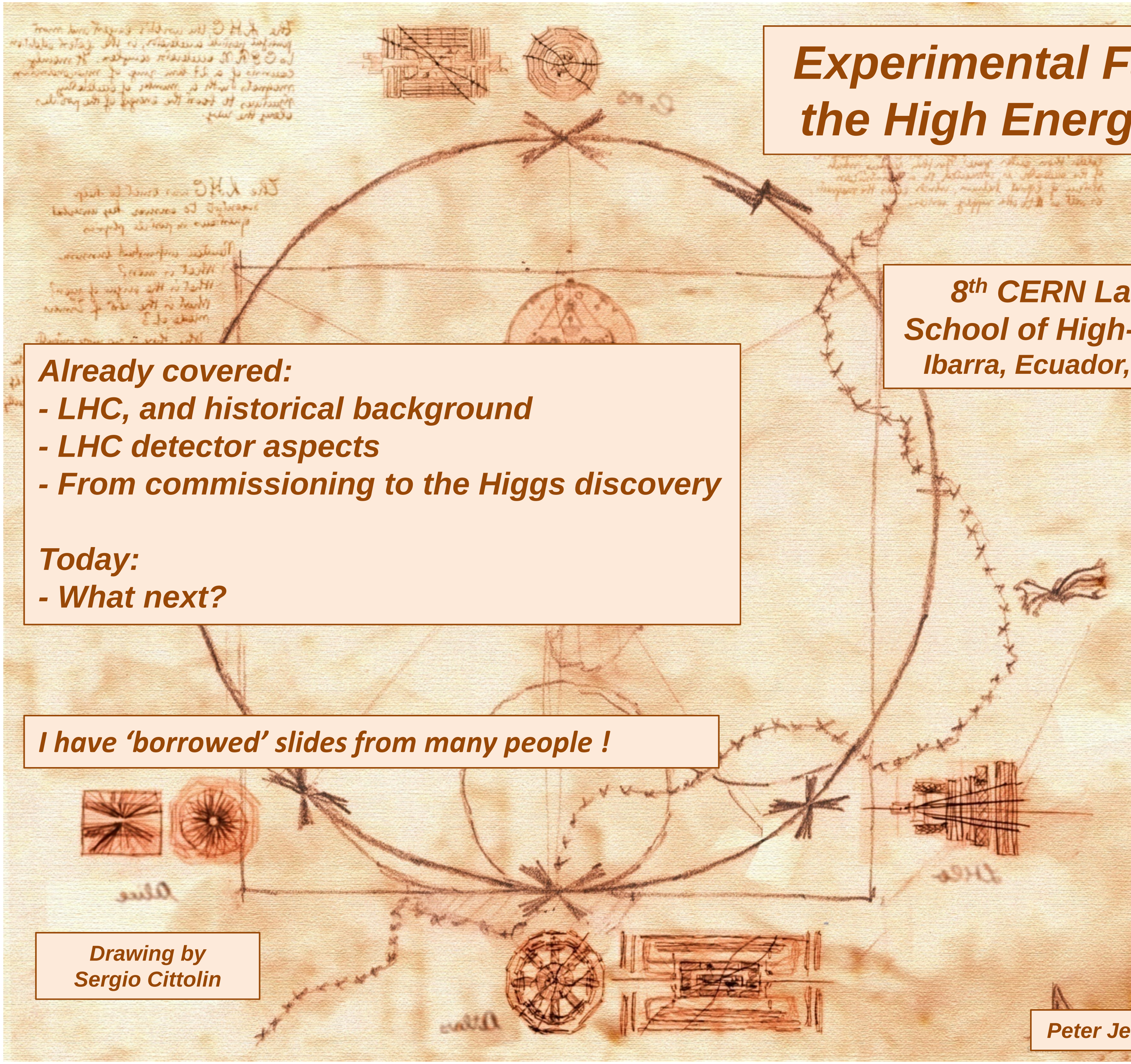
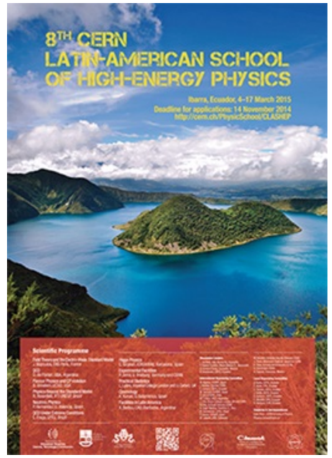


Experimental Facilities at the High Energy Frontier

8th CERN Latin-American School of High-Energy Physics
Ibarra, Ecuador, 4-17 March 2015



Already covered:
- ***LHC, and historical background***
- ***LHC detector aspects***
- ***From commissioning to the Higgs discovery***

Today:
- ***What next?***

I have 'borrowed' slides from many people !

Drawing by Sergio Cittolin

Peter Jenni, Freiburg and CERN

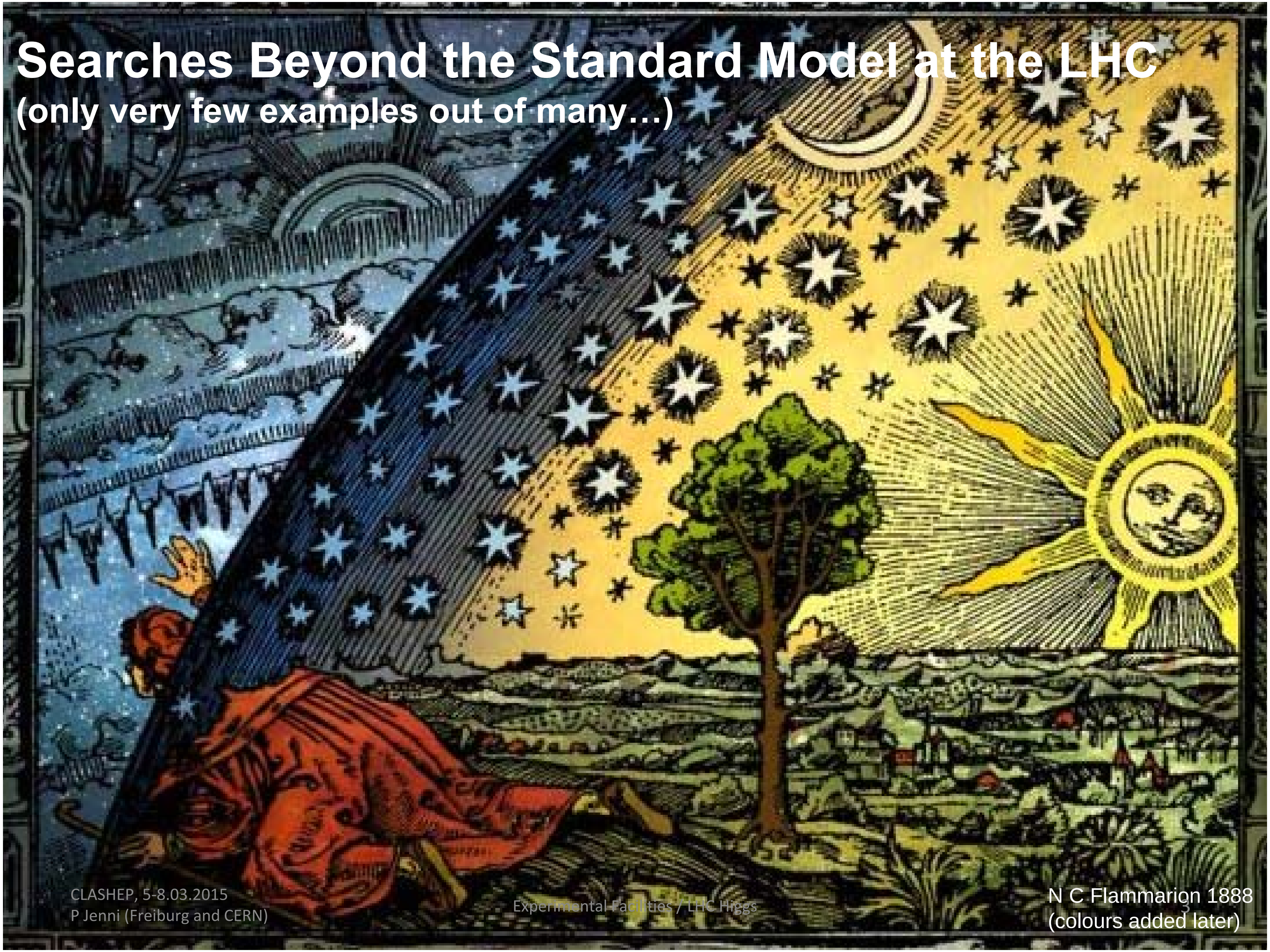
The SM is not a complete theory: LHC physics challenges

Some of the outstanding questions in fundamental physics were/are

(~✔)	**What is the origin of the elementary particle masses ?**	**ATLAS, CMS**
	What is the nature of the Universe dark matter ?	**ATLAS, CMS**
	Why is only matter observed in the Universe as primary constituents and not anti-matter ?	**LHCb**
	What are the features of the primordial plasma present ~10 μs after the Big Bang ?	**ALICE**
	What happened in the first moments of the Universe ~10^{-11} s after the Big Bang ?	**ATLAS, CMS**
	Are there other forces in addition to the known four ? **Are there additional (microscopic) space dimensions ?** **….**	**ATLAS, CMS**

Searches Beyond the Standard Model at the LHC

(only very few examples out of many…)



N C Flammarion 1888
(colours added later)

Supersymmetry (SUSY)

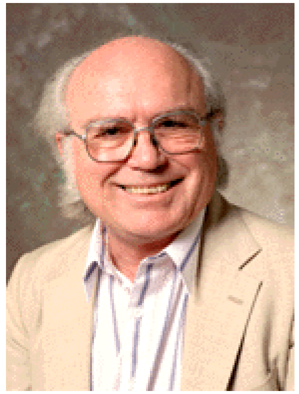
(Julius Wess and Bruno Zumino, 1974)

Establishes a symmetry between fermions (matter) and bosons (forces):

- **Each particle p with spin s has a SUSY partner $\tilde{p}$ with spin s -1/2**

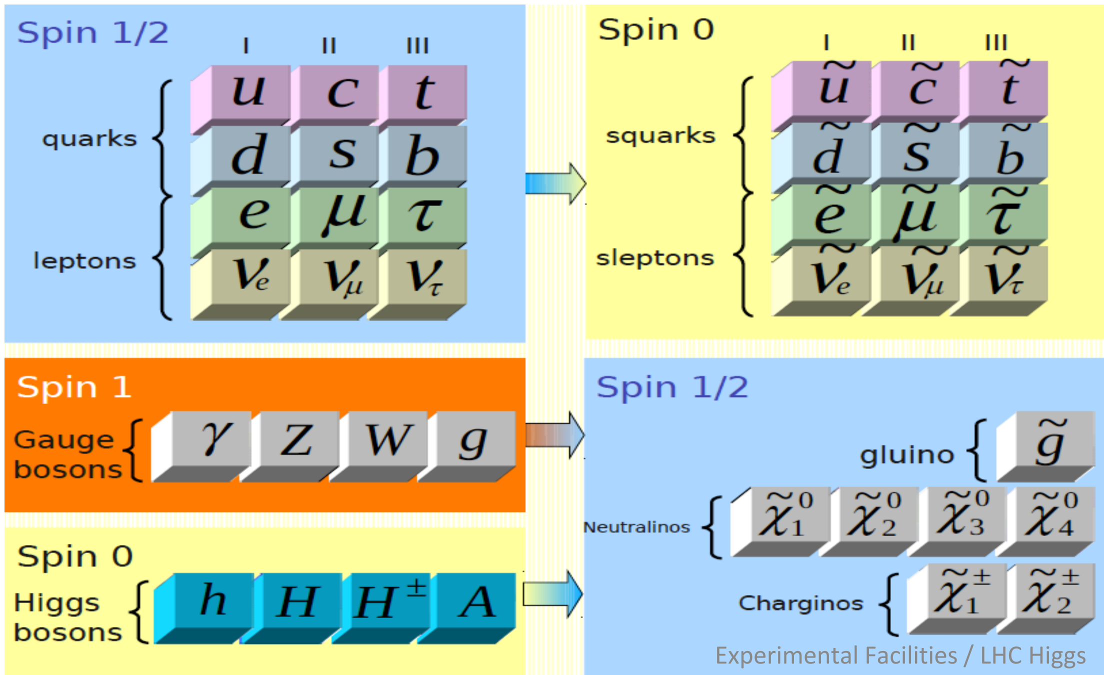
- **Examples** q (s=1/2) → $\tilde{q}$ (s=0) squark
  g (s=1) → $\tilde{g}$ (s=1/2) gluino

Julius Wess (1934 – 2007)



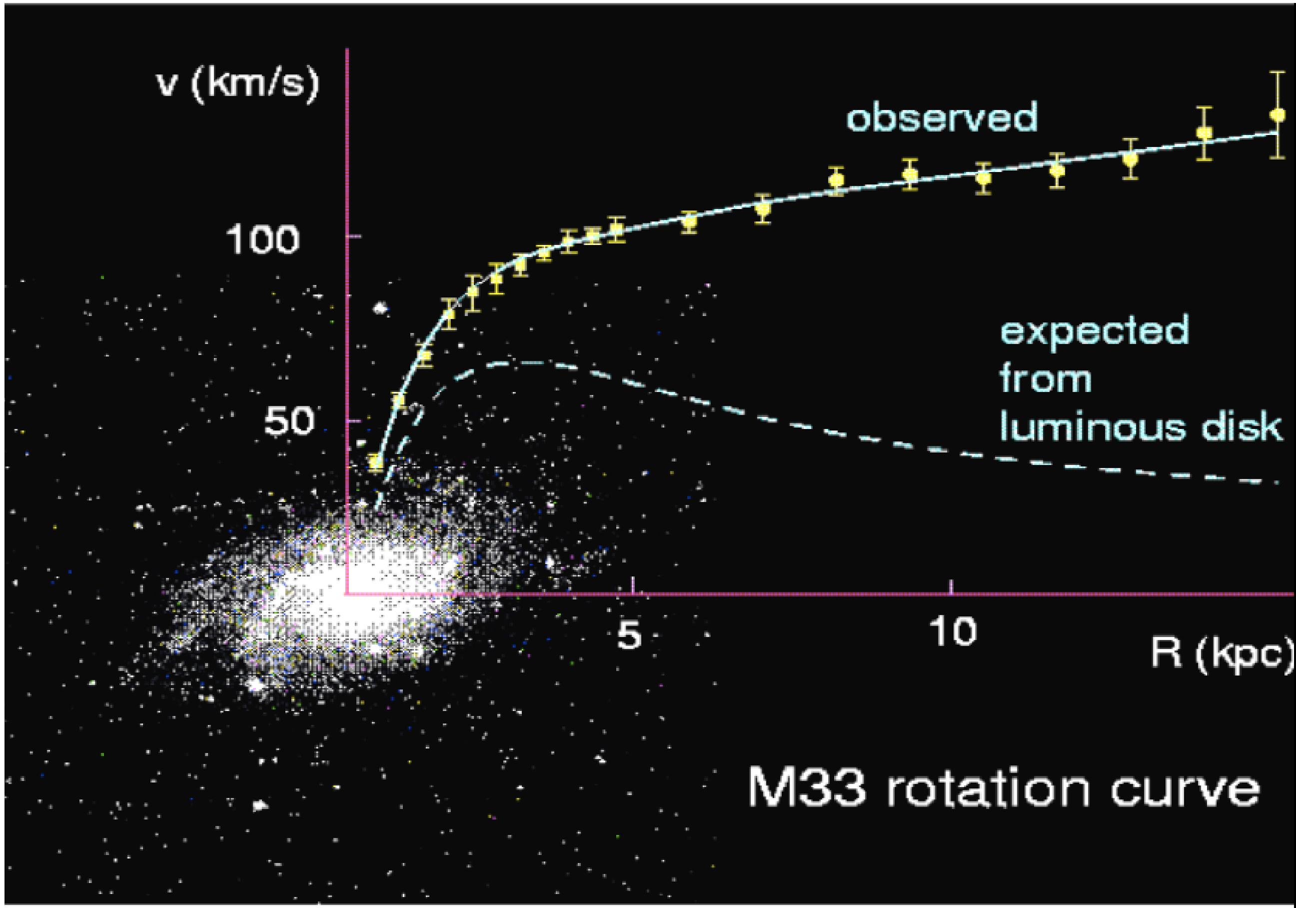
Bruno Zumino (1923 – 2014)

Our known world... **Maybe a new world?**



Motivation:

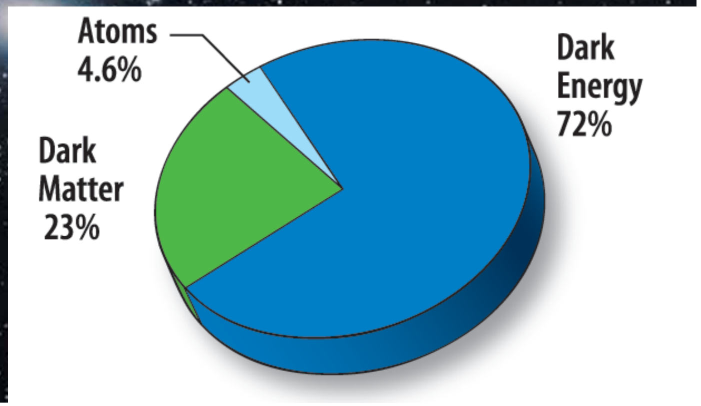
- *Unification (fermions-bosons, matter-forces)*
- *Solves some deep problems of the Standard Model*



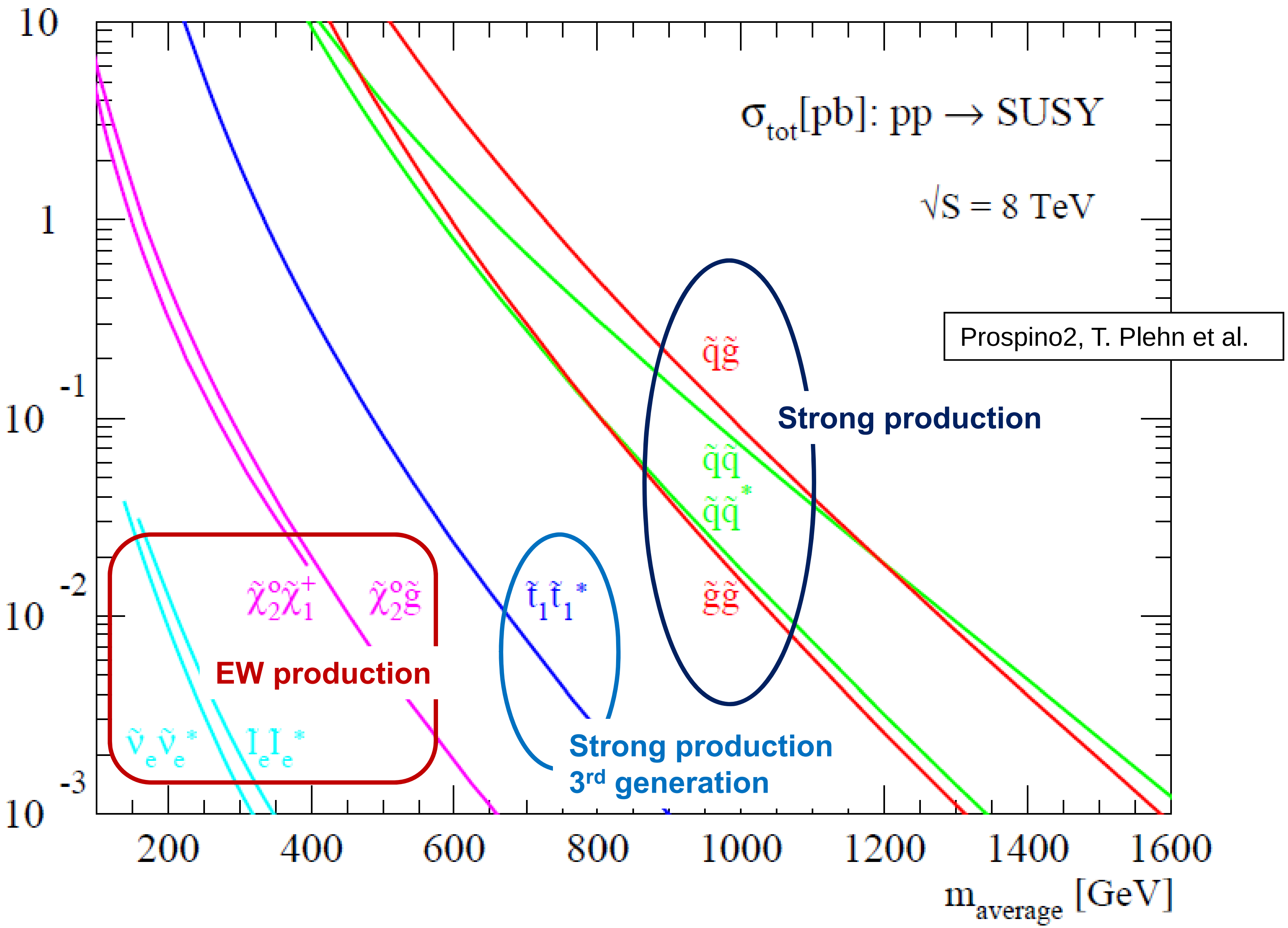
Vera Rubin ~ 1970

‘Supersymmetric’ particles ?

F. Zwicky 1898-1974

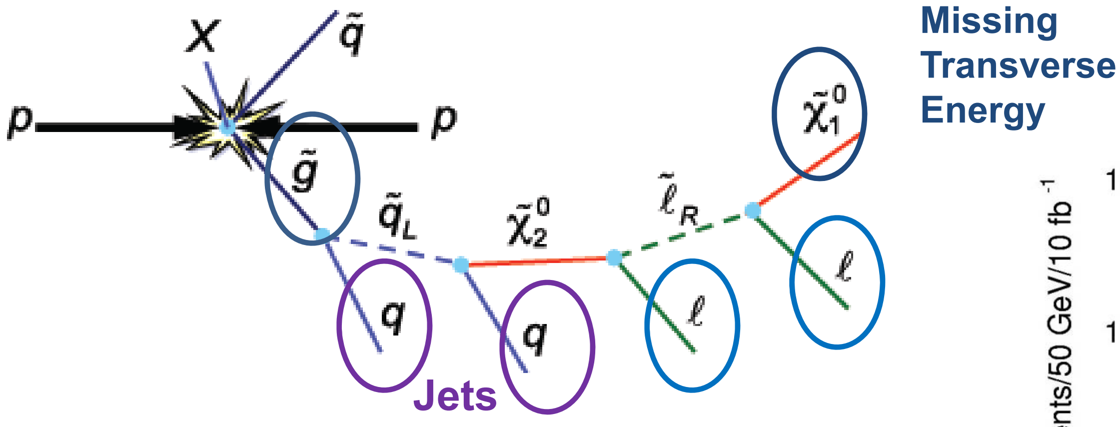


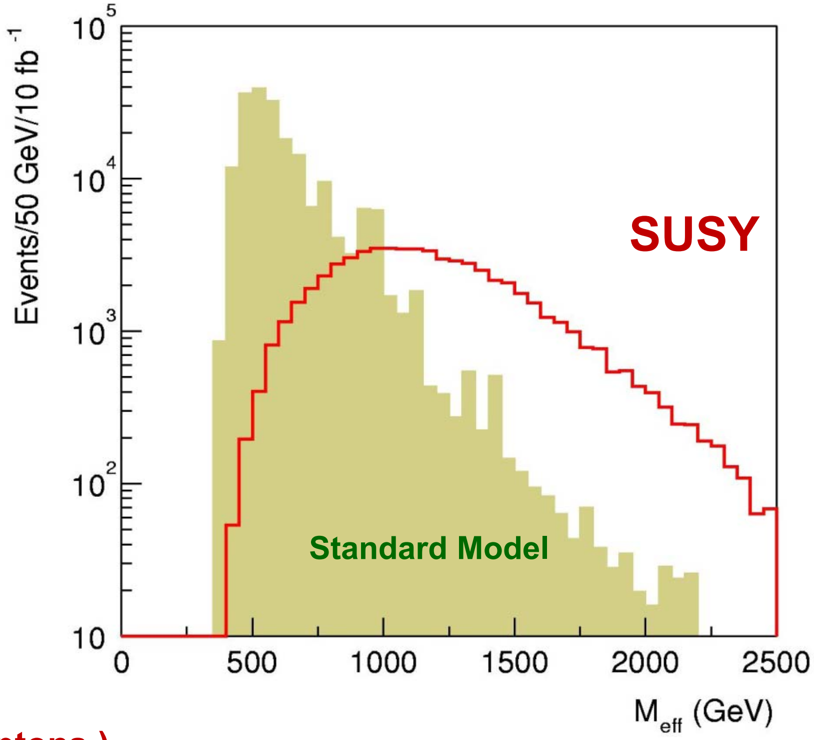
Expected production cross-sections at LHC



In practice SUSY searches at LHC are rather complicated

- **Complex (and model-dependent) squark/gluino cascades**



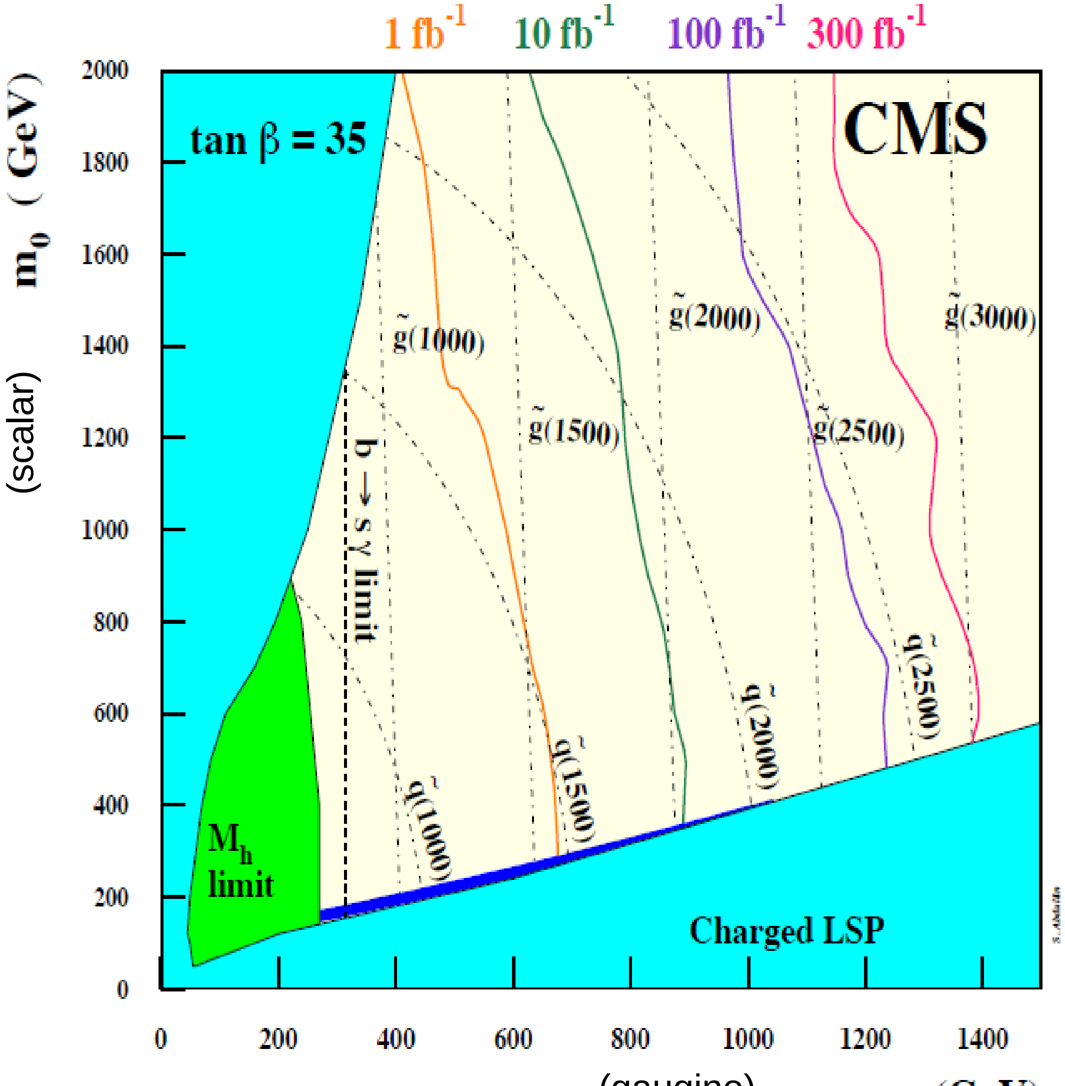


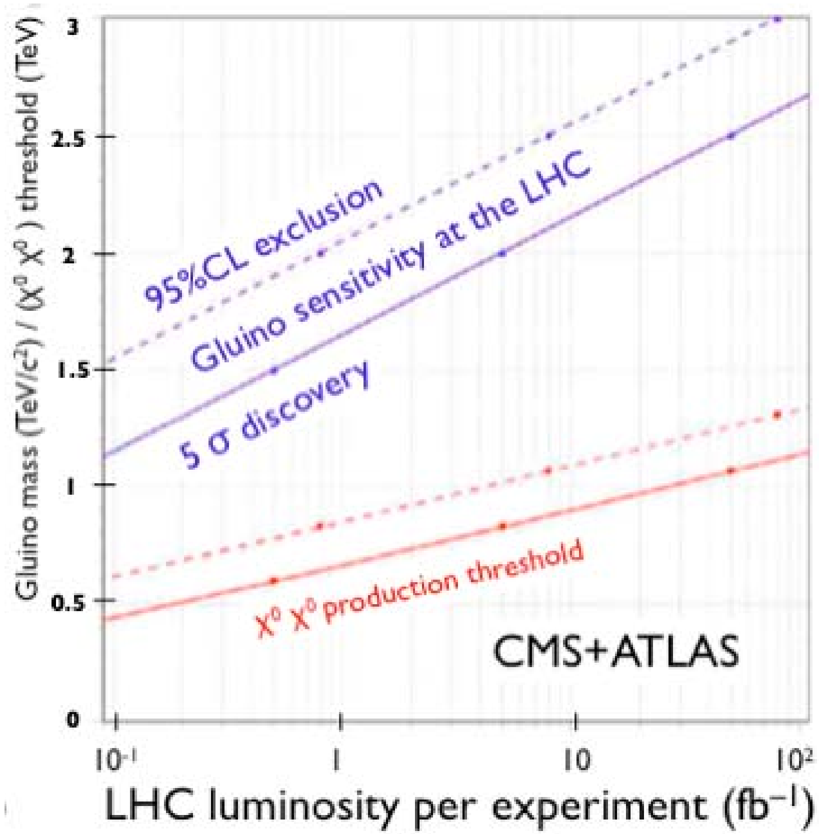
- **Focus on signatures covering large classes of models while strongly rejecting SM background**
  - **large missing E_T**
  - **High transverse momentum jets**
  - **Leptons**
    - **Perform separate analyses with and without lepton veto (0-lepton / 1-lepton / 2-leptons)**
  - **B-jets: to enhance sensitivity to third-generation squarks**
  - **Photons: typically for models with the gravitino as LSP**

Meff = Etmiss + Σ pT(jets)

Ultimate discovery reach for SUSY particles at the LHC (indicative plots, model-dependent…)

An old slide from well before the LHC start-up



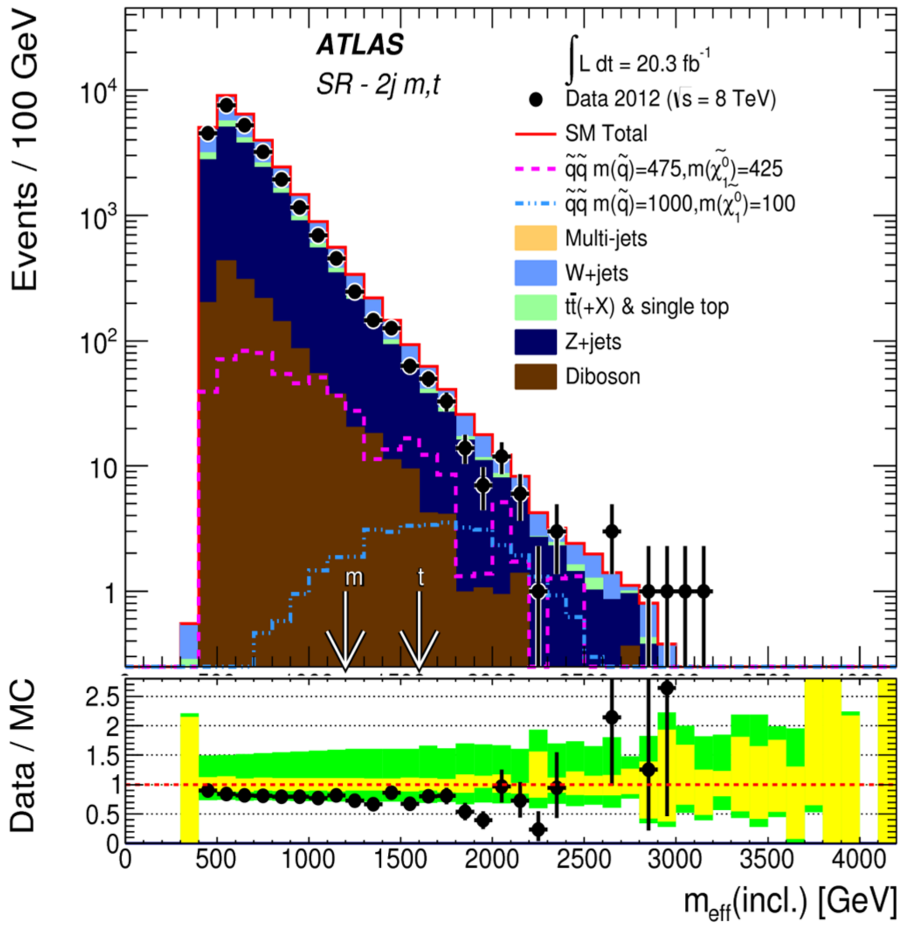


The mass scale probed for squarks and gluinos will be typically 2.5 TeV by 2017

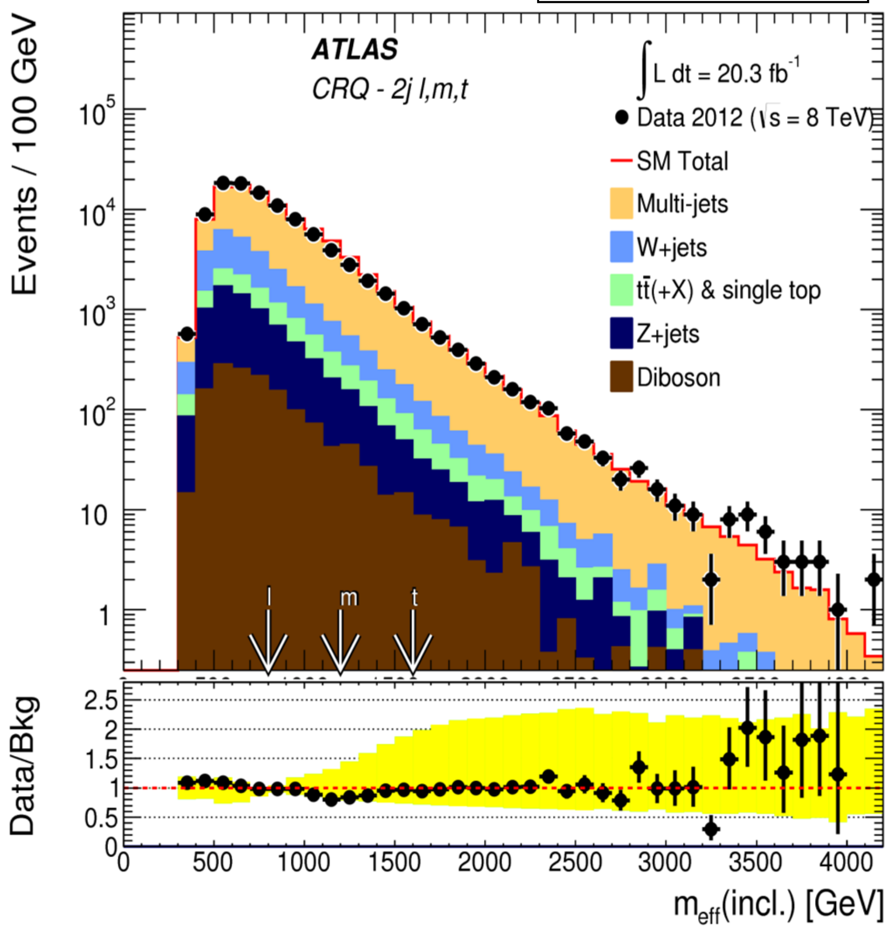
A random example from the 2012 data, to show the principle

0-lepton + 2−6 jets + high MET (based on Et-miss+jet triggers)

JHEP 09 (2014) 176



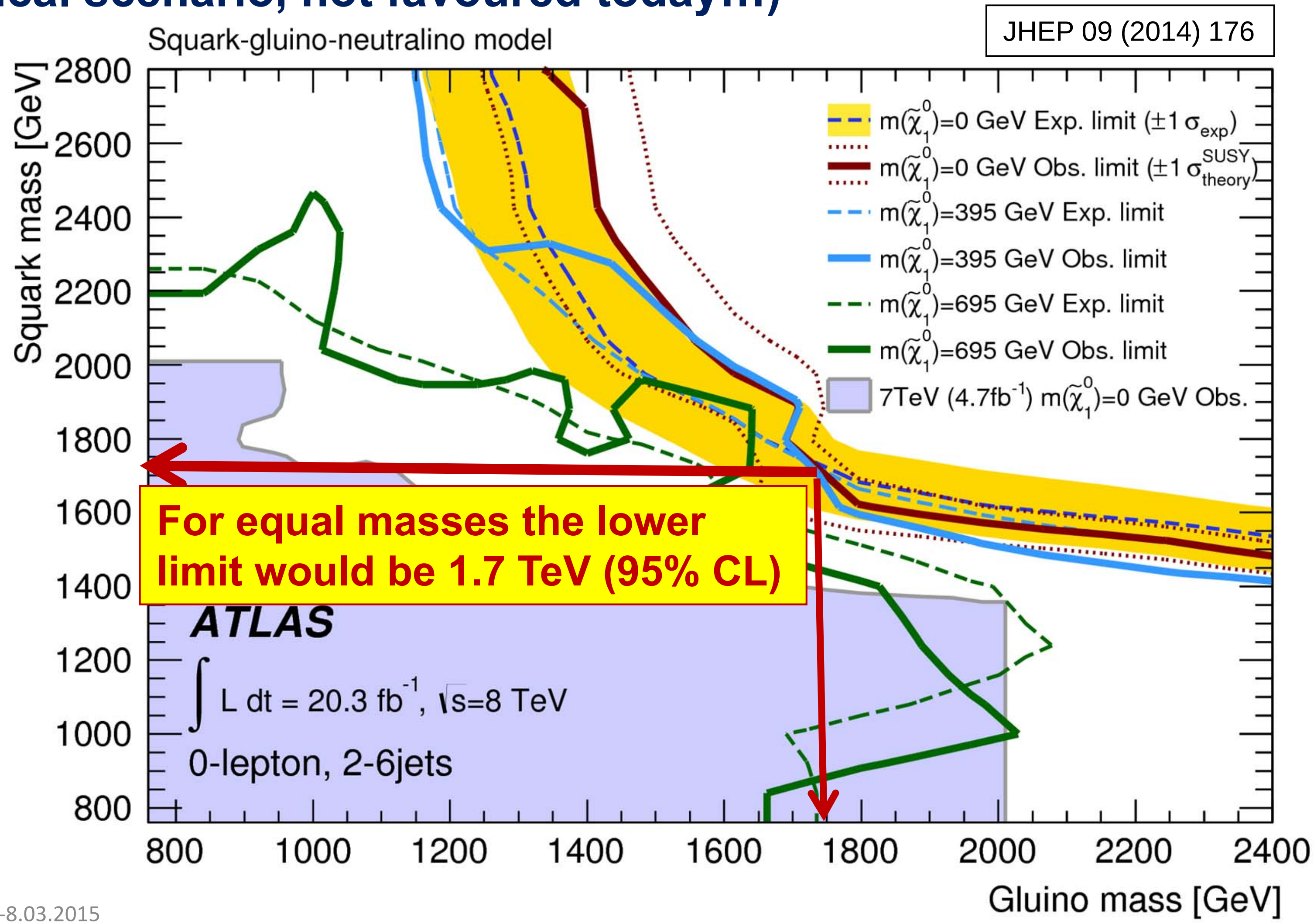
A signal region



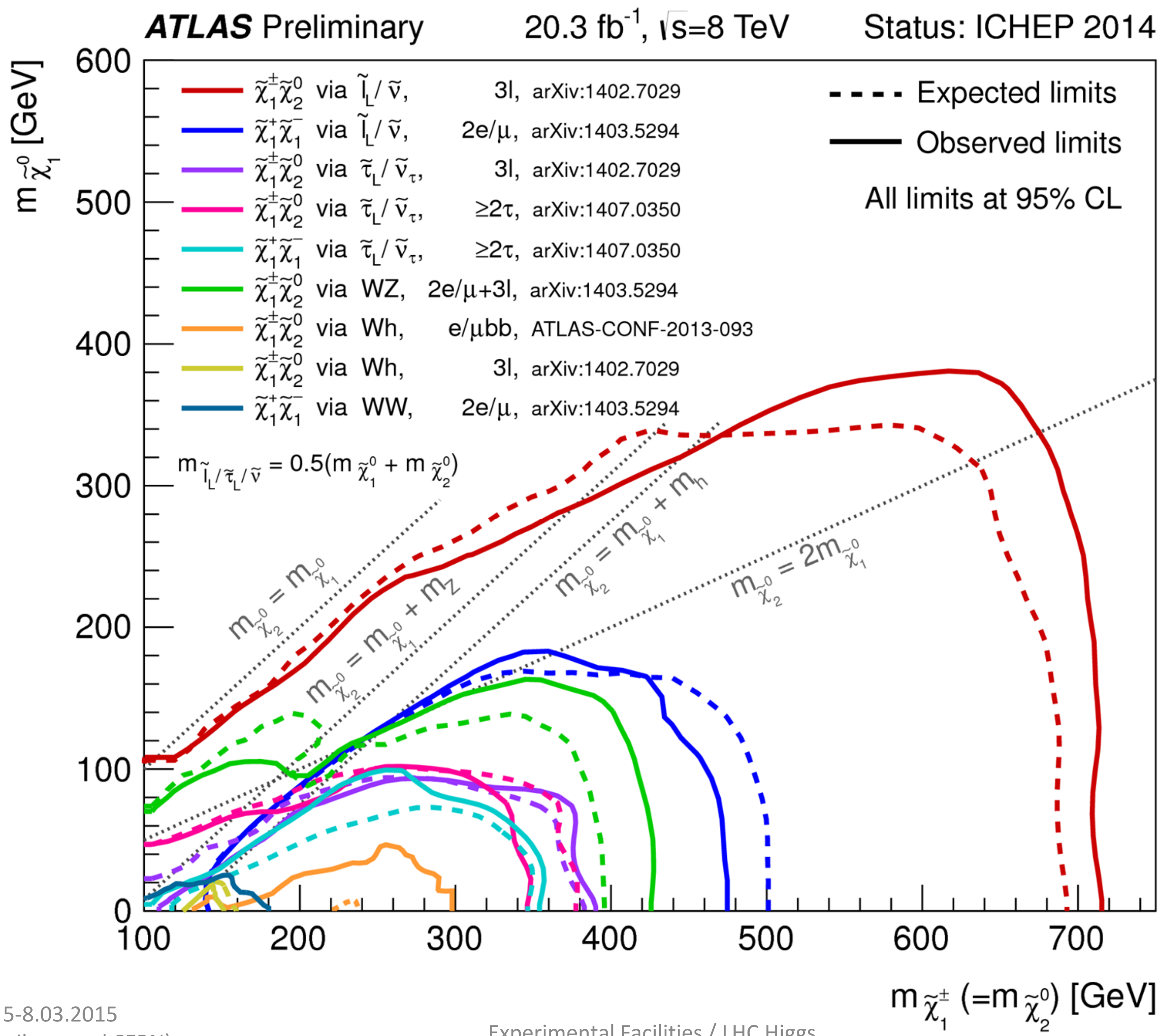
A control region where no signal is expected

