Luminosity for the 100 TeV collider

M.L.Mangano, contribution to the
"Luminosity discussion session", Jan 15 2015
IAS programme on The Future of High Energy Physics

- Critical parameter to determine the physics reach, and to define the requirements on the whole accelerator complex
- We need a reference goal luminosity to establish the implications for the accelerator (technological challenge and costs)
- The reference goal should be driven by physics considerations. But it must we weighed against cost and complexity

Luminosity *for pedestrians*

Luminosity

beam current

$$L \propto \frac{I_b^{(2*)}}{\beta^*}$$

determines the transverse
size of beam at the IP

To increase L, can either increase current, or reduce beam size at the IP

* depends on bunch structure

Synchrotron radiation power

these are obviously fixed by geography and magnets' field

$$P \propto N_p \frac{E^4}{R^2}$$

beam energy

orbit radius

$$\Rightarrow P_{FCC}/P_{LHC} \sim 3 \times 2500 / 16 \sim 500$$

Radiated synchrotron energy must be taken out of beam pipe, to avoid warming up magnets.

There are several physical constraints to how much power one can take out. E.g. power required for refrigeration (cannot exceed O(100 MW)), spacing between extraction points (limits how much energy is radiated within a single dipole), etc.

For fixed E and R, this sets a **limit to total beam current**

β*

Squeezing beams at IP requires
- stronger quadrupoles
- larger magnet aperture (since beams blow up after the squeeze)

The higher beam energy, w.r.t. LHC, requires even stronger B gradients, which favour smaller apertures (magnet closer to beam), in contrast with impact of smaller β* that demands larger apertures.

This also calls for a reduced distance from the IP of the focusing magnets (L*).
But smaller L* constrains how long the detector can be, and thus limits the rapidity coverage

The above constraints set **limits on how small β* can be**

Luminosity lifetime

$$\tau \propto \frac{I_b}{L}$$

the higher L, the more interactions, the sooner the bunches loose protons

Once luminosity drops, need to dump the beam and inject new beam.

Time is needed to refill, and this depends on injector chain.

When lumi lifetime becomes of order refill time, **integrated luminosity starts saturating vs further increase in instantaneous luminosity.**

It takes 4 LHC fills to complete an FCC fill (FCC has ~ 4 times more bunches than LHC). Each LHC fill requires its own injection, magnet ramps to 3 TeV, etc.

=> Estimate 5 hrs (to be improved to ~4 hrs with operational experience)

Alternative/upgrade:
Build new injector, bigger than LHC.
- require smaller-field magnets => faster ramps
- more bunches => fewer injection cycles

Ideally 100km injector in the FCC tunnel => $$$, interference with detectors, ..??

Bottom line

- There is headroom for optimization, but once energy and radius are chosen, there are hard intrinsic limits to the achievable integrated luminosity

Not discussed here, but there are other obvious difficulties:

- radiation impact on detectors, cavern, ...
    - these must be assessed now
- pileup issues
    - here we can be optimistic, and not let analysis difficulties limit luminosity at this time

FCC-hh luminosity

- The current FCC beam parameters were developed starting from the *least ambitious* goal, namely reproducing the HL-LHC luminosity.
- This gives a meaningful benchmark to start the exercise of optimization, an exercise that will take place in the years leading to the CDR.

FCC
preliminary considerations on luminosity and staging

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http://cern.ch/fcc

FCC goals and parameters

- **Consideration on FCC design goals (assumed operation 25 years)**
  - **Initial luminosity** should be equal to HL LHC luminosity ➔ **5E34/cm^2/s**
  - **Integrated luminosity in phase 1** (10 years) should be ~equal to LHC total luminosity ➔ O(3000 fb-1).
  - **FCC total luminosity should be one order higher than LHC total** ➔ O(30.000 fb-1)

- **Present FCC design parameters:**
  - **Phase 1:**
    - **5E34/cm^2/s (peak),** average 250 fb-1/year (stops incl.) ➔ 2500 fb-1 within total of 10 years (~HL LHC total luminosity)
  - **Phase 2:**
    - **2.5 E35/cm^2/s (peak),** average 1000 fb-1/year (stops incl.) ➔ 15000 fb-1 within 15 years (~1/2 LHC total luminosity).

