FNAL, Oct 4 2017

Physics at a 100 TeV pp collider

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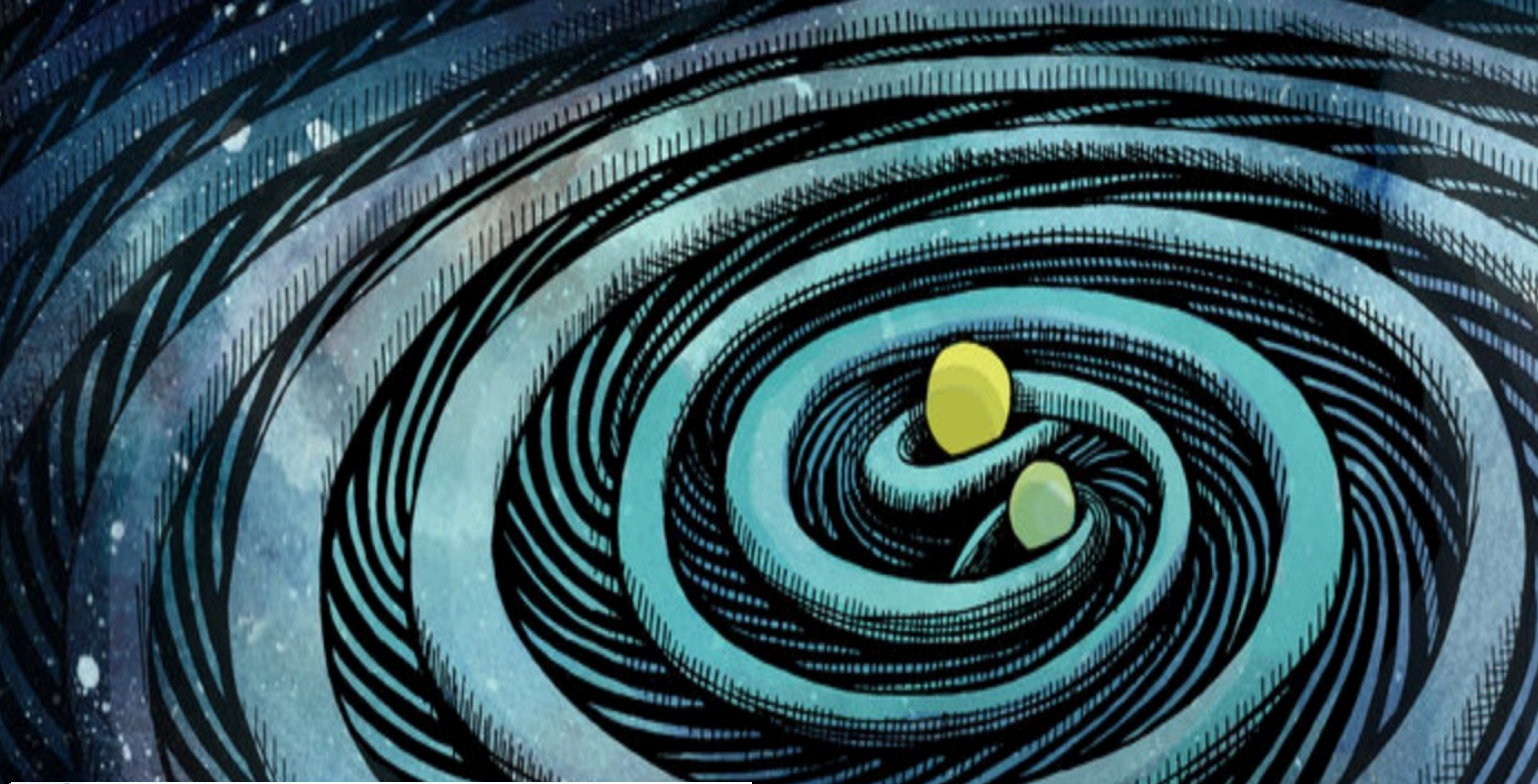
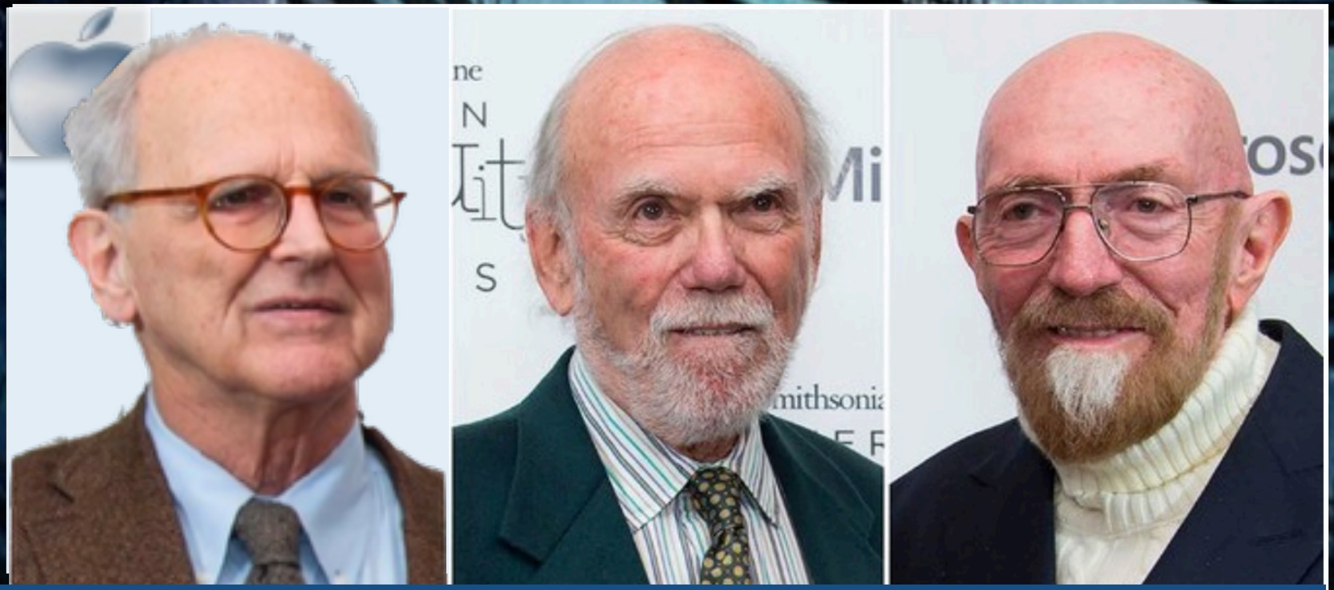
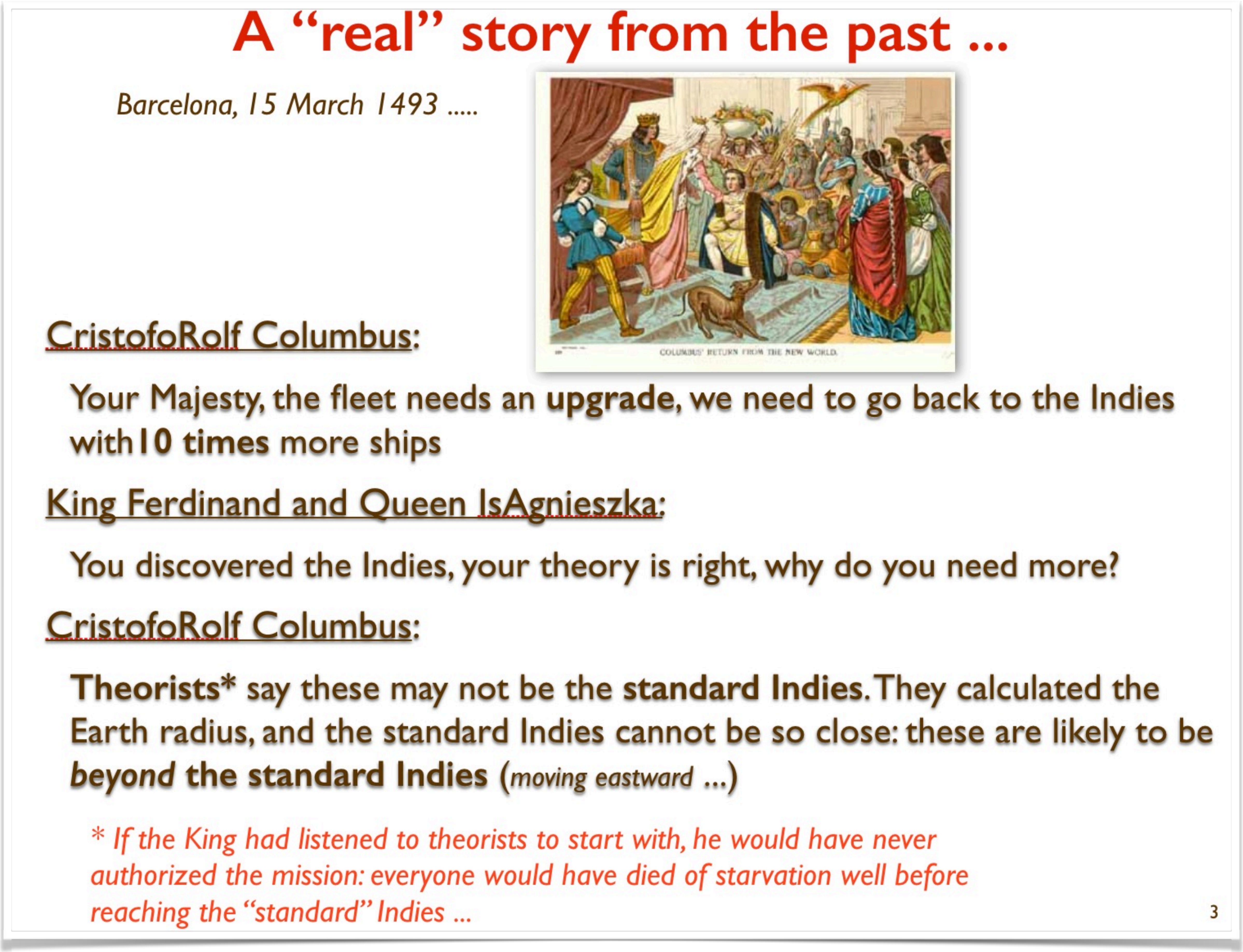




Rainer Weiss **Barry Barish** **Kip Thorne**

MLM, from talk given to Council, 2015, to justify HL-LHC ….



A "real" story from the past ...

Barcelona, 15 March 1493 .....

COLUMBUS' RETURN FROM THE NEW WORLD.

CristofoRolf Columbus:

Your Majesty, the fleet needs an **upgrade**, we need to go back to the Indies with **10 times** more ships

King Ferdinand and Queen IsAgnieszka:

You discovered the Indies, your theory is right, why do you need more?

CristofoRolf Columbus:

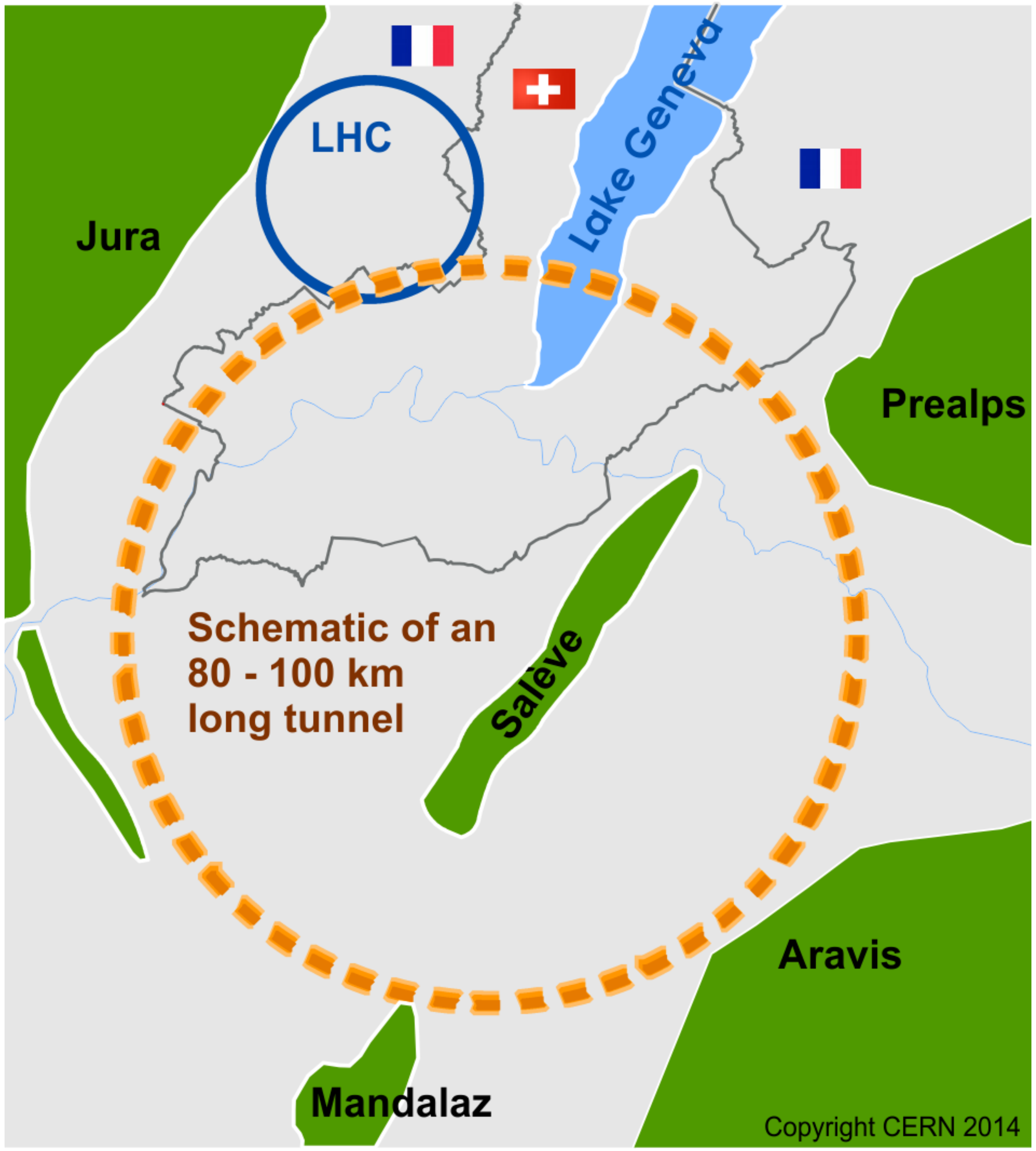
Theorists* say these may not be the **standard Indies.** They calculated the Earth radius, and the standard Indies cannot be so close: these are likely to be ***beyond* the standard Indies** (*moving eastward* ...)

* *If the King had listened to theorists to start with, he would have never authorized the mission: everyone would have died of starvation well before reaching the "standard" Indies ...*

3

The context of this talk: Future Circular Colliders (FCC)

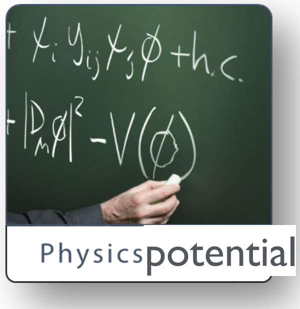
with emphasis on the pp facility, see Blondel Wine&Cheese for the e^+e^- facility

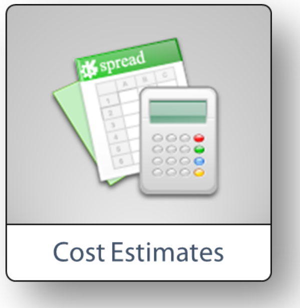


International FCC collaboration (CERN as host lab) to study:

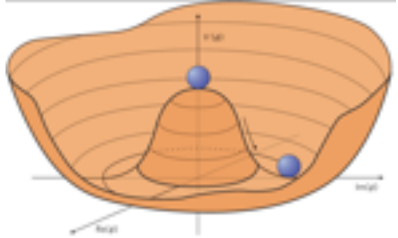
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

  ~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**



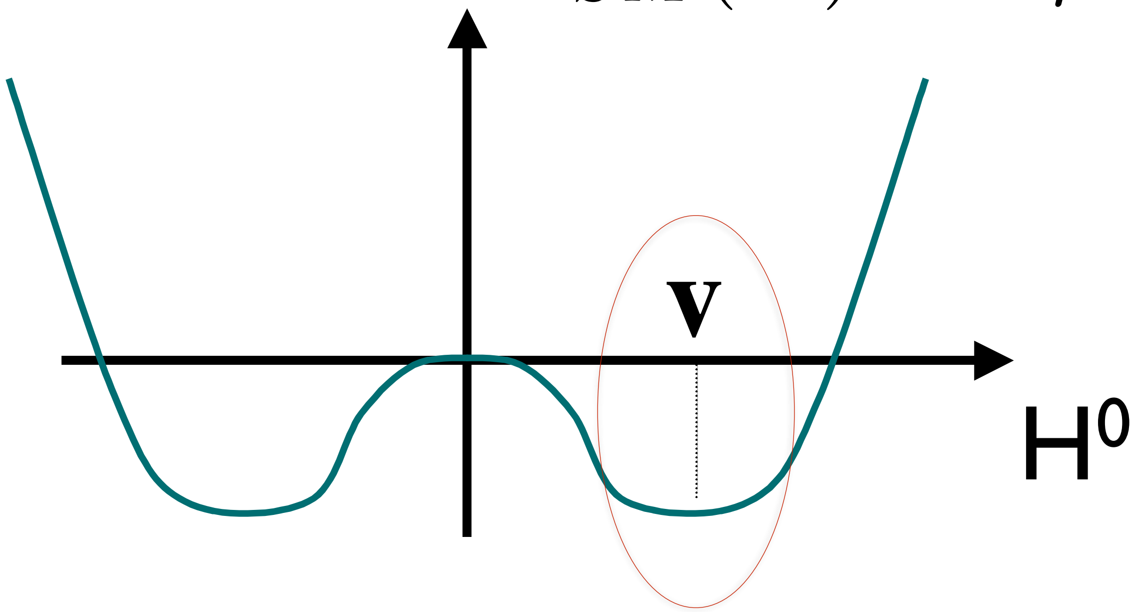


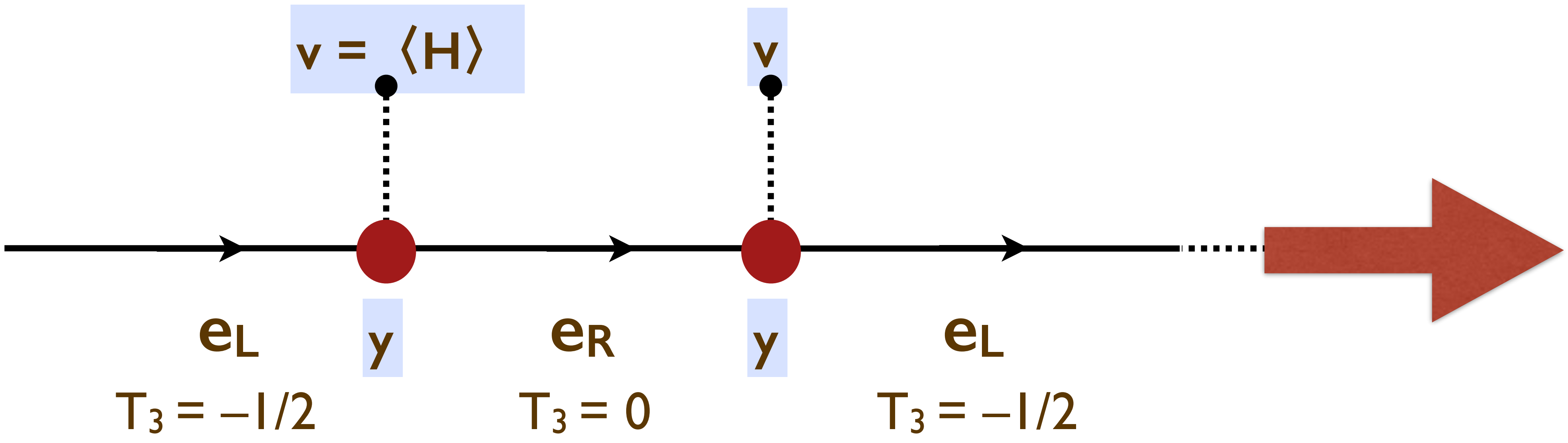
The Higgs mechanism in a nutshell …



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

$$H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix}$$

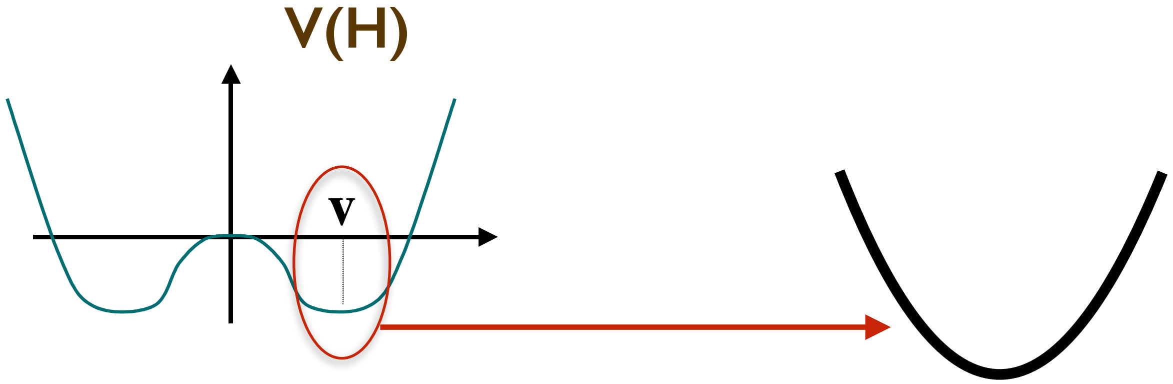




m = y v

How far have we tested the Higgs mechanism?

parameters of the potential

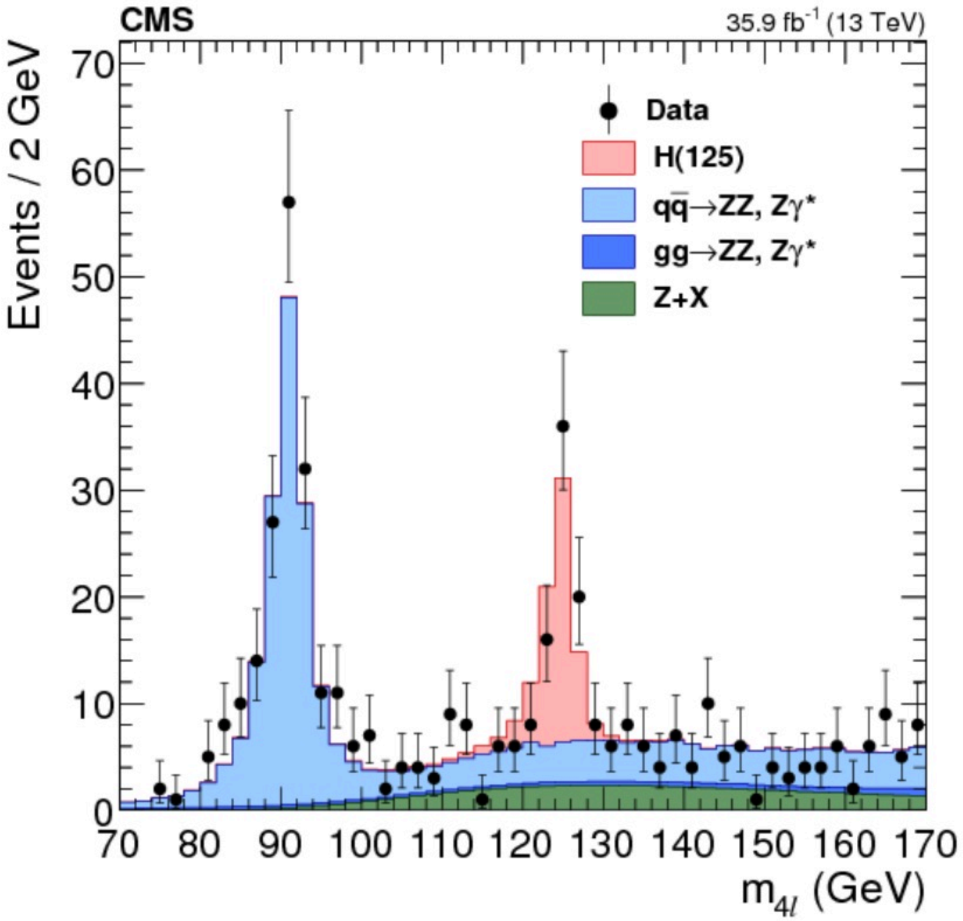


$V(H) \sim m_H^2\,(H-\mathbf{v})^2$

v=246 GeV, from
weak decays

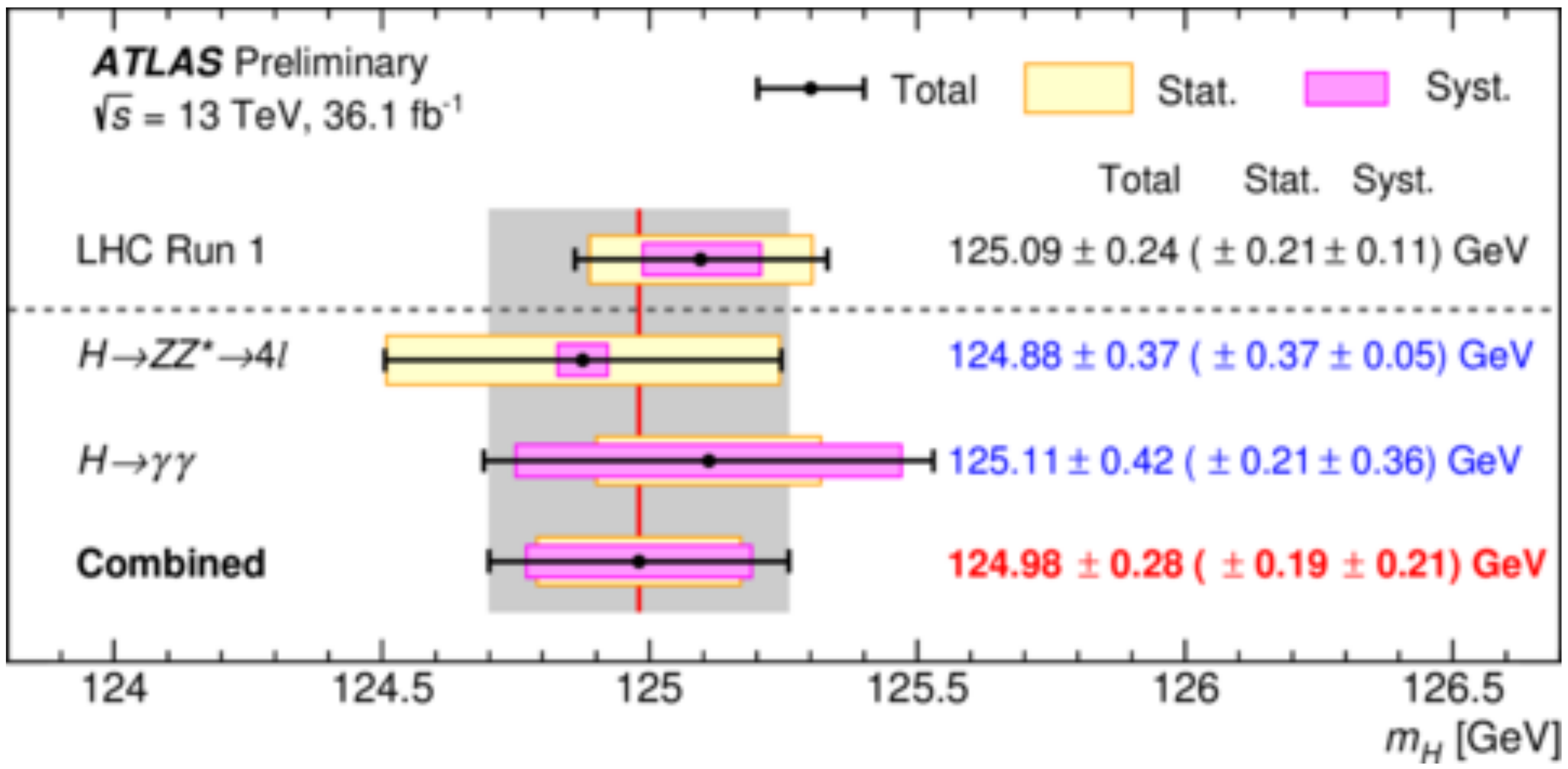
Higgs mass, 2017

CMS



arXiv:1706.09936

ATLAS



ATLAS-CONF-2017-046

3D likelihood fit (m_{4l}, ZZ bg, δm) ⇒

$m_H = 125.26 \pm 0.20_{stat} \pm 0.08_{syst}$ GeV

$= 125.26 \pm 0.22$ GeV

γγ and 4ℓ combination, run 1+2 ⇒

$m_H = 124.98 \pm 0.19_{stat} \pm 0.21_{syst}$ GeV

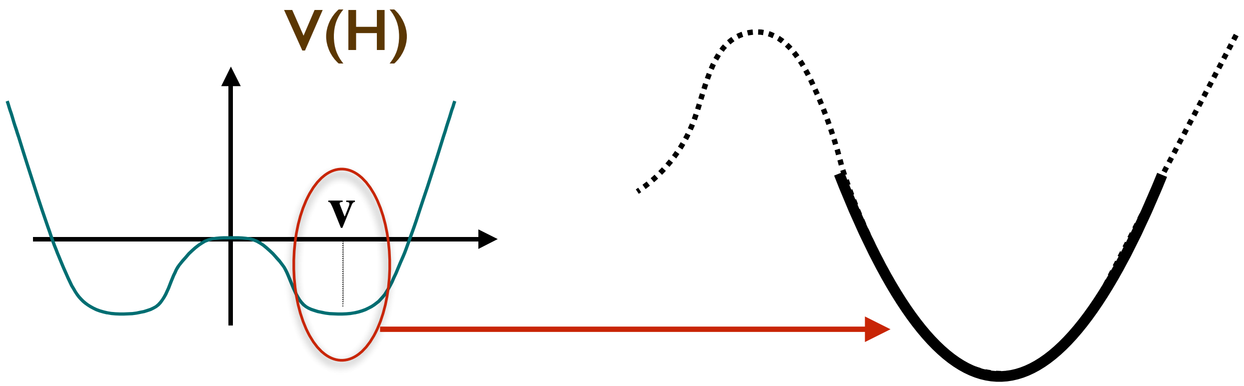
$= 124.98 \pm 0.26$ GeV

⇒ 2 x 10^{-3} precision ….

it took over 6 years from 1983 discovery to get below 5 x 10^{-3} on m_Z (1989: CDF, SLC, LEP)

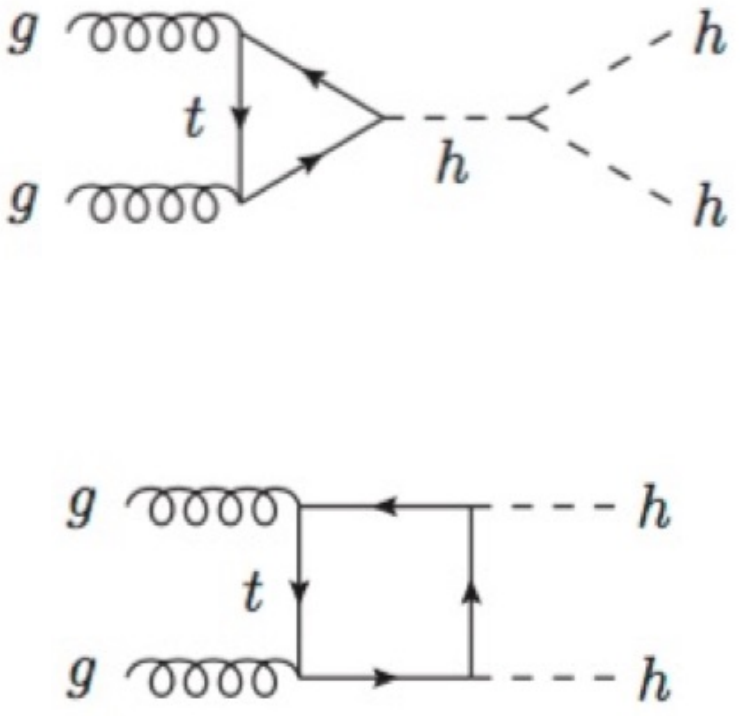
How far have we tested the Higgs mechanism?

