

# **Towards a definition of luminosity goals for the 100 TeV $\text{pp}$ collider**

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CERN PH-TH



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

from a recent talk given in Aspen ....

... 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:

Collider Reach ( $\beta$ ) Home Plots About

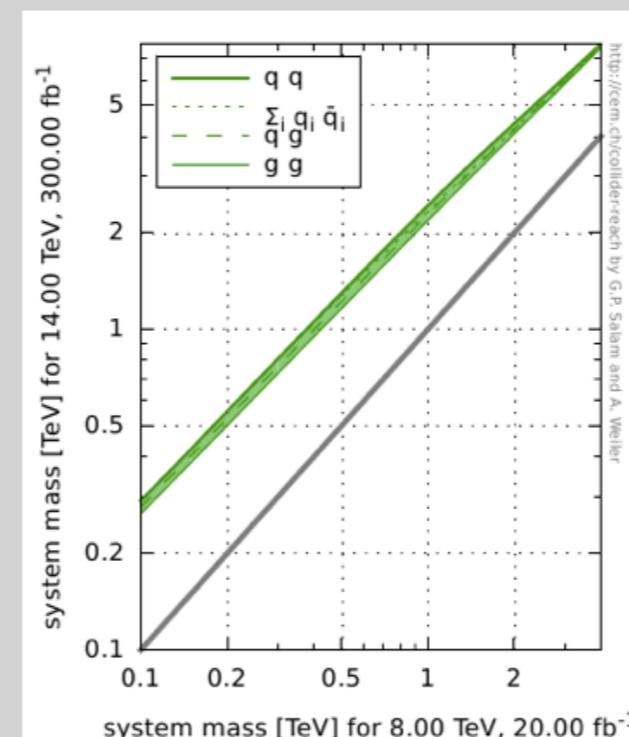
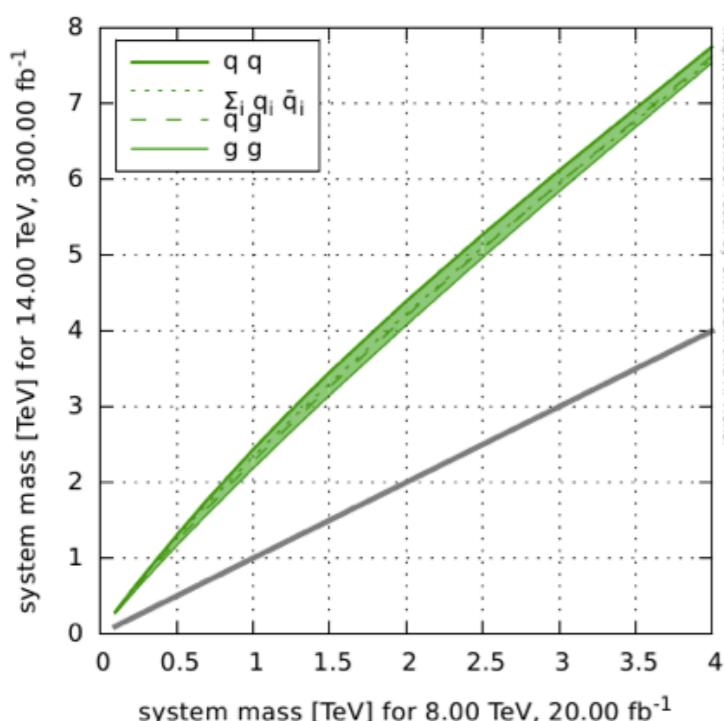
The Collider Reach tool gives you a quick (and dirty) estimate of the relation between the mass reaches of different proton-proton collider setups.

Collider 1: CoM energy 8 TeV, integrated luminosity 20  $\text{fb}^{-1}$   
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PDF: MSTW2008nnlo68cl

Submit

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

## Plots



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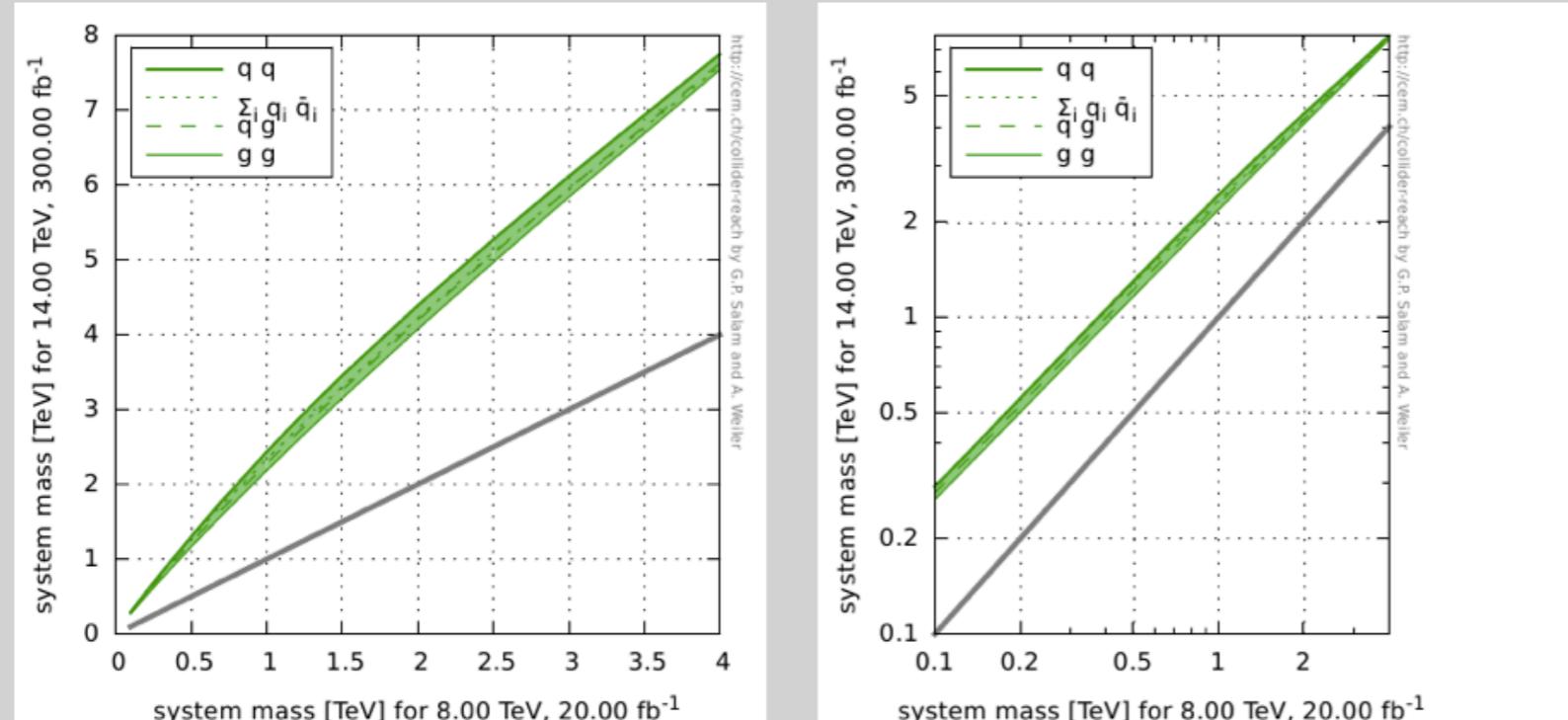
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## Plots



## 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  $E_{beam}^2$

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Initial Luminosity should allow to rapidly ( $\sim$ 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

