ATLAS Standard Model Workshop,
Lessons from Run 1 and Preparation for Run 2
Annecy, February 2014

Thoughts on QCD for Run 2

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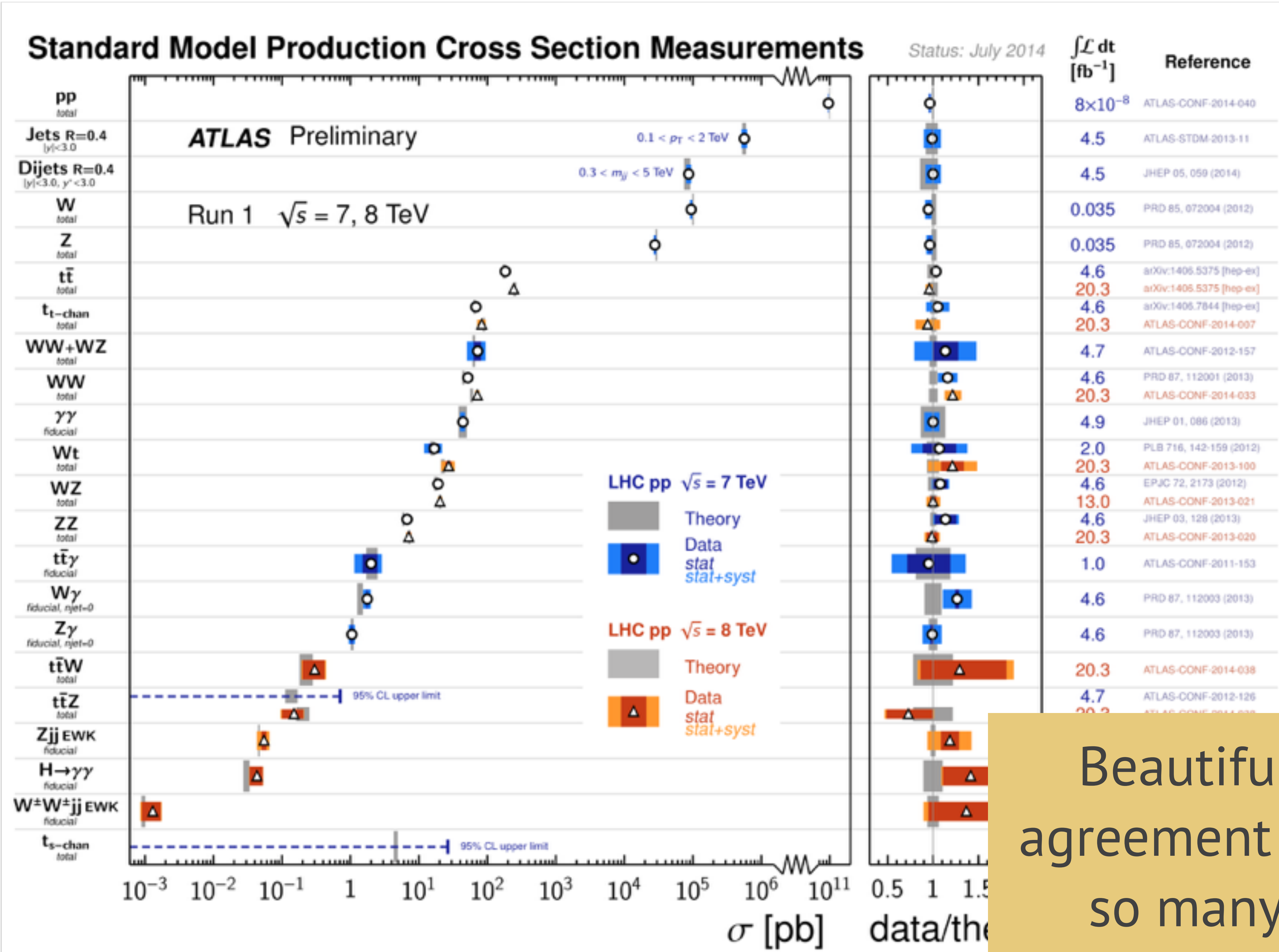
Why SM studies?

- Test and extend our understanding of QCD "tools" (MC's, etc.) — **just how good are the tools?**
- **Measure fundamental constants** (e.g. α_s, M_W) and fundamental non-perturbative inputs (**PDFs**) — such measurements can have decade-long staying power.
- Demonstrate **new physical effects** (cf. what condensed-matter physicists do all the time)

20 questions

[ ] VV tensions, jet vetoes, fiducial cross sections
[X] Are x2 scale variations sufficient? HT/2 v. MINLO?
[X] Z+j NLO discrepancies; interpretation and prospects for NNLO
[ ] Practical use of NNLO (not ntuples) and approx NNLO (not threshold); + when will NNLO come
[ ] Will NNLO V+jets be competitive for α_s?
[ ] Best scale, e.g. with DeltaPhi or DeltaR or jet-rate measurements (MINLO v etc.)
[ ] jet substructure, with %-level systematics control?
[ ] fixed-order v. MC: agreement, hadronisation, etc.
[X] jet-radius dependence: for which measurements, how small in R?
[ ] EW corrections at rts=13TeV, scale 1 TeV; state-of-knowledge
[ ] jet flavour, e.g. for inclusive X-scts; based on flav-kt?
[ ] Do TH uncertainties cancel in 7/8/13 TeV x-sct ratios
[ ] Regions of phase-space to discriminate BFKL/DGLAP
[ ] Best way to present meas. sensitive to # of quark&gluon-initiated jets
[ ] Photon isolation: study Frixione isolation?
[ ] Low-pt photons limited by frag.fns; can they be improved
[ ] Any new variables for binning x-scts? In order to get smaller uncertainties
[ ] Any TH reason to avoid small $\Delta R_{\gamma,jet}$
[X] Sym/Asymmetric cuts to avoid divergences in calcs
[ ] Correlations on scale uncertainties between phase-space regions



Beautiful agreement for so many measurements

Z p_T (>40 GeV)

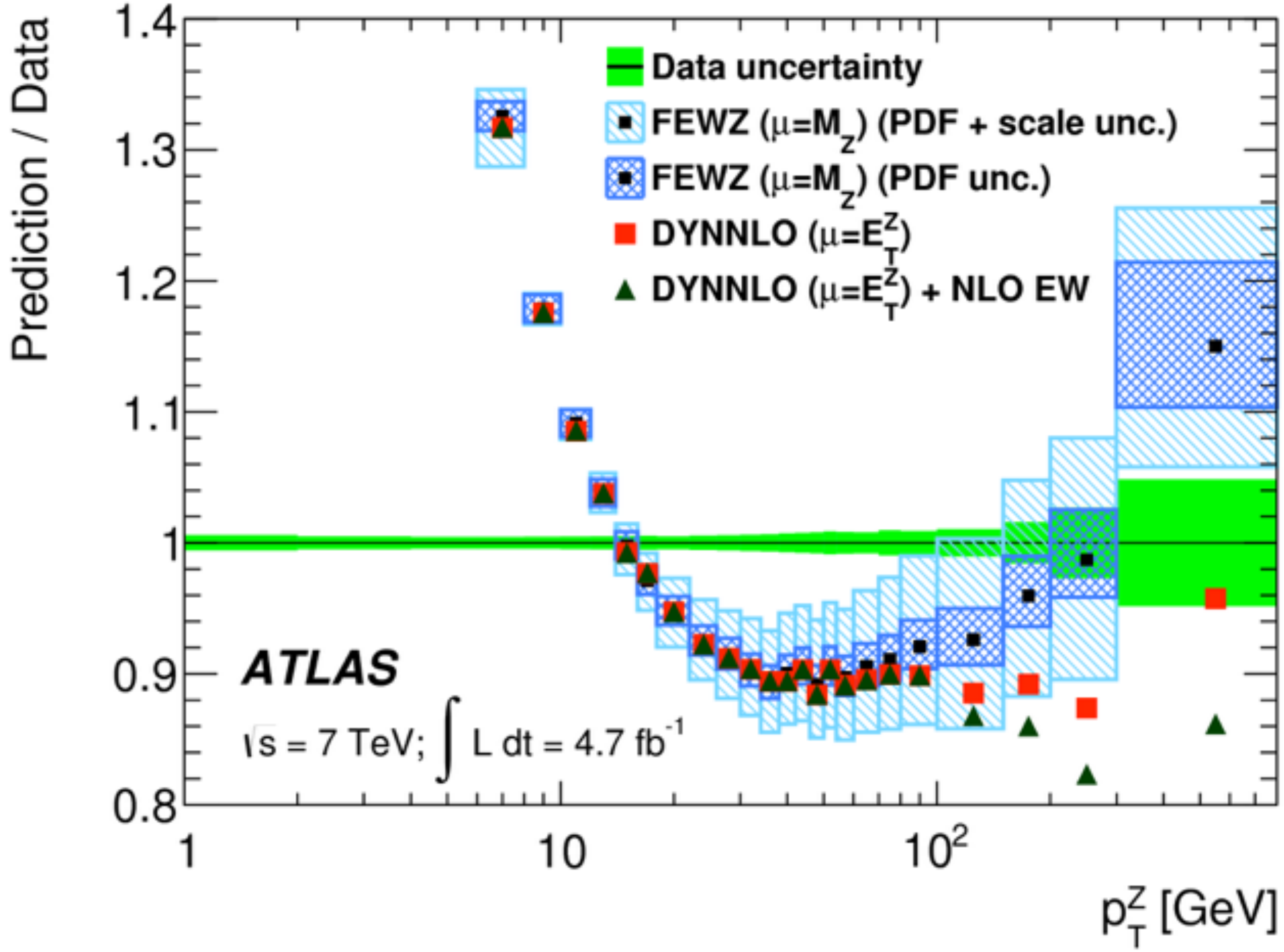
Z+j NLO discrepancies; interpretation and prospects for NNLO

Z p_T (> 40 GeV) should be a gold-plated observable:

- Experimentally very clean (errors < 1%)
- Theoretically clean too: free of large logs
  (NNLO for Z is NLO for Z p_{T}; NNLO still to come)

