HIGGS PHYSICS IN THE PRECISION ERA

Higgs 2021, Stony Brook, via Zoom, 18 October 2021

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What are we trying to achieve?

Higgs is the last particle of the SM.

So the SM is complete, right?

The Lagrangian and interactions: two out of three qualitatively new!

$$\mathscr{L}_{\mathrm{SM}} = \cdots + |D_\mu \phi|^2 + \psi_i y_{ij} \psi_j \phi - V(\phi)$$

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Higgs potential (→ self-interaction).

Holds the SM together.

Unobserved

Why do Yukawa couplings matter to everyone?

Because, within SM **conjecture**, they set quark and electron masses

$\psi_i y_{ij} \psi_j \phi$

Up quarks (mass ~ 2.2 MeV) are lighter than down quarks (mass ~ 4.7 MeV)

proton (up+up+down): 2.2 + 2.2 + 4.7 + … = 938.3 MeV

neutron (up+down+down): 2.2 + 4.7 + 4.7 + … = 939.6 MeV

So protons are **lighter** than neutrons,
→ protons are stable,
giving us hydrogen

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Bohr radius

$$a_0 = \frac{4\pi\epsilon_0 \hbar^2}{m_e e^2} = \frac{\hbar}{m_e c \alpha} \propto \frac{1}{y_e}$$

electron Yukawa determines size of all atoms & energy levels of all chemical reactions

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proton (up+up+down): 2.2 + 2.2 + 4.

neutron (up+down+down): 2.2

S... ...ghter ..., ...re stable, giving us hydrogen

We are establishing the existence of crucial new interactions
We wouldn't consider QED established if we'd only tested it to O(10%)

Boh...

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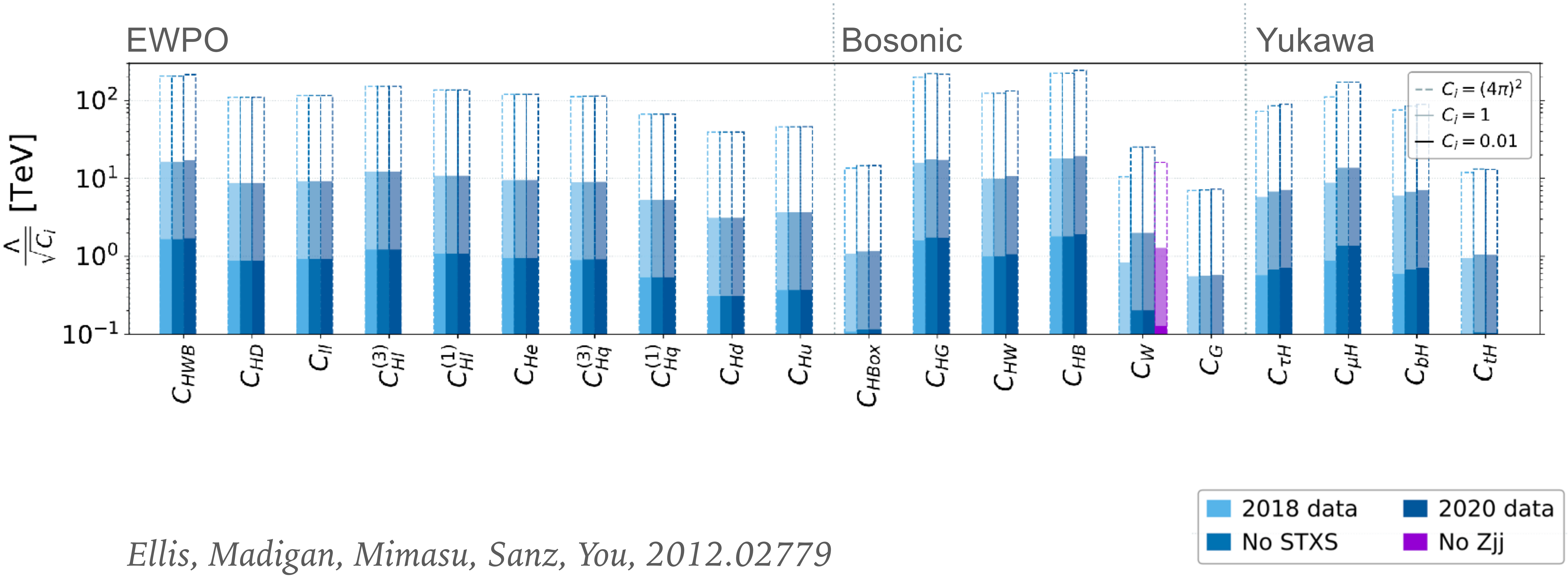
We are (indirectly) searching for new physics



Ellis, Madigan, Mimasu, Sanz, You, 2012.02779

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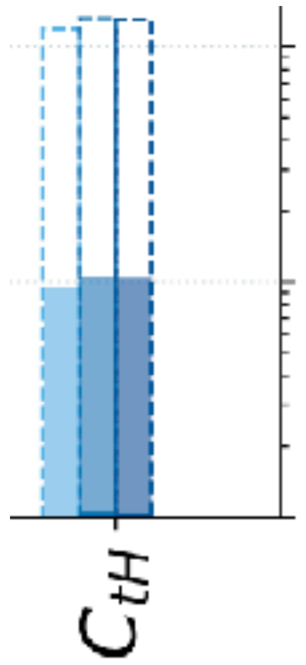

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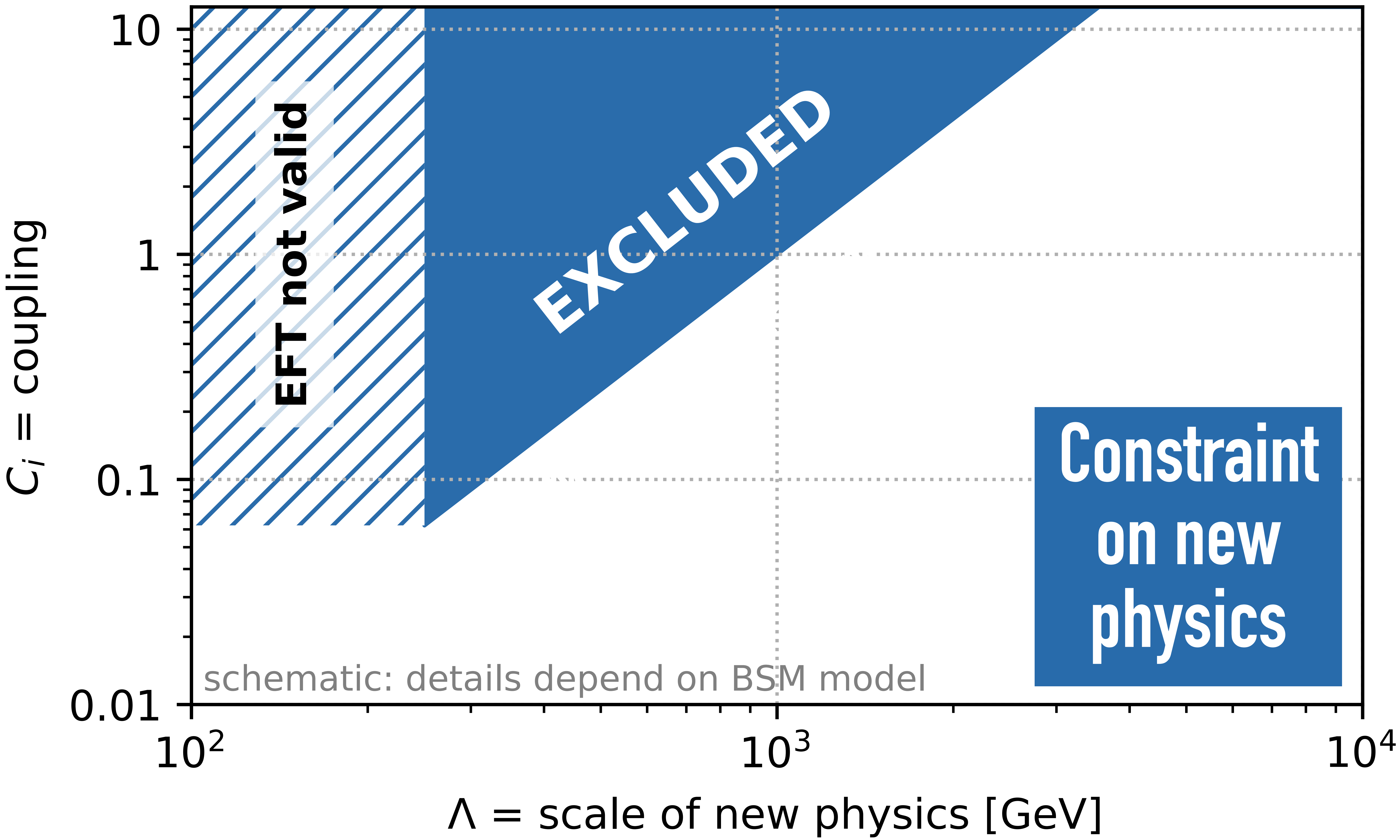

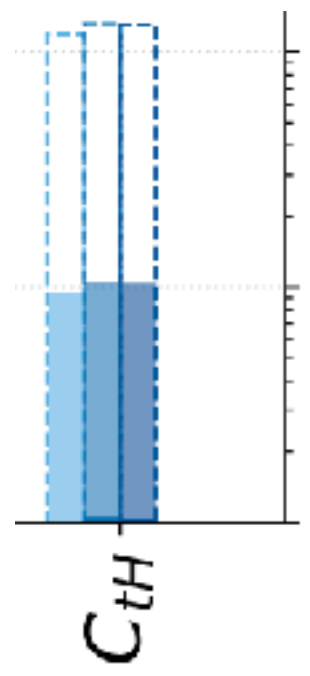

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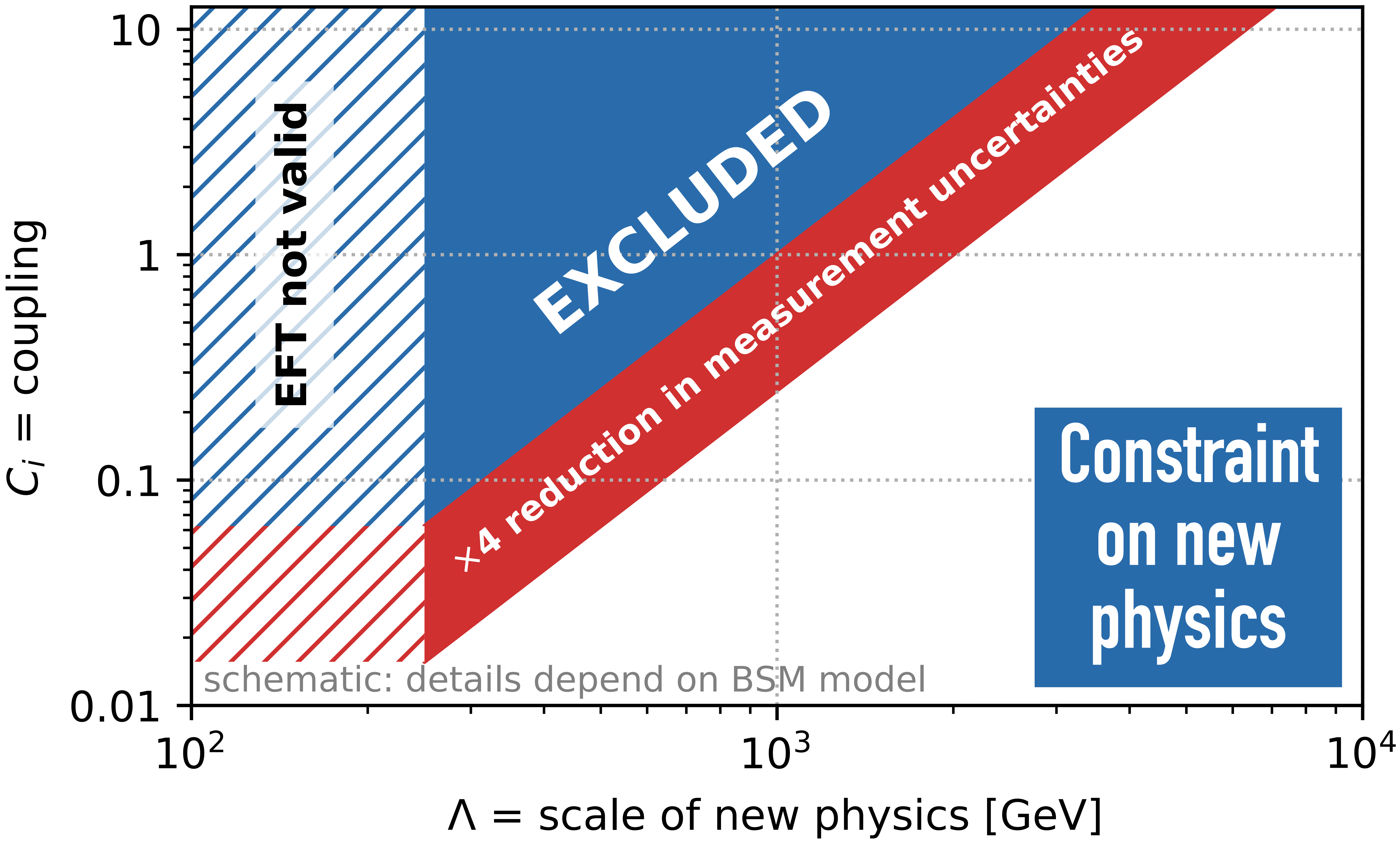

