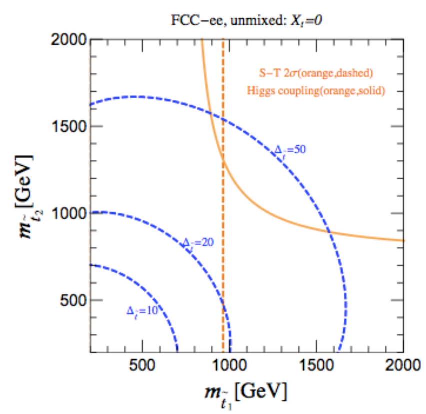
Probing at a Higgs factory:

Look for O(loop*v/m) [SUSY] or O(v/f) [global] Higgs coupling deviations; precision electroweak corrections.

[Thamm, Torre, Wulzer]



[Fan, Reece, Wang]



Where we'll be @ Higgs factory:
Sensitive to kinematic holes at LHC.

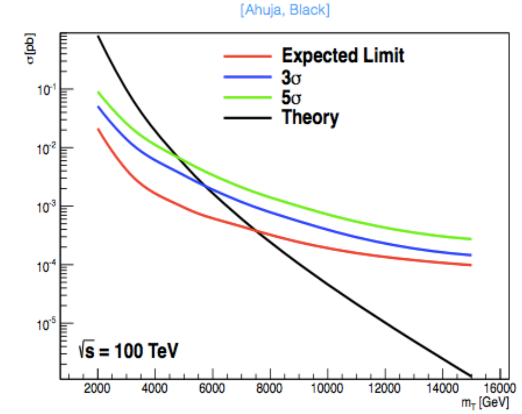
~1-2% level

Colorful naturalness

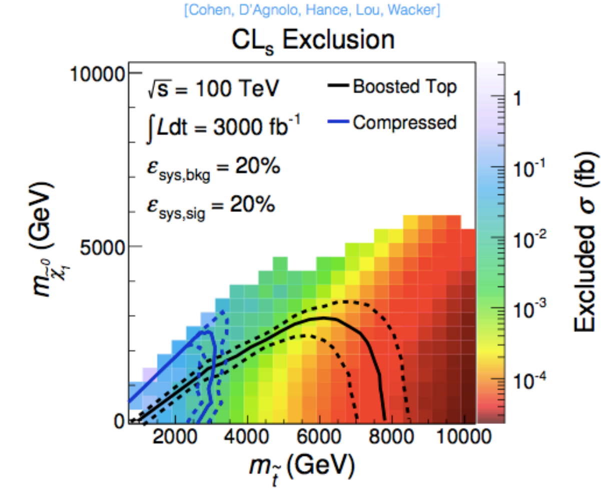
Probing at 100 TeV:

Look for the light partner states

[Ahuja, Black]



[Cohen, D'Agnolo, Hance, Lou, Wacker]



Where we'll be @ 100 TeV: "generically"

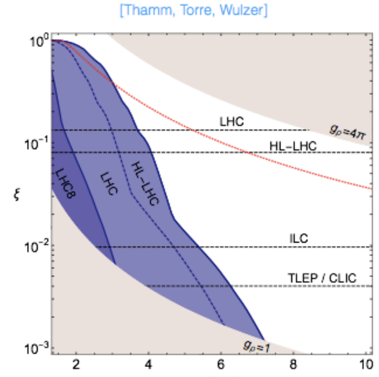
~.05% level

Neutral naturalness

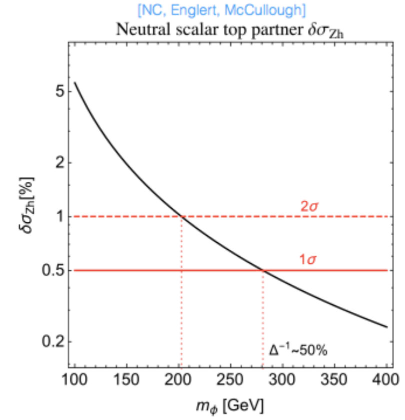
Probing at a Higgs factory:

Look for **O**(loop*v/m) oblique [SUSY] or **O**(v/f) [global] Higgs coupling deviations.