Important because uniquely sensitive to **α_s x gluon x quark**

ATLAS Z pT: NNLO / Data



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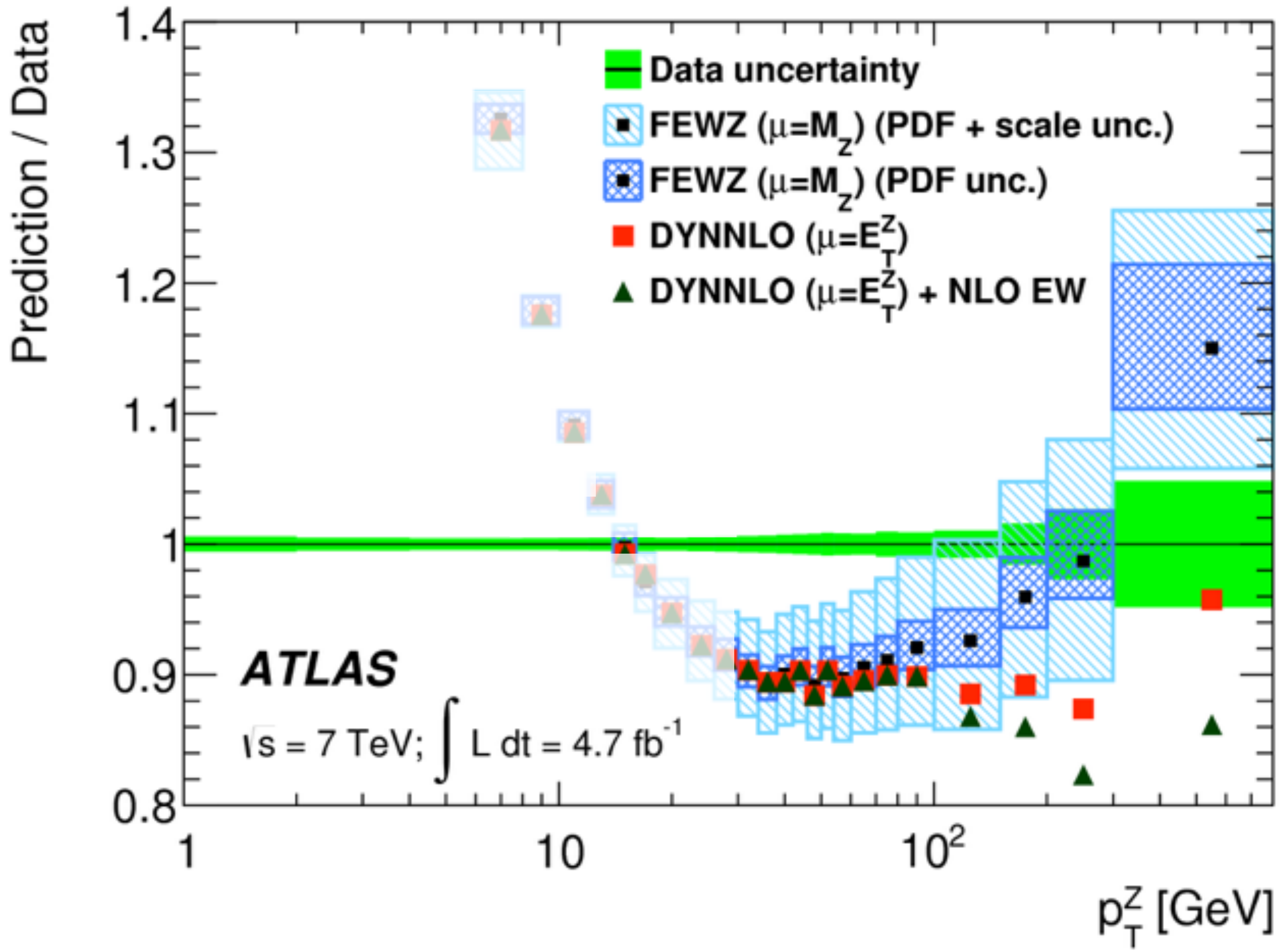

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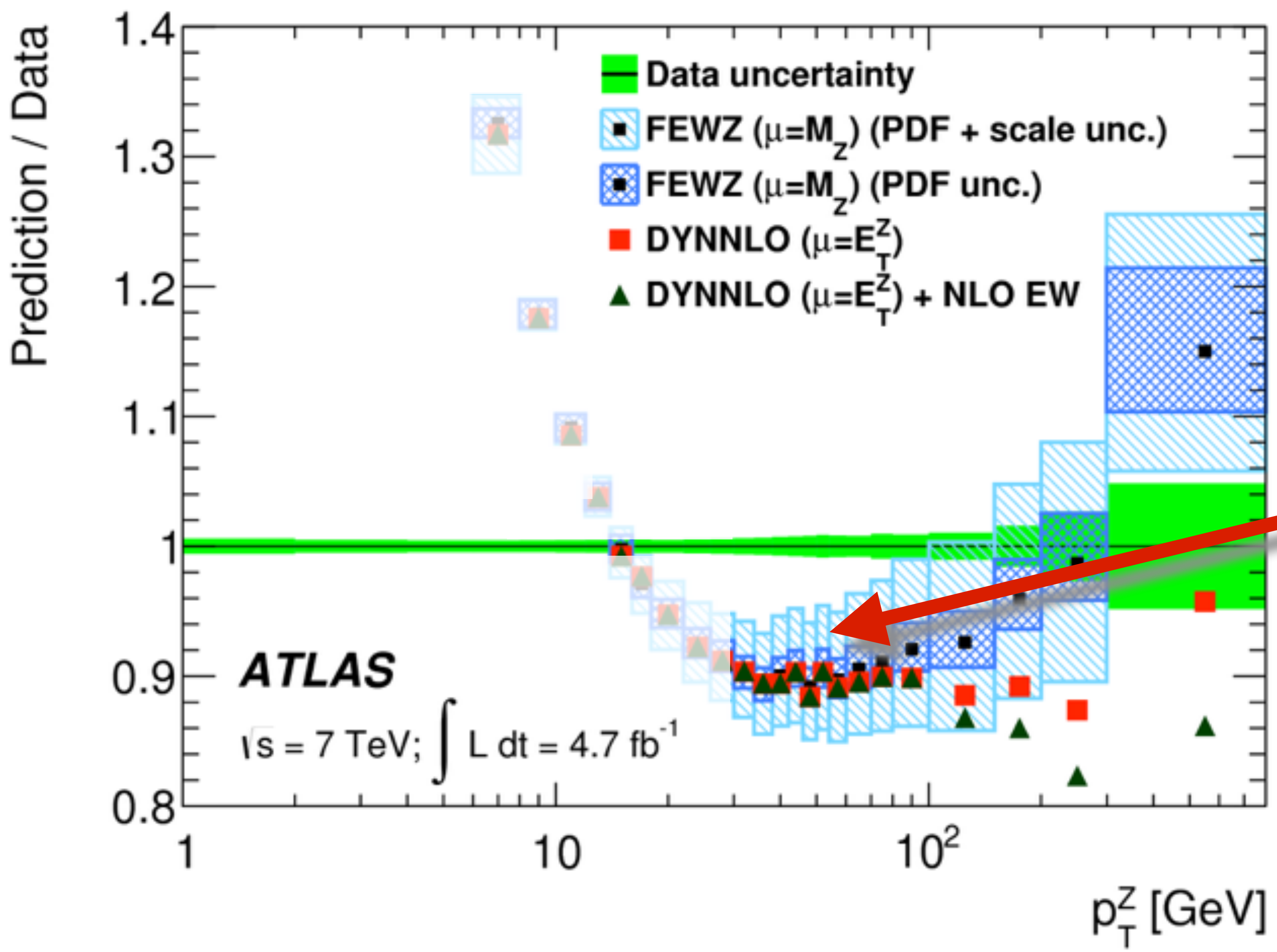
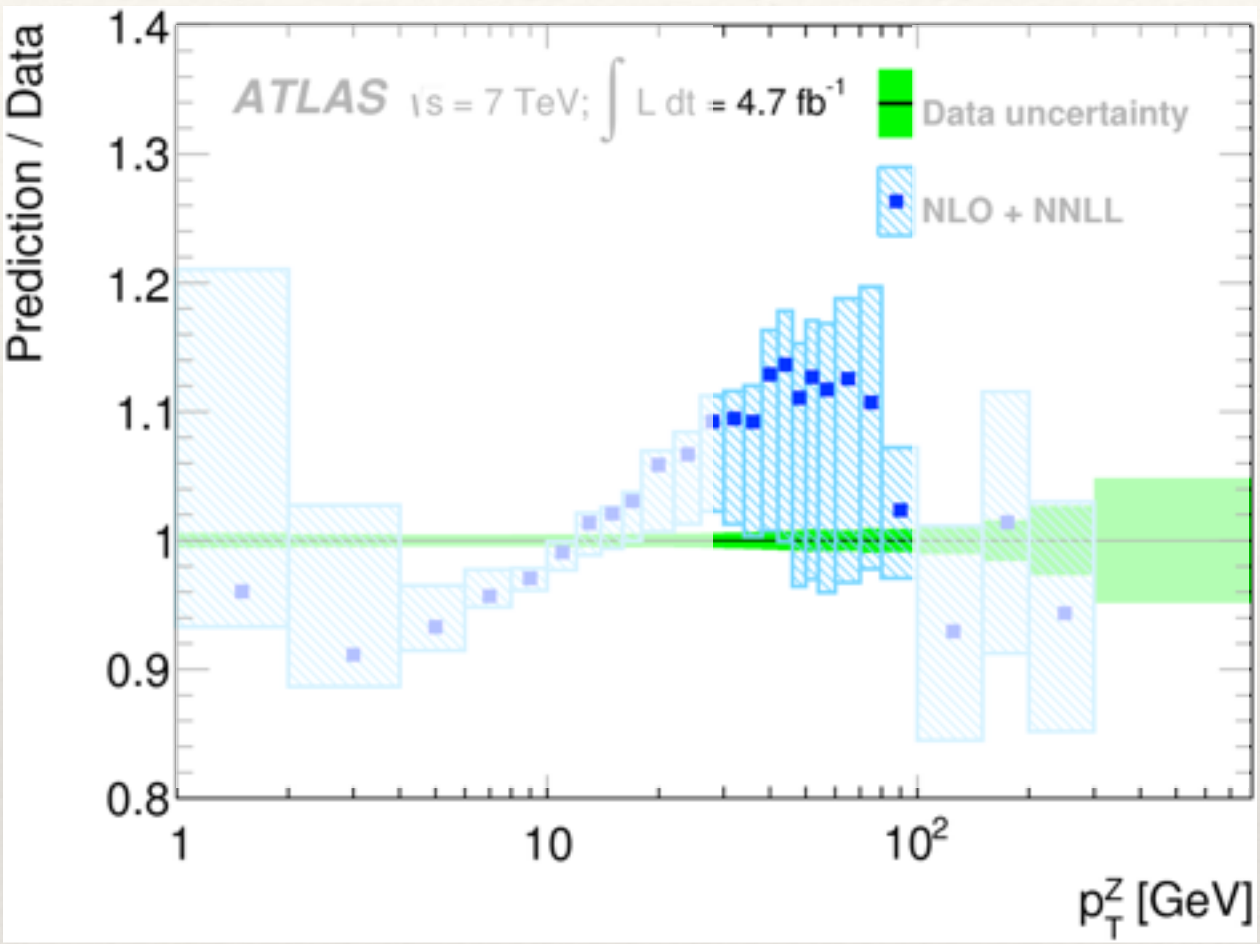
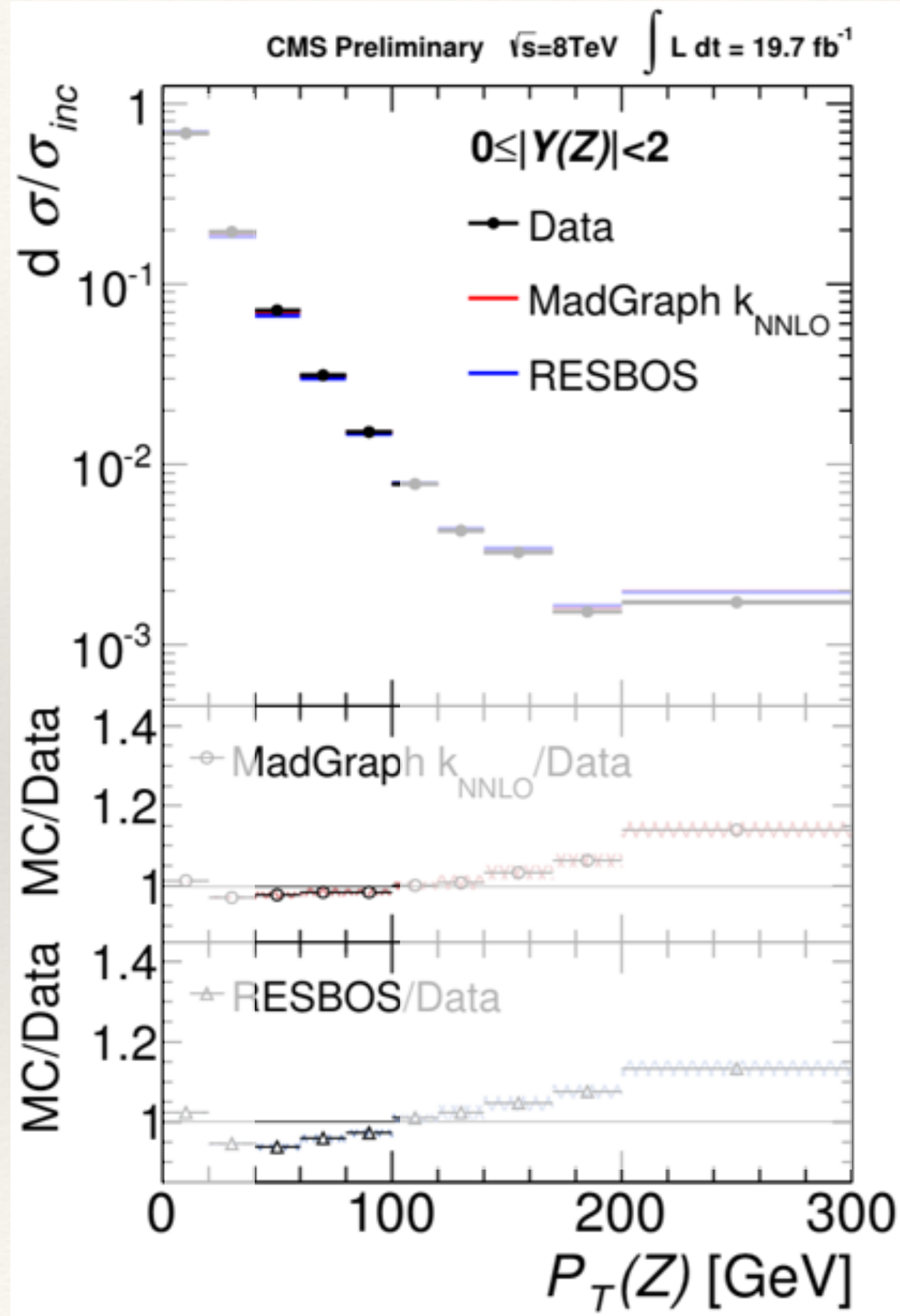