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

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

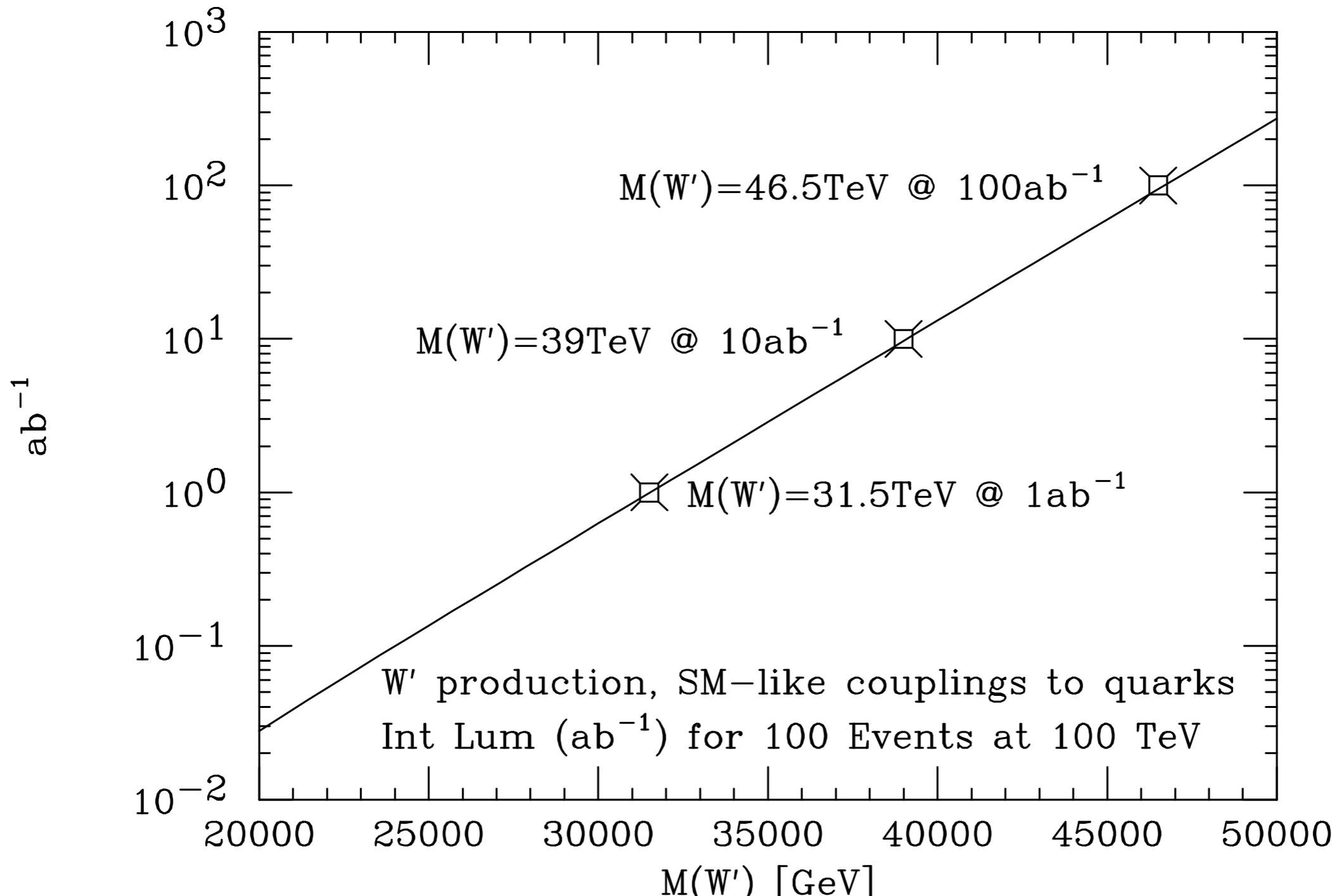
$$\sigma(M, g) \propto \frac{g^2}{S} \frac{L(x)}{x}$$

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

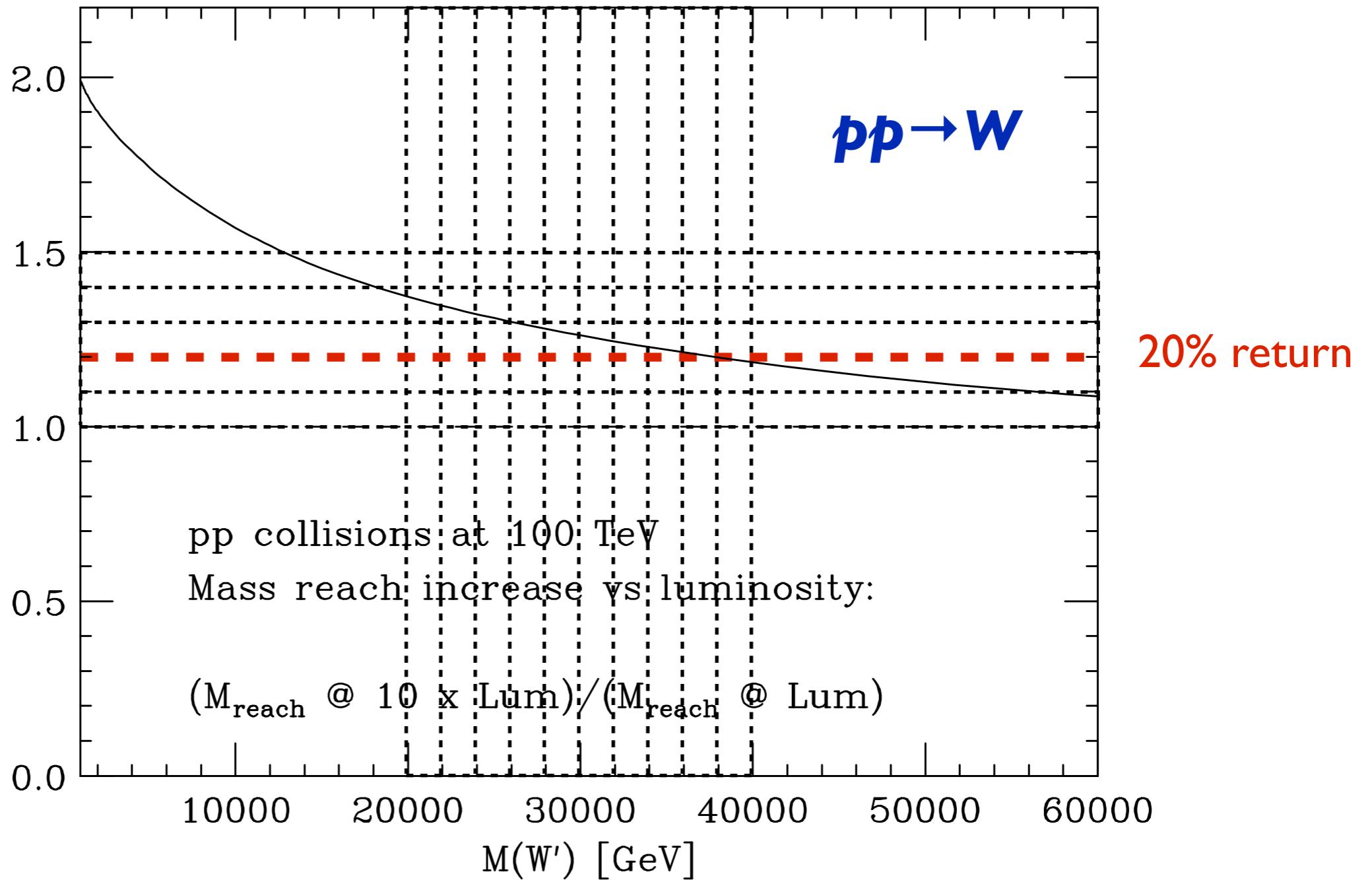
# **Extension of the discovery reach at high mass**

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

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



At  $L=O(ab^{-1})$ ,  $\text{Lum} \times 10 \Rightarrow \sim M + 7 \text{ TeV}$



$\text{Lum} \times 10 \Rightarrow$  relative gain much larger at low mass than at high mass

- One could argue that the  $10 \times$  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)

