PDFs and searches: observations from simplistic studies

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in collaboration with Andi Weiler (CERN & DESY)

PDF4LHC
CERN, 16 May 2014

Collider Reach

from 8 TeV to 13...14...100 TeV

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

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

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

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

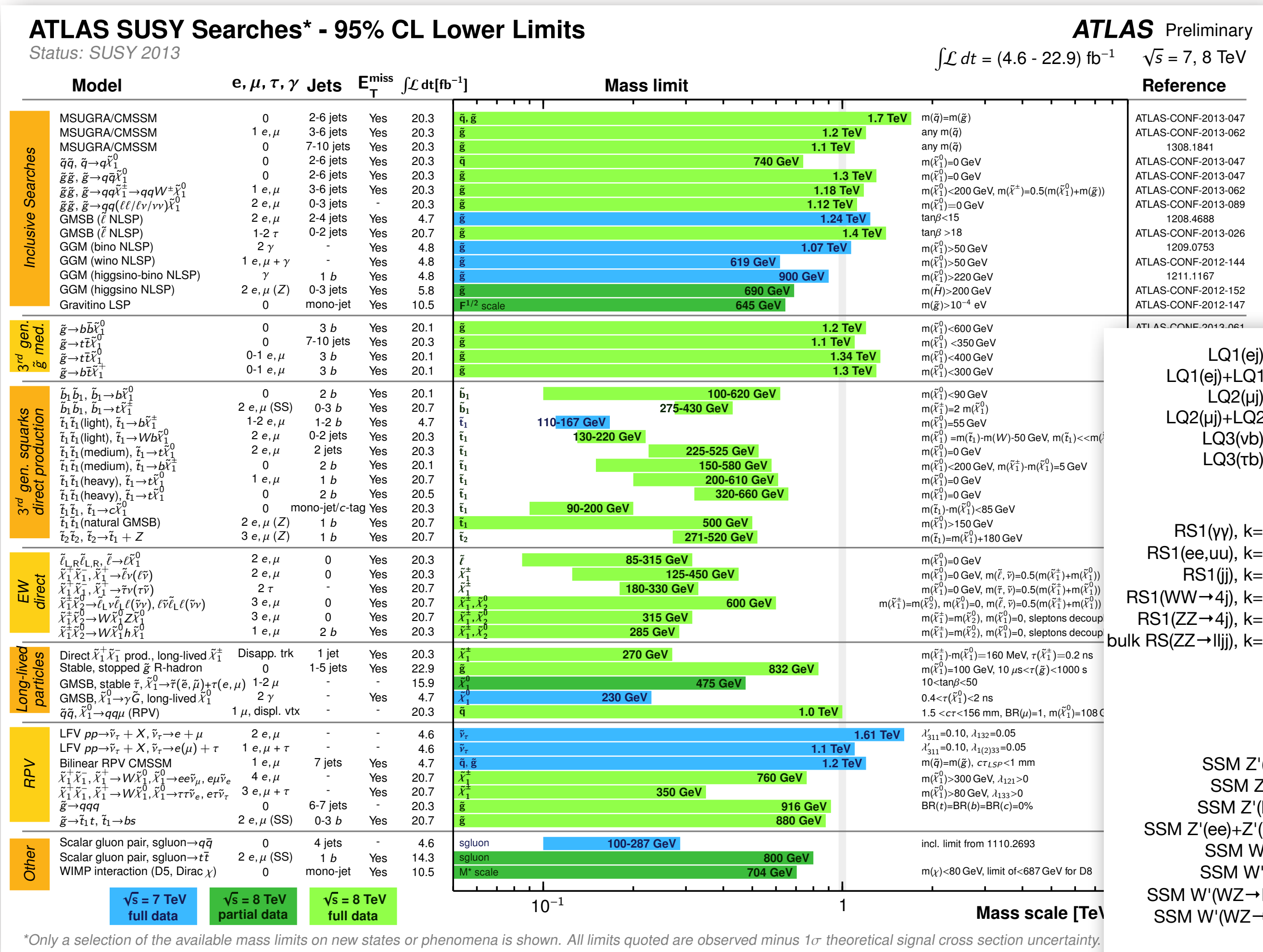
The proper way of doing it:

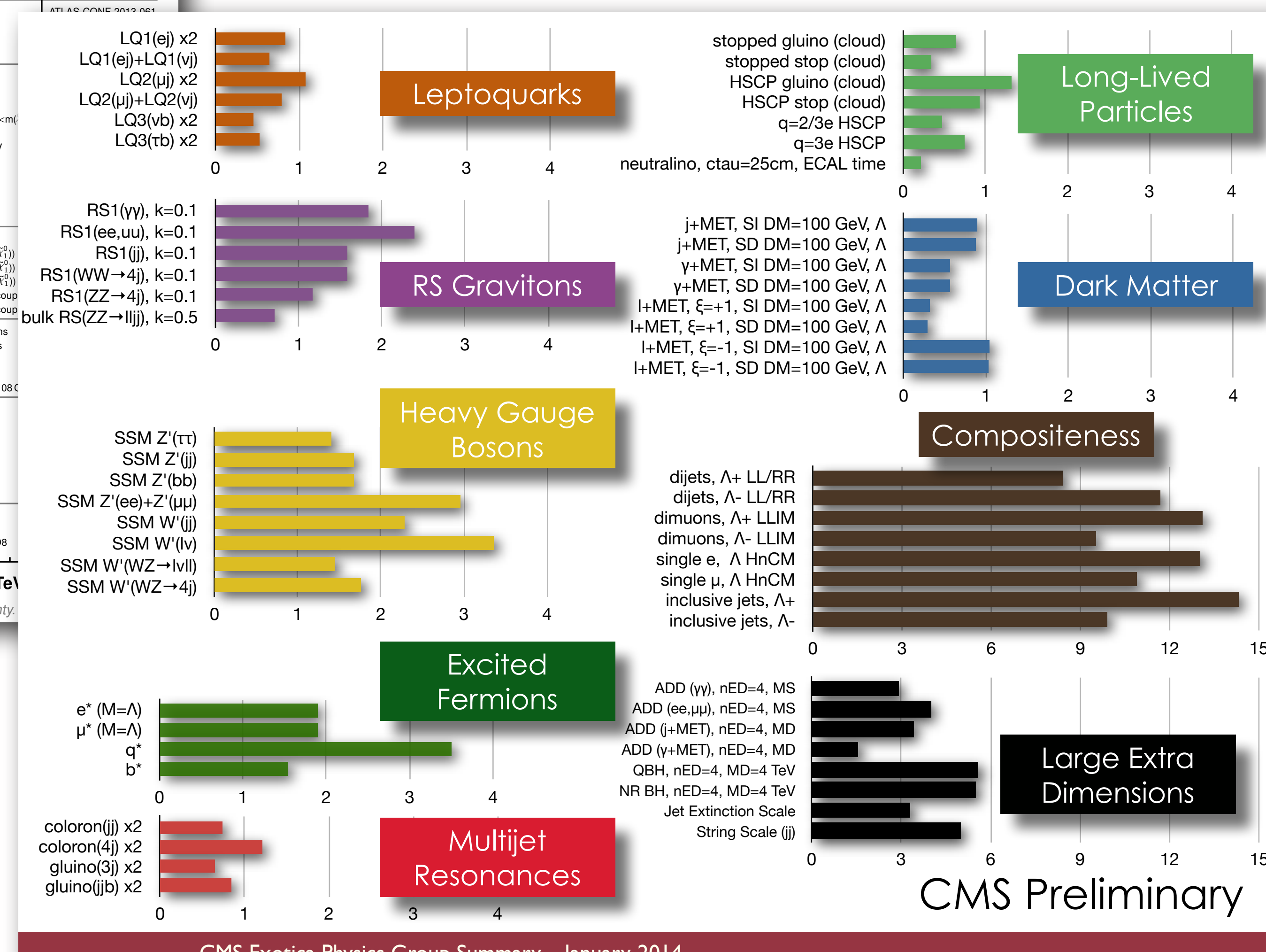
Generate Monte Carlo events for signal and background,
process them through a detector simulation,
design and carry out an optimal analysis,
work out discovery/exclusion reach.

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





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^{-1})

↓

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^{-1} (assume # of background events scales same way)

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.

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 $M_{\rm high}$ is then

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

The tools we use for this are LHAPDF and HOPPET

most plots with MSTW2008 NNLO PDFs

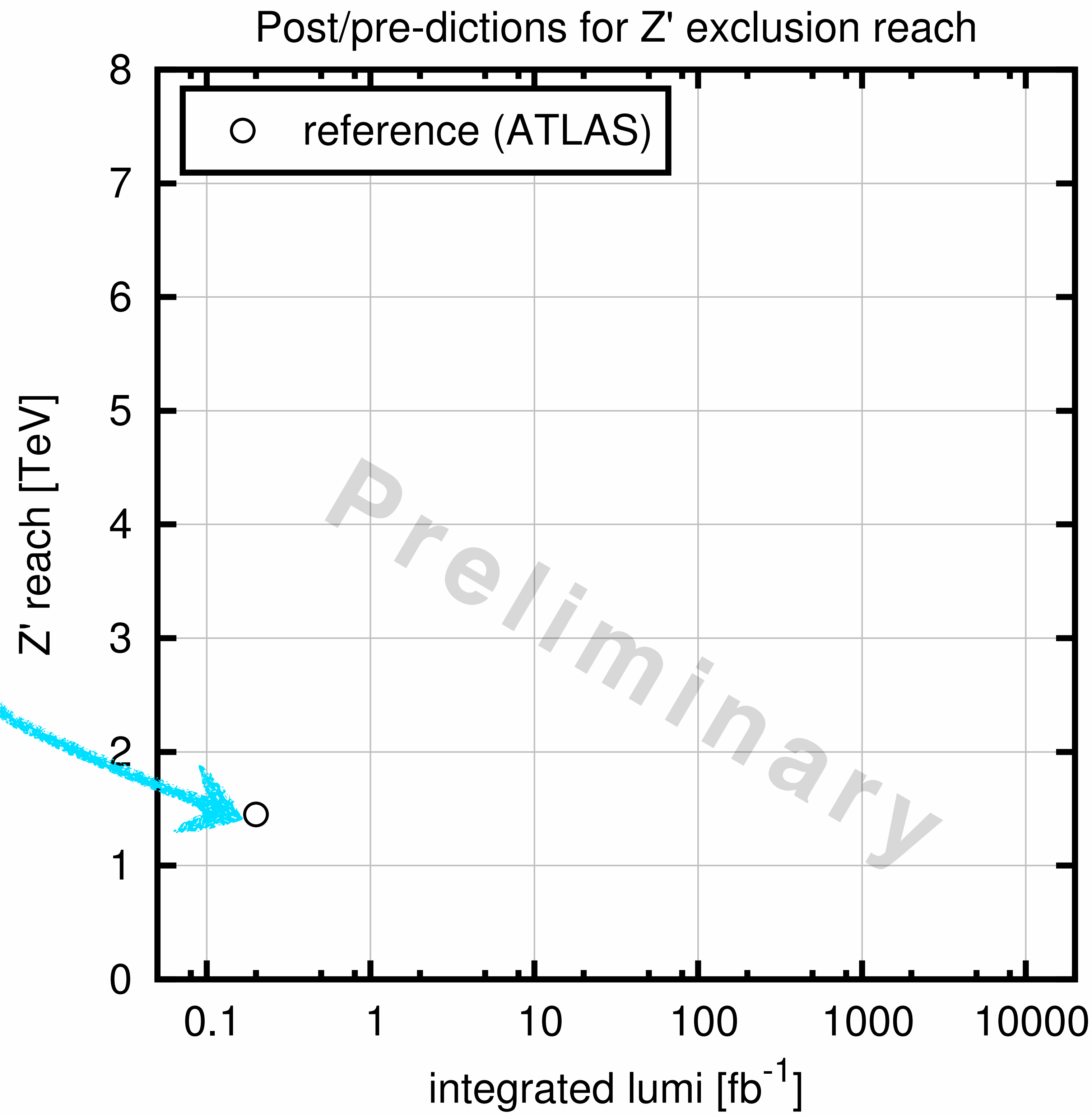
$$\mathcal{L}_{ij}(M^2, s) = \int_\tau^1 \frac{dx}{x} x f_i(x, M^2) \frac{\tau}{x} f_j\left(\frac{\tau}{x}, M^2\right) \qquad \tau \equiv \frac{M^2}{s}$$

i & j parton

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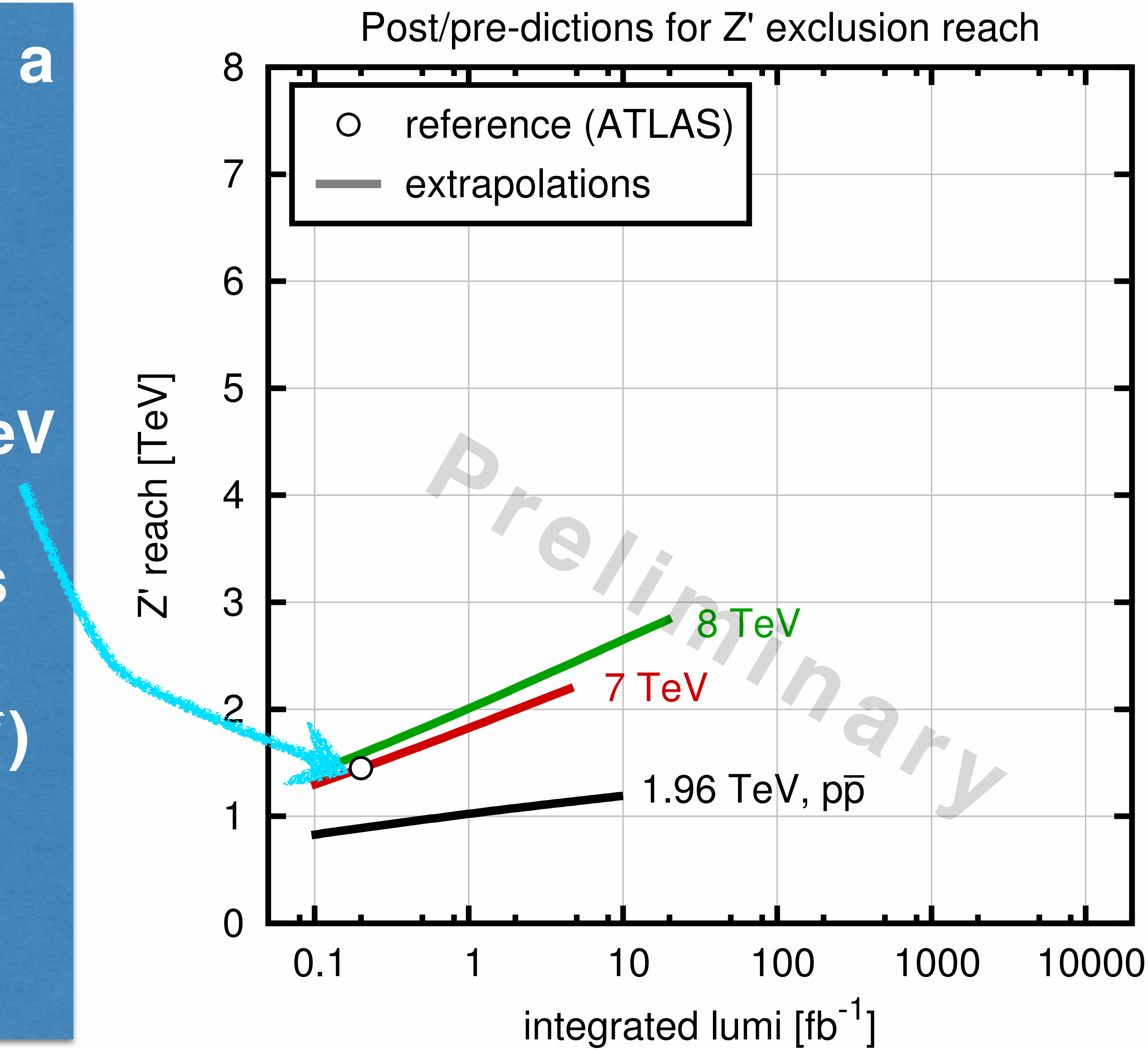
"Predict" exclusions at other lumis & energies (assume $q\bar{q}$)



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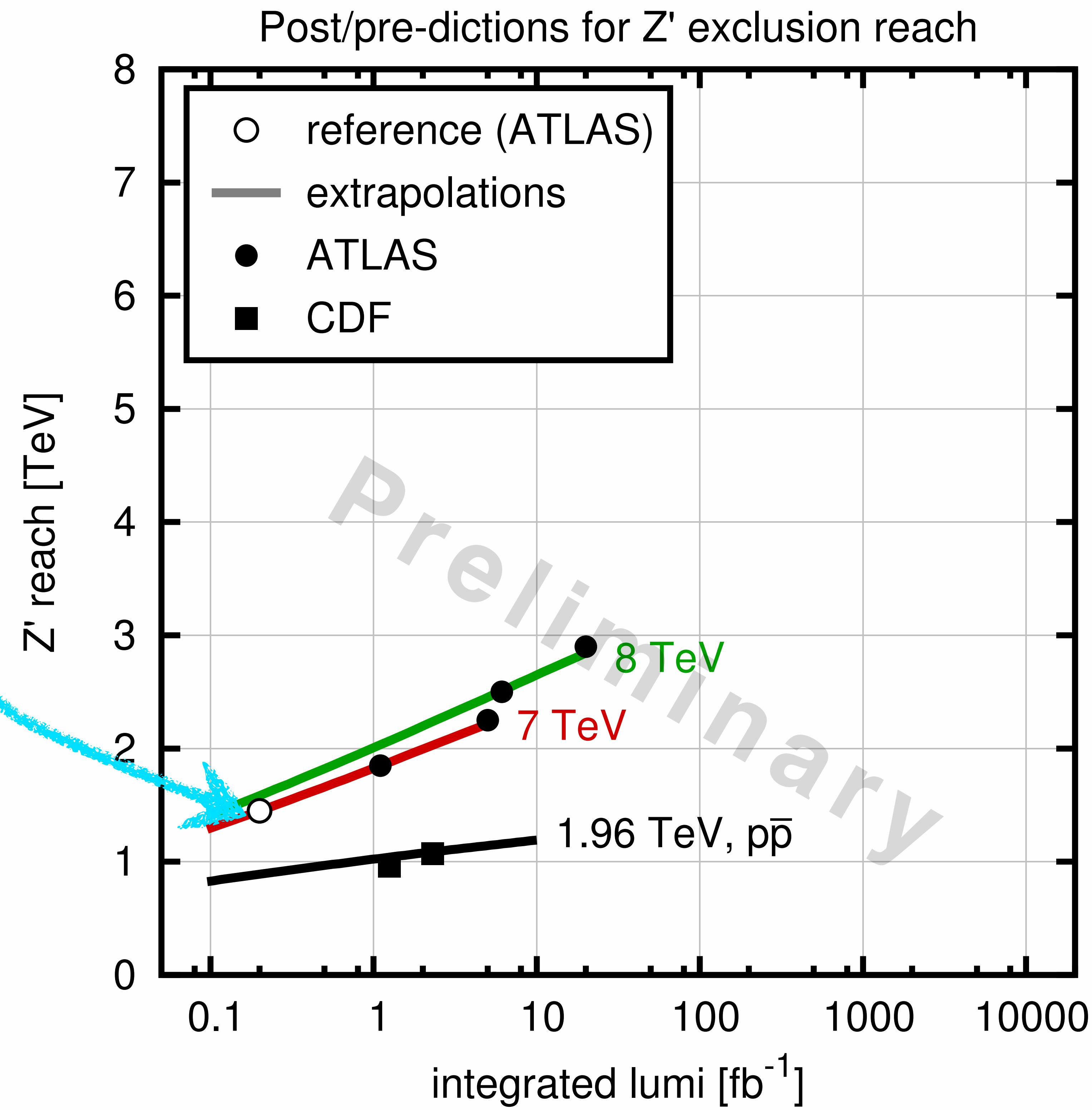
Compare to actual exclusions