2-σ discrepancy in region where (N)NLO should be reliable

CMS doesn't compare to pure fixed-order (sees 5-7% discrepancy with RESBOS)

BDMT prediction looks 20% higher in same region: not clear why.





Z p_T mystery needs solving

The discrepancy feeds into other observables (e.g. jet dist^n in Z+jet events).

Is theory uncertainty badly underestimated? Will NNLO solve the problem? What's the real scope for resummation to modify distribution for p_T > 40 GeV?

Or are PDFs substantially wrong? (Z p_T is never an input; while much less precise incl. jets are an input – why?)

Do CMS and ATLAS data agree?

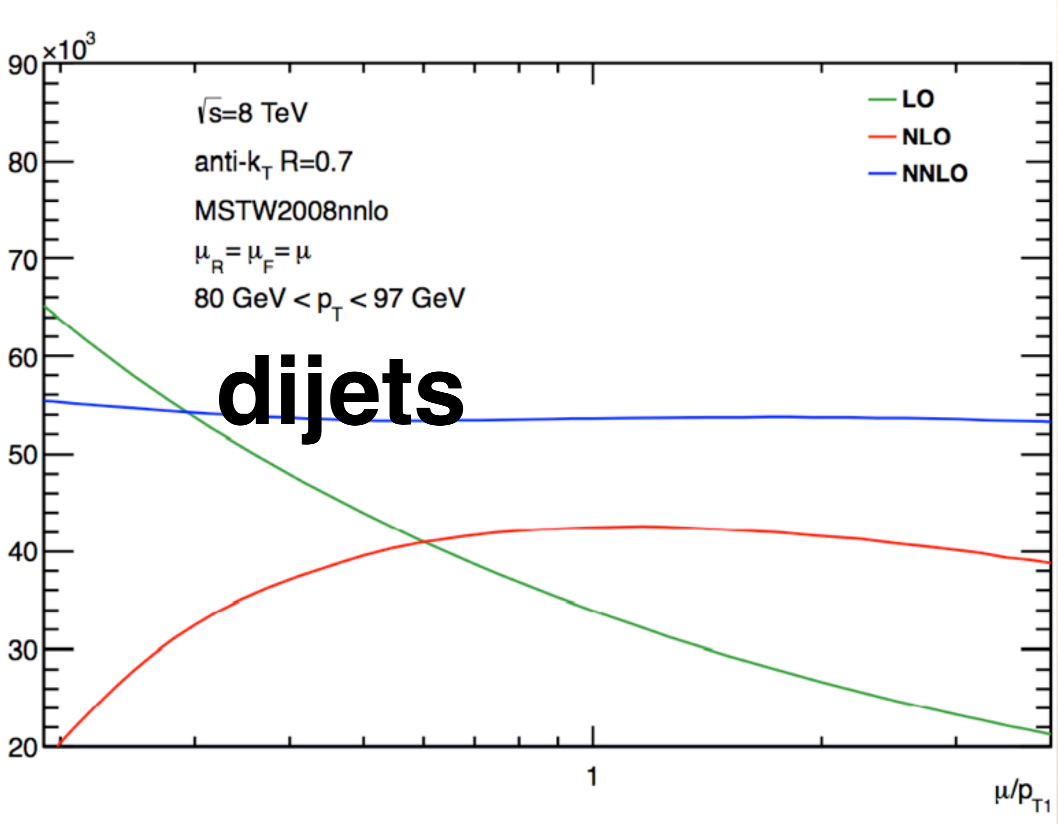
Scale Variation

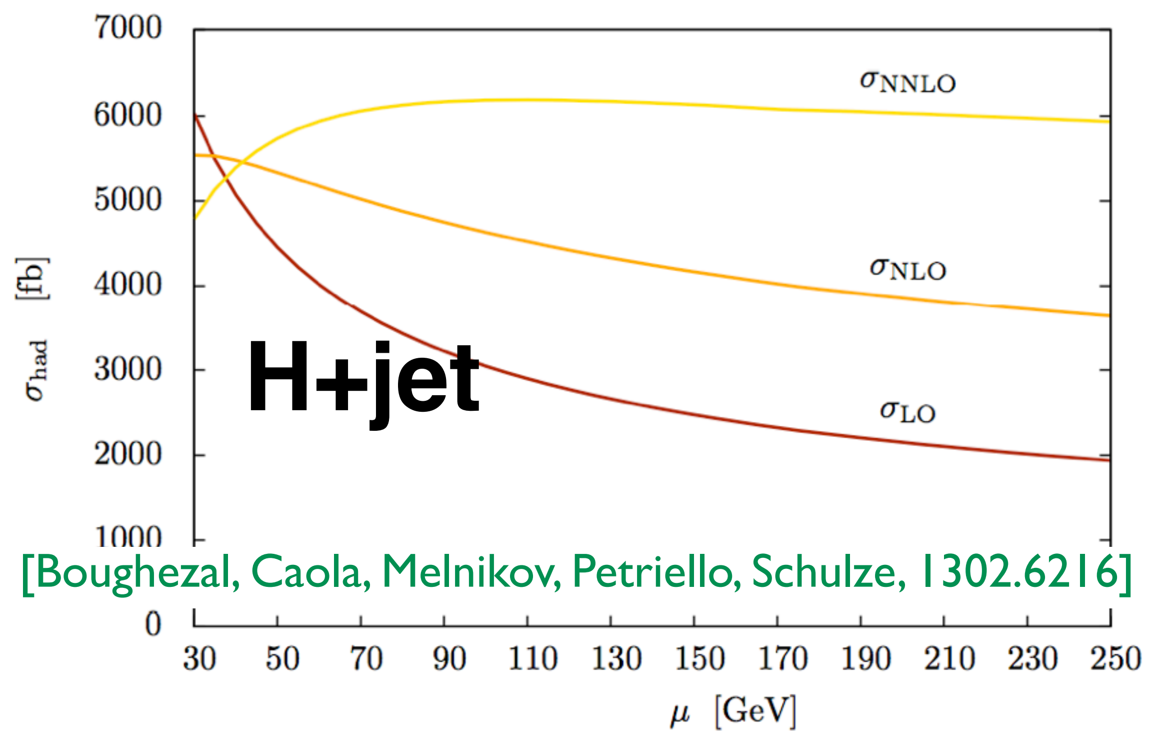
We have a **convention** – choose a central (possibly dynamical) scale, and calculate with x2 and x1/2 scale variations.