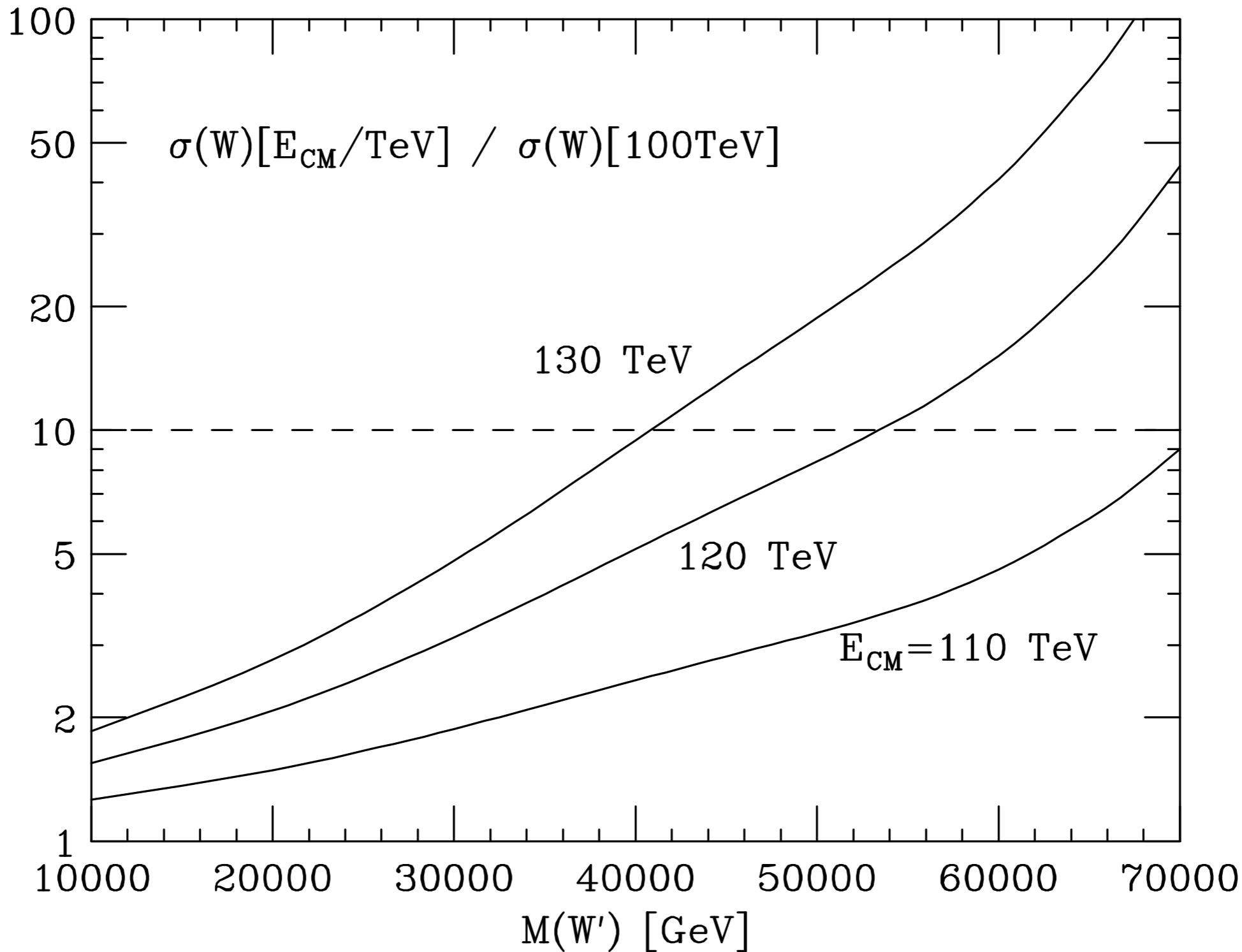
See e.g. *the history of Tevatron achievements: after  $1\text{ fb}^{-1}$ , limited progress at the high-mass end, but plenty of results at “low” mass ( $W$ , top and  $b$  physics, Higgs sensitivity, ....)*

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

ATLAS/CMS HL docs	$300/\text{fb}$	$3000/\text{fb}$
95% excl (ATLAS)	<b>6.5 TeV</b>	7.8 TeV
$5\sigma$ (CMS)	5.1 TeV	<b>6.2 TeV</b>

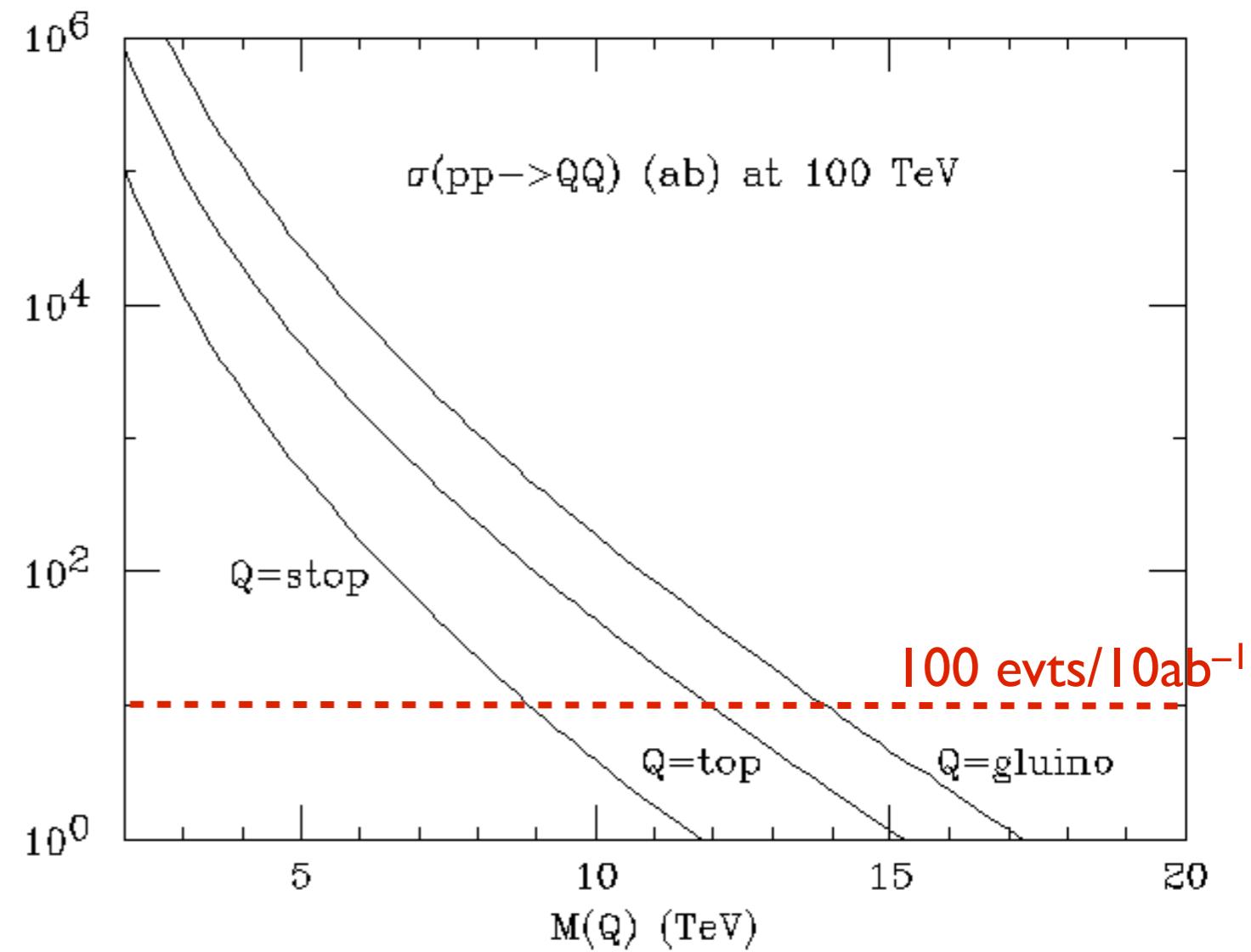
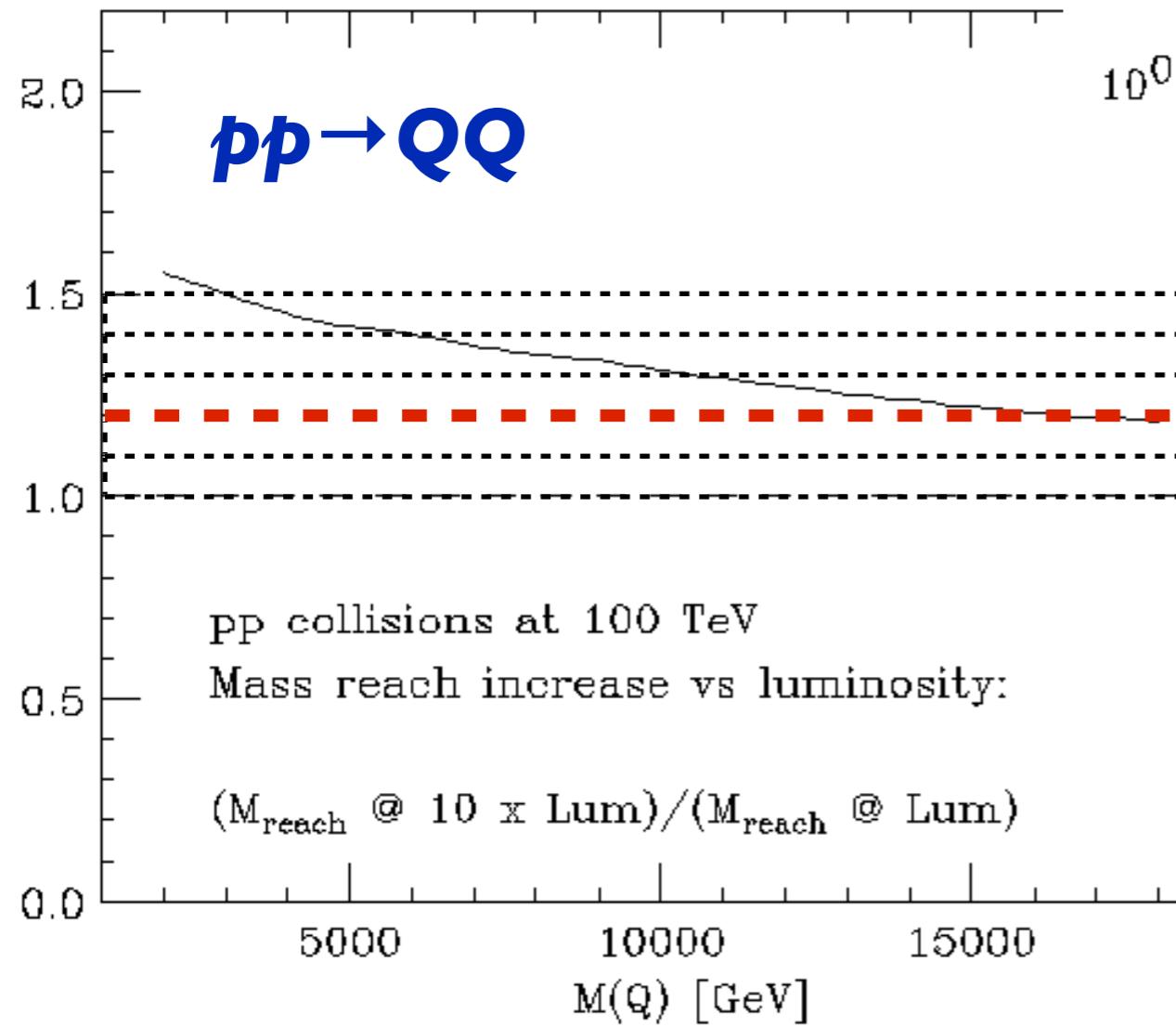
- $\Delta M/M \sim 20\% \Rightarrow$  the LHC reaches the threshold of saturation of the mass reach already at  $300\text{ fb}^{-1}$ . Notice that 95% exclusion at 300 makes unlikely the  $5\sigma$  discovery at 3000. In fact the main justification for the HL-LHC is the higher-statistics study of the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

