Higgs and Beyond Workshop Summary

Tohoku

Jim Brau

June 8, 2013

The Future Begins Now!

- Following half a century of building anticipation, a Higgs boson has been discovered
  - now we are compelled to discover its properties
- The LHC experiments will continue to refine our understanding of this recently discovered particle
- We must also plan our arsenal of new tools to complement the LHC capabilities
  - options for the future include precision measurements and advancing to higher energy

One half century
from Higgs conception to discovery

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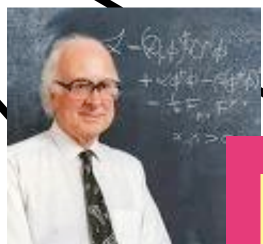
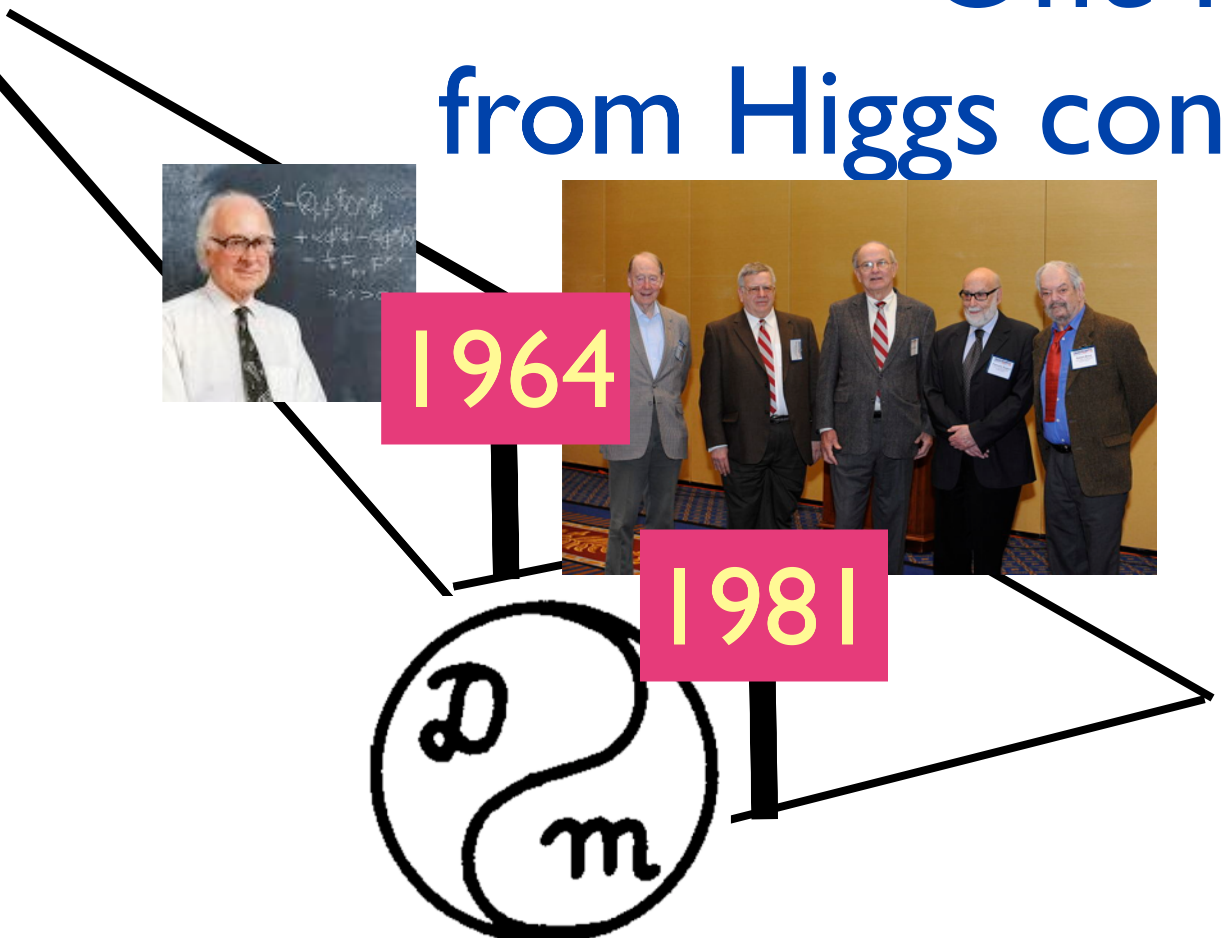


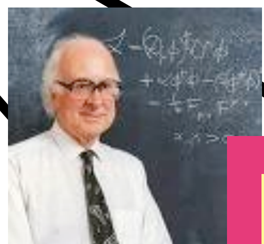
1964

One half century
from Higgs conception to discovery



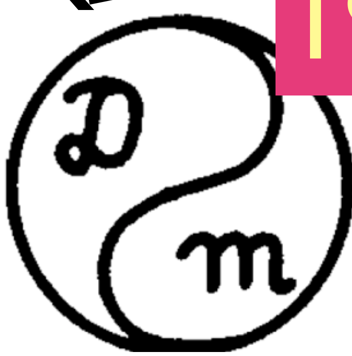
Problem #1 of HEP - scalars
Okun, Lepton-Photon ‘81

One half century from Higgs conception to discovery



1964

1981



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CERN Council approves the LHC

1994

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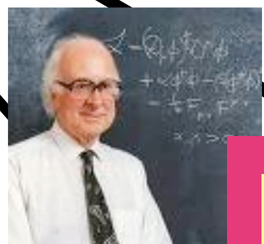

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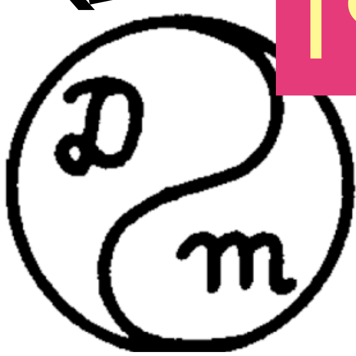

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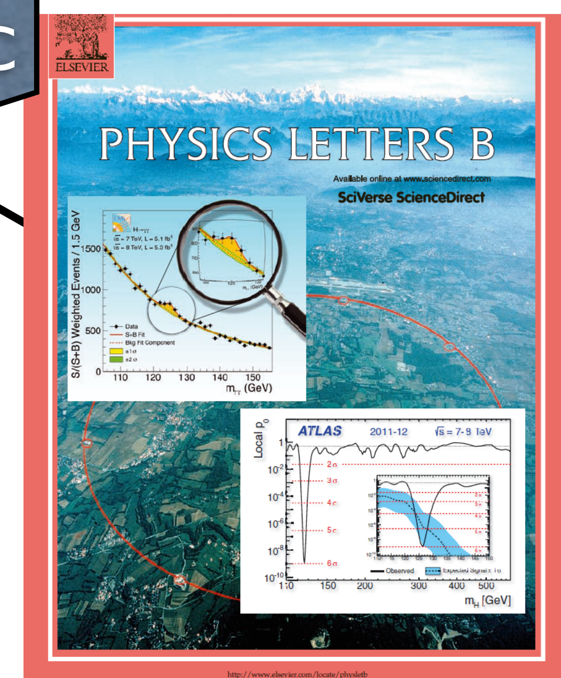
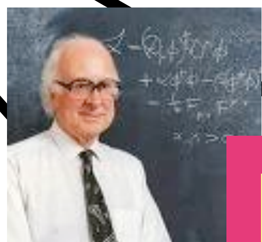


One half century
from Higgs conception to discovery



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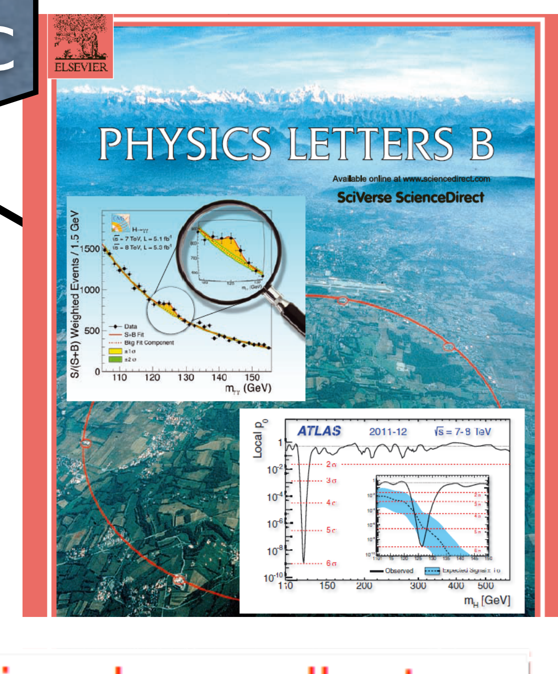


A triumph for experiment! Extremely tough signals: small rates, huge backgrounds.

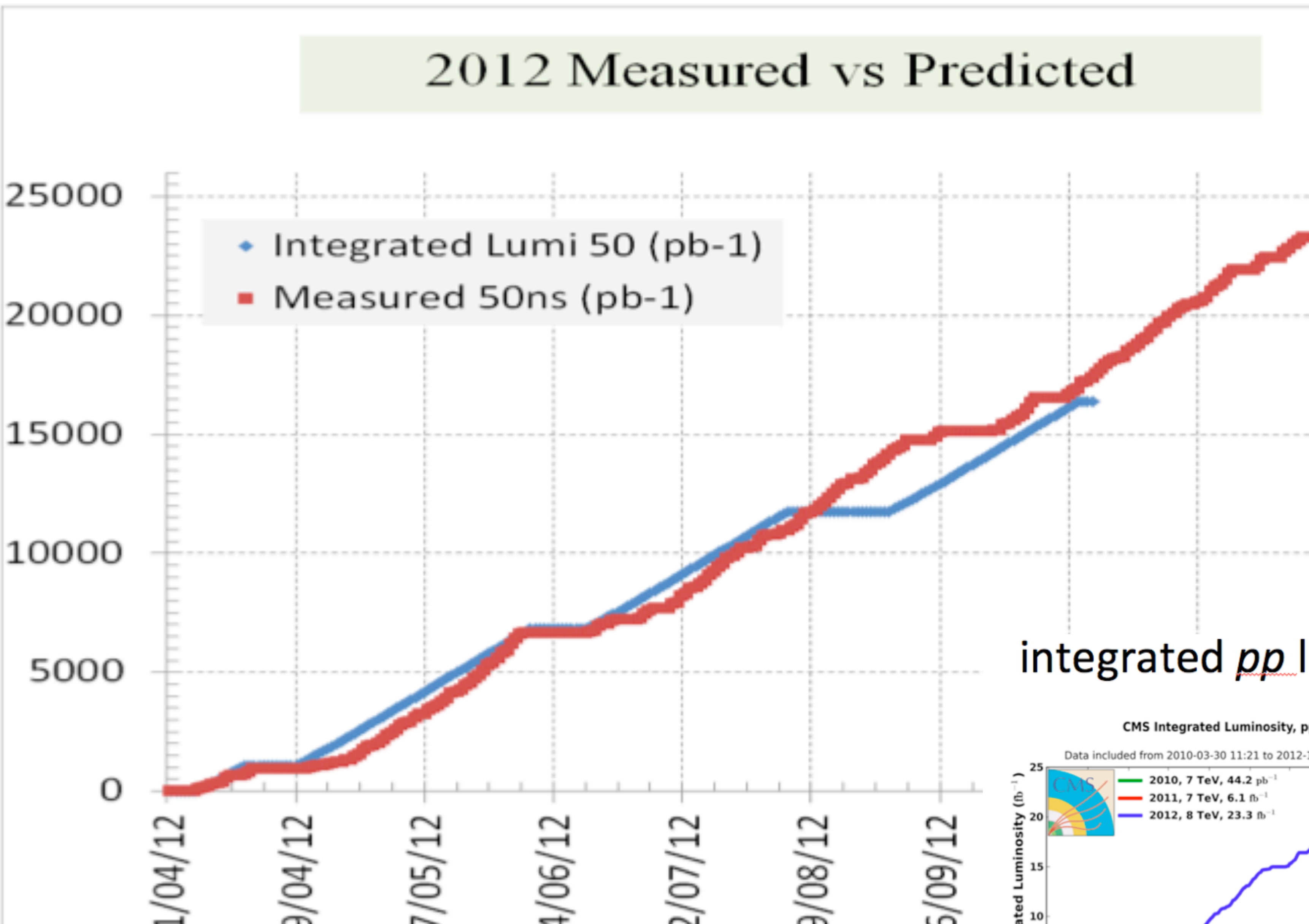
A triumph for theory: amazing that we can predict production, decay, to such levels of accuracy! All governed by a remarkably

Michael Dine

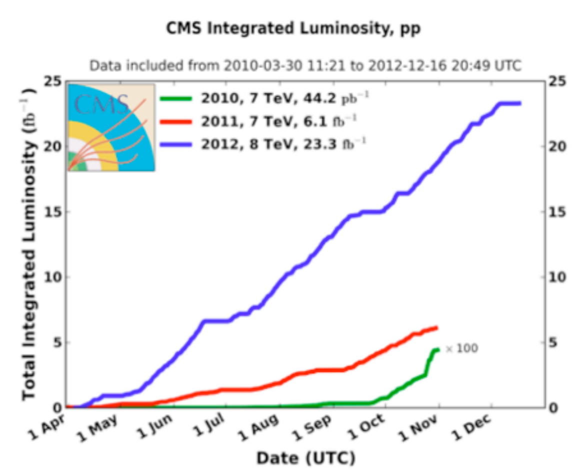
and TRIUMPH FOR MACHINES!

Steve Myers, CMAC

2012



integrated *pp* luminosity 2010-12

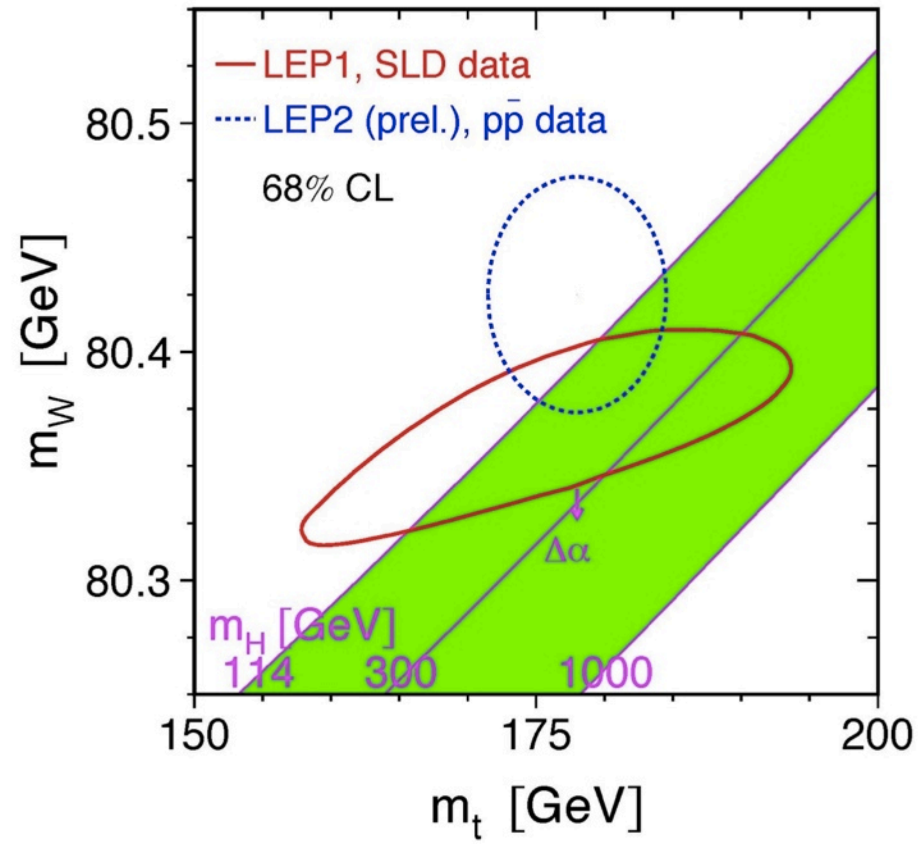


- 2010: **0.04 fb^{-1}**
  - 7 TeV CoM
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - 7 TeV CoM
  - Exploring the limits
- 2012: **23.3 fb^{-1}**
  - 8 TeV CoM
  - Production

Frank Zimmerman

Indirect evidence long ago

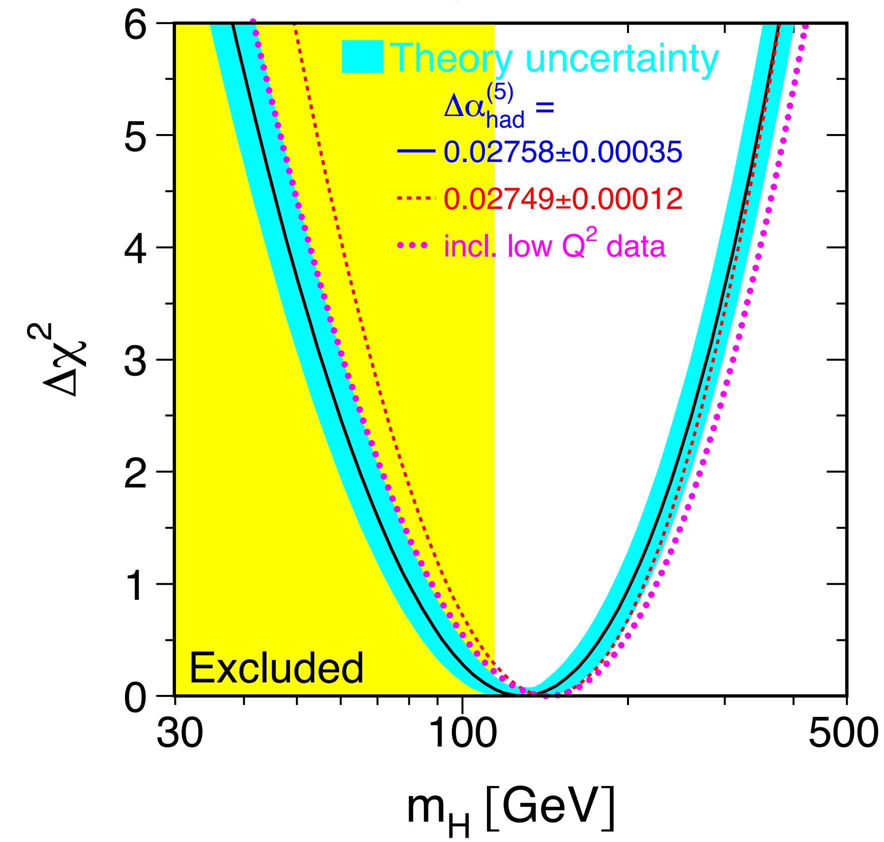
- LEP/SLC Z-pole measurements plus m_t, m_W, and Γ_W from Tevatron run-1 and LEP-II
- $M_H = 129^{+74}_{-49}$ GeV

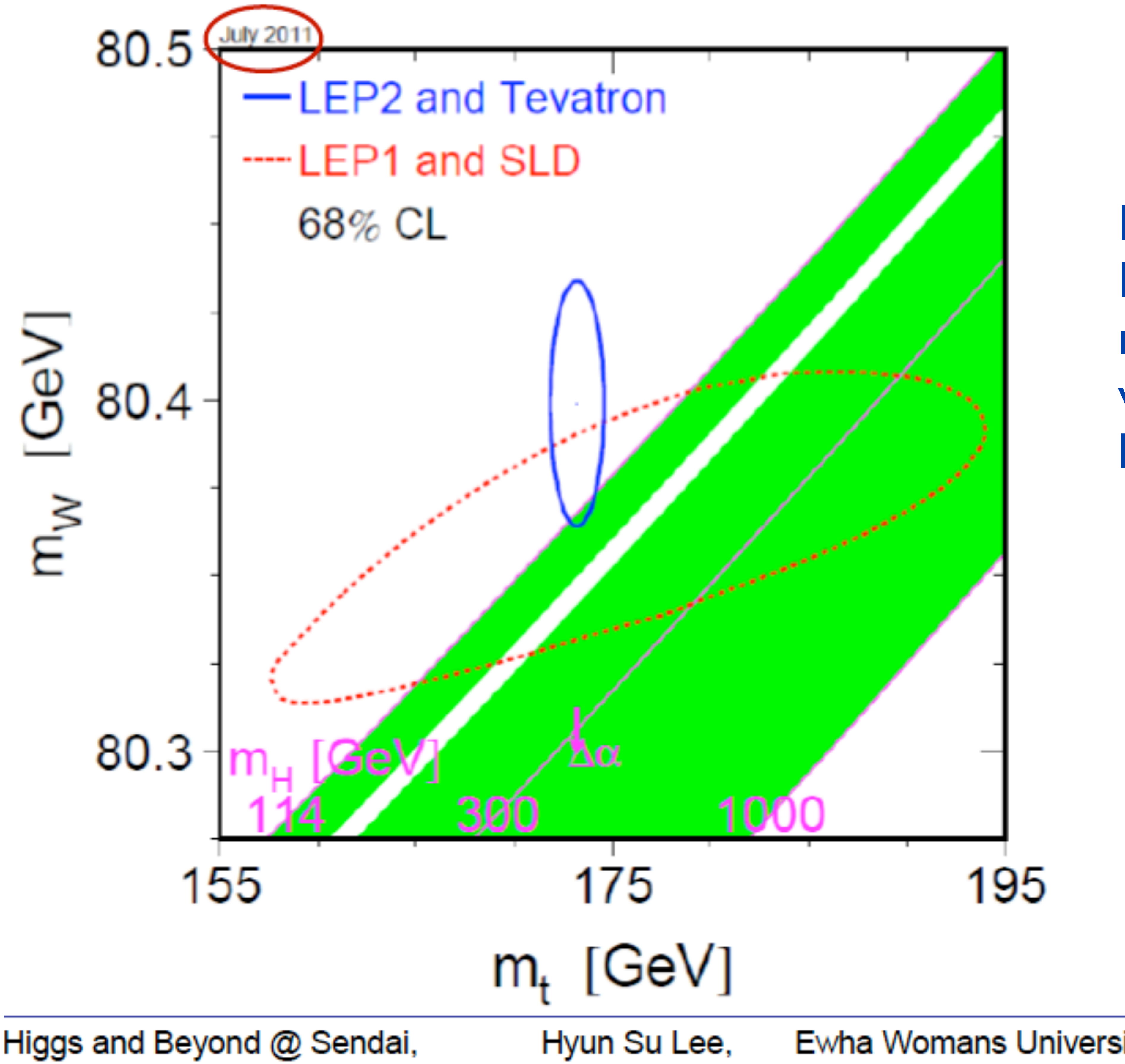


Precision Electroweak Measurements on the Z Resonance
The ALEPH, DELPHI, L3, OPAL, SLD Collaborations,
the LEP Electroweak Working Group,
the SLD Electroweak and Heavy Flavour Groups

7 September 2005

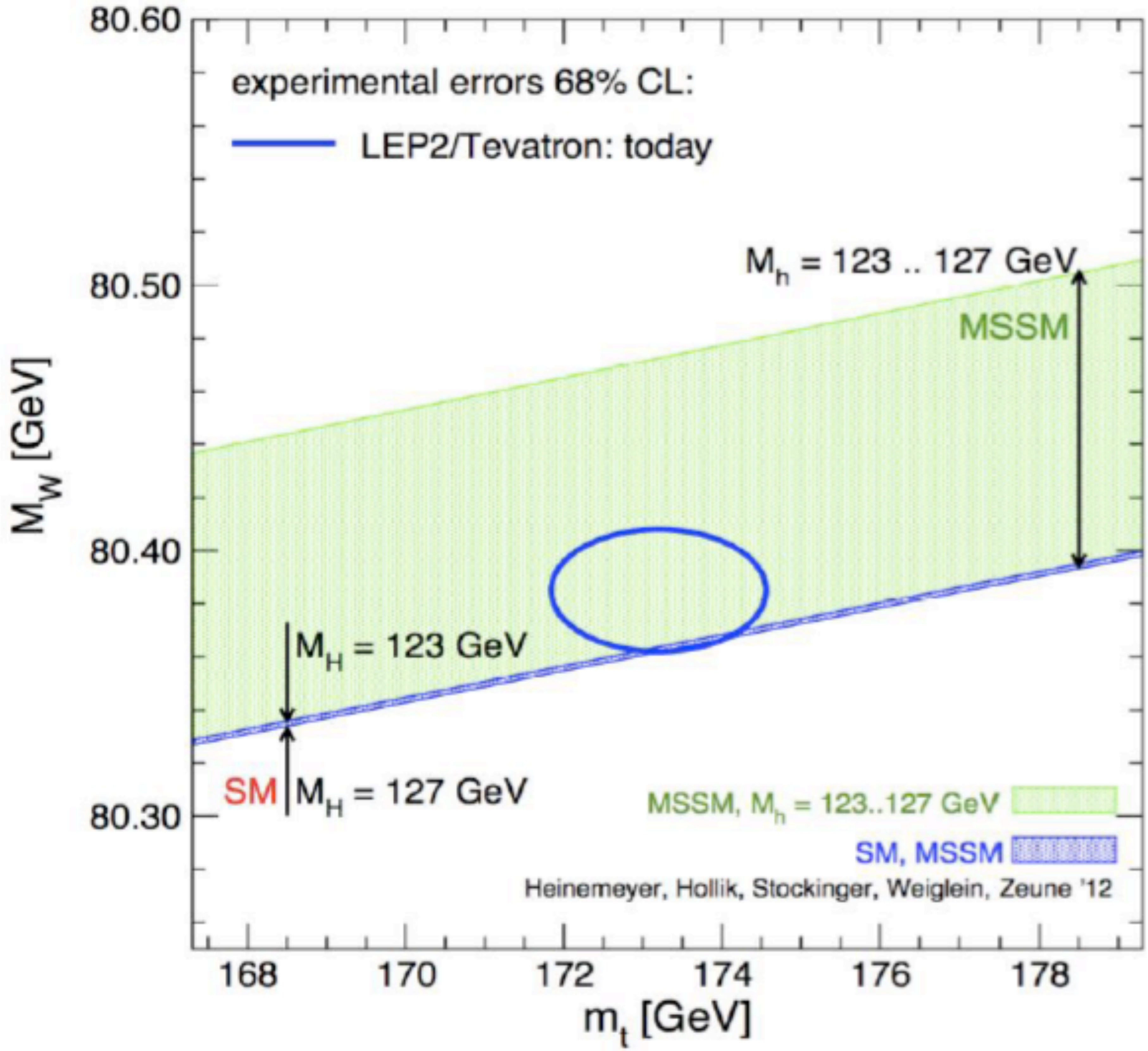
CERN-PH-EP/2005-041 and hep-ex/0509008
Published in Physics Reports: Volume 427 Nos. 5-6 (May 2006) 257-454.





By 2011, the EW precision measurements were narrowing hiding places

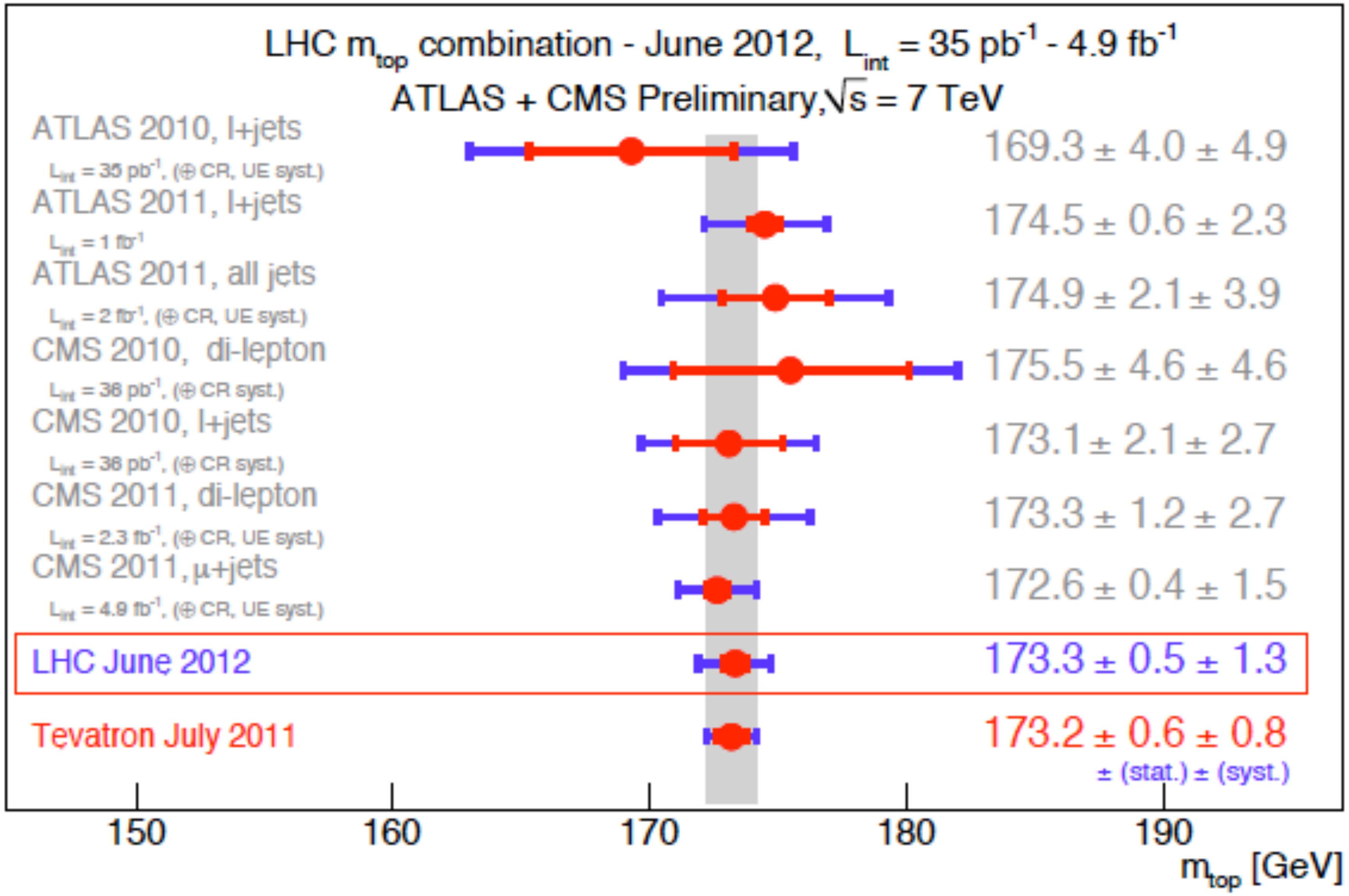
Hyun Su Lee



Tevatron has continued to tighten EW precision constraints

Hyun Su Lee

Combination of ATLAS and CMS



Measurement of the top quark mass at the LHC reached a great precision. Some results are not included in this combination and succeeded to reduce systematic uncertainty.

➔Expect to obtain much better combined result in the future.

Miho Yamada

Combination of ATLAS and CMS results on the mass of the top quark using up to 4.9 fb^{-1} of data
ATLAS-CONF-2012-095

July 4, 2012

- Direct evidence appears with discovery
  - ATLAS
  - CMS

Francesco Conventi
Serguei Ganjour
+others

Questions abound; Answers emerging

- Is this the SM Higgs?
- Does this particle, itself, fully explain electroweak symmetry breaking and the origin of mass for all particles?

