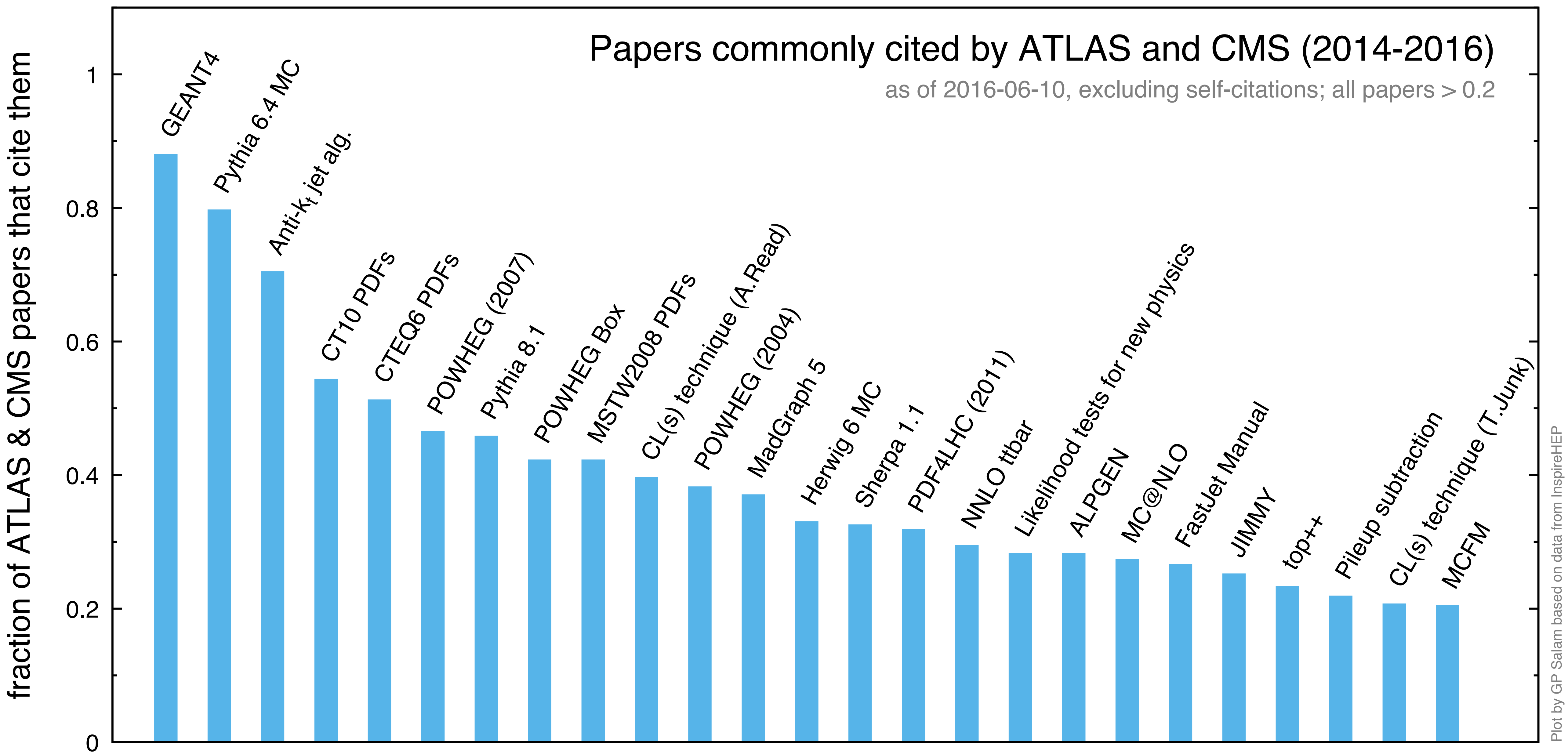
QCD THEORY OVERVIEW
TOWARDS PRECISION AT LHC

Gavin Salam, CERN

Fourth Annual Large Hadron Collider Physics Conference
14 June 2016, Lund, Sweden

WHAT DO ATLAS & CMS USE MOST FREQUENTLY?



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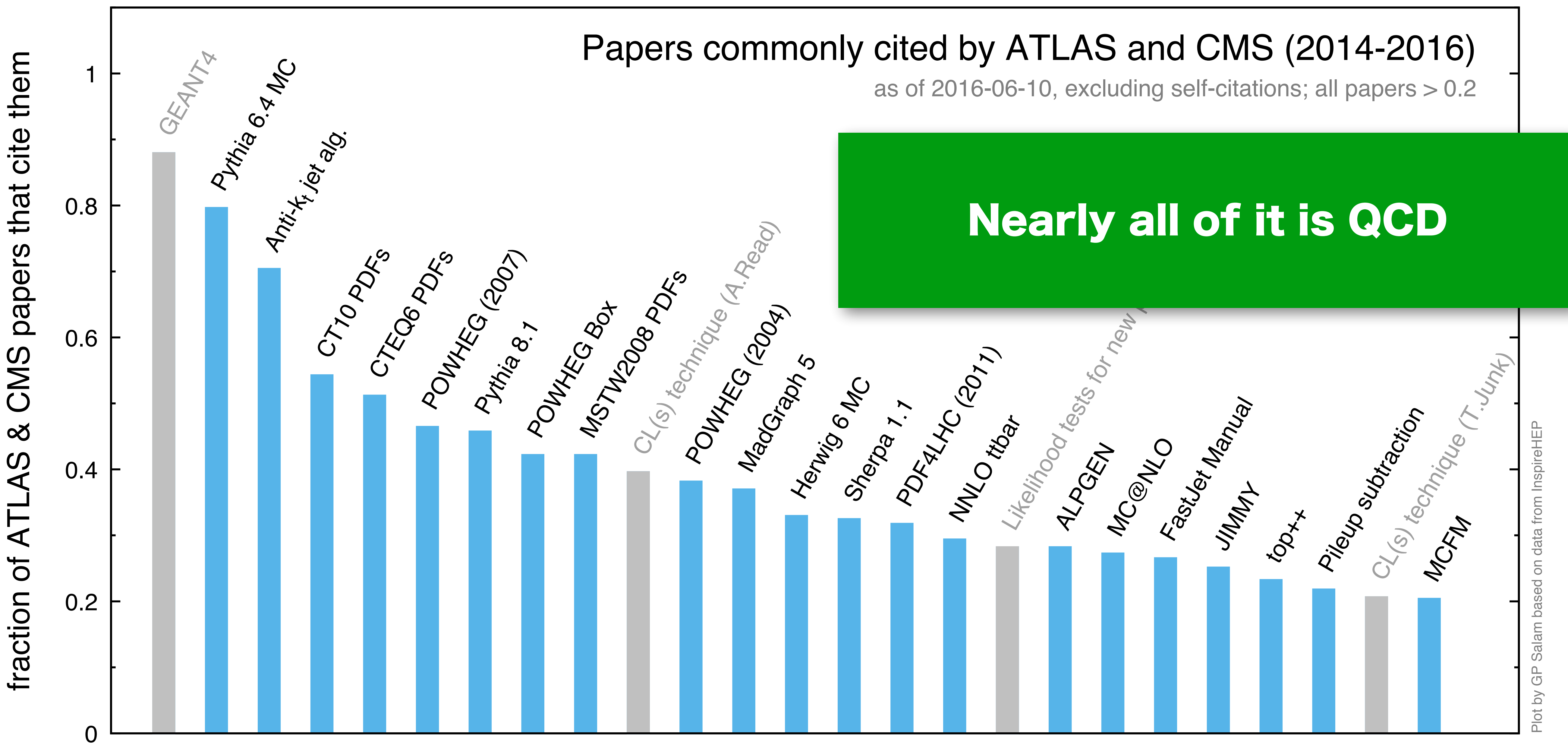

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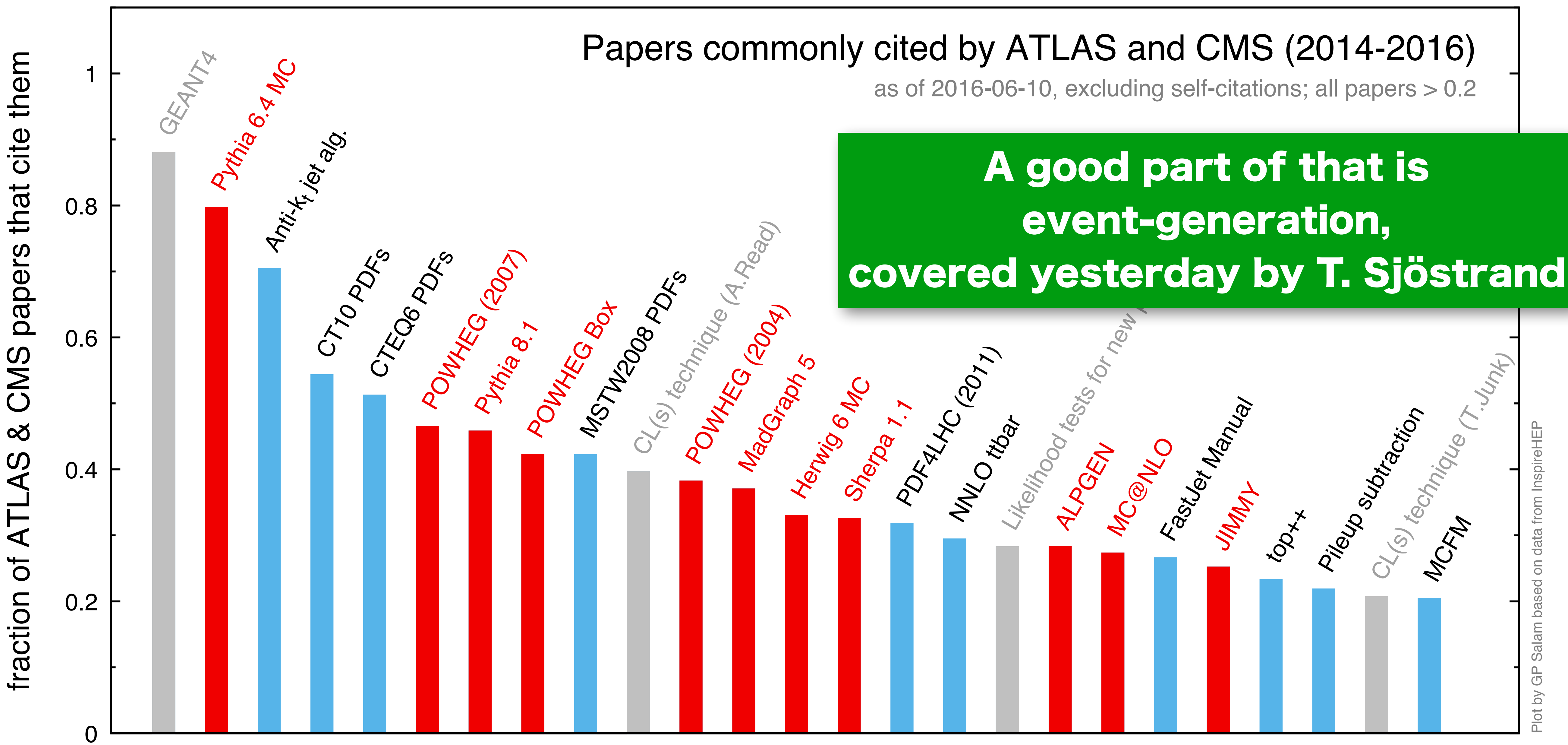

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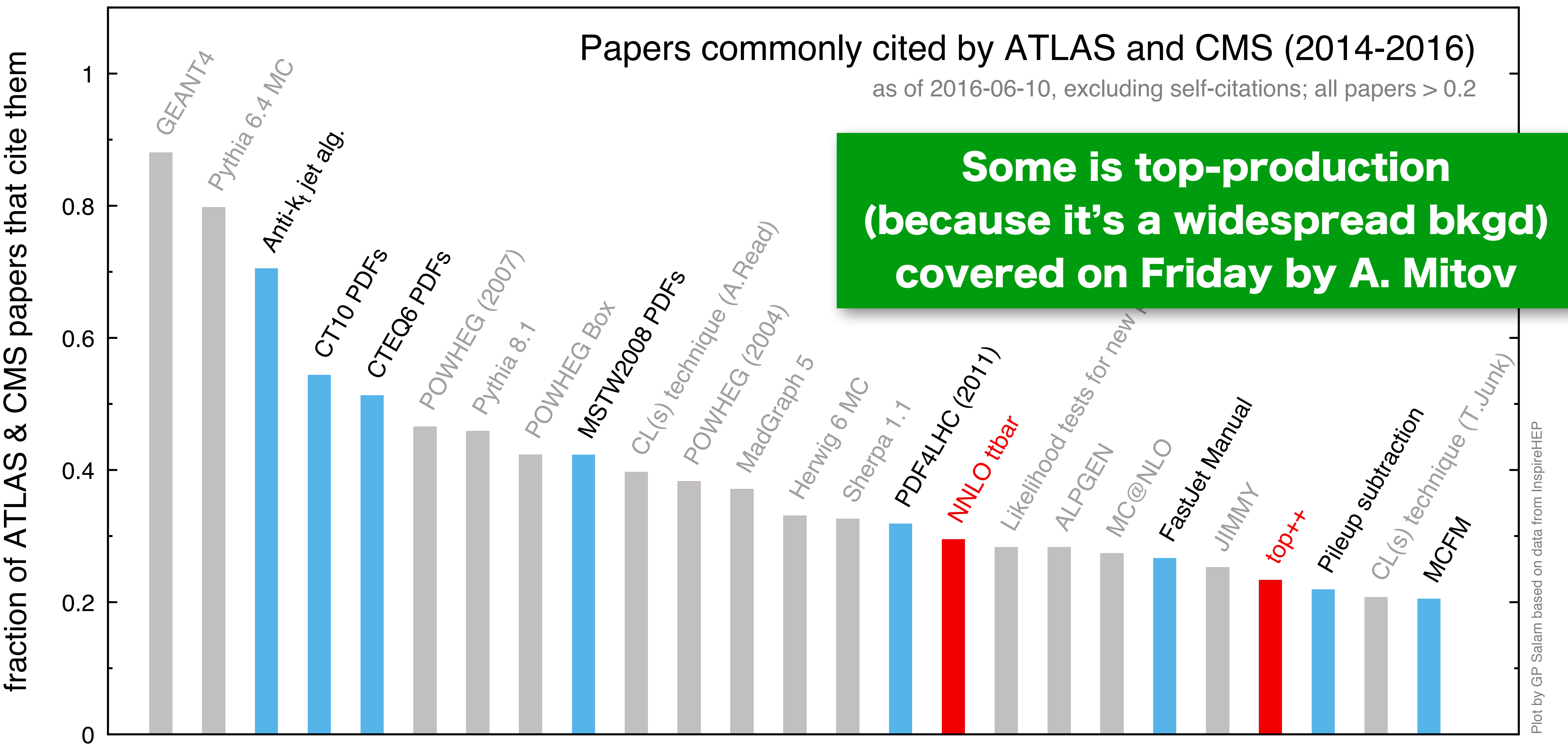