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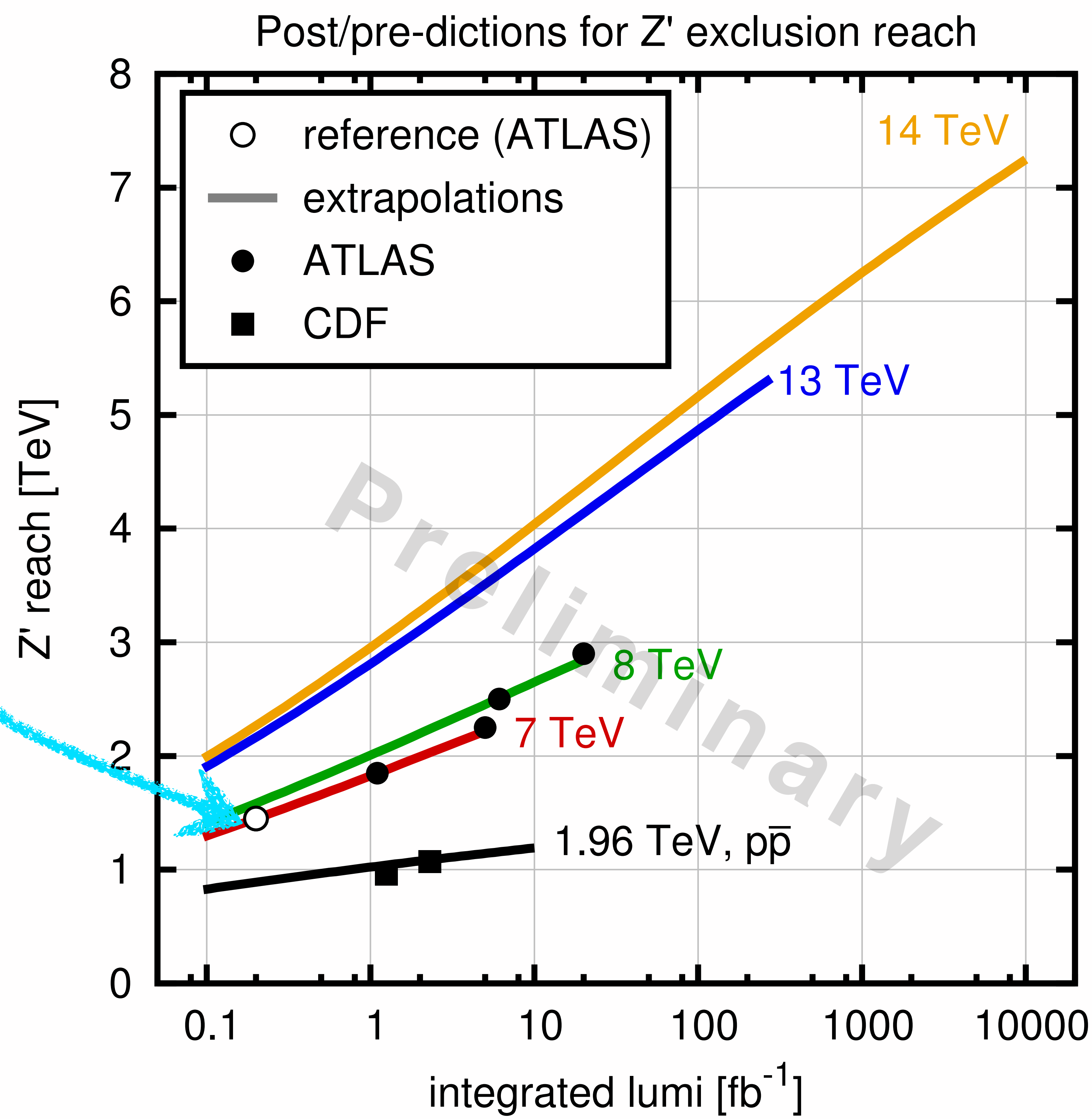
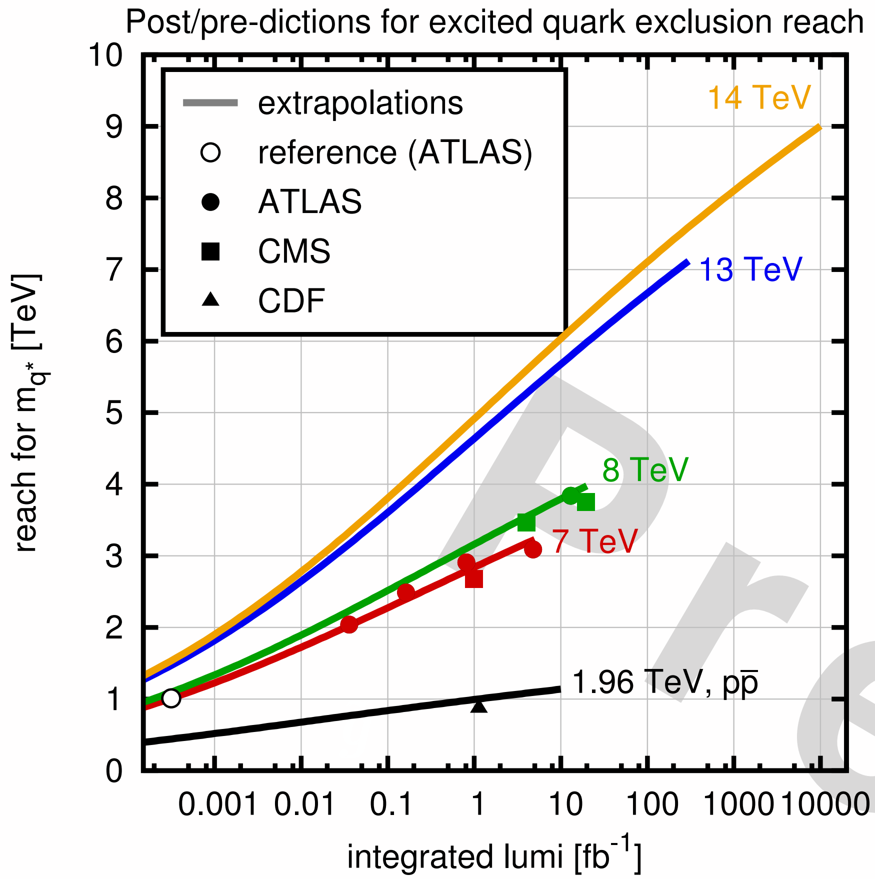
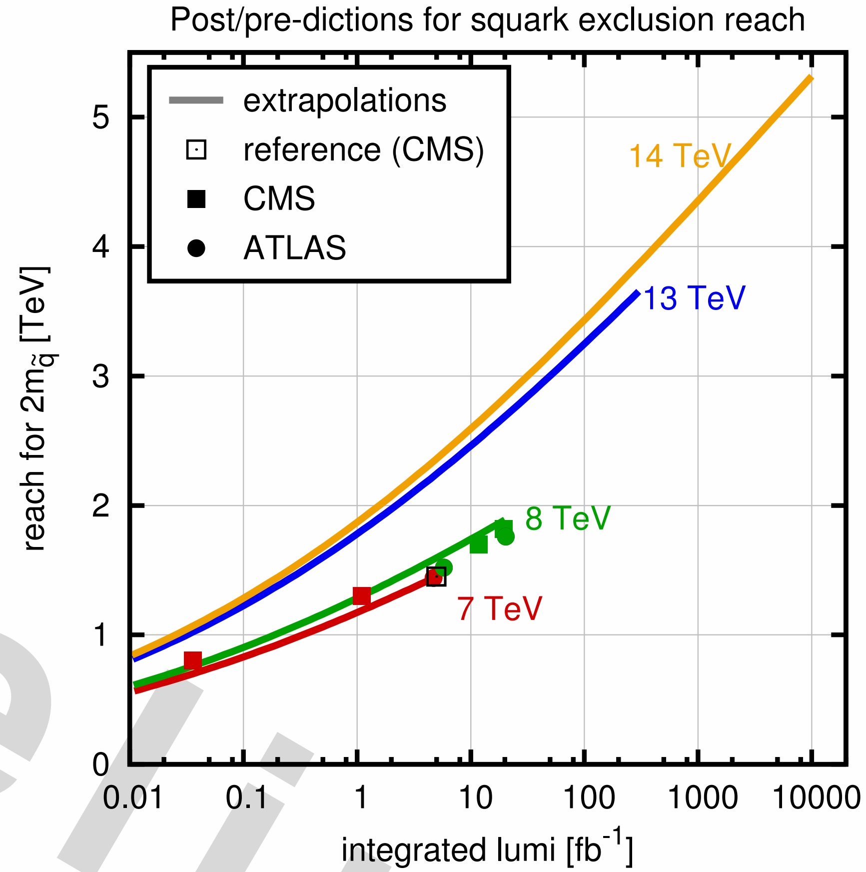
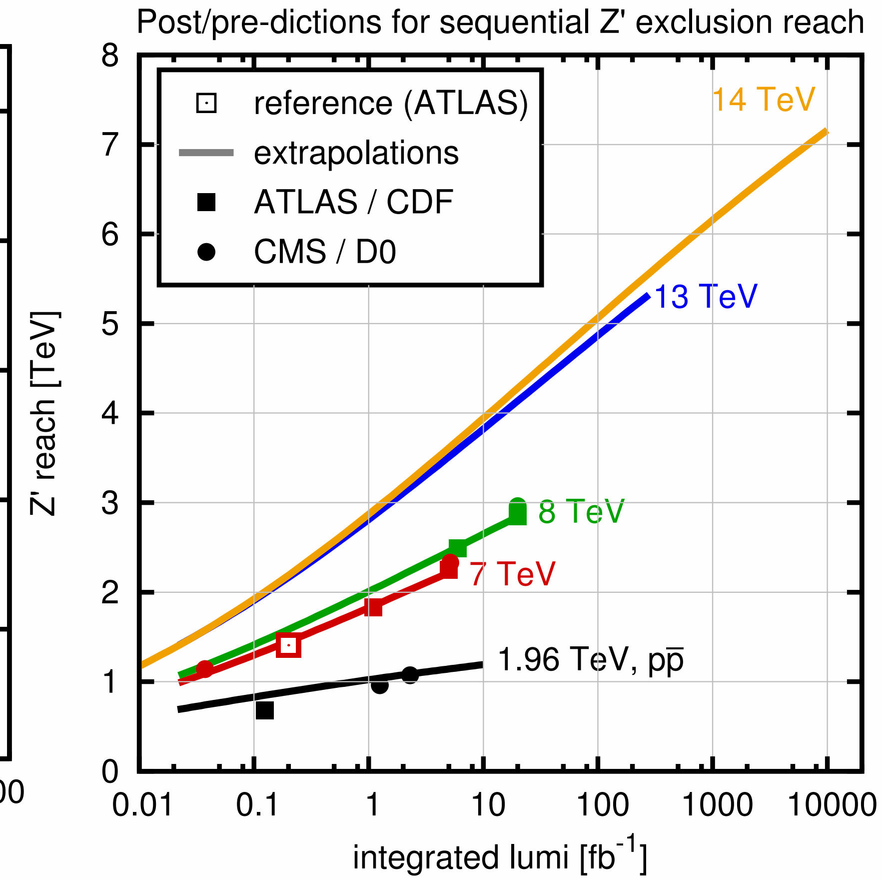
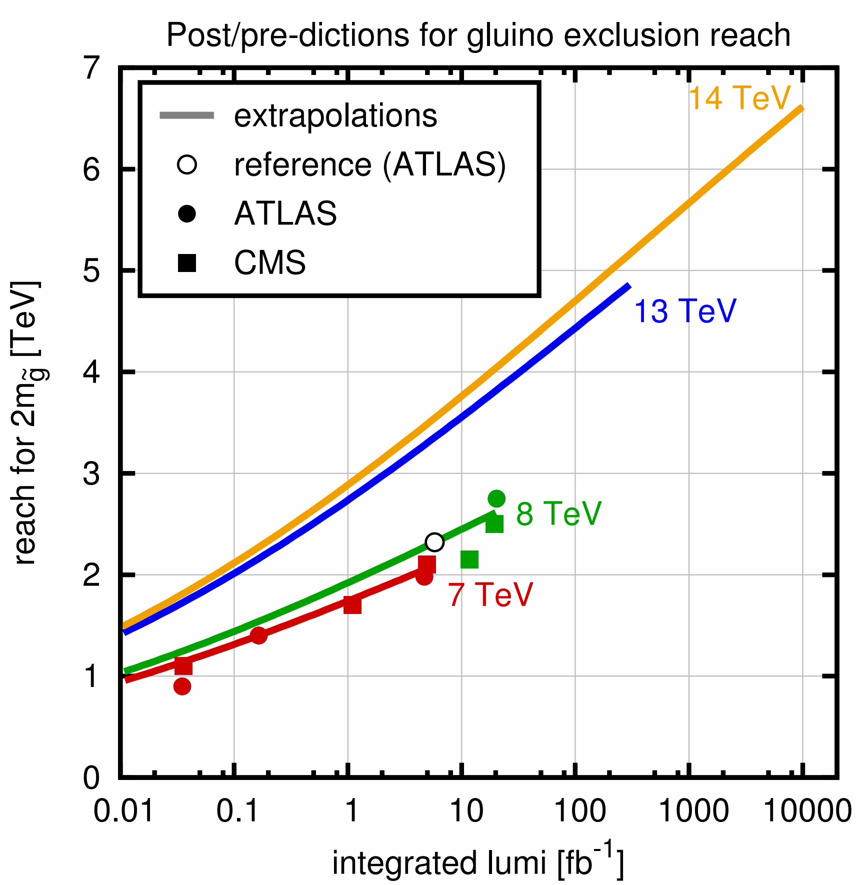


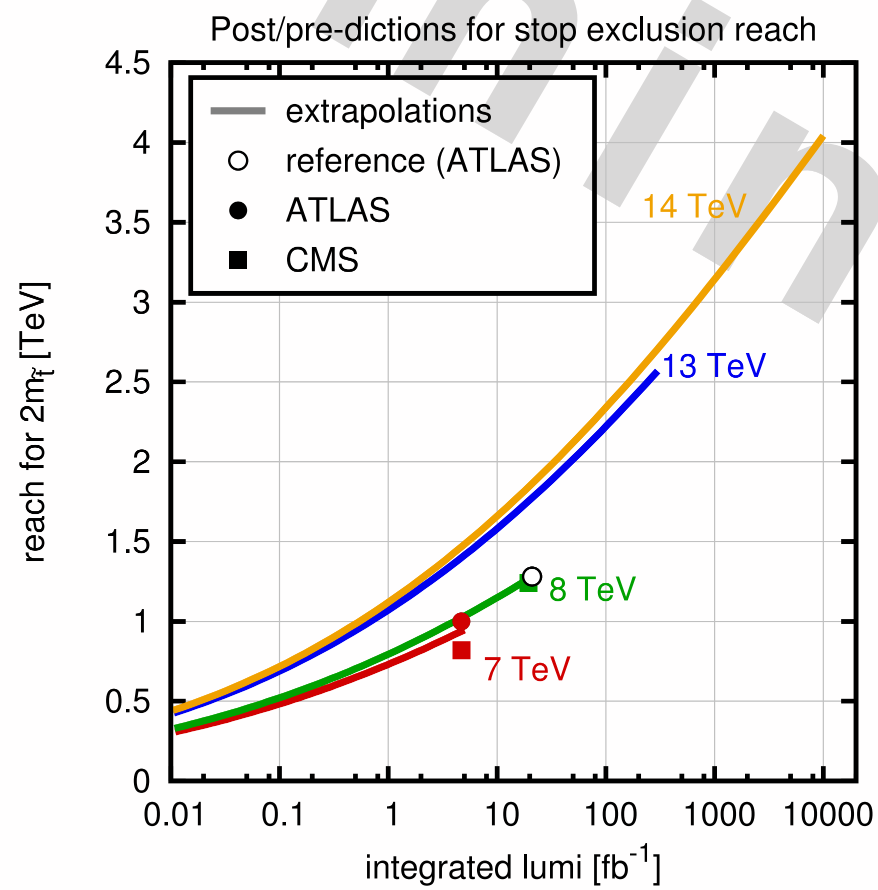
Maybe it only works so well because it's a simple search?
(Signal & Bkgd are both $q\bar{q}$ driven)

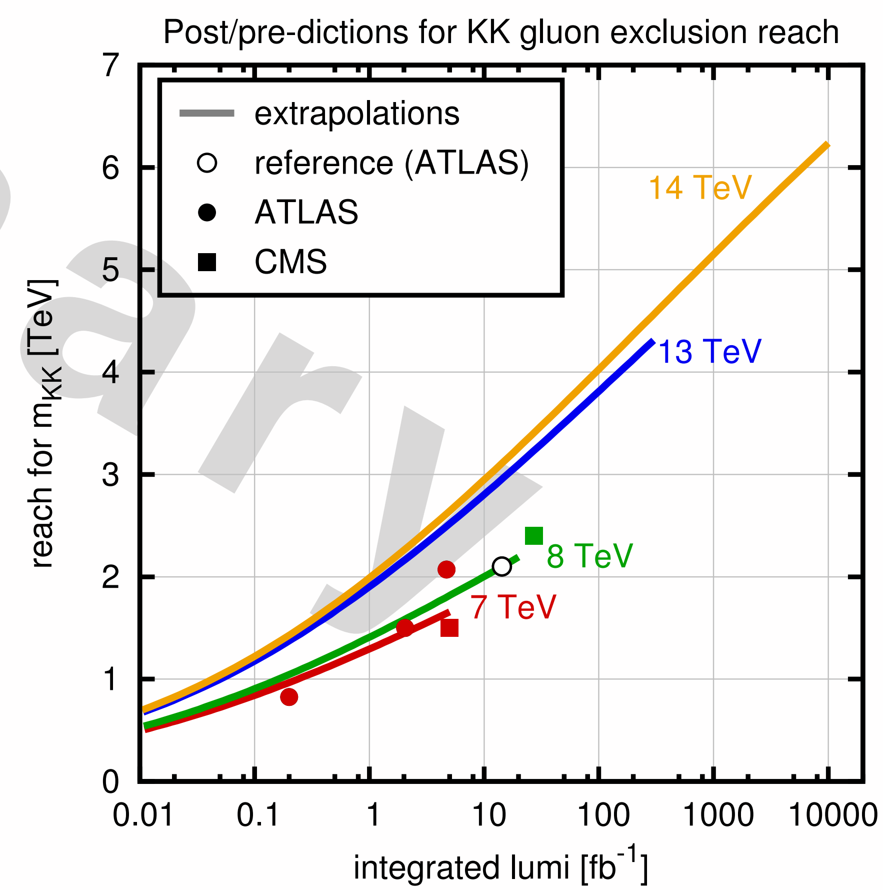

Post/pre-dictions for excited quark exclusion reach
extrapolations
reference (ATLAS)
ATLAS
CMS
CDF
14 TeV
13 TeV
8 TeV
7 TeV
1.96 TeV, $p\bar{p}$
reach for m_{q^*} [TeV]
integrated lumi [fb^{-1}]
0.001 0.01 0.1 1 10 100 1000 10000
0 1 2 3 4 5 6 7 8 9 10


Post/pre-dictions for squark exclusion reach
extrapolations
reference (CMS)
CMS
ATLAS
14 TeV
13 TeV
8 TeV
7 TeV
reach for $2m_{\tilde{q}}$ [TeV]
integrated lumi [fb^{-1}]
0.01 0.1 1 10 100 1000 10000
0 1 2 3 4 5

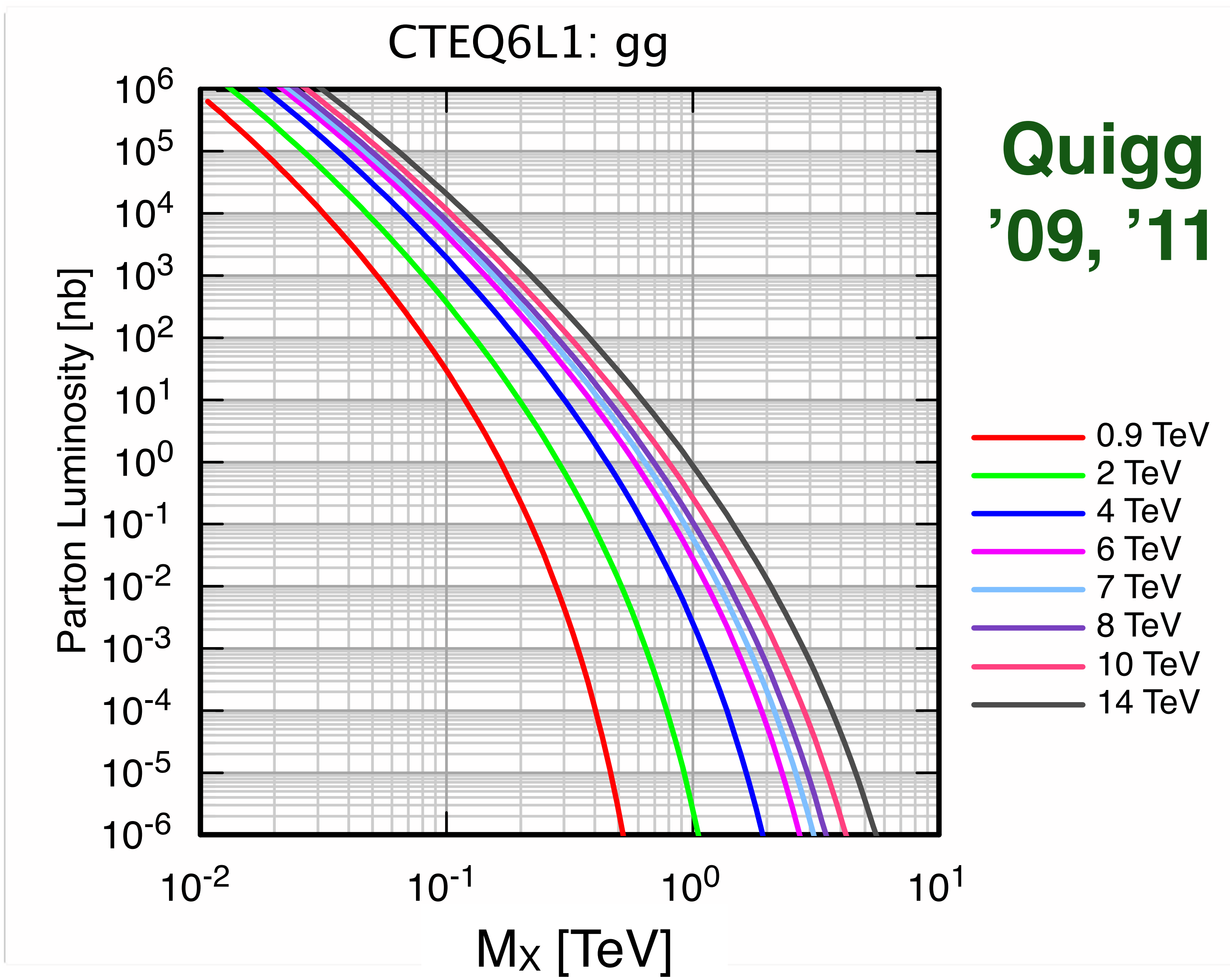

Post/pre-dictions for sequential Z' exclusion reach
reference (ATLAS)
extrapolations
ATLAS / CDF
CMS / D0
14 TeV
13 TeV
8 TeV
7 TeV
1.96 TeV, $p\bar{p}$
Z' reach [TeV]
integrated lumi [fb^{-1}]
0.01 0.1 1 10 100 1000 10000
0 1 2 3 4 5 6 7 8


Post/pre-dictions for gluino exclusion reach
extrapolations
reference (ATLAS)
ATLAS
CMS
14 TeV
13 TeV
8 TeV
7 TeV
reach for $2m_{\tilde{g}}$ [TeV]
integrated lumi [fb^{-1}]
0.01 0.1 1 10 100 1000 10000
0 1 2 3 4 5 6 7


Post/pre-dictions for stop exclusion reach
extrapolations
reference (ATLAS)
ATLAS
CMS
14 TeV
13 TeV
8 TeV
7 TeV
reach for $2m_{\tilde{t}}$ [TeV]
integrated lumi [fb^{-1}]
0.01 0.1 1 10 100 1000 10000
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5


