Aspen Center for Physics
Exploring the Physics Frontier with Circular Colliders
Jan 27 - Feb 1 2015

Towards a definition of luminosity goals for the 100 TeV pp collider

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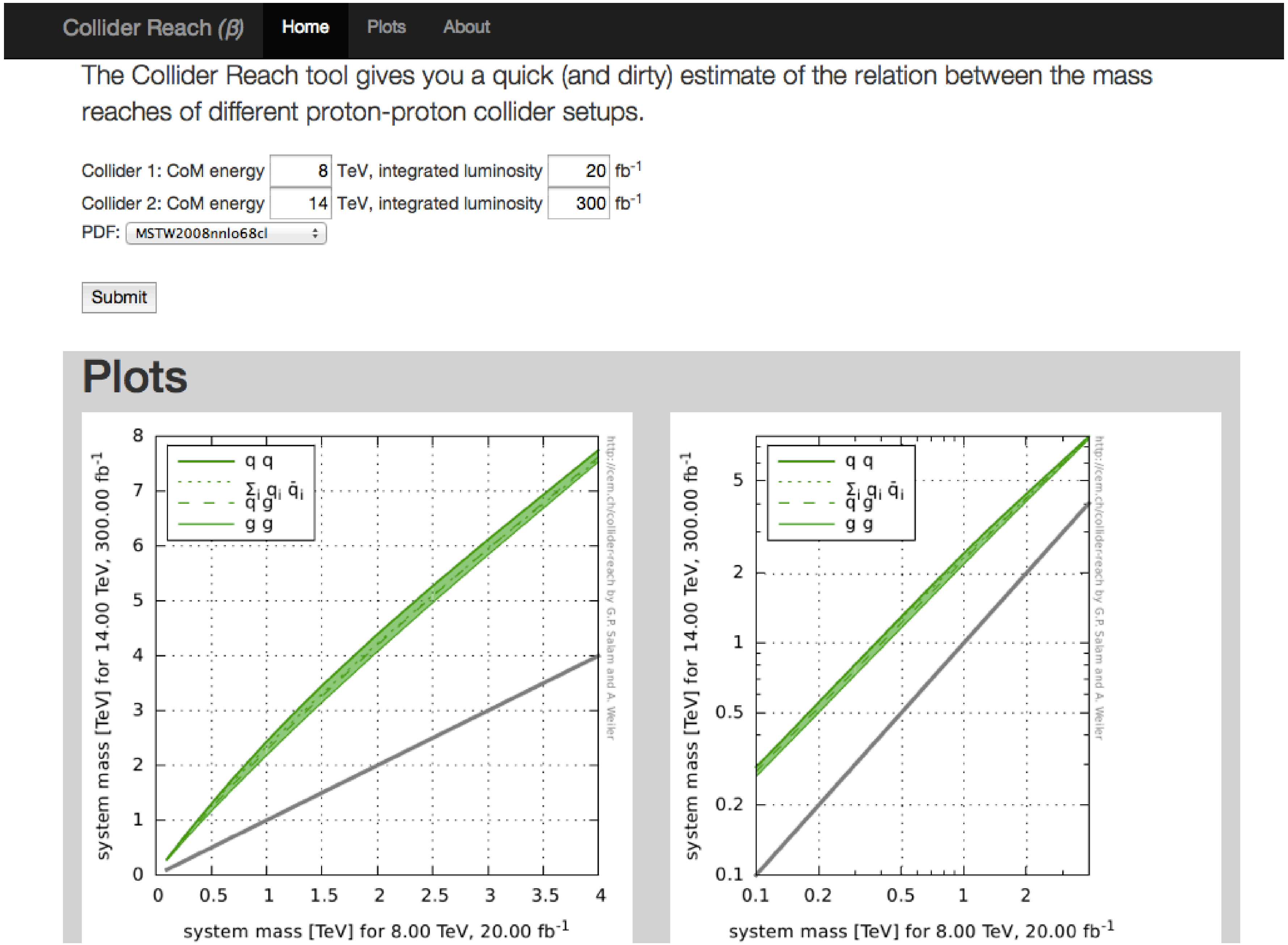
- what are the physics drivers of the luminosity goals ?
- how ambitious should the luminosity goals be ?
- is there a minimum acceptable luminosity ?

with input from discussions initiated at HK IAS, HKUST: I. Hinchliffe, C.Quigg, A.Kotwal, C.Young, W.Yao, W. Chou, ...

Useful tool to explore luminosity/energy dependence of discovery reach:



G.Salam and A.Weiler,
http://cern.ch/collider-reach

Recent papers addressing the luminosity issue

Mass Reach Scaling for Future Hadron Colliders, T.Rizzo, http://arxiv.org/abs/1501.05583

High Energy Colliding Beams; What Is Their Future? B. Richter, http://arxiv.org/abs/1409.1196

> *" .... restricting the luminosity to what will be achieved at HL-LHC gives the new machine a limited vision, and will (and **should**) **seriously lower the likelihood that it will be funded**."*

... question is: what does it mean to "restrict the luminosity that will be achieved"? Should L necessarily scale like E_{beam}^2

Physics considerations on luminosity goals

Ultimate Luminosity must guarantee:

- 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
- High statistics for studies of new particles to be discovered at the LHC
- High statistics for Higgs studies

Initial Luminosity should allow to rapidly (~1st year) surpass the exploration potential of the LHC

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

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

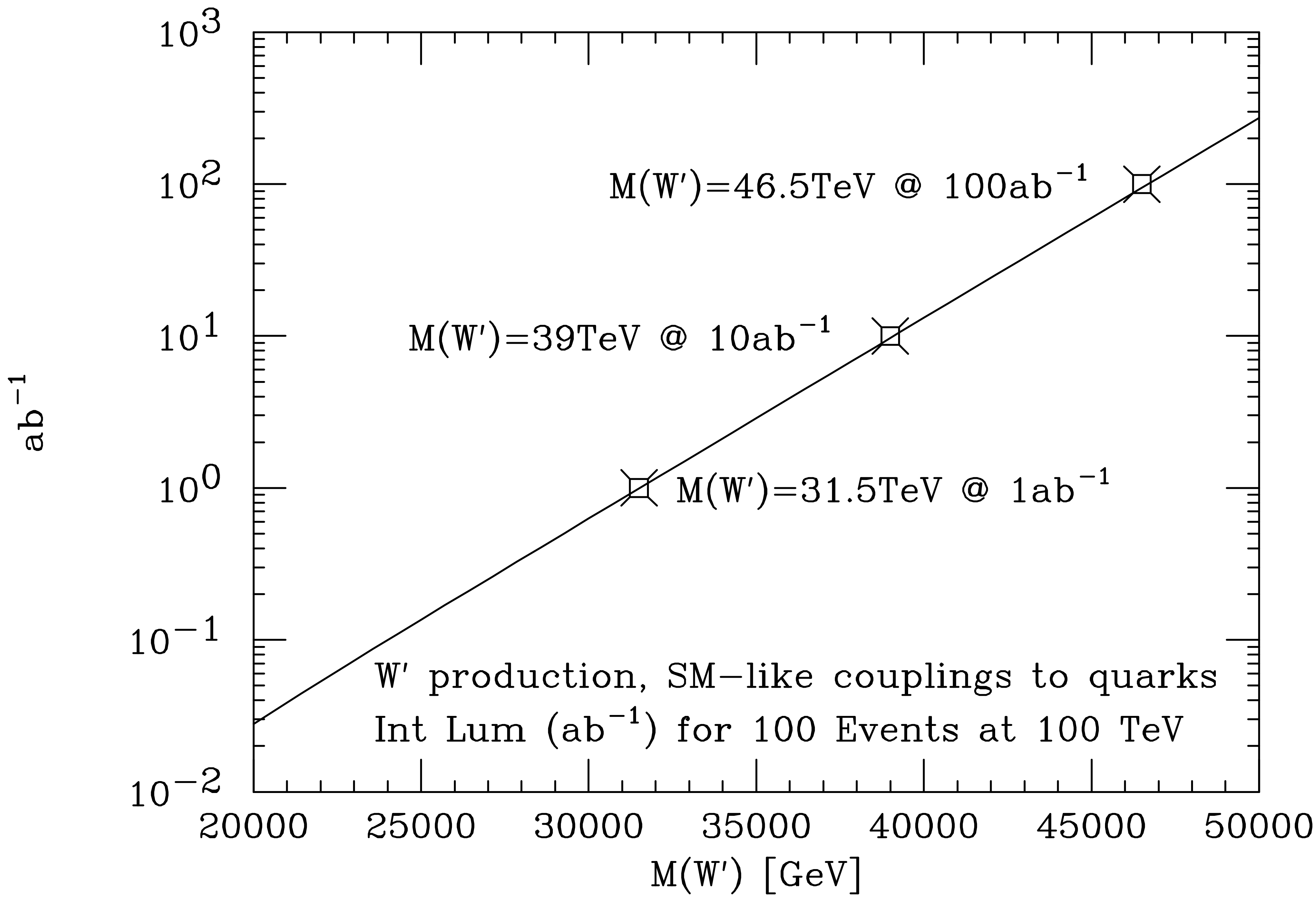
$$\sigma(M,g) \propto \frac{g^2}{S}\, \frac{L(x)}{x}$$