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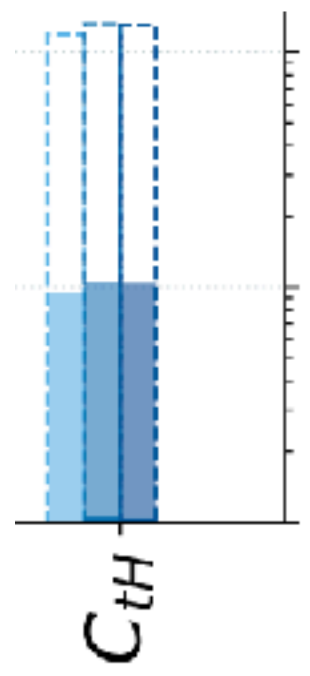
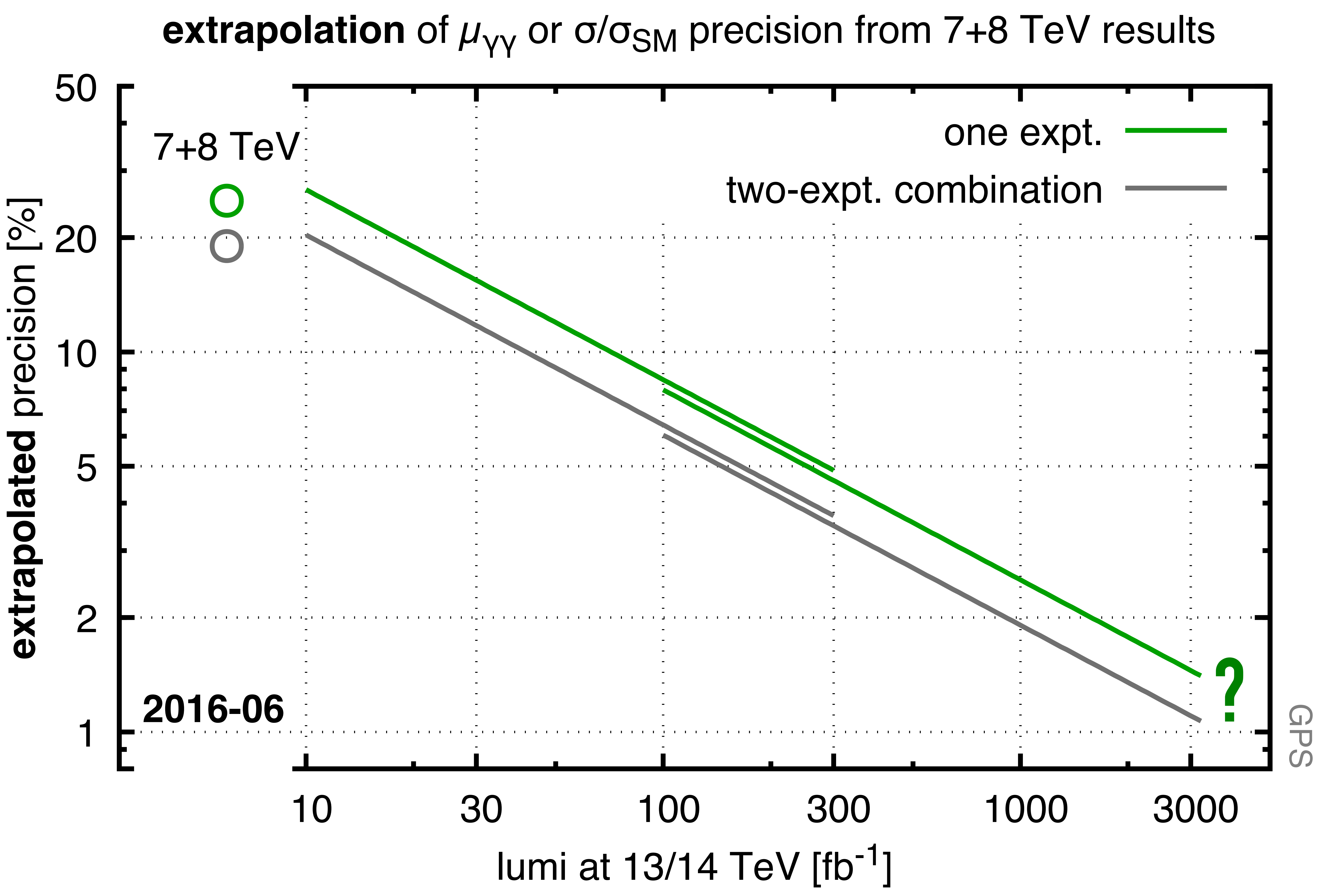


H → γγ, an indirect probe of the top Yukawa, HWW and contact ggH couplings



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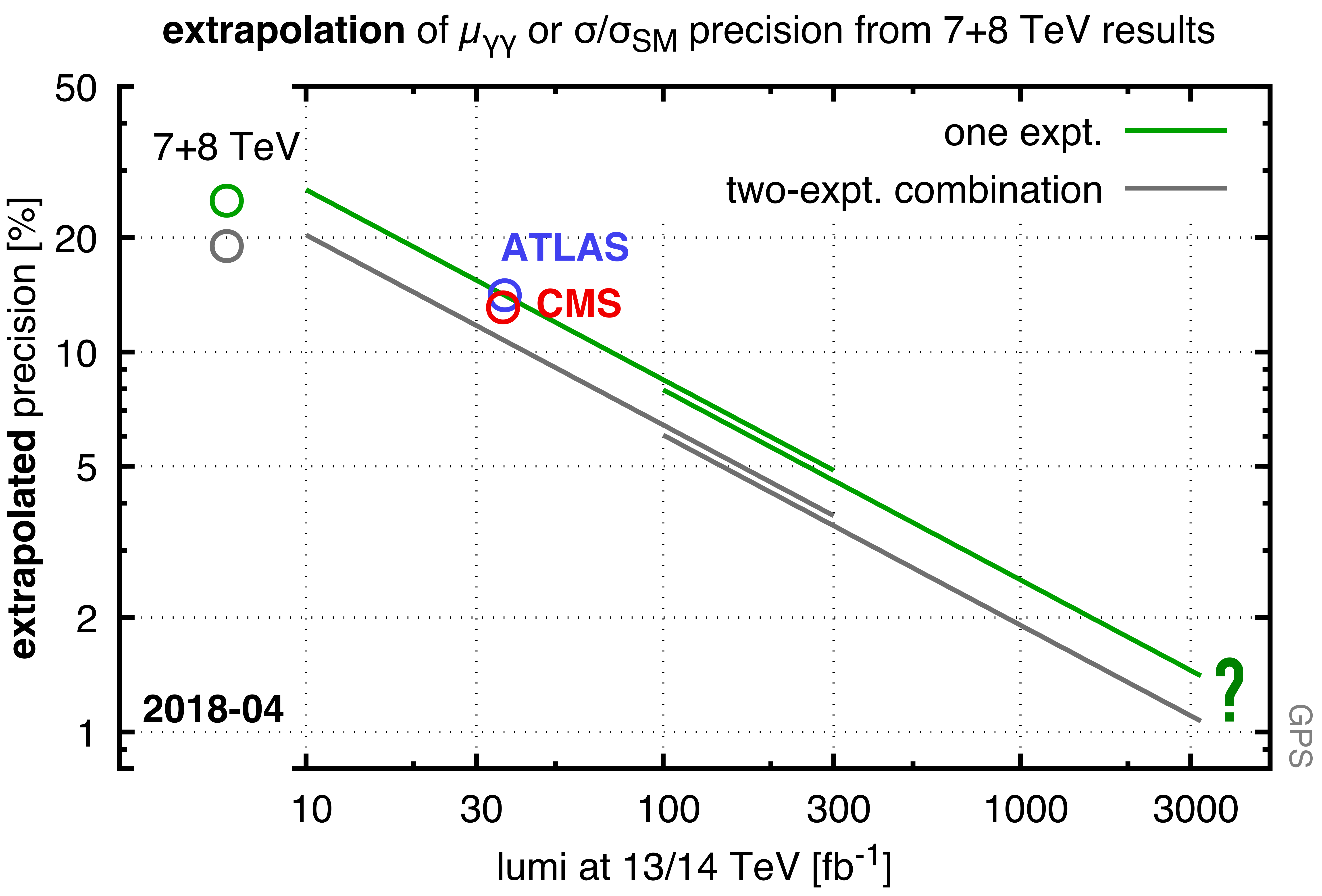

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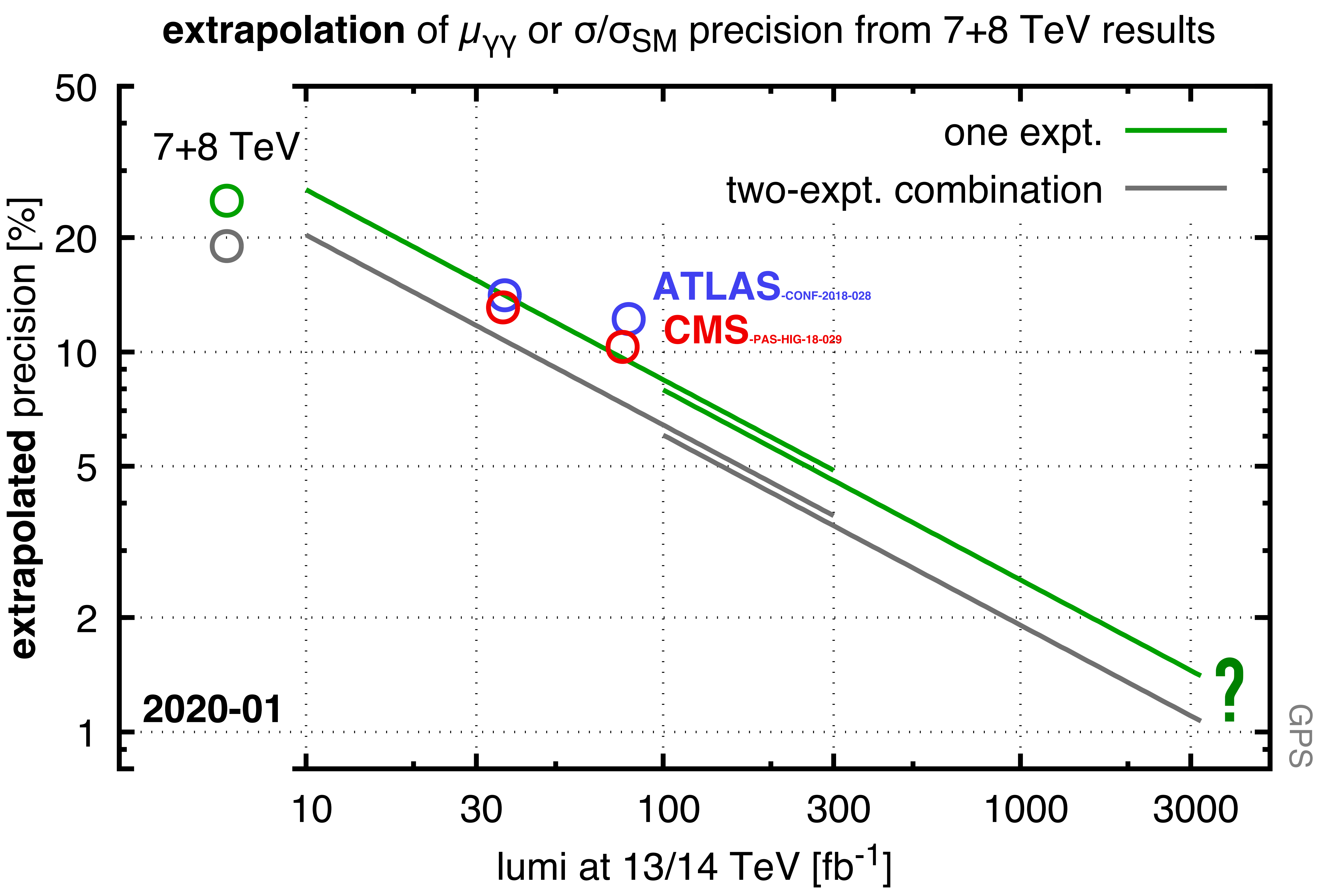

