ATLAS Physics & Performance Week Plenary

CERN, 11 September 2015

Priorities for Run 2 in the light of Run 1

Gavin Salam (CERN)

A personal view

- You already have a pretty clear & comprehensive picture of what you'll be doing
- My views in this talk will necessarily be incomplete
- At some level it's a selection of what I find most interesting

Higgs Physics

A sector unlike any other of the standard model

Elementary scalar,
φ^4 (one of theorists' favourite toy models),
Yukawa couplings

Of utmost importance to pin it down:

Novelty of structure ⇒ potential for surprises

Narrow width ⇒ privileged portal to new sectors

Higgs Precision

- Roughly 10x more Higgs bosons produced in ggH than in run 1
  Precision on original discovery channels: **O(15-20%) → O(5-7%)**
- Is being matched by theory improvements (cf. N3LO Higgs cross section, NNLO H+jet, etc., improved PDF consistency)

There's room for deviations to appear at several σ

“New” channels (prod^n & decay)

- VBF, VH, ttH (×3.5) should also all go above 5σ/exp.
- H → ττ, bb should go above 5σ/exp.

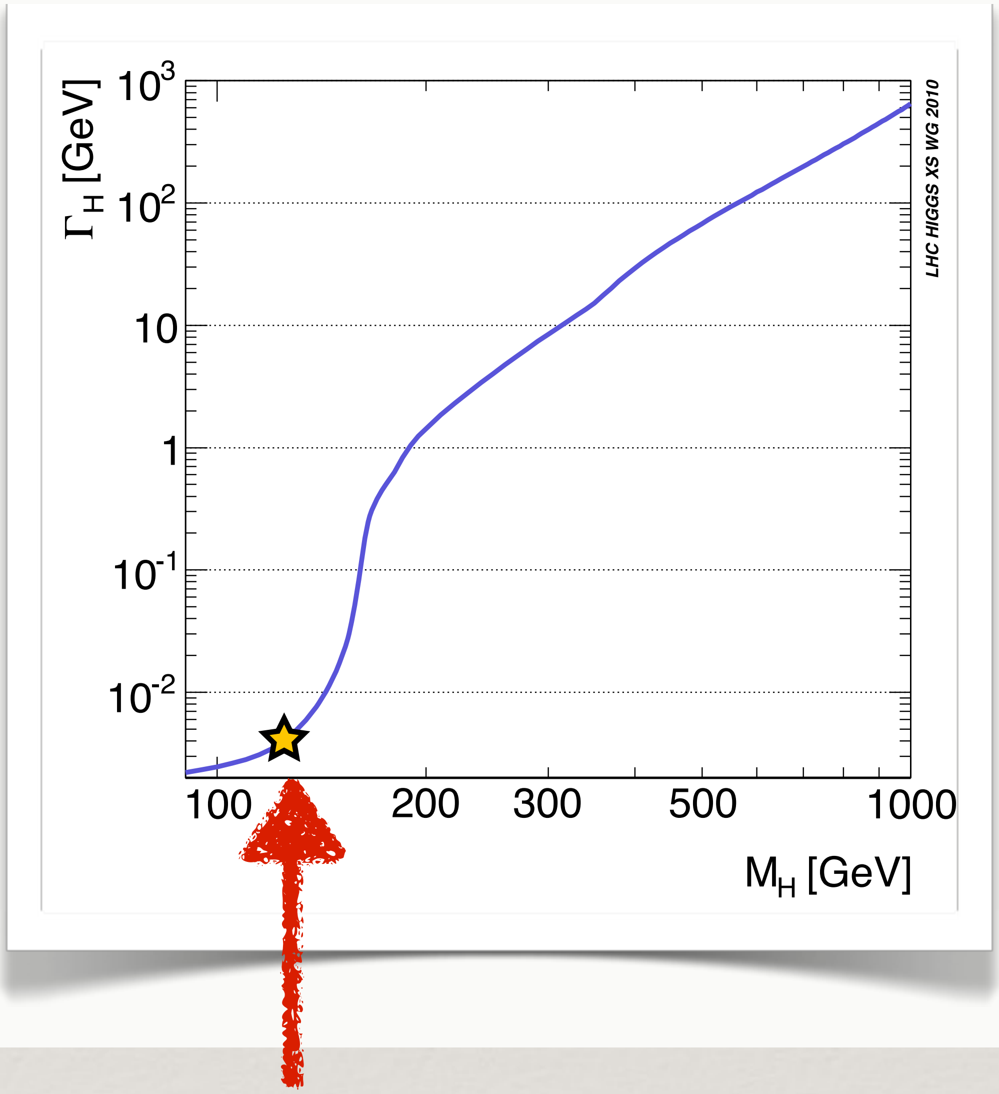
All core Higgs elements will be in place by the end of Run 2

- H → μμ barely above 1σ (unless enhanced)
(and keep an eye on μτ of course)

Higgs: as BSM portal

Material taken from talk by J. Shelton

- A light SM-like Higgs is narrow:



$$\Gamma_h(125\ \text{GeV}) = 4.1\ \text{MeV}$$

Comparison:
top, W, Z all have
width of O(1GeV)

Higgs: as BSM portal

Material taken from talk by J. Shelton

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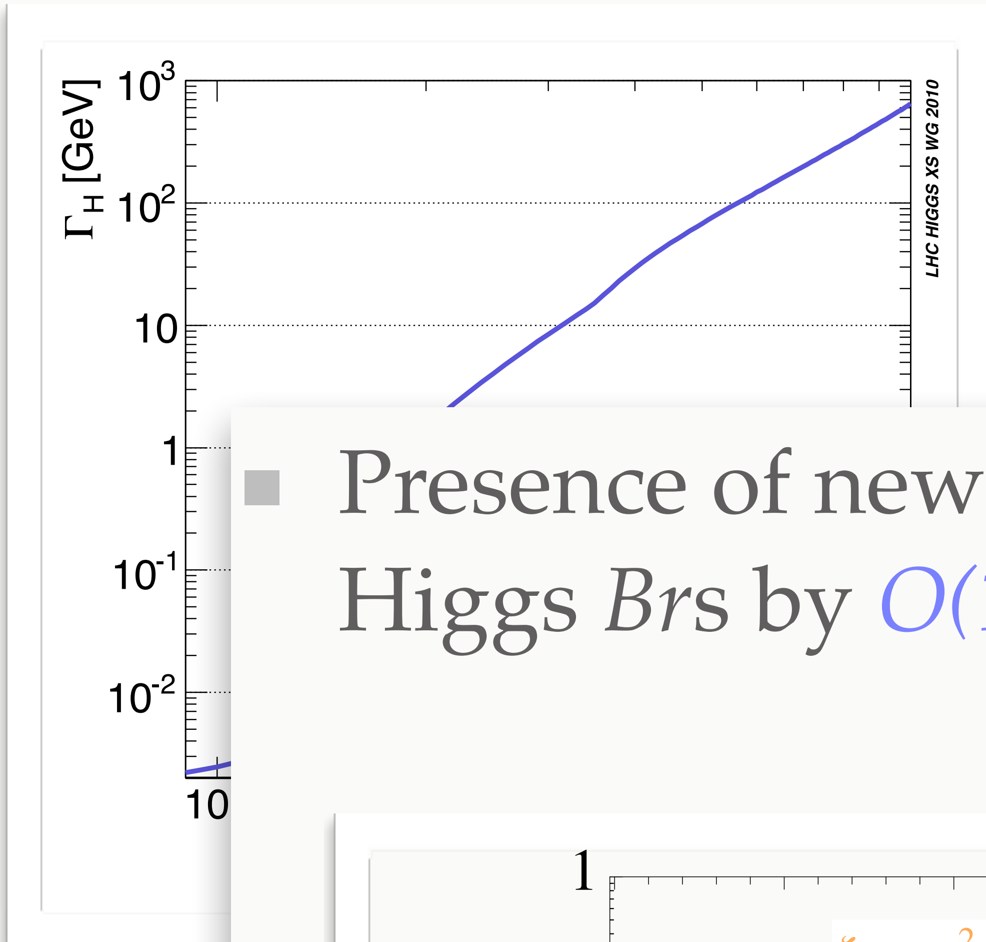


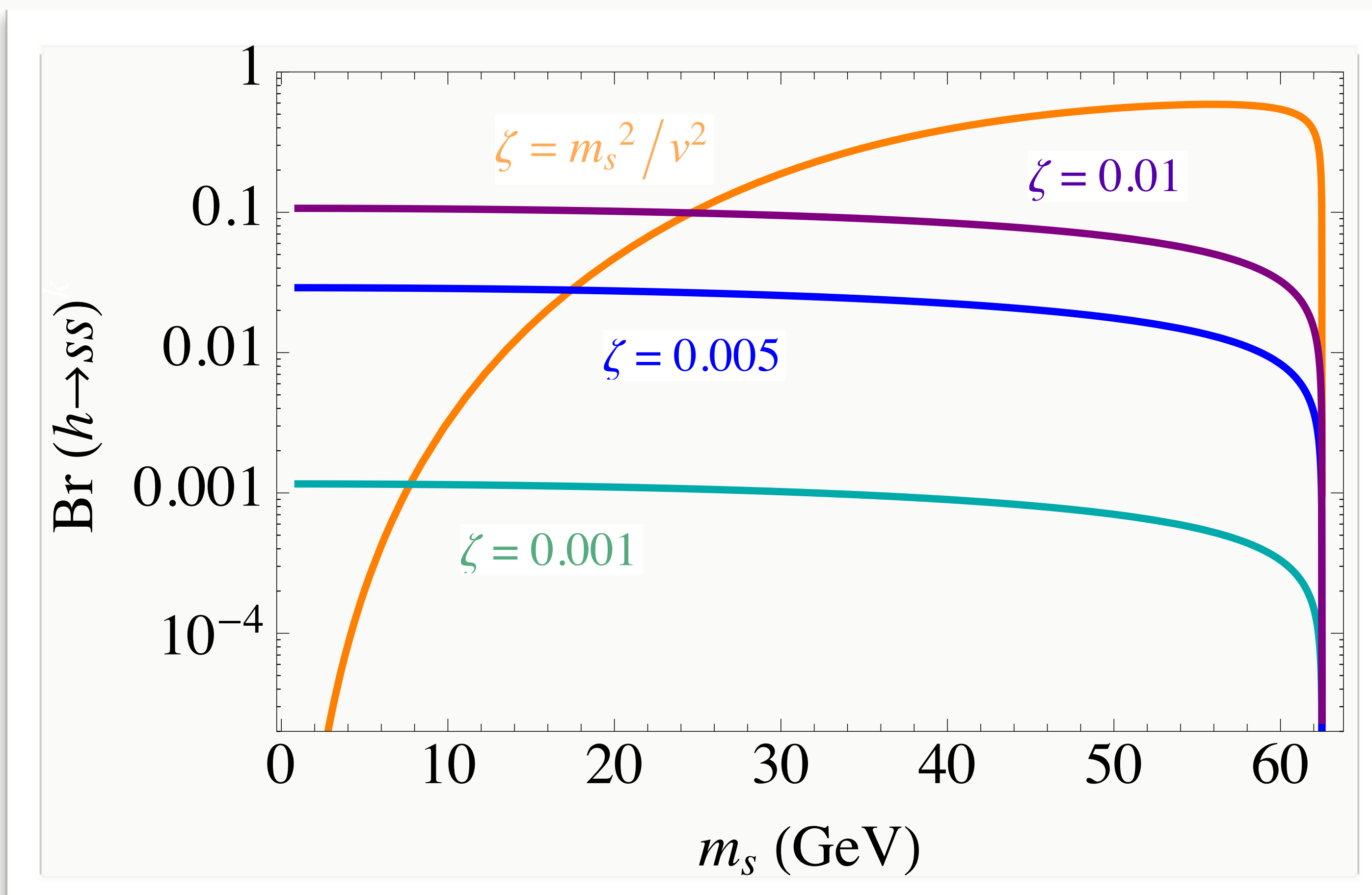
$\Gamma_h(125$

C

top

wic

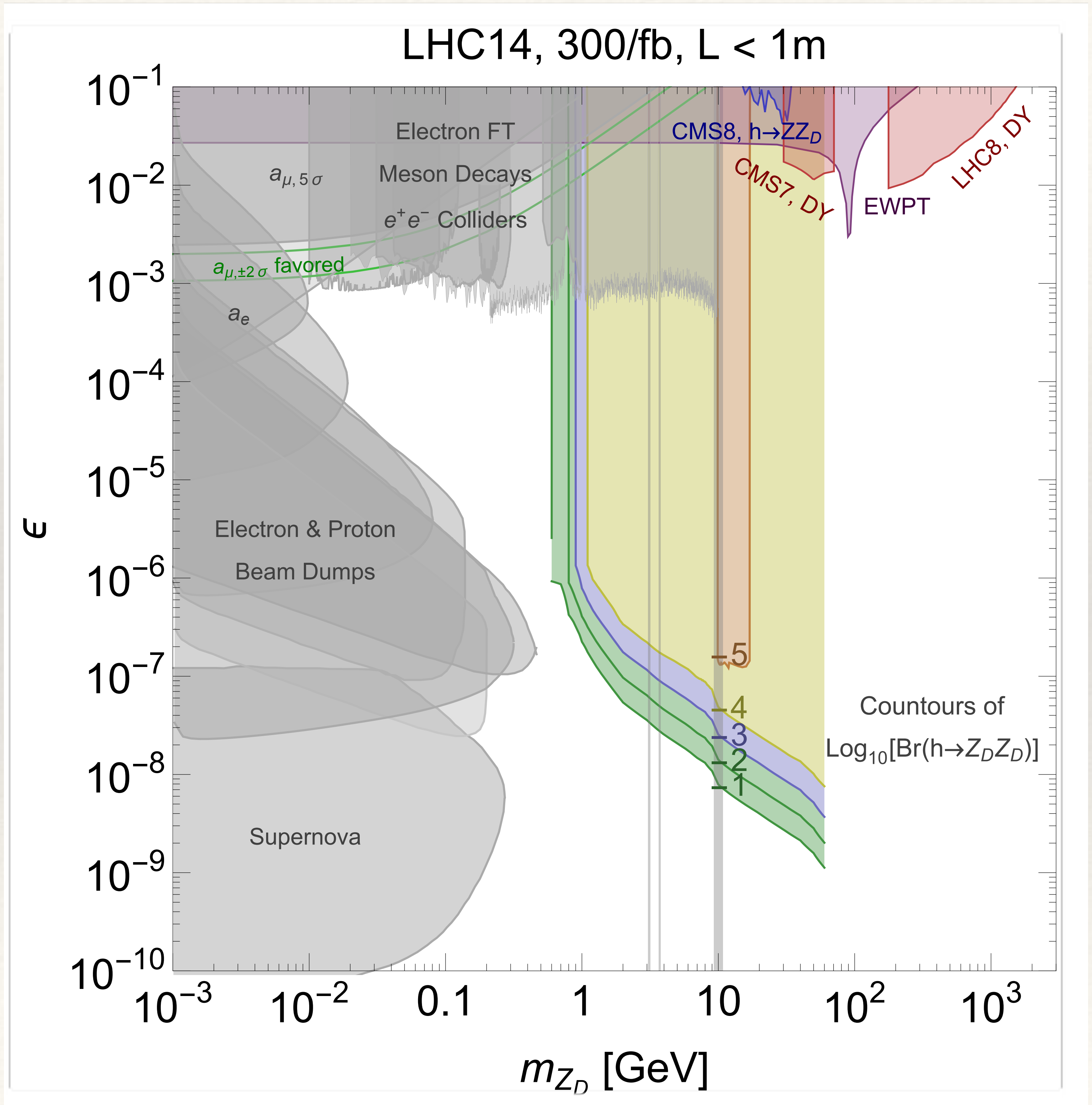
- Presence of new light degrees of freedom can distort Higgs *Brs* by *O(1)* even for small couplings



