Collider reach$^{\beta}$

Estimating the reach of (hadron) colliders
using parton luminosities

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Wine & cheese seminar, about work in progress,
Princeton University, February 28, 2014

It’s common to want to estimate the ability of a given collider to search for new particle/phenomenon “X”.

E.g.

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

What can high-luminosity LHC (3000fb^{-1}) find/exclude and how does that compare to LHC as originally planned (300fb^{-1})?

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

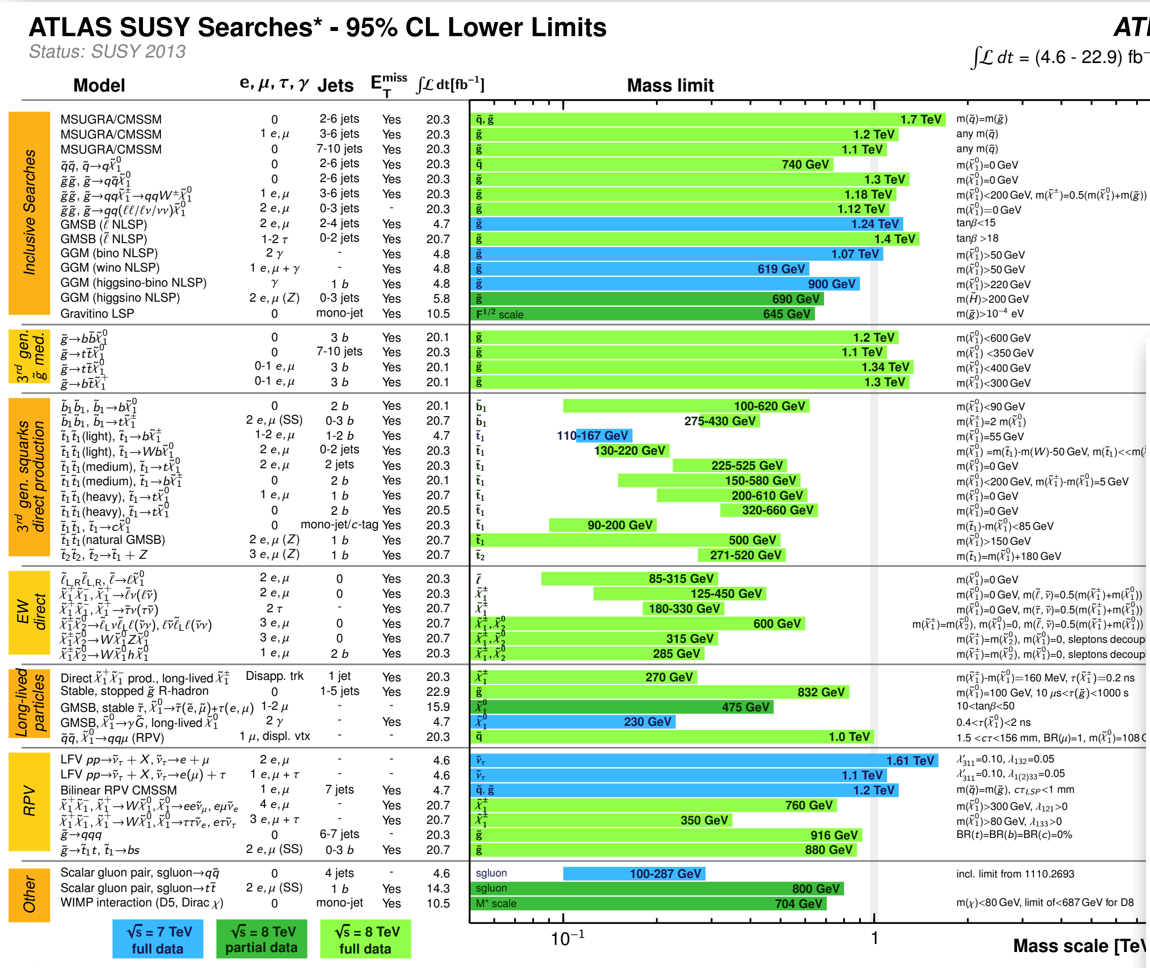
The proper way of doing it:

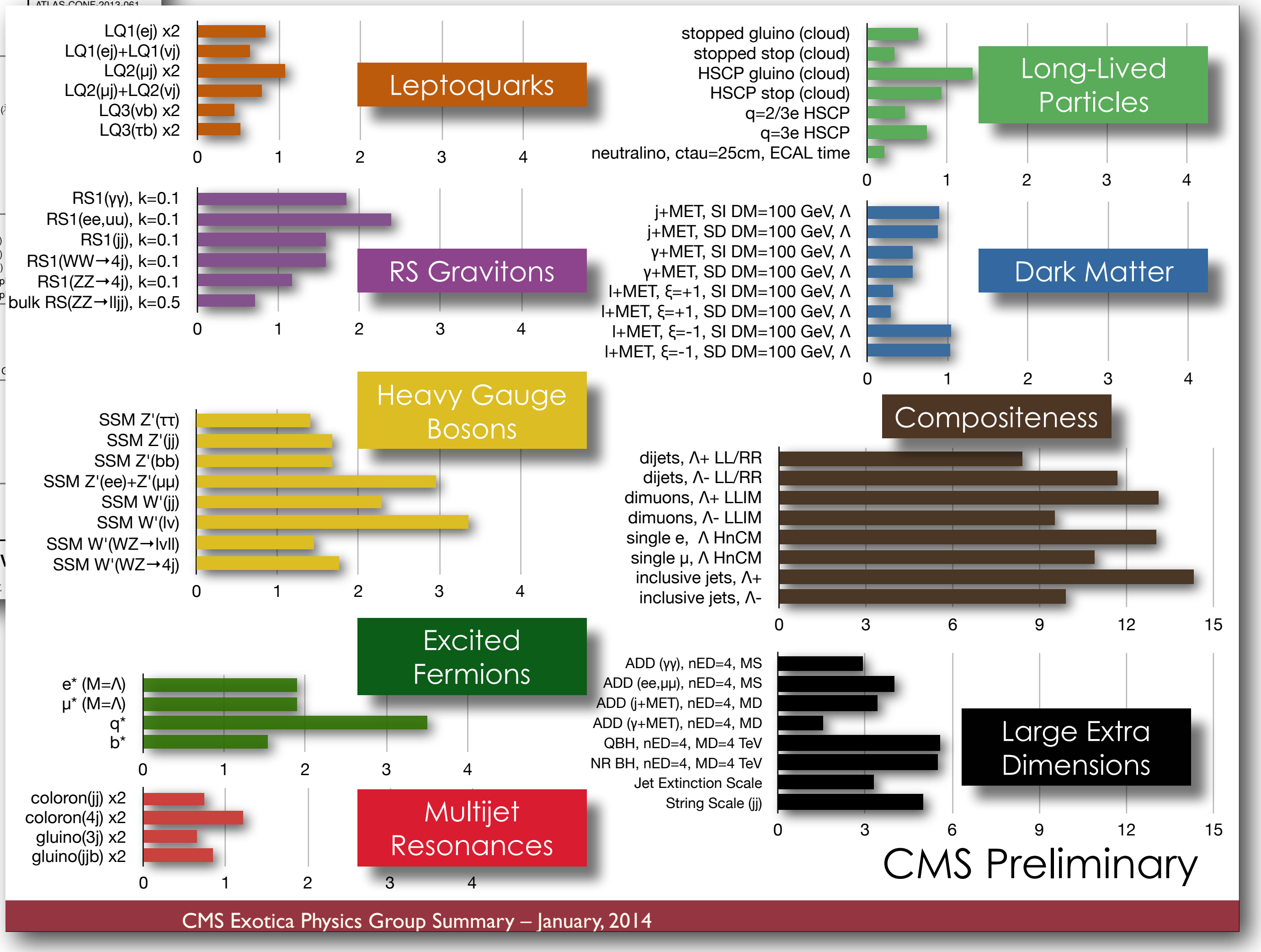
Generate Monte Carlo events for signal and background,
process them through a detector simulation,
design and carry out an optimal analysis,
work out discovery/exclusion reach.

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





Can we leverage that experience to guesstimate future reaches?

A rough way of doing it

Suppose ATLAS/CMS are currently sensitive to gluinos of 1250 GeV (95% CL_s, 8 TeV, 20 fb^{-1})

↓

Work out how many signal events that corresponds to

↓

Find out for what gluino mass you would get the same number of signal events at 14 TeV with 300 fb^{-1} (assume # of background events scales same way)

This is too simplistic

Backgrounds may not scale in the same way as signal

New irreducible backgrounds may appear at higher scales

Reconstruction efficiencies may depend on mass scale

Detector effects (e.g. granularity), and run conditions (pileup) vary enormously across energy scales and luminosities

⬆

It can’t possibly work!

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Calculating mass for constant # of signal events is pretty straightforward

But it still requires some work and setup

E.g. you need to equip yourself with different cross section calculators for each new physics process (Prospino/Pythia/…), run them for a range of masses, etc.

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↑

can we get an iPhone app?

What we’re discussing is solution of the following equation for M_{high}

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

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

Dependence on *M* and on √s mostly comes about through parton distribution functions (PDFs) & simple dimensions.

Consider a resonance of mass M. Cross section $\propto$ **partonic luminosity** and a **$1/M^2$ factor for dimensions**

Coefficient for ij scattering channel (e.g. $q\bar{q}$, gg)

$$N(M,s) \sim \frac{1}{M^2}\sum_{ij} C_{ij}\mathcal{L}_{ij}(M^2,s)$$

Parton luminosity for ij scattering channel

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

i & j parton densities

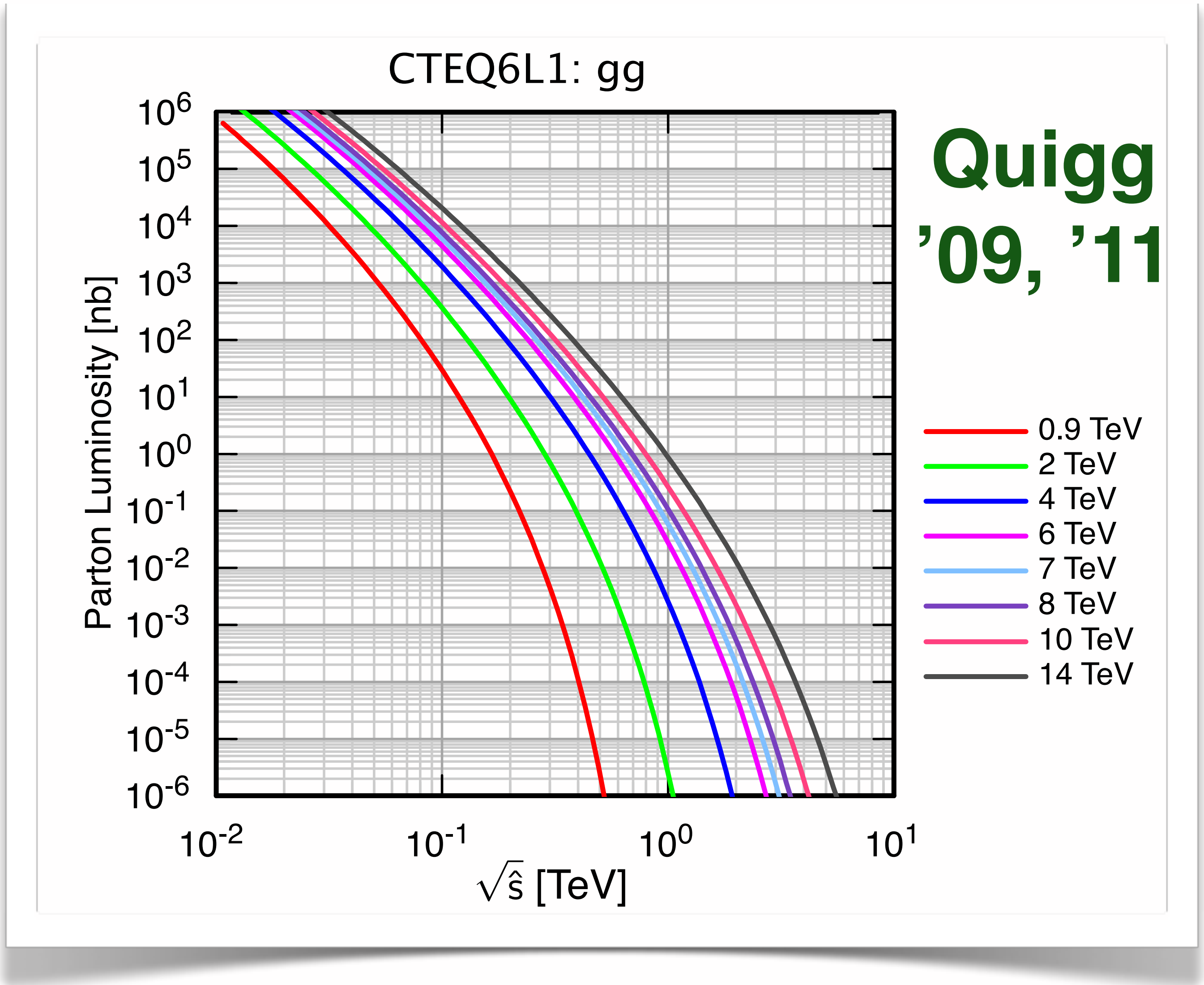
Assume dominance of a single partonic scattering channel, ij (you have to know enough physics to figure out which is most appropriate).

Equation we solve to find M_{high} is then

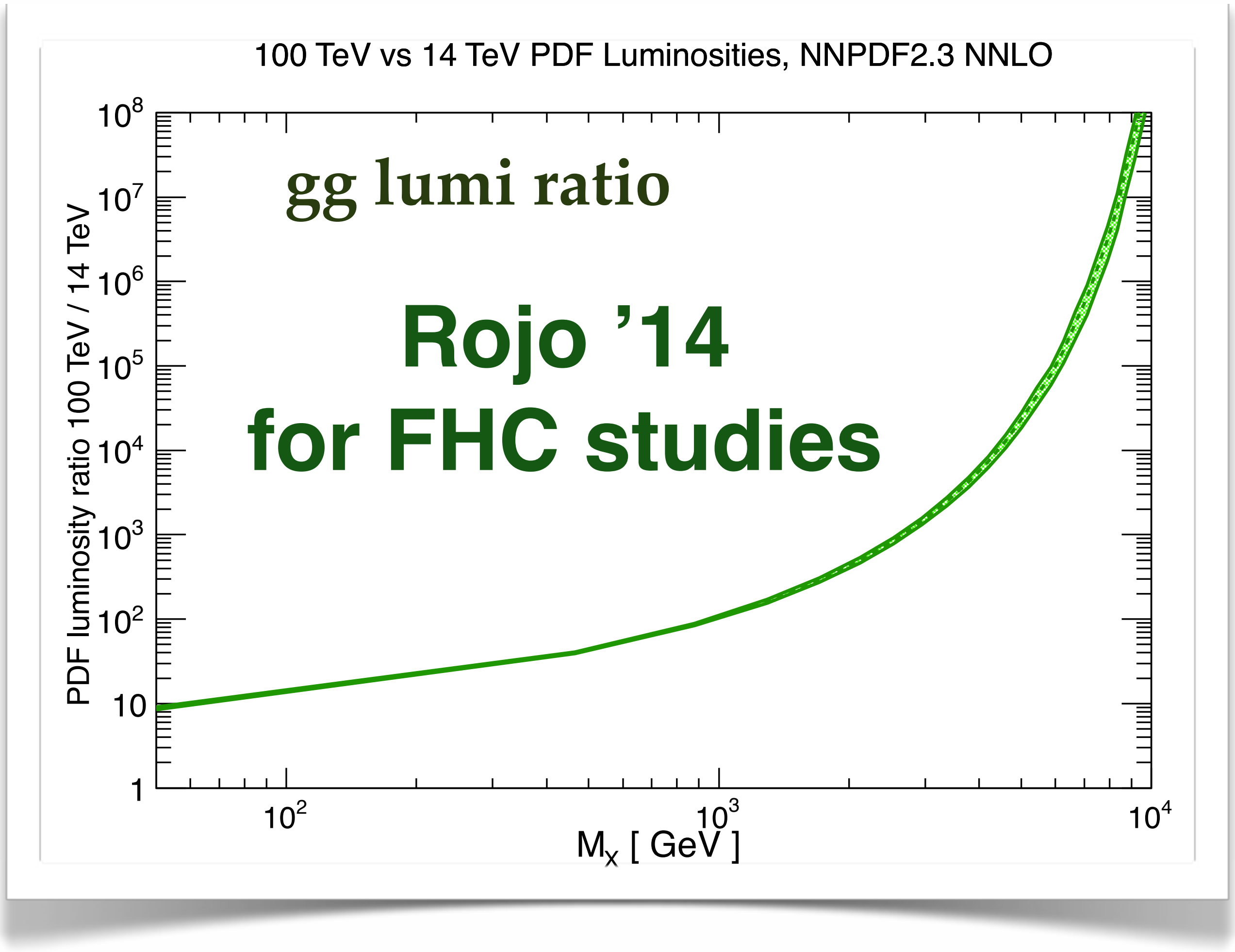
$$\frac{\mathcal{L}_{ij}(M^2_{\text{high}}, s_{\text{high}})}{\mathcal{L}_{ij}(M^2_{\text{low}}, s_{\text{low}})} \times \frac{\text{lumi}_{\text{high}}}{\text{lumi}_{\text{low}}} = \frac{M^2_{\text{high}}}{M^2_{\text{low}}}$$

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

A side remark:
Studying partonic luminosities is a standard technique



Quigg '09, '11



gg lumi ratio

Rojo '14 for FHC studies

How do we differ?

