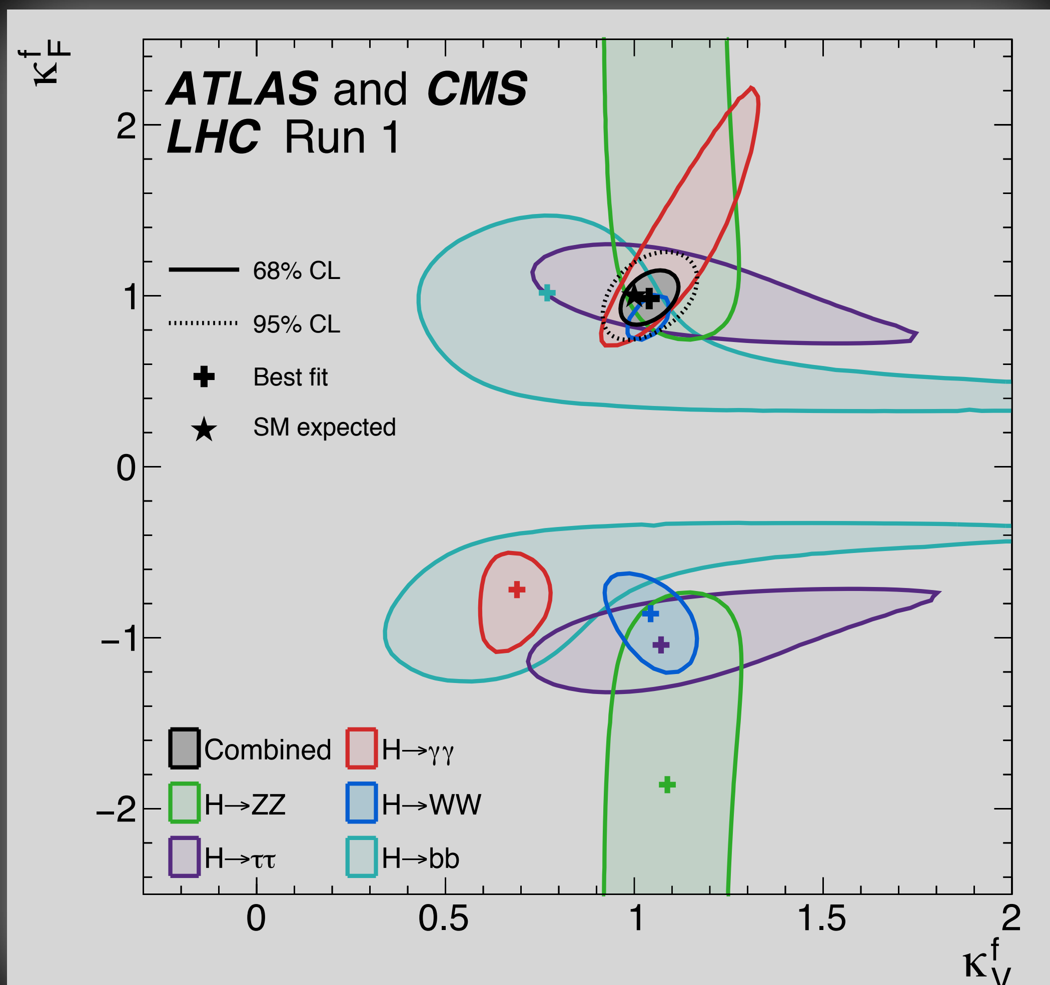
Future Circular Collider Studies

B. Di Micco
Università degli Studi di Roma Tre & I.N.F.N.
for RDFA WG1

Particle physics: where do we stand?
(understanding the present to build up the future)

k_V coupling to vectors, k_F coupling to fermions



$$
\begin{aligned}
\mathcal{L} = \\
&-\frac{1}{4g'^4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^a_{\mu\nu}W^{\mu\nu a} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{\mu\nu a} \\
&+\bar{Q}_i i \not{D} Q_i + \bar{u}_i i \not{D} u_i + \bar{d}_i i \not{D} d_i + \bar{L}_i i \not{D} L_i + \bar{\ell}_i i \not{D} \ell_i \\
&+\left(Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i \ell_j H + c.c. \right) \\
&-\lambda (H^\dagger H)^2 + \lambda v^2 H^\dagger H - (D^\mu H)^\dagger D_\mu H
\end{aligned}
$$

$$
-(D^\mu H)^\dagger D_\mu H \rightarrow -(\partial^\mu H)^\dagger \partial_\mu H - 2\frac{M_W^2}{v}W^{+\mu}W^-_\mu H - \frac{M_Z^2}{v}Z^\mu Z_\mu H + \ldots
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h → γγ, WW, ZZ, ττ observed
h → tt (observed indirectly)
h → bb :-(

h → μμ HL-LHC   h → hh HL-LHC ???

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h → ee (:-) :-) :-)) h → uu,dd,ss :o) :oO) :oOO)

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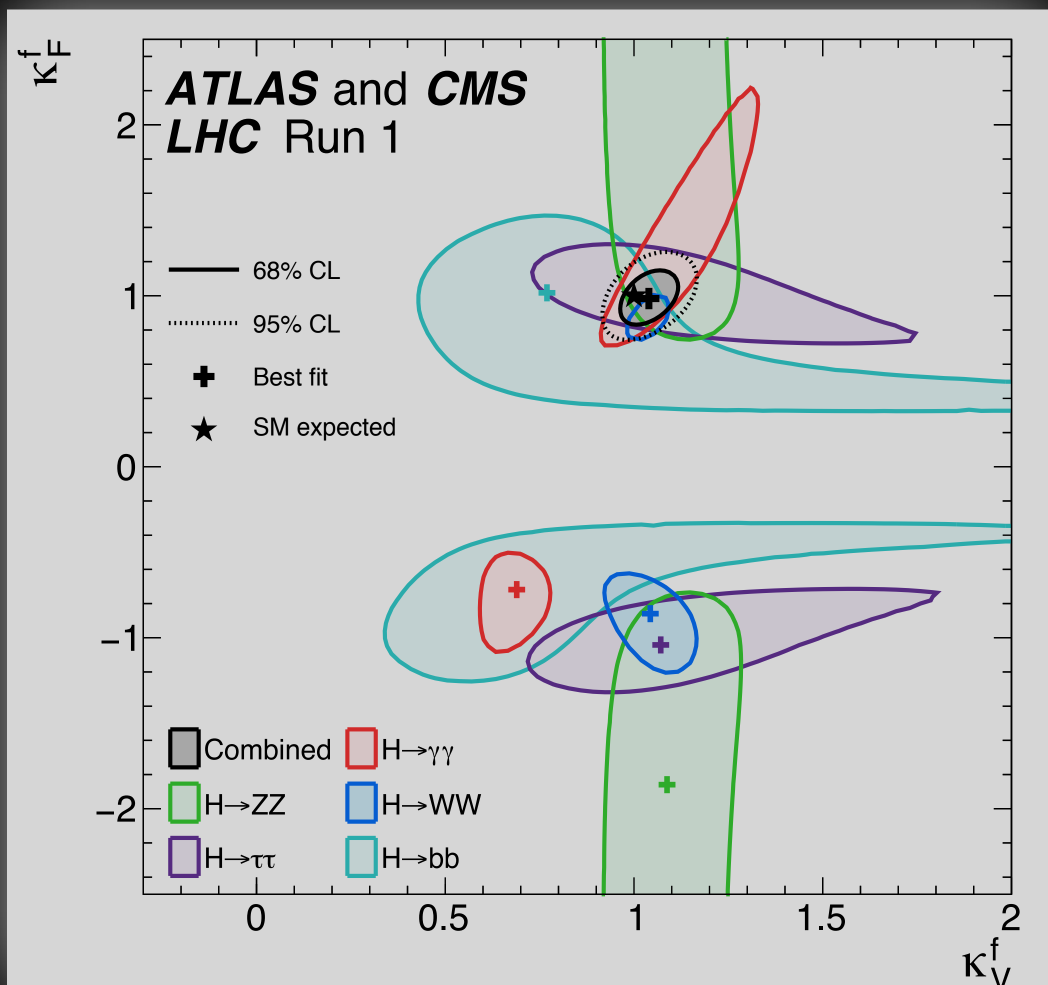

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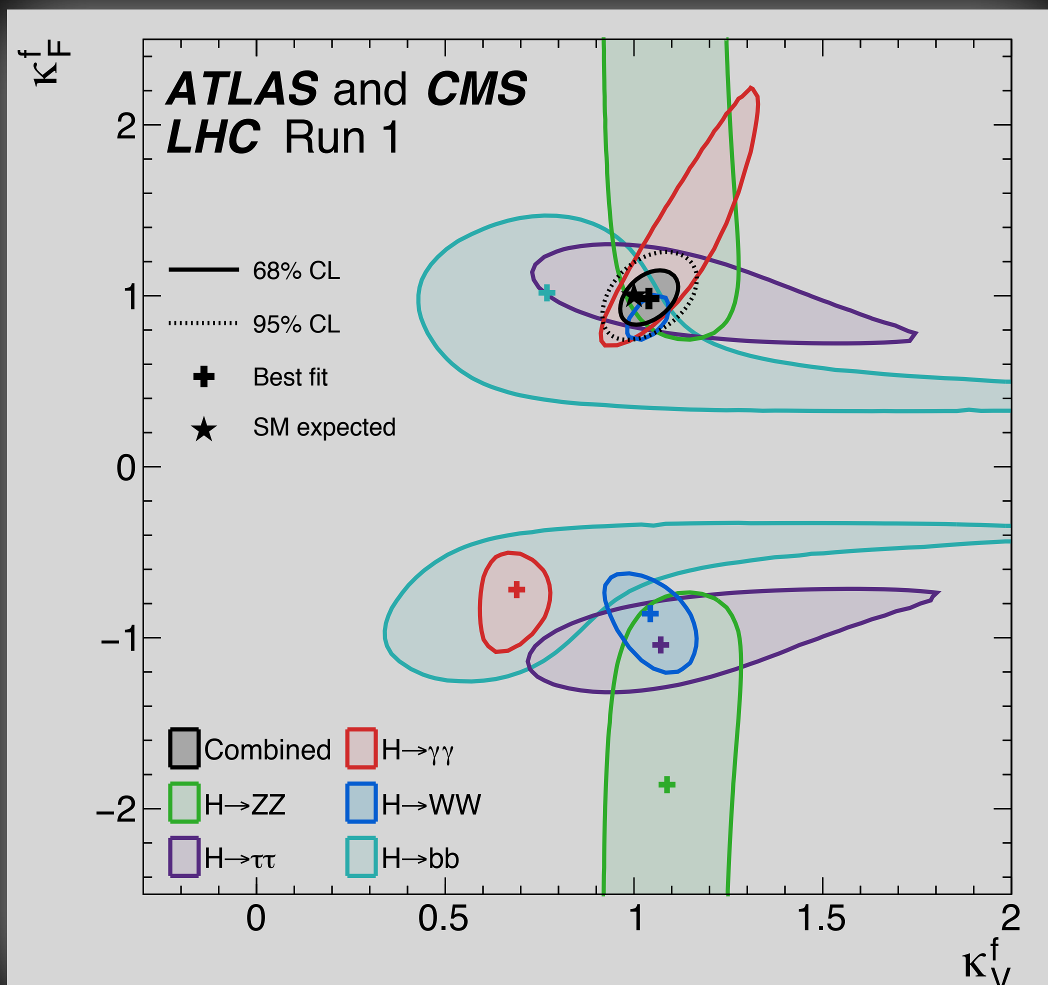

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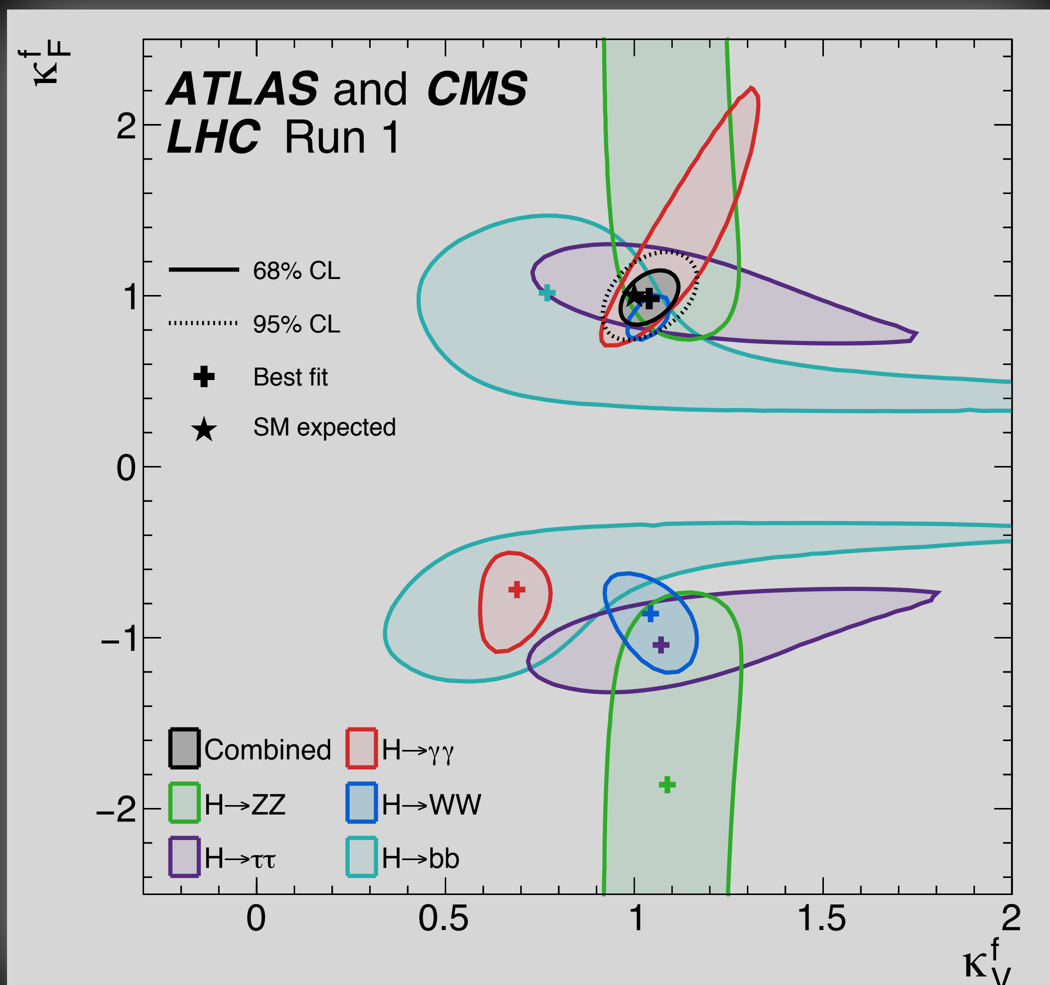

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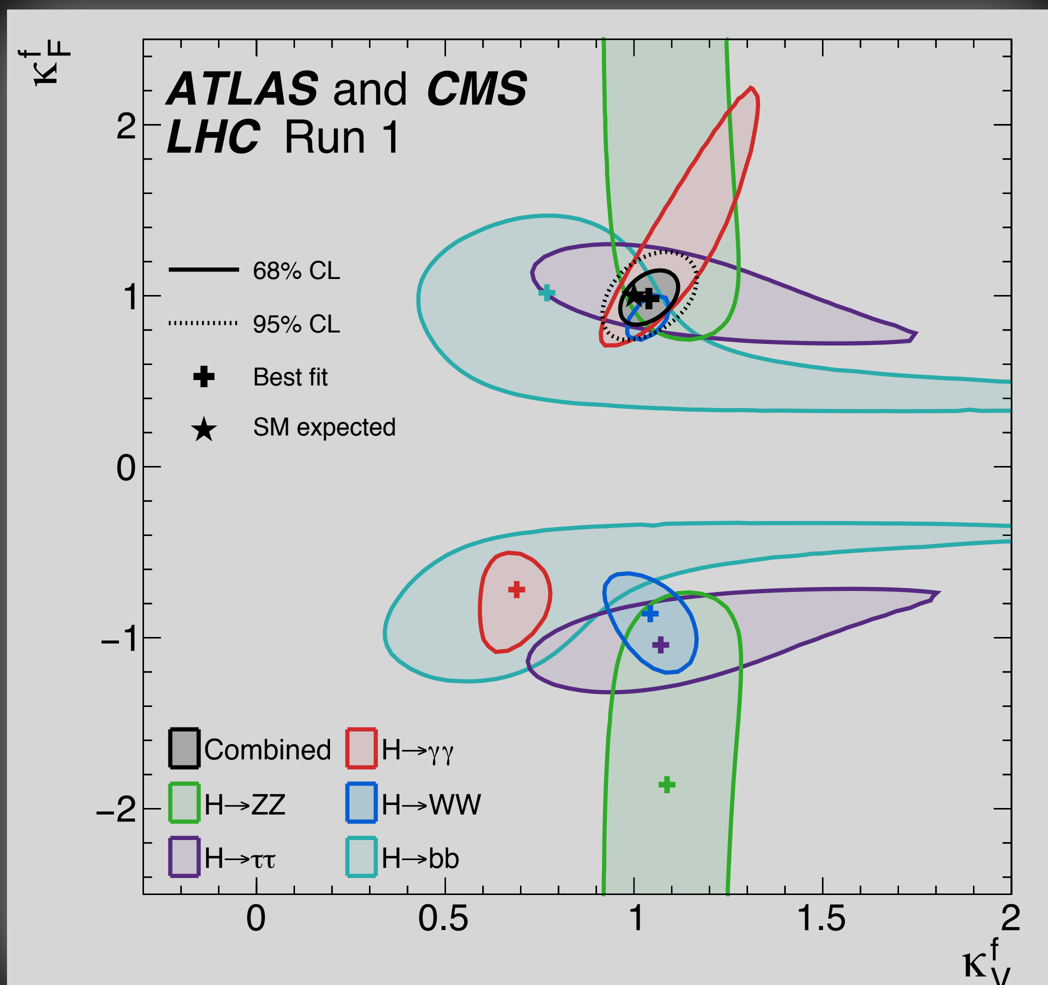

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Not much left to test, but still:

- is the Higgs boson responsible for light lepton masses?
- is the Higgs boson the only field having a potential term?
- Where is gravity?