A new boson was found at LHC
- 126 GeV: It's a very region that LEP/SLC experiments indicate
- Spin/parity 0+
- Decays are being measured

  hγγ, hZZ, hWW*, hττ, hbb, ...*

- The boson looks like the SM Higgs boson

Shinya KANEMURA

- Is it scalar or pseudoscalar?
- Is it elementary or composite?
- Does it couple to particle mass?
- Are quantum loop corrections known?
- What are its self-couplings?
- ......

Introduction

Scalar field in the SM is problematic

$$\delta m_H^2 = \frac{\Lambda_{cutoff}^2}{16\pi^2}$$

Problem of quadratic divergences

Hierarchy problem

Ideas of new physics to solve the problem

- Supersymmetry
- Dynamical Symmetry Breaking (Technicolor)
- Little Higgs mechanism
- Extra Dimensions
- …

Higgs sector = Window for new physics

Naturnalness: Theorists Dogma or Still an Important Clue?

Most theoretical speculation about Physics Beyond the Standard Model, and especially TeV scale physics, has started with the principle of naturalness.

Technicolor, Supersymmetry, Randall Sundrum, Large Extra Dimensions, Little Higgs.... – all involve problem of constructing natural theories.

Naturalness: Theorists Dogma or Still an Important Clue?

Most theoretical speculation about Physics Beyond the Standard Model, and espec
with the principle of naturalı

Technicolor, Supersymmetr
Dimensions, Little Higgs....
natural theories.

Michael [

Michael Dine

Fine tuning

The large radiative corrections look particularly absurd, if, say, $\Lambda_{\text{new physics}} = M_p$. Says something like

$$m_H^2 = 36,127,890,984,789,307,394,520,932,878,928,933,023$$

$$-36,127,890,984,789,307,394,520,932,878,928,917,398$$

This looks crazy!

Phenomenological questions

- Is the newly discovered Higgs boson related to dark matter
  - Models of the Higgs field often contain particles with dark matter properties (eg. SUSY)
  - Strong, independent arguments suggest dark matter particles (WIMPs) have masses comparable to heaviest particles connected to the Higgs field (~100 GeV)

Cosmology

The rationale for precision measurements

"The whole history of physics proves that a new discovery is quite likely lurking at the next decimal place."

F.k. Richtmeyer (1931)

"A precision experiment is justified if it can reveal a flaw in our theory or observe a previously unseen phenomenon, not simply because the experiment happens to be feasible..."

S. L. Glashow, 1305.5482

✓ Dark radiation

Ultra-light relativistic degrees of freedom at the recombination epoch.

Fuminobu Takahashi

- Hidden gauge symmetry is a plausible candidate for dark radiation, which may be probed by the invisible Higgs decay.

3. Summary

- SU(2) triplet fermion with a B-L charge zero is the best candidate for dark matter from the viewpoint of minimality. It is also consistent with the MSSM with the simplest SUSY breaking (AMSB/PGM).

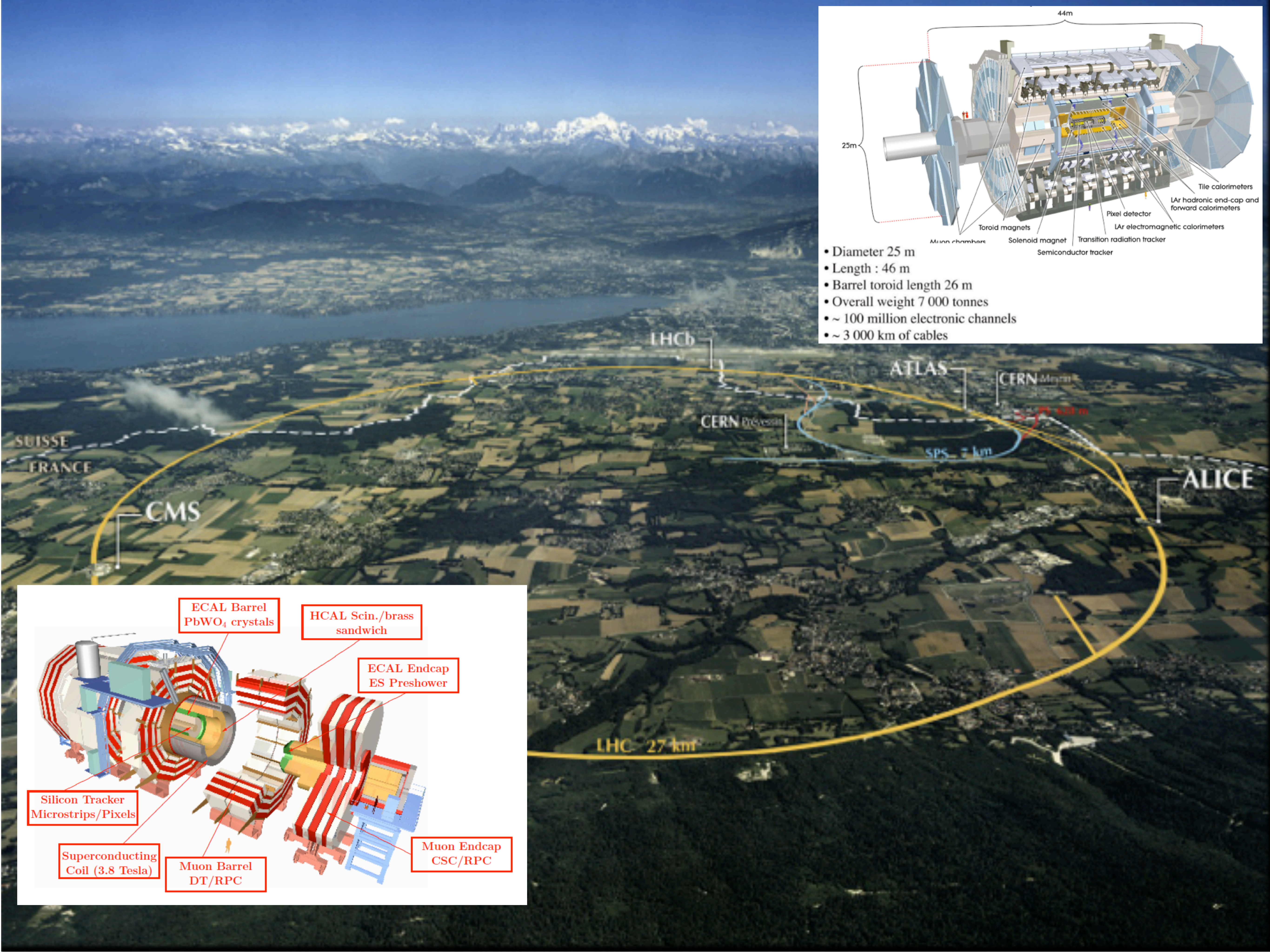
- Before LHC starts, the limit on the wino mass was 94 GeV < Wino mass < 2.7 TeV. Now, current limit is 110 GeV < Wino mass < 2.7 TeV. When we seriously take the thermal leptogenesis, the limit should be 110 GeV < Wino mass << 1 TeV.

- Several phenomenology of the wino dark matter has been considered: expected signals at the LHC, direct detection, indirect detection, and the ILC. Whole mass range can be tested in future.

Shigeki Matsumoto

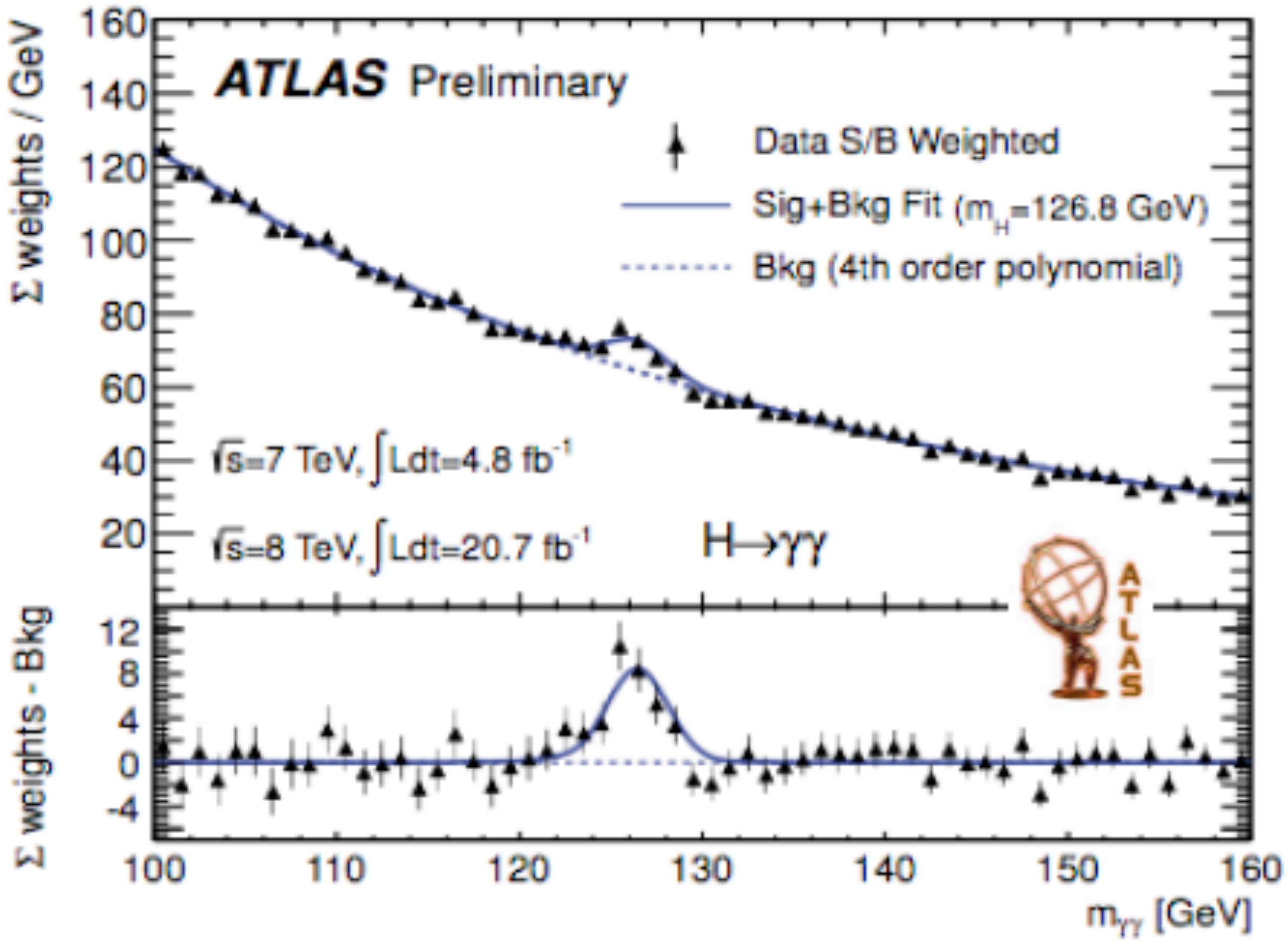
Phenomenological questions

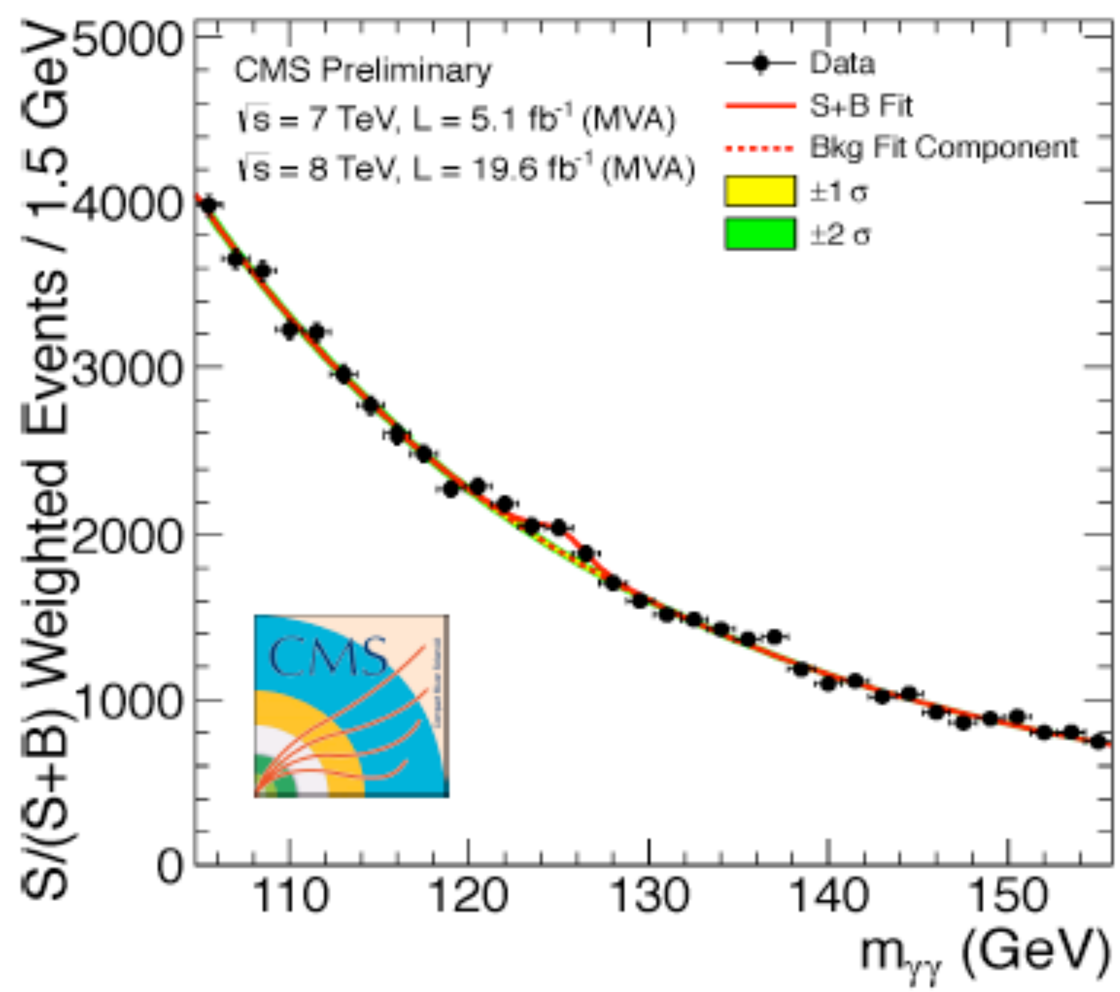
- Why is the matter of the universe overwhelmingly dominant over anti-matter?
  - Is this related to the Higgs sector?
  - baryogenesis at the Electroweak Phase Transition?



44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker
• Diameter 25 m
• Length : 46 m
• Barrel toroid length 26 m
• Overall weight 7 000 tonnes
• ~ 100 million electronic channels
• ~ 3 000 km of cables
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km
ECAL Barrel
PbWO4 crystals
HCAL Scin./brass
sandwich
ECAL Endcap
ES Preshower
Silicon Tracker
Microstrips/Pixels
Superconducting
Coil (3.8 Tesla)
Muon Barrel
DT/RPC
Muon Endcap
CSC/RPC

Inclusive Background Fit



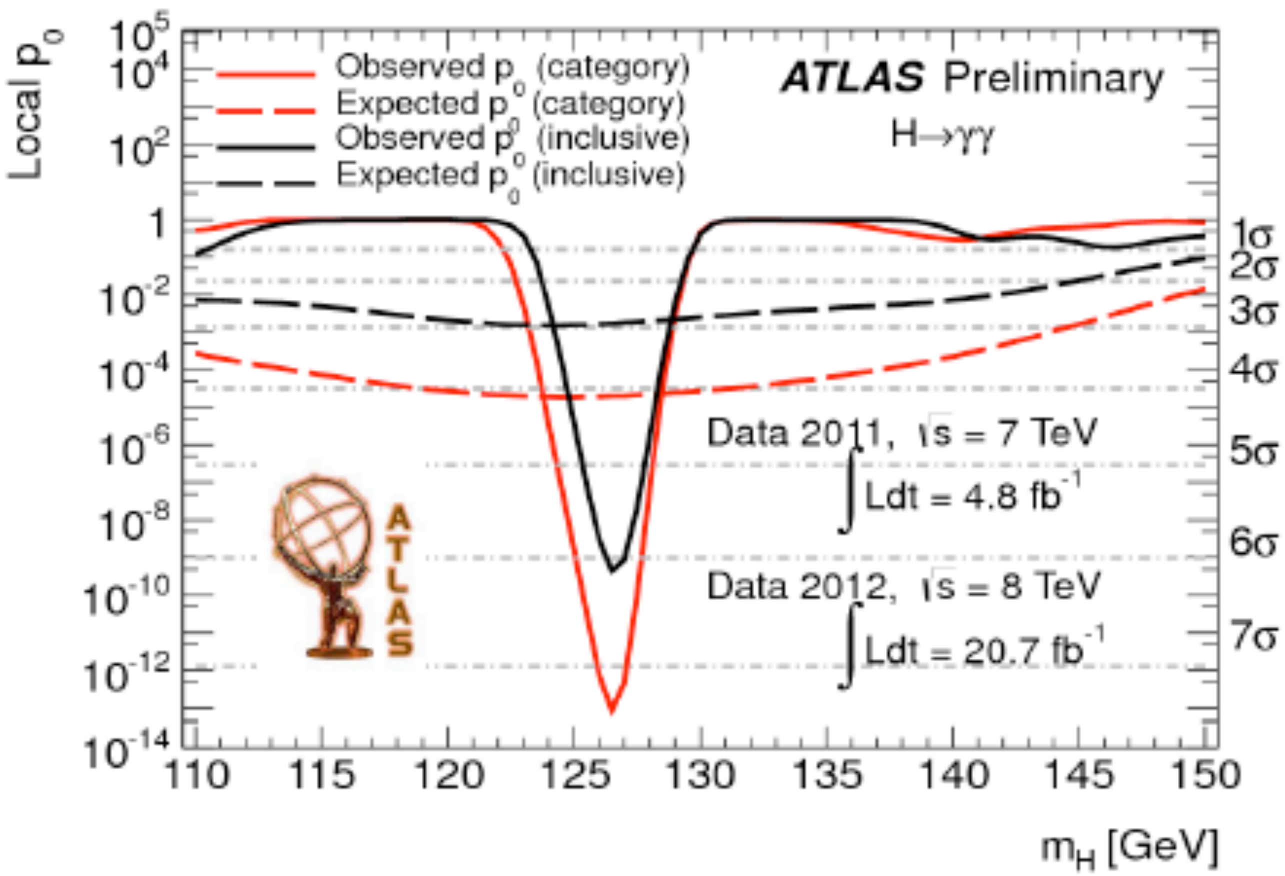


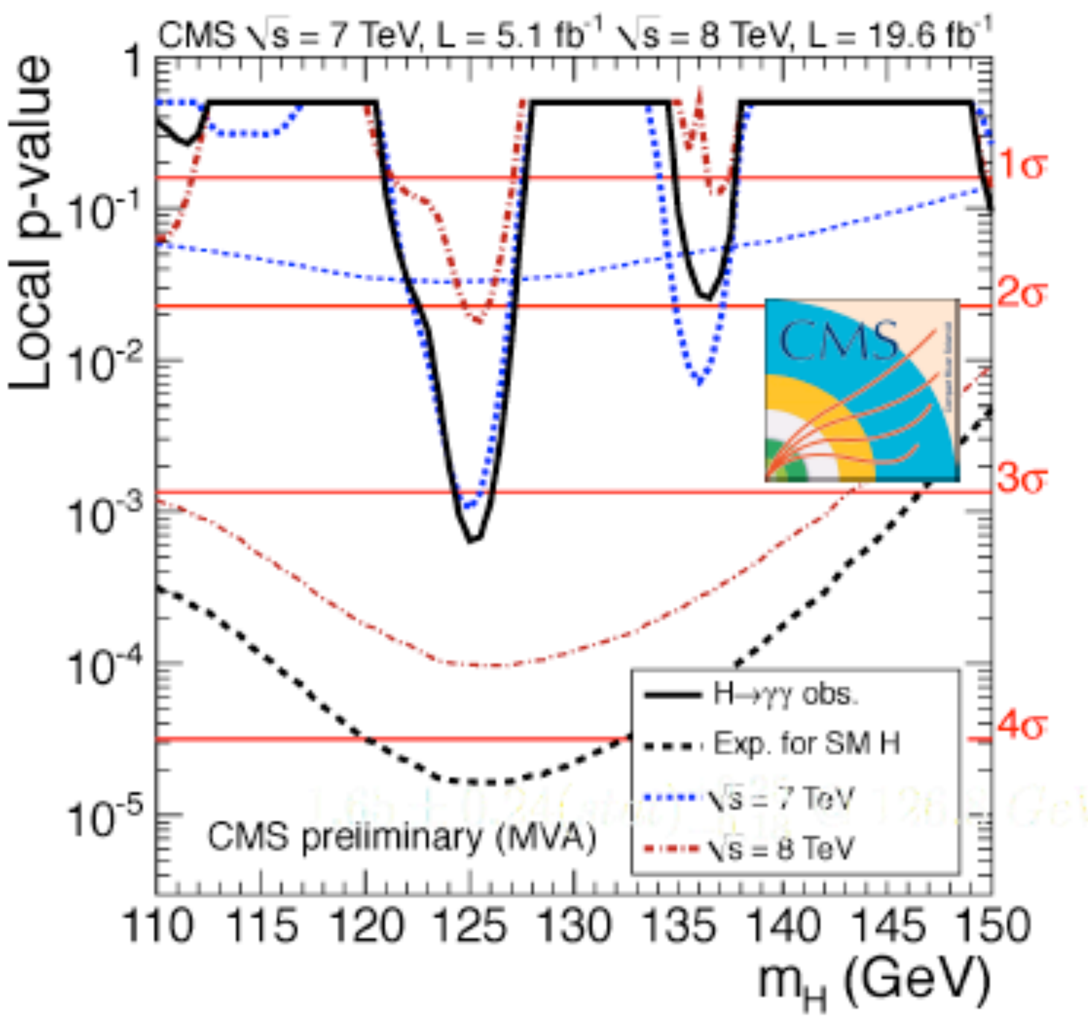
- From inclusive analysis ATLAS estimated the fiducial cross section ($|\eta| < 2.37$):

$$\sigma_{fid} \times BR = 56.2 \pm 10.5 \text{ (stat)} \pm 6.5 \text{ (syst)} \pm 2.0 \text{ (lumi) fb.}$$

Results

- Comparable expected significance between ATLAS and CMS MVA analysis.



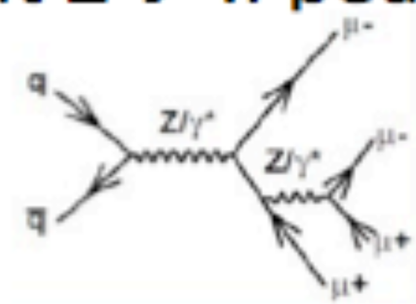


√s = 7+8 TeV	Exp.	Obs.
ATLAS	4.1	7.4
CMS MVA	4.2	3.2

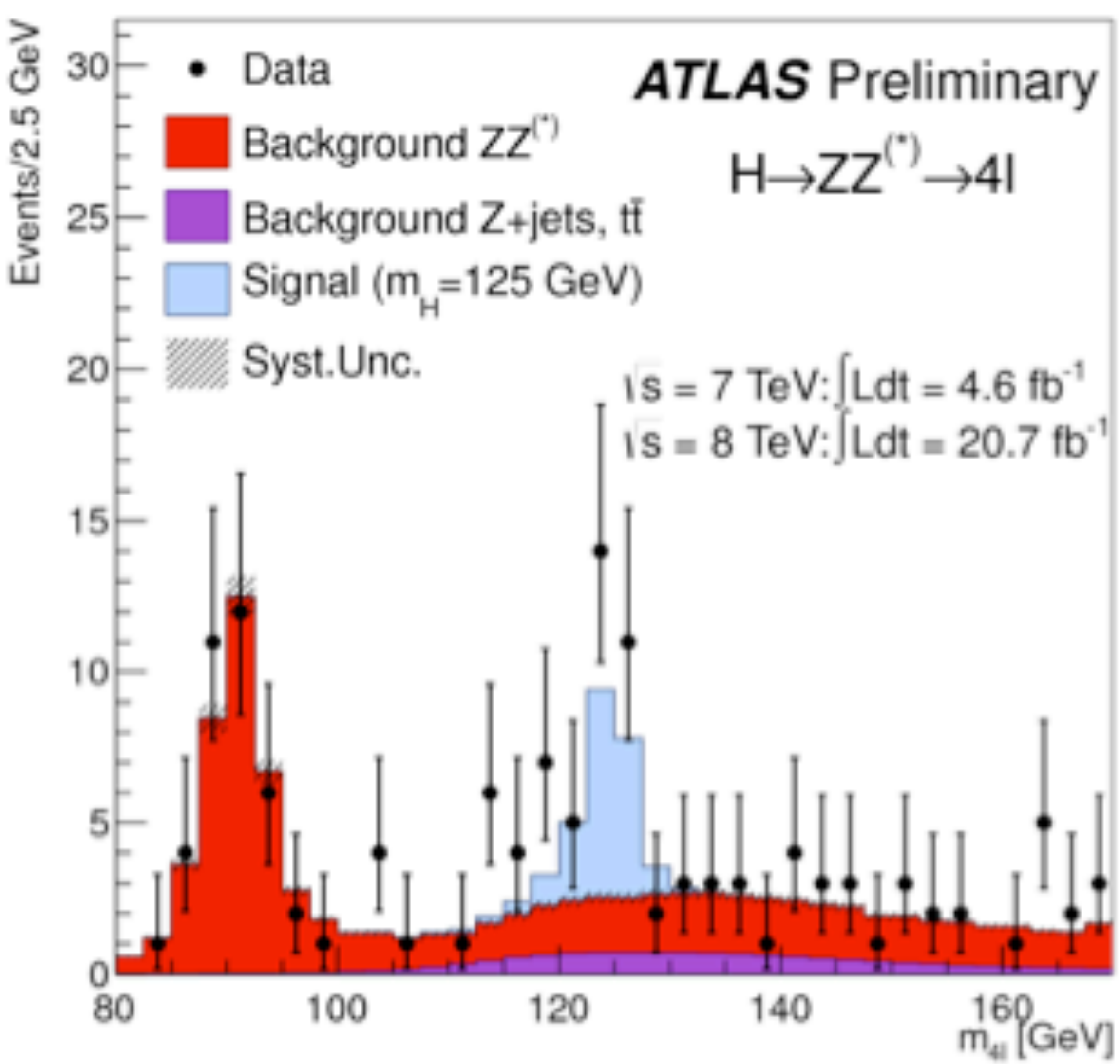
Matteo Sani

$h \rightarrow ZZ^{(*)} \rightarrow 4l$: m_{4l} distributions

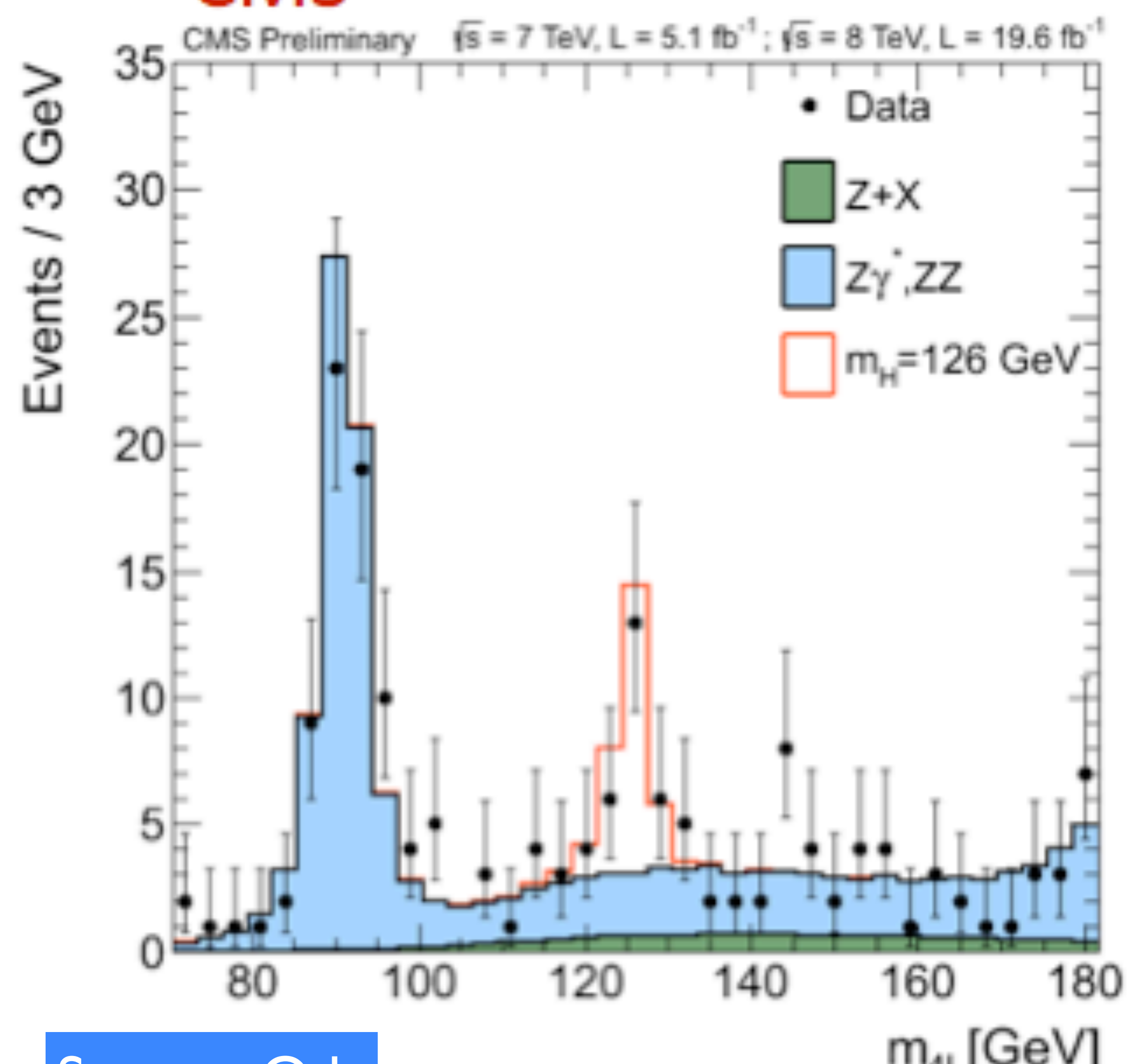
- A clear peak exceeding expected backgrounds is seen around m_{4l}=125 GeV by both ATLAS and CMS.
- Single resonant $Z \rightarrow 4l$ peak is seen at right position and height.



