

# PDFs and searches: observations from simplistic studies

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PDF4LHC  
CERN, 16 May 2014

# Collider Reach



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Types of questions that are natural to ask about future searches:

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How soon will LHC@13TeV beat 8TeV searches?

What can high-lumi LHC ( $3000\text{fb}^{-1}$ ) do compared to original LHC plan ( $300\text{fb}^{-1}$ )?

What is the gain from a future 33/50/100/150 TeV collider?

## **The proper way of doing it:**

Generate Monte Carlo events for signal and background,  
process them through a detector simulation,  
design and carry out an optimal analysis,  
work out discovery/exclusion reach.

**This is very time consuming (months of work!),  
and not always easy to do optimally.**

**Can we find an alternative that's  
easy, quick and adequately good?**

(and in the process maybe learn some general lessons?)

# There are already many well-designed searches

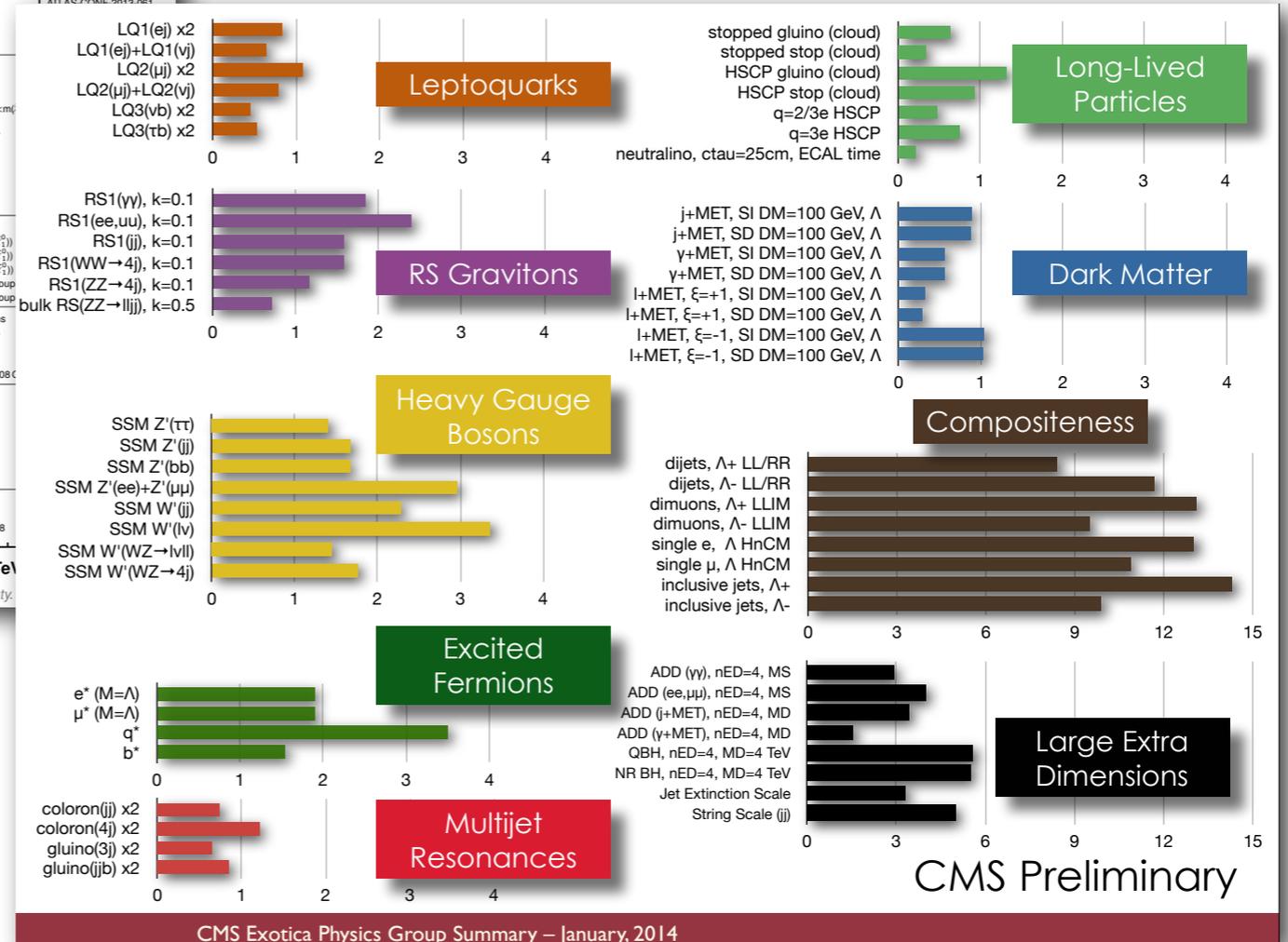
**ATLAS SUSY Searches\* - 95% CL Lower Limits** ATLAS Preliminary  
 Status: SUSY 2013  $\int \mathcal{L} dt = (4.6 - 22.9) \text{ fb}^{-1}$   $\sqrt{s} = 7, 8 \text{ TeV}$

Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference
<b>Inclusive Searches</b>						
MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{g}, \tilde{g}$ 1.7 TeV	ATLAS-CONF-2013-047
MSUGRA/CMSSM	1 $e, \mu$	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	ATLAS-CONF-2013-062
MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	1308.1841
$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{q}\tilde{q}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	ATLAS-CONF-2013-047
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{q}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	ATLAS-CONF-2013-047
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{q}_1^0 + qqW^{\pm}\tilde{q}_1^0$	1 $e, \mu$	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	ATLAS-CONF-2013-062
GMSB ( $\tilde{L}$ NLSP)	2 $e, \mu$	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	ATLAS-CONF-2013-089
GMSB ( $\tilde{L}$ NLSP)	2 $e, \mu$	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	1208.4688
GMSB ( $\tilde{L}$ NLSP)	1-2 $\tau$	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	ATLAS-CONF-2013-026
GGM (bino NLSP)	2 $\gamma$	-	Yes	4.8	$\tilde{g}$ 1.07 TeV	1209.0753
GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	ATLAS-CONF-2012-144
GGM (higgsino-bino NLSP)	$\gamma$	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	1211.1167
GGM (higgsino NLSP)	2 $e, \mu, Z$	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	ATLAS-CONF-2012-152
Gravitino LSP	0	mono-jet	Yes	10.5	$\tilde{g}$ 645 GeV	ATLAS-CONF-2012-147
<b>3<sup>rd</sup> gen. <math>\tilde{g}</math> med.</b>						
$\tilde{g} \rightarrow b\tilde{b}\tilde{q}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	$m(\tilde{q}_1^0) < 600 \text{ GeV}$
$\tilde{g} \rightarrow t\tilde{t}\tilde{q}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{q}_1^0) < 350 \text{ GeV}$
$\tilde{g} \rightarrow t\tilde{t}\tilde{q}_1^0$	0-1 $e, \mu$	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{q}_1^0) < 400 \text{ GeV}$
$\tilde{g} \rightarrow b\tilde{t}\tilde{q}_1^0$	0-1 $e, \mu$	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{q}_1^0) < 300 \text{ GeV}$
<b>3<sup>rd</sup> gen. squarks direct production</b>						
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{q}_1^0$	2 $e, \mu$ (SS)	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{q}_1^0) < 90 \text{ GeV}$
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{q}_1^0$	2 $e, \mu$ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 275-430 GeV	$m(\tilde{q}_1^0) = 2 m(\tilde{q}_1^0)$
$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1 \rightarrow b\tilde{q}_1^0$	1-2 $e, \mu$	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{q}_1^0) = 55 \text{ GeV}$
$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow Wb\tilde{q}_1^0$	2 $e, \mu$	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-220 GeV	$m(\tilde{q}_1^0) = m(\tilde{t}_1) - m(W) - 50 \text{ GeV}, m(\tilde{q}_1^0) < m(\tilde{t}_1)$
$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow t\tilde{q}_1^0$	2 $e, \mu$	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV	$m(\tilde{q}_1^0) = 0 \text{ GeV}$
$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow b\tilde{q}_1^0$	1 $e, \mu$	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{q}_1^0) < 200 \text{ GeV}, m(\tilde{q}_1^0) - m(\tilde{q}_1^0) = 5 \text{ GeV}$
$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{q}_1^0$	0	2 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{q}_1^0) = 0 \text{ GeV}$
$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{q}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{q}_1^0) = 0 \text{ GeV}$
$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 $e, \mu, Z$	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{q}_1^0) - m(\tilde{q}_1^0) < 85 \text{ GeV}$
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{q}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 271-520 GeV	$m(\tilde{q}_1^0) > 150 \text{ GeV}$
$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 $e, \mu, Z$	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{q}_1^0) > 150 \text{ GeV}$
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu, Z$	1 b	Yes	20.7	$\tilde{t}_2$ 271-520 GeV	$m(\tilde{q}_1^0) - m(\tilde{q}_1^0) = 180 \text{ GeV}$
<b>EW direct</b>						
$\tilde{L}_L\tilde{L}_L, \tilde{L} \rightarrow \tilde{L}\tilde{q}_1^0$	2 $e, \mu$	0	Yes	20.3	$\tilde{L}$ 85-315 GeV	$m(\tilde{q}_1^0) = 0 \text{ GeV}$
$\tilde{L}_L\tilde{L}_L, \tilde{L} \rightarrow \tilde{L}\nu(\tilde{\nu})$	2 $e, \mu$	0	Yes	20.3	$\tilde{L}$ 125-450 GeV	$m(\tilde{q}_1^0) = 0 \text{ GeV}, m(\tilde{L}) = 0.5(m(\tilde{q}_1^0) + m(\tilde{q}_1^0))$
$\tilde{L}_L\tilde{L}_L, \tilde{L} \rightarrow \tilde{L}\nu(\tilde{\nu})$	2 $\tau$	-	Yes	20.7	$\tilde{L}$ 180-330 GeV	$m(\tilde{q}_1^0) = 0 \text{ GeV}, m(\tilde{L}) = 0.5(m(\tilde{q}_1^0) + m(\tilde{q}_1^0))$
$\tilde{L}_L\tilde{L}_L, \tilde{L} \rightarrow \tilde{L}\nu(\tilde{\nu})$	3 $e, \mu$	0	Yes	20.7	$\tilde{L}$ 315 GeV	$m(\tilde{q}_1^0) = m(\tilde{q}_1^0), m(\tilde{q}_1^0) = 0, m(\tilde{L}) = 0.5(m(\tilde{q}_1^0) + m(\tilde{q}_1^0))$
$\tilde{L}_L\tilde{L}_L, \tilde{L} \rightarrow W\tilde{q}_1^0, \tilde{L} \rightarrow \tilde{L}\nu(\tilde{\nu})$	3 $e, \mu$	0	Yes	20.7	$\tilde{L}$ 285 GeV	$m(\tilde{q}_1^0) = m(\tilde{q}_1^0), m(\tilde{q}_1^0) = 0, \text{ sleptons decoupled}$
$\tilde{L}_L\tilde{L}_L, \tilde{L} \rightarrow W\tilde{q}_1^0, \tilde{L} \rightarrow \tilde{L}\nu(\tilde{\nu})$	1 $e, \mu$	2 b	Yes	20.3	$\tilde{L}$ 285 GeV	$m(\tilde{q}_1^0) = m(\tilde{q}_1^0), m(\tilde{q}_1^0) = 0, \text{ sleptons decoupled}$
<b>Long-lived particles</b>						
Direct $\tilde{L}_L\tilde{L}_L$ prod., long-lived $\tilde{L}_L$	Disapp. trk	1 jet	Yes	20.3	$\tilde{L}_L$ 270 GeV	$m(\tilde{q}_1^0) - m(\tilde{q}_1^0) = 160 \text{ MeV}, \tau(\tilde{L}_L) = 0.2 \text{ ns}$
Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 832 GeV	$m(\tilde{q}_1^0) = 100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$
GMSB, stable $\tilde{L}, \tilde{L} \rightarrow \tilde{L}\nu(\tilde{\nu}) + \tau(e, \mu)$	1-2 $\mu$	-	-	15.9	$\tilde{L}$ 475 GeV	$10^{-10} < \text{BR} < 50$
GMSB, $\tilde{L} \rightarrow \gamma G$ , long-lived $\tilde{L}$	2 $\gamma$	-	-	4.7	$\tilde{L}$ 230 GeV	$0.4 < \tau(\tilde{L}) < 2 \text{ ns}$
$\tilde{q}\tilde{q}, \tilde{L} \rightarrow q\tilde{q}\mu$ (RPV)	1 $\mu$ , displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	$1.5 < c\tau < 156 \text{ mm}, \text{BR}(\mu) = 1, m(\tilde{q}_1^0) = 108 \text{ GeV}$
<b>RPV</b>						
LFV $pp \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e + \mu$	2 $e, \mu$	-	-	4.6	$\tilde{\nu}_e$ 1.61 TeV	$A_{131} = 0.10, A_{132} = 0.05$
LFV $pp \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_e$ 1.1 TeV	$A_{131} = 0.10, A_{12133} = 0.05$
Bilinear RPV CMSSM	1 $e, \mu$	7 jets	Yes	4.7	$\tilde{g}, \tilde{g}$ 1.2 TeV	$m(\tilde{q}) = m(\tilde{g}), c\tau_{\text{LSP}} < 1 \text{ mm}$
$\tilde{L}_L\tilde{L}_L, \tilde{L} \rightarrow W\tilde{q}_1^0, \tilde{L} \rightarrow ee\tilde{\nu}_e, e\mu\tilde{\nu}_e$	4 $e, \mu$	-	Yes	20.7	$\tilde{L}$ 760 GeV	$m(\tilde{q}_1^0) > 300 \text{ GeV}, A_{131} > 0$
$\tilde{L}_L\tilde{L}_L, \tilde{L} \rightarrow W\tilde{q}_1^0, \tilde{L} \rightarrow \tau\tilde{\nu}_e, e\tau\tilde{\nu}_e$	3 $e, \mu + \tau$	-	Yes	20.7	$\tilde{L}$ 350 GeV	$m(\tilde{q}_1^0) > 80 \text{ GeV}, A_{131} > 0$
$\tilde{g} \rightarrow q\tilde{q}$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	$\text{BR}(\tau) = \text{BR}(\mu) = \text{BR}(c) = 0\%$
$\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow b\tilde{q}_1^0$	2 $e, \mu$ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV	
<b>Other</b>						
Scalar gluon pair, sgluon $\rightarrow q\tilde{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693
Scalar gluon pair, sgluon $\rightarrow t\tilde{t}$	2 $e, \mu$ (SS)	1 b	Yes	14.3	sgluon 800 GeV	
WIMP interaction (DS, Dirac $\chi$ )	0	mono-jet	Yes	10.5	$\tilde{L}^*$ scale 704 GeV	$m(\chi) < 80 \text{ GeV}$ , limit of $\sim 687 \text{ GeV}$ for D8

Legend:  $\sqrt{s} = 7 \text{ TeV}$  full data (blue),  $\sqrt{s} = 8 \text{ TeV}$  partial data (green),  $\sqrt{s} = 8 \text{ TeV}$  full data (red)

Mass scale [TeV] on x-axis (log scale from  $10^{-1}$  to 1)

\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus  $1\sigma$  theoretical signal cross section uncertainty.



How do we leverage that experience to guesstimate future reaches?

# A *rough* way of doing it

Suppose ATLAS/CMS are currently sensitive to  $Z'$  of  
3 TeV (95%  $CL_s$ , 8 TeV, 19 fb<sup>-1</sup>)



Work out how many signal events that corresponds to



Find out for what  $Z'$  mass you would get the same  
number of signal events at 14 TeV with 300 fb<sup>-1</sup>  
(assume # of background events scales same way)

What we're discussing is solution of the following equation for  $M_{\text{high}}$

$$\frac{N_{\text{signal-events}}(M_{\text{high}}^2, 14 \text{ TeV}, \text{Lumi})}{N_{\text{signal-events}}(M_{\text{low}}^2, 8 \text{ TeV}, 19 \text{ fb}^{-1})} = 1$$

Many complications (e.g. coupling constants & other prefactors) mostly cancel in the ratio.

Dependence on  $M$  and on  $\sqrt{s}$  mostly comes about through parton distribution functions (PDFs) & simple dimensions.

Instead of cross section ratio, use **parton luminosity ratio**

Assume dominance of a single partonic scattering channel,  $ij$  (you have to know enough physics to figure out which is most appropriate).

Equation we solve to find  $M_{\text{high}}$  is then

$$\frac{\mathcal{L}_{ij}(M_{\text{high}}^2, s_{\text{high}})}{\mathcal{L}_{ij}(M_{\text{low}}^2, s_{\text{low}})} \times \frac{\text{lumi}_{\text{high}}}{\text{lumi}_{\text{low}}} = \frac{M_{\text{high}}^2}{M_{\text{low}}^2}$$

The tools we use for this are  
LHAPDF and HOPPET  
most plots with MSTW2008 NNLO PDFs

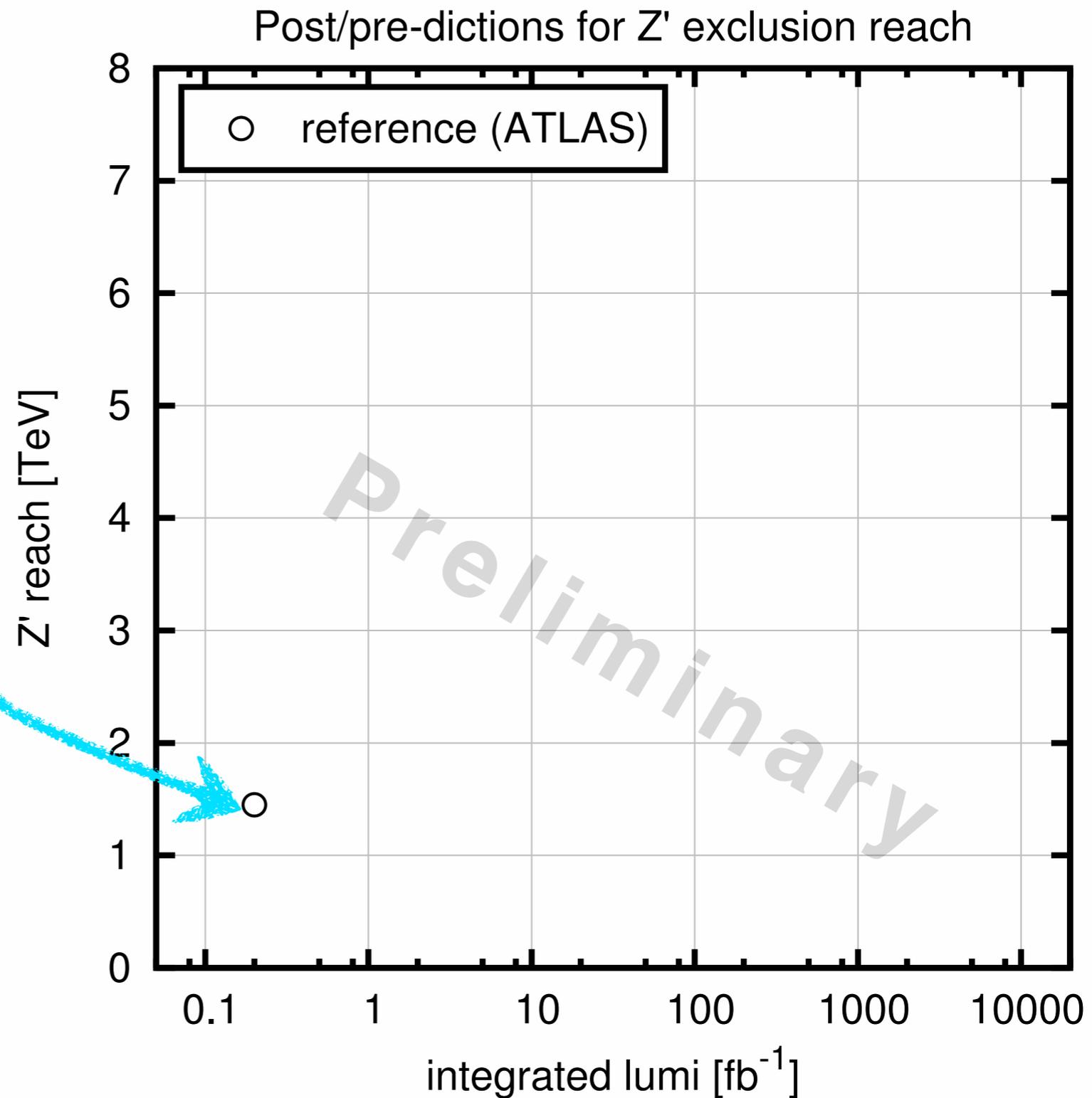
$$\mathcal{L}_{ij}(M^2, s) = \int_{\tau}^1 \frac{dx}{x} x f_i(x, M^2) \frac{\tau}{x} f_j\left(\frac{\tau}{x}, M^2\right) \quad \tau \equiv \frac{M^2}{s}$$

i & j parton

Does it work?

