HIGGS AT HL-LHC THEORY INTRO

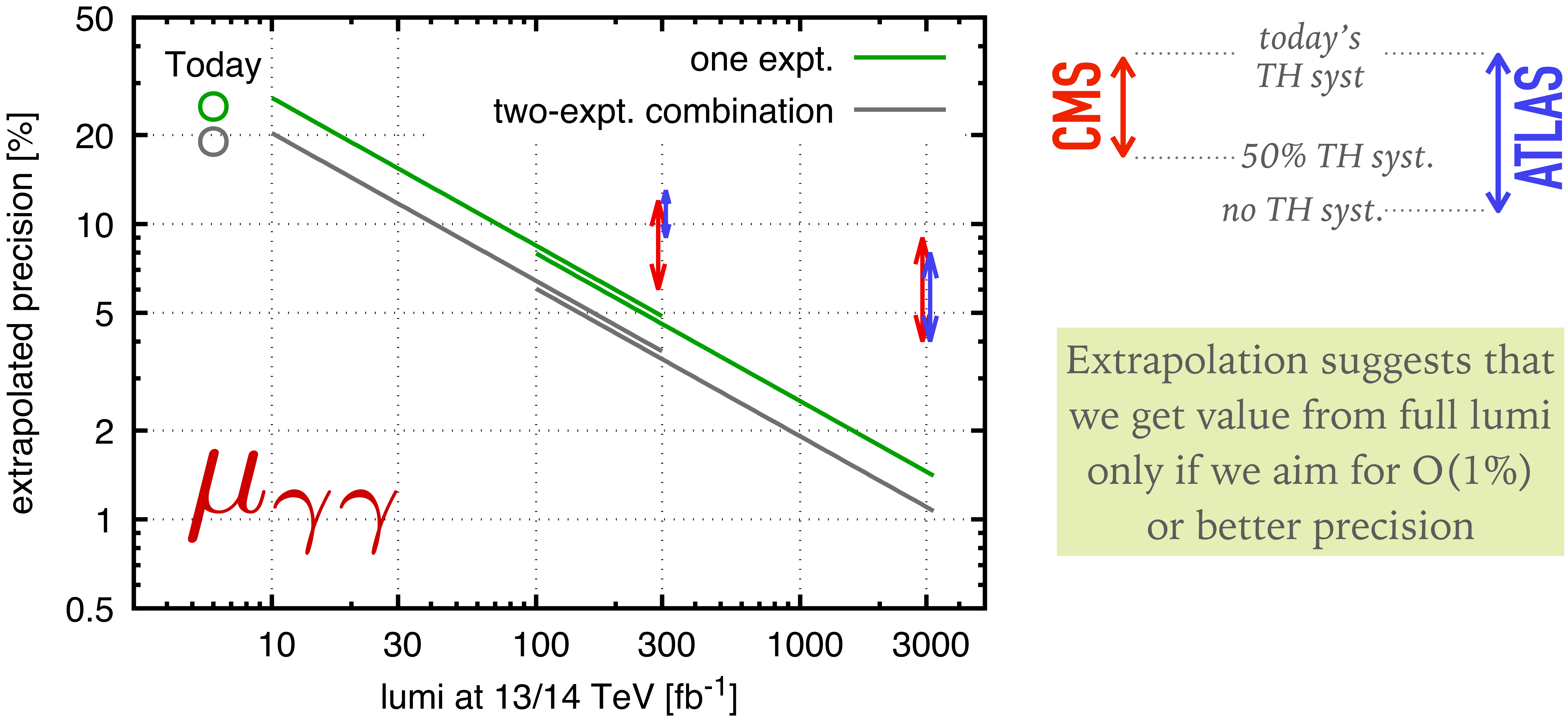
Gavin Salam, CERN

Higgs at HL-LHC, preparatory meeting for HL-LHC workshop at Aix-les-Bains

31 May 2016, CERN

what precision should we have as a target?