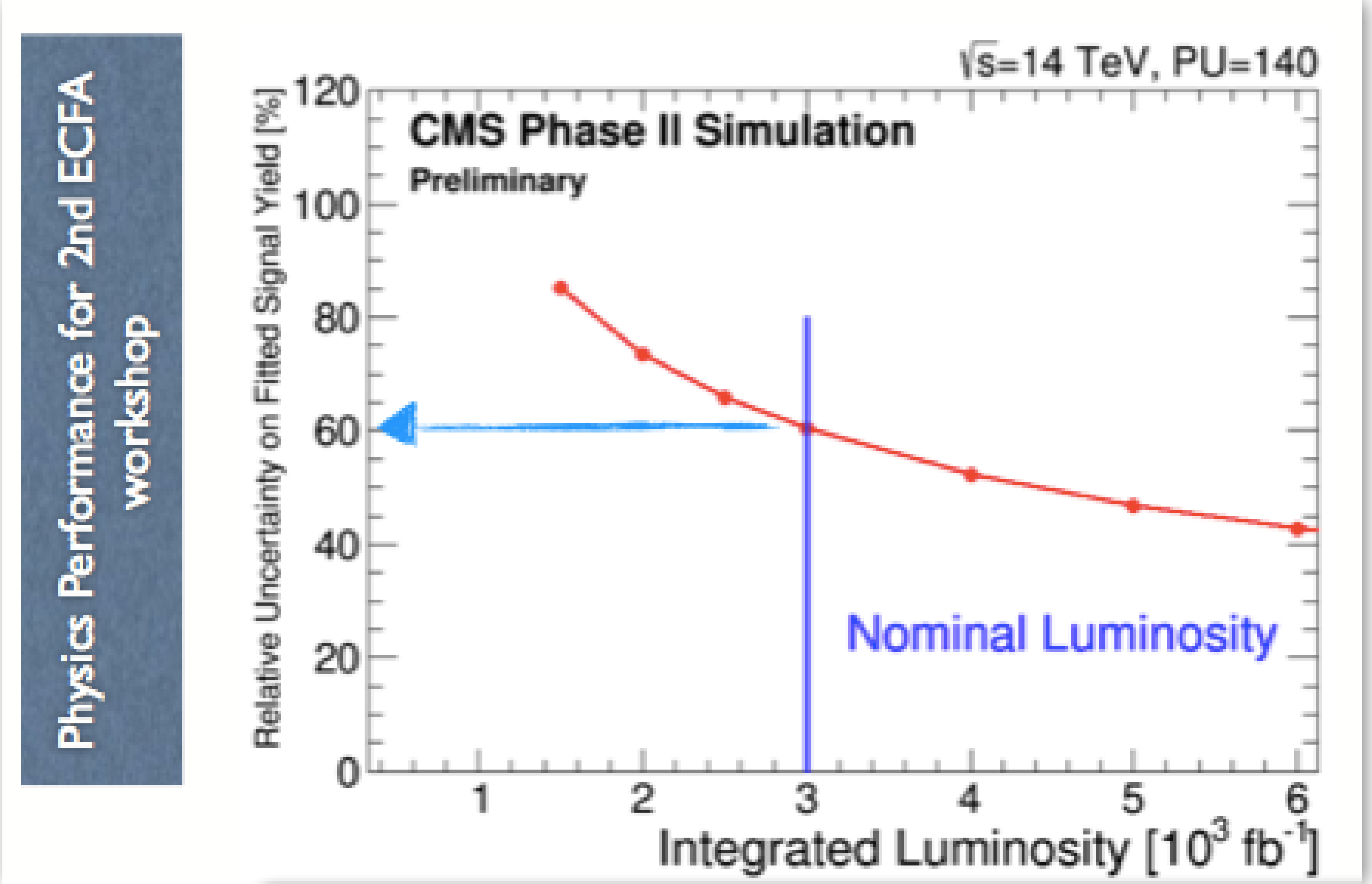
parameters of the potential



V(H) ~ $m_H^2 (H-v)^2$ + ???

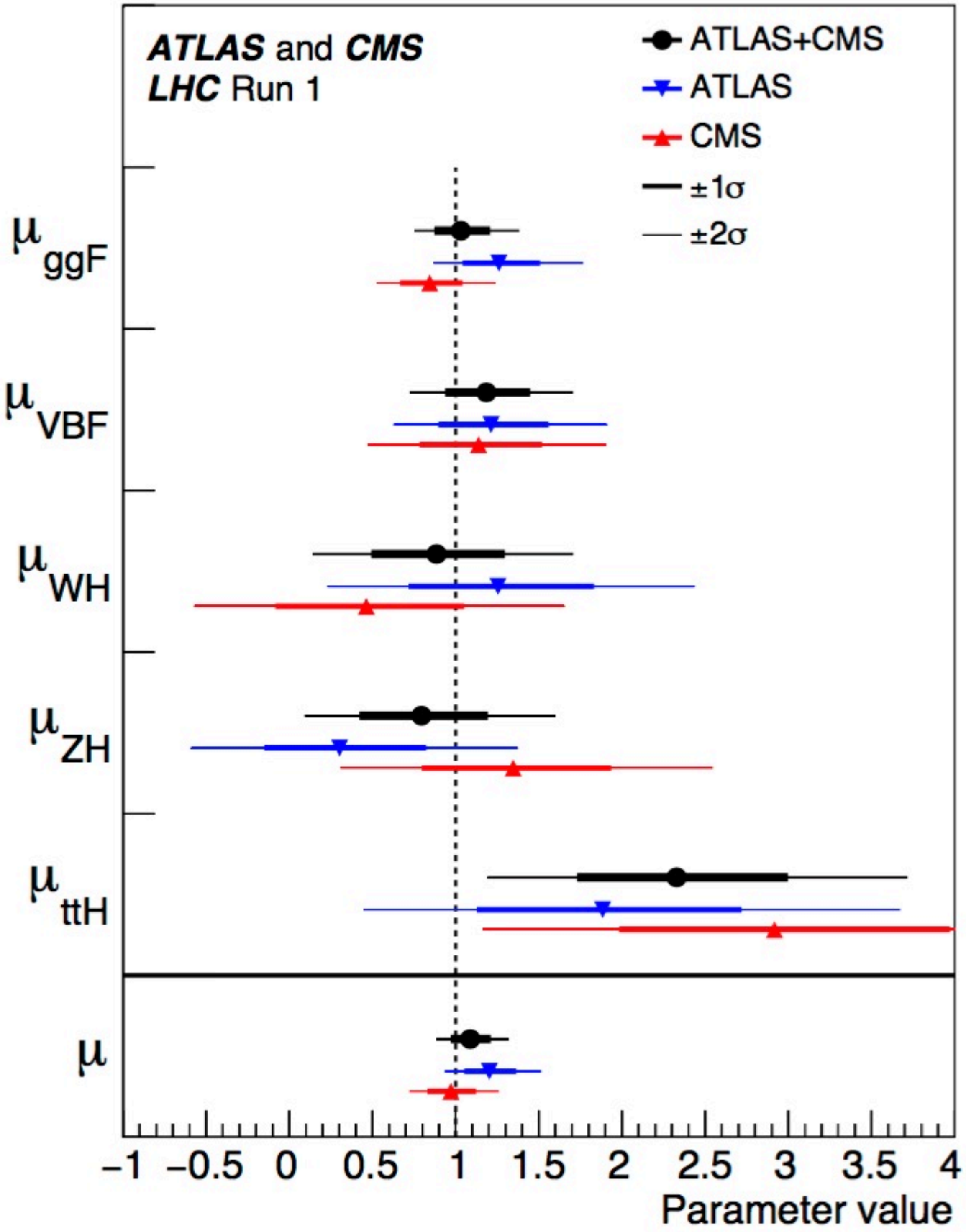
Probing the cubic term of the Higgs potential will require at least 100x the current LHC statistics, and possibly more





Higgs couplings: global fit of run 1 data

$\mu = \sigma \times BR / [\sigma \times BR]_{SM}$
assuming SM BR's in data



ATLAS+CMS
JHEP 1608 (2016) 045

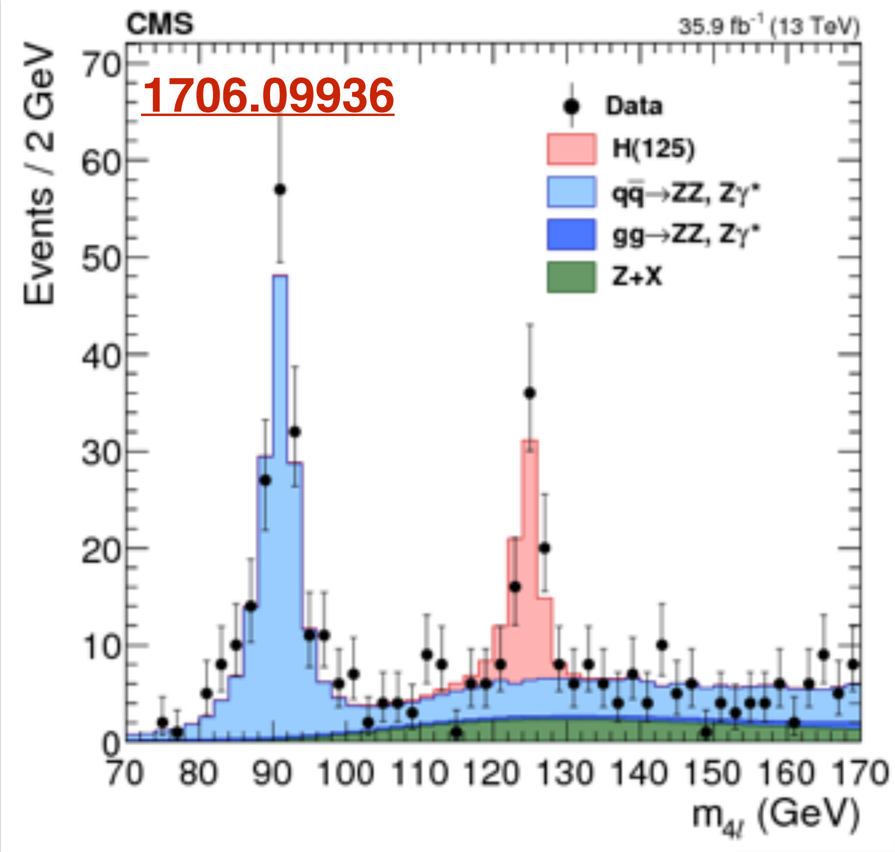
$\mu = 1.09 \pm 0.11$

- combination of different production and decay channels, explicit constraints on individual couplings are much less precise than 10% !!

- essential to establish couplings individually, through combinations of different production and decay channels

μ=(obs rate)/(SM rate), 2017

pp→H→4ℓ



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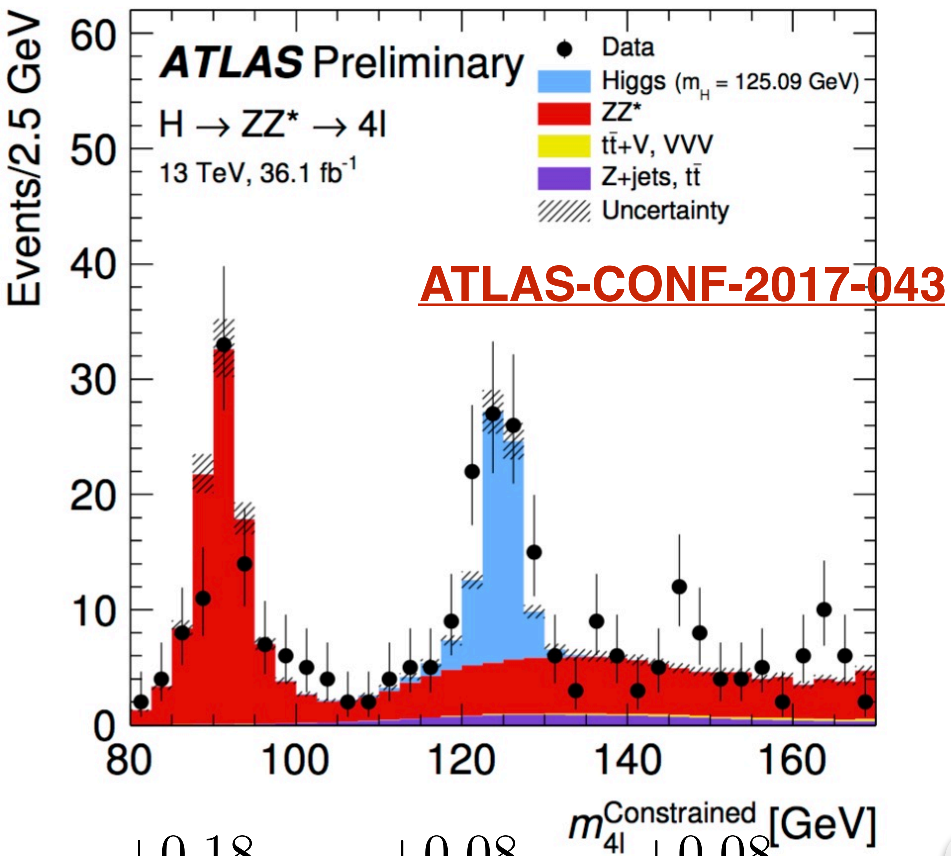
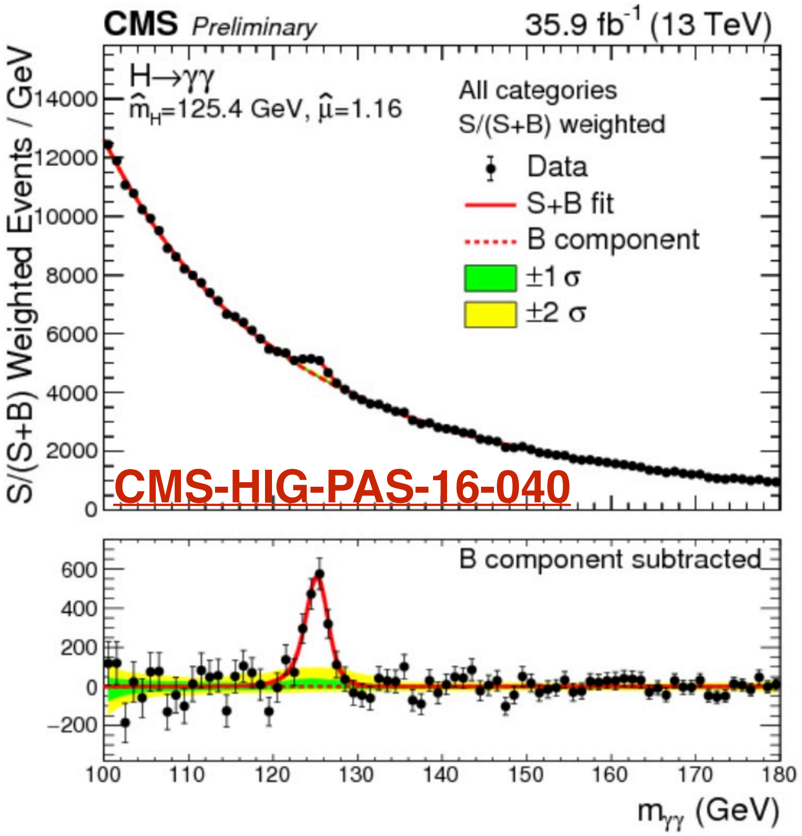


ATLAS-CONF-2017-043

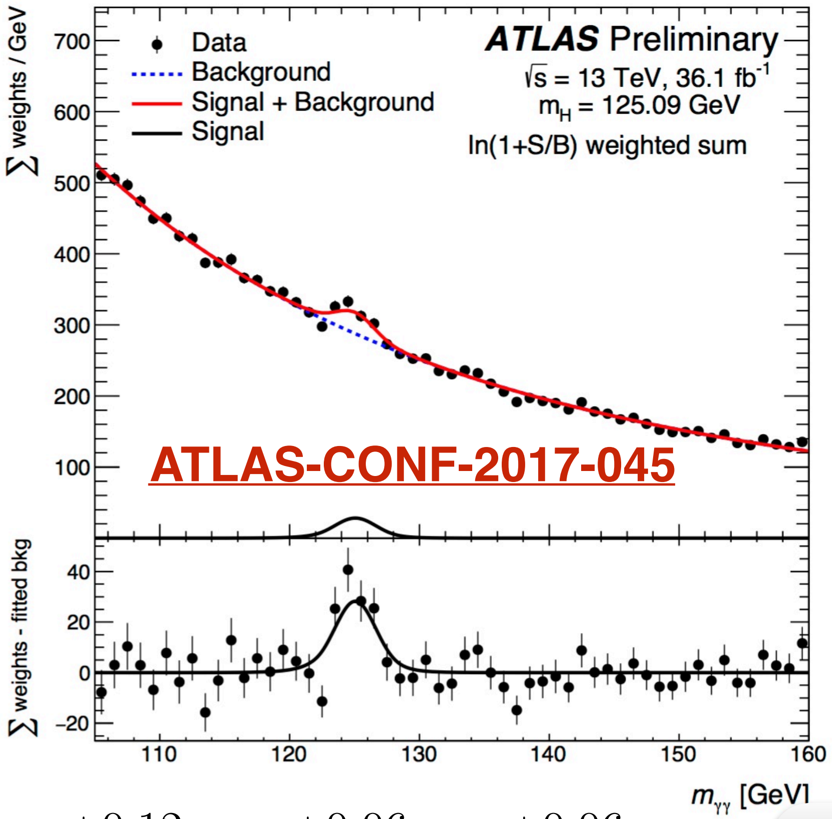
$$\mu = 1.05\,^{+0.15}_{-0.14}\,_{(stat)}\,^{+0.11}_{-0.09}\,_{(syst)} = \boxed{1.05\,^{+0.19}_{-0.17}}$$

$$\mu = 1.28\,^{+0.18}_{-0.17}\,_{(stat)}\,^{+0.08}_{-0.06}\,_{(exp)}\,^{+0.08}_{-0.06}\,_{(TH)} = \boxed{1.28\,^{+0.21}_{-0.19}}$$

pp→H→γγ



CMS-HIG-PAS-16-040



ATLAS-CONF-2017-045

$$\mu = 1.16\,^{+0.11}_{-0.10}\,_{(stat)}\,^{+0.09}_{-0.08}\,_{(exp)}\,^{+0.06}_{-0.05}\,_{(TH)} = \boxed{1.16\,^{+0.15}_{-0.14}}$$

$$\mu = 0.99\,^{+0.12}_{-0.11}\,_{(stat)}\,^{+0.06}_{-0.05}\,_{(exp)}\,^{+0.06}_{-0.05}\,_{(TH)} = \boxed{0.99 \pm 0.14}$$

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 <u>deep understanding of their dynamical nature</u>, 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 <u>no clue as to what is its dynamical origin</u>, 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, <u>regardless of whether they eventually match the SM assumption or require new physics</u>

- 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 / $m_{Plank,GUT}$ (hierarchy problem)?
- ...

- 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.

Why do we care so much?

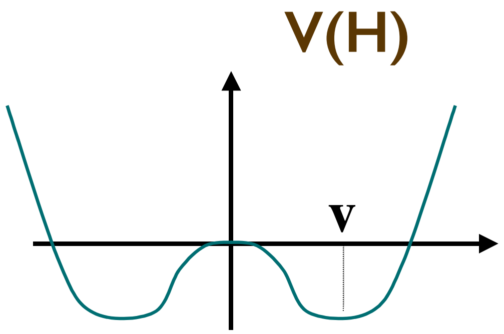
The Higgs boson is directly connected to several questions:

- 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 hierarchy problem: what protects the smallness of m_H / $m_{\text{Plank,GUT,...}}$?

Higgs selfcouplings

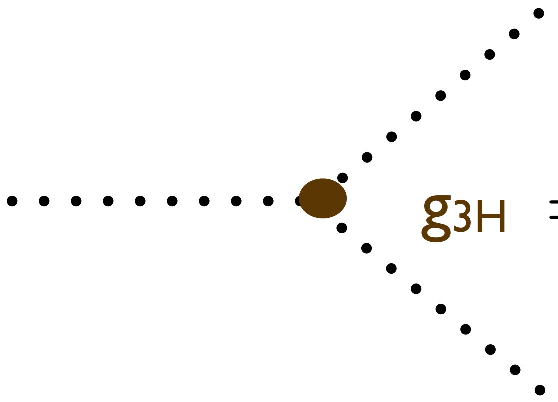
The Higgs sector is defined in the SM by two parameters, **μ** and **λ**:

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

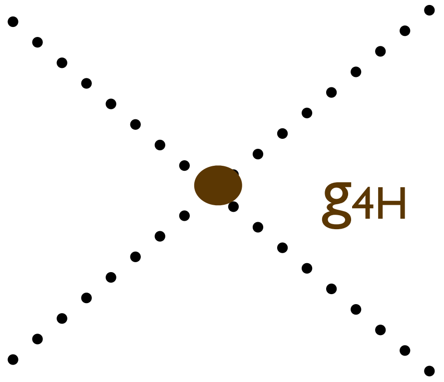


$$\frac{\partial V_{SM}(H)}{\partial H}\Big|_{H=v} = 0 \quad \text{and} \quad m_H^2 = \frac{\partial^2 V_{SM}(H)}{\partial H \partial H^*}\Big|_{H=v} \quad \Rightarrow \quad \boxed{\begin{aligned} \mu &= m_H \\ \lambda &= \frac{m_H^2}{2v^2} \end{aligned}}$$

These relations uniquely determine the strength of Higgs selfcouplings in terms of the two now-known parameters m_H and v



$$g_{3H} \Rightarrow 4\lambda v = \boxed{\frac{2m_H^2}{v}}$$

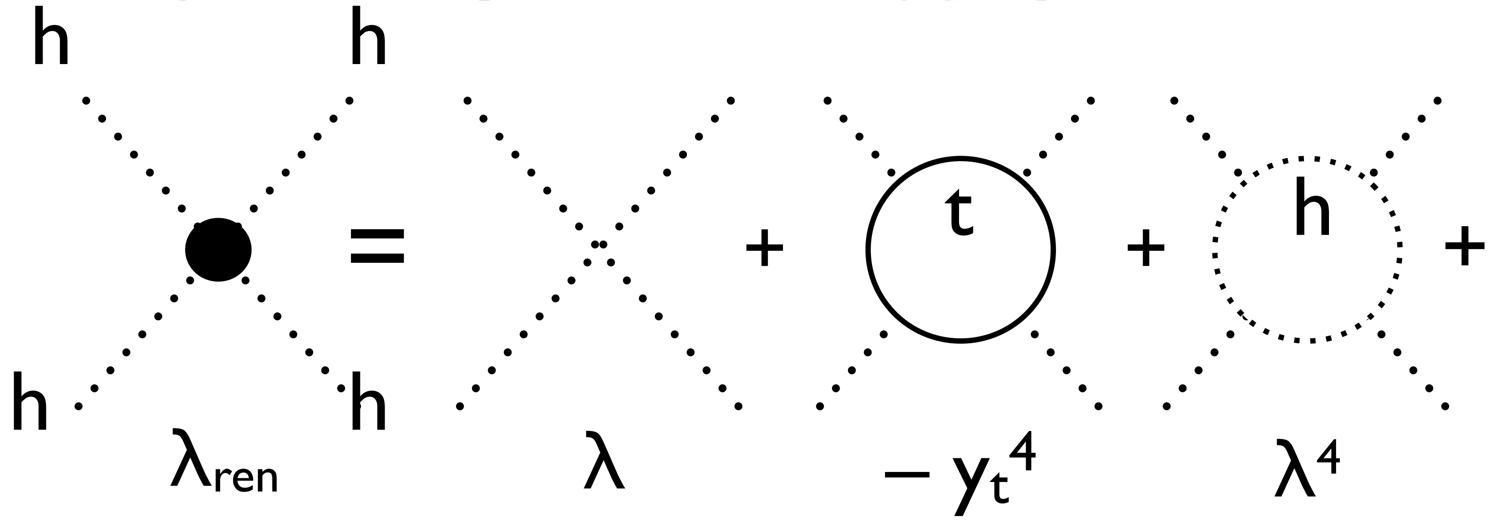


$$g_{4H} \Rightarrow \lambda = \boxed{\frac{m_H^2}{2v^2}}$$

These relations between Higgs self-couplings, m_H and v entirely depend on the functional form of the Higgs potential. Their measurement is therefore an important test of the SM nature of the Higgs mechanism