  - **Gives total luminosity ~17500 fb-1 over 25 years FCC operation**

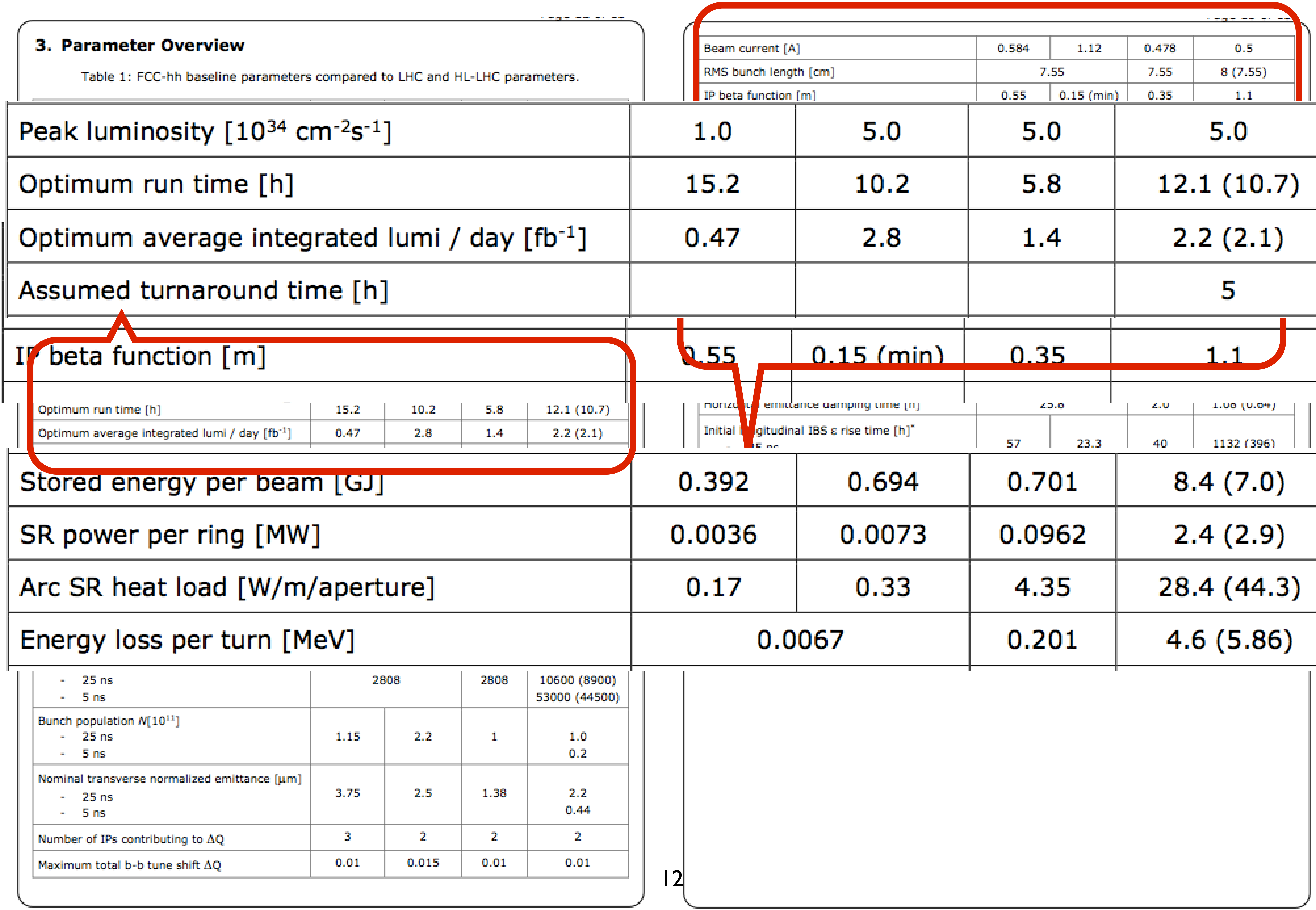
FCC performance determining parameters

- **Baseline parameters:**
  - Beam optics scaled from LHC, accounting for Nb3Sn ➔ beta=1.1m
  - Conservative beam-beam tune shift limit ➔ 0.01 (2 experiments)
  - Beam (bunch) parameters similar to present LHC beam ➔3.5 times more bunches
  - Baseline beam current 0.5 A, total synchrotron radiation 2 x 2.5 MW.
  - Turn-around time 5 hours assumed (pre-injectors well understood)

- Synchrotron radiation loss and heat extraction from cold mass is major design issue and performance determining factor.
  - Dissipated power proportional to total beam current.
  - Limit set to 2 x 2.5 MW beam power for dimensioning of magnet and cooling systems (present assumptions 100 MW refrigerator power)
    - This fixes the total beam current ➔ machine protection, dumps,…
    - Difficult to upgrade later since the complete magnet, vacuum and cryogenic systems need to be dimensioned accordingly!
  - Luminosity 5E34/cm^2/s, 250 fb-1/year (~125 days effective operation)

Current FCC-hh parameters

FCC-ACC-SPC-0001



3. Parameter Overview

Table 1: FCC-hh baseline parameters compared to LHC and HL-LHC parameters.