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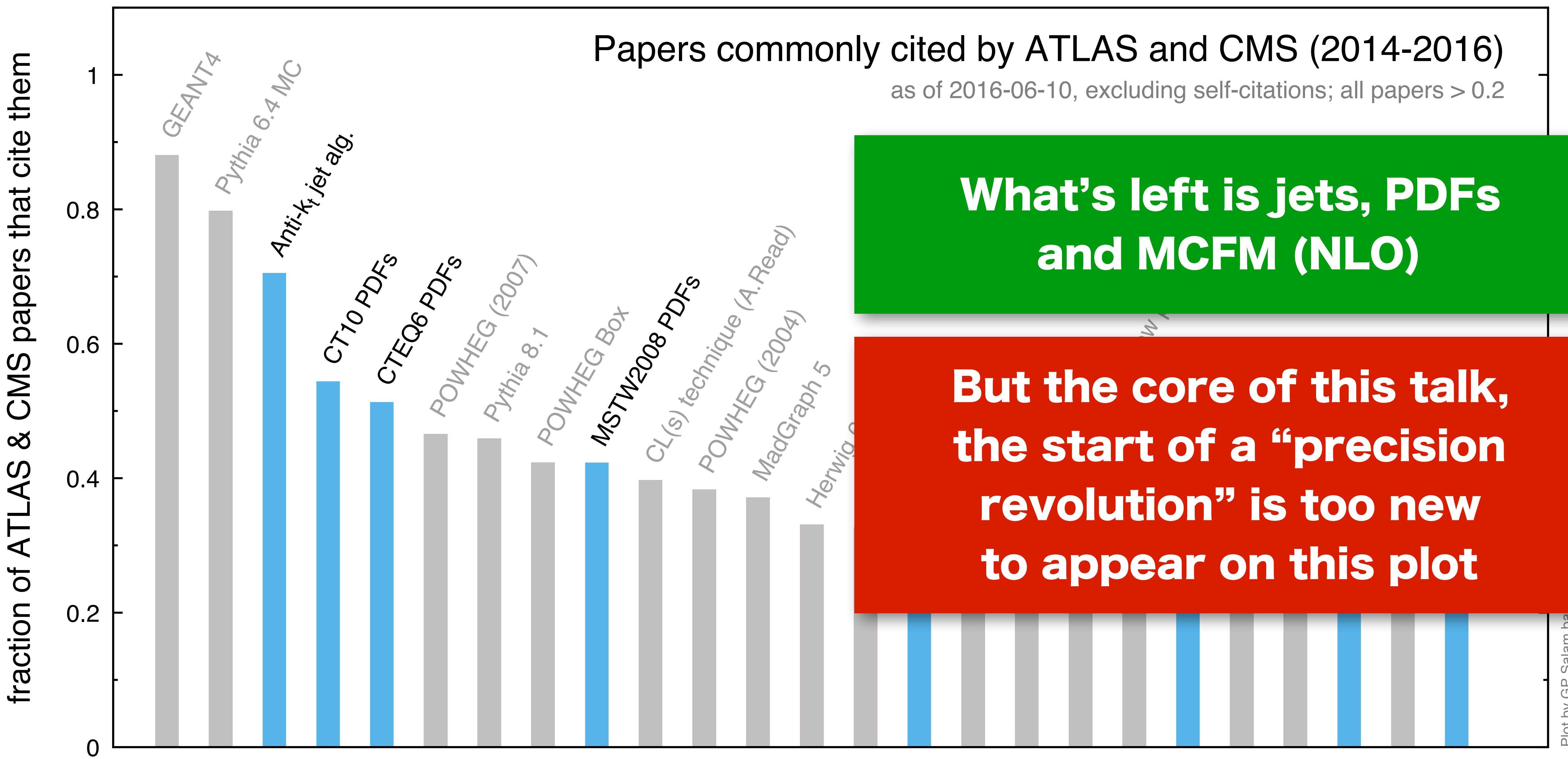


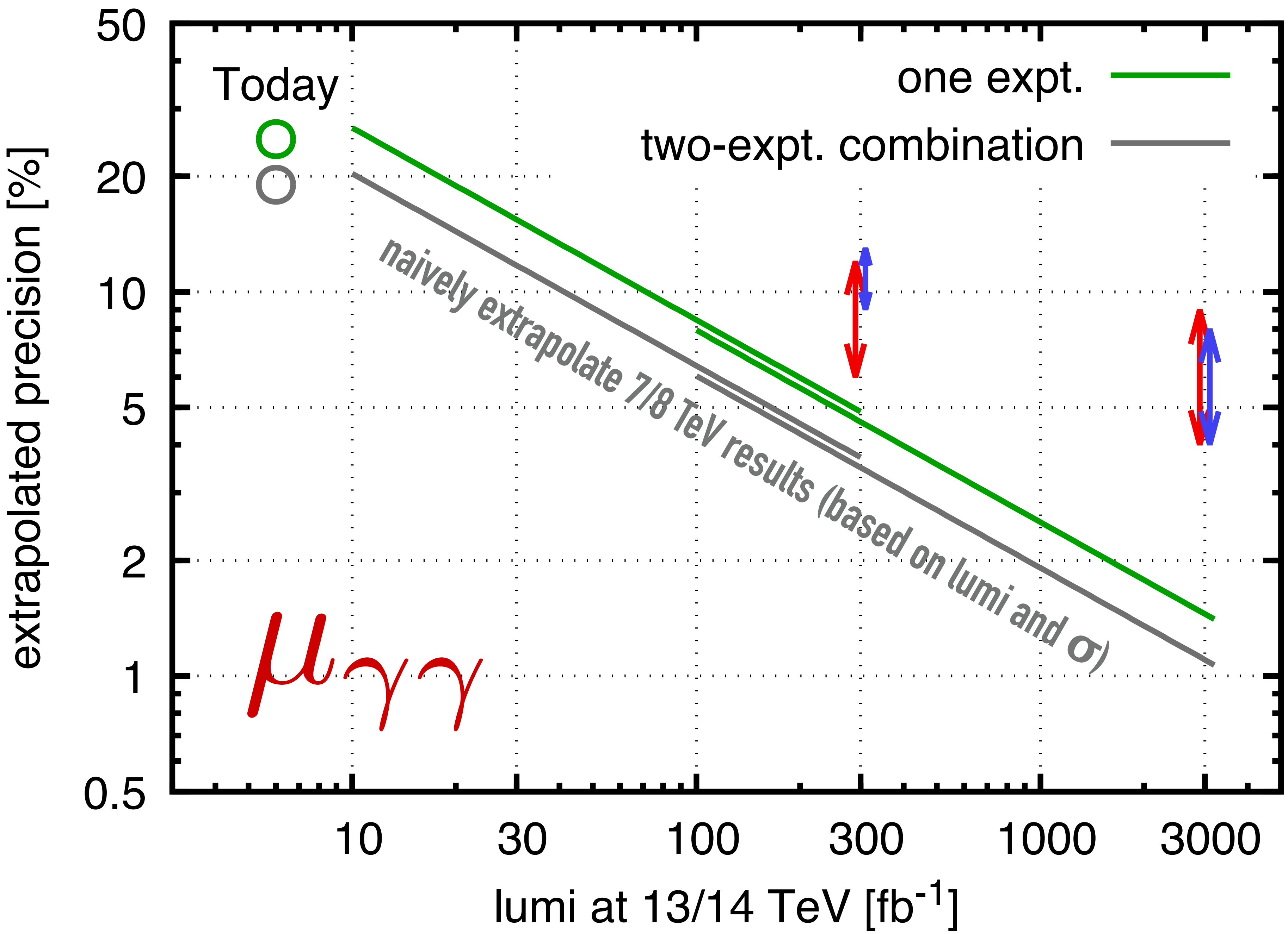
What's left is jets, PDFs and MCFM (NLO)

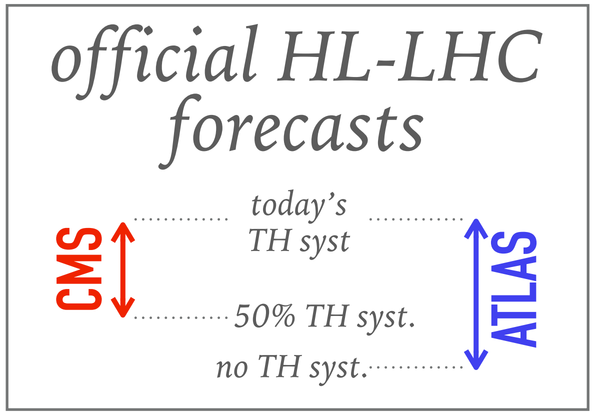
But the core of this talk, the start of a "precision revolution" is too new to appear on this plot

what precision will we want?

what precision do we have?

LONG-TERM HIGGS PRECISION?



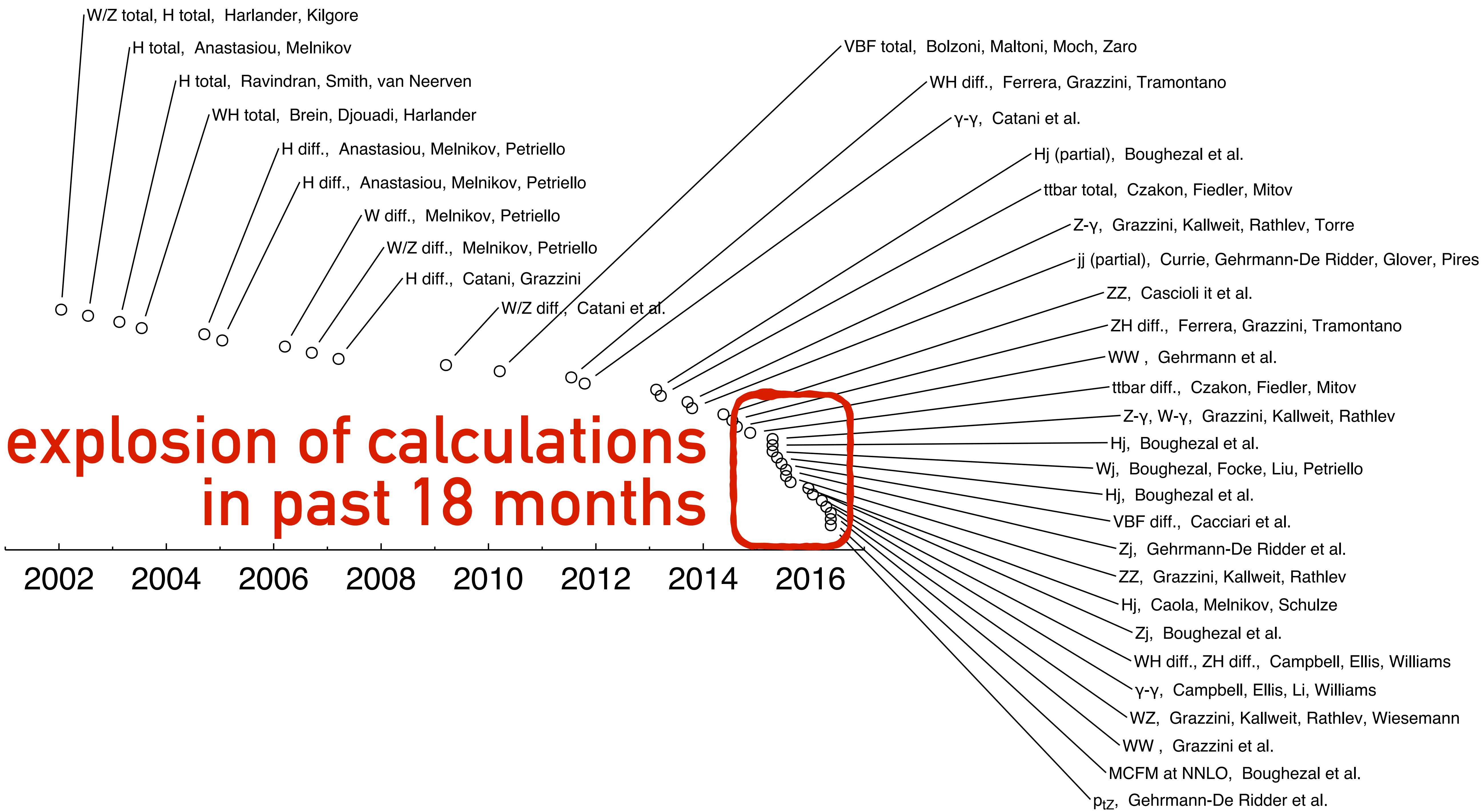


Naive extrapolation suggests LHC has long-term potential to do Higgs physics at **1% accuracy**

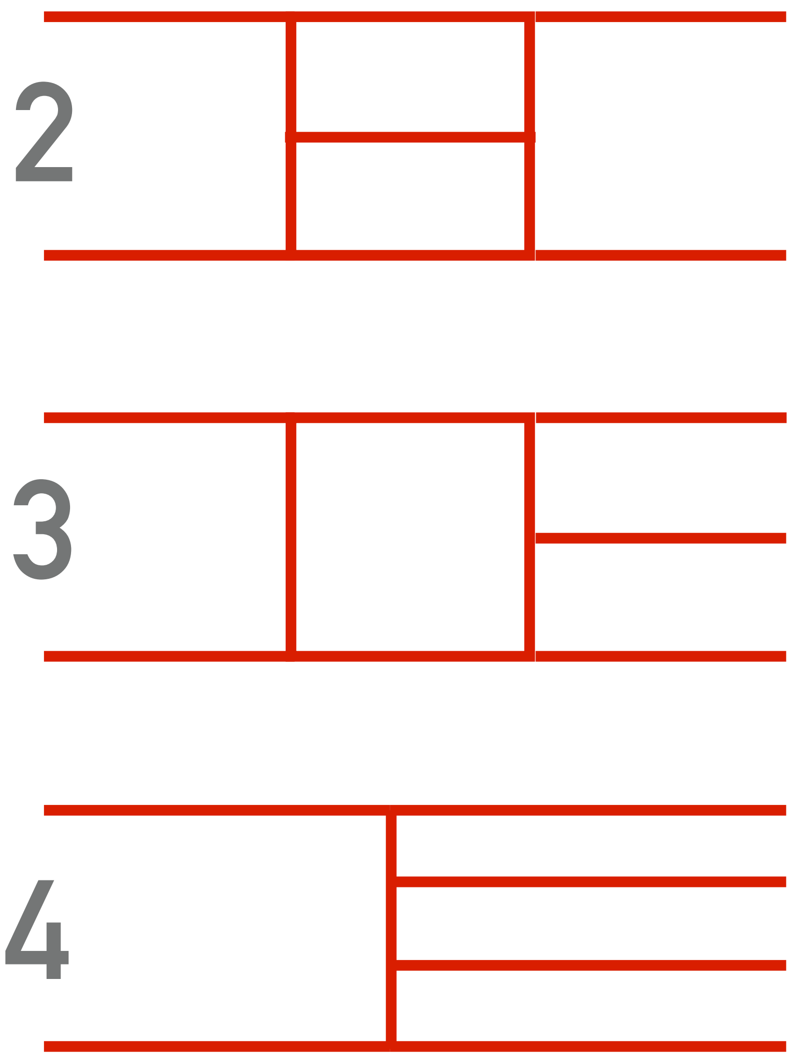
nnlo

NNLO hadron-collider calculations v. time

let me know of any significant omissions



NNLO INGREDIENTS (for a 2→2 process)