# 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 ?

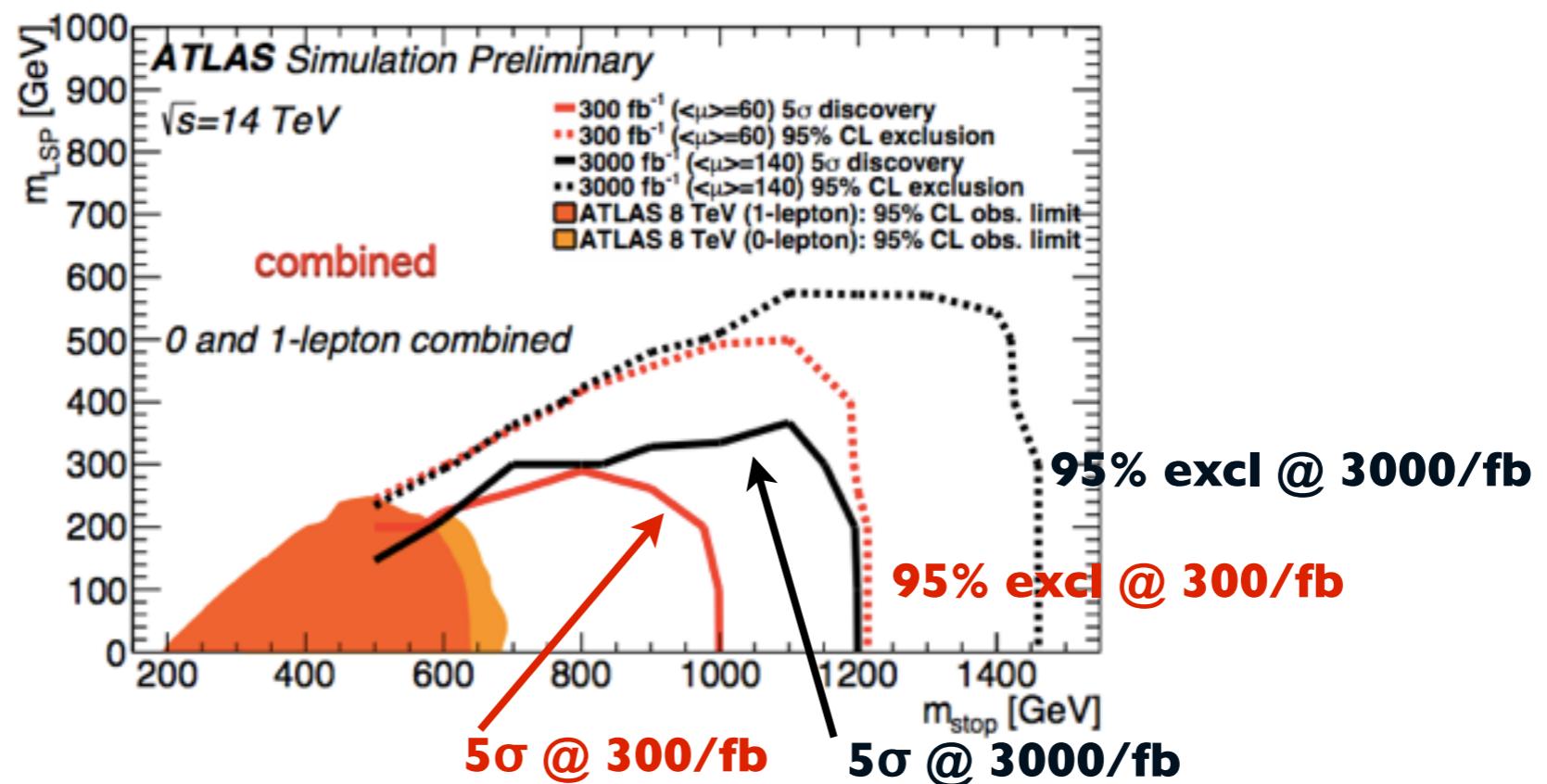
## Example: discovery reach for pair production of strongly-interacting particles



# **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

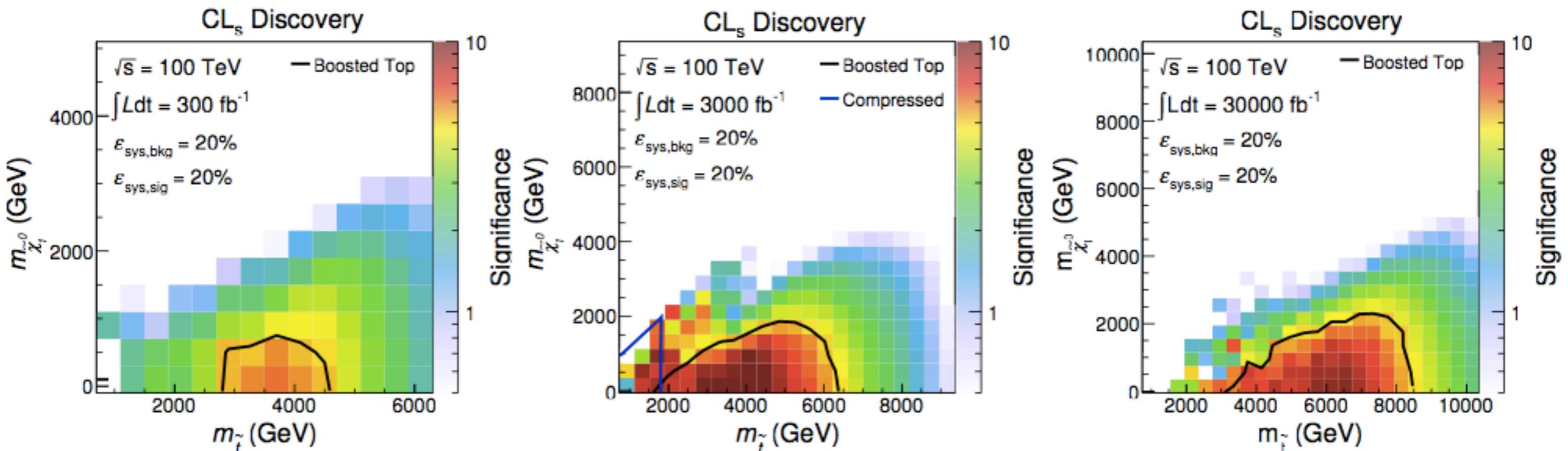
from Mike Hance's talk

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

[arXiv:1406.4512](https://arxiv.org/abs/1406.4512)