Simple example: one new scalar

$$\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$$

Higgs portal window into dark sectors



A dark U(1)

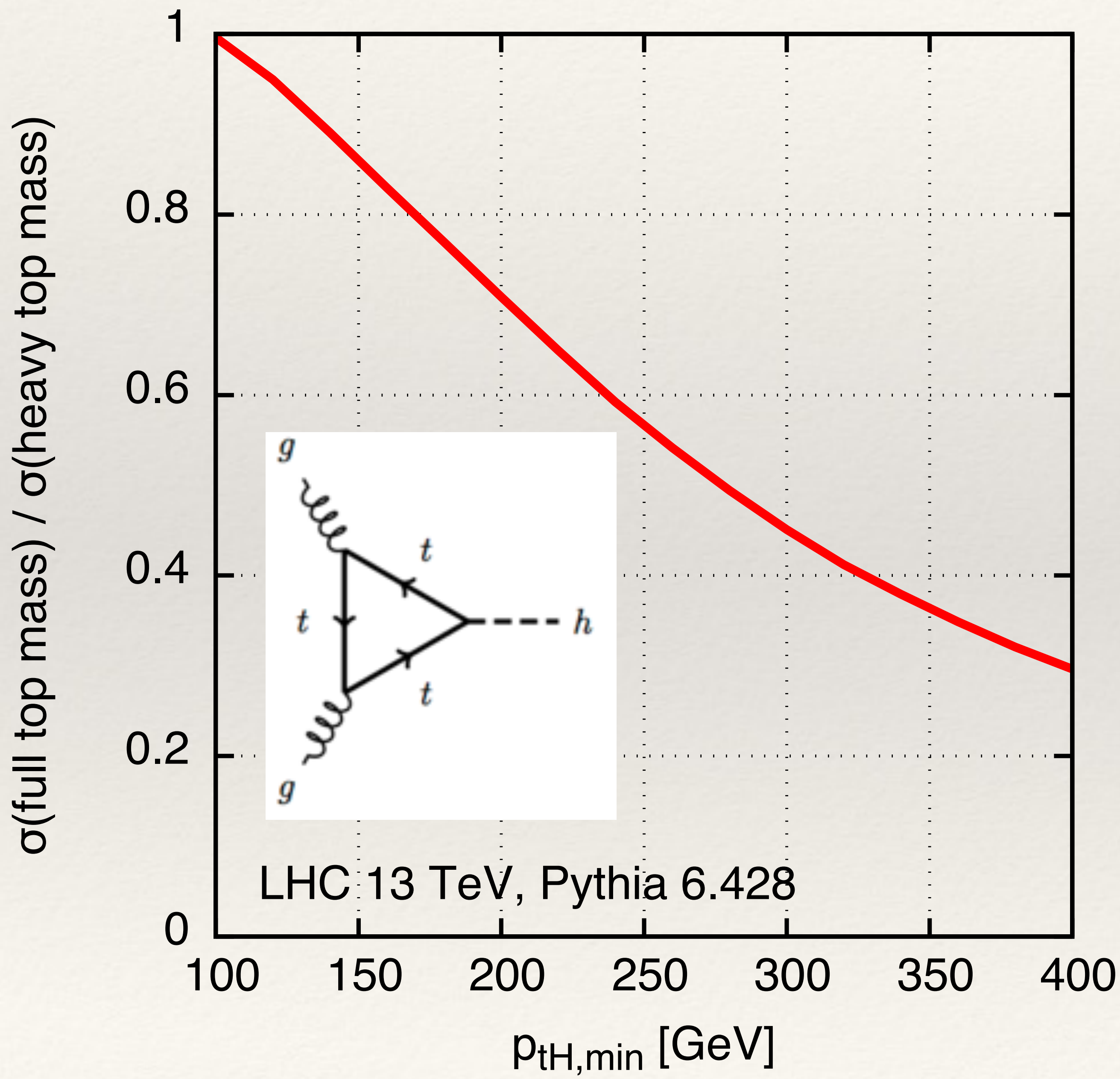
$h \to Z_D Z_D \to 4l$

(possibly displaced)

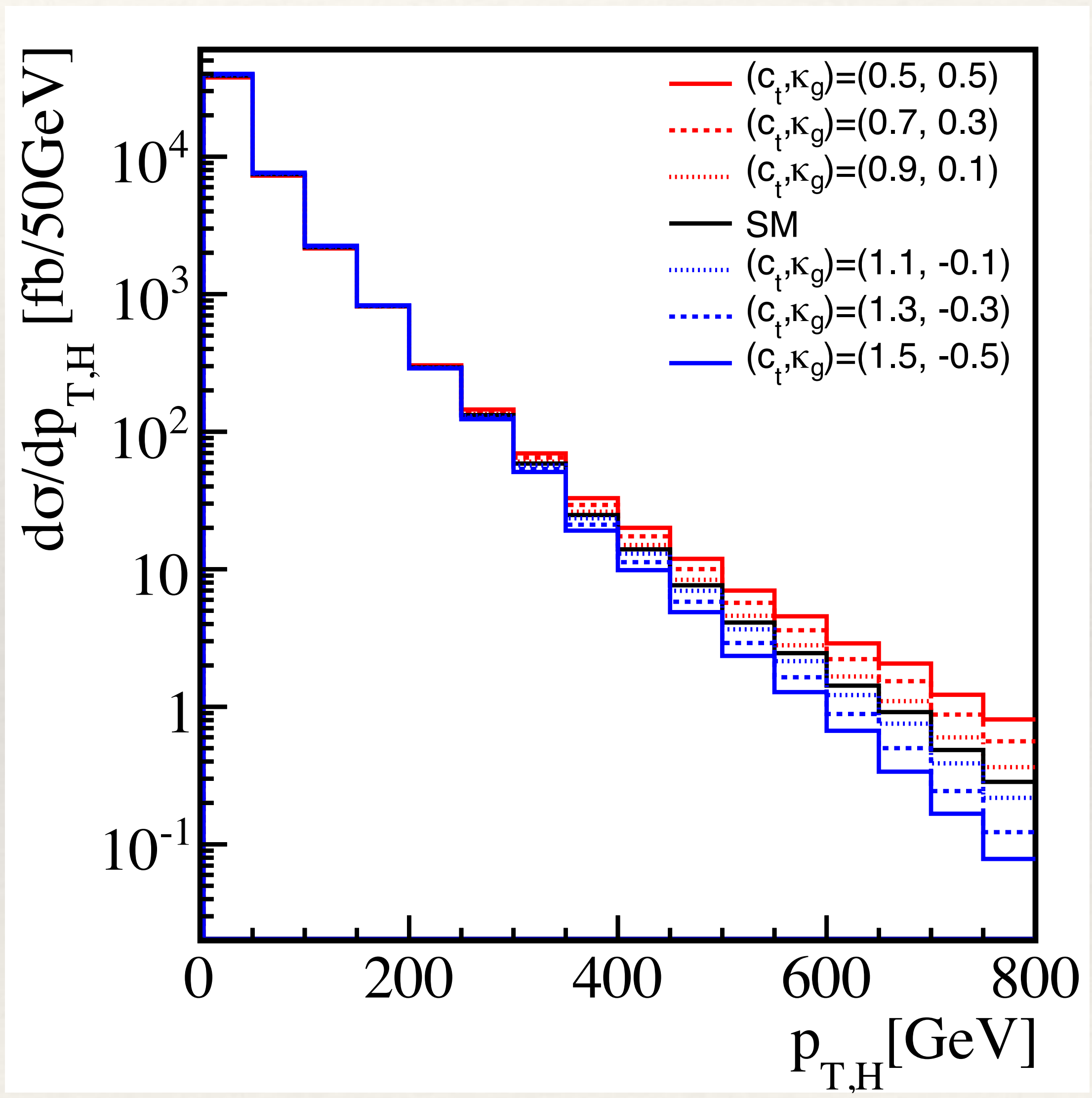
Curtin, Essig, Gori, Shelton
1412.0018

What's in the "top" loop?

Effect from finite top mass



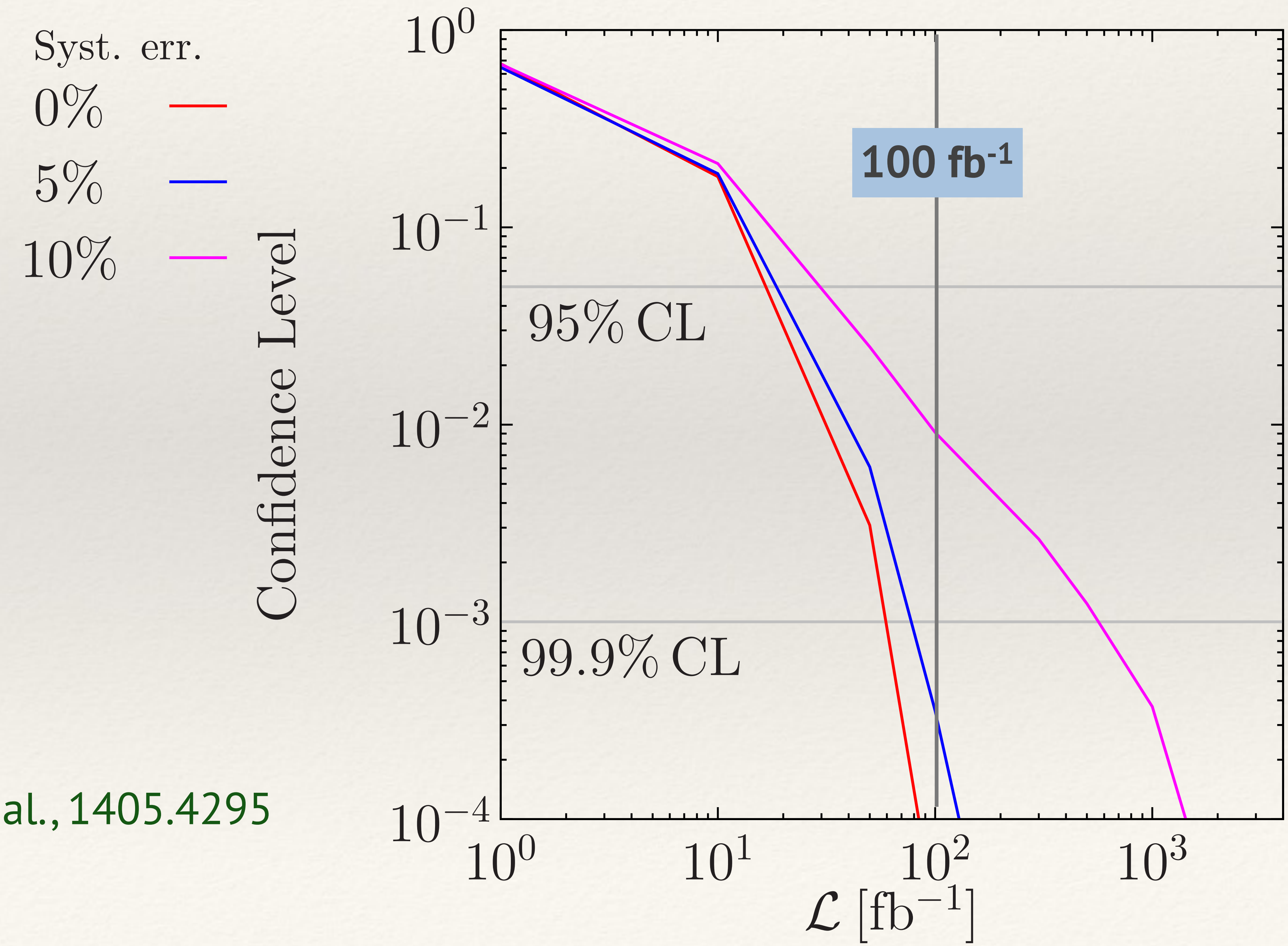
Varying c_t, κ_g with $c_t + \kappa_g = 1$



Schlaffer et al., 1405.4295

First probes with 100 fb^{-1}

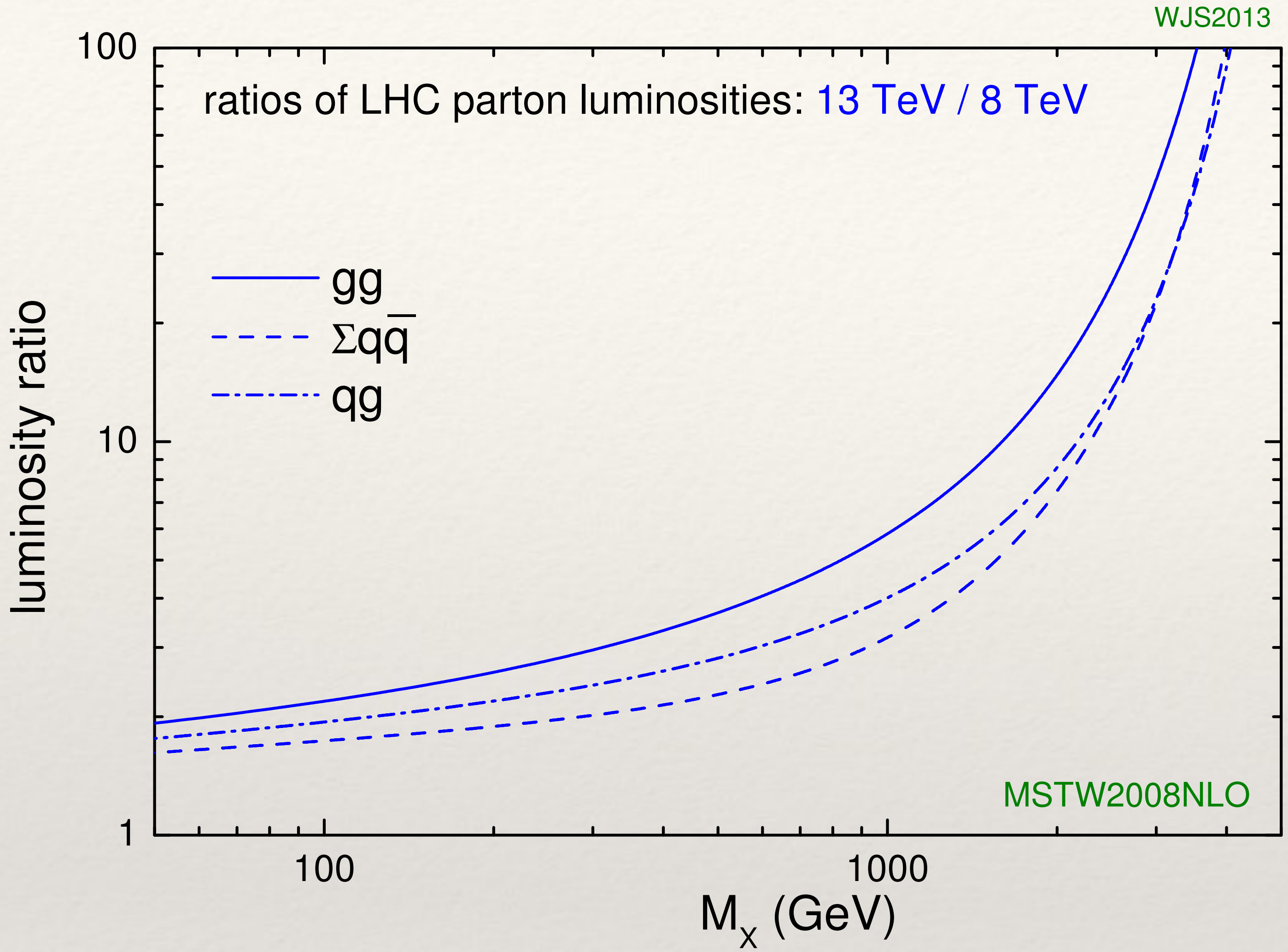
Sensitivity to H → ττ
with point-like κ_g = 0.5