Beam current [A]	0.584	1.12	0.478	0.5
RMS bunch length [cm]	7.55		7.55	8 (7.55)
IP beta function [m]	0.55	0.15 (min)	0.35	1.1

Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	5.0	5.0	5.0
Optimum run time [h]	15.2	10.2	5.8	12.1 (10.7)
Optimum average integrated lumi / day [fb^{-1}]	0.47	2.8	1.4	2.2 (2.1)
Assumed turnaround time [h]				5

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Initial l gitudinal IBS ε rise time [h]*	57	23.3	40	1132 (396)

Stored energy per beam [GJ]	0.392	0.694	0.701	8.4 (7.0)
SR power per ring [MW]	0.0036	0.0073	0.0962	2.4 (2.9)
Arc SR heat load [W/m/aperture]	0.17	0.33	4.35	28.4 (44.3)
Energy loss per turn [MeV]	0.0067		0.201	4.6 (5.86)

- 25 ns - 5 ns	2808		2808	10600 (8900) 53000 (44500)
Bunch population $N [10^{11}]$ - 25 ns - 5 ns	1.15	2.2	1	1.0 0.2
Nominal transverse normalized emittance [μm] - 25 ns - 5 ns	3.75	2.5	1.38	2.2 0.44
Number of IPs contributing to ΔQ	3	2	2	2
Maximum total b-b tune shift ΔQ	0.01	0.015	0.01	0.01

FCC performance upgrade

- Parameters that might be improved with operational experience:
  - Optics improvements to reduce beta ➔ **beta from 1.1 m to 0.3 m**
  - Increased beam-beam tune shift limit and corresponding increase in beam brightness via synchrotron radiation damping ➔ **0.01 to 0.03.**
  - Installation of crab cavities to compensate for crossing angle
  - Turnaround time reduced to 4 hours.

- **Effective improvement factor wrt baseline is 4 – 5**
  - **Luminosity 2.5E35/cm^2/s (peak), ~1000 fb-1/year**
  - **(~125 days eff. operation)**

- Further improvement might be achieved via significant improvement on the turn-around time
  - Potential to gain factor 2 in integrated luminosity by decreasing from 4 hours to 1 hour
  - Maybe only achievable with new injector ➔ major cost and effort

Summary

- Phase 1: baseline luminosity 5E34/cm^2/s (peak)
    - Integral ~250 fb-1/year (with operation model 125 days/year)
    - 10 years phase 1 operation
    - **Total accumulated lumi in phase 1: 2500 fb-1.**

- Phase 2: upgrade luminosity 2.5E35/cm^2/s (peak)
    - Integral ~1000 fb-1/year (with operation model 125 days/year)
    - 15 years phase 2 operation
    - **Total accumulated lumi in phase 1: 15000 fb-1.**

- **Total accumulated luminosity over 25 years 17500 fb-1 (w/o new injector)**

Physics considerations on luminosity goals

Higher luminosity buys:

- Extension of the discovery reach at the high mass end
- Extension of the discovery reach for rare processes at masses well below the kinematical edge
- Higher statistics for studies of new particles to be discovered at the LHC
- Higher statistics for studies of the Higgs

$$\sigma(M,g) \propto \frac{g^2}{M^2}\, L(x = M/\sqrt{S})$$

At fixed mass, cross sections grow when S grows, since

$$L(x) \sim \frac{1}{x^\alpha}\,\log(\frac{1}{x})\;, \quad \alpha < 1$$

assuming
$f(x) \sim 1/x^{1+\alpha}$

To scale the discovery reach in mass as the growth in energy, means however to keep $x=M/\sqrt{S}$ constant. Then