ATLAS



CMS



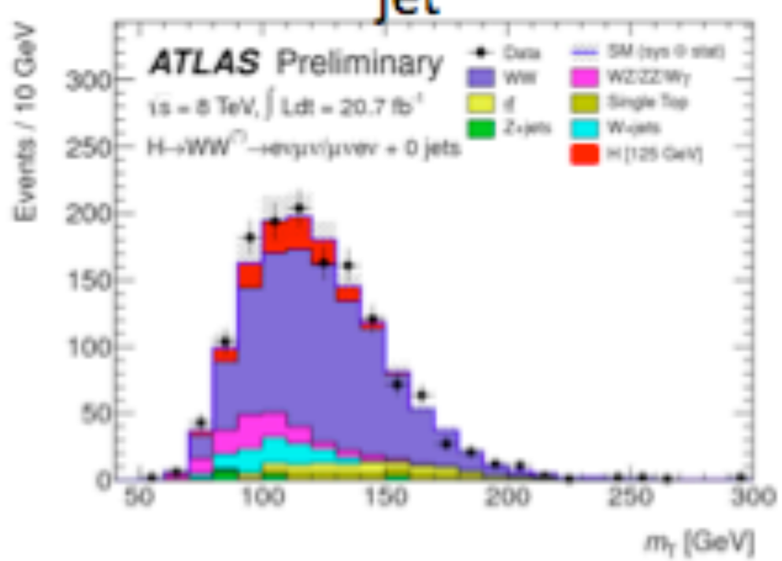
Susumu Oda

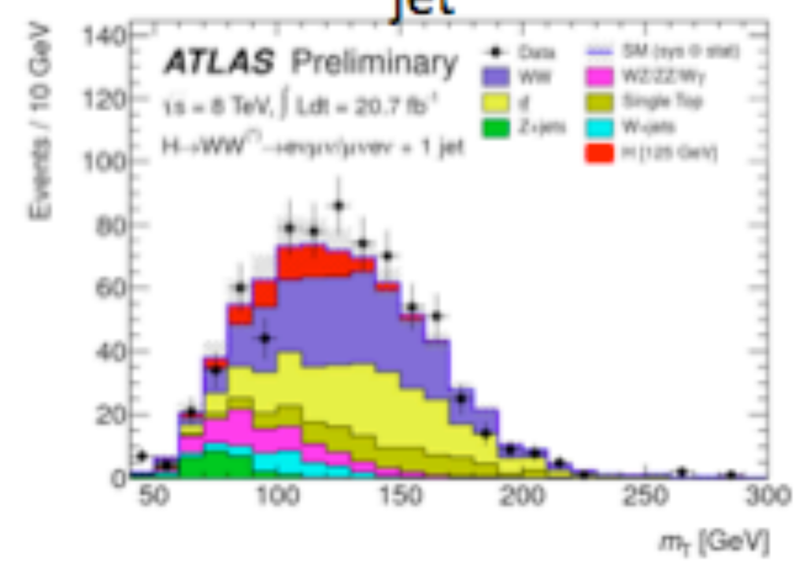
h→WW$^{(*)}$→lνlν: m_T distributions

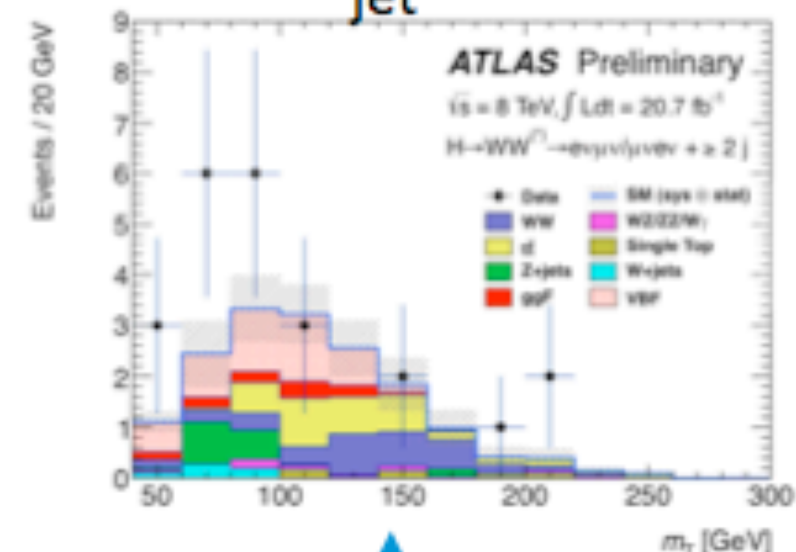
- Different flavor results are shown.
- Data well agree with the expectation including 125 GeV Higgs signals.

N_{jet}=0 | N_{jet}=1 | N_{jet}>=2

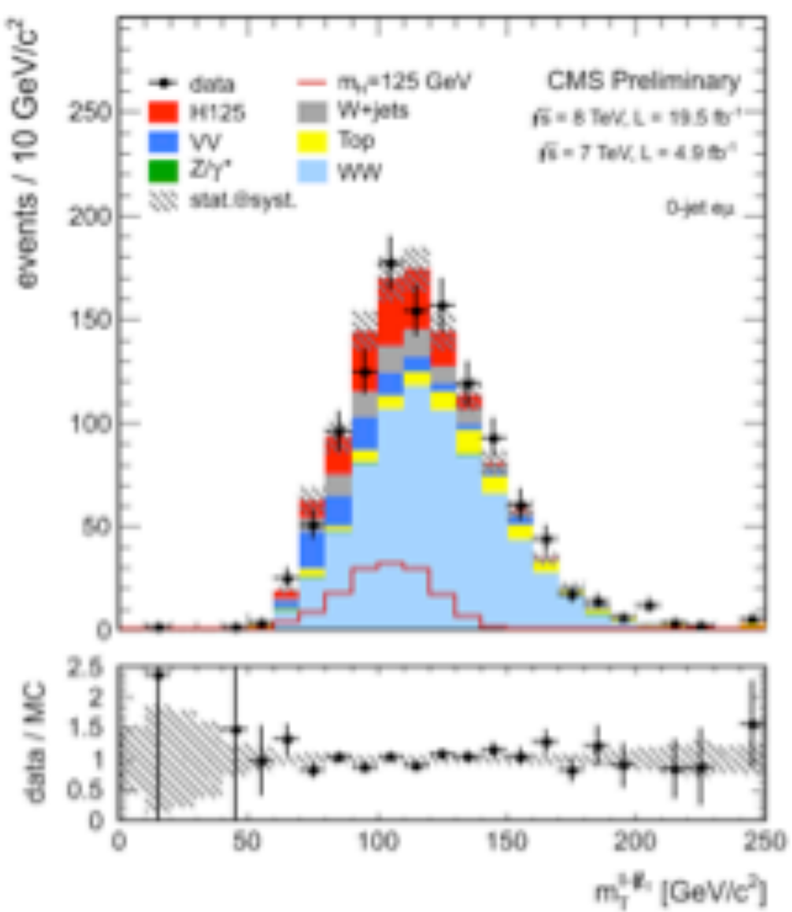
ATLAS

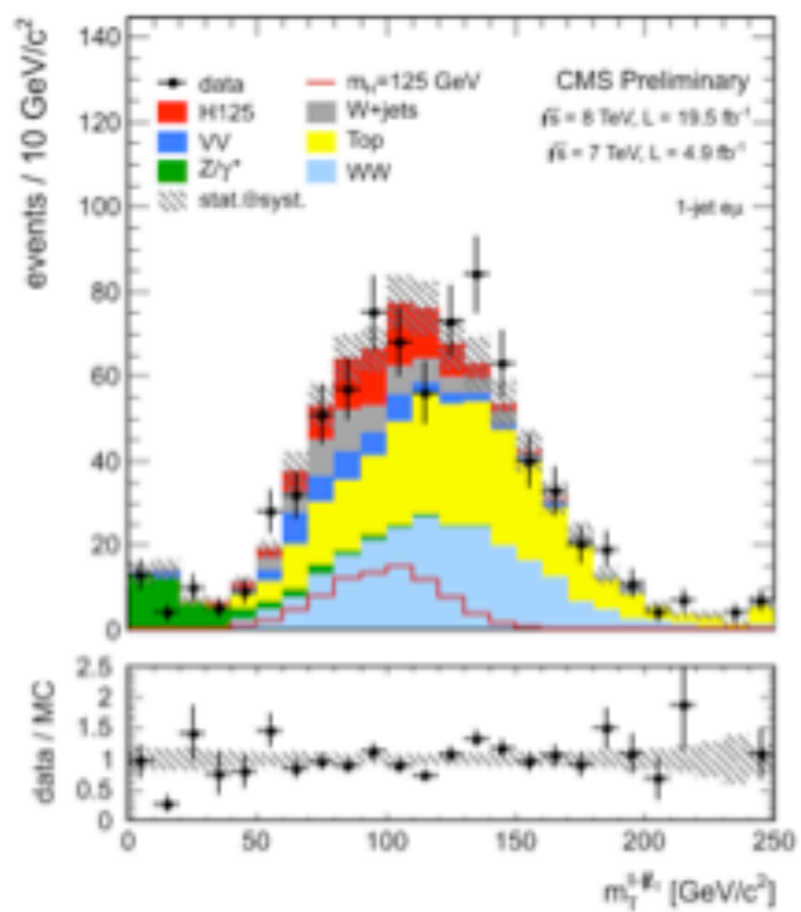






CMS





- For the VBF analysis
- m_{jj}>500 GeV
- $|\Delta y_{jj}|$>2.8
- No jets (p_T>20 GeV) in rapidity gap
- Require both lepton in rapidity gap

Susumu Oda

Conclusion

ATLAS and CMS have performed searches for $H \rightarrow \tau\tau$ decays in 17.6 and 25.3fb^{-1} and for $H \rightarrow \mu\mu$ in 20.7fb^{-1}.

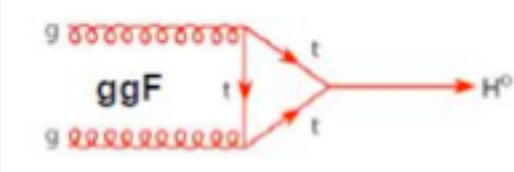
- VBF and ggF couplings consistent with SM
- First hint of $H \rightarrow \tau\tau$
- Promising $H \rightarrow \mu\mu$ analysis for the future

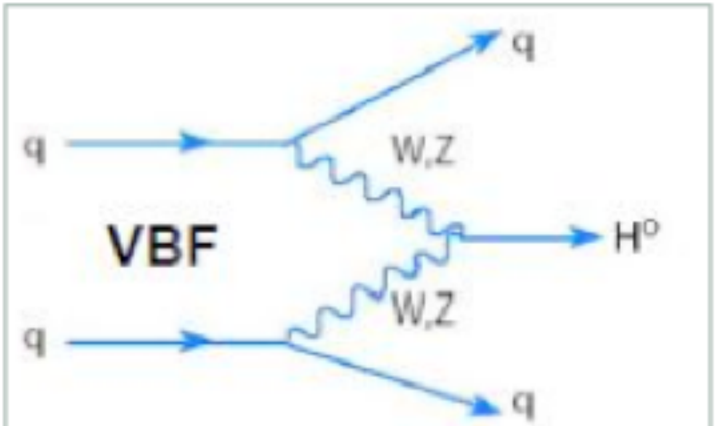
The sensitivities are

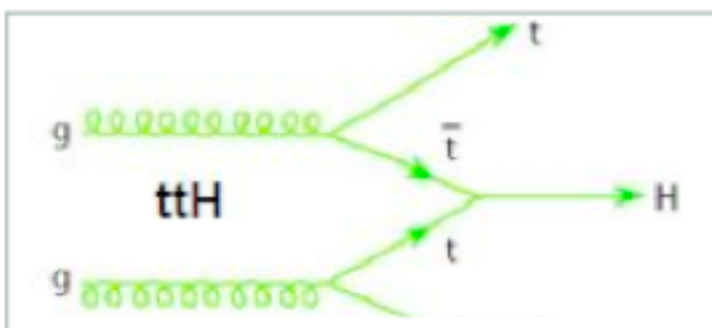
	ATLAS	CMS	ATLAS
	$H \rightarrow \tau\tau$	$H \rightarrow \tau\tau$	$H \rightarrow \mu\mu$
expected	1.2	0.77	8.2
observed	1.9	1.8	9.8
σ/σ_{SM}	0.7±0.7	1.1±0.4	

Harald Fox

- **Search for H→bb not possible in dominant production mechanism**
  - Gluon fusion production: large multi-jet backgrounds
- **Search for H→bb in associated production**
  - No loops & suppress backgrounds







Summary

Search for H→bb
- Results of Atlas & CMS
- Test of fermion final state
- Coupling to quarks

Challenging
- ggF: multi-jet backgrounds
- Study associated productions
  - No loops: ttH, VH, VBF

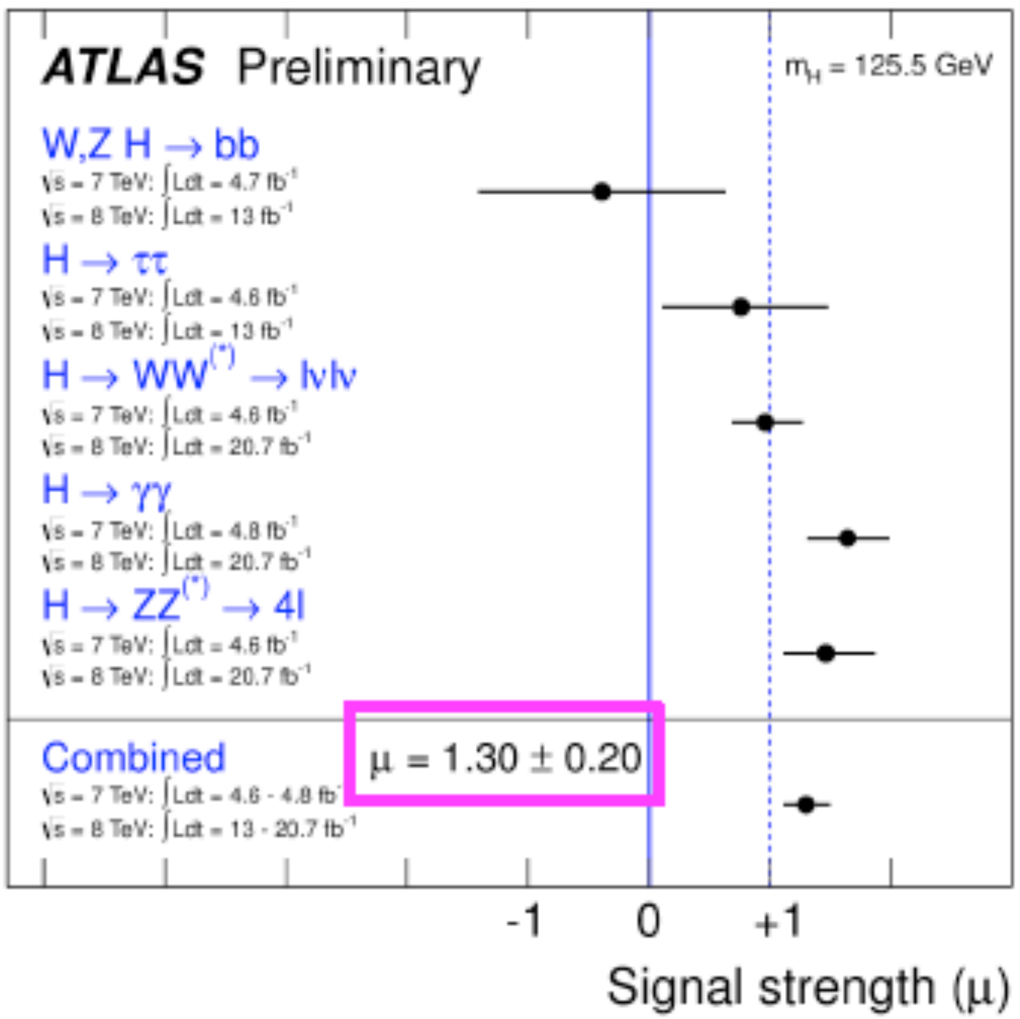
Prod.	Atlas limit obs. (exp.)		CMS limit obs. (exp.)	
ggF	-		-	
ttH	13.1 (10.5)	[5 /fb]	5.8 (5.2)	[5+5 /fb]
VBF	-		3.6 (3.0)	[19 /fb]
VH	1.8 (1.9)	[5+13 /fb]	1.9 (1.0)	[5+19 /fb]

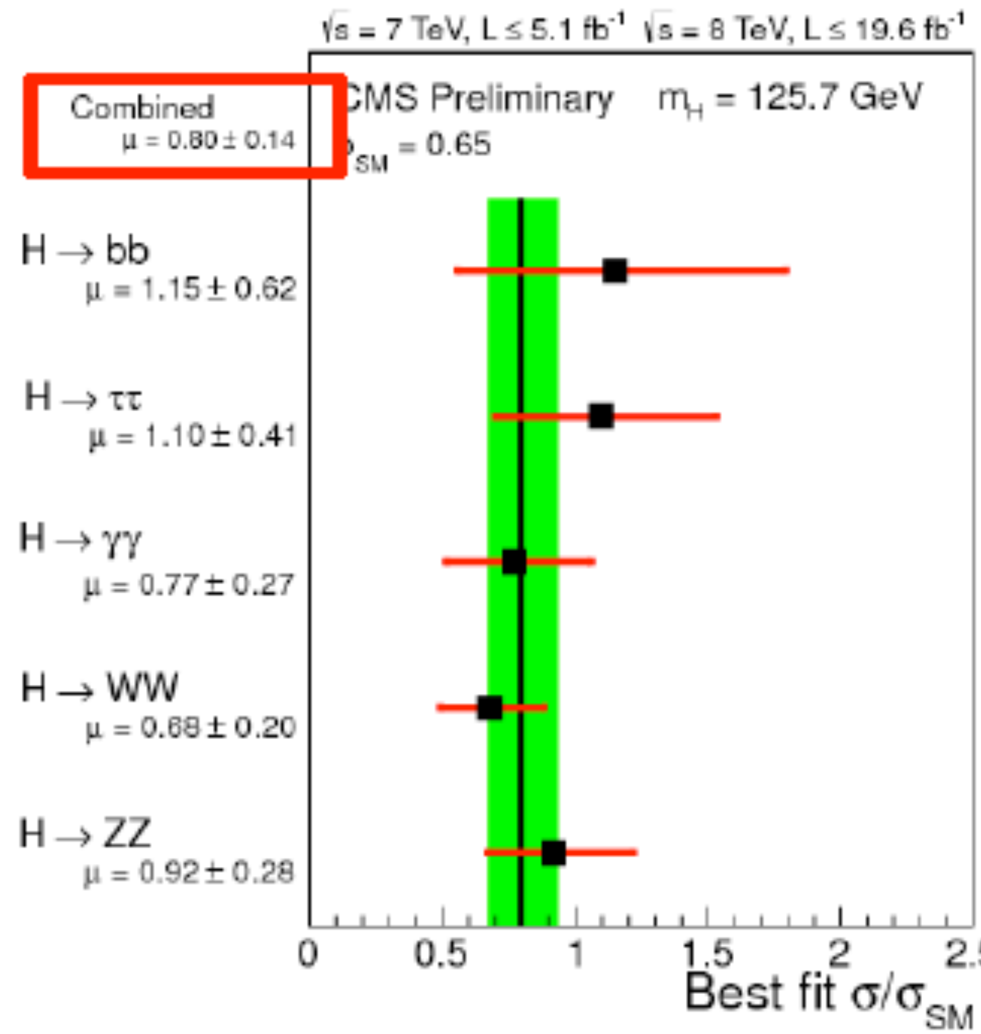
CMS: H→bb in VH with significance of 2.1σ (2.1σ exp.)

Tristan du Pree

combined CMS: $\mu = 0.80 \pm 0.14$

combined ATLAS: $\mu = 1.30 \pm 0.20$





Good internal consistency for both experiments.

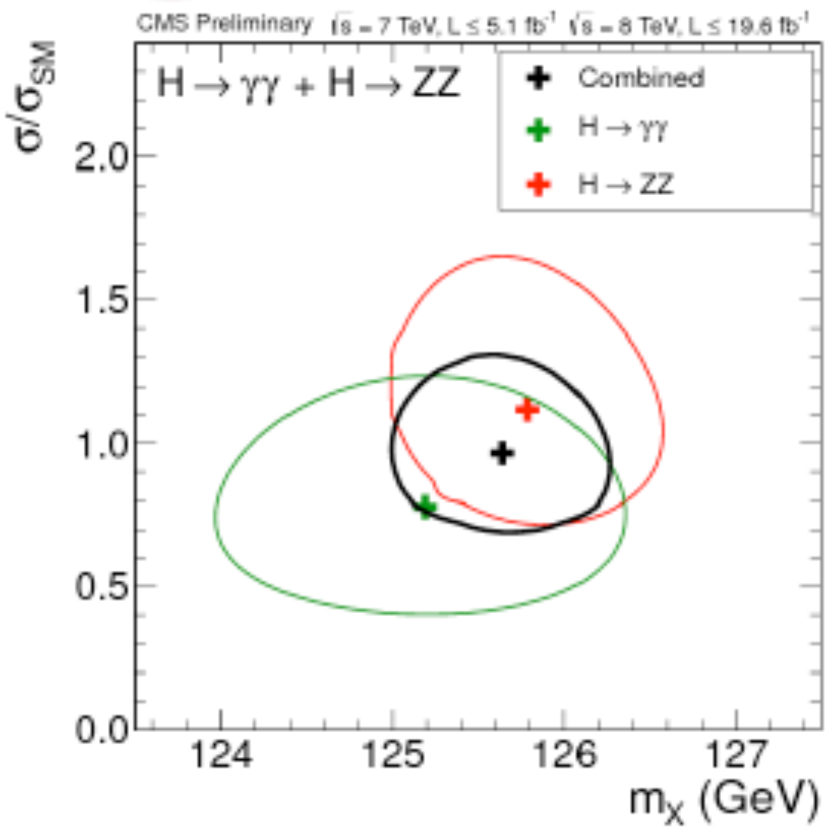
ATLAS consistent with SM at 9% (but ~40% with flat pdfs for theory unc)

CMS consistent with SM at 16%

Alessio Bonato

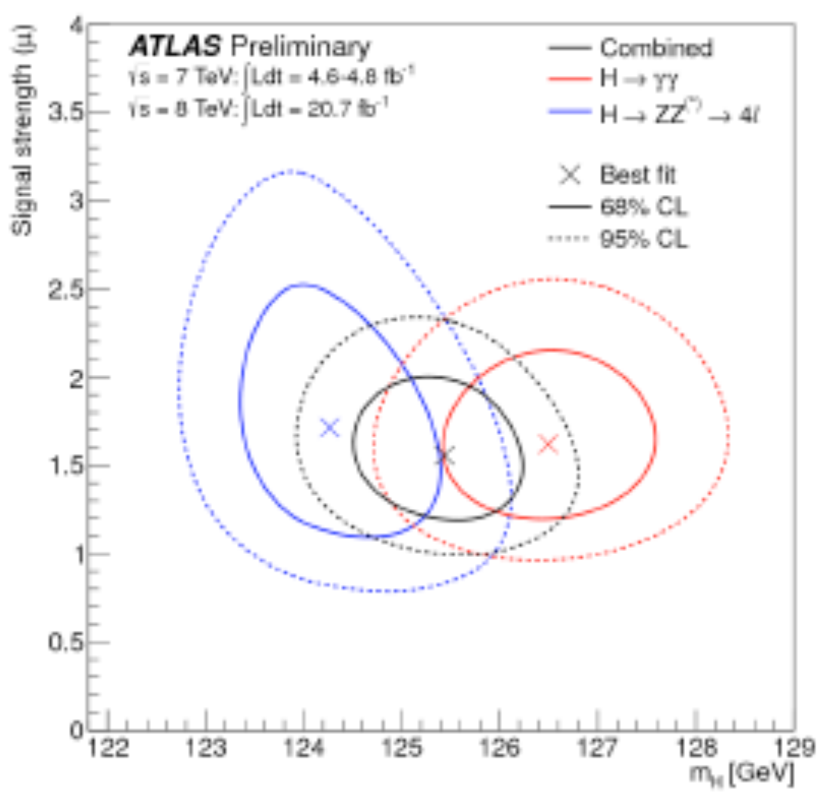
14

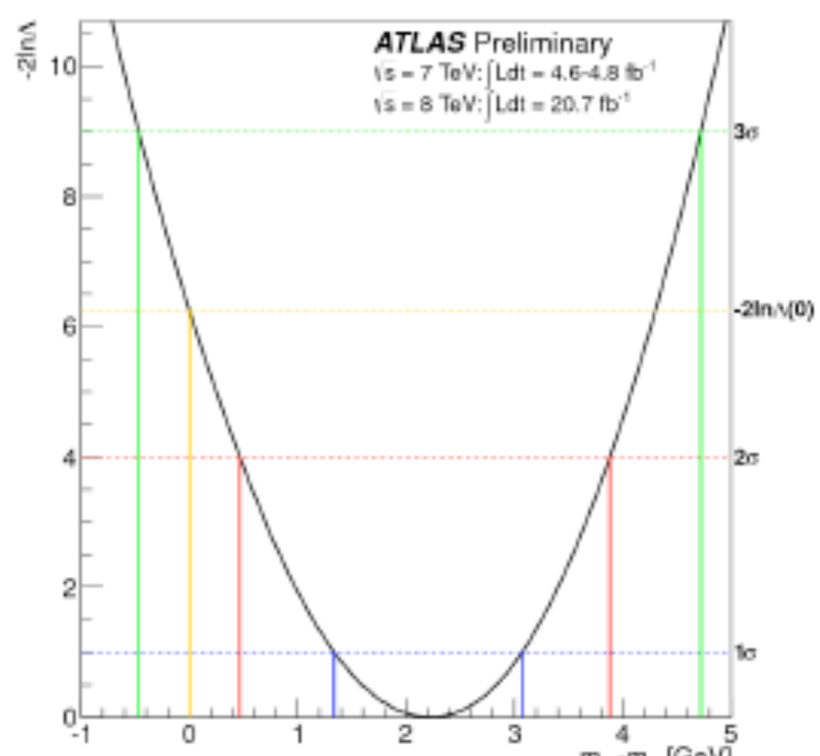
ATLAS result	CMS result
$M_H = 125.5 \pm 0.2\,(stat.)\,^{+0.5}_{-0.6}\,(syst.)$ GeV	$M_H = 125.7 \pm 0.3\,(stat.) \pm 0.3\,(syst.)$ GeV



Mass and couplings to SM fields correlated in SM H. Scan L as a function of M_H and μ (fix relative signal strengths to SM value).

Nice compatibility across CMS channels. Difference btw ATLAS individual measurements studied in detail.

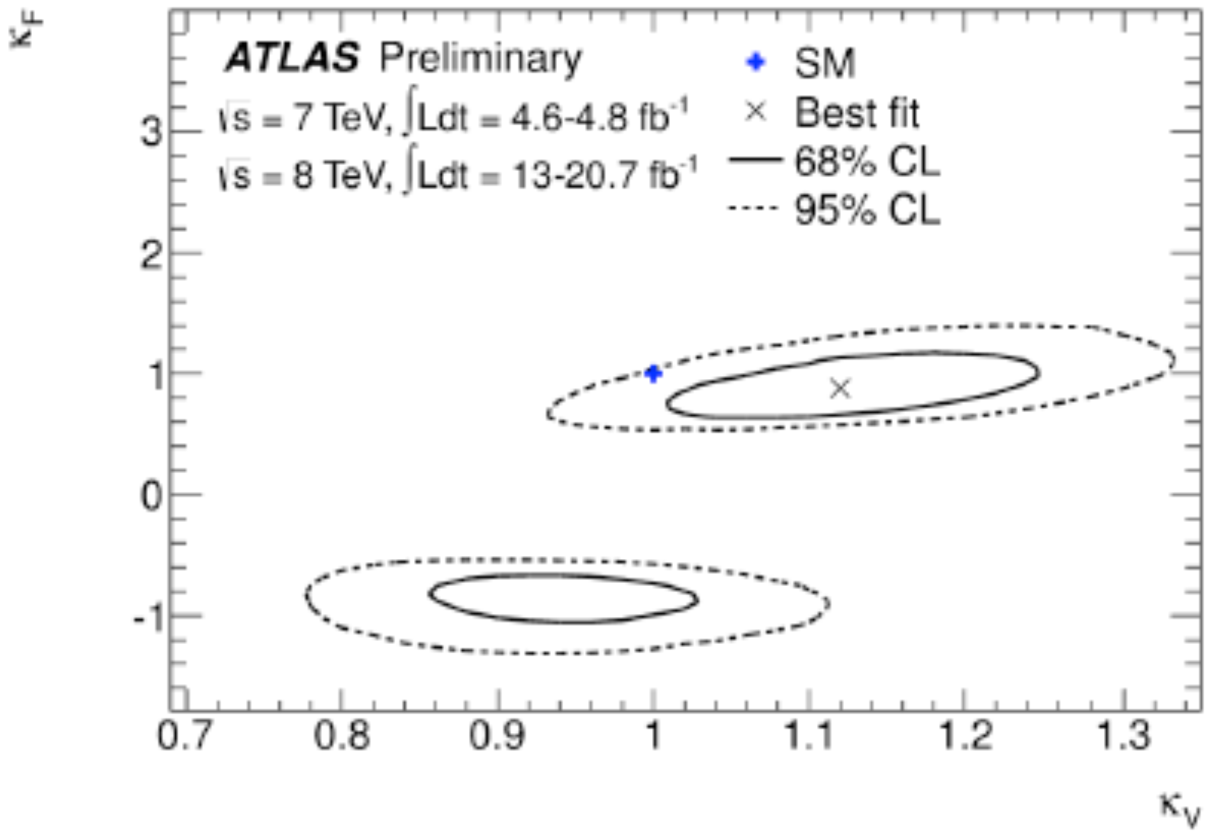


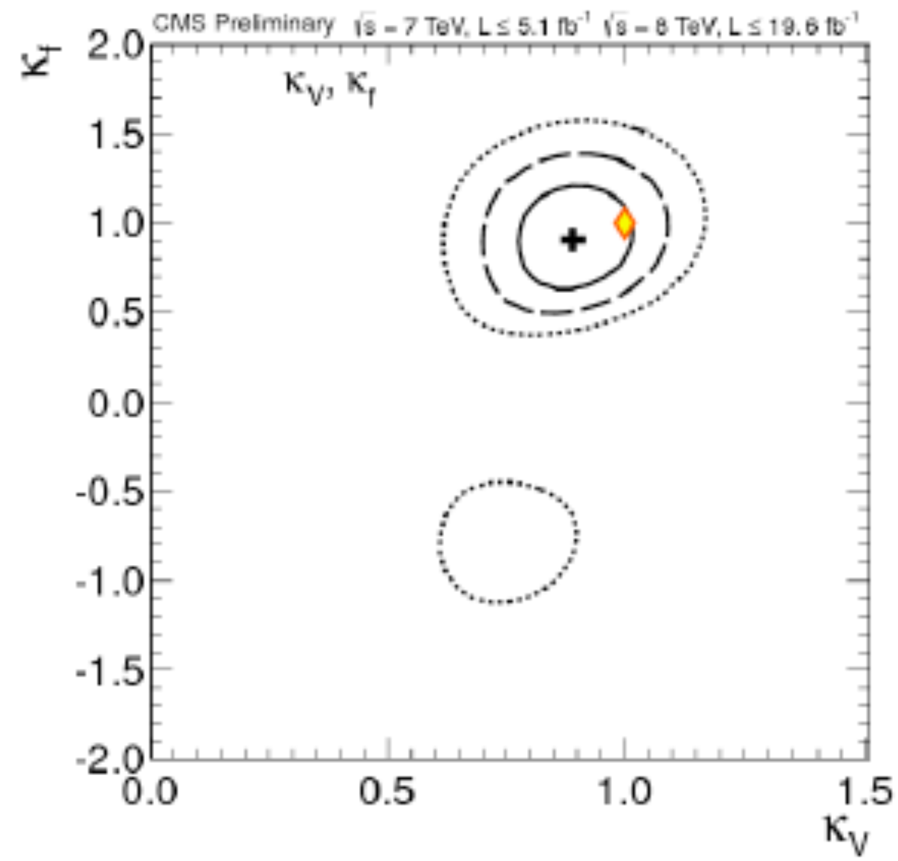


- ΔM=0 hyp. (→ matching measurements) compatible with observation at 1.5%
- Sensitivity to different assumption on p.d.f. of exp. systematics, γγ vs ZZ compatibility can increase to 8%

Alessio Bonato

k_V / k_F





Relative sign between k_F and k_V arbitrary in SM (2 out 4 quadrants).

