Luminosity goals for a 100-TeV pp collider

Ian Hinchliffe[a,*], Ashutosh Kotwal[b,†], Michelangelo L. Mangano[c,‡], Chris Quigg[d,§], Lian-Tao Wang[e,¶]

[a] Phyiscs Division, Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA

[b] Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
Duke University, Durham, North Carolina 27708, USA

[c] PH Department, TH Unit, CERN, CH-1211 Geneva 23, Switzerland

[d] Theoretical Physics Department, Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510 USA
Institut de Physique Théorique Philippe Meyer, École Normale Supérieure
24 rue Lhomond, 75231 Paris Cedex 05, France

[e] Department of Physics and Enrico Fermi Institute, University of Chicago, Chicago, IL 60637 USA

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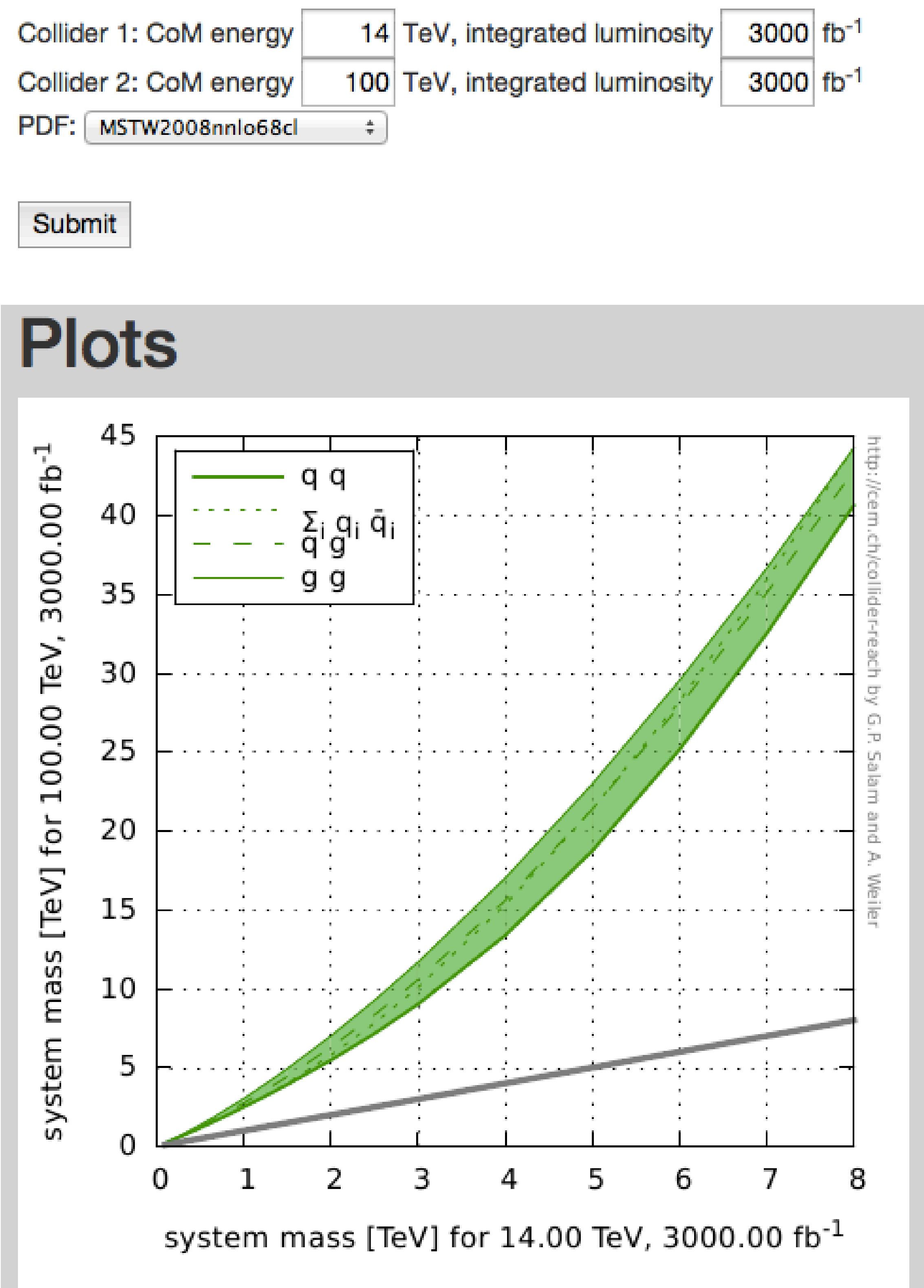
Abstract