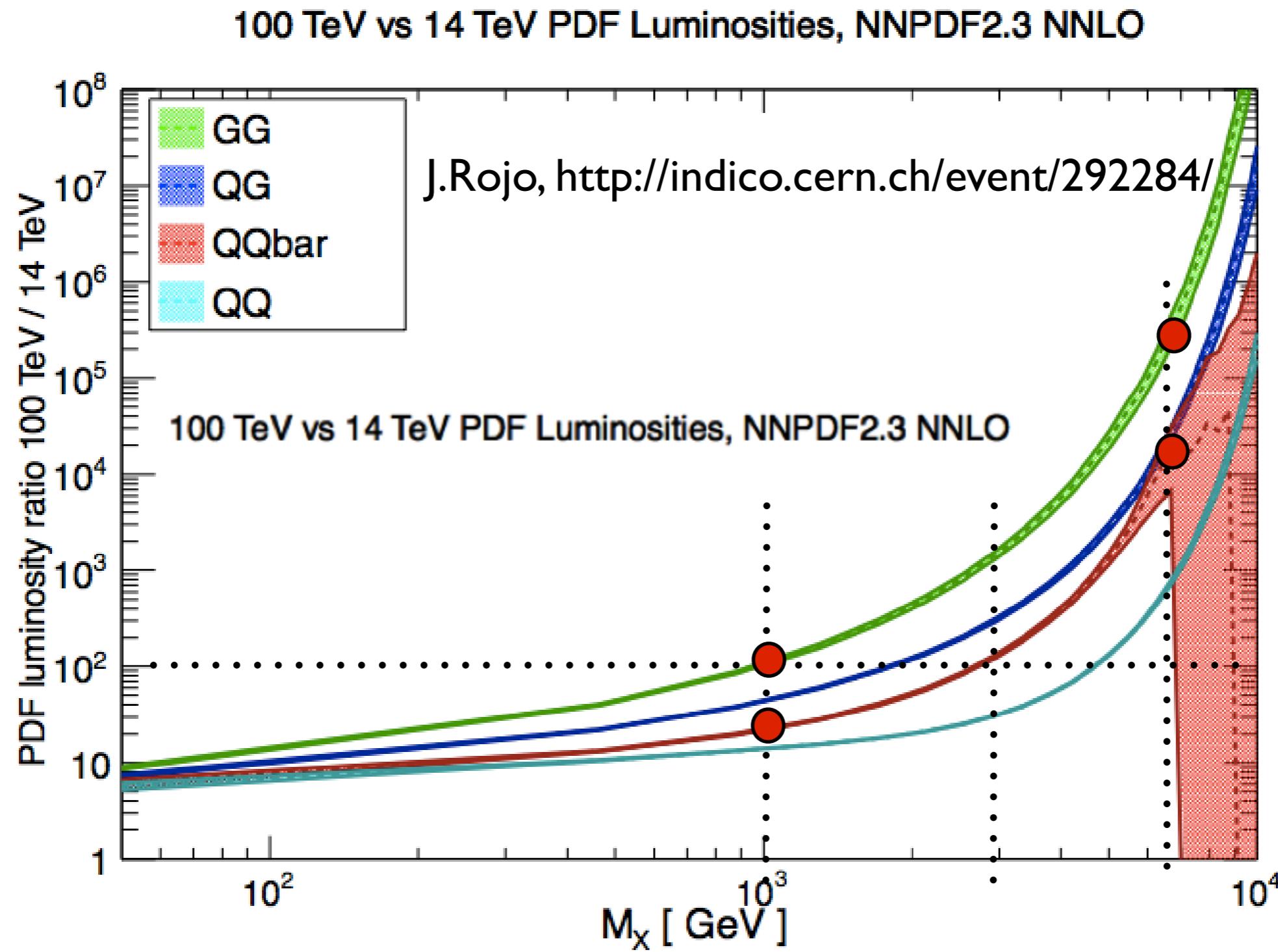
Will 3 ab $^{-1}$  be enough at 100 TeV?

- Scale  $E_T^{\text{miss}}$  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 :**

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

⇒ 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.**

**$m_X \sim 1$  TeV :**

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

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**$m_X \sim 1 \text{ TeV}$  :**

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

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

# Higher statistics for Higgs studies

$$R(E) = \sigma(E \text{ TeV})/\sigma(14 \text{ TeV})$$

**NLO rates**

	$\sigma(14 \text{ TeV})$	$R(33)$	$R(40)$	$R(60)$	$R(80)$	$R(100)$
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.

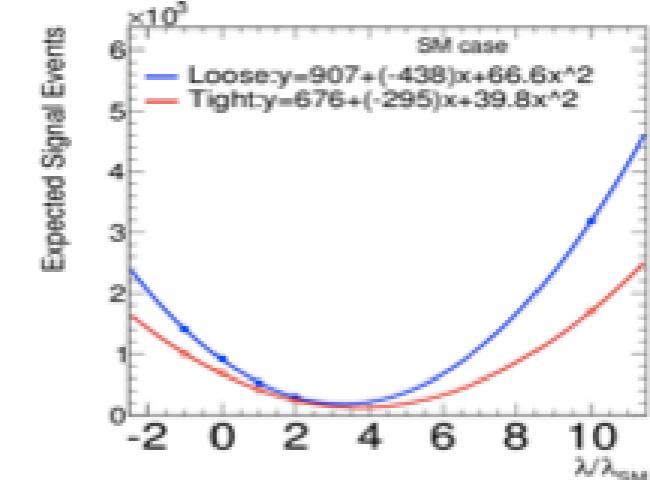
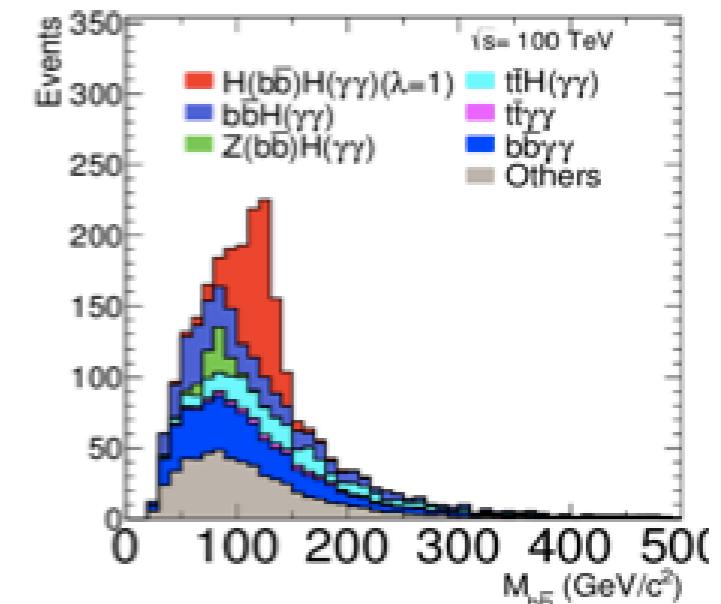
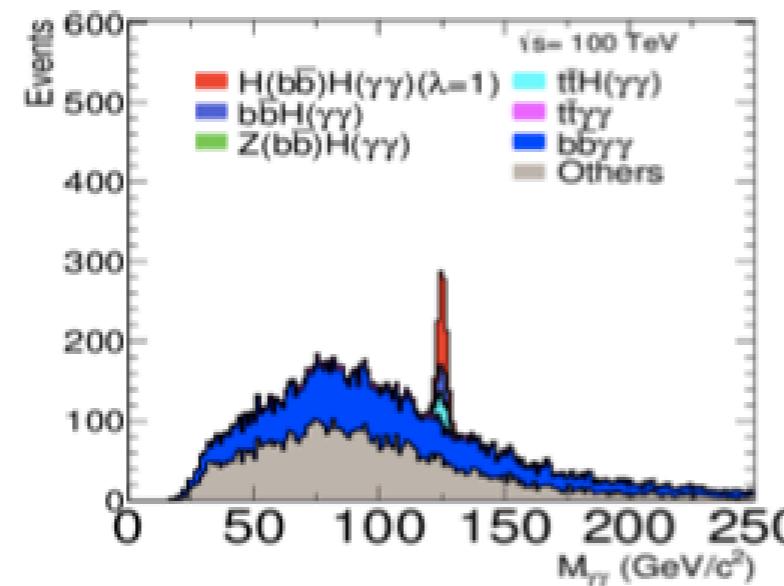
# Example: H selfcoupling at 100 TeV => see this afternoon session

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](http://ias.ust.hk/program/shared_doc/201501fhep/Weiming%20Yao_Jan%2021.pdf)