Schlaffer et al., 1405.4295

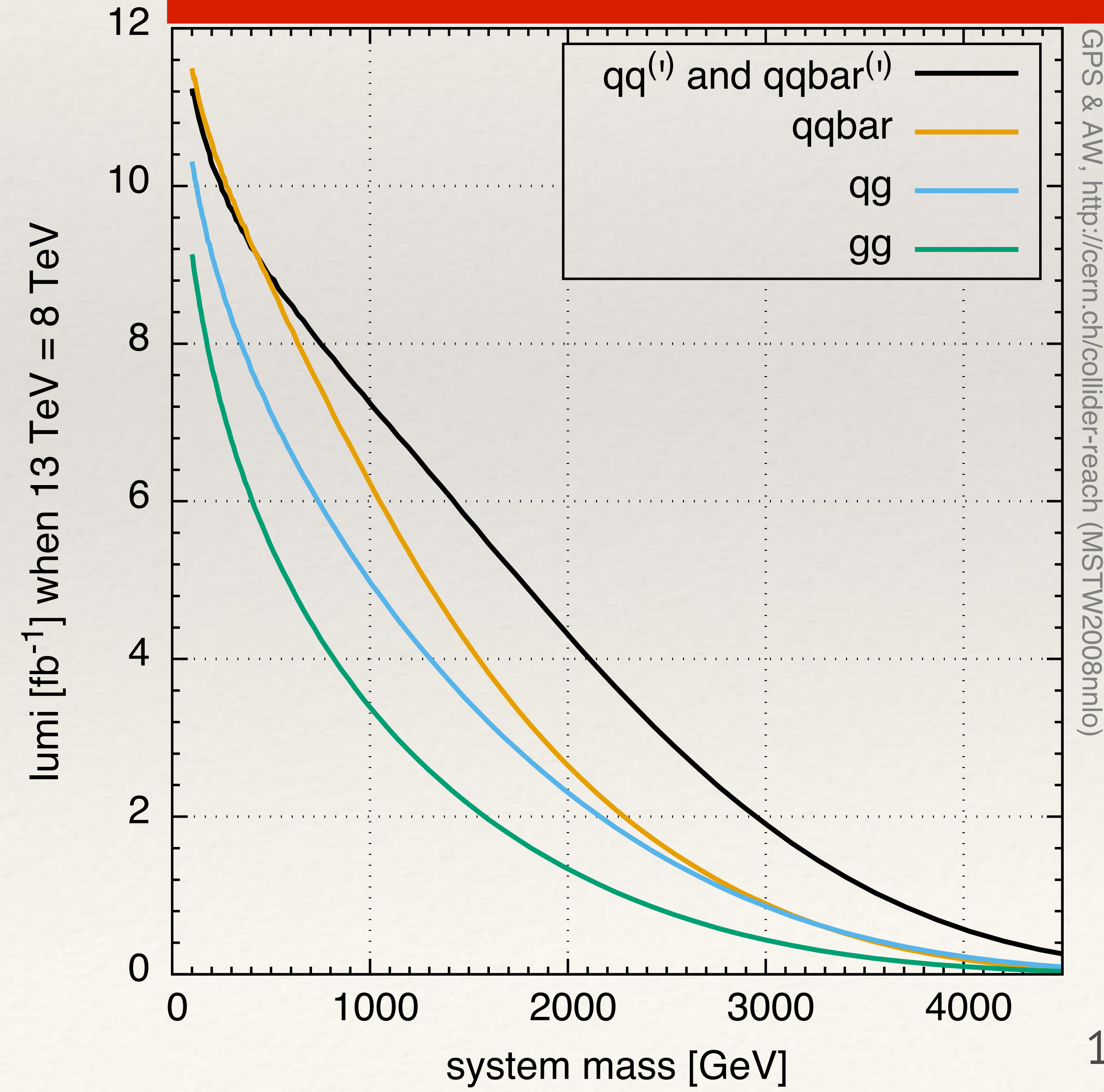
Searches

Early discovery? Lumi ratios

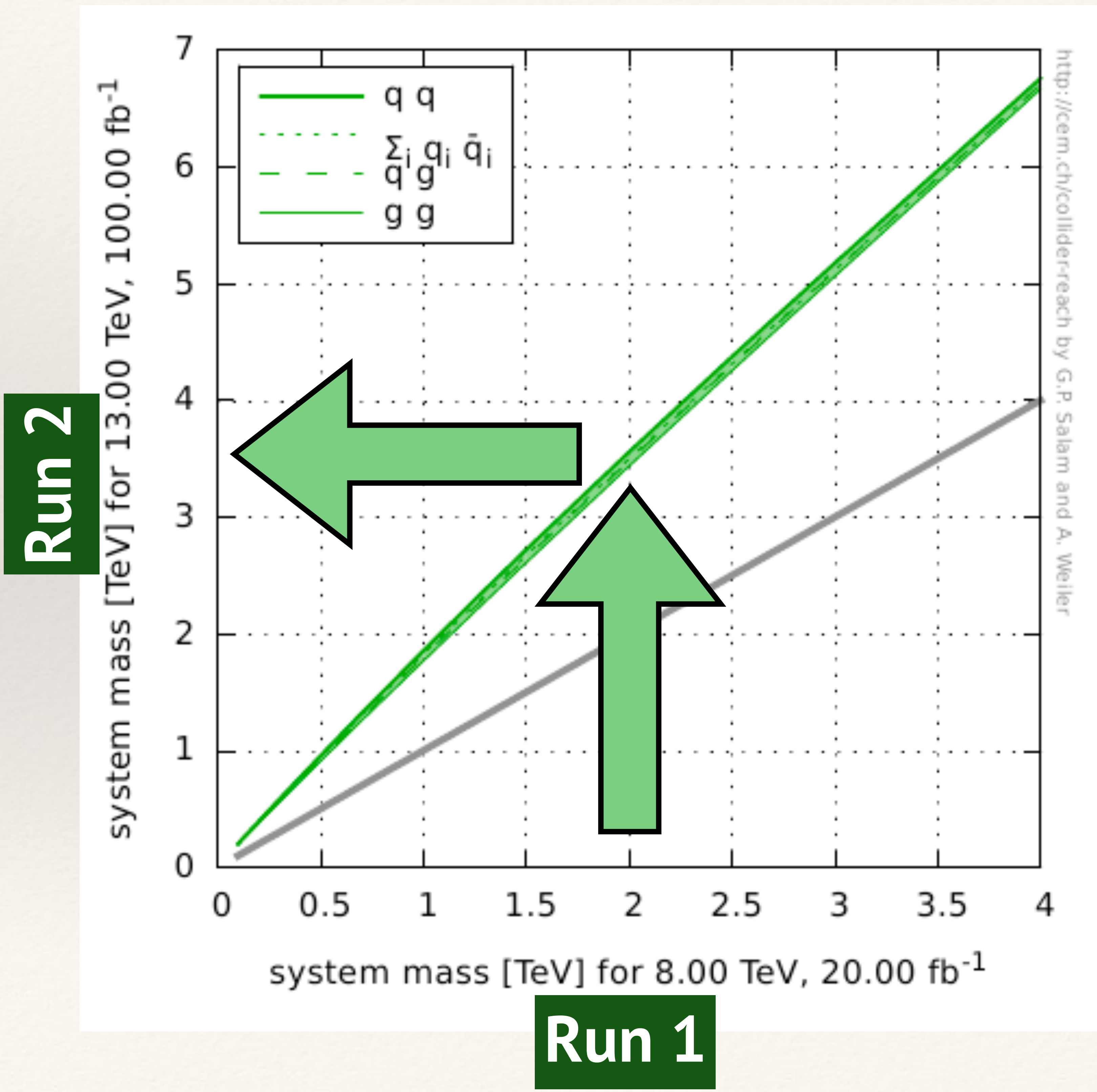


$20fb^{-1}$/(lumi ratio)

Lumi (fb^{-1}) when 13 TeV matches 8 TeV



Reach with 100fb^{-1}@13TeV



With 100 fb^{-1}, you gain slightly more than a factor of

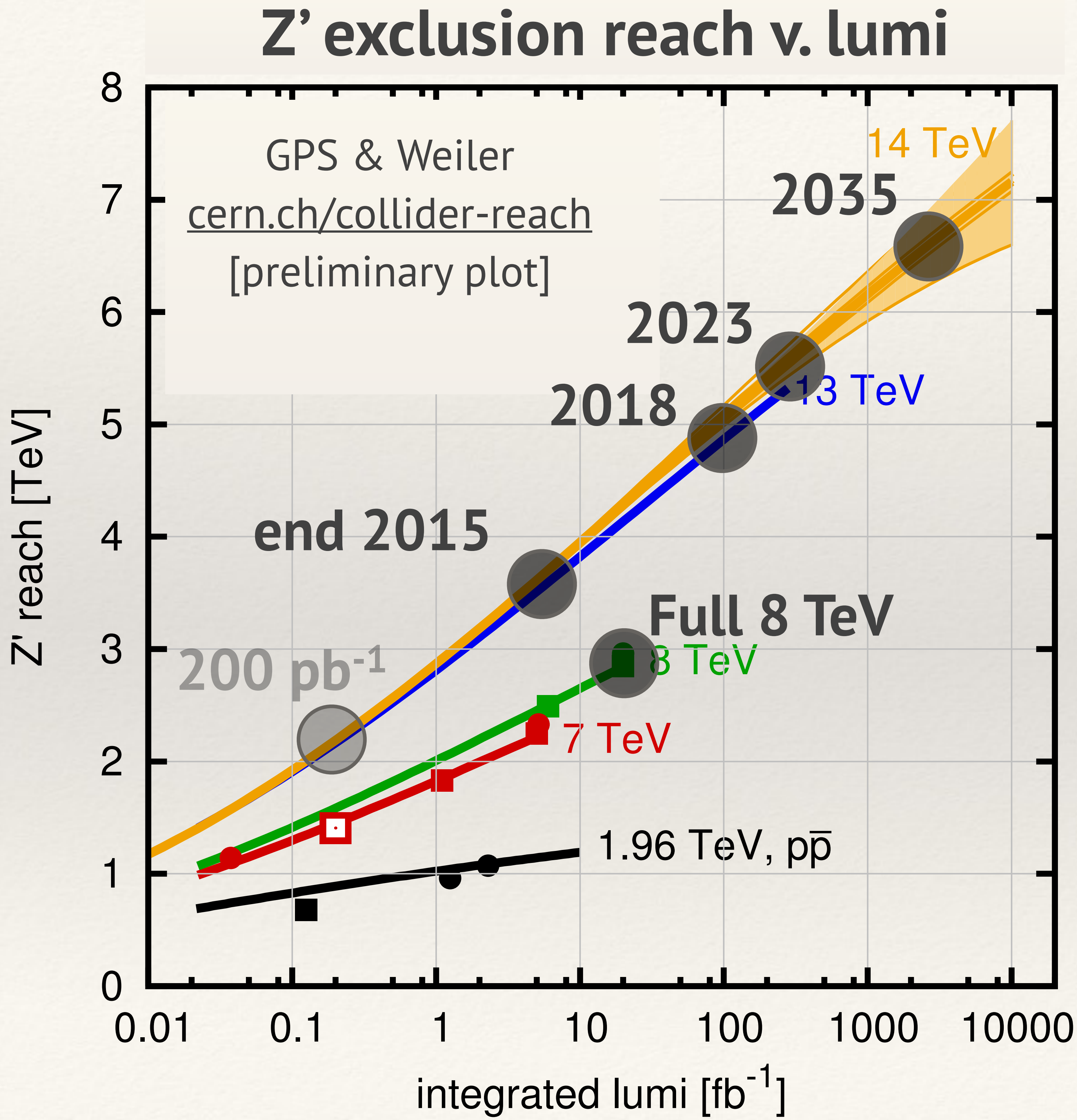
13/8 ≃ 1.6

in reach relative to the 8 TeV run

(For 53 fb^{-1} = 20x$(13/8)^2$, you get exactly that factor).

http://cern.ch/collider-reach

time-evolution of Z' reach

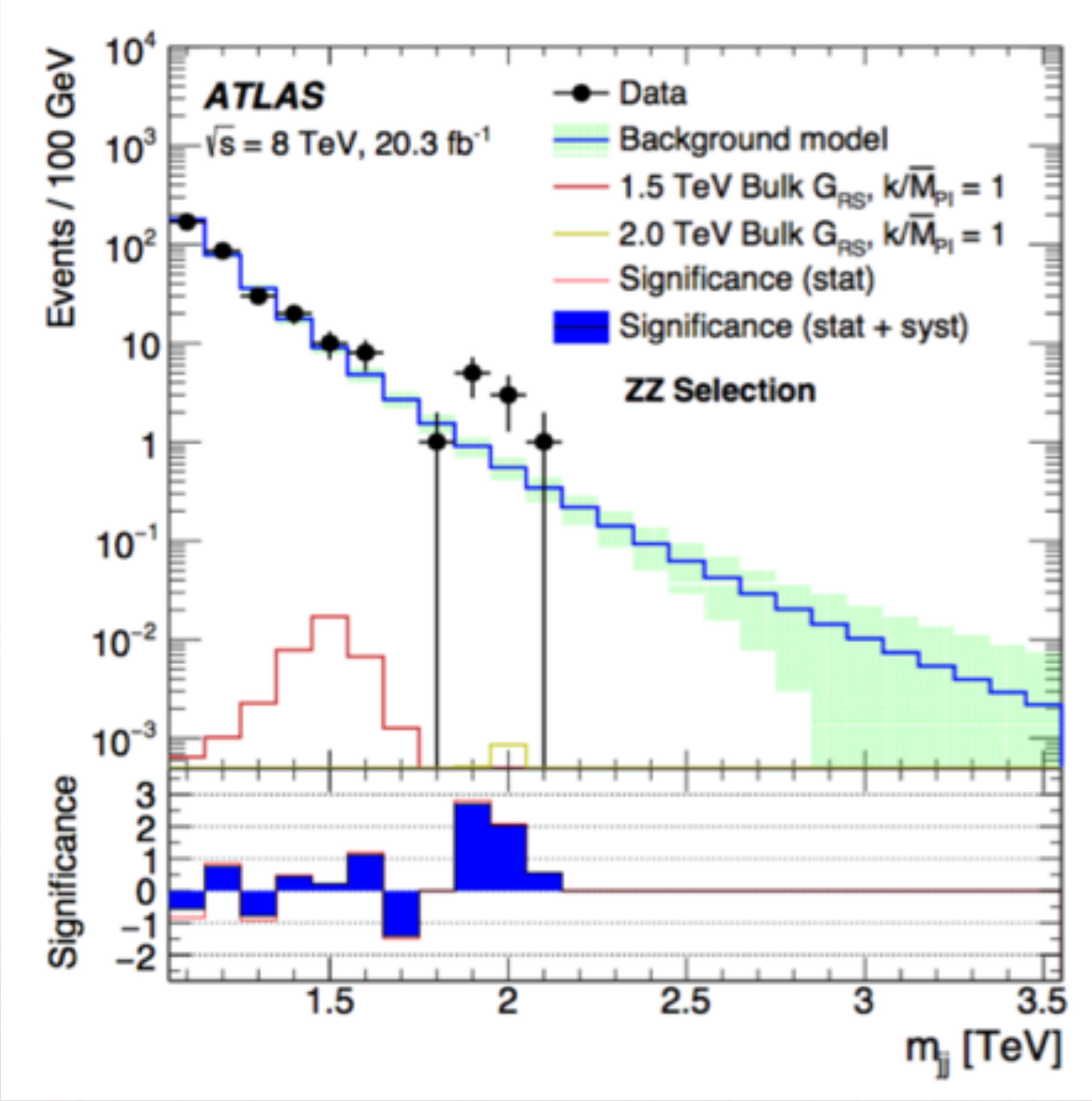


By the end of the year, most searches should beat 8 TeV results

[Some, e.g. excited quarks, will surpass 8 TeV with just 0.2 fb^{-1}]

Subsequent years bring steady improvement

Boosted analyses (jet substructure) from niche to mainstream



But how do you do boosted physics on angular scales ~ 0.1 when calo granularity is ~ 0.1?