Interpretation of the results

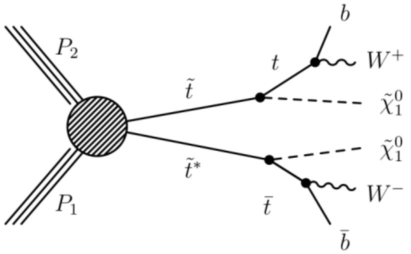
Example: phenomenological MSSM models containing only squarks of the 1st and 2nd generation, gluino and light neutralinos (the simple classical scenario, not favoured today…)

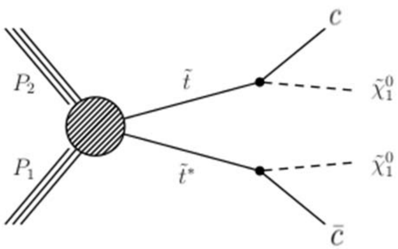


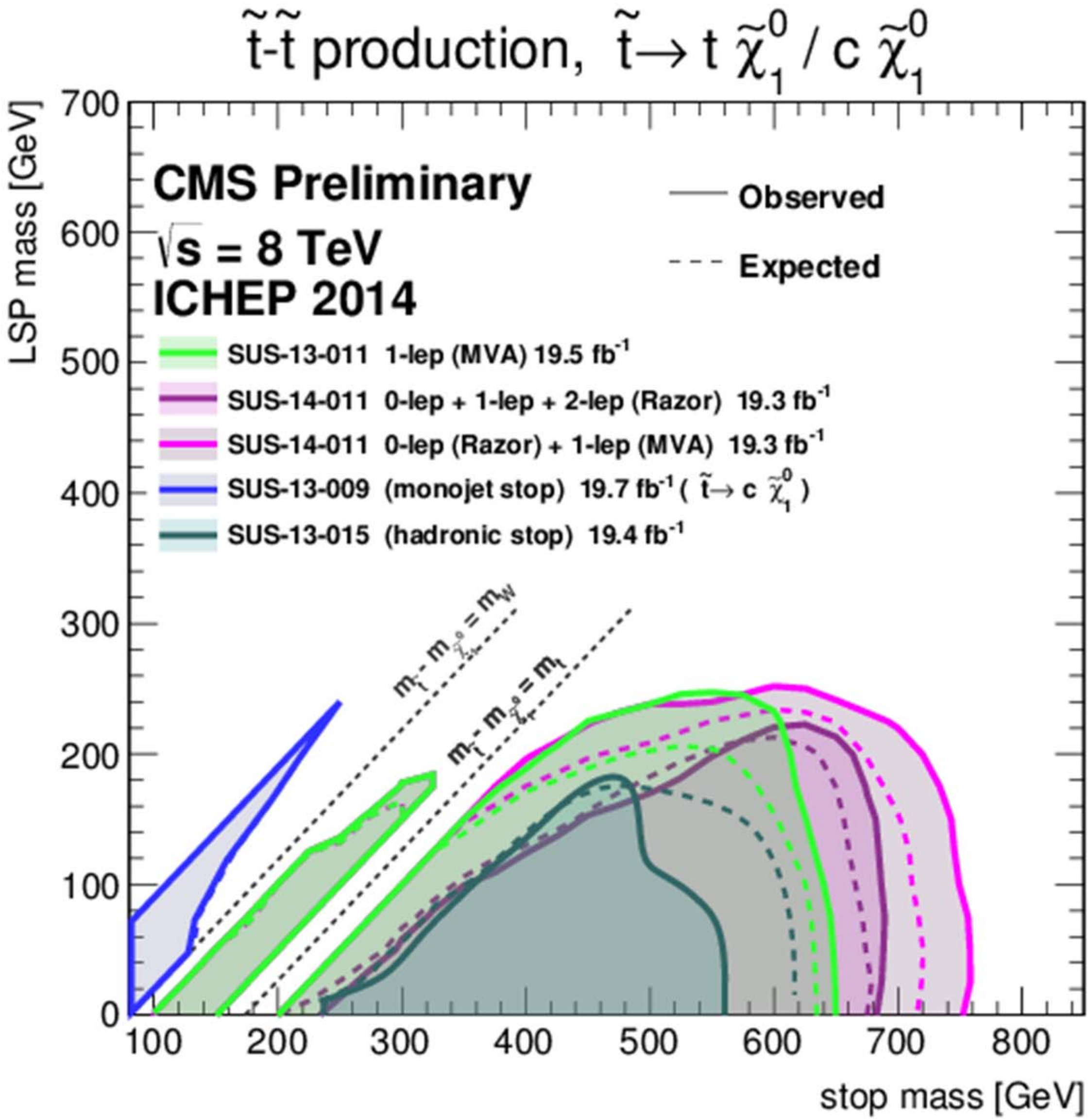
Example of chargino and neutralino limits from electroweak productions



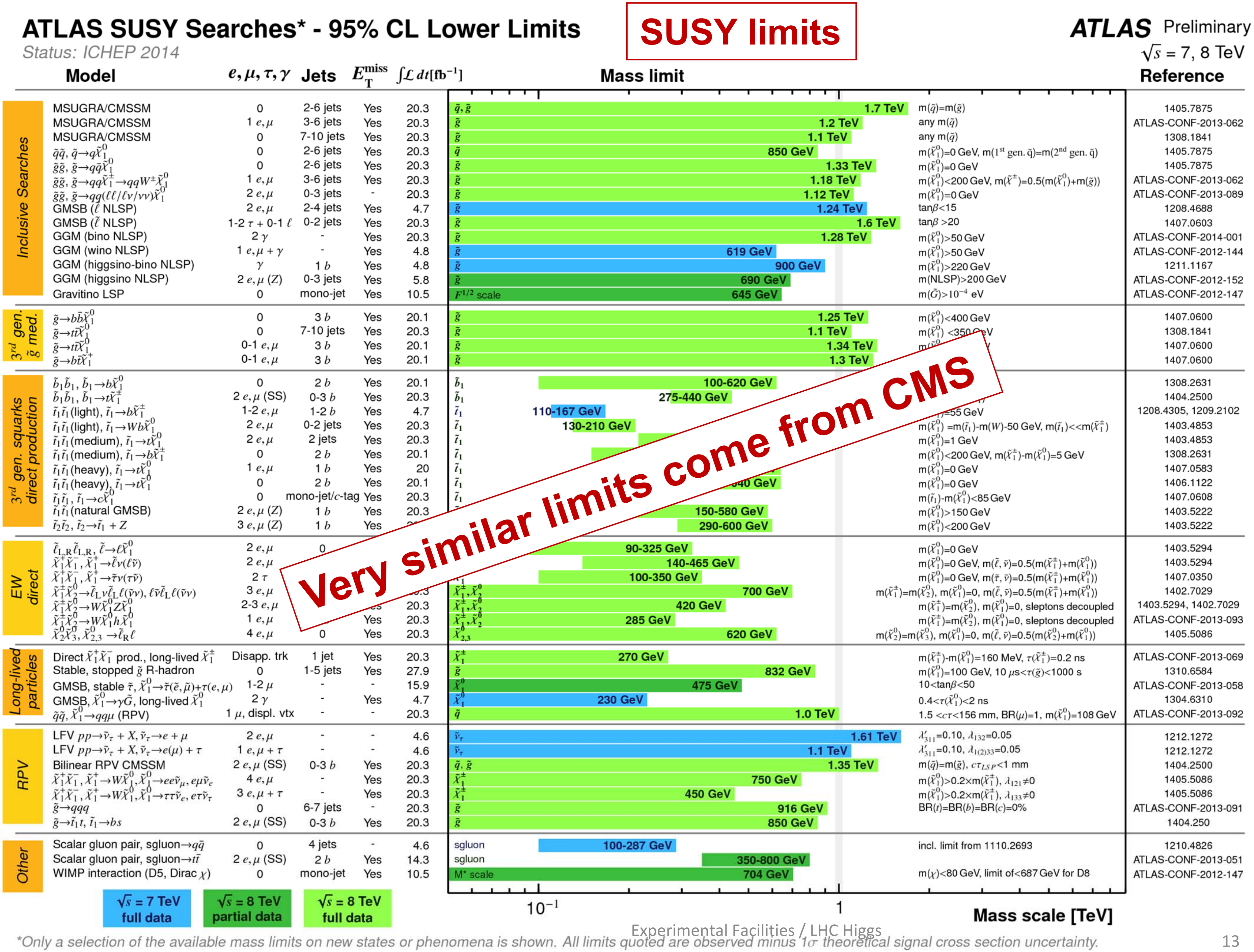
Example of limits for stop pair production







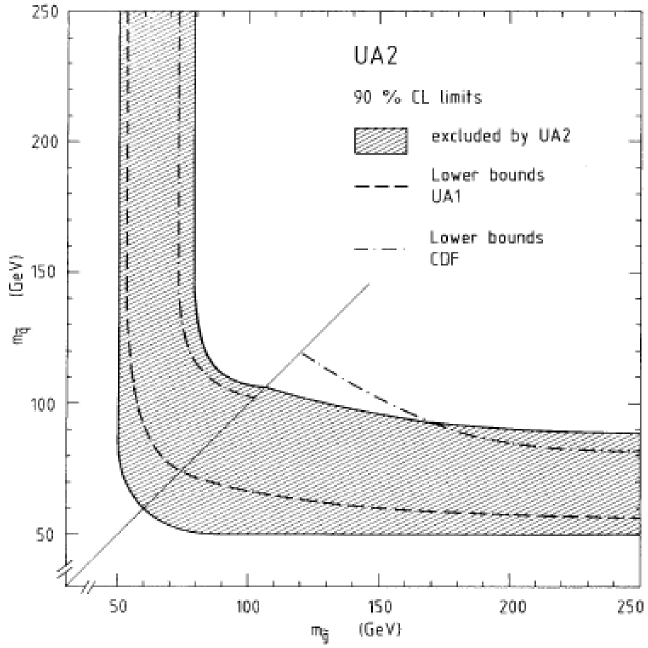
SUSY limits



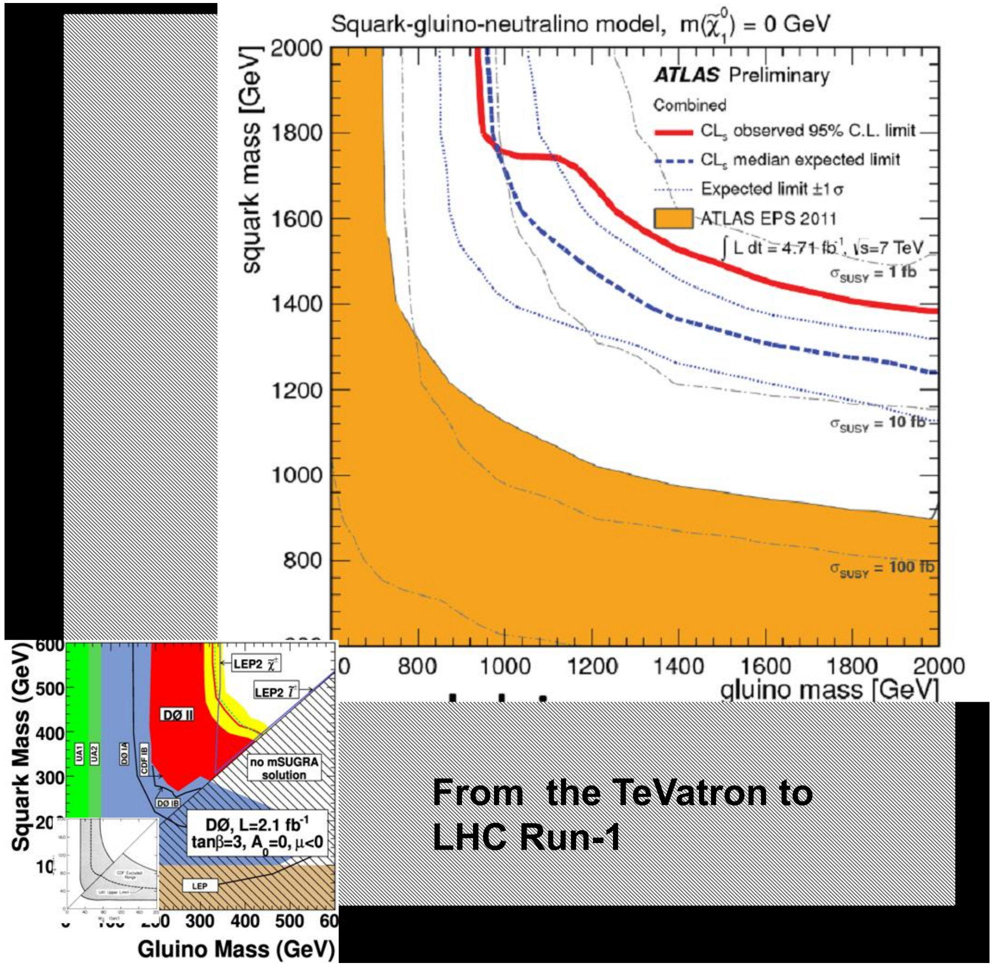
Very similar limits come from CMS

Our theory friends predicted since long 'SUSY just around the corner…'

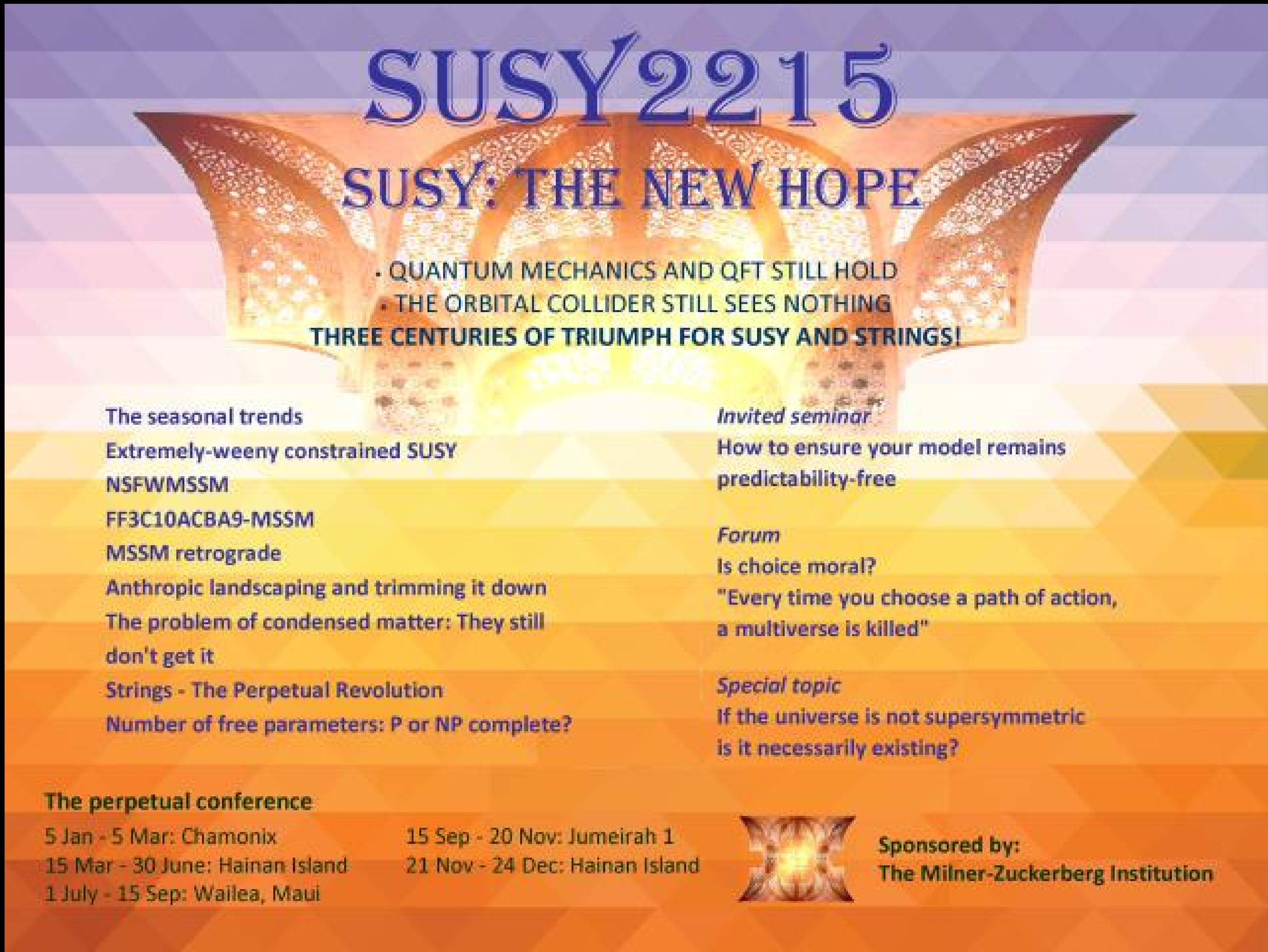
First attempt with the upgraded UA2 experiment at the CERN $p\bar{p}$



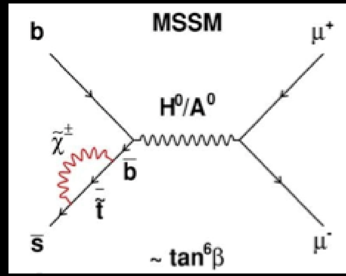
Phys. Lett. B235 (1990) 363



On a personal note:
The search for SUSY has been a motivation for me for 30 years, and in spite of exclusion limits only so far I have not given up hopes yet!


SUSY2215
SUSY: THE NEW HOPE
• QUANTUM MECHANICS AND QFT STILL HOLD
• THE ORBITAL COLLIDER STILL SEES NOTHING
THREE CENTURIES OF TRIUMPH FOR SUSY AND STRINGS!
The seasonal trends
Extremely-weeny constrained SUSY
NSFWMSSM
FF3C10ACBA9-MSSM
MSSM retrograde
Anthropic landscaping and trimming it down
The problem of condensed matter: They still don't get it
Strings - The Perpetual Revolution
Number of free parameters: P or NP complete?
Invited seminar
How to ensure your model remains predictability-free
Forum
Is choice moral?
"Every time you choose a path of action, a multiverse is killed"
Special topic
If the universe is not supersymmetric is it necessarily existing?
The perpetual conference
5 Jan - 5 Mar: Chamonix
15 Mar - 30 June: Hainan Island
1 July - 15 Sep: Wailea, Maui
15 Sep - 20 Nov: Jumeirah 1
21 Nov - 24 Dec: Hainan Island
Sponsored by:
The Milner-Zuckerberg Institution

First signs of new physics could also come from accurate measurements of clean processes for which the Standard Model makes very precise predictionsthe known SM processes are at play



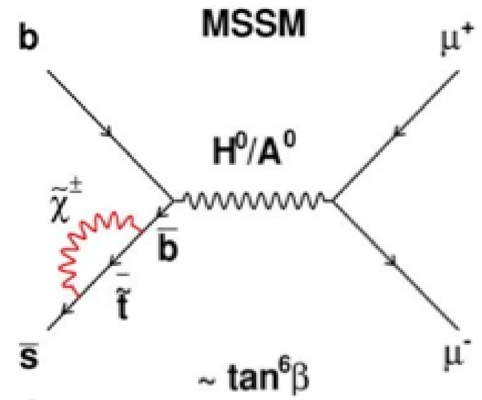
Measured deviations could indicate that something more than just the known SM processes are at play

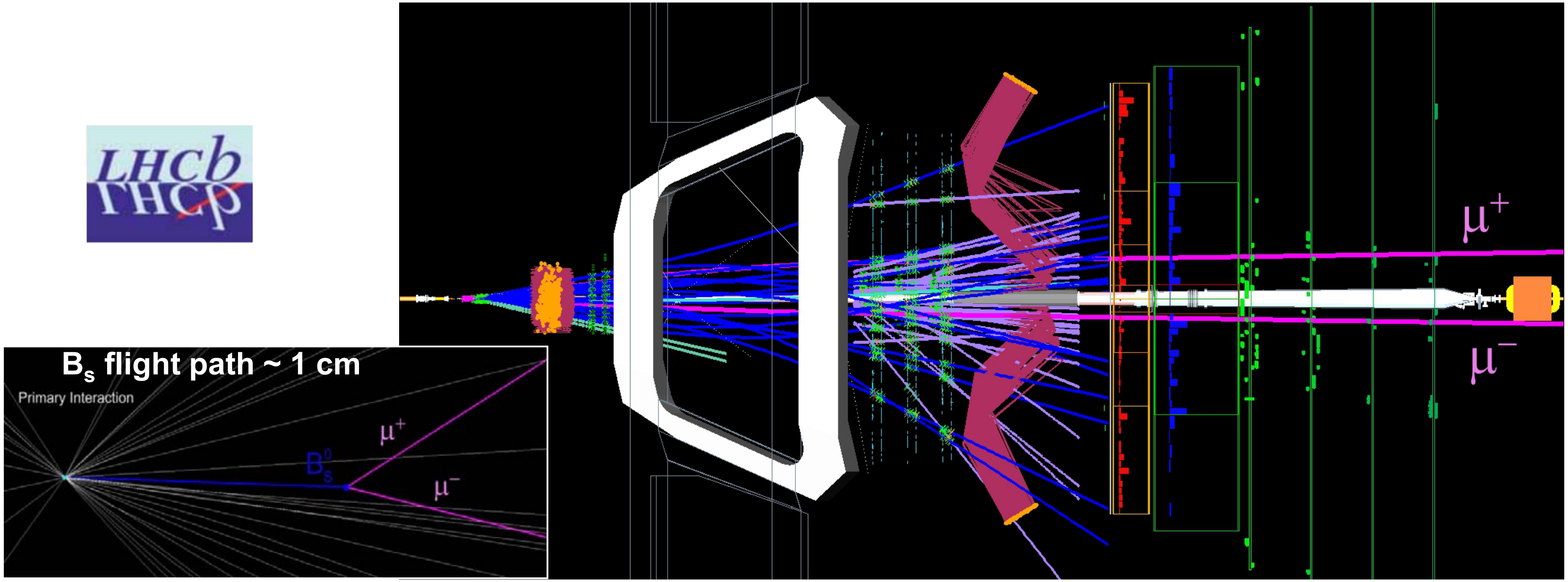
The search for $B_{s\,(d)} \rightarrow \mu\,\mu$

Very rare decay sensitive to New Physics (in particular to models with high *tan β*)

Precise predictions in SM:
$BR(B_s \rightarrow \mu\,\mu) = 3.56 \pm 0.30 \times 10^{-9}$
$BR(B_d \rightarrow \mu\,\mu) = 1.07 \pm 0.10 \times 10^{-10}$

Very clean experimental signature





The search for $B_{s\,(d)} \rightarrow \mu\,\mu$

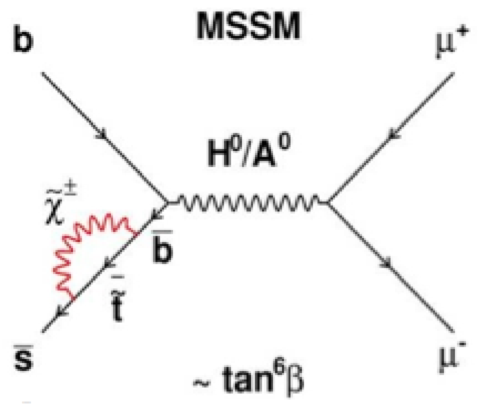
LHCb Phys. Rev. Lett. 110 (2013) 101805

CMS Phys. Rev. Lett. 111 (2013) 101804

Very rare decay sensitive to New Physics (in particular to models with high *tan β*)

Precise predictions in SM:
$BR(B_s \rightarrow \mu\,\mu) = 3.56 \pm 0.30 \times 10^{-9}$
$BR(B_d \rightarrow \mu\,\mu) = 1.07 \pm 0.10 \times 10^{-10}$

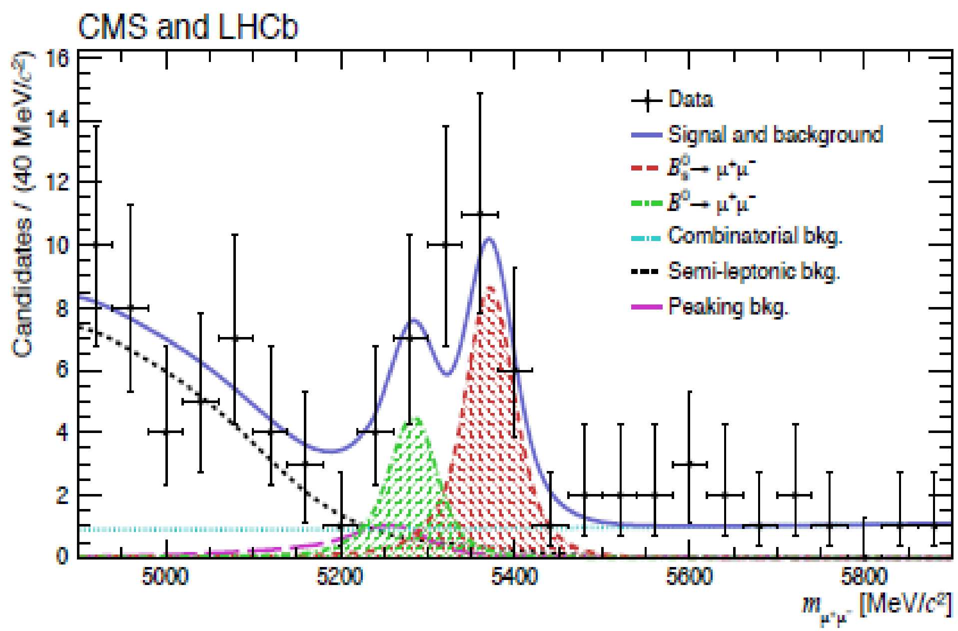
Very clean experimental signature



Measured with the full data sets of LHCb and CMS, and a common simultaneous fit

$BR(B_s \rightarrow \mu\,\mu) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$
$BR(B \rightarrow \mu\,\mu) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$

In good agreement with the SM prediction within the present measurement errors

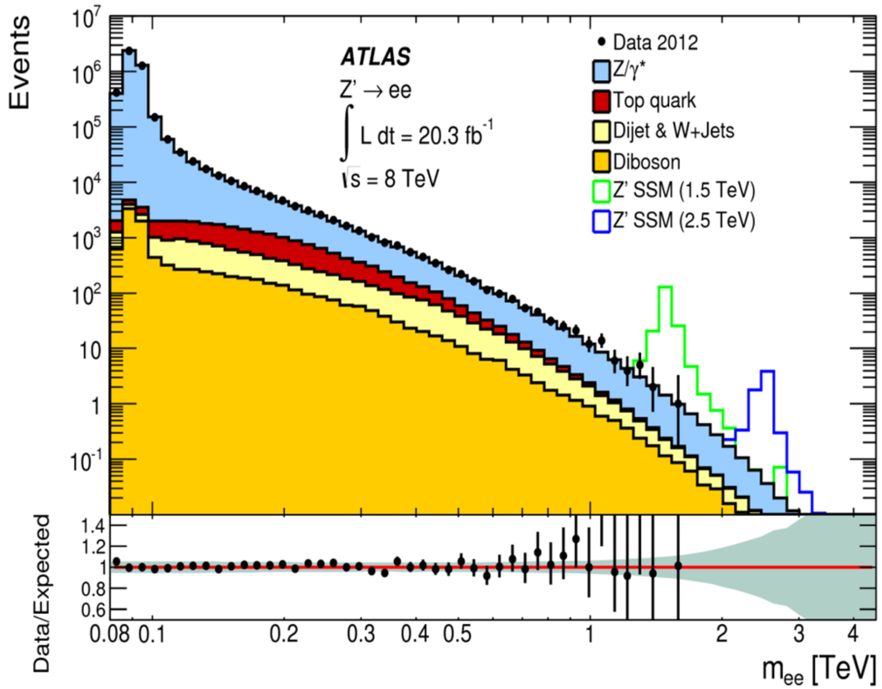


LHCb + CMS presented at CKM 2014 Vienna

Searches for heavy W and Z like particles

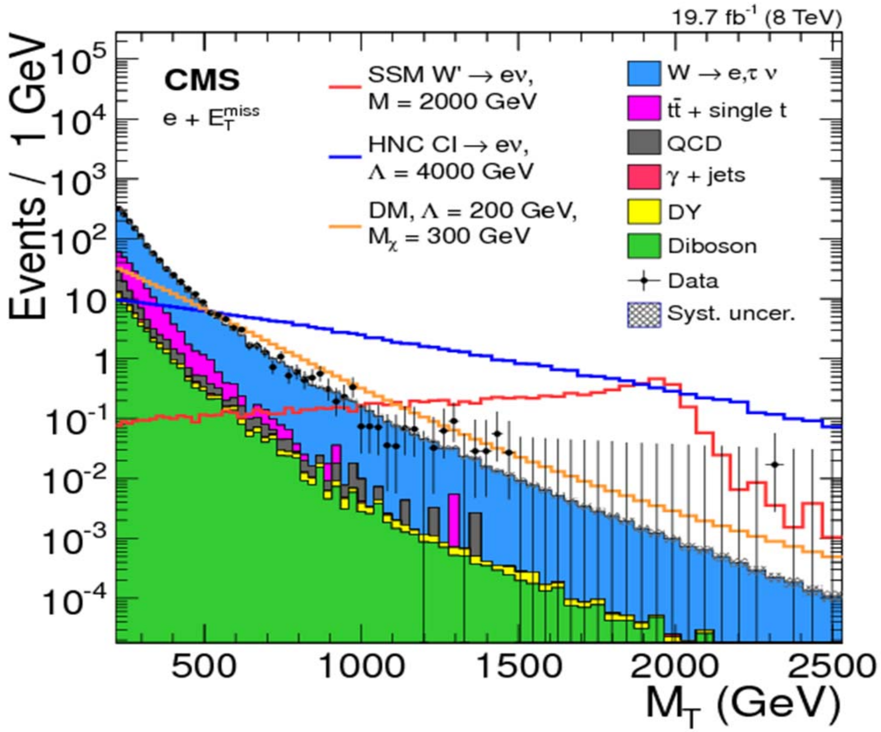
These searches are quite straight-forward, following basically the same analyses as for the familiar W and Z bosons

Z': Di-lepton pairs



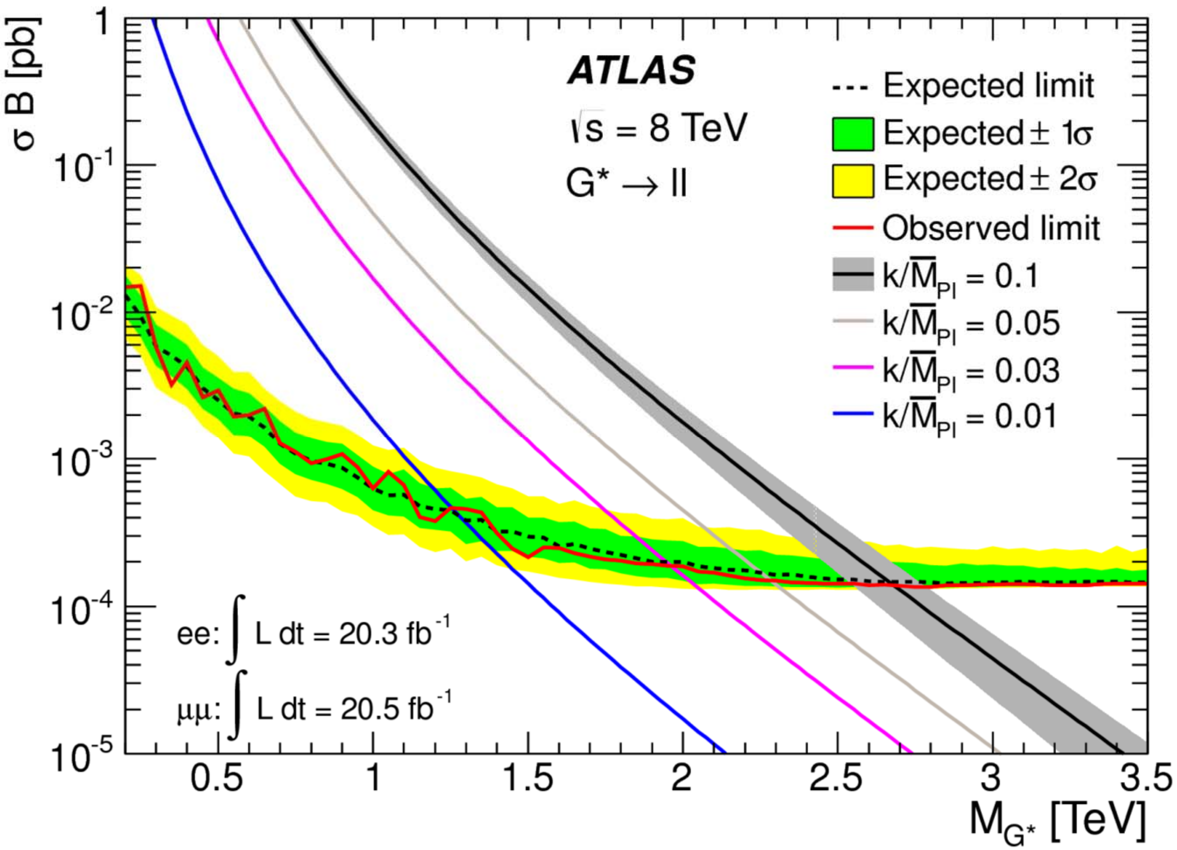
Phys. Rev. D 90 (2014) 052005

W': Lepton + ETmiss



arXiv:1408.2745v1[hep-ex] sub. to Phys. Rev. D

Lower mass limits, at 95% CL, for spin-2 Randall-Sundrum Gravitons

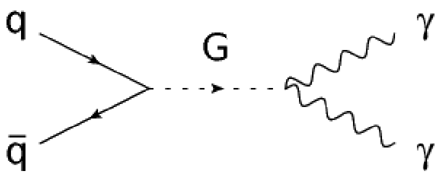


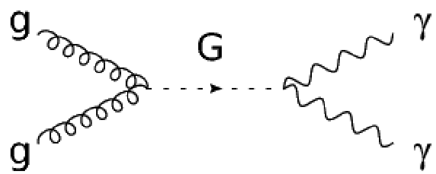
Phys. Rev. D 90 (2014) 052005

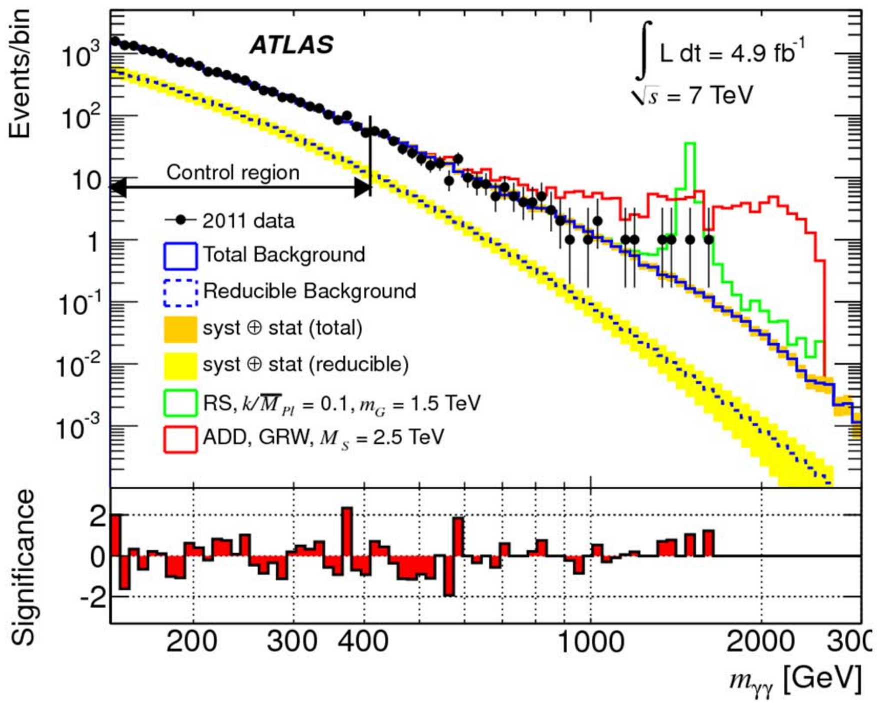
R Sundrum
L Randall
F Gianotti

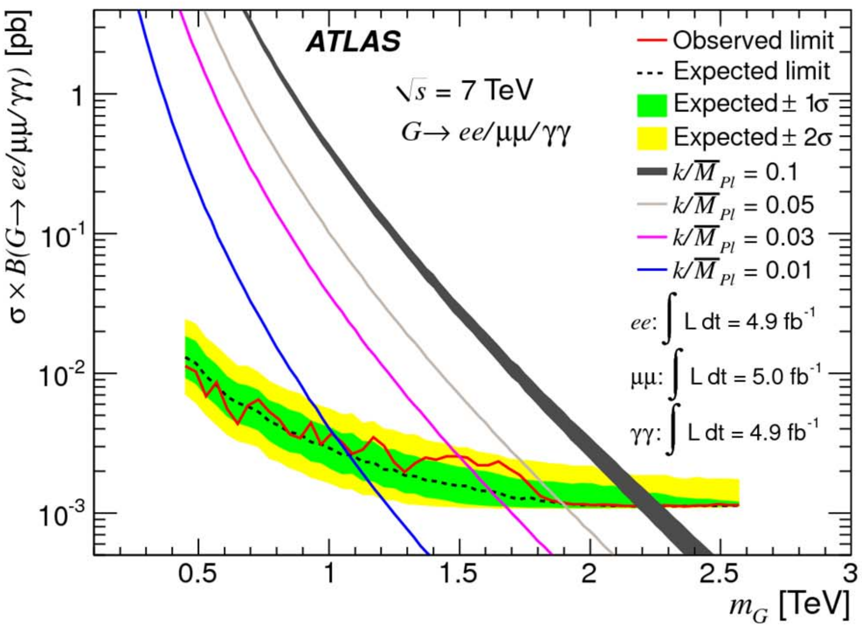
New particles decaying into two photons

Example for a search of extra dimension signals (Kaluza-Klein Graviton in the Randall-Sundrum and Arkani-Hamed, Dimopoulos and Dvali models)





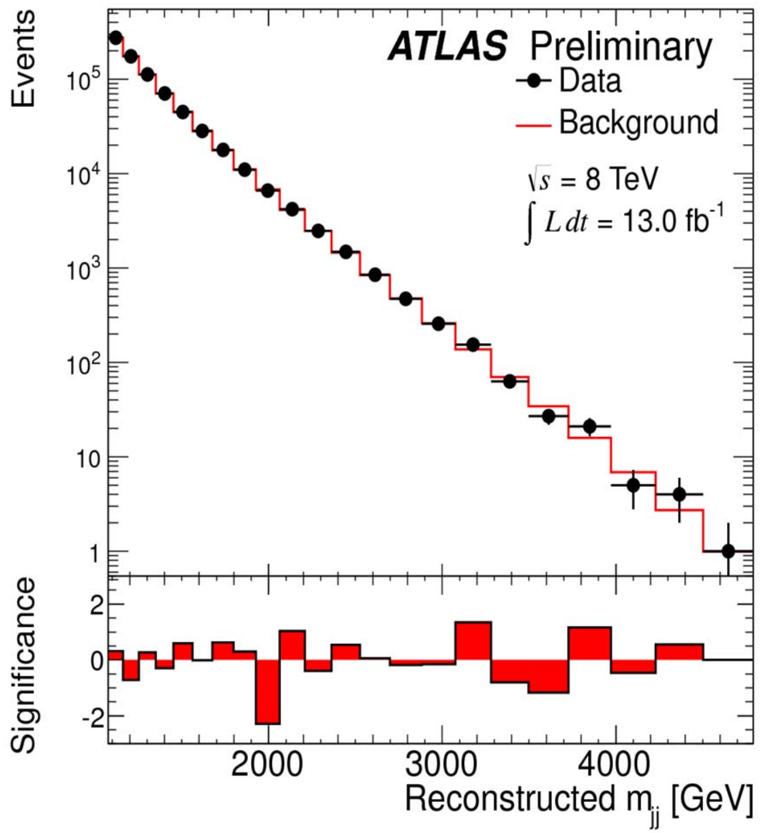




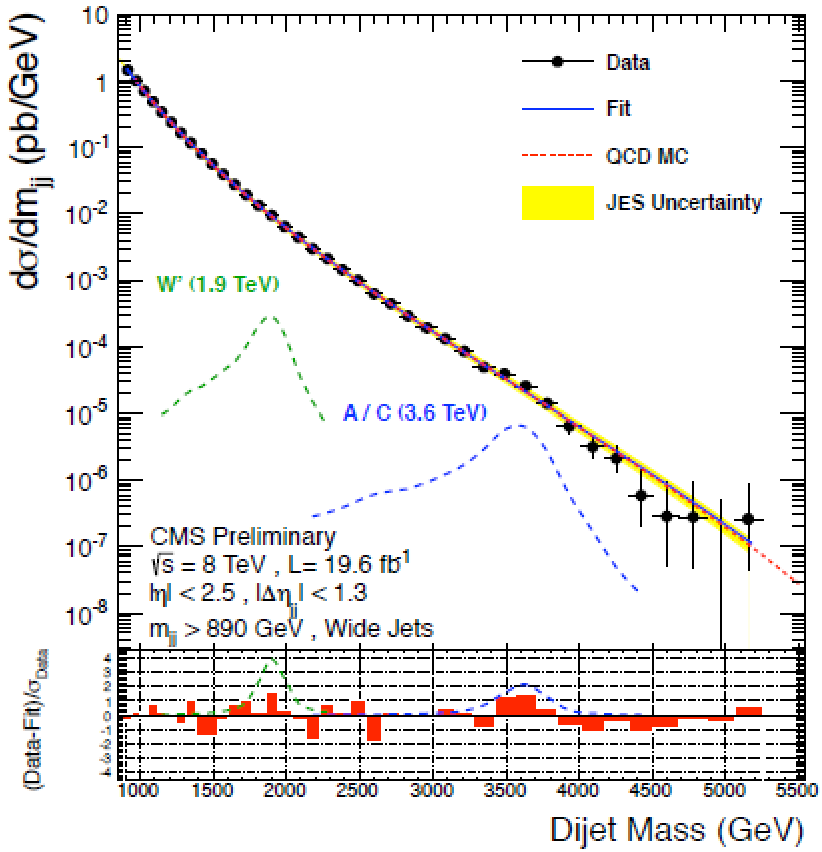
New J Phys 15 (2013) 043007

Example of searches for New Physics as deviations from QCD behaviour of hadronic jet distributions