Try a Z' search. Take a baseline analysis:

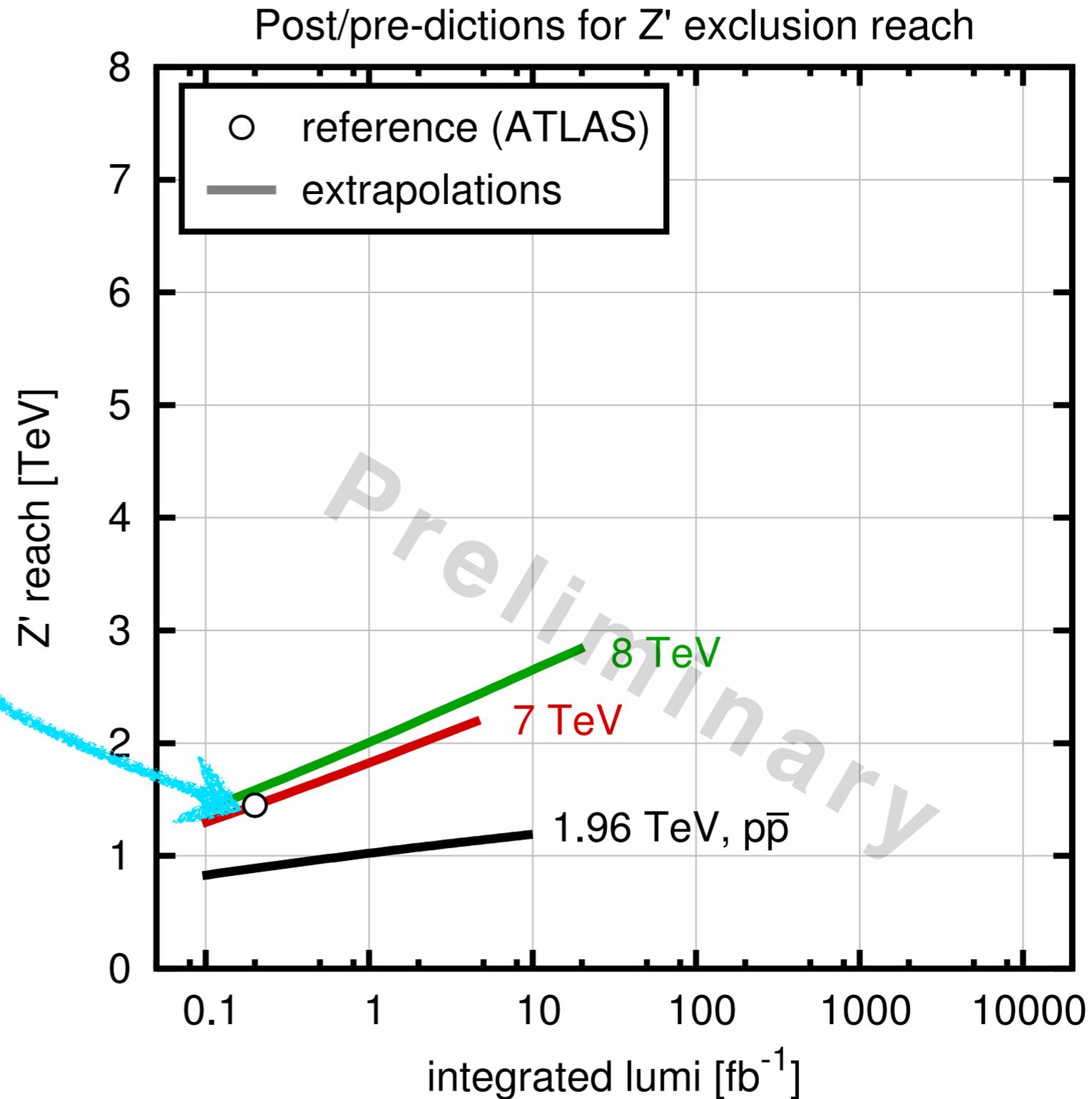
ATLAS,  
0.2 fb<sup>-1</sup> @ 7 TeV  
excludes M < 1450 GeV



Try a  $Z'$  search. Take a baseline analysis:

ATLAS,  
 $0.2 \text{ fb}^{-1}$  @ 7 TeV  
excludes  $M < 1450 \text{ GeV}$

“Predict” exclusions  
at other lumis &  
energies (assume  $q\bar{q}$ )

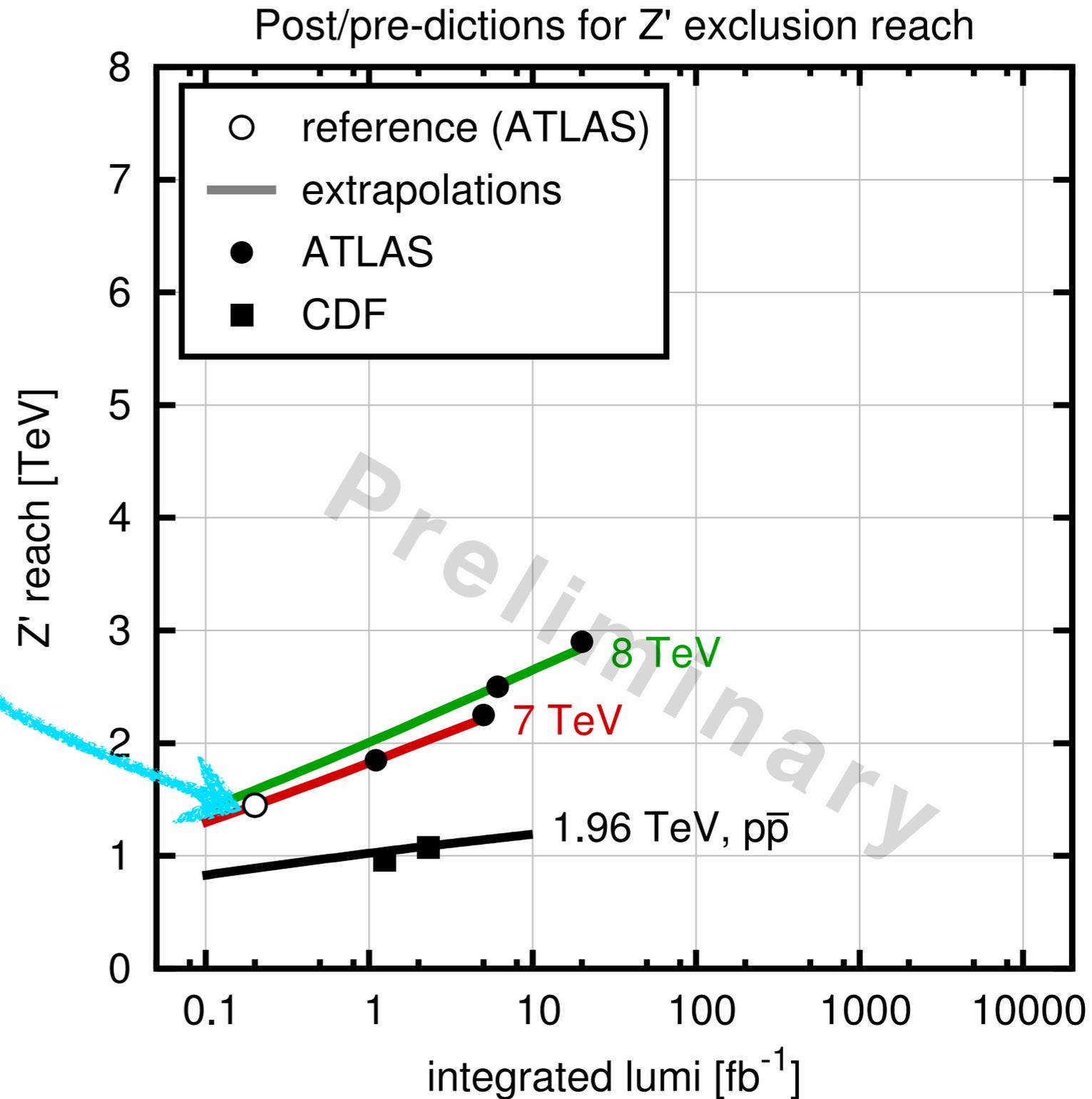


Try a  $Z'$  search. Take a baseline analysis:

ATLAS,  
 $0.2 \text{ fb}^{-1}$  @ 7 TeV  
excludes  $M < 1450 \text{ GeV}$

“Predict” exclusions  
at other lumis &  
energies (assume  $q\bar{q}$ )

Compare to actual  
exclusions

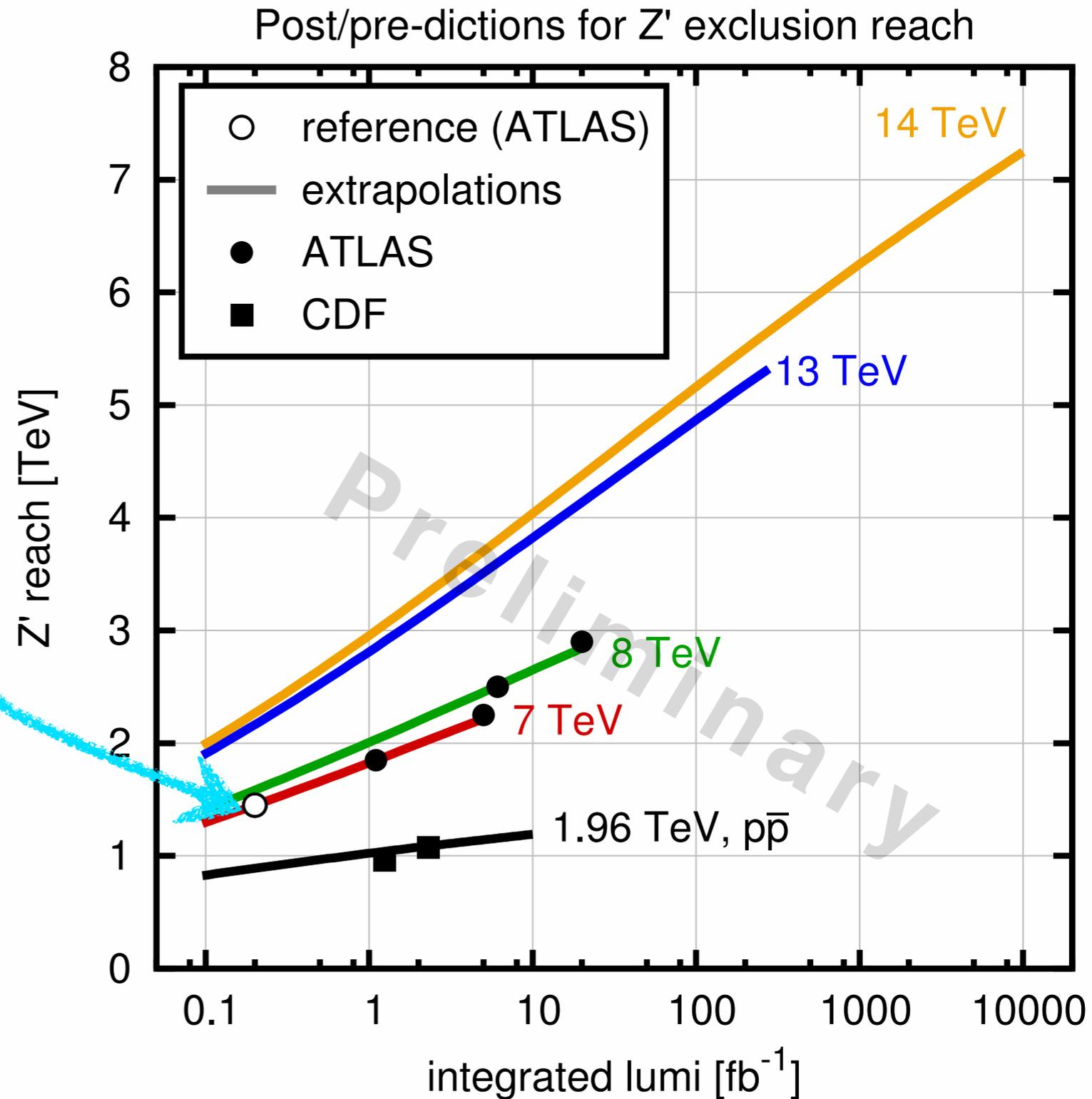


Try a  $Z'$  search. Take a baseline analysis:

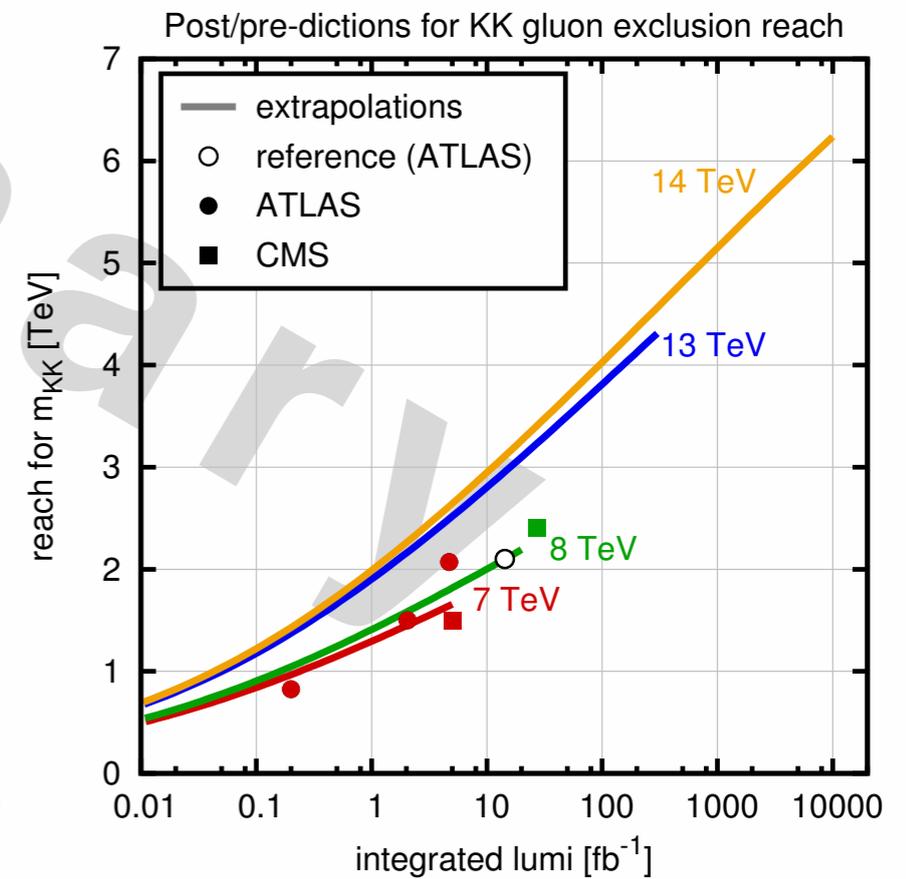
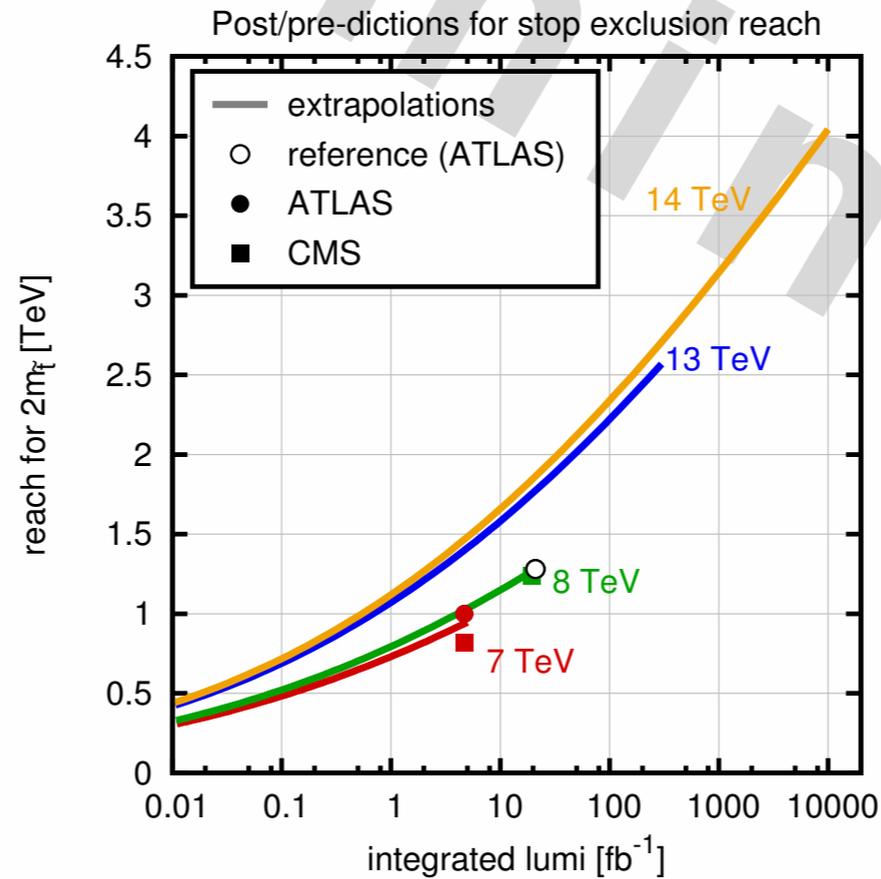
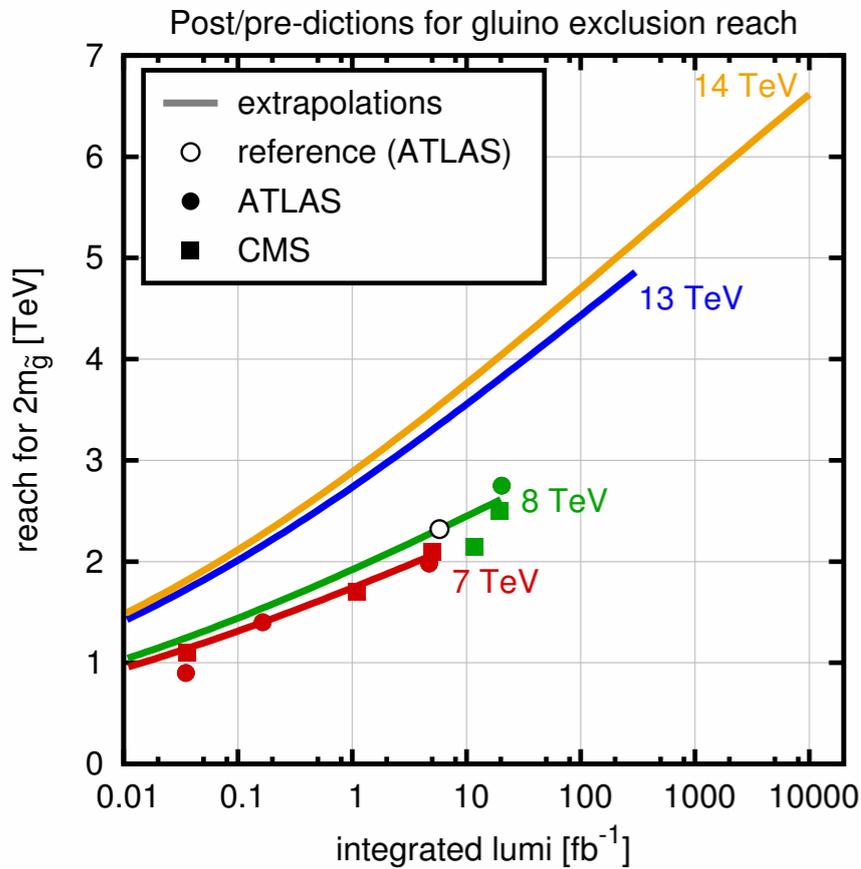
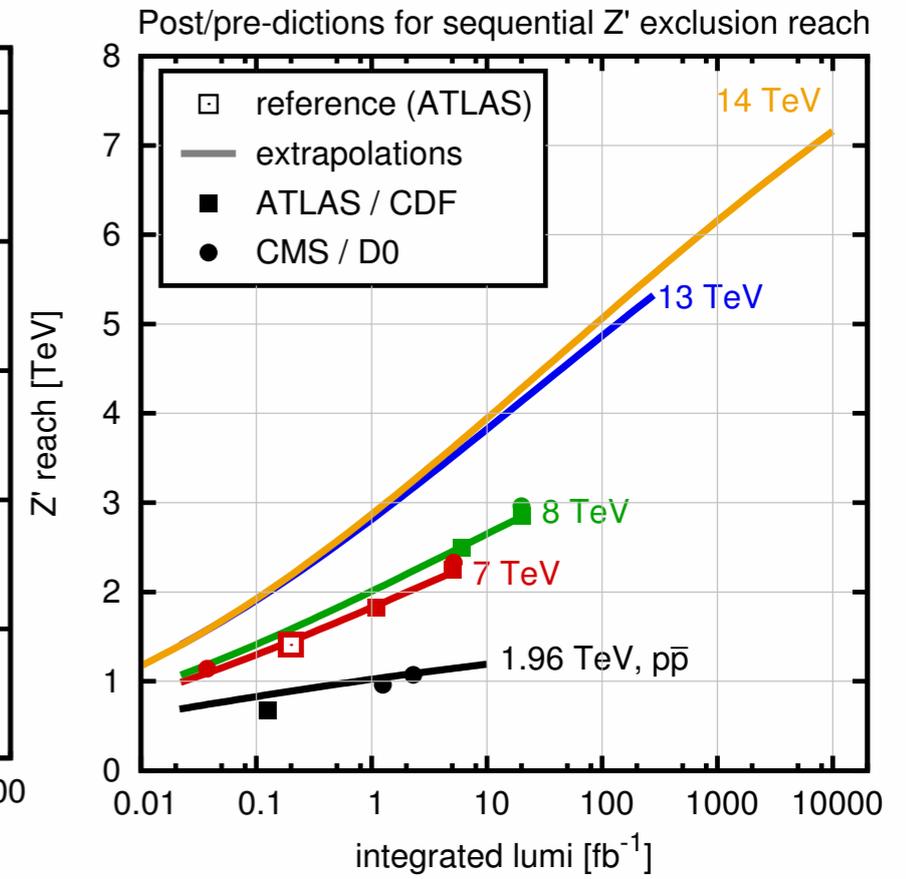
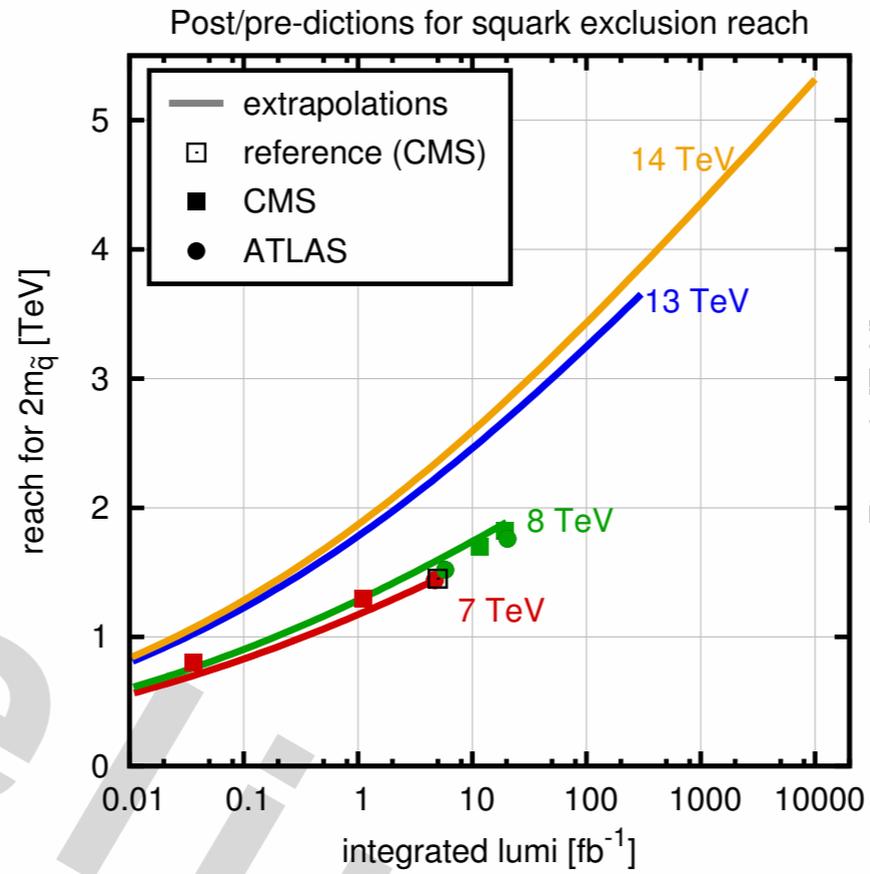
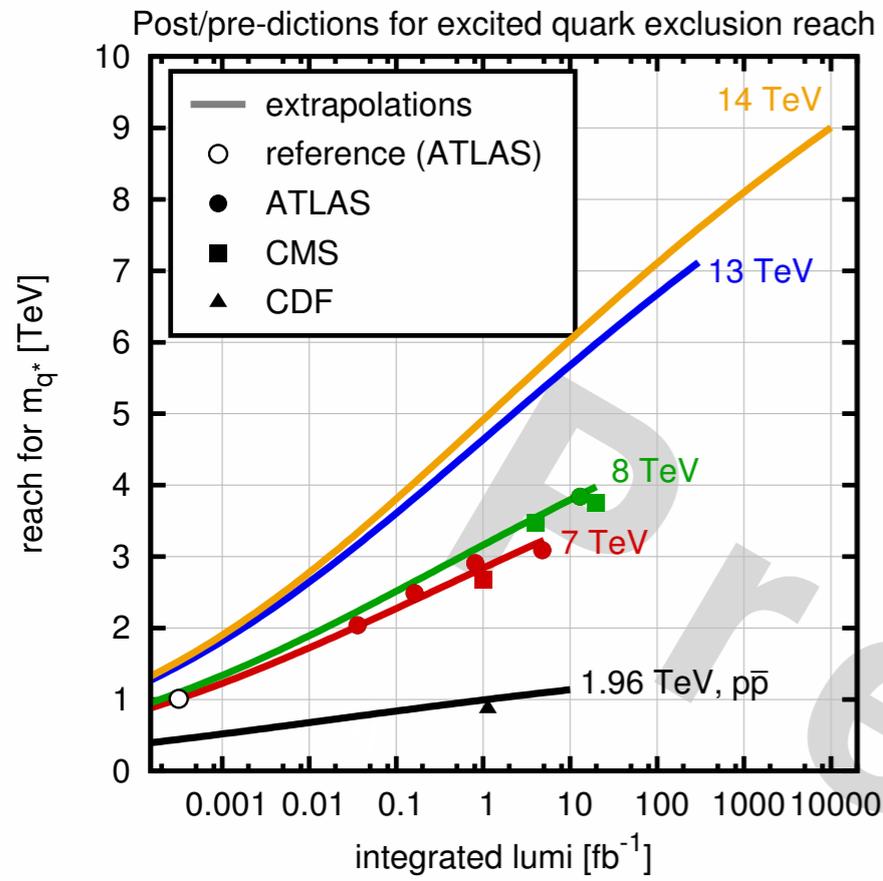
ATLAS,  
 $0.2 \text{ fb}^{-1}$  @ 7 TeV  
excludes  $M < 1450 \text{ GeV}$

