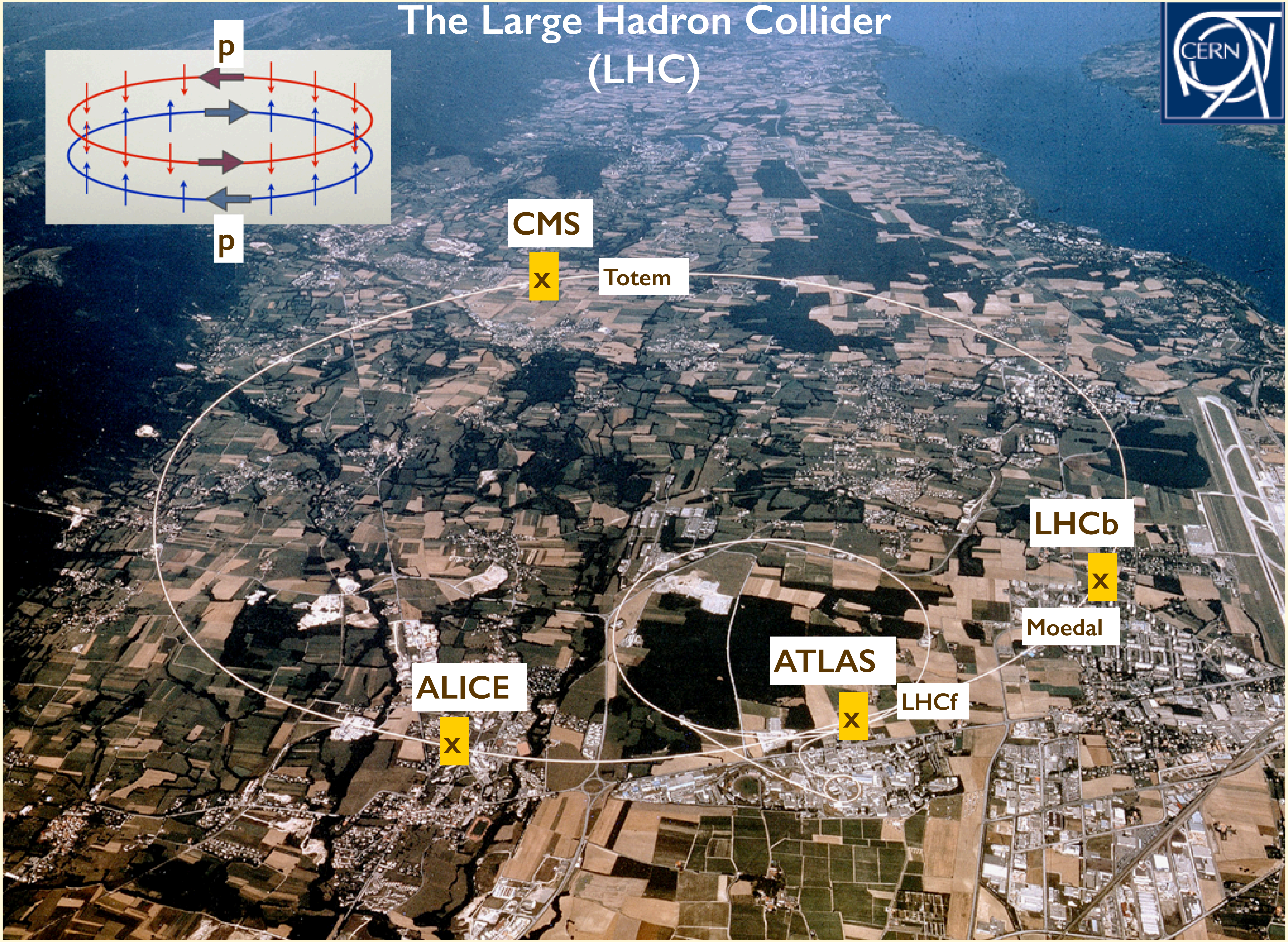
The Large Hadron Collider and Beyond: Future Paths in High Energy Physics

Dipartimento di Fisica
Universita' di Torino

Michelangelo L. Mangano
CERN, Theory Department

THE LHC

The Large Hadron Collider (LHC)

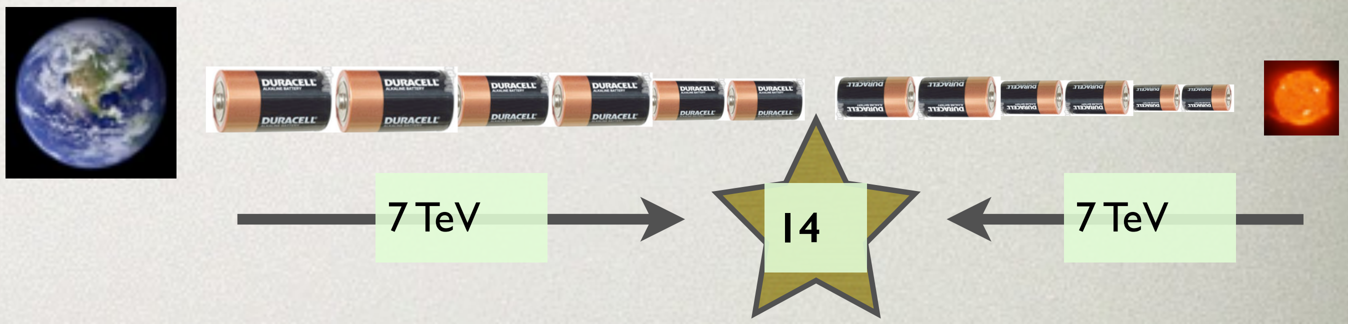


THE LHC ACCELERATOR

- 1232 LHC dipoles, plus ~600 other smaller magnets

- E_{beam} = 7000 GeV ~ $7\text{x}10^{12}$ eV ~ 5 trillions 1.5V batteries

~ 100 M km of batteries,
about d[Earth-Sun]



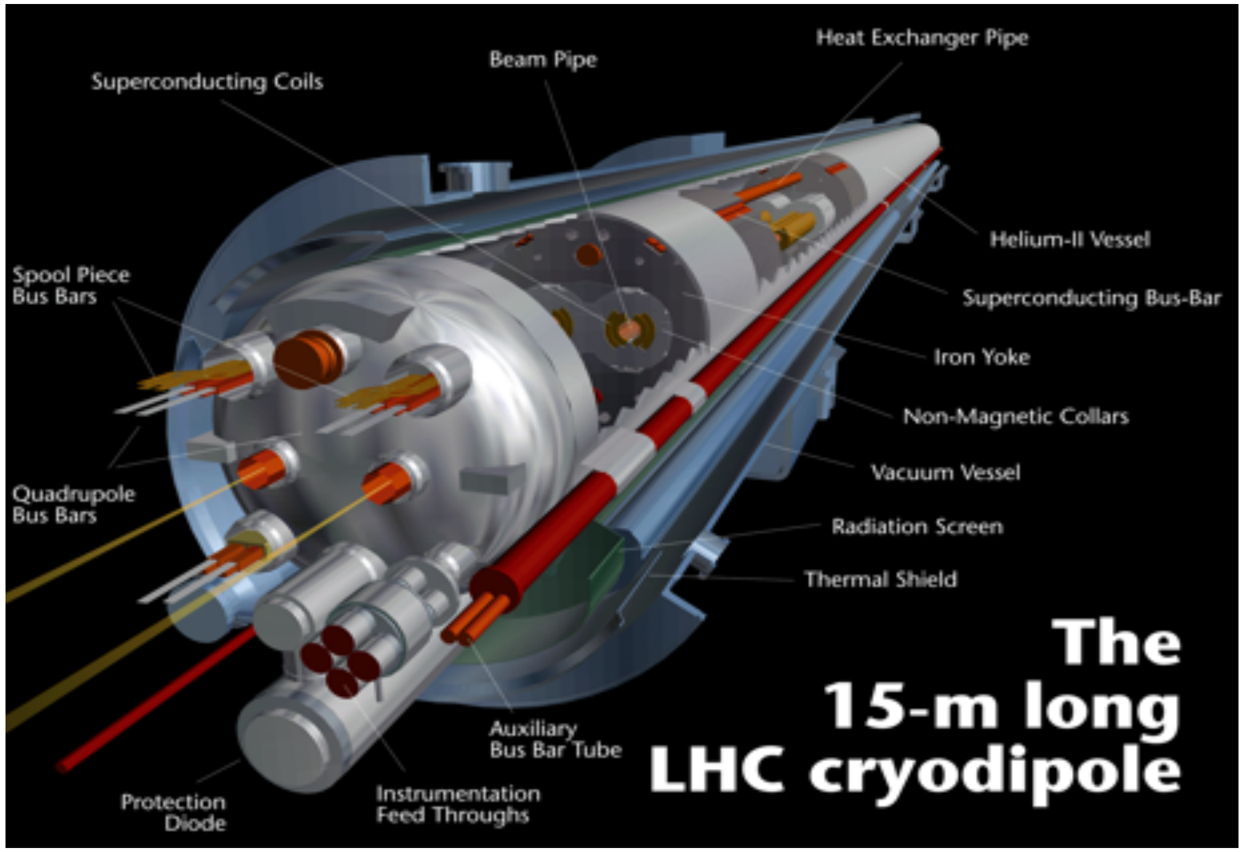
- E_{beam} = 7000 GeV ~ 7500 $m_{\text{proton}}\, c^2$
  - $E=mc^2 / \sqrt{[1-v^2/c^2]} \Rightarrow v = 0.999\,999\,99\, c$

- N_{proton} ~ 10^{11}/bunch x 2800 bunches/beam x 2 beams ~ 10^{14}

- Energy stored ~ 350 MJ ~ 80kg of TNT ~ Train running full speed

The LHC dipole

- 1232 LHC dipoles, plus ~600 other smaller magnets



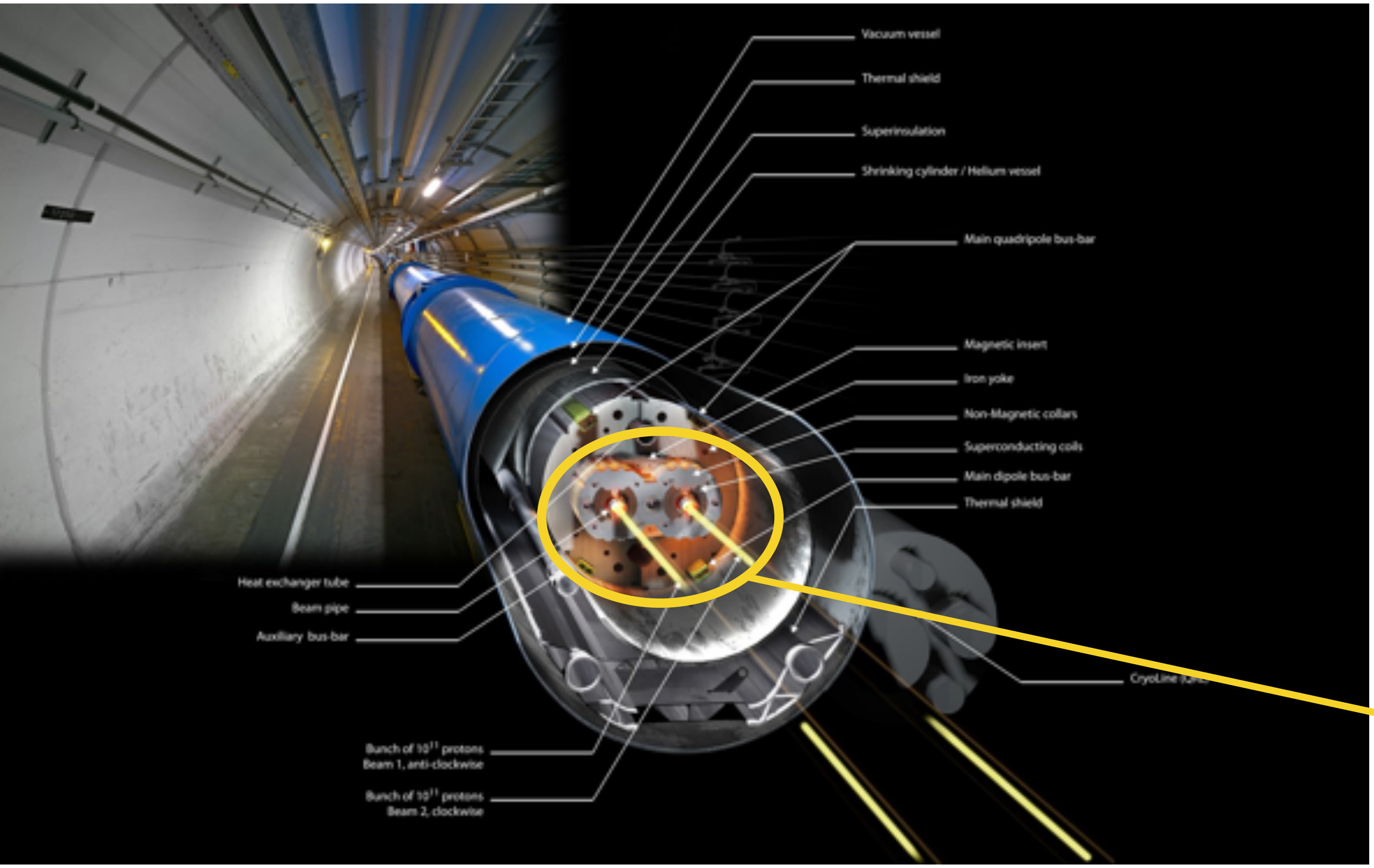
- B field = 83,000 Gauss
  - Ni Ti SC cable

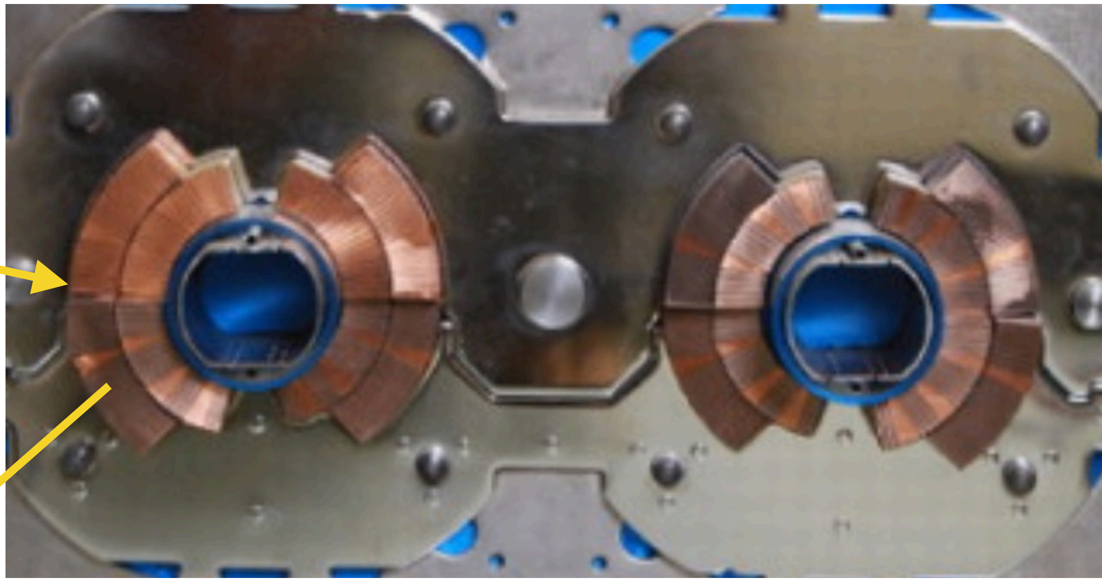
(Earth's field ~ 0.5 Gauss)

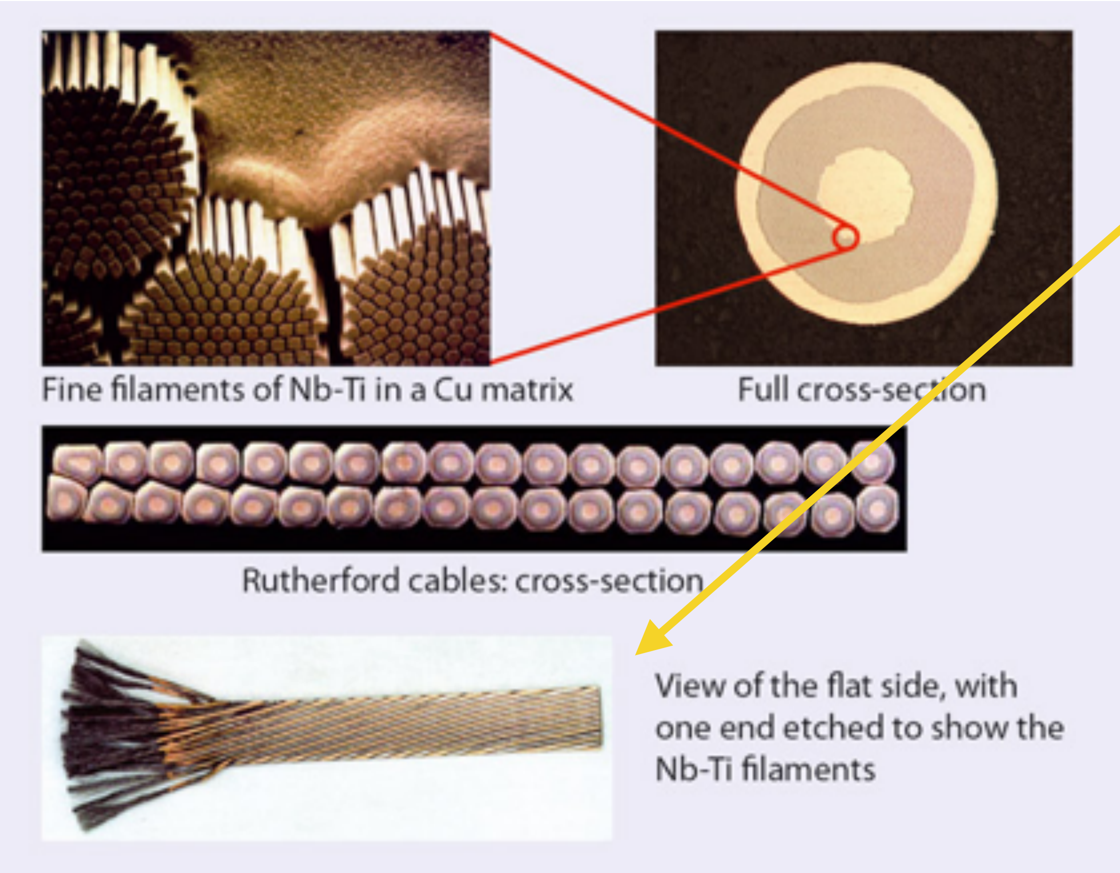
- T = $1.9K^0$ = – 456 F
  - superfluid liquid Helium

- 35 tonnes
- 15 m long
- Stress at the collar: 150 MPa
  - ~ 22,000 psi
  - ~ 1,500 kg/cm^2