## Updating $\text{HH} \rightarrow \text{bb}\gamma\gamma$ at Tev100

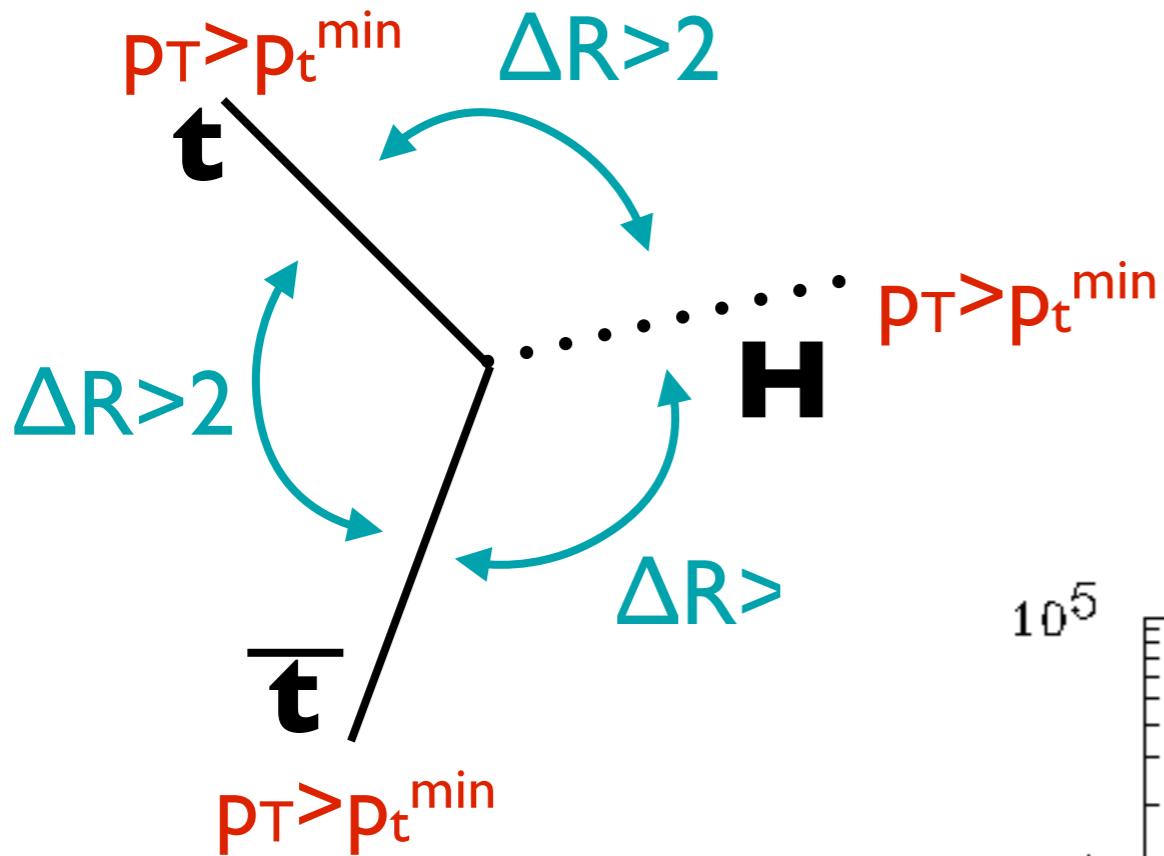
- Using Delphes 3.1.14 and the results depends on detector performance assumed.
- Including  $\text{jj}\gamma\gamma$ ,  $\text{bbj}\gamma$ ,  $\text{t}\bar{t}\gamma$ ,  $\text{tt}\gamma\gamma$  with ATLAS  $f\gamma = 0.0093e(-E_t/27.5)$  for HL-LHC
- Tighten  $m_{\gamma\gamma}$  window from 10 GeV used for snowmass to 6 GeV.

Sample	$\sigma$ [fb]	Generated in:	Skinned in:	Ave.	Expected [Stat+sys]
$\text{H}(b\bar{b})\text{H}(\gamma\gamma)(\lambda=1)$	0.0015	0.01	0.01	0.0015	0.0015
$\text{H}(b\bar{b})\text{H}(\gamma\gamma)(\lambda=0)$	0.0015	0.01	0.01	0.0015	0.0015
$\text{H}(b\bar{b})\text{H}(\gamma\gamma)(\lambda=2)$	0.0015	0.01	0.01	0.0015	0.0015
$\text{H}(t\bar{t})\gamma\gamma$	0.0015	0.01	0.01	0.0015	0.0015
$\text{Z}(b\bar{b})\gamma\gamma$	0.0015	0.01	0.01	0.0015	0.0015
$\text{Z}(t\bar{t})\gamma\gamma$	0.0015	0.01	0.01	0.0015	0.0015
$t\bar{t}\gamma\gamma$	0.0015	0.01	0.01	0.0015	0.0015
$b\bar{b}\gamma\gamma$	0.0015	0.01	0.01	0.0015	0.0015
$\text{Z}(b\bar{b})\text{H}(\gamma\gamma)$	0.0015	0.01	0.01	0.0015	0.0015
$\text{Z}(t\bar{t})\text{H}(\gamma\gamma)$	0.0015	0.01	0.01	0.0015	0.0015
$t\bar{t}\text{H}(\gamma\gamma)$	0.0015	0.01	0.01	0.0015	0.0015
$b\bar{b}\text{H}(\gamma\gamma)$	0.0015	0.01	0.01	0.0015	0.0015
$\text{Others}$	-	-	-	-	0.0015
<b>Total</b>	<b>0.0093</b>	<b>0.01</b>	<b>0.01</b>	<b>0.0093</b>	<b>0.0093</b>

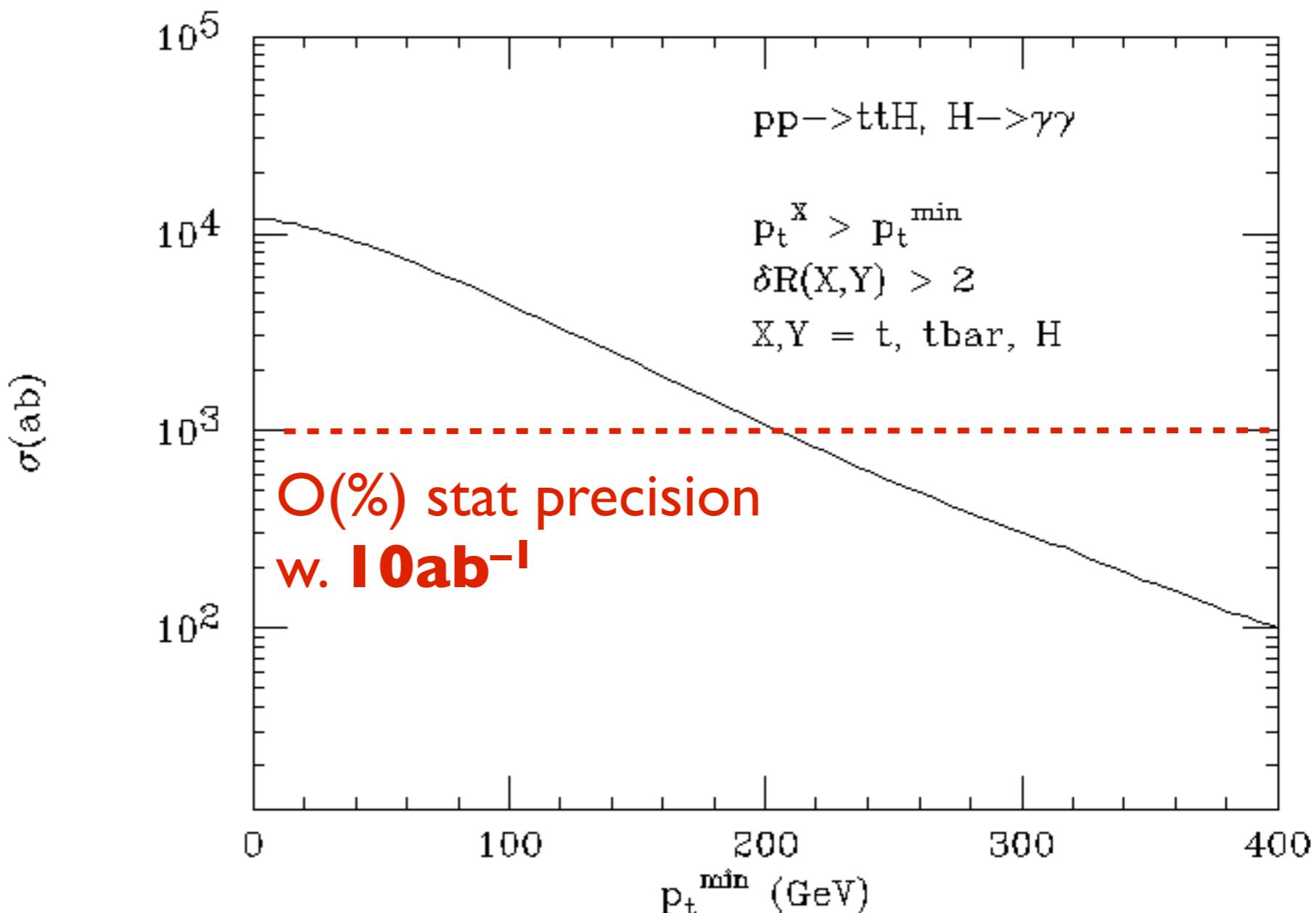


- Significance = 16.5 with 3 ab-1.
- H coupling  $d\lambda/\lambda = 15\%$  with  $d\sigma/d\lambda = -0.51$
- ArXiv:1412.7154 reported 40% using ATLAS photon ID eff.
- To achieve 5% precision, we need to combine with other channels or get more integrated luminosity ( $\sim 30$  ab-1).
- Also start to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