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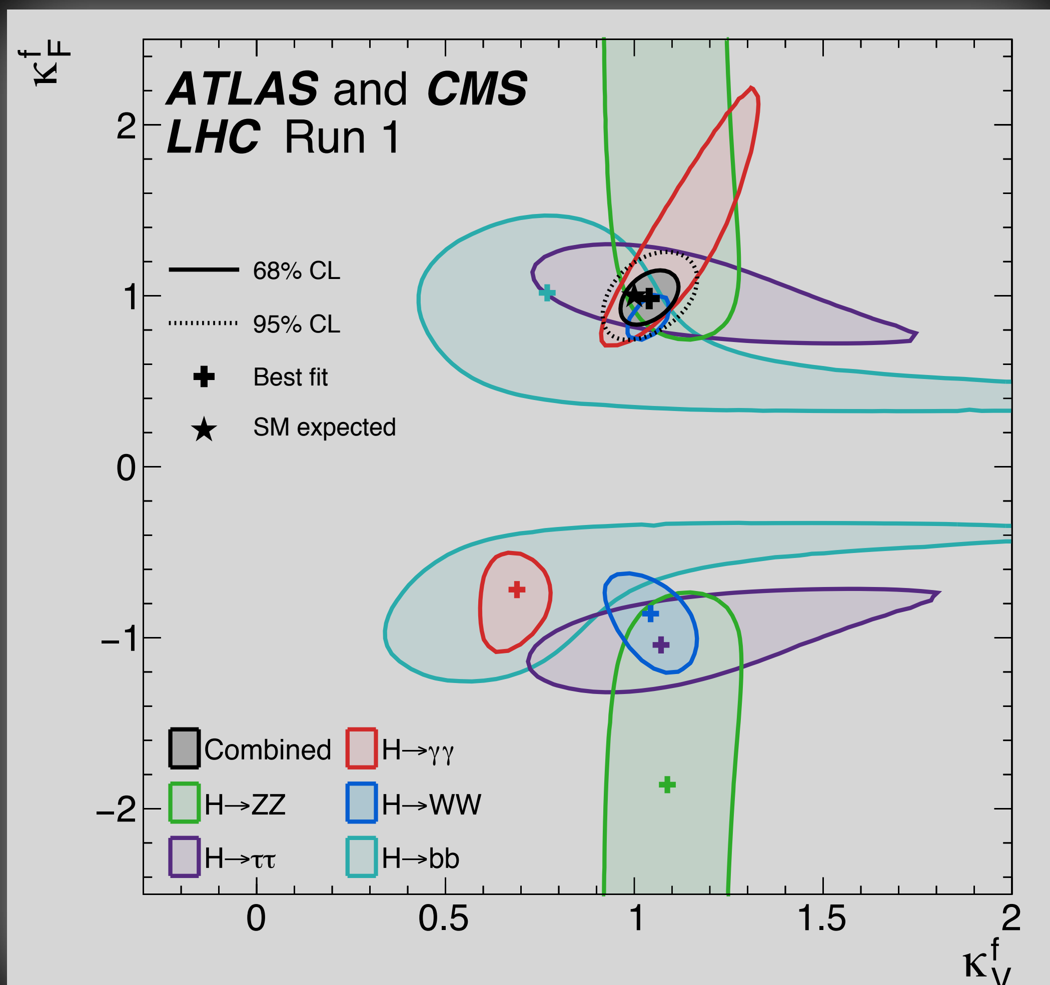

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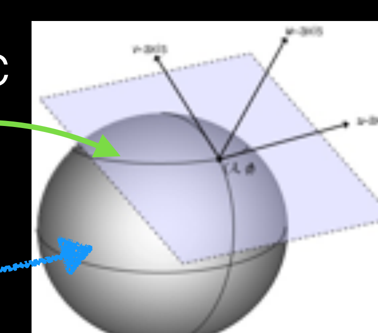
Here is it!! Einstein-Hilbert action

$$S = \int \left[\frac{1}{2}M_{\rm pl}^2 R + \mathcal{L}\right] d^4x\sqrt{-g}$$

metric

curvature



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Higgs potential, inflation and cosmological constant

$$S = \int \left[\frac{1}{2} M_{\rm pl}^2 R + \mathcal{L} \right] d^4x \sqrt{-g} = \int \left[\frac{1}{2} M_{\rm pl}^2 R - \frac{1}{2} \partial_\mu h \partial^\mu h + V(h) + \dots \right] d^4x \sqrt{-g}$$

Inflation model

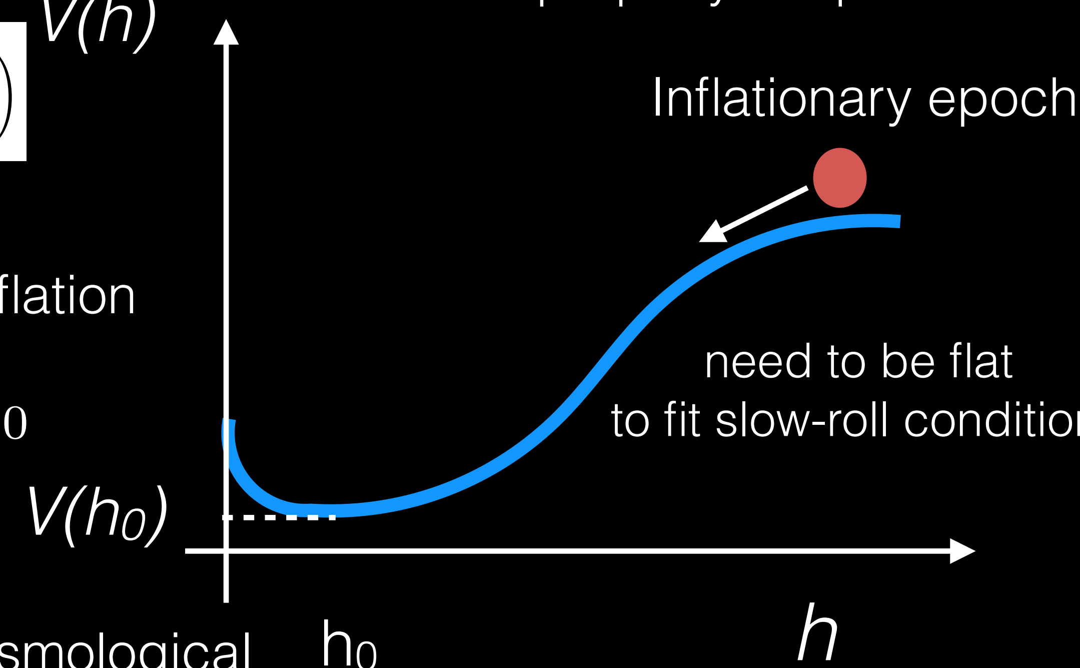
- need a scalar field (h is a scalar field)
- need a well shaped potential

$$V(\phi) >> \frac{1}{2}\dot{\phi}^2 \longrightarrow H^2 = \frac{8\pi G}{3} V(\phi) \simeq const. \longrightarrow a(t) \simeq e^{Ht} \quad \left(H(t) = \frac{\dot{a}}{a} \right)$$

slow-roll condition

universe radius, exponentially expanding during inflation

The Higgs potential could have such role if properly shaped



cosmological constant

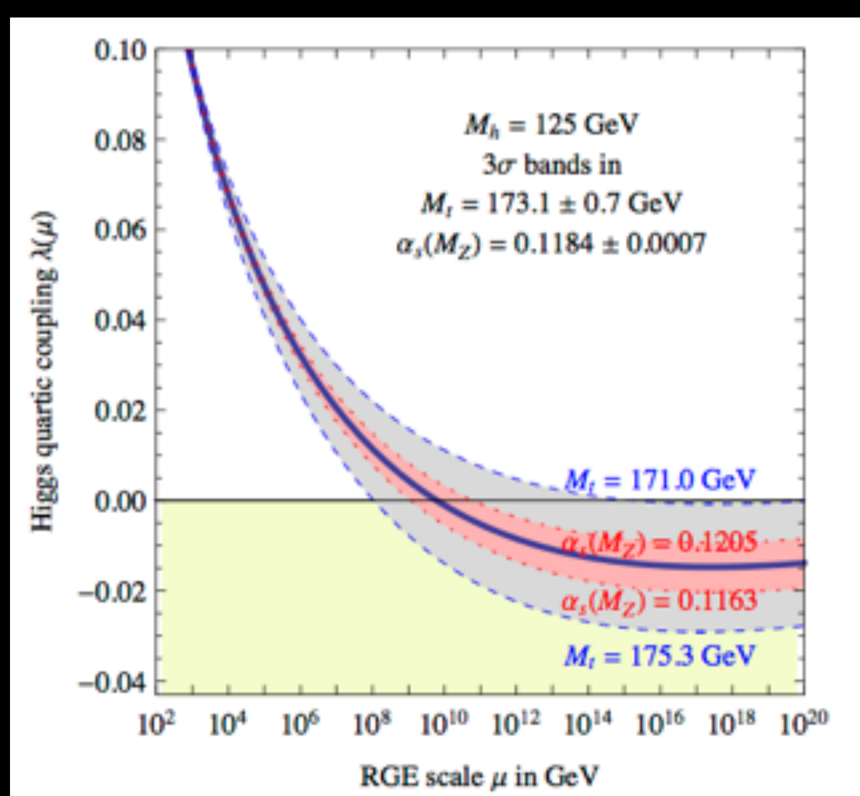
$h_0 = \langle 0 | \, h \, | 0 \rangle$ Higgs VEV

In order to make this to work $V(h) \sim \lambda h^4 \ \lambda \sim 10^{-13} \quad h >> h_0$

λ determined by the Higgs boson mass ($\lambda_{mh} \sim 0.129$)

It runs with the energy scale fixed by the *h* value.

Intringuing, λ nearly vanishes for high h value with the present value of top and Higgs mass.



The value of the potential at its minimum sets the cosmological constant (i.e. the amount of dark energy)

$$\frac{\Lambda c^4}{8\pi G} = V(h_0)$$

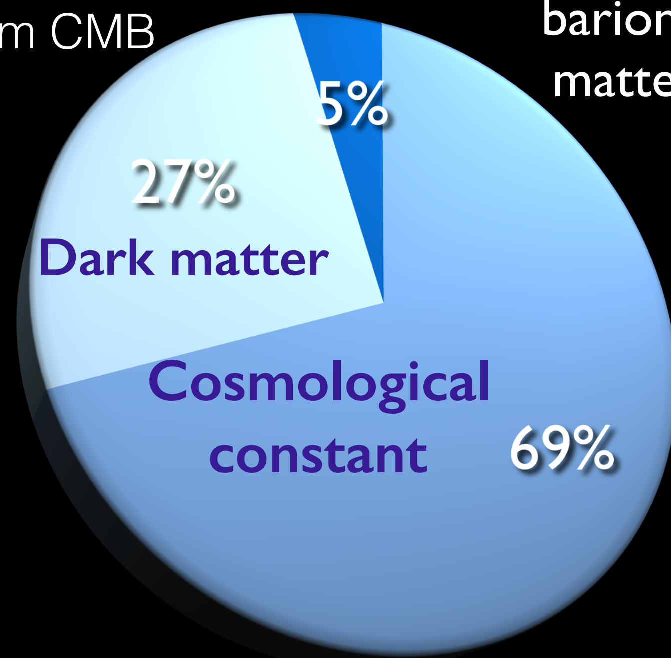
Understanding the Higgs potential is the last missing piece of the SM, and it could have fundamental cosmological implications.

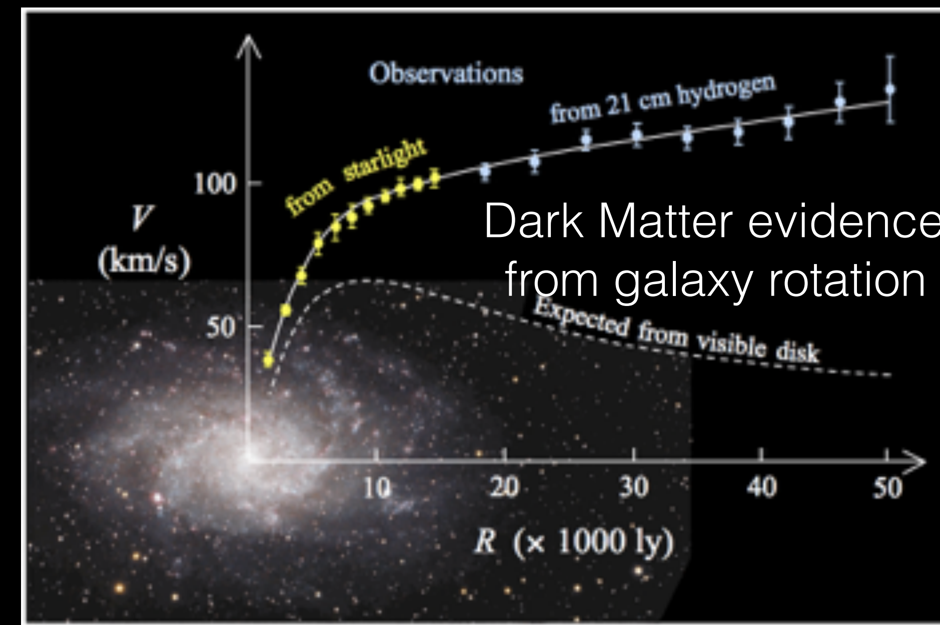
The Dark Matter

Universe energy content

Dark Matter evidence from CMB

barionic matter.

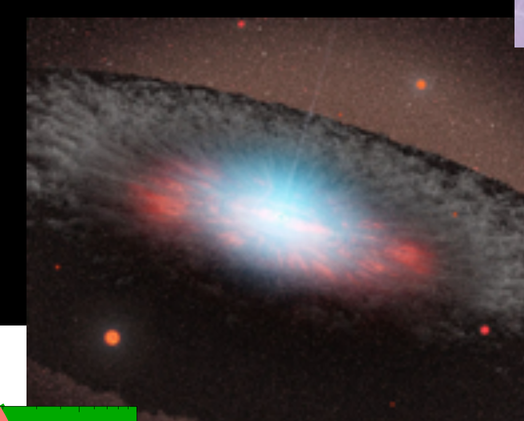




Possible explanations

- WIMP, Weak interacting Massive Particles nice explanation to motivate High Energy Physics but nothing forbids these particles to be at Plank mass and have negligible interaction with matter (look at it forever ??)

- Primordial black holes (black hole formed at the beginning of universe formation), renewed interest after gravitational wave observation from the collapse of two 30 solar mass black holes

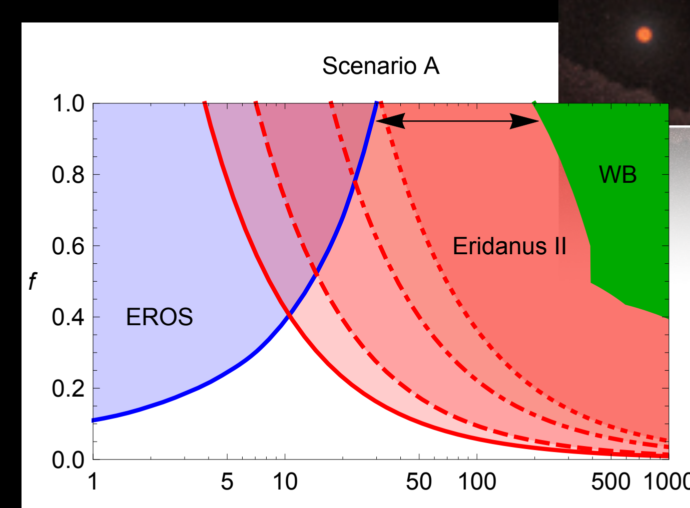


super-massive black hole, at the center of each galaxy are strongly thought to be of primordial origin (no other mechanism able to build up so much massive black hole)

Systematic PBH study arXiv: 1607.06077

1) black hole of ~ 30 M_{solar} and sublunar mass black holes still not excluded but could be excluded in the near future;

2) Planck mass black hole allowed and impossible to exclude at the moment



How do we go beyond (HL-)LHC ?