Reflects fact that physical scale choice is genuinely ambiguous and conveniently gives us an uncertainty estimate.

How reliable is scale variation?

[Gehrmann-De Ridder, Gehrmann, Glover, Pires, 1301.7310]





[Boughezal, Caola, Melnikov, Petriello, Schulze, 1302.6216]

There's no shortage of cases where (sometimes partial) NNLO is at or beyond edge of NLO scale variation

[Czakon, Fiedler & Mitov 1303.6254]

$t\bar{t}$ @ LHC8

$$\text{LO:} \quad 145^{+49}_{-34}\,\text{pb}$$

$$\text{NLO:} \quad 213^{+25}_{-27}\,\text{pb}$$

$$\text{NNLO:} \quad 239^{+9}_{-15}\,\text{pb}$$

top++, MSTW2008NNLO, $\mu = m_t$

Scale variation gives an uncertainty
But to what extent is it a measure of ***the*** uncertainty?

Toy model:

(1) Take a running coupling where

$\beta_0 = \beta_{0,QCD}$

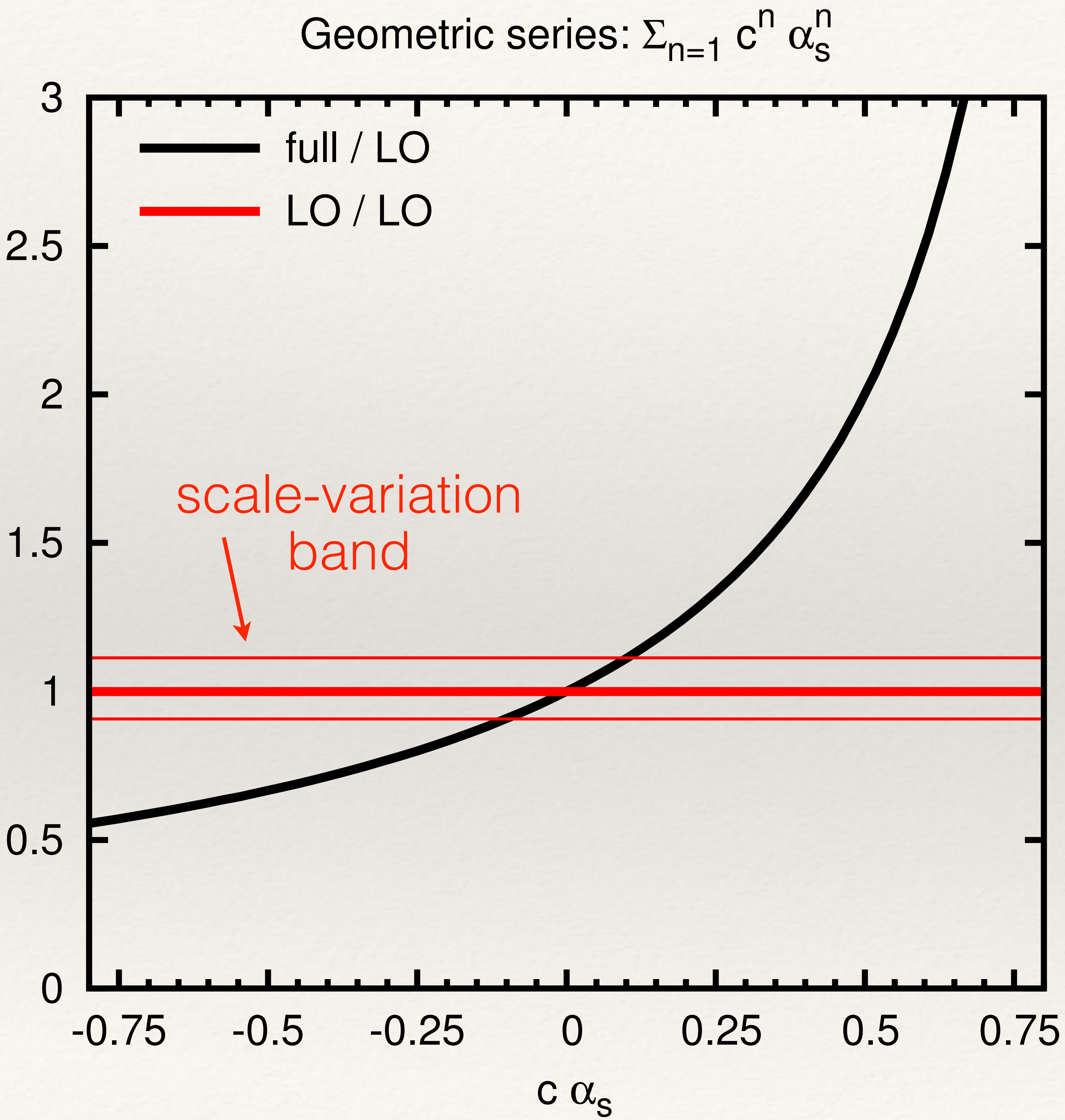
$\beta_1 = \beta_2 = \ldots = 0$

(2) Consider a simple perturbative series that you can sum to all orders. E.g.

$$\sigma = \frac{c\,\alpha_s(M)}{1 - c\alpha_s(M)} = c\,\alpha_s + c^2\alpha_s^2 + c^3\alpha_s^3 + \cdots$$

simplest possible series in QCD: corresponds to coupling at one scale expressed in terms of coupling at another (reference) scale M

Now examine truncations of series, as a function of c for $\alpha_s = 0.12$



LO: scale variation mostly useless.

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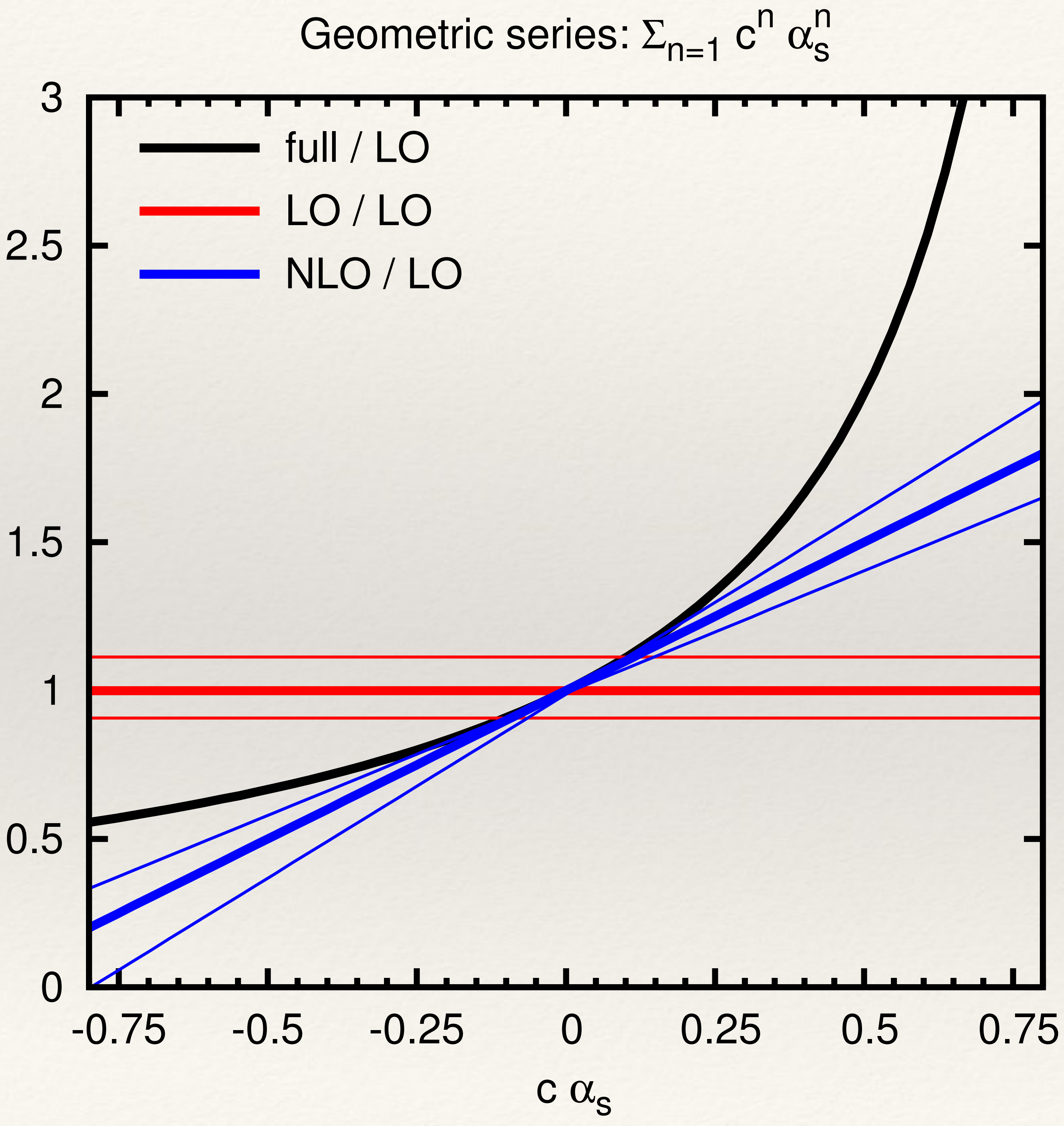