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

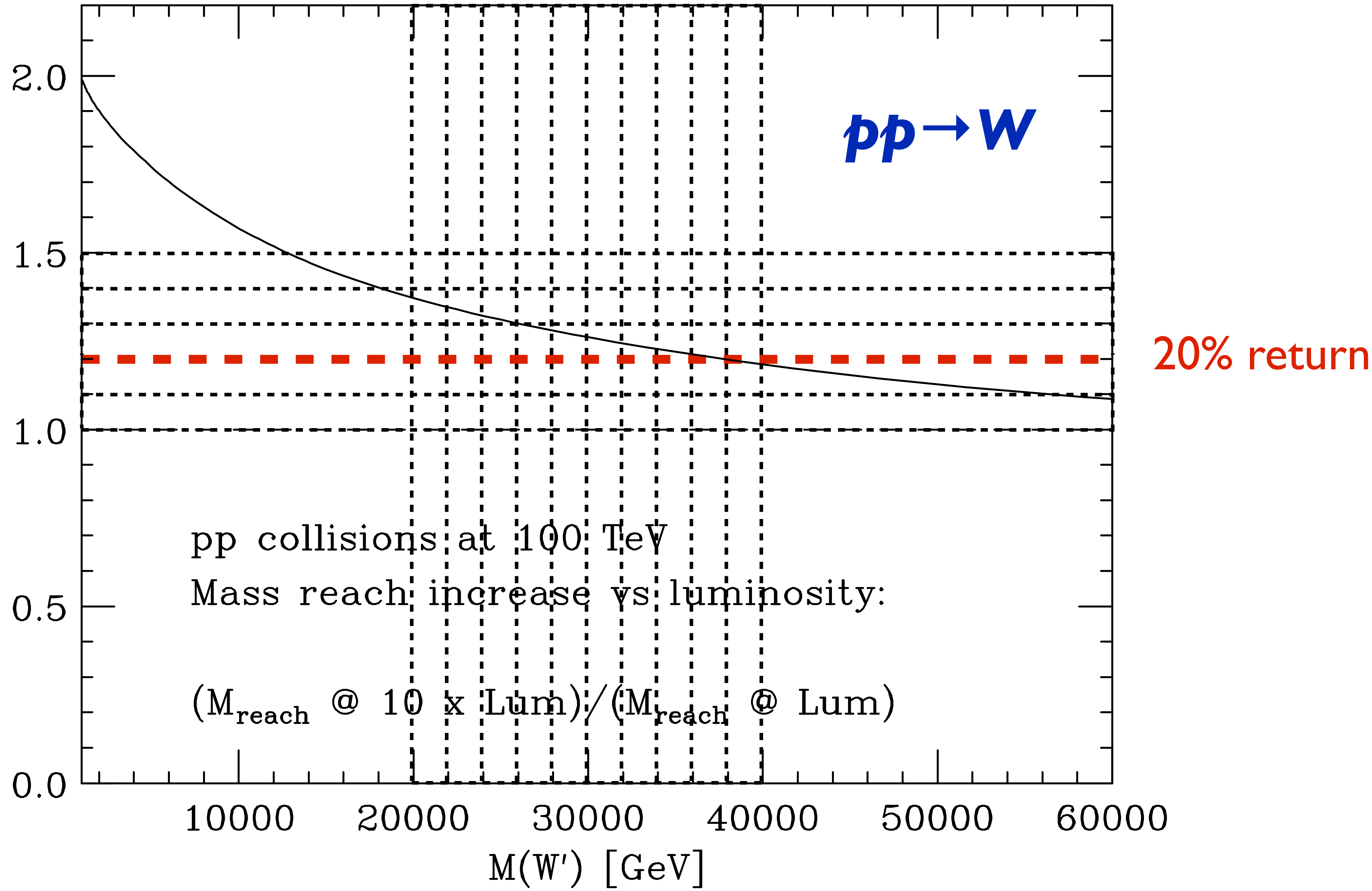
Extension of the discovery reach at high mass

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 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%) (unless there is a concrete physics case, e.g. testing a possible recurrent spectrum of resonances)

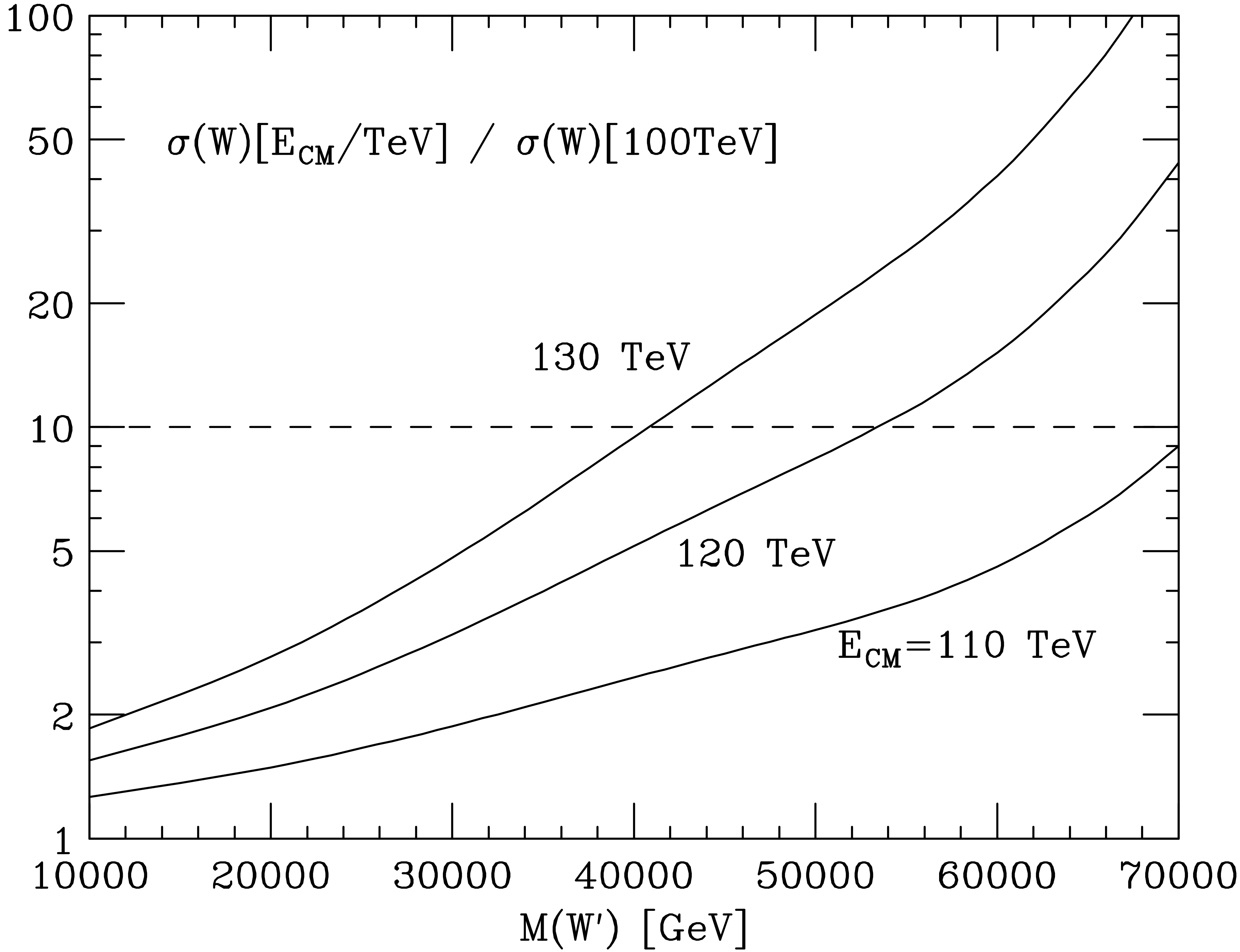
See e.g. the history of Tevatron achievements: after 1fb^{-1}, limited progress at the high-mass end, but plenty of results at "low" mass (W, top and b physics, Higgs sensitivity, ...)

