Future hadronic colliders

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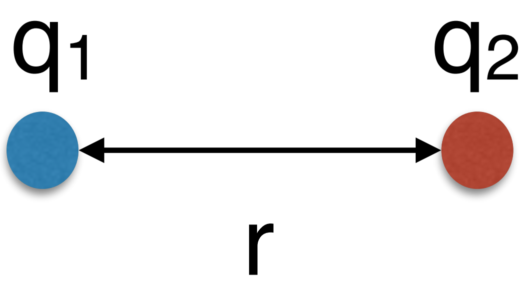
Electromagnetic vs Higgs dynamics

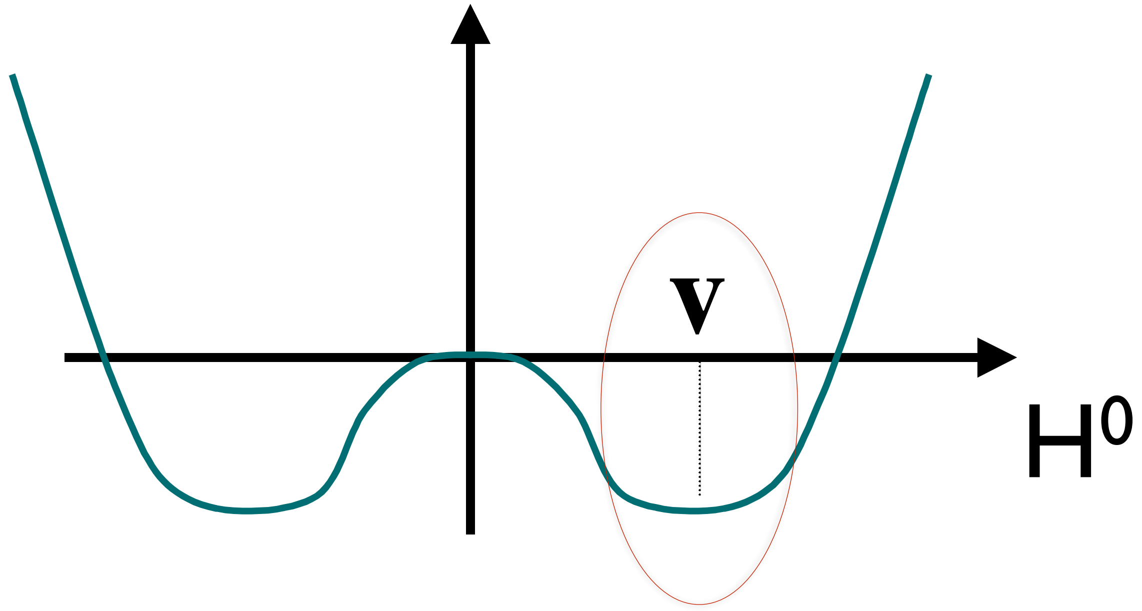


quantized,
in units of
fixed charge

$$V(r) = + \frac{q_1 \times q_2}{r^1}$$

sign fixed
by photon
spin

power determined by gauge
invariance/charge
conservation/Gauss theorem



any function of $|H|^2$ would be
ok wrt known symmetries

$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

both sign
and value
totally
arbitrary

>0 to ensure
stability, but
otherwise arbitrary

on the nature of EW symmetry breaking

- EW and strong interactions have free parameters (the symmetry groups, the strength of couplings, the charges of elementary particles). But at least we do have a deep understanding of their dynamical nature, namely the gauge principle. This allows us to speculate about an even deeper origin, e.g. from string theory or higher-dimensional Kaluza-Klein theories

- The Higgs mechanism relies of the quartic Higgs potential, in particular on the negative sign of its quadratic component. But we have no clue as to what is its dynamical origin, independently of whether we look at it with a SM or BSM perspective …

- Understanding the origin of the Higgs potential and the nature of Higgs interactions is a paramount puzzle of modern physics, regardless of whether they eventually match the SM assumption or require new physics

- Having established the existence of the Higgs is similar to having established inflation, through cosmological observations. The real question (for both Higgs and inflation) is now "**where does it come from?**"

a historical example: superconductivity

- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

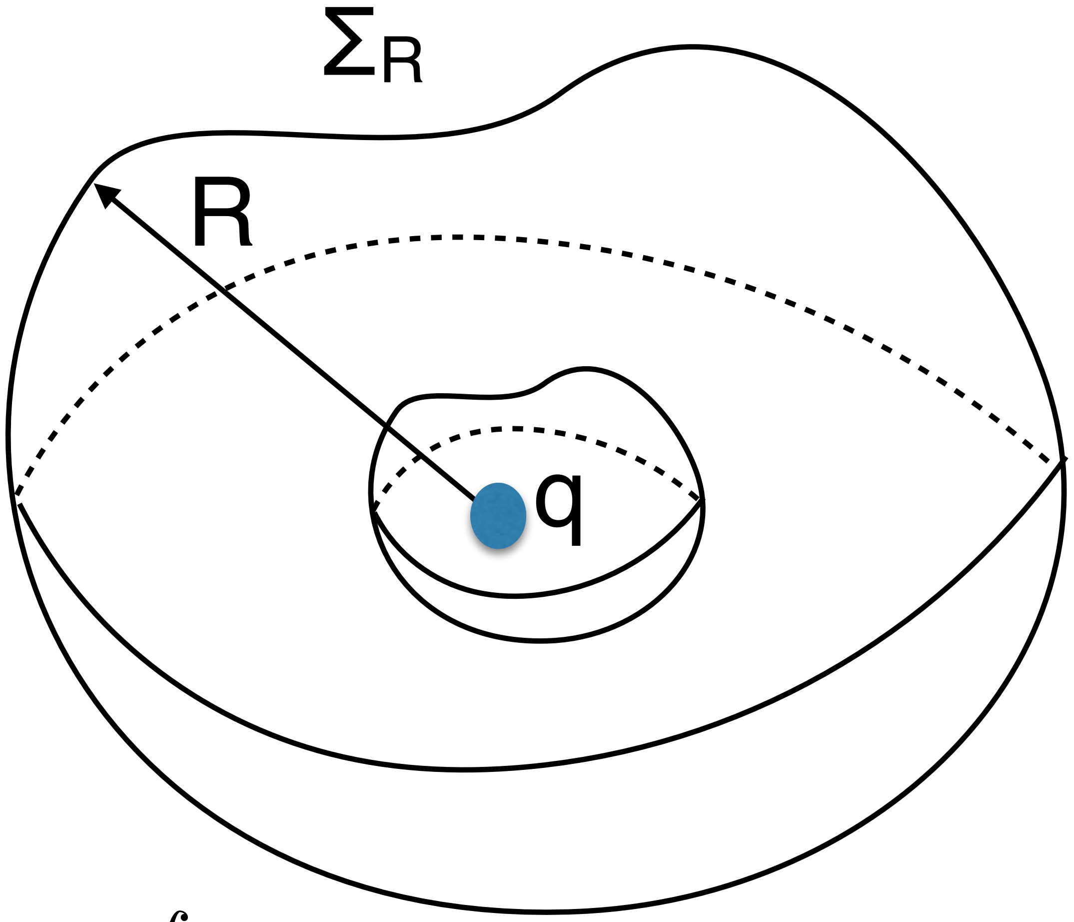
- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

The other *big* questions that press us to look *beyond* the Standard Model

- What's the real origin of EW symmetry breaking and particle's masses?
- What's the origin of Dark matter / energy ?
- What's the origin of matter/antimatter asymmetry in the universe?
- What's the origin of neutrino masses?
- What protects the smallness of m_H / $m_{\text{Plank,GUT}}$ (hierarchy problem)?
- ...

Decoupling of high-frequency modes

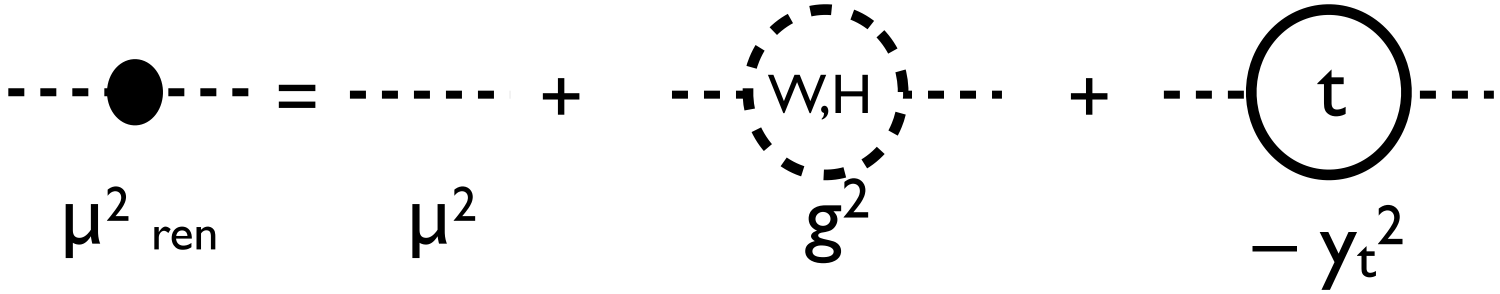
E&M



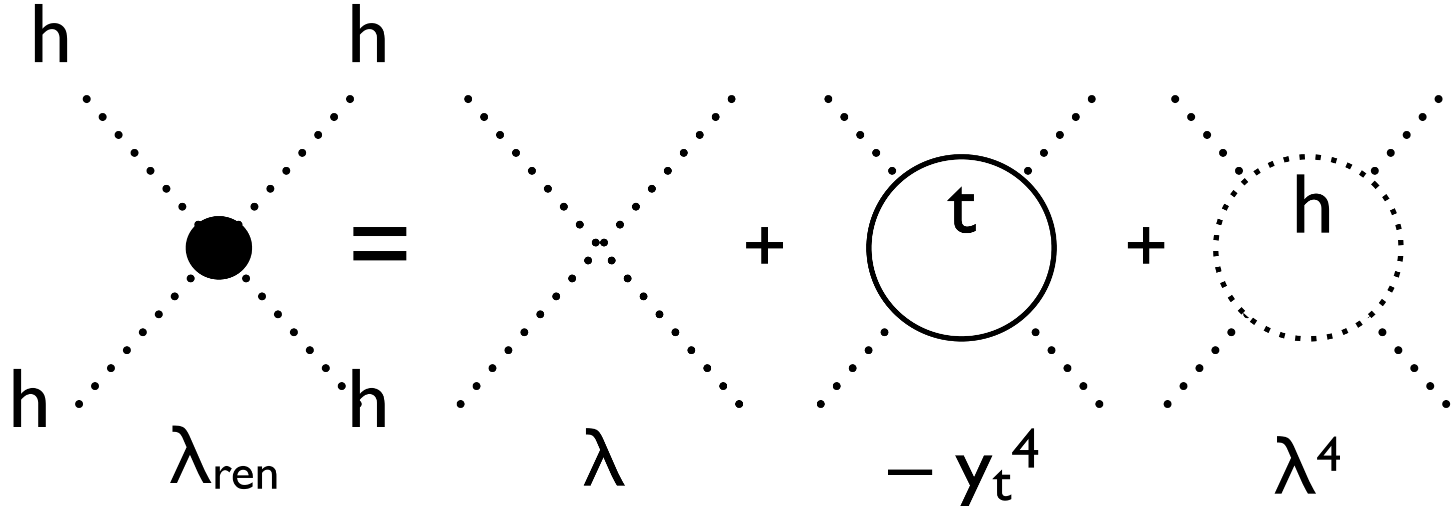
$$\int_{\Sigma_R} \vec{\nabla} V_q \cdot d\vec{\sigma} = 4\pi q, \quad \forall R$$

short-scale physics does not alter the charge seen at large scales

$$V_{SM}(H) = -\mu^2 \left|H\right|^2 + \lambda \left|H\right|^4$$



$$\Delta\mu^2 \sim (\ c_W\ m_W^2 - c_t\ m_t^2\ )\ x\ (\ \Lambda\ /\ v)^2$$



$$\Rightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4 \quad \propto a\ m_H^4 - b\ m_t^4$$

high-energy modes can change size and sign of both μ^2 and λ, dramatically altering the stability and dynamics

bottom line

- To predict the properties of EM at large scales, we don't need to know what happens at short scales
- The Higgs dynamics is sensitive to all that happens at any scale larger than the Higgs mass !!! A very unnatural **fine tuning** is required to protect the Higgs dynamics from the dynamics at high energy
- This issue goes under the name of **hierarchy problem**
- Solutions to the hierarchy problem require the introduction of new symmetries (typically leading to the existence of new particles), which decouple the high-energy modes and allow the Higgs and its dynamics to be defined at the "natural" scale defined by the measured parameters v and m_H

⇒ **naturalness**

- The hierarchy problem, and the search for a ***natural*** explanation of the separation between the EW and Planck scales, provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon.

- Lack of experimental evidence, so far, for a straightforward answer to naturalness (eg SUSY), forces us to review our biases, and to **take a closer look even at the most basic assumptions about Higgs** properties

- We often ask "is the Higgs like in SM?" ….The right way to set the issue is rather, more humbly, **"what is the Higgs?"** …
  - in this perspective, even innocent questions like whether the Higgs gives mass also to 1st and 2nd generation fermions call for experimental verification.

Aside from the issue of principle of finding the origin of EWSB, why do we care so much?

The Higgs boson is directly connected to several concrete questions:

- Is the Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g. $H^{\pm}$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?

- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?
  - does the PT wash out possible pre-existing baryon asymmetry?

- Is there a relation between any amongst Higgs/EWSB, baryogenesis, Dark Matter, inflation?

- Is there a deep reason for the apparent metastability of the Higgs vacuum?

The LHC experiments have been exploring a vast multitude of scenarios of physics beyond the Standard Model

- New gauge interactions (Z', W') or extra Higgs bosons
- Additional fermionic partners of quarks and leptons, leptoquarks, …
- Composite nature of quarks and leptons
- Supersymmetry, in a variety of twists (minimal, constrained, natural, RPV, …)
- Dark matter, long lived particles
- Extra dimensions
- New flavour phenomena
- unanticipated surprises …

No signal so far, except perhaps from flavour …

Key question for the future developments of HEP: Why don't we see the new physics we expected to be present around the TeV scale ?

- **Is the mass scale beyond the LHC reach ?**

- **Is the mass scale within LHC's reach, but final states are elusive to the direct search ?**

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios is the best hedge for the field:
- *precision*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*

Remark

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

The physics potential (the "case") of a future facility for HEP should be weighed against criteria such as:

(1) the **guaranteed deliverables:**

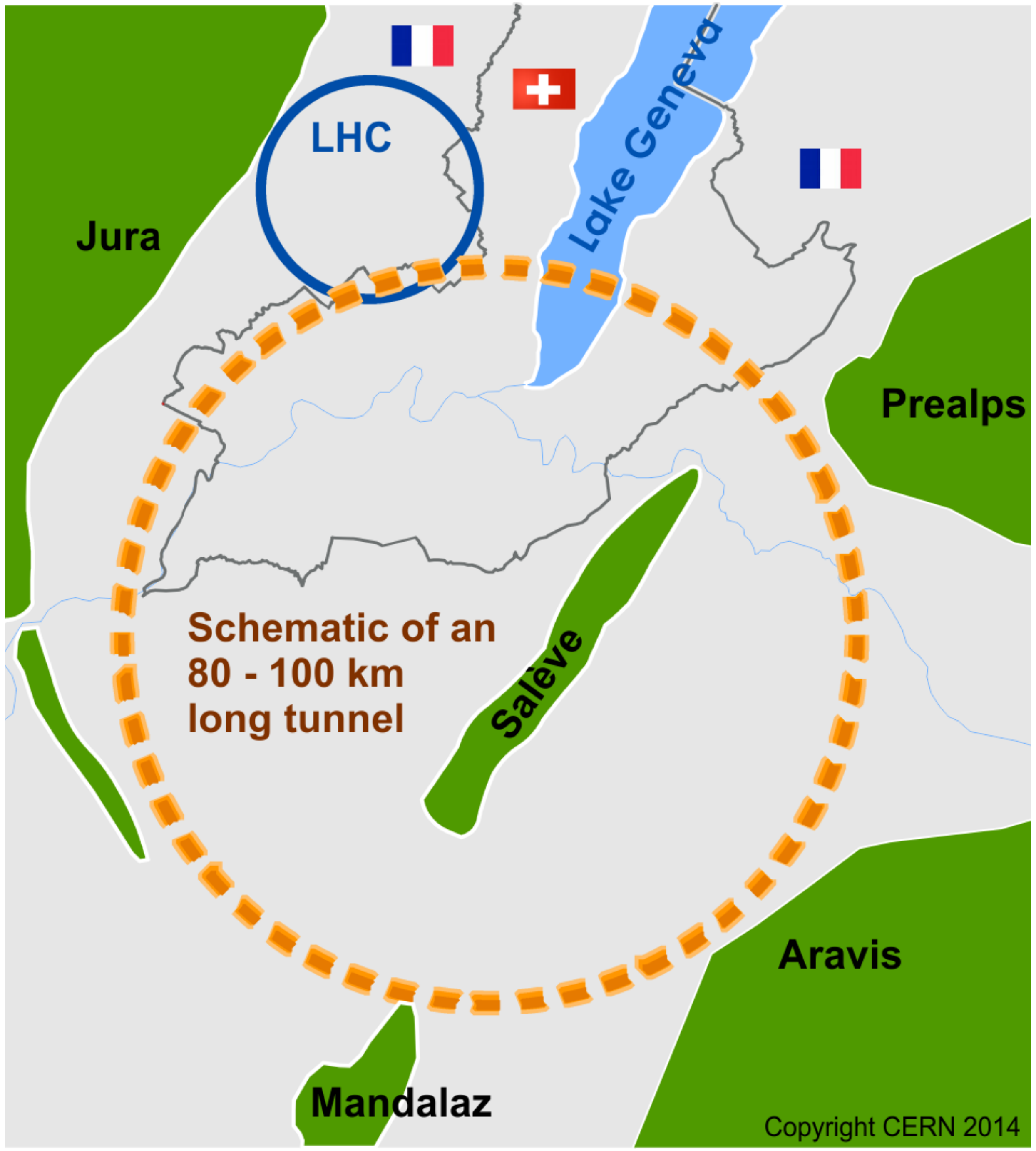
- knowledge that will be acquired independently of possible discoveries (*the value of "measurements"*)

(2) the **exploration potential:**

- target broad and well justified BSM scenarios .... *but guarantee sensitivity to more exotic options*
- exploit both direct (large Q^2) and indirect (precision) probes

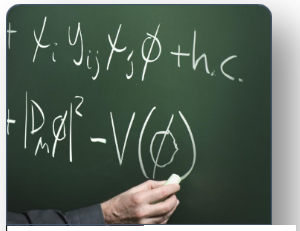
(3) the potential to provide conclusive **yes/no answers** to relevant, broad questions.

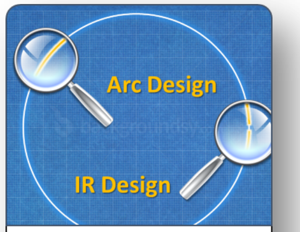
Future Circular Colliders (FCC)



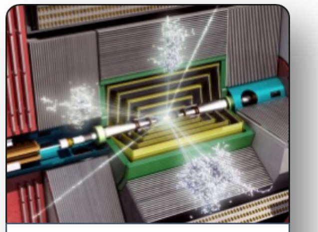
International FCC collaboration (CERN as host lab) to study:

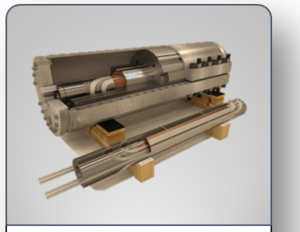
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements
  ~16 T ⇒ 100 TeV *pp* in 100 km
- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** integration of one IP, e from ERL
- **CDR for end 2018**


Physics potential



Collider Designs


Experiments


R&D Programs


Infrastructures


Cost Estimates

The potential of a Future Circular Collider

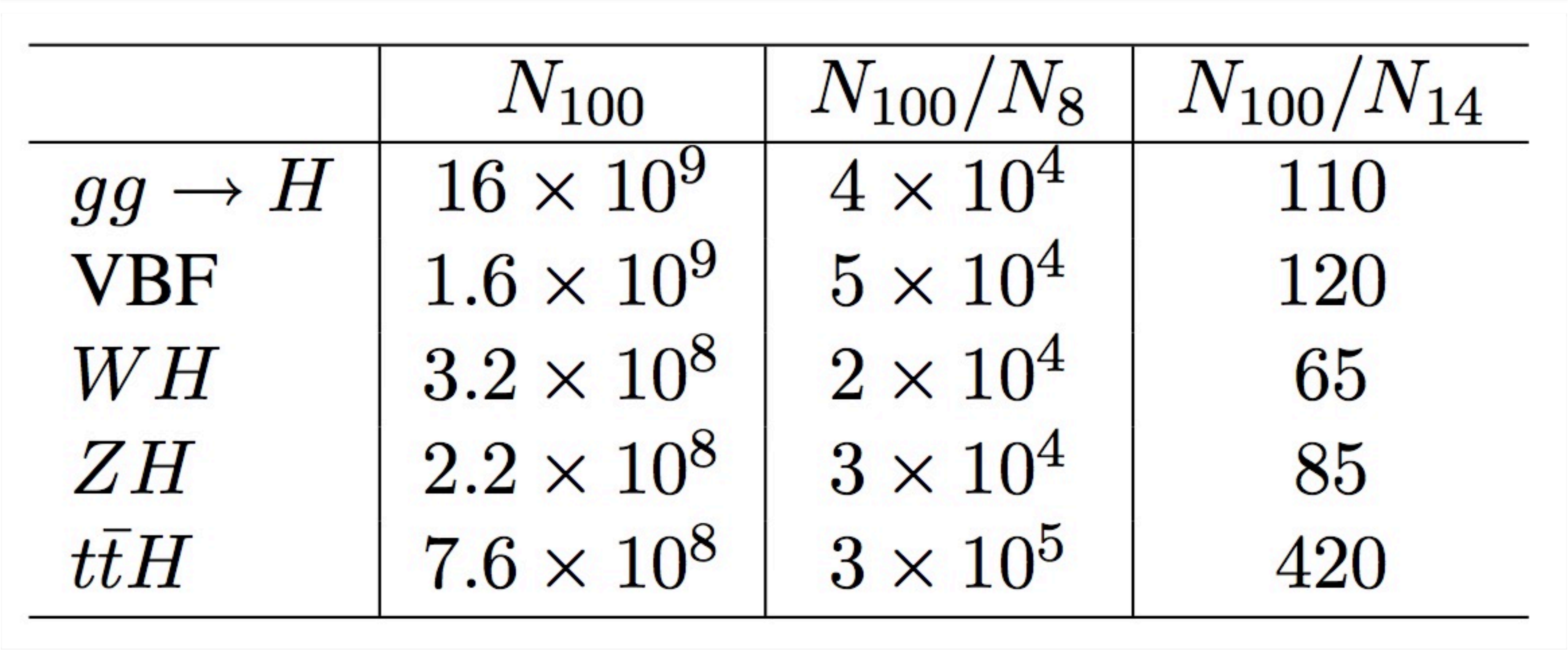
- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with unmatchable **precision and sensitivity**
- Exploration potential:
  - **mass reach enhanced** by factor ~ E / 14 TeV (will be 5–7 at 100 TeV, depending on integrated luminosity)
    - *statistics enhanced by several orders of magnitude for BSM phenomena brought to light by the LHC*
  - benefit from both direct (large Q^2) and indirect (precision) probes
- Provide firm Yes/No answers to questions like:
  - is the SM dynamics all there is at the TeV scale?
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - did baryogenesis take place during the EW phase transition?

a remark

- Last week you had Uta Klein covering eh, and Alain Blondel will discuss in detail next week the **FCC-ee**, so I'll focus on FCC-hh
- The **FCC-hh** is part of the whole FCC, and it's the full exploitation of the FCC complex that guarantees the maximal outcome
- But the **FCC-hh** experiments are extremely versatile, and potentially capable, stand alone, to address a major part of the whole FCC programme
- As **FCC-hh**, we must explore every corner of its potential, from the discovery reach, to the precision frontier.
- This puts the value of the individual projects in the right perspective, vis a vis possible future developments in HEP (eg discoveries at the LHC), in technology progress (eg time scale for 16T magnets), in the overall HEP landscape (eg approval of ILC, …), and in the political landscape (costs).
- And of course identifying areas where both ee and pp have independent sensitivity stimulates the assessment of synergy and complementarity ….

