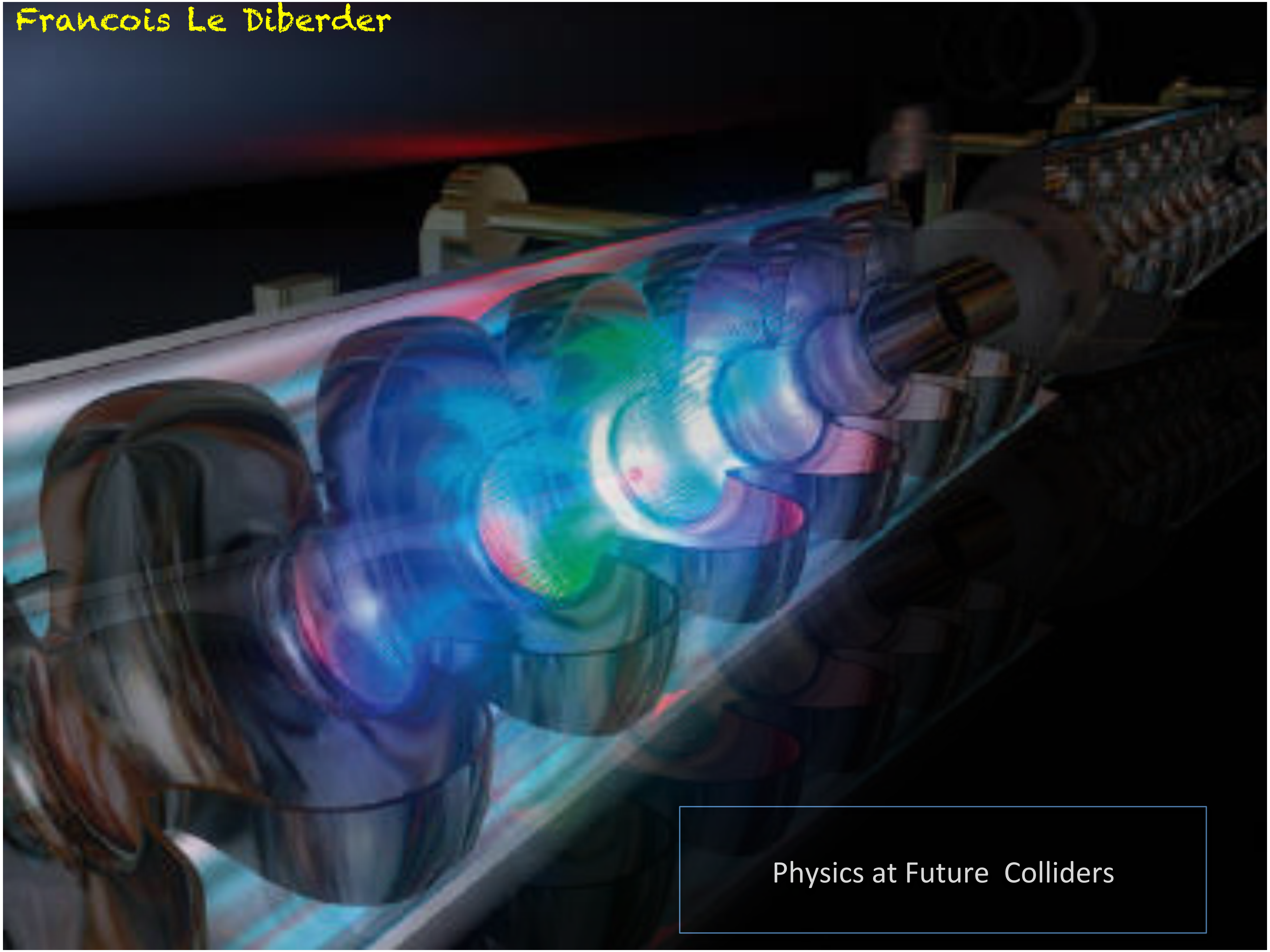
Francois Le Diberder



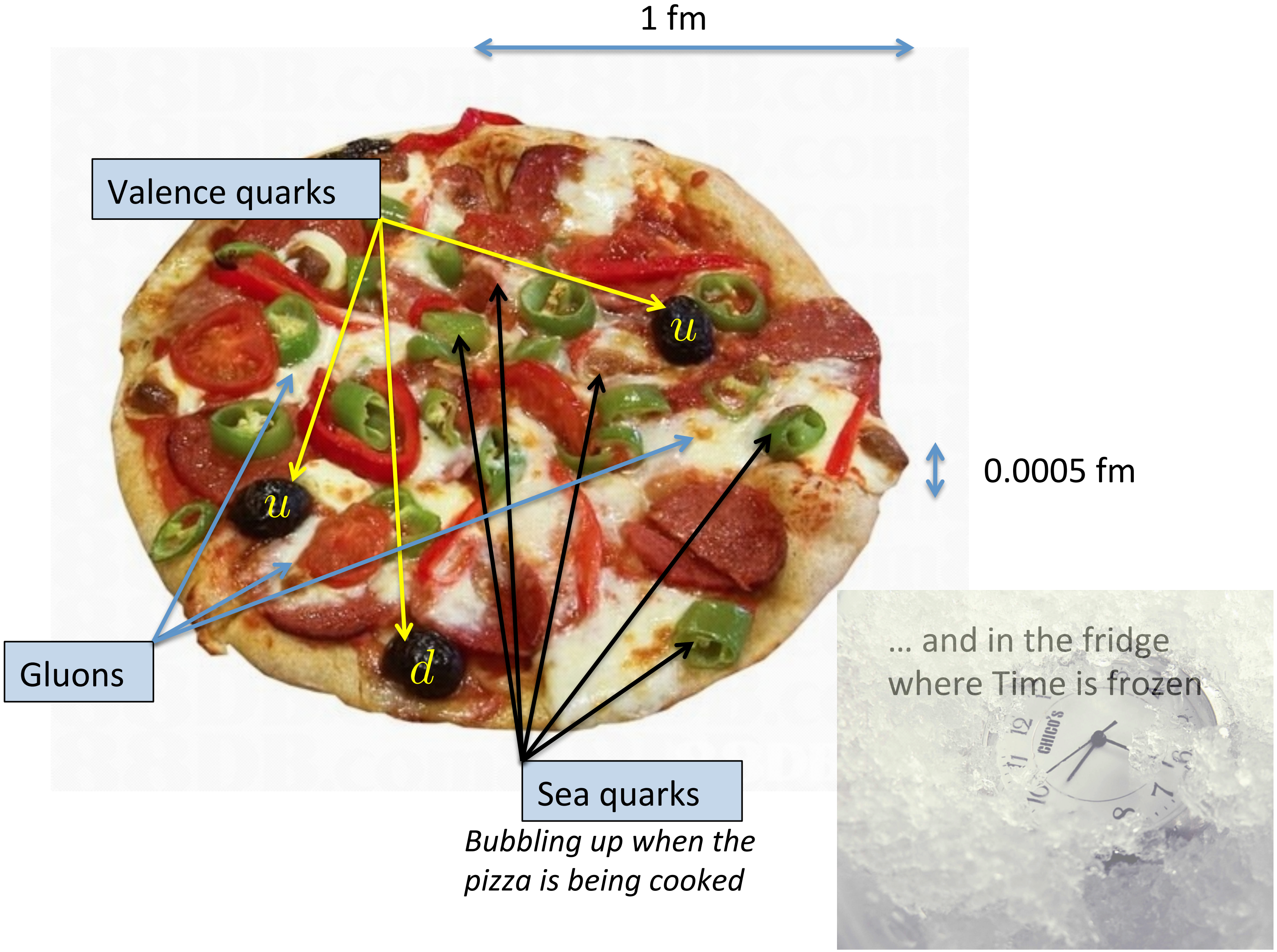
Physics at Future Colliders

Let’s start with

Physics at actual Collider

Proton in the LHC at 4 TeV/beam

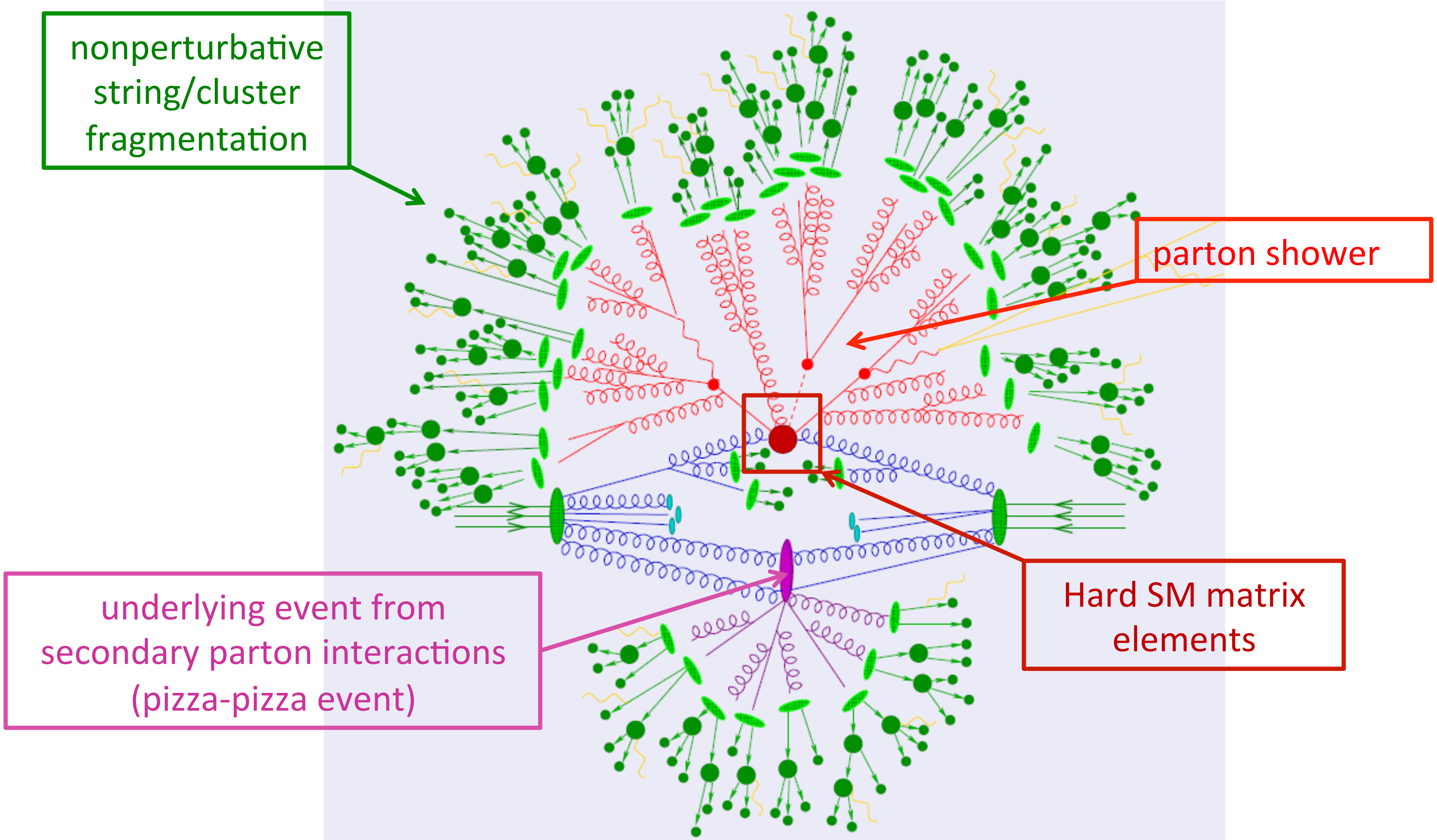
Is a Quantum Mechanics Frozen Pizza

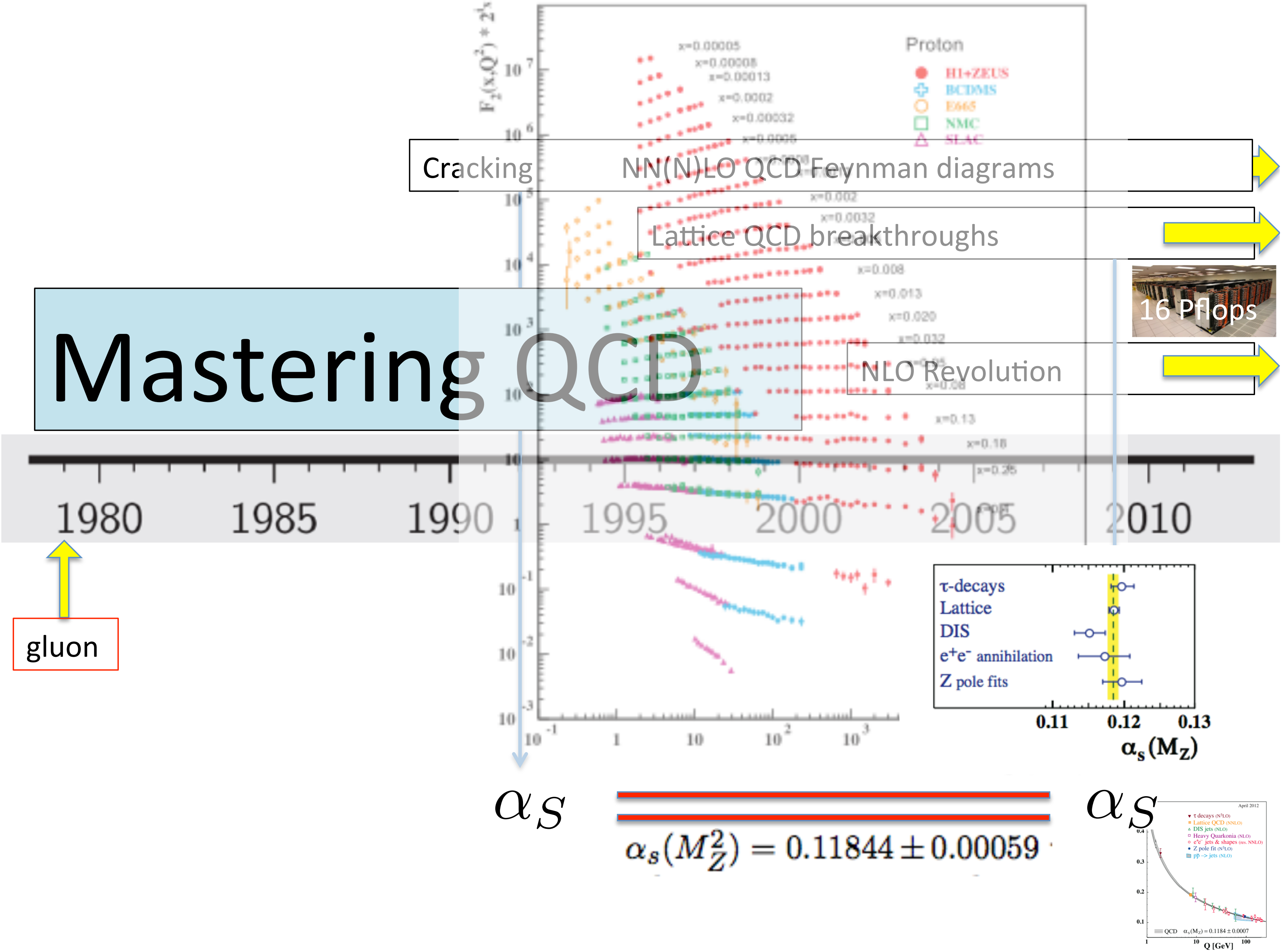



Pizza Pizza collisions

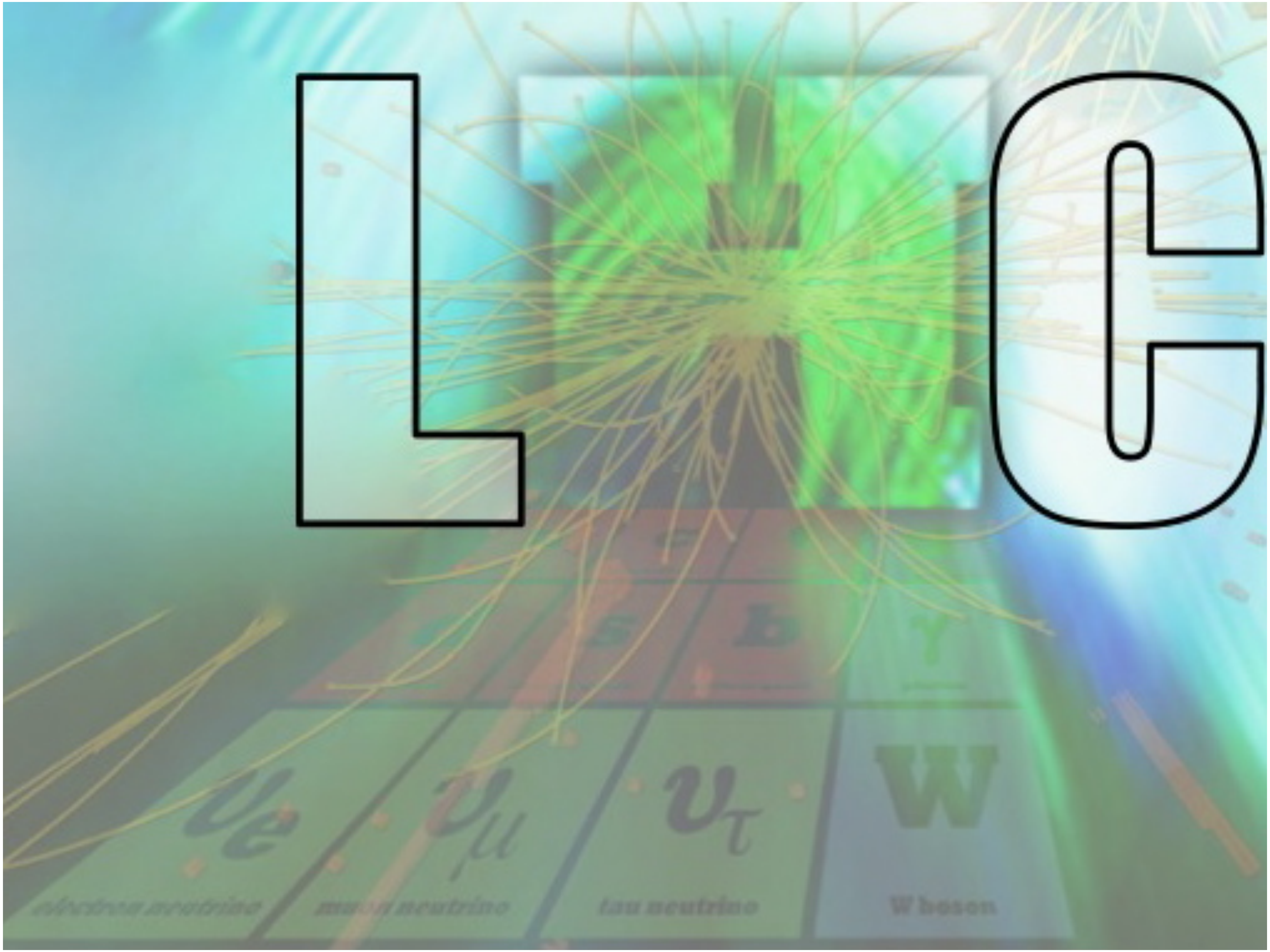

When two pizzas touch : they interact (violently)
the total cross-section is close to the geometrical cross-section
A rare pizza-pizza collision
where a “hard” scattering took place

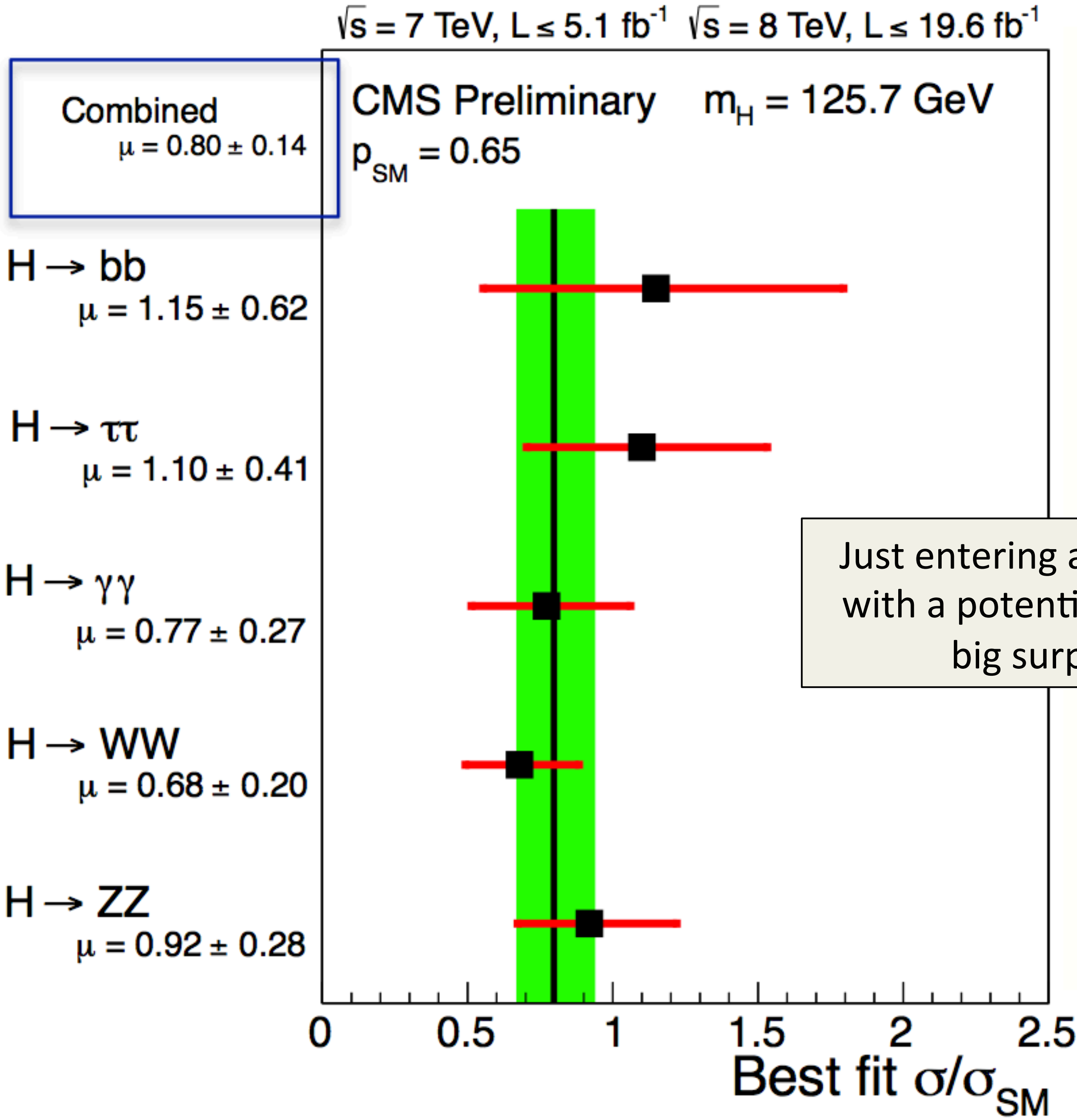
“Typical” hadron collider event




Mastering QCD
Cracking
NN(N)LO QCD Feynman diagrams