- Stored energy: 7 MJoule/dipole => ~ 10G Joule total





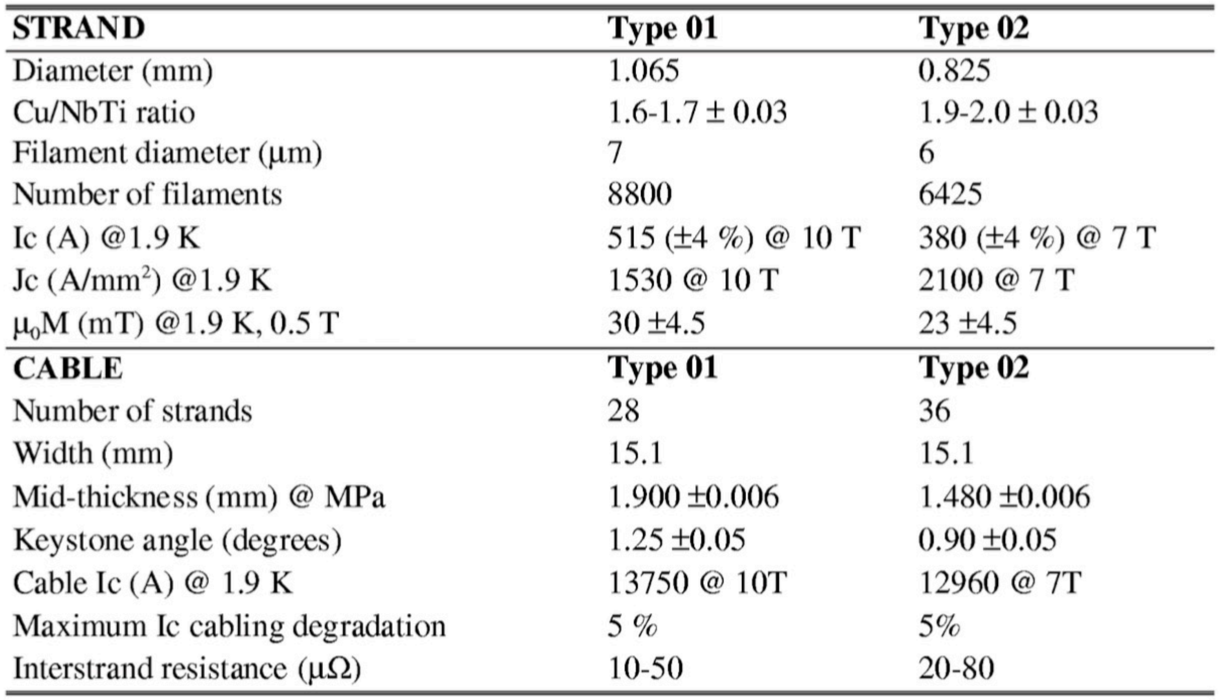


Fine filaments of Nb-Ti in a Cu matrix

Full cross-section

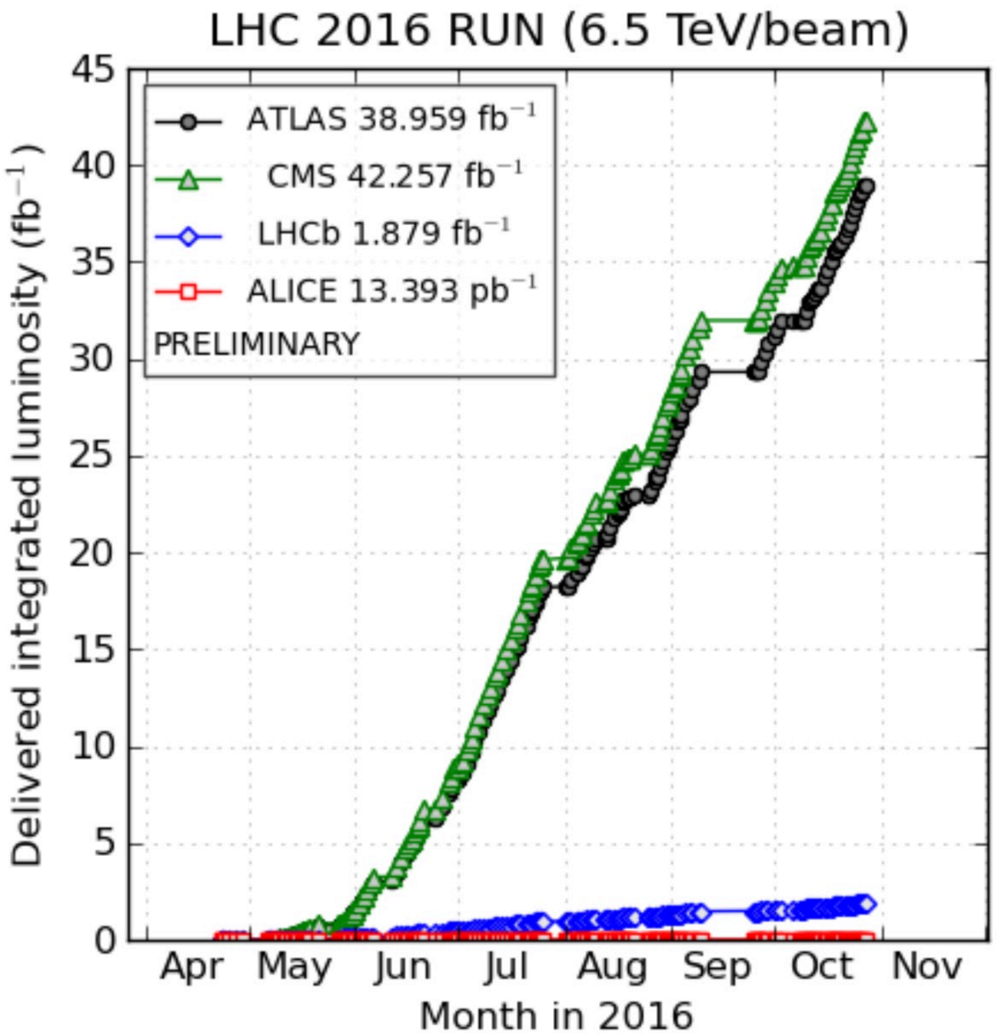
Rutherford cables: cross-section

View of the flat side, with one end etched to show the Nb-Ti filaments

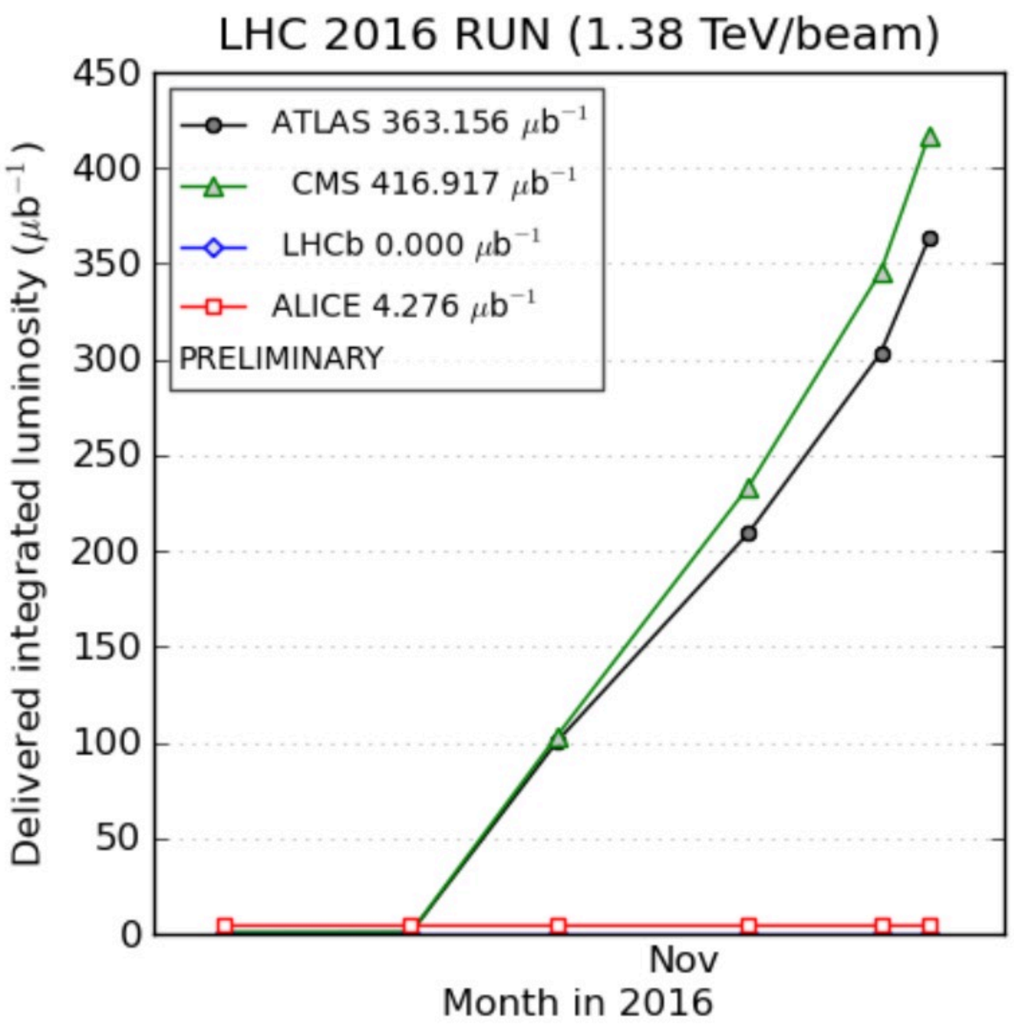


STRAND	**Type 01**	**Type 02**
Diameter (mm)	1.065	0.825
Cu/NbTi ratio	1.6-1.7 ± 0.03	1.9-2.0 ± 0.03
Filament diameter (µm)	7	6
Number of filaments	8800	6425
Ic (A) @1.9 K	515 (±4 %) @ 10 T	380 (±4 %) @ 7 T
Jc (A/mm^2) @1.9 K	1530 @ 10 T	2100 @ 7 T
μ_0M (mT) @1.9 K, 0.5 T	30 ±4.5	23 ±4.5
CABLE	**Type 01**	**Type 02**
Number of strands	28	36
Width (mm)	15.1	15.1
Mid-thickness (mm) @ MPa	1.900 ±0.006	1.480 ±0.006
Keystone angle (degrees)	1.25 ±0.05	0.90 ±0.05
Cable Ic (A) @ 1.9 K	13750 @ 10T	12960 @ 7T
Maximum Ic cabling degradation	5 %	5%
Interstrand resistance (µΩ)	10-50	20-80

Status of LHC running, 2016



(2016-11-17 17:39 including fill 5456; scripts by C. Barschel)



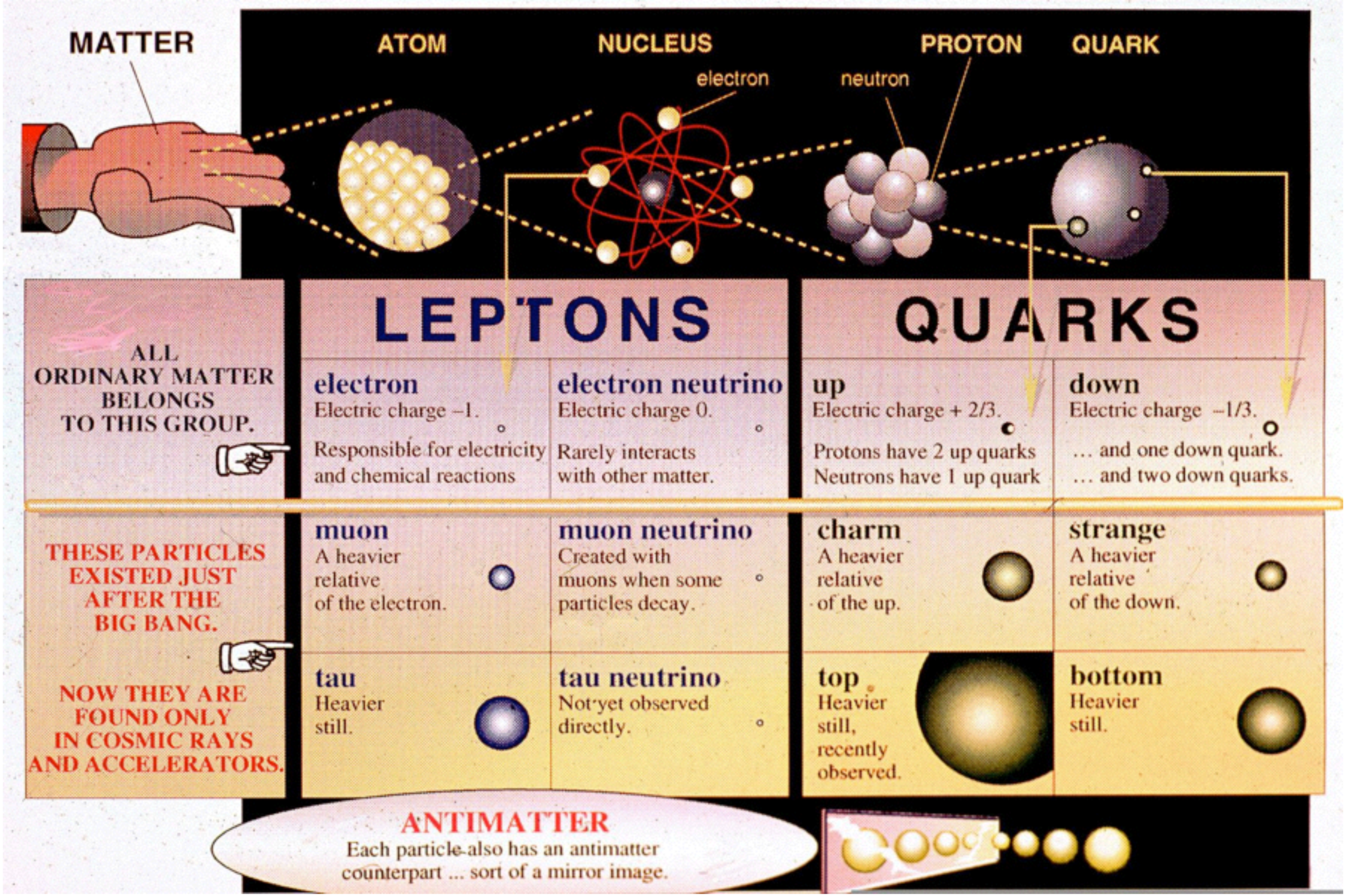
(generated 2016-11-17 17:39 including fill 5514)

2016 goal: 25 fb^{-1}
Delivered: ~40 fb^{-1}

Heavy Ion, p-Pb run
First phase at 5 TeV ~completed
Second phase at 8 TeV, next 2 weeks

Message: the LHC works extremely well, better than expected

The Standard Model of particle physics



	LEPTONS		**QUARKS**	
ALL ORDINARY MATTER BELONGS TO THIS GROUP.	**electron** Electric charge –1. Responsible for electricity and chemical reactions	**electron neutrino** Electric charge 0. Rarely interacts with other matter.	**up** Electric charge + 2/3. Protons have 2 up quarks Neutrons have 1 up quark	**down** Electric charge –1/3. … and one down quark. … and two down quarks.
THESE PARTICLES EXISTED JUST AFTER THE BIG BANG. NOW THEY ARE FOUND ONLY IN COSMIC RAYS AND ACCELERATORS.	**muon** A heavier relative of the electron.	**muon neutrino** Created with muons when some particles decay.	**charm** A heavier relative of the up.	**strange** A heavier relative of the down.
	tau Heavier still.	**tau neutrino** Not yet observed directly.	**top** Heavier still, recently observed.	**bottom** Heavier still.

ANTIMATTER
Each particle also has an antimatter counterpart … sort of a mirror image.

Status of the Standard Model

- < 1973: theoretical foundations of the SM
  - renormalizability of SU(2)xU(1) with Higgs mechanism for EWSB
  - asymptotic freedom, QCD as gauge theory of strong interactions
  - KM description of CP violation
- Followed by 40 years of consolidation:
  - **experimental** verification, via **discovery** of
    - **Fermions**: charm, tau, bottom, top (all discovered in the USA)
    - **Bosons**: gluon, W and Z, **Higgs** (all discovered in Europe)
  - **technical theoretical advances** (higher-order calculations, lattice QCD, ...)
  - **experimental** consolidation, via precision **measurement** of
    - EW radiative corrections
    - running of α_S and dynamics of strong interactions (jets, fragmentation, PDFs, …)
    - CKM matrix parameters, ….
- **NB: for dynamical quantities, the precision of predictions and the agreement with measurements has reached the % level for strong int's, and (sub)per-mille for weak int's** (for QED it's been at the per-billion level since a while ….)

The next step:
address the *big* questions that will take us *beyond* the Standard Model

- 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's the solution to the hierarchy problem?
- What's the real origin of EW symmetry breaking?
- ...

On these, one can now be tackled directly and concretely:

What's the mechanism at the origin of particles' masses: is the Higgs boson dynamics what prescribed by the SM, or are there other phenomena at work?

On particles’ masses

For a composite system the mass is obtained by solving the dynamics of the bound state ⇒ **$m=\langle E\rangle/c^2$** with **$\langle E\rangle=\langle T+U\rangle$**

Example: the proton mass. Dynamics of quarks and gluons inside the proton (they have negligible masses) ⇒ m_p = 938 MeV

But what about elementary particles? Elementary ⇒ no internal dynamics

Need to develop a new framework within which to understand the origin and value of, for example, the electron mass

However:

- Why do we need a mechanism to accommodate the masses of elementary particles?
- How about just assigning mass values as parameters?

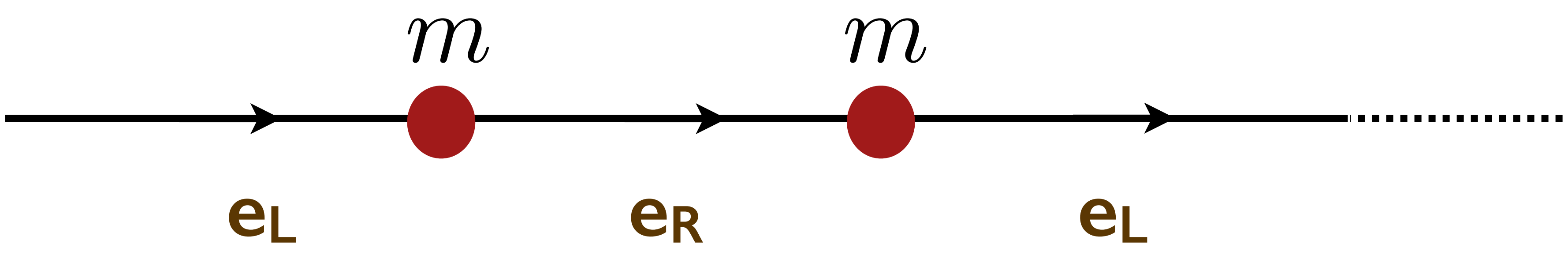
In other words:

WHY are particle physicists so *obsessed* with the problem of particles’ masses?

Parity asymmetry and mass for spin-1/2 particles

$$H \propto i\overline{\psi_L}\,\partial\cdot\gamma\,\psi_L + i\overline{\psi_R}\,\partial\cdot\gamma\,\psi_R + m\,\overline{\psi_L}\,\psi_R$$

$\gamma_5\,\psi_{L,R} = \pm\,\psi_{L,R}$

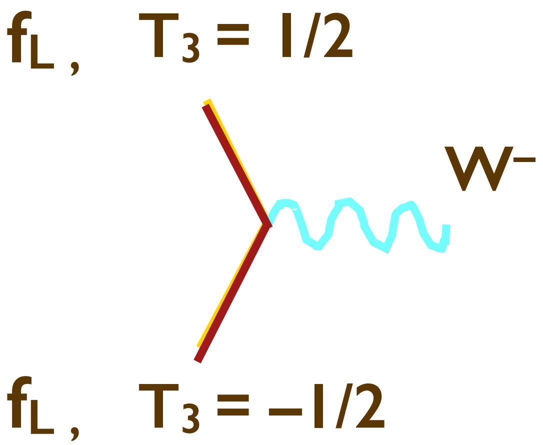


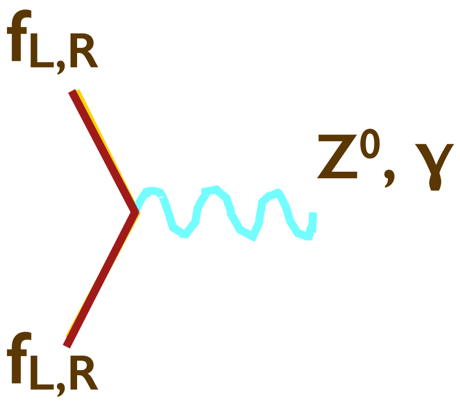
For a massive particle, chirality does not commute with the Hamiltonian, so it cannot be conserved

Chirality eigenstates cannot be Hamiltonian (physical) eigenstates

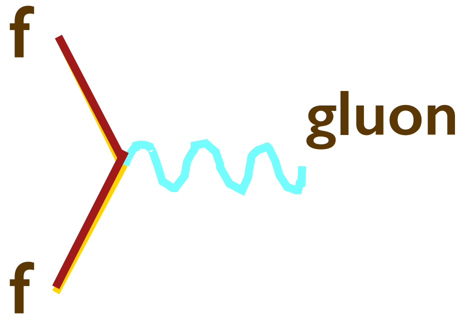
Nothing wrong with that in principle .... unless chirality is associated to a conserved charge!

$SU(2)_L \otimes U(1)$





SU(3)



L-chirality	R-chirality
$\begin{pmatrix} u_{2/3} \\ d_{-1/3} \end{pmatrix}_L^{i=1,2,3}$	$u^i{}_R$, $d^i{}_R$
$\begin{pmatrix} \nu \\ e^- \end{pmatrix}_L$	$e^-{}_R$

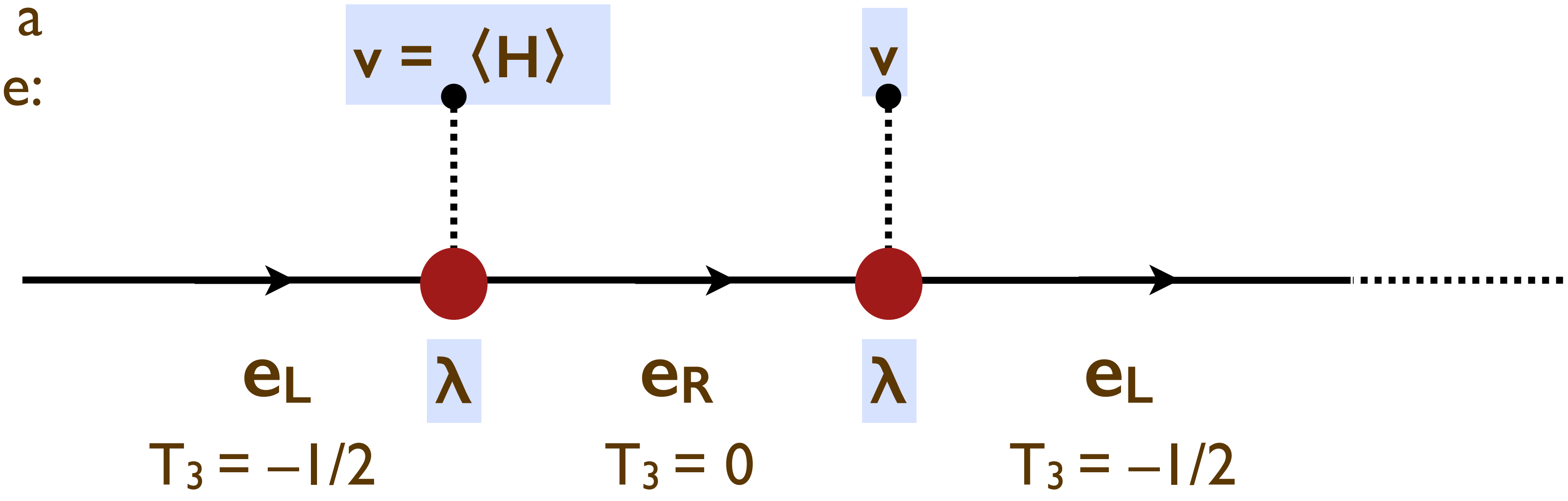
+ 2 more “families” differing from the 1st one only in the mass of their elements

The symmetry associated with the conservation of the weak charge must therefore be broken for leptons and quarks to have a mass

In this process, weak gauge bosons must also acquire a mass. This needs the existence of new degrees of freedom

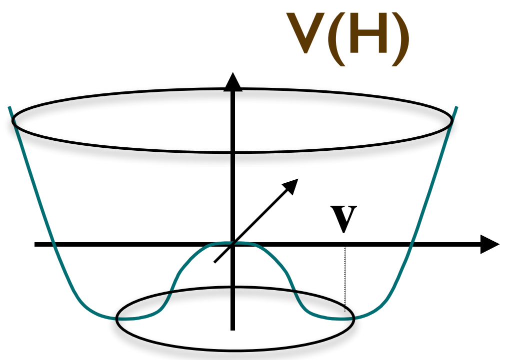
The SM solution ....

Propagation of a massive particle:



The transition between L and R states, and the absorption of the changes in weak charge, are ensured by the interaction with a background scalar field, **H**. Its "vacuum density" provides an infinite reservoir of weak charge.

This requires, at least, the existence of a complex EW-doublet scalar field **H,** whose potential acquires a minimum at $\langle H \rangle = v \neq 0$



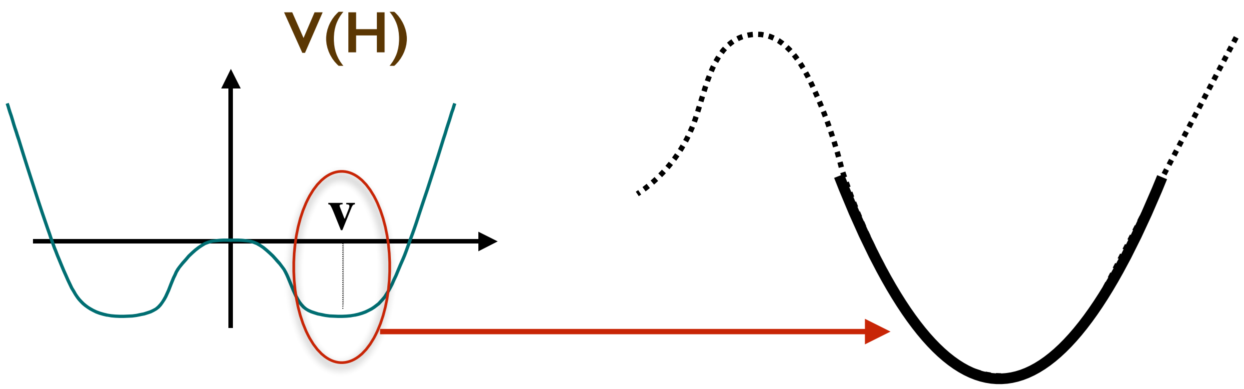
⇒ *Englert–Brout–Higgs–Guralnik–Hagen–Kibble mechanism*

The number "**v**" is the expectation value of the so-called **Higgs field**.
The quantity "**λ**" is characteristic of the particle interacting with the Higgs field.
It can easily be shown that **this interaction leads to a mass m** $\propto$ **λ v**

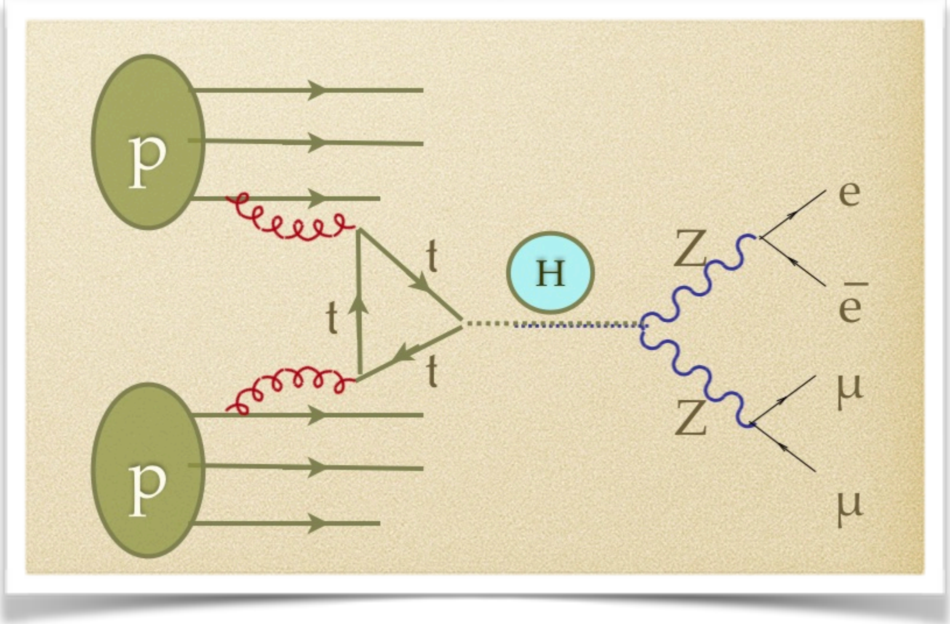
First general consequences of this model

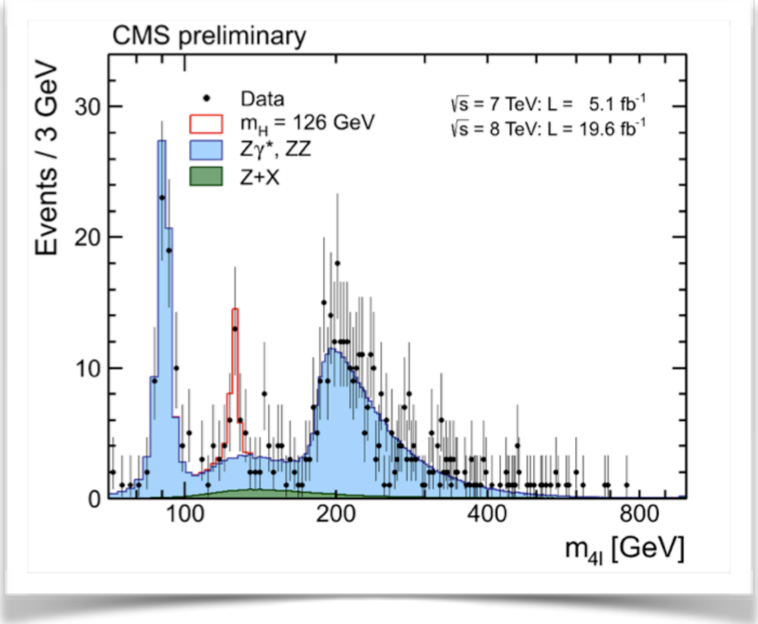
- Small oscillations around the minimum => a scalar particle (the “Higgs boson”)
- Couplings of H to SM particles proportional to their mass
- 3 out of 4 components of complex doublet field provide longitudinal degrees of freedom to weak gauge bosons $W^{+/-}$ and Z^0

What have we tested so far of this hypothesis?