The usual two ways

1) High intensity frontier (precision physics)
   Higgs, W and Z factories

   circular: FCC-ee, CepC
   linear: ILC, CLIC

2) High energy frontier physics

   as high as money, politic and technology allows
   FCC-pp, SppC

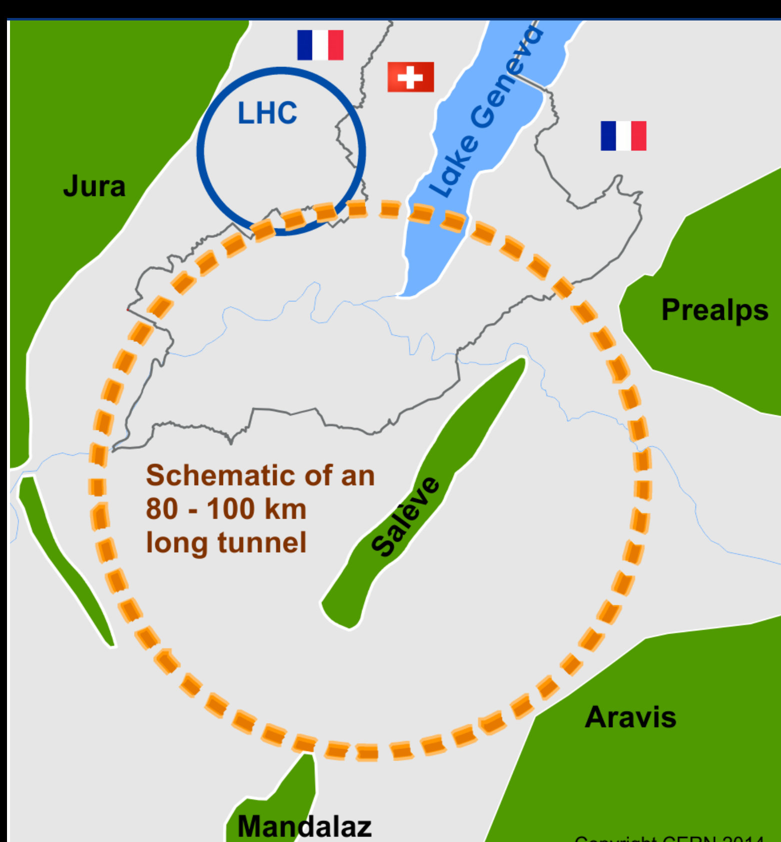
Where, what when to build

Chinese project

- original idea to build a 50 km e^+e^- collider;
- moving to a 100 km e^+e^- (CepC) followed by a 100 km pp collider (SppC)

- timeline:
  - CDR 2017; TDR 2022; operation: 2030

CERN project



- build a circular collider 100 km length under Geneve lake;

- main target: pp collisions at 100 TeV, use e^+e^- as a possibility to start constructing the tunnel and functionalities while waiting that magnet technology for pp becomes mature;

- 90 - 100 km fits well geological structure (going for a detailed 97.75 km version)

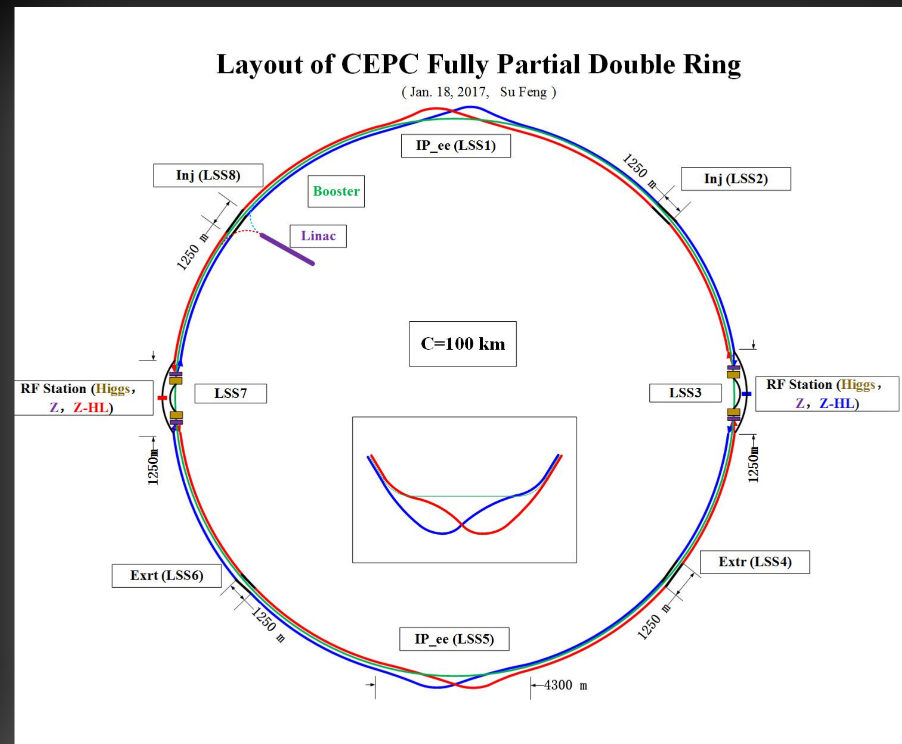
- timeline: prepare a full proposal for the end of 2019 for the European strategy update

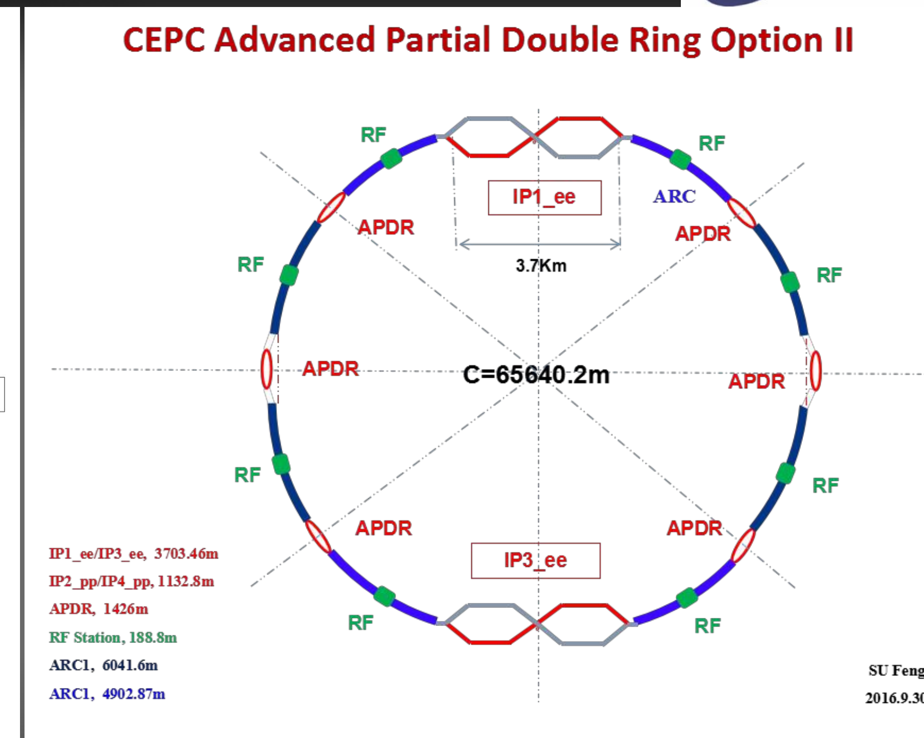
The e+e- colliders

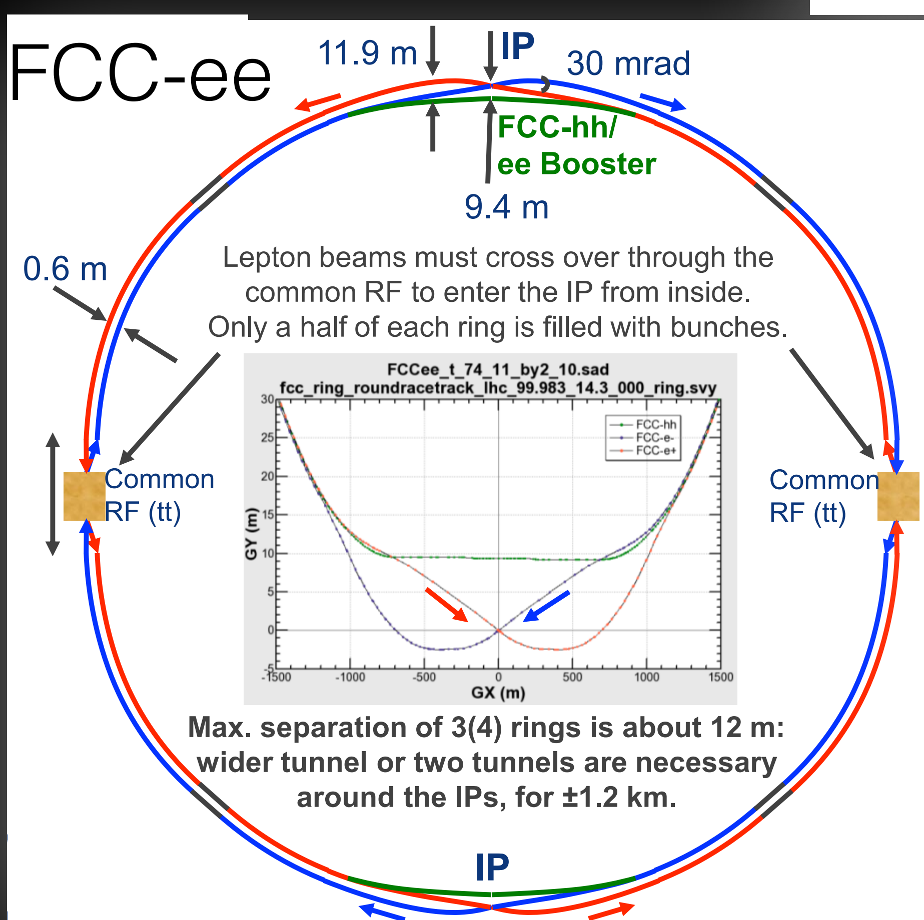
Two options under investigation:
Lumi target: 5×10^{34} cm^2/s

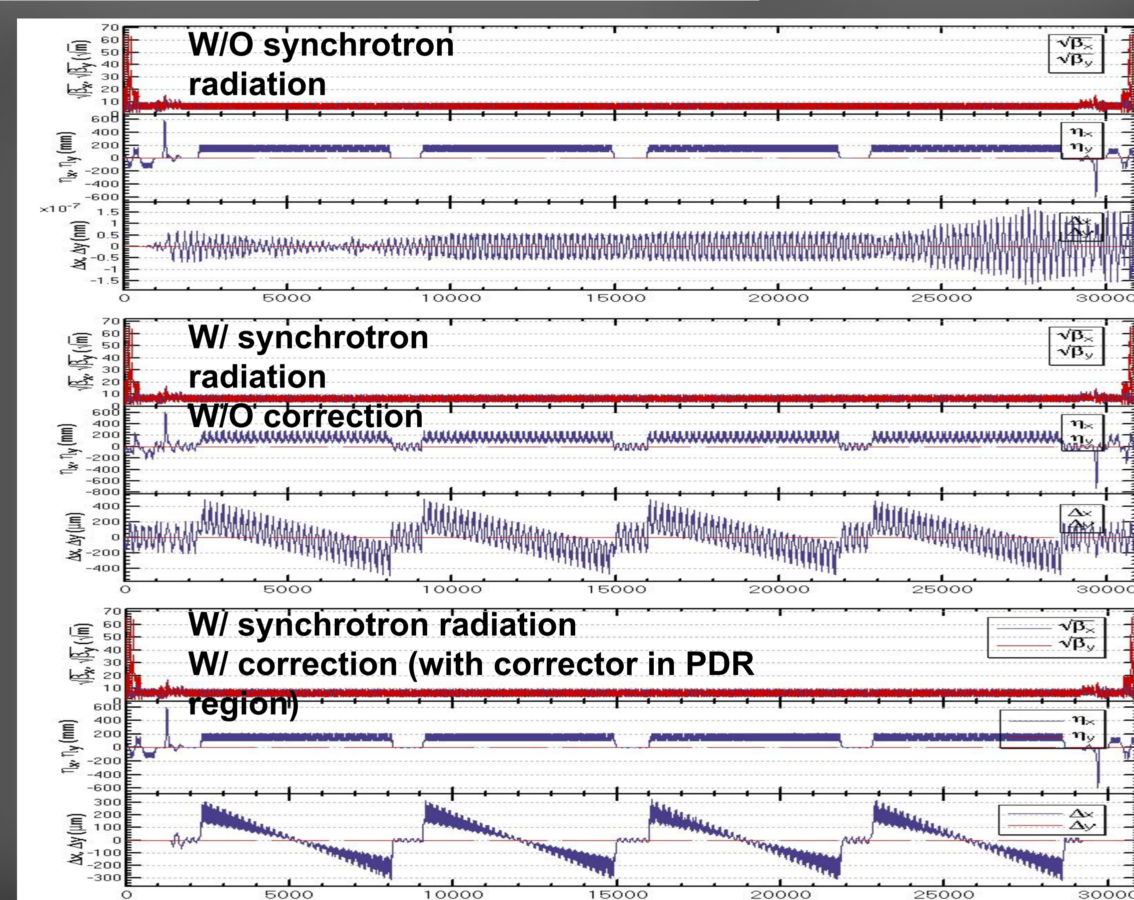
1) FPDR: 1 booster to accelerate electrons to the nominal energy, 1 accumulator to store the beams and increase luminosity. Merge at RF entrance to use just one cavity;

2) APDR: use one ring to accelerate both e^+ and e^-, separate at IP to reduce beam-beam interactions









APDR suffers from sawtooth effect: orbit changes along the beam line due to synchrotron radiation

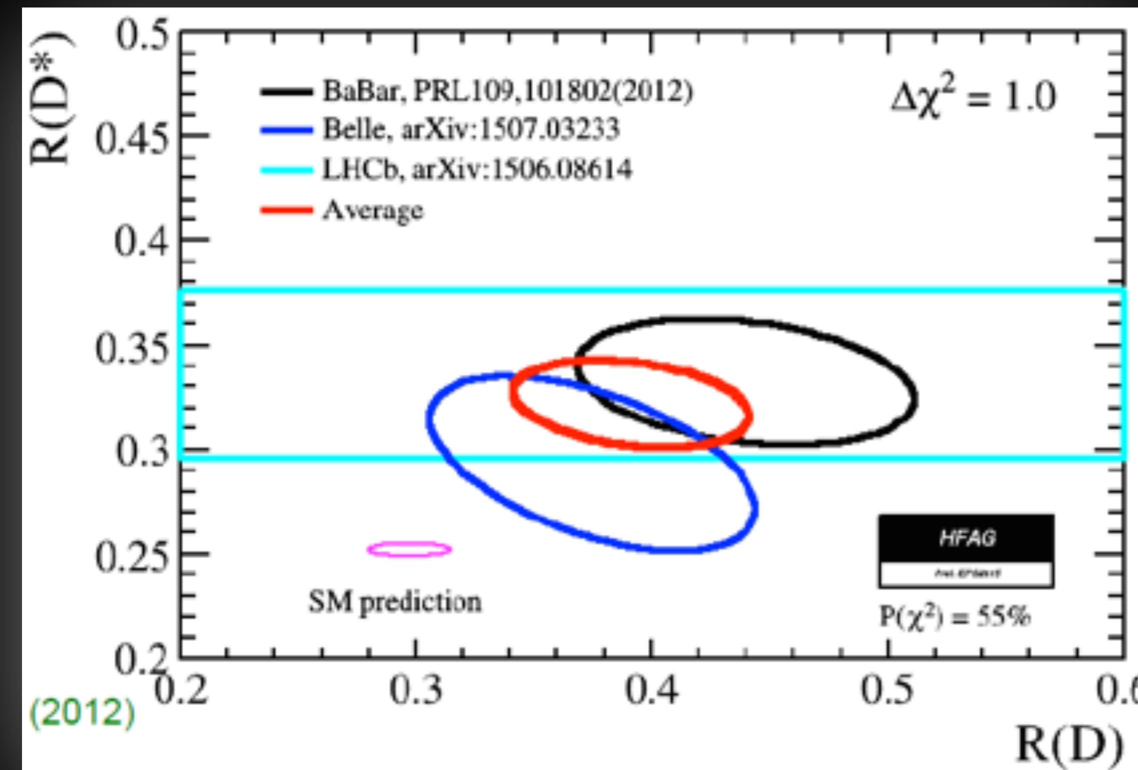
FPDR: sawtooth can be corrected by tamperng the magnets in the PDR region

In both 1) and 2) add a 3rd 100 km single ring to boost leptons up to the design energy

The high intensity way

Thanks to F. Bedeschi

- **Present SM deviation from flavor:**
  - LHCb ~3.5 σ :
    - $B_d \to K^{*0}\mu\mu$
    - $B_s \to \Phi\mu\mu$
  - R(D)
    - ~3.9 σ $R(D^{(*)}) = BR(\bar{B} \to D^{(*)}\tau\bar{\nu})/BR(\bar{B} \to D^{(*)}l\bar{\nu})$
  - $(g\text{-}2)_\mu$
    - > 3σ



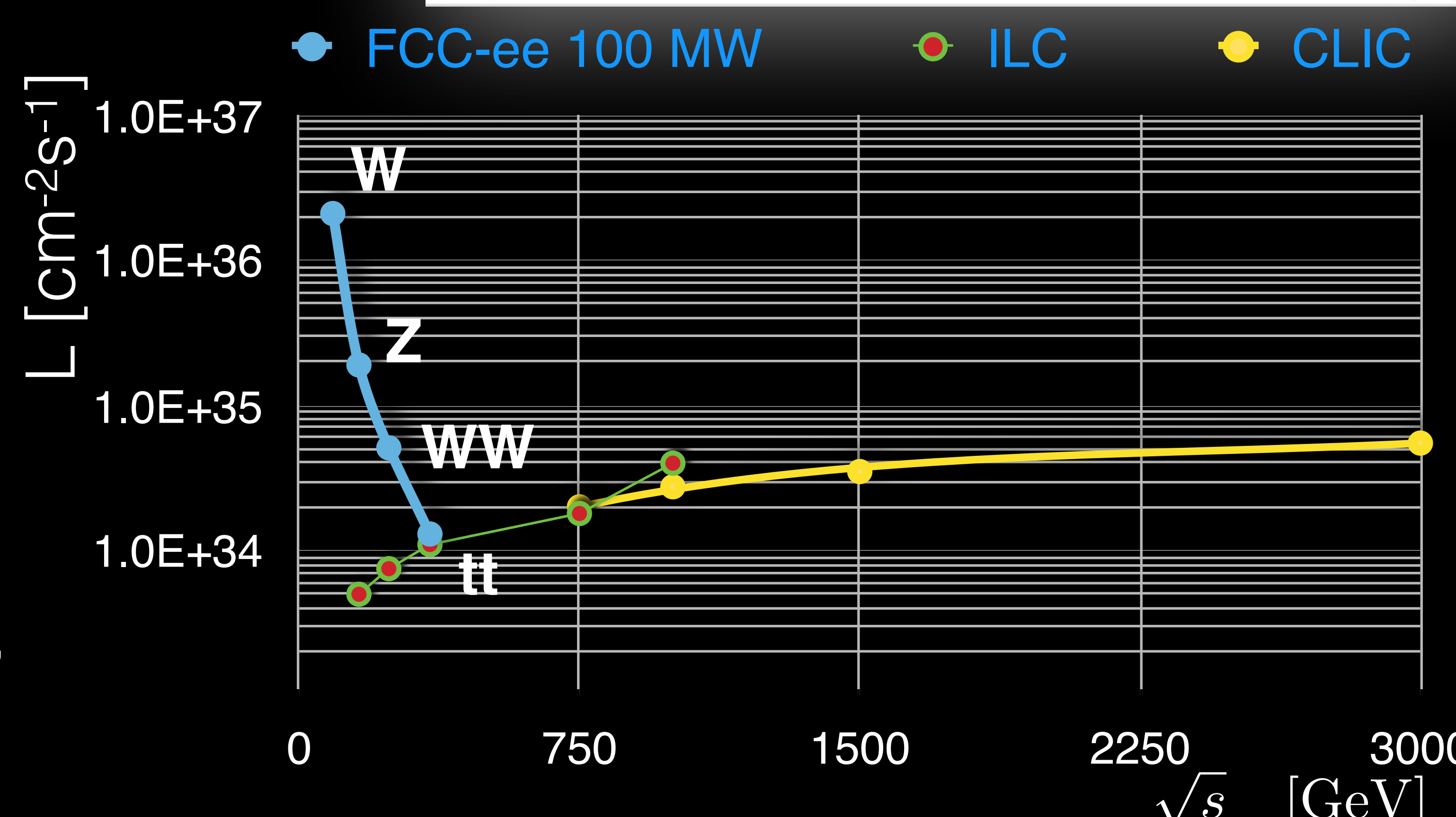
Could increase could decrease, what would we learn?