Lattice QCD breakthroughs
16 Pflops
NLO Revolution
1980
1985
1990
1995
2000
2005
2010
gluon
Proton
H1+ZEUS
BCDMS
E665
NMC
SLAC
τ-decays
Lattice
DIS
e+e- annihilation
Z pole fits
0.11
0.12
0.13
$\alpha_s(M_Z)$
α_S
$\alpha_s(M_Z^2) = 0.11844 \pm 0.00059$
α_S
Q [GeV]

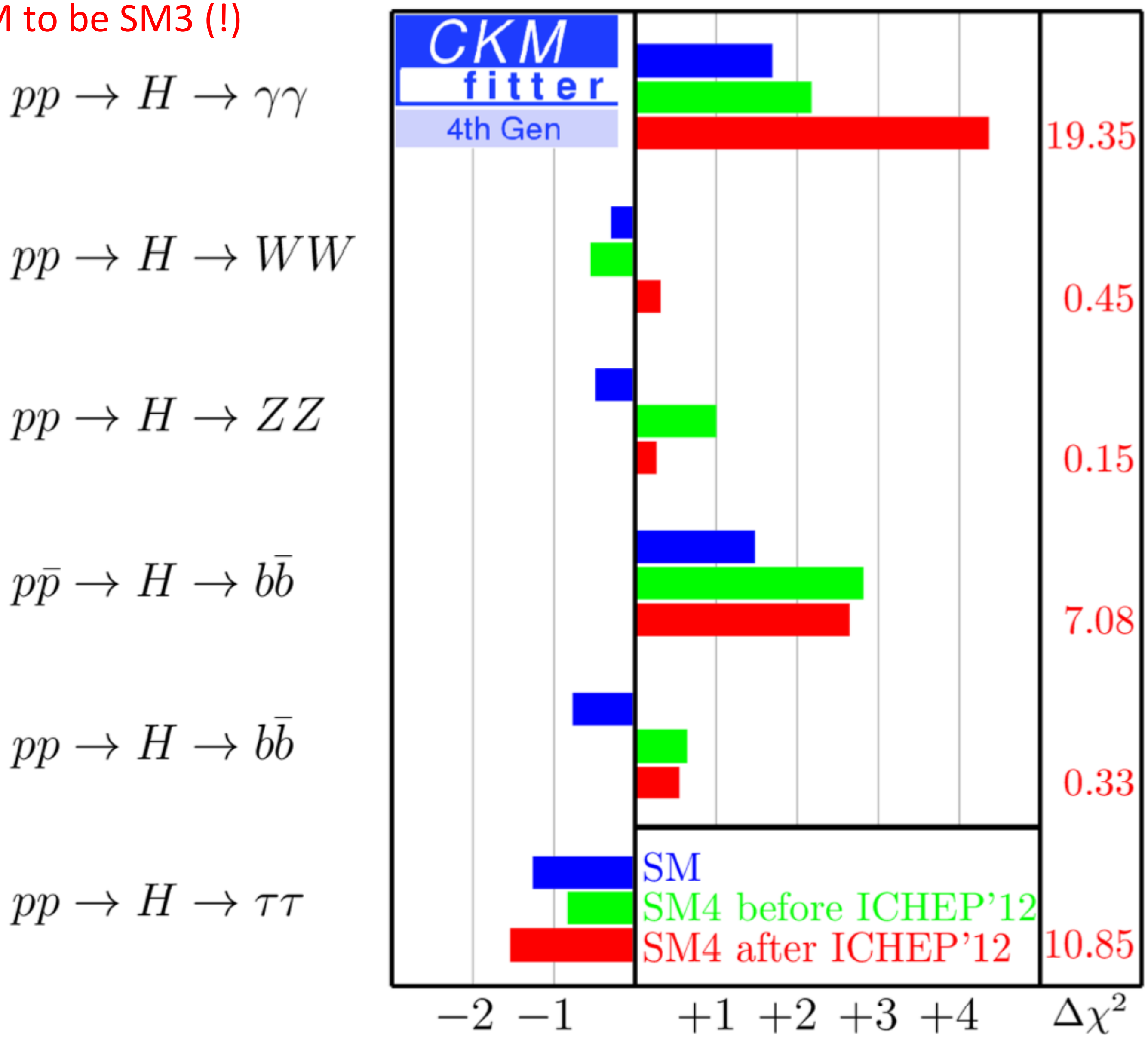

LHC pushing the limits on new phenomena BSM
ATLAS SUSY Searches* - 95% CL Lower Limits
Status: LP 2013
ATLAS Preliminary
Mass limit
Reference
Mass scale [TeV]

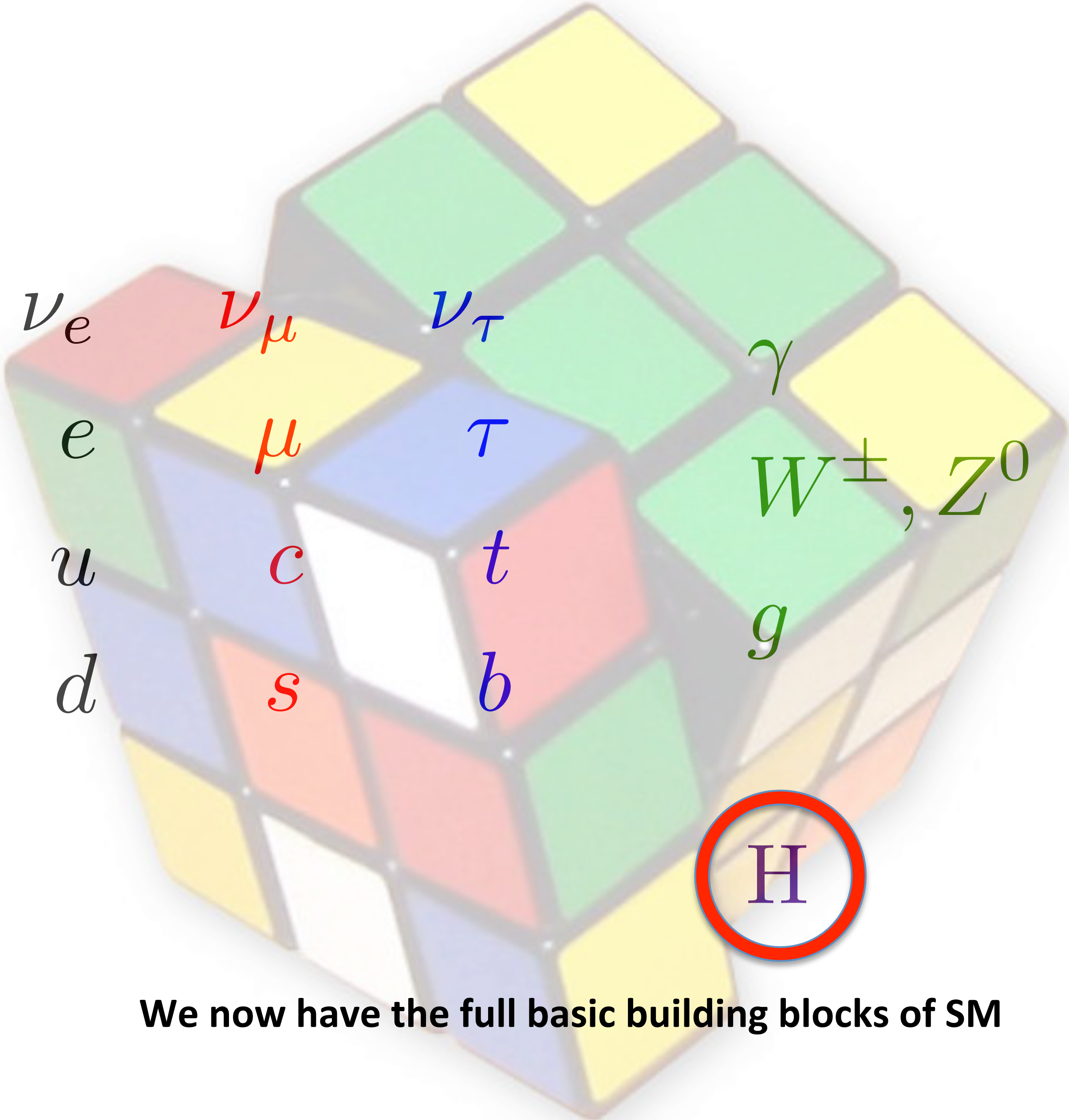

L
C
W
tau neutrino
W boson



Just entering a new world with a potential for many big surprises

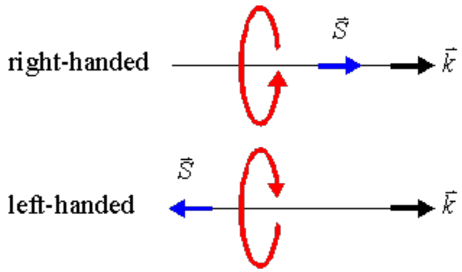
Already powerful enough to constrain SM to be SM3 (!)

