Future of Accelerator Physics

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pp@LHC, Pisa
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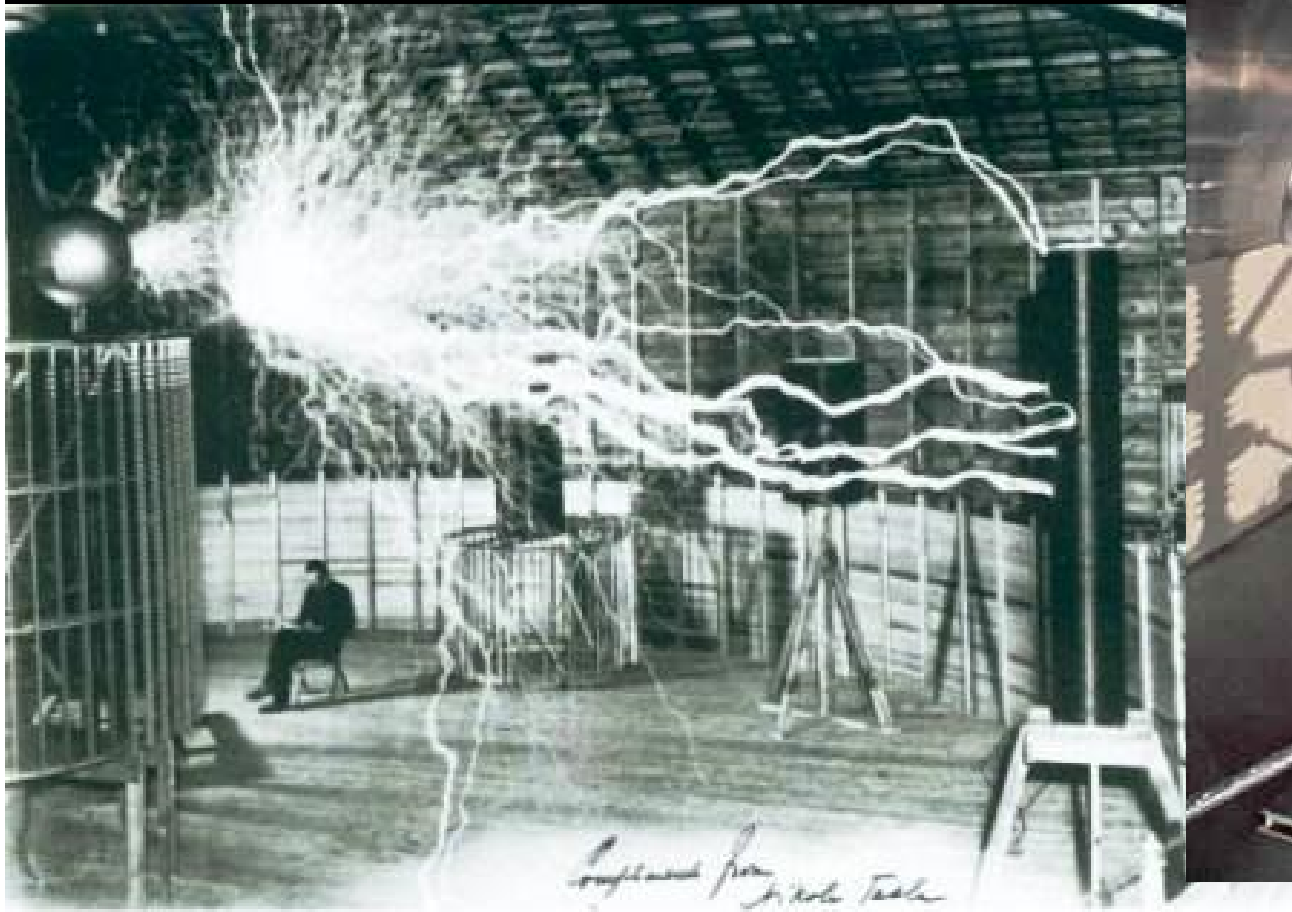
QUESTIONS

- What are we talking about?
- Where are we now?
- Do we know where we are going?
- Do we need new accelerators?
- What could we build? Now, later, far future?
- What can we do now?

Potential new machines



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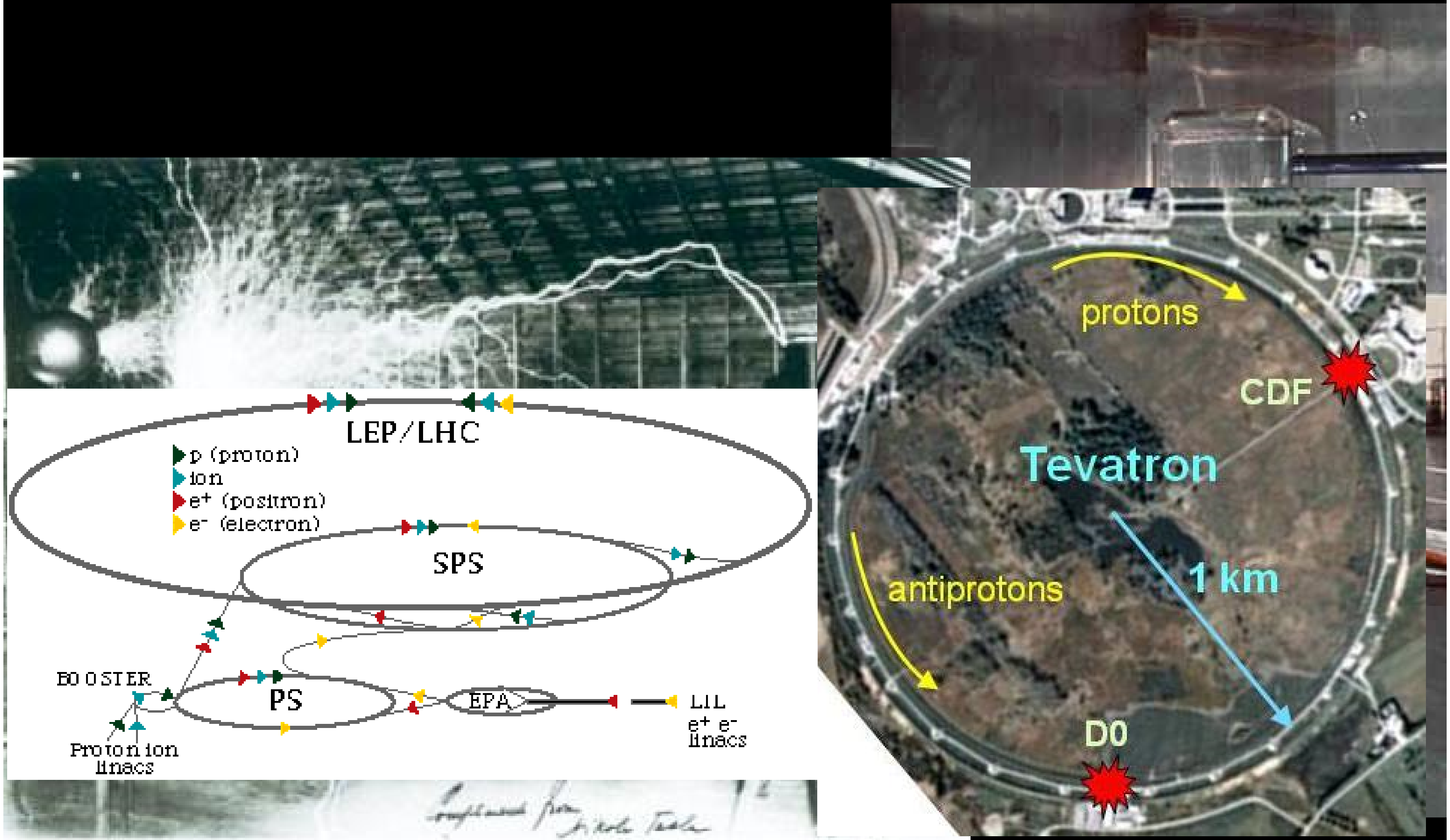

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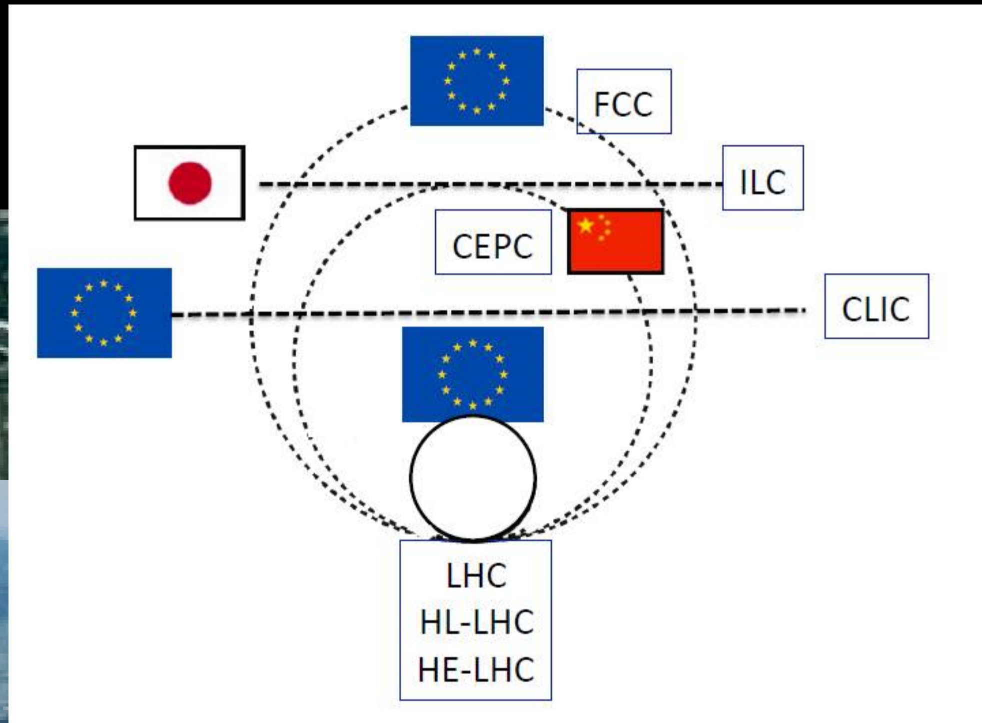
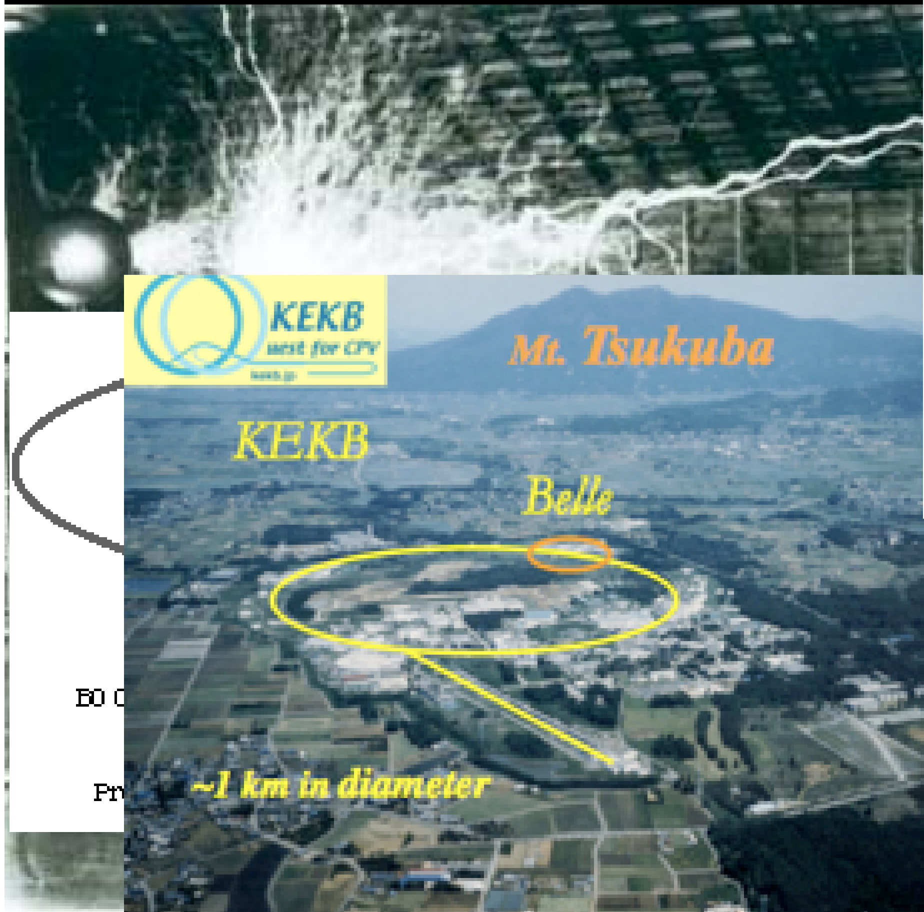
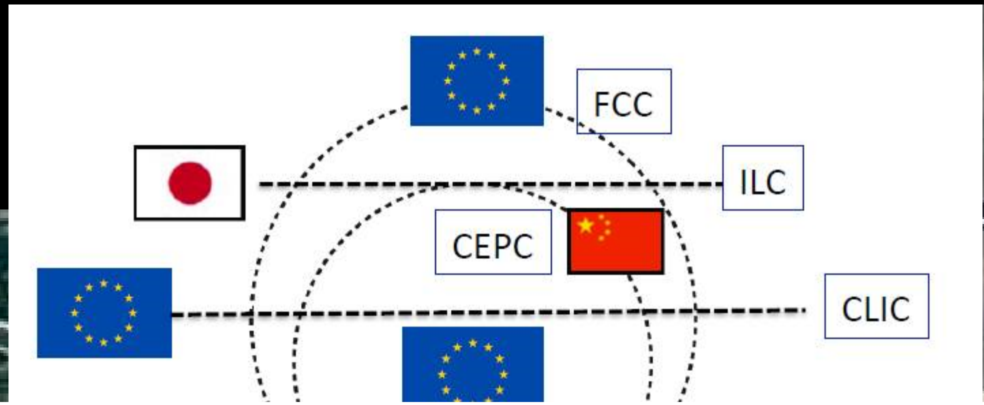
❖ Future in EU and Asia

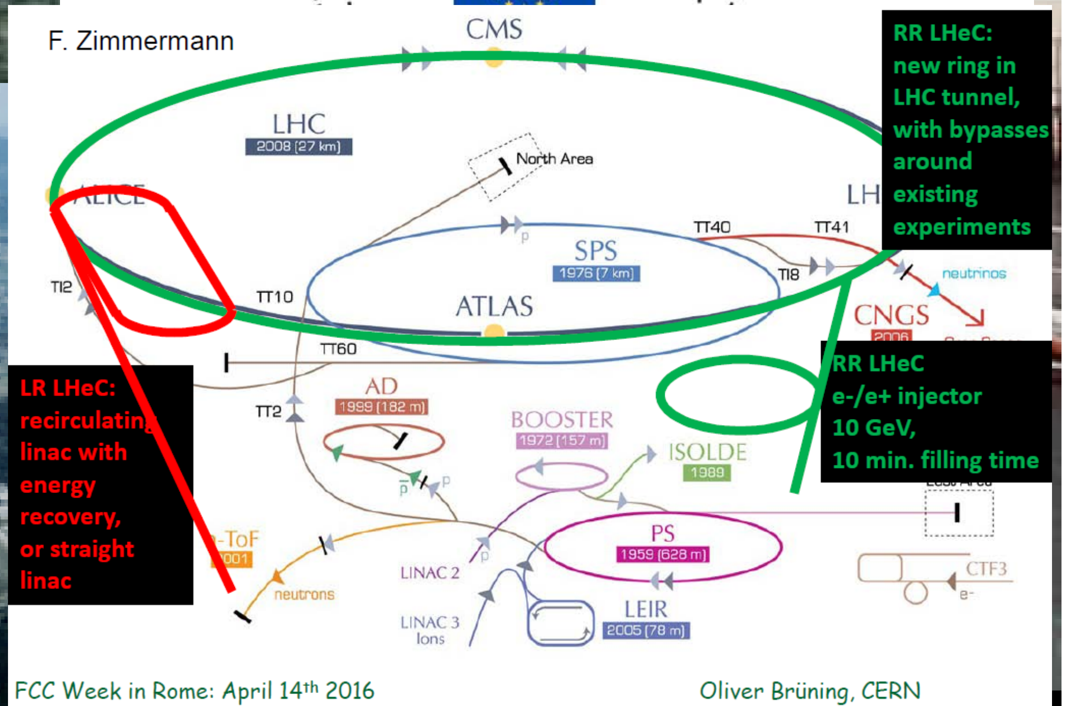




Potential new machines

- Future in EU and Asia
- In addition:
  - **Electron-hadron colliders**





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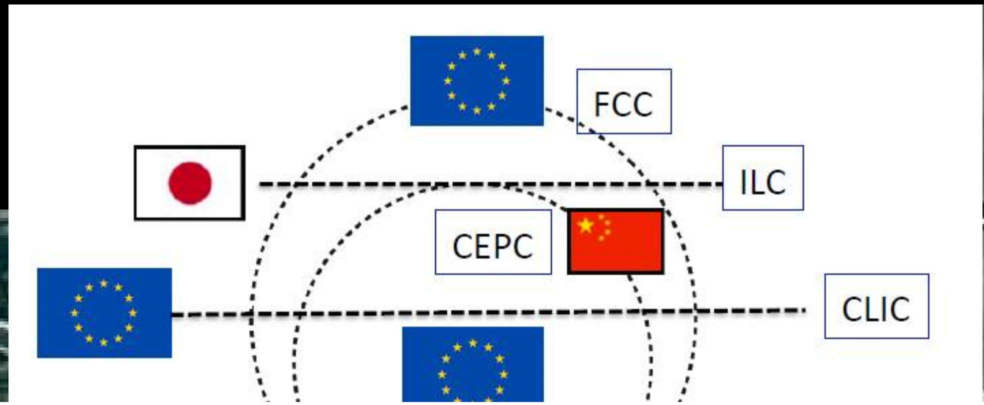
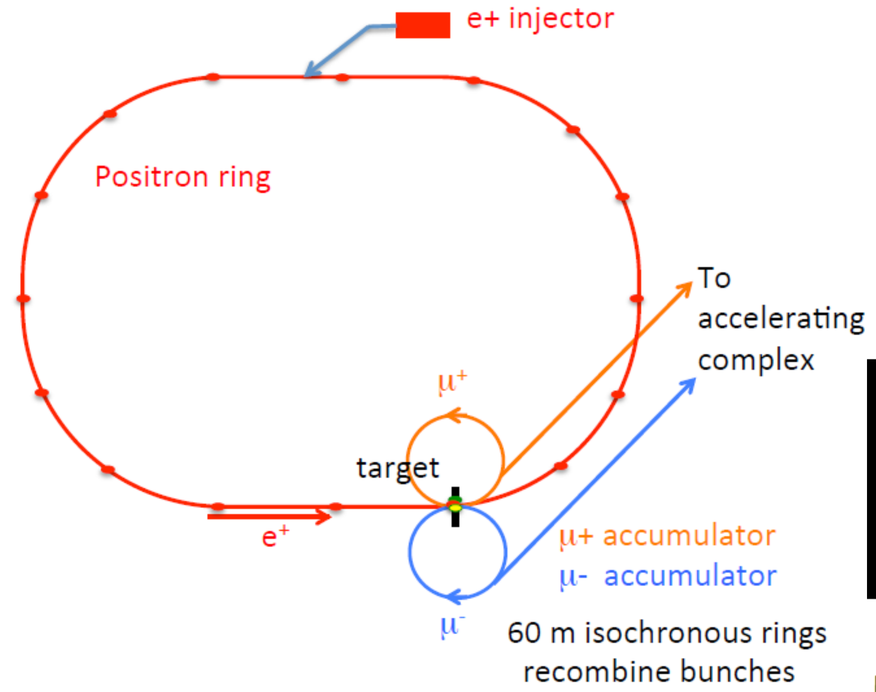
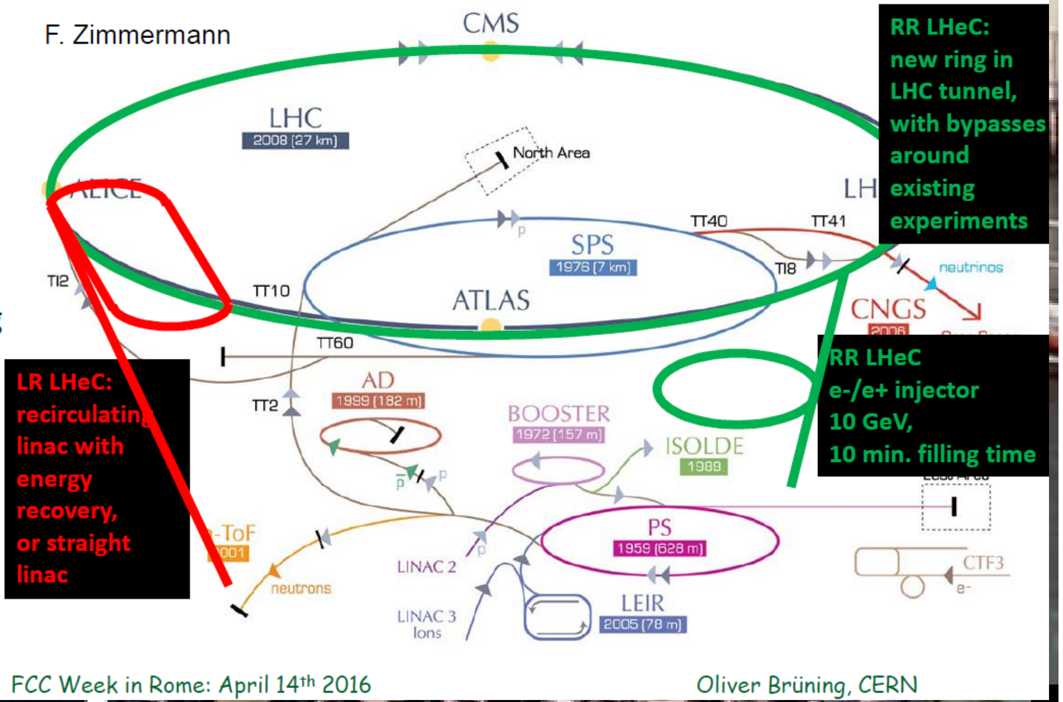
  - **Muon collider**

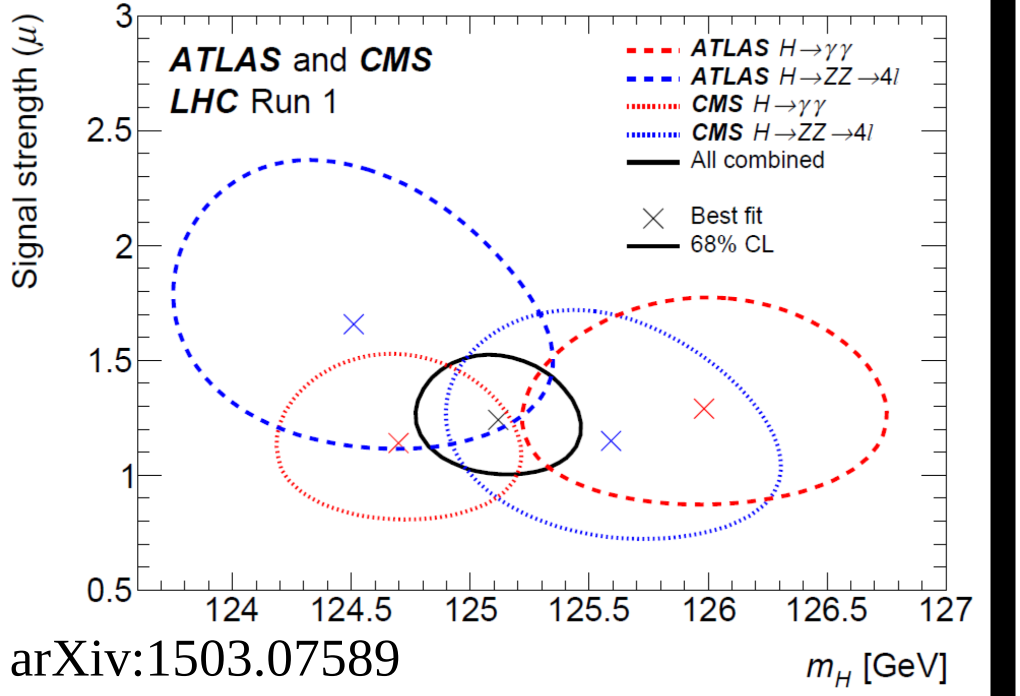






LHC →Great Success SM! (1)

❖ Higgs discovered!



arXiv:1503.07589

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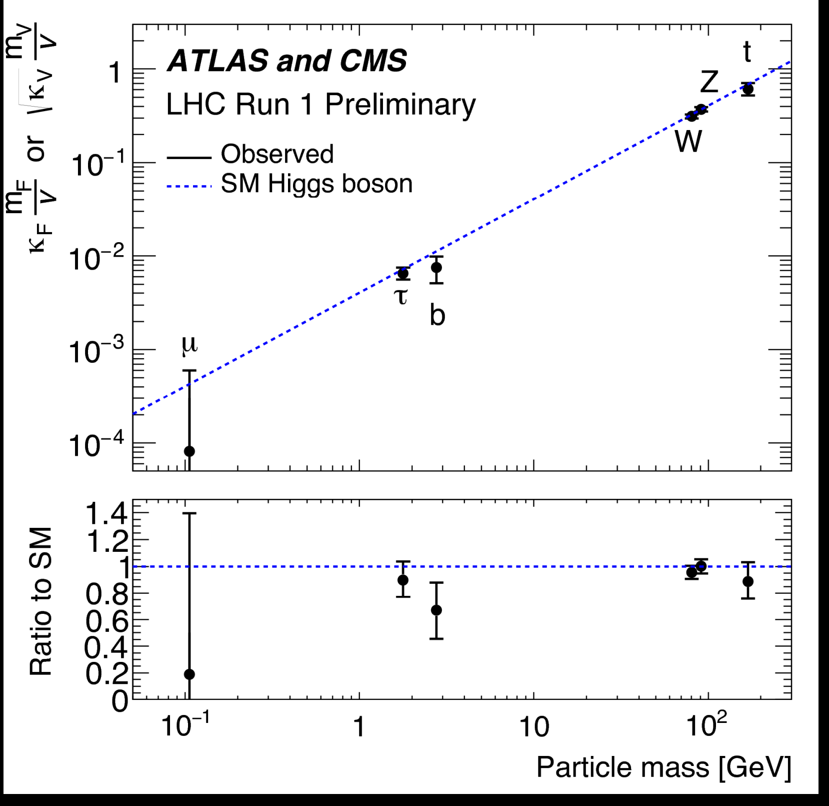