2-loop 2→2

1-loop 2→3

tree 2→4

sum

calculations here enabled pp → VV

within scope of existing tools

ideas for handling sum of singularities enabled pp → X + jet(s)

$f(z)$ is some function with finite limit for $z \to 0$

"SLICING"

$$\sigma = \left(c - \ln\frac{1}{\text{cut}}\right) \cdot f(0) + \int_{\text{cut}}^{1} dz \frac{f(z)}{z}$$

virtual & counterterm:
get from soft-collinear resummation

real part:
use MC integration (cut has to be small, but not too small)

qT-subtraction: Catani, Grazzini
N-jettiness subtraction: Boughezal, Focke, Liu, Petriello; Gaunt, Stahlhofen, Tackmann, Walsh

$f(z)$ is some function with finite limit for $z \to 0$

LOCAL SUBTRACTION

$$\sigma = c \cdot f(0) + \int_0^1 dz \left[\frac{f(z)}{z} - \frac{f(0)}{z} \right]$$

virtual & counterterm:

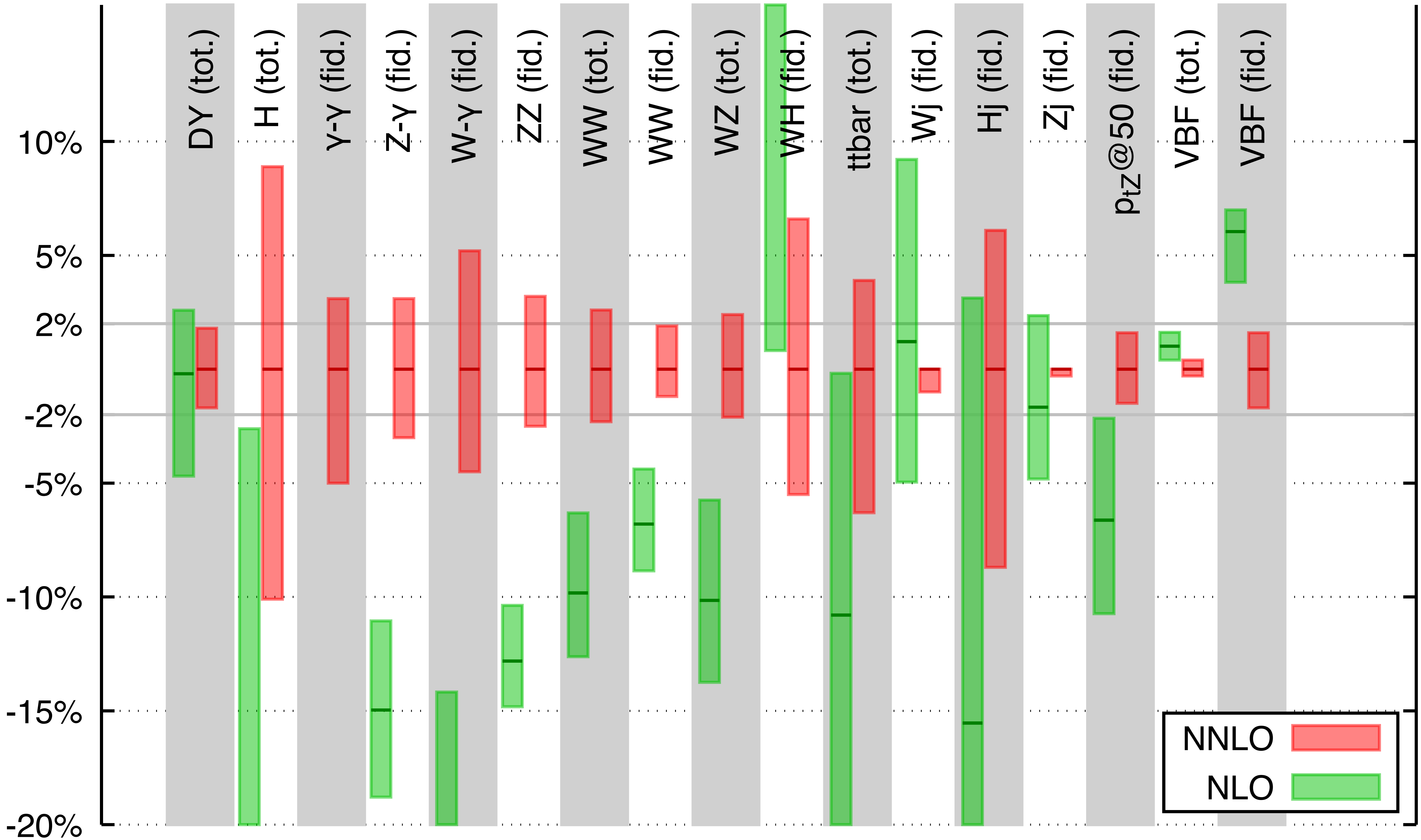
may need (tough)
analytic calc^n

real part:

MC integration is finite
even without cut

Sector decomposition: Anastasiou, Melnikov, Petriello; Binoth, Heinrich
Antennae subtraction: Kosower; Gehrmann, Gehrmann-de Ridder, Glover
Sector-improved residue subtraction: Czakon; Boughezal, Melnikov, Petriello
CoLorFul subtraction: Del Duca, Somogyi, Trocsanyi
Projection-to-Born: Cacciari, Dreyer, Karlberg, GPS, Zanderighi

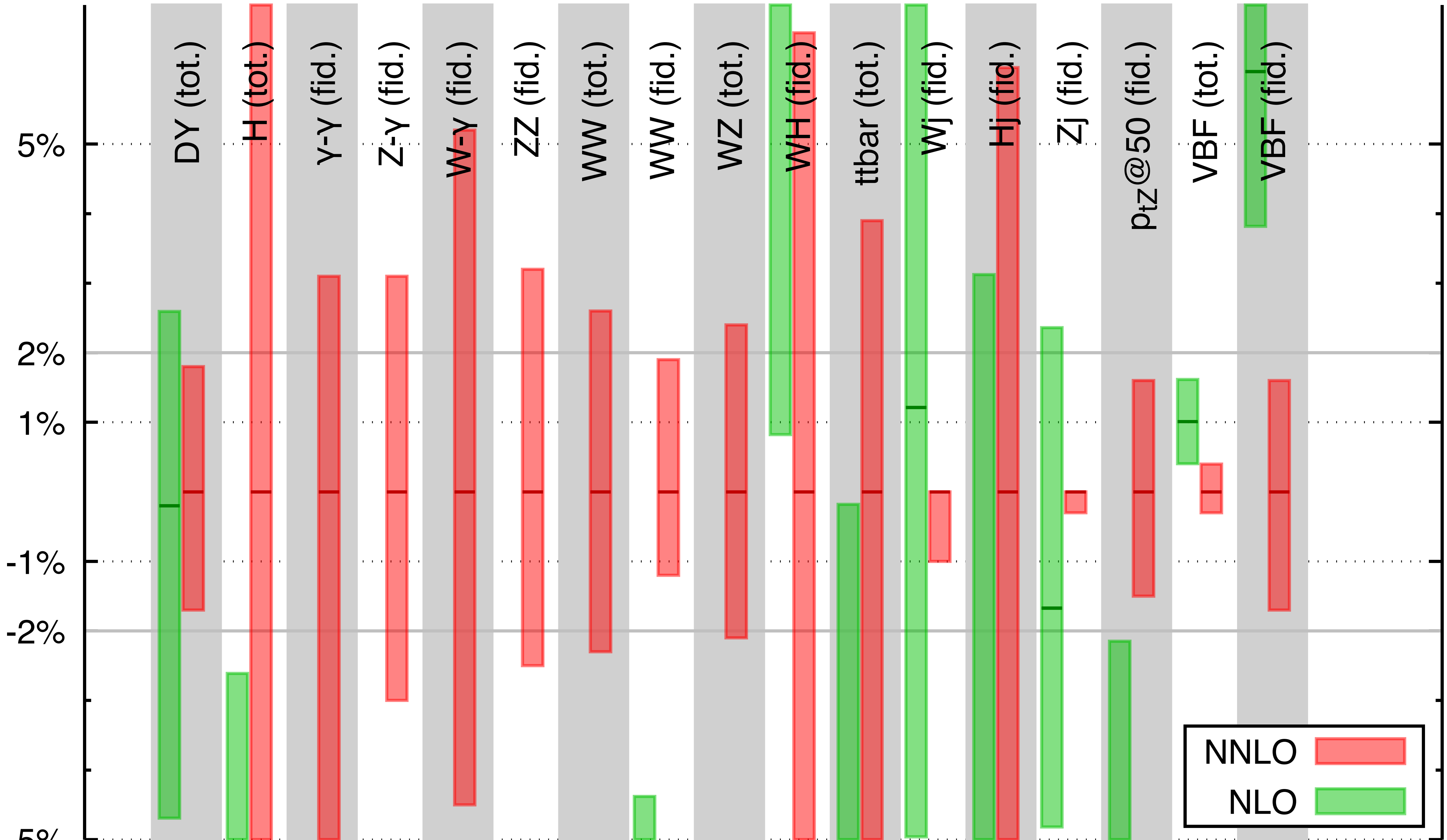
WHAT PRECISION AT NNLO?



For many processes NNLO scale band is ~±2%

But only in 3/17 cases is NNLO (central) within NLO scale band…

WHAT PRECISION AT NNLO?



For many processes NNLO scale band is ~±2%

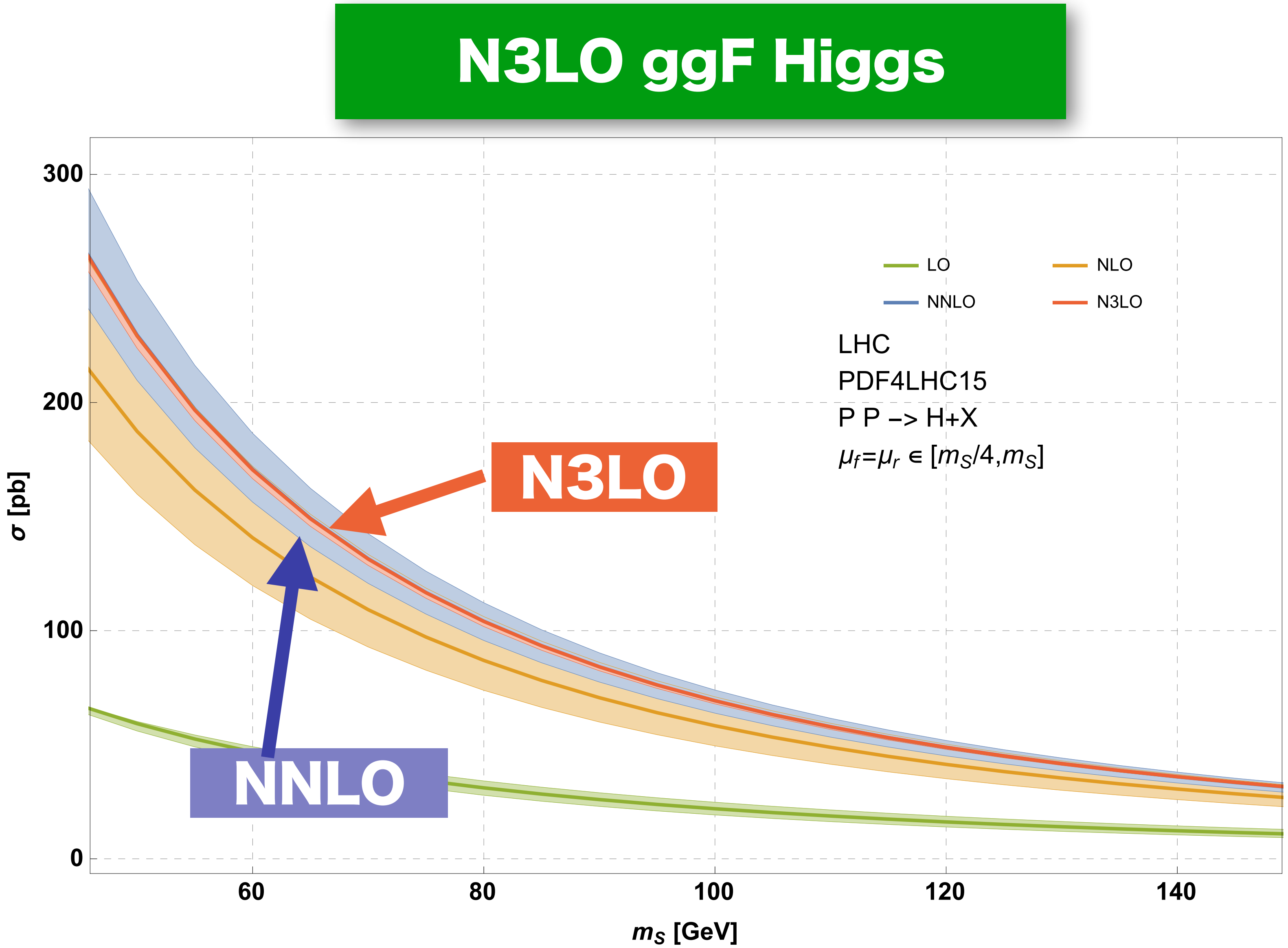
But only in 3/17 cases is NNLO (central) within NLO scale band…

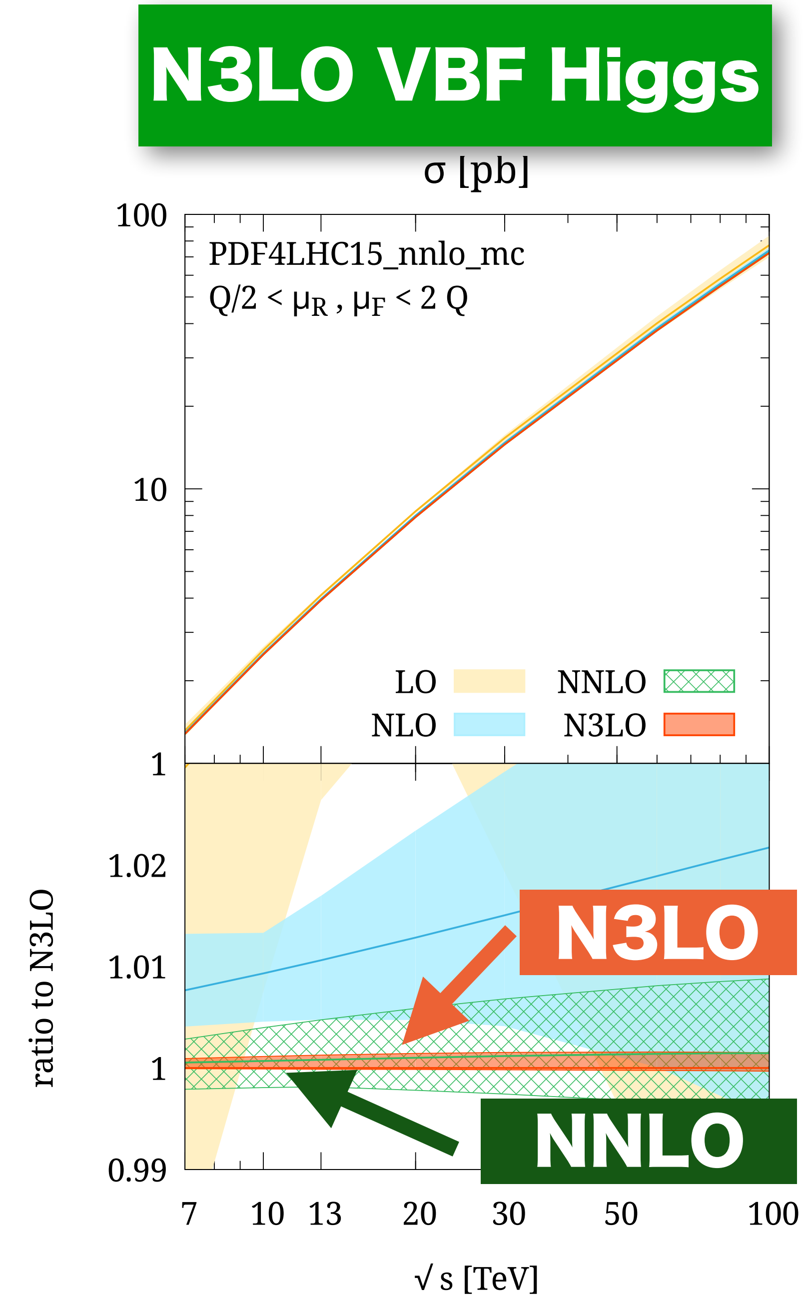
n3lo

Higgs via gluon fusion	**Higgs via weak-boson fusion**	**PDFs?**

N3LO CONVERGENCE?

