Physics at future colliders

2015 CERN-Fermilab HCP Summer School

29 June 2015

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The challenge:
answering the *big* questions

- **What's the origin of Dark matter / energy ?**
- **What's the origin of matter/antimatter asymmetry in the universe?**
- **What's the origin of neutrino masses?**
- **What's the origin of EW symmetry breaking?**
- **What's the solution to the hierarchy problem?**
- **...**

The directions

- Direct exploration of physics at the weak scale
  - High-energy colliders (e^+e^-, *pp*, e*p*; linear/circular; muons?)
- 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, ...

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

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$\Rightarrow$

- target broad and well justified scenarios
- consider the potential of given facilities to provide conclusive answers to relevant (*and answerable!*) questions
- 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.

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- **Baryogenesis**
  - did it arise at the cosmological EW phase transition ?

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  - what's the underlying dynamics? weakly interacting? strongly interacting ? other interactions, players at the weak scale besides the SM Higgs ?

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- **Hierarchy problem**
  - "natural" solution, at the TeV scale?

I will therefore focus on the discussion of future facilities on the high-energy frontier ....

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

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 ... 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***

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- 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 and beyond

Key issue in addressing these questions, after LHC8
(and, hopefully not, but possibly after LHC14)

Why don't we see the new physics ?

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Readiness to address both scenarios is the best hedge for the field:

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

The known faces at the energy frontier, beyond HL-LHC, are CLIC, ILC

The new kids in town:
circular colliders

The context

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 2×10^4 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

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)

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

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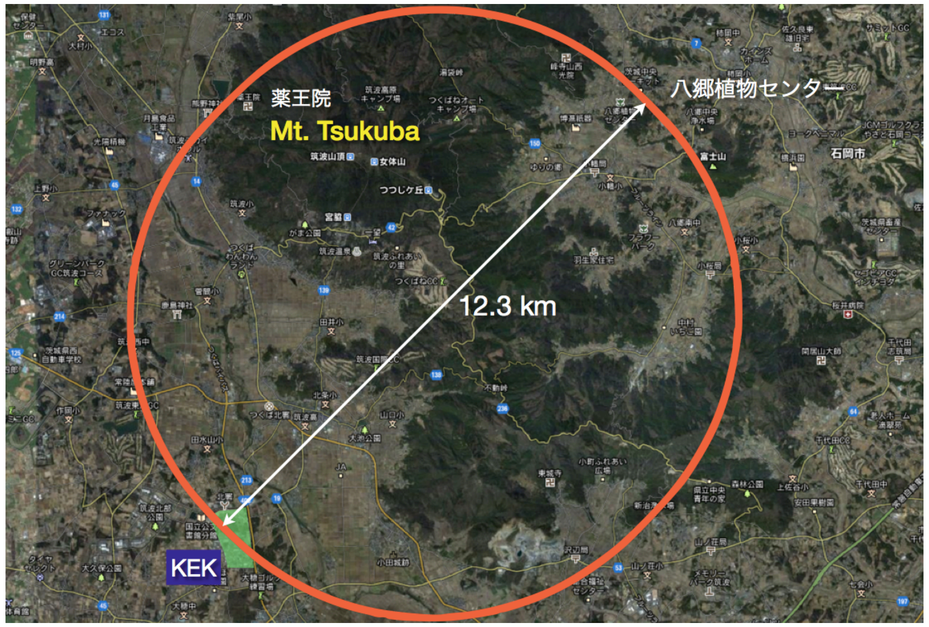

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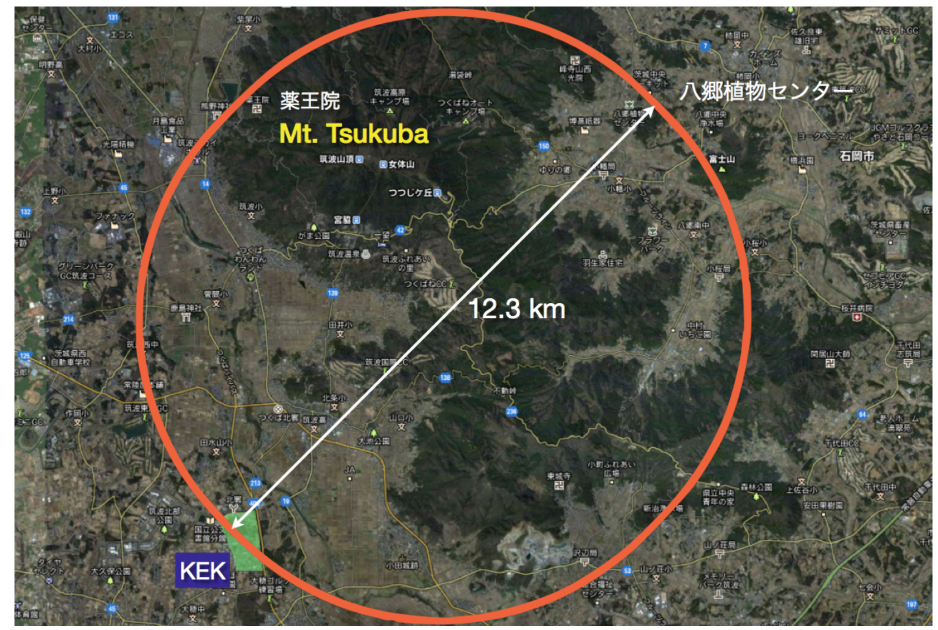

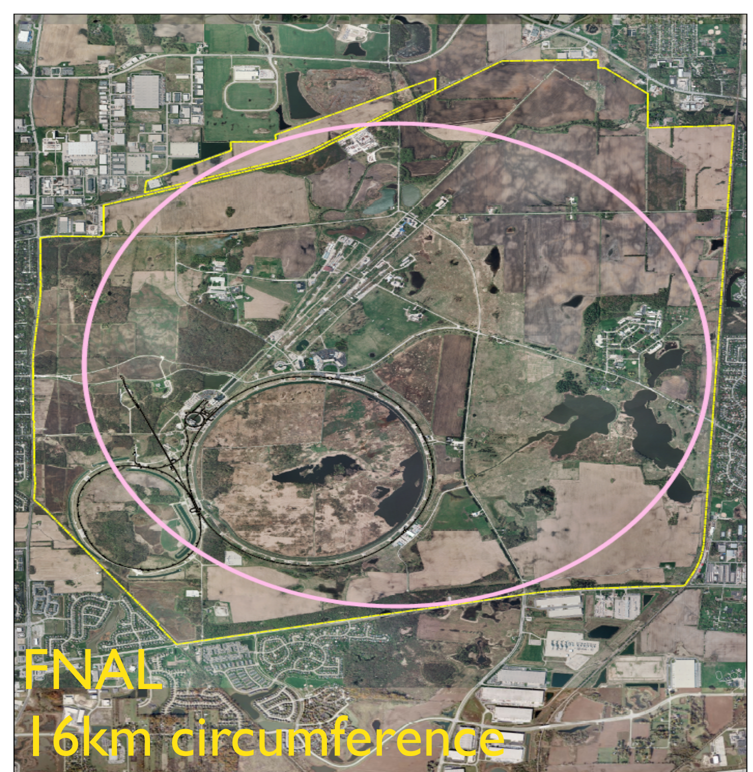

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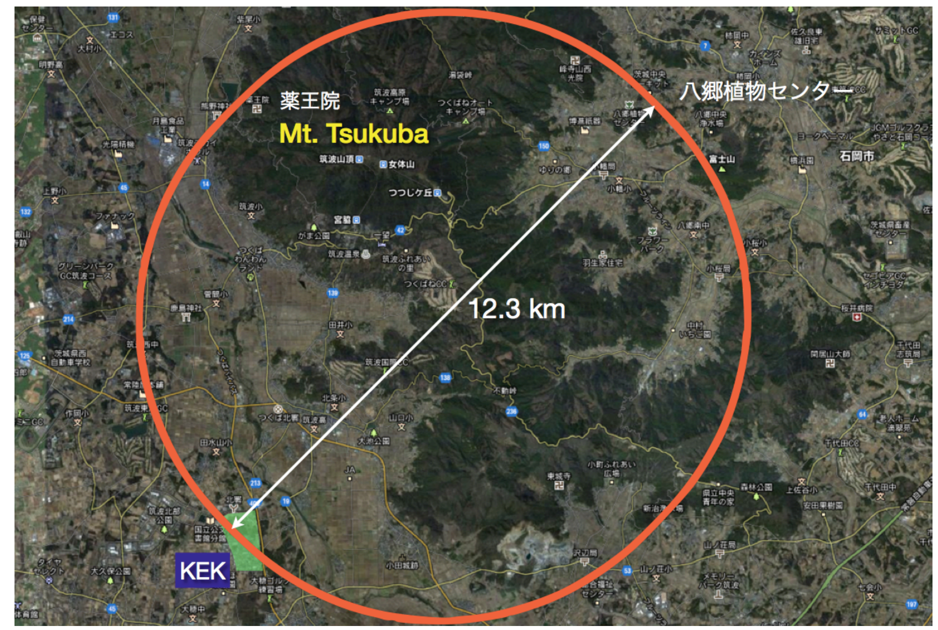
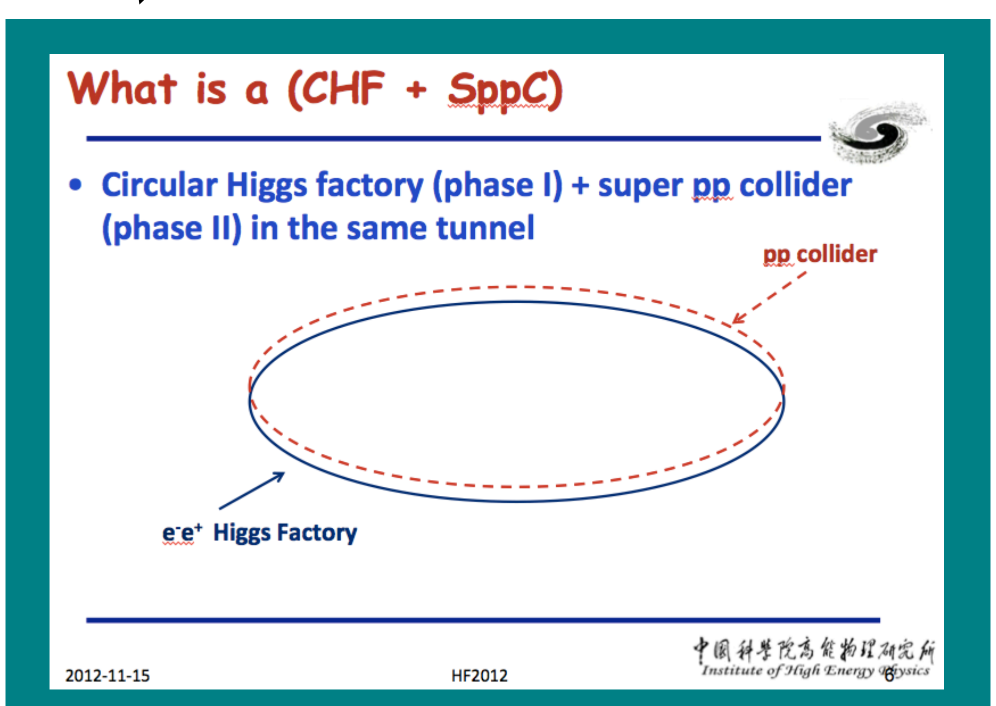
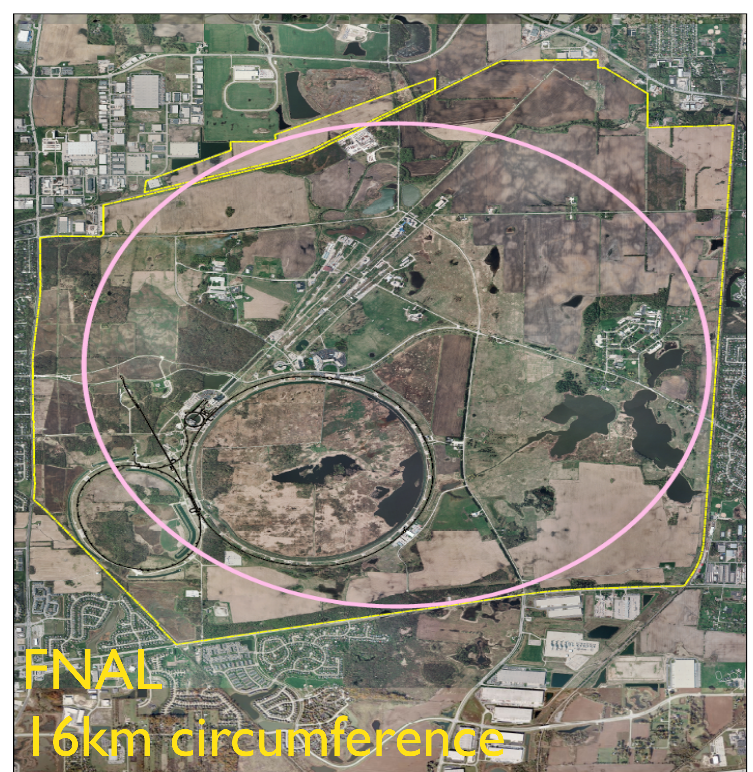


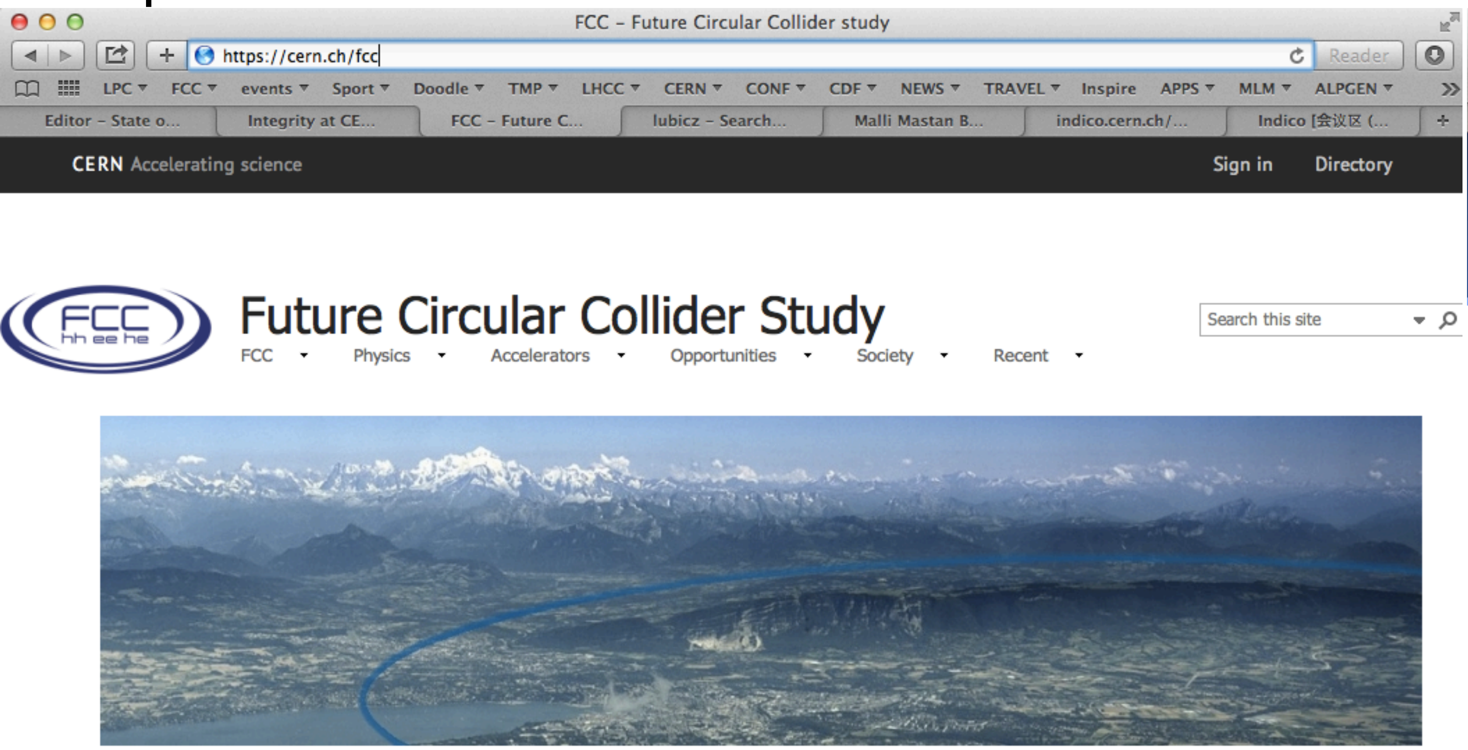




Final report:
http://www-bd.fnal.gov/icfabd/HF2012.pdf

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

http://cern.ch/fcc



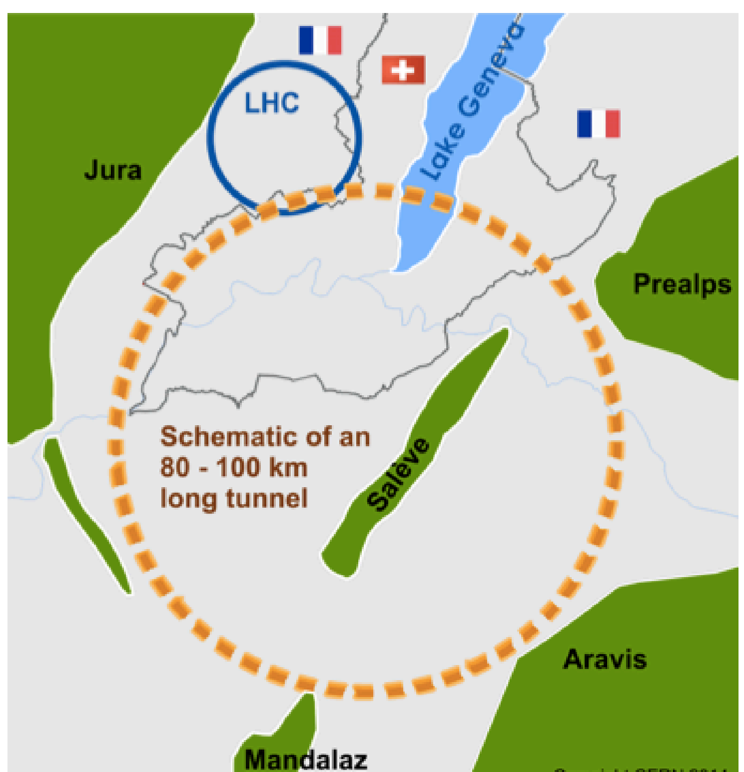
http://cepc.ihep.ac.cn

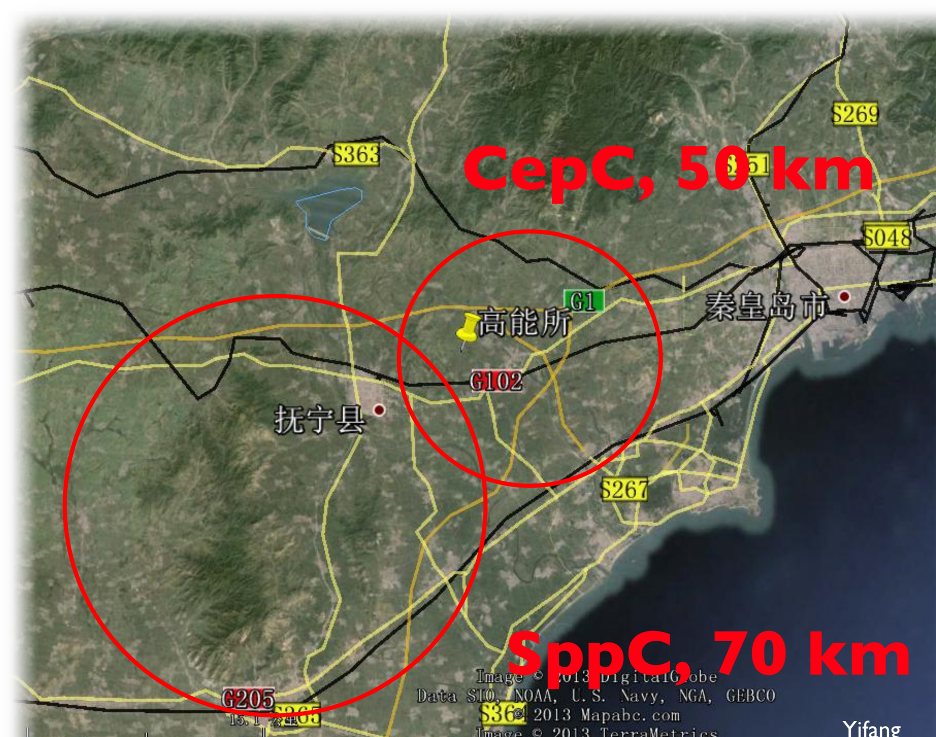
Forming an international collaboration to study:

- ***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)
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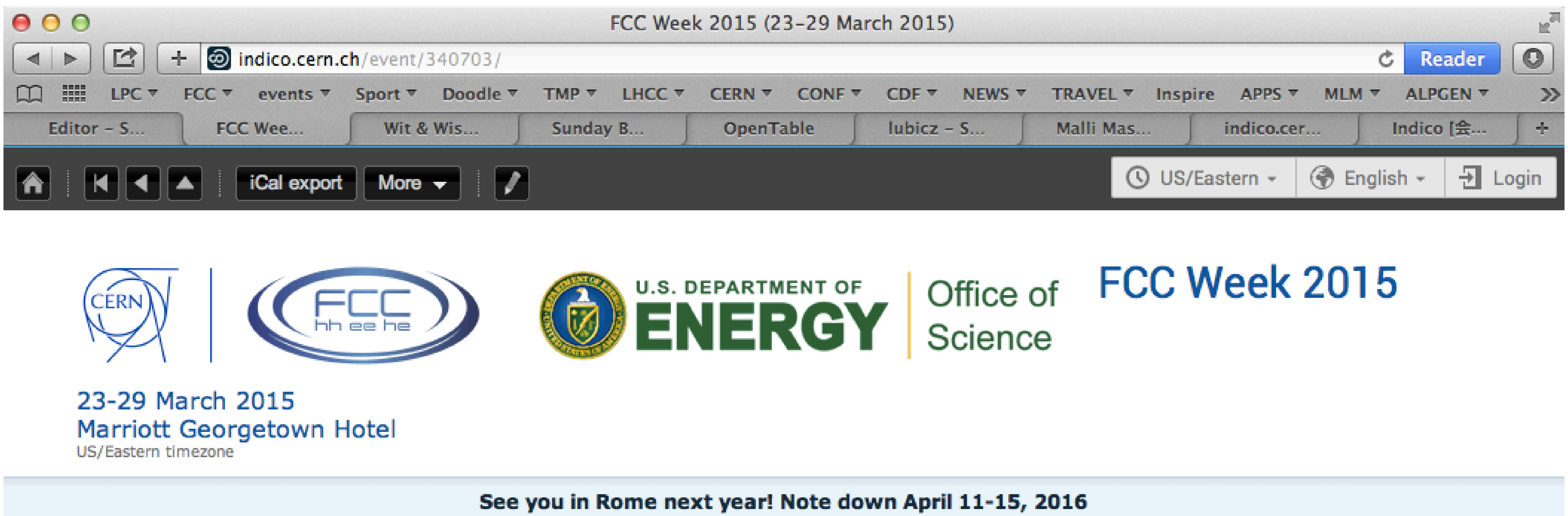
There is a live webcast for this event.
Future Circular Collider Study Kickoff Meeting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See you in Rome next year! Note down April 11-15, 2016


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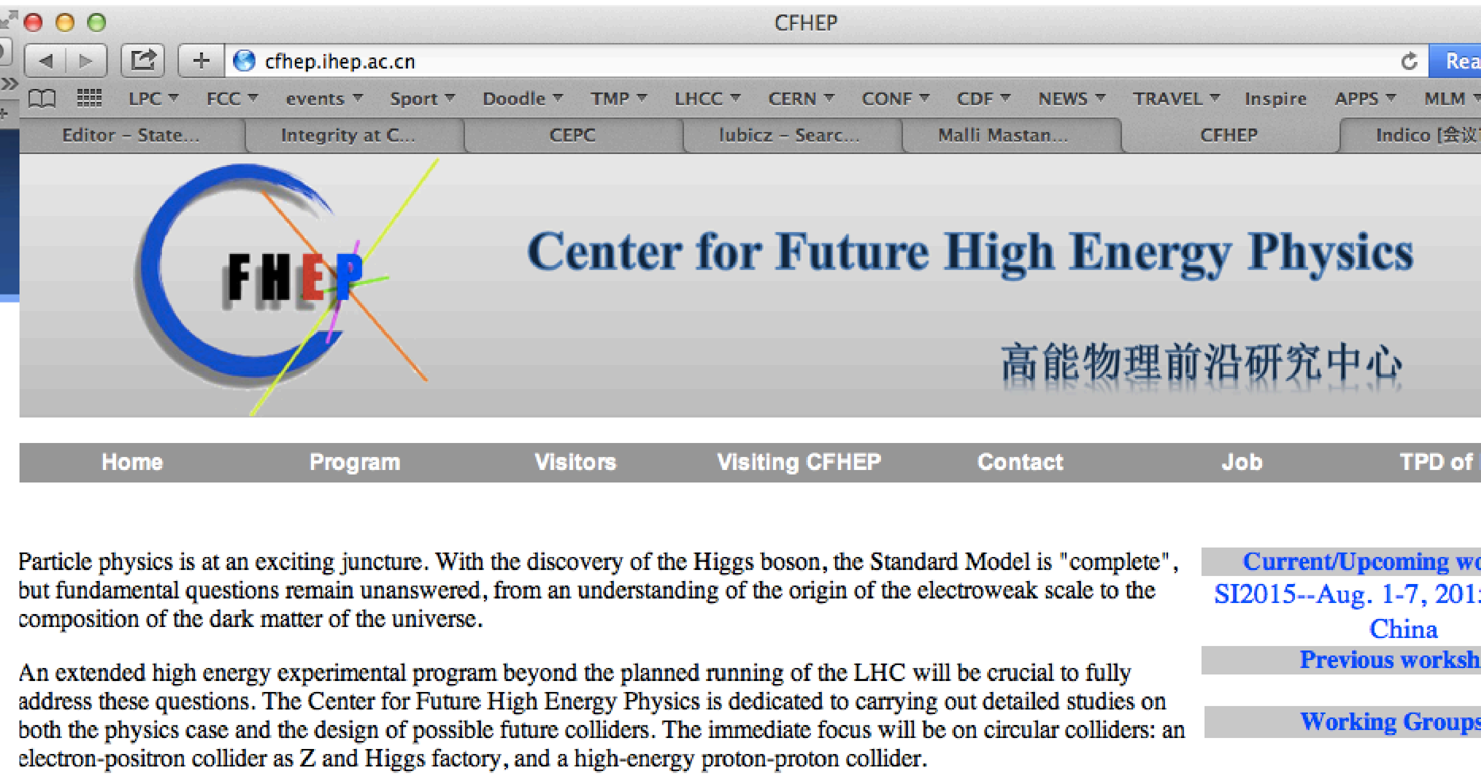
Future High Energy Circular Colliders
The Standard Model (SM) of particle physics can describe the strong, weak and electromagnetic interactions under the framework of quantum gauge field theory. The theoretical predictions of SM are in excellent agreement with the past experimental measurements. Especially 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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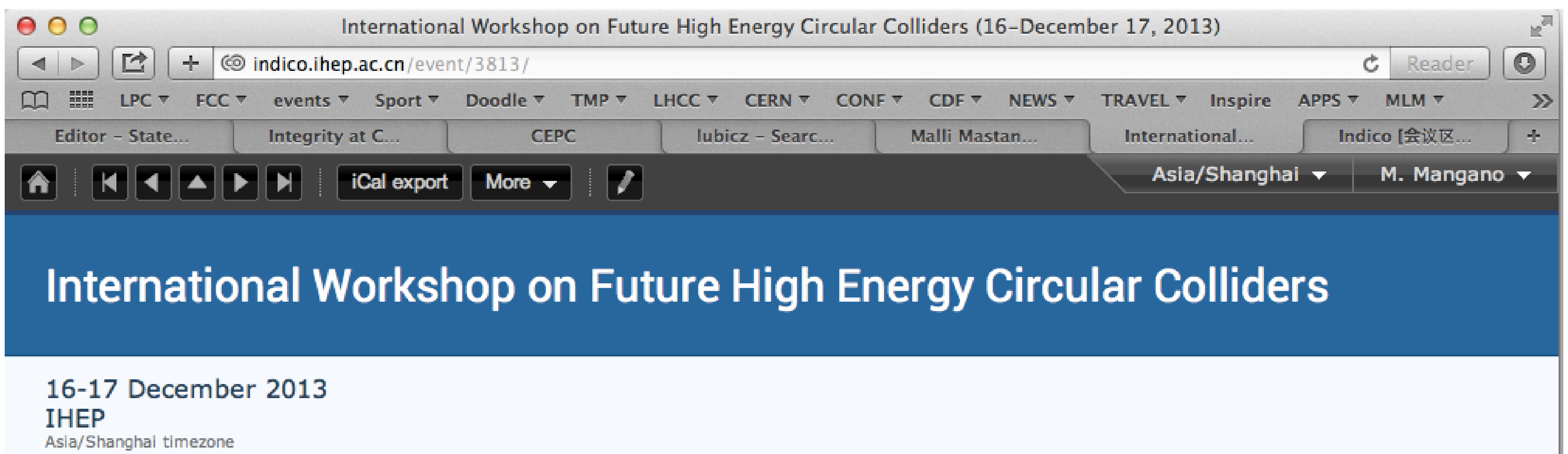
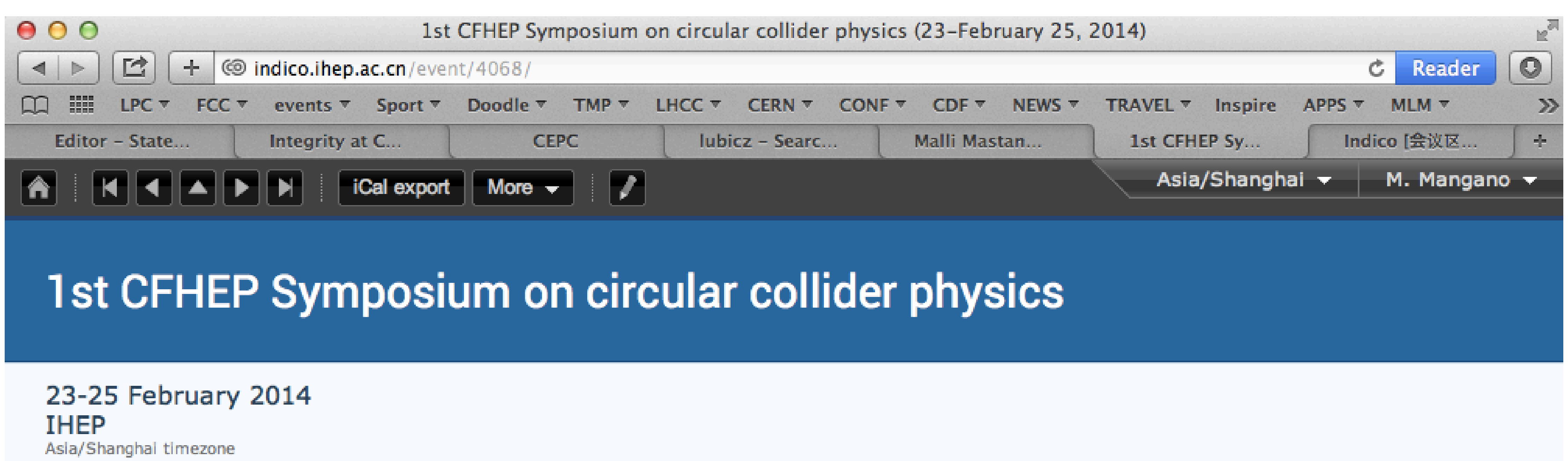
Particle physics is at an exciting juncture. With the discovery of the Higgs boson, the Standard Model is "complete", but fundamental questions remain unanswered, from an understanding of the origin of the electroweak scale to the composition of the dark matter of the universe.
An extended high energy 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)
indico.ihep.ac.cn/event/3813/
Asia/Shanghai
M. Mangano
International Workshop on Future High Energy Circular Colliders
16-17 December 2013
IHEP
Asia/Shanghai timezone


1st CFHEP Symposium on circular collider physics (23–February 25, 2014)
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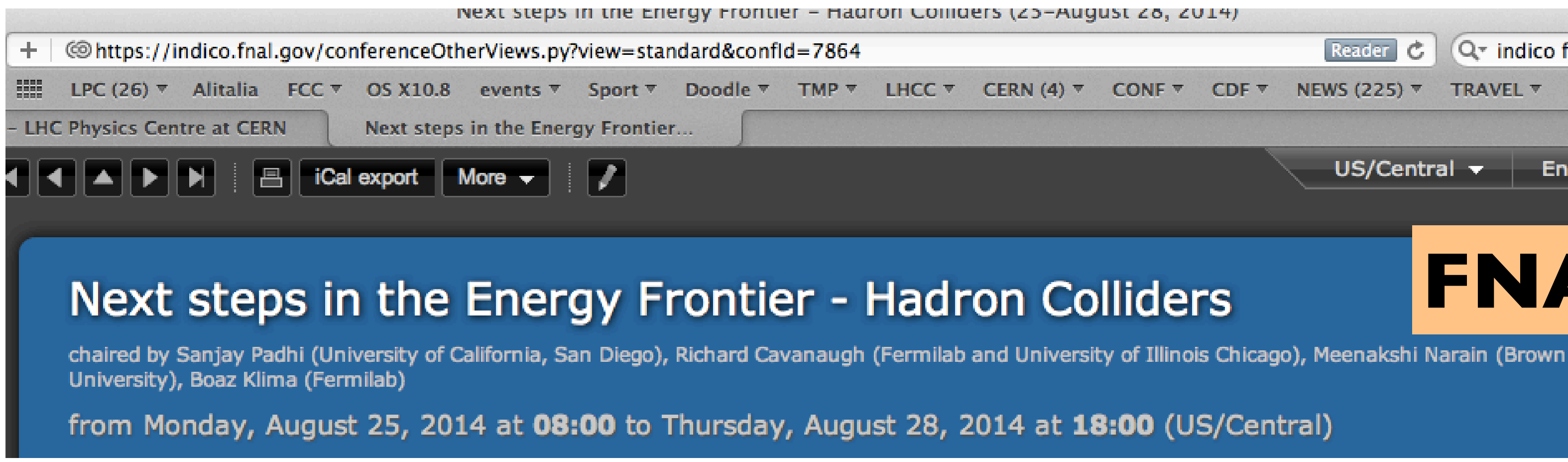
Asia/Shanghai
M. Mangano
1st CFHEP Symposium on circular collider physics
23-25 February 2014
IHEP
Asia/Shanghai timezone

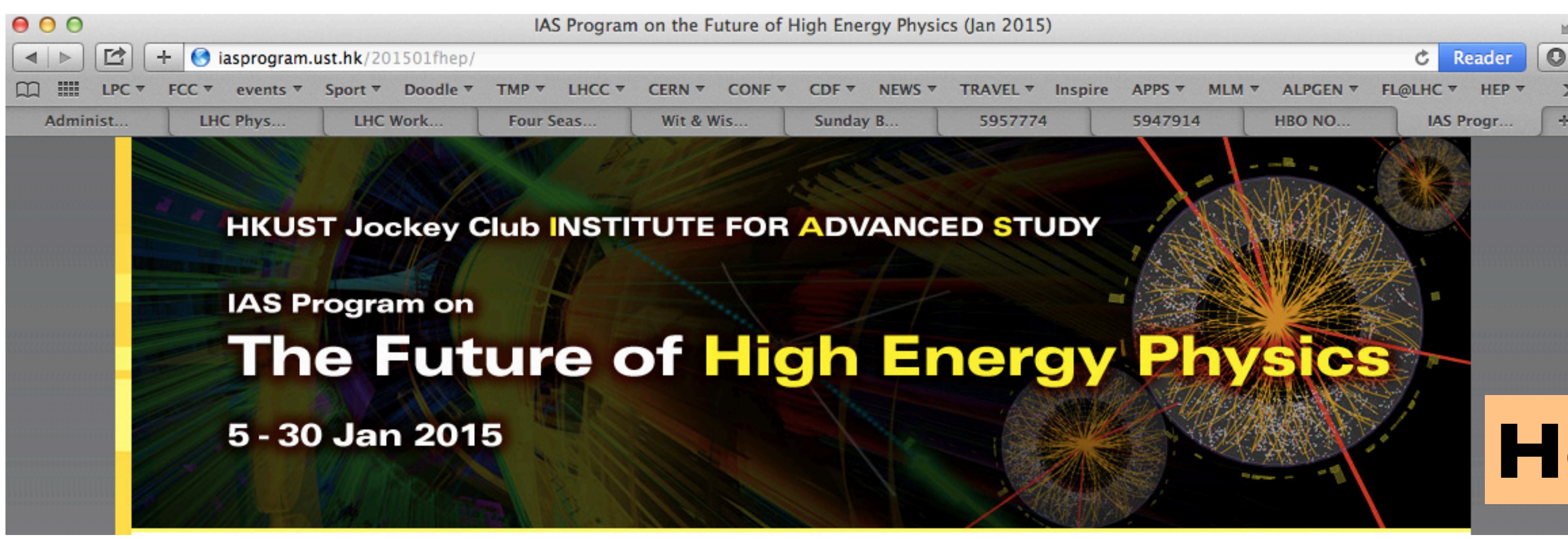
Physics workshops spontaneously organized all over the world document better than anything else the physics results, and the interest of the community ....

SLAC

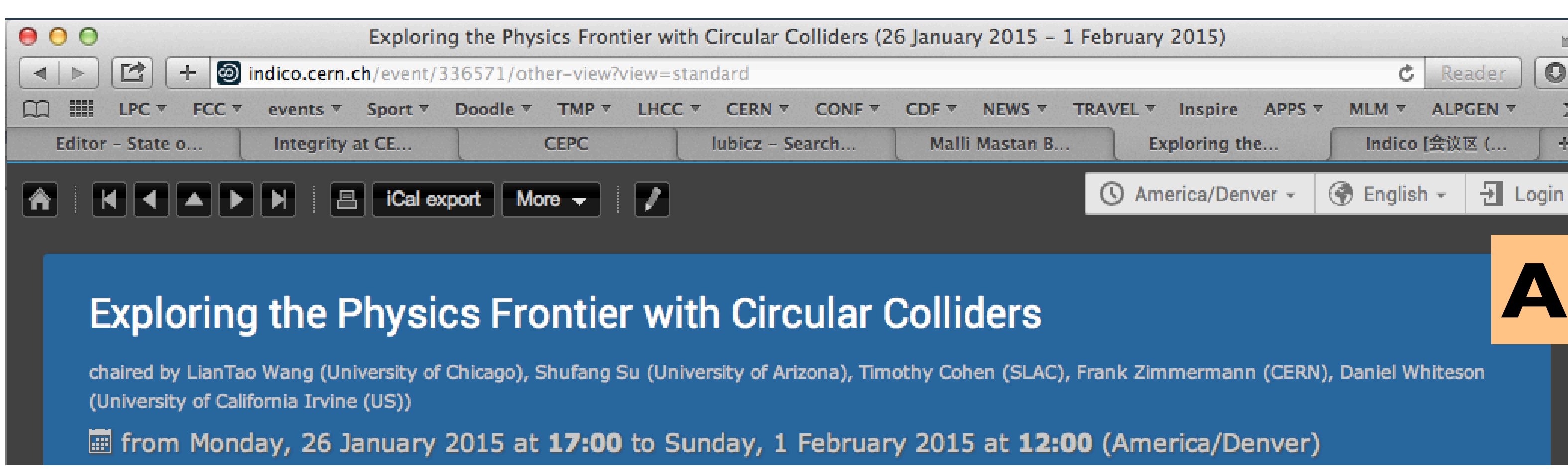
FNAL



Hong Kong



Aspen



Key goals of a future circular collider complex

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

FCC-hh parameters and lum goals

Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP_{main} [$cm^{-2}s^{-1}$]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

- **Phase 1 (baseline): 5 x 10^{34} $cm^{-2}s^{-1}$ (peak),**
  250 fb^{-1}/year (averaged)
  2500 fb^{-1} within 10 years (~HL LHC total luminosity)

- **Phase 2 (ultimate): ~2.5 x 10^{35} $cm^{-2}s^{-1}$ (peak),**
  1000 fb^{-1}/year (averaged)
  ➔ 15,000 fb^{-1} within 15 years

- **Yielding total luminosity O(20,000) fb^{-1} over ~25 years of operation**

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.

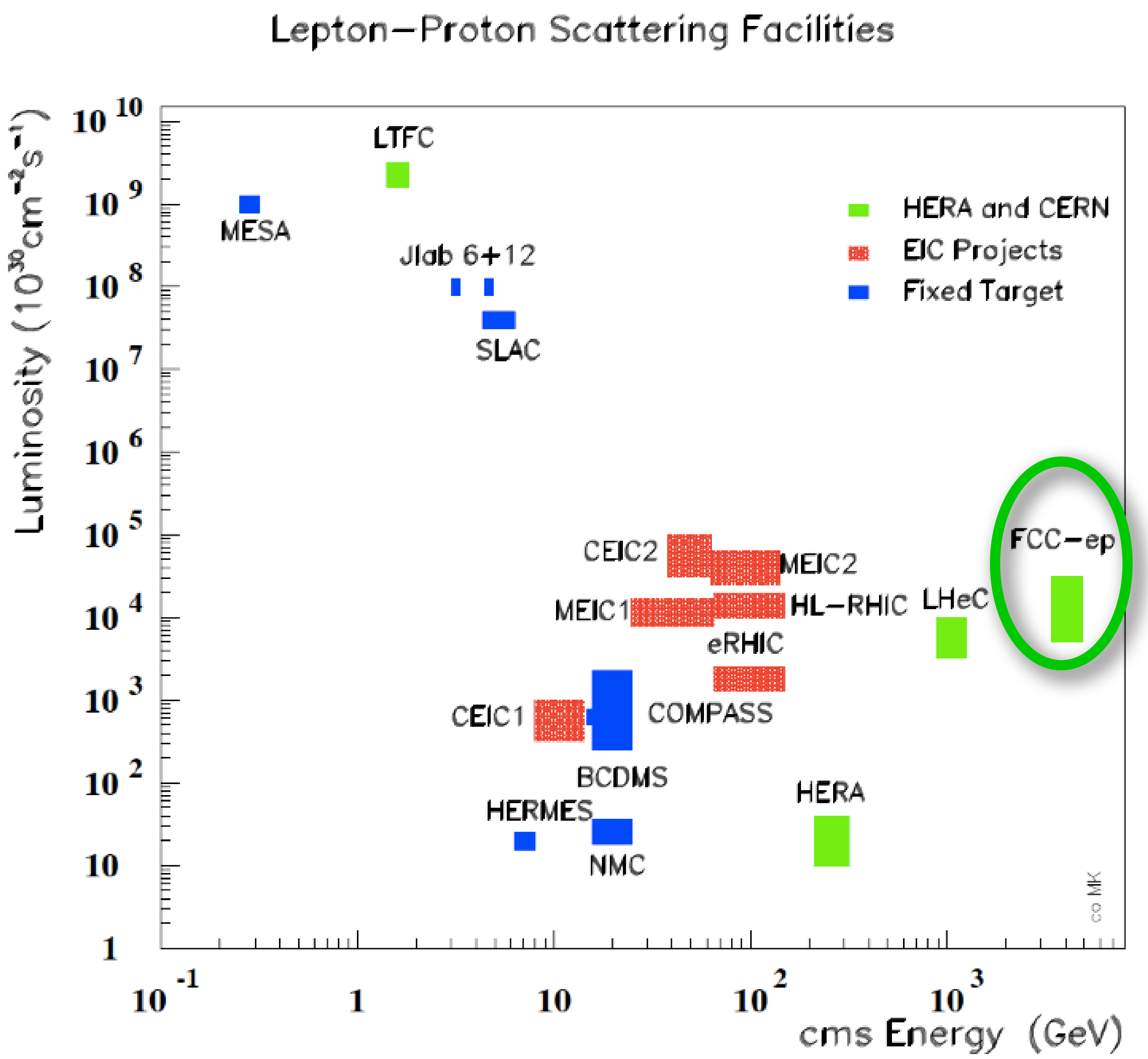
   A_{LR}, A_{FB}^{pol} etc

6. more and upgrades….