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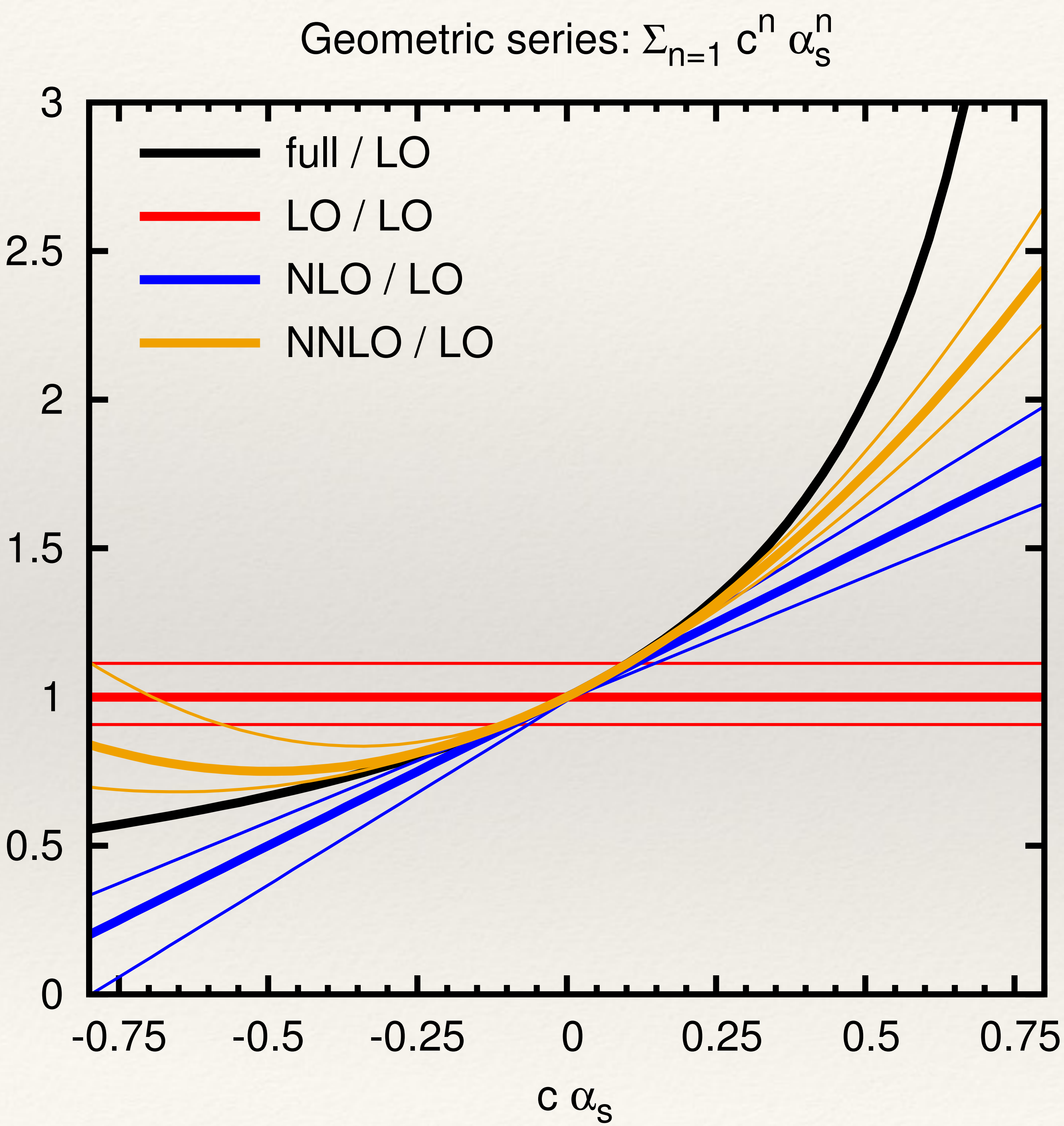

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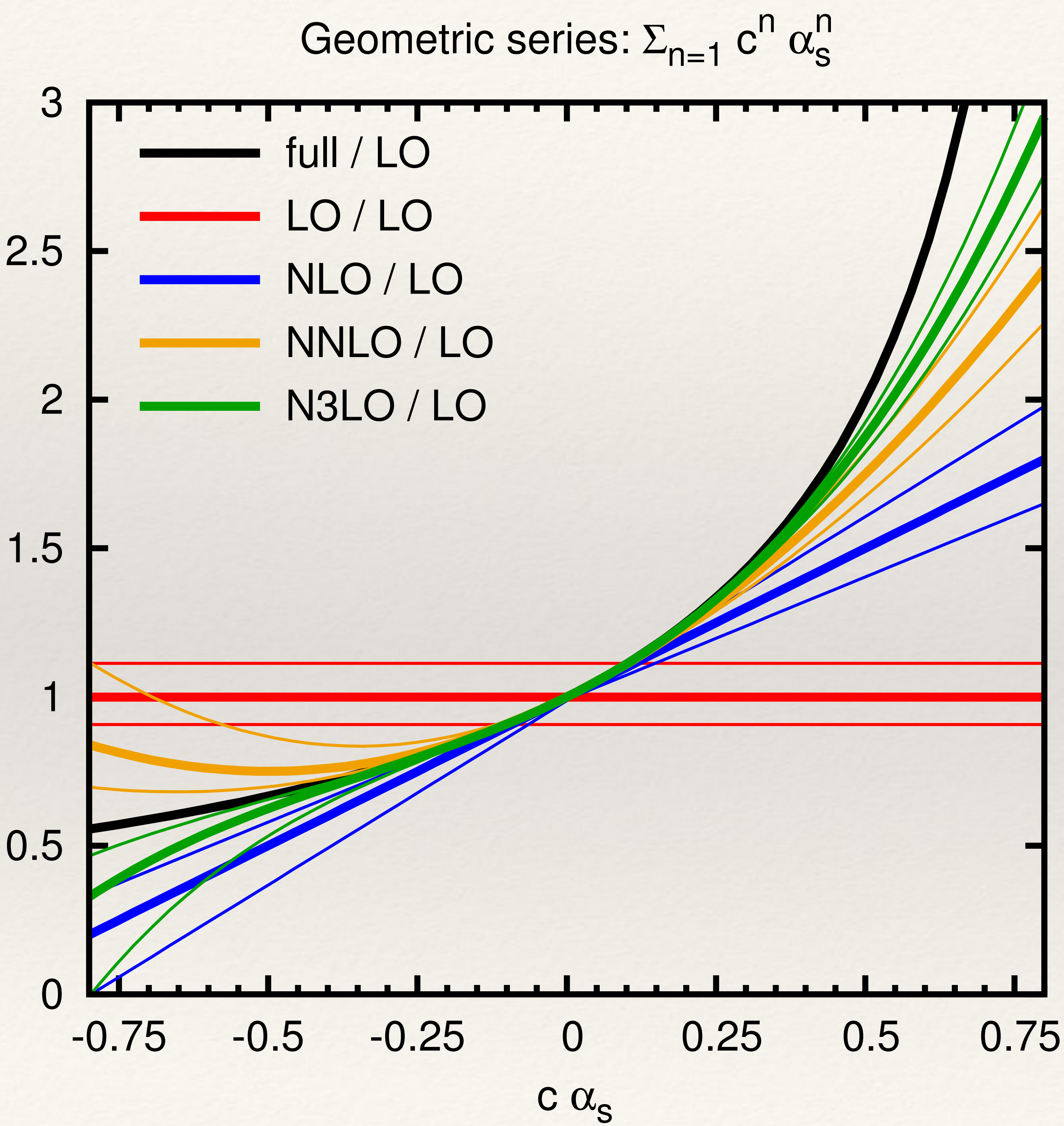

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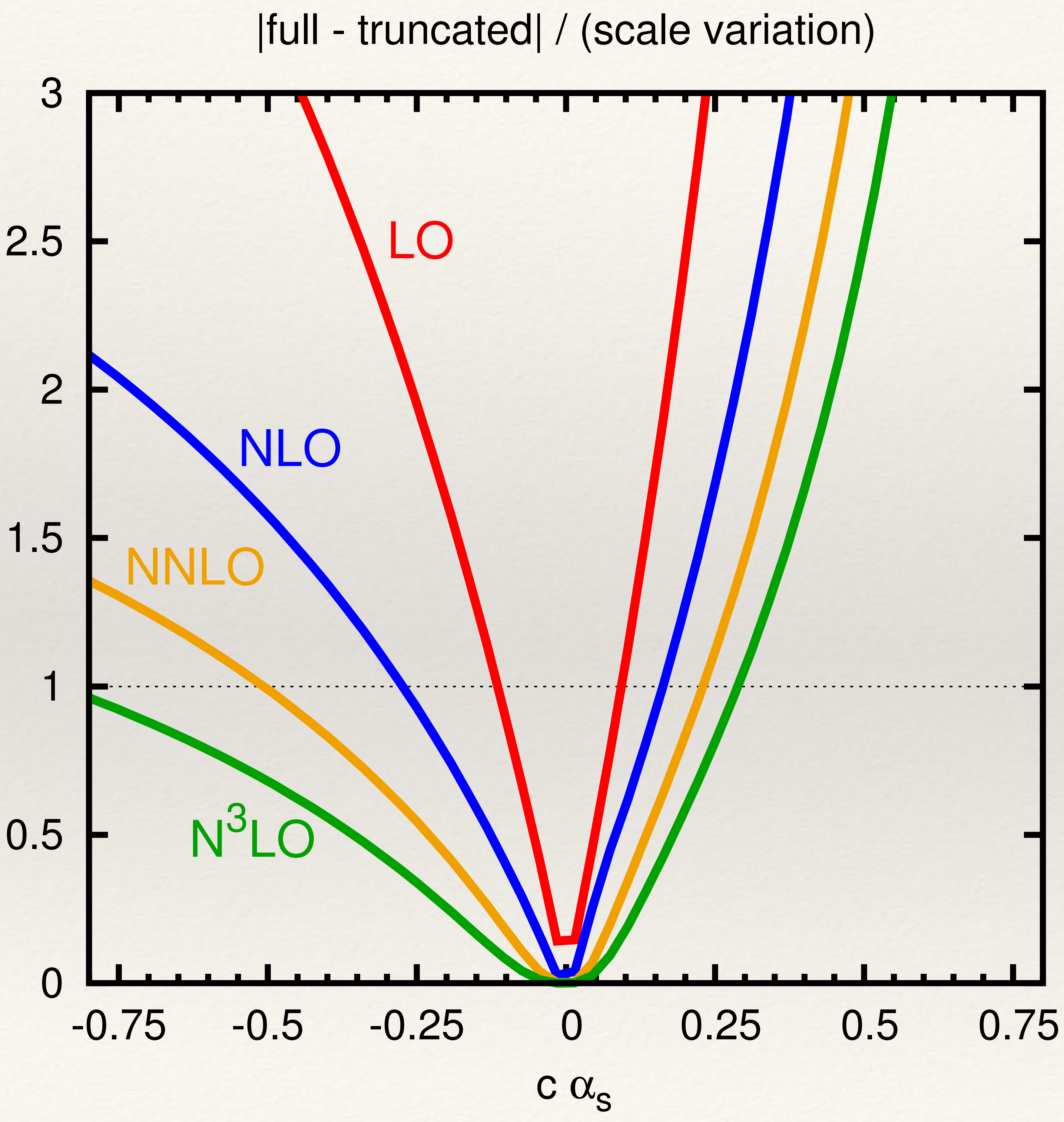