“Predict” exclusions  
at other lumis &  
energies (assume  $q\bar{q}$ )

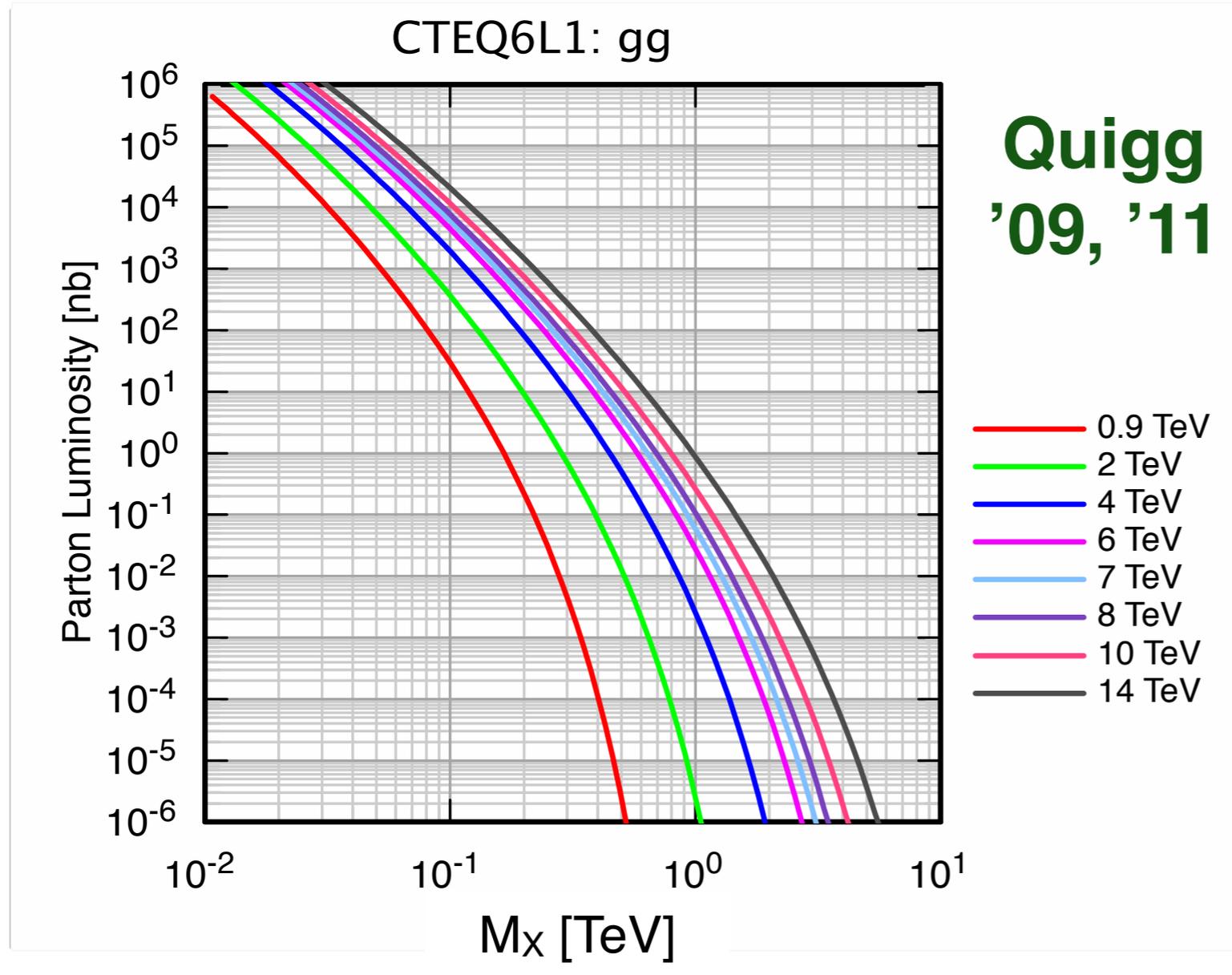
Compare to actual  
exclusions



Maybe it only works so well because it's a simple search?  
(Signal & Bkgd are both  $q\bar{q}$  driven)



# Why does (should) it work?



Parton luminosities fall off very fast with increasing  $M_X$

Even when you make a mistake (e.g. wrong partonic mix) the impact on estimated  $M_X$  reach is modest

x2 in lumi  $\sim$  10% in  $M_X$

From your iPhone  
(or a generic browser)  
[cern.ch/collider-reach](http://cern.ch/collider-reach)

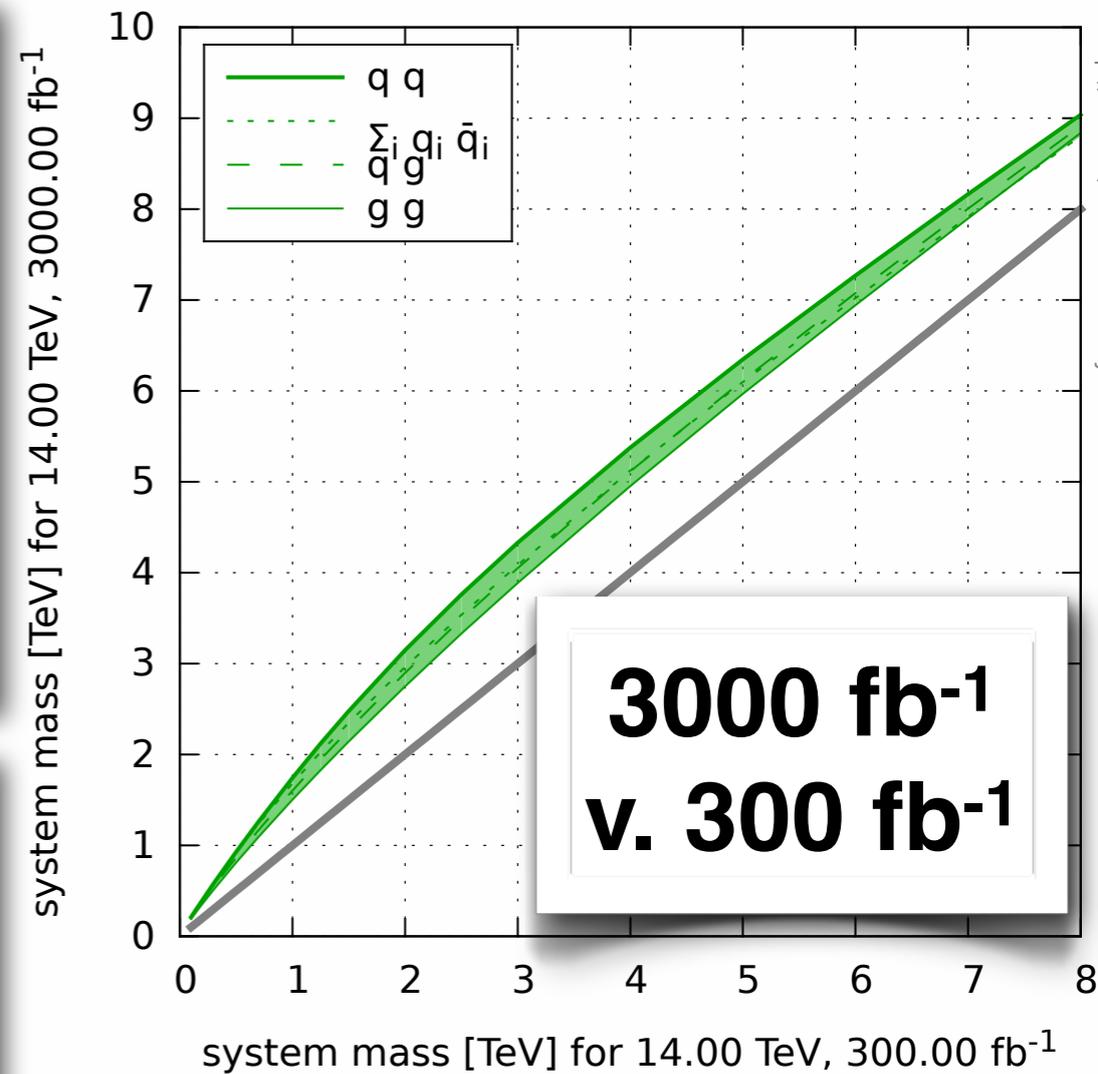
# Rule of Thumb #2

(apparently not widely known previously)

Increase luminosity by factor 10  
→ **reach increases by constant**  
 **$\Delta m \approx 0.07\sqrt{s}$**

i.e. for  $\sqrt{s}=14$  TeV, reach goes by up  
 $\sim 1$  TeV

No deep reason — a somewhat  
random characteristic of large-x PDFs.  
Only holds for  $0.15 \lesssim M/\sqrt{s} \lesssim 0.6$

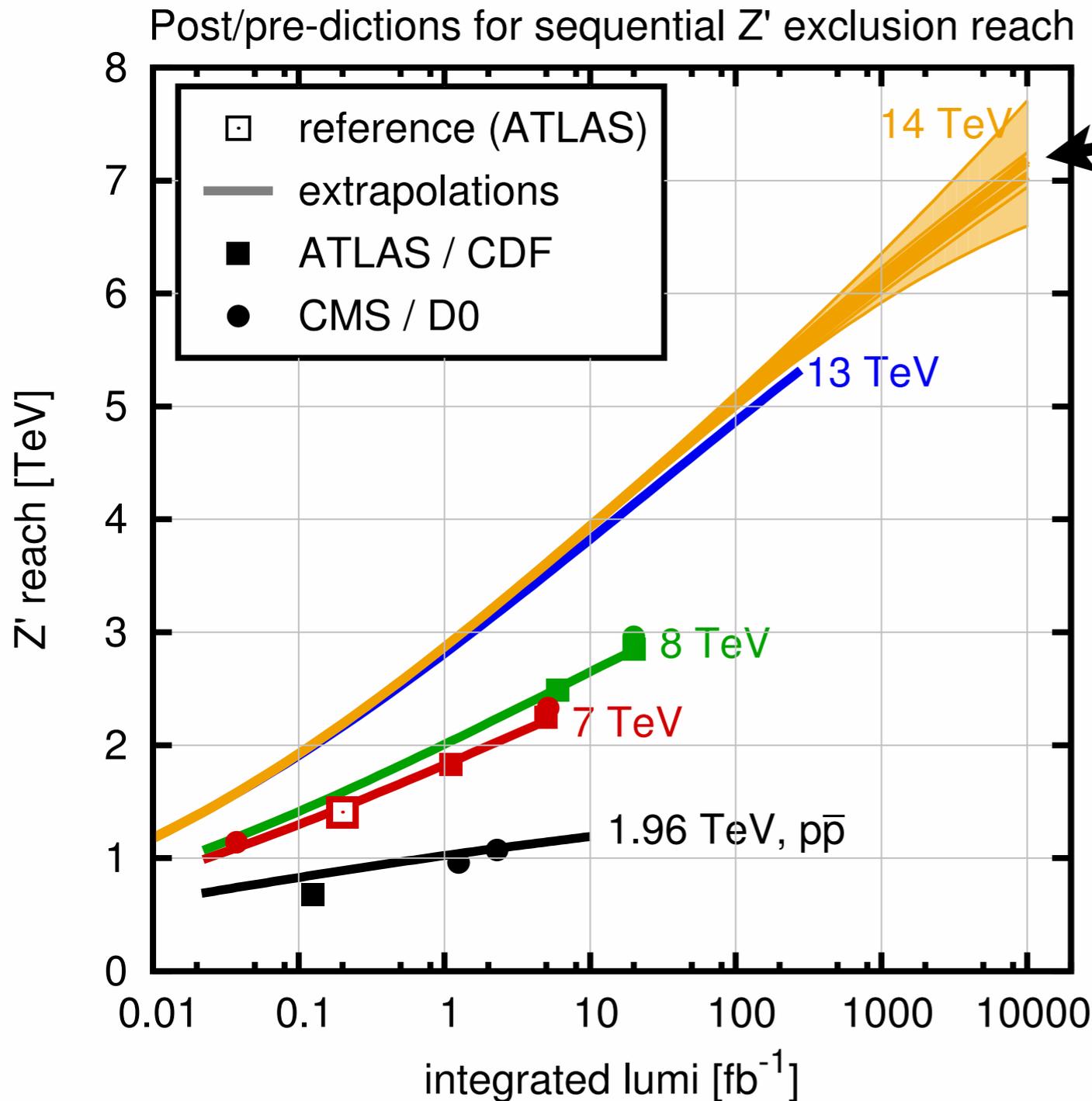


Differences between PDFs?  
PDF uncertainties?