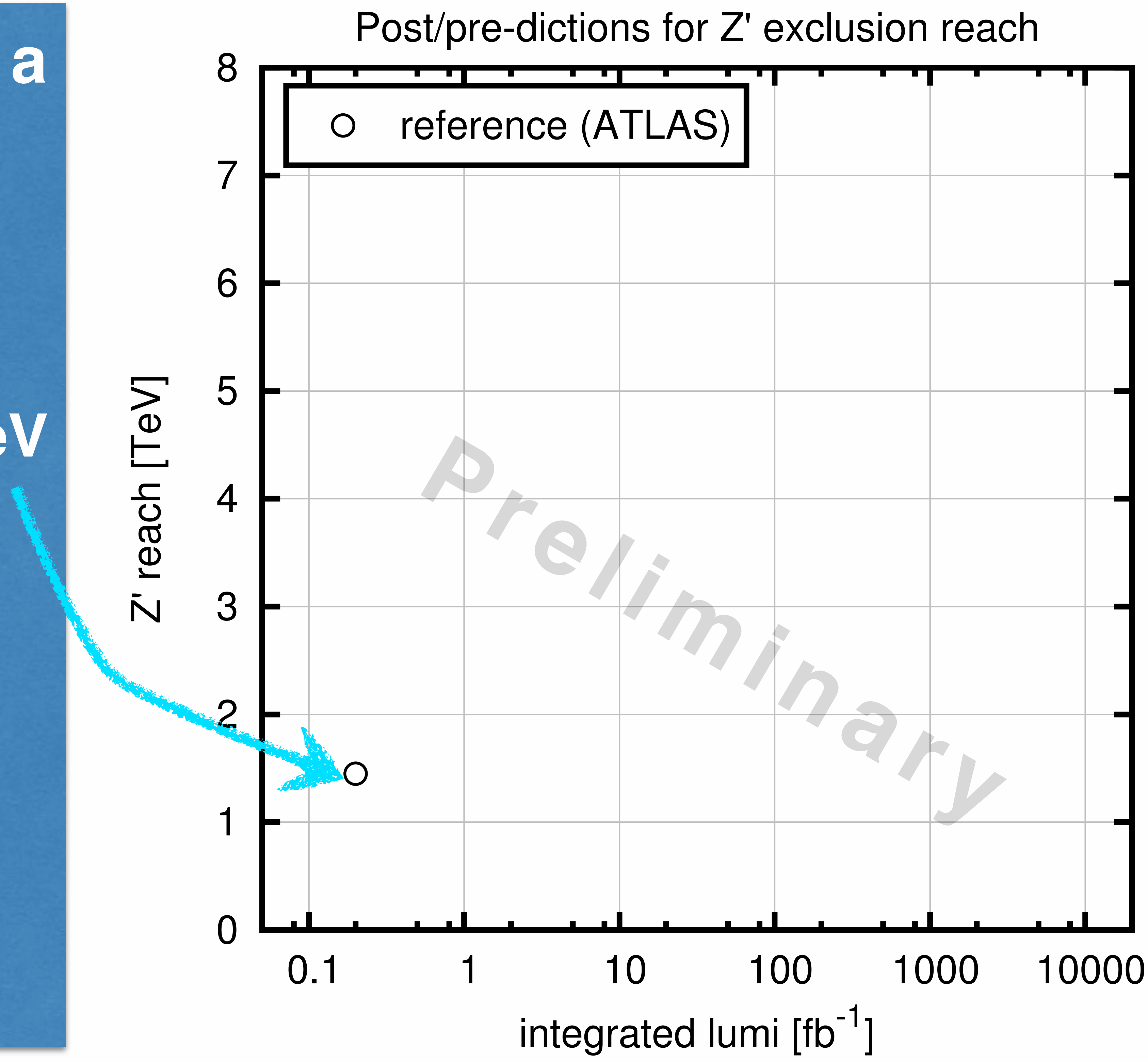
Study one key question: **relate reaches [TeV]** of different colliders

Validate the approach **by postdicting** LHC and Tevatron results

Does it work?

Try a Z' search. Take a baseline analysis:

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



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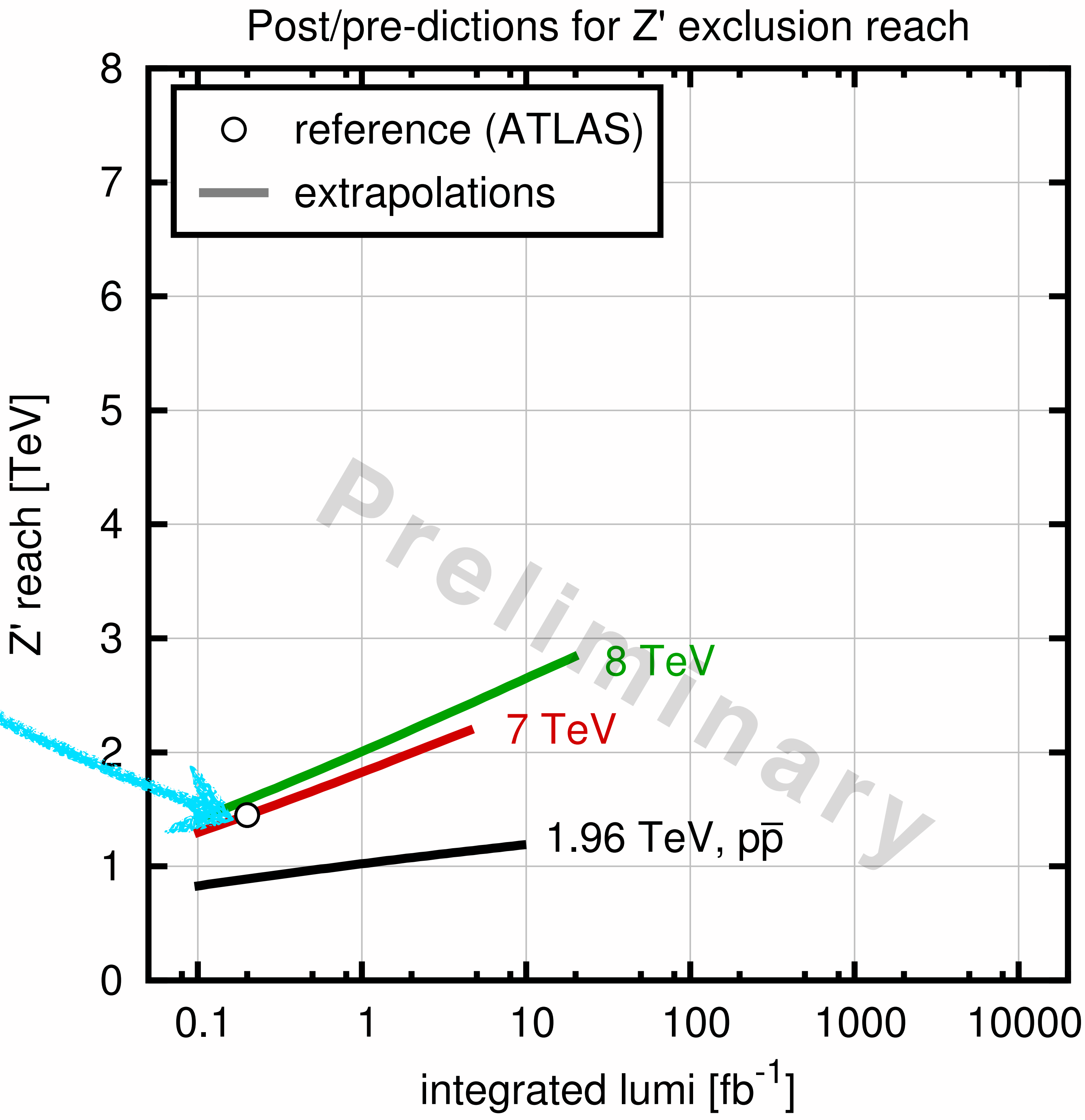
"Predict" exclusions at other lumis & energies (assume $q\bar{q}$)



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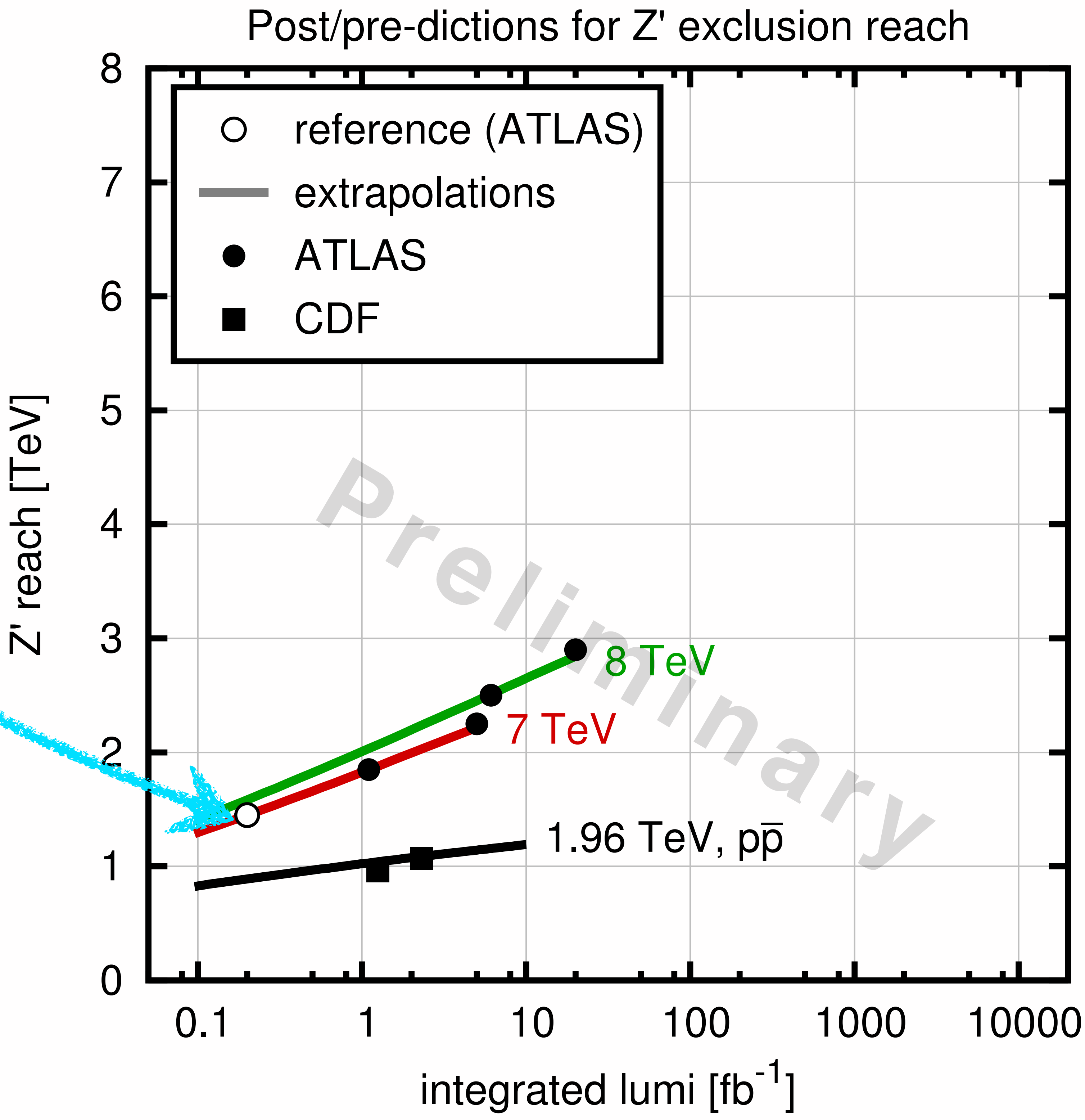
Compare to actual exclusions



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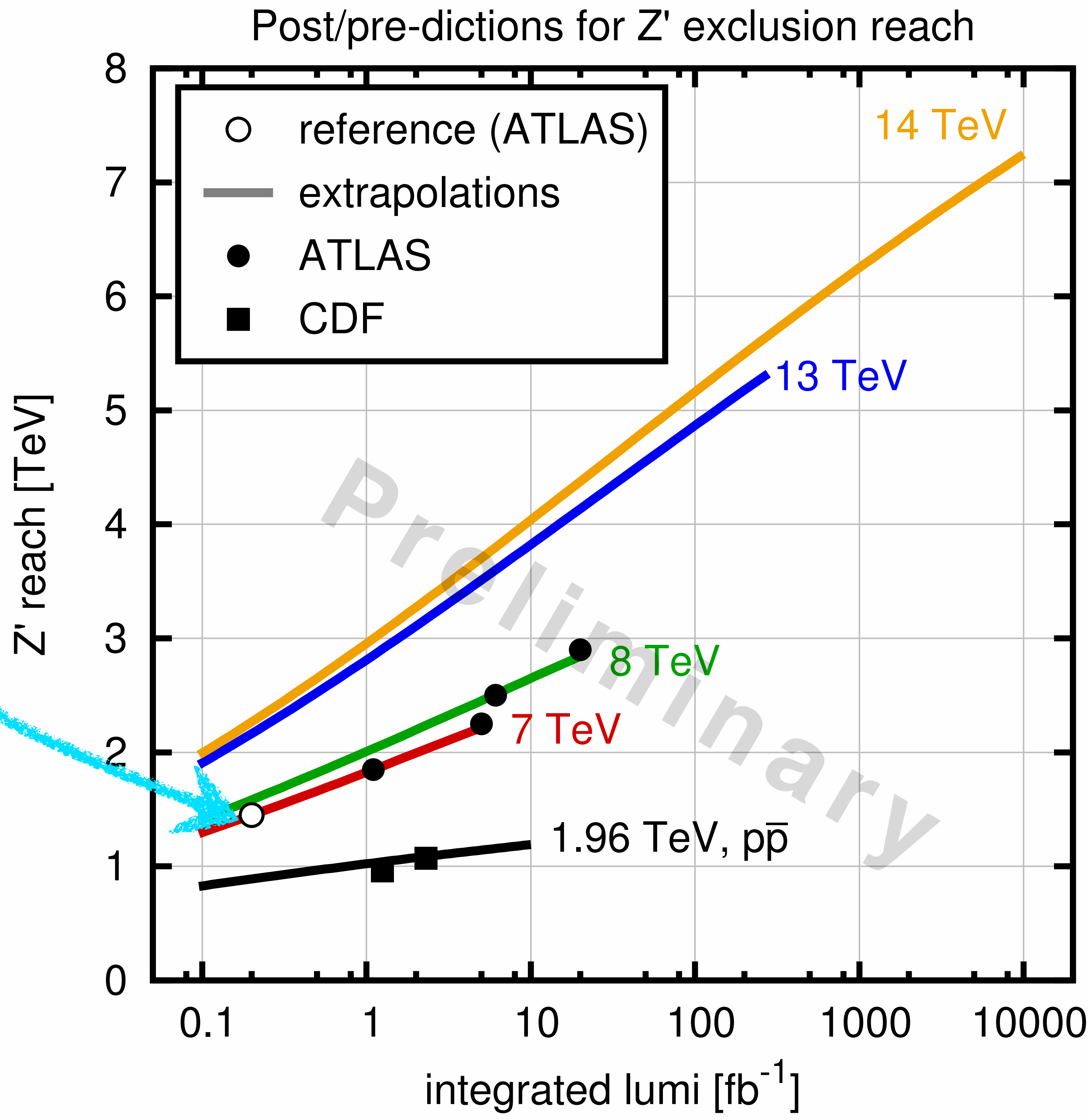


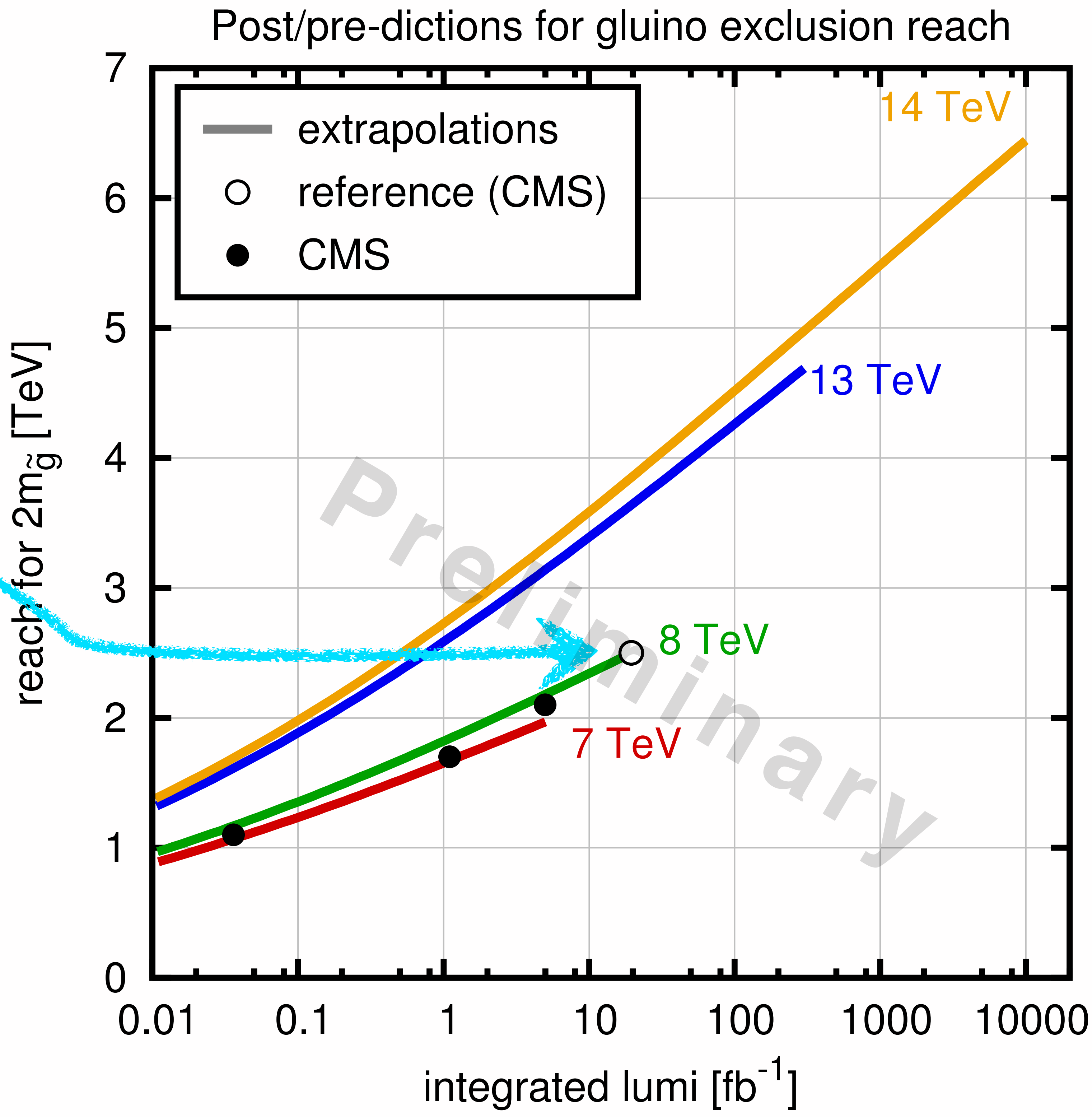
Maybe it only works so well because it's a simple search?
(Signal & Bkgd are both $q\bar{q}$ driven)

Try a SUSY example, gluinos. Baseline:

CMS, 20 fb^{-1} @ 8 TeV
excludes $M_{\tilde{g}}$<1250 GeV
i.e. $2M_{\tilde{g}} < 2.5$ TeV

“Predict” exclusions at other lumis & energies (assume *gg*)

Compare to actual exclusions



Still works OK, despite (poor) assumption of same signal and background channels *[see also later]*