Anastasiou et al, 1602.00695 *Dreyer & Karlberg, 1606.00840*





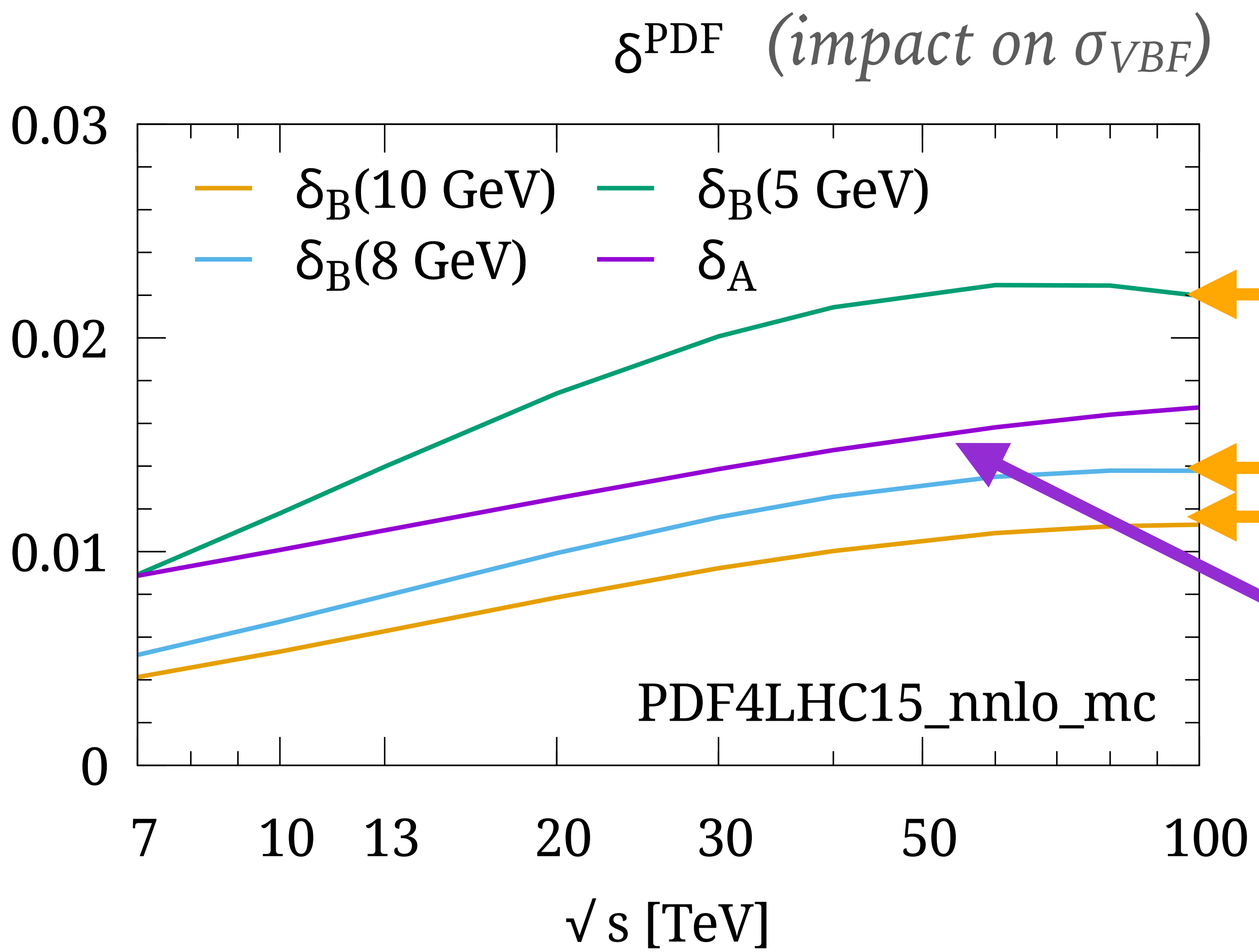
VBF converges much faster than ggF

But both calc[ns] share feature that NNLO fell outside NLO scale band, while N3LO (with good central scale choice) is very close to NNLO

N3LO PDFS ?

N3LO splitting functions not known. But N3LO DIS coefficient functions are known and their impact for quarks is >> NNLO splitting-function scale variation (~0.1%)

Dreyer & Karlberg, 1606.00840



impact of N3LO coefficient functions non-negligible on PDFs

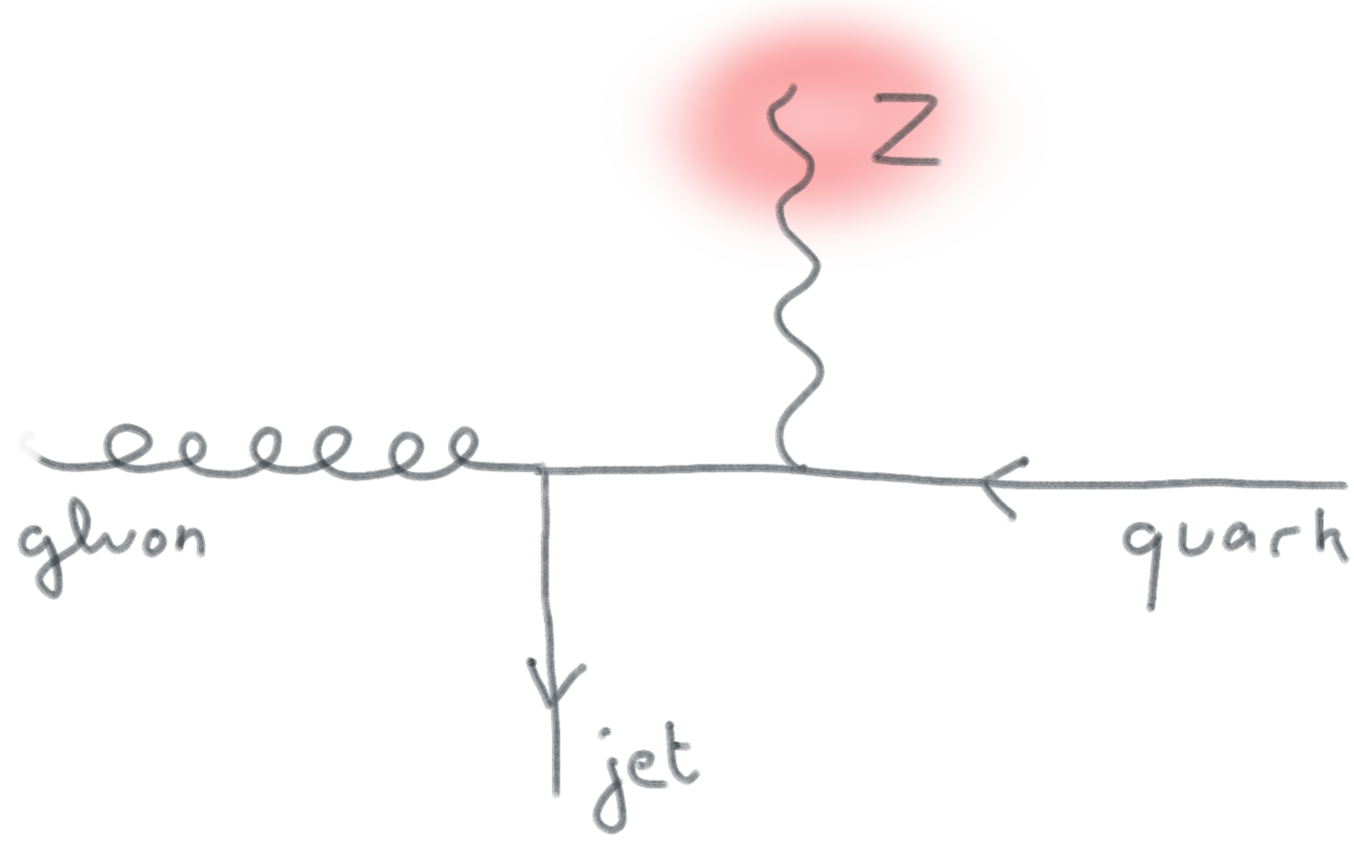
$$\frac{1}{2}\left(\frac{\text{NNLO}}{\text{NLO}} - 1\right)$$

First results on N3LO splitting-fn moments e-Print: arXiv:1605.08408

First Forcer results on deep-inelastic scattering and related quantities

B. Ruijl, T. Ueda, J.A.M. Vermaseren (NIKHEF, Amsterdam), J. Davies, A. Vogt (Liverpool U., Dept. Math.).

Z P_T: the "ideal" hard process for testing NNLO precision?

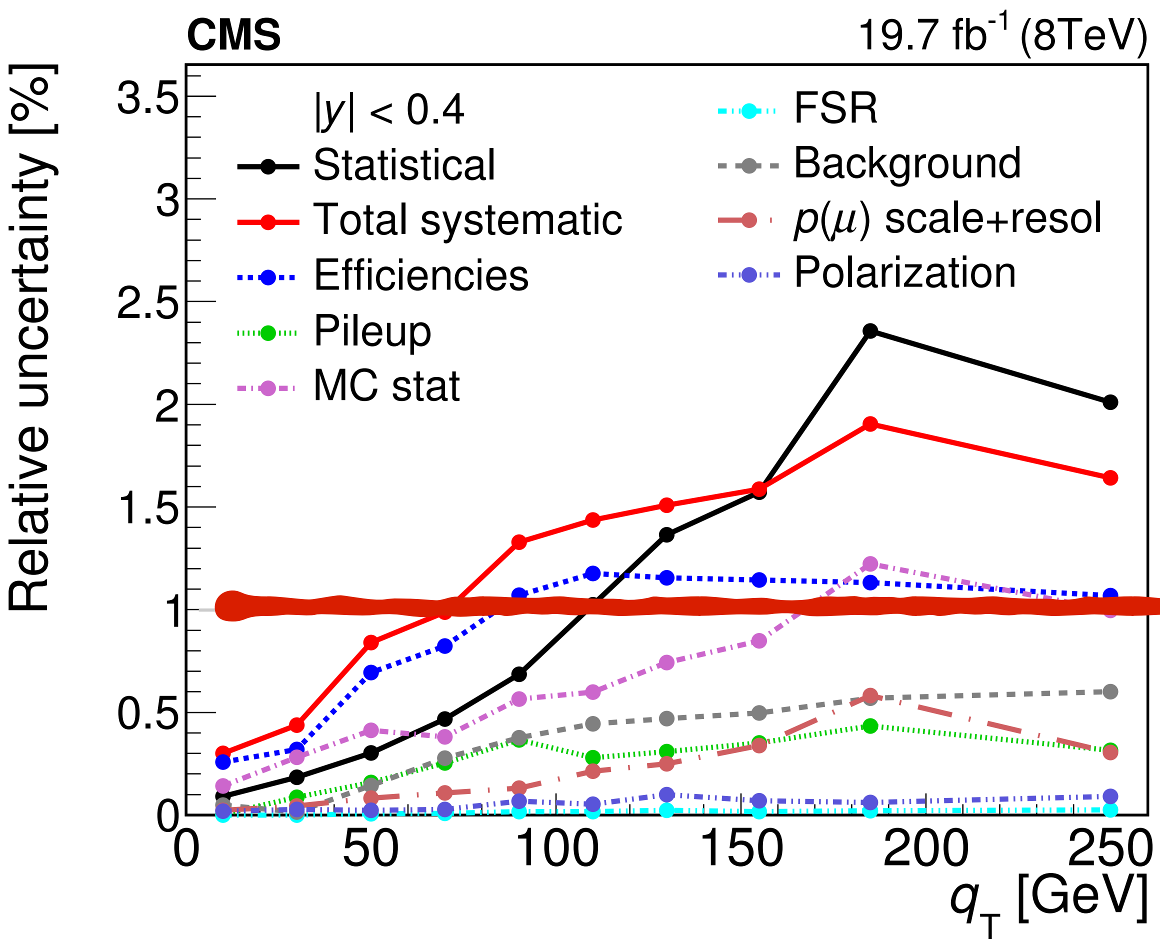


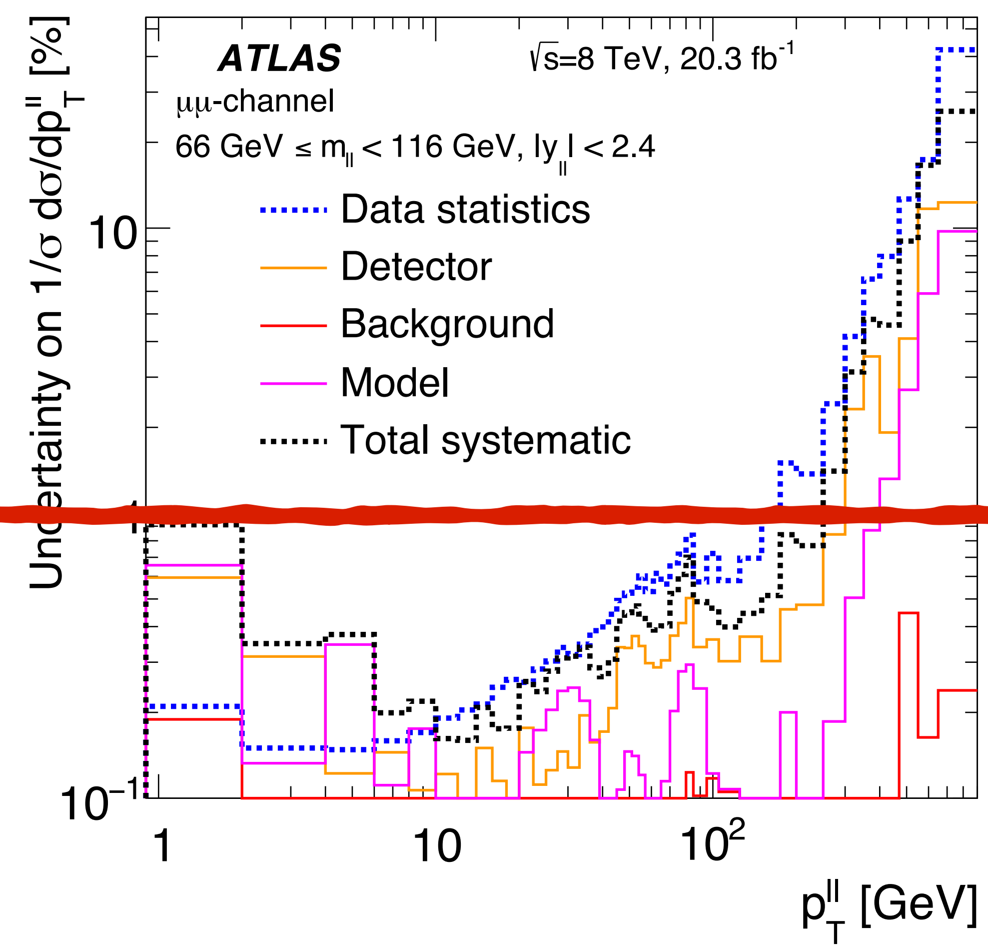
For both data and theory, Z p_T is an immediate testing ground for 1% effects.