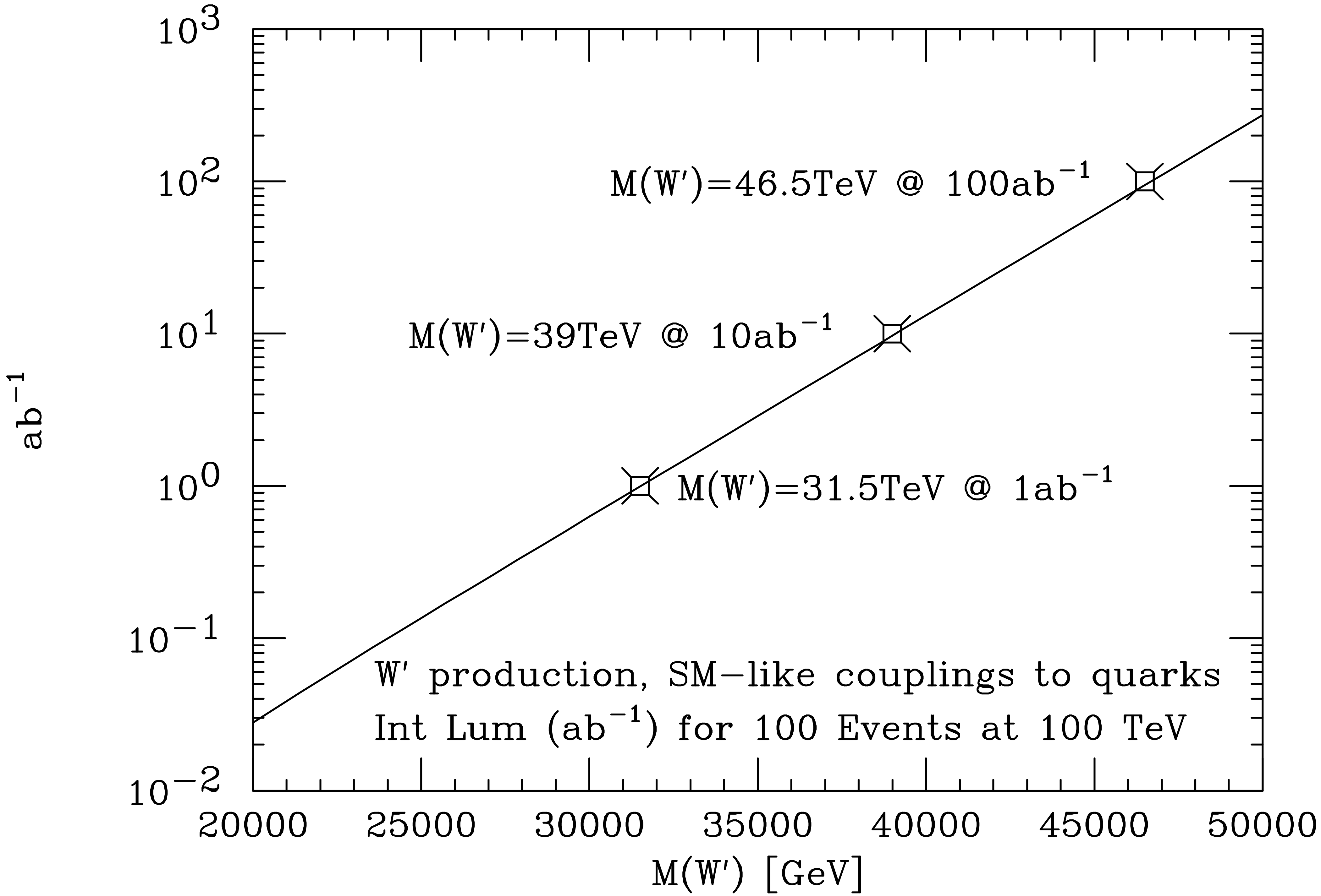
$$\sigma(M,g) \propto \frac{g^2}{S}\,\frac{L(x)}{x}$$

Thus the cross-sections for searches go like 1/S, and the machine luminosity may need to grow accordingly.