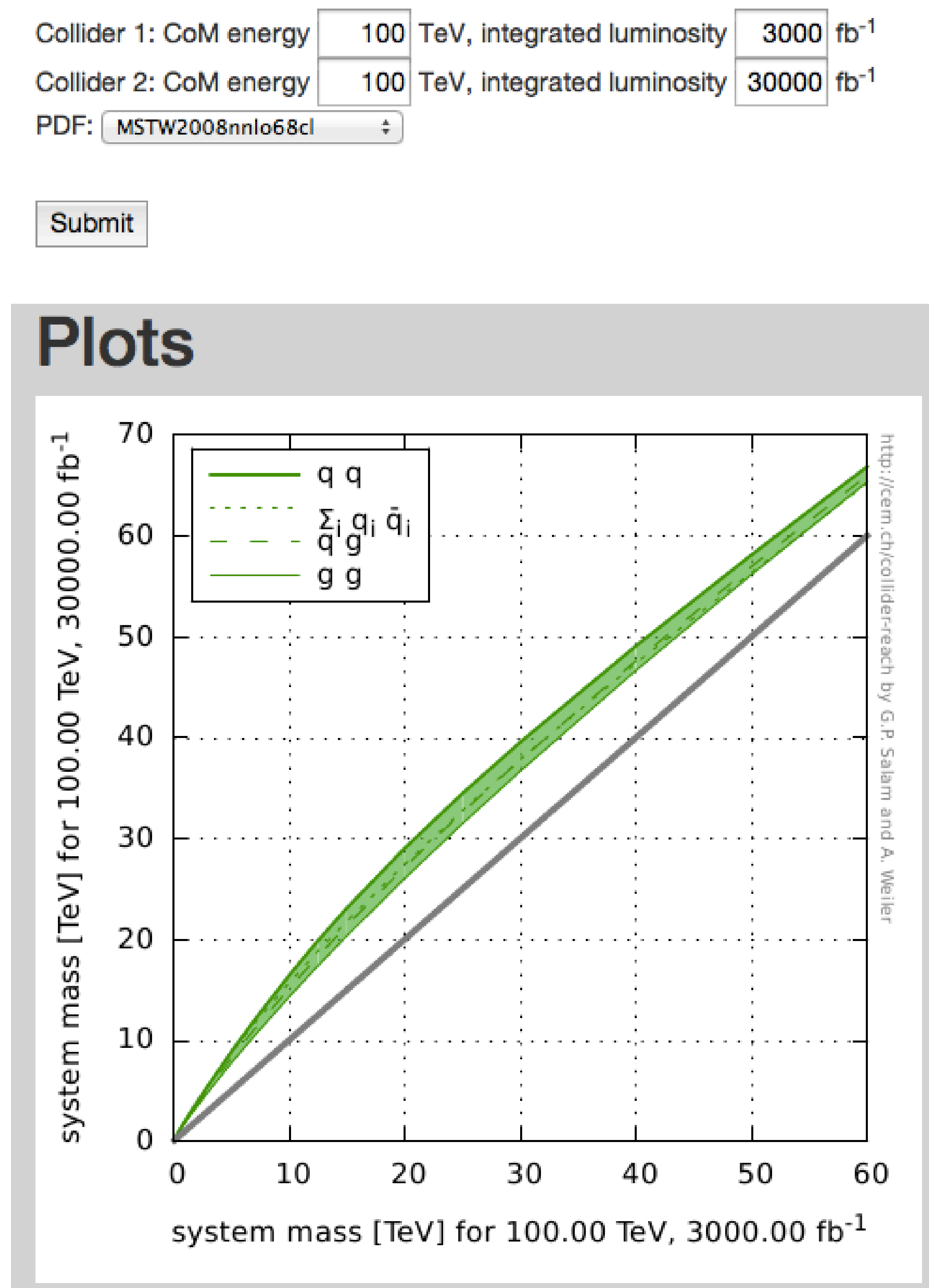
We consider diverse examples of science goals that provide a framework to assess luminosity goals for a future 100-TeV proton-proton collider.

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

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

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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

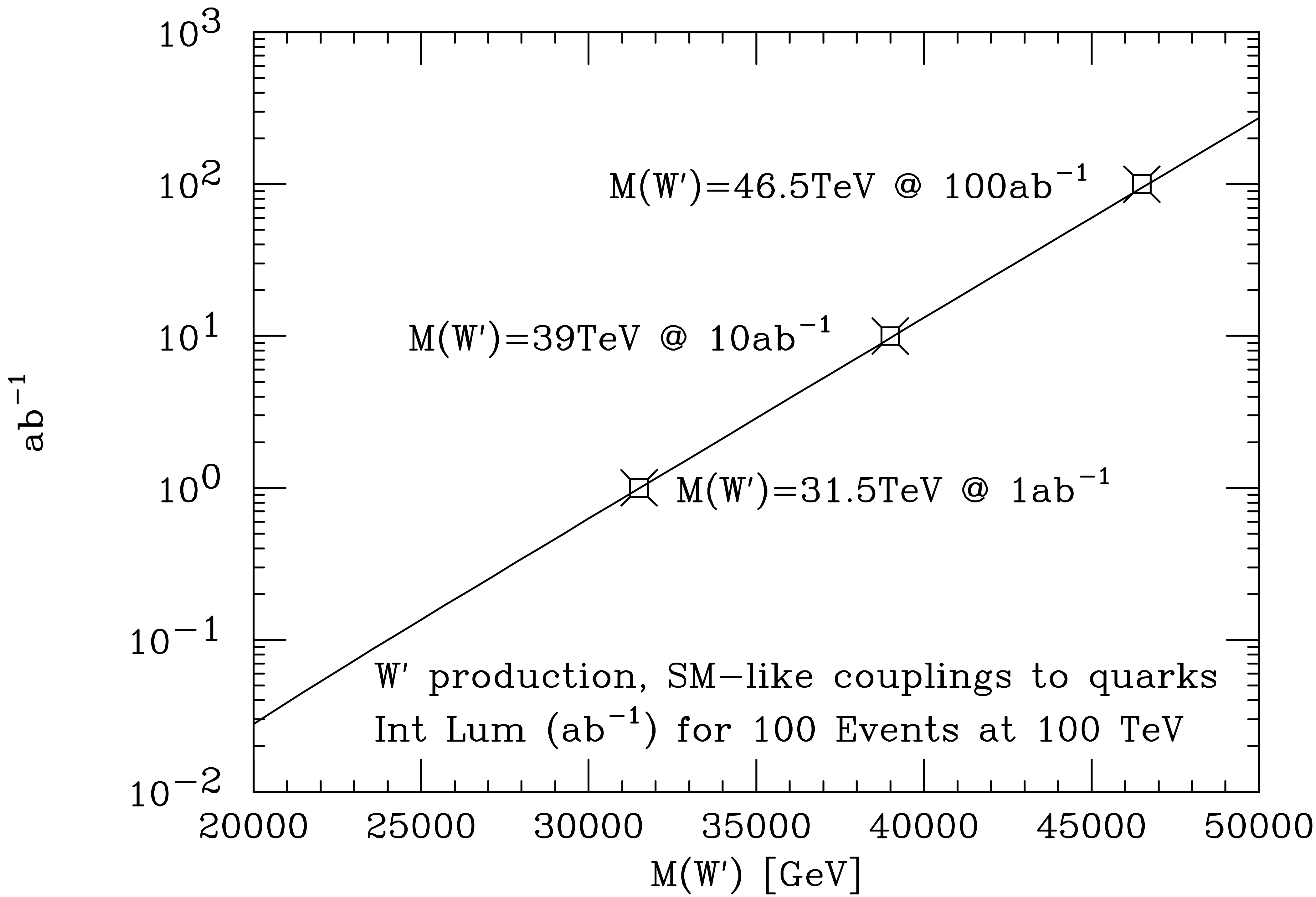
$$\sigma(M,g) \propto \frac{g^2}{S}\, \frac{L(x)}{x}$$