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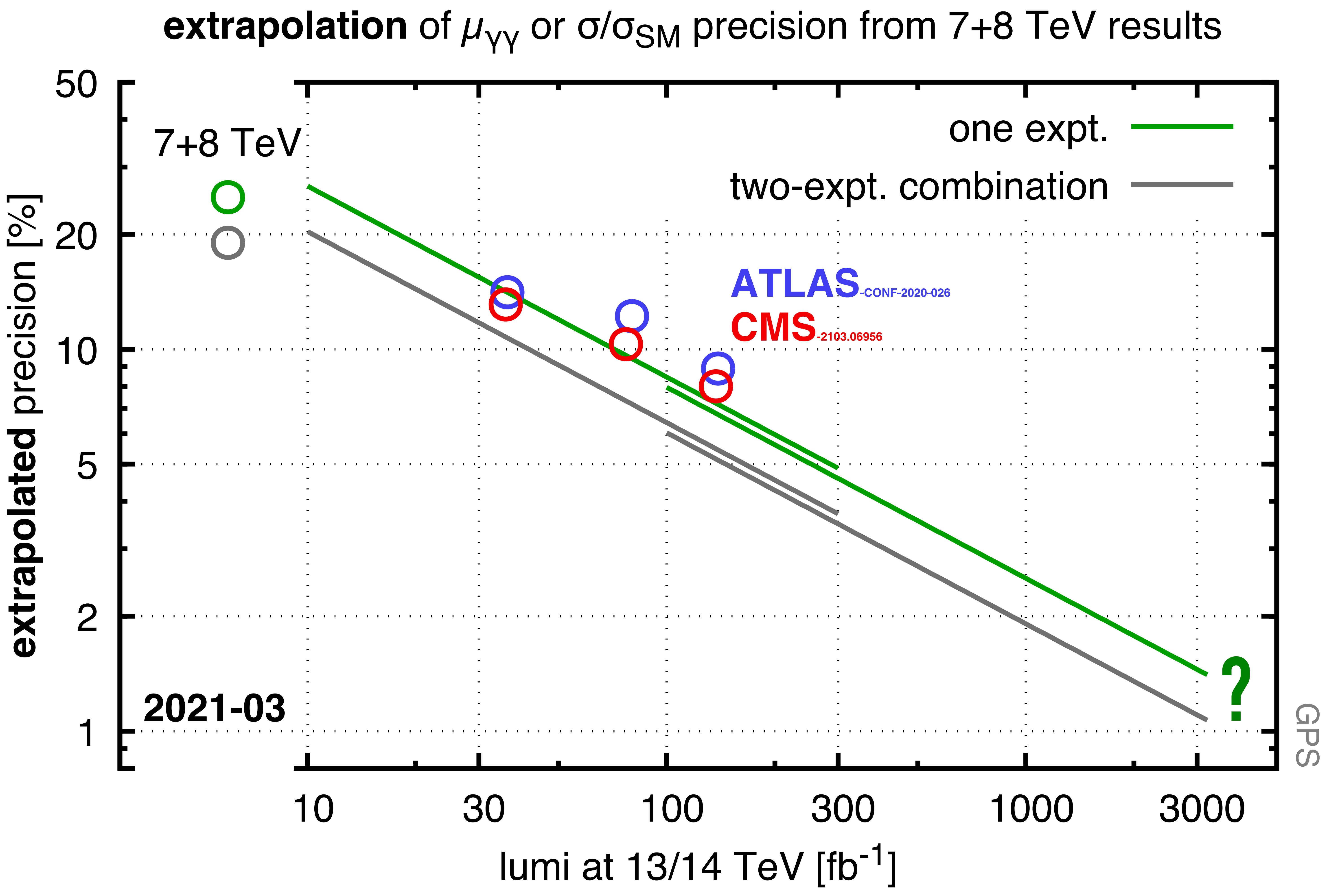

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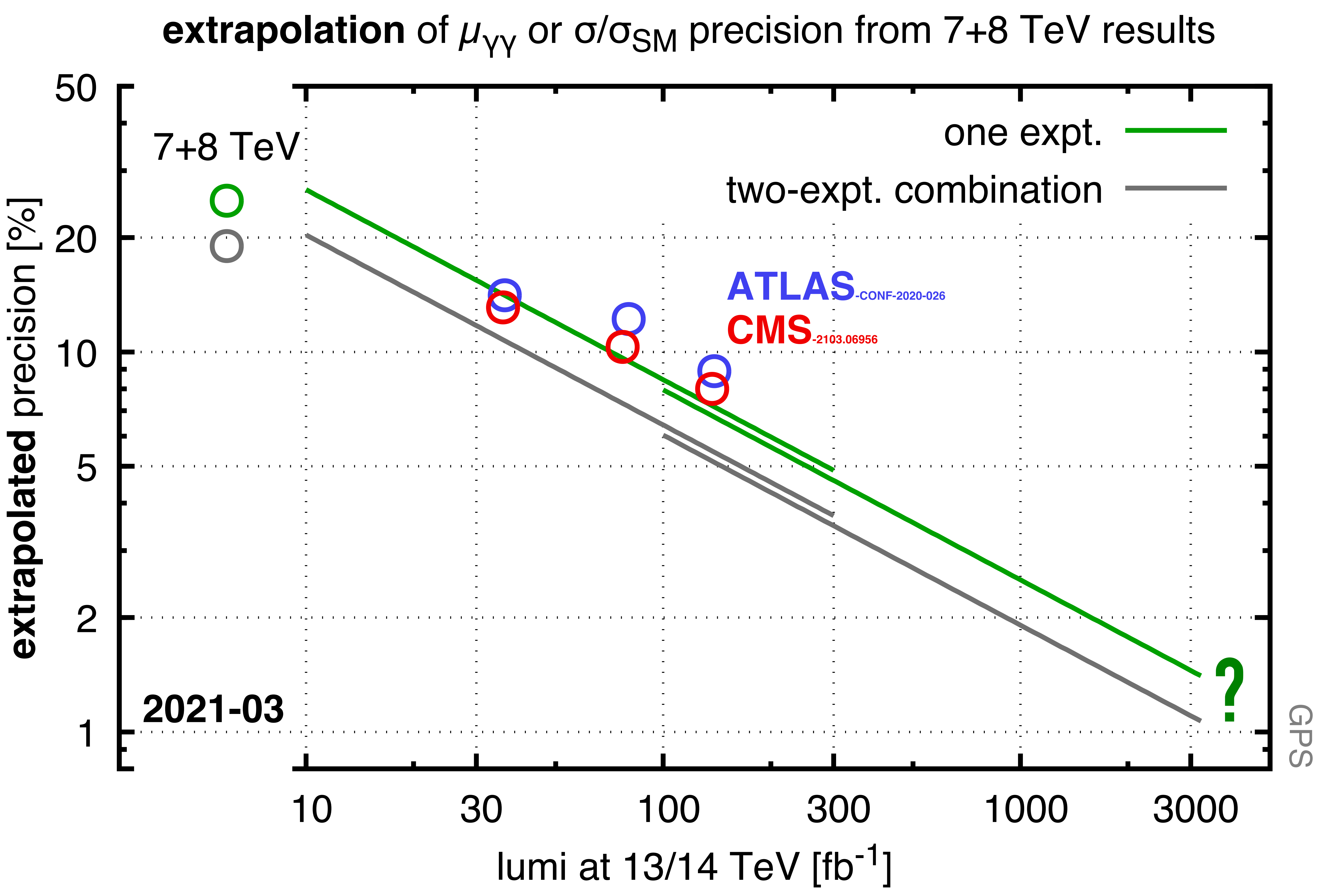


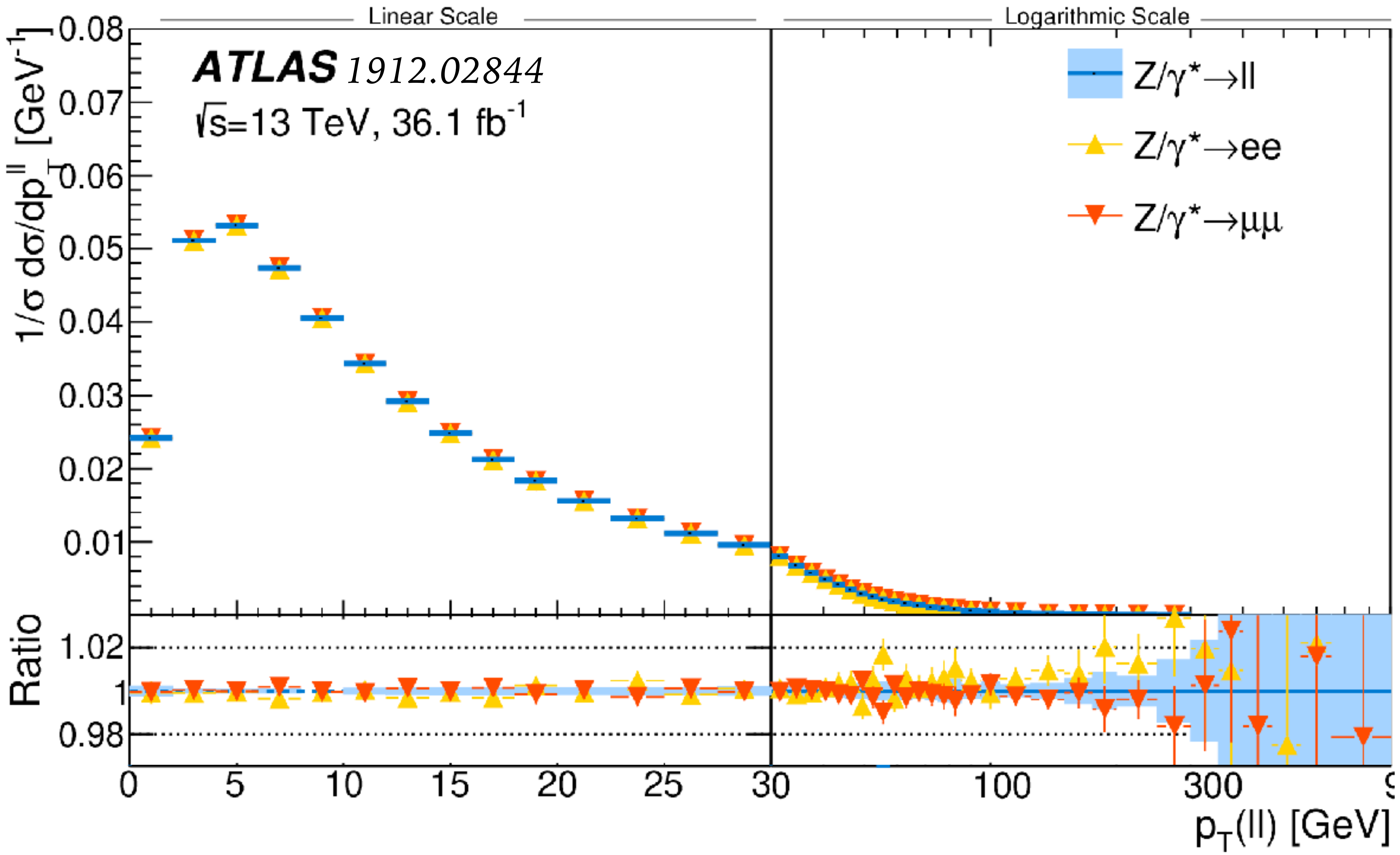
today's ATLAS and CMS total uncertainties (ratio to SM) are at the 8-9% level

5-6% stat.
3-6% syst.
~5% theo.

what is possible experimentally?

[in a quasi-ideal world]

Z p_T distribution — a showcase for LHC precision



Normalised distribution's statistical and systematic errors well below 1% all the way to $p_T \sim 200$ GeV

Largest normalisation err is luminosity then lepton ID

$$\sigma_{\text{fid}} = 736.2 \pm 0.2\ \text{(stat)} \pm 6.4\ \text{(syst)} \pm 15.5\ \text{(lumi)}\ \text{pb}$$

Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS

Table 4: Summary of contributions to the relative systematic uncertainty in σ_{vis} (in %) at $\sqrt{s} = 13$ TeV in 2015 and 2016. The systematic uncertainty is divided into groups affecting the description of the vdM profile and the bunch population product measurement (normalization), and the measurement of the rate in physics running conditions (integration). The fourth column indicates whether the sources of uncertainty are correlated between the two calibrations at $\sqrt{s} = 13$ TeV.

