High Energy Physics: the future challenges

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19-29 October 2015

Michelangelo L. Mangano
michelangelo.mangano@cern.ch
CERN, PH-TH

The challenges

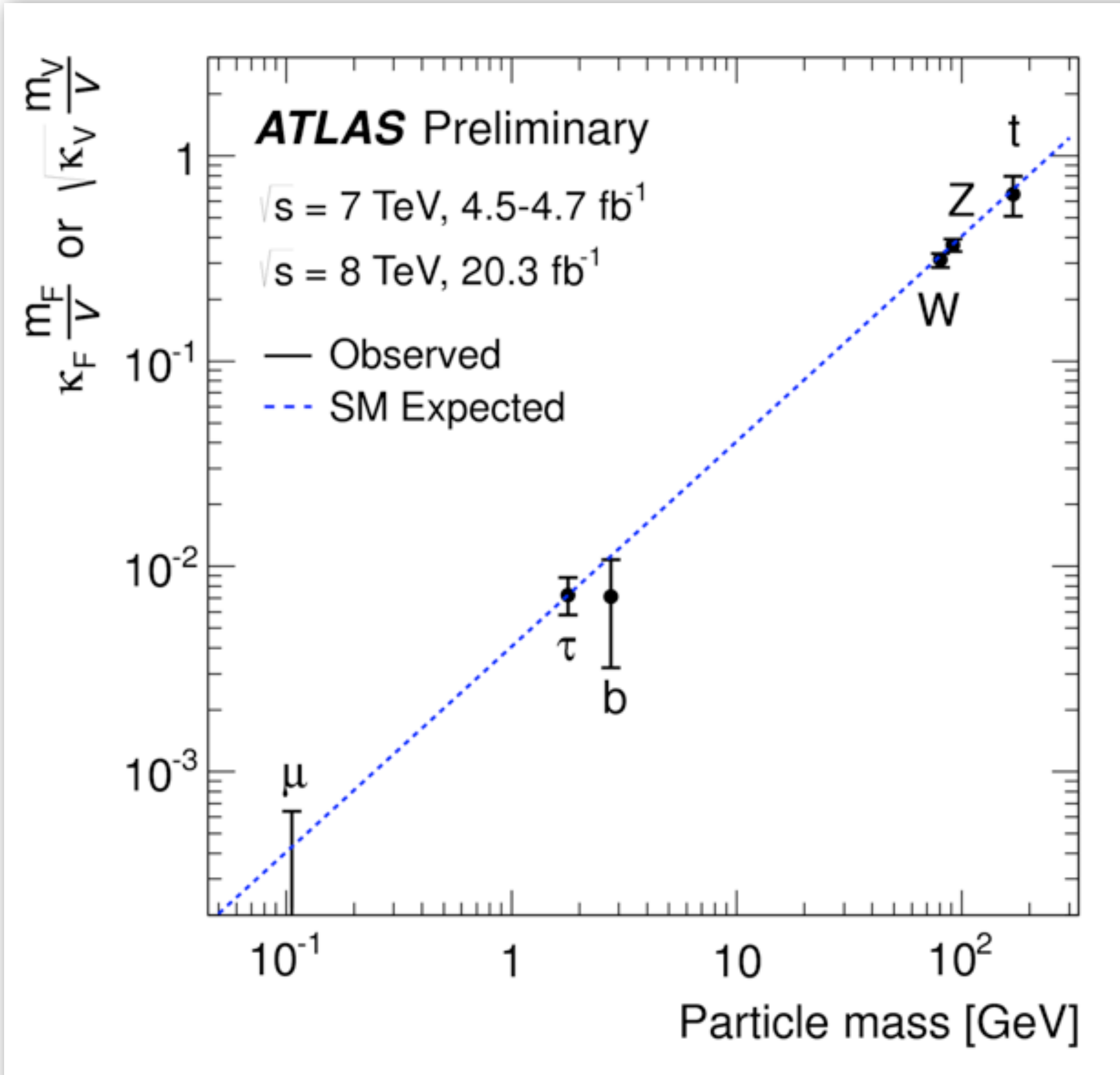
- **The ultimate challenge:**
  - ***answering the* big questions *about the fundamental laws of the universe***
- **The technological challenge:**
  - ***accelerators, detectors, data acquisition and processing***
- **The socio-political challenge:**
  - ***human resources & timescales,***
  - ***costs & competition with other expanding fields of science,***
  - **...**

The ultimate 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 answer to the big questions will likely come from a series of partial steps, addressing issues that, step by step, will emerge from data
- E.g. the discovery of neutrino masses and of the Higgs are not a final word, they are just the beginning of new lines of exploration
  - Neutrinos:
    - Majorana or Dirac?
    - Do they violate CP? Enough to allow for leptogenesis?
    - ...
  - Higgs:
    - see next ...

Run 1 of the LHC determined, with a precision of ±20%, that the Higgs boson gives a mass to SM particles



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   Most theories beyond the SM have more Higgs bosons

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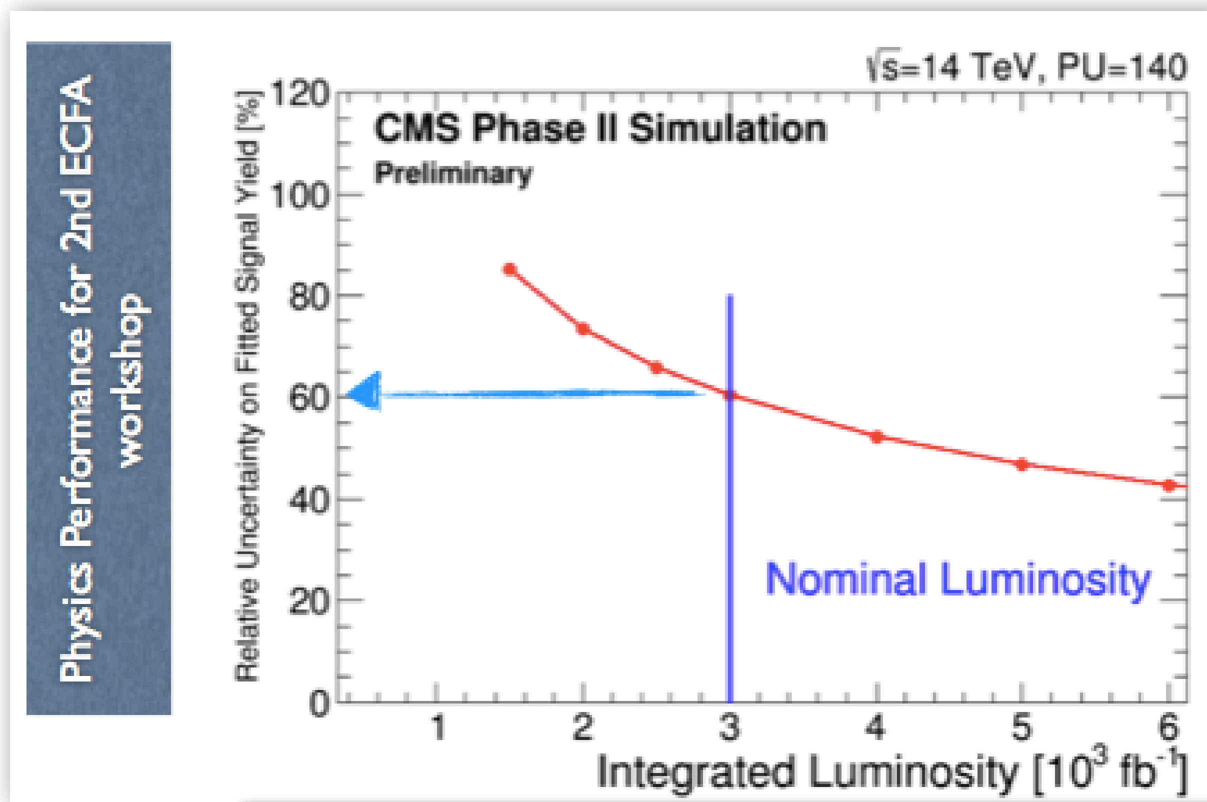

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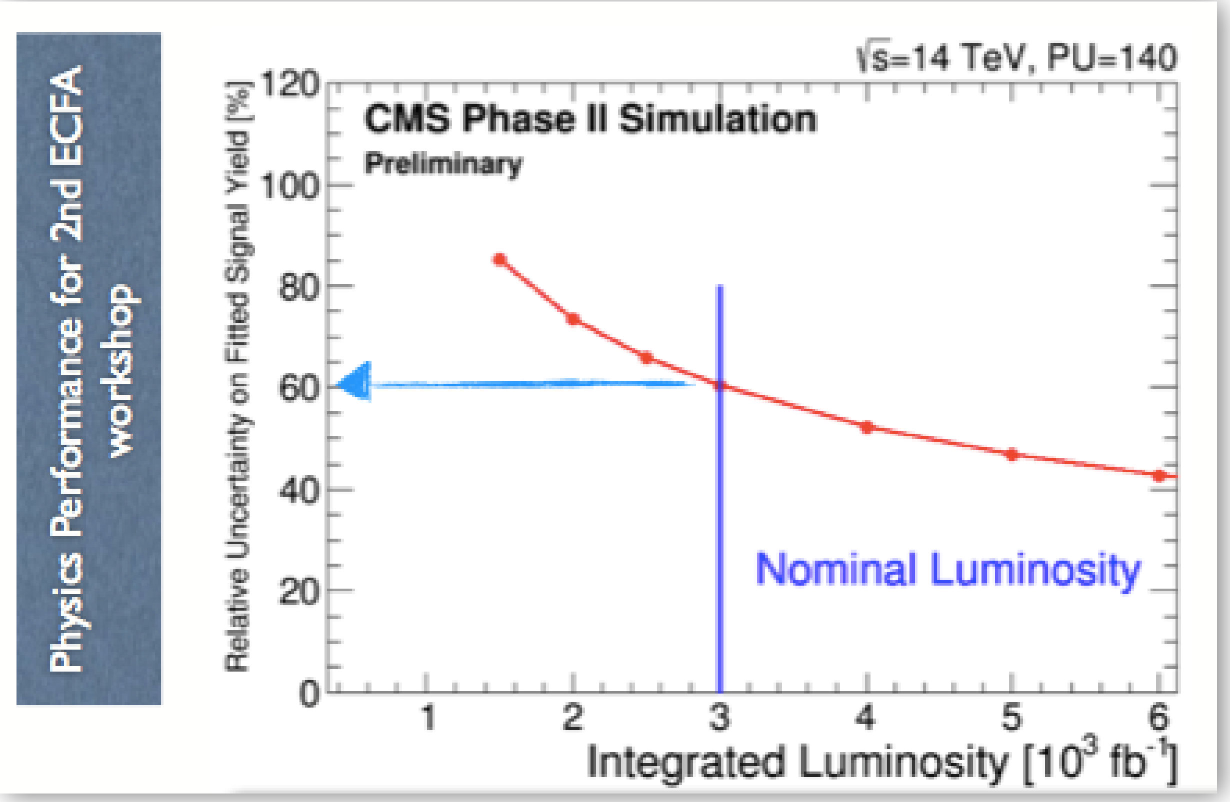
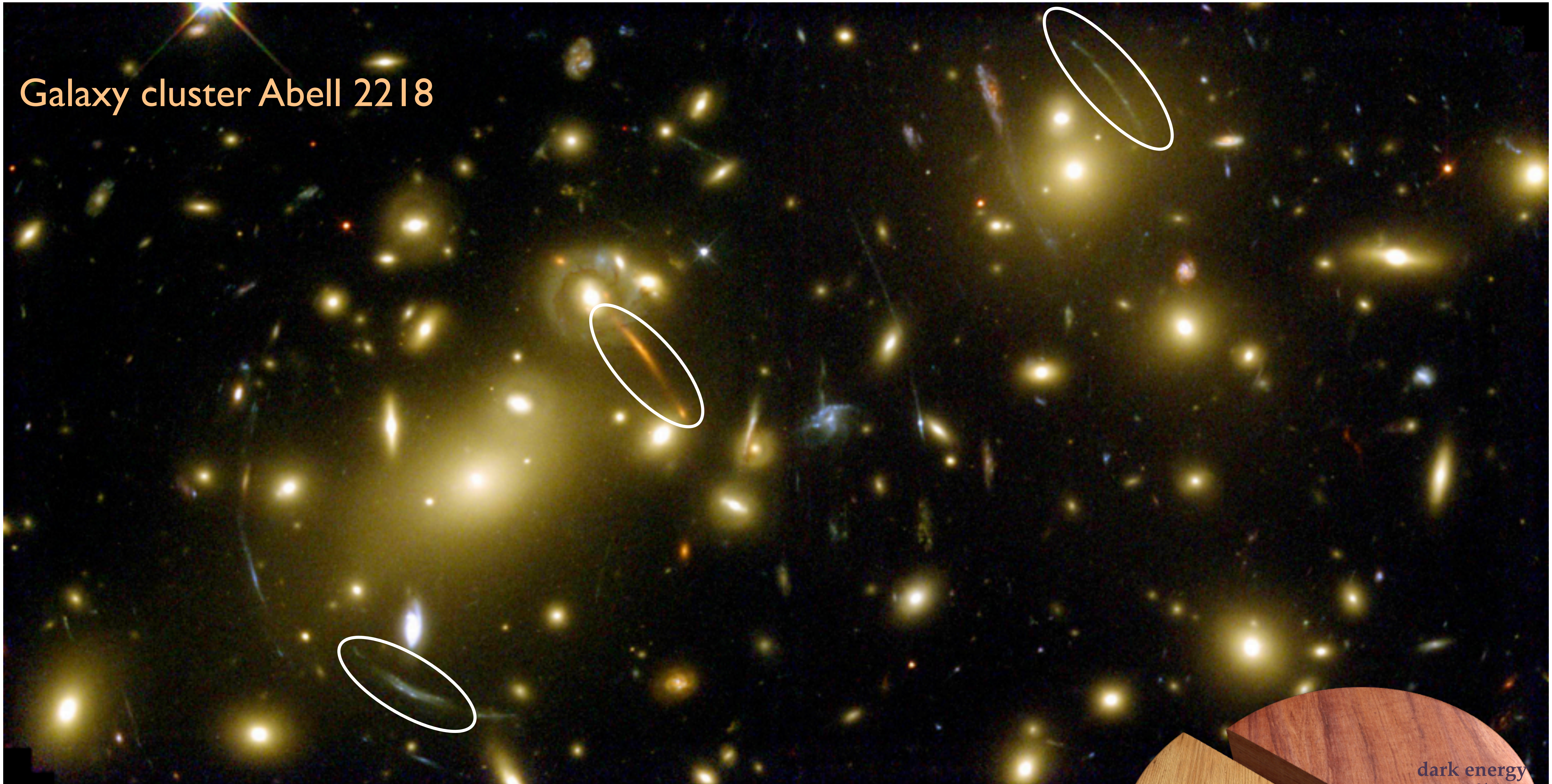


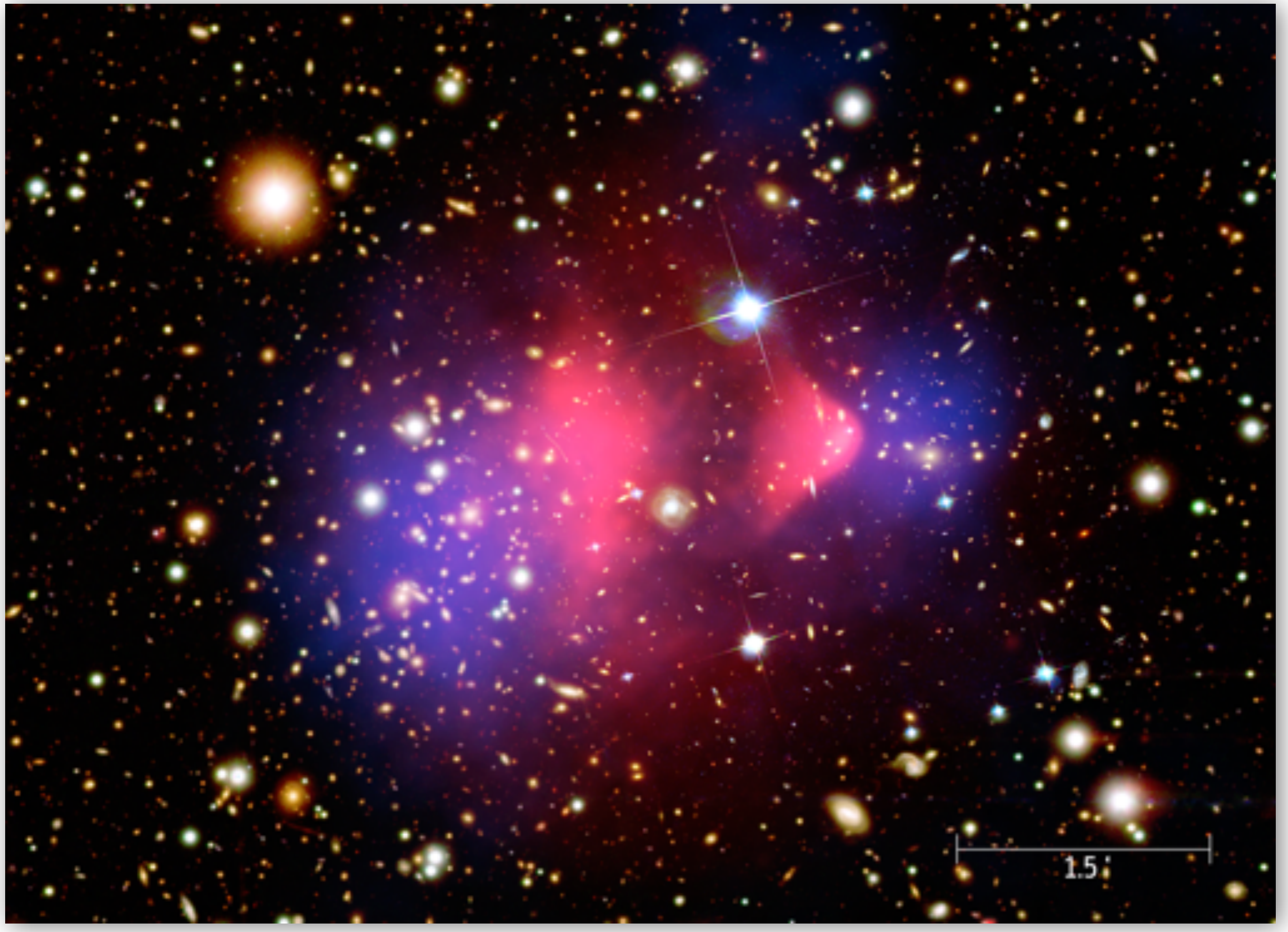
The measurement of Higgs self-interactions has broad implications on issues such as the nature of the EW phase transition during the Big Bang

What is Dark Matter?



The modeling of Dark Matter has become more and more articulate. From a single source (WIMP, axion, neutrino, ...) to the possibility of dark hidden worlds

Evidence building up for self-interacting DM



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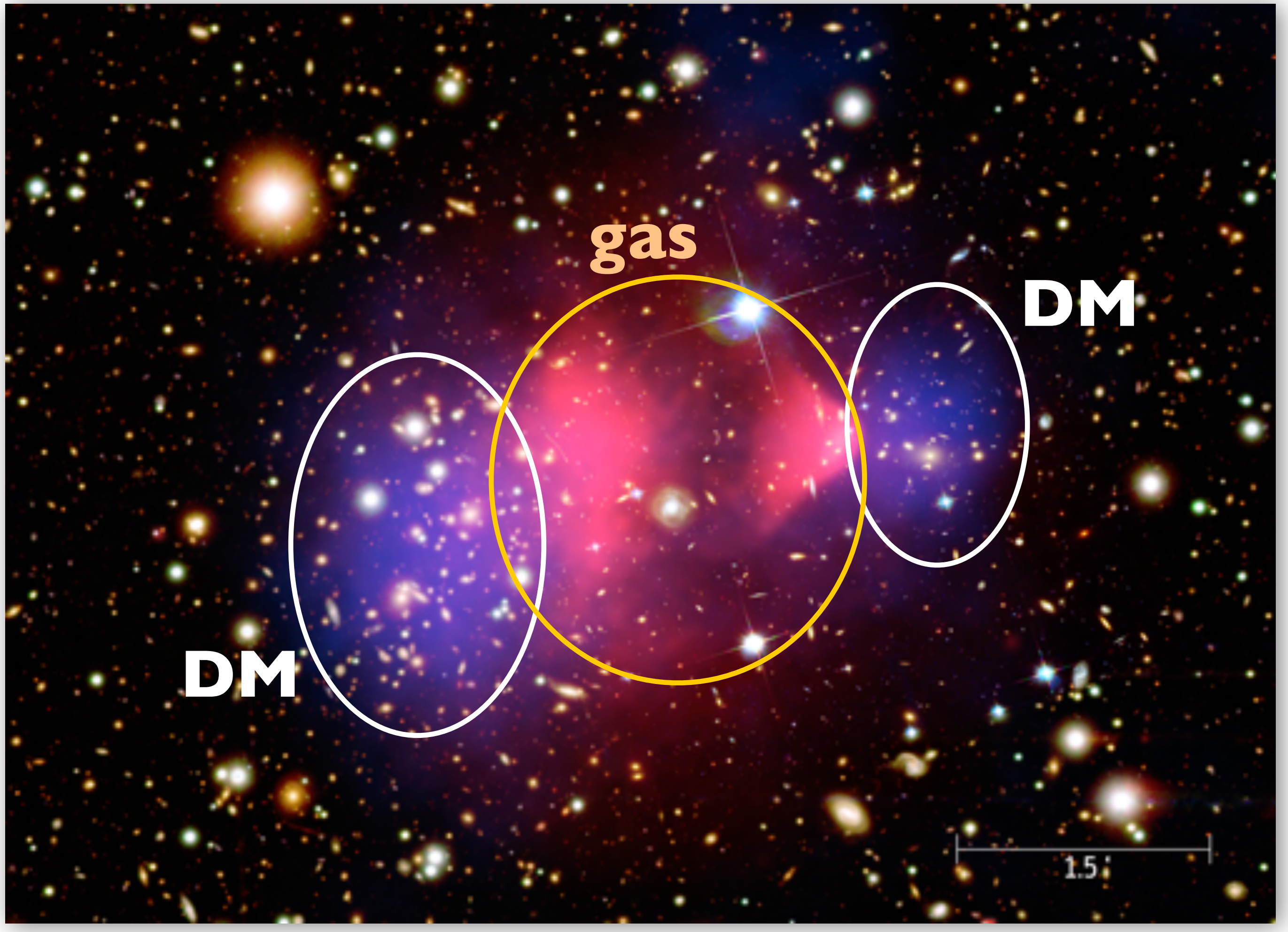

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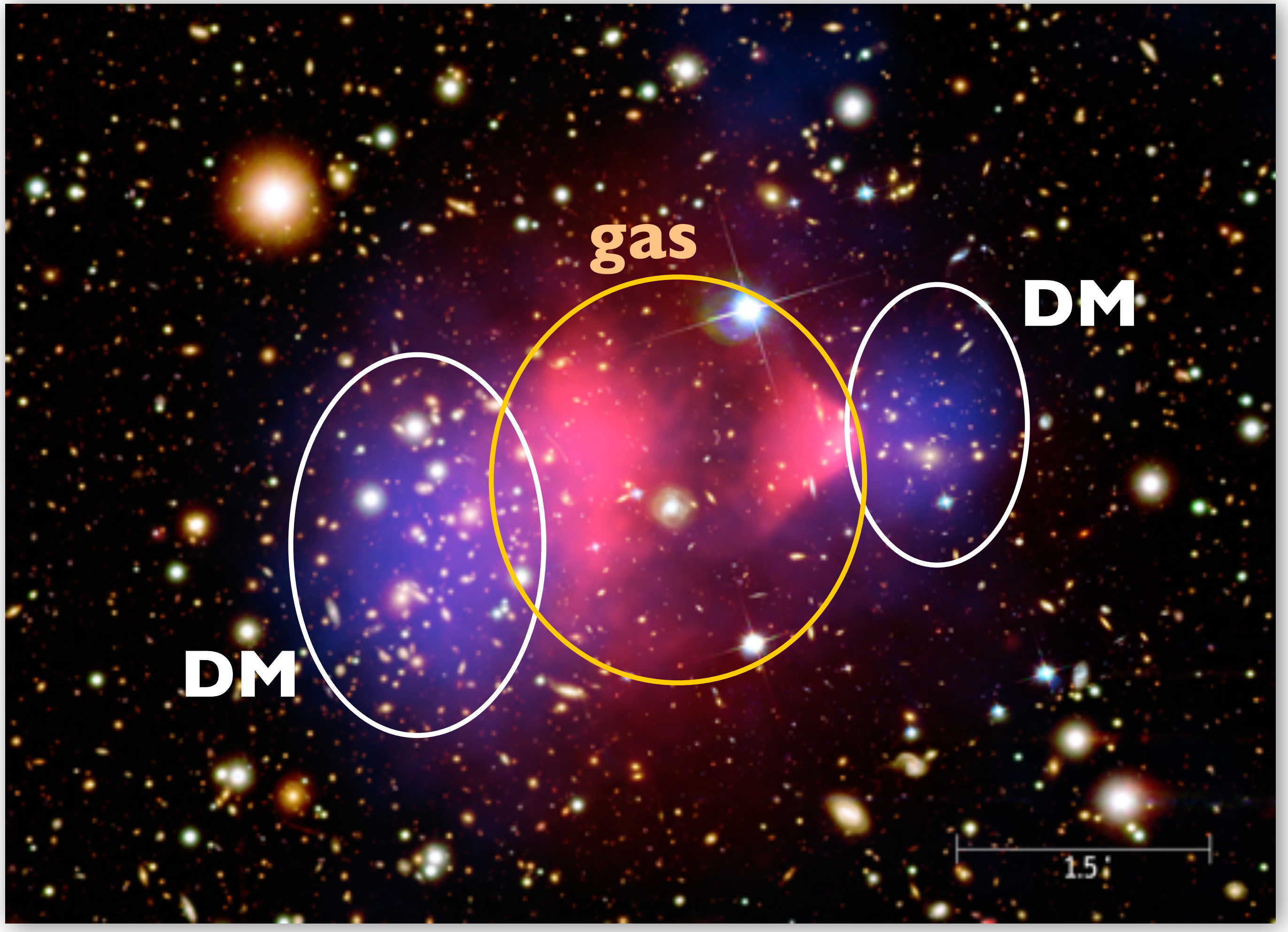