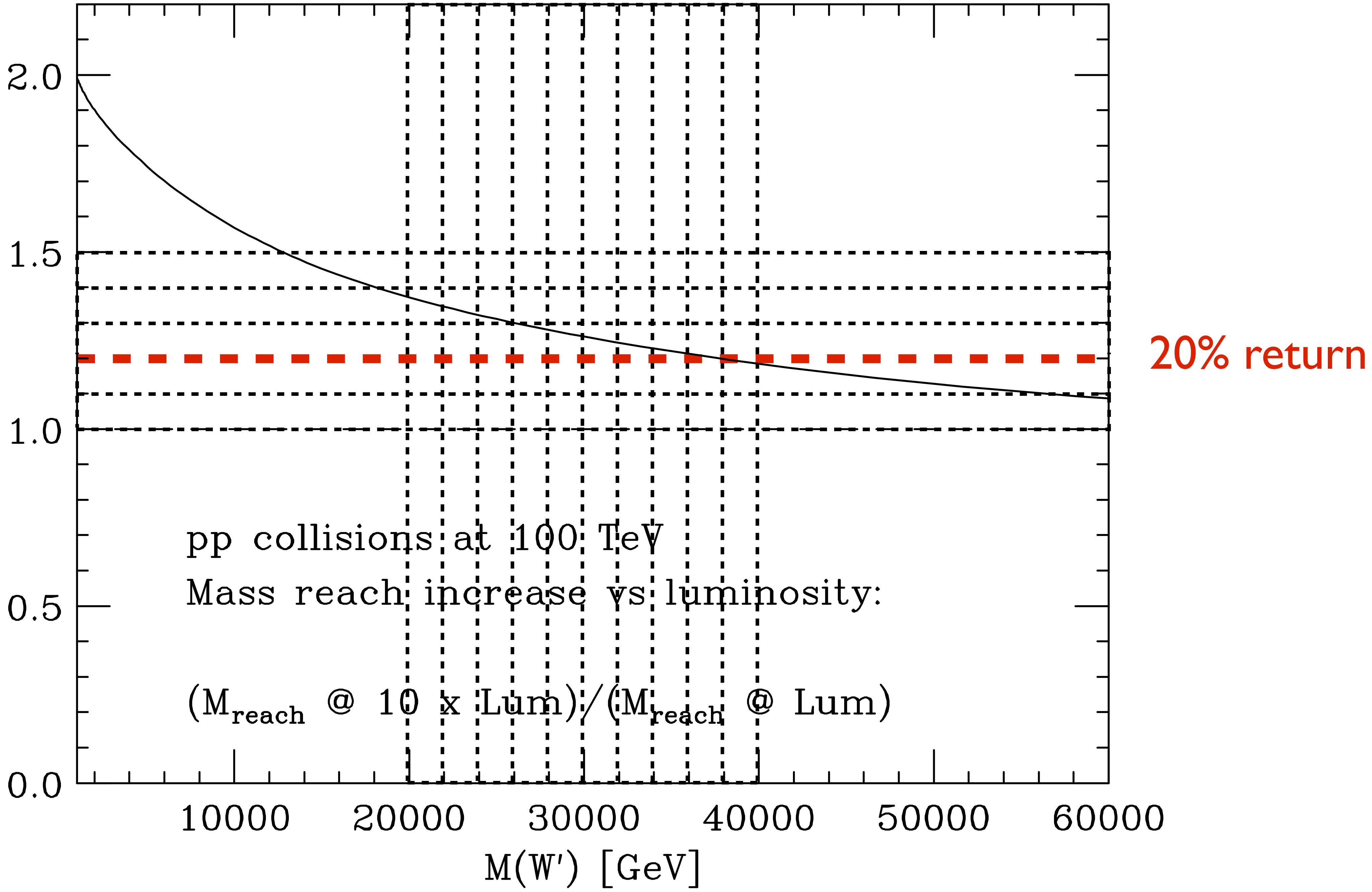
Extension of the discovery reach at high mass

Example: discovery reach of 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$_{\mathrm{I}}$x 10 ⇒ ~ M + 7 TeV



Lum x 10 ⇒ relative gain much larger at low mass than at high mass

- One could argue that the 10 x increase in lum is not justified if the increase in sensitivity is below a level of O(20%).