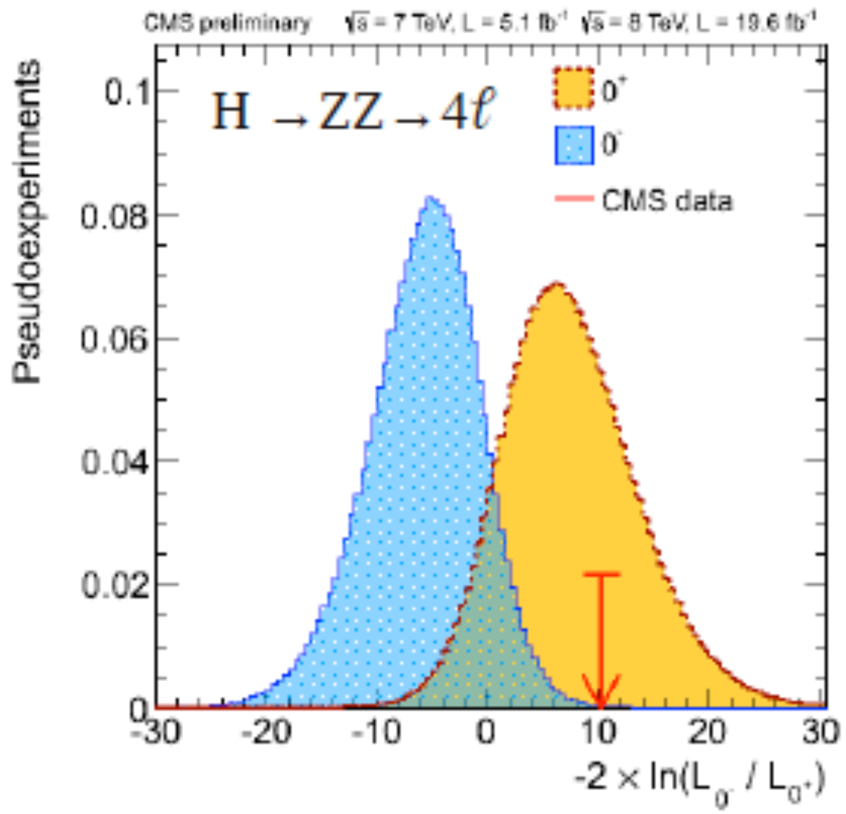
Over-fluctuation in ATLAS Hγγ obs yields allows negative k_F (t-loop enters in γγ-decay with negative sign).

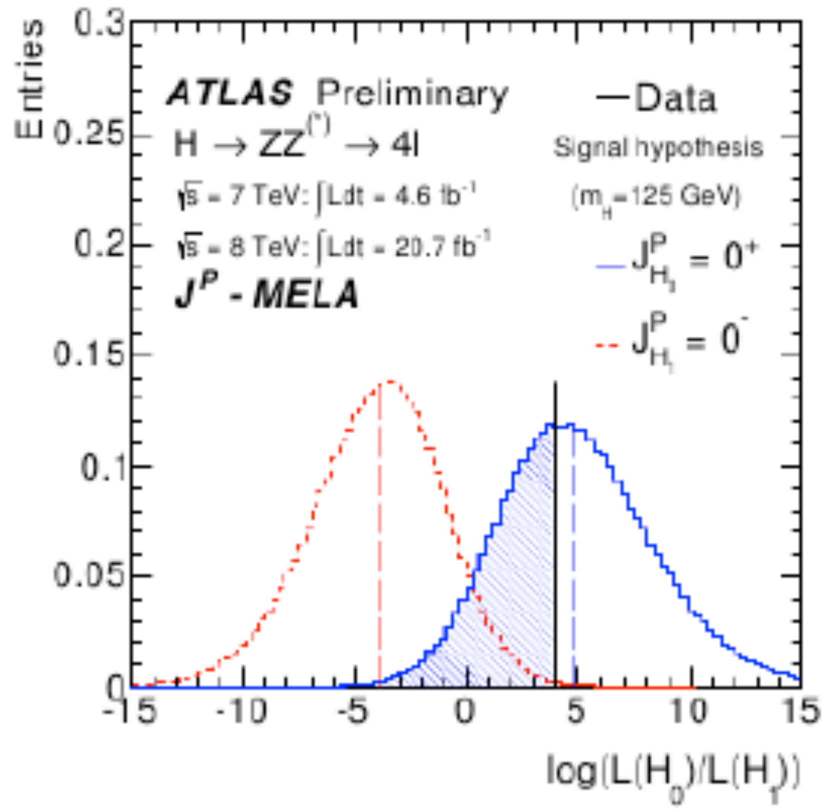
95% CL region of CMS all in positive k_F.

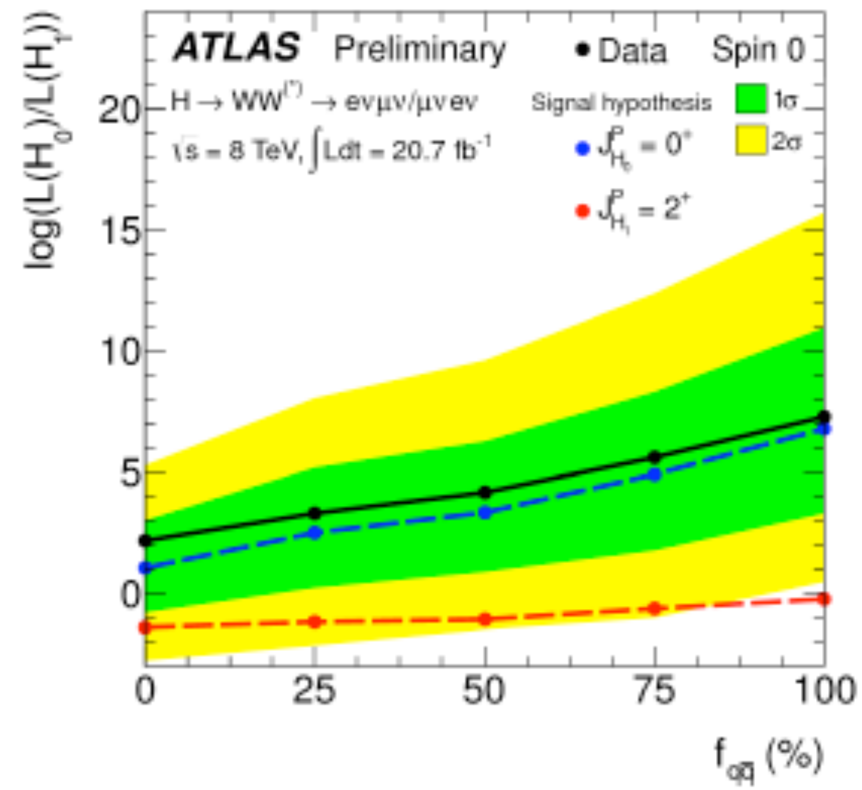
Both ATLAS and CMS compatible with SM.

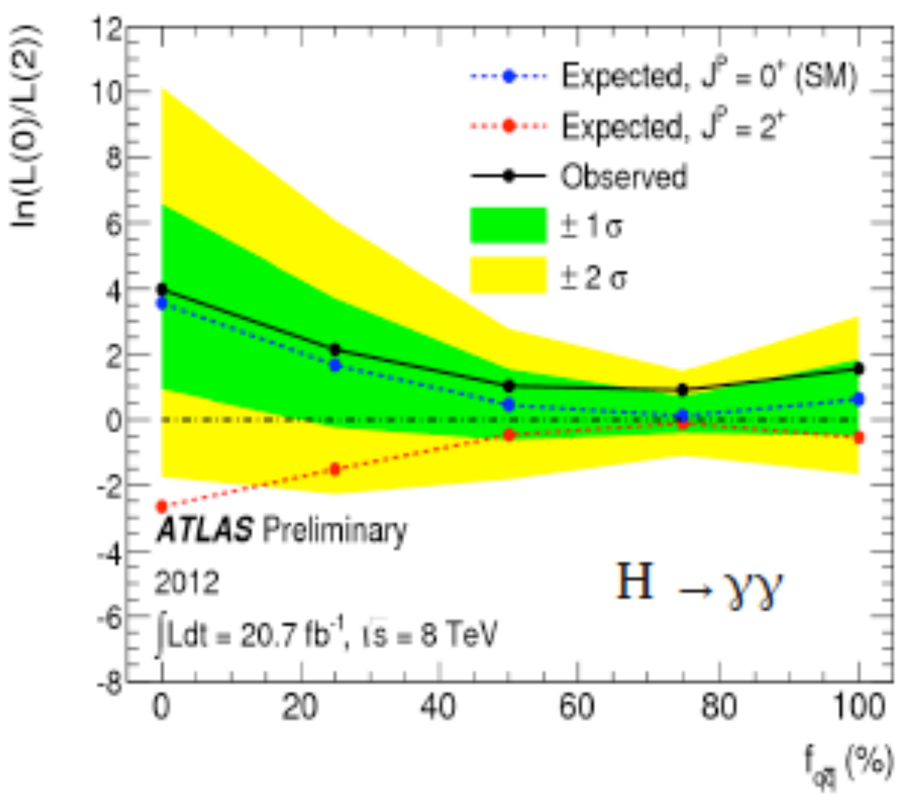
Alessio Bonato

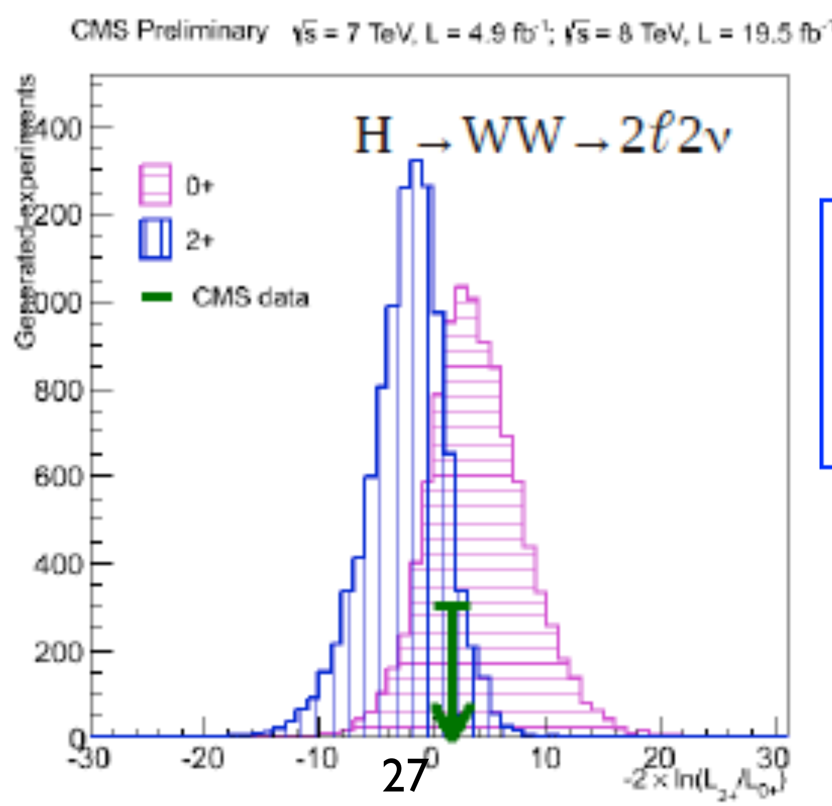
Scalar particle highly favored









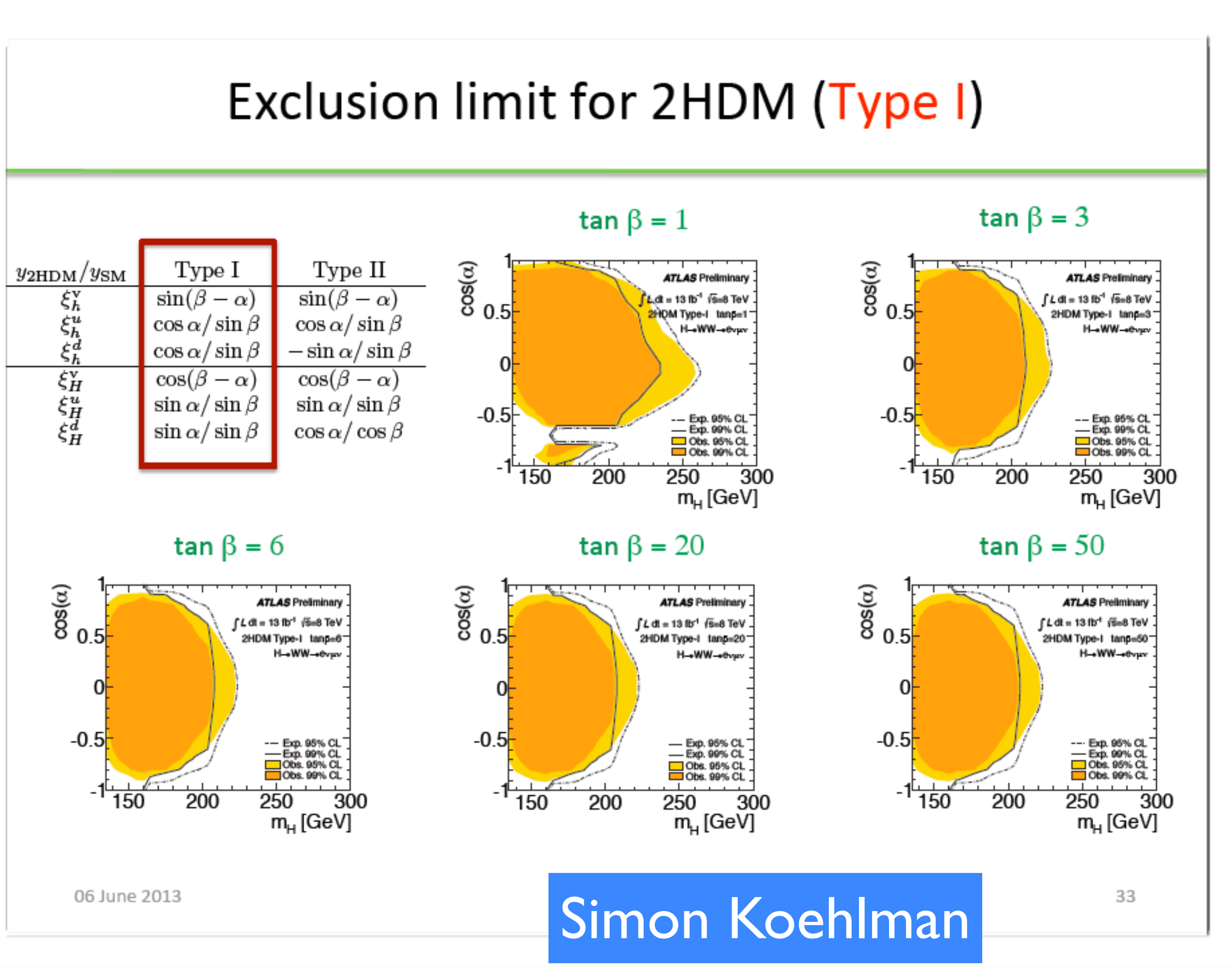


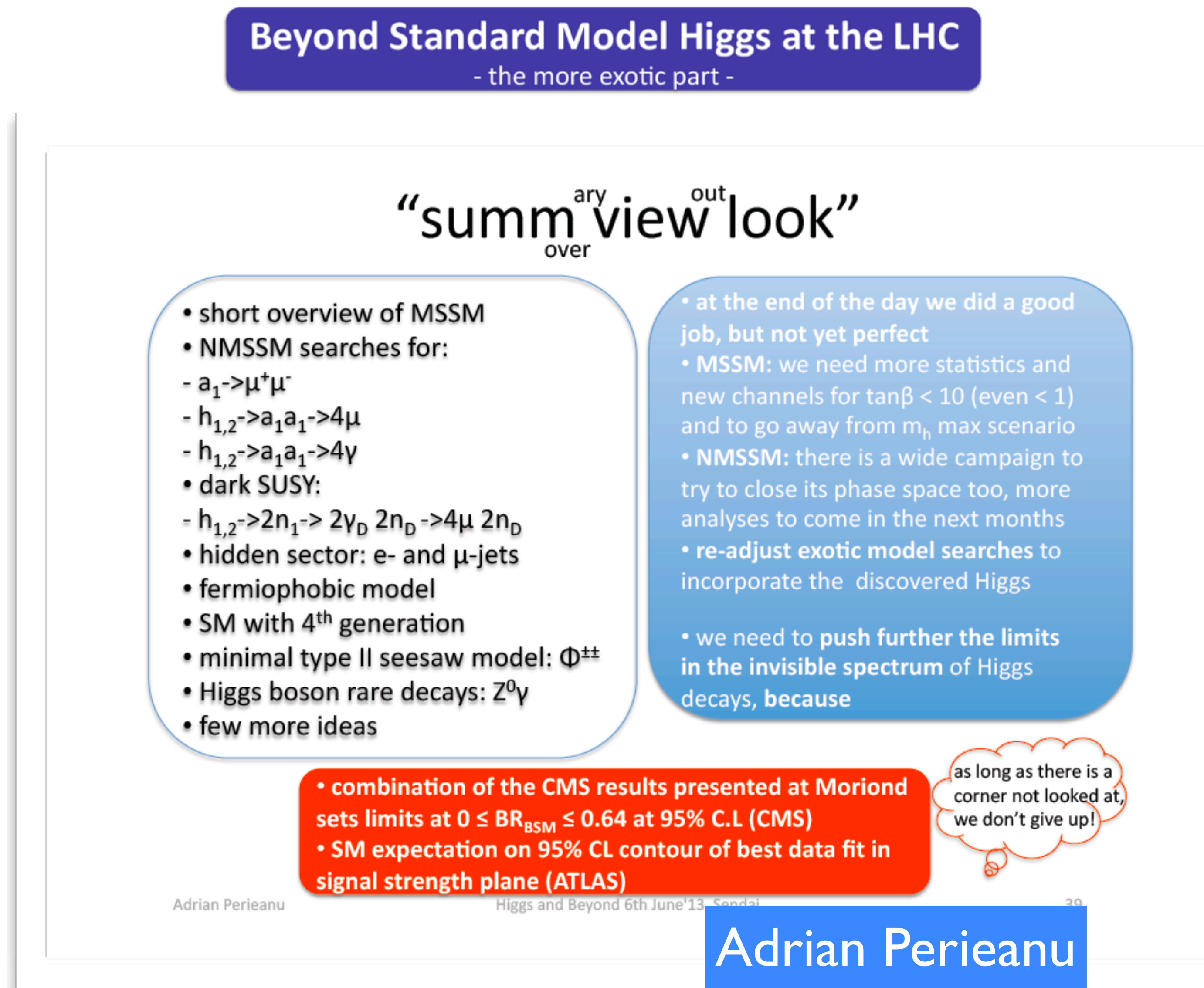
J^P analyses of individual channels disfavor all of the **tested** alternative J^P hypotheses against SM 0+, in most of the cases at > 2σ CL.

Alessio Bonato

BSM Higgs

Searches for Higgs in 2HDM at the LHC





- Also, constraints on charged Higgs
- And high-mass Higgs searches

- So far, the 126 GeV state looks like a Standard Model Higgs boson
- But - we have only started to measure its properties
- More channels and precision will come

Shinya KANEMURA

Beyond the Standard Model

There are many reasons to consider New Physics of BSM

- Unification of Law
  - Paradigm of Grand Unification
  - Yukawa structure (flavor)
- Problem in the SM Higgs
  - Hierarchy Problem
- BSM Phenomena
  - Dark Matter, Neutrino Mass,
  - Baryon Asymmetry of Universe
  - Inflation
  - Dark Energy
- New Physics is necessary

At which scale?

If TeV scale, they should have connection with Higgs physics

New Physics Scenarios

- Supersymmetry
- Extra dimensions
- Technicolor
- Little Higgs
- Heavy gauge boson (GUT, ...)
- Left-right symmetry
- Compositeness
- Vector-like quark, 4th gen.
- Heavy neutrino
- Hidden Valley

Koji Terashi

- Supersymmetry at low energy scales

  - solves the gauge hierarchy problem.
  - leads to gauge coupling unification.
  - offers a good dark matter candidate.
    (the lightest superparticle if neutral. w/ R-parity conservation)
  - explains how electroweak symmetry breaking occurs.
  - ...
  - gives a SM-like Higgs boson.

Kwang Sik Jeong

- NMSSM requires less fine-tuning.

  - m_h=125 GeV does not require heavy stops.
  - For stops around 1 TeV, we need λ around or larger than 0.6.

SUMMARY

SUSY < O(TeV) after Higgs discovery

motivations	model	LHC/ILC/other signals
126 GeV Higgs + naturalness	implies beyond MSSM (e.g. NMSSM) See talk by K.S.Jeong !	light stop and light Higgsino.
126 GeV Higgs + muon g-2 (>3σ !!)	difficult in simple models (1) general MSSM (2) model building	(1) "g-2 motivated MSSM" --> can be tested by non-colored particle search at LHC/ILC. (2) example: "V-GMSB" --> barely alive. tested soon.
126 GeV Higgs + Dark Matter	* No problem in simple models (e.g., CMSSM/mSUGRA).	
126 GeV Higgs + coupling unification	* "light gauginos/Higgsinos + heavy scalars" scenario works well. Wino Dark Matter See talk by S.Matsumoto !	

Koichi Hamaguchi

Higgs boson as a gauge field
in extra dimensions
-- Pinning it down at LHC and ILC

Yutaka Hosotani

Physics
OSAKA UNIVERSITY

with Funatsu, Hatanaka, Orikasa, Shimotani

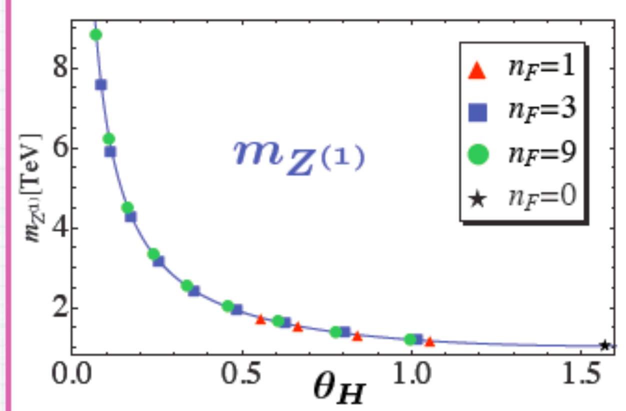
1301.1744 [PLB 722 (2013) 94]

Summary

SO(5)xU(1) Gauge-Higgs unification: promising

Universality

$\theta_H, m_{KK}, \lambda_3^H, \lambda_4^H, m_{Z^{(1)}}$



Low energy physics : close to SM

Signals LHC/ILC

$Z^{(1)}$: $5.9 \sim 2.4$ TeV ($\theta_H : 0.12 \sim 0.36$)

λ_3^H , λ_4^H

$F^{(1)}, \bar{F}^{(1)}$: stable (exp : $m_{F^{(1)}} > 0.5$ TeV)

Discovering Walking Technicolor at LHC and on the Lattice

Approx. Scale Symmetry

→ **Techni-dilaton**

↔ **125 GeV Composite Higgs**

Conclusion

Koichi Yamawaki

- A light composite Higgs can be generated in the Walking Technicolor (Strongly coupled theory) as a Pseudo-NG boson of Scale Symmetry (Techni-dilaton), which is Weakly coupled to the SM particles.
- Techni-dilaton is consistently identified with the 125 GeV Higgs

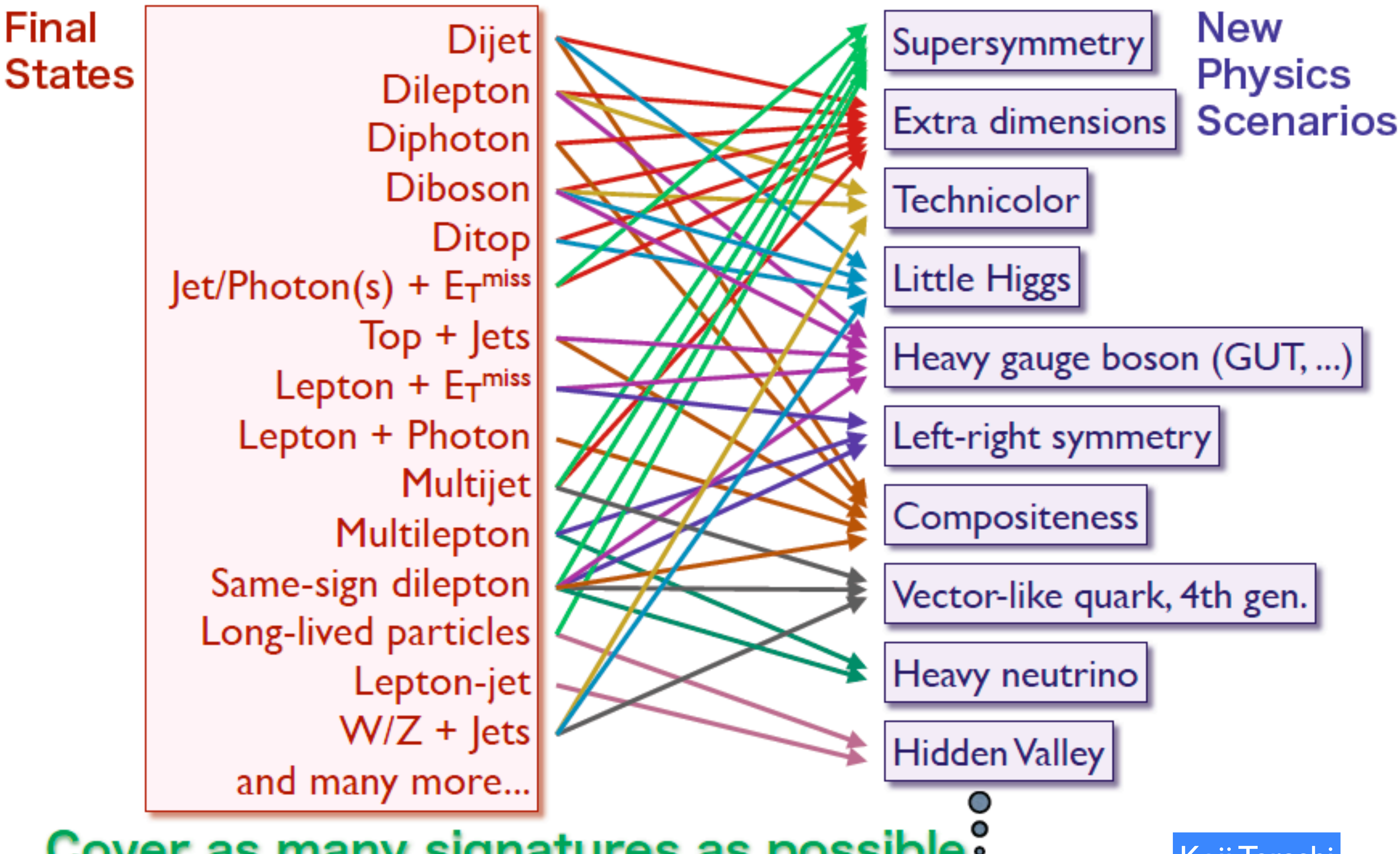
SUMMARY

- Large/highly warped XD can be tested at the LHC.
- KK-DM with KK-parity .. 1/R<1.5 TeV in UED
- DM+LHC7&LHC8+EWPT+Higgs already started to probe a part of parameter space
- LHC 14 and future DM searches(Direct/Indirect) will give us more answers for XD