[Thamm, Torre, Wulzer]



[NC, Englert, McCullough]



Where we'll be @ Higgs factory:

~1% level (global)
~50% level (SUSY)

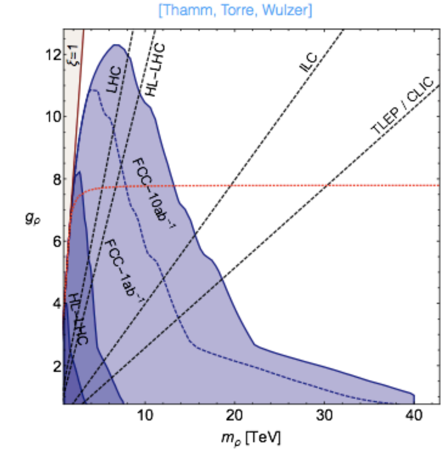
Even if the light natural states are neutral, there are heavier states with SM charges

Neutral naturalness

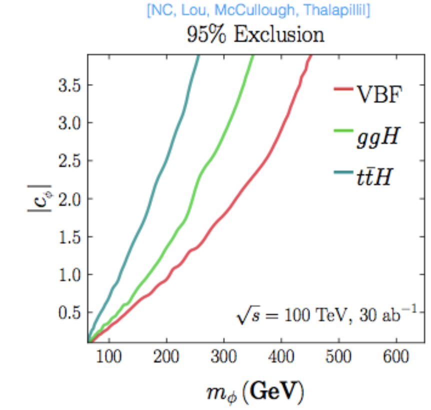
Probing at 100 TeV

Look for the UV completion, or probe light states via the Higgs portal.

[Thamm, Torre, Wulzer]



[NC, Lou, McCullough, Thalapillil]



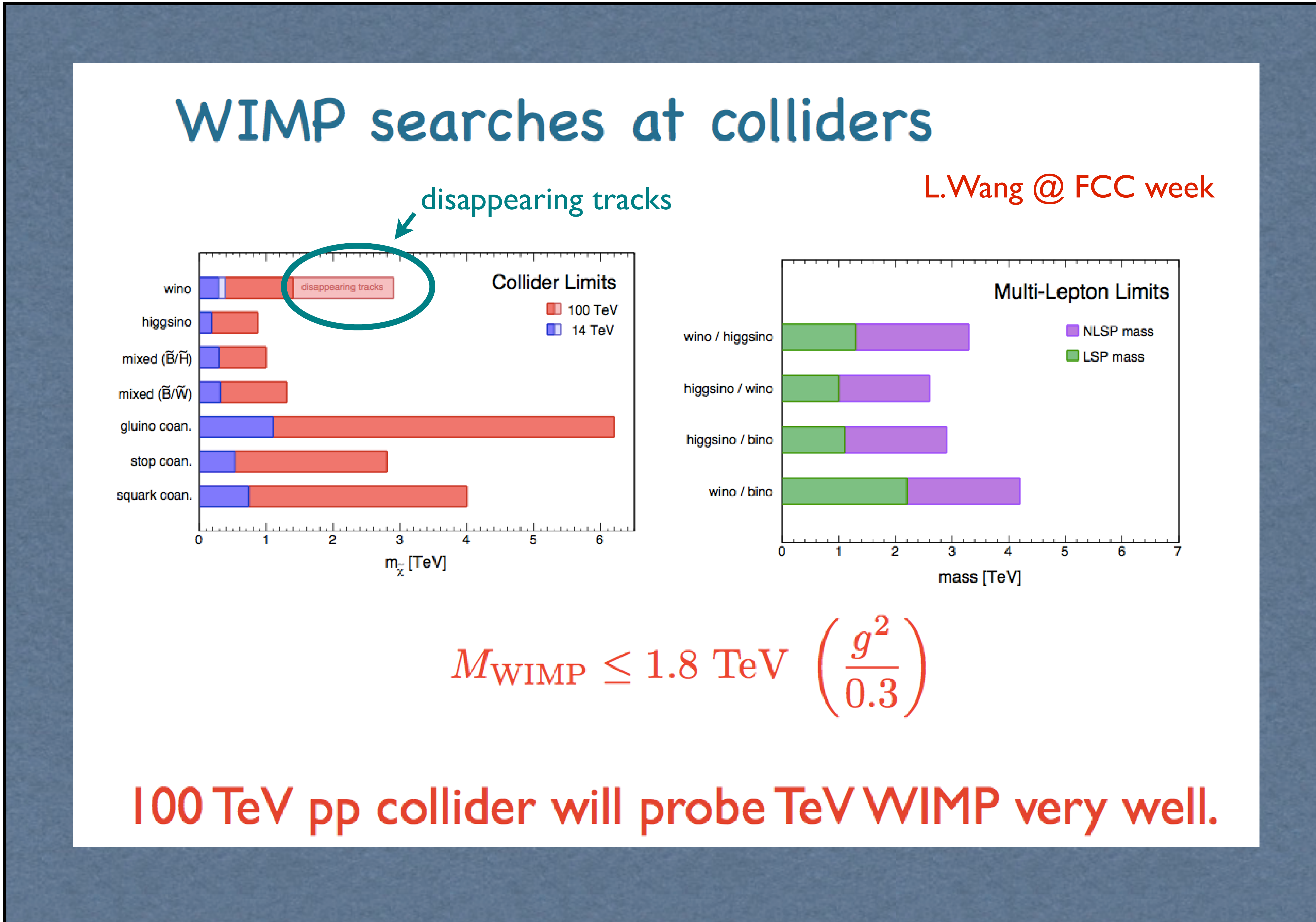
Where we'll be @ 100 TeV:

~1% level

Direct production of Dark Matter

- The search for WIMP dark matter is largely out of the reach for the LHC. L.Wang @ FCC week
  - LHC 14: reach to about a couple hundred GeV.
- 100 TeV pp Collider significantly enhance the reach, a fact of 5-7 enhancement.
- More detailed studies necessary. New ideas needed: more channels, detector design...
- At the same time, it is clear that this should be one of the main motivations for going to a 100 TeV pp collider.

Towards no-lose arguments for Dark Matter scenarios:



recall: A possible TLEP running programme

1. ZH threshold scan and 240 GeV running (200 GeV to 250 GeV)
   5+ years @2 10^35 /cm2/s => 210^6 ZH events
   ++ returns at Z peak with TLEP-H configuration
   for detector and beam energy calibration

   Higgs boson HZ studies
   + WW, ZZ etc..

2. Top threshold scan and (350) GeV running
   5+ years @5 10^34 /cm2/s ➔ 10^6 ttbar pairs ++Zpeak

   Top quark mass
   Hvv Higgs boson studies

3. Z peak scan and peak running , TLEP-Z configuration ➔ 10^12 Z decays
   → transverse polarization of 'single' bunches for precise E_beam calibration
   2 years

   Mz, Γ_Z R_b etc…
   Precision tests and
   rare decays

4. WW threshold scan for W mass measurement and W pair studies
   1-2 years ➔ 10^8 W pairs ++Zpeak

   M_W, and W properties
   etc…

5. Polarized beams (spin rotators) at Z peak 1 year at BBTS=0.01/IP => 10^{11} Z decays.

   A_{LR}, A_{FB}^{pol} etc

6. more and upgrades….

P.Janot

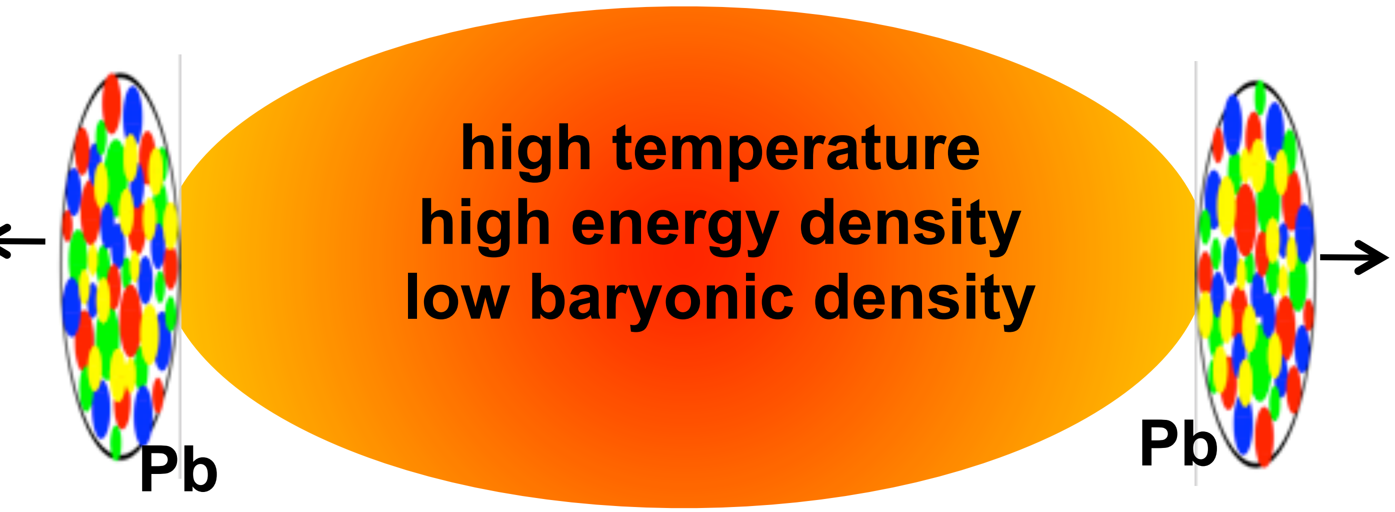
From the global programme, 1–2 orders of magnitude more precise measurements of EW parameters