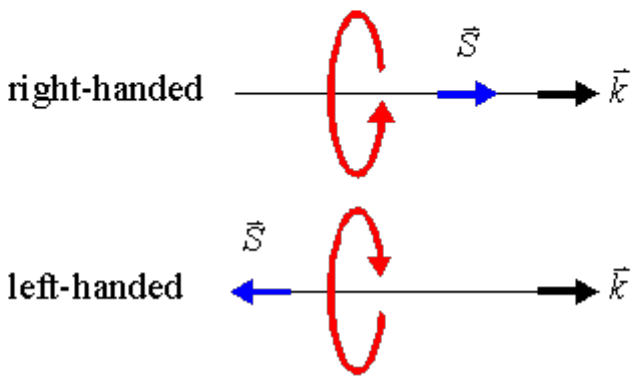




We now have the full basic building blocks of SM

To mention just one of the many aspects of the SM riddle

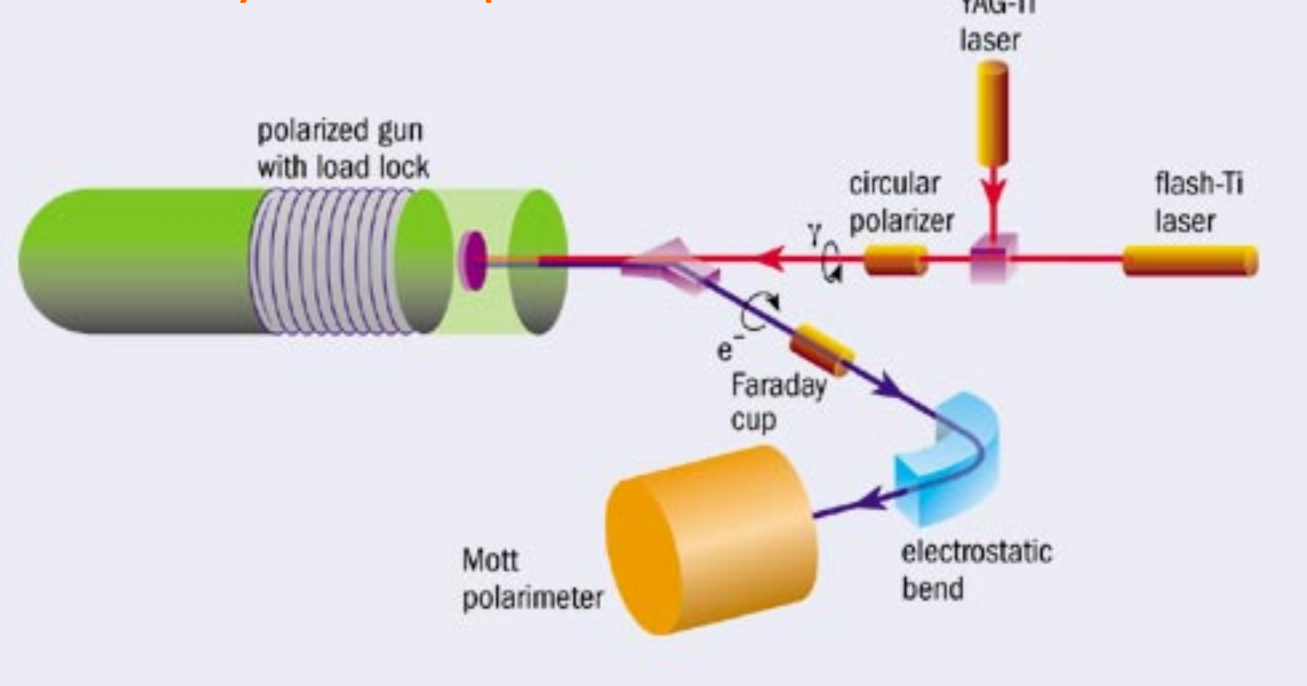


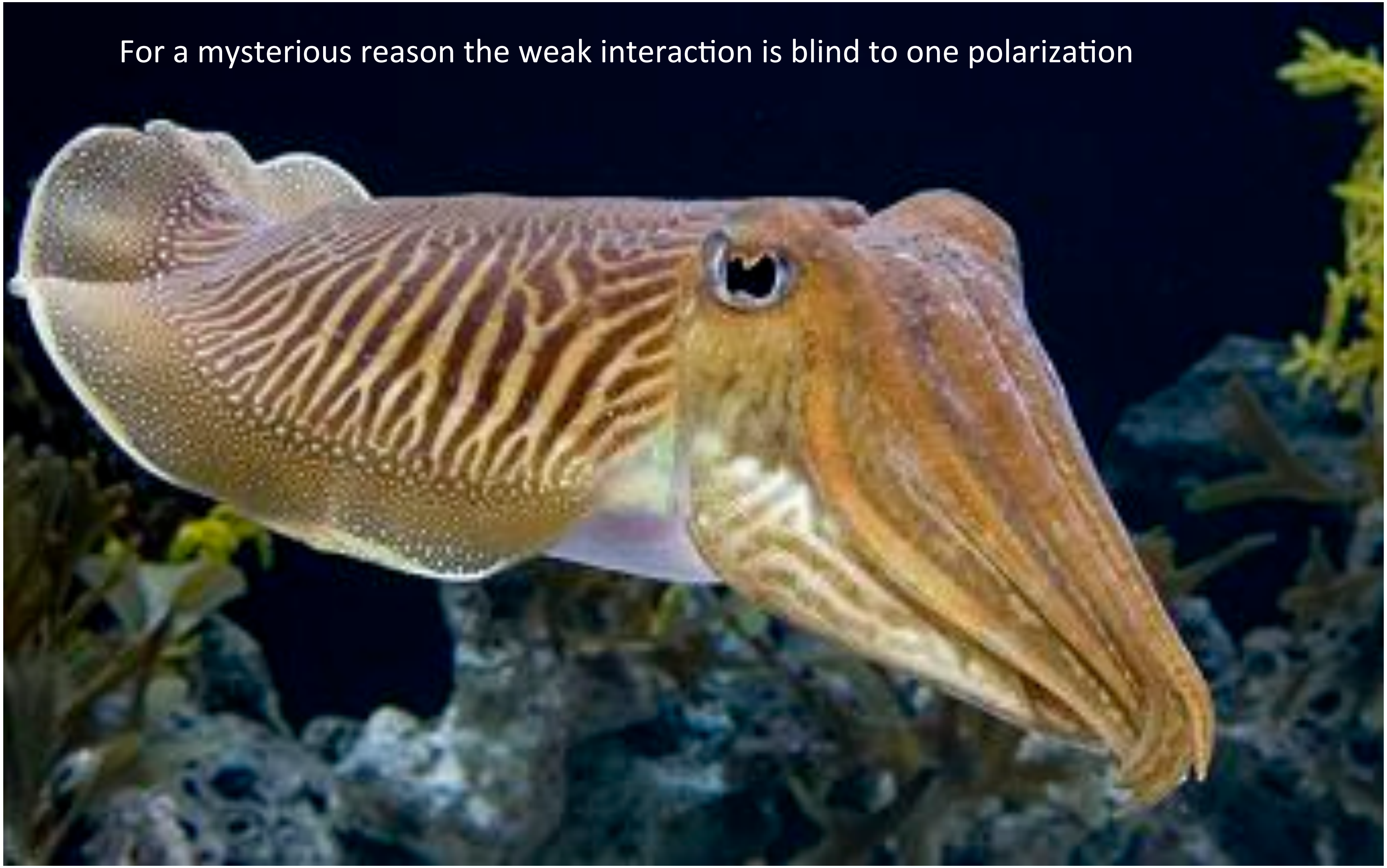


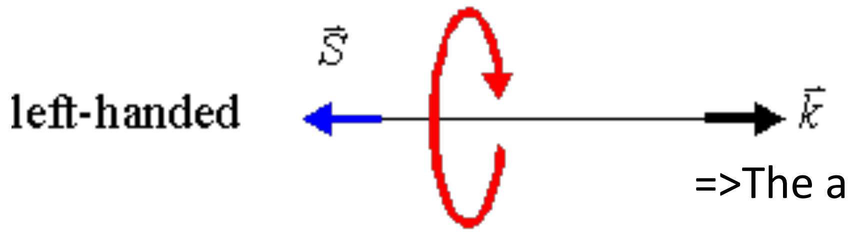
The same is true for matter-particles, but they spin around twice slower. they are referred to as Spin ½ because of that (while the force-particles are referred to as Spin 1).

But all of them do spin !

We know very well how to polarize electrons





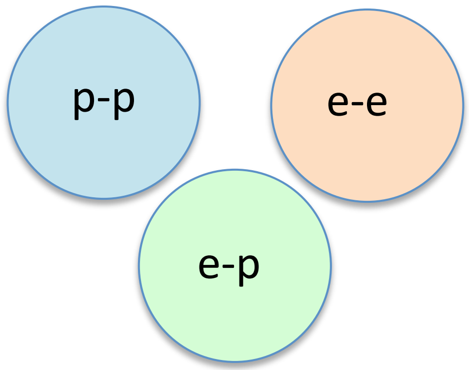


It can see only left-handed matter-particles !!!

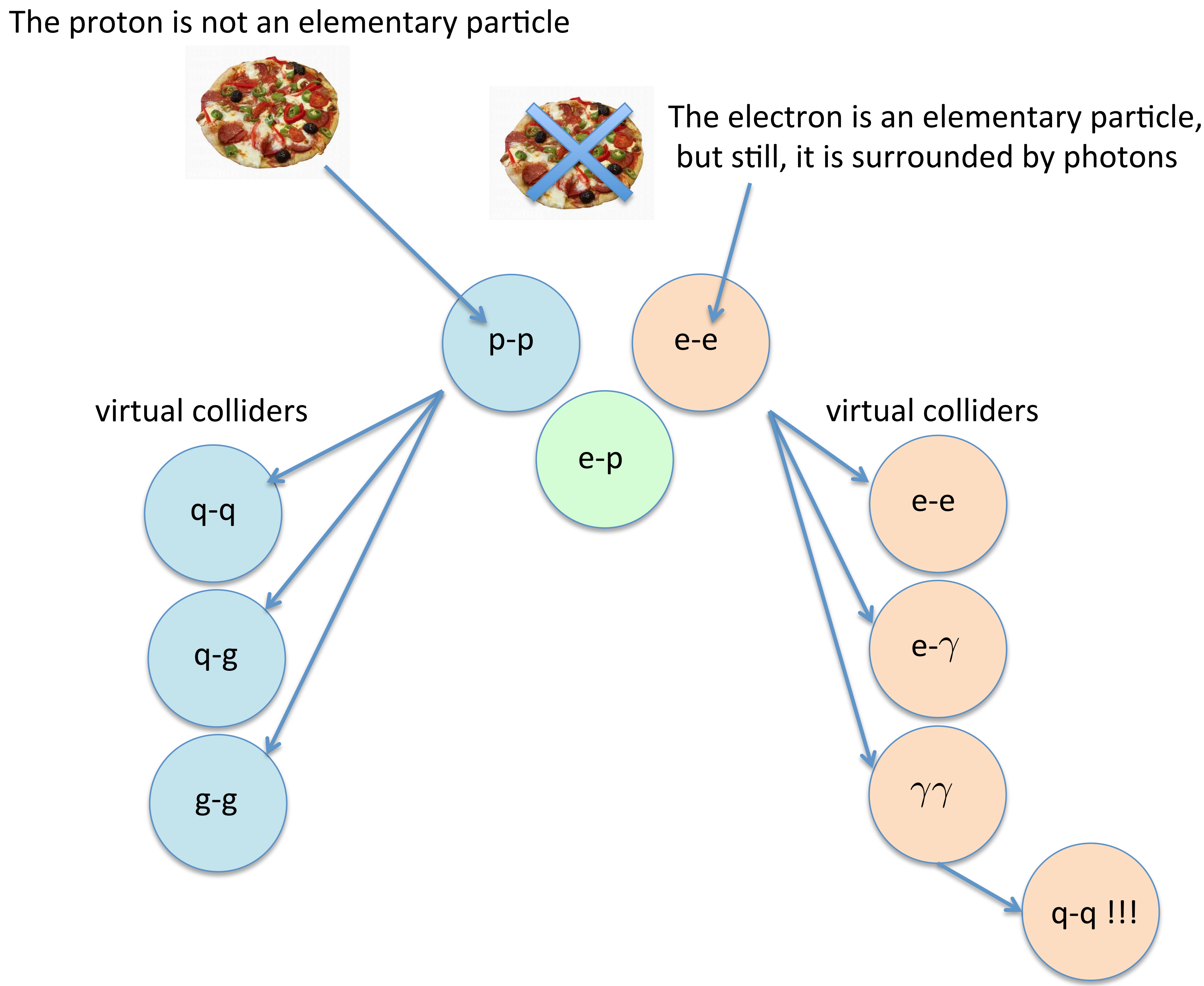
=>The ability to use polarized beam is a key element.

But this is not the subject of the present lecture, let’s move on.

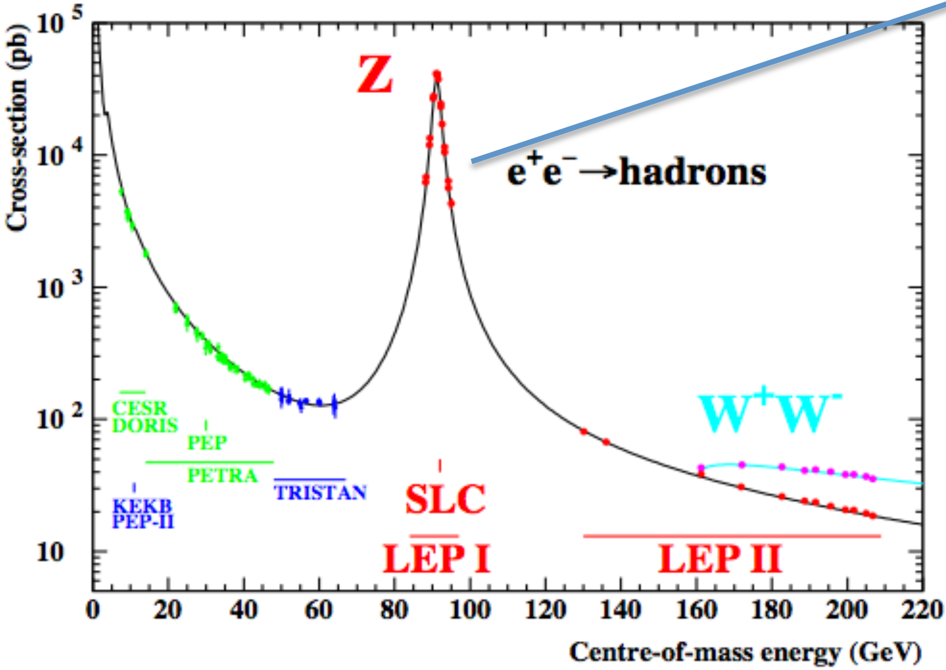
Physics at next Collider(s)

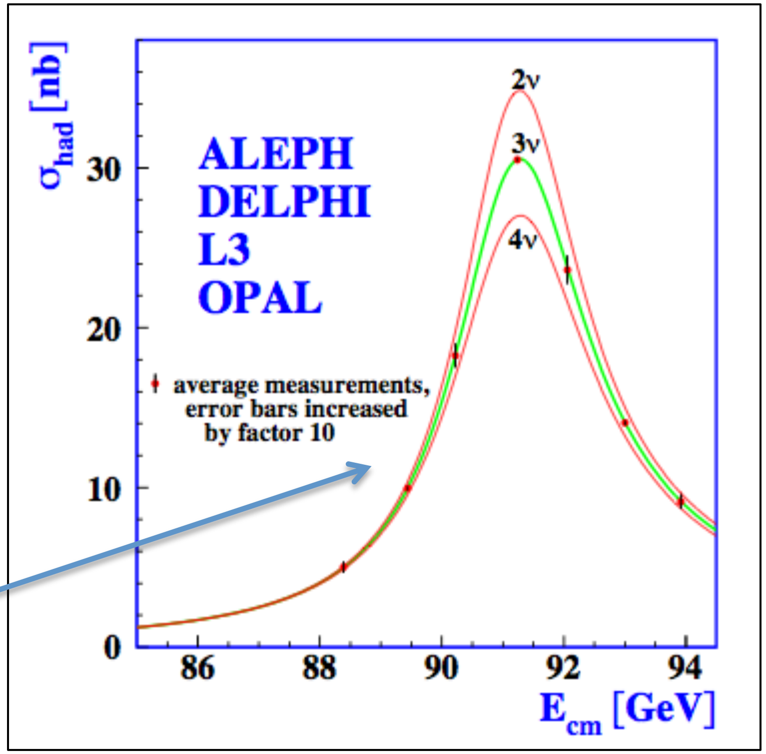


History tought us that the interplay between
p-p & e-e & e-p colliders is intrumental
in allowing progresses
in our understanding of Physics

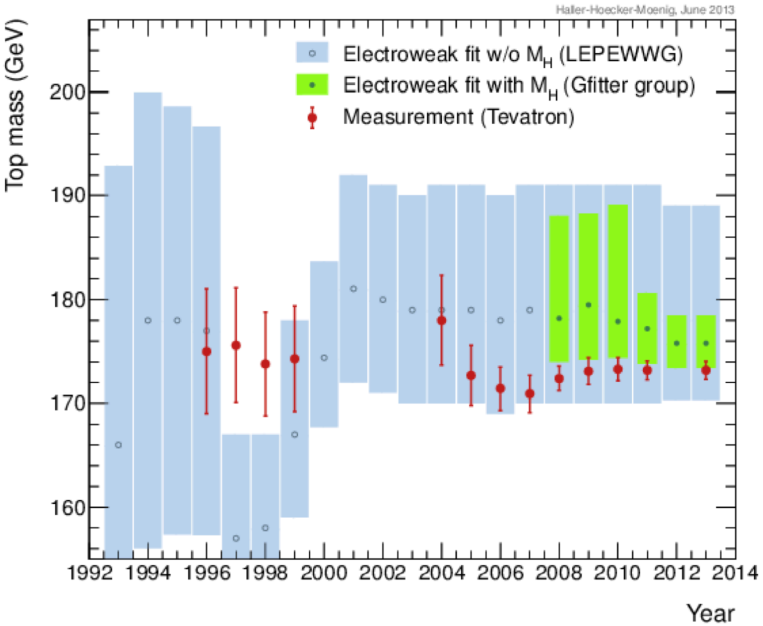

The proton is not an elementary particle
The electron is an elementary particle,
but still, it is surrounded by photons
p-p
e-e
e-p
virtual colliders
q-q
q-g
g-g
virtual colliders
e-e
e-γ
$\gamma\gamma$
q-q !!!