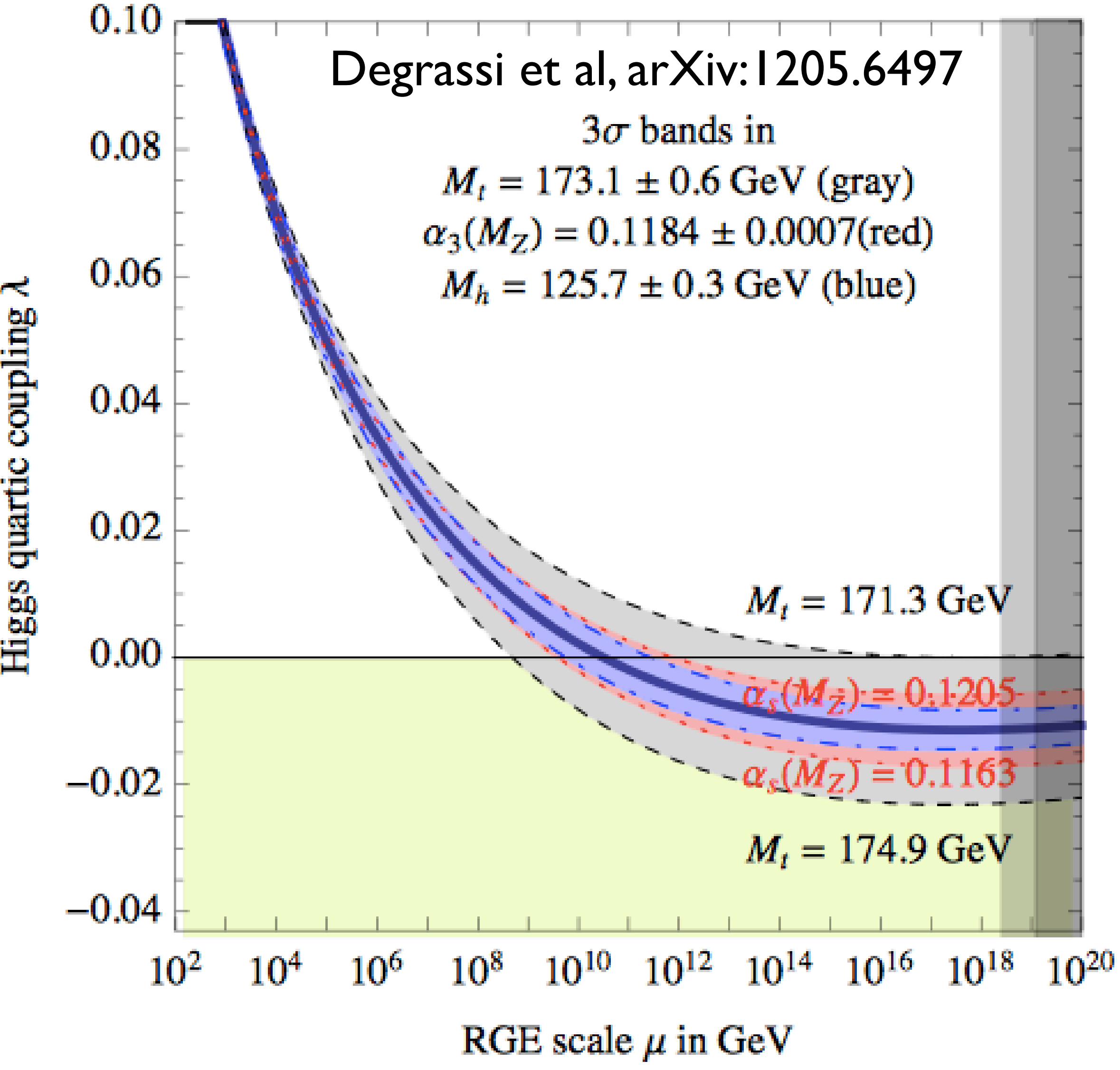
(meta)Stability of the Higgs potential

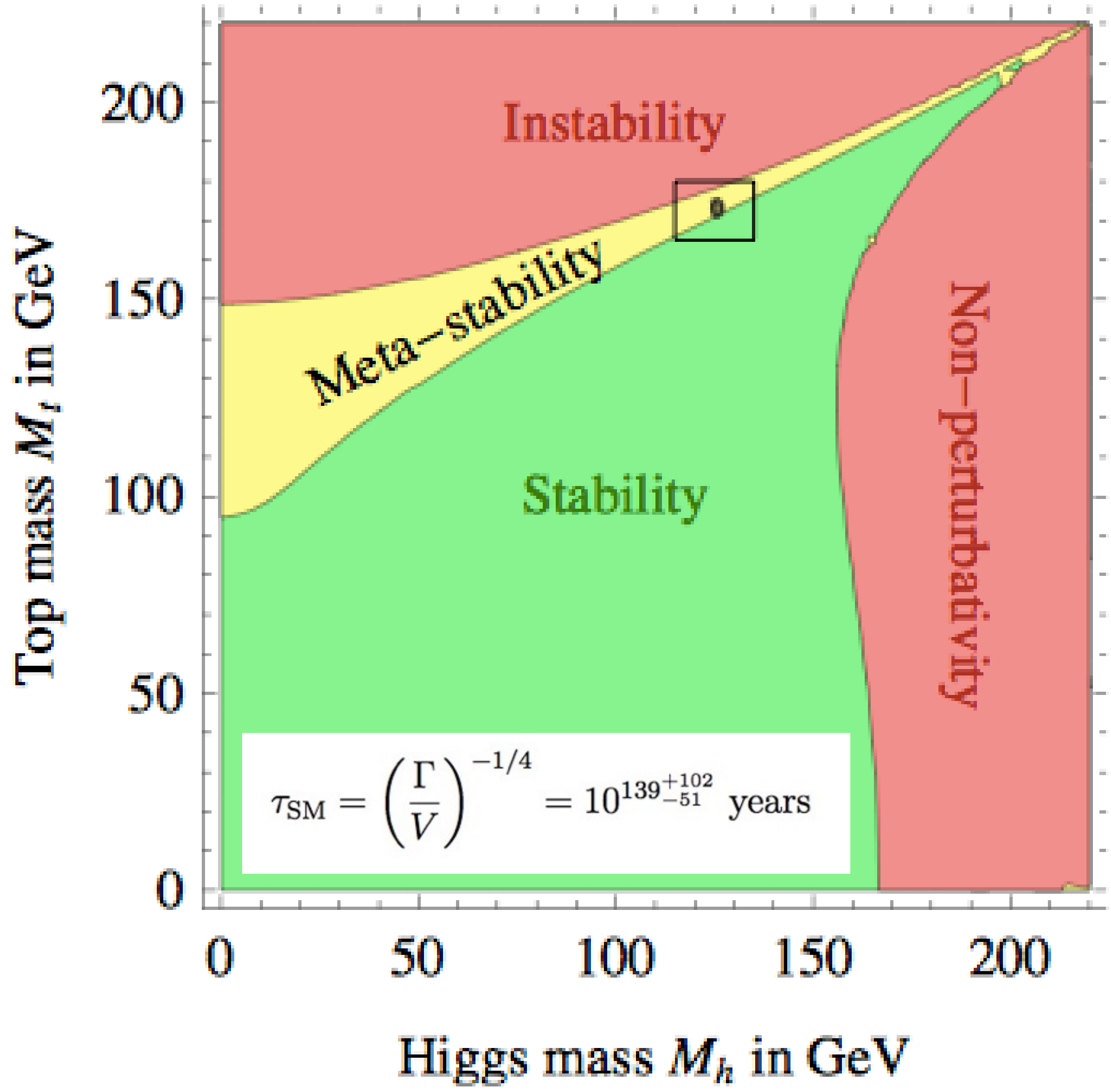
Higgs selfcoupling and coupling to the top are the key elements to define the stability of the Higgs potential



$$\Rightarrow \frac{d\lambda}{d\log\mu} \propto \lambda^4 - y_t^4$$

$$\propto a\, m_H^4 - b\, m_t^4$$

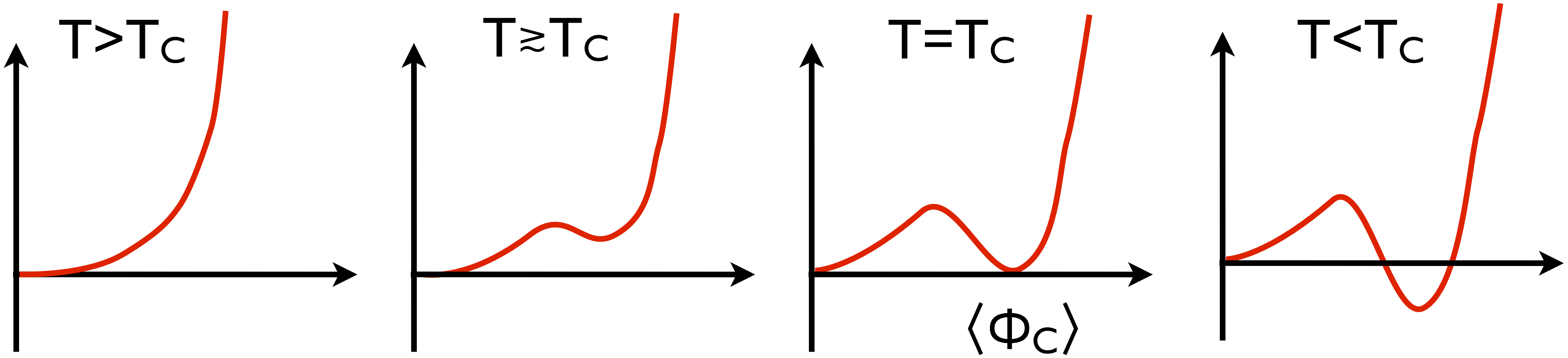

Degrassi et al, arXiv:1205.6497



Not an issue of concern for the human race…. but the closeness of mtop to the critical value where the Higgs selfcoupling becomes 0 at M_{Planck} (namely 171.3 GeV) might be telling us something fundamental about the origin of EWSB … incidentally, y_{top}=1 (?!)

The nature of the EW phase transition

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.

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**

The basic motivation for Future Circular Colliders

- HEP has two priorities:
  - **explore the physics of electroweak symmetry breaking:**
    - experimentally, via the measurement of Higgs properties, Higgs interactions and selfinteractions, couplings of gauge bosons, flavour phenomena, etc
    - theoretically, to understand the nature of the hierarchy problem and identify possible natural solutions (to be subjected to exptl test)
  - **explore the origin of known departures from the SM** (DM, neutrino masses, baryon asymmetry of the universe)

The physics case of FCCs builds on the belief that these two directions are deeply intertwined, and equally worth investigating

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

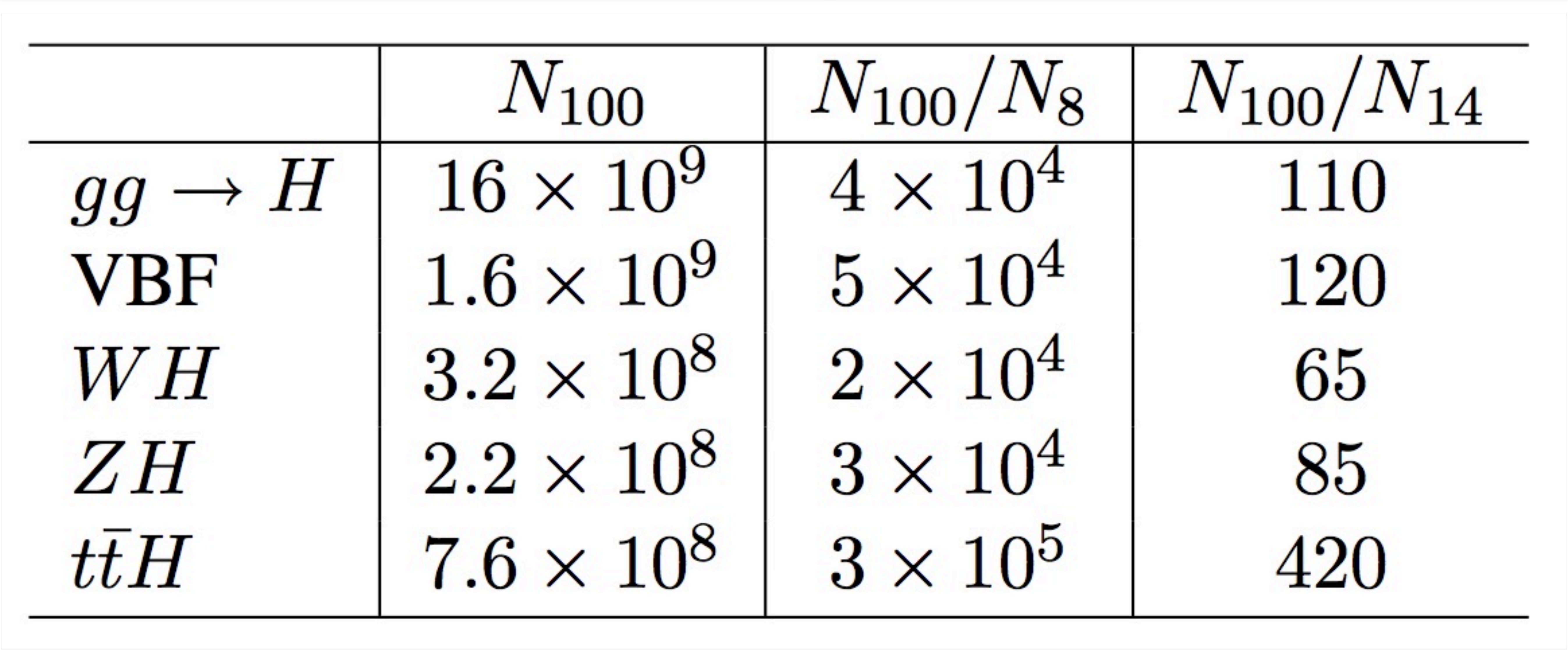
Readiness to address both scenarios is the best hedge for the field:
- *precision*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*

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?

Higgs physics

SM Higgs rates at 100 TeV



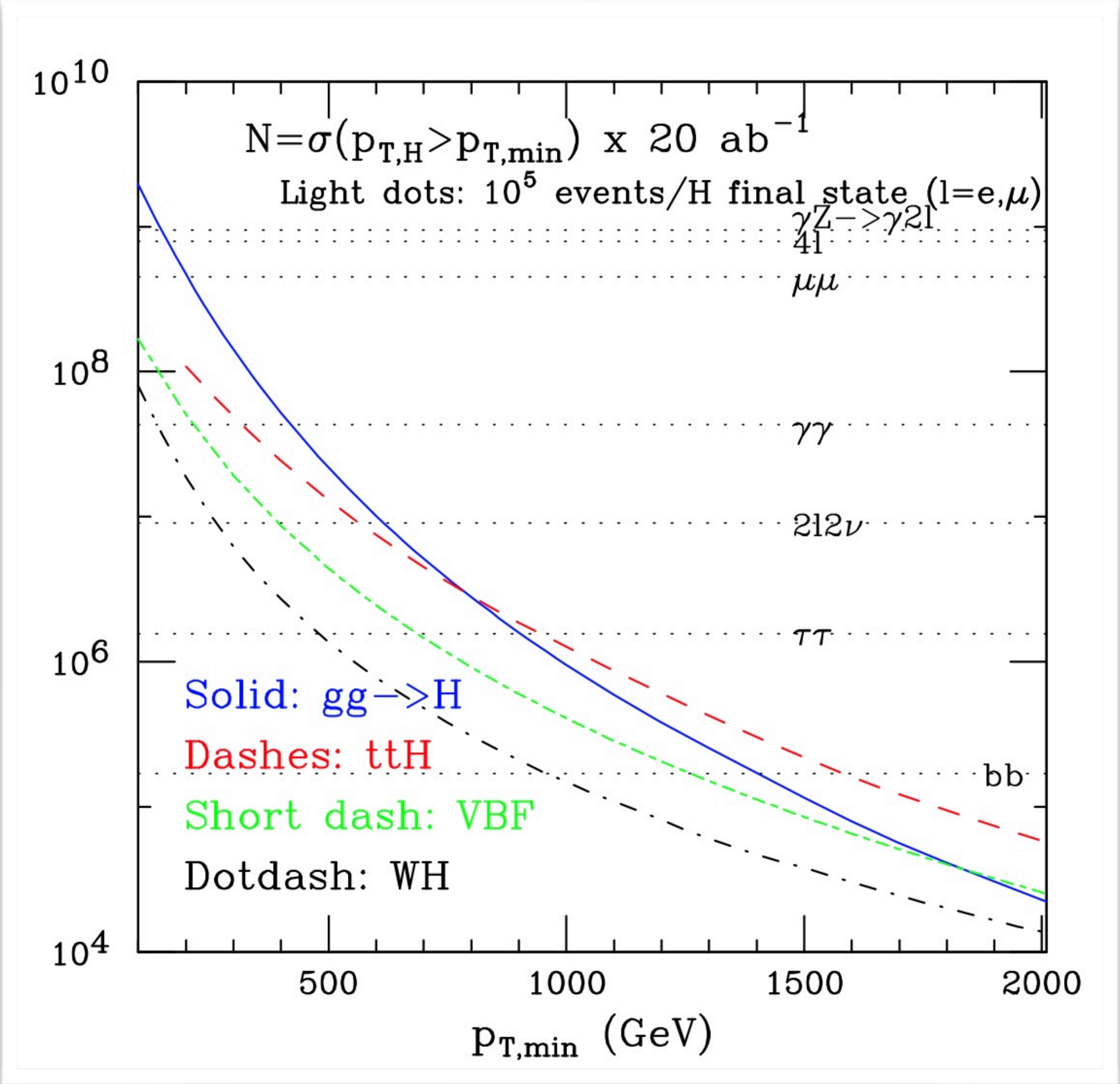
	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

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

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

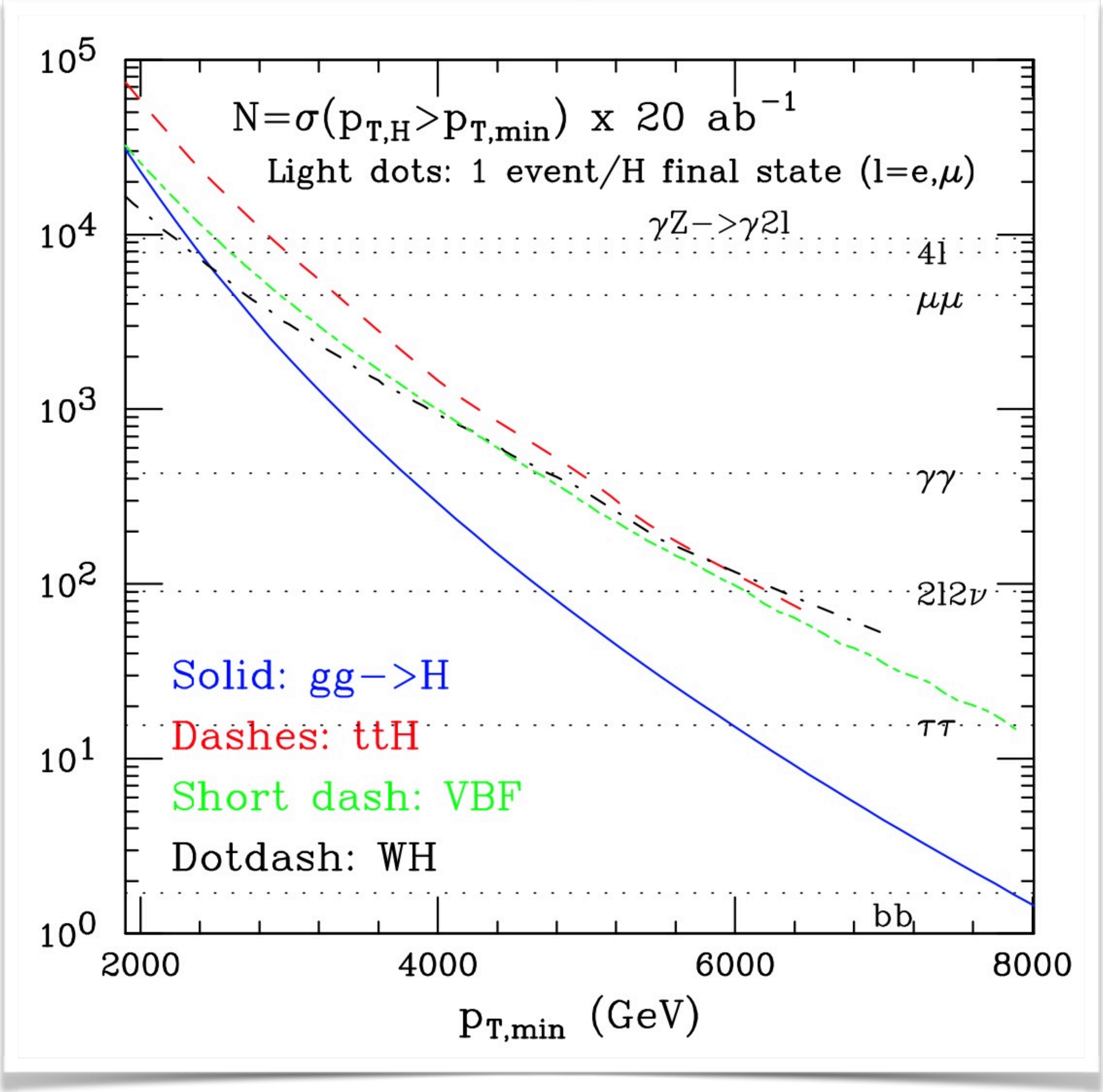
$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

H at large p_T



- Hierarchy of production channels changes at large p_T(H):
    - σ(ttH) > σ(gg→H) above 800 GeV
    - σ(VBF) > σ(gg→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)

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

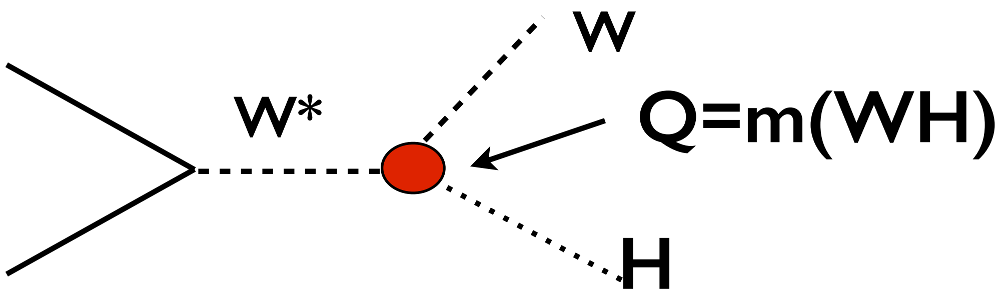
⇒ **kinematic reach** probes large

Λ even if precision is low

e.g. δO=15% at Q=1 TeV ⇒ Λ~2.5 TeV

Examples

$\delta BR(H\to WW^*)$



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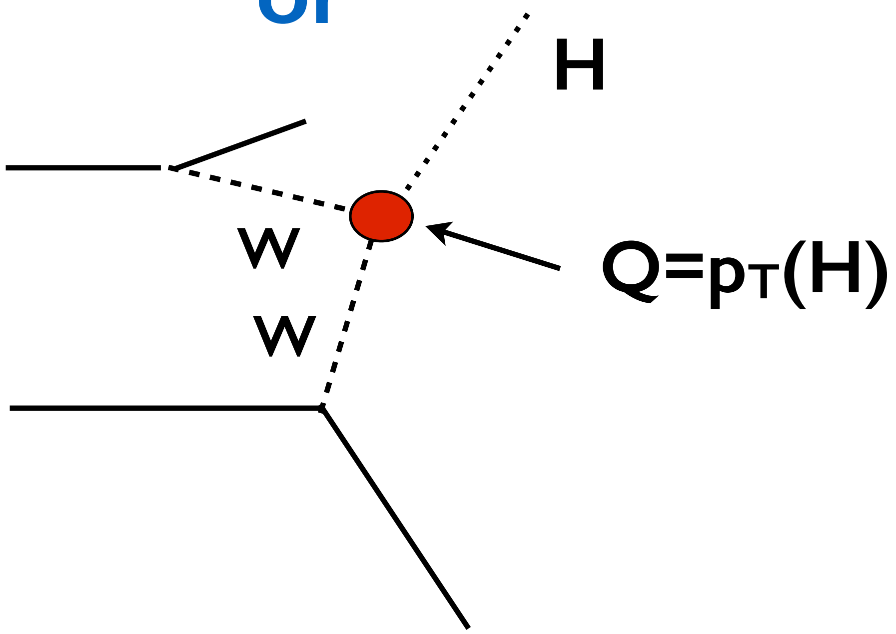
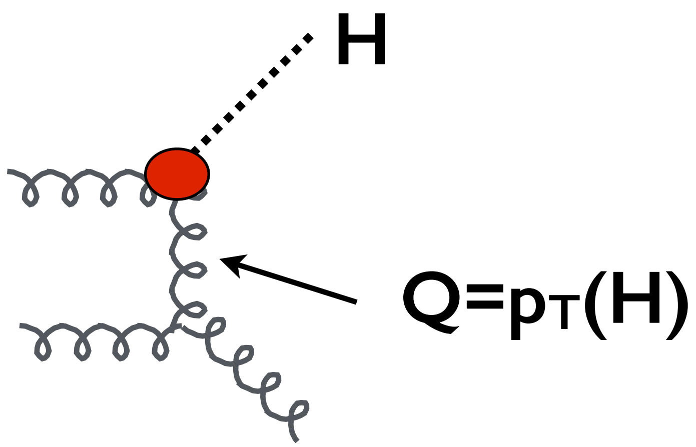


$\delta BR(H\to gg)$



Examples of deviations of the Higgs p_T spectrum from SM, in presence of new particles in the ggH loop

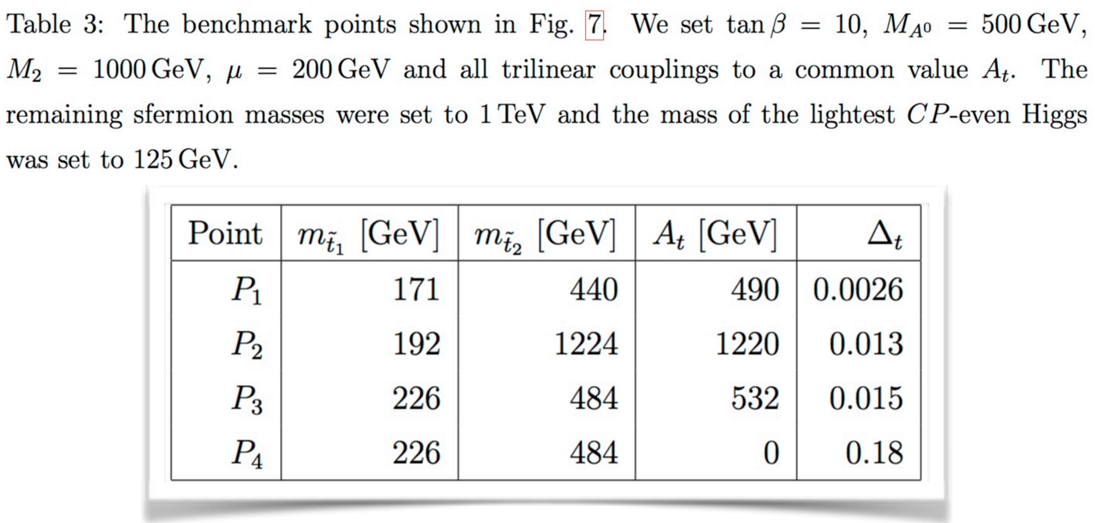
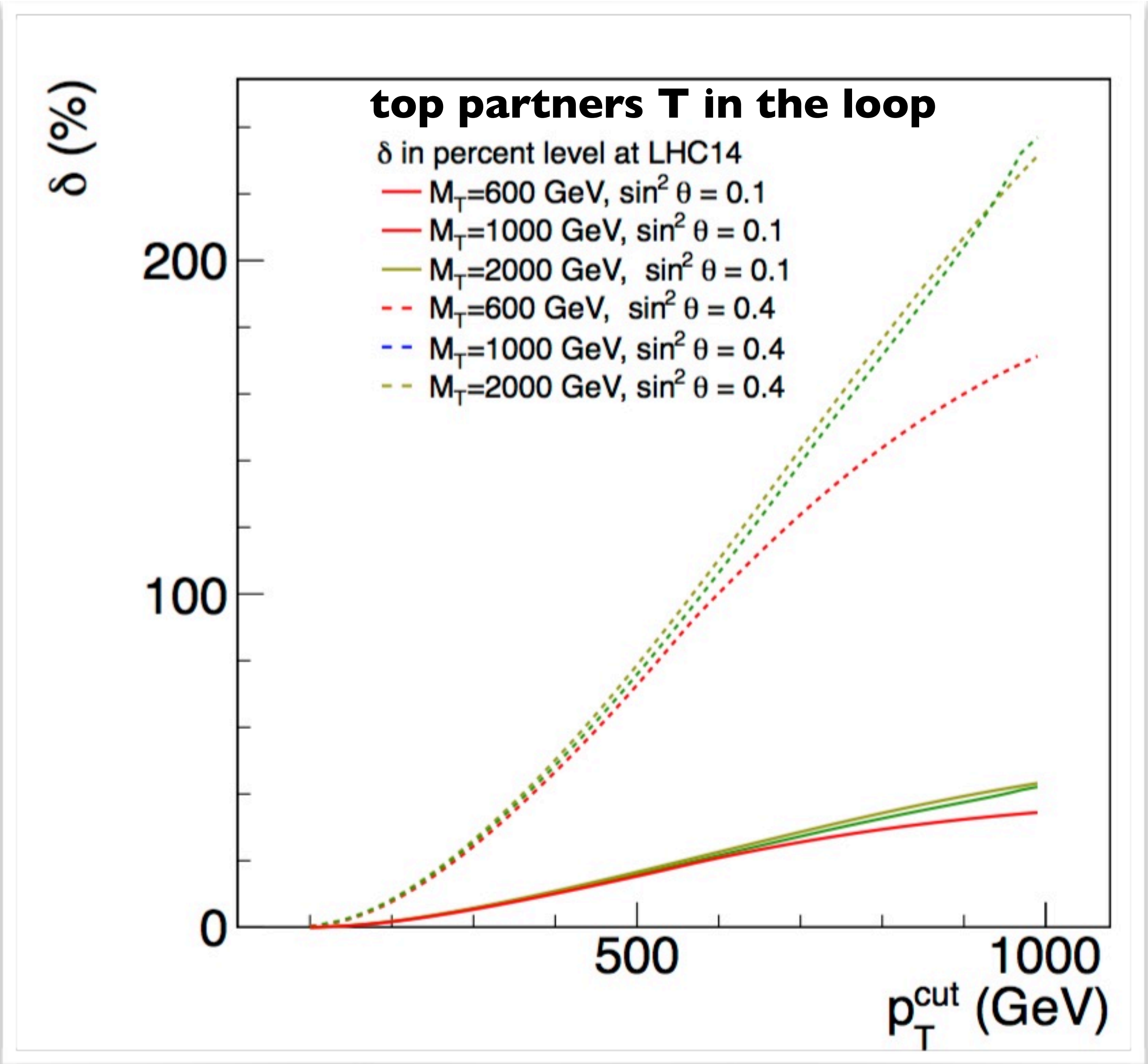


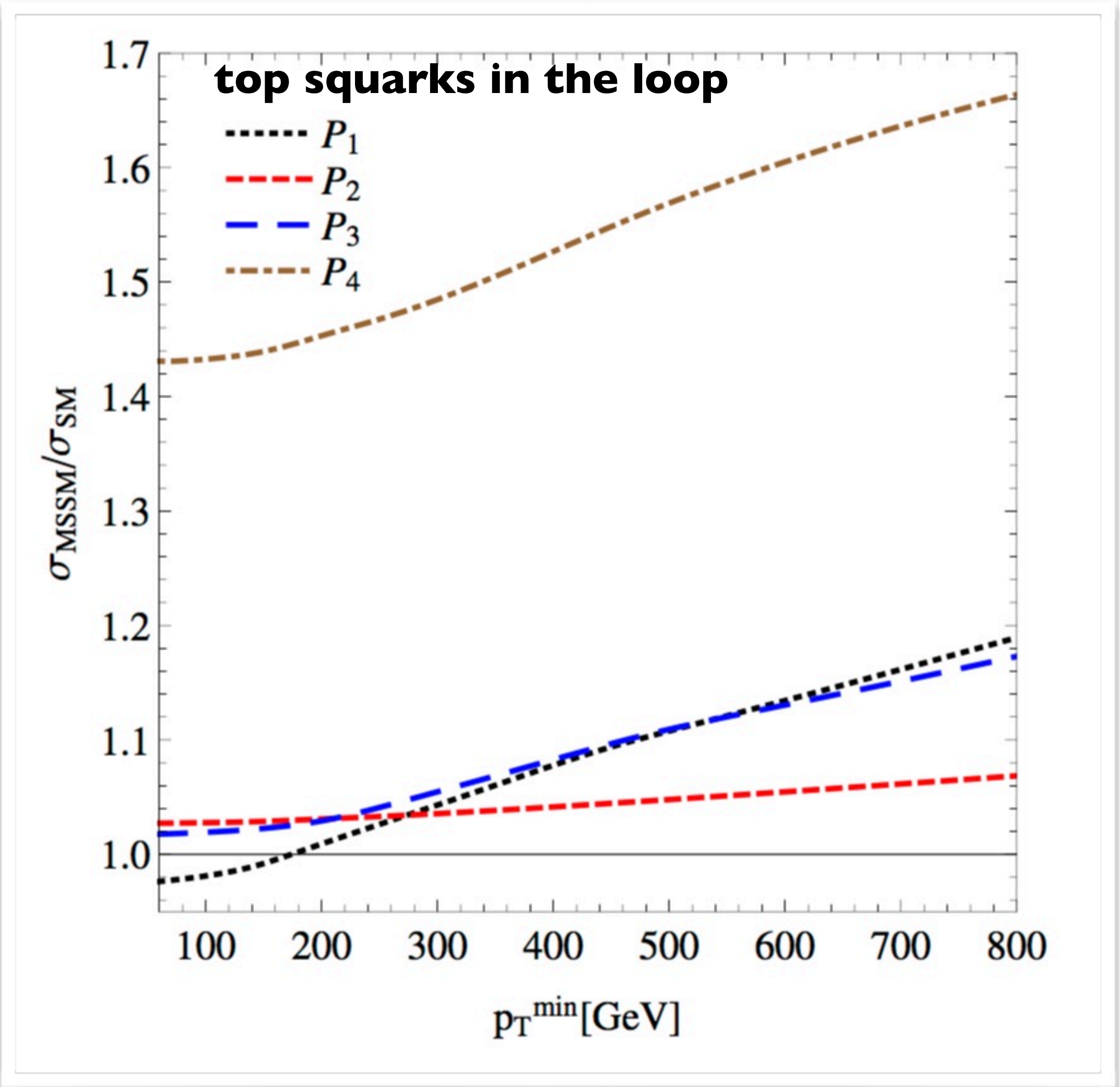
Table 3: The benchmark points shown in Fig. 7. We set $\tan\beta = 10$, $M_{A^0} = 500\,\text{GeV}$, $M_2 = 1000\,\text{GeV}$, $\mu = 200\,\text{GeV}$ and all trilinear couplings to a common value A_t. The remaining sfermion masses were set to 1 TeV and the mass of the lightest CP-even Higgs was set to 125 GeV.