NAIVELY EXTRAPOLATE 7+8 TEV RESULTS (based on lumi and σ)



Extrapolation suggests that we get value from full lumi only if we aim for O(1%) or better precision

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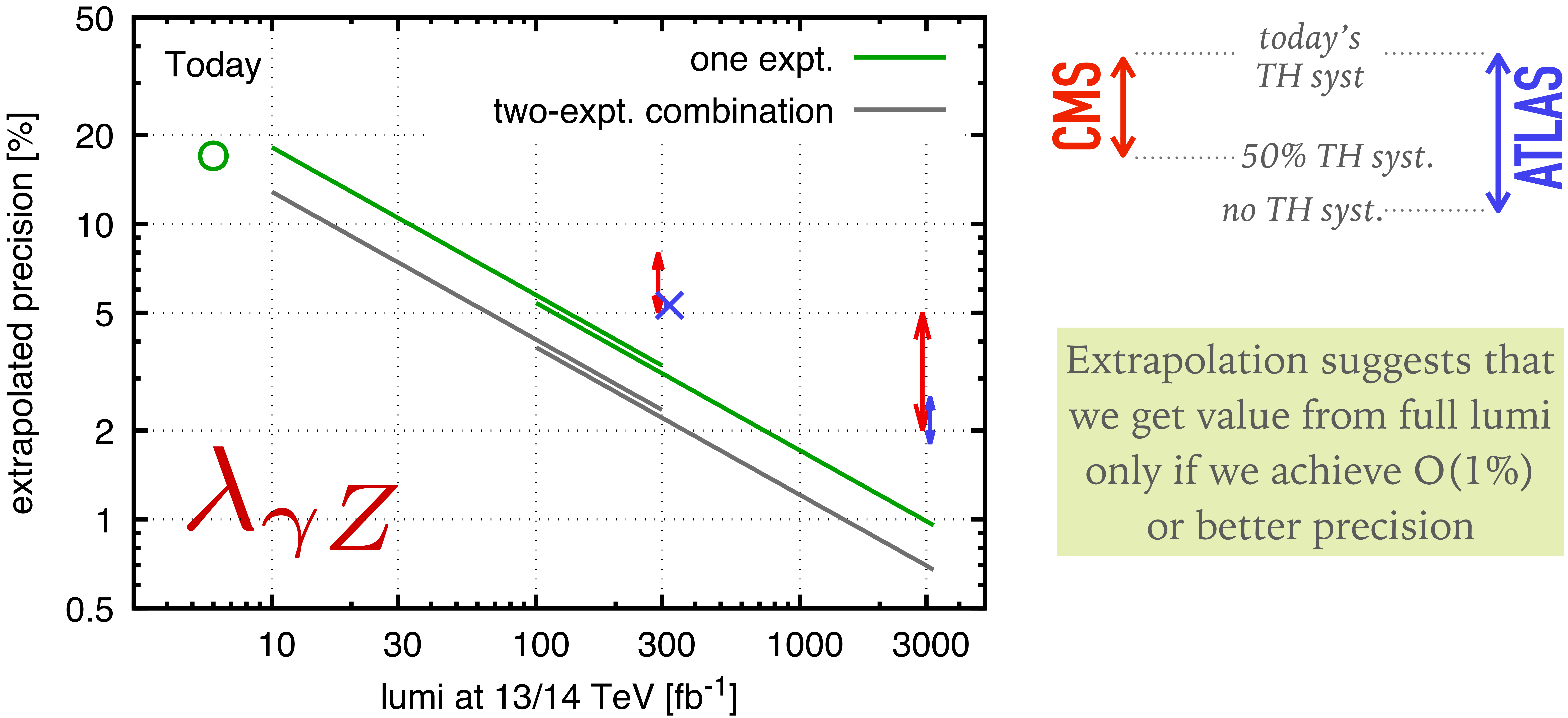