Search for resonances in the di-jet mass spectrum



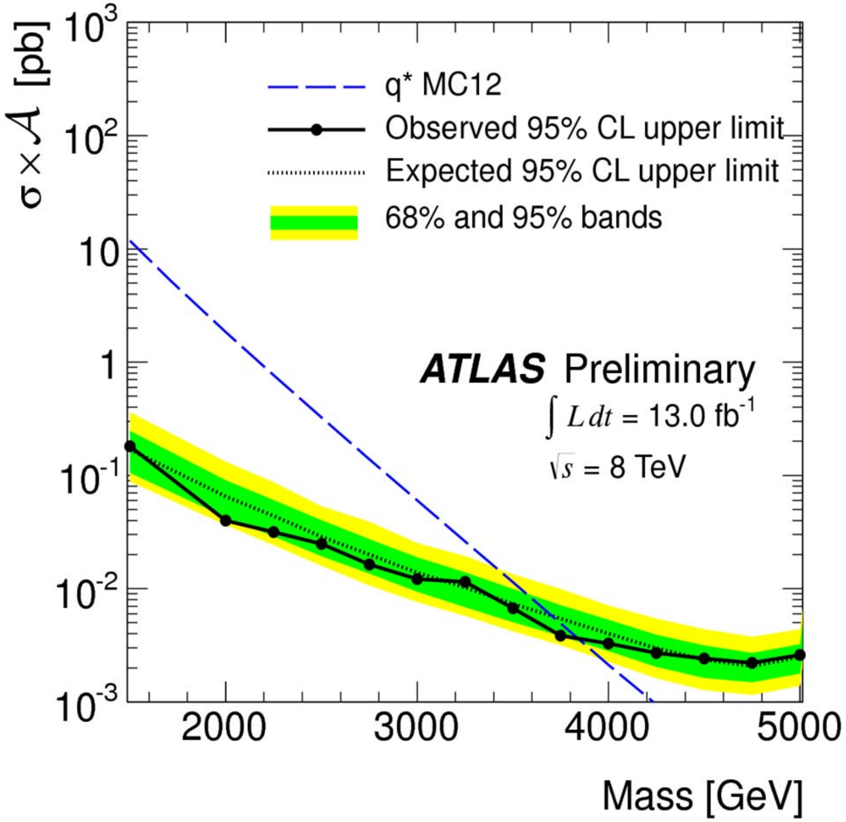
ATLAS-CONF-2012-148



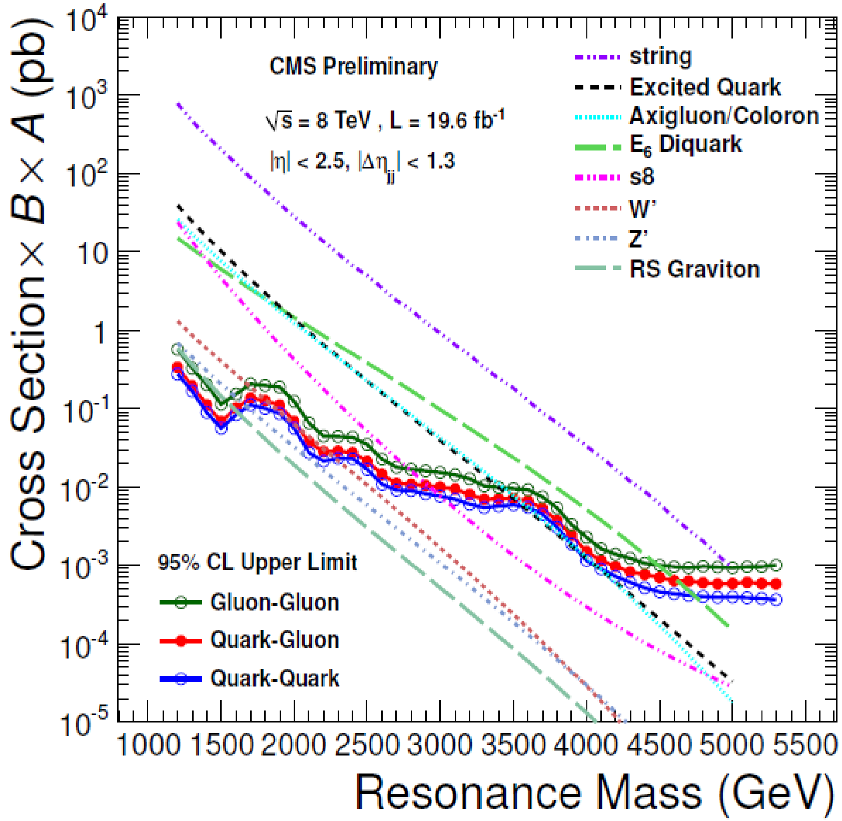
CMS-EXO-12-059

Example of searches for New Physics as deviations from QCD behaviour of hadronic jet distributions

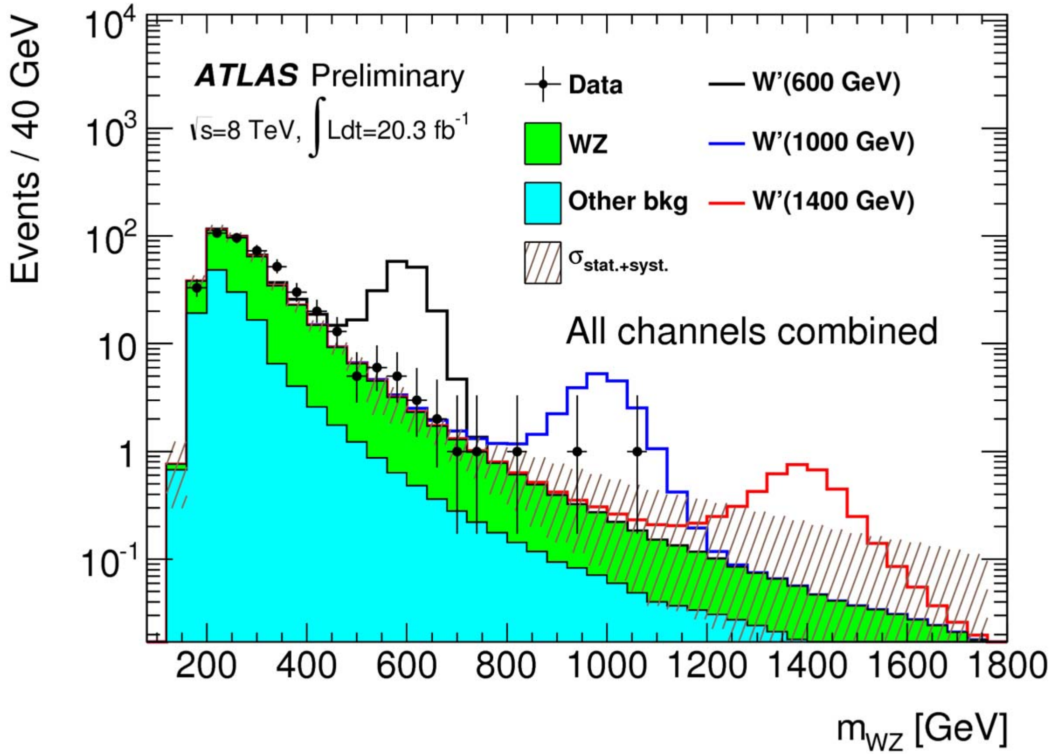
Search for resonances in the di-jet mass spectrum



ATLAS-CONF-2012-148

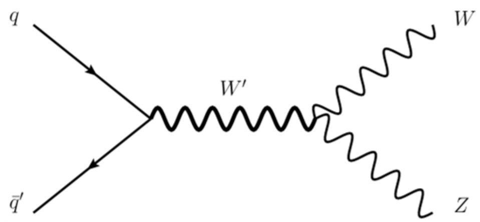


CMS-EXO-12-059

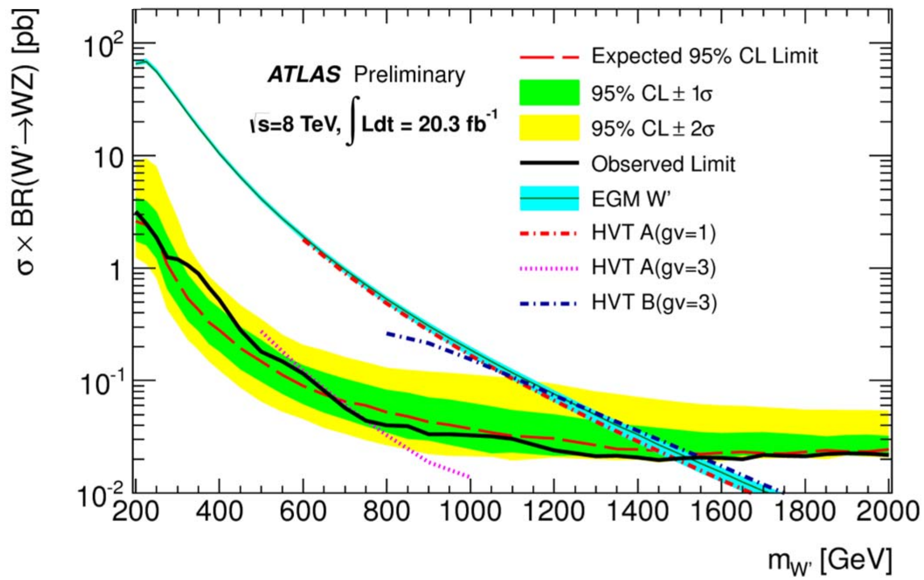


Search for a WZ resonance in all lepton final states

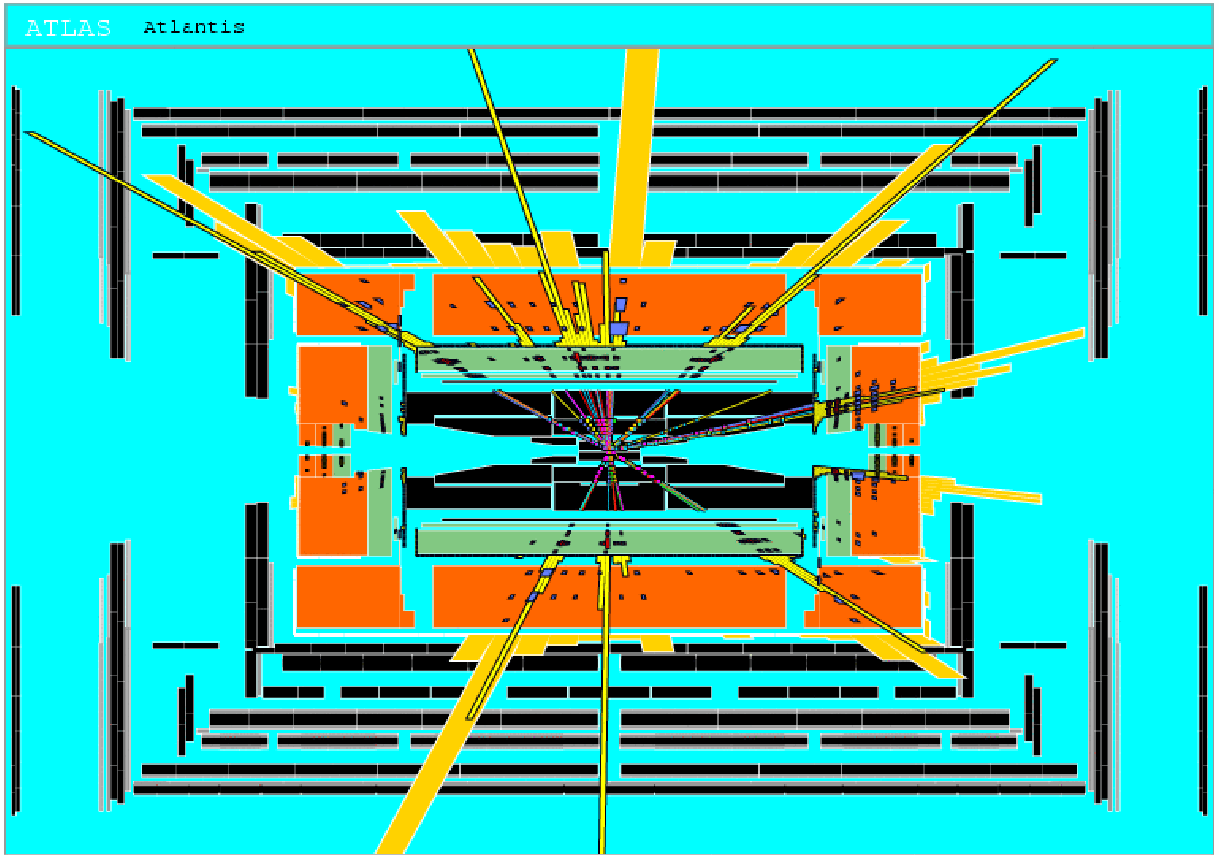
Example: W' → WZ



ATLAS-CONF-2014-015



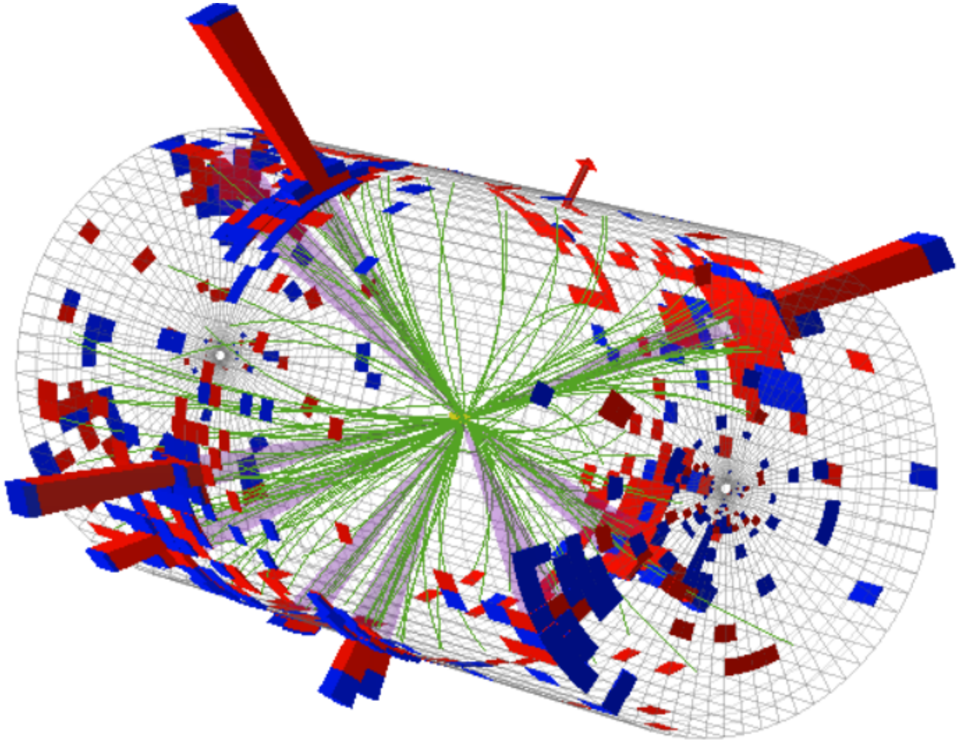
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



Simulation of a black hole event with M_{BH} ~ 8 TeV in ATLAS

They decay immediately through Stephen Hawking radiation

If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC

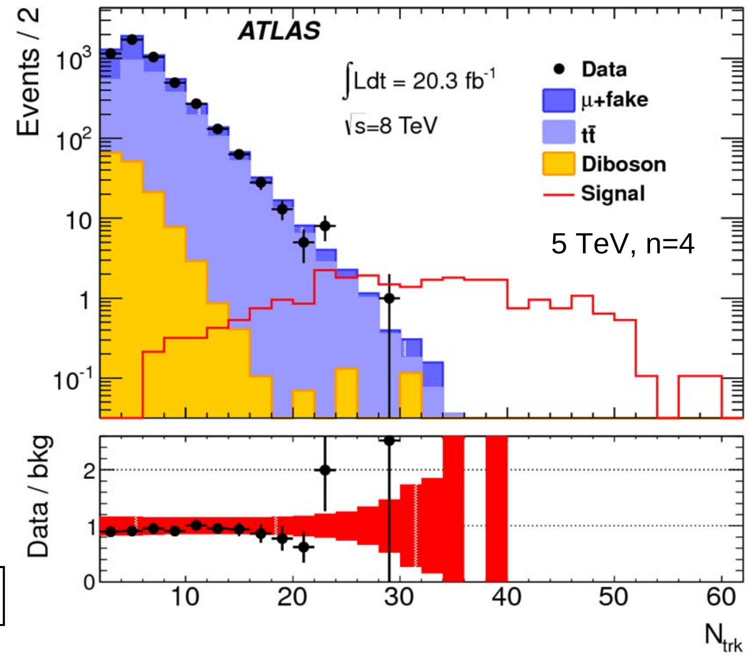


CMS Experiment at LHC, CERN
Data recorded: Mon May 23 21:46:26 2011 EDT
Run/Event: 165567 / 347495624
Lumi section: 280
Orbit/Crossing: 73255853 / 3161

A real 'candidate' event of a 'black hole' in CMS with 9 jets and ST = 2.6 TeV

They decay immediately through Stephen Hawking radiation

Search for Microscopic Black Hole production in models wth large extra dimensions
(Arkani-Hamed, Dimopoulos, Dvali)



Decay into many objects (jets, leptons, photons)

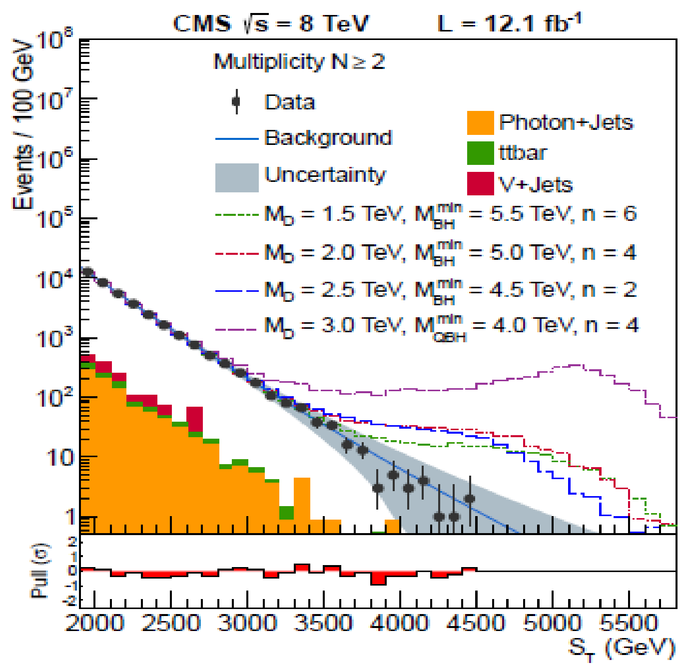
Phys Rev D88 (2013) 072001

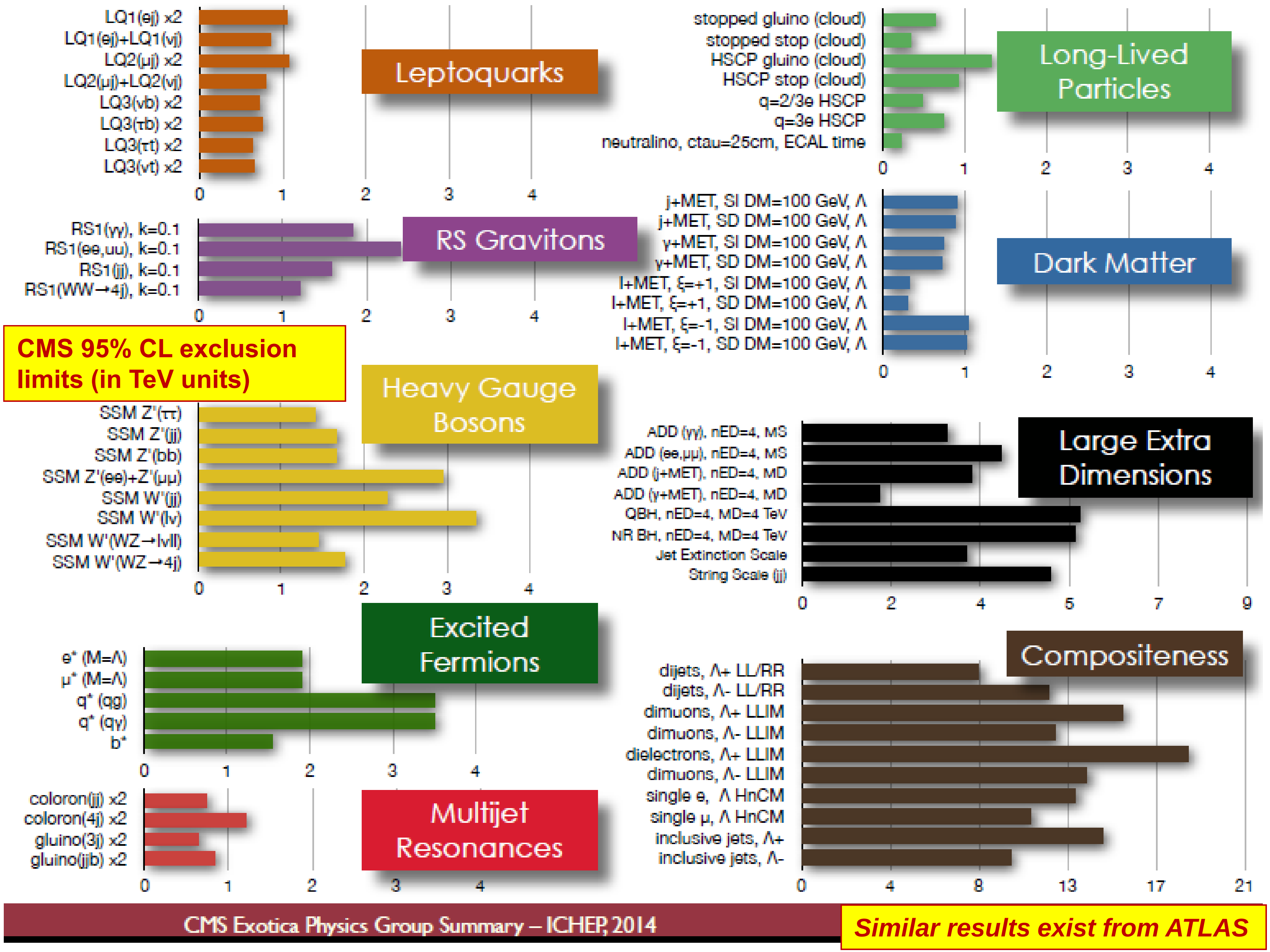
Examples: **(ATLAS) two same sign muons and large multiplicity, (CMS) any three objects**

($S_T = \Sigma P_T$: scalar sum of the E_T of the N objects in the event)

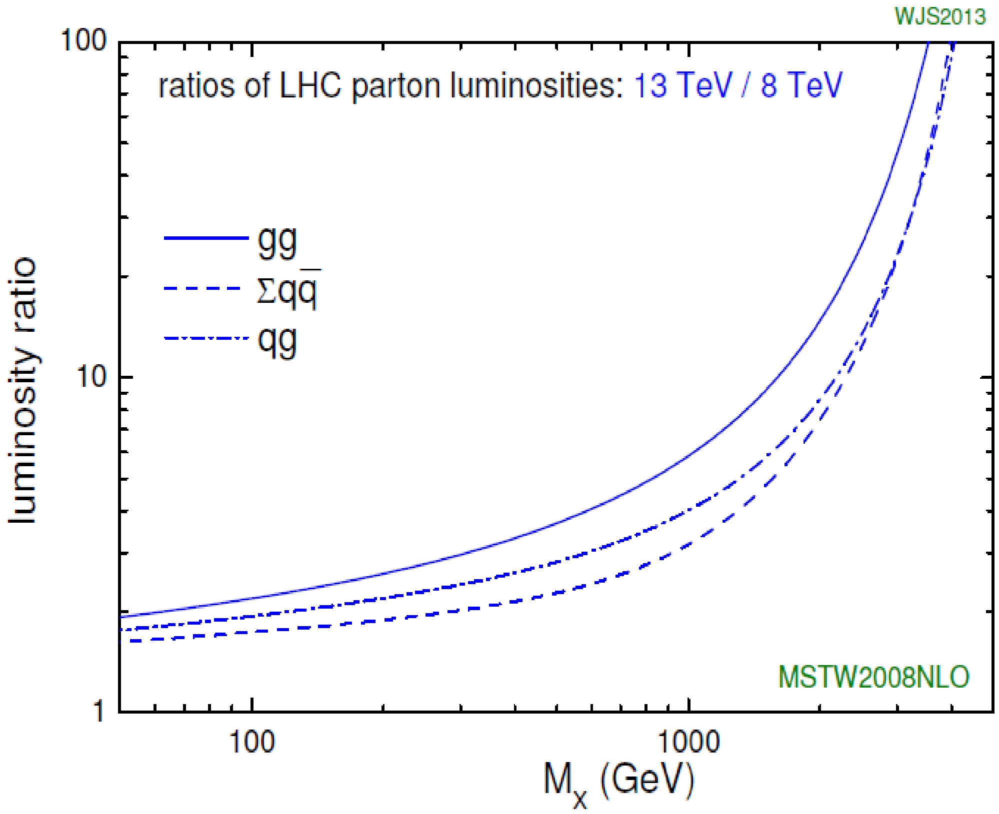
No deviation is seen for events with at least 3 objects with > 50 GeV pT

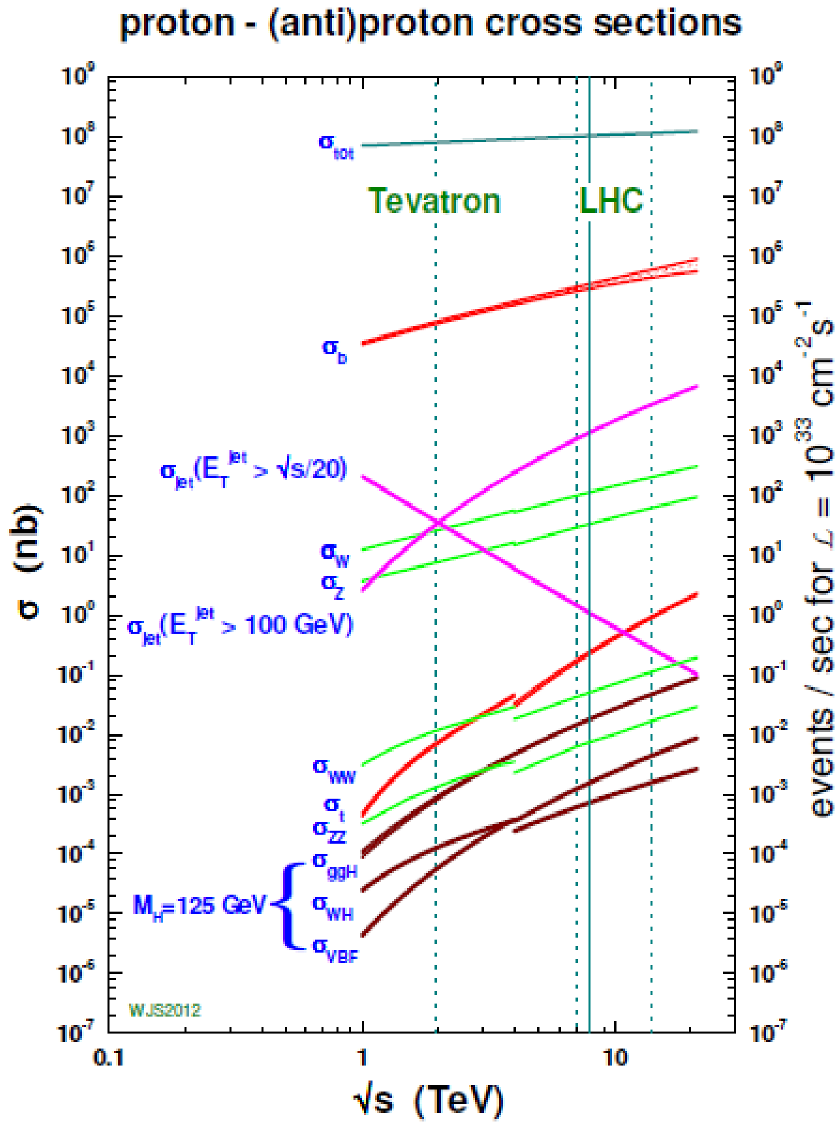
JHEP 07 (2013) 178



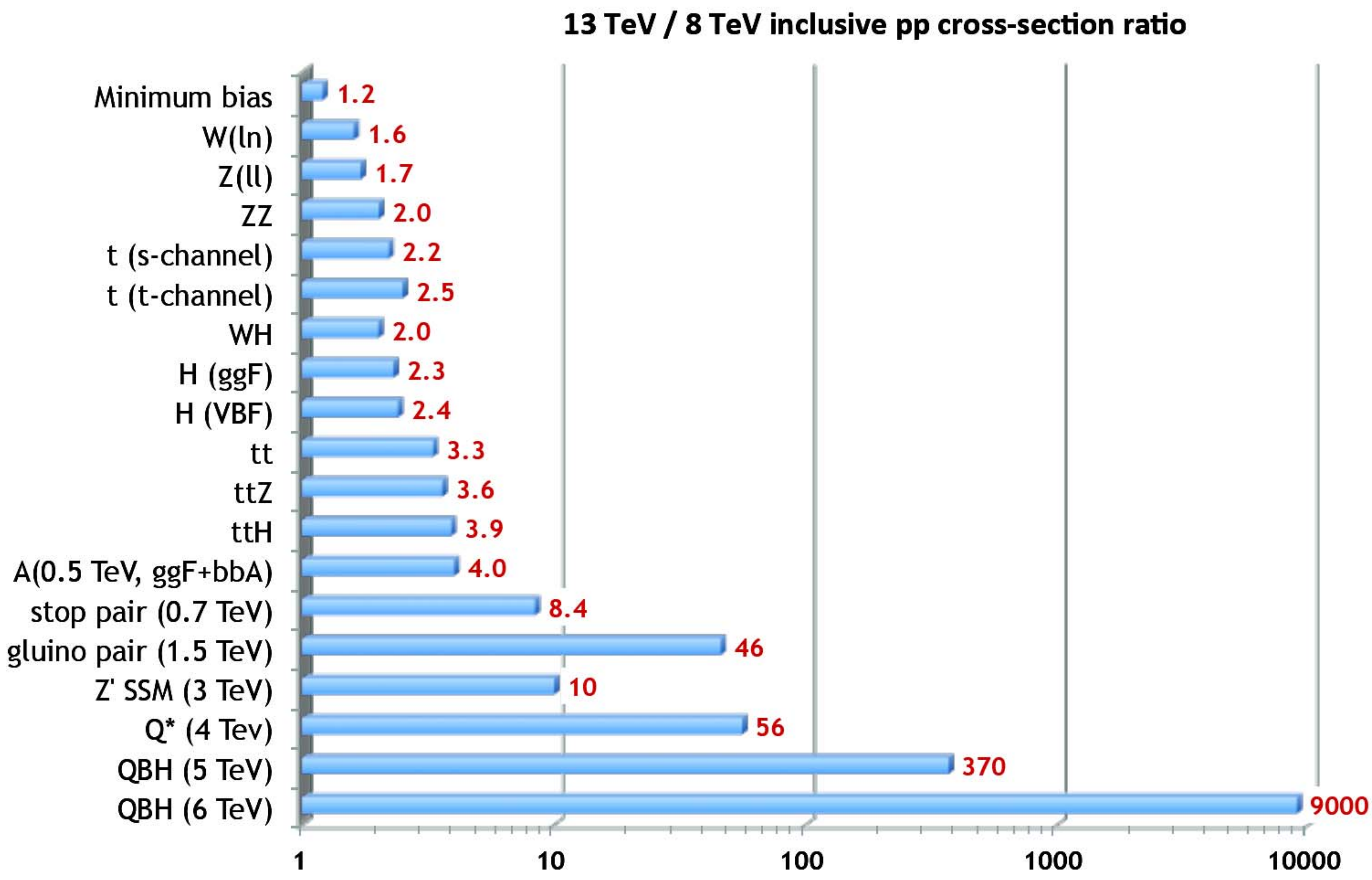

CMS 95% CL exclusion limits (in TeV units)
Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(τt) x2
LQ3(νt) x2
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
neutralino, ctau=25cm, ECAL time
Dark Matter
j+MET, SI DM=100 GeV, Λ
j+MET, SD DM=100 GeV, Λ
γ+MET, SI DM=100 GeV, Λ
γ+MET, SD DM=100 GeV, Λ
l+MET, ξ=+1, SI DM=100 GeV, Λ
l+MET, ξ=+1, SD DM=100 GeV, Λ
l+MET, ξ=-1, SI DM=100 GeV, Λ
l+MET, ξ=-1, SD DM=100 GeV, Λ
Large Extra Dimensions
ADD (γγ), nED=4, MS
ADD (ee,μμ), nED=4, MS
ADD (j+MET), nED=4, MD
ADD (γ+MET), nED=4, MD
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
CMS Exotica Physics Group Summary – ICHEP, 2014
Similar results exist from ATLAS

The search for high-mass objects will be exciting with the much higher cross sections in the coming LHC run

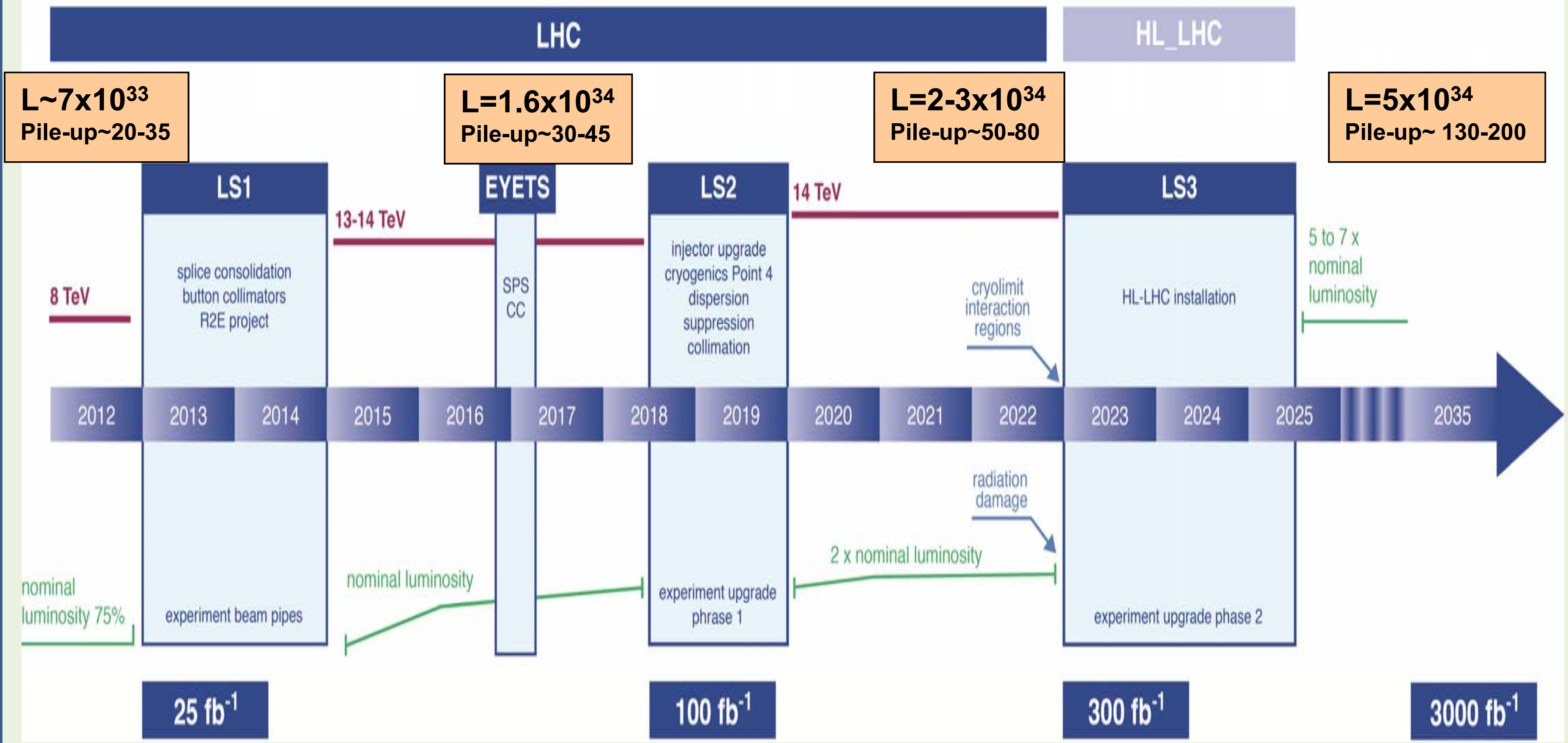


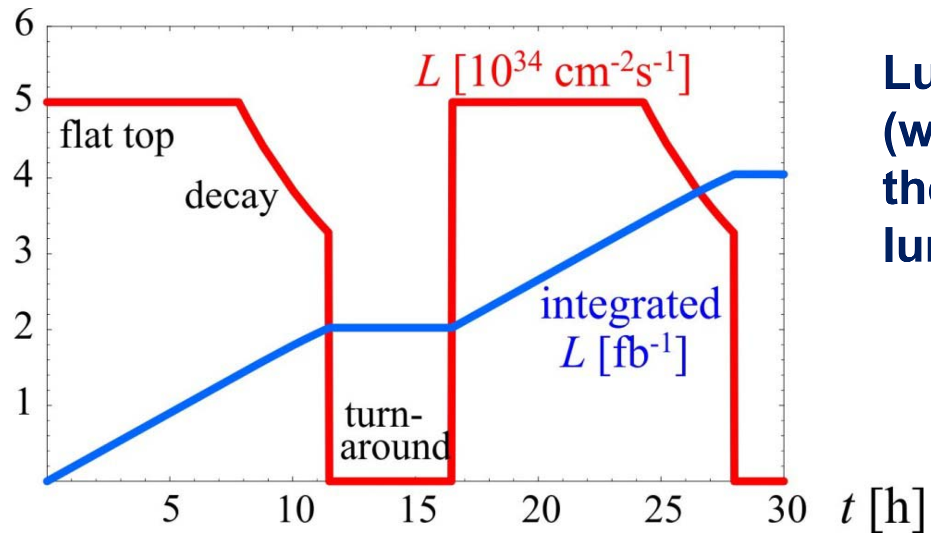


W J Stirling; many interesting plots can be found on his web:
http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html


13 TeV / 8 TeV inclusive pp cross-section ratio
Minimum bias 1.2
W(ln) 1.6
Z(ll) 1.7
ZZ 2.0
t (s-channel) 2.2
t (t-channel) 2.5
WH 2.0
H (ggF) 2.3
H (VBF) 2.4
tt 3.3
ttZ 3.6
ttH 3.9
A(0.5 TeV, ggF+bbA) 4.0
stop pair (0.7 TeV) 8.4
gluino pair (1.5 TeV) 46
Z' SSM (3 TeV) 10
Q* (4 Tev) 56
QBH (5 TeV) 370
QBH (6 TeV) 9000
1
10
100
1000
10000

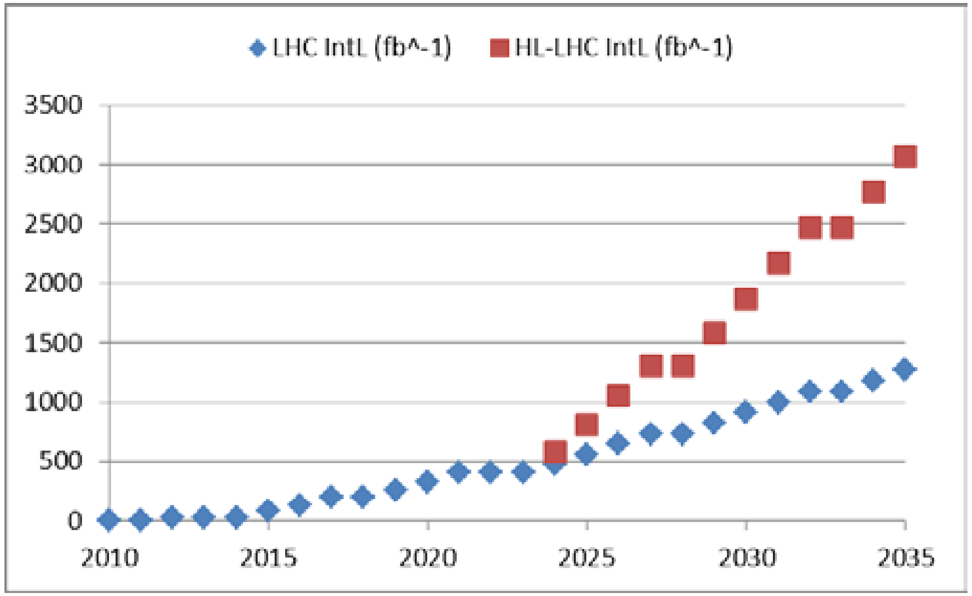
New LHC / HL-LHC Plan





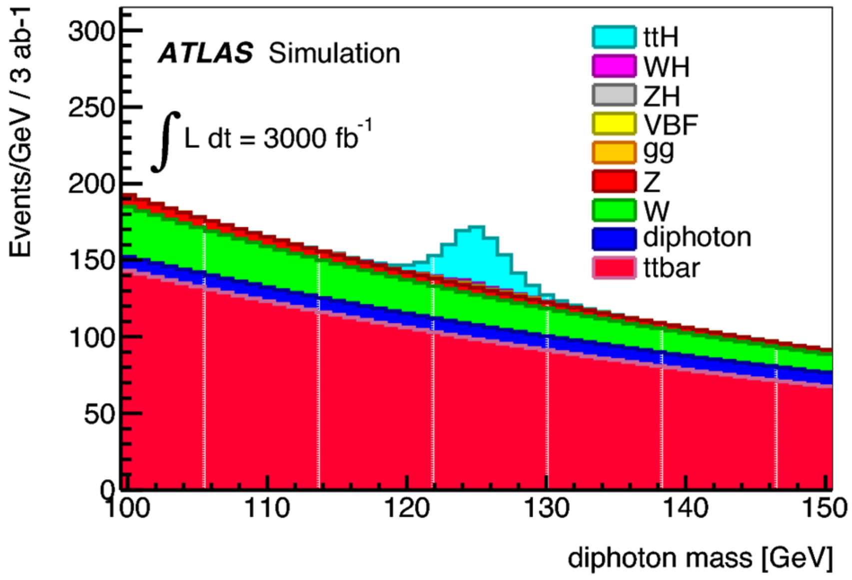
Luminosity cycle for HL-LHC (with ‘levelling’, optimized for the experiments and integrated luminosity)