Point	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{t}_2}$ [GeV]	A_t [GeV]	Δ_t
P_1	171	440	490	0.0026
P_2	192	1224	1220	0.013
P_3	226	484	532	0.015
P_4	226	484	0	0.18

(See also
Azatov and Paul arXiv:1309.5273v3)

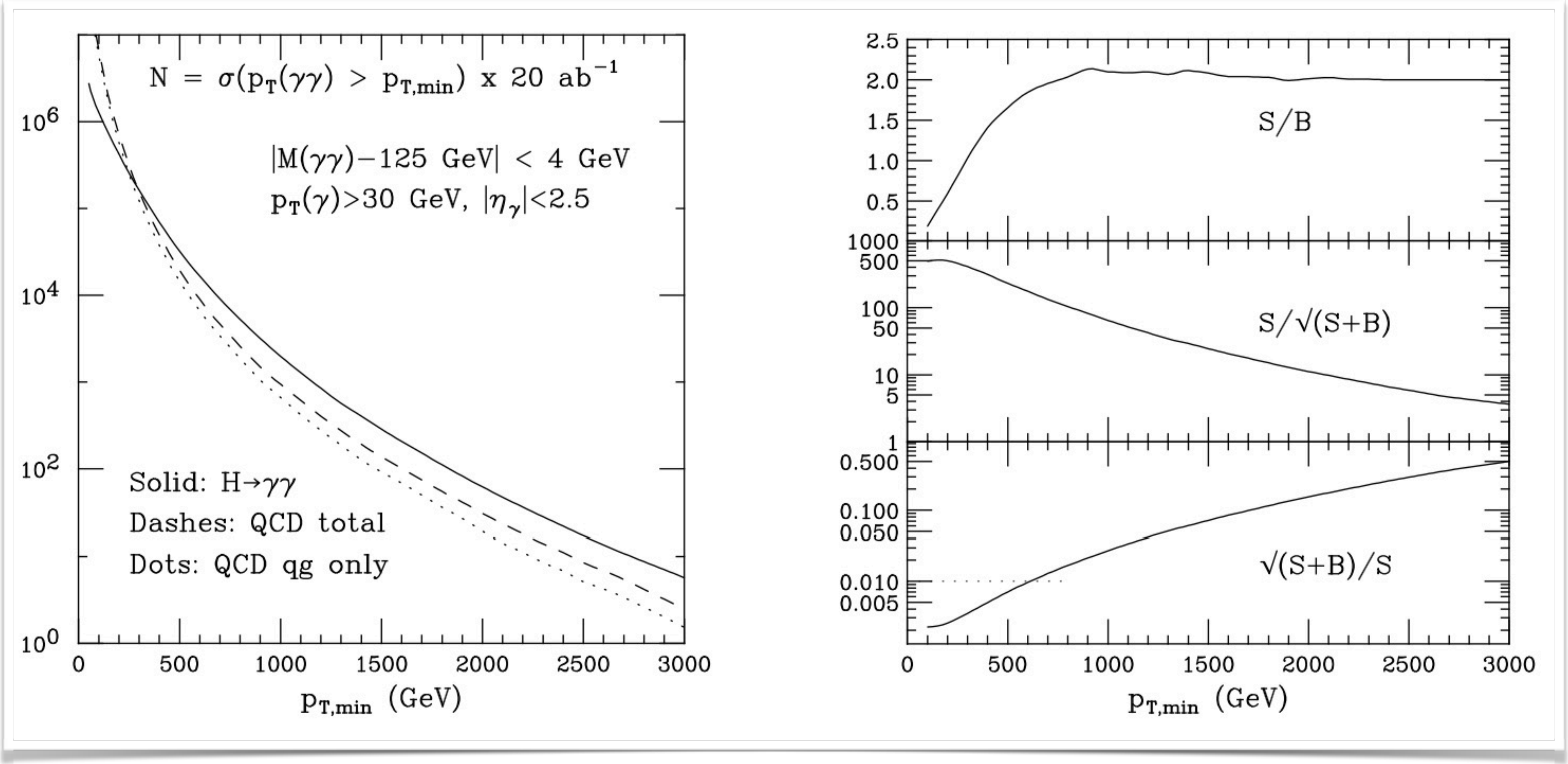


Banfi Martin Sanz, arXiv:1308.4771



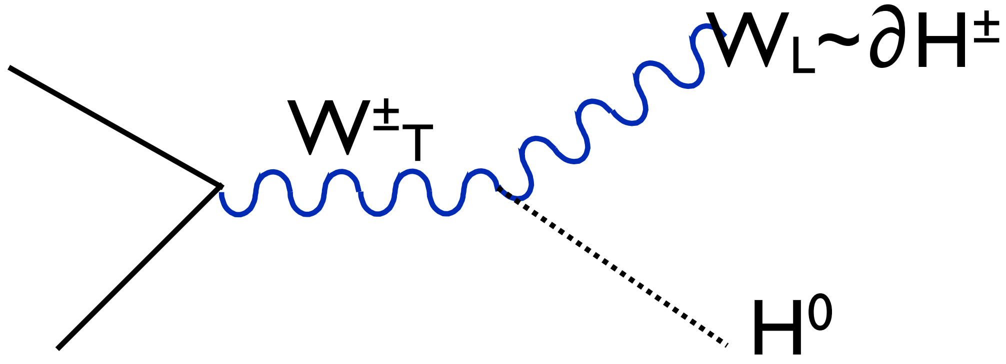
Grojean, Salvioni, Schlaffer, Weiler arXiv:1312.3317

gg→H→γγ at large p_T at 100 TeV



- At 1 TeV, statistical sensitivity (accounting for bg) well below 10% !!
- What is a best BSM probe: BR(γγ) or shape of p_T(H)?
  - answer likely BSM-model dependent
    - ==> synergy/complementarity !!

VH prodution at large m(VH)

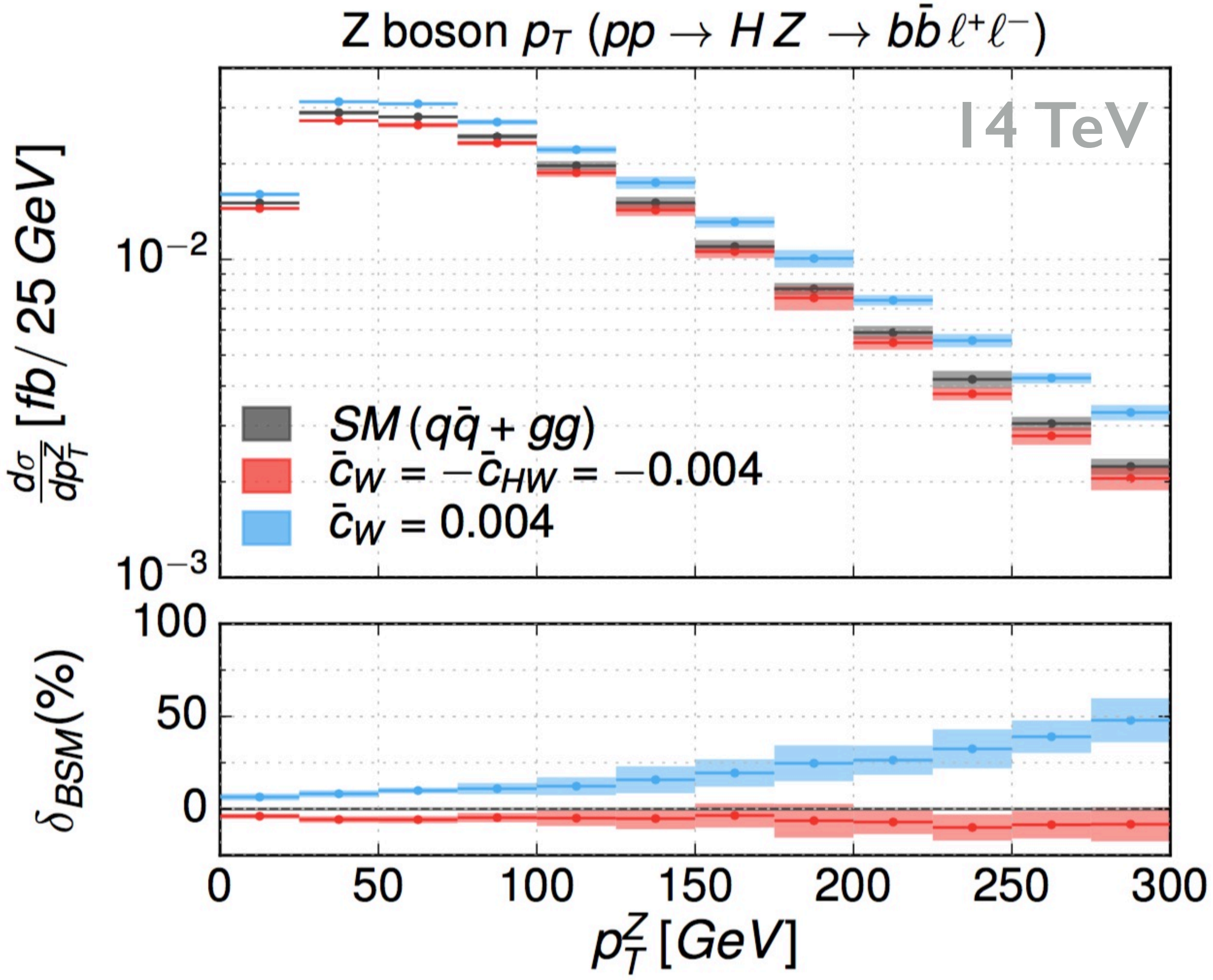


See e.g.
Biekötter, Knochel, Krämer, Liu, Riva,
arXiv:1406.7320

In presence of a higher-dim op such as:

$$L_{D=6} = \frac{ig}{2}\frac{c_W}{\Lambda^2}\left(H^\dagger \sigma^a D^\mu H\right) D^\nu V^a_{\mu\nu}$$

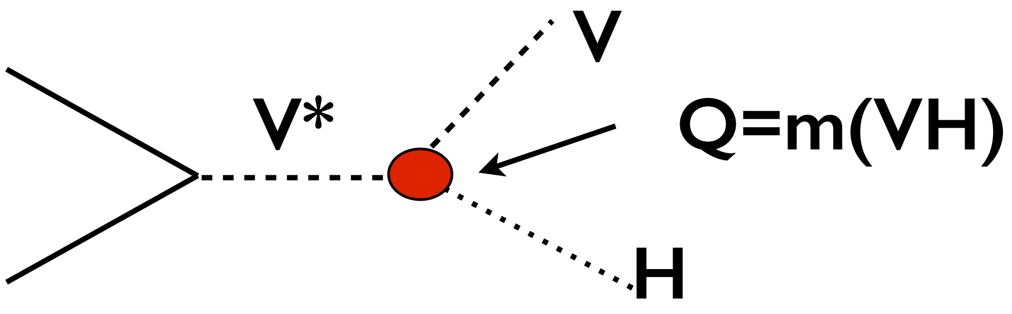
$$\frac{\sigma}{\sigma_{SM}} \sim \left(1 + c_W \frac{\hat{s}}{\Lambda^2}\right)^2$$

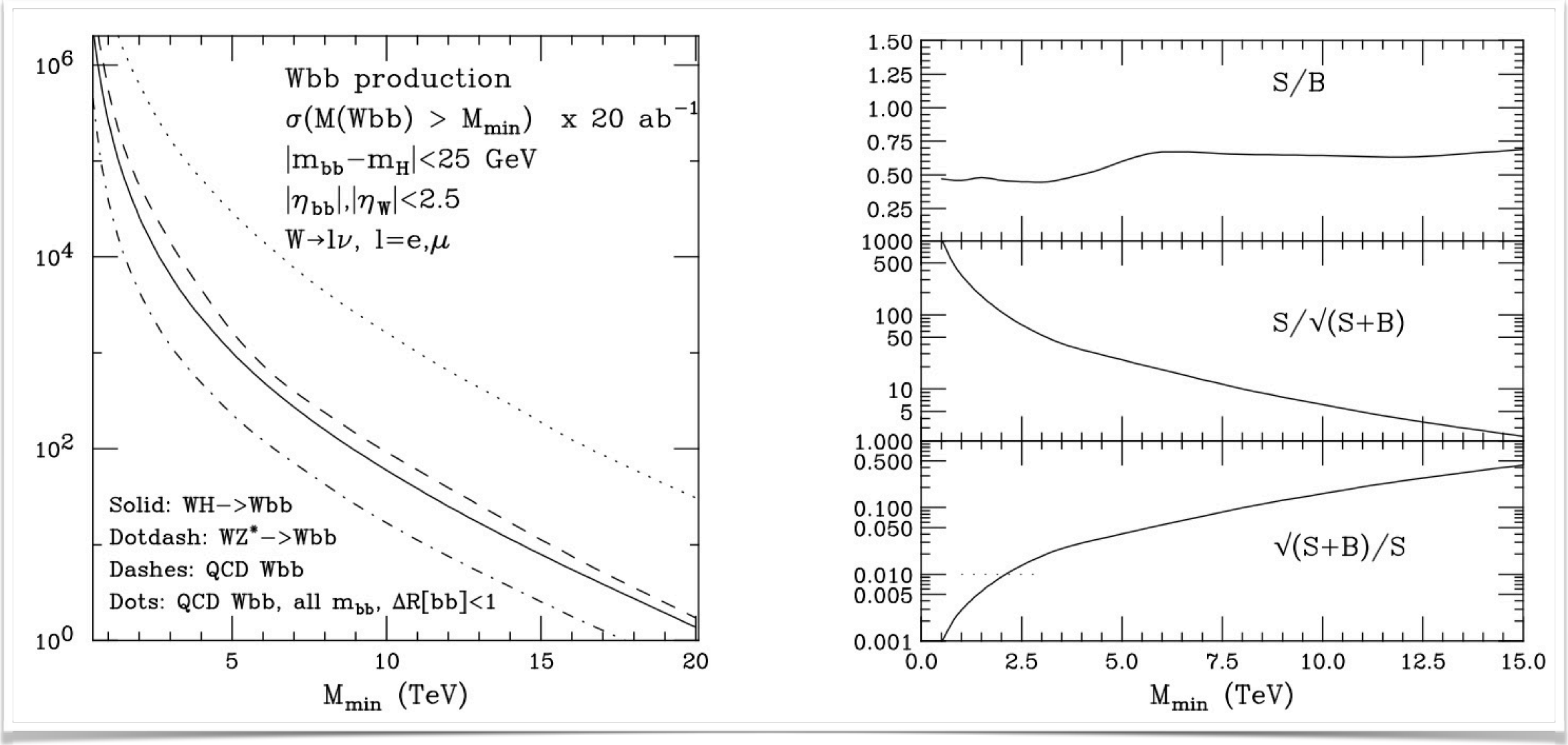


Mimasu, Sanz, Williams, arXiv:1512.02572v

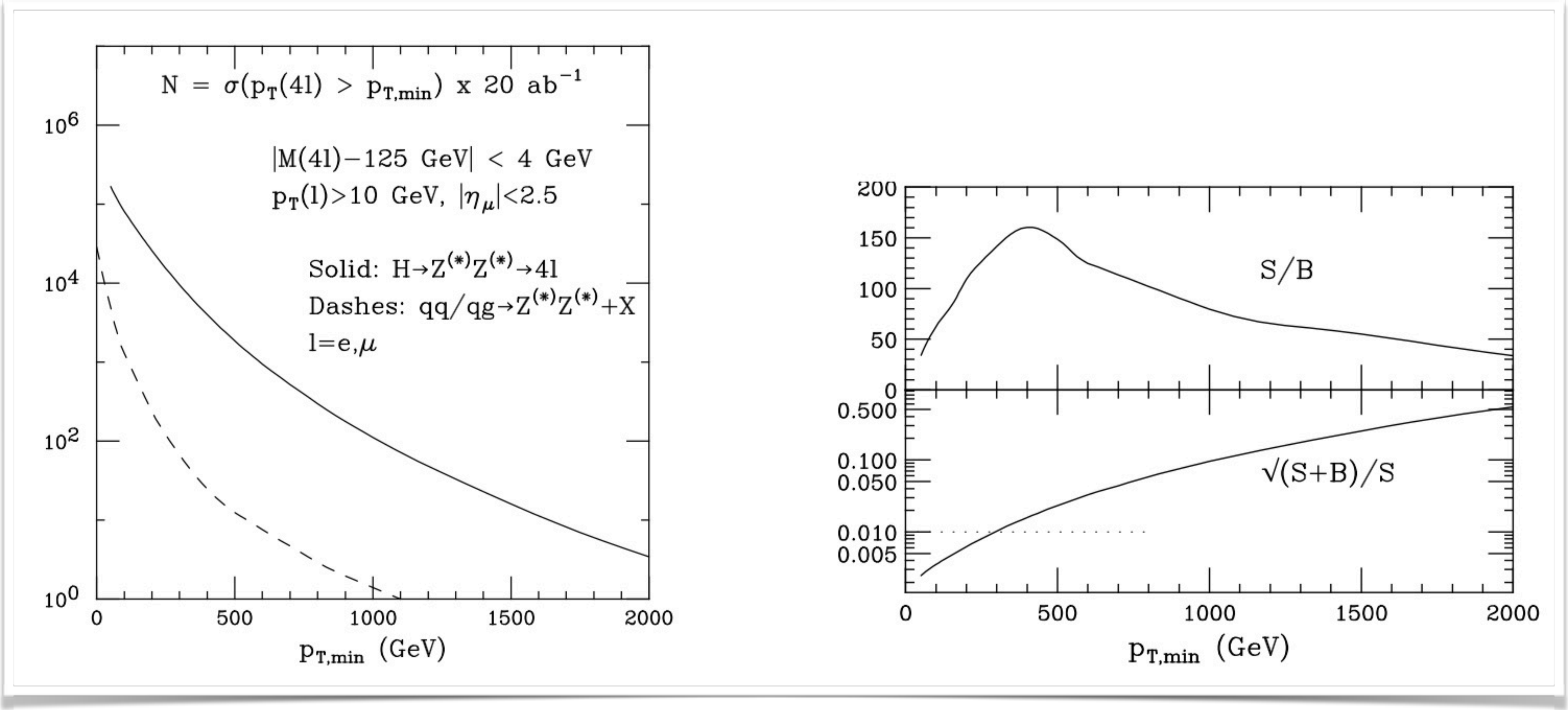
WH→Wbb at large M_{WH}

100 TeV





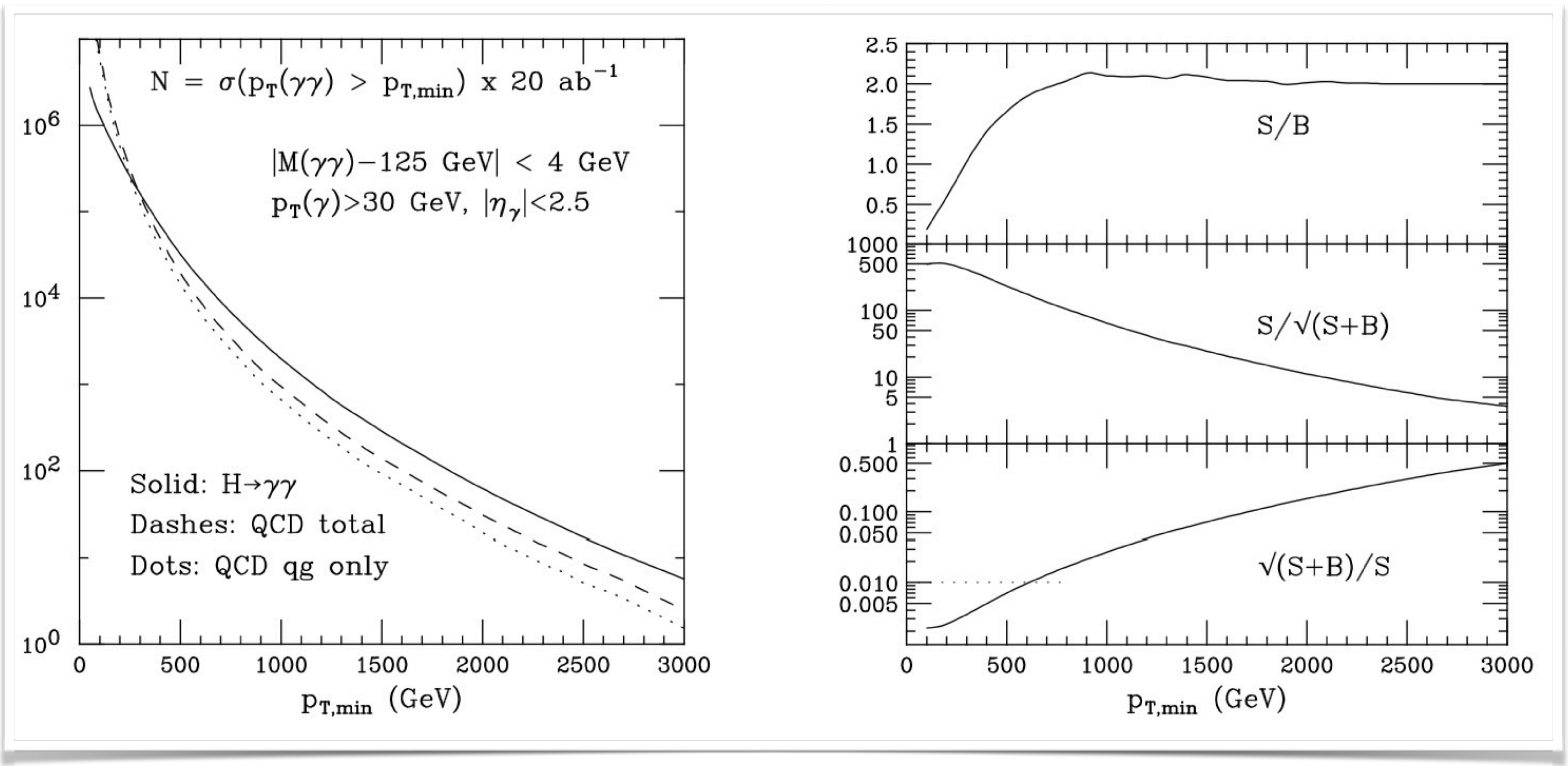
gg→H→ZZ*→4l at large p_T



- 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%

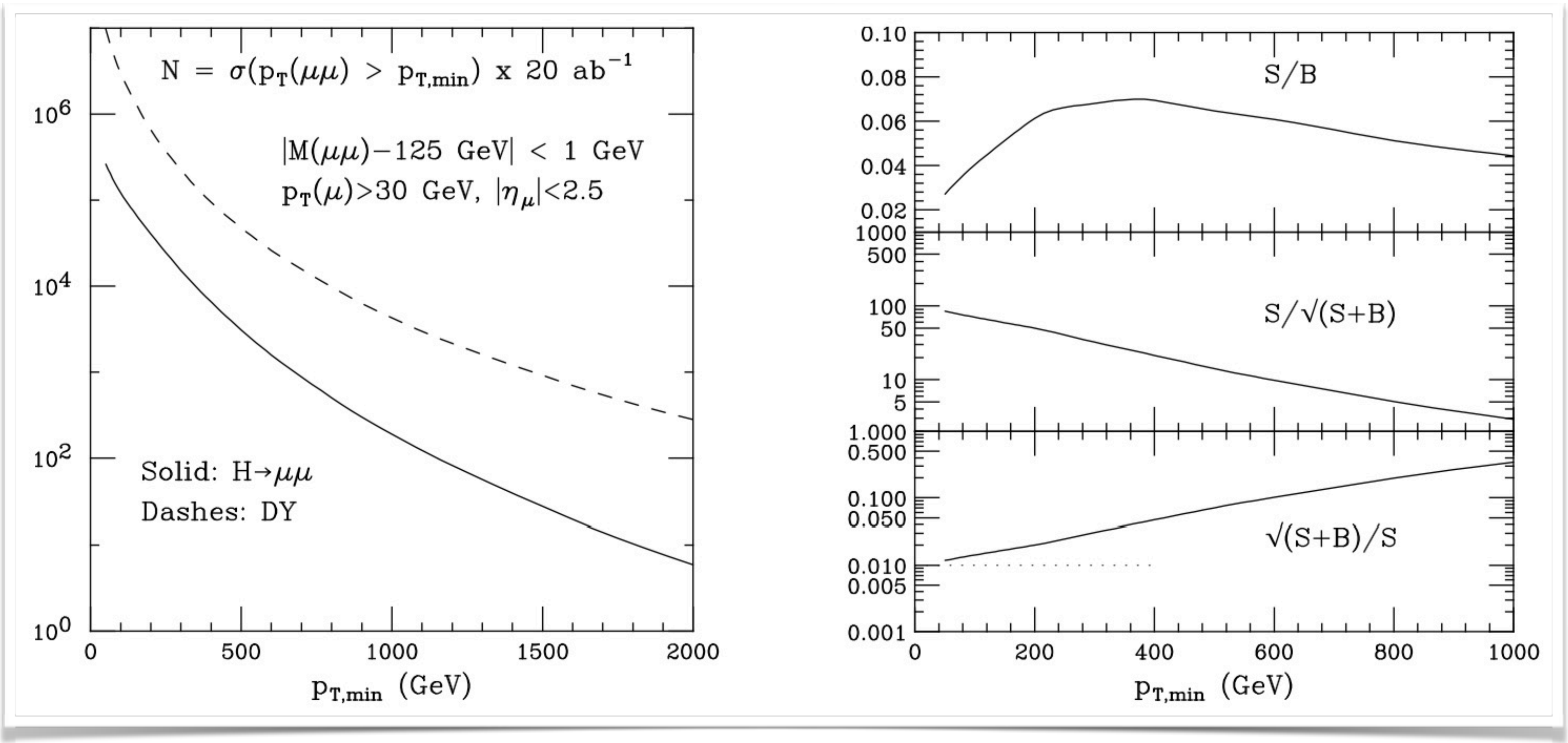
gg→H→γγ at large p_T



- At LHC, S/B in the H→γγ channel is O(few %)
- At FCC, for p_T(H)>300 GeV, S/B~1
- Exptl systematics on BR(μμ)/BR(γγ)? (use same fiducial selection to remove H modeling syst's)
- Exptl mass resolution at large pt(H)?
- Potentially accurate probe of the H pt spectrum up to large pt