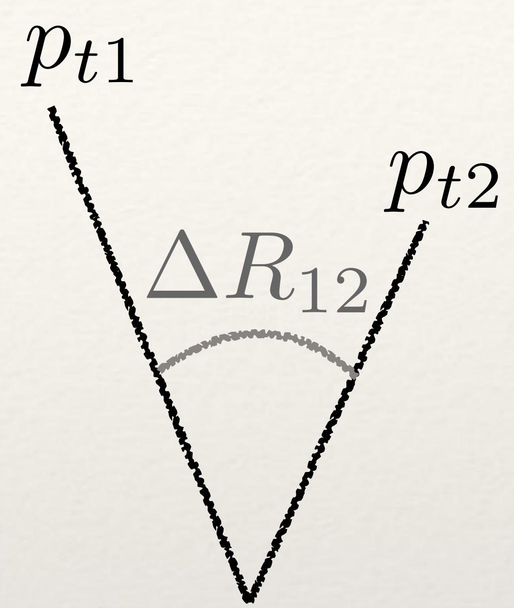
- Katz, Son & Tweedie, http://arxiv.org/abs/1010.5253
- Son, Spethmann, Tweedie, http://arxiv.org/abs/1204.0525
- http://arxiv.org/abs/1307.6908 (Snowmass study)
- Schaetzel & Spannowsky, http://arxiv.org/abs/1308.0540
- An earlier talk of mine
- Larkoski, Maltoni & Selvaggi, http://arxiv.org/abs/1503.03347
- CMS particle flow studies
- Bressler et al, http://arxiv.org/abs/arXiv:1506.02656

Calo-granularity issue

Two-prong mass formula

$$m \simeq \sqrt{p_{t1} p_{t2}} \Delta R_{12}$$

p_T = 2TeV → ΔR~0.1



Problems:

- Hadronic calorimeter (0.1x0.1) starts to have insufficient angular resolution
- Tracking much better, but it gives poor p_t measurement (sees only 60% with large fluctuations)

Beating calo-granularity

Rewrite mass two-prong mass formula as

$$p_{t,\text{jet}} \equiv p_{t1} + p_{t2}$$

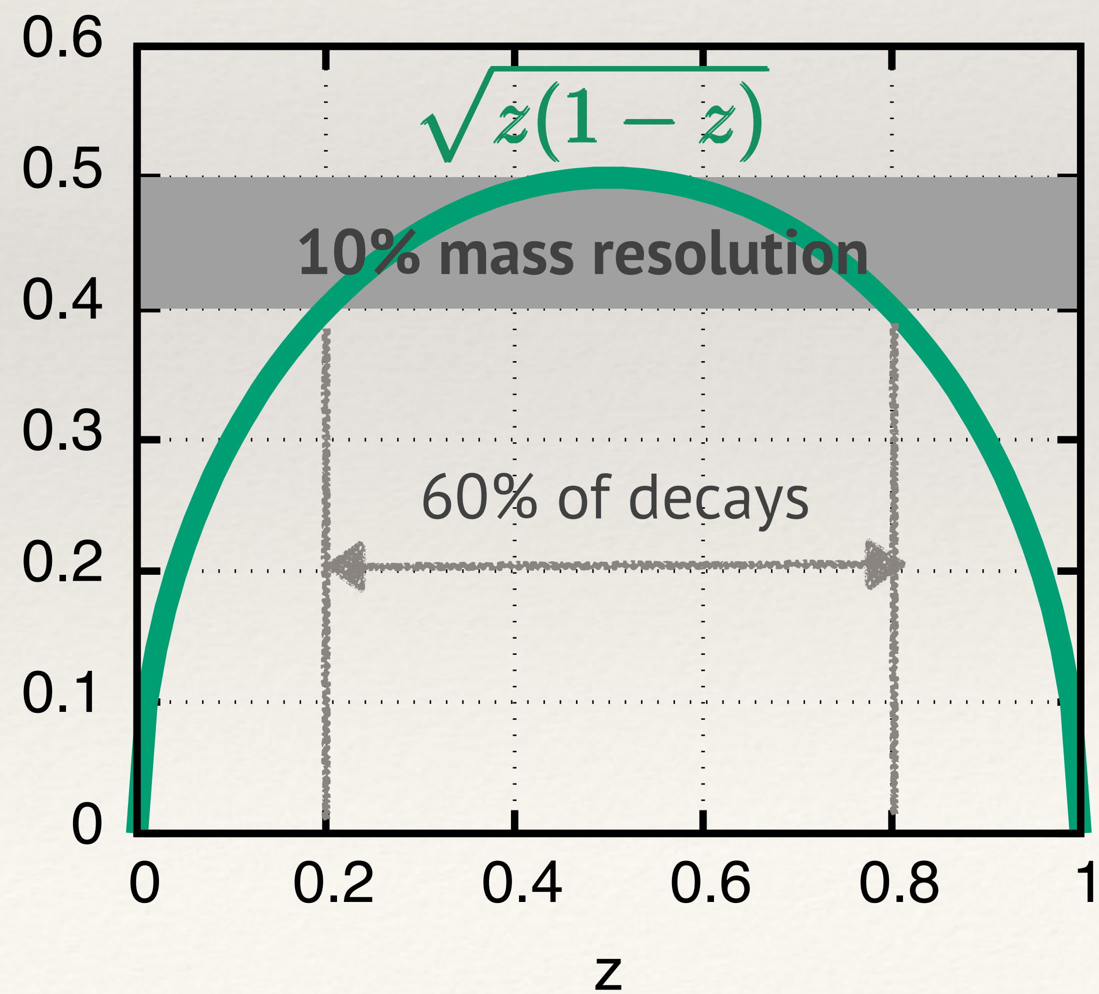
$$z \equiv \frac{p_{t1}}{p_{t,\text{jet}}}$$

$$m = \sqrt{z(1-z)}\, p_{t,\text{jet}} \Delta R_{12}$$

Use different detector subsystems to for different parts of formula:

- Calo for $p_{t,\text{jet}}$
- Tracks (and/or EM) for ΔR_{12}
- Tracks (and/or EM) for z

(fluctuations on z don't matter so much)



Beating calo-granularity

Rewrite mass two-prong mass formula as

$$p_{t,\text{jet}} \equiv p_{t1} + p_{t2}$$

$$m = \sqrt{z(1$$

Use diffe

subsystems

parts (

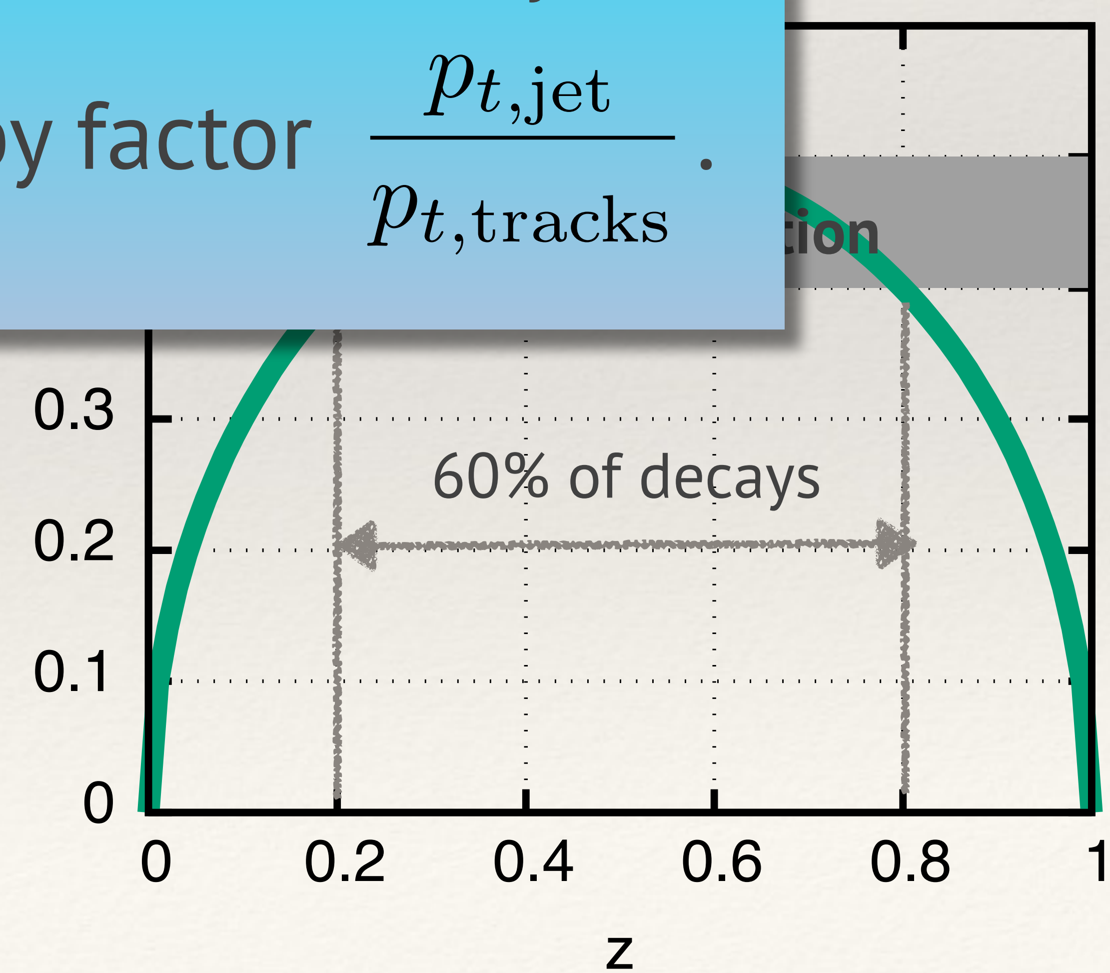
Practical approach:

1) Take track constituents of jet

2) Rescale them by factor $\frac{p_{t,\text{jet}}}{p_{t,\text{tracks}}}$.

- Calo for $p_{t,\text{jet}}$
- Tracks (and/or EM) for ΔR_{12}
- Tracks (and/or EM) for z

(fluctuations on z don't matter so much)



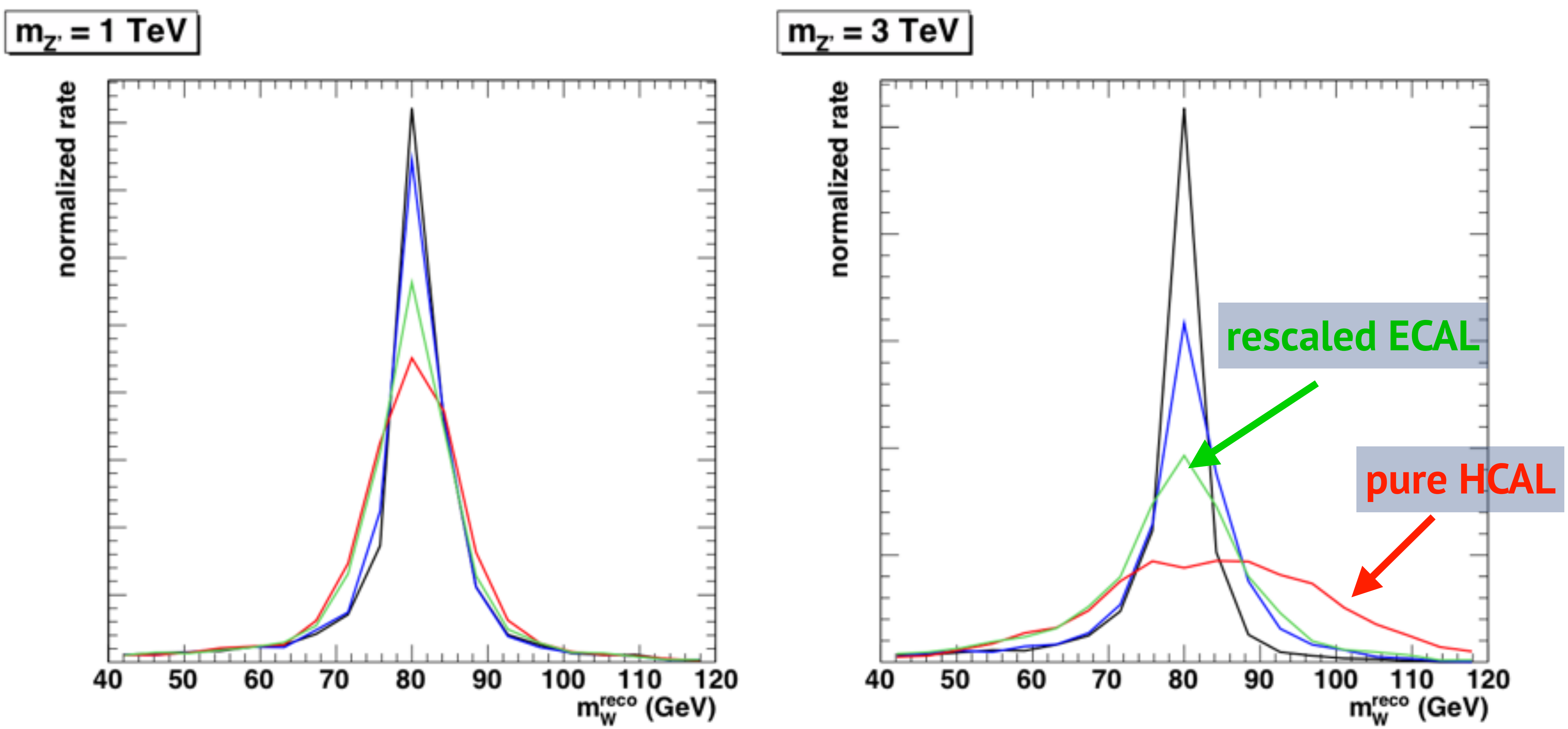


FIG. 12: *Distributions of the reconstructed hadronic W mass for 1 and 3 TeV* $Z' \to WW \to (l\nu)(q\bar{q}')$. *Displayed are particle-level (black), idealized particle-flow (blue), rescaled ECAL (green), and pure HCAL (red). Detector models are described in more detail in the text.*