Seong Chan Park

“Main” Signatures

Personal “illustrative” view



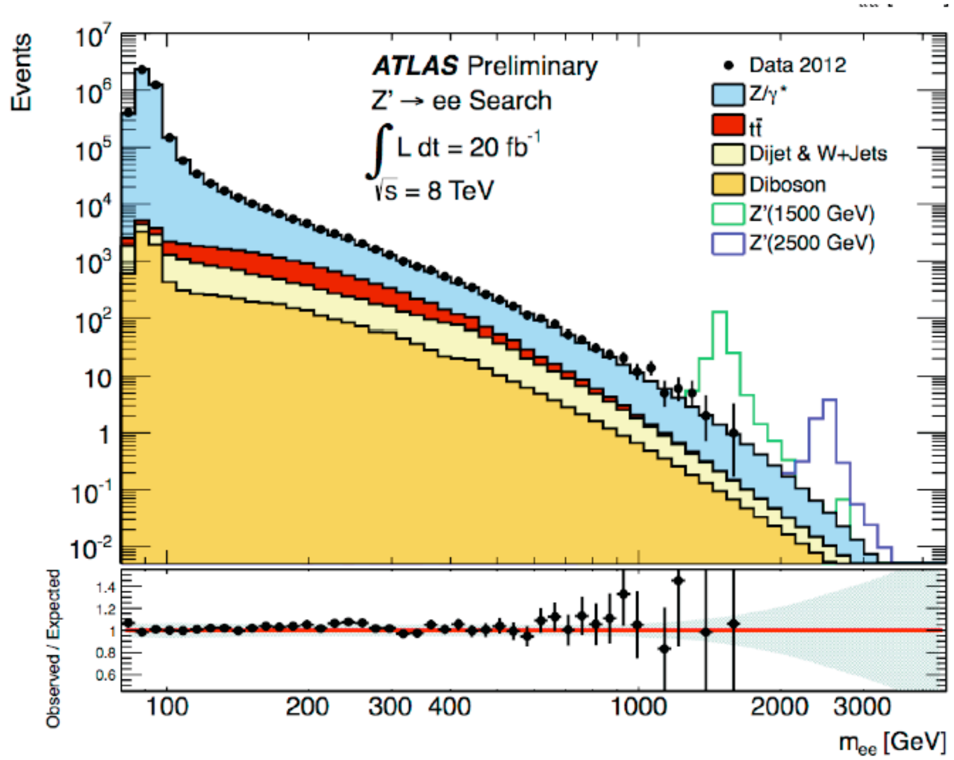
Cover as many signatures as possible

Koji Terashi

Exotics Searches at Atlas : Heavy Resonances

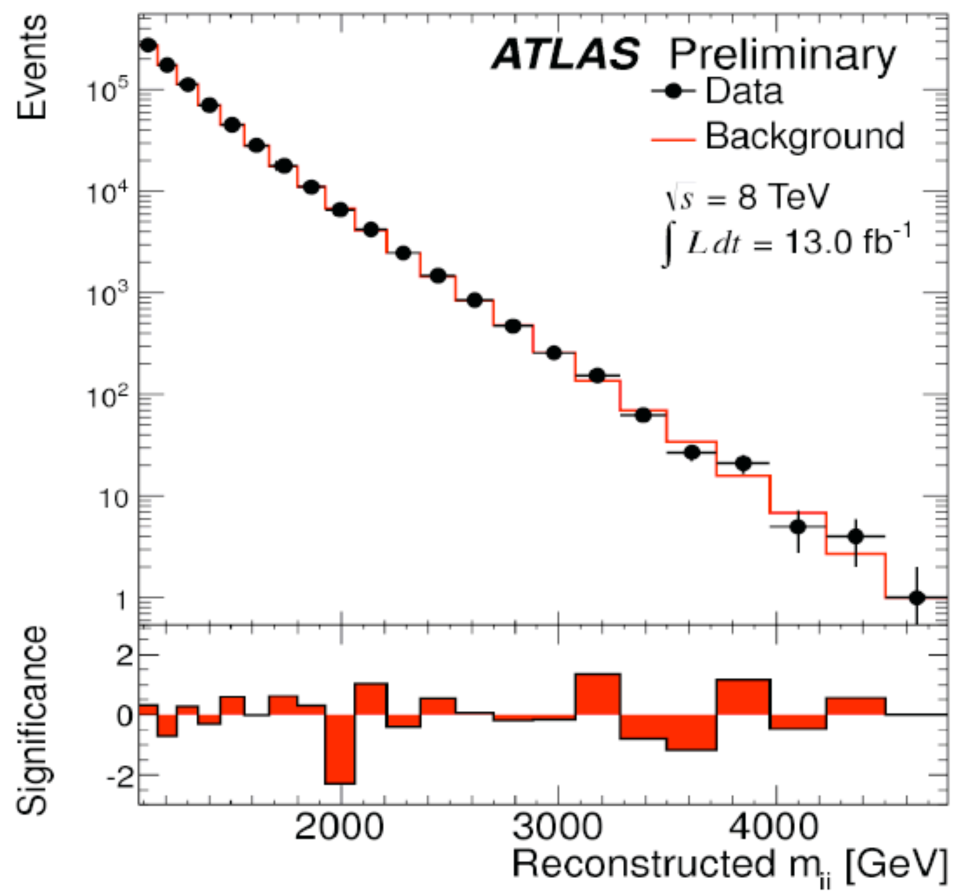
- Dileptons
- Diphotons
- Dijets
- Photon+jets
- Top-antitop resonances
- Top + b resonances
- Lepton + MET
- Dibosons

Francesco Conventi



Exclusion regions:

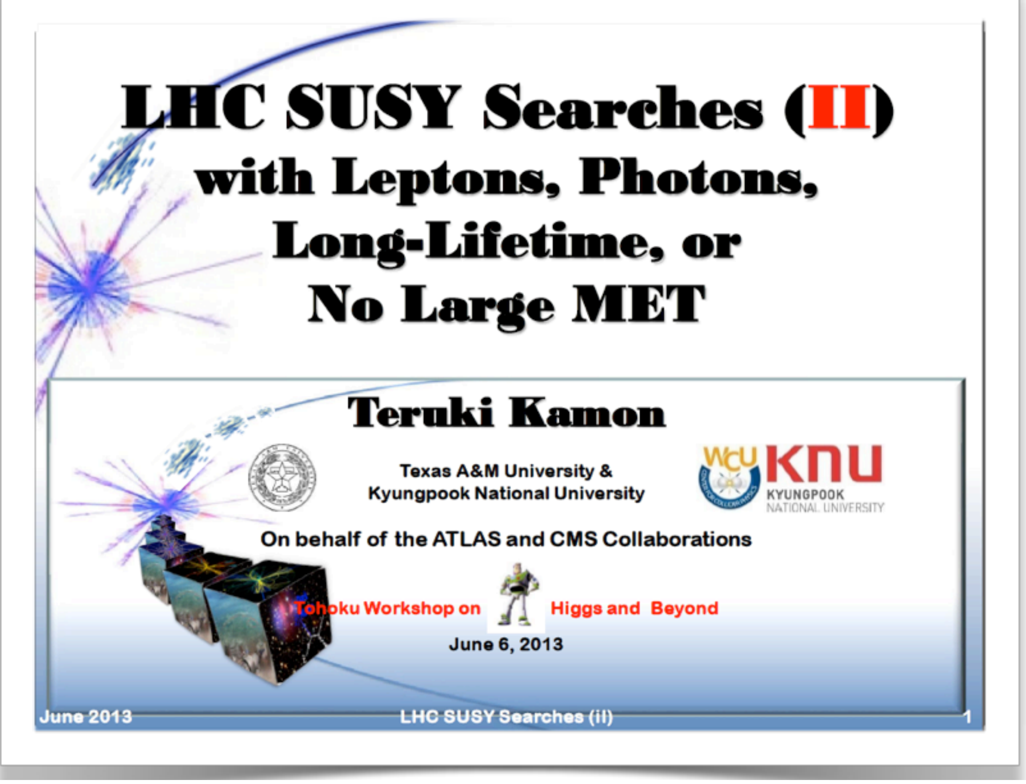
$M_{Z'}$ < 2.86 TeV @ 95% CL (SSM)
$M_{Z'}$ < 2.38-2.54 TeV @ 95% CL (E_6 models)
M_{G*} < 2.47 TeV @ 95% CL (RS gravitons, k/M_{Pl}=0.1)

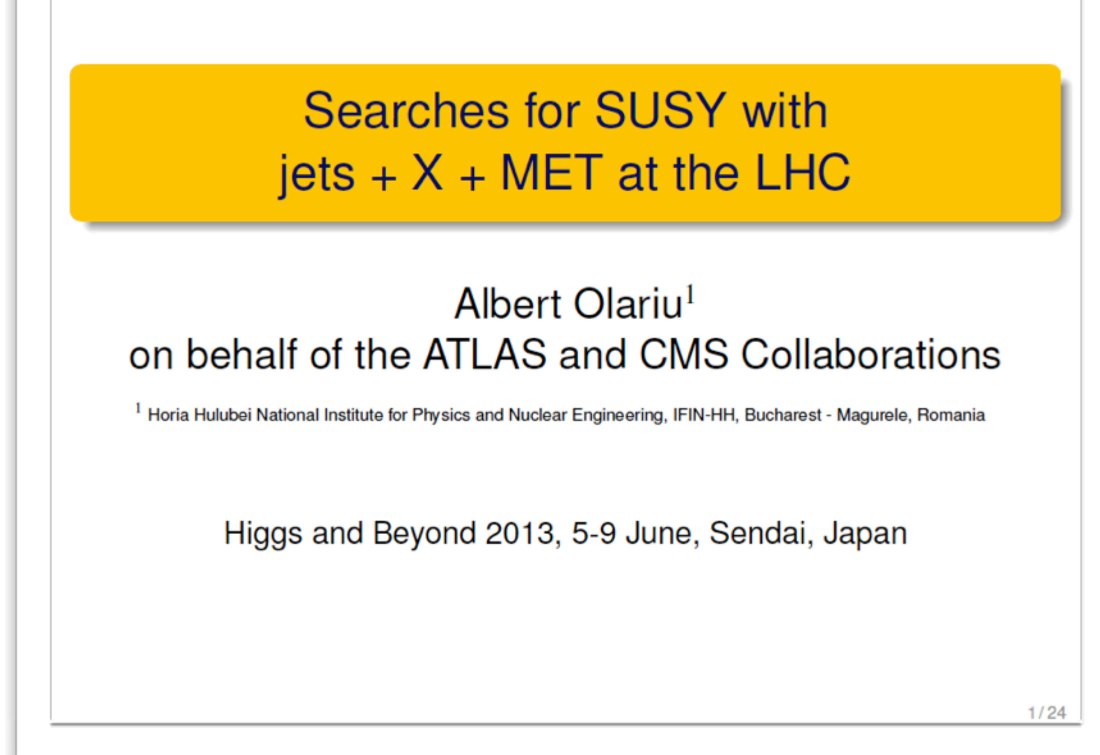


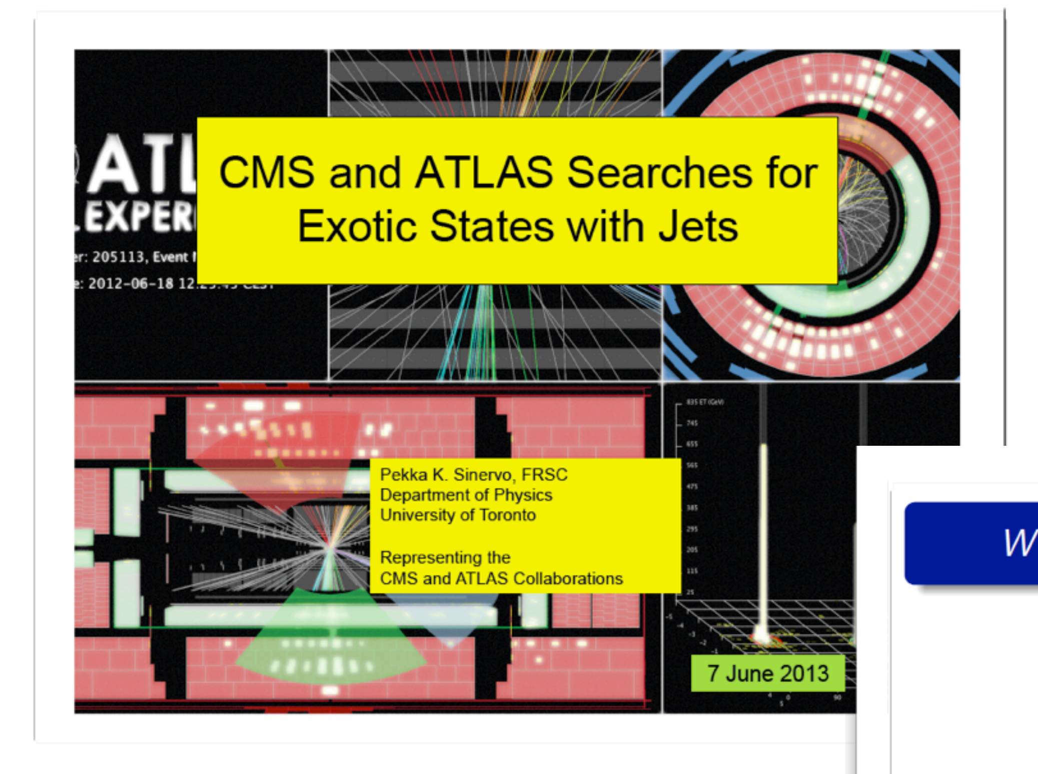
Lower Limit on σ x A
(excited quark model)
M_{q*} < 3.84 TeV
@ 95% CL
95% CL Lower limit on quark contact interactions
Λ > 7.6 TeV

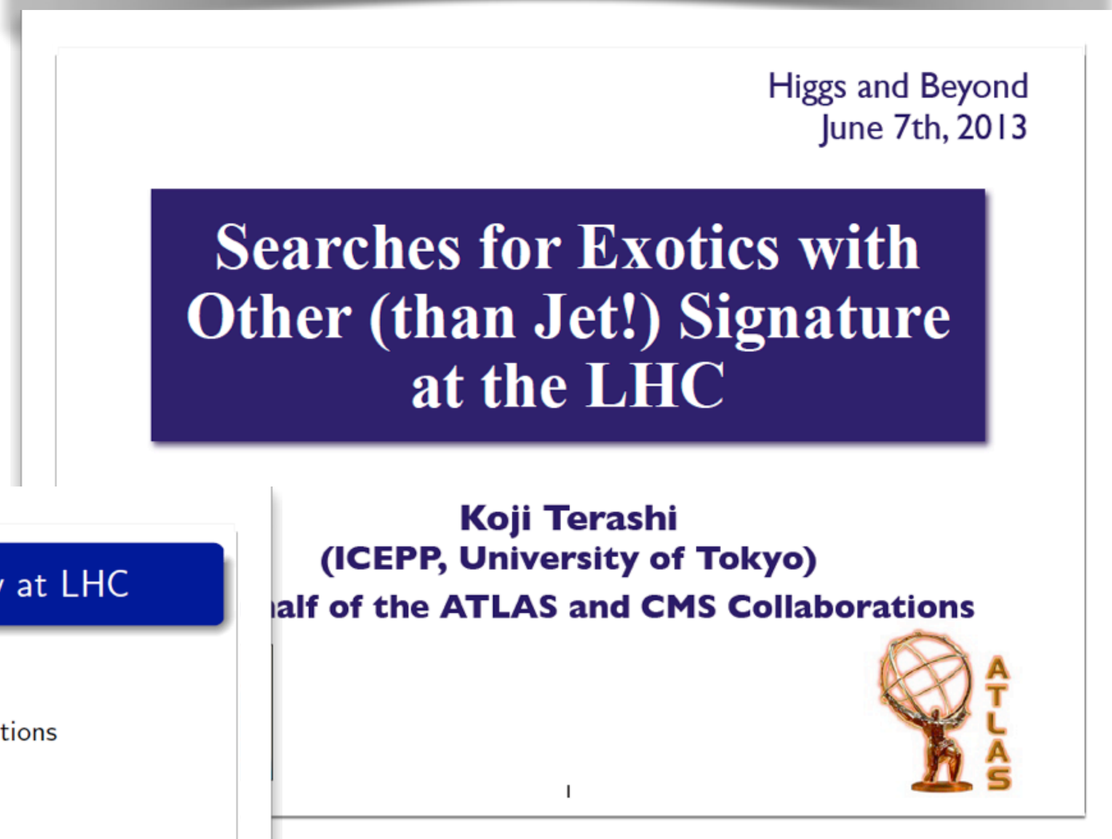
BSM Searches

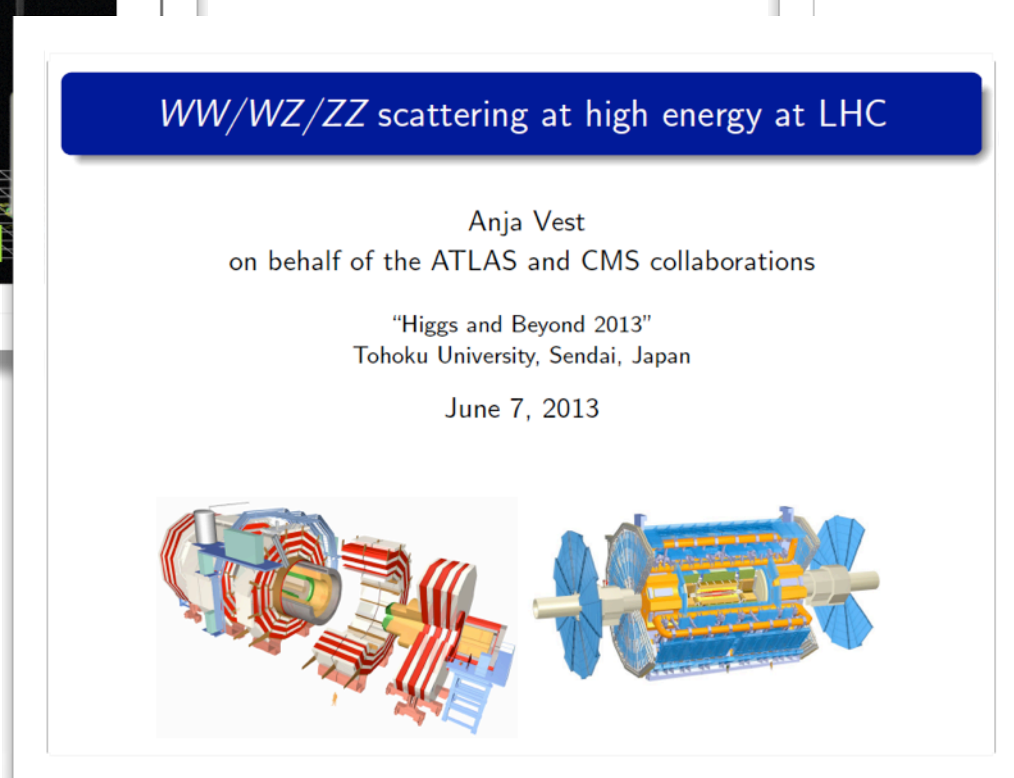
Teruki Kamon
Albert Olariu
Pekka Sinervo
Koji Terashi
Anja Vest



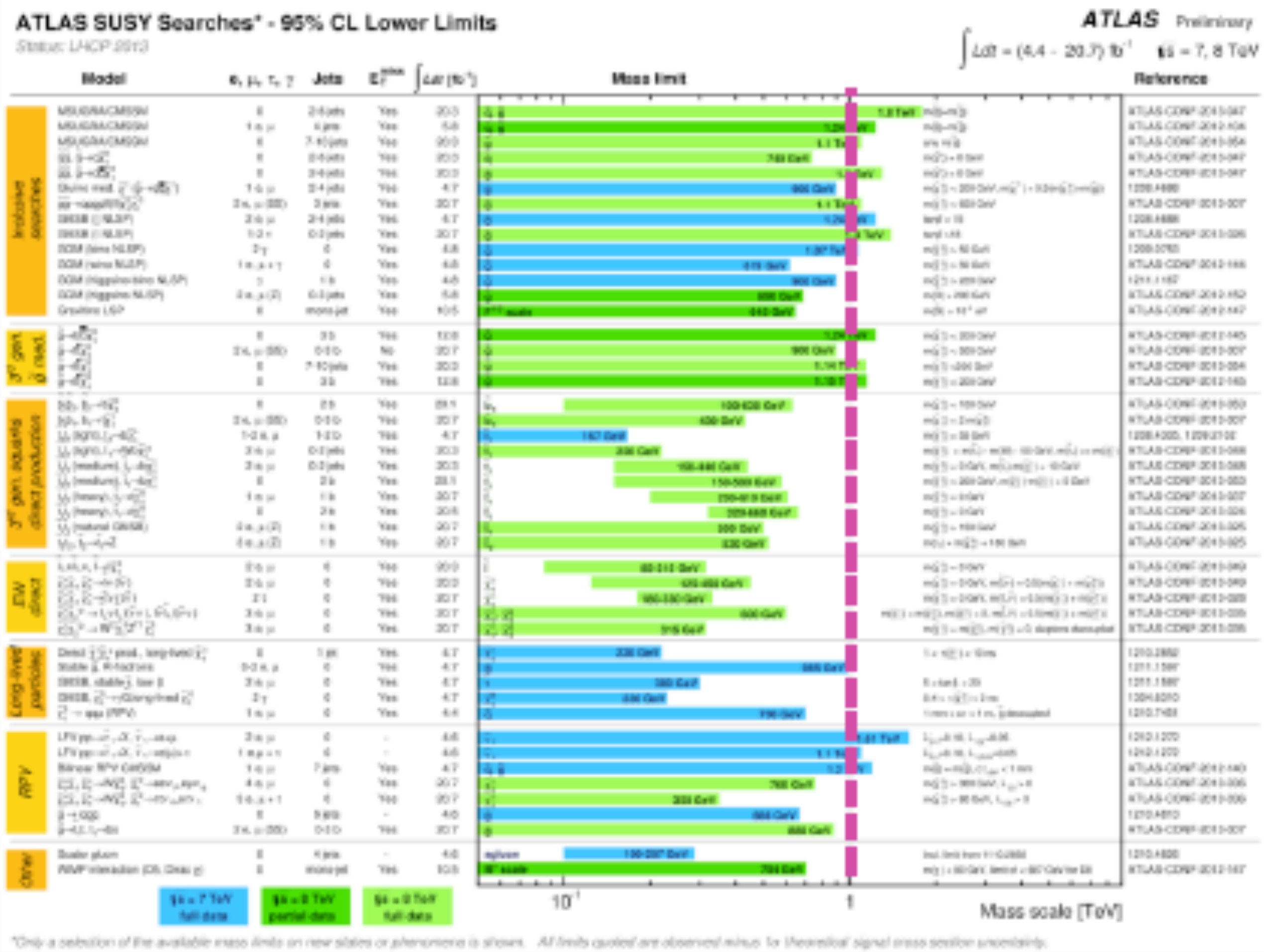


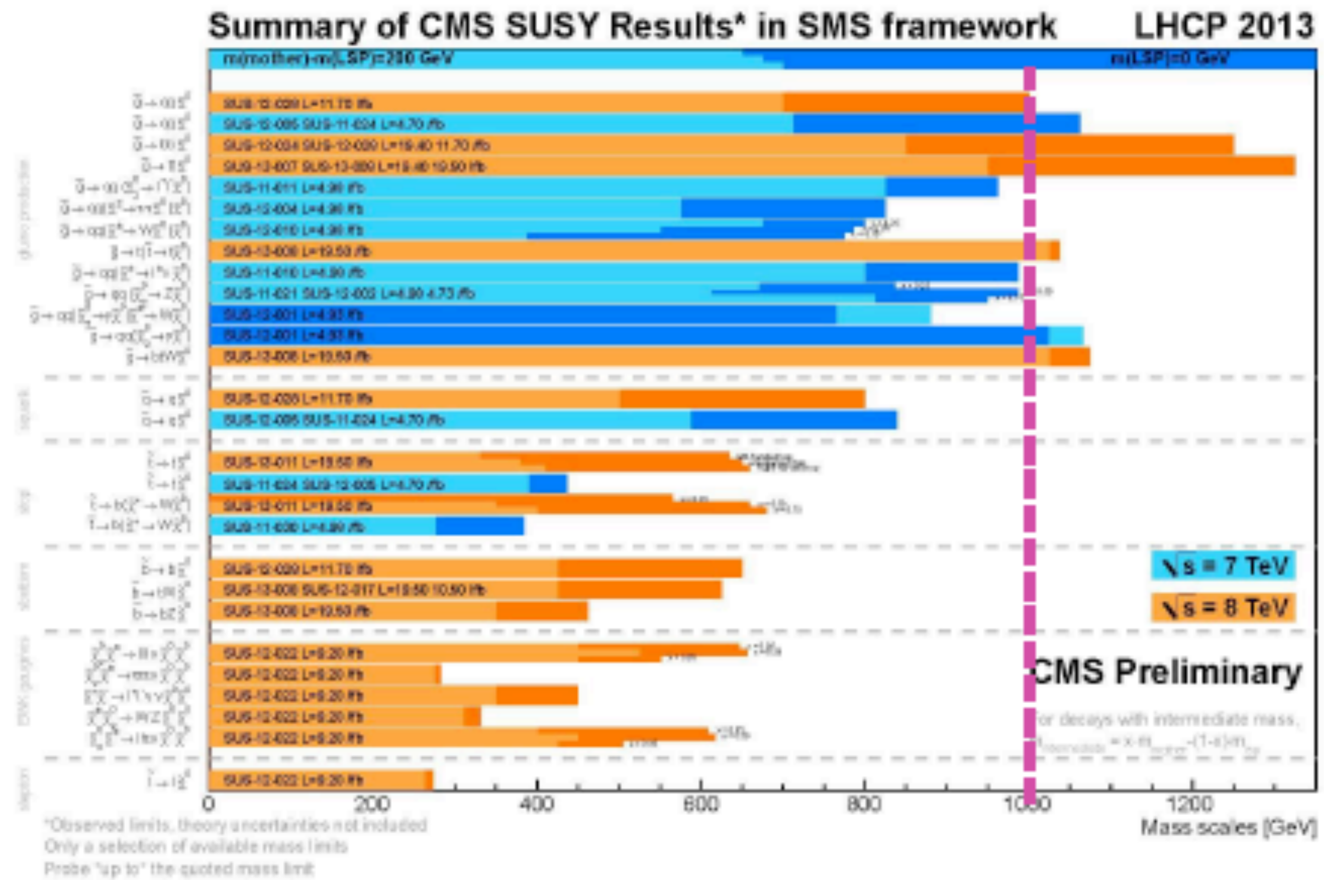


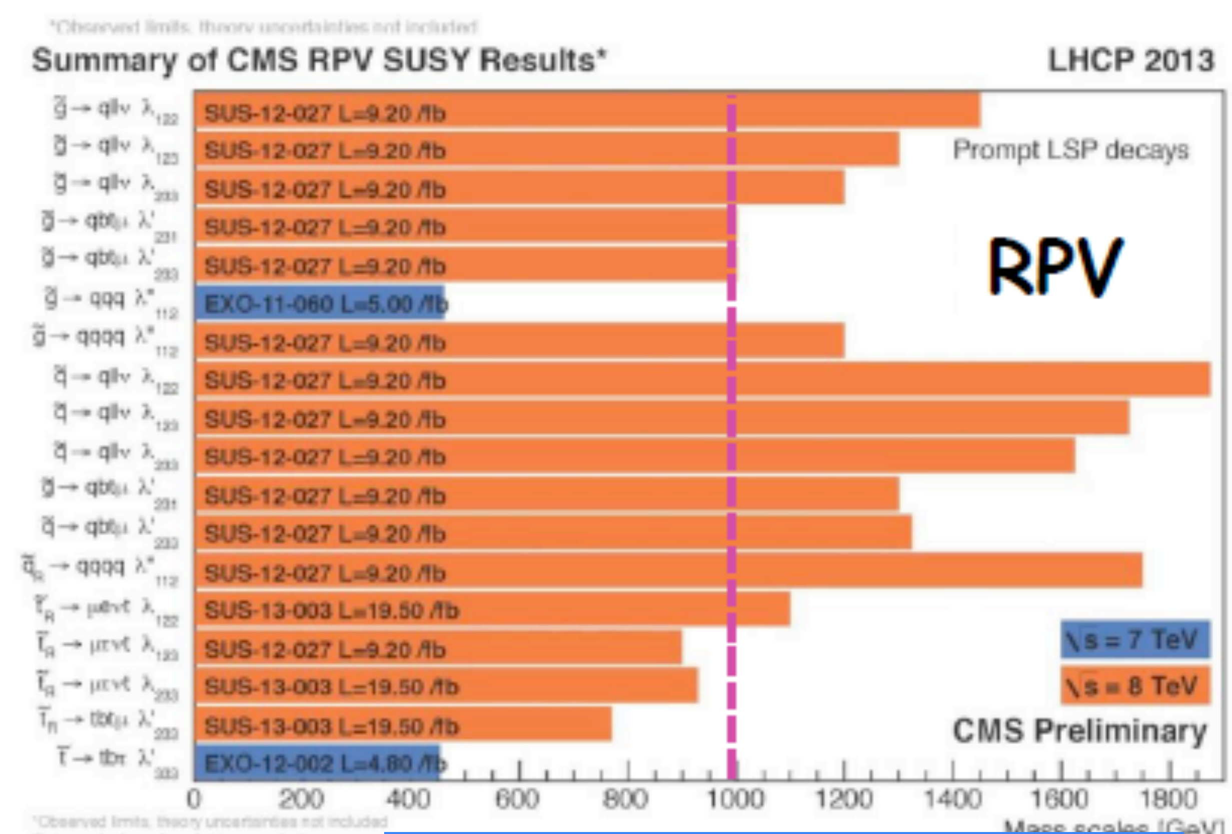




Summary





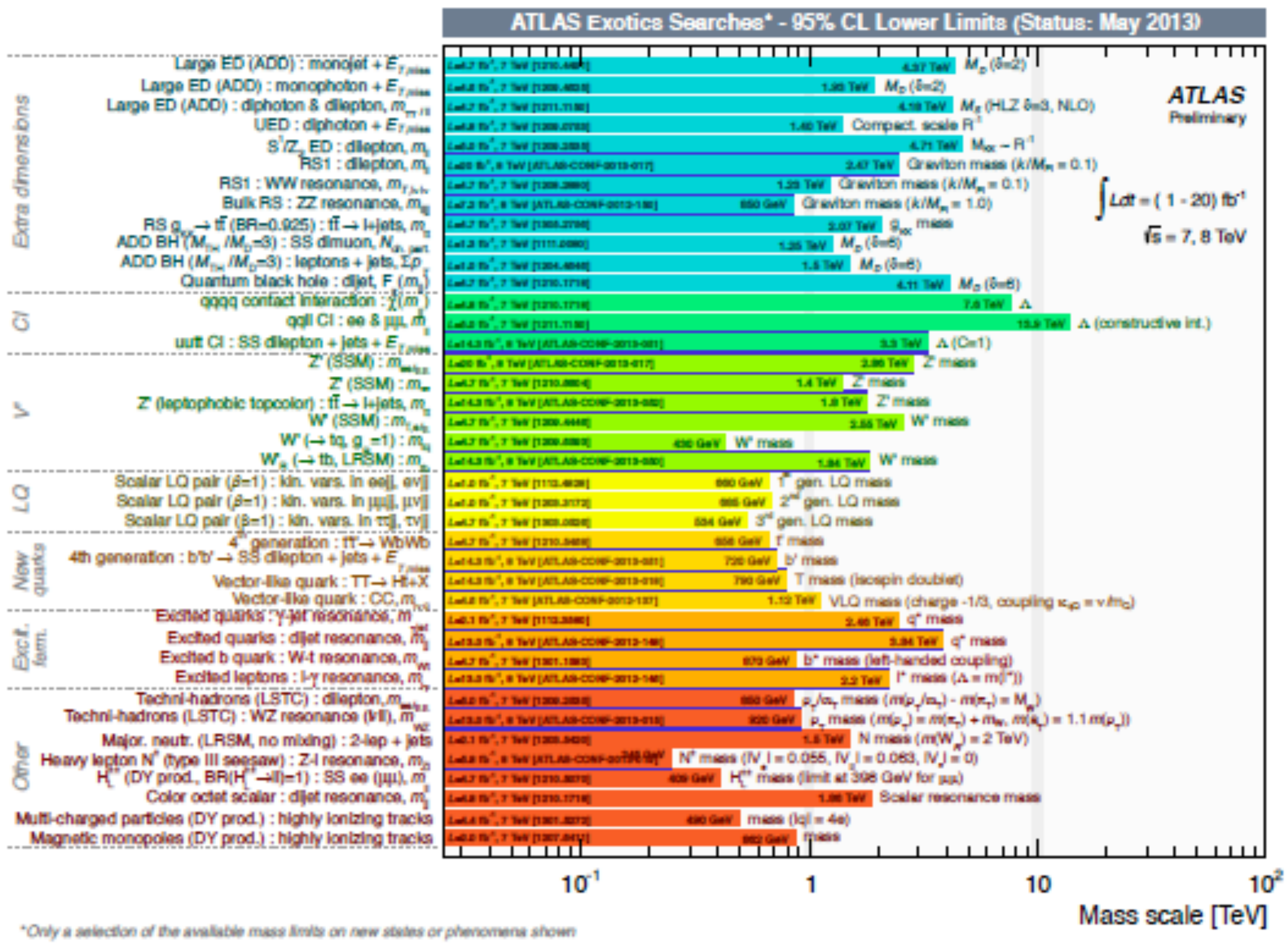


- Probing a TeV scale → No hints of SUSY (yet) in very diverse SUSY search programs, including physics beyond minimal scenarios.
- LHC13/LHC33, & ILC/TLEP along with direct/indirect DM programs
- Upgraded detectors to maintain or improve physics object reconstruction …