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

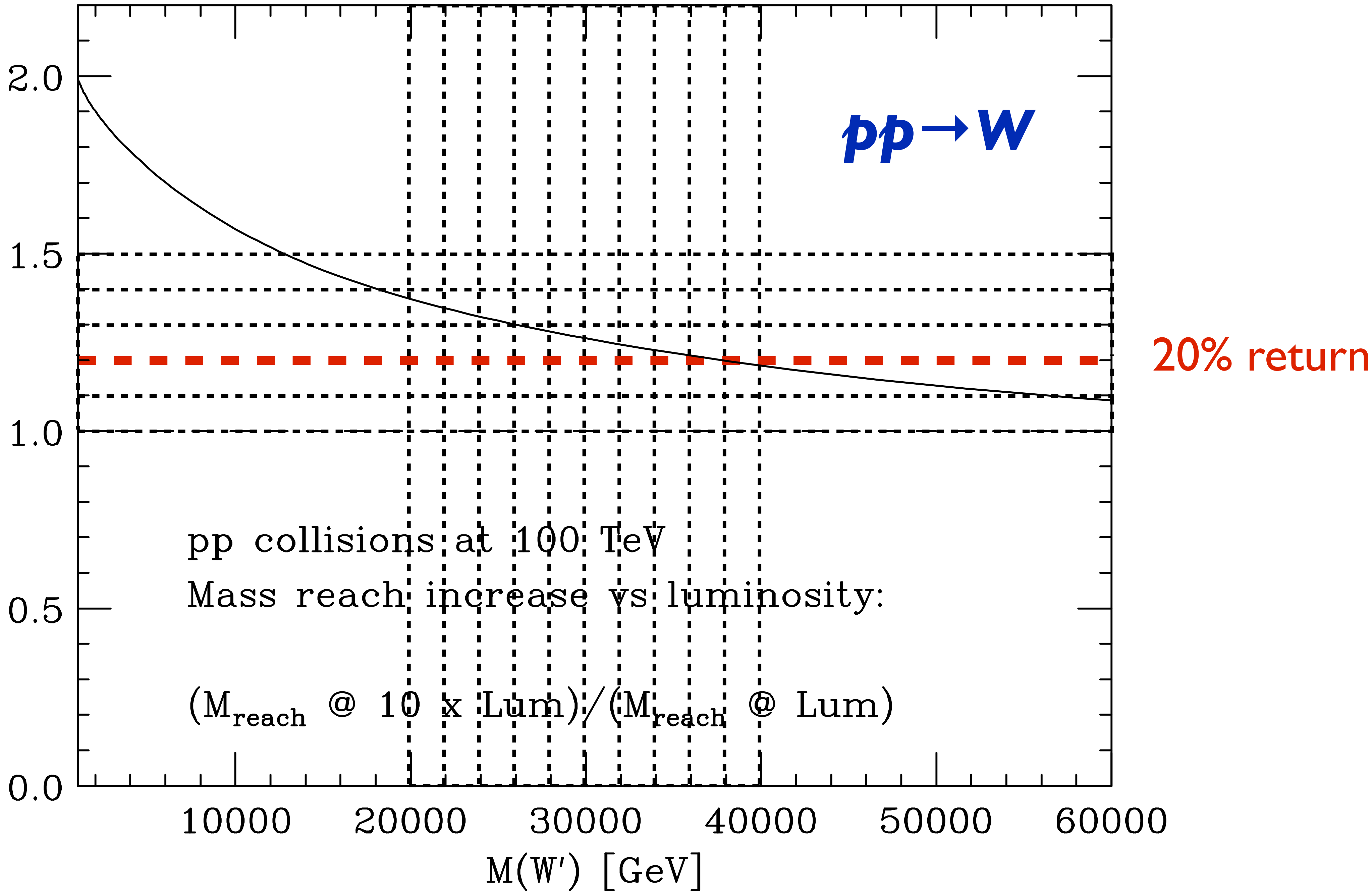
Extension of the discovery reach at high mass

Example: discovery reach of **W' with SM-like couplings**

NB For SM-like Z', $\sigma_{Z'}$ BR_{lept} ~ 0.1 x $\sigma_{W'}$ 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)

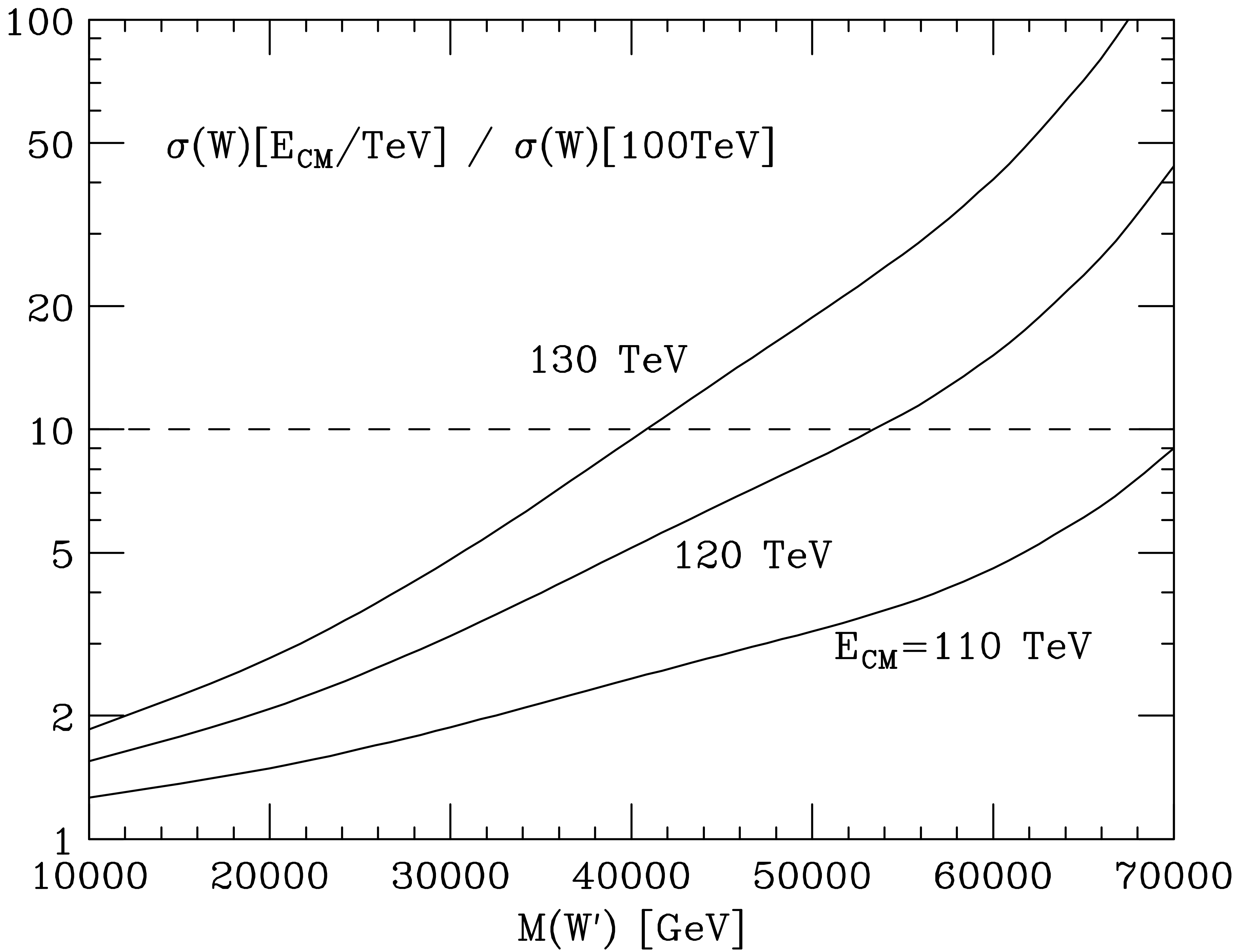
See e.g. the history of Tevatron achievements: after $1 fb^{-1}$, limited progress at the high-mass end, but plenty of results at "low" mass (W, top and b physics, Higgs sensitivity, ...)