Higgs physics

SM Higgs rates at 100 TeV



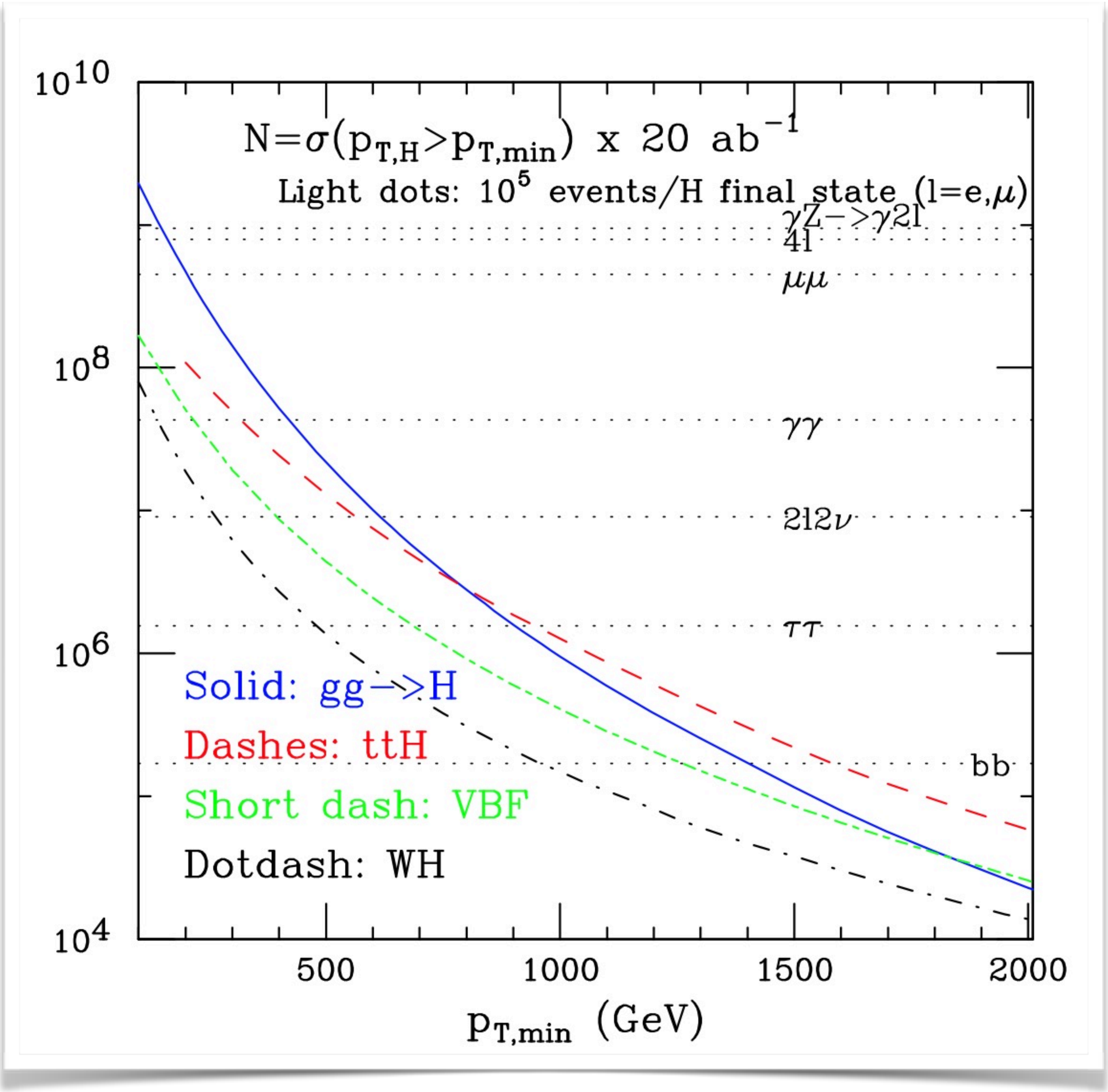
	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

$N_{100} = \sigma_{100\,\text{TeV}} \times 20\ \text{ab}^{-1}$

$N_8 = \sigma_{8\,\text{TeV}} \times 20\ \text{fb}^{-1}$

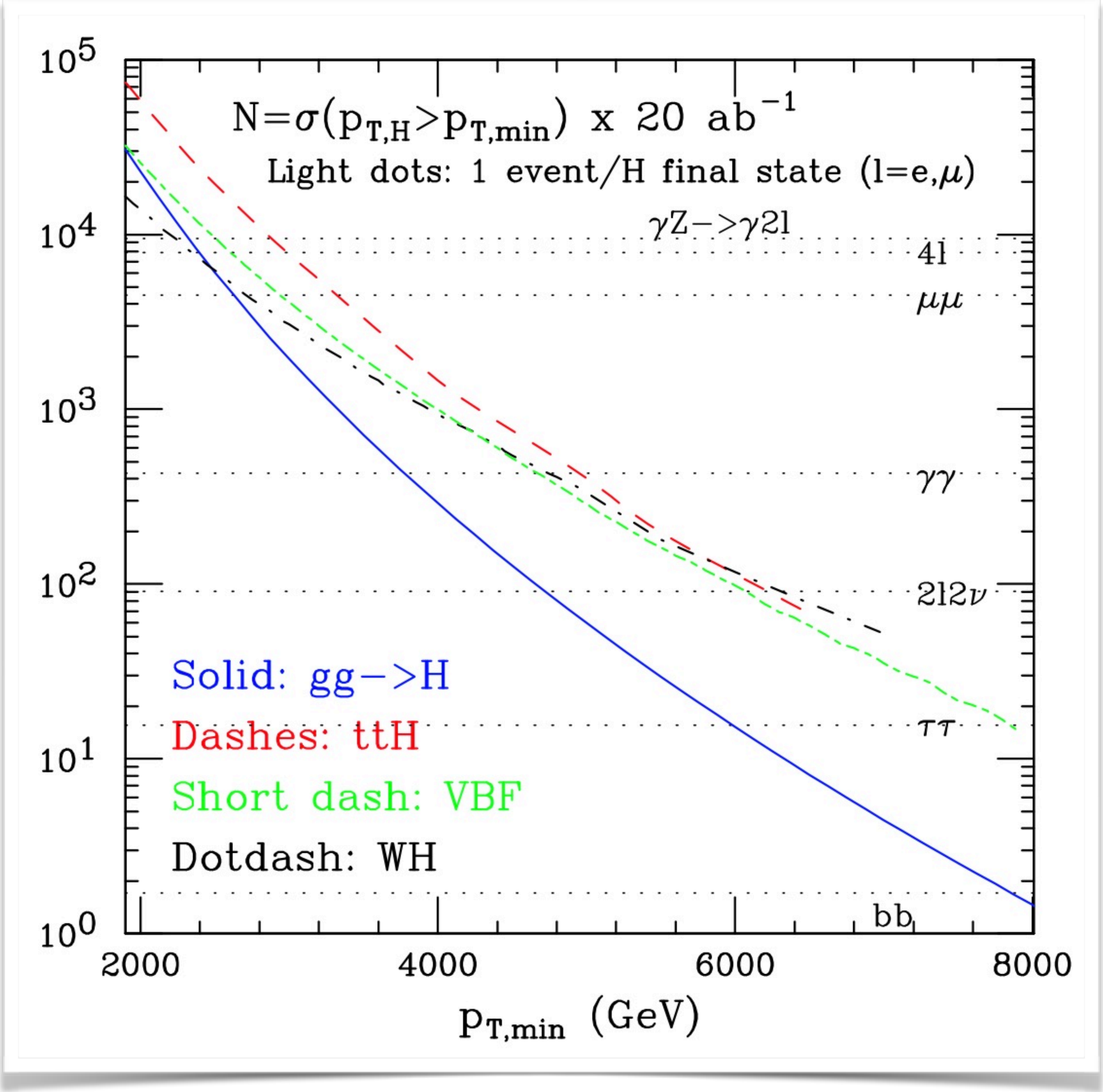
$N_{14} = \sigma_{14\,\text{TeV}} \times 3\ \text{ab}^{-1}$

H at large p_T



- Hierarchy of production channels changes at large $p_T(H)$:
  - $\sigma(ttH) > \sigma(gg \to H)$ above 800 GeV
  - $\sigma(VBF) > \sigma(gg \to H)$ above 1800 GeV

H at large p_T



- Statistics in potentially visible final states out to several TeV

Remarks

- Higher statistics shifts the balance between systematic and statistical uncertainties. It can be exploited to define different signal regions, with better S/B, better systematics, pushing the potential for better measurements beyond the "systematics wall" of low-stat measurements.
- We often talk about "**precise**" Higgs measurements. What we actually aim at, is "**sensitive**" tests of the Higgs properties, where *sensitive* refers to the ability to reveal BSM behaviours.
- *Sensitivity* may not require extreme precision
  - Going after "sensitivity", rather than *just* precision, opens itself new opportunities …

Higgs as a BSM probe: precision vs dynamic reach

$$\boxed{L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots}$$

$$O = |\langle f|L|i\rangle|^2 = O_{SM}\left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

For H decays, or inclusive production, μ~O(v,m_H)

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$$

⇒ **precision** probes large Λ

e.g. δO=1% ⇒ Λ ~ 2.5 TeV

For H production off-shell or with large momentum transfer Q, μ~O(Q)

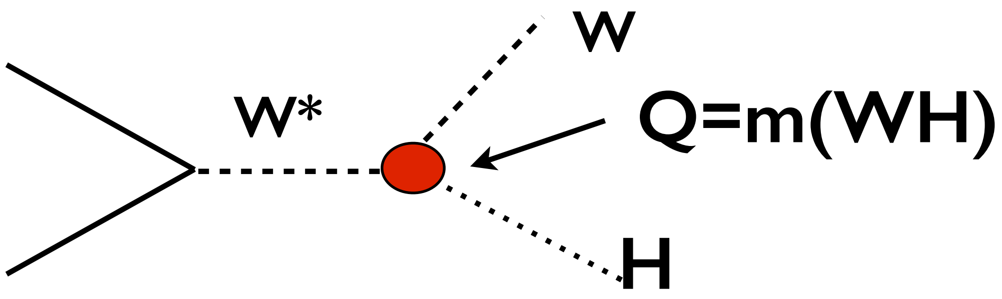
$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

⇒ **kinematic reach** probes large Λ even if precision is low

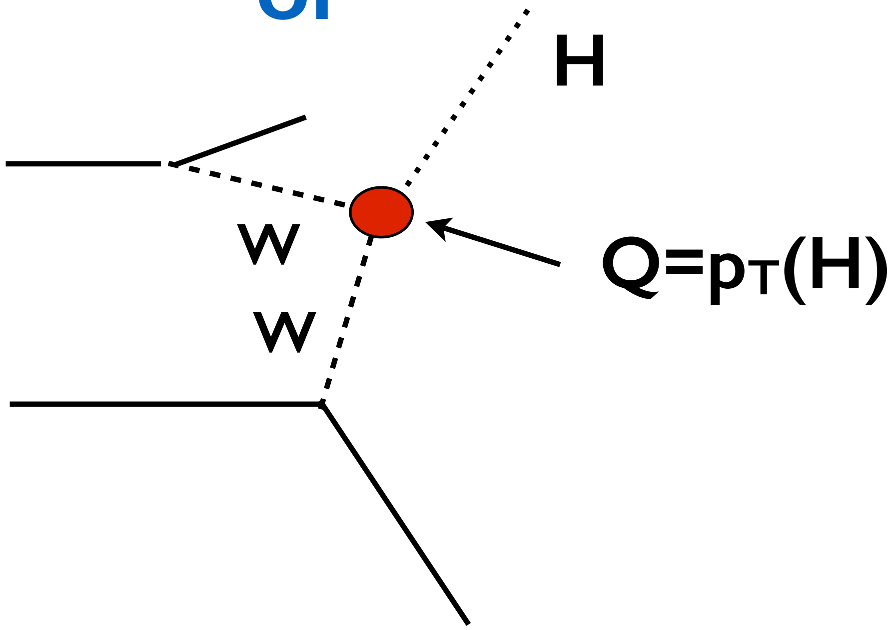
e.g. δO=15% at Q=1 TeV ⇒ Λ~2.5 TeV

Examples

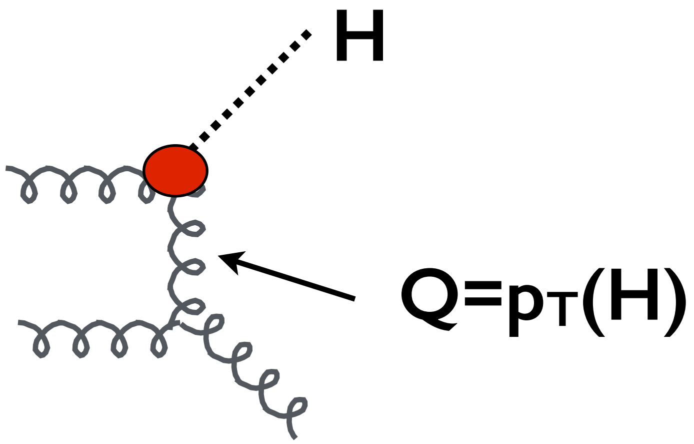
$\delta BR(H\to WW^*)$ ⟷



or

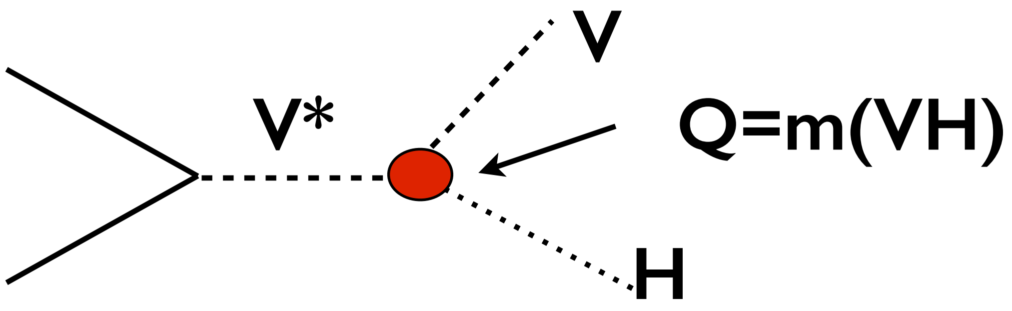


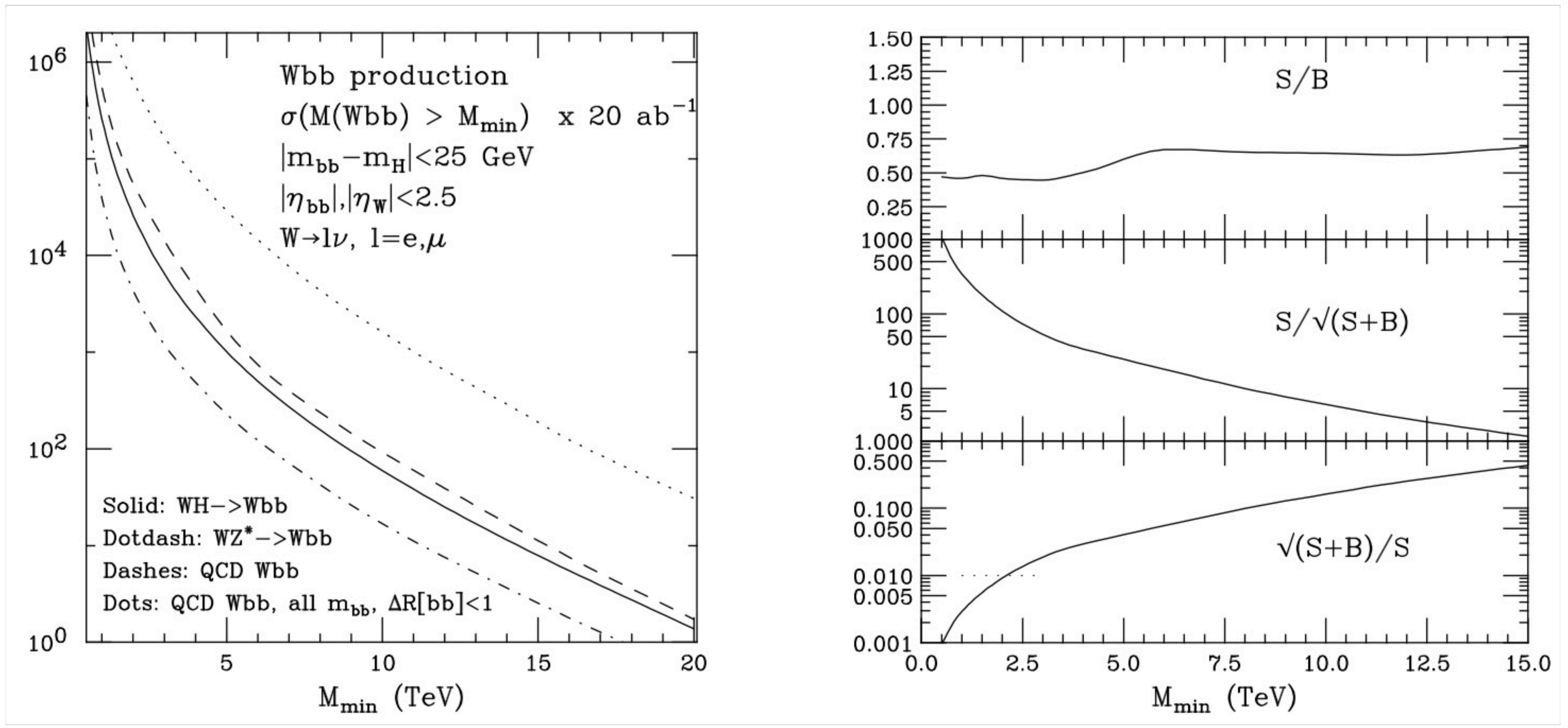
$\delta BR(H\to gg)$ ⟷



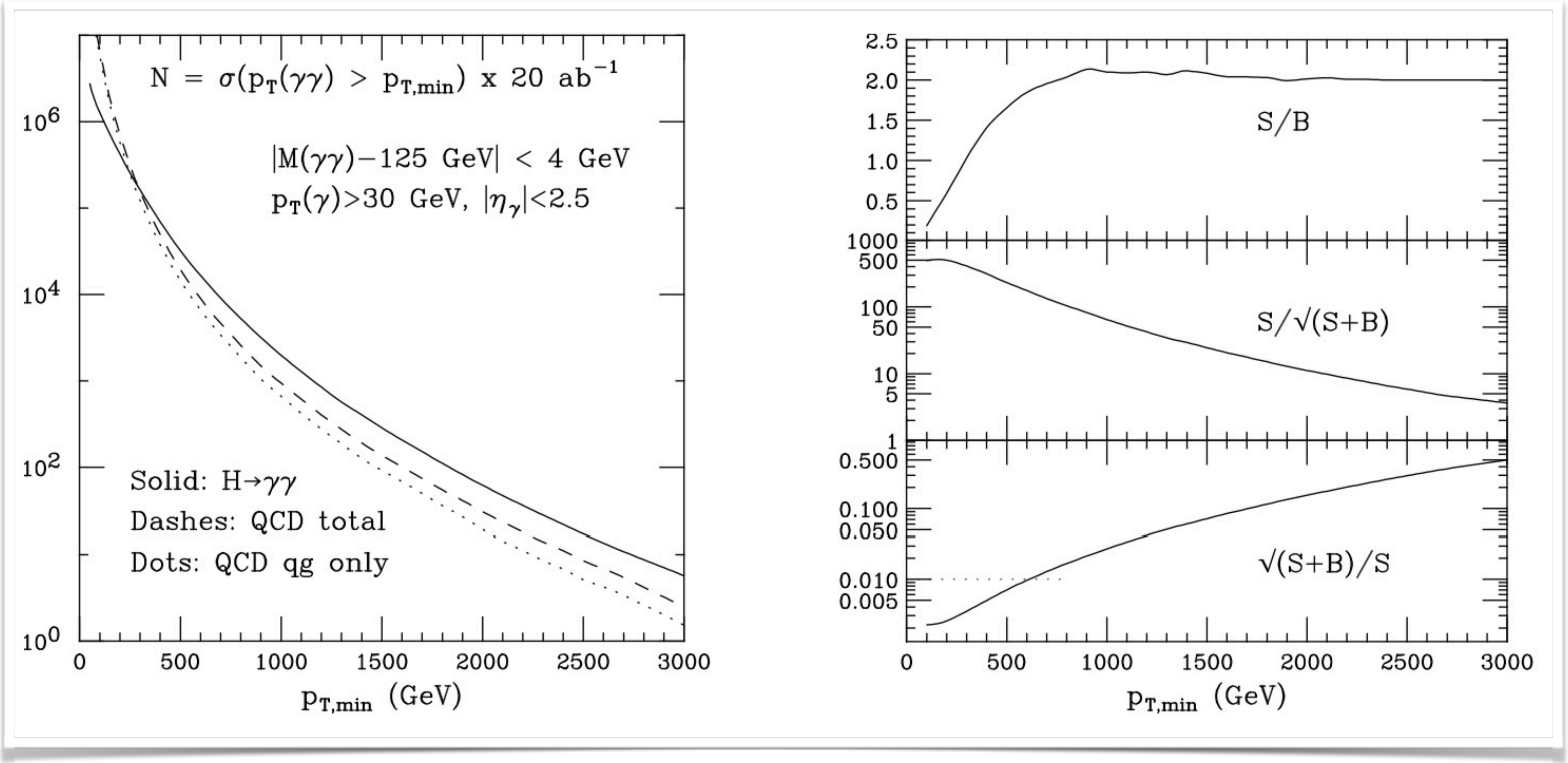
WH→Wbb at large M_{WH}

100 TeV





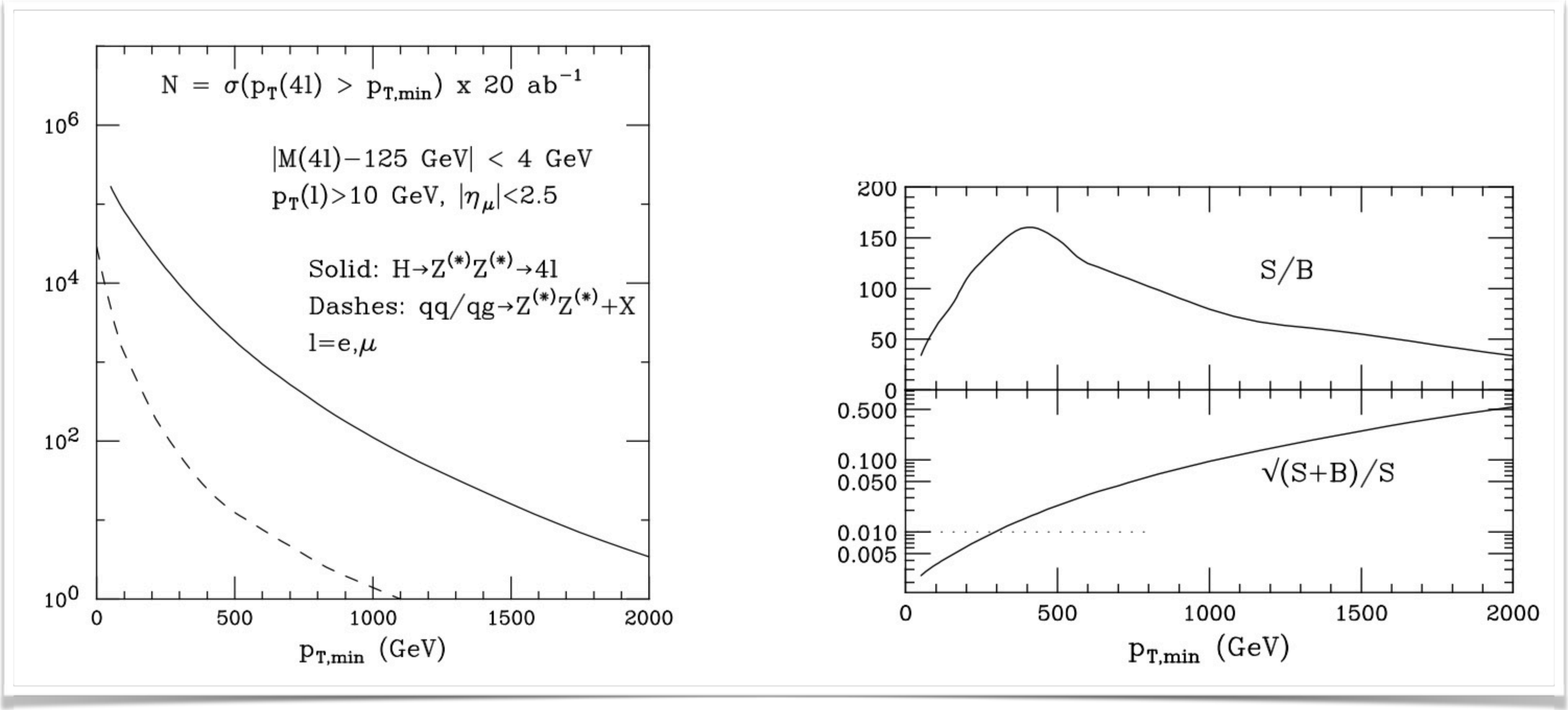
$gg \to H \to \gamma\gamma$



- At LHC, S/B in the $H \to \gamma\gamma$ channel is O(few %)
- At FCC, for $p_T(H)>300$ GeV, S/B~1
- Potentially accurate probe of the H pt spectrum up to large pt:
  - What is a best BSM probe: BR(γγ) or shape of pT(H)?
    - answer likely BSM-model dependent
    - ==> synergy/complementarity !!