Post/pre-dictions for KK gluon exclusion reach
extrapolations
reference (ATLAS)
ATLAS
CMS
14 TeV
13 TeV
8 TeV
7 TeV
reach for m_{KK} [TeV]
integrated lumi [fb^{-1}]
0.01 0.1 1 10 100 1000 10000
0 1 2 3 4 5 6 7

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 ~ 10% in M_X

From your iPhone

(or a generic browser)

cern.ch/collider-reach

Rule of Thumb #2

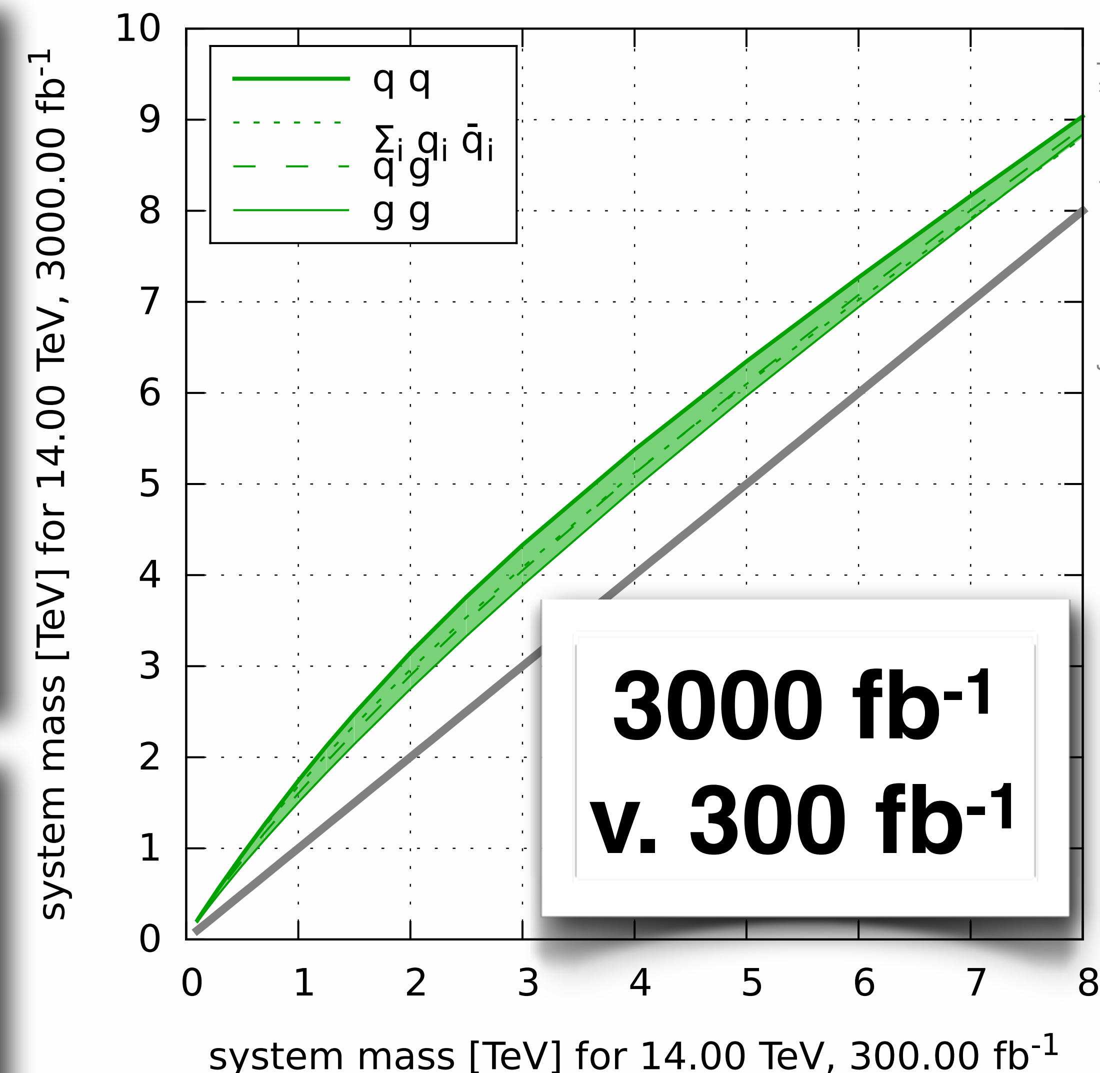
(apparently not widely known previously)

Increase luminosity by factor 10

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

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

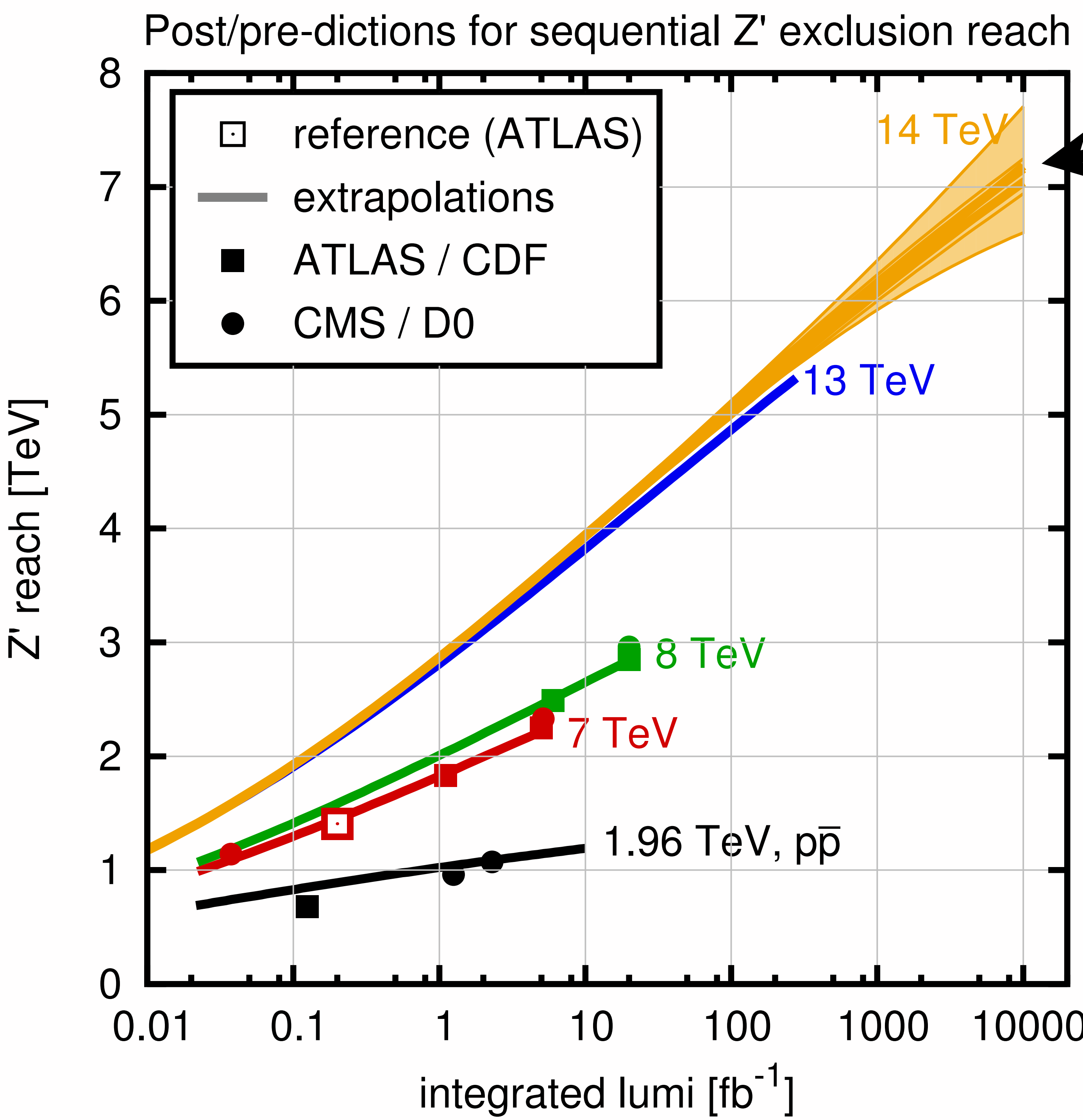


Differences between PDFs?
PDF uncertainties?

mostly small

But let's examine
one exception

Impact of PDF uncertainties

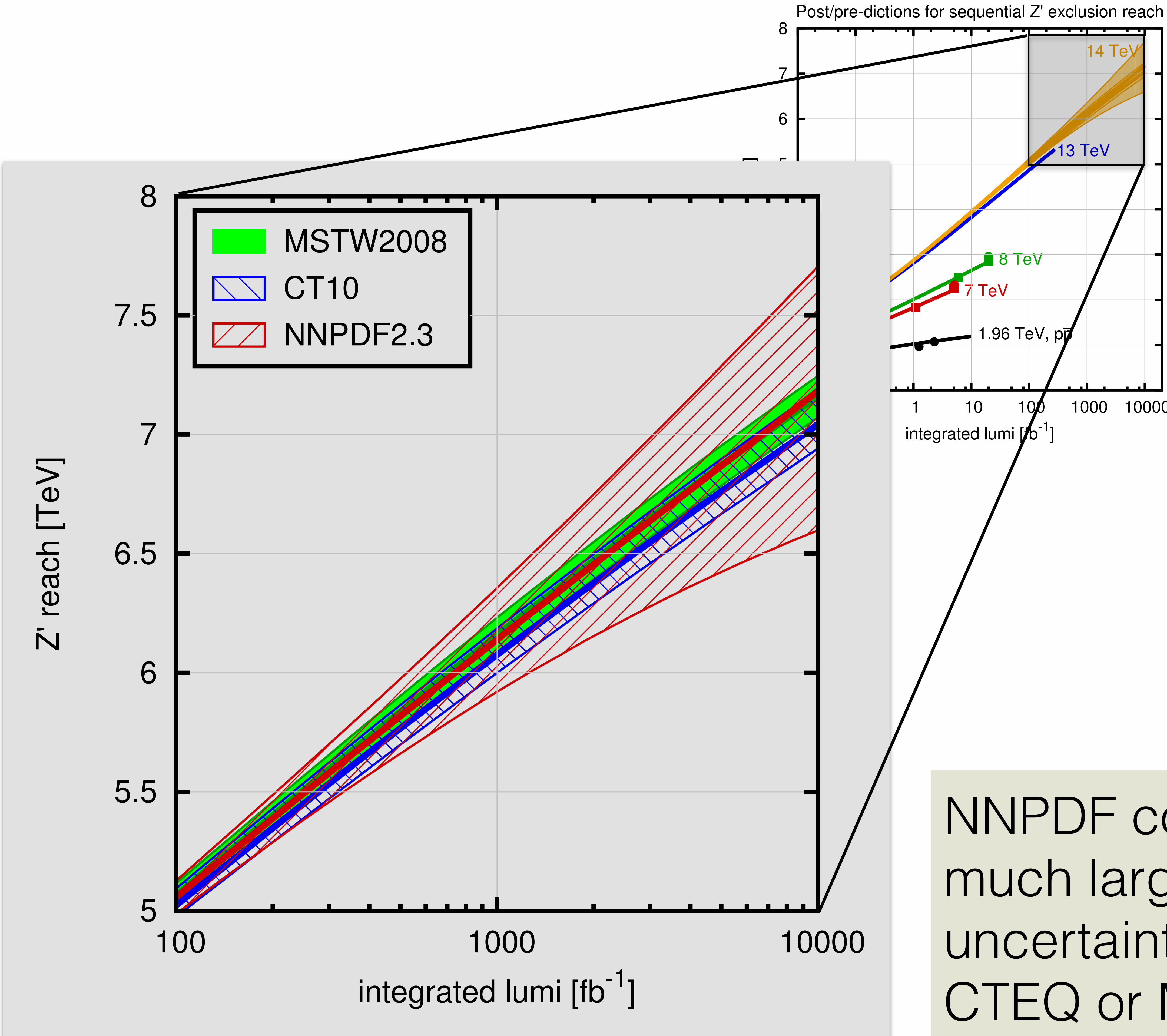


Envelope of CTEQ10 MSTW2008 & NNPDF23 results

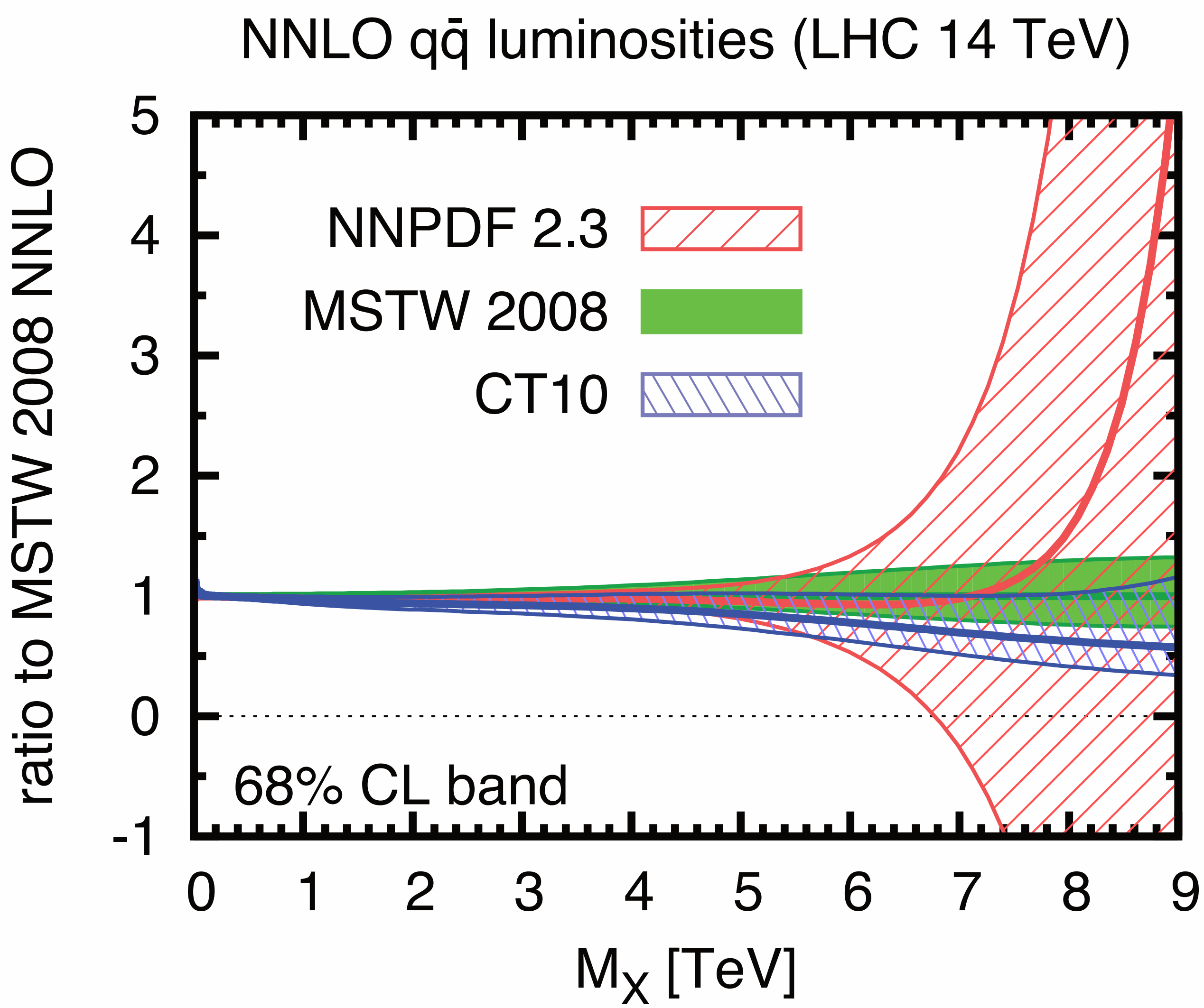
Caveats

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



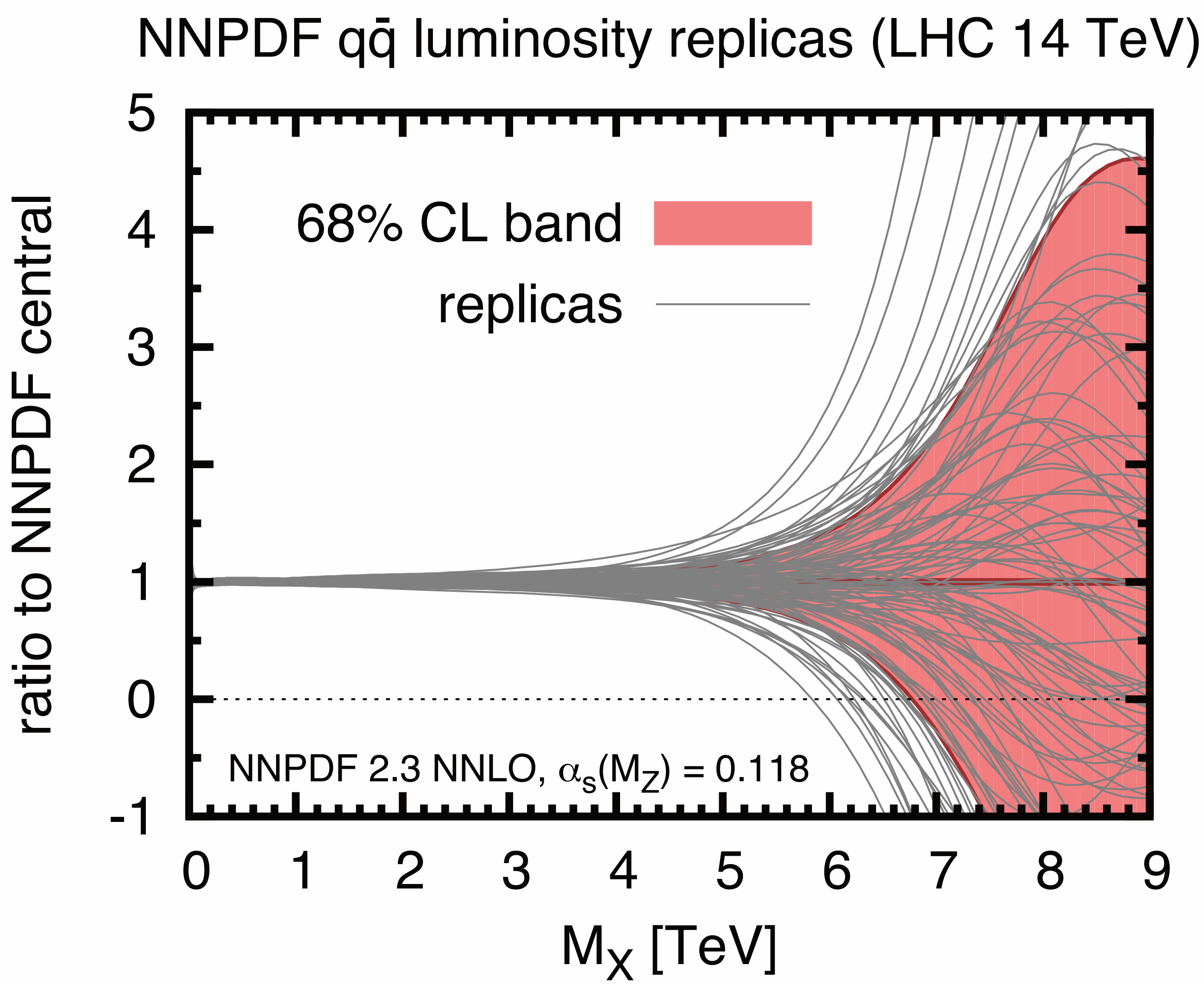
NNPDF comes with much larger uncertainties than CTEQ or MSTW



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



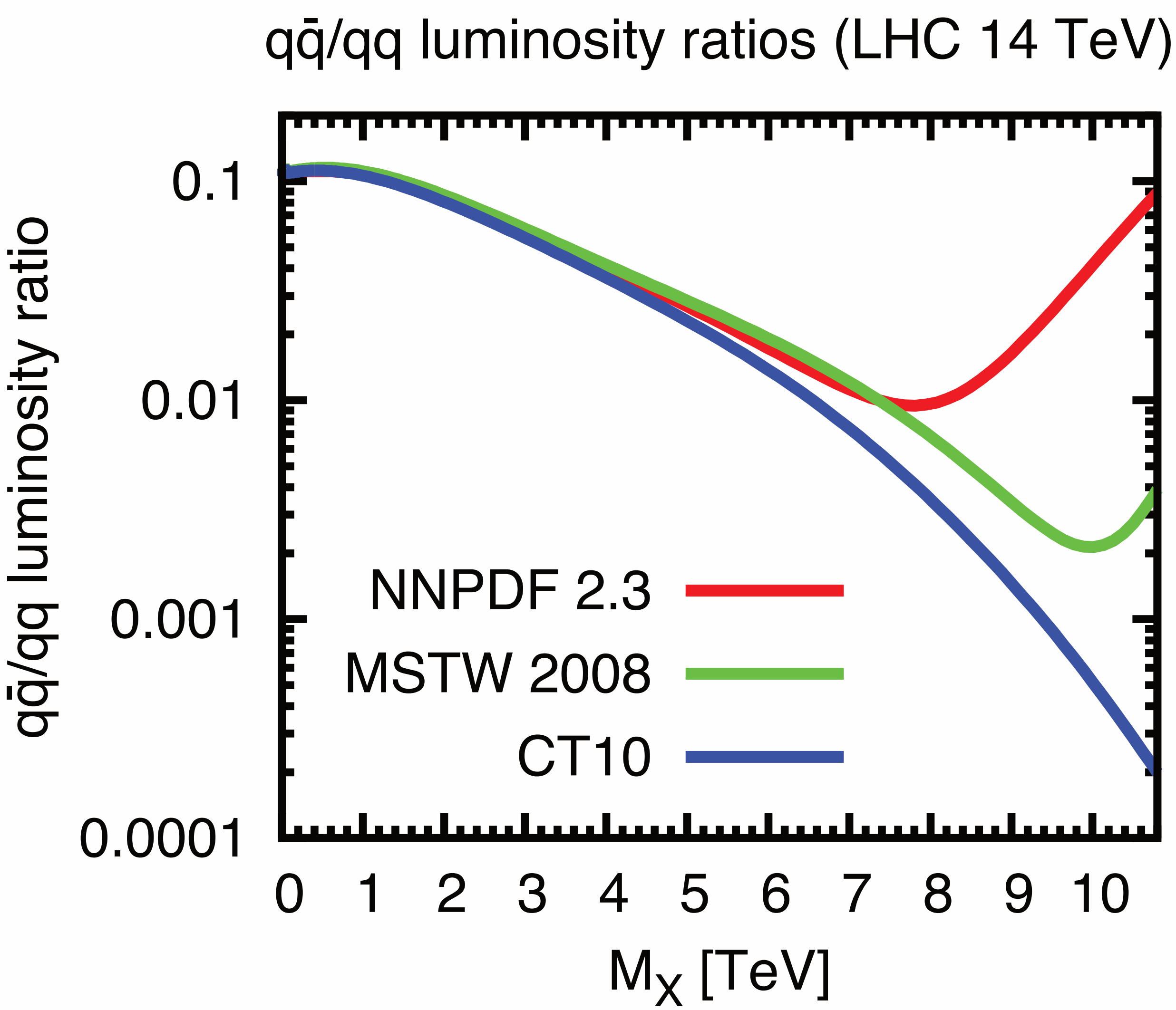
Observation #2

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?