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$$\sigma = \sum_{n=1} (c\,\alpha_s)^n$$

Higgs $(\mu = m_H)$

$$\mathcal{N} \times (\alpha_s^2 + 11\alpha_s^3 + 62\alpha_s^4)$$

Normalised to LO, what's missing from N^{p}LO is:

$$\sim c^{p+1}\alpha_s^{p+1}$$

Scale var^n (c » 1) gives:

$$\sim (p+1)\cdot c^p \alpha_s^{p+1} \quad *$$

Ratio scale uncertainty/ true missing higher orders:

$$\sim \frac{p+1}{c}$$

*coefficient is $\frac{23}{6\pi}\ln 2 \simeq 0.85$

For poorly converging series (c » 1), scale variation **parametrically** underestimates the uncertainty.

At higher orders (≡ for larger p) scale variation works further, but for large enough c inevitably breaks down

Other approaches?

Cacciari-Houdeau tries to get a prob. distribution for uncertainty; but shares limitations with scale variation (cannot detect large geometric growth of series)

David–Passarino: attempts "series acceleration" — does detect coefficient growth, though arguably fairly complicated

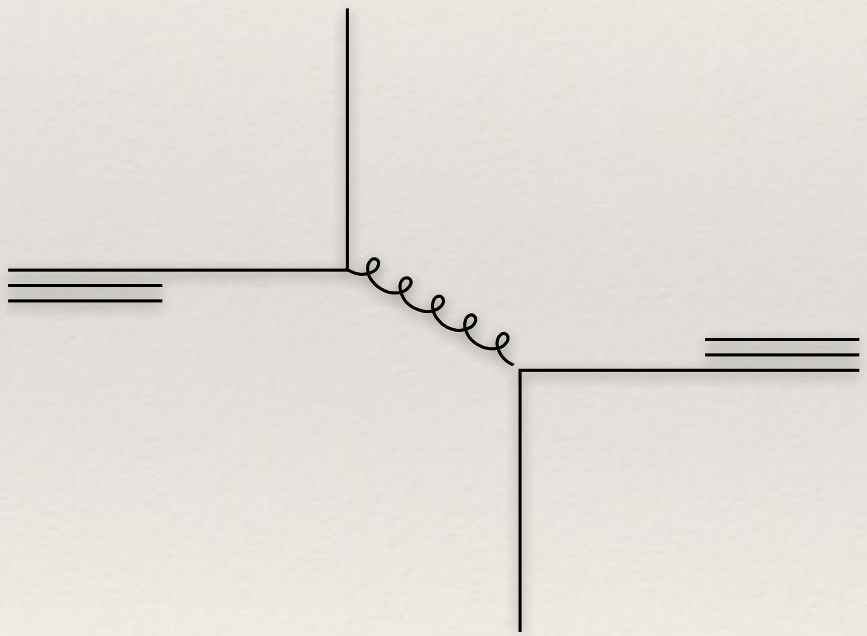
MINLO: tries to solve a different problem, i.e. scale & Sudakov setting in multi-scale problems; uncertainty is somehow a separate problem

Summary on scale variation

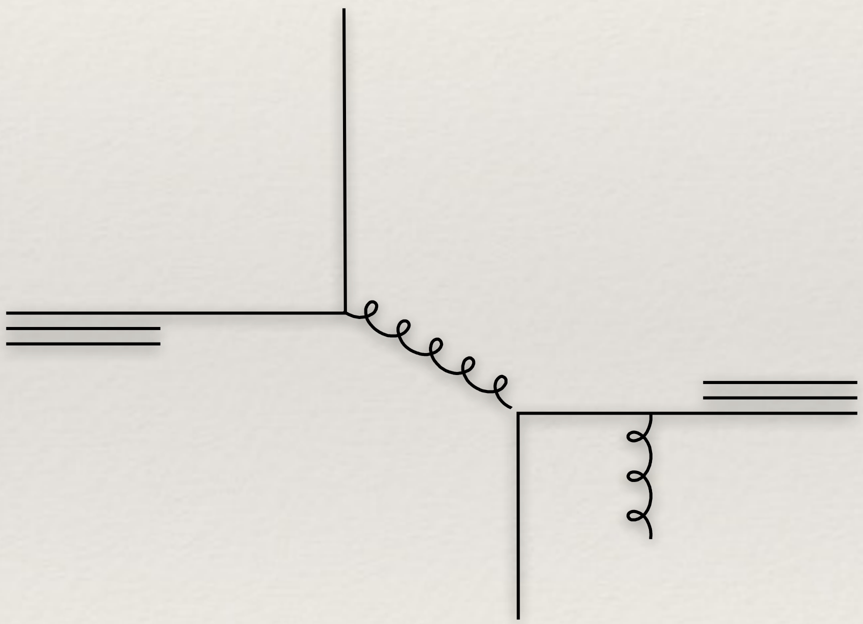
- Choice of scale is a genuine ambiguity
- But size of scale variation knows little about physics, only about coefficients of the series
- Scale variation doesn't correctly handle case when coefficients grow large.

Can one do better? Possibly, e.g. by supplementing scale variation uncertainties with information on growth of coefficients (à la David—Passarino, maybe with simplifications)

(A)Symmetric cuts



LO dijet/digamma/etc. configurations are symmetric



But symmetry broken even by tiny amount of ISR

Mathematical illustration

Hard 2→2 cross section: $\sigma_0(p_t) \sim \frac{1}{p_t^n} \quad [n \sim 5 \gg 1]$

NLO with symmetric cuts: $\sigma_{\text{sym-cut}}(p_t) \sim$
($p_{t1}, p_{t2} > pt$) $\sigma_0(p_t)(1 - \alpha_s \ln^2 n)$

[Due to ISR, which imbalances the event]

Large double-log is considered dangerous, so symmetric cuts are widely deprecated. [Frixione-Ridolfi '97]

Asymmetric cuts

$p_{t1} > p_t \qquad p_{t2} > (1-\varepsilon)\, p_t$

ε=0: equivalent to symmetric cuts

$$\sigma_{\text{sym-cut}}(p_t) \sim \sigma_0(p_t)(1 - \alpha_s \ln^2 n)$$

Take **ε ~ 0.5**, i.e. cut mostly on hardest jet

$$\sigma_{p_{t1}\text{-cut}}(p_t) \sim \sigma_0(p_t)(1 + \alpha_s \ln^2 n)$$

[schematically...]

Take **ε ~ 0.1—0.2**, i.e. standard asym. cut

$$\sigma_{\epsilon}(p_t) \sim \sigma_0(p_t)(1 + \alpha_s f(n, \epsilon))$$

Asymmetric cuts just make a bad problem more complex

A possible solution?

$$\tfrac{1}{2}(p_{t1} + p_{t2}) \equiv \tfrac{1}{2}H_{T2} > p_t\,, \qquad p_{t2} > (1-\epsilon)p_{t1}$$