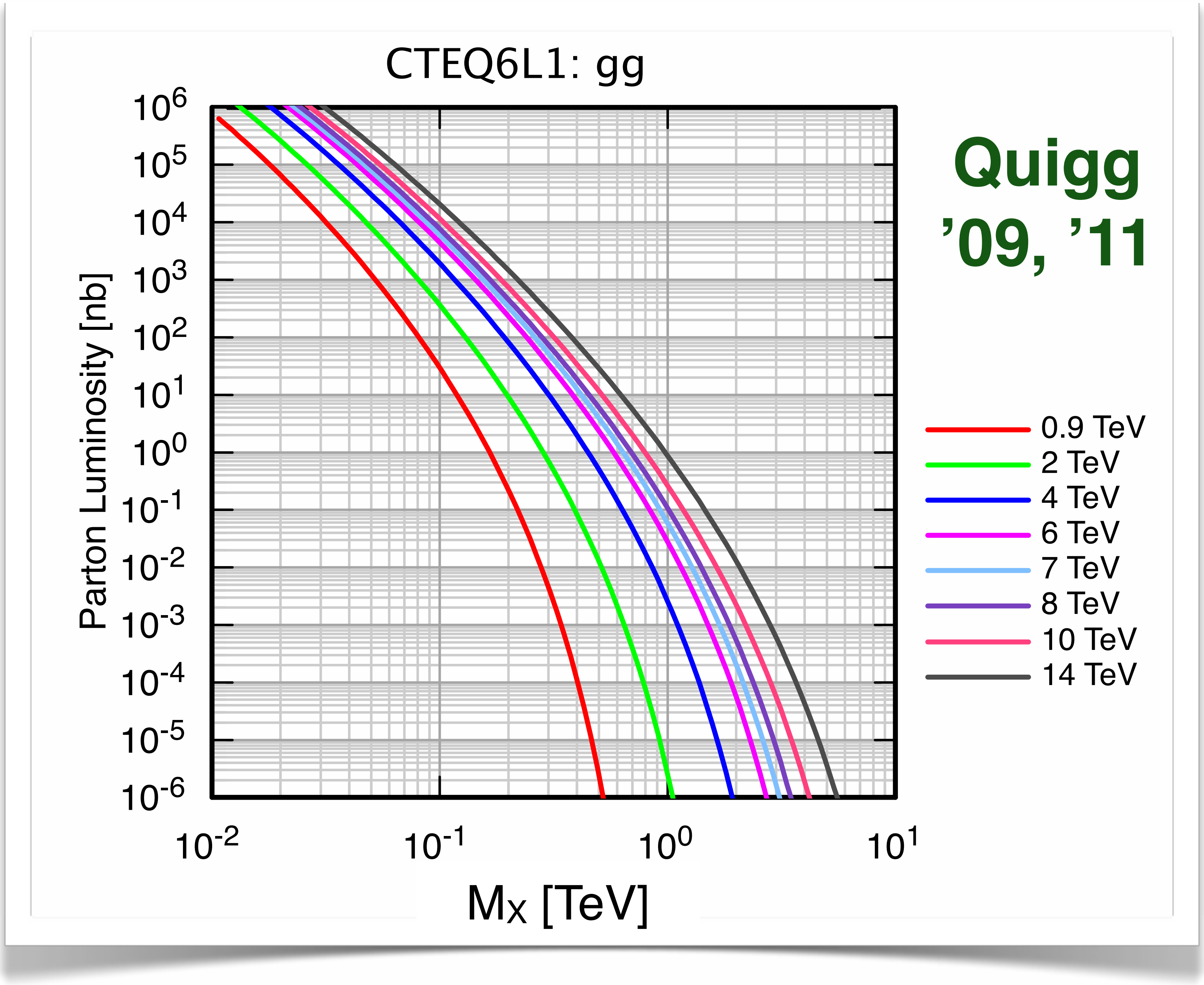
ATLAS

Search	Signal	Bgd	E_{CM}[TeV]	$\mathcal{L}_{\text{int}}$[fb^{-1}]	Expected [GeV]	`collider-reach` [GeV]
Sequential Z'	$\sum \bar{q}_i q_i$	$\sum \bar{q}_i q_i$	7	0.2	1450 [?]	(base-line)
			7	1.1	1850 [?]	1849
			7	5	2200 [?]	2219
			8	6.1	2550 [?]	2510
			8	20	2900 [?]	2844
Stop ($m_{\text{LSP}} = 0\,\text{GeV}$)	gg	gg	7	4.7	500 [?]	(base-line)
			8	20.5	650 [?]	675
Excited quark	gq	gg	7	$315 \cdot 10^{-6}$	1010 [?]	(base-line)
			7	$36 \cdot 10^{-3}$	2040 [?]	2026 (gq)
			7	$163 \cdot 10^{-3}$	2490 [?]	2395 (gq)
			7	0.81	2910 [?]	2790 (gq)
			7	4.8	3090 [?]	3220 (gq)
			8	13	3840 [?]	3865 (gq)

CMS

Search	Signal	Bgd	E_{CM}[TeV]	$\mathcal{L}_{\text{int}}$[fb^{-1}]	Expected [GeV]	`collider-reach` [GeV]
gluinos ($m_{\text{LSP}} = 100\,\text{GeV}$)	gg	$gg/gq/qq$	7	0.036	550 [?]	(base-line)
			7	1.1	850 [?]	855
			7	4.98	1050 [?]	1005
			8	19.5	1250 [?]	1275
squarks ($m_{\text{LSP}} = 100\,\text{GeV}$)	gg	$gg/gq/qq$	7	0.036	400 [?]	(base-line)
			7	1.1	650 [?]	663
			7	4.98	725 [?]	801
			8	19.5	910 [?]	1033
T-quarks ($\text{Br}(T \to tZ) = 1$)	gg	$gg/gq/qq$	7	1.14	510 [?]	(base-line)
			7	5	550 [?]	629
			8	19.6	813 [?]	827

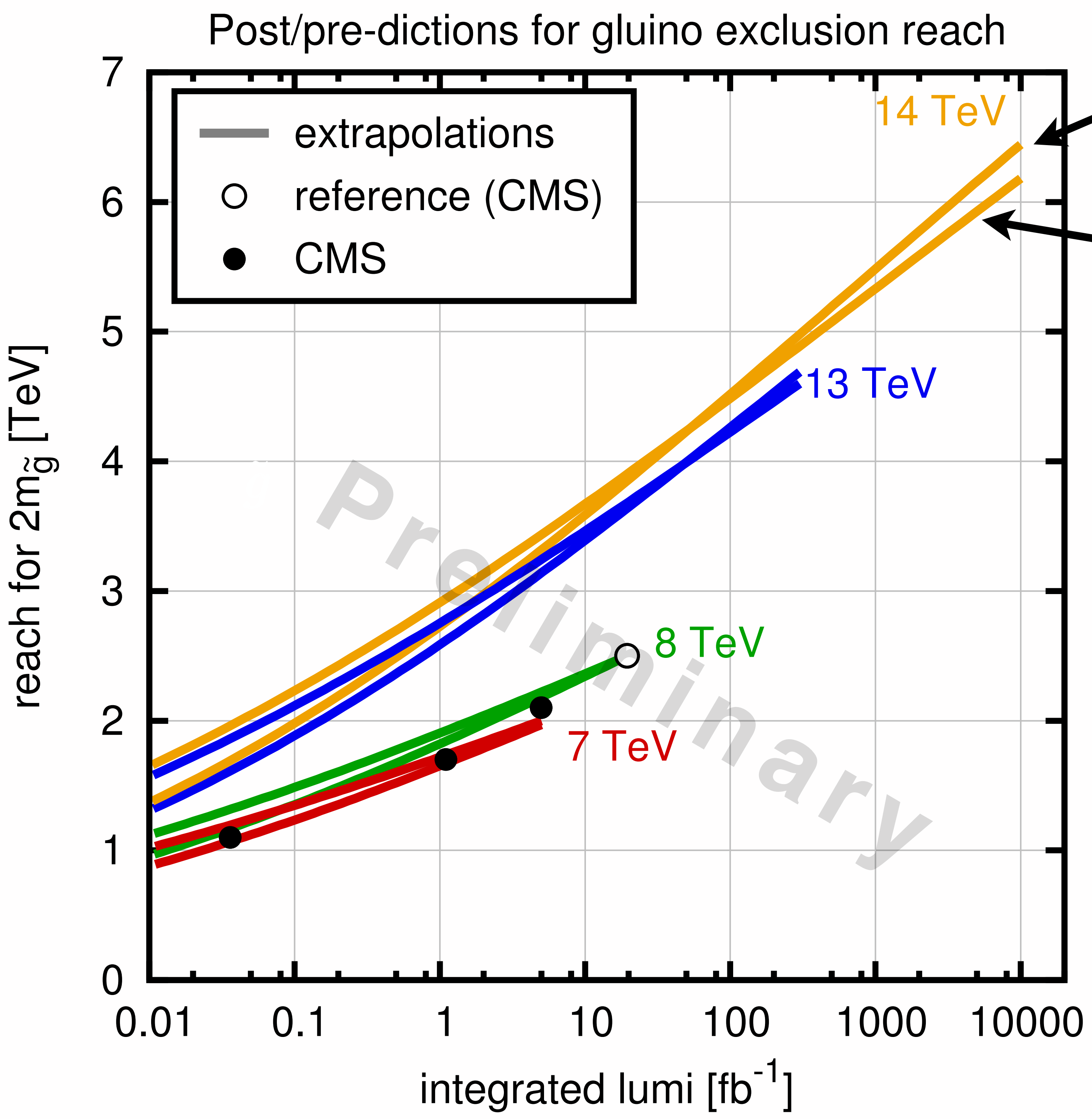
Why does it work?



Parton luminosities fall off very fast with increasing M_X

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

x2 in lumi ~ 10% in M_X



Post/pre-dictions for gluino exclusion reach

Signal gg; bkgd: gg

Signal gg; bkgd: qg

Scattering channel matters, but not too much

Future colliders

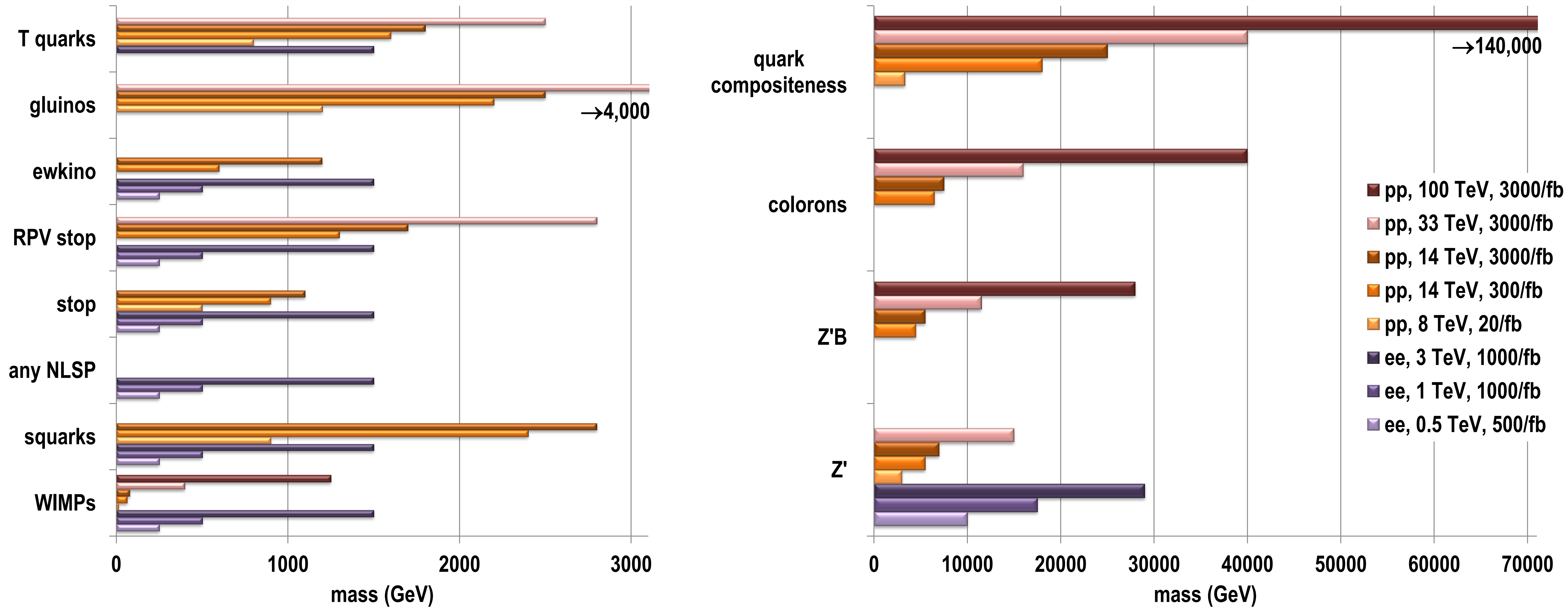
- We’re ignoring all subtleties, just going for a base-line check

- If our estimate differs a lot from sophisticated simulations, something interesting has happened:

  - brick-wall (new irreducible backgrounds, granularity of assumed detectors, …)

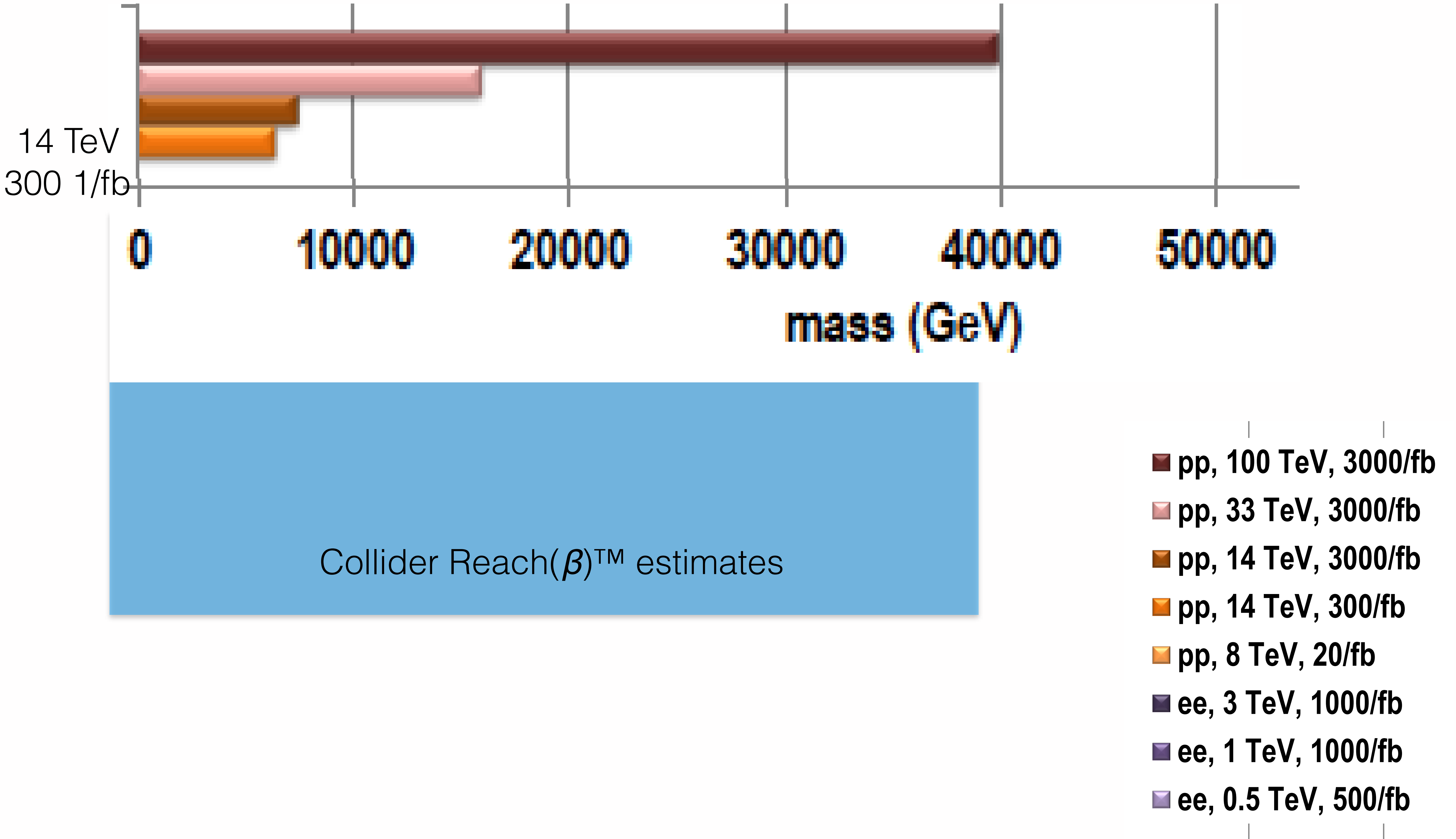
  - overly conservative or non-optimal estimates

Future colliders comparison



Energy Frontier Snowmass study (1311.0299)