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

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**

- *$\Delta M/M \sim 20\% \Rightarrow$ the LHC reaches the threshold of saturation of the mass reach already at $300 fb^{-1}$. 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 $L(100) \sim 15ab^{-1}$***

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 ?

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)**

Example: direct stop production

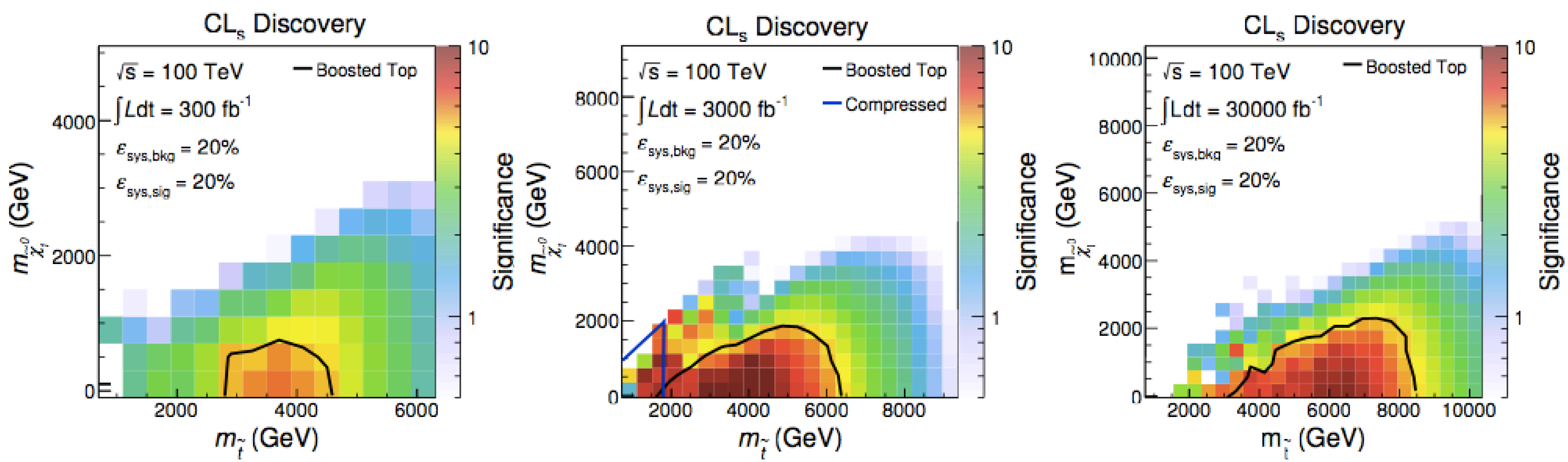
from Mike Hance's talk

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

arXiv:1406.4512

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

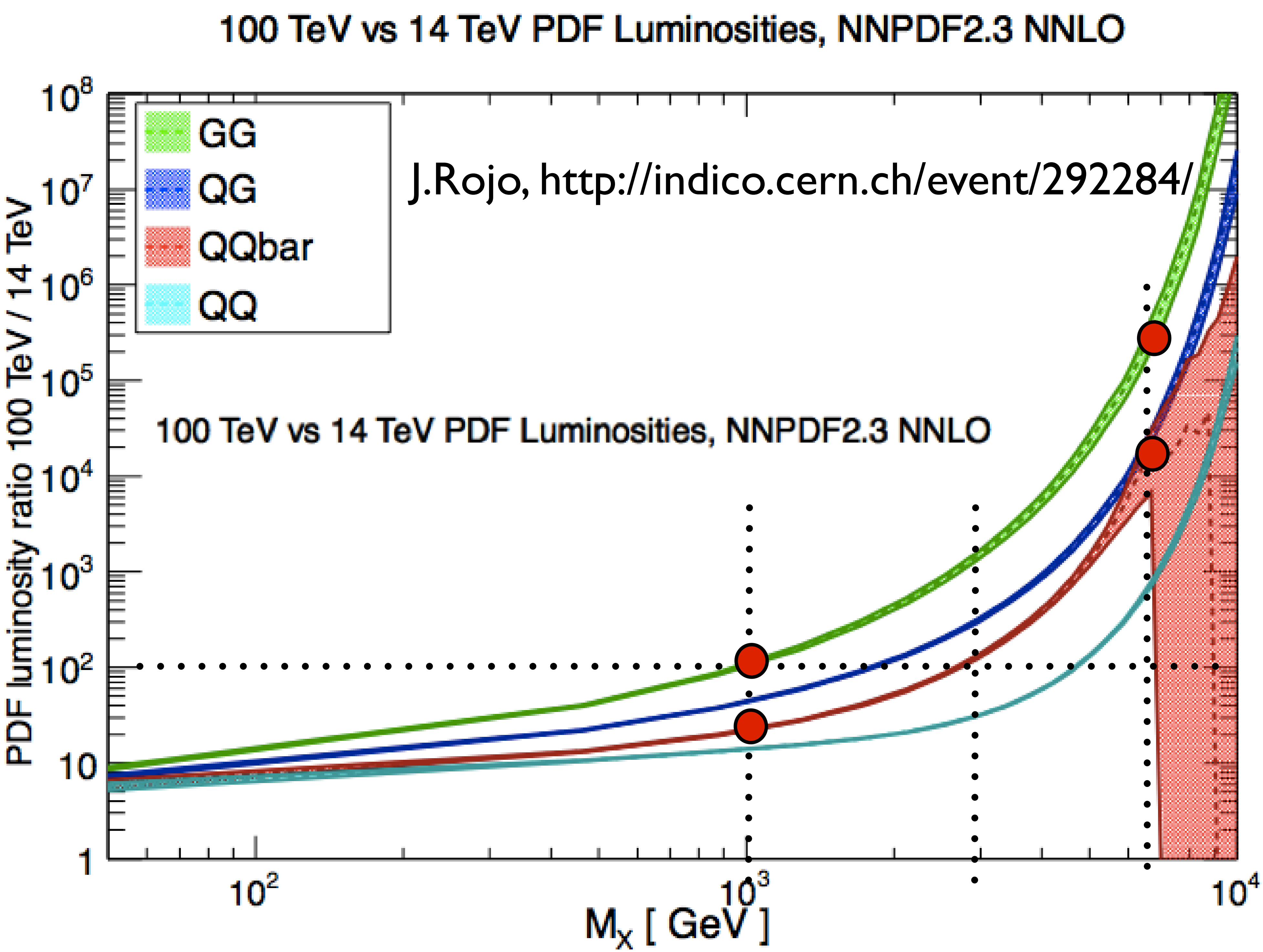
- Scale E_T^{miss} cuts for higher masses, going from 0.3 ab^{-1} to 30 ab^{-1}



Mike Hance (LBNL) | 23 / 25 | Colored SUSY- January 30, 2015

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 :