- Beyond this level, extra lum is not justified by the desire to push the mass reach

See e.g. the history of Tevatron achievements: after 1fb^{-1}, limited progress at the high-mass end, but plenty of results at "low" mass (W, top and b physics, Higgs sensitivity, ...)

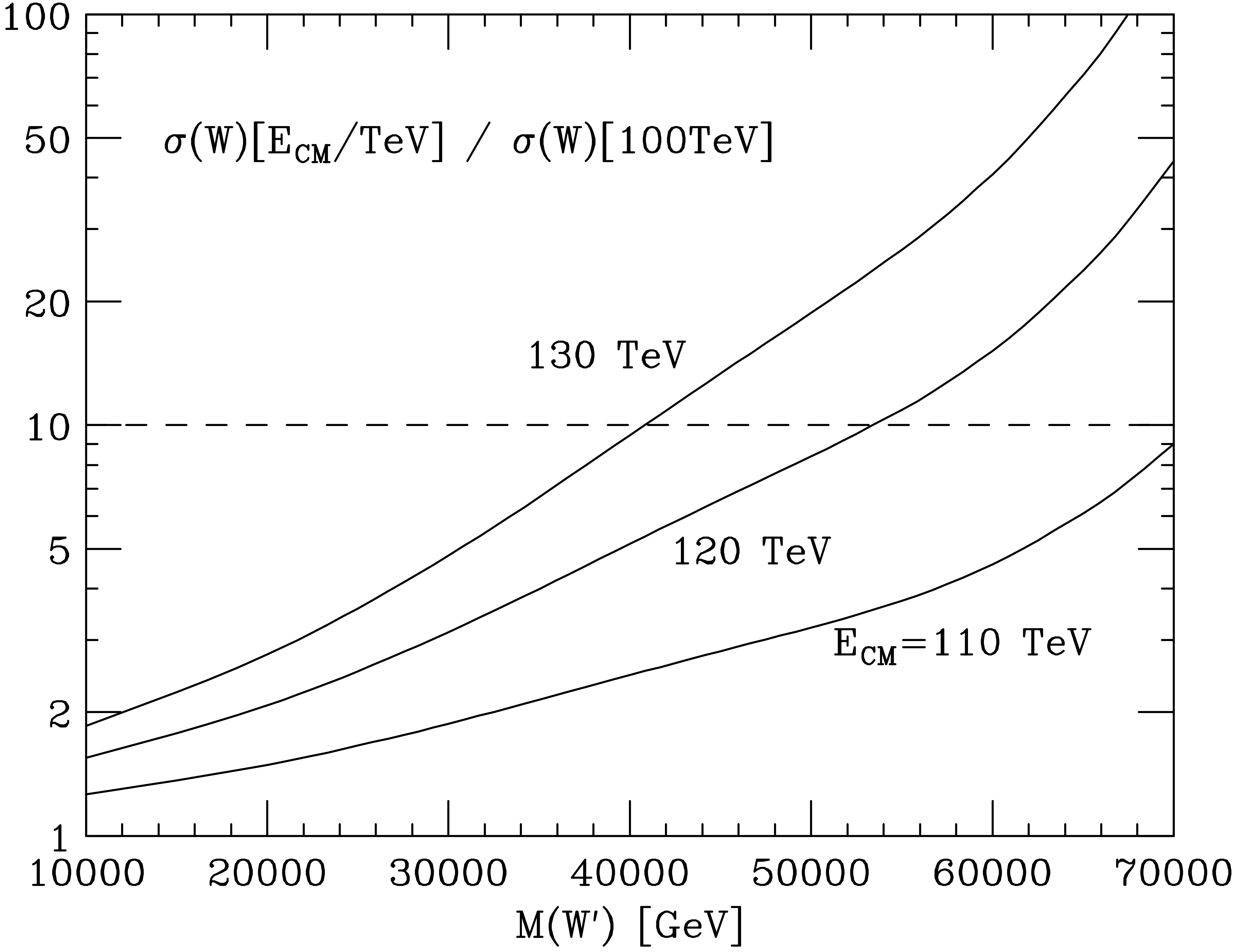
Example from HL-LHC studies: Z' → e^+e^-