**mostly small**

But let's examine  
one exception

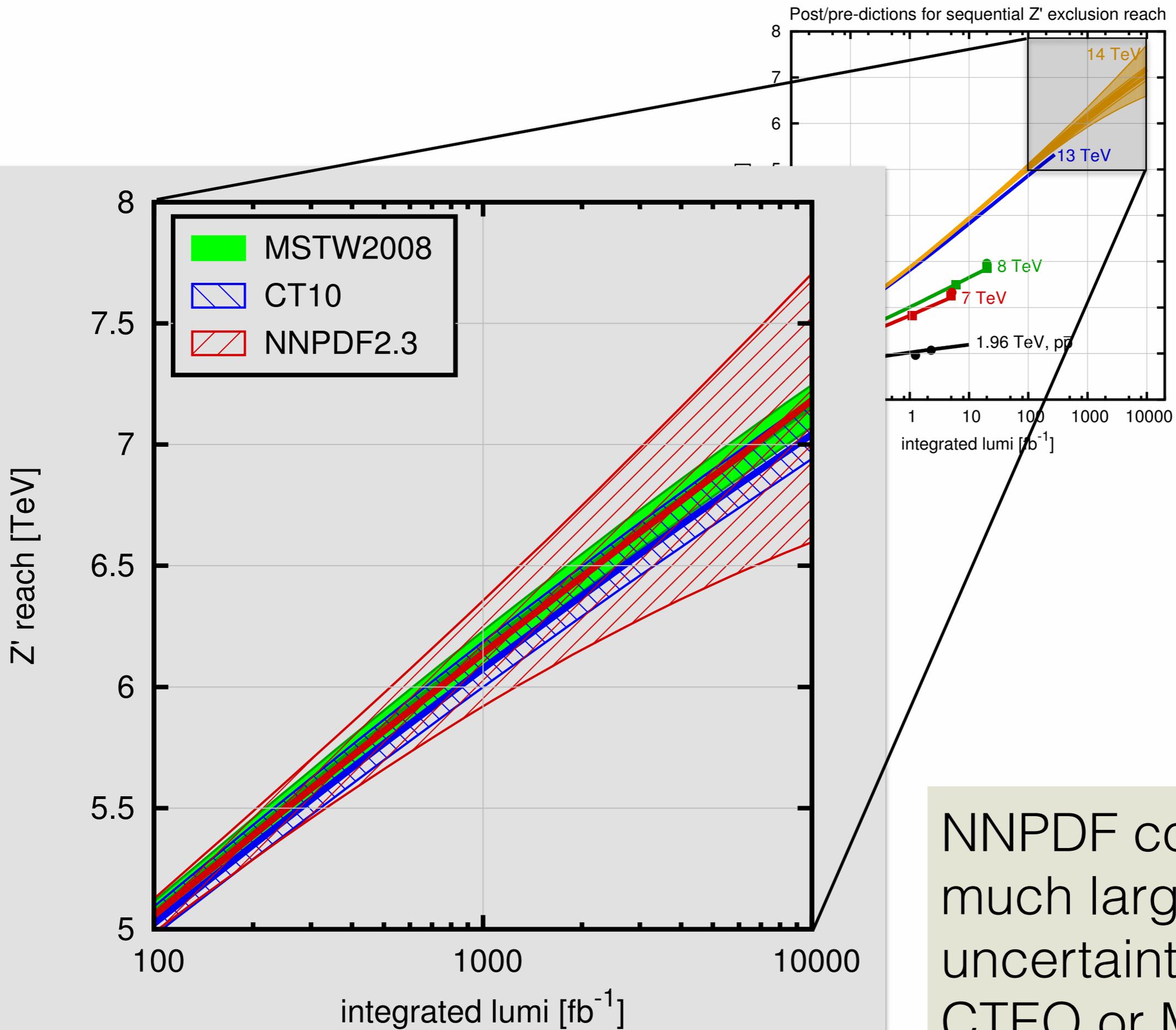
# Impact of PDF uncertainties



Envelope of CTEQ10  
MSTW2008 & NNPDF23  
results

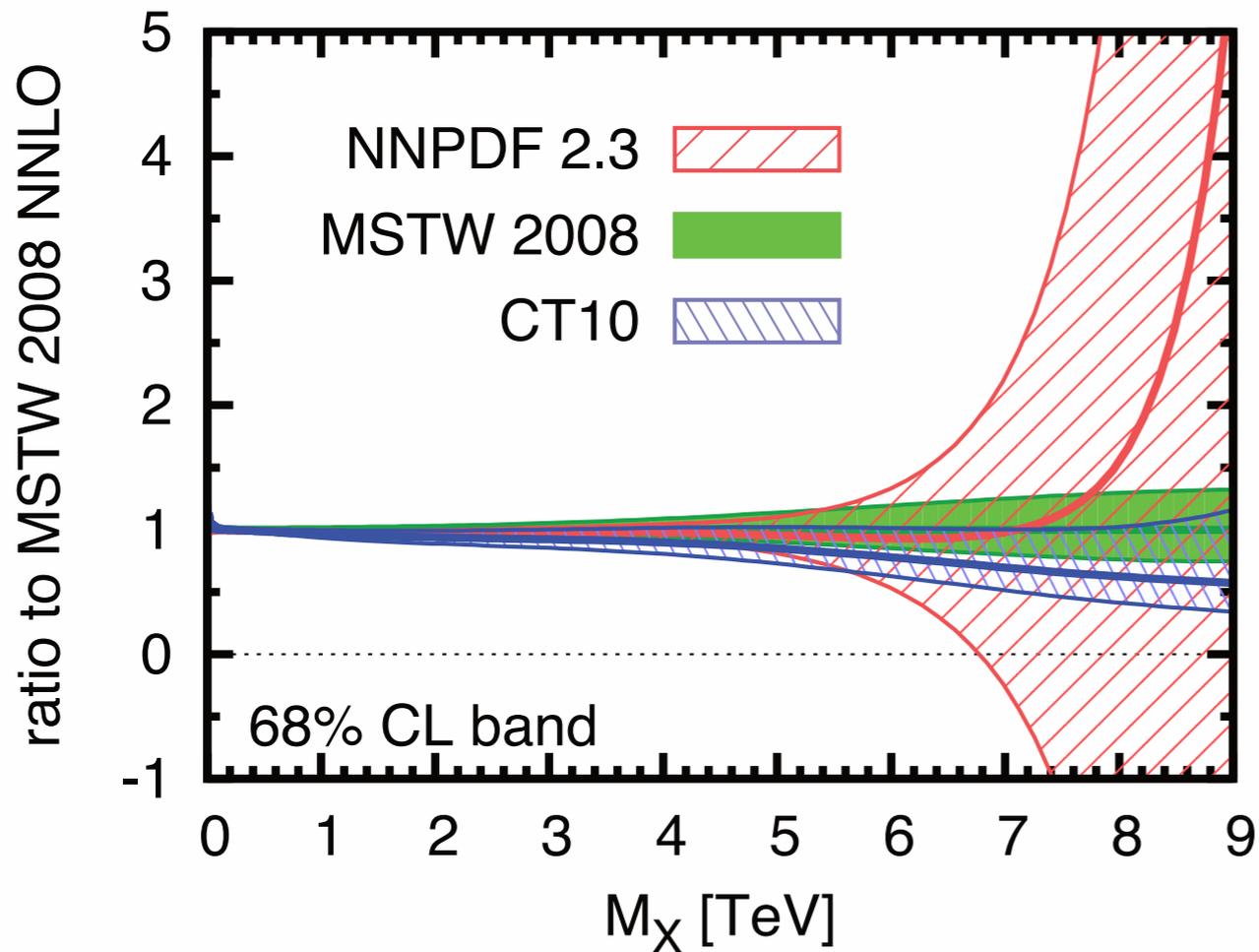
## Caveats

- 1) Implicit assumption of narrow Z' is debatable at high  $M_{Z'}/\sqrt{s}$
- 2) PDF uncertainties don't play identically here and in actual search



NNPDF comes with much larger uncertainties than CTEQ or MSTW

NNLO  $q\bar{q}$  luminosities (LHC 14 TeV)

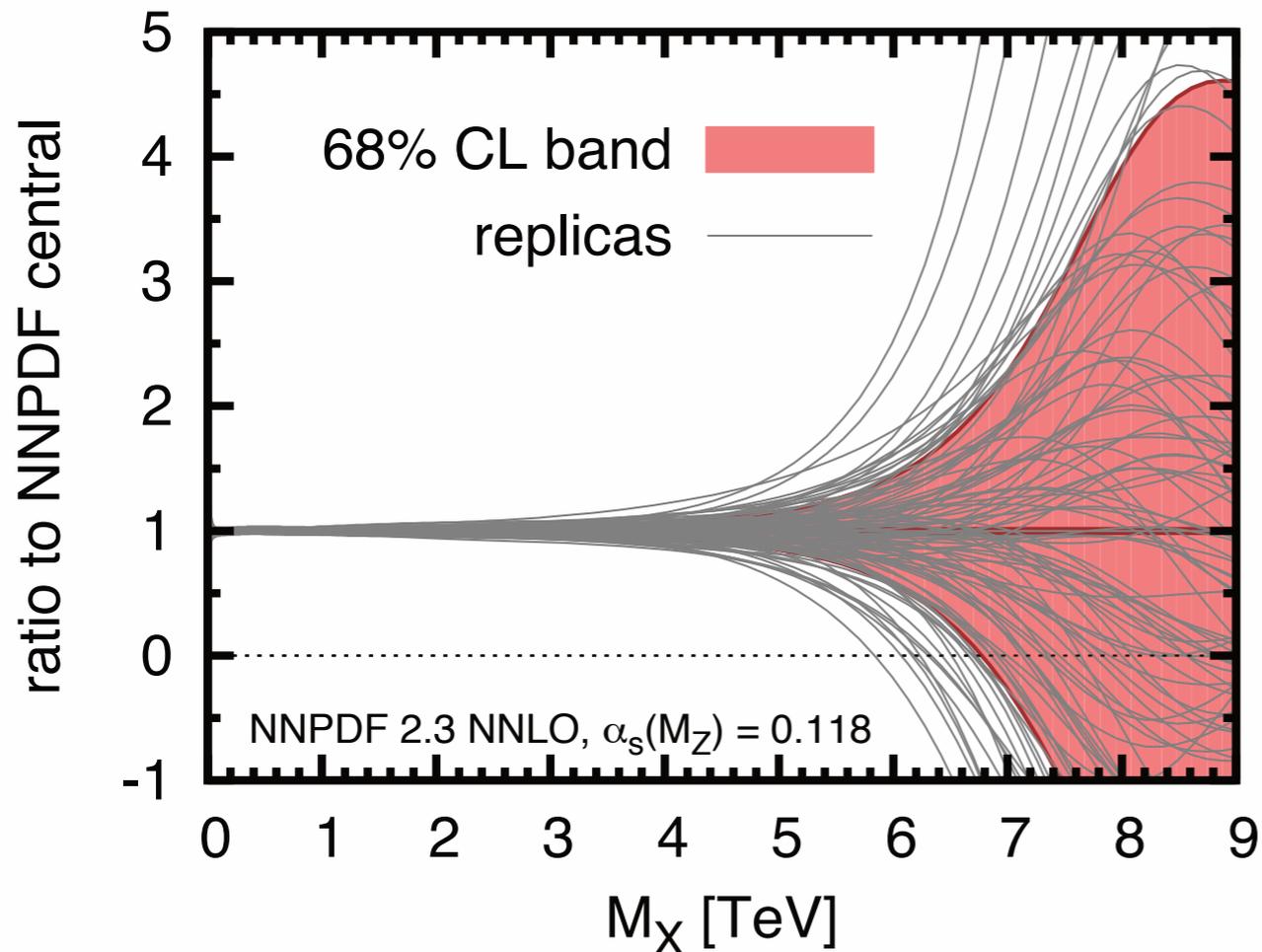


## Observation #1

For  $x > 0.4$ , NNPDF uncertainties grow much larger than CTEQ & MSTW's

This is perhaps not unreasonable: NNPDF more accurately reflects absence of anti-quark constraints at large  $x$

NNPDF  $q\bar{q}$  luminosity replicas (LHC 14 TeV)



## Observation #2

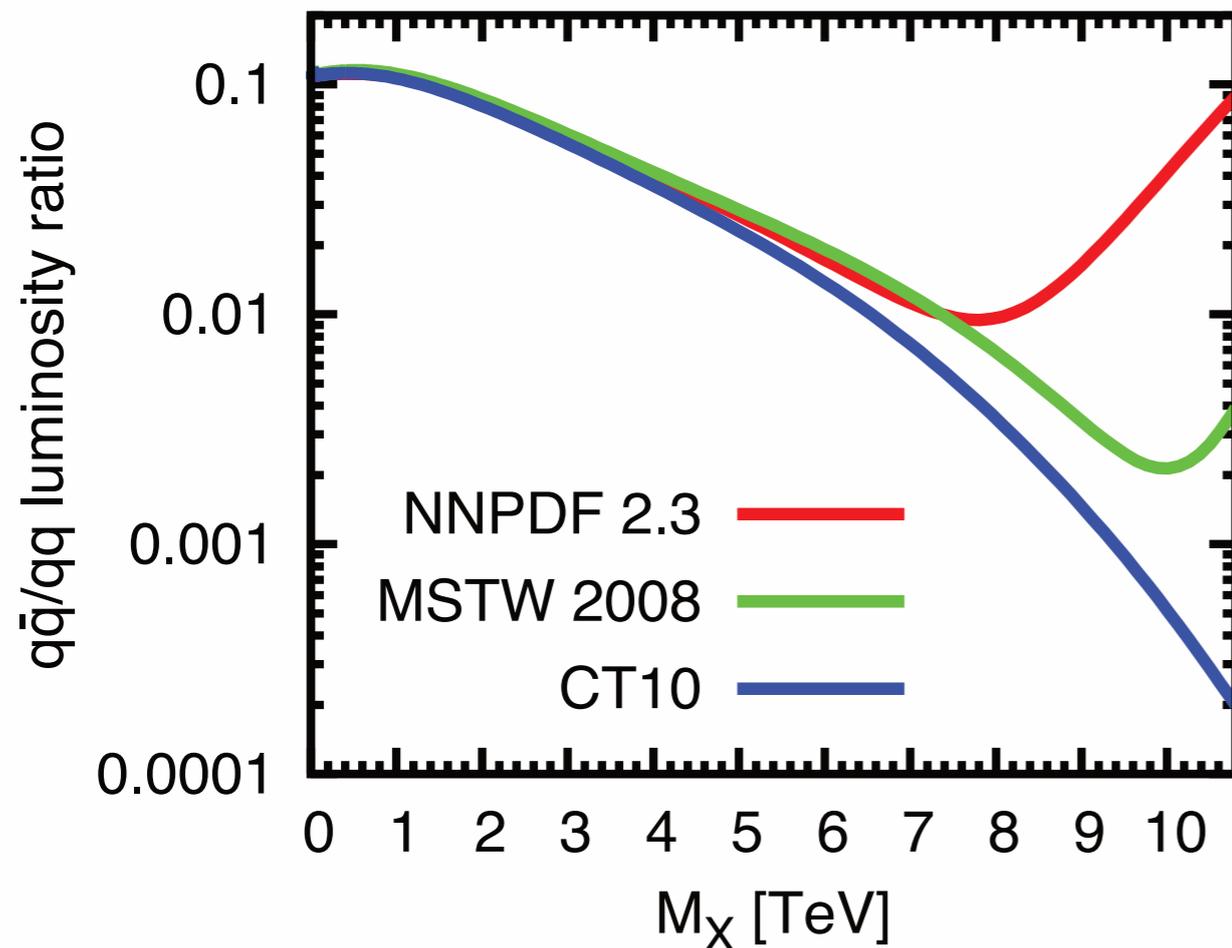
NNPDF replicas start to go negative for  $x > 0.4$

Negative PDFs at small  $x$  have long been accepted if  $F_L > 0$

To know how acceptable at large  $x$ , must study NNLO  
DY  $x$ -sect (beyond scope of our study so far)

Anyway being resolved in NNPDF3?

$q\bar{q}/qq$  luminosity ratios (LHC 14 TeV)



### Observation #3

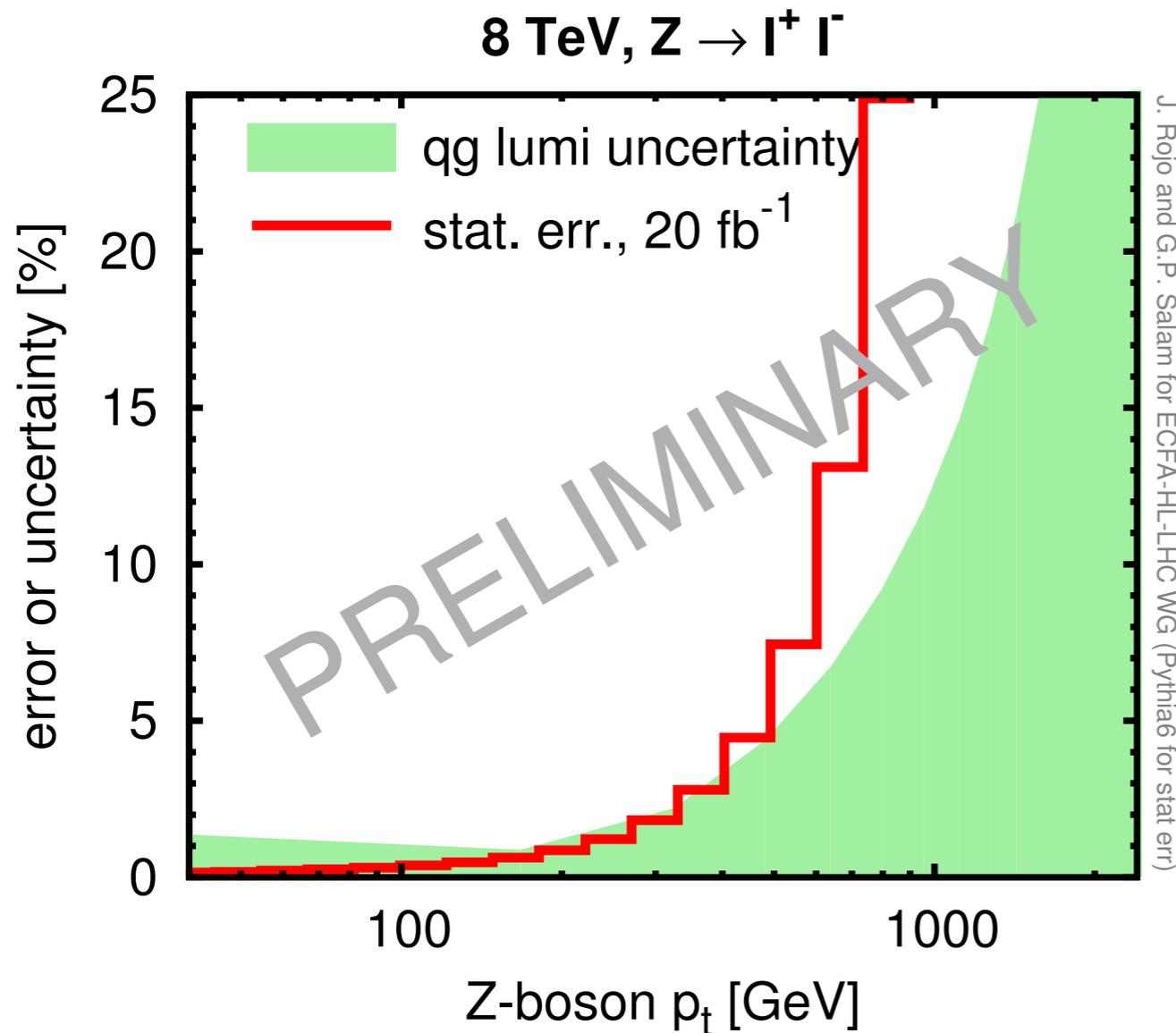
$q\bar{q}/qq$  lumi increases  
for  $x > 0.5$  in NNPDF  
( $x > 0.7$  in MSTW)

Even if not constrained by data, this runs counter to our physical expectations (counting rules, etc.)

Maybe sets in at too high  $x$  to be a practical issue?

Is there a  
**roadmap**  
for PDFs at LHC?

# e.g. of HL-LHC precision SM measurement: $Z p_t$ spectrum



[Studies with Juan Rojo and Andi Weiler for ECFA HL-LHC workshop in October 2013]

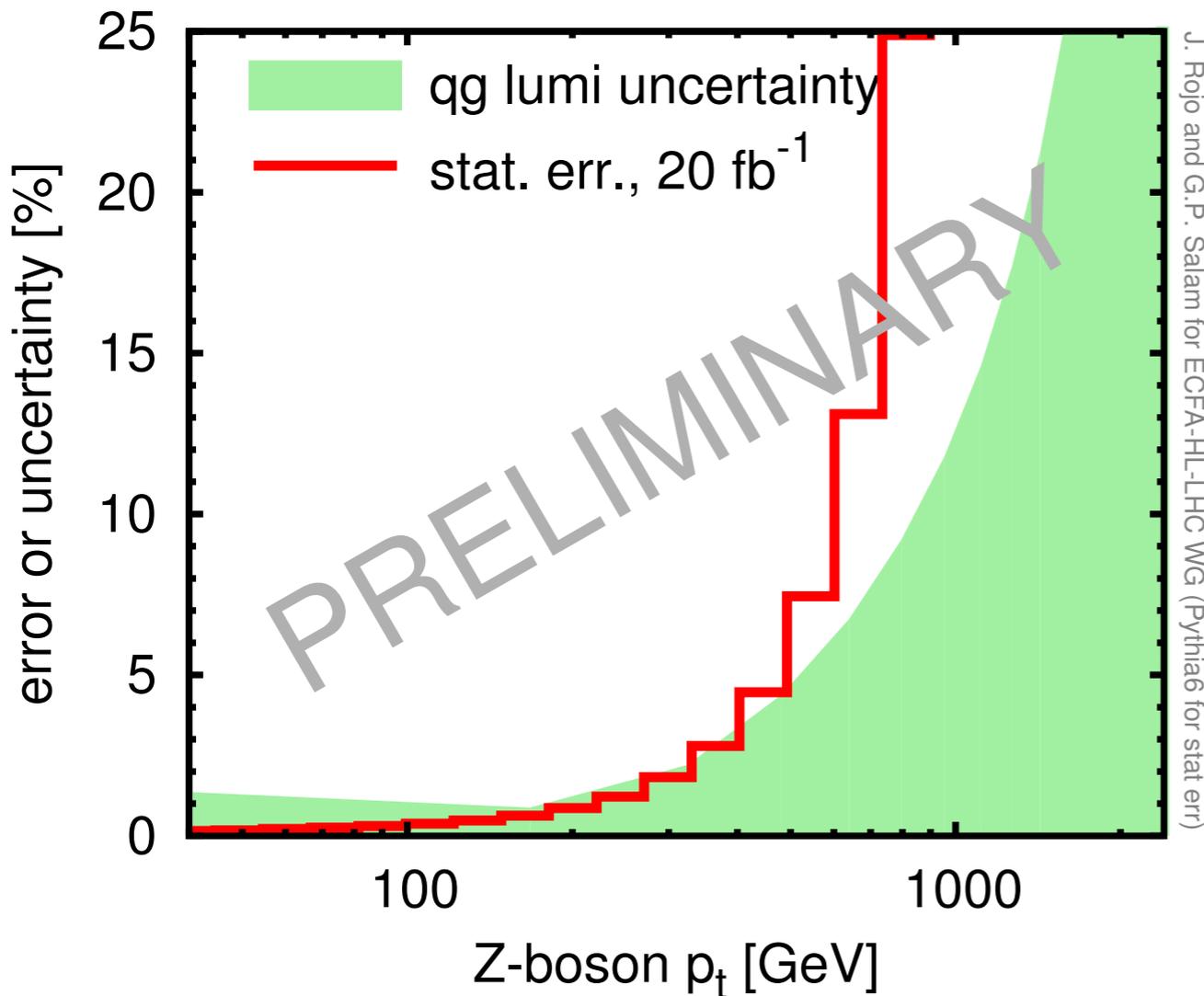
Emerging realisation that the  $Z p_t$  spectrum is a potentially very precise handle on PDFs  
[quark  $\times$  glue  $\times \alpha_s$ ]

Today, will mainly be a vital confirmation(?) of existing knowledge.