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

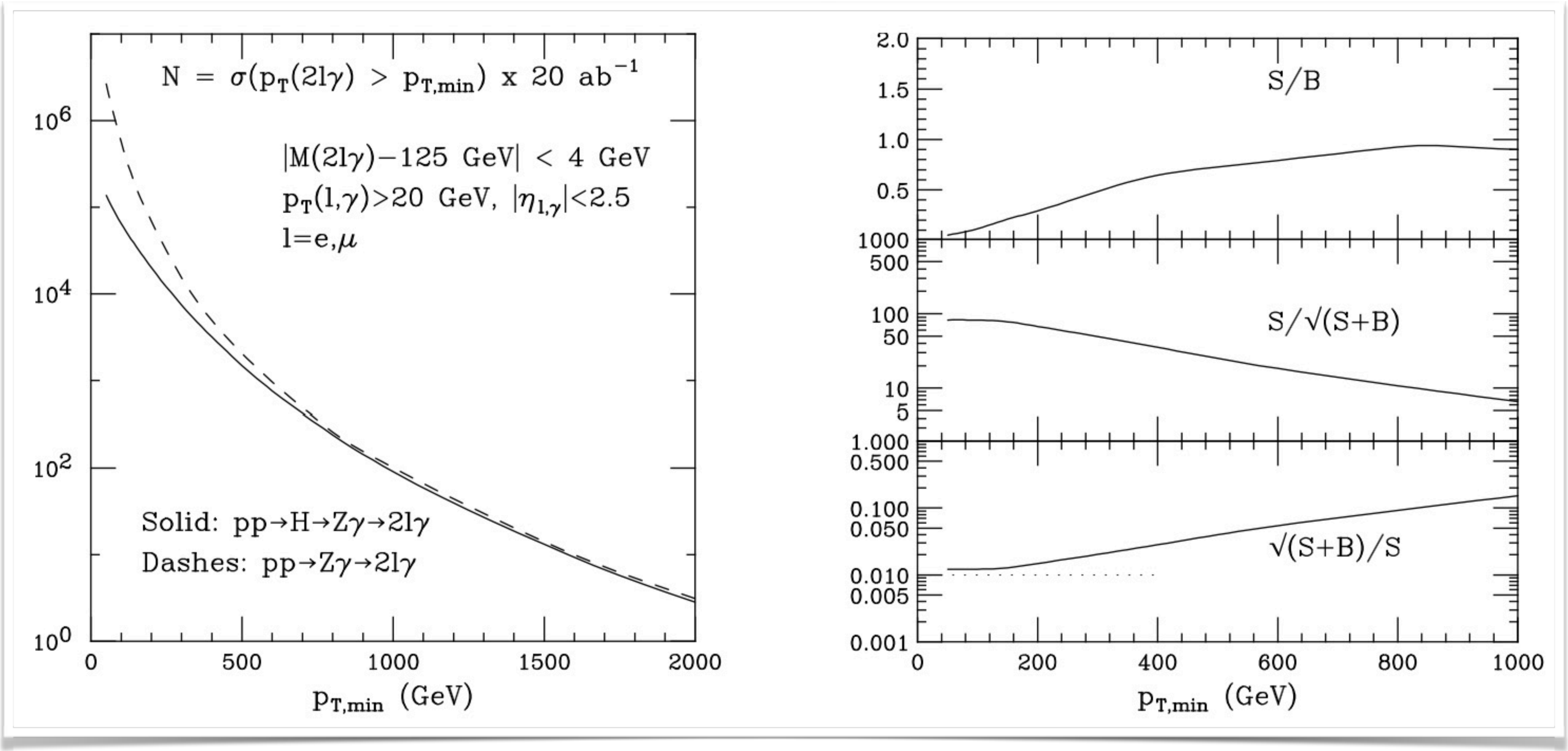
gg→H→μμ at large p_T



- 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 at large p_T

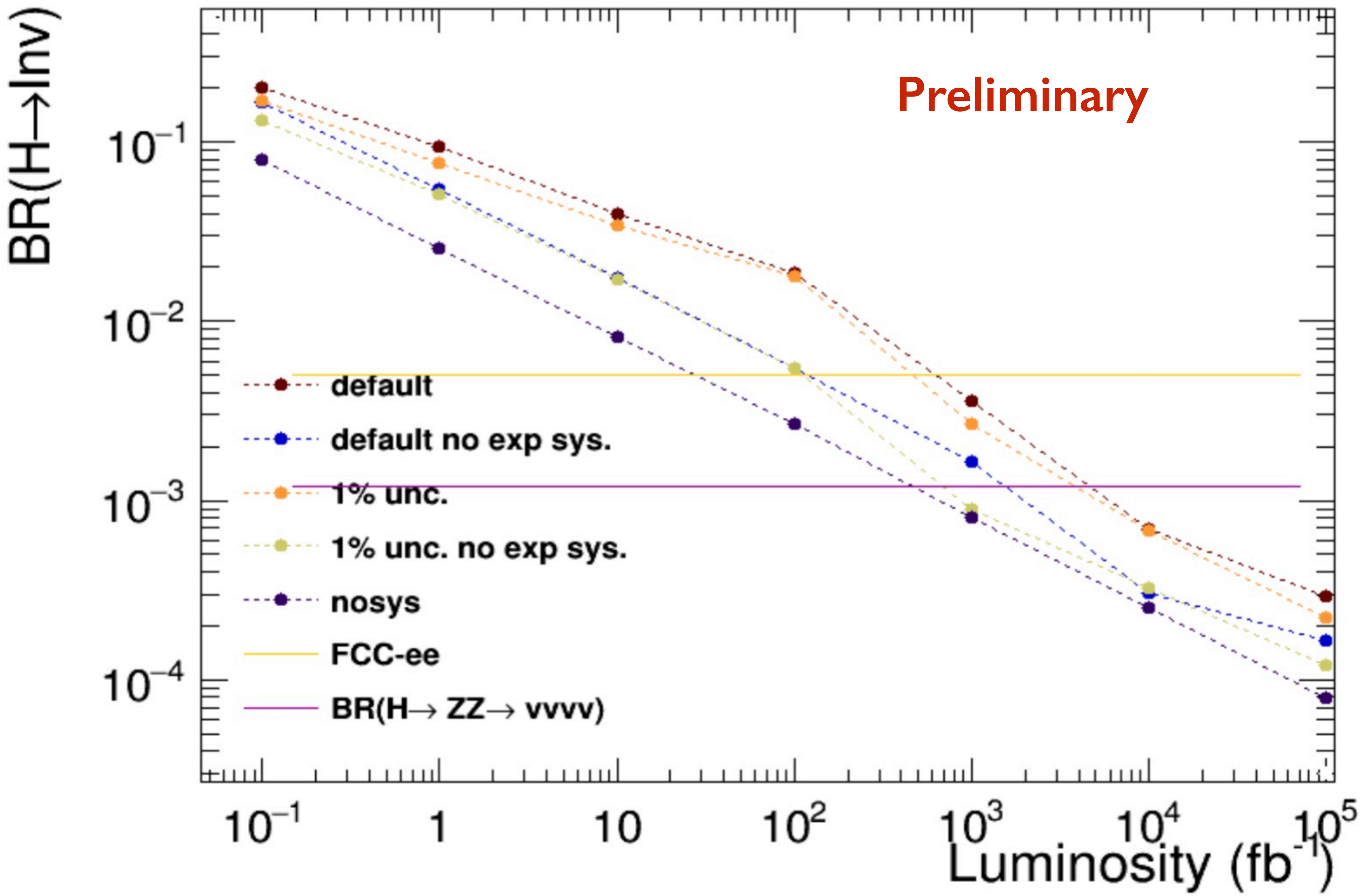


- S/B → 1 at large p_T
- Stat reach ~1% at pT~100 GeV
- Exptl systematics on BR(Zγ)/BR(γγ)?

$p_{T,min}$ (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}

Higgs couplings @ FCC

g_{HXY}	ee [240+350 (4IP)]	pp [100 TeV] 30ab^{-1}	ep [60GeV/50TeV], 1ab^{-1}
ZZ	0.15%	under study	
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%	< 0.1%	
Γ_{tot}	1%		

- detailed study, stat+syst
- rather detailed, stat only (understood/limited/negligible theory syst)
- parton level S and B (from ratios, negligibleTH syst, small exp syst)
- very preliminary estimates of exp/th syst (not stat-limited)

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→γγ)/BR(H→ZZ*)

loop-level tree-level

BR(H→μμ)/BR(H→ZZ*)

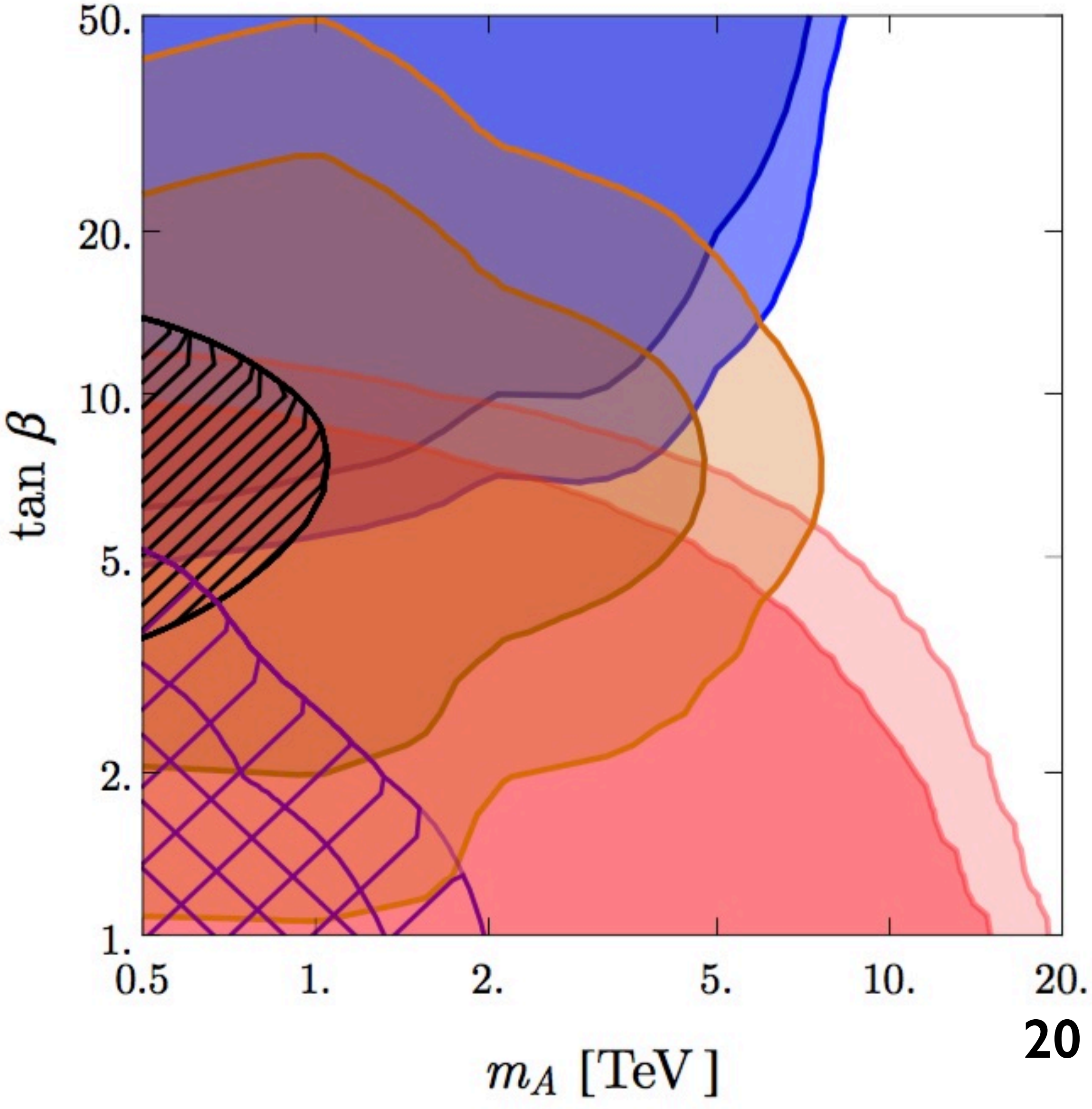
2nd gen’n Yukawa gauge coupling

BR(H→γγ)/BR(H→Zγ)

different EW charges in the loops of the two procs

MSSM Higgs @ 100 TeV

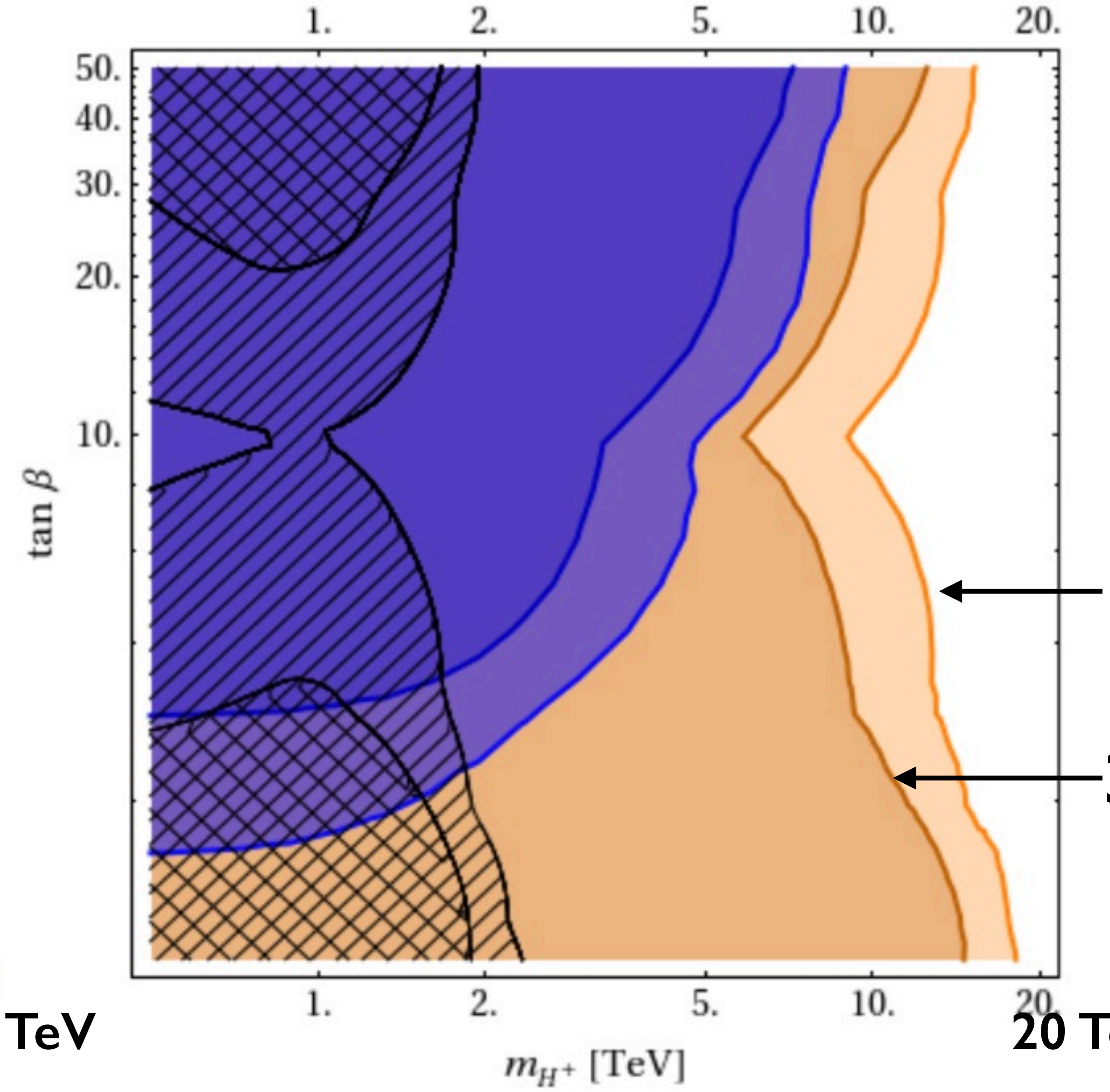
🟦 $bbH^0/A^0 \to bb\tau\tau$
🟧 $bbH^0/A^0 \to bbtt$
🟥 $t(t)H^0/A^0 \to t(t)tt$



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*

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

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

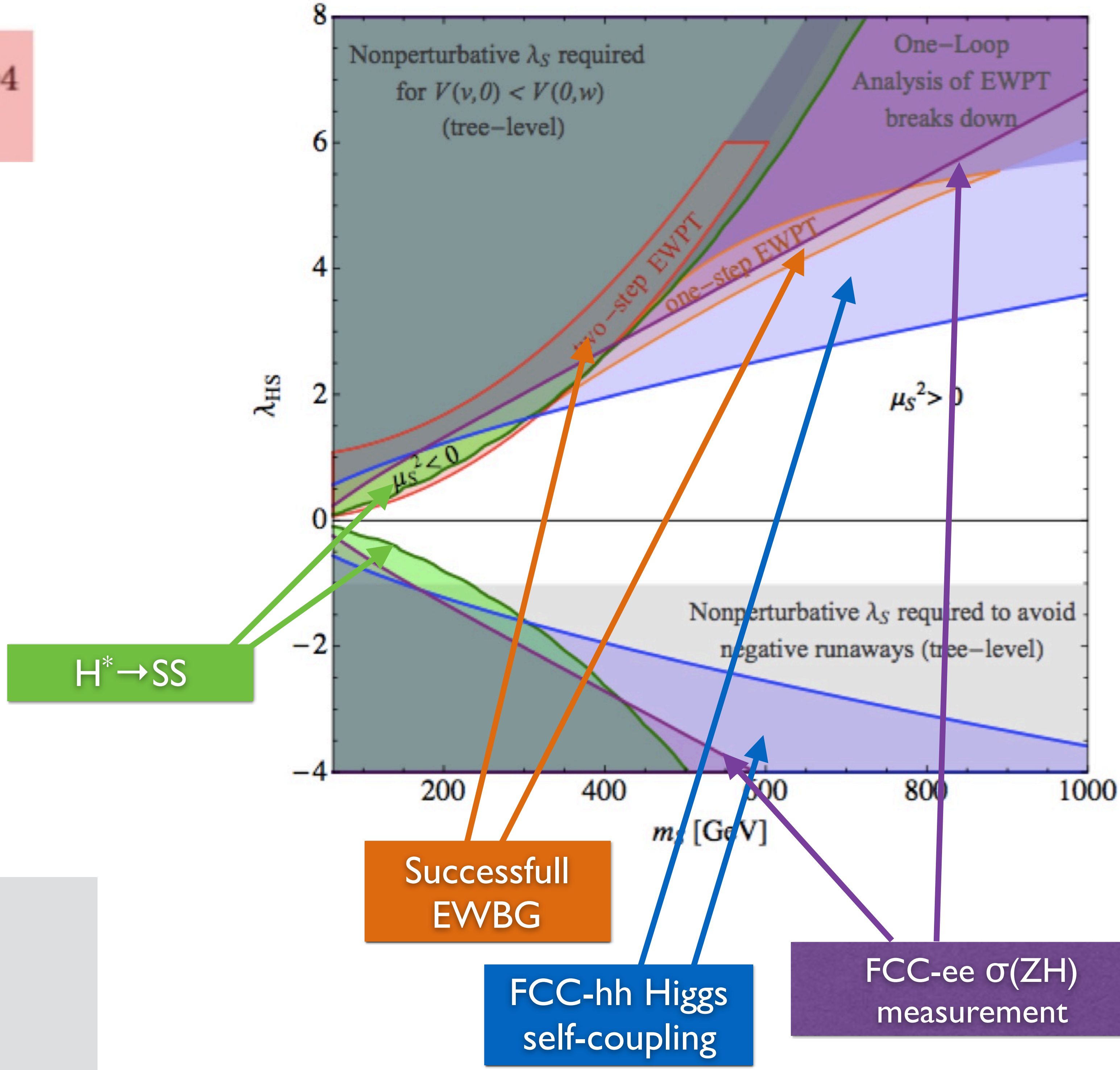
Two regions with strong EWPT

Only Higgs Portal signatures:
h*→SS direct production
Higgs cubic coupling
σ(Zh) deviation (> 0.6% @ TLEP)

⇒ Appearance of first "no-lose"

arguments for classes of compelling scenarios of new physics

Curtin, Meade, Yu, arXiv:1409.0005



H*→SS

Successfull EWBG

FCC-hh Higgs self-coupling

FCC-ee σ(ZH) measurement

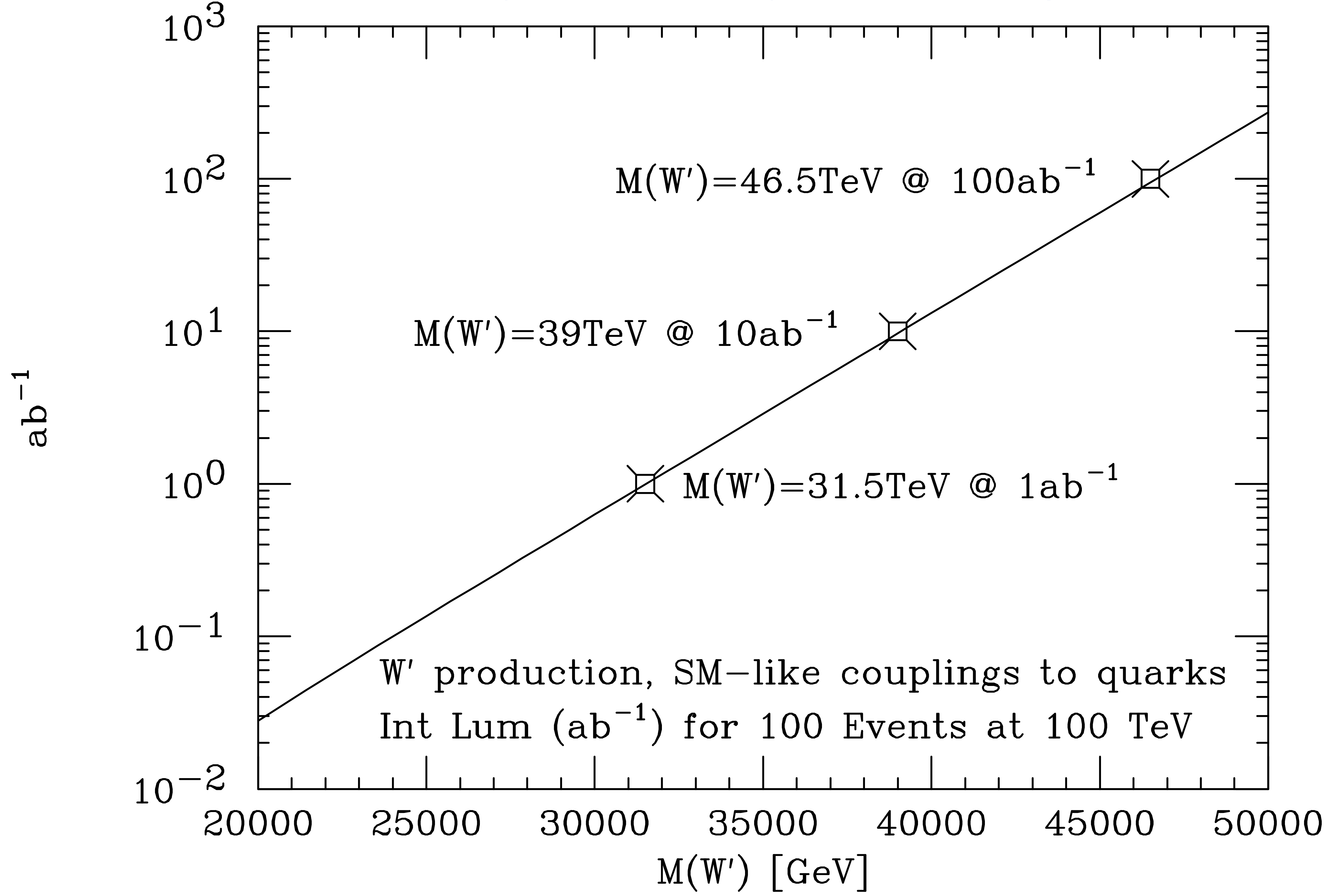
Direct discovery potential at the highest masses

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

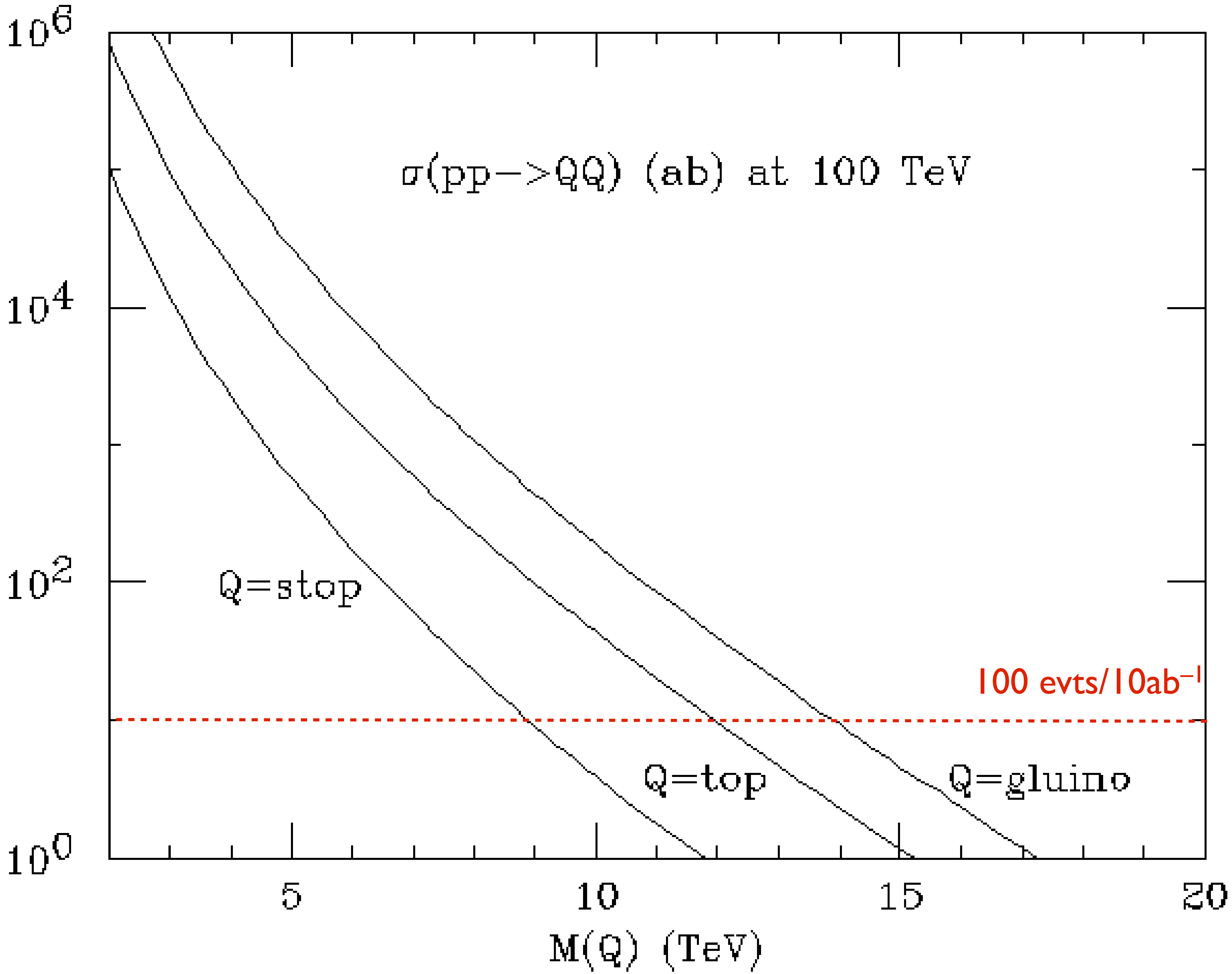
Example: **W' with SM-like couplings**

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

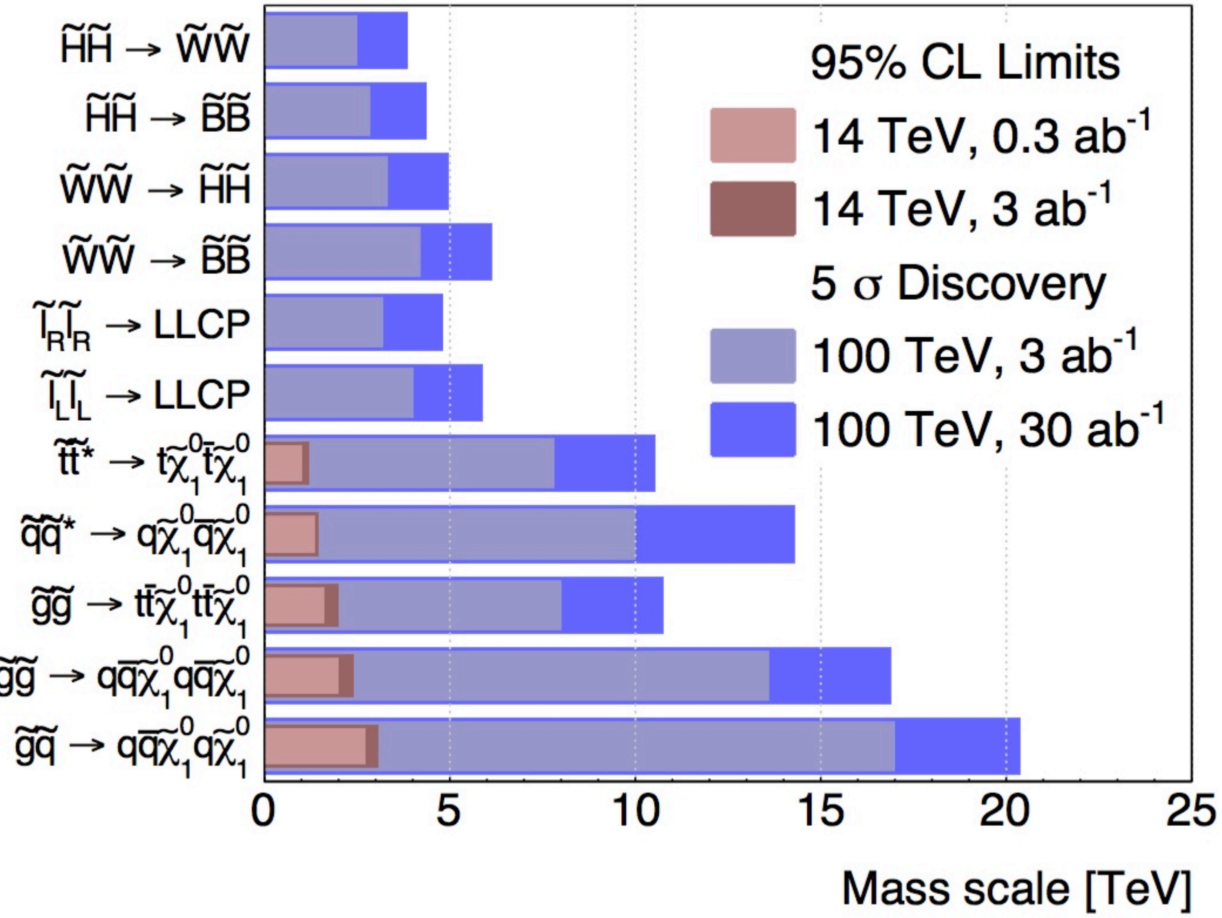
Discovery reach for pair production of strongly-interacting particles