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

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

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At lower masses the increase is less pronounced.
m_X ~ 1 TeV :

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

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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

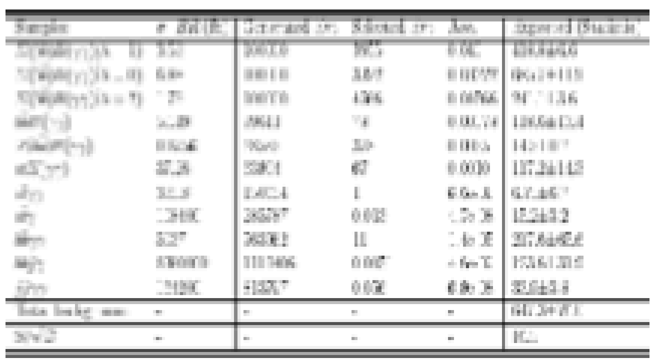
- Gains in the range 10-50, however ....
- => needs detailed studies, considering also the prospects to study rare decays, selfcouplings,etc.etc.

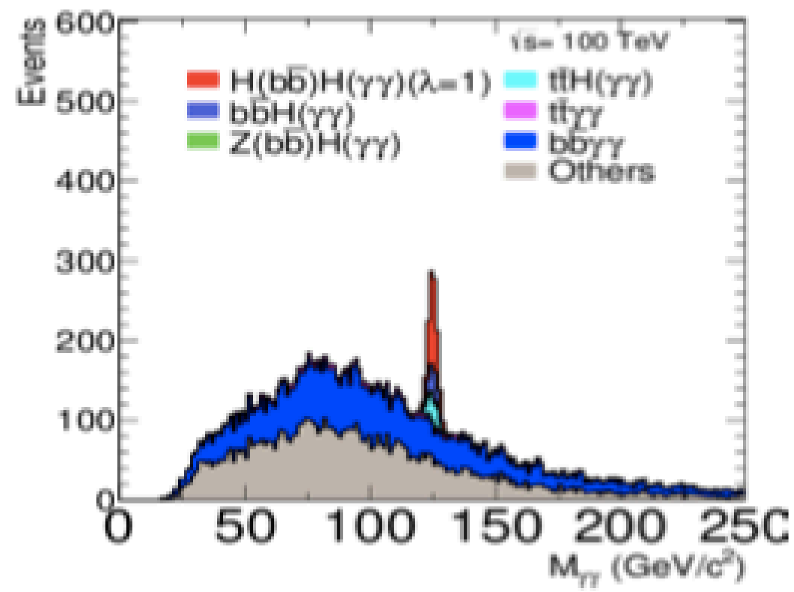
Example: H selfcoupling at 100 TeV

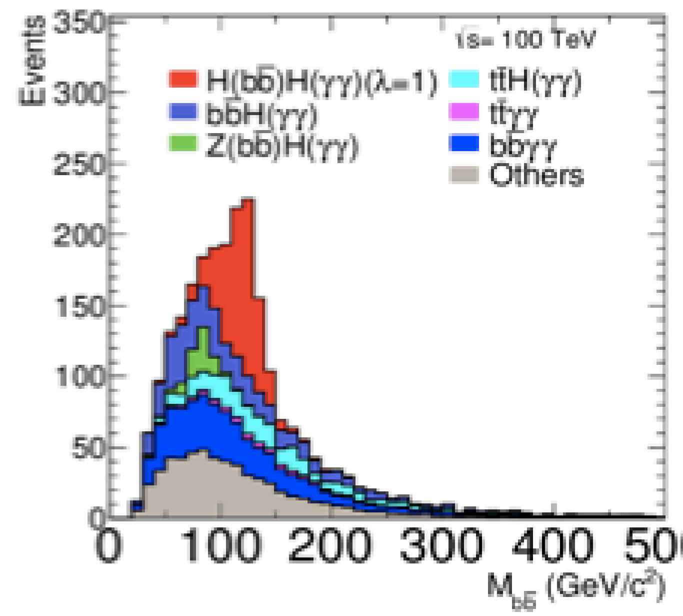
W.Yao, update of http://arxiv.org/abs/1308.6302,
shown at "IAS programme on The Future of High Energy Physics", Hong Kong, January 2015
http://ias.ust.hk/program/shared_doc/201501fhep/Weiming%20Yao_Jan%2021.pdf