Example from HL-LHC studies: $Z' \rightarrow e^+e^-$

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**

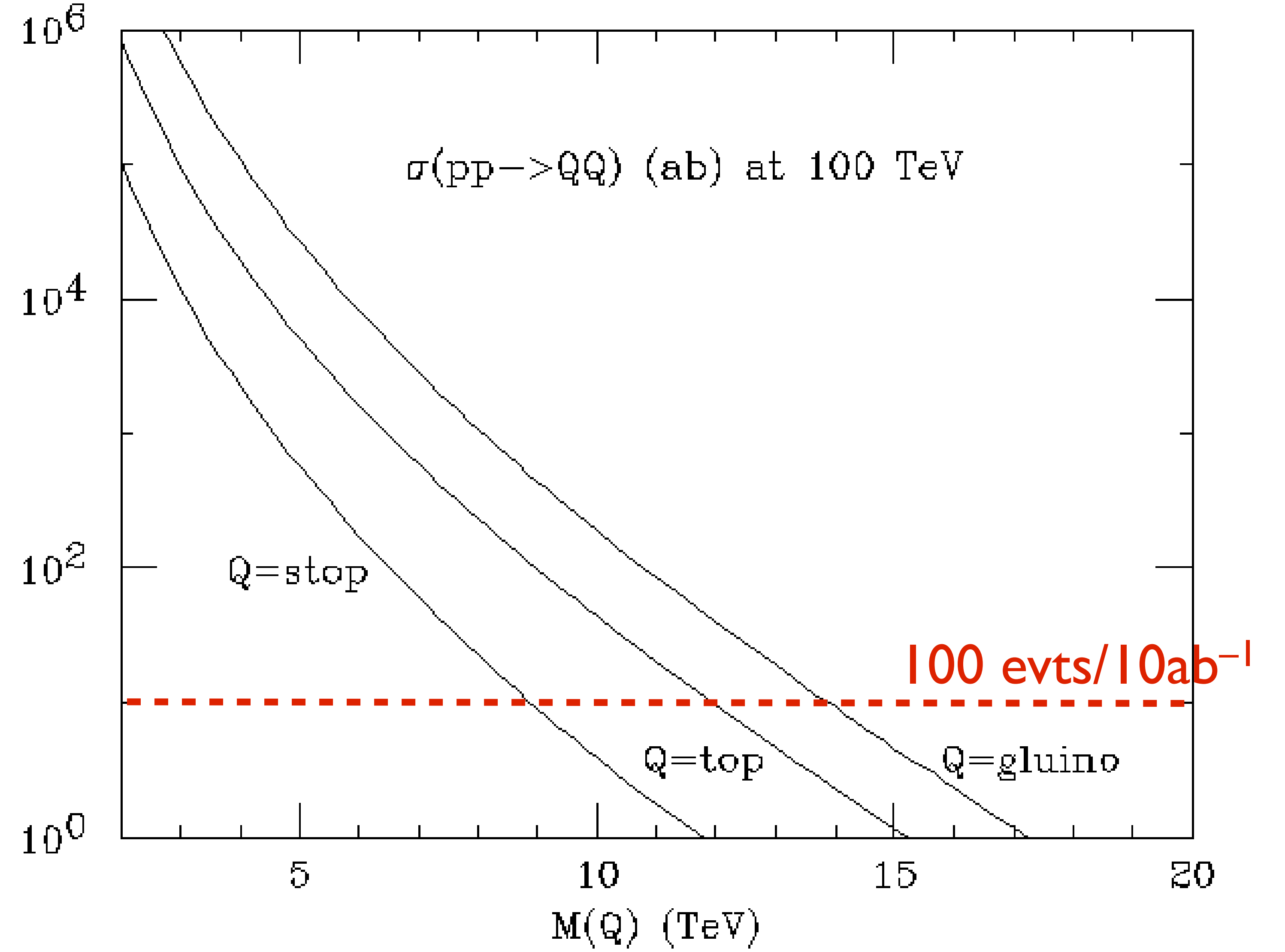
- *ΔM/M ~ 20% ⇒ the LHC reaches the threshold of saturation of the mass reach already at 300fb^{-1} . Notice that 95% exclusion at 300 makes unlikely the 5σ discovery at 3000. In fact the main justification for the HL-LHC is the higher-statistics study of the Higgs, not the extension of the mass reach*
- *In this case,* ***the scaling*** $L \propto E_{beam}^2$ ***gives L(100) ~ 15ab***$^{-1}$