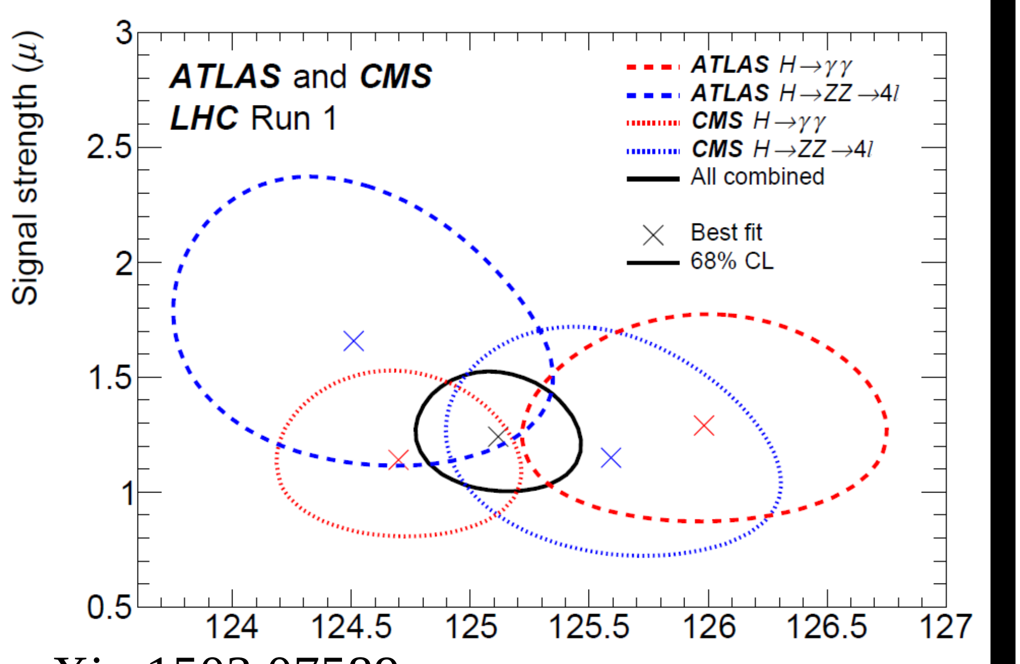

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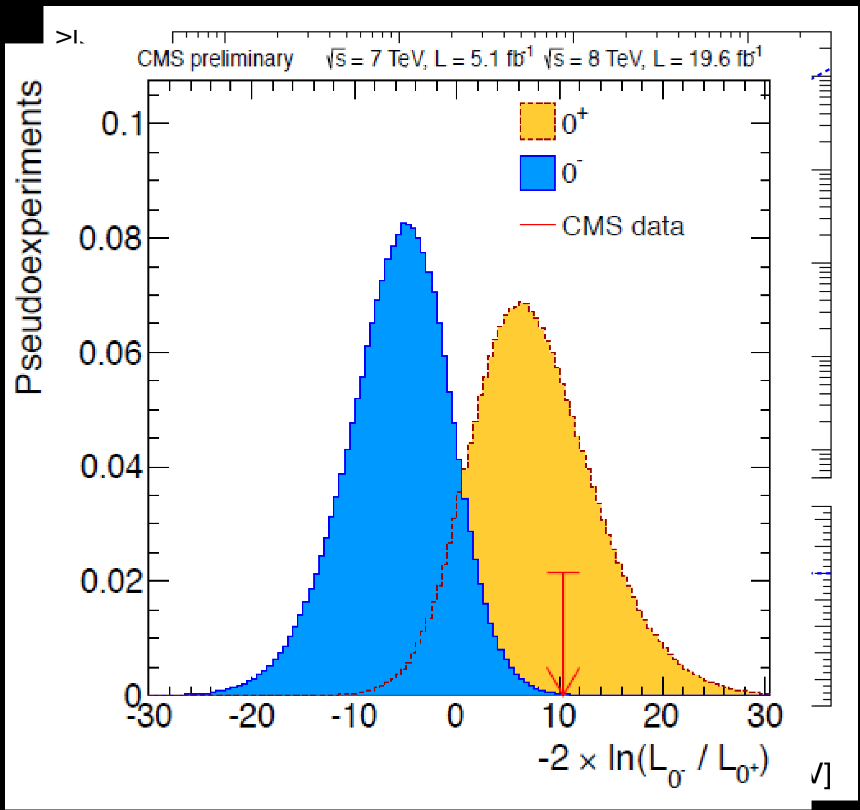
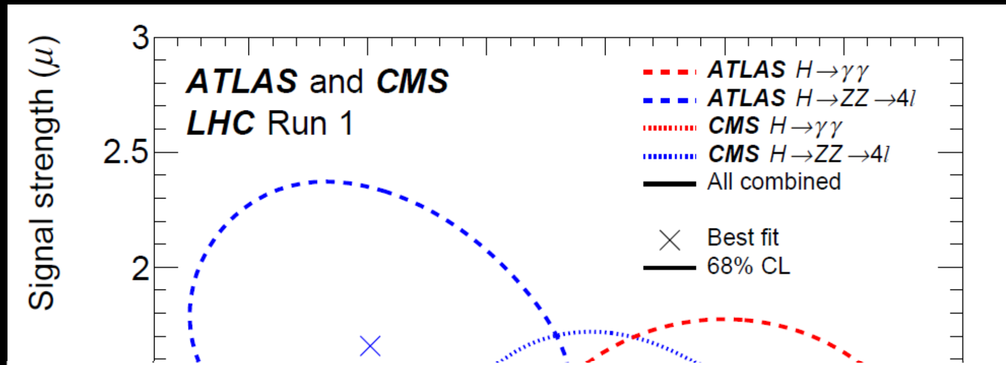
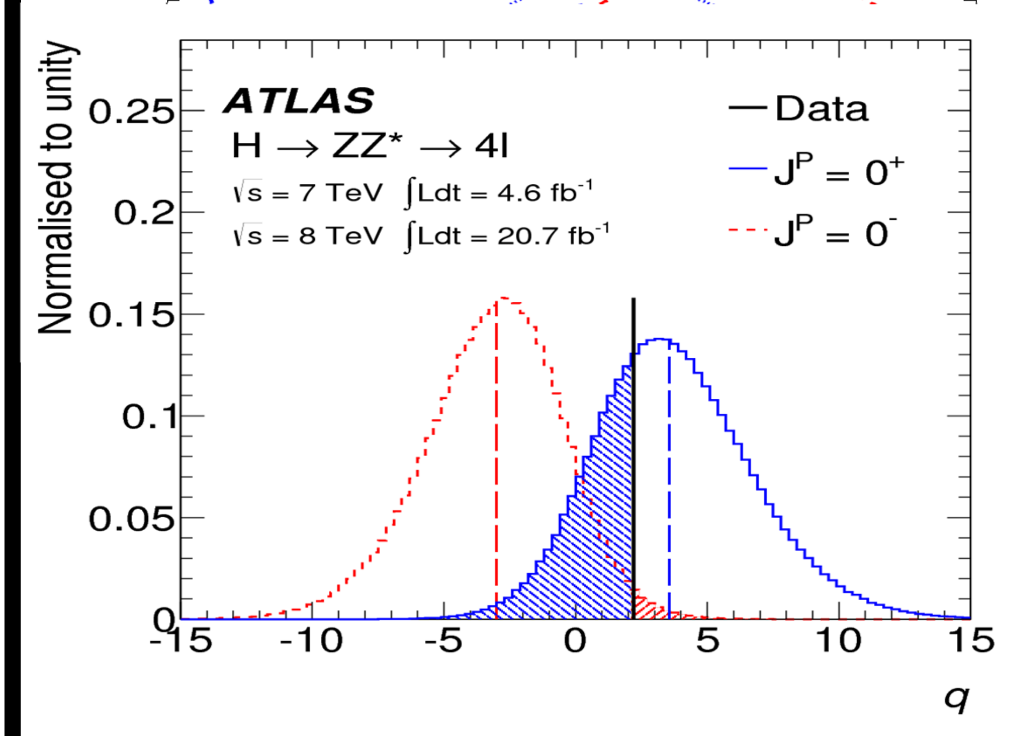
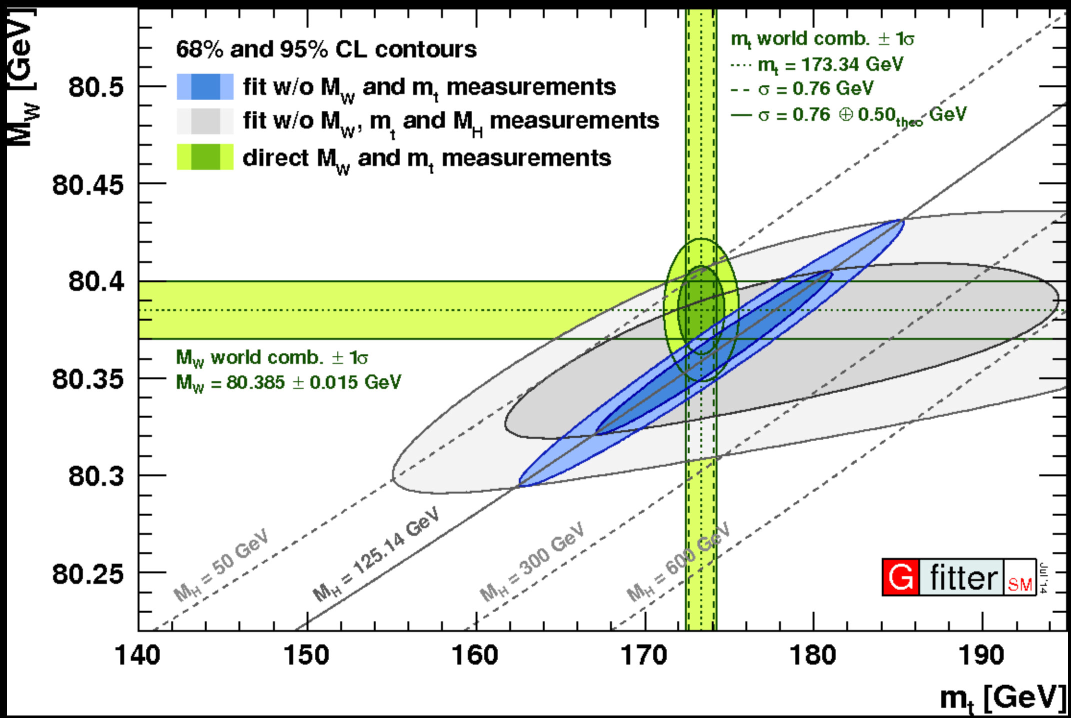


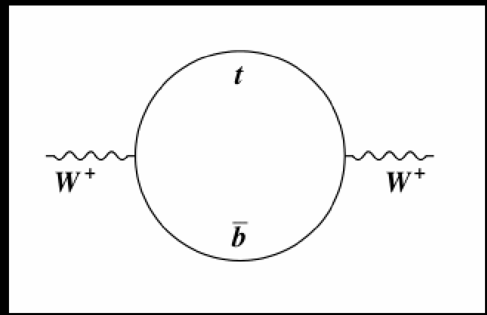


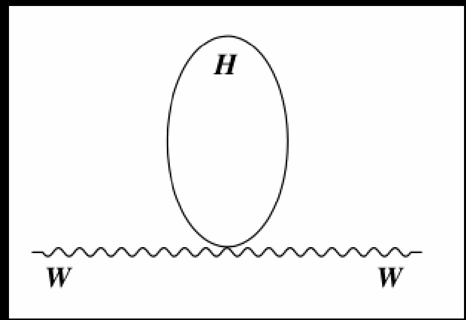


LHC → Great Success SM! (2)

- Also indirect measur. sensitive to radiative corrections
  - Mtop, Mw, M_H







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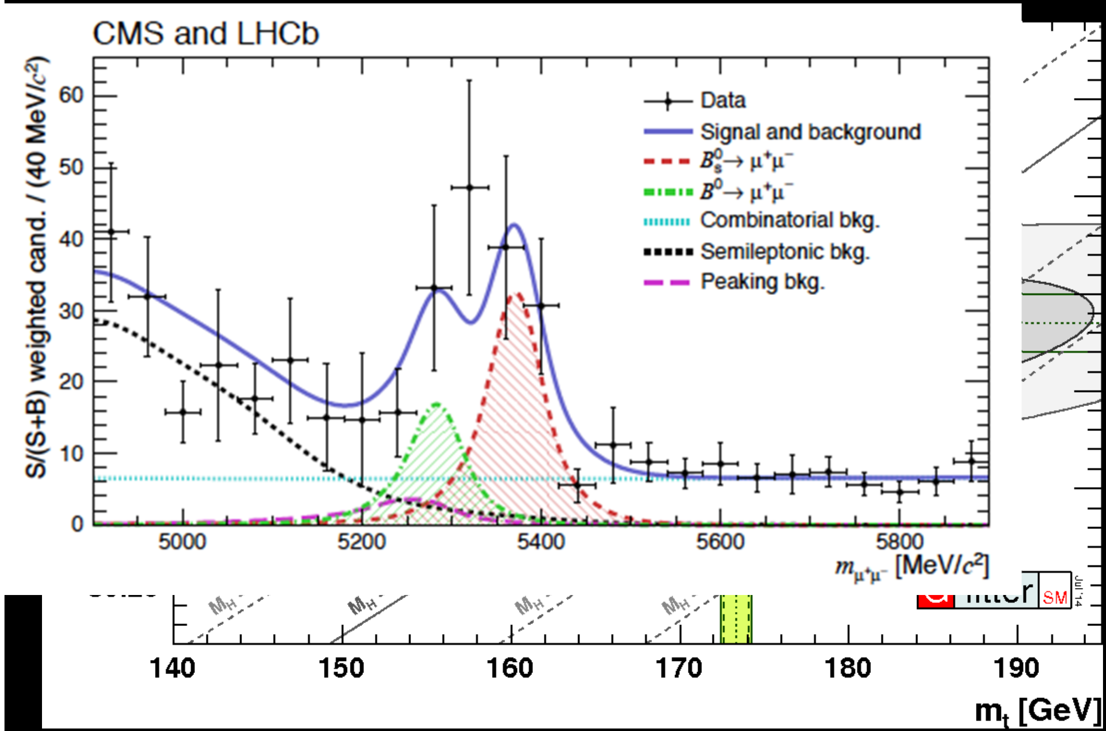

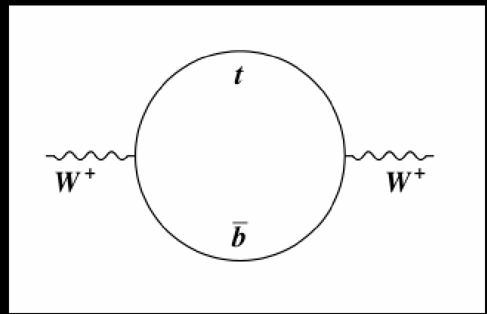

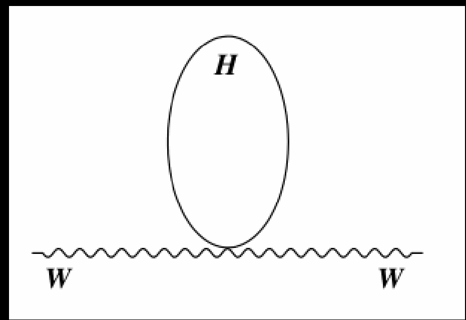

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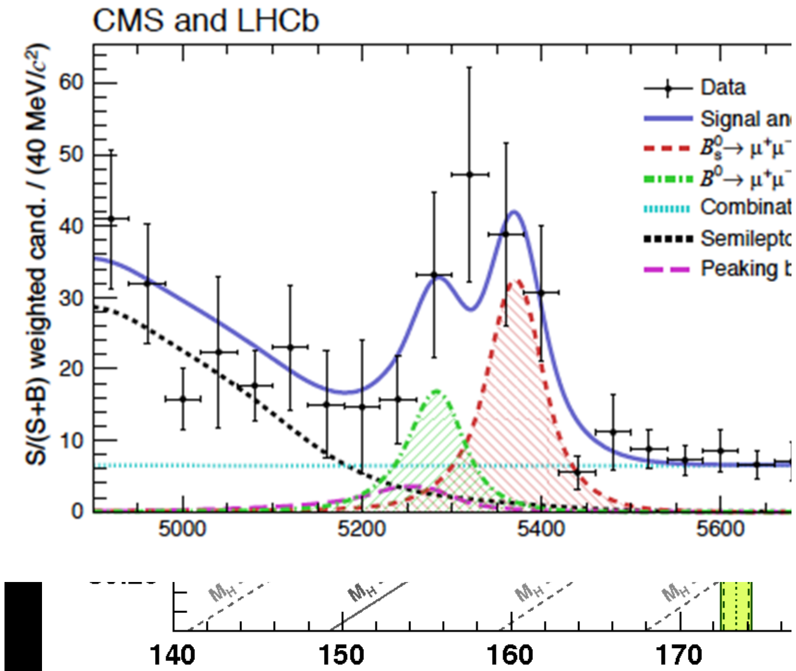
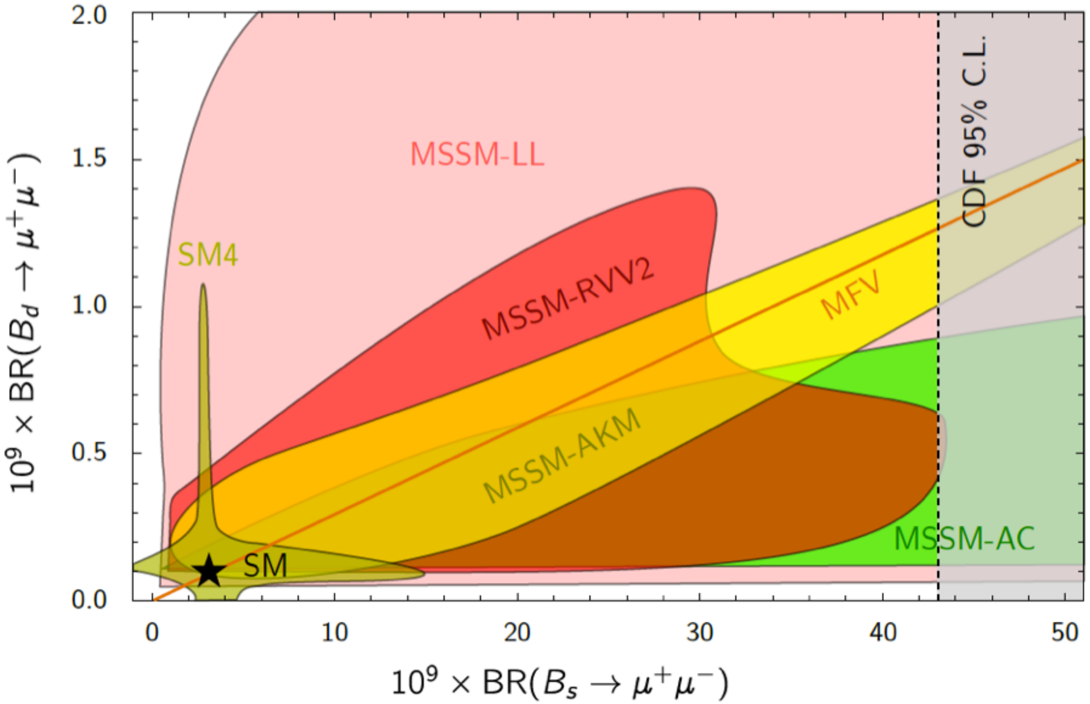
  - Stronger constraints on new physics





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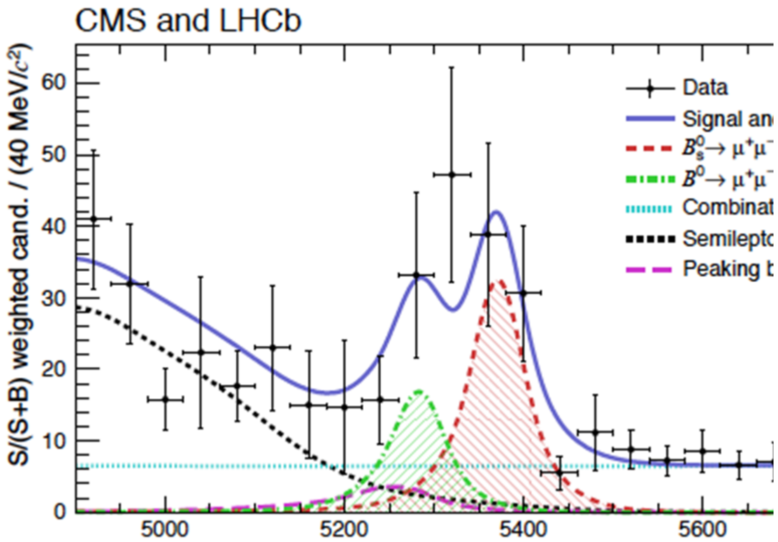
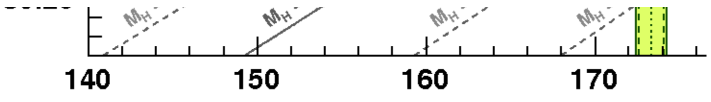
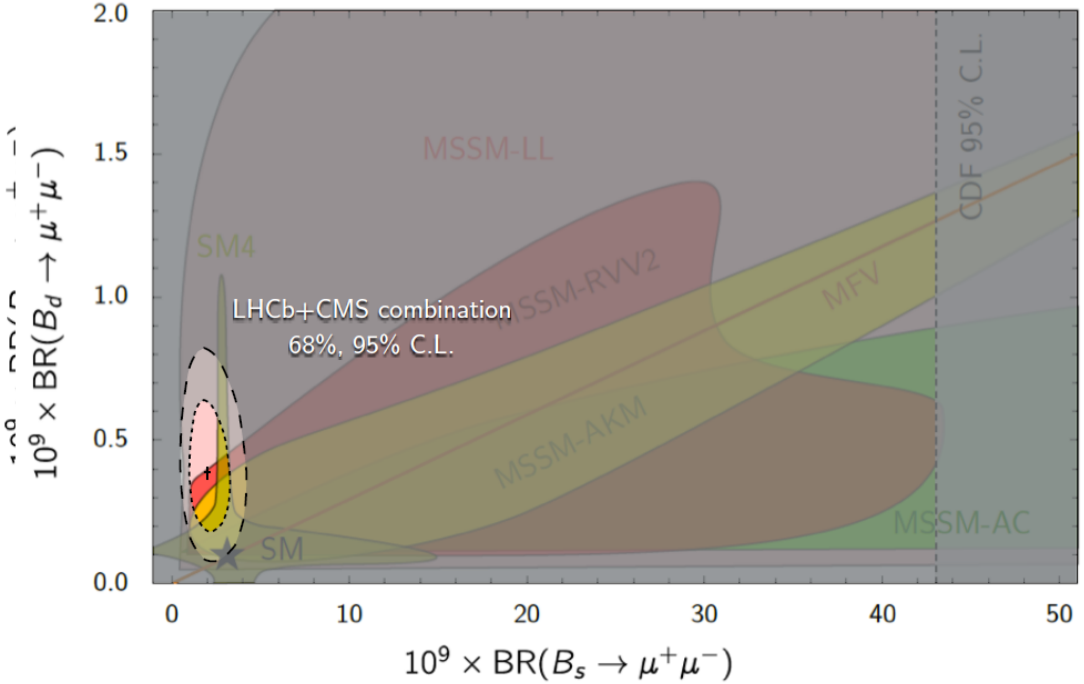




[D. Straub http://arxiv.org/abs/1205.6094]



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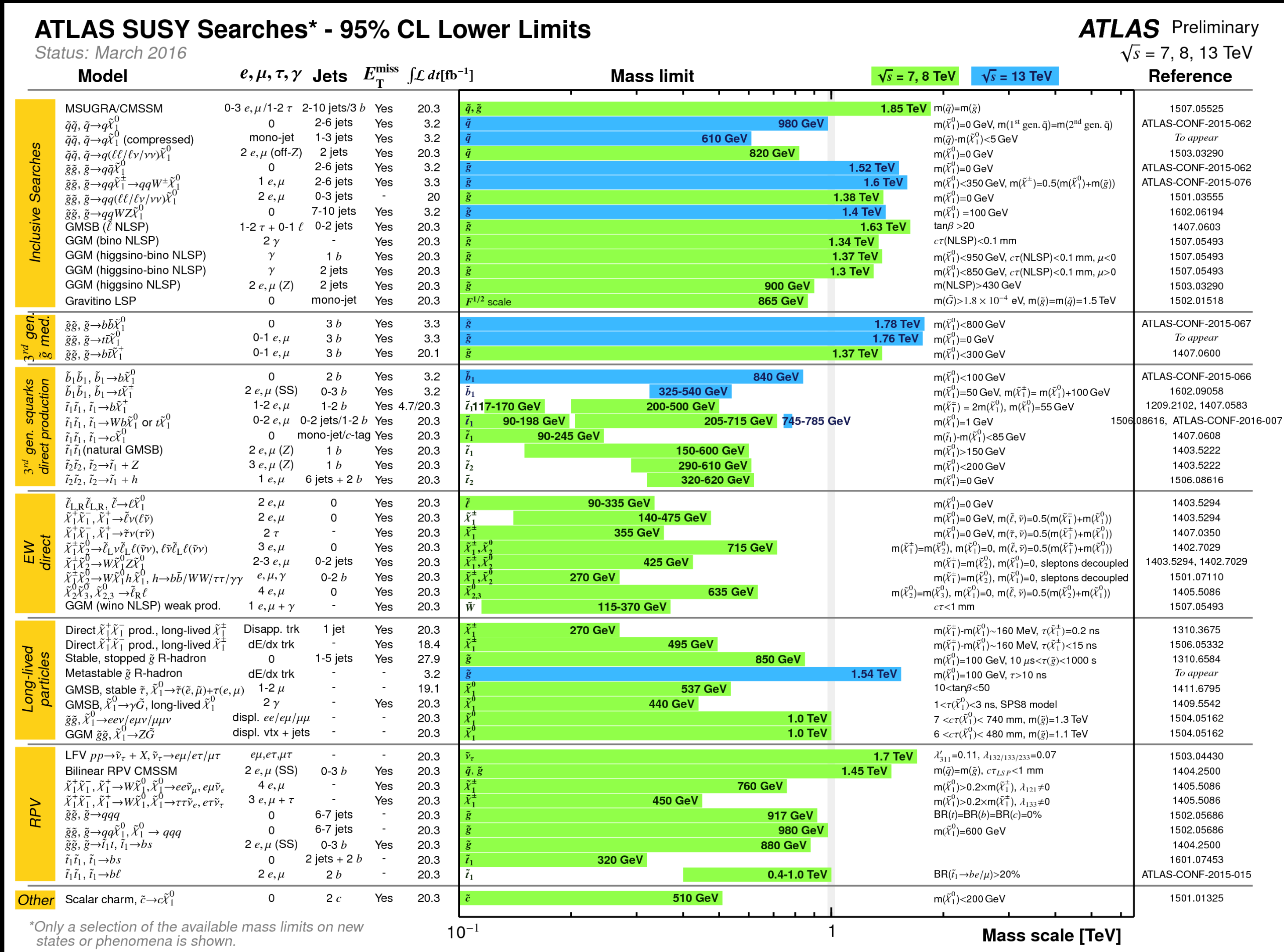

