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

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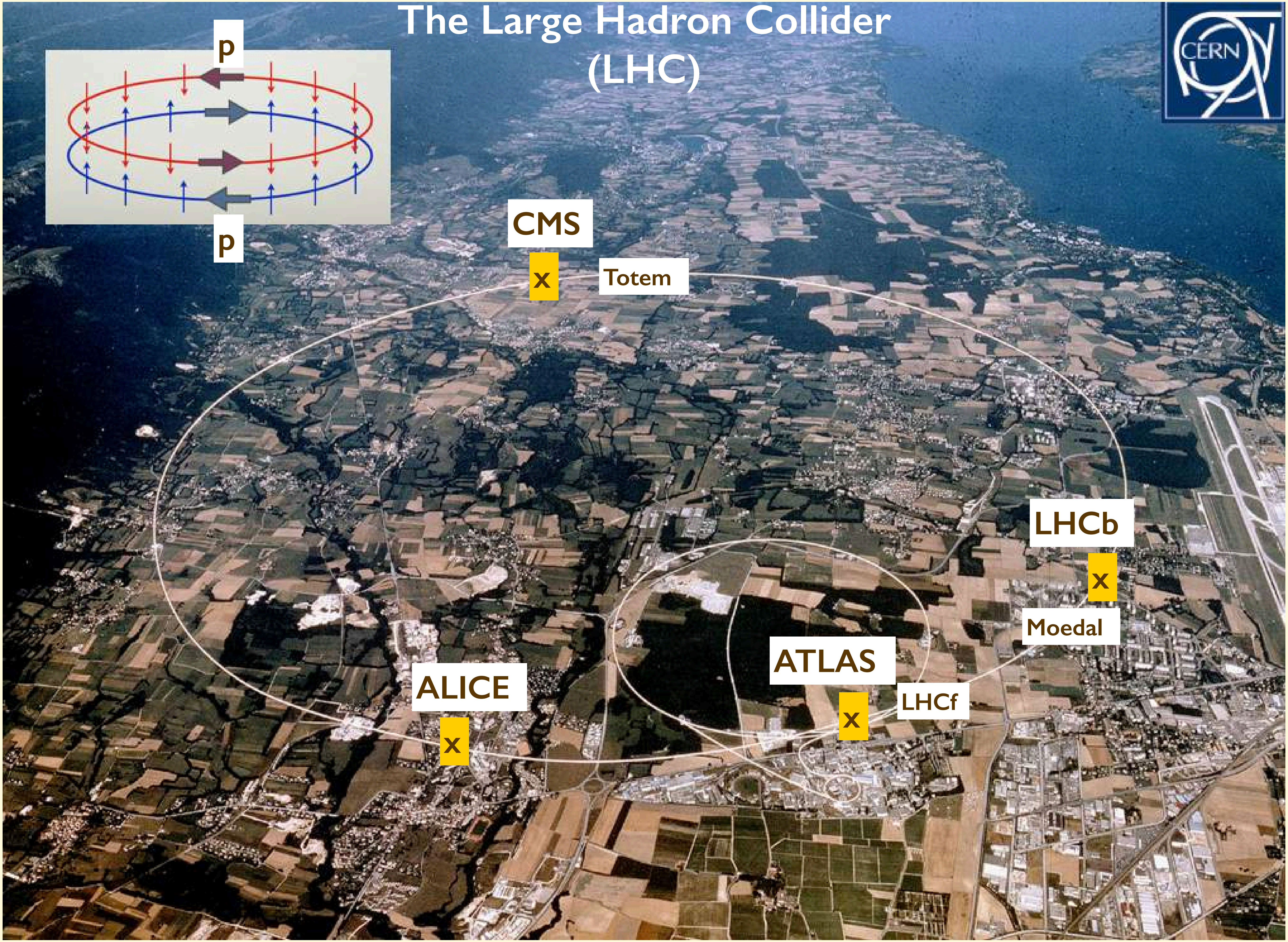
THE LHC

The Large Hadron Collider (LHC)

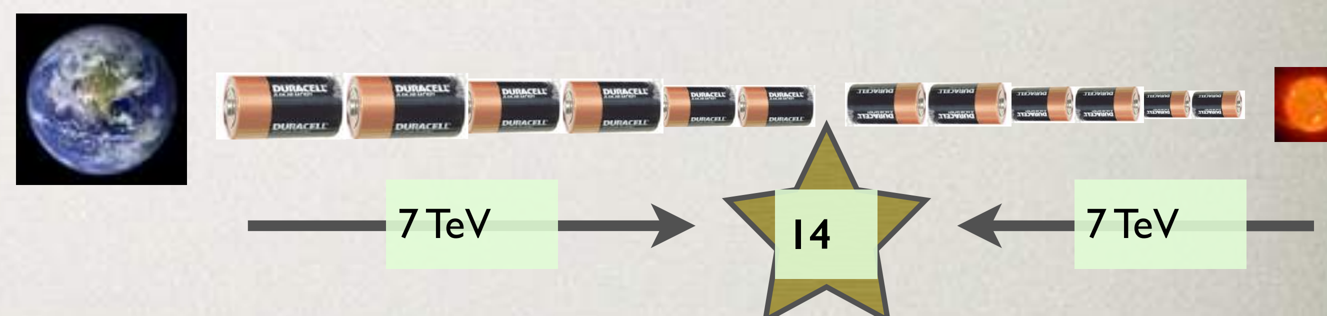


THE LHC ACCELERATOR

- 1232 LHC dipoles, plus ~600 other smaller magnets

- E_{beam} = 7000 GeV ~ 7×10^{12} eV ~ 5 trillions 1.5V batteries

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



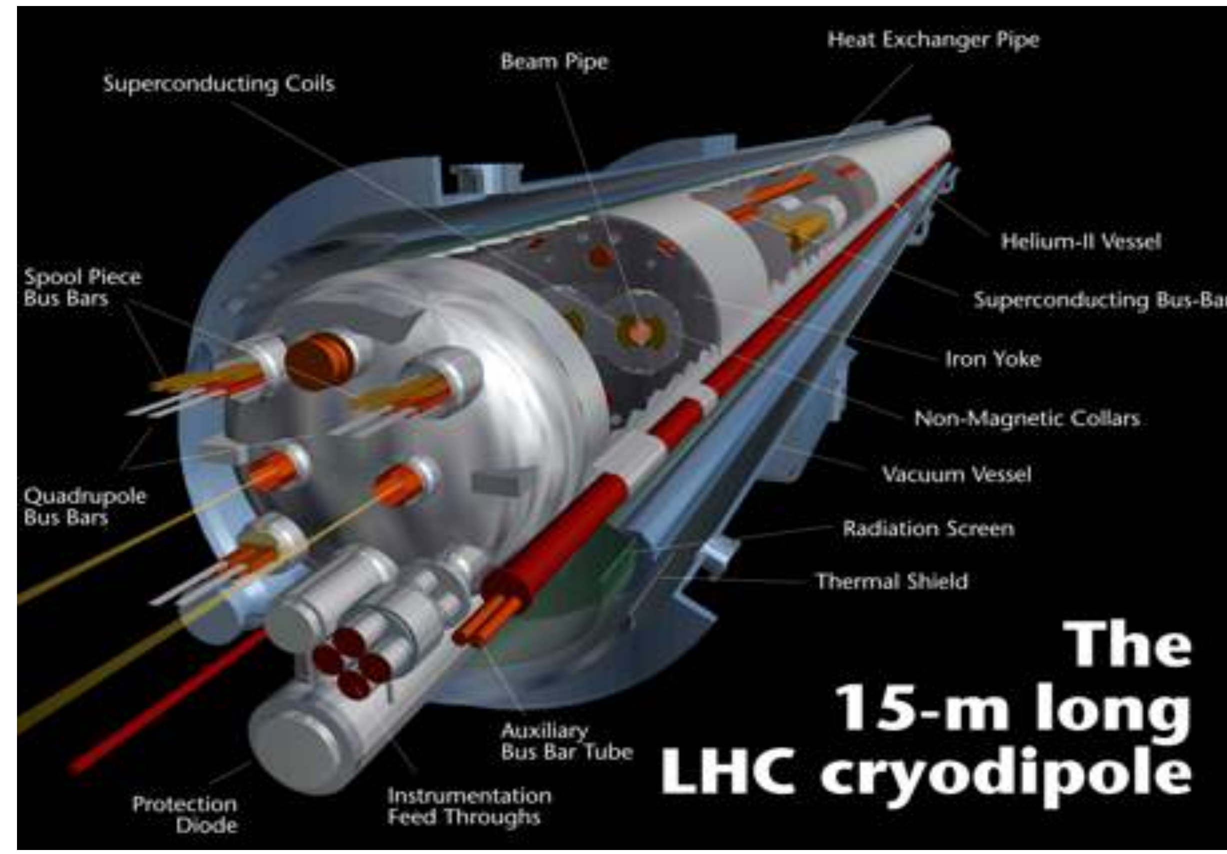
- E_{beam} = 7000 GeV ~ 7500 m_{proton} c^2
  - $E=mc^2 / \sqrt{[1-v^2/c^2]}$ ⇨ v = 0.999 999 99 c

- 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



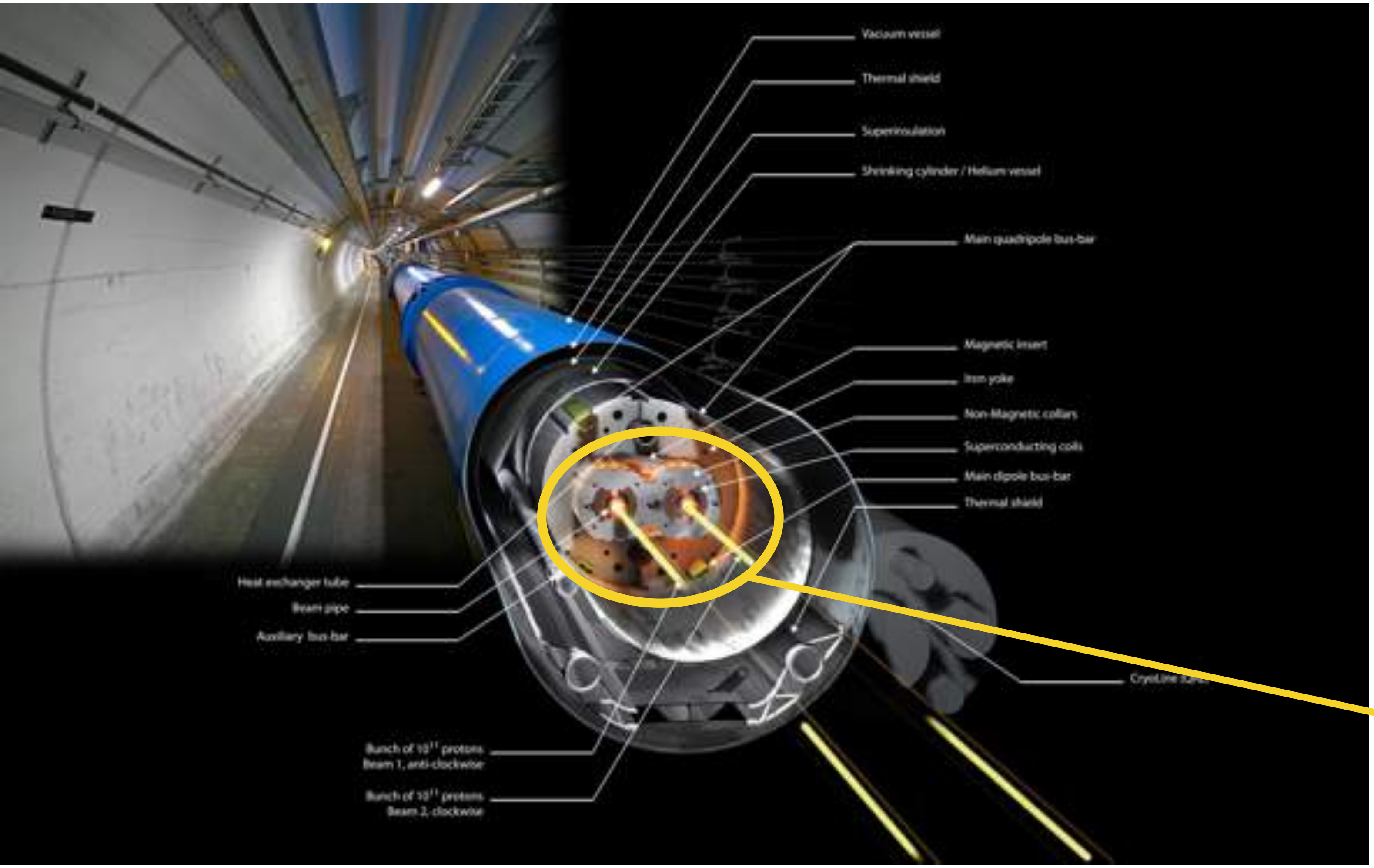
- B field = 83,000 Gauss
  - Ni Ti SC cable

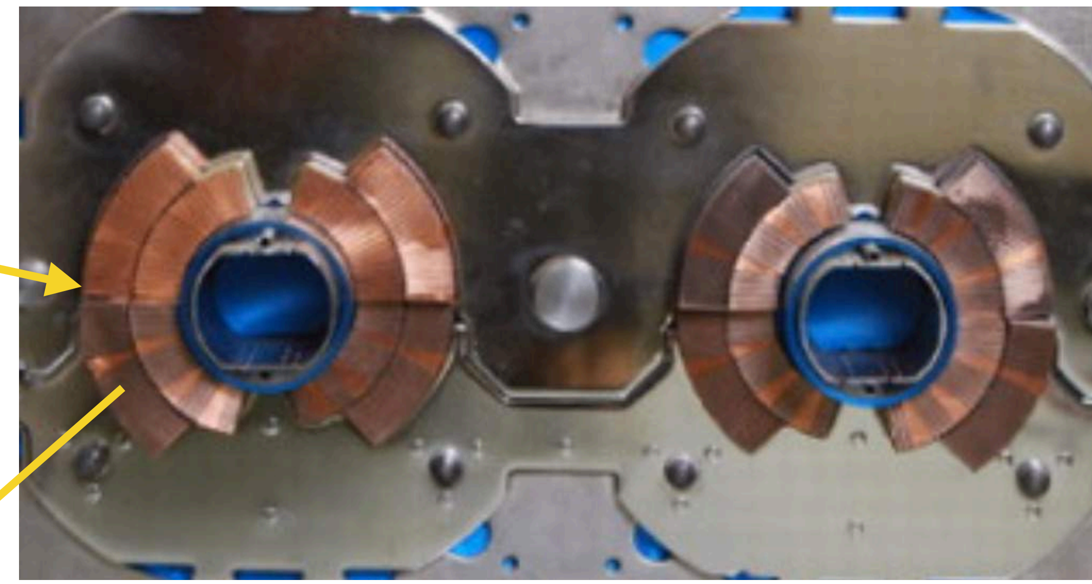
  (Earth's field ~ 0.5 Gauss)

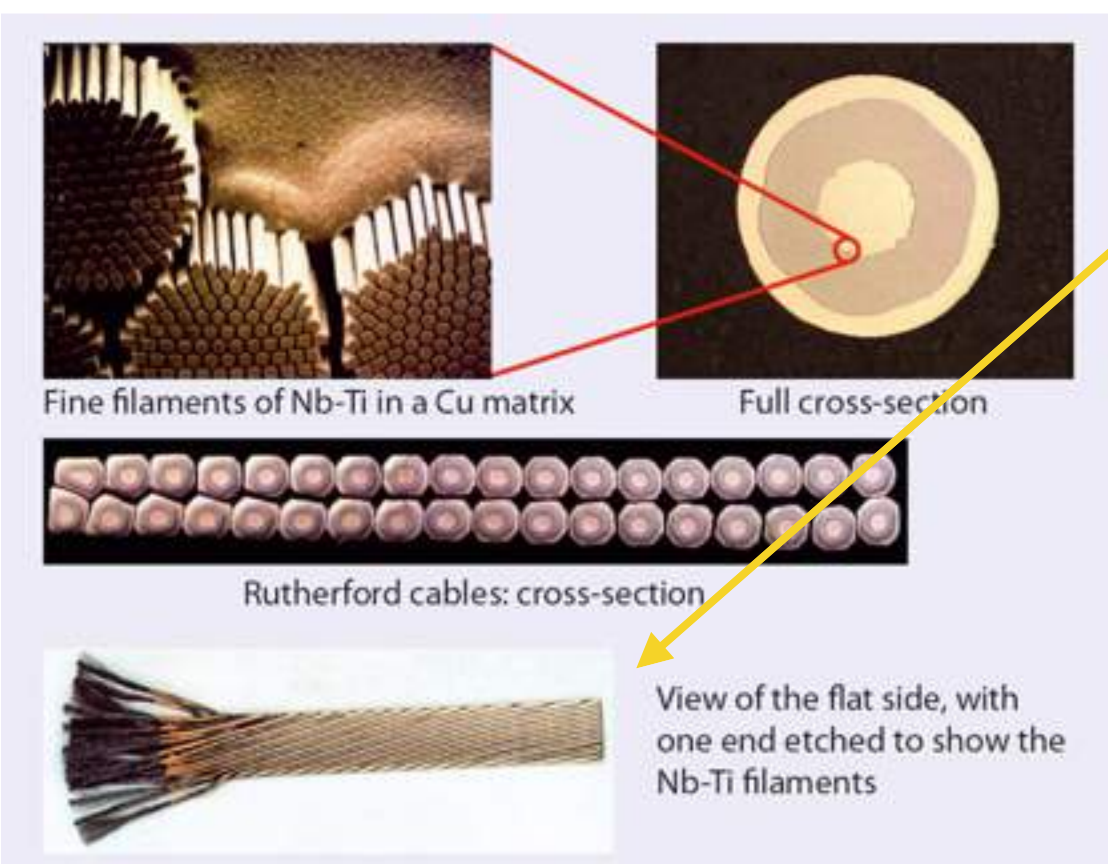
- T = $1.9K^0$ = – 456 F
  - superfluid liquid Helium

- 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

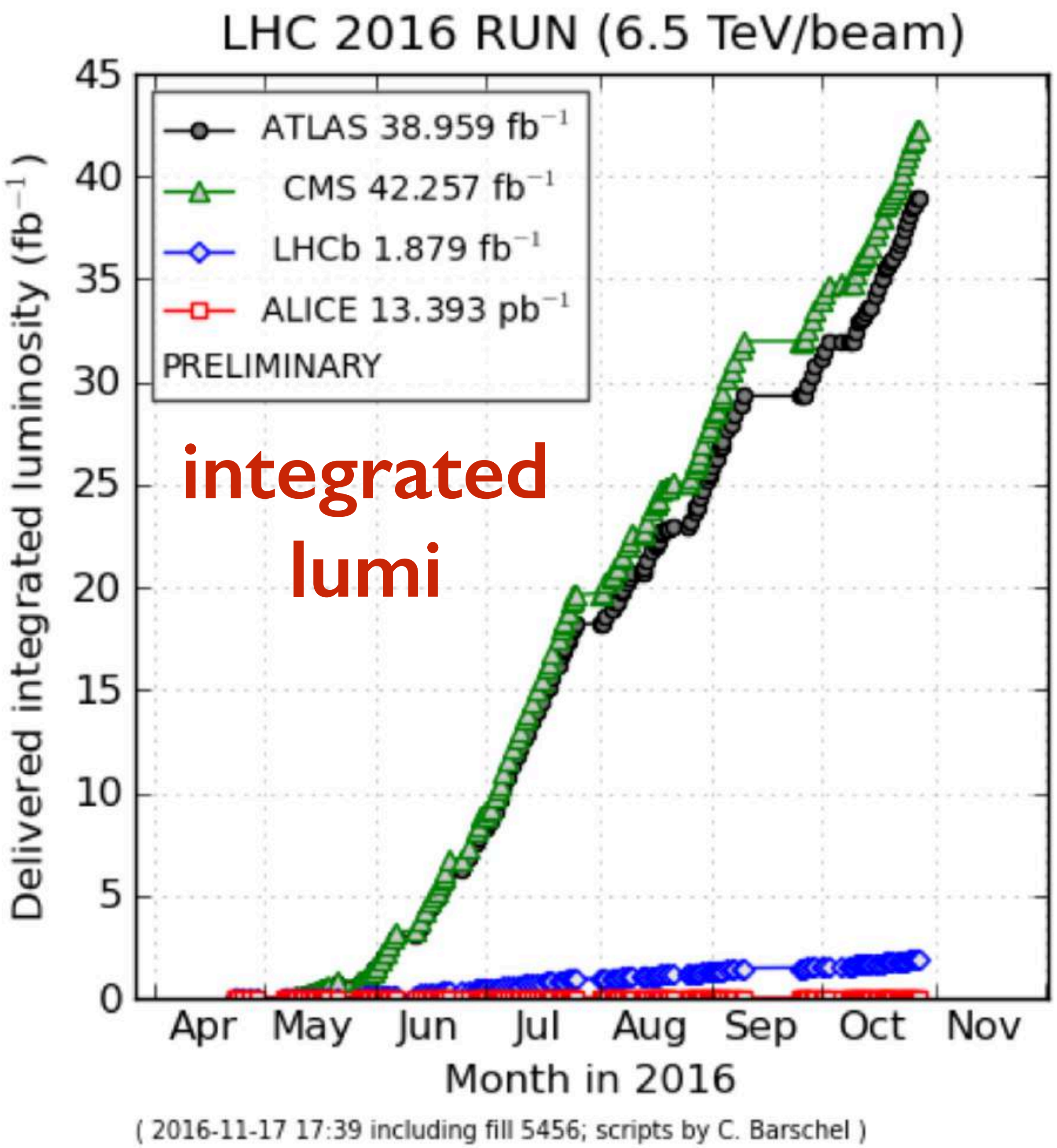


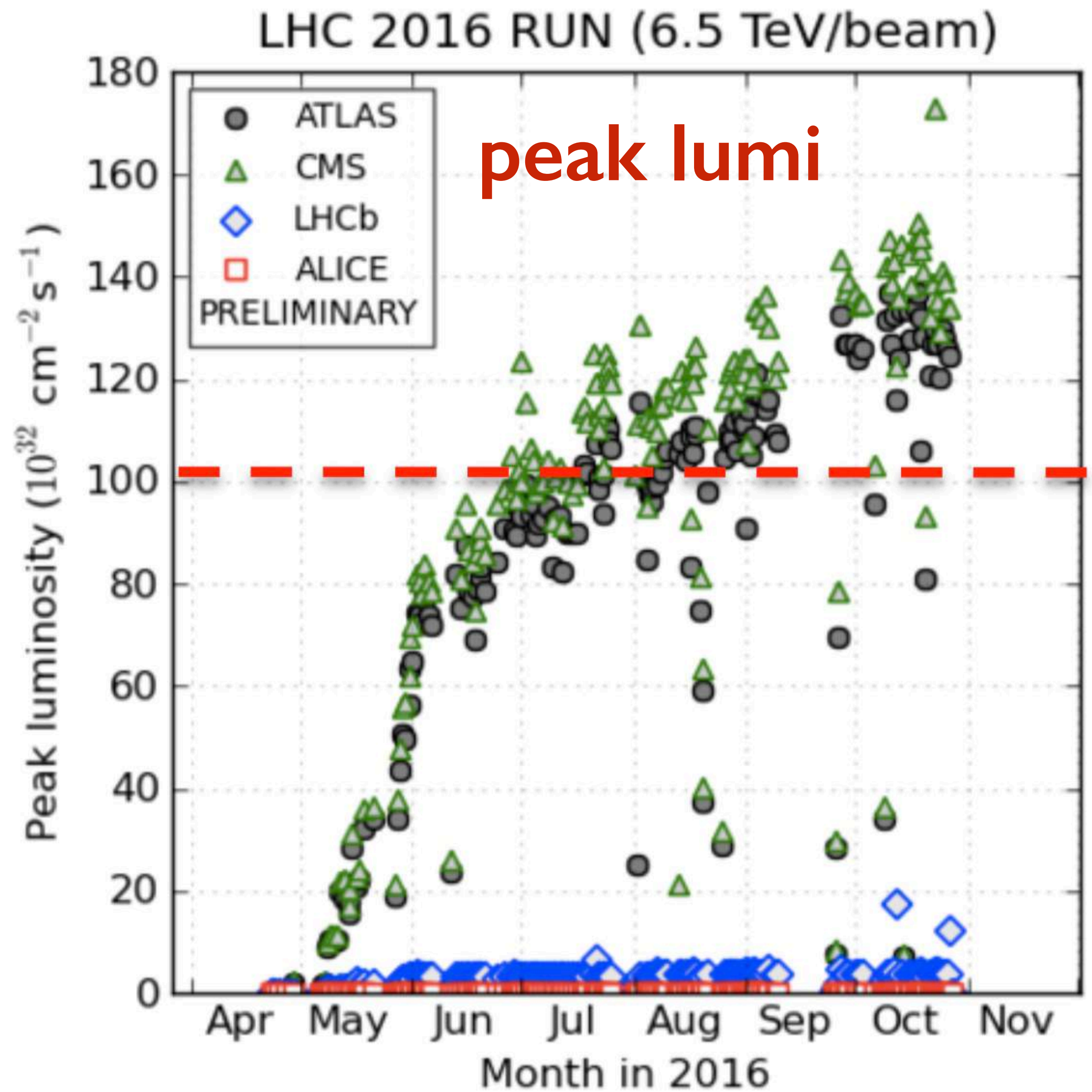




STRAND	Type 01	Type 02
Diameter (mm)	1.065	0.825
Cu/NbTi ratio	1.6-1.7 ± 0.03	1.9-2.0 ± 0.03
Filament diameter (μm)	7	6
Number of filaments	8800	6425
Ic (A) @1.9 K	515 (±4 %) @ 10 T	380 (±4 %) @ 7 T
Jc (A/mm^2) @1.9 K	1530 @ 10 T	2100 @ 7 T
μ_0M (mT) @1.9 K, 0.5 T	30 ±4.5	23 ±4.5
CABLE	**Type 01**	**Type 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

LHC pp running, 2016





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

NB Operations included several periods of machine development studies to improve future performance, as well as setup and physics with $\beta^*=2.5$km for the measurement of σ_{el} , σ_{tot} and ρ by ATLAS and TOTEM

Message: the LHC works extremely well, better than expected!