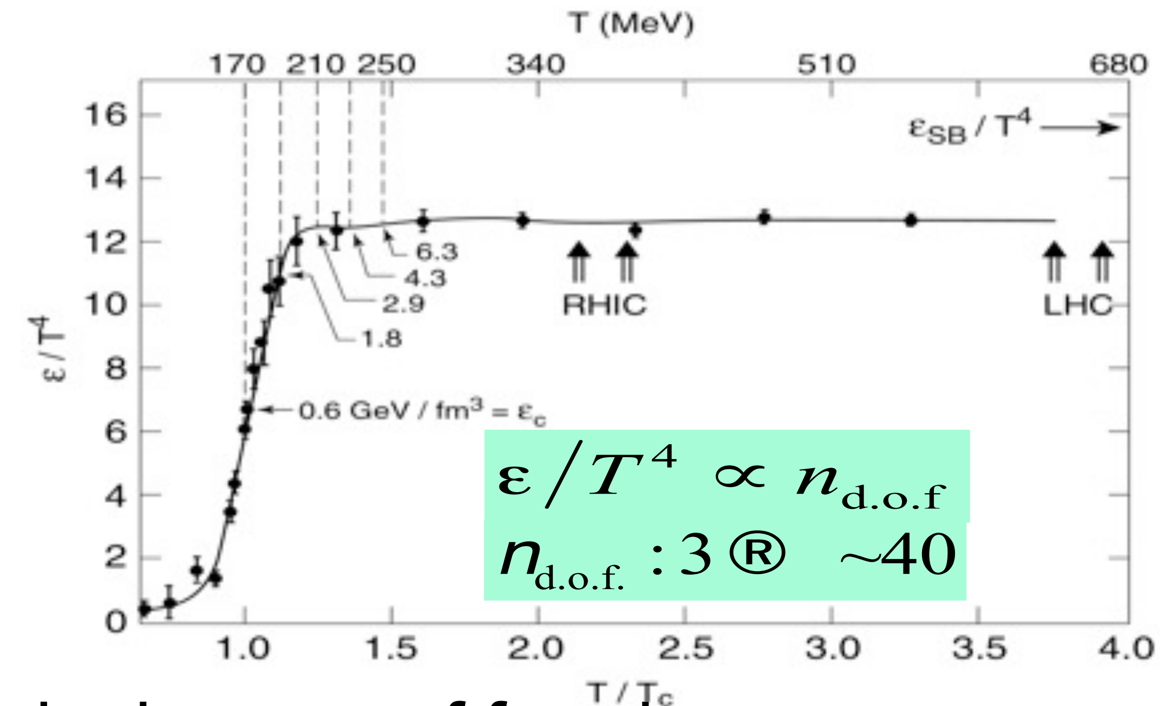
X	Physics	Present precision		TLEP stat Syst Precision	TLEP key	Challenge
M_Z MeV/c2	**Input**	91187.5 ±2.1	Z Line shape scan	**0.005 MeV** **<±0.1 MeV**	E_cal	QED corrections
Γ_Z MeV/c2	**$\Delta\rho$ (T)** **(no $\Delta\alpha$!)**	2495.2 ±2.3	Z Line shape scan	**0.008 MeV** **<±0.1 MeV**	E_cal	QED corrections
R_l	α_s , δ_b	20.767 ± 0.025	Z Peak	**0.0001** **± 0.002** **- 0.0002**	Statistics	QED corrections
N_ν	**Unitarity of PMNS, sterile ν's**	2.984 ±0.008	Z Peak Z+γ(105/161)	**0.00008** **±0.004** **0.0004-0.001**	->lumi meast Statistics	**QED corrections to Bhabha scat.**
R_b	δ_b	0.21629 ±0.00066	Z Peak	**0.000003** **±0.000020 - 60**	Statistics, small IP	Hemisphere correlations
A_{LR}	**$\Delta\rho$, ε_3 ,$\Delta\alpha$ (T, S)**	0.1514 ±0.0022	Z peak, polarized	**±0.000015**	4 bunch scheme	Design experiment
M_W MeV/c2	**$\Delta\rho$, ε_3 , ε_2, $\Delta\alpha$ (T, S, U)**	80385 ± 15	Threshold (161 GeV)	**0.3 MeV** **<1 MeV**	E_cal & Statistics	QED corections
m_{top} MeV/c2	**Input**	173200 ± 900	Threshold scan	**10 MeV**	E_cal & Statistics	Theory limit at 100 MeV?

Other aspects

- The FCC will redefine the scope and role of the HEP laboratory that will host it, w.r.t. scope and role of previous HEP labs.
- For CERN, the scale of the project may require not just international participation, beyond the CERN member states, but also engagement of other science communities (low-energy nuclear physics, light sources, medical sciences, applied accelerator physics, advanced technology, ...)
- While the above has not entered our radars as yet, the least we can envisage today is maintaining at the FCC a rich and diverse HEP programme, fully exploiting the injector chain (fixed target experiments) and the beam options (heavy ions). The FCC study is mandated to explore these opportunities as well, and assess their impact on the whole project.