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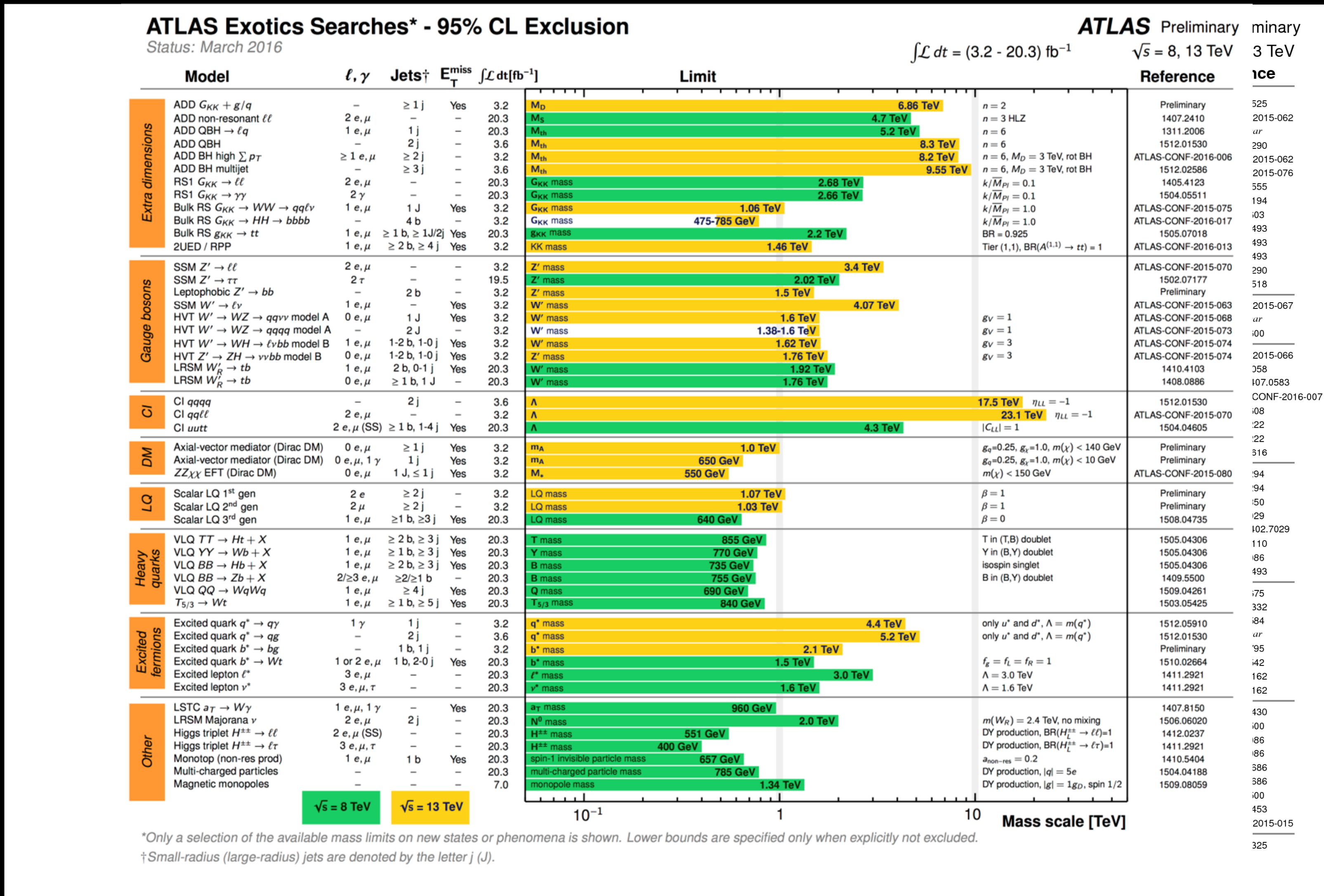

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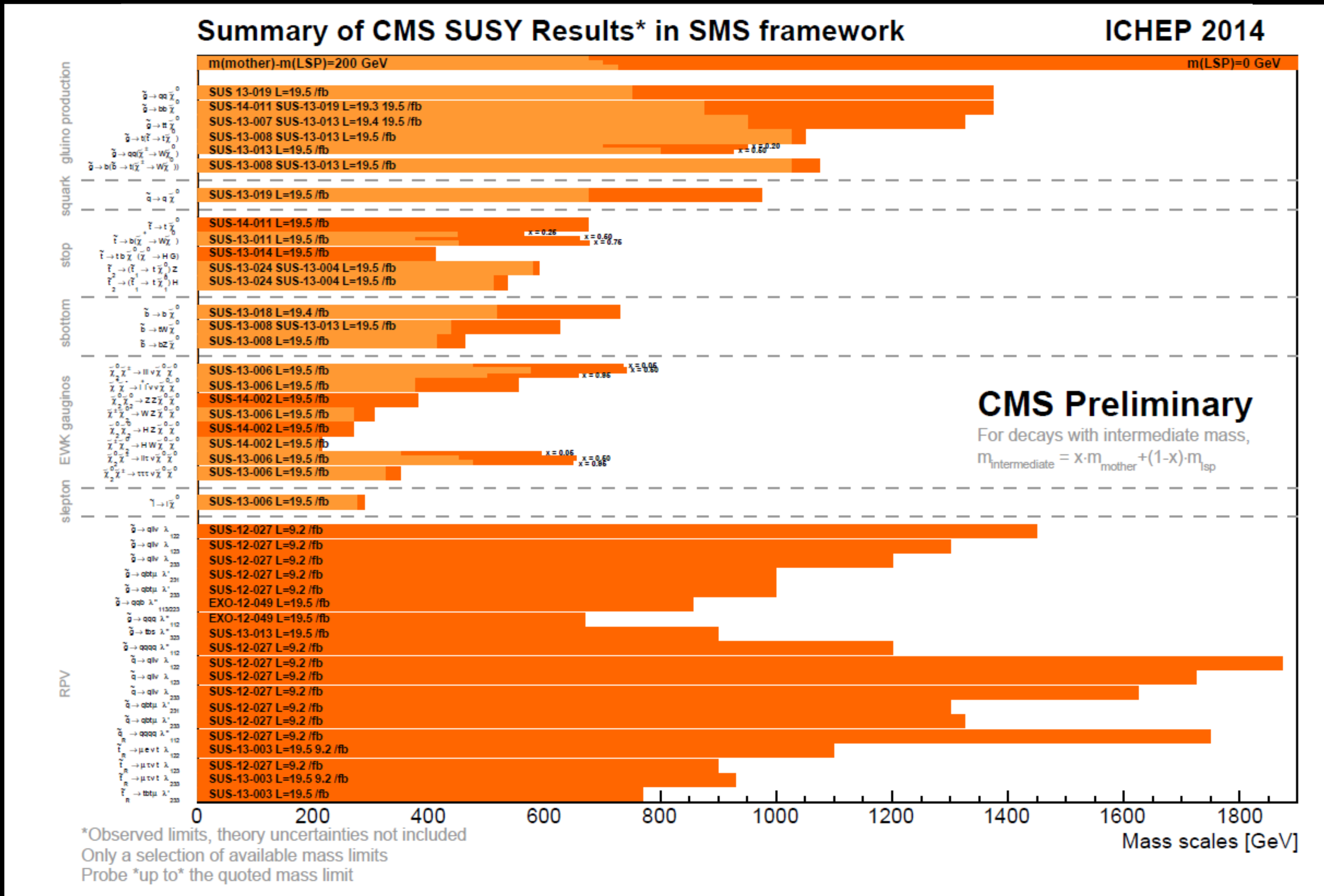

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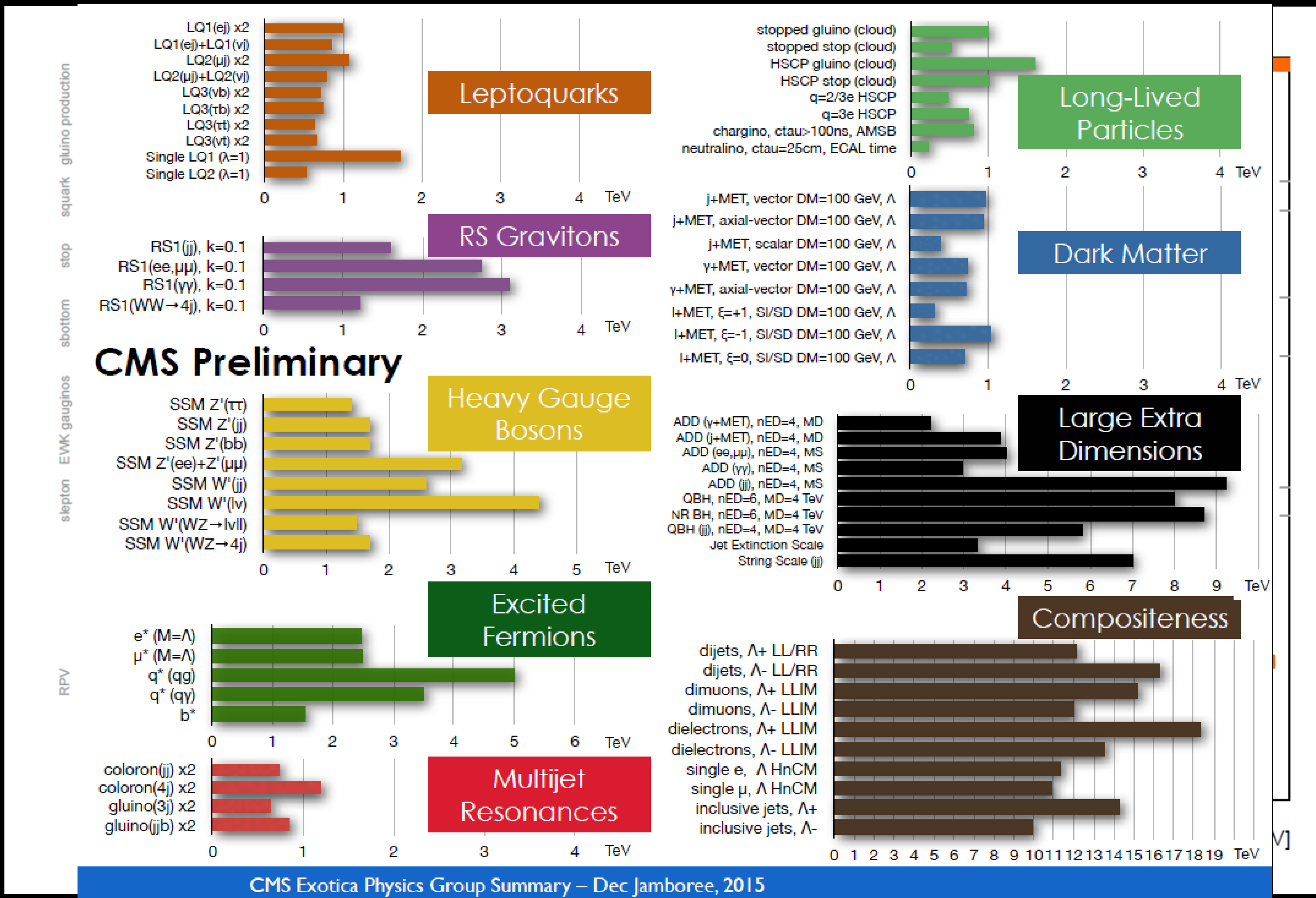

However .....

Many of our past expectations have been shattered

Naturalness as guiding principle

G. Giudice, FCC meeting, Rome 2016

Technicolor → no fundamental Higgs **No!**

Supersymmetry → $m_h \lesssim 120$ GeV, $\tilde{m}_t \lesssim 300$ GeV, $\tilde{m}_g \lesssim 1$ TeV **No!**

Extra dimensions → hell breaks loose at TeV **No!**

Composite Higgs → $\Delta BR_h \sim O(1)$ **No!**

Change of paradigm?

Hints? (....weak)

❖ Di-photons?

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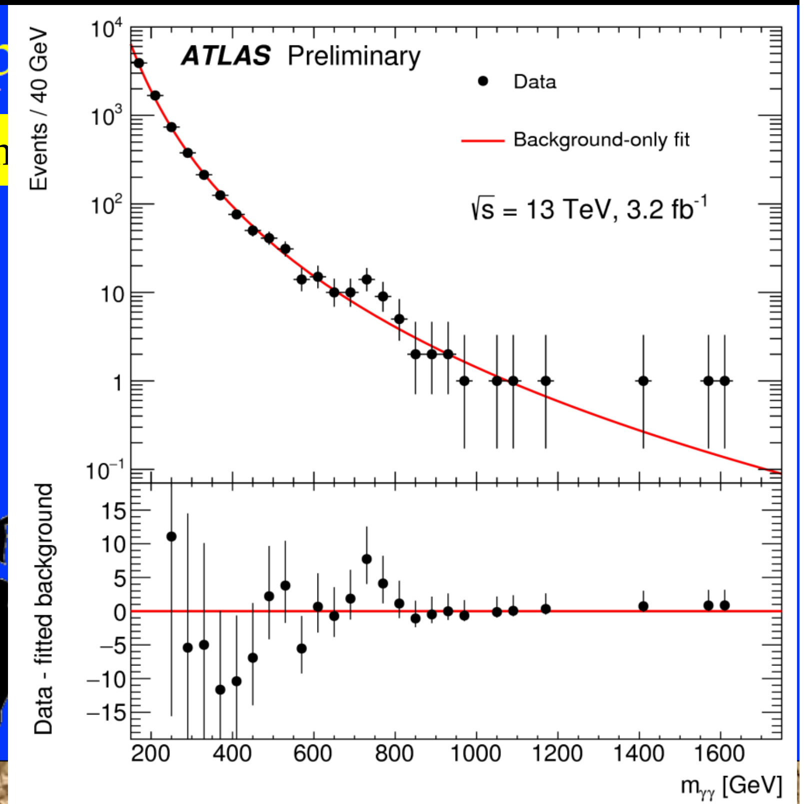
  - Atlas: 3.6/1.8 σ



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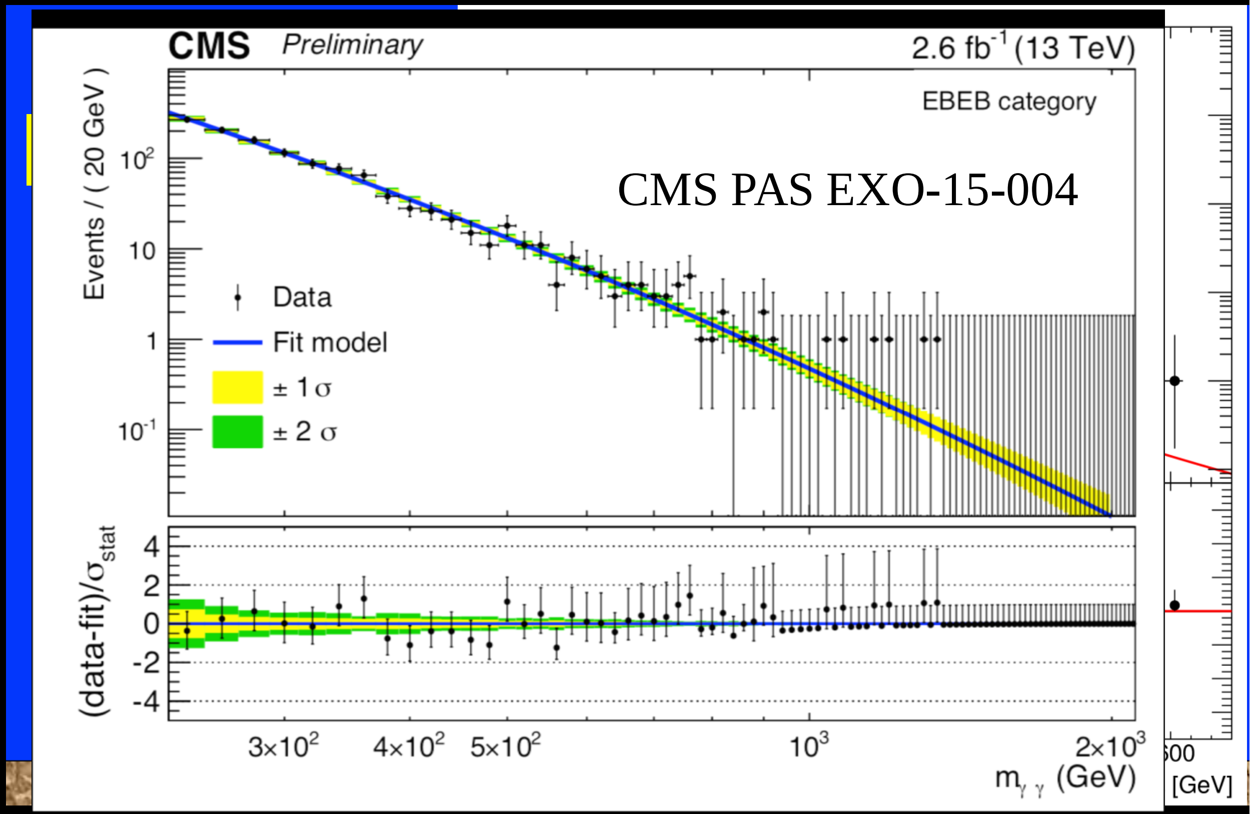

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- Flavor:
  - LHCb ~3.5 σ :
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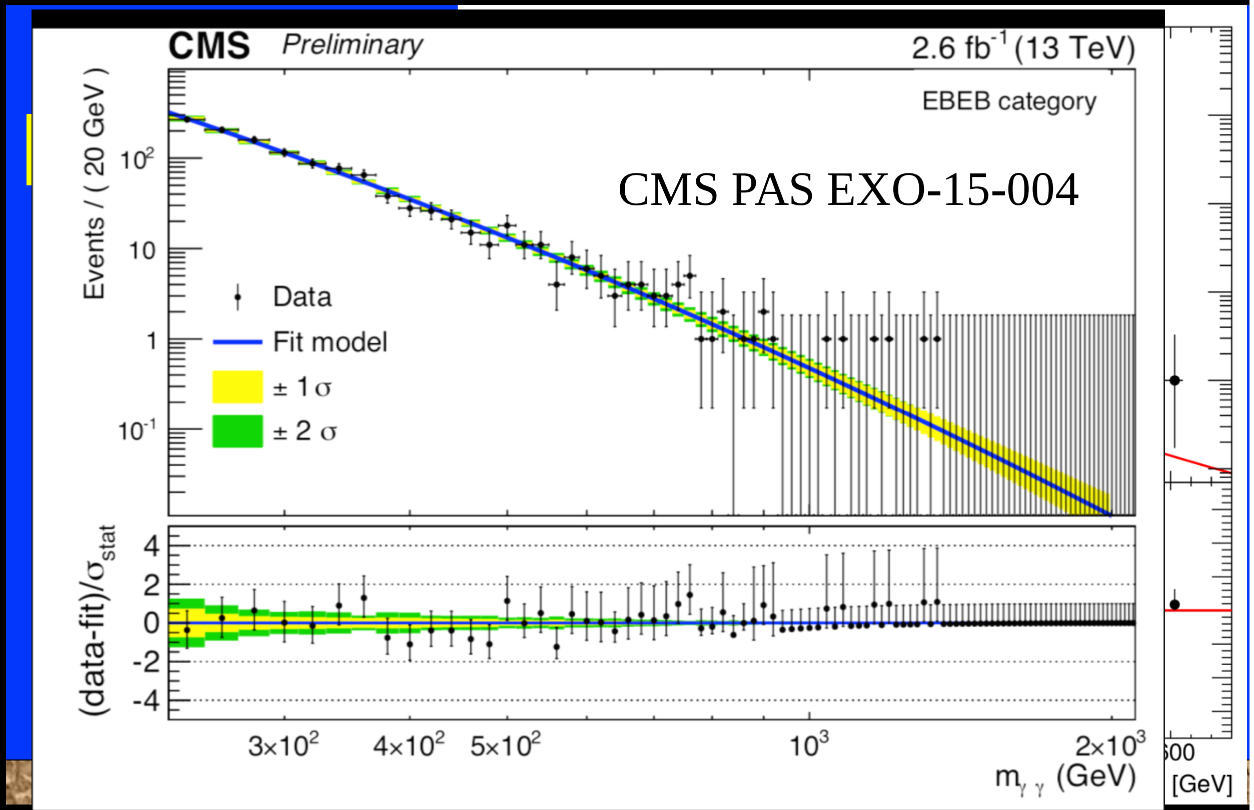

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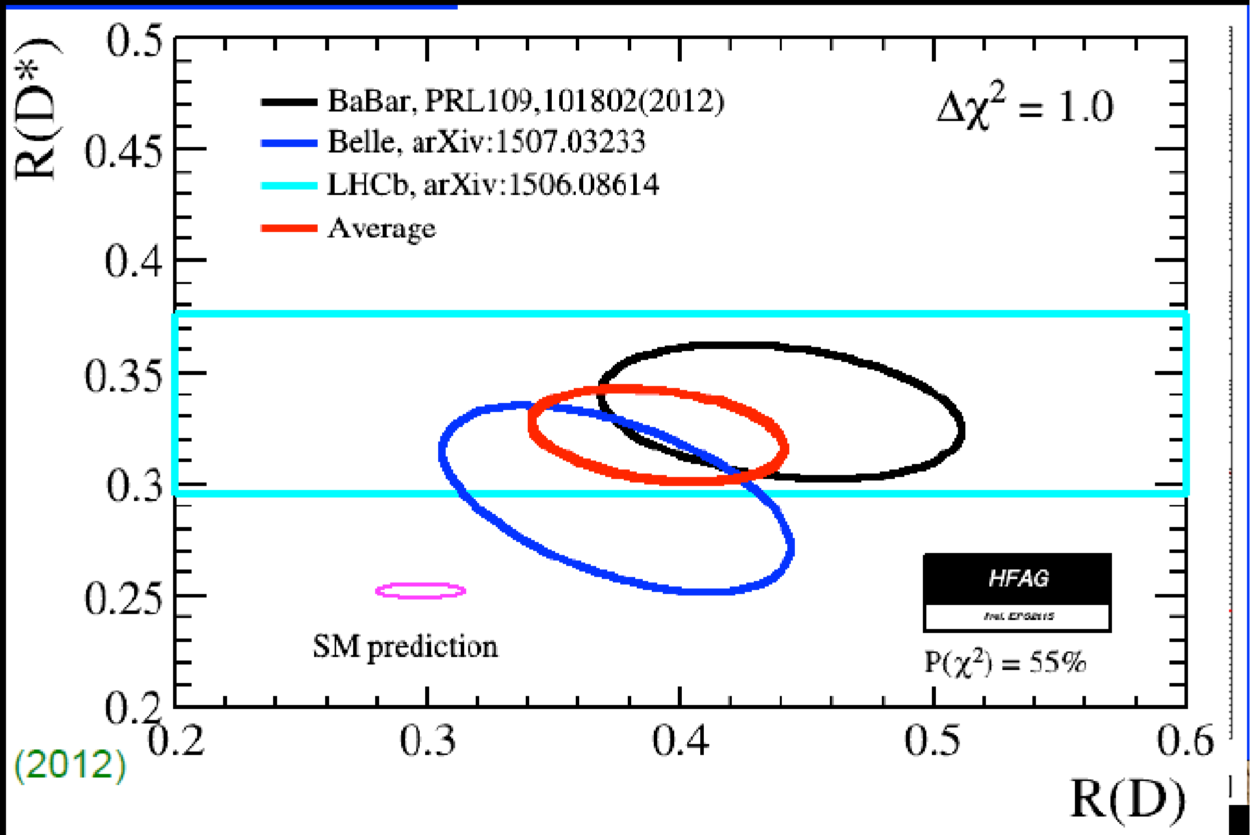
  - R(D)
    - ~3.9 σ



$$R(D^{(*)}) = BR(\bar{B} \rightarrow D^{(*)}\tau\bar{\nu}) / BR(\bar{B} \rightarrow D^{(*)}l\bar{\nu})$$

Directions?

- "Confusion is the best moment in science"
- "…privilege of being in a state of confusion"
  - G. Giudice: FCC week, Rome, April 2016

- the discussion of the **future** in HEP must start from the understanding that there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee discoveries*** beyond the SM, and ***answers*** to the big questions of the field:
  - M. Mangano: 98° ECFA meeting, Nov. 2015

Directions?

- Proposed criteria to evaluate future facilities (MLM):
  - Guaranteed deliverables
  - Exploration potential
    - Target broad well justified BSM scenarios
  - Potential to provide conclusive answers to relevant broad questions

- Additional practical criteria apply
  - When will the technology needed to build it be available?
  - Are the expected construction and operation costs acceptable?