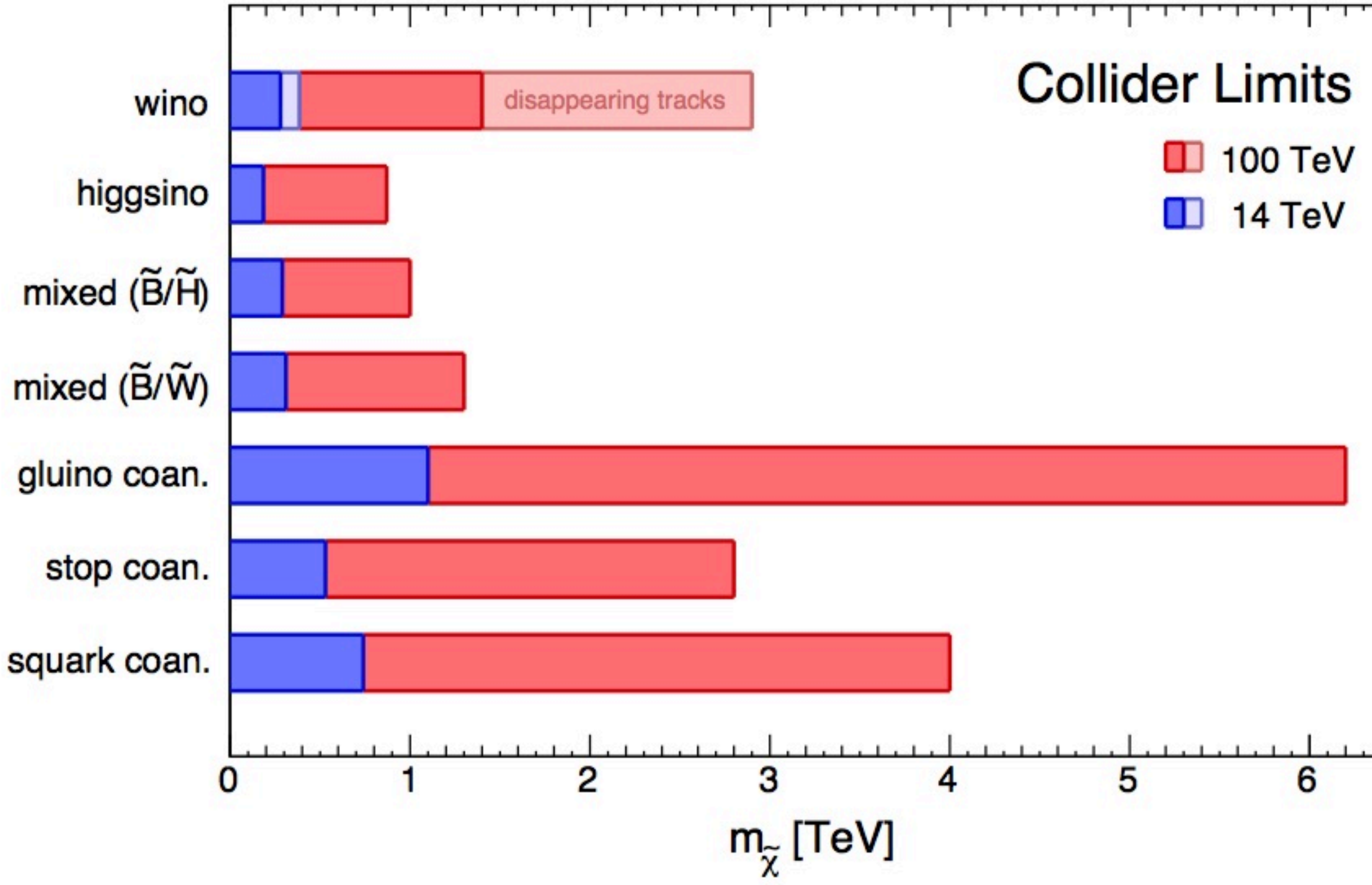


Dark Matter

- 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





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

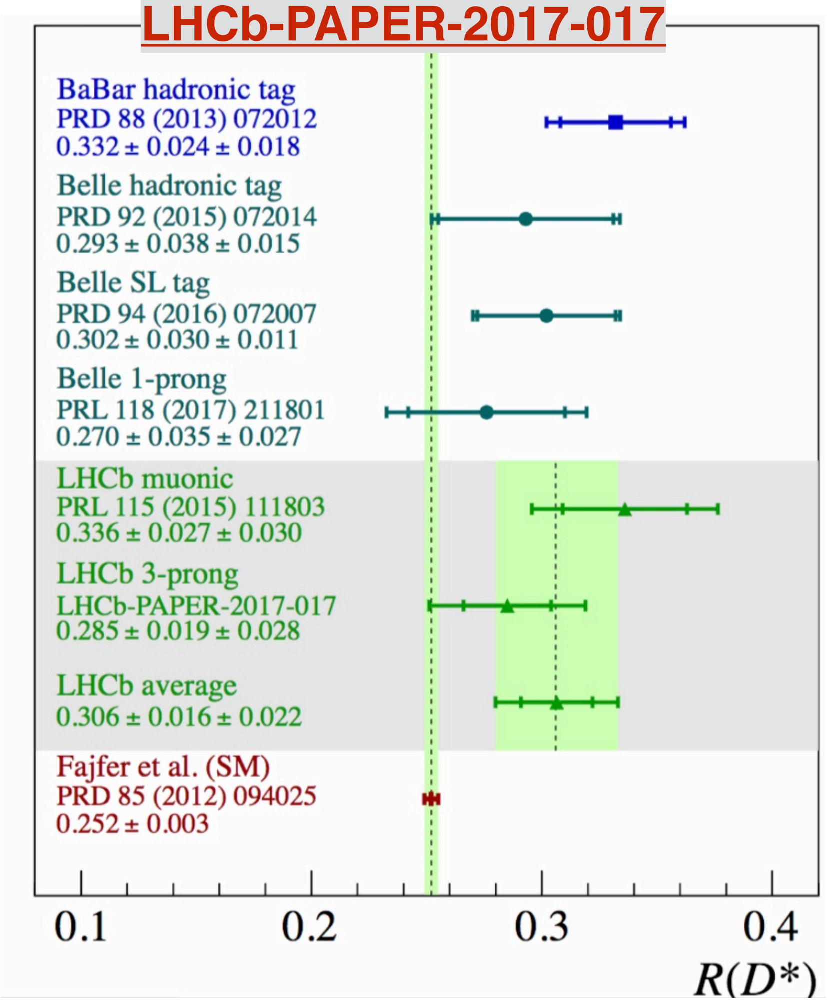
possibility to find (or rule out) thermal WIMP DM candidates

Flavour anomalies at LHC & Bfact's

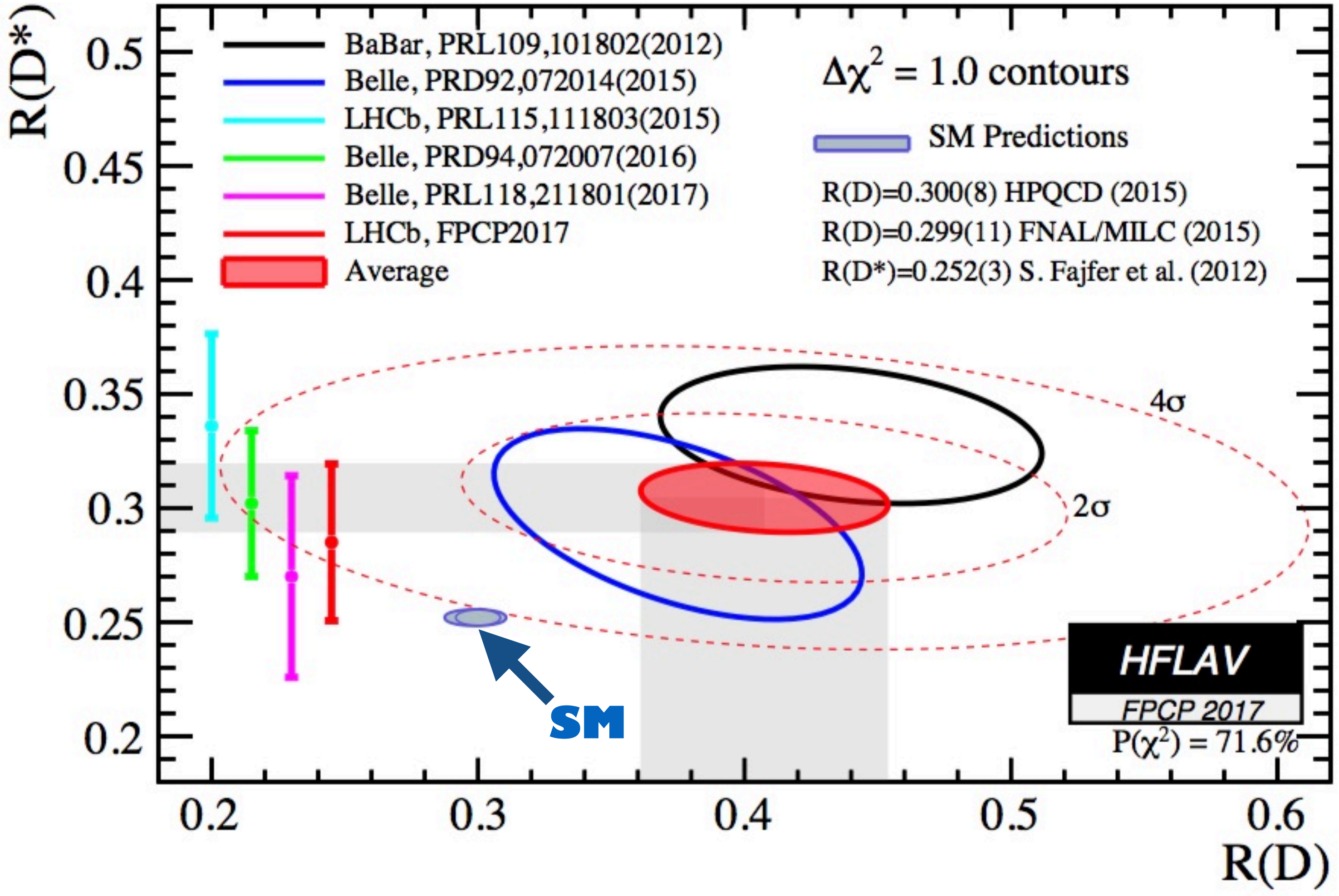
$b \to c\ell\nu$

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

LHCb-PAPER-2017-017

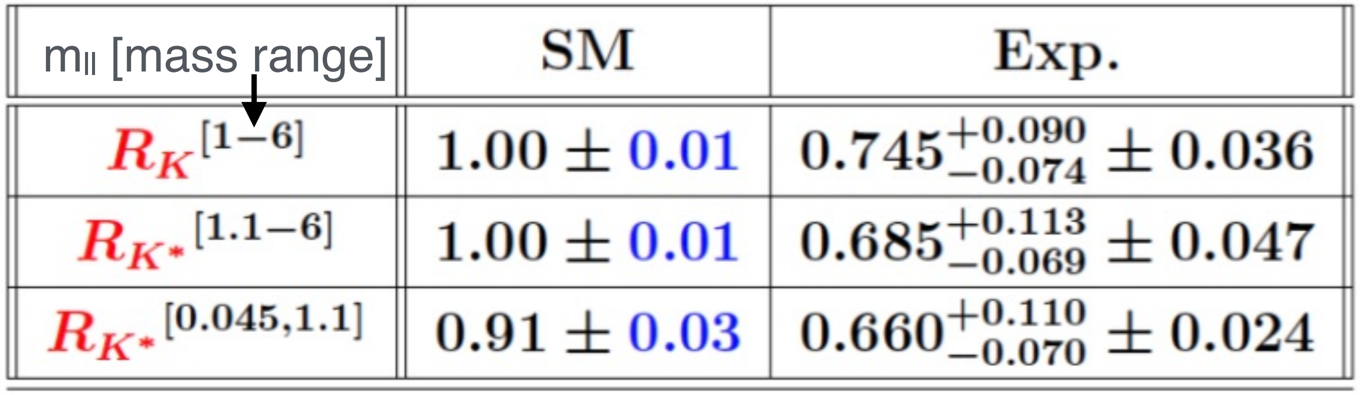


Overall combination of R(D) and R(D*) is 4.1σ from SM



$b \to s\ell\ell$

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



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	$0.660^{+0.110}_{-0.070} \pm 0.024$

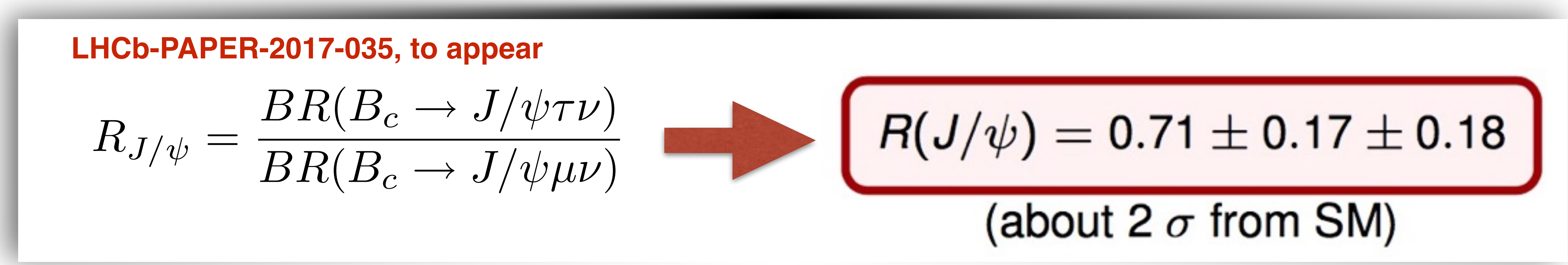
LHCb, PRL 113 (2014) 151601 , arXiv:1705.05802

Remarks

The above observables are theoretically robust: small and reliable uncertainties

Other anomalies at the 2-3σ level exist, but subject to less robust estimates of QCD uncertainties

Statistics still plays a dominant role (esp for R_K). More data will also allow use of new final states with independent exptl systematics … eg



LHCb-PAPER-2017-035, to appear

$$R_{J/\psi} = \frac{BR(B_c \to J/\psi \tau \nu)}{BR(B_c \to J/\psi \mu \nu)} \Rightarrow \boxed{R(J/\psi) = 0.71 \pm 0.17 \pm 0.18}$$

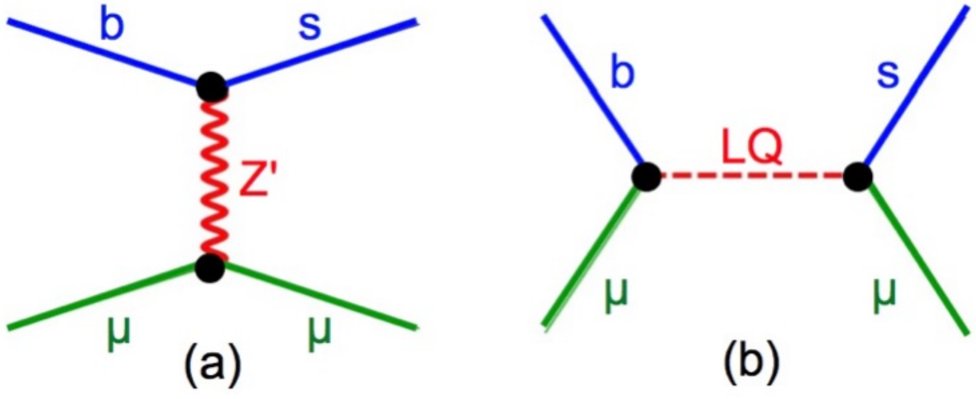
(about 2 σ from SM)

The fact that SM deviations of this type, variety and size are phenomenologically acceptable, gives a sign of how little we still know about <u>“what’s out there”</u> at the TeV scale, and our openness towards surprises (see also the story of the 750 GeV γγ resonance)

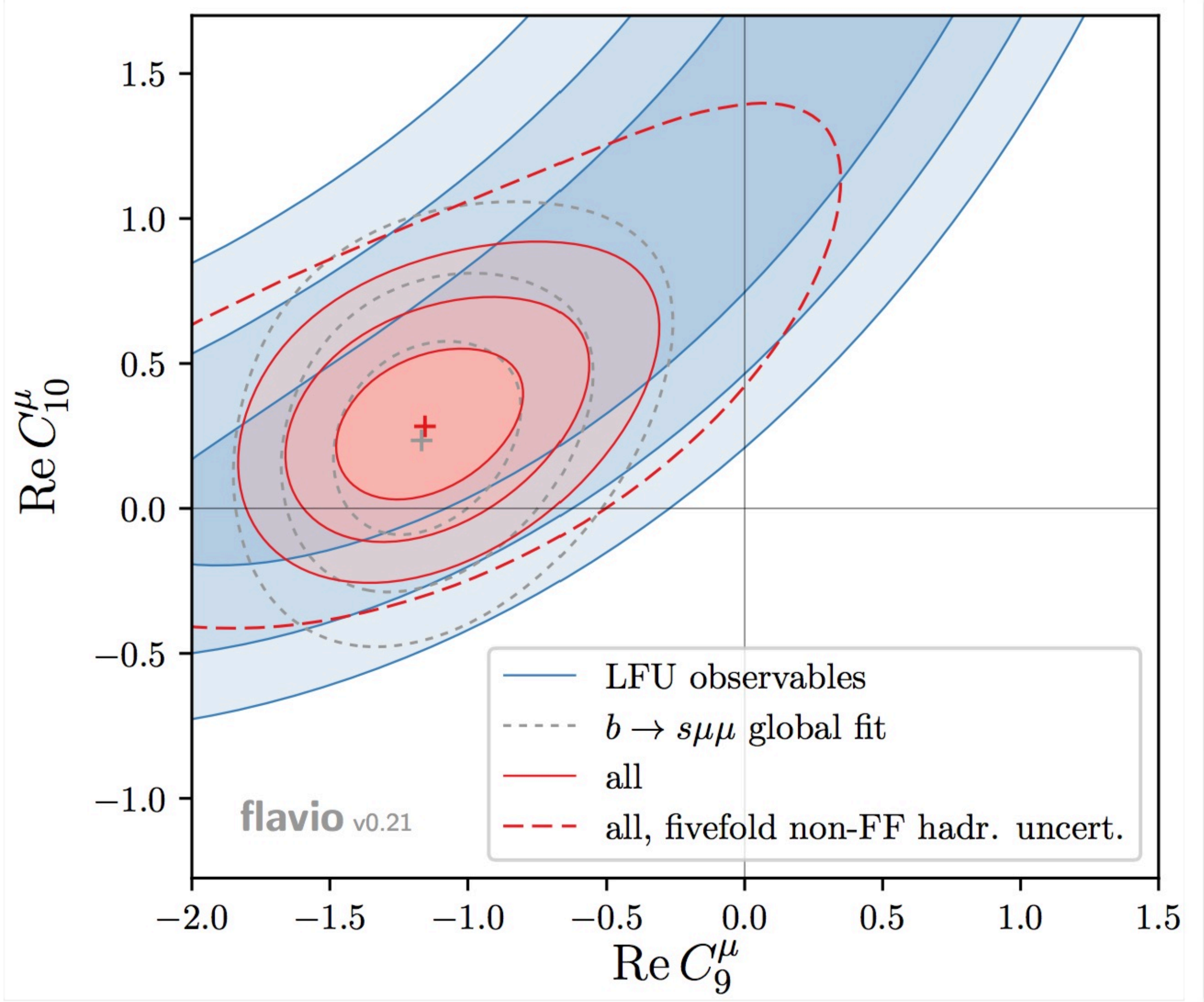
Example of EFT interpretation of R_K

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

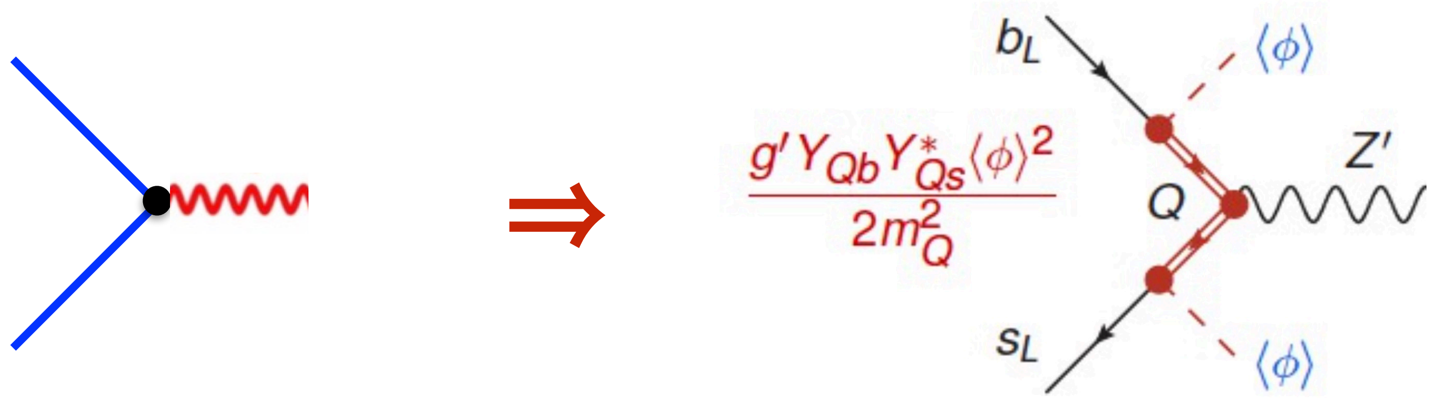
Possible explicit realizations:



Altmannshoffer et al, arxiv:1704.05435



where, e.g. ,



Upper limits on Z' and Leptoquark masses are model-dependent, and constrained also by other low-energy flavour phenomenology, but typically lie in the range of 1→O(10) TeV

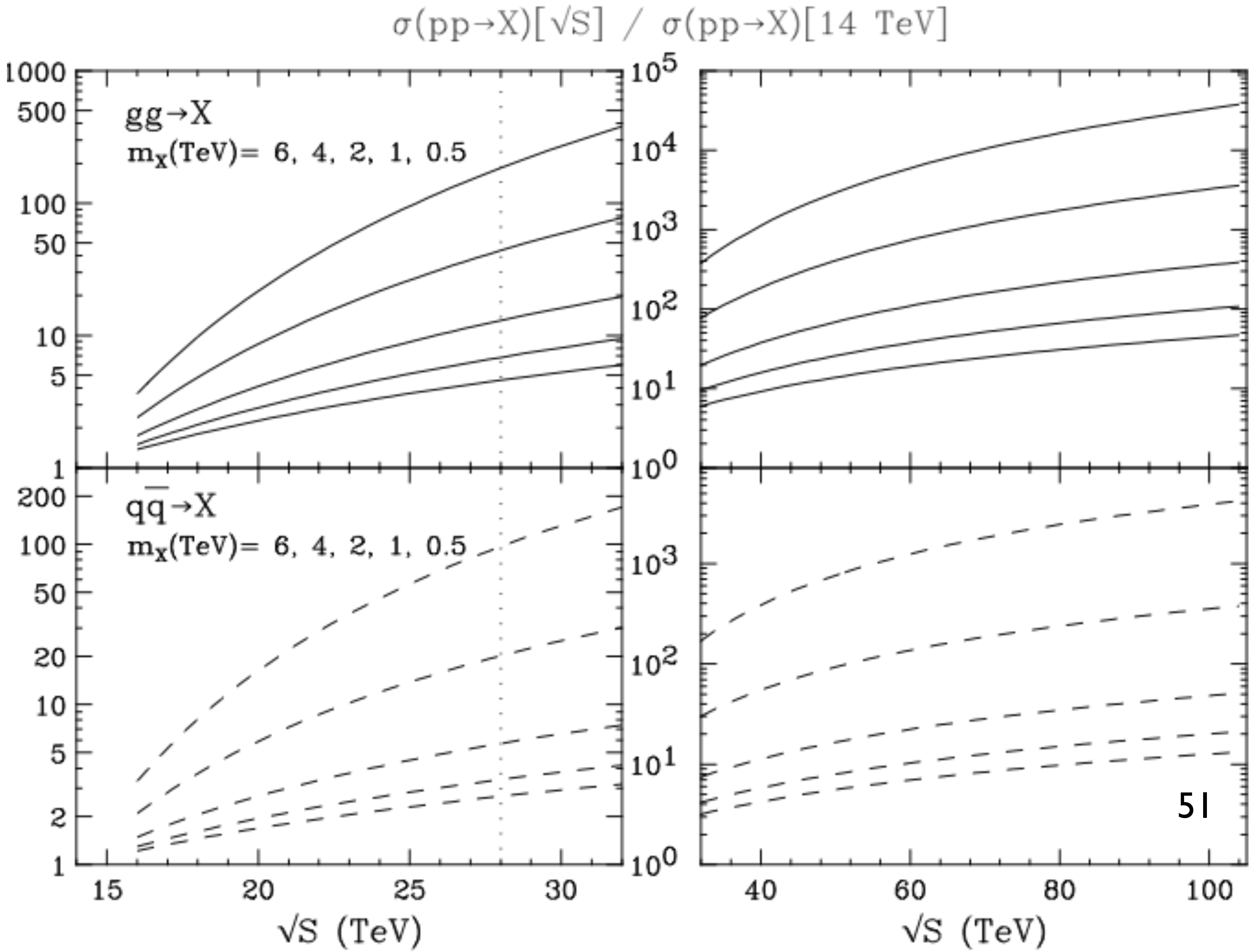
⇒ if anomalies confirmed, we may want a no-lose theorem to identify the next facility!

100 TeV ?

200 TeV ?

28 TeV ?

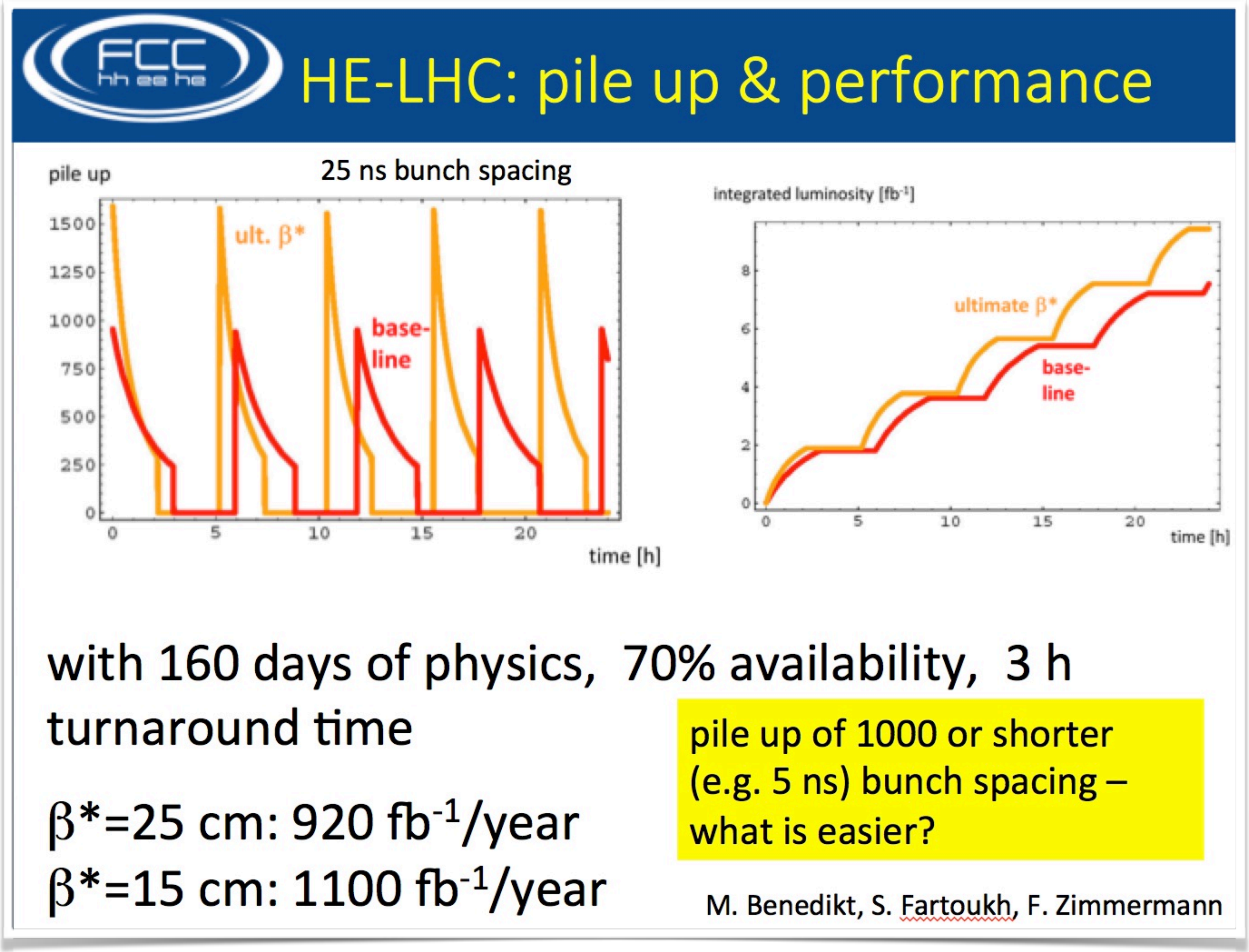
Evolution, with beam energy, of scenarios with the discovery of a new particle at the LHC



Possible questions/options

- If $m_X \sim 6$ 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 $m_X \sim 0.5$ 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 (27 TeV), prelim performance estimates



HE-LHC: pile up & performance

with 160 days of physics, 70% availability, 3 h turnaround time

β*=25 cm: 920 fb^{-1}/year

β*=15 cm: 1100 fb^{-1}/year

pile up of 1000 or shorter (e.g. 5 ns) bunch spacing – what is easier?