P.Janot

NB: **TLEP = FCC-ee**

FCC-eh parameters and lum goals



175 GeV e- beam from FCC-ee and 50 TeV p beam from FCC-hh

Highest centre-of-mass energy ep collider, ~6 TeV

Luminosity $\sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$

Reference literature

- **FCC-ee**: "First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164
- **FCC-eh**: no document as yet, see however
  - "A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector", J.Phys. G39 (2012) 075001
- **FCC-hh**: no document as yet (in progress, expected by end of 2015). See Twiki page:

  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider
- **CEPC/SPPC**: Physics and Detectors pre-CDR completed, to be posted soon on
  - http://cepc.ihep.ac.cn/preCDR/volume.html

See also:

- Physics Briefing Book to the European Strategy Group (ESG 2013)
- Planning the Future of U.S. Particle Physics (Snowmass 2013): Chapter 3: Energy Frontier, arXiv:1401.6081

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 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)

Higgs physics

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:
$\sigma(ttH, p_T^{top} > 500\ \text{GeV}) \Rightarrow R(100) = 250$

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

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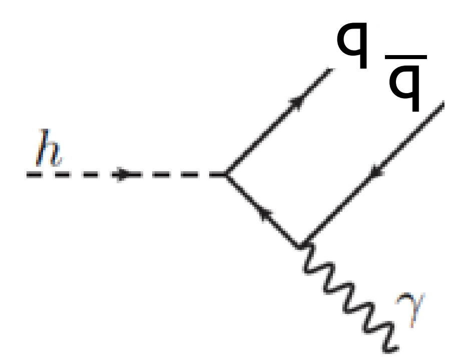
$H \rightarrow J/\Psi\,\gamma$ → y_c

$H \rightarrow \phi\,\gamma$ → y_s

50 evts

$H \rightarrow \rho\,\gamma$

$H \rightarrow \omega\,\gamma$ → y_u, y_d



$e^+e^- \rightarrow H$

L = 10 ab^{-1}

$\kappa_e < 2.2$ at 3σ

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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

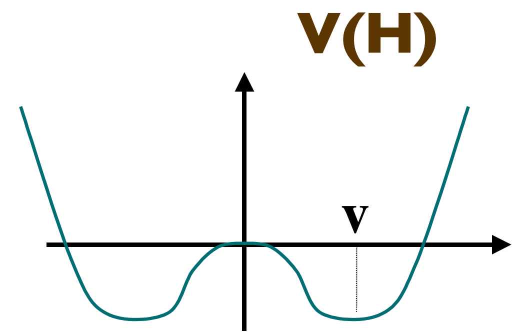
g_{HXY}	FCC-ee	FCC-hh	
ZZ	0.16%		
WW	0.85%		
γ γ	1.7%		
Zγ		1% ?	→ extrapolation from HL-LHC estimates
tt		1% ?	→ from ttH/ttZ
bb	0.88%		
τ τ	0.94%		
cc	1.0%		
ss	H→Vγ, in progr.		
μμ	6.4%	2% ?	→ extrapolation from HL-LHC estimates
uu,dd	H→Vγ, in progr.		
ee	e^+e^-→H, in progr.		
HH		5% ?	→ from HH →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

FCC-hh ambitious but possible targets?

Higgs selfcouplings

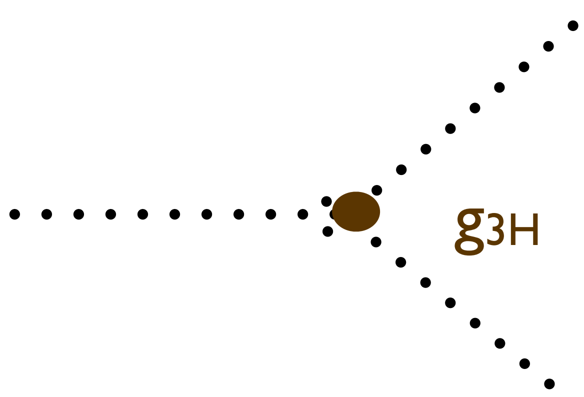
The Higgs sector is defined in the SM by two parameters, **μ** and **λ**:

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

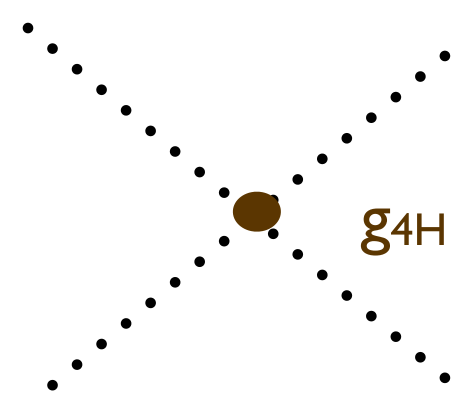


$$\frac{\partial V_{SM}(H)}{\partial H}|_{H=v} = 0 \quad \text{and} \quad m_H^2 = \frac{\partial^2 V_{SM}(H)}{\partial H \partial H^*}|_{H=v} \quad \Rightarrow \quad \begin{array}{lcl} \mu & = & m_H \\ \lambda & = & \frac{m_H^2}{2v^2} \end{array}$$

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



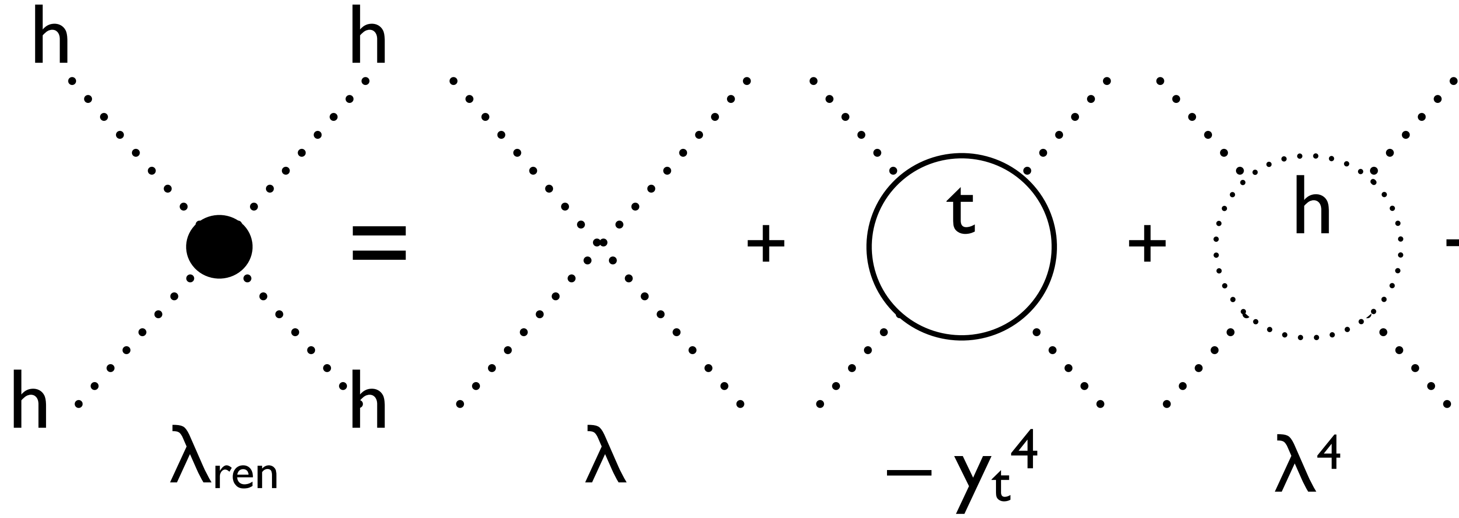
$g_{3H} \Rightarrow 6\lambda \, v = \frac{3m_H^2}{v}$ ~O(m_{top})



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

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

(meta)Stability of the Higgs potential

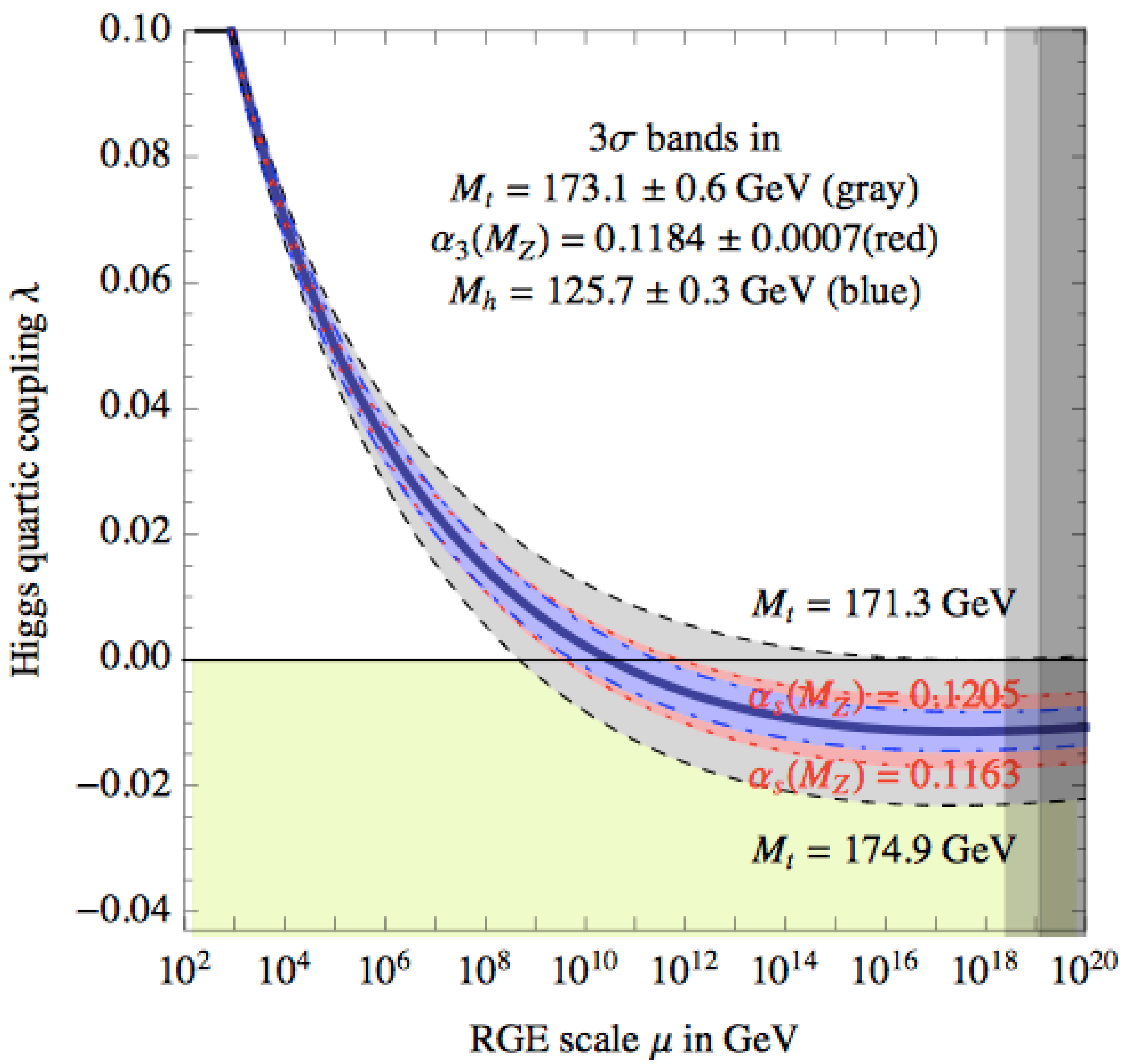


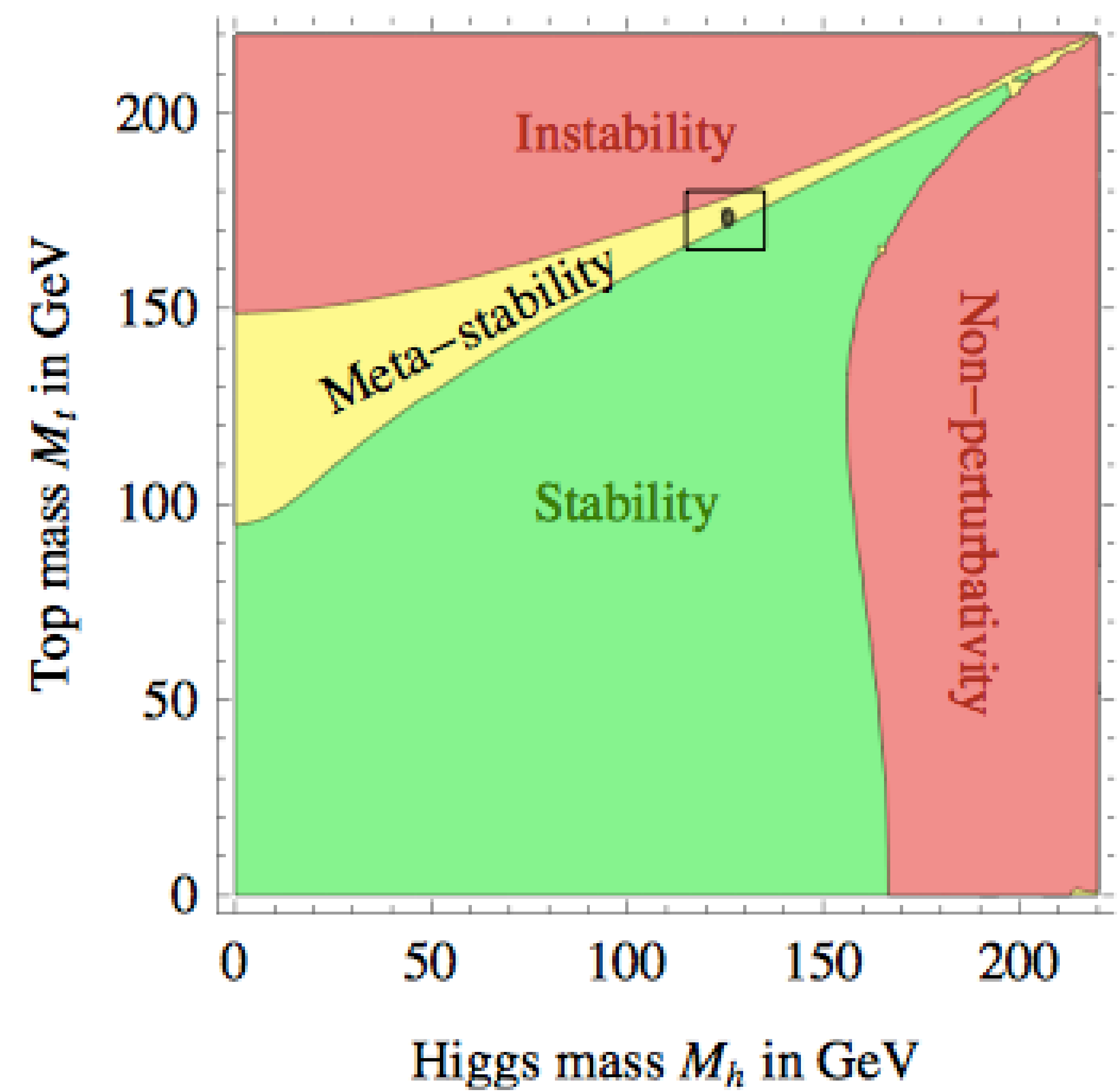
$$\Rightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4$$

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

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





Higgs selfcouplings: pp→HH

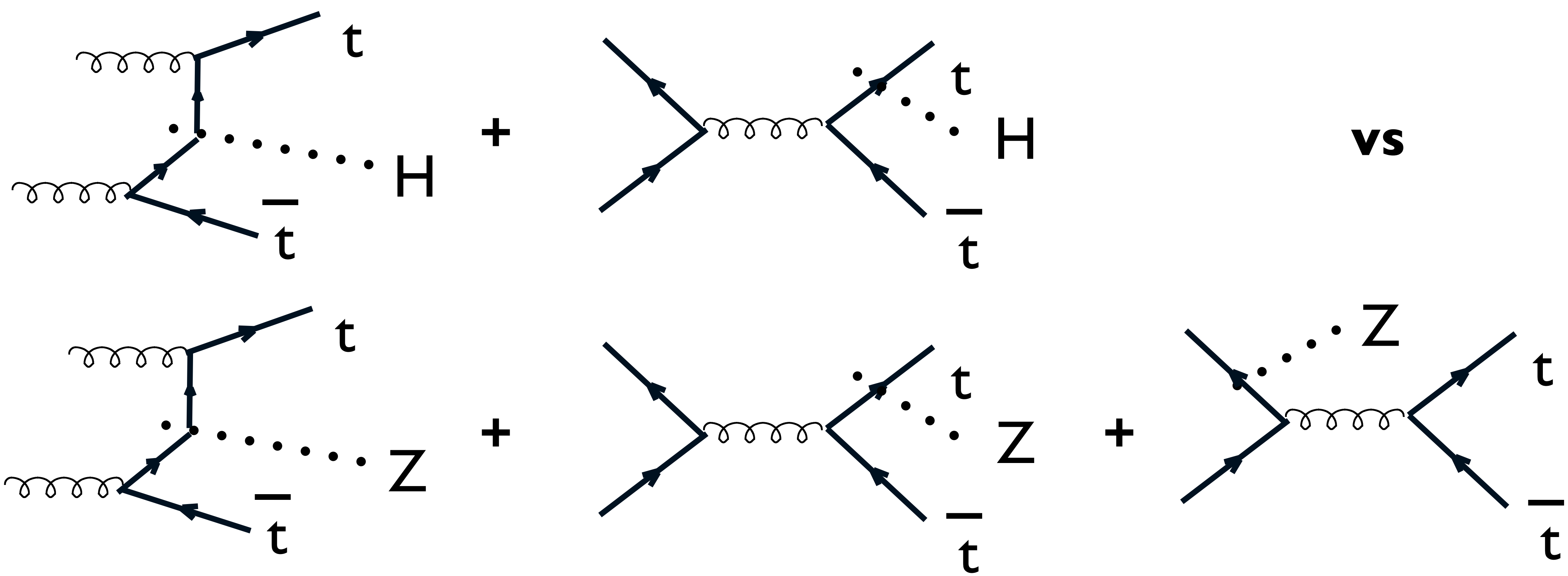
- gg→HH (most promising?) , qq→HHqq (via VBF)
- Reference benchmark process: HH→bb γγ
- Goal: 5% (or better) precision for SM selfcoupling

$HH \to b\bar{b}\gamma\gamma$	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 ✓ $c \to b$ & $j \to \gamma$ included ✓ Background systematics ○ $b\bar{b}\gamma\gamma$ not matched ✓ $m_{\gamma\gamma} = 125 \pm 1$ GeV	✓ Full EFT approach ○ No $c \to b$ & $j \to \gamma$ ✓ Marginalized ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 5$ GeV ✓ Jet $/W_{had}$ veto	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included ○ No marginalization ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 3$ GeV

Work in progress to compare studies, harmonize performance assumptions, optimize, etc
⇒ ideal benchmarking framework

M.Son, HH summary at FCC week

y_{top} from $pp \to tt\ H / pp \to tt\ Z$



To the extent that the qqbar → tt Z/H contributions are subdominant:

- **Identical production dynamics:**

  o correlated QCD corrections, correlated scale dependence
  o correlated α_S systematics

- **$m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:**

  o correlated PDF systematics
  o correlated m_{top} systematics

For a given y_{top}, we expect $\sigma(ttH)/\sigma(ttZ)$ to be predicted with great precision

NLO scale dependence:

Scan μ_R and μ_F independently, at $\mu_{R,F} = [0.5, 1, 2]\ \mu_0$, with $\mu_0 = m_H+2m_t$

	$\delta\sigma(ttH)$	$\delta\sigma(ttZ)$	**$\sigma(ttH)/\sigma(ttZ)$**	**$\delta[\sigma(ttH)/\sigma(ttZ)]$**
14 TeV	± 9.8%	± 12.3%	**0.608**	**±2.6%**
100 TeV	± 9.6%	± 10.8%	**0.589**	**±1.2%**

PDF dependence (CTEQ6.6 -- similar for others)

	$\delta\sigma(ttH)$	$\delta\sigma(ttZ)$	**$\delta[\sigma(ttH)/\sigma(ttZ)]$**
14 TeV	± 4.8%	± 5.3%	**±0.75%**
100 TeV	± 2.7%	± 2.3%	**±0.48%**

** The uncertainty reduction survives after applying kinematical cuts to the final states*

** Both scale and PDF uncertainties will be reduced further, well before FCC!*

More in general ...