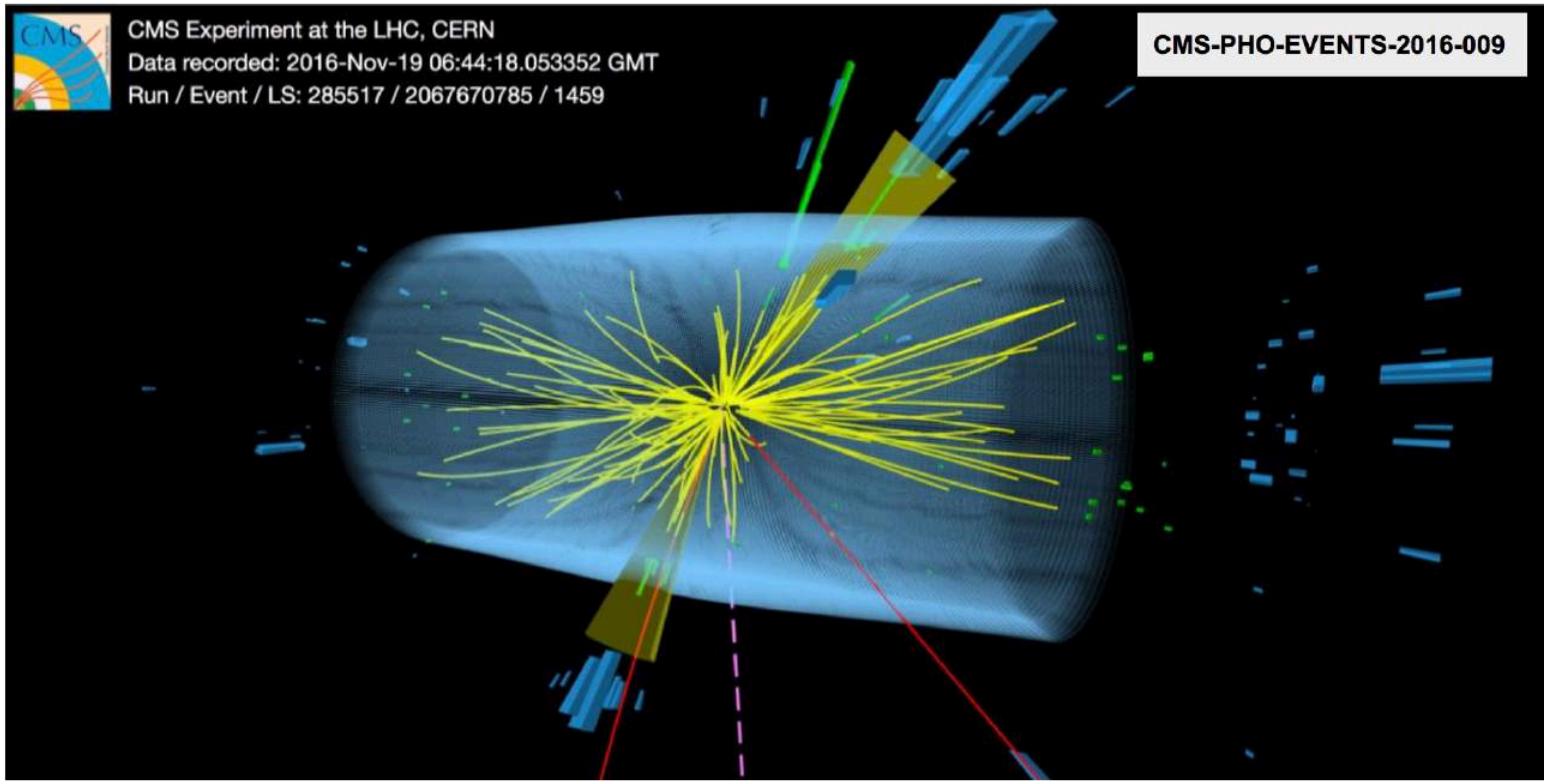
LHC p Pb running, 2016

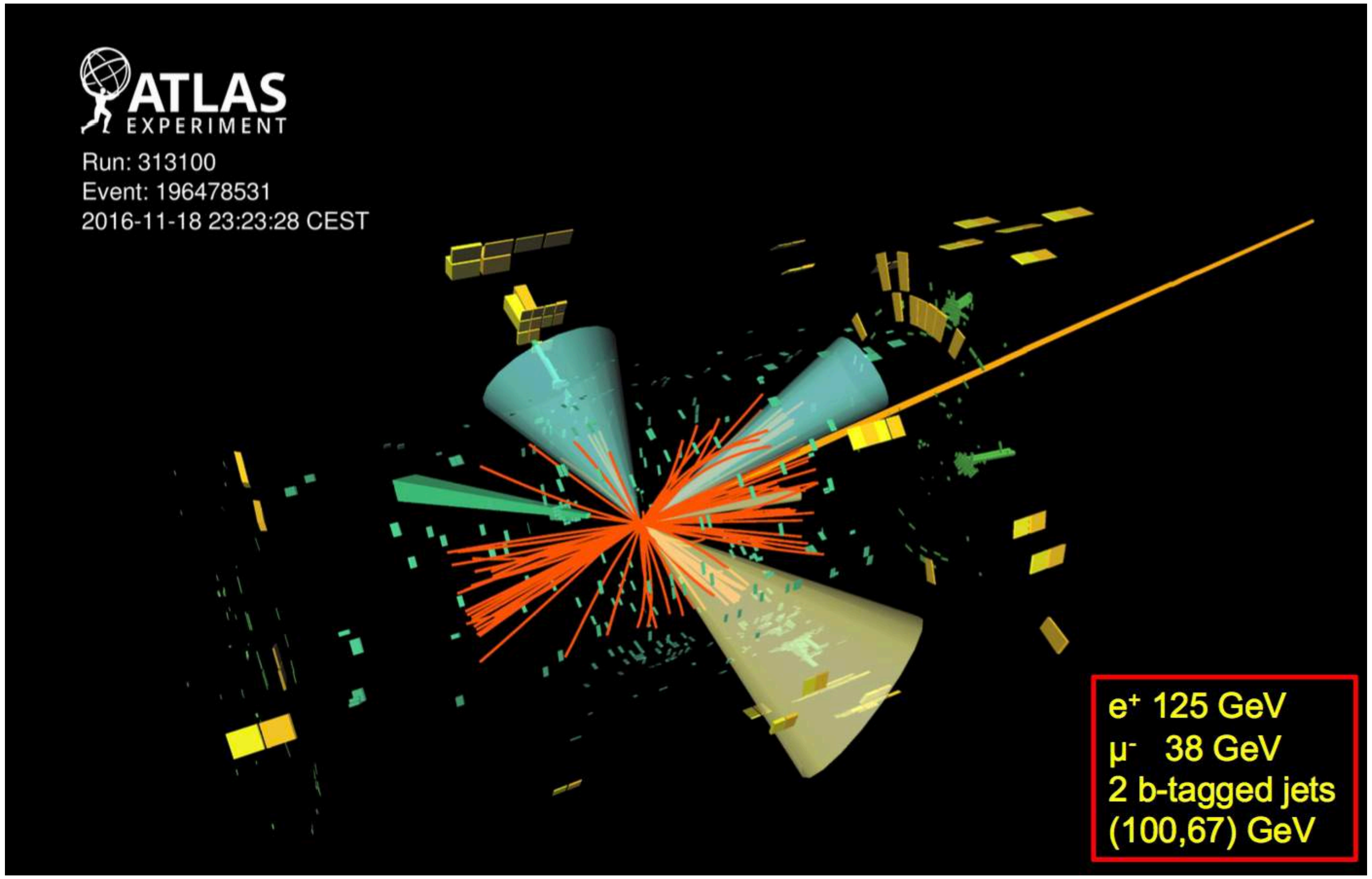
Configuration	Goal		Achieved
5 TeV p-Pb **(E_{beam}=4 Z TeV)**	ALICE	700×10^{6} min bias events	**780×10^{6}**
8 TeV p-Pb **(E_{beam}=6.5 Z TeV)**	ATLAS - CMS	50 nb^{-1}	**69.5 - 65.5 nb^{-1}**
	LHCb - ALICE	10 nb^{-1}	**14 - 13 nb^{-1}**
	LHCf	9-12 h at 10^{28} $cm^{-2}s^{-1}$	**9.5 h**
8 TeV Pb-p **(E_{beam}=6.5 Z TeV)**	ATLAS - CMS	50 nb^{-1}	**124 - 118 nb^{-1}**
	ALICE - LHCb	10 nb^{-1}	**25 - 19 nb^{-1}**

…. all goals surpassed

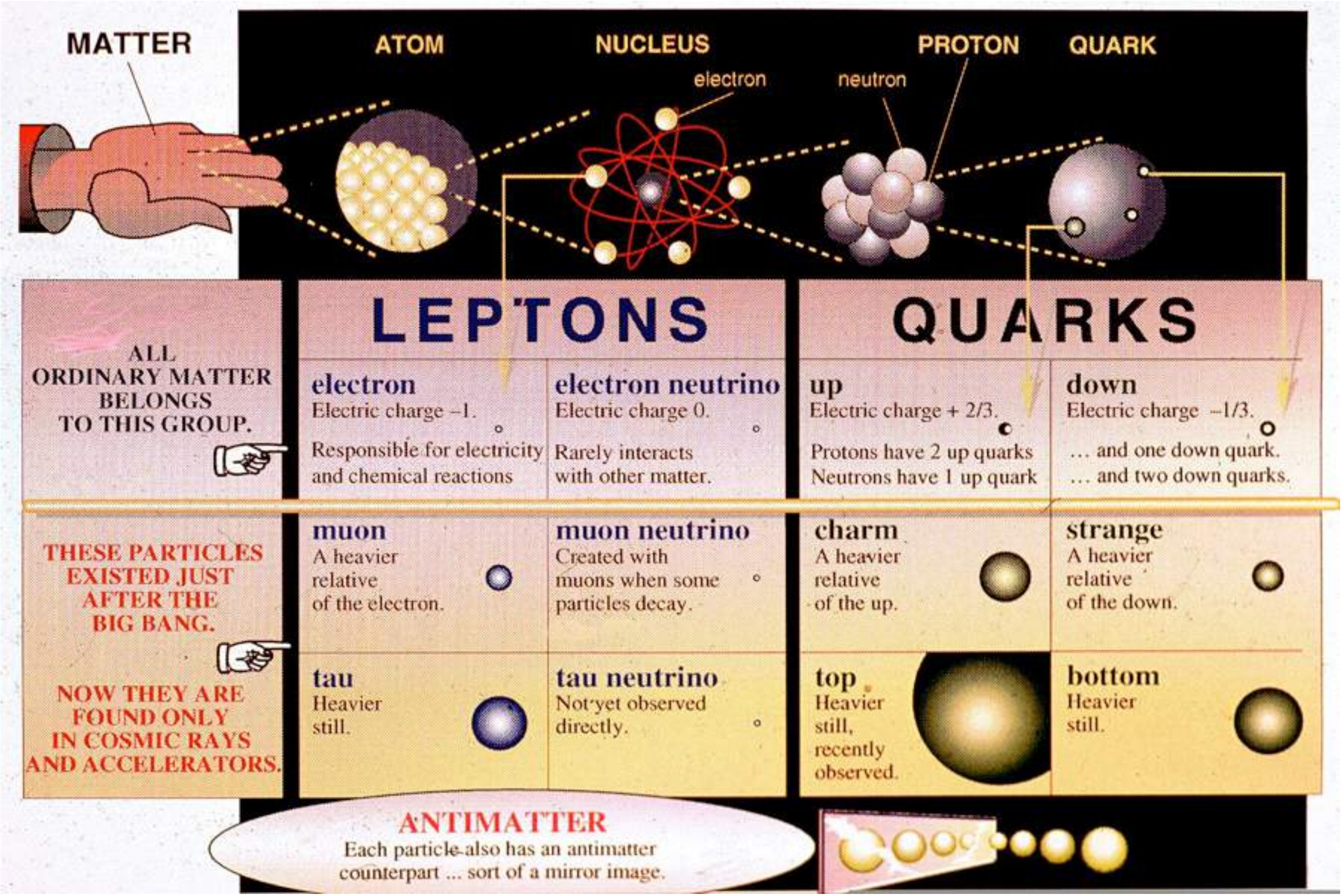
NB: On Nov 30 the p-Pb run achieved a max luminosity ~ 9 x design!

first candidates of t-tbar production in p-Pb collisions





The Standard Model of particle physics



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 real origin of EW symmetry breaking and particle's masses?
- What protects the smallness of m_H / $m_{Plank,GUT}$ (hierarchy problem)?
- ...

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 ⇒ $\mathbf{m=<E>/c^2}$ with $\mathbf{<E>=<T+U>}$

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?

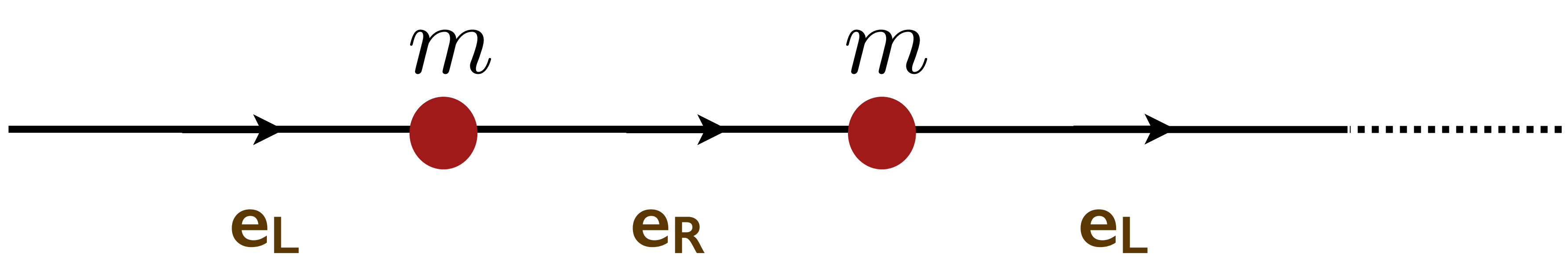
In other words:

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

Parity asymmetry and mass for spin-1/2 particles

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

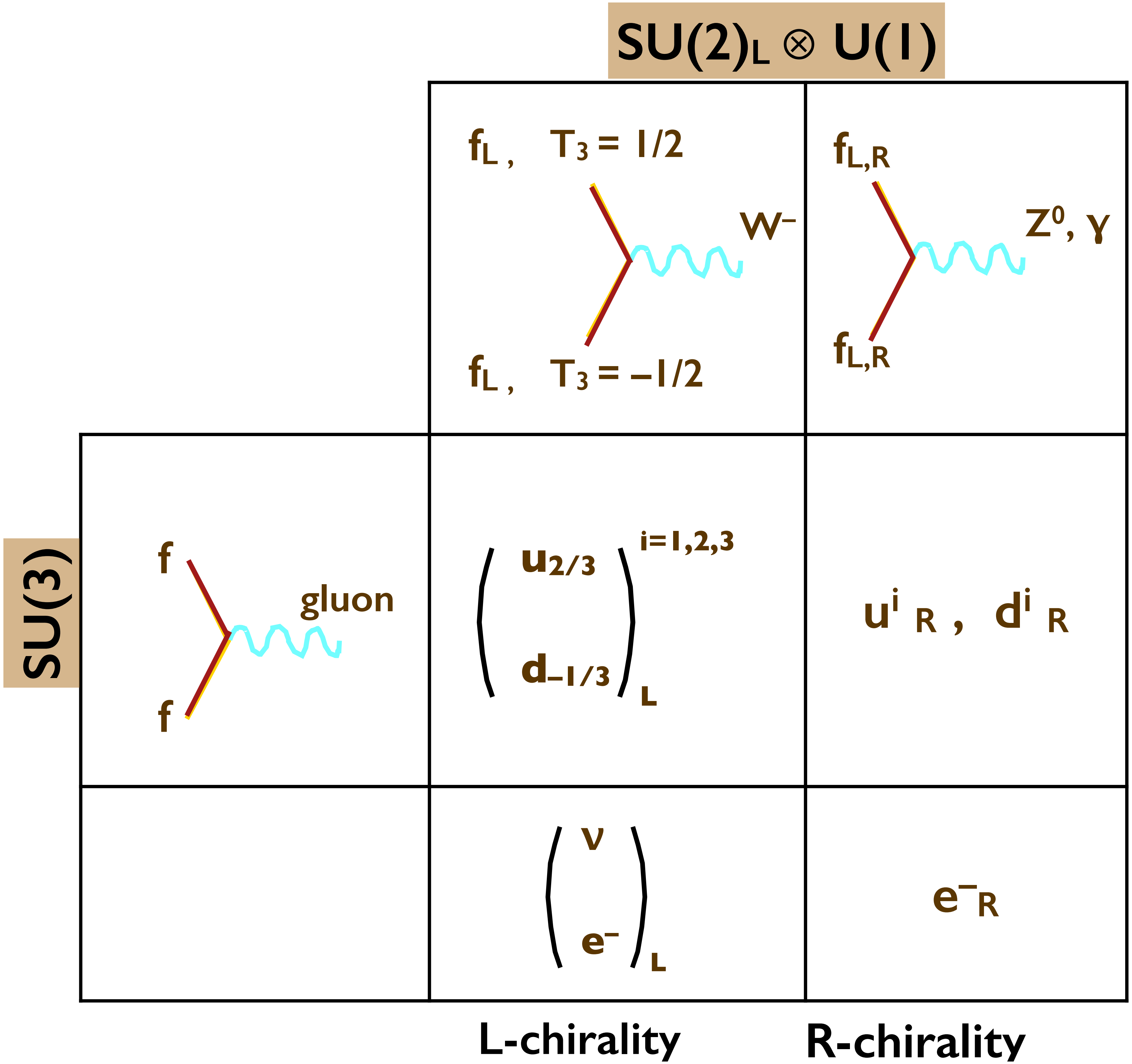
$\gamma_5\,\psi_{L,R} = \pm\,\psi_{L,R}$



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

Chirality eigenstates of a massive particle cannot be Hamiltonian (physical) eigenstates

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



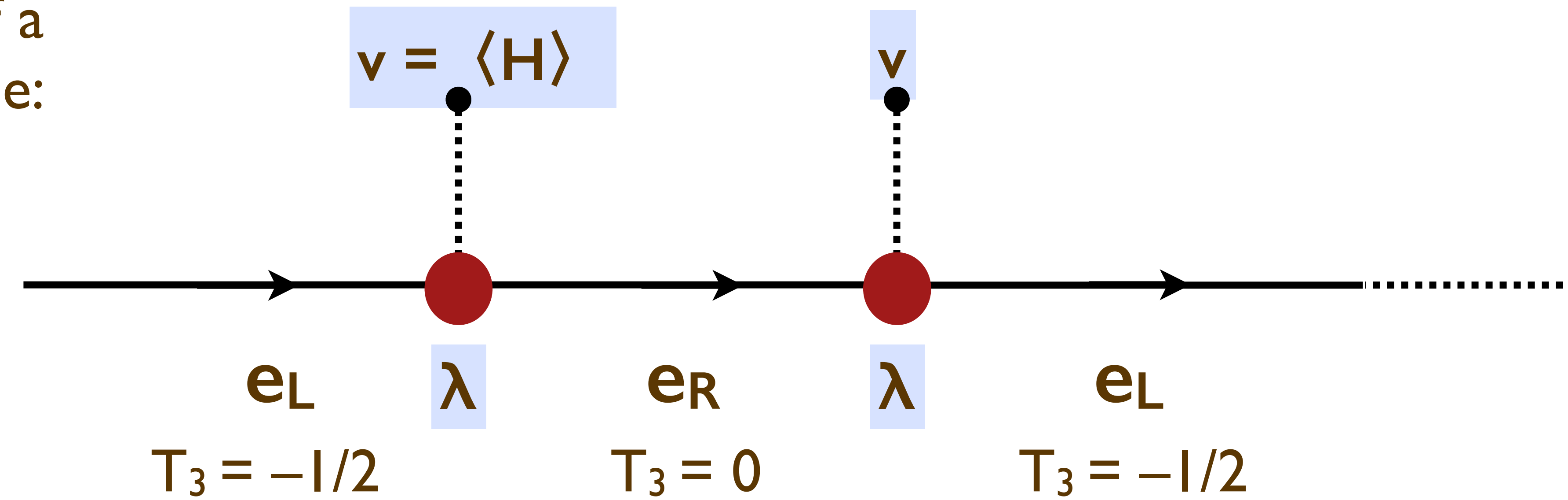
+ 2 more "families" differing from the 1st one only in the mass of their elements

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

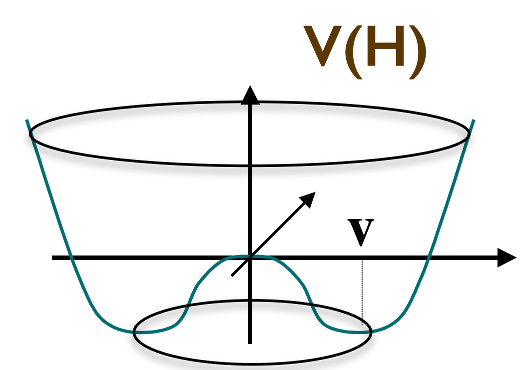
The SM solution ....