Source	2015 [%]	2016 [%]	Corr
Normalization uncertainty			
Bunch population			
Ghost and satellite charge	0.1	0.1	Yes
Beam current normalization	0.2	0.2	Yes
Beam position monitoring			
Orbit drift	0.2	0.1	No
Residual differences	0.8	0.5	Yes
Beam overlap description			
Beam-beam effects	0.5	0.5	Yes
Length scale calibration	0.2	0.3	Yes
Transverse factorizability	0.5	0.5	Yes
Result consistency			
Other variations in σ_{vis}	0.6	0.3	No
Integration uncertainty			
Out-of-time pileup corrections			
Type 1 corrections	0.3	0.3	Yes
Type 2 corrections	0.1	0.3	Yes
Detector performance			
Cross-detector stability	0.6	0.5	No
Linearity	0.5	0.3	Yes
Data acquisition			
CMS deadtime	0.5	<0.1	No
Total normalization uncertainty	1.3	1.0	—
Total integration uncertainty	1.0	0.7	—
Total uncertainty	1.6	1.2	—

Luminosity: the systematic common to all measurements

- has hovered around 2% for many years (except LHC*b*)
- CMS has recently shown that they can get it down to 1.2%
- a major achievement, because it matters across the spectrum of precision LHC results

the master formula

$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

m_H (GeV)	Cross Section (pb)	TH Gaussian %	±PDF %	$\pm\alpha_s$ %
125.00	4.858E+01	±3.9	±1.9	±2.6

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Alex Huss's talk tomorrow
(including a conceptual surprise)

HXSWG YR 4 gg→H uncertainties

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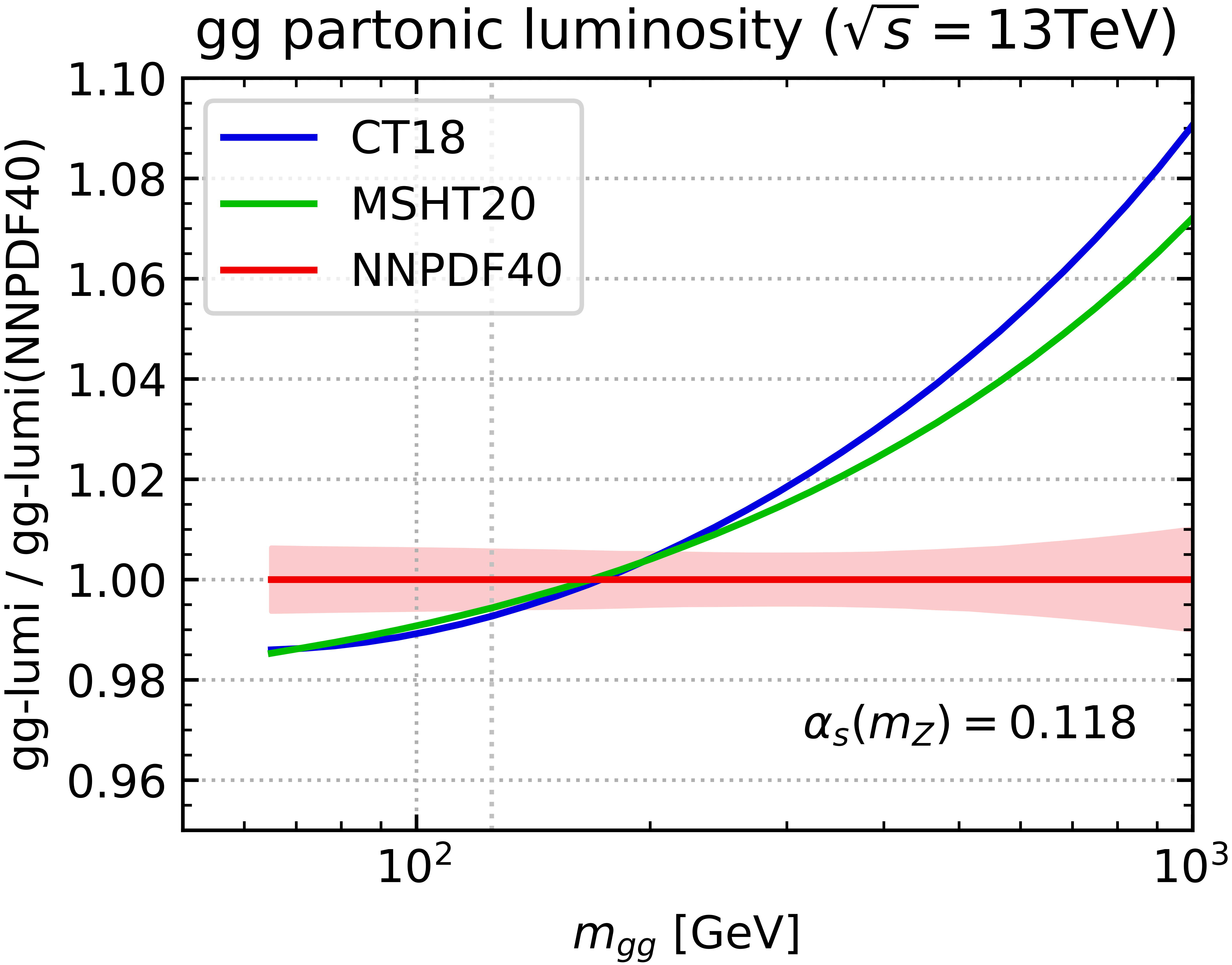
Comparing modern PDF sets



gg-lumi, ratio to PDF4LHC15 @ m_H

PDF4LHC15	1.0000	±	0.0184
CT18	0.9914	±	0.0180
MSHT20	0.9930	±	0.0108
NNPDF40	0.9986	±	0.0058

$\times 3$

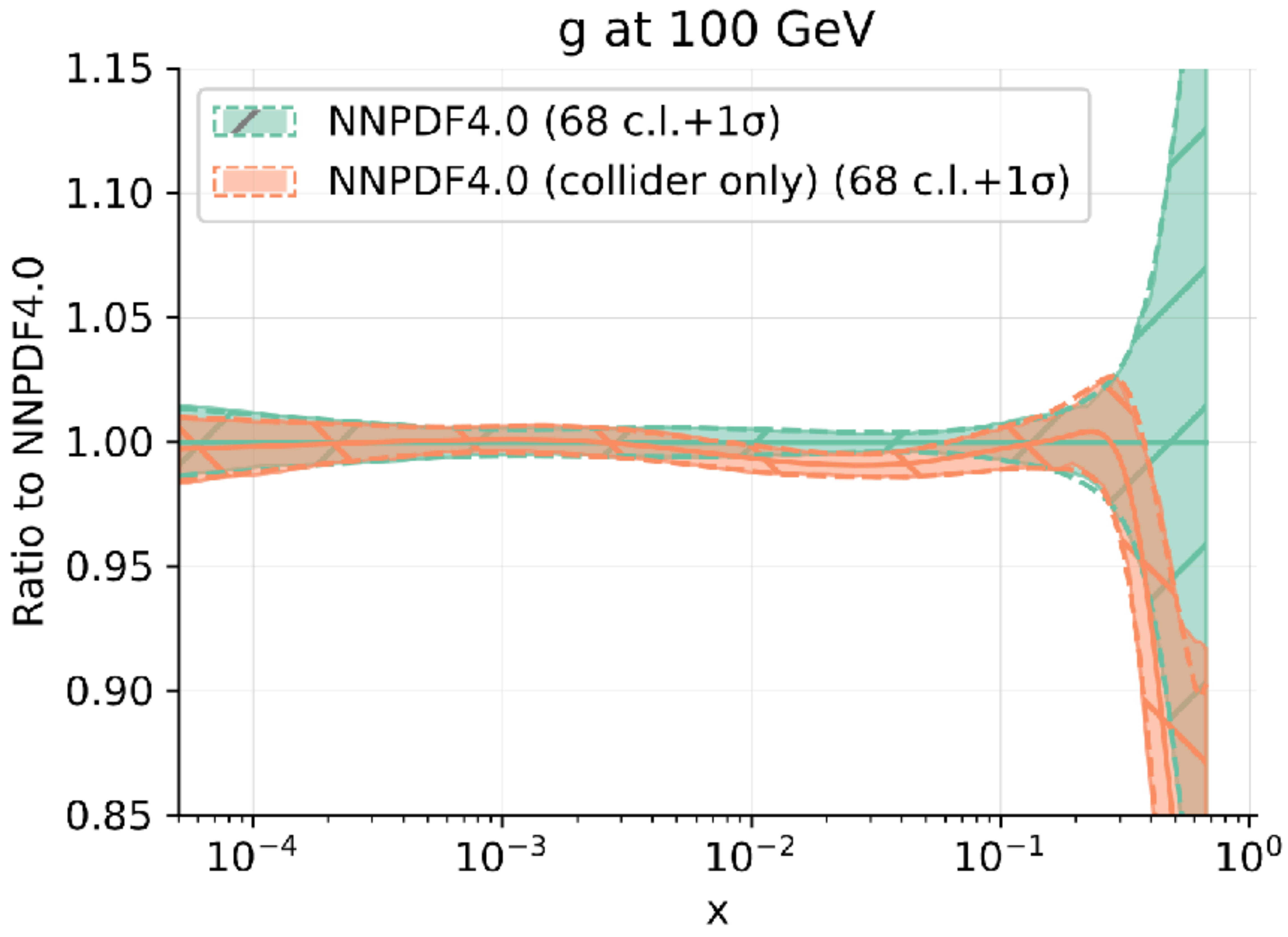
Amazing that MSHT20 & NNPDF40 are reaching %-level precision

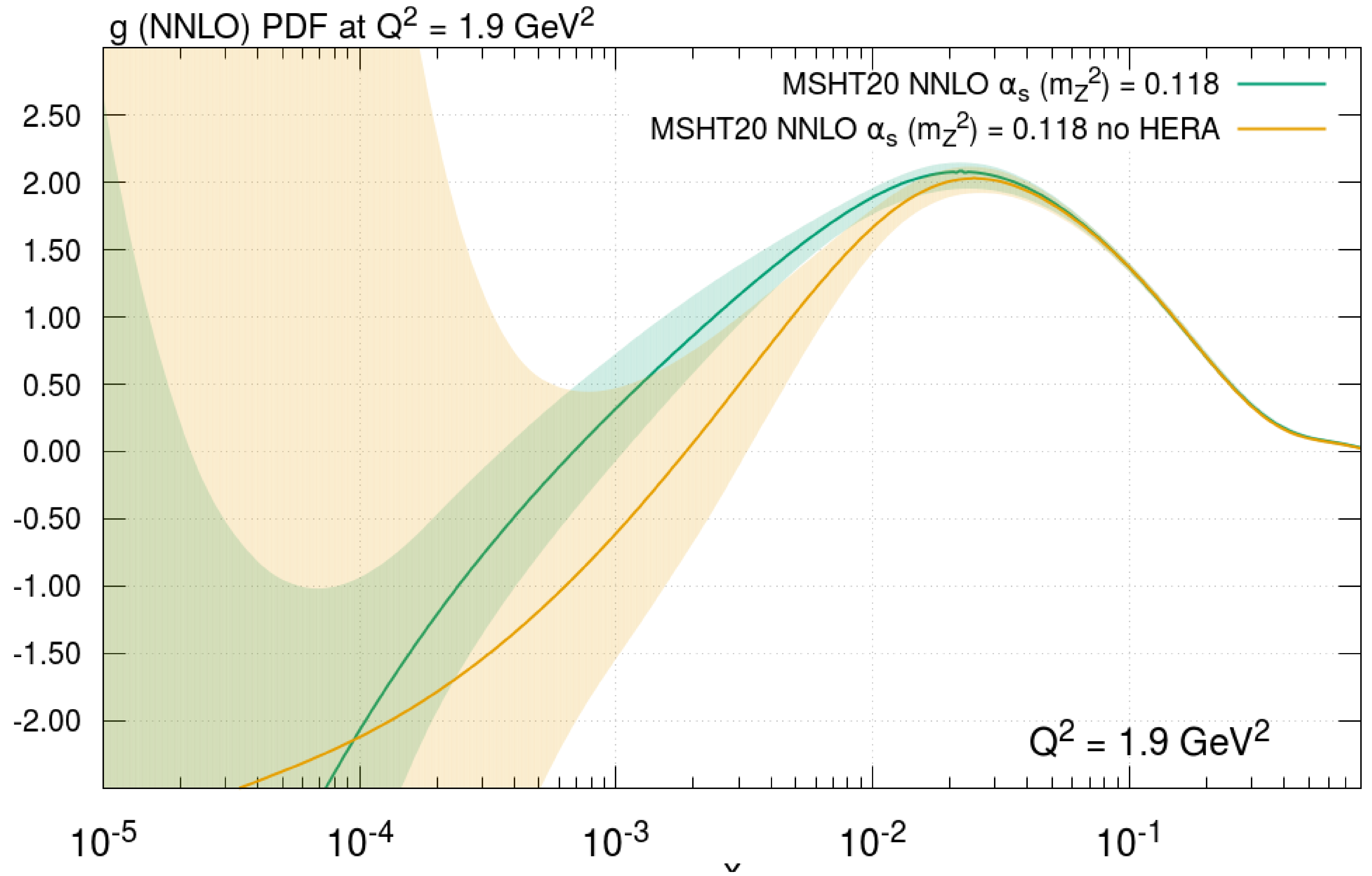
Differences include

- methodology (replicas & NN fits, tolerance factors, etc.)
- data inputs
- treatment of charm