$p_{T,min}$	δ_{stat}
100	**0.2%**
400	**0.5%**
600	**1%**
1600	10%

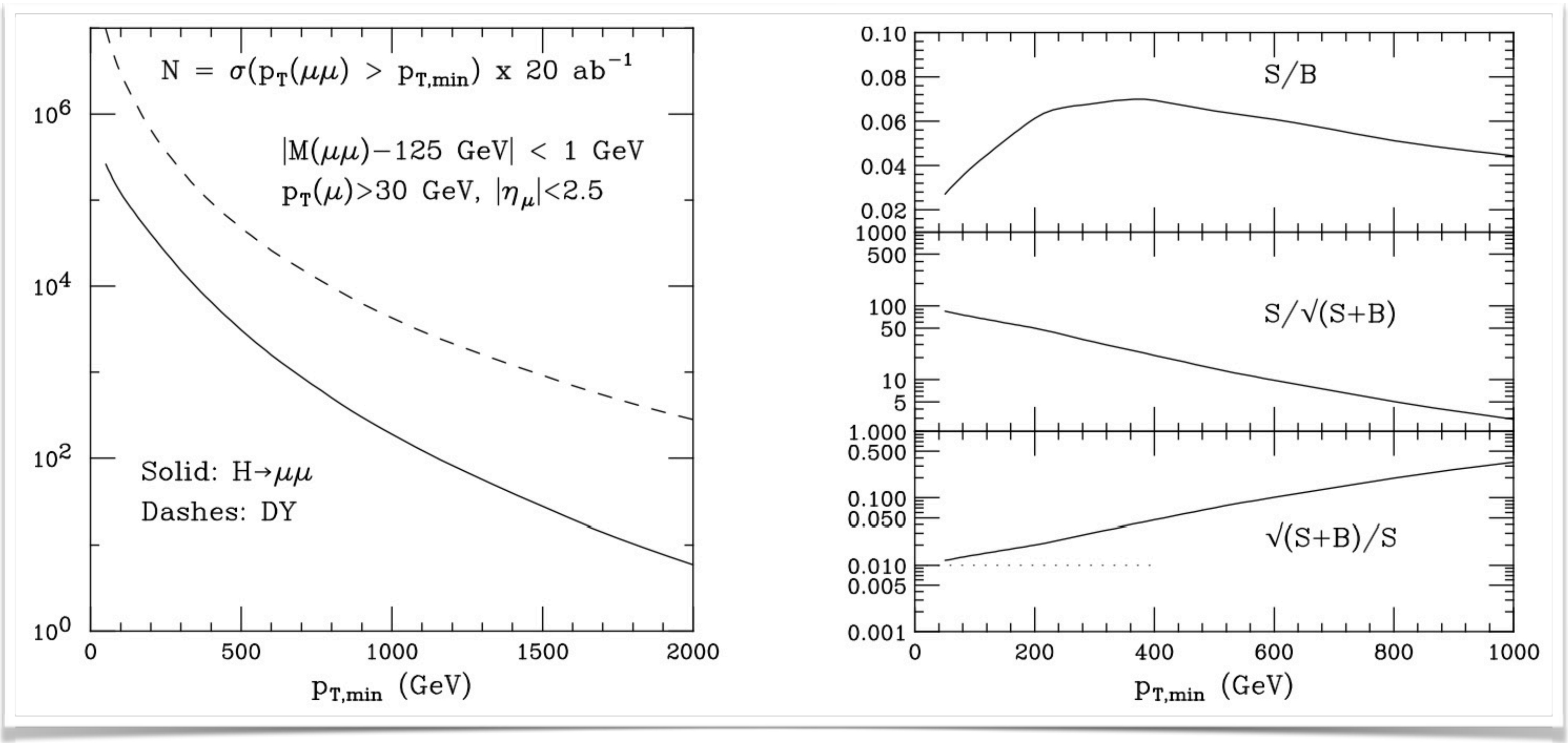
gg→H→ZZ*→4l



- S/B ~ 1 for inclusive production at LHC
- Practically bg-free at large p_T at 100 TeV, maintaining large rates

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.3%**
300	**1%**
1000	10%

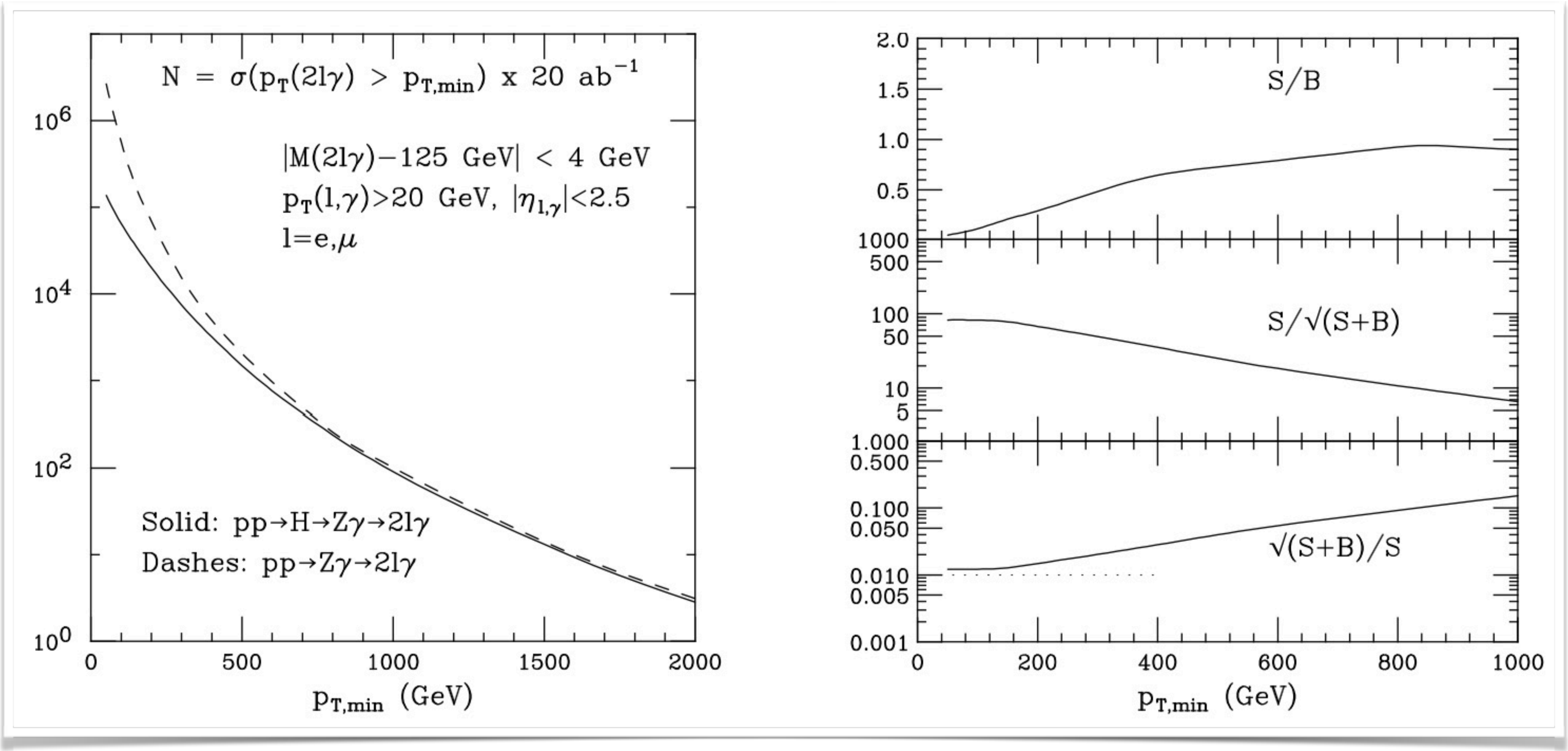
gg→H→μμ



- Stat reach ~1% at p_T~100 GeV
- Exptl systematics on BR(μμ)/BR(γγ)? (use same fiducial selection to remove H modeling syst's)

$p_{T,min}$ (GeV)	δ_{stat}
100	**1%**
500	10%

gg→H→Zγ→ℓℓγ

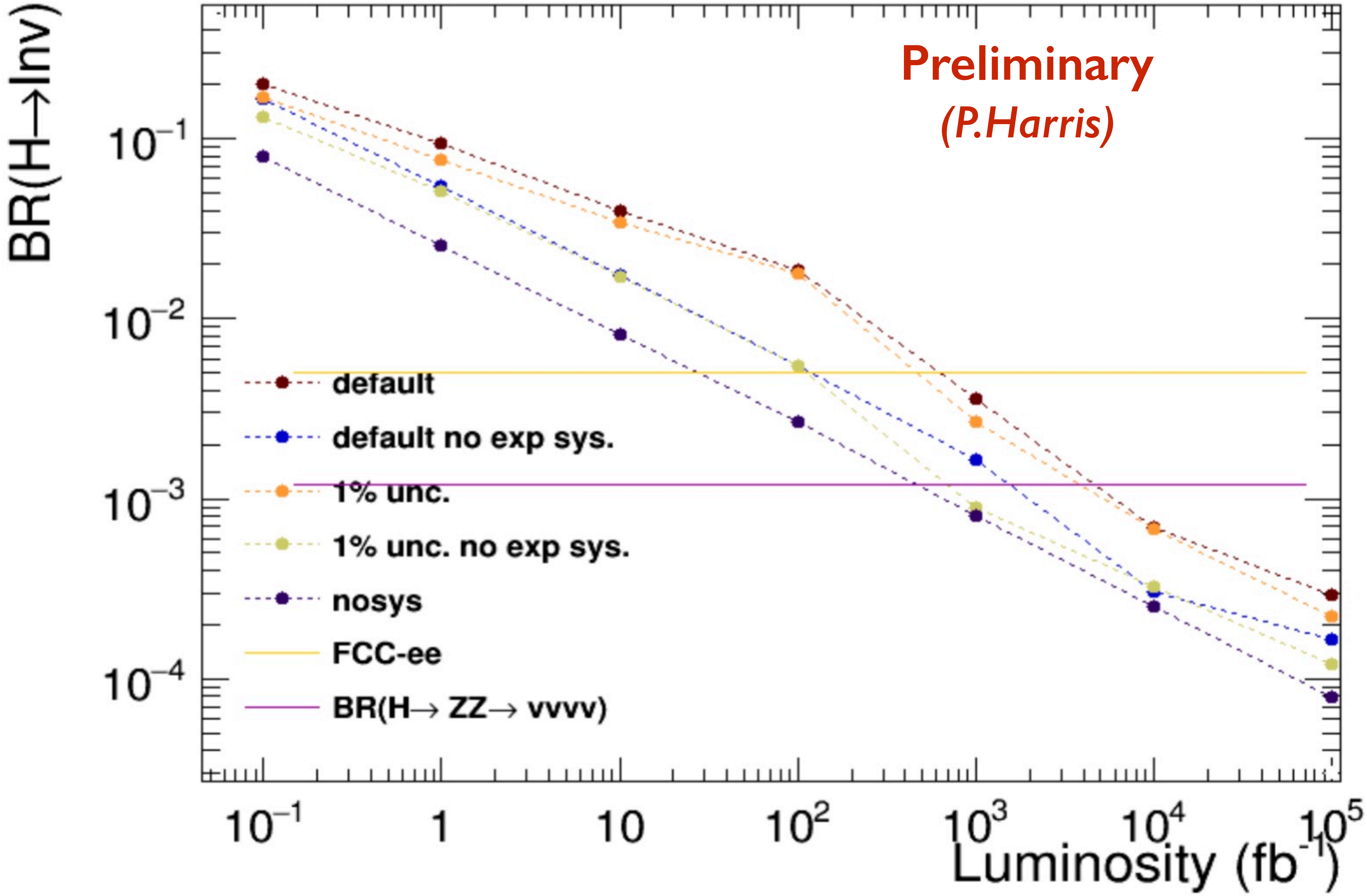


- S/B → 1 at large p_T
- Stat reach ~1% at pT~100 GeV
- Exptl systematics on BR(Zγ)/BR(γγ)?

$p_{T,min}$ (GeV)	δ_{stat}
100	**1%**
900	10%

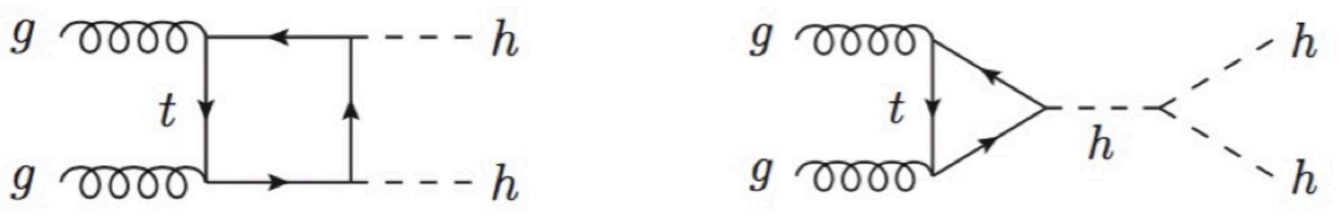
BR(H→inv) in H+X production at large p_T(H)

Constrain bg pt spectrum from Z→νν to the % level using NNLO QCD/EW to relate to measured Z→ee, W and γ spectra



SM sensitivity with 1ab^{-1}, can reach few x 10^{-4} with 30ab^{-1}

H selfcoupling determination, from gg→HH→γγbb



	$\Delta_S = 0.00$	$\Delta_S = 0.01$	$\Delta_S = 0.015$	$\Delta_S = 0.02$	$\Delta_S = 0.025$
$r_B = 0.5$	2.7%	3.4%	4.1%	4.9%	5.8%
$r_B = 1.0$	3.4%	3.9%	4.6%	5.3%	6.1%
$r_B = 1.5$	3.9%	4.4%	5.0%	5.7%	6.4%
$r_B = 2.0$	4.4%	4.8%	5.4%	6.0%	6.8%
$r_B = 3.0$	5.2%	5.6%	6.0%	6.6%	7.3%

- overall rescaling of background rate $n_B \to r_B \times n_B$
- uncertainty on signal rate $\Delta_S = \dfrac{\Delta\sigma(pp \to hh)}{\sigma(pp \to hh)}$

Results updated/confirmed with improved analysis by M.Selvaggi, https://indico.cern.ch/event/613195/

Higgs couplings @ FCC

g_{HXY}	ee [240+350 (4IP)]	pp [100 TeV] 30ab^{-1}	ep [60GeV/50TeV], 1ab^{-1}
ZZ	0.15%	<1%	
WW	0.19%		
bb	0.42%		0.2%
cc	0.71%		1.8%
gg	0.80%		
ττ	0.54%		
μμ	6.2%	<1%	
γγ	1.5%	<0.5%	
Zγ		<1%	
tt	~13%	1%	
HH	~30%	3.5%	under study
uu,dd	H->ργ, under study		
ss	H->φγ, under study		
BR_{inv}	< 0.45%	few 10^{-4}	
Γ_{tot}	1%		

One should not underestimate the value of FCC-hh standalone precise “ratios-of-BRs" measurements:

- independent of α_S, m_b, m_c, Γ_{inv} systematics
- sensitive to BSM effects that typically influence BRs in different ways. Eg

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

loop-level tree-level

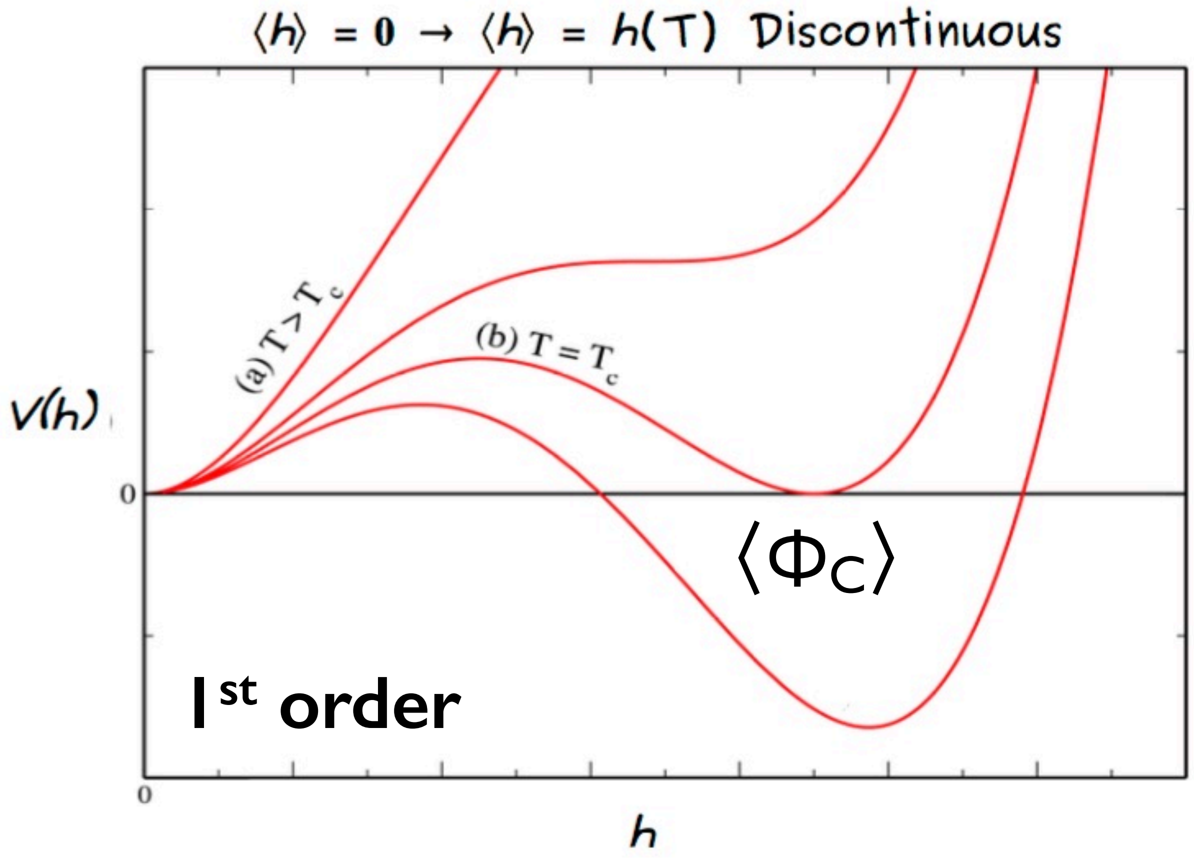
$BR(H\to\mu\mu)/BR(H\to ZZ^*)$

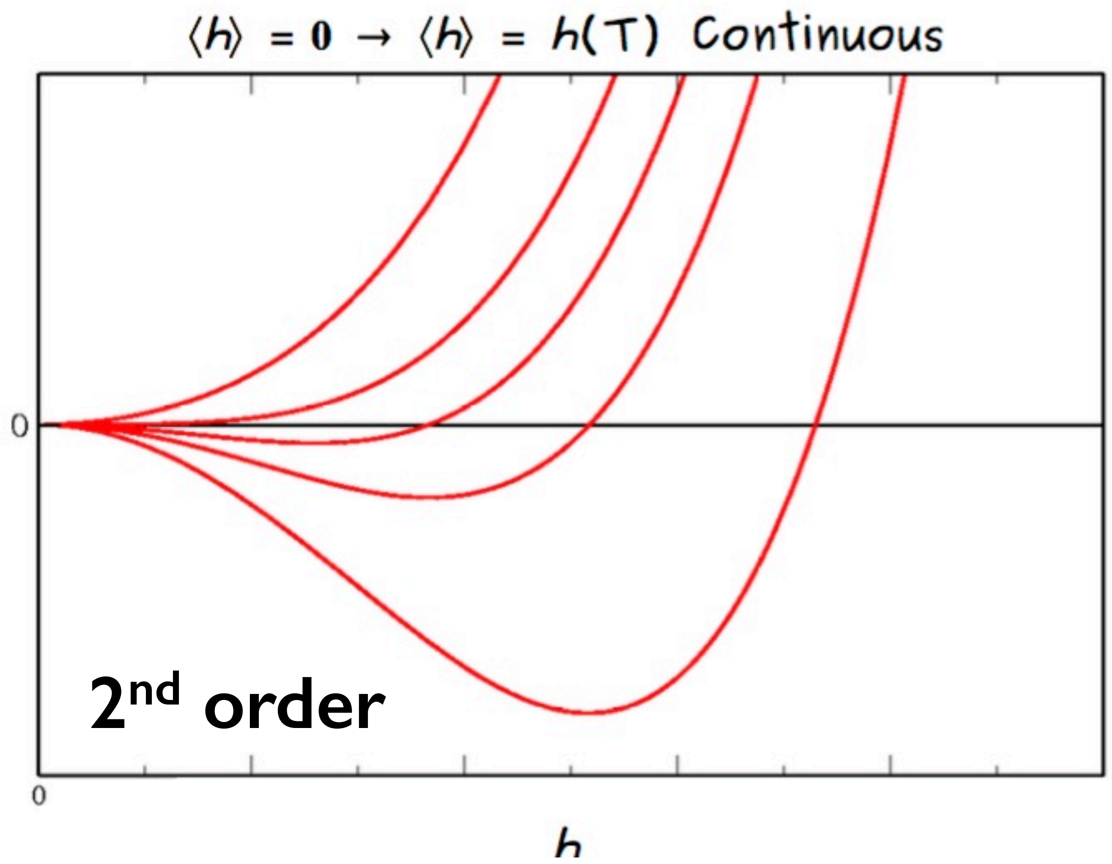
2nd gen’n Yukawa gauge coupling

$BR(H\to\gamma\gamma)/BR(H\to Z\gamma)$

different EW charges in the loops of the two procs

The nature of the EW phase transition


$\langle h \rangle = 0 \to \langle h \rangle = h(T)$ Discontinuous


$\langle h \rangle = 0 \to \langle h \rangle = h(T)$ Continuous

Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

Strong 1st order phase transition ⇒ $\langle \Phi_C \rangle > T_C$

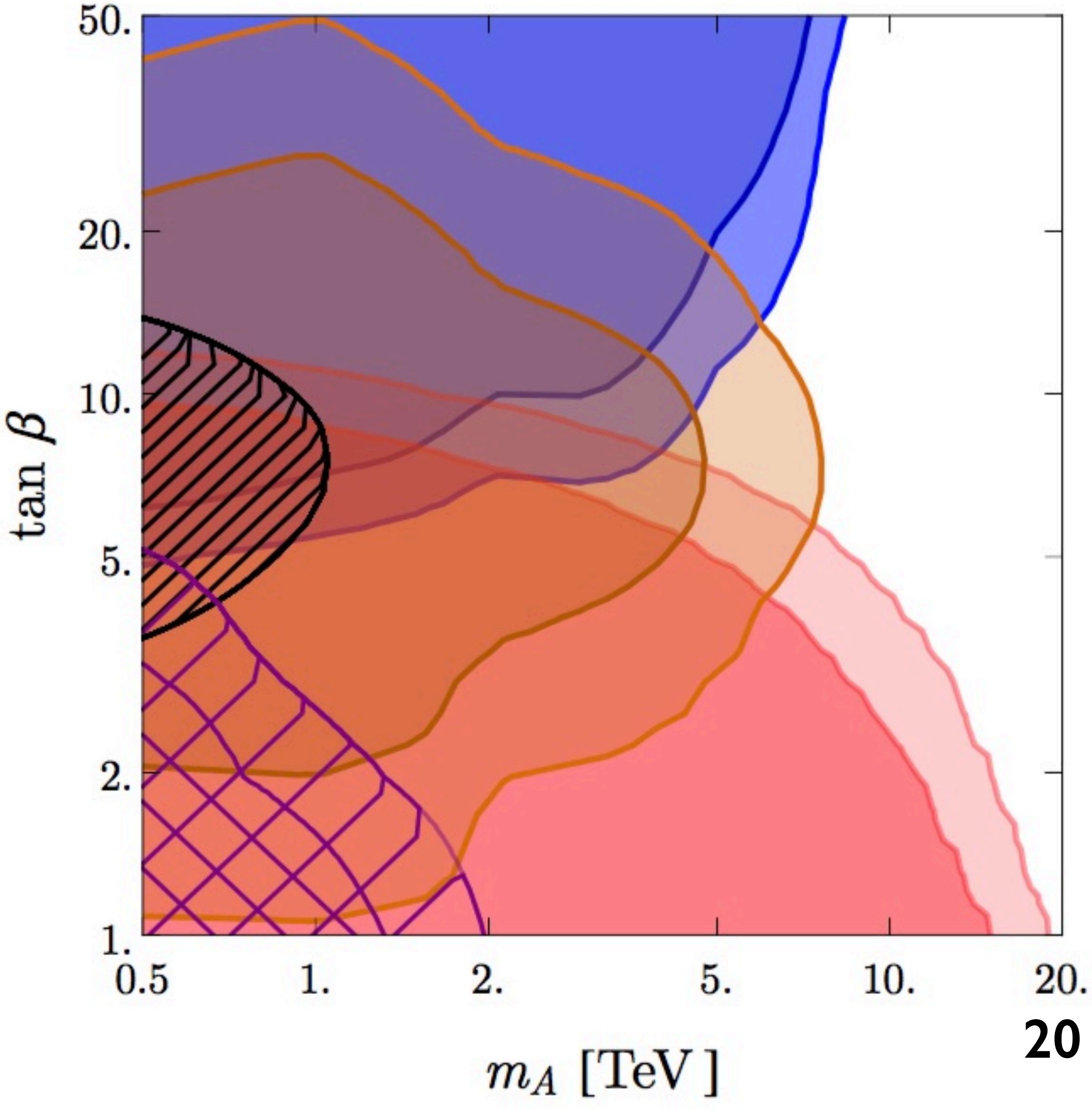
In the SM this requires $m_H \lesssim 80$ GeV, else transition is a smooth crossover.