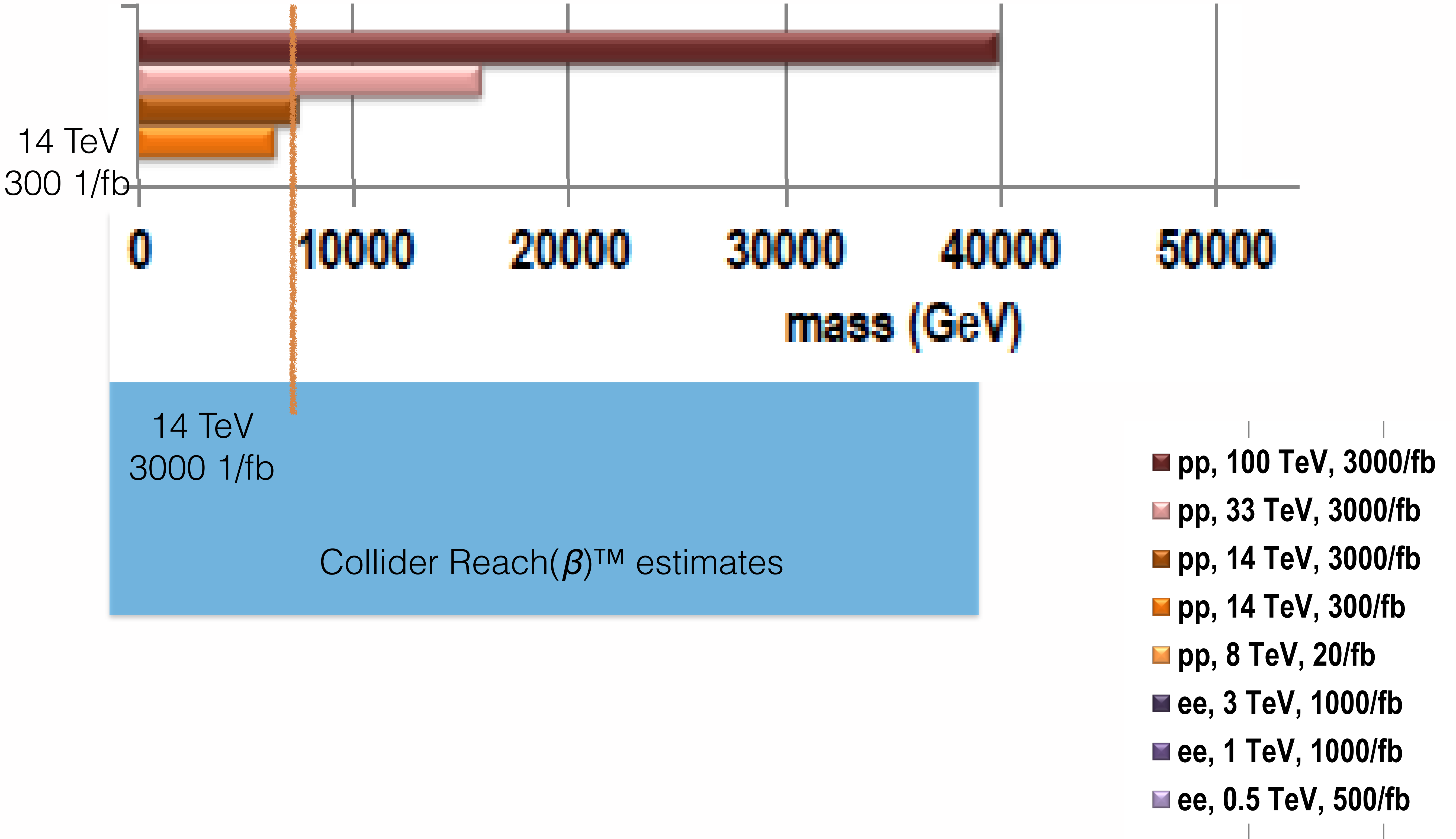
Colorons



14 TeV
300 1/fb

Collider Reach(β)™ estimates

Colorons

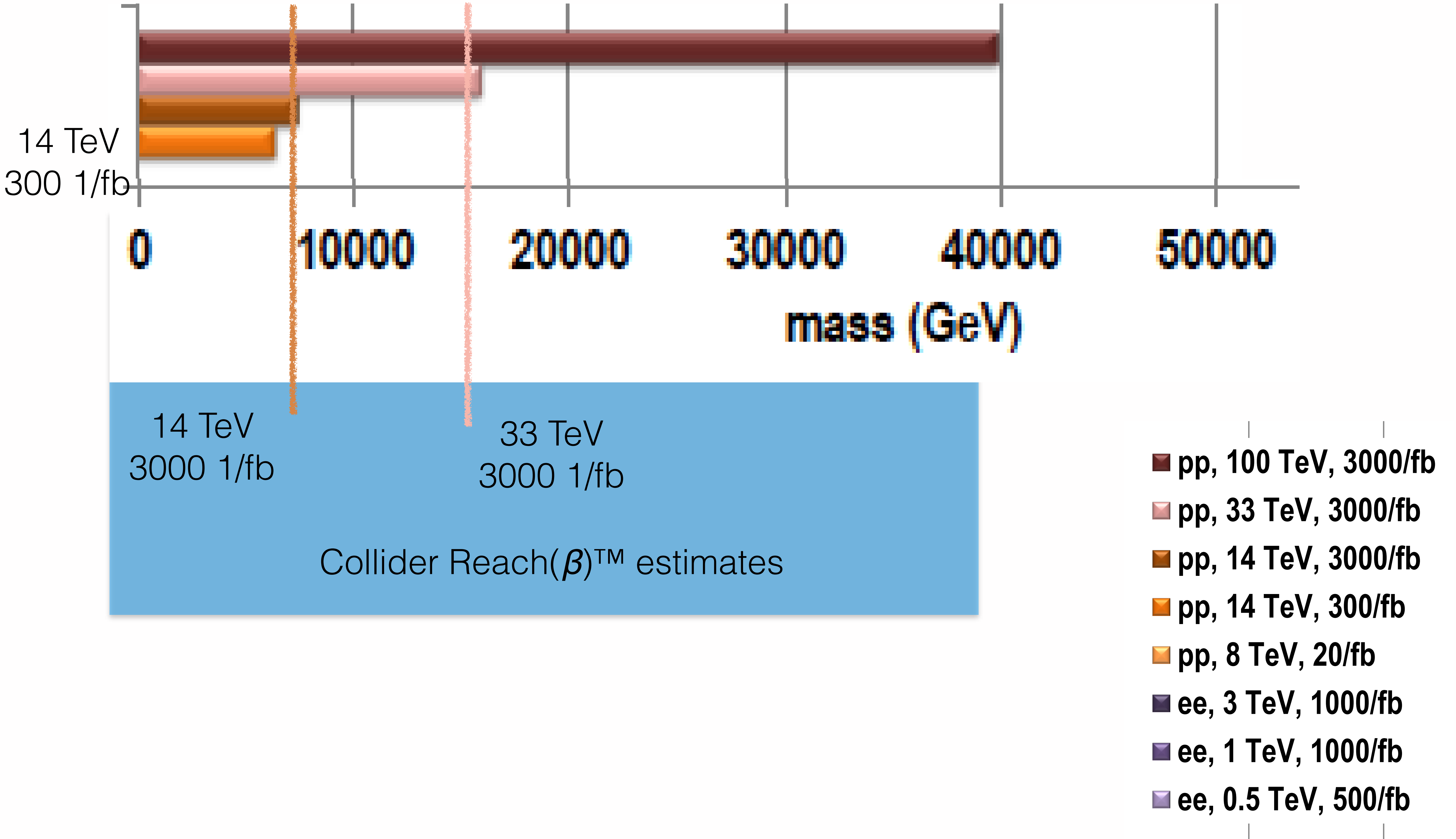


14 TeV
300 1/fb

14 TeV
3000 1/fb

Collider Reach(β)™ estimates

Colorons



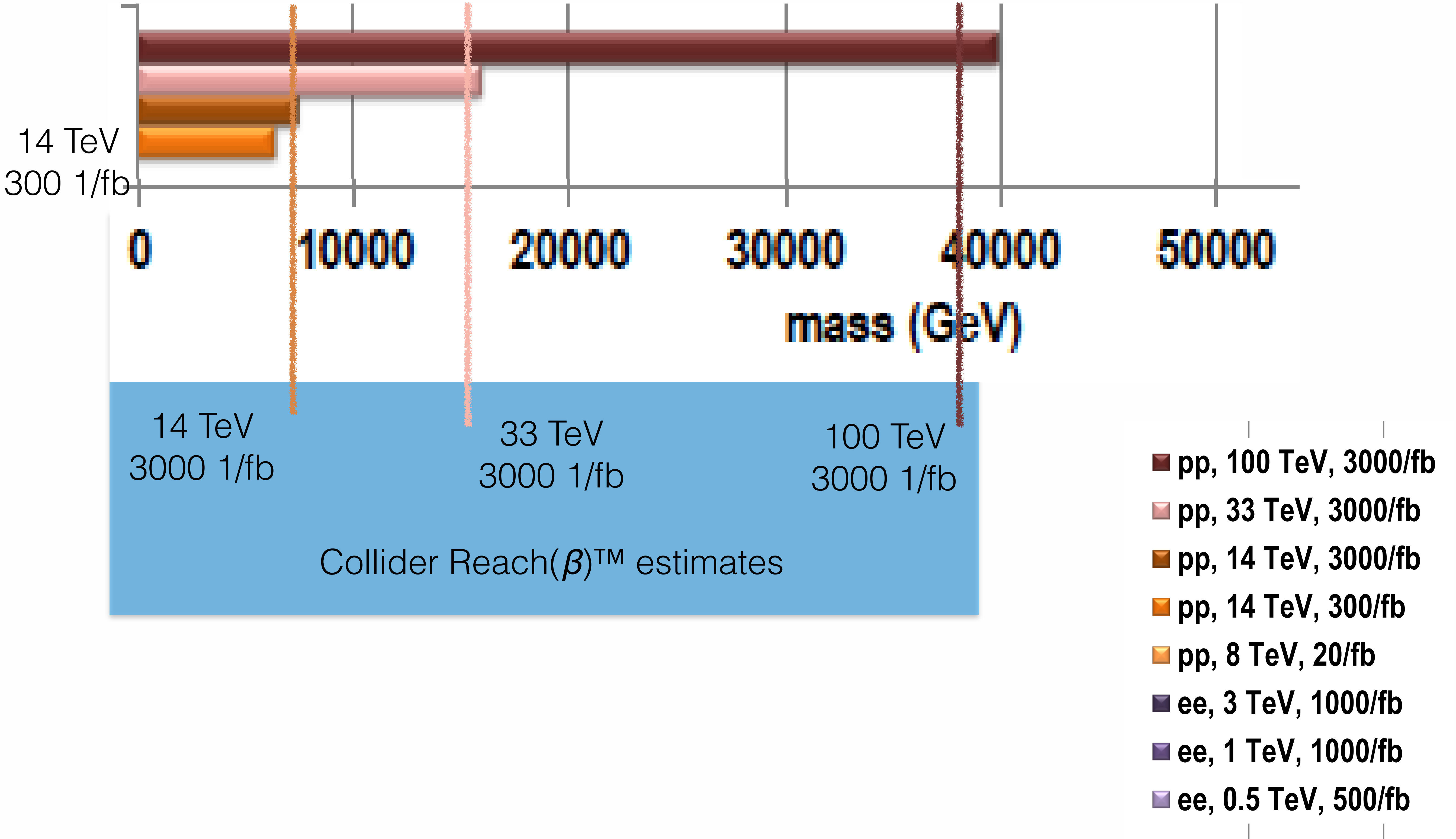
14 TeV
300 1/fb

14 TeV
3000 1/fb

33 TeV
3000 1/fb

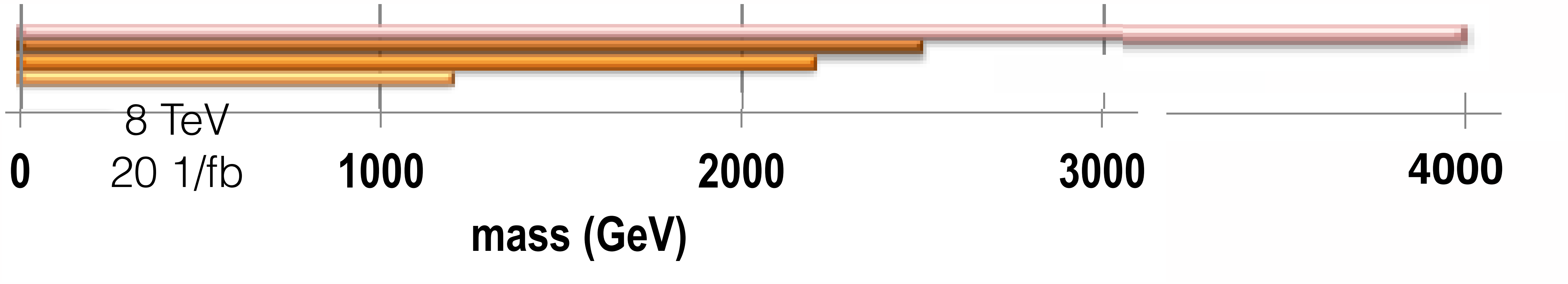
Collider Reach(β)™ estimates

Colorons



Collider Reach(β)™ estimates

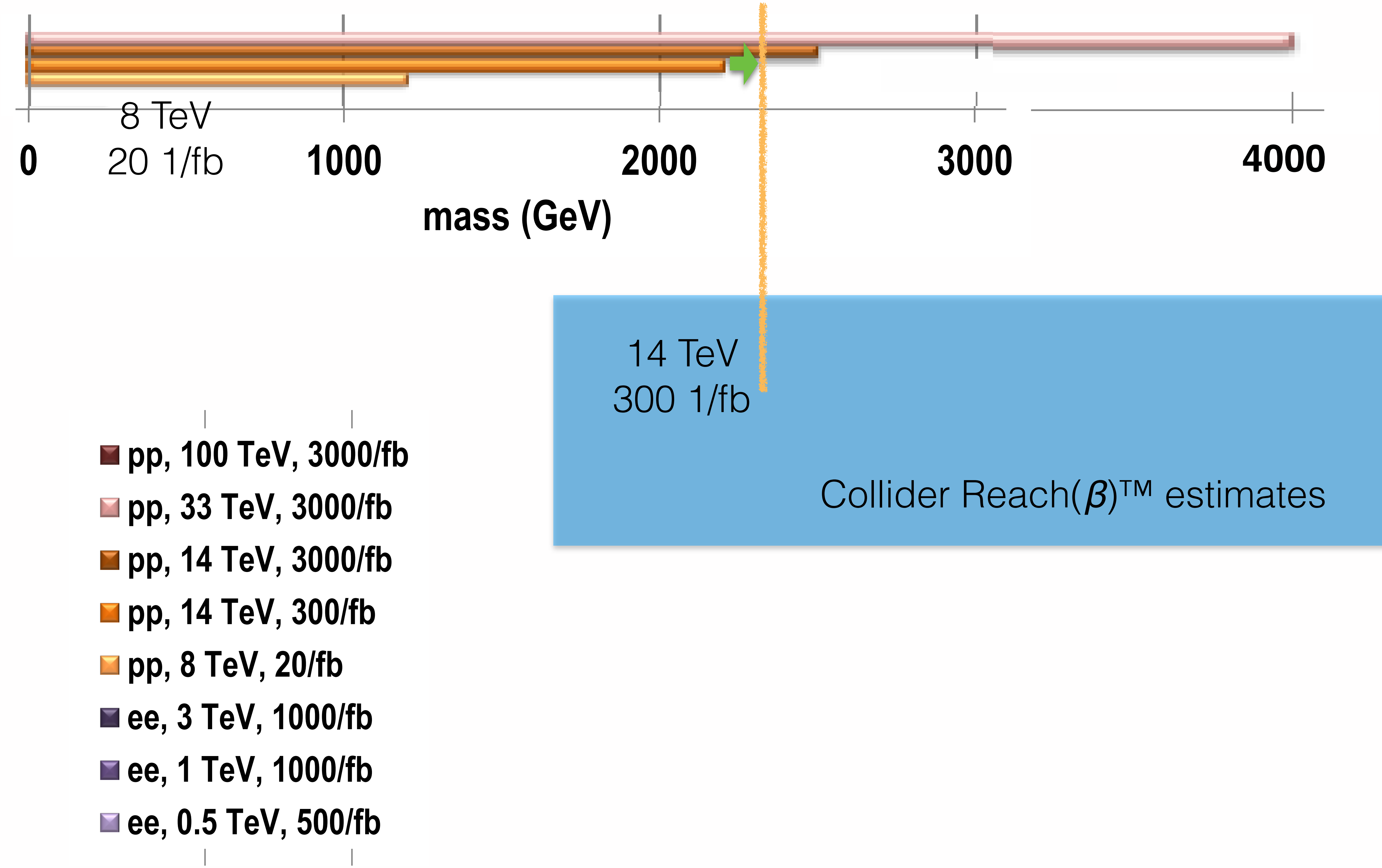
Gluinos



- ■ 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

Collider Reach(β)™ estimates

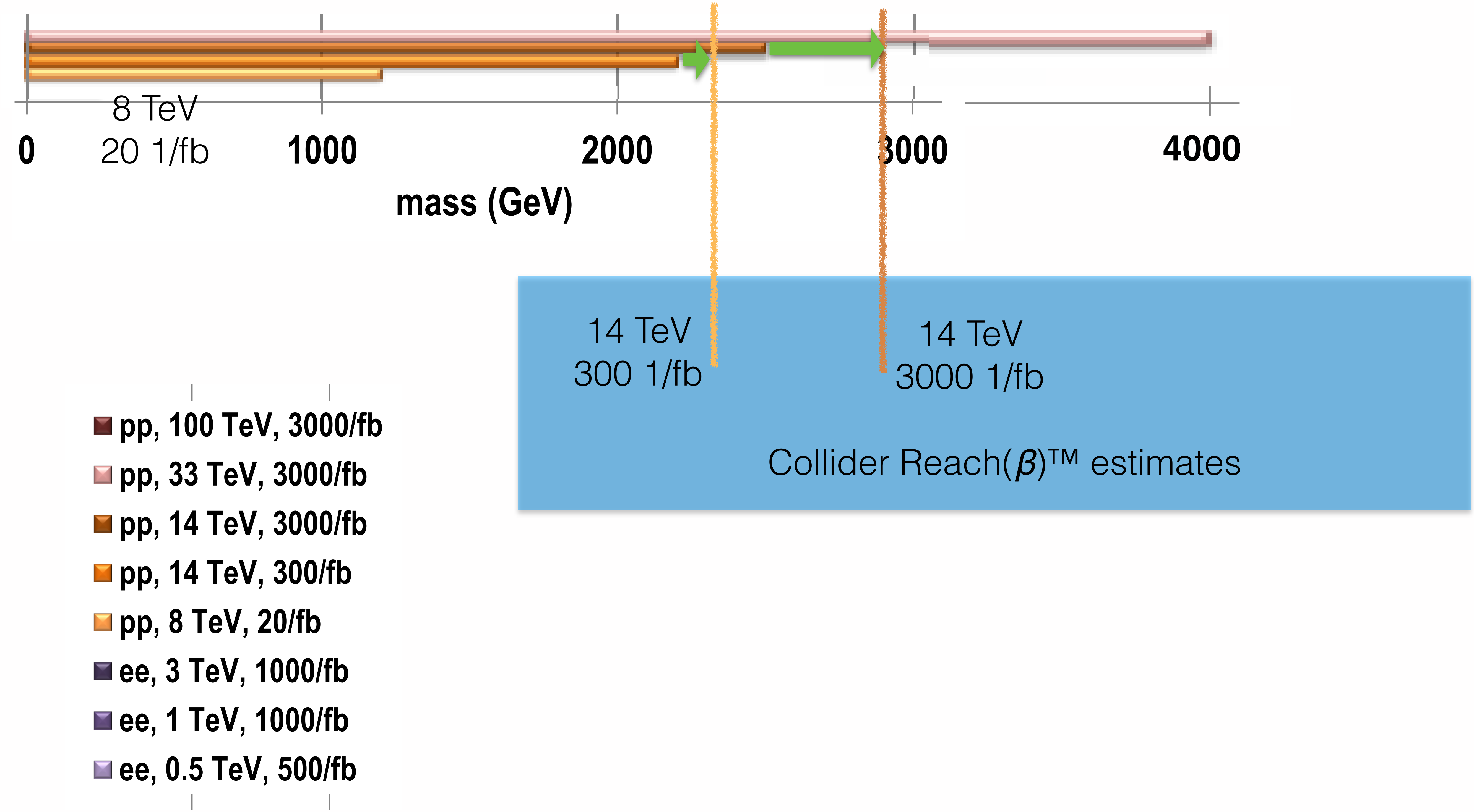
Gluinos



14 TeV
300 1/fb

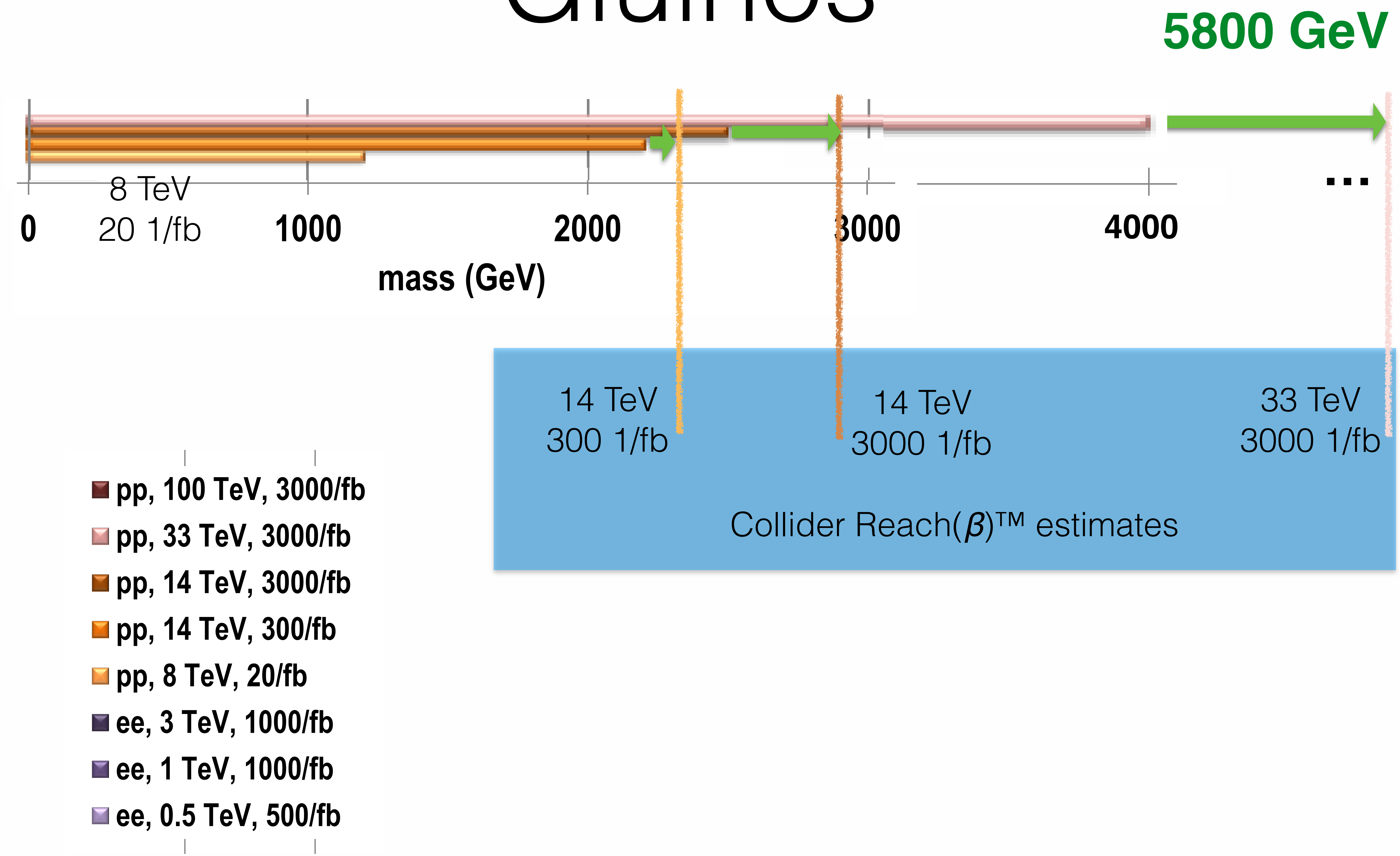
Collider Reach(β)™ estimates

Gluinos



Collider Reach(β)™ estimates

Gluinos



5800 GeV

8 TeV
20 1/fb