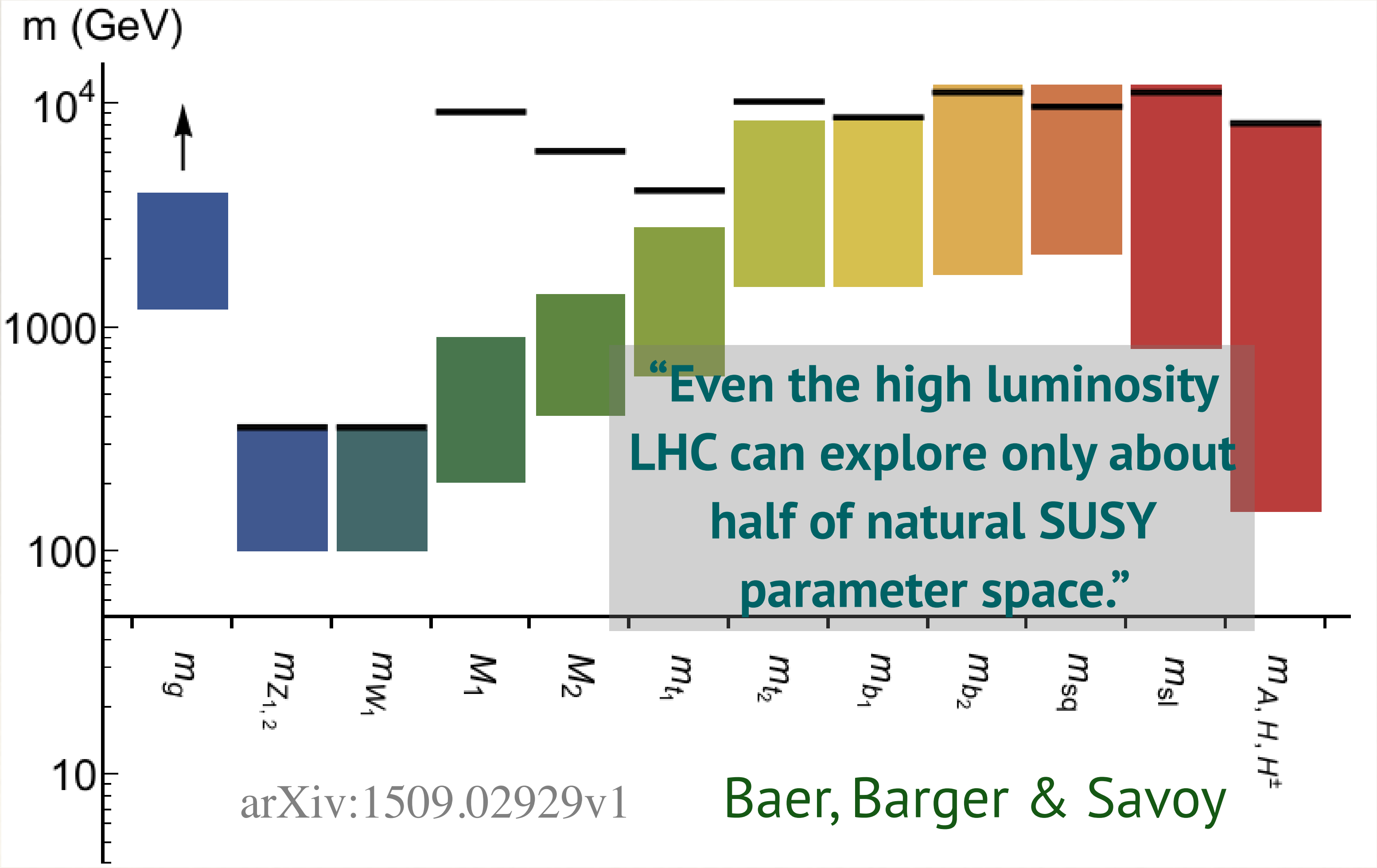
Katz, Son & Tweedie, 1010.5253

If you find nothing?

"In any case, within two or three years, the LHC is going to prove or disprove the existence of supersymmetry. If no superpartners are discovered, we will have to find an alternative solution to the hierarchy problem."

Arkani Hamed, in PH newsletter interview

SUSY Spectrum with allowable fine tuning



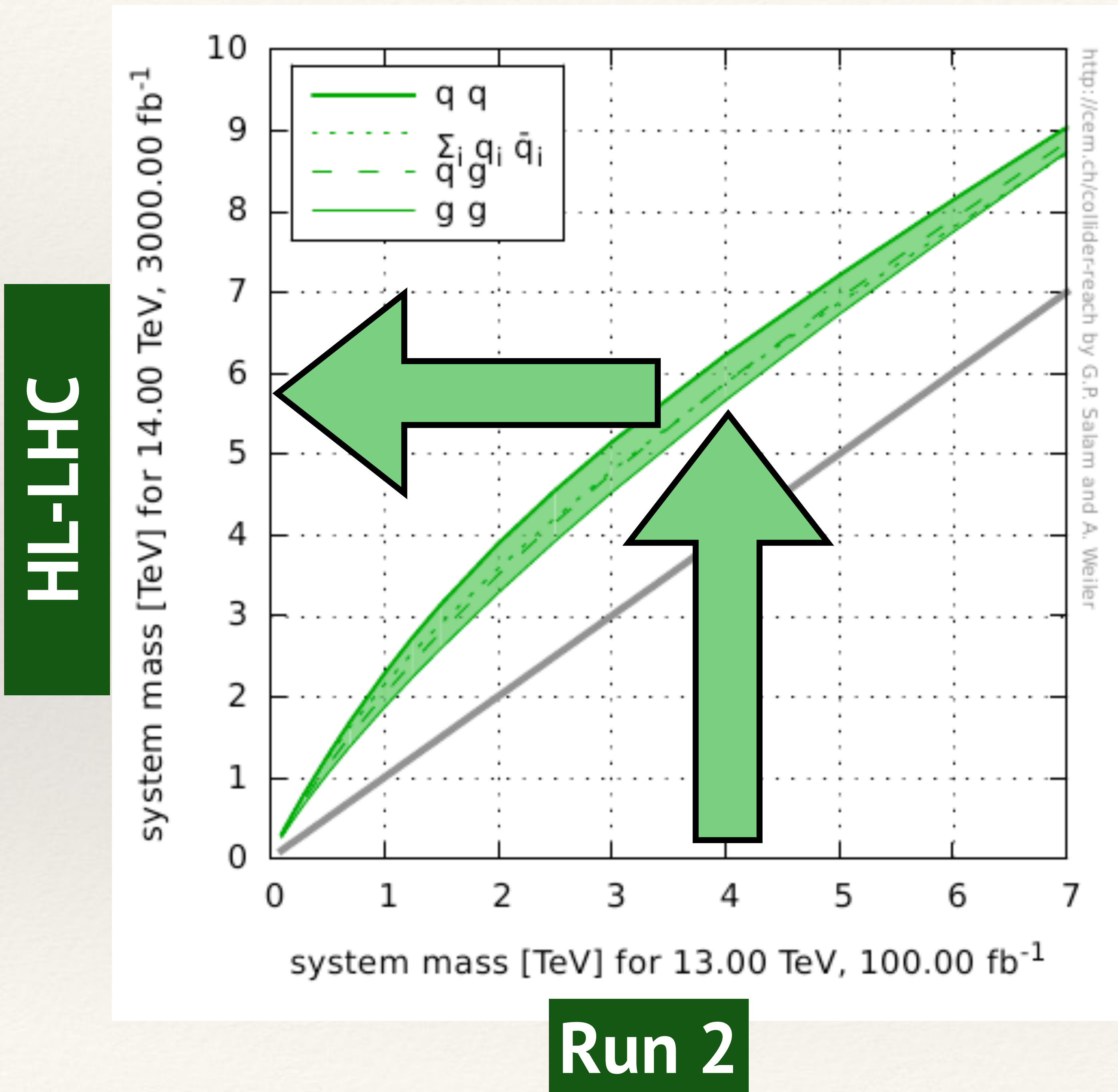
"Even the high luminosity LHC can explore only about half of natural SUSY parameter space."

Baer, Barger & Savoy

My view

Hierarchy problem is a deep question for theorists, possibly with surprises still to come (cf. relaxion). But as experimenters you should not let it constrain you too much

Still ~2 TeV to be gained beyond Run 2



Gain is most significant (logarithmically) at the lower end of the spectrum, i.e. for states with small cross sections (e.g. weakly coupled)

Standard Model

Precision revolution

NNLO revolution

NNLO is one of the most active areas in QCD now

After pioneering calculations for Higgs and Drell Yan more than 10 years ago, only recently many 2 → 2 processes computed at NNLO

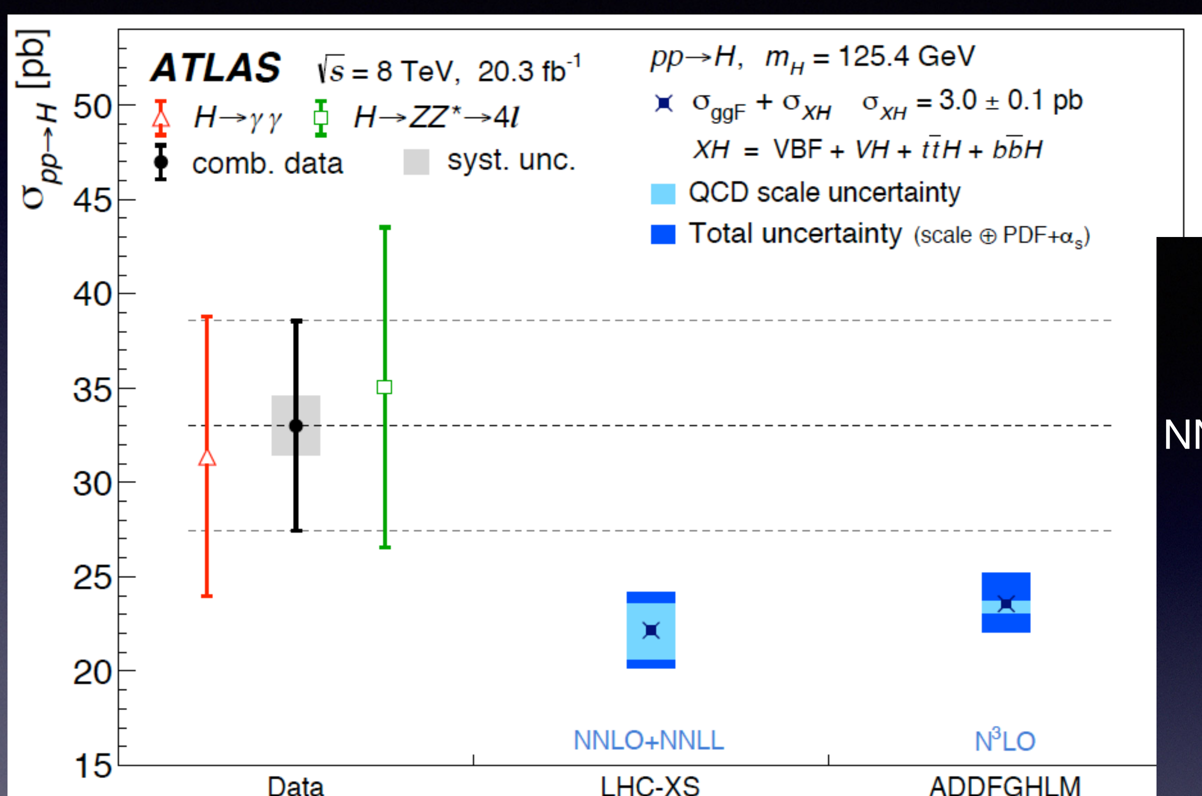
NNLO most important in three different situations

Benchmark processes (measured with highest accuracy)	Input to PDFs fits + backgrounds to Higgs studies	Very large NLO corrections (moderate precision needs NNLO)
- $Z \to l^+l^-$ - $W \to l\nu$ - ...	- Diboson - Boson + jet - top-pairs - ...	- Higgs - Higgs + jet - ...

Plus more reliable estimate of theory uncertainty

Still early days, but in the few cases examined (e.g. Higgs and Drell Yan, VV, Vγ, top ...), better agreement with data at NNLO

N^{3}LO Higgs production



NNLO + parton shower

NNLO+PS in it's infancy, currently three methods/approaches:

- MiNLO upgrade NLO X+1jet calculations to be NLO accurate for X production (X=H,V), NNLO reweighting in the Born variables
  Hamilton, Nason, Re, GZ '13
  Karlberg, Re, GZ '14
- UNNLOPS relies on NLO multi-jet merging, adds the precise difference between fixed-order real ME and PS approximation. Depends on merging scale. Virtual correction confined to lowest bin (not spread)
  Hoeche, Li, Prestel '14
- Geneva combines differential NNLO calculation for X with 0-jettiness (aka beam thrust) NNLL' resummation. Perform first two shower emissions by hand, such that they don't split the resummation
  Alioli, Bauer, Berggren, Tackmann, Walsh '15

Slides from Zanderighi @ LP15

Ultimate limitations on precision?

Likely to become a key question in the coming years; matters for the HL-LHC Higgs programme

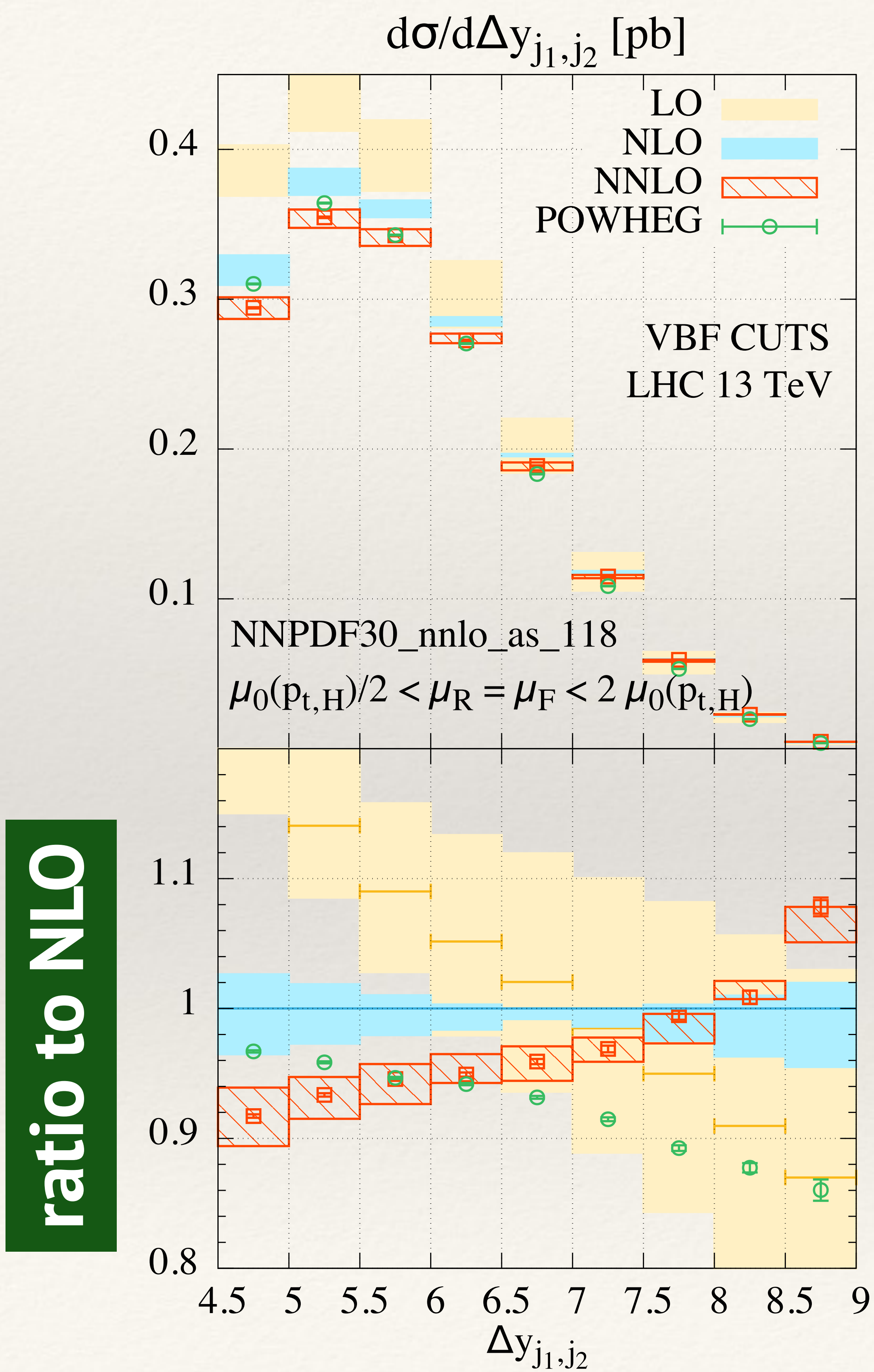
Experimentally

- If it's got leptons, then you should be fine (e.g. 0.4% on $d\sigma_Z/dp_t$ normalised to σ_Z; but not so great for ttbar?)
- With jets, how good can you get (e.g. also if MCs get better)?