High-density QCD in the final state: the Quark Gluon Plasma

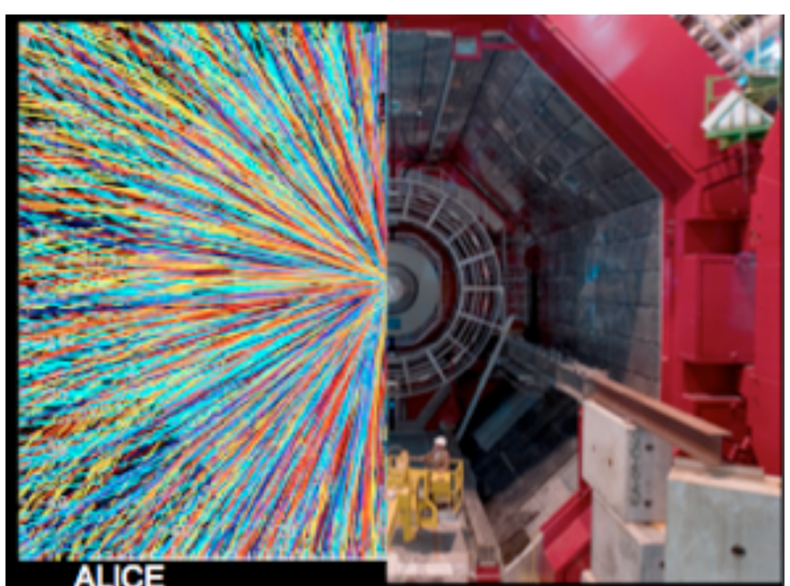


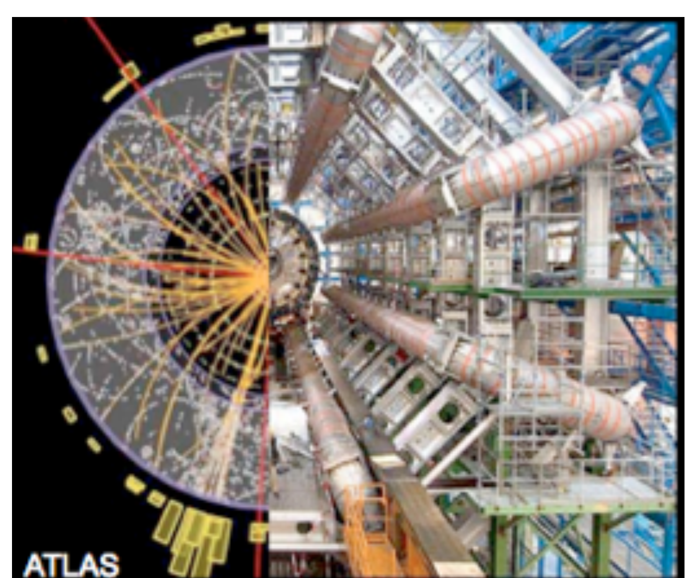


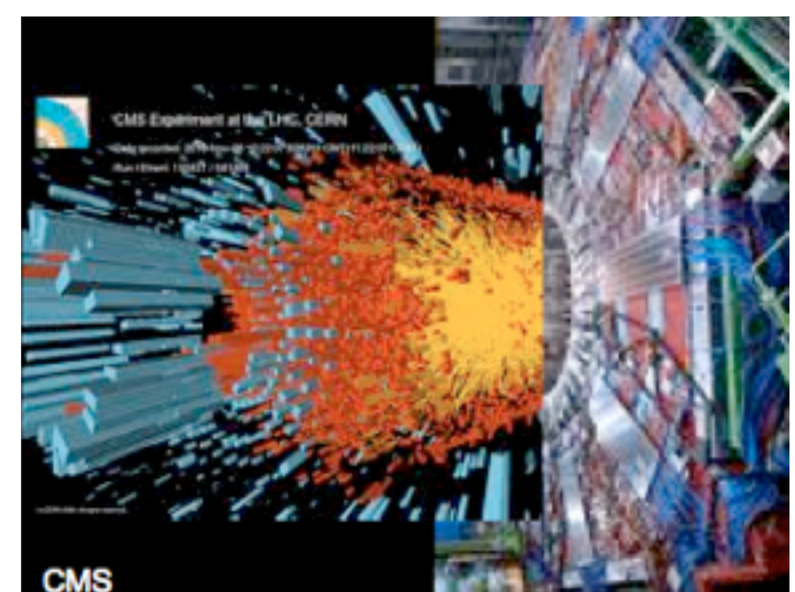
- Lattice QCD predicts phase transition at T_c~170 MeV