Guaranteed deliverables

- Detailed study of Higgs boson
  - Higgs is VERY special
  - Beyond HL-LHC precision
- Extreme precision physics
  - EWK sector
  - Heavy Flavor sector

Higgs couplings

- Deviation from SM: $\delta \sim v^2/M^2$ $v = 246$ GeV
  - M scale of new physics
  - $M \sim 1 - 10$ TeV → $\delta \sim 6 - 0.6\%$

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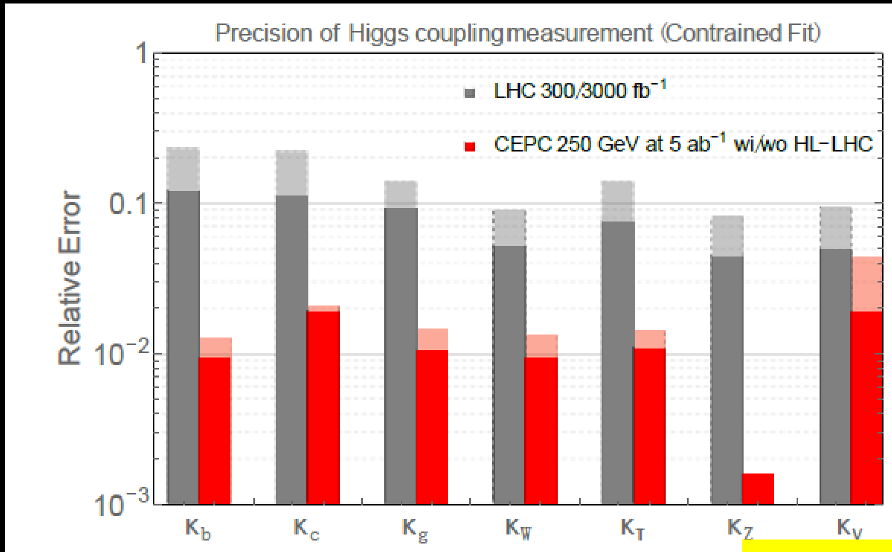

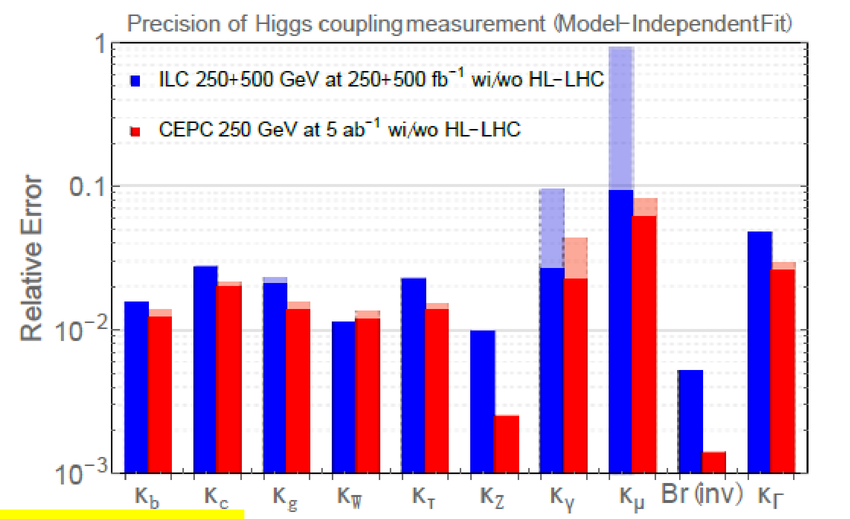

CepC pre-CDR

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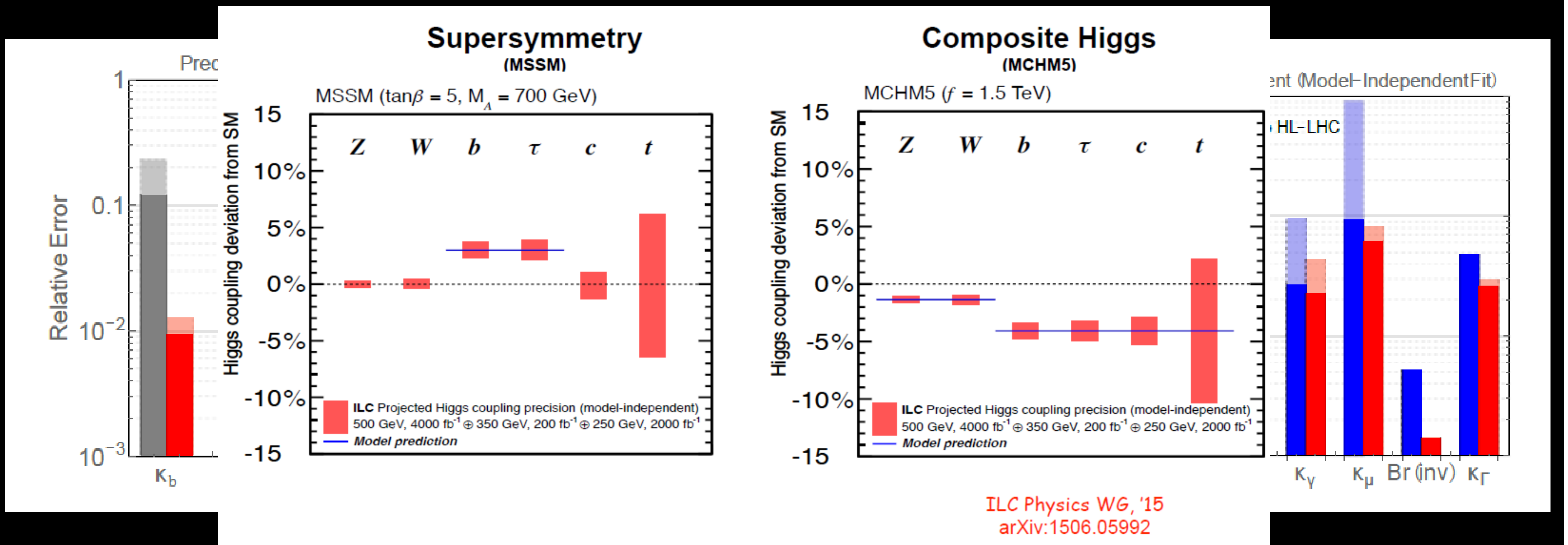


Higgs couplings

M. Klute LCWS 2015

Uncertainties	HL-LHC*	μ-	CLIC	ILC**	CEPC	FCC-ee
m_H [MeV]	40	0.06	40	30	5.5	8
Γ_H [MeV]	-	0.17	0.16	0.16	0.12	0.04
g_{HZZ} [%]	2.0	-	1.0	0.6	0.25	0.15
g_{HWW} [%]	2.0	2.2	1.0	0.8	1.2	0.2
g_{Hbb} [%]	4.0	2.3	1.0	1.5	1.3	0.4
$g_{H\tau\tau}$ [%]	2.0	5	2.0	1.9	1.4	0.5
$g_{H\gamma\gamma}$ [%]	2.0	10	6.0	7.8	4.7	1.5
g_{Hcc} [%]	-	-	2.0	2.7	1.7	0.7
g_{Hgg} [%]	3.0	-	2.0	2.3	1.5	0.8
g_{Htt} [%]	4.0	-	4.5	18	-	-
$g_{H\mu\mu}$ [%]	4.0	2.1	8.0	20	8.6	6.2
g_{HHH} [%]	30	-	24	-	-	-

* Estimate for two HL-LHC experiments
** ILC lumi upgrade improves precision by factor 2

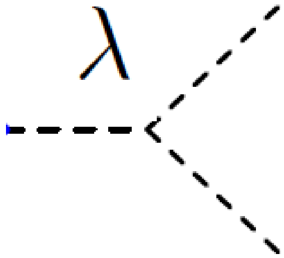
For ~10y operation. Lots of "!,*,?"
Every number comes with her own story.

Higgs self-couplings

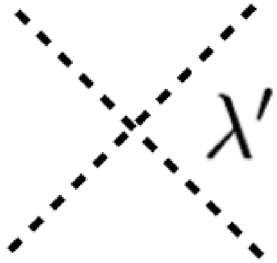
- in the SM : $V(H) = \frac{1}{2}M_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda' H^4$

$$\lambda = \lambda' = M_H^2/(2v^2) = 0.13$$

m_H directly related to Higgs dynamics !

- 

needs HH in final states



needs HHH

out of reach !

- BSM : Max λ deviations compatible with no other BSM observation: few % to ~20%

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$

Gupta et al, arXiv:1305.6397

→ target for both TH and EXP accuracies !

Higgs self-couplings

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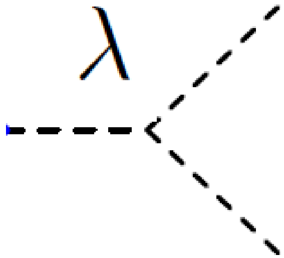
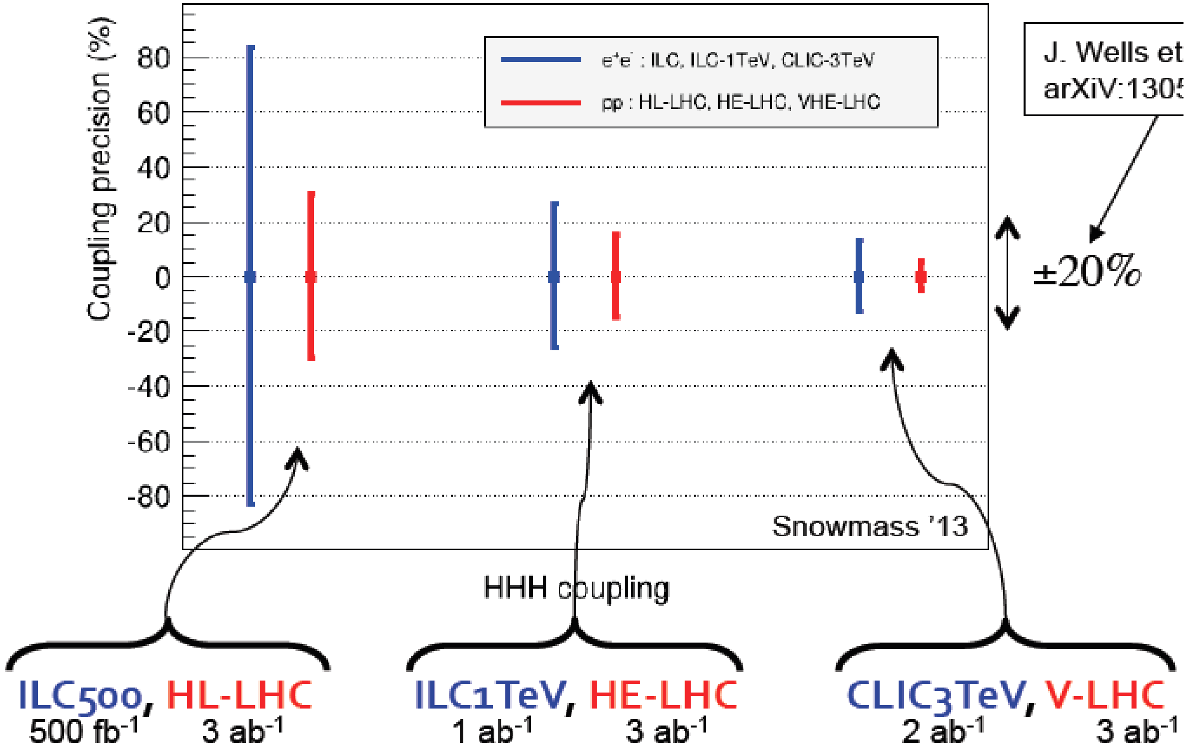


- needs
  in fina



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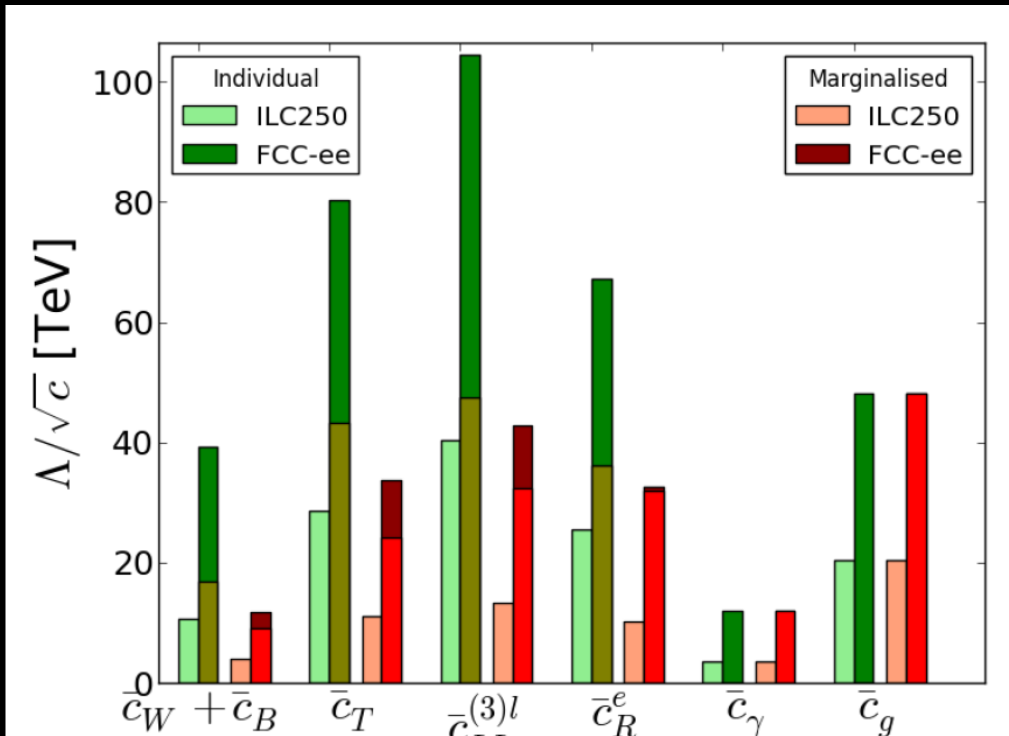
Precision in EFT

- Constrain Wilson coefficients/mass scale due to new physics with precise EWK/flavor measurements

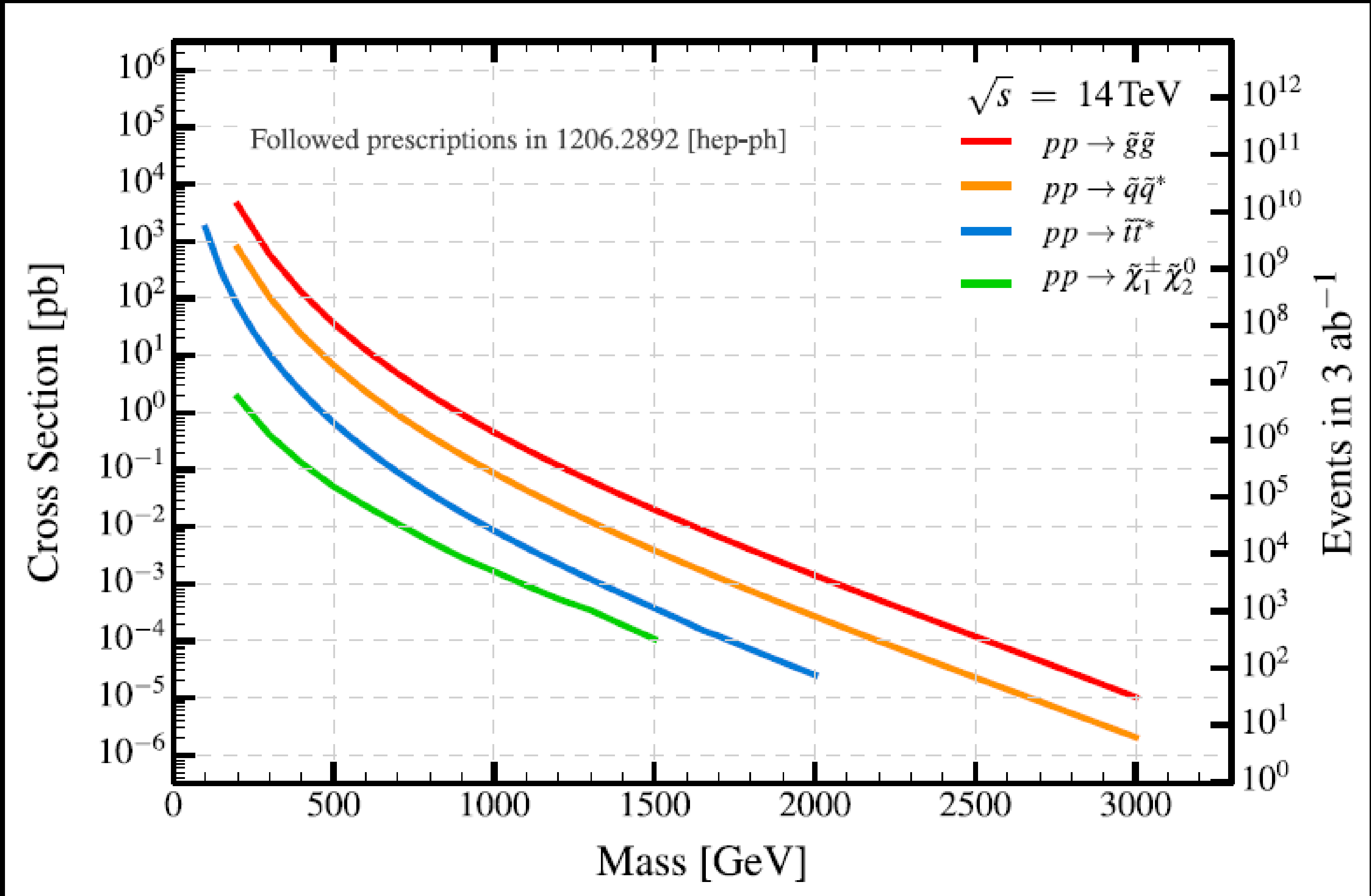
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$



John Ellis & Tevong You, arXiv:1510.04561

Exploration potential

- Search reach scaled from HL-LHC (2-3 TeV for SUSY)



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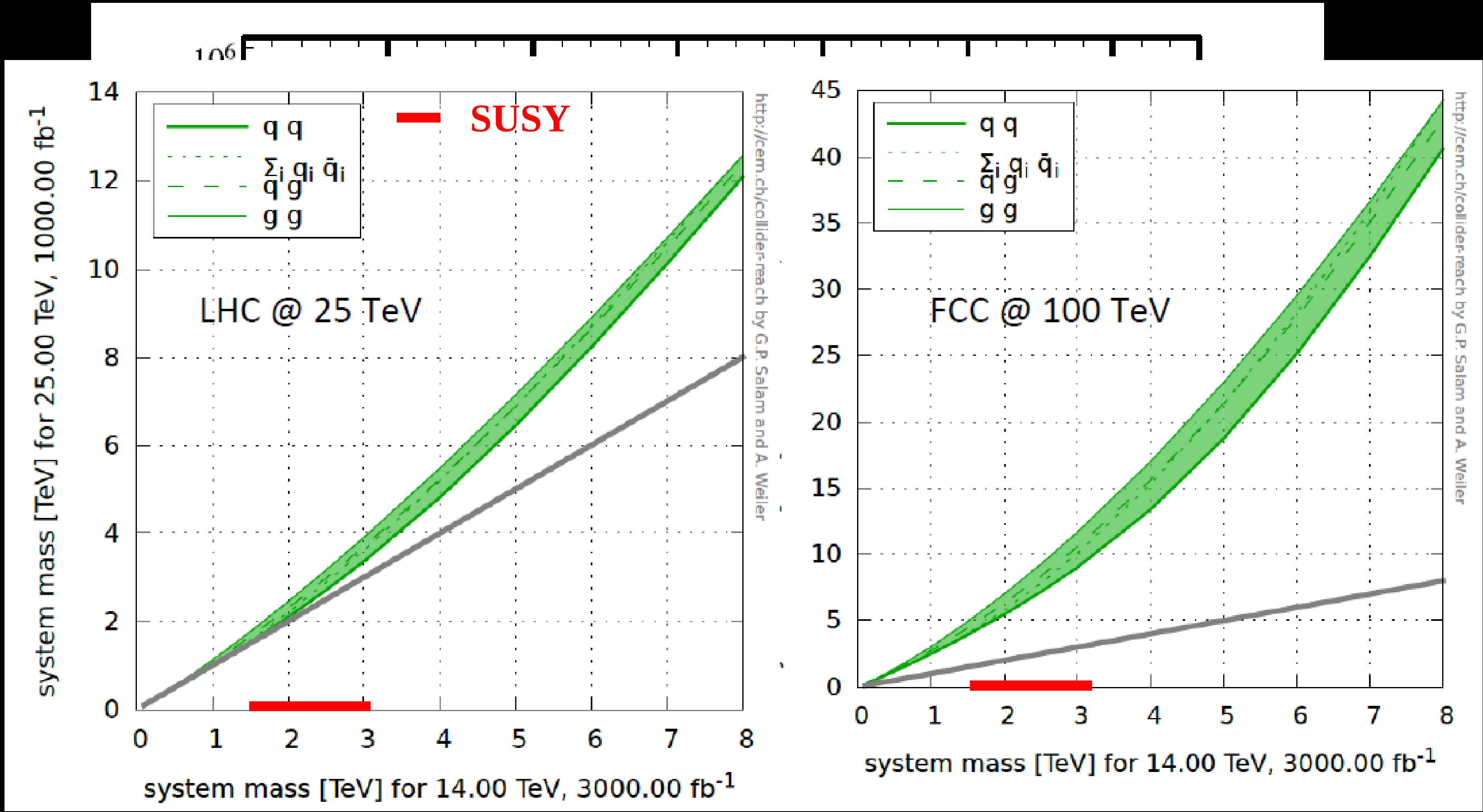

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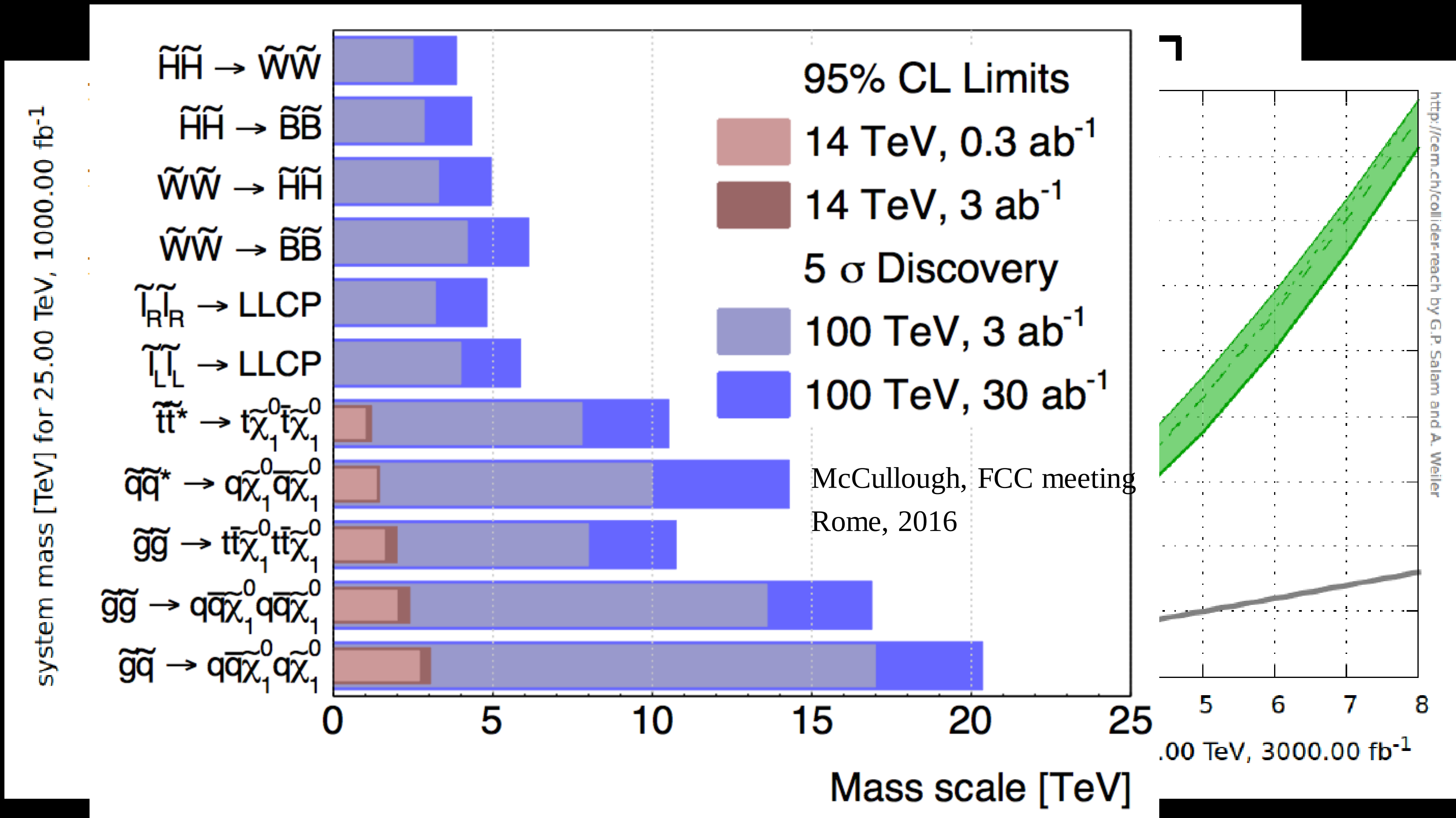
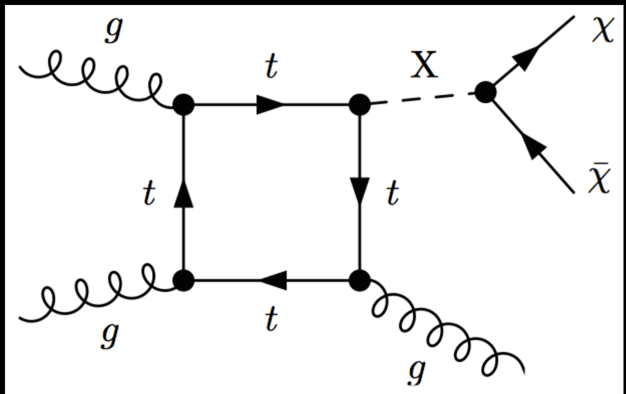
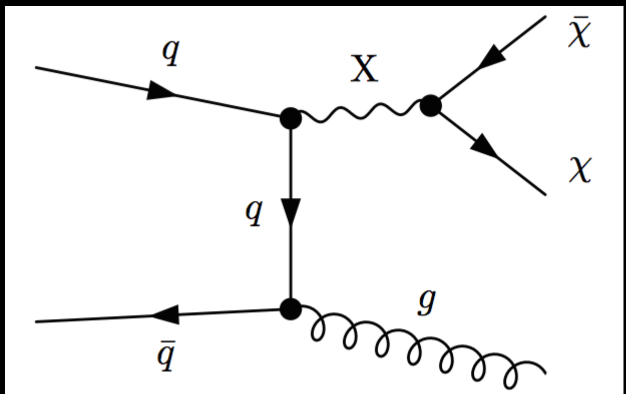
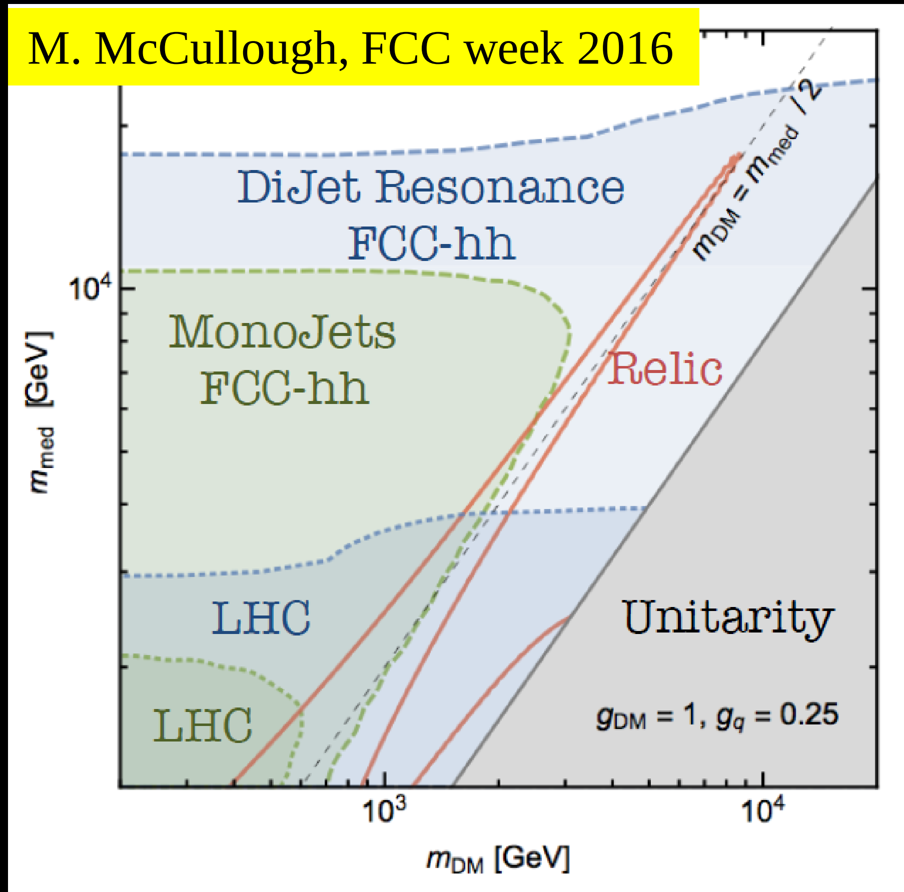


Conclusive answers?