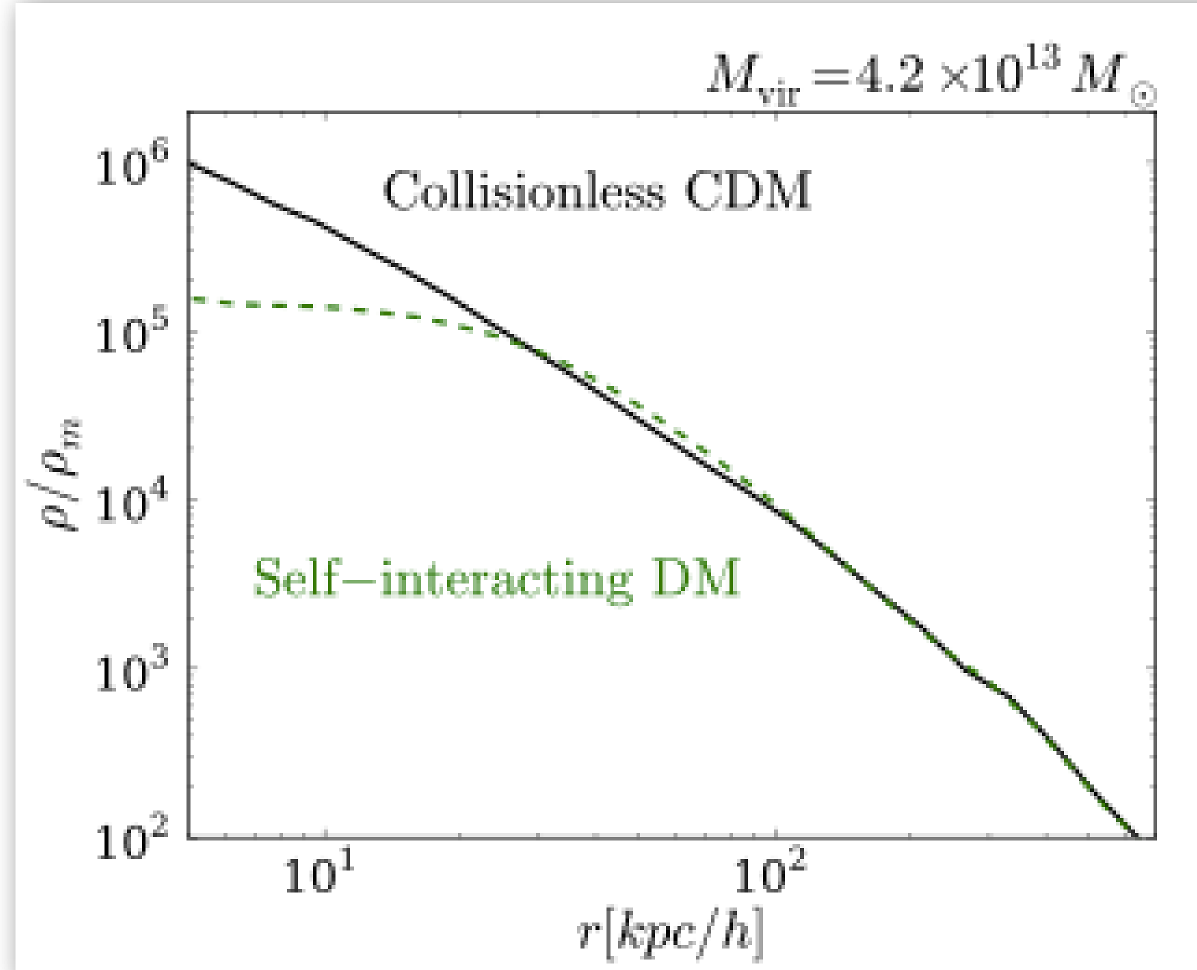

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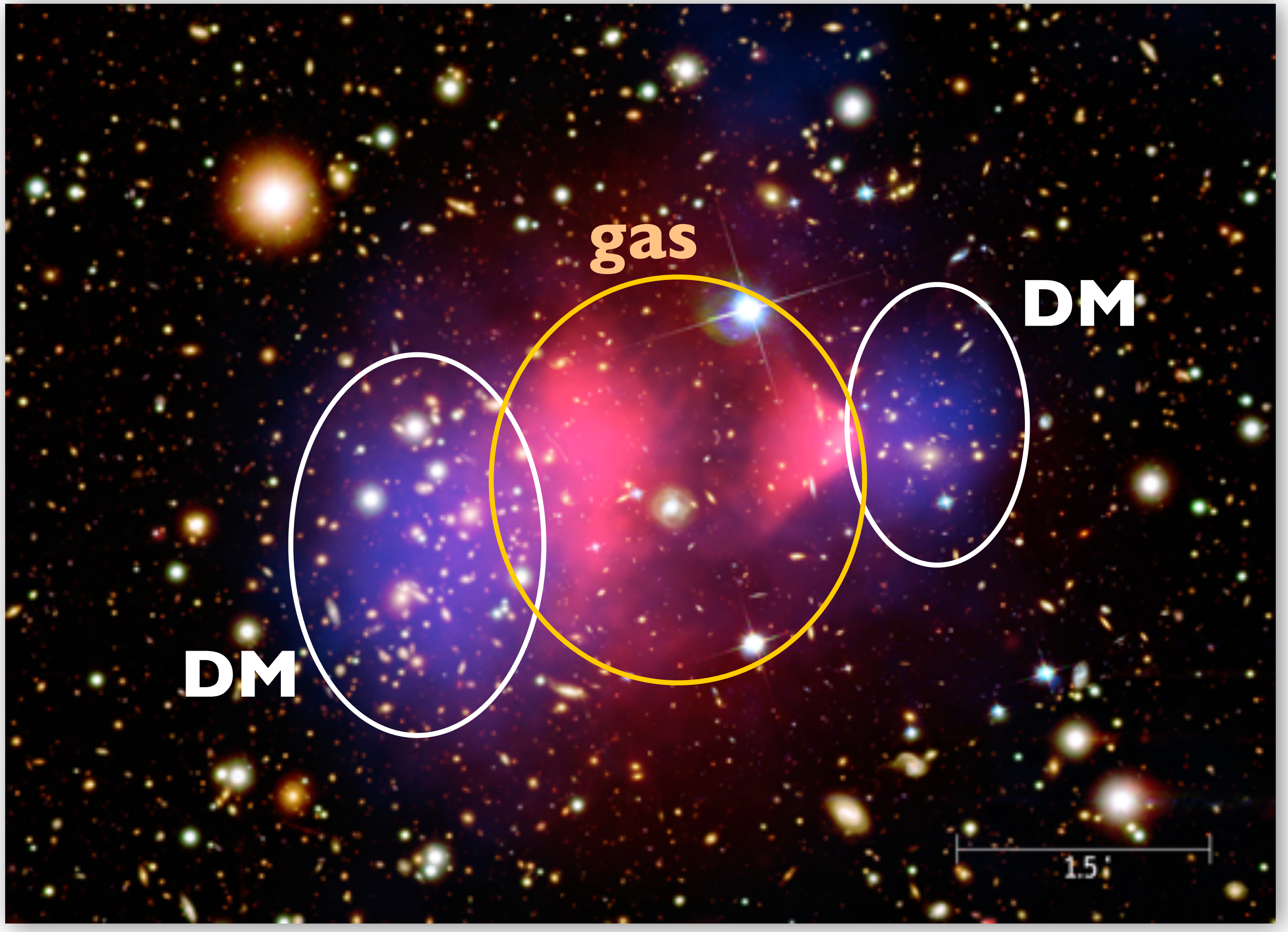

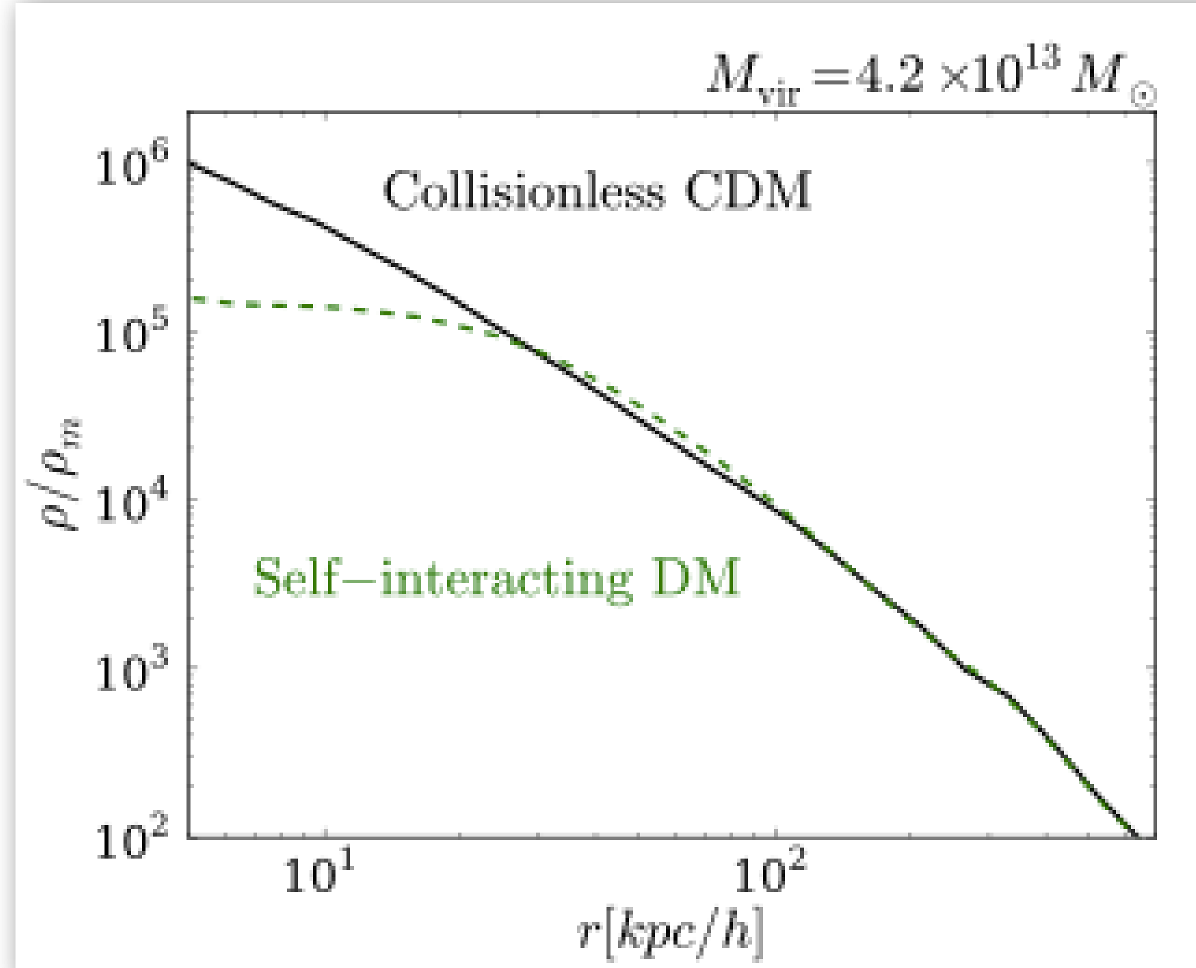

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Growing interest in models with rich sectors of "dark" particles, coupled to the SM ones via <u>weakly interacting</u> "portals"

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The search for Dark Matter particles at the LHC continues, independently of these scenarios, and remains one of the key goals of future runs ....

The experimental directions

- Direct exploration of physics at the weak scale
    - High-energy colliders (e^+e^-, pp, ep; 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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$\Rightarrow$

- 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"*)

The near and long-term future of fields like neutrinos, flavour, cosmology, ... have clear priorities and defined facilities.

The future of the energy frontier, beyond the LHC, is still in the process of being defined

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

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

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

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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 $2x10^4$ 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)

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10:05 **Fermilab Site Filler** *15'*

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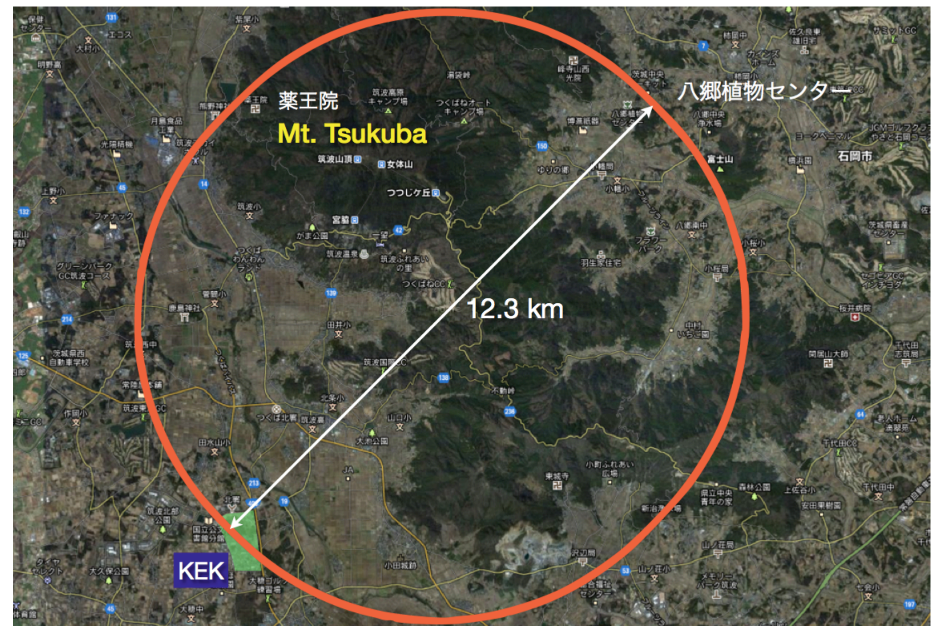

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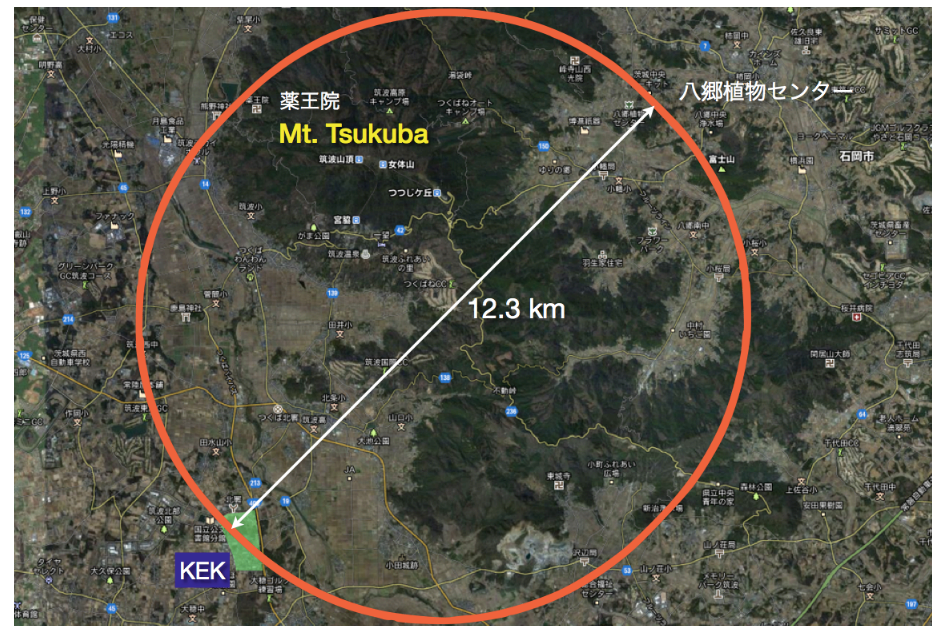

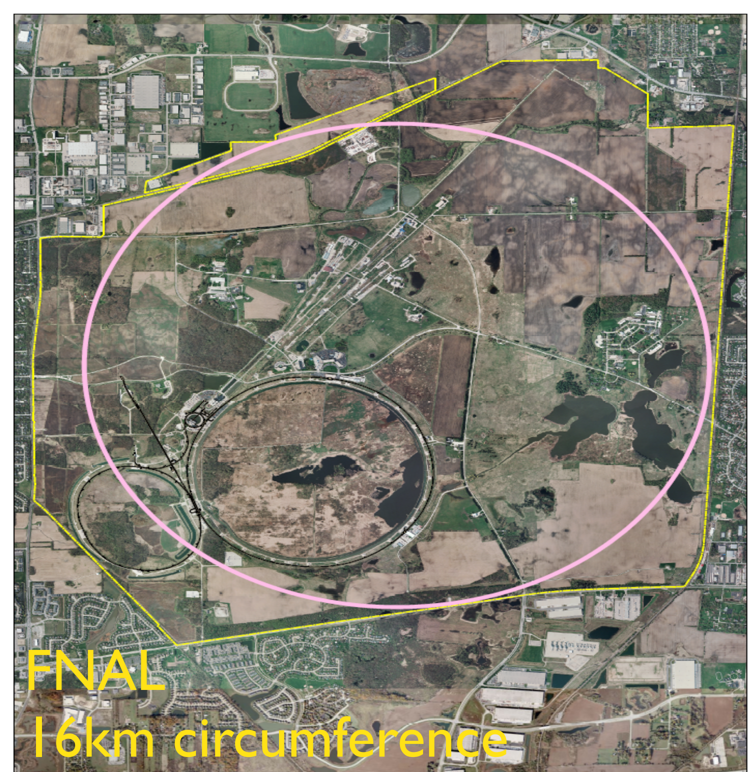

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Accelerators for a Higgs Factory: Linear vs. Circular (HF2012) (14–November 16, 2012)

indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=5775

Accelerators for a Higgs Factory: Linear vs. Circular (HF2012)

chaired by Weiren Chou (Fermilab)

from Wednesday, November 14, 2012 at **08:00** to Friday, November 16, 2012 at **17:00** (US/Central)
at **Fermilab (One West, Wilson Hall)**
Batavia, IL 60510 USA

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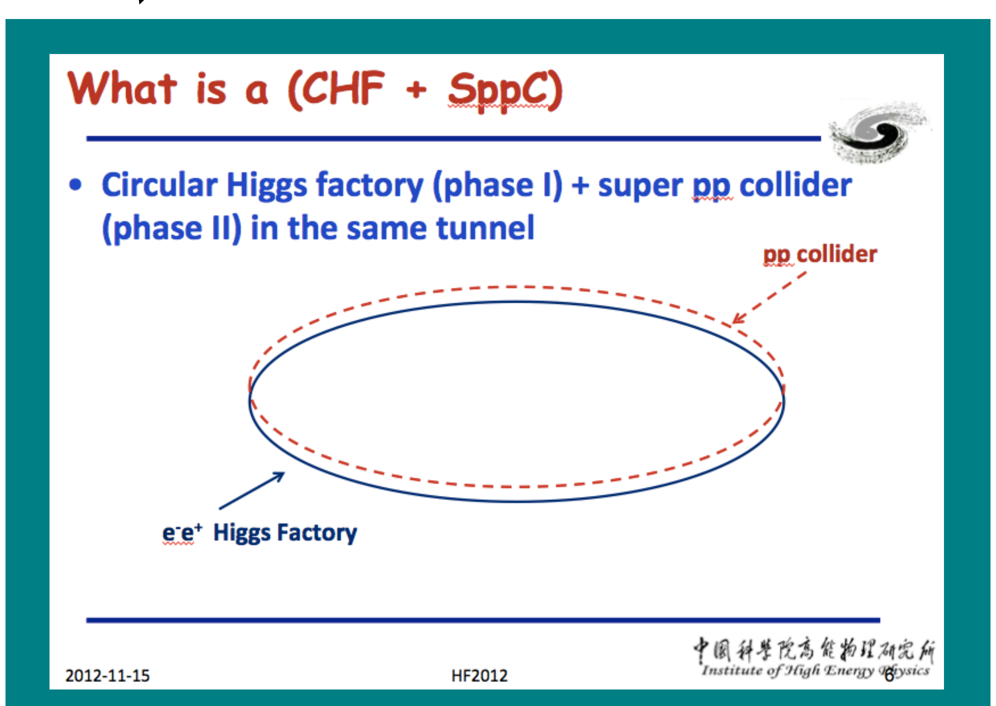
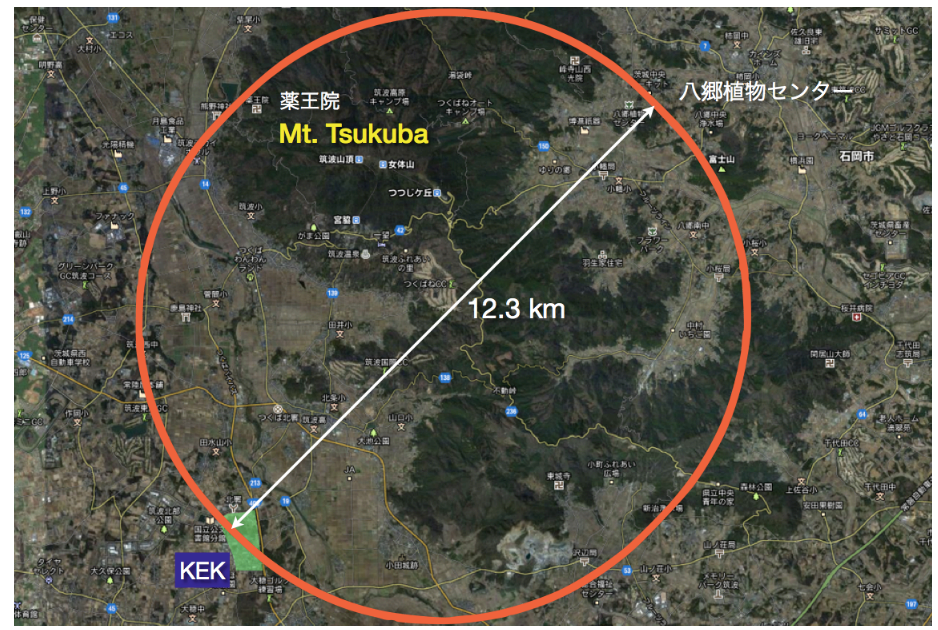
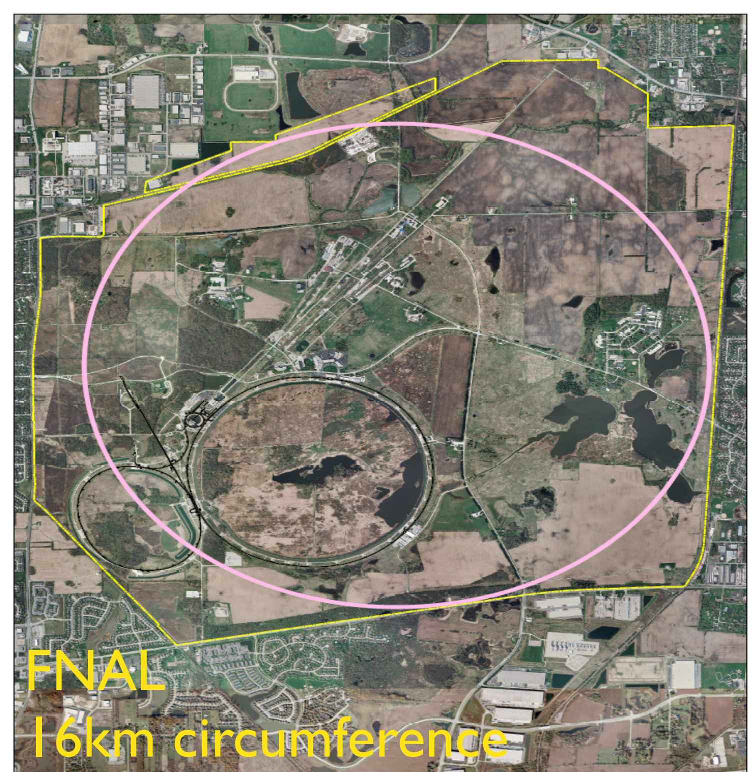


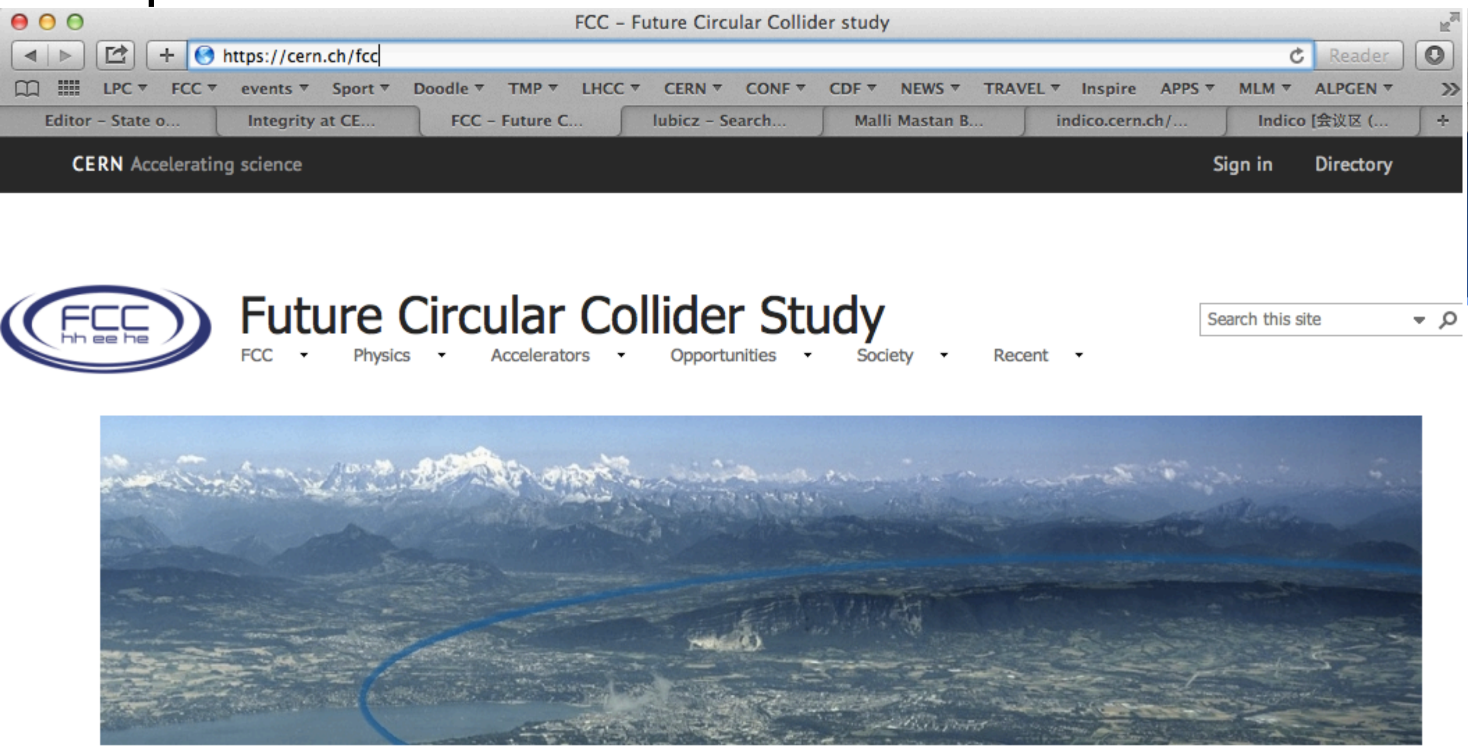




Final report:
http://www-bd.fnal.gov/icfabd/HF2012.pdf

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

http://cern.ch/fcc



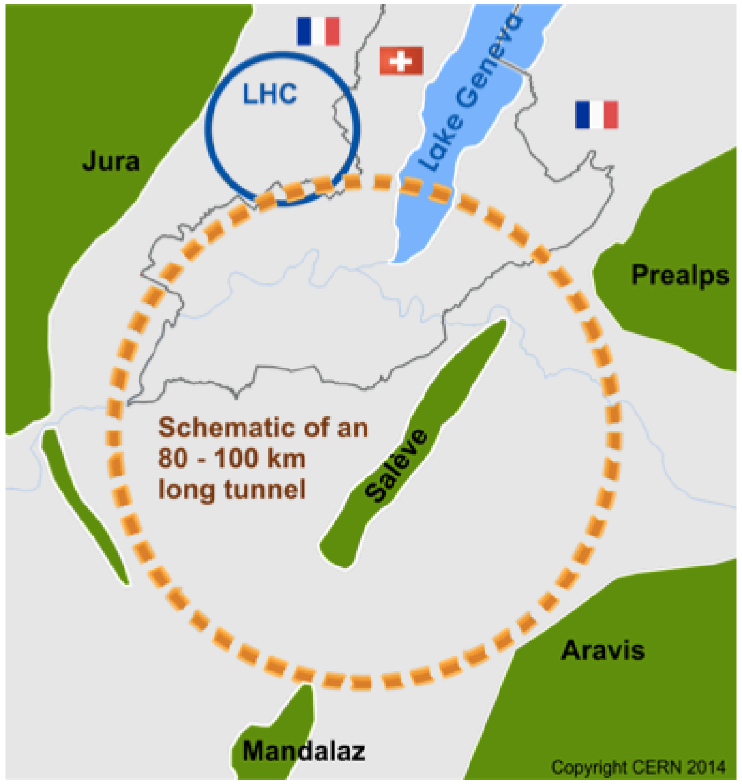
http://cepc.ihep.ac.cn

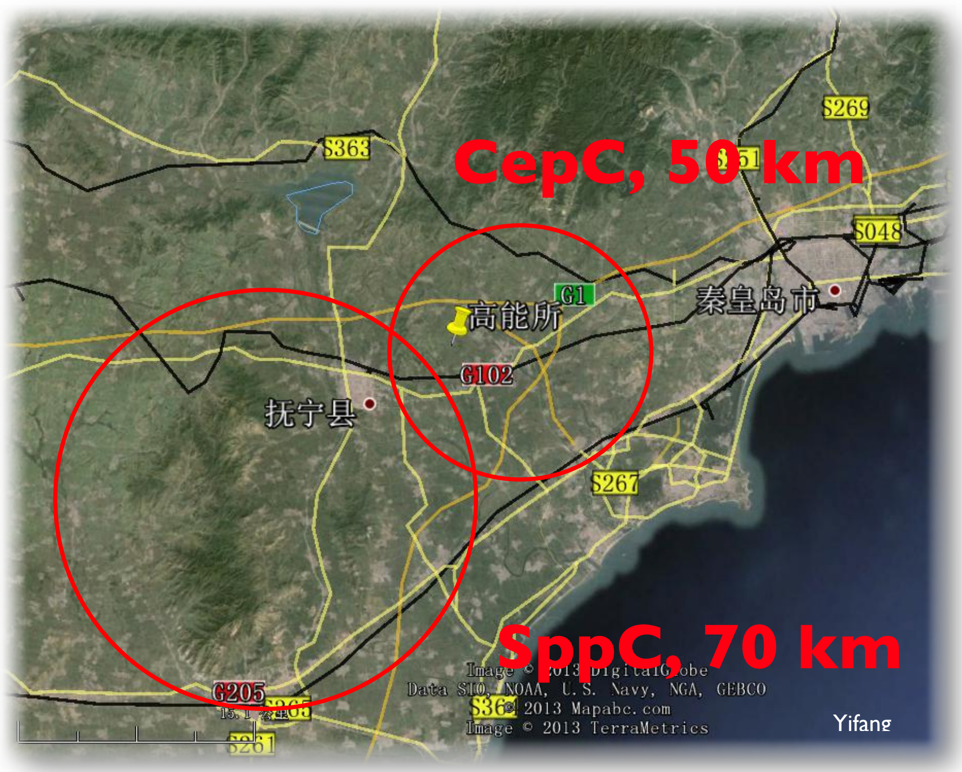
Forming an international collaboration to study:

- *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)
indico.cern.ch/event/282344/
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Future Circular Collider Study Kickoff Meeting
12-15 February 2014
University of Geneva - UNI MAIL
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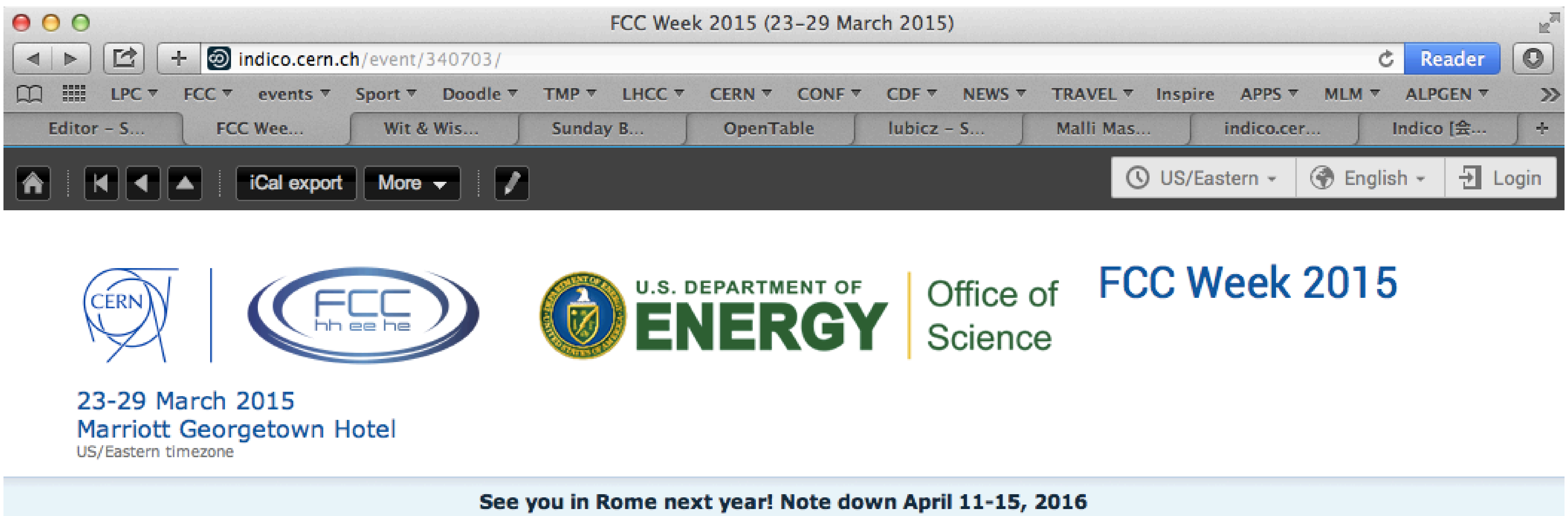
Search
There is a live webcast for this event.
Future Circular Collider Study Kickoff Meeting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See you in Rome next year! Note down April 11-15, 2016


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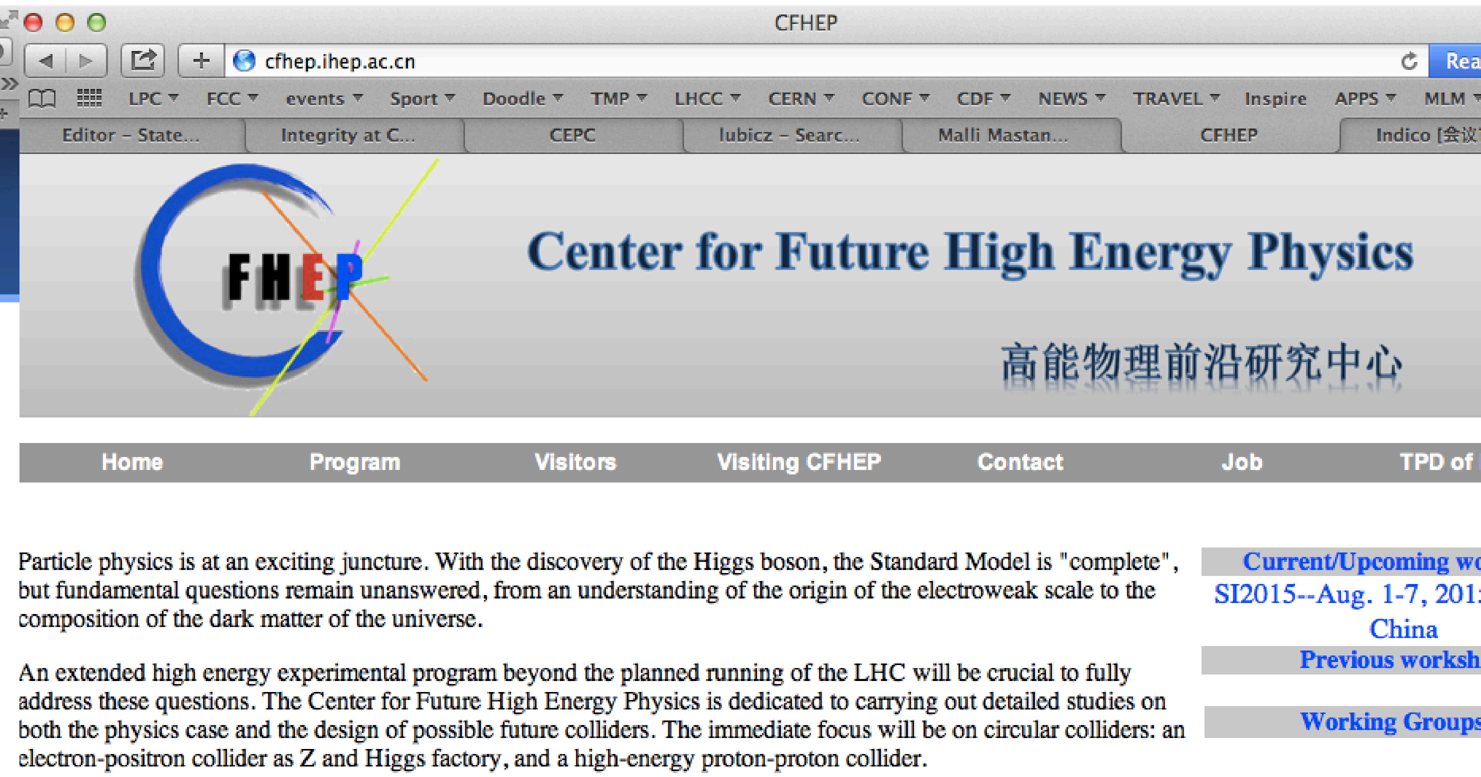
Future High Energy Circular Colliders
The Standard Model (SM) of particle physics can describe the strong, weak and electromagnetic interactions under the framework of quantum gauge field theory. The theoretical predictions of SM are in excellent agreement with the past experimental measurements. Especially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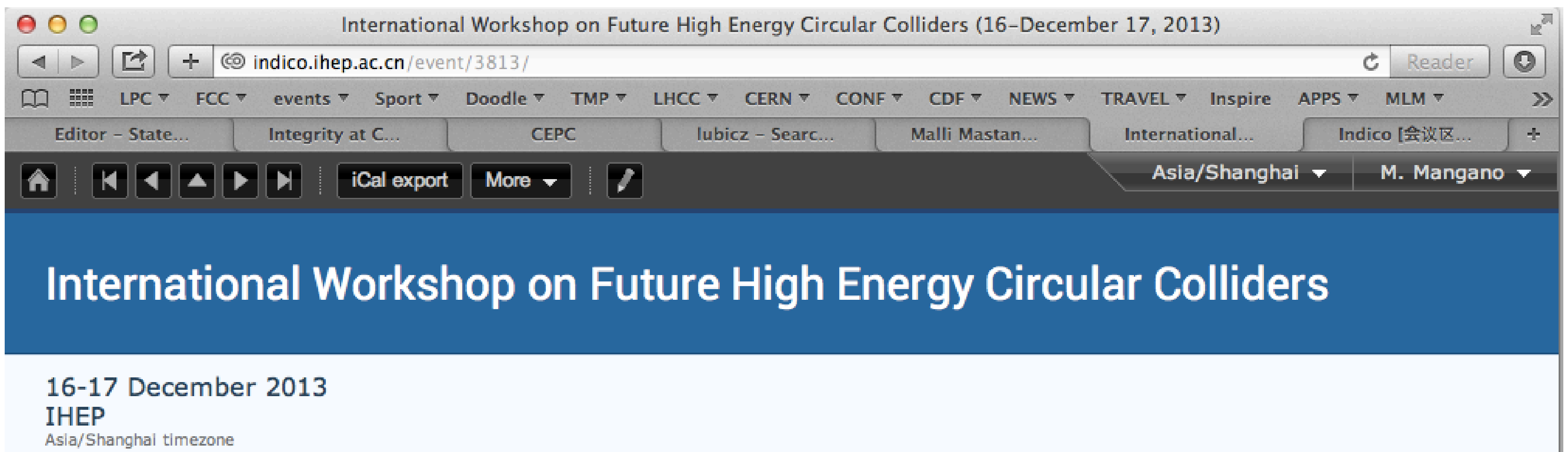
Particle physics is at an exciting juncture. With the discovery of the Higgs boson, the Standard Model is "complete", but fundamental questions remain unanswered, from an understanding of the origin of the electroweak scale to the composition of the dark matter of the universe.
An extended high energy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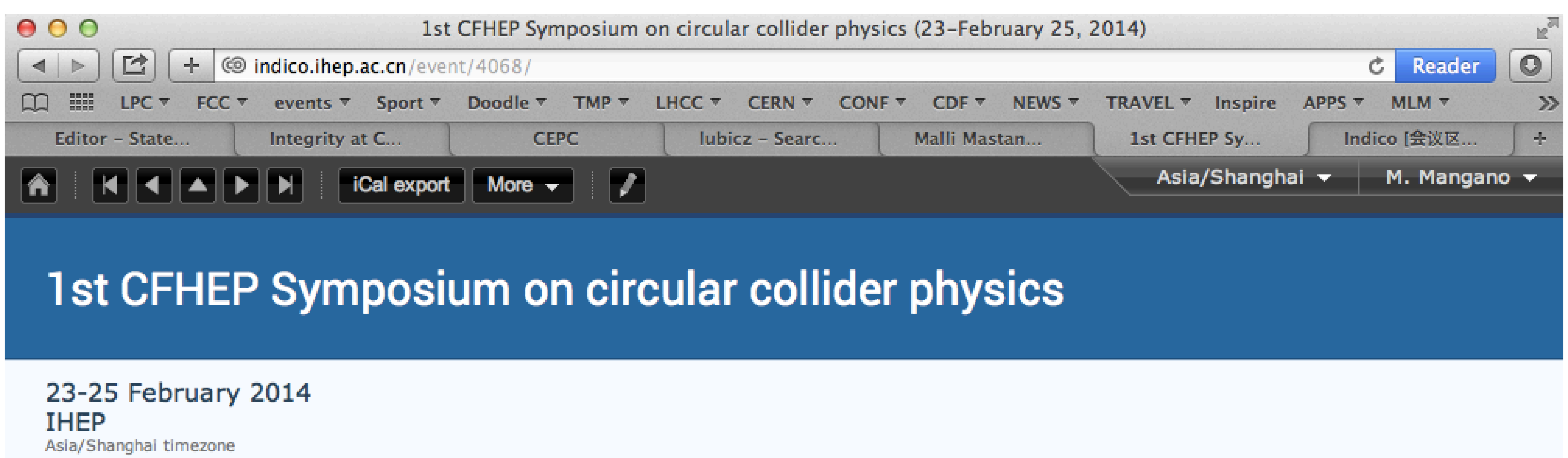
Asia/Shanghai
M. Mangano
International Workshop on Future High Energy Circular Colliders
16-17 December 2013
IHEP
Asia/Shanghai timezone


1st CFHEP Symposium on circular collider physics (23–February 25, 2014)
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1st CFHEP Symposium on circular collider physics
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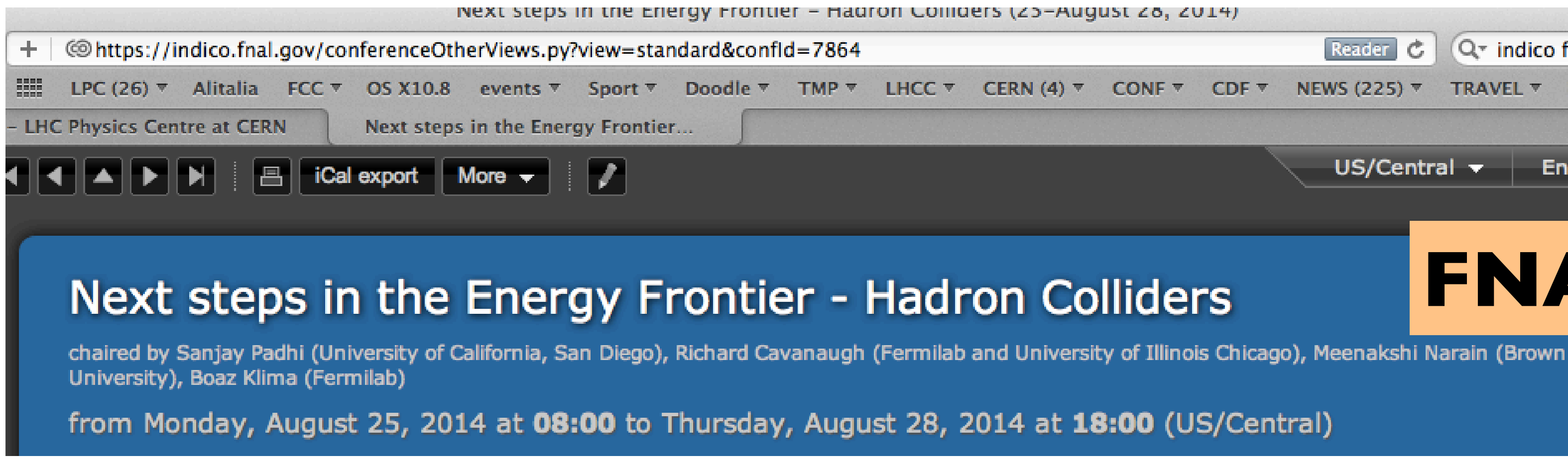
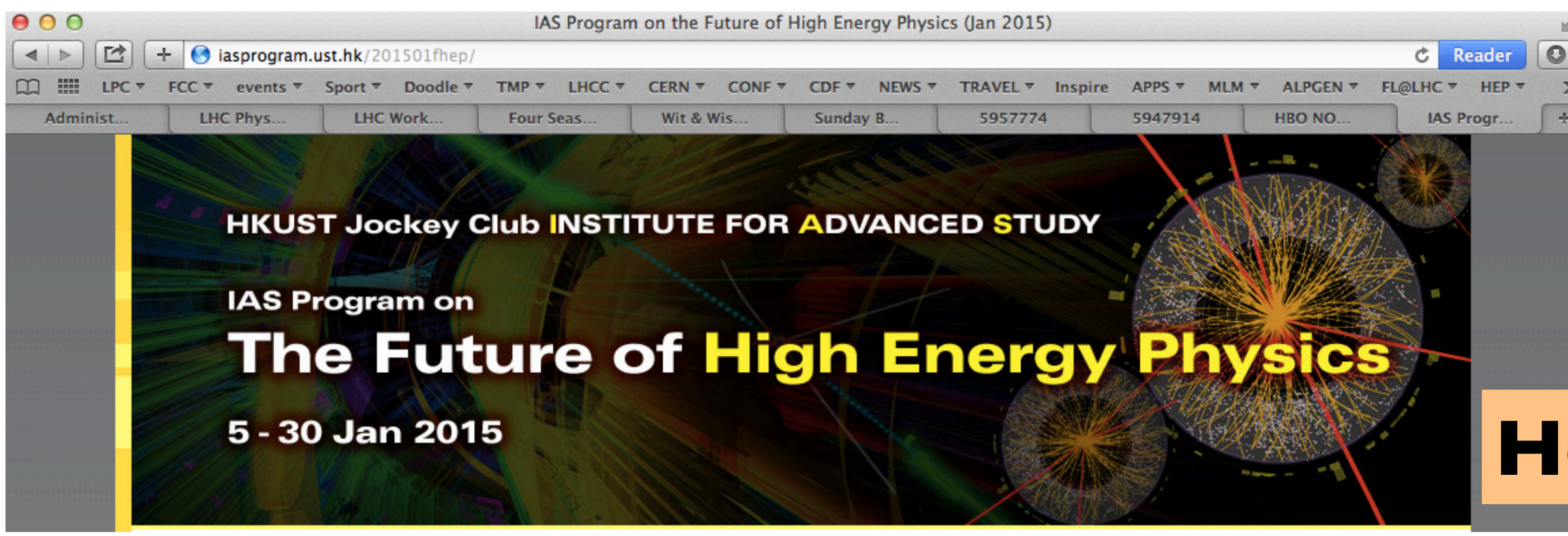
Physics workshops spontaneously organized all over the world document better than anything else the physics results, and the interest of the community ....

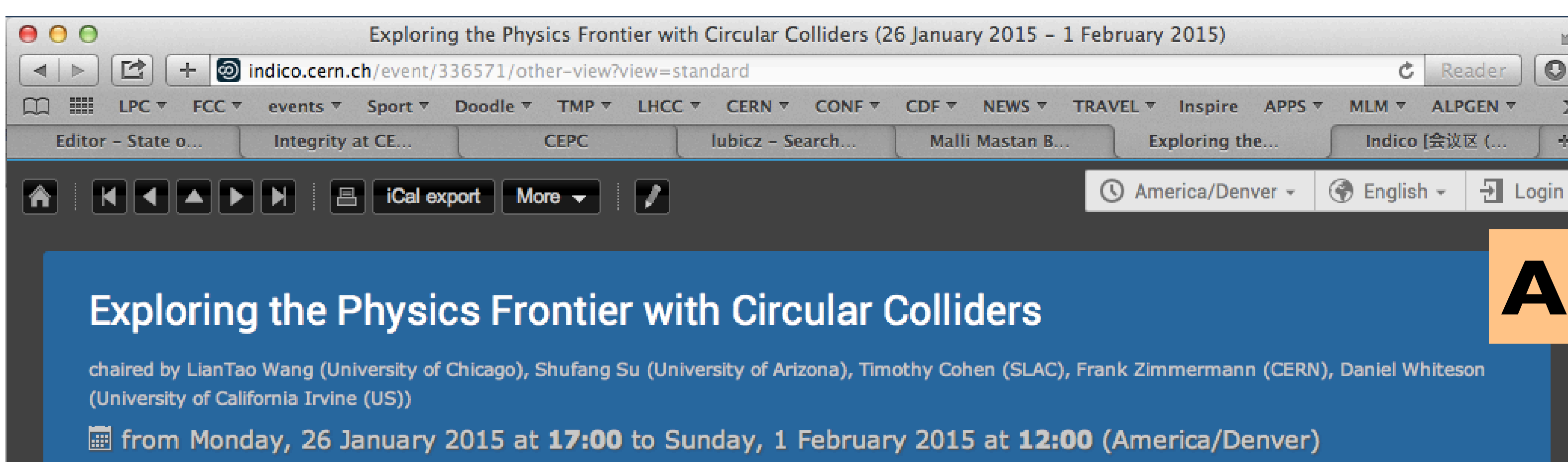
SLAC



FNAL



Hong Kong



Aspen

Key goals of a future circular collider complex

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- Thorough **measurements** of the Higgs boson and its dynamics

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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*
  - *relevance of ep programme*

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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

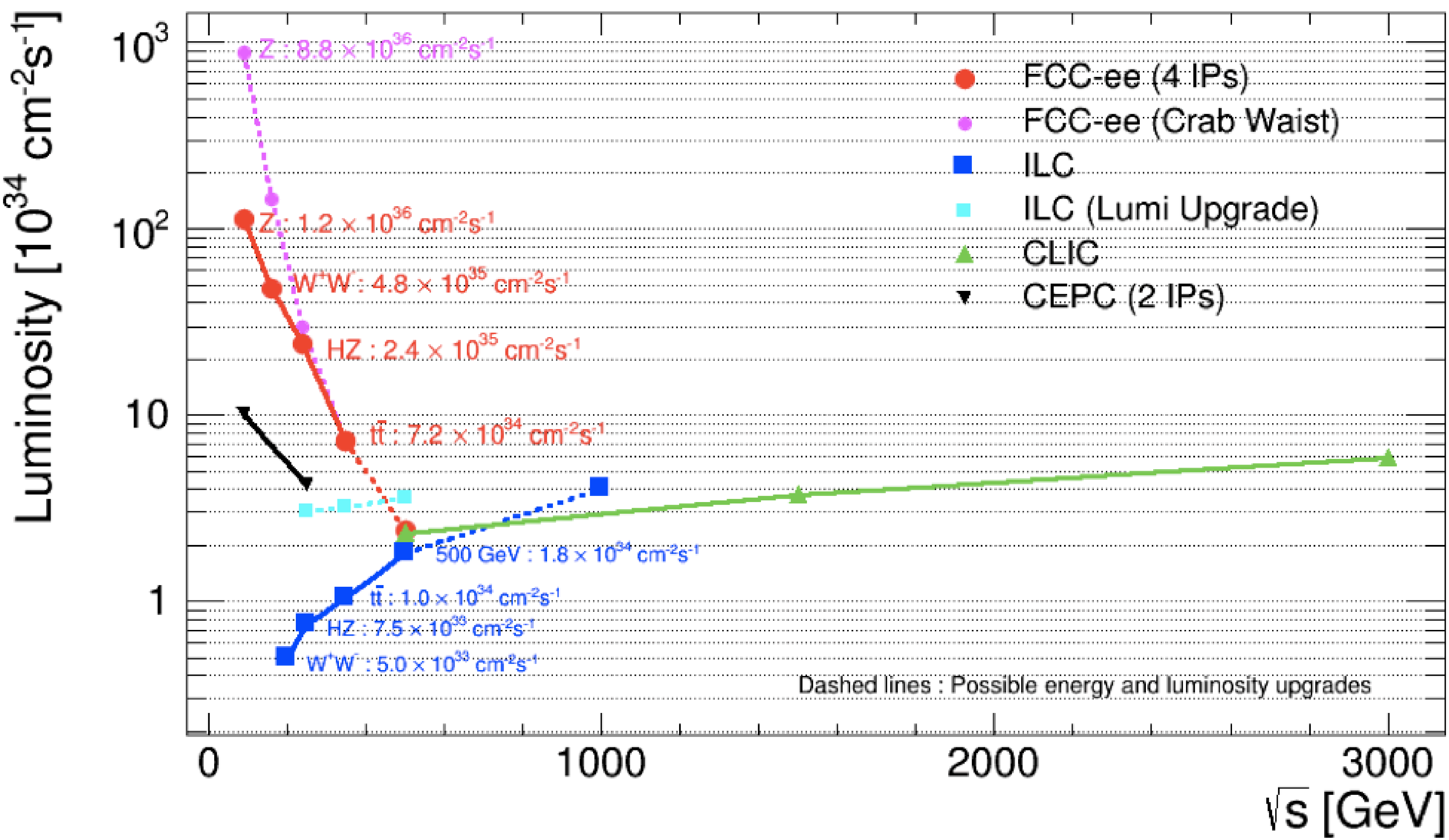
Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP_{main} [$cm^{-2}s^{-1}$]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

- **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**

FCC-ee energy and lum goals



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

   M_Z, 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.