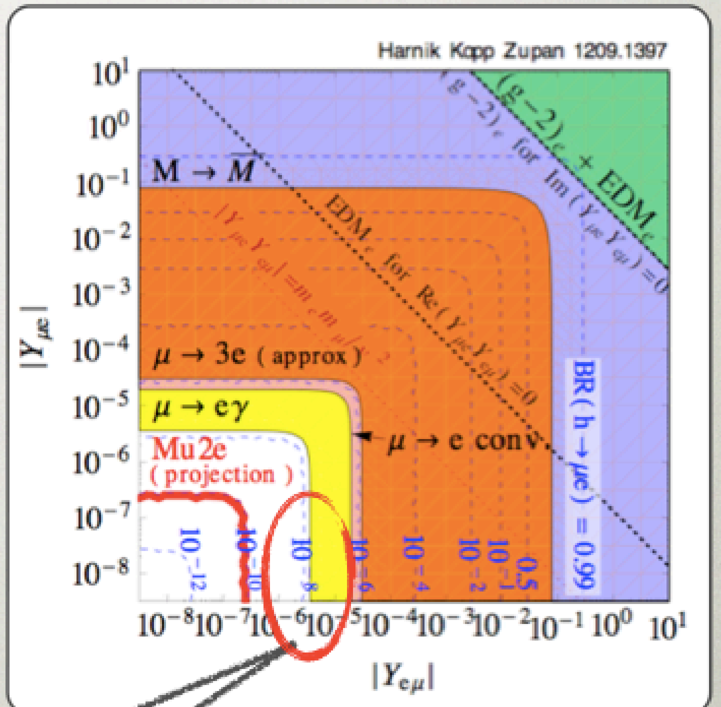
- Statistics allows to bring the precision in the measurement of BR ratios to sub-% level (e.g. $B(\to\gamma\gamma)/B(H\to ZZ^*)$. Relying on the sub-% measurement of benchmark BR's from FCC-ee, FCC-hh can export this precision to other channels it has access to.

- Experimental feasibility, and theoretical implications, of these measurements are under study

- Several of these new ideas can be already explored at HL-LHC

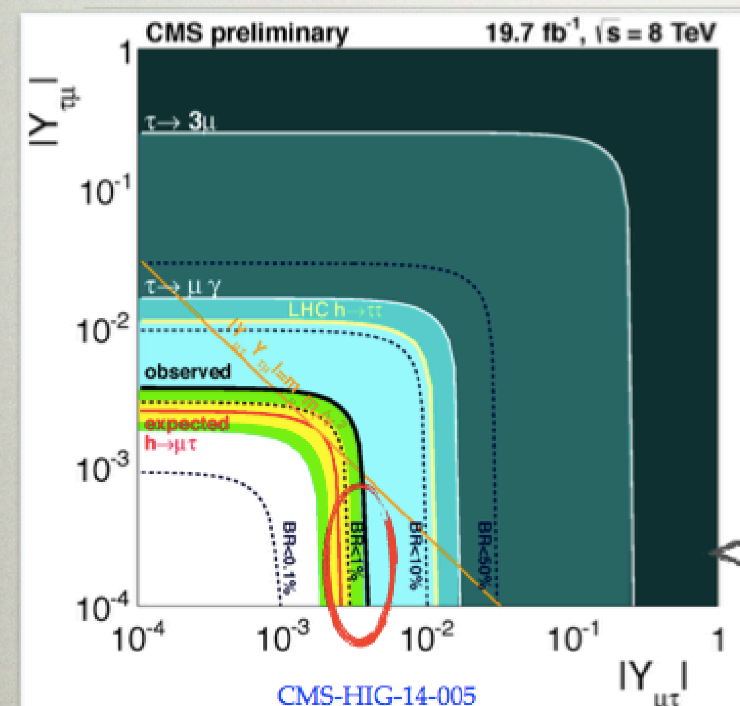
$h \to \mu e$

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

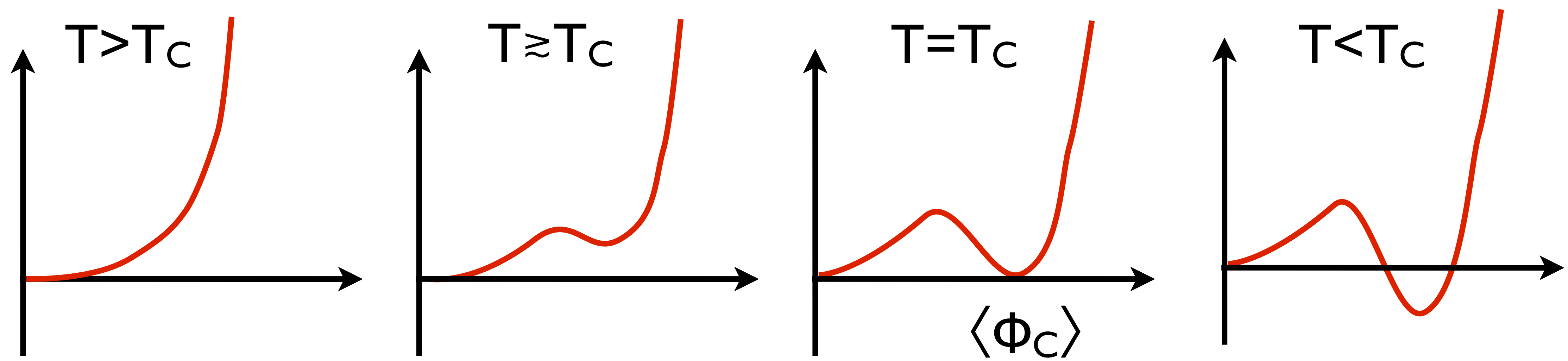


- what can one do with 10^9 Higgses @100TeV?

$h \to \tau\mu$

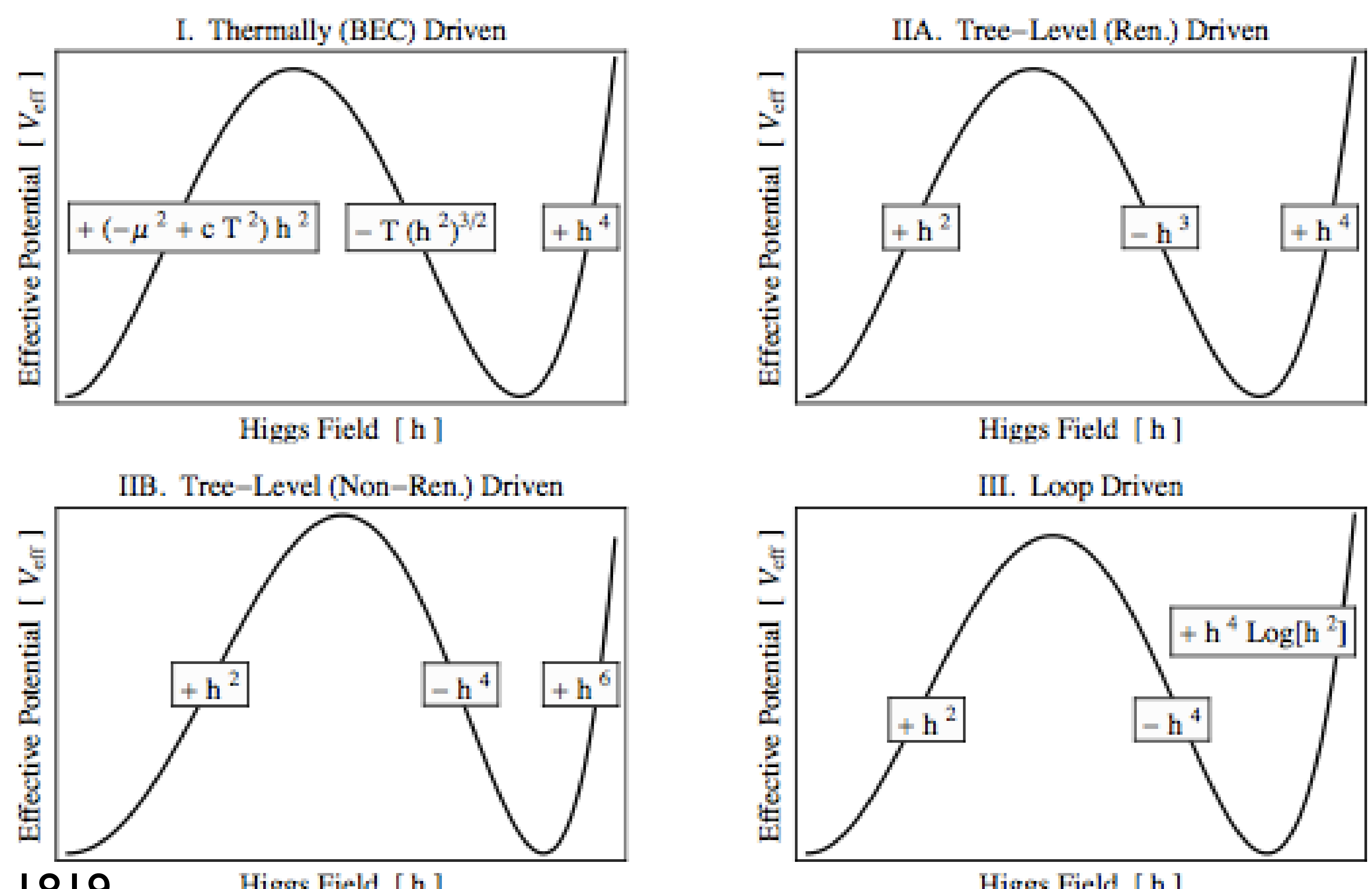


- right now: 2j channel statistics limited, 0j+1j not
- how about with $\sim 10^9$ *h*? *LHC8* $\Rightarrow$ *100 TeV 3 ab*$^{-1}$
- assume same scaling for signal and bckg
  - $Br \sim 10^{-2} \Rightarrow Br \sim 10^{-4}$
  - $\Lambda \sim 0.2$ TeV $\Rightarrow \Lambda \sim 2$TeV
- if bckg free
  -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



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



Chung et al,
http://arxiv.org/abs/1209.1819

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

BSM Higgs Sectors

D.Curtin @ FCC week

Big Picture Motivations

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

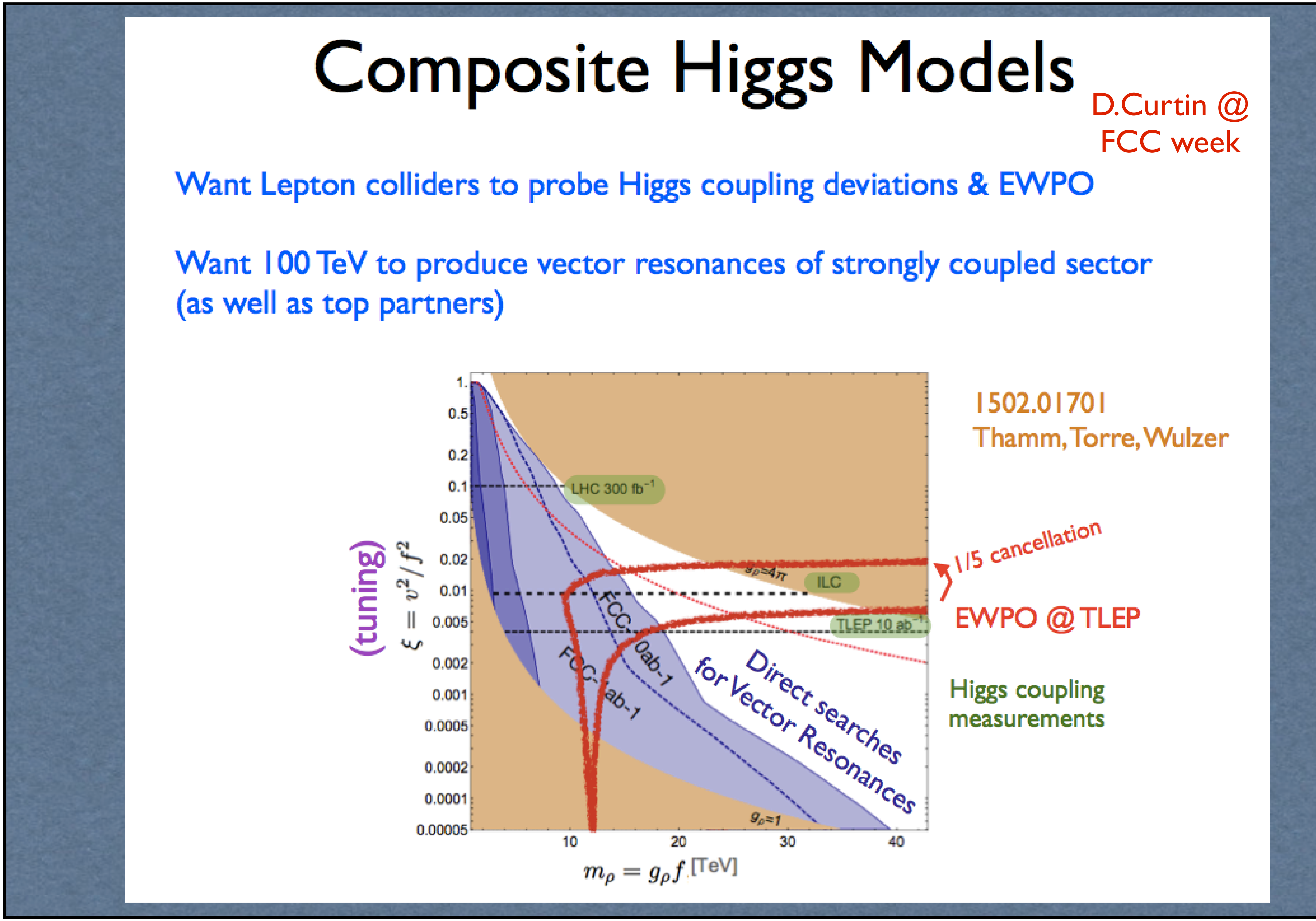
IR Models

- 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



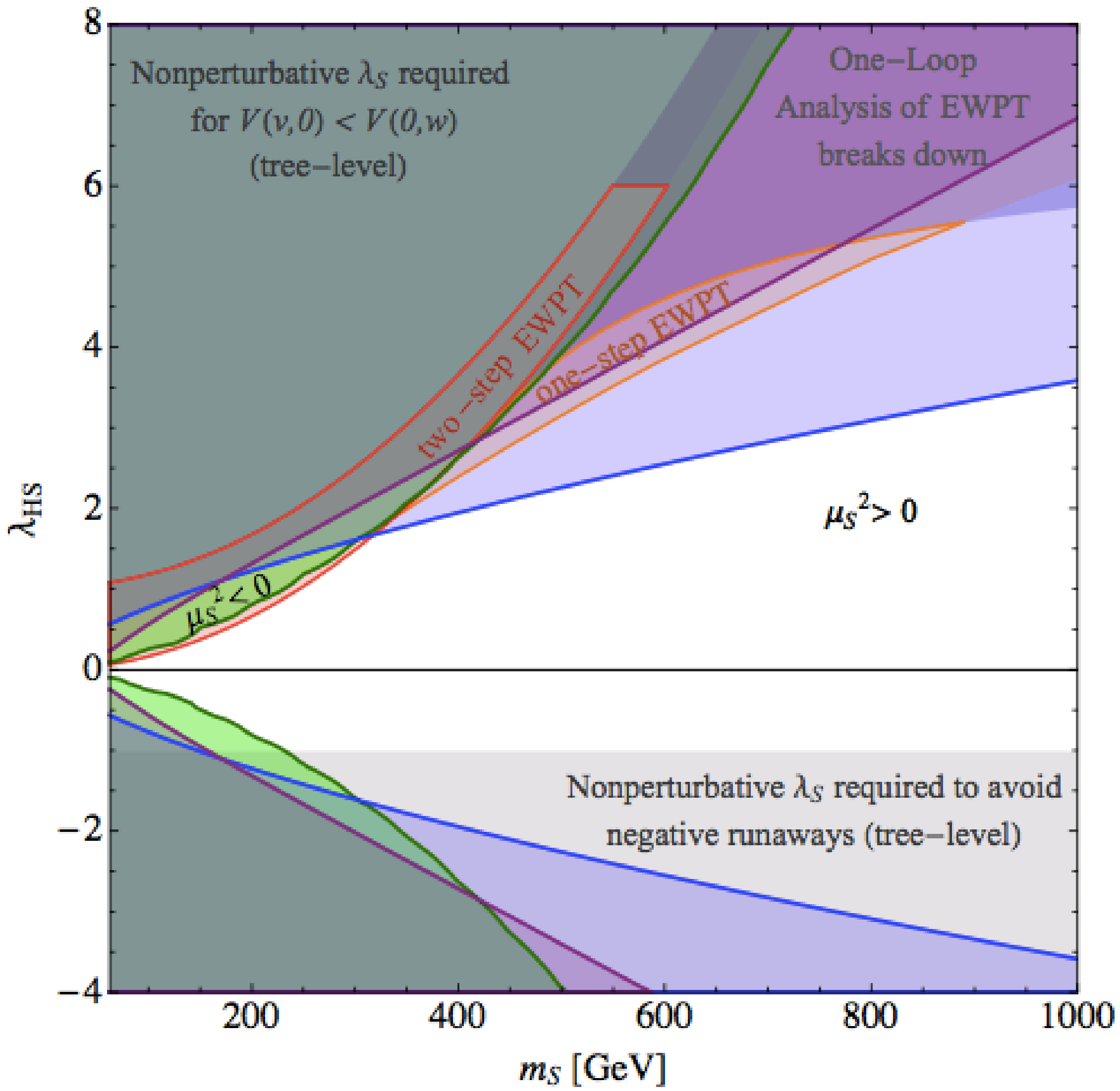
Interplay of EW precision tests (Tera-Z@FCC-ee), Higgs BR measurements (H@FCC-ee) and direct resonance searches (10-30 TeV, @ FCC-hh)

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*→SS direct production
- Higgs cubic coupling
- σ(Zh) deviation (> 0.6% @ TLEP)

100 TeV collider could cover *entire* parameter space.

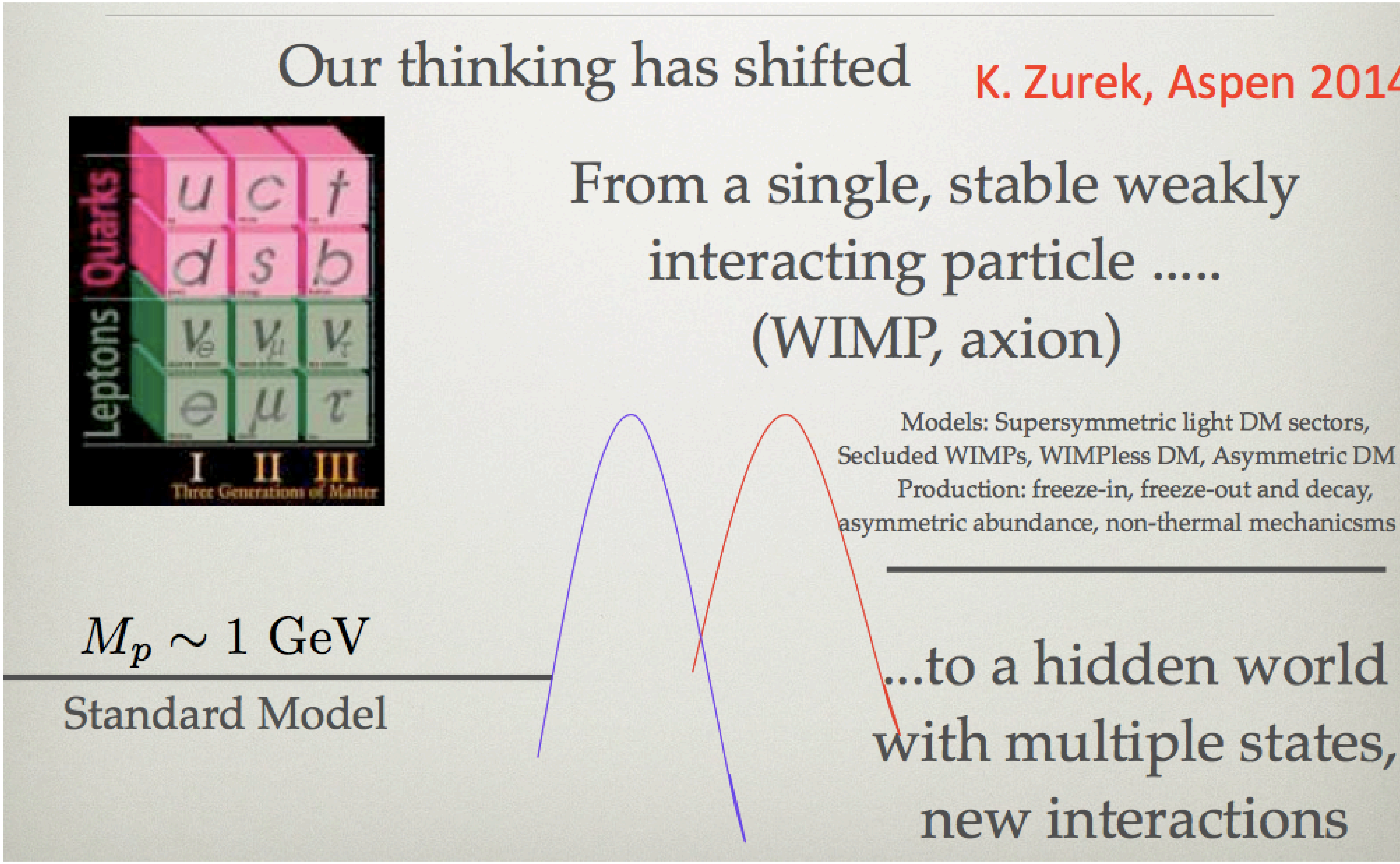
TLEP (super ILC) can cover *some* of parameter space.