(& unlike Z & W prod[n] *it's sensitive to* α_s *& the gluon distribution)*

Z p_T: run 1 measurements have already reached 0.5–1% !

(normalised to fiducial Z cross section)

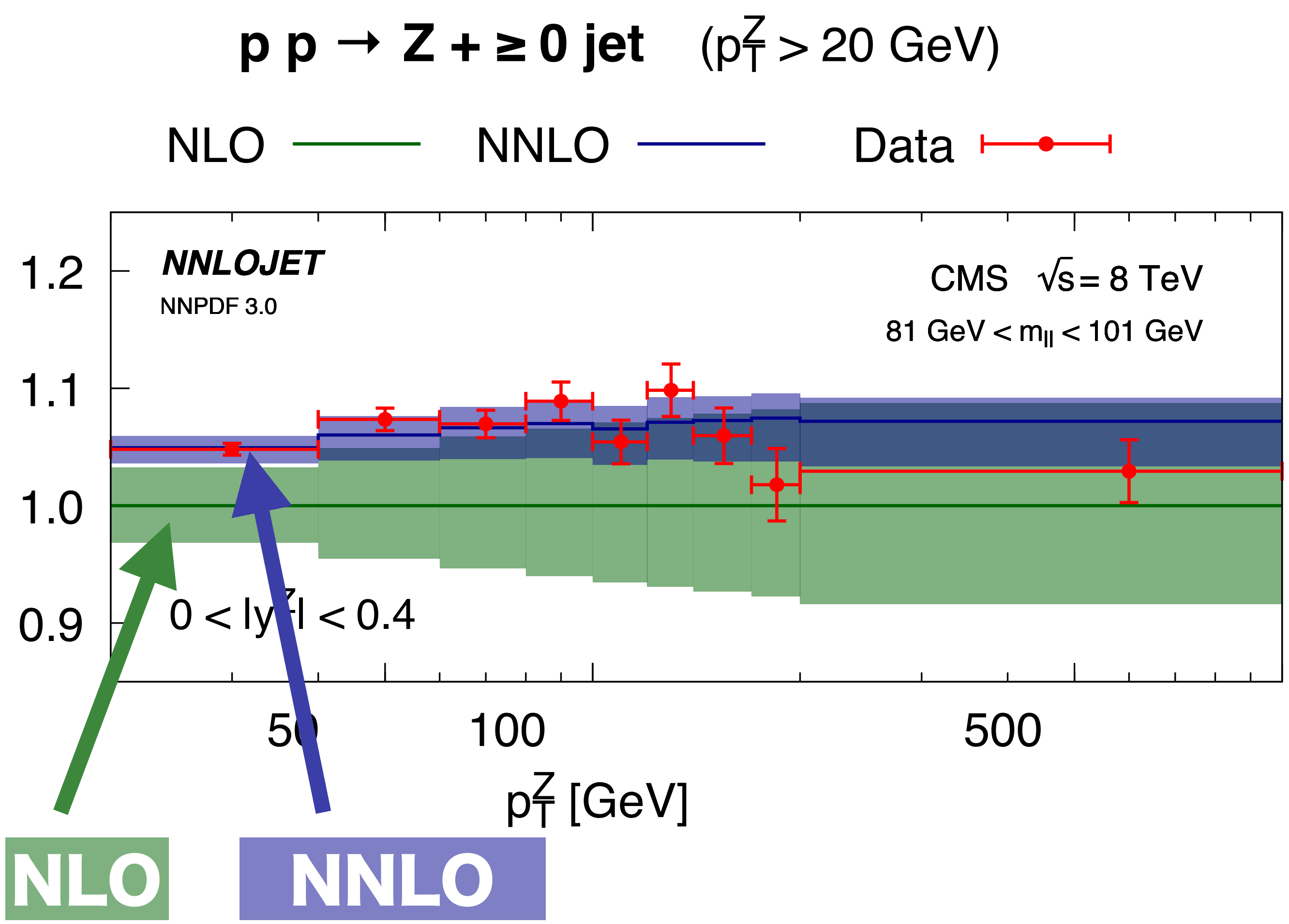


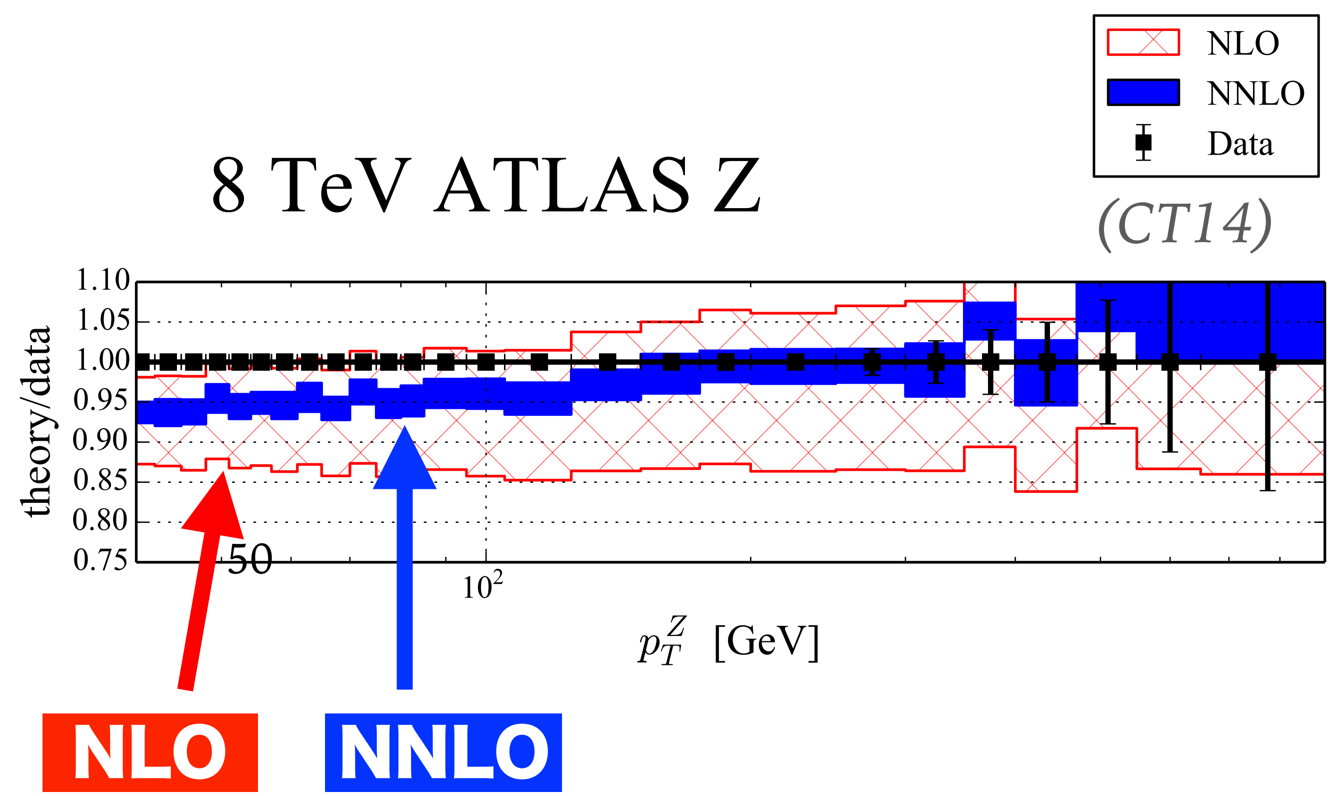


1%

Z p_T: Data v. two theory calculations

NNLO ~ ±1.5 %





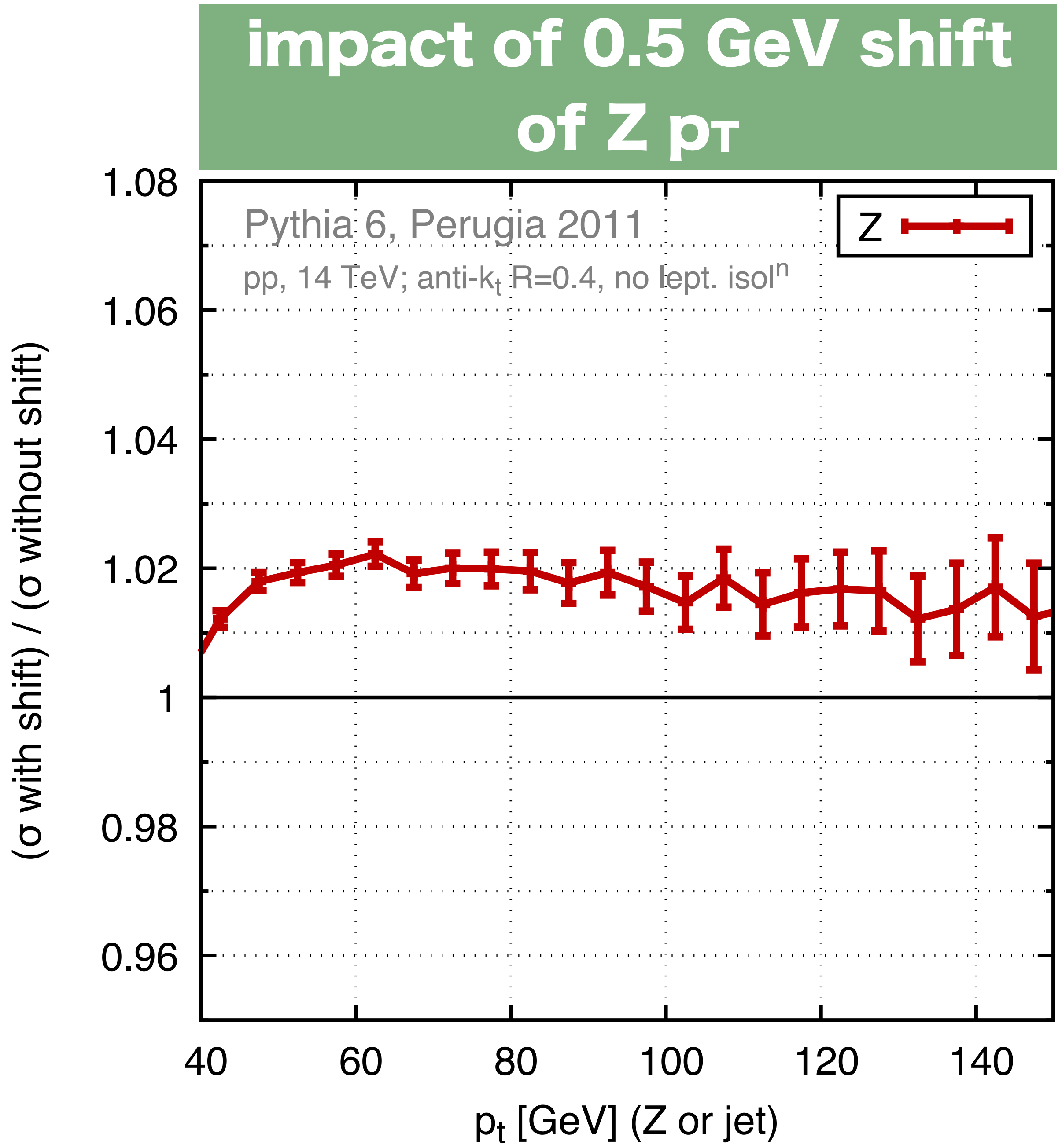
Gehrmann-de Ridder, Gehrmann Glover, Huss & Morgan

arXiv:1605.04295

Boughezal, Liu & Petriello ’16 preliminary

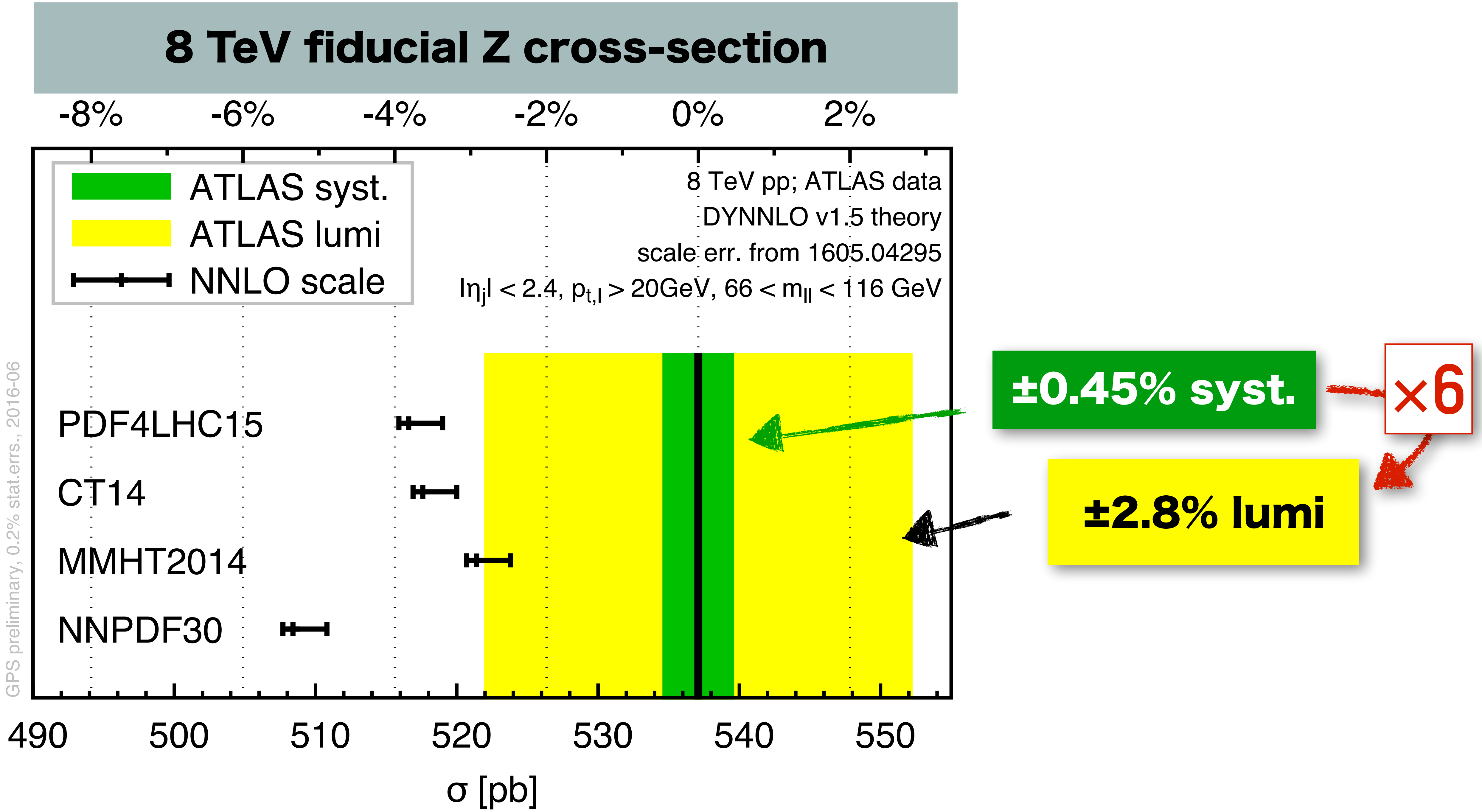
CAVEAT #1: Non-perturbative effects in Z (& H?) p_T