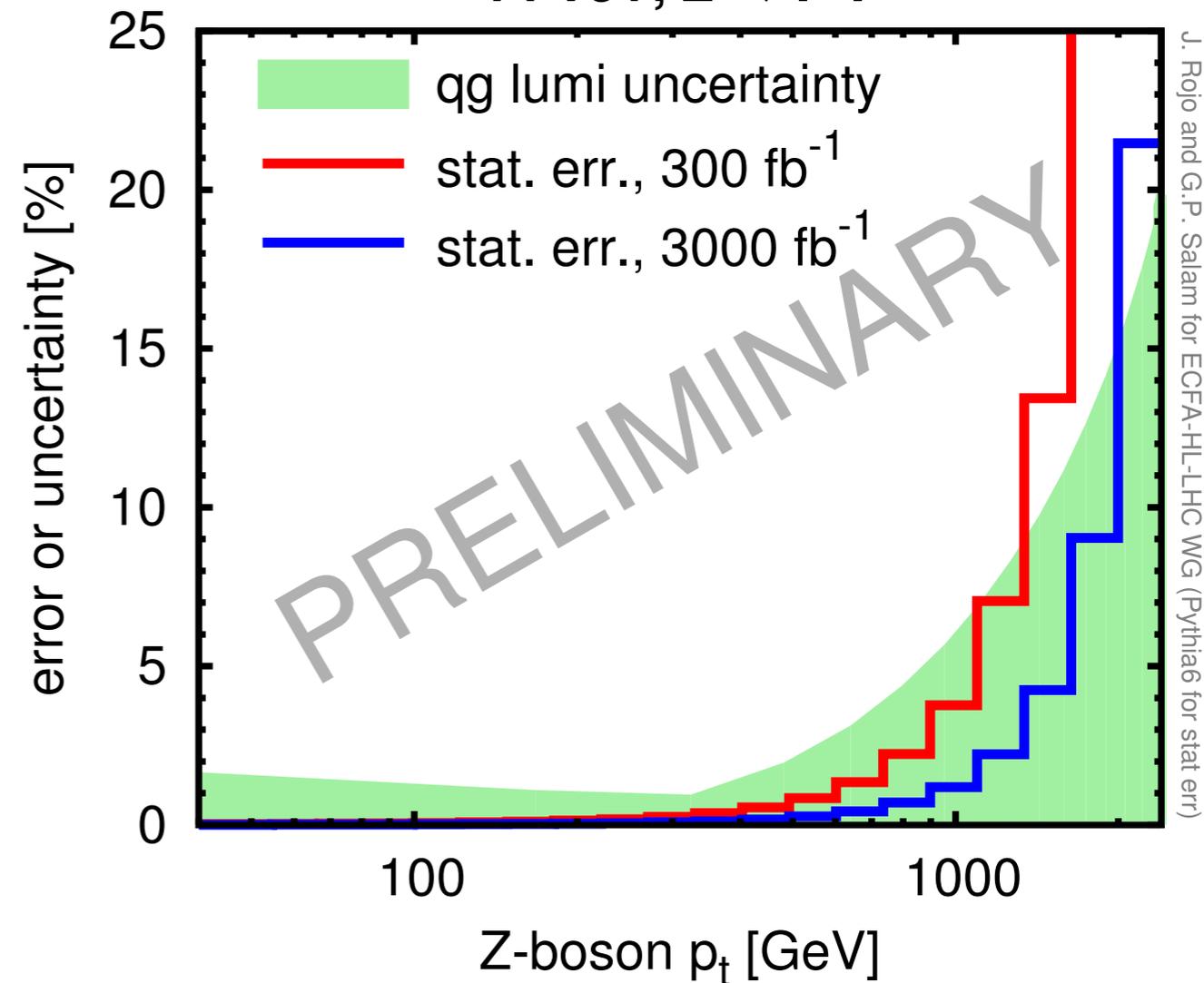
$t\bar{t}$  is also a powerful handle, cf. [1303.7215](#)

# e.g. of HL-LHC precision SM measurement: $Z p_t$ spectrum

8 TeV,  $Z \rightarrow l^+ l^-$



14 TeV,  $Z \rightarrow l^+ l^-$



For  $p_t \sim 1$  TeV, HL-LHC could bring **5x gain in precision!**  
[but only if theory prediction is good enough — today only NLO]

What other processes will bring high precision?

This can motivate measurements and form part of HL-LHC programme (might there even be benefits from additional low-energy running?)

A roadmap now can also motivate future precise theoretical calculations

# Summary

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Differences between large- $x$  antiquark PDF uncertainties in various PDF sets are not surprising in their own right.

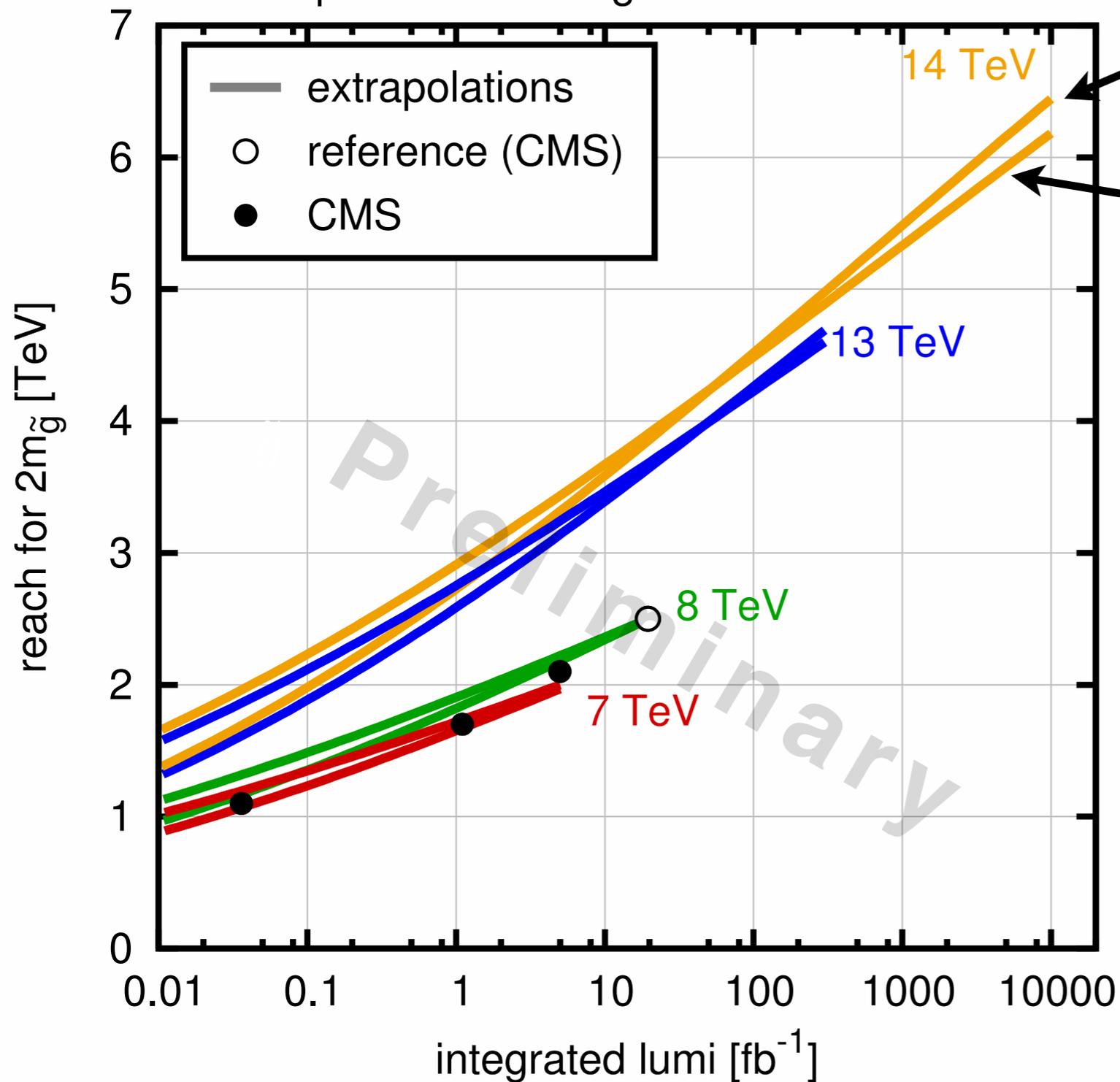
What amount of physical insight should be incorporated into fits? Should stiffness of fitting functions be an explicit parameter in fits? (E.g. XYZ stiff fit, XYZ not so stiff fit).

**Roadmap** for PDF fits? What's the interplay with future collider plans? What theory progress is needed on what timescale?

# BACKUP SLIDES

Why does it work?

Post/pre-dictions for gluino exclusion reach



Signal gg; bkgd: gg

Signal gg; bkgd: qg

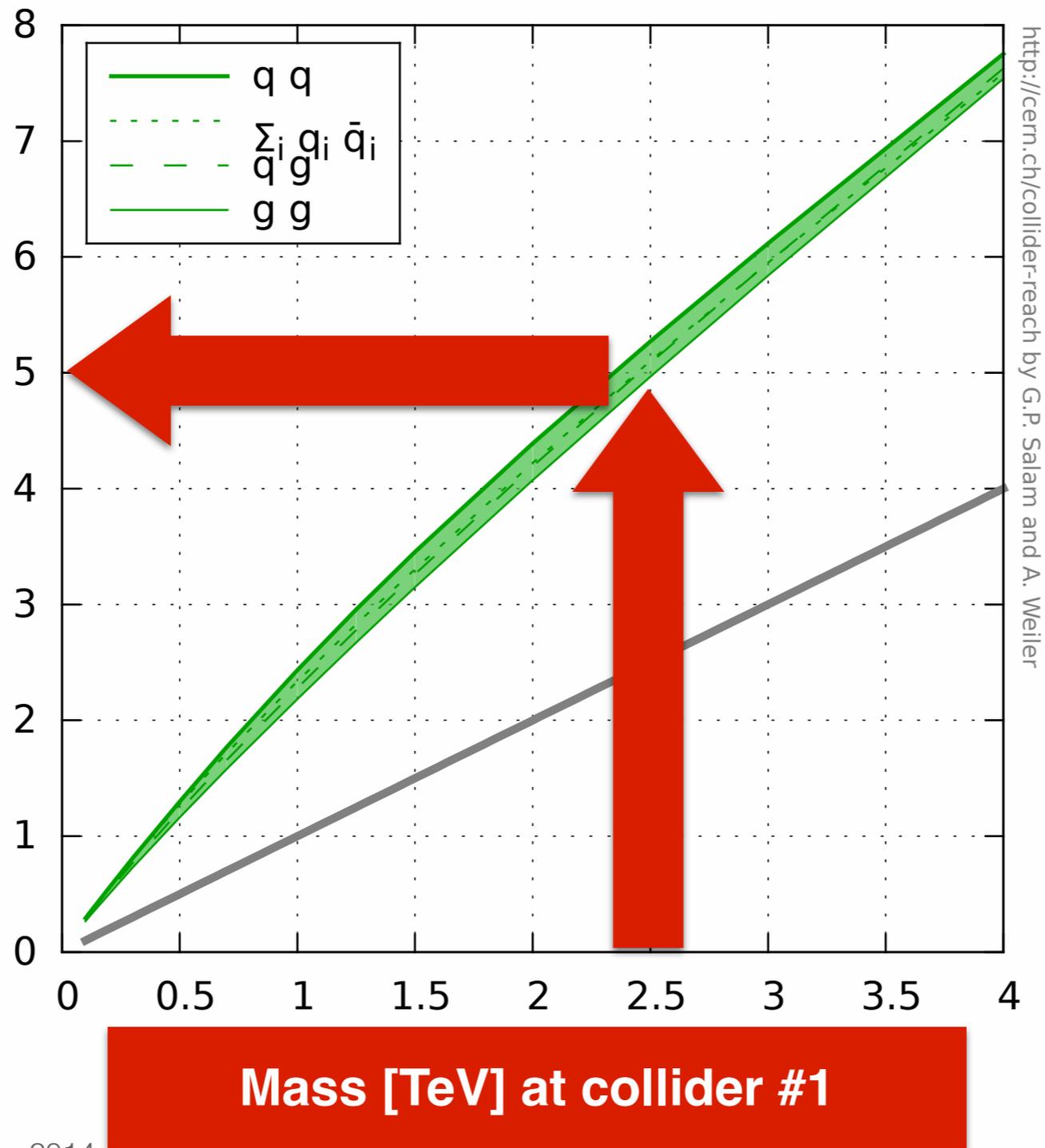
Scattering channel matters, but not too much

From your iPhone  
(or a generic browser)  
[cern.ch/collider-reach](http://cern.ch/collider-reach)

From your Android Phone  
(or a generic browser)  
[cern.ch/collider-reach](http://cern.ch/collider-reach)

Collider 1: CoM energy  TeV, integrated luminosity  fb<sup>-1</sup>  
 Collider 2: CoM energy  TeV, integrated luminosity  fb<sup>-1</sup>  
 PDF:

**Mass [TeV] at  
collider #2**



Collider 1: CoM energy

8

TeV, integrated luminosity

20

$\text{fb}^{-1}$

Collider 2: CoM energy

14

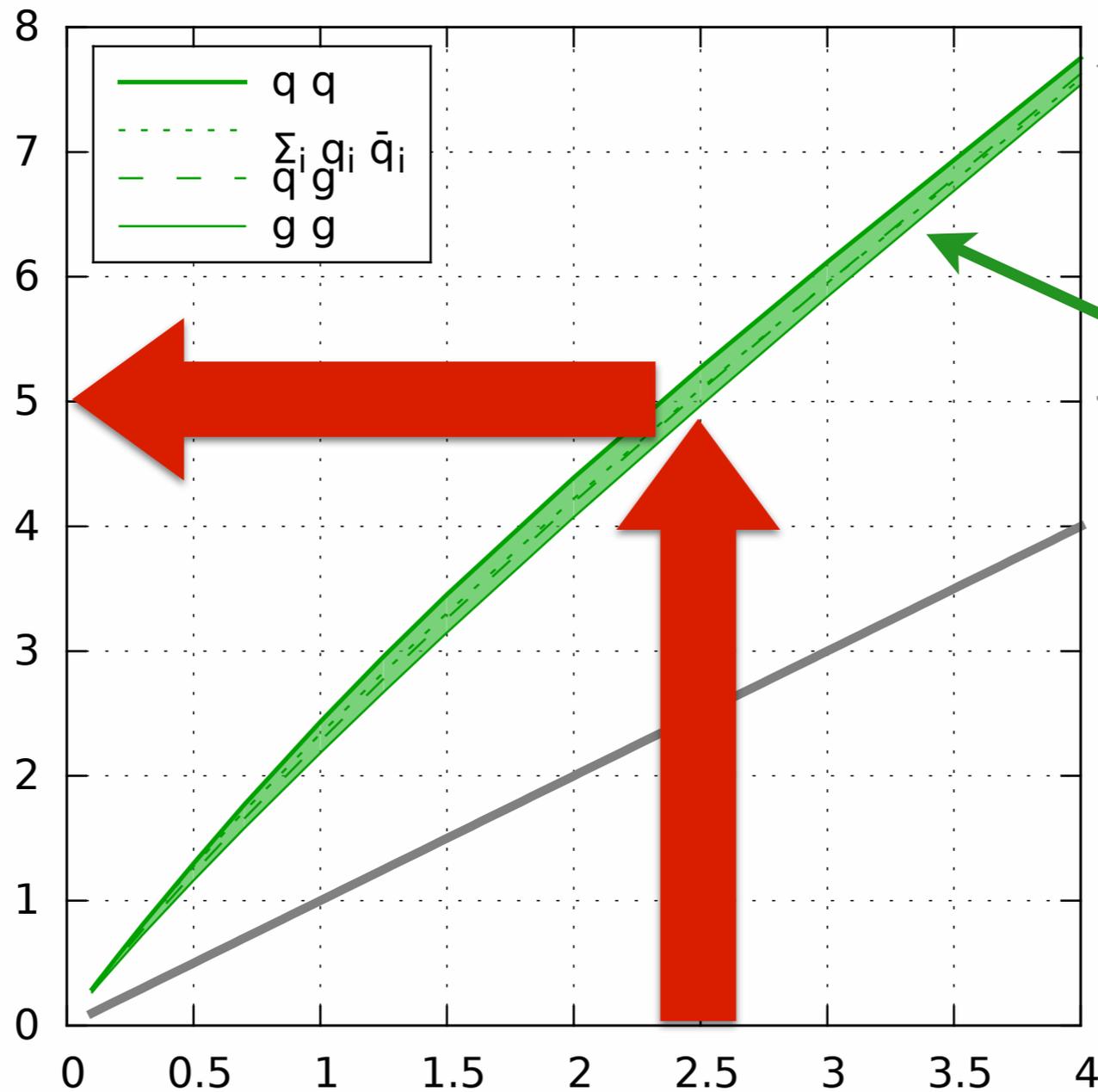
TeV, integrated luminosity

300

$\text{fb}^{-1}$

PDF:

MSTW2008nnlo68cl



Mass [TeV] at  
collider #2

Spread of  
partonic  
channels  
(assume same  
channel for  
S & B)

Mass [TeV] at collider #1

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  TeV, integrated luminosity  fb<sup>-1</sup>

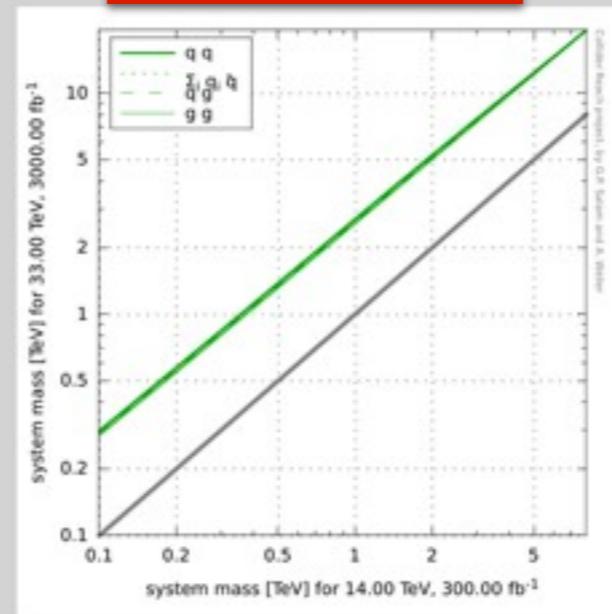
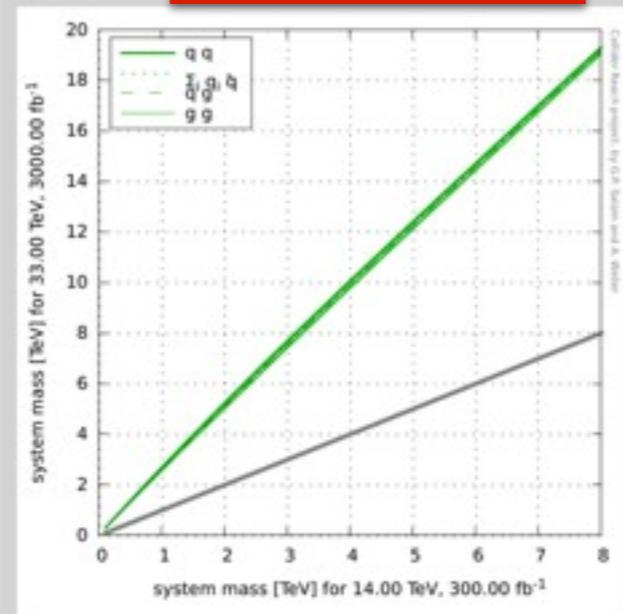
Collider 2: CoM energy  TeV, integrated luminosity  fb<sup>-1</sup>