At this level, QED effects probably no longer optional

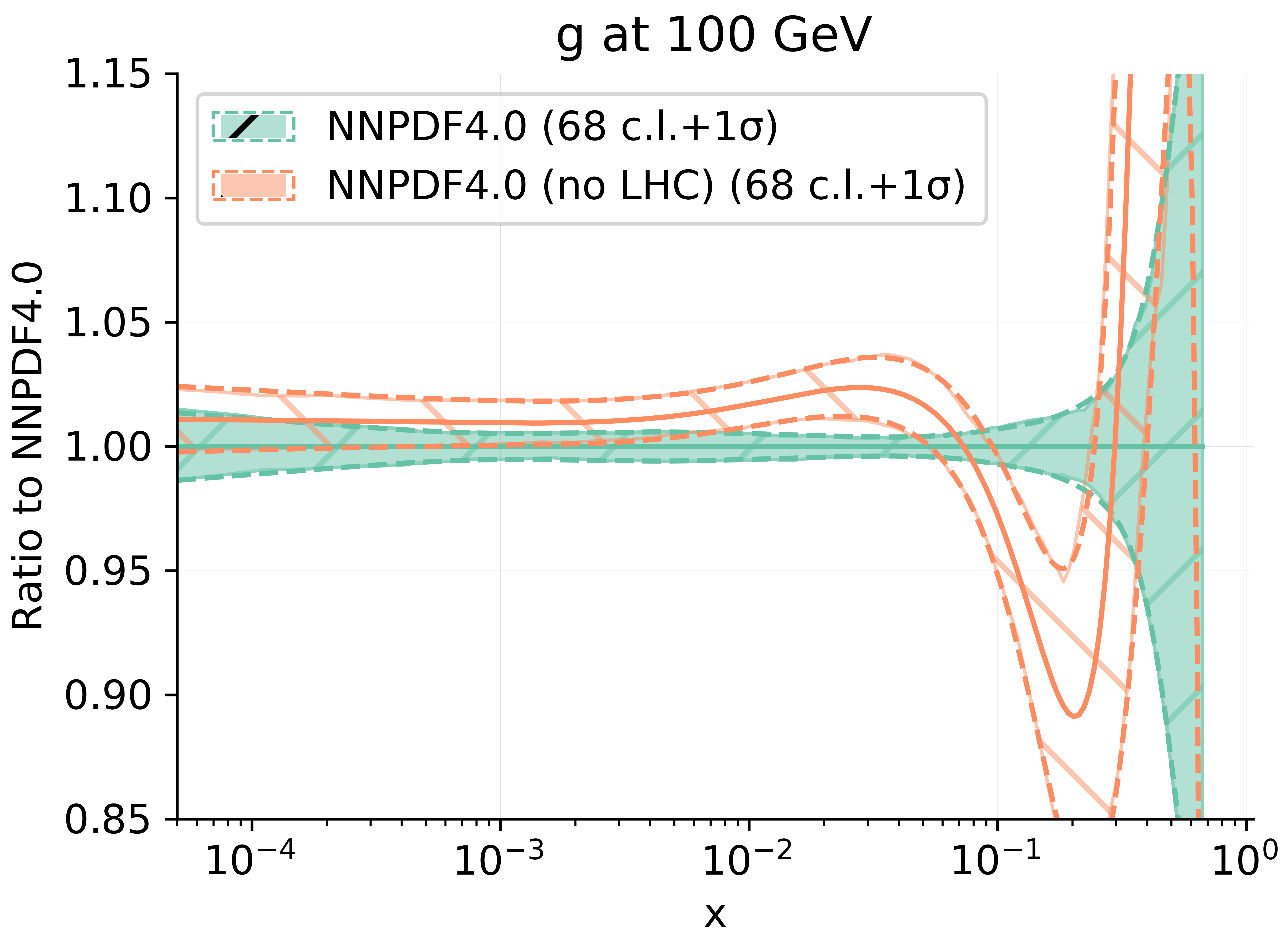
Removing DIS data (and associated worries about sizeable Λ^2/Q^2 corrections)





Reassuring indications that results are not (substantially) affected by Λ^2/Q^2 corrections from low-Q^2 DIS part of fit

Removing LHC data



- LHC data appears to be dominant in constraining the gluon
- One clear question is how to interpret gg-lumi uncertainties $\lesssim 1\,\%$ when all input cross sections @ hadron colliders have larger theory uncertainties.

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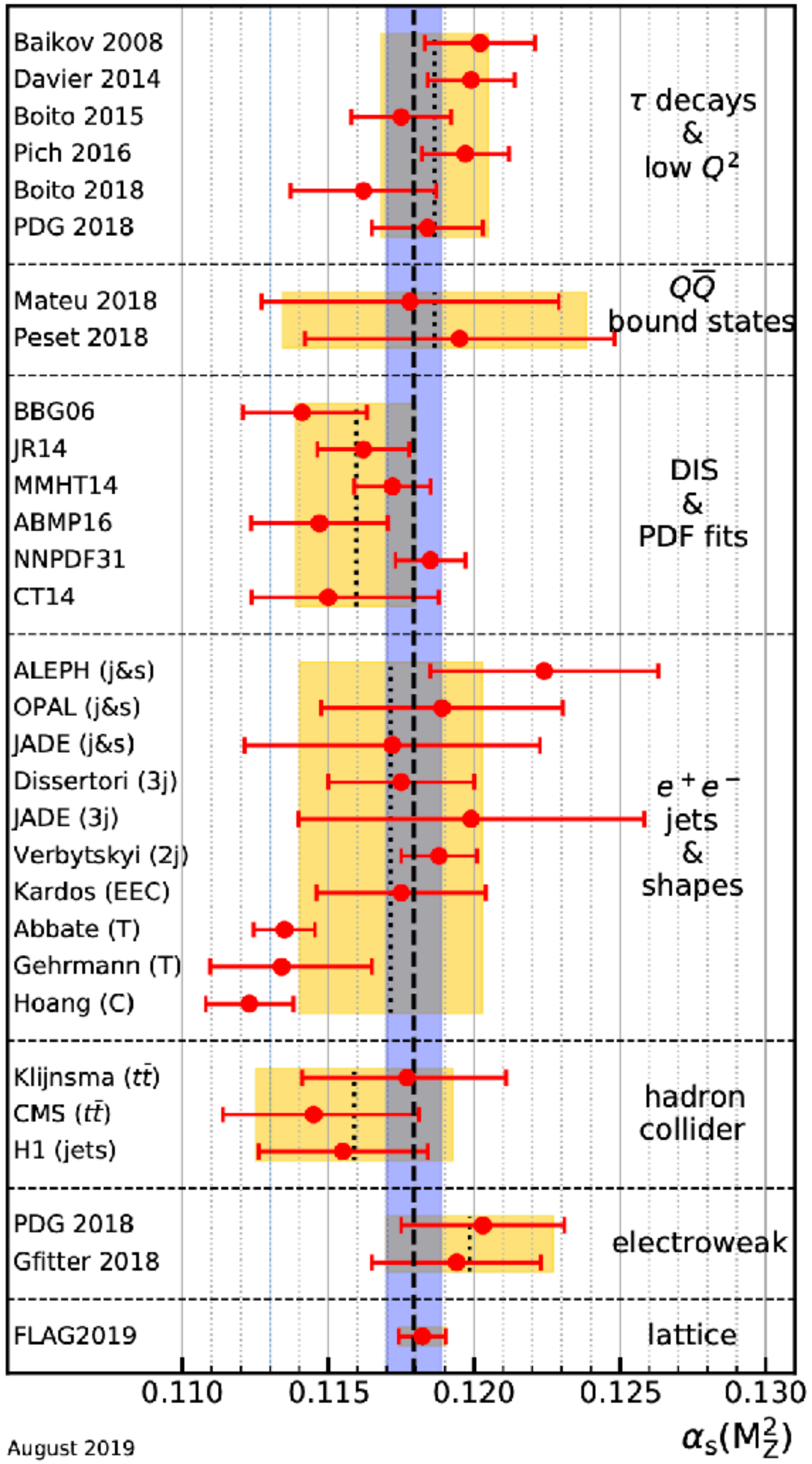


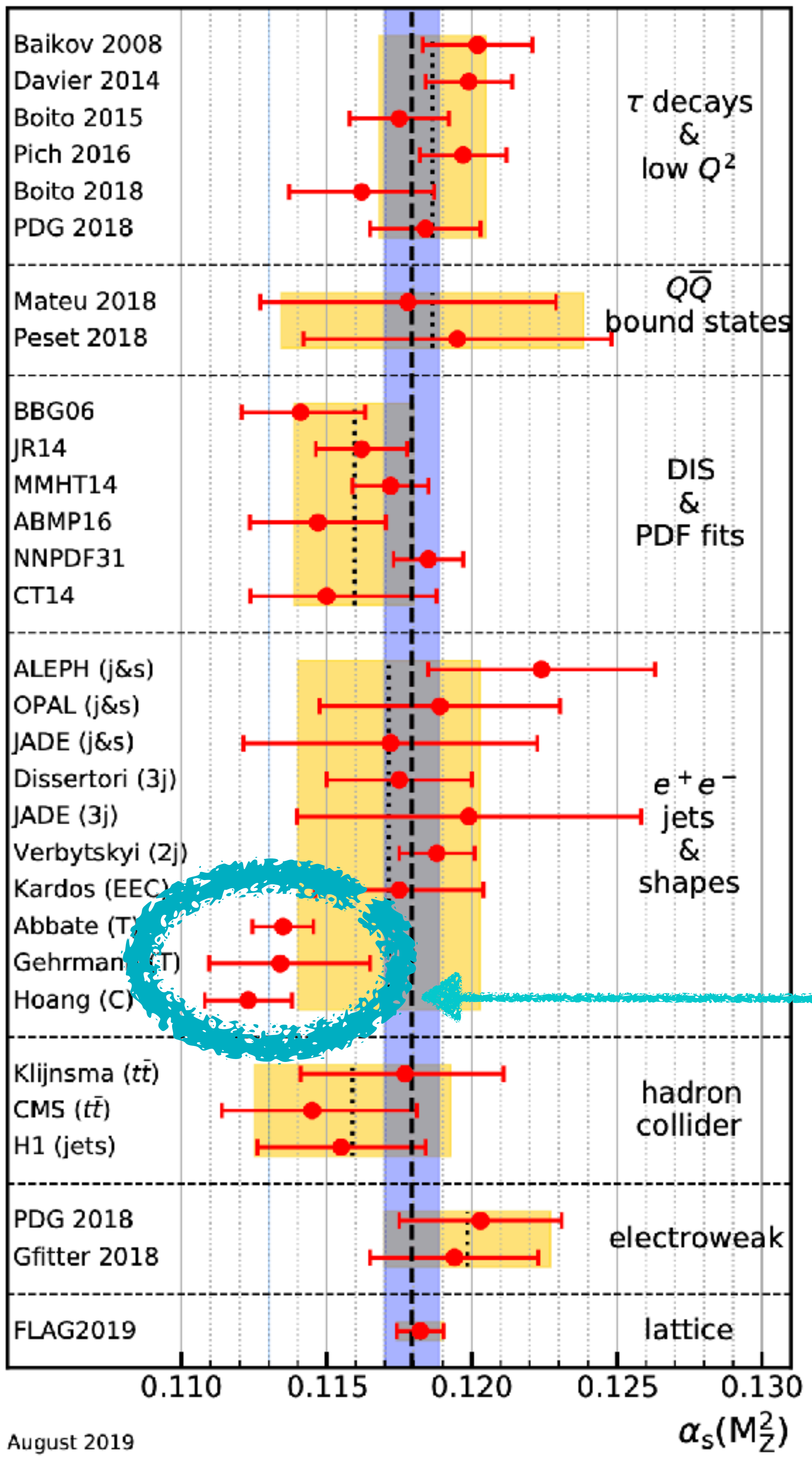
The strong coupling

HXSWG YR4	0.1180 ± 0.0015
PDG 2019	0.1179 ± 0.0010
ALPHA lattice (step scaling)	0.1185 ± 0.0008

Impact of ±0.0010 on $\sigma_{gg\to H}$ is **±2.1%** (NNPDF40+ihixs)

Until we get FCC-ee Z hadronic width measurement, I don't see any way forward that isn't (step scaling) lattice-based

Lattice determinations of the strong coupling
2101.04762
Luigi Del Debbio[a], Alberto Ramos[b,1]