Potential complimentarily!

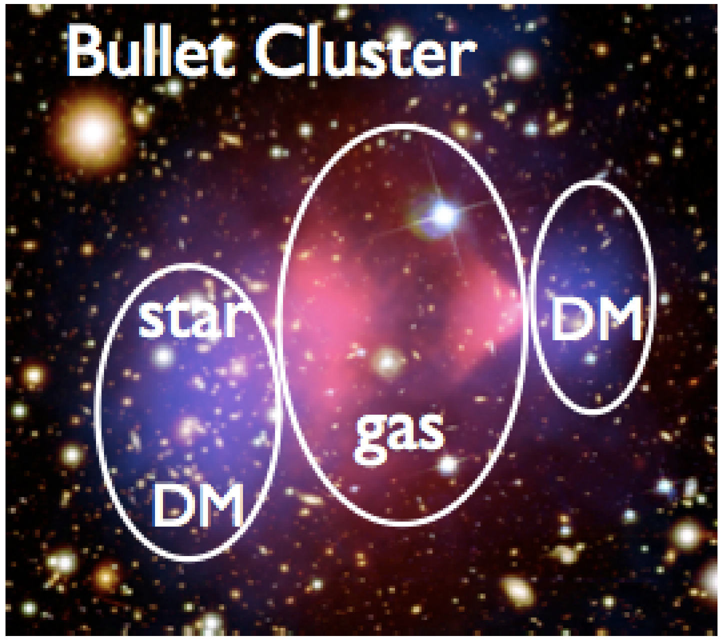
1409.0005 DC, Patrick Meade, Tien-Tien Yu

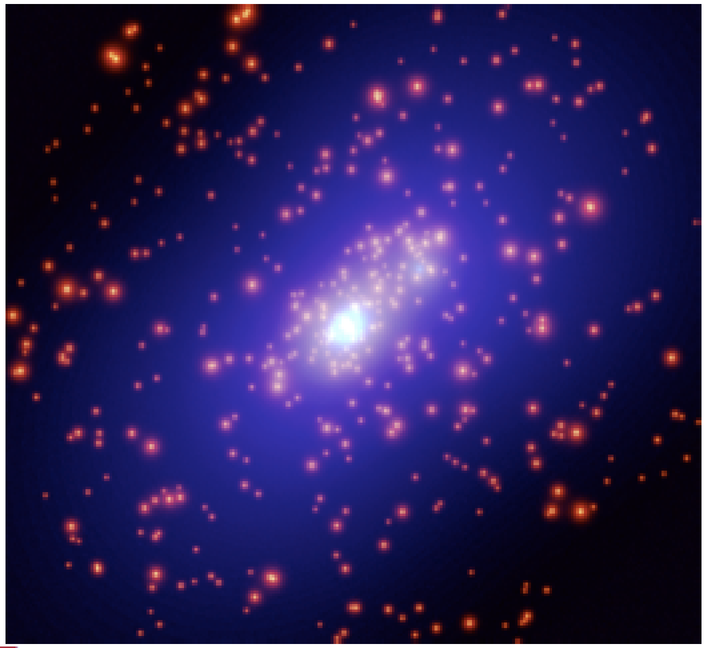
⇒ Appearance of first “**no-lose**” arguments for classes of compelling scenarios of new physics

Dark Matter


Our thinking has shifted
K. Zurek, Aspen 2014
Quarks
Leptons
u c t
d s b
ν_e ν_μ ν_τ
e μ τ
I II III
Three Generations of Matter
From a single, stable weakly interacting particle .....
(WIMP, axion)
Models: Supersymmetric light DM sectors, Secluded WIMPs, WIMPless DM, Asymmetric DM ..
Production: freeze-in, freeze-out and decay, asymmetric abundance, non-thermal mechanicsms ..
$M_p \sim 1$ GeV
Standard Model
...to a hidden world with multiple states, new interactions

Evidence building up for self-interacting DM





- A really large scattering cross section!

a nuclear-scale cross section

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

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

SIDM indicates a new mass scale

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

Dark Matter search

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- DM could be explained by BSM models that would leave no signature at any future collider (e.g. axions).

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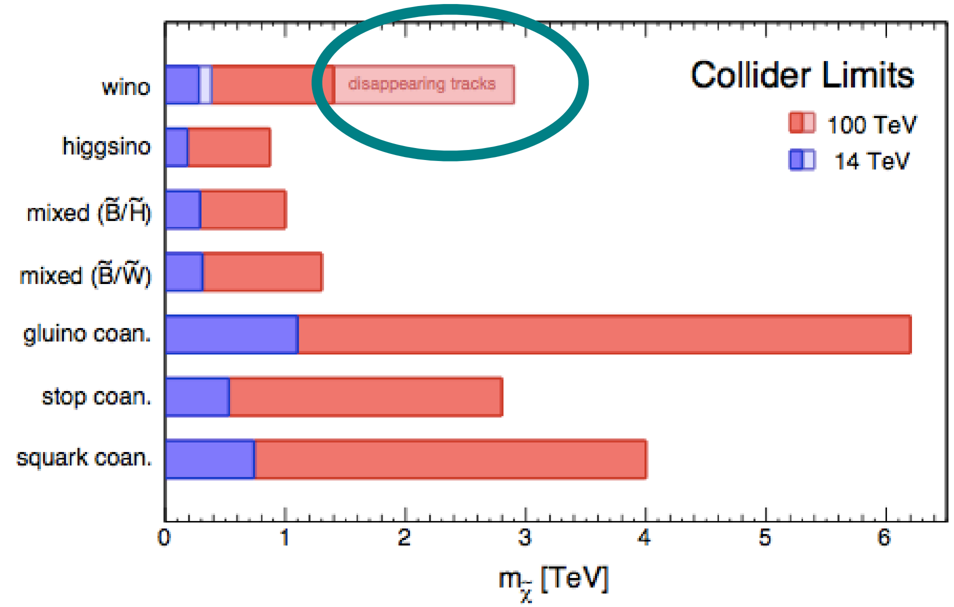
  - can WIMPS, detectable in direct and indirect (DM annihilation) experiments, be discovered at future colliders?
  - what are the opportunities w.r.t. new DM scenarios (e.g. interacting DM, asymmetric DM, ...)?

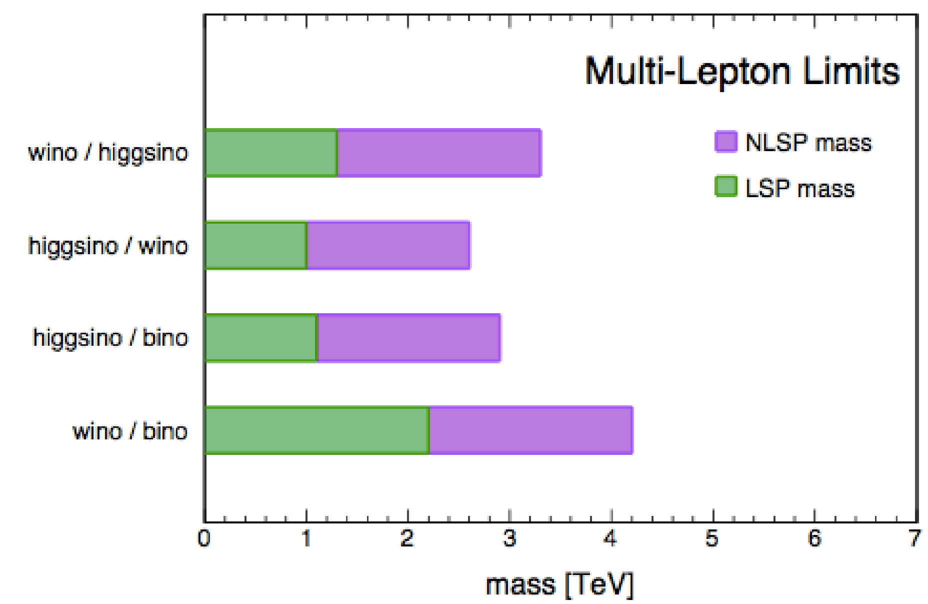
Towards no-lose arguments for Dark Matter scenarios:

WIMP searches at colliders

L.Wang @ FCC week

disappearing tracks



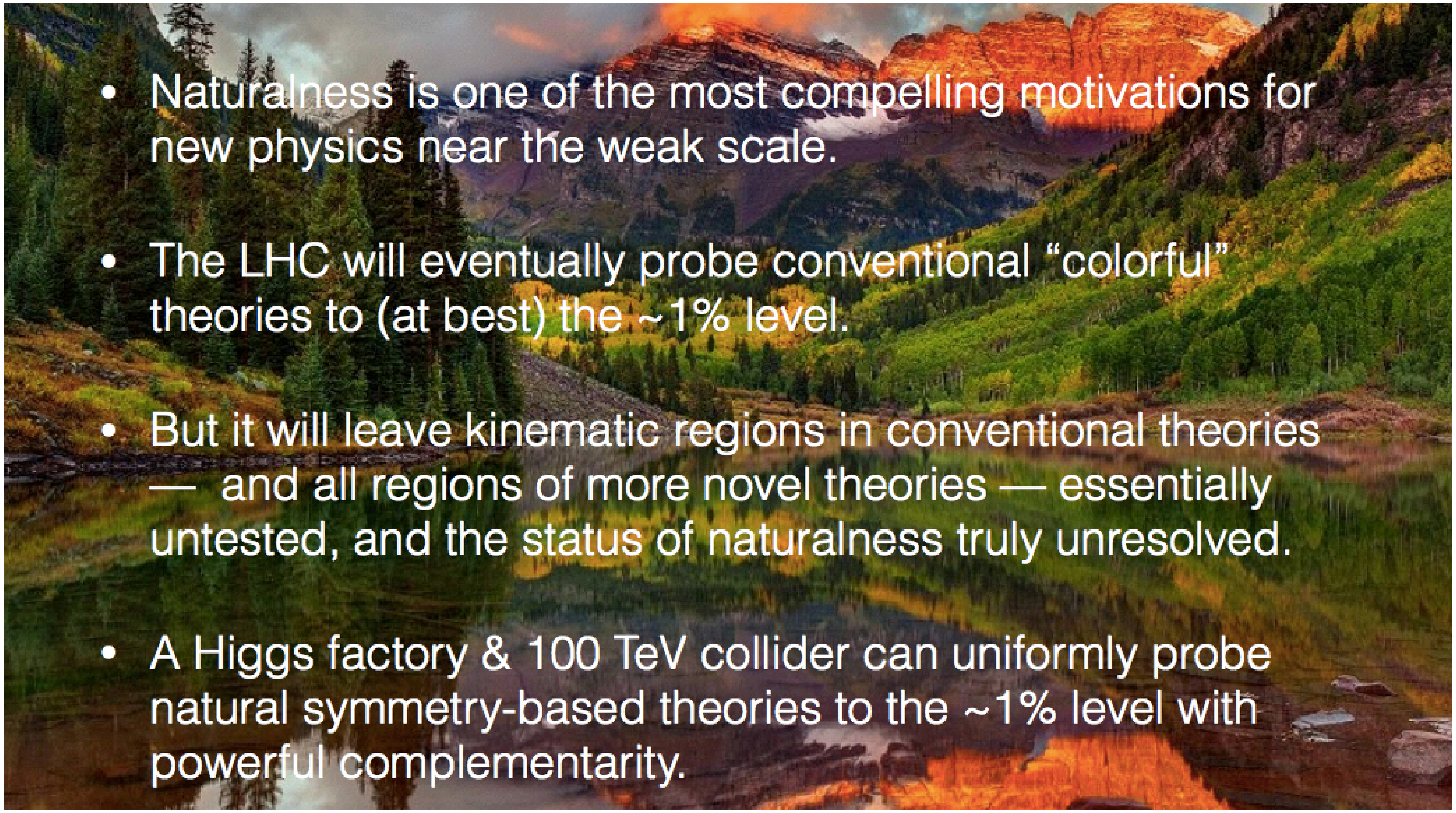


$$M_{\rm WIMP} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3}\right)$$

100 TeV pp collider will probe TeV WIMP very well.

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!



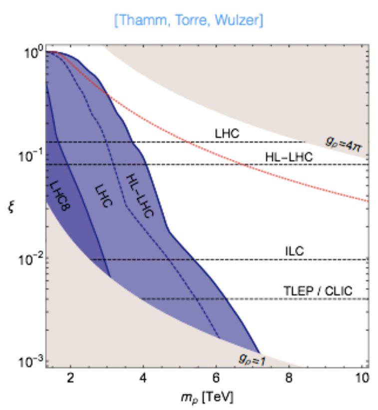
N.Craig @ FCC week

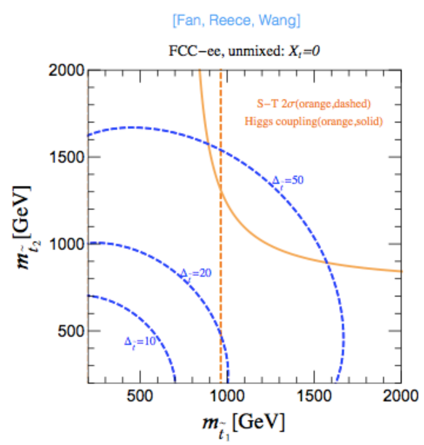
N.Craig

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.





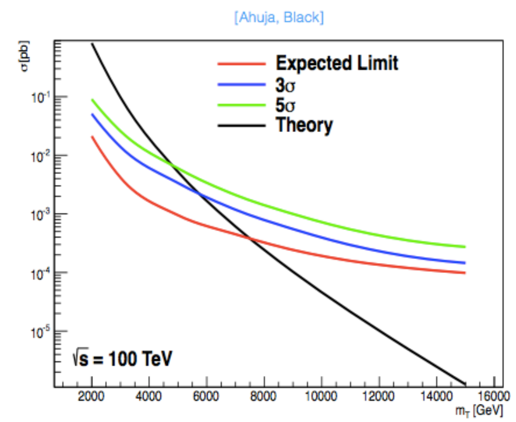
Where we'll be @ Higgs factory:
Sensitive to kinematic holes at LHC.

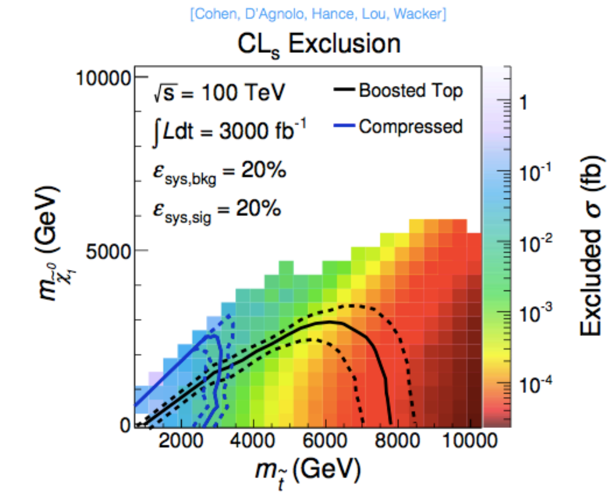
~1-2% level

Colorful naturalness

Probing at 100 TeV:

Look for the light partner states





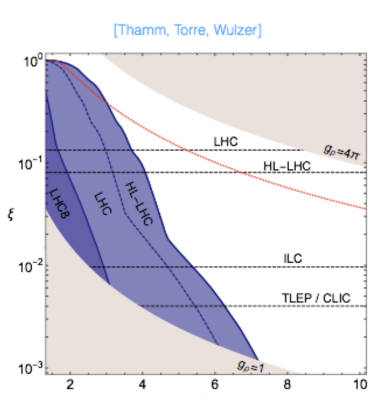
Where we'll be @ 100 TeV: "generically"

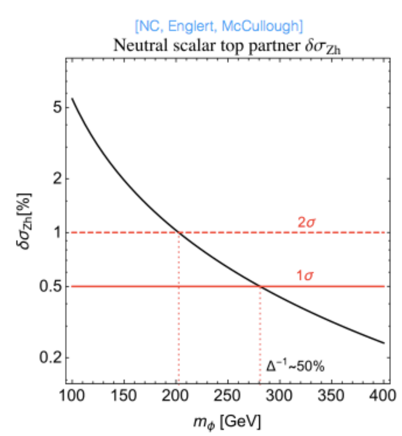
~.05% level

Neutral naturalness

Probing at a Higgs factory:

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





Where we'll be @ Higgs factory:

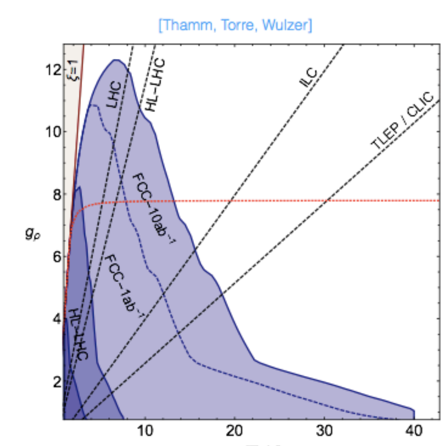
~1% level (global)
~50% level (SUSY)

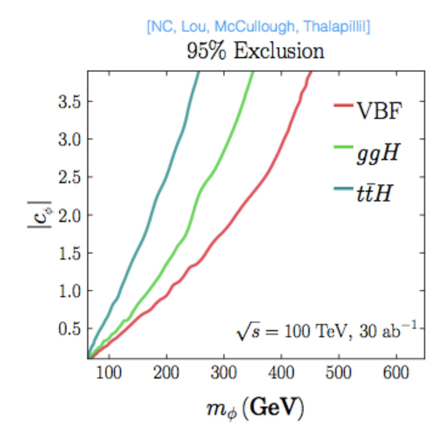
Even if the light natural states are neutral, there are heavier states with SM charges

Neutral naturalness

Probing at 100 TeV

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





Where we'll be @ 100 TeV:

~1% level

SM observables

Global FCC-ee programme, beyond the Higgs: 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 $Z+\gamma$(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?

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

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

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

=> 10^{12} W bosons from top decays => *probe rare W decays ?*

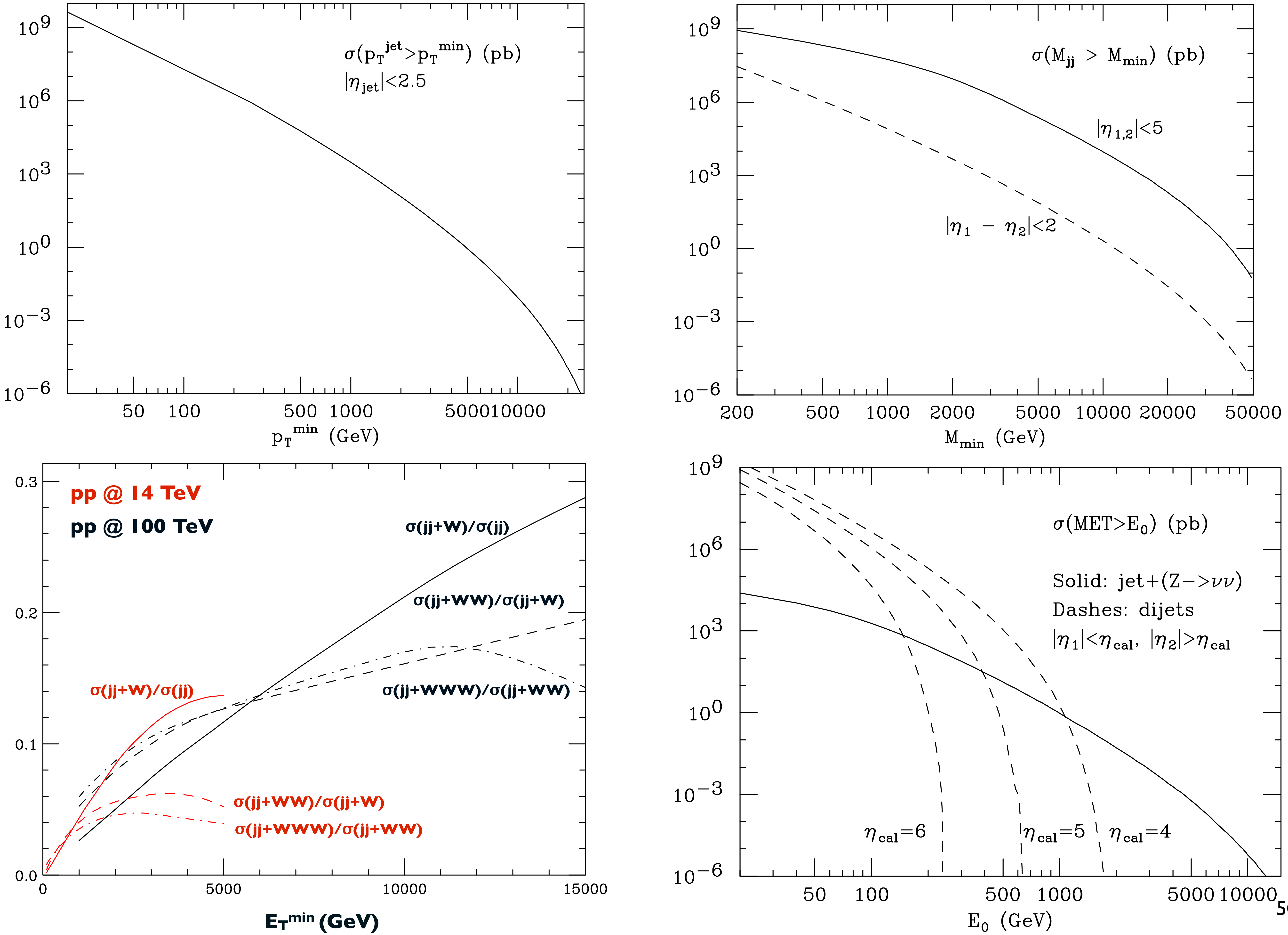
=> 10^{12} b hadrons from top decays (particle/antiparticle tagged)