- Dark matter (simplified models)
  - 100 TeV pp could cover all parameter space allowed by cosmological bounds







M. McCullough, FCC week 2016

The need

❖ Summary (assuming we build everything):

- Detailed Higgs studies and precision physics are guaranteed deliverables
  - Guidelines for new theories
- Exploration potential could be expanded from 2-3 TeV up to 10-20 TeV
- Dark matter could be very seriously constrained
- If (few) new physics hints are confirmed HL-LHC most likely not sufficient to fully explore the resulting new physics scenarios

Build what?

- Could build now ... almost
  - ILC/CepC/FCC-ee
  - LHeC
- Need more R&D
  - HE-LHC, FCC-hh/SppC
  - CLIC
- Not yet demonstrated
  - PWFA = «Plasma WakeField Acceleration»
  - Muon collider
- Potential extensions
  - ILC/CLIC → PWFA
  - CepC/FCC-ee/LHeC → Muon collider

Machines with known technology

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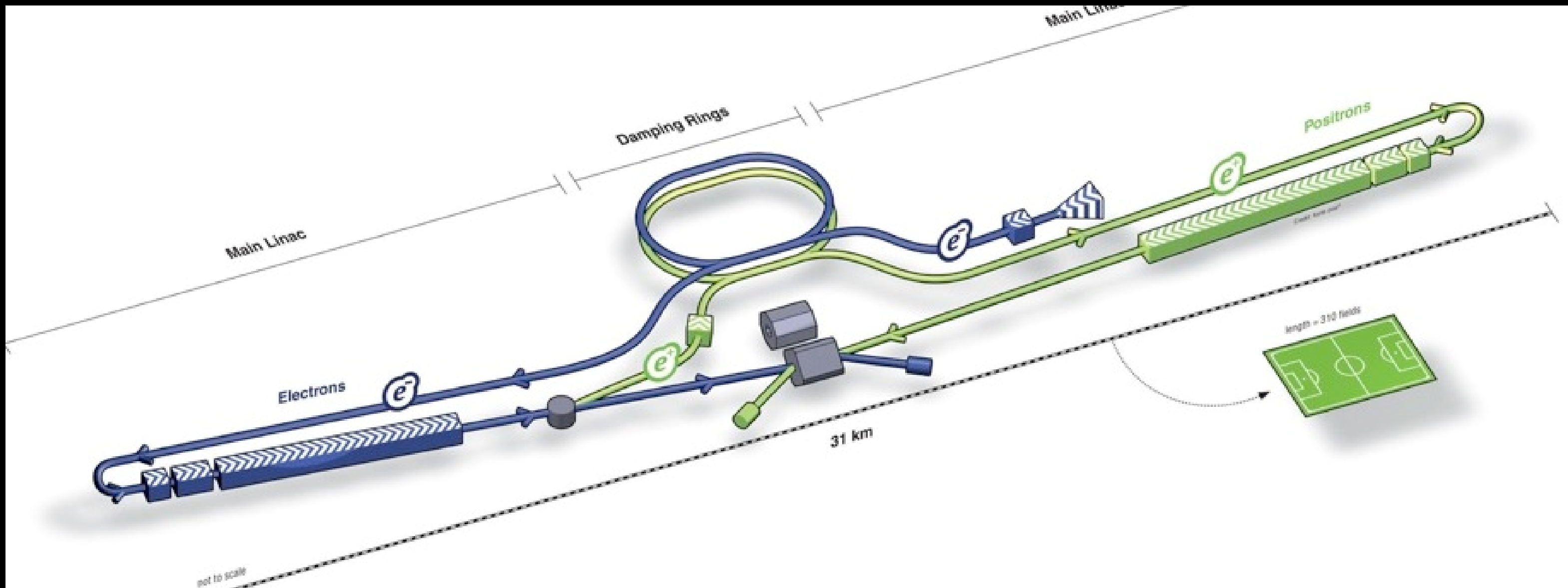
  - SC Linac 500 GeV (→1 TeV)
  - Detailed TDR/Engineering



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  - SC Linac 500 GeV (→1 TeV)
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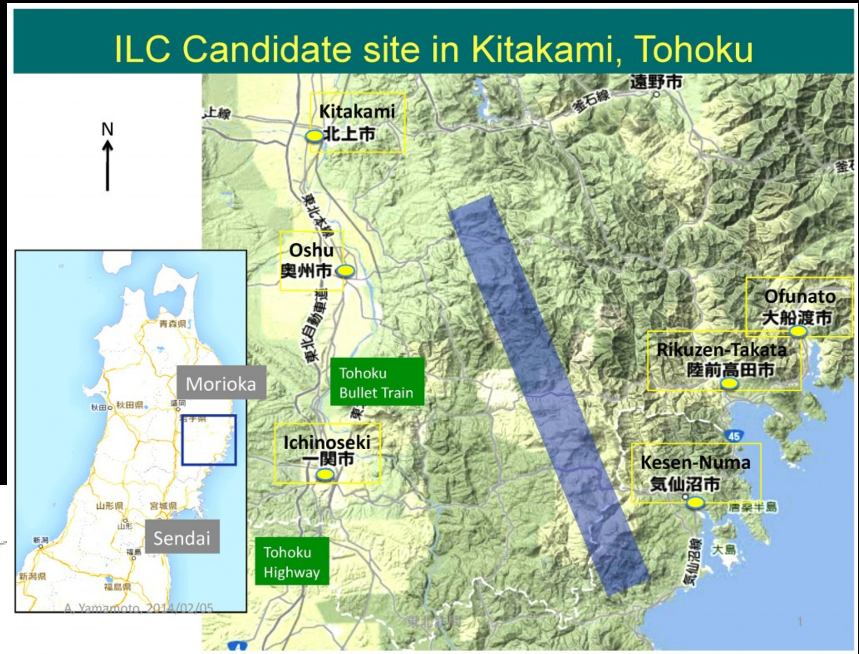
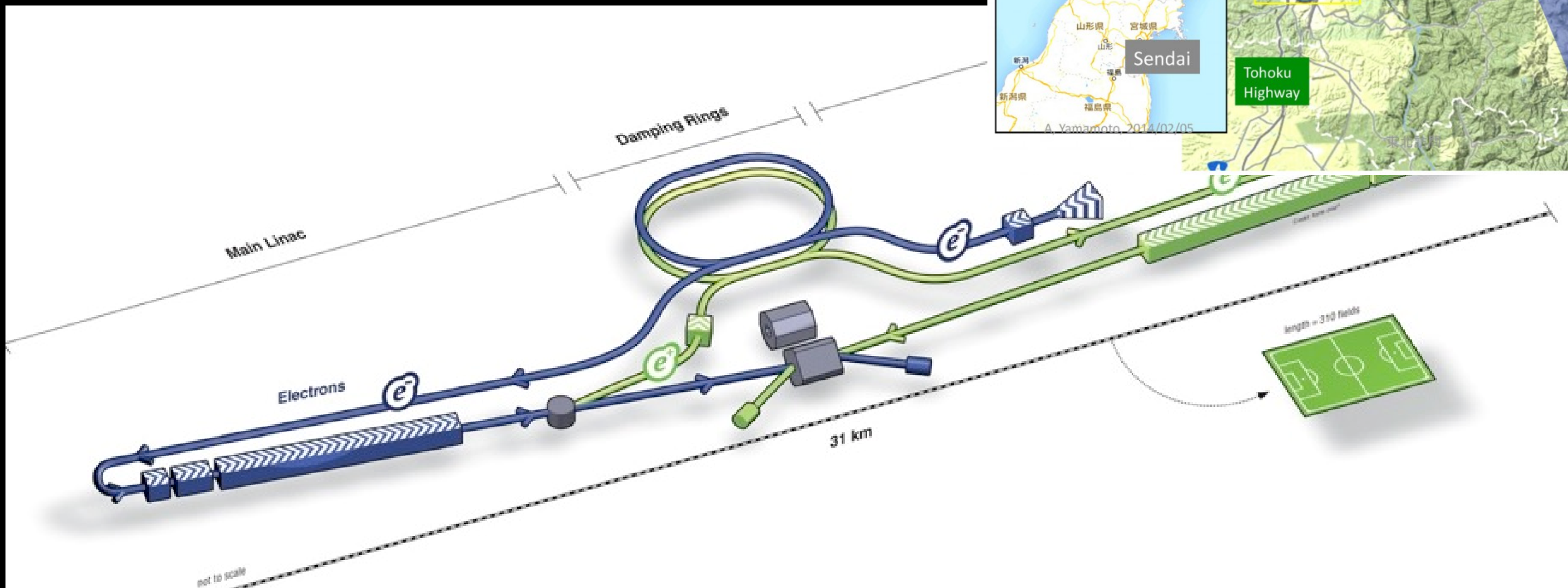
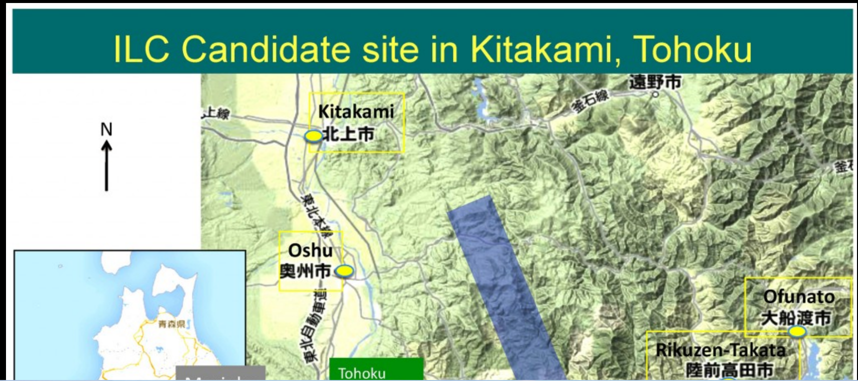
  - Site chosen/Review by MEXT

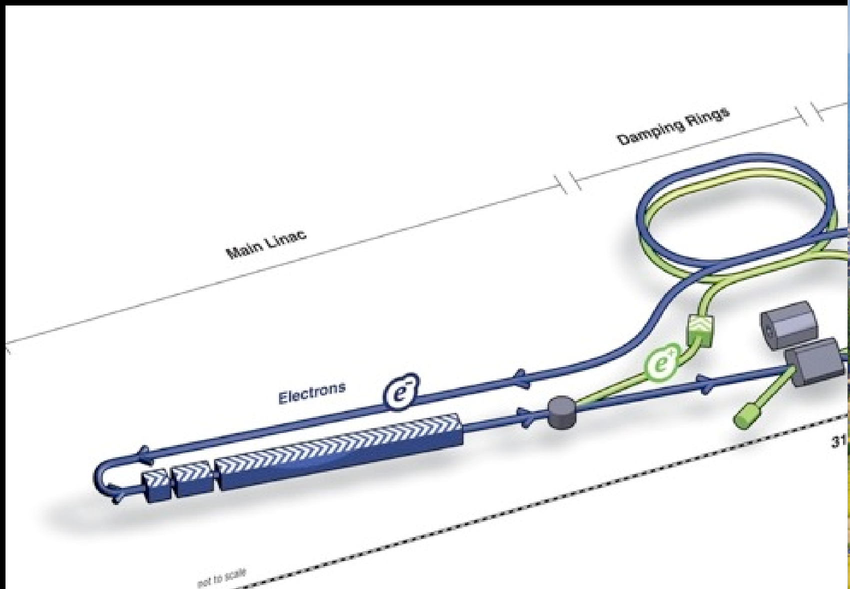




Machines with known technology

- ILC: linear e+e- collider
  - SC Linac 500 GeV (→1 TeV)
  - Detailed TDR/Engineering
  - Site chosen/Review by MEXT
  - Govnmt negotiation 2-3 yr





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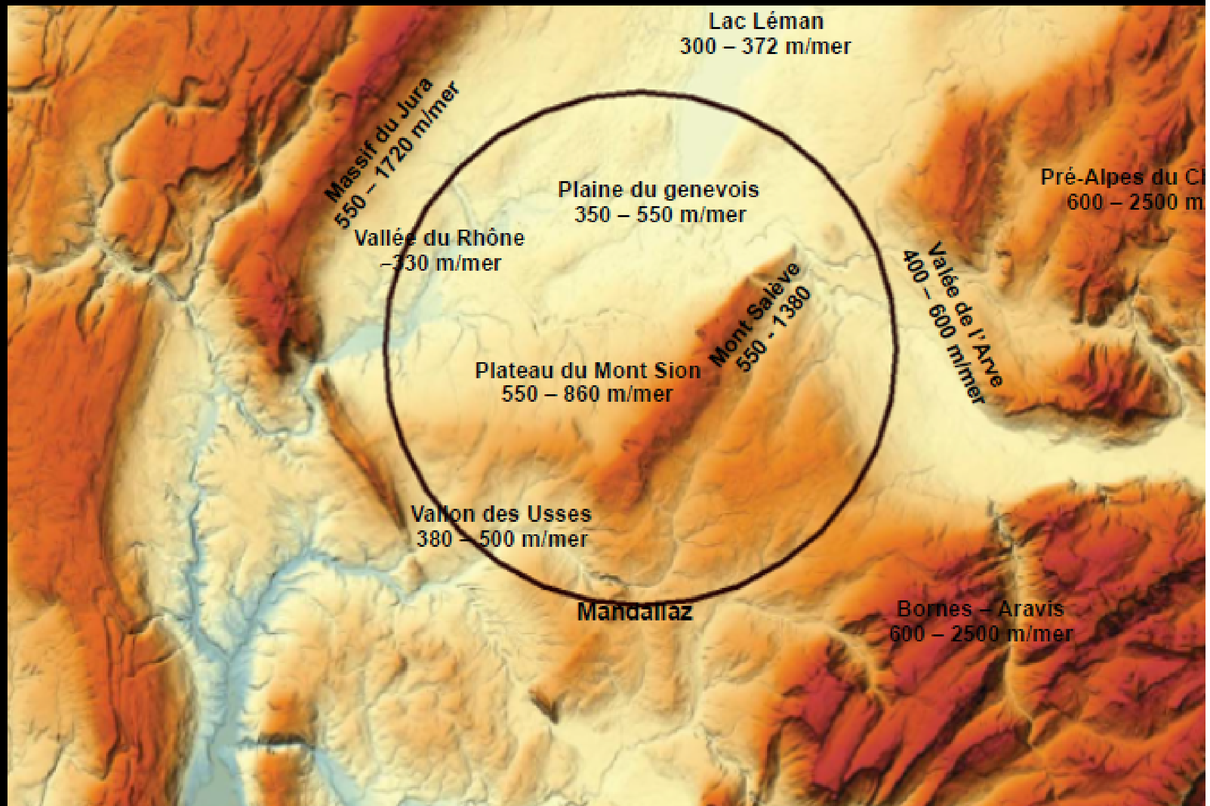
- FCC-ee: circular e+e- collider
  - ~100 km tunnel
  - → 350 GeV
  - CDR by 2018
  - Beam 2035?



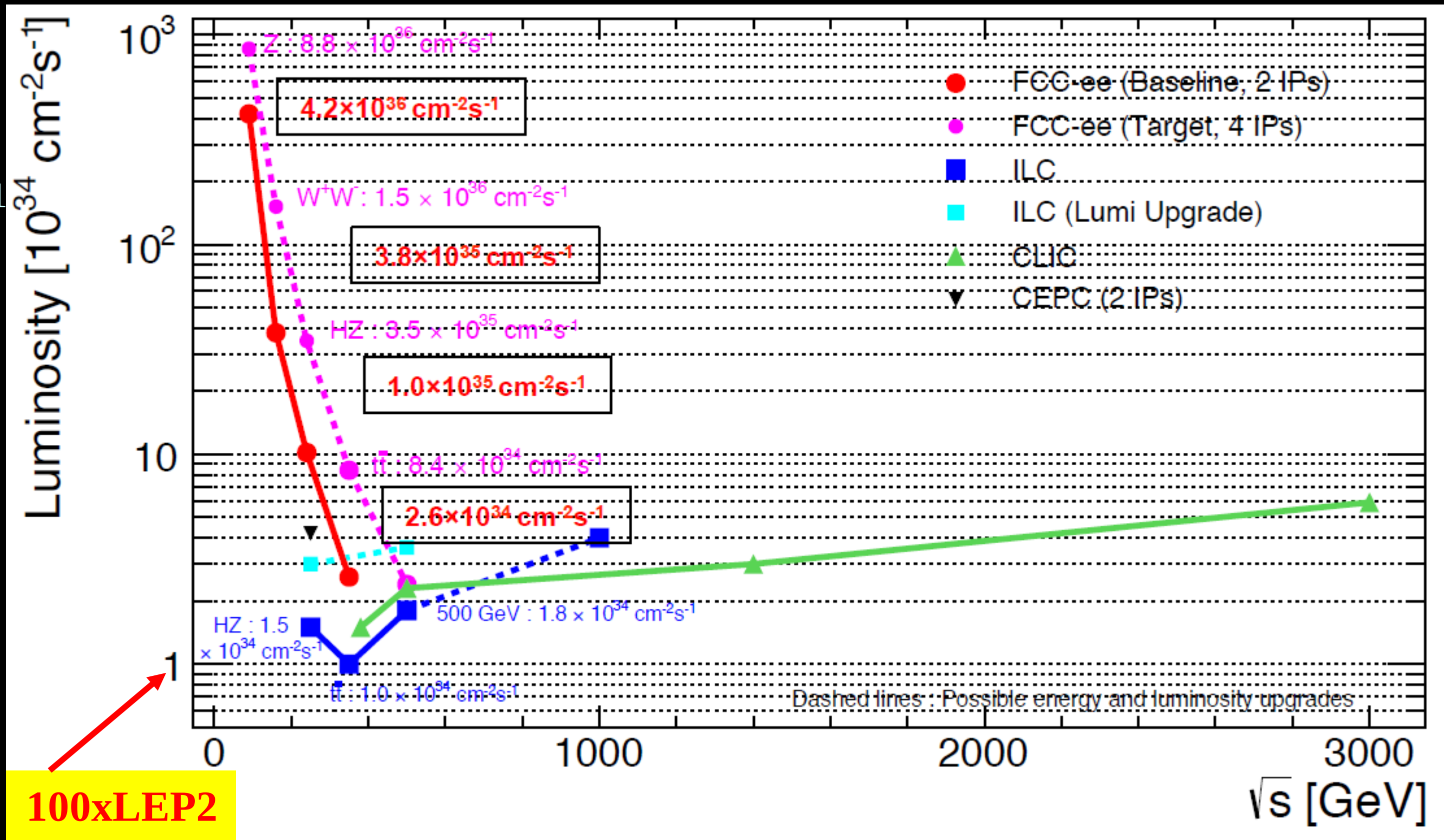
Machines with known technology

- FCC-ee: circular e+e- collider
  - ~100 km tunnel
  - → 350 GeV
  - CDR by 2018
  - Beam 2035?
- CepC: circular e+e- collider
  - 54 km tunnel
  - 240 GeV
  - Pre-CDR finished
  - CDR by 2016/17
  - Beam 2028-30?

Figure 3.3: Illustration of the CEPC-SPPC ring sited in Qinghuangdao. The small circle is 50 km, and the big one 100 km. Which one will be chosen depends on the funding scenario.