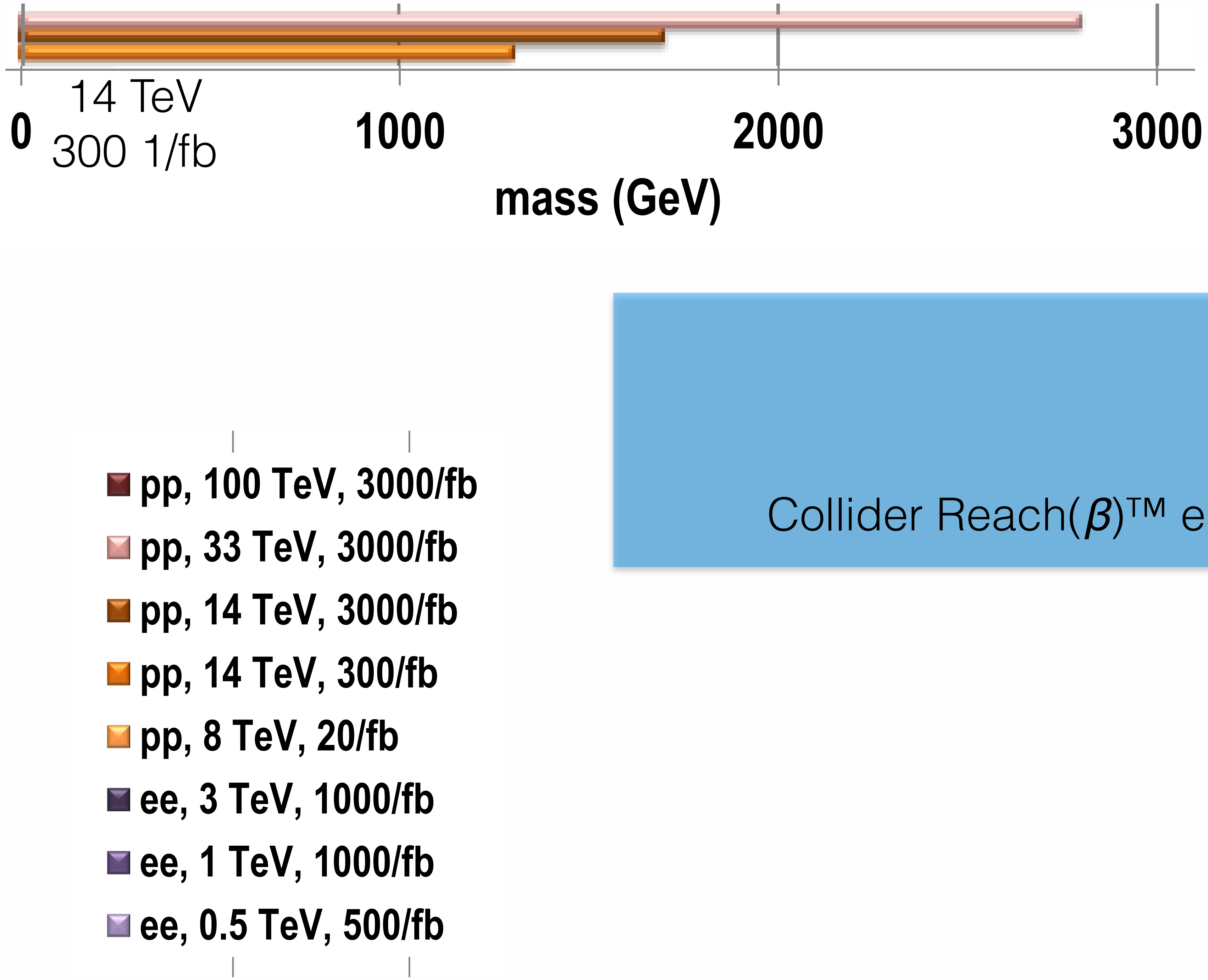
14 TeV
300 1/fb

14 TeV
3000 1/fb

33 TeV
3000 1/fb

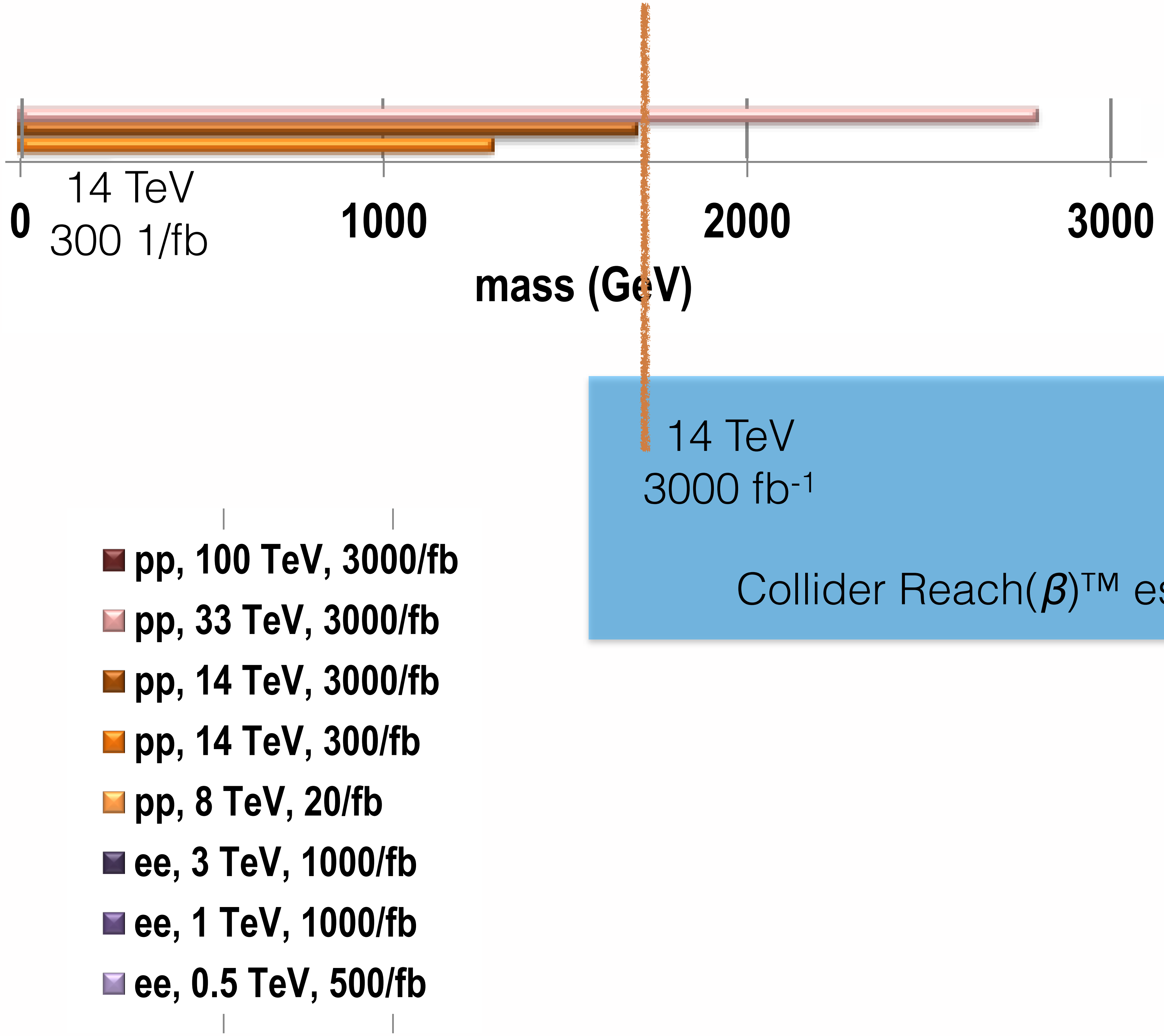
Collider Reach(β)™ estimates

RPV stops



Collider Reach(β)™ estimates

RPV stops

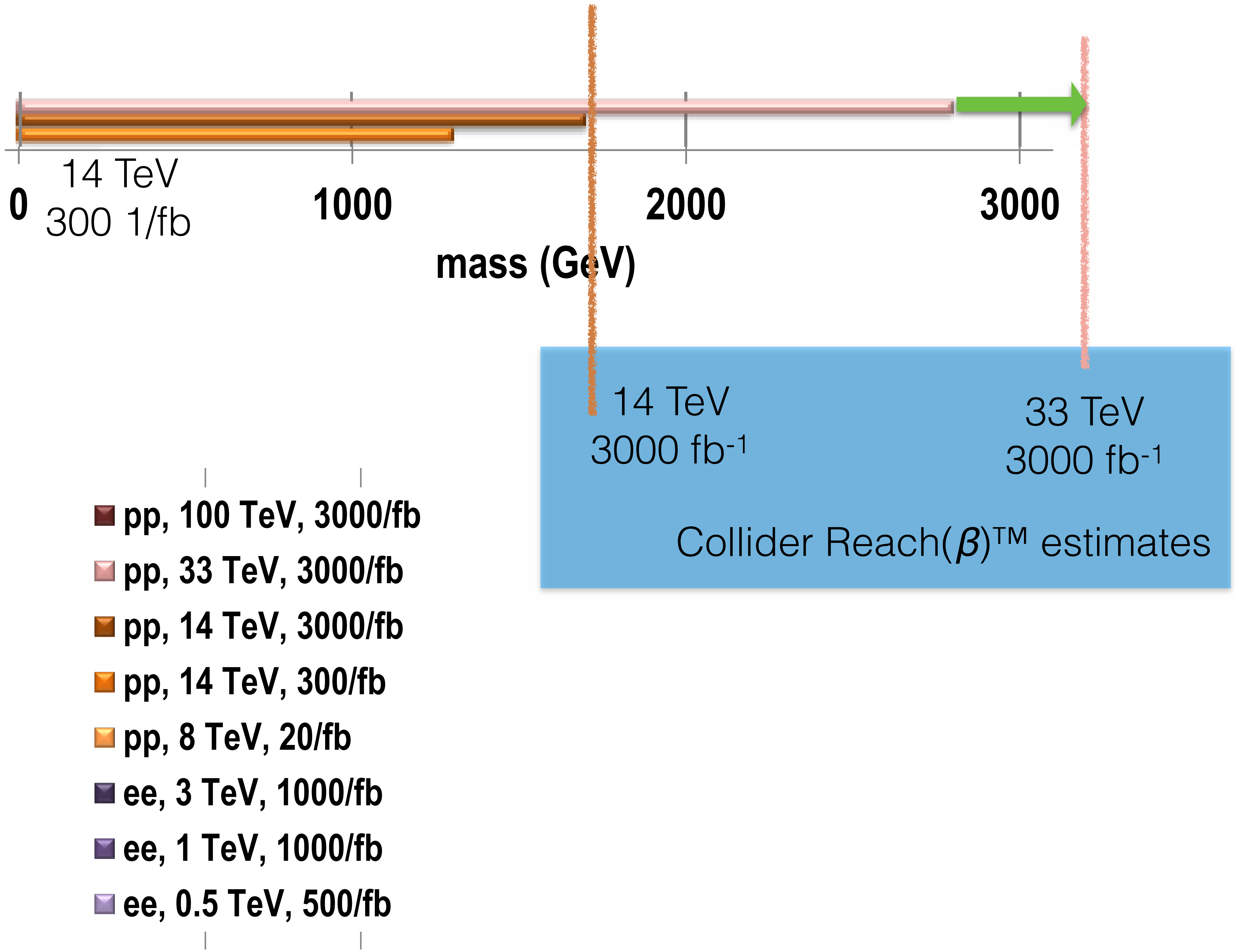


14 TeV
300 1/fb

14 TeV
3000 fb^{-1}

Collider Reach(β)™ estimates

RPV stops

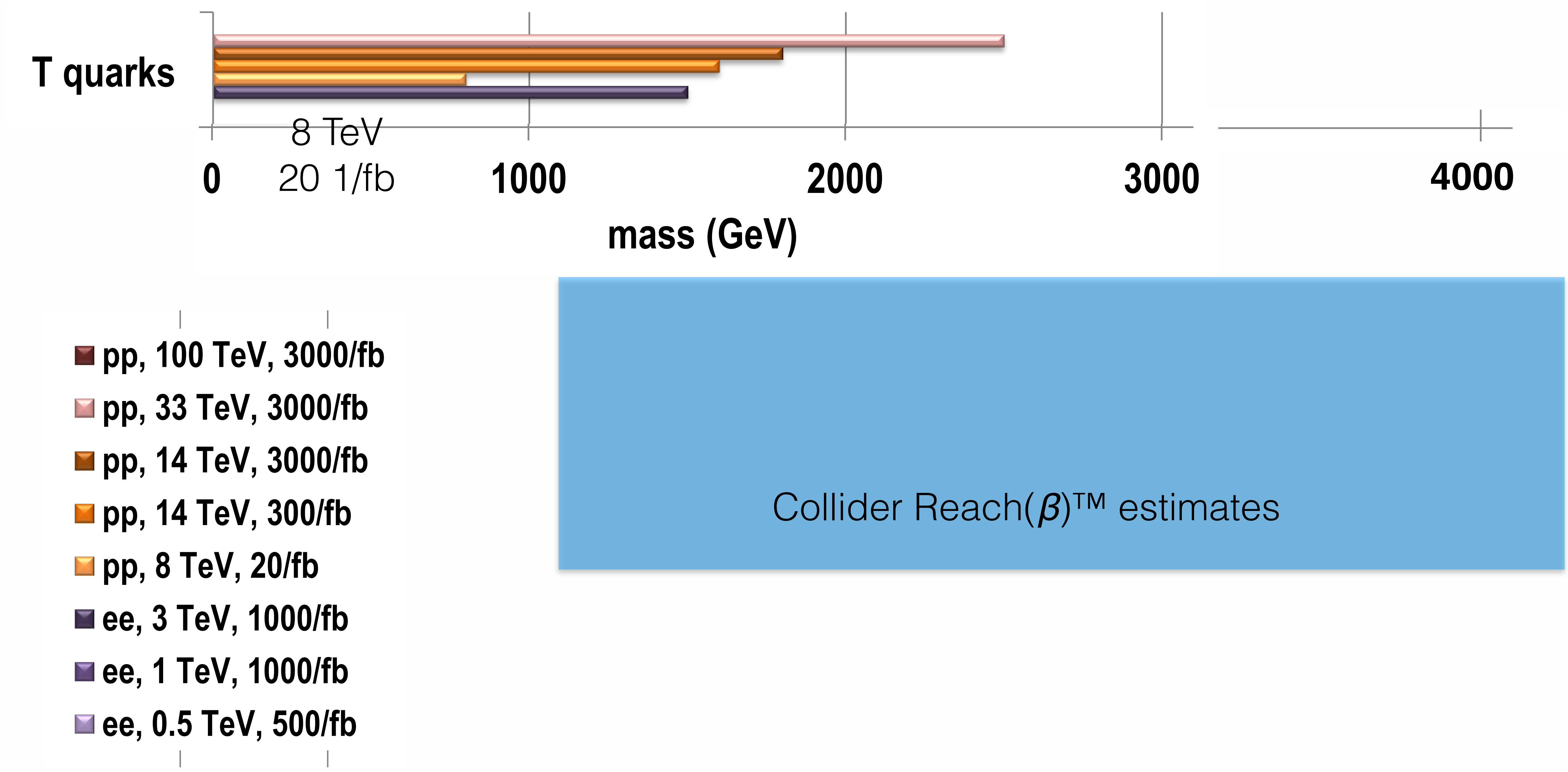


14 TeV
3000 fb^{-1}

33 TeV
3000 fb^{-1}

Collider Reach(β)™ estimates

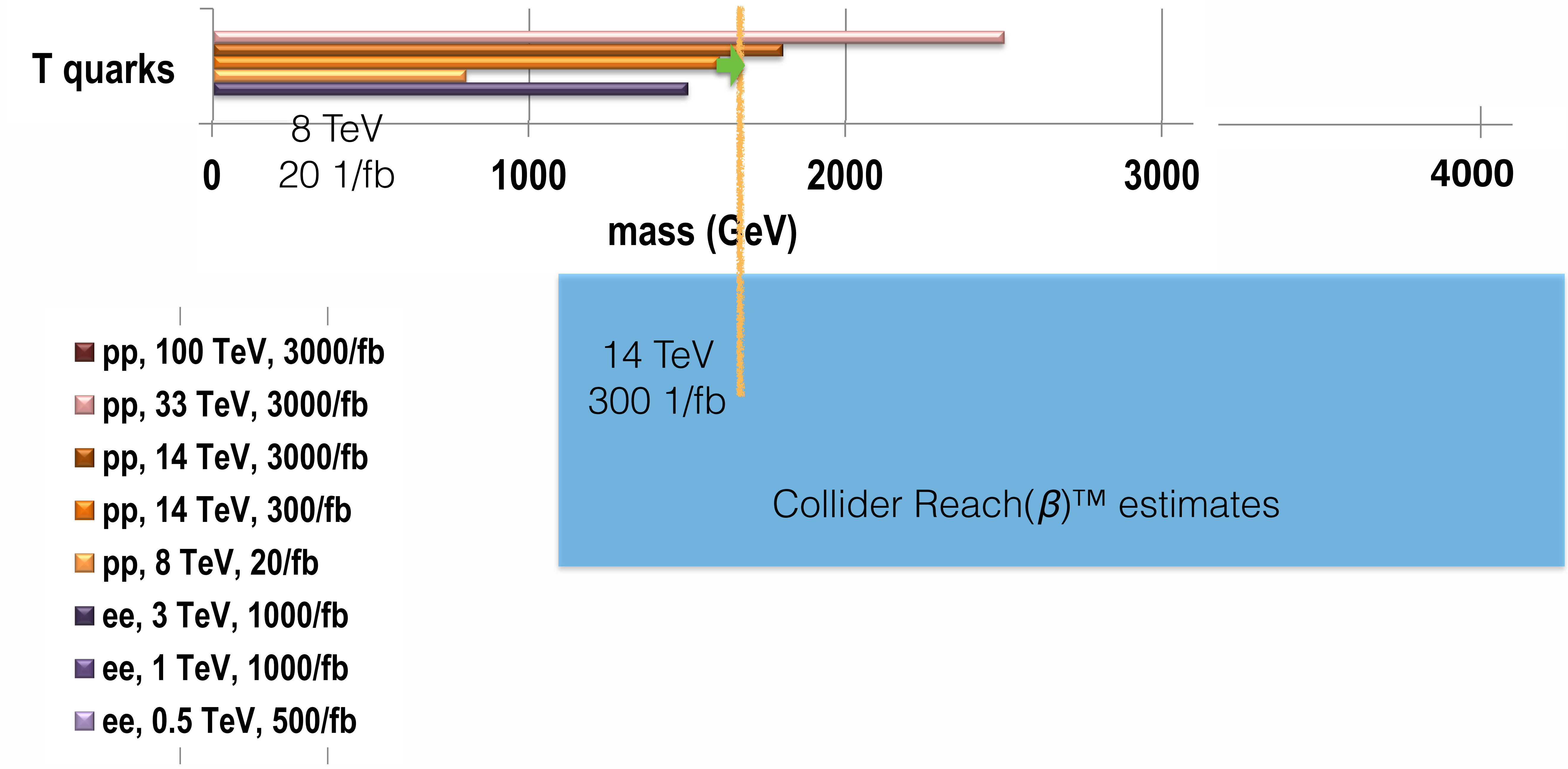
T Quarks



8 TeV
20 1/fb

Collider Reach(β)™ estimates

T Quarks

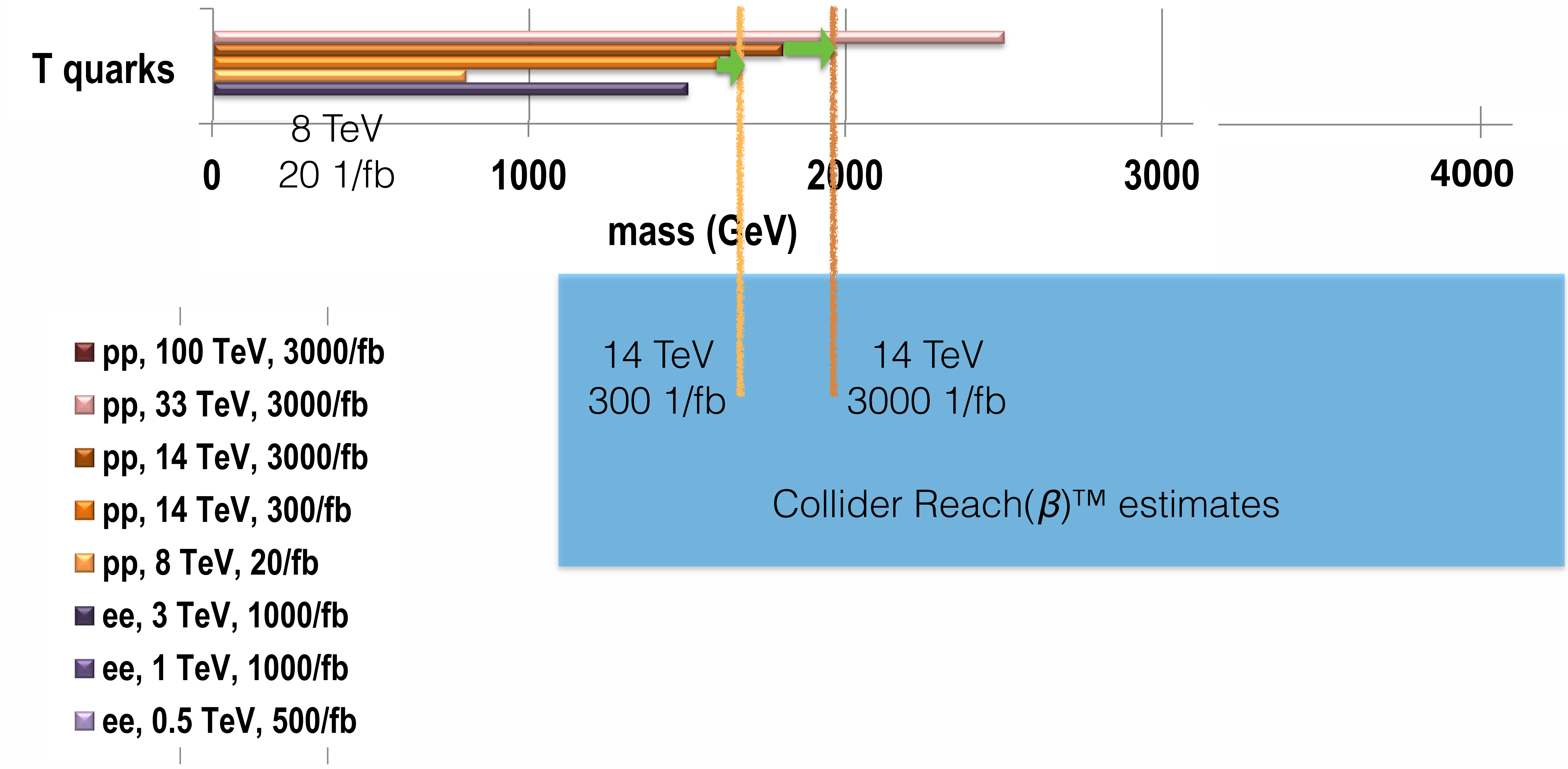


8 TeV
20 1/fb

14 TeV
300 1/fb

Collider Reach(β)™ estimates

T Quarks



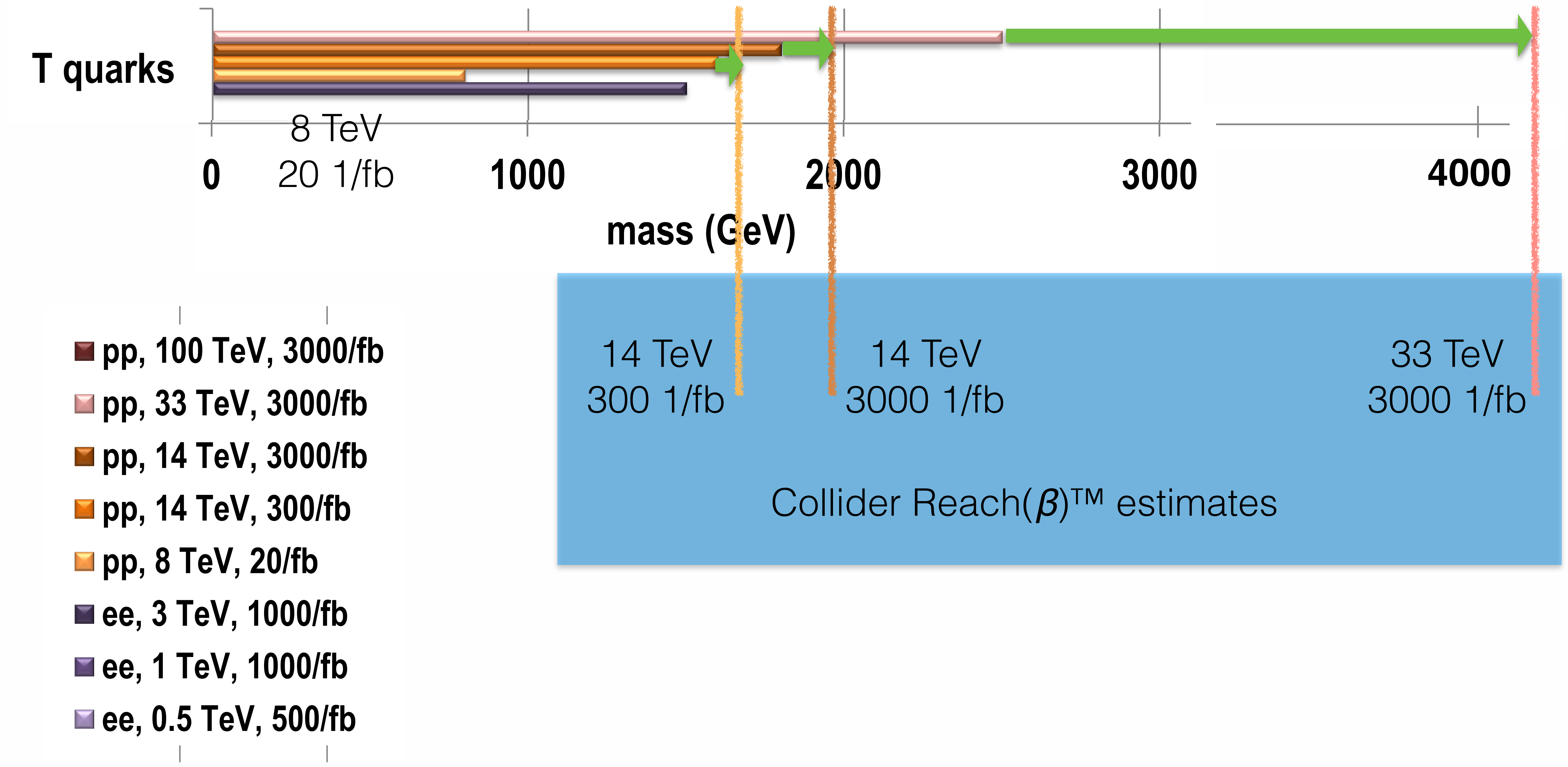
8 TeV
20 1/fb

14 TeV
300 1/fb

14 TeV
3000 1/fb

Collider Reach(β)™ estimates

T Quarks