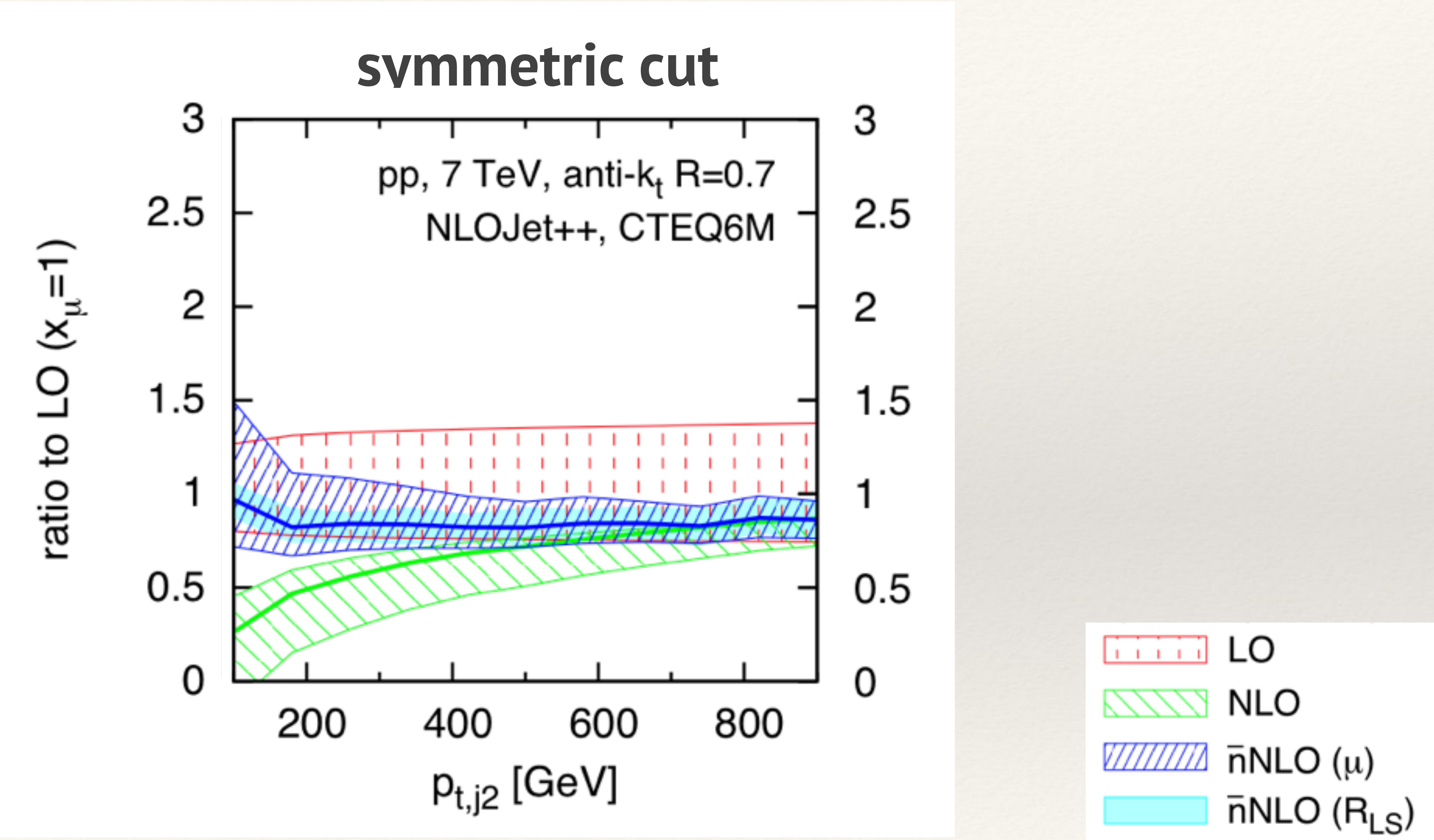
ISR of momentum $p_{t,ISR}$ leaves H_{T2} almost unchanged

$$\tfrac{1}{2}H_{T2} \to \tfrac{1}{2}H_{T2} + \mathcal{O}\left(\frac{p_{t,ISR}^2}{H_T}\right)$$

because impact of ISR mostly balances in jets 1 and 2.

If ε is moderate, e.g. ε = 0.5, perturbation theory should be well behaved (no large logs of *n* or of ε)

Performance?



Rubin, GPS & Sapeta '10 [LoopSim nNLO]

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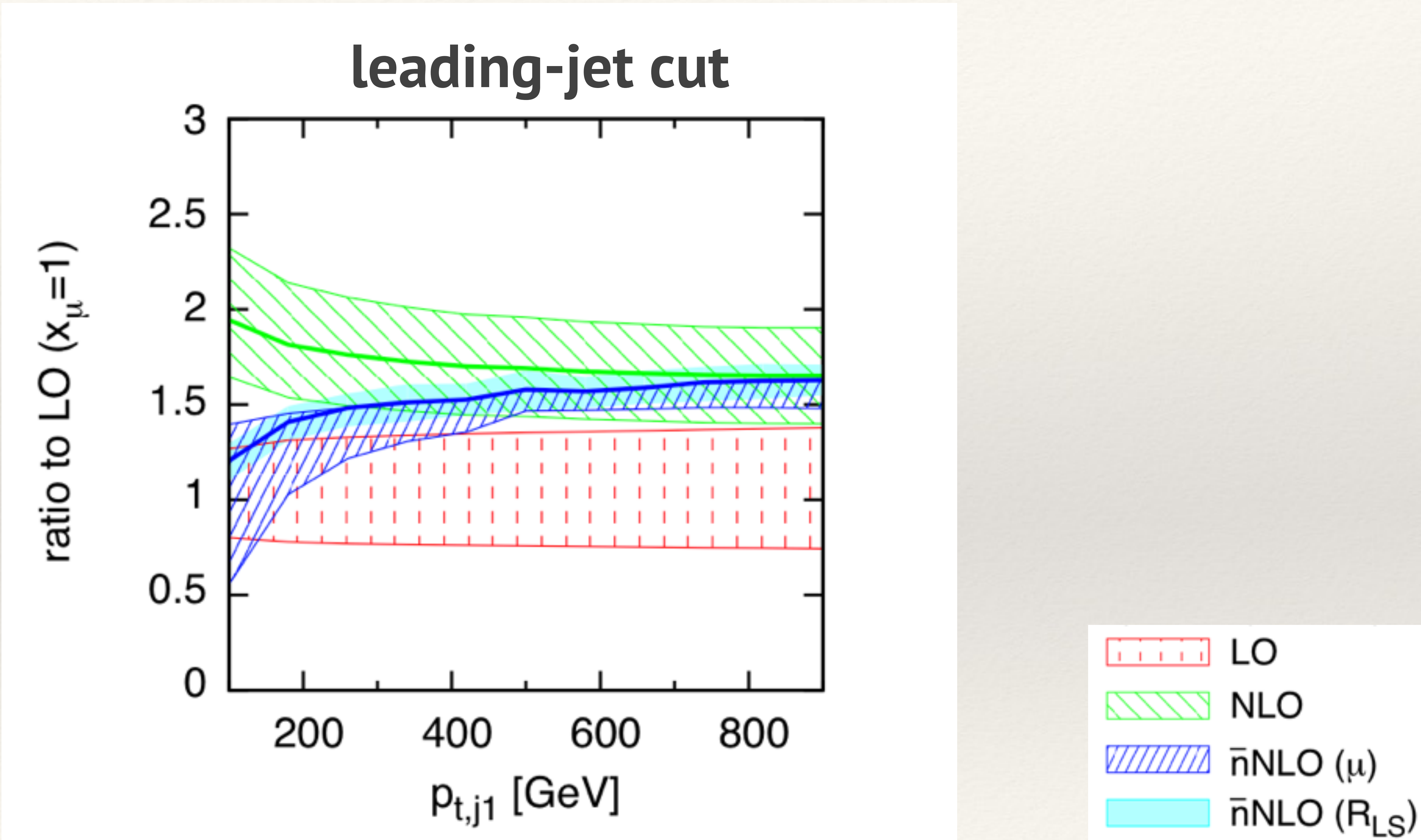

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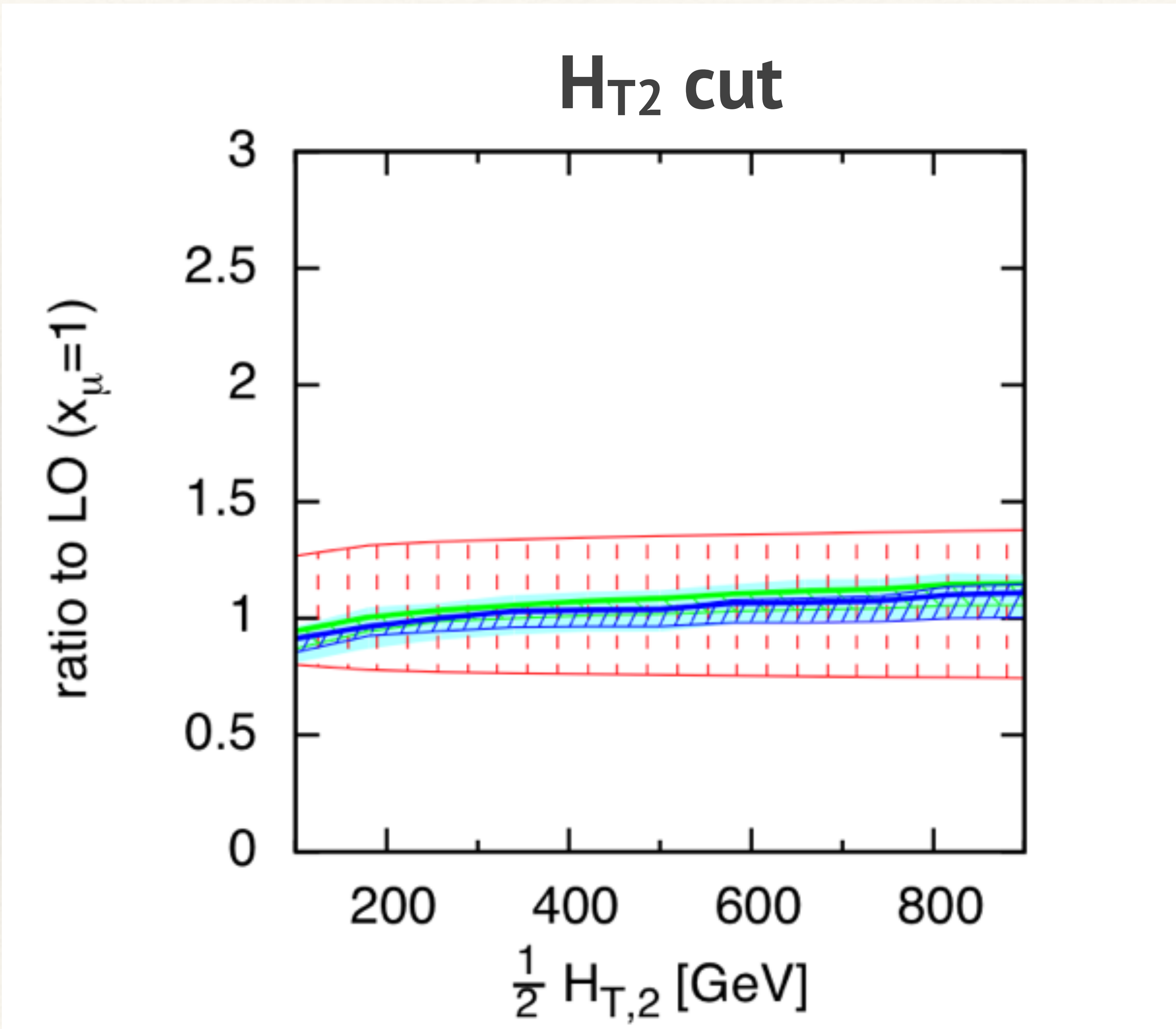
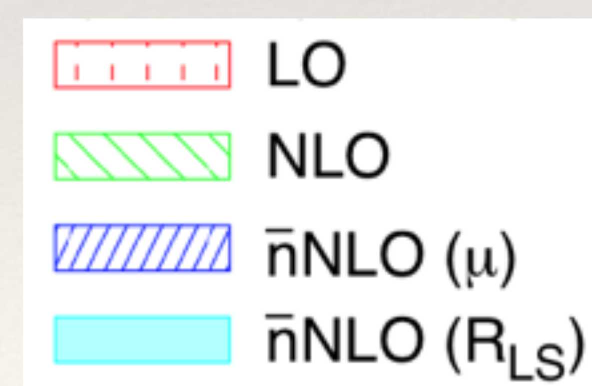