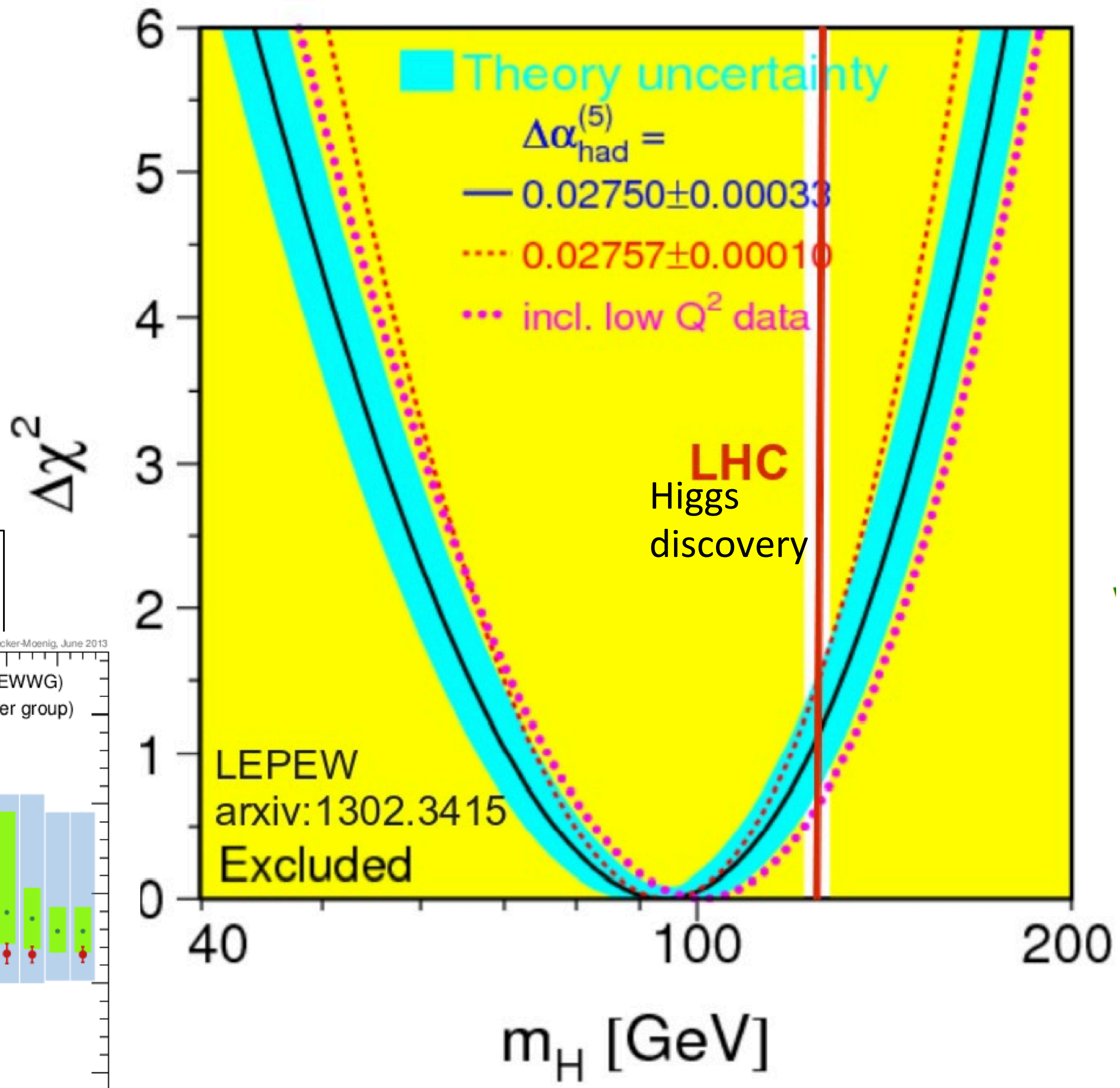
The beauty of lepton collider's Physics





The top mass first inferred and then measured directly





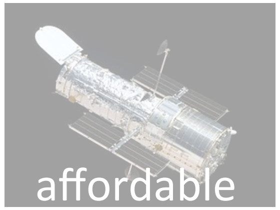
The Higgs mass first inferred and then measured directly

very precise absolute measurements
will pave the way to solve the mysterious SM riddle

The dream-machine

flexibility

Clean Luminosity



Mature technology

$SU(2)_L$

Full SM reach

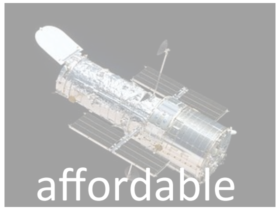
The dream-machine

LC collider

flexibility

e-e collider

Clean Luminosity



Mature technology

LC collider

$SU(2)_L$

LC collider

Full SM reach

LC collider

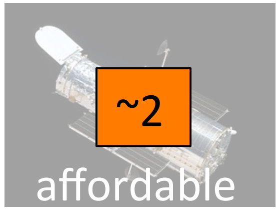
The dream-machine

LC collider

flexibility

e-e collider

Clean Luminosity



Mature technology

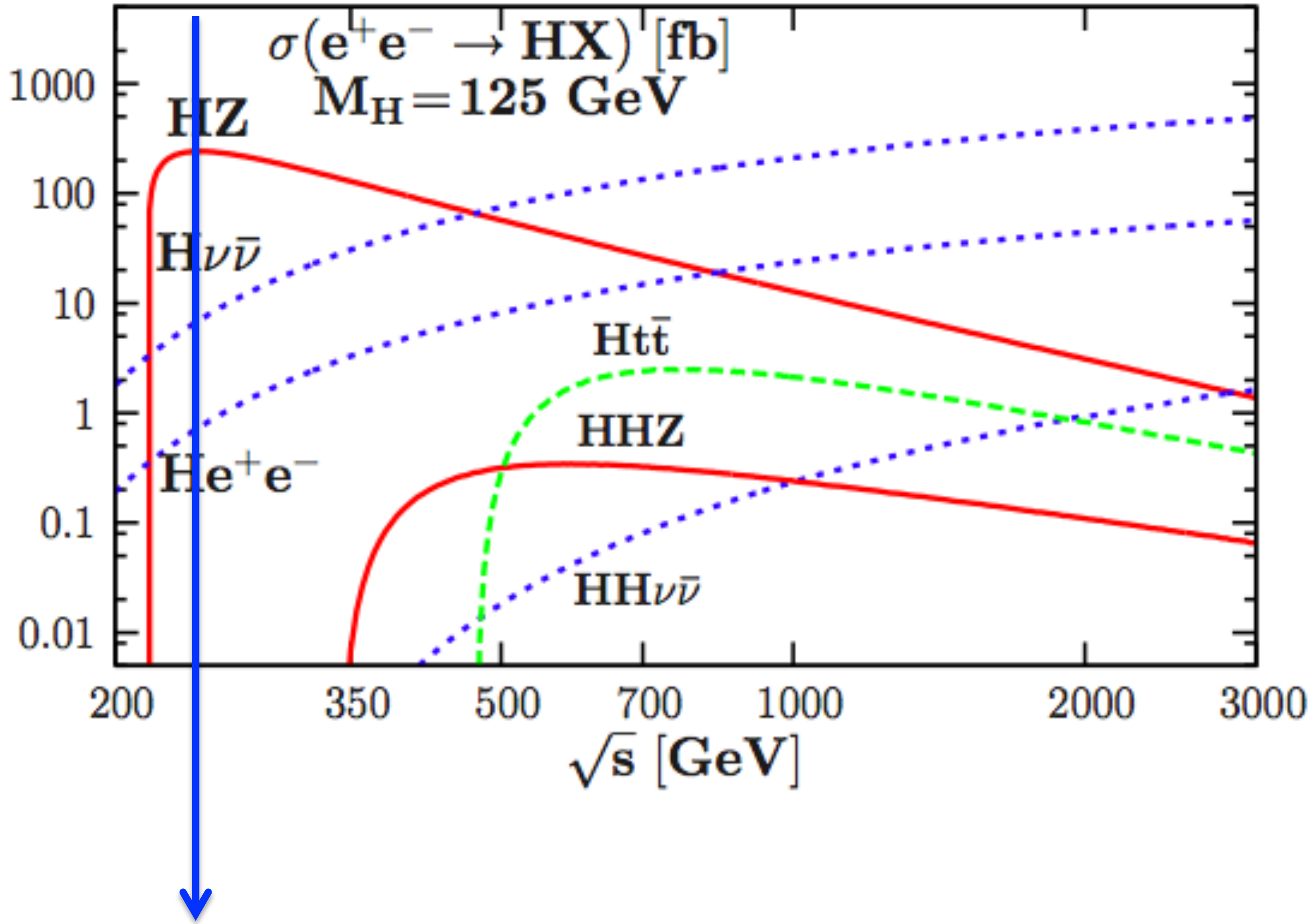
LC collider

$SU(2)_L$

LC collider

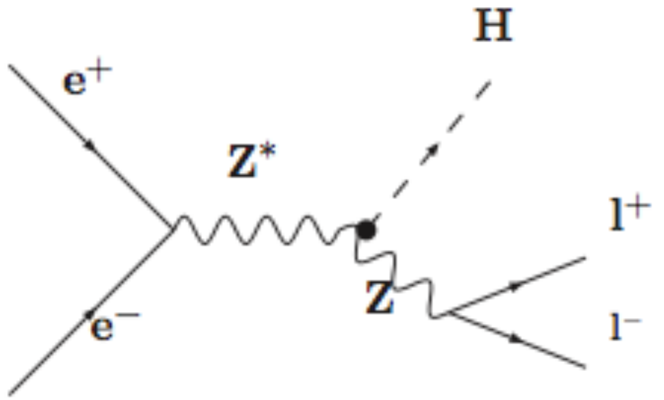
Full SM reach

LC collider



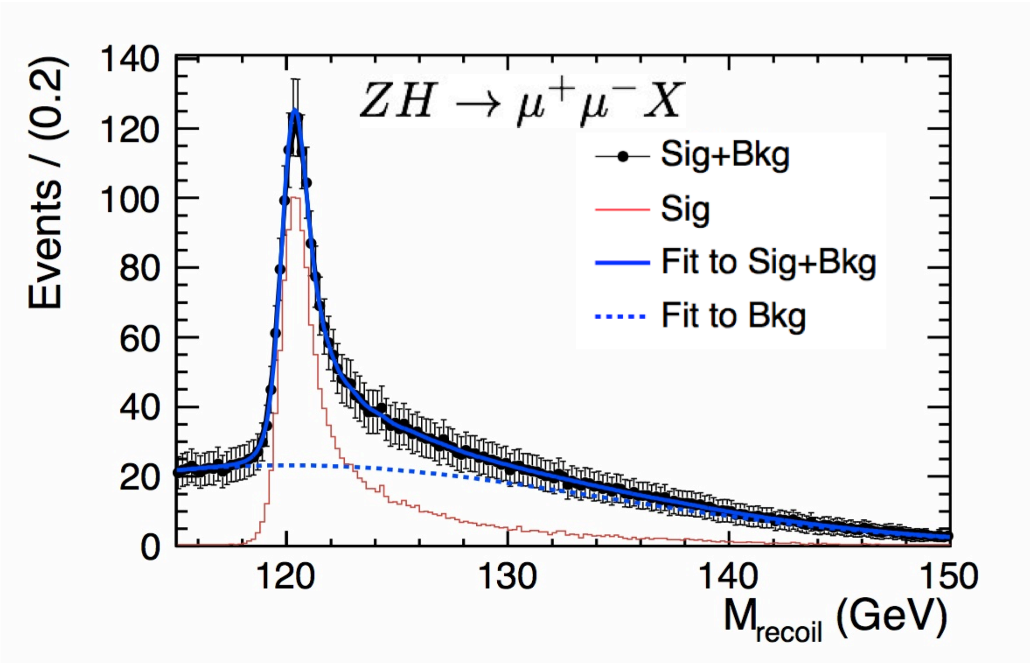
250 GeV is the entrance to Higgs world

Higgs-strahlung Process:



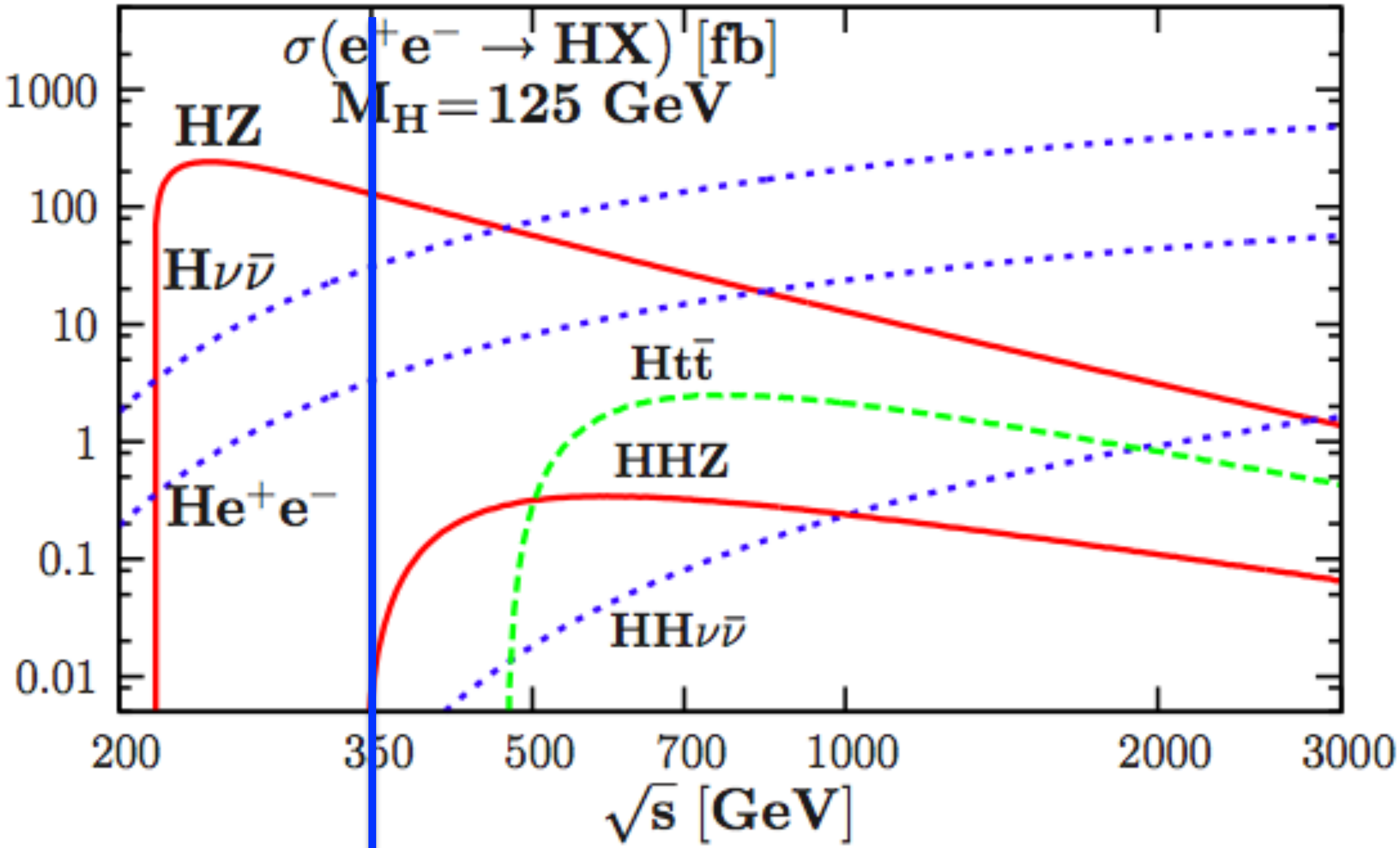
$$M_H^2 = (\sqrt{s} - E_Z)^2 - P_Z^2$$

$$g_{ZZH}^2 \propto \sigma = N/L\epsilon$$



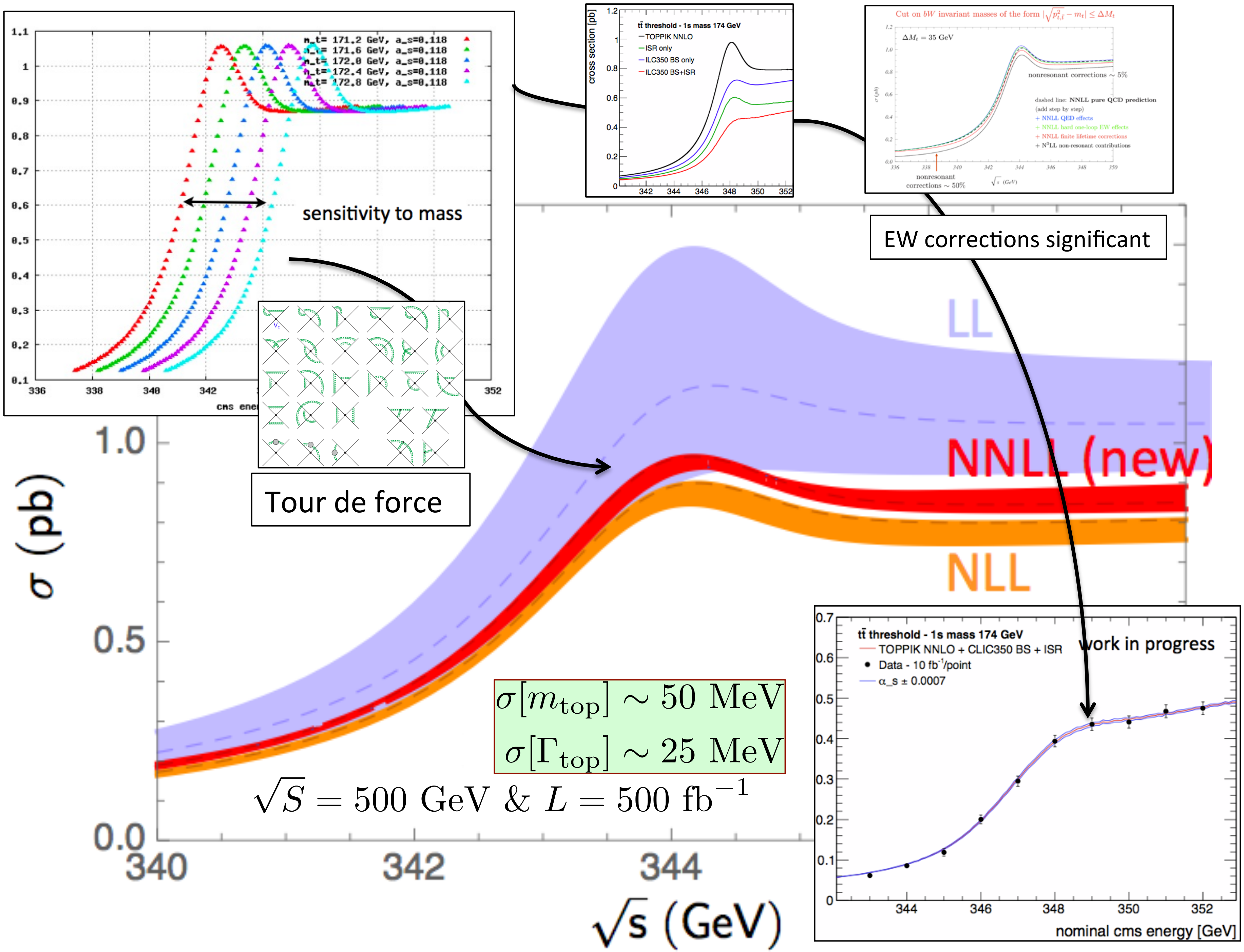
Invisible Higgs decays !

Two simultaneous thresholds : $t\bar{t}$ and HHZ

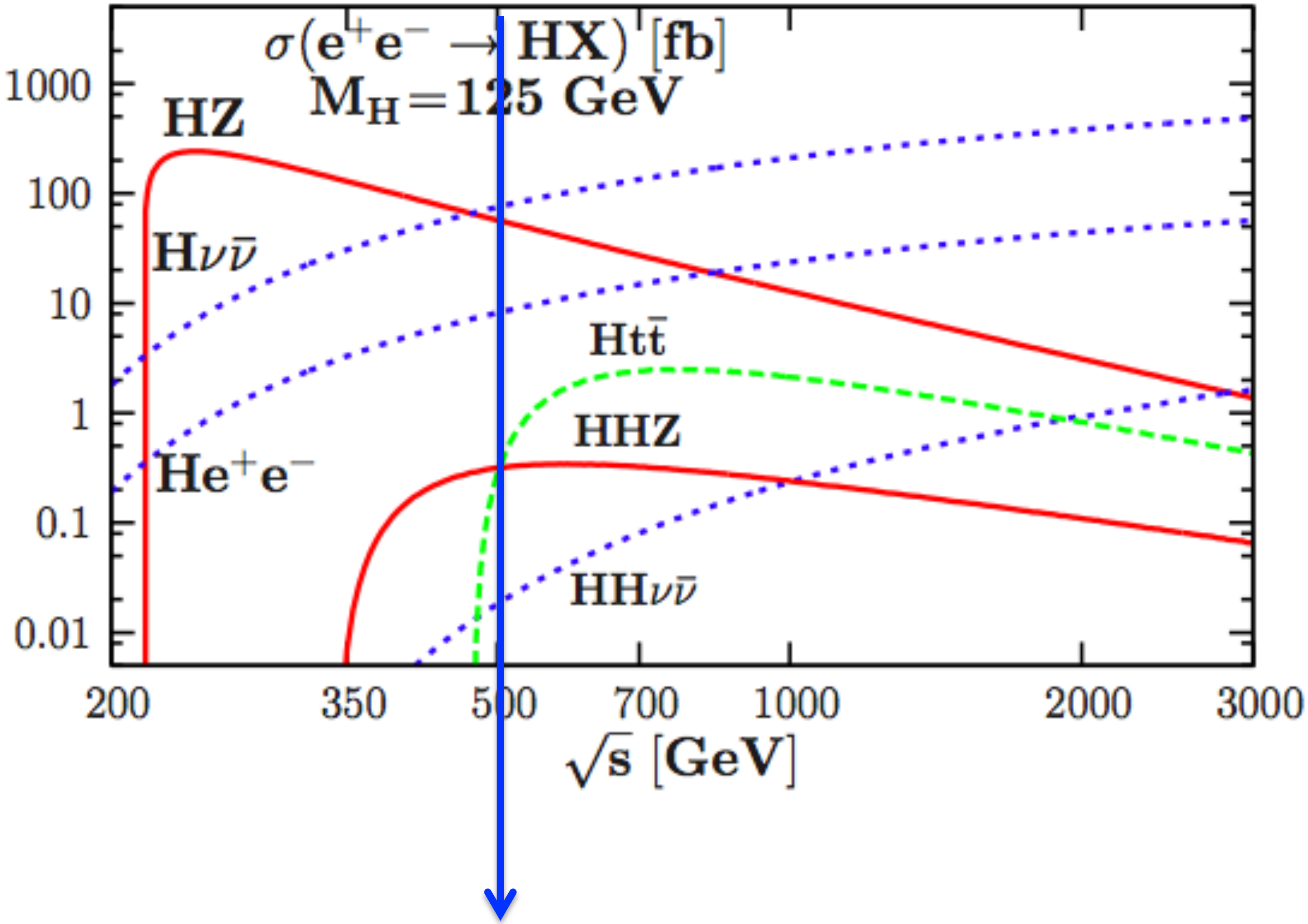


$t\bar{t}$ threshold

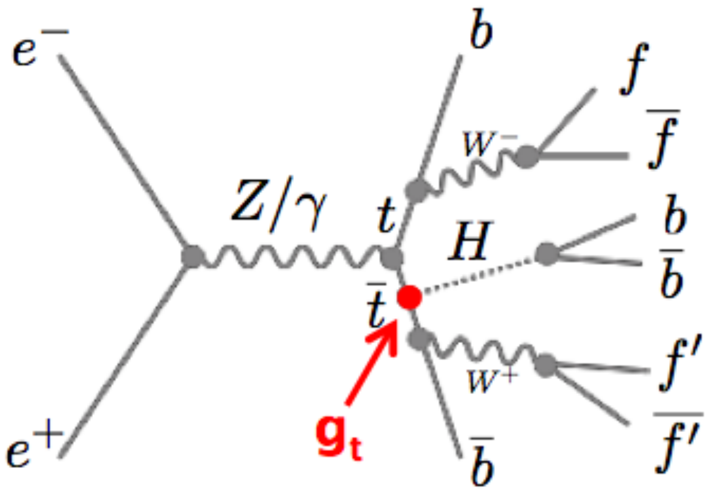
350 GeV is the entrance to top world

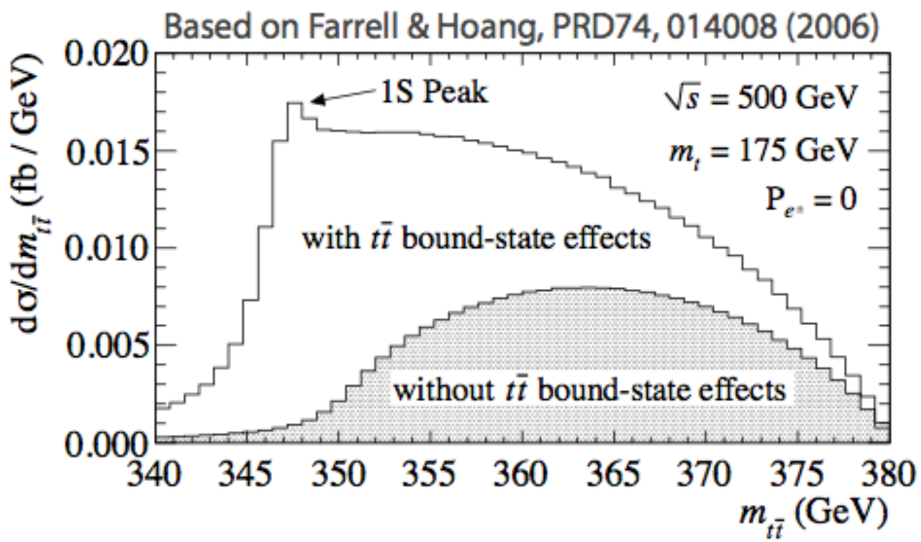


sensitivity to mass
Tour de force
EW corrections significant
LL
NNLL (new)
NLL
$\sigma[m_{\text{top}}] \sim 50$ MeV
$\sigma[\Gamma_{\text{top}}] \sim 25$ MeV
$\sqrt{S} = 500$ GeV & $L = 500$ fb^{-1}
σ (pb)
√s (GeV)
tt̄ threshold - 1s mass 174 GeV
TOPPIK NNLO
ISR only
ILC350 BS only
ILC350 BS+ISR
cross section [pb]
nonresonant corrections ~ 5%
nonresonant corrections ~ 50%
work in progress
TOPPIK NNLO + CLIC350 BS + ISR
Data - 10 fb^{-1}/point
α_s ± 0.0007
nominal cms energy [GeV]



500 GeV is the portal to the whole SM

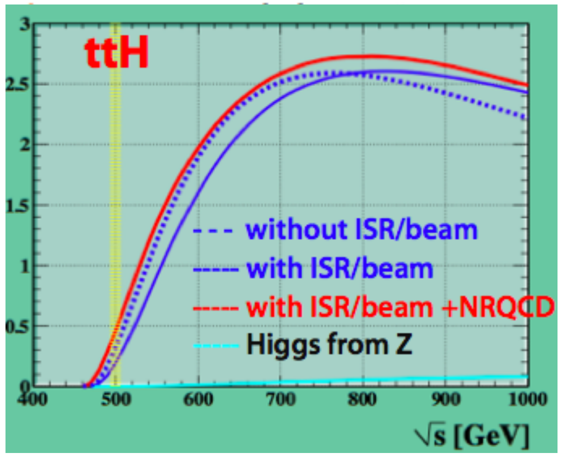




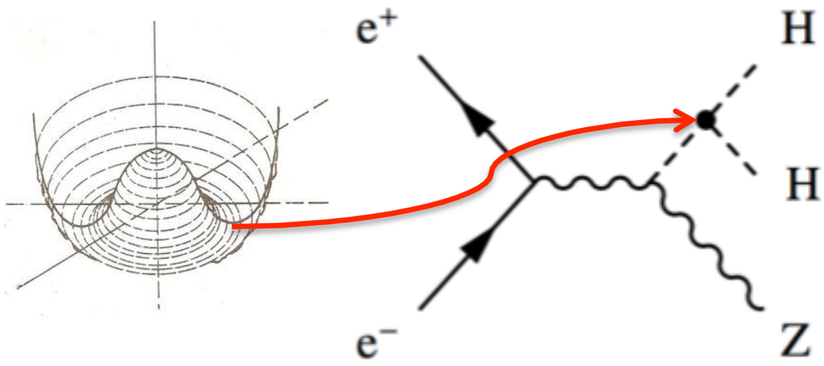
6-jet + lepton cut flow

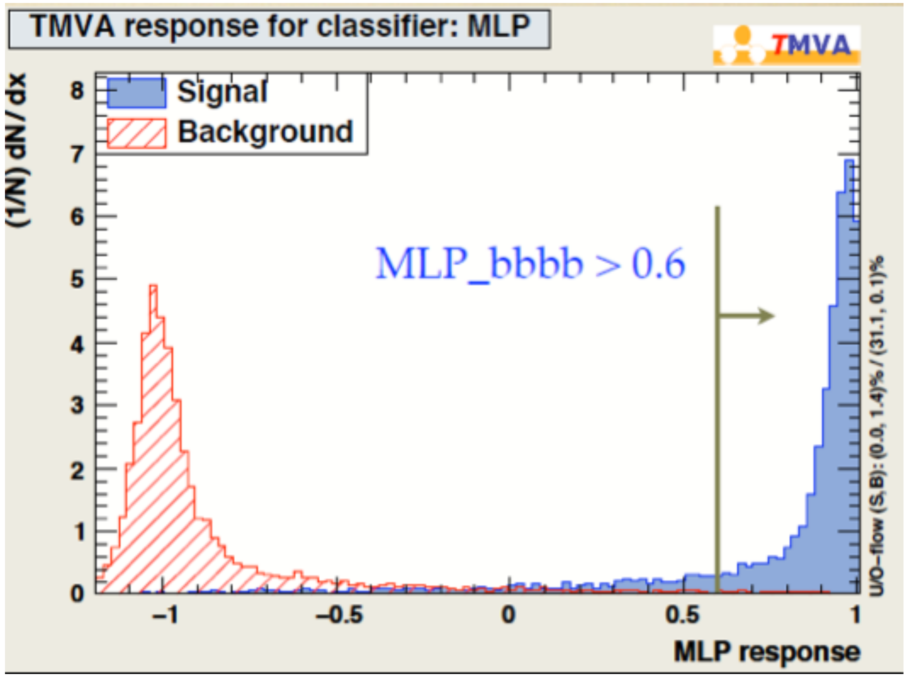
L = 1 ab^{-1}, polarized beams

cut \ sample	ttH (6J)	ttH (8J/4J)	tt	ttZ	ttg*-> ttbb	significance
no cuts	282.	358.	980739.	2407.	1160.	0.3
# isolated lepton = 1	180.	49.0	340069.	791.	398	0.3
thrust < 0.77	146.	37.7	144999.	617.	266.	0.4
$Y_{5\to4}$ > 0.005	126.	25.8	12298.	416.	114.	1.1
4x btag	49.0	4.2	173.	53.3	37.8	2.8
mass cuts	39.5	1.6	23.0	33.9	13.2	3.7