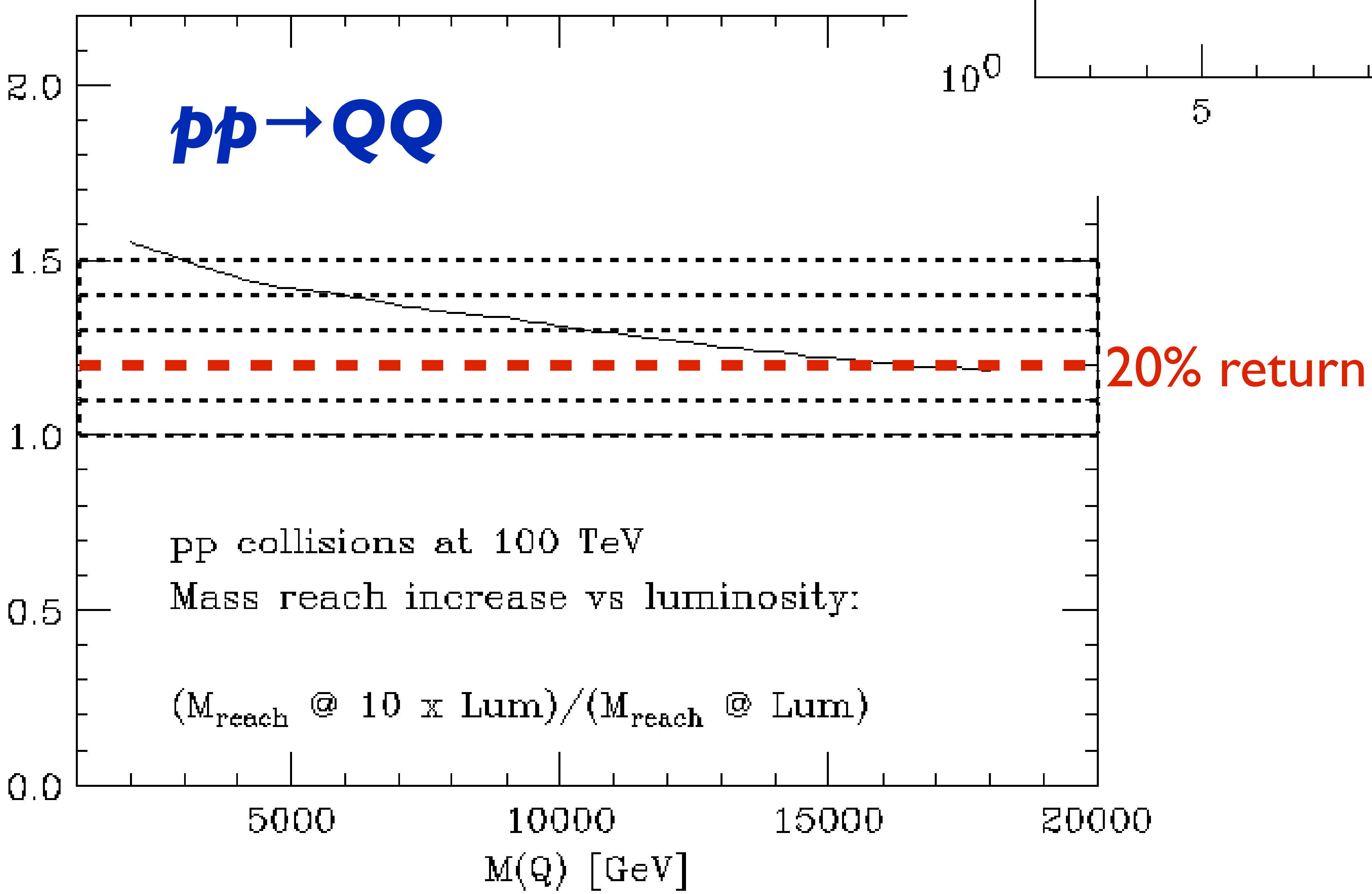
Luminosity vs CM Energy



- 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 the magnets, or to increase Lx10 ?

Example: discovery reach for pair production of strongly-interacting particles

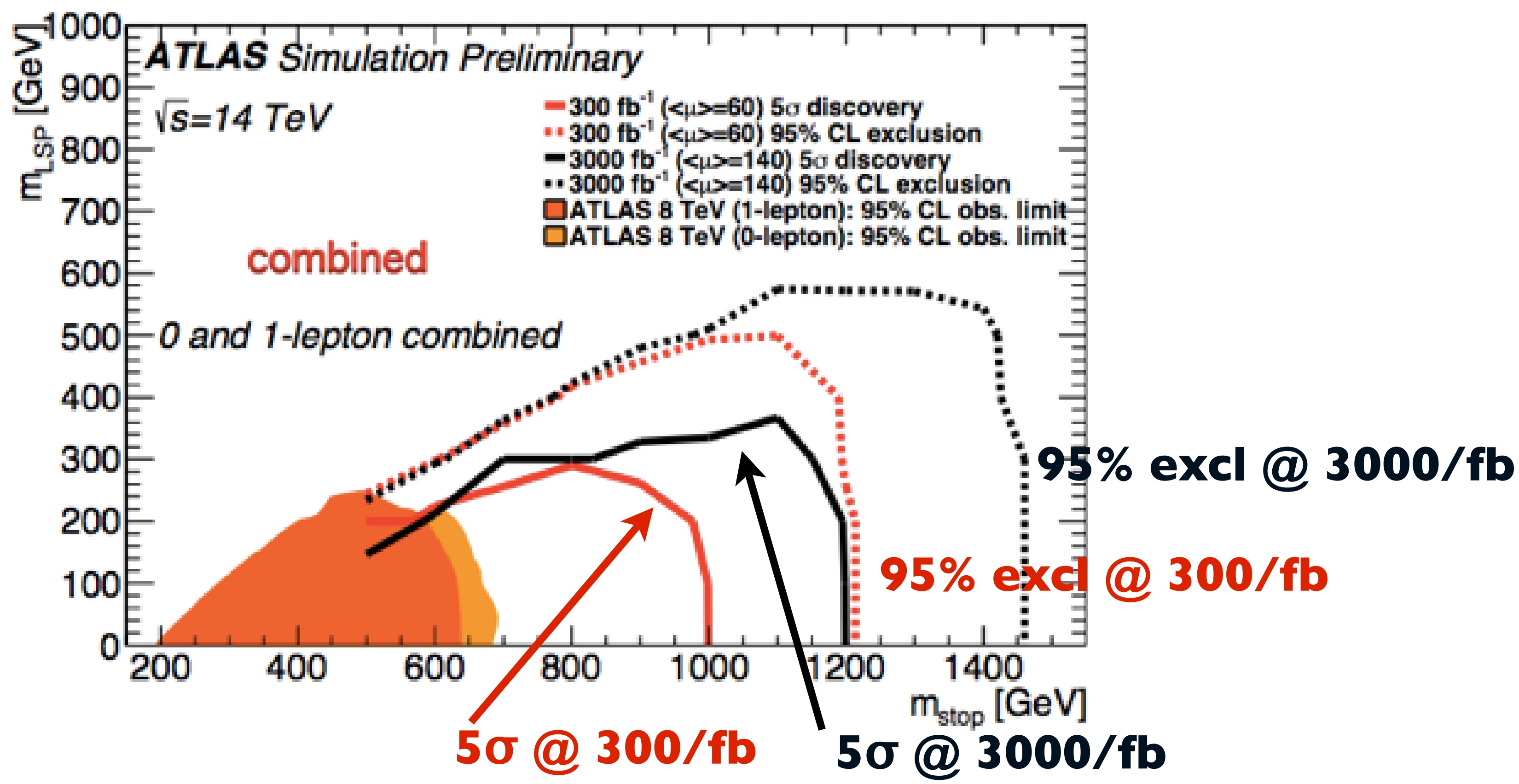




Extension of the discovery reach at low mass

- 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)