- Inclusive Z & H cross sections should have $\sim\Lambda^2/M^2$ corrections ($\sim 10^{-4}$?)
- Z (&H) p_T **not inclusive** so corrections can be $\sim\Lambda/M$.
- Size of effect can't be probed by turning MC hadronisation on/off [maybe by modifying underlying MC parameters?]
- Shifting Z p_T by a finite amount illustrates what could happen



0.5 GeV is perhaps conservative(?)
But suggests up to 2% effects could be present.

X-sections normalised to Z are great, if we understand Z production



Up to 5% discrepancy?

Are NNLO scale errors (~0.5%) a reliable indicator of uncertainties?

Does it matter, given the large luminosity uncertainty?

HOW DO EXPERIMENTS COMPARE FOR LUMINOSITY DETERMINATIONS?

→ Appdx

Experiment pp running period $\sqrt{s}$ (TeV)	ALICE 2010 7.0	ATLAS 2012 8.0	CMS 2012 8.0		LHCb 2012 8.0	
Absolute-calibration method	*vdM*	*vdM*	*vdM*	*vdM*	Combined	BGI
Calibration uncertainty $\Delta \sigma_{vis} / \sigma_{vis}$ (%)	3.5	1.2	2.3	1.47	1.12	1.43
μ or total–rate dependence (%)	-	1.4	< 0.1		0.17	
Long-term stability (%)	1.5	0.6	1.0		0.22	
Subtraction of luminosity backgrounds (%)	3.0	0.2	0.5		0.13	
Other luminosity-dependent effects (%)	1.5		0.5		-	
Total luminosity uncertainty (%)	5.0	1.9	2.6	1.5	1.2	1.5

From yesterday's talk by W. Kozanecki

LHCb can do ±1.1%. Can that be transferred to the other experiments?
(e.g. with fiducial J/Ψ measurements? Or some other way?)

ATLAS's final lumi. error has improved relative to that used for fiducial Z x-sct.
Can key legacy 8 TeV results be updated with new lumi?

luminosity is potential *keystone measurement* for LHC precision programme

closing remarks

THE THINGS I DIDN'T COVER

- **strong coupling:** hasn't seen real progress in several years.
  - Need to exclude/validate 0.113.
  - My view: highest prec. will come from progress in lattice
- **PDFs:** maybe we need a roadmap of how we're going to increase precision here? (E.g. which processes are robust & sensitive)
- **Jets:** there are many "systematics" in jet physics
  - perturbative radiation (esp. at small R, log R effects)
  - hadronisation ($\sim 1/R$)
  - underlying event ($\sim R^2$)

  If we're to use them for precision physics we'll probably need measurements over a range of R (0.2 – 0.7?) that goes beyond the R values intended for normal analyses

KEY MESSAGES

- major progress in NNLO calculations
- we're on the eve of a **new precision era: 1–2%**
- many things will need to come together for precision to become ubiquitous
  - QCD inputs: couplings & PDFs
  - QCD "modelling": hadronisation & UE?
  - Insight into how we make cuts
  - Choice of a few good processes to measure (e.g. just how good are leptons?)
  - LHC machine knowledge, esp. luminosity error?

an exciting time ahead as we learn to do precision across the spectrum of LHC physics!

EXTRA SLIDES

Processes currently known through NNLO

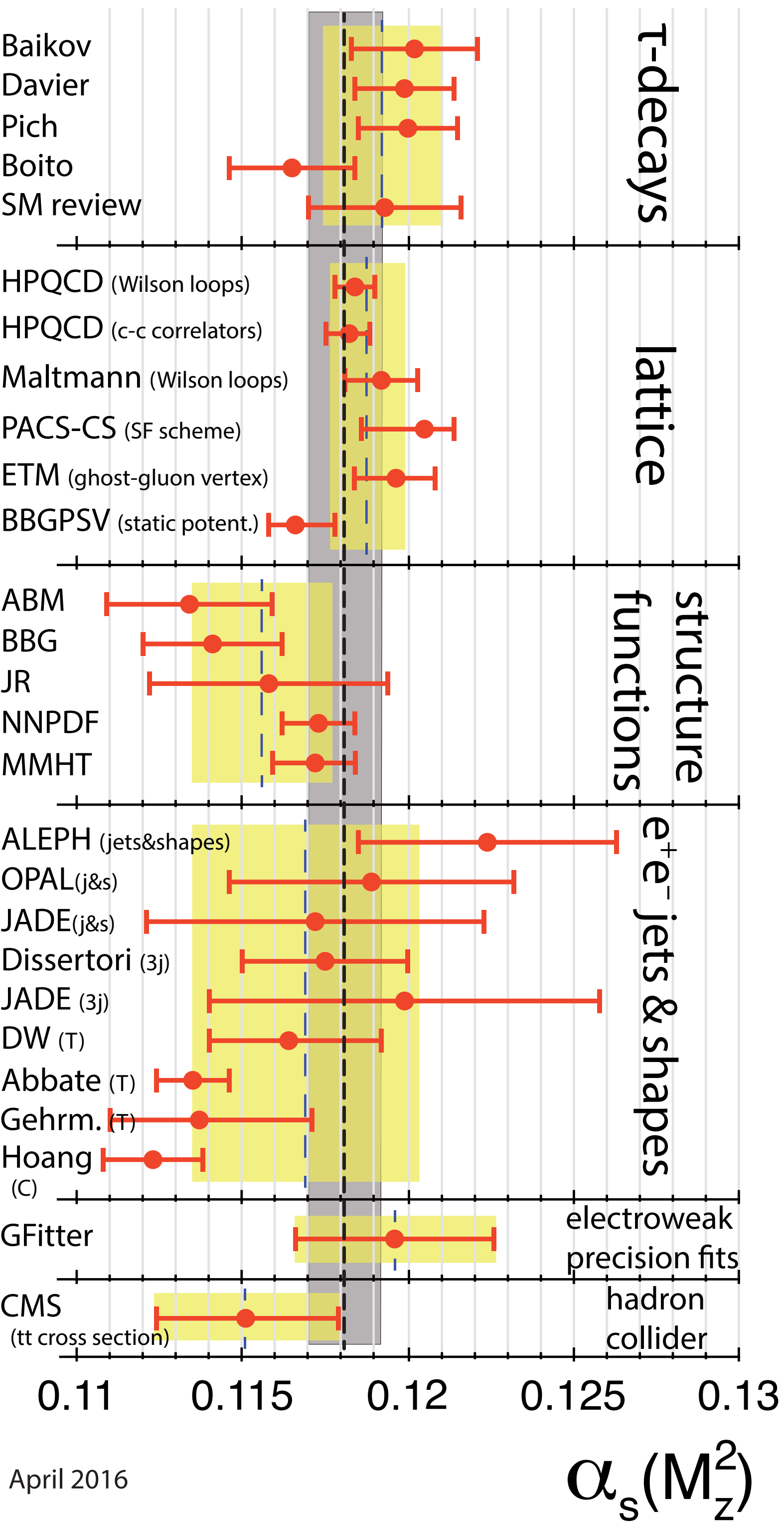
dijets	O(3%)	gluon-gluon, gluon-quark	PDFs, strong couplings, BSM
H+0 jet	O(3-5 %)	fully inclusive (N3LO)	Higgs couplings
H+1 jet	O(7%)	fully exclusive; Higgs decays, infinite mass tops	Higgs couplings, Higgs p_t, structure for the ggH vertex.
tT pair	O(4%)	fully exclusive, stable tops	top cross section, mass, p_t, FB asymmetry, PDFs, BSM
single top	O(1%)	fully exclusive, stable tops, t-channel	V_{tb}, width, PDFs
WBF	O(1%)	exclusive, VBF cuts	Higgs couplings
W+j	O(1%)	fully exclusive, decays	PDFs
Z+j	O(1-3%)	decays, off-shell effects	PDFs
ZH	O(3-5 %)	decays to bb at NLO	Higgs couplings (H-> bb)
ZZ	O(4%)	fully exclusive	Trilinear gauge couplings, BSM
WW	O(3%)	fully inclusive	Trilinear gauge couplings, BSM
top decay	O(1-2 %)	exclusive	Top couplings
H -> bb	O(1-2 %)	exclusive, massless	Higgs couplings, boosted

done ~ in past year

K. Melnikov @ KITP

the inputs

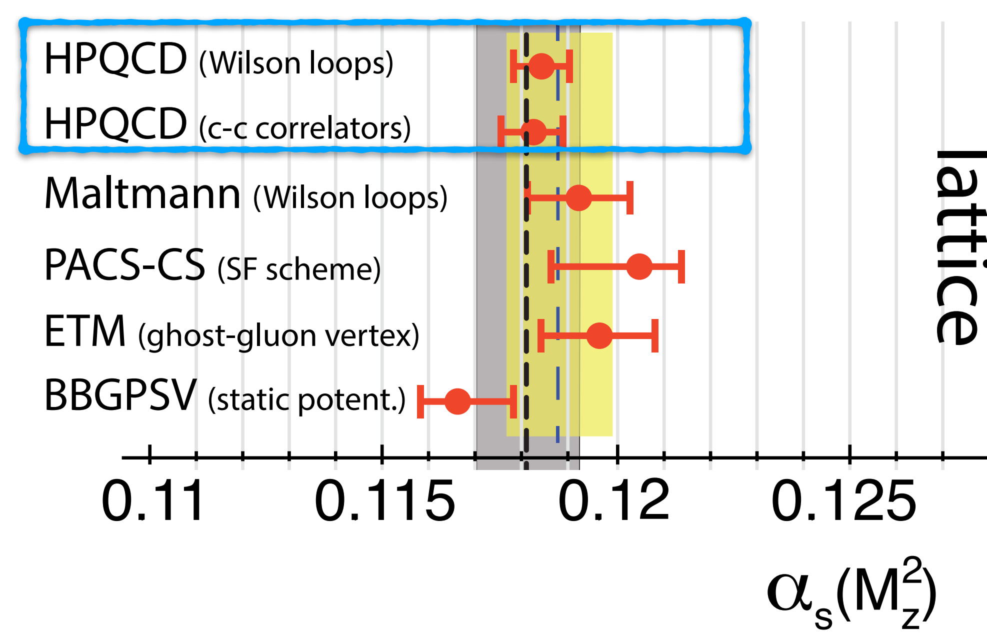
strong coupling (e.g. ±2.6% on ggF)
PDFs (e.g. ±1.9% on ggF)



PDG World Average: $\alpha_s(M_Z) = 0.1181 \pm 0.0011$ (0.9%)

- Most consistent set of independent determinations is from lattice
- Two best determinations are from same group (HPQCD, 1004.4285, 1408.4169)
  $\alpha_s(M_Z) = 0.1183 \pm 0.0007$ (0.6%) [heavy-quark correlators]
  $\alpha_s(M_Z) = 0.1183 \pm 0.0007$ (0.6%) [Wilson loops]
- Error criticised by FLAG, who suggest

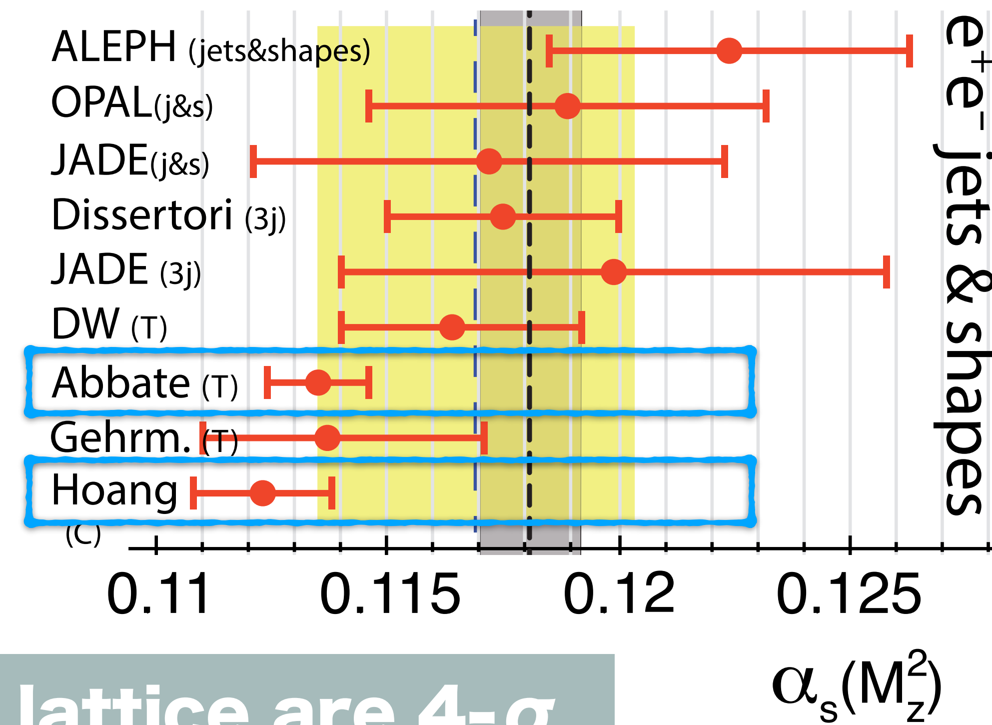
$\alpha_s(M_Z) = 0.1184 \pm 0.0012$ (1%)



- Worries include missing perturbative contributions, non-perturbative effects in 3–4 flavour transition at charm mass [addressed in some work], etc.