High
Luminosity
LHC



Projected integrated luminosity

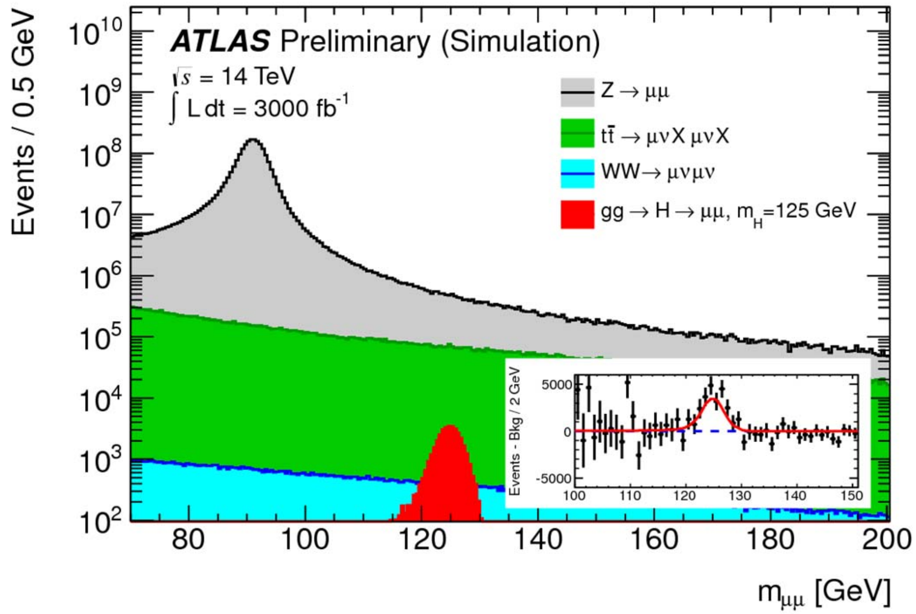
Outlook for HL-LHC on the Higgs physics



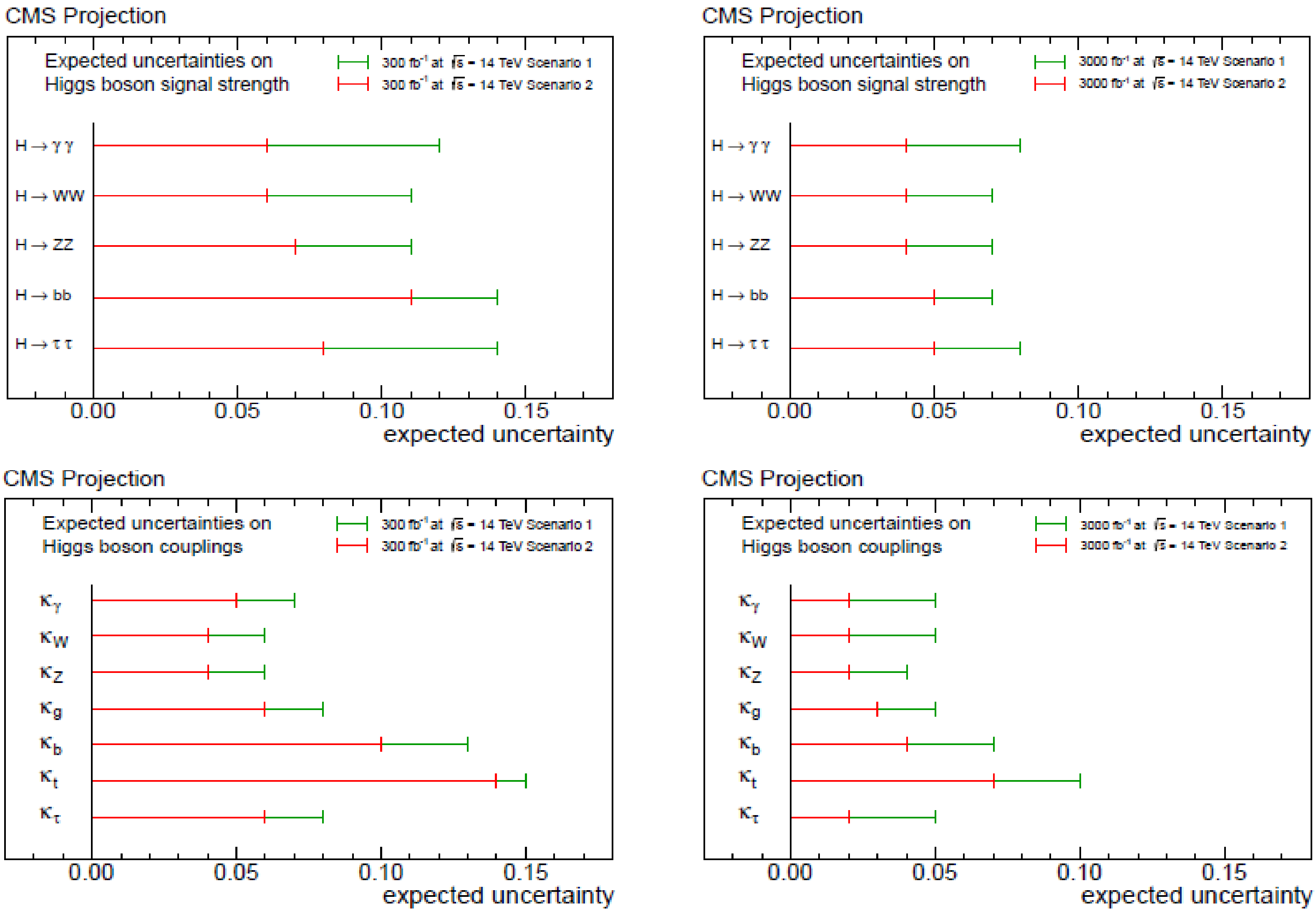
ttH with H → γγ for 3000 fb^{-1}

ATL-PHYS-PUB-2013-007, arXiv:1307.7292[hep-ex]

H → μμ for 3000 fb^{-1}



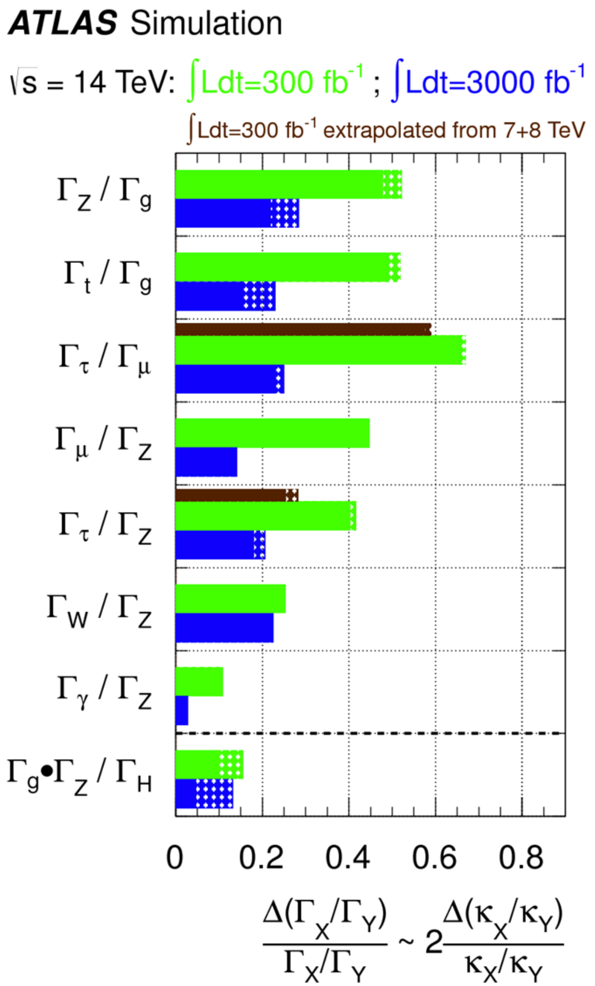
Outlook for HL-LHC on the Higgs physics

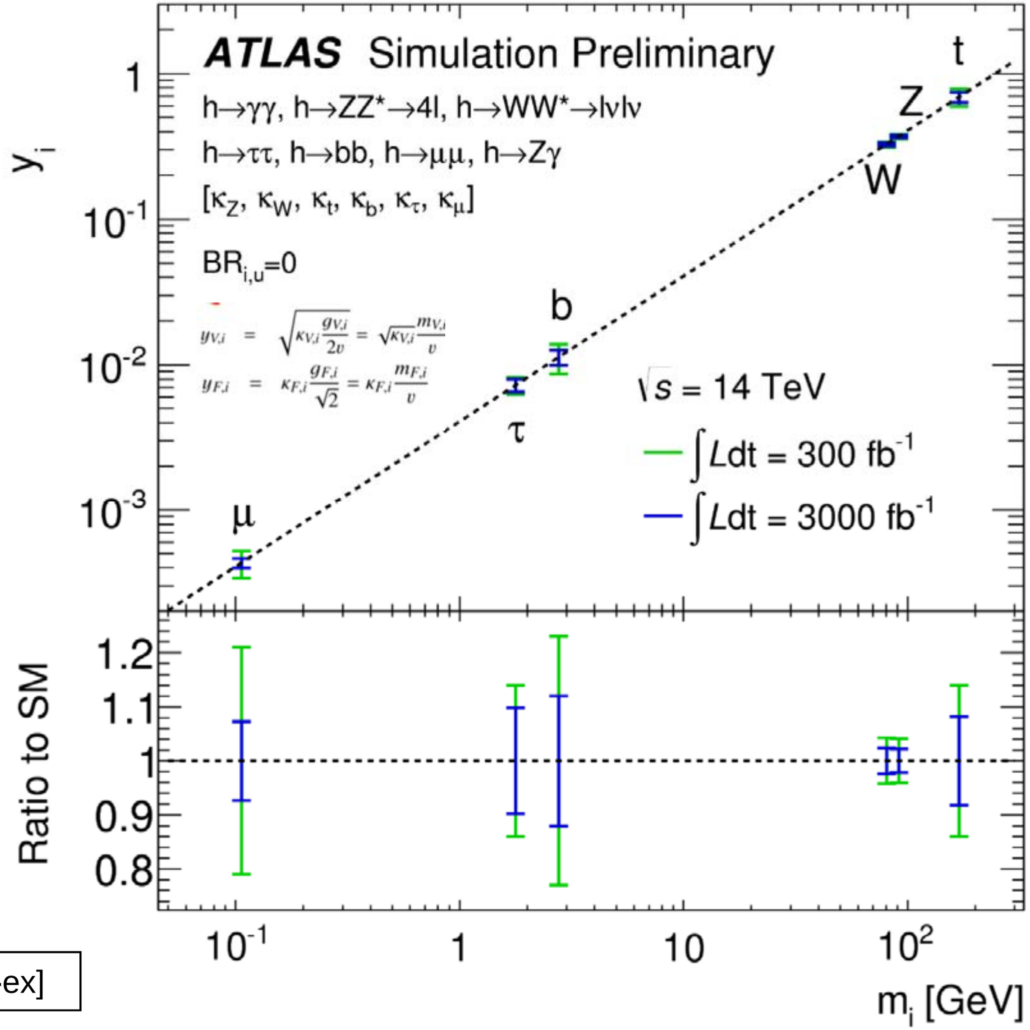


CMS NOTE-13-002, arXiv:1307.7135 [hep-ex]

CMS considers two extrapolation scenarios:
Scenario 1: systematic errors are left unchanged
Scenario 2: theoretical errors scaled by 0.5, other syst. errors scaled by √luminosity

Outlook for HL-LHC on the Higgs physics





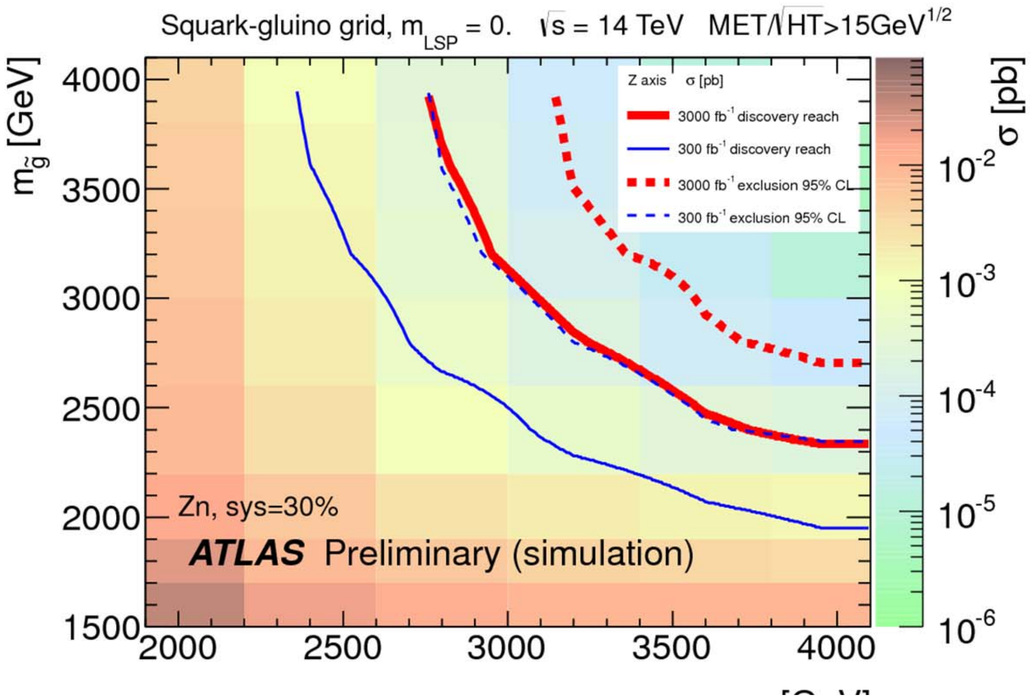
ATL-PHYS-PUB-2013-007, arXiv:1307.7292[hep-ex]

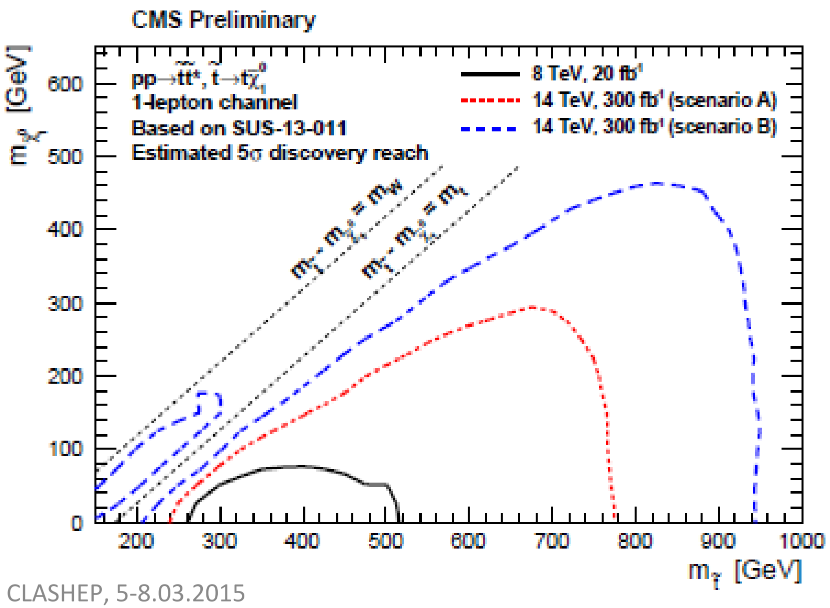
Higgs decay widths in the Standard Model ($M_H = 126$ GeV)

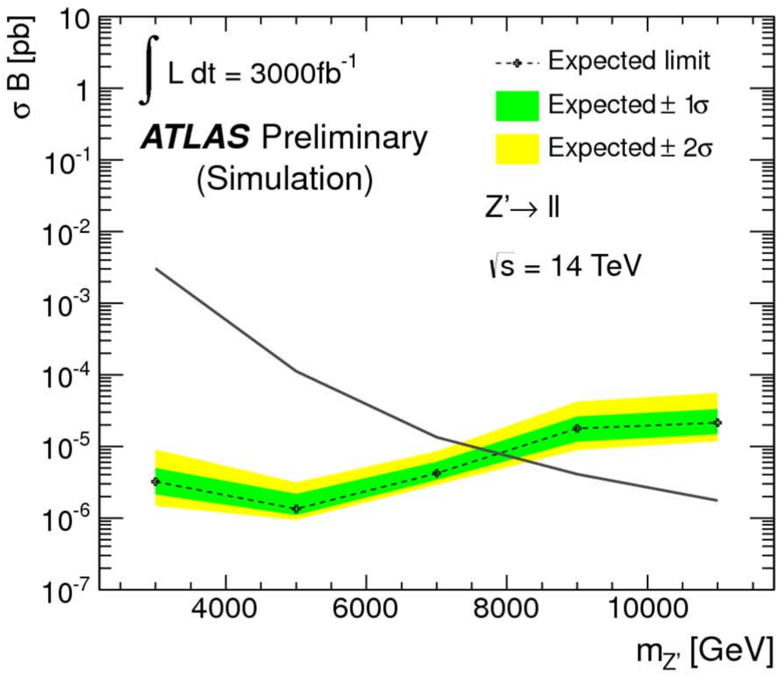
Channel	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
$H \to b\bar{b}$	2.36	−2.3% +2.3%	+3.3% −3.2%	+0.0% −0.0%	+0.0% −0.0%	+2.0% −2.0%
$H \to \tau^+\tau^-$	$2.59 \cdot 10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+2.0% −2.0%
$H \to \mu^+\mu^-$	$8.99 \cdot 10^{-4}$	+0.0% −0.0%	+0.0% −0.0%	−0.1% −0.0%	+0.0% −0.1%	+2.0% −2.0%
$H \to c\bar{c}$	$1.19 \cdot 10^{-1}$	−7.1% +7.0%	−0.1% +0.1%	+6.2% −6.1%	+0.0% −0.1%	+2.0% −2.0%
$H \to gg$	$3.57 \cdot 10^{-1}$	+4.2% −4.1%	−0.1% +0.1%	+0.0% −0.0%	−0.2% +0.2%	+3.0% −3.0%
$H \to \gamma\gamma$	$9.59 \cdot 10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%
$H \to Z\gamma$	$6.84 \cdot 10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+0.0% −0.1%	+5.0% −5.0%
$H \to WW$	$9.73 \cdot 10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
$H \to ZZ$	$1.22 \cdot 10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%

[LHC Higgs Cross Section Working Group Collaboration, arXiv:1307.1347]

Examples of SUSY and Z' mass reaches at HL-LHC



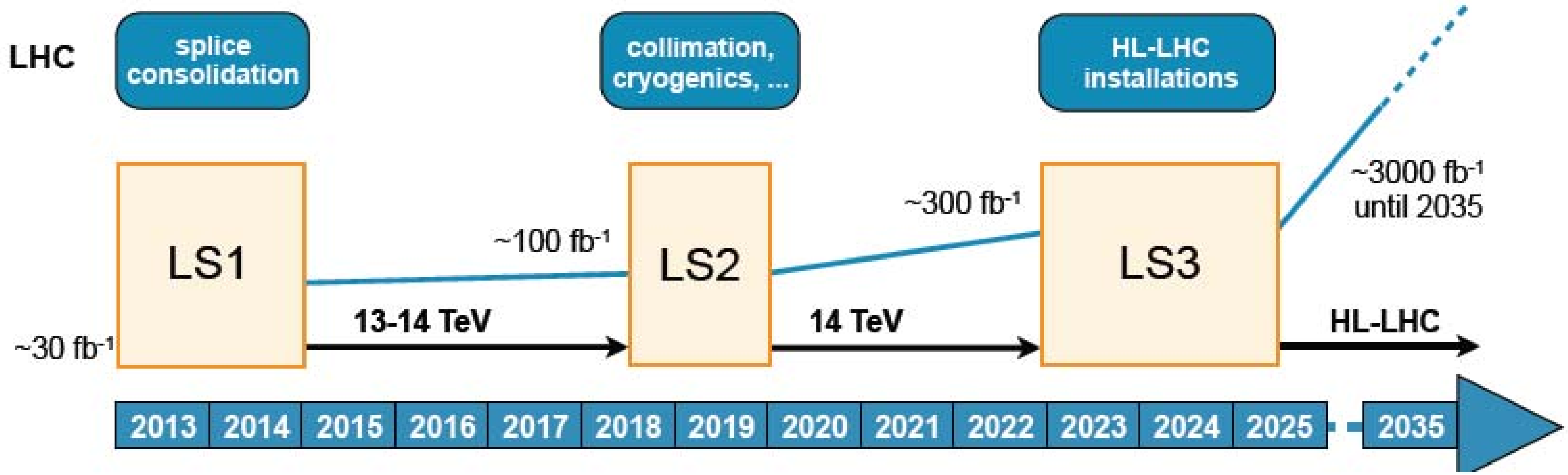




ATL-PHYS-PUB-2013-007, arXiv:1307.7292[hep-ex]

CMS NOTE-13-002, arXiv:1307.7135 [hep-ex]

ATLAS Upgrade Roadmap



ATLAS Phase-0

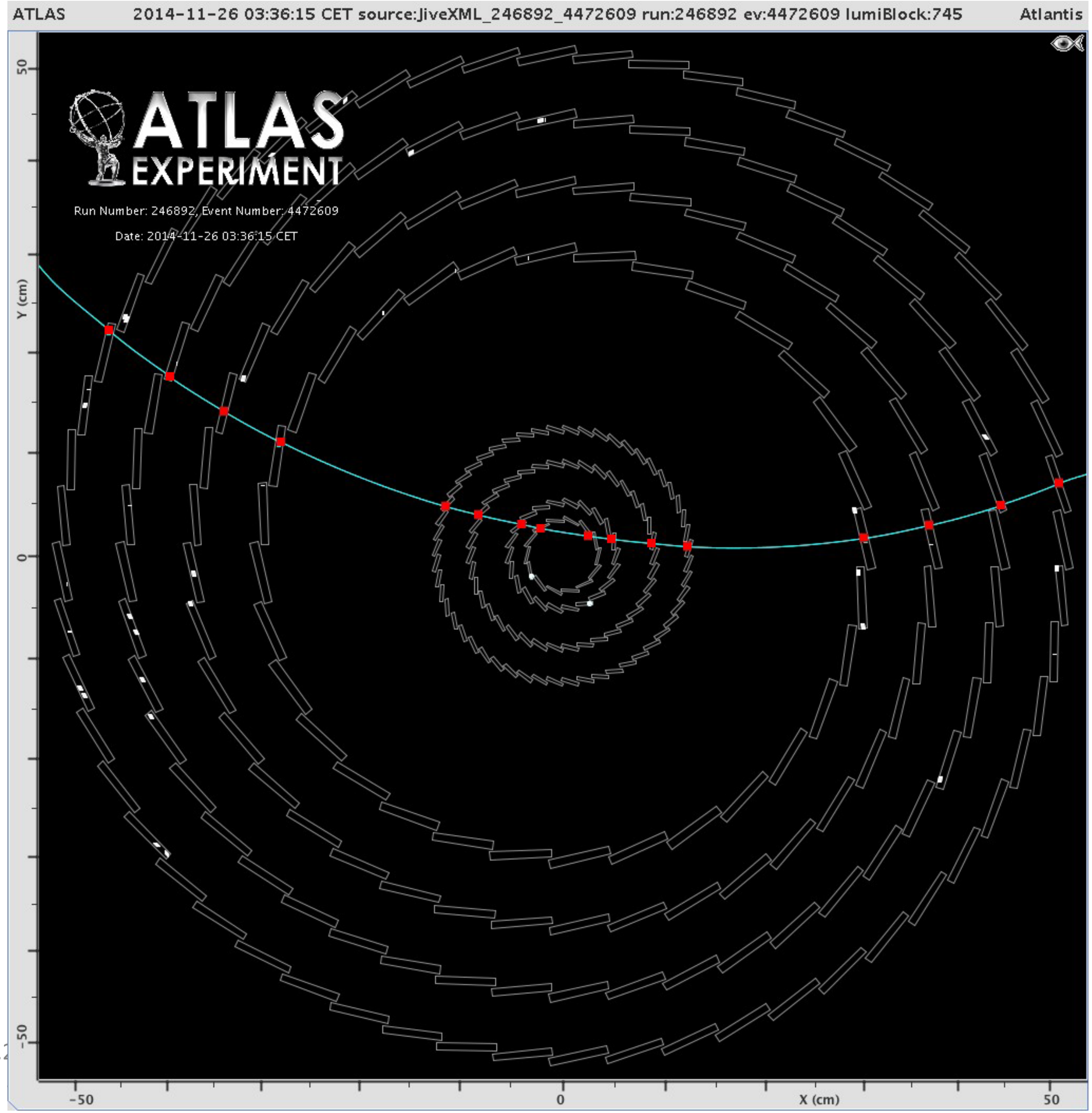
New inner pixel layer
Detector consolidation
2015: FTK deployment

ATLAS Phase-1

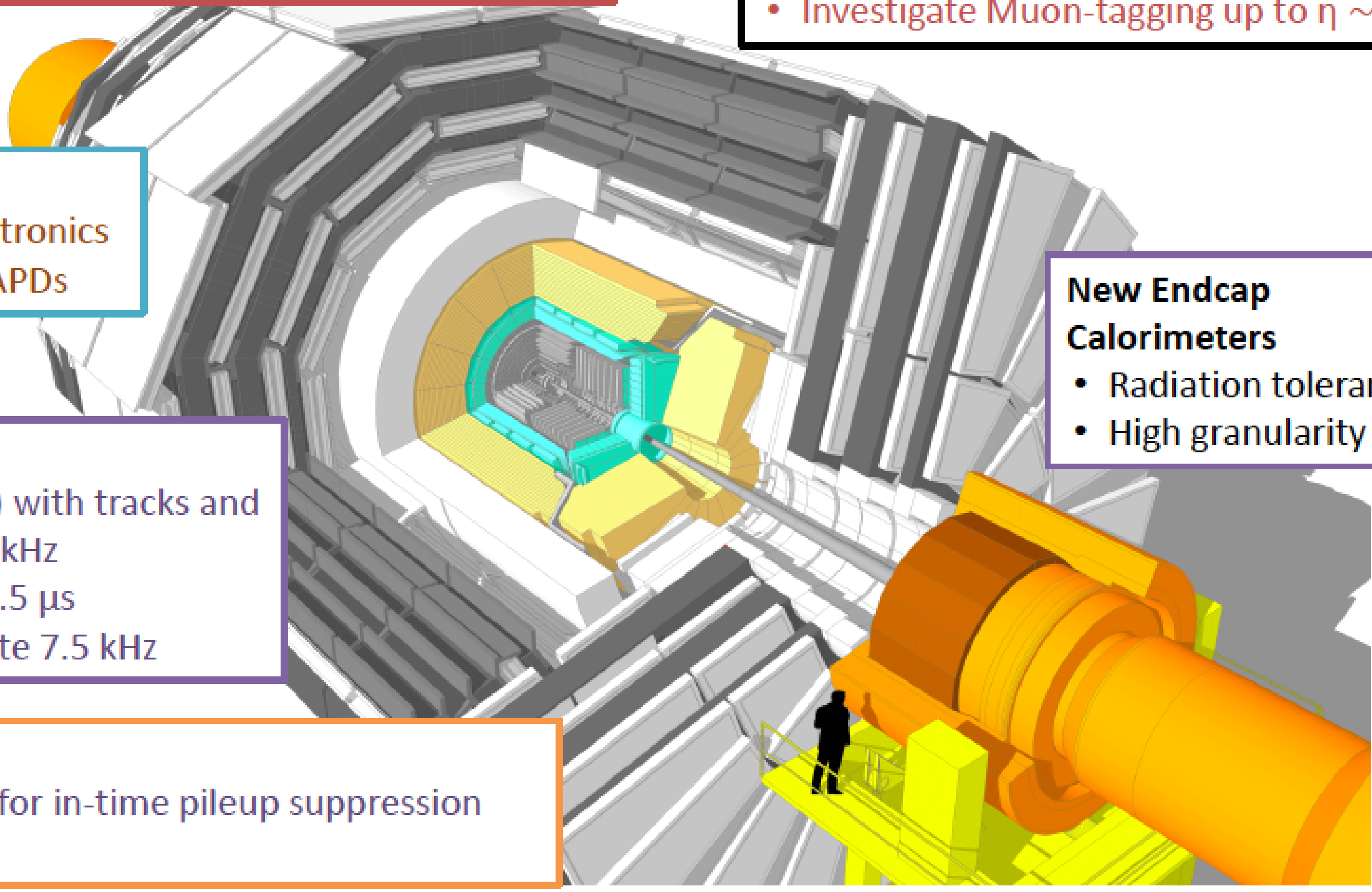
Improve L1 Trigger, NSW and LAr electronics to cope with higher rates

ATLAS Phase-2

Prepare for 140-200 pile-up events
Replace Inner Tracker
New L0/L1 trigger scheme
Upgrade muon/calorimeter electronics
Upgrade of DAQ detector readout


ATLAS
2014-11-26 03:36:15 CET source:JiveXML_246892_4472609 run:246892 ev:4472609 lumiBlock:745
Atlantis
ATLAS EXPERIMENT
Run Number: 246892, Event Number: 4472609
Date: 2014-11-26 03:36:15 CET
Y (cm)
X (cm)
50
0
-50
-50
0
50

CMS Phase II Upgrade



New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to $\eta \sim 4$

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to $\eta \sim 3$

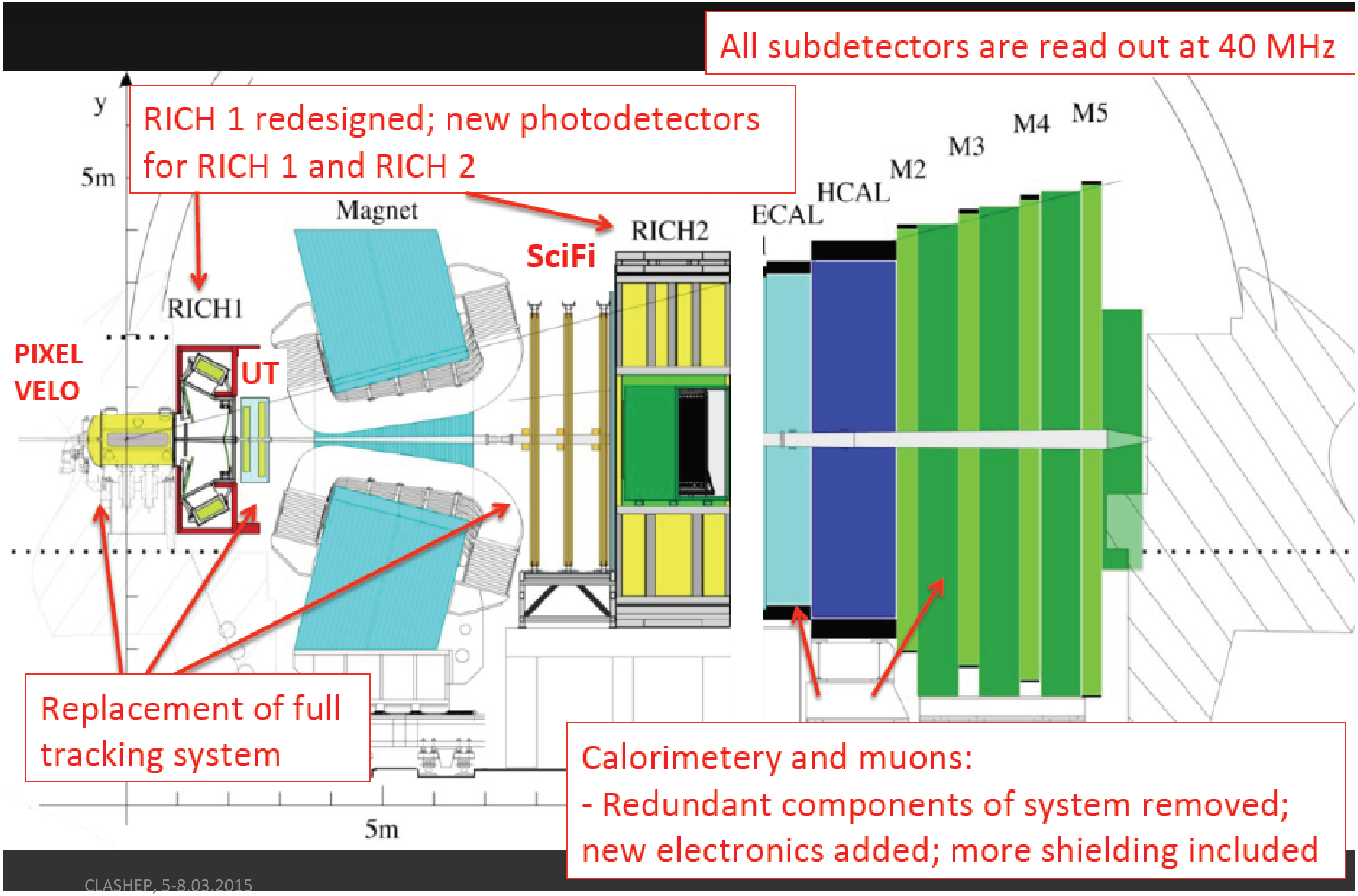
Barrel ECAL
- Replace FE electronics
- Cool detector/APDs

New Endcap Calorimeters
- Radiation tolerant
- High granularity

Trigger/DAQ
- L1 (hardware) with tracks and rate up $\sim$ 750 kHz
- L1 Latency 12.5 µs
- HLT output rate 7.5 kHz

Other R&D
- Fast-timing for in-time pileup suppression
- Pixel trigger

LHCb Upgrade



ALICE Upgrade

New Inner Tracking System (ITS)
- improved pointing precision
- less material -> thinnest tracker at the LHC

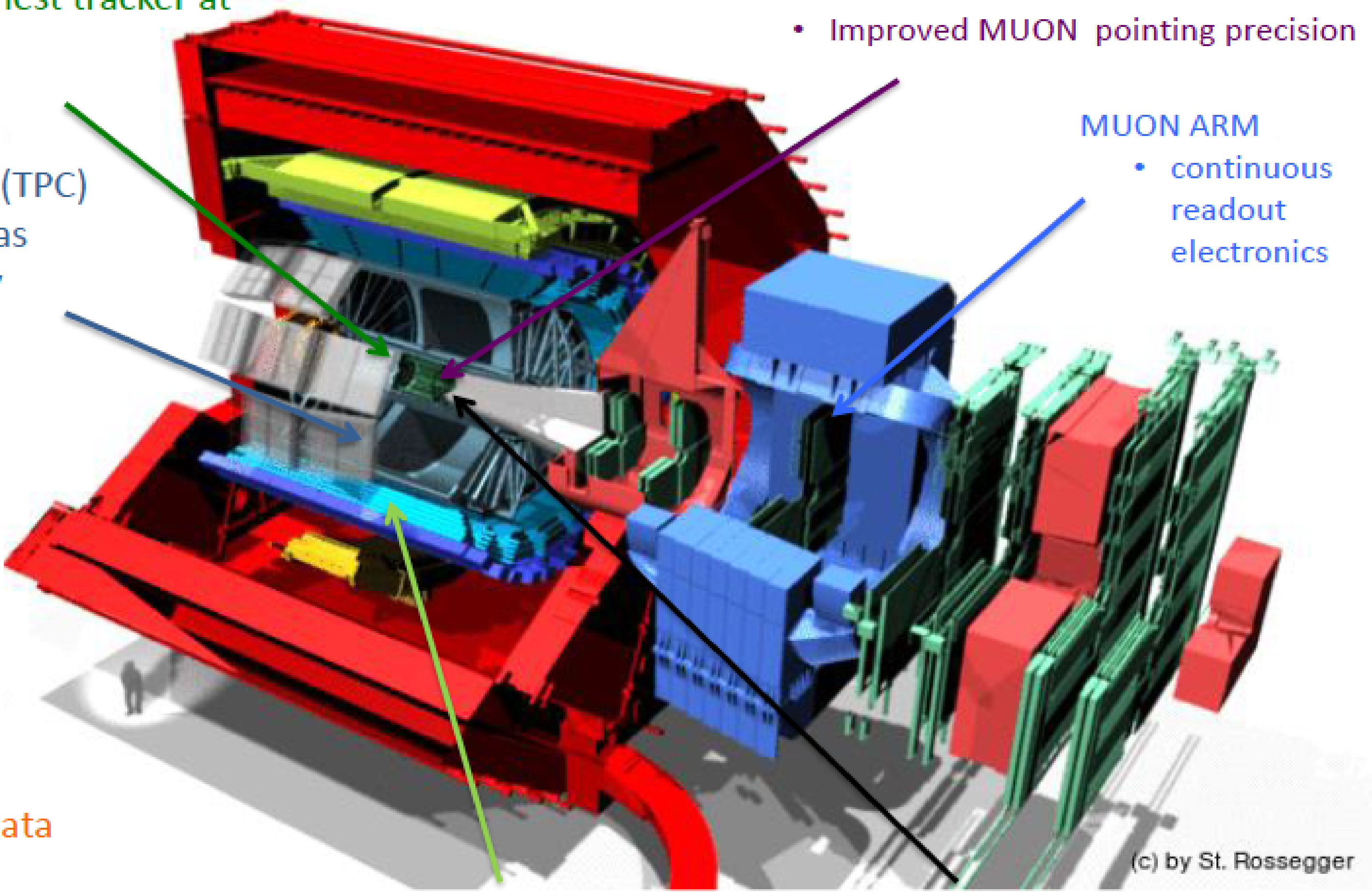
Time Projection Chamber (TPC)
- New Micropattern gas detector technology
- continuous readout

New Central Trigger Processor (CTP)

Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

MUON ARM
- continuous readout electronics



TOF, TRD
- Faster readout

New Trigger Detectors (FIT)

What about the future beyond LHC ?

The future of European particle physics has been broadly debated, and a road map established, in the framework of an Update of the European Strategy for Particle Physics, during 2012 and 2013 (approved by CERN Council, May 2013)

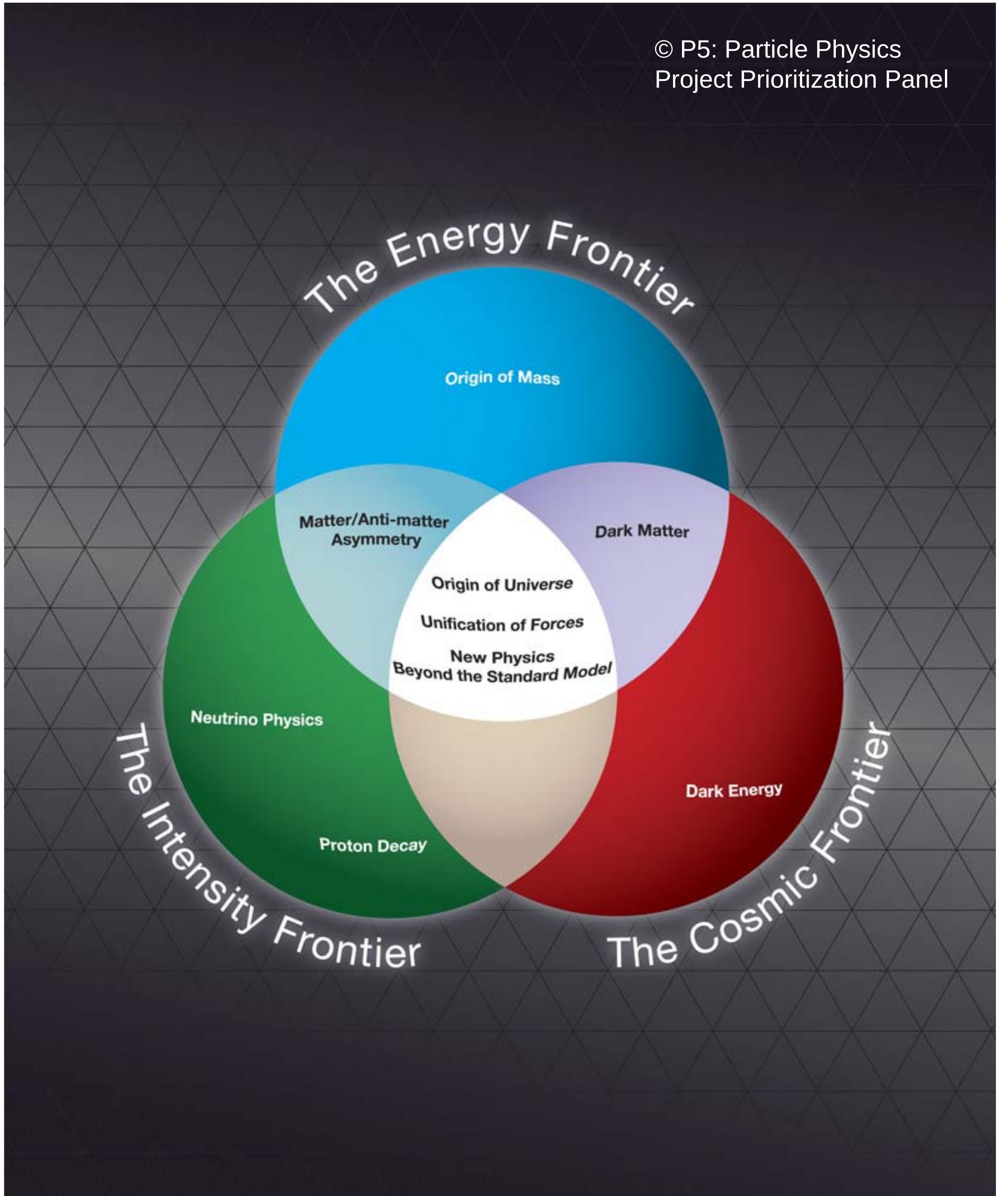
European Strategy for Particle Physics

http://council.web.cern.ch/council/en/EuropeanStrategy/ESArchive.html

The famous three pillars of particle physics

When considering the scientific input the science landscape for the European Strategy for Particle Physics, one was very much aware of this complementarity

Another primordial consideration was the need to see the European Strategy within a global context of facilities worldwide, taking into account the global aspects of planning for future facilities



US High Energy Physics Strategic Plan: P5

P5 Report was submitted by HEPAP on May 22, 2014.