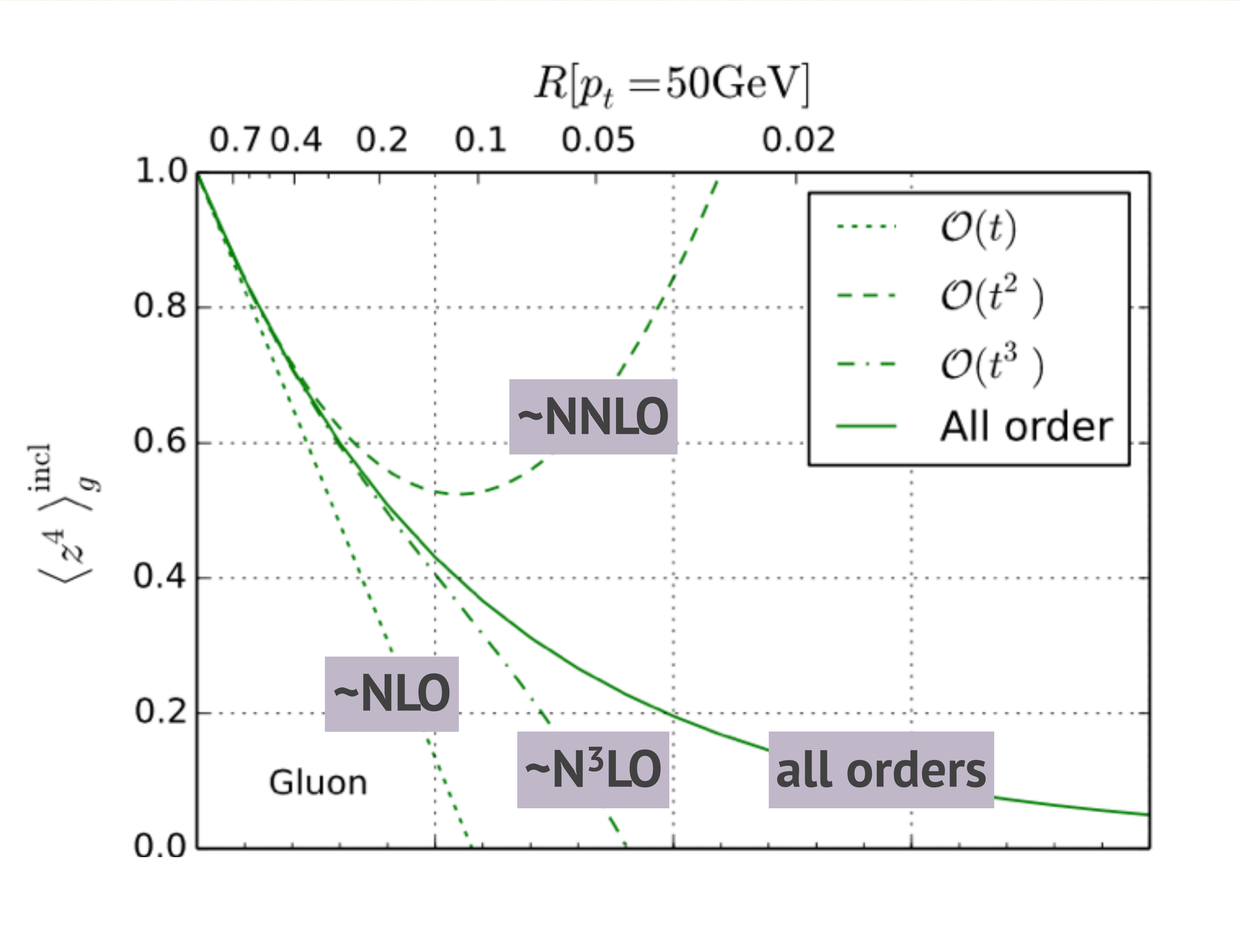
Asymmetric cuts summary

- Asymmetric cuts fine tune cancellation between two different physical effects (interplay of ISR with steeply falling cross section, and logs of ε)
- That's dangerous.
- **Self-balancing cuts,** e.g. on $\mathbf{H_{T2}}$, appear to do better based both on analytic considerations and (n)NLO convergence (also from some simple Pythia studies with ISR turned on/off)

Small jet radii — how small?

- Heavy-ion physics regularly uses small R (e.g. 0.2)
- Small R can be useful in pp to reject pileup jets (e.g. for VBF, where tracking not accessible for forward jets)
- I think it's interesting to explore R as small as experimentally possible
- New calculations give us insight into what happens perturbatively at small R. [Dasgupta, Dreyer, GPS Soyez '14]

Small-R corrections for gluon-induced part of inclusive spectrum

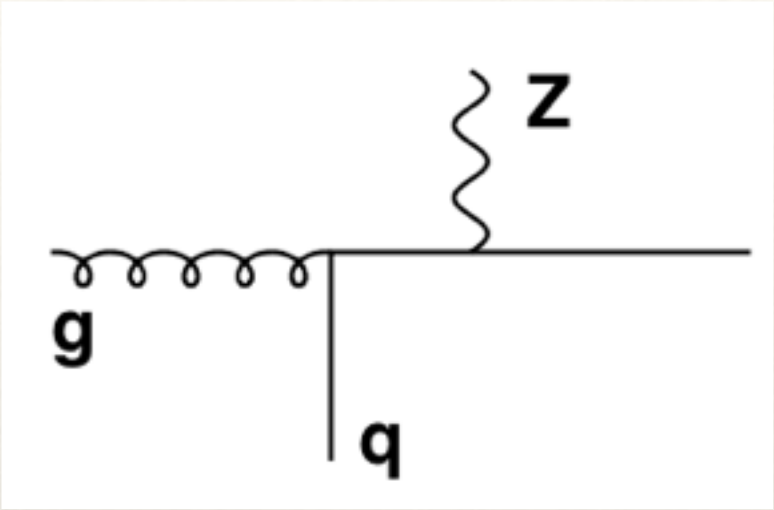


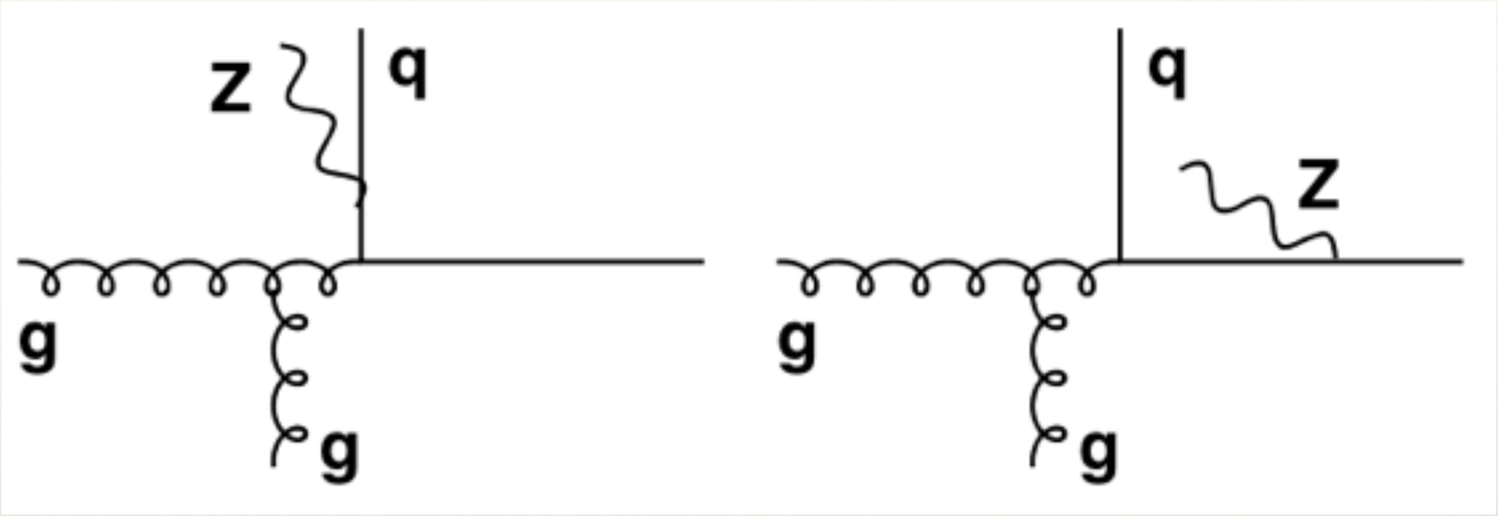
Suggests that NLO *may* be insufficient for R=0.4 (cf. caveats)

But all-order small-R effects can be resummed

Detailed pheno to follow

New physical effects





LO Z+jet topology

Dominates if bin in Z p_T

new NLO Z+jet topologies

Dominate if bin in leading jet p_T
Z effectively a light degree of freedom (restoring EW symmetry)

It would be fun to demonstrate dominance of these topologies at high p_T

Conclusions

- Z p_T distribution is important; deserves dedicated effort to resolve TH-EXP discrepancies (e.g. ATLAS-CMS, understanding different theory calculations, etc.)
- Scale variation is guaranteed to fail for some observables; arguably needs to be supplemented with other info from perturbative series
- Making series look better always helps: asymmetric cuts is one area that needs revisiting
- Exploring new phase space (small-R, "light" EW bosons) is interesting in its own right

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