ATLAS/CMS HL docs	300/fb	3000/fb
95% excl (ATLAS)	**6.5 TeV**	7.8 TeV
5σ (CMS)	5.1 TeV	**6.2 TeV**

- ΔM/M ~ 20% ⇒ the LHC reaches the threshold of saturation of the mass reach

  already at 300fb^{-1} . Notice that 95% exclusion at 300 makes unlikely the 5σ discovery at 3000. In fact the main justification for the HL-LHC is the higher-statistics study of the Higgs, not the extension of the mass reach
- In this case, the scaling $L \propto E_{beam}^2$ would give L(100) ~ 15ab^{-1}

Luminosity vs CM Energy

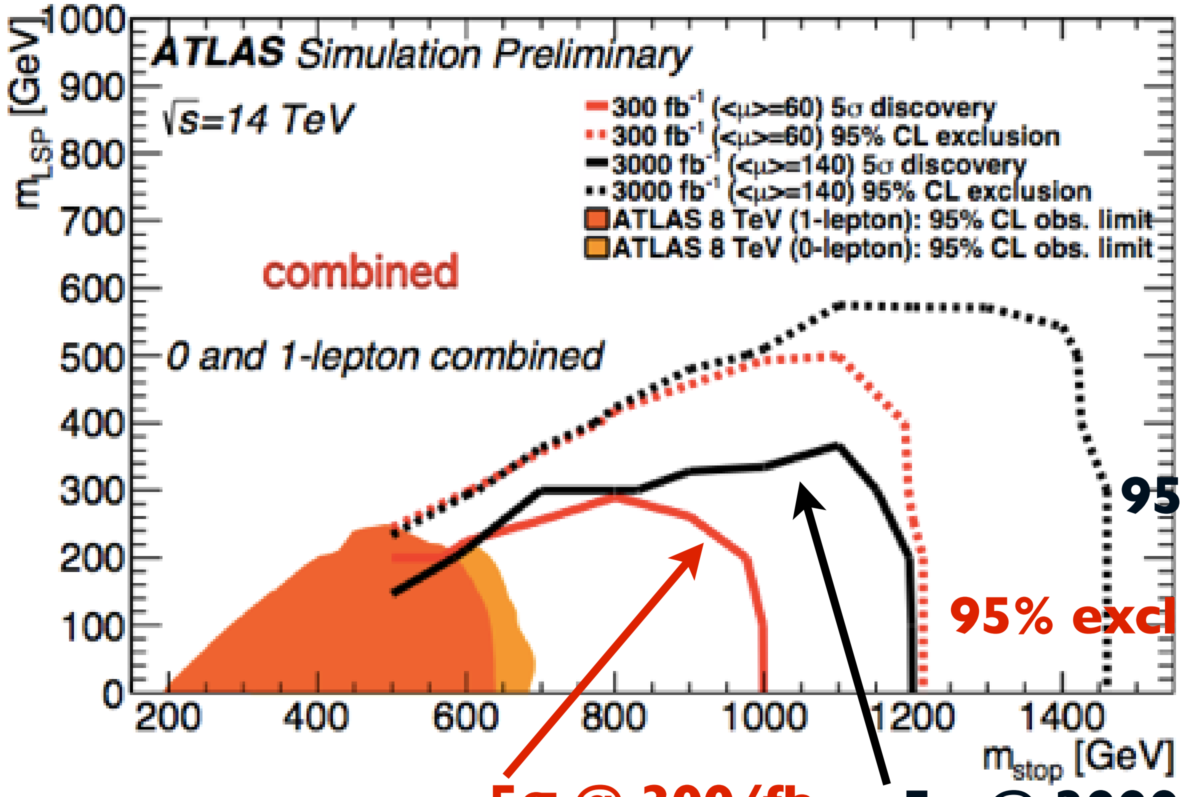


- At around 40 TeV, a 20% increase in energy buys a factor of 5 in rate. 30% in energy buys a factor 10 in rate.
- What will be less challenging ? To upgrade some of the magnets, or to increase Lx10 ?

Extension of the discovery reach at low mass

- The extension power of higher lum can be important at lower masses, e.g. for processes with very suppressed rates, or difficult to separate from the bg.
- In this case, though, one might benefit more from improved detection efficiency than from pure luminosity.
- The luminosity discussion is extremely process dependent (bg's, detector performance, pileup issues, etc)

HL-LHC example: Direct stop searches (ATLAS Snowmass doc)