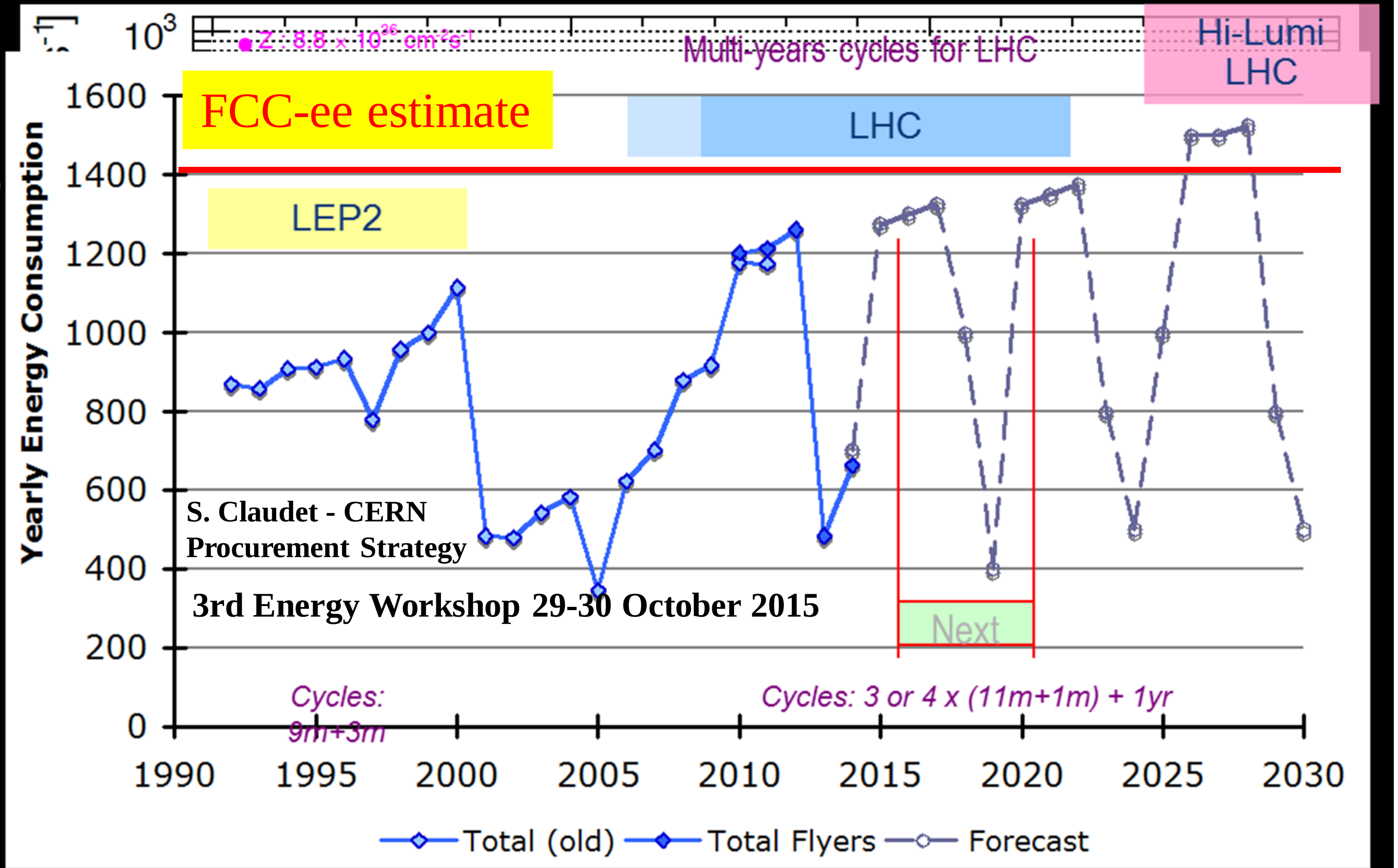
e+e- luminosity comparison

- Planning for extreme luminosities!
- Reference:
  - LEP1:
    - 3.4×10^{31}
  - LEP2:
    - 1×10^{32}



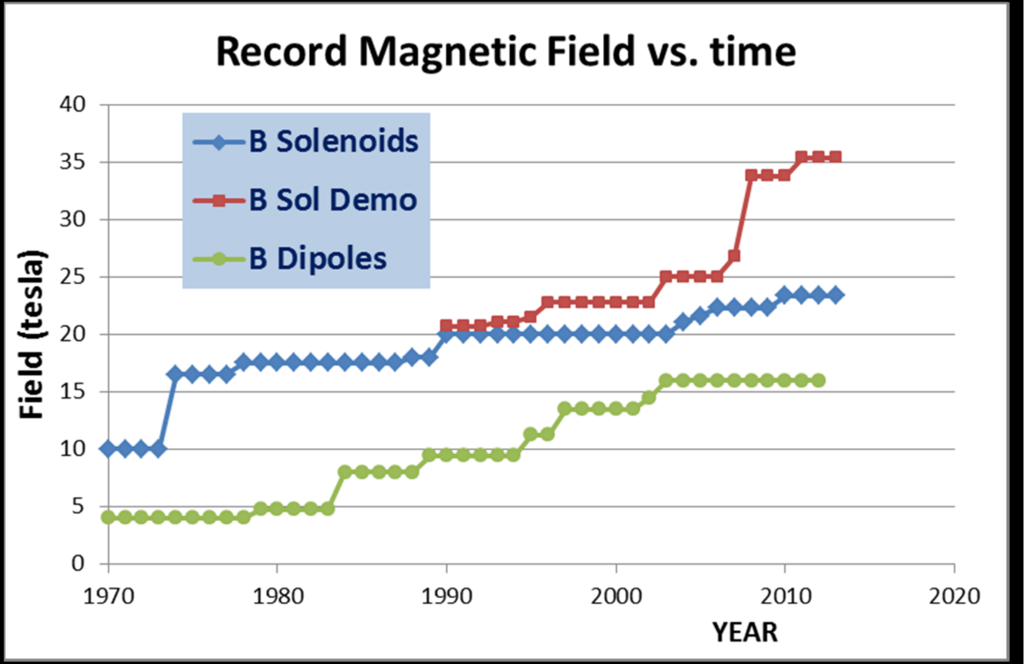
e+e- luminosity comparison

- Planning for extreme luminosities!
- Reference:
  - LEP1:
    - 3.4x10³
  - LEP2:
    - 1x10³²
- Power OK



Machines needing R&D

- HE-LHC/FCC-hh/SppC:
  - Share tunnels with LHC, FCC-ee, CepC
- Need high field Nb_3Sn magnets
  - 8 T (LHC) → 16 T
    - 20 T with HTS



Courtesy of Gijs de Rijk,

FCC week, Rome 2016

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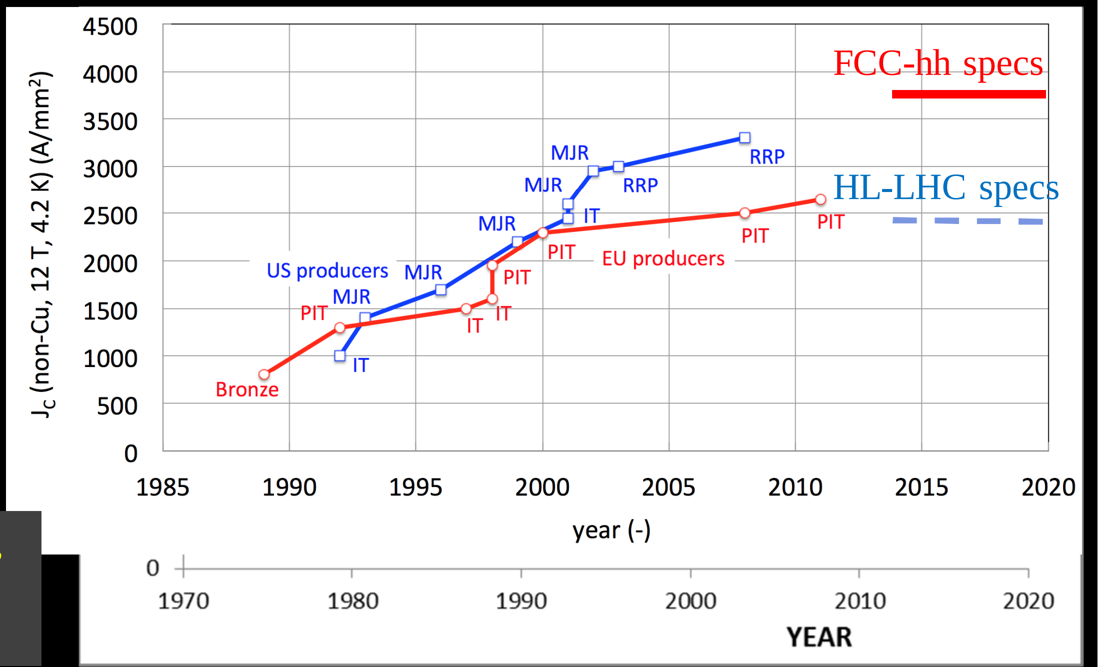

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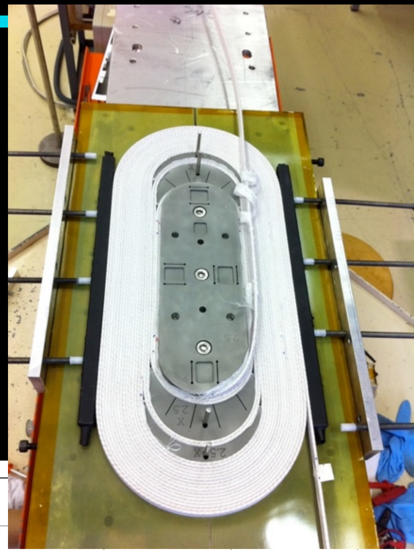
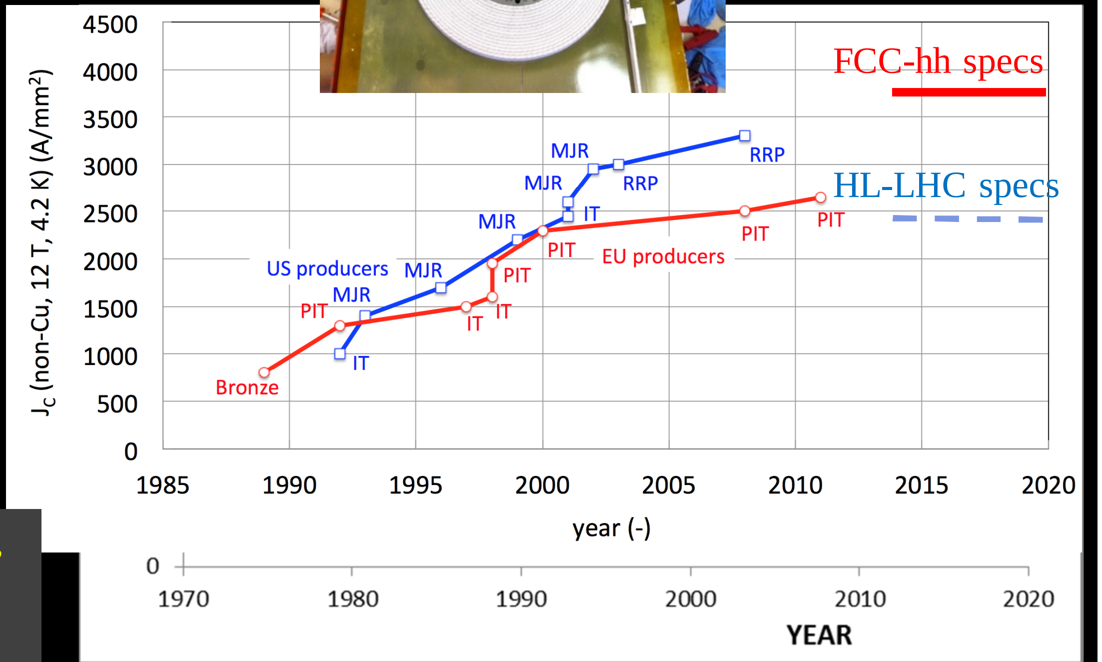
  - Conductor
  - Complex construction
    - Wind and react





Courtesy of Gijs de Rijk,

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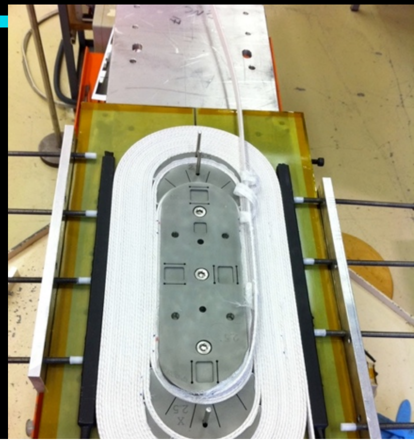
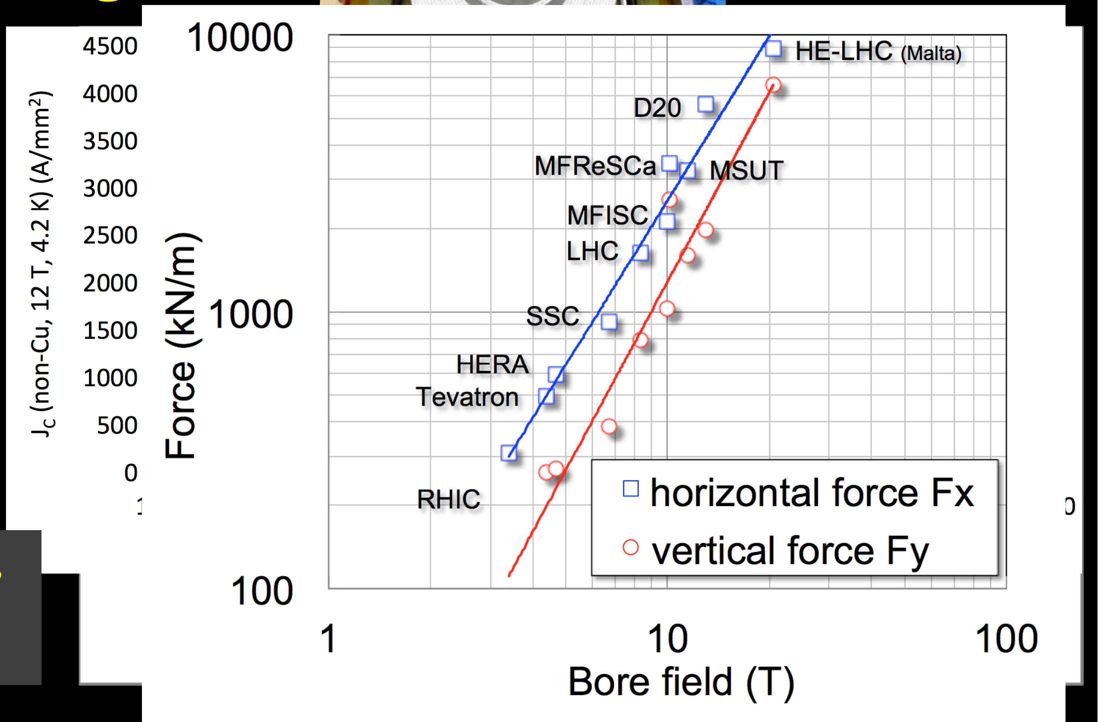
  - Conductor
  - Complex construction
    - Wind and react
  - Large forces



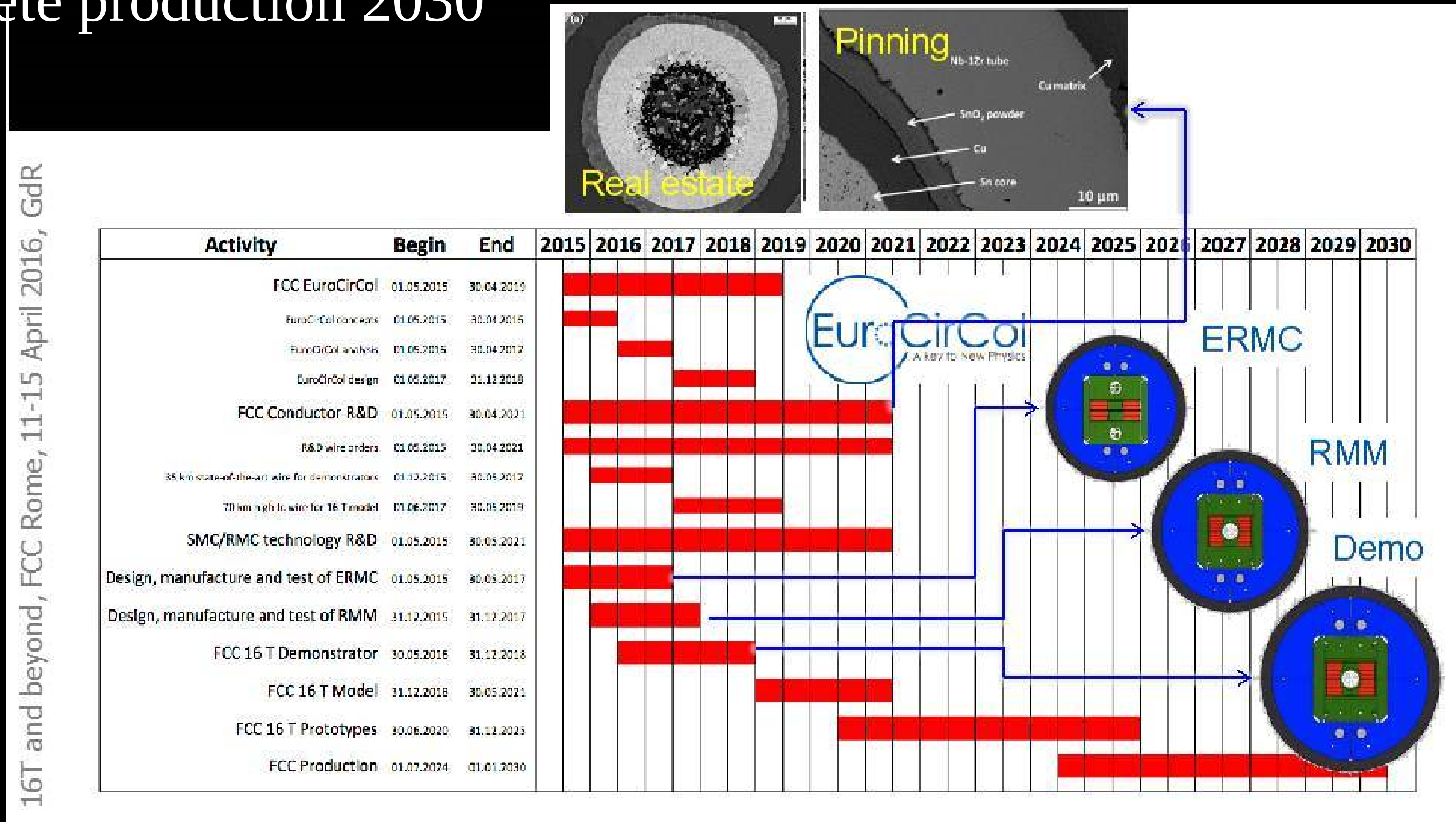


Courtesy of Gijs de Rijk,

FCC week, Rome 2016

Magnet R&D

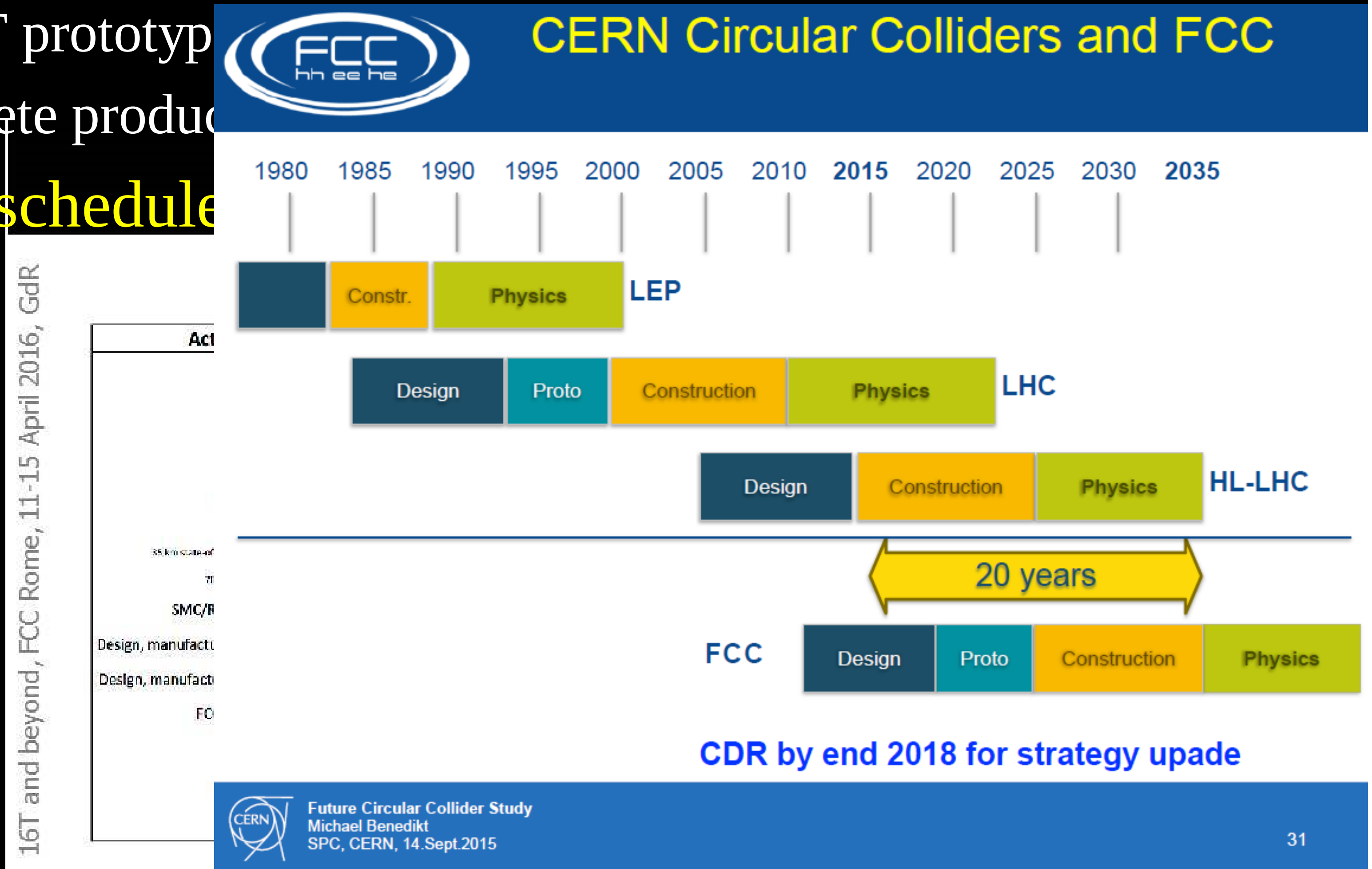
- CERN plan for FCC magnets
  - 1° 16 T prototype by mid 2020’s
  - Complete production 2030



Activity	Begin	End
FCC EuroCirCol	01.05.2015	30.04.2019
EuroCirCol concepts	01.05.2015	30.04.2016
EuroCirCol analysis	01.05.2016	30.04.2017
EuroCirCol design	01.05.2017	31.12.2018
FCC Conductor R&D	01.05.2015	30.04.2021
R&D wire orders	01.05.2015	30.04.2021
35 km state-of-the-art wire for demonstrators	01.12.2015	30.05.2017
70 km high Jc wire for 16 T model	01.06.2017	30.05.2019
SMC/RMC technology R&D	01.05.2015	30.05.2021
Design, manufacture and test of ERMC	01.05.2015	30.05.2017
Design, manufacture and test of RMM	31.12.2015	31.12.2017
FCC 16 T Demonstrator	30.05.2016	31.12.2018
FCC 16 T Model	31.12.2018	30.05.2021
FCC 16 T Prototypes	30.06.2020	31.12.2025
FCC Production	01.07.2024	01.01.2030

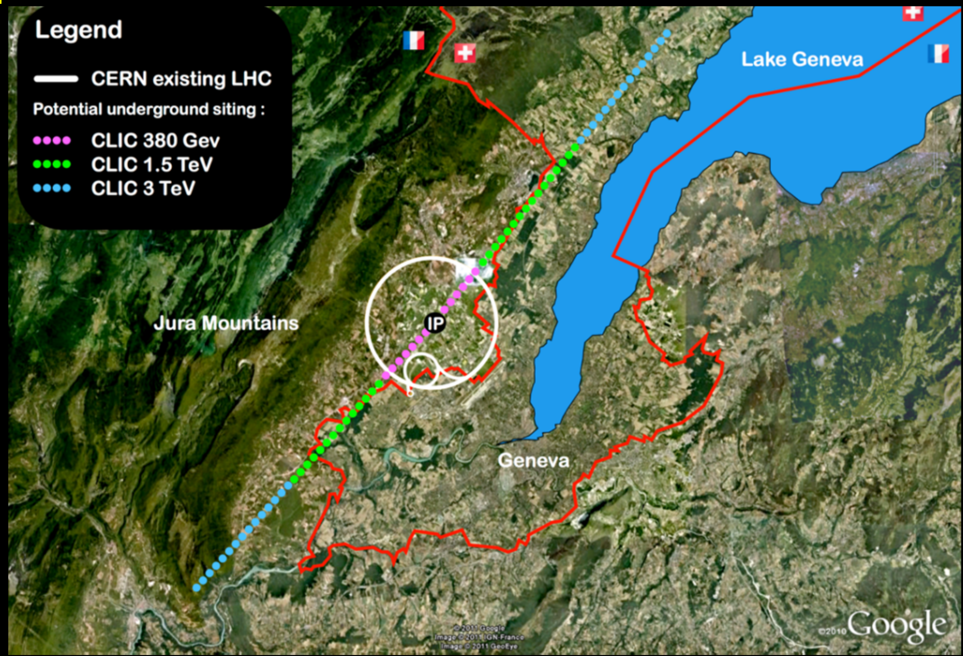
Magnet R&D

- CERN plan for FCC magnets
  - 1° 16 T prototyp
  - Complete produc
- FCC-hh schedule



Machines needing R&D

- CLIC: Linear e+e- collider
  - 380 GeV → 3 TeV
  - Room temp. Linac
    - 100 MV/m @ 12 GHz



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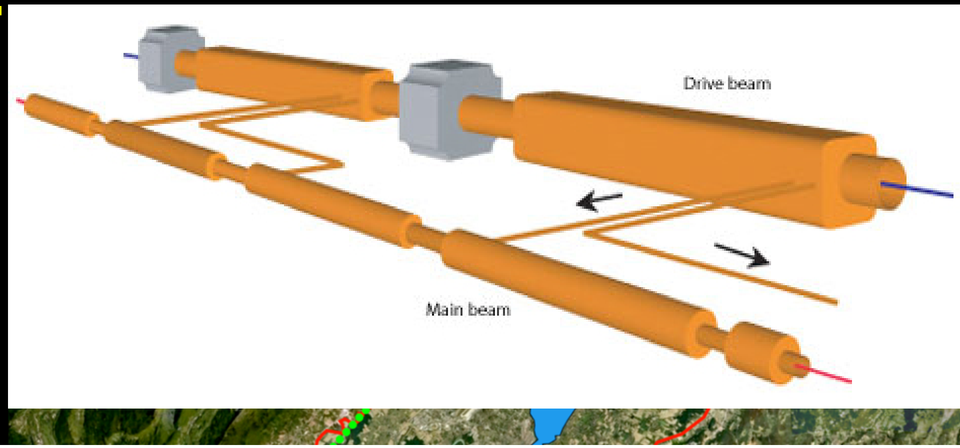
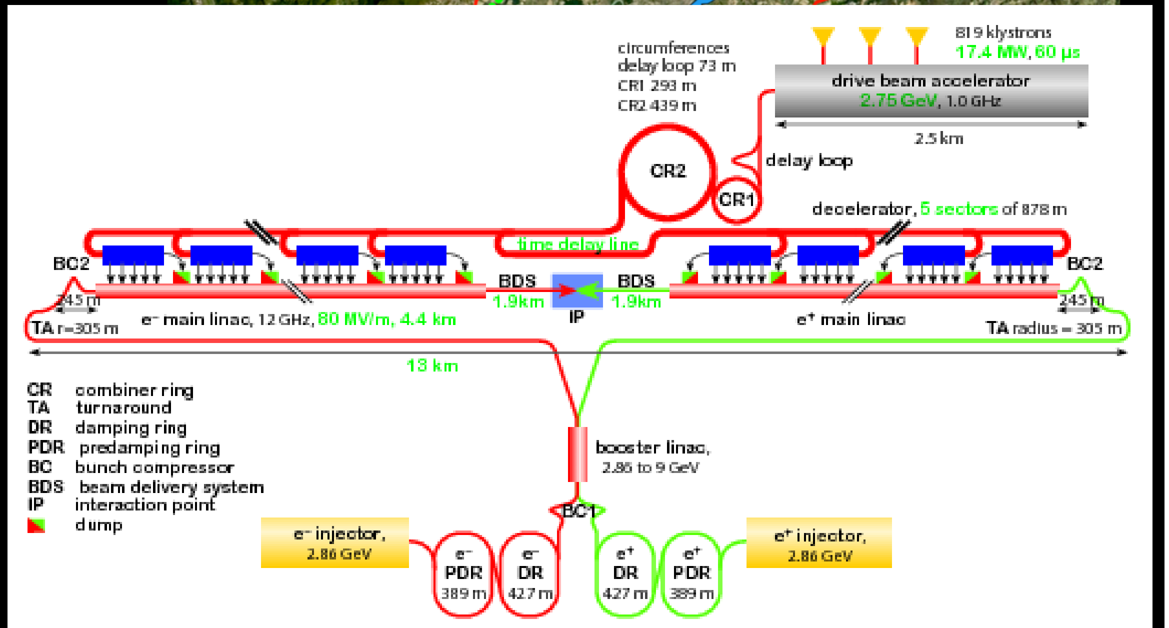
  - Klystrons→Drive beam