How this would impact our future choices?

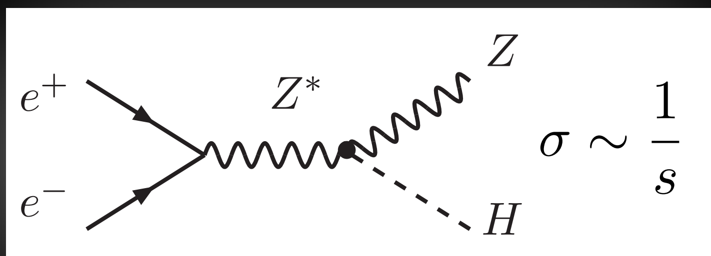
The future high intensity way

ILC/CLIC: Higgs factory, W^+W^- and tt(bar) threshold scan - energy 250 / 500 GeV, possible increase to 1 TeV

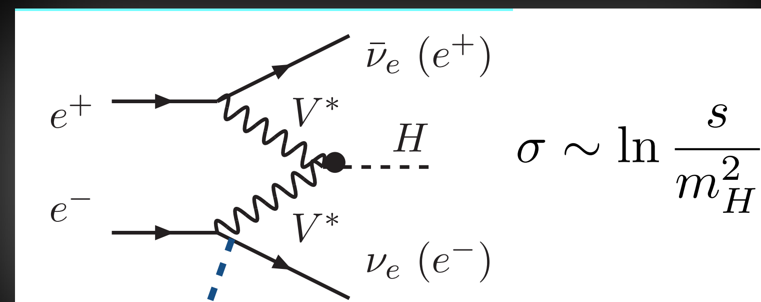
FCC-ee (CERN), CepC (China) 100 km circular collider W,Z, Higgs factory, W^+W^- , ttbar threshold scan



Measuring Higgs couplings at e^+e^-



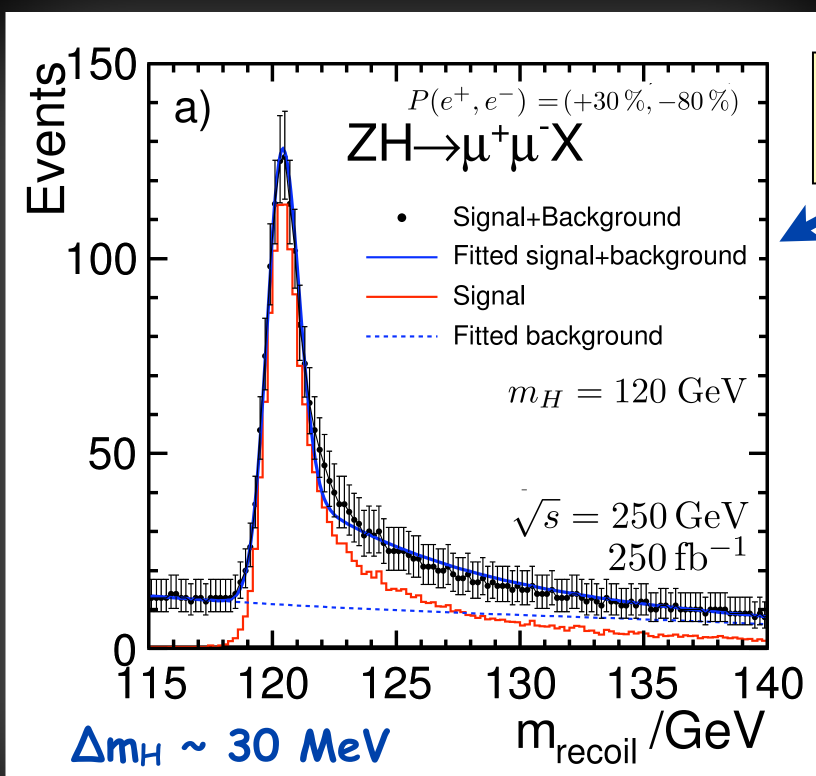
Higgs strahlung



VBF production

2 energy regimes:

threshold: 250 GeV (ZH)
high energy: VBF.



- reconstruct the Higgs mass from the recoiling muons;
- measure the invisible BR with high accuracy
- measure the Higgs width with high accuracy

old-CEPC

new-CEPC will be close to FCC-ee

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

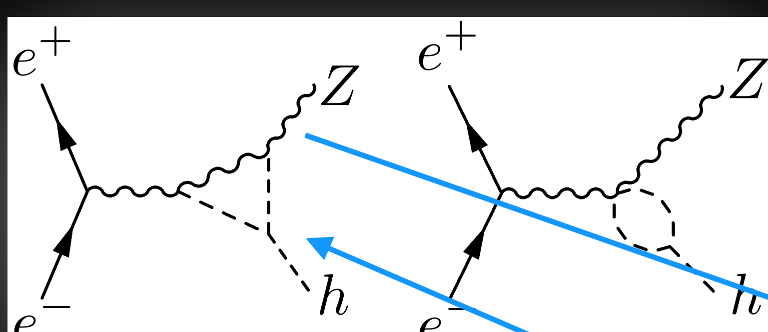
For ~10y operation. Lots of "!,*,?"
Every number comes with her own story.

What do we learn from precision?

- Composite Higgs $\frac{\Delta g_H}{g_H} \cong 6\% \left(\frac{1\ \text{TeV}}{f}\right)^2$ — $f \approx$ 246 GeV [vev, "natural value"]; $f \approx$ O(1 TeV) [LEP bounds, assuming no new physics in loops]
- Top partner $\frac{\Delta g_{h\_gg}}{g_{h\_gg}} \cong 3\% \left(\frac{1\ \text{TeV}}{M}\right)^2$ — M ≥ 0.7 TeV
- SUSY (tanβ≥5) $\frac{\Delta g_{h\_bb}}{g_{h\_bb}} \cong 1.6\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2$ — m_A lower bounds depend strongly on tanβ

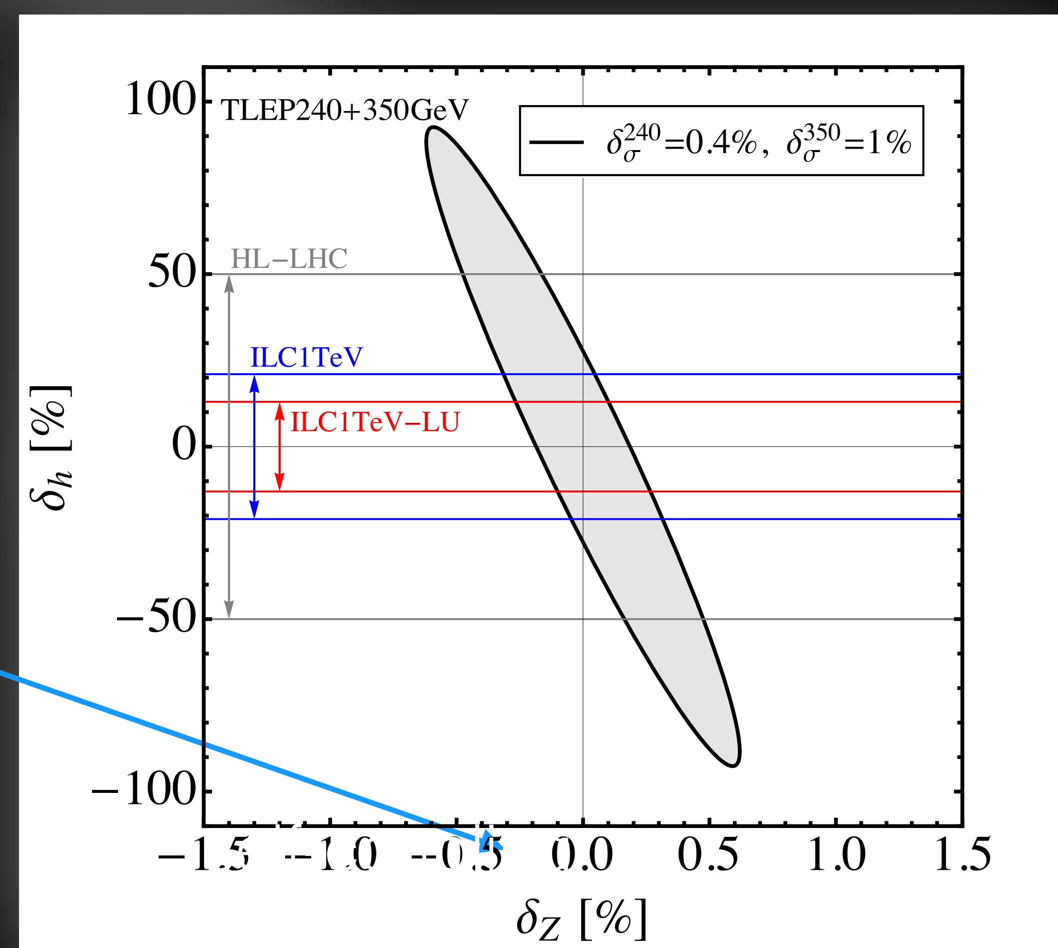
- New physics typically requires ~% precision.
- Per mill (not in the target of HL-LHC) in order to probe scales larger than the direct searches at 14 TeV LHC (going in the range 1- 10 TeV range in new particle mass)

Higgs self-coupling can be measured indirectly with the *Zh* cross section measurement (arXiv:1312:3322)



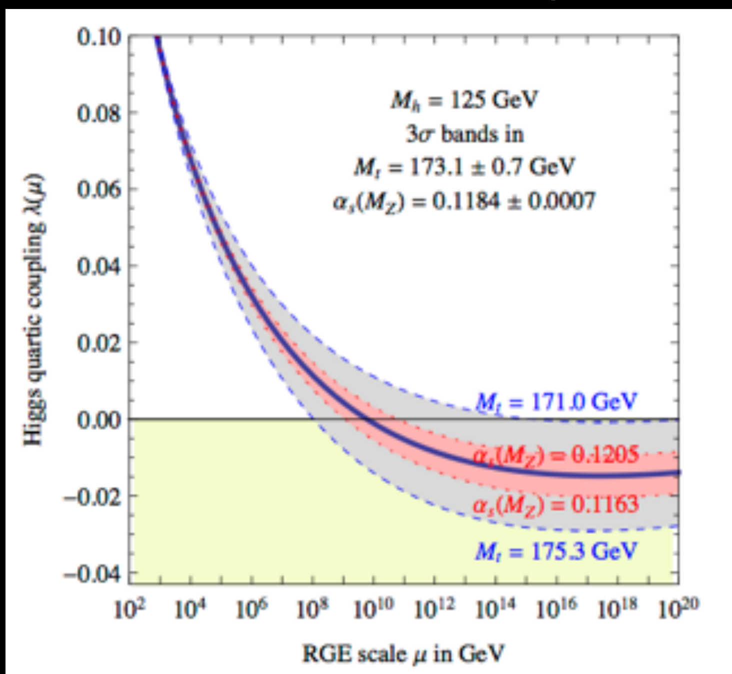
$$V(h) = V(h_0) + \lambda h_0^2 \frac{h^2}{2} + \frac{\lambda}{4} h^4 + \lambda h_0 h^3$$

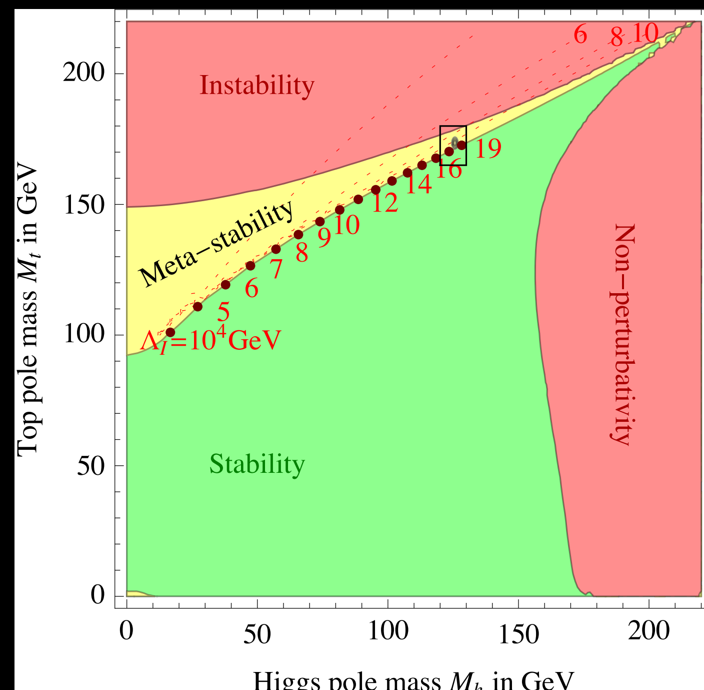
~ 28% accuracy at FCC-ee, CepC



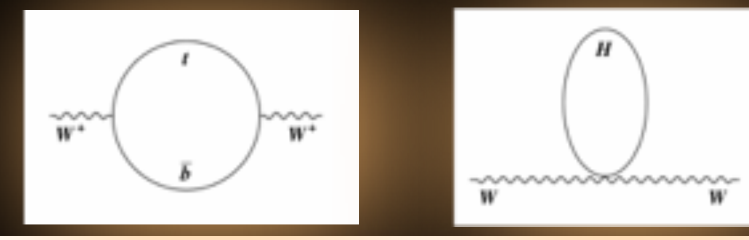
What do we learn from precision?