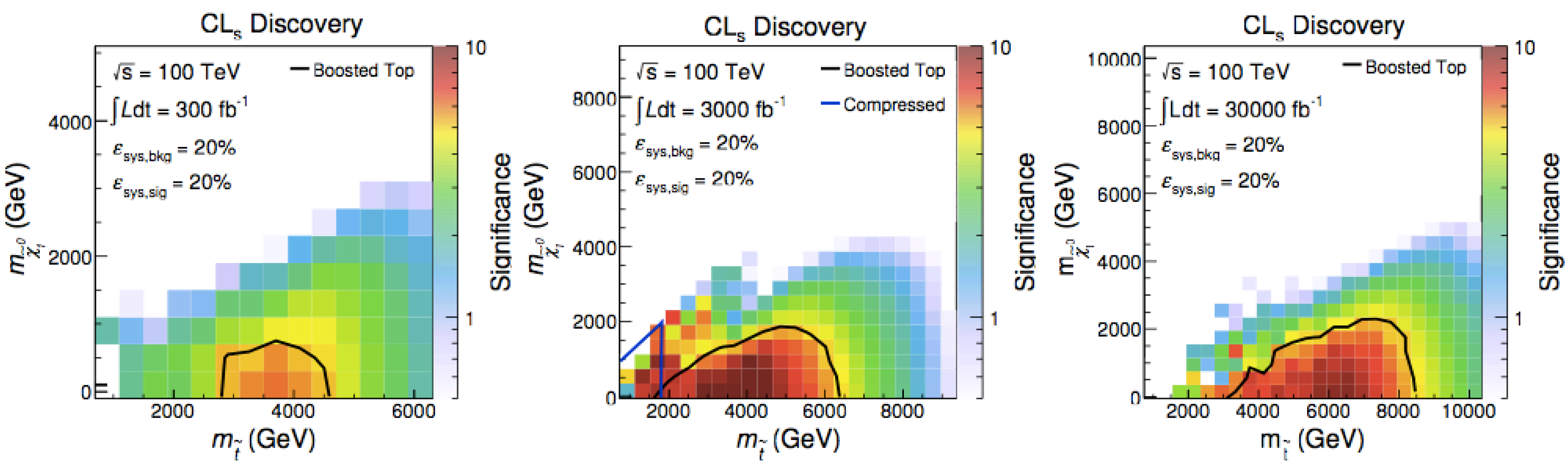
Example: direct stop production

from Mike Hance's talk

$pp \to \tilde{t}\tilde{t}^* \to t\tilde{\chi}_1^0 \bar{t}\tilde{\chi}_1^0$ – Beyond 3 ab^{-1} arXiv:1406.4512

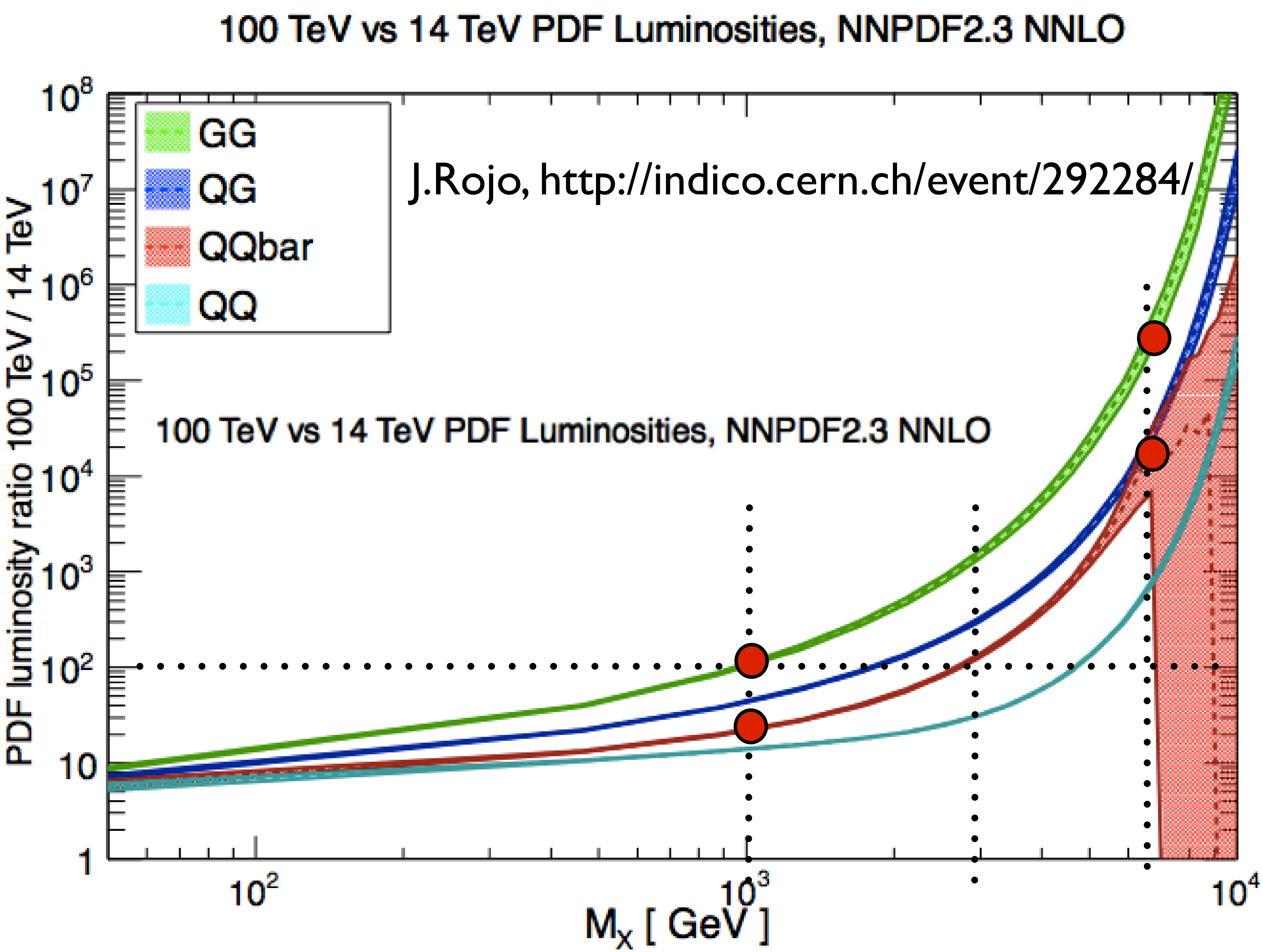
Will 3 ab^{-1} be enough at 100 TeV?

- Scale E_T^{miss} cuts for higher masses, going from 0.3 ab^{-1} to 30 ab^{-1}



Recognizing that higher luminosity is mostly needed to better explore "low" masses, rather than the highest masses, may lead to different perspective on the design of detectors

Higher statistics for studies of particles discovered at the LHC



At the edge of the HL-LHC discovery reach, namely
$m_X \sim 6.5$ TeV :

$$\sigma(100\,\text{TeV}) / \sigma(14\,\text{TeV}) \sim \begin{cases} 10^4 \text{ for q-qbar} \to X \\ 10^5 \text{ for } gg \to X \end{cases}$$

⇒ improve by orders of magnitude the precision of the measurements of particle **X** discovered at the mass-end of the LHC reach

At lower masses the increase is less pronounced.
$m_X \sim 1$ TeV :

$$\sigma(100\,\text{TeV}) / \sigma(14\,\text{TeV}) \sim \begin{cases} \sim 25 \text{ for q-qbar} \to X \\ \sim 10^2 \text{ for } gg \to X \end{cases}$$

Once again, it's the "low"-mass physics that benefits the most from luminosity

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

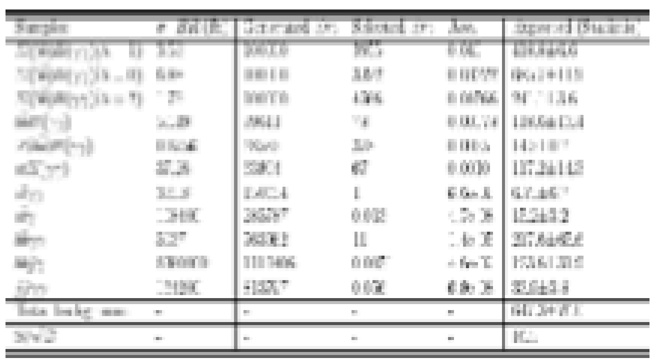
- Gains in the range 10-50, however ....
- => needs detailed studies, considering also the prospects to study rare decays, selfcouplings,etc.etc.