Summary and Conclusions

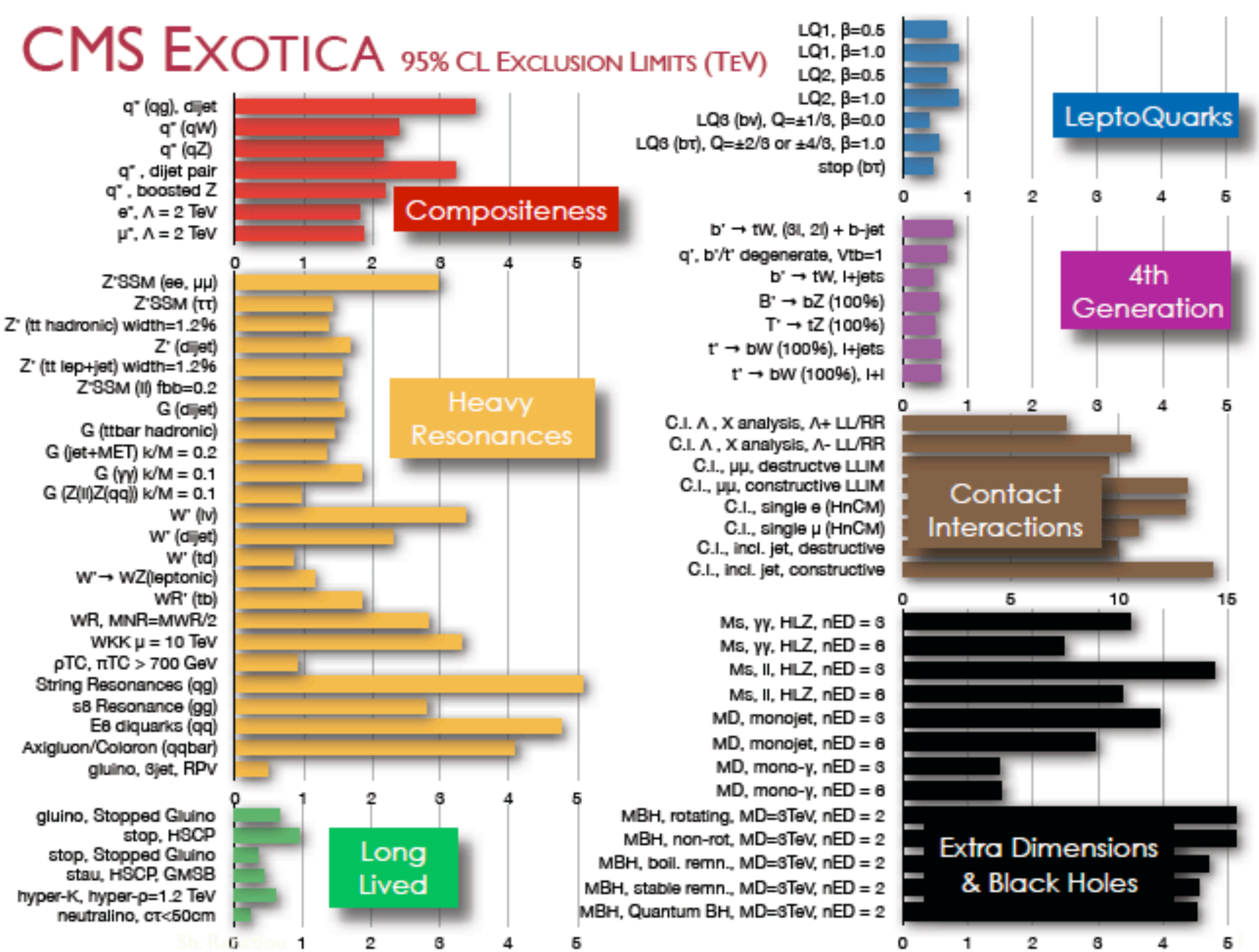
CMS and ATLAS successfully probing multi-TeV regime

- Summaries show that a large number of hypotheses tested
- But not able to cover all the topics



Next step is increase in pp energy and L coming in 2015

Pekka Sinervo (Koji Terashi)


CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)
q* (qg), dijet
q* (qW)
q* (qZ)
q*, dijet pair
q*, boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Compositeness
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (γγ) k/M = 0.1
G (Z(ll)Z(qq)) k/M = 0.1
W' (lν)
W' (dijet)
W' (td)
W'→ WZ(leptonic)
WR' (tb)
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
Heavy Resonances
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
Long Lived
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bν), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
LeptoQuarks
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
4th Generation
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
Contact Interactions
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2
Extra Dimensions & Black Holes

Alternative futures

1. Naturalness triumphs – new physics discoveries at 14 TeV.
2. Naturalnesss fails a little bit: where are the clues to the next energy scales
    1. Split supersymmetry: LHC discovery of light gluino. ILC establishes minimal standard model with extreme precision.
    2. Unsplit – ILC again establishes MSM. Intensity frontier provides evidence for a new scale at 10's of TeV ($\mu \rightarrow e + \gamma; \quad d_n$). *Eventually* able to probe this scale.
3. Big failure of naturalness

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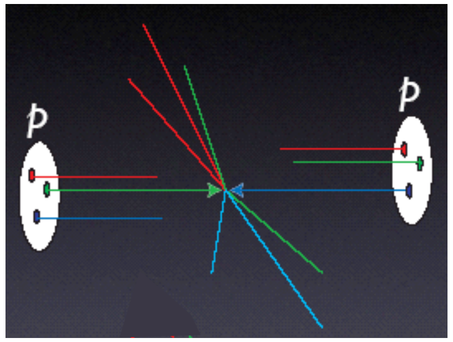
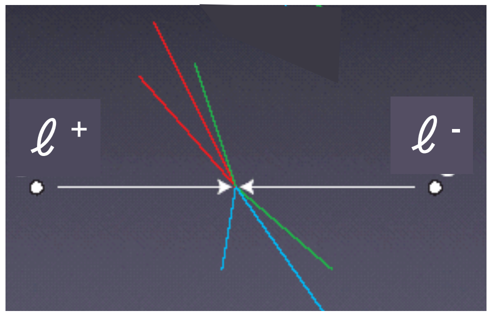
We must discover which future is reality

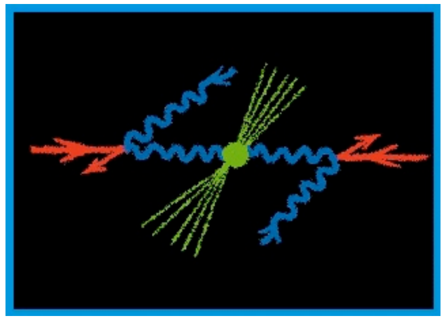
Michael Dine

We must discover which future is reality

- Depends on advances in accelerator facilities
  - Proton Colliders
    - LHC (through 2021)
    - HL-LHC
    - VHE-LHC
  - Lepton Colliders
    - ILC
    - CLIC
    - Rings
    - muC
  - Gamma-gamma Collider







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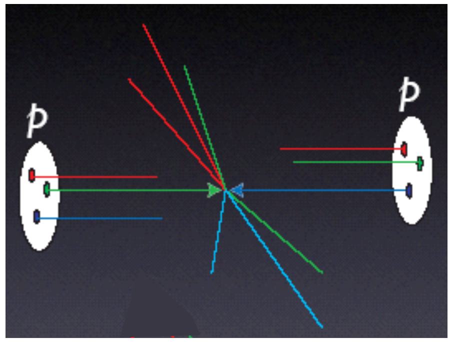
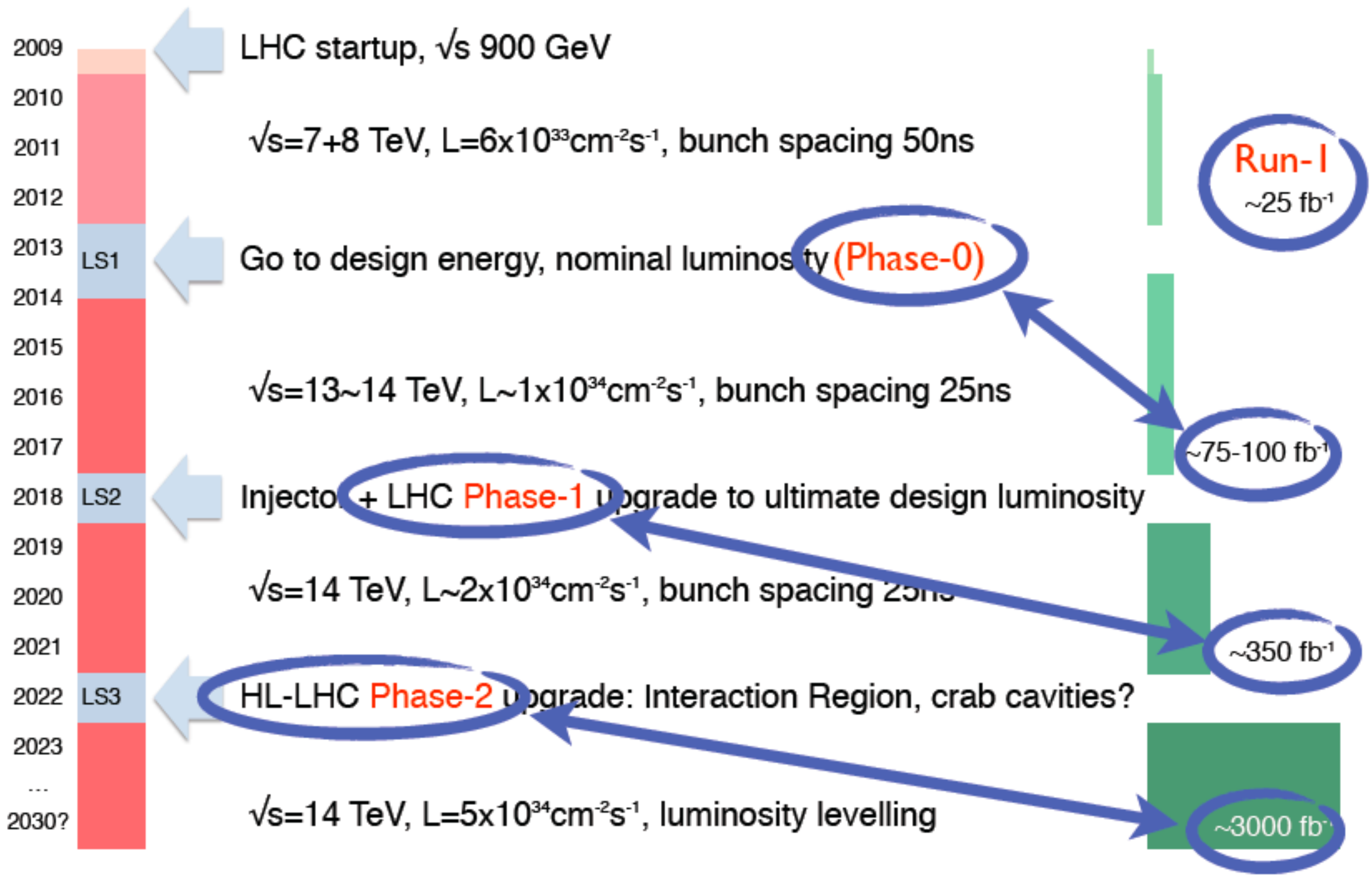
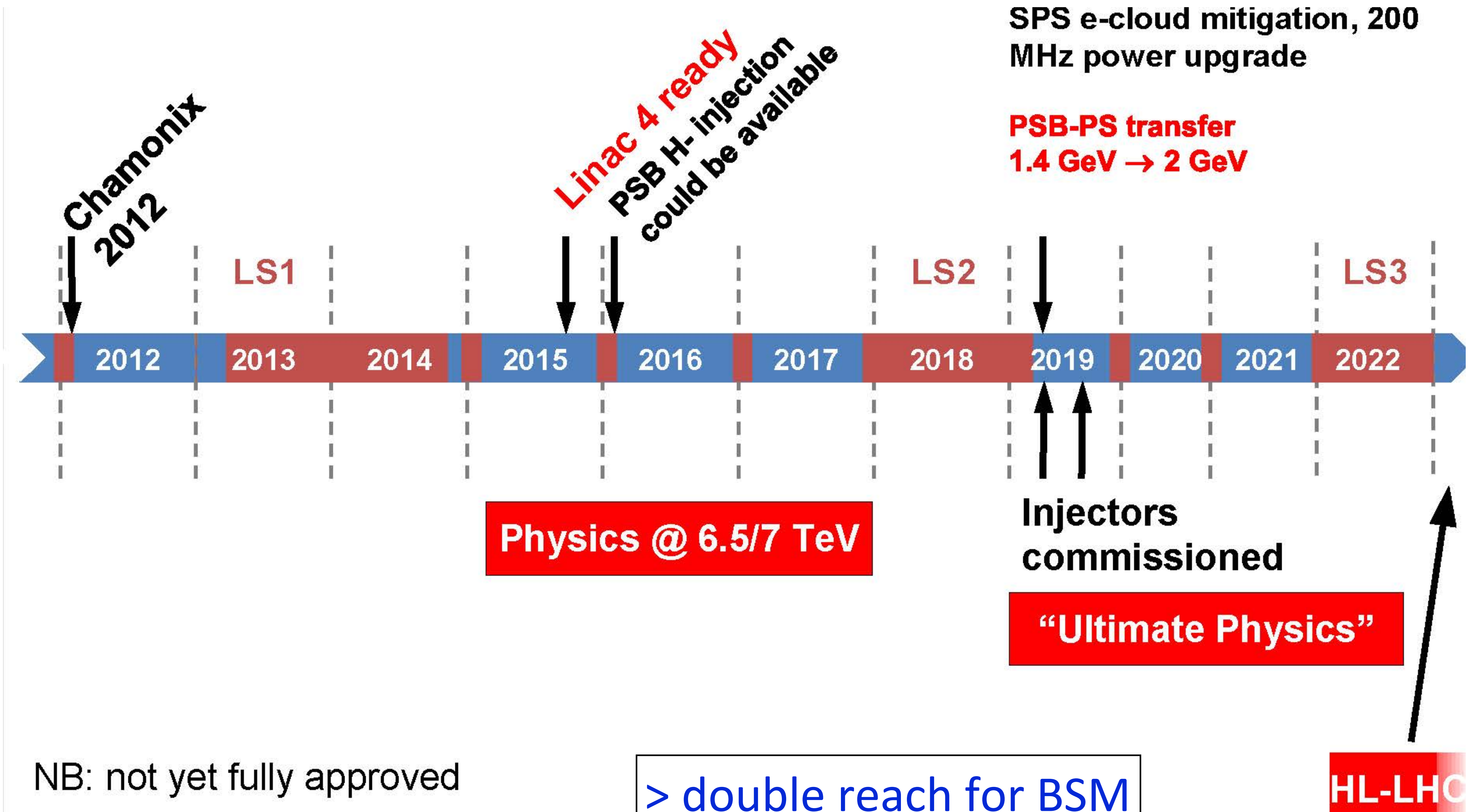


LHC has just started



example LHC time line – next ten years



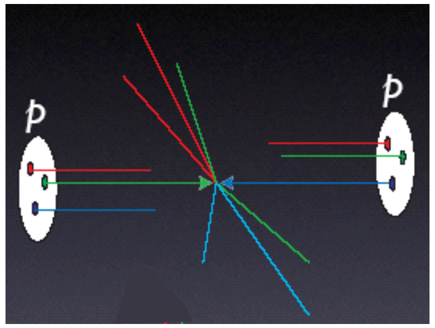
> double reach for BSM

Ralph Steinhagen, ICHEP2012

"400/fb by 2021?"

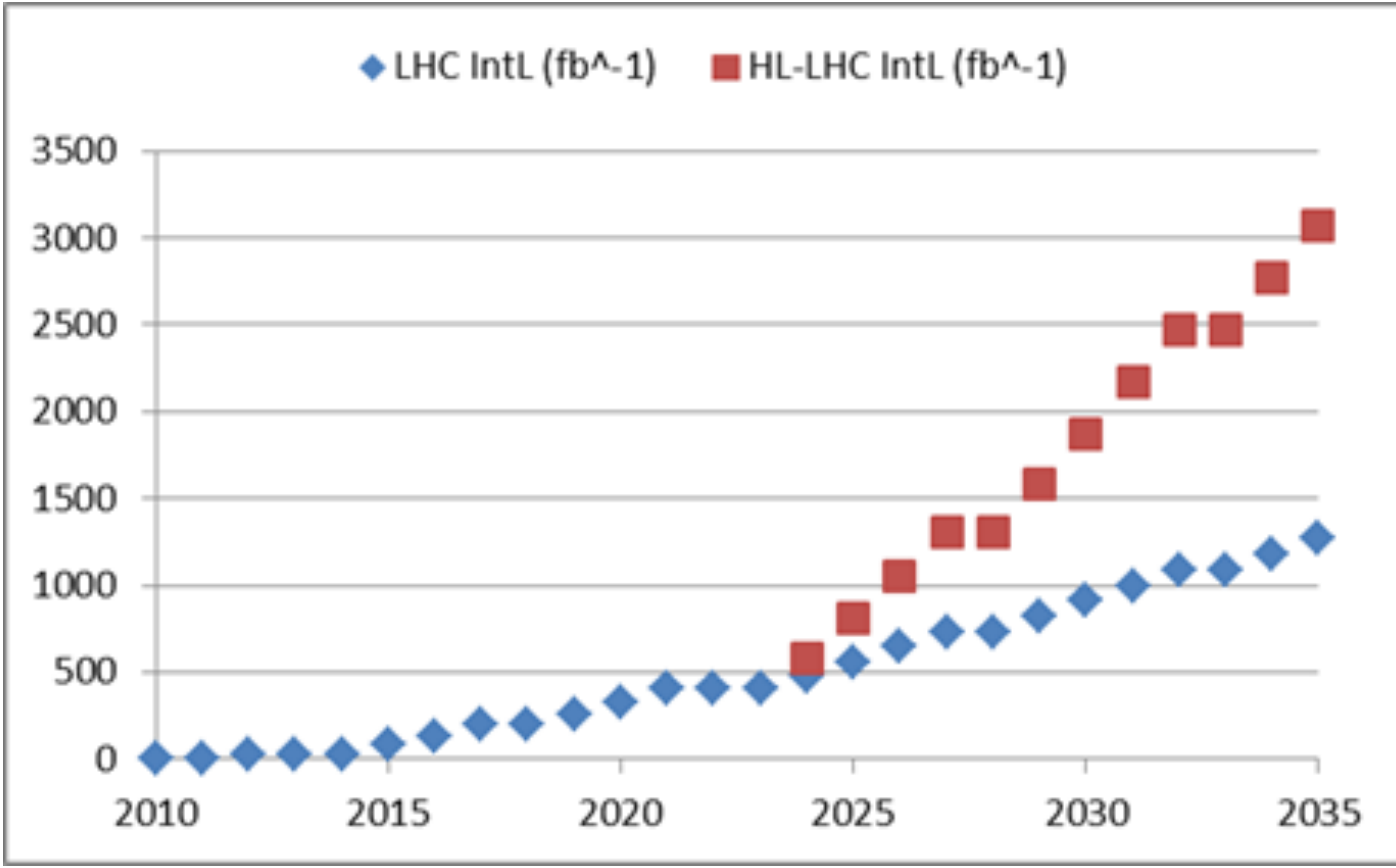
Frank Zimmerman

Proton Colliders



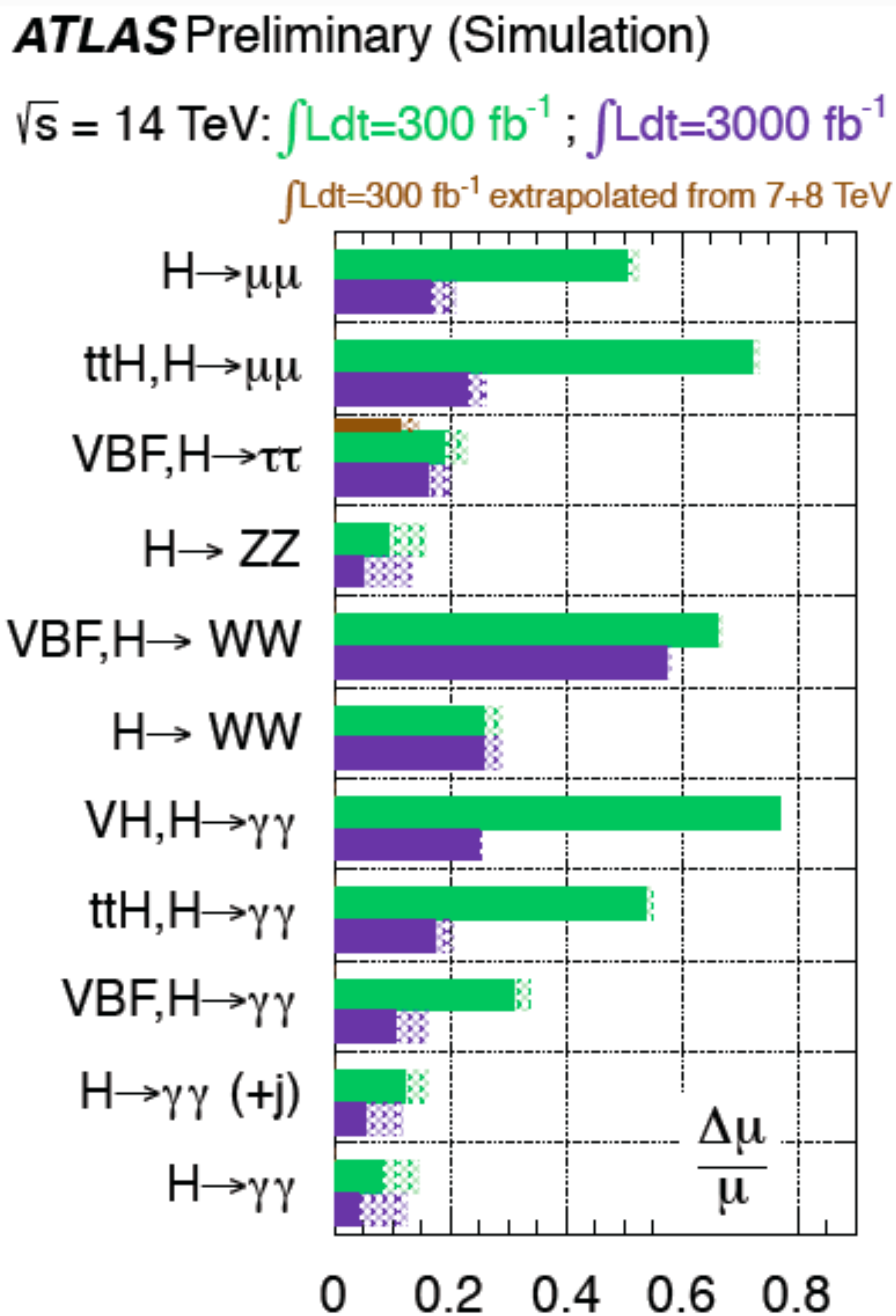
- HL-LHC
  - $\mathscr{L} = 5 \cdot 10^{34} cm^{-2}s^{-1}$ with luminosity leveling for a total of 3000 fb^{-1}, expected pileup of ~140
    - challenge: maintain detector performance (for taus, photons, jets, b-tagging, missing ET, ...)
    - keep sensitivity for moderate p_T objects even at large η(e.g. to study vector boson fusion)
    - LHC experiments have big upgrade programs for detector components, readout, trigger, DAQ, computing

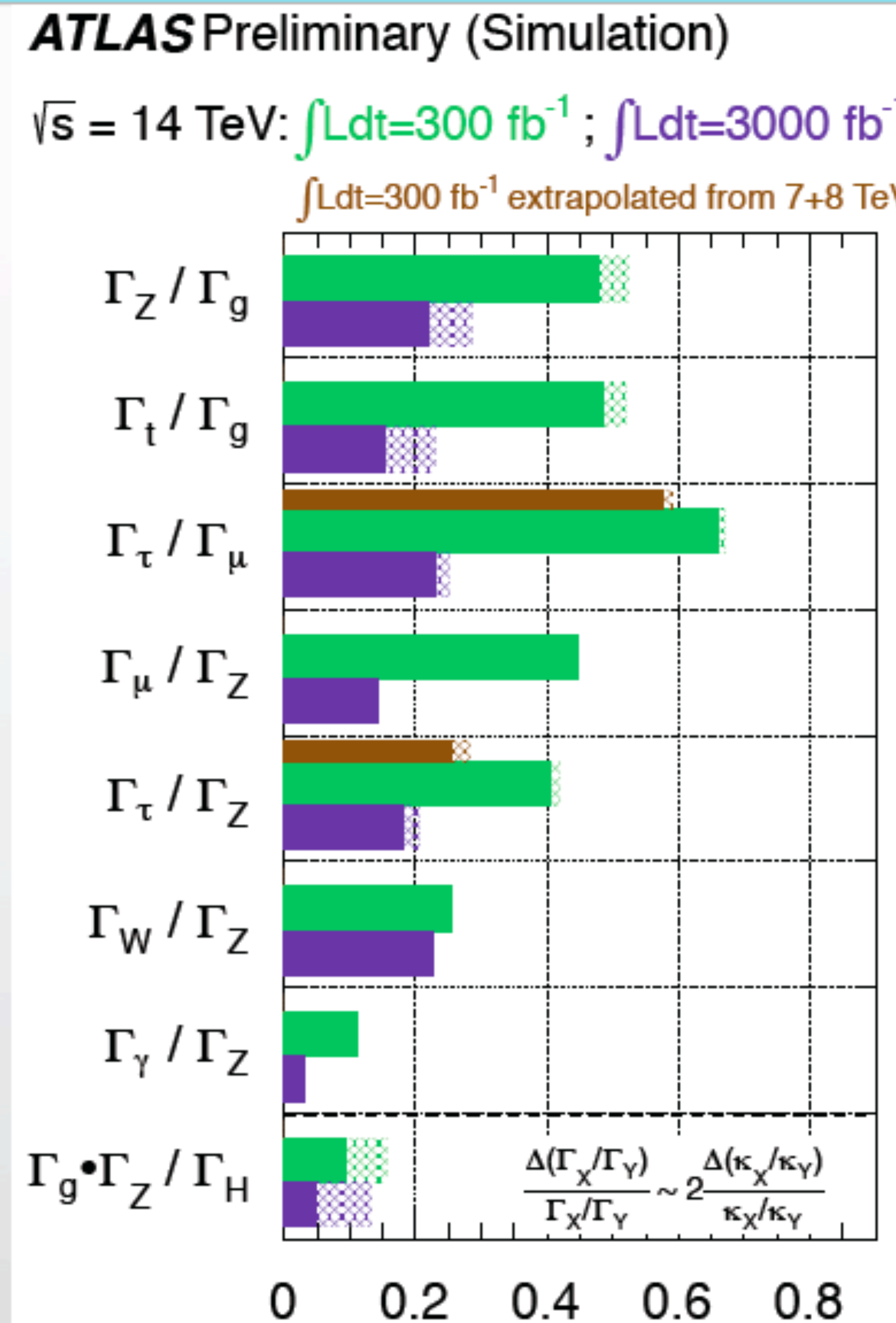
Frank Zimmerman



Frank Zimmerman

$\mu = (\sigma \times BR)/(\sigma \times BR)_{SM}$ ($\Delta\mu$ for SM g_{HXX})





HL-LHC Higgs boson couplings @3000 fb^{-1}

CMS Coupling	Uncertainty (%) 3000 fb^{-1}	
	Scenario 1	Scenario 2
κ_γ	5.4	1.5
κ_V	4.5	1.0
κ_g	7.5	2.7
κ_b	11	2.7
κ_t	8.0	3.9
κ_τ	5.4	2.0

Scenario 1: systematics as in 2012
Scenario 2: theory syst. scaled by a factor ½, other systematics scaled by 1/√L

- With 3000 fb^{-1} the Higgs couplings can be determined with high precision (1-4%)

Vladimir Rekovic

$HH \rightarrow bb\gamma\gamma$ (BR~0.27%)

sample	$\sigma\times$BR (fb)	simulated events	events passing selection	events expected in 3000 fb^{-1}
$HH \rightarrow b\bar{b}\gamma\gamma$ ($\lambda_{HHH} = 1$)	0.09	1020	42	10.7 (SM)
$HH \rightarrow b\bar{b}\gamma\gamma$ ($\lambda_{HHH} = 0$)	0.19	1020	32	17.9
$HH \rightarrow b\bar{b}\gamma\gamma$ ($\lambda_{HHH} = 2$)	0.04	1230	66	6.4
$\gamma\gamma b\bar{b}$	111	3.1×10^4	1	1.1
$ZH(Z\rightarrow b\bar{b}, H\rightarrow\gamma\gamma)$	0.04	5×10^5	11600	2.8
$b\bar{b}H(H\rightarrow\gamma\gamma)$	0.124	5×10^4	71	0.5
$\gamma\gamma jj$	2×10^3	5×10^5	0.004	0.1
$jjjj$	1.8×10^8	4.6×10^6	0	0
$t\bar{t}H(H\rightarrow\gamma\gamma)$	1.71	1.2×10^5	379	13.6
$t\bar{t}$ ($\geq$ 1 leptonic W decay)	5.0×10^5	1×10^7	74†	1.1
Total Background	-	-	-	19.2

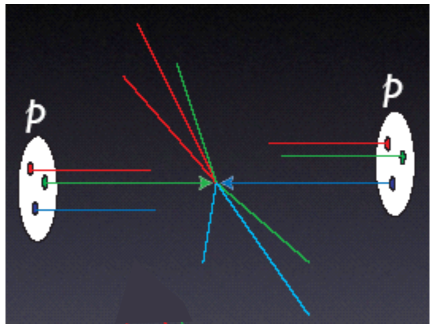
ATLAS-PHYS-PUB-2013-001

combining with another channel with similar performances

($HH\rightarrow\tau\tau bb$?) and 2 exp.s, one should reach Δg_{HHH} ~30% !