M. Benedikt, S. Fartoukh, F. Zimmermann

=> O(15 ab^{-1}) over 15-20 years

Systematics studies* of the full physics potential at O(28) TeV, with O(15 ab^{-1}), need to be carried out

* except for straightfwd mass-reach extrapolations from LHC

E.g. HH at 28 TeV (back of the envelope)

σ_{HH}(28 TeV)/σ_{HH}(14 TeV) ~ 4   Lum(28)~ 4 Lum(14 TeV)

=> N_{HH}(28) ~ 16 N_{HH}(14)

=> $\delta\lambda_{HHH}$ (28) ~ $\delta\lambda_{HHH}$ (HL-LHC) / 4 ~ 10%

Expect to carry out an overall evaluation of the physics potential during 2018 (in the context of the HL-LHC Physics workshop, https://indico.cern.ch/event/647676)

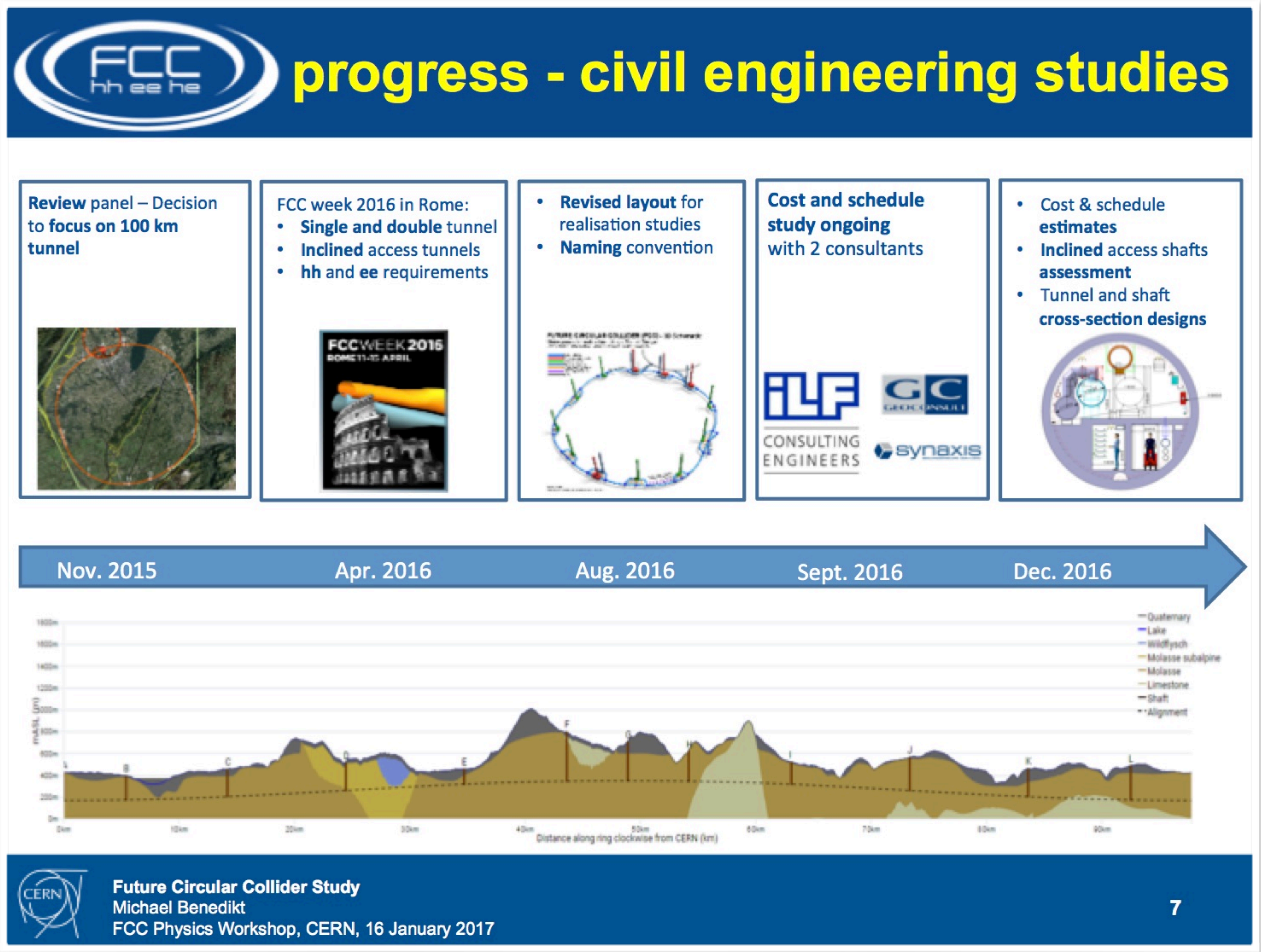
What does the HE-LHC entail?

- **Necessary:**
  - empty the tunnel (more time & $s than removing LEP)
  - full replacement of the magnets (today's cost ~4xLHC. First prototypes in ~2026)
  - upgrade of RF, cryogenics, collimation, beam dumps, …
- **Very likely:**
  - major upgrade of SPS, if need to inject at O(1 TeV) (magnets, RF, transfer lines, cryo if SC, …)
  - major overhaul of detectors (radiation damage after HL-LHC, use of new technologies)

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

- 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

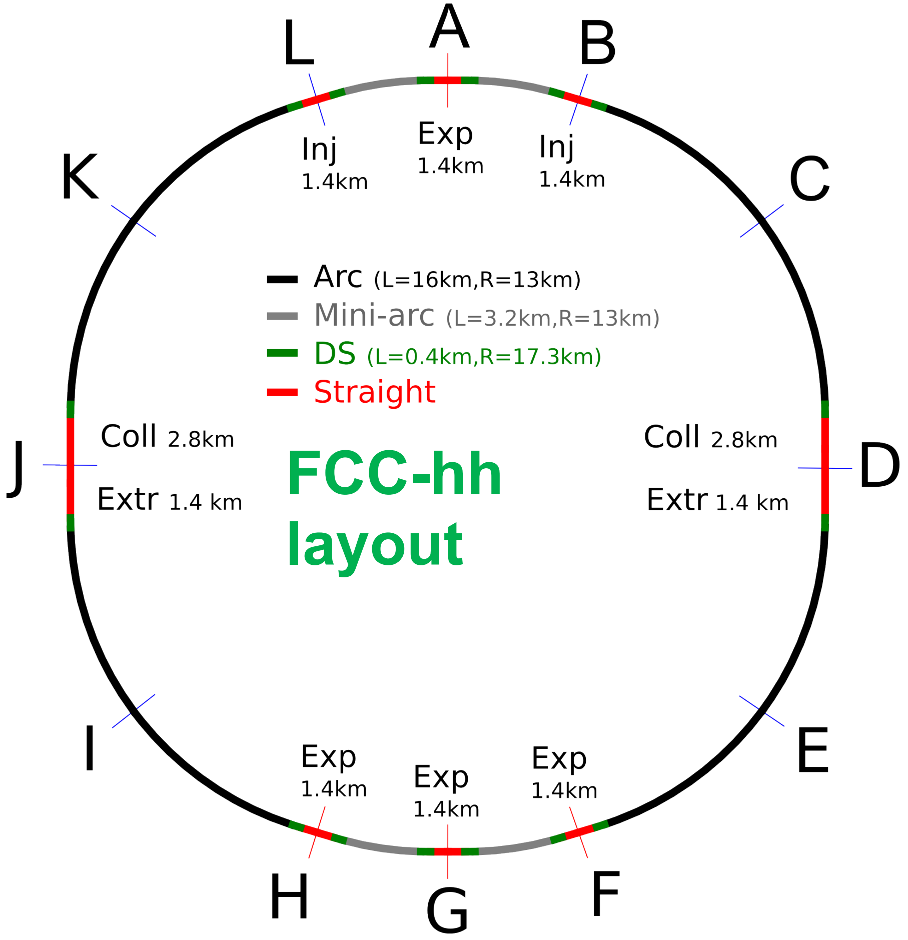
- Cost & schedule **estimates**
- **Inclined** access shafts **assessment**
- Tunnel and shaft **cross-section designs**

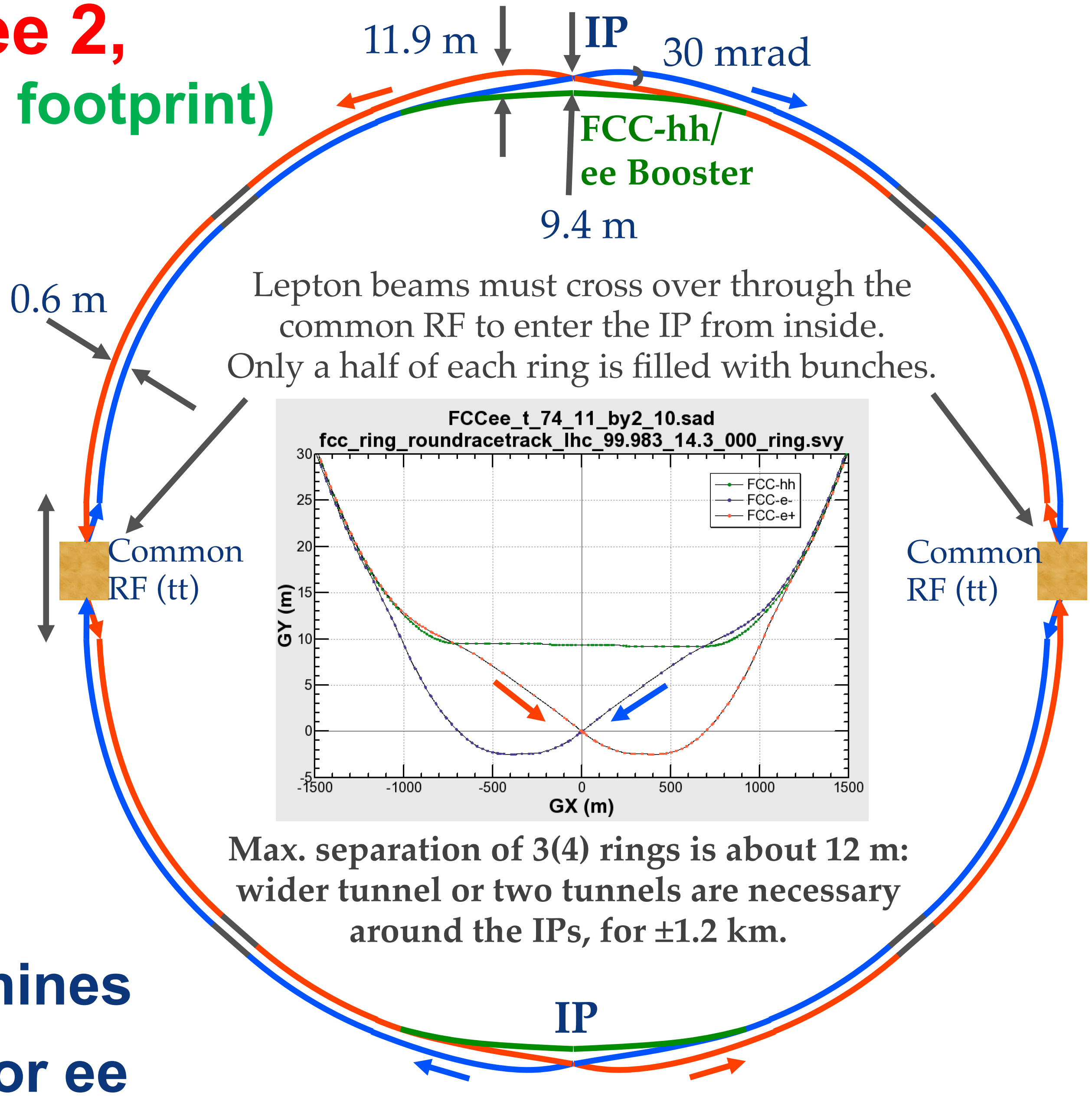
Nov. 2015 — Apr. 2016 — Aug. 2016 — Sept. 2016 — Dec. 2016

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.

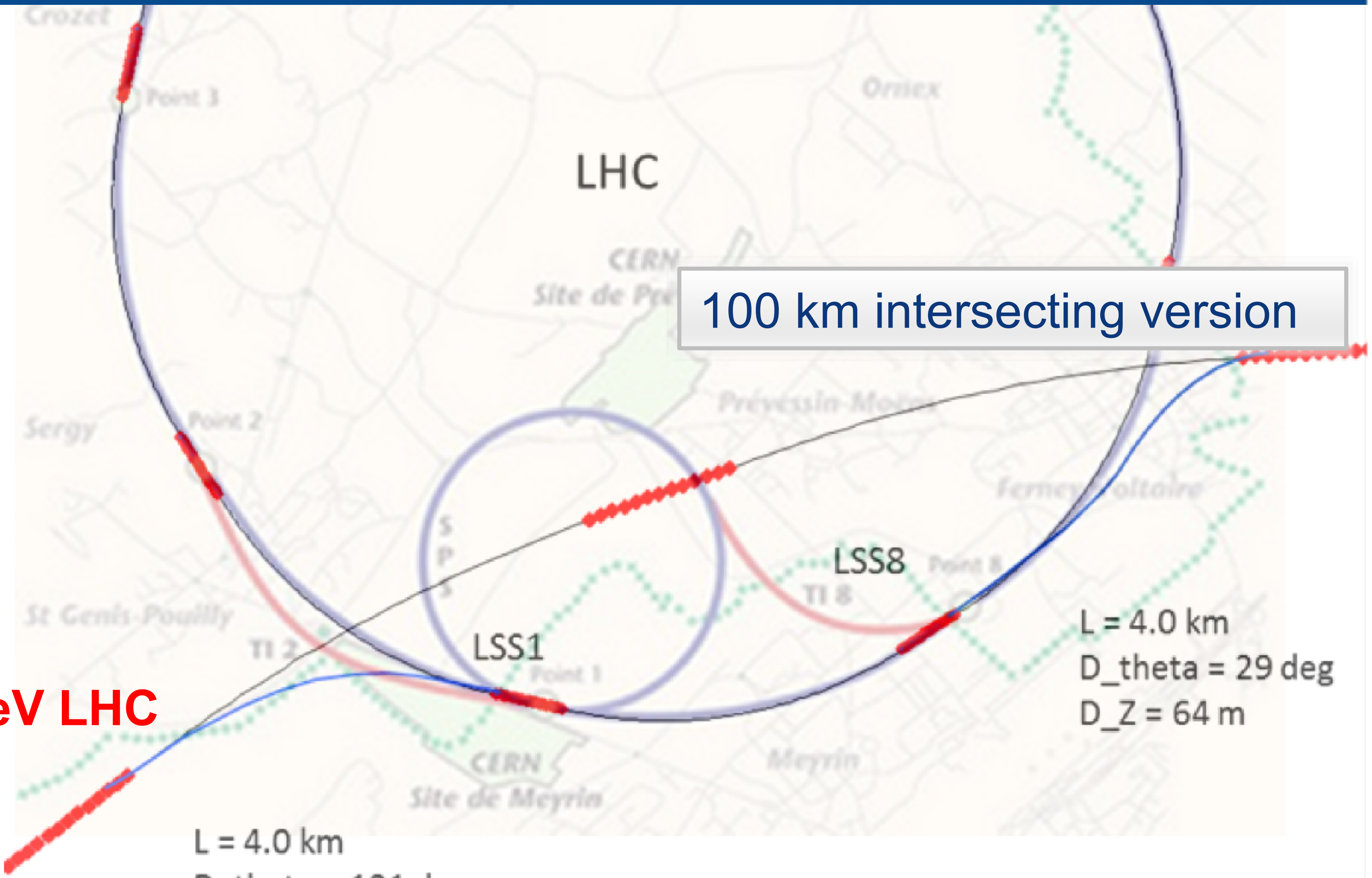
Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.

- **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$_{\text{upgrade}}$ → FCC**



100 km intersecting version

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

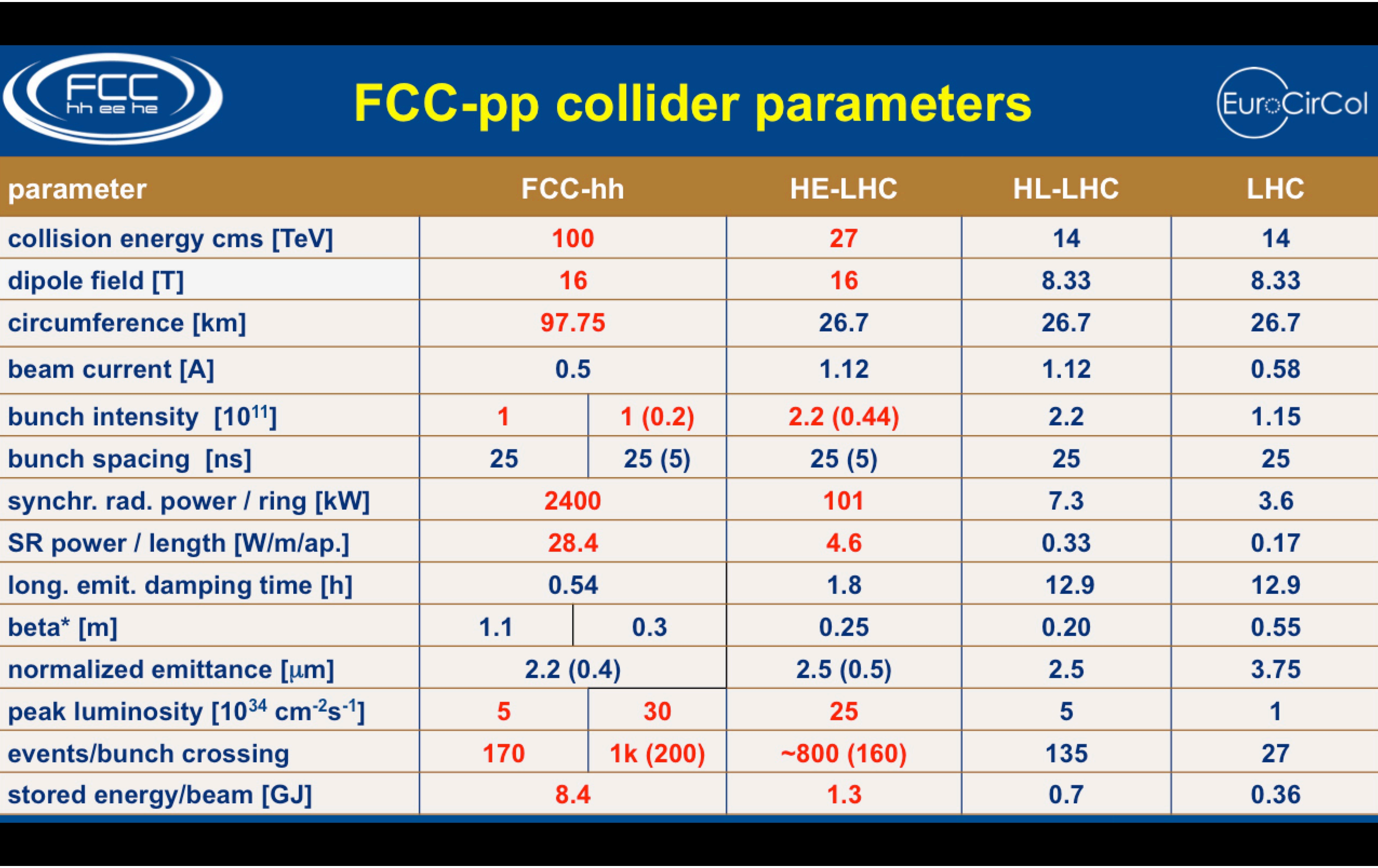
L = 4.0 km
D_theta = 131 deg
D_Z = 110 m

Current baseline:

- **Injection energy 3.3 TeV LHC**

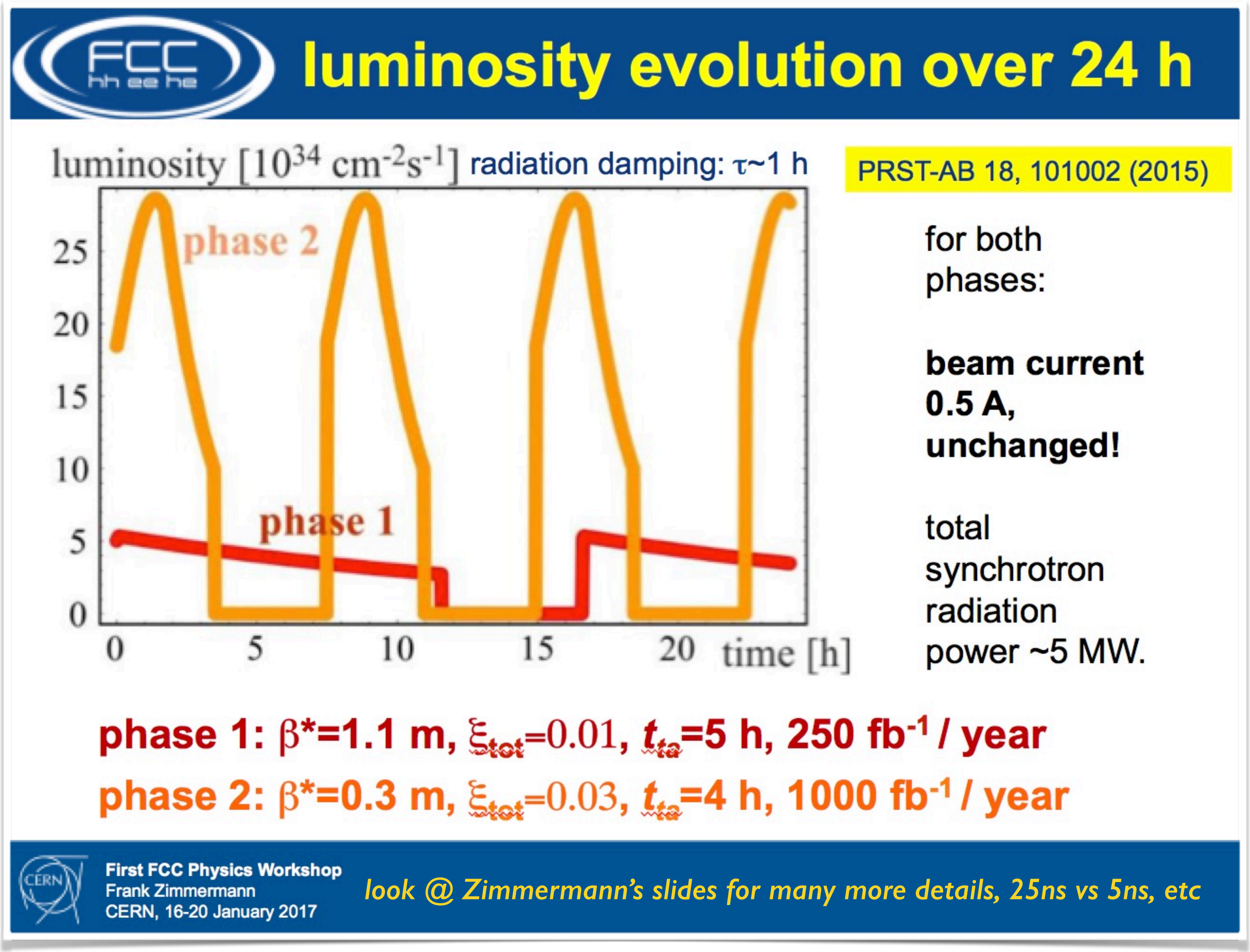
Alternative option:

- **Injection around 1.5 TeV**
- **SPS$_{\text{upgrade}}$ 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

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

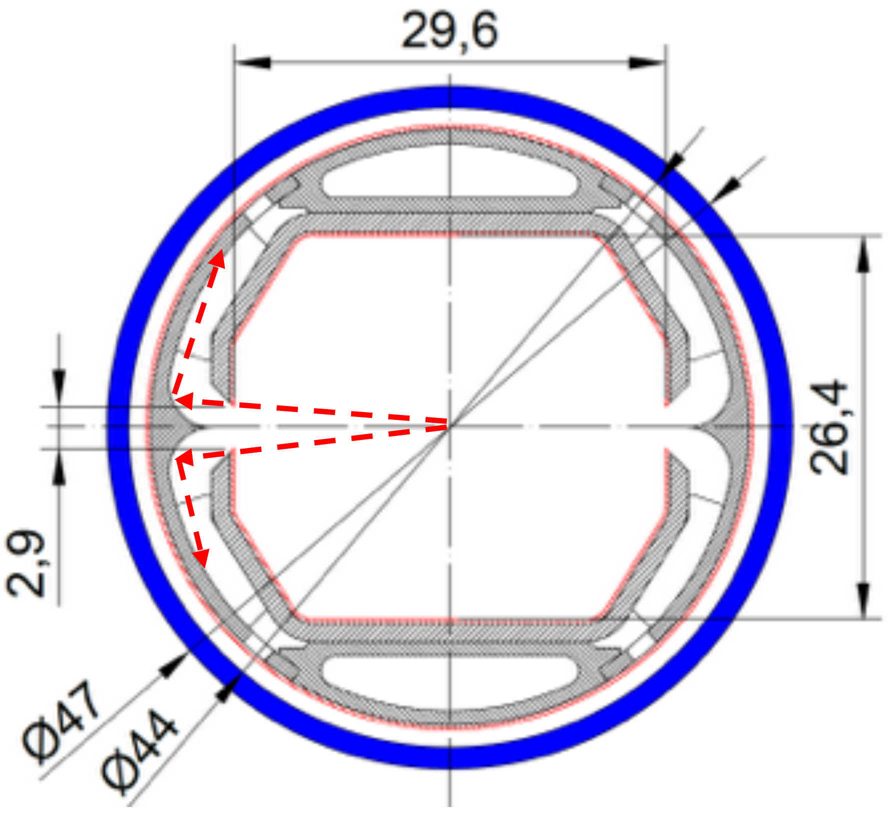
First FCC Physics Workshop
Frank Zimmermann
CERN, 16-20 January 2017

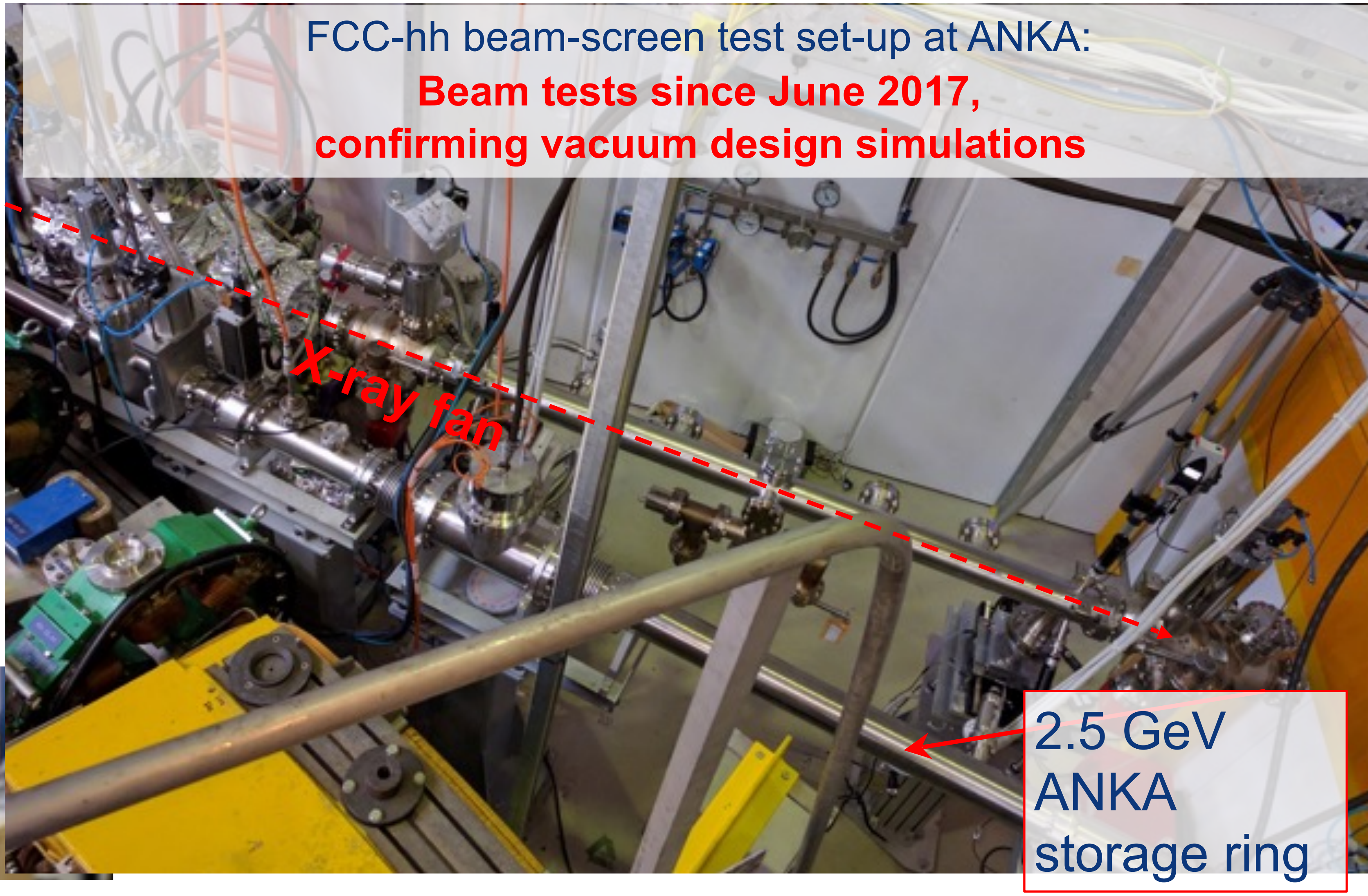
look @ Zimmermann's slides for many more details, 25ns vs 5ns, etc