Updating HH→bbγγ at Tev100

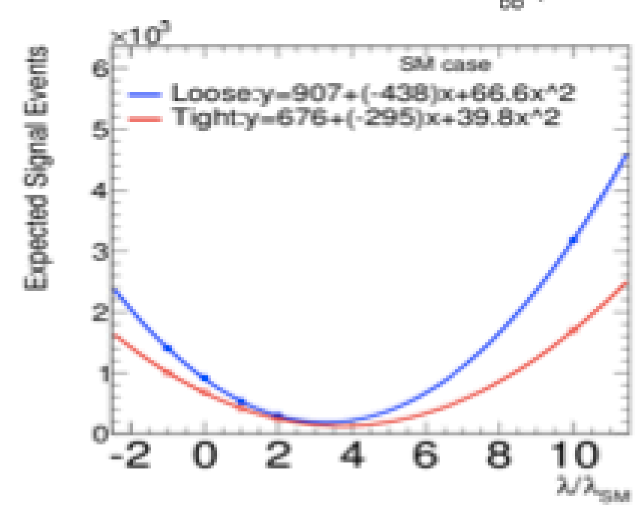
- Using Delphes 3.1.14 and the results depends on detector performace assumed.
- Including jjγγ, bbjγ, ttγ, ttγγ with ATLAS fγ=0.0093e(-Et/27.5) for HL-LHC
- Tighten mγγ window from 10 GeV used for snowmass to 6 GeV.







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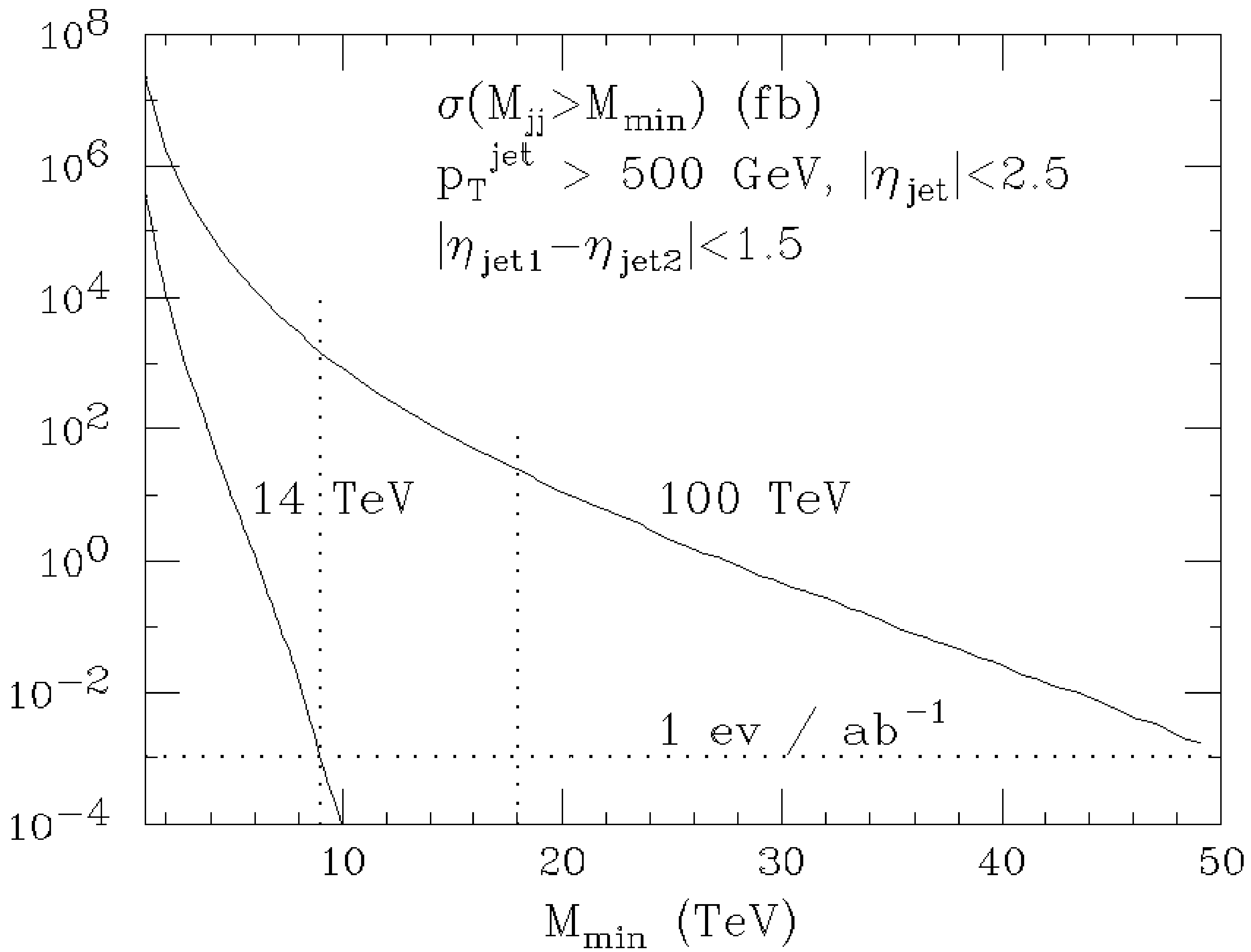
Initial luminosity, or: what's the minimum lum to take us beyond the HL-LHC ?