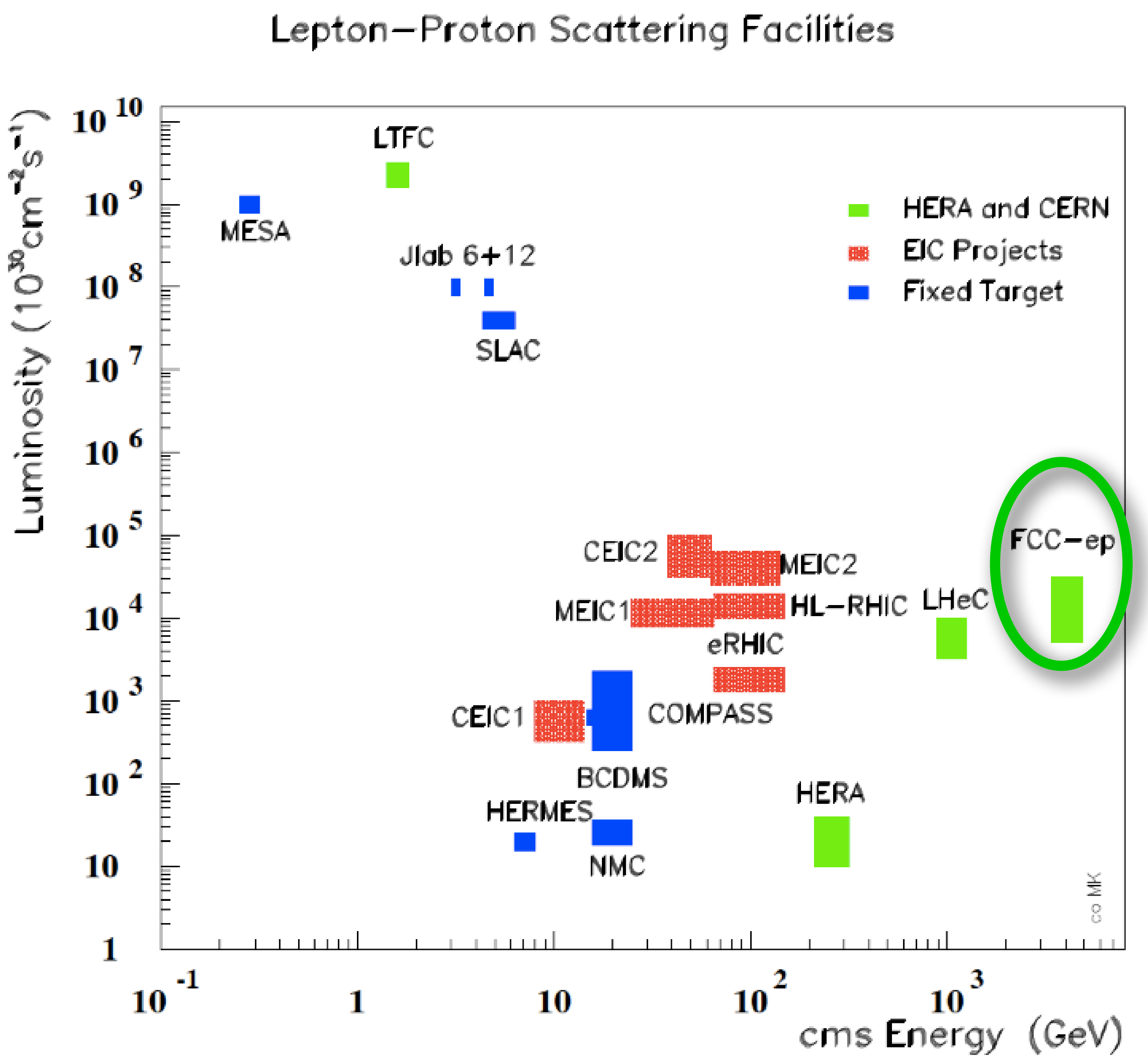
   A_{LR}, A_{FB}^{pol} etc

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

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, see:
  - 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

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

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model indep. fit of 240 GeV data

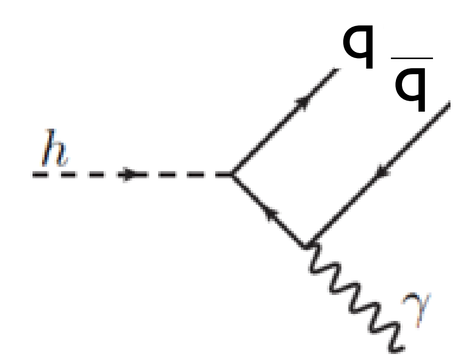
$H \to J/\Psi\,\gamma$ → y_c

$H \to \phi\,\gamma$ → 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

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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 arXiv:1507.08169
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
BR_{exo}	0.48%	$< 10^{-6}$?	→ for specific channels, like H→eμ, ...

FCC-hh ambitious but possible targets?

More in general ...

- Statistics allows to bring the precision in the measurement of BR ratios to sub-% level (e.g. B($\rightarrow\gamma\gamma$)/B($H\rightarrow ZZ^*$). 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

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
- ....

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

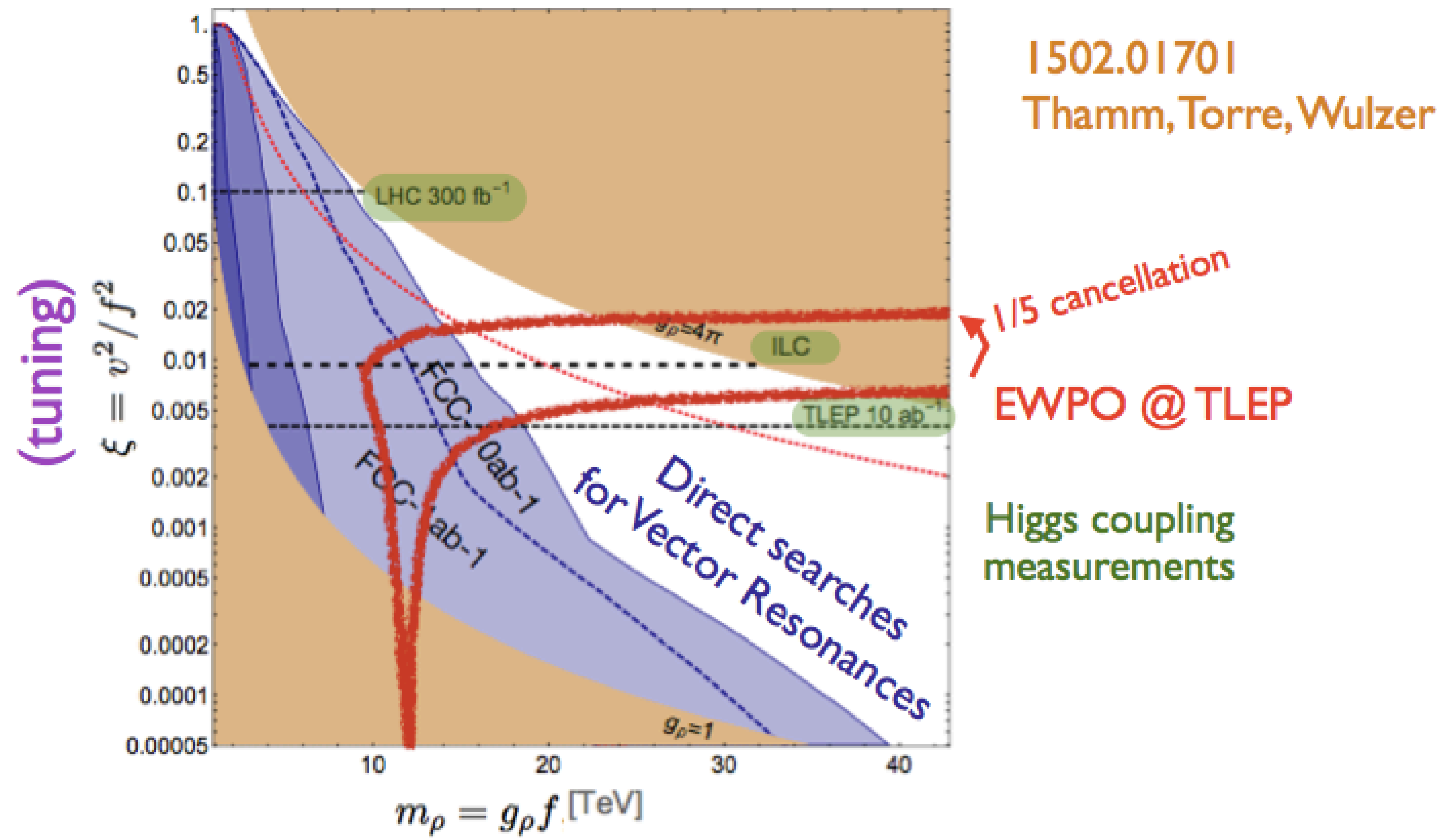
UV Completions & Rest of Theory

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)

Dark Matter search

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- We would like to understand whether the FCC can answer more specific questions, such as:

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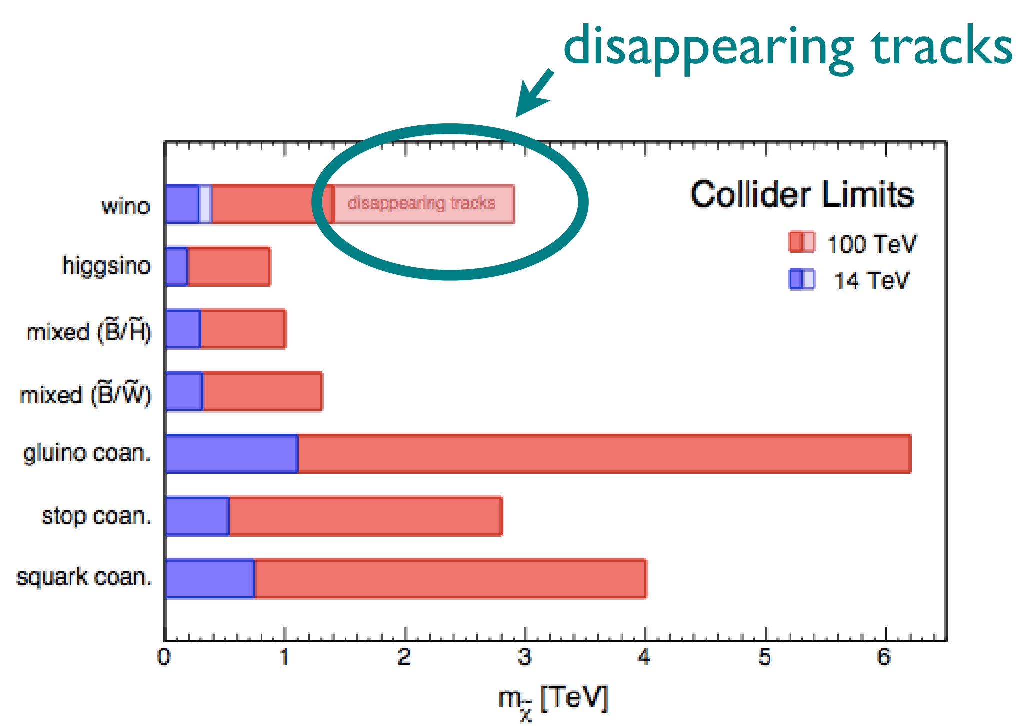
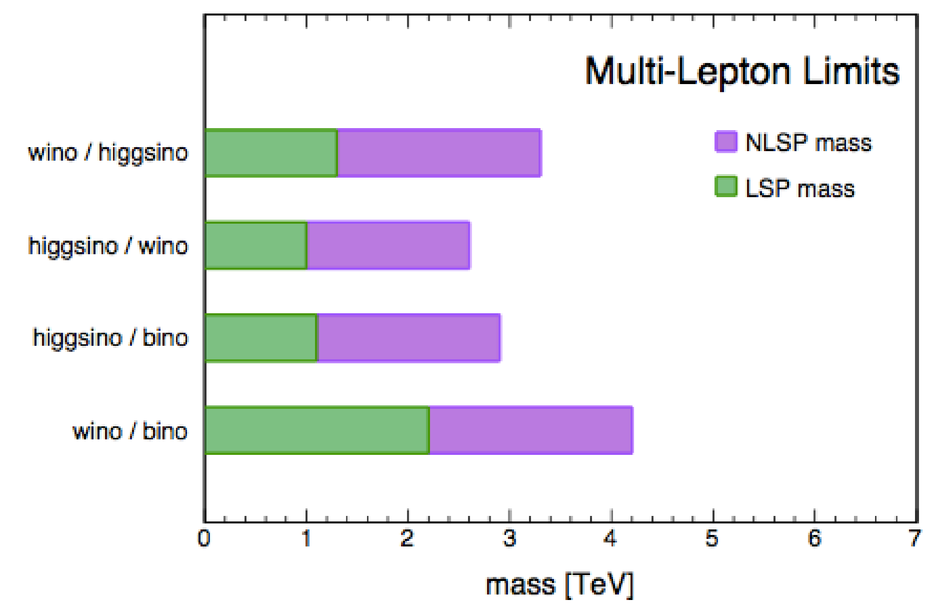
  - can WIMPS, detectable in direct and indirect (DM annihilation) experiments, be discovered at future colliders?
  - what are the opportunities w.r.t. new DM scenarios (e.g. interacting DM, asymmetric DM, ...)?

Towards no-lose arguments for Dark Matter scenarios:

WIMP searches at colliders

L.Wang @ FCC week





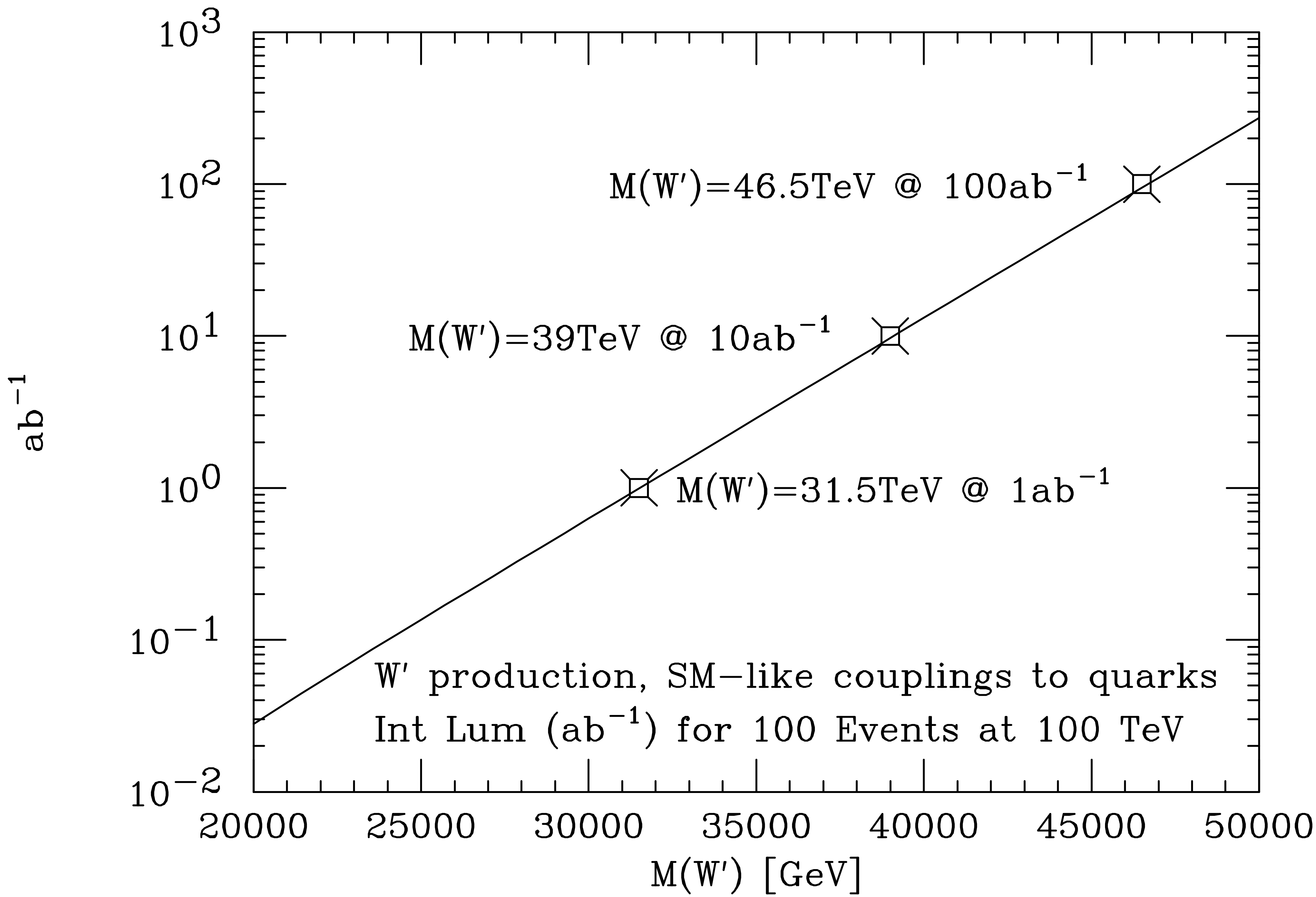
$$M_{\rm WIMP} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3}\right)$$

100 TeV pp collider will probe TeV WIMP very well.

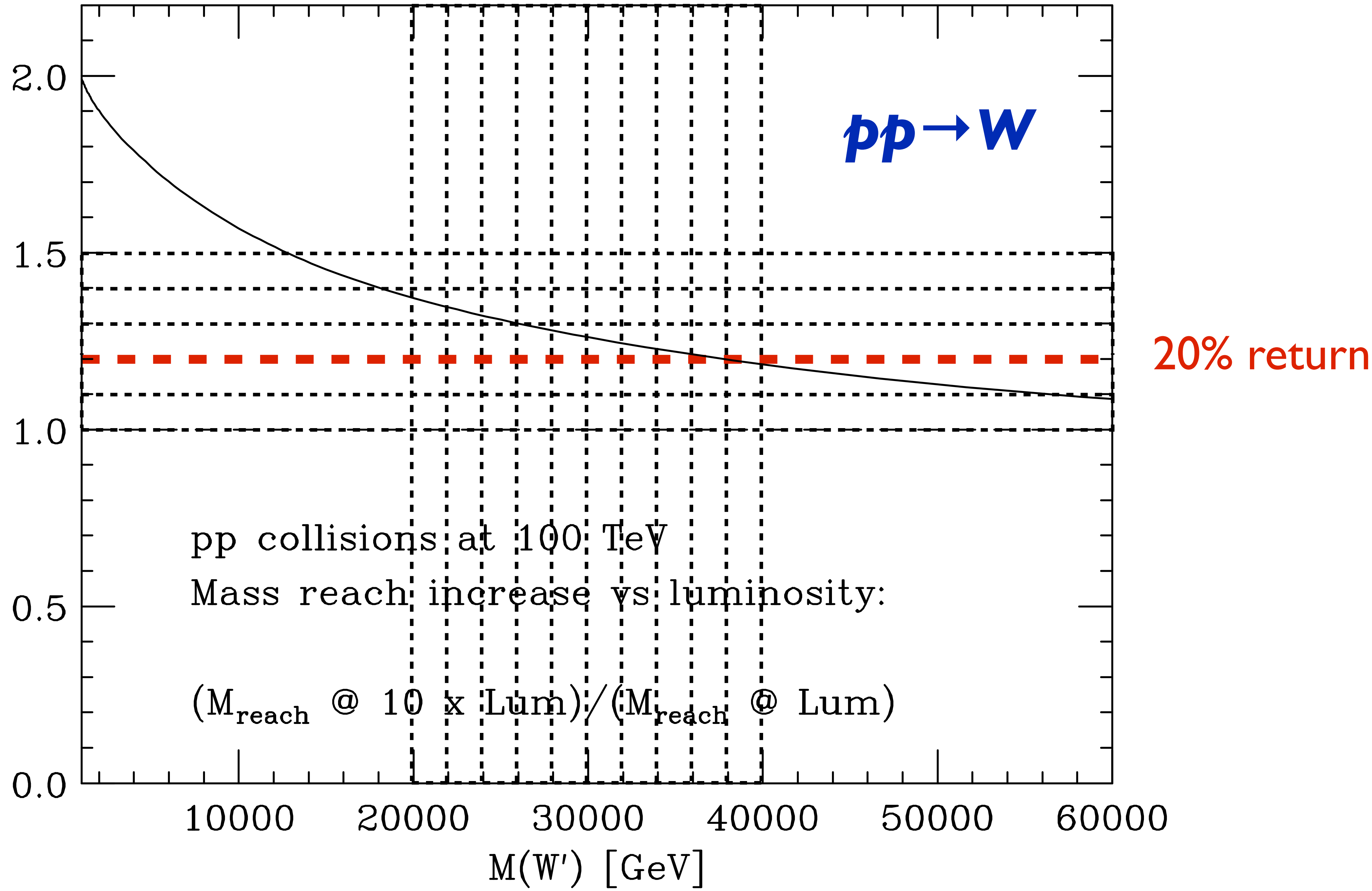
Extension of the discovery reach at high mass

Example: discovery reach of **W' with SM-like couplings**

NB For SM-like Z', $\sigma_{Z'}\, BR_{lept} \sim 0.1 \times \sigma_{W'}\, BR_{lept}$, ⇒ rescale lum by ~ 10

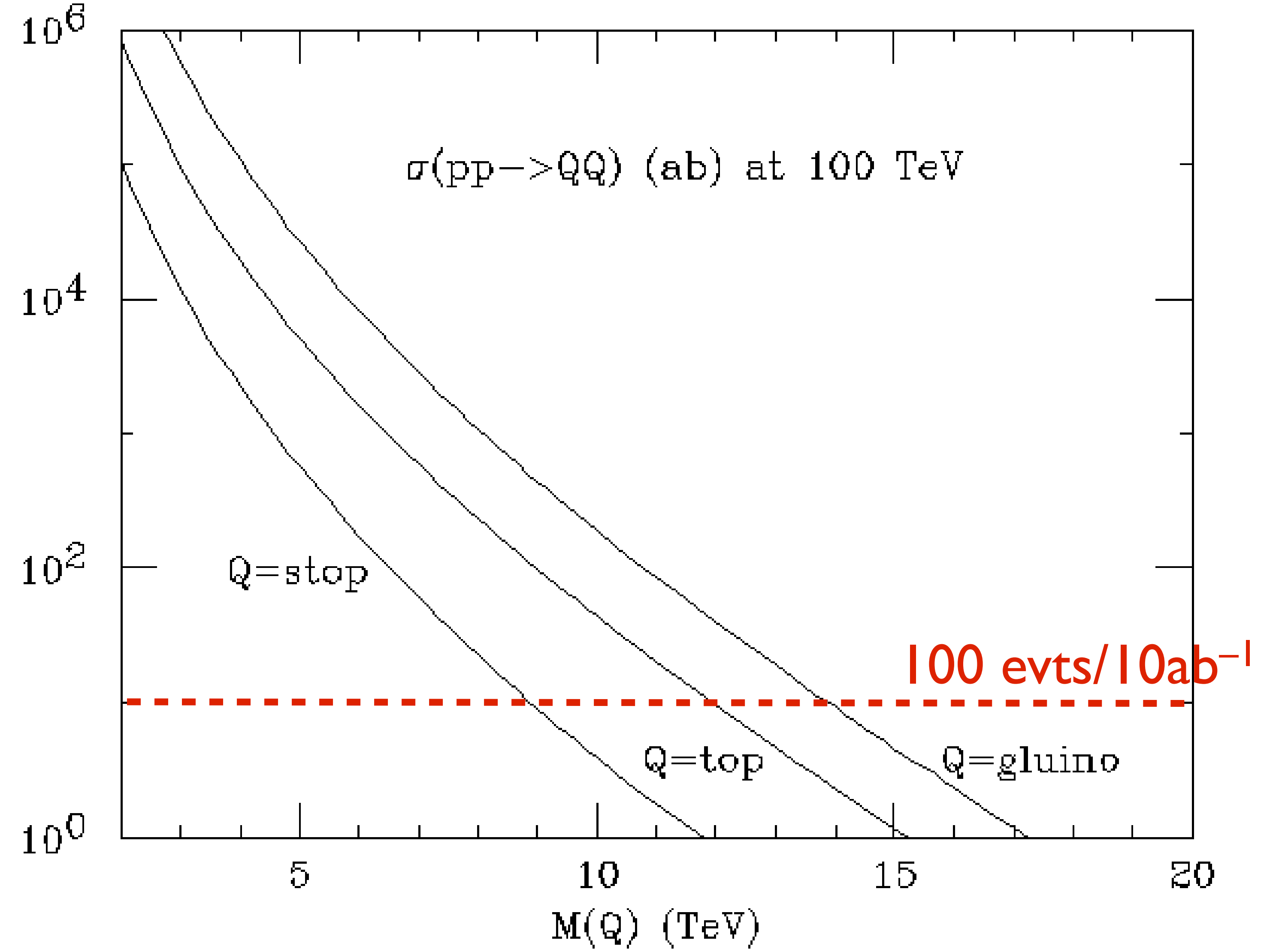


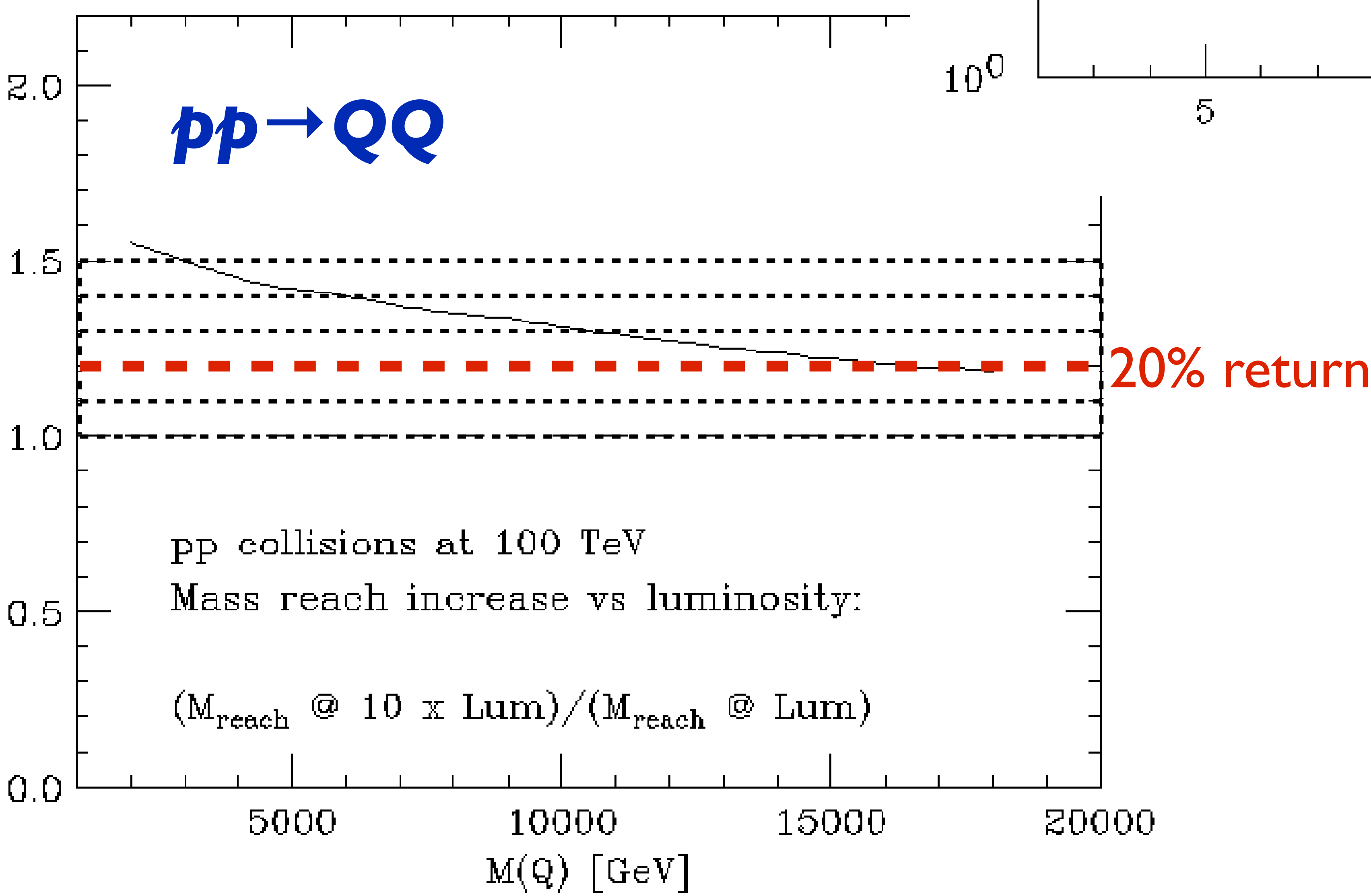
At L=O(ab^{-1}), Lum x 10 ⇒ ~ M + 7 TeV



Lum x 10 ⇒ relative gain much larger at low mass than at high mass

Example: discovery reach for pair production of strongly-interacting particles



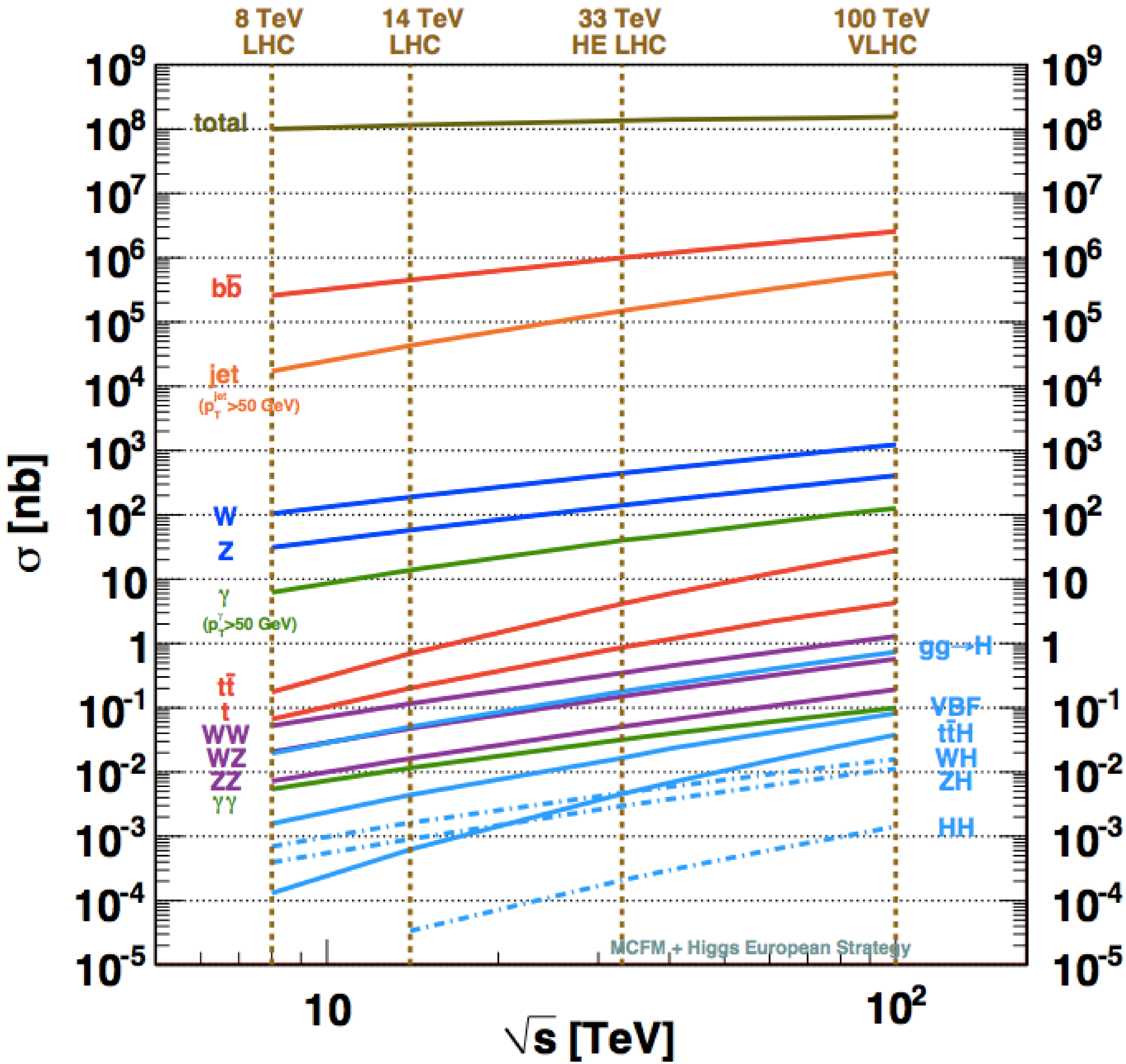


SM observables

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+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?