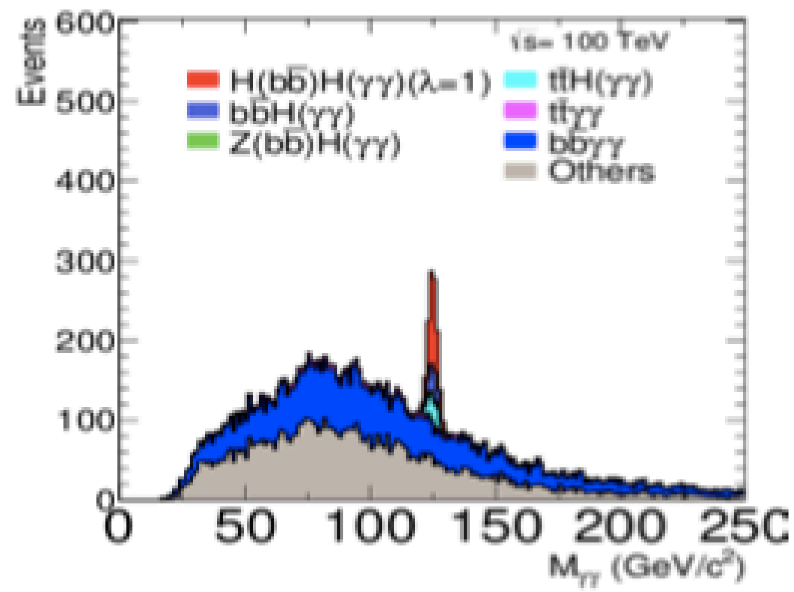
Example: H selfcoupling at 100 TeV

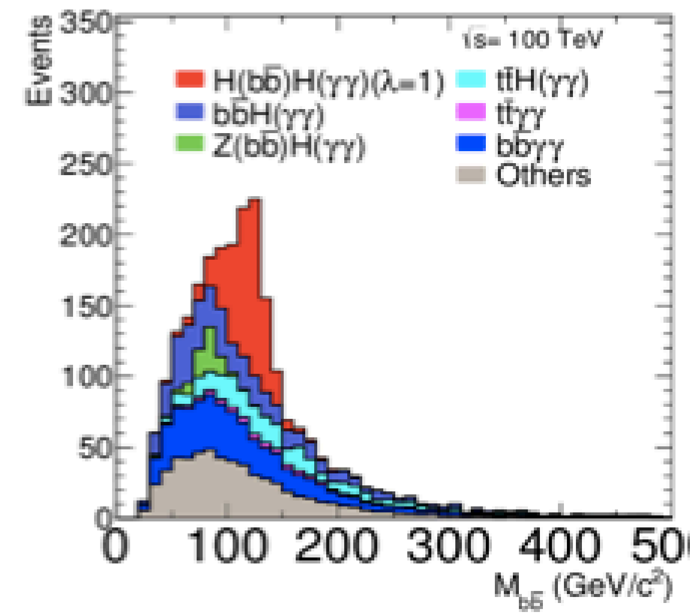
W.Yao, update of http://arxiv.org/abs/1308.6302,
shown at "IAS programme on The Future of High Energy Physics", Hong Kong, January 2015
http://ias.ust.hk/program/shared_doc/201501fhep/Weiming%20Yao_Jan%2021.pdf

Updating HH→bbγγ at Tev100

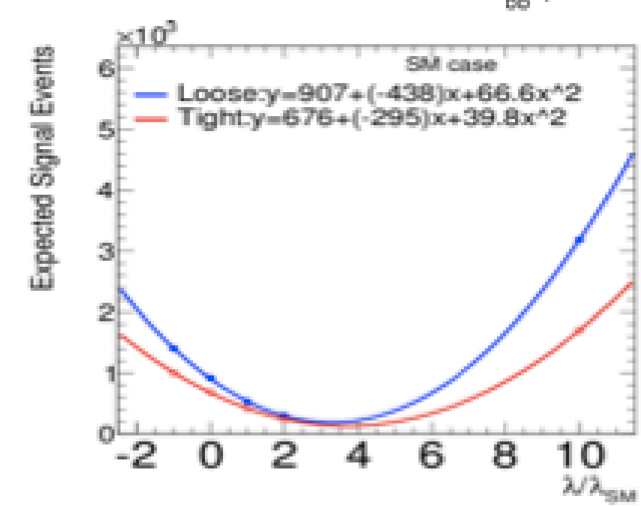
- Using Delphes 3.1.14 and the results depends on detector performace assumed.
- Including jjγγ, bbjγ, ttγ, ttγγ with ATLAS fγ=0.0093e(-Et/27.5) for HL-LHC
- Tighten mγγ window from 10 GeV used for snowmass to 6 GeV.







- Significance = 16.5 with 3 ab-1.
- H coupling dλ/λ=15% with dσ/dλ=-0.51
- ArXiv:1412.7154 reported 40% using ATLAS photon ID eff.
- To achieve 5% precision, we need to combine with other channels or get more integrated luminosity (~30 ab-1).
- Also start to probe Higgs coupling in VBF, ttHH channels.



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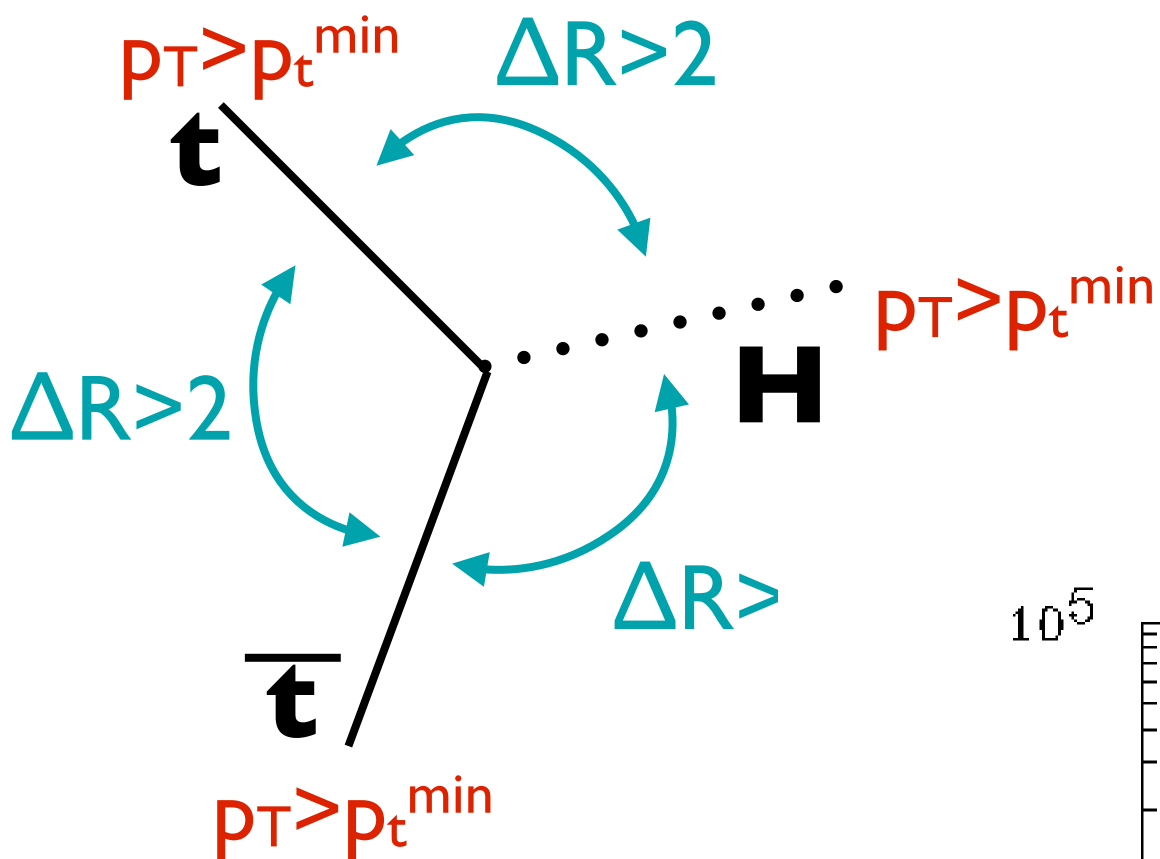
Fast Simulation Setup

- Focus on $HH \to bb\gamma\gamma$ channel as baseline.
- Signal: Madgraph V1.5.14+pythia6.2
- Background: MadGraph5.14 with MLM matching up to 1 partons
- Simulated with Delphes V3.1.2 with ATLAS responses
  - Ecal smeared with: $\sigma_{ET}/E_T = 0.20/\sqrt{E_T} \oplus 0.17\%$
  - Use the anti-kT for jets with a radius of 0.5
  - btag eff. at 75% for b, 18.8% for c and 1% for mistag, up $|\eta|<2.5$
  - Including faking photon contributions:
    - Fake rate =0.0093exp(-Et(GeV)/27) from ATLAS
    - Fake photon Et scaled from Jet Et by 75% with σ=0.12
- For future studies, we should converge the expected detector performances.
  - Tracking coverage, lepton ID efficiency, and fakes
  - Jet resolutions, missing Et resolution, and pile-up rejections.