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 SU(2)-doublet scalar field **H**, whose potential acquires a minimum at $\langle H \rangle = v \neq 0$



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

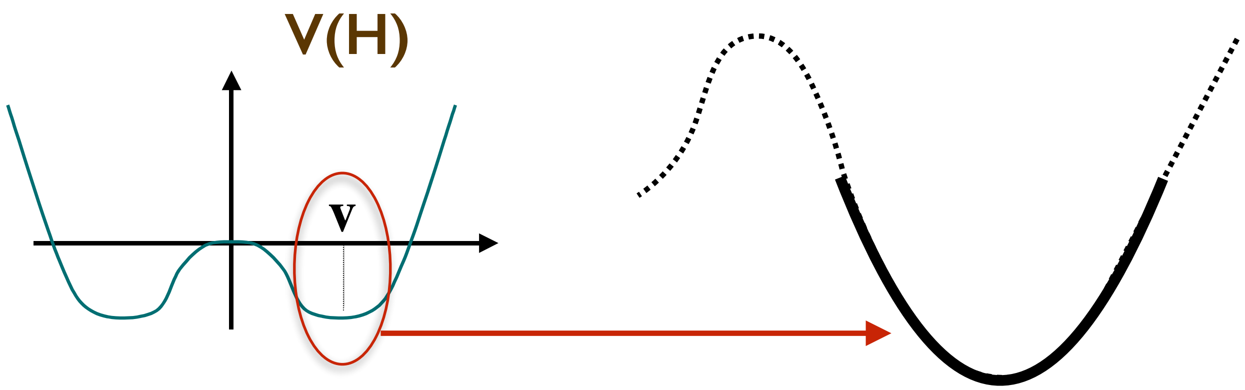
The number "**v**" is the expectation value of the so-called **Higgs field**.
The quantity "**λ**" is characteristic of the particle interacting with the Higgs field.
It can easily be shown that **this interaction leads to a mass m ∝ λ v**

First general consequences of this model

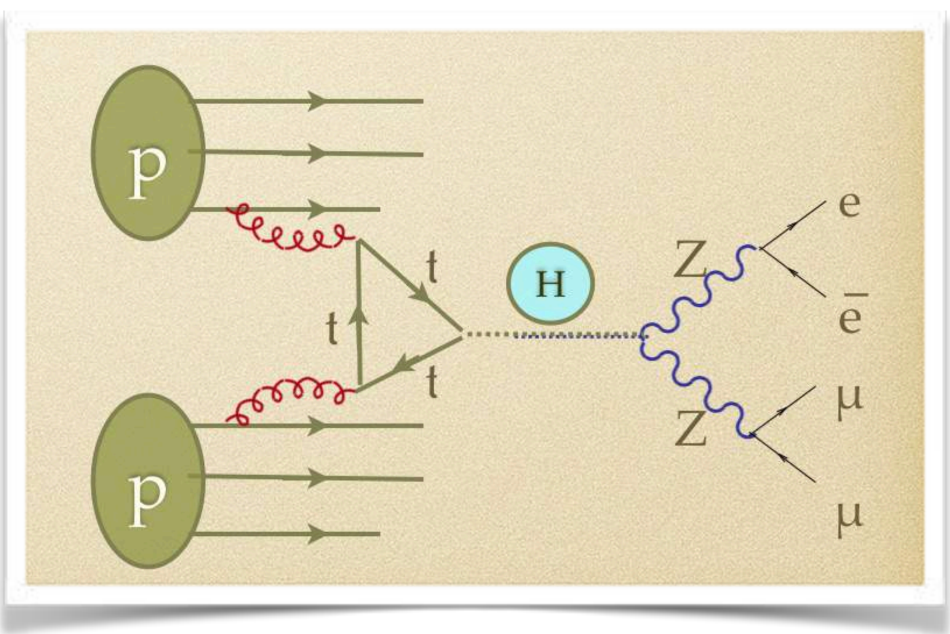
- Small oscillations around the minimum => a scalar particle (the “Higgs boson”)
- Couplings of H to SM particles proportional to their mass
- 3 out of 4 components of complex doublet field provide longitudinal degrees of freedom to weak gauge bosons $W^{+/-}$ and Z^0

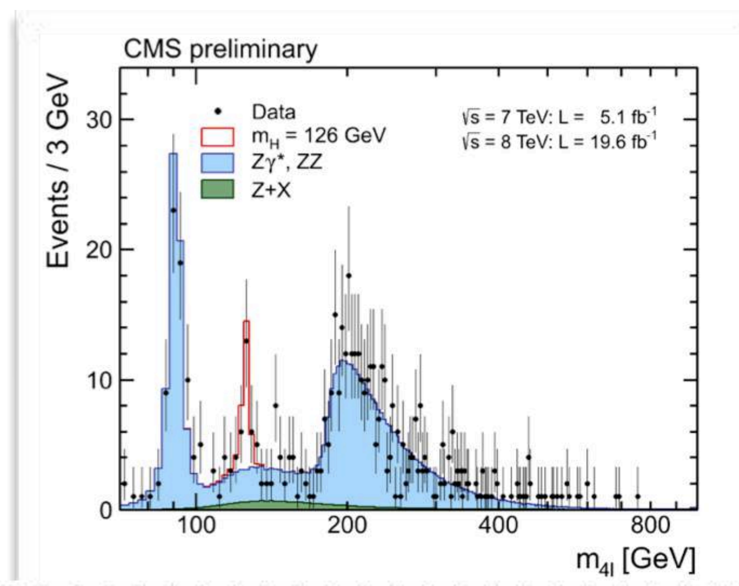
How far have we tested this theory?

parameters of the potential



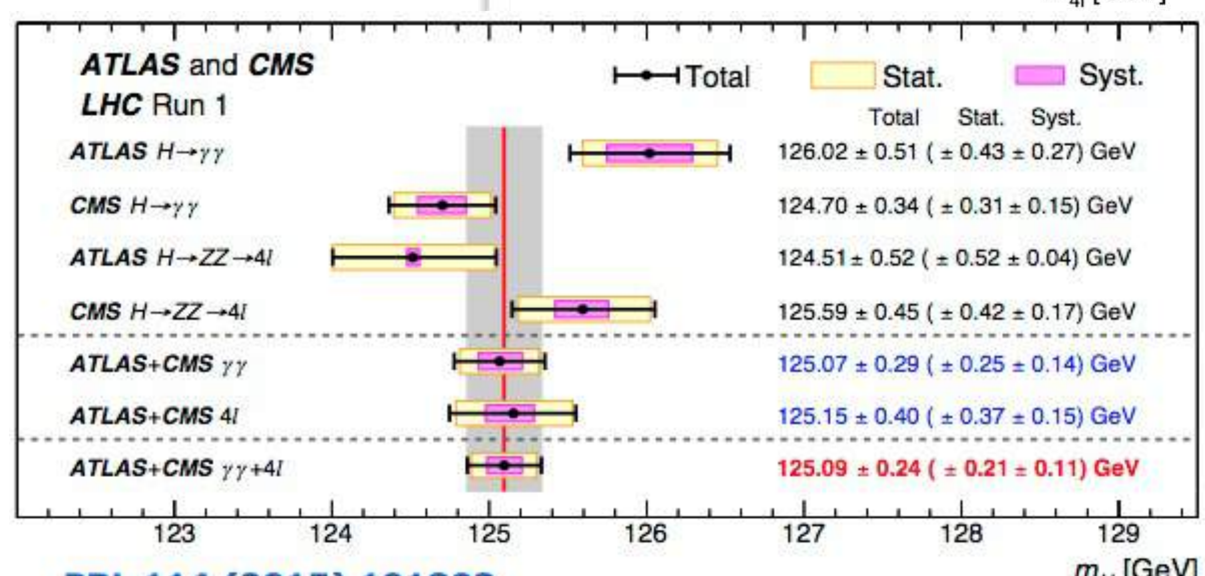
$V(H) \sim m_H^2\,(H-v)^2 \quad + ???$





ATLAS+CMS
PRL 114 (2015) 191803

$\delta m/m = 0.2\%$



PRL 114 (2015) 191803

Run 2, CMS, m(4l), now compatible with ATLAS run 1

$m_H = 124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{sys.})\ \text{GeV}$

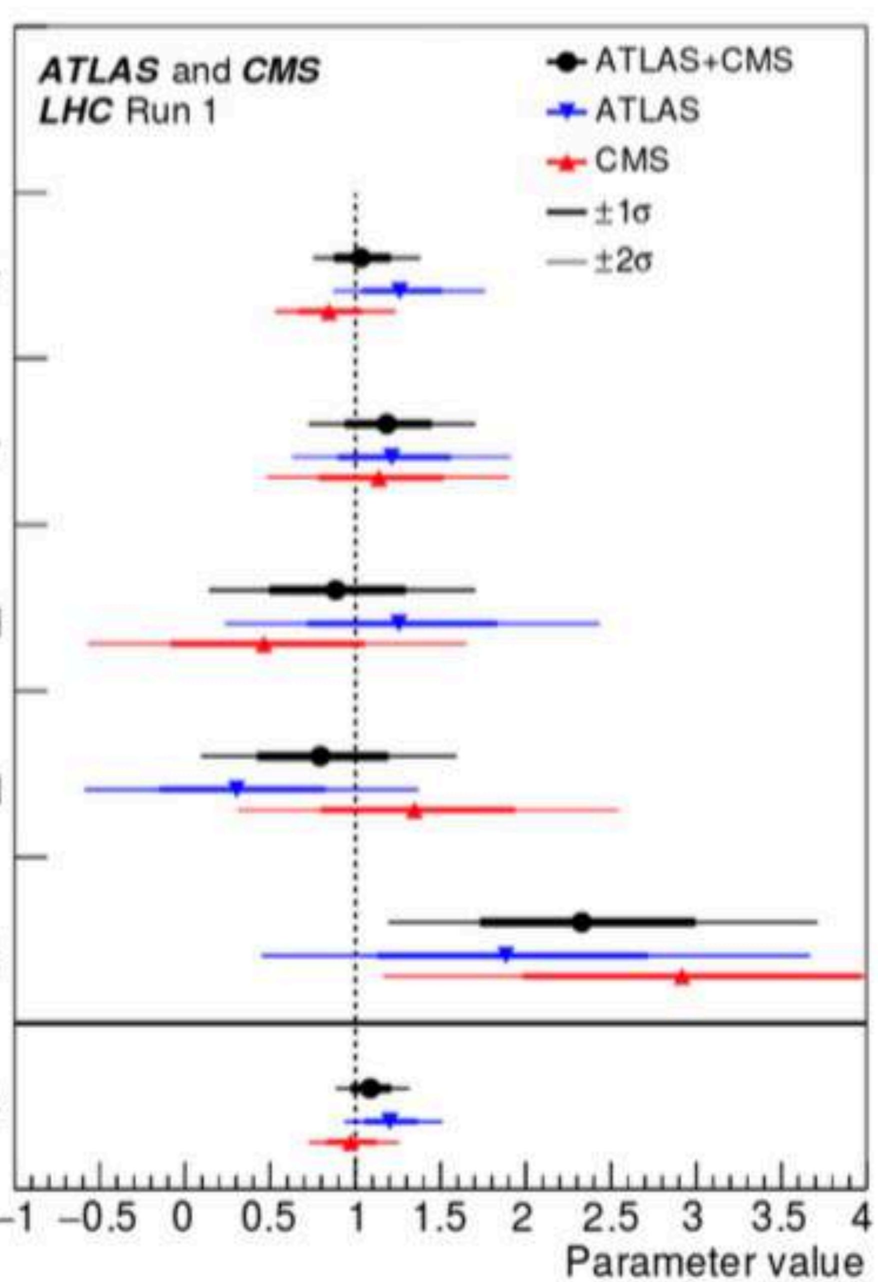
How far have we tested this theory?

couplings

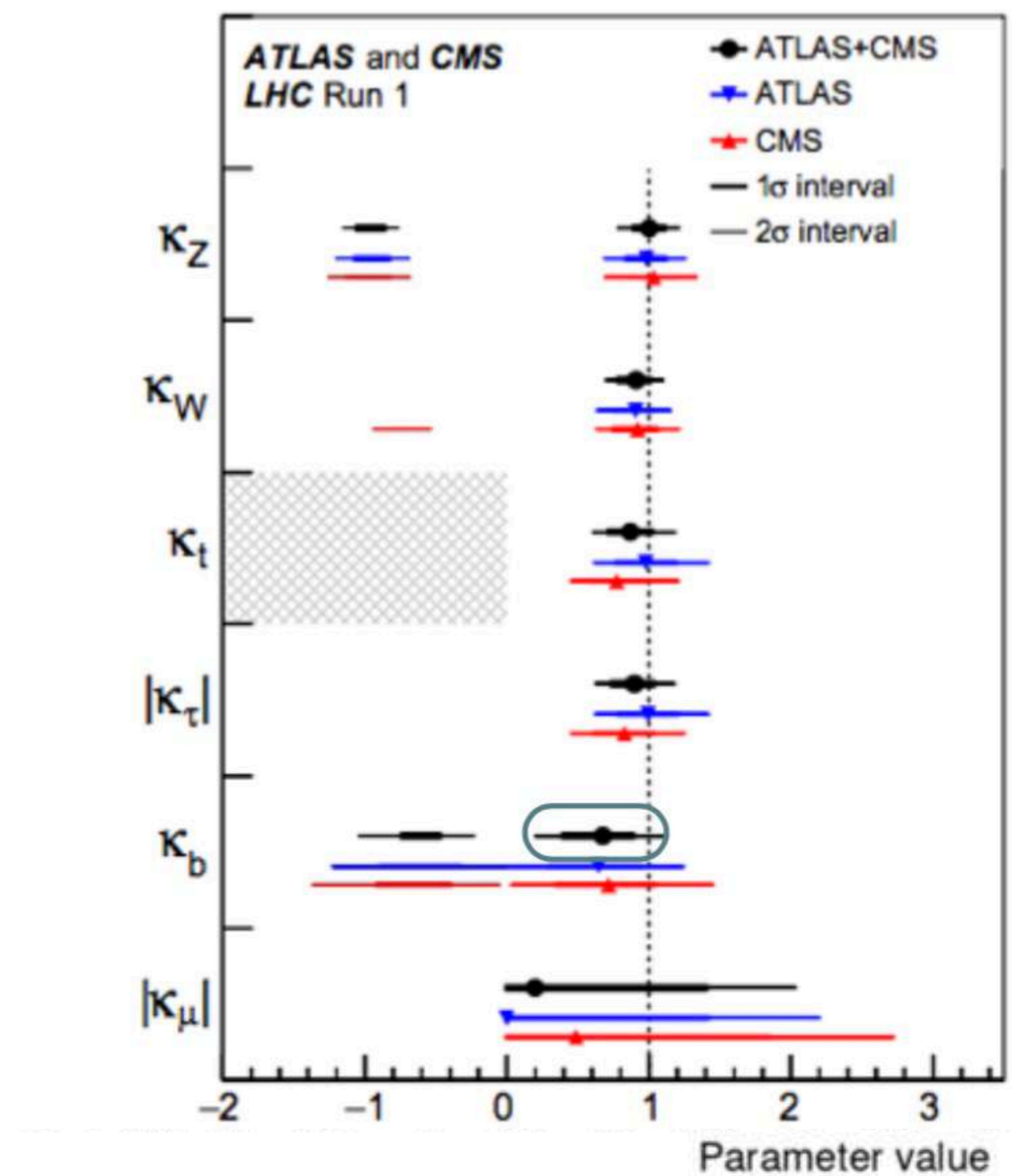
ATLAS+CMS
[JHEP 1608 (2016) 045]

μ = 1.09 ± 0.11

(μ=σxBR)
assume
SM BR

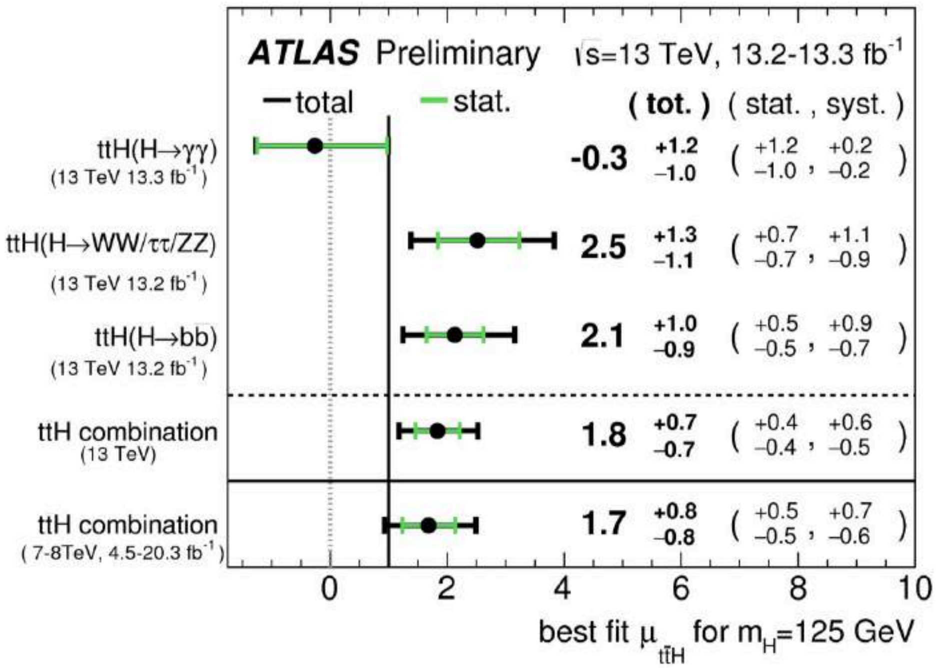


$$\kappa_j^2 = \sigma_j/\sigma_j^{SM} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{SM}$$



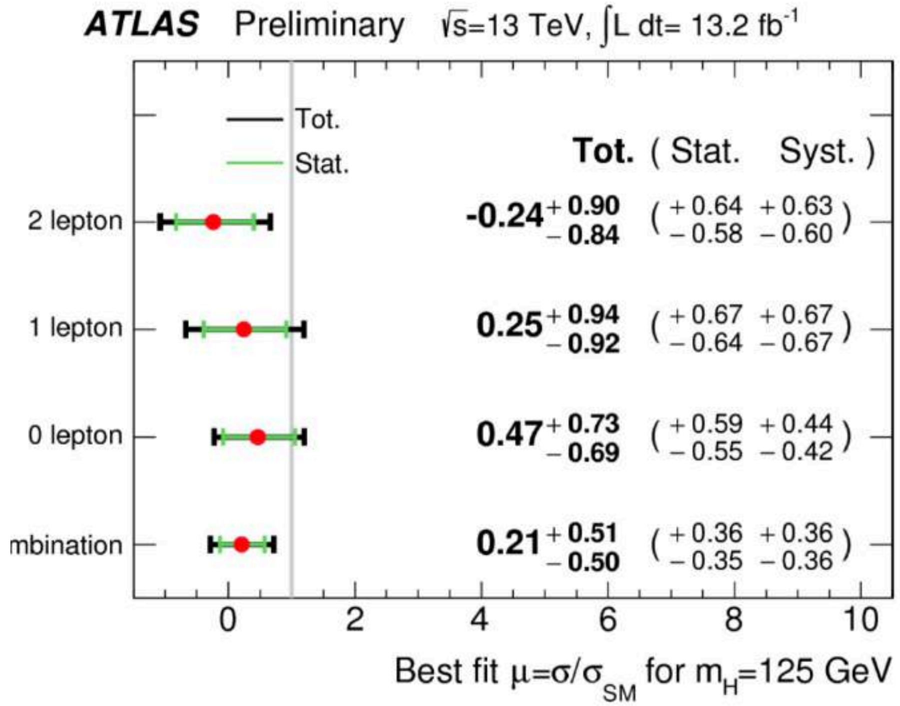
Highlights of 2015-16 Higgs measurements

ttH



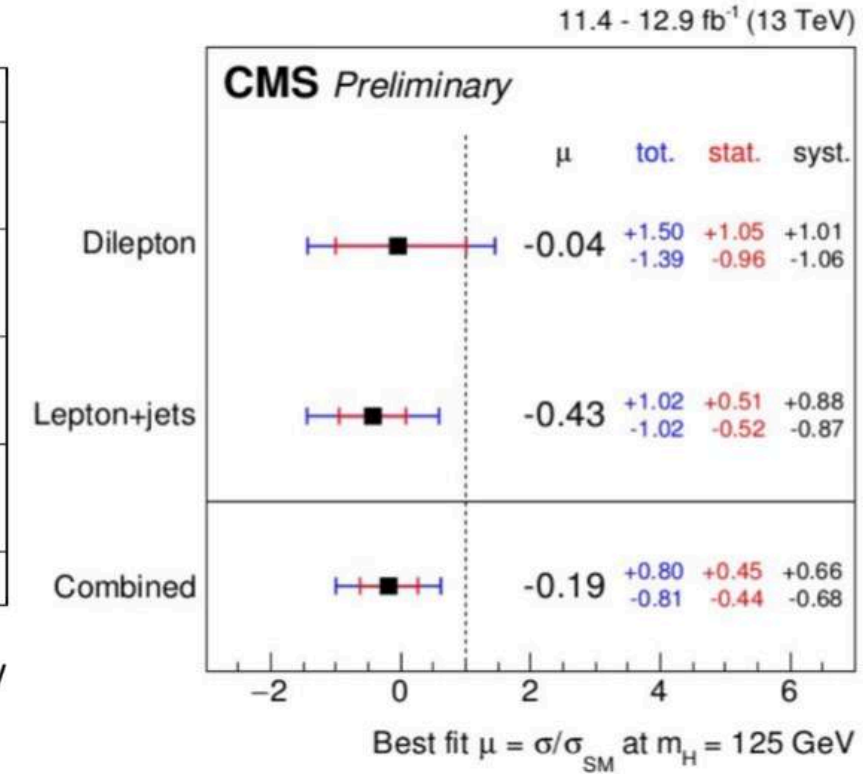
too much ....

VH(bb)

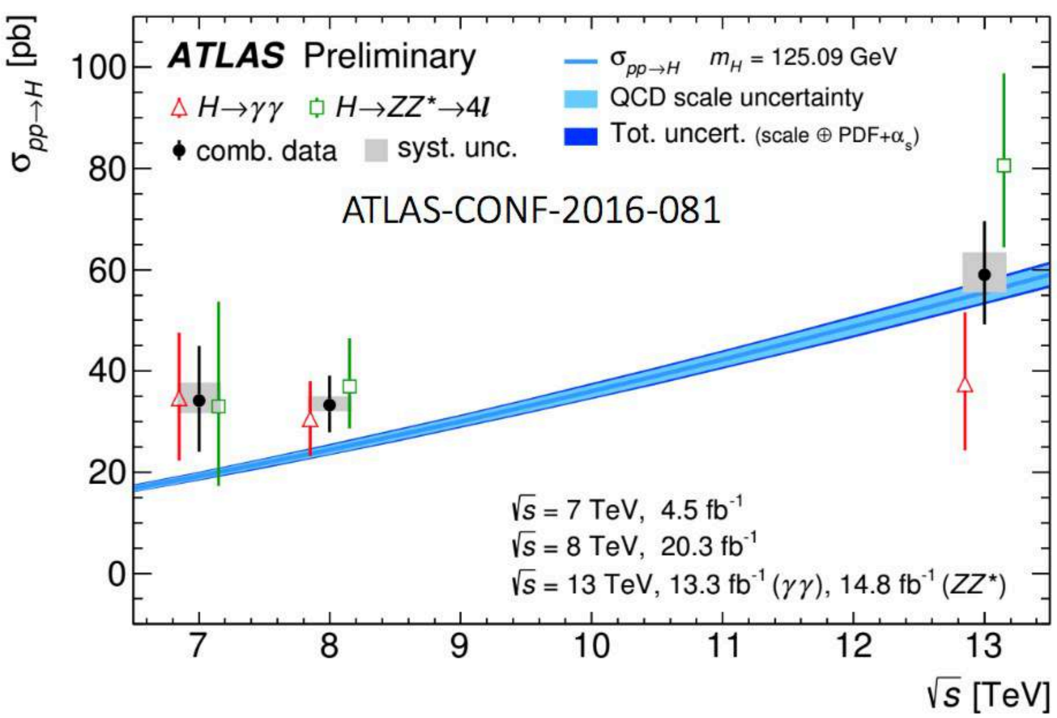


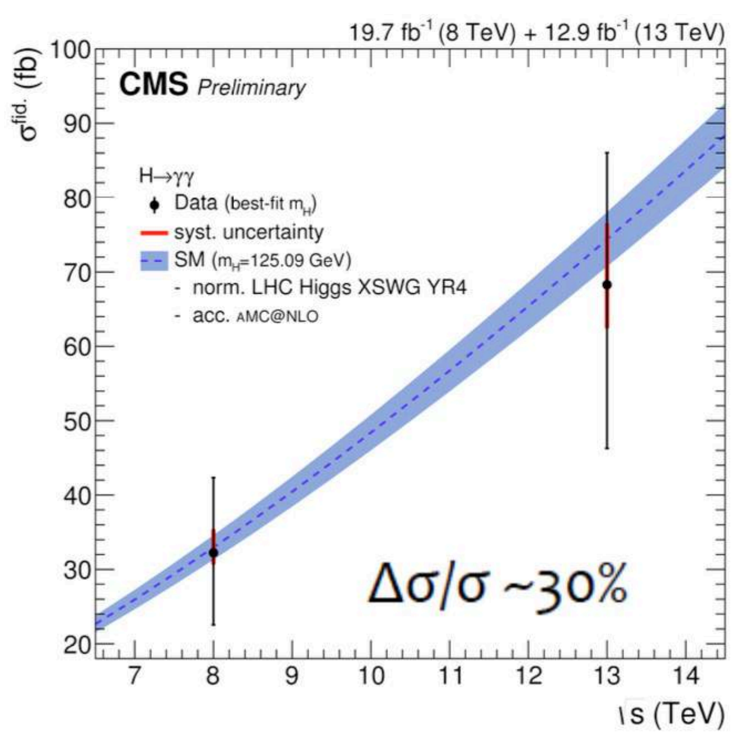
too little ....

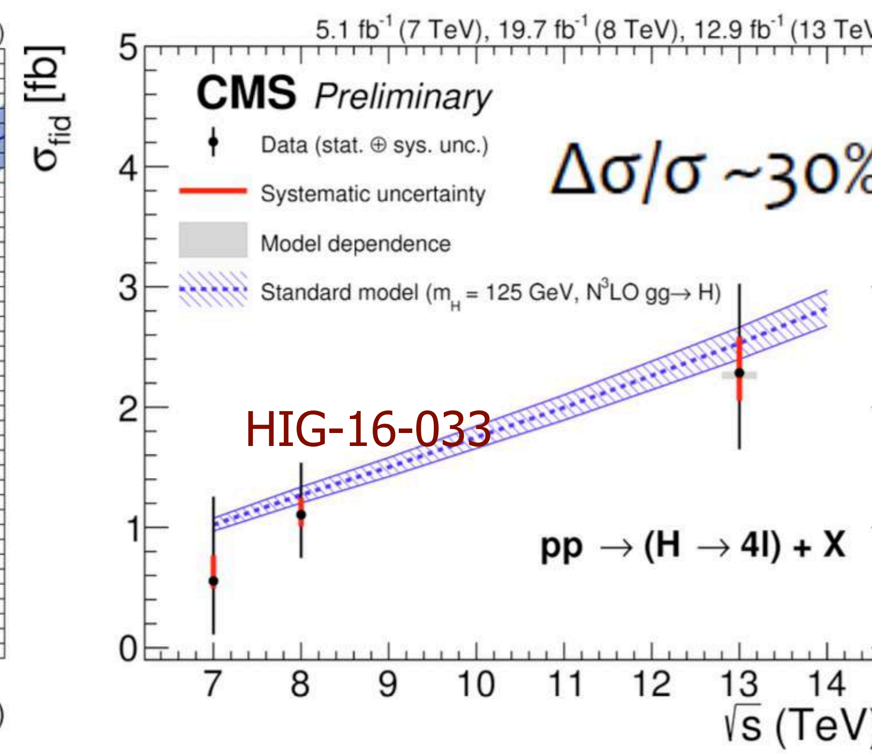
ttH (→bb)



....