Rates at 8 - 100 TeV



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 ?*

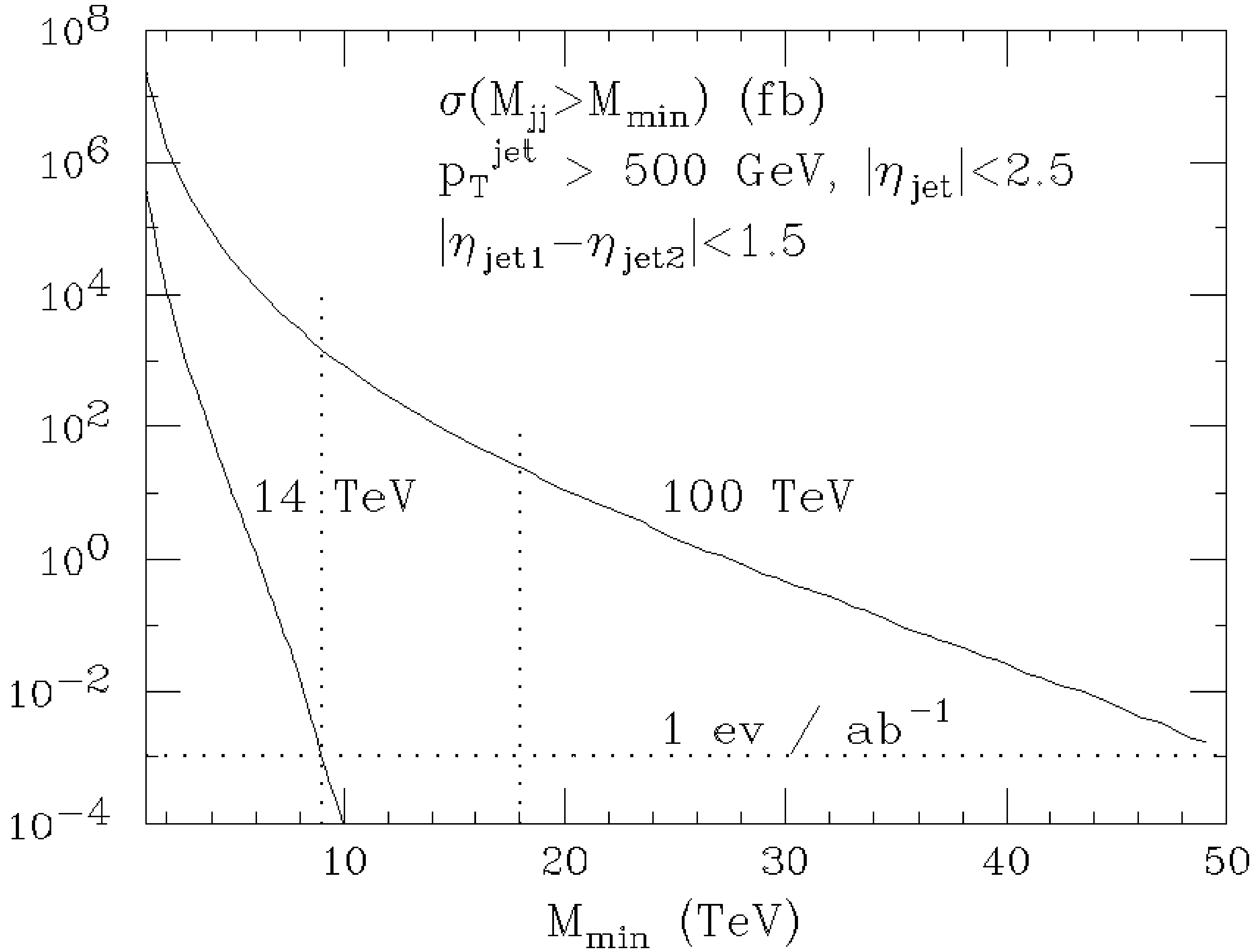
=> 10^{12} b hadrons from top decays (particle/antiparticle tagged)

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

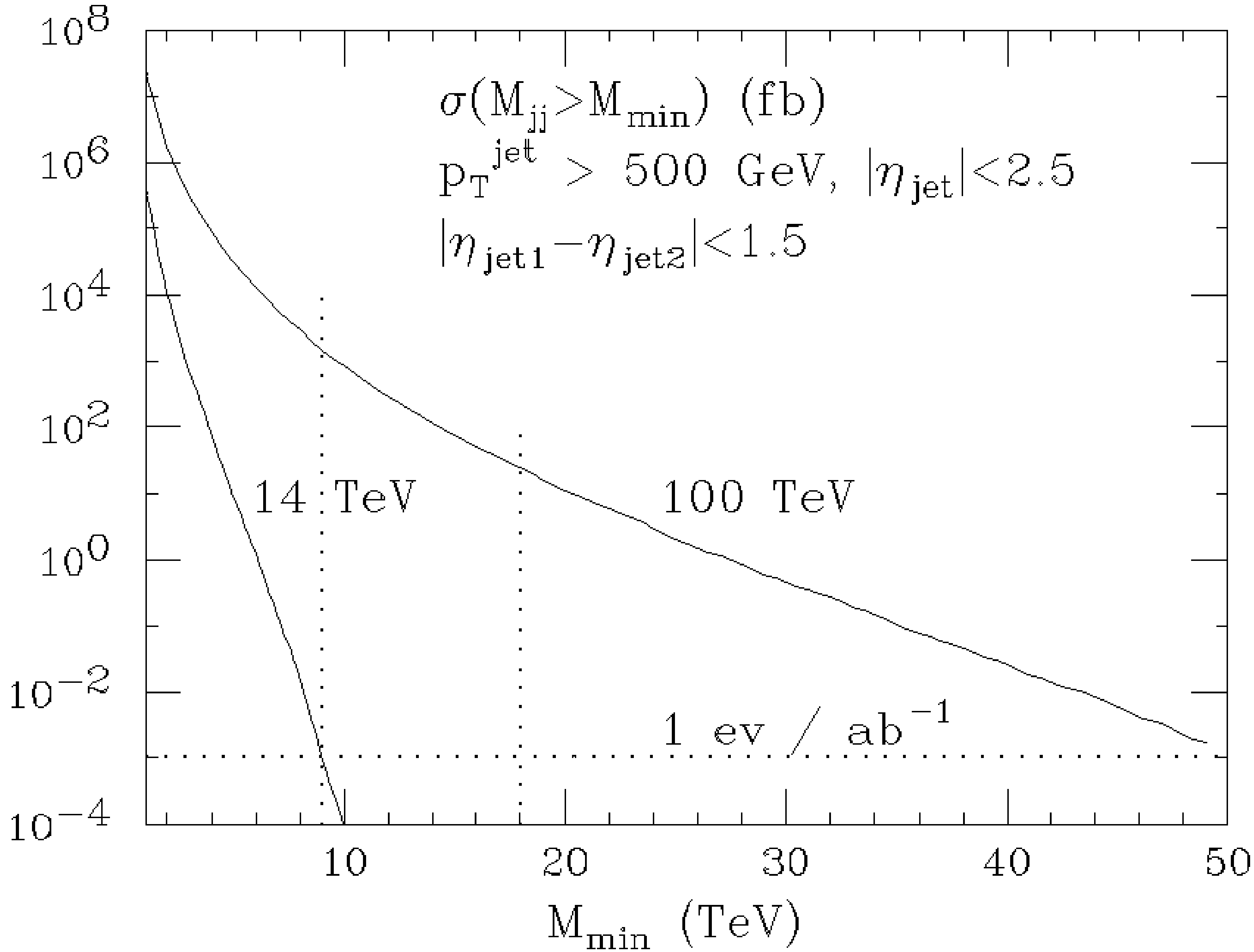
=> few x10^{11} $t \to W \to$ charm hadrons

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

Example: dijet production at large mass



Example: dijet production at large mass



- 1 pb^{-1} to recover sensitivity of HL-LHC ⇒< 1 day @ 10^{32}

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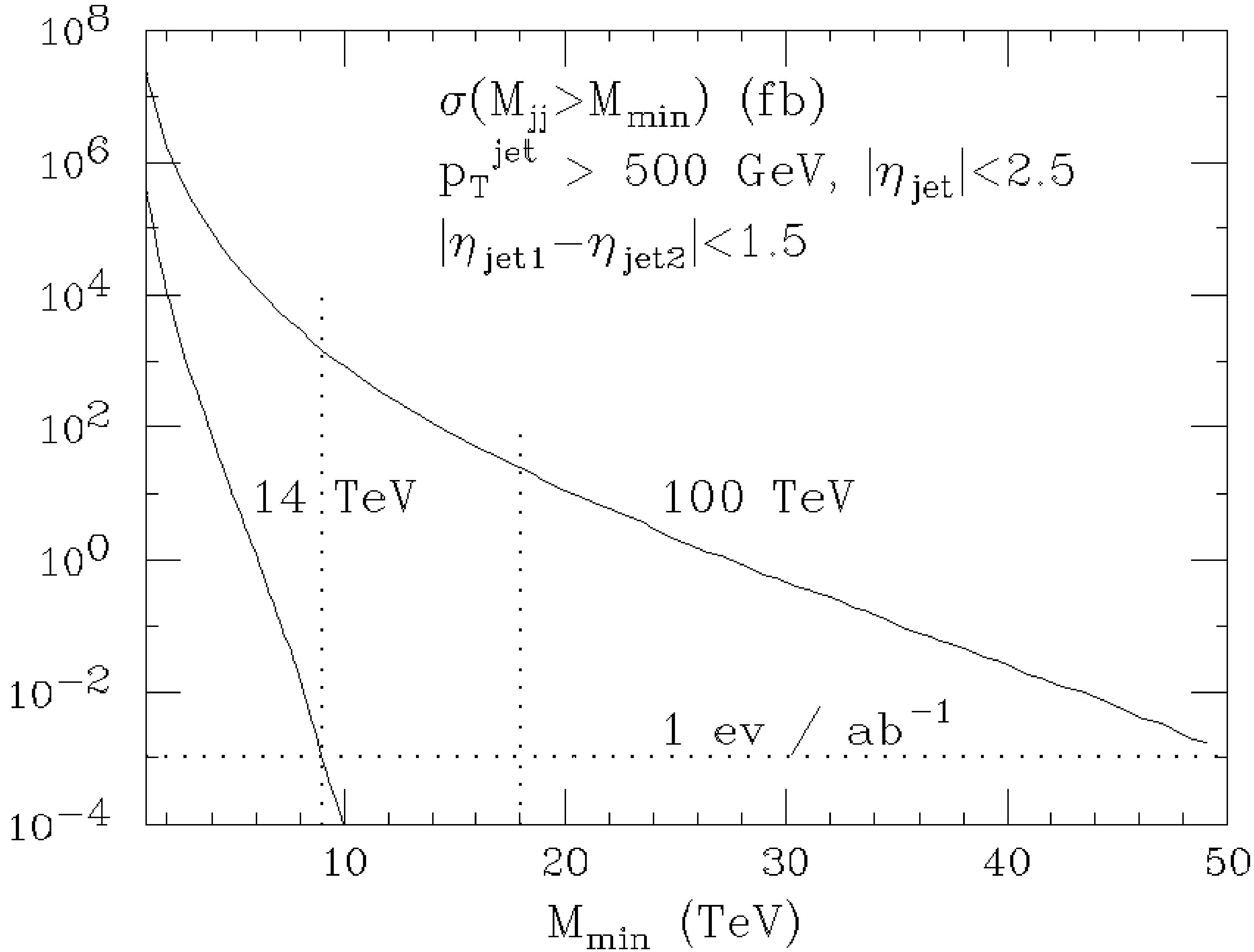
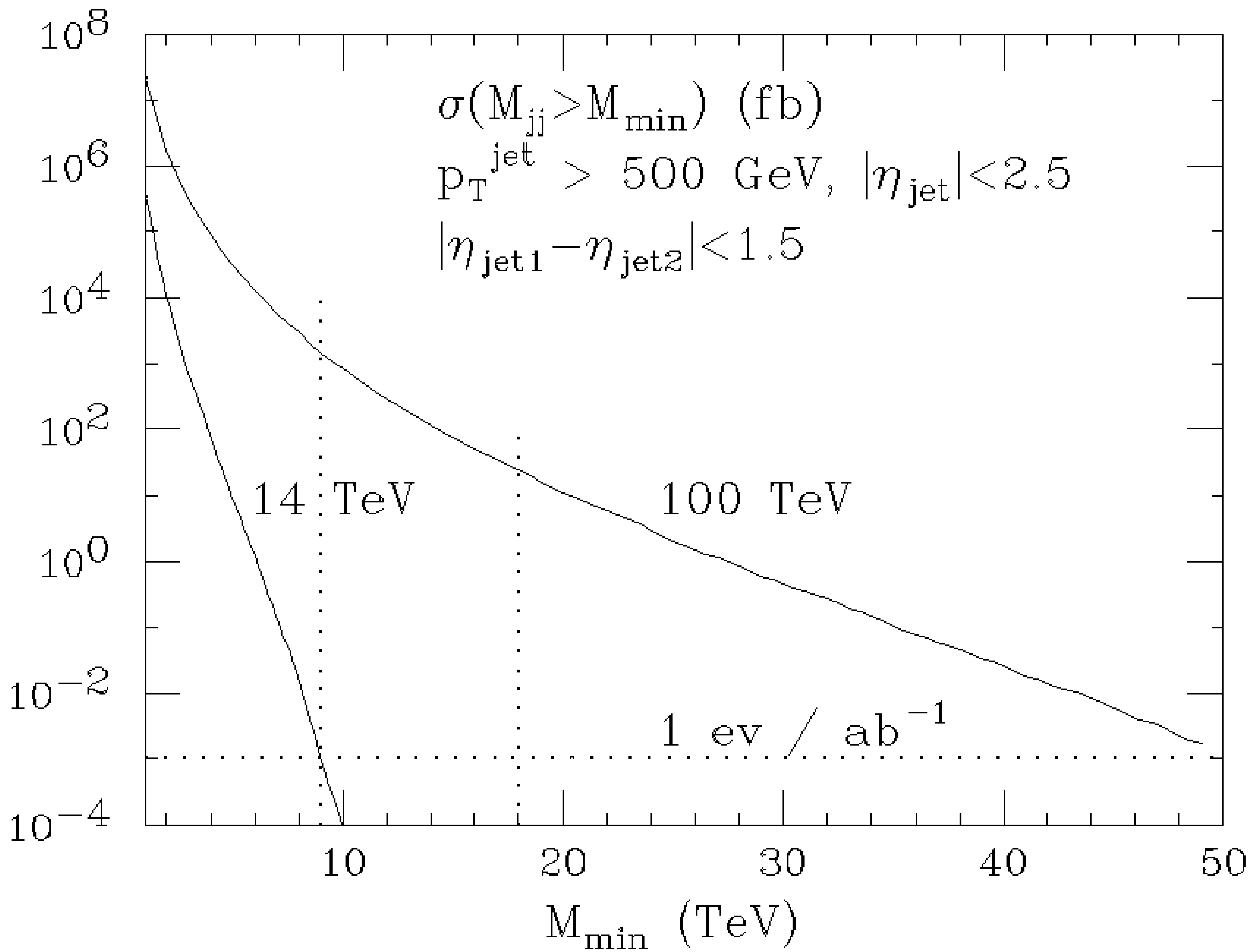


- 1 pb^{-1} to recover sensitivity of HL-LHC ⇒< 1 day @ 10^{32}
- 50pb^{-1} to 2x the sensitivity of HL-LHC ⇒< 1 month @ 10^{32}

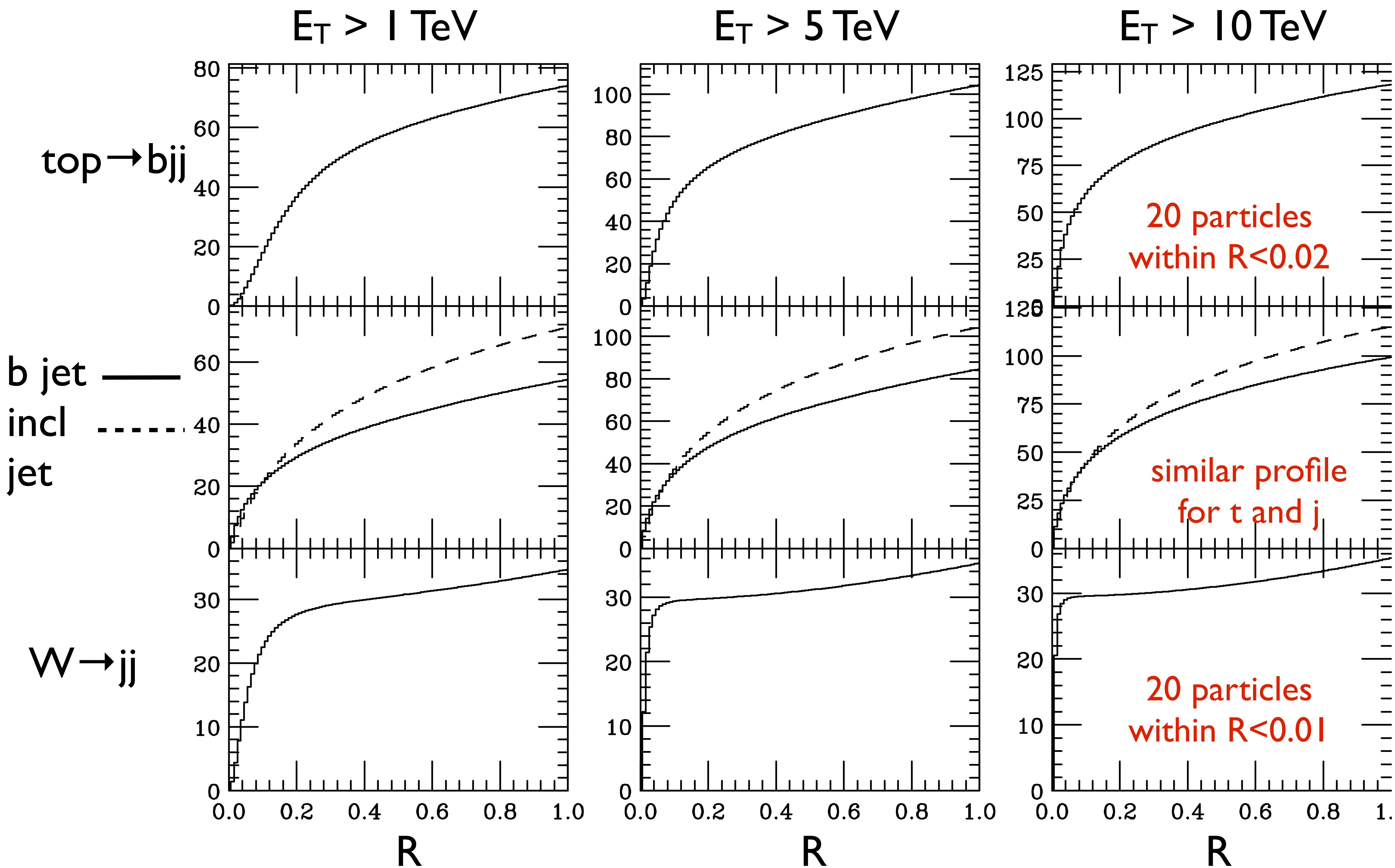
Example: dijet production at large mass



- 1 pb^{-1} to recover sensitivity of HL-LHC ⇒< 1 day @ 10^{32}
- 50pb^{-1} to 2x the sensitivity of HL-LHC ⇒< 1 month @ 10^{32}
- 1fb^{-1} to 3x the sensitivity of HL-LHC ⇒< 1 year @ $2x10^{32}$

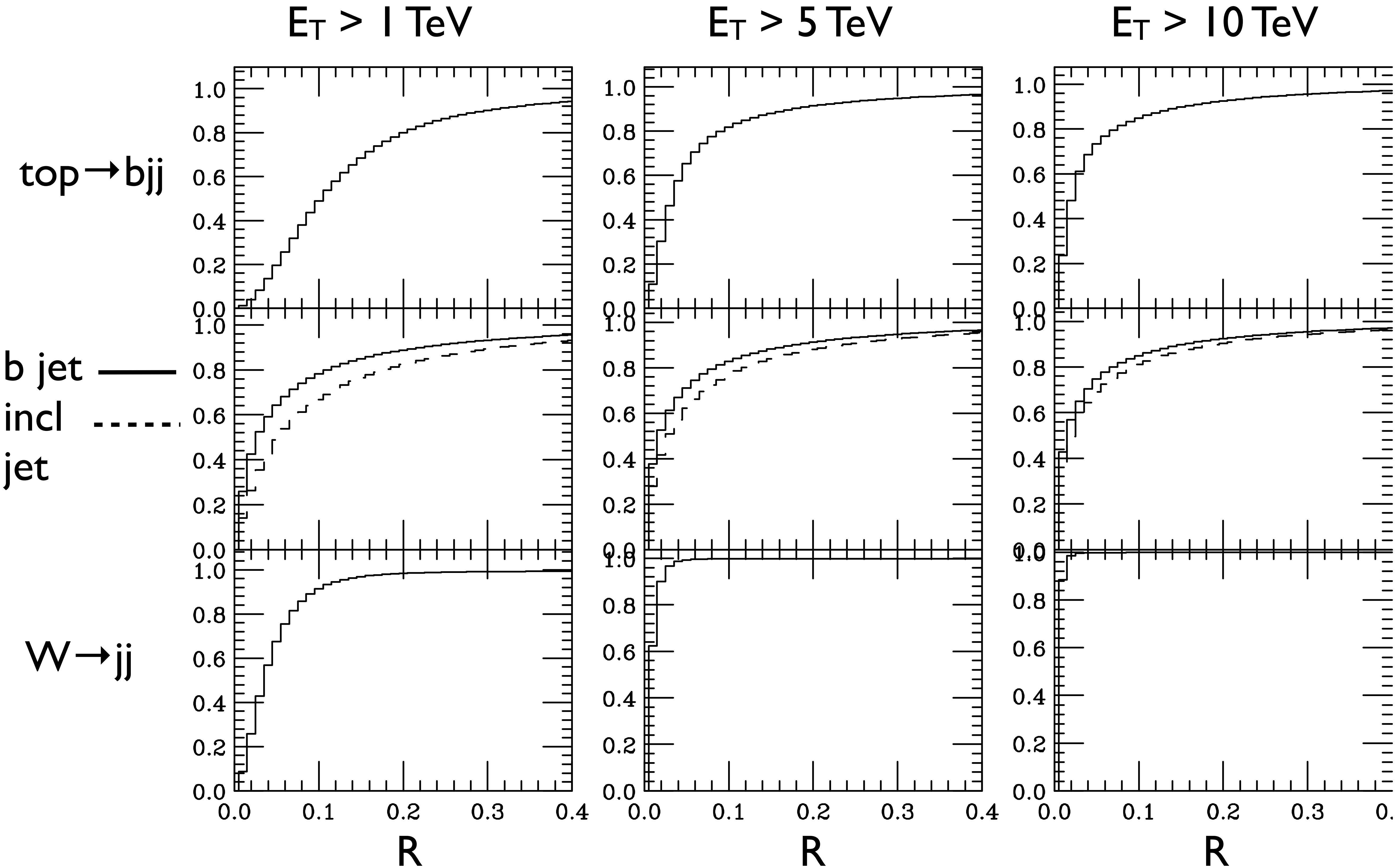
Jet properties at high E_T

Average particle multiplicity shape: N_{part} (r<R)