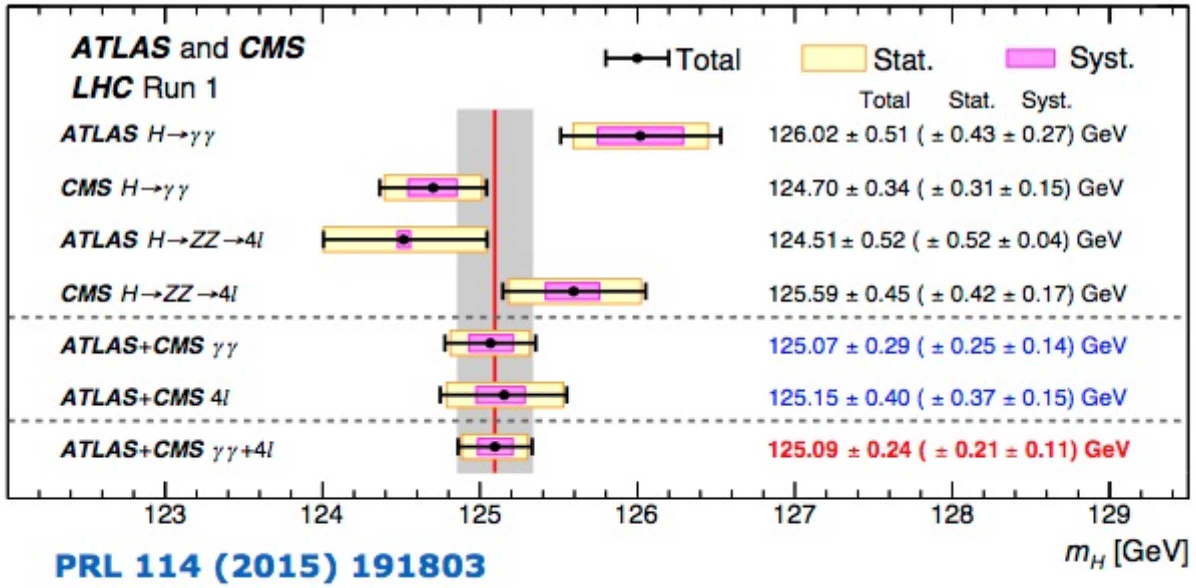
$V(H) \sim m_H^2\,(H-v)^2 \quad + ???$





ATLAS+CMS
PRL 114 (2015) 191803

δm/m = 0.2%



PRL 114 (2015) 191803

What have we tested so far of this hypothesis?

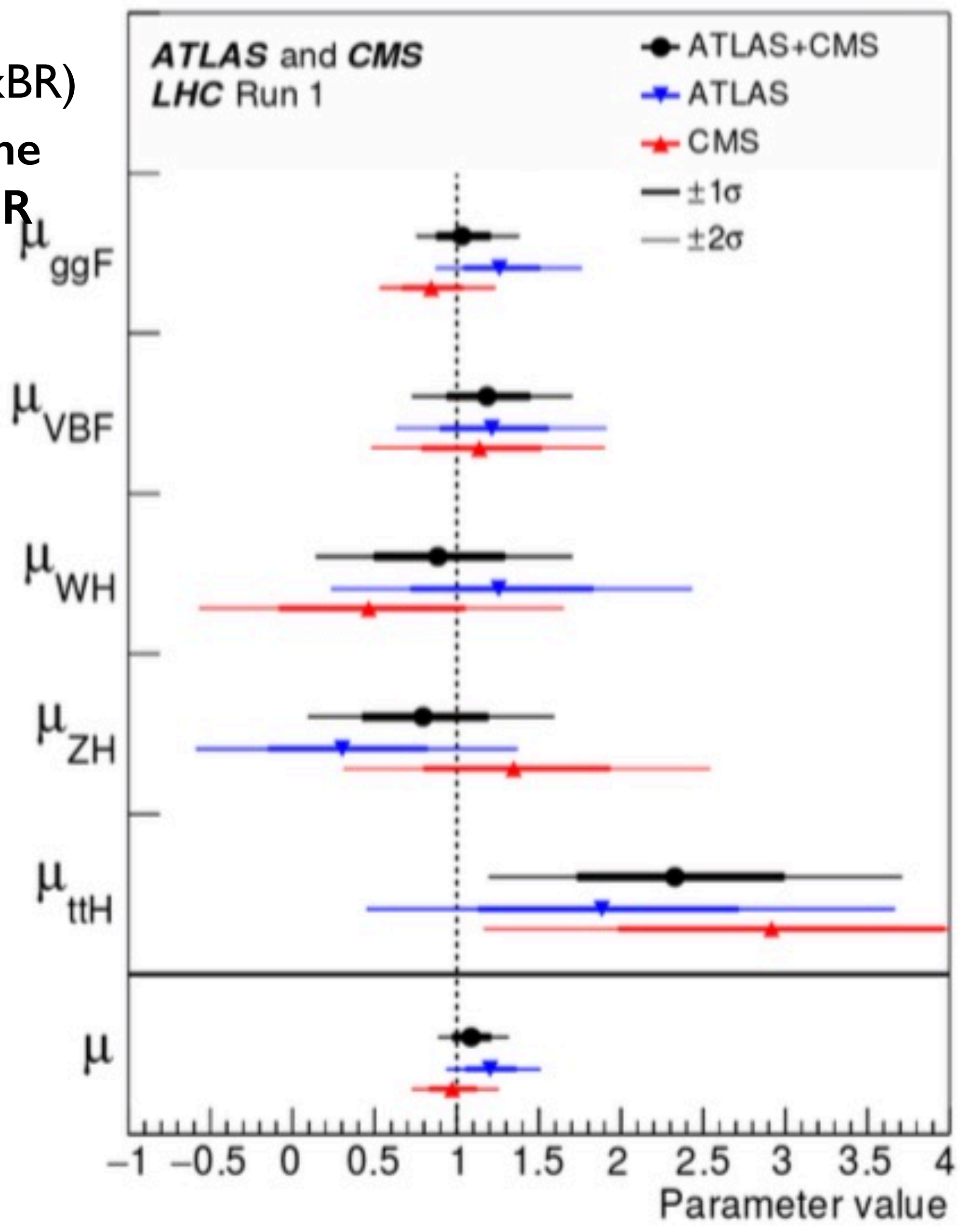
couplings

ATLAS+CMS
JHEP 1608 (2016) 045

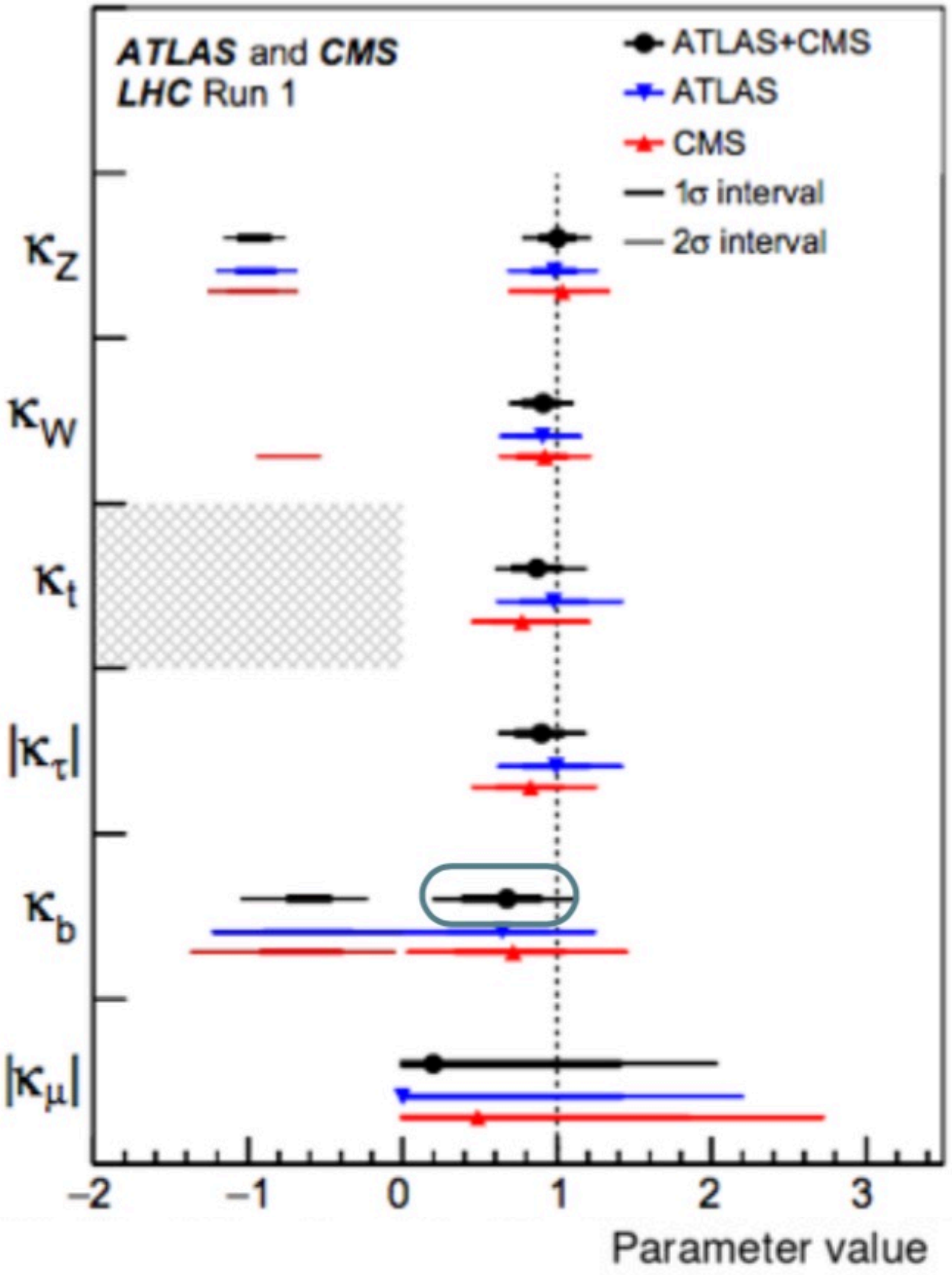
μ = 1.09 ± 0.11

(μ=σxBR)

assume SM BR

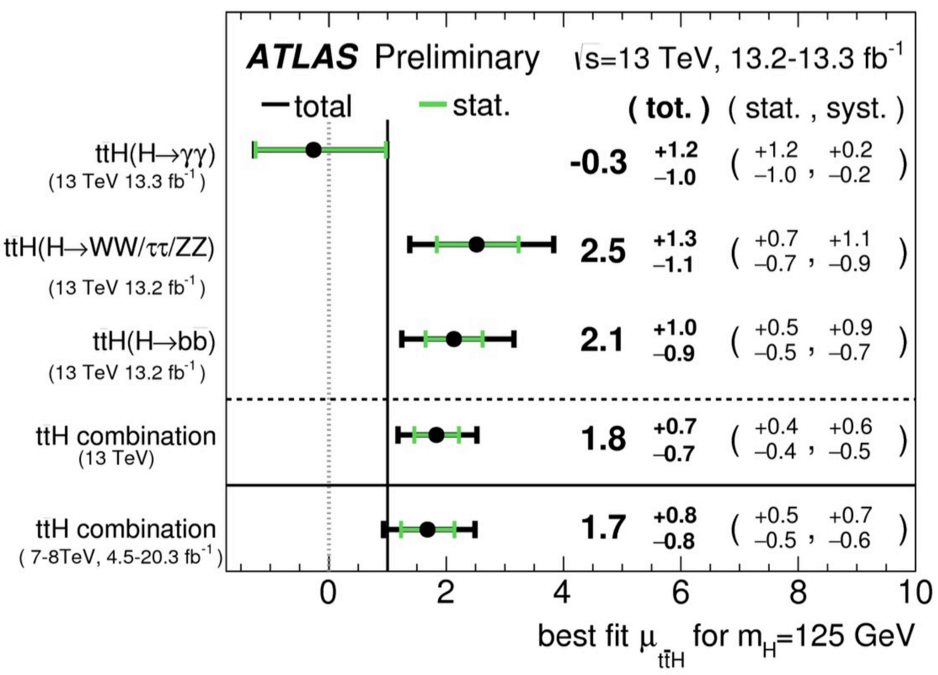


$$\kappa_j^2 = \sigma_j/\sigma_j^{SM} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{SM}$$



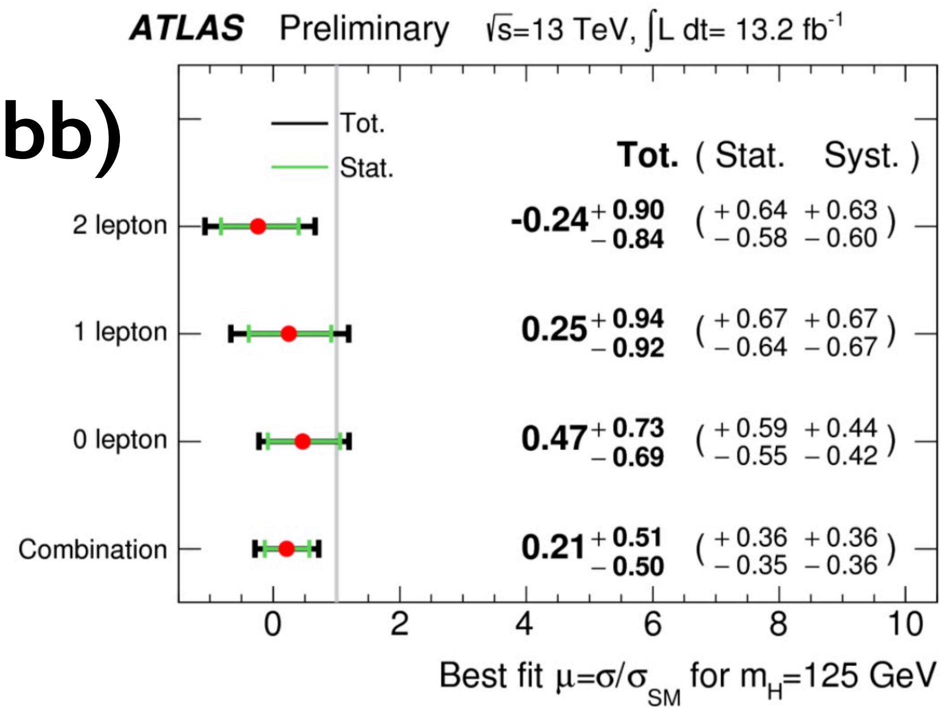
Highlights of 2015-16 Higgs measurements

ttH

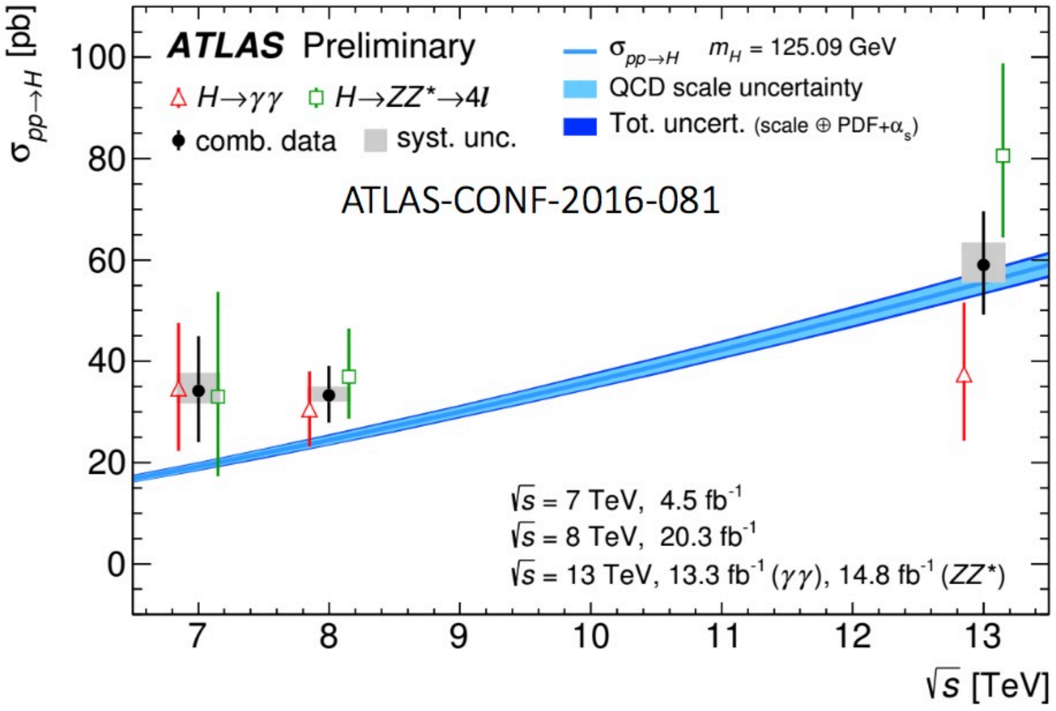


too much ….

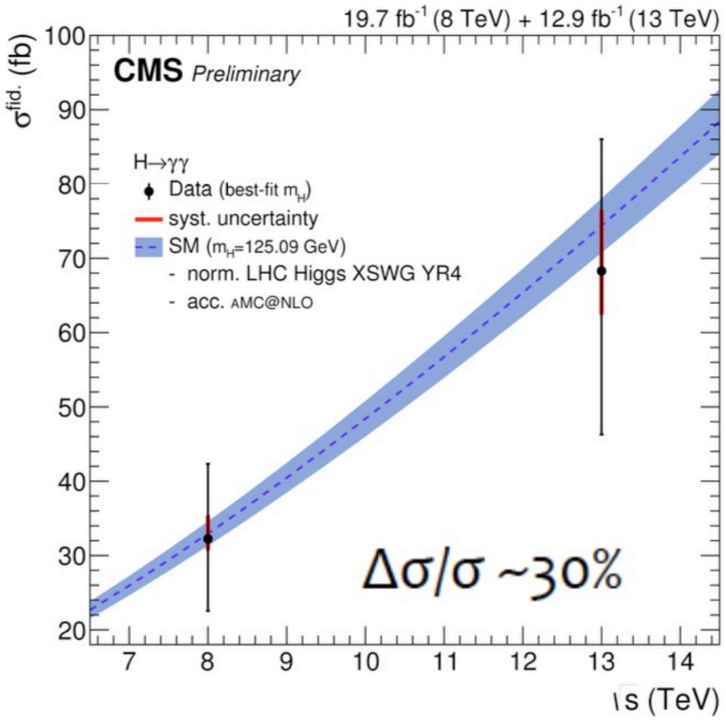
VH(bb)



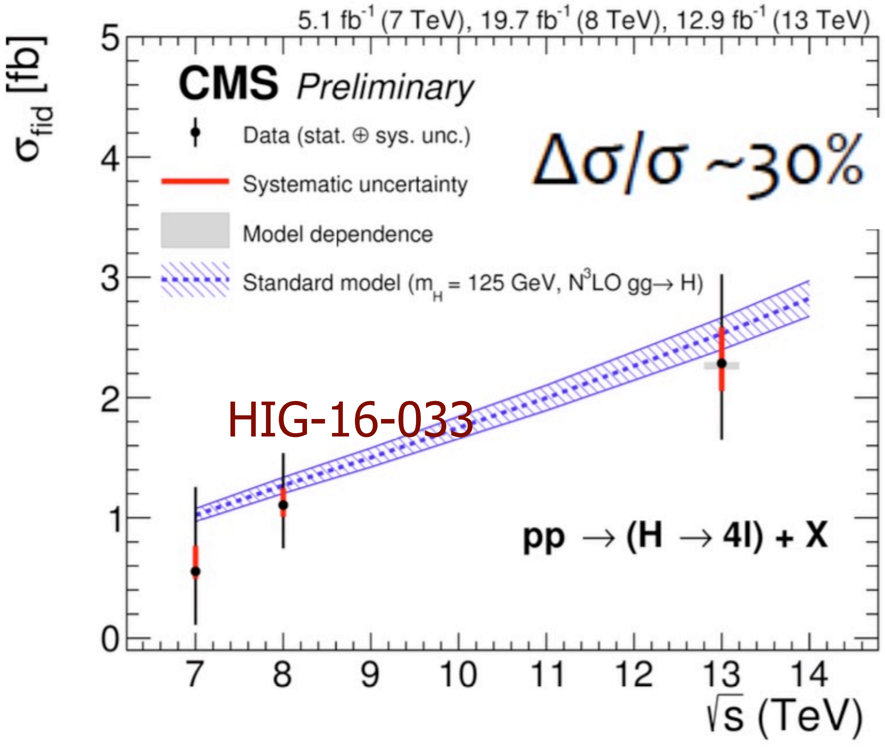
too little ….