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?***

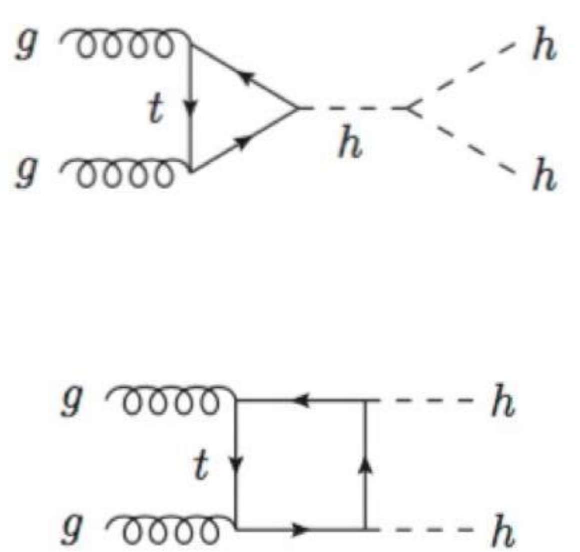
    - *Most theories beyond the SM have more Higgs bosons*

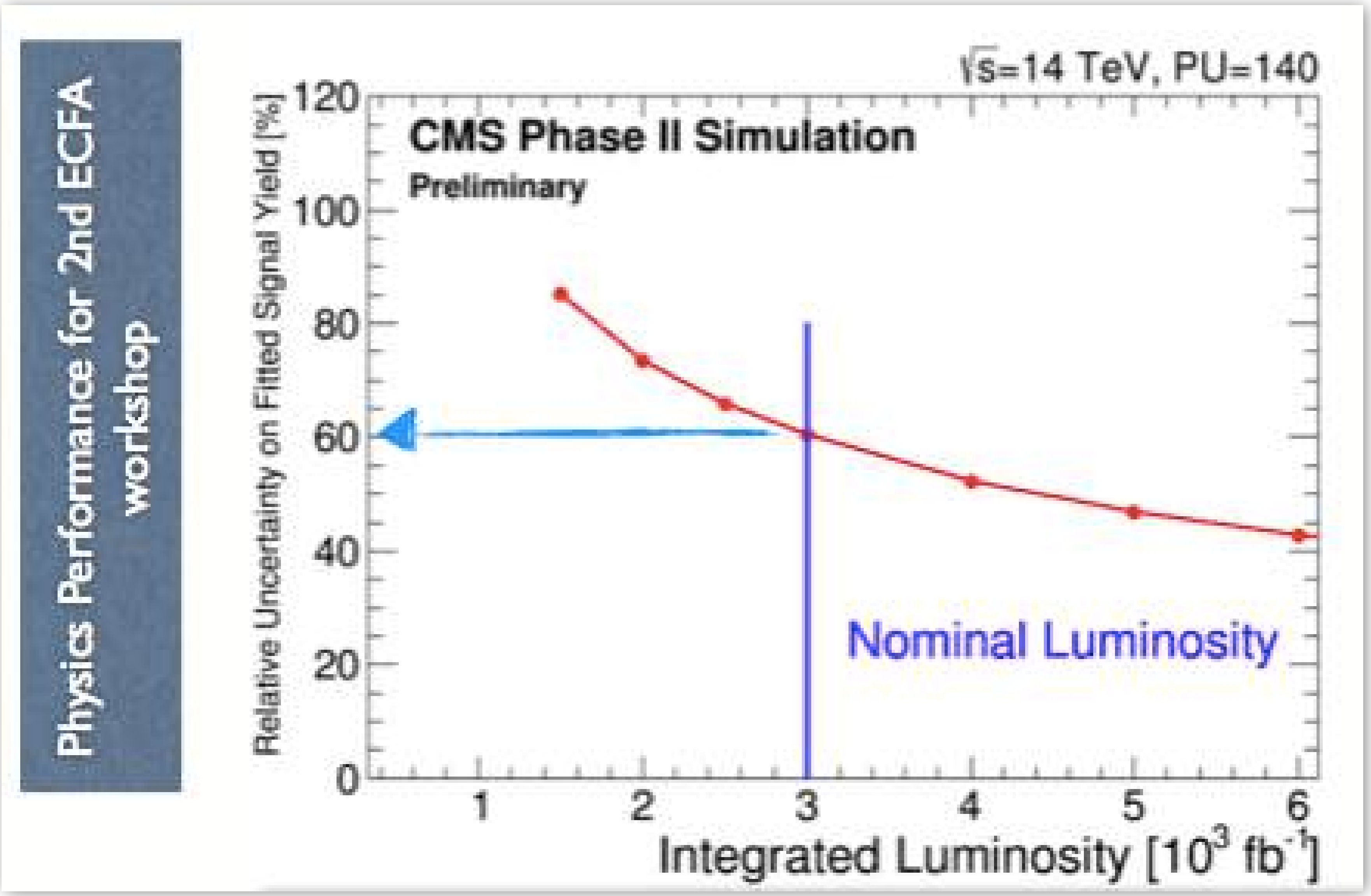
5. What gives mass to the Higgs ??

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





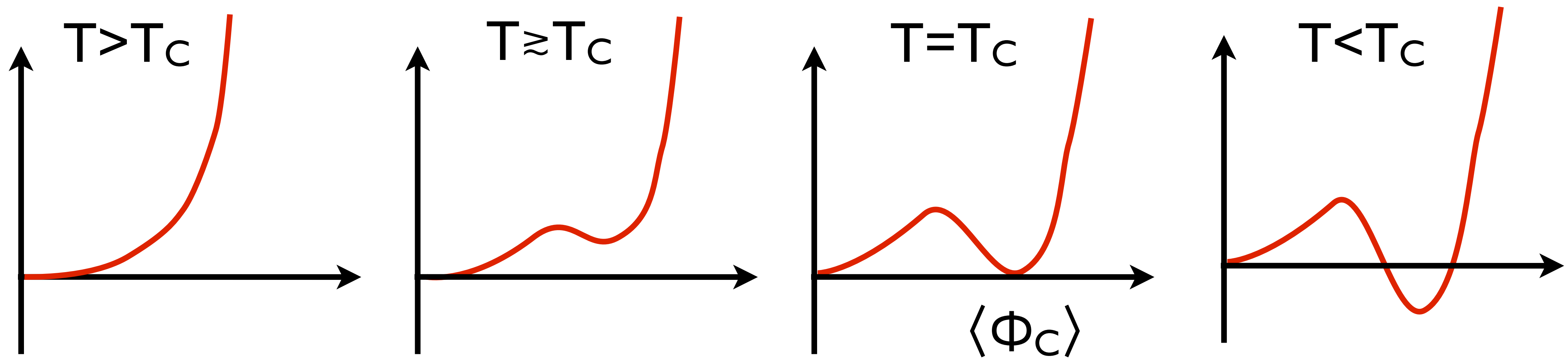
Why do we care so much?

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 / $m_{Plank,GUT,...}$?

Example: 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 $\Rightarrow \langle \Phi_C \rangle > T_C$

In the SM this requires $m_H \lesssim 80$ GeV.

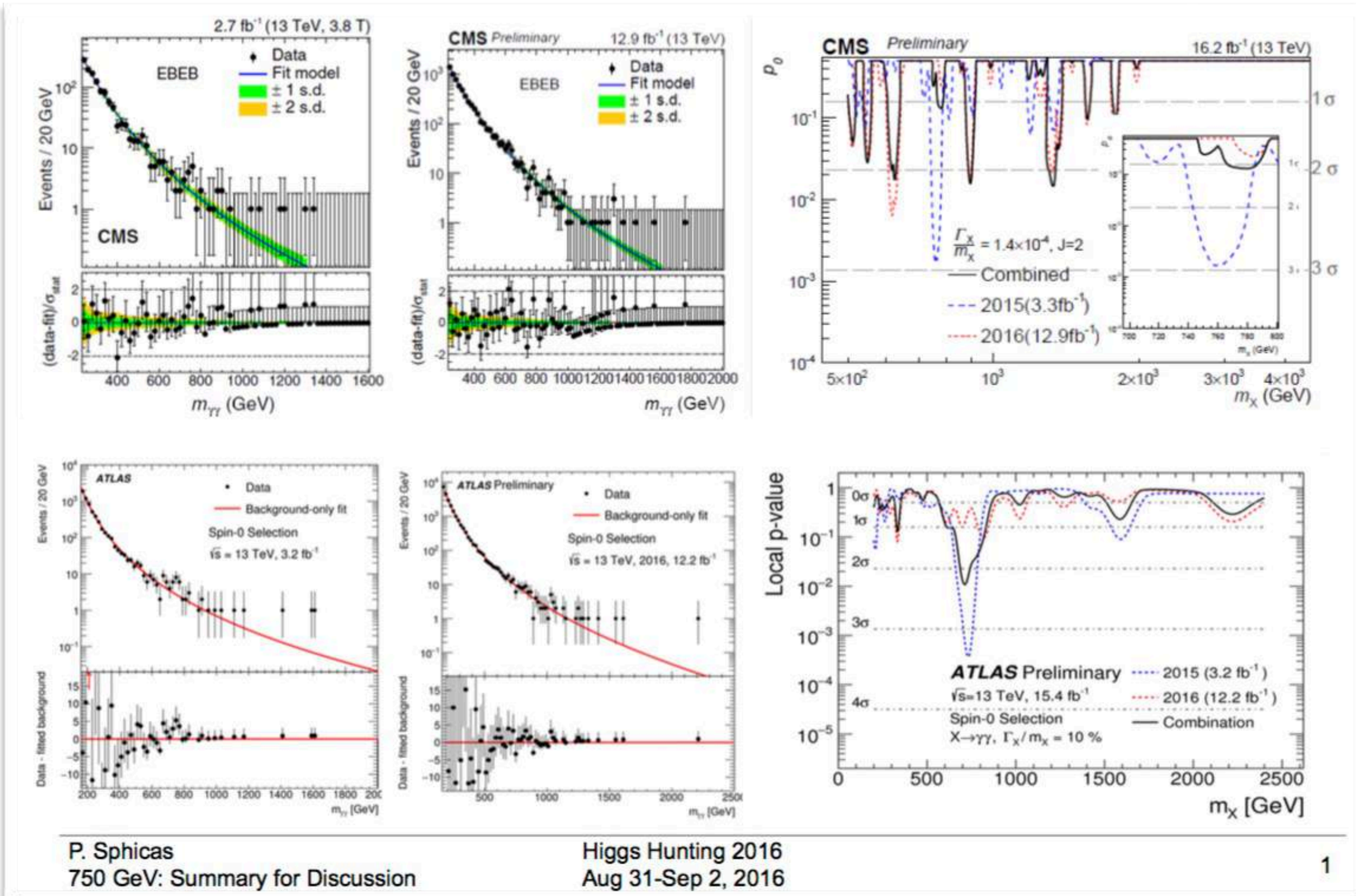
Since $m_H = 125$ GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

Beyond the Higgs

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

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

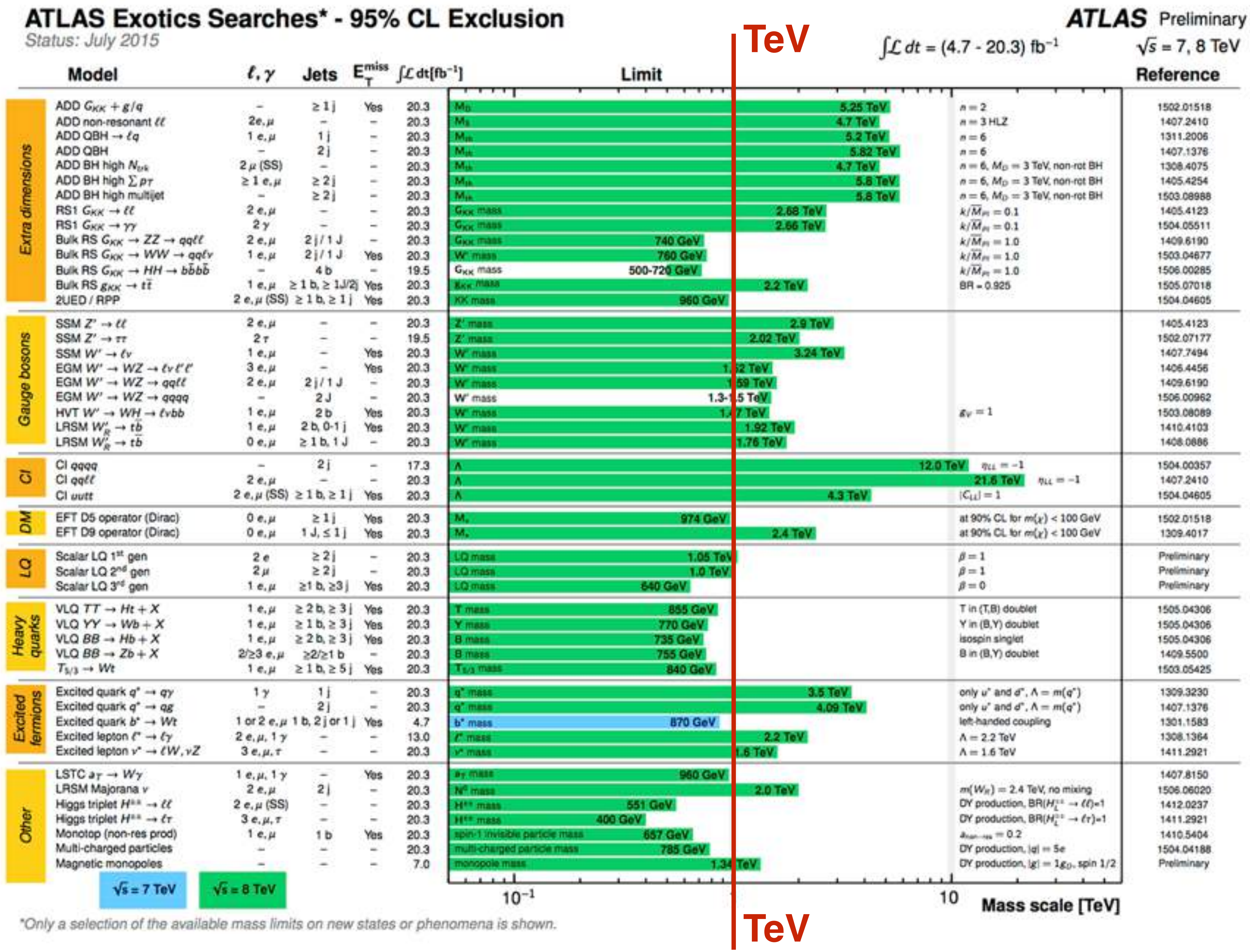
750 GeV, Summer 2016



=> the resonant signal is not confirmed. But …

… little we know about the TeV scale!!

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



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

Flavour anomalies left over from run 1, some examples

$$R(K) = \frac{B \to K\mu^+\mu^-}{B \to Ke^+e^-} = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$

LHCb, arXiv:1406.6482

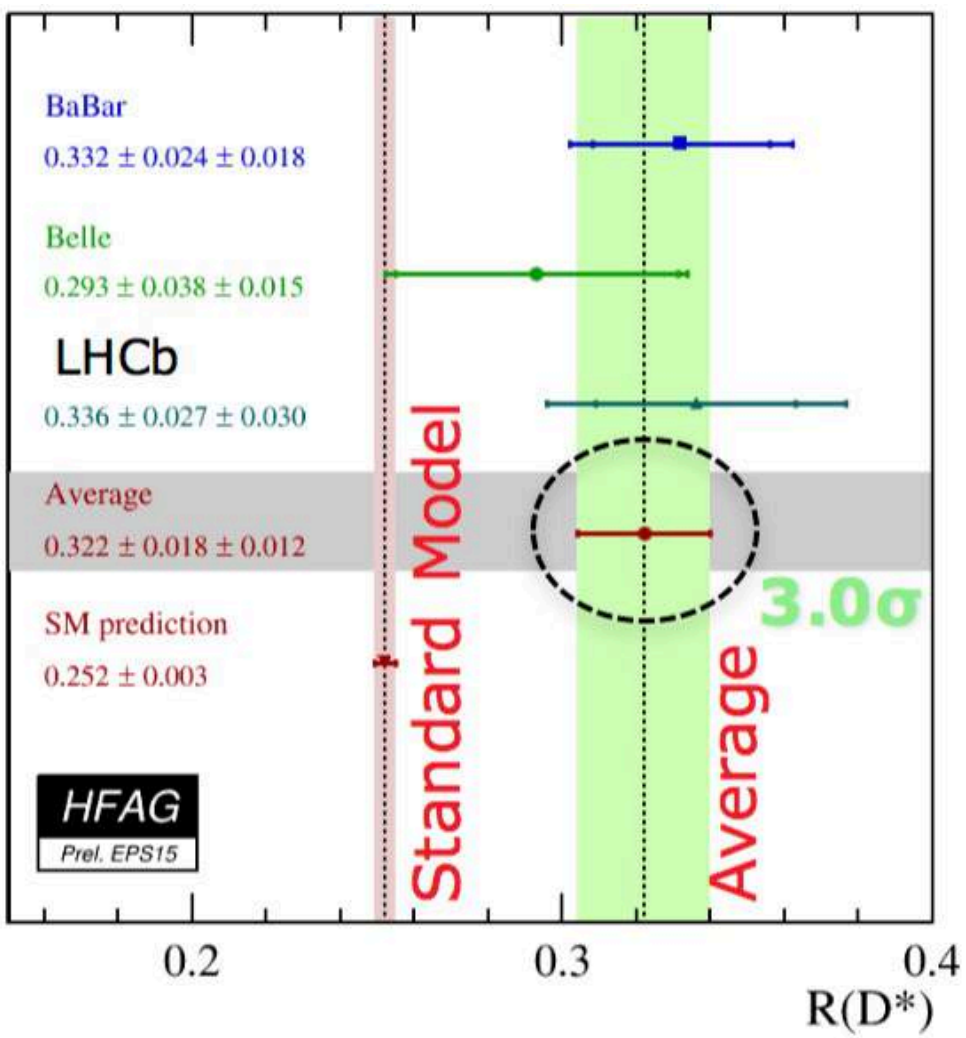
$$R(K^*) = \frac{B \to K^* \mu^+ \mu^-}{B \to K^* e^+ e^-}$$

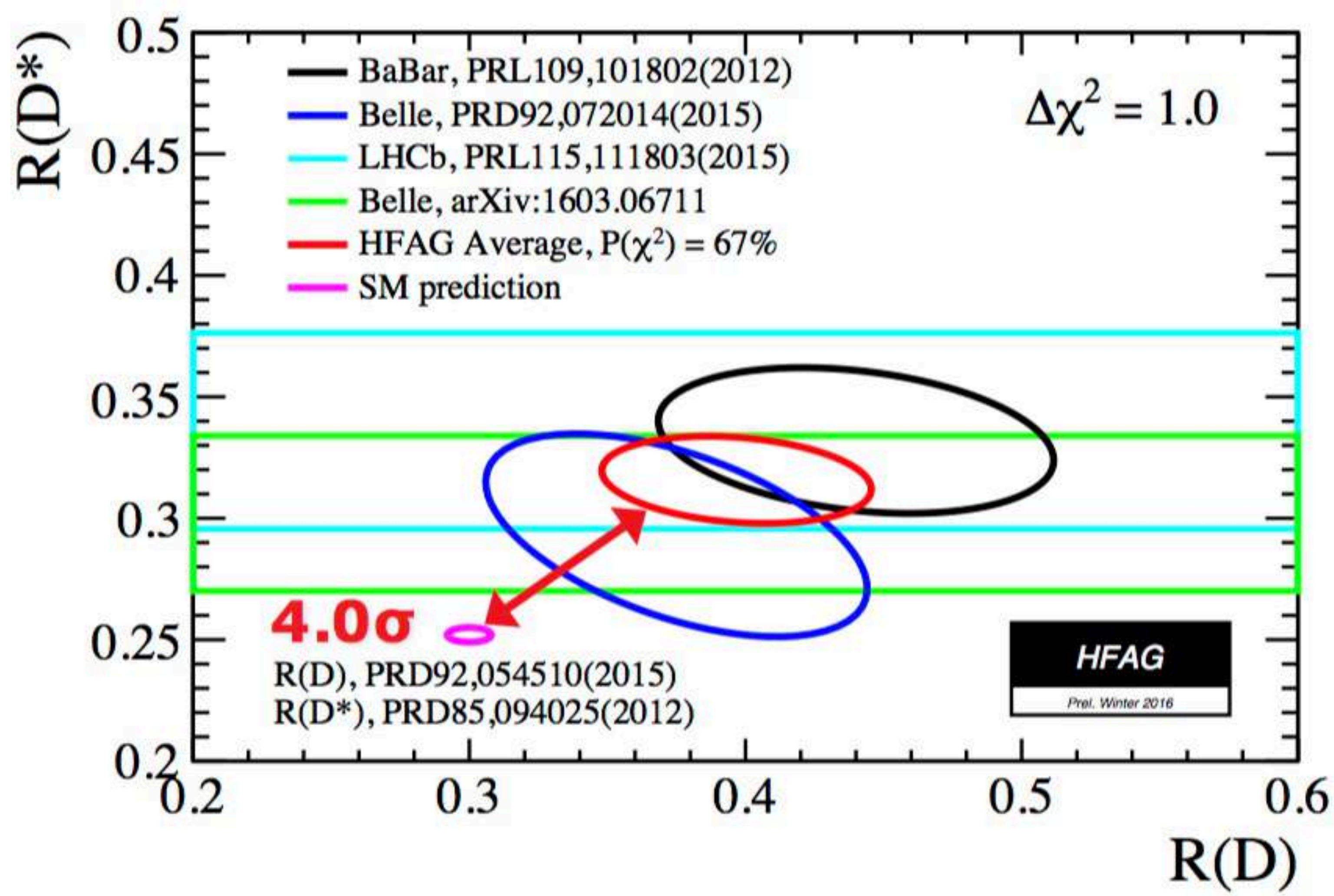
April 18 2017, https://indico.cern.ch/event/580620/

LHCb Preliminary	low-q^2	central-q^2
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\ 0.110}_{-\ 0.070} \pm 0.024$	$0.685\ ^{+\ 0.113}_{-\ 0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]
SM	**0.92 ± 0.02**	**1.00 ± 0.01**

Flavour anomalies left over from run 1, some examples

$$R(D^{(*)}) = BR(B^0 \rightarrow D^{(*)}\tau\nu) \ / \ BR(B^0 \rightarrow D^{(*)}\mu\nu)$$