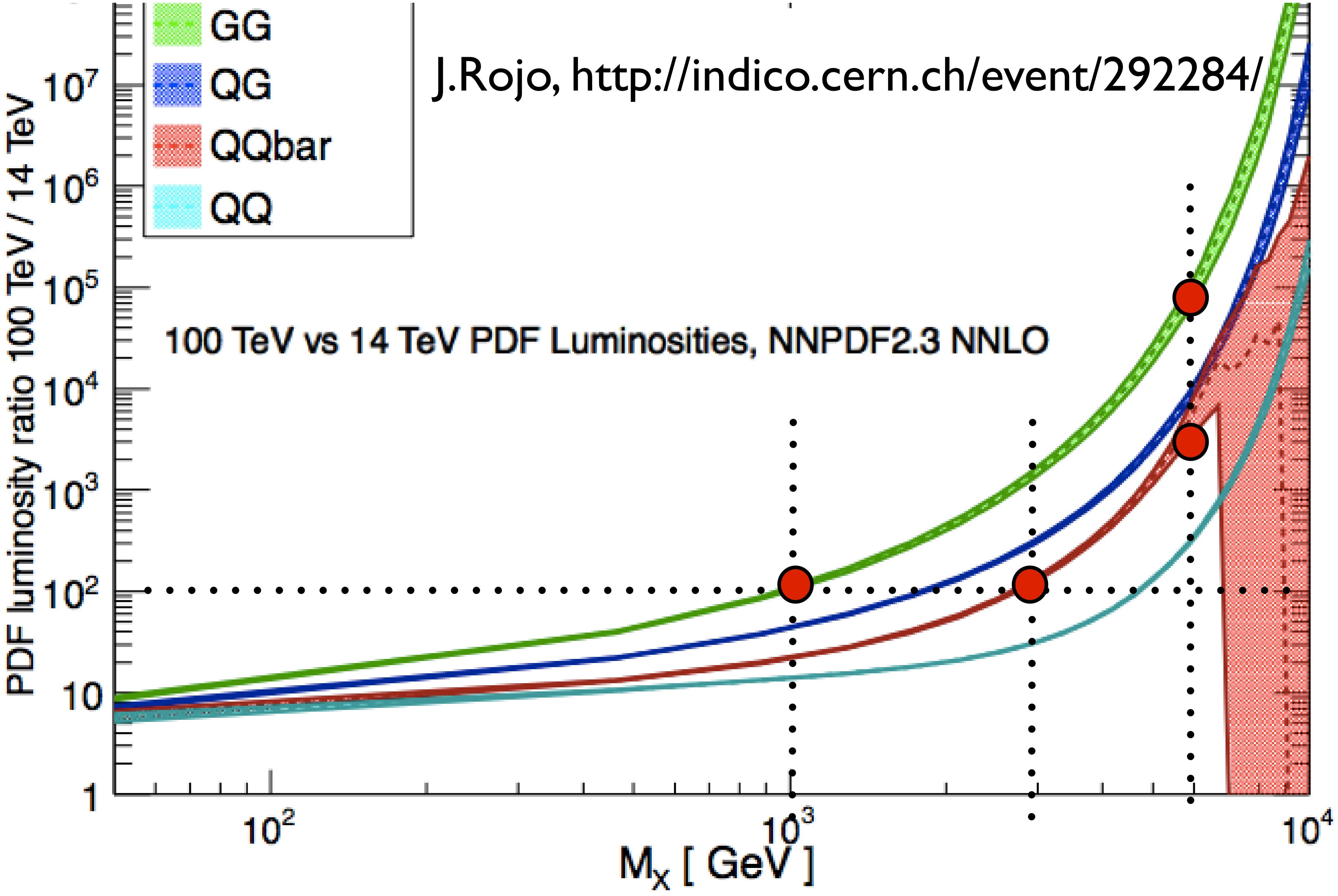
95% excl @ 3000/fb

95% excl @ 300/fb

5σ @ 300/fb

5σ @ 3000/fb

Higher statistics for studies of particles discovered at the LHC



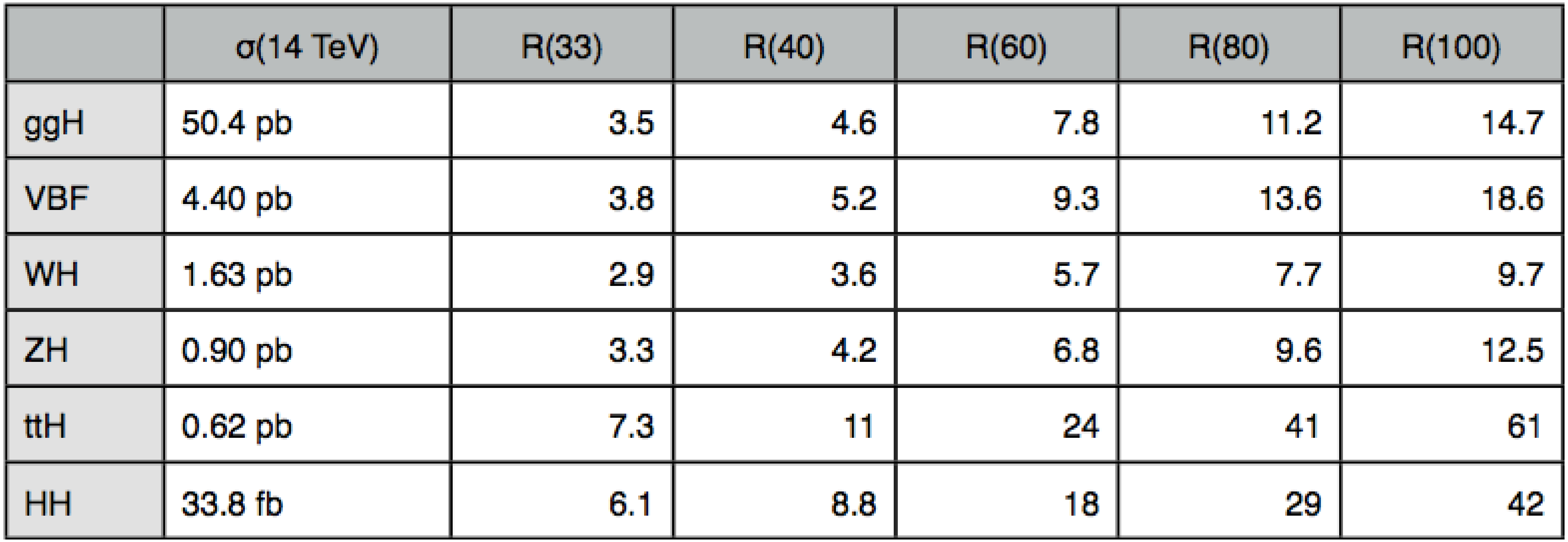
Considering the current LHC limits on new physics, particles to be discovered in future LHC runs, in the mass range above 0.5-1 TeV, could be studied at 100 TeV with statistics larger by at least a factor of 100, keeping the same LHC luminosity

For particles at the edge of the LHC reach (i.e. M~6 TeV for single, or 3 TeV for pair-production), the increase in statistics ranges between 10^3 and 10^5

Higher statistics for Higgs studies

R(E) = σ(E TeV)/σ(14 TeV)

NLO rates



	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

- Gains in the range 10-50, however ....
- => needs detailed studies, considering also the prospects to study rare decays, selfcouplings,etc.etc.

Tentative conclusions

- The goal of O(10 ab^{-1}) seems justified by the current perspective on
  - extension of the mass reach
  - high-statistics studies of possible new physics to be discovered at (HL)-LHC
  - high-statistics studies of the Higgs
- More aggressive luminosity goals may be required by specific measurements, but do not seem justified by generic arguments. Further work on ad hoc scenarios is nevertheless desirable.