Observation #3

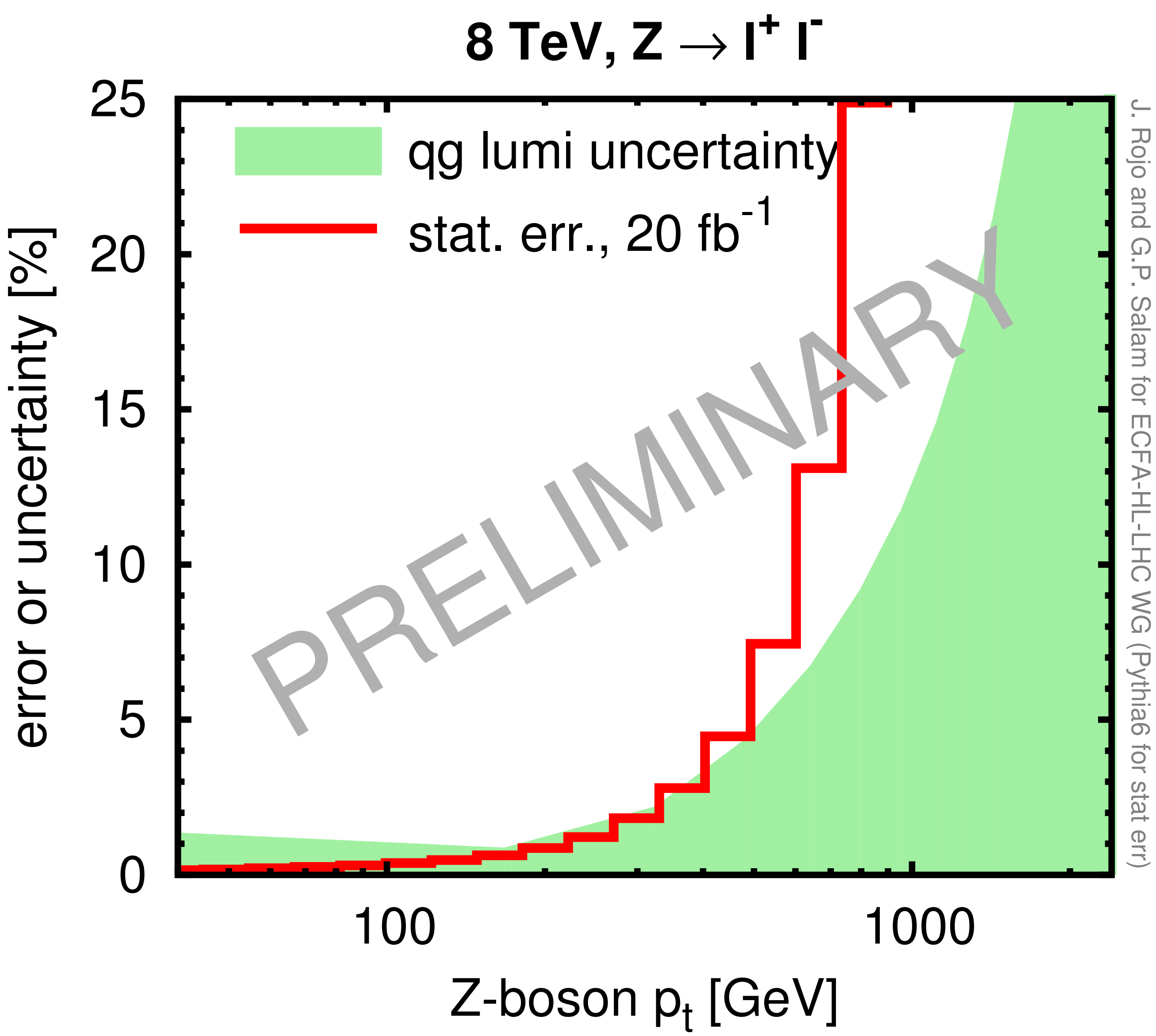
qqbar/qq lumi increases for $x > 0.5$ in NNPDF ($x > 0.7$ in MSTW)

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



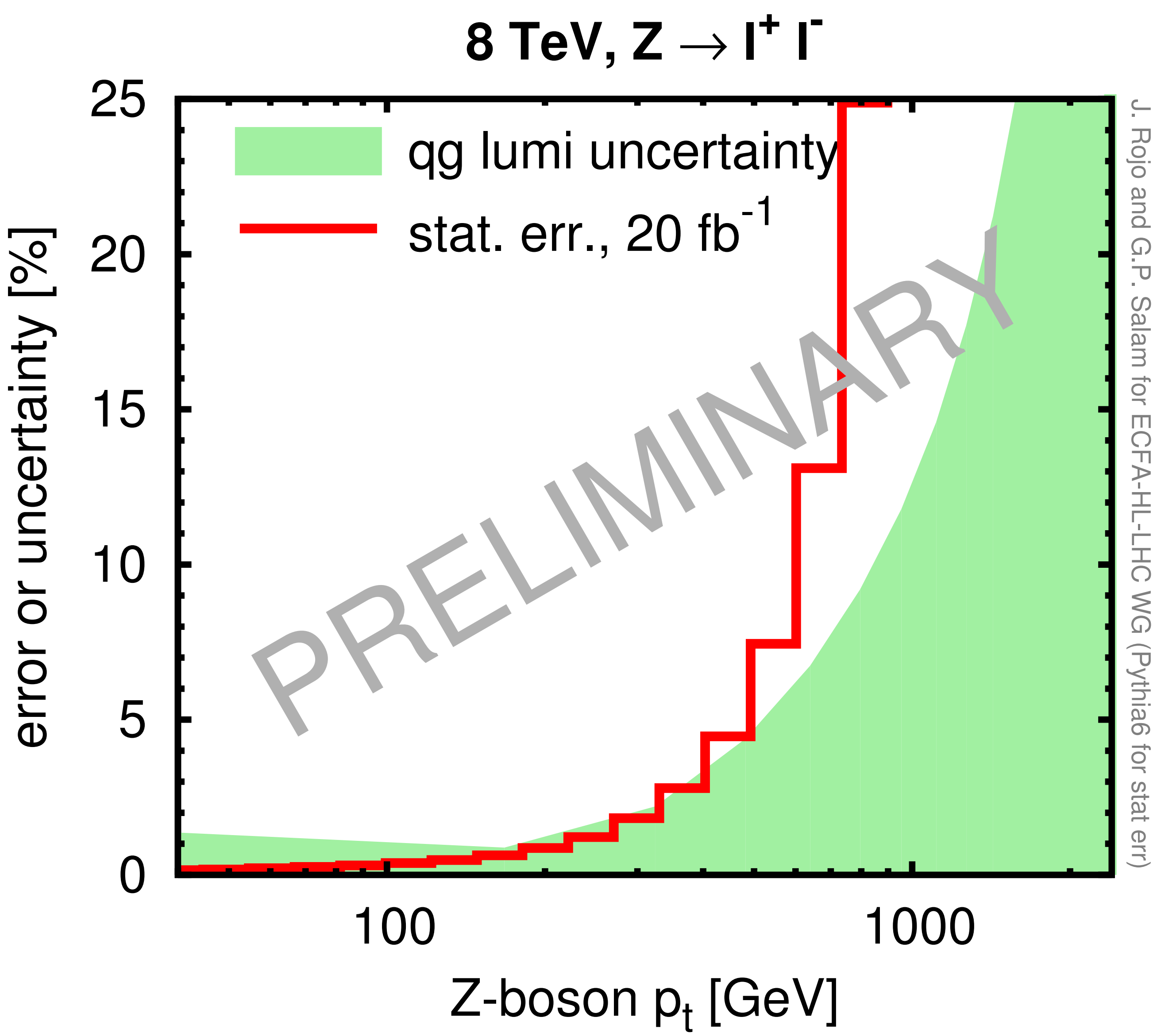
[Studies with Juan Rojo and Andi Weiler for ECFA HL-LHC workshop in October 2013]

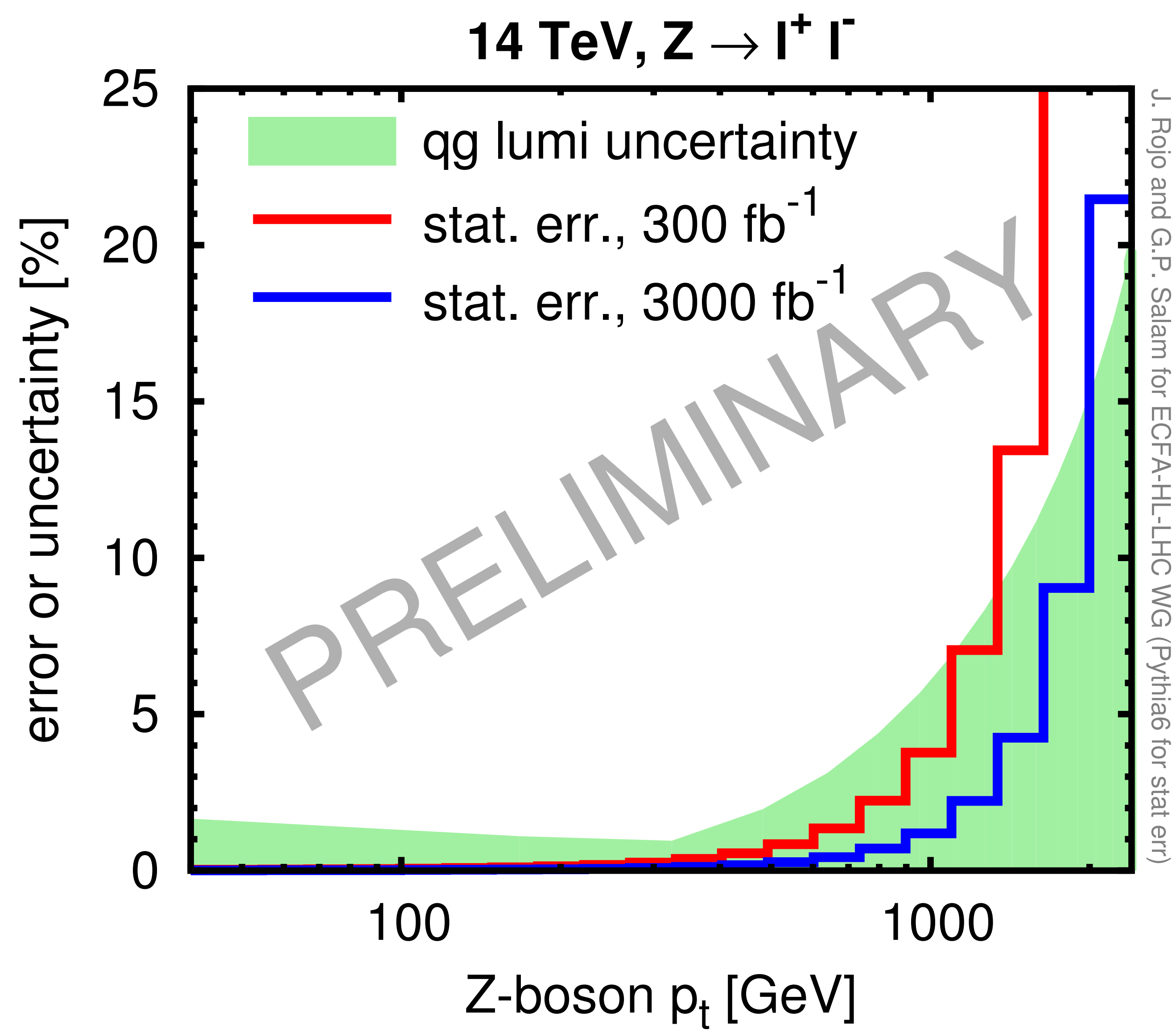
Emerging realisation that the Z p_t spectrum is a potentially very precise handle on PDFs [quark × glue × α_s]

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





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

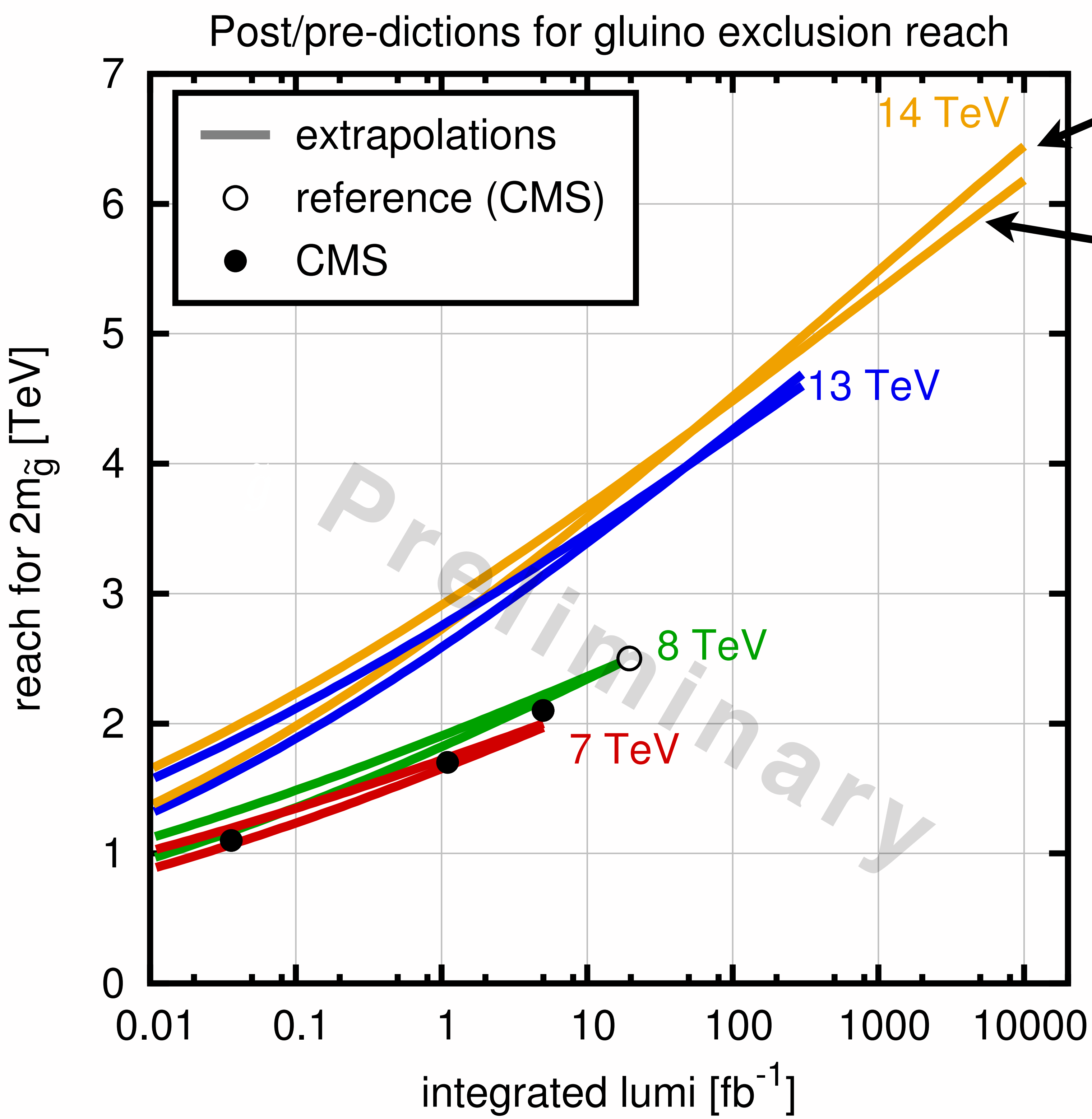
Differences between large-x antiquark PDF uncertainties in various PDF sets are not surprising in their own right.

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?



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

From your Android Phone

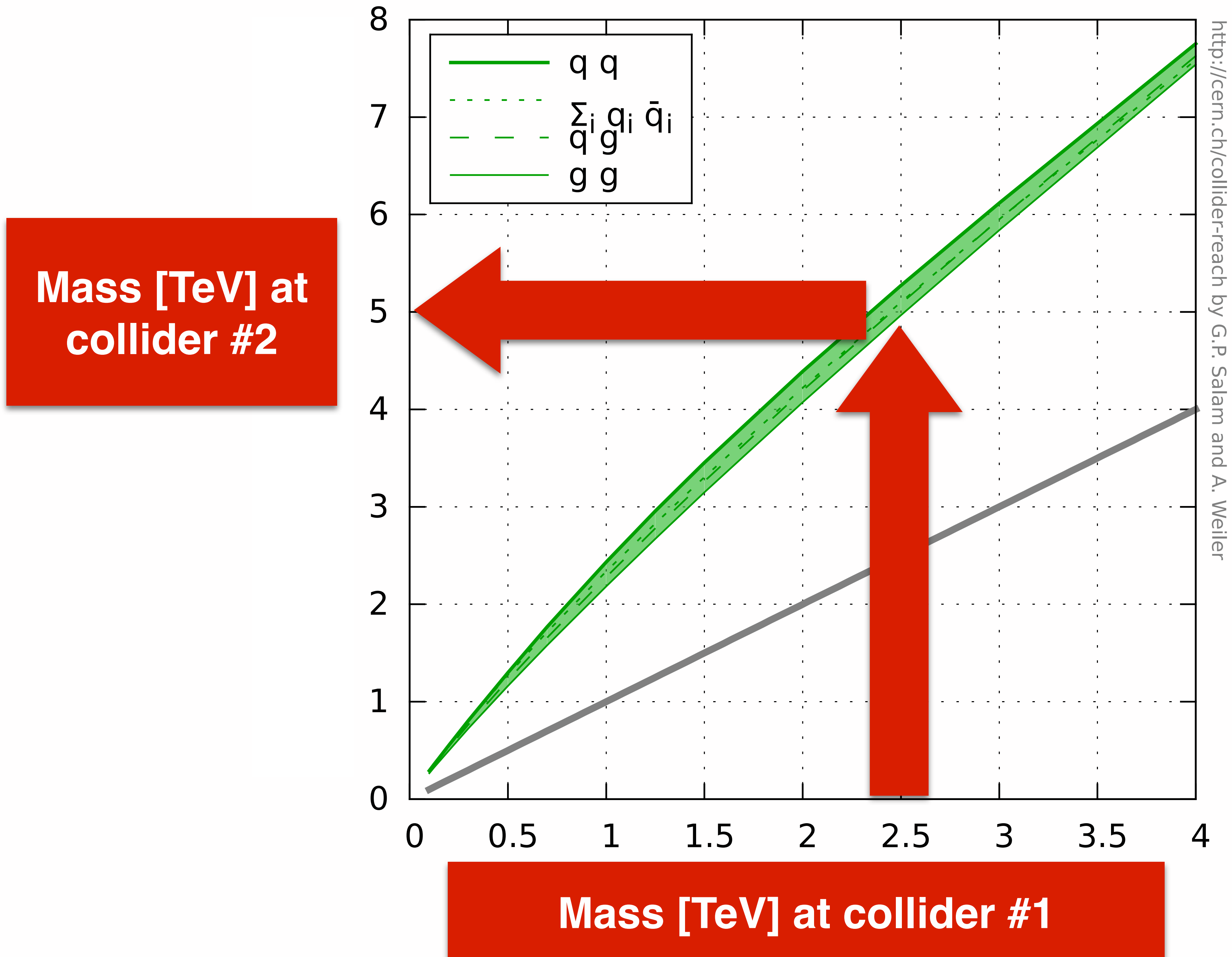
(or a generic browser)