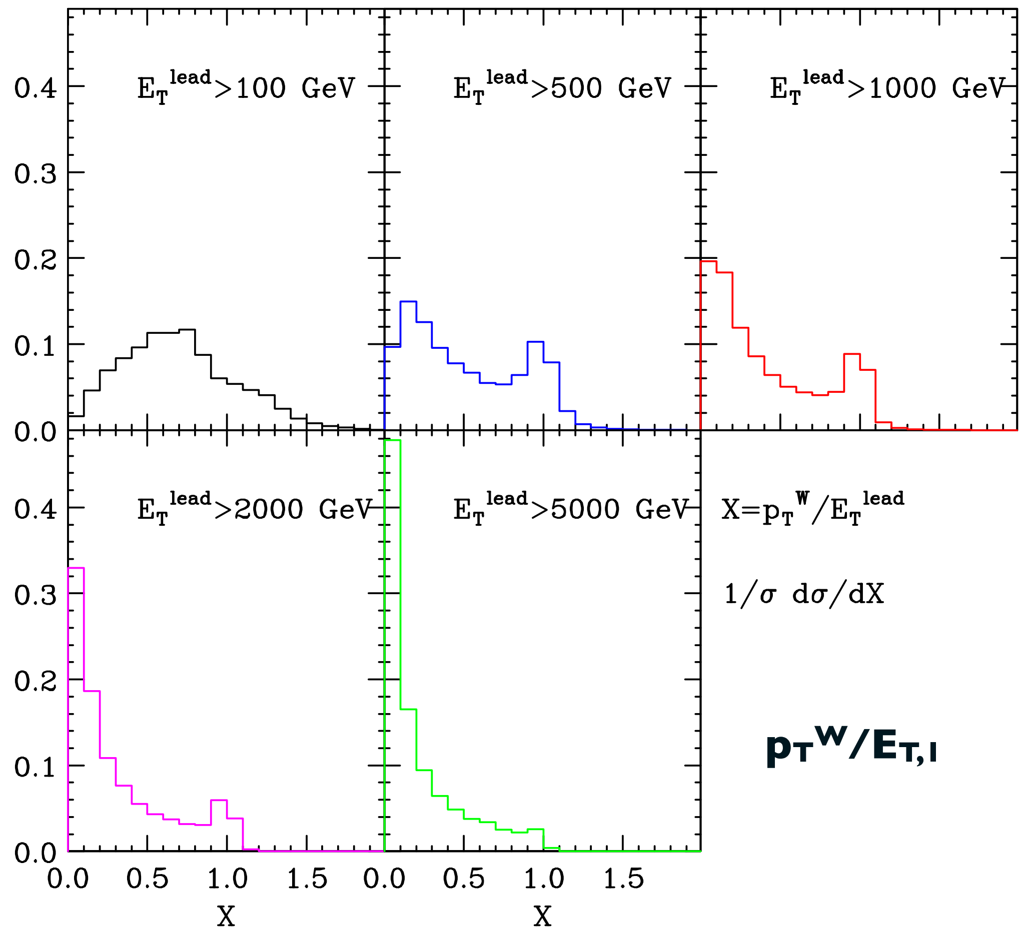
=> 10^{11} $t \to W \to$ taus => *reach for tau rare decays?*

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

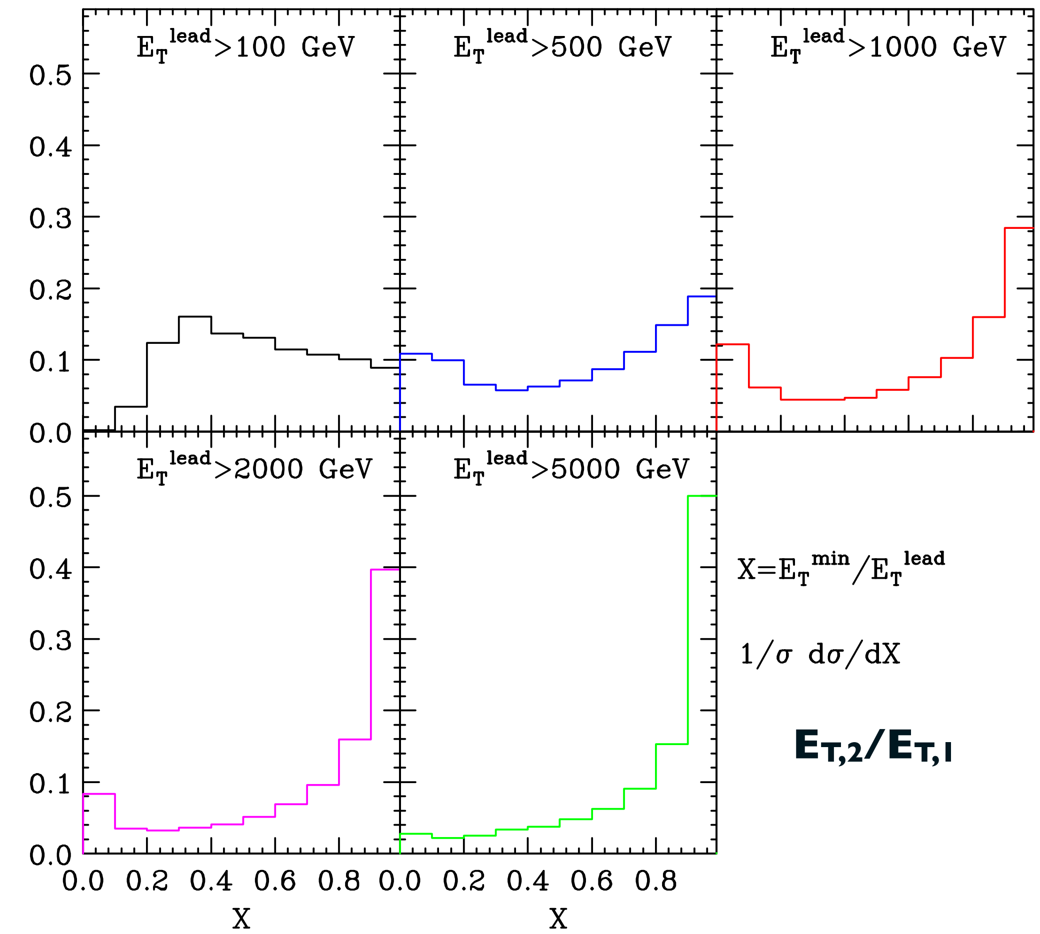
=> plenty of new studies and opportunities for measurements become available ..... few examples

Extreme kinematic regimes possible at 100 TeV

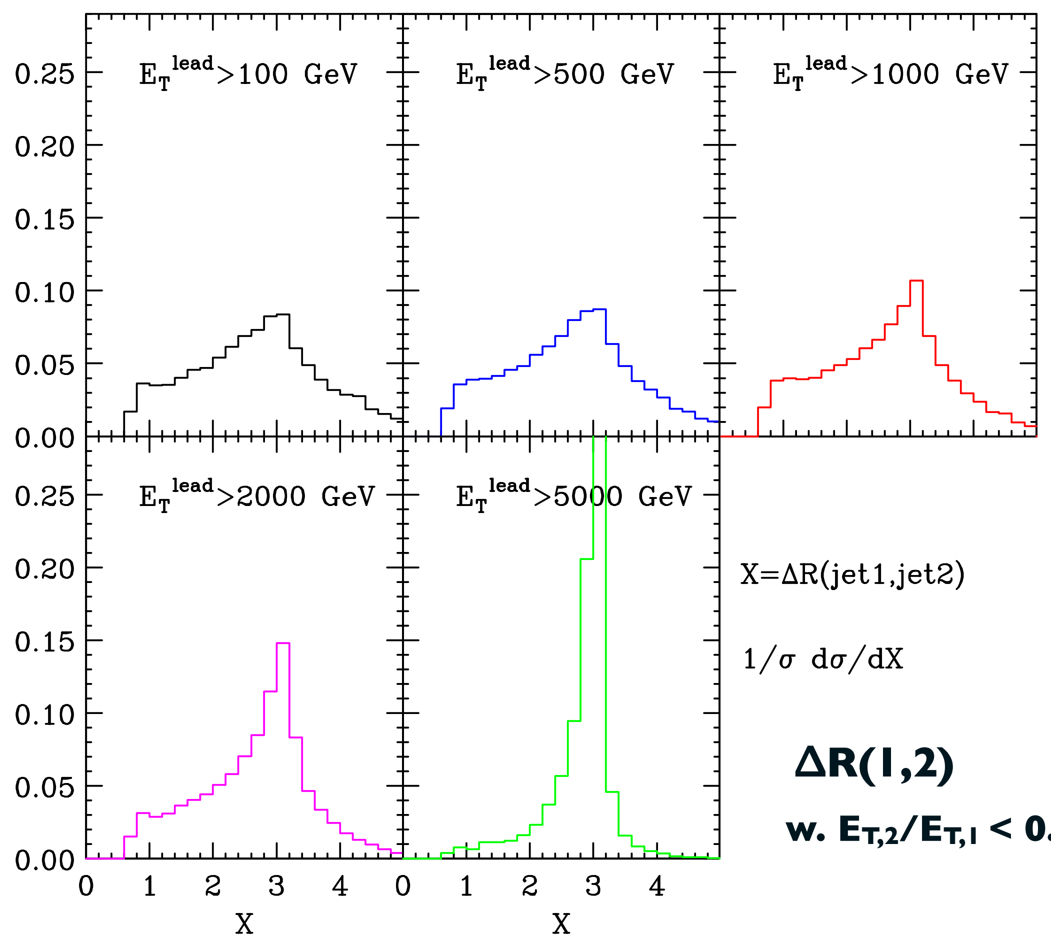




$p_T^W/E_{T,1}$

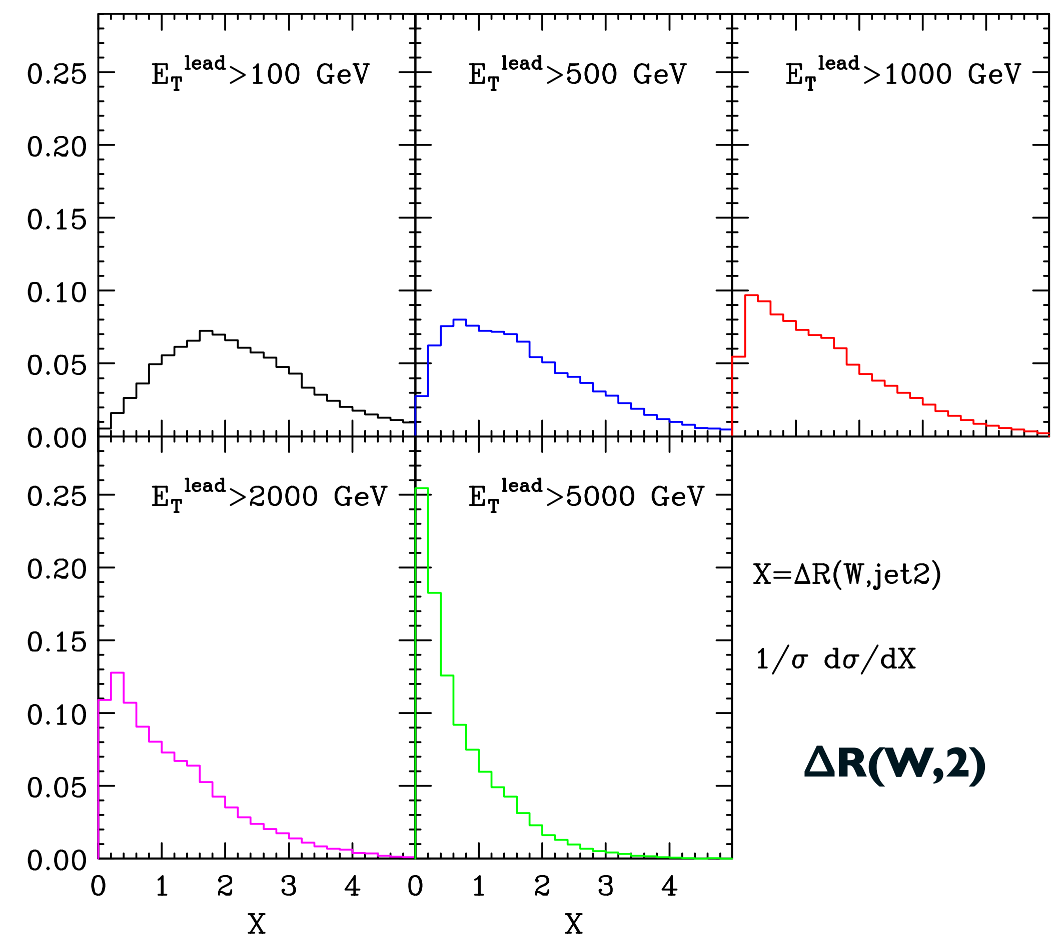


$E_{T,2}/E_{T,1}$



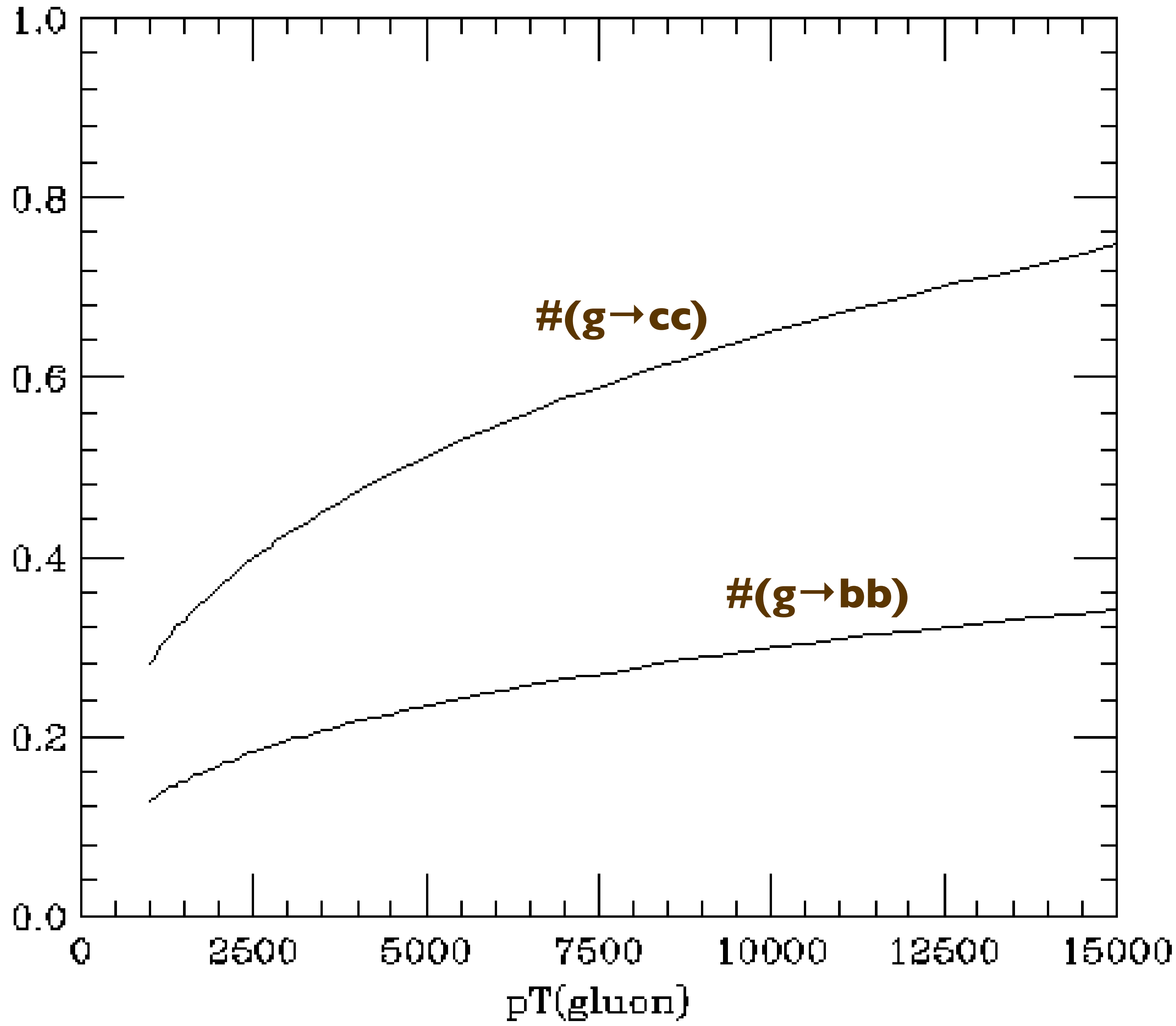
$\Delta R(1,2)$

w. $E_{T,2}/E_{T,1} < 0.2$



$\Delta R(W,2)$

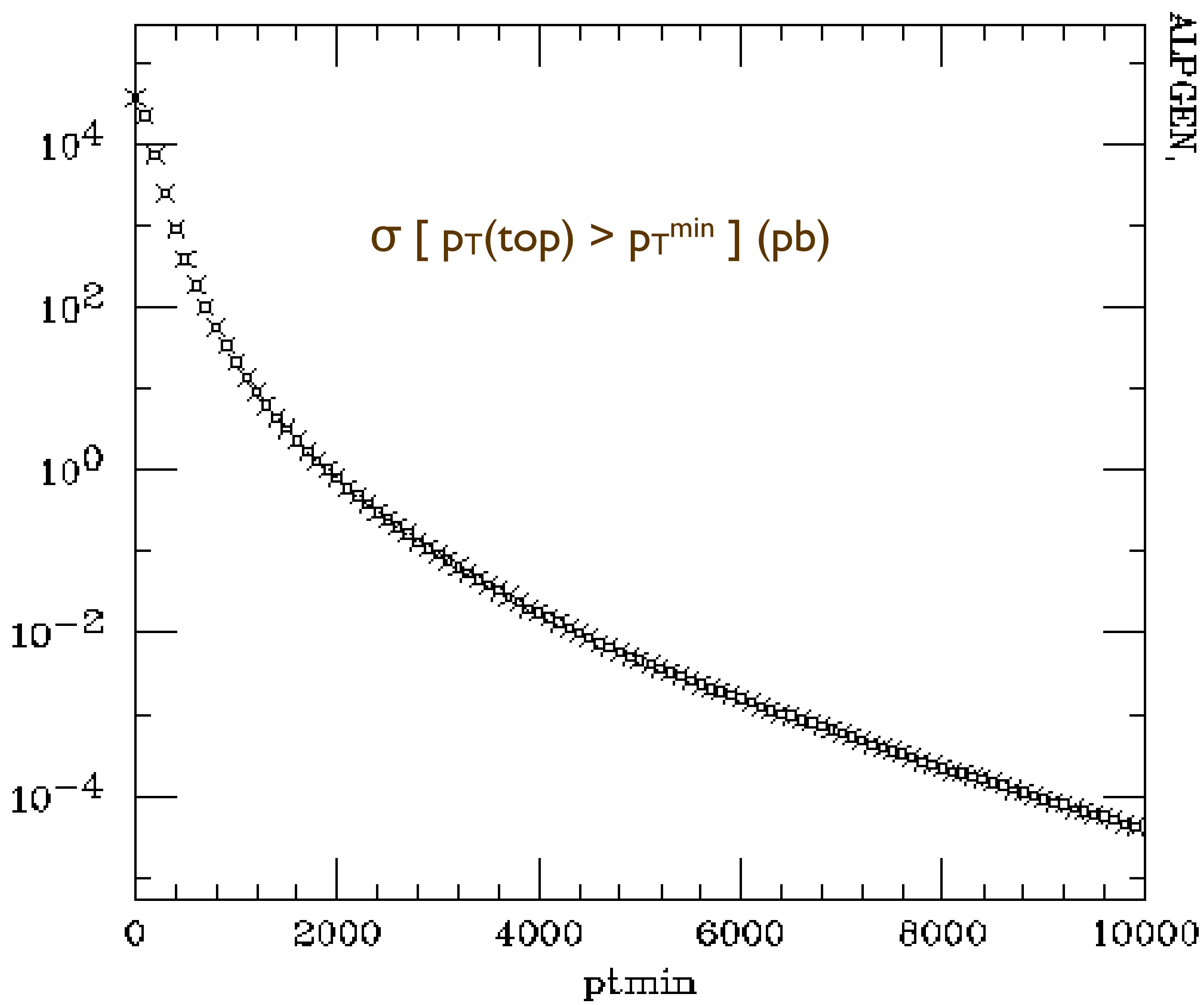
NB: large hvq production (and thus semileptonic decays) **in gluon jets at large pT**

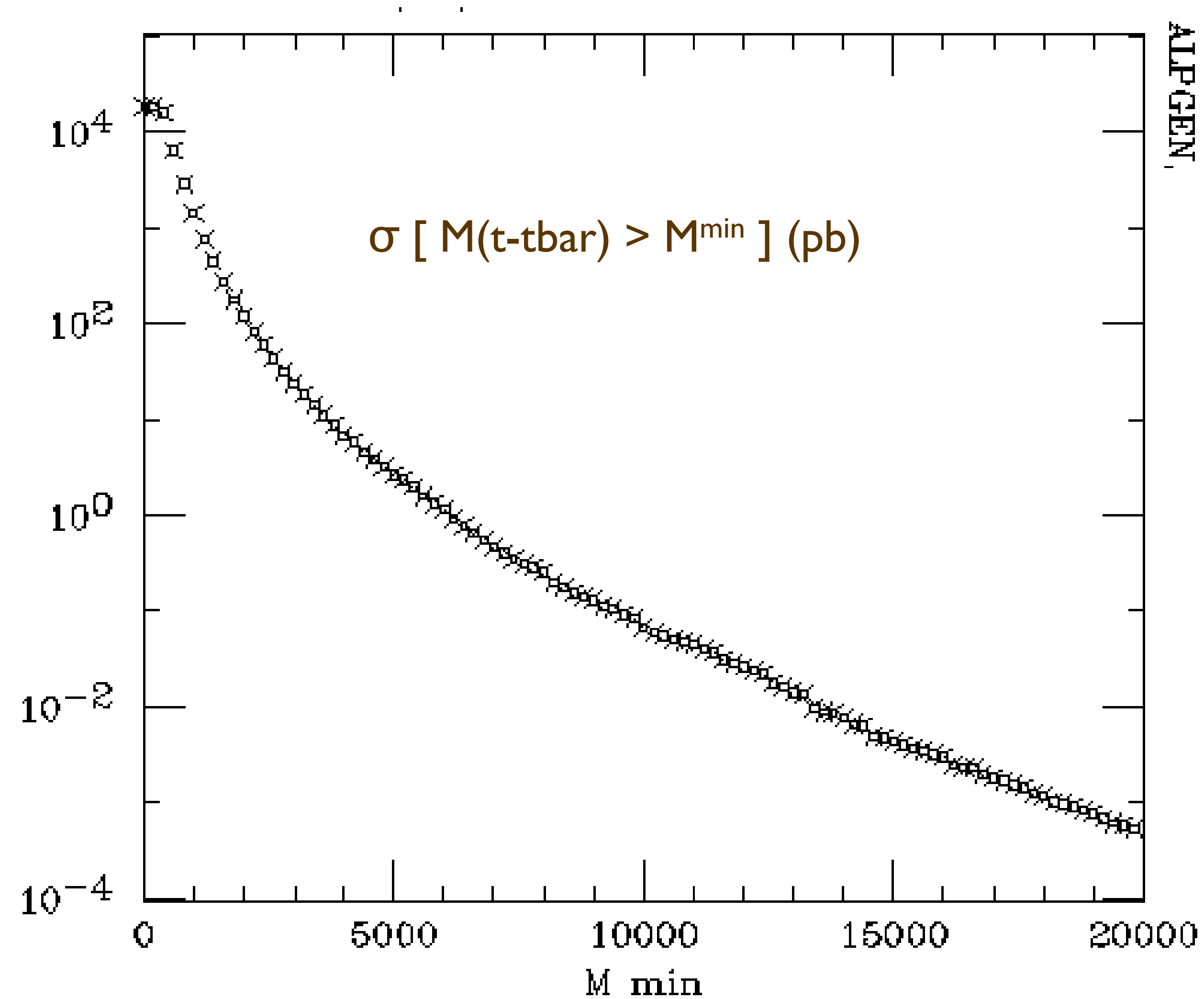


Above 10 TeV, each gluon jet contains one pair of charm or bottom quarks !!