Since $m_H = 125$ GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

- **Probe higher-order terms of the Higgs potential (selfcouplings)**
- **Probe the existence of other particles coupled to the Higgs**

MSSM Higgs @ 100 TeV

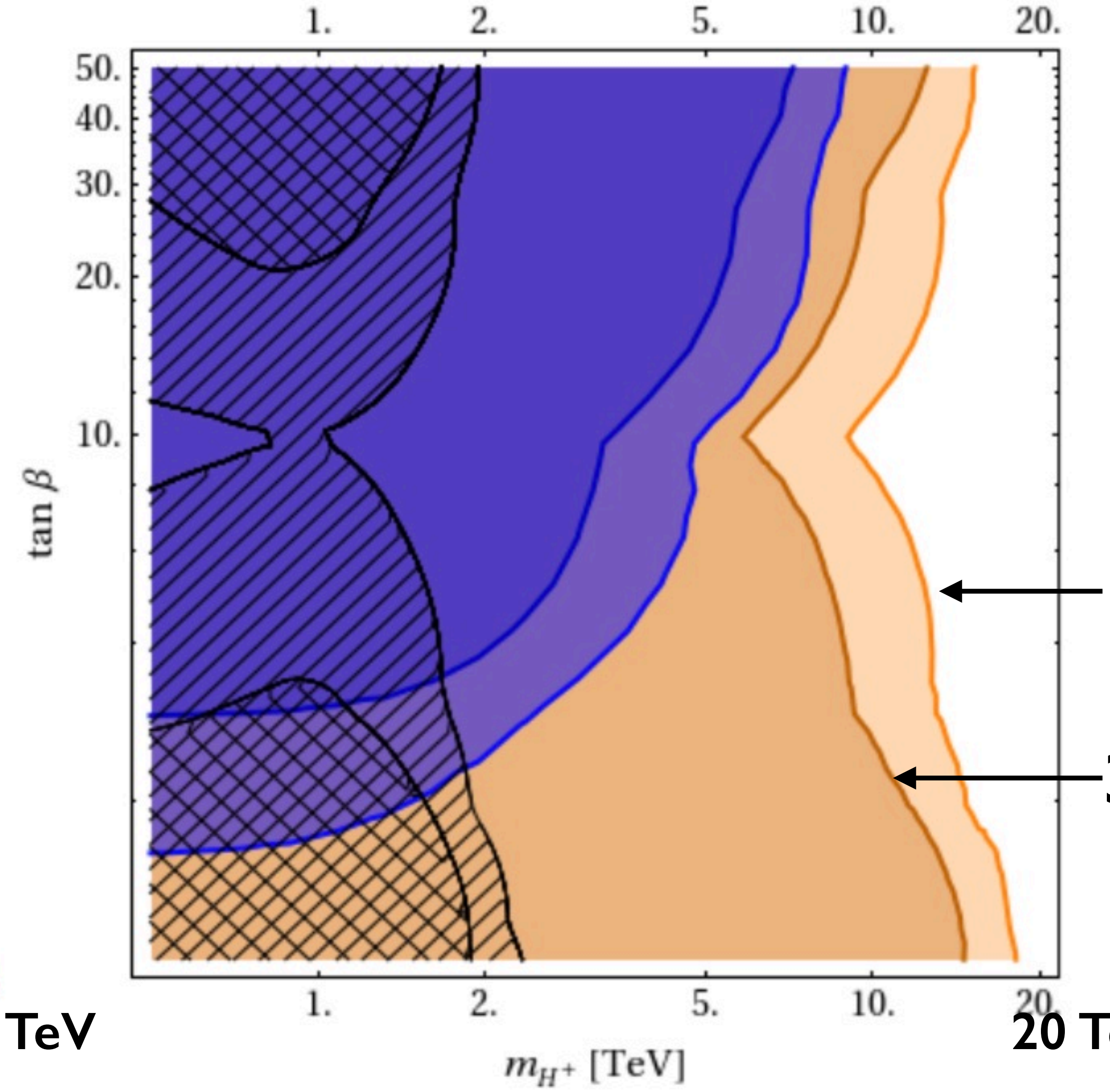
- 🟦 $bbH^0/A^0 \to bb\tau\tau$
- 🟧 $bbH^0/A^0 \to bbtt$
- 🟥 $t(t)H^0/A^0 \to t(t)tt$



20 TeV

- 🟦 $tbH^+ \to tb\tau\nu$
- 🟧 $tbH^+ \to tbtb$

- ▨ LHC 3 ab^{-1}
- ▩ LHC 0.3 ab^{-1}



30 ab^{-1}

3 ab^{-1}

20 TeV

N. Craig, J. Hajer, Y.-Y. Li, T. Liu, H. Zhang, arXiv:1605.08744

J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu, arXiv:1504.07617

Minimal stealthy model for a strong EW phase transition: *the most challenging scenario for discovery*

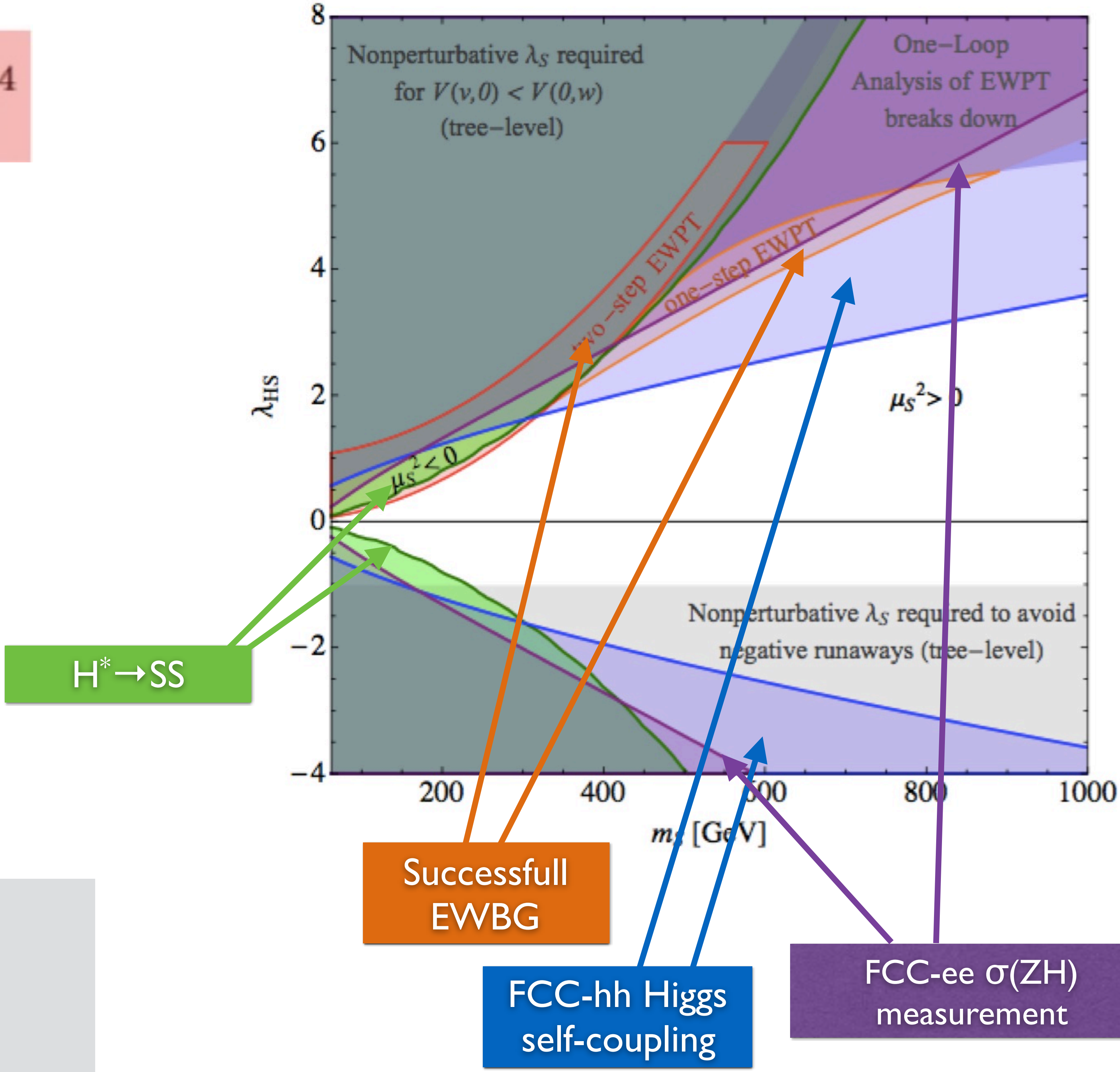
$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4$$

Unmixed SM+Singlet.
No exotic H decay, no H-S mixing,
no EWPO, …

Two regions with strong EWPT

Only Higgs Portal signatures:
- $h^* \to SS$ direct production
- Higgs cubic coupling
- σ(Zh) deviation (> 0.6% @ TLEP)

Curtin, Meade, Yu, arXiv:1409.0005



$H^* \to SS$

Successfull EWBG

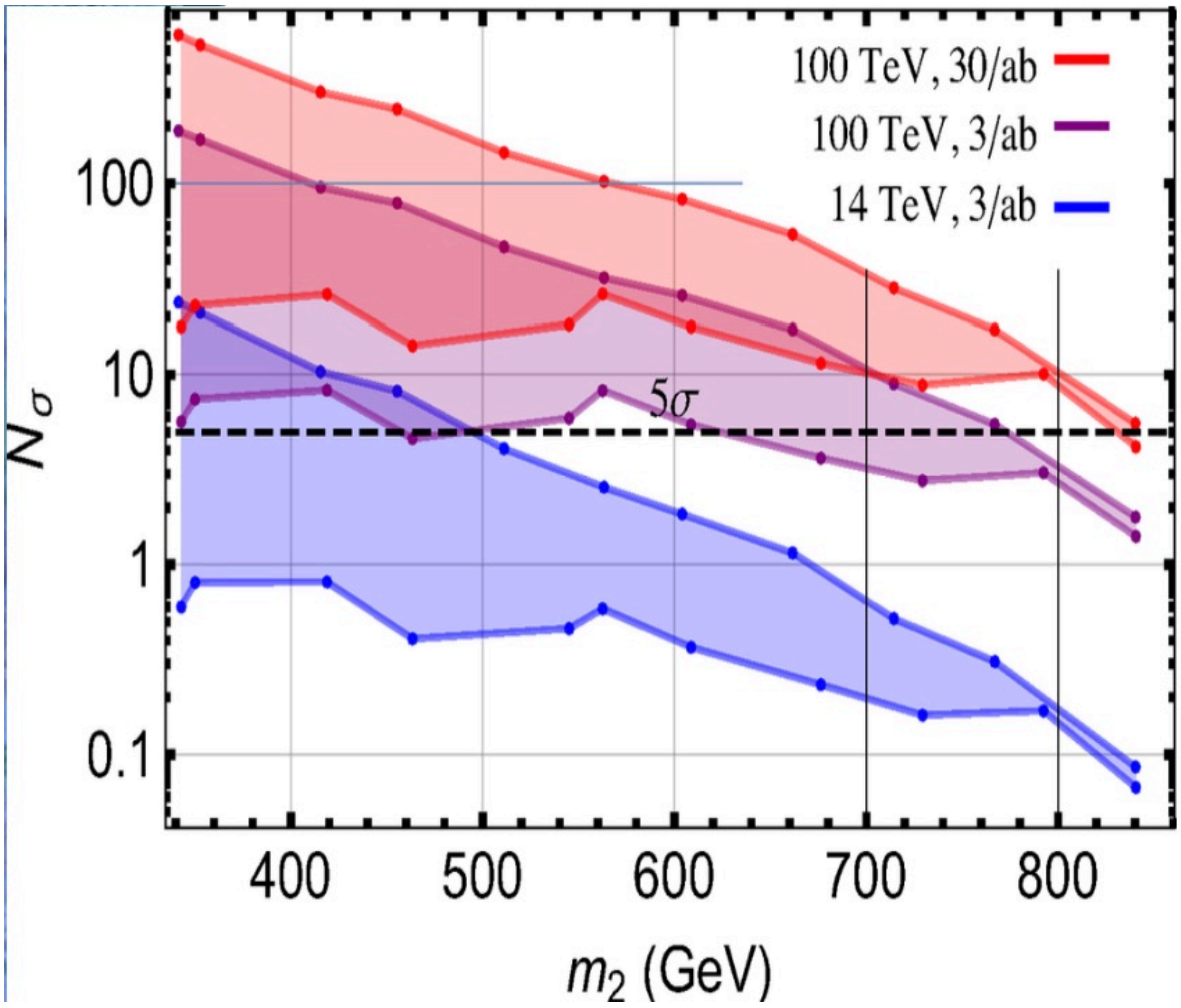
FCC-hh Higgs self-coupling

FCC-ee σ(ZH) measurement

⇒ Appearance of first "no-lose" arguments for classes of compelling scenarios of new physics

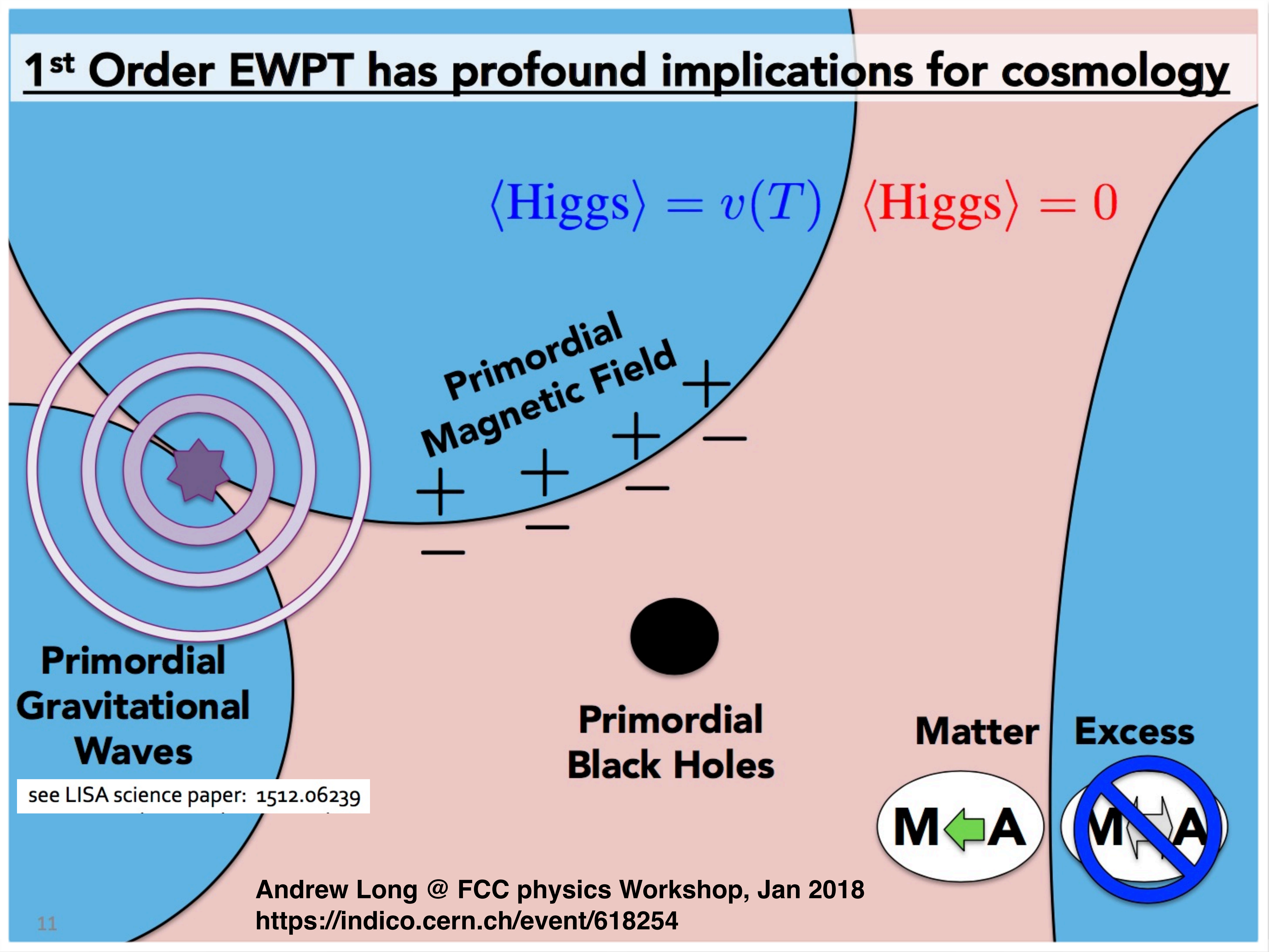
Sensitivity to extra Higgs bosons enabling a 1st order EWPT

$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$



Notice role of energy and of luminosity

Kotwal, No, Ramsey-Musolf, Winslow, arXiv:1605.06123



1st Order EWPT has profound implications for cosmology

$\langle \text{Higgs} \rangle = v(T)$ $\langle \text{Higgs} \rangle = 0$

Primordial Magnetic Field

Primordial Gravitational Waves

see LISA science paper: 1512.06239

Primordial Black Holes

Matter Excess

Andrew Long @ FCC physics Workshop, Jan 2018
https://indico.cern.ch/event/618254

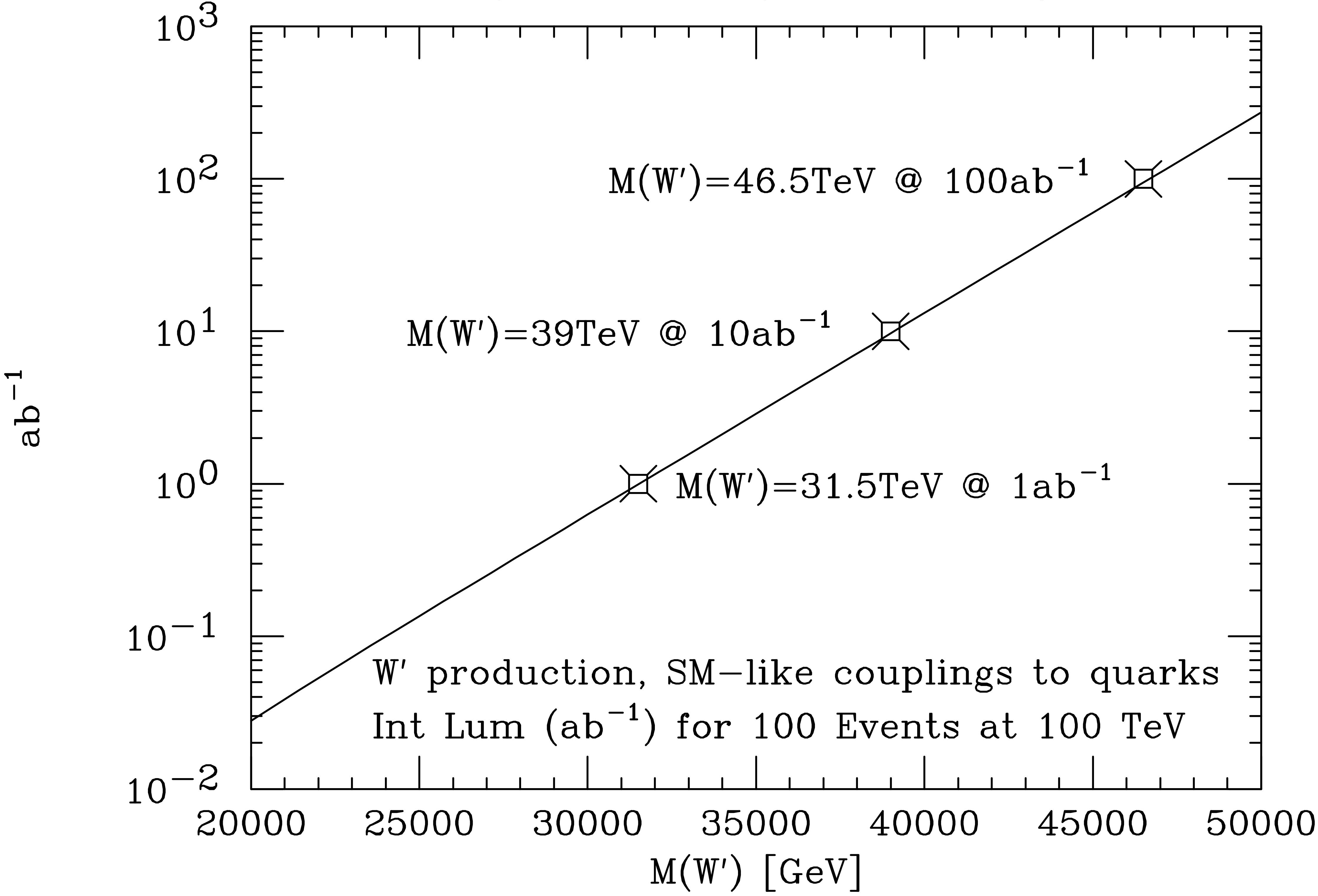
Direct discovery potential at the highest masses

at high mass, the reach of FCC-hh searches for BSM phenomena like Z', W', SUSY, LQs, top partners, etc.etc. scales trivially by ~5-7, depending on total luminosity …

New gauge bosons: discovery reach

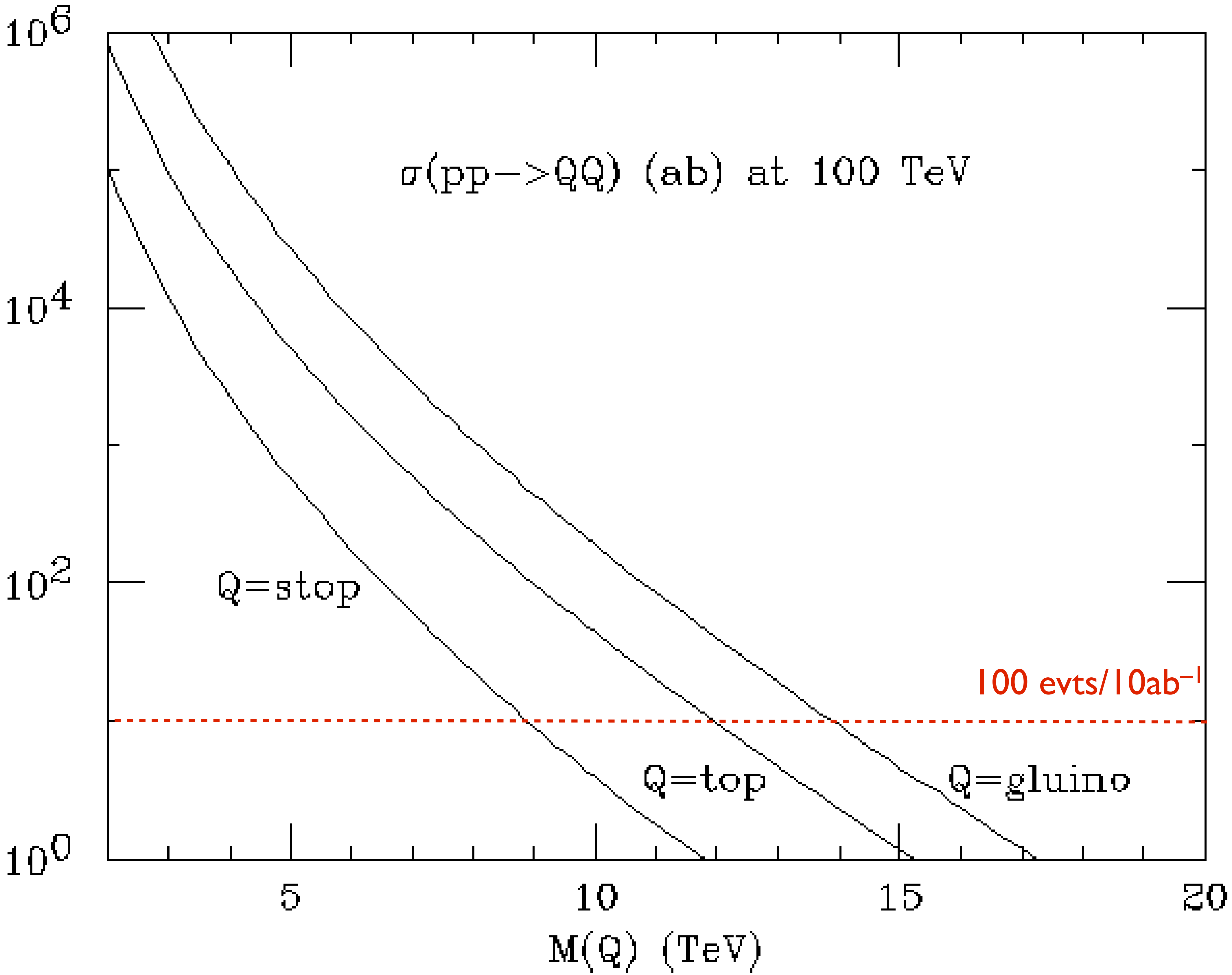
Example: **W' with SM-like couplings**

NB For SM-like Z', $\sigma_{Z'}$ BR_{lept} ~ 0.1 x $\sigma_{W'}$ BR_{lept} , ⇒ rescale lum by ~ 10



At L=O(ab^{-1}), Lum x 10 ⇒ ~ M + 7 TeV

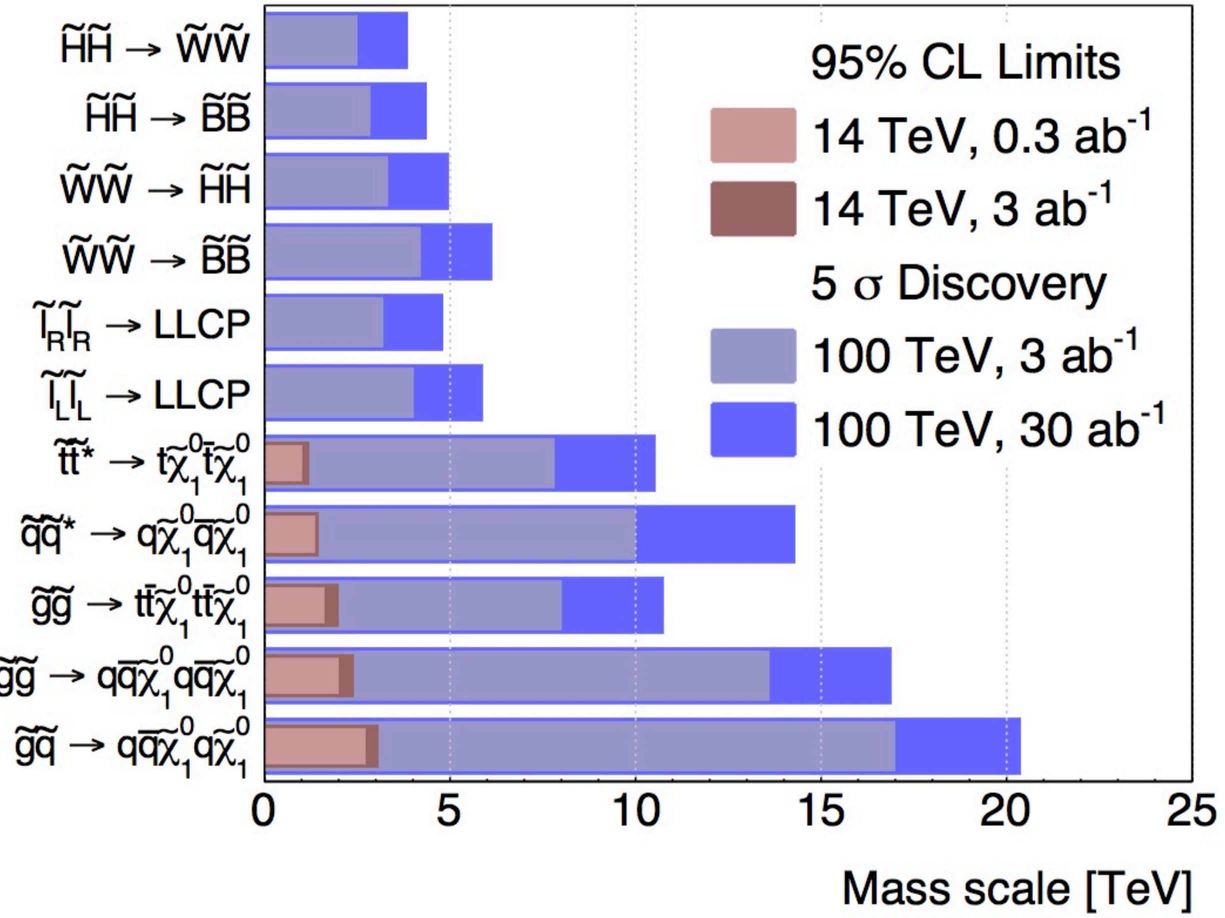
Discovery reach for pair production of strongly-interacting particles

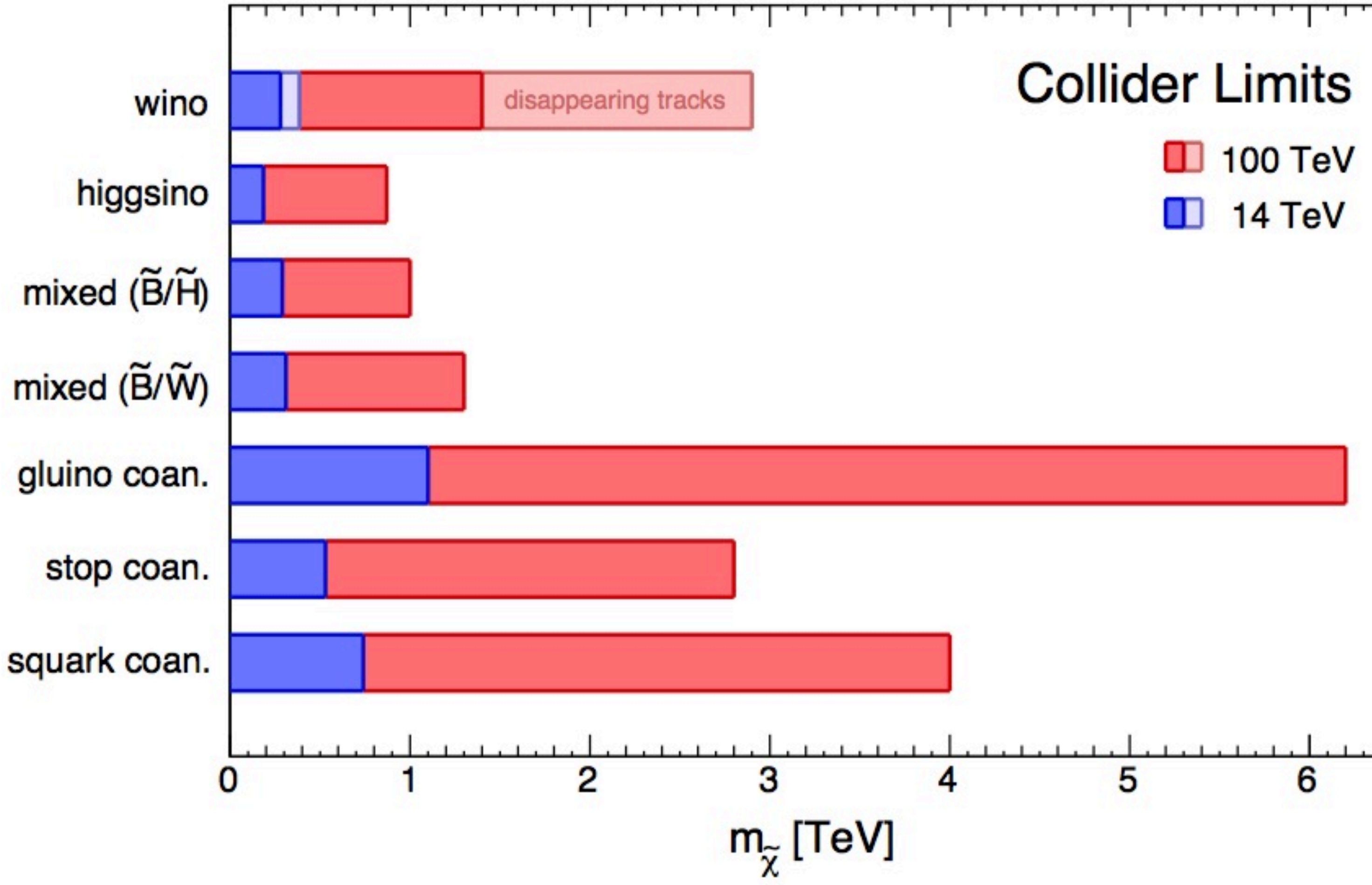


Dark Matter

- DM could be explained by BSM models that would leave no signature at any future collider (e.g. axions).
- More in general, no experiment can guarantee an answer to the question ”what is DM?”
- Scenarios in which DM is a WIMP are however compelling and theoretically justified
- **We would like to understand whether a future collider can answer more specific questions, such as:**
  - do WIMPS contribute to DM?
  - can WIMPS, detectable in direct and indirect (DM annihilation) experiments, be discovered at future colliders? Is there sensitivity to the explicit detection of DM-SM mediators?
  - what are the opportunities w.r.t. new DM scenarios (e.g. interacting DM, asymmetric DM, ...)?