ATLAS-CONF-2016-081



Δσ/σ ~30%



Δσ/σ ~30%

HIG-16-033

just about right …

Open Higgs issues for LHC and beyond

1. *This limited precision,* due to low statistics, *is not sufficient to probe most of possible scenarios alternative to the SM:* ***will the SM withstand more accurate tests?***
   - *Goal: push precision of coupling measurements to the % level*

2. *The Higgs mechanism has only been tested on a fraction of the SM particles,* due to low statistics: ***do the other particles (e.g. muon, charm, etc) interact with the Higgs as predicted by the SM?***
   - *Example: more than 10x the current statistics is required to establish* $H \to \mu\mu$ *at* 5σ

3. *Neutrino masses are not a SM ingredient:* ***how do neutrinos acquire their mass?***
   - *The LHC plays a role in exploring possible answers*

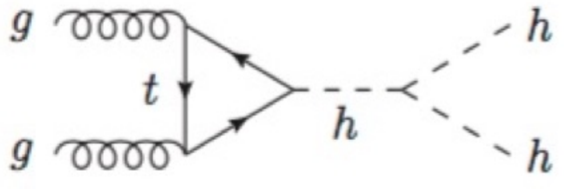
4. ***Are there more Higgs bosons?***
   - *Most theories beyond the SM have more Higgs bosons*

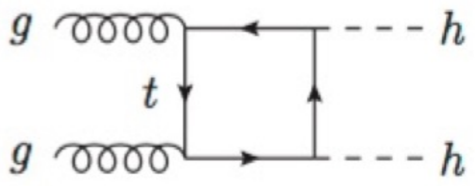
5. What gives mass to the Higgs ??

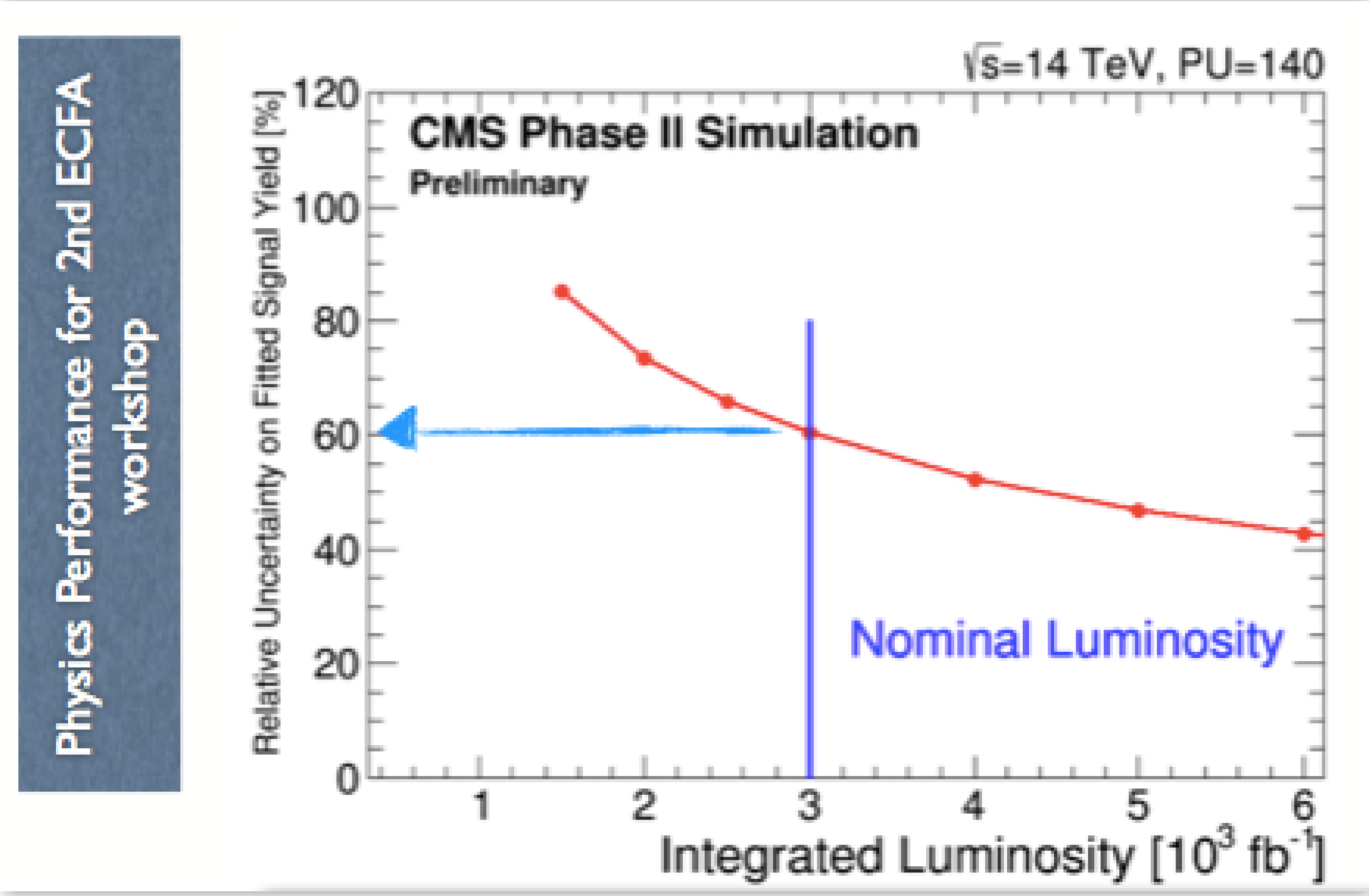
Obvious question, with a trivial answer in the SM: the Higgs gives mass to itself!

But less trivial answers can arise in beyond-the-SM scenarios

Testing how the Higgs interacts with itself (*this is how we probe the origin of the Higgs mass*) will require at least 100x the current LHC statistis, and possibly more






Physics Performance for 2nd ECFA workshop

Why do we care so much?

The Higgs boson is directly connected to several key questions:

- What's the real origin of the Higgs potential, which breaks EW symmetry?
  - underlying strong dynamics? composite Higgs?
  - RG evolution from GUT scales, changing sign to quadratic term in V(H)?
  - 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?

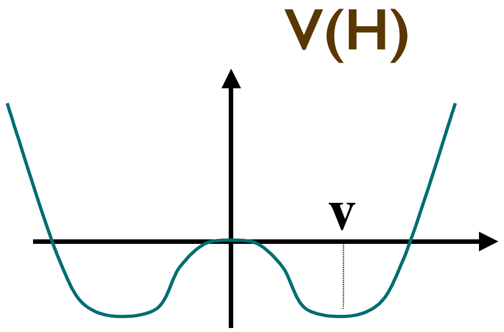
- Is there a relation between Higgs, EWSB, baryogenesis and Dark Matter?

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

Higgs selfcouplings

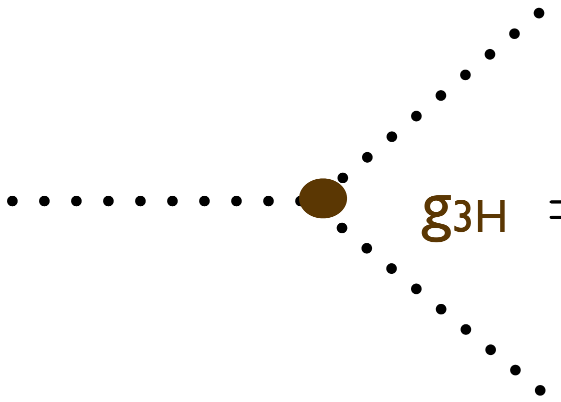
The Higgs sector is defined in the SM by two parameters, **μ** and **λ**:

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

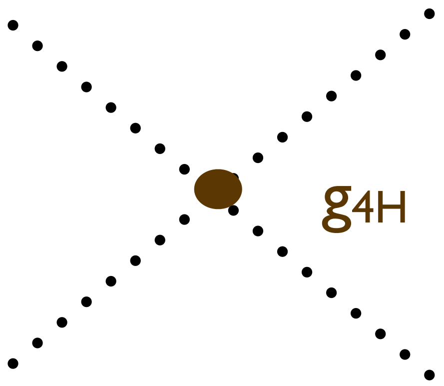


$$\frac{\partial V_{SM}(H)}{\partial H}\Big|_{H=v} = 0 \quad \text{and} \quad m_H^2 = \frac{\partial^2 V_{SM}(H)}{\partial H \partial H^*}\Big|_{H=v} \quad \Rightarrow \quad \boxed{\begin{array}{rcl} \mu & = & m_H \\ \lambda & = & \dfrac{m_H^2}{2v^2} \end{array}}$$

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



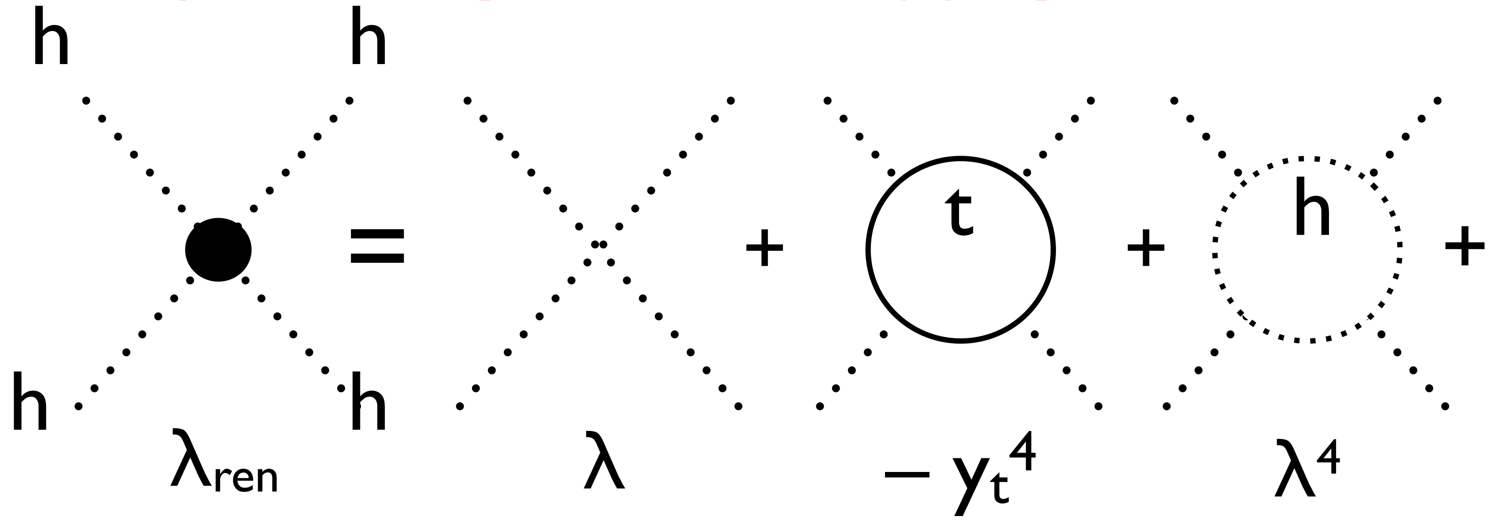
$$g_{3H} \Rightarrow 4\lambda v = \boxed{\frac{2m_H^2}{v}}$$



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

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

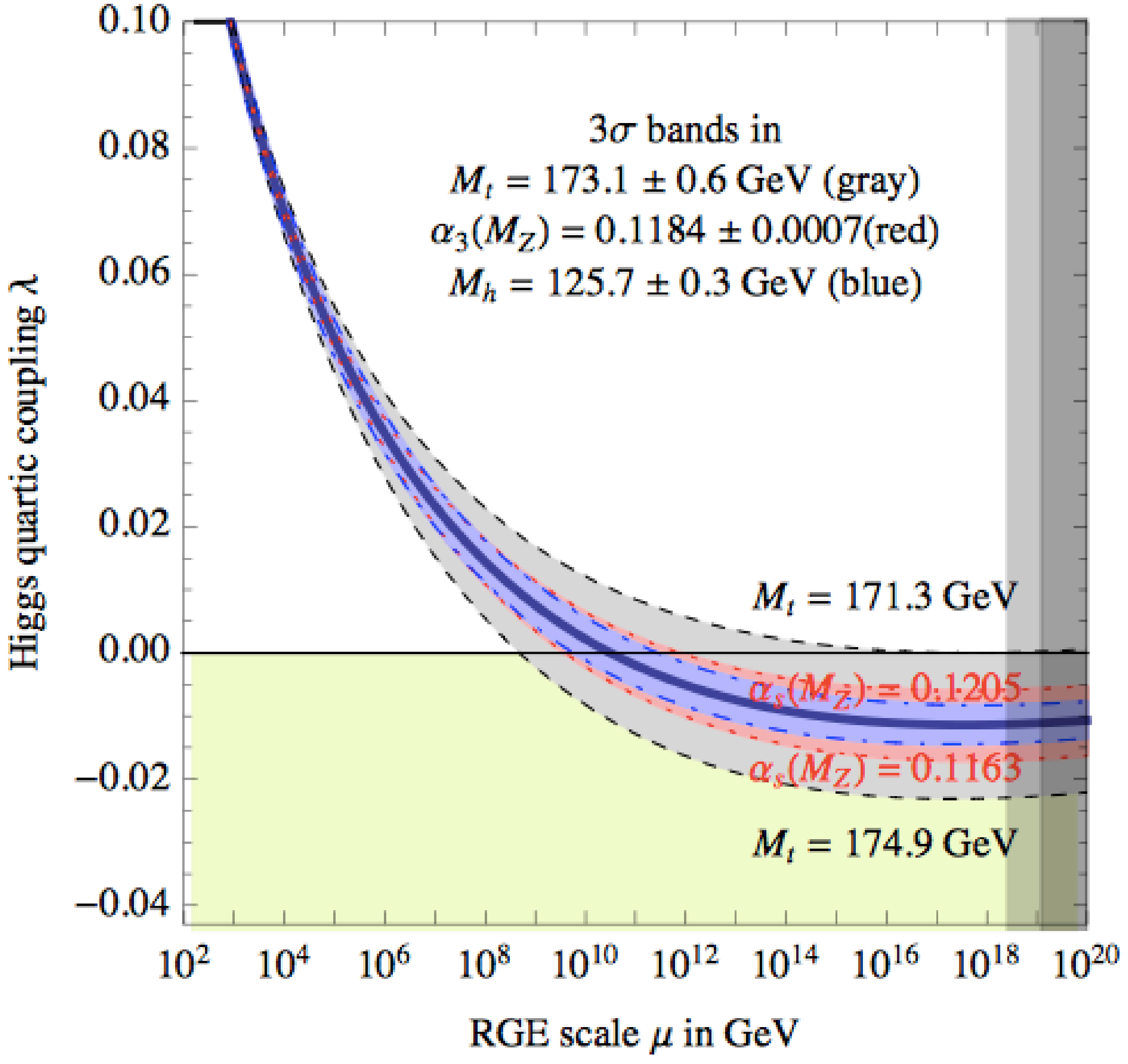


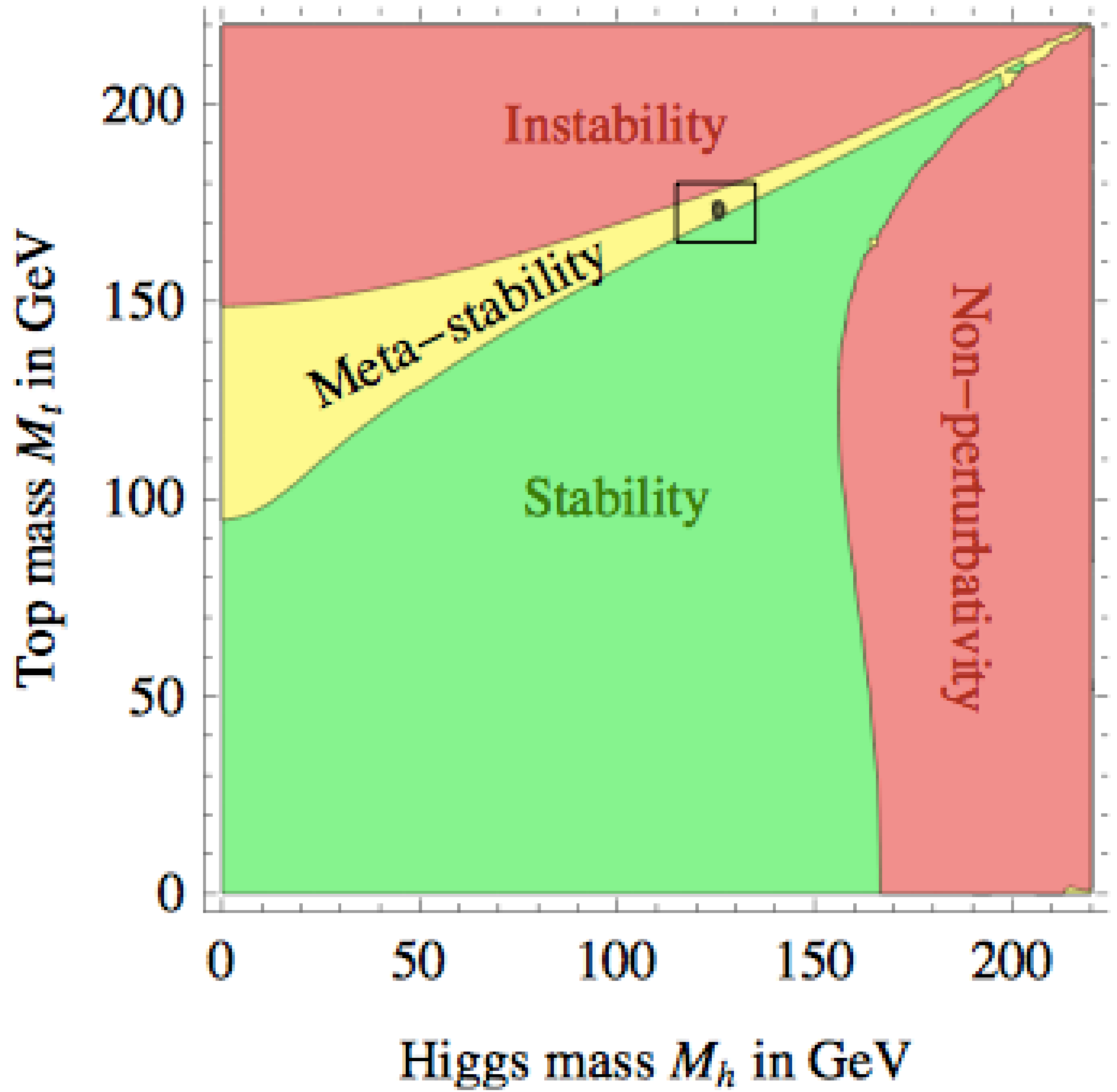
$$\Rightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4$$

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

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

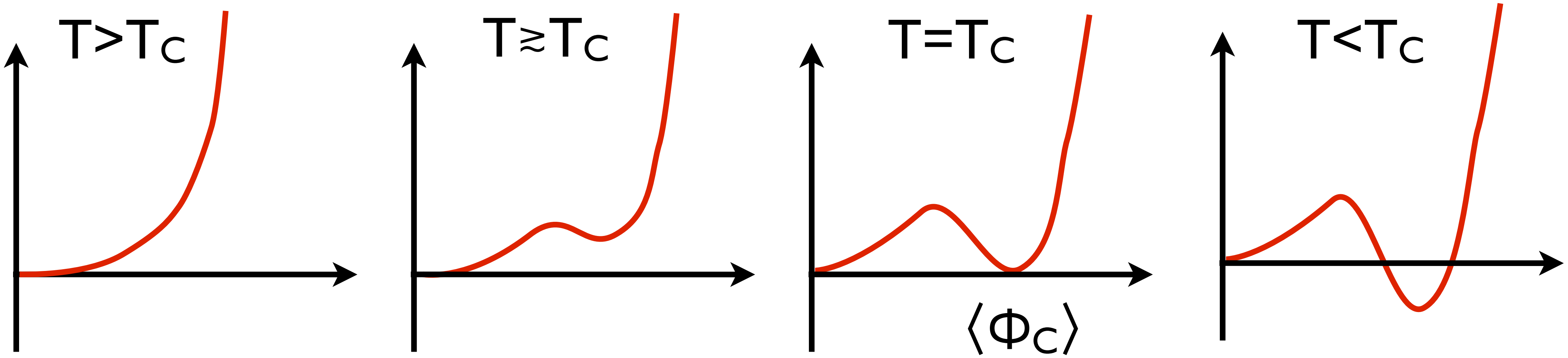
Degrassi et al, http://arxiv.org/pdf/1205.6497





The nature of the EW phase transition

Strong 1st order phase transition required to generate 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

Understanding the role of the EWPT in the evolution or generation of the baryon asymmetry of the Universe is a key target for the LHC and future accelerators

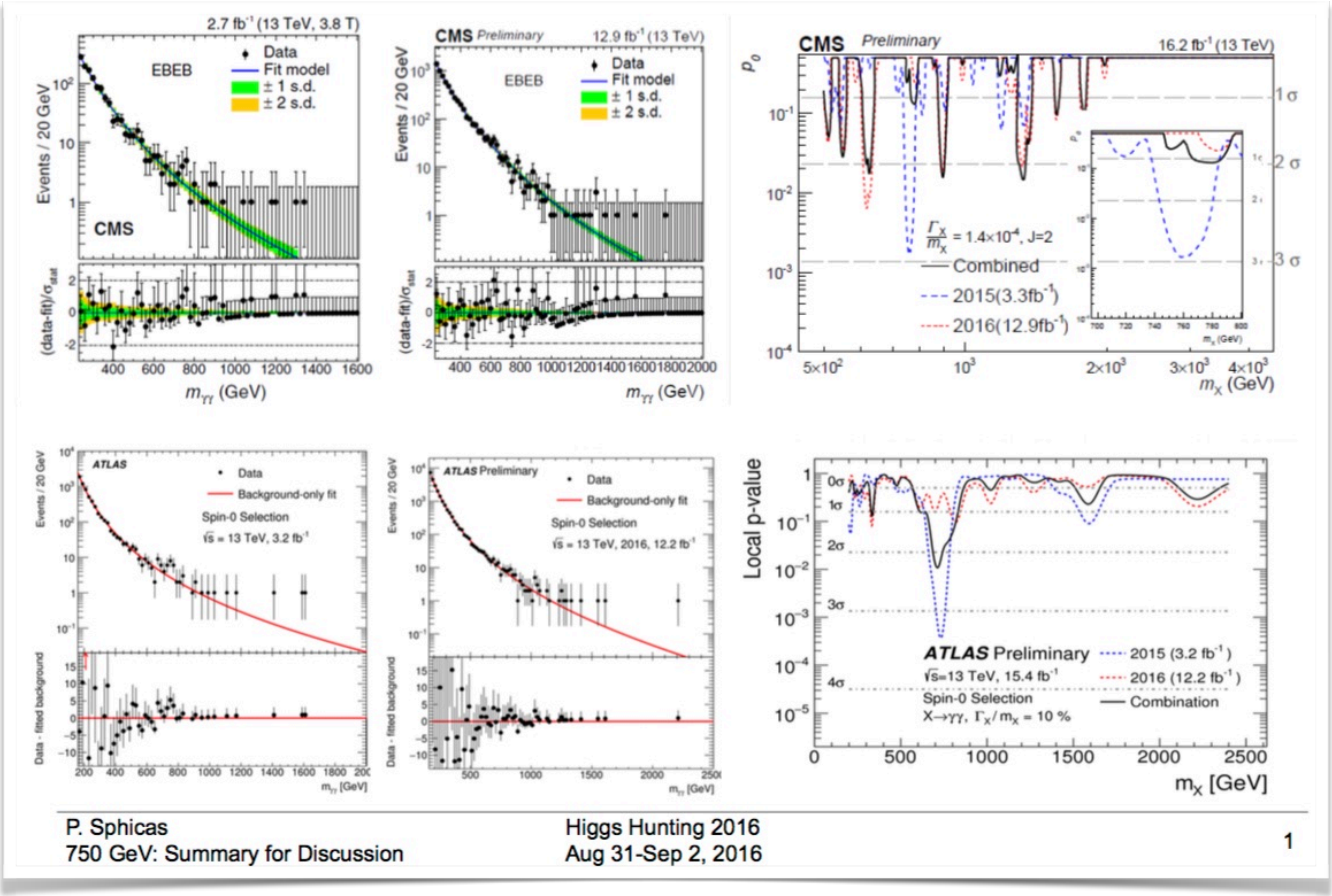
- Experimental probes:
    - study of triple-Higgs couplings (... and quadruple, etc)
    - search for components of an extended Higgs sector (e.g. 2HDM, extra singlets, ...)
    - search for new sources of CP violation, originating from (or affecting) Higgs interactions