Theoretically

- How do we handle non-perturbative effects?
- Do hadronic observables converge at NNLO?
- PDFs, α_s ?

VBF Higgs



NNLO effects are up to 10%
What happens at N^3LO?

Hadronisation strangely small in MCs, ~1%. Is this right?

MPI/UE can be 5%. How well do we understand this?

We may get differential N3LO in next couple of years.

Experimental comparisons of leptonic & hadronic sides of Z+jet could bring insight too

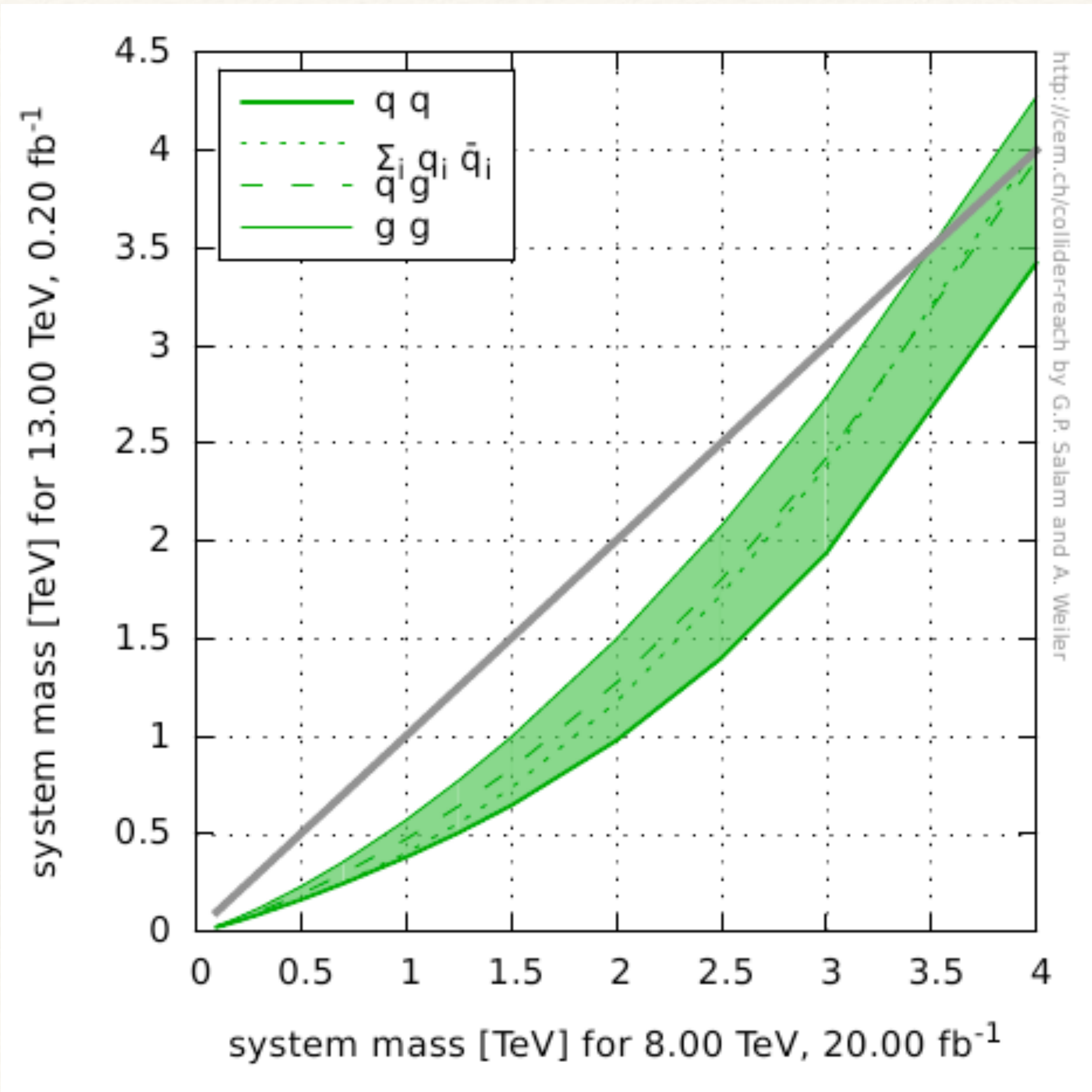
Cacciari, Dreyer, Karlberg, GPS & Zanderighi '05

Conclusions

- For searches, progress will be faster in the coming two years than for a long time to come (but there's still a lot to gain in ultimate reach after Run 2).
- Boosted techniques likely to play a major role: may need to be taken beyond today's standards
- For Higgs, we (you) will have a pretty solid picture by the end of Run 2. There's room for surprises.
- We may be at a turning point for precision QCD: starting to probe the ultimate limits of what we can do?

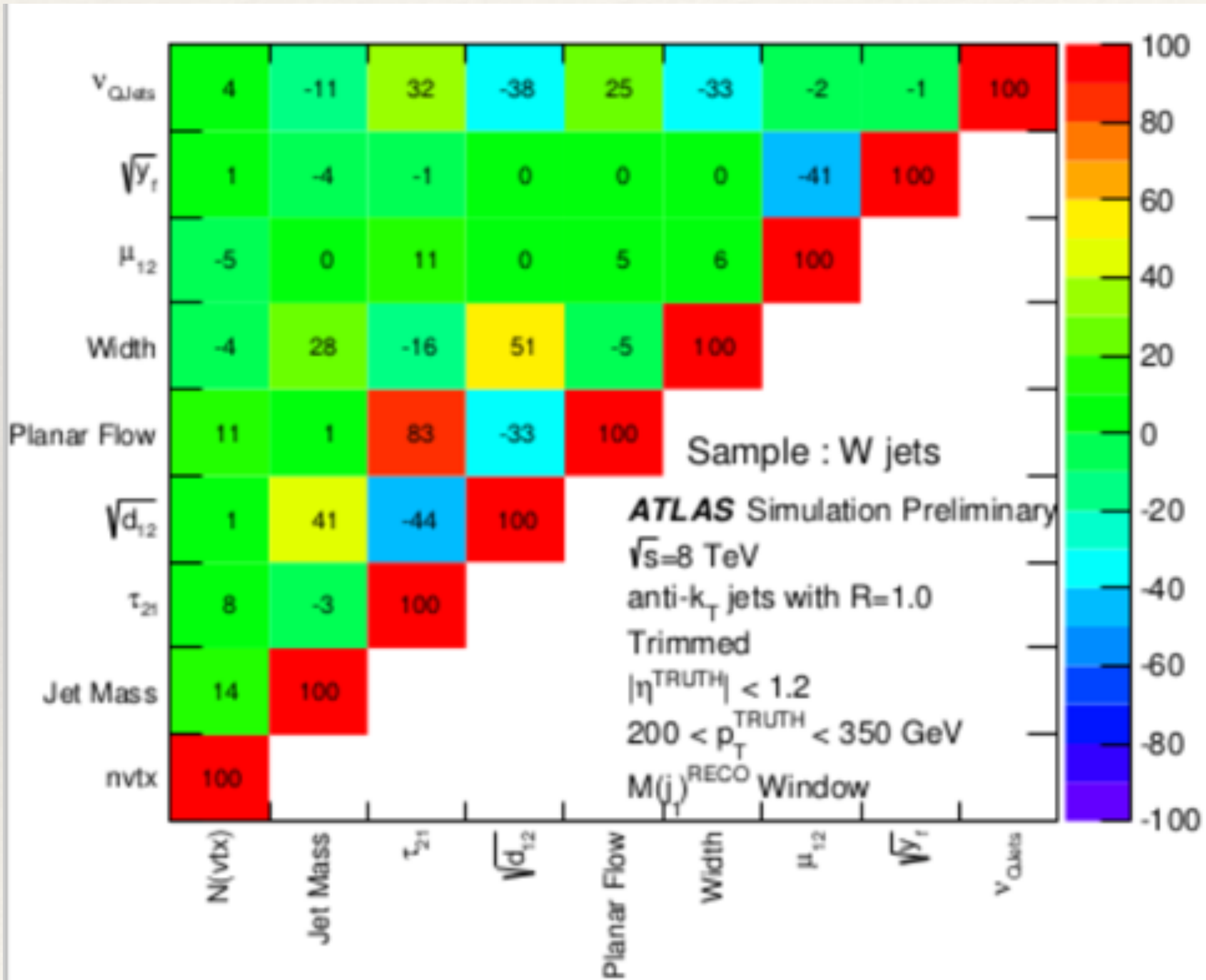
Backup slides

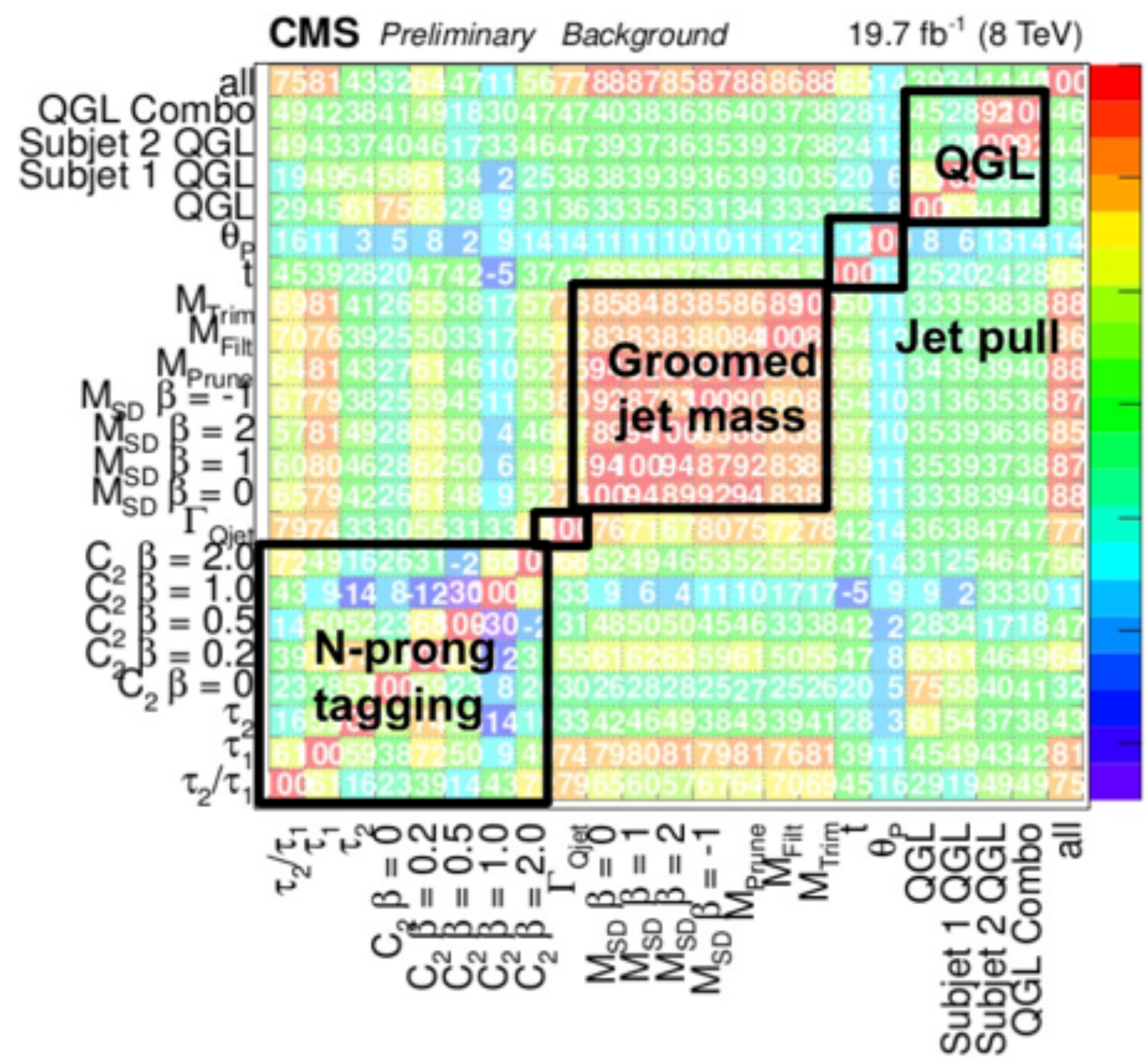
200 pb^{-1} @ 13 TeV



Range of techniques studied by ATLAS & CMS

W/Z taggers (and correlations between them)





Comments from Boost 2014

- More rigorous comparisons to focus on just a few taggers, before we move on to Run2
- Caveat: need to add systematics to these curves!
  - This is non trivial! Correlations also need to be properly taken into account

Emily Thompson

i think we agree on this point: “be careful how we extend our conclusions to the larger community” (david m.)

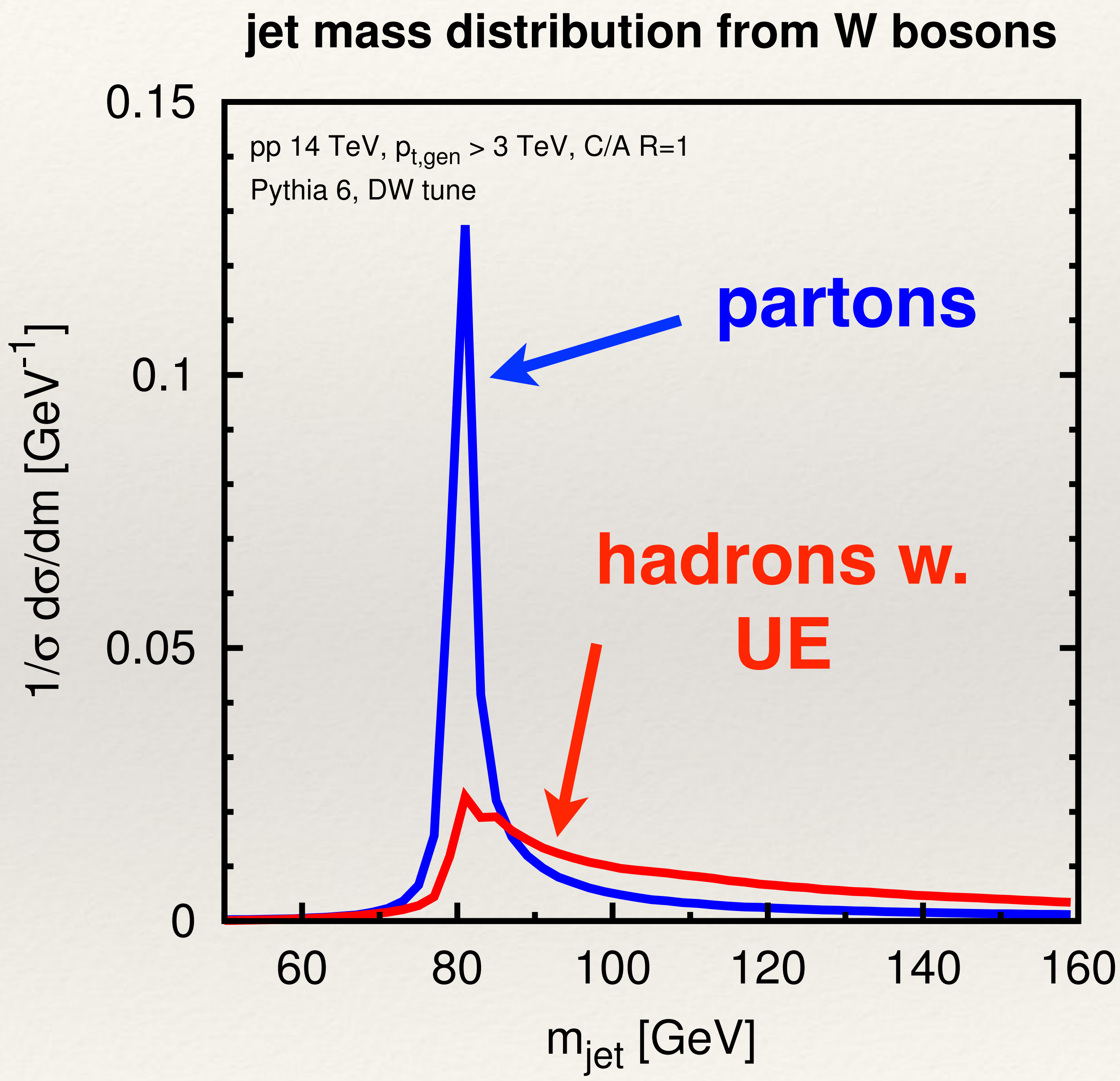
Bottom line

We have many good tools

Balance between simplicity and performance still to be found?