PDF:

**linear plot**

**log-log plot**

Plots

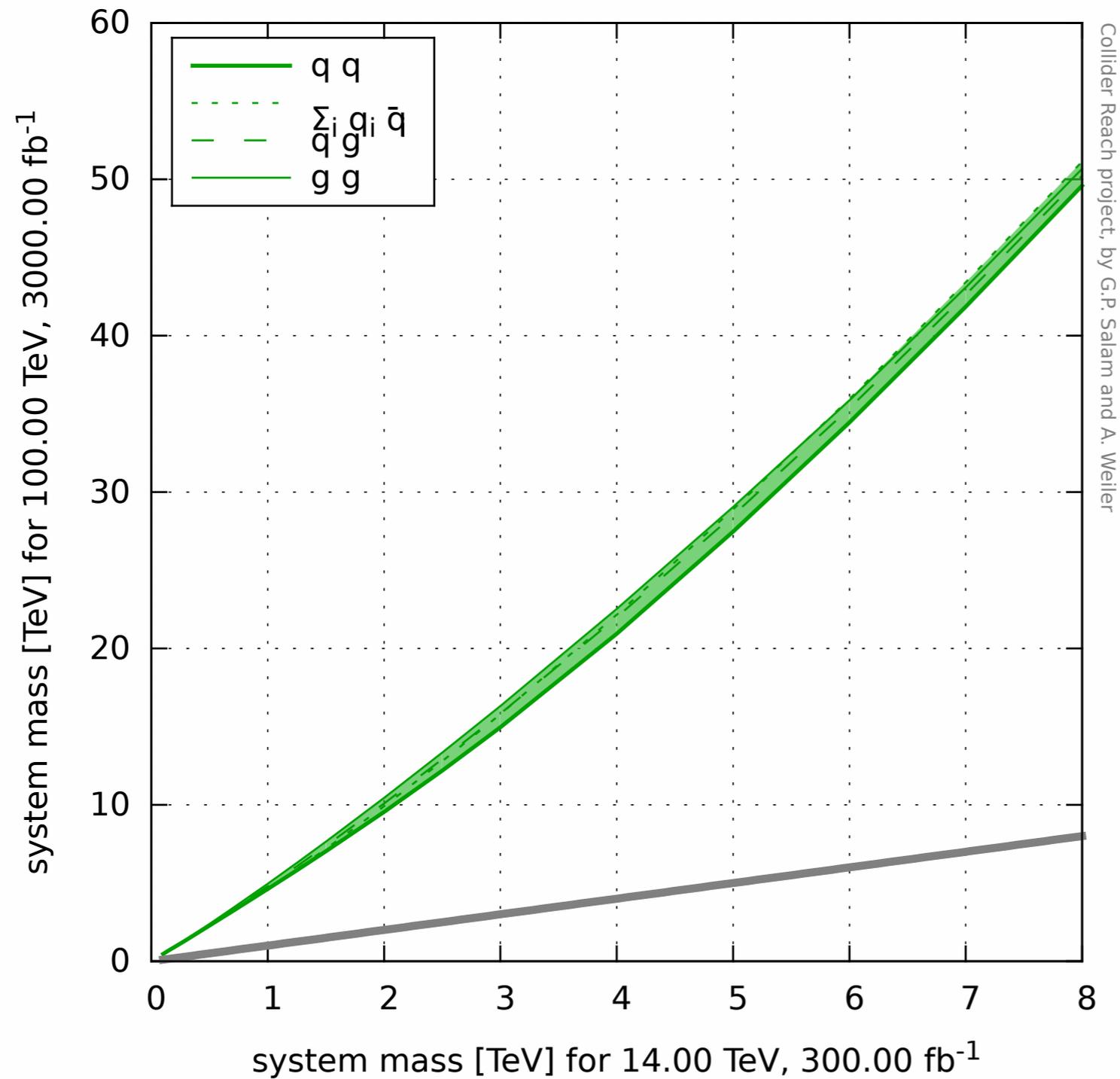


Download: [collider.pdf](#), [colliderloglog.pdf](#), plot generation [log file](#)

The PDF choice was CT10nlo.LHgrid

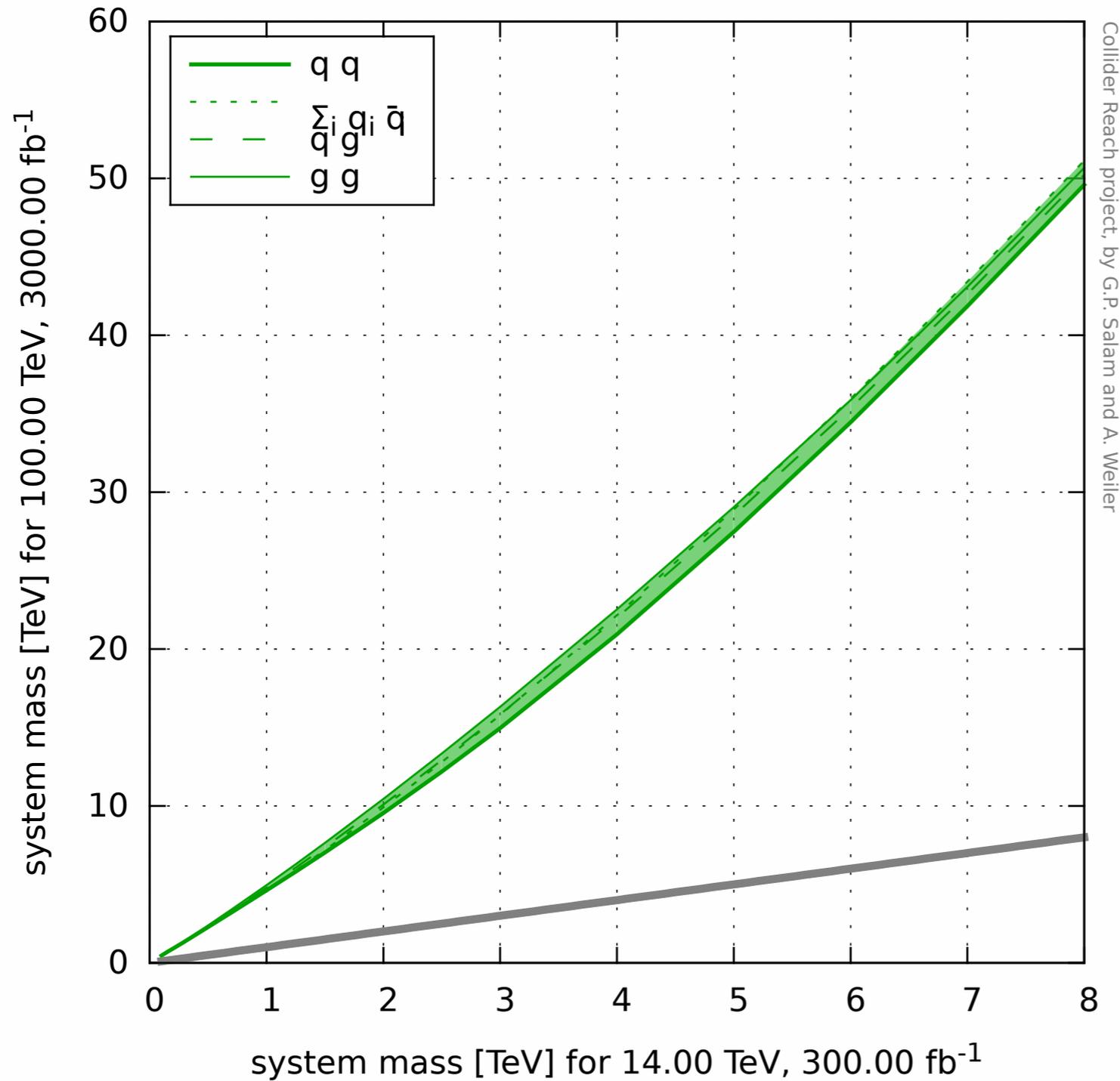
Original mass	gg	qg	allqq	qqbar
100.	283.	291.	298.	297.
125.	350.	359.	368.	367.
150.	416.	427.	438.	437.
200.	547.	562.	576.	575.
300.	806.	827.	848.	847.
500.	1317.	1350.	1386.	1382.
700.	1822.	1866.	1916.	1907.
1000.	2570.	2628.	2702.	2680.
1250.	3188.	3256.	3349.	3314.
1500.	3802.	3879.	3990.	3939.
2000.	5018.	5110.	5251.	5169.
2500.	6223.	6327.	6488.	6380.
3000.	7417.	7530.	7703.	7578.
4000.	9782.	9904.	10082.	9945.
5000.	12120.	12246.	12417.	12284.
6000.	14439.	14565.	14726.	14601.
7000.	16748.	16871.	17021.	16905.
8000.	19053.	19169.	19310.	19206.

14 TeV<sub>300 fb<sup>-1</sup></sub> → 100 TeV<sub>3 ab<sup>-1</sup></sub>



Collider Reach project, by G.P. Salam and A. Weiler

# 14 TeV<sub>300 fb<sup>-1</sup></sub> → 100 TeV<sub>3 ab<sup>-1</sup></sub>



The PDF choice was CT10nlo.LHgrid

Original mass	gg	qg	allqq	qqbar
100.	469.	465.	462.	457.
125.	585.	579.	575.	568.
150.	702.	693.	687.	679.
200.	937.	923.	912.	902.
300.	1414.	1386.	1365.	1350.
500.	2394.	2332.	2279.	2261.
700.	3401.	3300.	3206.	3194.
1000.	4956.	4793.	4619.	4640.
1250.	6287.	6072.	5818.	5892.
1500.	7647.	7382.	7038.	7187.
2000.	10444.	10090.	9552.	9905.
2500.	13337.	12908.	12185.	12781.
3000.	16319.	15833.	14954.	15795.
4000.	22531.	21986.	20933.	22162.
5000.	29050.	28508.	27467.	28894.
6000.	35863.	35366.	34451.	35960.
7000.	43079.	42620.	41854.	43411.
8000.	50671.	50230.	49590.	51132.

# When you've lost your XPhone

# Rule of Thumb #1

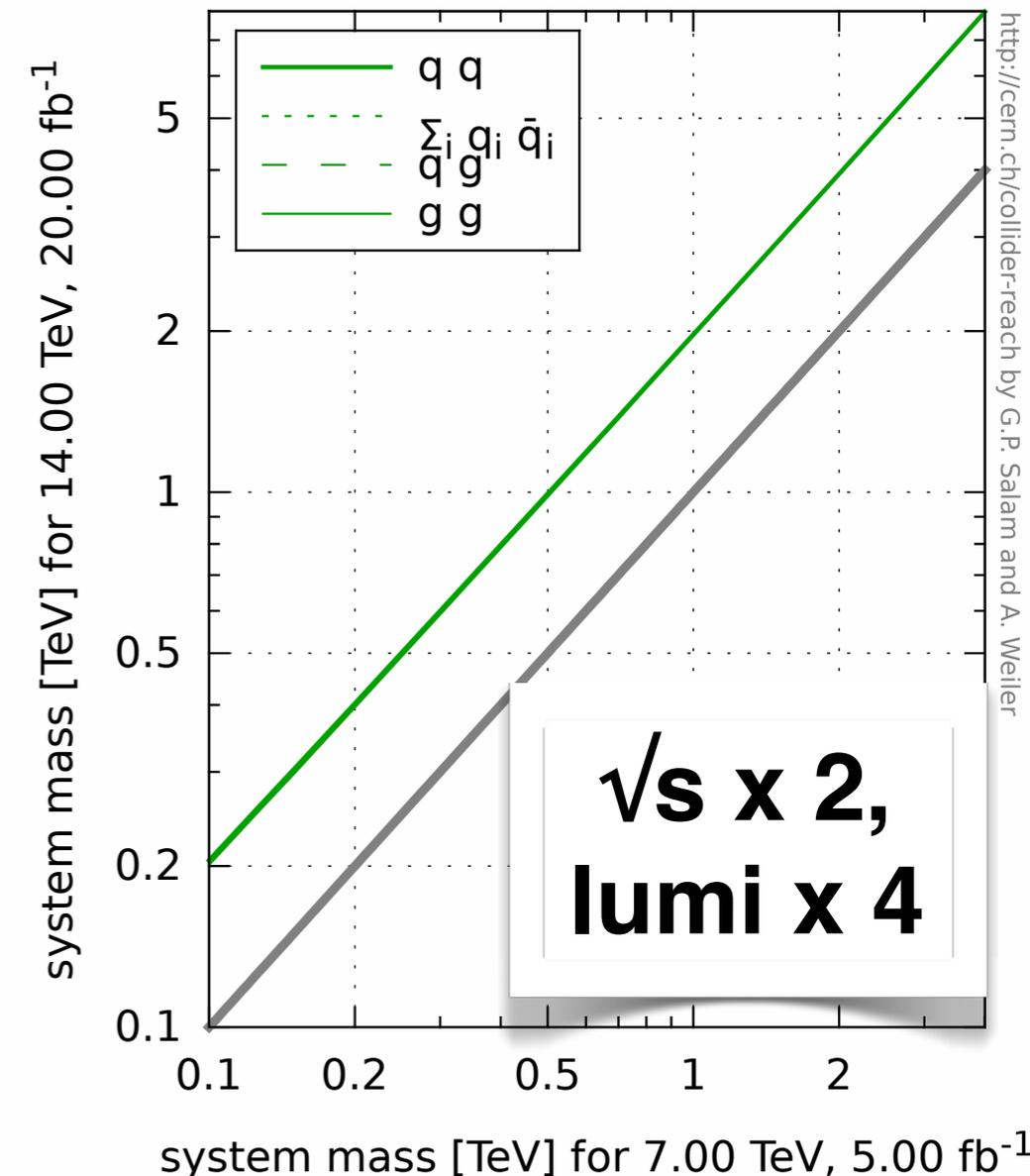
(well known among practitioners)

Increase collider energy by factor  $X$   
& increase luminosity by a factor  $X^2$

→ **reach goes up by a factor  $X$**

[Because you keep same Bjorken- $x$  &  
luminosity increase compensates for  
 $1/\text{mass}^2$  scaling of cross sections]

PDF scaling variations are small effect



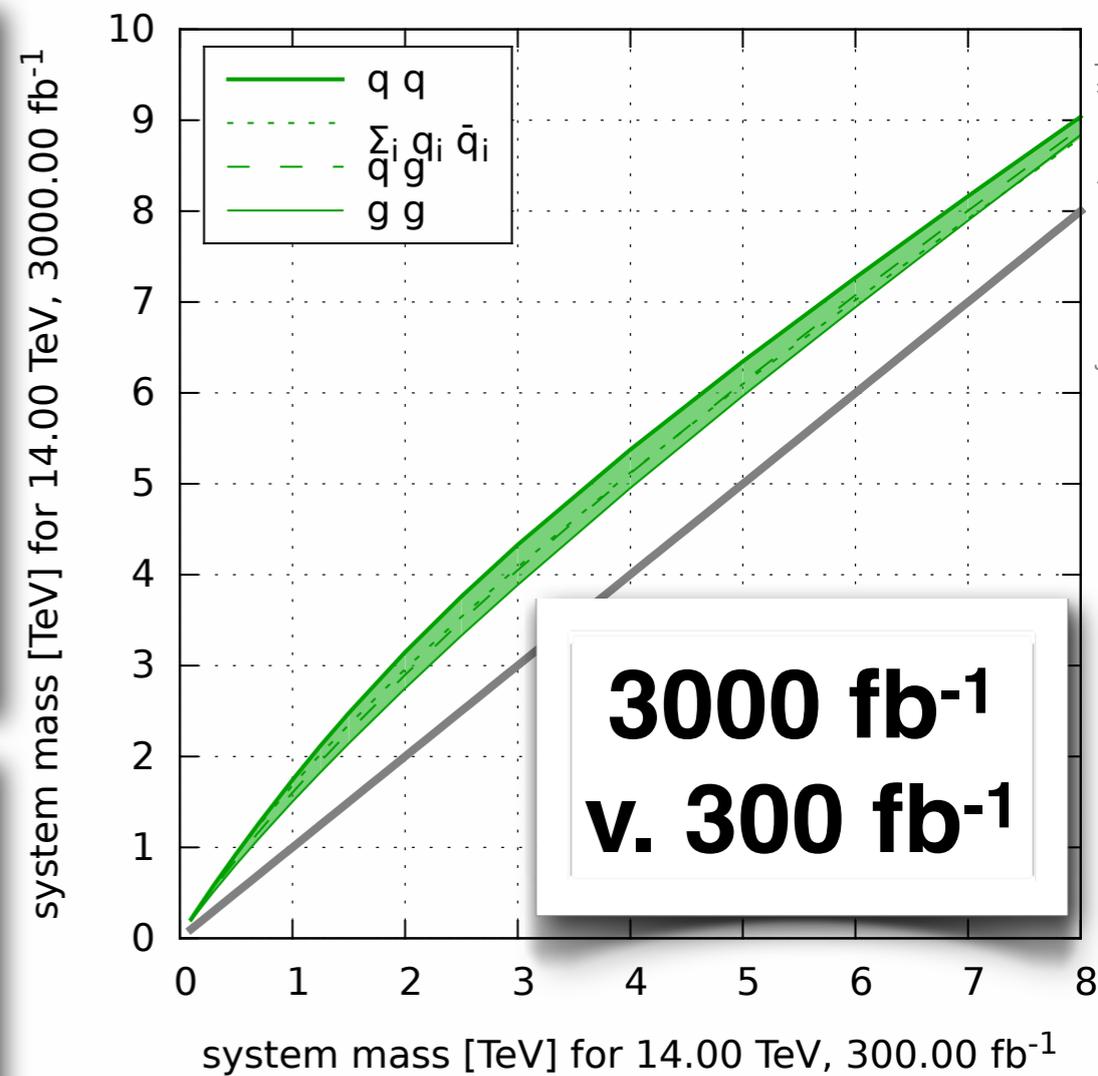
# Rule of Thumb #2

(apparently not widely known previously)

Increase luminosity by factor 10  
→ **reach increases by constant**  
 **$\Delta m \approx 0.07\sqrt{s}$**

i.e. for  $\sqrt{s}=14$  TeV, reach goes by up  
1 TeV

No deep reason — a somewhat  
random characteristic of large-x PDFs.  
Only holds for  $0.15 \lesssim M/\sqrt{s} \lesssim 0.6$



# Consequence of rule #2

(may be a bit fragile & only for  $S \approx B$ )

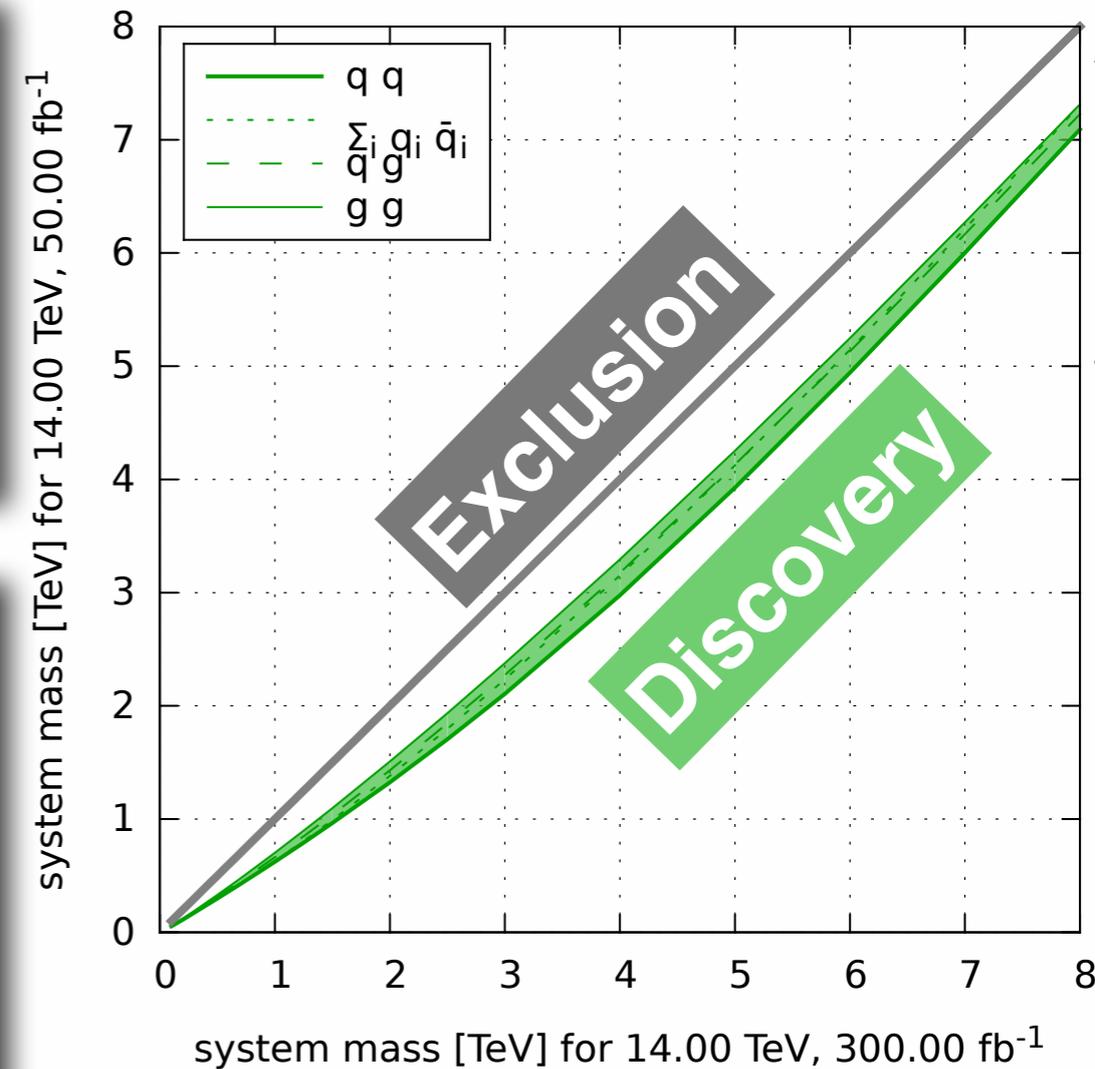
Exclusion is  $2\text{-}\sigma$   
Discovery is  $5\text{-}\sigma$

Need  $(5/2)^2 = 6.25$  increase in lumi to go from one to the other.