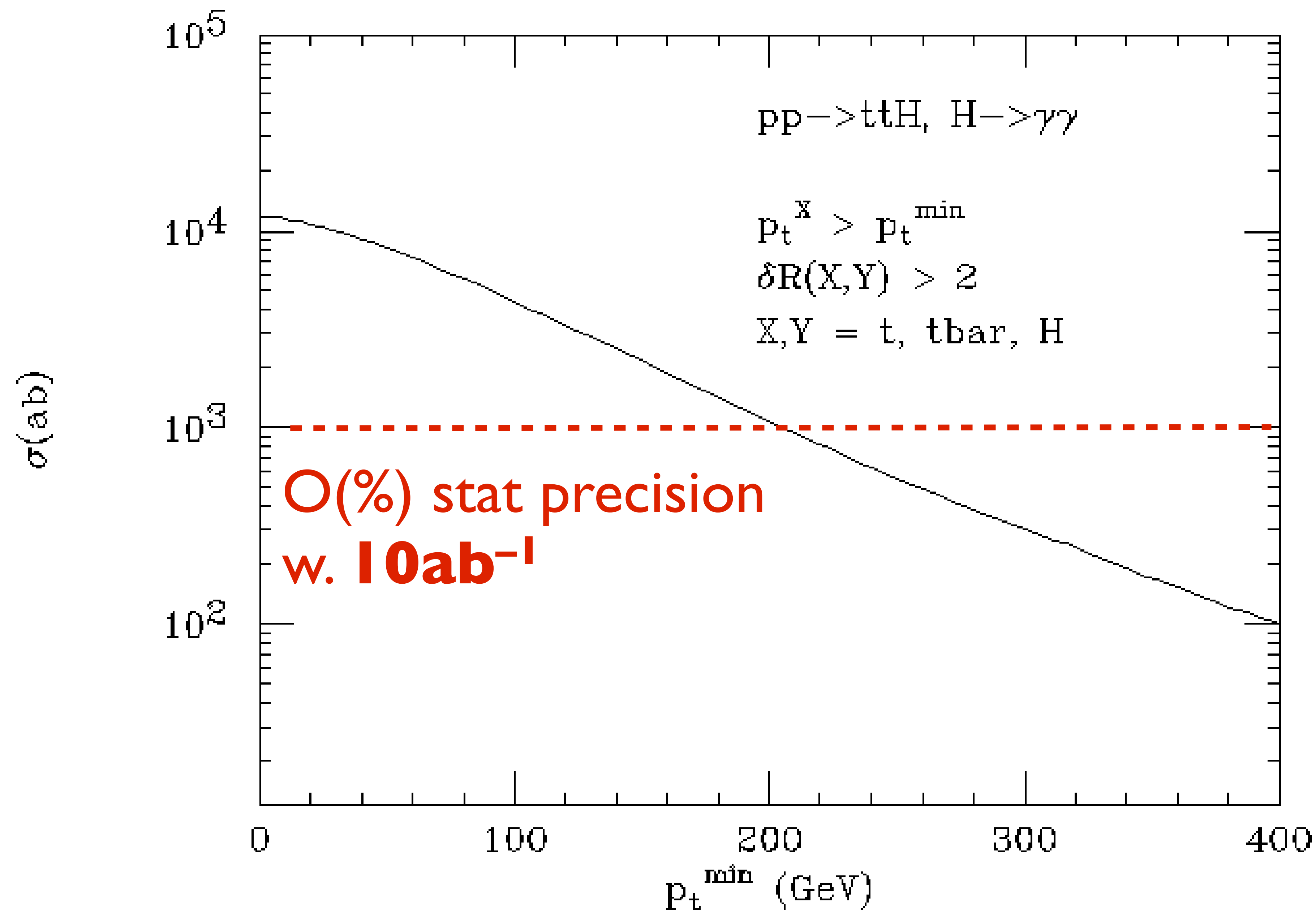
W.Yao, at "IAS programme on The Future of High Energy Physics", Hong Kong, January 2015
http://ias.ust.hk/program/shared_doc/201501fhep/Weiming%20Yao_Jan%2021.pdf

Example, ttH at large pt



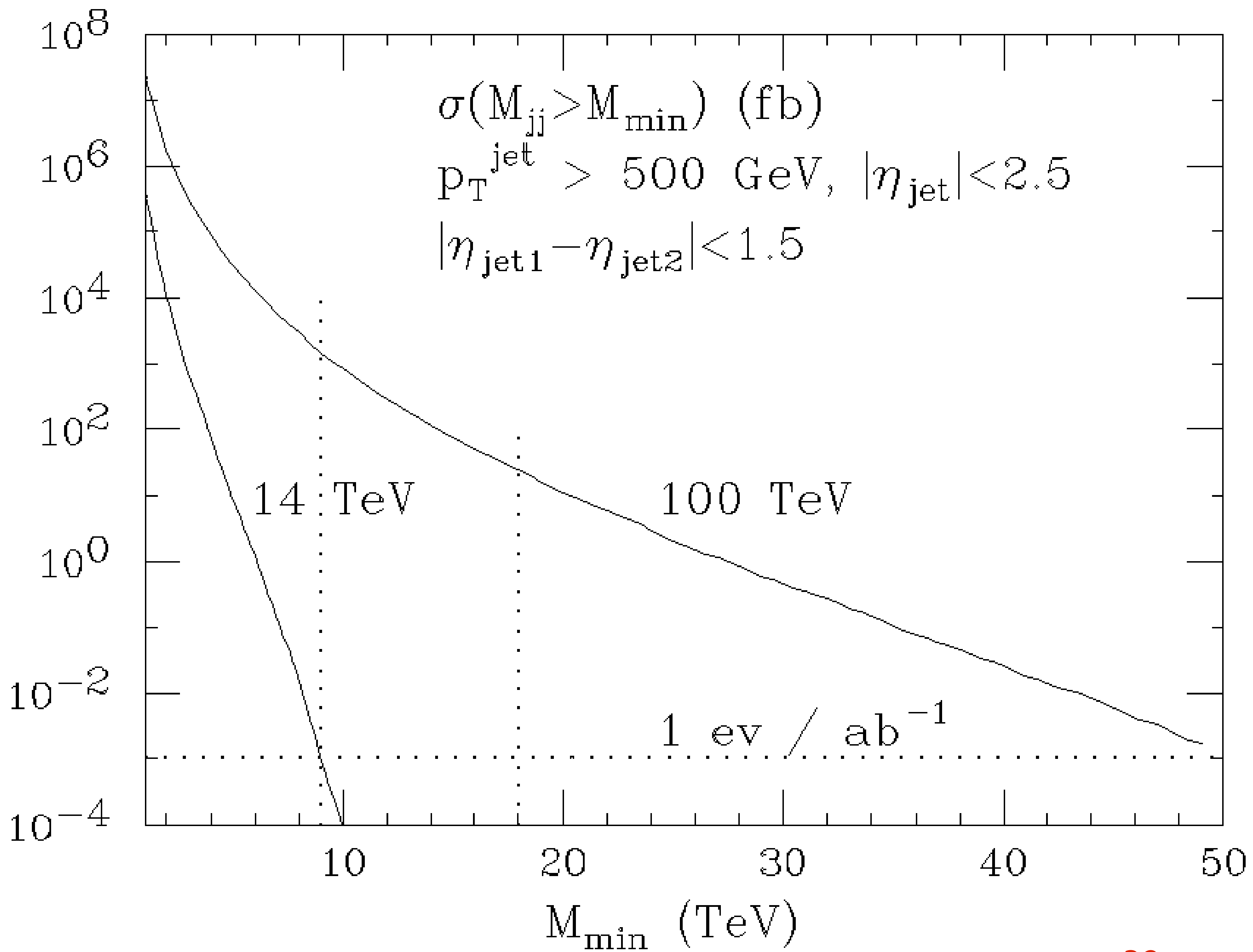
Goal: %-level measurement of $\sigma(ttH)$ / $\sigma(ttZ)$