8 TeV
20 1/fb

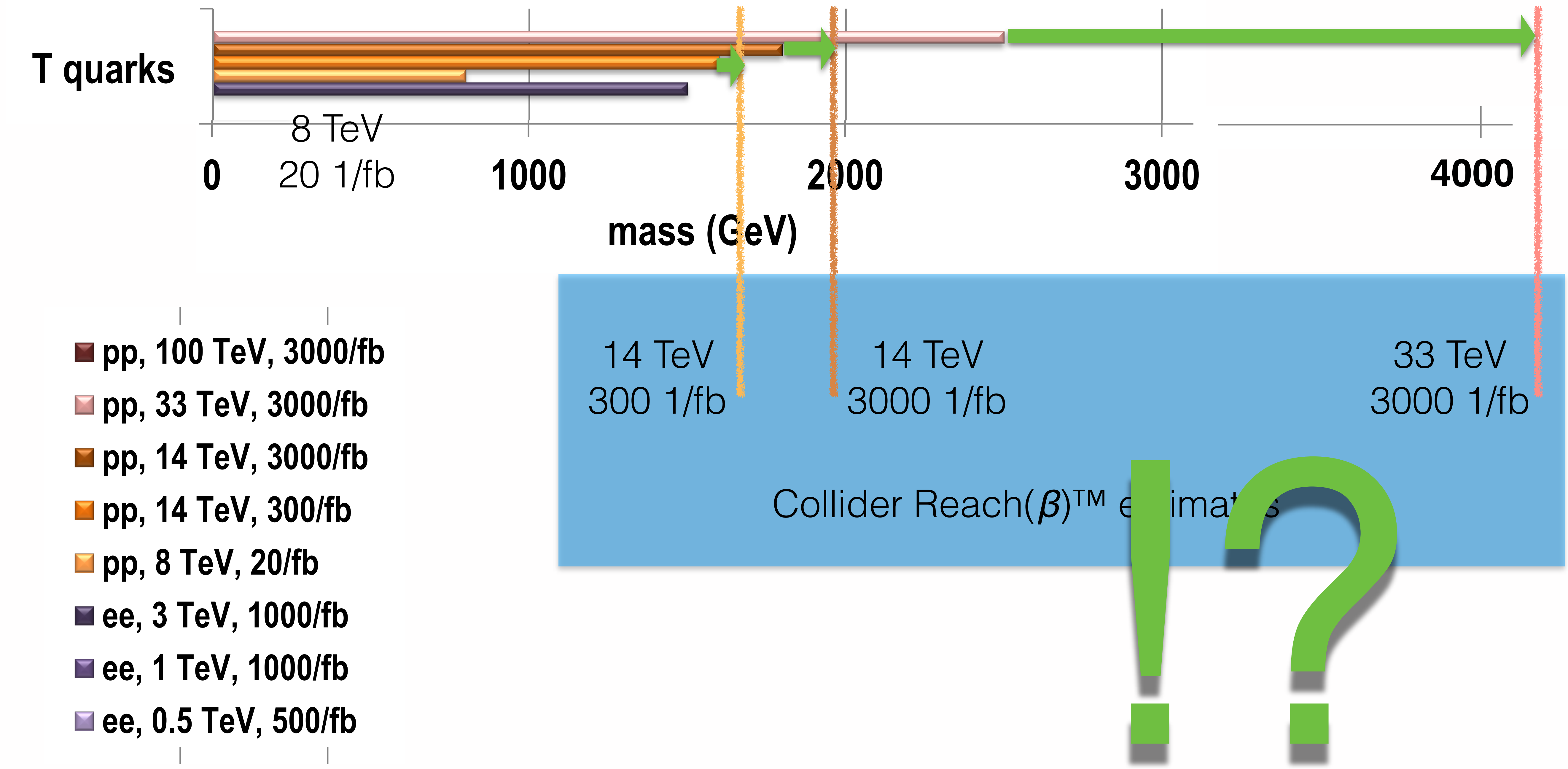
14 TeV
300 1/fb

14 TeV
3000 1/fb

33 TeV
3000 1/fb

Collider Reach(β)™ estimates

T Quarks



14 TeV
300 1/fb

14 TeV
3000 1/fb

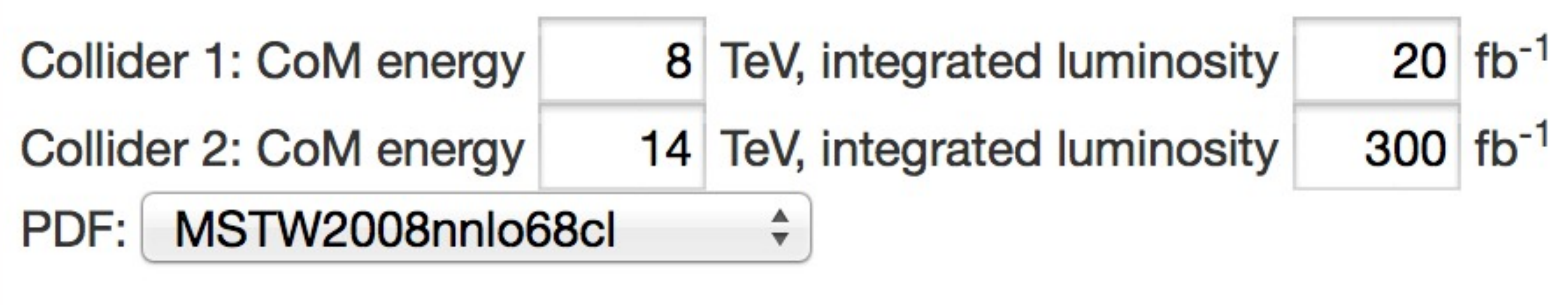
33 TeV
3000 1/fb

Collider Reach(β)™ e imat s

From your iPhone

(or a generic browser)

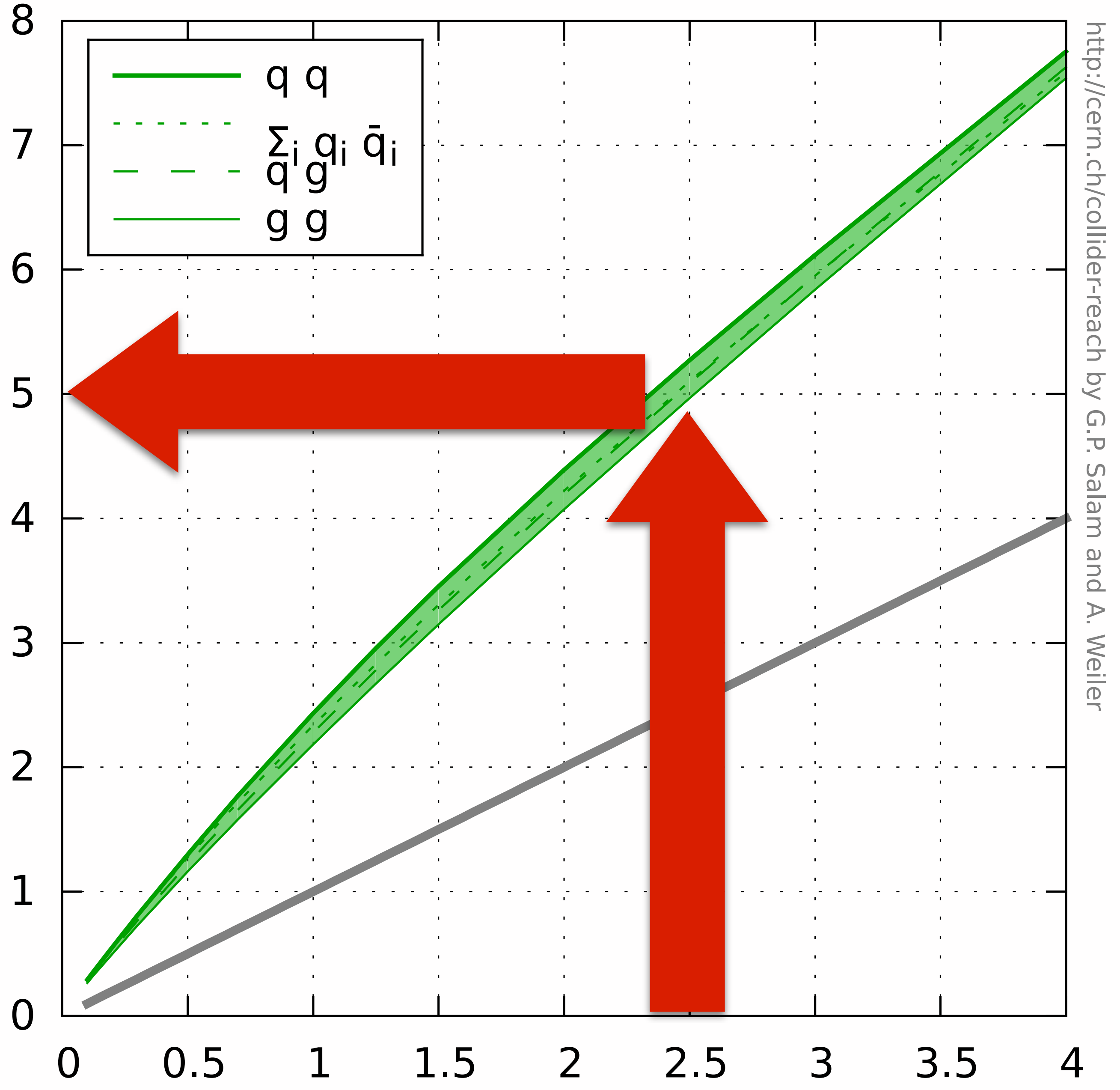
cern.ch/collider-reach



Collider 1: CoM energy 8 TeV, integrated luminosity 20 fb^{-1}

Collider 2: CoM energy 14 TeV, integrated luminosity 300 fb^{-1}

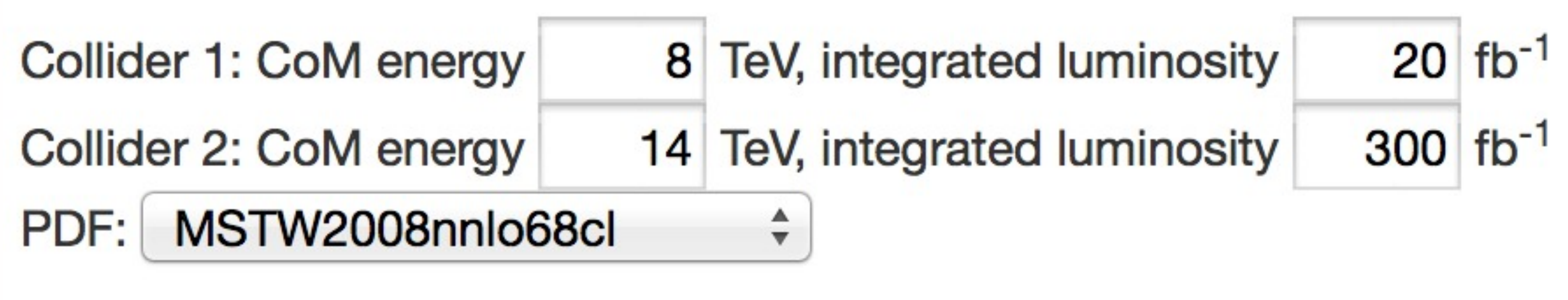
PDF: MSTW2008nnlo68cl



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

Mass [TeV] at collider #2

Mass [TeV] at collider #1



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Collider 2: CoM energy 14 TeV, integrated luminosity 300 fb^{-1}