Using rule #2:

discovery reach is about  $0.05\sqrt{s}$   
below exclusion reach

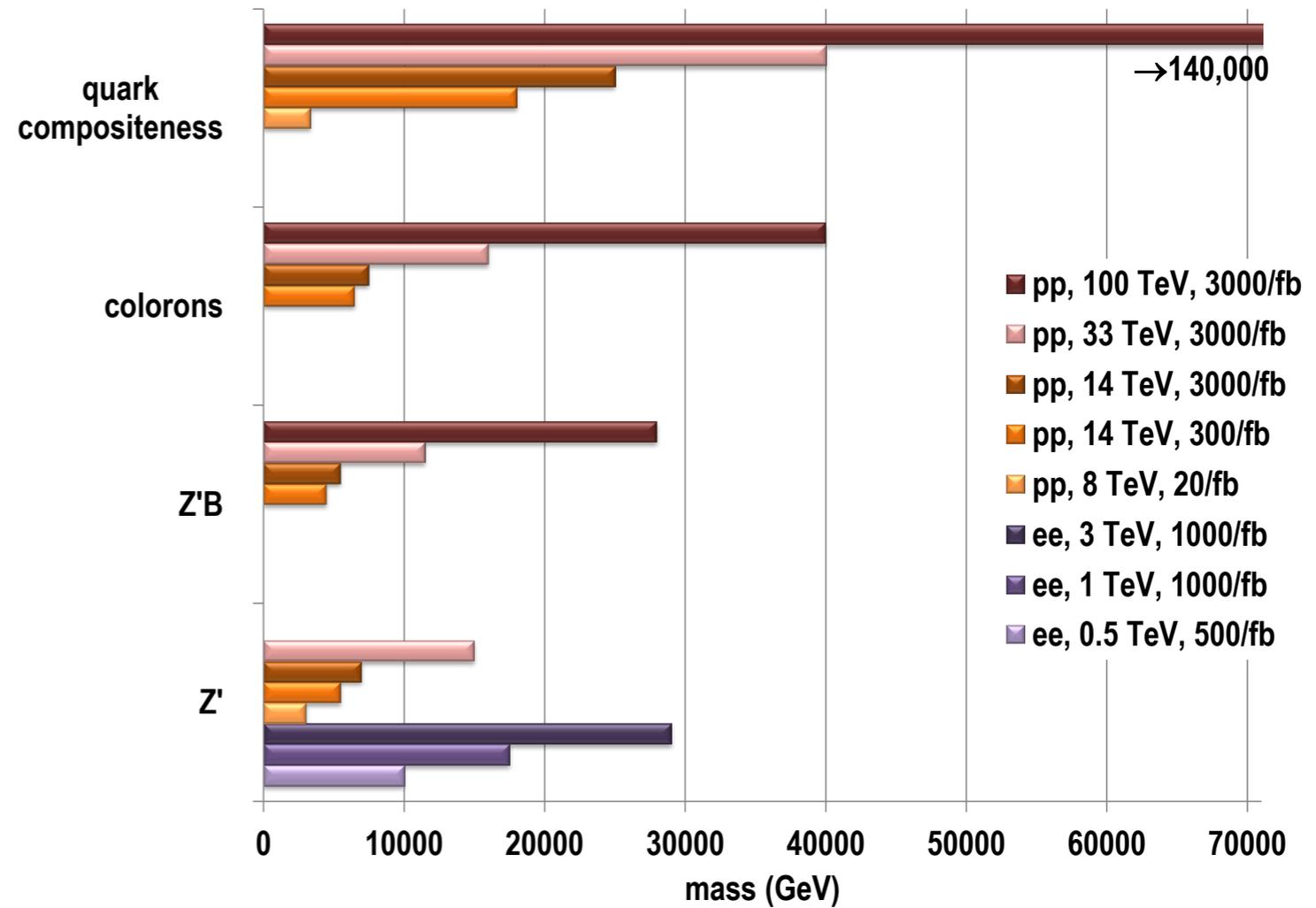
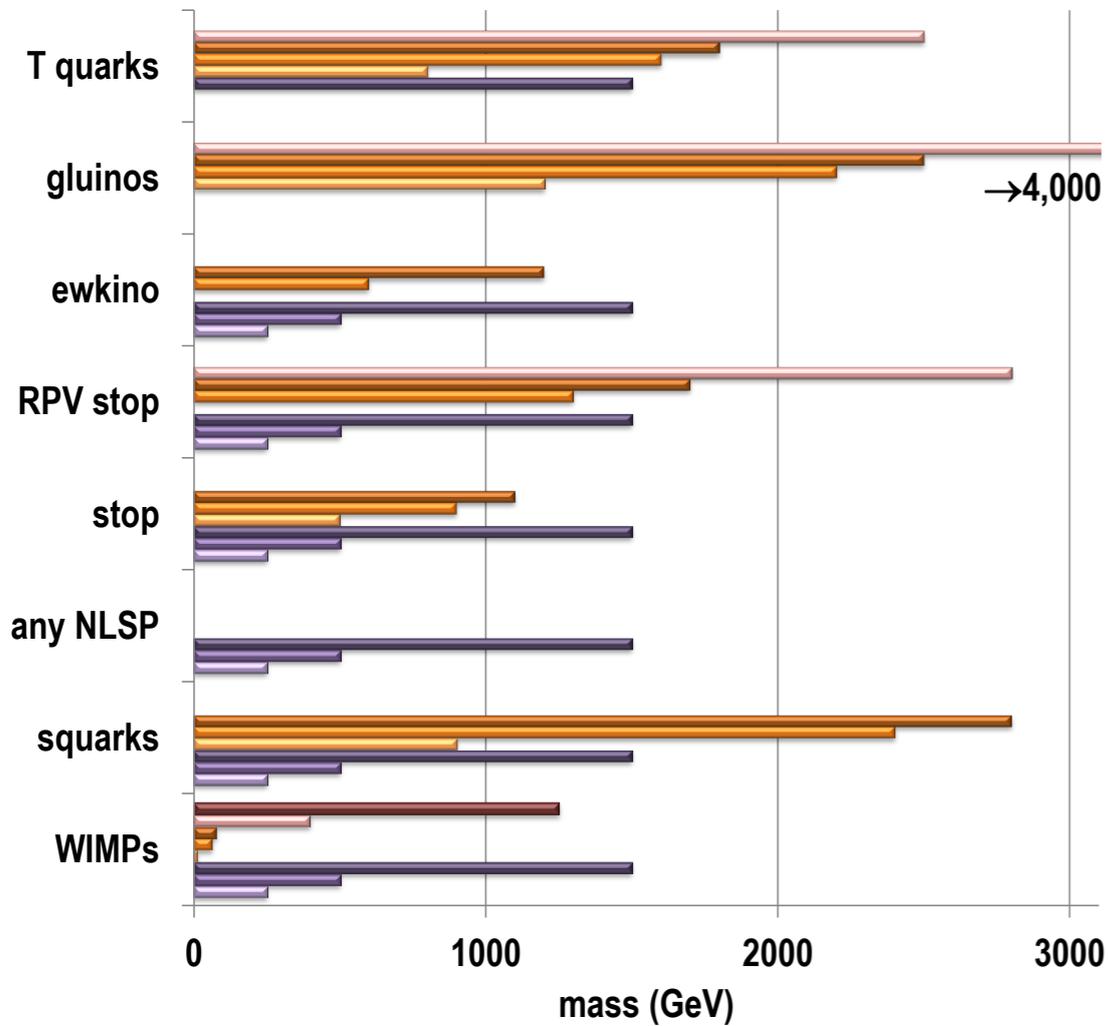
$\sim 0.8$  TeV at 14 TeV



# Future colliders

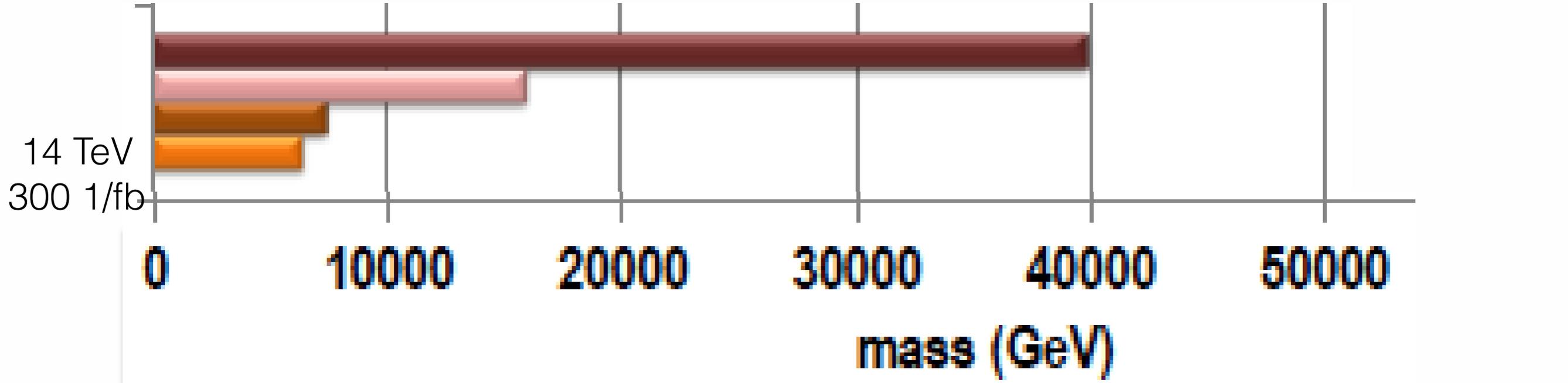
- We're ignoring all subtleties, just going for a baseline check
- If our estimate differs a lot from sophisticated simulations, something interesting has happened:
  - brick-wall (new irreducible backgrounds, granularity of assumed detectors, ...)
  - overly conservative or non-optimal estimates

# Future colliders comparison



Energy Frontier Snowmass study ([1311.0299](https://arxiv.org/abs/1311.0299))

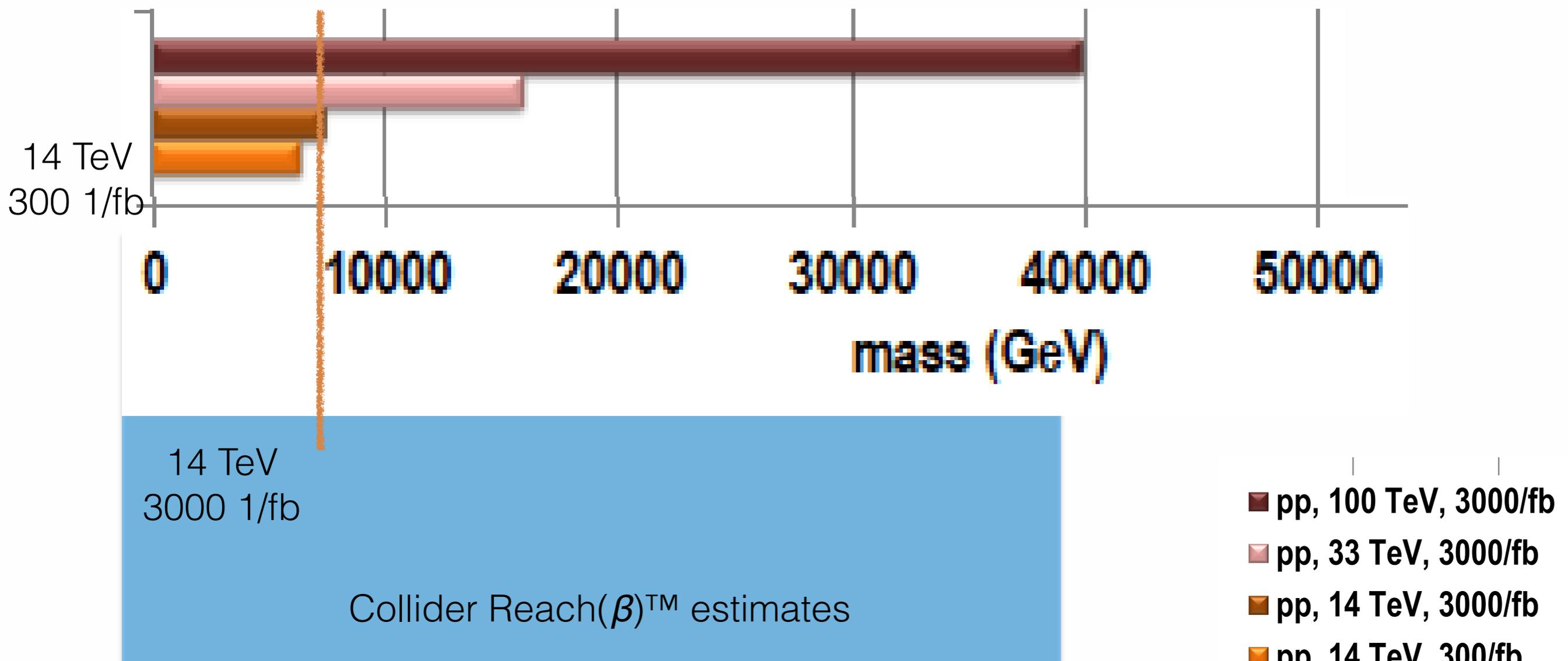
# Colorons



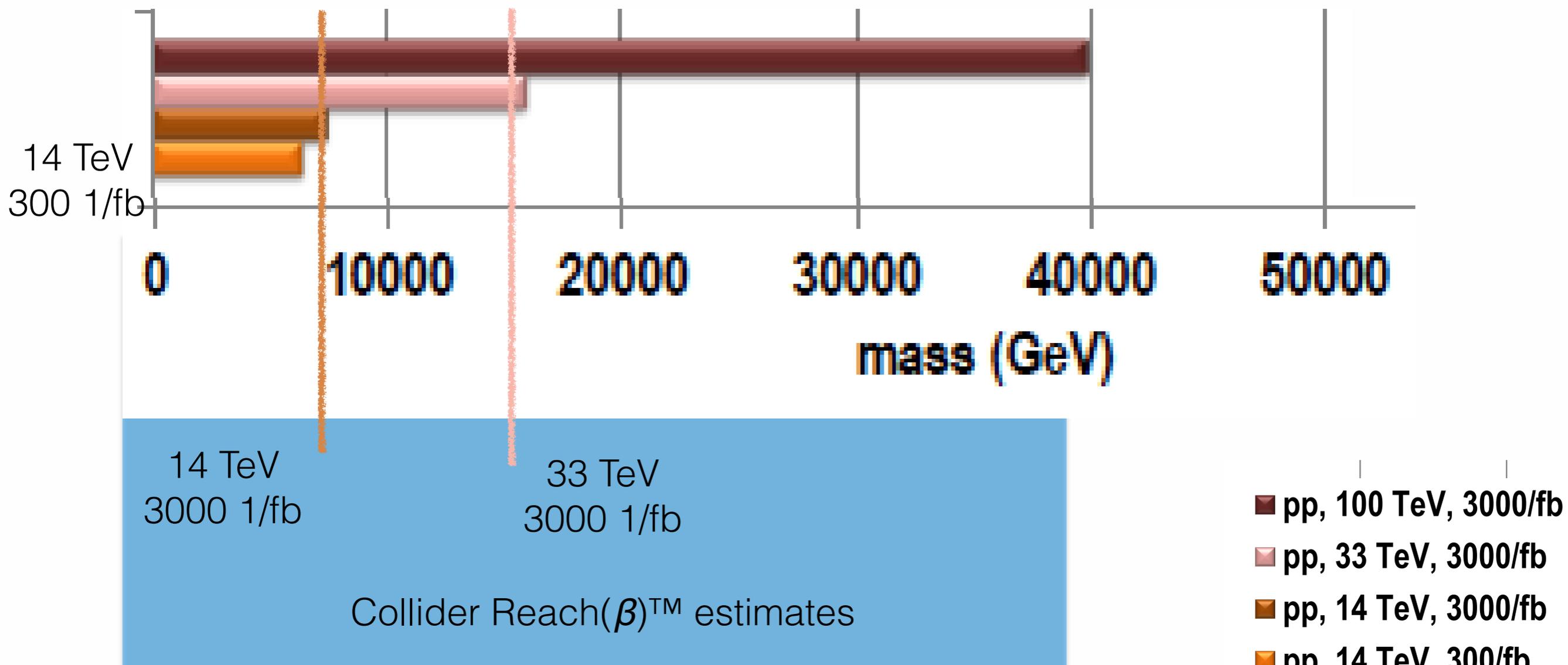
Collider Reach( $\beta$ )™ estimates

- pp, 100 TeV, 3000/fb
- pp, 33 TeV, 3000/fb
- pp, 14 TeV, 3000/fb
- pp, 14 TeV, 300/fb
- pp, 8 TeV, 20/fb
- ee, 3 TeV, 1000/fb
- ee, 1 TeV, 1000/fb
- ee, 0.5 TeV, 500/fb