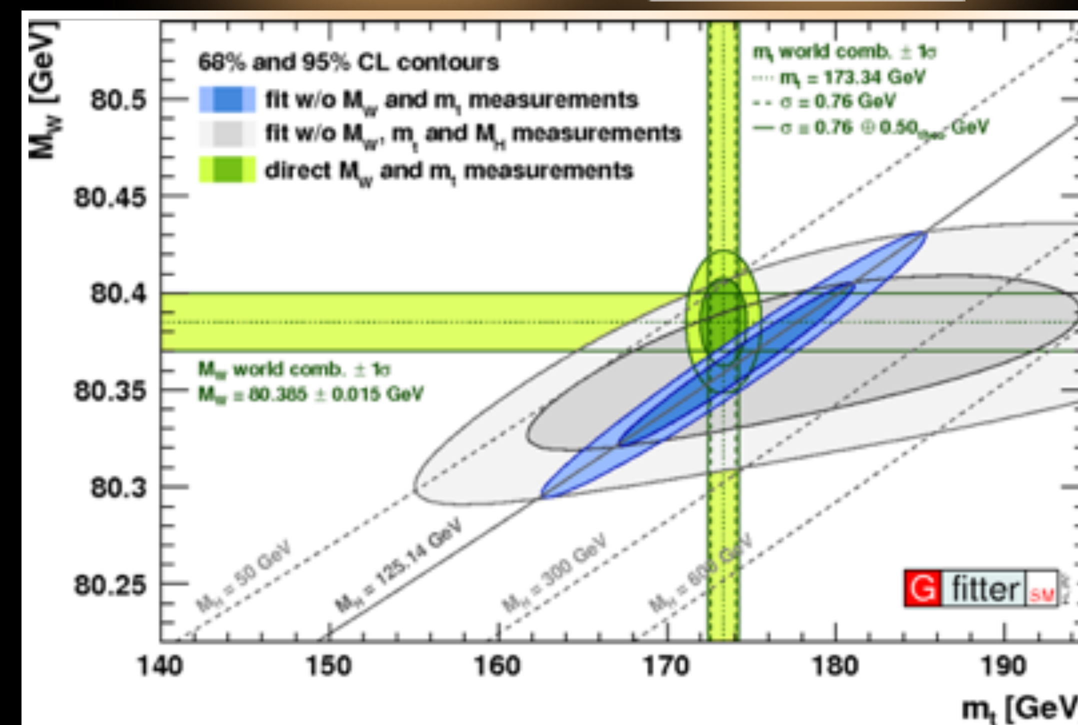
Impact of top and Higgs mass on the Higgs potential at large scale

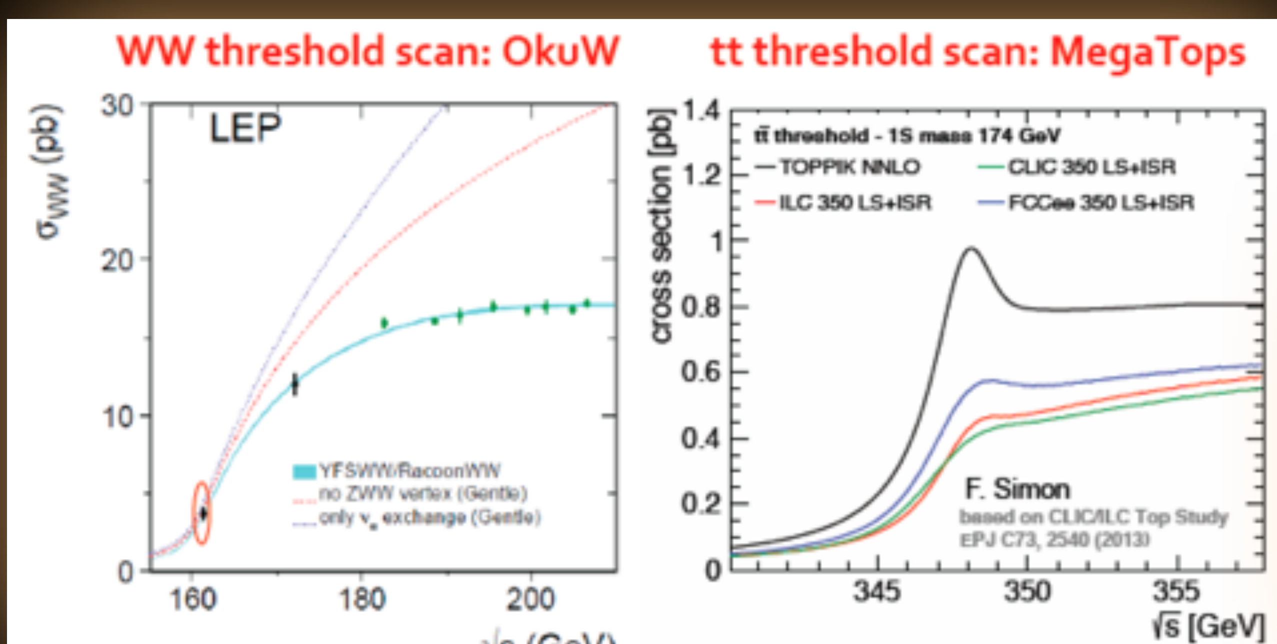




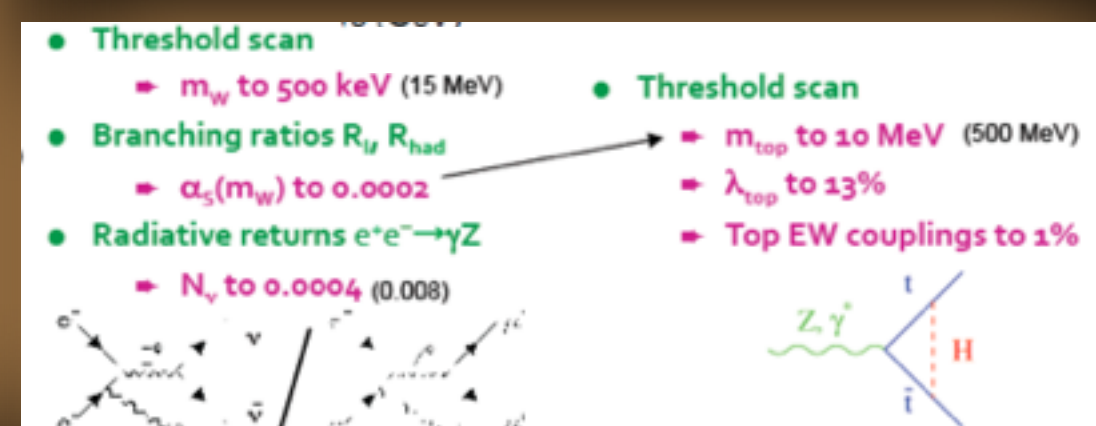
global electroweak fit







Δm_H ~ 8 MeV @FCC-ee

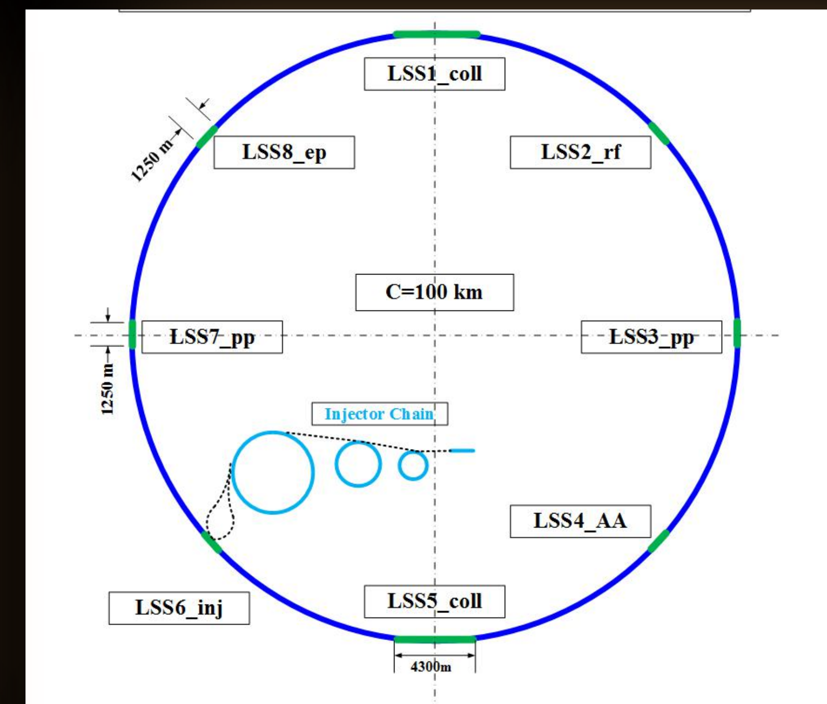


B. Di Micco IFAE-2017 Trieste 19 - 21 April 2017

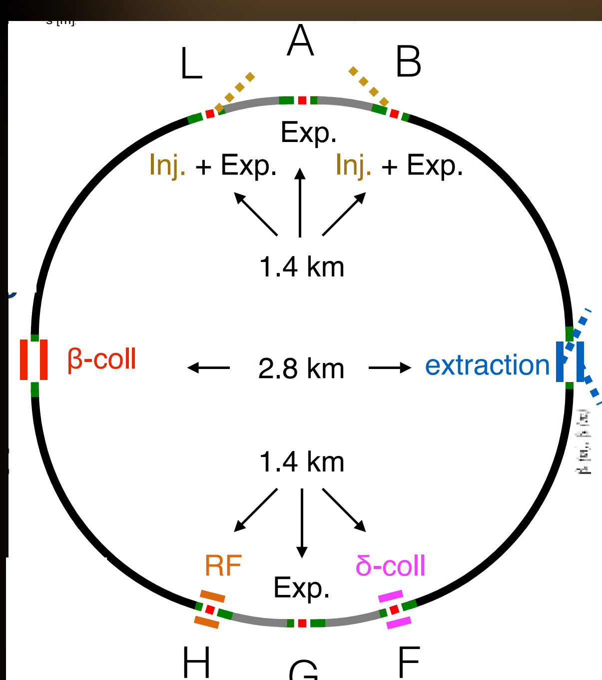
The hh colliders

SppC

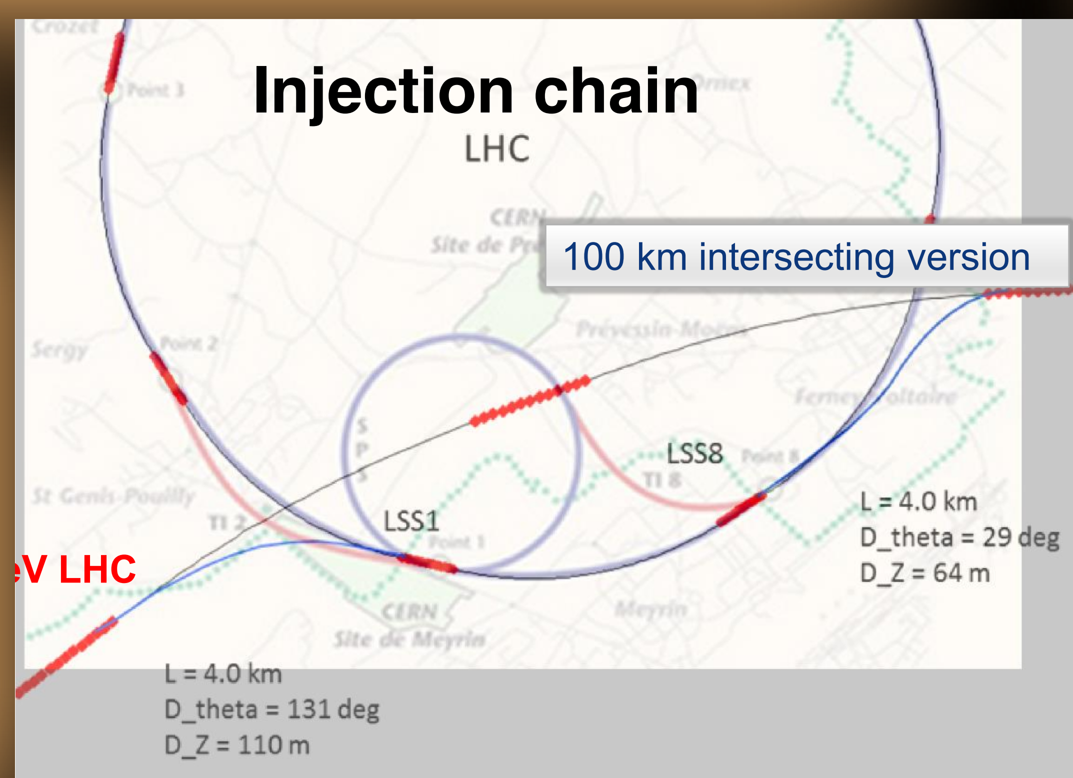
- Baseline design
  - Tunnel circumference: 100 km
  - Dipole magnet field: 12 T, using iron-based HTS technology
  - Center of Mass energy: >70 TeV
  - Injector chain: 2.1 TeV
  - Relatively lower luminosity for the first phase, higher for the second phase
- Energy upgrading phase
  - Dipole magnet field: 20 -24T, iron-based HTS technology
  - Center of Mass energy: >125 TeV
  - Injector chain: 4.2 TeV (adding a high-energy booster ring in the main tunnel in the place of the electron ring and booster)
- Development of high-field superconducting magnet technology
  - Starting to develop required HTS magnet technology; before applicable iron-based HTS wire are available, models by YBCO and LTS wires can be used for specific studies (magnet structure, coil winding, stress, quench protection method etc.)



FCC-hh



placed on top of the e^+e^- booster



Two options under study for injection

1) LHC @3.3 TeV;
2) upgrade SPPS to 6-7 T SC magnets, with 1T/s ramping up and 1.5 TeV injection energy
3) Max lumi: 3×10^{35} $cm^{-2}s^{-1}$

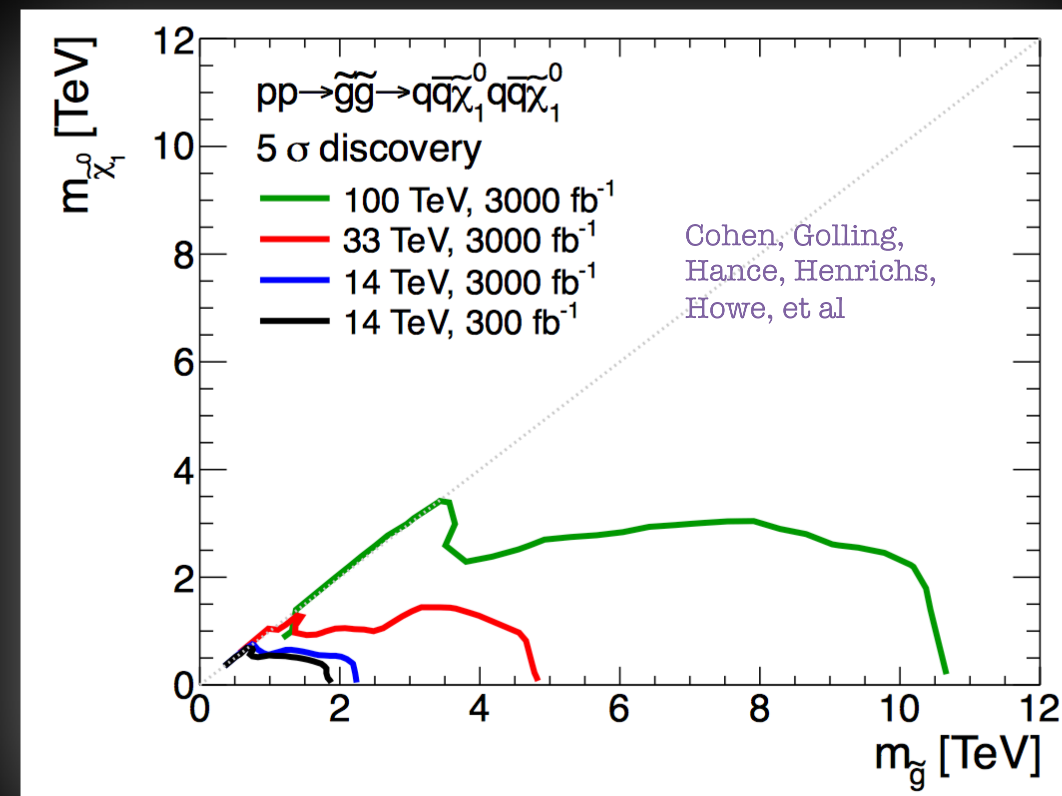
Magnets: develop Nb_3Sn magnets, trying to increase current density.

Use of HTS in HTL/LTS hybrid to reach fields beyond 16T.

What do we learn from high energy?

SUSY

- at leading order SUSY set $m_h < m_Z$;
- m_h ~ 125 GeV needs large SUSY rad. corrections through s-quark loops (SUSY scale in the 1-10 TeV range);
- still able to solve the hierarchy problem with a fine tuning at ~ 1%
- if we are lucky, DM could be found in that energy range



Hierarchy problem and fine tuning in few lines

Li-gong Bian, arXiv: 1303.2402

$$(m_H^0)^2 = (m_H)^2 - \frac{2\Lambda^2}{(4\pi)^2 v^2}\left[3(m_H)^2 - 12(m_t)^2 + 6(m_W)^2 + 3(m_Z)^2\right]$$

bare mass

physical mass (125.09 GeV)

cut-off, M_{pl} (if no SUSY otherwise Λ_{SUSY})

h_0 ~ 246 GeV

Fine tuning still moves from 10^{-30} to ~ 1%

FCC-hh could be the final word on SUSY

Higgs self-coupling

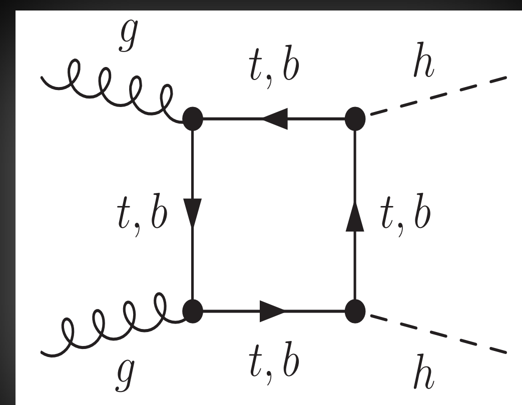
$$V(h) = V(h_0) + \lambda h_0^2 \frac{h^2}{2} + \frac{\lambda}{4} h^4 + \lambda h_0 h^3$$