SUSY and DM reach at 100 TeV





$$M_{\text{WIMP}} \leq 1.8\ \text{TeV}\left(\frac{g^2}{0.3}\right)$$

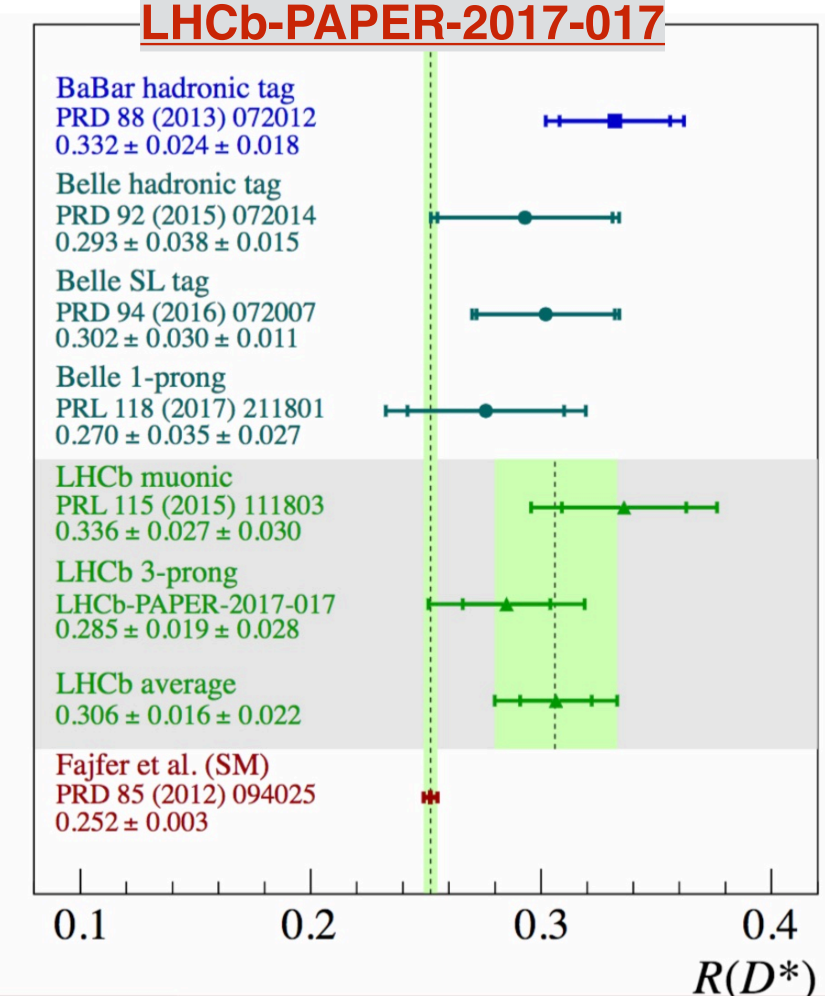
possibility to find (or rule out) thermal WIMP DM candidates

Flavour anomalies at LHC & Bfact's

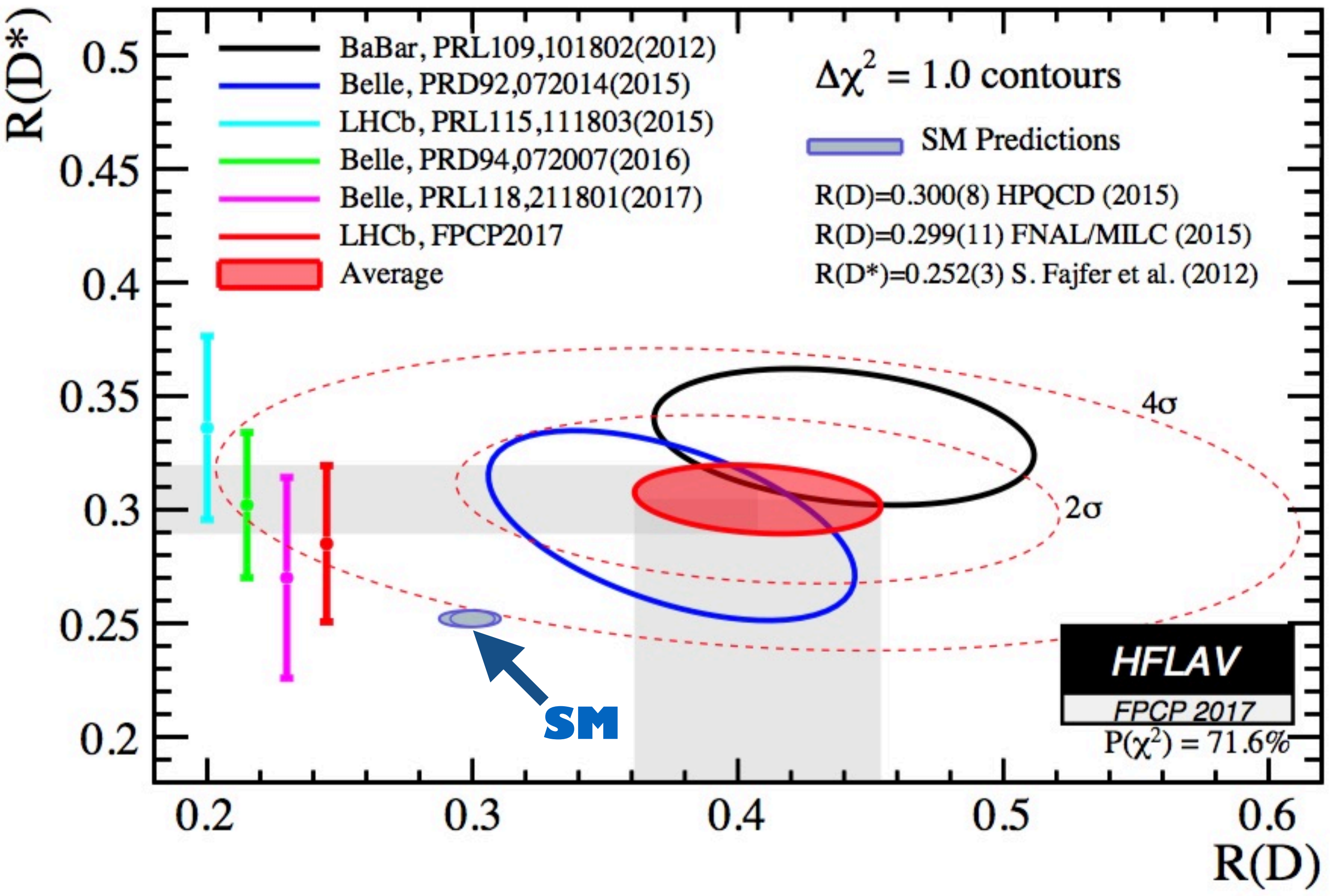
$b \to c \ell \nu$

$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\mu\nu)}$$

LHCb-PAPER-2017-017



Overall combination of R(D) and R(D*) is 4.1σ from SM



$b \to s \ell \ell$

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

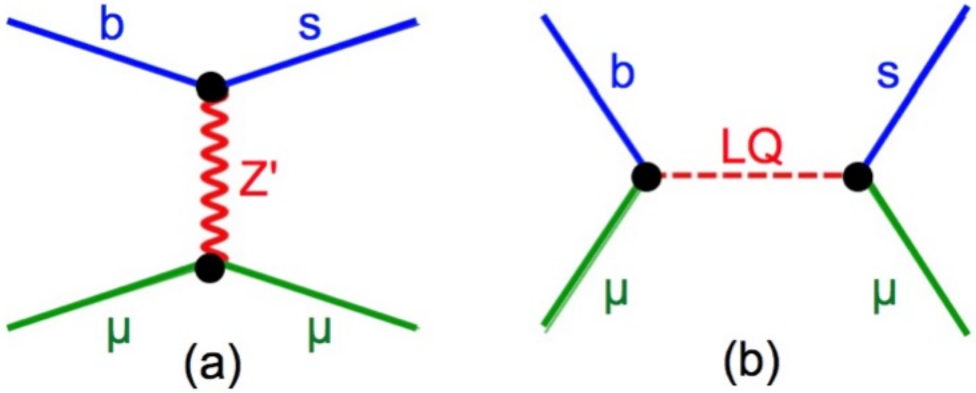
m_{ll} [mass range]	SM	Exp.
$R_K{}^{[1-6]}$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074} \pm 0.036$
$R_{K^*}{}^{[1.1-6]}$	1.00 ± 0.01	$0.685^{+0.113}_{-0.069} \pm 0.047$
$R_{K^*}{}^{[0.045,1.1]}$	0.91 ± 0.03	$0.660^{+0.110}_{-0.070} \pm 0.024$

LHCb, PRL 113 (2014) 151601 , arXiv:1705.05802

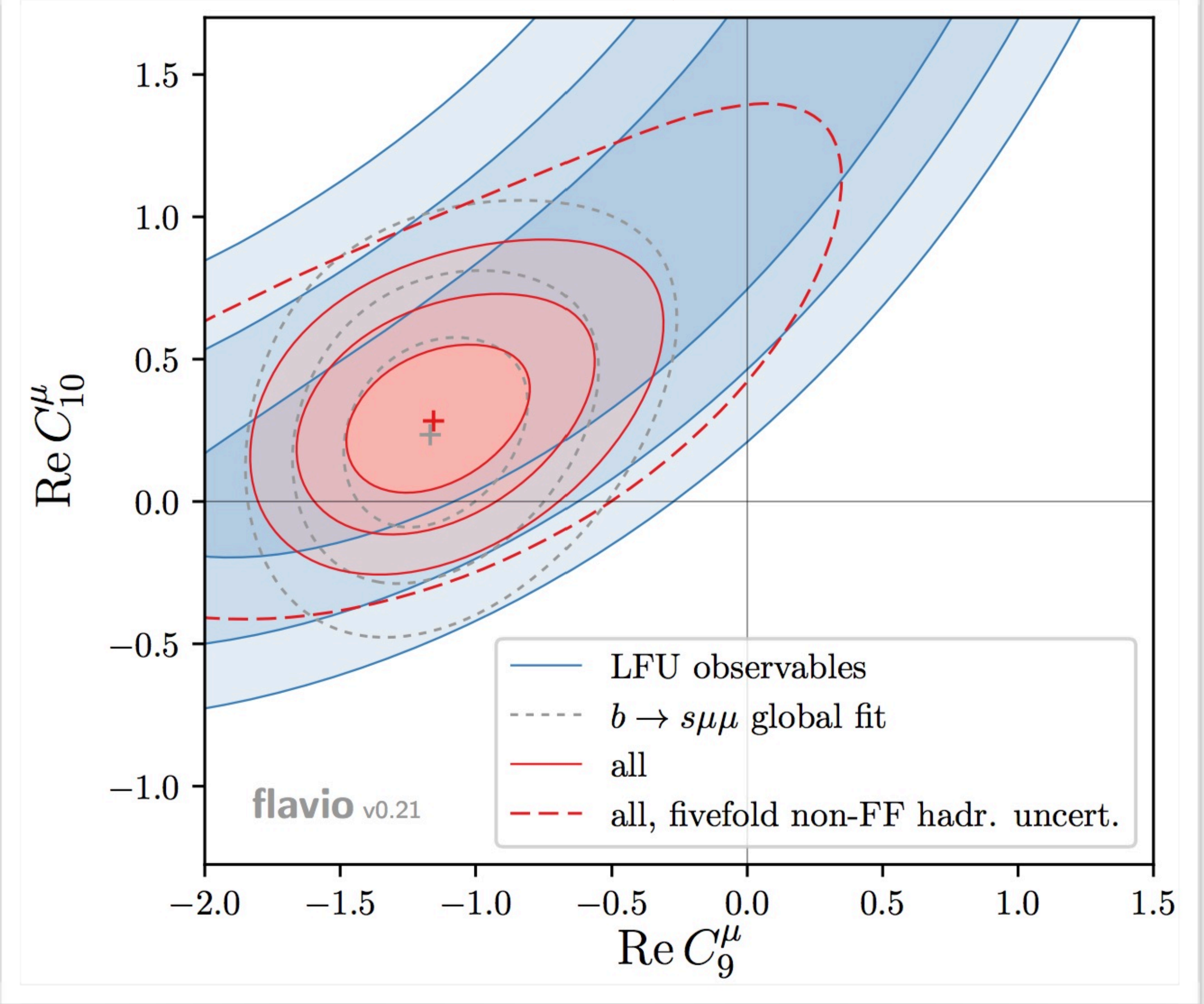
Example of EFT interpretation of R_K

$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

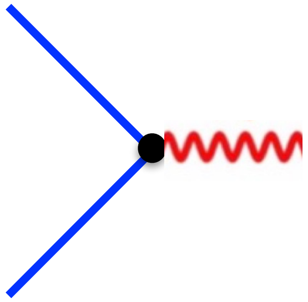
Possible explicit realizations:



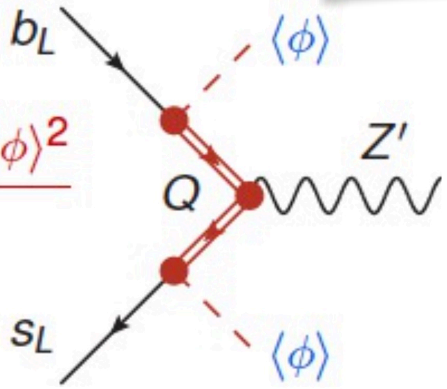
Altmannshoffer et al, arxiv:1704.05435



where, e.g. ,



$$\Rightarrow \quad \frac{g' Y_{Qb} Y_{Qs}^* \langle\phi\rangle^2}{2m_Q^2}$$



Upper limits on Z' and Leptoquark masses are model-dependent, and constrained also by other low-energy flavour phenomenology, but the mass range is upper limited

⇒ if anomalies confirmed, we may want a no-lose theorem to identify the next facility!

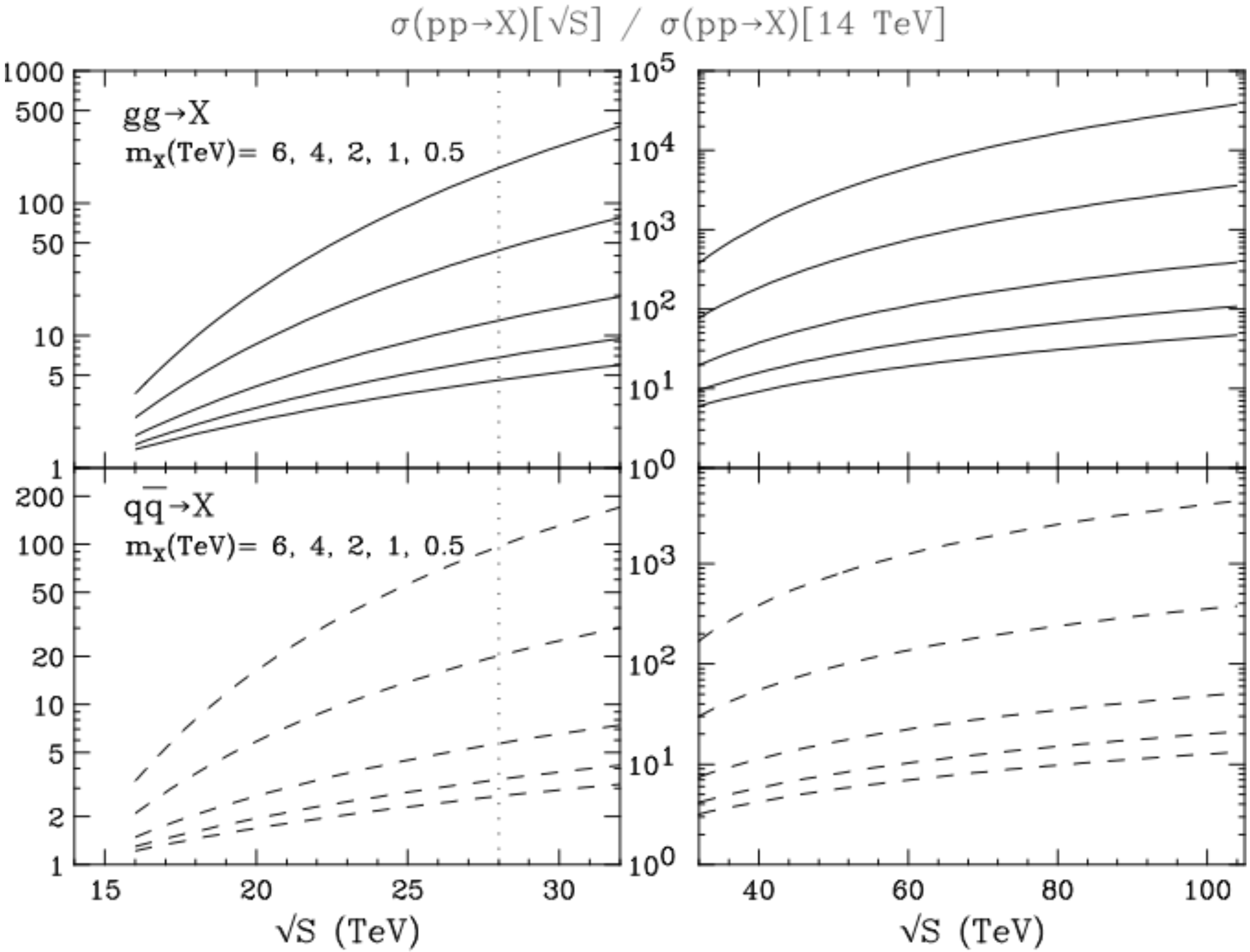
See eg Allanach, Gripaios & You, 1710.06363

100 TeV ?

200 TeV ?

27 TeV in the LHC tunnel, replacing current magnets with those developed for FCC ?

Evolution, with beam energy, of scenarios with the discovery of a new particle at the LHC



Possible questions/options

- If m_X ~ 6 TeV in the gg channel, rate grows x 200 @28 TeV:
  - Do we wait 40 yrs to go to pp@100TeV, or fast-track 28 TeV in the LHC tunnel?
  - Do we need 100 TeV, or 50 is enough ($\sigma_{100}/\sigma_{14} \sim 4 \cdot 10^4$, $\sigma_{50}/\sigma_{14} \sim 4 \cdot 10^3$) ?
  - .... and the answers may depend on whether we expect partners of X at masses $\gtrsim 2m_X$ ($\Rightarrow$ *28 TeV would be insufficient ....*)
- If m_X ~ 0.5 TeV in the qqbar channel, rate grows x10 @100 TeV:
  - Do we go to 100 TeV, or push by x10 $\int L$ at LHC?
  - Do we build CLIC?
- etc.etc.

HE-LHC potential

- **Reach at high mass:**
  - $M \rightarrow 2 \times M_{LHC}$
  - implications on models, naturalness, …. ?

- **Guaranteed deliverables:**
  - Higgs selfcoupling:
    - first estimates: **$\delta\lambda \sim \pm 30\%$** (https://arxiv.org/abs/1802.04319)
  - Higgs properties, top and EW observables, …:
    - under study

- **No-lose theorems:**
  - microscopic origin of current flavour anomalies?

- All of this to be explored during the running CERN Workshop on HL/HE-LHC physics

Workshop on the physics of HL-LHC, and perspectives at HE-LHC

30 October 2017 to 1 November 2017
CERN
Europe/Zurich timezone

https://indico.cern.ch/event/647676/

Next mtg of Higgs, BSM and flavour WGs: April 4-6 at FNAL, https://indico.fnal.gov/event/16151/

Next general mtg: June 18-20, CERN, https://indico.cern.ch/event/686494/

Workshop twiki pages: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop

To join the mailing list, click here

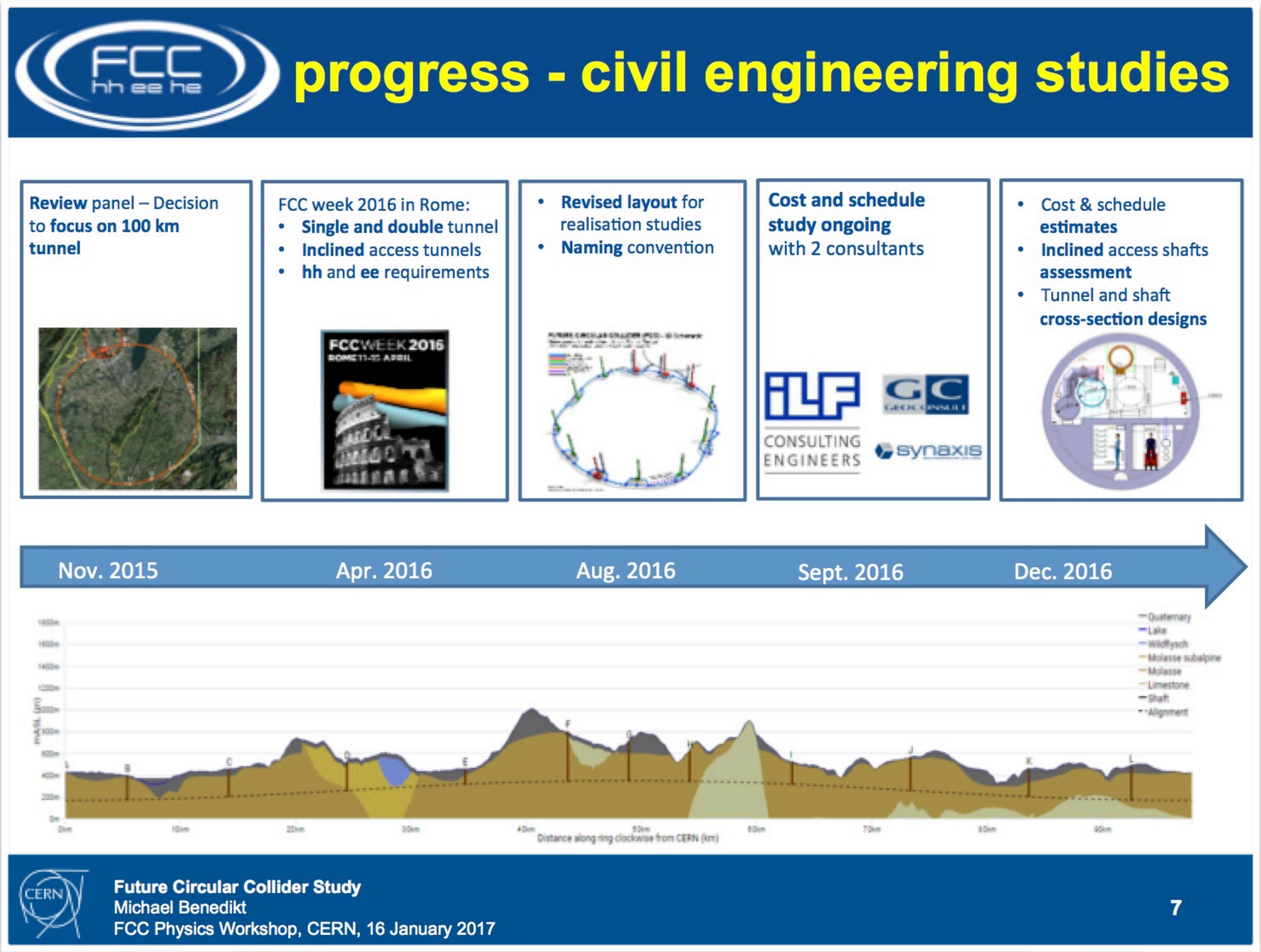
What does the HE-LHC entail?