(MLM and H-S Shao, in progress)



Initial luminosity, or:
what’s the minimum lum to
take us beyond the HL-LHC ?

Example: dijet production at large mass



- 1 pb^{-1} to recover sensitivity of HL-LHC ⇒< 1 day @ 10^{32}
- 50pb^{-1} to 2x the sensitivity of HL-LHC ⇒< 1 month @ 10^{32}
- 1fb^{-1} to 3x the sensitivity of HL-LHC ⇒< 1 year @ $2x10^{32}$

For resonances: at the edge of the HL-LHC discovery reach, namely $m_X \sim 6.5$ TeV :

$$\sigma(100\,\text{TeV}) / \sigma(14\,\text{TeV}) \sim \begin{cases} 10^4 \text{ for q-qbar} \rightarrow X \\ 10^5 \text{ for gg} \rightarrow X \end{cases}$$

This means:

- If **X** is discovered at the HL-LHC, it can be confirmed at 100 TeV with $10^{-(4\div5)}$ of the HL-LHC luminosity, i.e. O(30-300 pb^{-1})
  - => $L < 5 \times 10^{31}$ in the 1st year
- A luminosity of O(0.1 – 1 fb^{-1}) allows the discovery of particles just beyond the HL-LHC reach
  - => $L < 2 \times 10^{32}$ in the 1st year

Top quark studies

$$\sigma(14 \rightarrow 100\ \text{TeV}) = 0.9 \rightarrow 34\ \text{nb}$$

$$\boldsymbol{\sigma(100\ \text{TeV}) / \sigma(14\ \text{TeV}) \sim 40}$$

This means:

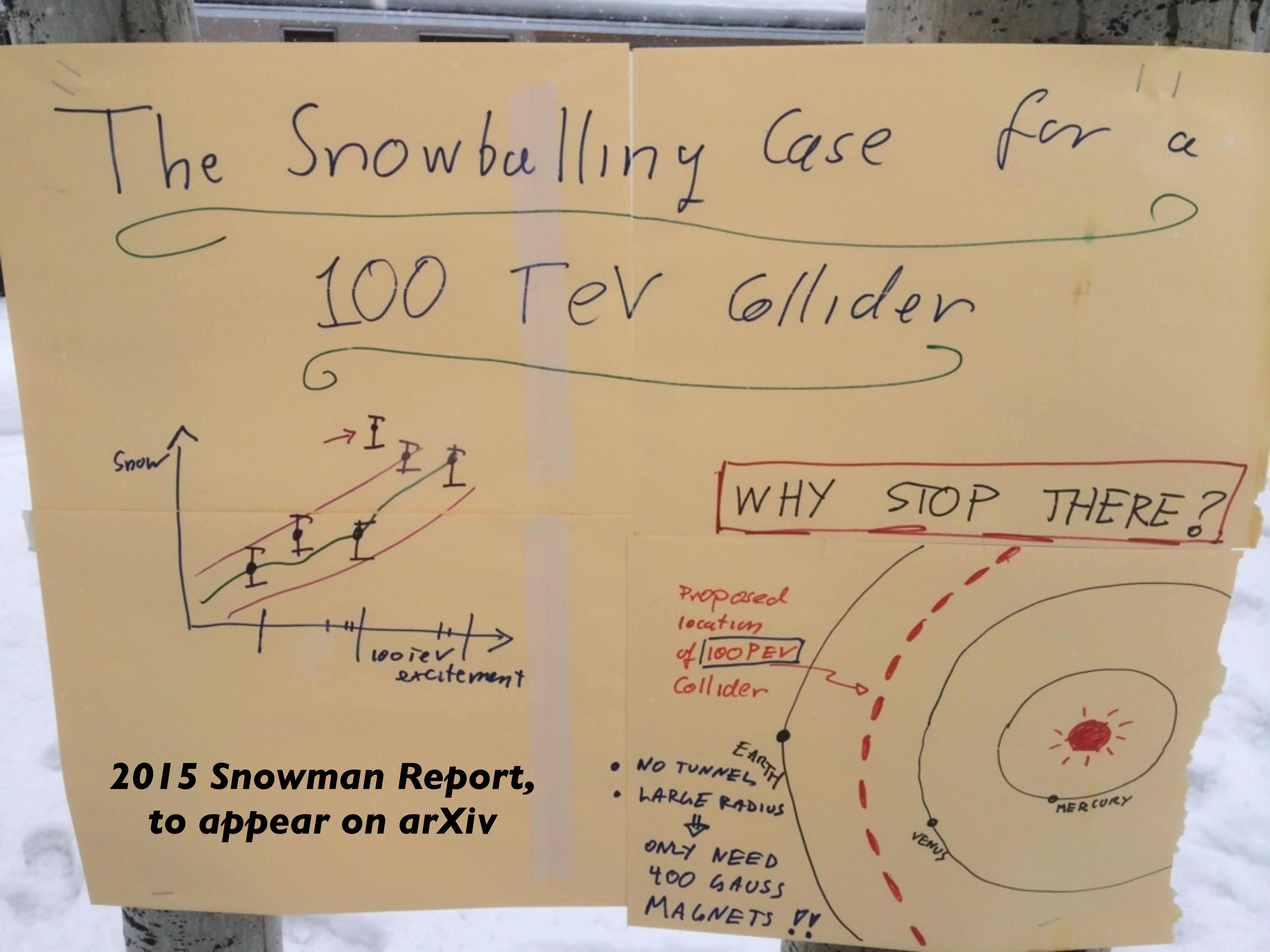
- Need ~100 fb^{-1} to reproduce the statistics of HL-LHC
- ⇒ 1 year at 2×10^{34}

Conclusions

- The goal of O(10-20 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
- Startup at 10^{32} is enough to quickly move to discovery region
- **More aggressive** luminosity goals may be required by specific measurements, but do not seem justified by generic arguments. Further work on ad hoc scenarios (particularly at low mass, elusive signatures, etc) is nevertheless desirable.
- For a large class of after-LHC scenarios, **less aggressive** lumi goals are also fully acceptable as optimal compromise between physics return and technical/experimental challenges


- DEGREES OF SUCK +
NO FOOD
NO BEER
NO GIRLS
NO SNOW
LOW LUM
NO FCC
ASPEN YOUTH EXPERIENCE


DPF's Snowma...n meeting 2015
MICHELANGELO
jared
joel
ahmed
david
suzanne



2015 Snowman Report, to appear on arXiv