Example: dijet production at large mass



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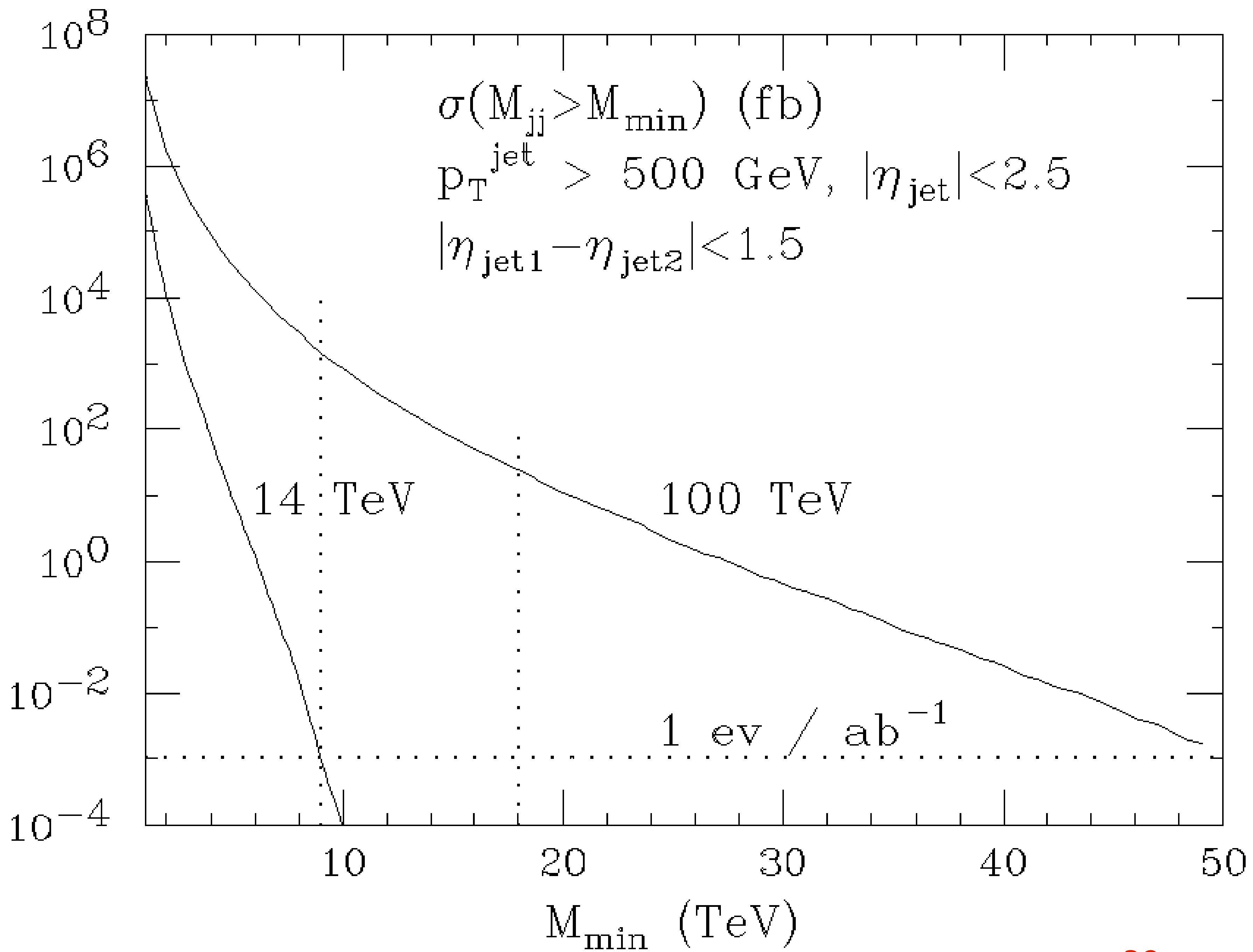

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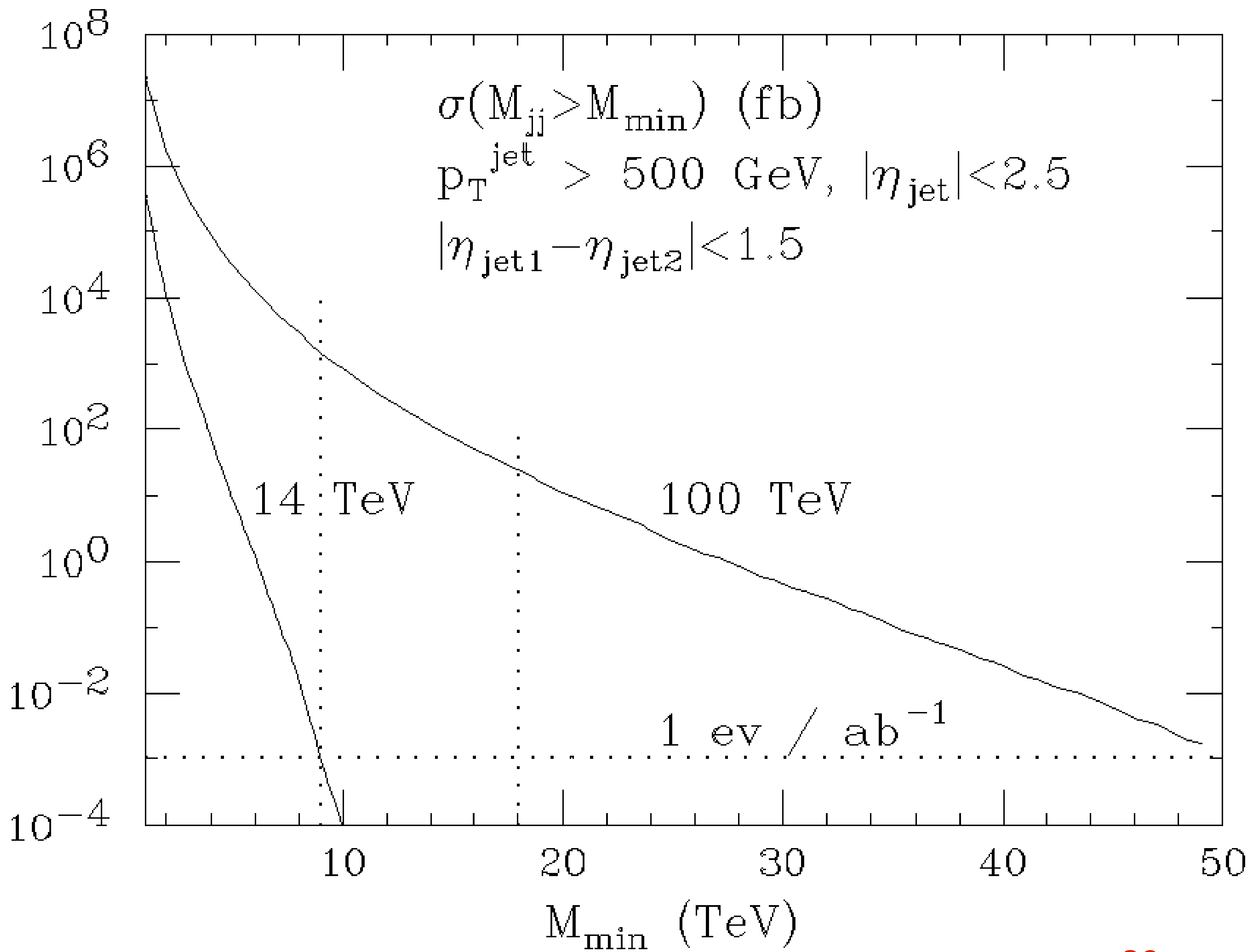