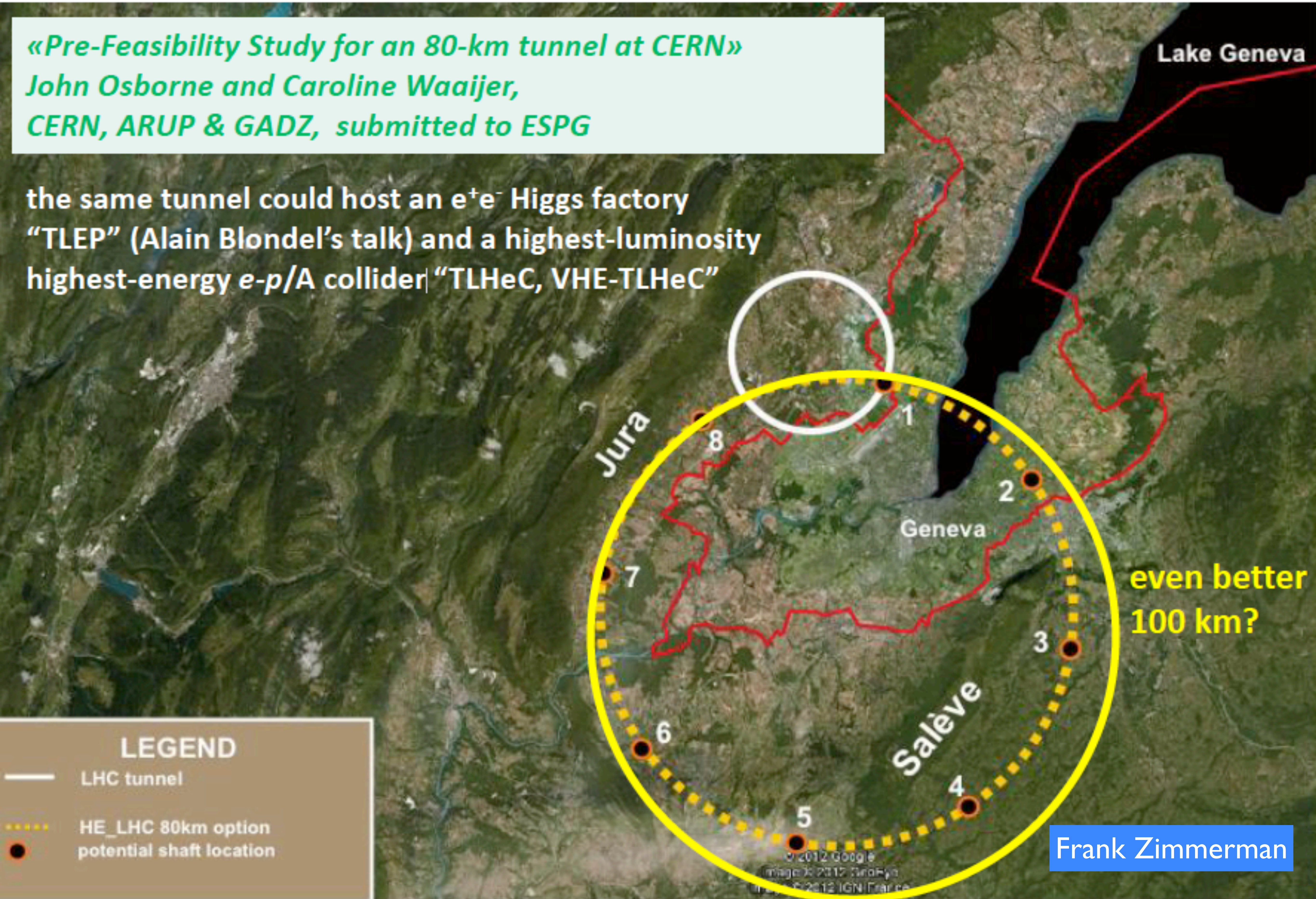
Barbara Mele

Proton Colliders



- VHE-LHC
  - 80 km (100 km) electron ring could set the stage for a future very high energy hadron collider (Ecm = 100 TeV)
    - as LEP preceded the LHC
  - Proposed lepton collider ring (TLEP) in part motivated by this long term possibility
  - VHE-LHC needs physics justification

80-km tunnel for VHE-LHC – “best” option



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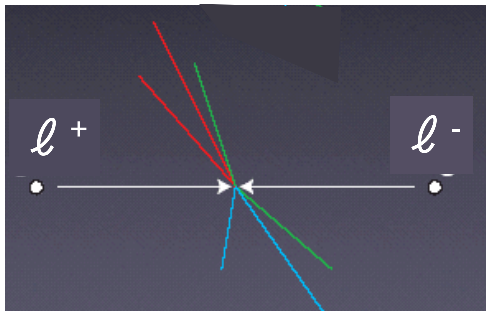
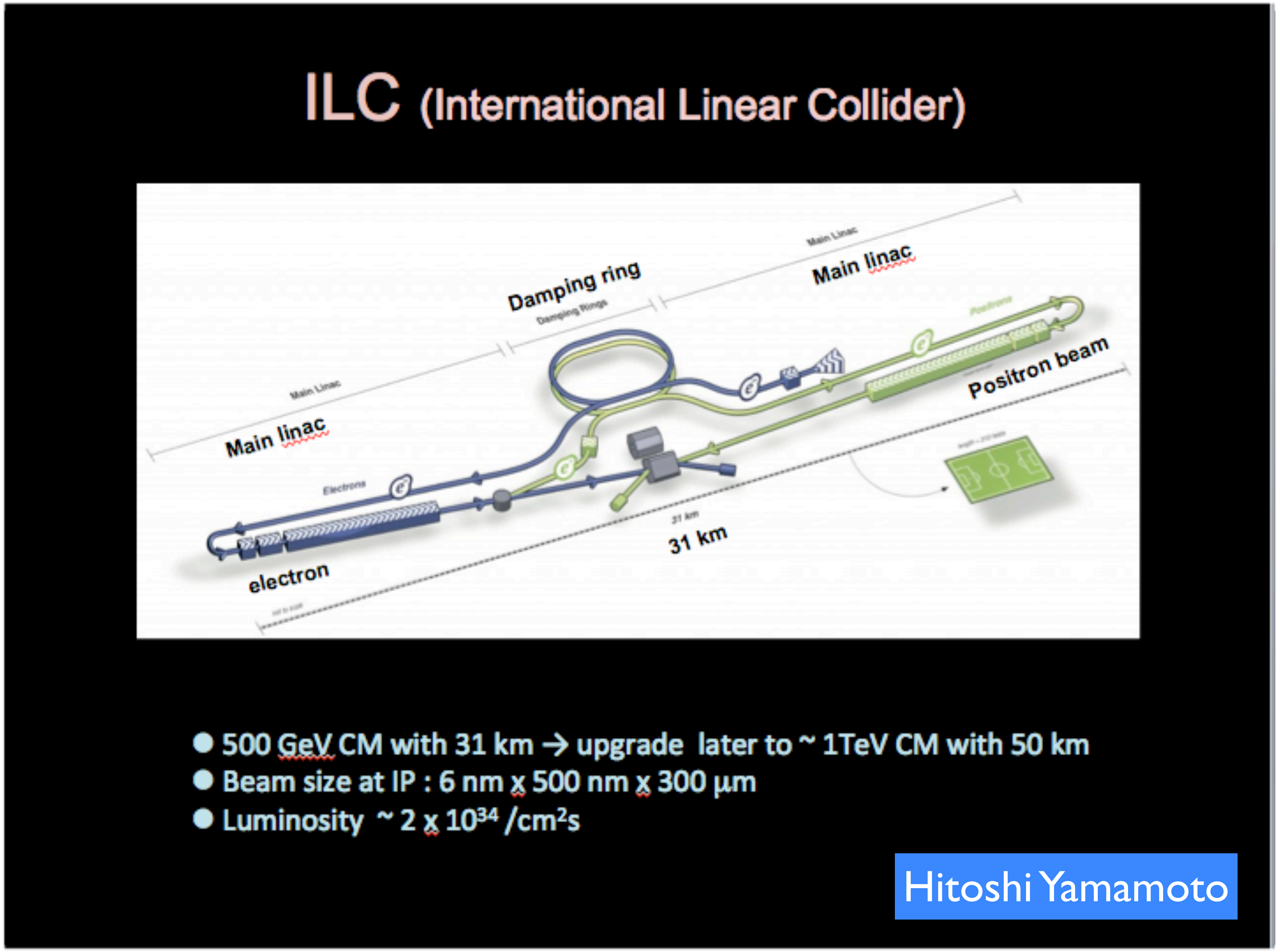
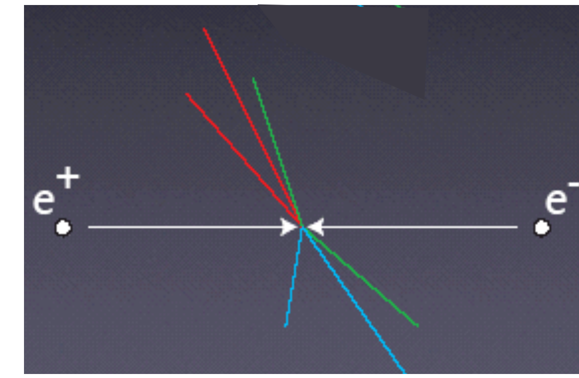






staging

$\sqrt{s}$ = 250 GeV
350 GeV
500 GeV
1 TeV

ILC Technical Design Report (with costs) completed in 2013 following
nearly decade of dedicated ILC R&D by the Global Design Effort (ICFA)
June 12 - completed version delivered to ICFA in world-wide event
includes detailed baseline designs for two complementary detectors:
SiD and ILD

JAHEP

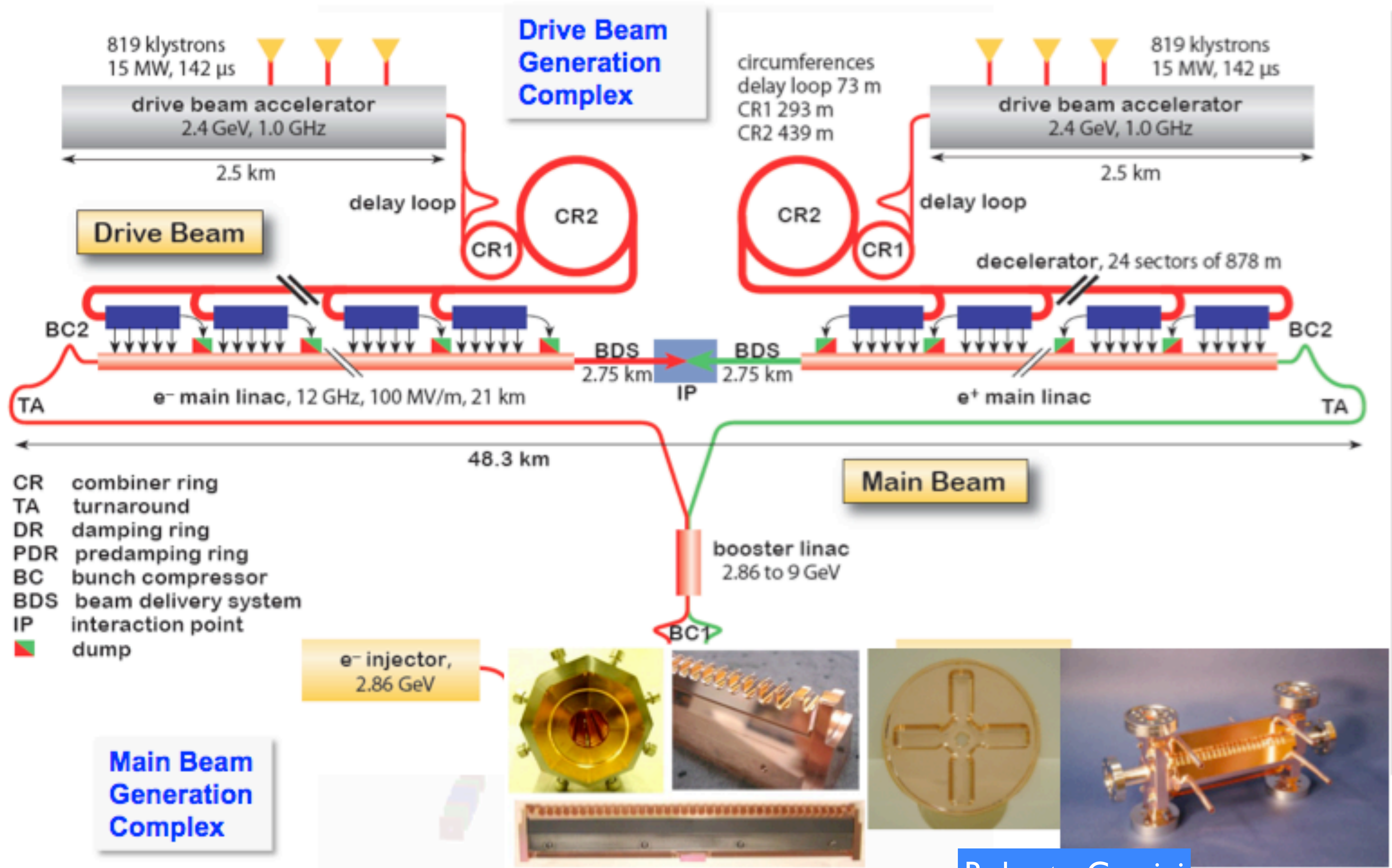
- A proposal for staging of ILC (October 2012)
  - Staging
    - A Higgs factory with a CM energy of ~250 GeV to start
    - Upgraded in stages to ~500 GeV (RDR baseline)
    - Technical expandability to ~1 TeV to be secured

  This is now an official proposal of the Japanese HEP community.

  - Guideline for cost sharing
    - The host country to cover 50% of the expenses (construction) of the overall project of the 500 GeV machine.
    - The actual contribution, however, should be left to negotiations among the governments.

Hitoshi Yamamoto

CLIC Layout at 3 TeV



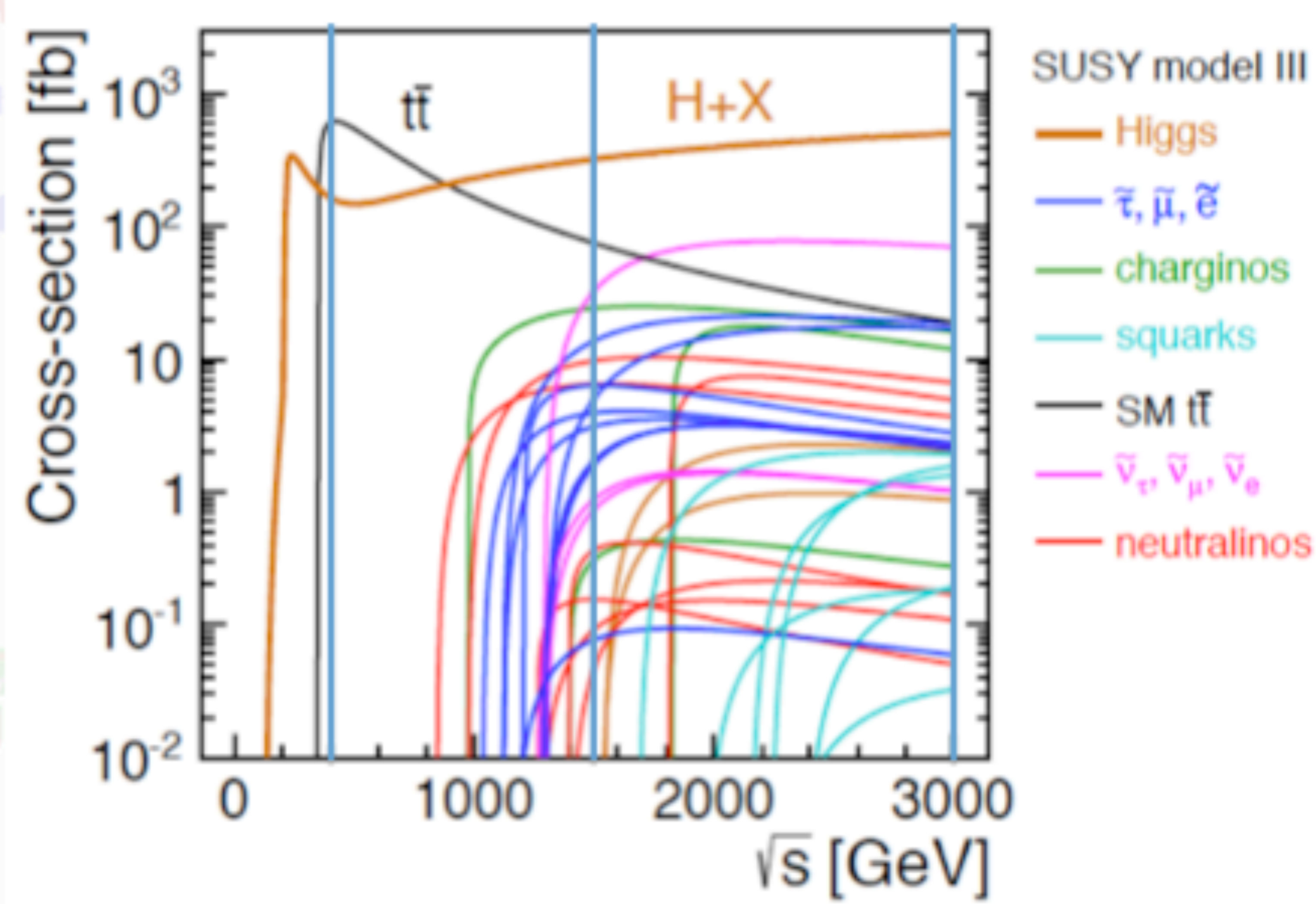
Roberto Corsini

CLIC physics potential

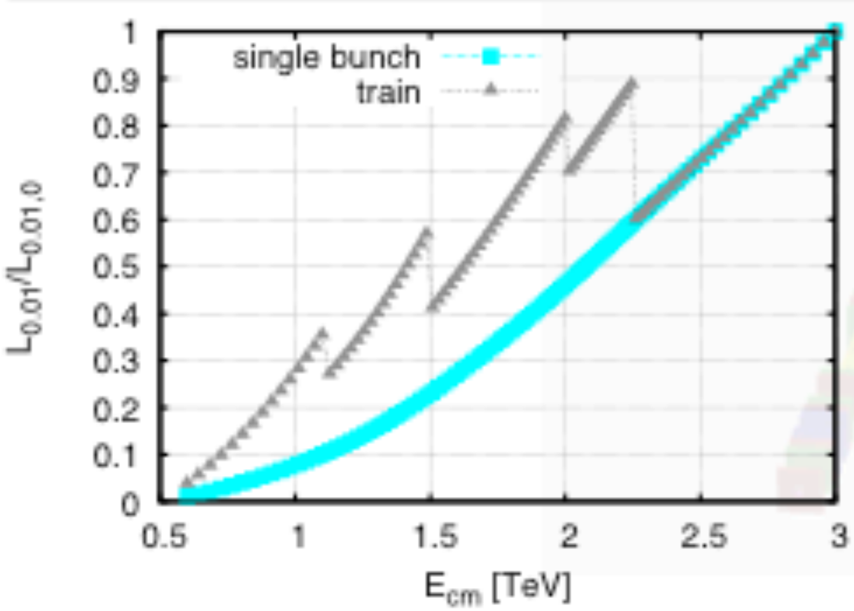
LHC complementarity at the energy frontier:
- How do we build the optimal machine given a physics scenario (partly seen at LHC ?)

Examples highlighted in the CDR:
- Higgs physics (SM and non-SM)
- Top
- SUSY
- Higgs strong interactions
- New Z' sector
- Contact interactions
- Extra dimensions

Detailed studies at 350 (500), 1400 and 3000 GeV for these processes



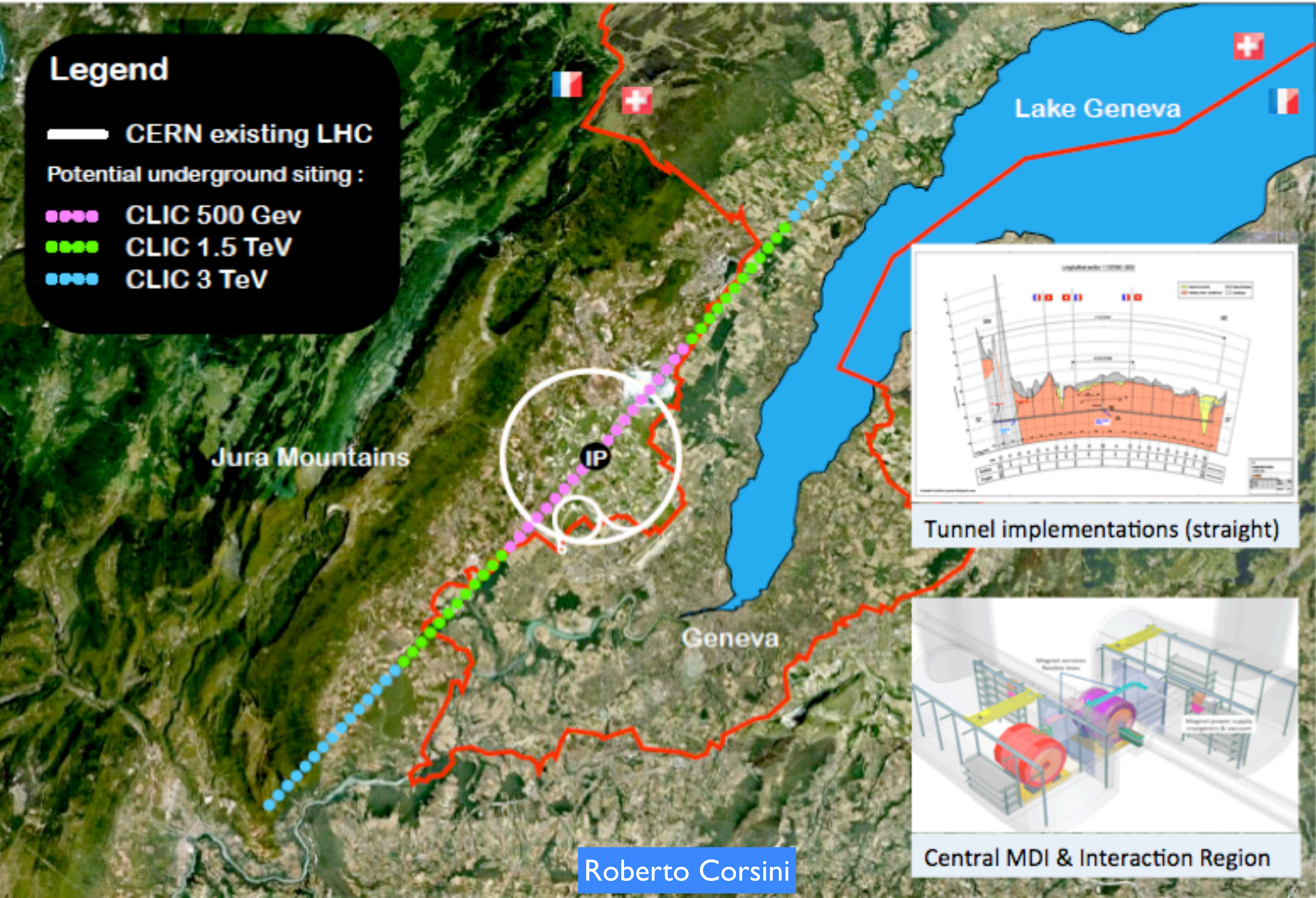
Operation at lower than nominal energy



Stage 1: ~350-375 GeV => Higgs and top physics
Stage 2: ~1.5 TeV => ttH, ννHH + New Physics (lower mass scale)
Stage 3: ~3 TeV => New Physics (higher mass scale)

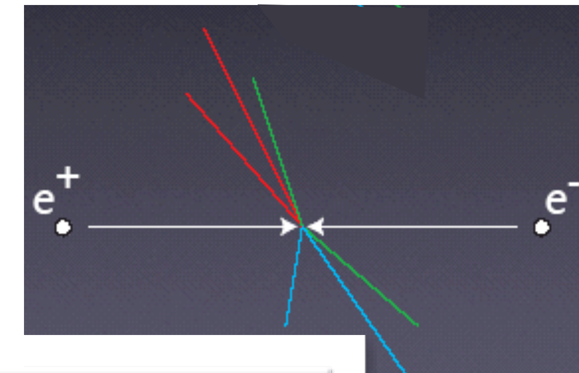
Roberto Corsini

CLIC near CERN



Roberto Corsini

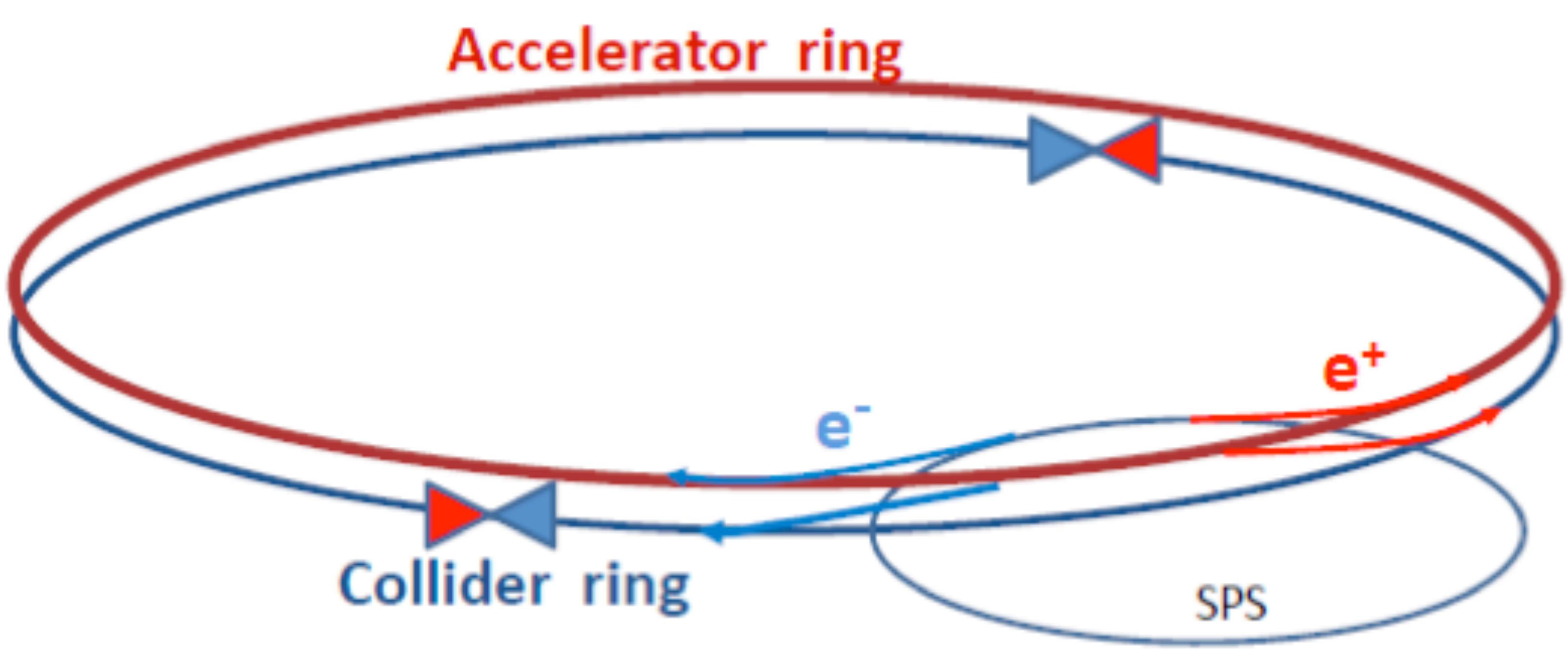
Ring Collider



How can one increase over LEP 2 (average) luminosity by a factor 500 without exploding the power bill?

Answer is in the B-factory design: a very low vertical emittance ring with higher intrinsic luminosity and a small value of β_y^*

electrons and positrons have a much higher chance of interacting
  → much shorter lifetime (few minutes)
    → feed beam continuously with a ancillary accelerator



Storage ring has separate beam pipes for e+ and e-

Alain Blondel

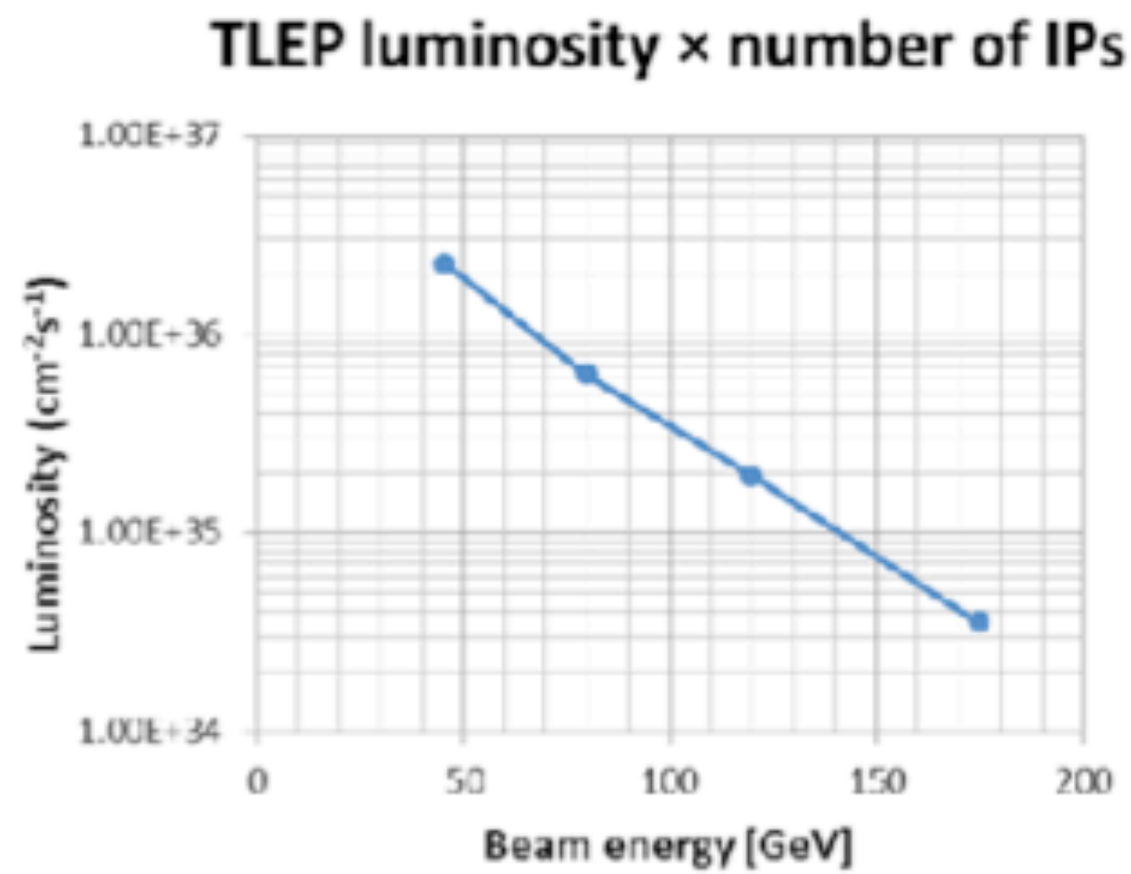
TLEP: A HIGH-PERFORMANCE CIRCULAR e^+e^- COLLIDER TO STUDY THE HIGGS BOSON

M. Koratzinos, A.P. Blondel, U. Geneva, Switzerland; R. Aleksan, CEA/Saclay, France; O. Brunner, A. Butterworth, P. Janot, E. Jensen, J. Osborne, F. Zimmermann, CERN, Geneva, Switzerland; J. R. Ellis, King's College, London; M. Zanetti, MIT, Cambridge, USA.

http://arxiv.org/abs/1305.6498.