Beyond the Higgs

The LHC experiments have been exploring a vast multitude of BSM scenarios

- **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 …**

750 GeV, Summer 2016



P. Sphicas
750 GeV: Summary for Discussion

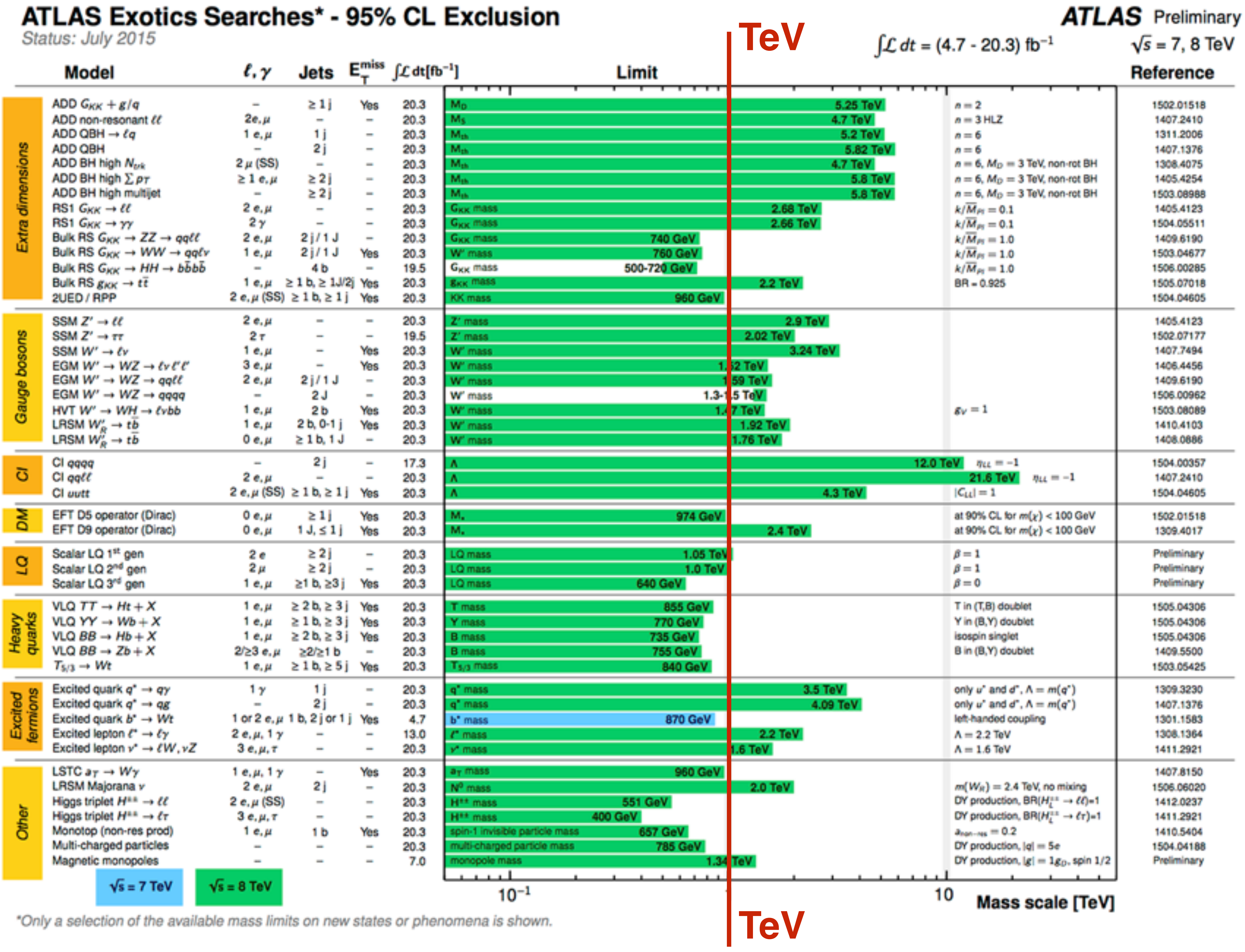
Higgs Hunting 2016
Aug 31-Sep 2, 2016

1

=> the resonant signal is not confirmed. But …

… little we know about the TeV scale!!

So far, no *conclusive* signal of physics beyond the SM



ATLAS Exotics Searches* - 95% CL Exclusion
Status: July 2015

ATLAS Preliminary
$\int\mathcal{L}\,dt = (4.7 - 20.3)\ \mathrm{fb}^{-1}$
$\sqrt{s}$ = 7, 8 TeV

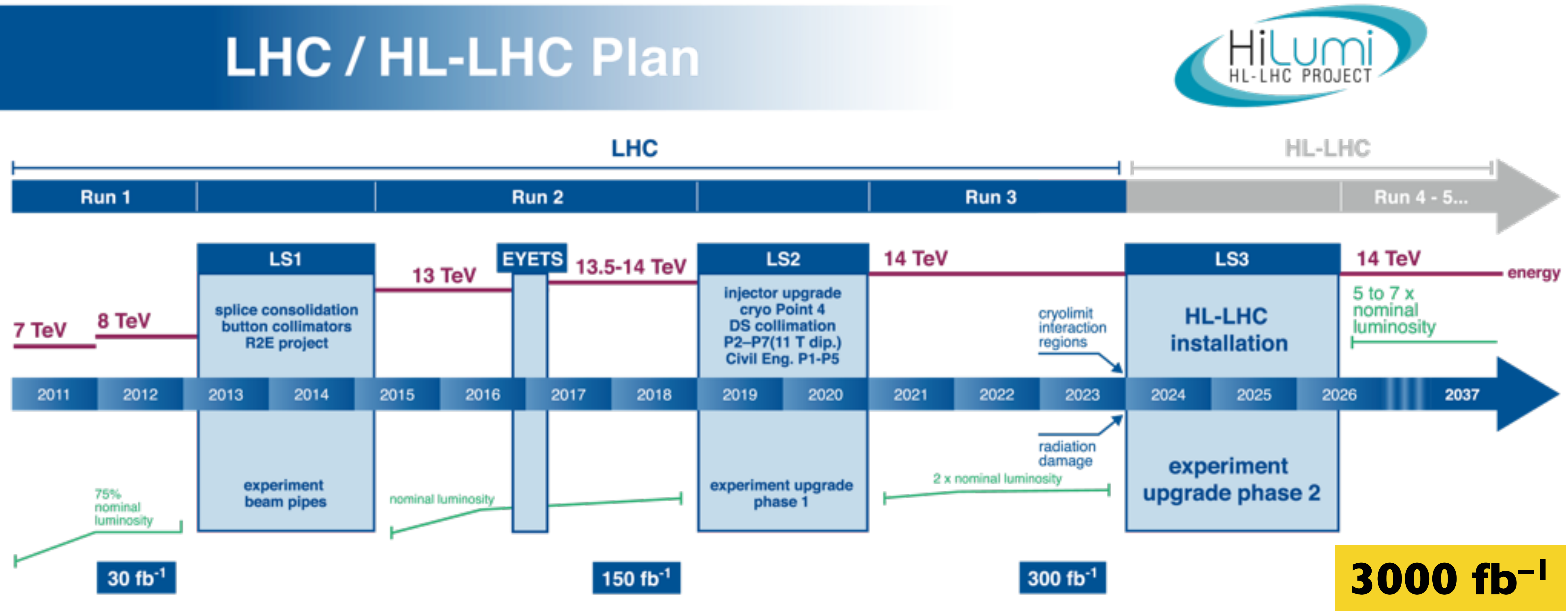
	Model	ℓ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK}+g/q$	–	≥ 1 j	Yes	20.3	M_D 5.25 TeV	$n=2$	1502.01518
	ADD non-resonant $\ell\ell$	2e,μ	–	–	20.3	M_S 4.7 TeV	$n=3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	1 e,μ	1 j	–	20.3	M_{th} 5.2 TeV	$n=6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n=6$	1407.1376
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	M_{th} 4.7 TeV	$n=6$, $M_D=3$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e,μ	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n=6$, $M_D=3$ TeV, non-rot BH	1405.4254
	ADD BH high multijet	–	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n=6$, $M_D=3$ TeV, non-rot BH	1503.08988
	RS1 $G_{KK}\to\ell\ell$	2 e,μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl}=0.1$	1405.4123
	RS1 $G_{KK}\to\gamma\gamma$	2 γ	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl}=0.1$	1504.05511
	Bulk RS $G_{KK}\to ZZ\to qq\ell\ell$	2 e,μ	2 j / 1 J	–	20.3	G_{KK} mass 740 GeV	$k/\overline{M}_{Pl}=1.0$	1409.6190
	Bulk RS $G_{KK}\to WW\to qq\ell\nu$	1 e,μ	2 j / 1 J	Yes	20.3	W' mass 760 GeV	$k/\overline{M}_{Pl}=1.0$	1503.04677
	Bulk RS $G_{KK}\to HH\to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 500-720 GeV	$k/\overline{M}_{Pl}=1.0$	1506.00285
	Bulk RS $g_{KK}\to t\bar{t}$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	2 e,μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	KK mass 960 GeV		1504.04605
Gauge bosons	SSM $Z'\to\ell\ell$	2 e,μ	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z'\to\tau\tau$	2 τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	SSM $W'\to\ell\nu$	1 e,μ	–	Yes	20.3	W' mass 3.24 TeV		1407.7494
	EGM $W'\to WZ\to\ell\nu\ell'\ell'$	3 e,μ	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W'\to WZ\to qq\ell\ell$	2 e,μ	2 j / 1 J	–	20.3	W' mass 1.59 TeV		1409.6190
	EGM $W'\to WZ\to qqqq$	–	2 J	–	20.3	W' mass 1.3-1.5 TeV		1506.00962
	HVT $W'\to WH\to\ell\nu bb$	1 e,μ	2 b	Yes	20.3	W' mass 1.47 TeV	$g_V=1$	1503.08089
	LRSM $W'_R\to t\bar{b}$	1 e,μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R\to t\bar{b}$	0 e,μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	17.3	Λ 12.0 TeV	$\eta_{LL}=-1$	1504.00357
	CI $qq\ell\ell$	2 e,μ	–	–	20.3	Λ 21.6 TeV	$\eta_{LL}=-1$	1407.2410
	CI $uutt$	2 e,μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.3 TeV	$\lvert C_{LL}\rvert=1$	1504.04605
DM	EFT D5 operator (Dirac)	0 e,μ	≥ 1 j	Yes	20.3	M_* 974 GeV	at 90% CL for $m(\chi)<100$ GeV	1502.01518
	EFT D9 operator (Dirac)	0 e,μ	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi)<100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	20.3	LQ mass 1.05 TeV	$\beta=1$	Preliminary
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	20.3	LQ mass 1.0 TeV	$\beta=1$	Preliminary
	Scalar LQ 3rd gen	1 e,μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta=0$	Preliminary
Heavy quarks	VLQ $TT\to Ht+X$	1 e,μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY\to Wb+X$	1 e,μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB\to Hb+X$	1 e,μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB\to Zb+X$	2/≥3 e,μ	≥2/≥1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	$T_{5/3}\to Wt$	1 e,μ	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		1503.05425
Excited fermions	Excited quark $q^*\to q\gamma$	1 γ	1 j	–	20.3	q* mass 3.5 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1309.3230
	Excited quark $q^*\to qg$	–	2 j	–	20.3	q* mass 4.09 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1407.1376
	Excited quark $b^*\to Wt$	1 or 2 e,μ	1 b, 2 j or 1 j	Yes	4.7	b* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^*\to\ell\gamma$	2 e,μ, 1 γ	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda=2.2$ TeV	1308.1364
	Excited lepton $\nu^*\to\ell W,\nu Z$	3 e,μ,τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda=1.6$ TeV	1411.2921
Other	LSTC $a_T\to W\gamma$	1 e,μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e,μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R)=2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm}\to\ell\ell$	2 e,μ (SS)	–	–	20.3	$H^{\pm\pm}$ mass 551 GeV	DY production, BR($H_L^{\pm\pm}\to\ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm}\to\ell\tau$	3 e,μ,τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm}\to\ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e,μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res}=0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert=5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert=1g_D$, spin 1/2	Preliminary

*Only a selection of the available mass limits on new states or phenomena is shown.

Beyond the limelight

- Incredibly reach flavour physics programme
  - precise measurements of CKM from charm/b decays
  - rare processes ($B_{d,s} \to \mu\mu$ decays, …)
  - BSM probes, e.g. decays anomalies or lepton flavour violation
- Thorough and extensive studies of QCD dynamics in non-perturbative regimes
  - exotic hadrons: tetra- and pentaquark spectroscopy, glueball searches via exclusive diffractive pp reactions, …
  - total, elastic and diffractive cross sections
  - hadron production in the fwd region (implications for modeling of cosmic-ray showers in the atmosphere)
  - collective phenomena in pp, pA and AA collisions (the "ridge" effect)
  - nuclear PDF determinations with the pA programme
  - heavy ion collisions, QGP

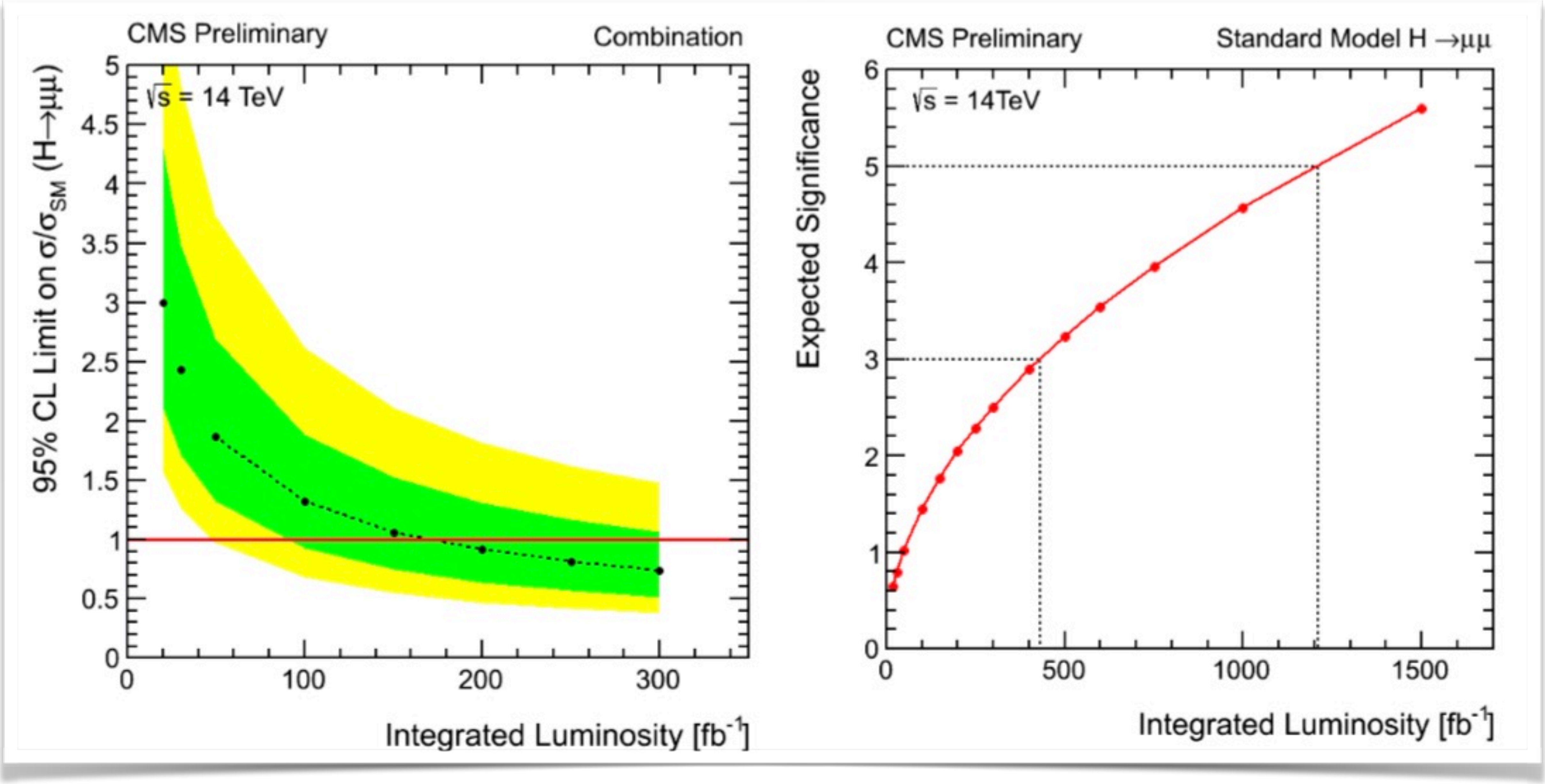
Long-term LHC plan



The 40fb^{-1} so far are just ~1% of the final statistics

==>> the LHC physics programme has barely started! <<==

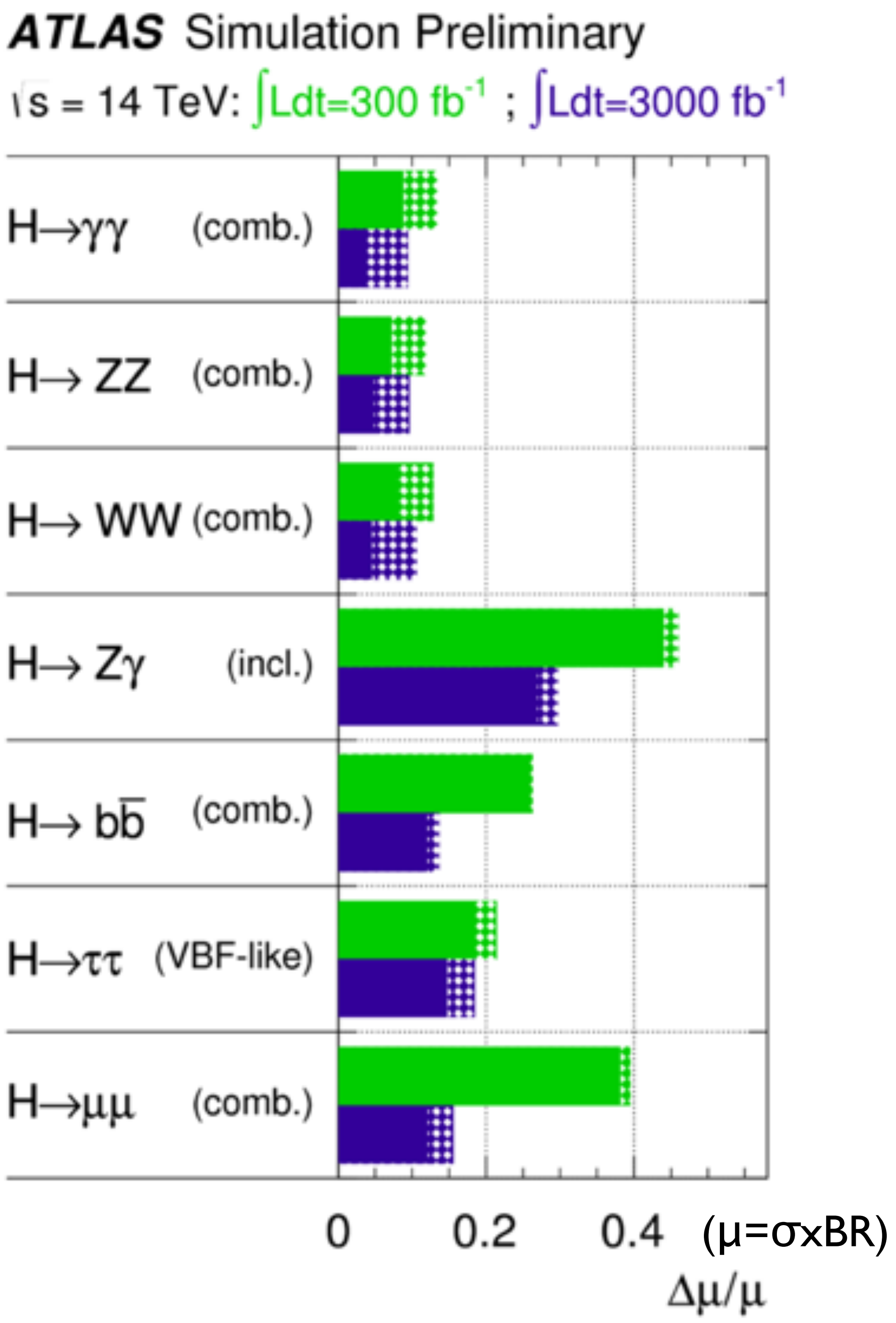
Projections for H couplings to 2^{nd} generation