Principles in use today

#1: the jet mass is a fragile observable.



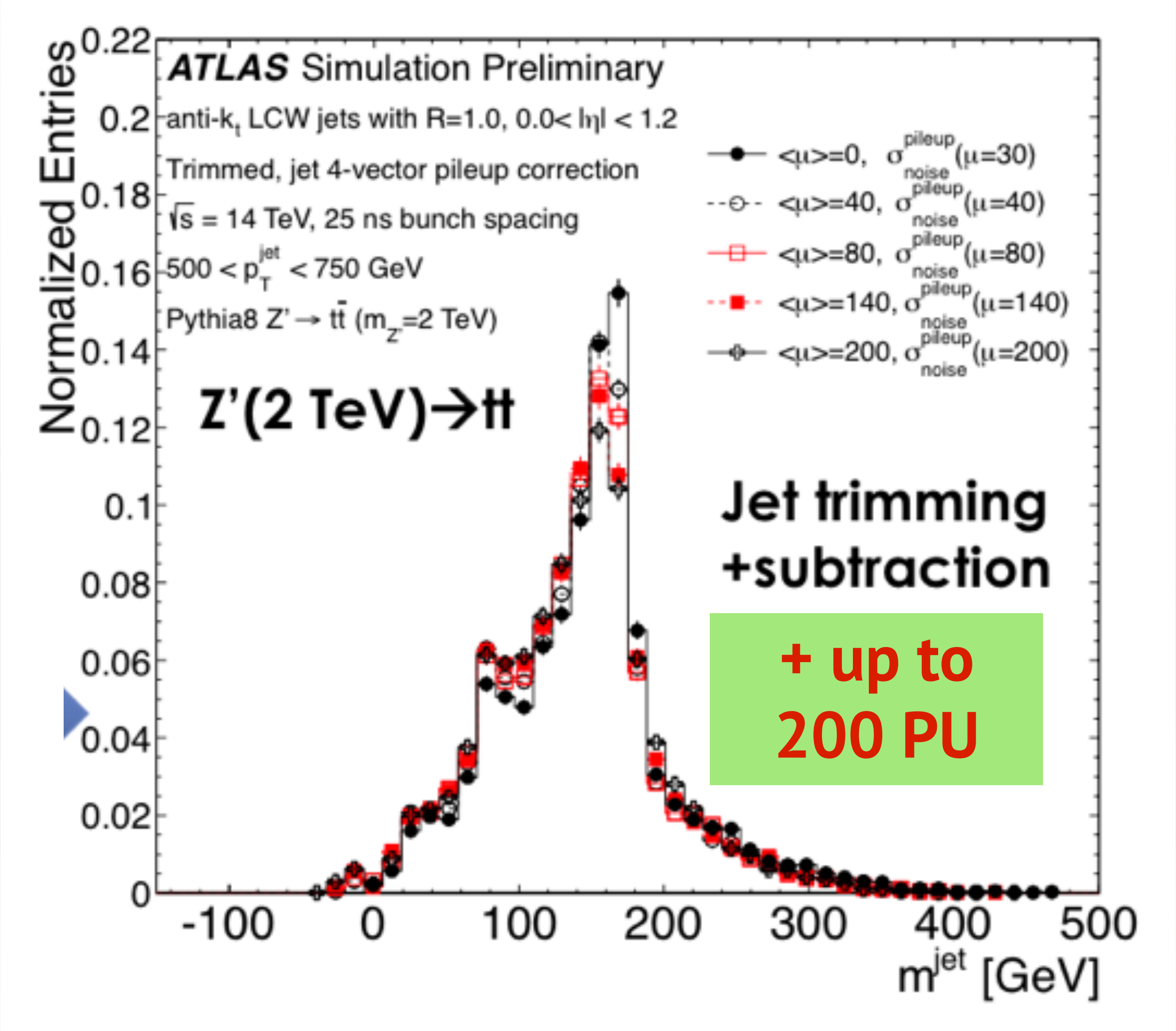
Principles in use today

#1: the jet mass is a fragile observable.

So people usually use a **groomed mass**:

filtering/trimming/pruning

(or you can go to smaller R ~ few x M/p_t)

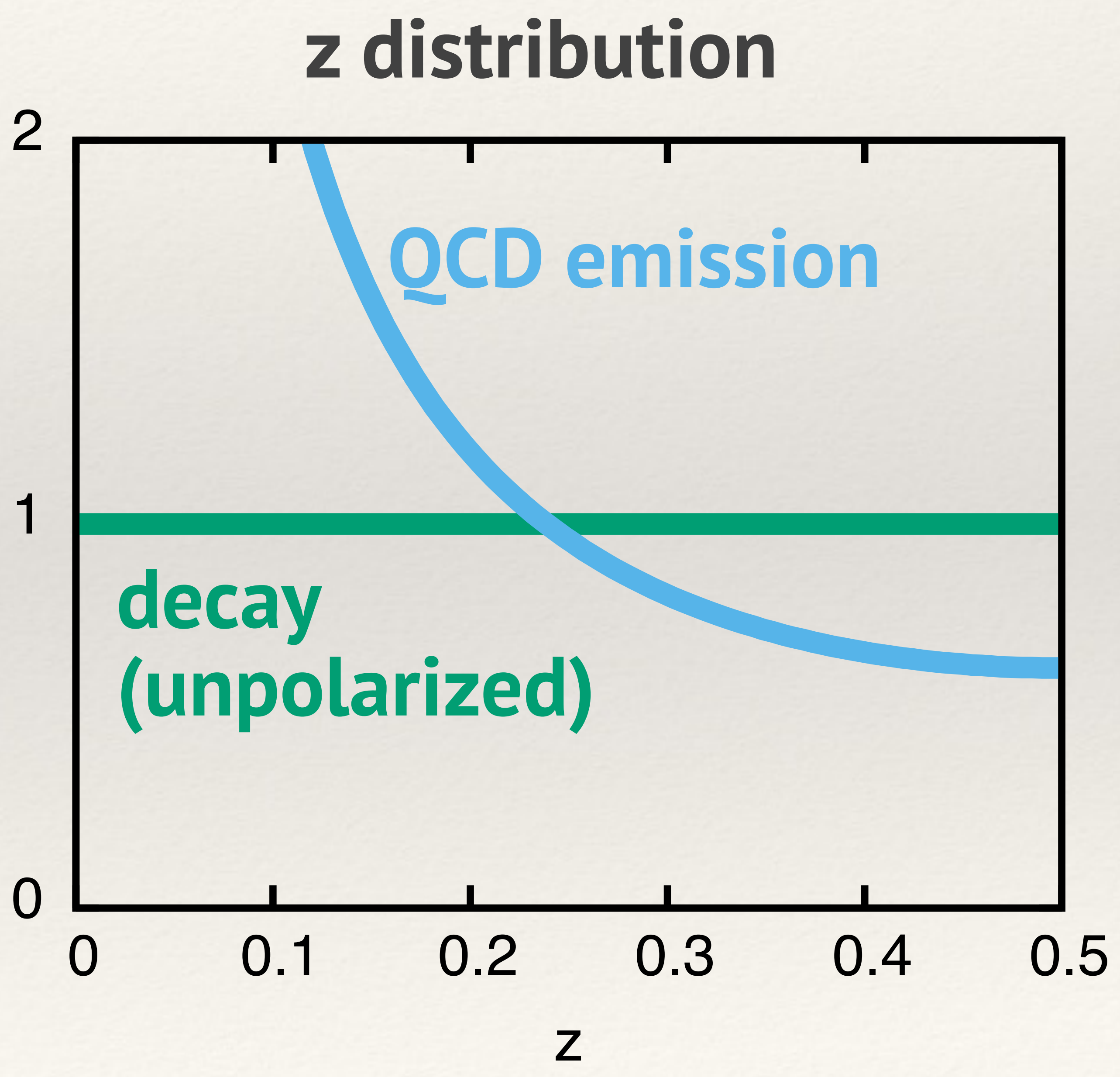


Principles in use today

#2: QCD gluon emission is soft; V/H→qq is not

Identify two-prong structure and cut on "z" (momentum fraction between prongs)

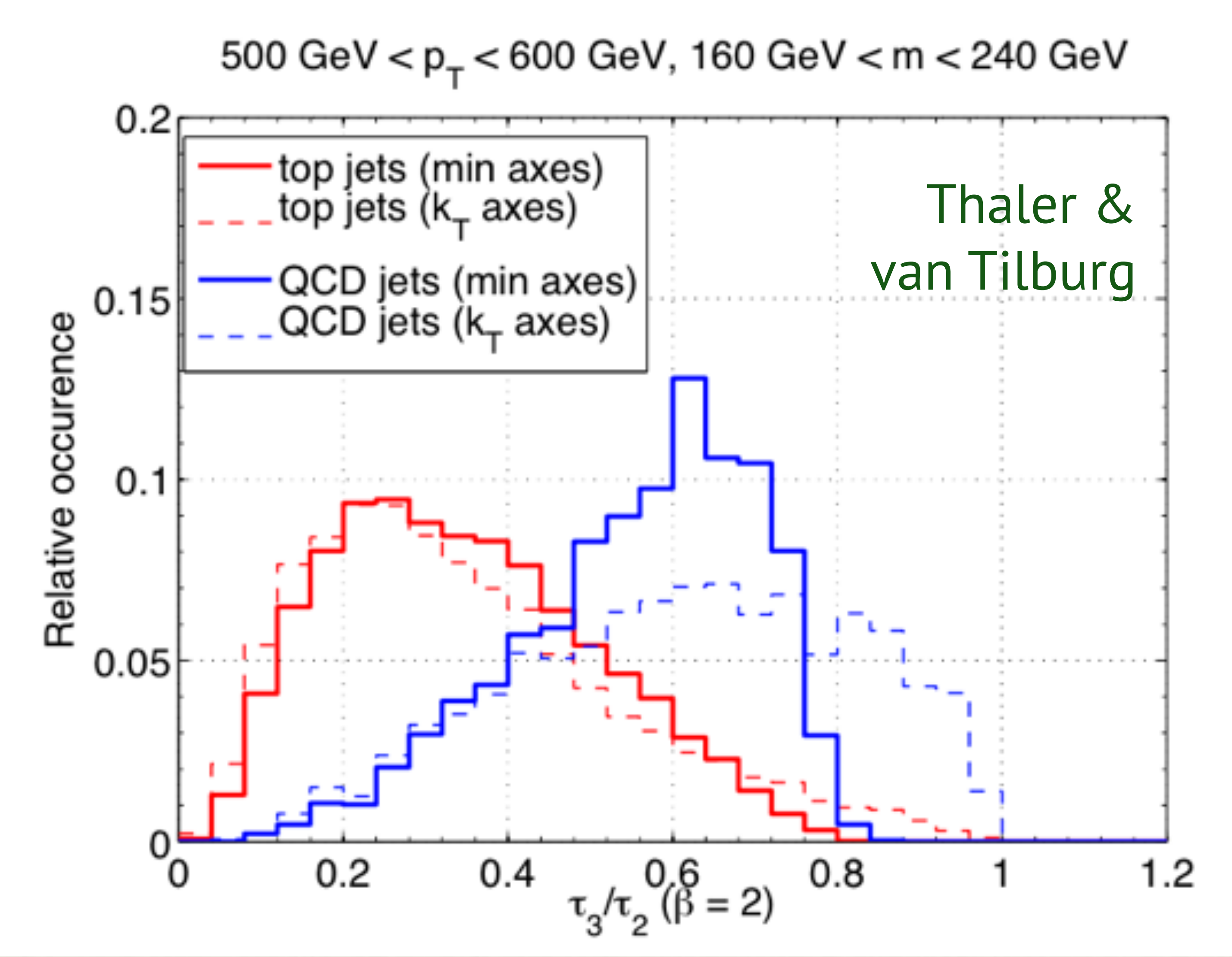
[done by mass-drop taggers/pruning/trimming/]



Principles in use today

#3: Radiation patterns differ in V/H/top v. QCD

Cut on variables sensitive to deviation from exact n-prong structure, e.g. N-subjettiness

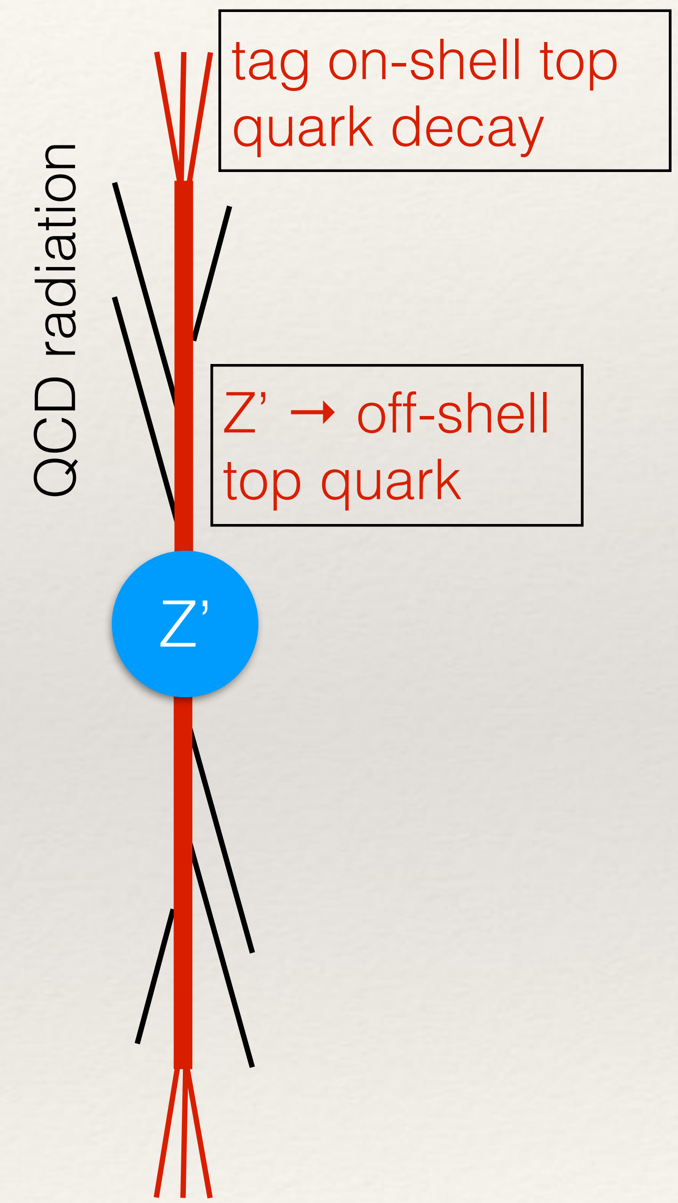


$$\frac{\tau_n}{\tau_{n-1}}; \quad \tau_n = \min_{\text{n axes}} \sum_i p_{ti} \min(\Delta R_{i,\text{axis-1}}, \ldots, \Delta R_{i,\text{axis-n}})$$