# Example, ttH at large pt

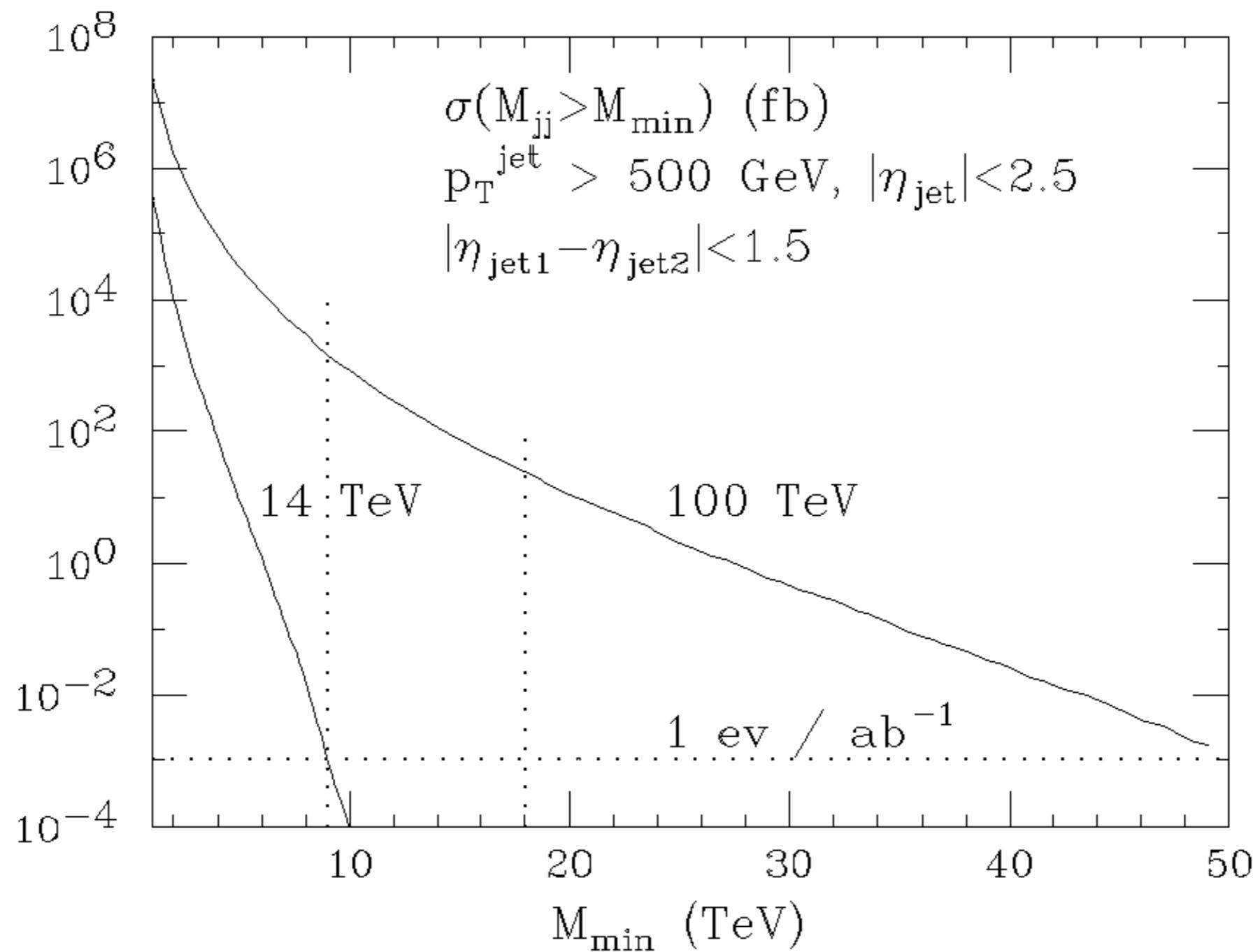


Goal: %-level measurement of  
 $\sigma(\text{ttH}) / \sigma(\text{ttZ})$   
(MLM and H-S Shao, in progress)