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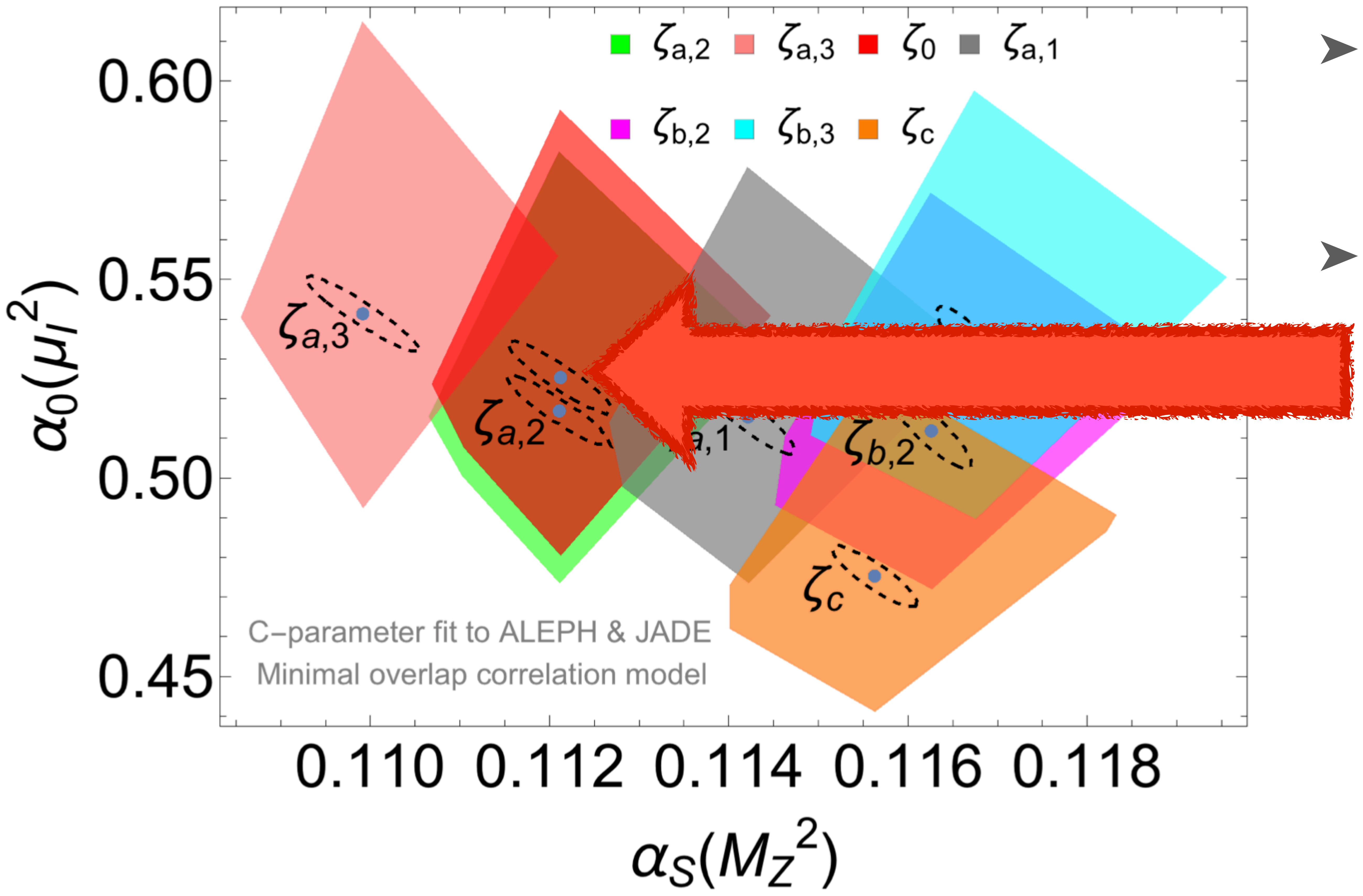
e^+e^- C-parameter [SCET]	0.1123 ± 0.0015
e^+e^- Thrust [SCET]	0.1135 ± 0.0011

Aside from EW fit and ALPHA lattice, most determinations depend, in some way or other, on measurements that are uncomfortably close / sensitive to non-perturbative physics

C-param fits with different assumptions for Λ/Q correction (between 2 & 3-jet limits)



- measurement essentially looks at rate of 3rd jet emission in $e^+e^- \to q\bar{q}$
- 0.1123 ± 0.0015 ↔ *assumption* about the structure of Λ/Q corrections, based on the 2-jet limit

Luisoni, Monni & GPS, 2012.00622

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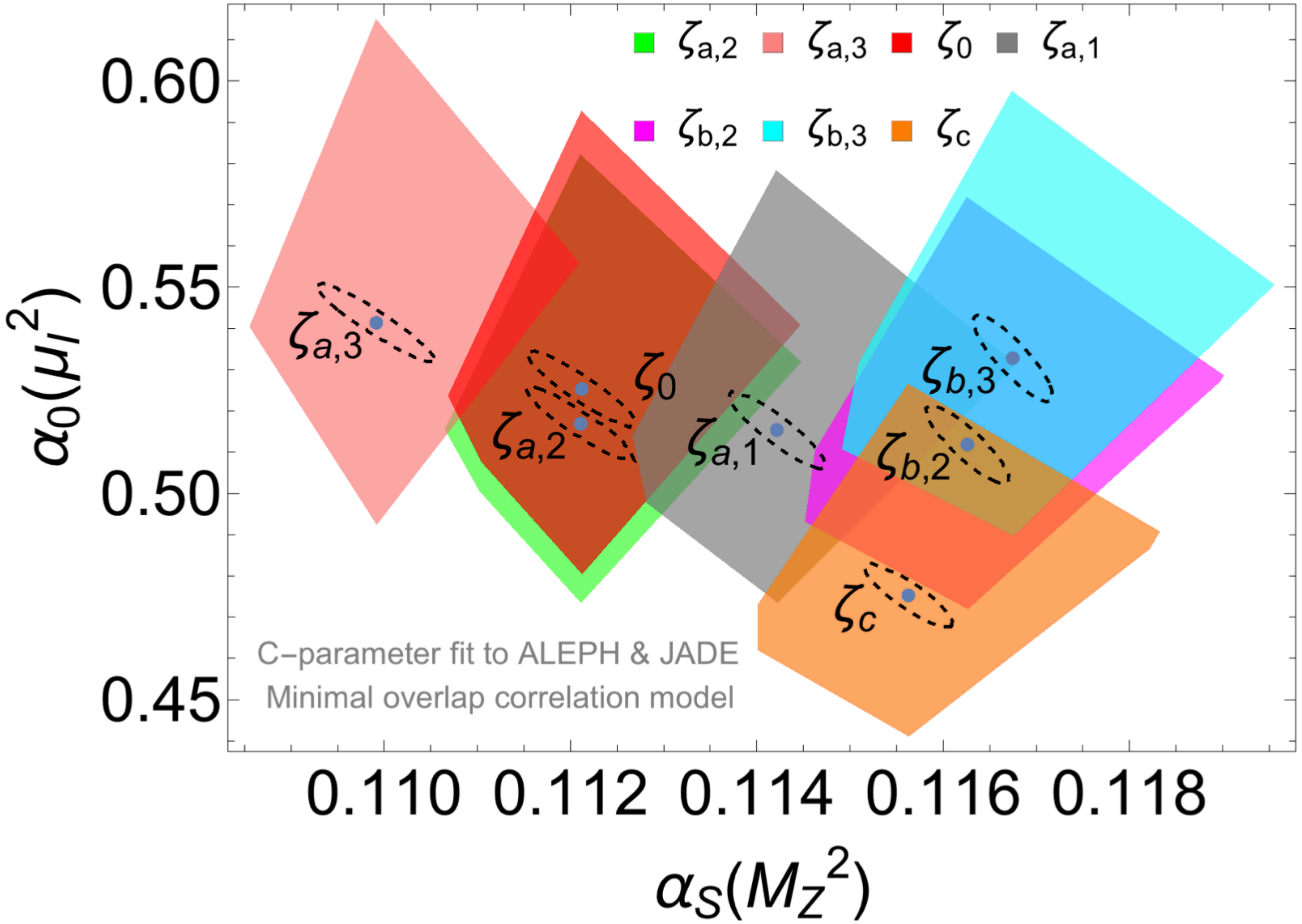

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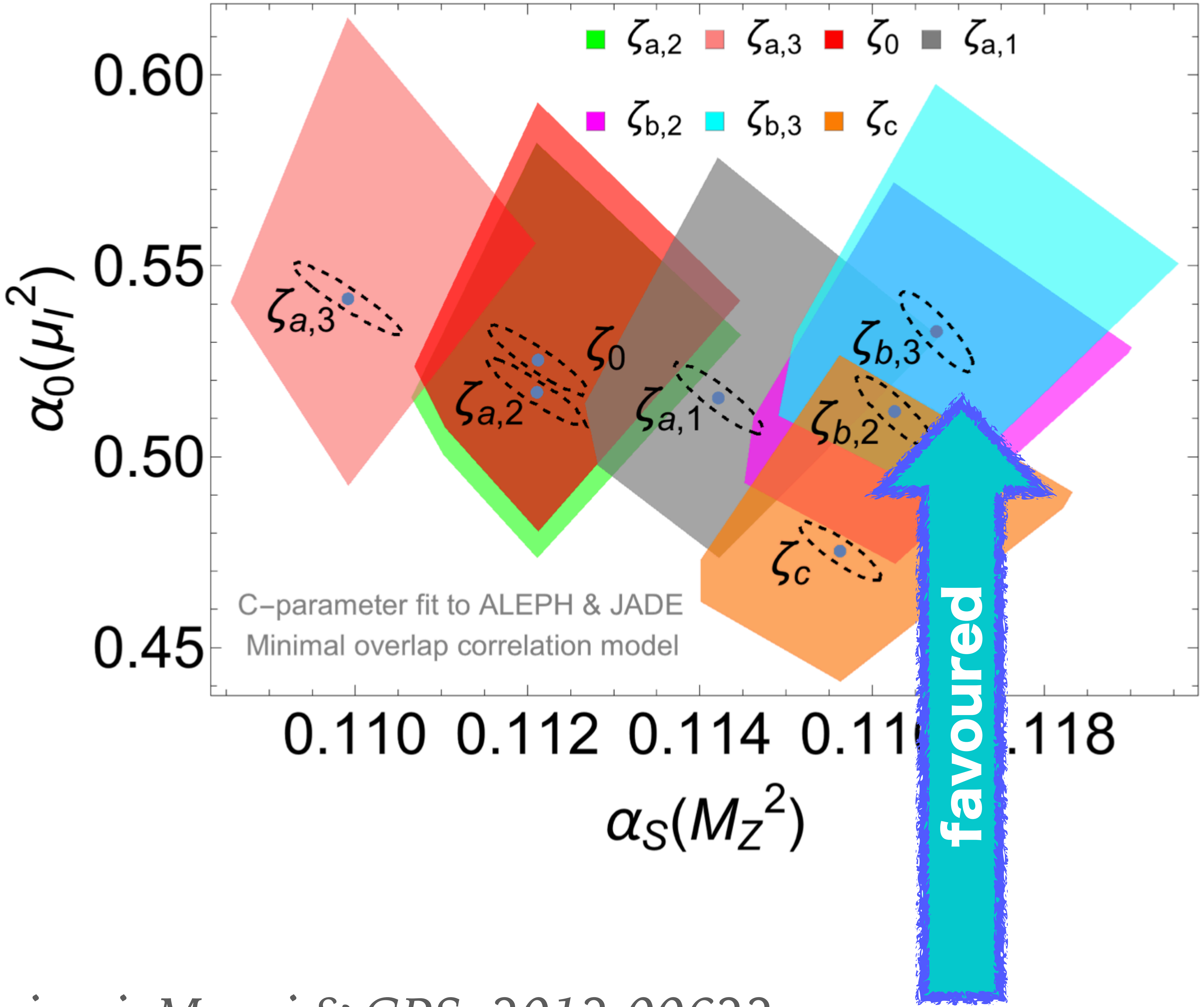

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Caola, Ferrario Ravasio, Limatola, Melnikov & Nason, 2108.08897

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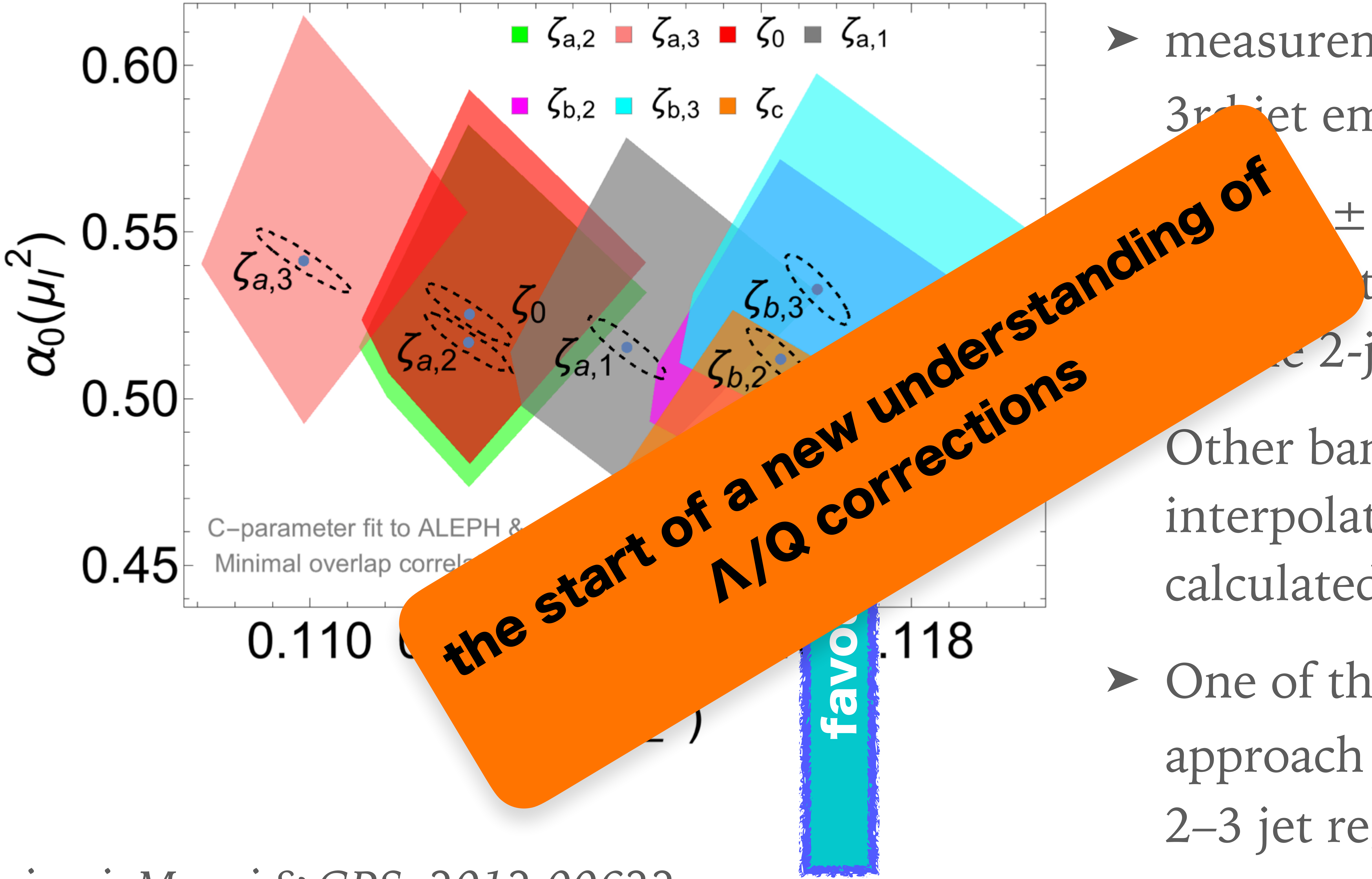

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Luisoni, Monni & GPS, [2012.00622]
Caola, Ferrario Ravasio, Limatola, Melnikov & Nason, [2108.08897]

the non-perturbative part

$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

What is value of p in $(\Lambda/Q)^p$?