E+E- EVENT SHAPES AND JET RATES

- Two "best" determinations are from same group (Hoang et al, 1006.3080,1501.04111)
  $\alpha_s(M_Z) = 0.1135 \pm 0.0010$ (0.9%) [thrust]
  $\alpha_s(M_Z) = 0.1123 \pm 0.0015$ (1.3%) [C-parameter]



thrust & "best" lattice are 4-σ

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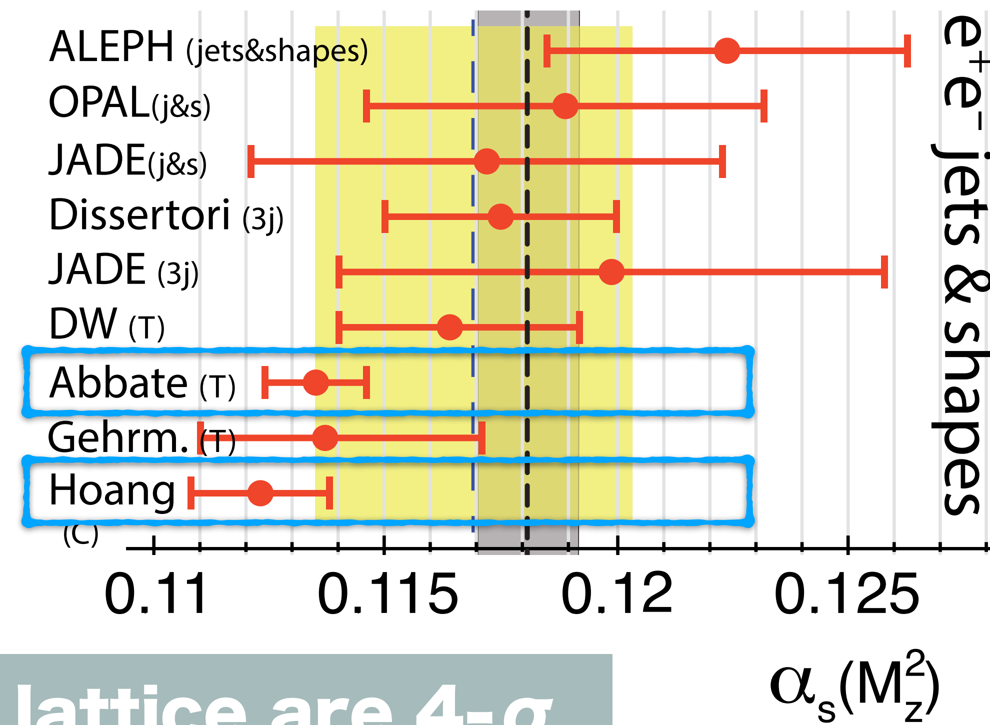
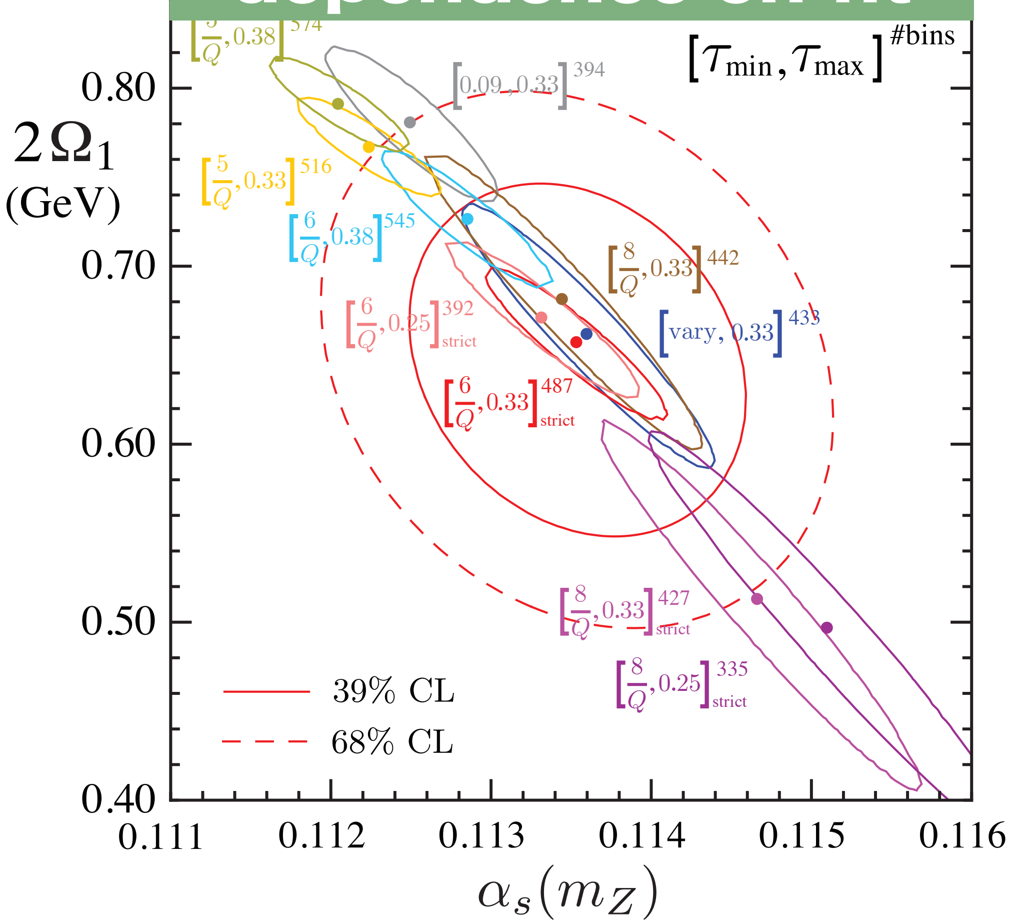


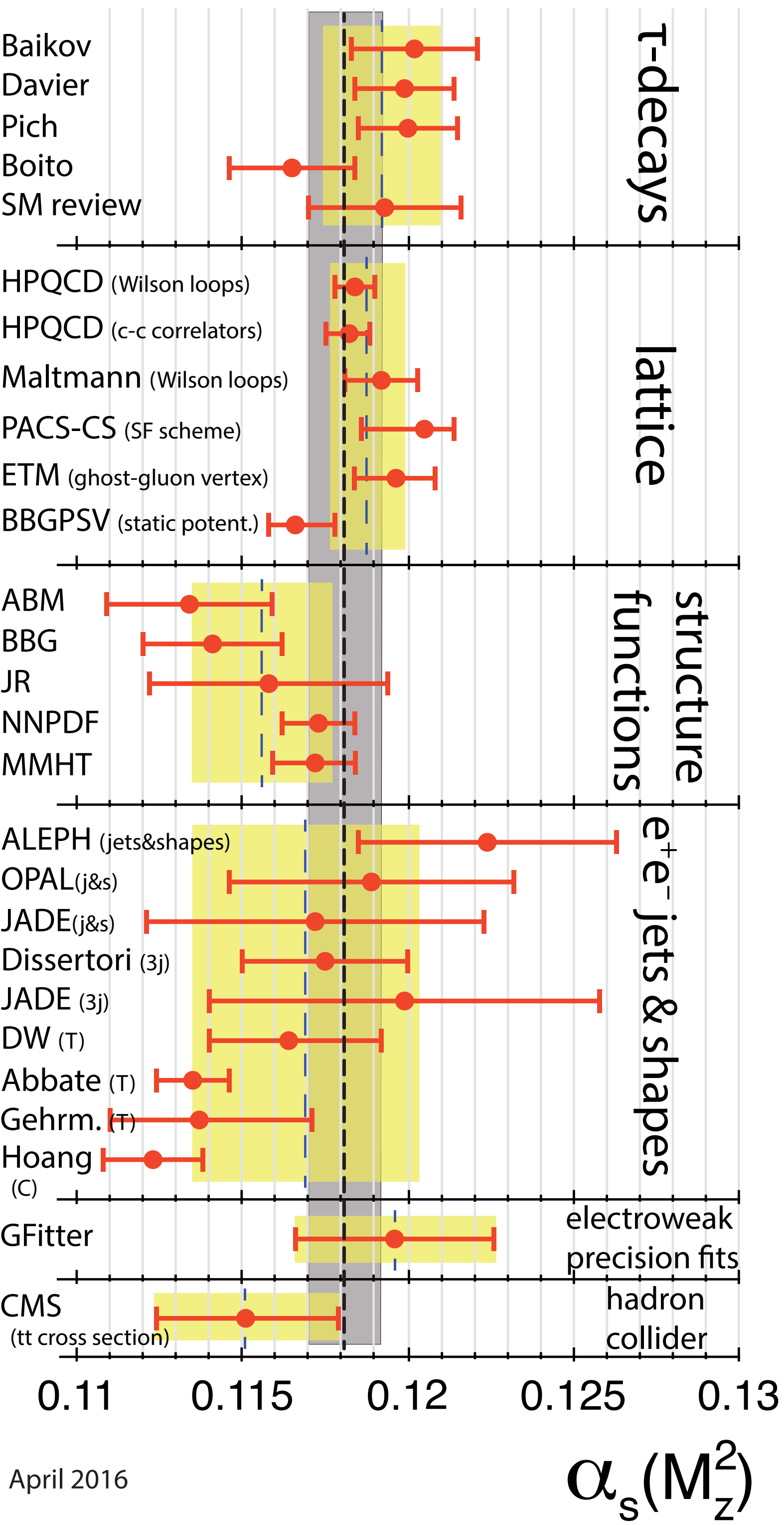
dependence on fit



thrust & "best" lattice are 4-σ

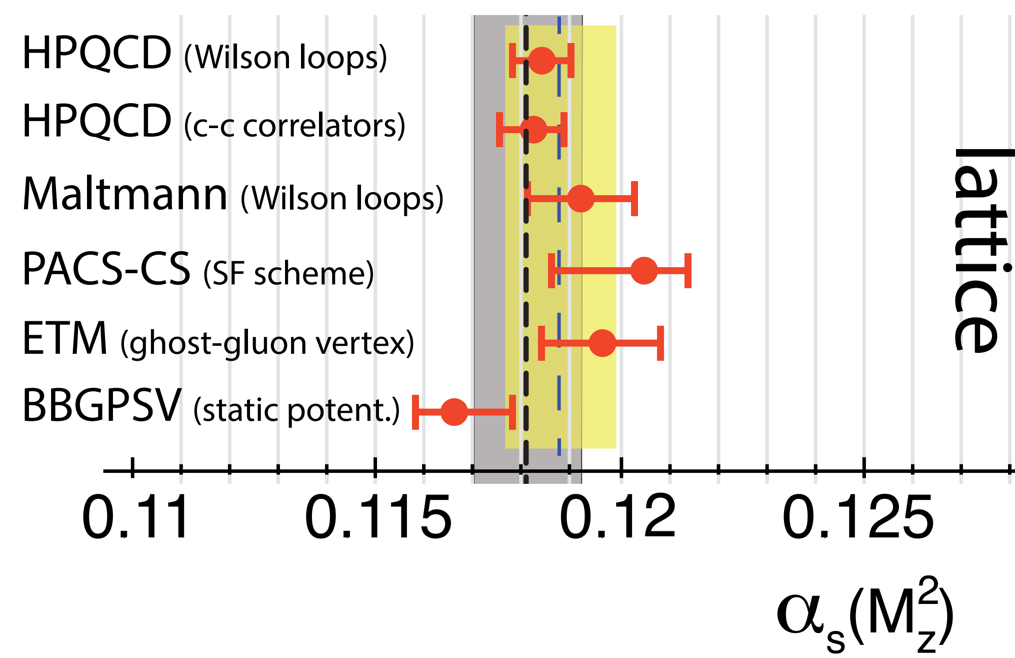
<u>Comments:</u>

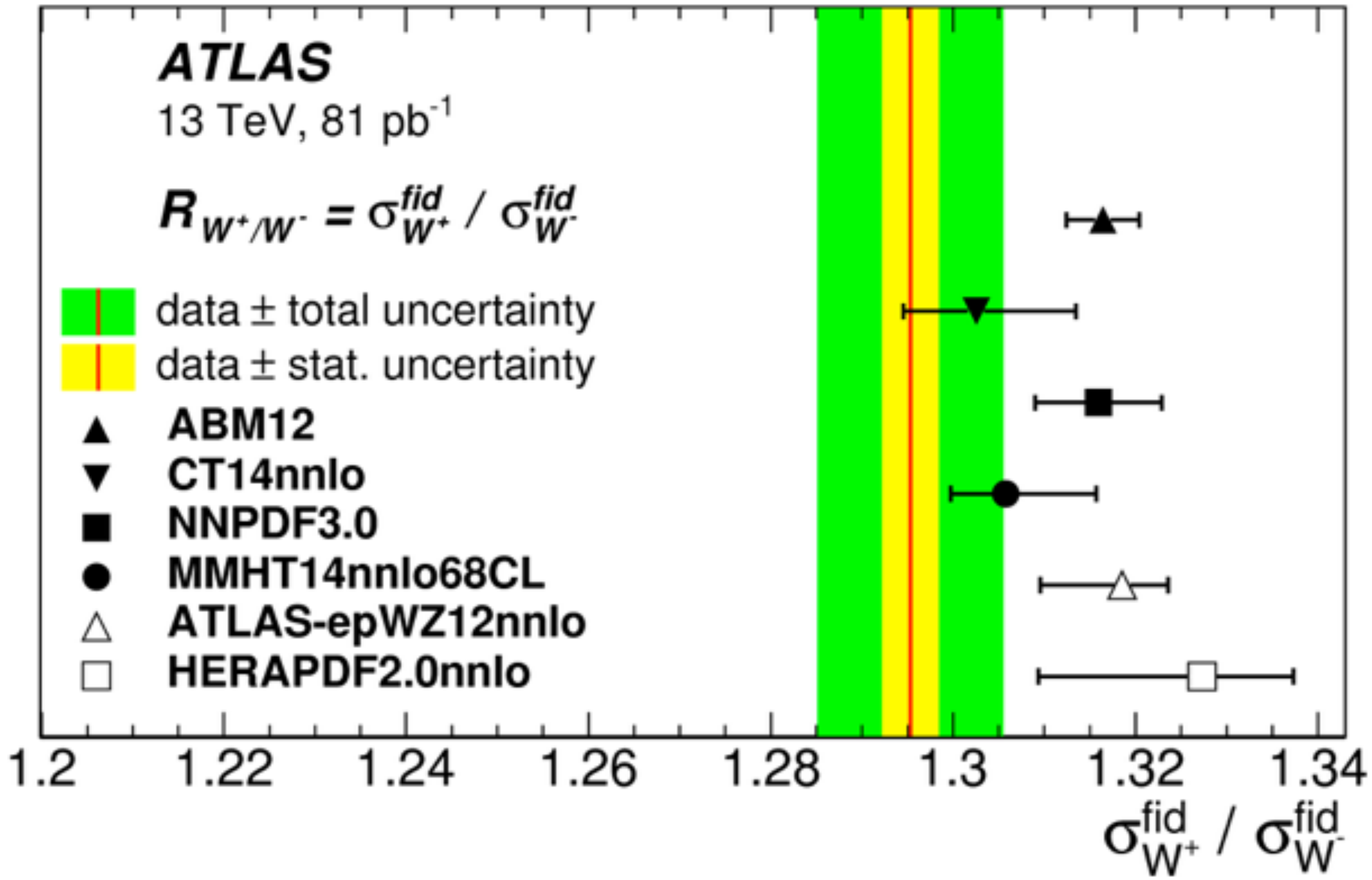
- thrust & C-parameter are highly correlated observables
- Analysis valid far from 3-jet region, but not too deep into 2-jet region — at LEP, not clear how much of distribution satisfies this requirement
- thrust fit shows noticeable sensitivity to fit region (C-parameter doesn't)



PDG World Average: $\alpha_s(M_Z) = 0.1181 \pm 0.0011$ (0.9%). WHAT WAY FORWARD?