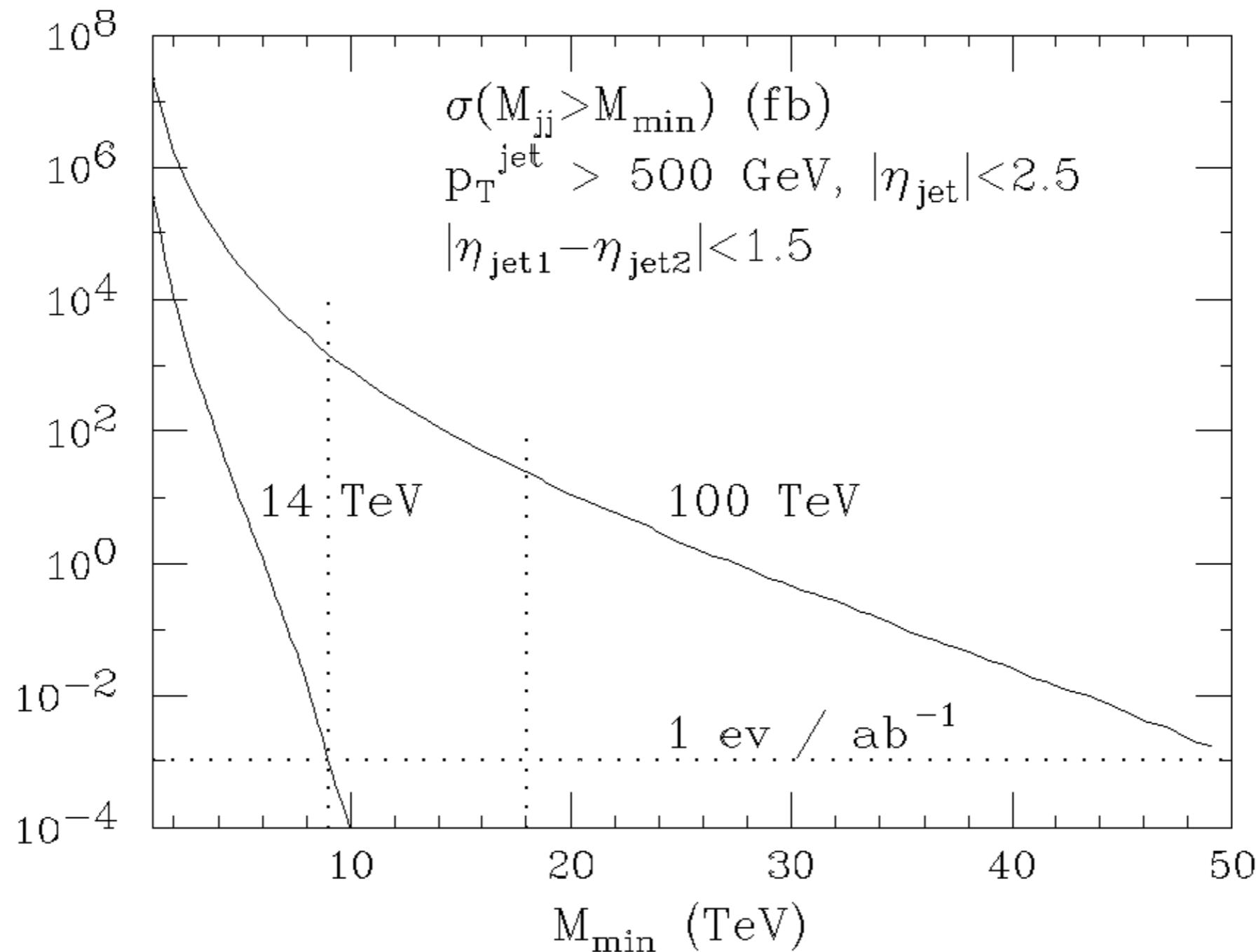


**Initial luminosity, or:  
what's the minimum lum to  
take us beyond the HL-LHC ?**

## Example: dijet production at large mass

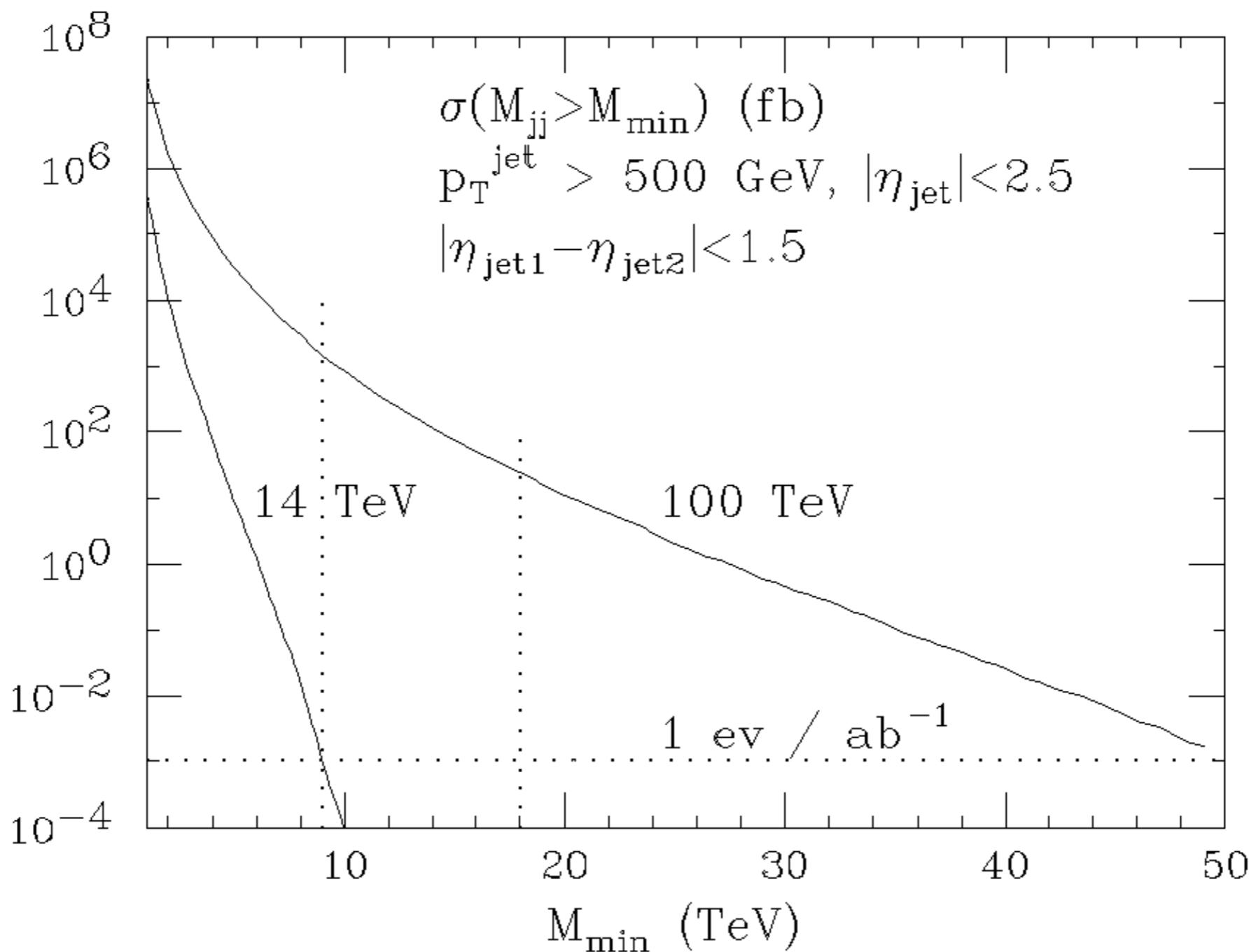


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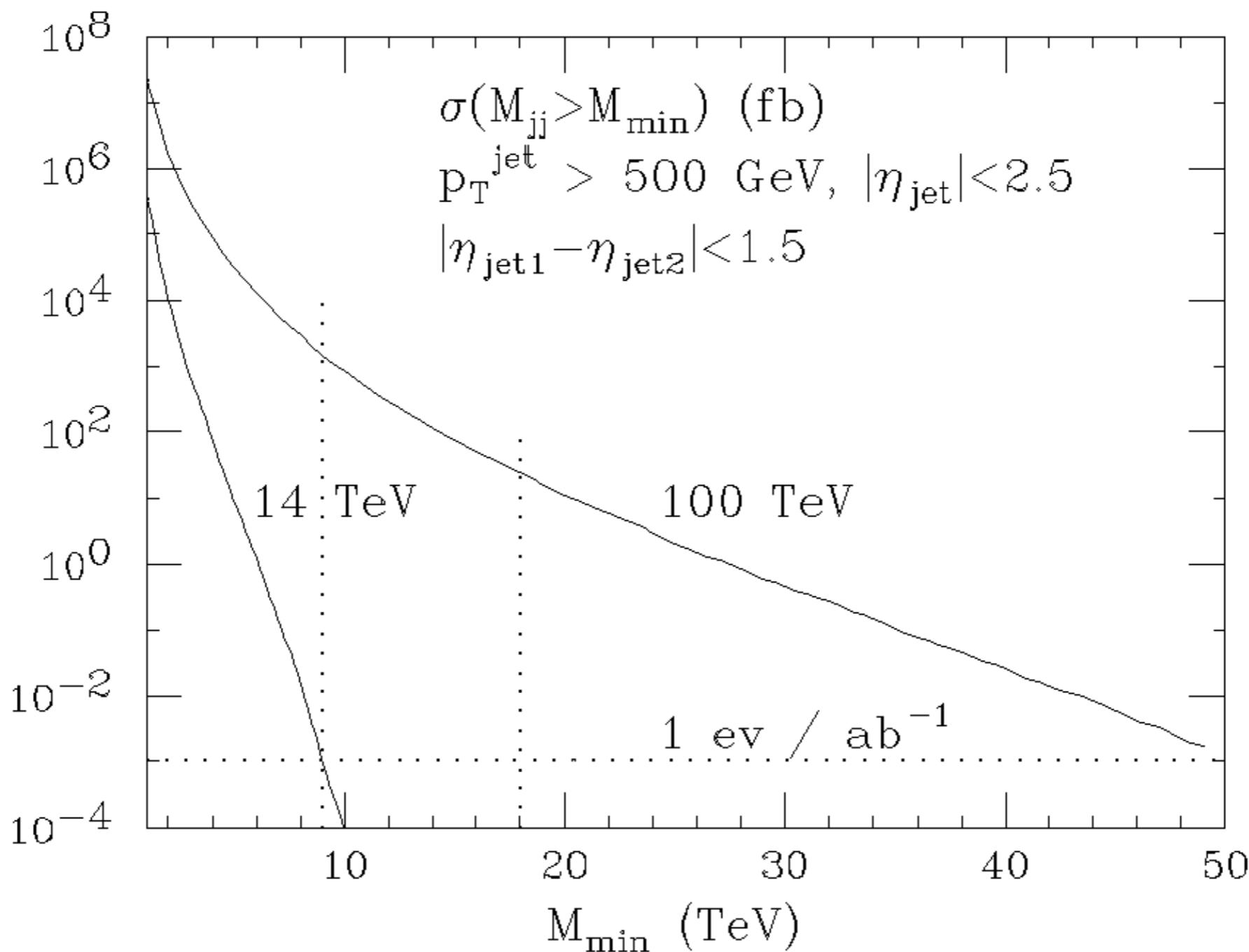
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- 50 pb $^{-1}$  to 2x the sensitivity of HL-LHC  $\Rightarrow < 1 \text{ month } @ 10^{32}$
- 1 fb $^{-1}$  to 3x the sensitivity of HL-LHC  $\Rightarrow < 1 \text{ year } @ 2 \times 10^{32}$

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

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

**This means:**

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

## Top quark studies

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

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

**This means:**

- Need  $\sim 100 \text{ fb}^{-1}$  to reproduce the statistics of HL-LHC
- $\Rightarrow 1 \text{ year at } 2 \times 10^{34}$

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- **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