Inclusive t-tbar production: cross sections

$\sigma \sim 30\text{nb} \Rightarrow 3 \times 10^{10}$ pairs / 1000 fb^{-1}





Process	σ_{NLO}(8 TeV) [fb]	σ_{NLO}(100 TeV) [fb]	ρ
$pp \to W^+W^-W^\pm$ (4FS)	$8.73 \cdot 10^1\ {}^{+6\%}_{-4\%}\ {}^{+2\%}_{-2\%}$	$4.25 \cdot 10^3\ {}^{+9\%}_{-9\%}\ {}^{+1\%}_{-1\%}$	49
$pp \to W^+W^-Z$ (4FS)	$6.41 \cdot 10^1\ {}^{+7\%}_{-5\%}\ {}^{+2\%}_{-2\%}$	$4.01 \cdot 10^3\ {}^{+9\%}_{-9\%}\ {}^{+1\%}_{-1\%}$	63
$pp \to \gamma W^\pm Z$	$7.11 \cdot 10^1\ {}^{+8\%}_{-7\%}\ {}^{+2\%}_{-1\%}$	$3.61 \cdot 10^3\ {}^{+12\%}_{-12\%}\ {}^{+1\%}_{-1\%}$	51
$pp \to W^\pm ZZ$	$2.16 \cdot 10^1\ {}^{+7\%}_{-6\%}\ {}^{+2\%}_{-2\%}$	$1.36 \cdot 10^3\ {}^{+10\%}_{-10\%}\ {}^{+1\%}_{-1\%}$	63
$pp \to \gamma ZZ$	$2.24 \cdot 10^1\ {}^{+4\%}_{-3\%}\ {}^{+2\%}_{-2\%}$	$6.62 \cdot 10^2\ {}^{+8\%}_{-9\%}\ {}^{+2\%}_{-1\%}$	30
$pp \to ZZZ$	$5.97 \cdot 10^0\ {}^{+3\%}_{-3\%}\ {}^{+2\%}_{-2\%}$	$2.55 \cdot 10^2\ {}^{+5\%}_{-7\%}\ {}^{+2\%}_{-1\%}$	43
$pp \to W^+W^-W^\pm\gamma$ (4FS)	$6.78 \cdot 10^{-1}\ {}^{+8\%}_{-6\%}\ {}^{+2\%}_{-2\%}$	$7.42 \cdot 10^1\ {}^{+8\%}_{-8\%}\ {}^{+1\%}_{-1\%}$	109
$pp \to W^+W^-W^\pm Z$ (4FS)	$3.48 \cdot 10^{-1}\ {}^{+8\%}_{-7\%}\ {}^{+2\%}_{-2\%}$	$5.95 \cdot 10^1\ {}^{+7\%}_{-7\%}\ {}^{+1\%}_{-1\%}$	171
$pp \to W^+W^-W^+W^-$ (4FS)	$3.01 \cdot 10^{-1}\ {}^{+7\%}_{-6\%}\ {}^{+2\%}_{-2\%}$	$4.11 \cdot 10^1\ {}^{+7\%}_{-6\%}\ {}^{+1\%}_{-1\%}$	137
$pp \to W^+W^-ZZ$ (4FS)	$2.01 \cdot 10^{-1}\ {}^{+7\%}_{-6\%}\ {}^{+2\%}_{-2\%}$	$3.34 \cdot 10^1\ {}^{+6\%}_{-6\%}\ {}^{+1\%}_{-1\%}$	166
$pp \to W^\pm ZZZ$	$3.40 \cdot 10^{-2}\ {}^{+10\%}_{-8\%}\ {}^{+2\%}_{-2\%}$	$7.06 \cdot 10^0\ {}^{+8\%}_{-7\%}\ {}^{+1\%}_{-1\%}$	208
$pp \to ZZZZ$	$8.72 \cdot 10^{-3}\ {}^{+4\%}_{-4\%}\ {}^{+3\%}_{-2\%}$	$8.05 \cdot 10^{-1}\ {}^{+4\%}_{-4\%}\ {}^{+2\%}_{-1\%}$	92
$pp \to W^+W^-W^+W^-\gamma$ (4FS)	$5.18 \cdot 10^{-3}\ {}^{+8\%}_{-7\%}\ {}^{+3\%}_{-2\%}$	$1.58 \cdot 10^0\ {}^{+6\%}_{-5\%}\ {}^{+1\%}_{-1\%}$	305
$pp \to ZZZZZ$	$1.07 \cdot 10^{-5}\ {}^{+5\%}_{-4\%}\ {}^{+3\%}_{-2\%}$	$2.04 \cdot 10^{-3}\ {}^{+3\%}_{-3\%}\ {}^{+2\%}_{-1\%}$	191

Table 2: Production of multiple vector bosons at the LHC and at a 100 TeV FCC-hh. The rightmost column reports the ratio ρ of the FCC-hh to the LHC cross sections. Theoretical uncertainties are due to scale and PDF variations, respectively. Monte-Carlo-integration error is always smaller than theoretical uncertainties, and is not shown.

P.Torrielli, arXiv:1407.1623

Process	$\sigma_{\rm NLO}$(8 TeV) [fb]	$\sigma_{\rm NLO}$(100 TeV) [fb]	ρ
$pp \to t\bar{t}\gamma$	$6.50 \cdot 10^2\ ^{+12\%}_{-13\%}\ ^{+2\%}_{-2\%}$	$1.24 \cdot 10^5\ ^{+11\%}_{-11\%}\ ^{+1\%}_{-1\%}$	192
$pp \to t\bar{t}Z$	$1.99 \cdot 10^2\ ^{+10\%}_{-12\%}\ ^{+3\%}_{-3\%}$	$5.63 \cdot 10^4\ ^{+9\%}_{-10\%}\ ^{+1\%}_{-1\%}$	282
$pp \to t\bar{t}W^{\pm}$	$2.05 \cdot 10^2\ ^{+9\%}_{-10\%}\ ^{+2\%}_{-2\%}$	$1.68 \cdot 10^4\ ^{+18\%}_{-16\%}\ ^{+1\%}_{-1\%}$	82
$pp \to t\bar{t}\gamma j$	$1.22 \cdot 10^2\ ^{+17\%}_{-18\%}\ ^{+3\%}_{-3\%}$	$6.07 \cdot 10^4\ ^{+8\%}_{-10\%}\ ^{+1\%}_{-1\%}$	498
$pp \to t\bar{t}Zj$	$3.51 \cdot 10^1\ ^{+15\%}_{-18\%}\ ^{+4\%}_{-4\%}$	$2.77 \cdot 10^4\ ^{+7\%}_{-9\%}\ ^{+1\%}_{-1\%}$	789
$pp \to t\bar{t}W^{\pm}j$	$3.59 \cdot 10^1\ ^{+18\%}_{-18\%}\ ^{+2\%}_{-2\%}$	$1.36 \cdot 10^4\ ^{+14\%}_{-13\%}\ ^{+1\%}_{-1\%}$	379
$pp \to t\bar{t}W^{\pm}jj$	$5.67 \cdot 10^0\ ^{+24\%}_{-23\%}\ ^{+3\%}_{-2\%}$	$6.52 \cdot 10^3\ ^{+11\%}_{-14\%}\ ^{+1\%}_{-1\%}$	1150
$pp \to t\bar{t}W^+W^-$ (4FS)	$2.27 \cdot 10^0\ ^{+11\%}_{-13\%}\ ^{+3\%}_{-3\%}$	$1.10 \cdot 10^3\ ^{+9\%}_{-9\%}\ ^{+1\%}_{-1\%}$	486
$pp \to t\bar{t}\gamma\gamma$	$2.23 \cdot 10^0\ ^{+14\%}_{-13\%}\ ^{+2\%}_{-1\%}$	$4.81 \cdot 10^2\ ^{+13\%}_{-11\%}\ ^{+1\%}_{-1\%}$	216
$pp \to t\bar{t}Z\gamma$	$1.11 \cdot 10^0\ ^{+12\%}_{-13\%}\ ^{+2\%}_{-2\%}$	$4.20 \cdot 10^2\ ^{+10\%}_{-9\%}\ ^{+1\%}_{-1\%}$	378
$pp \to t\bar{t}W^{\pm}Z$	$9.71 \cdot 10^{-1}\ ^{+10\%}_{-11\%}\ ^{+3\%}_{-2\%}$	$1.68 \cdot 10^2\ ^{+16\%}_{-13\%}\ ^{+1\%}_{-1\%}$	173
$pp \to t\bar{t}ZZ$	$4.47 \cdot 10^{-1}\ ^{+8\%}_{-10\%}\ ^{+3\%}_{-2\%}$	$1.58 \cdot 10^2\ ^{+15\%}_{-12\%}\ ^{+1\%}_{-1\%}$	353

Table 3: Production of a top-antitop pair in association with up to two electroweak vector bosons, and with an electroweak boson and up to two jets, at the LHC and at a 100 TeV FCC-hh. The rightmost column reports the ratio ρ of the FCC-hh to the LHC cross sections. Processes $pp \to t\bar{t}Vj(j)$ feature a cut of $p_T(j) > 100$ GeV. Theoretical uncertainties are due to scale and PDF variations, respectively. Monte-Carlo-integration error is always smaller than theoretical uncertainties, and is not shown.

P.Torrielli, arXiv:1407.1623

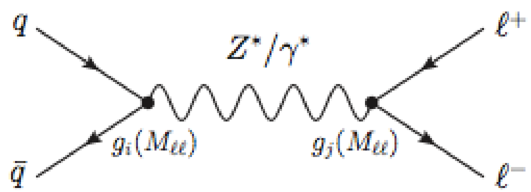
Process	$\sigma_{\rm NLO}$(8 TeV) [fb]	$\sigma_{\rm NLO}$(100 TeV) [fb]	ρ
$pp \to H\ (m_t, m_b)$	$1.44 \cdot 10^4\ ^{+20\%}_{-16\%}\ ^{+1\%}_{-2\%}$	$5.46 \cdot 10^5\ ^{+28\%}_{-27\%}\ ^{+2\%}_{-2\%}$	38
$pp \to Hjj$ (VBF)	$1.61 \cdot 10^3\ ^{+1\%}_{-0\%}\ ^{+2\%}_{-2\%}$	$7.40 \cdot 10^4\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-1\%}$	46
$pp \to Ht\bar{t}$	$1.21 \cdot 10^2\ ^{+5\%}_{-9\%}\ ^{+3\%}_{-3\%}$	$3.25 \cdot 10^4\ ^{+7\%}_{-8\%}\ ^{+1\%}_{-1\%}$	269
$pp \to Hb\bar{b}$ (4FS)	$2.37 \cdot 10^2\ ^{+9\%}_{-9\%}\ ^{+2\%}_{-2\%}$	$1.21 \cdot 10^4\ ^{+2\%}_{-10\%}\ ^{+2\%}_{-2\%}$	51
$pp \to Htj$	$2.07 \cdot 10^1\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$5.21 \cdot 10^3\ ^{+3\%}_{-5\%}\ ^{+1\%}_{-1\%}$	252
$pp \to HW^\pm$	$7.31 \cdot 10^2\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$1.54 \cdot 10^4\ ^{+5\%}_{-8\%}\ ^{+2\%}_{-2\%}$	21
$pp \to HZ$	$3.87 \cdot 10^2\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$8.82 \cdot 10^3\ ^{+4\%}_{-8\%}\ ^{+2\%}_{-2\%}$	23
$pp \to HW^+W^-$ (4FS)	$4.62 \cdot 10^0\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$1.68 \cdot 10^2\ ^{+5\%}_{-6\%}\ ^{+2\%}_{-1\%}$	36
$pp \to HZW^\pm$	$2.17 \cdot 10^0\ ^{+4\%}_{-4\%}\ ^{+2\%}_{-2\%}$	$9.94 \cdot 10^1\ ^{+6\%}_{-7\%}\ ^{+2\%}_{-1\%}$	46
$pp \to HW^\pm\gamma$	$2.36 \cdot 10^0\ ^{+3\%}_{-3\%}\ ^{+2\%}_{-2\%}$	$7.75 \cdot 10^1\ ^{+7\%}_{-8\%}\ ^{+2\%}_{-1\%}$	33
$pp \to HZ\gamma$	$1.54 \cdot 10^0\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$4.29 \cdot 10^1\ ^{+5\%}_{-7\%}\ ^{+2\%}_{-2\%}$	28
$pp \to HZZ$	$1.10 \cdot 10^0\ ^{+2\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$4.20 \cdot 10^1\ ^{+4\%}_{-6\%}\ ^{+2\%}_{-1\%}$	38
$pp \to HW^\pm j$	$3.18 \cdot 10^2\ ^{+4\%}_{-4\%}\ ^{+2\%}_{-1\%}$	$1.07 \cdot 10^4\ ^{+2\%}_{-7\%}\ ^{+2\%}_{-1\%}$	34
$pp \to HW^\pm jj$	$6.06 \cdot 10^1\ ^{+6\%}_{-8\%}\ ^{+1\%}_{-1\%}$	$4.90 \cdot 10^3\ ^{+2\%}_{-6\%}\ ^{+1\%}_{-1\%}$	81
$pp \to HZj$	$1.71 \cdot 10^2\ ^{+4\%}_{-4\%}\ ^{+1\%}_{-1\%}$	$6.31 \cdot 10^3\ ^{+2\%}_{-7\%}\ ^{+2\%}_{-1\%}$	37
$pp \to HZjj$	$3.50 \cdot 10^1\ ^{+7\%}_{-10\%}\ ^{+1\%}_{-1\%}$	$2.81 \cdot 10^3\ ^{+2\%}_{-5\%}\ ^{+1\%}_{-1\%}$	80

Table 1: Production of a single Higgs boson at the LHC and at a 100 TeV FCC-hh. The rightmost column reports the ratio ρ of the FCC-hh to the LHC cross sections. Theoretical uncertainties are due to scale and PDF variations, respectively. Monte-Carlo-integration error is always smaller than theoretical uncertainties, and is not shown. For $pp \to HVjj$, on top of the transverse-momentum cut of section 2, I require $m(j_1, j_2) > 100$ GeV, j_1 and j_2 being the hardest and next-to-hardest jets, respectively. Processes $pp \to Htj$ and $pp \to Hjj$ (VBF) do not feature jet cuts.

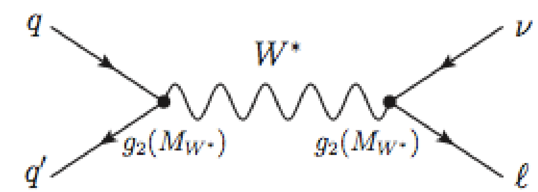
P.Torrielli, arXiv:1407.1623

Running Electroweak Couplings as a Probe of New Physics

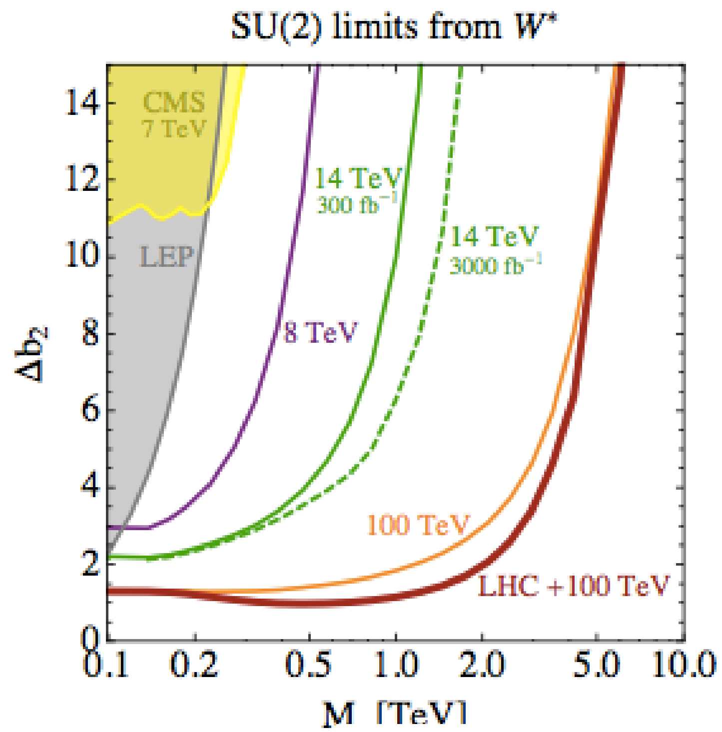
D.Alves, J. Galloway, J.Ruderman, J.Walsh *arXiv:1410.6810*

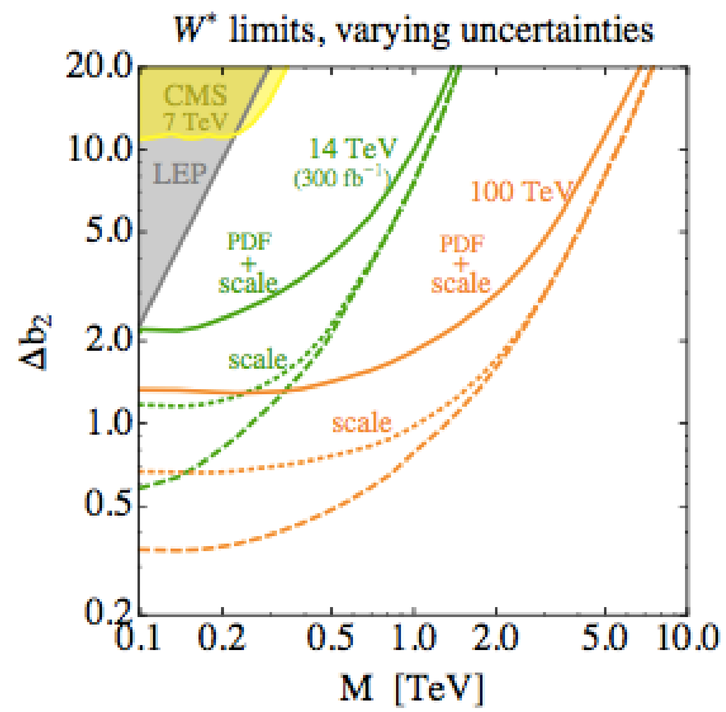


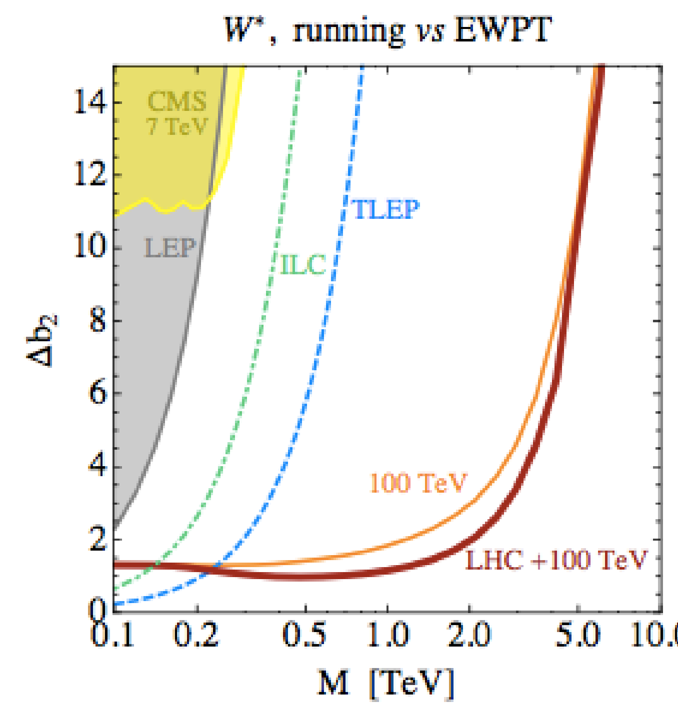
$$\frac{d\sigma}{dm_{ll}} \Rightarrow \alpha_{1,2}(q)$$