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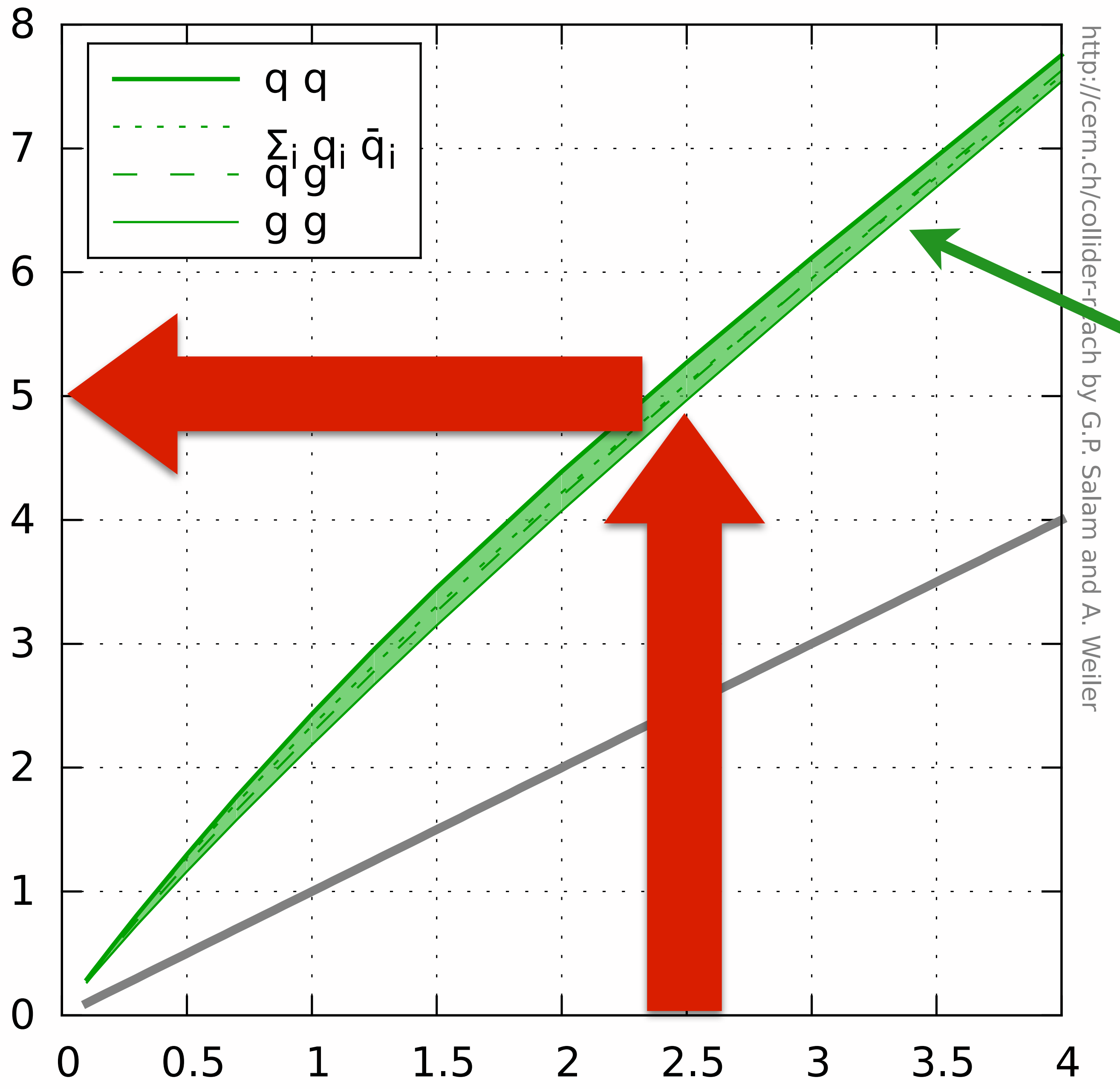


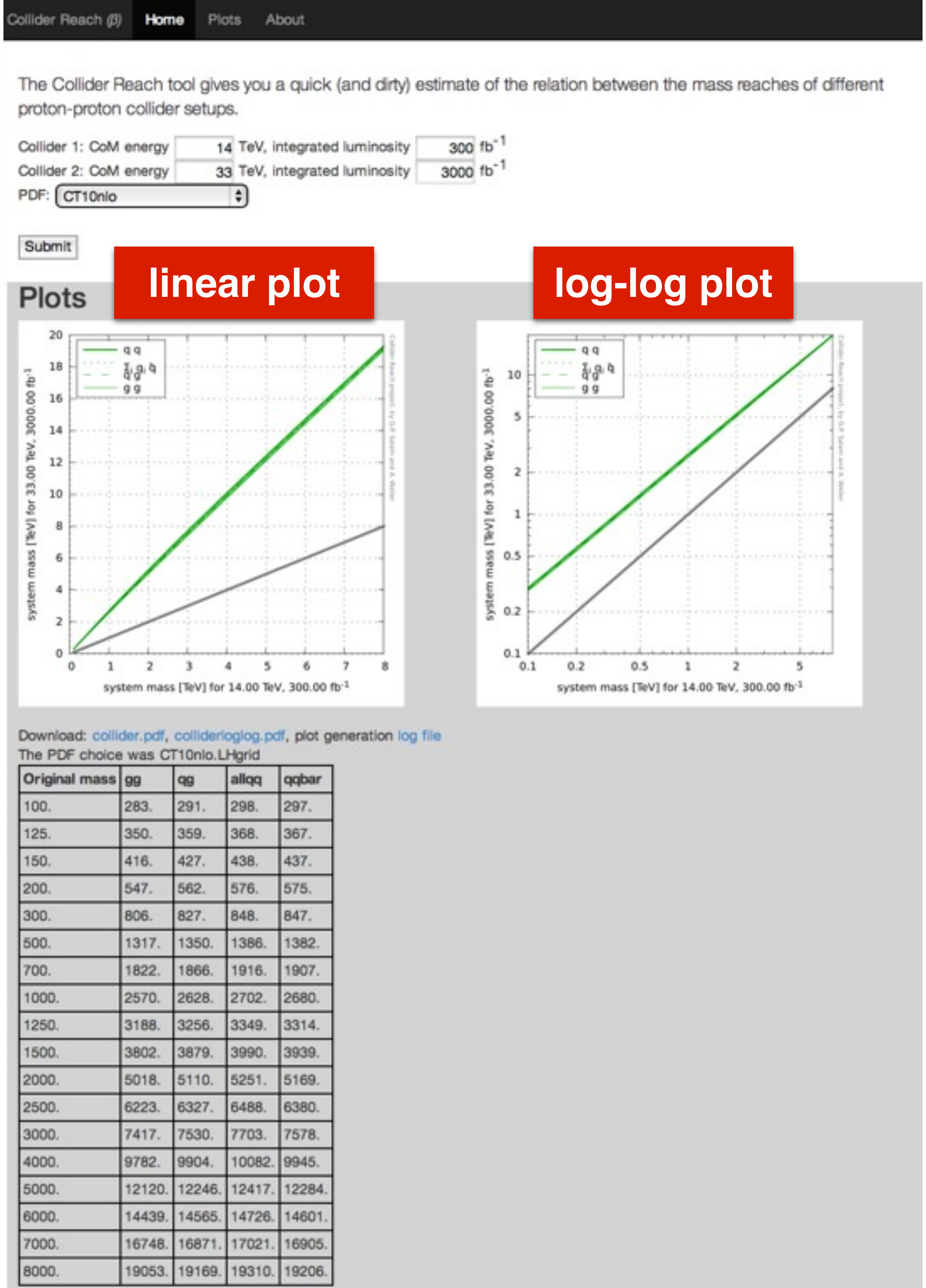
http://cern.ch/collider-reach by G.P. Salam and A. Weiler

Mass [TeV] at collider #2

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

Mass [TeV] at collider #1

cern.ch/collider-reach



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

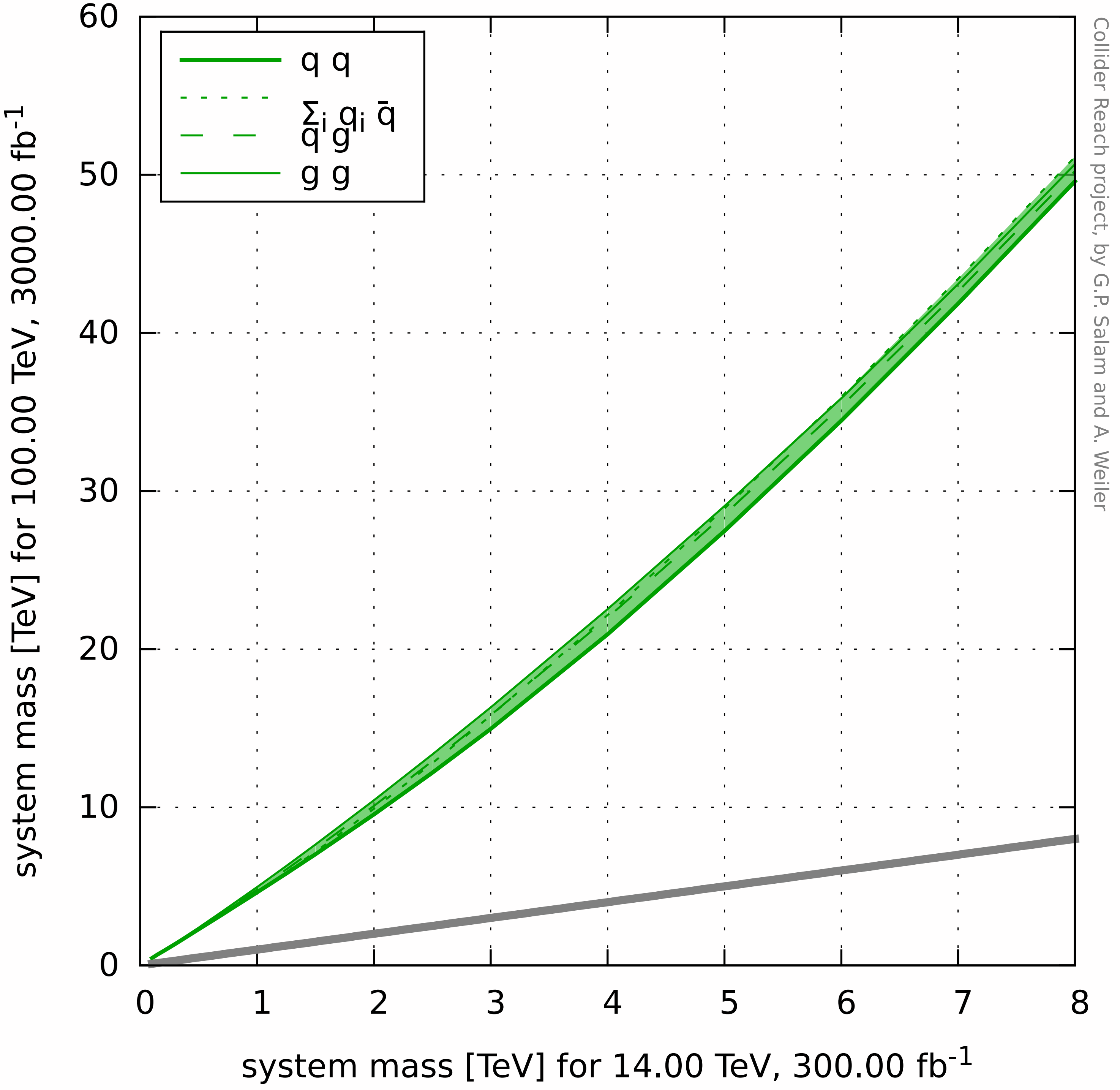
Collider 1: CoM energy 14 TeV, integrated luminosity 300 fb^{-1}
Collider 2: CoM energy 33 TeV, integrated luminosity 3000 fb^{-1}
PDF: CT10nlo

Plots

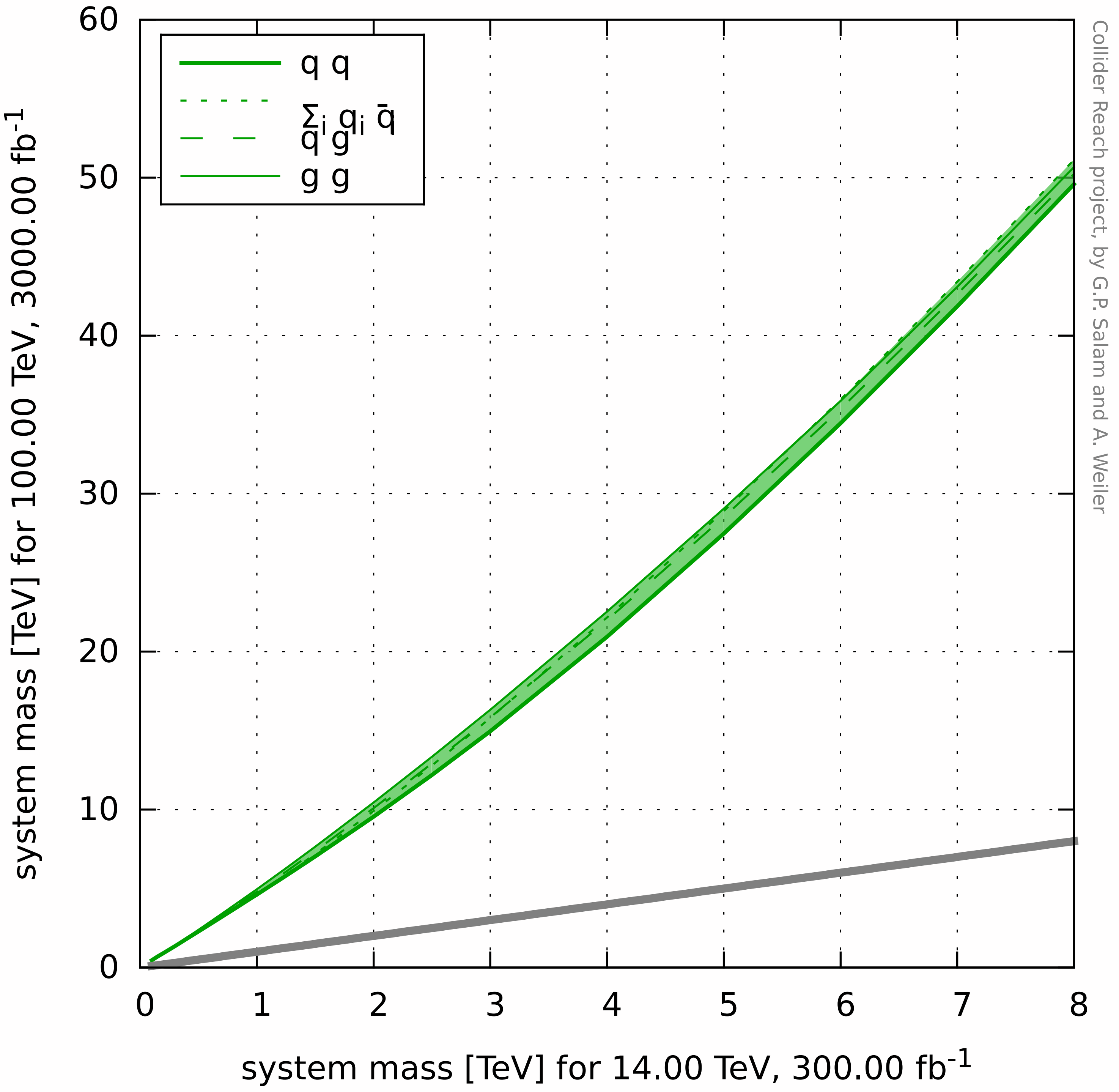
Download: collider.pdf, colliderloglog.pdf, plot generation log file
The PDF choice was CT10nlo.LHgrid

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.