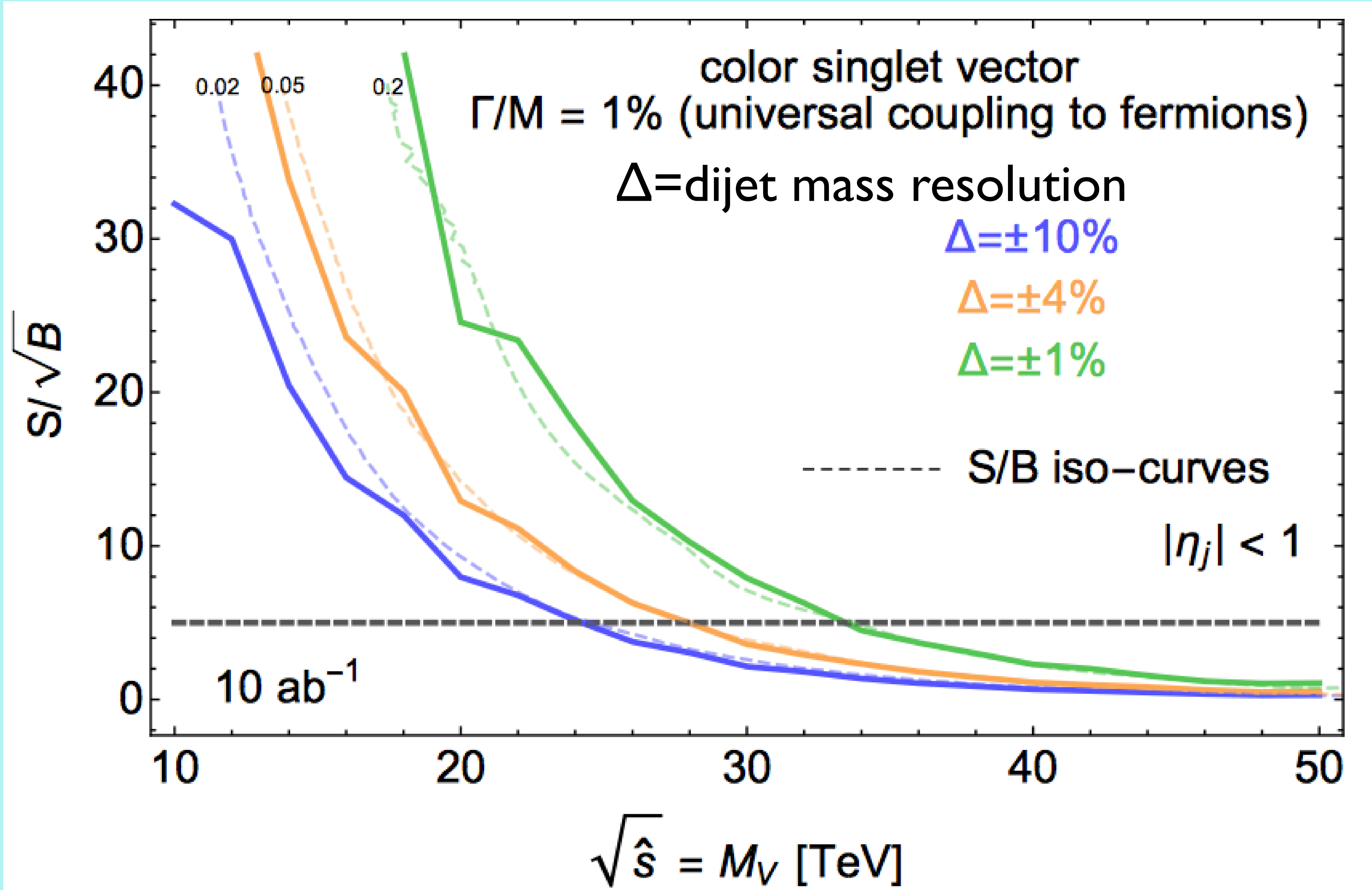


R=0.01 => 1cm at 1m

Energy shape: E(r<R) / E(r<1)



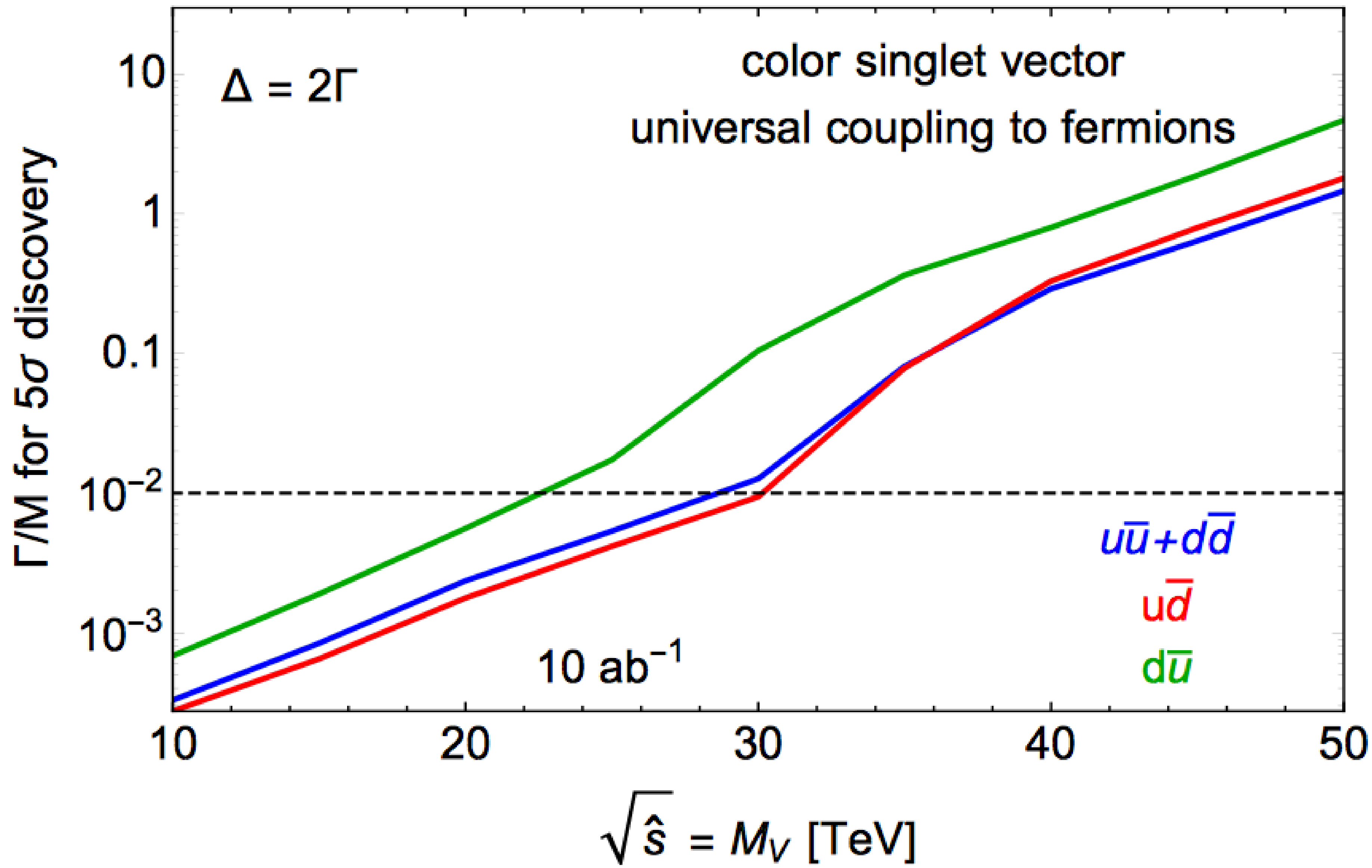
Discovery reach in dijet channel, weakly coupled case



MINIMUM WIDTH FOR DISCOVERY

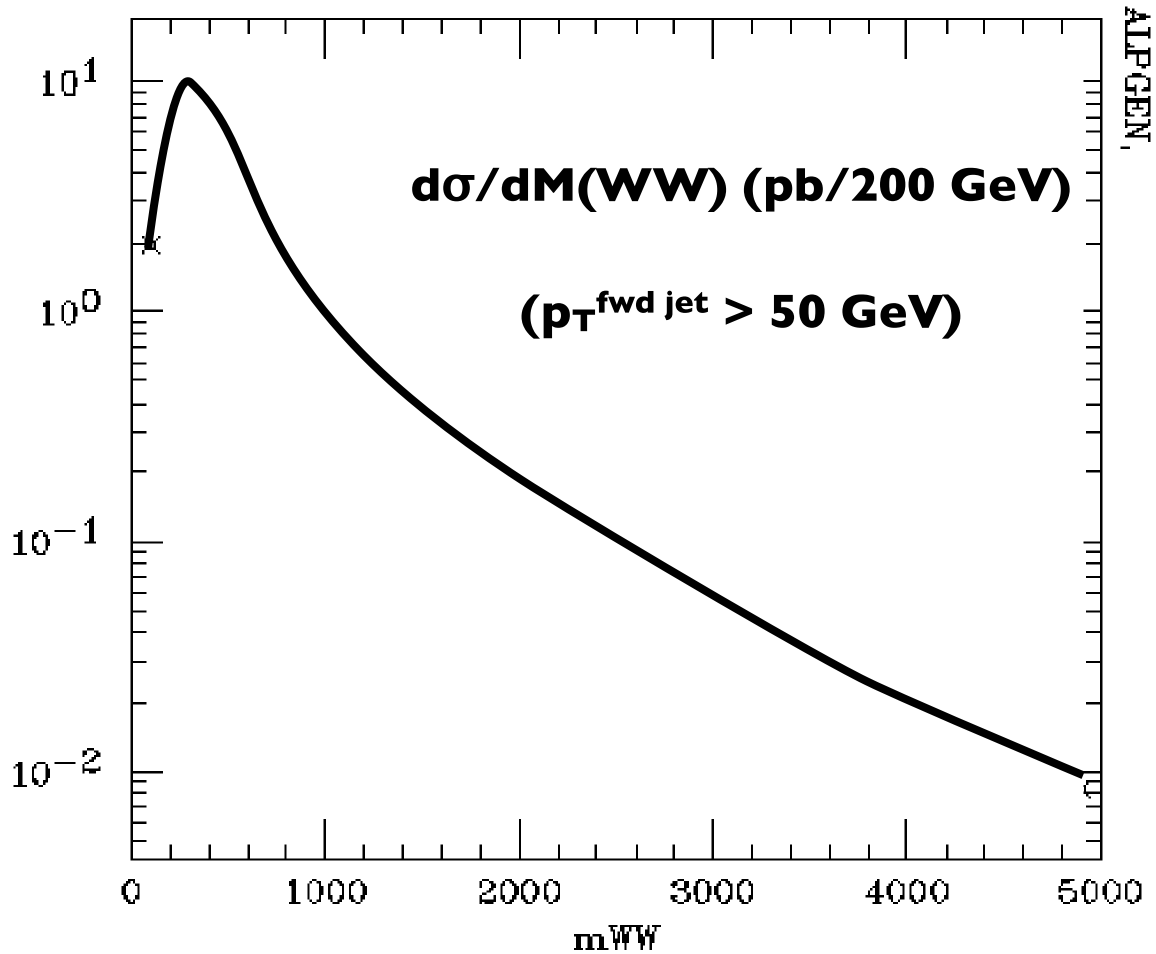
The production cross section is proportional to the partial width and therefore it determines the minimum width needed for discovery

This is important to know the resolution needed to be sensitive to these resonances

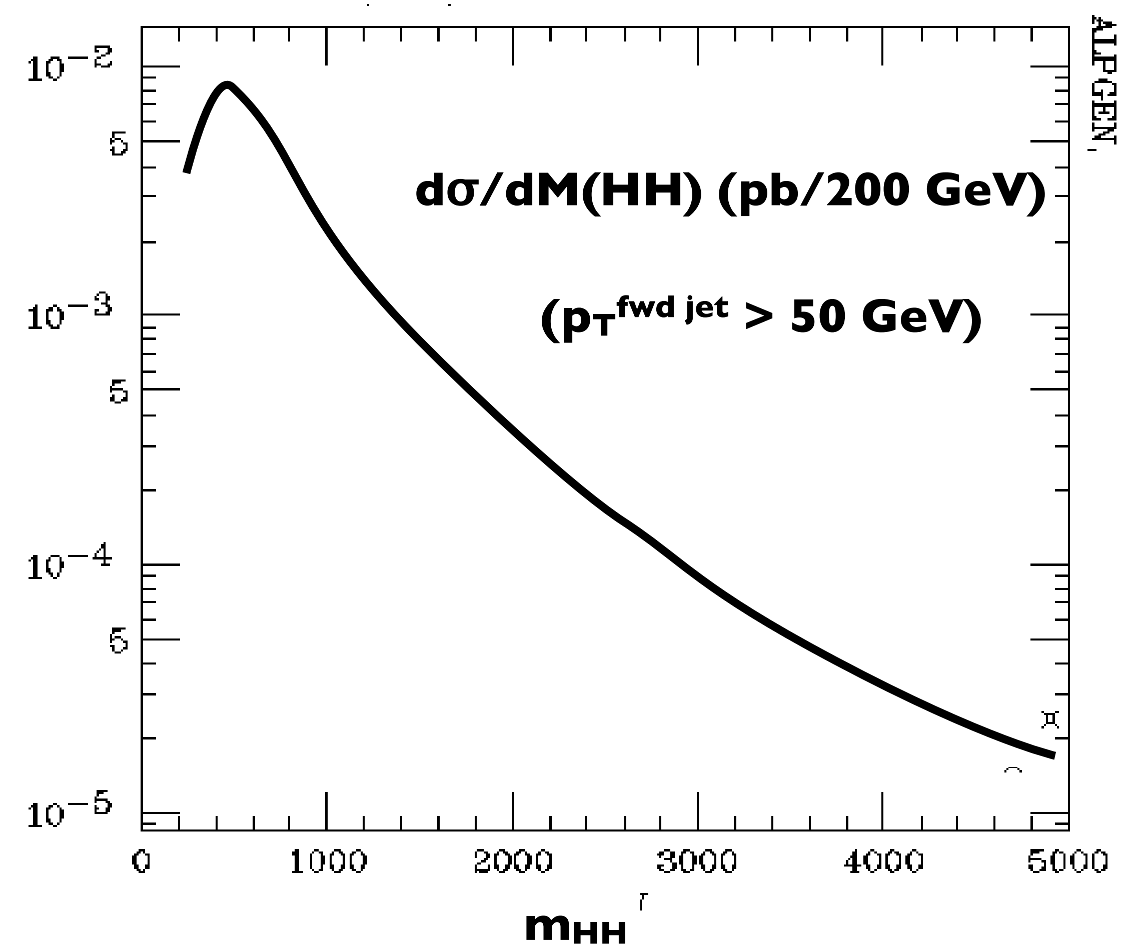


EWSB probes: high mass WW/HH in VBF

SM rates at 100 TeV

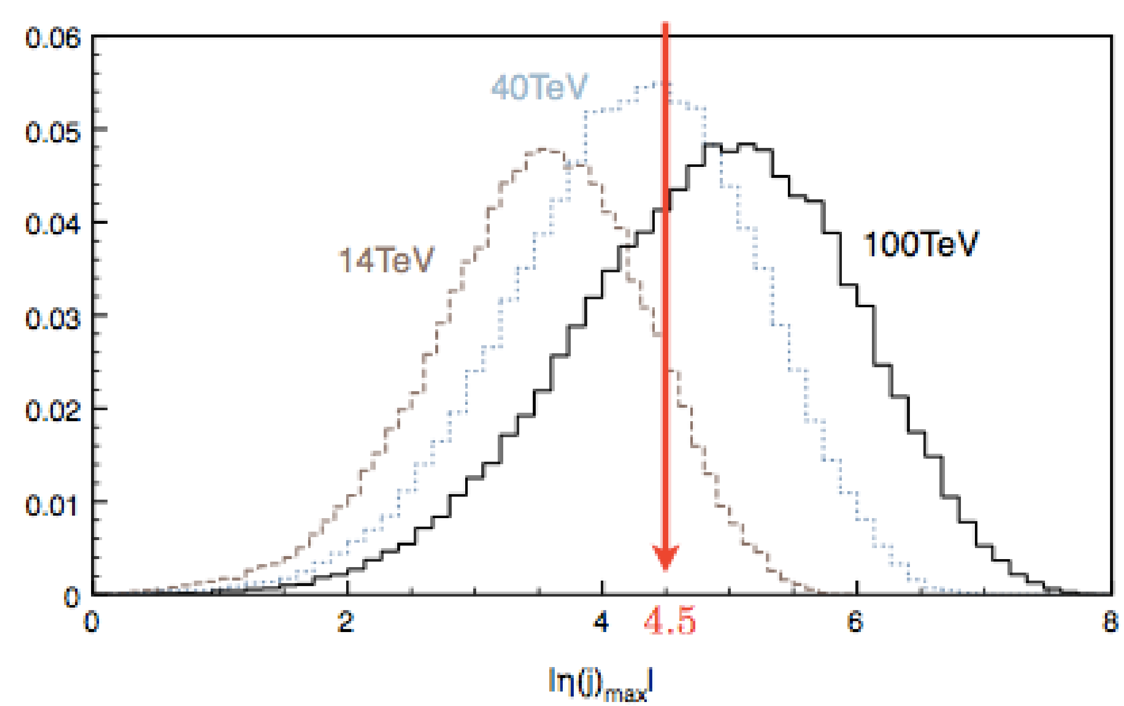


100 fb with M(WW) ≳ 3 TeV



1 fb with M(HH) ≳ 2 TeV

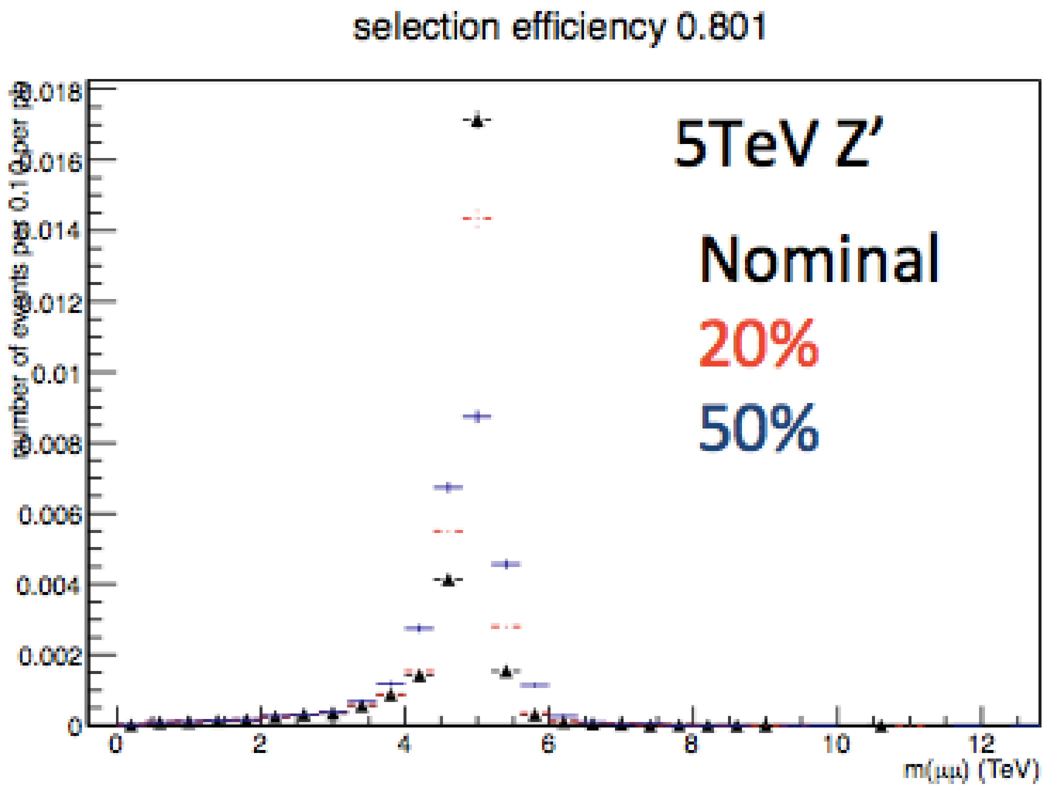
Fwd jet η spectrum

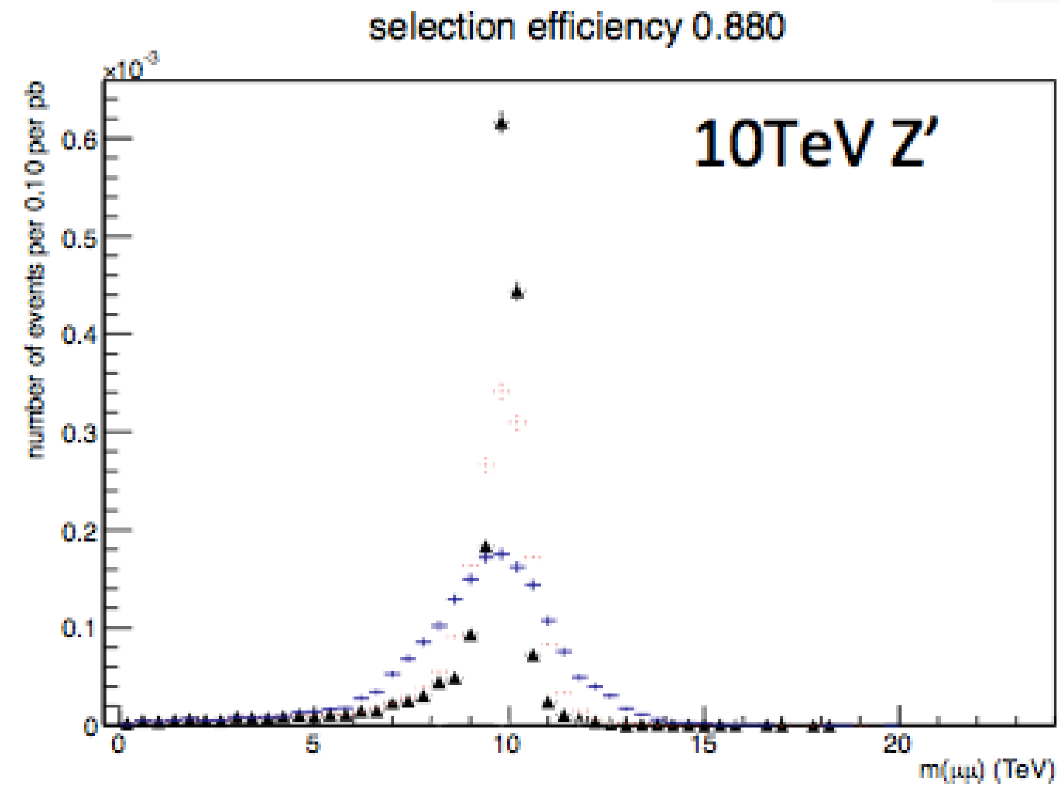


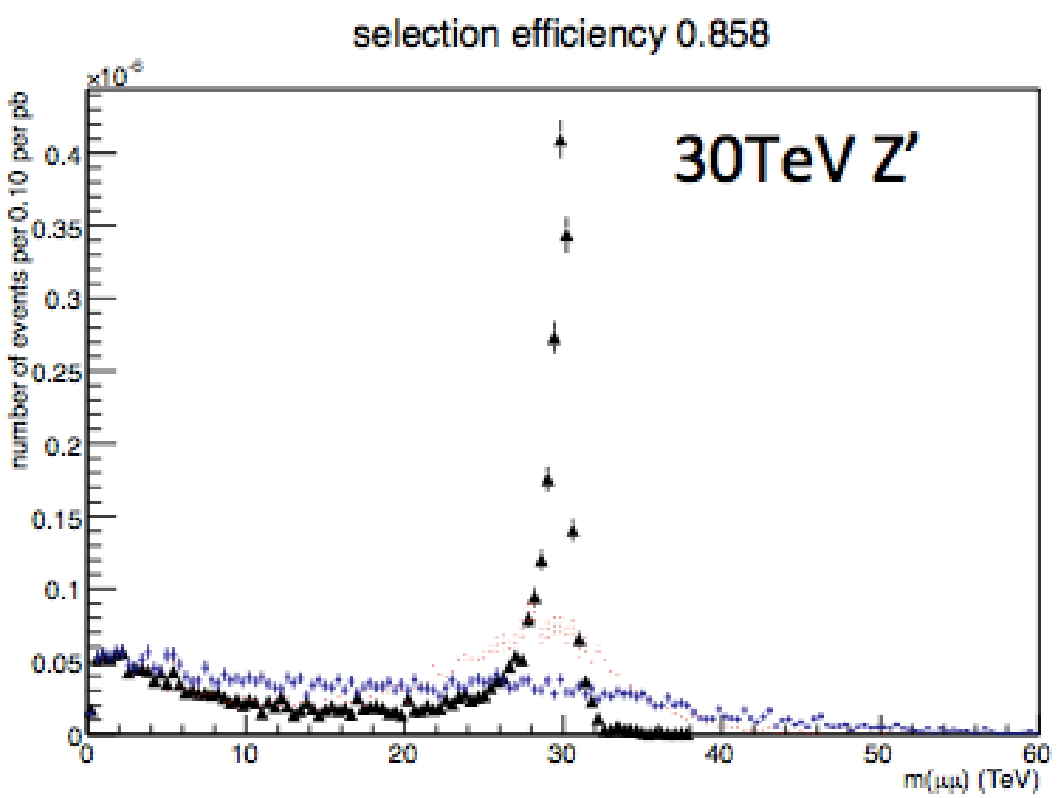
Muons

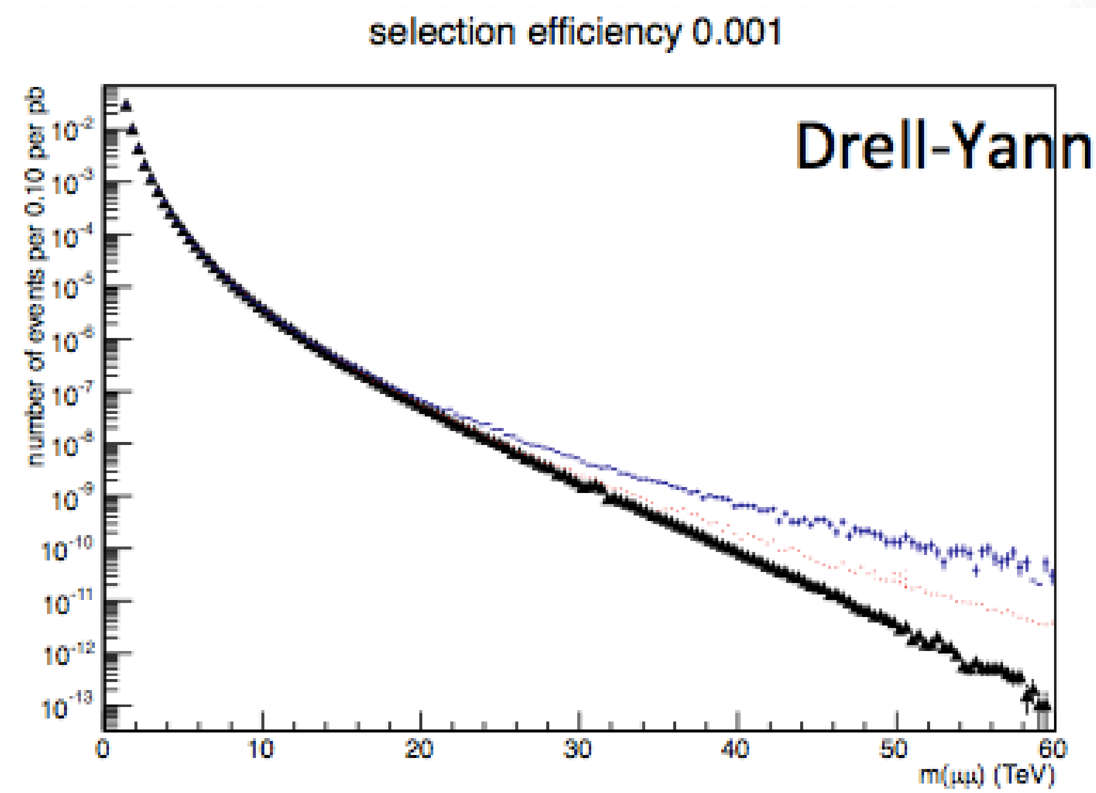
Results by Clement Helsens,
FCC mtg Febr 6 2014,
http://indico.cern.ch/event/297201/
and updates

impact of different assumptions on **muon momentum resolution at 10 TeV**
(nominal: natural Z' width, 3% in this case)