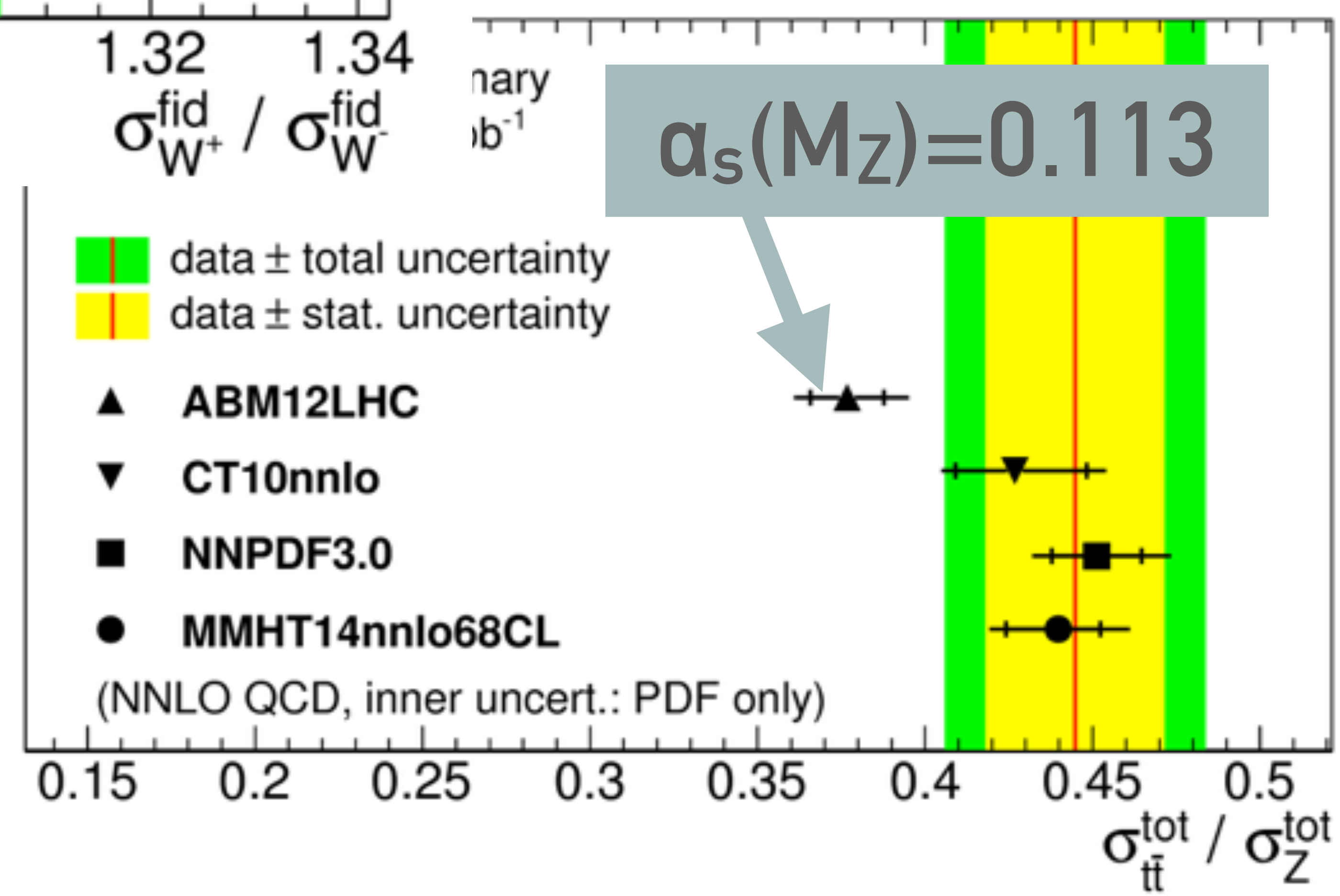
- For gluon-fusion & ttH, this comes in squared. It also correlates with the PDFs and affects backgrounds.
- To go beyond 1%, best hope is probably lattice QCD — on a 10-year timescale, there will likely be enough progress that multiple groups will have high-precision determinations





cross-section ratios (W^+/W^-, ttbar/Z) show tensions with some PDFs

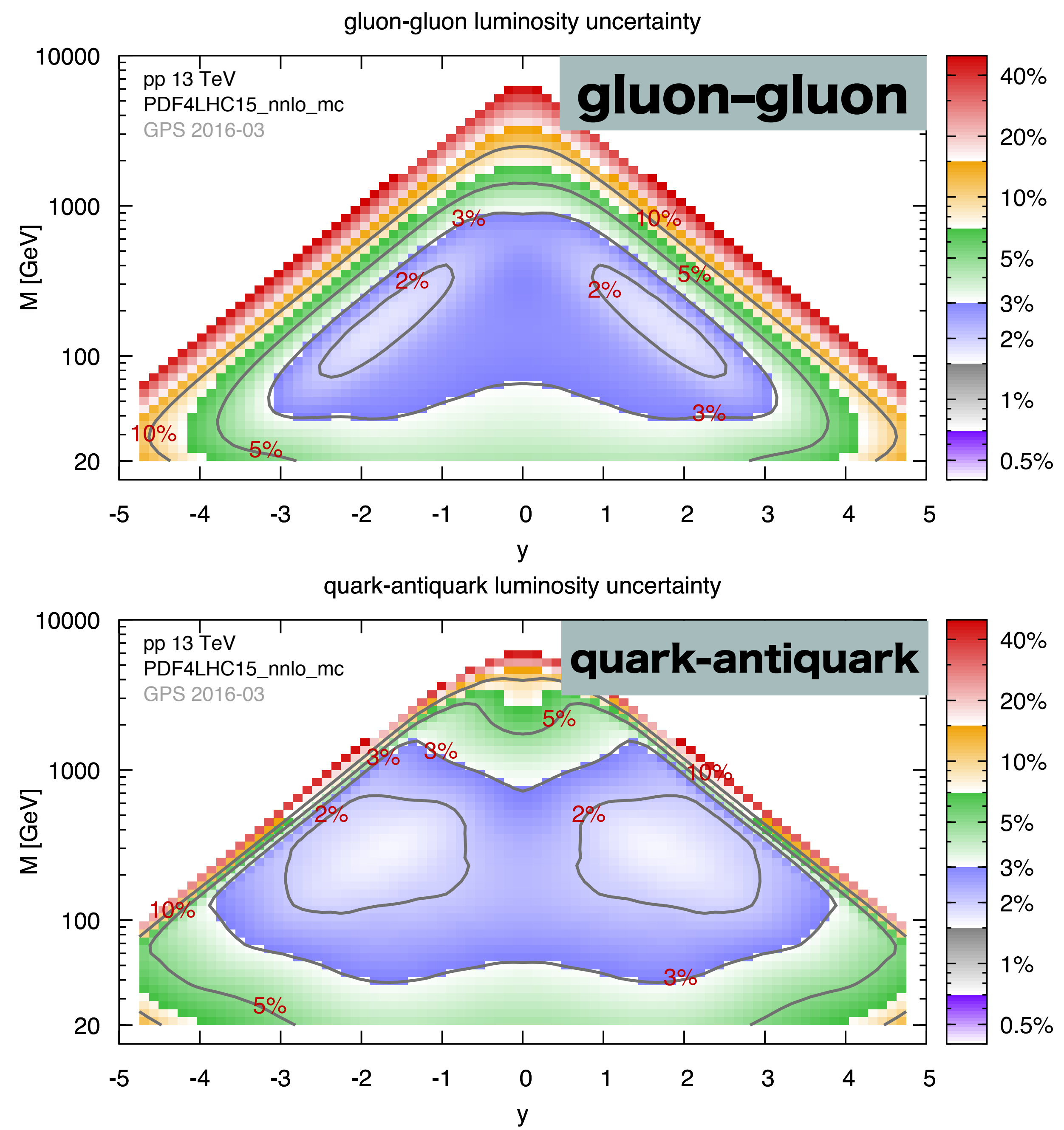
ATLAS-CONF-2015-049



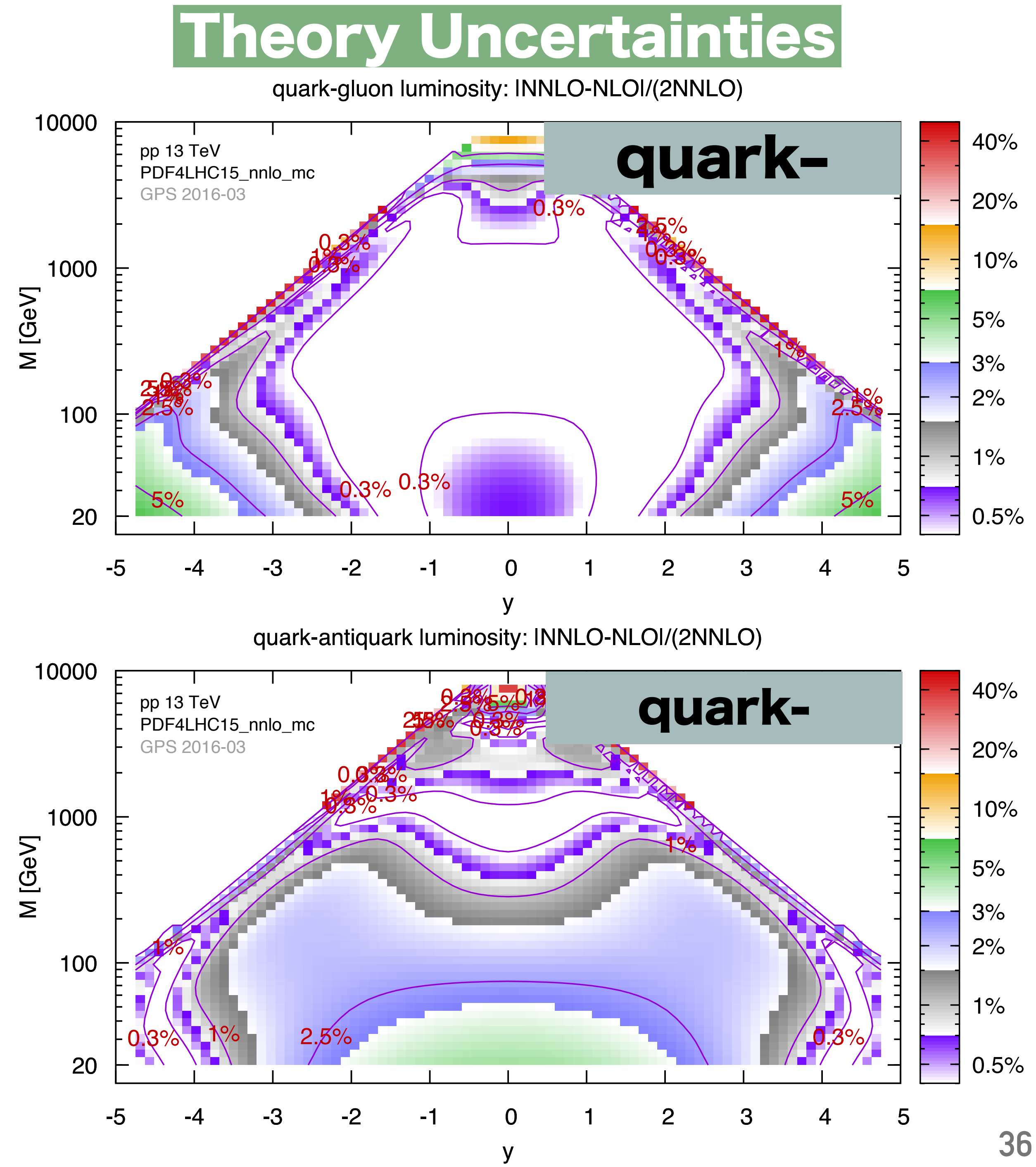
NB: top-quark mass choice affects this plot

PDFs: what route for progress?

- Current status is 2–3% for core "precision" region
- Path to 1% is not clear — e.g. Z p_T's strongest constraint is on qg lumi, which is already best known (why?)
- It'll be interesting to revisit the question once ttbar, incl. jets, Z p_T, etc. have all been incorporated at NNLO
- **Can expts. get better lumi determination? 0.5%?**



PDF THEORY UNCERTAINTIES



arXiv.org > hep-ph > arXiv:1510.03865

High Energy Physics – Phenomenology

PDF4LHC recommendations for LHC Run II

Jon Butterworth, Stefano Carrazza, Amanda Cooper-Sarkar, Albert De Roeck, Joel Feltesse, Stefano Forte, Jun Gao, Sasha Glazov, Joey Huston, Zahari Kassabov, Ronan McNulty, Andreas Morsch, Pavel Nadolsky, Voica Radescu, Juan Rojo, Robert Thorne

(Submitted on 13 Oct 2015 (v1), last revised 12 Nov 2015 (this version, v2))

We provide an updated recommendation for the usage of sets of parton distribution functions (PDFs) and the assessment of PDF and PDF+α_s uncertainties suitable for applications at the LHC Run II. We review developments since the previous PDF4LHC recommendation, and discuss and compare the new generation of PDFs, which include substantial information from experimental data from the Run I of the LHC. We then propose a new prescription for the combination of a suitable subset of the available PDF sets, which is presented in terms of a single combined PDF set. We finally discuss tools which allow for the delivery of this combined set in terms of optimized sets of Hessian eigenvectors or Monte Carlo replicas, and their usage, and provide some examples of their application to LHC phenomenology.

arXiv.org > hep-ph > arXiv:1603.08906

High Energy Physics – Phenomenology

Recommendations for PDF usage in LHC predictions

A. Accardi, S. Alekhin, J. Blümlein, M.V. Garzelli, K. Lipka, W. Melnitchouk, S. Moch, R. Placakyte, J.F. Owens, E. Reya, N. Sato, A. Vogt, O. Zenaiev

(Submitted on 29 Mar 2016)

We review the present status of the determination of parton distribution functions (PDFs) in the light of the precision requirements for the LHC in Run 2 and other future hadron colliders. We provide brief reviews of all currently available PDF sets and use them to compute cross sections for a number of benchmark processes, including Higgs boson production in gluon-gluon fusion at the LHC. We show that the differences in the predictions obtained with the various PDFs are due to particular theory assumptions made in the fits of those PDFs. We discuss PDF uncertainties in the kinematic region covered by the LHC and on averaging procedures for PDFs, such as advocated by the PDF4LHC15 sets, and provide recommendations for the usage of PDF sets for theory predictions at the LHC.