self-coupling

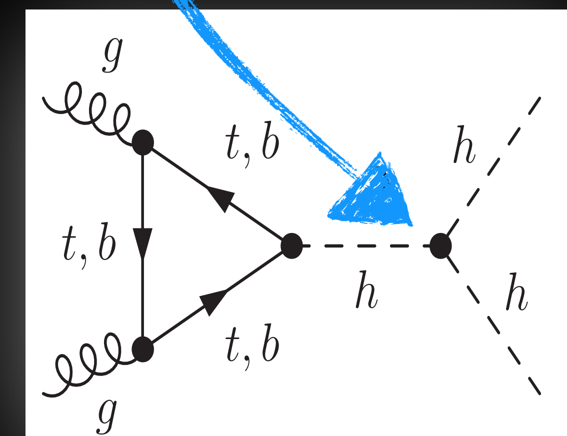
hh production mechanism

The self-coupling is directly accessible in pp → hh production

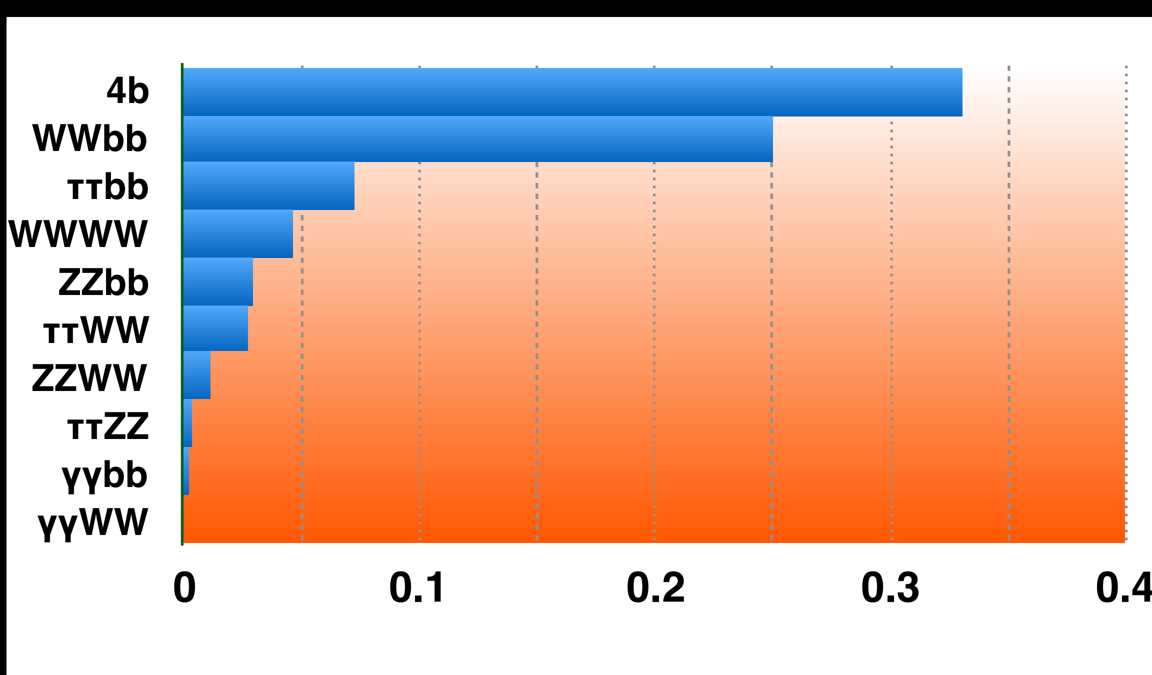
box



triangle



hh branching ratio to various decay final states



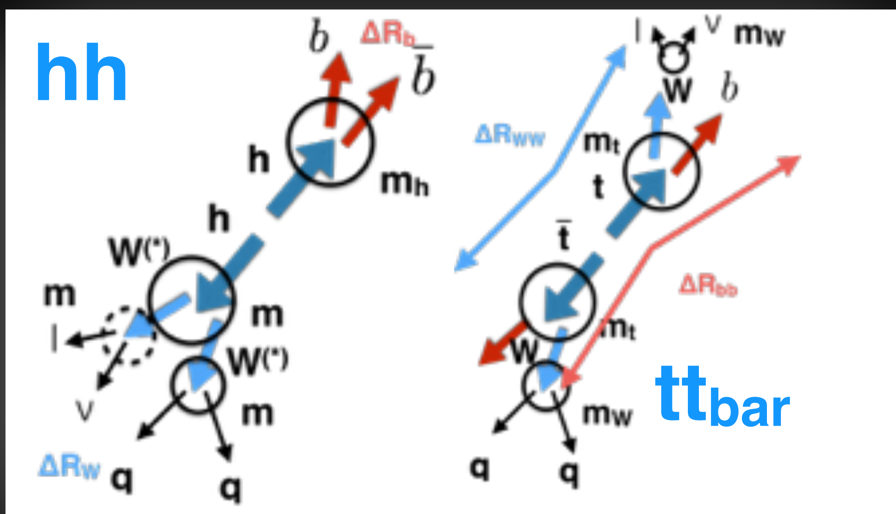
results from the 2016 FCC physics report (30 ab^{-1})

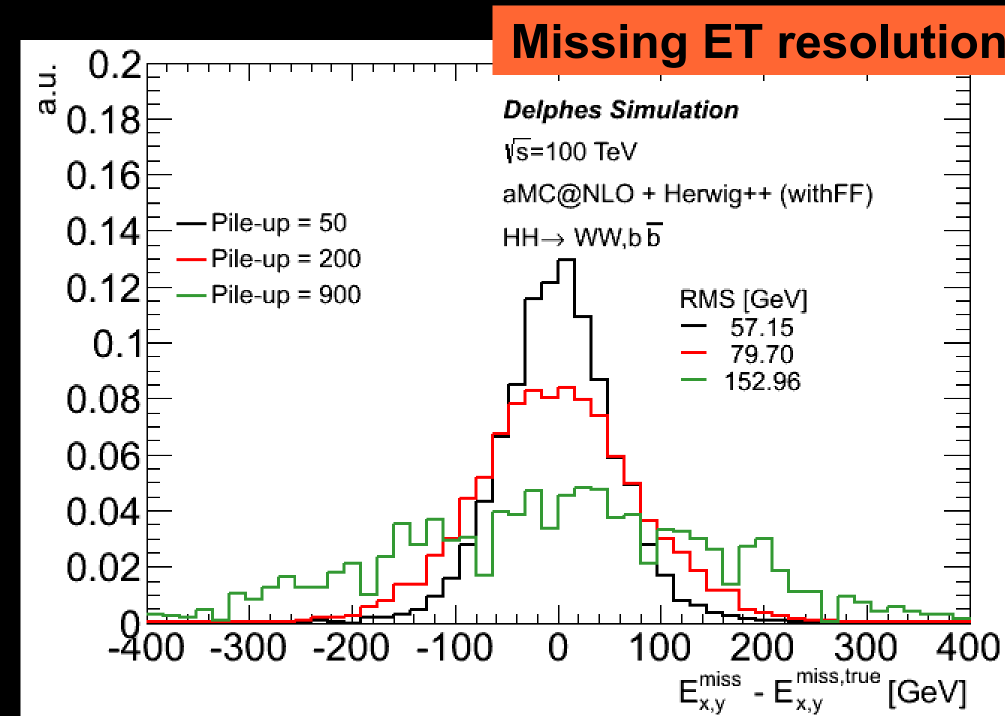
	Δσ/σ	Δλ/λ
γγbb	1.3%	2.5%
4b	25% (S/B ~2%)	200%
ZZbb, 4l	~30%	~40%

30 ab^{-1} is a long FCC run (15 years) need to study more channels to improve the result in order to better constraint the Higgs potential in a shorter time

The WWbb and ZZbb cases

Very different signal and background topologies, they can be exploited with advanced analysis techniques





first studies -studies in extreme pile-up conditions

WWbb event yield

3 ab^{-1} PU 200	Object selection	Final selection	ε
hh-WWbb	$5.4 \cdot 10^4$	273	$8.5 \cdot 10^{-4}$
t-t$_{bar}$	$3.6 \cdot 10^9$	$3.4 \cdot 10^5$	
S/B$_{kg}$	$1.5 \cdot 10^{-5}$	$8.0 \cdot 10^{-4}$	

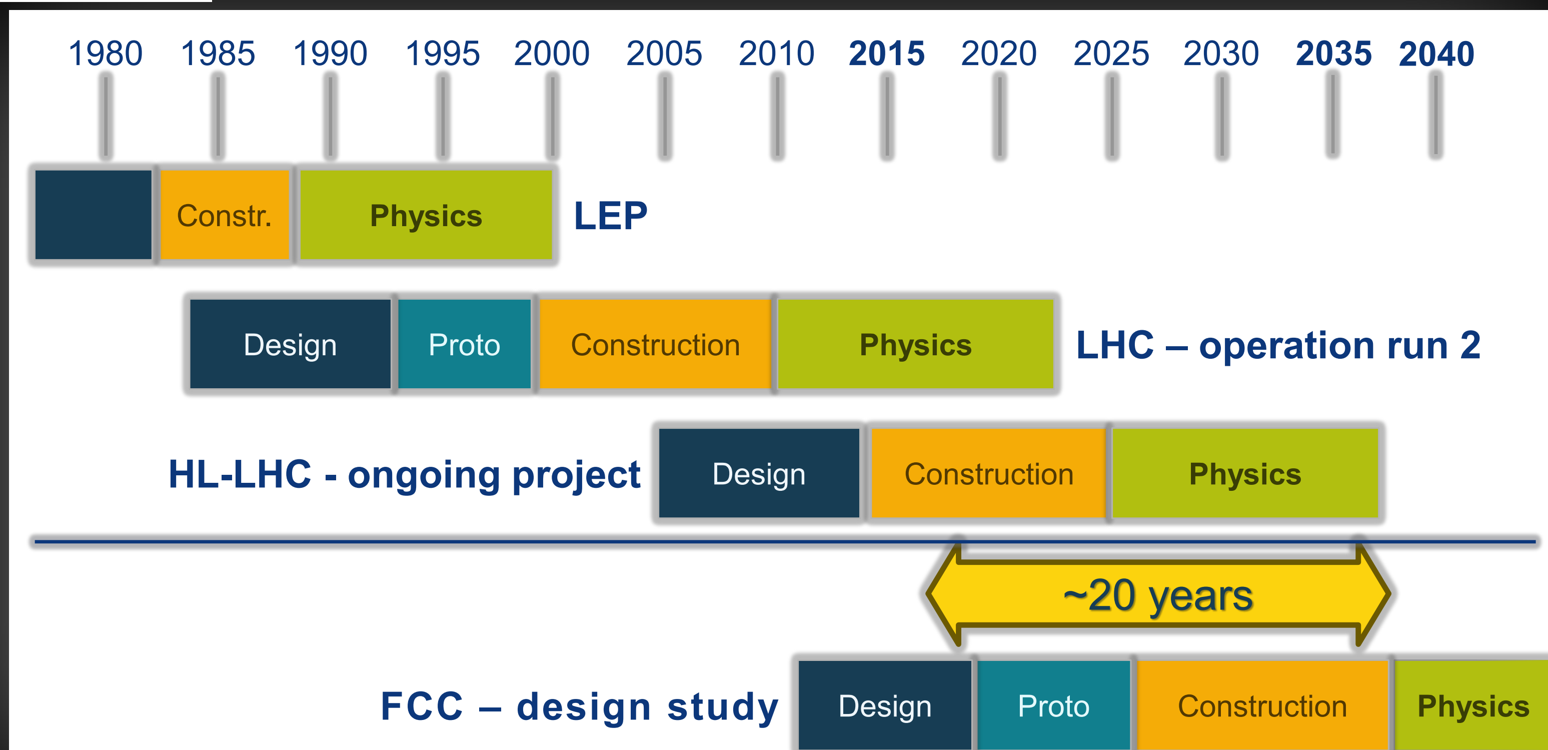
low S/B pointing to the need of using advanced analysis technique for analysis optimisation

ZZbb → 4l bb

	σ·L· Br(hh→ZZbb→4lbb)	no b-jet req.	with b-jet	ε (no b-jet)	ε (b-jet)
4μ	161	61	12,1	38%	7,4%
4e	161	40	7,7	25%	4,8%
Tot	322	101	20	31%	6,2%

high impact from b-tagging, at FCC-hh forward detector becomes crucial

Timeline of the projects



FCC approach

give priority to the pp solution, timeline constrained by magnet technology evolution and by HL-LHC timeline

1st Milestone: Pre-CDR (by the end of 2014) ;2nd Milestone: R&D funding from MOST (in Mid 2016); 3rd Milestone: CEPC CDR Status Report (by the end of 2016); 4th Milestone: CEPC CDR Report (by the end of 2017);5th Milestone: CEPC TDR Report and Proto (by the end of 2022);6th Milestone: CEPC construction (by the end of 2030);

CepC approach

give priority to the e^+e^- option, use possible pp evolution to add physics motivations

Conclusions and considerations

1) I think it is clear that studying the Higgs potential and its self-coupling is the next target of particle physics:

    1) it is a no-loose bet, or we find it as in SM or we have something new;
    2) it has deep implications on cosmology, in one direction or another (e.g. arXiv: 1505.04825);

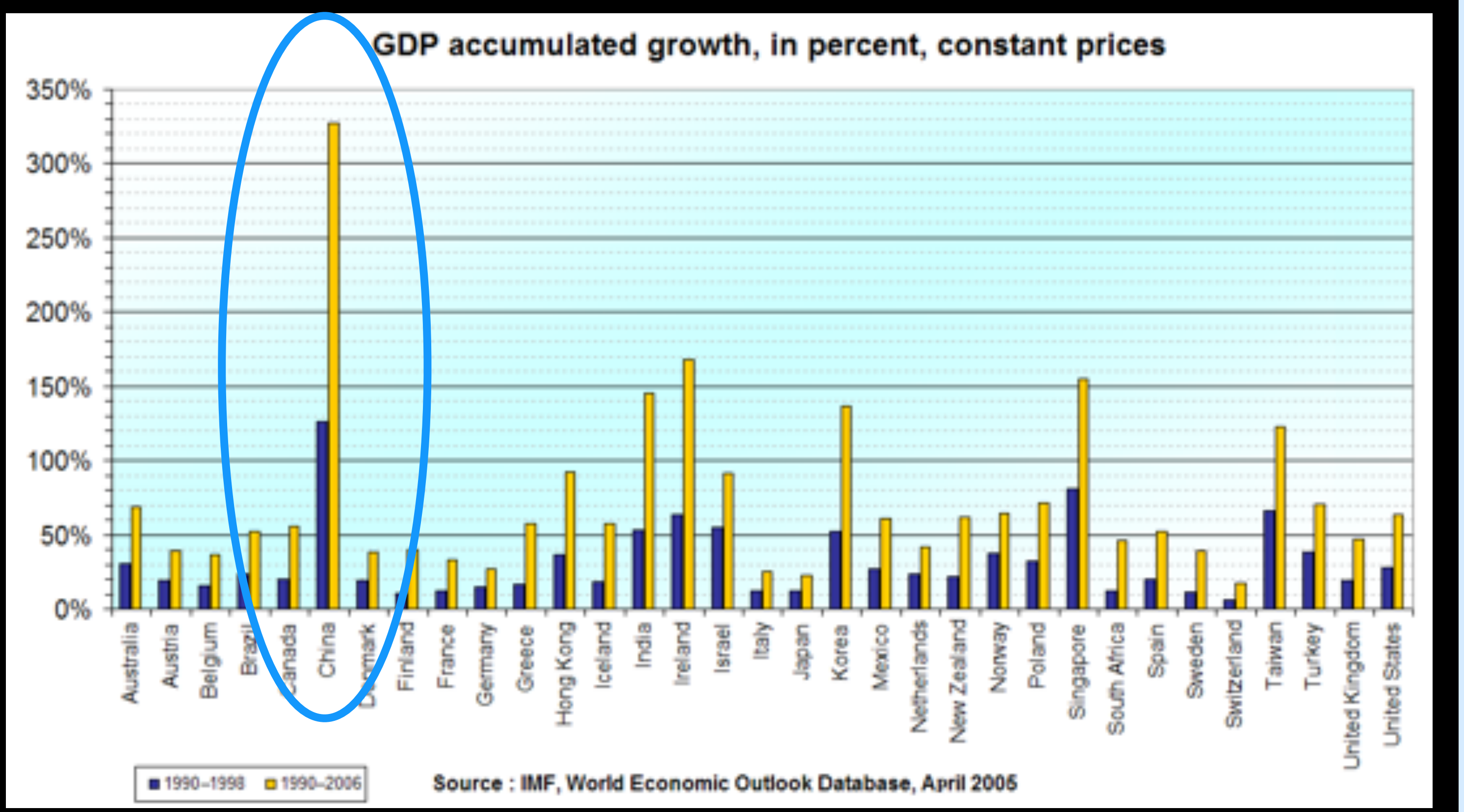
2) at the moment, the only way to study it with high accuracy is with a 100 TeV pp collider, that's add up new physics search in the unexplored 1-10 TeV range;

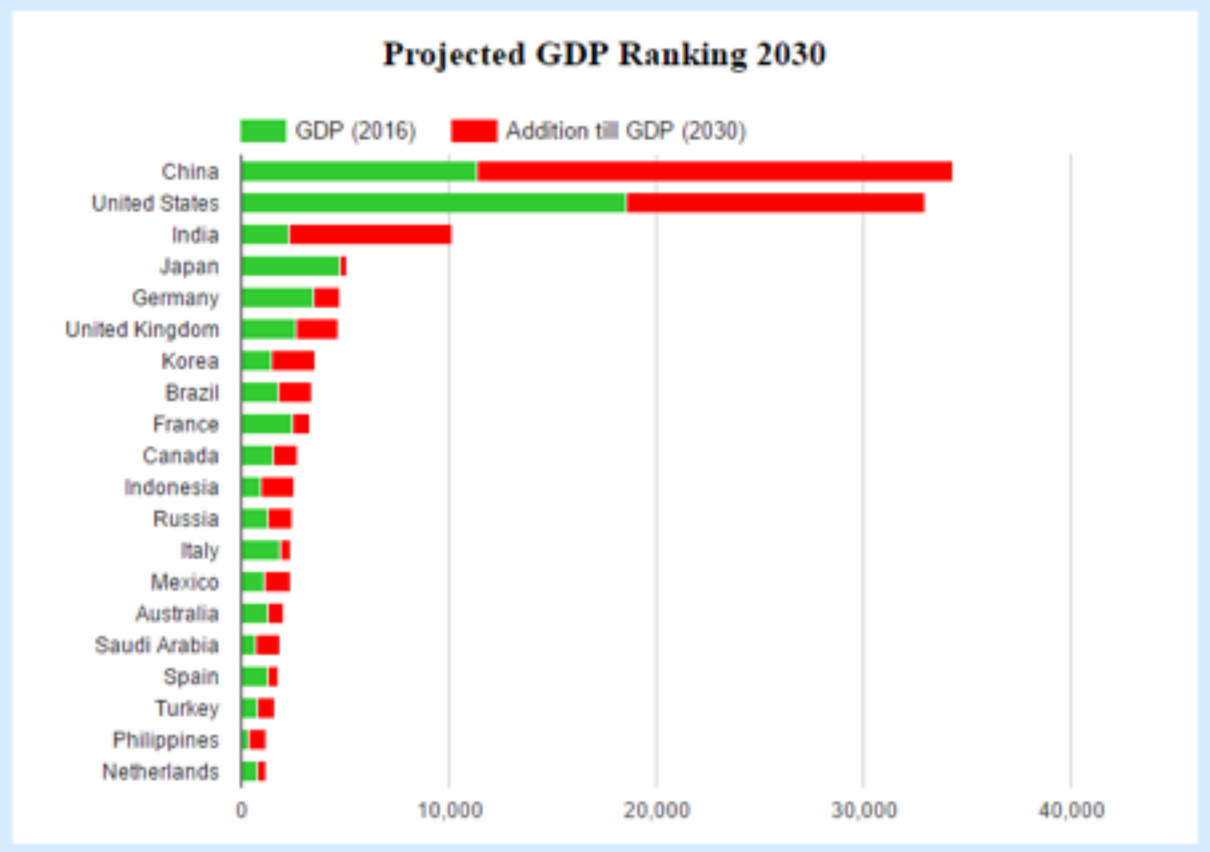
3) at the moment, we don't have the magnet technology to reach this target: magnet technology development is the primary goal;