Table 1: TLEP parameters at different energies

	TLEP Z	TLEP W	TLEP H	TLEP t
E_{beam} [GeV]	45	80	120	175
circumf. [km]	80	80	80	80
beam current [mA]	1180	124	24.3	5.4
#bunches/beam	4400	600	80	12
#e−/beam [10^{12}]	1960	200	40.8	9.0
horiz. emit. [nm]	30.8	9.4	9.4	10
vert. emit. [nm]	0.07	0.02	0.02	0.01
bending rad. [km]	9.0	9.0	9.0	9.0
κ_ε	440	470	470	1000
mom. c. α_c [10^{-5}]	9.0	2.0	1.0	1.0
$P_{loss,SR}$/beam [MW]	50	50	50	50
β^*_x [m]	0.5	0.5	0.5	1
β^*_y [cm]	0.1	0.1	0.1	0.1
σ^*_x [μm]	124	78	68	100
σ^*_y [μm]	0.27	0.14	0.14	0.10
hourglass F_{hg}	0.71	0.75	0.75	0.65
E^{SR}_{loss}/turn [GeV]	0.04	0.4	2.0	9.2
$V_{RF,tot}$ [GV]	2	2	6	12
$\delta_{max,RF}$ [%]	4.0	5.5	9.4	4.9
ξ_x/IP	0.07	0.10	0.10	0.10
ξ_y/IP	0.07	0.10	0.10	0.10
f_s [kHz]	1.29	0.45	0.44	0.43
E_{acc} [MV/m]	3	3	10	20
eff. RF length [m]	600	600	600	600
f_{RF} [MHz]	700	700	700	700
δ^{SR}_{rms} [%]	0.06	0.10	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	0.19	0.22	0.17	0.25
$\mathcal{L}$/IP[10^{32}cm^{-2}s^{-1}]	5600	1600	480	130
number of IPs	4	4	4	4
beam lifet. [min]	67	25	16	20



Note: we consistently use 4 IPs as this is the least extrap from LEP2
It is expected that luminosity grows like sqrt(N_{IP})

So total luminosity for a machine with 2 IP should be

L (2.IP) = L (4.IP)/sqrt(2)

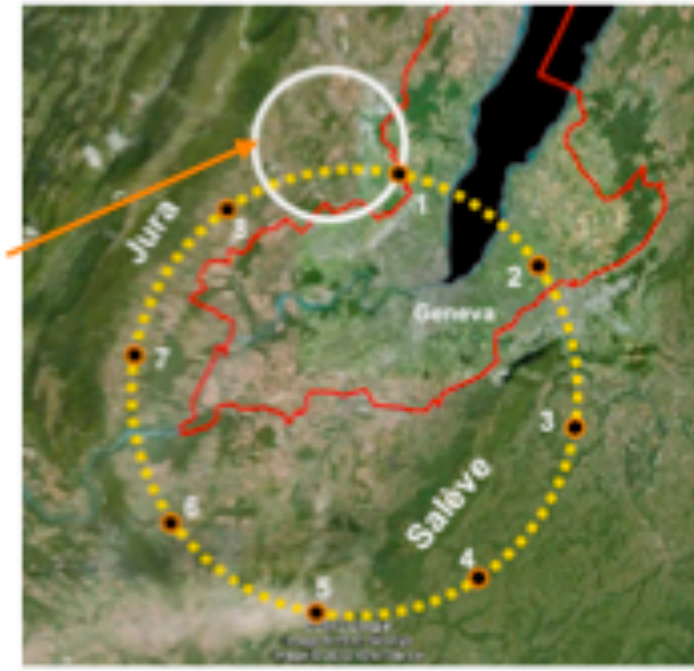
This will need to be verified by proper simulation.

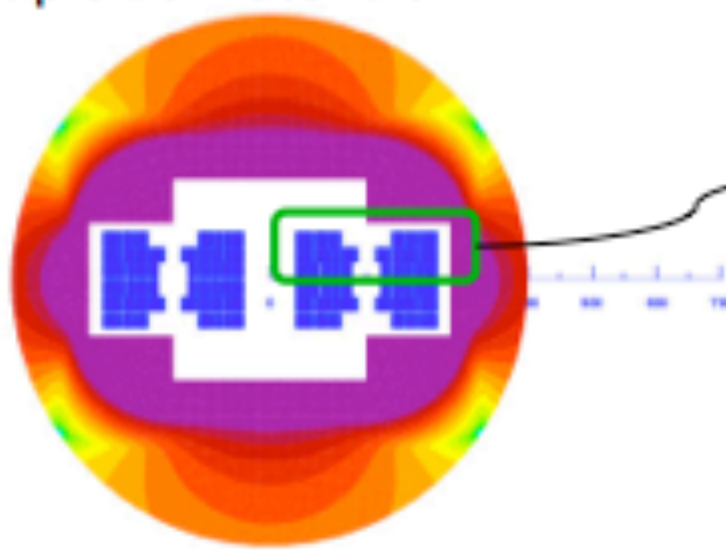
Alain Blondel

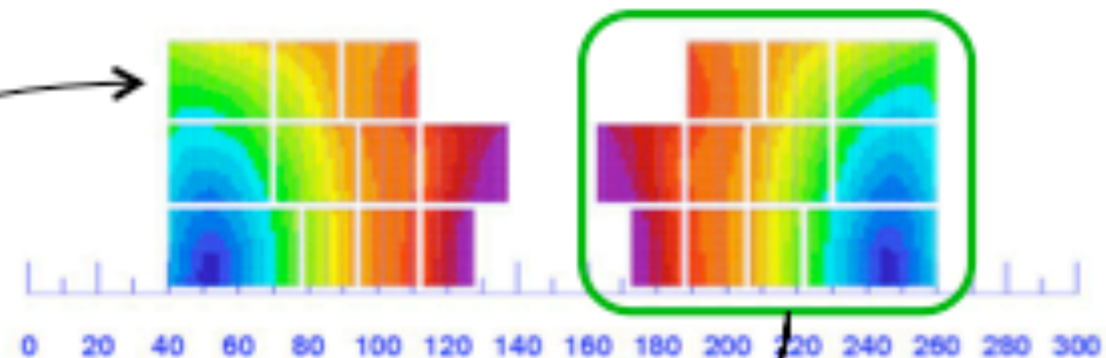
Alain Blondel Higg

The Next-to-Next Facility

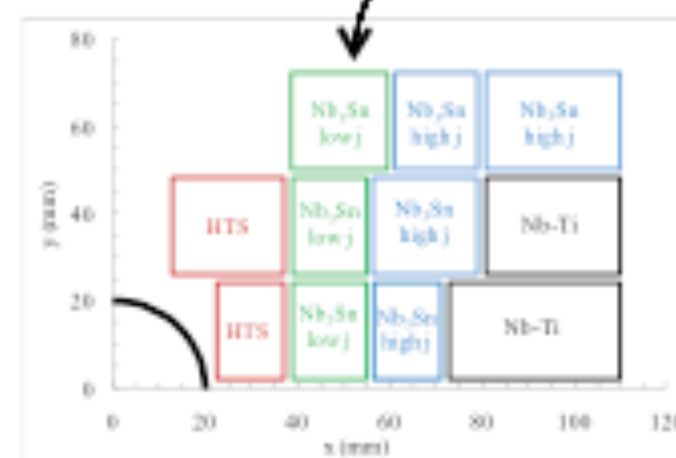
- TLEP can be upgraded to VHE-LHC
  - Re-use the 80 km tunnel to reach 80-100 TeV pp collisions
    - Or re-use the LHC tunnel to reach 27-33 TeV pp collisions
  - In both cases, need to develop 16-20 T SC magnets
    - Needs lots of R&D and time (TLEP won't delay VHE-LHC)
  - First consistent conceptual design
    - Using multiple SC materials







L. Rossi



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

20 T field!

Alain Blondel

Ring Collider

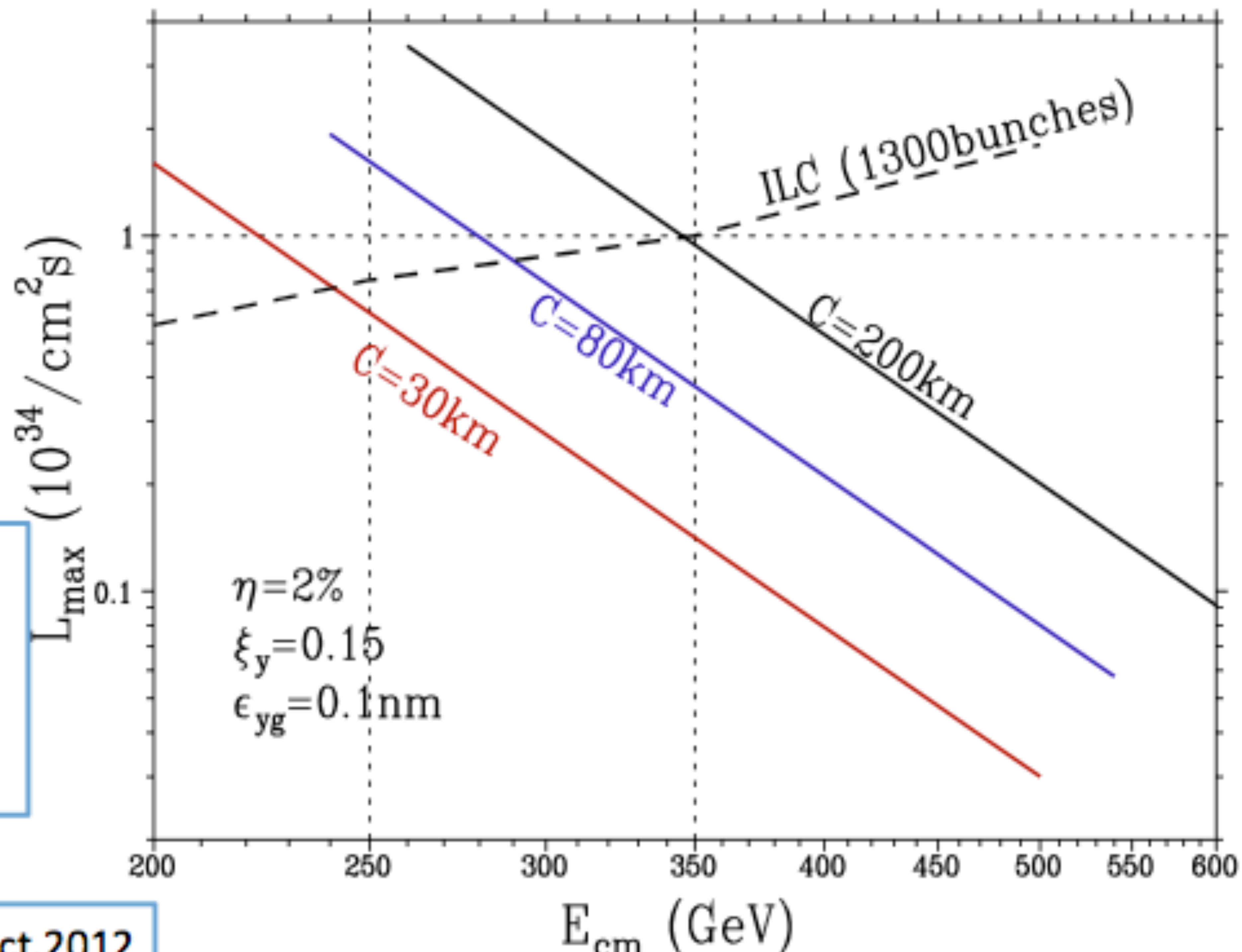
- LEP3 was proposed first 2 years ago but
  - Not easy to fit to LHC tunnel
  - No advantage of using the tunnel for future proton machine
  - Energy limited to 240GeV
  - Does not fit with LHC schedule
- Green field projects
  - such as Super TRISTAN and Chinese Higgs Factory
  - must start from scratch. Too expensive
- Community now concentrate on **TLEP**
  - 80km circumference
  - Tunnel can be reused later for HE-LHC
  - Earliest possibility is to start operation around 2030 (construction in parallel with HL-LHC operation)
  - 3 energy regions for 80km ring
    - TLEP-Z: operated at Z-pole
    - TLEP-H: at 240GeV (→ZH)
    - TLEP-t: at ttbar threshold

Kaoru Yokoya

Luminosity vs. Energy

example with

- η=2%
- ξ_y=0.15
- ε_{gy}=0.1nm
- P_{SR}=50MW/ beam



Actual design luminosity depends on how optimistic or conservative up to factor 2

Yokoya, Arlington, Oct.2012

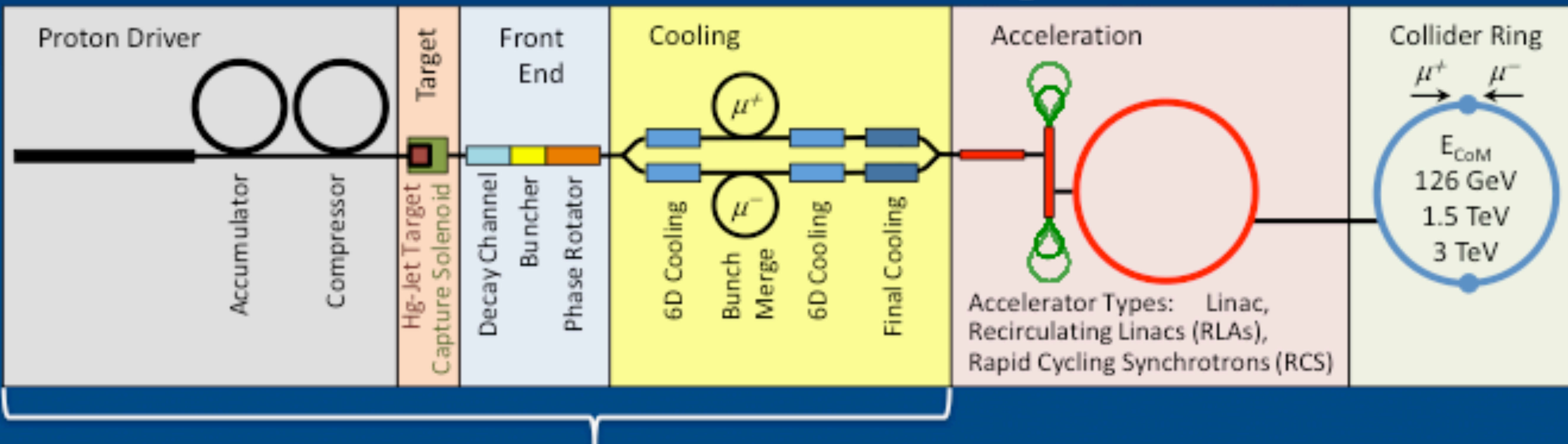
Comparison of ILC and Ring Colliders

- ILC
  - Can be extended to higher energies
  - Can be converted to a photon collider
  - Site power consumption lower
    (e.g., 160MW at 500GeV to be compared with >300MW at TLEP 350GeV)
  - Polarized positron feasible
  - Much less remaining issues
- Ring colliders
  - Potentially higher luminosity at low energies (e.g., 240GeV in TLEP)
  - More than one IP possible (if do not care about the cost)
- Cost
  - Ring collider is not so cheap as considered a year ago
  - Cost of TLEP 350GeV is comparable or even higher than the cost of 500GeV ILC
- In any case, detailed design of a ring collider absolutely needed for serious comparison

Kaoru Yokoya

Muon Collider Concept

Muon Collider Block Diagram



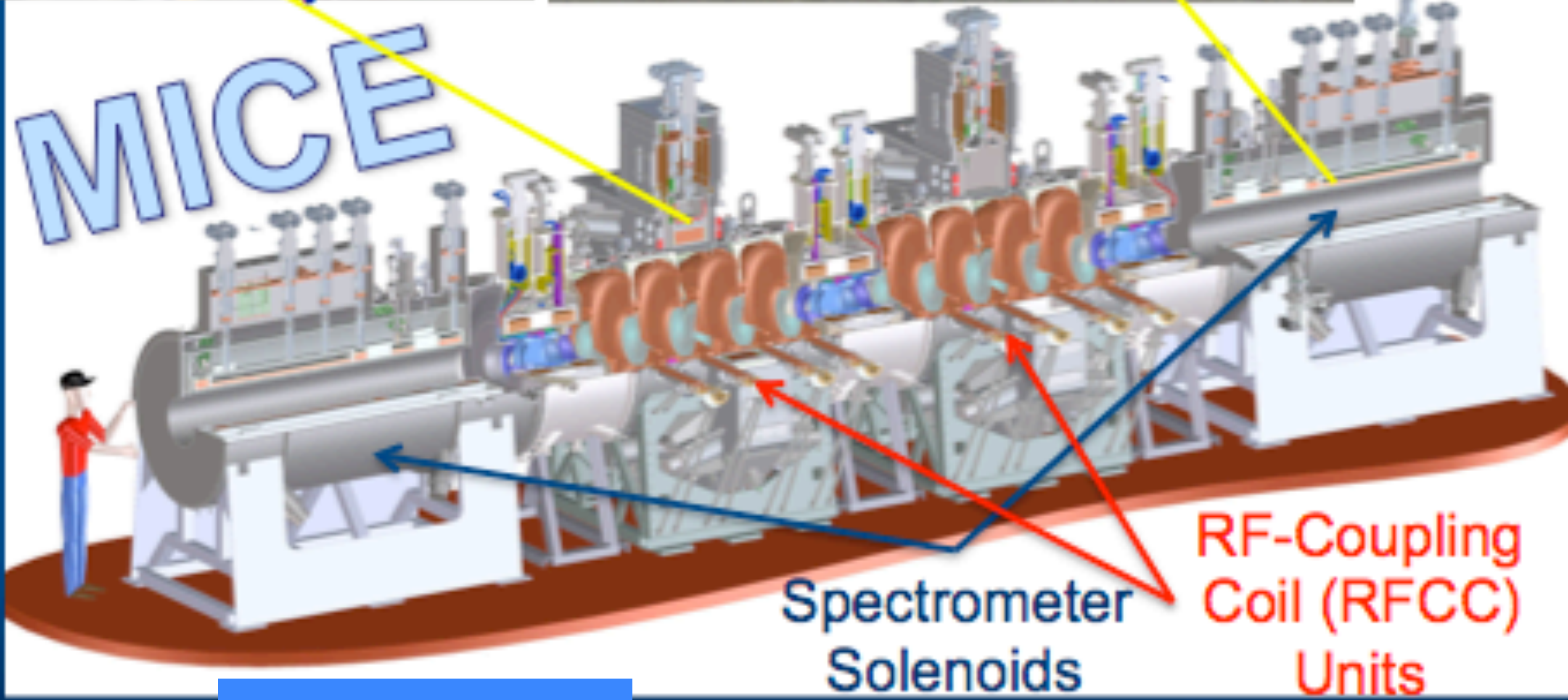
Proton source:
For example PROJECT X at 4 MW, with 2±1 ns long bunches

Goal:
Produce a high intensity μ beam whose 6D phase space is reduced by a factor of ~10^6-10^7 from its value at the production target

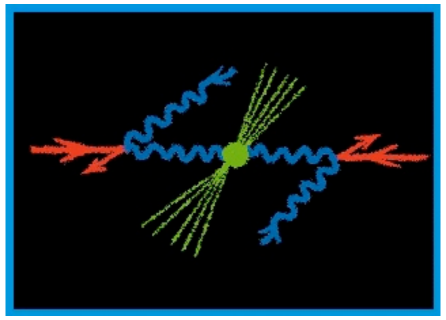
Collider: $\sqrt{s}$ = 3 TeV
Circumference 4.5km
$L = 3\times10^{34}$ cm^{-2}s^{-1}
μ/bunch = 2×10^{12}
$\sigma(p)/p$ = 0.1%
$\varepsilon_{\perp N}$ = 25 µm, $\varepsilon_{//N}$=72 mm
β^* = 5mm
Rep. Rate = 12 Hz

Recent Progress I - MICE

- Currently preparing for MICE Step IV
- Includes:
  - Spectrometer Solenoids
  - First Focus Coil
- Provides:
  - Direct measurement of interactions with absorber materials
  - Important simulation input



Gamma-gamma Collider

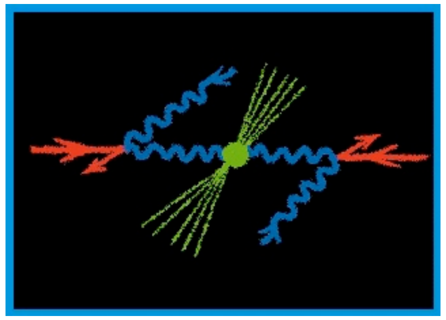


A. de Roeck

Golden processes	PLC2000 proc.
$\gamma\gamma \to H, h \to b\bar{b}$	SM/MSSM Higgs, $M_{H,h} < 160$ GeV
$\gamma\gamma \to H \to WW(^*)$	SM Higgs, $140 < M_H < 190$ GeV
$\gamma\gamma \to H \to ZZ(^*)$	SM Higgs, $180 < M_H < 350$ GeV
$\gamma\gamma \to H \to \gamma\gamma$	SM Higgs, $120 < M_H < 160$ GeV
$\gamma\gamma \to H \to t\bar{t}$	SM Higgs, $M_H > 350$ GeV
$\gamma\gamma \to H, A \to b\bar{b}$	MSSM heavy Higgs, interm. $\tan\beta$
$\gamma\gamma \to H^+H^-$	large cross sections
$\gamma\gamma \to \tilde{f}\bar{\tilde{f}},\ \tilde{\chi}_i^+\tilde{\chi}_i^-$	large cross sections
$\gamma\gamma \to \tilde{g}\tilde{g}$	measurable cross sections
$\gamma\gamma \to S[\tilde{t}\bar{\tilde{t}}]$	$\tilde{t}\bar{\tilde{t}}$ stoponium
$\gamma e \to \tilde{e}^-\tilde{\chi}_1^0$	$M_{\tilde{e}^-} < 0.9 \times 2E_0 - M_{\tilde{\chi}_1^0}$
$\gamma\gamma \to \gamma\gamma$	non-commutative theories
$e\gamma \to eG$	extra dimensions
$\gamma\gamma \to \phi$	Radions
$e\gamma \to \tilde{e}\tilde{G}$	superlight gravitions
$\gamma\gamma \to W^+W^-$	anom. W inter., extra dimensions
$\gamma e \to W^-\nu_e$	anom. W couplings
$\gamma\gamma \to 4W/(Z)$	WW scatt., quartic anom. W,Z
$\gamma\gamma \to t\bar{t}$	anomalous top quark interactions
$\gamma e \to \bar{t}b\nu_e$	anomalous Wtb coupling
$\gamma\gamma \to$ hadrons	total $\gamma\gamma$ cross section
$\gamma e \to e^-X,\ \nu_e X$	NC and CC structure functions
$\gamma g \to q\bar{q},\ c\bar{c}$	gluon in the photon
$\gamma\gamma \to J/\psi\ J/\psi$	QCD Pomeron

Maria Krawczyk

Gamma-gamma Collider



A. de Roeck

Golden processes

PLC2000 proc.

$\gamma\gamma \to H, h \to b\bar{b}$

$\gamma\gamma \to H \to WW(^*)$

$\gamma\gamma \to H \to ZZ(^*)$

$\gamma\gamma \to H \to \gamma\gamma$

$\gamma\gamma \to H \to t\bar{t}$

$\gamma\gamma \to H, A \to b\bar{b}$

$\gamma\gamma \to H^+H^-$

$\gamma\gamma \to \tilde{f}\bar{\tilde{f}},\ \tilde{\chi}_i^+\tilde{\chi}_i^-$

$\gamma\gamma \to \tilde{g}\tilde{g}$

$\gamma\gamma \to S[\tilde{t}\bar{\tilde{t}}]$

$\gamma e \to \tilde{e}^-\tilde{\chi}_1^0$

$\gamma\gamma \to \gamma\gamma$

$e\gamma \to eG$

$\gamma\gamma \to \phi$

$e\gamma \to \tilde{e}\tilde{G}$

$\gamma\gamma \to W^+W^-$

$\gamma e \to W^-\nu_e$

$\gamma\gamma \to 4W/(Z)$

$\gamma\gamma \to t\bar{t}$

$\gamma e \to \bar{t}b\nu_e$

$\gamma\gamma \to$ hadrons

$\gamma e \to e^-X,\ \nu_e X$

$\gamma g \to q\bar{q},\ c\bar{c}$

$\gamma\gamma \to J/\psi\ J/\psi$

9 good reasons to build PLC

LHC2FC CERN (2009), Photon 2007

1. Precision measurements of the light Higgs boson production (->bb) and distinguishing SM-like scenarios
2. Testing Higgs selfinteraction
3. Higher mass reach and covering LHC wedge
4. Establishing CP property of Higgs bosons
5. Search for SUSY particles
6. Complementarity to ILC and LHC
7. Photon structure and QCD tests
8. Anomalous W and t couplings
9. New physics in $\gamma\gamma \to \gamma\gamma$

Maria Krawczyk

3 New Designs that will Produce 10K Higgs/year

- HFiTT: Higgs Factory in Tevatron Tunnel
  - Fermilab specific
- SILC: SLC-ILC-Style $\gamma\gamma$ Higgs Factory
  - SLAC specific
- SAPPHiRE: Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons
  - Developed at CERN, but can be built elsewhere

- Detector and beam environment not more difficult than what we are experiencing at the LHC

Mayda Velasco

→ 3 machines in 1: e^-e^-, $e^-\gamma$, $\gamma\gamma$

Vision of Future Facilities (I)

- A personal view
  - LHC will continue to advance particle physics through the 2020s (LHC ⇒ HL-LHC)
  - The ILC is the ideal complement to the LHC; turn on could happen while HL-LHC operates
    - Technology is developed; cost well understood
      - result of decade of intense GDE R&D program (ICFA)
    - Major Higgs production mechanisms now known at the ILC ⇒ No lose theorem ($\gamma\gamma$ Collider is an option)
    - M_h = 125GeV makes many decay modes accessible
      - Does 125GeV boson have the required properties of the vacuum condensate?
    - Japanese preparing to host - rare opportunity should not let pass

Expected Precision and Deviation

Combined Fit with LHC data

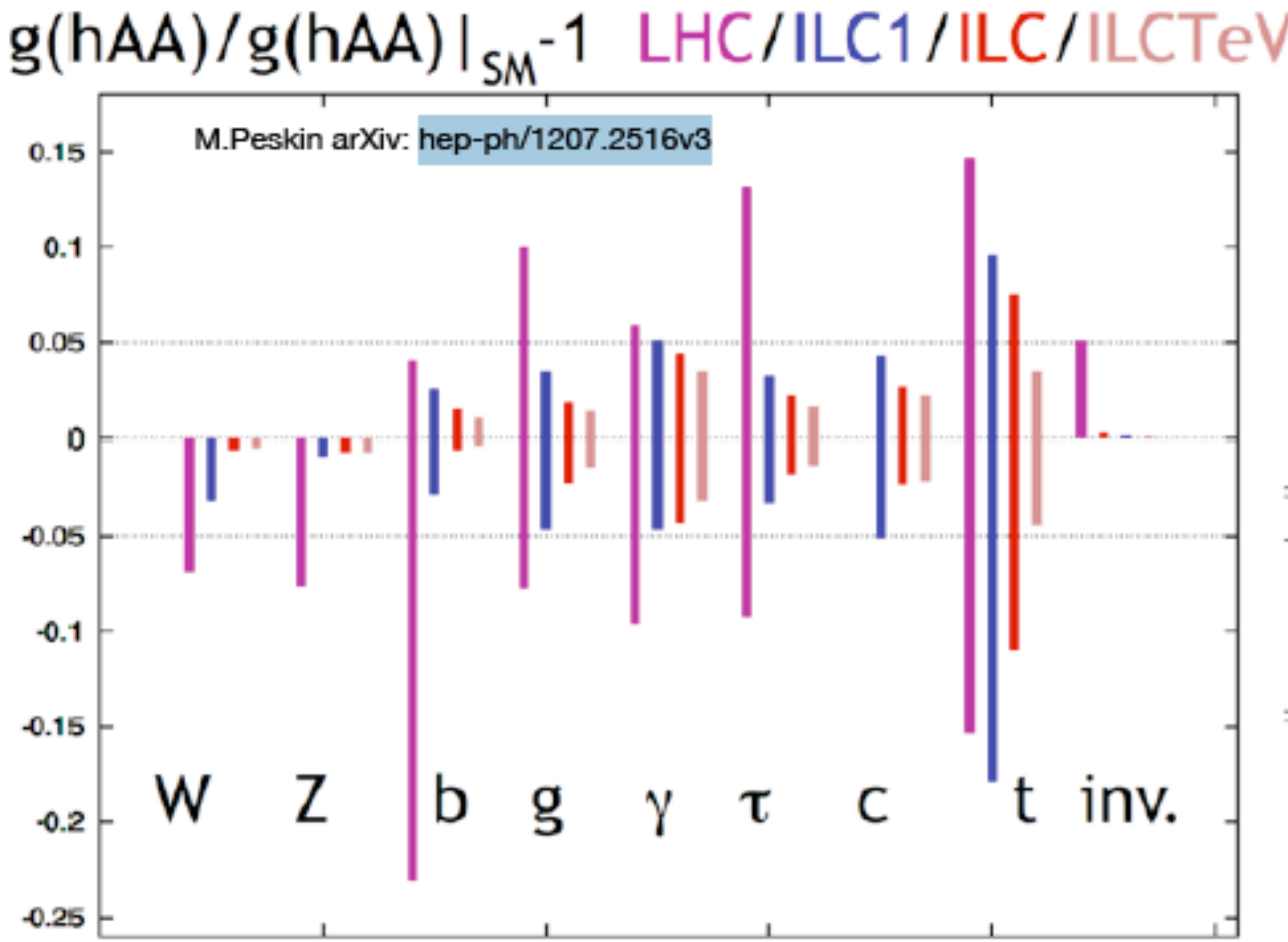


Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC program up to 500 GeV with 500 fb^{-1} ('ILC'), and for a program with 1000 fb^{-1} for an upgraded ILC at 1 TeV ('ILCTeV'). More details of the presentation are given in the caption of Fig. 1. The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

Assumed Luminosities

LHC = LHC14TeV: 300fb^{-1}

HLC = ILC250: 250fb^{-1}

ILC = ILC500: 500fb^{-1}

ILCTeV = ILC1000: 1000fb^{-1}

Maximum deviation when nothing but the 125 GeV object would be found at LHC

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	10%[a], 100%[b]
LHC 14 TeV, 3 ab^{-1}	8%	10%	15%

R.S.Gupta, H.Rzehak, J.D.Wells arXiv: 1206.3560v1

Mixing with singlet

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \frac{g_{hff}}{g_{h_{SM}ff}} = \cos\theta \simeq 1 - \frac{\delta^2}{2}$$

Composite Higgs

$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\%(1\ \mathrm{TeV}/f)^2$$

$$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM4}) \\ 1 - 9\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM5}). \end{cases}$$

SUSY

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

Fingerprinting is possible or we will get lower bounds on the BSM scale!

Keisuke Fujii

Steps to realize ILC are under way

Vision of Future Facilities (II)

- Beyond HL-LHC/ILC era
  - First, need physics justification for higher energy
    - just as the earlier experiments anticipated the top quark and Higgs mass, LHC/ILC will probe mass scales beyond their direct reach

      $\Rightarrow$ might find energy scale of new physics
  - VHE-LHC is a possible future hadron collider
  - CLIC and muon Collider offer competing options for high energy lepton colliders once either(both) technology is developed

Conclusion

- Discovery of a Higgs boson ushered in a new era in particle physics
- Very large effort has been mounted to study this new particle and to search for other new physics
  - excellent presentations at "Higgs and Beyond"
- Several well motivated options for future
- It is a good time to be a Particle Physicist

...and

- Thank you to the organizers for an excellent workshop