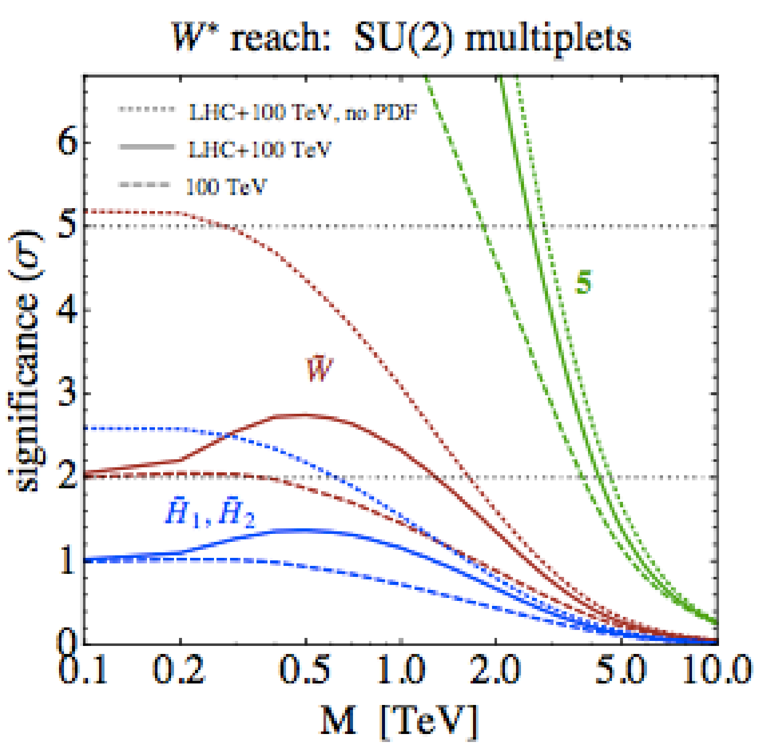


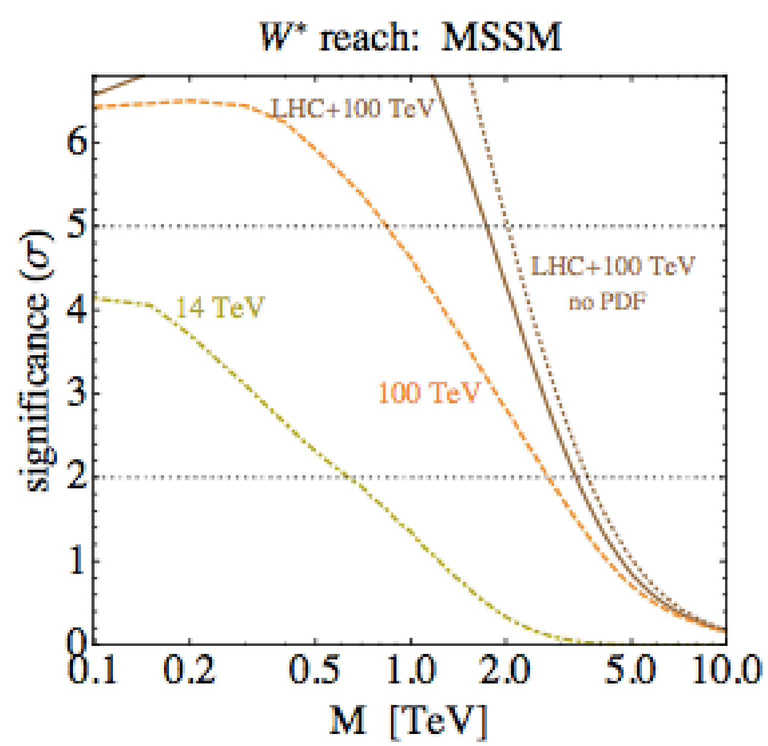
$$\frac{d\sigma}{dM_T} \Rightarrow \alpha_2(q)$$



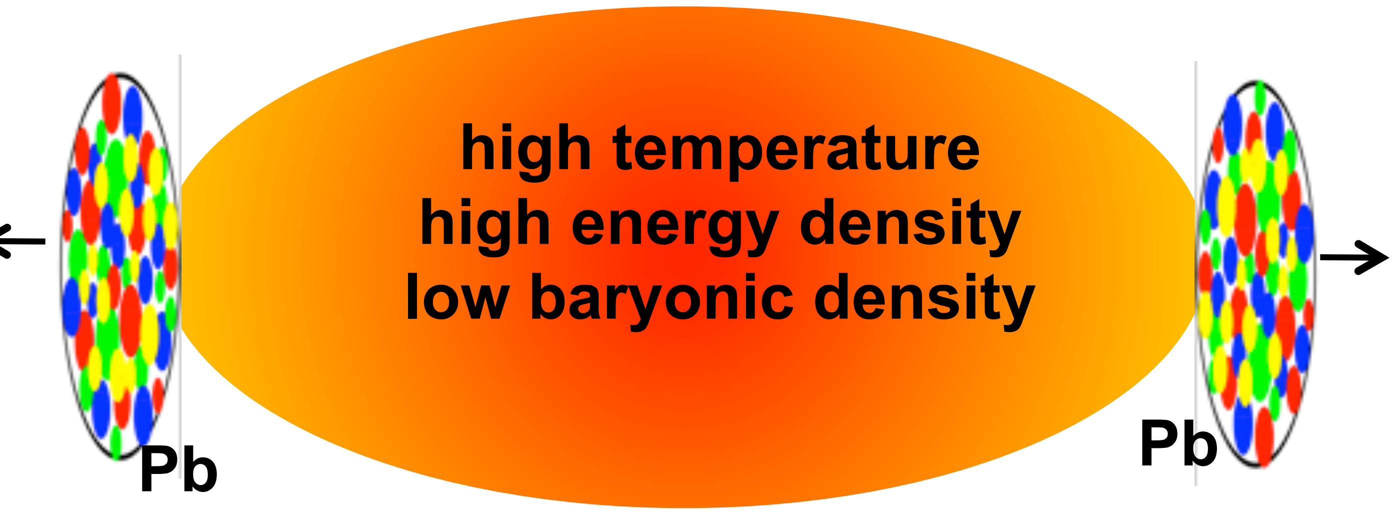


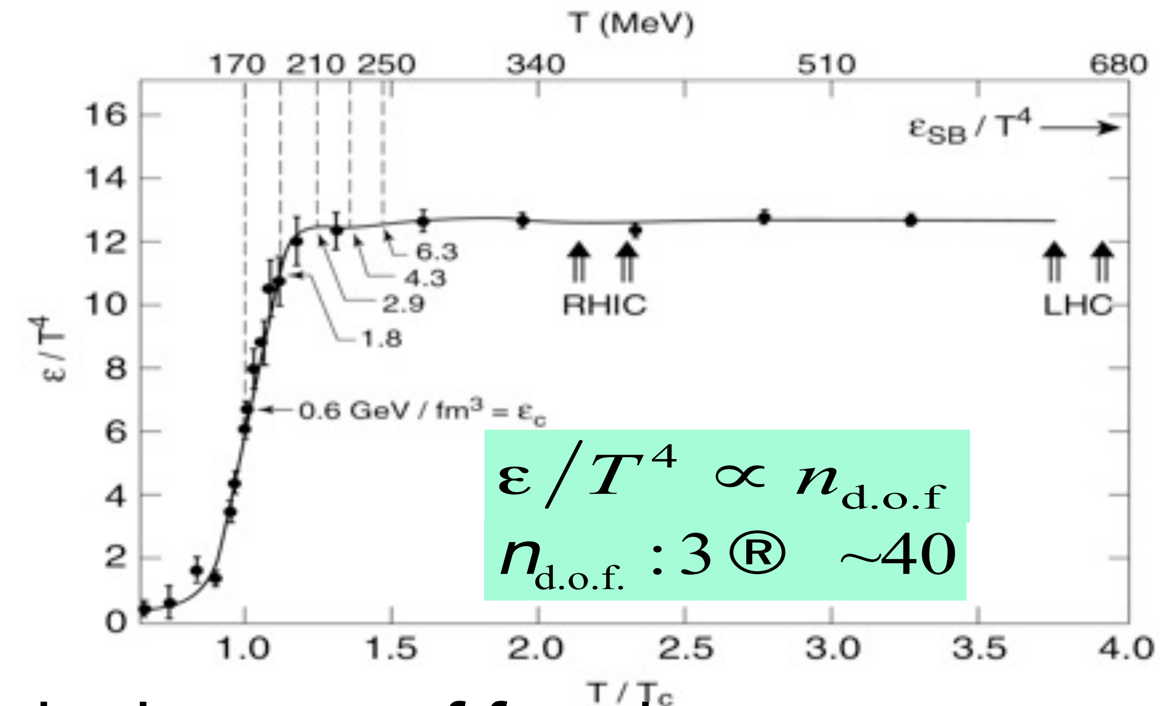






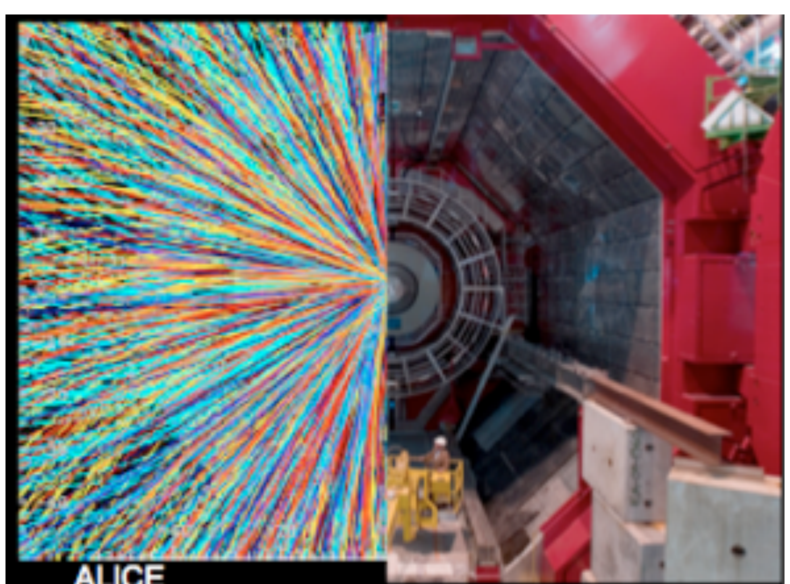
High-density QCD in the final state: the Quark Gluon Plasma

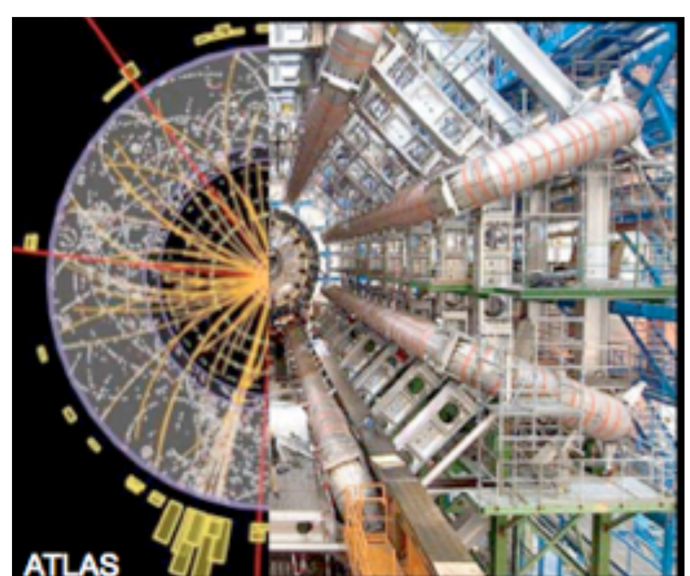


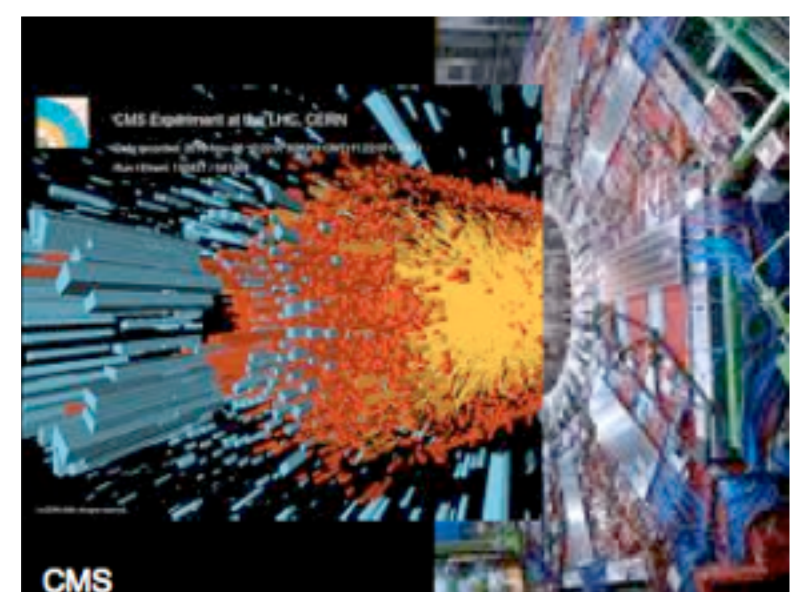


- Lattice QCD predicts phase transition at T_c~170 MeV
  → **Quark-Gluon Plasma**
- Confinement is removed

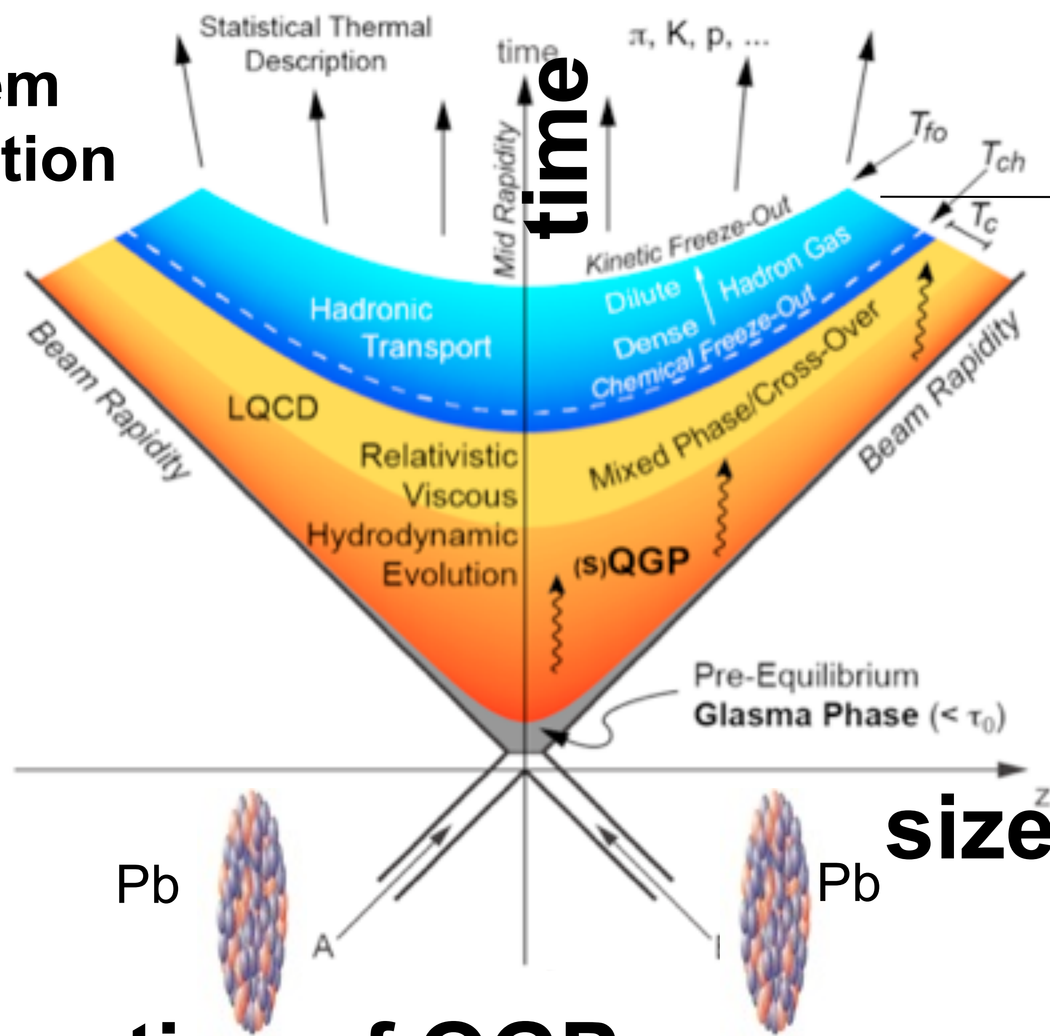
- Partonic degrees of freedom
- Unique opportunity to study in the laboratory spatially-extended multi-particle QCD system

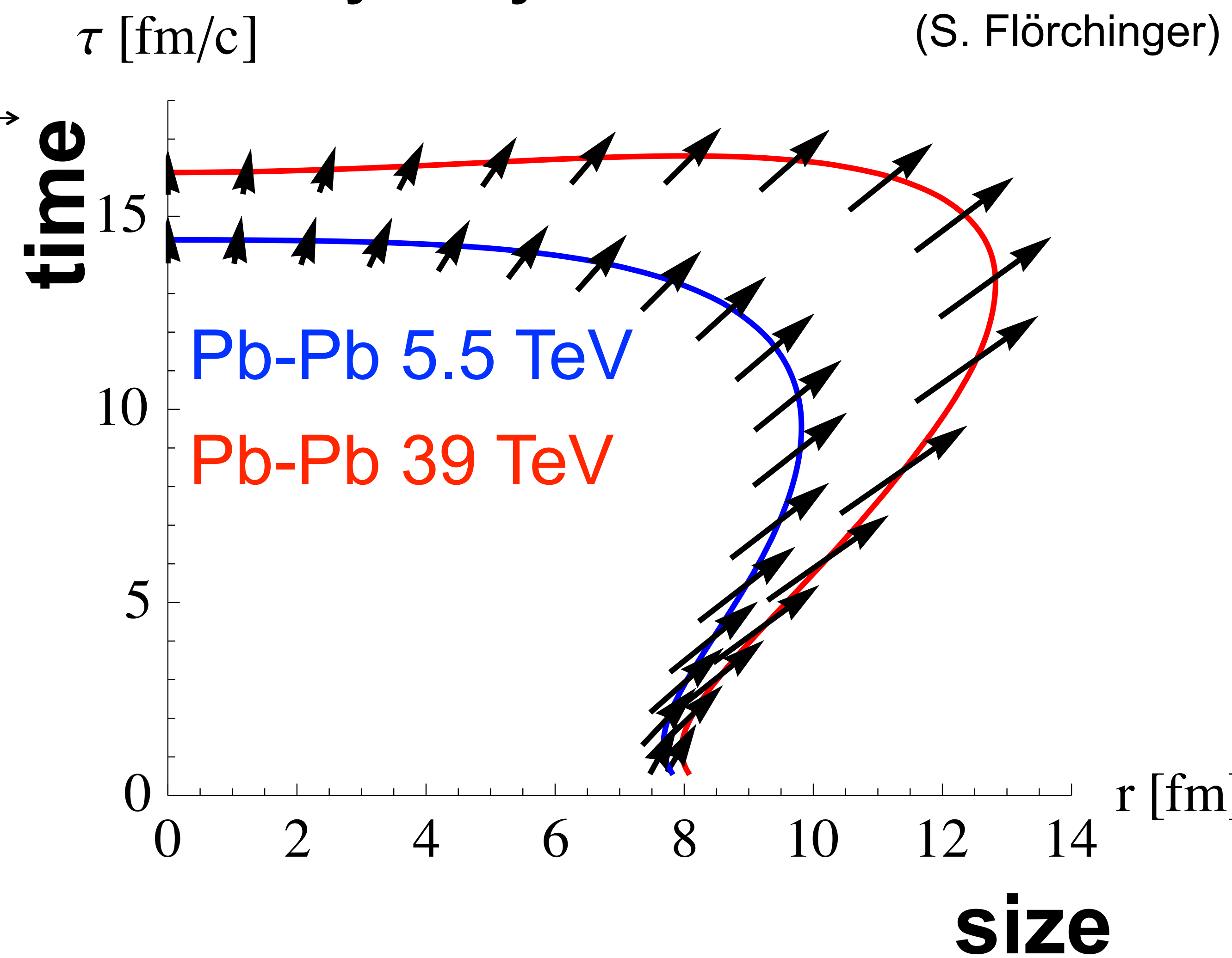






Quark-Gluon Plasma studies at FCC





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?

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
- 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 ....*