- LEP event-shape (C-parameter, thrust) fit troubles came about because $p = 1$
  $\Lambda \sim 0.5\,\text{GeV} \to (\Lambda/20\text{GeV}) \sim 2.5\,\%$
- Jet physics at LHC is dirty because $p = 1$ (hadronisation & MPI)
- Hadron-collider inclusive and rapidity-differential Drell-Yan cross sections are believed to have $p = 2$ (Higgs hopefully also), so leptonic / photonic decays should be clean, aside from isolation.
  $\Lambda \sim 0.5\,\text{GeV} \to (\Lambda/125\text{GeV})^2 \sim 0.002\,\%$
  [Beneke & Braun, hep-ph/9506452; Dasgupta, hep-ph/9911391]
- But at LHC, we're also interested in Z, W and Higgs production with non-zero p_T
  Nobody knew if we have $(\Lambda/p_T)^p$ with $p = 1$ (a disaster) or $p = 2$ (all is fine)

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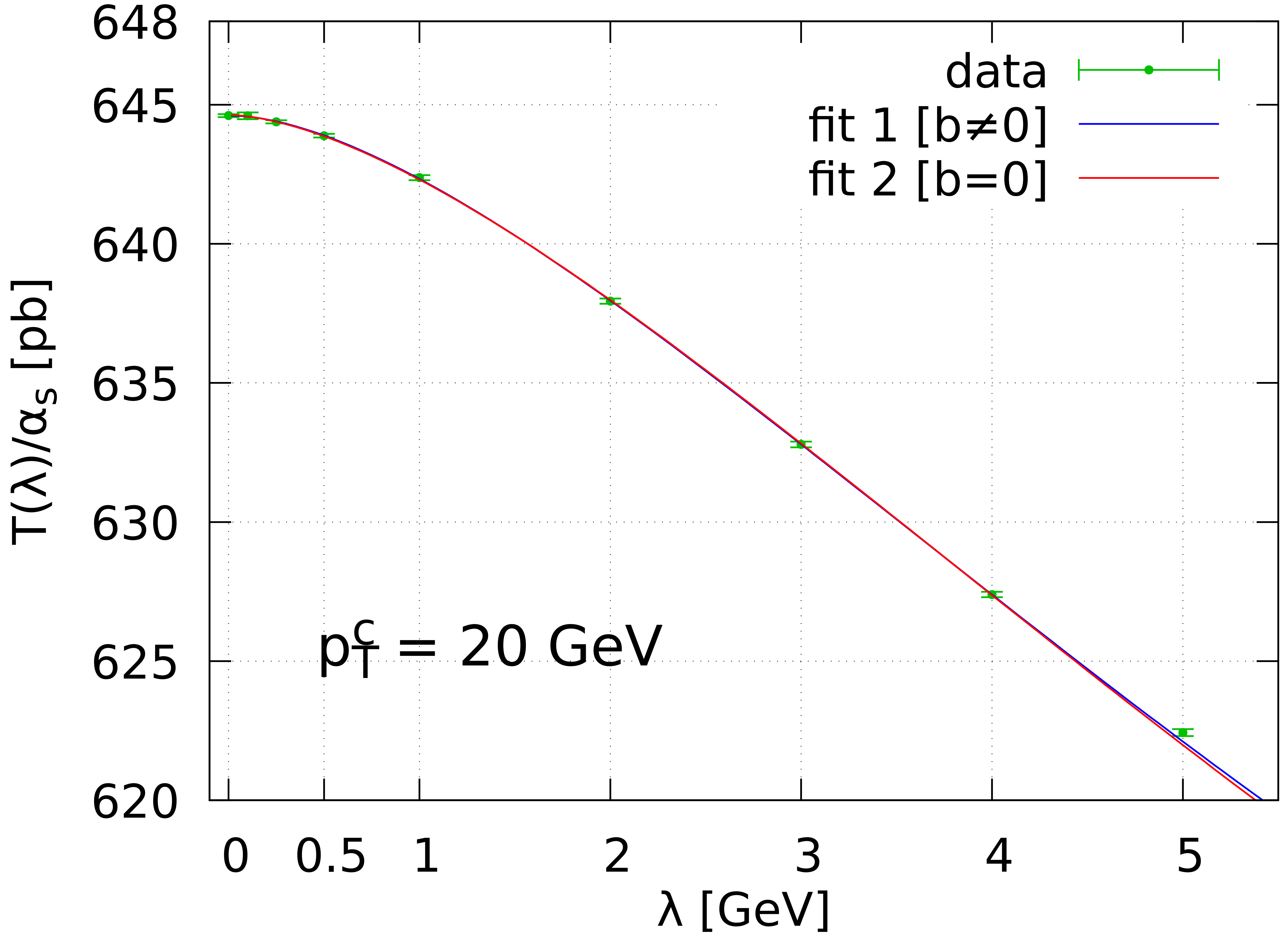

- Explicit calculations with an effective gluon mass (λ) can provide an answer
- Flatness in plot for $\lambda \to 0$ indicates **absence of $p = 1$** (linear) contribution
- arguably the most important result of the year, because it lays foundations for precision physics at non-zero p_T

Ferraro Ravasio, Limatola & Nason, 2011.14114

+ analytic demonstration in Caola, Ferrario Ravasio, Limatola, Melnikov & Nason, 2108.08897

beyond the fixed-order formula

parton shower Monte Carlos

Take example of ATLAS boosted VH — stat (28%) ~ syst (24%)

ATLAS VH: 2008.02508,

Source of uncertainty		Avg. impact
Total		0.372
Statistical		0.283
Systematic		0.240
Experimental uncertainties		
Small-R jets		0.038
Large-R jets		0.133
E_T^{miss}		0.007
Leptons		0.010
	b-jets	0.016
b-tagging	c-jets	0.011
	light-flavour jets	0.008
	extrapolation	0.004
Pile-up		0.001
Luminosity		0.013
Theoretical and modelling uncertainties		
Signal		0.038
Backgrounds		0.100
↪ Z + jets		0.048
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→ *For large-R jets, the uncertainties in the energy and mass scales are […] as described in [81]*

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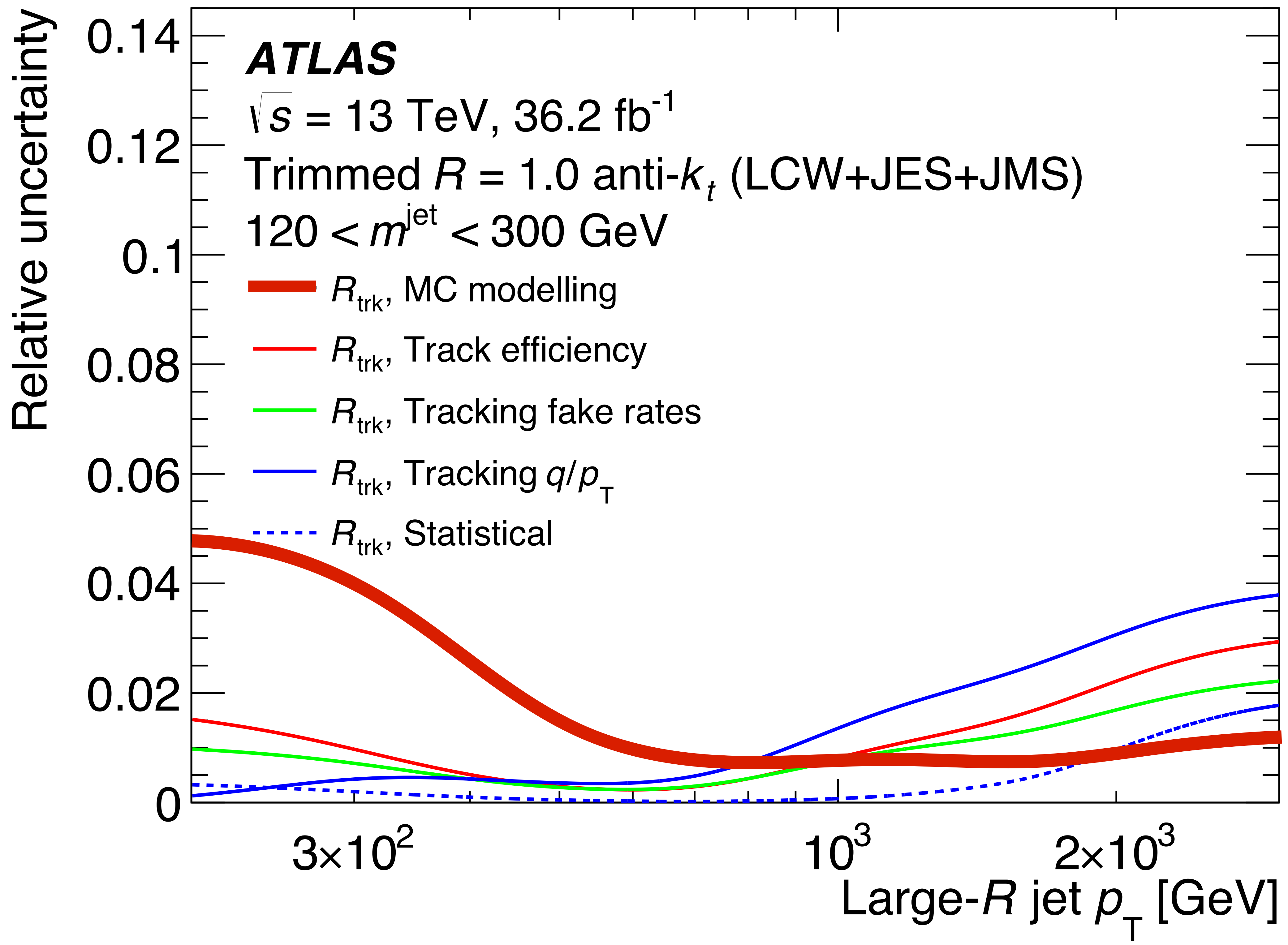