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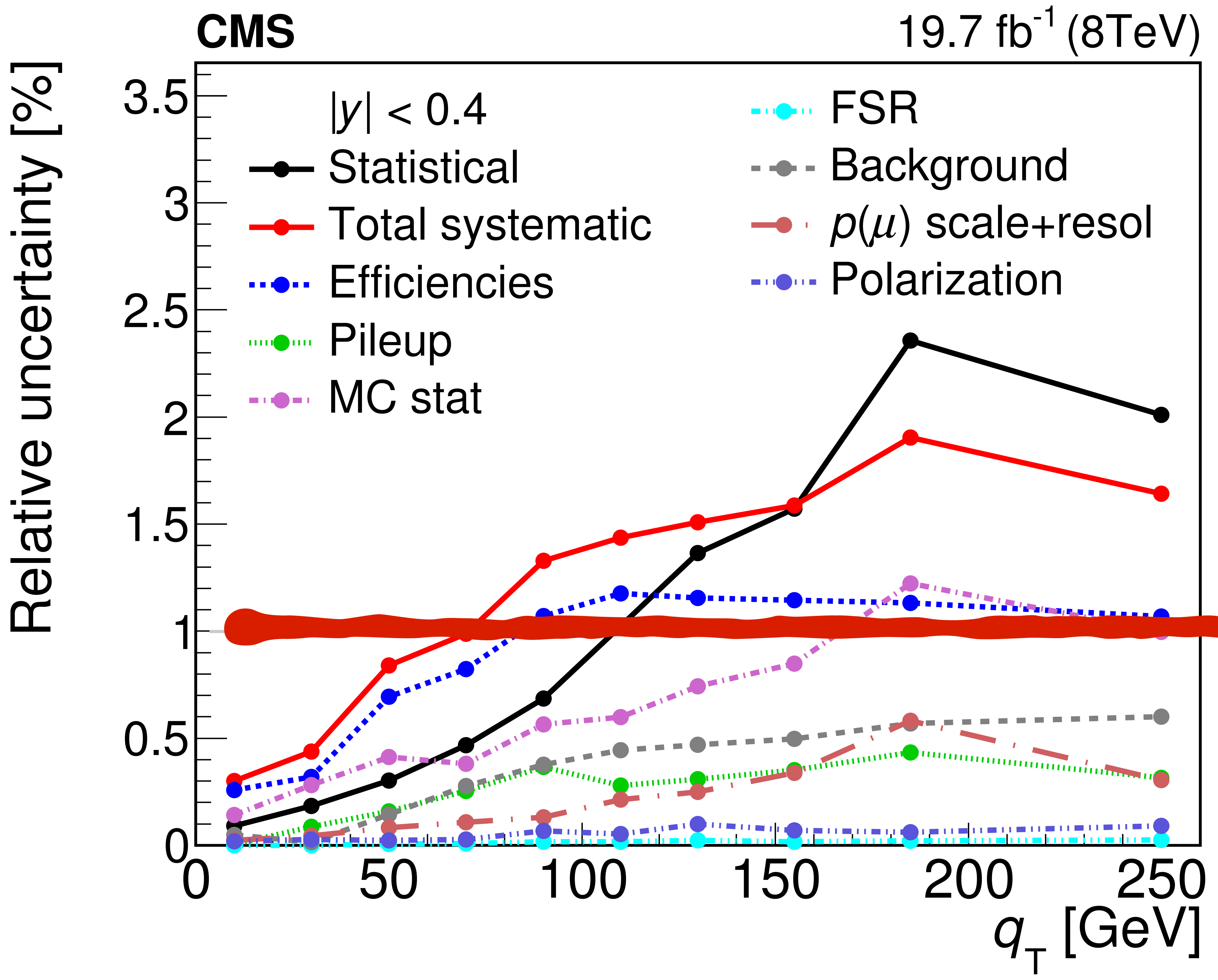
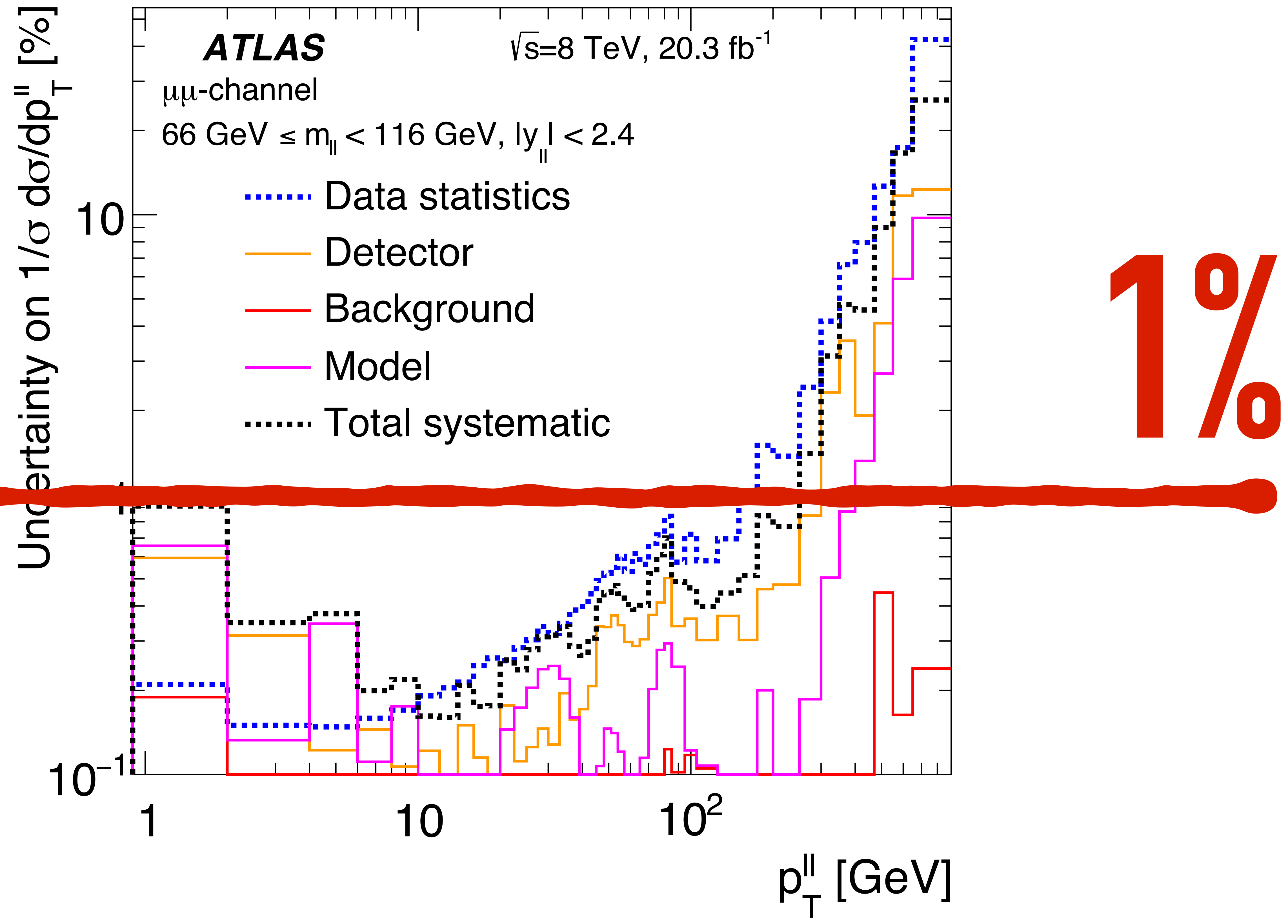