- **Necessary:**
  - empty the tunnel (more time & $s than removing LEP)
  - full replacement of the magnets (today's cost > LHC ones. First prototypes in ~2026)
  - upgrade of RF, cryogenics, collimation, beam dumps, …
  - major upgrade of SPS, to inject at O(1 TeV) (magnets, RF, transfer lines, cryo if SC, …)
- **Very likely:**
  - major overhaul of detectors (radiation damage after HL-LHC, use of new technologies)

=> it's like building the LHC ex-novo, and more

- very unlikely to be cheaper …
- … but not incompatible with a ~constant CERN budget
- nevertheless feasibility to be proven (eg magnets bigger than LHC's: will they fit in the tunnel ??)

Snapshots of the status of the FCC studies



progress - civil engineering studies

Review panel – Decision to **focus on 100 km tunnel**

FCC week 2016 in Rome:
- **Single and double** tunnel
- **Inclined** access tunnels
- **hh** and **ee** requirements

- **Revised layout** for realisation studies
- **Naming** convention

Cost and schedule study ongoing with 2 consultants

- Cost & schedule **estimates**
- **Inclined** access shafts **assessment**
- Tunnel and shaft **cross-section designs**

Nov. 2015

Apr. 2016

Aug. 2016

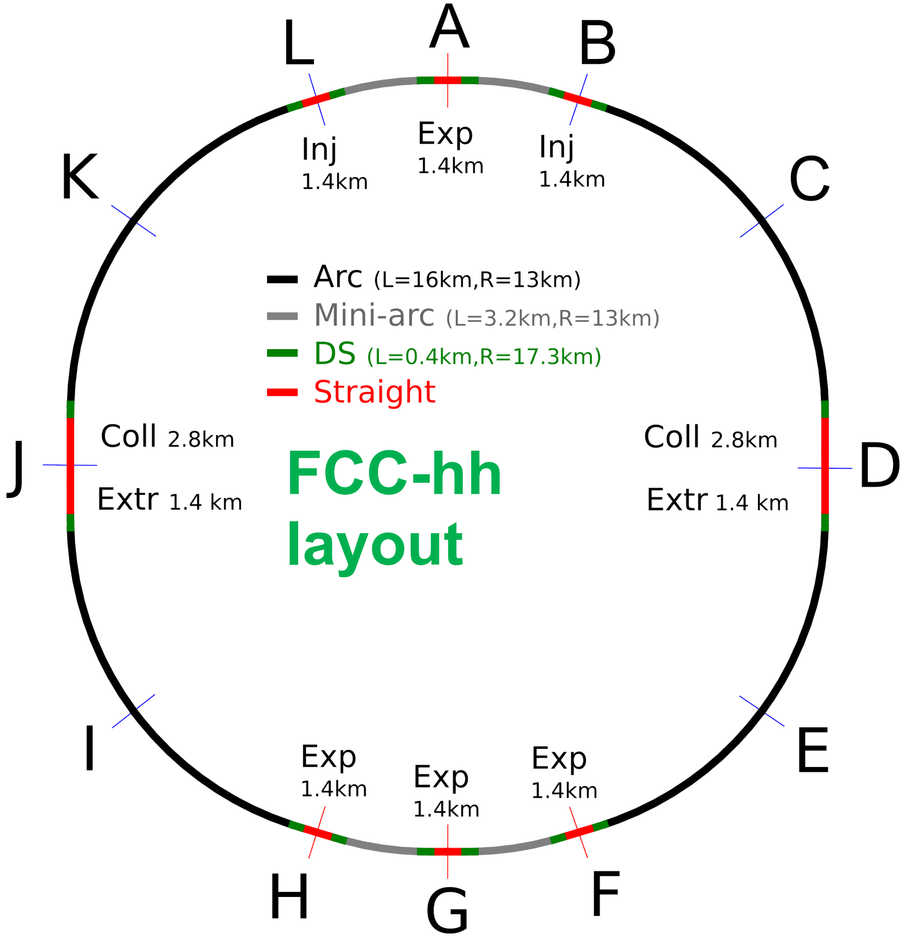
Sept. 2016

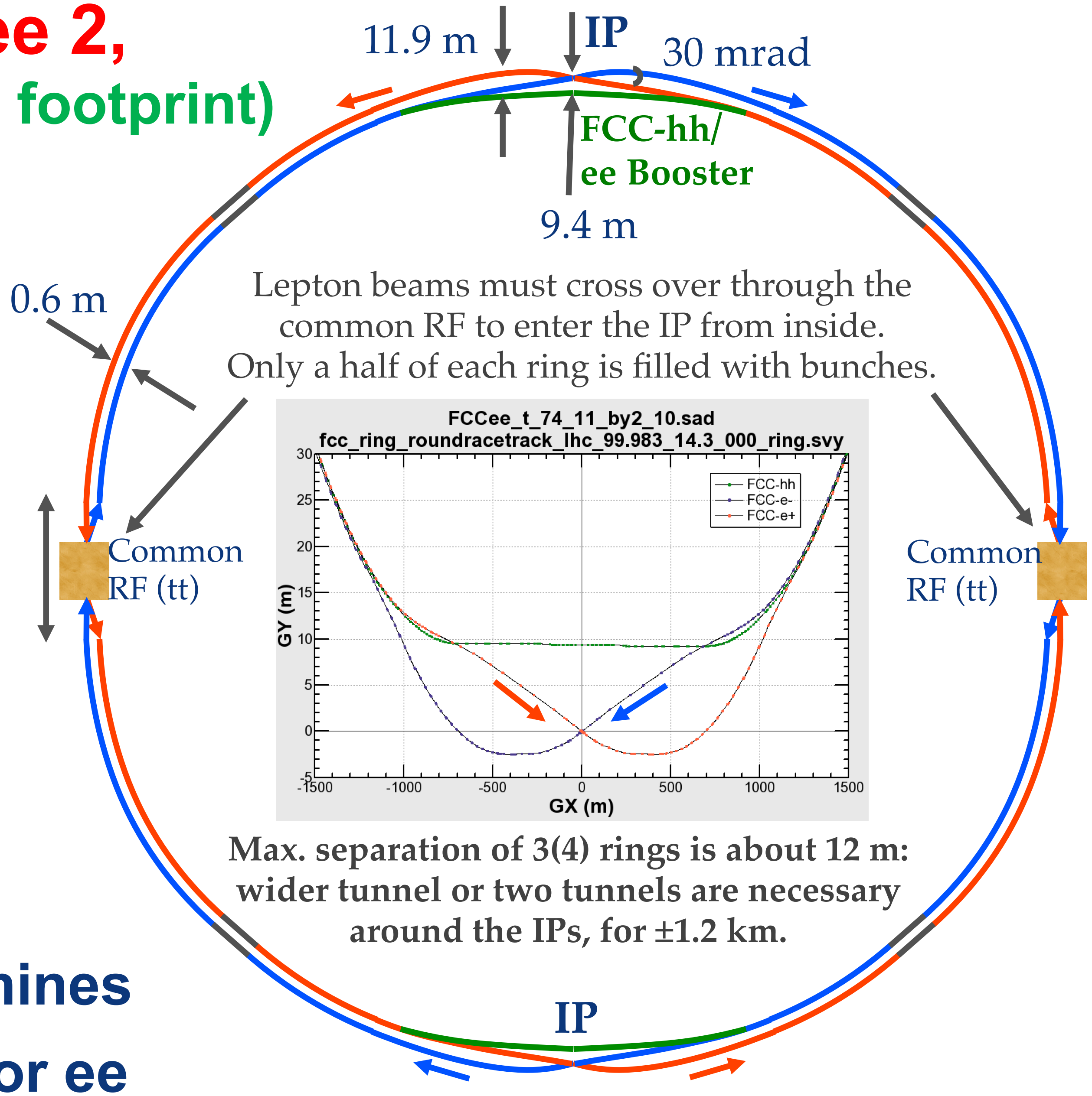
Dec. 2016

Future Circular Collider Study
Michael Benedikt
FCC Physics Workshop, CERN, 16 January 2017

Common layouts for hh & ee

FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)

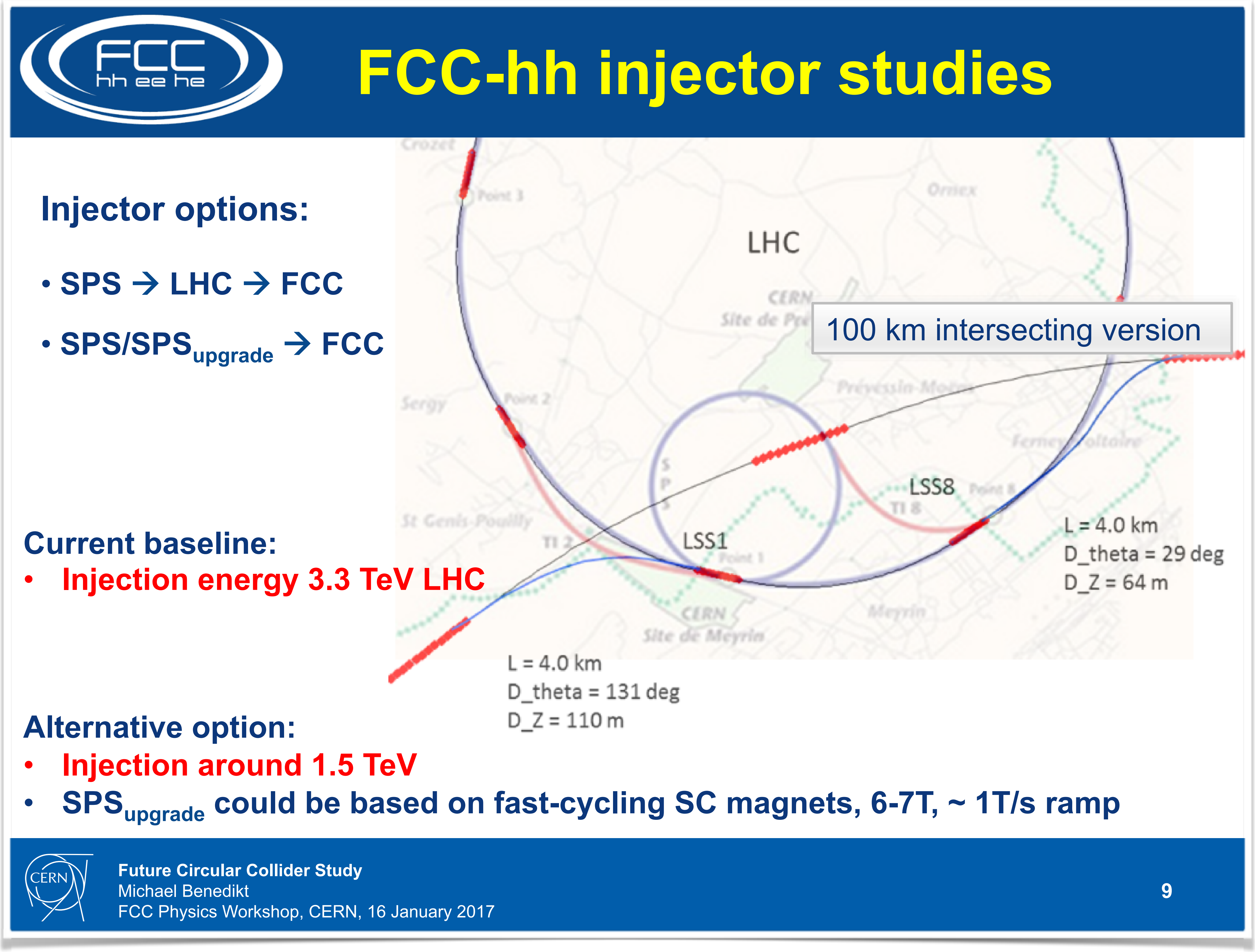




Lepton beams must cross over through the common RF to enter the IP from inside. Only a half of each ring is filled with bunches.

Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.

- **2 main IPs in A, G for both machines**
- **asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector**



FCC-hh injector studies

Injector options:

- **SPS → LHC → FCC**
- **SPS/SPS$_{upgrade}$ → FCC**

100 km intersecting version

L = 4.0 km
D_theta = 29 deg
D_Z = 64 m

L = 4.0 km
D_theta = 131 deg
D_Z = 110 m

Current baseline:

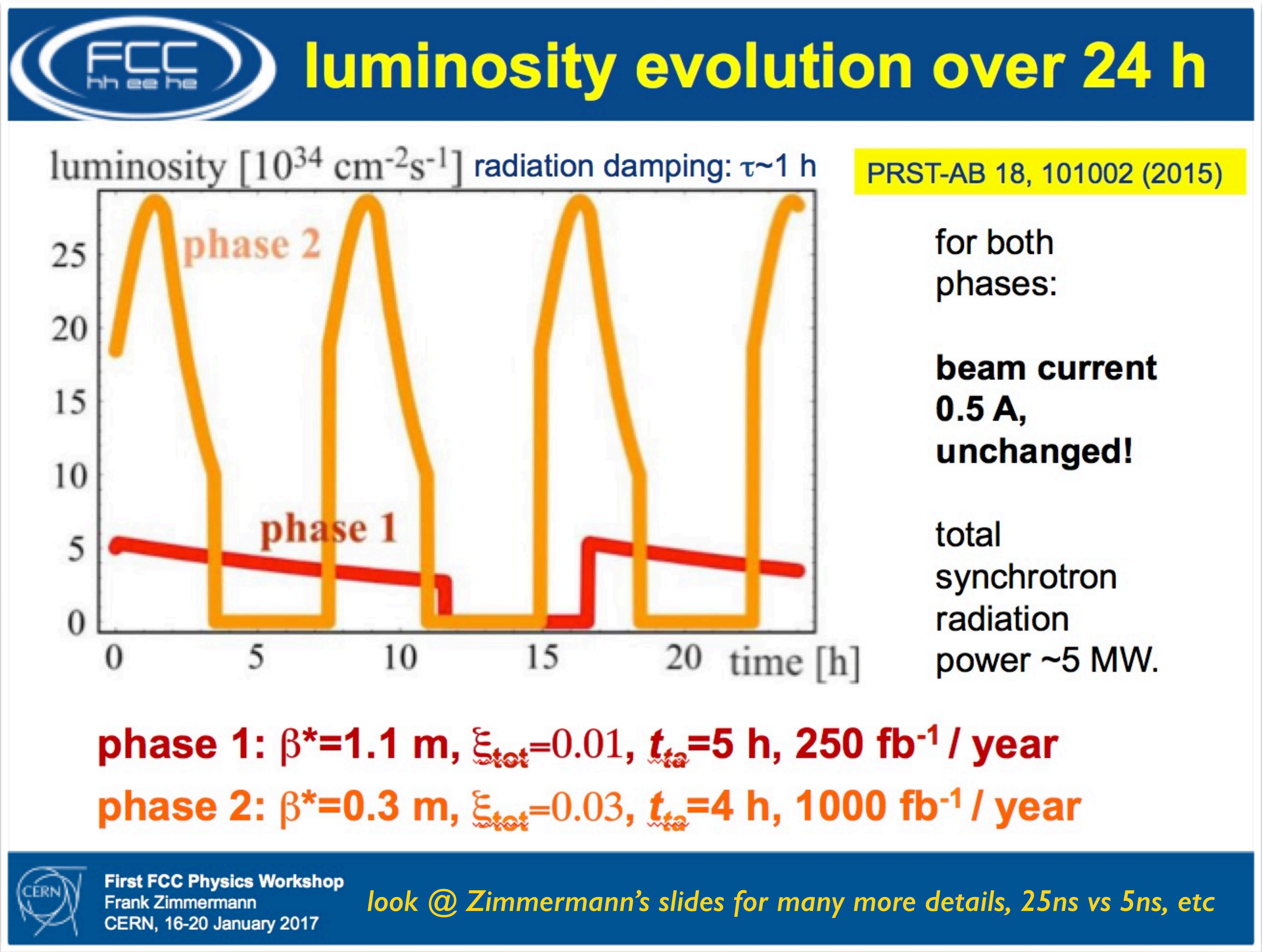
- **Injection energy 3.3 TeV LHC**

Alternative option:

- **Injection around 1.5 TeV**
- **SPS$_{upgrade}$ could be based on fast-cycling SC magnets, 6-7T, ~ 1T/s ramp**

FCC-pp collider parameters

parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.12	1.12	0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	2.2	1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.20	0.55
normalized emittance [μm]	2.2 (0.4)		2.5 (0.5)	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	25	5	1
events/bunch crossing	170	1k (200)	~800 (160)	135	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36



luminosity evolution over 24 h

radiation damping: τ~1 h

PRST-AB 18, 101002 (2015)

for both phases:

beam current 0.5 A, unchanged!

total synchrotron radiation power ~5 MW.

phase 1: β^*=1.1 m, ξ_{tot}=0.01, t_{ta}=5 h, 250 fb^{-1} / year

phase 2: β^*=0.3 m, ξ_{tot}=0.03, t_{ta}=4 h, 1000 fb^{-1} / year

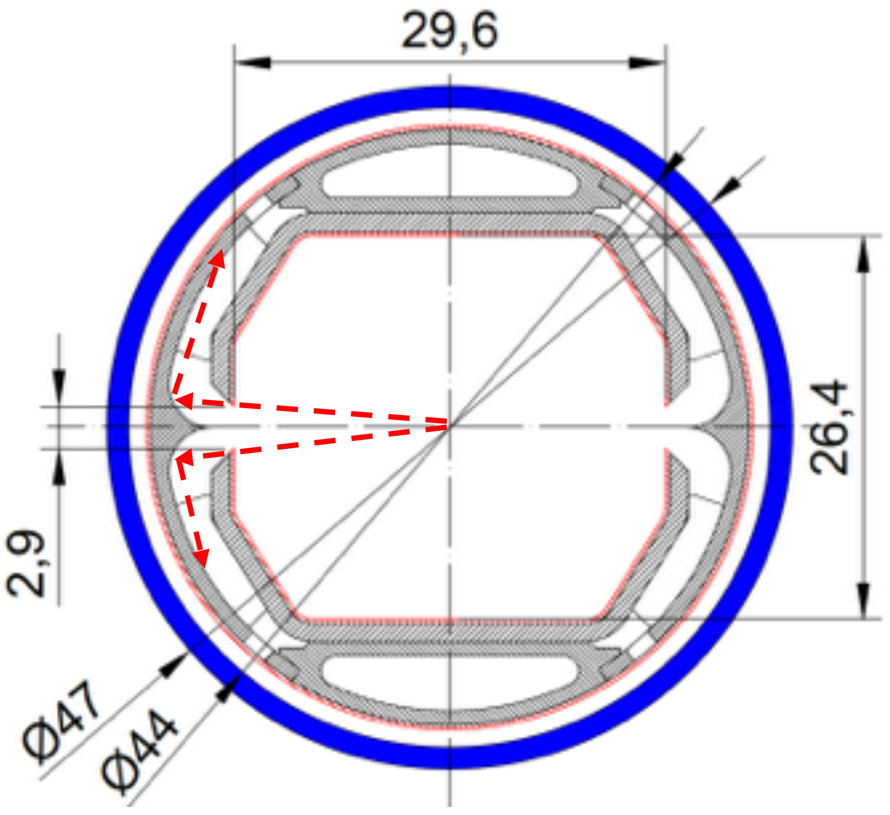
First FCC Physics Workshop
Frank Zimmermann
CERN, 16-20 January 2017

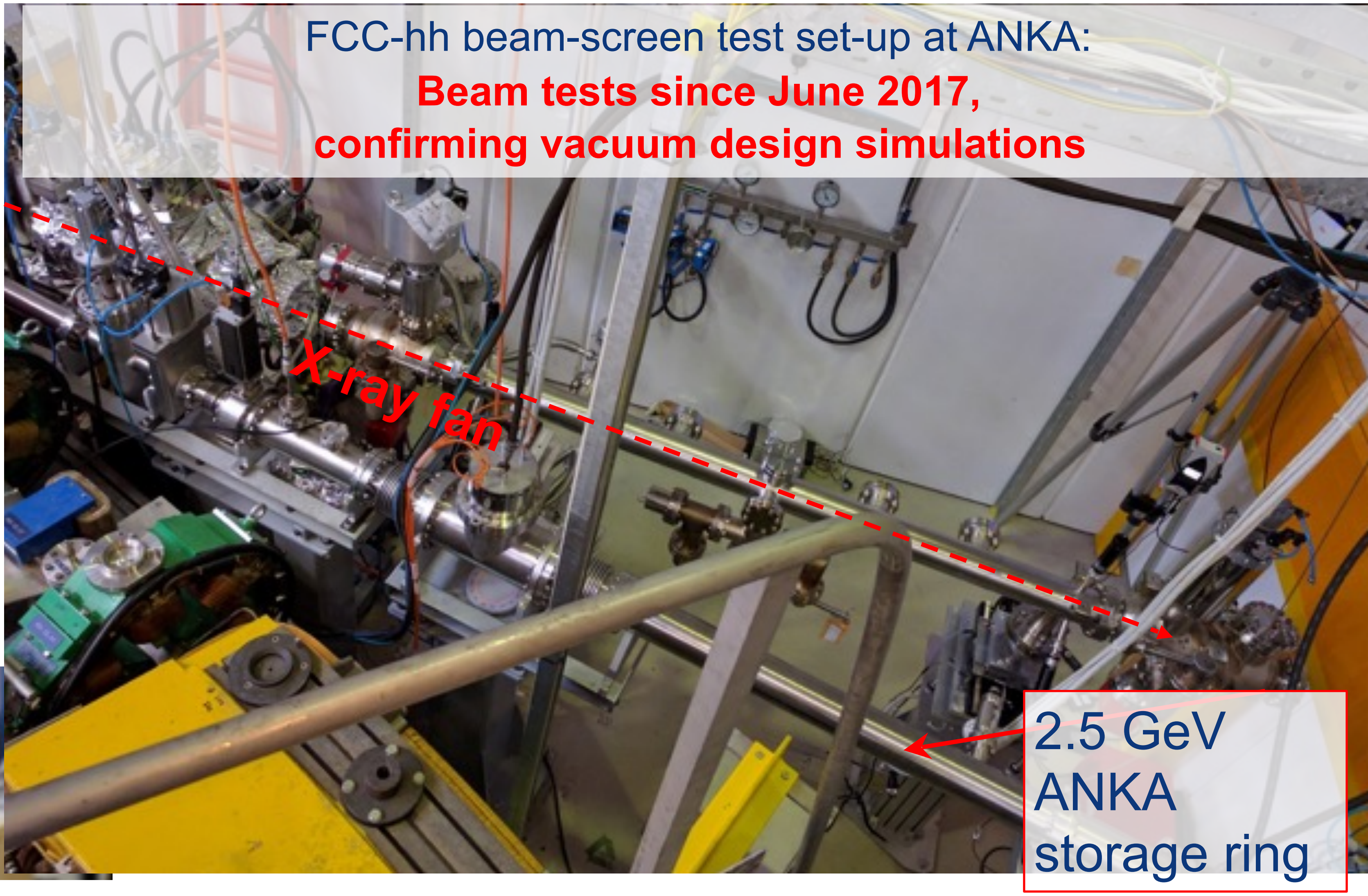
look @ Zimmermann's slides for many more details, 25ns vs 5ns, etc

FCC-hh cryogenic beam vacuum system

Synchrotron radiation **(~ 30 W/m/beam (@16 T field)** (LHC <0.2W/m) **~ 5 MW total load in arcs**

- **Absorption of synchrotron radiation at ~50 K** for cryogenic efficiency (**5 MW →100 MW cryoplant**)
- Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.