Coupling Htt at about 10%

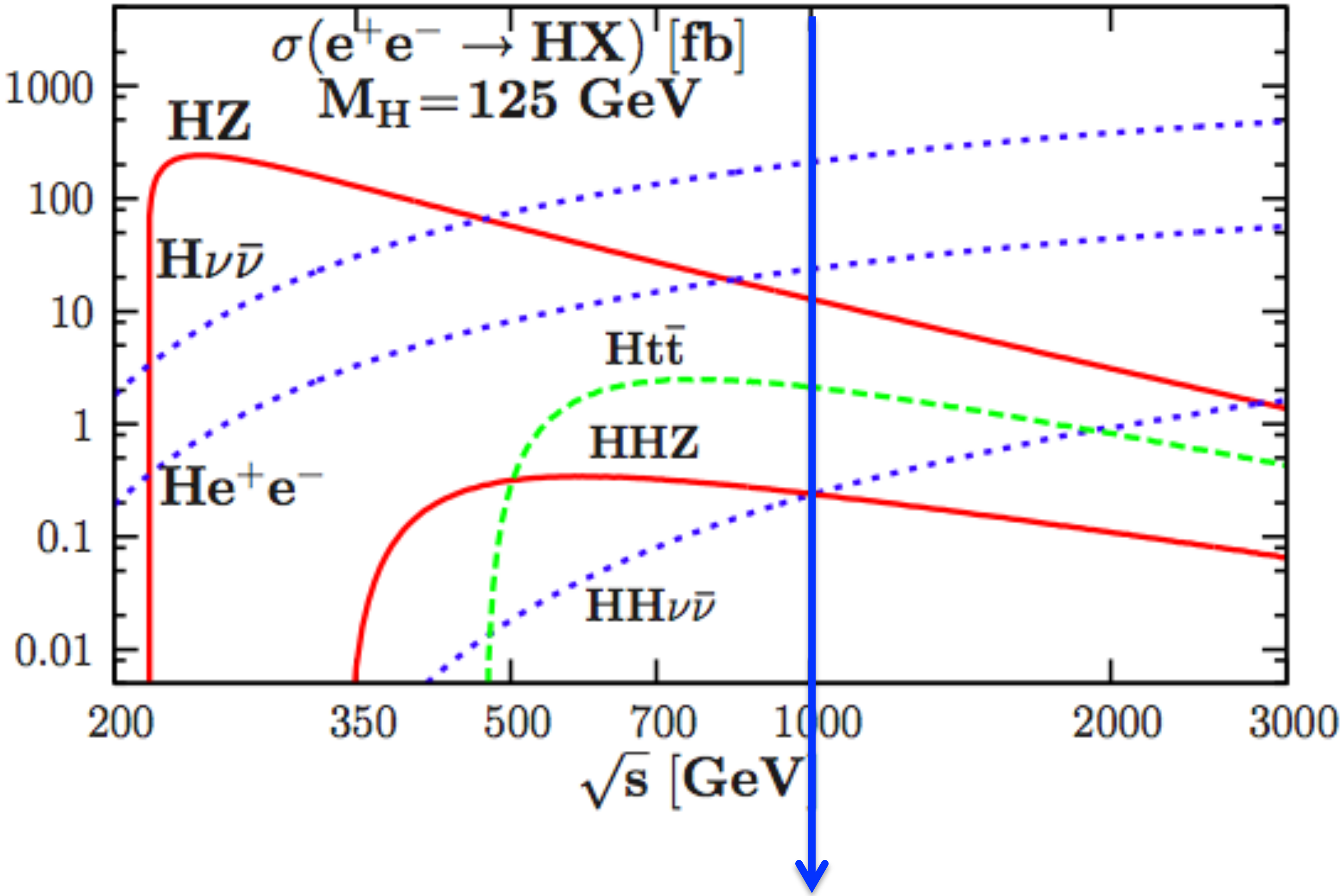




Energy (GeV)	Modes	signal	background	significance excess (I)	significance measurement (II)
500	$ZHH \to (l\bar{l})(b\bar{b})(b\bar{b})$	6.4	6.7	2.1σ	1.7σ
500	$ZHH \to (\nu\bar{\nu})(b\bar{b})(b\bar{b})$	5.2	7.0	1.7σ	1.4σ
500	$ZHH \to (q\bar{q})(b\bar{b})(b\bar{b})$	8.5	11.7	2.2σ	1.9σ
		16.6	129	1.4σ	1.3σ

Decay mode	BR.	# events in 1 ab^{-1}
qqbbbb	32%	146
ννbbbb	9%	42
qqbbWW*->qqbbqqqq	6%	28
llbbbb	4%	19
qqbbWW*->qqbbqqlν	3%	14
qqbbWW*->qqbblνqq	3%	14
others	43%	194
tt -> bbqqqq		~800,000
ZZZ, ZZH -> qqbbbb		~600

Coupling HHH at best about 20%



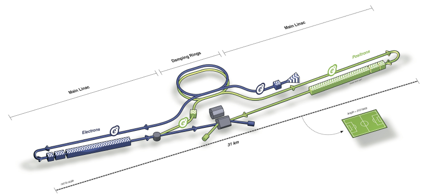
1000 GeV is the Vector-Vector world

August 2004

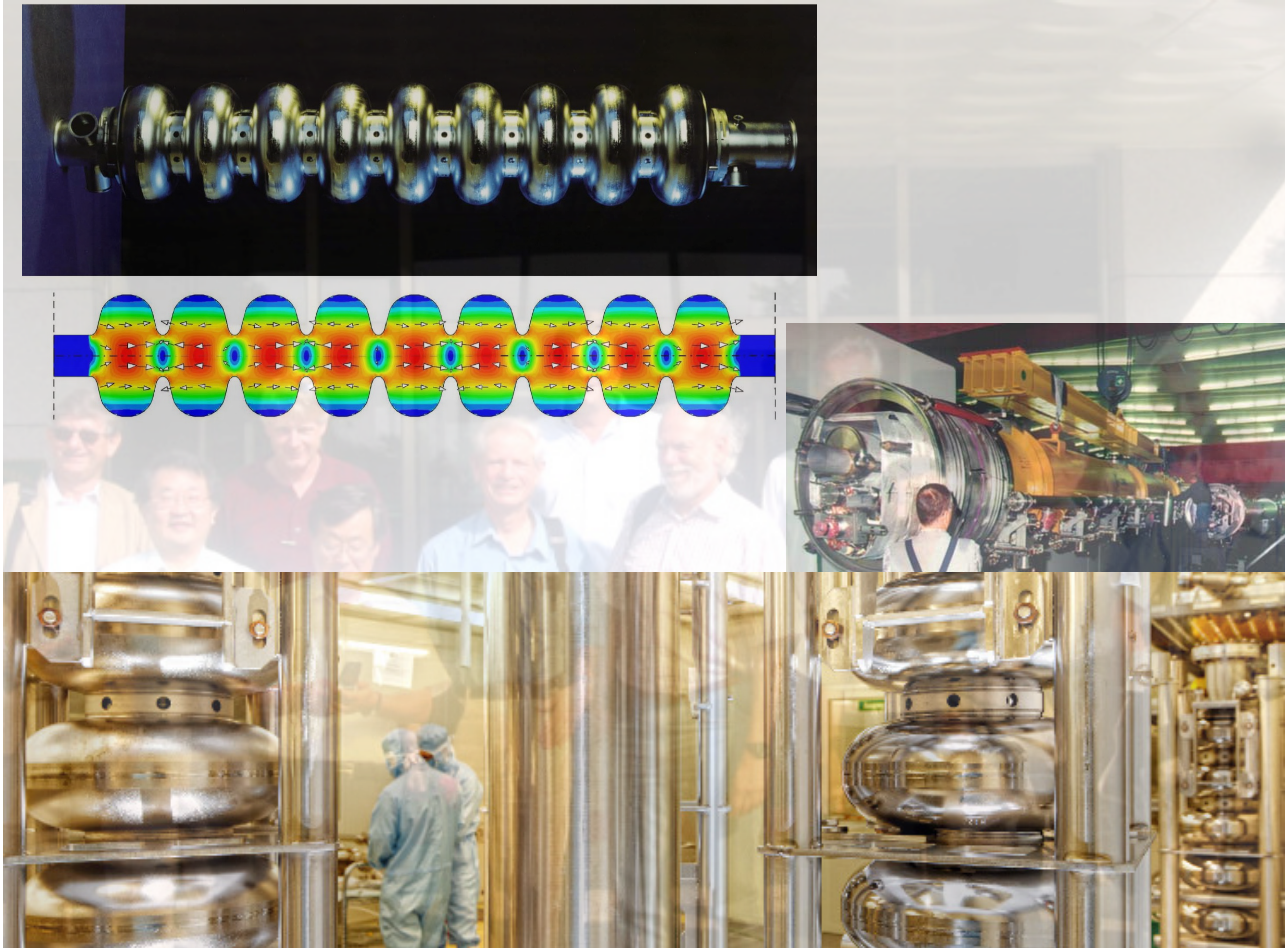
November 2004

March 2005

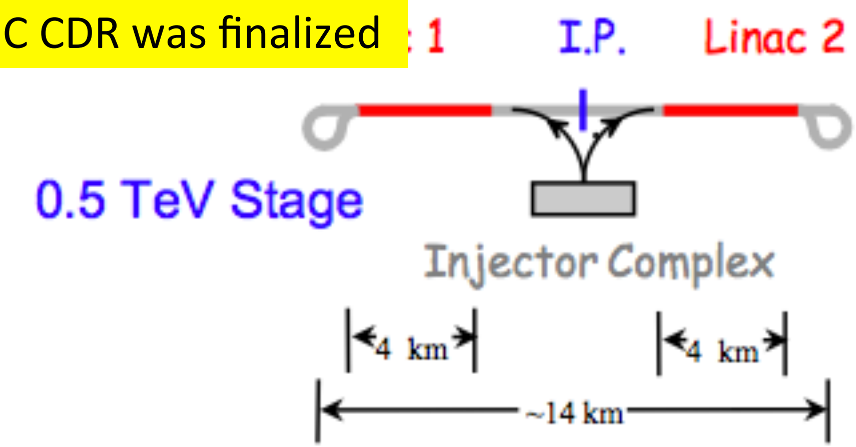
June 2013

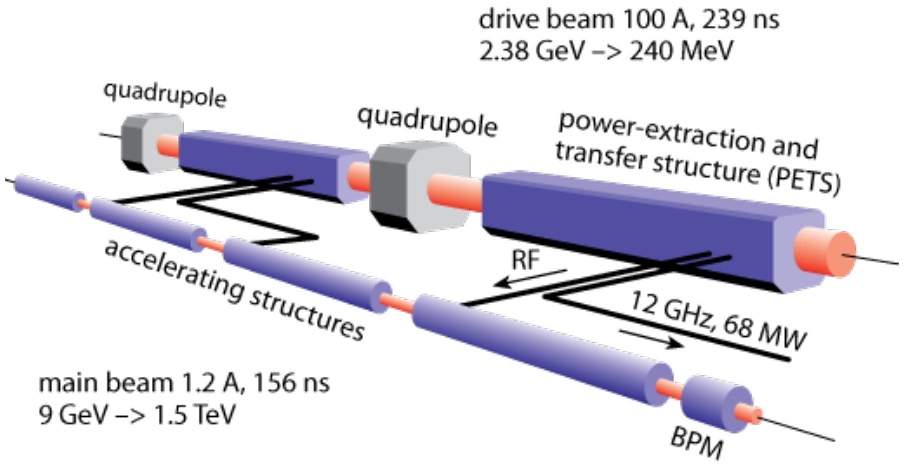


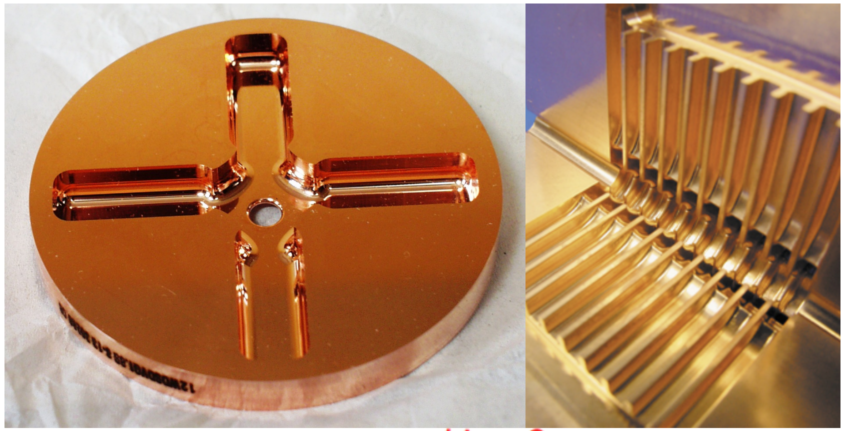
http://www.linearcollider.org/ILC/Publications/Technical-Design-Report

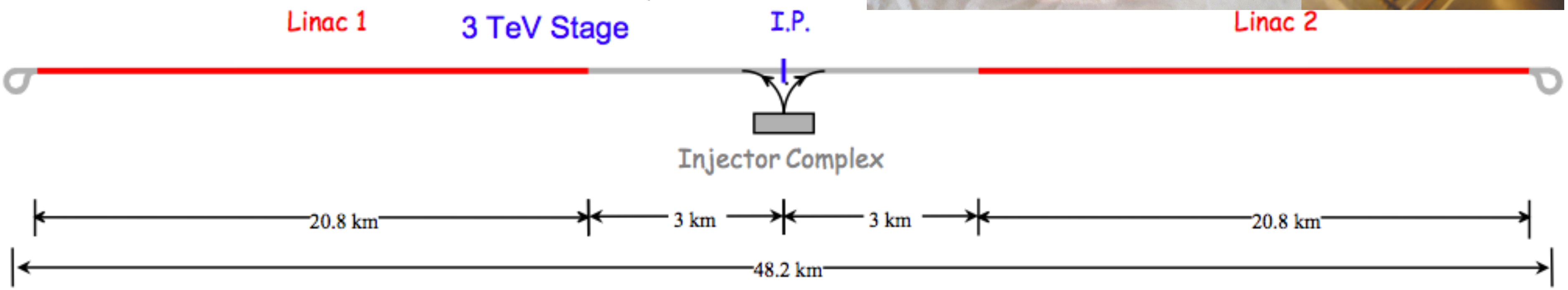


in Fall 2012 CLIC CDR was finalized










LINEAR COLLIDER COLLABORATION
Designing the world's next great particle accelerator
Director : Lyn Evans


And Light might come
from Japan

CERN Council approved updates European strategy for particle physics in May 2013

A very important issue for the strategy is preserving and building on the European model for cross-border research.

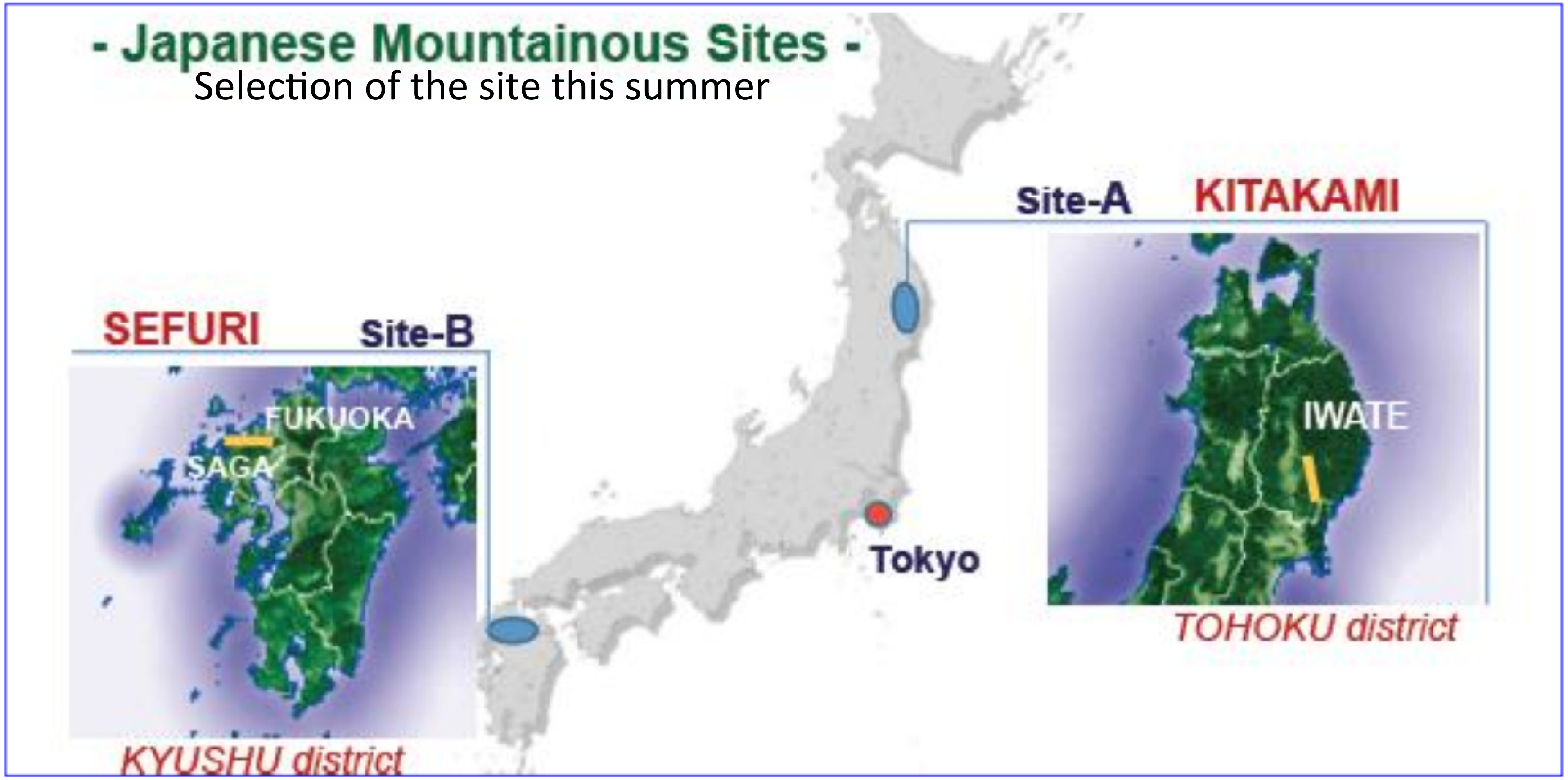
CERN, in close collaboration with research institutions in the CERN Member States and under the guidance of the CERN Council, will coordinate future European engagement with global particle physics projects in other regions.