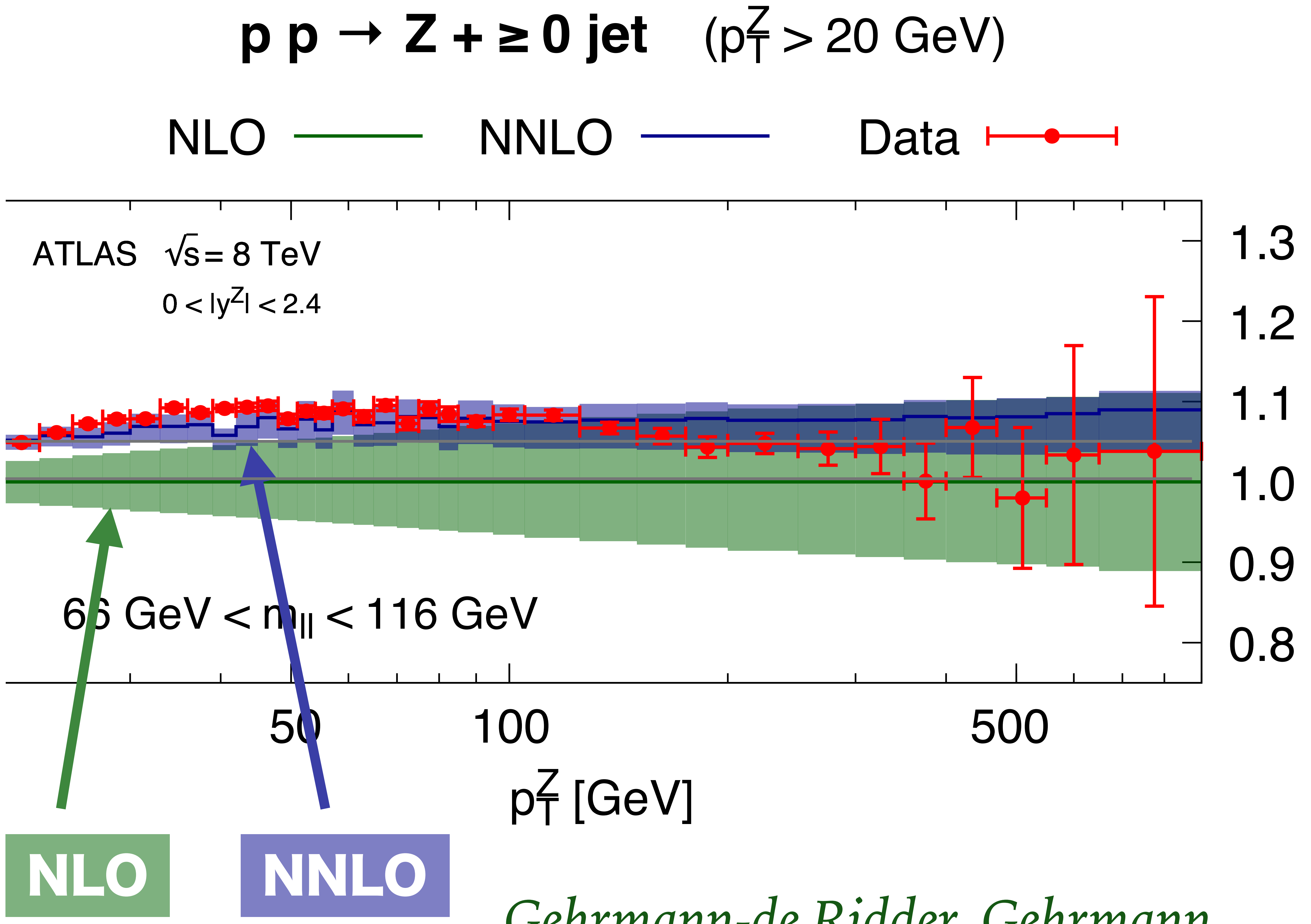
is 1% possible
at a hadron collider?