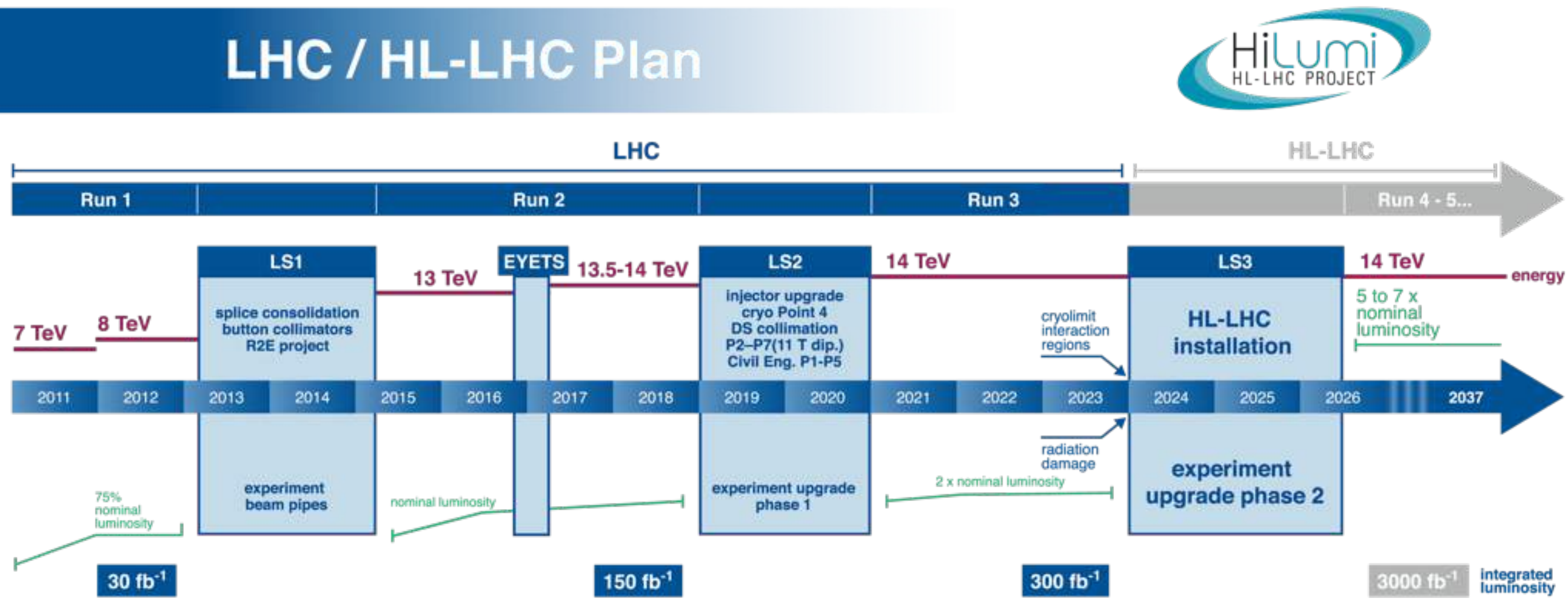


***NB** In run 2 LHCb has already collected more than twice the run 1 statistics of b hadrons*

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! <<==

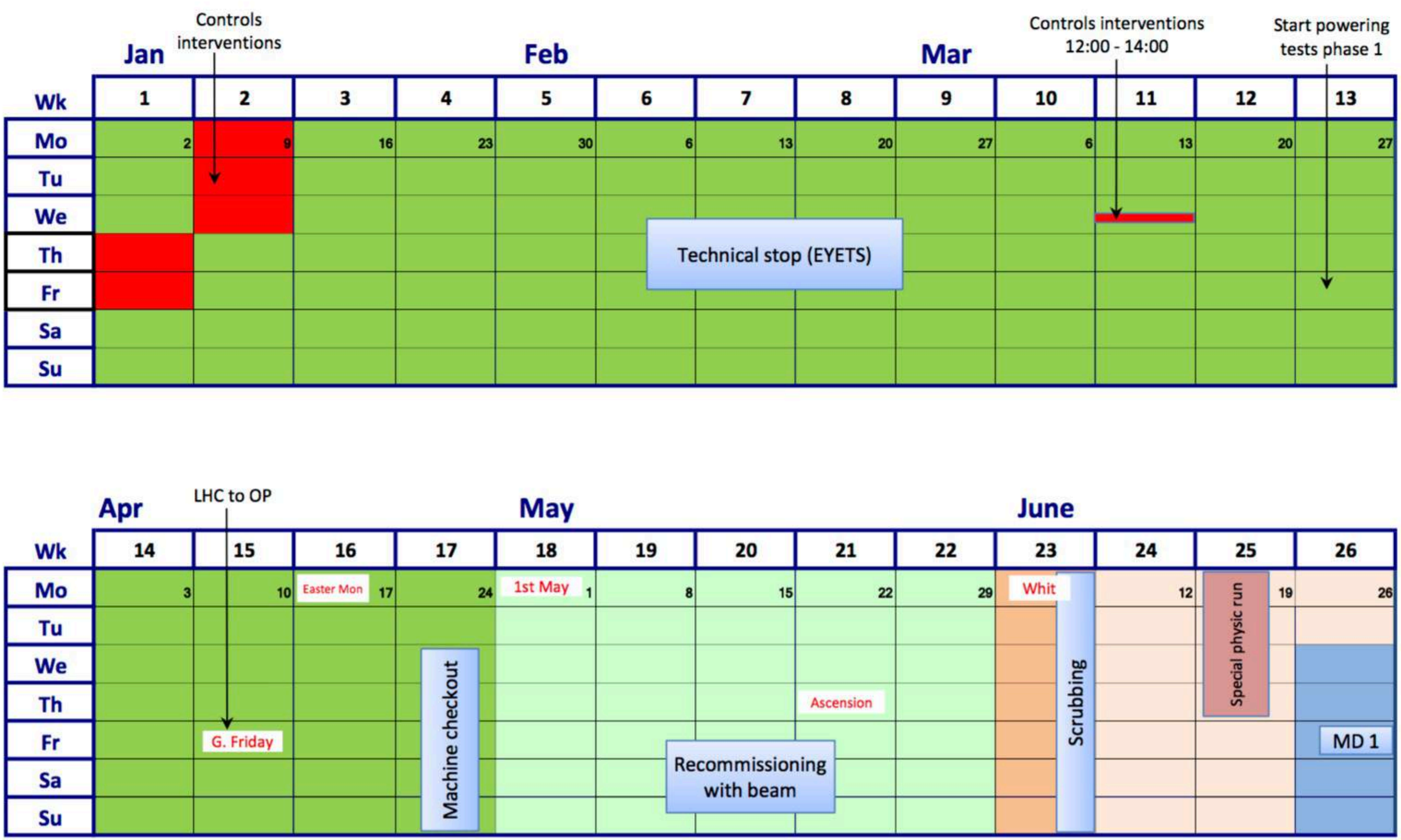
ML/RS

March 8, 2017

ver. 1.0

LHC Schedule 2017

Approved by the Reseach Board, 8 March 2017

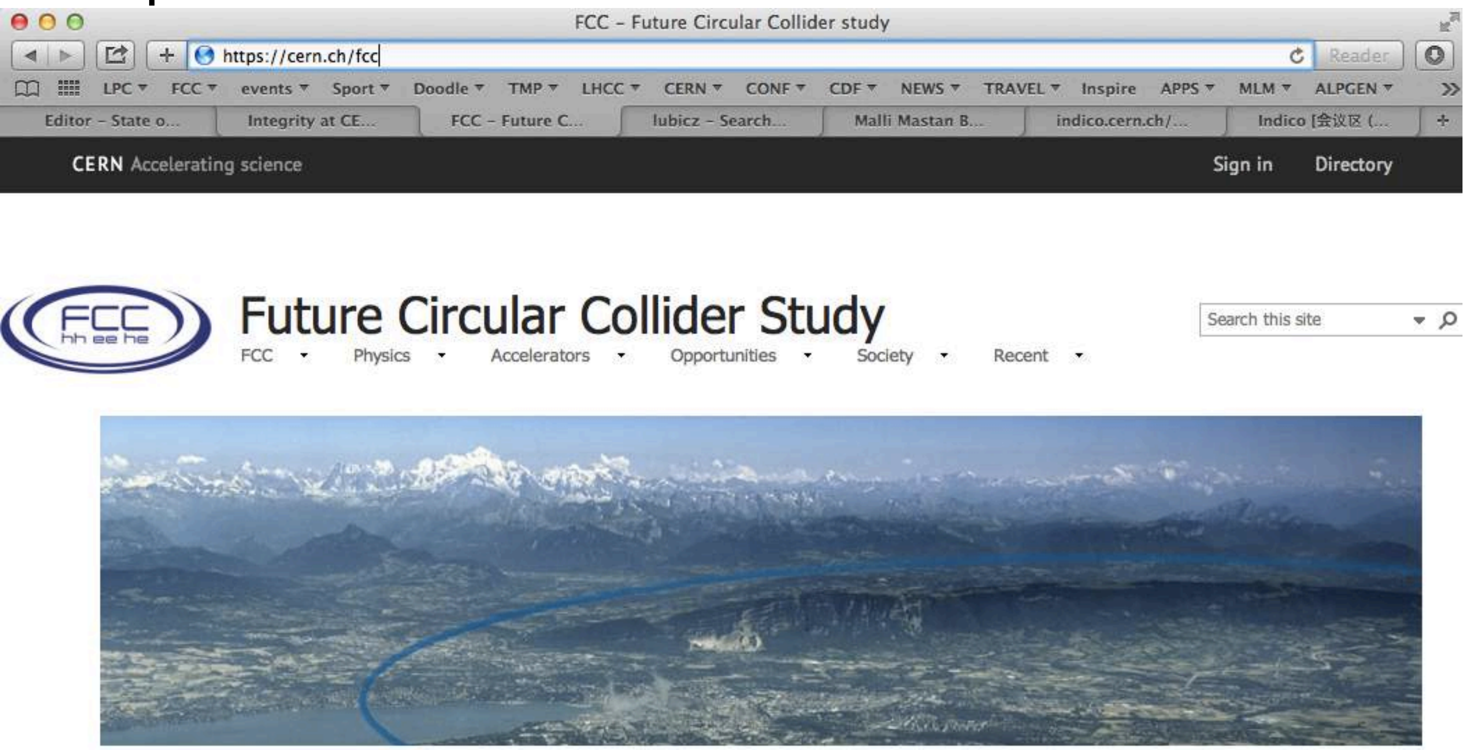


Beyond the LHC

Future Circular Colliders

http://cern.ch/fcc

http://cepc.ihep.ac.cn

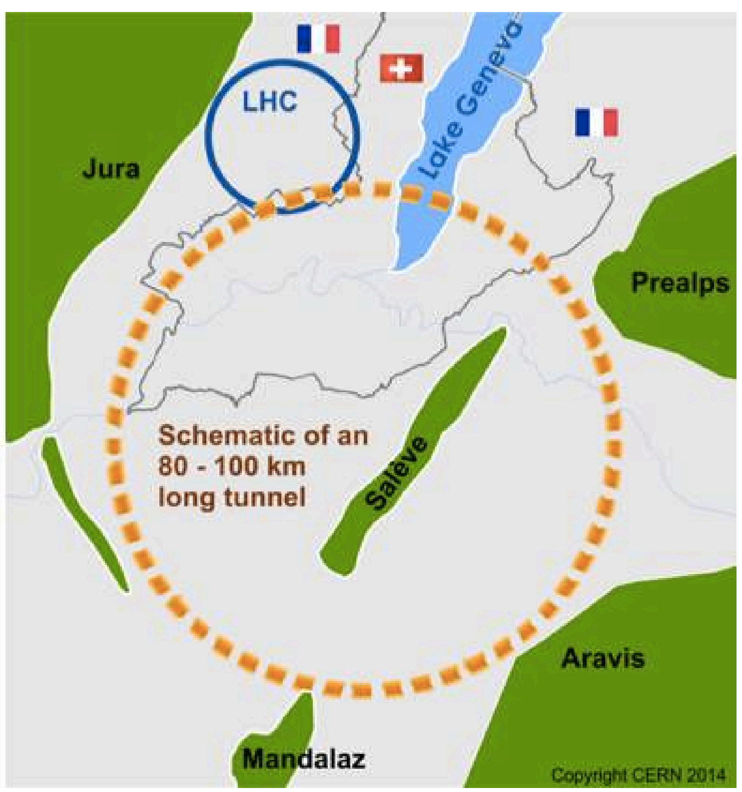


Forming an international collaboration to study:

- *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



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

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

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

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

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

Remark

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

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

(1) the **guaranteed deliverables:**

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

(2) the **exploration potential:**

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

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

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

- Questions to which firm Yes/No answers can likely be given:
  - 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?

[No Title]

lepton collider parameters

parameter	FCC-ee (400 MHz)					LEP2
Physics working point	Z		WW	ZH	tt_{bar}	
energy/beam [GeV]	45.6		80	120	175	105
bunches/beam	30180	91500	5260	780	81	4
bunch spacing [ns]	7.5	2.5	50	400	4000	22000
bunch population [10^{11}]	1.0	0.33	0.6	0.8	1.7	4.2
beam current [mA]	1450	1450	152	30	6.6	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	210	90	19	5.1	1.3	0.0012
energy loss/turn [GeV]	0.03	0.03	0.33	1.67	7.55	3.34
synchrotron power [MW]	100					22
RF voltage [GV]	0.4	0.2	0.8	3.0	10	3.5

identical FCC-ee baseline optics for all energies

FCC-ee: 2 separate rings, LEP: single beam pipe

Operation plan

FCC-ee run	Z pole	WW threshold	HZ	$t\bar{t}$ threshold	Above $t\bar{t}$ threshold
$\sqrt{s}$ [GeV]	90	160	240	350	> 350
$\mathcal{L}$ [ab^{-1}/year]	88	15	3.5	1.0	1.0
Years of operation	0.3 / 2.5	1	3	0.5	3
Events	$10^{12}/10^{13}$	10^{8}	2×10^{6}	2.1×10^{5}	7.5×10^{4}

plus possible runs at the Z peak (125 GeV) and around the Z pole (extraction of α_{QED} at M_Z)

Hadron collider parameters

parameter	FCC-hh		HE-LHC* *tentative	(HL) LHC
collision energy cms [TeV]	100		>25	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25
beta* [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	20 - 30	>25	(5) 1
events/bunch crossing	170	<1020 (204)	850	(135) 27
stored energy/beam [GJ]	8.4		1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		3.6	(0.35) 0.18

Operation plan

- **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

FCC-he & HE-LHC-ep parameters

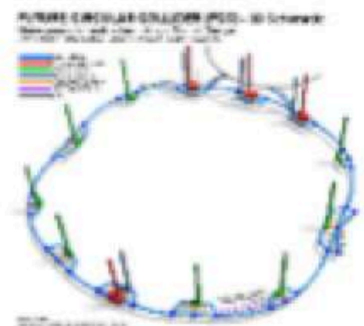
parameter	FCC-he	ep at HE-LHC	ep at HL-LHC	LHeC
E_p [TeV]	50	12.5	7	7
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	**3.5**	**1.7**	1.3	1.3
bunch spacing [ns]	25	25	25	25
protons / bunch [10^{11}]	1	2.5	2.2	1.7
$\gamma\varepsilon_p$ [μm]	2.2	2.5	2.0	3.75
electrons / bunch [10^9]	2.3	2.3	2.3	1.0
electron current [mA]	15	15	15	6.4
IP beta function β_p* [m]	15	10	7	10
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
proton-ring filling factor	0.8	0.8	0.8	0.8
luminosity [10^{33} cm^{-2}s^{-1}]	**11**	**9**	8	1.3

FCC 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

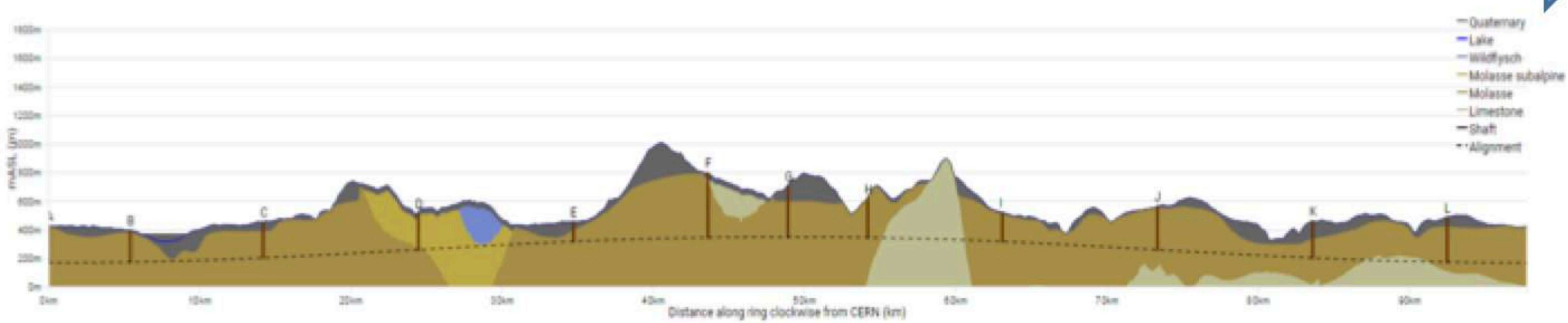


Cost and schedule study ongoing with 2 consultants

ILF CONSULTING ENGINEERS
GC GEOCONSULT
synaxis

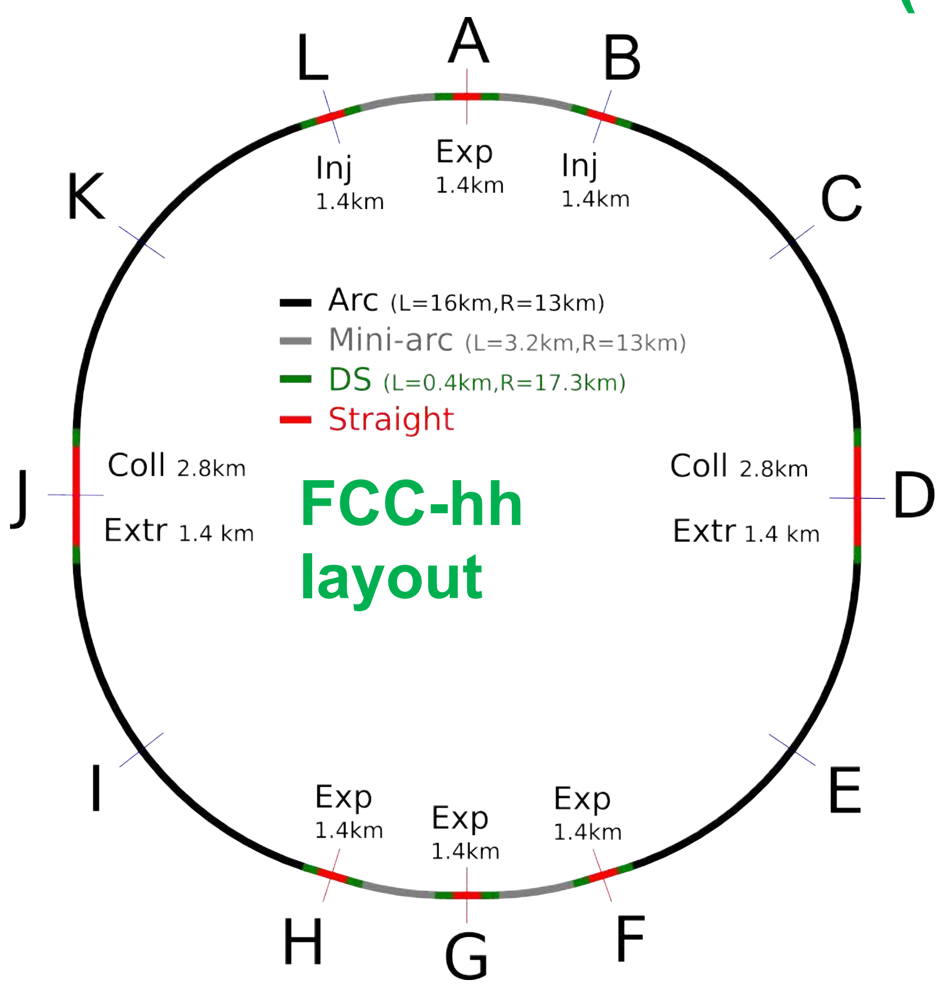
- Cost & schedule **estimates**
- **Inclined** access shafts **assessment**
- Tunnel and shaft **cross-section designs**

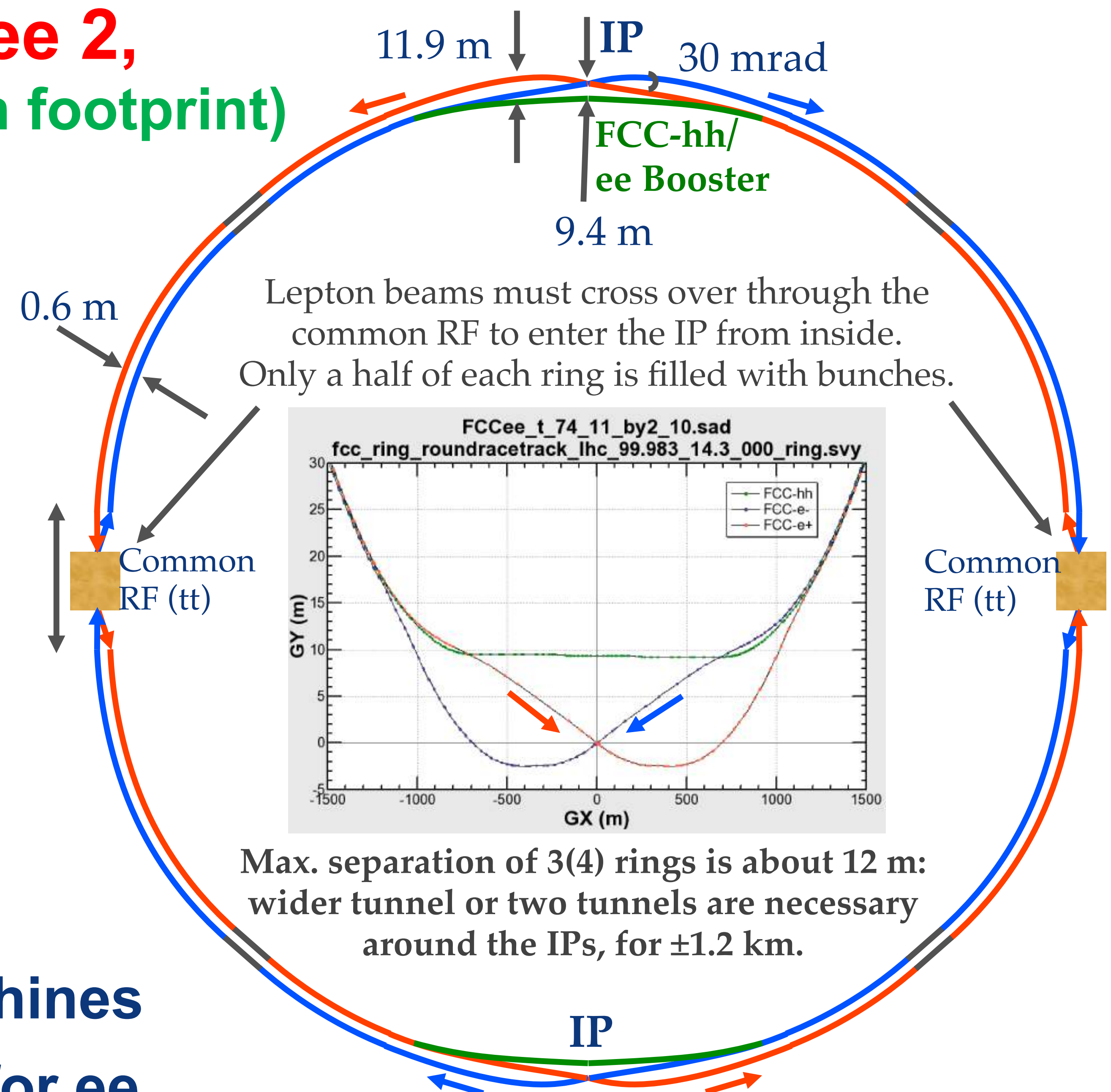
Nov. 2015 → Apr. 2016 → Aug. 2016 → Sept. 2016 → Dec. 2016



Common layouts for hh & ee

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



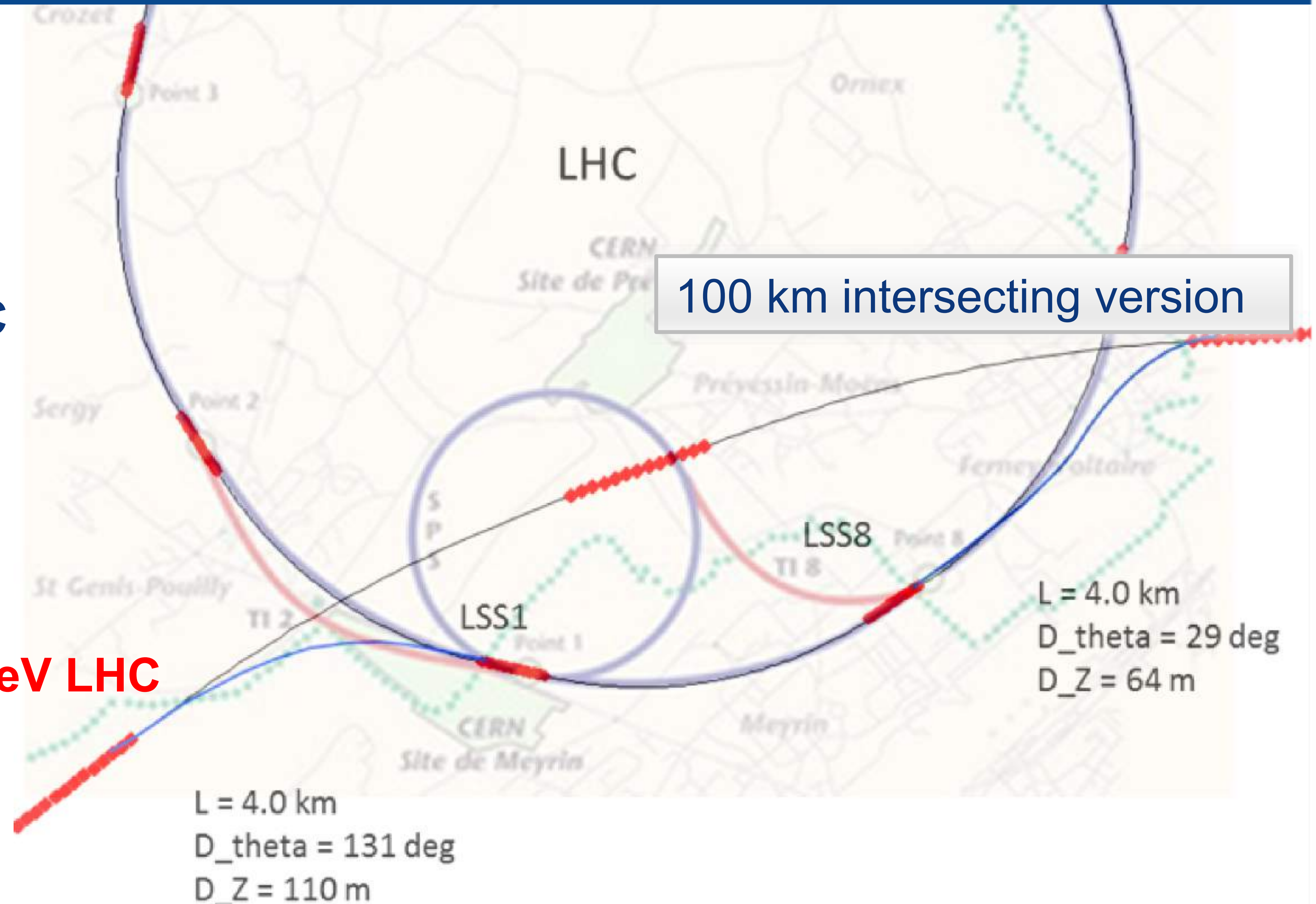


- 2 main IPs in A, G for both machines
- asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector

FCC-hh injector studies

Injector options:

- SPS → LHC → FCC
- SPS/$SPS_{upgrade}$ → FCC



Current baseline:

- **Injection energy 3.3 TeV LHC**

Alternative option:

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

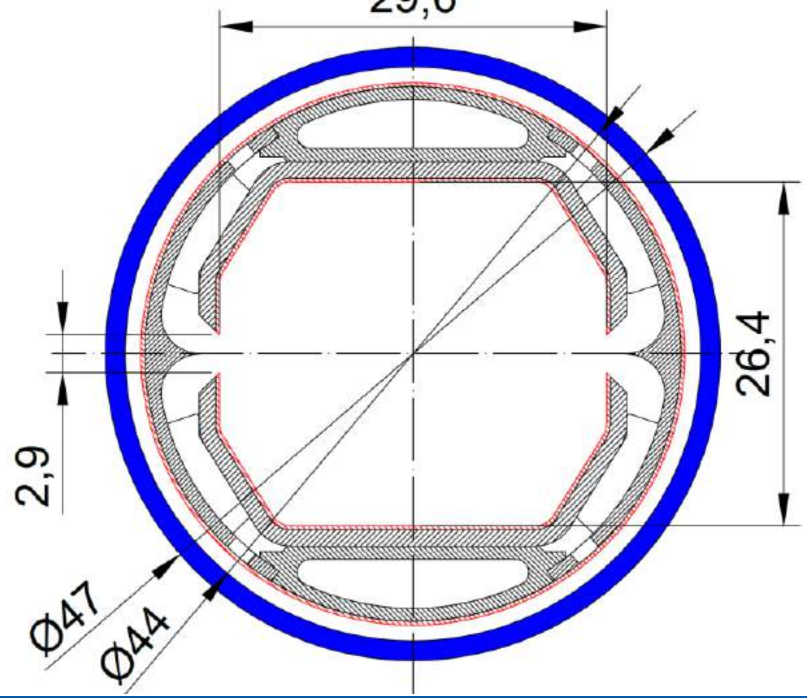
Synchrotron radiation beam screen prototype

High synchrotron radiation load of proton beams @ 50 TeV:

- **~30 W/m/beam (@16 T)** (LHC <0.2W/m)
- **5 MW total in arcs (@1.9 K!!!)**

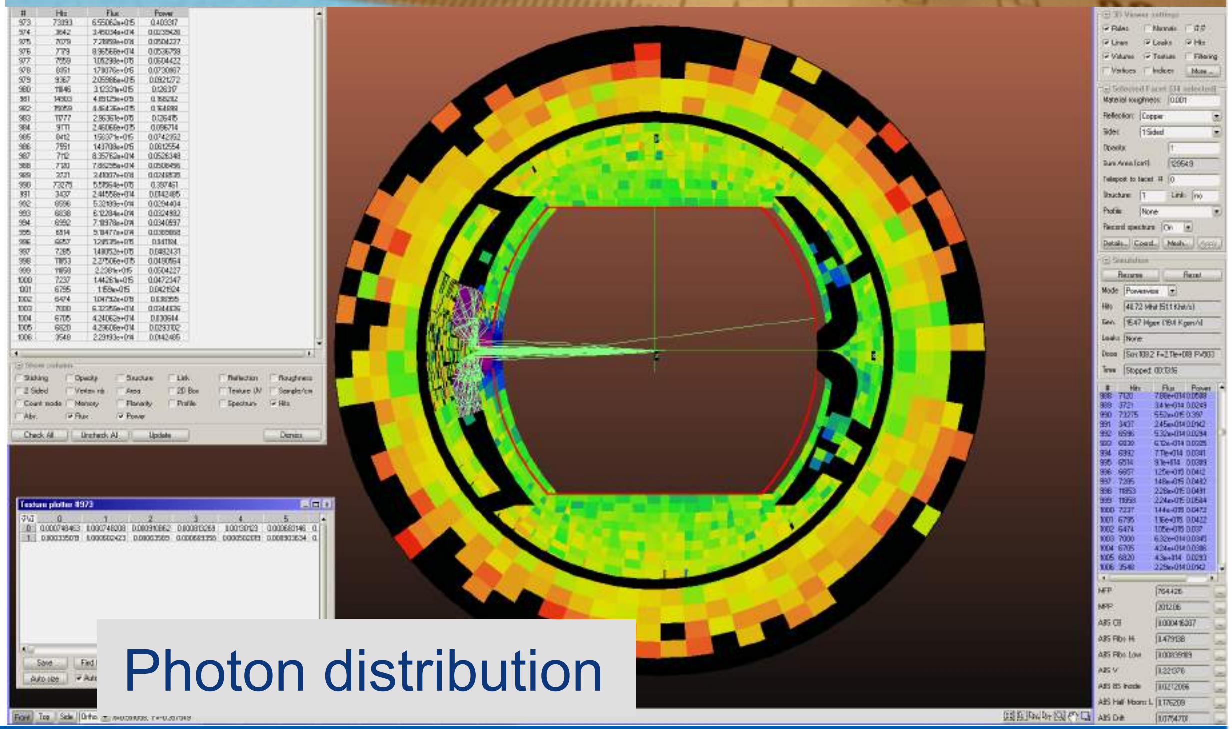
New Beam screen with ante-chamber

- absorption of synchrotron radiation at 50 K to reduce cryogenic power by a factor 50 to 100 MW total



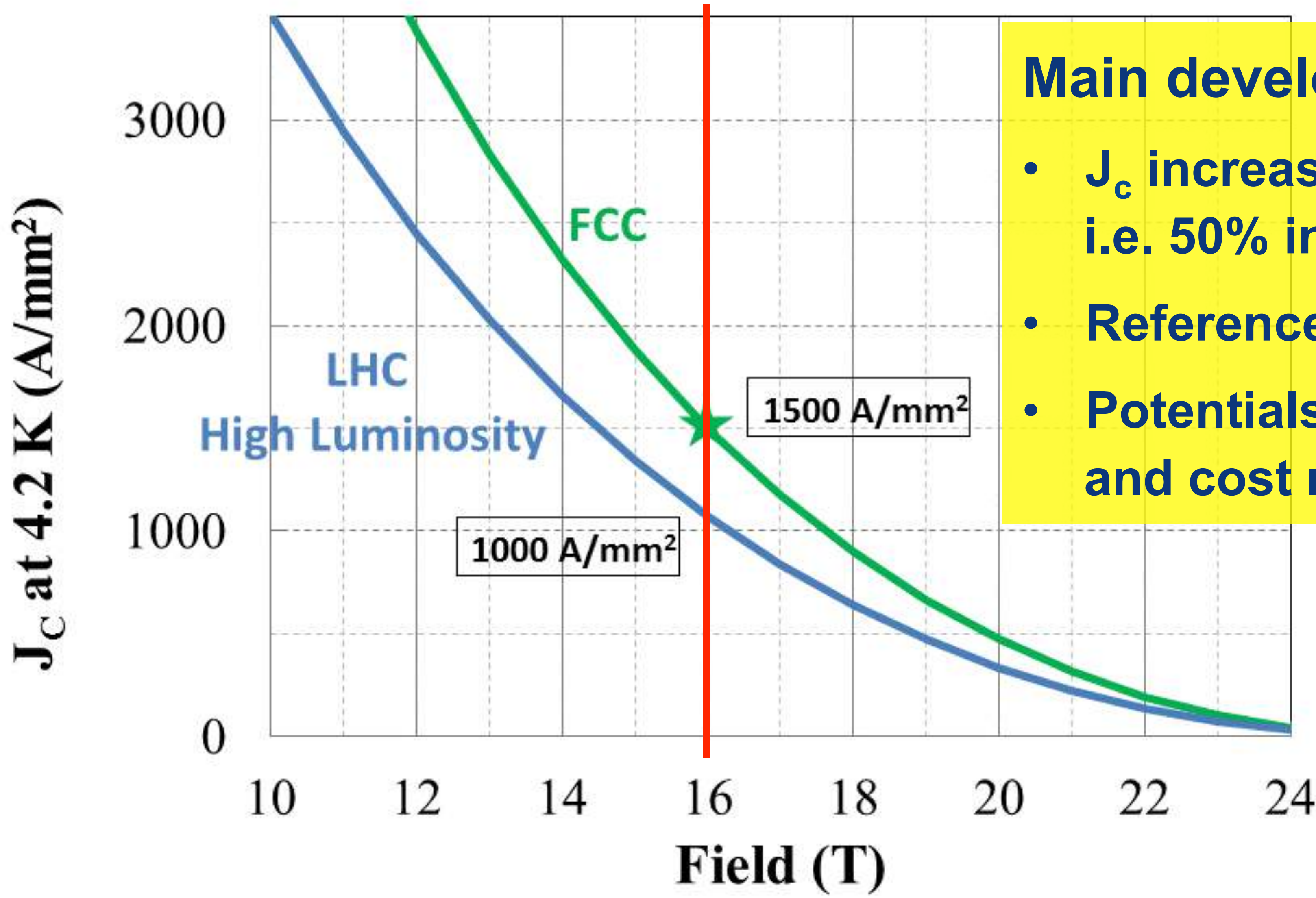
First FCC-hh beam screen prototype

Testing 2017 in ANKA within EuroCirCol



Nb_3Sn conductor program

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



Main development goals until 2020:

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

Collaborations FCC Nb_3Sn program

Procurement of state-of-the-art conductor for protoyping:

- Bruker– European,
- OST – US

Stimulate 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
- CERN/Bruker– European **industrial** contribution

Characterisation of conductor & research with universities:

- **Europe: Technical Univ. Vienna, Geneva University, University of Twente**
- **Applied Superconductivity Centre** at Florida State University

New US DOE MDP effort – US activity with **industry** (OST) and labs

Progress with FCC physics, 2016

- **FCC-ee events**: http://indico.cern.ch/category/5259/
  - Recent 2016 wshops:
    - 25 Nov *"LHC, FCC-ee, FCC-hh Interplay"*
    - 23-24 Nov *"2nd mini-workshop on FCC-ee detector requirements"*
    - 21-22 Nov *"Parton Radiation and Fragmentation from LHC to FCC-ee"*
    - 4-5 Feb *"10th FCC-ee physics workshop"*
    - 2-3 Feb FCC-ee Mini-Workshop: "*Physics Behind Precision*"

- **FCC-eh events**: http://lhec.web.cern.ch

- **FCC-hh events**: http://indico.cern.ch/category/5258/
  - Recent results: **"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

Reference literature

- **FCC-ee**:
  - "First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164
  - "High-precision α_s 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

Higgs couplings

Higgs couplings @ FCC-ee

	240 GeV	350 GeV
Total Integrated Luminosity (ab^{-1})	10	2.6
Number of Higgs bosons from $e^+e^- \to HZ$	2,000,000	340,000
Number of Higgs bosons from boson fusion	50,000	70,000

g_{HXY}	240	240+350 (4IP)	240+350 (2IP)
ZZ	0.16%	0.15%	0.18%
WW	0.85%	0.19%	0.23%
bb	0.88%	0.42%	0.52%
cc	1.0%	0.71%	0.87%
gg	1.1%	0.80%	0.98%
ττ	0.94%	0.54%	0.66%
μμ	6.4%	6.2%	7.6%
γγ	1.7%	1.5%	1.8%
Zγ			
tt		~13% from loop effects at tt production threshold	
HH	~30% from loop effects at ZH production		
uu,dd	H->ργ, under study		
ss	H->ϕγ, under study		
BR_{inv}	< 0.48%	< 0.45%	< 0.55%
Γ_{tot}		1%	

(SM: 0.12%)

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

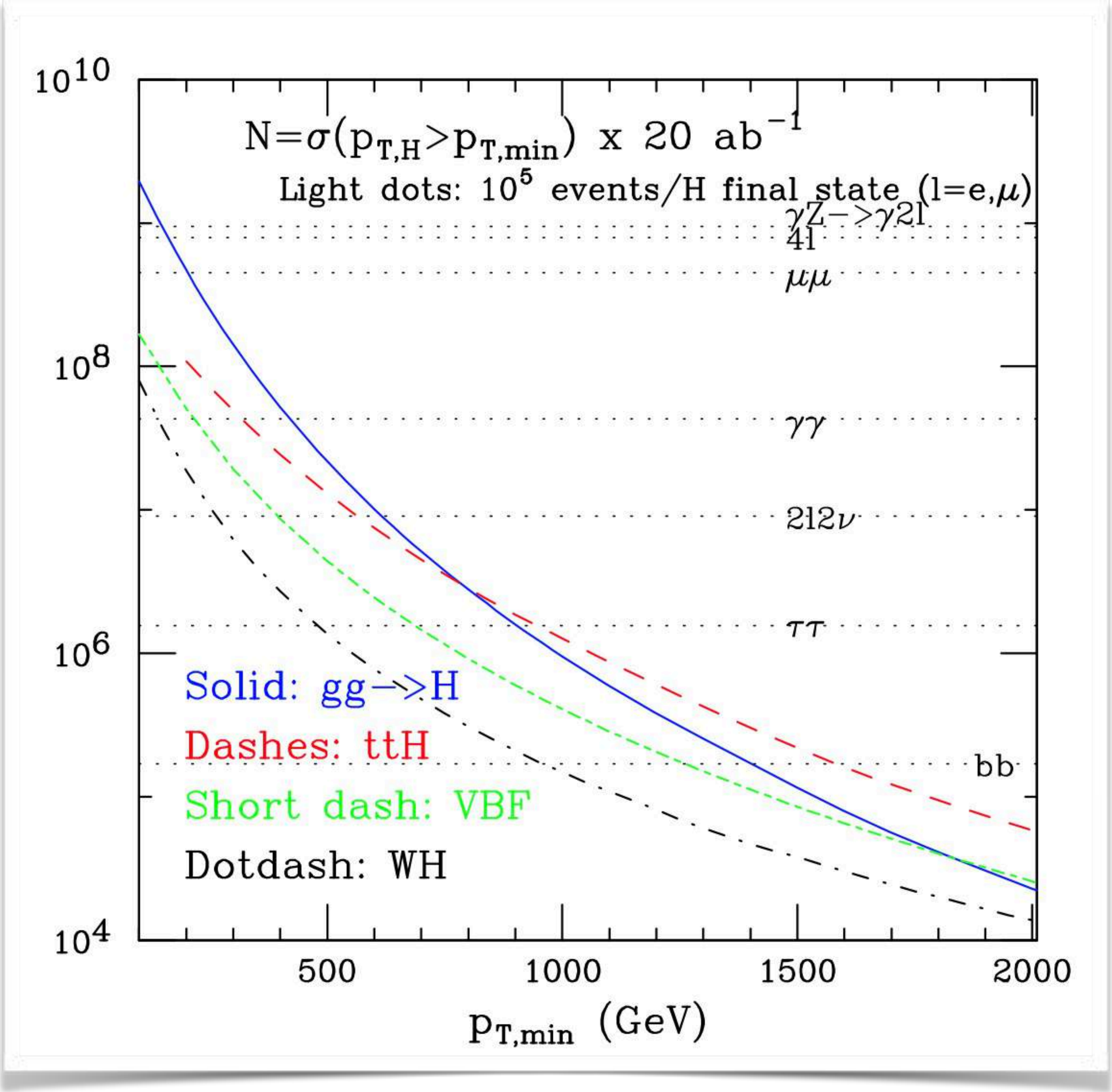
$N_{100} = \sigma_{100\,\text{TeV}} \times 20\ \text{ab}^{-1}$

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

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

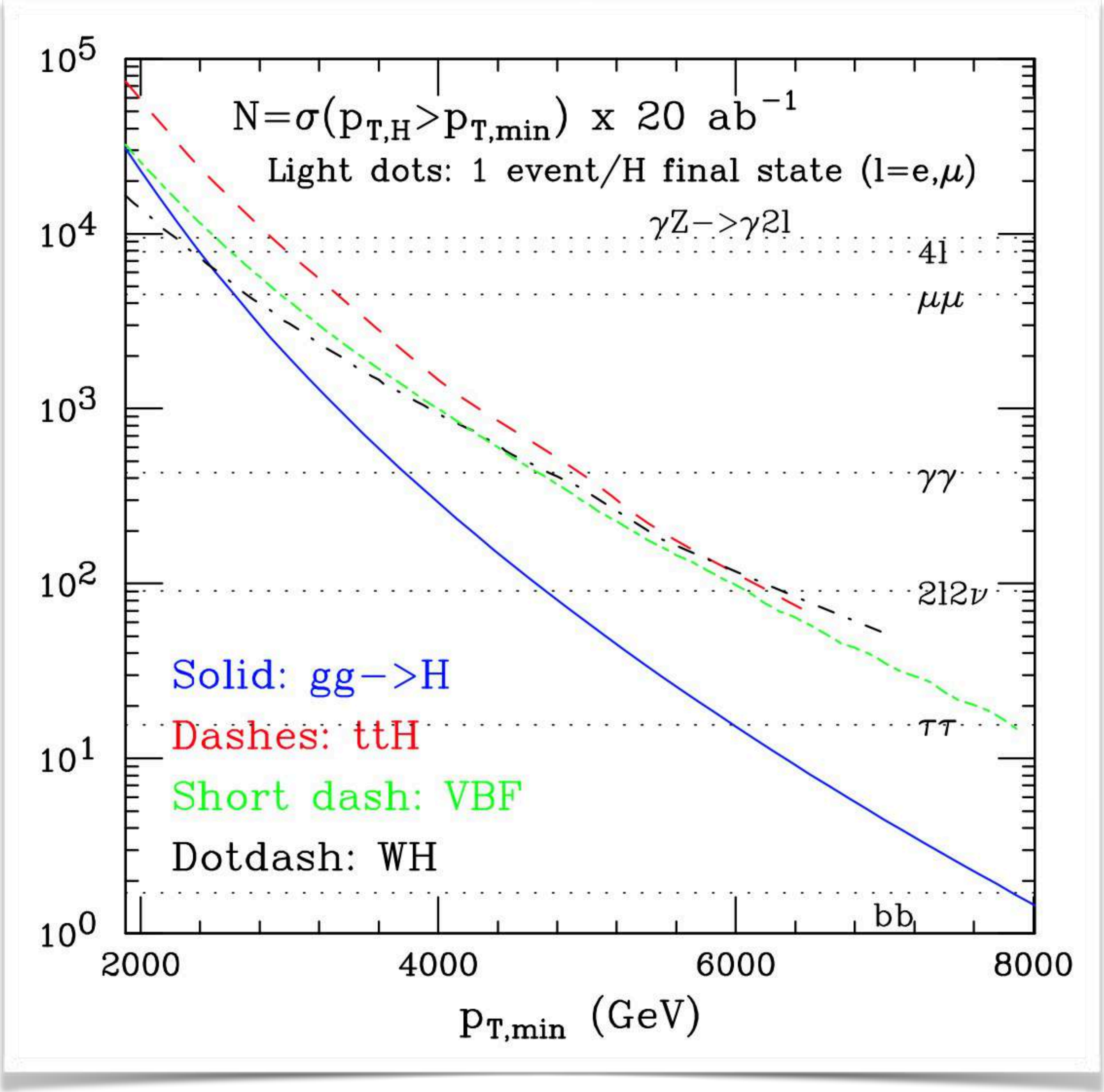
- Huge production rates imply:
  - can afford reducing statistics, with tighter kinematical cuts that reduce backgrounds and systematics
  - can explore new dynamical regimes, where new tests of the SM and EWSB can be done

H at large p_T



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

H at large p_T



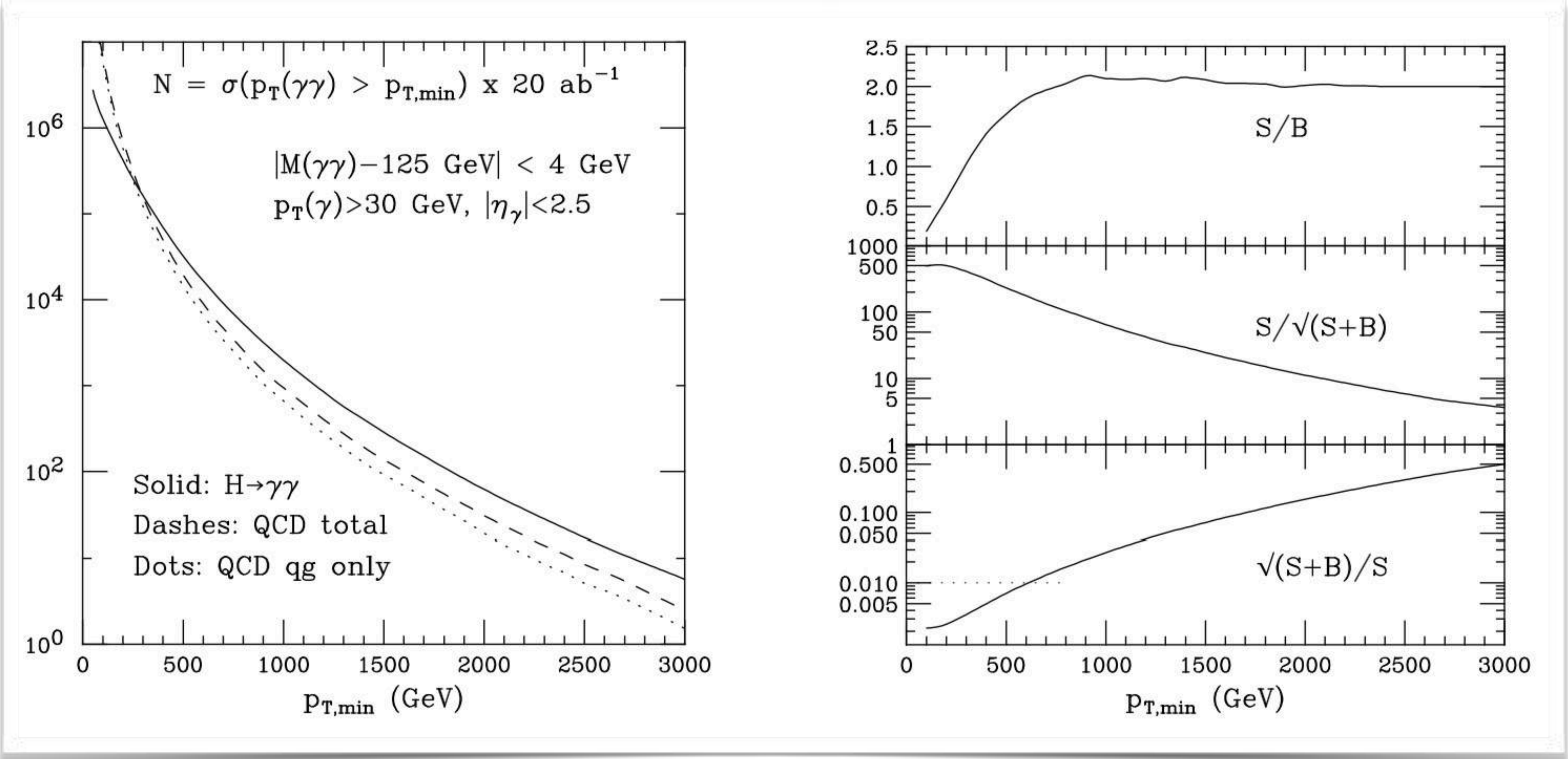
- Statistics in potentially visible final states out to several TeV

remarks

- Huge statistics and dynamical range allow to
  - select Higgs final states with reduced systematics (TH & exp) and backgrounds => improve precision
  - induce sensitivity to higher-dim operators
- Better discrimination of different production channels at large pt(H), and different hierarchy of rates, allows for more diverse studies of production modes

Examples: high-p_T, a clean environment for %-level BR measurements of H rare decays at 100 TeV