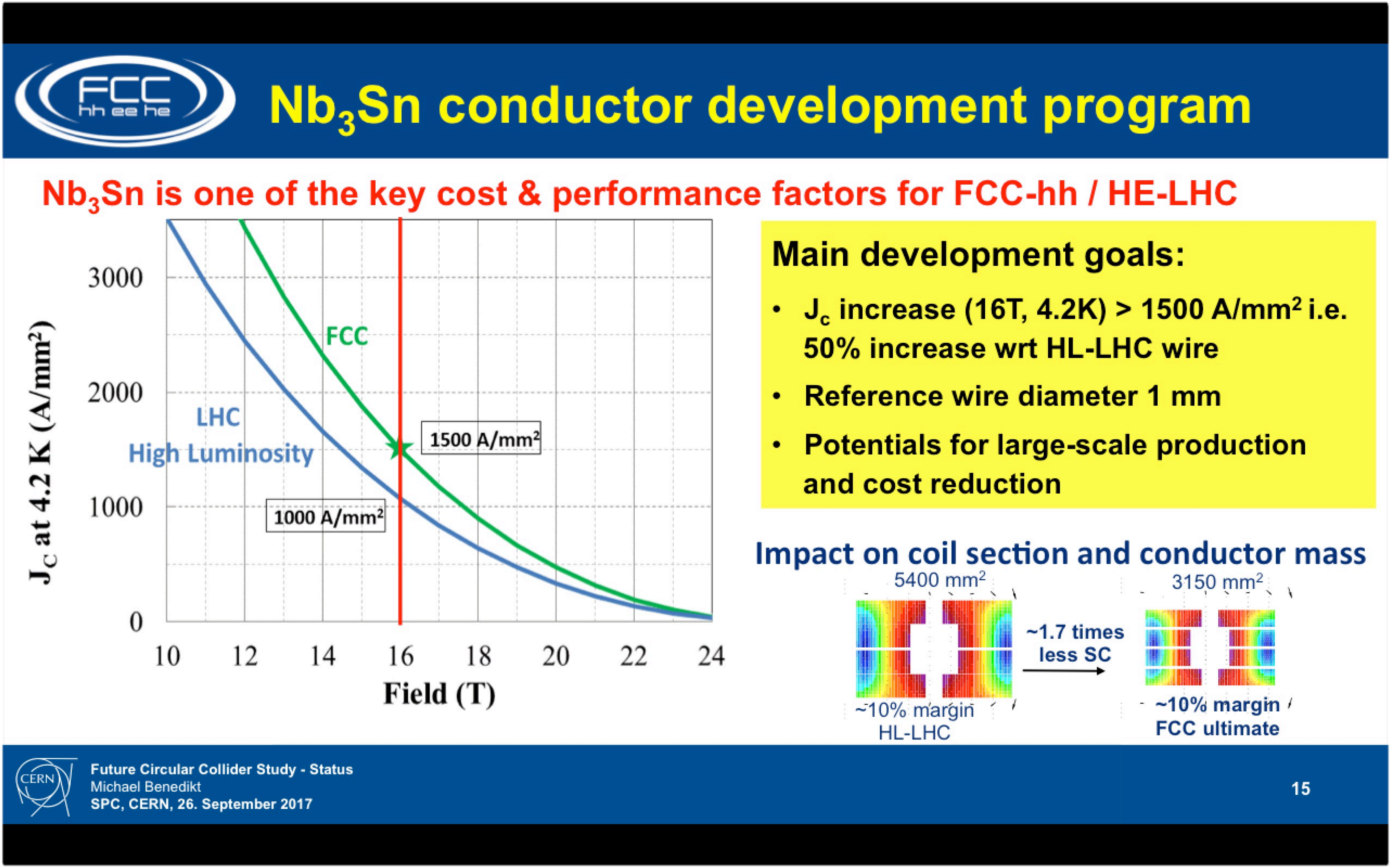




FCC-hh beam-screen test set-up at ANKA:

Beam tests since June 2017, confirming vacuum design simulations

2.5 GeV ANKA storage ring



Nb_3Sn conductor development program

Nb_3Sn is one of the key cost & performance factors for FCC-hh / HE-LHC

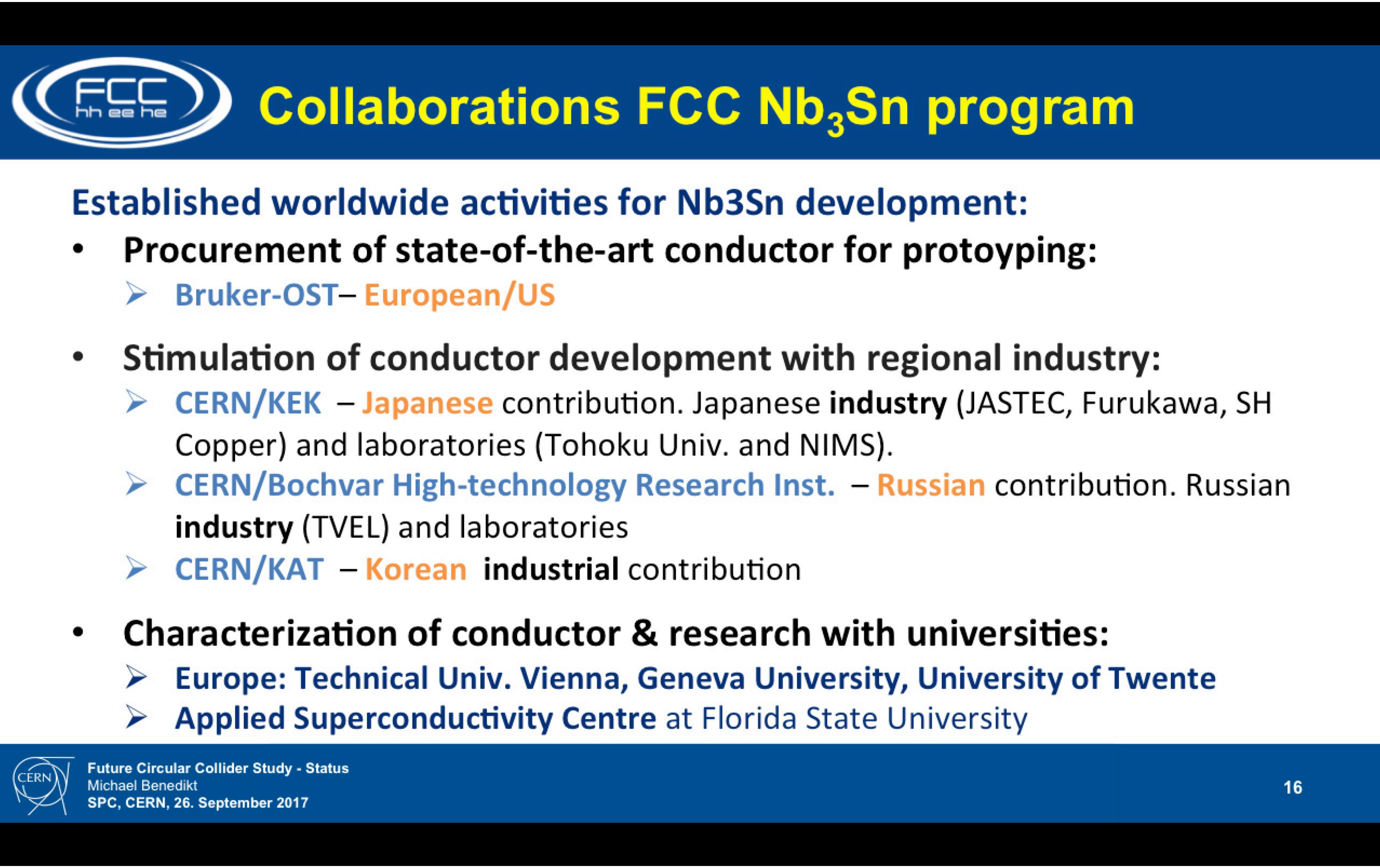
Main development goals:

- **J_c increase (16T, 4.2K) > 1500 A/mm² i.e. 50% increase wrt HL-LHC wire**
- **Reference wire diameter 1 mm**
- **Potentials for large-scale production and cost reduction**

Impact on coil section and conductor mass

Future Circular Collider Study - Status
Michael Benedikt
SPC, CERN, 26. September 2017

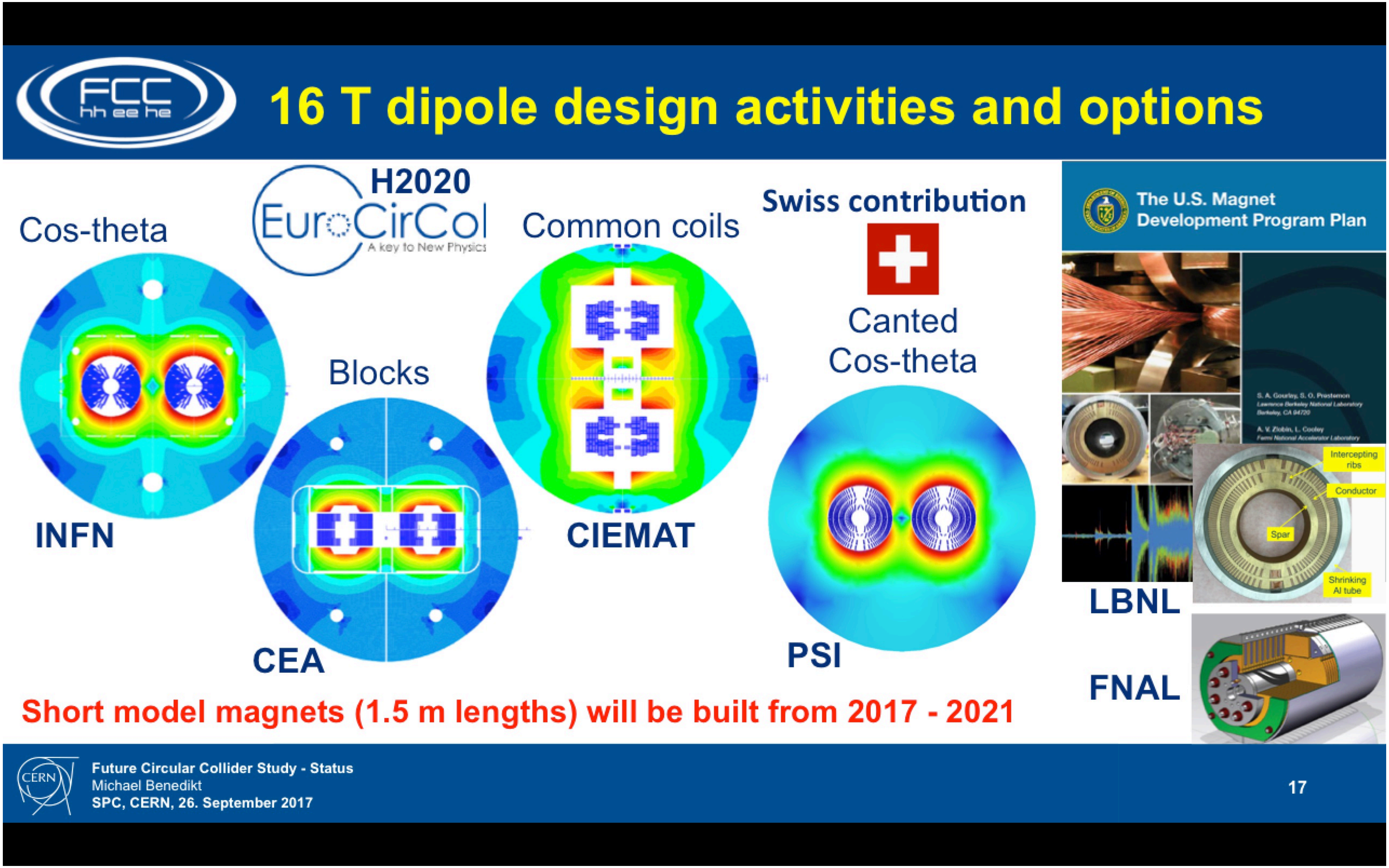
15



Collaborations FCC Nb_3Sn program

Established worldwide activities for Nb3Sn development:

- **Procurement of state-of-the-art conductor for protoyping:**
  - **Bruker-OST**– **European/US**
- **Stimulation of conductor development with regional industry:**
  - **CERN/KEK** – **Japanese** contribution. Japanese **industry** (JASTEC, Furukawa, SH Copper) and laboratories (Tohoku Univ. and NIMS).
  - **CERN/Bochvar High-technology Research Inst.** – **Russian** contribution. Russian **industry** (TVEL) and laboratories
  - **CERN/KAT** – **Korean** **industrial** contribution
- **Characterization of conductor & research with universities:**
  - **Europe: Technical Univ. Vienna, Geneva University, University of Twente**
  - **Applied Superconductivity Centre** at Florida State University



16 T dipole design activities and options

H2020 EuroCirCol
A key to New Physics

Cos-theta
INFN

Blocks
CEA

Common coils
CIEMAT

Swiss contribution
Canted Cos-theta
PSI

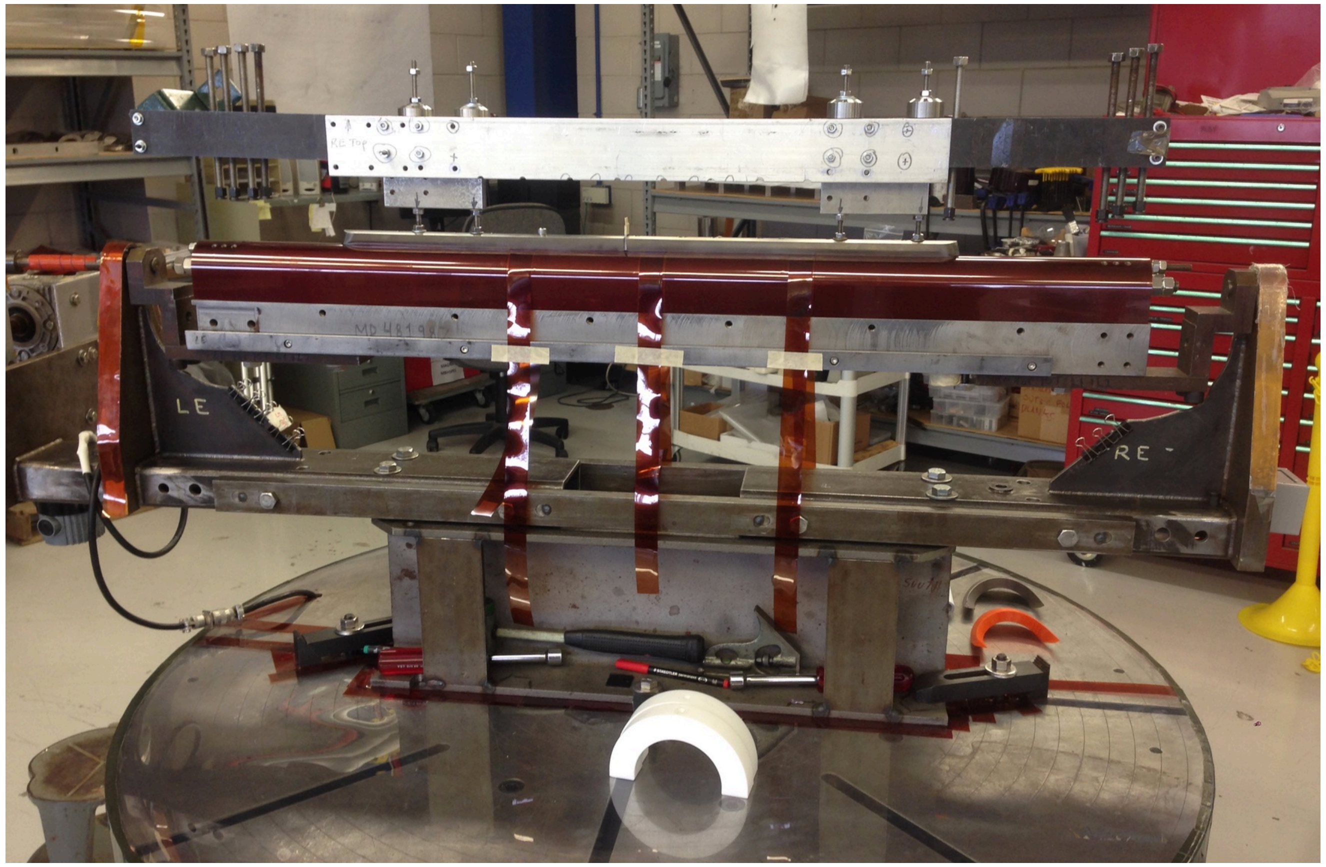
The U.S. Magnet Development Program Plan
S. A. Gourlay, S. O. Prestemon
Lawrence Berkeley National Laboratory
Berkeley, CA 94720
A. V. Zlobin, L. Cooley
Fermi National Accelerator Laboratory

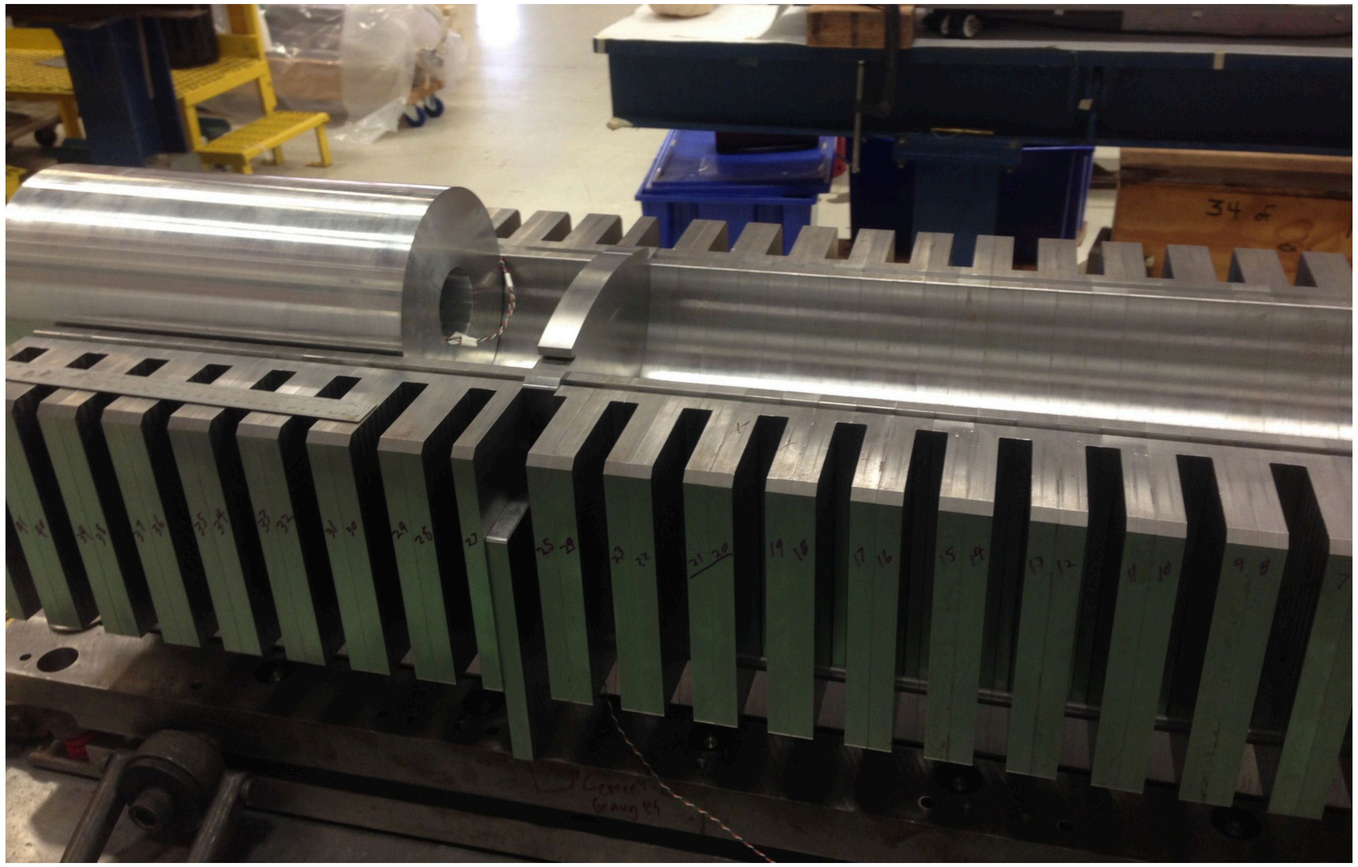
LBNL
FNAL

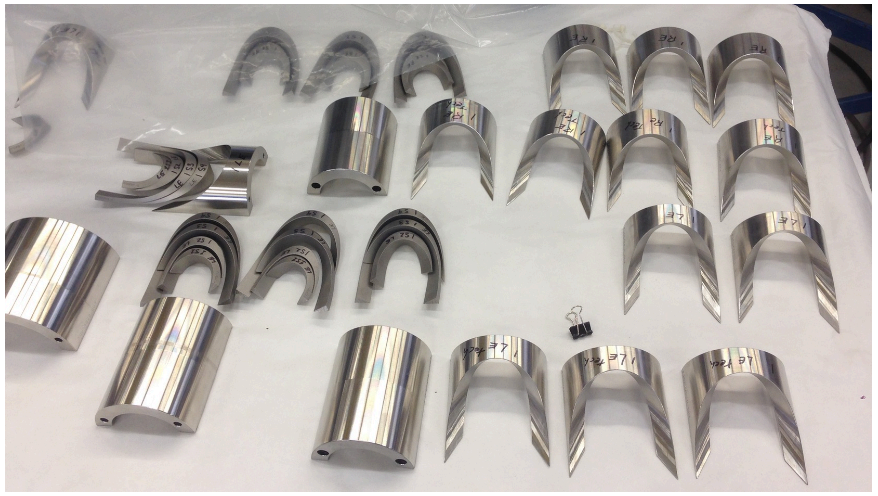
Short model magnets (1.5 m lengths) will be built from 2017 - 2021

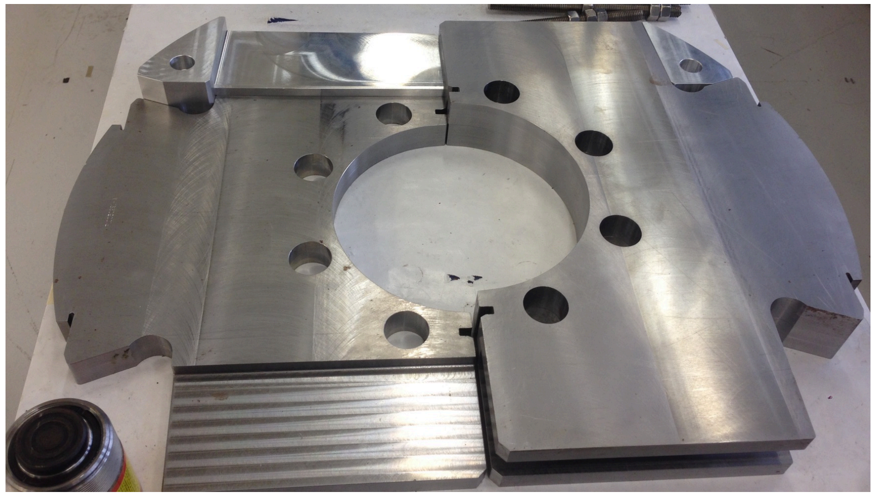
Future Circular Collider Study - Status
Michael Benedikt
SPC, CERN, 26. September 2017

15T dipole prototyping at FNAL (60mm aperture, L=1m)

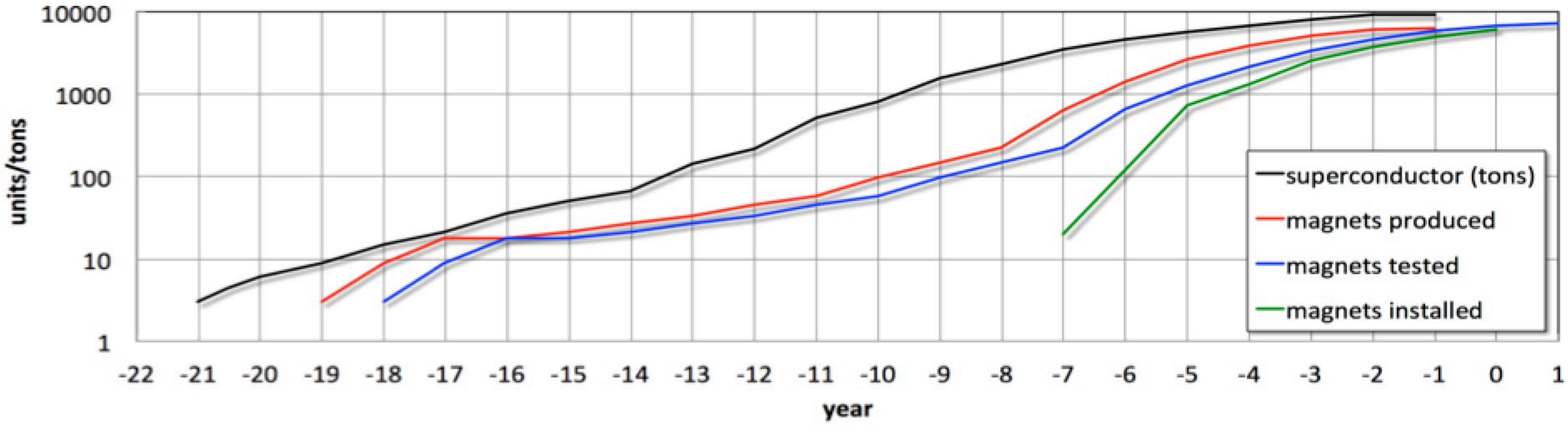






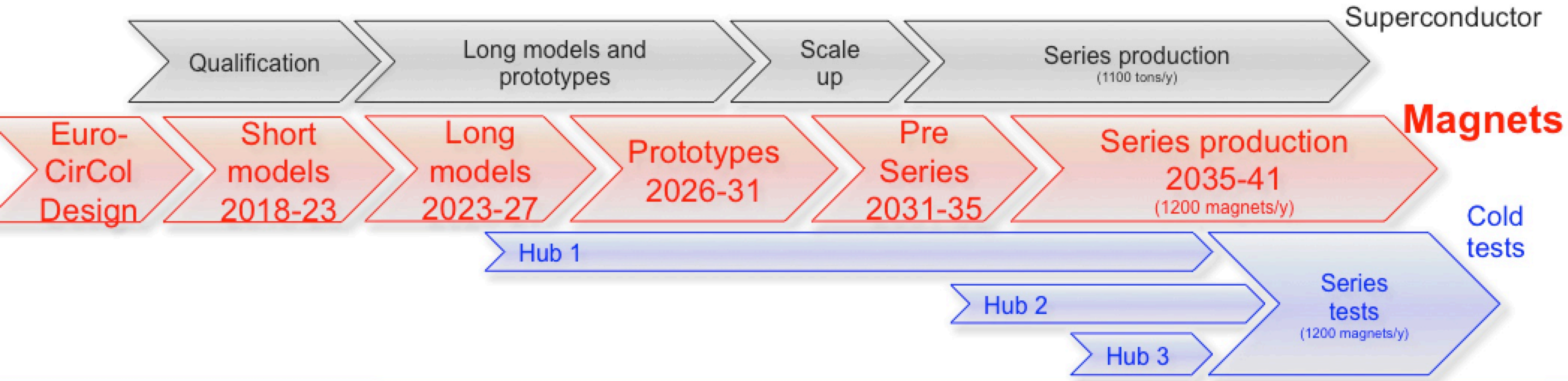


16 T magnet R&D schedule



Total duration of magnet program:

~20 years



Superconductor

Qualification

Long models and prototypes

Scale up

Series production
(1100 tons/y)

Magnets

Euro-CirCol Design

Short models 2018-23

Long models 2023-27

Prototypes 2026-31

Pre Series 2031-35

Series production 2035-41
(1200 magnets/y)

Cold tests

Hub 1

Hub 2

Hub 3

Series tests
(1200 magnets/y)