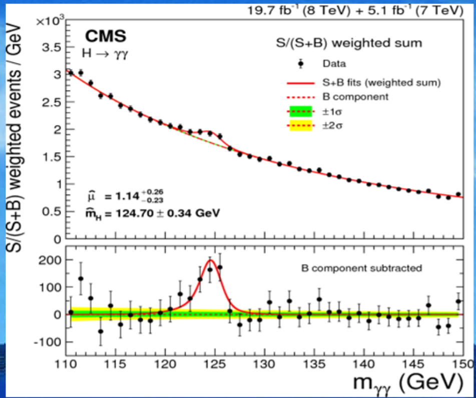
A strategic plan, executable over 10 years, in the context of a 20-year global vision, in *realistic* budget scenarios

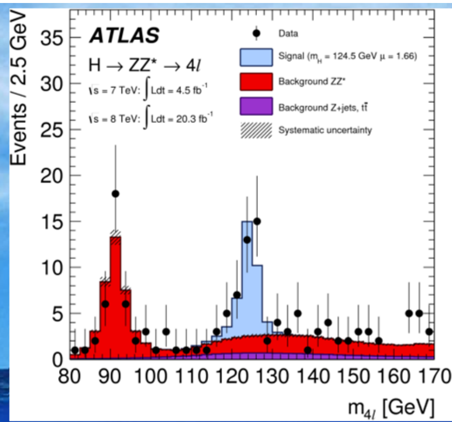
The plan was formulated by a panel of 25 scientists

The P5 plan is science-driven.

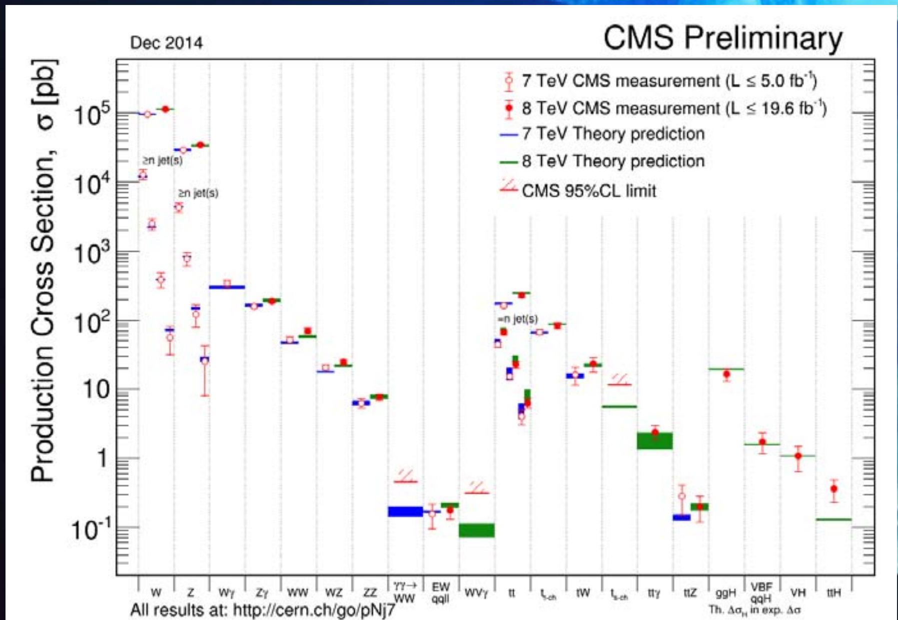
The 5 Science Drivers:

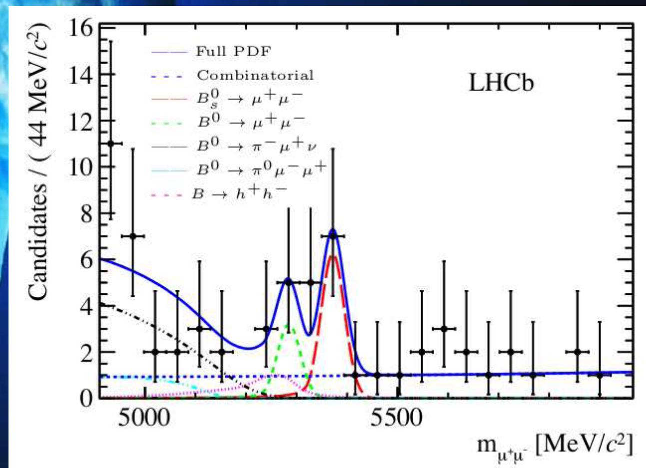
- **Use the Higgs boson as a new tool for discovery.**
- **Pursue the physics associated with neutrino mass.**
- **Identify the new physics of dark matter.**
- **Understand cosmic acceleration: dark energy and inflation.**
- **Explore the unknown: new particles, interactions, & physical principles.**





The High Energy Frontier





©Ralph A. Clevenger/CORBIS

Collider options for the high energy frontier

pp colliders

	Years	E_{cm} TeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Int. Luminosity fb^{-1}
Design LHC	2014-21	14	1-2	300
HL-LHC	2024-30	14	5	3000
HE-LHC	>2035	26-33*	2	100-300/y
V-LHC**	>2035	42-100		

* 16-20 T dipole field
** 80 km Tunnel

e+e- colliders

	Years	E_{cm} GeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Tunnel length km
ILC 250	<2030	250	0.75	
ILC 500		500	1.8	~30
ILC 1000		1000		~50
CLIC 500	>2030	500	2.3(1.3)	~13
CLIC 1400		1400(1500)	3.2(3.7)	~27
CLIC 3000		3000	5.9	~48
LEP3	>2024	240	1	LEP/LHC ring
TLEP	>2030	240	5	80 (ring)
TLEP		350	0.65	80 (ring)

Other options:

$\mu^+\mu^-$ and $\gamma\gamma$ colliders with similar physics as e^+e^- colliders

LHeC for ep collisions

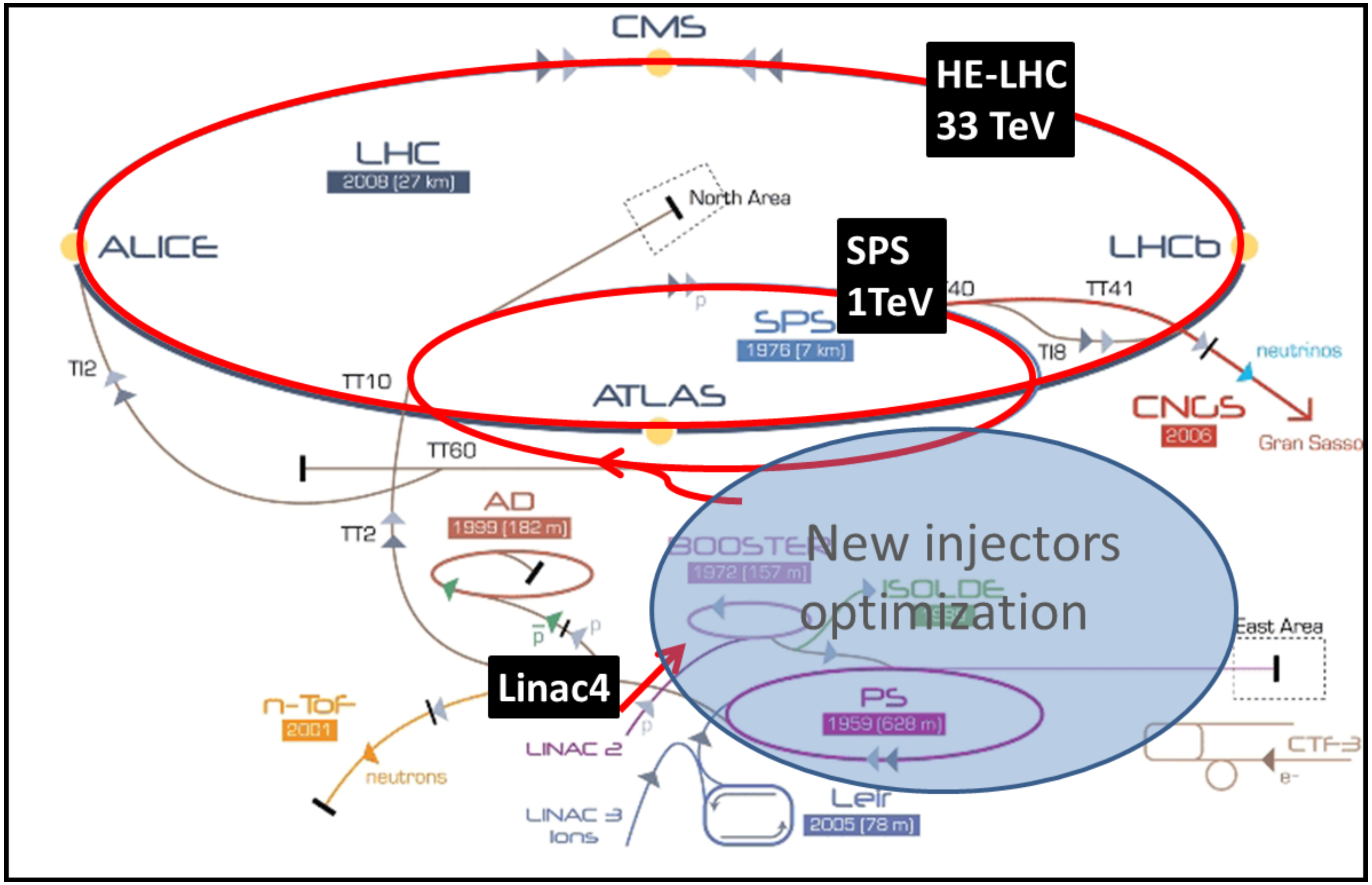
Slide from the European Strategy time

High Luminosity LHC

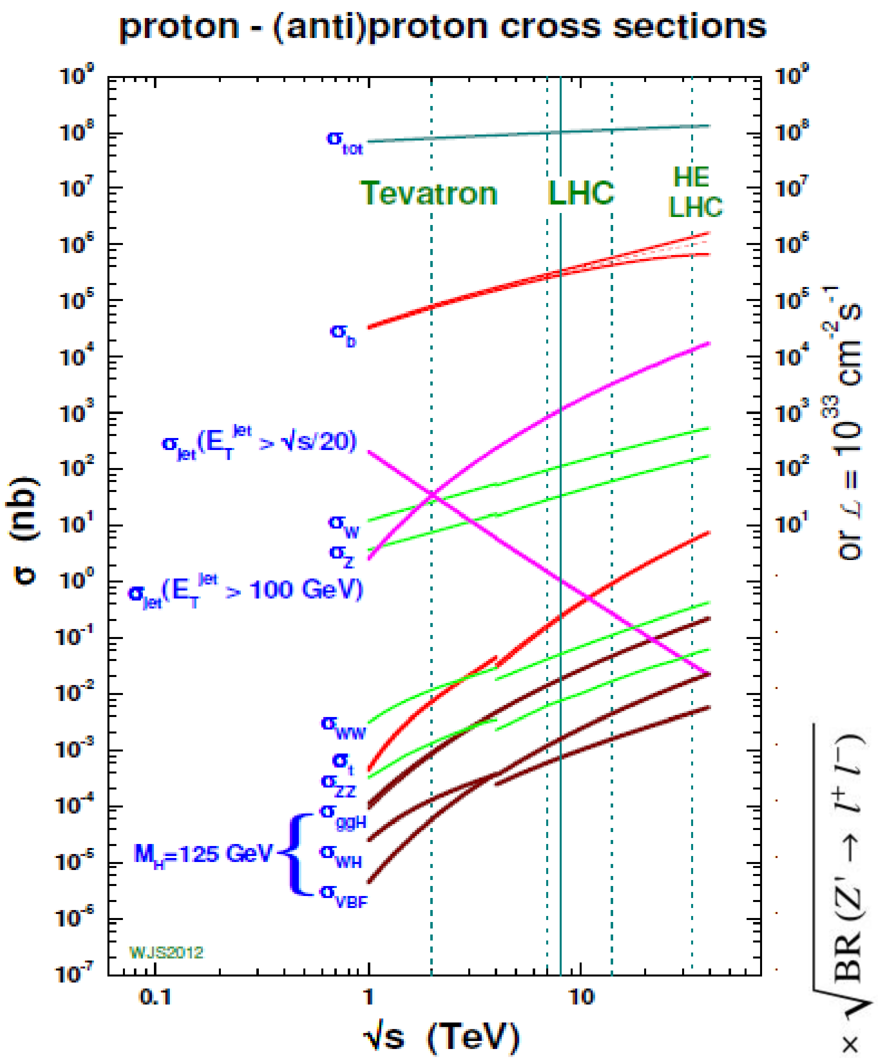
High Luminosity LHC Participants

Higher energy hadron colliders

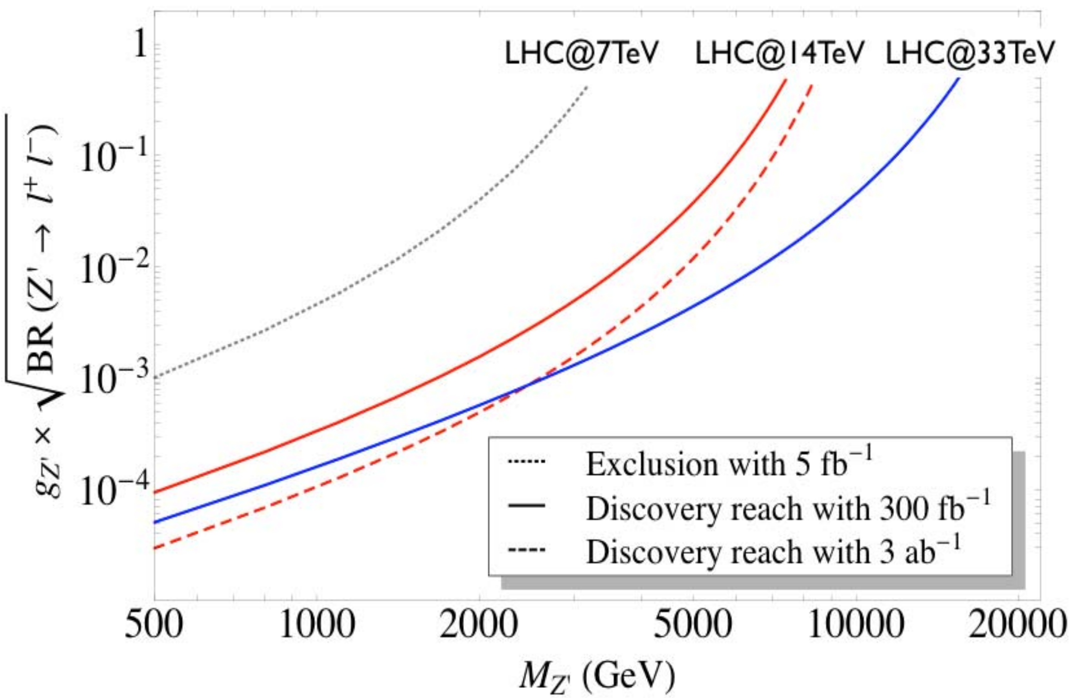
One option, called HE-LHC, would be to install a new collider in the present LHC tunnel, together with a fully upgraded injector chain



CERN-ATS-2012-237
ES Open Symp. Contr. ID=155

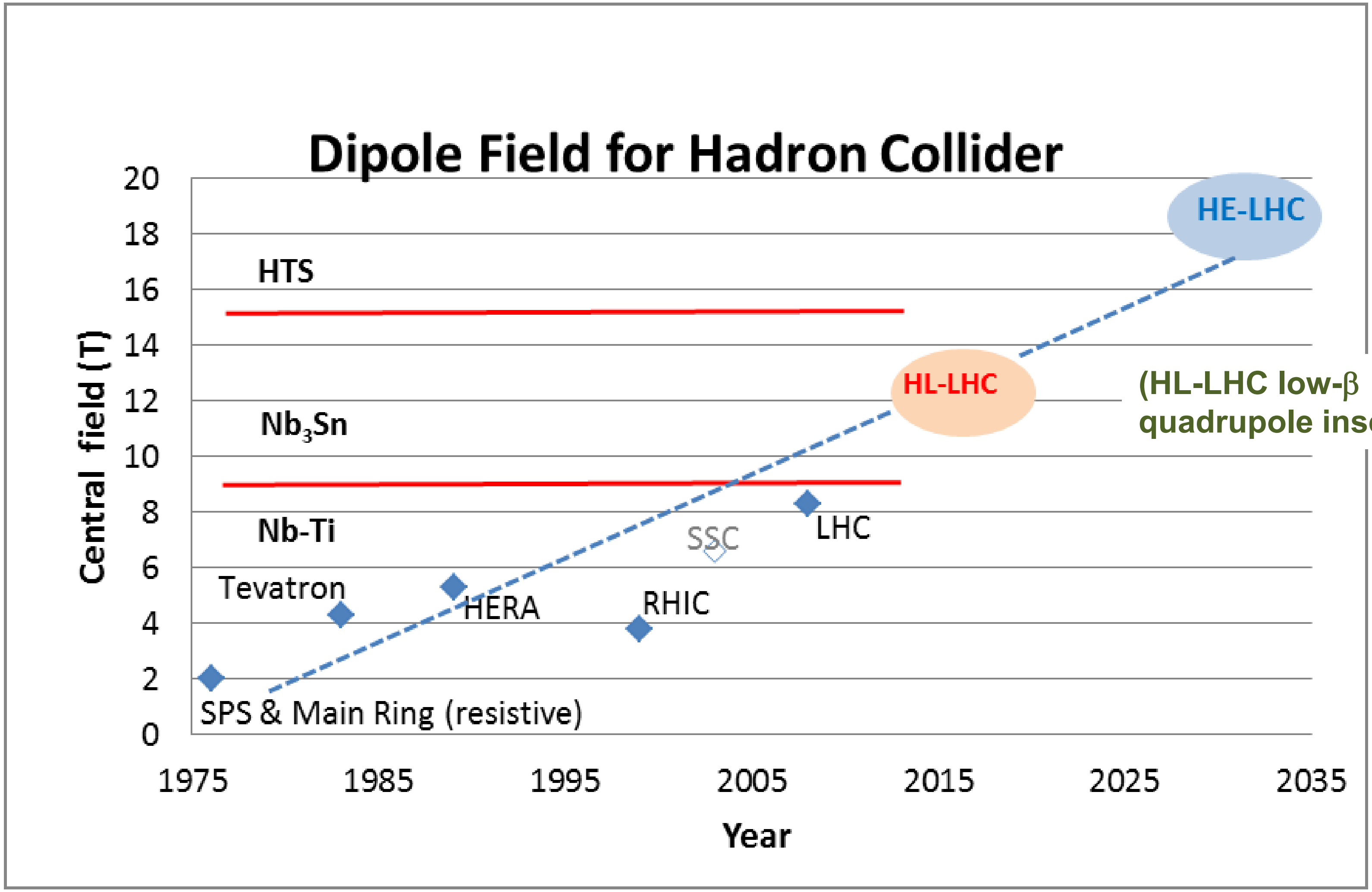


proton - (anti)proton cross sections
Tevatron
LHC
HE LHC
σ (nb)
√s (TeV)
or ℒ = 10^33 cm^-2 s^-1
σtot
σb
σjet(ET jet > √s/20)
σW
σZ
σjet(ET jet > 100 GeV)
σWW
σt
σZZ
σggH
σWH
σVBF
MH=125 GeV
WJS2012



LHC@7TeV
LHC@14TeV
LHC@33TeV
Exclusion with 5 fb^-1
Discovery reach with 300 fb^-1
Discovery reach with 3 ab^-1
MZ' (GeV)

Higher energy hadron colliders require further progress in the developments of high-field magnets



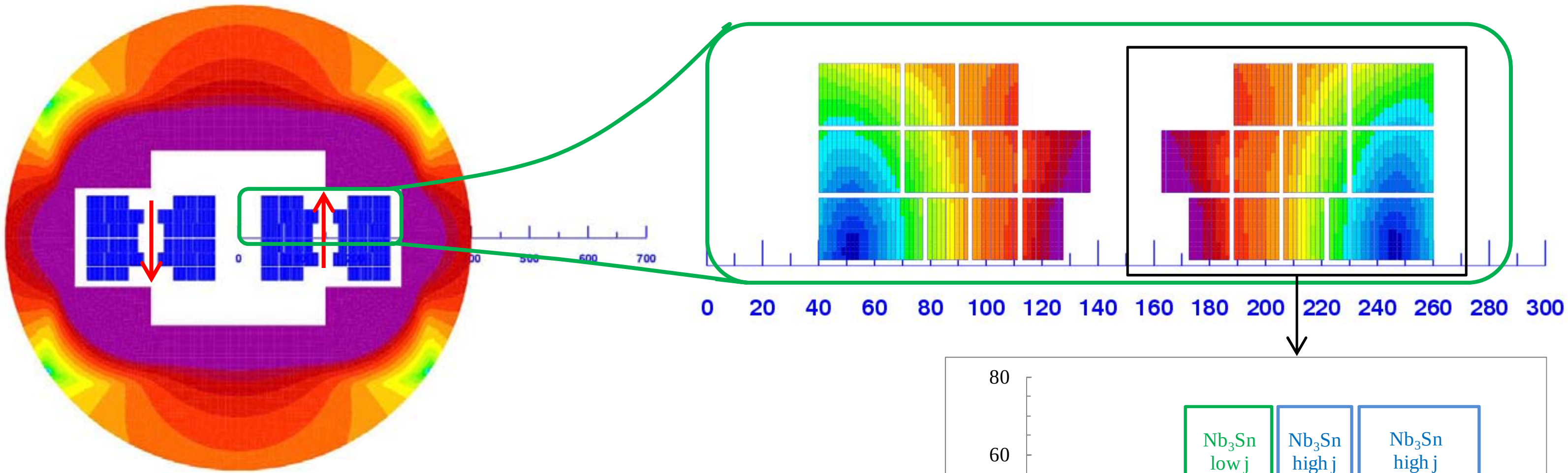
(HL-LHC low-β quadrupole insertions)

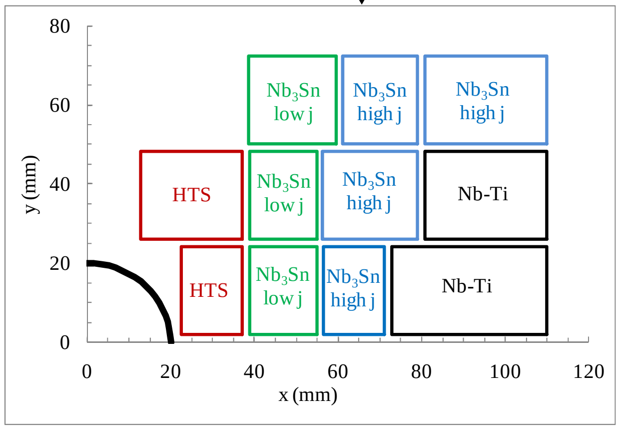
History of high-field magnets for hadron colliders

CERN-ATS-2012-237
ES Open Symp. Contr. ID=155

First conceptual layout of a 20 Tesla magnet that would fit into the LHC tunnel

L. Rossi and E. Todesco



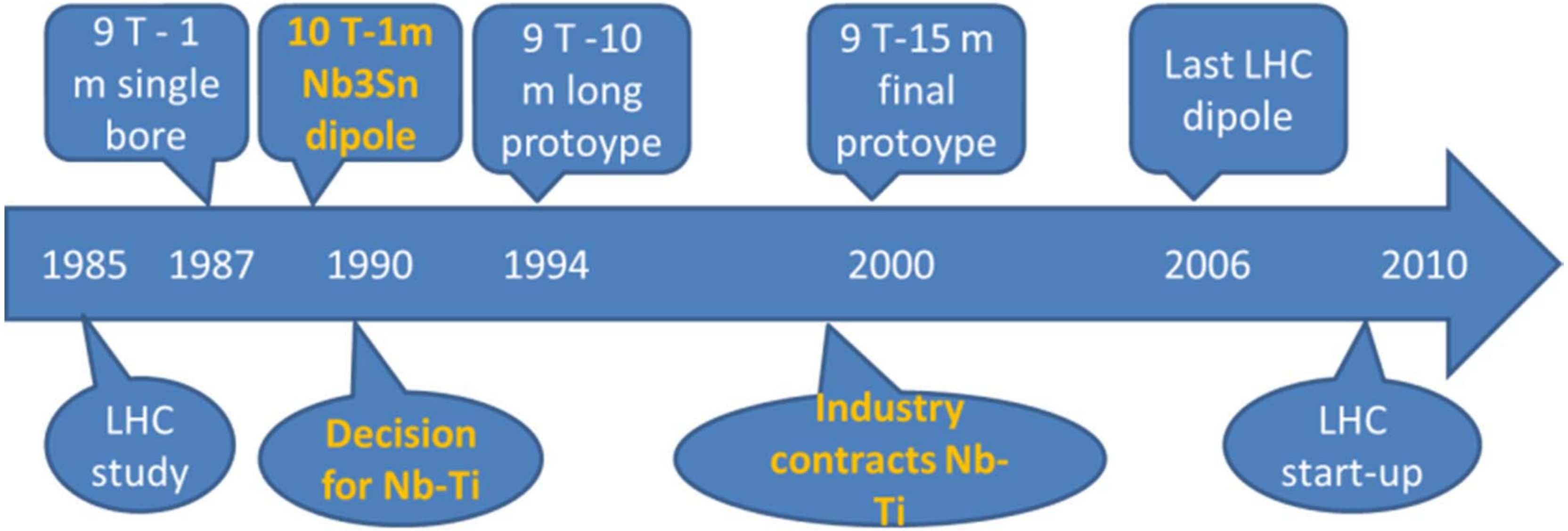


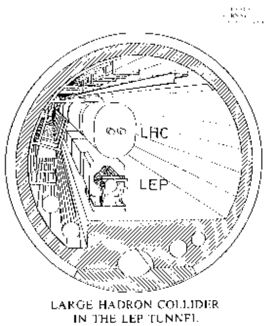
Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380
Nb3Sn (high Jc)	55	37%	13	380
Nb3Sn (Low Jc)	30	20%	15	190
HTS	24	16%	20.5	380

Magnet design: 40 mm bore (depends on injection energy: > 1 Tev)
Very challenging but feasable: 300 mm inter-beam; anticoils to reduce flux
Approximately 2.5 times more SC than LHC: 3000 tonnes!
Multiple powering in the same magnet for FQ (and more sectioning for energy)
Certainly only a first attempt: cosϑ and other shapes will be also investigated

	nominal LHC	HE-LHC
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40-45
#bunches / beam	2808	1404
bunch population [10^{11}]	1.15	1.29
initial transverse normalized emittance [μm]	3.75	3.75 (x), 1.84 (y)
number of IPs contributing to tune shift	3	2
maximum total beam-beam tune shift	0.01	0.01
IP beta function [m]	0.55	1.0 (x), 0.43 (y)
full crossing angle [μrad]	285 (9.5 $\sigma_{x,y}$)	175 (12 σ_{x0})
stored beam energy [MJ]	362	479
SR power per ring [kW]	3.6	62.3
longitudinal SR emittance damping time [h]	12.9	0.98
events per crossing	19	76
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0
beam lifetime [h]	46	13
integrated luminosity over 10 h [fb^{-1}]	0.3	0.5

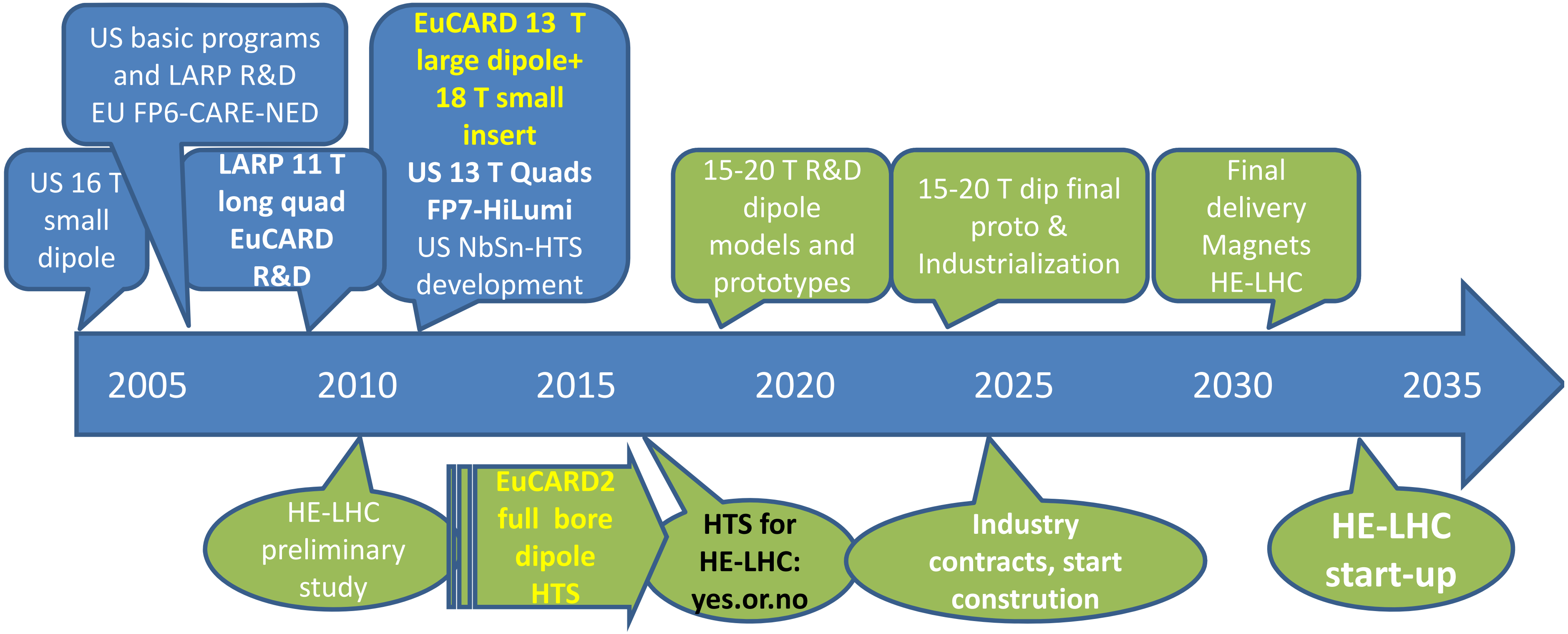
It took a long time to develop the magnets for LHC…





From L. Rossi, CERN

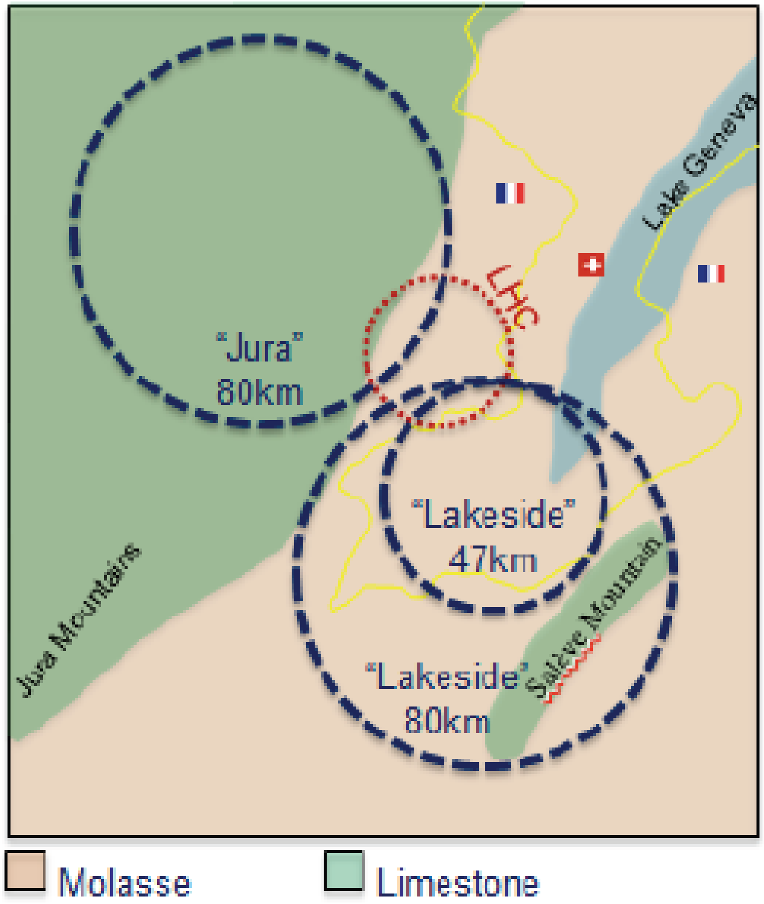
… so an intense R&D programme is required to continue rigorously now if HE-LHC should become a real option for following the HL-LHC in the 2030s

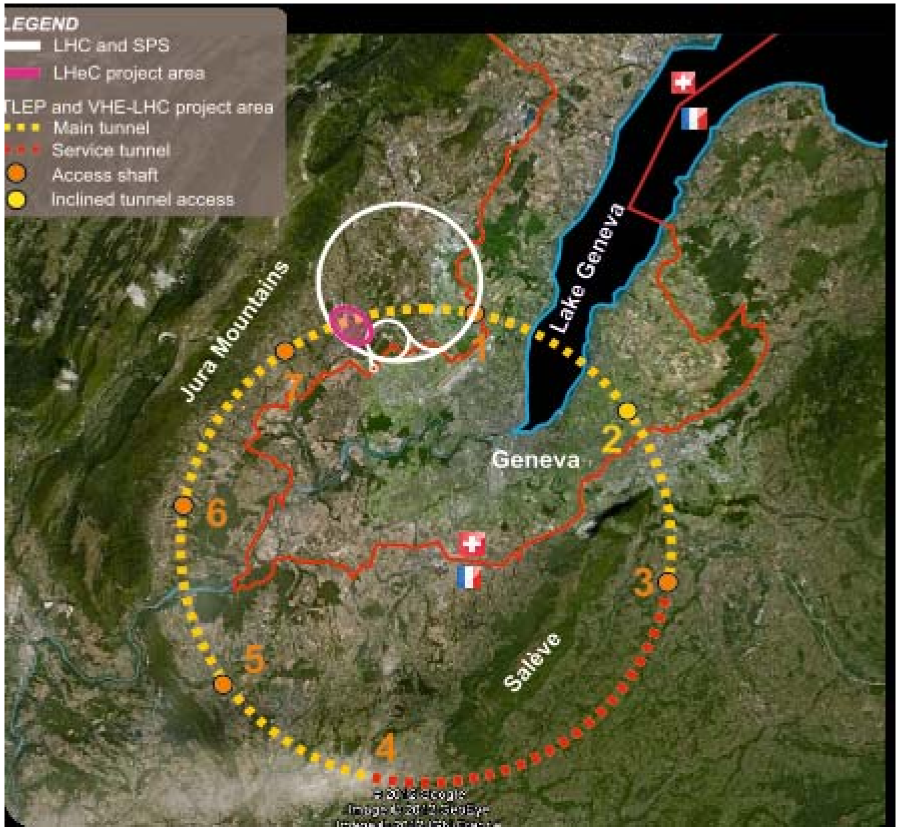


HL-LHC work as a test bed

From L. Rossi, CERN

Looking further ahead, options for a new ring tunnel



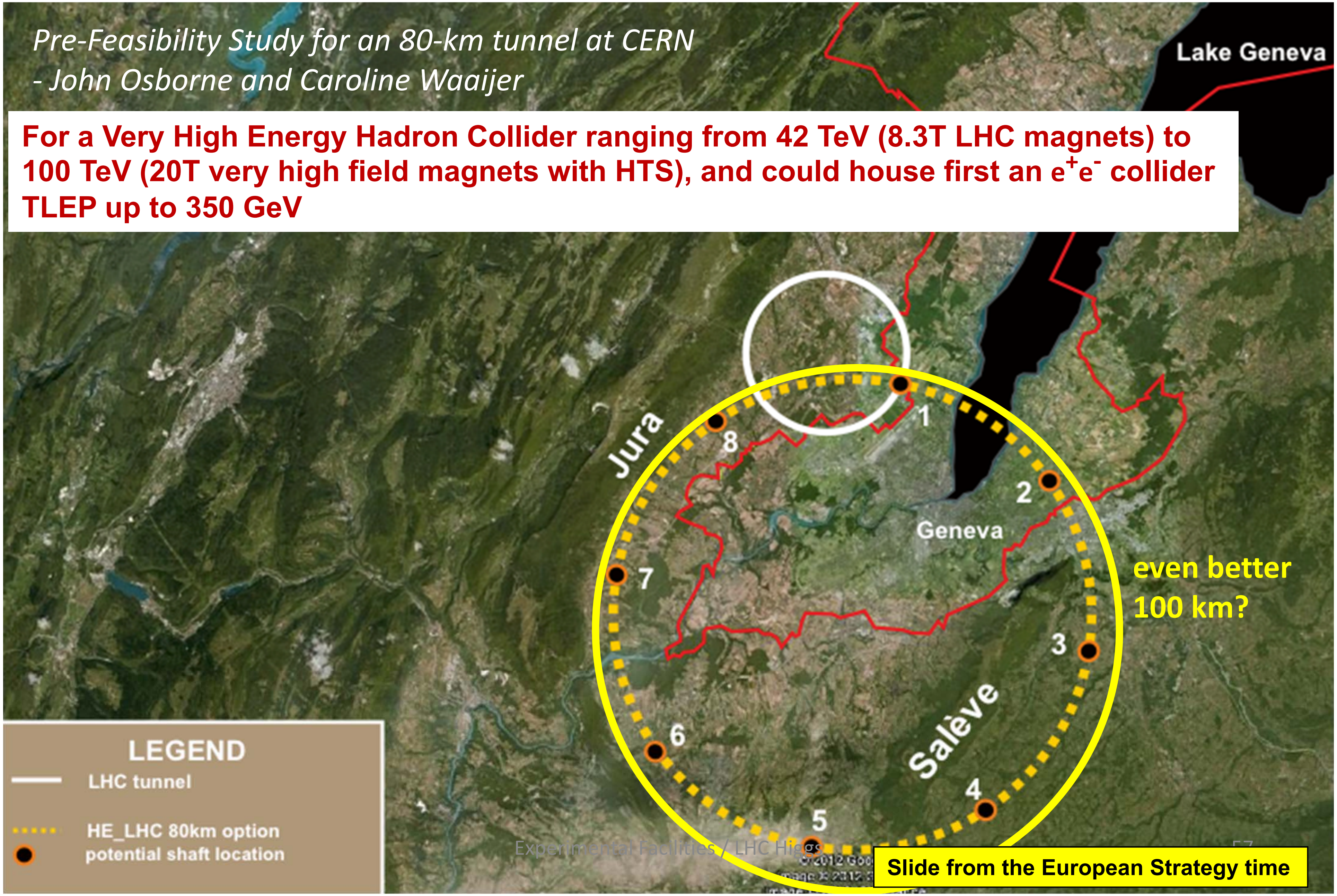


Slide from the European Strategy time

Lake-side option kept for further studies

Pre-Feasibility Study for an 80-km tunnel at CERN
- John Osborne and Caroline Waaijer

For a Very High Energy Hadron Collider ranging from 42 TeV (8.3T LHC magnets) to 100 TeV (20T very high field magnets with HTS), and could house first an e^+e^- collider TLEP up to 350 GeV



Parameters for the hadron collider 'family' at CERN

Parameter	LHC	HL-LHC		HE-LHC	VHE-LHC
c.m. energy [TeV]	14			33	100
circumference C [km]	26.7				80
dipole field [T]	8.33			20	20
dipole coil aperture [mm]	56			40	≤ 40
beam half aperture [cm]	2.2 (x), 1.8 (y)			1.3	≤ 1.3
injection energy [TeV]	0.45			>1.0	>3.0
no. of bunches	2808	2808	1404	2808	8420
bunch population [10^{11}]	1.125	2.2	3.5	0.81	0.80
init. transv. norm. emit. [μm]	3.73,	2.5	3.0	1.07	1.70
initial longitudinal emit. [eVs]	2.5			3.48	13.6
no. IPs contributing to tune shift	3	2	2	2	2
max. total beam-beam tune shift	0.01	0.021	0.028	0.01	0.01
beam circulating current [A]	0.584	1.12	0.089	0.412	0.401
RF voltage [MV]	16			16	22
rms bunch length [cm]	7.55			7.55	7.55
IP beta function [m]	0.55	$0.73 \rightarrow 0.15$		0.3	0.9
init. rms IP spot size [μm]	16.7	$15.6 \rightarrow 7.1$	$24.8 \rightarrow 7.8$	4.3	5.3

Stored energy [MJ]	362	694	601	4573
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1	(7.4)	5	5

O.Dominguez, L.Rossi, F.Zimmermann

Collider options for the high energy frontier

pp colliders

	Years	E_{cm} TeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Int. Luminosity fb^{-1}
Design LHC	2014-21	14	1-2	300
HL-LHC	2024-30	14	5	3000
HE-LHC	>2035	26-33*	2	100-300/y
V-LHC**	>2035	42-100		

* 16-20 T dipole field
** 80 km Tunnel

e+e- colliders

	Years	E_{cm} GeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Tunnel length km
ILC 250	<2030	250	0.75	
ILC 500		500	1.8	~30
ILC 1000		1000		~50
CLIC 500	>2030	500	2.3(1.3)	~13
CLIC 1400		1400(1500)	3.2(3.7)	~27
CLIC 3000		3000	5.9	~48
LEP3	>2024	240	1	LEP/LHC ring
TLEP	>2030	240	5	80 (ring)
TLEP		350	0.65	80 (ring)

Other options:

$\mu^+\mu^-$ and $\gamma\gamma$ colliders with similar physics as e^+e^- colliders