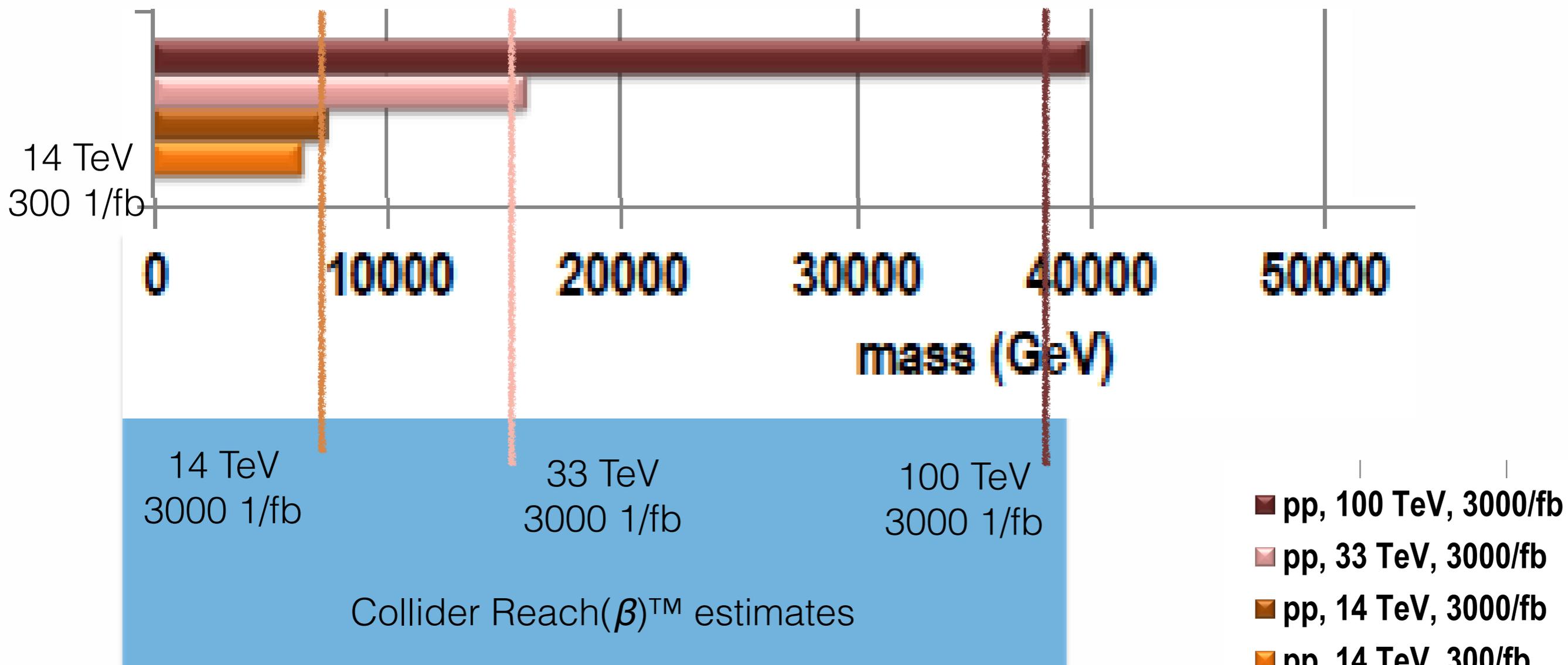
# Colorons



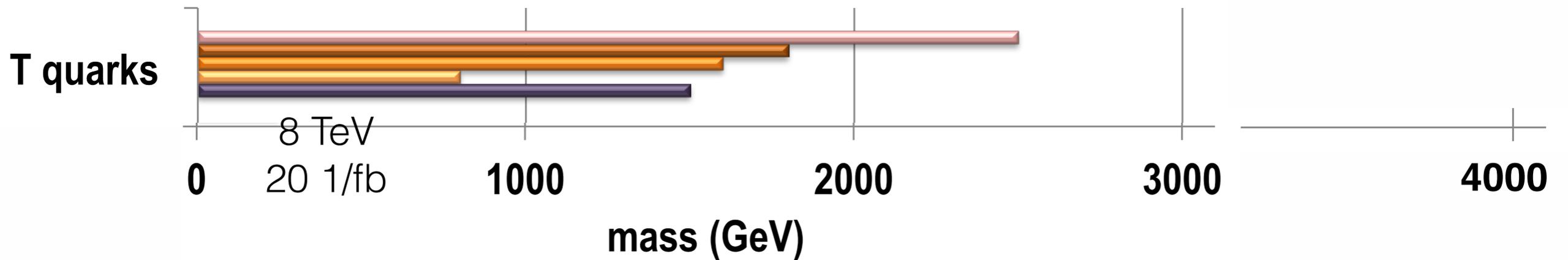
# Colorons



# Colorons



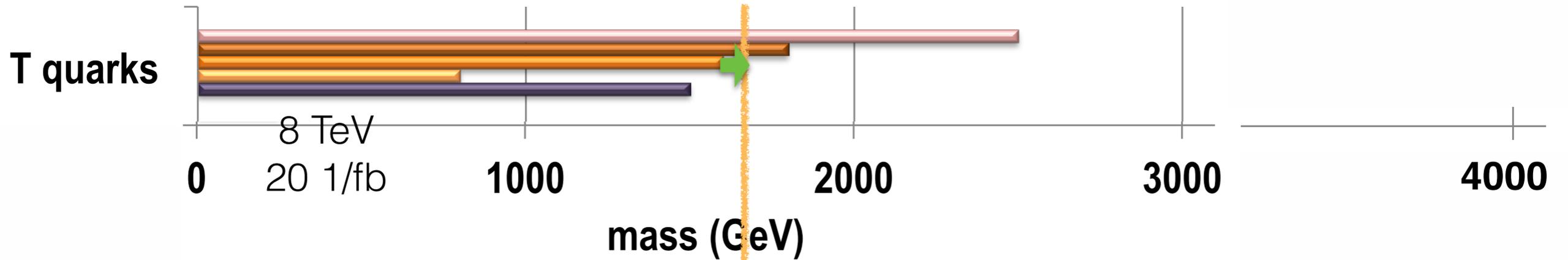
# T Quarks



- pp, 100 TeV, 3000/fb
- pp, 33 TeV, 3000/fb
- pp, 14 TeV, 3000/fb
- pp, 14 TeV, 300/fb
- pp, 8 TeV, 20/fb
- ee, 3 TeV, 1000/fb
- ee, 1 TeV, 1000/fb
- ee, 0.5 TeV, 500/fb

Collider Reach( $\beta$ )<sup>TM</sup> estimates

# T Quarks

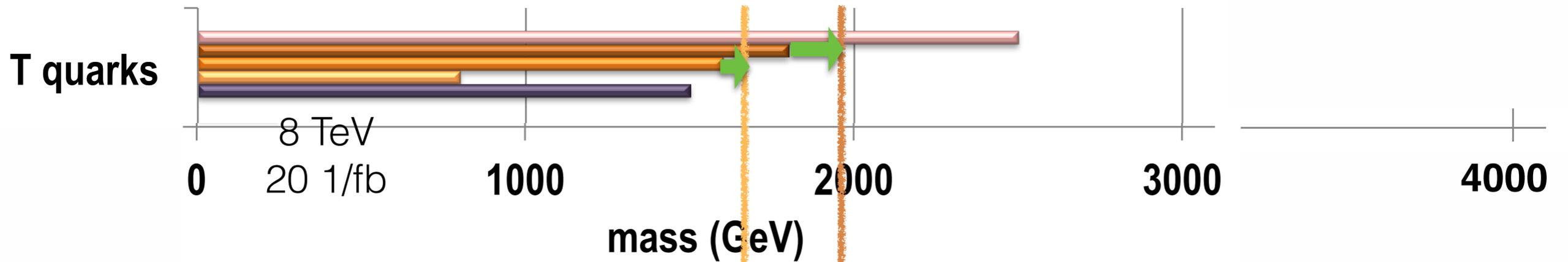


- pp, 100 TeV, 3000/fb
- pp, 33 TeV, 3000/fb
- pp, 14 TeV, 3000/fb
- pp, 14 TeV, 300/fb
- pp, 8 TeV, 20/fb
- ee, 3 TeV, 1000/fb
- ee, 1 TeV, 1000/fb
- ee, 0.5 TeV, 500/fb

14 TeV  
300 1/fb

Collider Reach( $\beta$ )<sup>TM</sup> estimates

# T Quarks



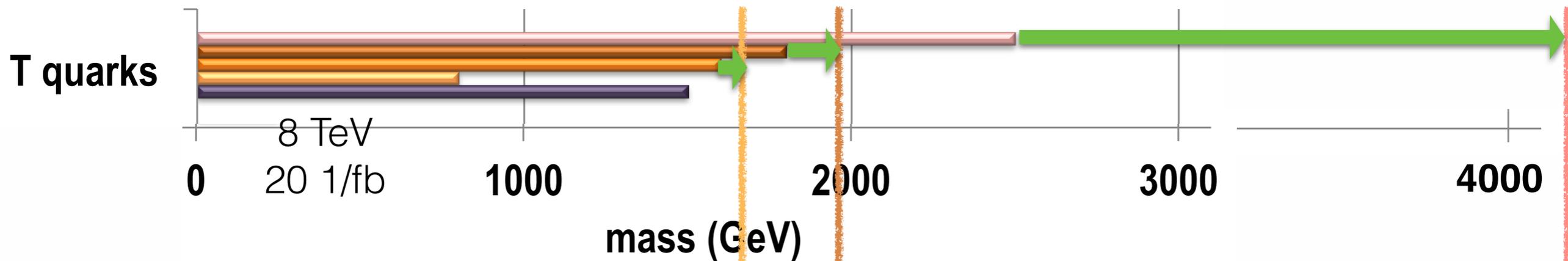
- pp, 100 TeV, 3000/fb
- pp, 33 TeV, 3000/fb
- pp, 14 TeV, 3000/fb
- pp, 14 TeV, 300/fb
- pp, 8 TeV, 20/fb
- ee, 3 TeV, 1000/fb
- ee, 1 TeV, 1000/fb
- ee, 0.5 TeV, 500/fb

14 TeV  
300 1/fb

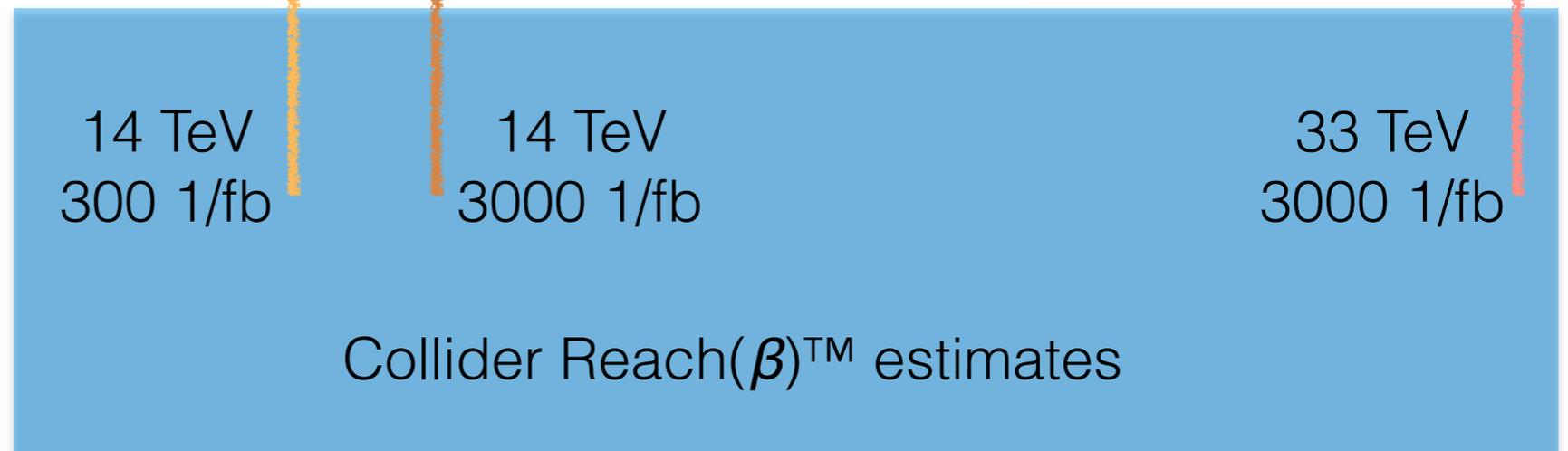
14 TeV  
3000 1/fb

Collider Reach( $\beta$ )<sup>TM</sup> estimates

# T Quarks

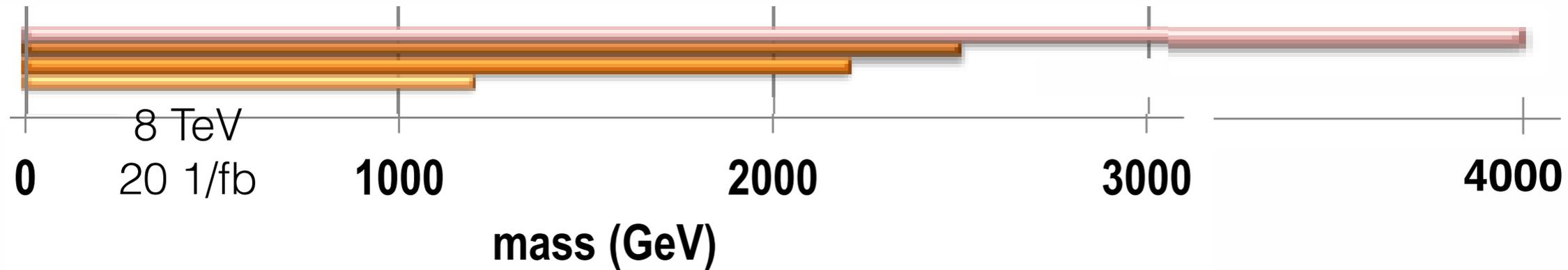


- pp, 100 TeV, 3000/fb
- pp, 33 TeV, 3000/fb
- pp, 14 TeV, 3000/fb
- pp, 14 TeV, 300/fb
- pp, 8 TeV, 20/fb
- ee, 3 TeV, 1000/fb
- ee, 1 TeV, 1000/fb
- ee, 0.5 TeV, 500/fb



**Issue seems to be detector granularity**

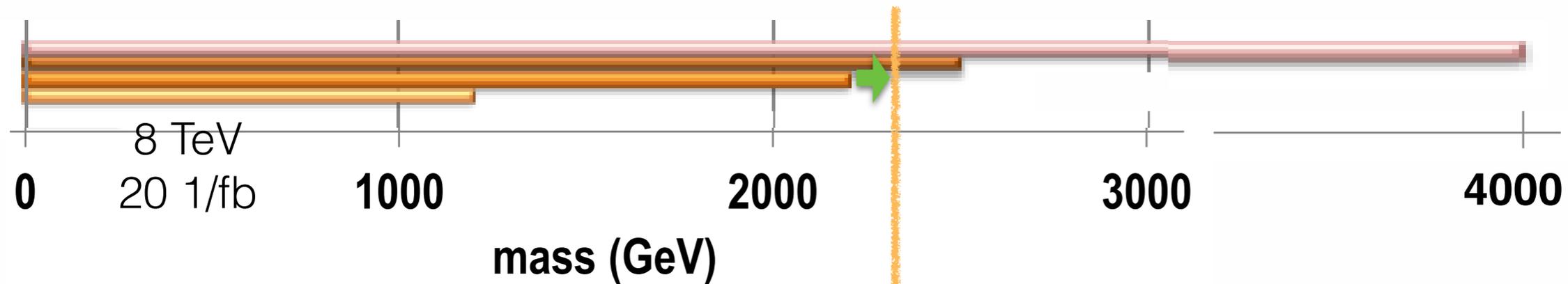
# Gluinos



- pp, 100 TeV, 3000/fb
- pp, 33 TeV, 3000/fb
- pp, 14 TeV, 3000/fb
- pp, 14 TeV, 300/fb
- pp, 8 TeV, 20/fb
- ee, 3 TeV, 1000/fb
- ee, 1 TeV, 1000/fb
- ee, 0.5 TeV, 500/fb

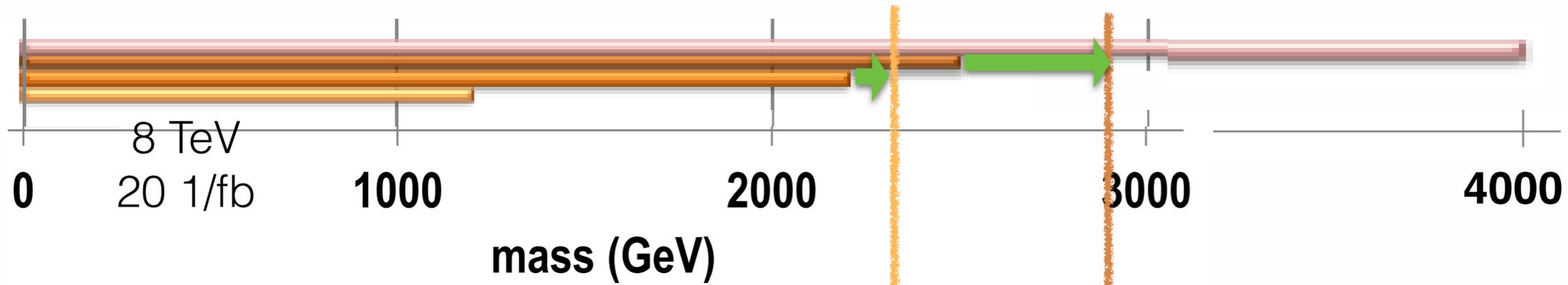
Collider Reach( $\beta$ )<sup>TM</sup> estimates

# Gluinos



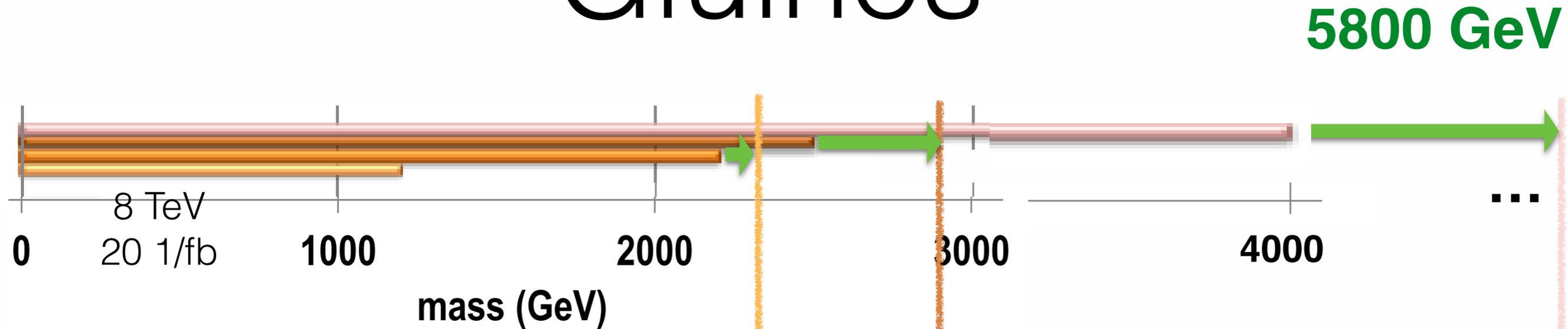
- pp, 100 TeV, 3000/fb
- pp, 33 TeV, 3000/fb
- pp, 14 TeV, 3000/fb
- pp, 14 TeV, 300/fb
- pp, 8 TeV, 20/fb
- ee, 3 TeV, 1000/fb
- ee, 1 TeV, 1000/fb
- ee, 0.5 TeV, 500/fb

# Gluinos



- pp, 100 TeV, 3000/fb
- pp, 33 TeV, 3000/fb
- pp, 14 TeV, 3000/fb
- pp, 14 TeV, 300/fb
- pp, 8 TeV, 20/fb
- ee, 3 TeV, 1000/fb
- ee, 1 TeV, 1000/fb
- ee, 0.5 TeV, 500/fb

# Gluinos



14 TeV  
300 1/fb

14 TeV  
3000 1/fb

33 TeV  
3000 1/fb

■ pp, 100 TeV, 3000/fb

■ pp, 33 TeV, 3000/fb

■ pp, 14 TeV, 3000/fb

■ pp, 14 TeV, 300/fb

■ pp, 8 TeV, 20/fb

■ ee, 3 TeV, 1000/fb

■ ee, 1 TeV, 1000/fb

■ ee, 0.5 TeV, 500/fb

Collider Reach( $\beta$ )<sup>TM</sup> estimates

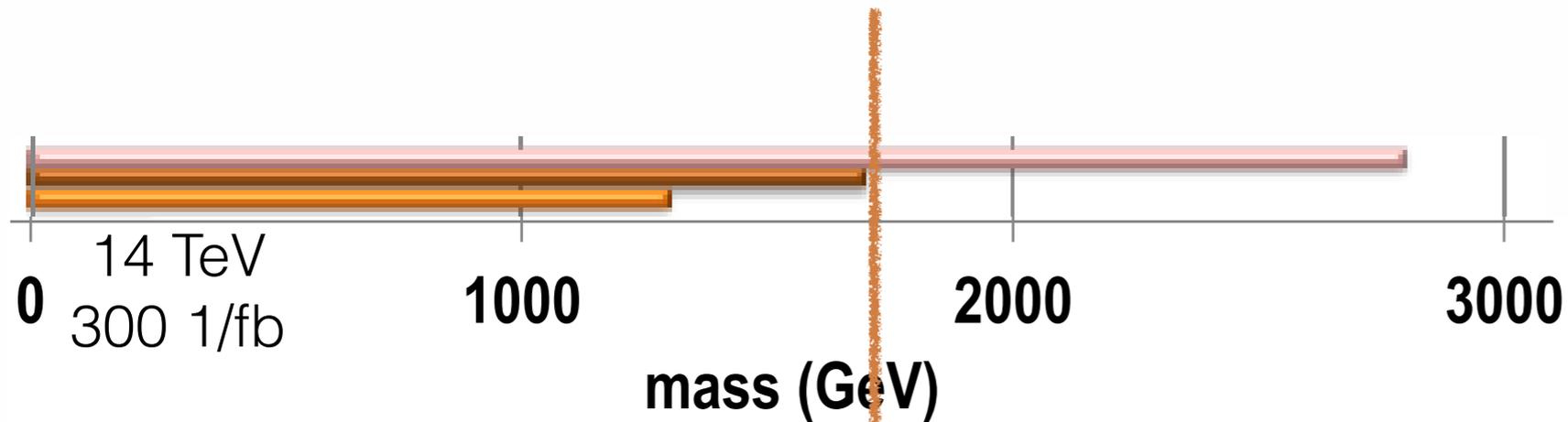
# RPV stops



Collider Reach( $\beta$ )<sup>TM</sup> estimates

- pp, 100 TeV, 3000/fb
- pp, 33 TeV, 3000/fb
- pp, 14 TeV, 3000/fb
- pp, 14 TeV, 300/fb
- pp, 8 TeV, 20/fb
- ee, 3 TeV, 1000/fb
- ee, 1 TeV, 1000/fb
- ee, 0.5 TeV, 500/fb

# RPV stops



14 TeV  
3000 fb<sup>-1</sup>

Collider Reach( $\beta$ )<sup>TM</sup> estimates

- pp, 100 TeV, 3000/fb
- pp, 33 TeV, 3000/fb
- pp, 14 TeV, 3000/fb
- pp, 14 TeV, 300/fb
- pp, 8 TeV, 20/fb
- ee, 3 TeV, 1000/fb
- ee, 1 TeV, 1000/fb
- ee, 0.5 TeV, 500/fb

# RPV stops