4) an e^+e^- option gives enough physics motivation to start building up the structure [just few given in these slides but can make all LEP physics with unprecedented accuracy] (tunnels, cryogenic, infrastructure), but should not delay the pp project when it will be ready to go;

5) we cannot build 2 machines like this in the world, need full international support to whoever decides to build it. Italy is collaborating both on CepC/SppC and FCC [trying to strength international collaboration, pushing chinese contribution to HL-LHC to have CERN support on CepC/SppC in return]

Year	Real GWP ($ billions, 1990 intl$)	Compound annual growth rate
2014 AD	77,868[2]	
2010 AD	62,220 (est. 41,090 in 1990 U.S. dollars)[6]	
2005 AD	43,070 (est. 31,300 in 1990 U.S. dollars)[citation needed]	
2000 AD	41,016.69	4.04%
1995 AD	33,644.33	4.09%
1990 AD	27,539.57	4.14%
1985 AD	22,481.11	3.62%
1980 AD	18,818.46	4.43%





Riguardo ai fondi di R&D la situazione e' la seguente:

- IHEP seed money (2015-2017): 11 Mrmb
- MOST (Ministry of Science/Technology) (2016): 36 Mrmb (additional 10 Mrmb expected in 2017)
- CAS (Chinese Academy of Science), Beijing Inn. fund, talent program: ~ 50 Mrmb

1 Mrmb ~ 135 k€

Totale finanziato finora ~ 100 Mrmb ~ 13.5 M€

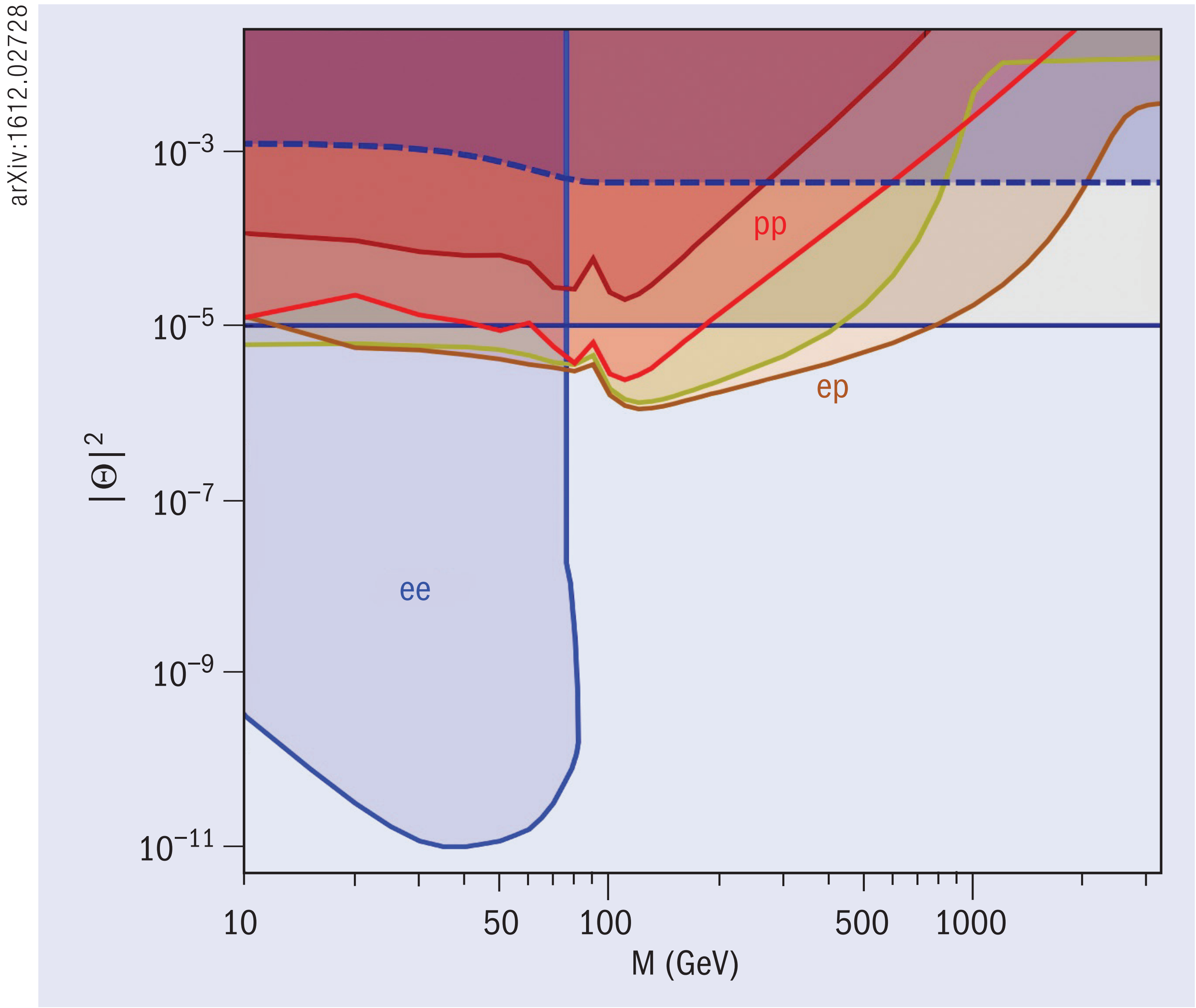


Fig. 2. The complementary role of the ee, pp and ep colliders in probing a sterile neutrino of mass M and mixing angle θ with ordinary neutrinos.

Exponential expansion

Assuming $\rho=\rho_0$ = constant.
And setting:

$$H_0 = \sqrt{\frac{8\pi G}{3}\rho_0 + \frac{\Lambda c^2}{3}}$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\ddot{a}}{a} = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}$$

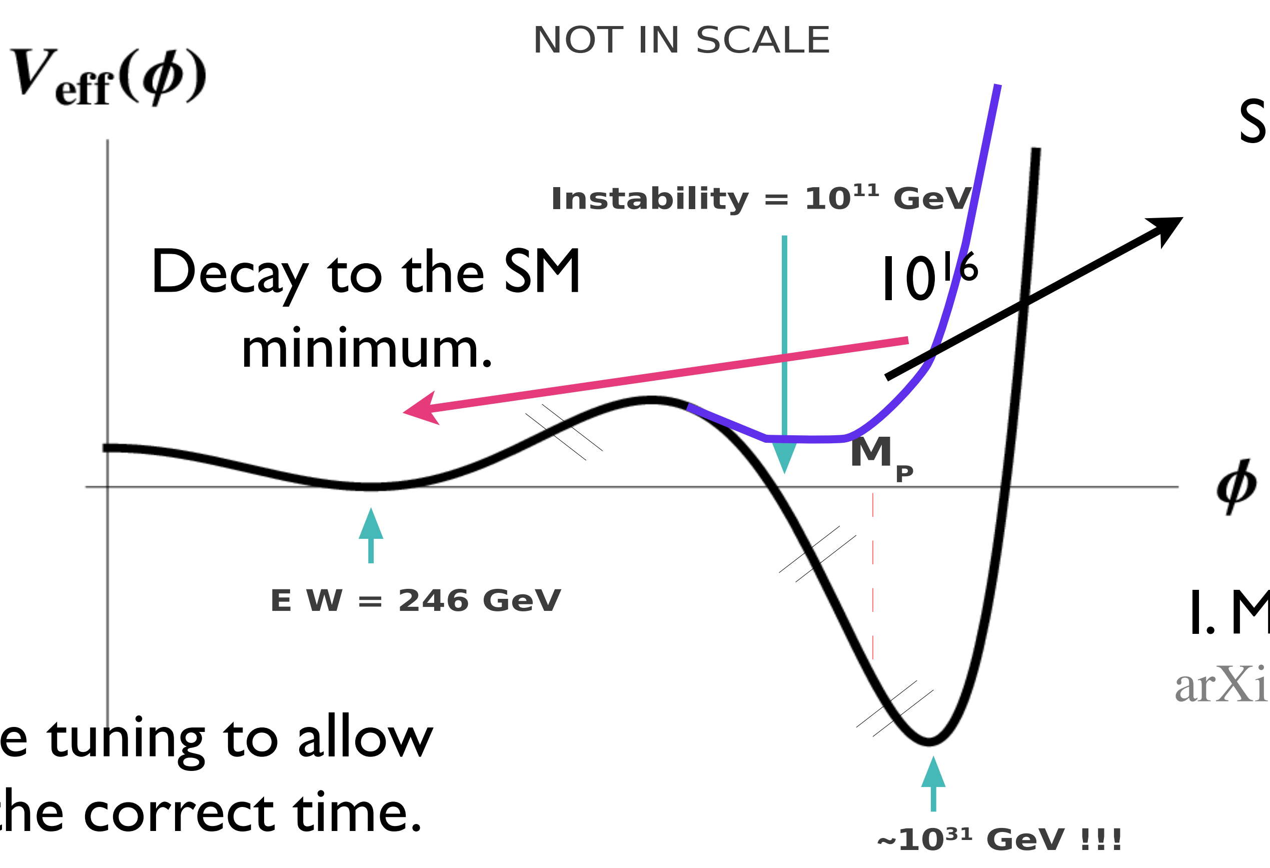
The non autocollapsing solution is: $a(t) = a(0)e^{H_0 t}$

Exponential expansion producing the universe inflation.
The condition $p=-\rho c^2$ is fullfilled by the rest energy of a scalar field.

$$H^2 \simeq \frac{V(\chi_0)}{3M^2} \equiv H_I^2$$

Planck mass.

$$M = \sqrt{\frac{\hbar c}{G}}$$

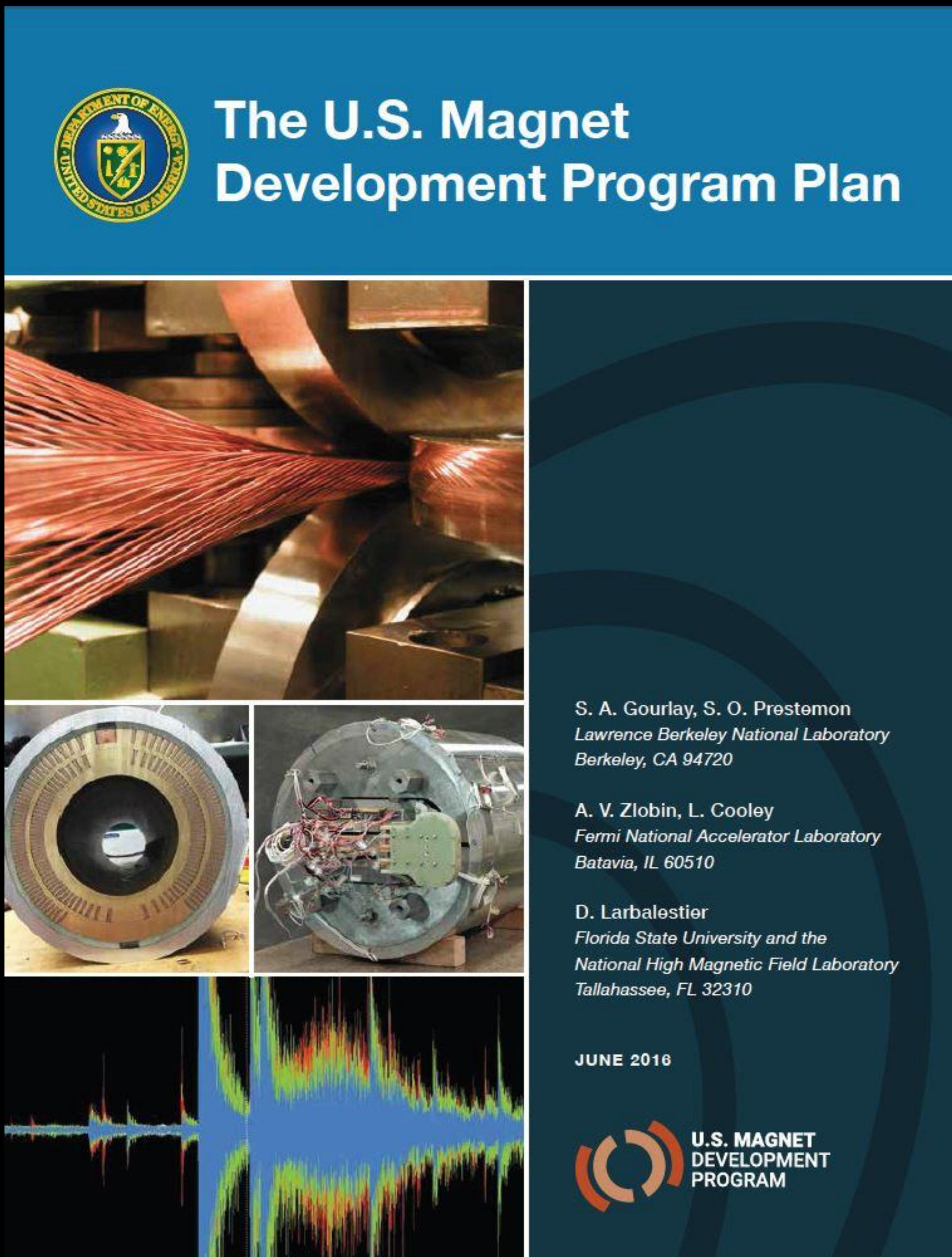


Shallow minimum at the inflation time.

False vacuum

I. Masina
arXiv:1403.5244v1

The potential needs a strong fine tuning to allow such transition happening with the correct time. (but...)



Program (MDP) Goals:

GOAL 1:

Explore the performance limits of Nb_3Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.

GOAL 2:

Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.

GOAL 3:

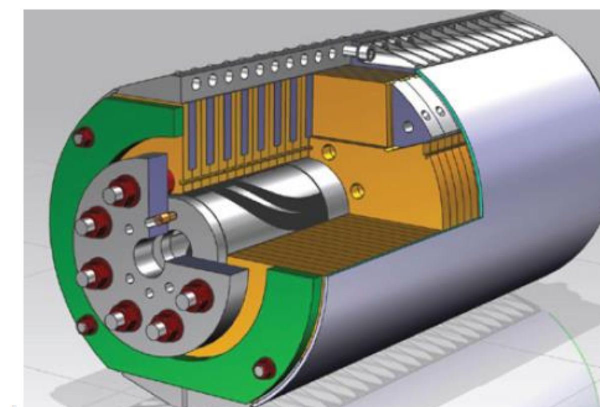
Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

GOAL 4:

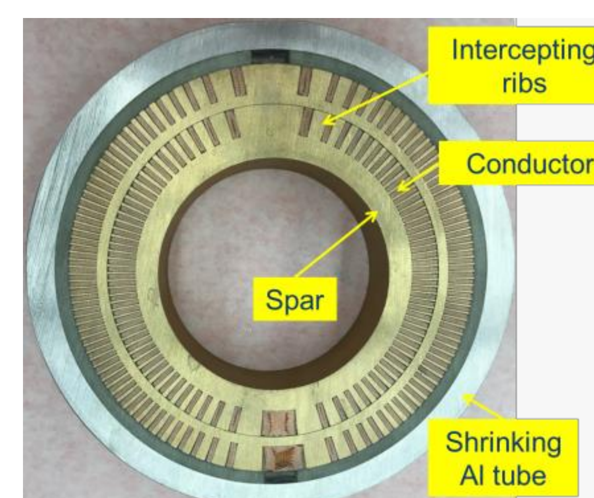
Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

Under Goal 1:

16 T cos theta dipole design

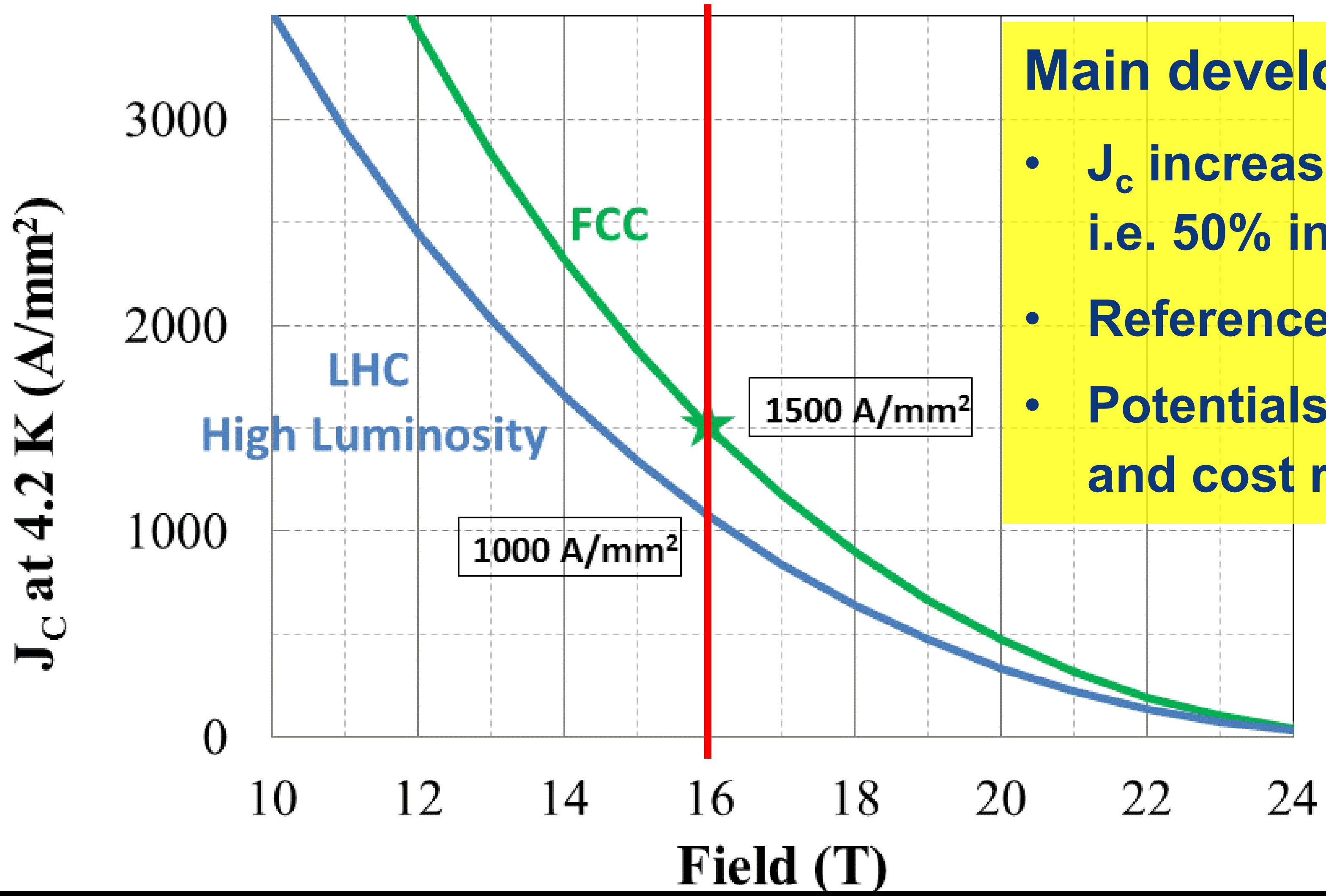


16 T canted cos theta (CCT) design



Nb_3Sn conductor program

Nb_3Sn is one of the major cost & performance factors for FCC-hh and requires highest attention

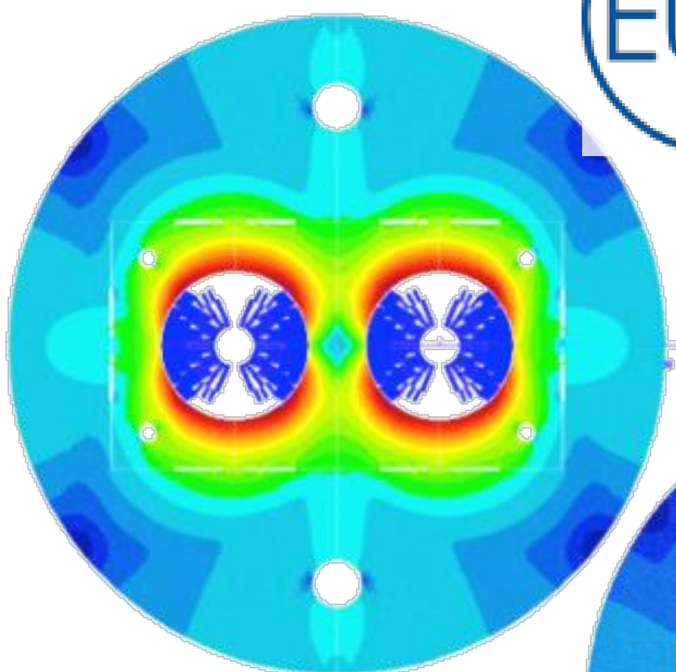


Main development goals until 2020:

- J_c increase (16T, 4.2K) > 1500 A/mm^2 i.e. 50% increase wrt HL-LHC wire
- Reference wire diameter 1 mm
- Potentials for large scale production and cost reduction

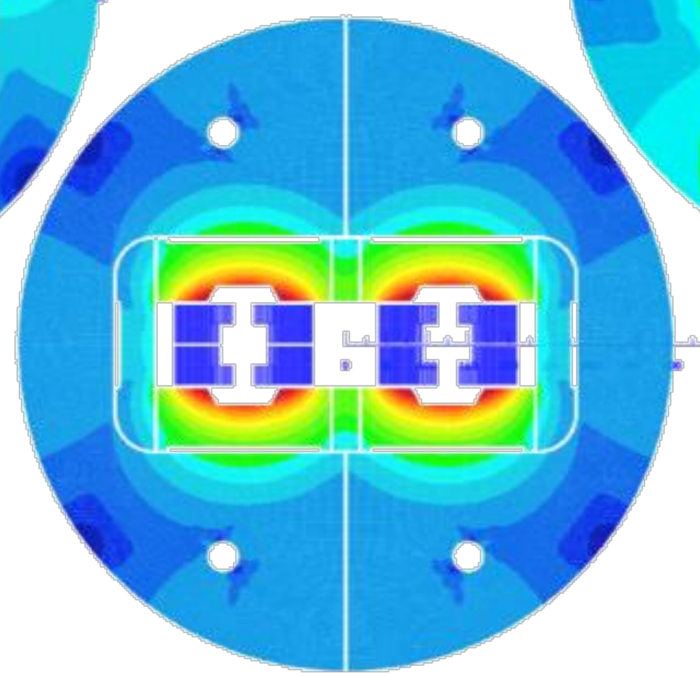
16 T dipole options and plans

Cos-theta

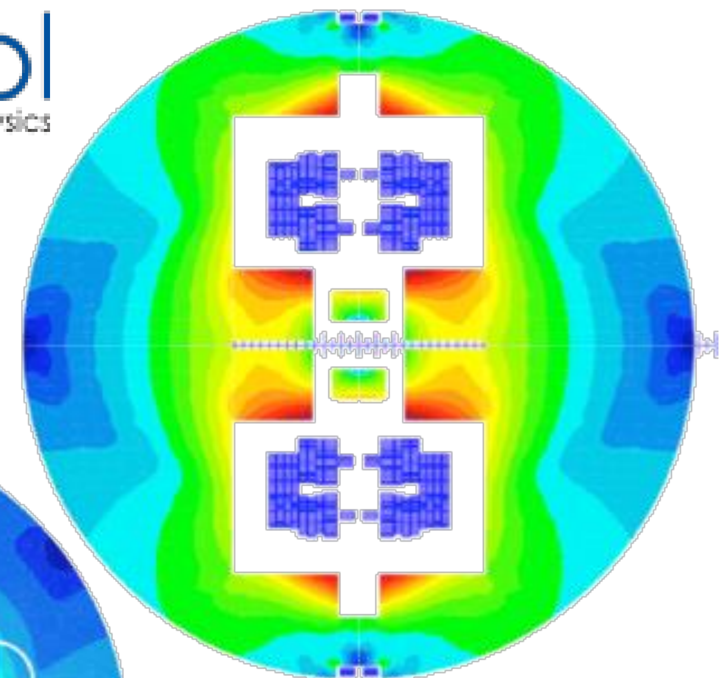


EuroCirCol
A key to New Physics

Blocks

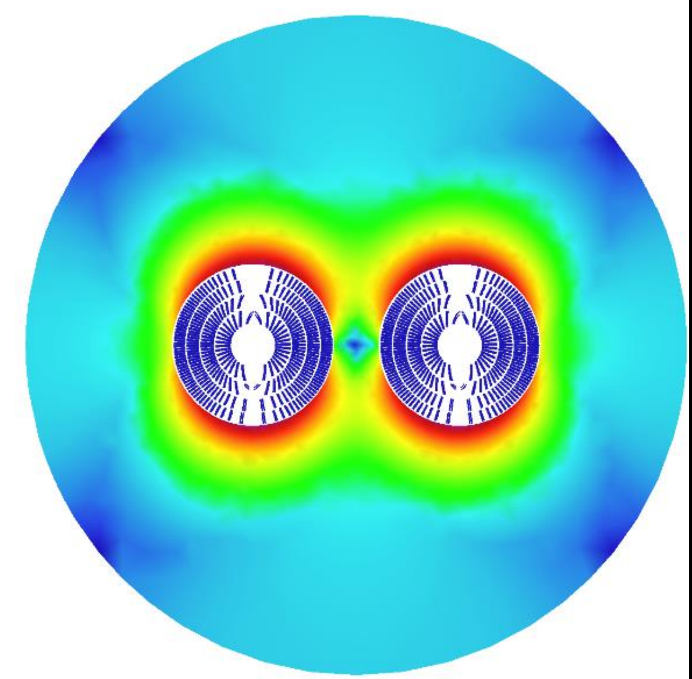


Common coils



Swiss contribution
via PSI

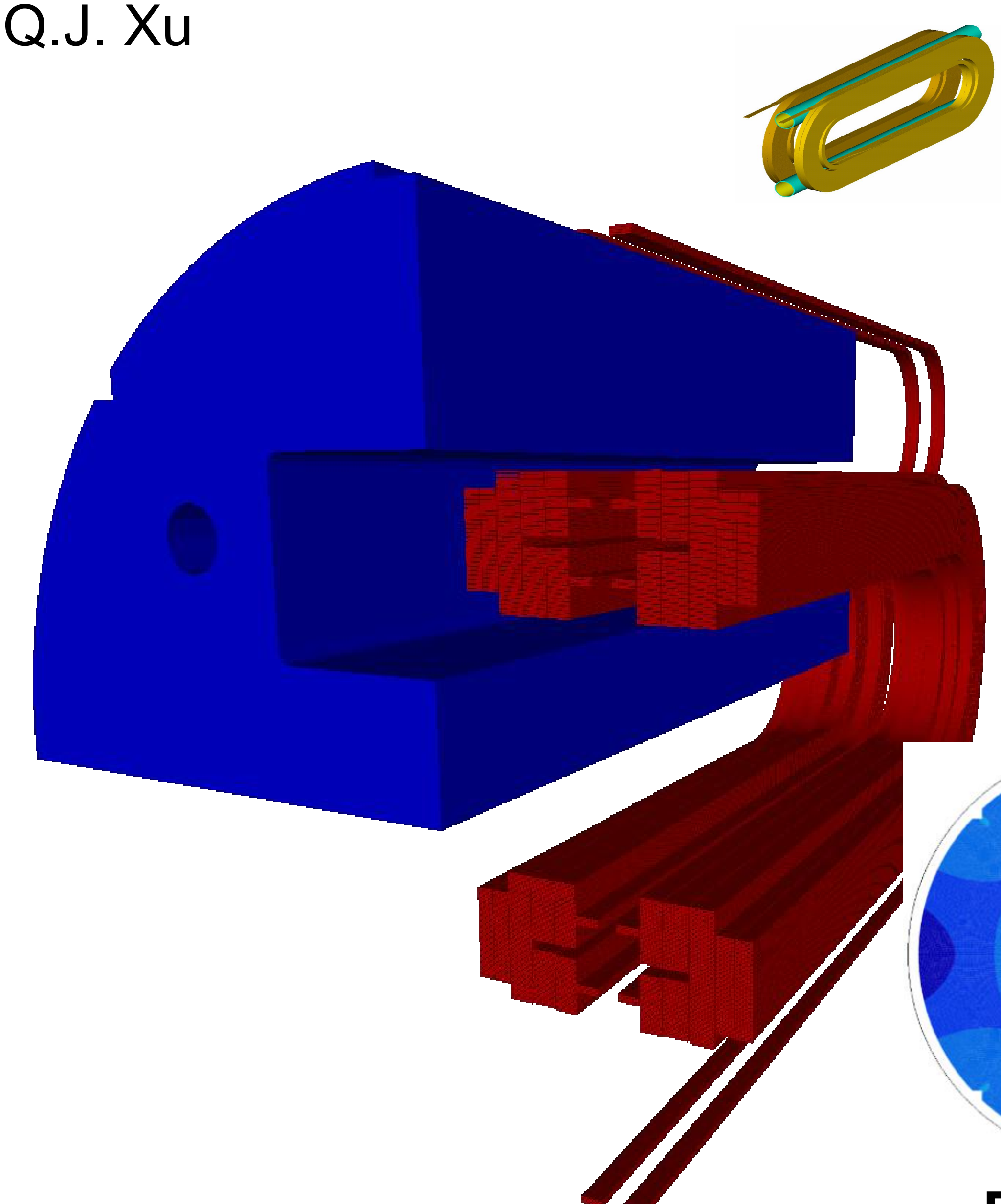
Canted
Cos-theta

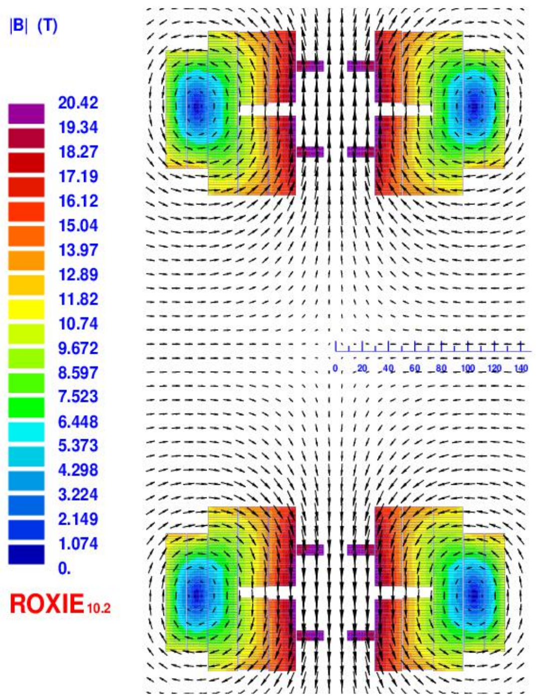


- **Down-selection of options mid 2017 for detailed design work**
- **Model production 2018 - 2022**
- **Prototype production 2023 - 2025**

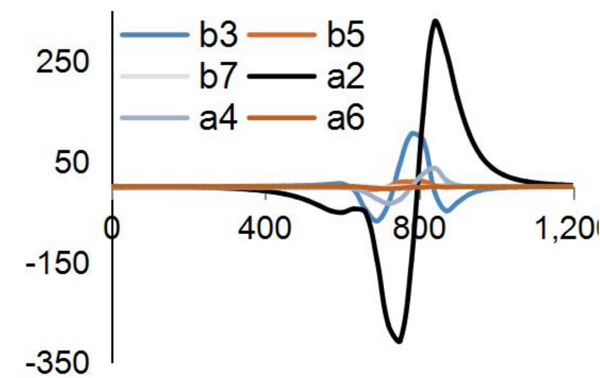
SppC 20T Nb_3Sn+HTS SC Dipole Conceptual Design

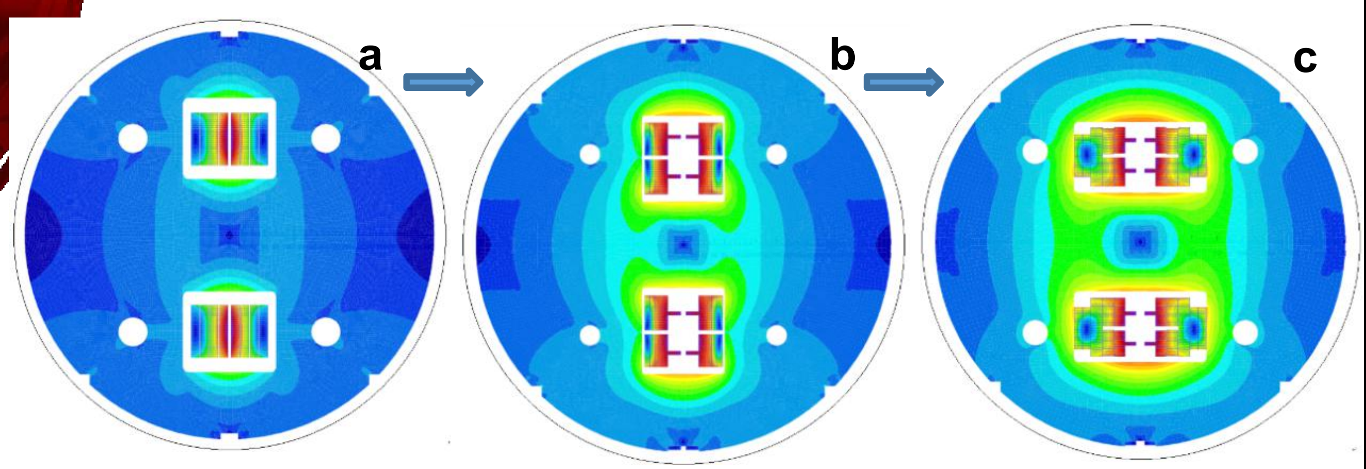
Q.J. Xu





High order multiples along axis





20-T common coil dipole magnet:
space for beam pipes: 2 * Φ50 mm, with the load line ratio of ~90% @ 4.2 K

R&D steps for fabrication of the 20-T dipole magnet with common coil configuration
a. a 15-T sub-scale magnet; **b.** a 15-T dipole magnet with 2 apertures; **c.** a 20-T dipole magnet with 2 apertures and 10^{-4} field quality