LHeC for ep collisions

Slide from the European Strategy time

international linear collider

ES Open Symp. Contr. ID=73,
ES Open Symp. Contr. ID=121

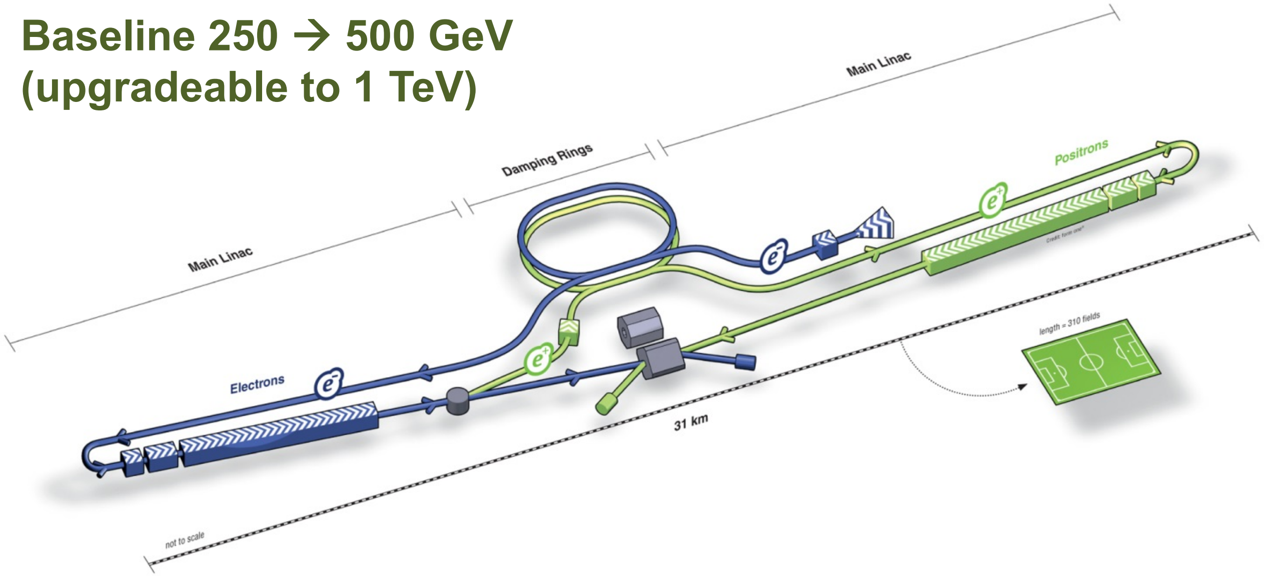
Mature detailed TDR studies based on extensive R&D

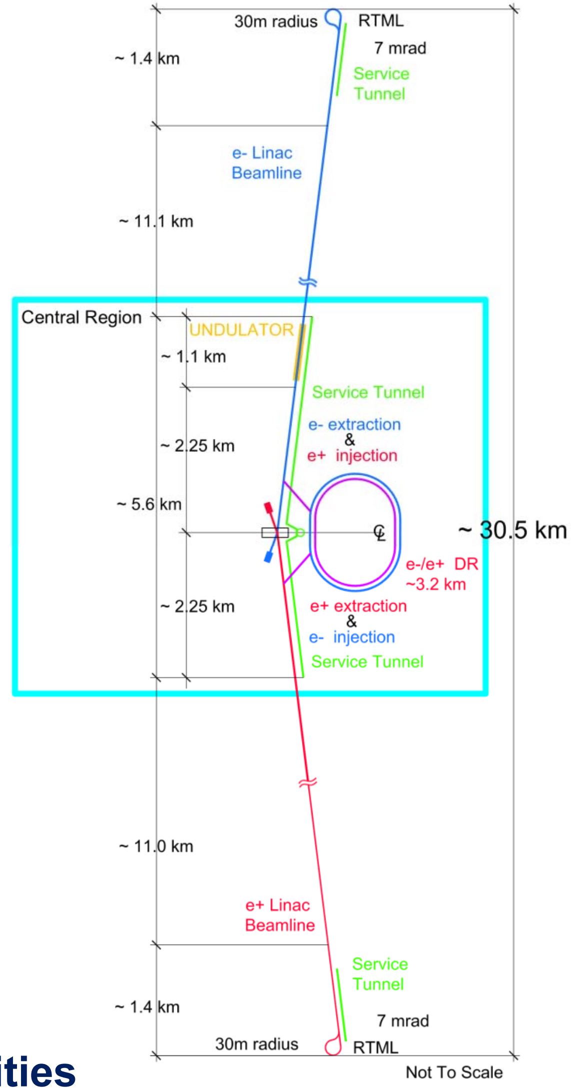
Industrial production of cavities (established for XFEL)

Major Japanese community initiative to host ILC as a global project

Goal to start data taking before 2030

Baseline 250 → 500 GeV (upgradeable to 1 TeV)





Two single beam linacs with 40 MV/m superconducting RF cavities

ilc international linear collider

Mature detailed TDR studies based on extensive R&D

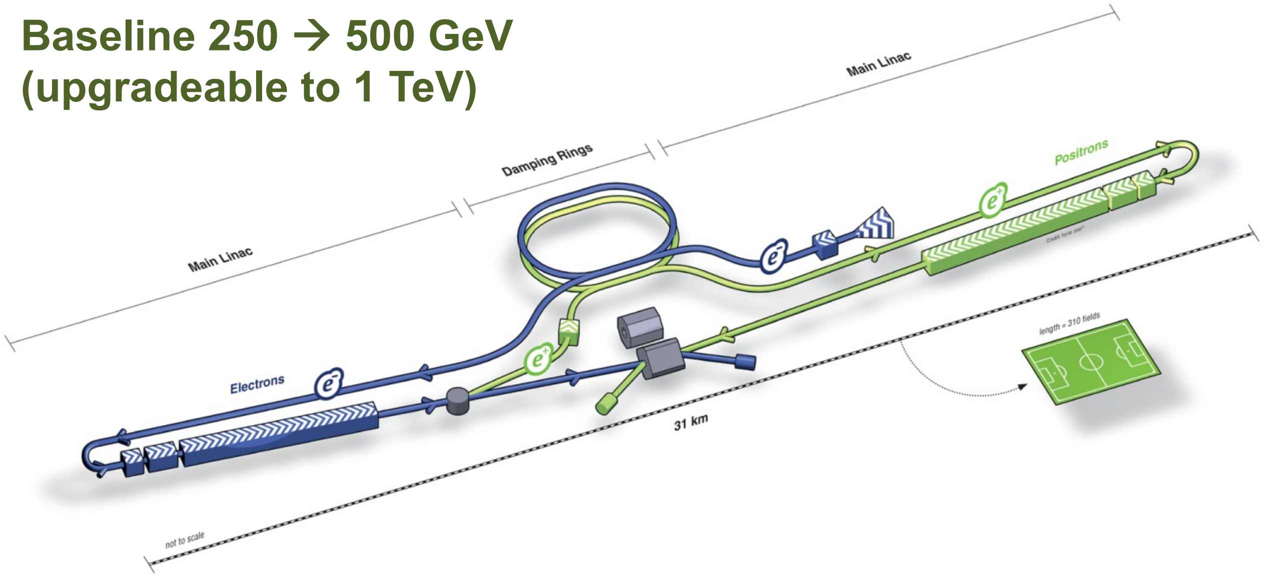
Industrial production of cavities (established for XFEL)

Major Japanese community initiative to host ILC as a global project

Goal to start data taking before 2030

Baseline 250 → 500 GeV (upgradeable to 1 TeV)

Kitakami mountain site selected (strong and stable granite bedrock)



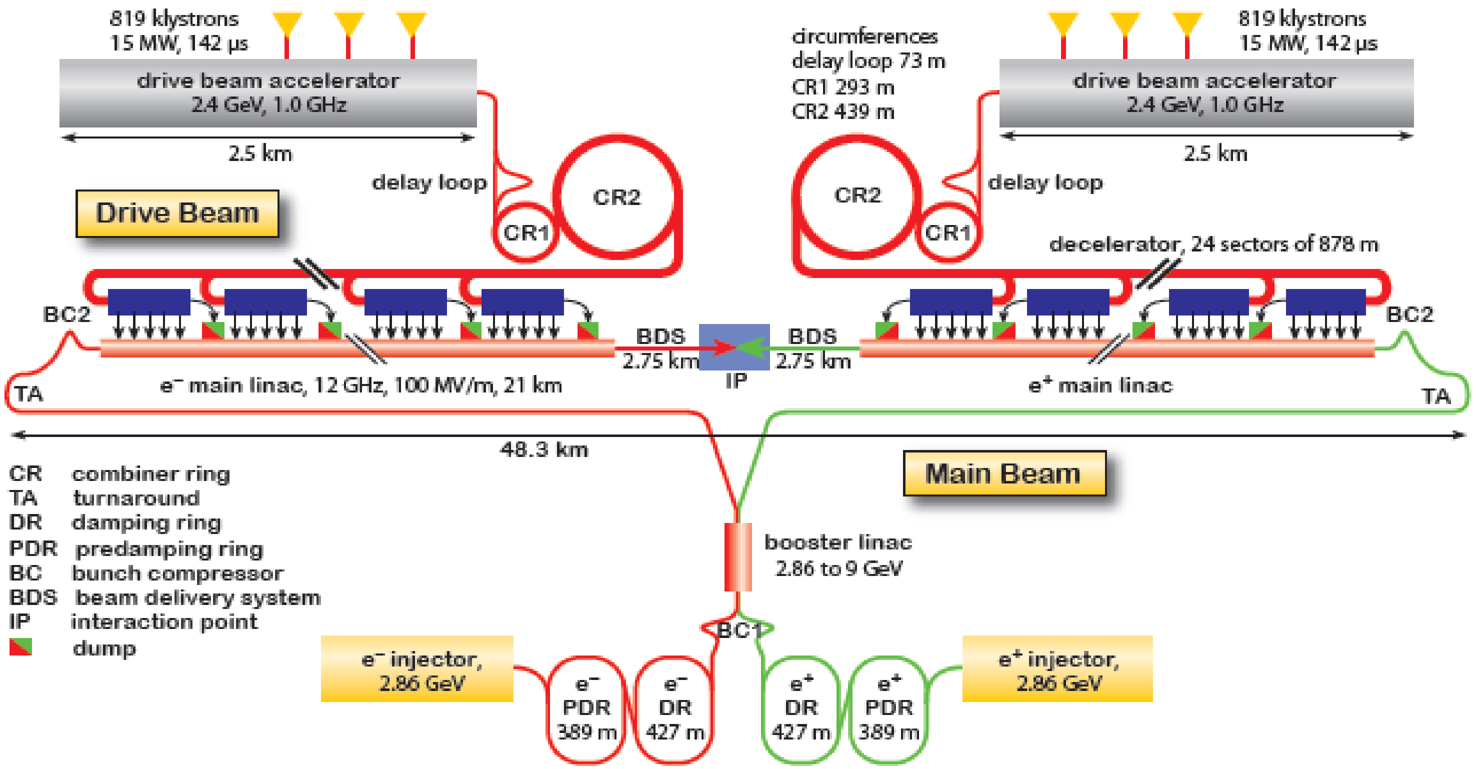
Two single beam linacs with 40 MV/m superconducting RF cavities

Compact Linear Collider CLIC

Detailed CDR studies based on extensive R&D

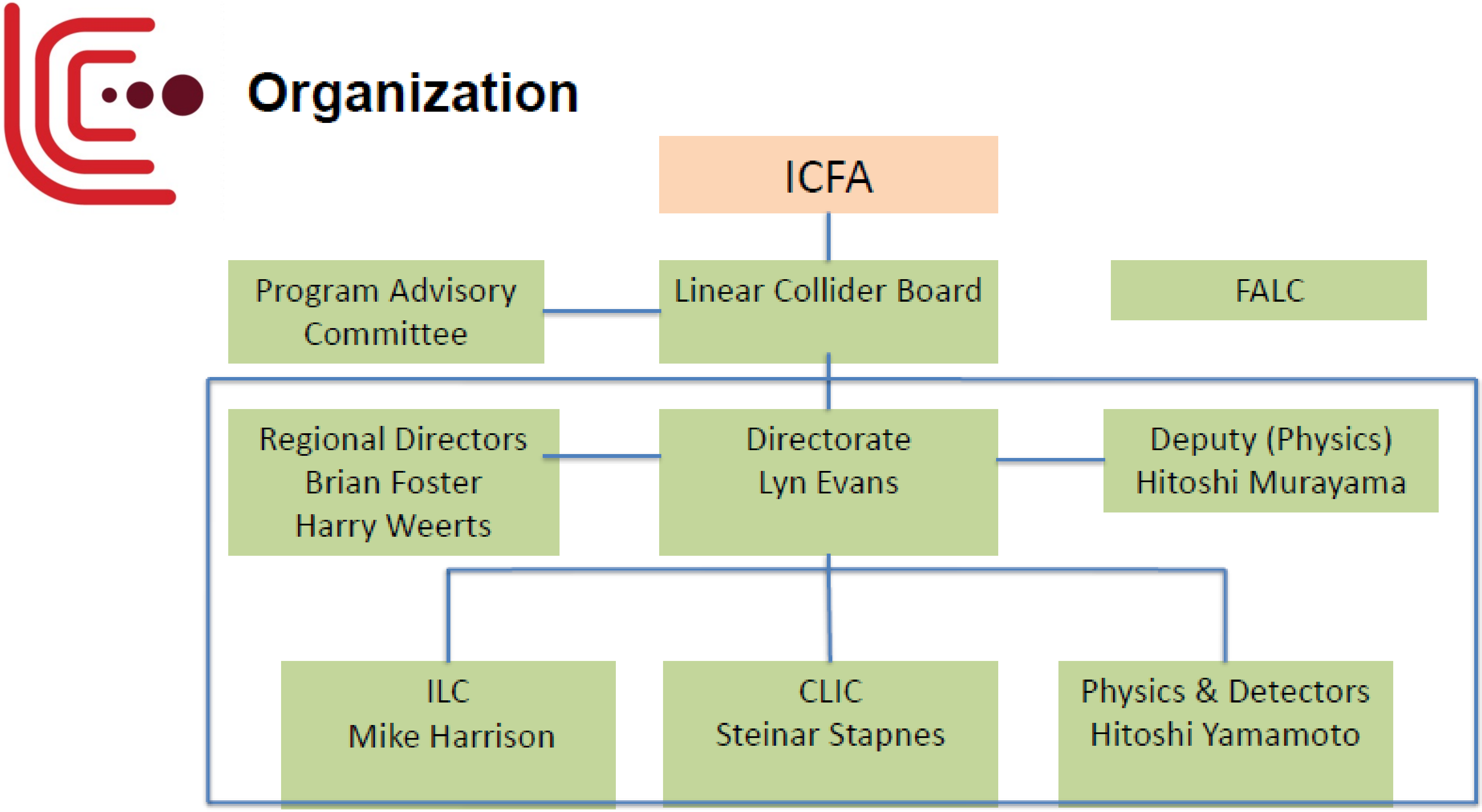
Prove of principle of the two-beam acceleration

ES Open Symp. Contr. ID=99

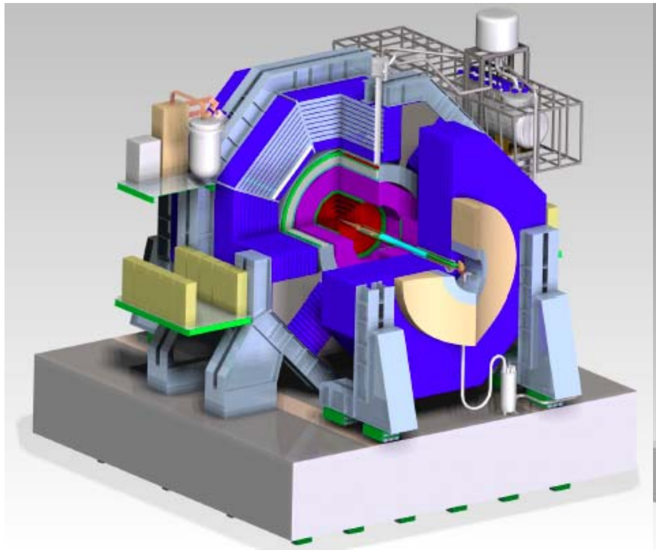
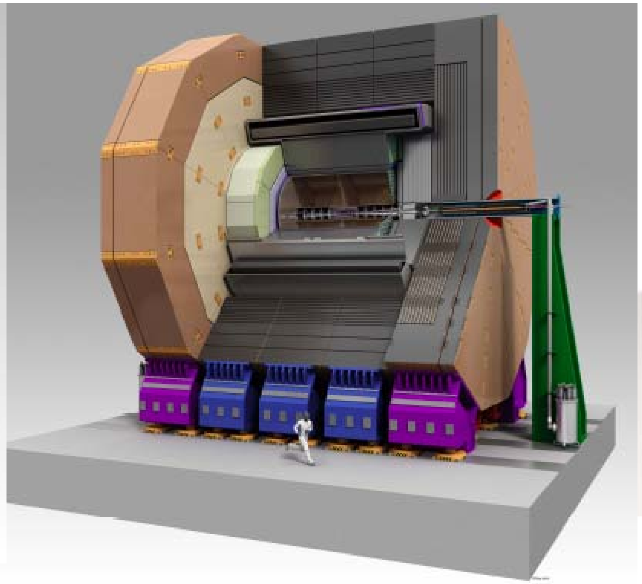
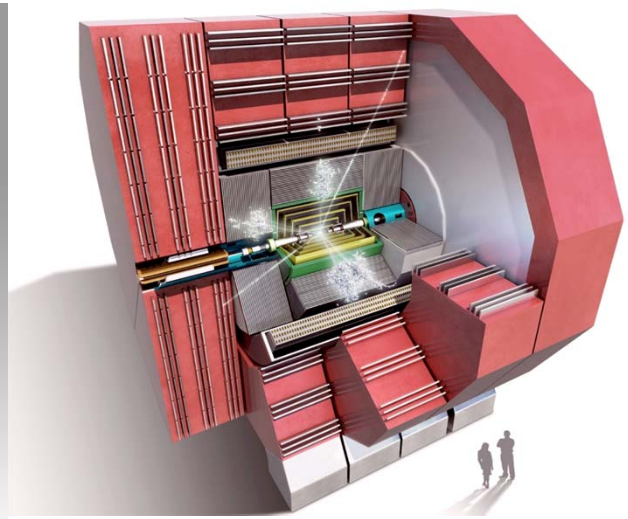


Two-beam acceleration system with a low energy high current drive beam powering the RF cavities at 100 MV/m of the main linac, energy upgradable in stages 500 – 3000 GeV

Common organization within the Linear Collider Collaboration has been set in place recently



Linear Collider Detectors

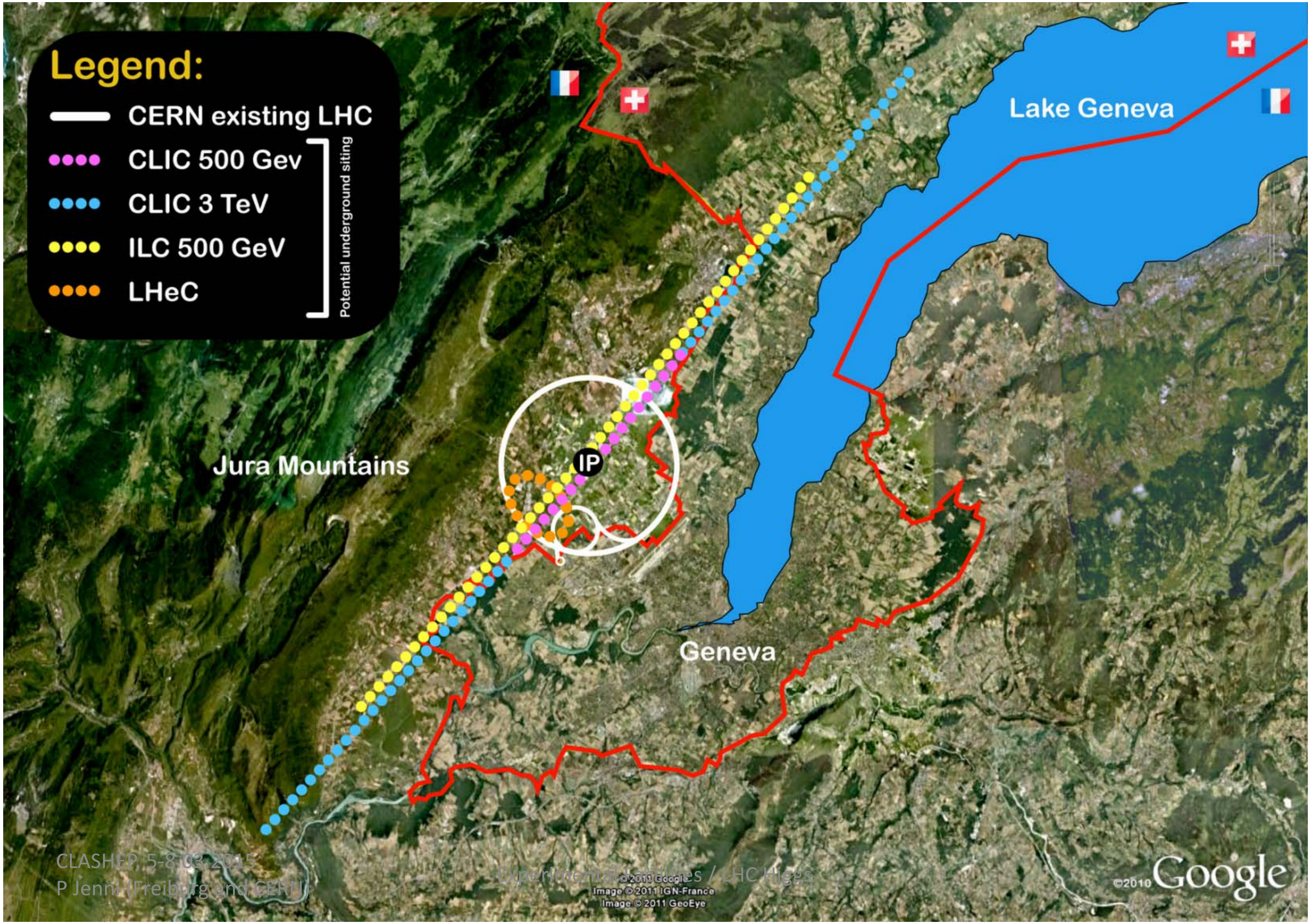




Main activities since publication of CLIC CDR (2012) and ILC DBD (2013)

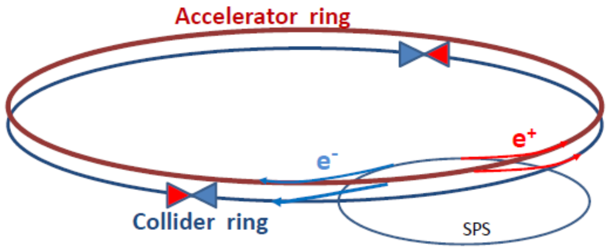
- **Detector R&D (fine-grained calorimetry, pixel R&D, TPC tracking)**
- **Detector optimisation**
  - **Optimise performance, integrate R&D knowledge, reduce occupancies and cost**
- **Physics studies**
  - **Precision Higgs physics**
  - **Precision Top physics**
  - **BSM physics**

Indicating the Scale for Liner Colliders

(Taken from C. Biscari, 'High Energy Accelerators', Krakow ES Symposium)



Circular e+e- Colliders



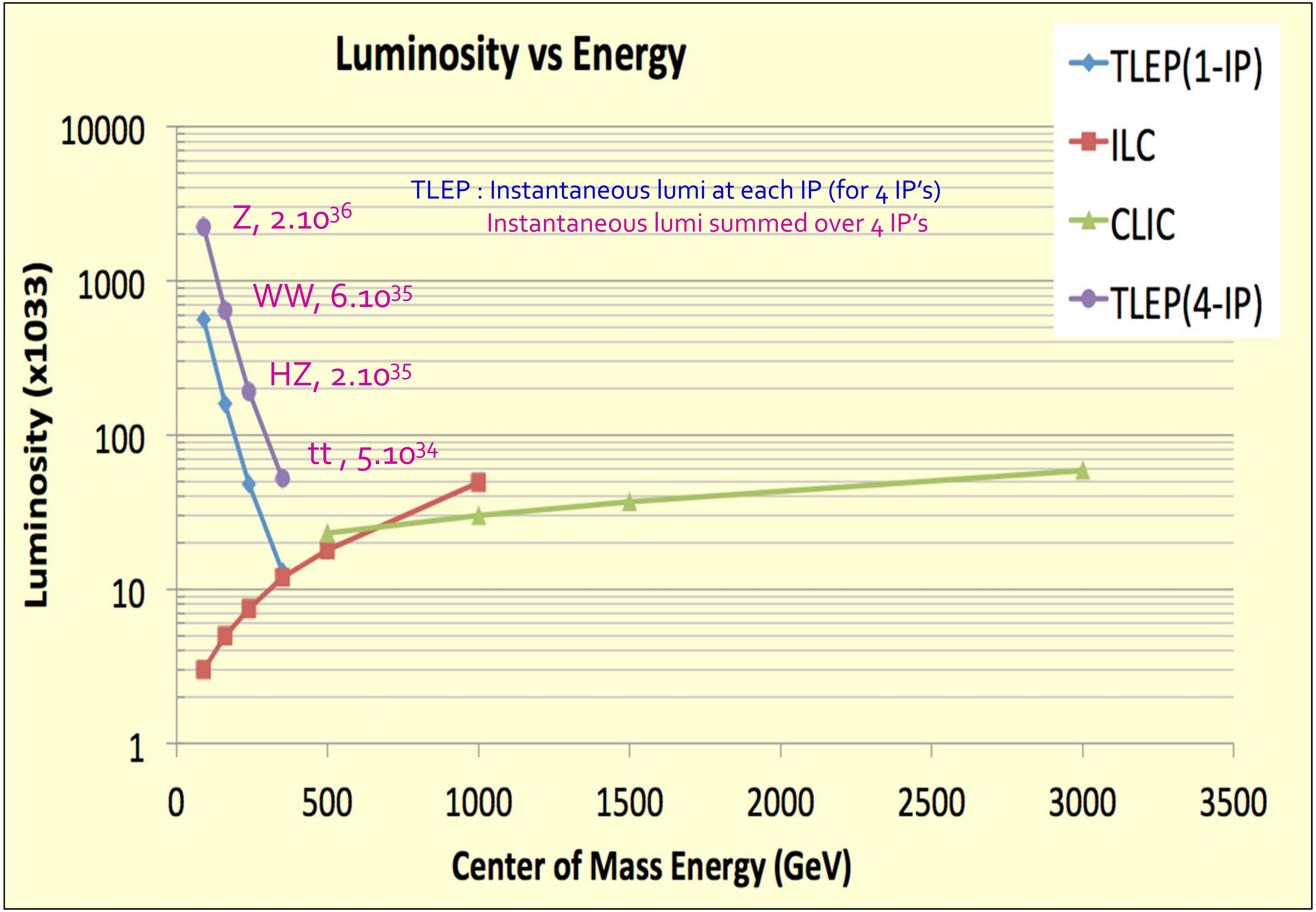
Strong revival of interest in 'conventional' Circular Colliders:

- **Very high luminosities achievable**
- **More than one experiment**

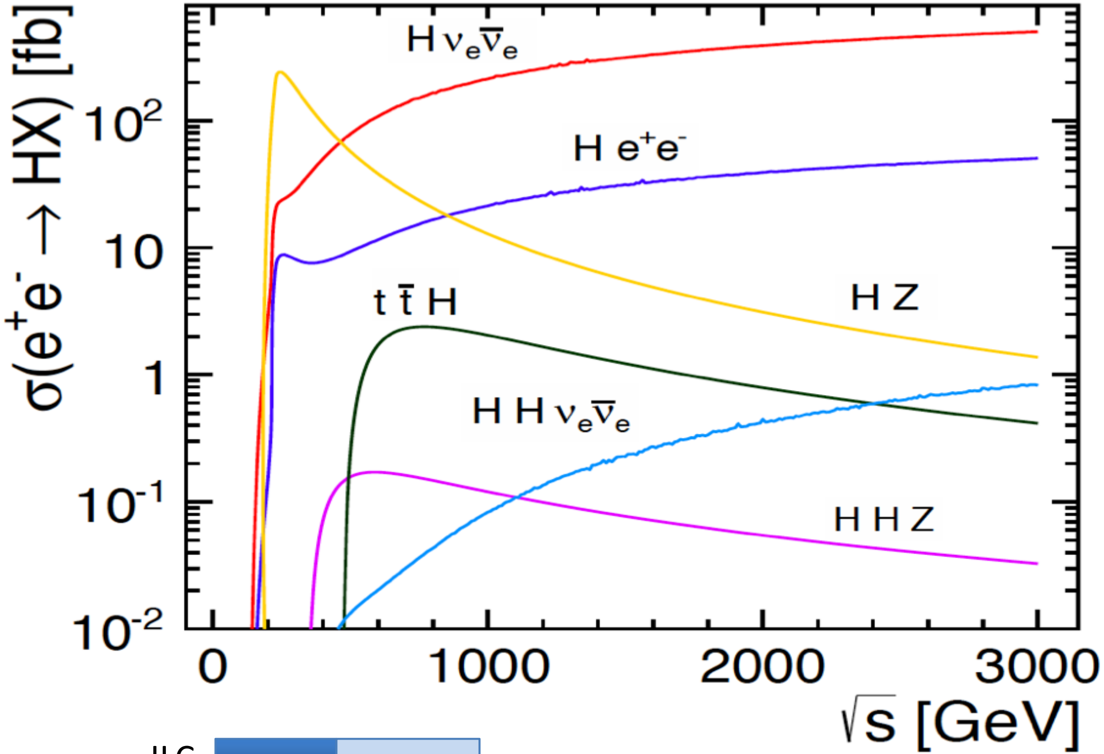
LEP3: 240 GeV machine in the LHC tunnel
TLEP: 350 GeV machine in a new 80-100 km tunnel

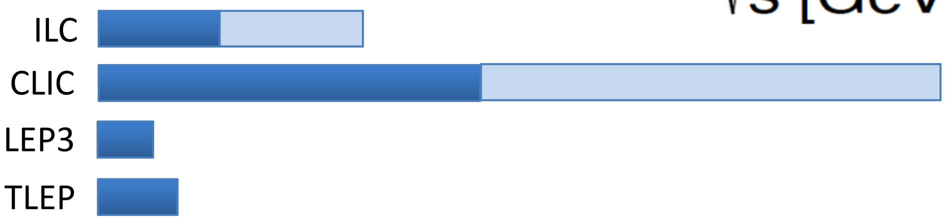
	LEP3	TLEP
circumference	26.7 km	80 km
max beam energy	120 GeV	175 GeV
max no. of IPs	4	4
luminosity at 350 GeV c.m.	-	0.7×10^{34} cm^{-2}s^{-1}
luminosity at 240 GeV c.m.	10^{34} cm^{-2}s^{-1}	5×10^{34} cm^{-2}s^{-1}
luminosity at 160 GeV c.m.	5×10^{34} cm^{-2}s^{-1}	2.5×10^{35} cm^{-2}s^{-1}
luminosity at 90 GeV c.m.	2×10^{35} cm^{-2}s^{-1}	10^{36} cm^{-2}s^{-1}

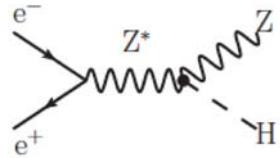
Slide from the European Strategy time


Luminosity vs Energy
TLEP(1-IP)
ILC
CLIC
TLEP(4-IP)
TLEP : Instantaneous lumi at each IP (for 4 IP's)
Instantaneous lumi summed over 4 IP's
Z, 2.10^36
WW, 6.10^35
HZ, 2.10^35
tt , 5.10^34
Luminosity (x1033)
10000
1000
100
10
1
0
500
1000
1500
2000
2500
3000
3500
Center of Mass Energy (GeV)

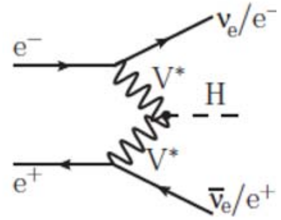
Precision Higgs measurements at e+e-



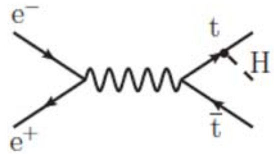




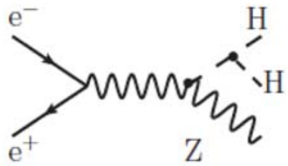
Mass
g_Z (m.i.)
BR´s
(LHC)-invisible



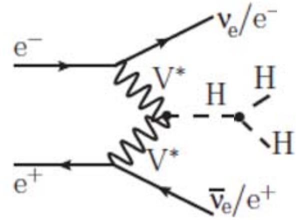
Γ_{tot}



g_t (ILC,CLIC)



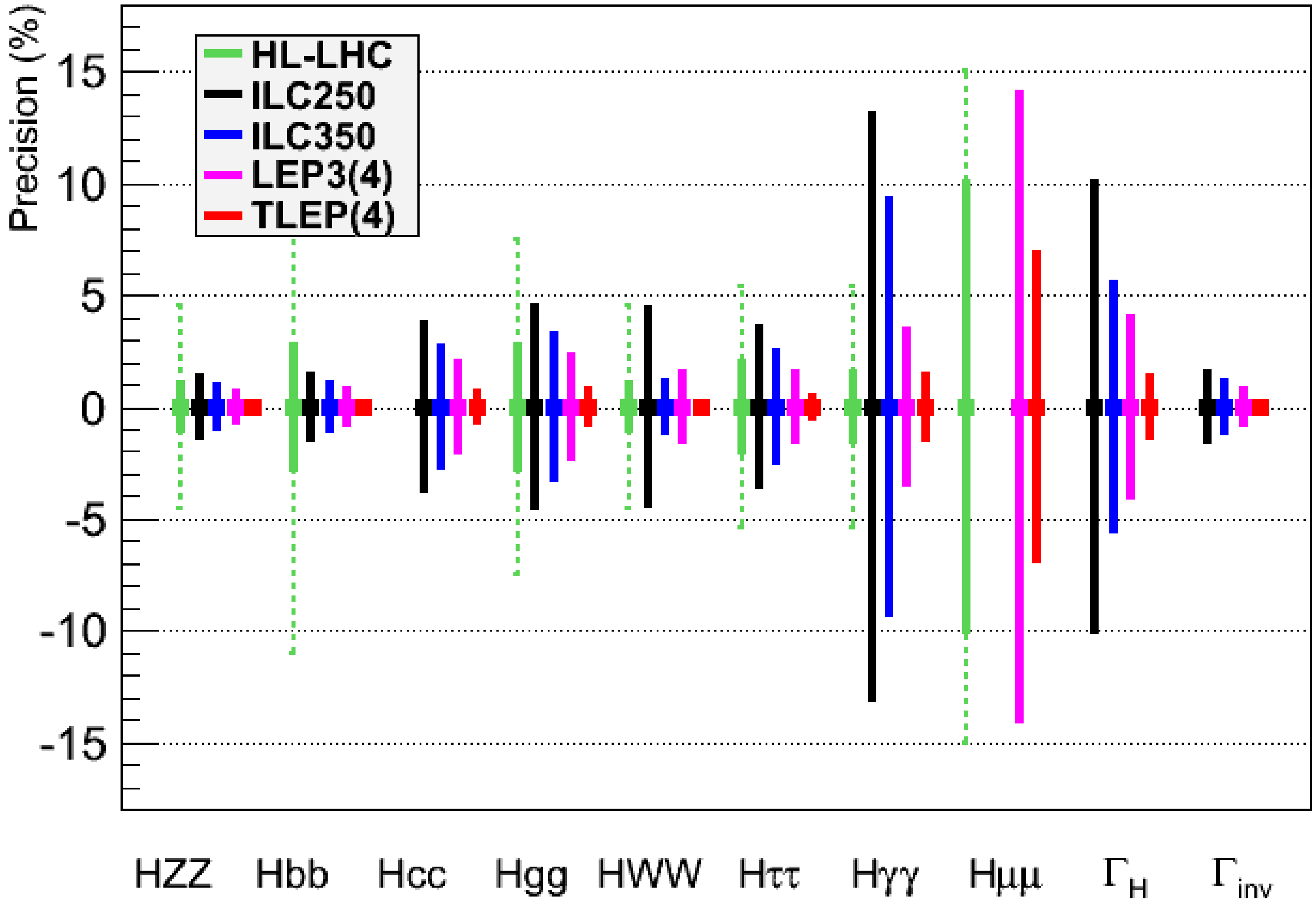
g_{HHH} (ILC500)



g_{HHH} (ILC1000, CLIC)

Many processes at different √s needed & accessible
HZ (at 250-350 GeV): recoil mass as anchor for model-independence

Tentative Higgs coupling summary



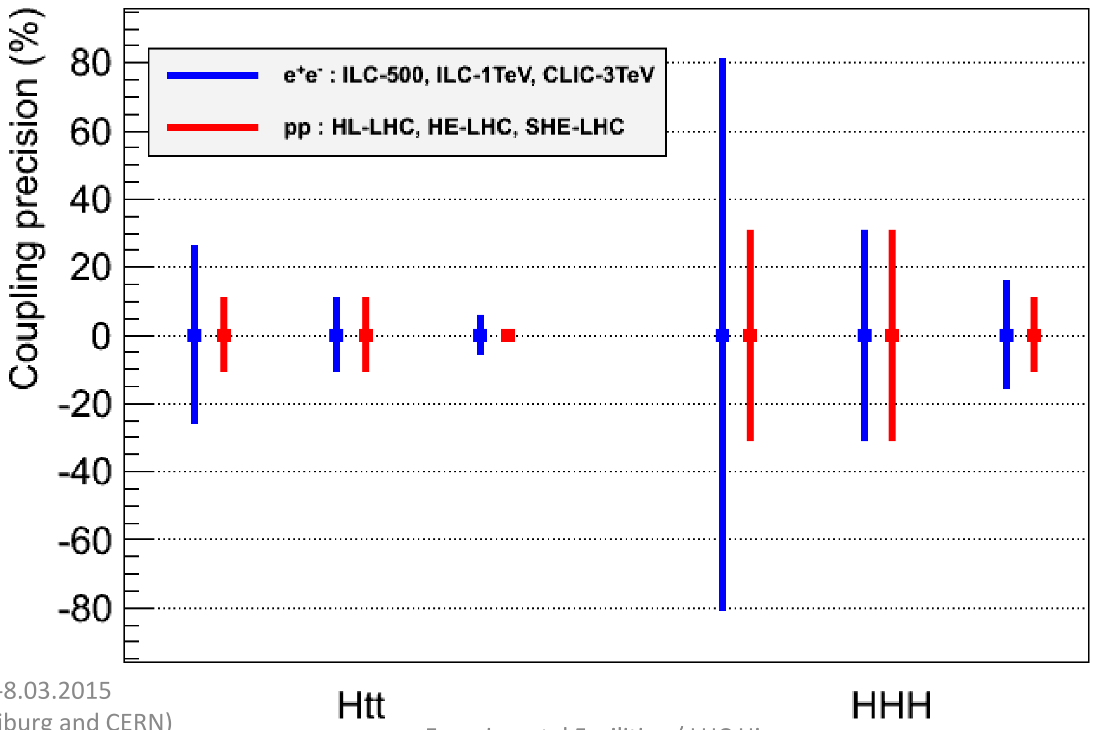
P Janot, TLEP

Looking even further ahead for Higgs couplings…

	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

Cross-section ratios at pp colliders w.r.t. the 14 TeV LHC

ES Open Symp. Contr. ID=176

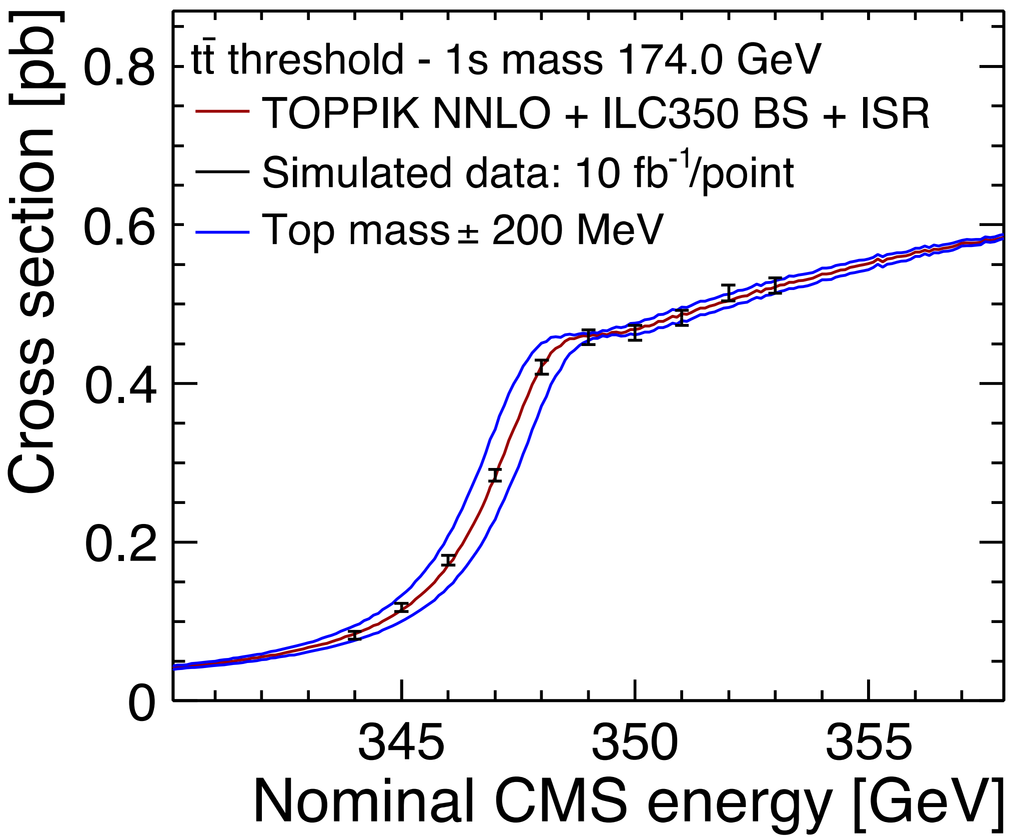


Ultimate precisions for Htt and HHH couplings for three generations of e+e- (blue) and pp (red) colliders

P Janot, TLEP

There are many examples of e+e- precision measurements to test the consistency and stability of the Standard Model