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



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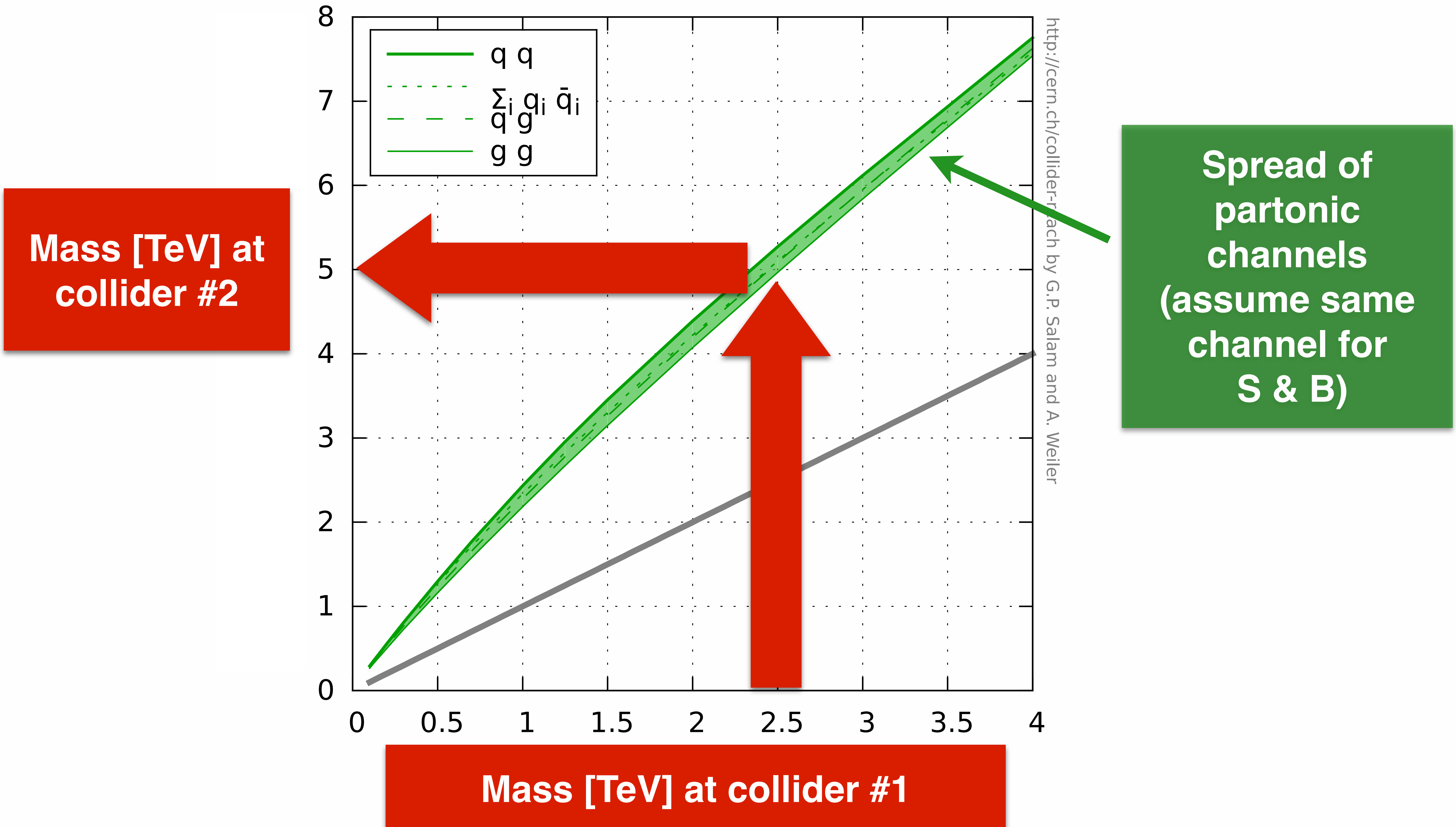
PDF: MSTW2008nnlo68cl



Collider Reach (β) Home Plots About

cern.ch/collider-reach

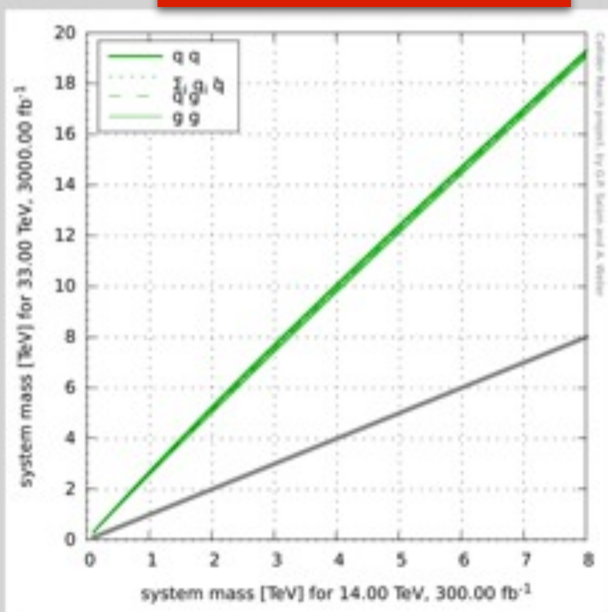
The Collider Reach tool gives you a quick (and dirty) estimate of the relation between the mass reaches of different proton-proton collider setups.

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

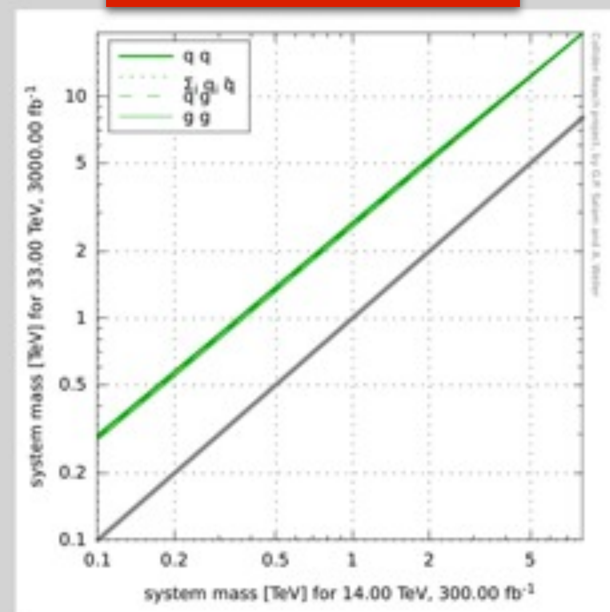
Submit

Plots

linear plot



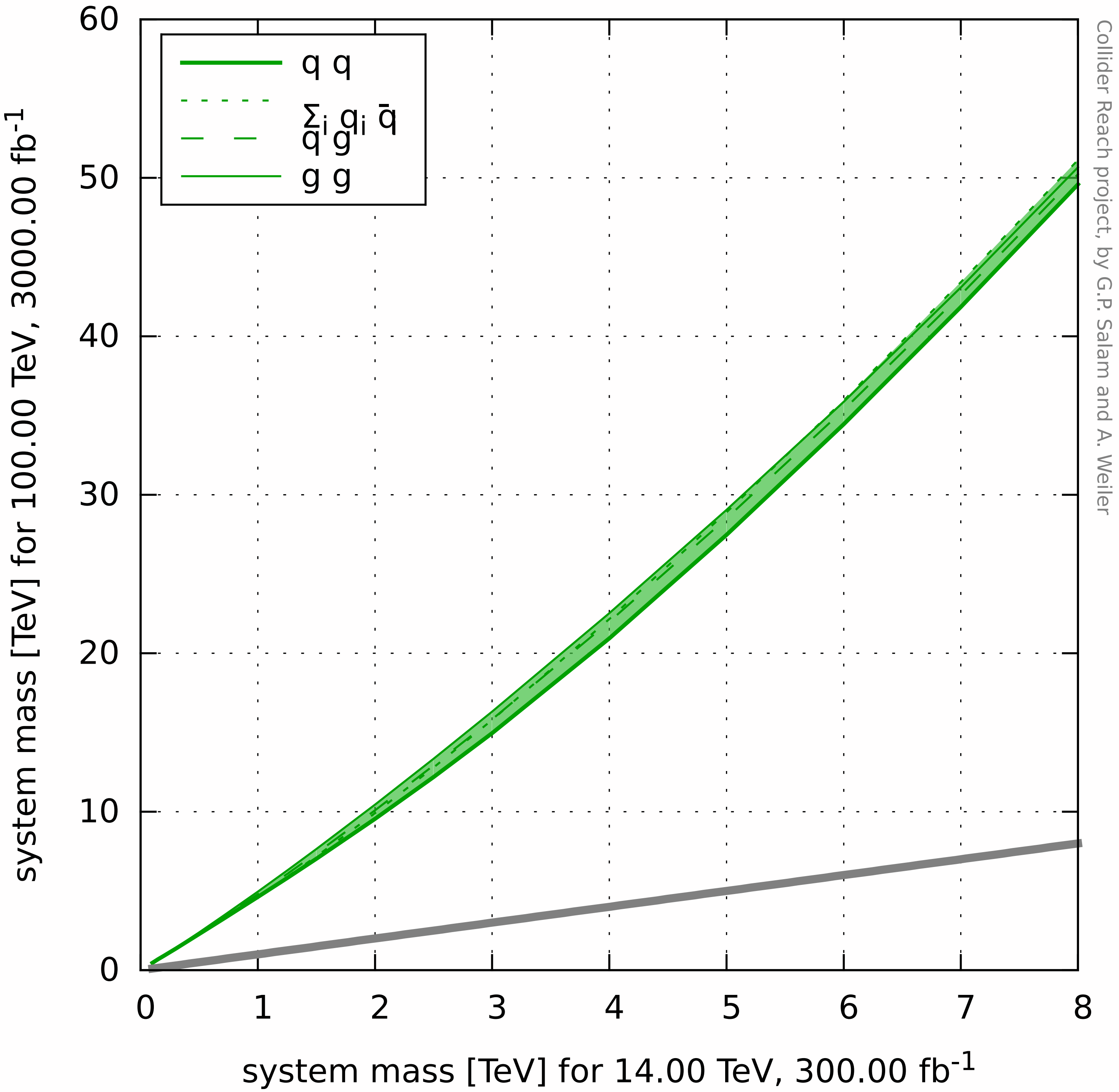
log-log plot



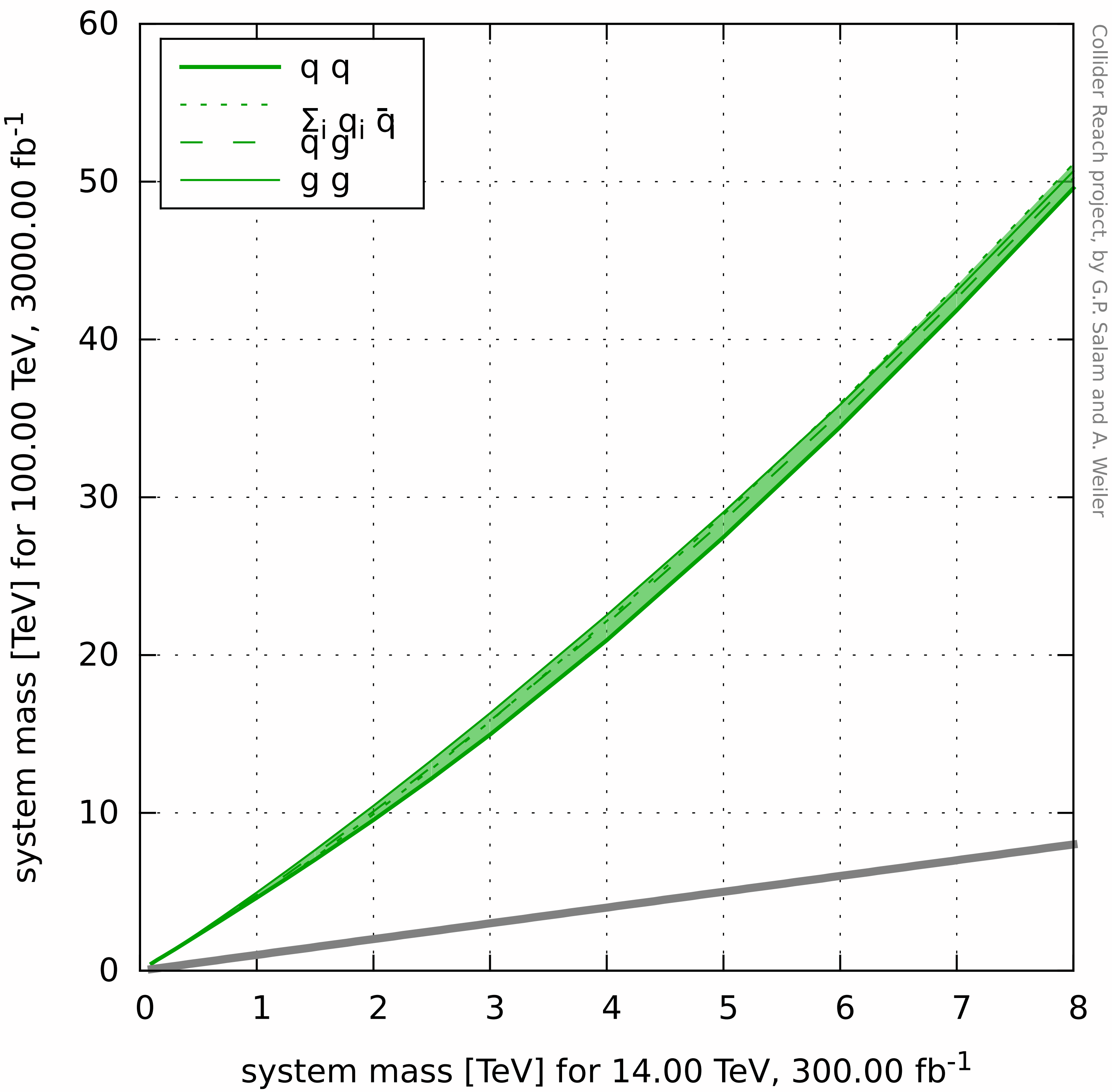
Download: collider.pdf, colliderloglog.pdf, plot generation log file
The PDF choice was CT10nlo.LHgrid

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$_{3\ ab^{-1}}$



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



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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

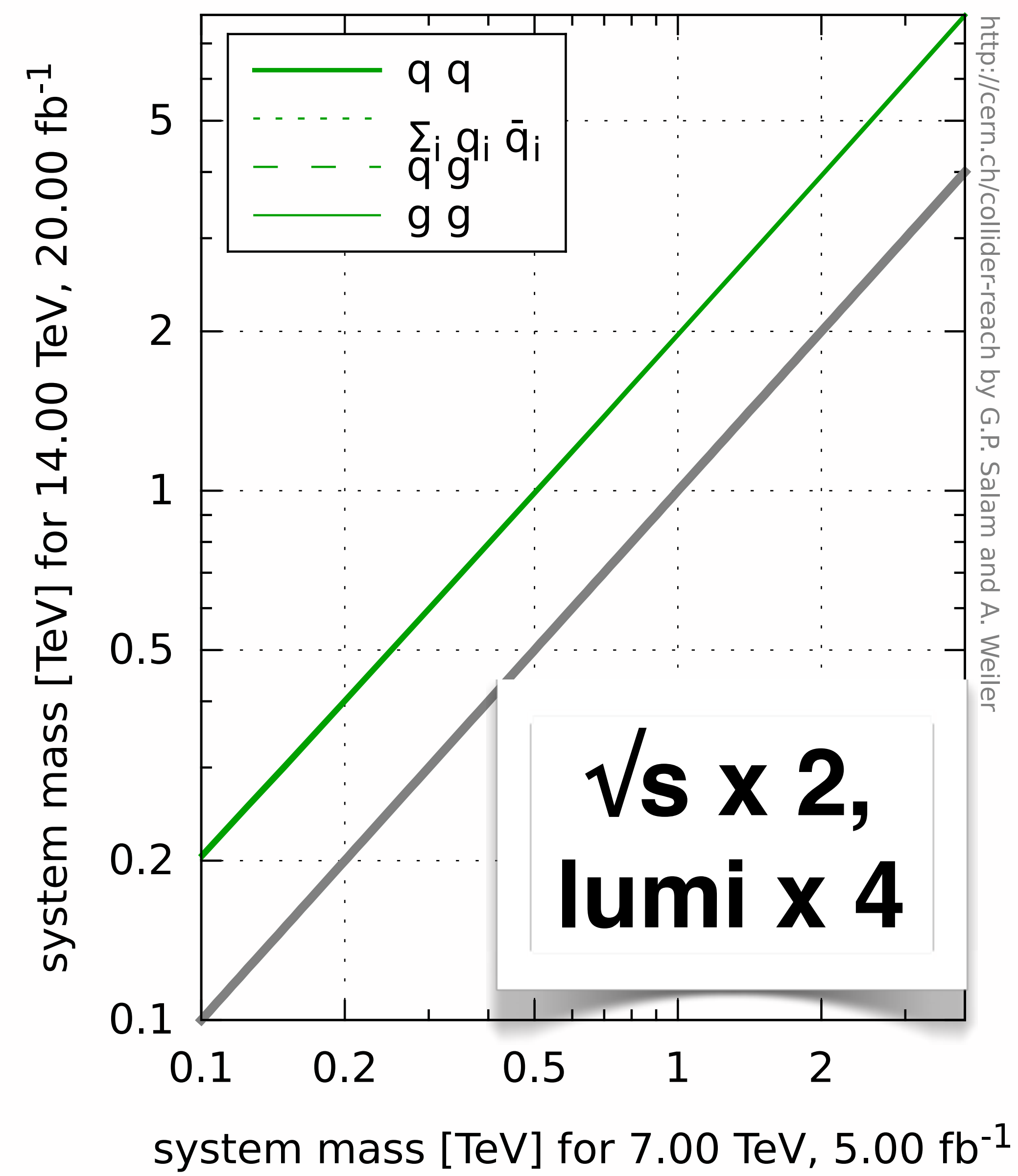
(well known among practitioners)

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/mass^2 scaling of cross sections]

PDF scaling variations are small effect



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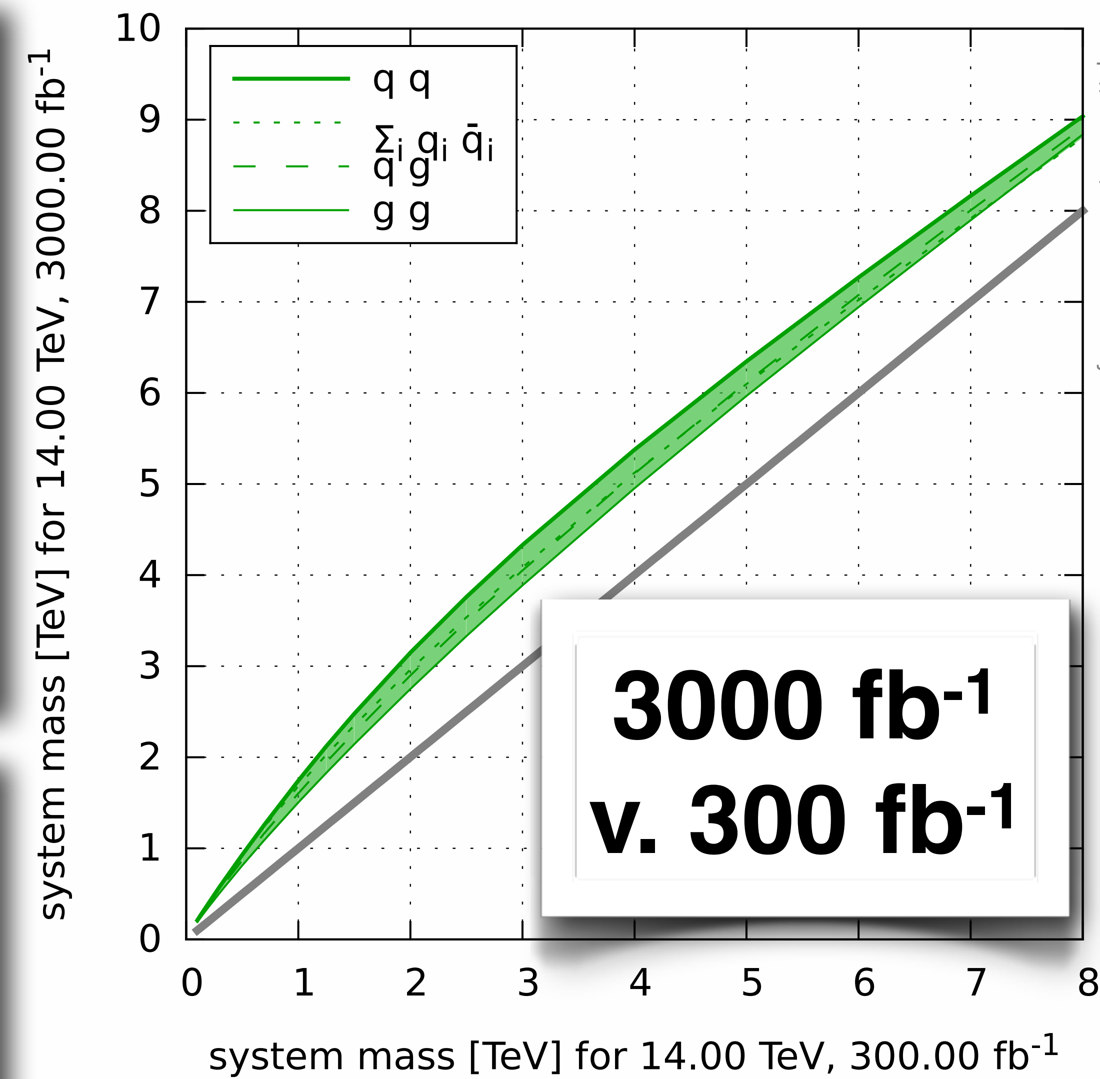
i.e. for $\sqrt{s}$=14 TeV, reach goes by up 1 TeV

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 ≲ B)