  → **Quark-Gluon Plasma**
- Confinement is removed

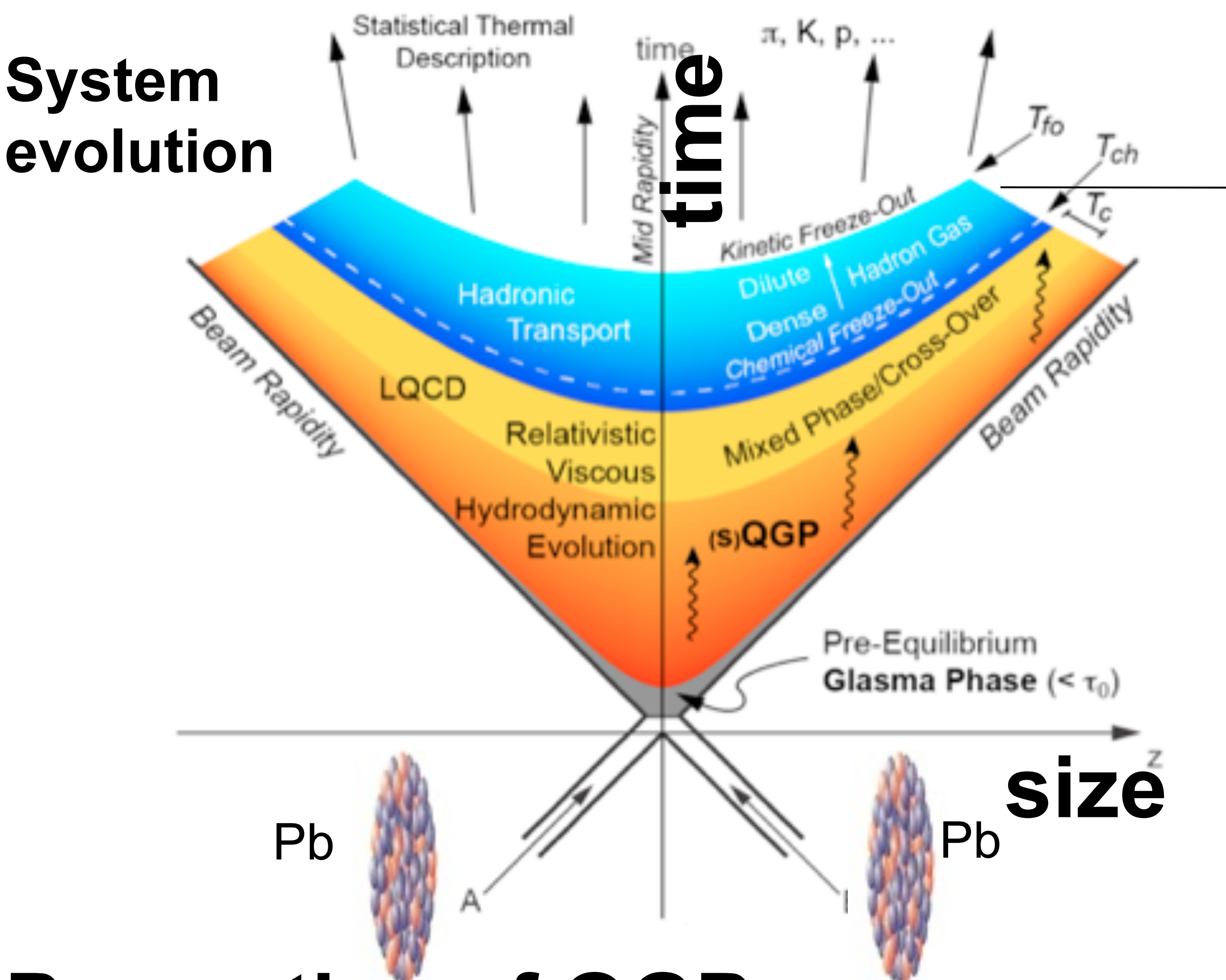
- Partonic degrees of freedom
- Unique opportunity to study in the laboratory spatially-extended multi-particle QCD system