Top quarks v. Top jets

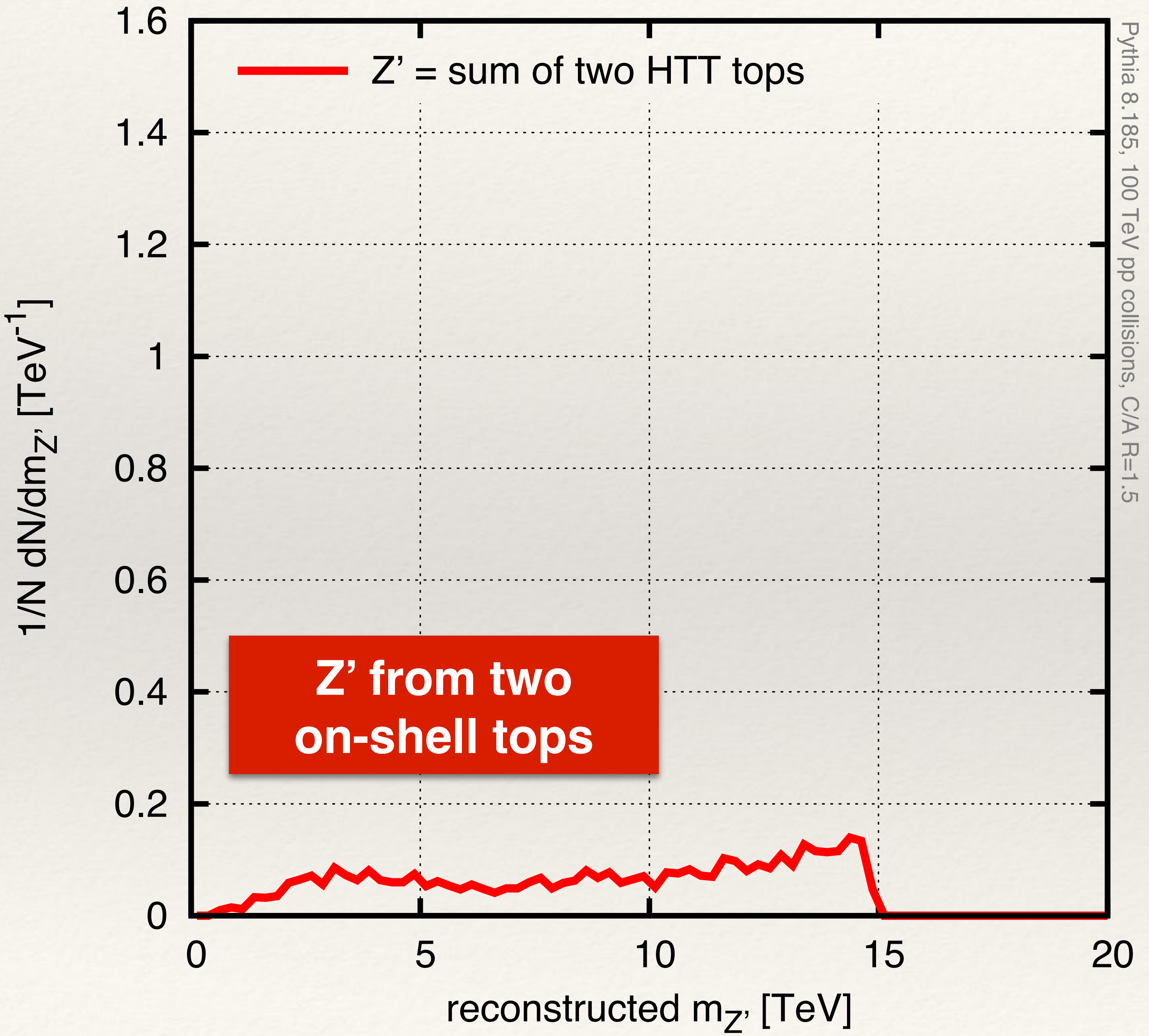
Top taggers often tag the top quark
at the moment of decay

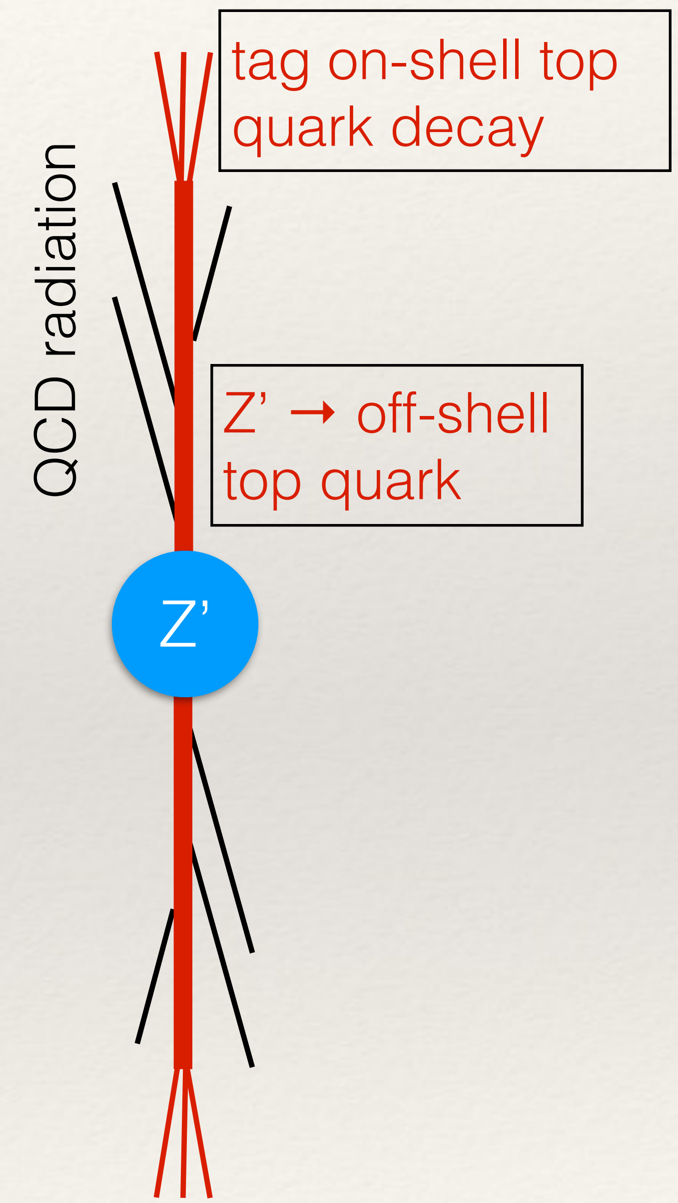
But many boosted top studies are resonance searches and resonance reconstruction needs
top at the moment of production



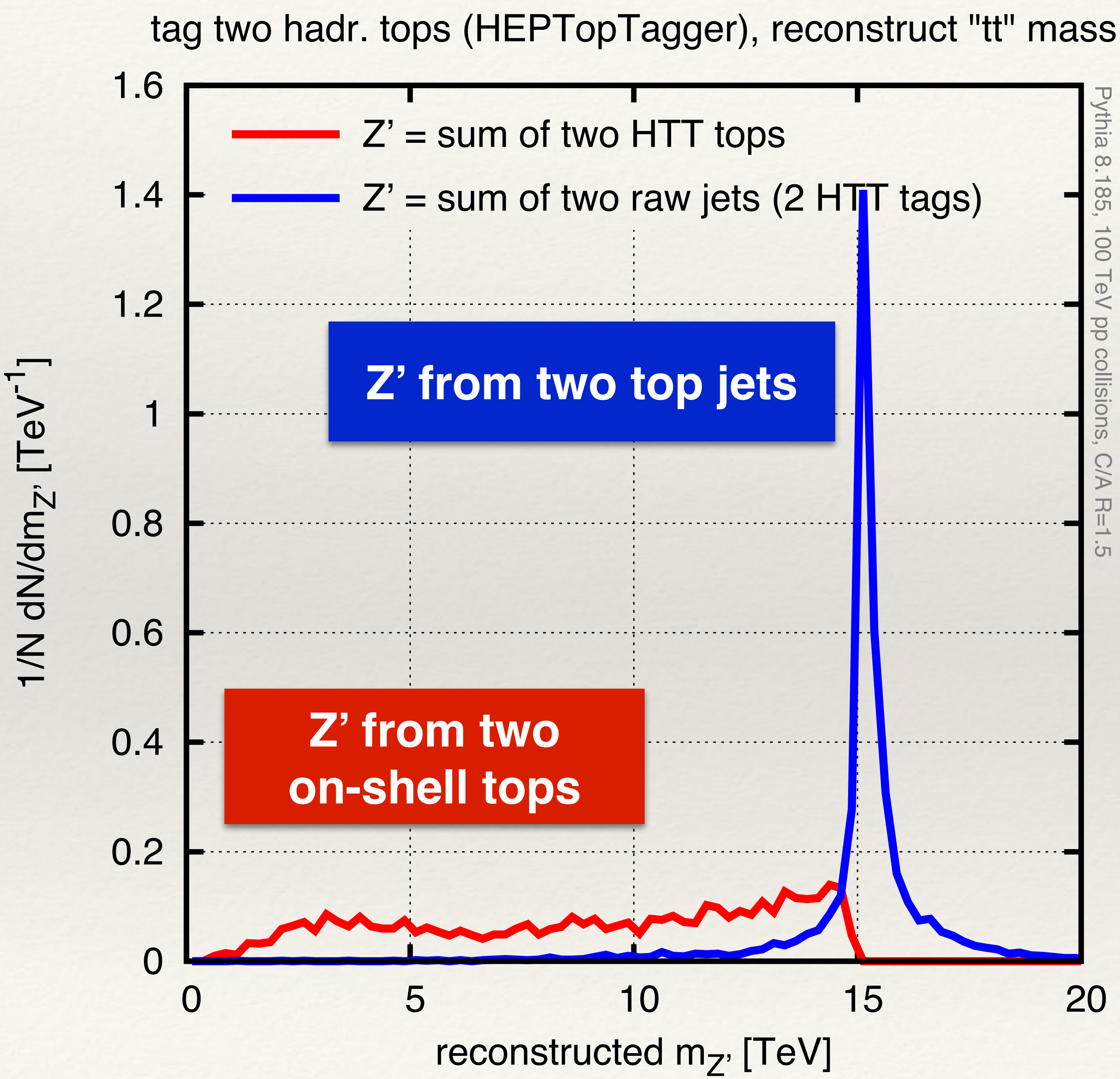
Top quarks v. Top jets

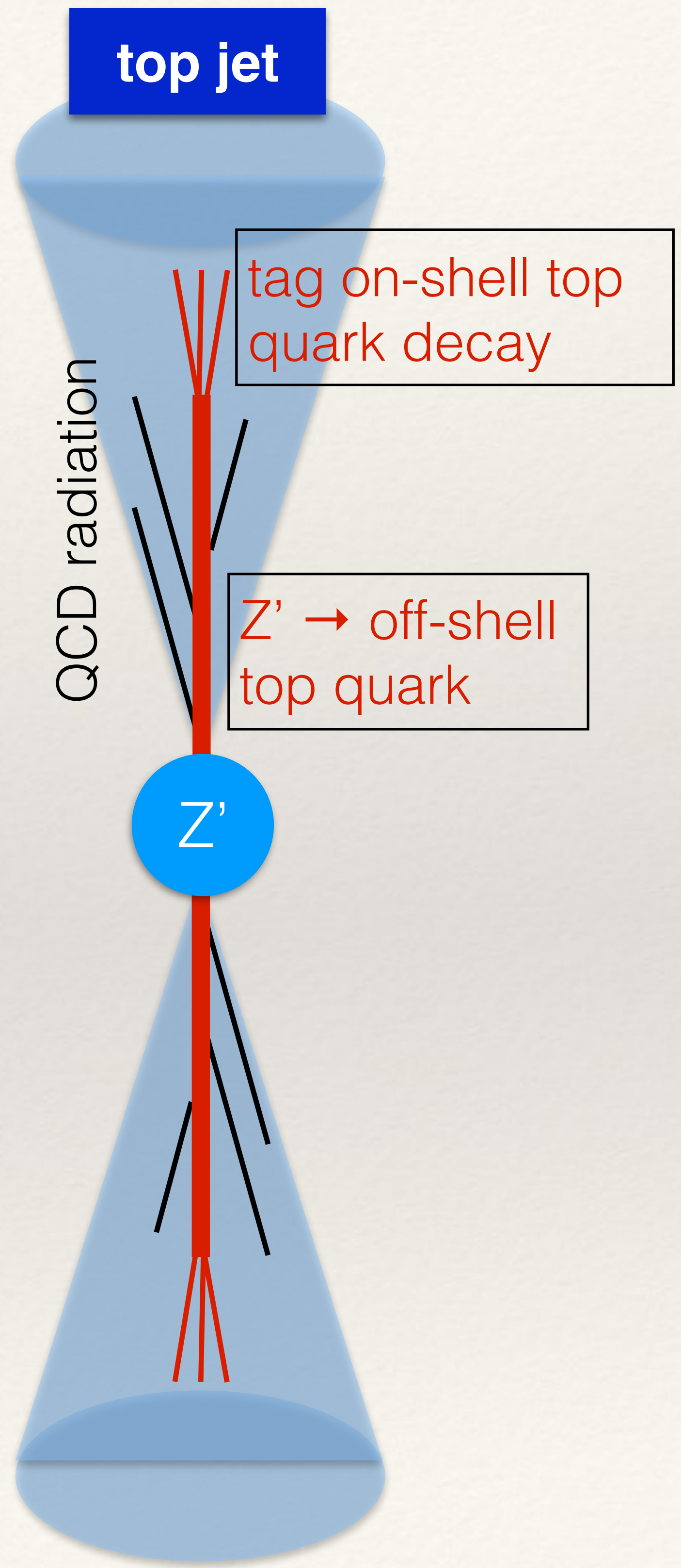
tag two hadr. tops (HEPTopTagger), reconstruct "tt" mass





Top quarks v. Top jets





cf work in progress Kasieczka et al

colour-neutral objects

cf. FCC talks by Maurizio Pierini

Colour neutral objects don't radiate outside cone defined by their opening angle.

QCD jets radiate at all angles.

That leaves a radiation gap of size $\sim \ln \frac{p_t}{4m}$

Like a rapidity gap in VBF, but much less affected by pileup, multiple interactions, etc.

Also like isolation cone around tau-leptons