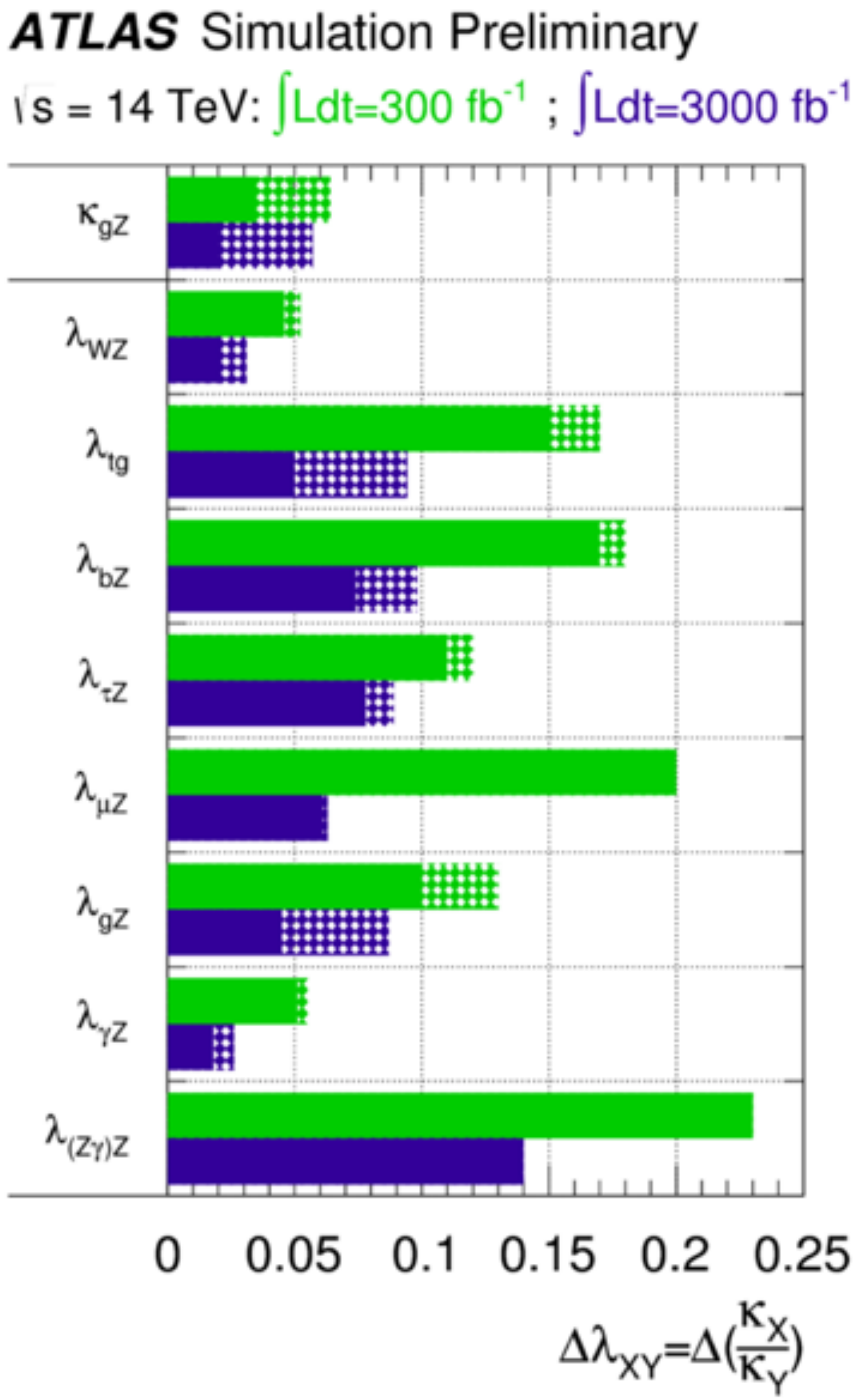


Projections from CMS-HIG-13-007

Projected precision on H couplings

ATL-PHYS-PUB-2014-016





solid areas: no TH systematics

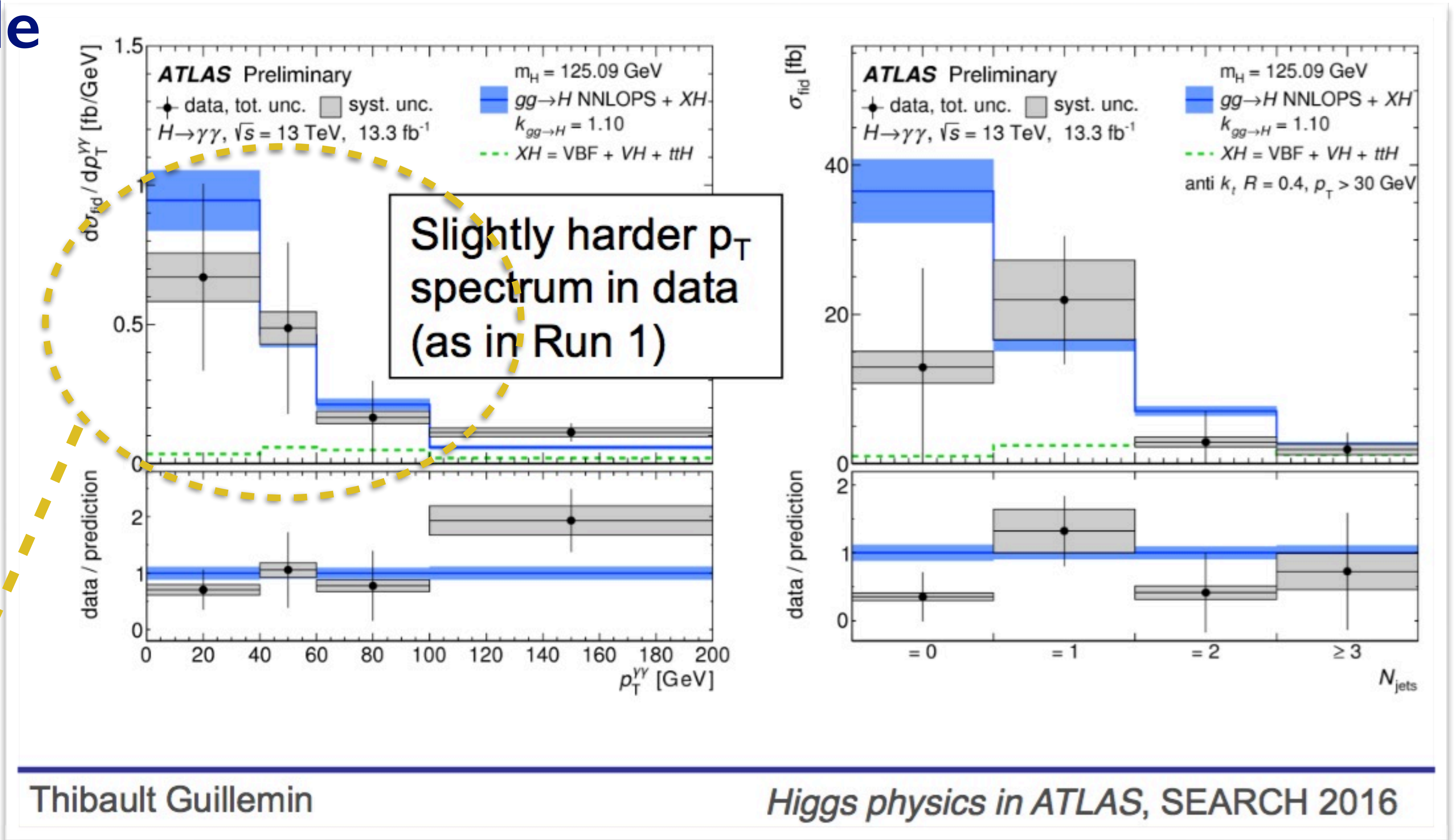
shaded areas: with TH systematics

Updates on the Higgs precision reach at HL-LHC were presented at the 2016 HL-LHC Workshop, Aix les Bains, Oct 4-7 2016:
(see V.Martin and M.Marono talks at
https://indico.cern.ch/event/524795/timetable/)

Current projections of future results are mostly extrapolations of today's analyses. Focus so far has been on exploring impact of higher luminosity and aging of detectors, to plan relevant upgrades and maintain or improve detector performance over the full LHC lifetime.

There is still plenty of room to design new analyses, exploiting in new ways the future huge statistics. Current projections should thus be seen as being likely rather conservative….

Example



Slightly harder p_T spectrum in data (as in Run 1)

Thibault Guillemin

Higgs physics in ATLAS, SEARCH 2016

- δstat ~ 5 δexp => ~25xL ~300fb^{-1} to equalize exp&stat uncert'y
- O(ab^{-1}) will provide an accurate, purely exptl determination of $p_T(H)$ in the theoretically delicate region 0-50 GeV, and strongly reduce/suppress th'l modeling systematics affecting other measurements (e.g. WW*)
- More in general, a global programme of higher-order calculations, data validation, MC improvements, PDF determinations, etc, will push further the TH precision….

Beyond the LHC

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

Today, the study of the physics potential of a future facility can at best document its performance, e.g. according to criteria such as:

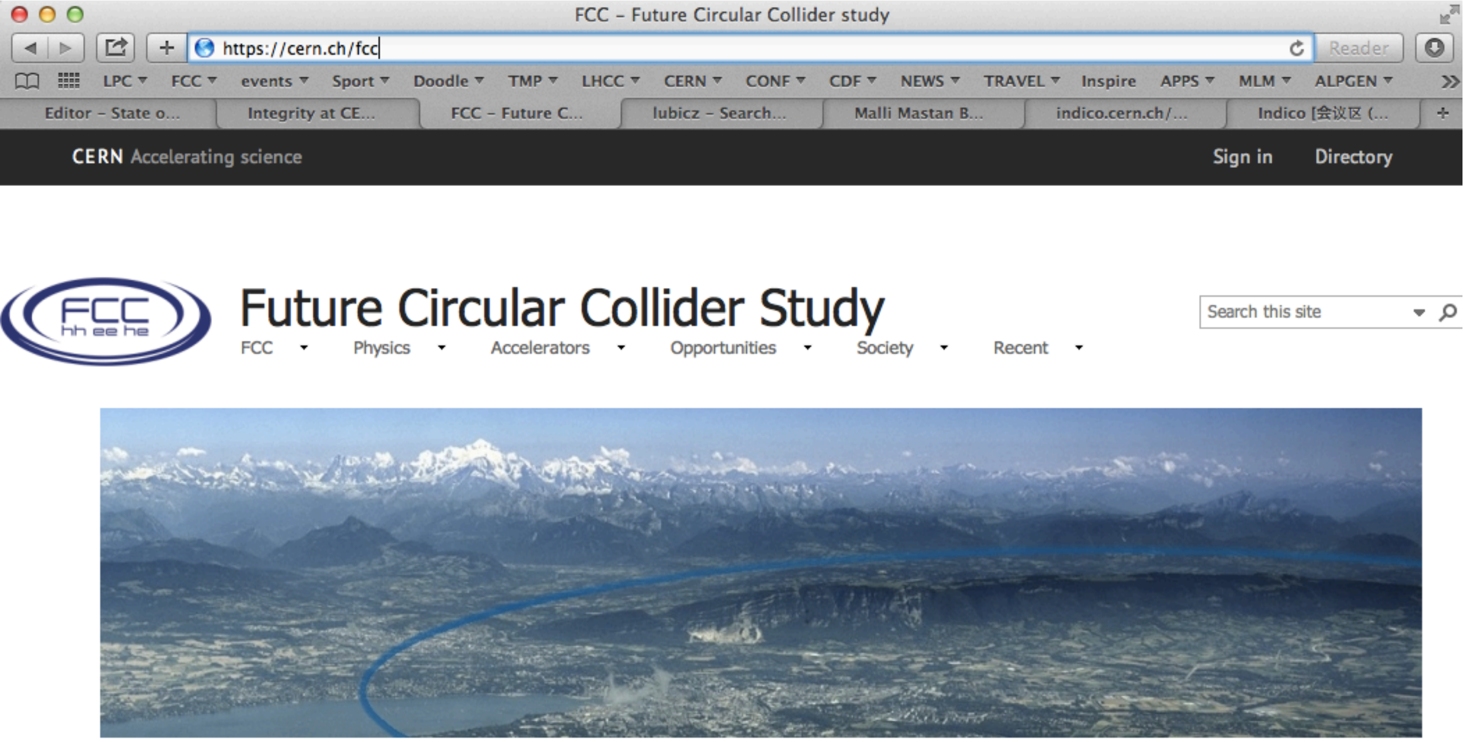
(1) the **guaranteed deliverables:**
- knowledge that will be acquired independently of possible discoveries (*the value of "measurements"*)

(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. E.g.
- *is DM a thermal WIMP?*
- *did baryogenesis take place during the EW phase transition?*
- *is there a TeV-scale solution to the hierarchy problem?*
- *are neutrinos Dirac or Majorana*
- …

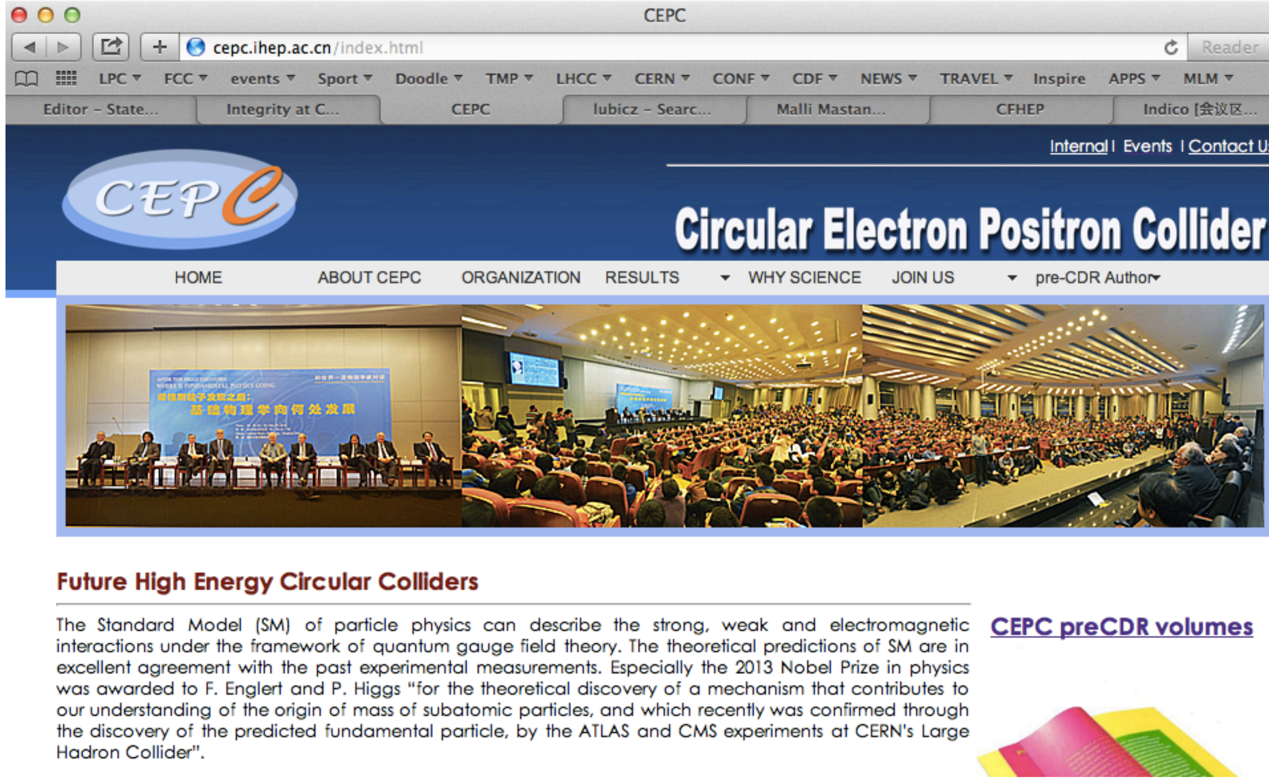
Future Circular Colliders

http://cern.ch/fcc



Future Circular Collider Study

http://cepc.ihep.ac.cn



Circular Electron Positron Collider

Future High Energy Circular Colliders

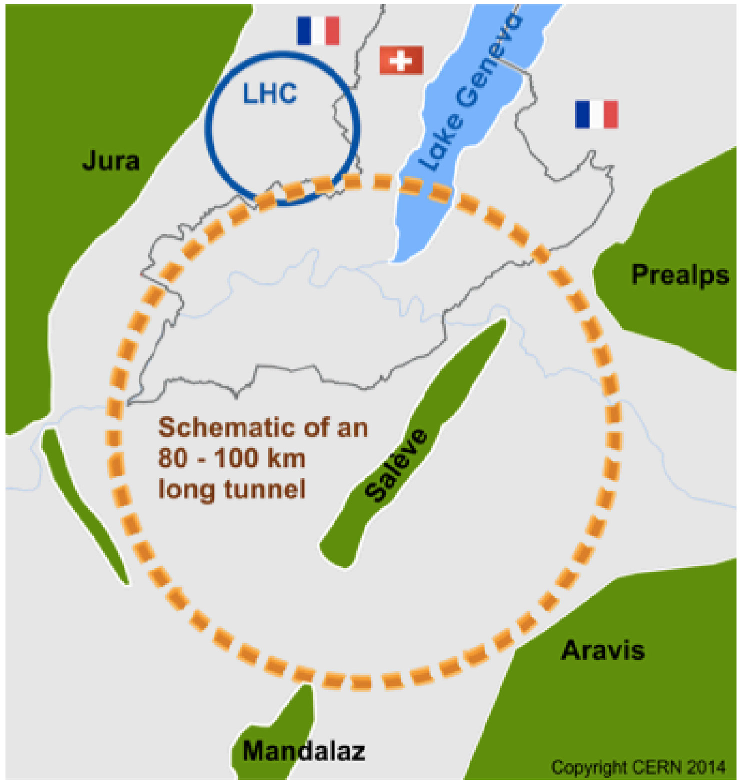
The Standard Model (SM) of particle physics can describe the strong, weak and electromagnetic interactions under the framework of quantum gauge field theory. The theoretical predictions of SM are in excellent agreement with the past experimental measurements. Especially the 2013 Nobel Prize in physics was awarded to F. Englert and P. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".

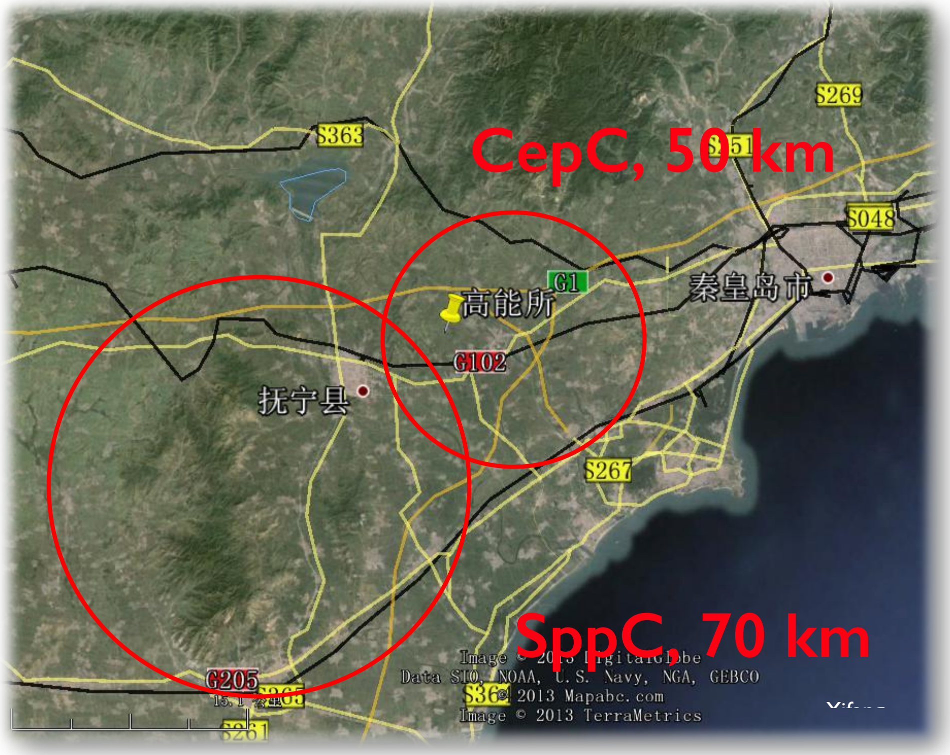
Forming an international collaboration to study:

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

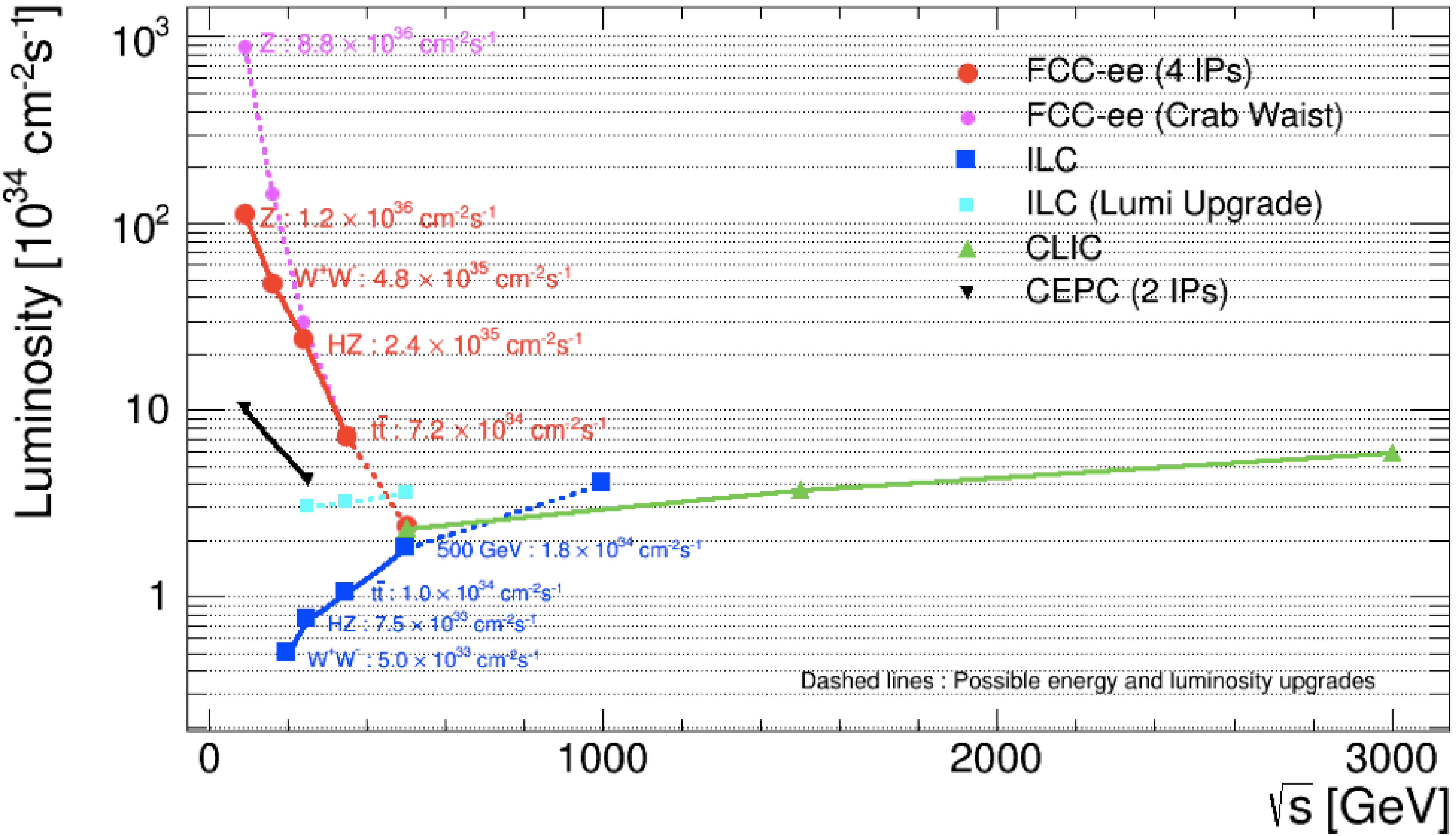
~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- ***e⁺e⁻* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area





FCC-ee energy and lum goals



FCC-hh parameters and lum goals

Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP$_{main}$ [cm^{-2}s^{-1}]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

- **Phase 1 (baseline): 5 x 10^{34} cm^{-2}s^{-1} (peak),**
  250 fb^{-1}/year (averaged)
  2500 fb^{-1} within 10 years (~HL LHC total luminosity)

- **Phase 2 (ultimate): ~2.5 x 10^{35} cm^{-2}s^{-1} (peak),**
  1000 fb^{-1}/year (averaged)
  ➔ 15,000 fb^{-1} within 15 years

- **Yielding total luminosity O(20,000) fb^{-1} over ~25 years of operation**

Focus on high-E pp colliders

- Guaranteed deliverables:
  - precision study of Higgs and top quark properties, and exploration of EWSB phenomena
  - *NB: outcome will be enhanced by synergy with results of an* e^+e^- *collider*

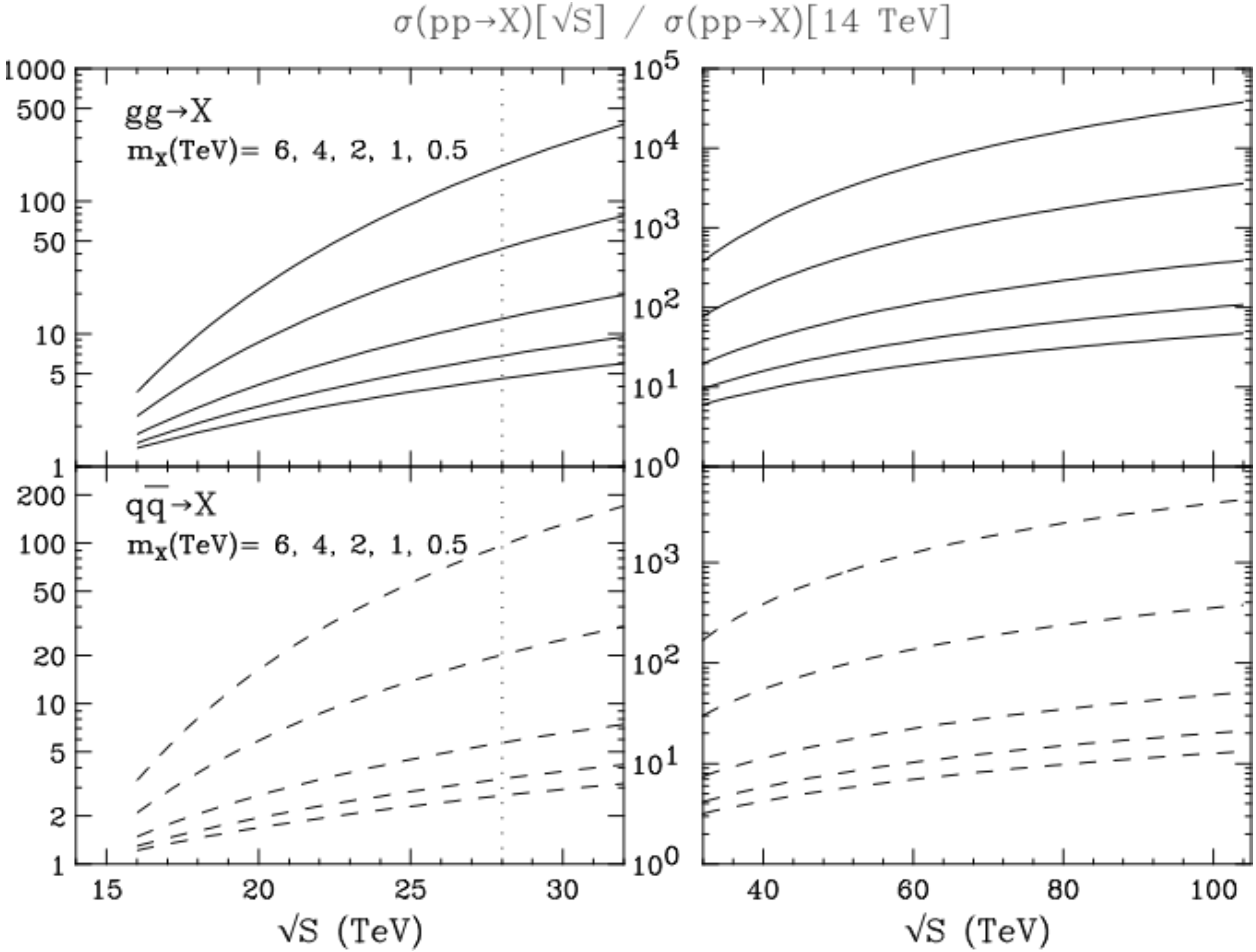
- Exploration potential:
  - mass reach enhanced by factor ~ E / 14 TeV (will be 5–7 at 100 TeV, depending on integrated luminosity)
  - statistics enhanced by several orders of magnitude for BSM phenomena brought to light by the LHC

- Possible Yes/No answers:
  - ~100 TeV needed to fully address questions tied to the TeV scale (e.g. WIMPs, EW Baryogenesis, TeV-scale naturalness)

- The weight of each item in the previous list depends on
  - the evolution of theoretical thinking, model building
  - the outcome of the LHC
  - the outcome of the full experimental landscape
    - flavour physics: at LHC, K & B factories, leptonic sector, g–2, EDMs, neutrinos
    - DM: direct and indirect searches, cosmological studies (*eg. is DM strongly selfinteracting?*)
    - Searches for axions, ALPs, dark photons, ...
    - ....