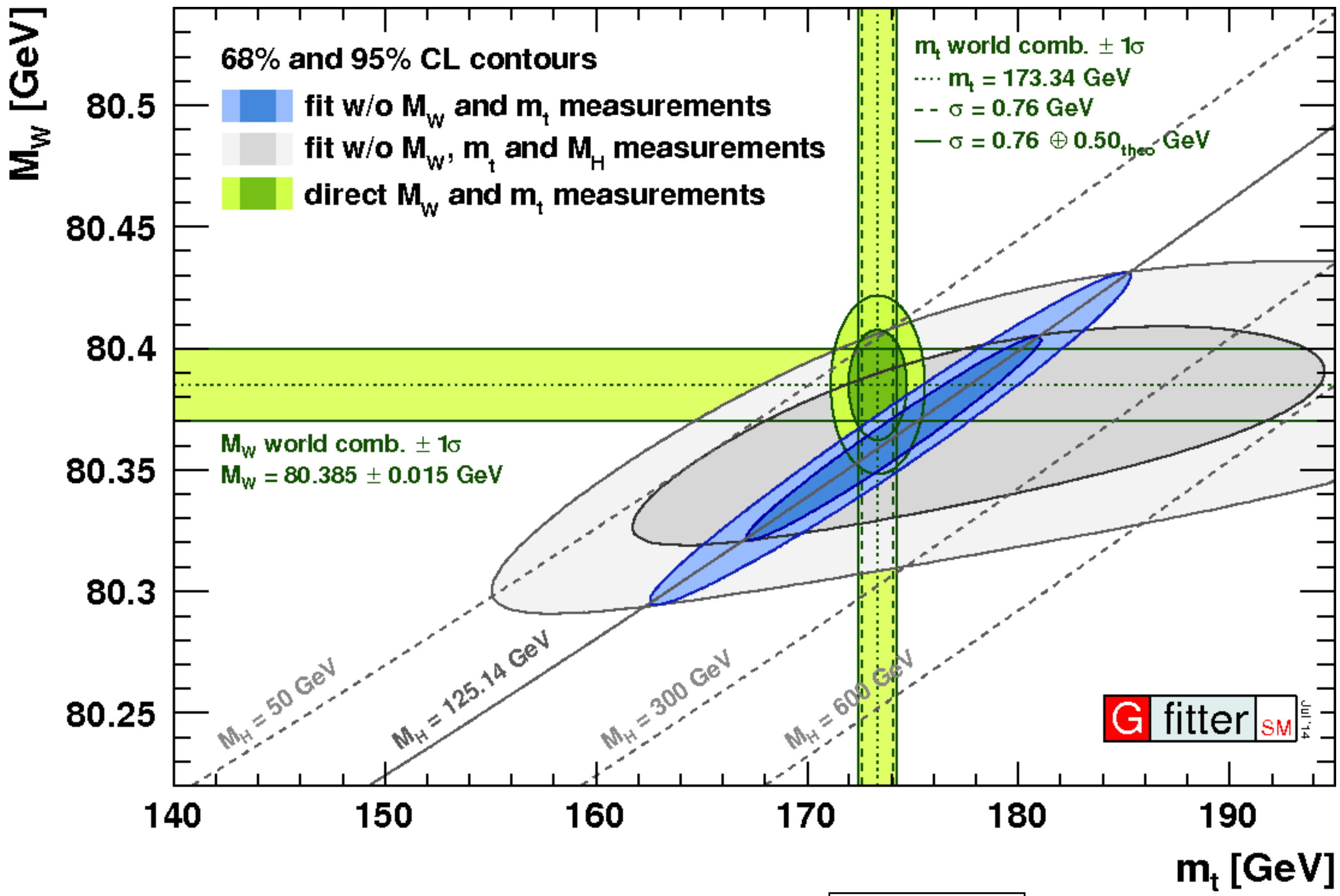
Prime example is the top mass measurement



- **Δm_{top} = 20 MeV (stat.)**
  100 MeV (theo.)
- **$\Delta\Gamma_{top}$ = 30 MeV**

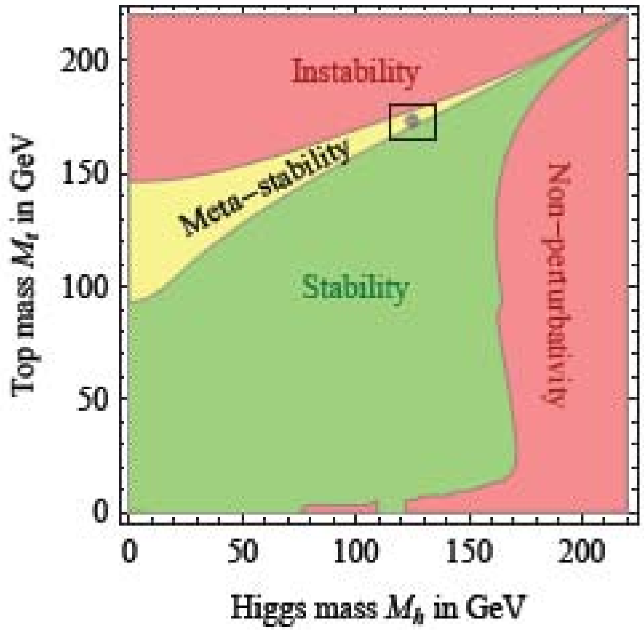
ES Open Symp. Contr. ID=69

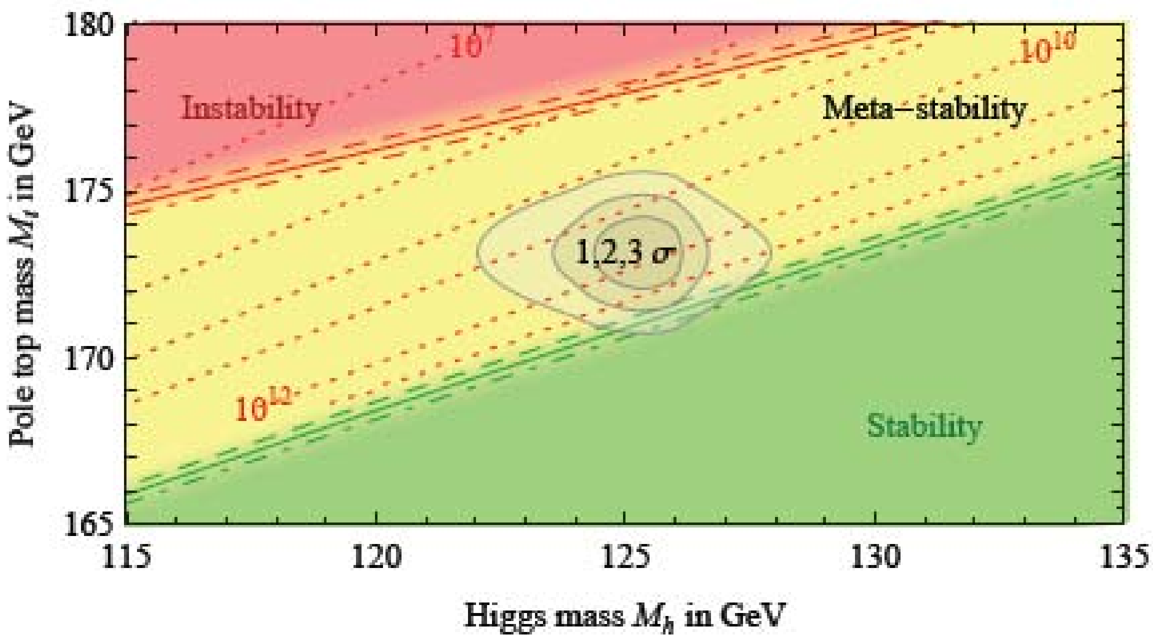
Test further the consistency of the SM w.r.t. the present situation



Gfitter group

Test further the vacuum stability of the SM w.r.t. the present situation





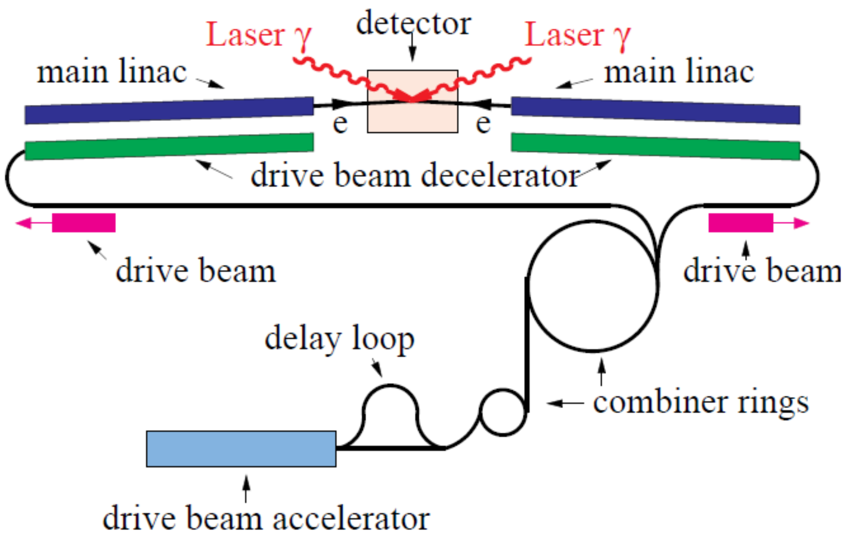
G Degrassi et al
arXiv: 1205.6497v1[hep-ph]

Examples of other (high energy) colliders that are/were discussed in the HEP community

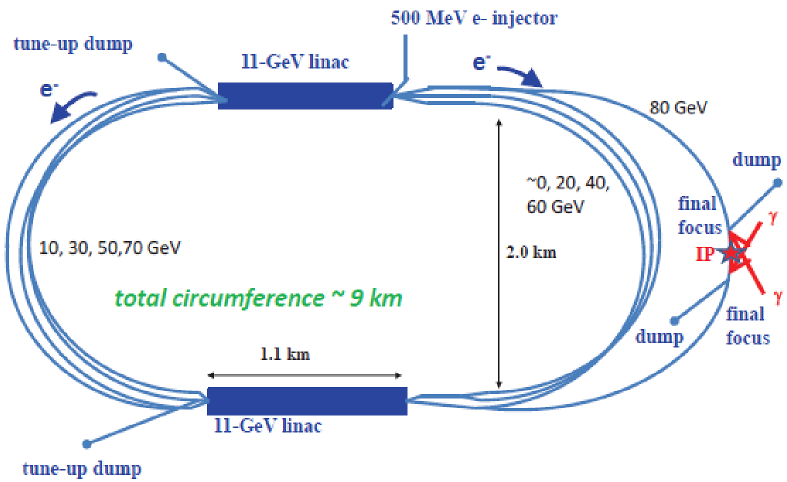
γγ collider options

Technology challenge of a high-power laser back-scatter system

CLIC technology based



SAPPHiRE
'a small γγ Higgs factory'

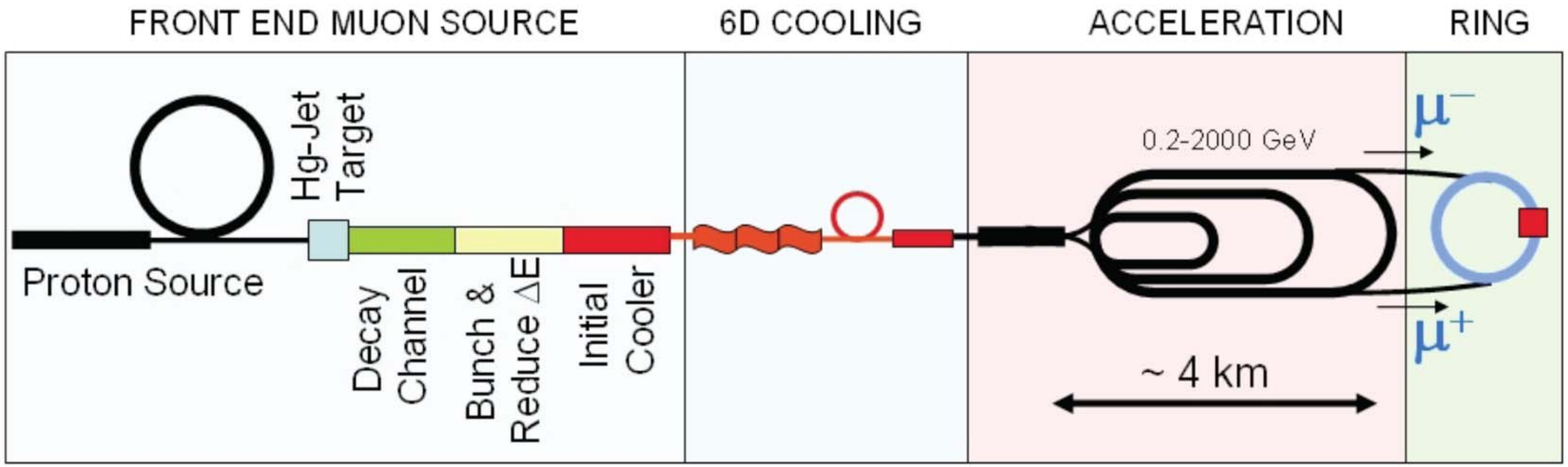


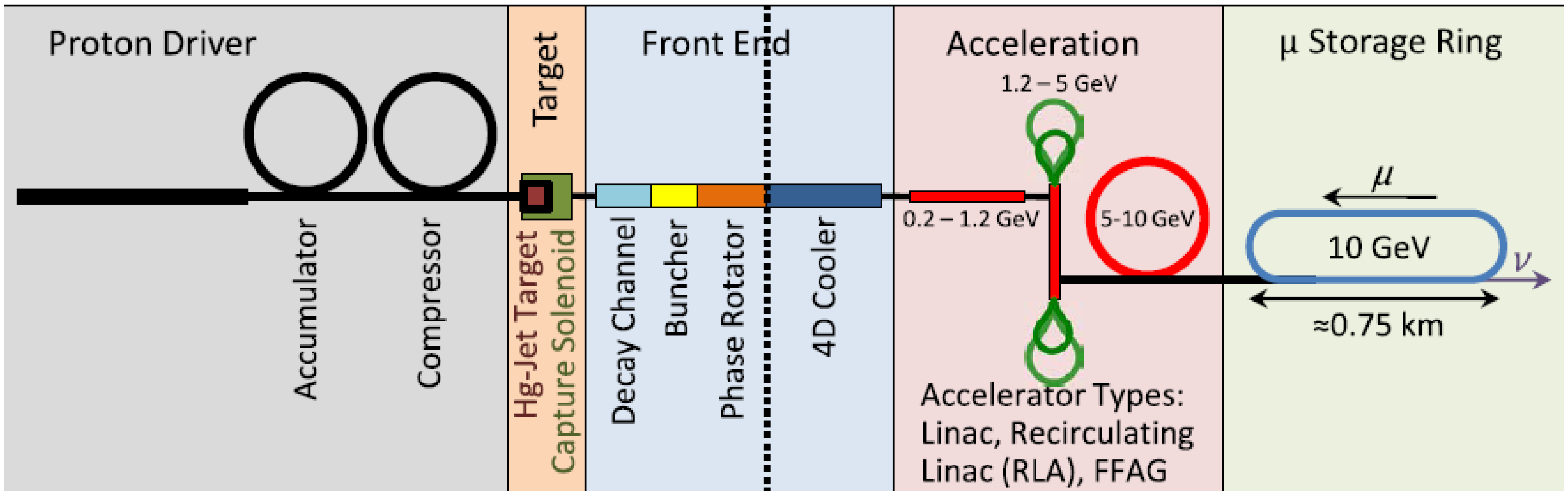
γγ collisions at Vs = 125.5 GeV (s-channel Higgs production)

ES Open Symp. Contr. ID=145

Muon Collider / Neutrino Factory

Many technical challenges, interesting potential (s-channel H production)

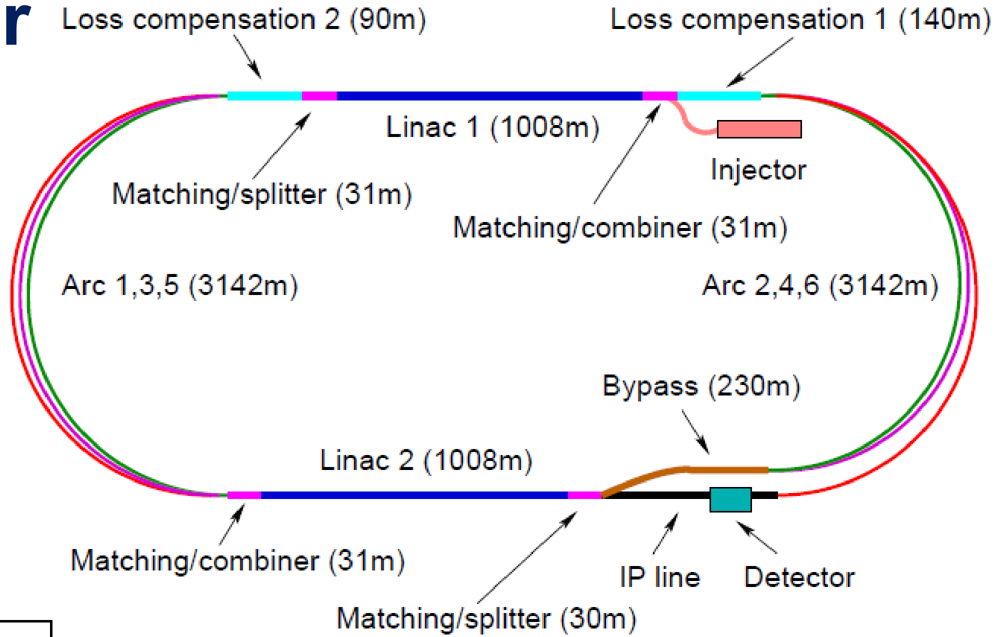




Electron Proton Collider

Detailed CDR has been published

Option of eA collisions



parameter [unit]	LHeC	
species	e	p, $^{208}Pb^{82+}$
beam energy (/nucleon) [GeV]	60	7000, 2760
bunch spacing [ns]	25, 100	25, 100
bunch intensity (nucleon) [10^{10}]	0.1 (0.2), 0.4	17 (22), 2.5
beam current [mA]	6.4 (12.8)	860 (1110), 6
rms bunch length [mm]	0.6	75.5
polarization [%]	90 (e^+ none)	none, none
normalized rms emittance [μm]	50	3.75 (2.0), 1.5
geometric rms emittance [nm]	0.43	0.50 (0.31)
IP beta function $\beta^*_{x,y}$ [m]	0.12 (0.032)	0.1 (0.05)
IP spot size [μm]	7.2 (3.7)	7.2 (3.7)
synchrotron tune Q_s	—	1.9×10^{-3}
hadron beam-beam parameter	0.0001 (0.0002)	
lepton disruption parameter D	6 (30)	
crossing angle	0 (detector-integrated dipole)	
hourglass reduction factor H_{hg}	0.91 (0.67)	
pinch enhancement factor H_D	1.35 (0.3 for e^+)	
CM energy [TeV]	1.3, 0.81	
luminosity / nucleon [10^{33} cm^{-2}s^{-1}]	1 (10), 0.2	

Interaction point 2 (now ALICE) with LHC

Two 10 GeV linac accelerators in an energy recovery race-track configuration, three turns giving 60 GeV e$^-$ or e+

Can reach Q^2_{max} ~ 1 TeV^2

ES Open Symp. Contr. ID=147, 156, 175

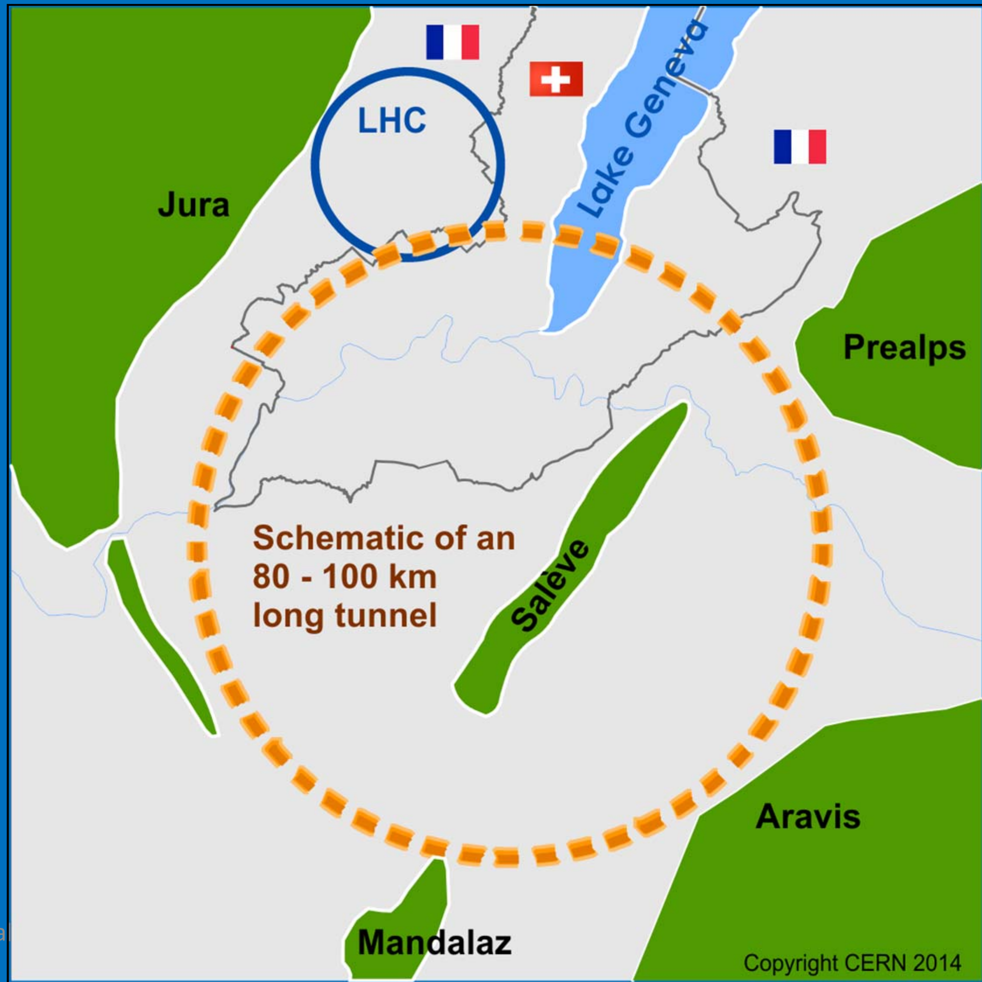
Recent developments, that may hopefully become experimental facilities in the decades to come…

A very exciting dream for a facility in Europe:

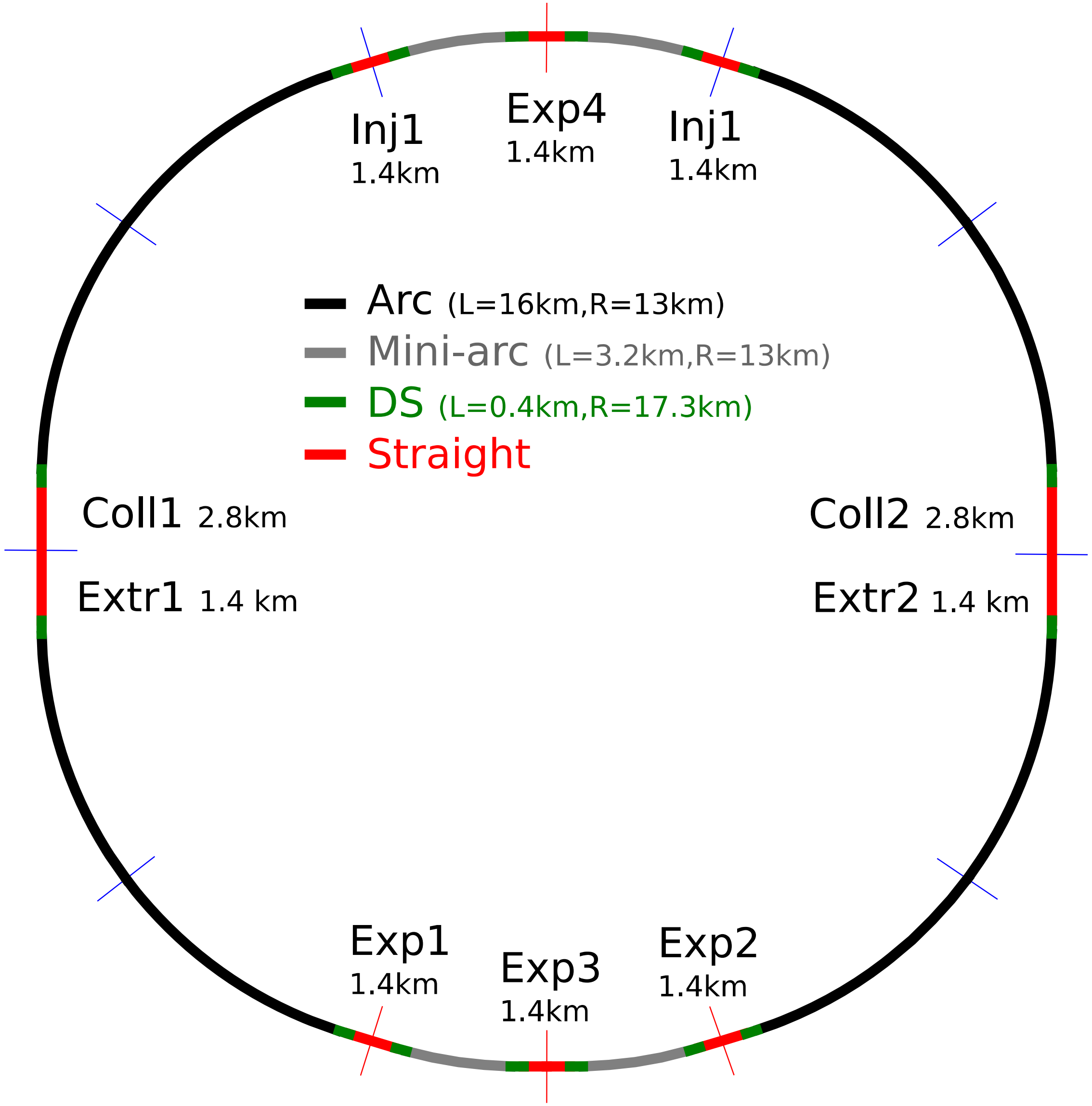
80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements (FCC-hh)

with possibility of e+-e- (FCC-ee) and p-e (FCC-he)

For a Very High Energy Hadron Collider ranging from 42 TeV (8.3T LHC magnets) to 100 TeV (20T very high field magnets with HTS), and could house first an e^+e^- collider up to 350 GeV



A possible FCC-hh ring configuration that is being studied

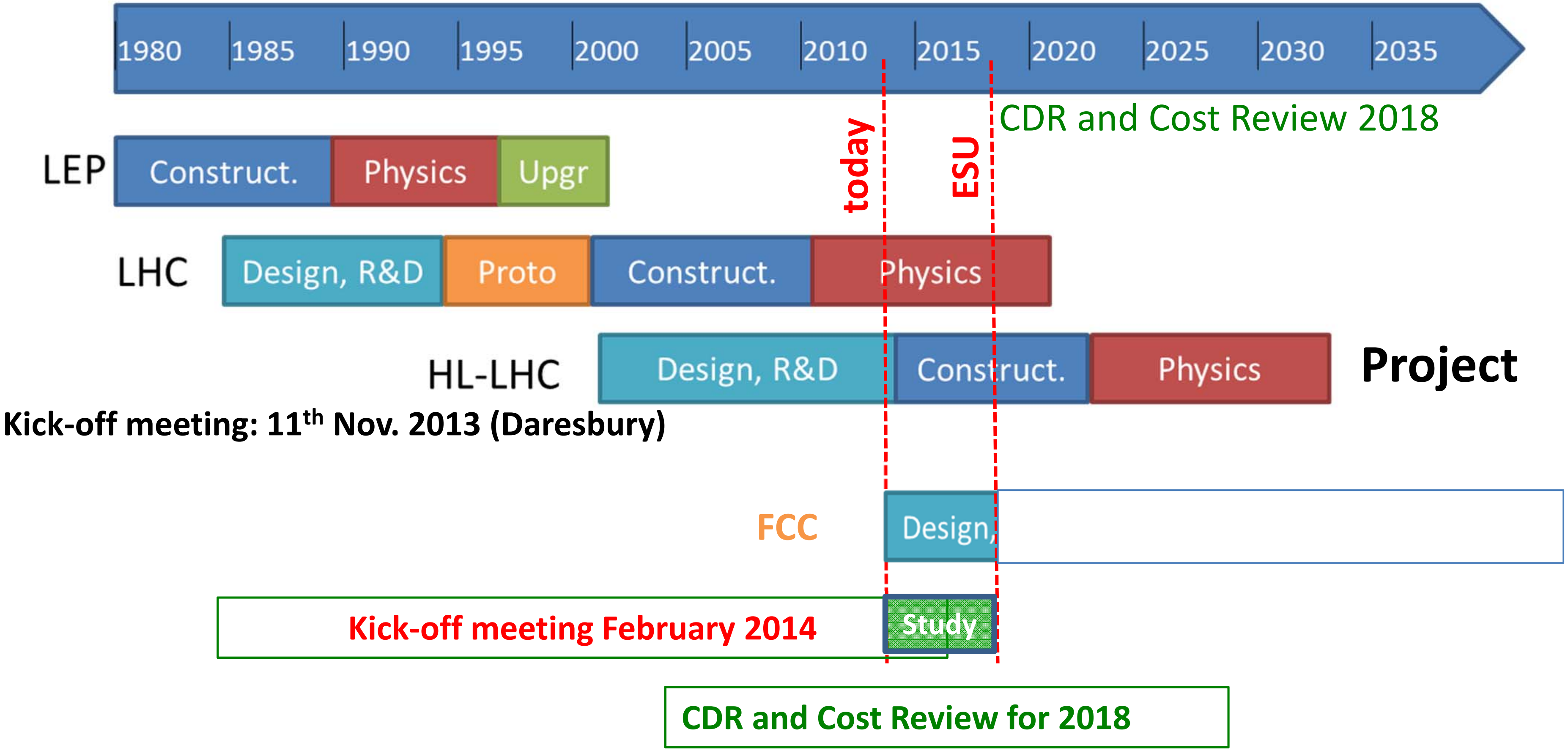


FCC Study Time Line

Explore options, now – spring 2015:

- Investigate **different options** in all technical areas, **taking a broad view**
- Deliverables: description/comparison of options with relative merits/cost, **understand relative impact of options on overall study/project**
- FCC workshop to converge to common baseline with small number of options
- **1st Yearly FCC Workshop 23 – 27 March 2015, Washington DC**
- Followed by review ~2 months later, begin June 2015

CERN roadmap and FCC planning



FCC-ee Key Parameters

Parameter	FCC-ee	LEP2
Energy/beam	45 – 175 GeV	105 GeV
Bunches/beam	**98 – 16700**	4
Beam current	**6.6 – 1450 mA**	3 mA
Luminosity/IP	**1.8-28** x 10^{34} $cm^{-2}s^{-1}$	0.0012 x 10^{34} $cm^{-2}s^{-1}$
Energy loss/turn	0.03-7.55 GeV	3.34 GeV
Synchr. power	**100 MW**	22 MW
RF Voltage	2.5 – **11 GV**	3.5 GV

Preliminary, subject to evolution

FCC-hh Key Parameters

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

Preliminary, subject to evolution

Machine protection is a major issue !

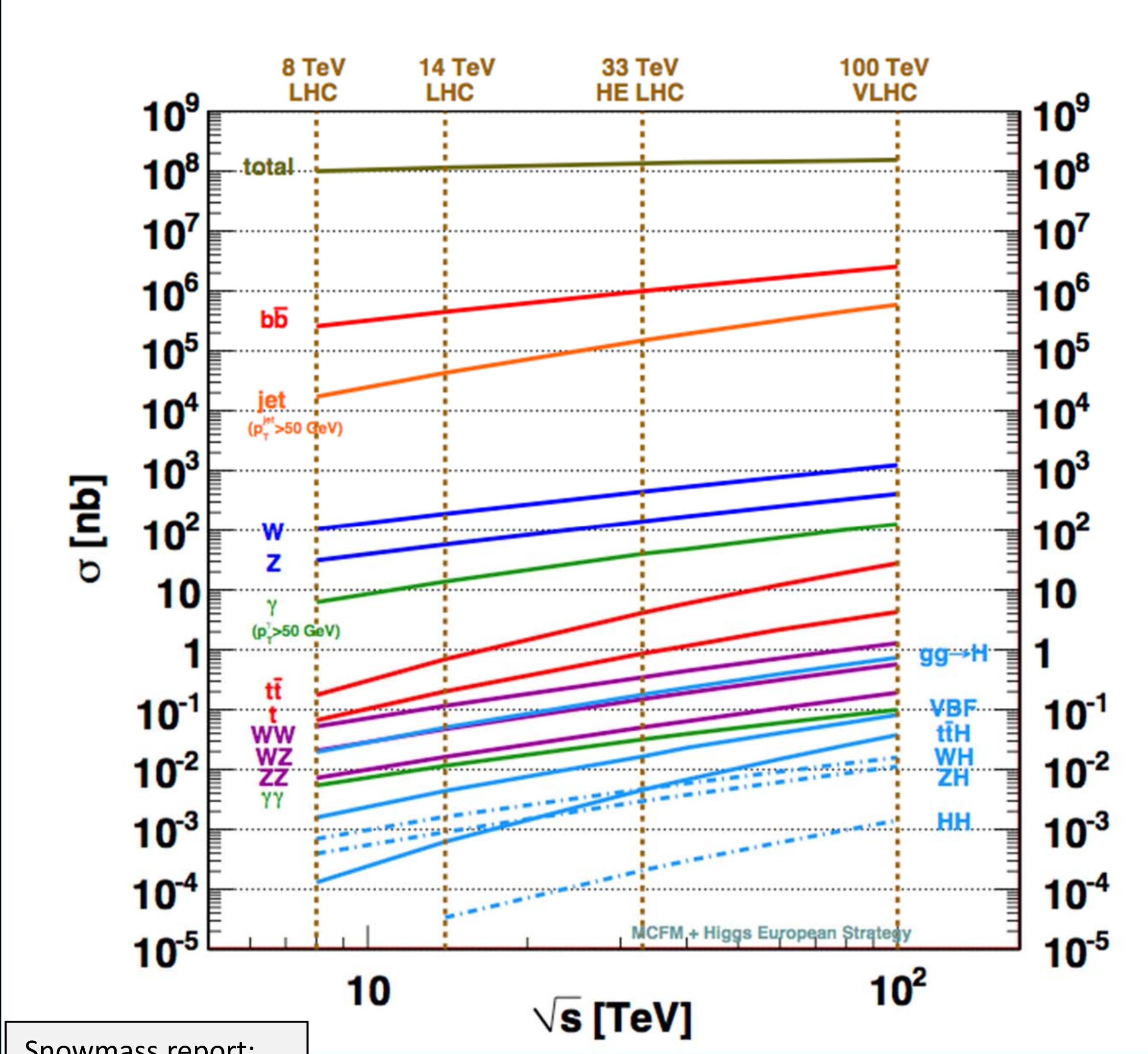
2 tons of TNT

energy per proton beam

***LHC*: 0.4 GJ** → ***FCC-hh*: 8 GJ (20x more !)**

- kinetic energy of Airbus A380 at 720 km/h
- can melt 12 tons of copper, or drill a 300-m long hole

Cross sections vs √s



Snowmass report: arXiv:1310.5189

Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~ 7
Z	~ 7
WW	~ 10
ZZ	~ 10
tt	~ 30
H	~ 15 (ttH ~ 60)
HH	~ 40
stop (m=1 TeV)	~ 10^3

(F Gianotti)

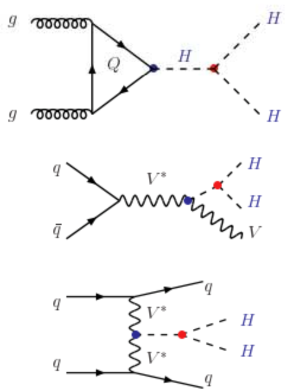
2. Double Higgs production

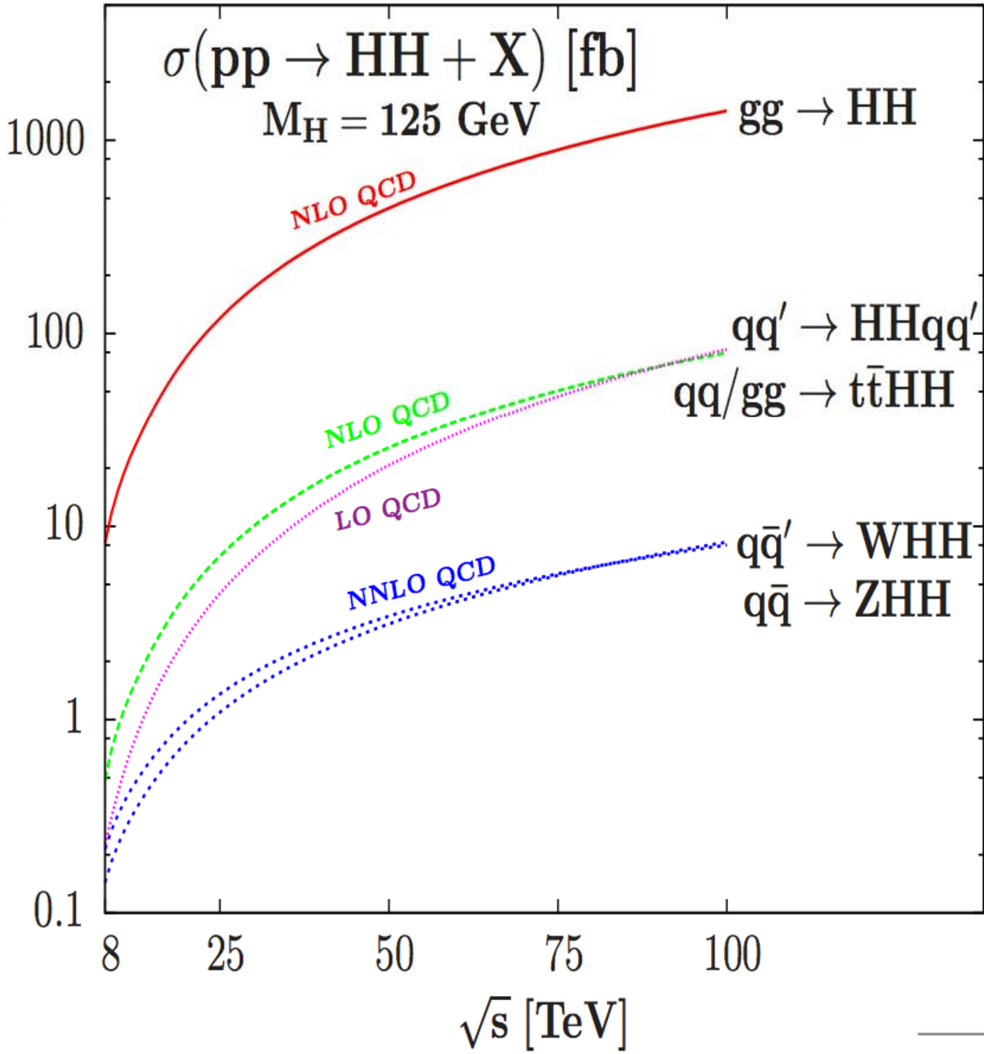
Big challenge: measure Higgs self-couplings and access to V_H

- g_{H^3} from $pp \to HH + X$
- g_{H^4} from pp→3H+X, maybe?