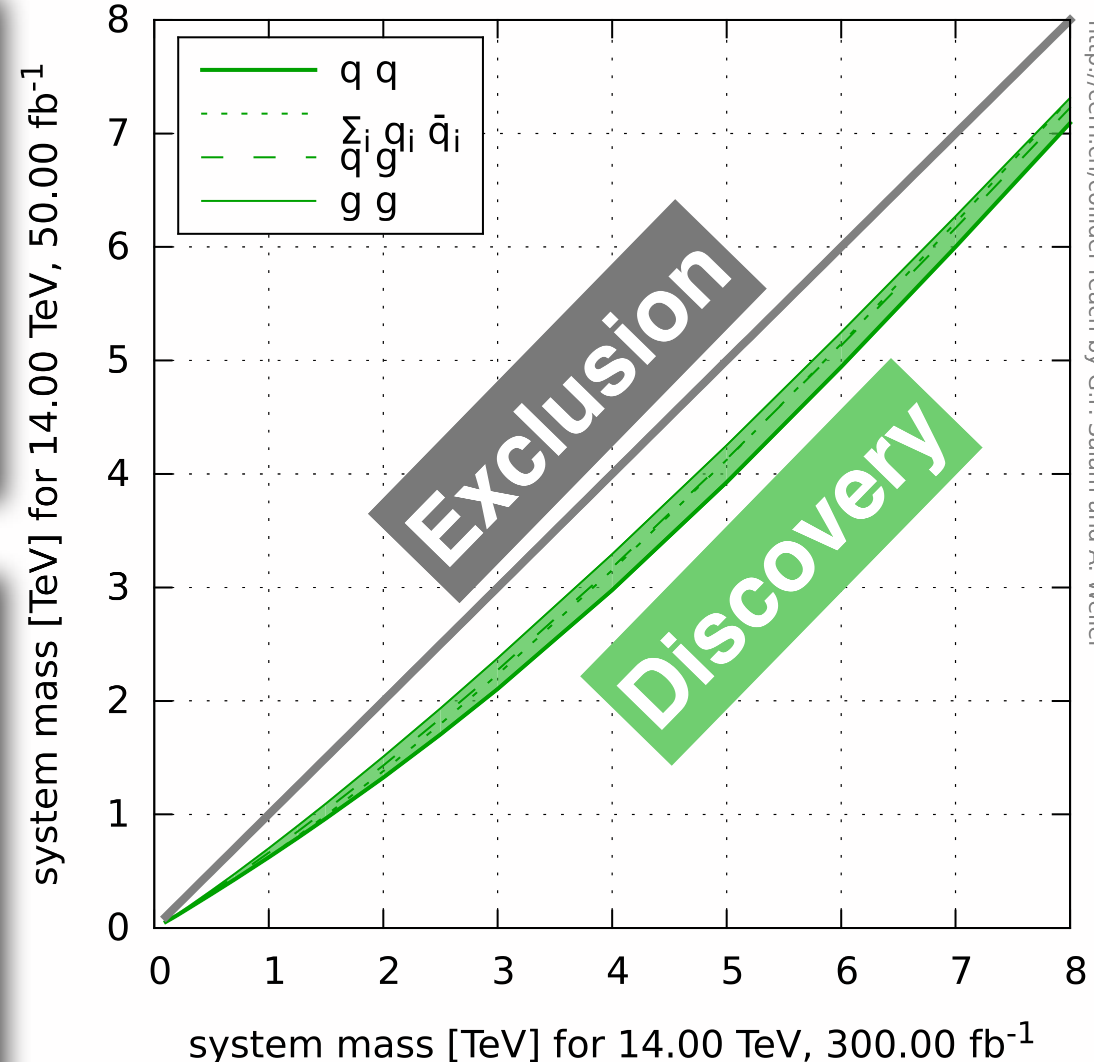
Exclusion is 2-**σ**
Discovery is 5-**σ**

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

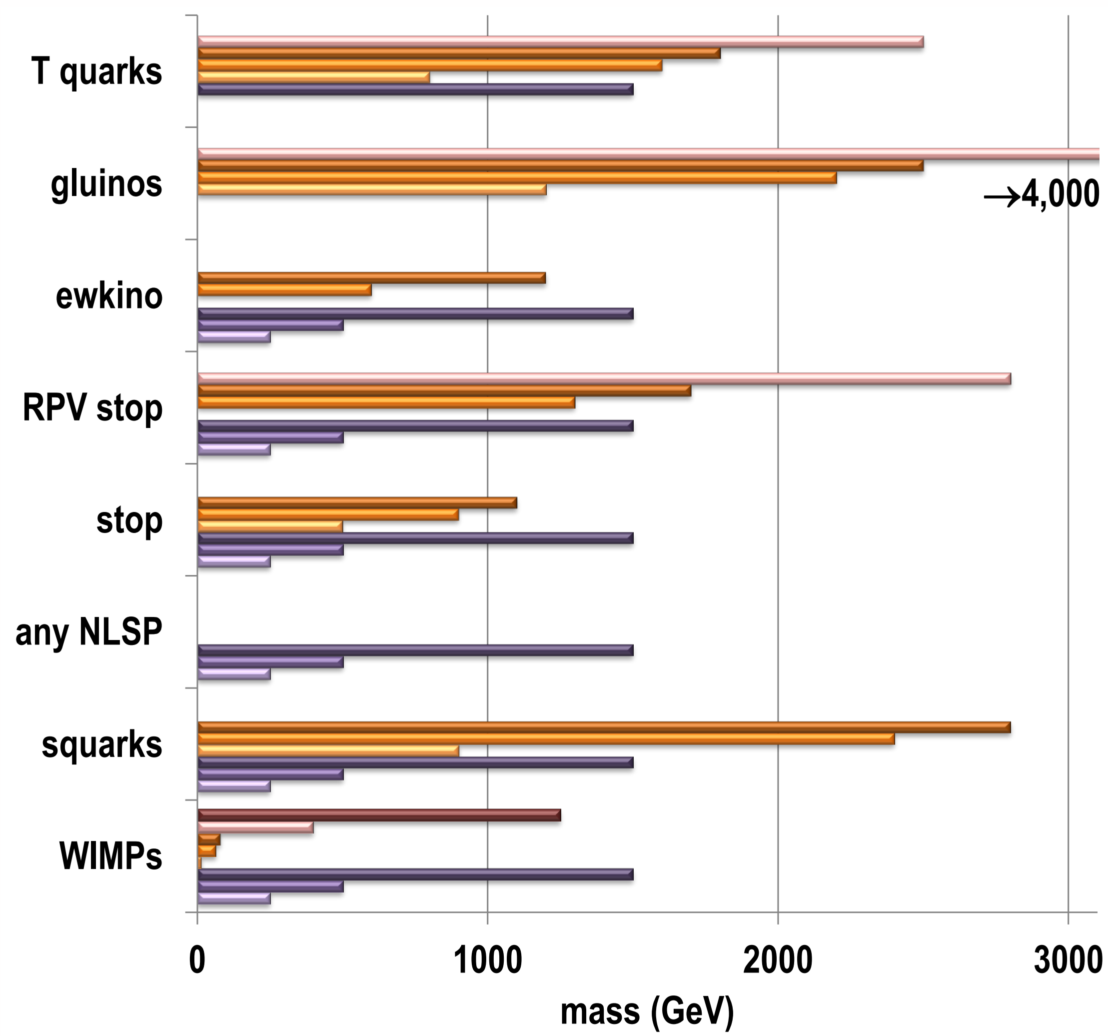
~ 0.8 TeV at 14 TeV

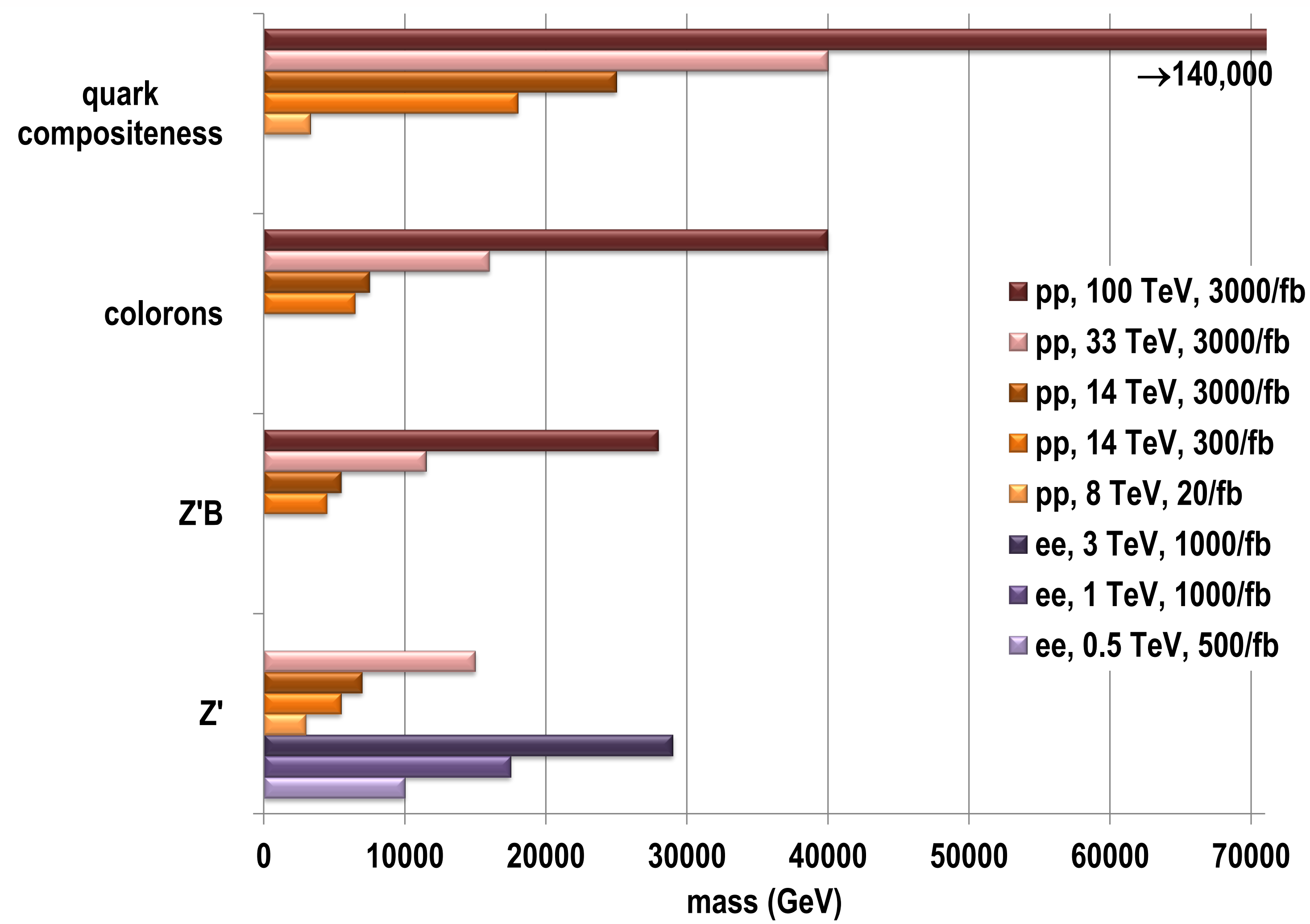


Future colliders

- 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

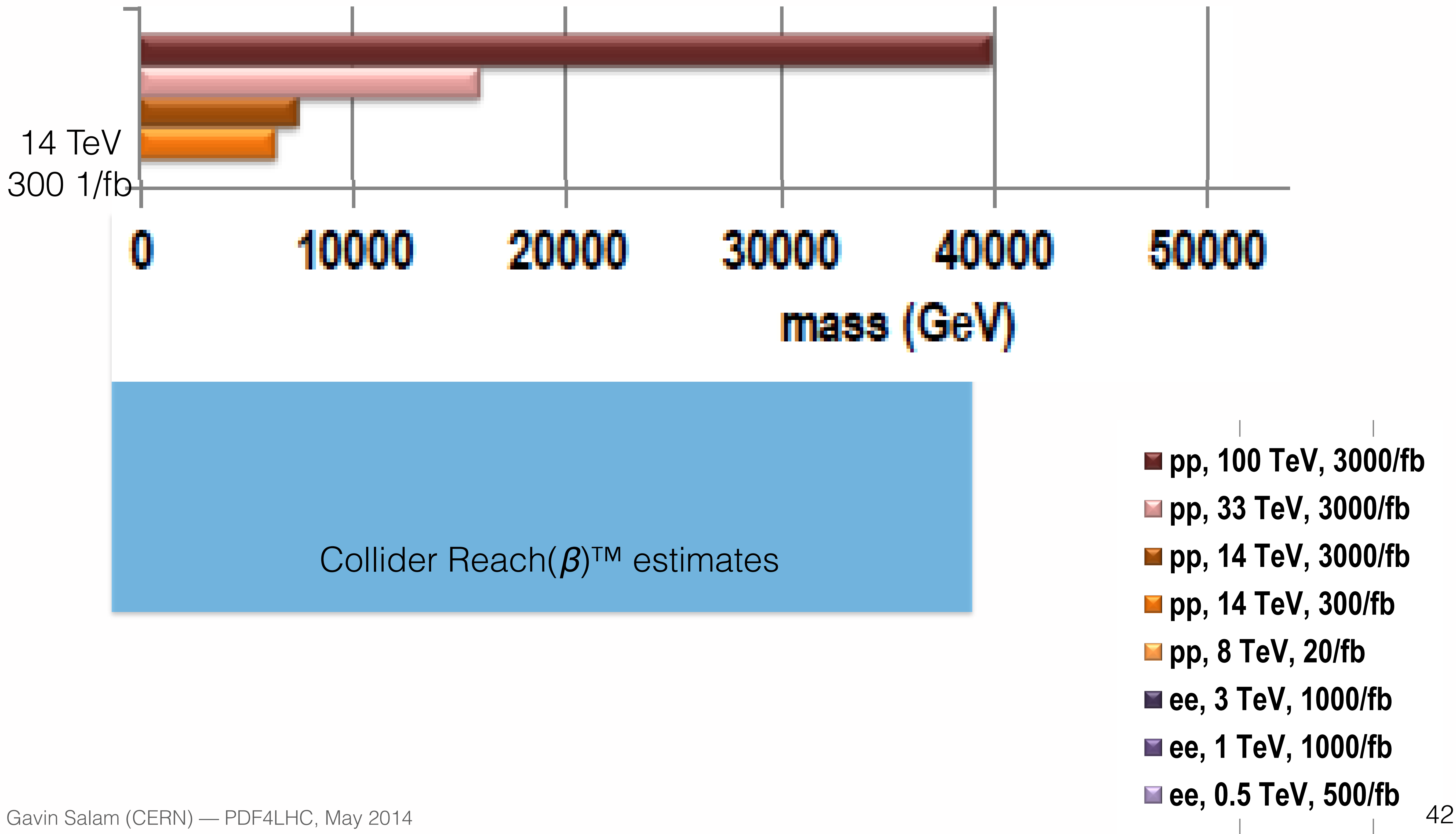
Future colliders comparison





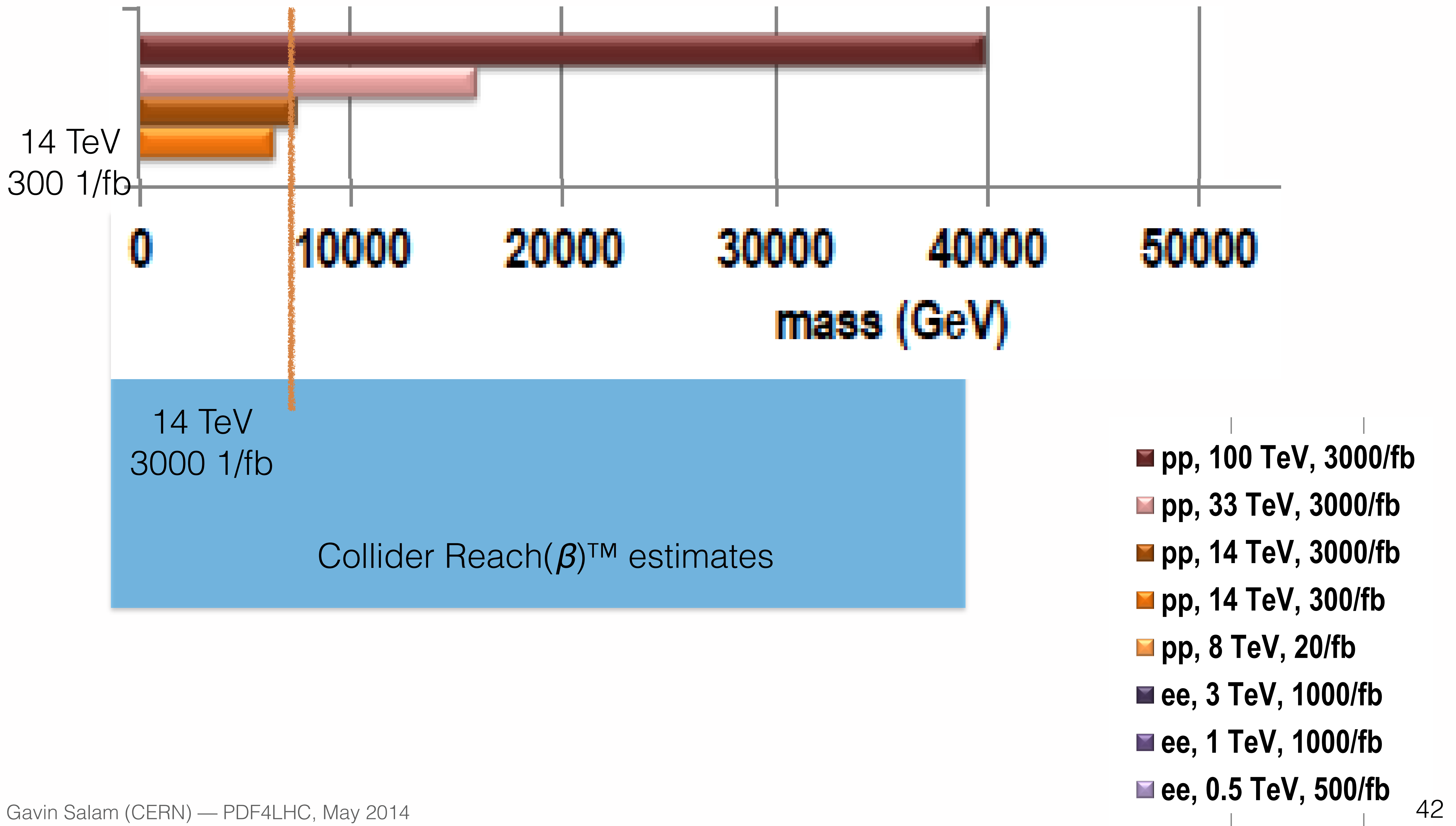
Energy Frontier Snowmass study (1311.0299)

Colorons



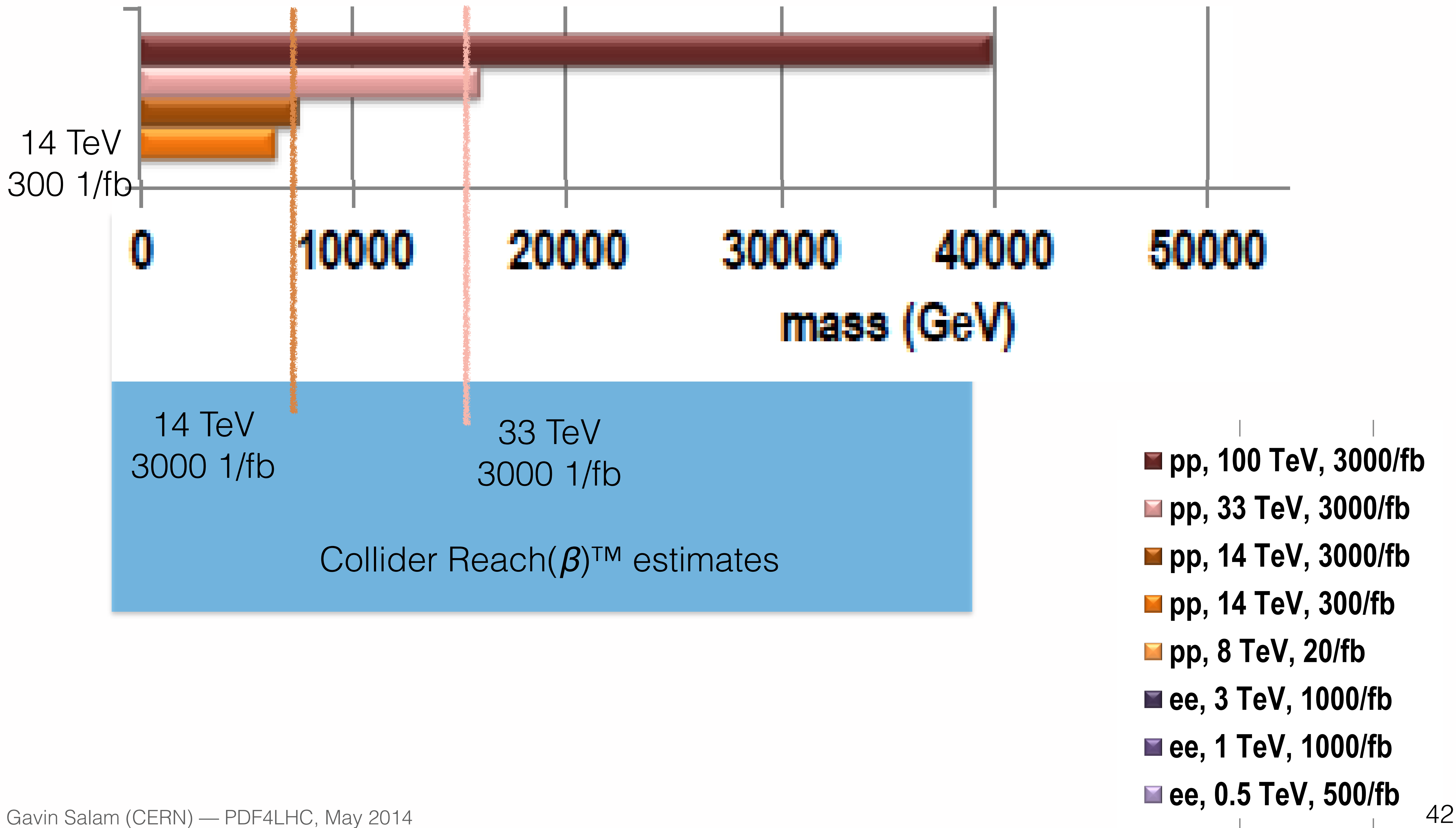
Collider Reach(β)™ estimates

Colorons

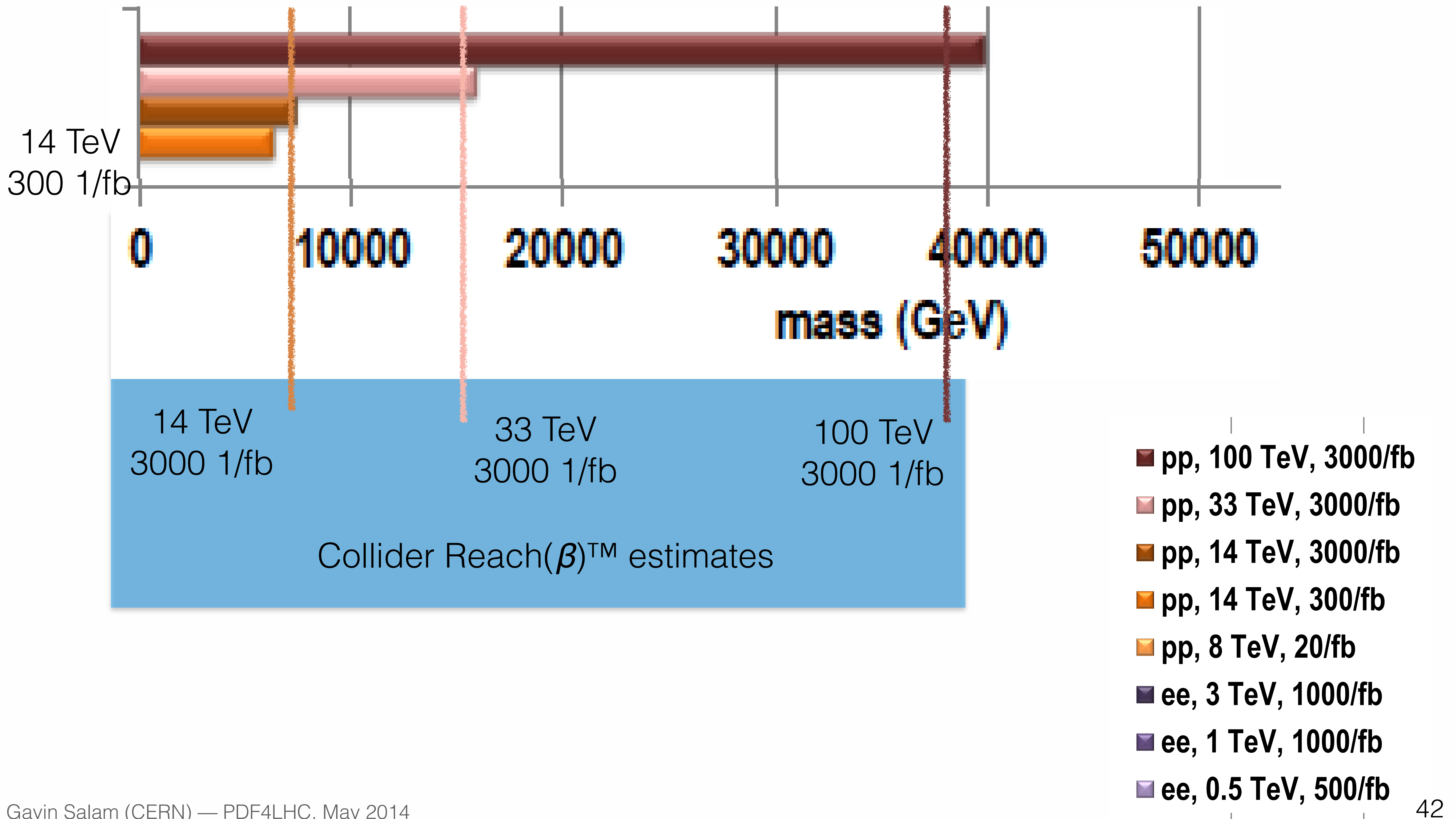


14 TeV
300 1/fb
0
10000
20000
30000
40000
50000
mass (GeV)
14 TeV
3000 1/fb
Collider Reach(β)™ estimates
pp, 100 TeV, 3000/fb
pp, 33 TeV, 3000/fb
pp, 14 TeV, 3000/fb
pp, 14 TeV, 300/fb
pp, 8 TeV, 20/fb
ee, 3 TeV, 1000/fb
ee, 1 TeV, 1000/fb
ee, 0.5 TeV, 500/fb