- Future developments in any of the points above will allow to sharpen and focus the assessment of the role of future pp colliders

Example: possible E evolution 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 ≳ $2m_X$ (⇒ *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.

Our 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...

Reference literature

- **FCC-ee**:
  - "First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164
  - "High-precision αs measurements from LHC to FCC-ee", arXiv:1512.05194
- **FCC-eh**: no document as yet, see however
  - "A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector", J.Phys. G39 (2012) 075001
- **FCC-hh**: ***"Physics at 100 TeV"***, Report, 5 chapters:
  - SM processes, arXiv:1607.01831
  - Higgs and EWSB studies, arXiv:1606.09408
  - BSM phenomena, arXiv:1606.00947
  - Heavy Ions at the FCC, arXiv:1605.01389
  - Physics opportunities with the FCC injectors, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

~700 pages

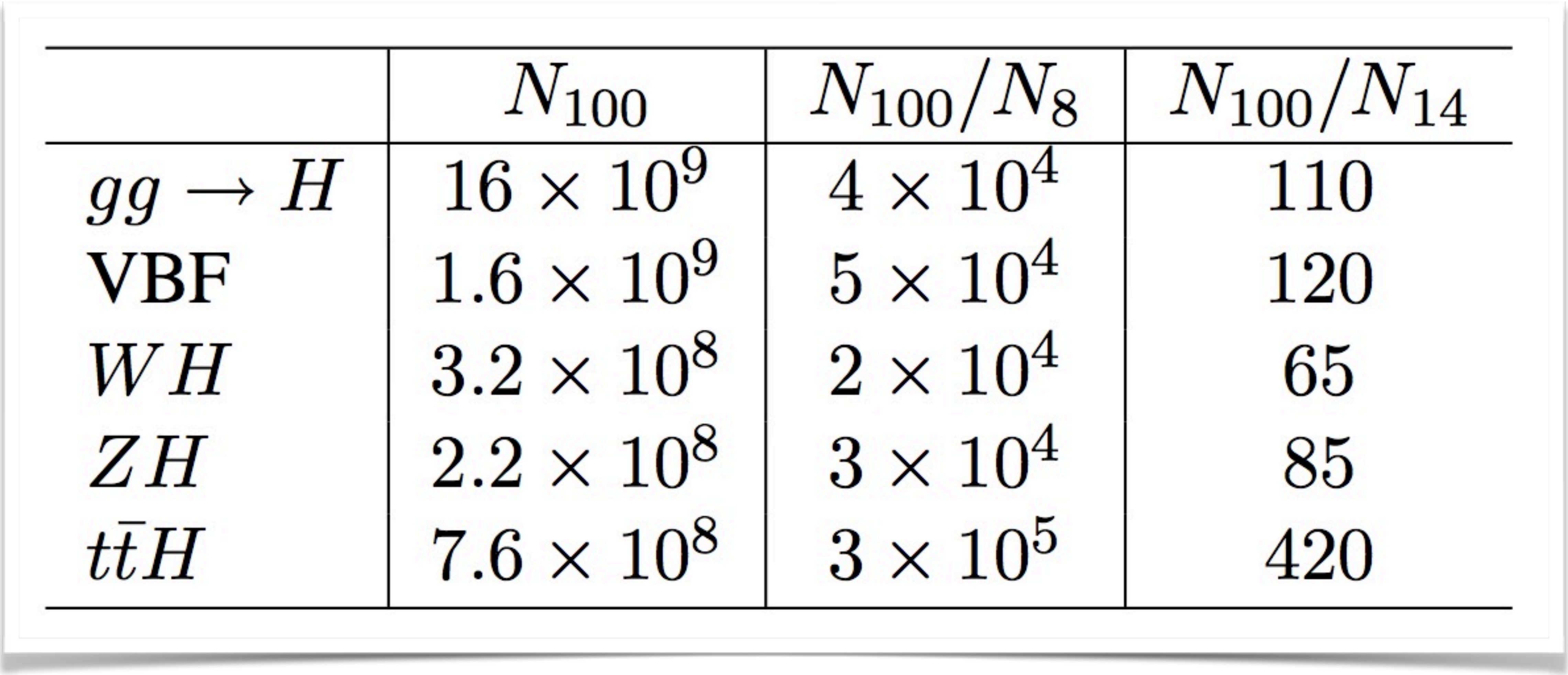
- **CEPC/SPPC**: Physics and Detectors pre-CDR completed, see:
  - http://cepc.ihep.ac.cn/preCDR/volume.html

See also:

- Physics Briefing Book to the European Strategy Group (ESG 2013)
- Planning the Future of U.S. Particle Physics (Snowmass 2013): Chapter 3: Energy Frontier, arXiv:1401.6081
- N. Arkani-Hamed, T. Han, M. Mangano, and L.-T. Wang, Physics Opportunities of a 100 TeV pp Collider, arXiv:1511.06495

Examples of the physics potential of the 100 TeV collider

SM Higgs 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

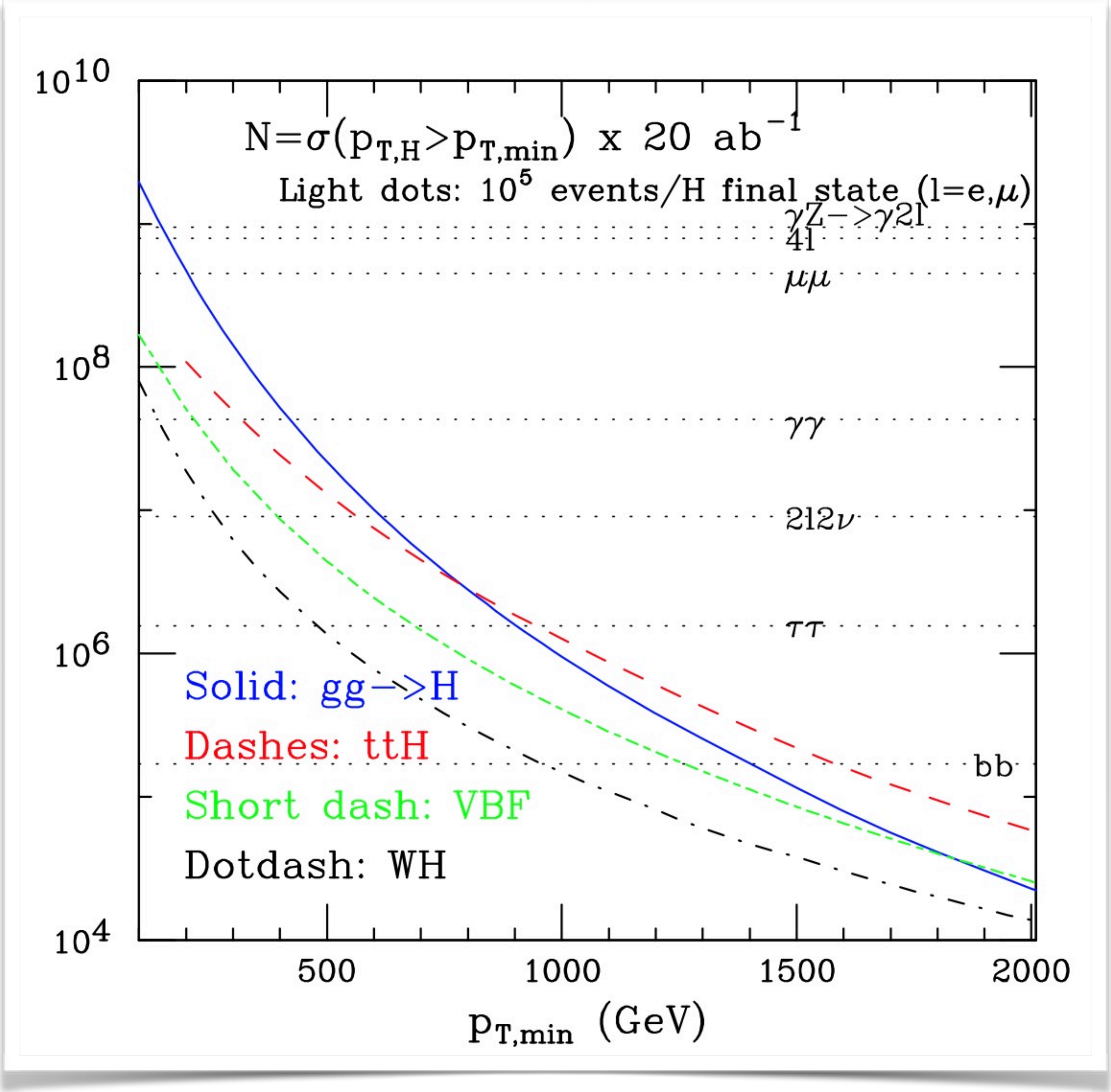
$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 20\ \mathrm{ab}^{-1}$

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

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

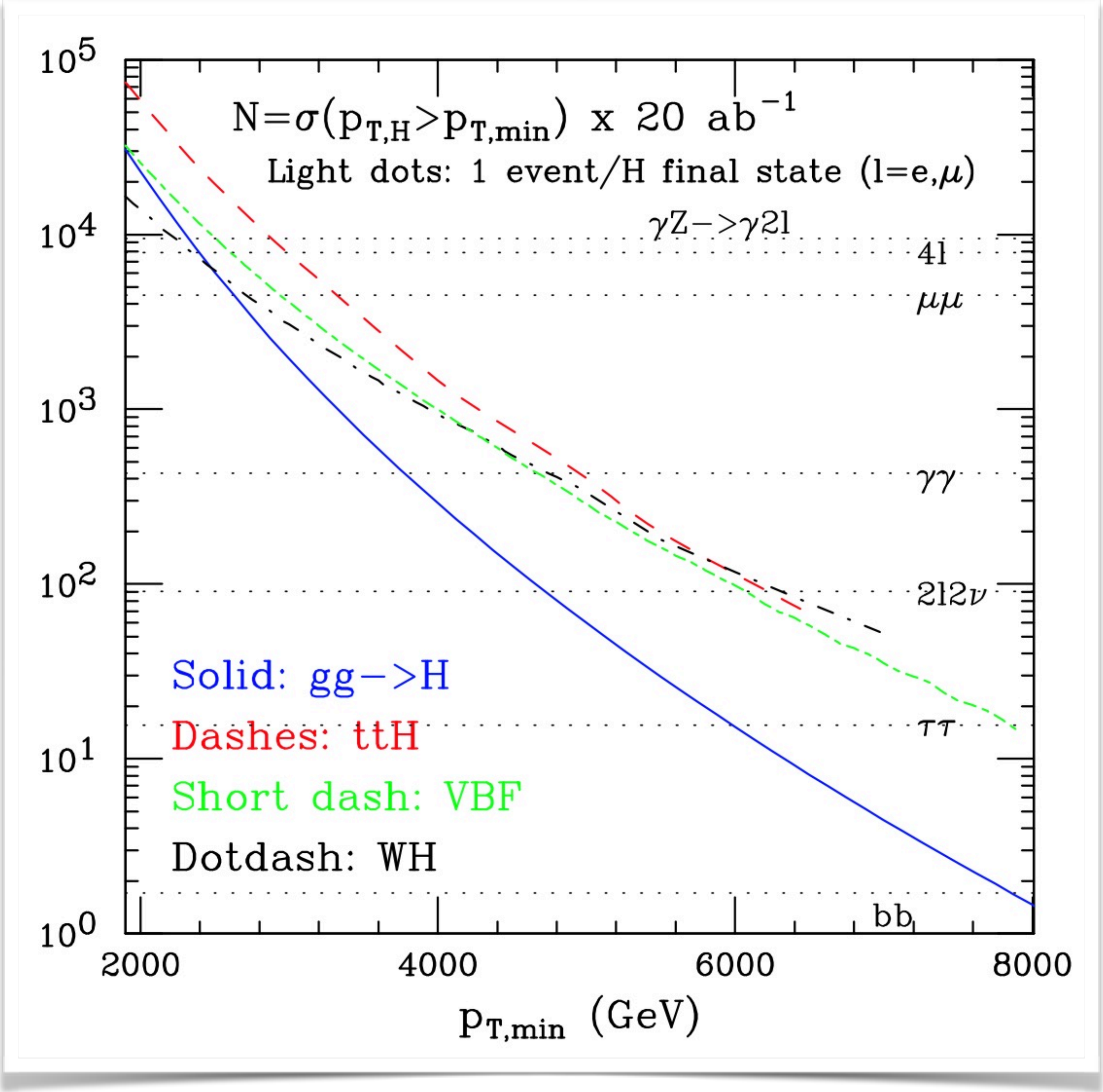
- Huge production rates imply:
  - can afford reducing statistics, with tighter kinematical cuts that reduce backgrounds and systematics
  - can explore new dynamical regimes, where new tests of the SM and EWSB can be done

H at large p_T



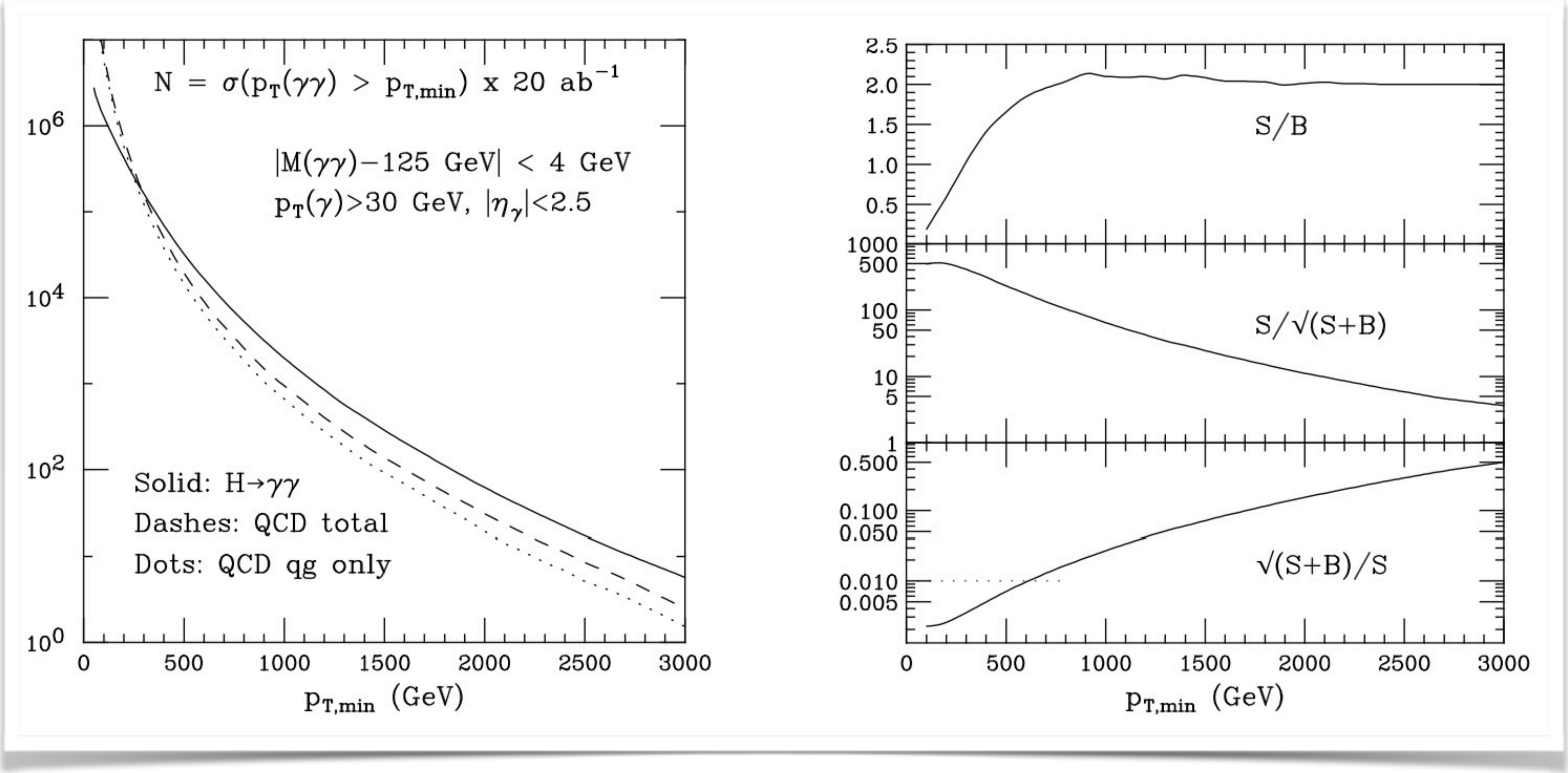
- Hierarchy of production channels changes at large $p_T(H)$:
  - σ(ttH) > σ(gg→H) above 800 GeV
  - σ(VBF) > σ(gg→H) above 1800 GeV

H at large p_T



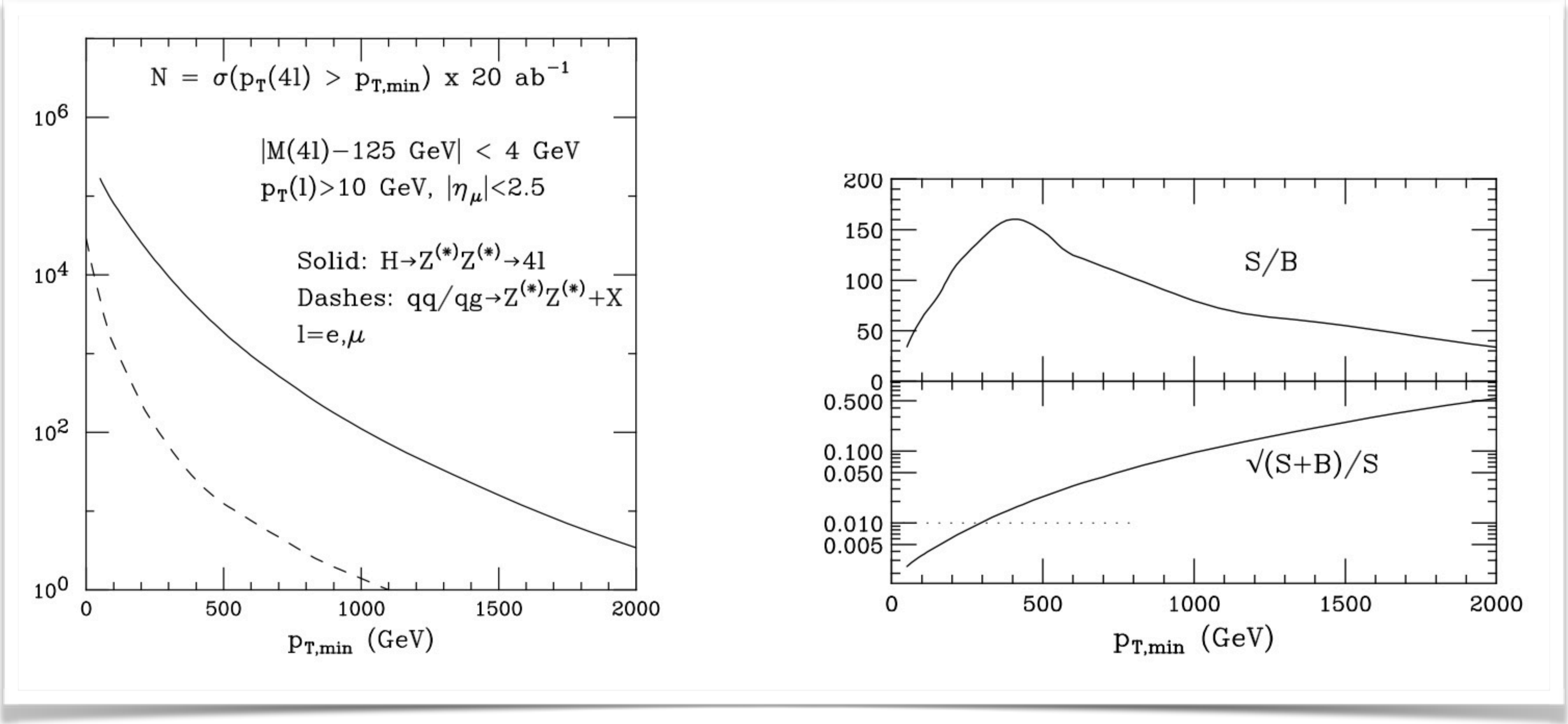
- Statistics in potentially visible final states out to several TeV

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
- Very clean probe of Higgs production up to large $p_T(H)$.
  - What's the sensitivity required to probe relevant BSM deviations from SM spectrum?
  - Exptl mass resolution at large pt(H)?