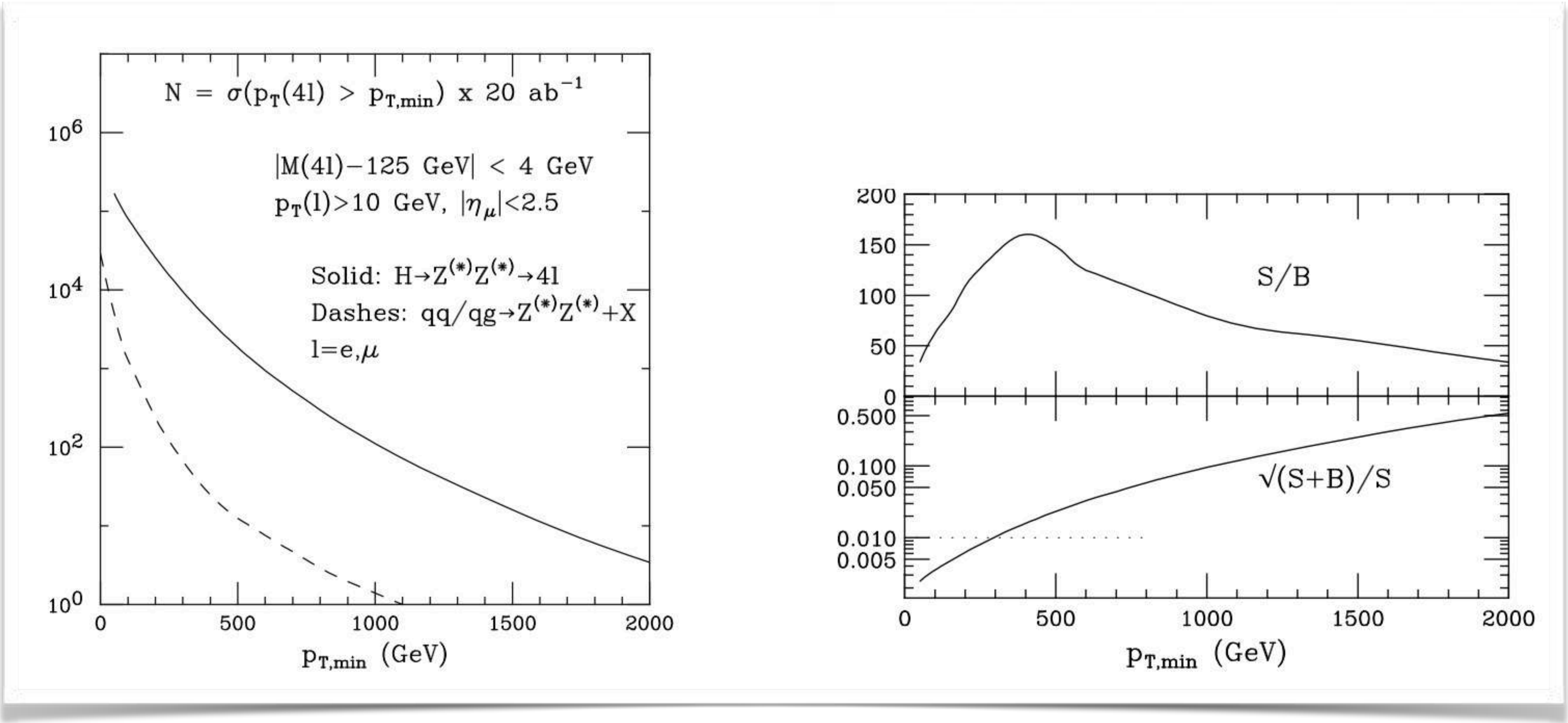
$gg \to H \to \gamma\gamma$ at large p_T



- At LHC, S/B in the $H \to \gamma\gamma$ channel is O(few %)
- At FCC, for $p_T(H)>300$ GeV, S/B~1
- 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

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

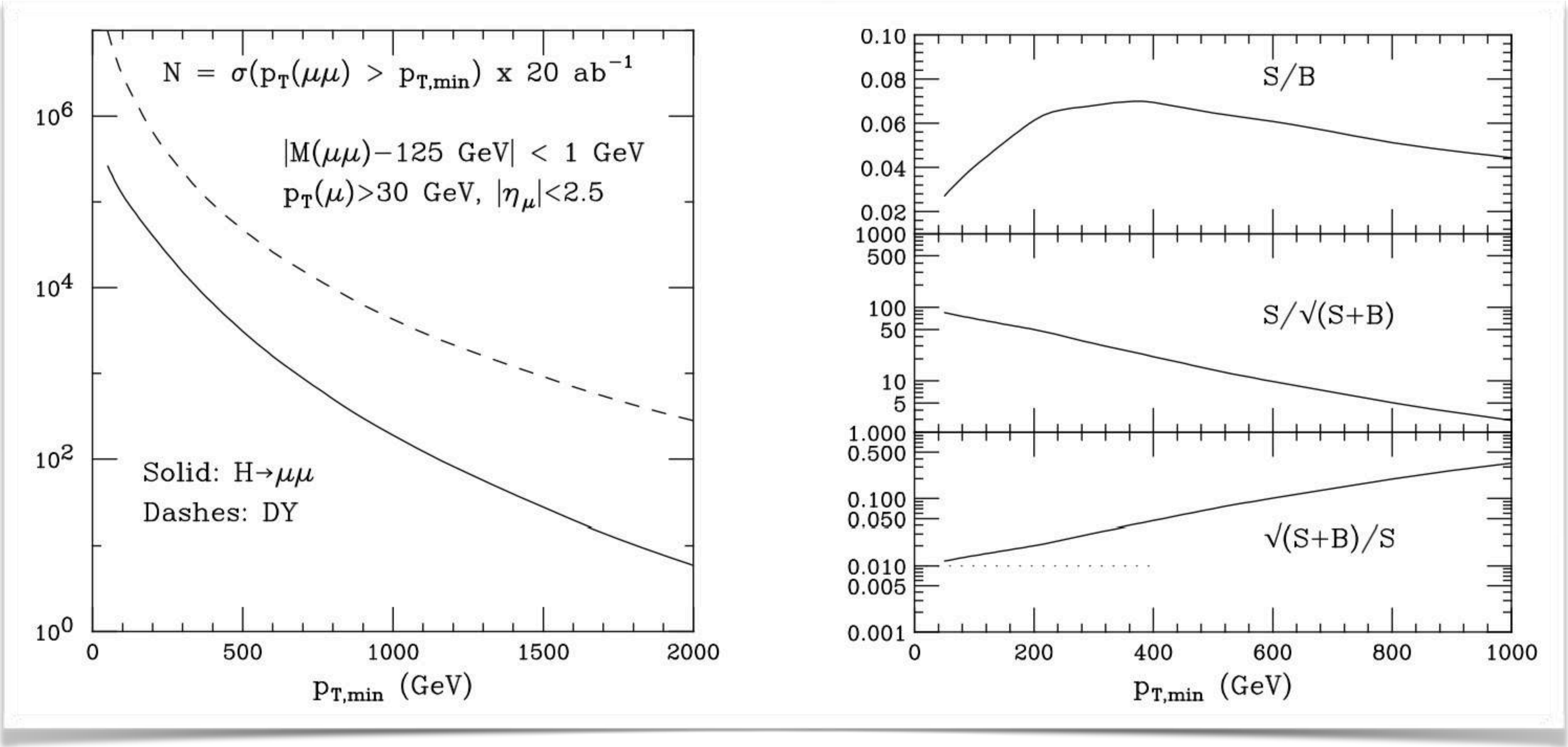
gg→H→ZZ*→4l at large p_T



- 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%

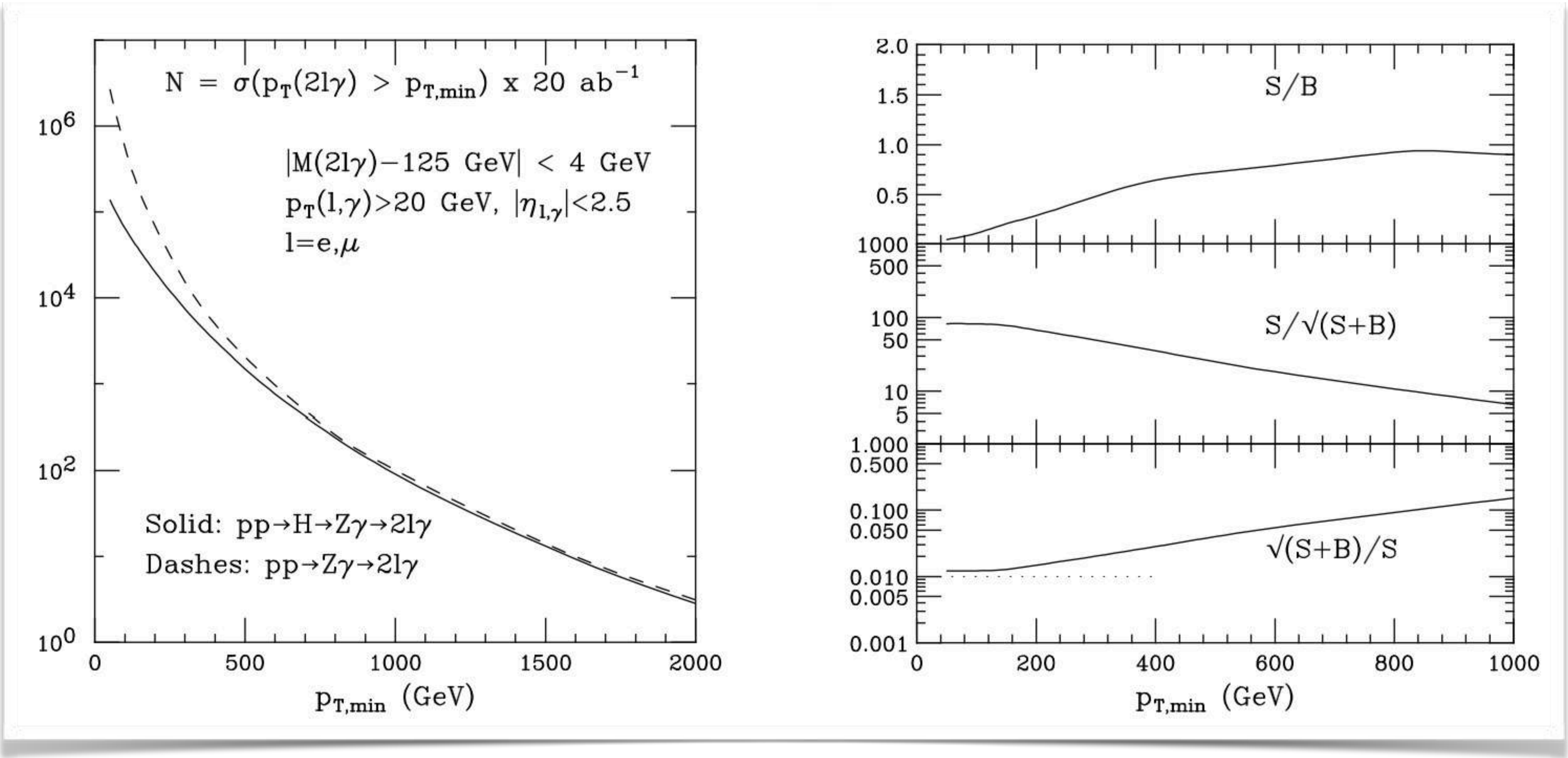
gg→H→μμ at large p_T



- 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%

$gg \to H \to Z\gamma \to \ell\ell\gamma$ 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%

Remarks

Using BR($H \to ZZ^*$) from FCC-ee (known at ~0.3% from δg_{HZZ}~0.15%), production ratios $\sigma(H \to XY)/\sigma(H \to ZZ^*)$ for p_T>100 GeV return the following stat precision on the **absolute value** of rare BRs

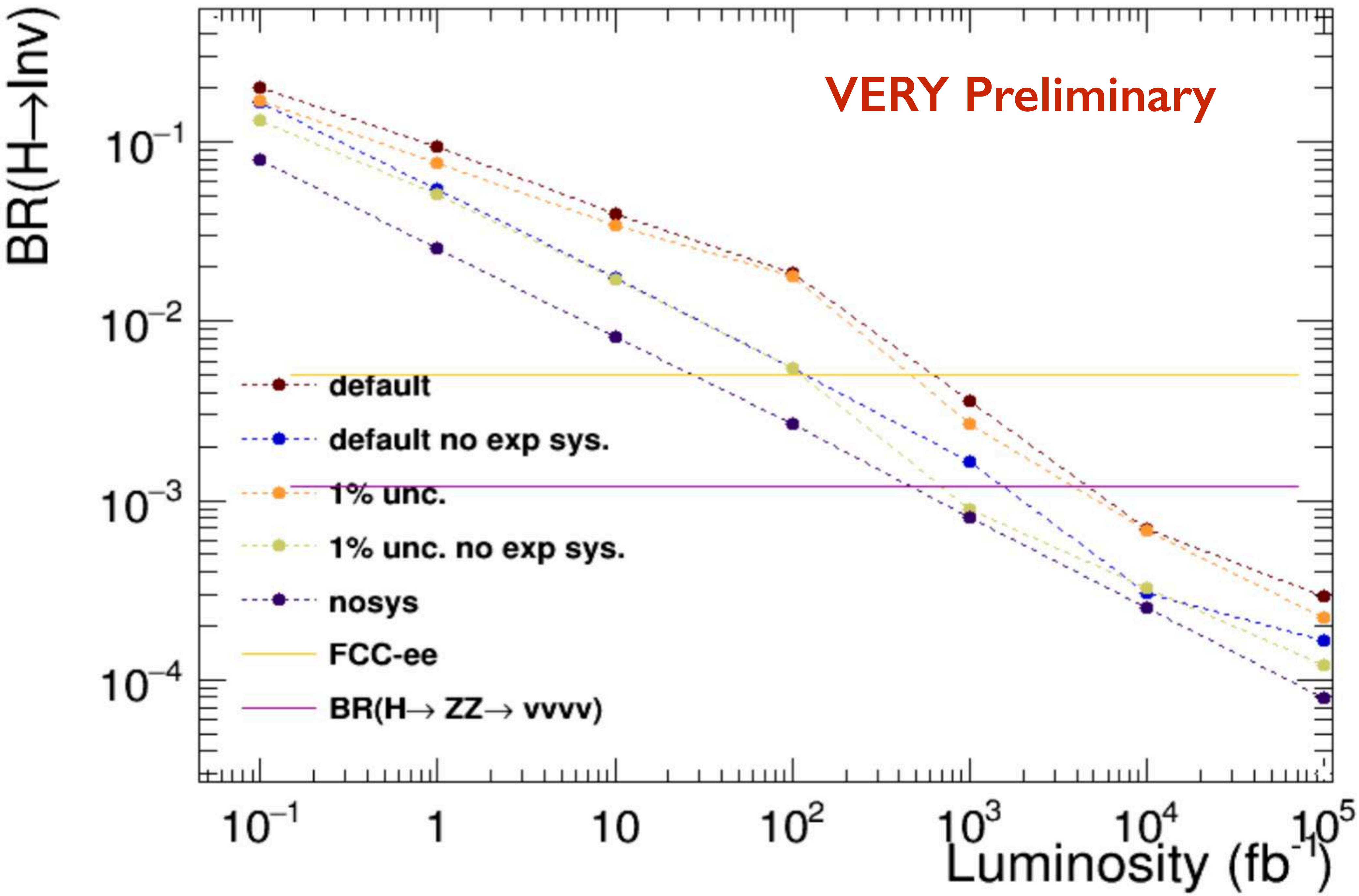
	γγ	Zγ	μμ
δ BR	~0.5%	~1%	~1%

Much larger statistics and p_T reach for modes like WW and ττ. Needs dedicated studies to check potential precision (e.g. study of bgs, systematics from corrections to common fiducial regions, impact of neutrinos, …), but it's unlikely one can match FCC-ee accuracy

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

P.Harris at FCC wshop, updated at Feb 21 WG mtg

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}

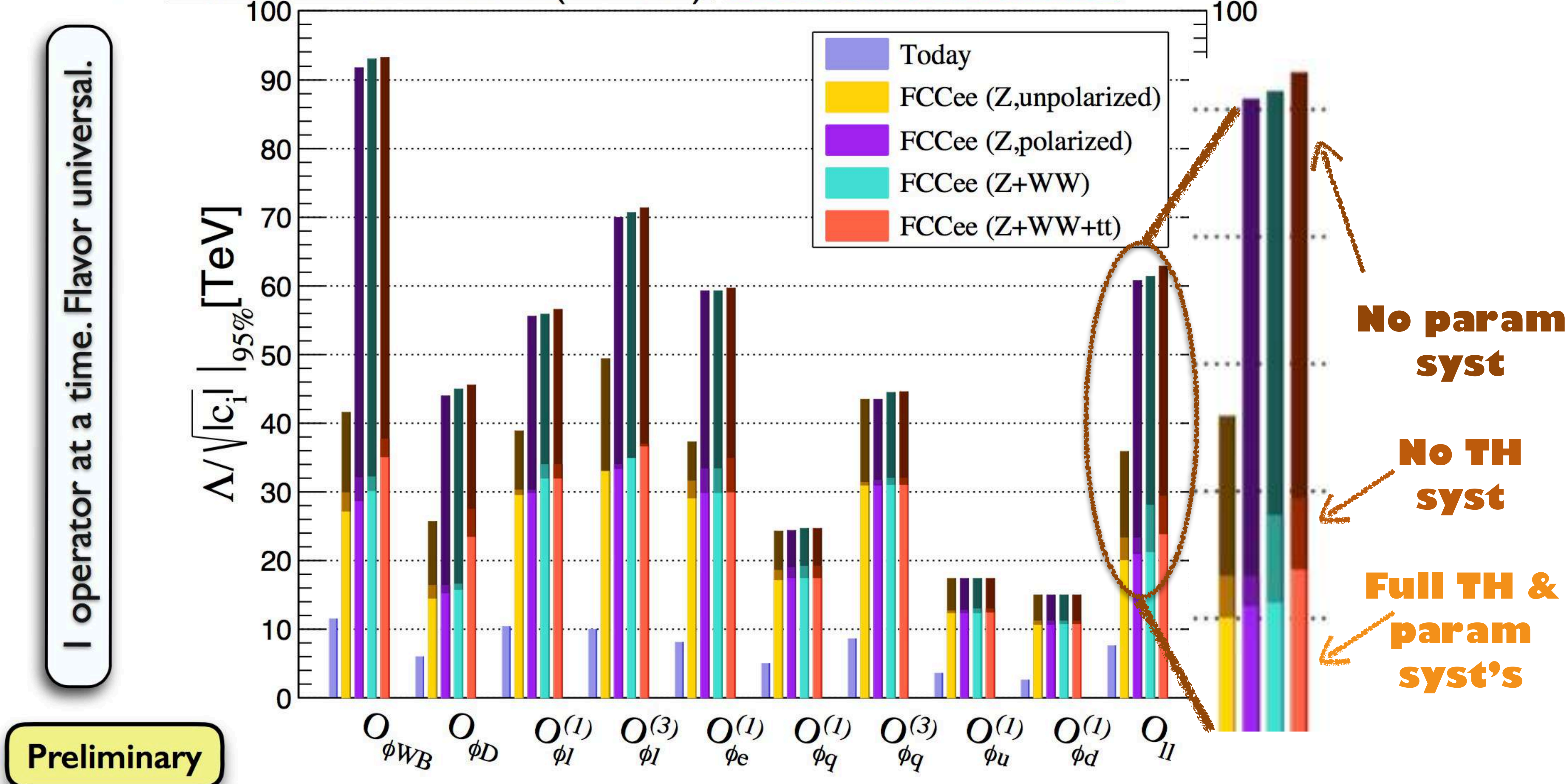
Higgs couplings @ FCC

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%	*see M.Tanaka at FCC wshop*
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)

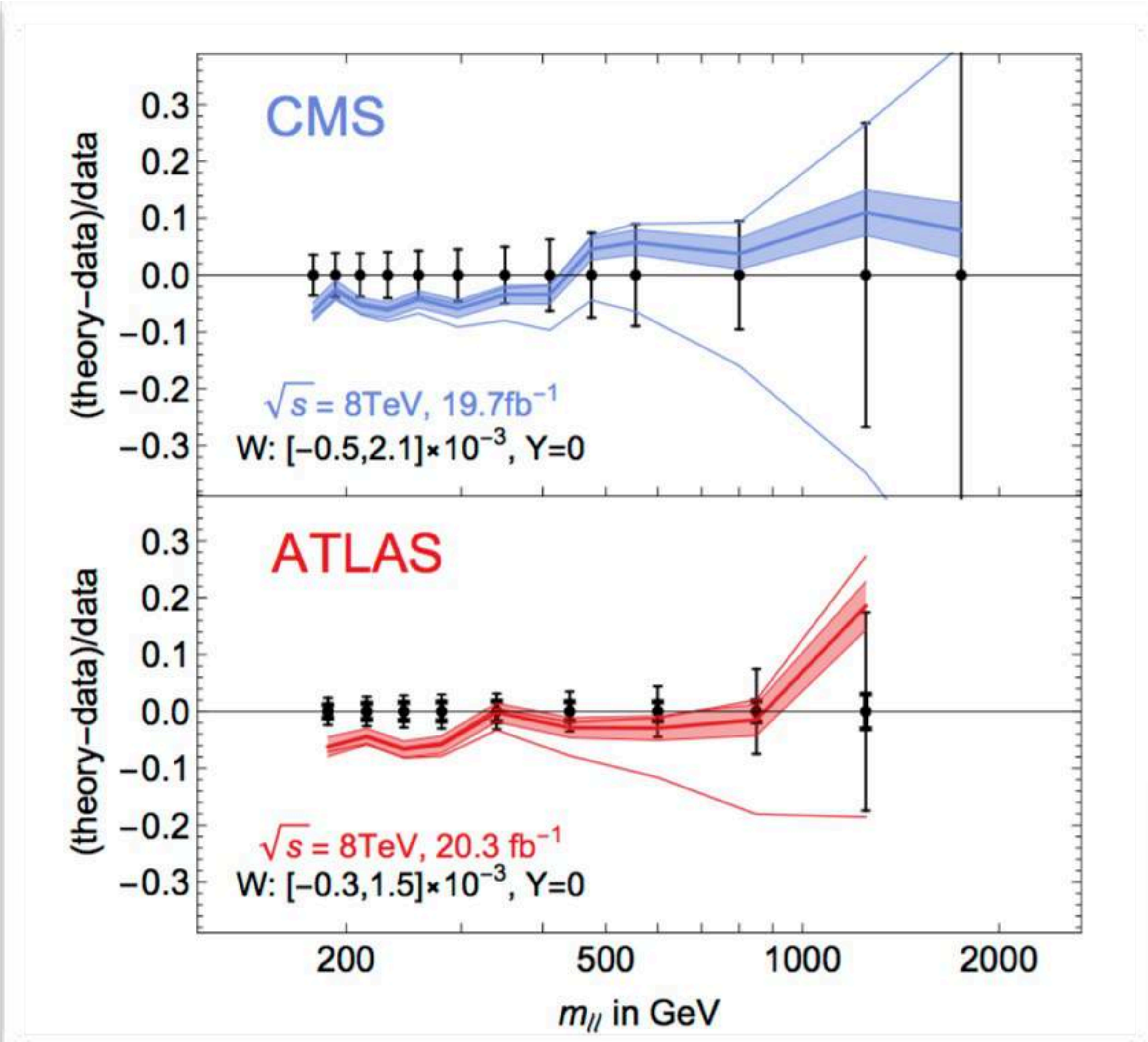
New physics scale reach with EWPT @ FCC-ee

- Dimension six SMEFT (EWPD): **Present vs. Future**



Probes of dim-6 op's with high-mass DY @ 100 TeV

Trade extreme precision for dynamical range, in pursuit of high-scale sensitivity



	universal form factor ($\mathcal{L}$)
W	$-\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$
Y	$-\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$

M.Farina et al, arXiv:1609.08157
Josh Ruderman at the W shop

FCC-pp

		LEP	ATLAS 8	CMS 8	LHC 13		100 TeV	ILC	TLEP	ILC 500 GeV
luminosity		$2\times10^7\,Z$	$19.7\,\text{fb}^{-1}$	$20.3\,\text{fb}^{-1}$	$0.3\,\text{ab}^{-1}$	$3\,\text{ab}^{-1}$	$10\,\text{ab}^{-1}$	$10^9\,Z$	$10^{12}\,Z$	$3\,\text{ab}^{-1}$
NC	$\text{W}\times10^4$	$[-19,3]$	$[-3,15]$	$[-5,22]$	±1.5	±0.8	±0.04	±3	±0.7	±0.3
	$\text{Y}\times10^4$	$[-17,4]$	$[-4,24]$	$[-7,41]$	±2.3	±1.2	±0.06	±4	±1	±0.2
CC	$\text{W}\times10^4$	—	±3.9		±0.7	±0.45	±0.02	—	—	—

FCC-ee

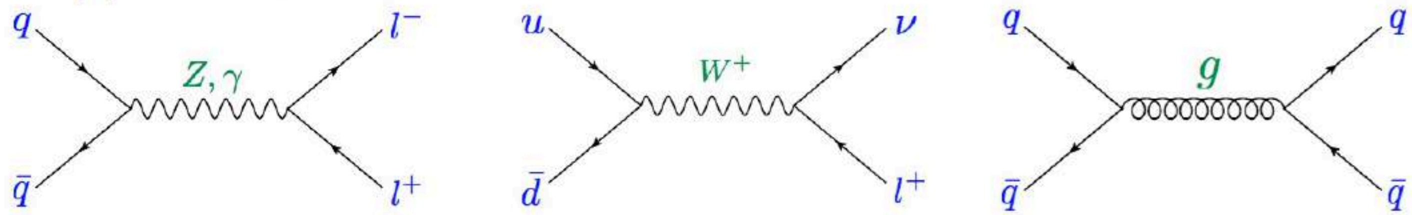
assumed syst's at 100 TeV:

- neutral: $\delta_{\rm cor} = \delta_{\rm unc} = 2\%$
- charged: $\delta_{\rm cor} = \delta_{\rm unc} = 5\%$

Josh Ruderman at the Wshop

$$\mathcal{L}_{\text{eff}} \supset \frac{1}{\Lambda_Y^2}(\partial_\rho B_{\mu\nu})^2 + \frac{1}{\Lambda_W^2}(D_\rho W^a_{\mu\nu})^2 + \frac{1}{\Lambda_Z^2}(D_\rho G^a_{\mu\nu})^2$$

- FCC-pp reach:

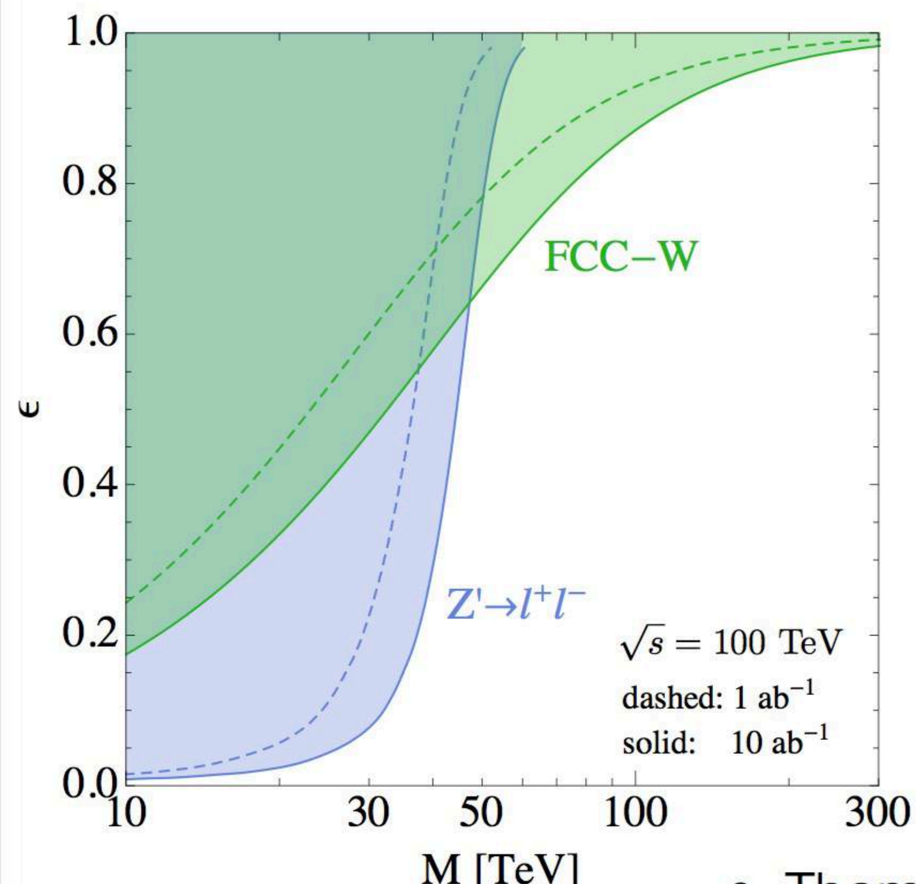


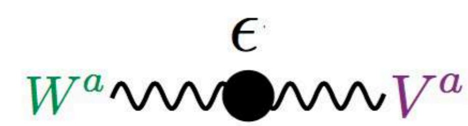
$\Lambda_Y \gtrsim 70$ TeV $\quad \Lambda_W \gtrsim 110$ TeV $\quad \Lambda_Z \gtrsim 90$ TeV

(preliminary)

ex) heavy vector triplet

$$\mathcal{L} \supset -\frac{1}{4}W^a_{\mu\nu}W_a^{\mu\nu} - \frac{1}{4}V^a_{\mu\nu}V_a^{\mu\nu} - \frac{\epsilon}{2}W^a_{\mu\nu}V_a^{\mu\nu} + \frac{M^2}{2}V^2$$





direct Z' reach from:

- Thamm, Torre, Wulzer **1502.01701**

Dark Matter

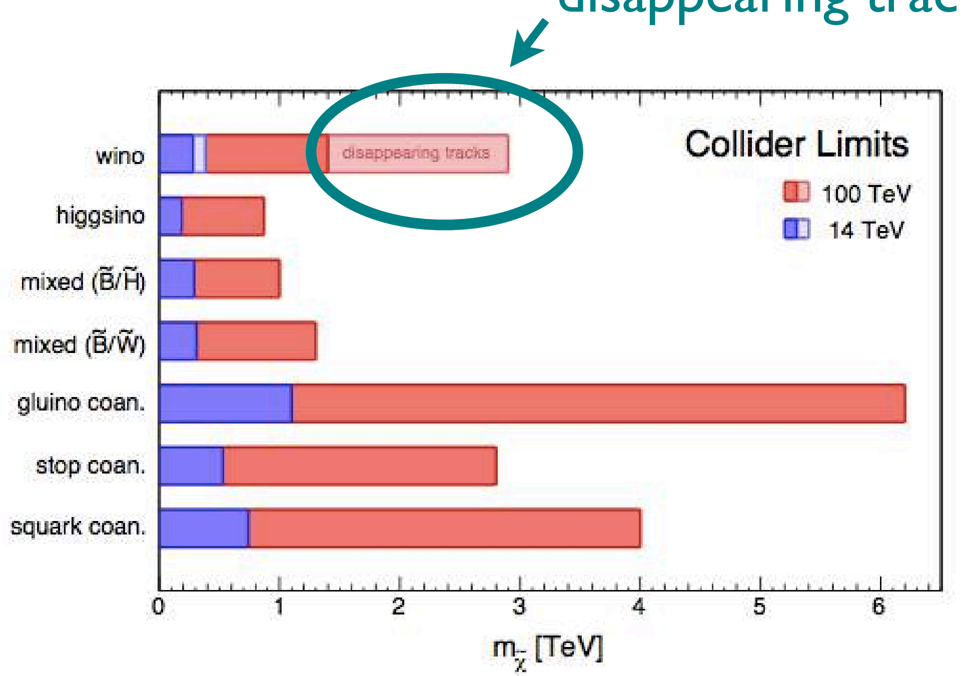
- DM could be explained by BSM models that would leave no signature at any future collider (e.g. axions).
- More in general, no experiment can guarantee an answer to the question ”what is DM?”
- Scenarios in which DM is a WIMP are however compelling and theoretically justified
- We would like to understand 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, ...)?

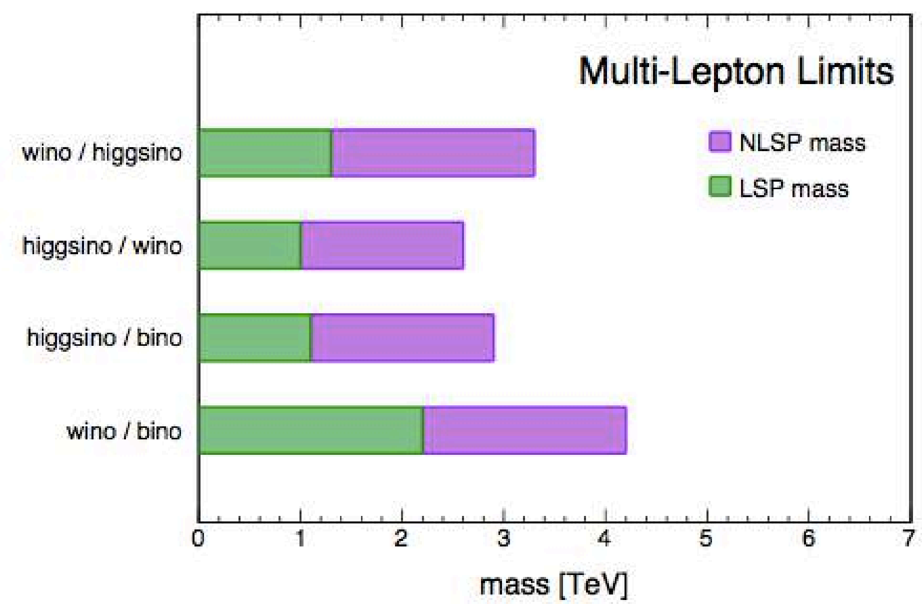
Towards no-lose arguments for some Dark Matter scenarios:

WIMP searches at colliders

L.Wang @ FCC week

disappearing tracks





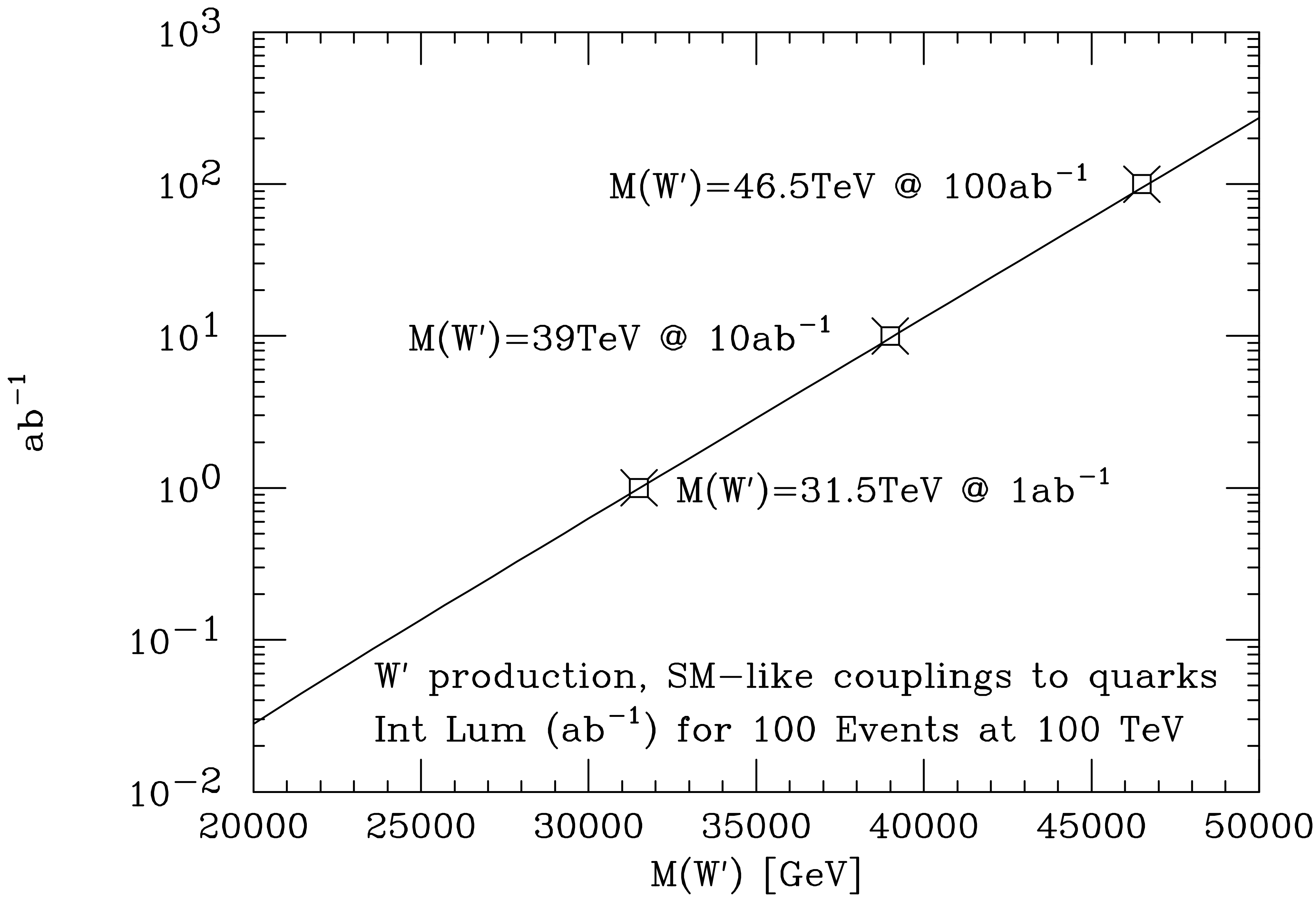
$$M_{\mathrm{WIMP}} \leq 1.8\ \mathrm{TeV}\ \left(\frac{g^2}{0.3}\right)$$

100 TeV pp collider will probe TeV WIMP very well.

New gauge bosons discovery reach

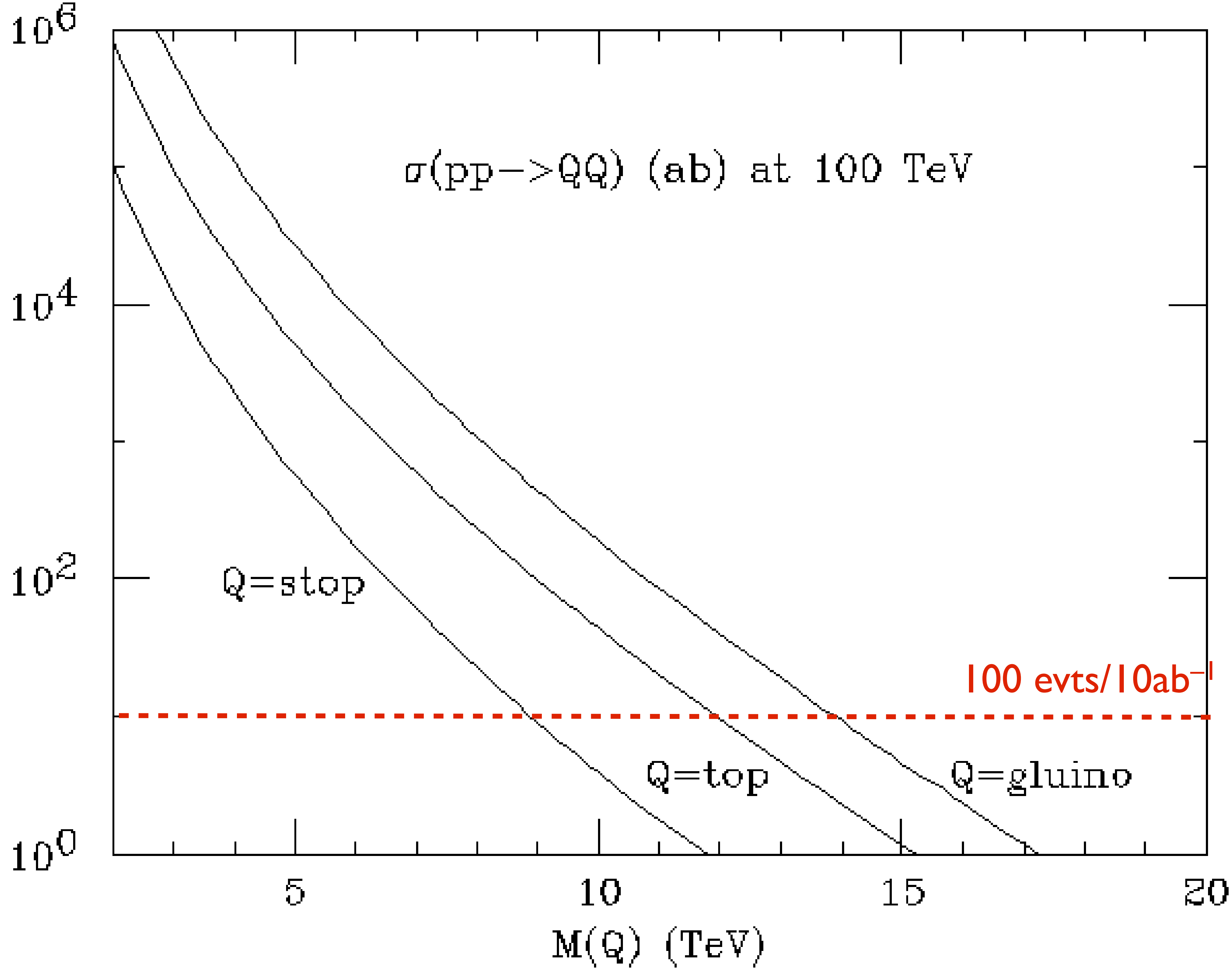
Example: **W' with SM-like couplings**

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

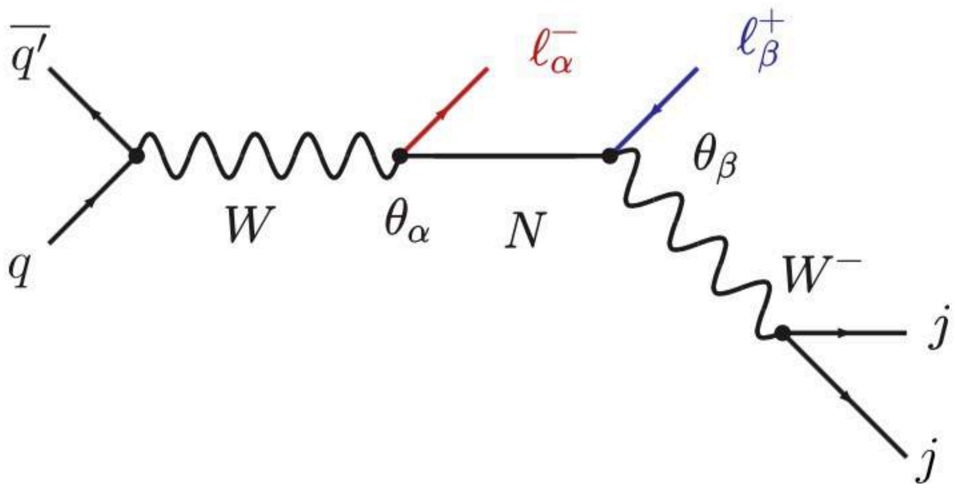


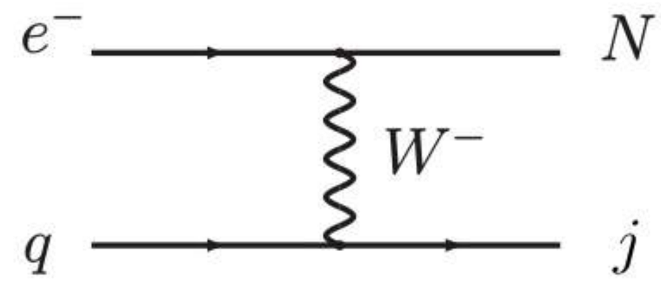
At L=O(ab^{-1}), Lum x 10 ⇒ ~ M + 7 TeV

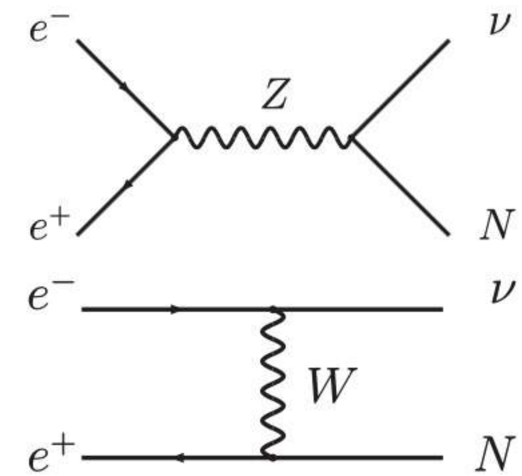
Discovery reach for pair production of strongly-interacting particles



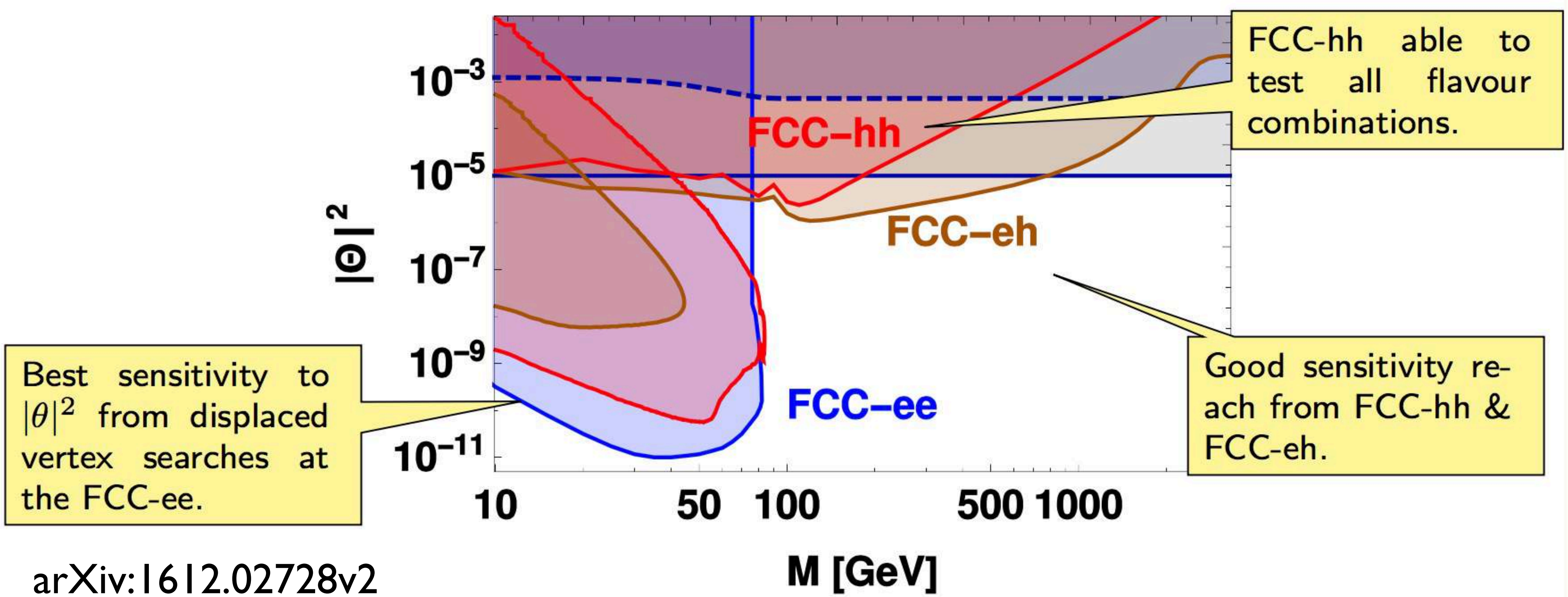
Golden signatures for heavy ν's at FCC





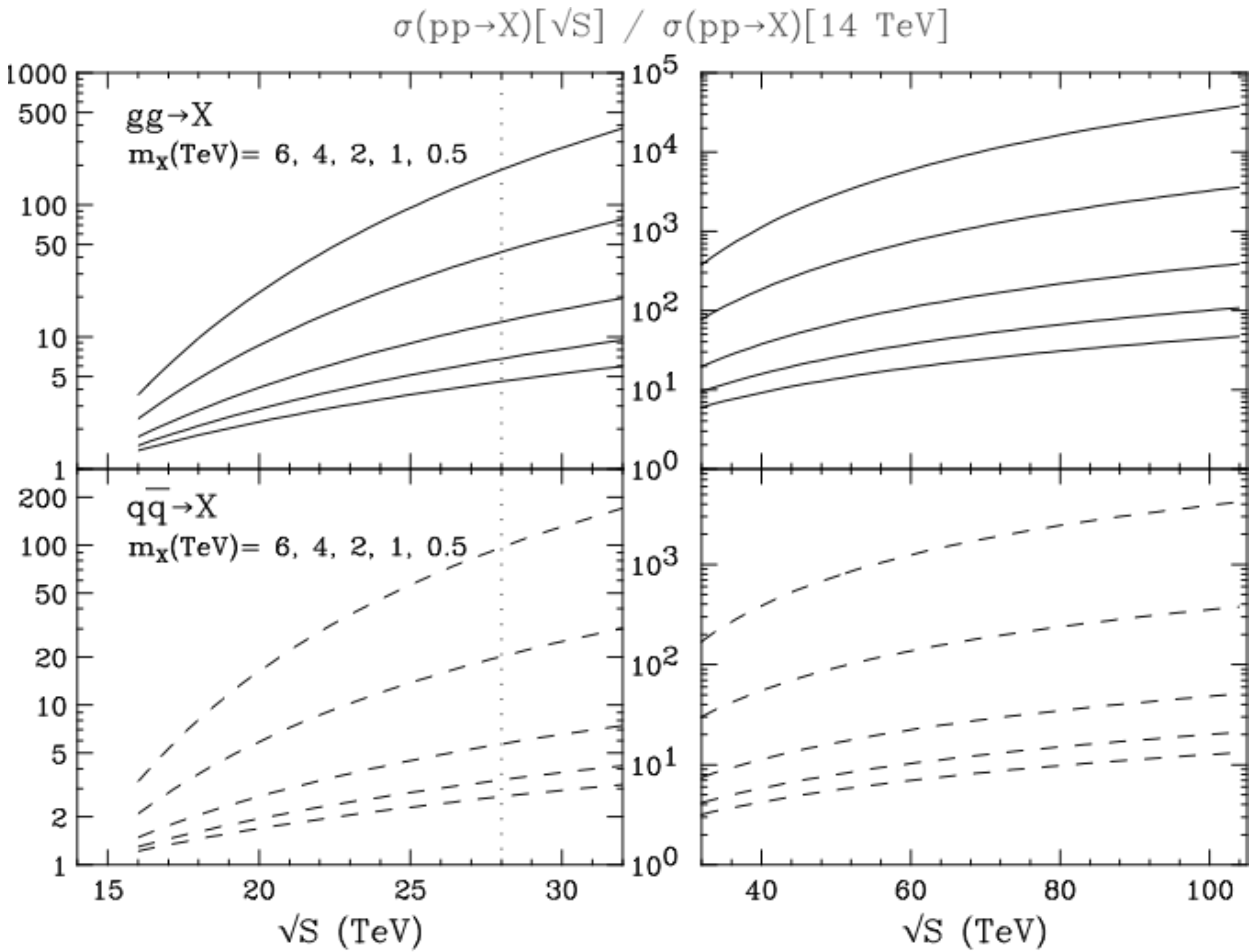


- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search



arXiv:1612.02728v2

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



Final remarks

- The accelerator performance, experimental ingenuity, and theoretical progress, make the LHC 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 surprises
- The study of the SM will not be complete until we exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.
- As a possible complement to the mature ILC and CLIC projects, 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.