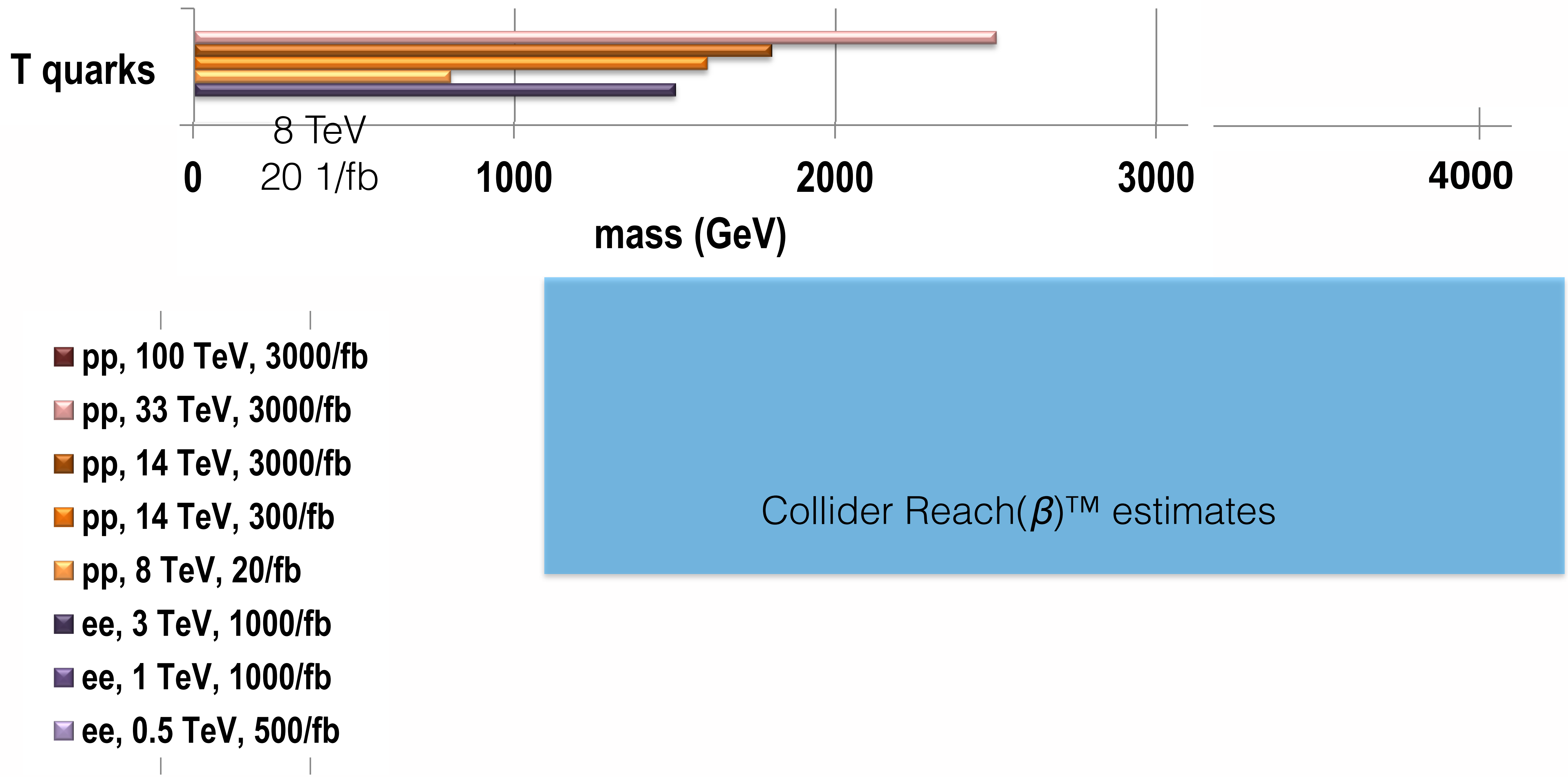
Colorons


14 TeV
300 1/fb
0
10000
20000
30000
40000
50000
mass (GeV)
14 TeV
3000 1/fb
33 TeV
3000 1/fb
Collider Reach(β)™ 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

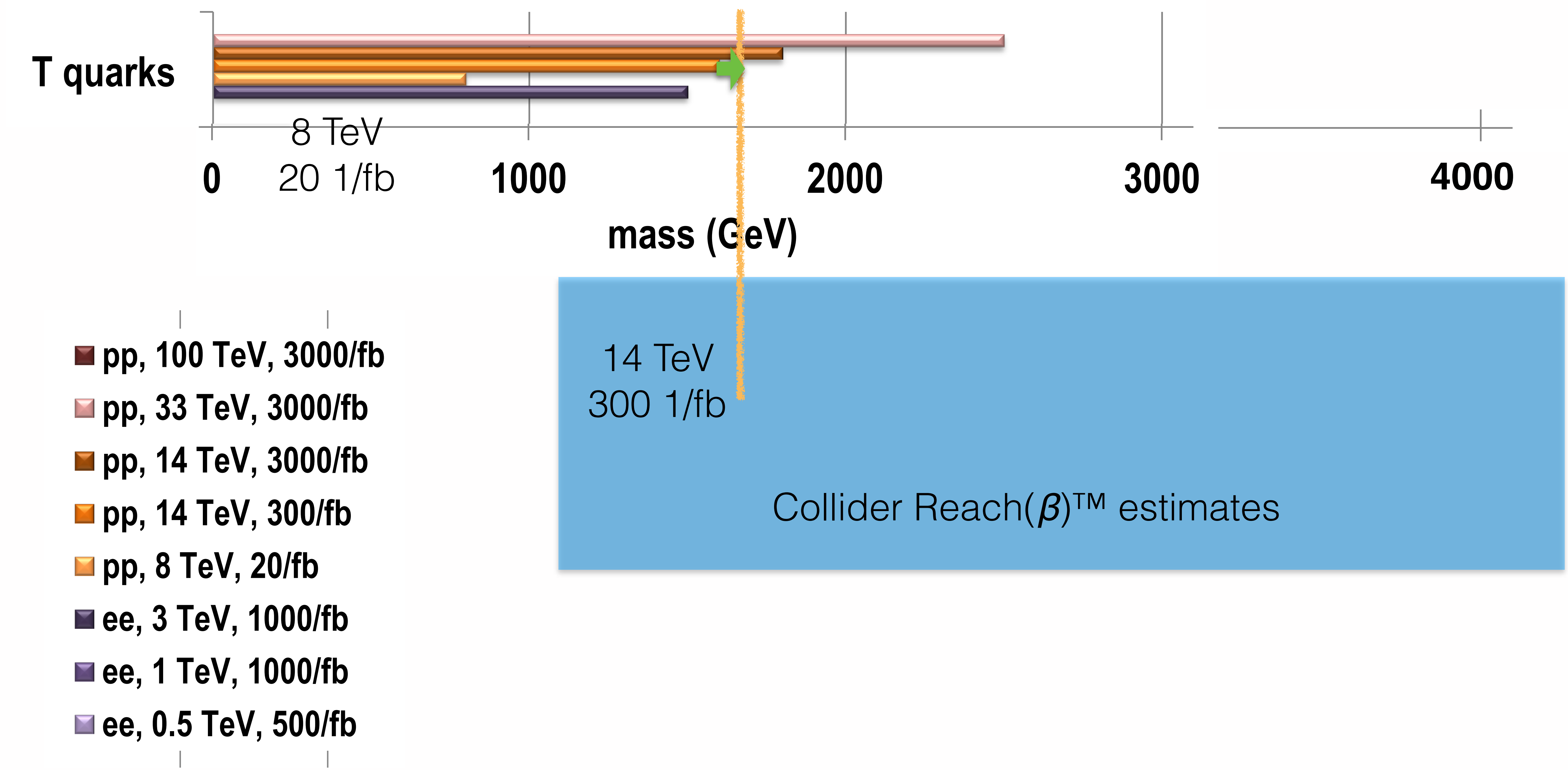

14 TeV
300 1/fb
0
10000
20000
30000
40000
50000
mass (GeV)
14 TeV
3000 1/fb
33 TeV
3000 1/fb
100 TeV
3000 1/fb
Collider Reach(β)™ estimates
pp, 100 TeV, 3000/fb
pp, 33 TeV, 3000/fb
pp, 14 TeV, 3000/fb
pp, 14 TeV, 300/fb
pp, 8 TeV, 20/fb
ee, 3 TeV, 1000/fb
ee, 1 TeV, 1000/fb
ee, 0.5 TeV, 500/fb

T Quarks



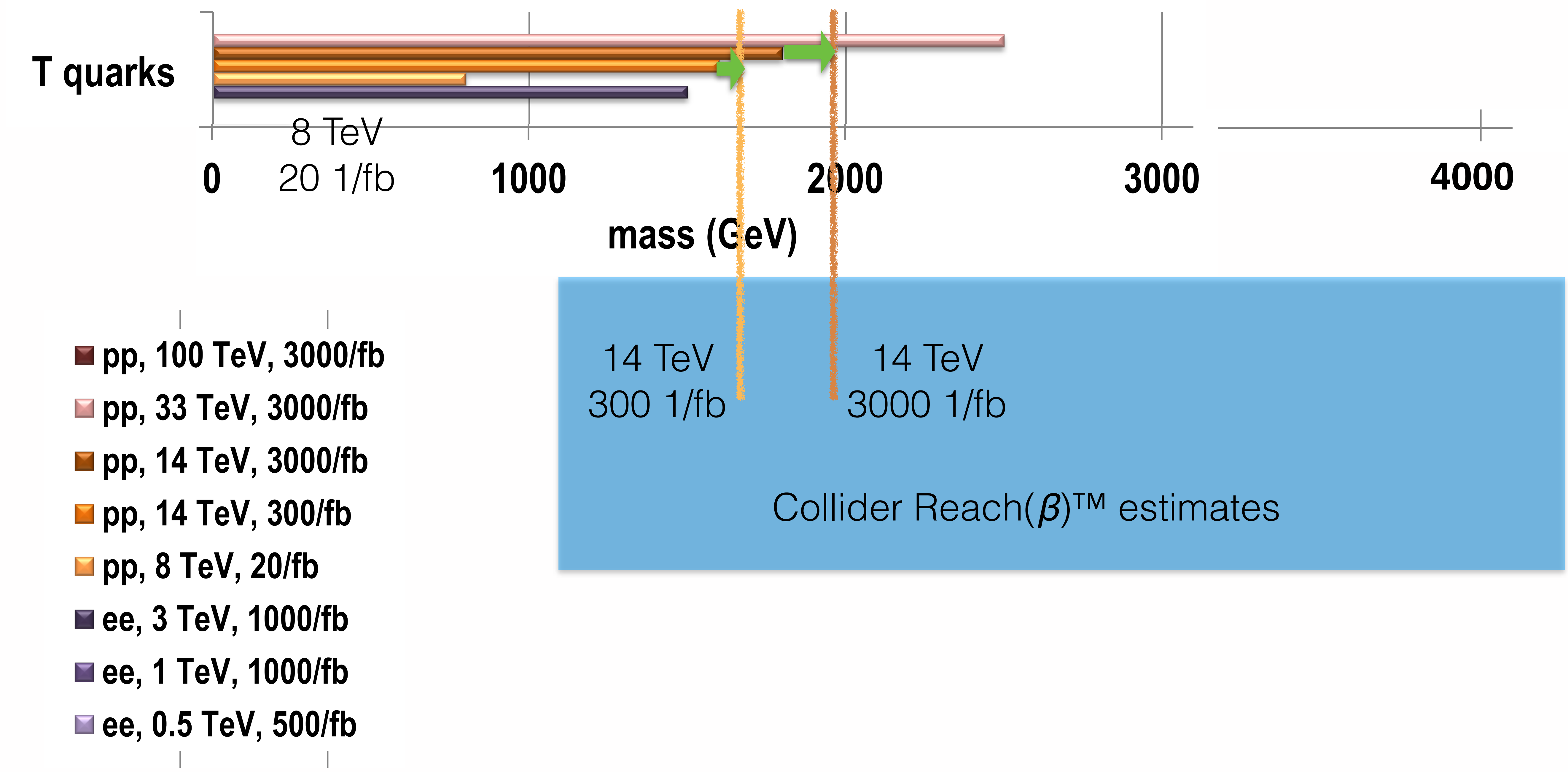
Collider Reach(β)™ estimates

T Quarks

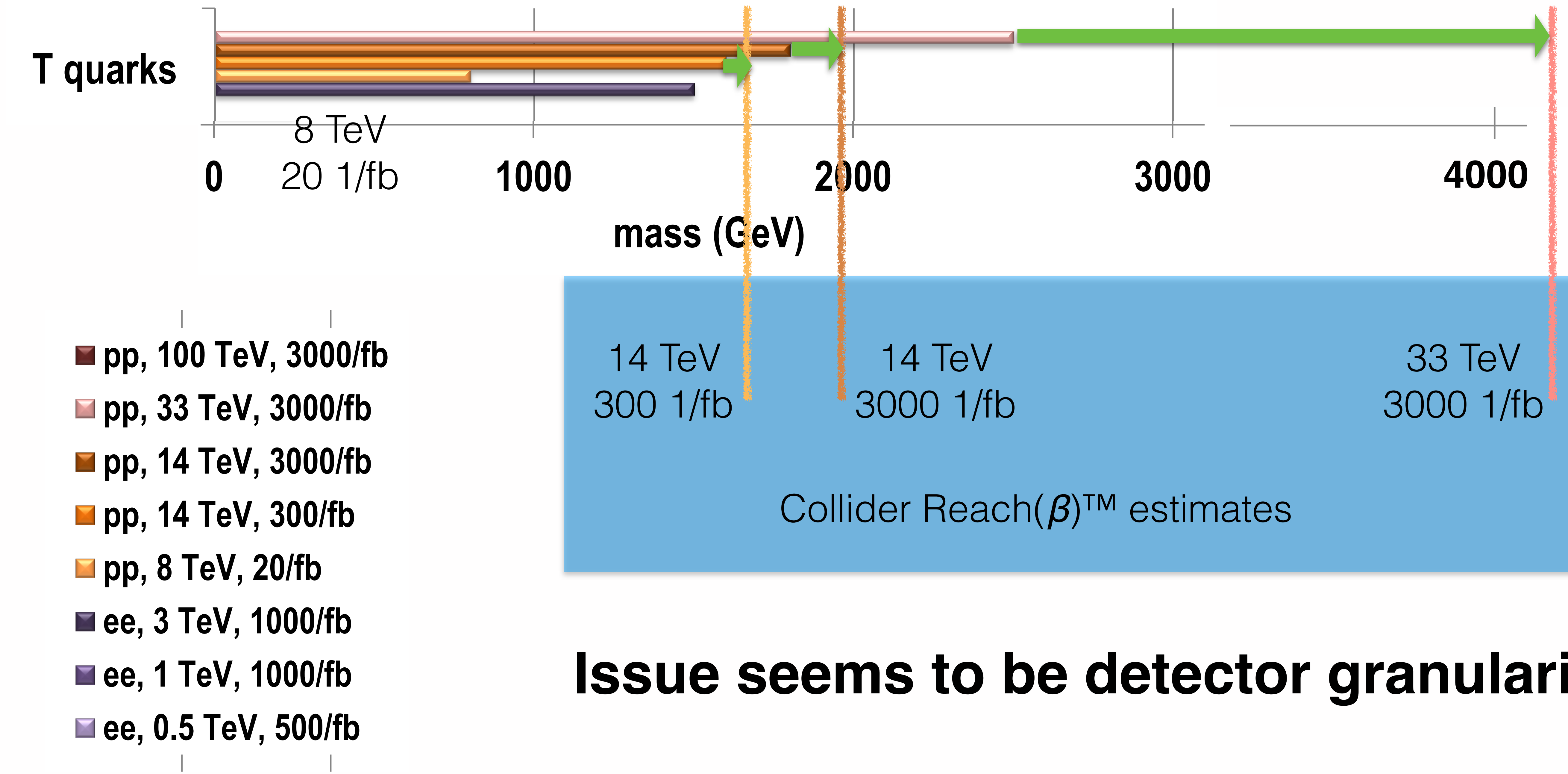


Collider Reach(β)™ estimates

T Quarks

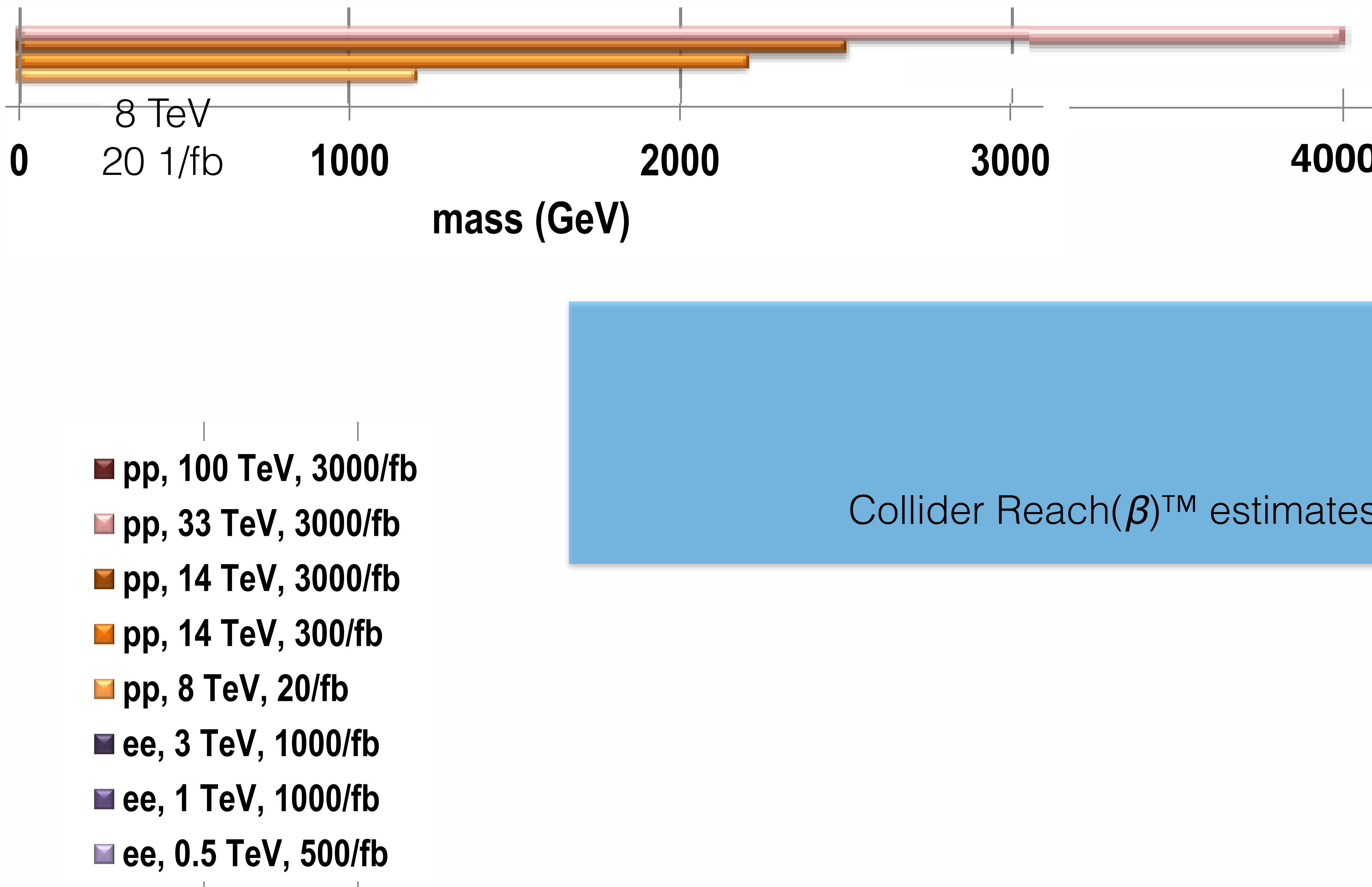

T quarks
8 TeV
20 1/fb
0
1000
2000
3000
4000
mass (GeV)
pp, 100 TeV, 3000/fb
pp, 33 TeV, 3000/fb
pp, 14 TeV, 3000/fb
pp, 14 TeV, 300/fb
pp, 8 TeV, 20/fb
ee, 3 TeV, 1000/fb
ee, 1 TeV, 1000/fb
ee, 0.5 TeV, 500/fb
14 TeV
300 1/fb
14 TeV
3000 1/fb
Collider Reach(β)™ estimates