The strategy notes that cross-border collaboration in science, as exemplified by the CERN model, pays dividends for Europe in terms of knowledge, innovation, education and training.

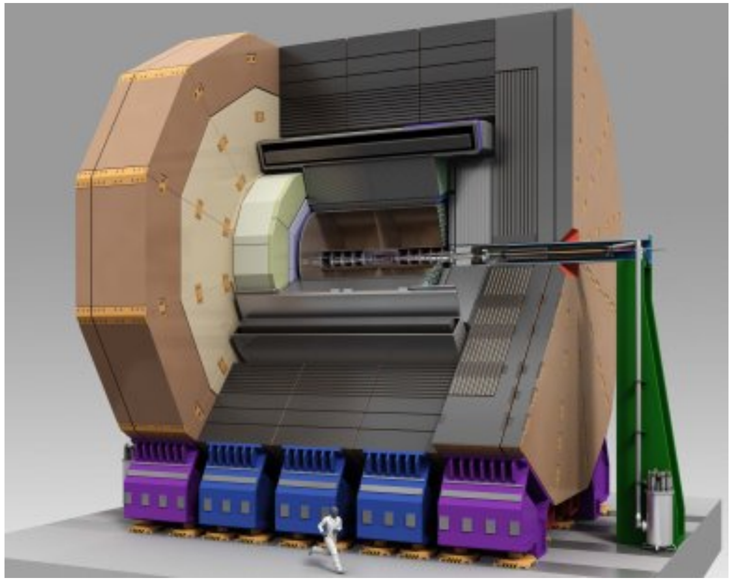
European Strategy Update

There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, w… participation. The initiative fr… particle physics community to h… is most welcome, and European groups are eager to participate. *Europe looks forward to a proposal from Japan to discuss a possible participation.*

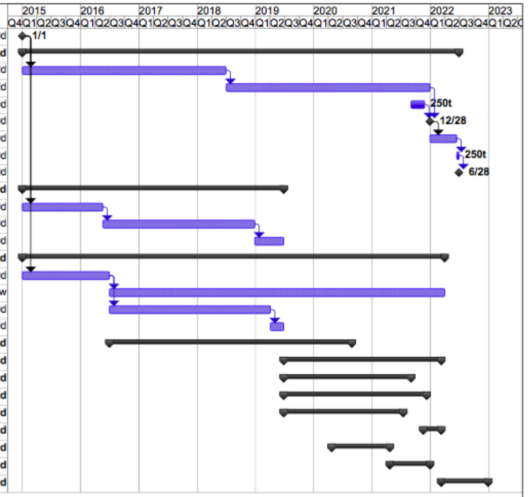
And Japan started high level international discussions


- Japanese Mountainous Sites -
Selection of the site this summer
Site-A
KITAKAMI
IWATE
TOHOKU district
SEFURI
Site-B
FUKUOKA
SAGA
KYUSHU district
Tokyo

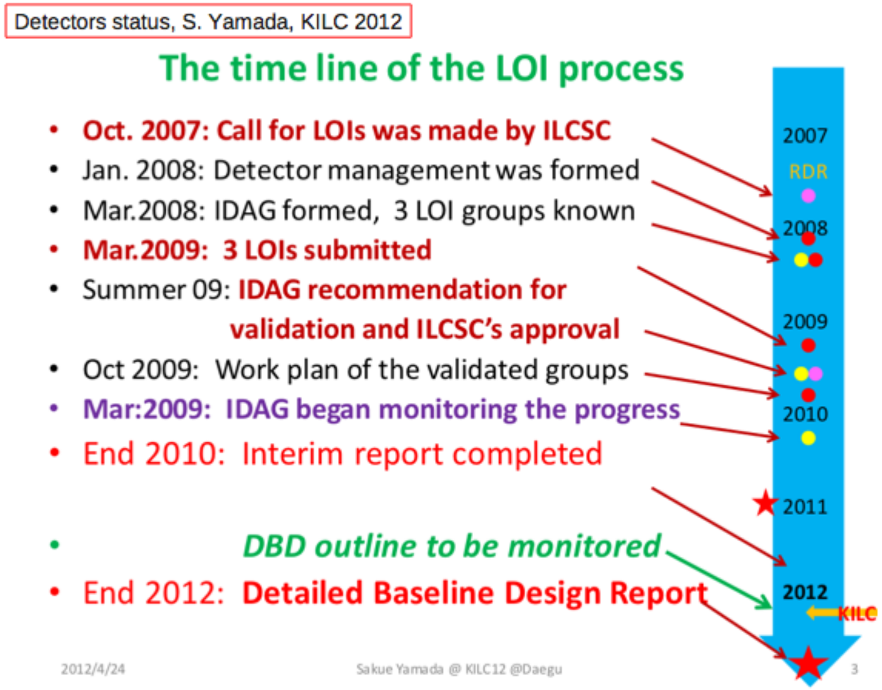
Y. Sugimoto

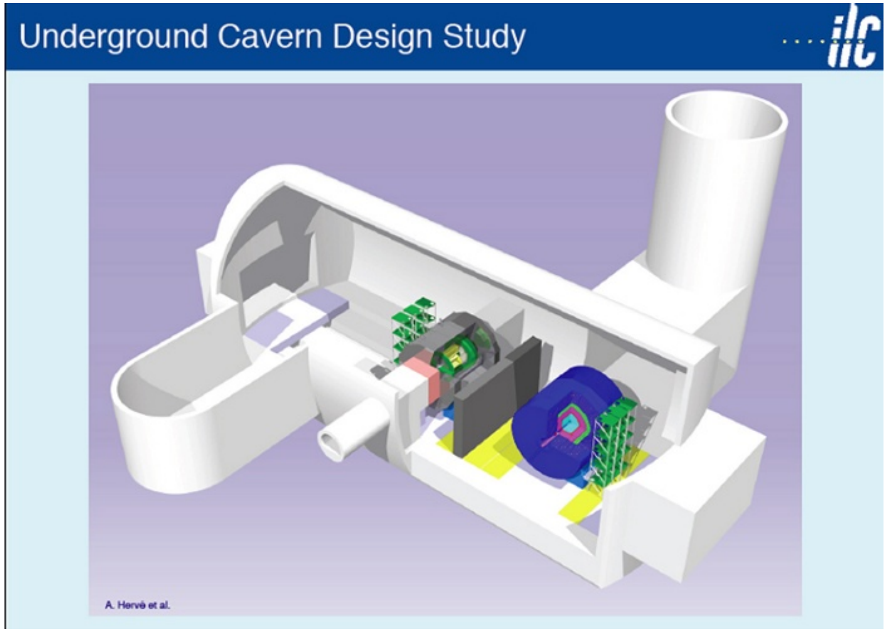


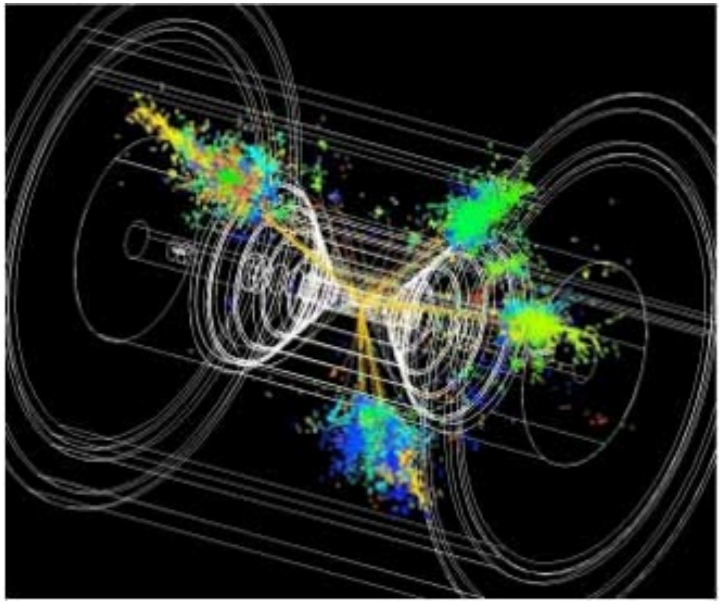
ID	Name	Duration
1	Ground breaking	0d
2	**Beam lines construction**	1954d
3	Tunnel	912d
4	Beamline harware install	912d
5	Beam line shield	60d
6	Start of beam commissioning	0d
7	BDS pre-commissioning	120d
8	Shield removal	10d
9	BDS ready for detectors	0d
10	**Experimental Hall**	1170d
11	Access tunnel	360d
12	Cavern	680d
13	Services	130d
14	**Detector construction on surface**	1890d
15	Surface assembly hall	390d
16	Detector assembly on surface	300w
17	Solenoid construction	720d
18	Solenoid surface test	60d
19	**Yoke pre-assembly**	1085d
25	**Detector assembly in cavern**	705d
26	**Yoke assembly**	570d
38	**Solenoid**	640d
49	**Barreal detectors**	535d
64	**Barrel inner detectors**	80d
67	**Endcap detectors**	260d
76	**QD0/FCALs install/cabling/test**	180d
82	**Commissioning**	210d



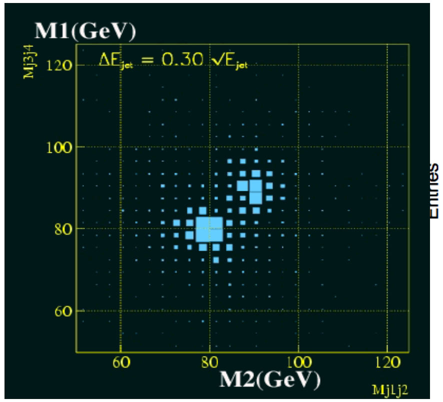
- Total construction time: ~8 years
- Detector underground construction: ~3 years



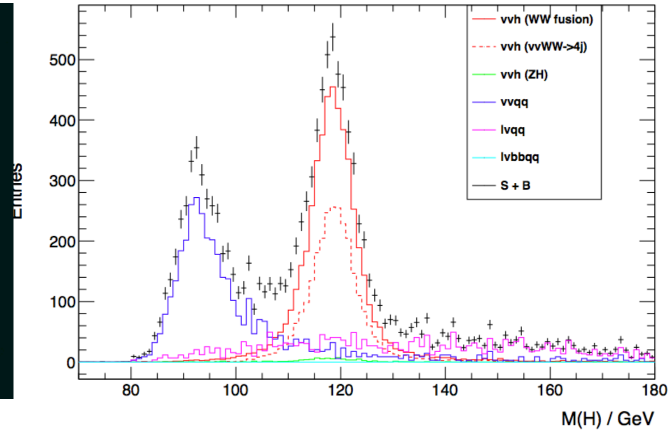


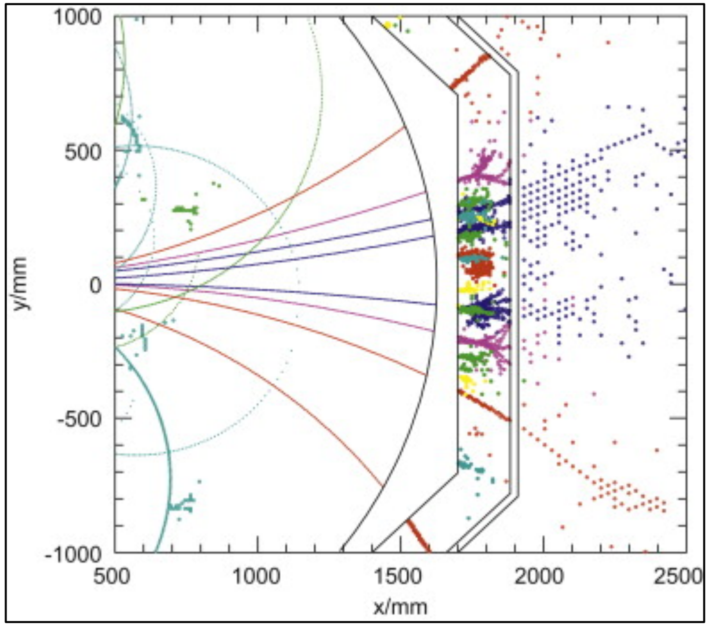


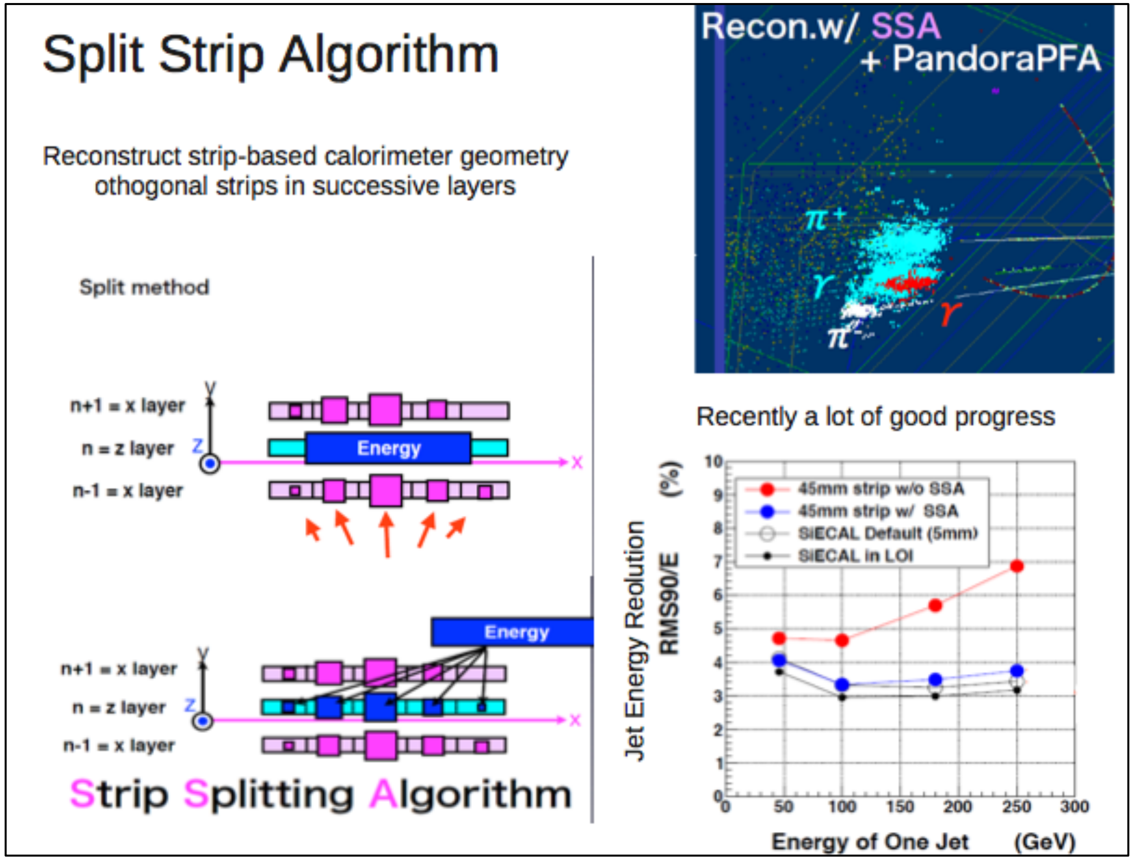
$e^+e^- \rightarrow \nu\bar{\nu}WW, \nu\bar{\nu}ZZ \quad W/Z \rightarrow jj$