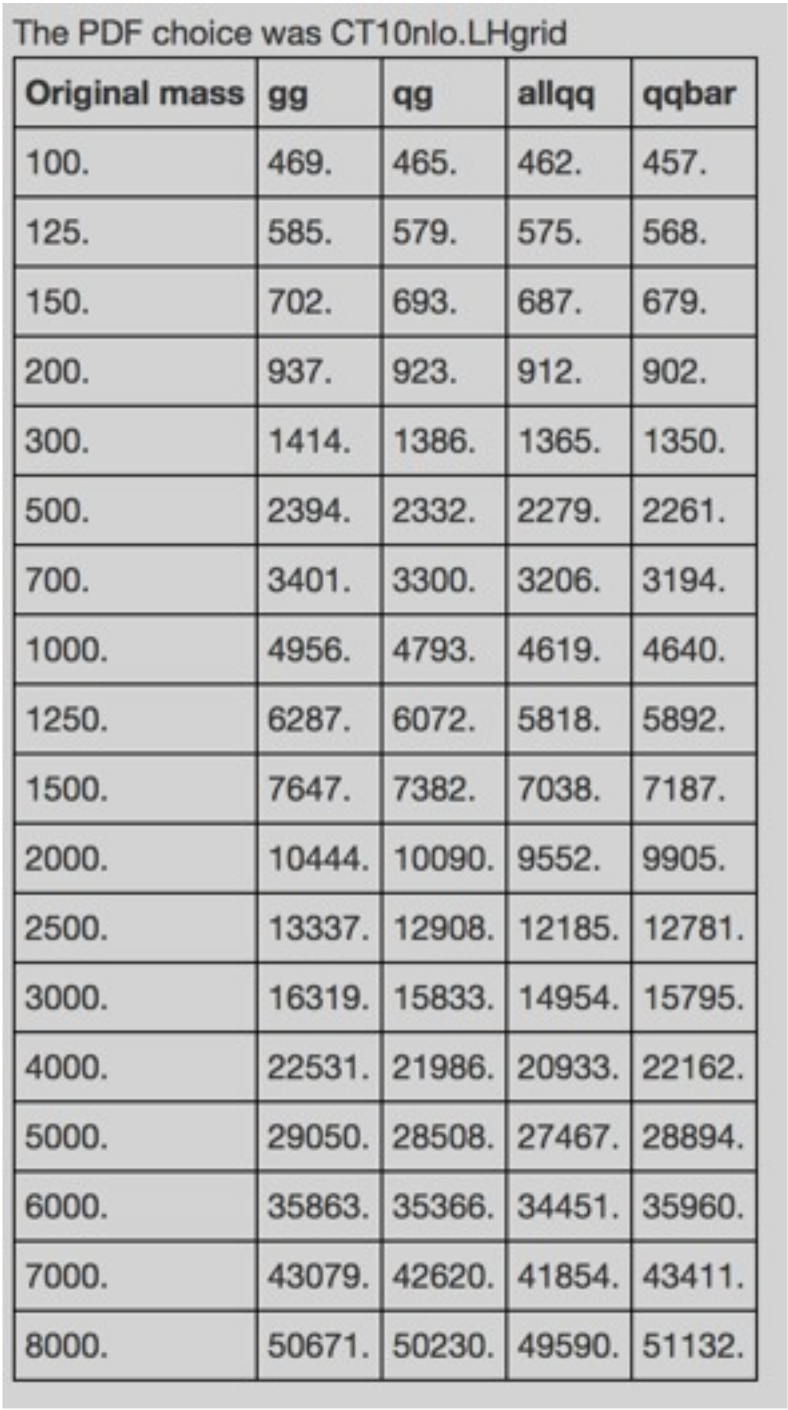
14 TeV$_{300\ fb^{-1}}$ → 100 TeV$_{3\ ab^{-1}}$



14 $\text{TeV}_{300\ \text{fb}^{-1}}$ → 100 $\text{TeV}_{3\ \text{ab}^{-1}}$



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



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 iPhone

Rule of Thumb #1

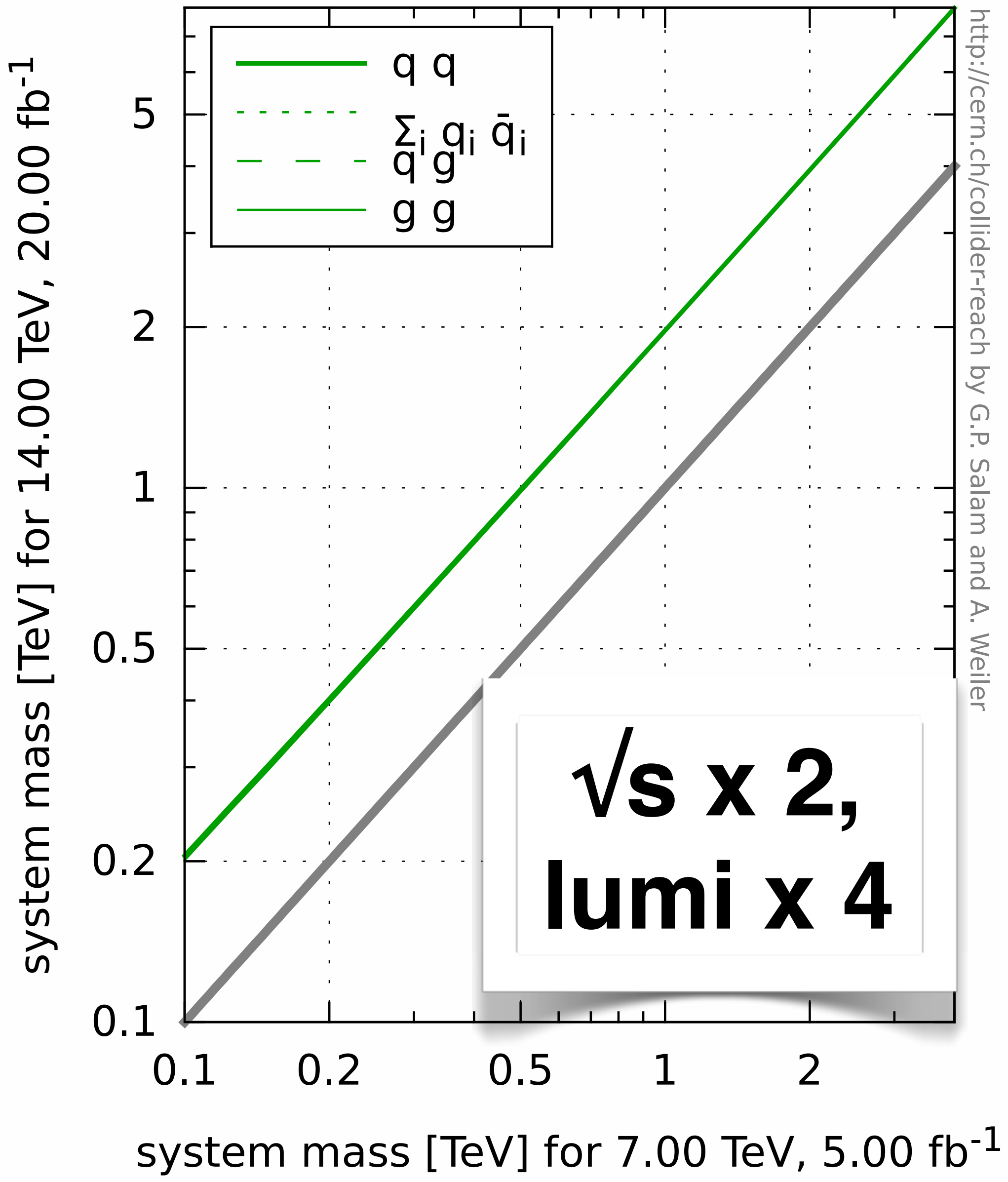
(well known among practitioners)

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



√s x 2, lumi x 4

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

Rule of Thumb #2

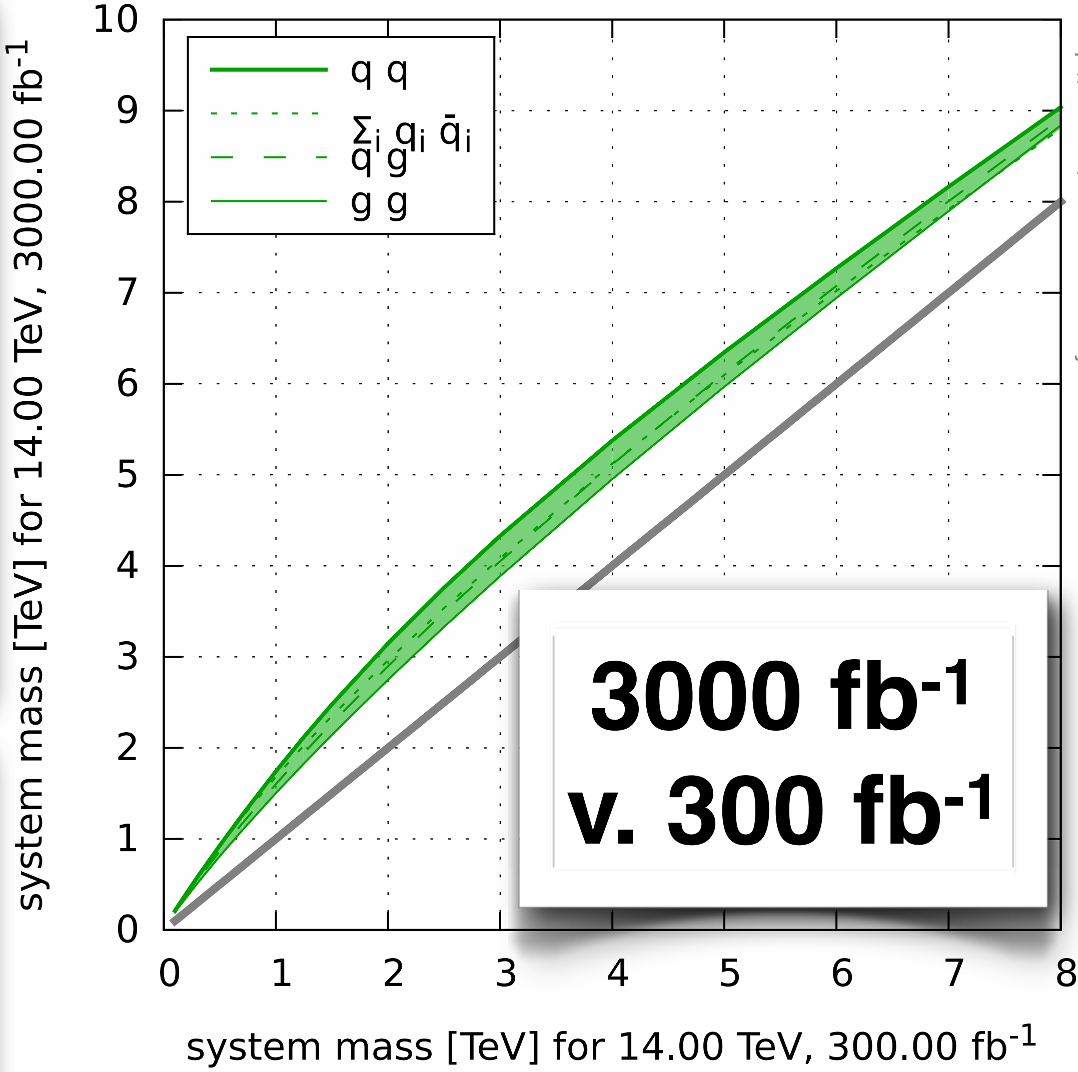
(apparently not widely known previously)

Increase luminosity by factor 10

→ reach increases by constant
$\Delta m = 0.07\sqrt{s}$

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 $0.15 \lesssim M/\sqrt{s} \lesssim 0.6$



3000 fb^{-1}
v. 300 fb^{-1}

Consequence of rule #2

(may be a bit fragile & only for S ≲ B)

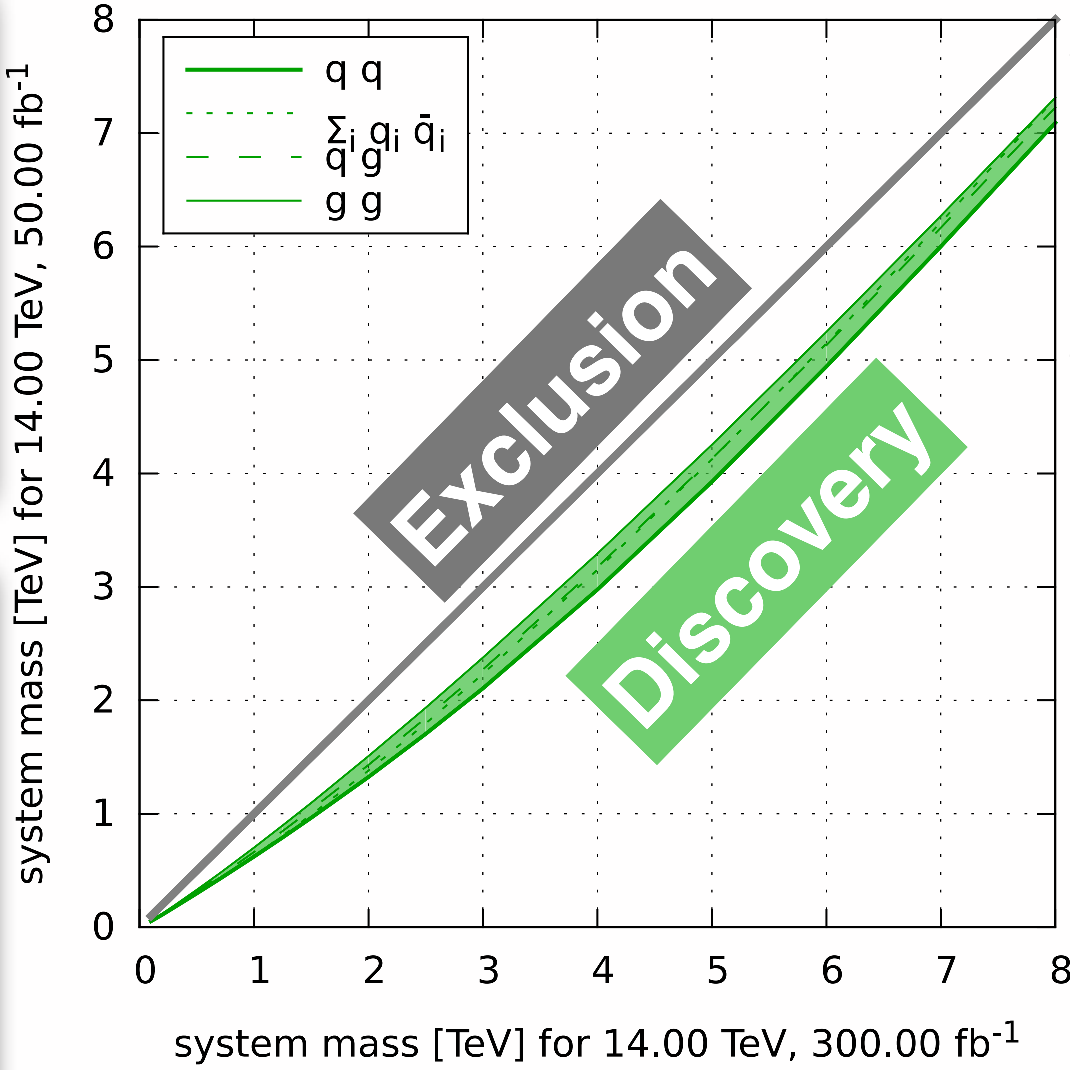
Exclusion is 2-**σ**
Discovery is 5-**σ**

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

~ 0.8 TeV at 14 TeV



Conclusions

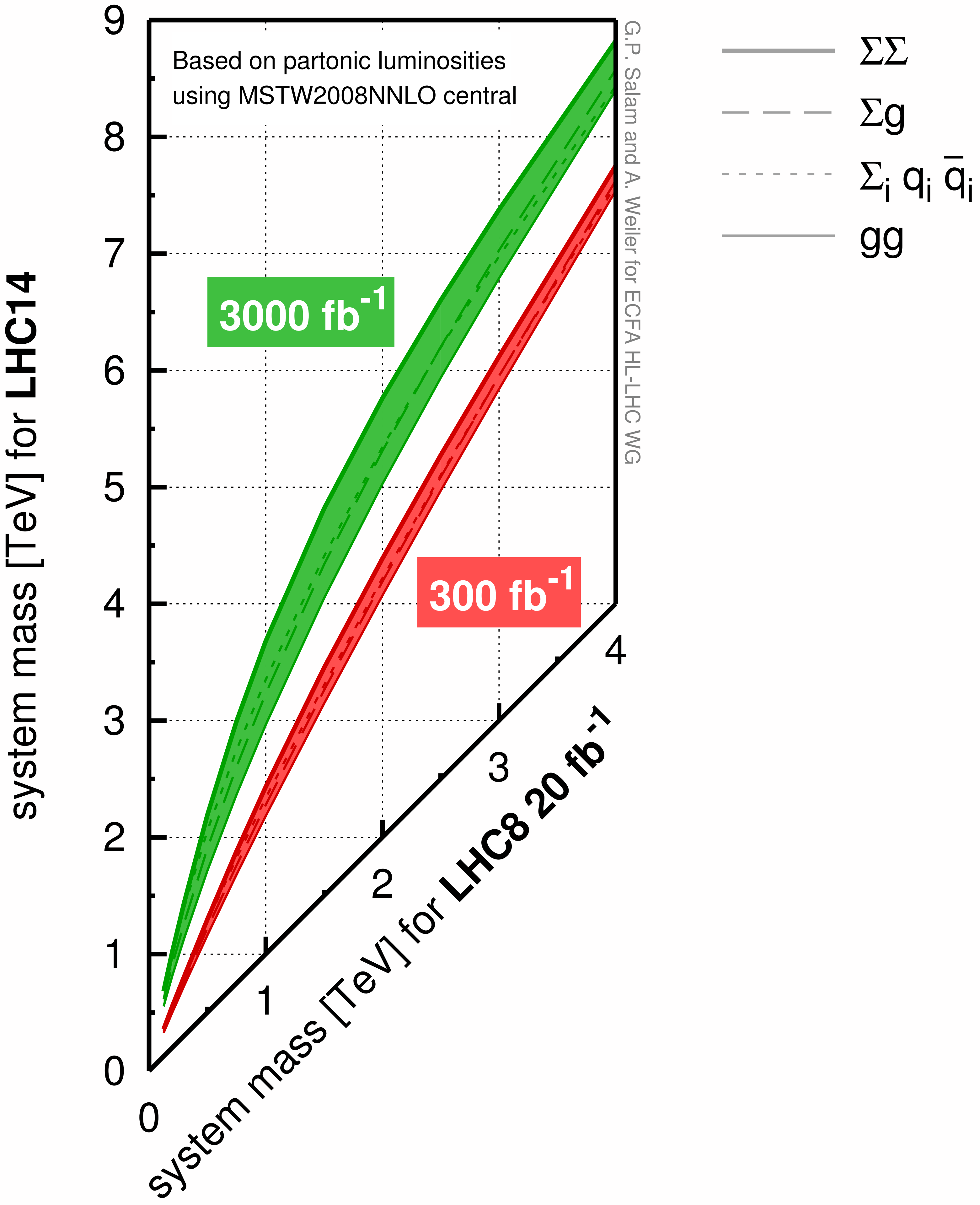
cern.ch/collider-reach

Based on LHAPDF, HOPPET and a PDF of your choice

BACKUP SLIDES

Assumptions

- We don’t need to worry about scaling of background vs. signal
- Reconstruction efficiencies, background rejection, etc all stay reasonably constant


Based on partonic luminosities
using MSTW2008NNLO central
3000 fb^{-1}
300 fb^{-1}
system mass [TeV] for **LHC14**
system mass [TeV] for **LHC8 20 fb^{-1}**
0
1
2
3
4
5
6
7
8
9
G.P. Salam and A. Weiler for ECFA HL-LHC WG
ΣΣ
Σg
$\Sigma_i q_i \bar{q}_i$
gg

G. Salam/AW

LHC comparison

1208.1447
ATLAS-CONF-2013-024

gg

stop limits [expected] (lsp = 0gev)
7TeV, 4.7 ifb 500 gev
8TeV, 20.5 ifb 650 gev ---> 675 GeV

qqbar

ATLAS EXOT-2011-06
ATLAS-CONF-2012-129
ATLAS-CONF-2013-017

sequential z-prime [expected]
7TeV, 1.1 ifb 1800 gev
8TeV, 6 ifb, 2550 gev ---> 2450 GeV
8TeV, 20 ifb 2800 gee ---> 2790 GeV

EXOT-2011-07
ATLAS-CONF-2012-088
ATLAS-CONF-2012-148

qg

excited quark q* [expected] (NB,sig ≠ bgd scaling)
7 TeV, 1 ifb 2900 gev
8 TeV, 5.8 ifb 3500 gev ---> 3700 GeV
8 TeV, 13 ifb 3700 gev ---> 3900 GeV

LHC comparison

1208.1447
ATLAS-CONF-2013-024

gg

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Baseline

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Baseline

Lumi method