T Quarks



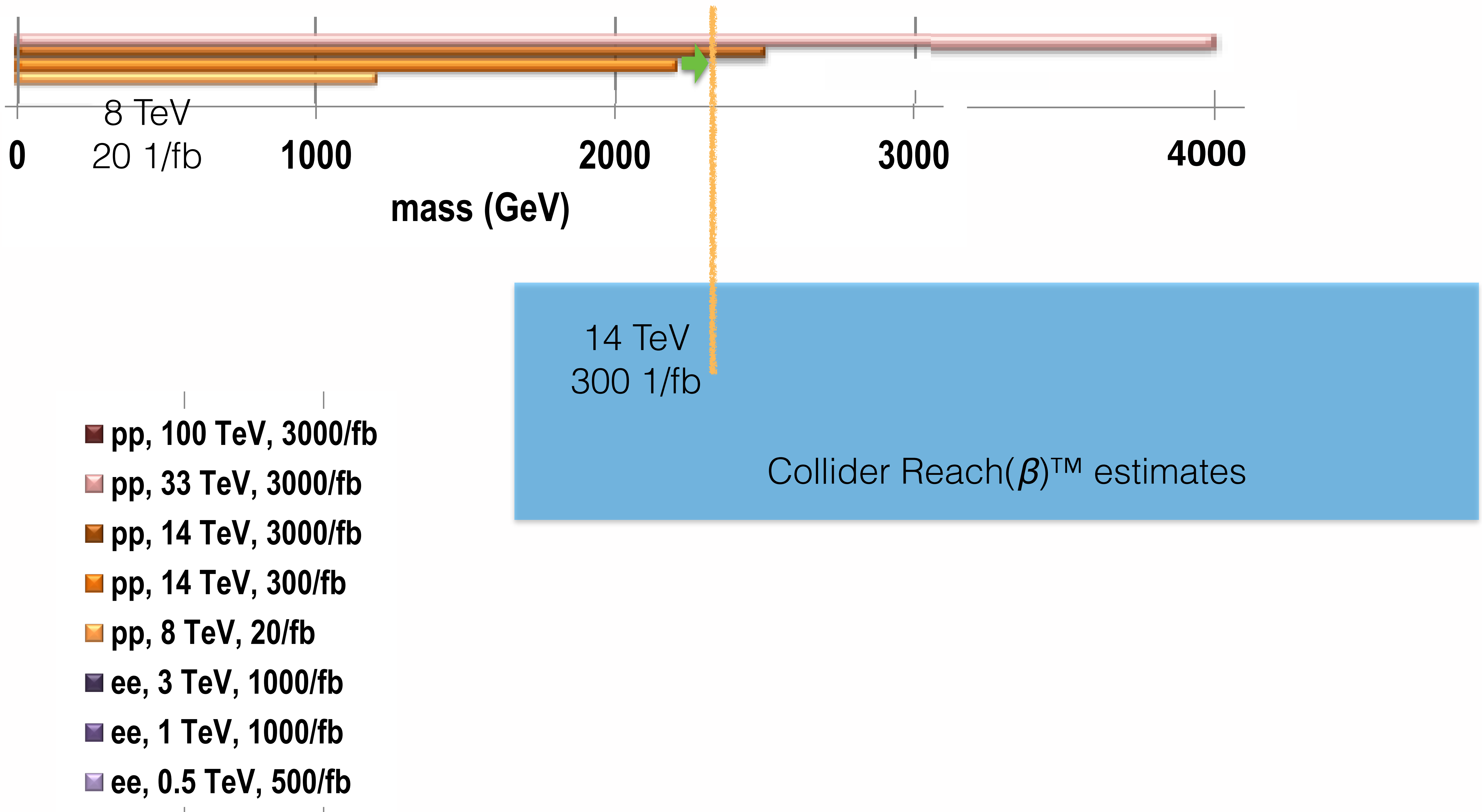
Issue seems to be detector granularity

Gluinos



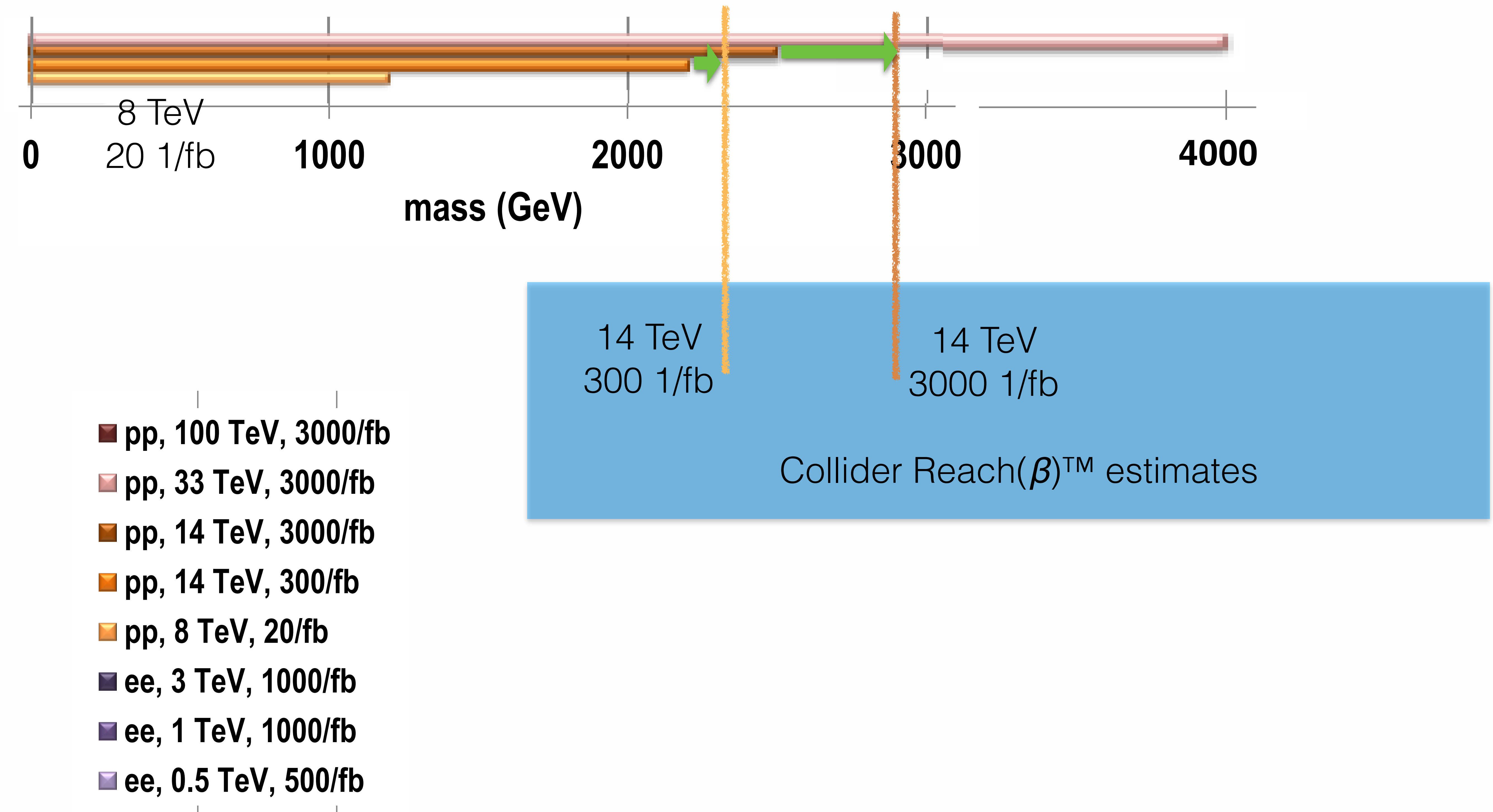
Collider Reach(β)™ estimates

Gluinos

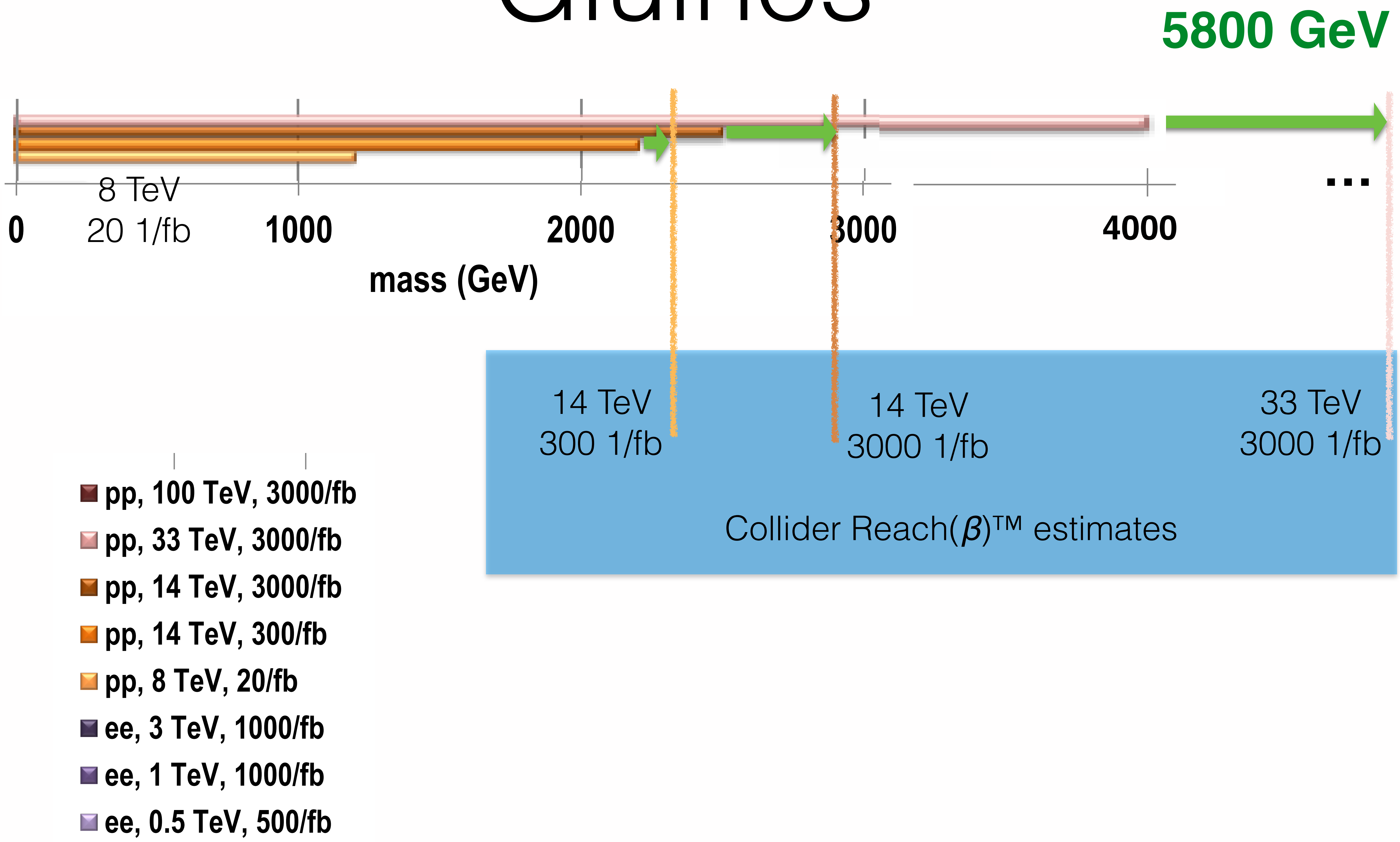


8 TeV
20 1/fb
0
1000
2000
3000
4000
mass (GeV)
14 TeV
300 1/fb
Collider Reach(β)™ estimates
pp, 100 TeV, 3000/fb
pp, 33 TeV, 3000/fb
pp, 14 TeV, 3000/fb
pp, 14 TeV, 300/fb
pp, 8 TeV, 20/fb
ee, 3 TeV, 1000/fb
ee, 1 TeV, 1000/fb
ee, 0.5 TeV, 500/fb

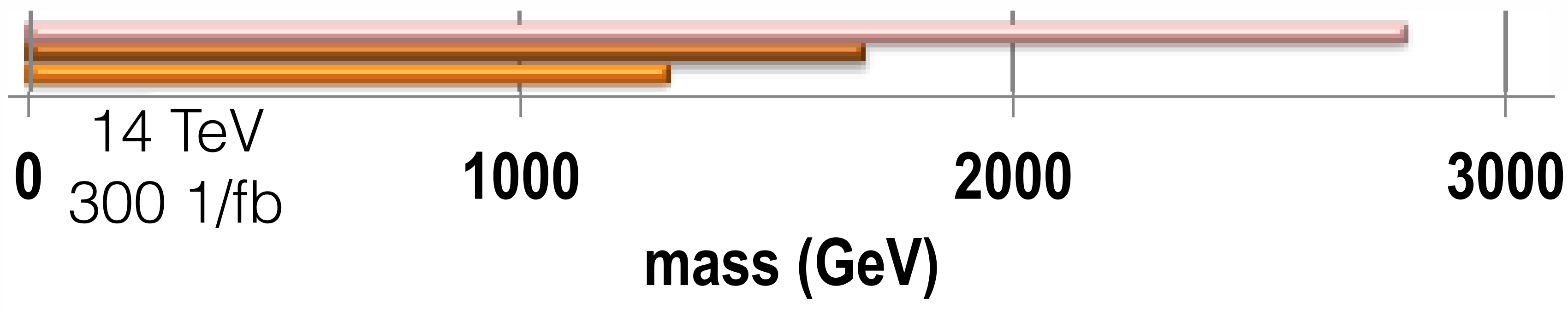
Gluinos


8 TeV
20 1/fb
0
1000
2000
3000
4000
mass (GeV)
14 TeV
300 1/fb
14 TeV
3000 1/fb
Collider Reach(β)™ 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

Gluinos

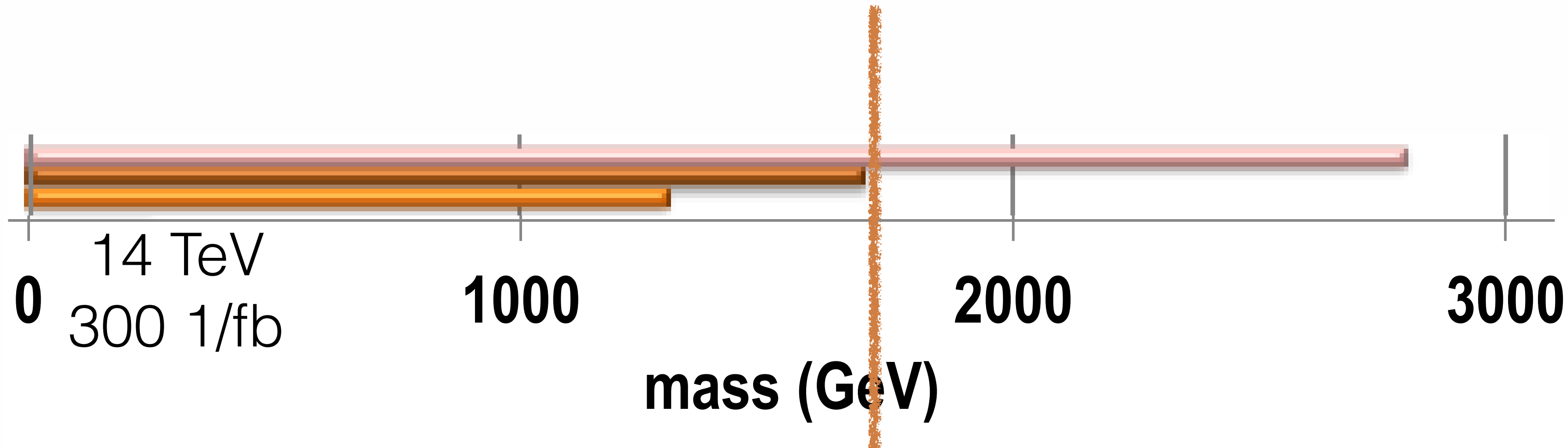

5800 GeV
8 TeV
20 1/fb
0
1000
2000
3000
4000
...
mass (GeV)
14 TeV
300 1/fb
14 TeV
3000 1/fb
33 TeV
3000 1/fb
Collider Reach(β)™ estimates
pp, 100 TeV, 3000/fb
pp, 33 TeV, 3000/fb
pp, 14 TeV, 3000/fb
pp, 14 TeV, 300/fb
pp, 8 TeV, 20/fb
ee, 3 TeV, 1000/fb
ee, 1 TeV, 1000/fb
ee, 0.5 TeV, 500/fb

RPV stops



Collider Reach(β)™ estimates

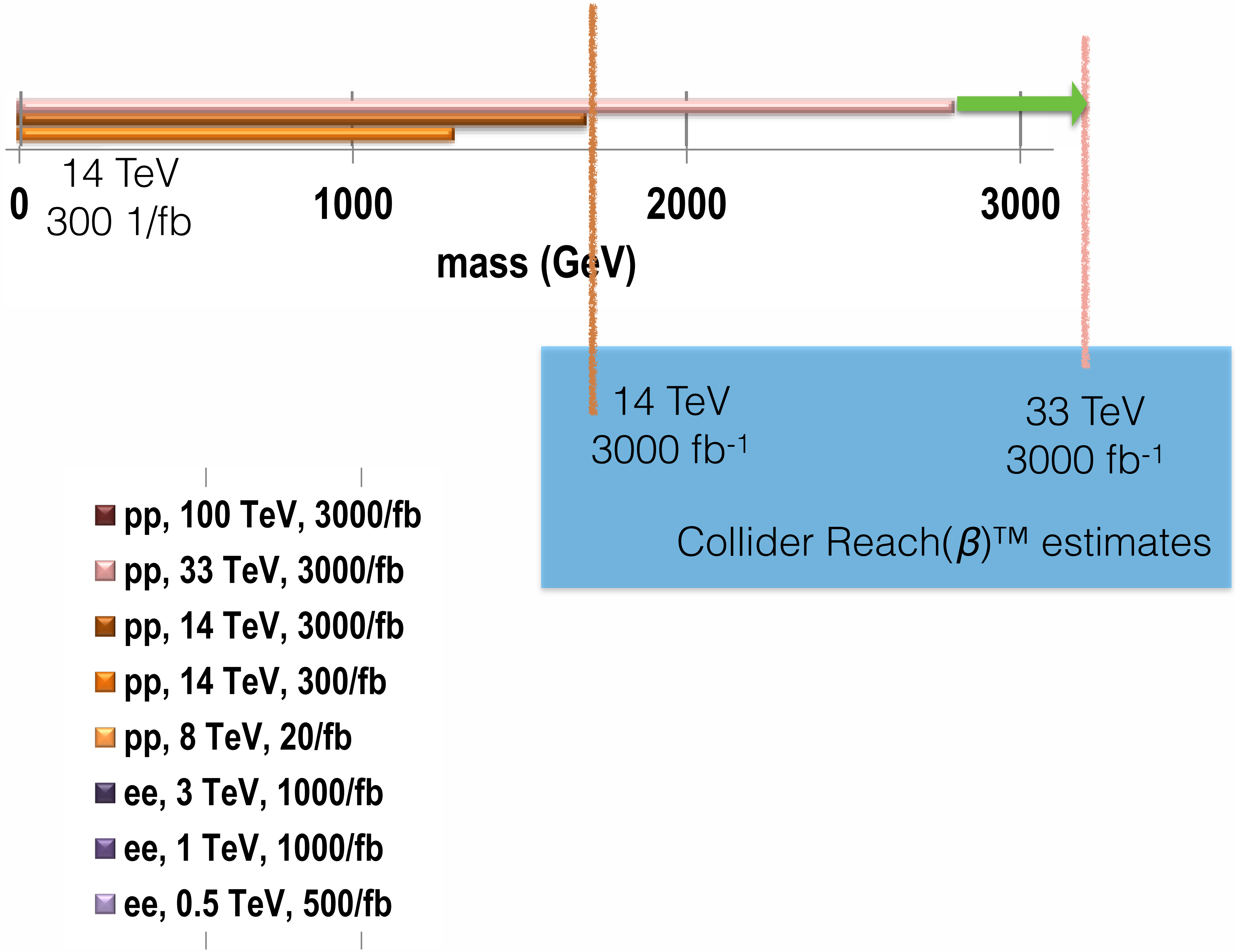
RPV stops



14 TeV
3000 fb^{-1}

Collider Reach(β)™ estimates

RPV stops


14 TeV
300 1/fb
0
1000
2000
3000
mass (GeV)
14 TeV
3000 fb-1
33 TeV
3000 fb-1
Collider Reach(β)™ 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