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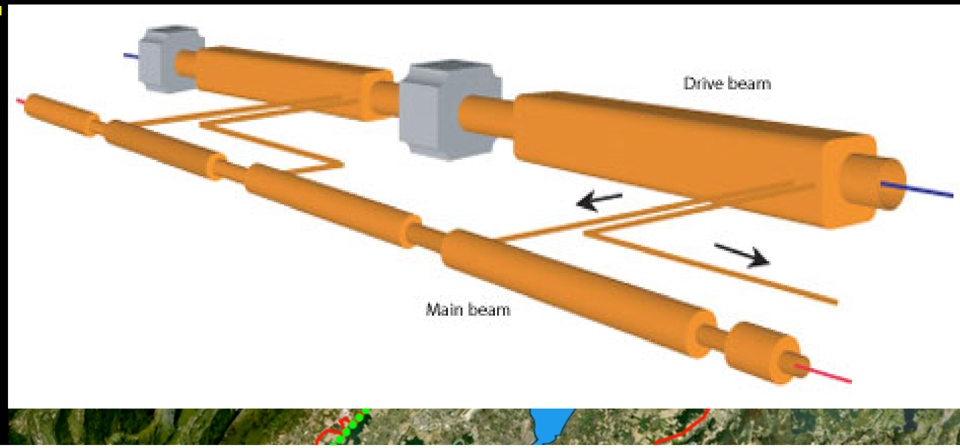
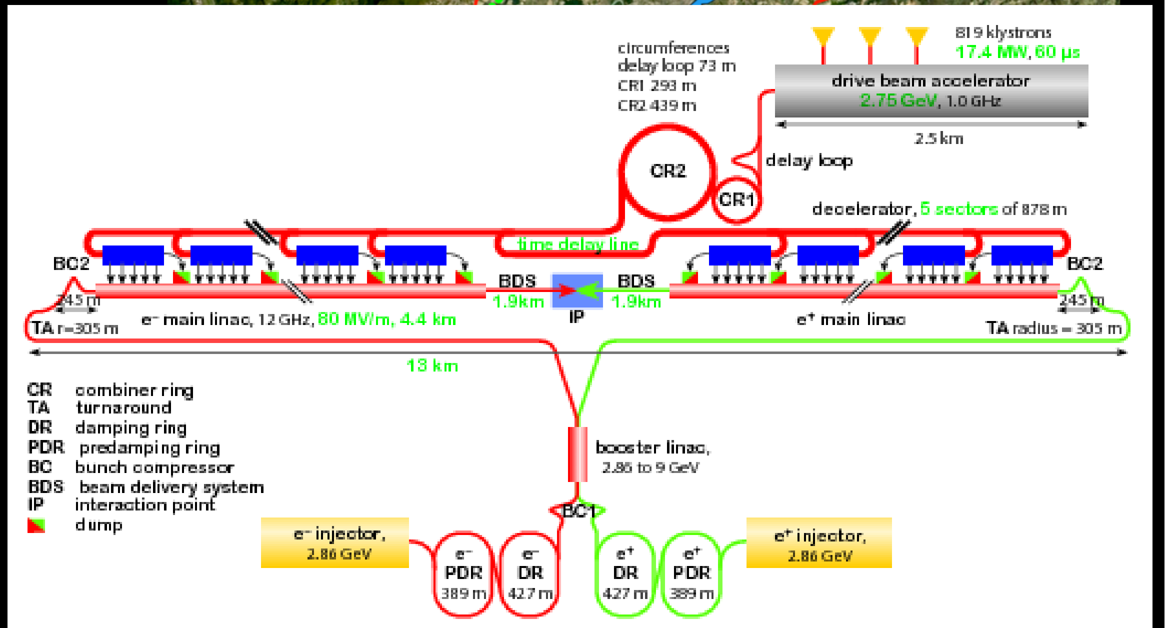


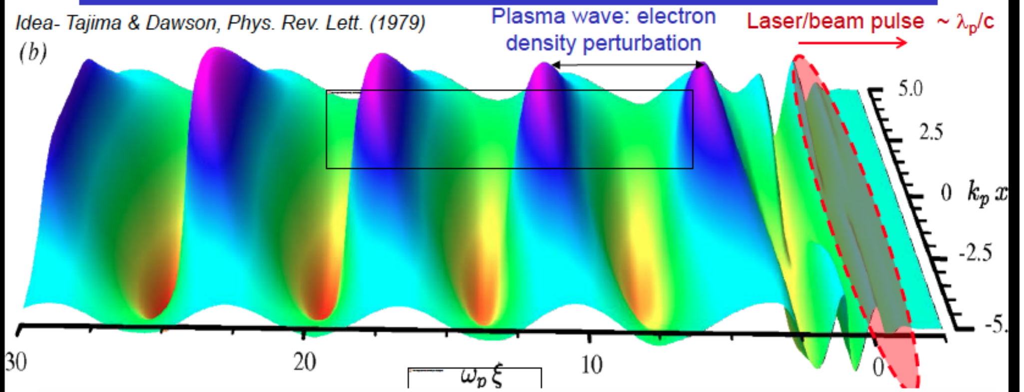
- Challenges:
  - RF breakdown
  - RF power transfer
  - 600 MW @ 3 TeV
  - Final focus
  - Beamstrahlung
  - Alignment



LWFA/PWFA

- Plasma acceleration R&D:
  - Many GeV/m !
  - Laser driven (LWFA)
  - Particle driven (PWFA)
  - Significant progress:

Excitation of Plasma Waves



$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Option #3:	Option #4:
Short intense e-/e+/p bunch	Short intense laser pulse
10^{18}cm^{-3}, 100 GV/m, λ_p~30μm	10^{17}cm^{-3}, 30 GV/m, λ_p~100μm

LWFA/PWFA

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  - Significant progress:
    - Positron

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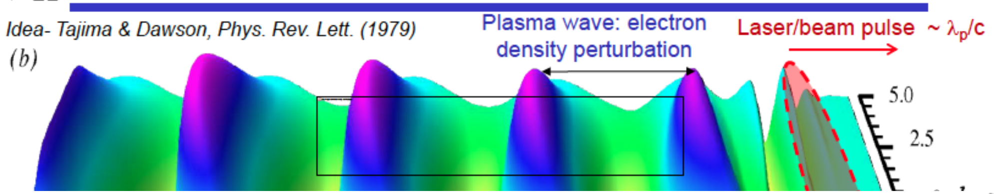
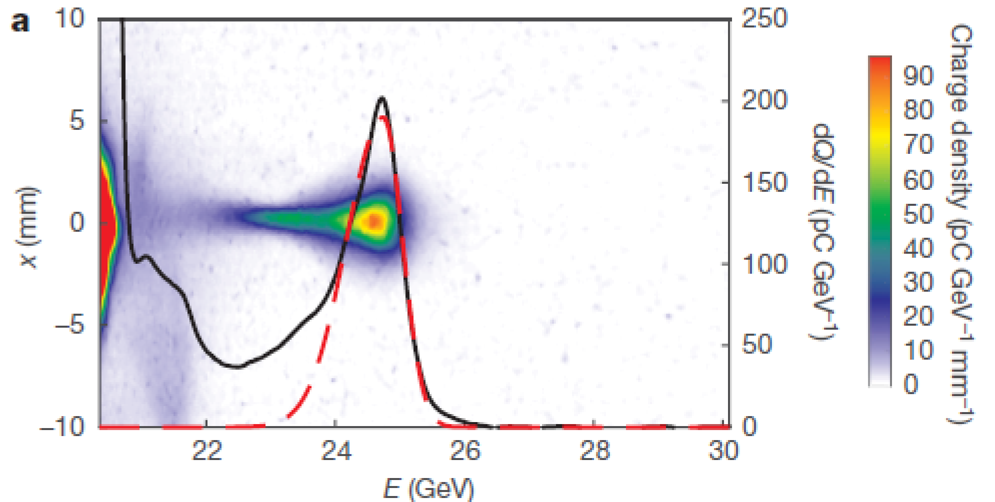


LETTER

Nature 524, 442–445 (27 August 2015)
doi:10.1038/nature14890

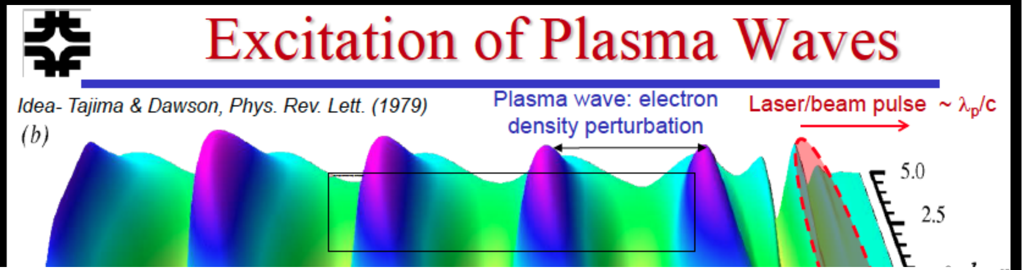
Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield

S. Corde[1,2], E. Adli[1,3], J. M. Allen[1], W. An[4,5], C. I. Clarke[1], C. E. Clayton[4], J. P. Delahaye[1], J. Frederico[1], S. Gessner[1], S. Z. Green[1], M. J. Hogan[1], C. Joshi[4], N. Lipkowitz[1], M. Litos[1], W. Lu[6], K. A. Marsh[4], W. B. Mori[4,5], M. Schmeltz[1], N. Vafaei-Najafabadi[4], D. Walz[1], V. Yakimenko[1] & G. Yocky[1]



LWFA/PWFA

- ❖ Plasma acceleration R&D:
  - Many GeV/m !
  - Laser driven (LWFA)
  - Particle driven (PWFA)
  - Significant progress:
    - Positron
    - Multistage

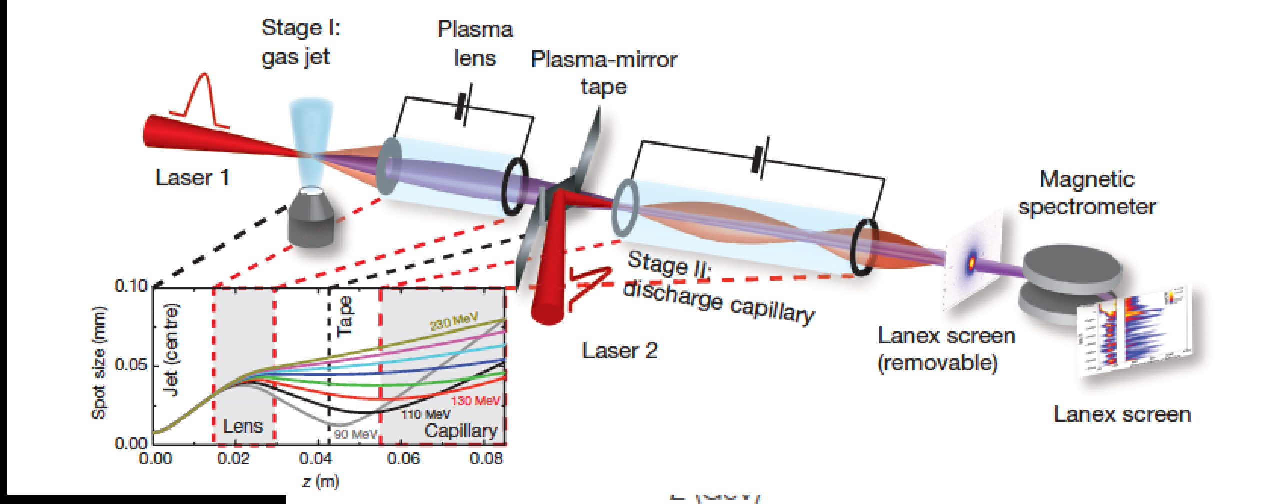


LETTER

Nature 530, 190–193 (11 February 2016)
doi:10.1038/nature16525

Multistage coupling of independent laser-plasma accelerators

S. Steinke[1], J. van Tilborg[1], C. Benedetti[1], C. G. R. Geddes[1], C. B. Schroeder[1], J. Daniels[1,3], K. K. Swanson[1,2], A. J. Gonsalves[1], K. Nakamura[1], N. H. Matlis[1], B. H. Shaw[1,2], E. Esarey[1] & W. P. Leemans[1,2]



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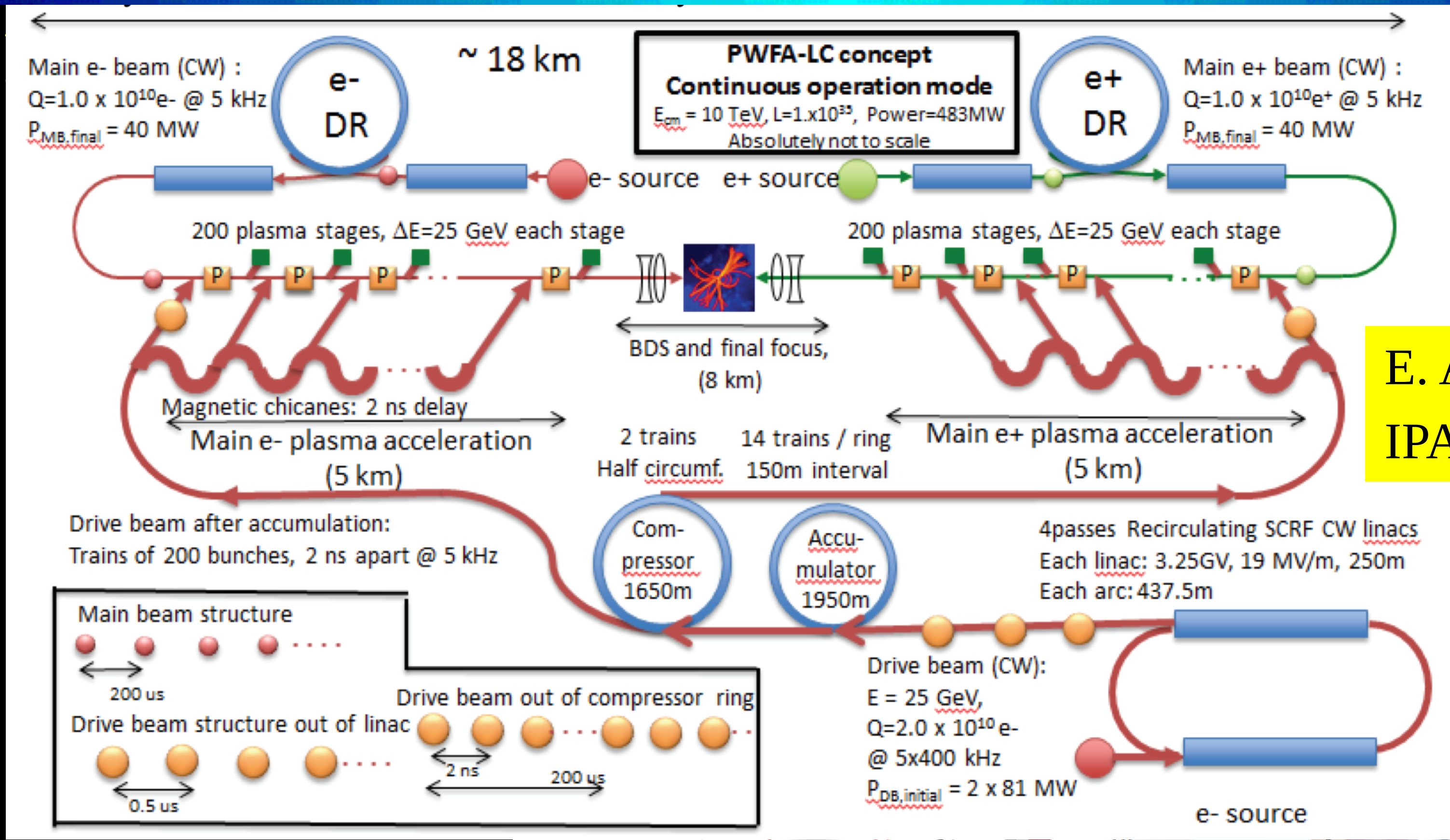
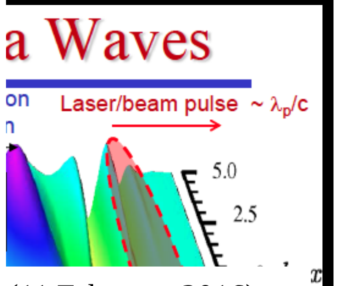


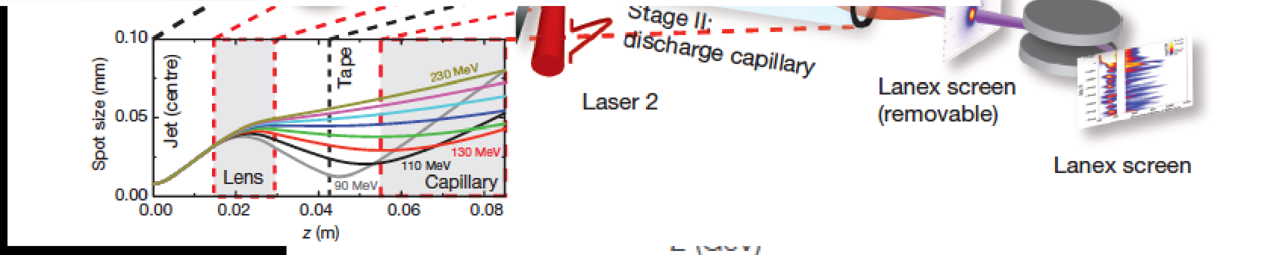


(11 February 2016)

E. Adli et al., IPAC 2014

Swanson[1,2], A. J. Gonsalves[1],

- Linear colliders
  - > 10 TeV



Muon colliders

- Circular μ+μ– collider
  - 125 GeV → 10 TeV
  - No beamstrahlung
  - Low power
- Two approaches:

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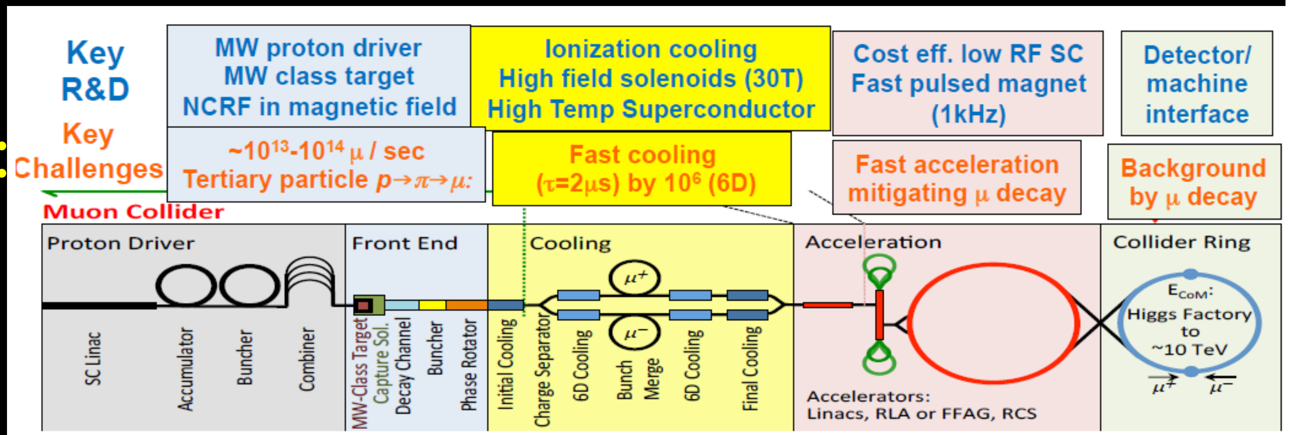

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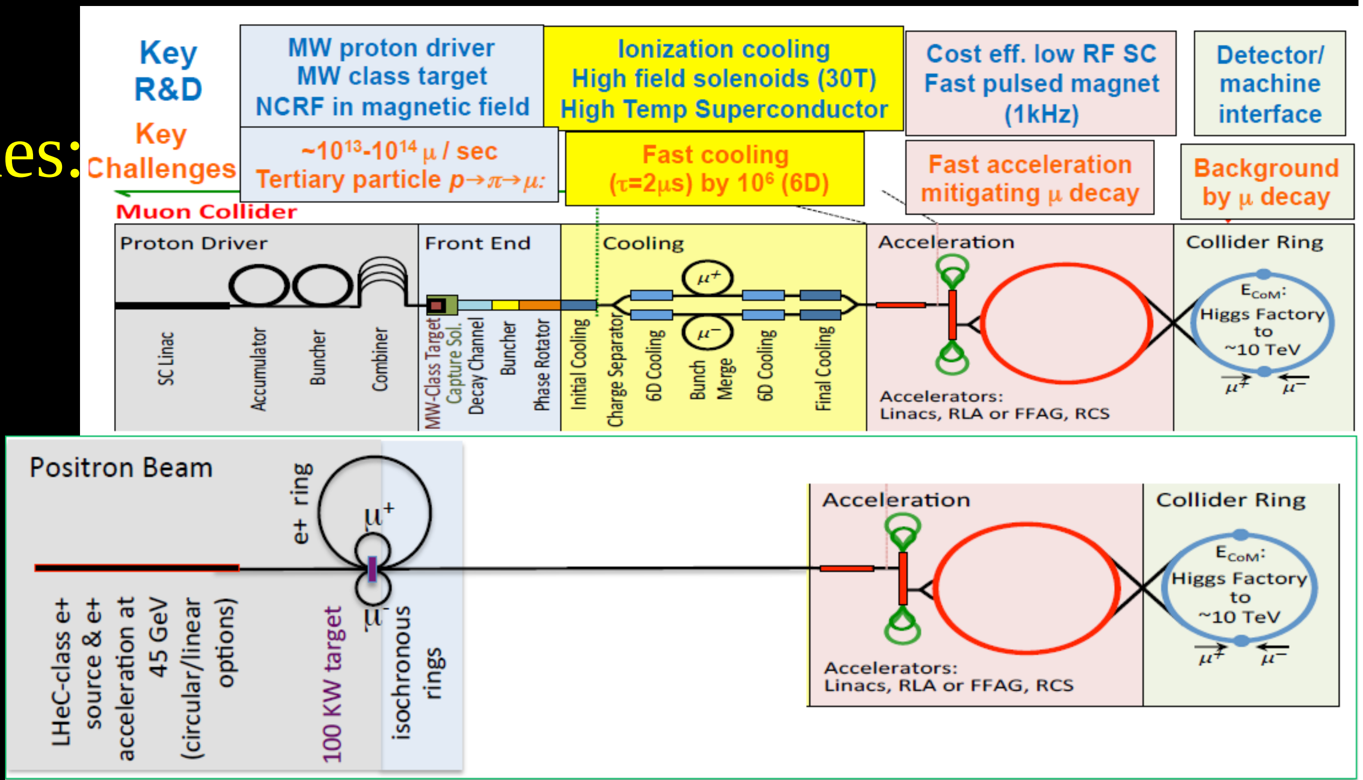

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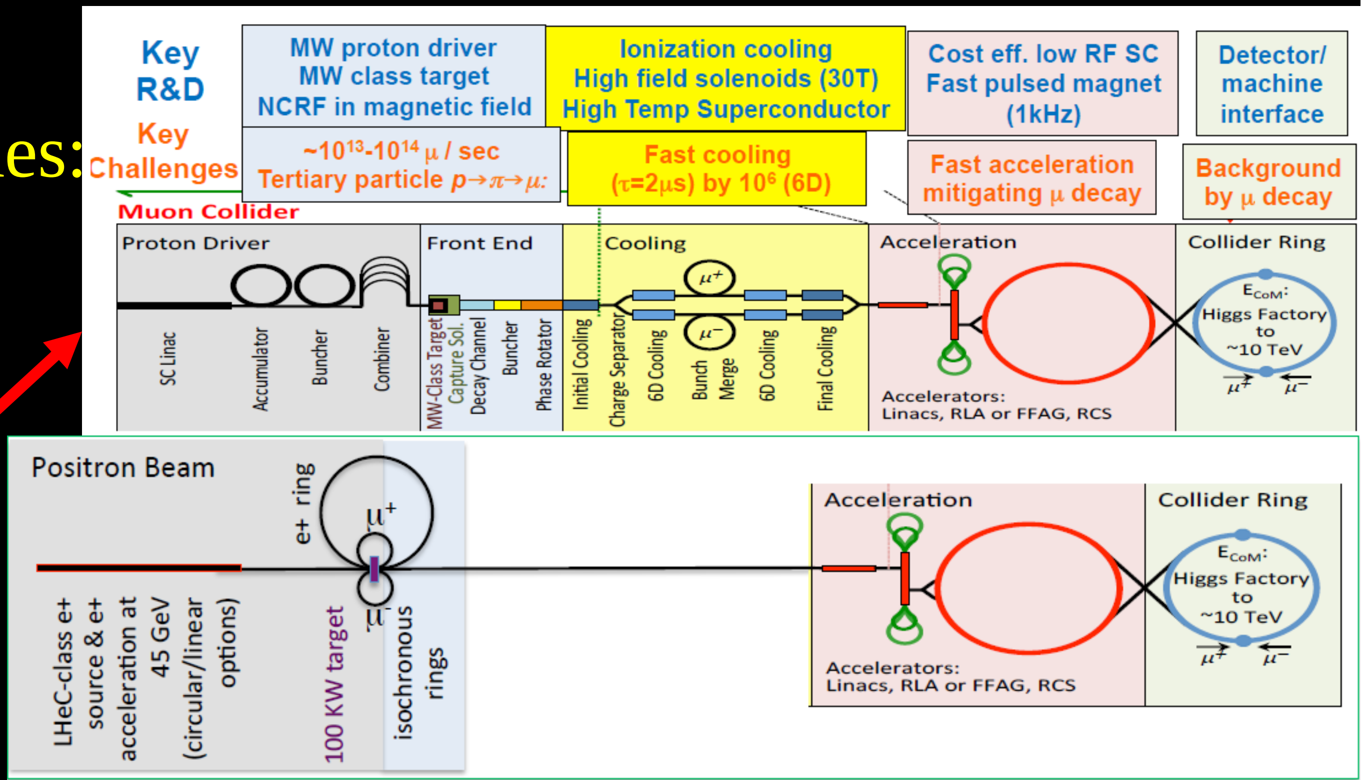