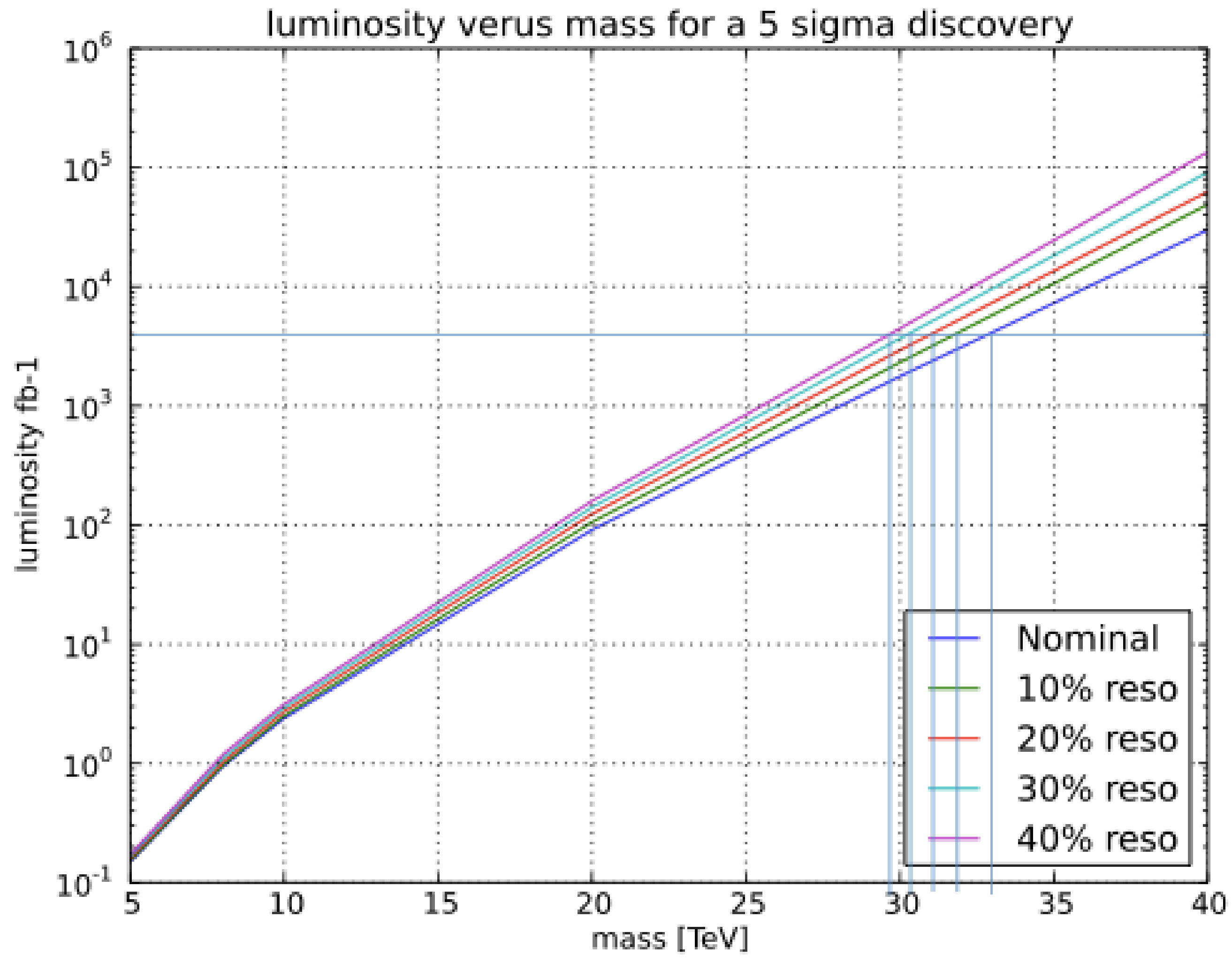




Sensitivity

Luminosity (fb^{-1}) to discover at 5sigma

	5TeV	8TeV	10TeV	20TeV	30TeV	40TeV
Nominal	0.15	0.93	2.39	91.2	1770	29983
10%	0.15	0.96	2.51	106.1	2312	48914
20%	0.16	1.02	2.72	123.9	2932	62653
30%	0.16	1.09	2.93	140.9	3674	91116
40%	0.17	1.18	3.14	159.4	4462	134534



To follow the ongoing studies on the design of FCC-hh detectors, see

FCC-hh Detector subgroup (Werner Riegler):
https://indico.cern.ch/category/6069/
FCC-hh Detector magnets subgroup (Herman ten Kate):
https://indico.cern.ch/category/6244/

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 ....*

backup slides

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	σ_{NLO}(8 TeV) [fb]	σ_{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

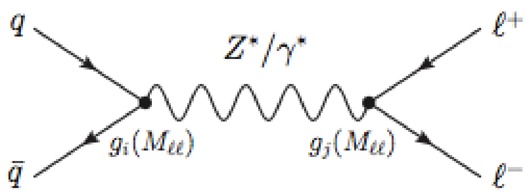
Process	$\sigma_{\text{NLO}}(8\text{ TeV})$ [fb]	$\sigma_{\text{NLO}}(100\text{ TeV})$ [fb]	ρ
$pp \to H\ (m_t, m_b)$	$1.44 \cdot 10^4\ ^{+20\%}_{-16\%}\ ^{+1\%}_{-2\%}$	$5.46 \cdot 10^5\ ^{+28\%}_{-27\%}\ ^{+2\%}_{-2\%}$	38
$pp \to Hjj$ (VBF)	$1.61 \cdot 10^3\ ^{+1\%}_{-0\%}\ ^{+2\%}_{-2\%}$	$7.40 \cdot 10^4\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-1\%}$	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.

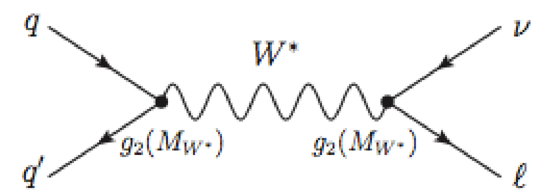
P.Torrielli, arXiv:1407.1623

Running Electroweak Couplings as a Probe of New Physics

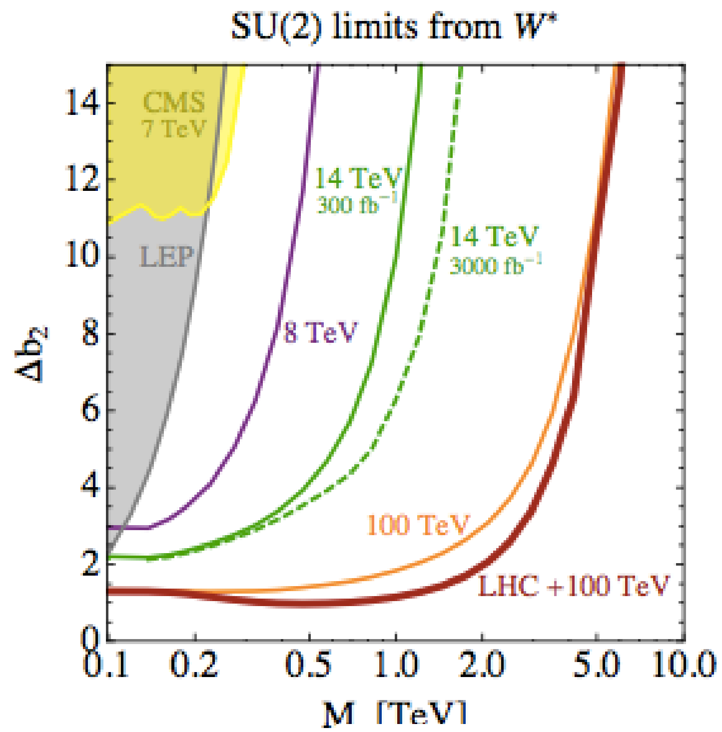
D.Alves, J. Galloway, J.Ruderman, J.Walsh *arXiv:1410.6810*

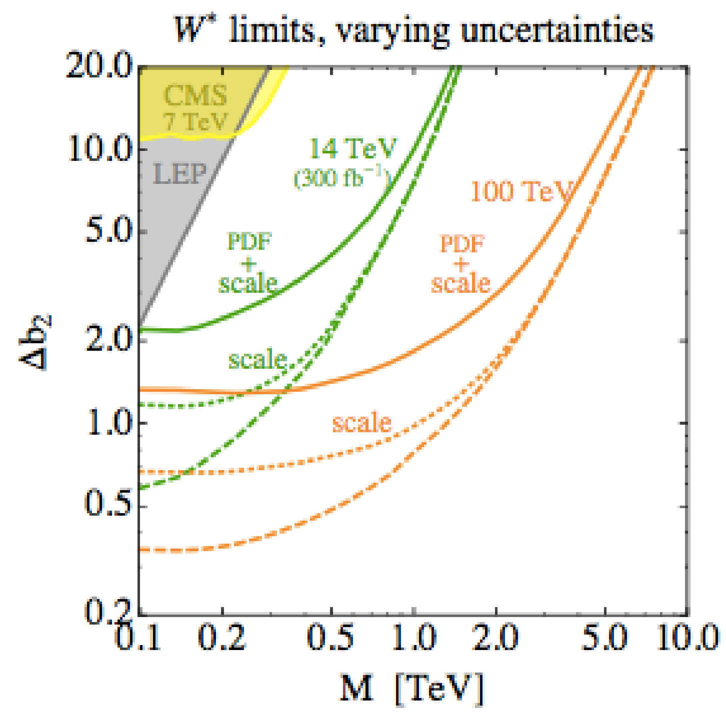


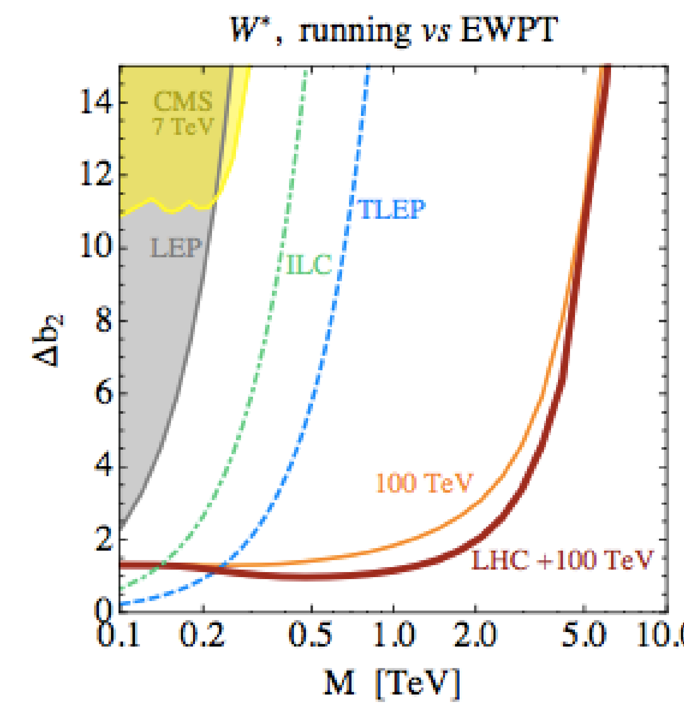
$$\frac{d\sigma}{dm_{ll}} \Rightarrow \alpha_{1,2}(q)$$

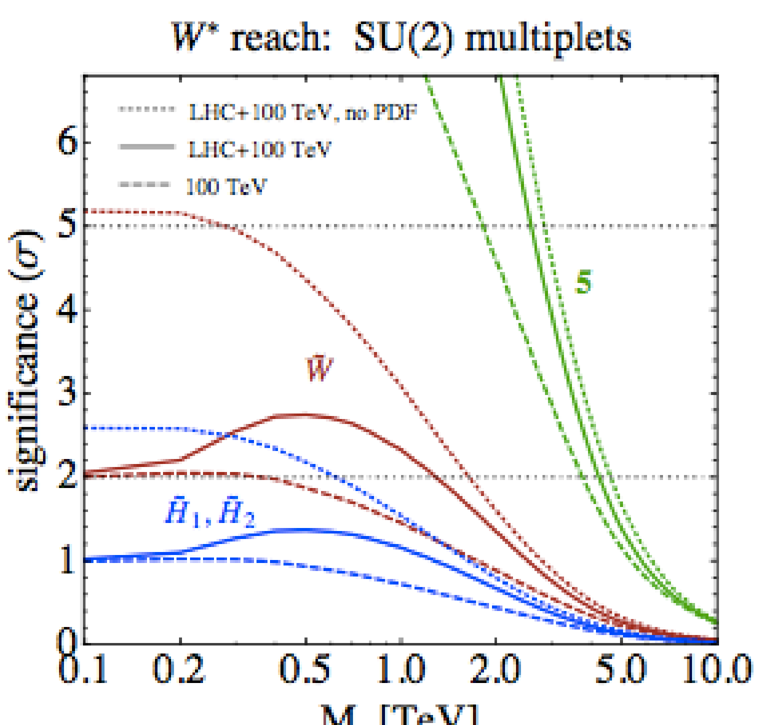


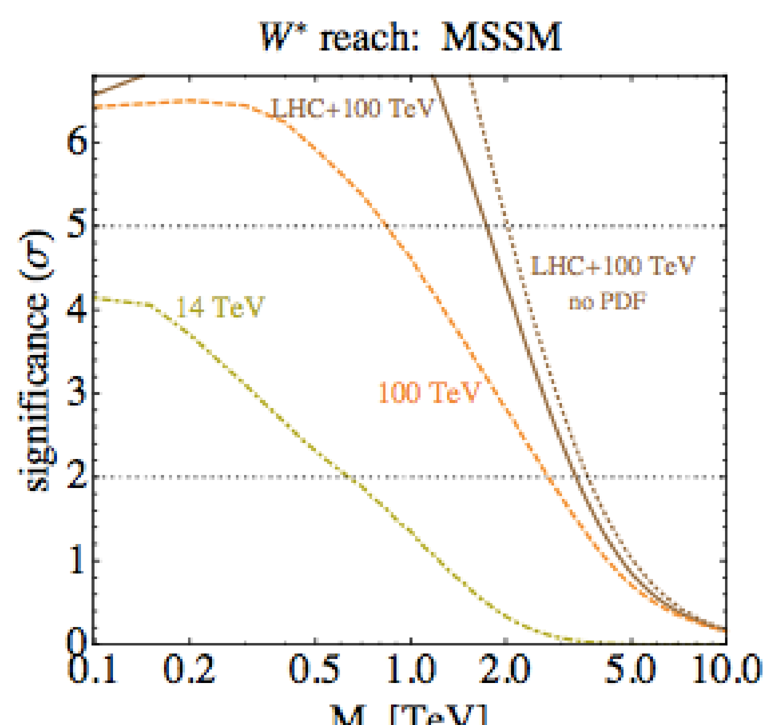
$$\frac{d\sigma}{dM_T} \Rightarrow \alpha_2(q)$$



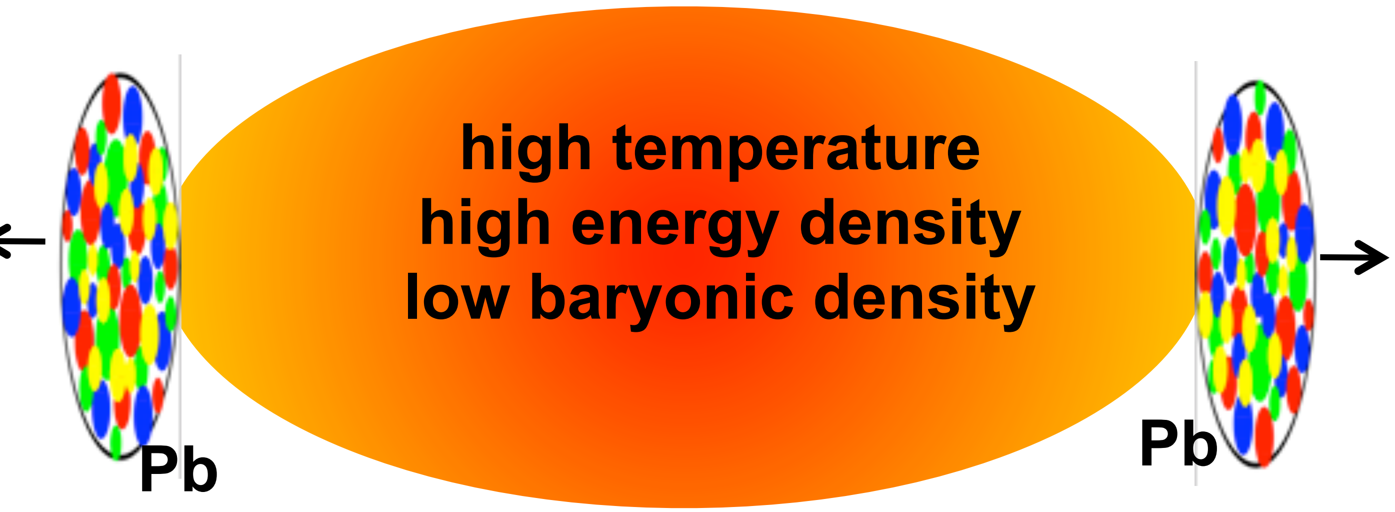


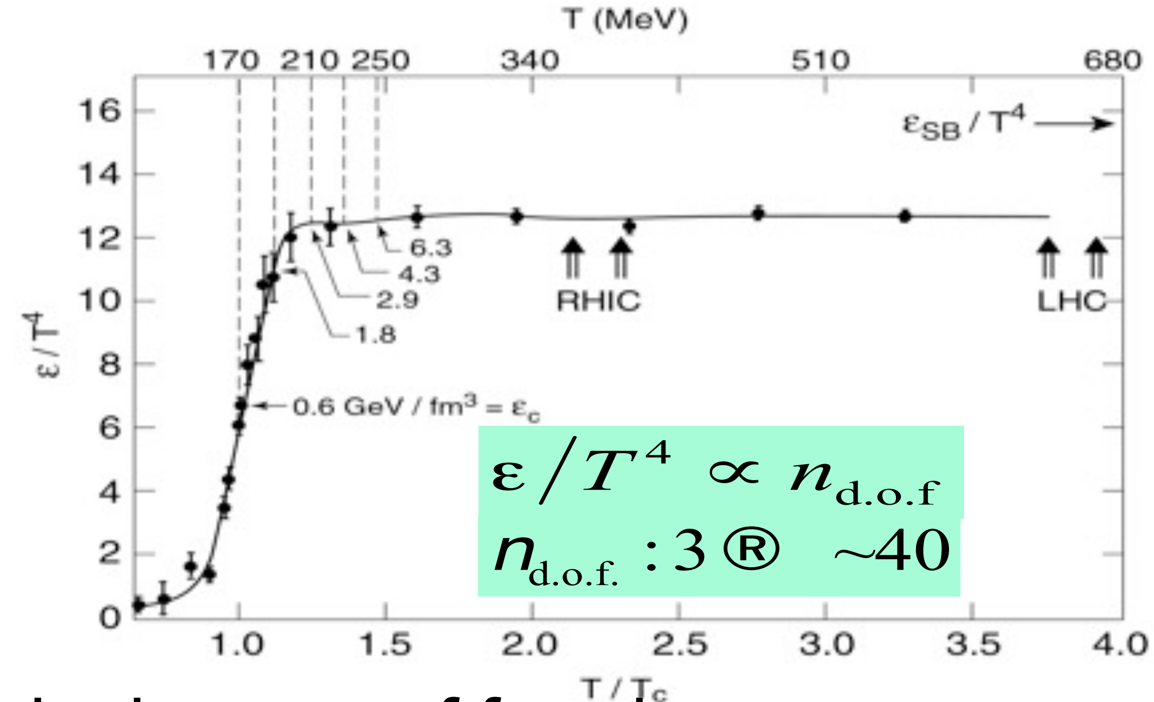




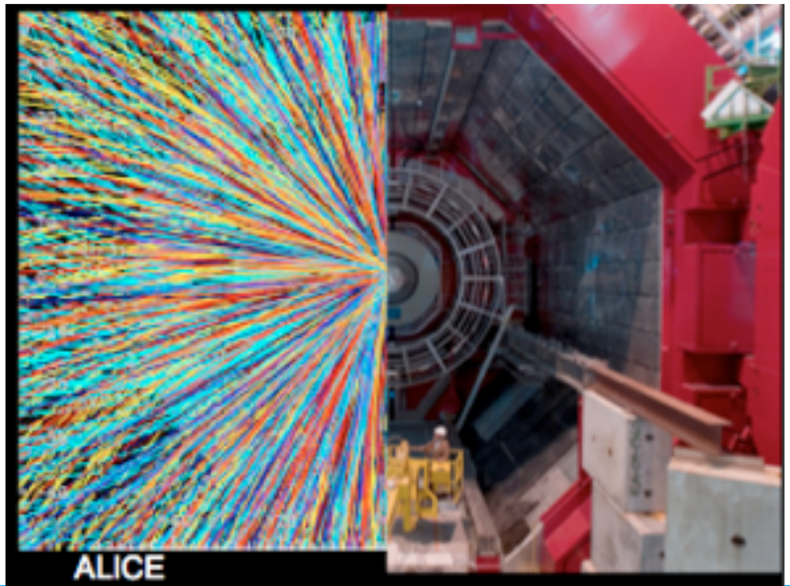


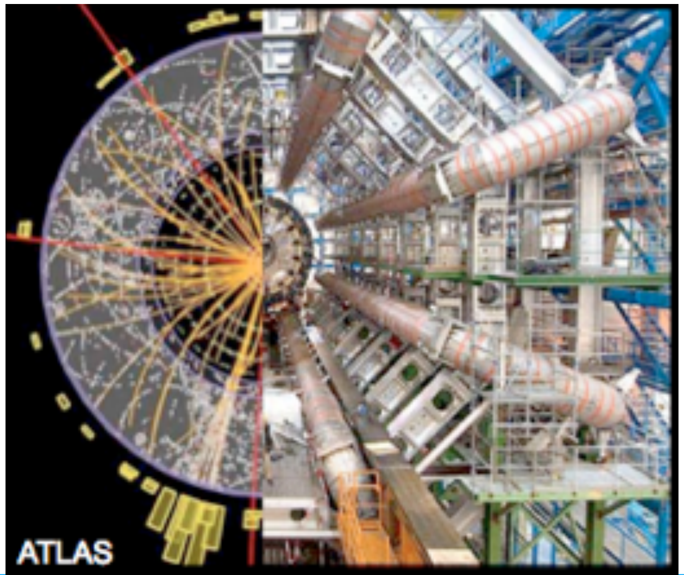
High-density QCD in the final state: the Quark Gluon Plasma

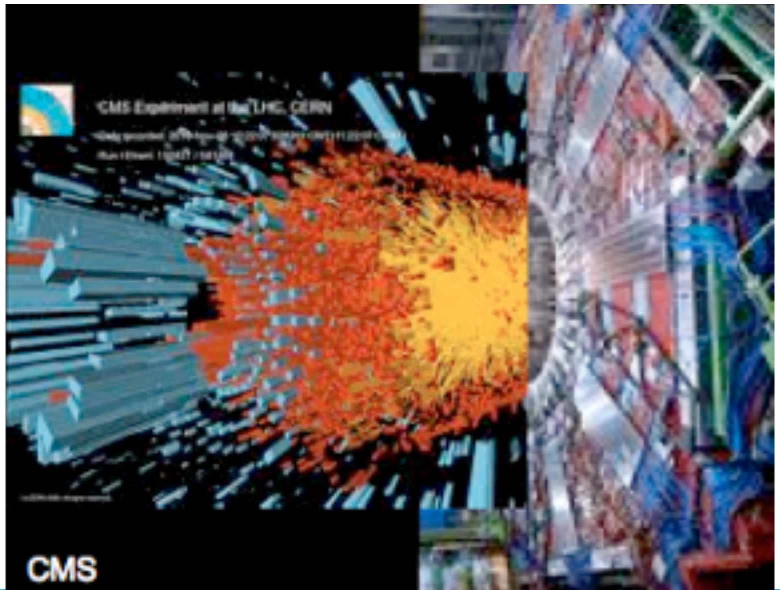




- Lattice QCD predicts phase transition at T_c~170 MeV
  → **Quark-Gluon Plasma**
- Confinement is removed
- Partonic degrees of freedom
- Unique opportunity to study in the laboratory spatially-extended multi-particle QCD system

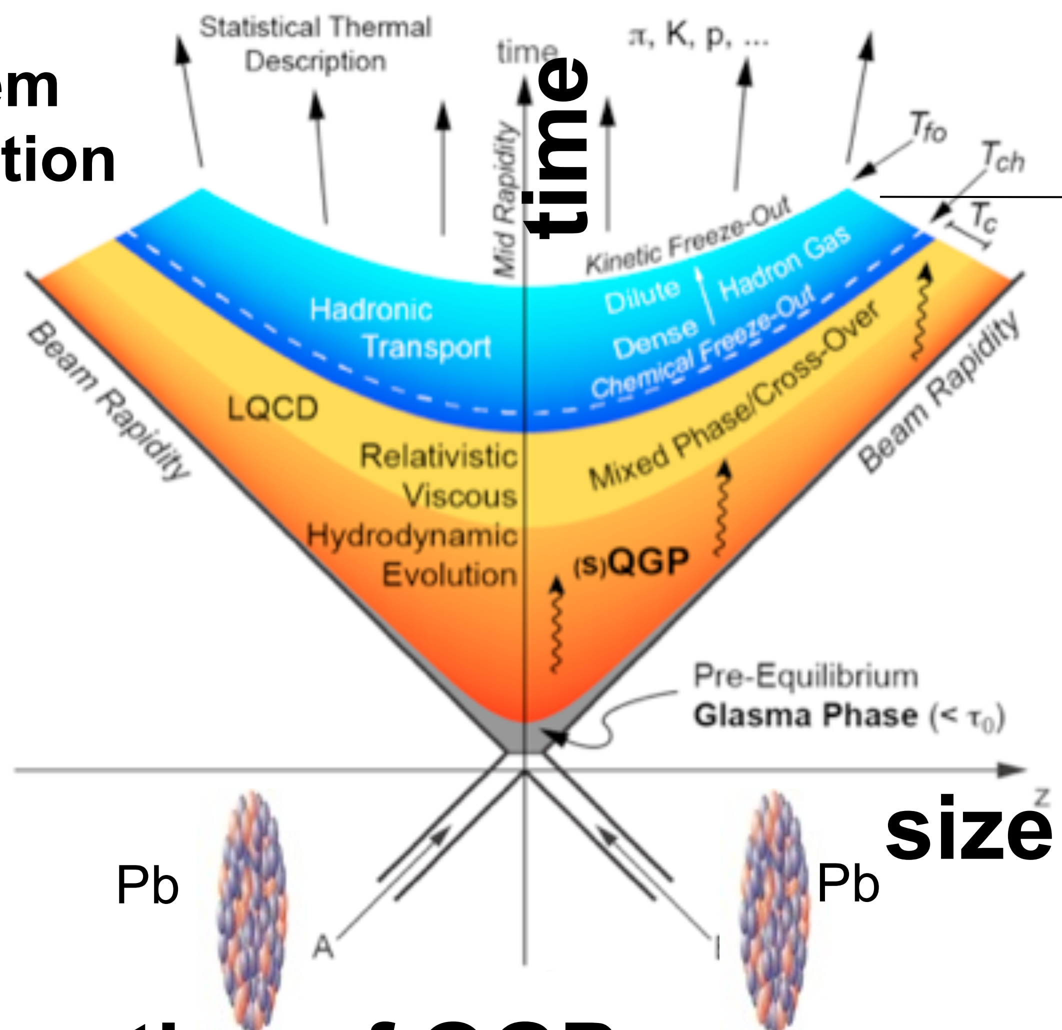


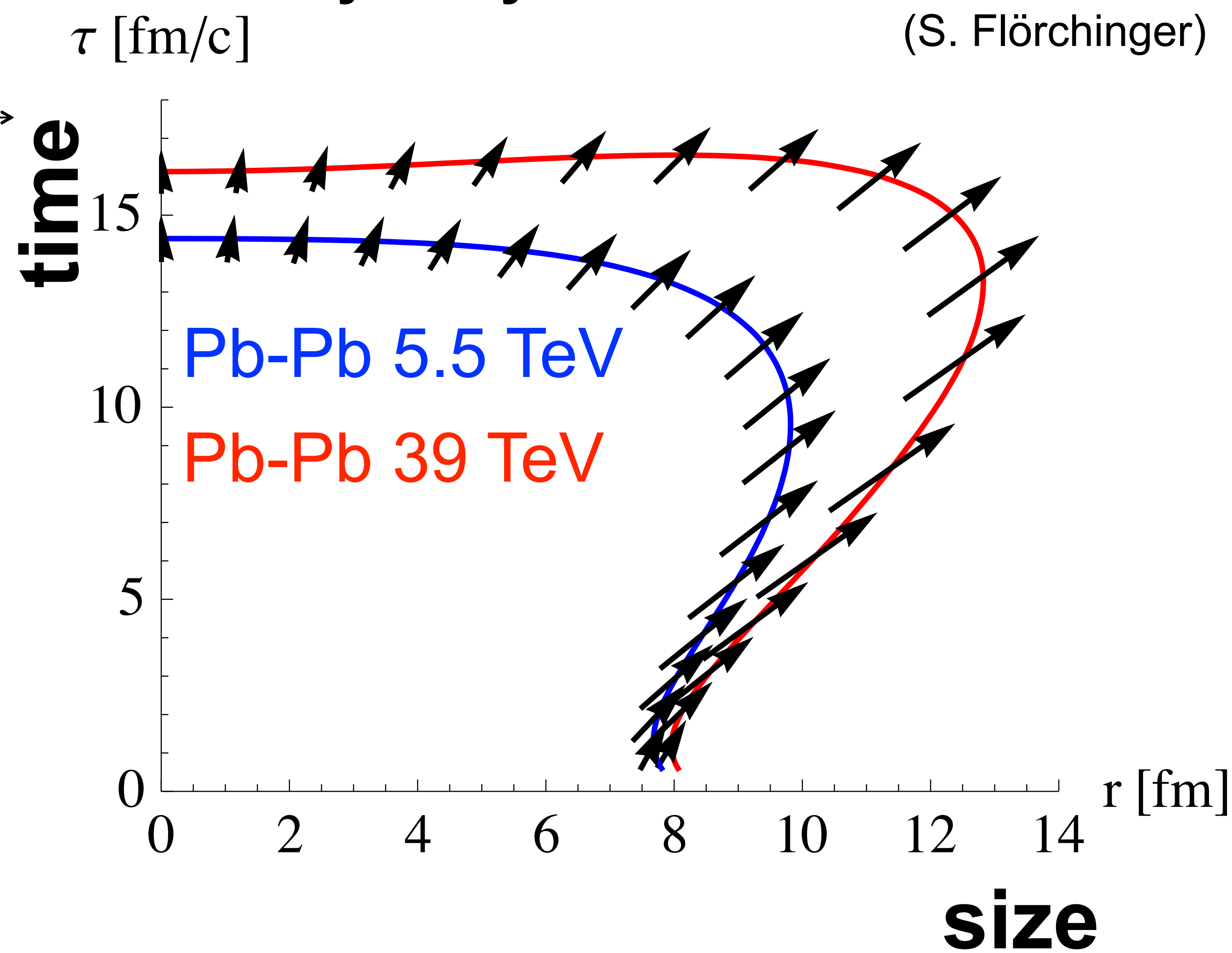




Quark-Gluon Plasma studies at FCC

System evolution





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?