Various processes for HH prod:

$gg \to HHX$ by far dominant

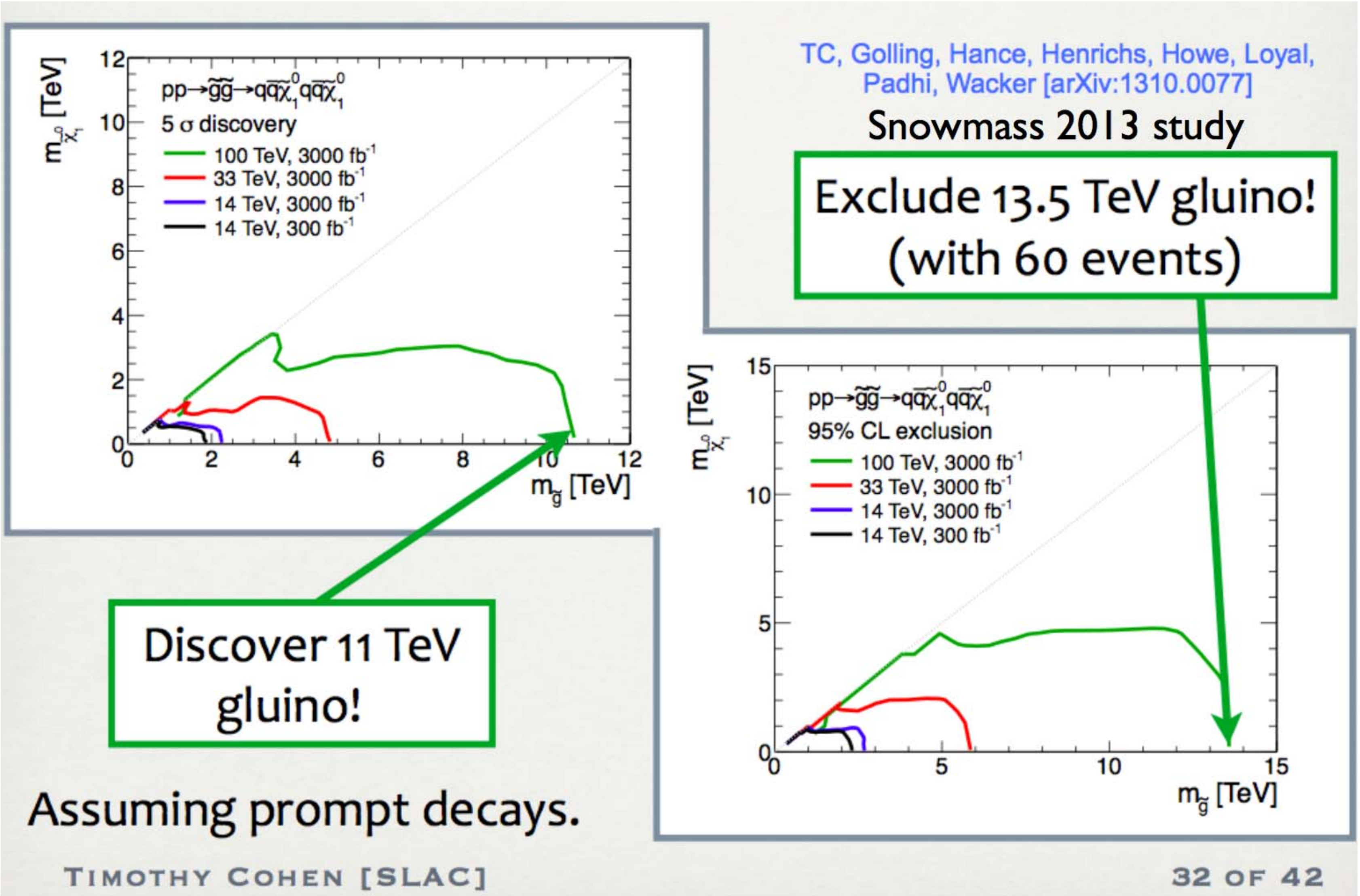




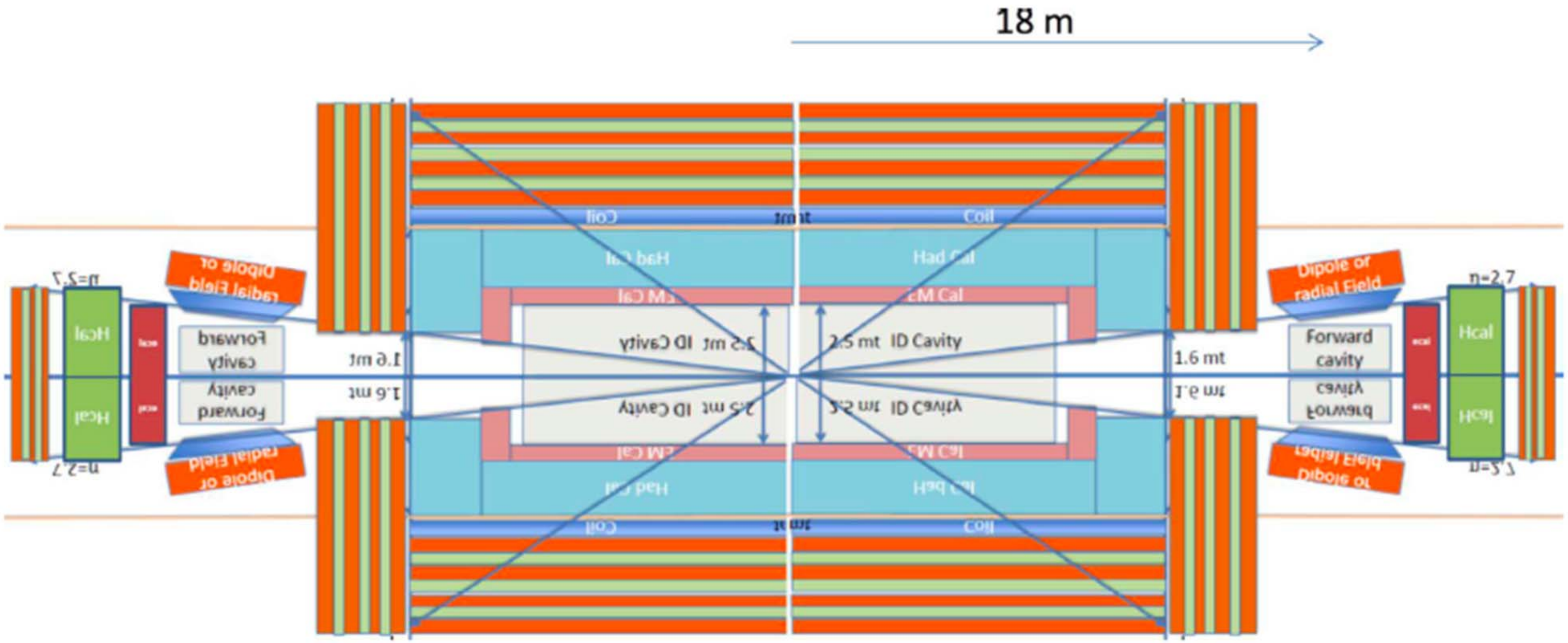
Baglio et al., arXiv:1212.5581

– distributions: $\frac{d\sigma}{dM_{HH}}, \theta_{HH}$?

– test sensitivity to λ_{HHH}?


TC, Golling, Hance, Henrichs, Howe, Loyal, Padhi, Wacker [arXiv:1310.0077]
Snowmass 2013 study
Exclude 13.5 TeV gluino! (with 60 events)
5 σ discovery
100 TeV, 3000 fb-1
33 TeV, 3000 fb-1
14 TeV, 3000 fb-1
14 TeV, 300 fb-1
[TeV]
95% CL exclusion
Discover 11 TeV gluino!
Assuming prompt decays.
Timothy Cohen [SLAC]
32 of 42

Option 1: Solenoid-Yoke + Dipoles (CMS inspired)



Solenoid: 5-6 m diameter, 5-6 T, 23 m long

+ massive Iron yoke for flux return (shielding) and muon tagging.

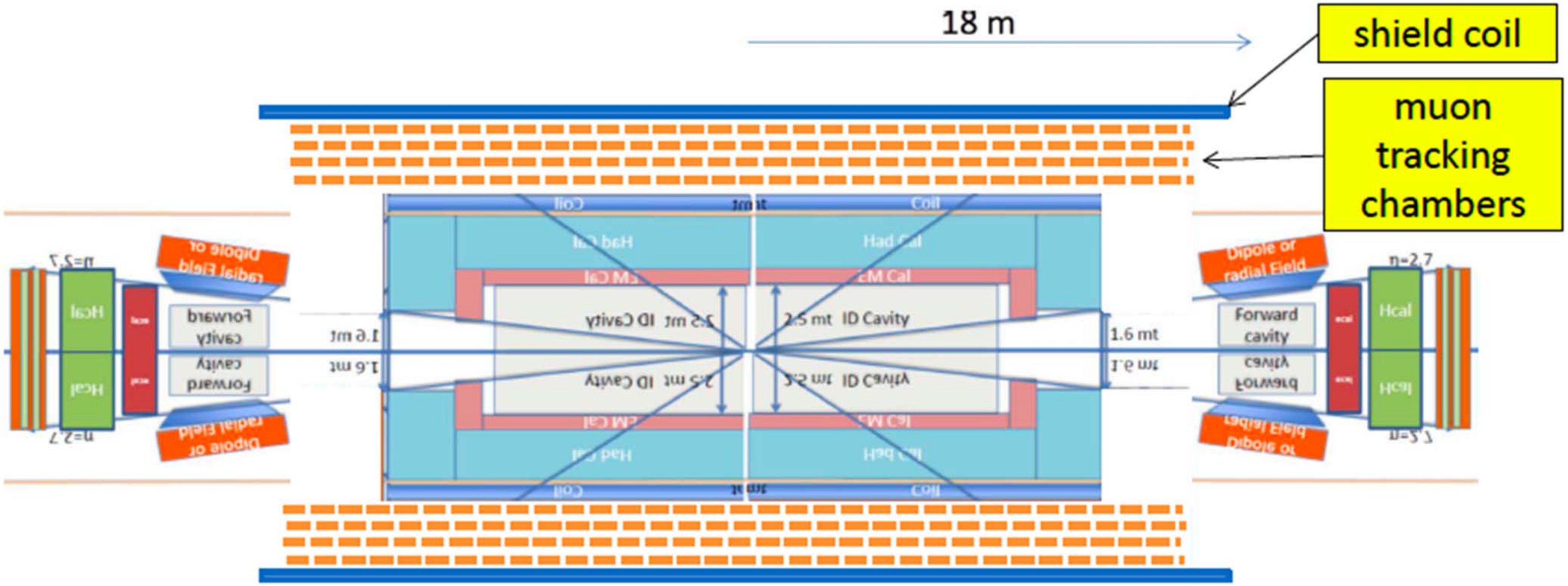
Dipoles: 10 Tm with return yoke placed at 18 m.

Practically no coupling between dipoles and solenoid.

They can be designed independently at first.

H ten Kate et al. FCC-hh detector studies

Option 2: Twin Solenoid + Dipoles



Twin Solenoid: the original 6 T, 12 m x 23 m solenoid + now with a shielding coil {concept proposed for the 4th detector @ILC, also an option for the LHeC in the case of large solenoid; and this technique is in all modern MRI magnets!}.

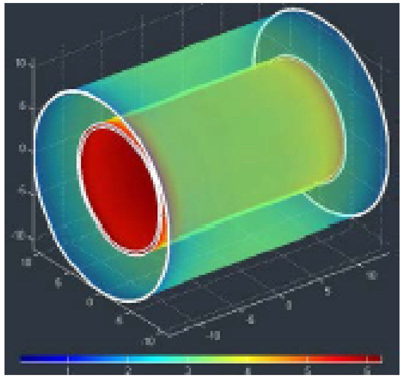
Gain?

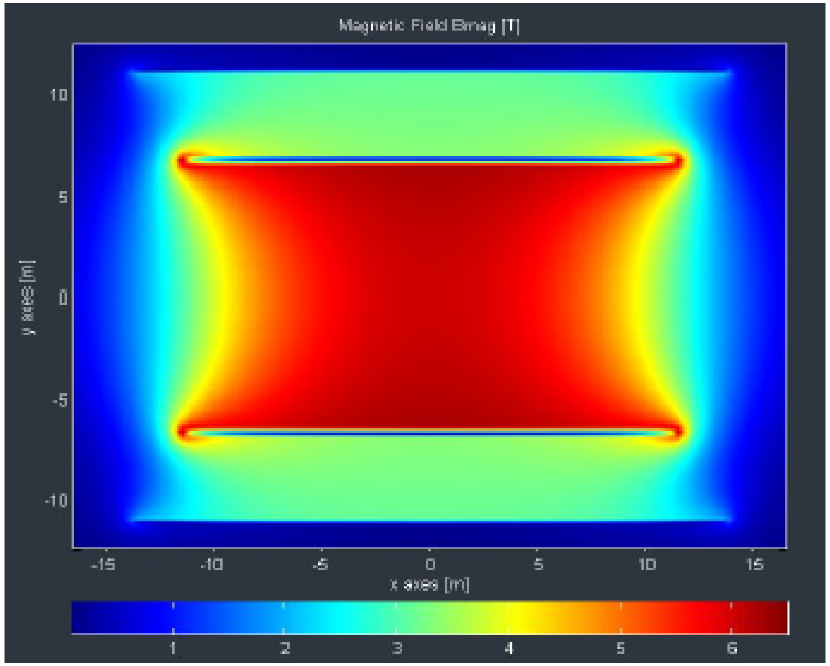
+ **Muon tracking space:** nice new space with 3 T for muon tracking in 4 layers.
+ **Very light:** 2 coils + structures, ≈ 5 kt, only ≈4% of the option with iron yoke!
+ **Smaller:** outer diameter is less than with iron .

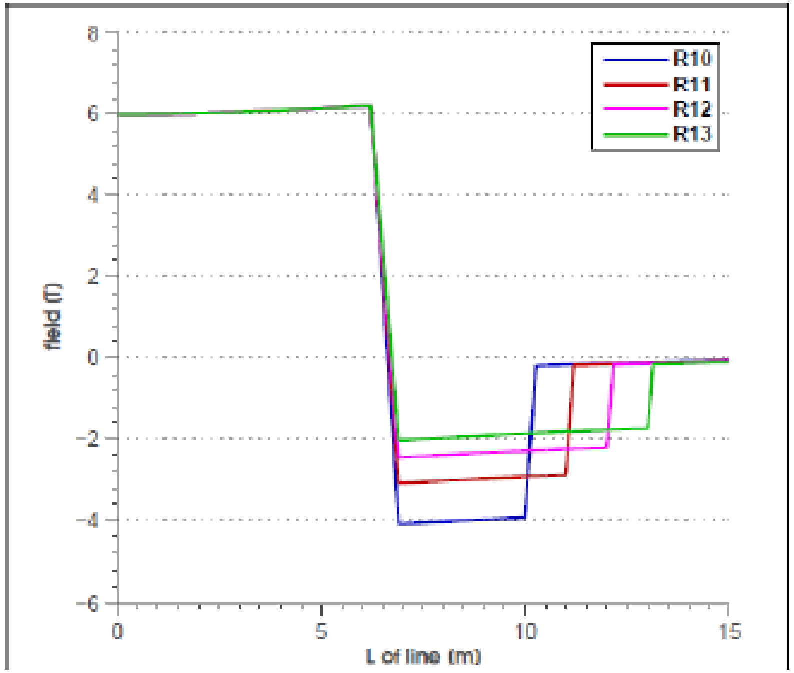
H ten Kate et al. FCC-hh detector studies

Twin Solenoid - field in main coil and gap

- Example: 6 T in 12 m bore, 23 m long.
- 2-4 T in gap depending on gap size, to be tuned.
- ≈2 T in a 6 m gap or ≈ 4 T in a 3 m gap.
- Many ways to adjust to specific requests.



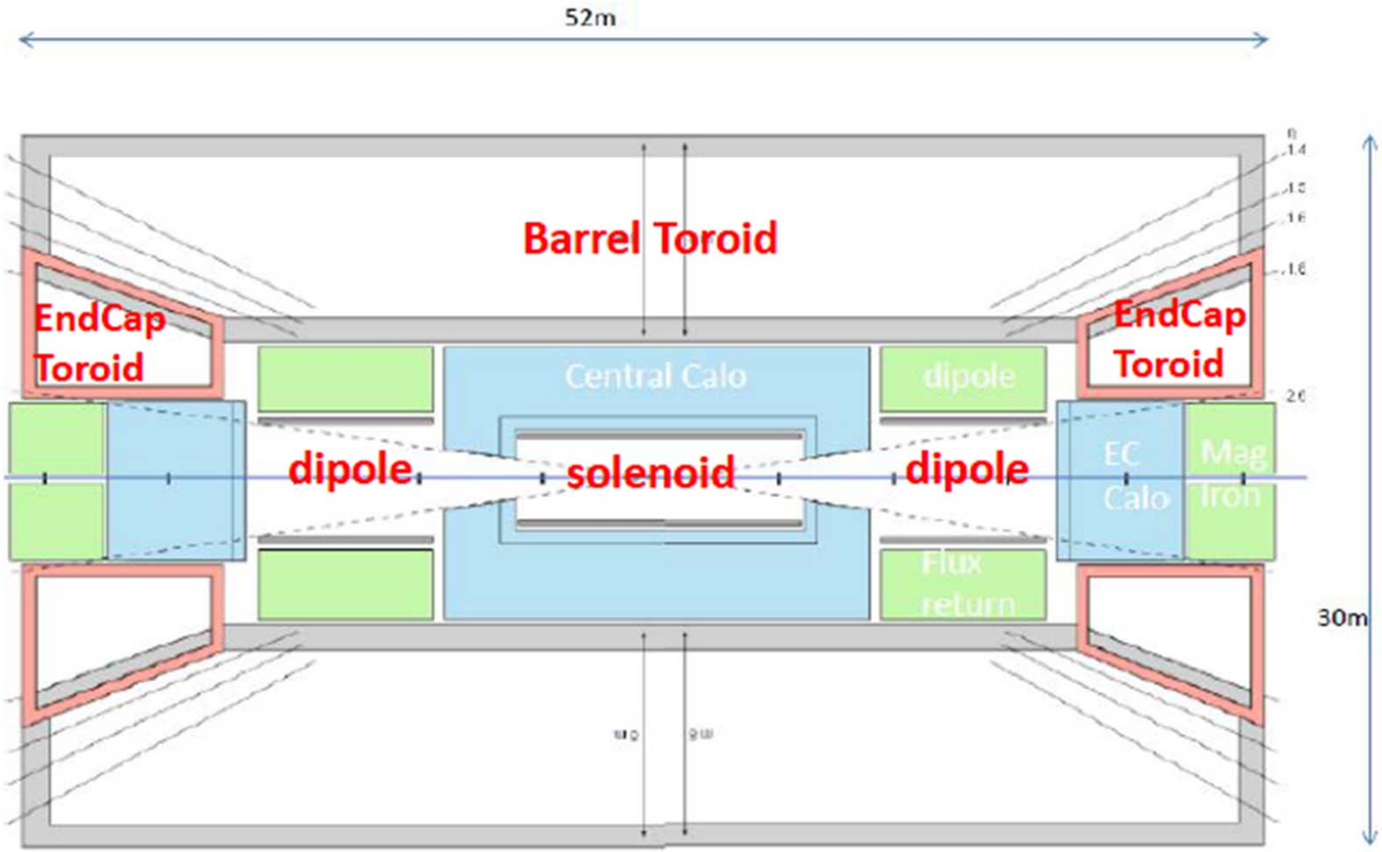




12

H ten Kate et al. FCC-hh detector studies

Option 3: Toroids + Solenoid + Dipoles (ATLAS +)

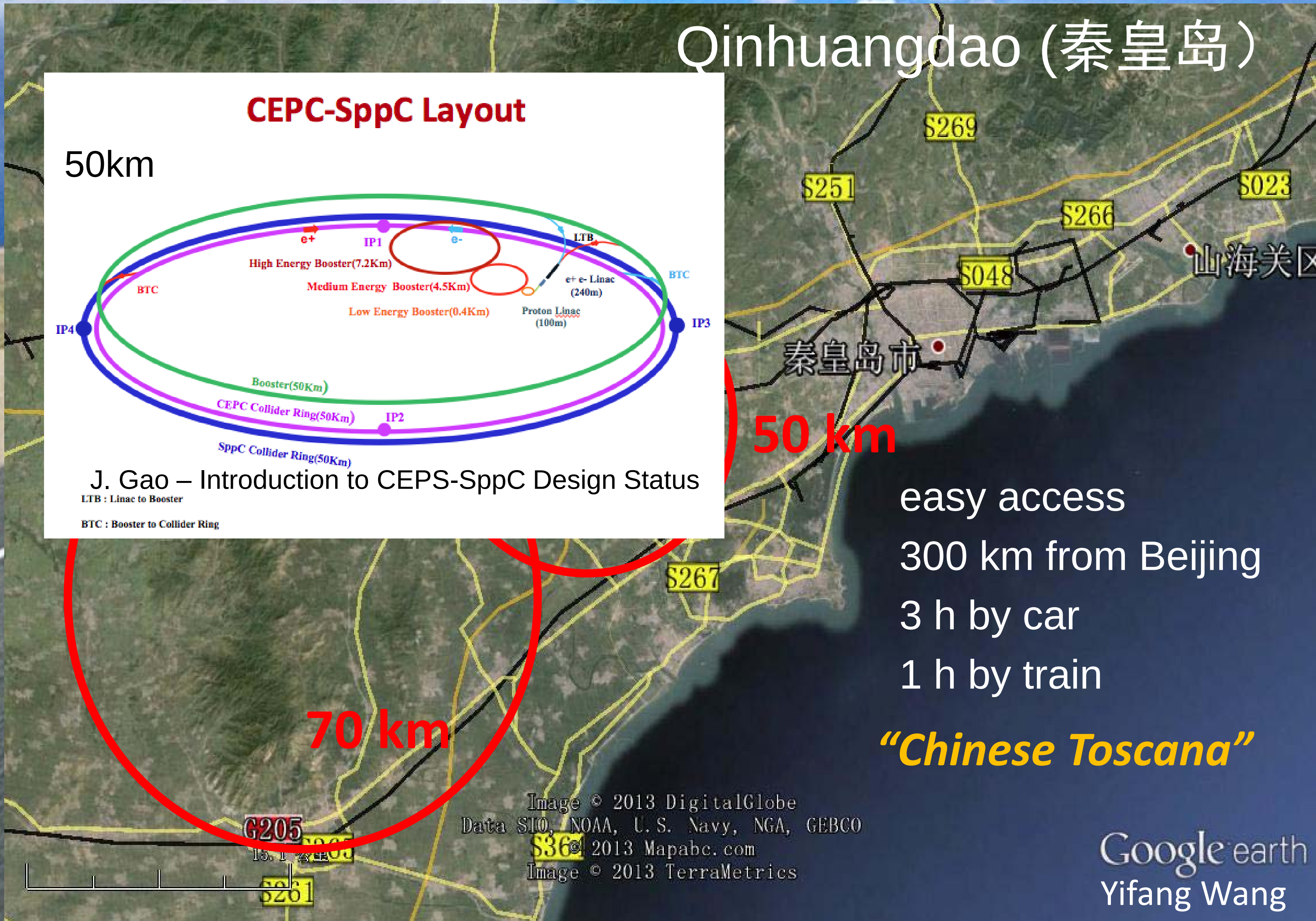


- Air core Barrel Toroid with 7 x muon bending power BL^2.
- 2 End Cap Toroids to cover medium angle forward direction.
- 2 Dipoles to cover low-angle forward direction.
- Overall dimensions: 30 m diameter x 51 m length (36,000 m^3).

H ten Kate et al. FCC-hh detector studies

CepC/SppC study (CAS-IHEP)

e^+e^- collisions; then *pp* collisions



easy access

300 km from Beijing

3 h by car

1 h by train

"Chinese Toscana"

Yifang Wang

Scientific Goals stated for CepC/SppC

- **CEPC (e+e-: 90-250 GeV)**
  - Higgs Factory: Precision study of Higgs(m_H, J^{PC}, couplings)
    - Same as SM prediction ? Other Higgs ? Composite ? New properties ? CP effect ？
  - Z & W factory: precision test of SM
    - New phenomena ? Rare decays ?
  - Flavor factory: b, c, t and QCD studies
- **SppC (pp: 50-100 TeV)**
  - Directly search for new physics beyond SM
  - Precision test of SM
    - e.g., h^3 & h^4 couplings

Complementary with each other

(Yifang Wang)

CERN's position w.r.t. to the high energy frontier, as expressed recently by its Director for Accelerators and Technology, Frederick Bordry

- **CERN is presently exploiting the physics potential of the LHC**
- **After the long shutdown LS1 the LHC will operate at 13 TeV in 2015 and later towards 14 TeV (2015-2023). Goal 300 fb^{-1}**
- **The high luminosity project HL-LHC will allow to collect ten times more data (2025 - mid 2030ies) Goal of 3'000 fb-1**
- **Depending on the physics findings of the LHC "precision" e+e- linear colliders might be built in Japan (ILC) or at CERN (CLIC)**
- **CERN is hosting a study performed in international collaboration for a Future Circular Colliders in the Geneva area with a circumference of 80 – 100km:**
  - **pp-collider (FCC-pp) defining the infrastructure requirements**
  - **e+e- collider (FCC-ee) as potential intermediate step**
  - **p-e (FCC-ep) option**
  - **HE-LHC is also a possible option: High Field Magnets in the present LHC tunnel**

Time line of the LHC project

1984	Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne.
1987	Workshop on Physics at Future Accelerators, La Thuile, Italy. The Rubbia “Long-Range Planning Committee” recommends the Large Hadron Collider as the right choice for CERN’s future.
1990	European Committee for Future Accelerators (ECFA) LHC Workshop, Aachen (discussion of physics, technologies and designs for LHC experiments)
1992	General Meeting on LHC Physics and Detectors, Evian les Bains (4 general-purpose experiment designs presented along with their physics performance)
1993	Three Letters of Intent submitted to the CERN peer review committee LHCC. ATLAS and CMS selected to proceed to a detailed technical proposal.
1994	The LHC accelerator approved for construction
1996	ATLAS and CMS Technical Proposals approved.
1997	Formal approval for ATLAS and CMS to move to construction (materials cost ceiling of 475 MCHF)
1997	Construction commences (after approval of detailed engineering design of subdetectors (magnets, inner tracker, calorimeters, muon system, trigger and data acquisition))
2000	Assembly of experiments commences, LEP accelerator is closed down to make way for the LHC.
2008	LHC experiments ready for pp collisions. LHC starts operation. An incident stops LHC operation.
2009	LHC restarts operation, pp collisions recorded by LHC detectors
2010	LHC collides protons at high energy (centre of mass energy of 7 TeV)
2012	LHC operates at 8 TeV: discovery of a Higgs-like boson.

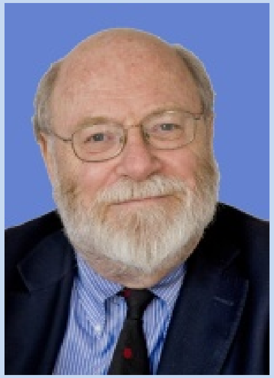
It took a long time, and we already had a tunnel…

It was a very long road from first dreams to the fantastic scientific instrument we have now with the LHC and its experiments, and many visionaries deserve credit for it…

Herwig Schopper, CERN DG 1981 - 1988

Carlo Rubbia, CERN DG 1989 - 1993
Giorgio Brianti, first LHC Project Leader, until 1993

Sir Chris Llewellyn Smith, CERN DG 1994 - 1998
Lorenzo Foa († 2014), Research Director 1994 - 1998
Lyn Evans, LHC Project Leader 1994 - 2008



Luciano Maiani, CERN DG 1999 - 2003
Roger Cashmore, Research Director 1999 – 2003

Robert Aymar, CERN DG 2004 - 2008
Jos Engelen, Research Director 2004 - 2008

Rolf Dieter Heuer, CERN DG since 2009
Sergio Bertolucci, Research Director since 2009
Steve Myers, Director of Accelerators and Technology 2009 – 2013
(here shown together with the ATLAS and CMS Spokespersons Fabiola Gianotti and Joe Incandela, on the famous 4th July 2012)

Another example where we have to be even more patient…

SLAC – PUB – 4081
September 1986
(A/E)

Table I. Parameters of some 10 TeV (c.m.) linear colliders compared to the parameters of the SLC. The c.m. energy spread, σ_{E^*}/E^*, is the contribution of beamstrahlung only.

MACHINE	L.L.C.			SLC
E^* (TeV)	10			0.1
$\mathcal{L}$ ($cm^{-2}s^{-1}$)	10^{34}			6×10^{30}
σ_{E^*}/E^* (%)	10			0.04
β^* (cm)	0.1			0.5
D	0.1			1.0
P (MW)	1	3	10	0.16
f (Hz)	3000	9000	30,000	180
N (e^+ or e^-)	4.1×10^8	4.1×10^8	4.1×10^8	5×10^{10}
ϵ_N (M)	4×10^{-9}	1.2×10^{-8}	4×10^{-8}	3×10^{-5}
σ_{r_0} (micron)	6.4×10^{-4}	1.1×10^{-3}	2×10^{-3}	1.5
σ_z (mm)	3.4×10^{-4}	1×10^{-3}	3.4×10^{-3}	1.5

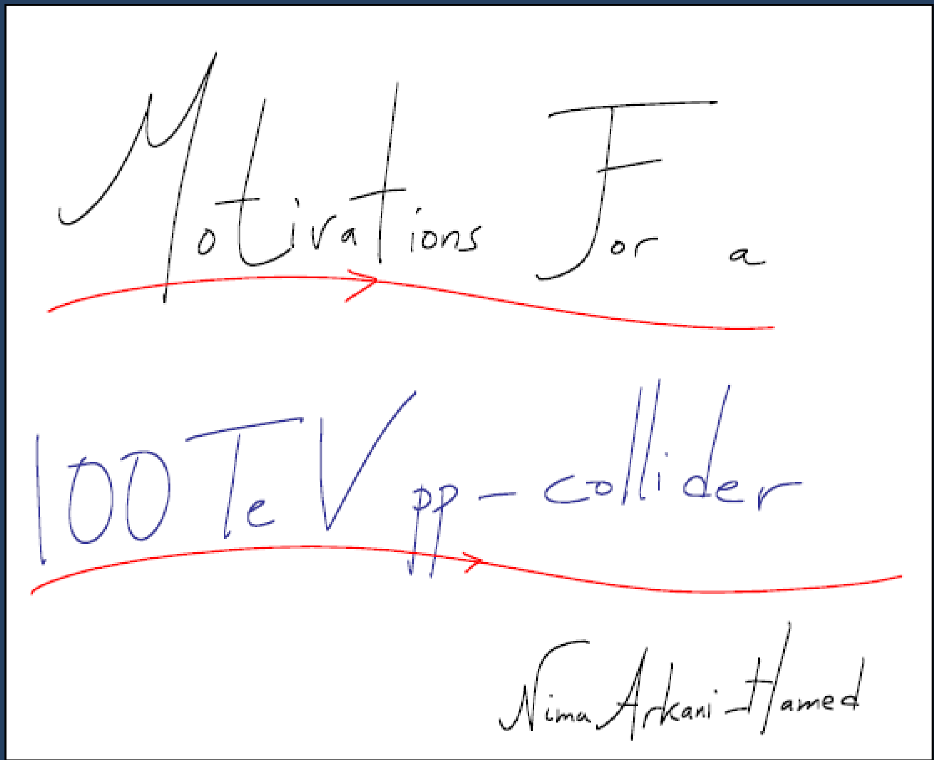
…

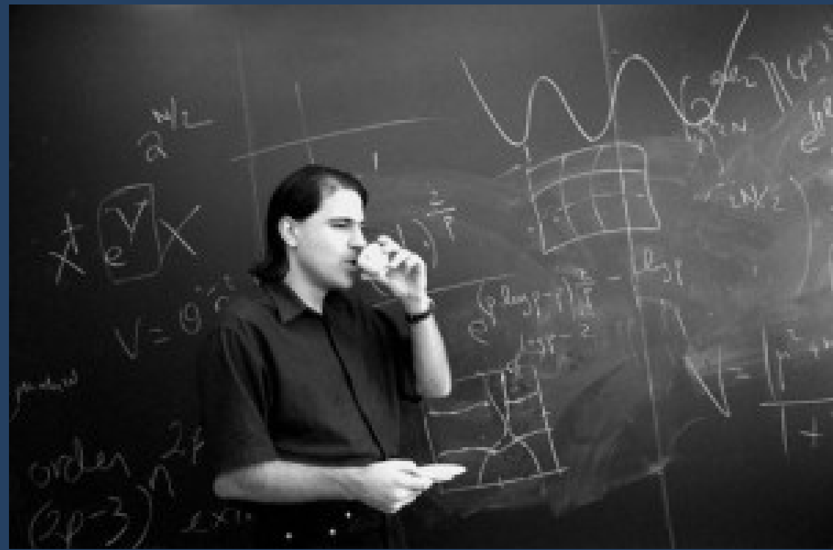
that will occur. I do not believe that the next step in linear colliders beyond the SLC will be the 10 TeV machine described in my Table. That is too big a distance from the parameters of the SLC to be covered in a single step. Thus we will have to see a machine of $1 \pm 1/2$ TeV as a "intermediate" machine. It is "intermediate" only when compared to the machine of Table I — it will be a very exciting research tool in its own right. Our

…

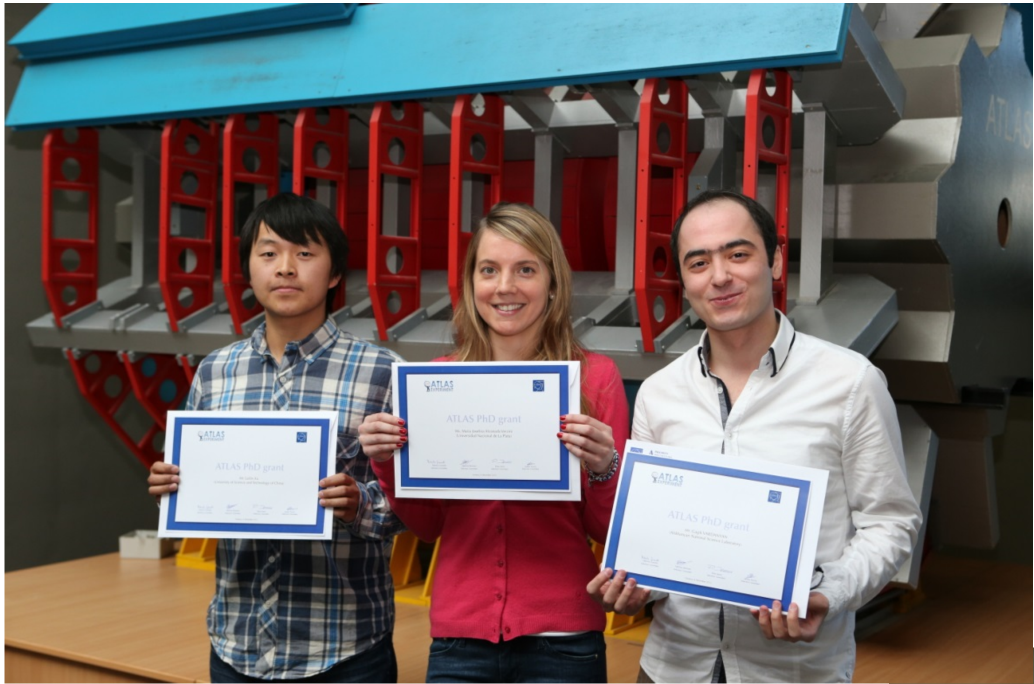
Burt Richter

From a very fascinating talk of ‘my friend’ Nima Arkani Hamed





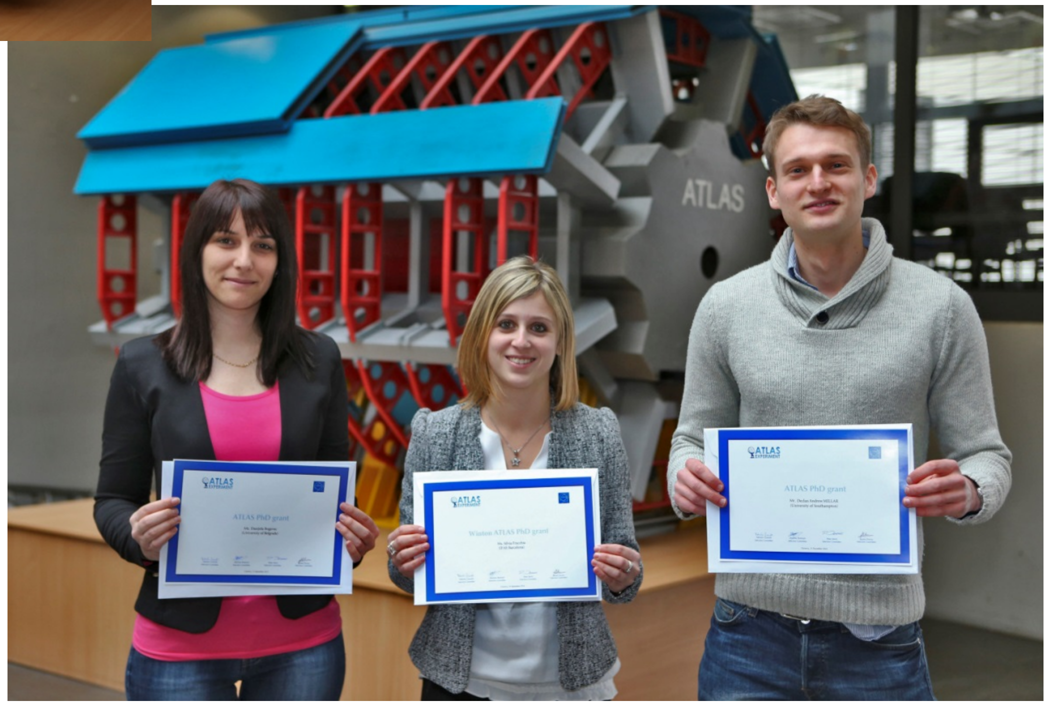
(At ISHP2013 Beijing in the same session)



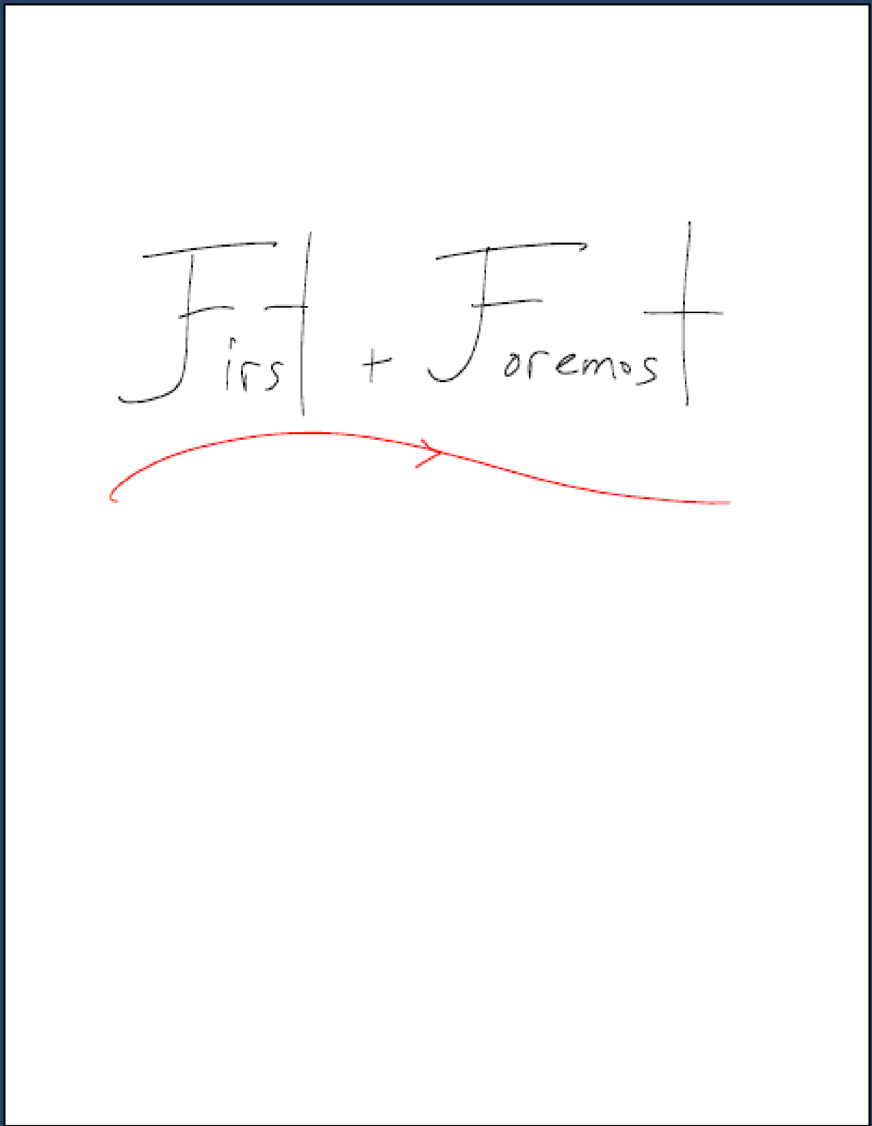
F Gianotti and PJ used their Milner Fundamental Physics Prize in ATLAS to sponsor 2-years PhD grants

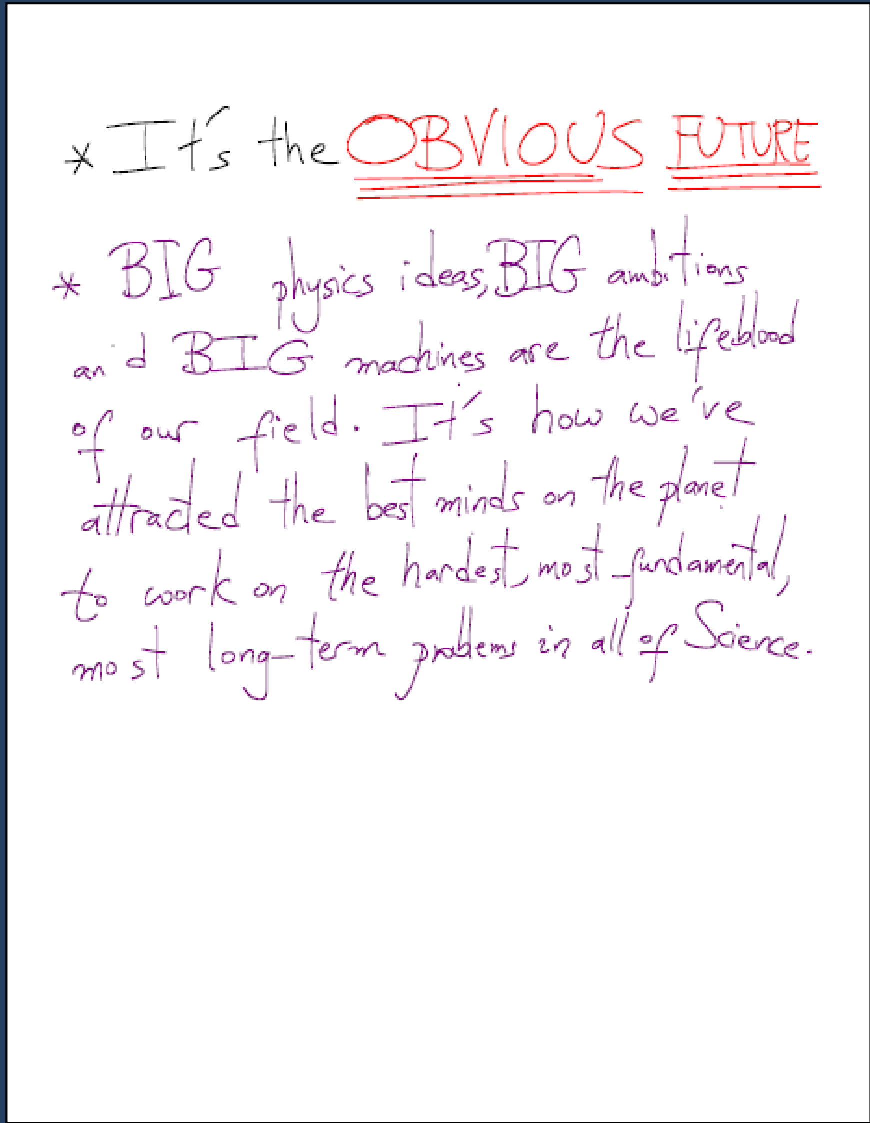
PhD Grants 2014

PhD Grants 2015



There will be another round starting in 2016; application will open soon, see CERN Web





(Nima Arkani Hamed at ISHP2013 Beijing)

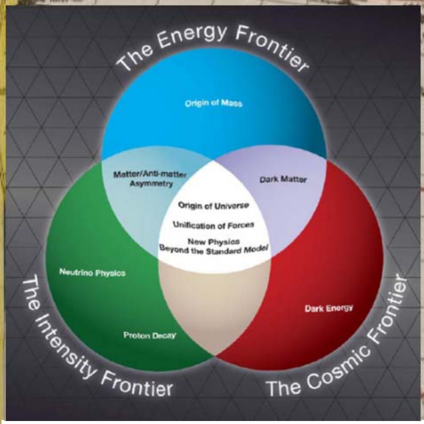
Obviously, how to proceed will depend on first LHC13 results.

But in every scenario I can imagine, we will need the 100 TeV pp machine

*EVERY student/post-doc/ person with a pulse (esp. under 35) I know is EXTREMELY excited by the prospects of a 100 TeV collider, + enthusiastic to work on this physics.

(Nima Arkani Hamed at ISHP2013 Beijing)

The journey into new physics territory at the high-energy frontier has only just begun with the LHC, nevertheless…



… we need to make timely plans and courageous decisions on a global scale in order to 'plant the right seeds for the future', also beyond LHC

Thank you for your attention

J Blaeu 1664