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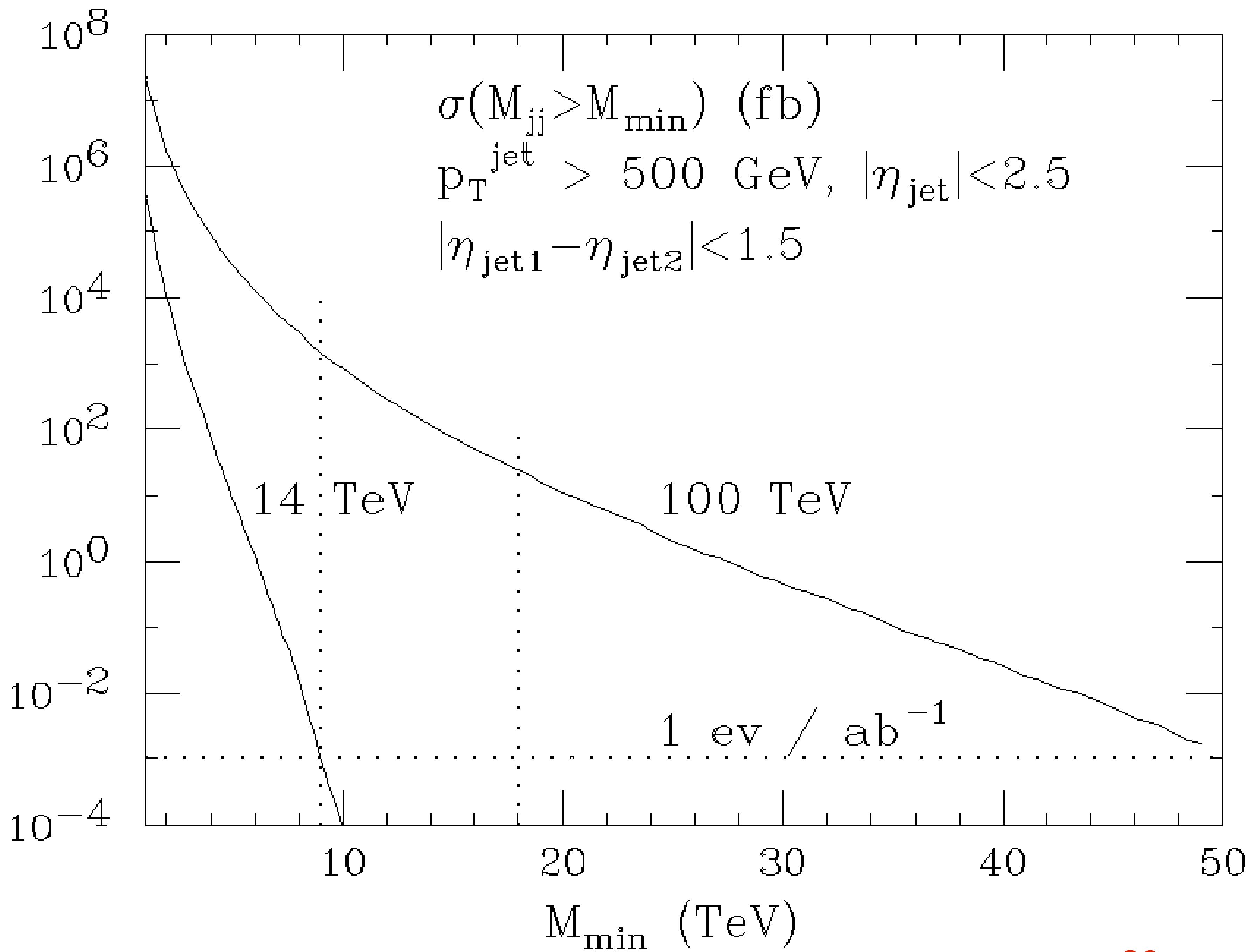

- 1 pb^{-1} to recover sensitivity of HL-LHC ⇒< 1 day @ 10^{32}
- 50pb^{-1} to 2x the sensitivity of HL-LHC ⇒< 1 month @ 10^{32}
- 1fb^{-1} to 3x the sensitivity of HL-LHC ⇒< 1 year @ 2x10^{32}

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

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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 < $5\text{x}10^{31}$ 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 < 2×10^{32} in the 1st year

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- The goal of an integrated luminosity in the range of 10-20 ab^{-1} per experiment, corresponding to an ultimate instantaneous luminosity approaching 2×10^{35}, seems well-matched to our current perspective on extending the discovery reach for new phenomena at high mass scales, high- statistics studies of possible new physics to be discovered at (HL)-LHC, and incisive studies of the Higgs boson's properties.

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- Specific measurements may set more aggressive luminosity goals, but we have not found generic arguments to justify them. The needs of precision physics arising from new physics scenarios to be discovered at the HL-LHC, to be suggested by anomalies observed during the e+e− phase of a future circular collider, or to be discovered at 100 TeV, may well drive the need for even higher statistics. Such requirements will need to be established on a case-by-case basis, and no general scaling law gives a robust extrapolation from 14 TeV. Further work on ad hoc scenarios, particularly for low-mass phenomena and elusive signatures, is therefore desirable.

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- For a large class of new-physics scenarios that may arise from the LHC, less aggressive luminosity goals are acceptable as a compromise between physics return and technical or experimental challenges. In particular, even luminosities in the range of 10^{32} are enough to greatly extend the discovery reach of the 100 TeV collider over that of the HL-LHC, or to enhance the precision in the measurement of discoveries made at the HL-LHC