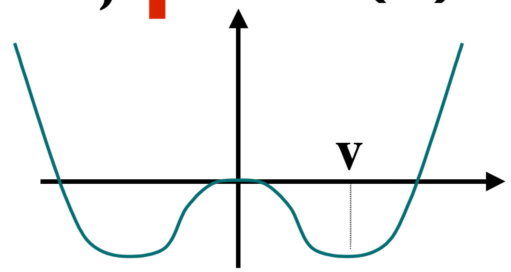
Higher energy

- 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?

Higgs selfcouplings

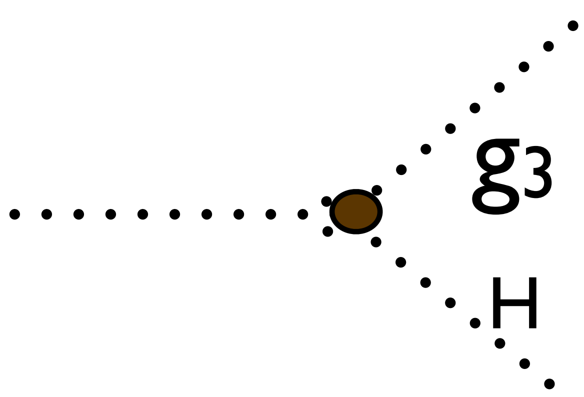
The Higgs sector is defined in the SM by two parameters, μ and λ:

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

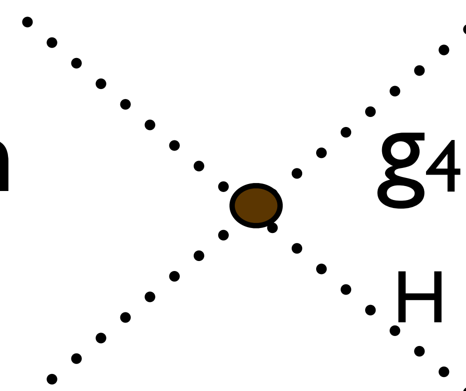


$$\frac{\partial V_{SM}(H)}{\partial H}|_{H=v} = 0 \quad \text{and} \quad m_H^2 = \frac{\partial^2 V_{SM}(H)}{\partial H \partial H^*}|_{H=v} \quad \Rightarrow \quad \begin{array}{rcl} \mu & = & m_H \\ \lambda & = & \frac{m_H^2}{2v^2} \end{array}$$

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



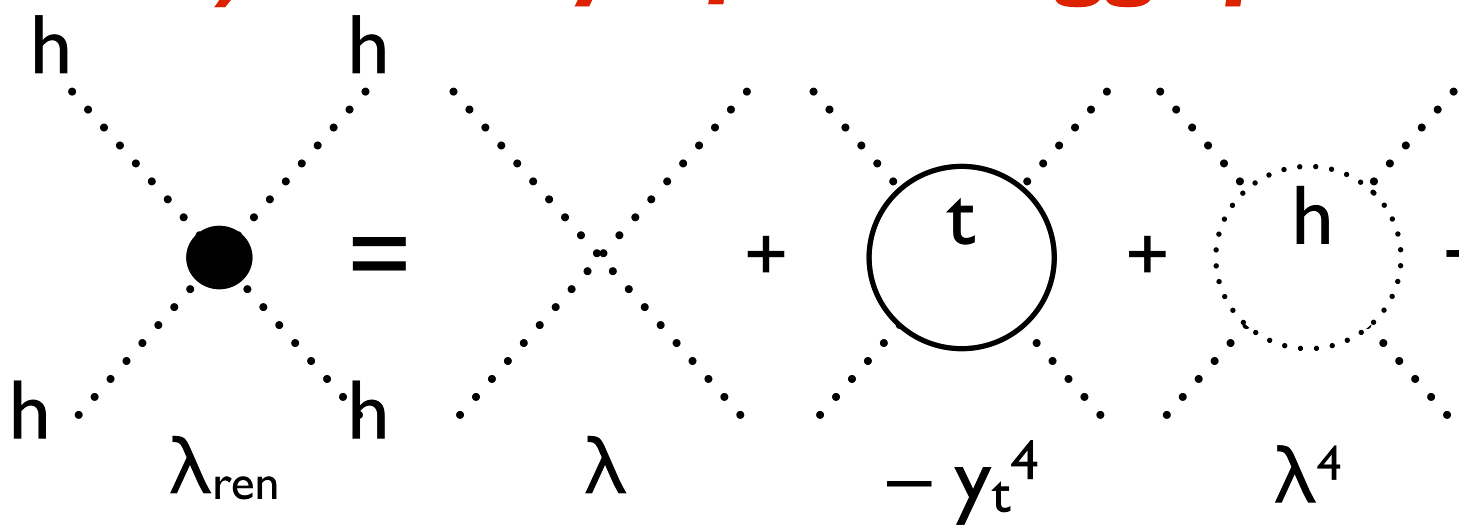
$$\Rightarrow 6\lambda\, v = \frac{3m_H^2}{v}$$ ~O(m_{top})



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

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

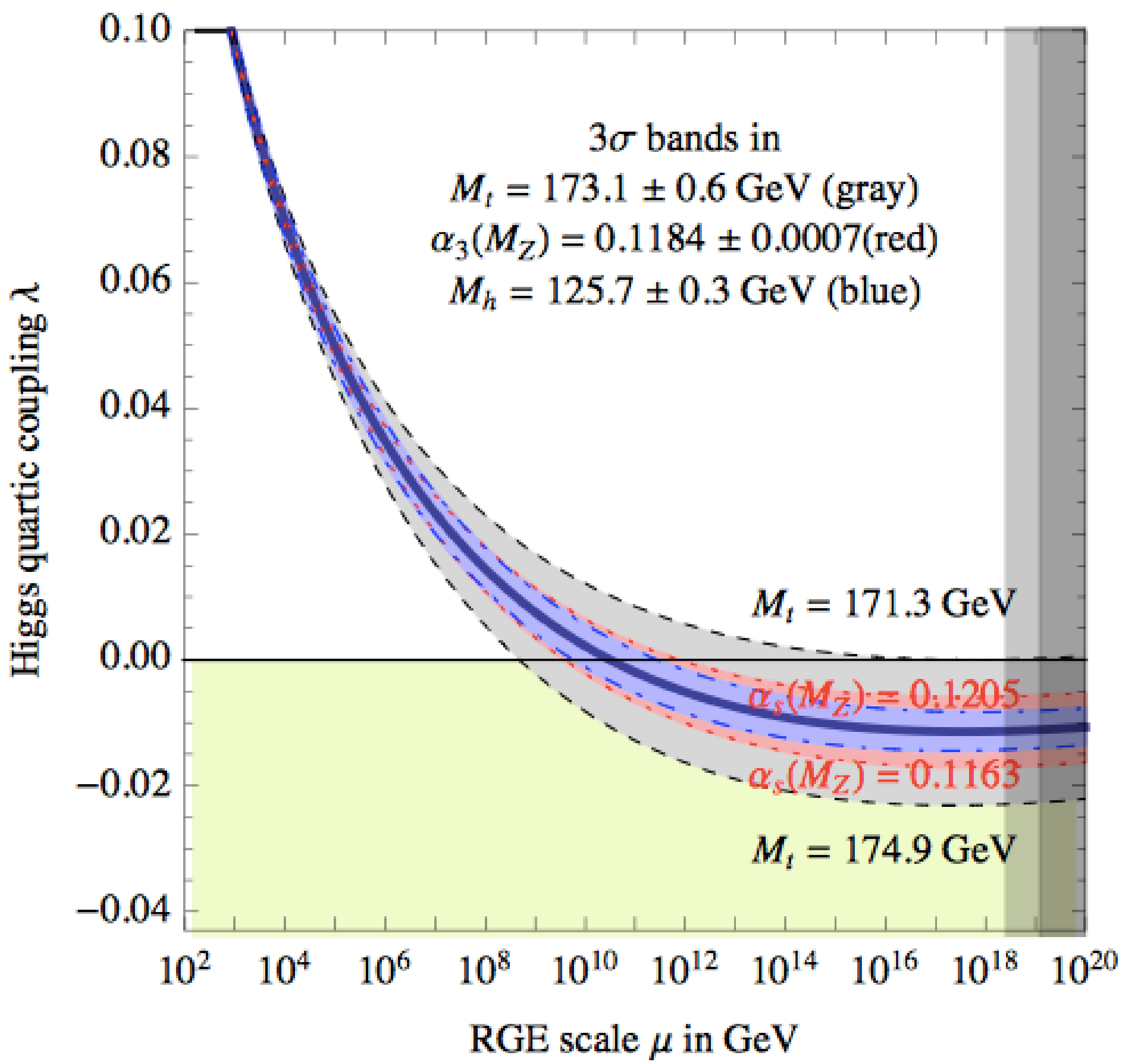
(meta)Stability of the Higgs potential



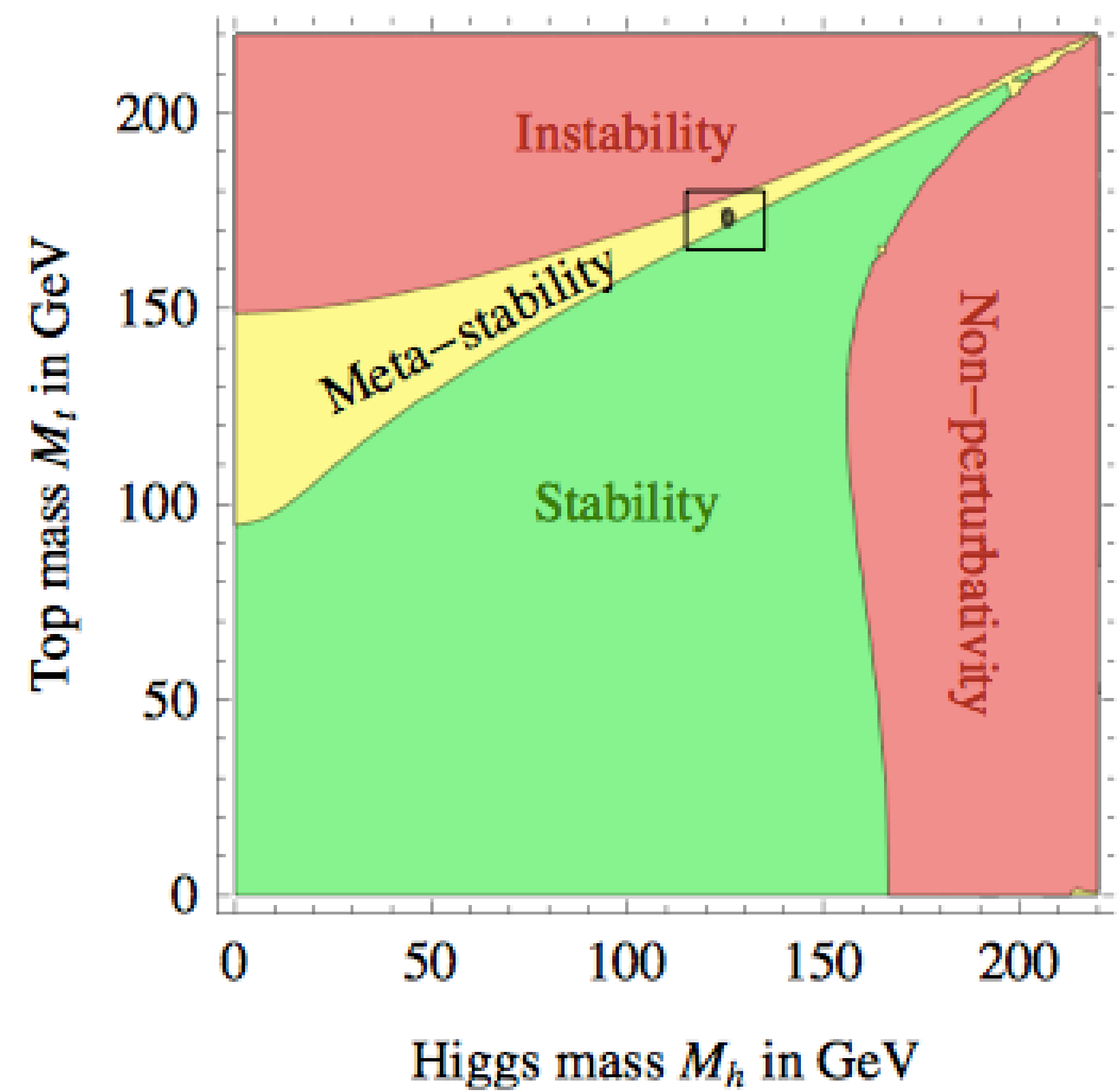
$$\Rightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4$$

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

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



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



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)
$\mathrm{FCC}_{@100\mathrm{TeV}}$ 3/ab	30~40%	30%	15%
$\mathrm{FCC}_{@100\mathrm{TeV}}$ 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

ttH/ttZ

- Potential % theory precision for ttH coupling
- Goal: % level exptl precision ⇒

  > 10 K events

ttH (pb)	ttZ (pb)	ttH/ttZ
33.9 $[^{+7.06\%}_{-8.29\%}]_{Scale}$ $[^{+0.941\%}_{-1.26\%}]_{PDF}$	57.9 $[^{+8.93\%}_{-9.46\%}]_{Scale}$ $[^{+0.901\%}_{-1.20\%}]_{PDF}$	0.585 $[^{+1.29\%}_{-2.02\%}]_{Scale}$ $[^{+0.0526\%}_{-0.0758\%}]_{PDF}$

- reference benchmark procs: H→bb and H→γγ
- establish requirements to cancel exptl syst's in ratios ttH/ttZ

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- reference benchmark procs: H→bb and H→γγ
- establish requirements to cancel exptl syst's in ratios ttH/ttZ

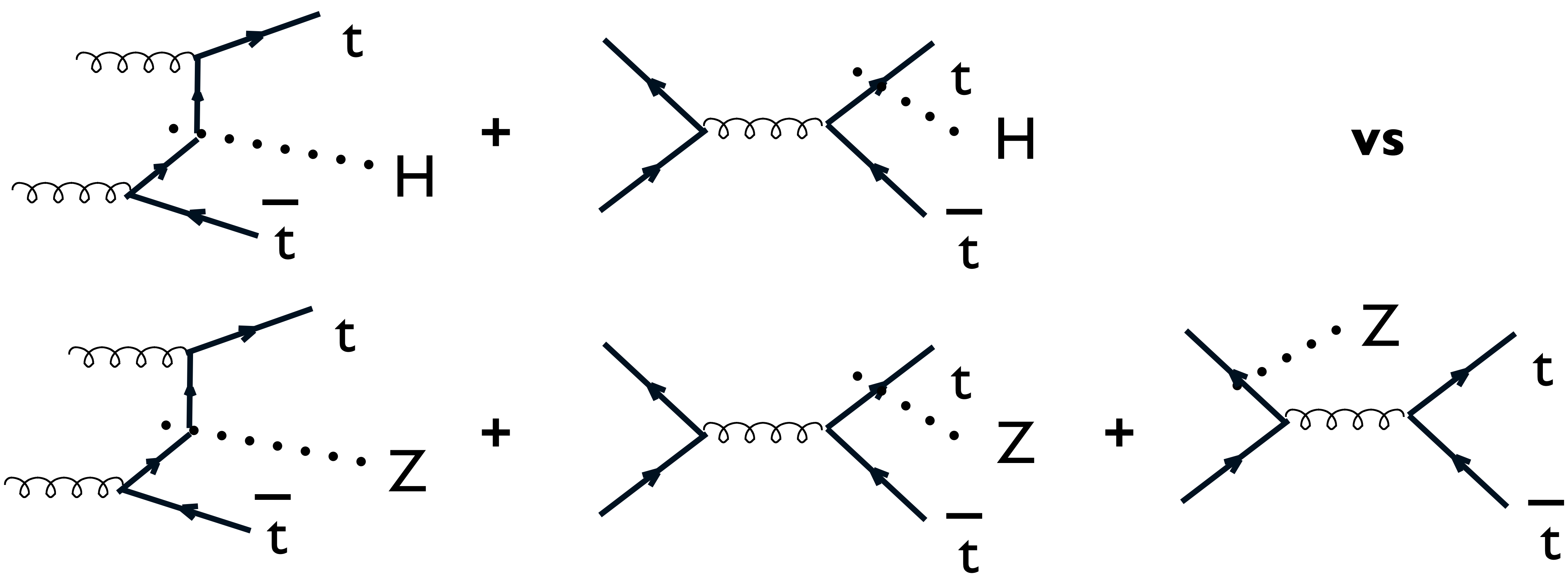
tt + (H→γγ): b tagging, lept eff/acc, γ eff, $m_{\gamma\gamma}$, ...

$$p_{T,j} > 25\text{ GeV}, |\eta_j| < 2.5,$$
$$p_{T,b} > 25\text{ GeV}, |\eta_b| < 2.5,$$
$$p_{T,\gamma} > 25\text{ GeV}, |\eta_\gamma| < 2.5,$$
$$120\text{ GeV} < m_{\gamma\gamma} < 130\text{ GeV},$$
$$p_{T,\ell^\pm/\tau^\pm} > 20\text{ GeV}, |\eta_{\ell^\pm/\tau^\pm}| < 2.5,$$
$$E_{T,\text{miss}} > 20\text{ GeV},$$
$$\Delta R_{jj} > 0.4, \Delta R_{bj} > 0.4, \Delta R_{bb} > 0.4.$$

In 30ab^{-1}
~**100K** (semi-)leptonic ttH signal events
~**12K** irreducible bg (ttγγ)

(H-S Shao, preliminary, H&BSM@100 TeV wshop)

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] μ_0 , with $\mu_0 = m_H+2m_t$

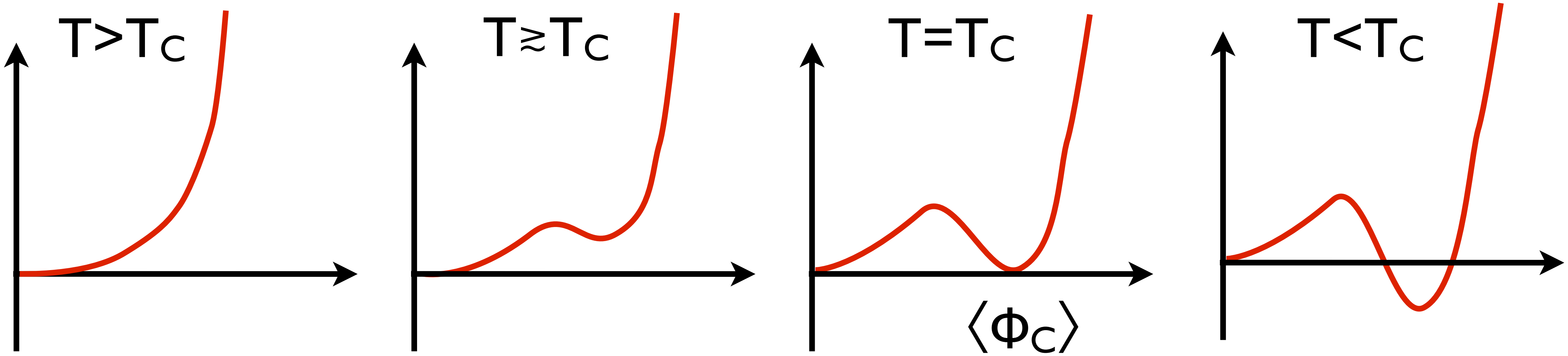
	δσ(ttH)	δσ(ttZ)	**σ(ttH)/σ(ttZ)**	**δ[σ(ttH)/σ(ttZ)]**
14 TeV	± 9.8%	± 12.3%	**0.608**	**±2.6%**
100 TeV	± 9.6%	± 10.8%	**0.589**	**±1.2%**

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

	δσ(ttH)	δσ(ttZ)	**δ[σ(ttH)/σ(ttZ)]**
14 TeV	± 4.8%	± 5.3%	**±0.75%**
100 TeV	± 2.7%	± 2.3%	**±0.48%**

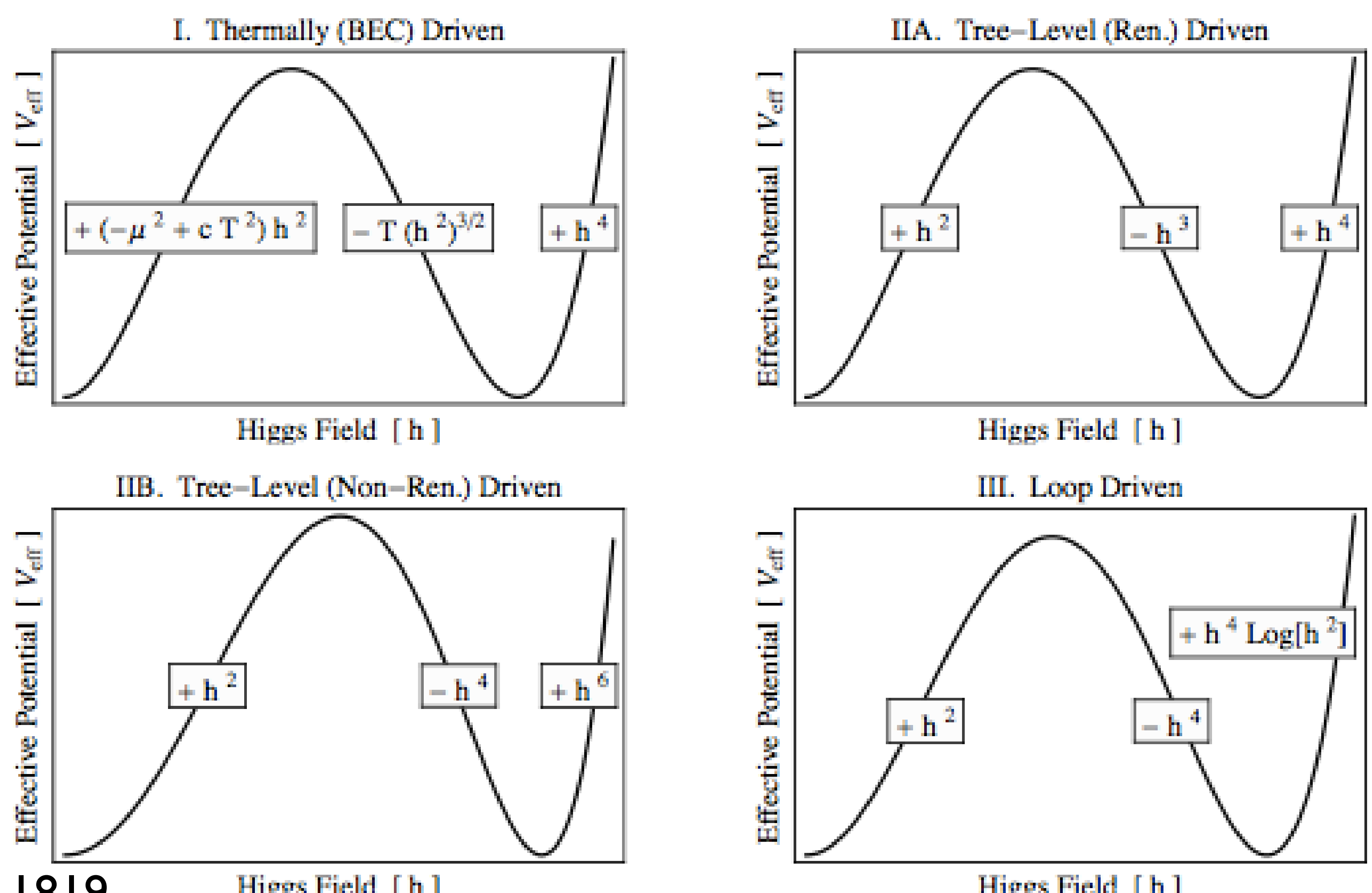
* *The uncertainty reduction survives after applying kinematical cuts to the final states*

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



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

In the SM this requires $m_H \lesssim 80$ GeV $\Rightarrow$ 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