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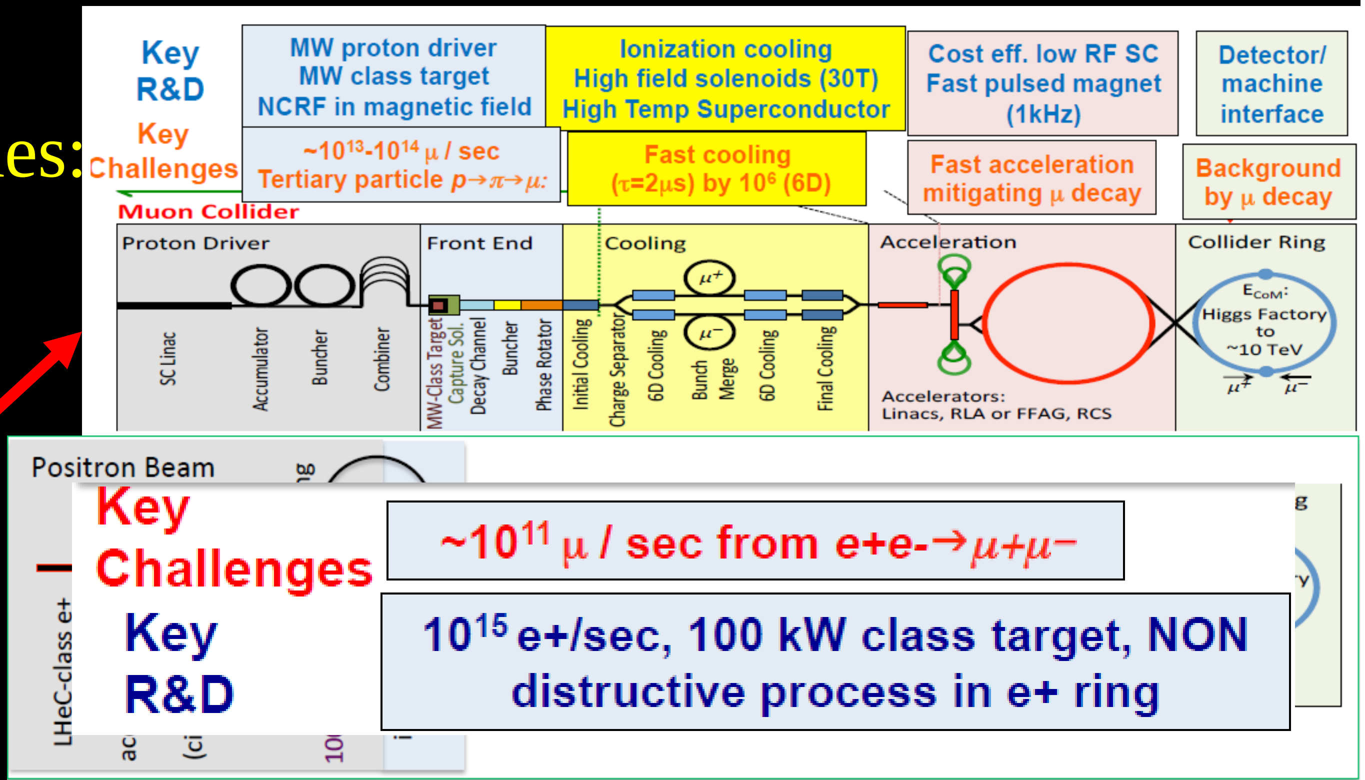

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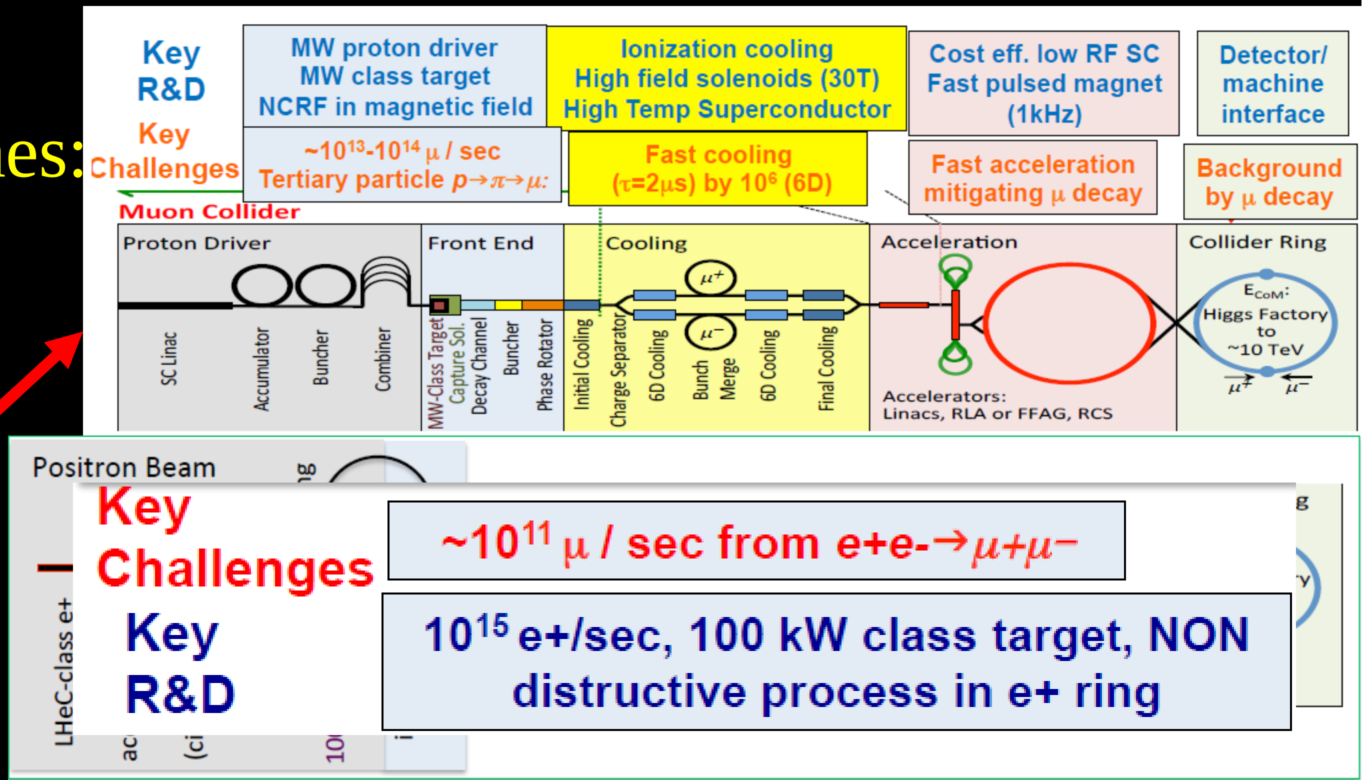
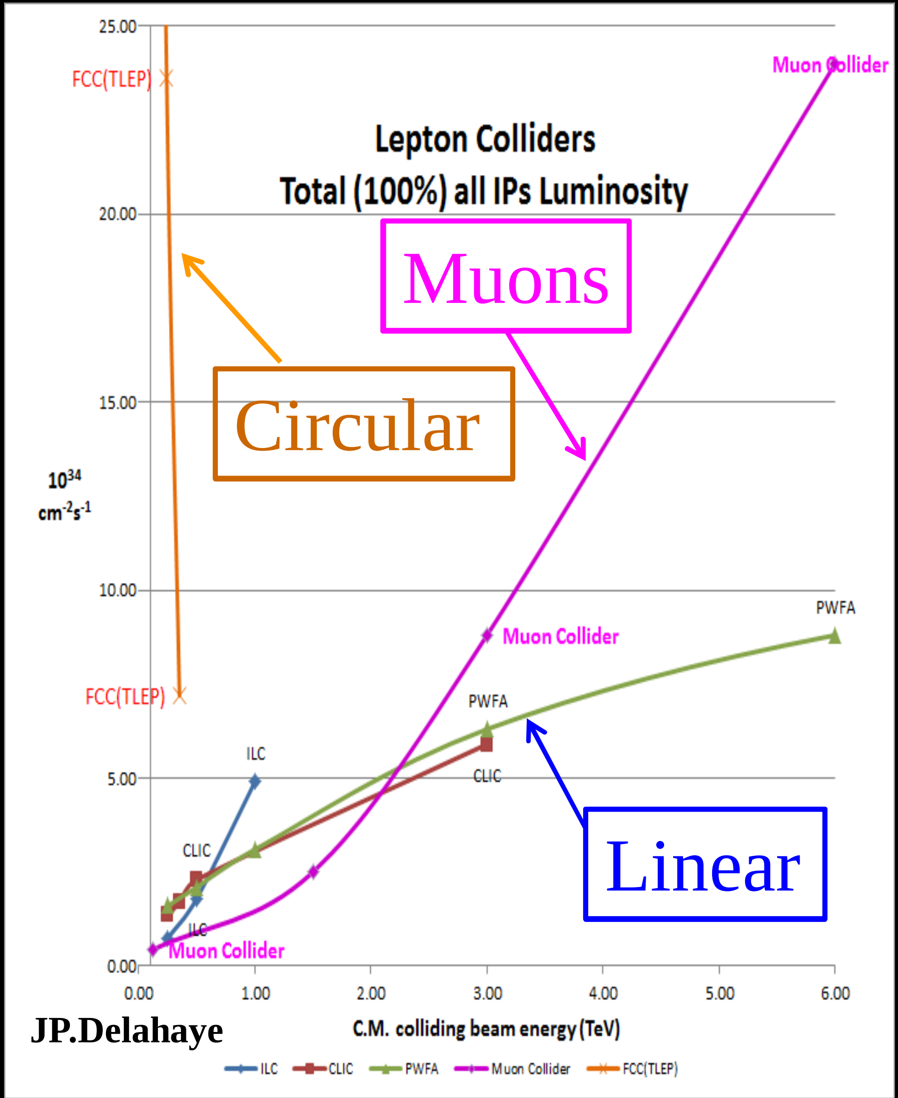


Scaling lepton machines to high energy



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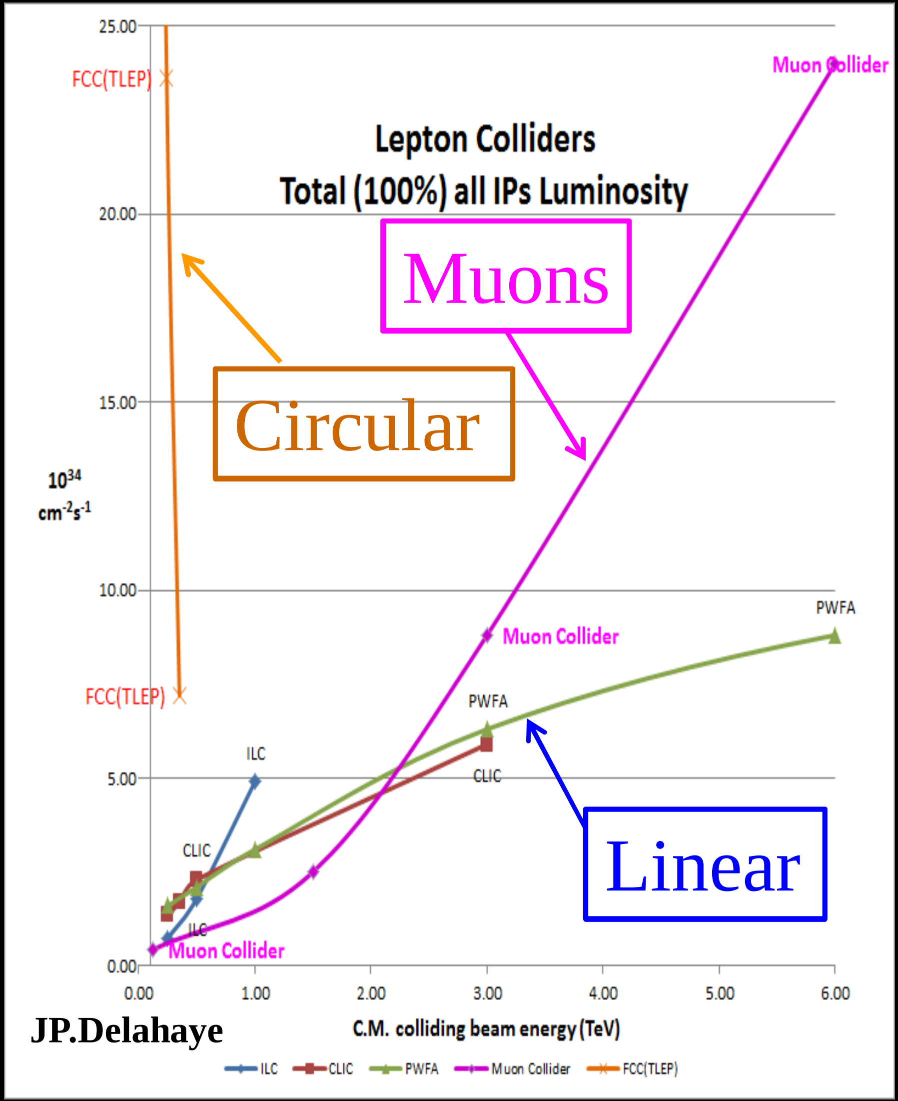

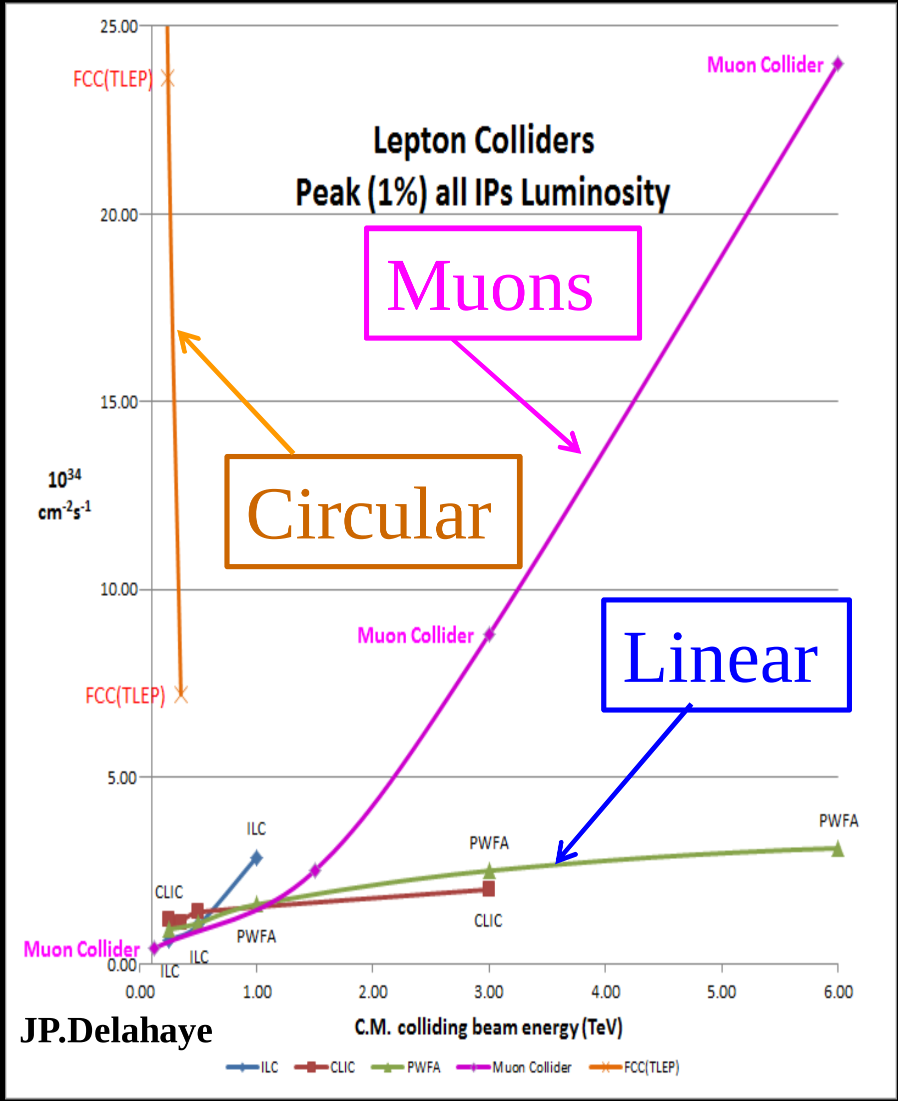

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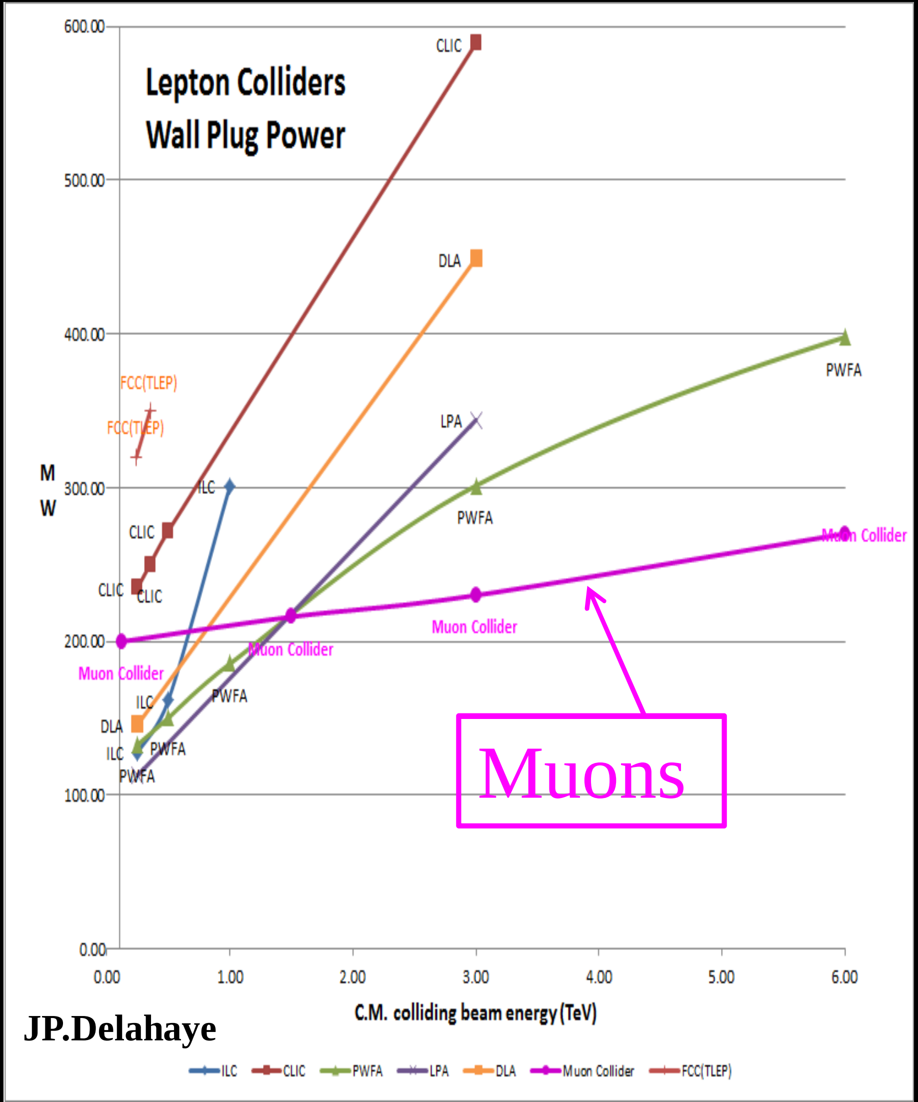

- Muon colliders:
  - Most convenient option above 1.5 TeV

Options

- How long can you stretch HL-LHC?
  - Then FCC-ee or hh?
    - Magnets/money
    - Time gap?
      - Extreme flavor as filler?
  - Backup
    - HE and/or LHeC?
    - HE → Several year gap in running experiments

- What could start construction in early ’20s?
  - ILC/CepC → Could be operational by early ’30s
  - Could complement each other Lumi: CepC/Energy: ILC

Decision times

- ILC:
  - Japan MEXT review completed (2015)
  - Governament negotiations for 2-3 years
- FCC:
  - CDR by 2018 – to be discussed at the next European strategy update (2019-2020)
- CepC:
  - Pre-CDR done (2015)
  - Machine CDR by end of 2016
  - Detector CDR by end of 2017
  - Substantial R&D funds requested ... ?

Conclusions (1)

- State of HEP is complex
  - Many new results do not yet indicate a clear way
  - However a straightforward path appears

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- Given enough time many other options become feasible
  - 100 TeV pp, 10 TeV ee or μμ colliders

Conclusions (2)

- Invest in R&D for new accelerator related technologies
  - So many exciting developments!

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- Continue to think about these issues to give our contributions to the upcoming European strategy
- A useful starting point from the Italian HEP community

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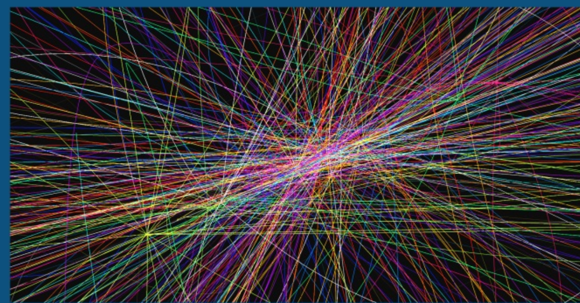
Laboratori Nazionali di Frascati
FRASCATI PHYSICS SERIES

INFN Commissione Scientifica Nazionale 1 (CSN1)



What Next: White Paper of CSN1

Proposal for a long term strategy for accelerator based experiments

Frascati Phys. Ser. 60 (2015) pp. 1-291
ISBN 978-88-864-0999-5

Editors
F. Bedeschi, R. Tenchini, J. Walsh

Conclusions (3)

- Several detector R&D activities started recently on FCC/CepC (ILC may re-start)
  - Very large synergy (also with HL-LHC and other present or past Italian activities)

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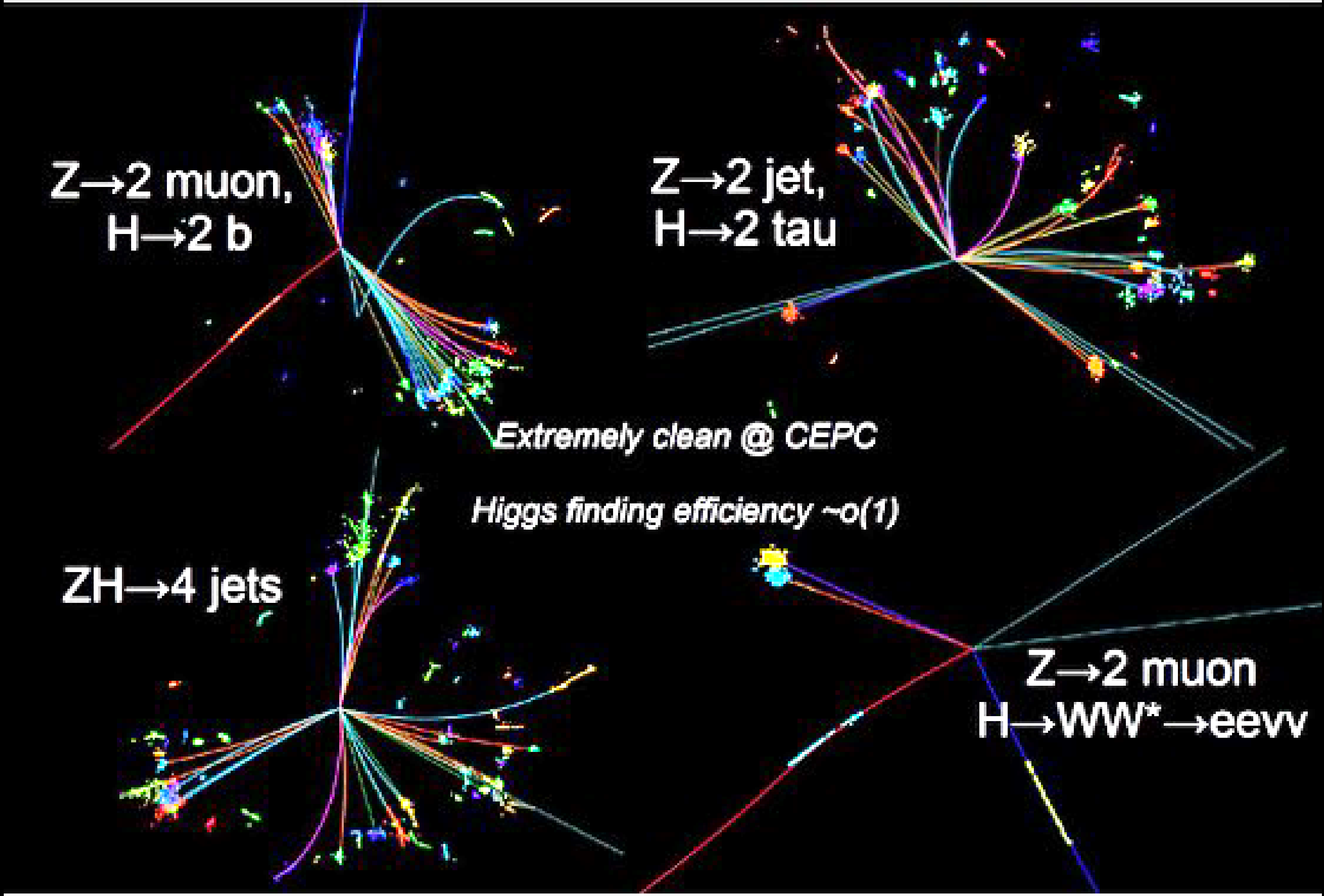
- Italian community?

ADDITIONAL SLIDES

ZH in e+e- simulations



Muon collider on Higgs energy

- S/N not optimal
  - $\sigma_H \sim$ 5-15 pb
  - $Z+Z\gamma \sim$ 300 pb