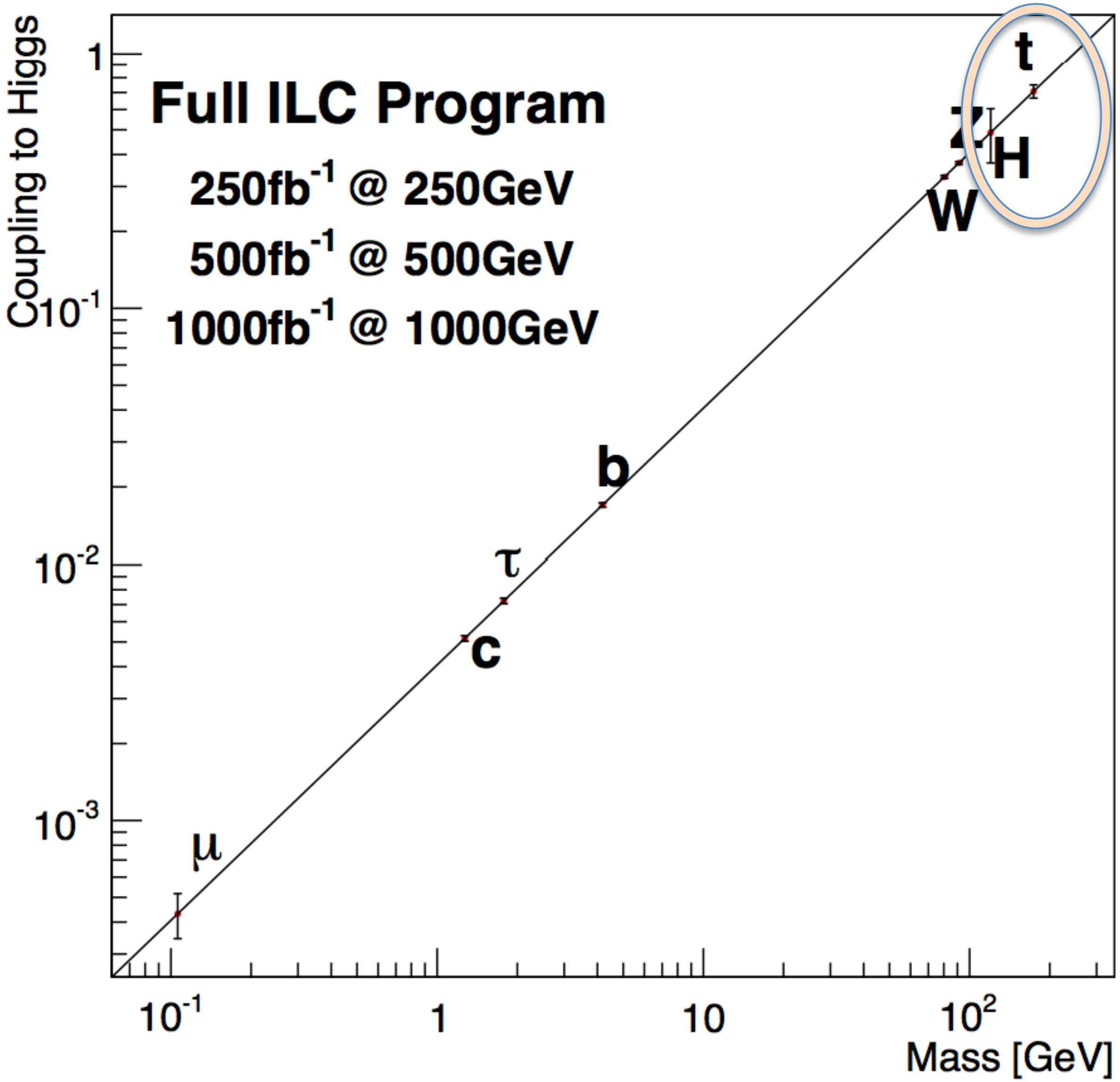
$e^+ + e^- \rightarrow \nu\bar{\nu}H \rightarrow \nu\bar{\nu}(WW^*) \rightarrow \nu\bar{\nu} + 4\text{jets}$





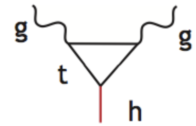


process	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [fb^{-1}]	(P_{e^-}, P_{e^+})	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$	$\Delta g/g$
$t\bar{t}h$	500	500	(-0.8,+0.3)	35%	18%
Zhh	500	500	(-0.8,+0.3)	64%	104%
$t\bar{t}h$	1000	1000	(-0.8,+0.2)	8.7%	4.0%
$\nu\bar{\nu}hh$	1000	1000	(-0.8,+0.2)	38%	28%



The most challenging

Γ_{gg}



$\Gamma_{\gamma\gamma}$

$\Gamma_{\rm invisible}$

$$\Gamma_{\rm tot} = \frac{\Gamma(h \to ZZ)}{BR(h \to ZZ)}$$

Mode	LHC	ILC(250)	ILC500	ILC(1000)
WW	4.1 %	1.9 %	0.24 %	0.17 %
ZZ	4.5 %	0.44 %	0.30 %	0.27 %
$b\bar{b}$	13.6 %	2.7 %	0.94 %	0.69 %
gg	8.9 %	4.0 %	2.0 %	1.4 %
$\gamma\gamma$	7.8 %	4.9 %	4.3 %	3.3 %
$\tau^+\tau^-$	11.4 %	3.3 %	1.9 %	1.4 %
$c\bar{c}$	–	4.7 %	2.5 %	2.1 %
$t\bar{t}$	15.6 %	14.2 %	9.3 %	3.7 %
$\mu^+\mu^-$	–	–	–	16 %
self	–	–	104%	26 %
BR(invis.)	$<$ 9%	$<$ 0.44 %	$<$ 0.30 %	$<$ 0.26 %
$\Gamma_T(h)$	20.3%	4.8 %	1.6 %	1.2 %

LHC projections are realistic, but are:
1) dealing only with subset of channels, yet,
2) preliminary (more important things to do :-),
3) cannot really assess experimental limitations to come,
4) cannot foresee theoretical progresses (20 years from now!)

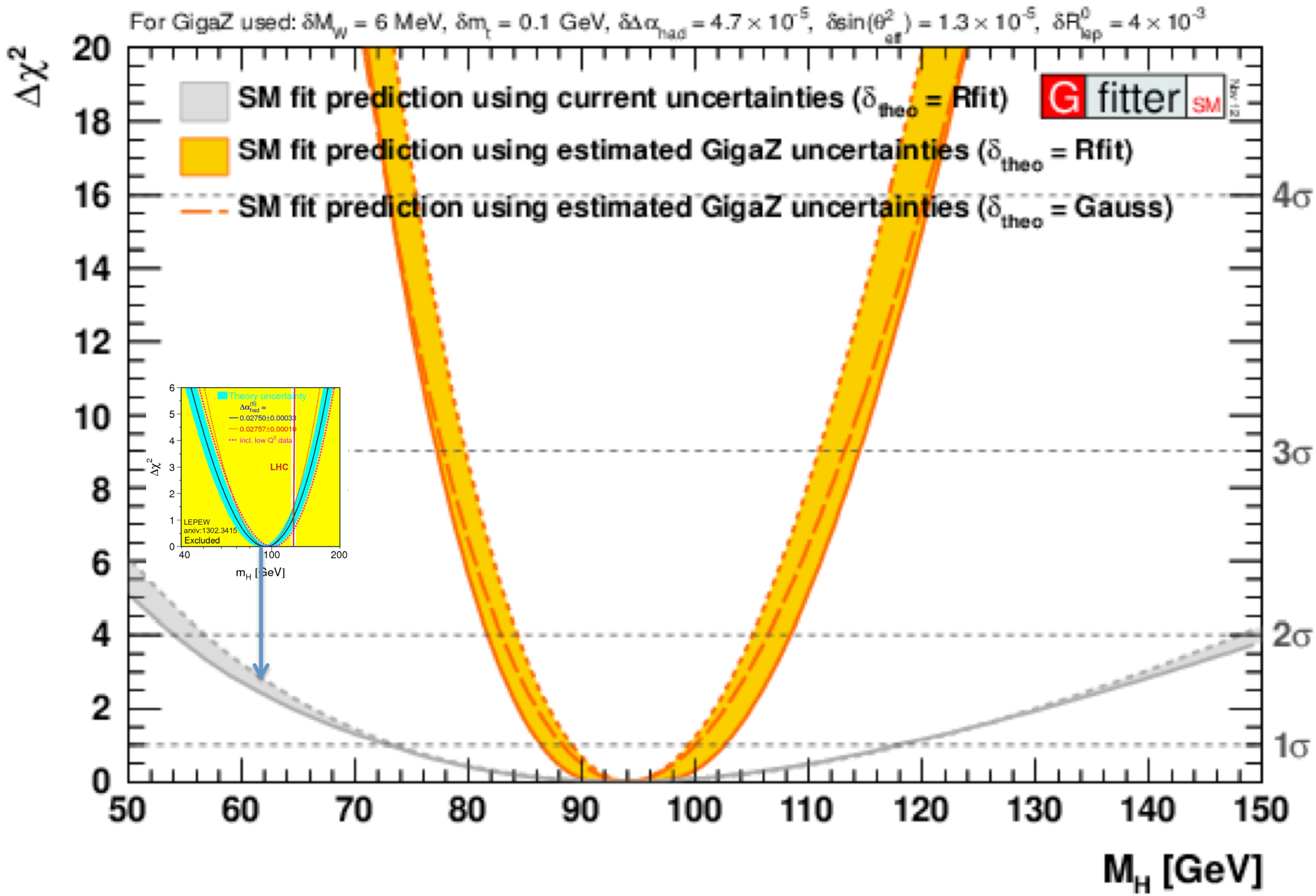
LC projections realistic but are:
1) dealing with (full) Monte Carlo only,
2) often preliminary (lack of manpower),
3) not boosted by real data in hand

But, undoubtly

A Quantitative & Qualitative difference between HL-LHC and LC

exp&the systematics limited

exp-statistically limited



For GigaZ used: δM_W = 6 MeV, δm_t = 0.1 GeV, $\delta\Delta\alpha_{had} = 4.7 \times 10^{-5}$, $\delta\sin(\theta^2_{eff}) = 1.3 \times 10^{-5}$, $\delta R^0_{lep} = 4 \times 10^{-3}$
SM fit prediction using current uncertainties (δ_{theo} = Rfit)
SM fit prediction using estimated GigaZ uncertainties (δ_{theo} = Rfit)
SM fit prediction using estimated GigaZ uncertainties (δ_{theo} = Gauss)
G fitter SM
$\Delta\chi^2$
M_H [GeV]
4σ
3σ
2σ
1σ
Theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02750±0.00033
0.02757±0.00010
incl. low Q^2 data
LHC
LEPEW
arxiv:1302.3415
Excluded
m_H [GeV]

LC collider

e-e collider

flexibility

Clean Luminosity

Mature technology

$SU(2)_L$

Full SM reach

LC collider

LC collider

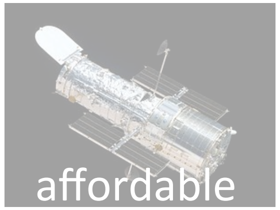
LC collider

A lot of challenges (for you) ahead

(if the ILC goes forward)

Many other dream-machines

(at High Energy)



flexibility

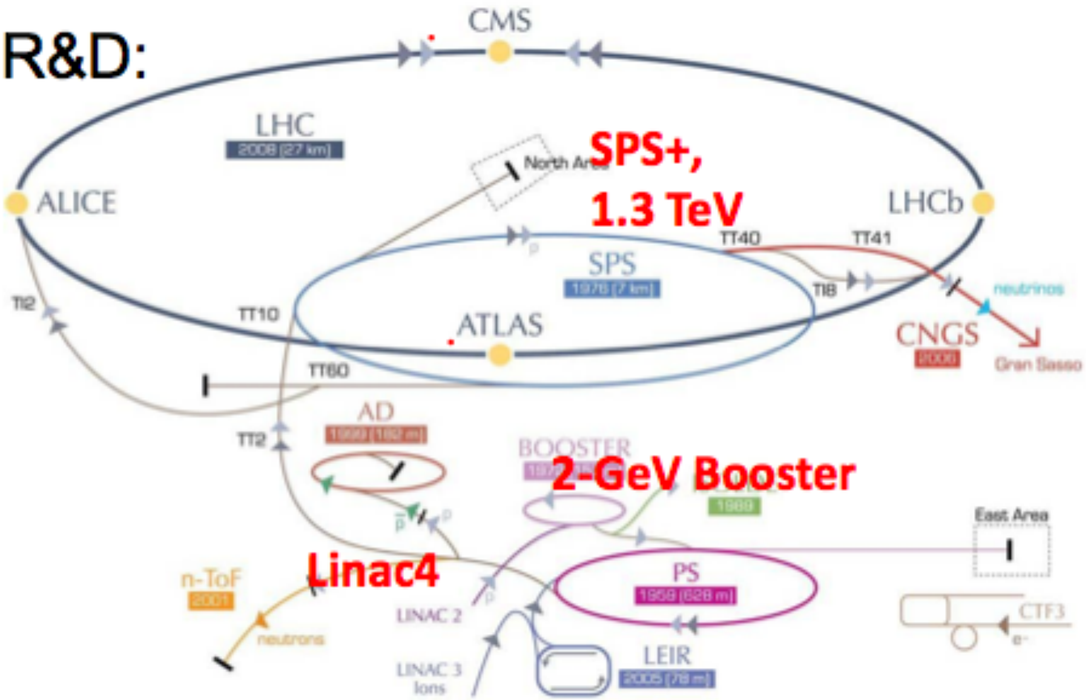
Clean Luminosity

Mature technology

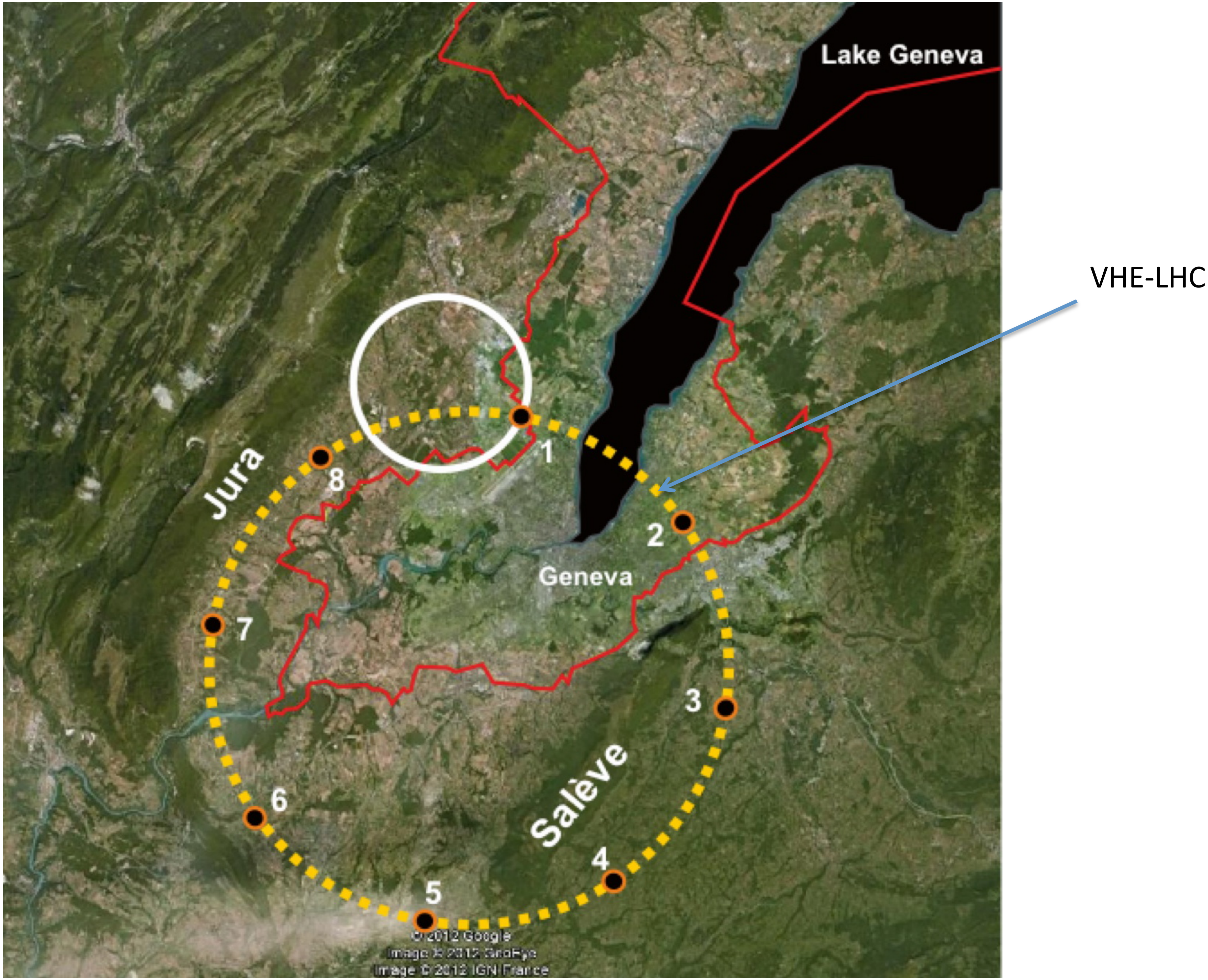
$SU(2)_L$

Full SM reach

HE-LHC – main Issues and R&D:



- High-field 20T dipole magnets based on Nb_3Sn, Nb_3Al, and HTS
- High-gradient quadrupole magnets for arc and IR
- Fast cycling SC magnets for ~1.3 TeV injector
- Emittance control in regime of strong SR damping and IBS
- Cryogenic handling of SR heat load (first analysis; looks manageable)
- Dynamic vacuum


Lake Geneva
VHE-LHC
Jura
Geneva
Salève
1
2
3
4
5
6
7
8
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Muon Collider Conceptual Layout

Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.

Compressor Ring
Reduce size of beam.

Target
Collisions lead to muons with energy of about 200 MeV.

Muon Capture and Cooling
Capture, bunch and cool muons to create a tight beam.

Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.

Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.

Collider Ring
Bring positive and negative muons into collision at two locations 100 meters underground.