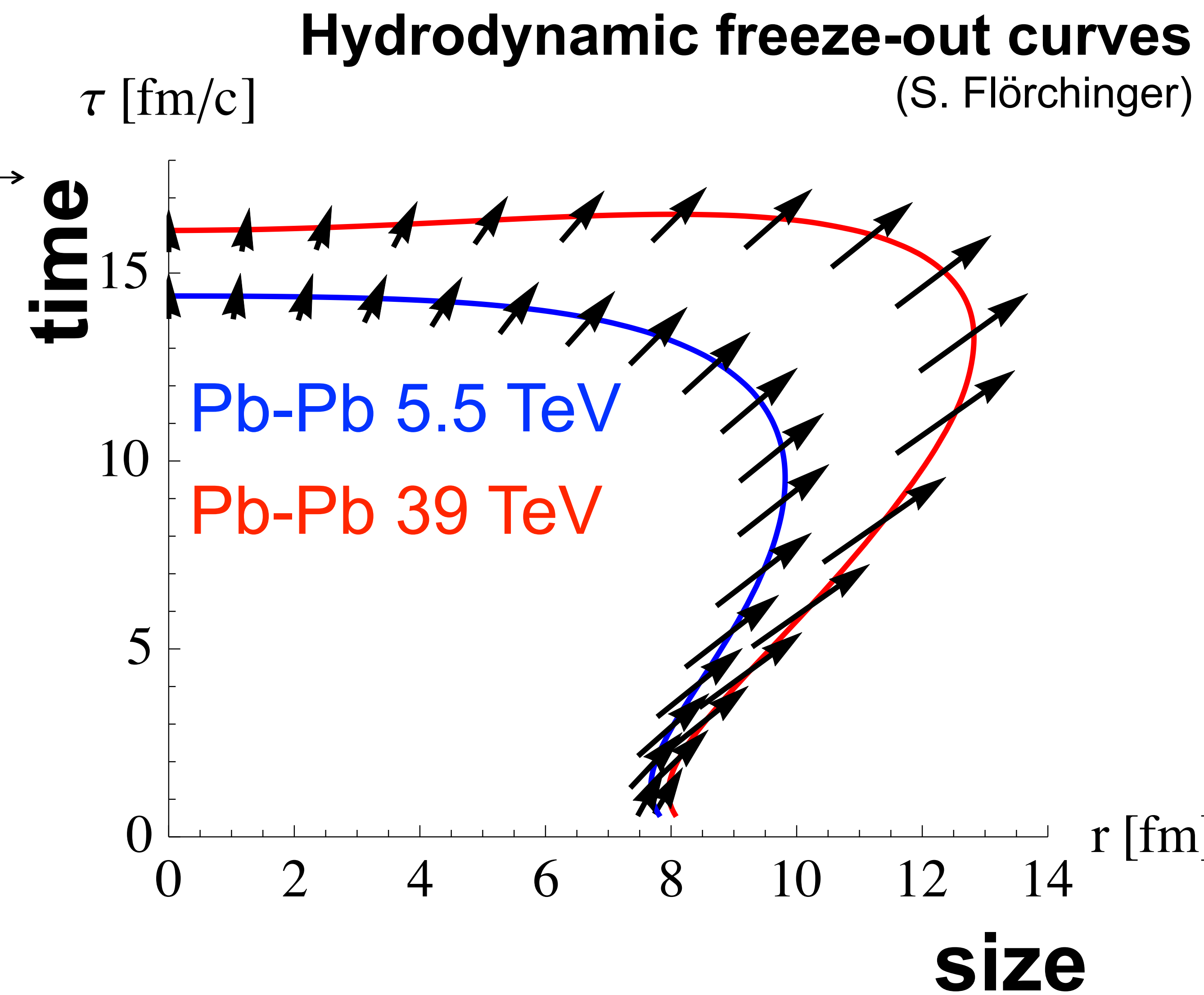






Quark-Gluon Plasma studies at FCC





Properties of QGP:

- QGP volume increases strongly
- QGP lifetime increases
- Collective phenomena enhanced (better tests of QGP transport)
- Initial temperature higher
- Equilibration times reduced

Quark-Gluon Plasma studies at FCC

Questions to be addressed in future studies include:

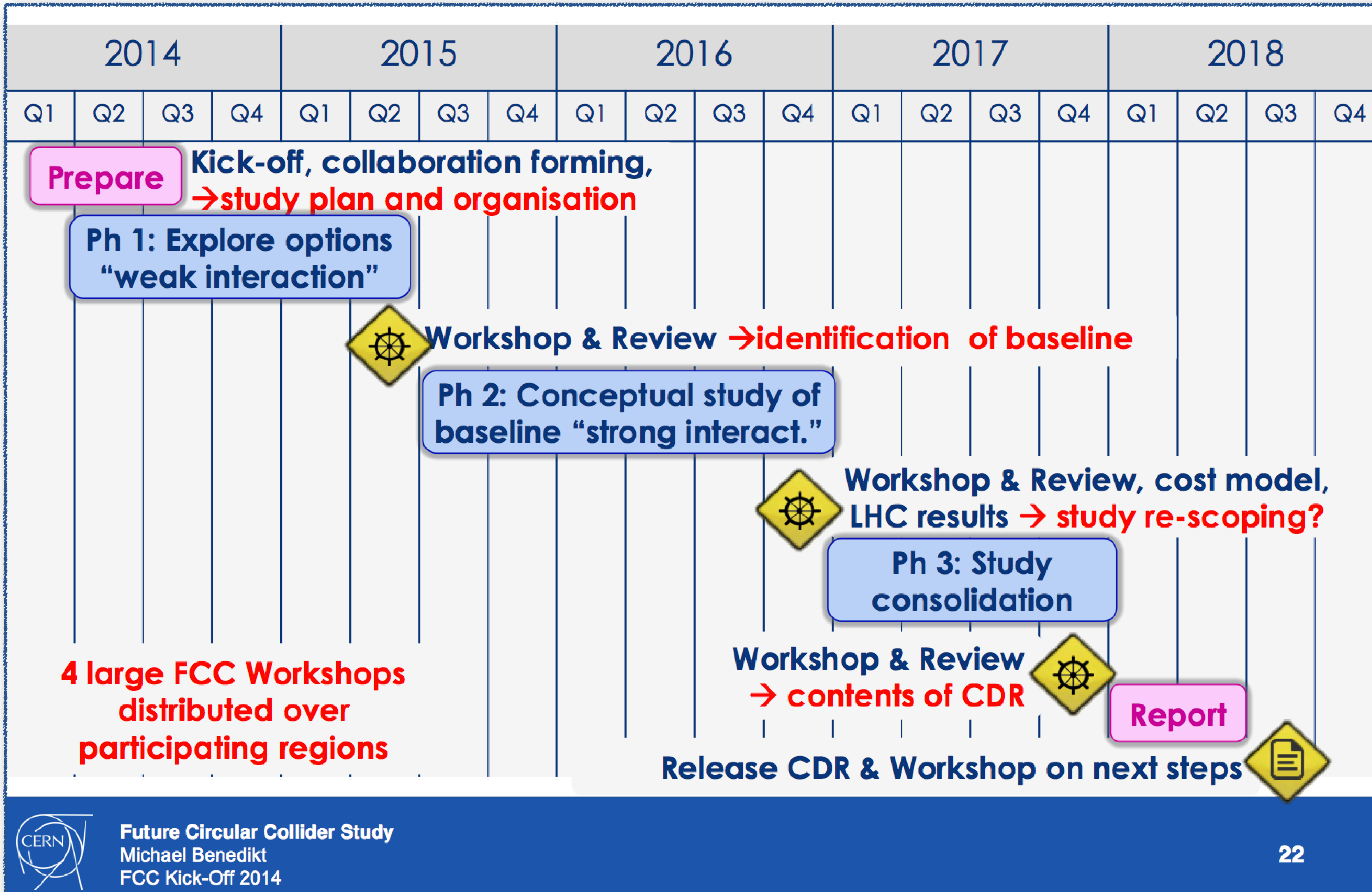
Higher Temp.

- Larger **number of degrees of freedom** in QGP at FCC energy? → g+u+d+s**+charm** ?
- Changes in the **quarkonium spectra**? does **Υ(1S) melt** at FCC?

Higher energy

- How do studies of **collective flow** profit from **higher multiplicity and stronger expansion**? More stringent **constraints on transport properties** such as shear viscosity or other properties not accessible at the LHC
- **Hard probes** are sensitive to medium properties. At FCC, **longer in-medium path length and new, rarer probes** become accessible. How can both features be exploited?

The 5-year international FCC design study



- **Goal of this effort:** Conceptual design report (CDR) and first cost estimate ready for the next Strategy Group assessment (~2018)
- **Likely next step:** Commission a full technical design report (TDR), ready for the following Strategy Group assessment (~2024)
- **Plausible next step at 2024 Strategy Review:** Review TDR and updated cost estimate, in view of LHC14@300fb^{-1} results and more. Recommend CERN Council to approve, abort, or postpone.

==> we have ~10 years to articulate the physics case, focusing on the physics discussion and on the study of LHC results

Conclusions and final remarks

- Major progress in the last year in the definition of the physics opportunities and challenges for future circular colliders
- ee and eh assessment of physics potential very mature, clear path outlined for the required theoretical efforts (precision!!) and well-defined detector requirements
- hh a bit behind, much work to be done, but concrete efforts to develop physics-driven performance benchmarks for detector design have started
- Rapidly increasing engagement of the theory community
- From the BSM perspective, the future circular collider facility is not just a quantitative upgrade of the LHC, but allows a deeper, and in some cases conclusive, exploration of fundamental theoretical issues
- For the Higgs, the future circular collider complex will be more than a *factory*. Rather a "Higgs valley*": multiple independent, synergetic and complementary approaches to achieve precision (couplings), sensitivity (rare and forbidden decays) and perspective (role of Higgs dynamics in broad issues like EWSB and vacuum stability, baryogenesis, naturalness, etc)

** in the sense of Silicon Valley ....*

The challenge: pulling (and holding) it together

- Civil engineering and technology:
  - caverns, magnets, cryogenics
- Costs: !!
- Sociology:
  - keep up the excitement and motivation over a 50 yr time window