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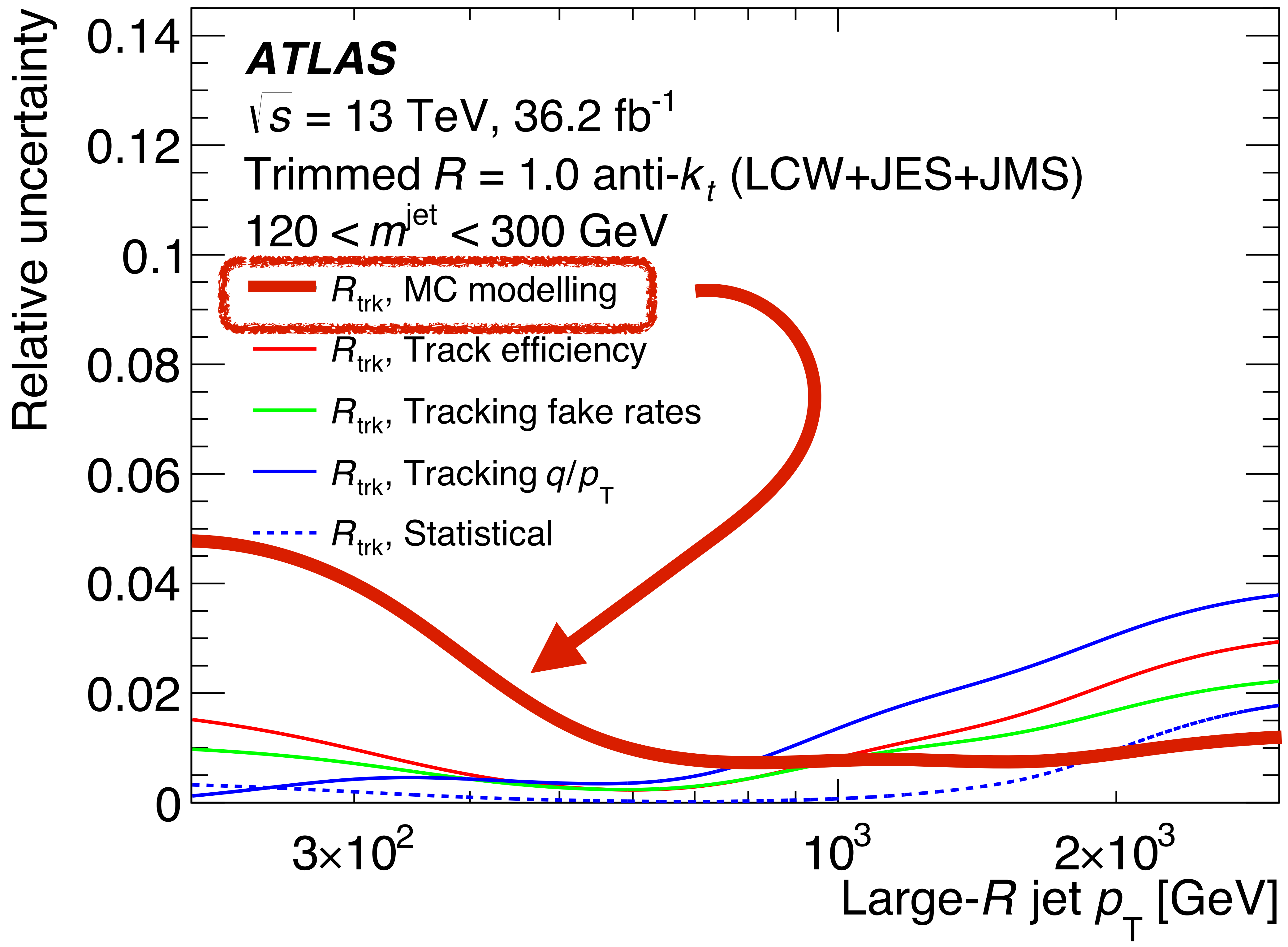
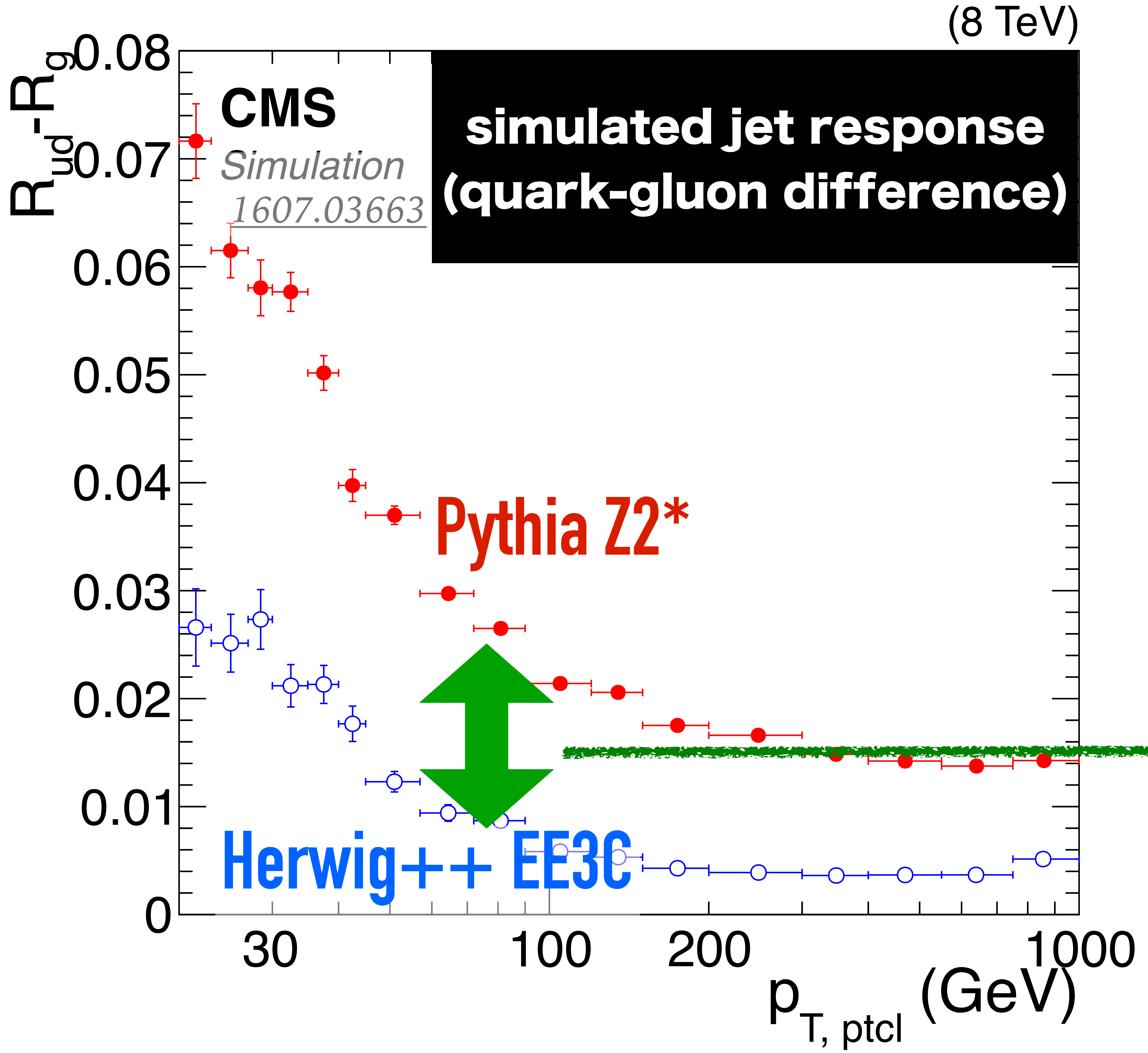
↪ Diboson		0.032
↪ Multijet		0.009
MC statistical		0.092

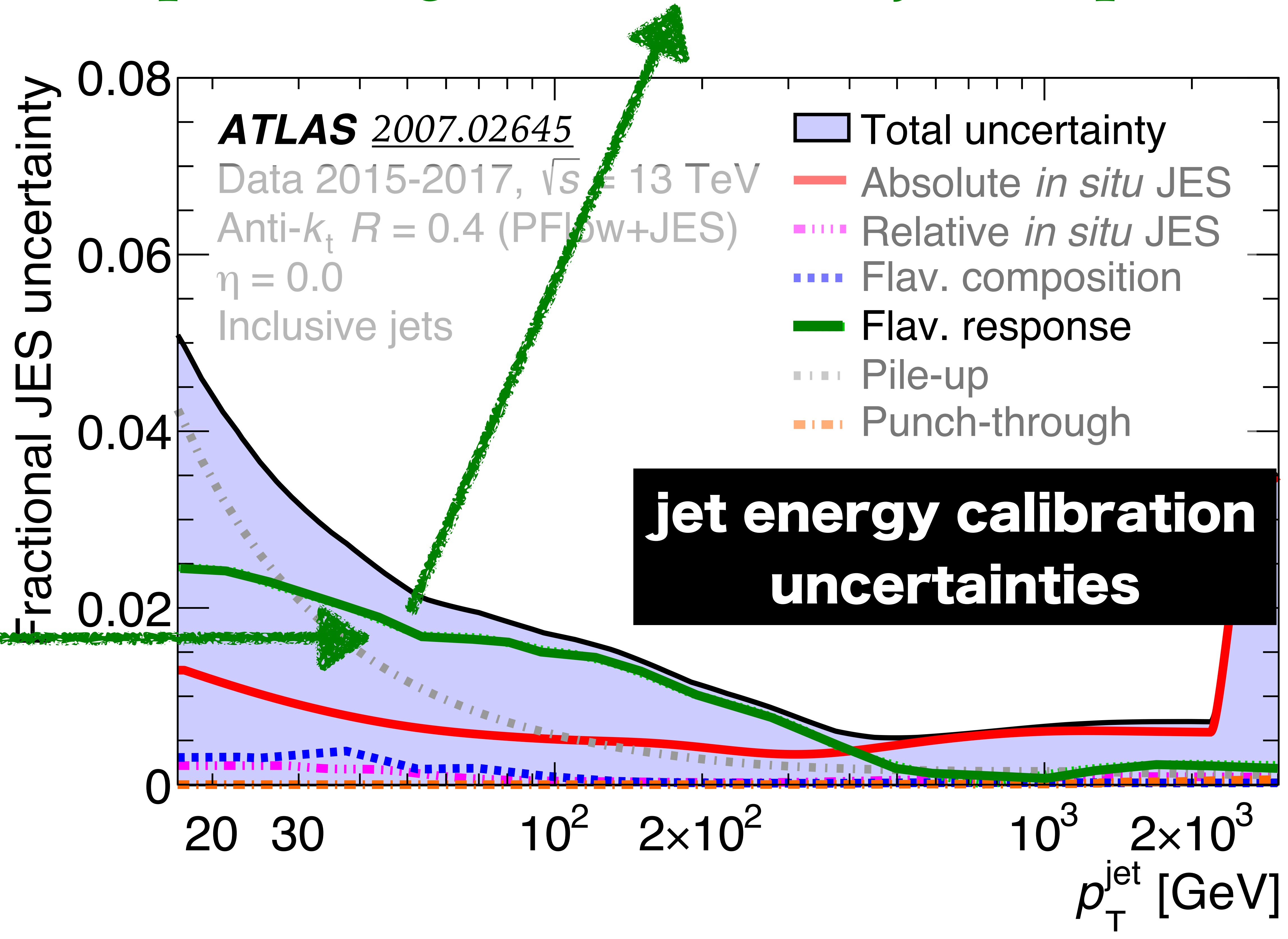
For large-R jets, the uncertainties in the energy and mass scales are […] as described in [81]



But imperfections matter: e.g. for jet energy calibration (affects ~1500 papers)



Largest uncertainty source is poor understanding of [parton shower simulations of] quark v. gluon-induced jet responses



Resummation @N3LL, but parton showers only LL? Now evolving to NLL

Deductor	FHP	PanLocal	PanGlobal
$k_t\theta$ ("Λ") ordered	k_t ordered	$k_t\sqrt{\theta}$ ordered	k_t or $k_t\sqrt{\theta}$ ordered
Recoil ⊥: local +: local −: global	**Recoil** ⊥: global +: local −: global	**Recoil** ⊥: local +: local −: local	**Recoil** ⊥: global +: local −: local
Tests analytical /numerical for thrust	**Tests** analytical for thrust & multiplicity	**Tests** numerical for many observables	**Tests** numerical for many observables

Nagy & Soper
2011.04777 (+past decade)

Forshaw, Holguin & Plätzer
2003.06400

Dasgupta, Dreyer, Hamilton, Monni, GPS & Soyez 2002.11114
Hamilton, Medves, GPS, Scyboz, Soyez, 2011.10054
Karlberg, GPS, Scyboz, Verheyen, 2103.16526

See talks by Siegert & Plätzer

future colliders

Will e+e− colliders make precision easy?

Table 1.1. Relative statistical uncertainty on $\sigma_{\mathrm{HZ}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{XX})$ and $\sigma_{\nu\bar{\nu}\mathrm{H}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{XX})$, as expected from the FCC-ee data, obtained from a fast simulation of the CLD detector and consolidated with extrapolations from full simulations of similar linear-collider detectors (SiD and CLIC).

$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma\mathrm{BR})/\sigma\mathrm{BR}$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$\mathrm{H} \to$ any	±0.5		±0.9	
$\mathrm{H} \to \mathrm{bb}$	±0.3	±3.1	±0.5	±0.9
$\mathrm{H} \to \mathrm{cc}$	±2.2		±6.5	±10
$\mathrm{H} \to \mathrm{gg}$	±1.9		±3.5	±4.5
$\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-$	±1.2		±2.6	±3.0
$\mathrm{H} \to \mathrm{ZZ}$	±4.4		±12	±10
$\mathrm{H} \to \tau\tau$	±0.9		±1.8	±8
$\mathrm{H} \to \gamma\gamma$	±9.0		±18	±22
$\mathrm{H} \to \mu^+\mu^-$	±19		±40	
$\mathrm{H} \to$ invisible	<0.3		<0.6	

Notes. All numbers indicate 68% CL intervals, except for the 95% CL sensitivity in the last line. The accuracies expected with $5\,\mathrm{ab}^{-1}$ at 240 GeV are given in the middle column, and those expected with $1.5\,\mathrm{ab}^{-1}$ at $\sqrt{s} = 365$ GeV are displayed in the last column.

- Up to $\sim \times 10$ reduction in uncertainties
- Interpreting 0.3% for $H \to b\bar{b}$ will require substantial improvements in parametric inputs
- Much of the statistics involves hadronic modes — how well will we be able to exploit them?
- Agreement between e^+e^- and LHC will be powerful validation of hadron colliders as precision machines

conclusions

Conclusions

- Across much of Higgs physics, theory / MC uncertainties are among the dominant systematic uncertainties — addressing them will be key to benefitting from $\times 20$ statistics of the next 15 years.
- Perturbative calculations are making amazing strides (cf. Alex Huss's talk tomorrow) → technically immensely challenging, and making remarkable progress
- Other aspects (parameters, PDFs, parton showers, non-perturbative contributions) force us to address conceptually complicated questions, e.g.
  - non-perturbative corrections, with remarkable progress (& good news) this past year!