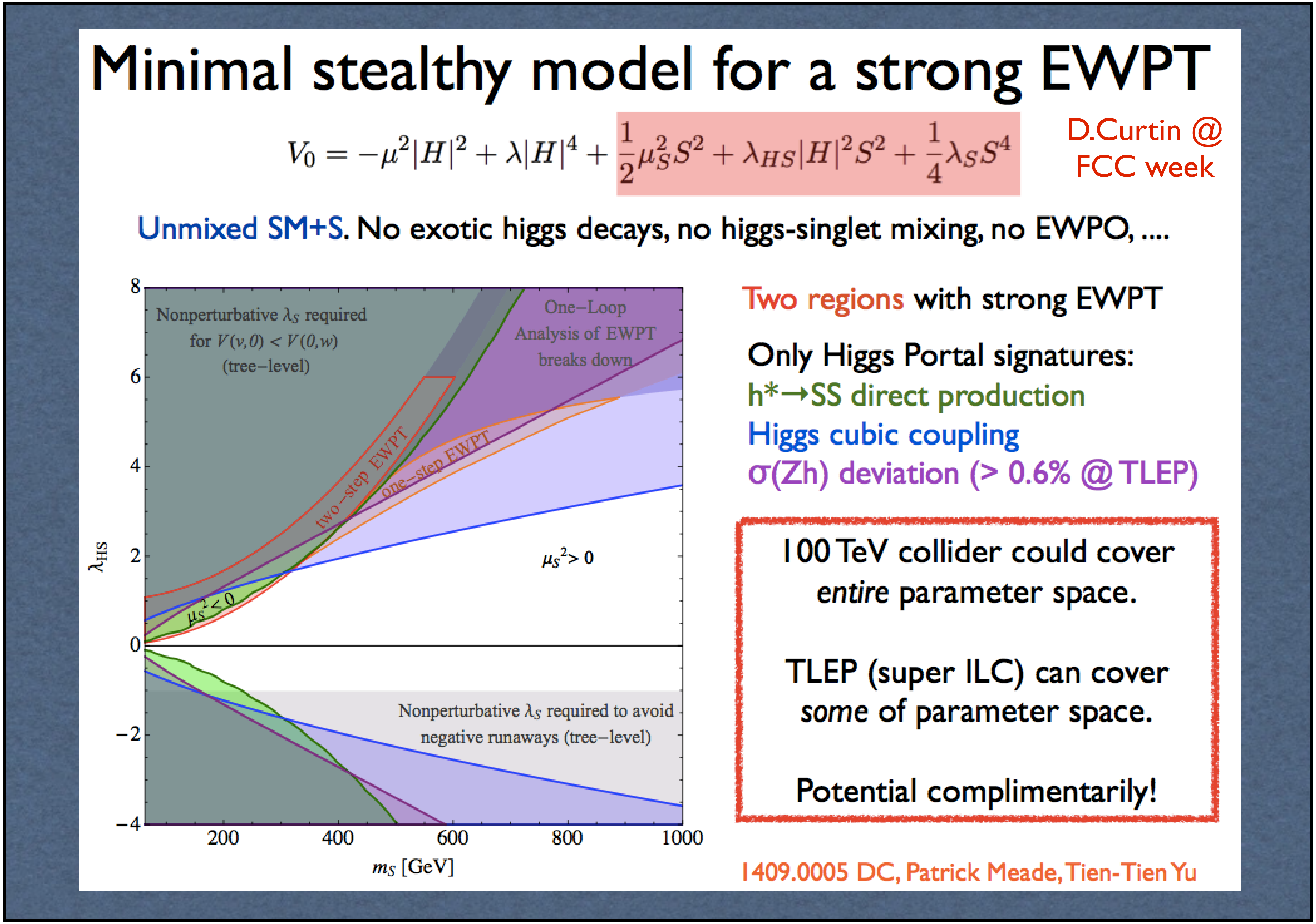
gg→H→4 *lept's* at large p_T



- Statistics sufficient for a per-mille level measurement of B(H→γγ)/B(H→4ℓ)
  - exptl systematics??
- Use precise B(H→4ℓ) from FCC-ee to achieve per-mille precision on B(H→γγ)

Summary of Higgs precision reach at FCC-hh

- (sub)-% precision in (ratios of) BRs to WW, ZZ, γγ, γZ
- ~% level for y_{top} from ttH and for H->μμ
- ≲5% precision for SM H selfcoupling λ



Minimal stealthy model for a strong EWPT

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

D.Curtin @
FCC week

Unmixed SM+S. No exotic higgs decays, no higgs-singlet 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)

100 TeV collider could cover *entire* parameter space.

TLEP (super ILC) can cover *some* of parameter space.

Potential complimentarily!

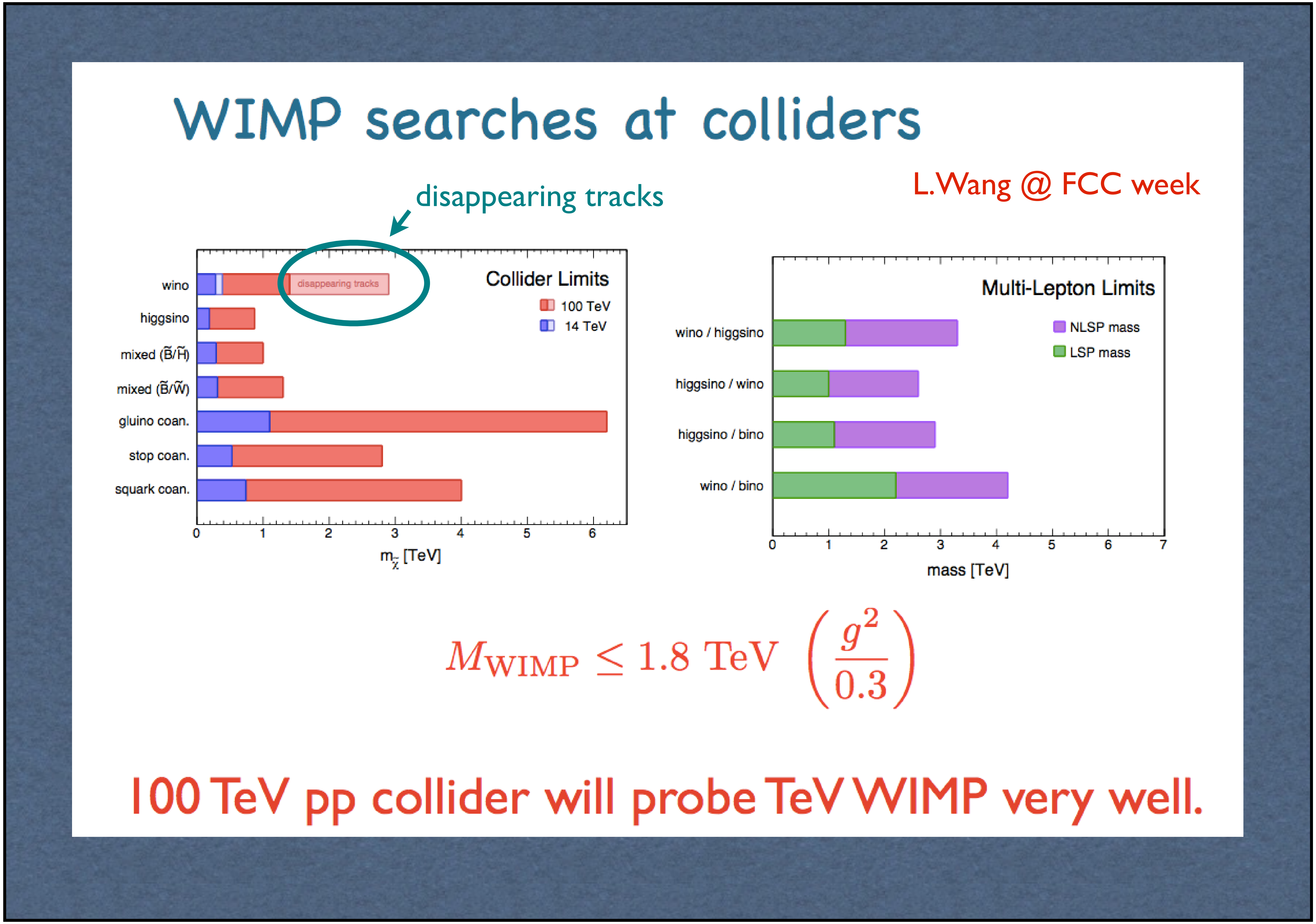
1409.0005 DC, Patrick Meade, Tien-Tien Yu

⇒ Appearance of first “**no-lose**” arguments for classes of compelling scenarios of new physics

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?
  - what are the opportunities w.r.t. new DM scenarios (e.g. interacting DM, asymmetric DM, ...)?

Towards no-lose arguments for some Dark Matter scenarios:



WIMP searches at colliders

disappearing tracks

L.Wang @ FCC week

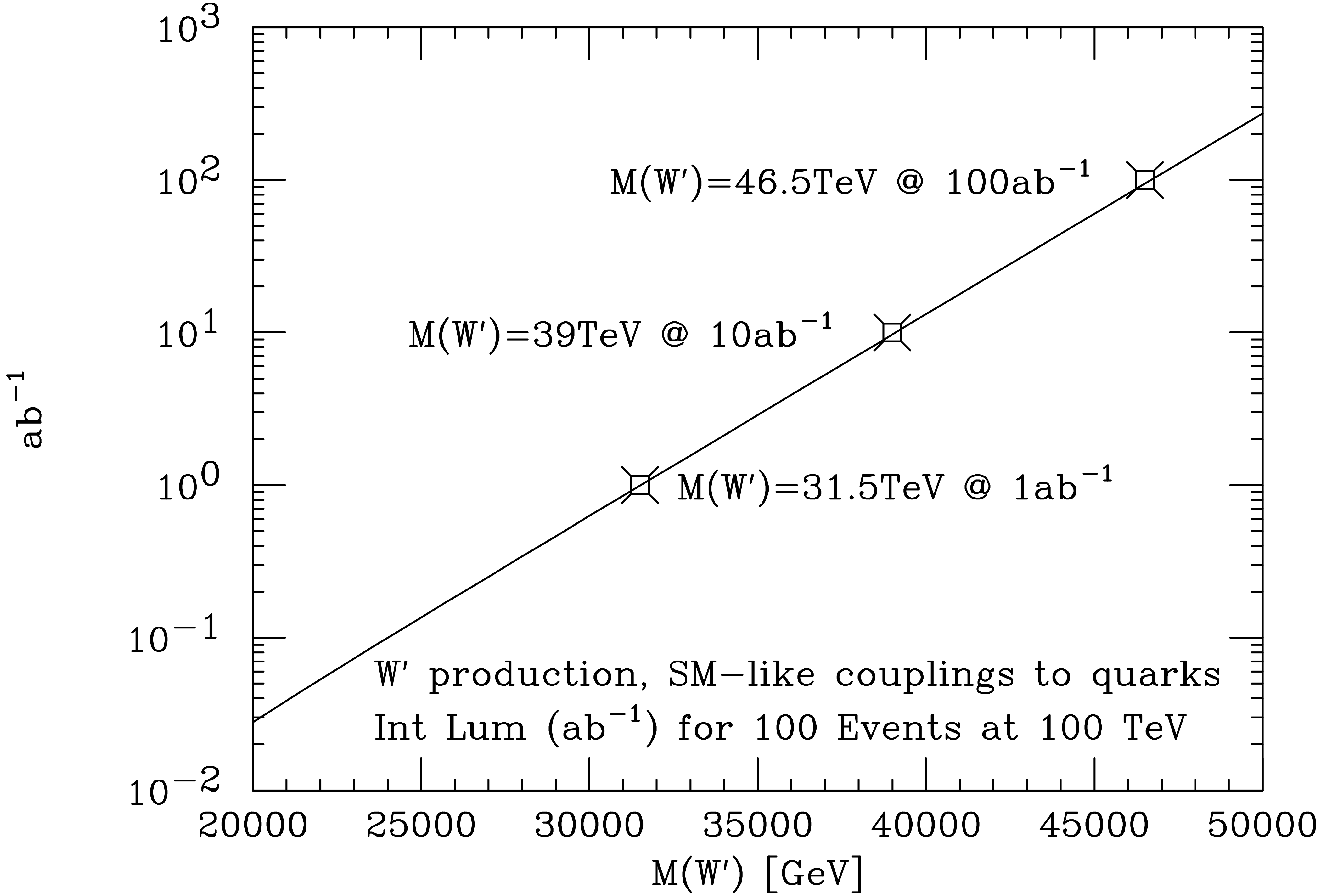
$$M_{\mathrm{WIMP}} \leq 1.8\ \mathrm{TeV}\ \left(\frac{g^2}{0.3}\right)$$

100 TeV pp collider will probe TeV WIMP very well.

New gauge bosons discovery reach

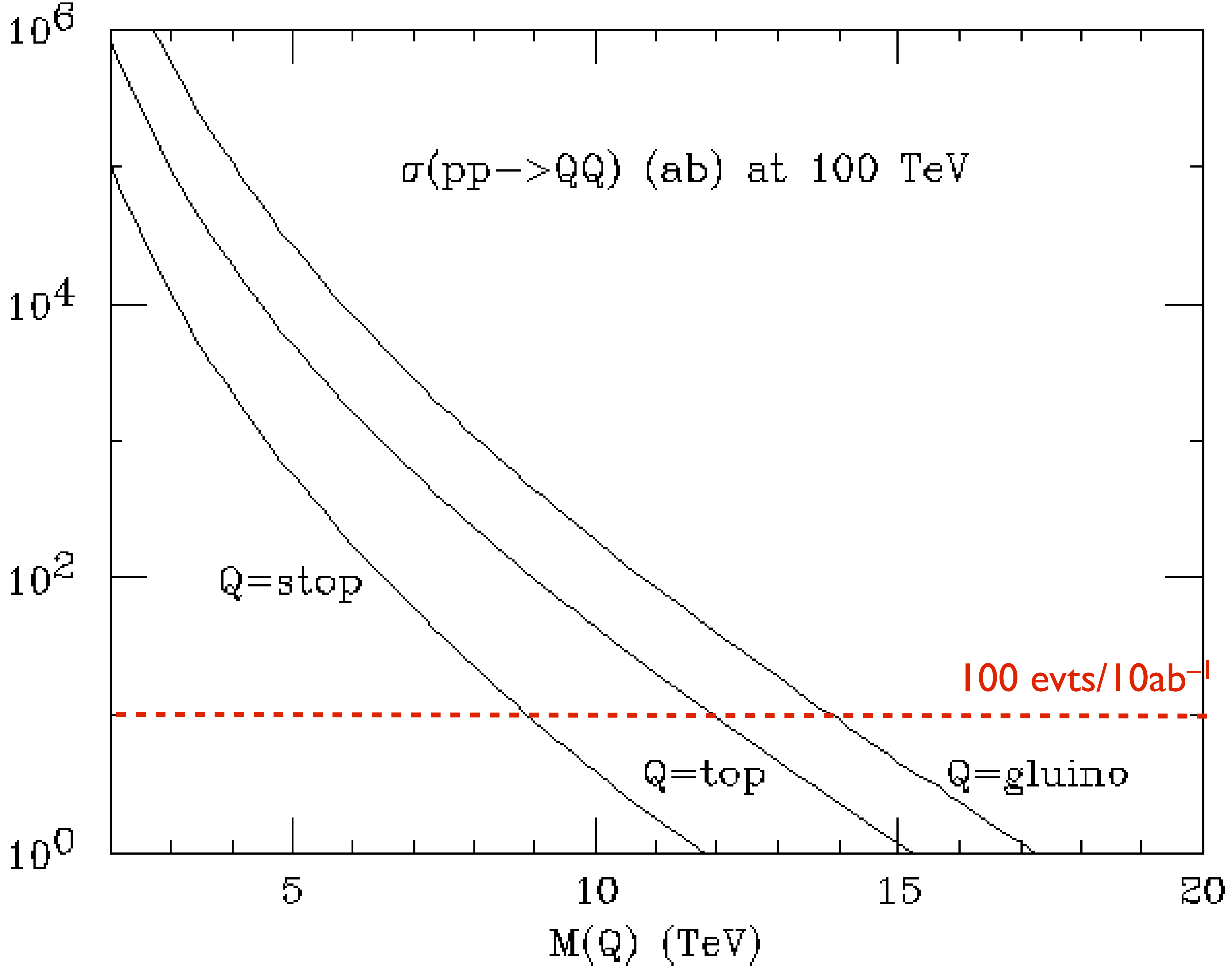
Example: **W' with SM-like couplings**

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

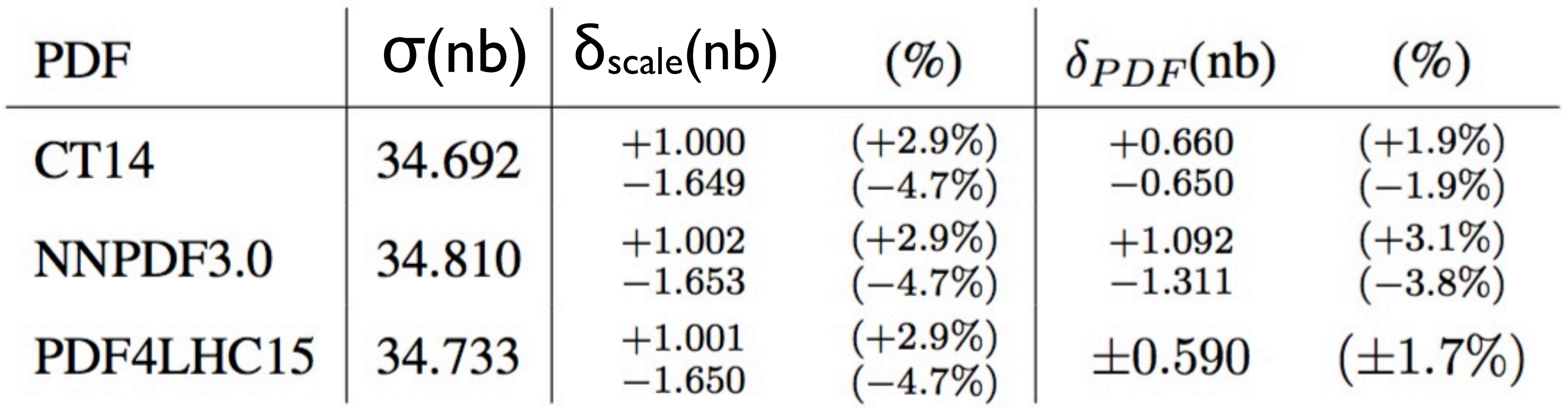


At L=O(ab^{-1}), Lum x 10 ⇒ ~ M + 7 TeV

Discovery reach for pair production of strongly-interacting particles



Top quark production



PDF	σ(nb)	δ_{scale}(nb)	(%)	δ_{PDF}(nb)	(%)
CT14	34.692	$+1.000$ -1.649	$(+2.9\%)$ (-4.7%)	$+0.660$ -0.650	$(+1.9\%)$ (-1.9%)
NNPDF3.0	34.810	$+1.002$ -1.653	$(+2.9\%)$ (-4.7%)	$+1.092$ -1.311	$(+3.1\%)$ (-3.8%)
PDF4LHC15	34.733	$+1.001$ -1.650	$(+2.9\%)$ (-4.7%)	± 0.590	$(\pm 1.7\%)$

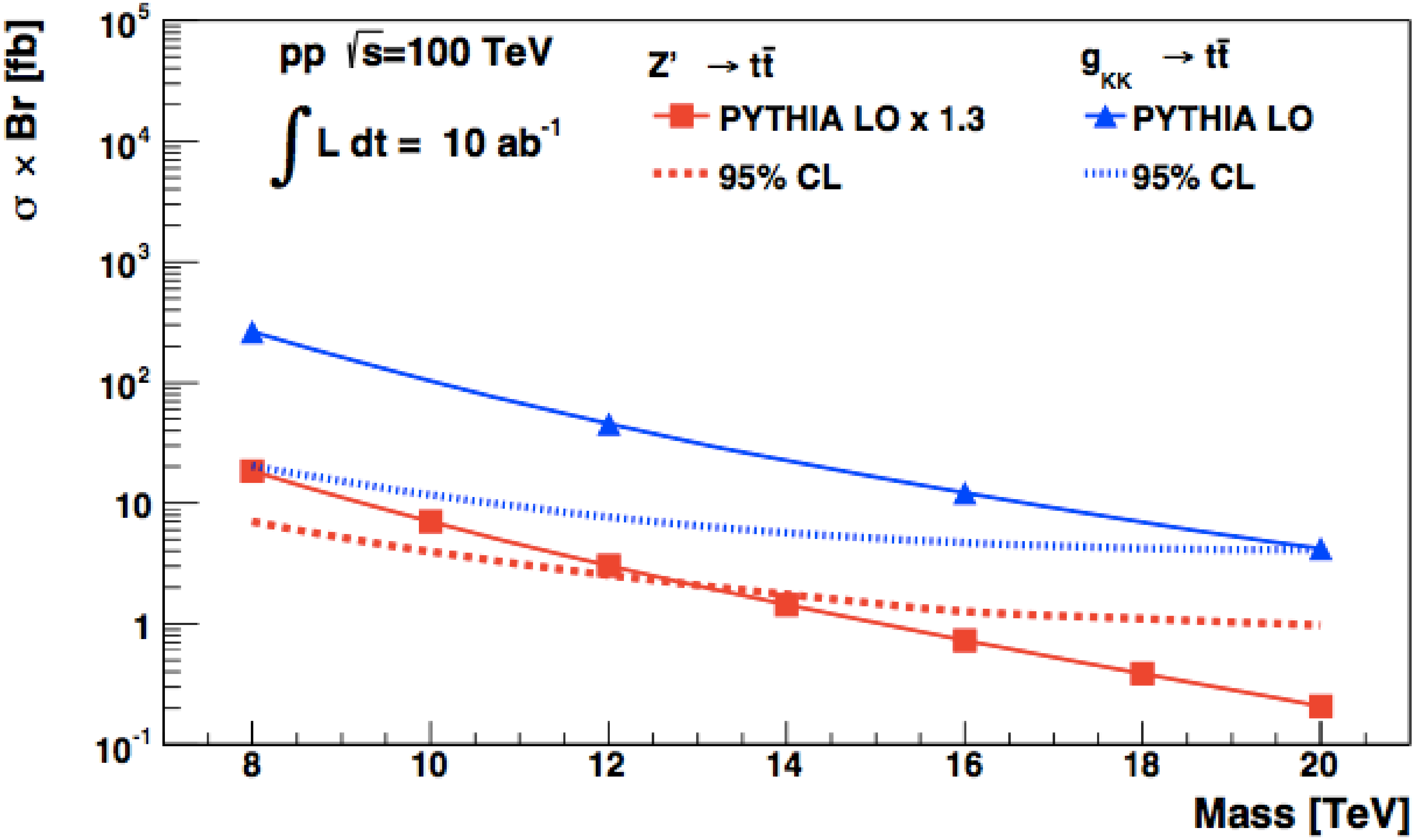
$\sigma_{tot}(100\ \text{TeV}) \sim 35 \times \sigma_{tot}(14\ \text{TeV})$

- ⇒ about 10^{12} top quarks produced in 20 ab^{-1}
  - rare and forbidden top decays
  - 10^{12} fully inclusive W decays, triggerable by "the other W"
    - rare and forbidden W decays
    - 3 10^{11} W→charm decays
    - 10^{11} W→tau decays (*)
  - 10^{12} fully charge-tagged b hadrons

(*) NB: From LEP2 BR(W->τ) / BR(W->e/μ) ~ 1.066 ± 0.025 => ~ 2.5 σ off ….

Sensitivity to ttbar resonances

Auerbach, Chekanov, Proudfoot, Kotwal, arXiv:1412.5951



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. The full LHC programme, and a following FCC-like facility, will be required to complete this exploration
- The BSM-search programme at the LHC is more than a 1-experiment/1-measurement deal. It features hundreds of stand-alone individual measurements of separate probes, it's the most complete and reaching enterprise available today and in the near future to explore in depth physics at the TeV scale with an immense discovery potential and still ample room for progress
- As a possible complement to the mature ILC and CLIC projects, plans are underway to define the possible continuation of this programme after the LHC, 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 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.