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**

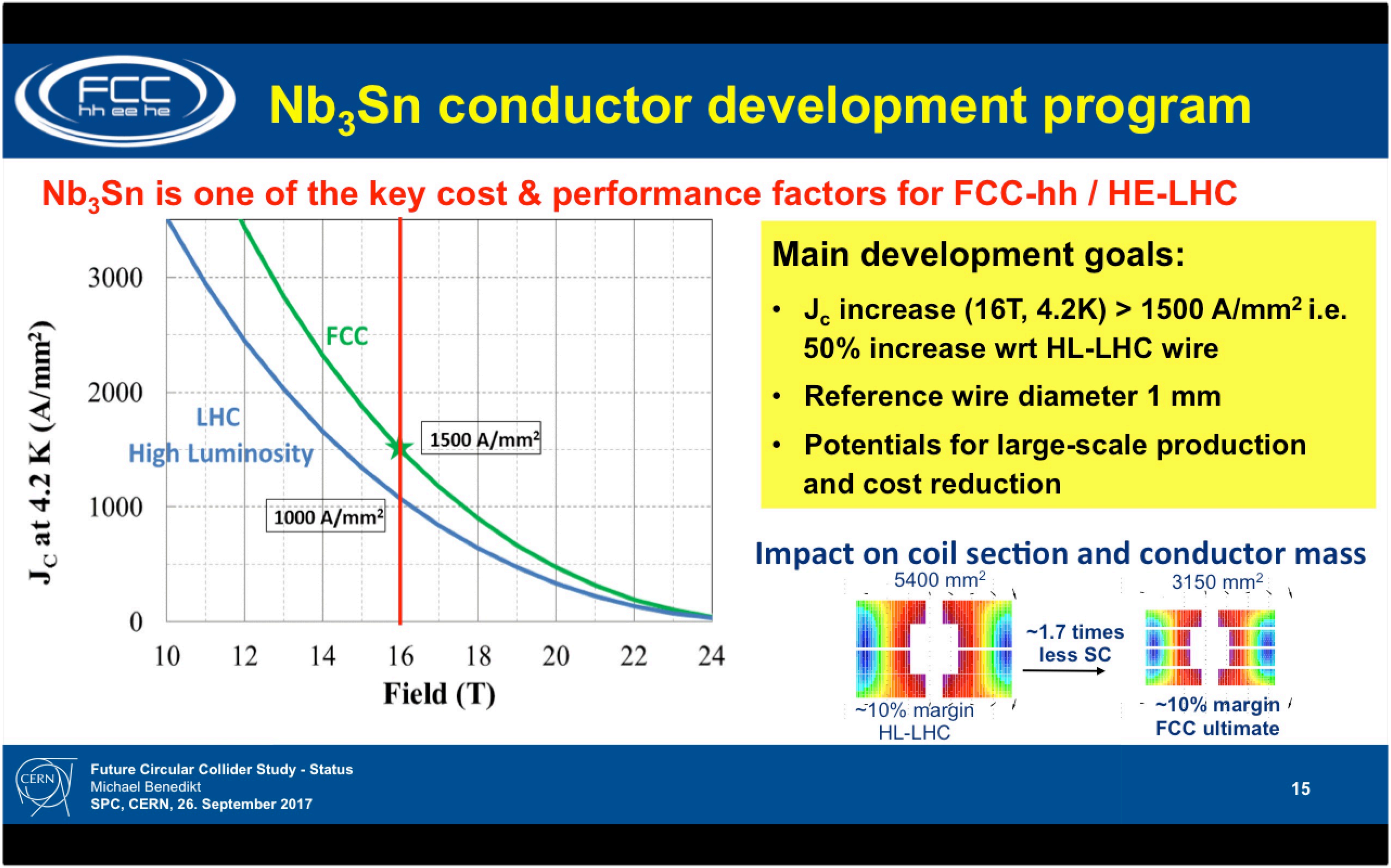
- **Absorption of synchrotron radiation at ~50 K** for cryogenic efficiency (**5 MW →100 MW cryoplant**)
- Provision of beam vacuum, suppression of photo-electrons, electron cloud effect, impedance, etc.





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

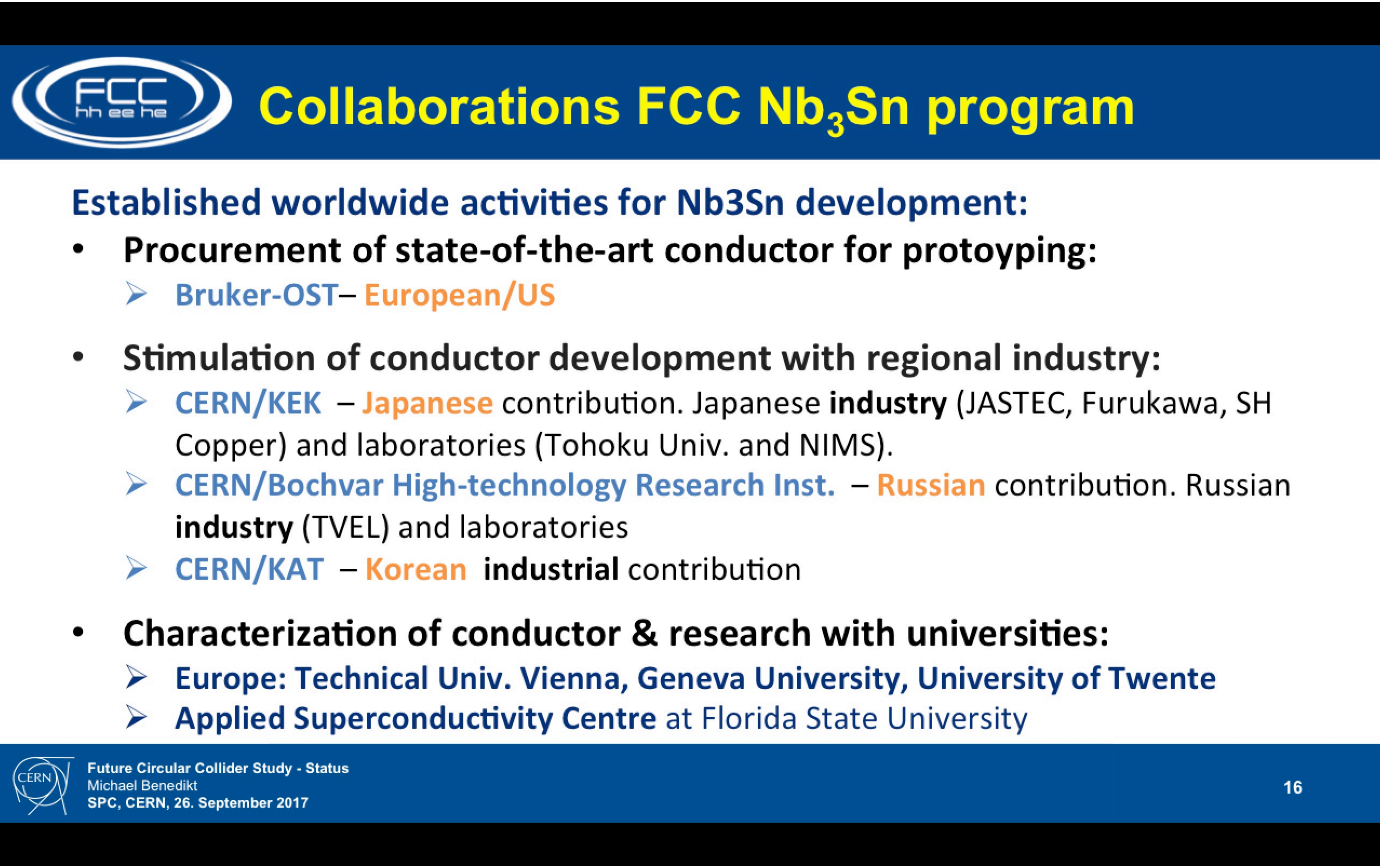
Nb_3Sn is one of the key cost & performance factors for FCC-hh / HE-LHC

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



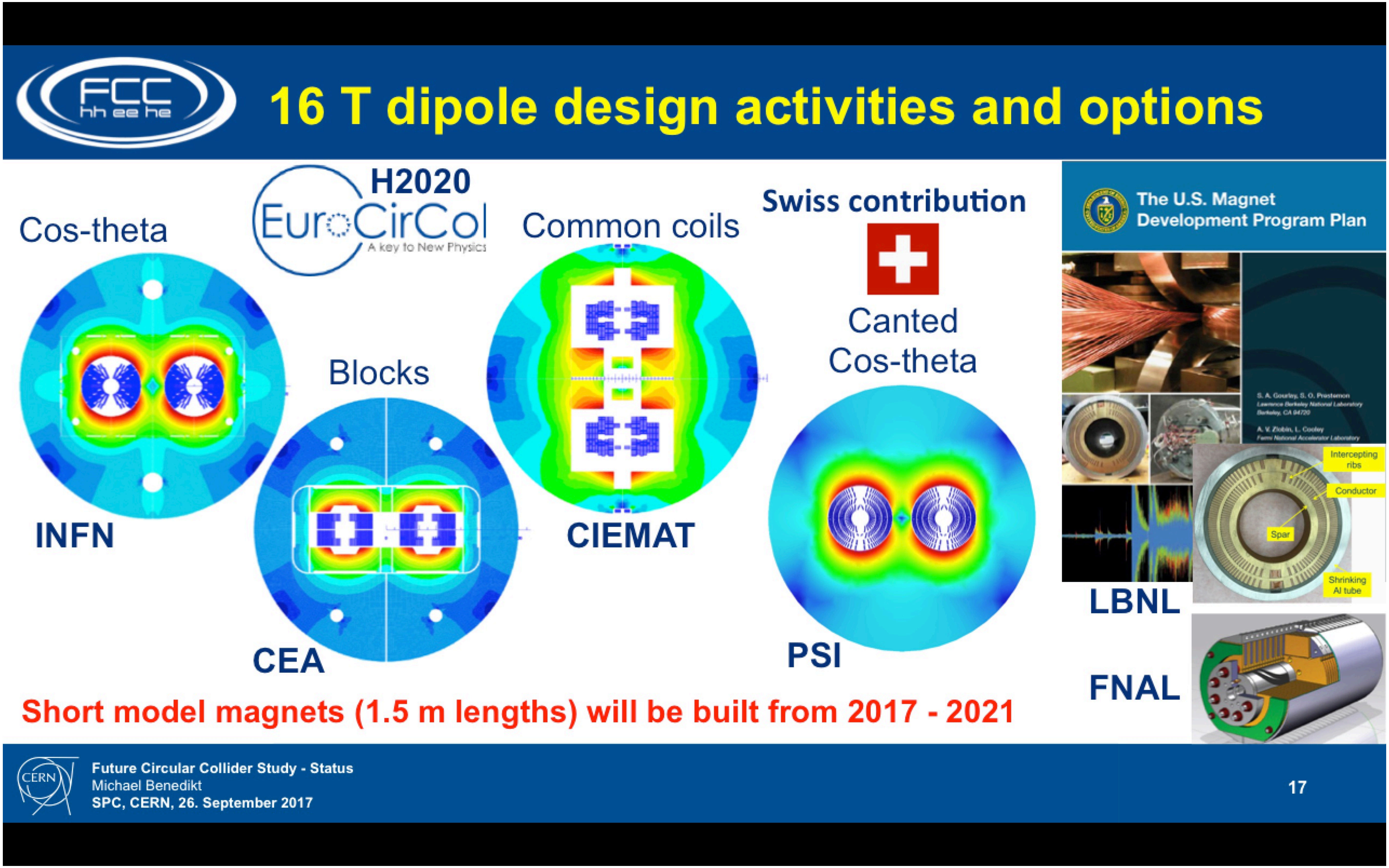
Collaborations FCC Nb$_3$Sn program

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

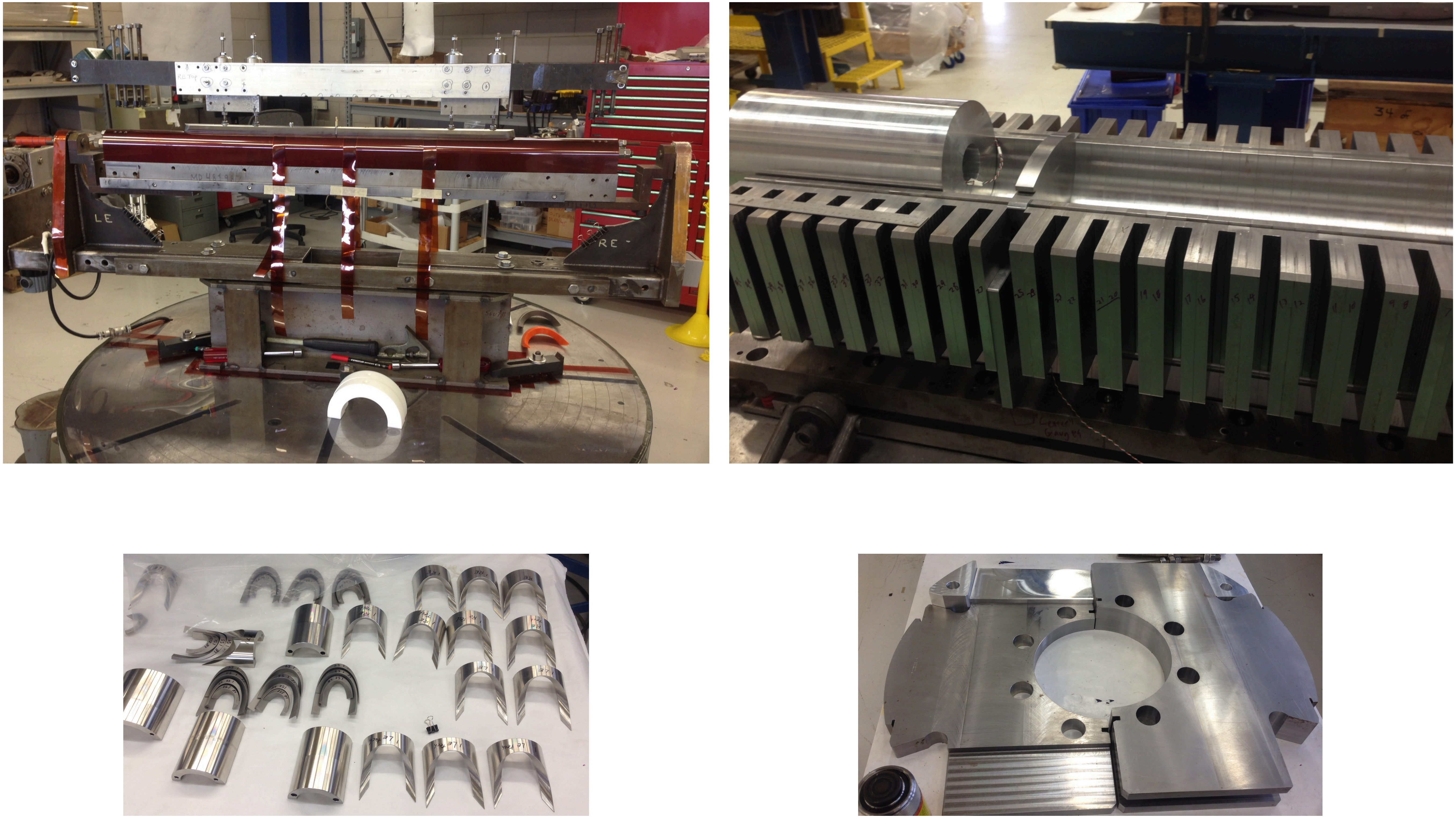
A. V. Zlobin, L. Cooley
Fermi National Accelerator Laboratory

LBNL

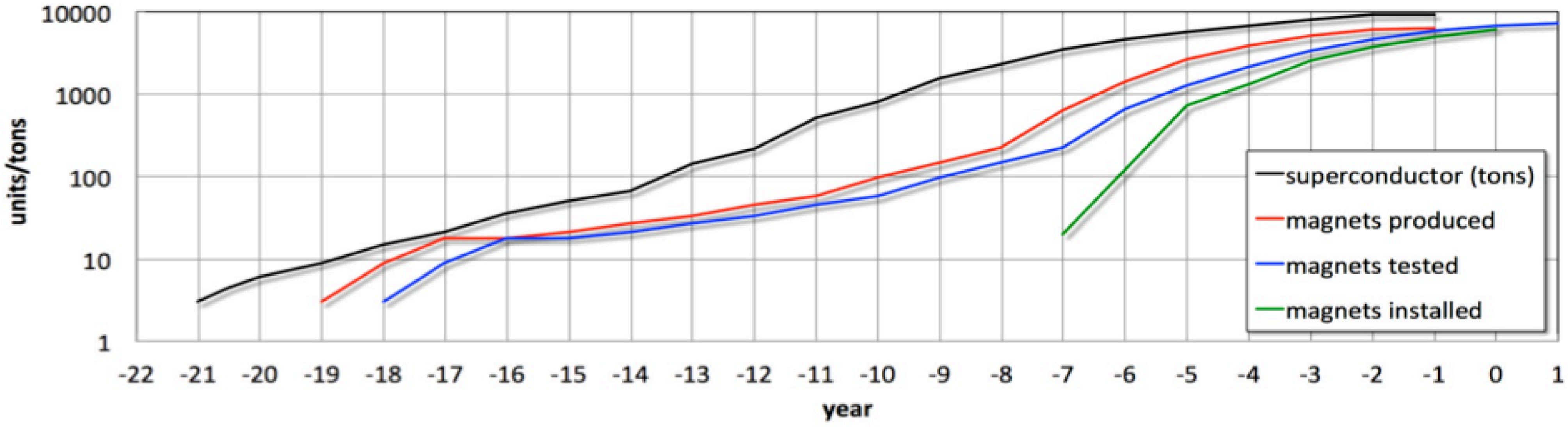
FNAL

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

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

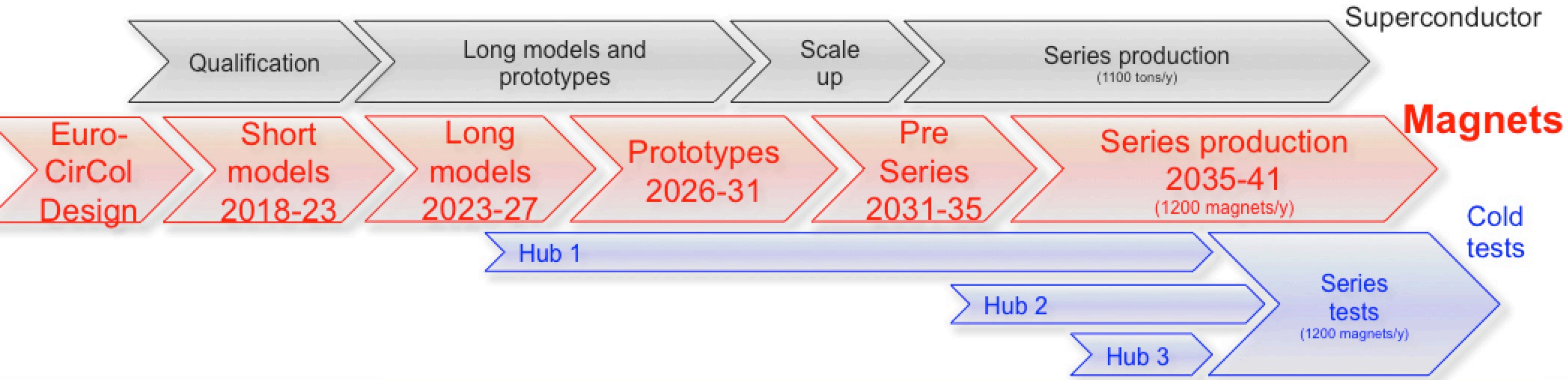


16 T magnet R&D schedule



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

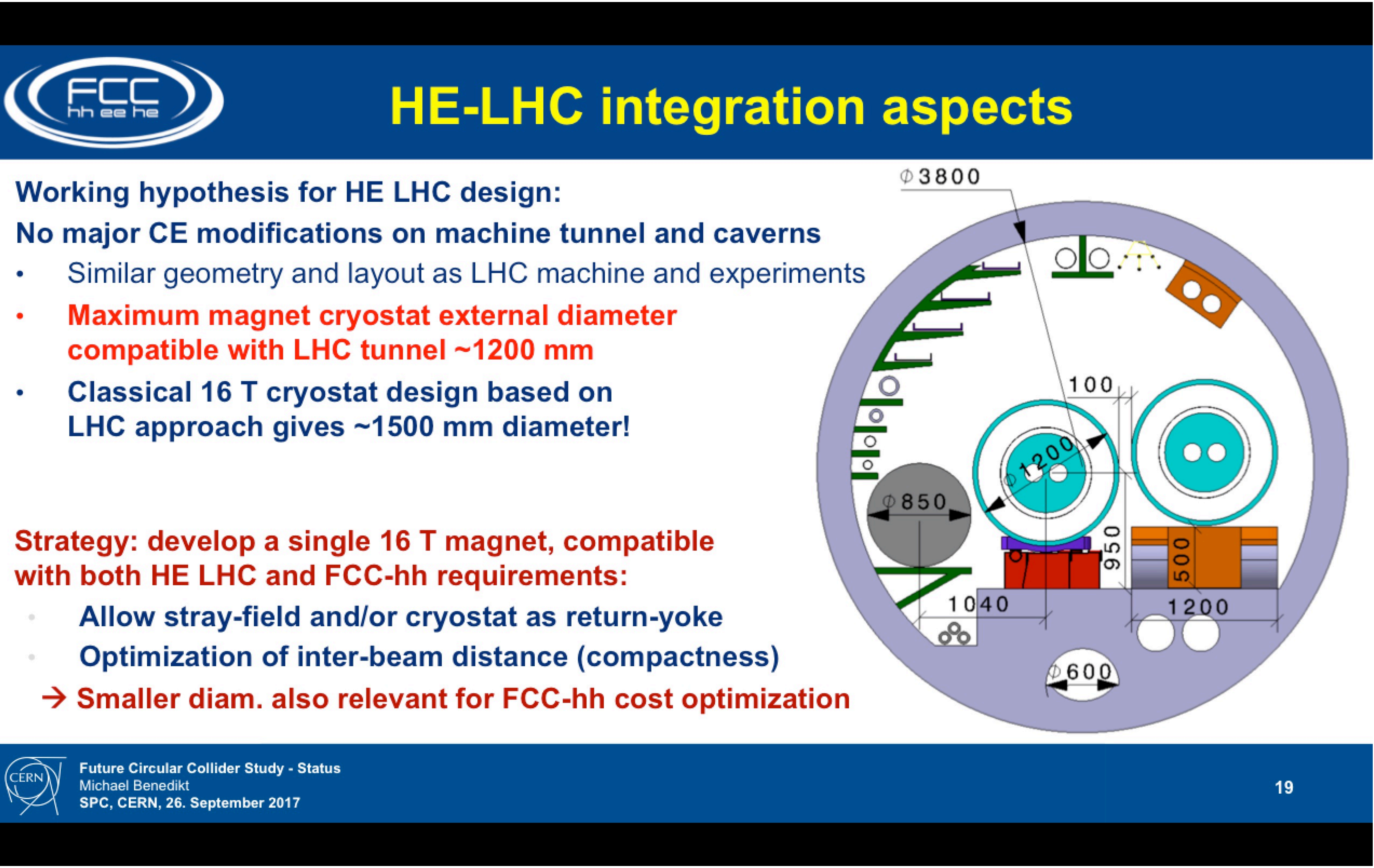
Hub 1

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

Reference detector

earlier design

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

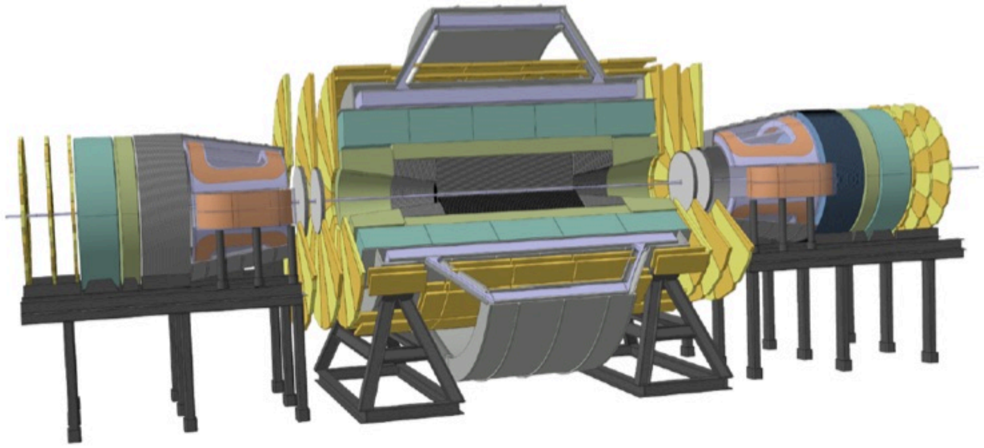
- 65 GJ stored energy
- 28 m diameter
- >30 m shaft
- multi billion project

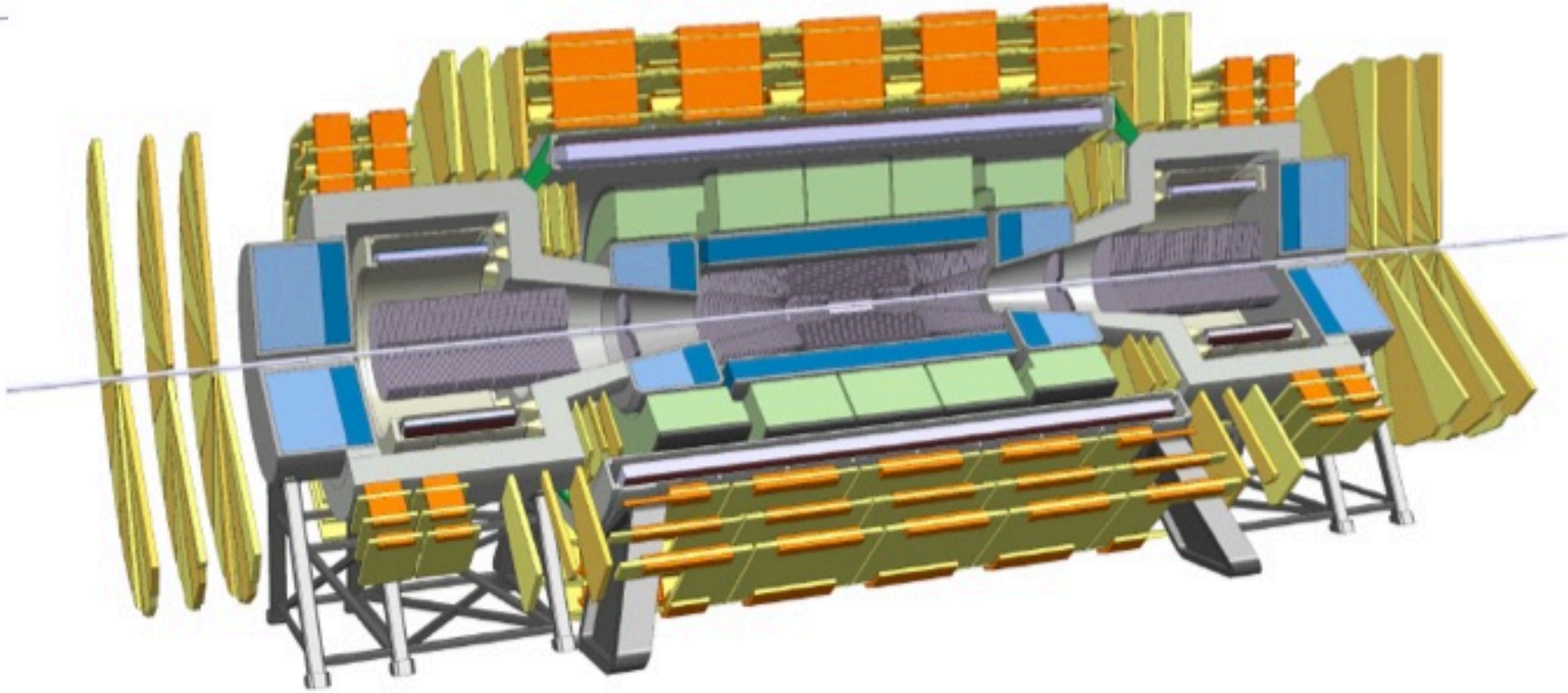
→

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

Final remarks

- FCC-hh physics studies today focus on exploring possible scenarios, assessing the physics potential, defining benchmarks for the accelerator and detector design and performance, in order to better inform the discussions that will take place when the time for decisions comes...

- The interplay of the three colliders (ee, eh and hh) is crucial to the full exploitation of the FCC physics potential

- 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 must take account of the fuller picture, to reflect the future data (and the impact they will have on the theoretical thinking) from the LHC, as well as other current and future experiments in areas ranging from flavour physics to searches for dark matter, axions, ALPs, ….