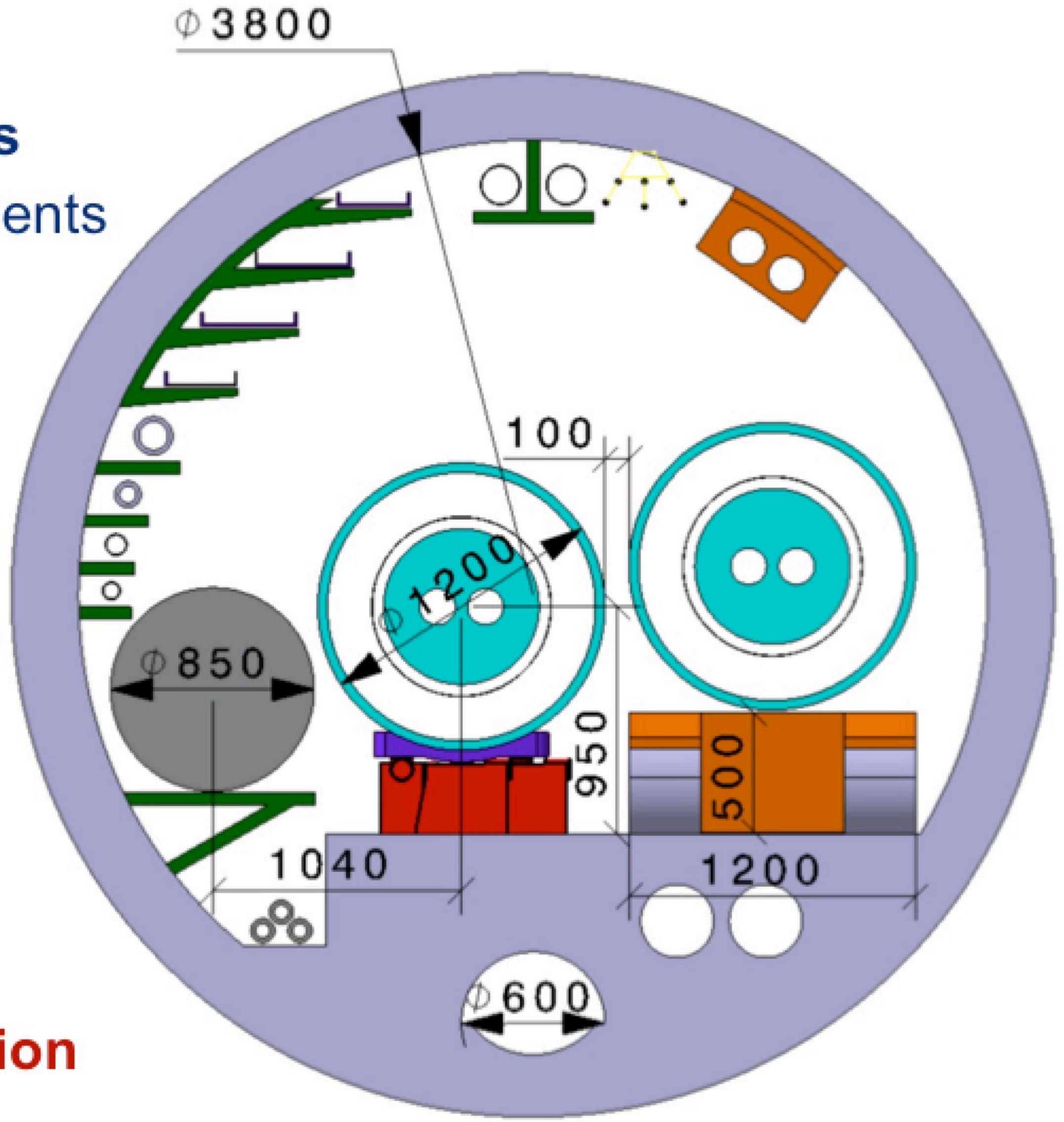
Would follow on HL-LHC Nb_3Sn program with long models with industry from 2023/24

HE-LHC integration aspects

Working hypothesis for HE LHC design:

No major CE modifications on machine tunnel and caverns

- Similar geometry and layout as LHC machine and experiments
- **Maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm**
- **Classical 16 T cryostat design based on LHC approach gives ~1500 mm diameter!**

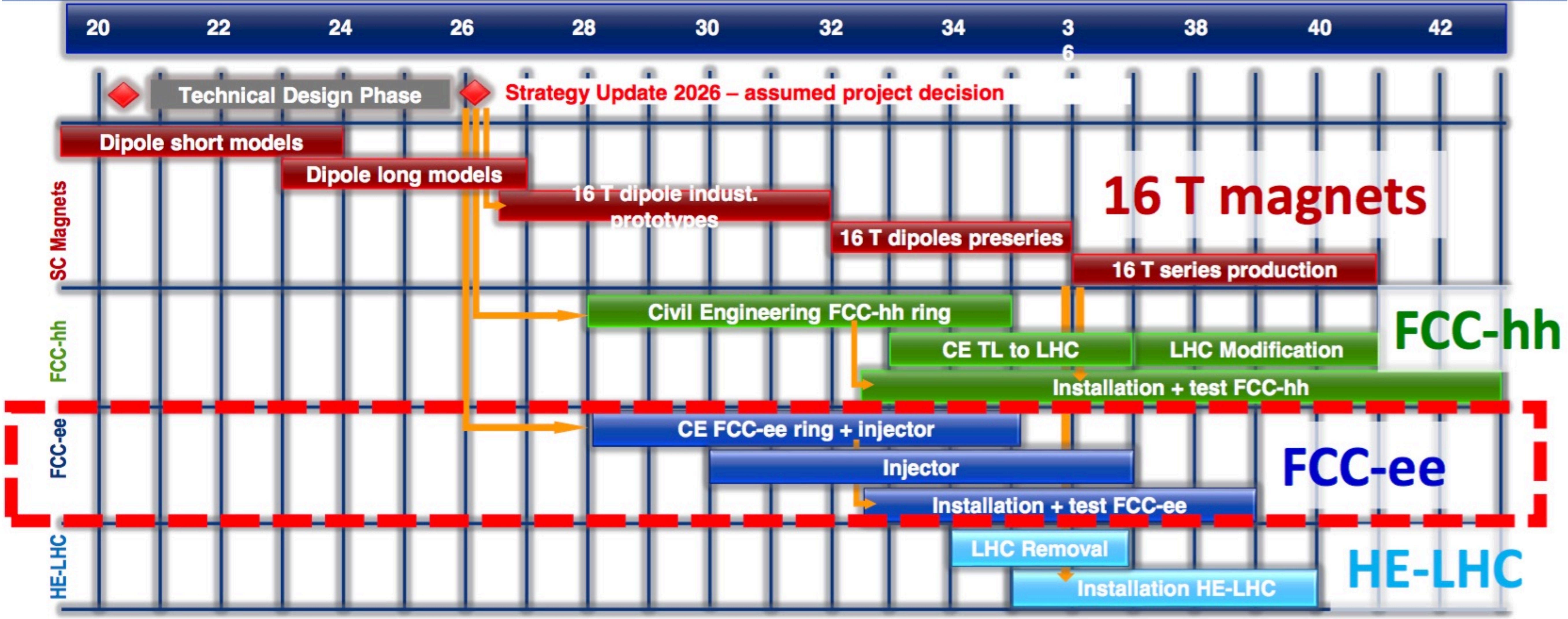


Strategy: develop a single 16 T magnet, compatible with both HE LHC and FCC-hh requirements:

- **Allow stray-field and/or cryostat as return-yoke**
- **Optimization of inter-beam distance (compactness)**

→ Smaller diam. also relevant for FCC-hh cost optimization

Technical Schedule for each the 3 Options



schedule constrained by 16 T magnets & CE
→ earliest possible physics starting dates

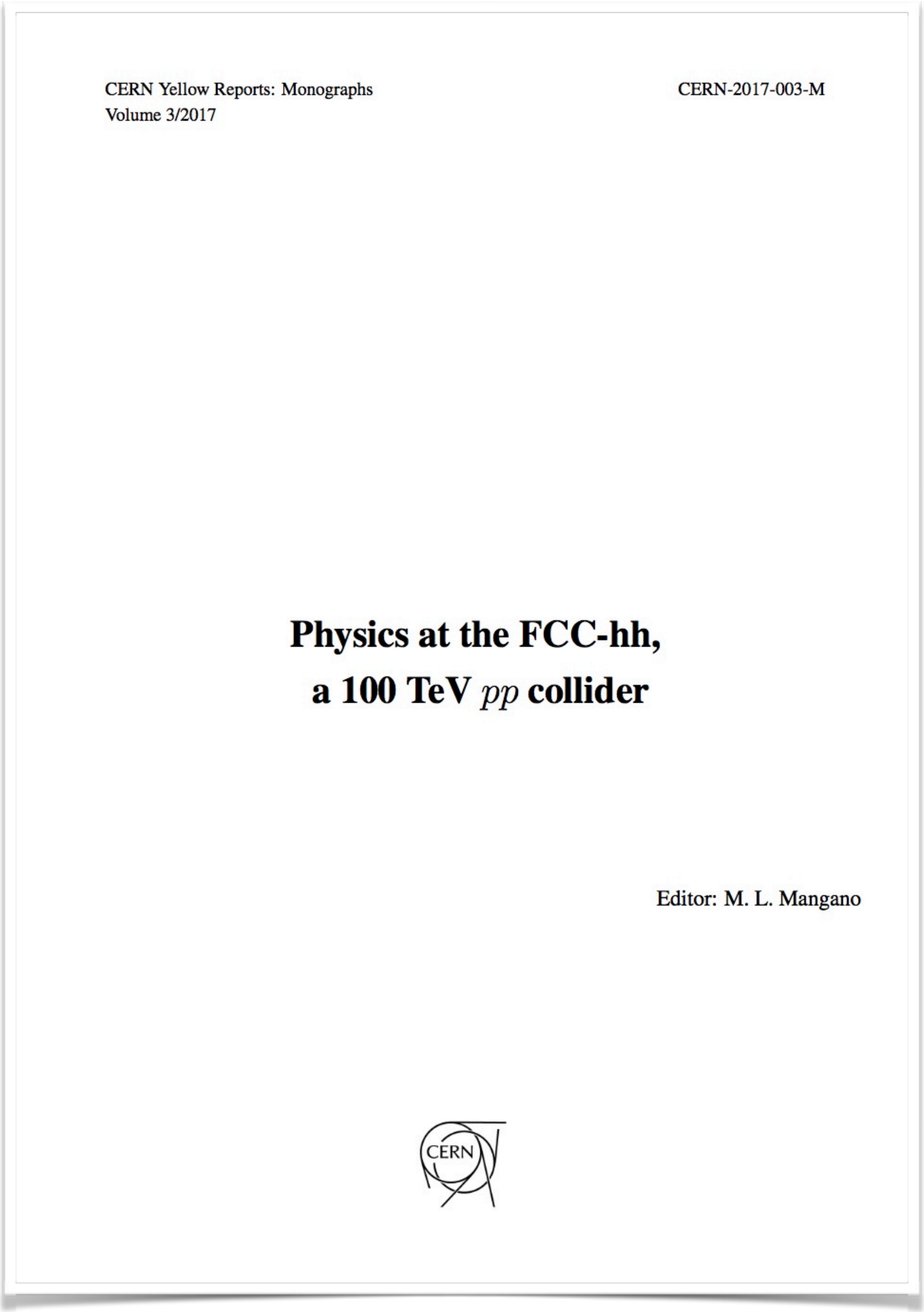
- FCC-hh: 2043
- FCC-ee: 2039
- HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)

M. Benedikt

Final remarks

- The study of the SM will not be complete until we exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.
- As a possible complement to the mature ILC and CLIC projects, the FCC is emerging as an important candidate future facility, with the same goals of thoroughness, precision and breadth that inspired the LEP/LHC era
- The physics case of a 100 TeV collider is very clear as a long-term goal for the field, simply because no other proposed or foreseeable project can have direct sensitivity to such large mass scales.
- Nevertheless, the precise route followed to get there (via CLIC? via HE-LHC? via FCC-ee? …) must take account of the fuller picture, to emerge from the LHC as well as other current and future experiments in areas ranging from flavour physics to dark matter searches. The right time scale for this assessment is probably ~8-10 yrs from now

Additional material



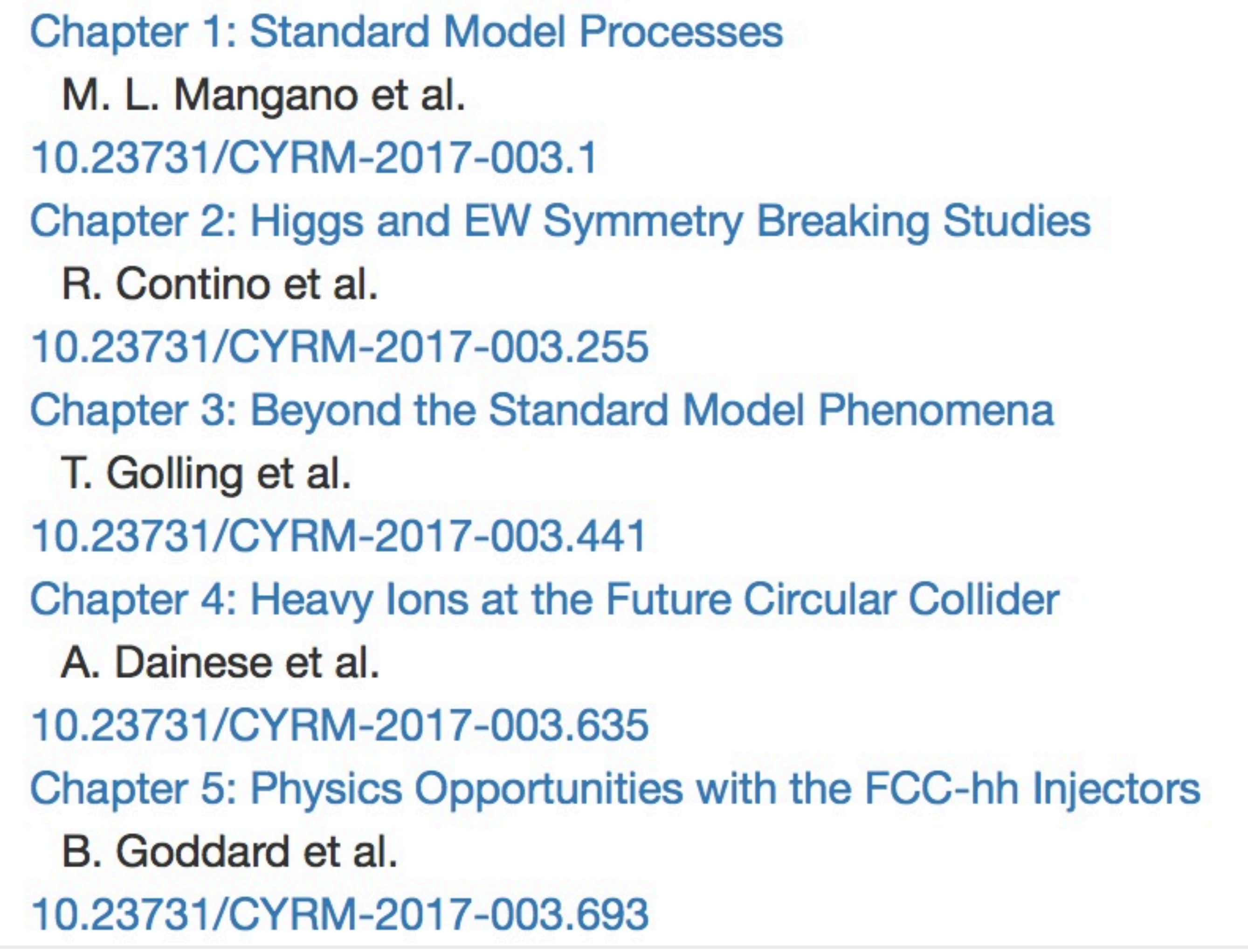
CERN Yellow Reports: Monographs
Volume 3/2017

CERN-2017-003-M

Physics at the FCC-hh,
a 100 TeV pp collider

Editor: M. L. Mangano

https://cds.cern.ch/record/2270978



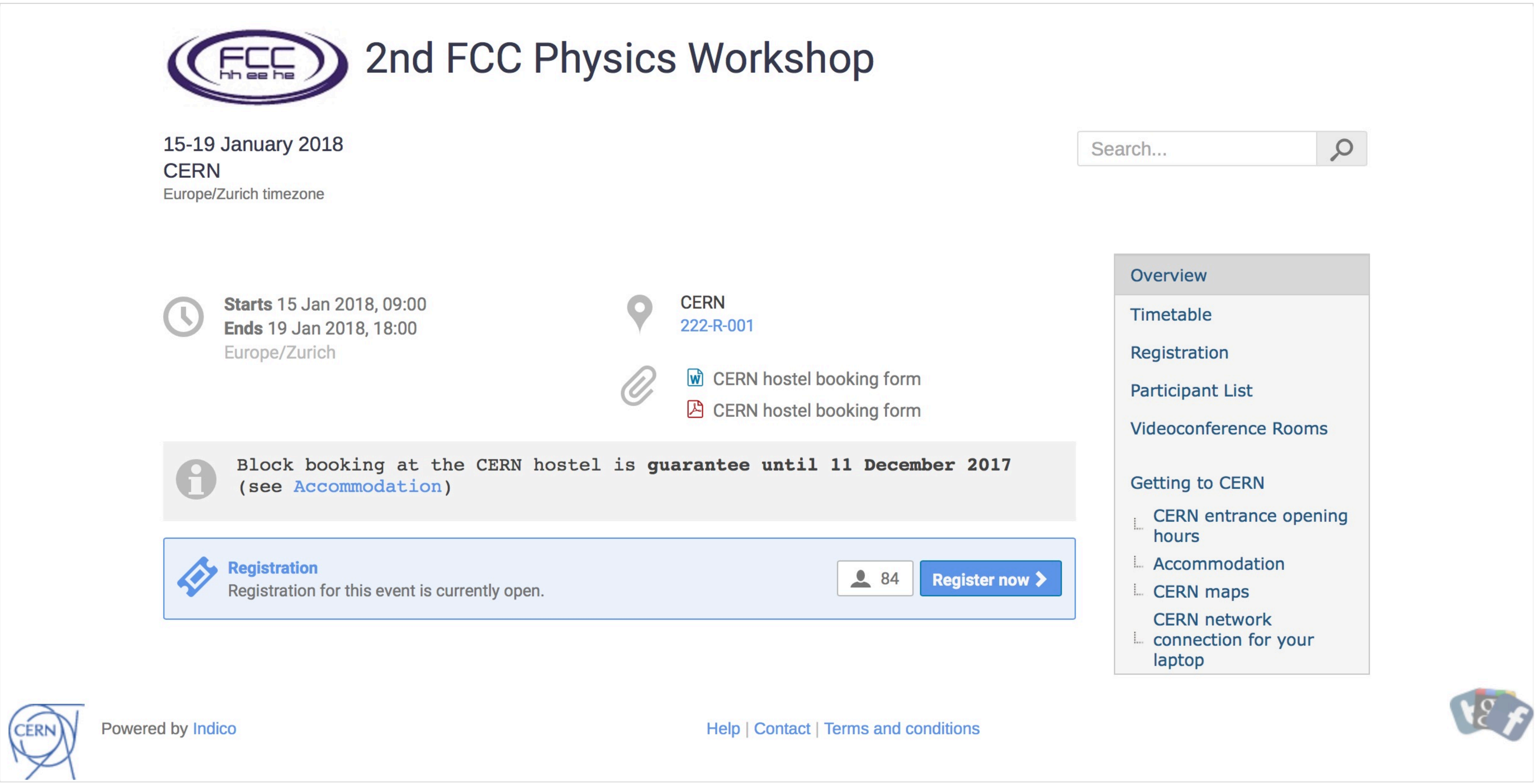
Chapter 1: Standard Model Processes
M. L. Mangano et al.
10.23731/CYRM-2017-003.1

Chapter 2: Higgs and EW Symmetry Breaking Studies
R. Contino et al.
10.23731/CYRM-2017-003.255

Chapter 3: Beyond the Standard Model Phenomena
T. Golling et al.
10.23731/CYRM-2017-003.441

Chapter 4: Heavy Ions at the Future Circular Collider
A. Dainese et al.
10.23731/CYRM-2017-003.635

Chapter 5: Physics Opportunities with the FCC-hh Injectors
B. Goddard et al.
10.23731/CYRM-2017-003.693



2nd FCC Physics Workshop

15-19 January 2018
CERN
Europe/Zurich timezone

Starts 15 Jan 2018, 09:00
Ends 19 Jan 2018, 18:00
Europe/Zurich

CERN
222-R-001

CERN hostel booking form
CERN hostel booking form

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Block booking at the CERN hostel is guarantee until 11 December 2017
(see Accommodation)
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Registration
Registration for this event is currently open.

https://indico.cern.ch/event/618254/

Reference detector

earlier design

6 T, 12 m bore solenoid, 10 Tm dipoles, shielding coil

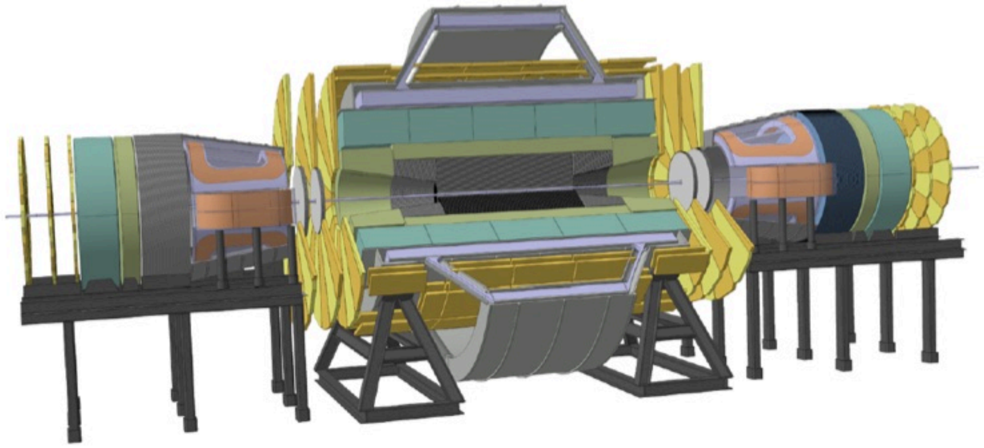
- 65 GJ stored energy
- 28 m diameter
- >30 m shaft
- multi billion project

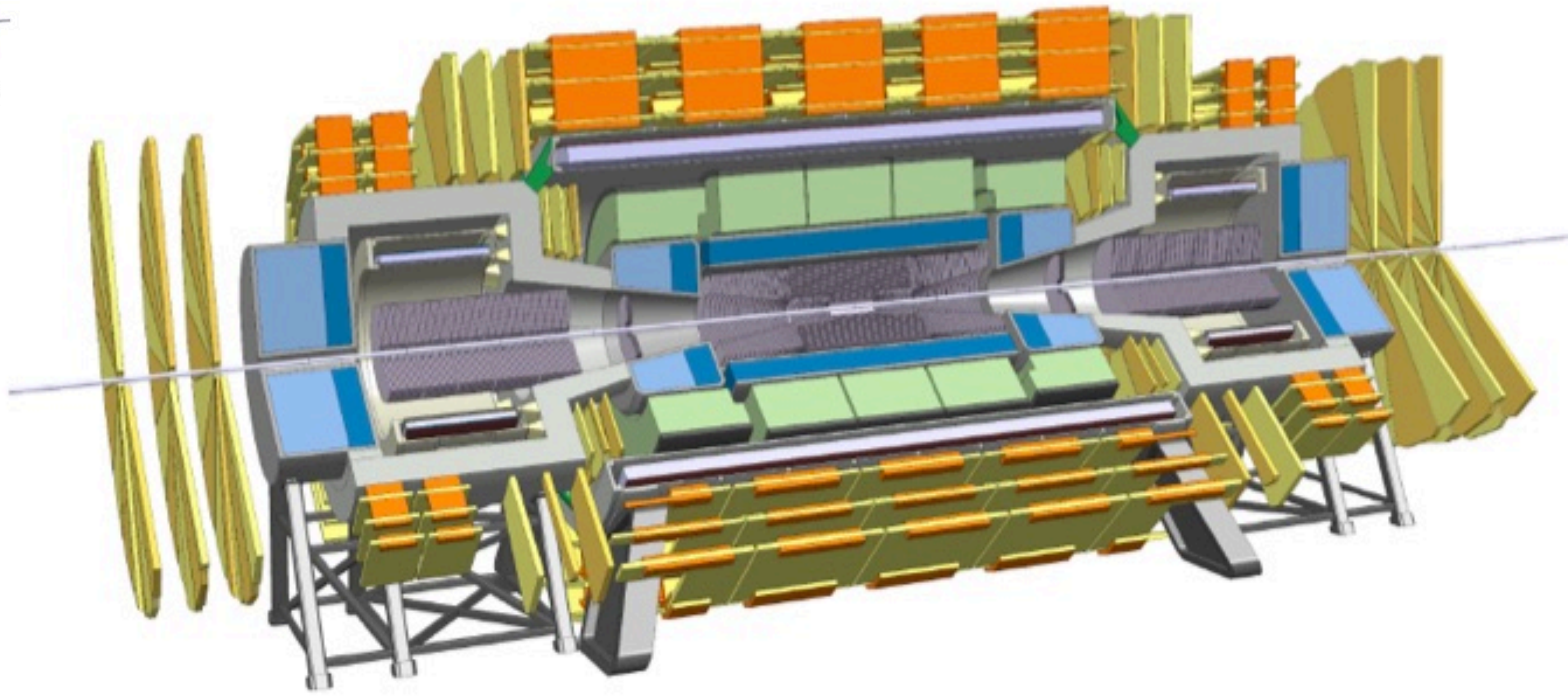
→

current design

4 T, 10 m bore solenoid, 4 T forward solenoids, no shielding coil

- 14 GJ stored energy
- rotational symmetry for tracking!
- 20 m diameter (~ ATLAS)
- 15 m shaft
- ~1 billion project





latest l^* = 40 m

W. Riegler et al.

- **Detector design** group leader: Werner Riegler
  - Indico site of mtgs: http://indico.cern.ch/category/8920/
  - join the mailing list
- **Physics Simulation** subgroup leaders: Heather Gray & Filip Moortgat
  - Indico site of mtgs: http://indico.cern.ch/category/6067/
  - join the mailing list
- Monthly mtgs of each group, if interested register to the mailing lists