Z pT: run 1 measurement has already reached 0.5–1% !



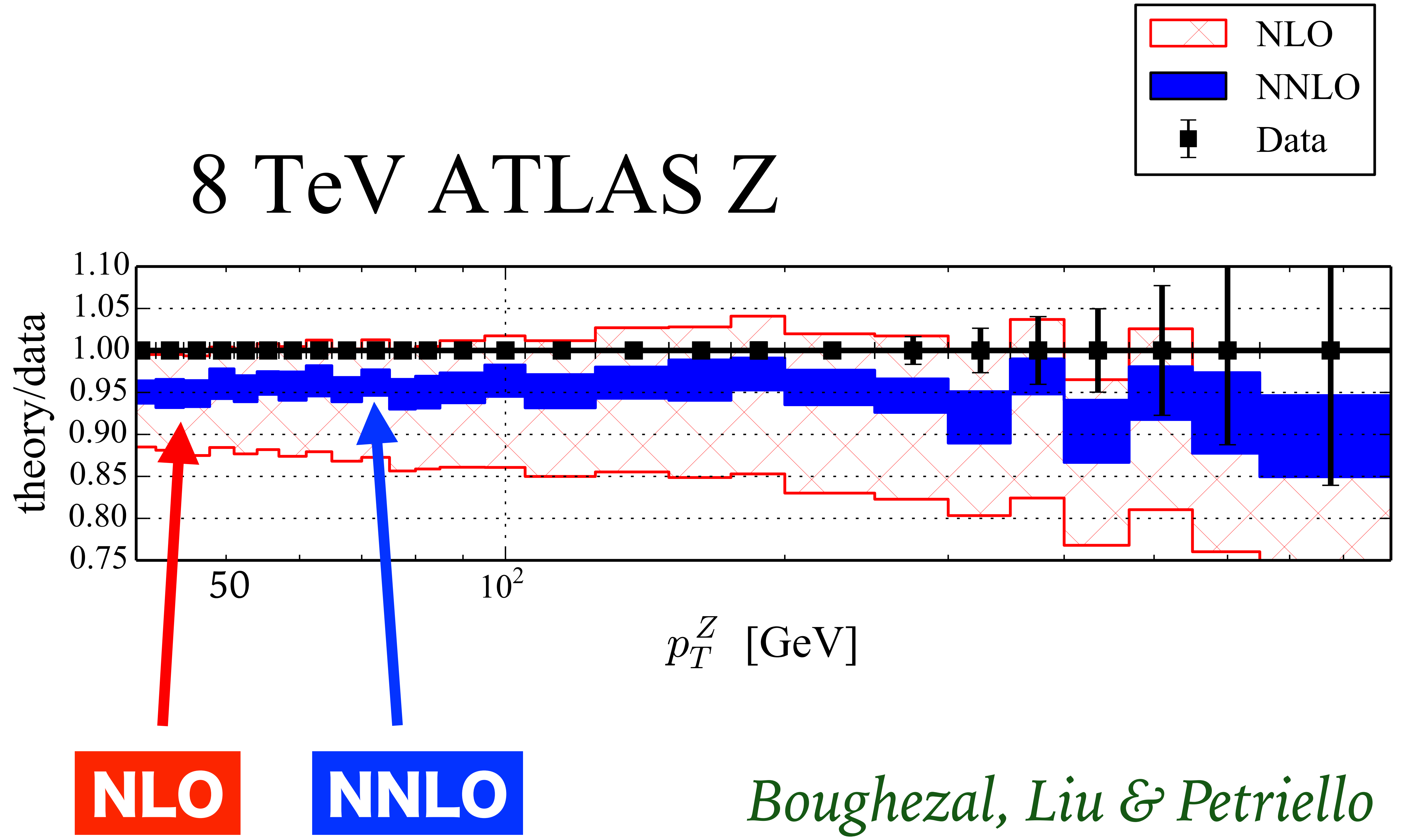


Z p_T: Data v. two theory calculations



Gehrmann-de Ridder, Gehrmann Glover, Huss & Morgan

arXiv:1605.04295



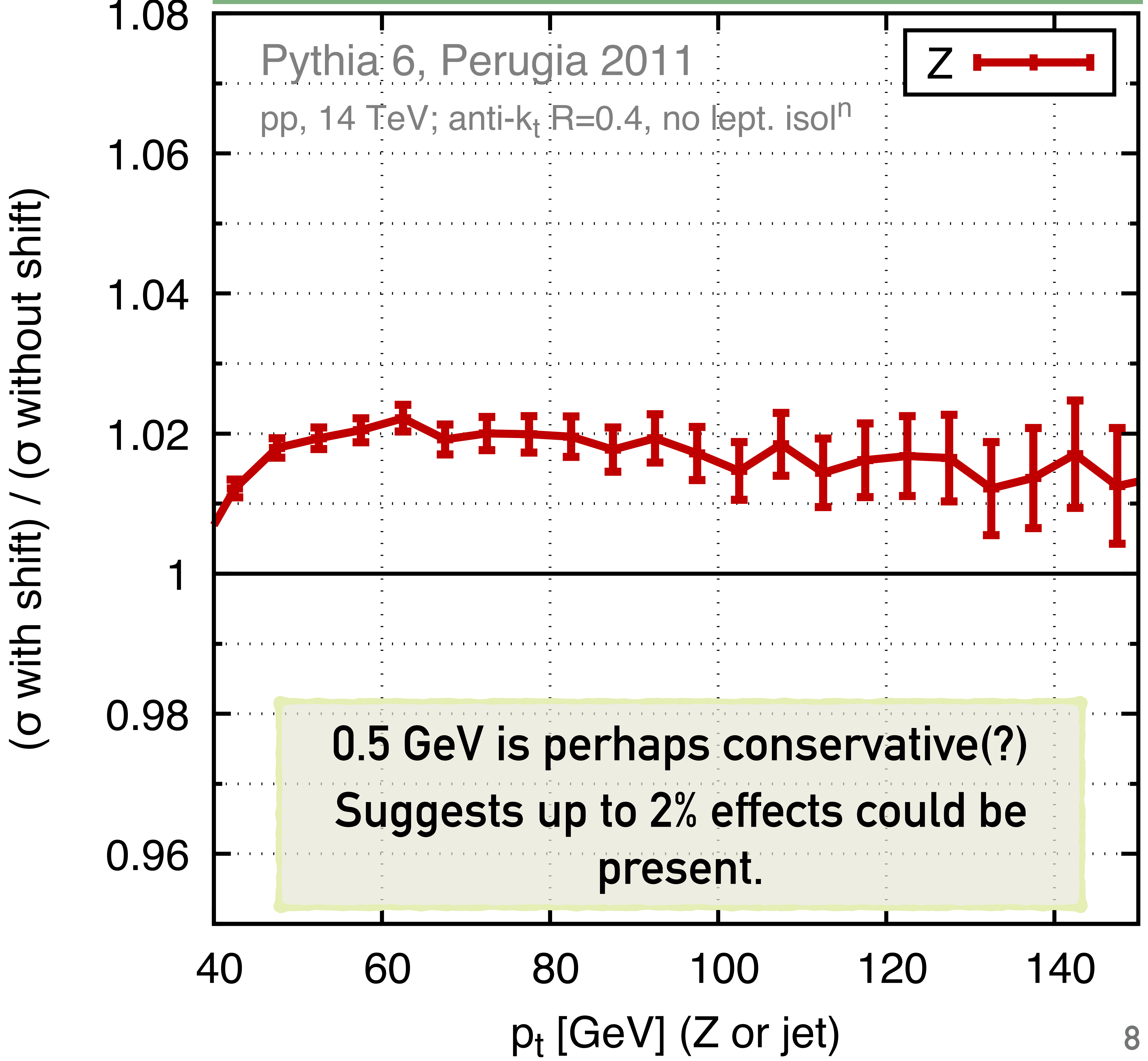
Boughezal, Liu & Petriello '16 preliminary (including EW corr.)

NNLO ~ ±1.5 %

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

impact of 0.5 GeV shift of Z p_T



recent higgs theory progress

take gluon fusion as main example

GLUON-FUSION (13 TEV)

LHC HXSWG Yellow Report 3 (2013, NNLO)

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	+(PDF+α_s) %	-(PDF+α_s) %
125.0	43.92	+7.4	-7.9	+7.1	-6.0

$$\sigma = 48.58\,\mathrm{pb}^{+2.22\,\mathrm{pb}\,(+4.56\%)}_{-3.27\,\mathrm{pb}\,(-6.72\%)}\;(\mathrm{theory}) \pm 1.56\,\mathrm{pb}\,(3.20\%)\;(\mathrm{PDF}+\alpha_s)\,.$$

Anastasiou et al., (1602.00695, N3LO)

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CMS scenario 2 (reduction by 50%) already achieved!

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+11% from scale choice, PDFs, N3LO, …

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almost no reduction in uncertainty?!

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GLUON-FUSION (13 TEV)

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$\delta(\text{scale})$	$\delta(\text{trunc})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\ \text{pb}}_{-1.15\ \text{pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

added linearly $^{+4.6\%}_{-6.7\%}$

added in quadrature $^{+2.1\%}_{-3.1\%}$

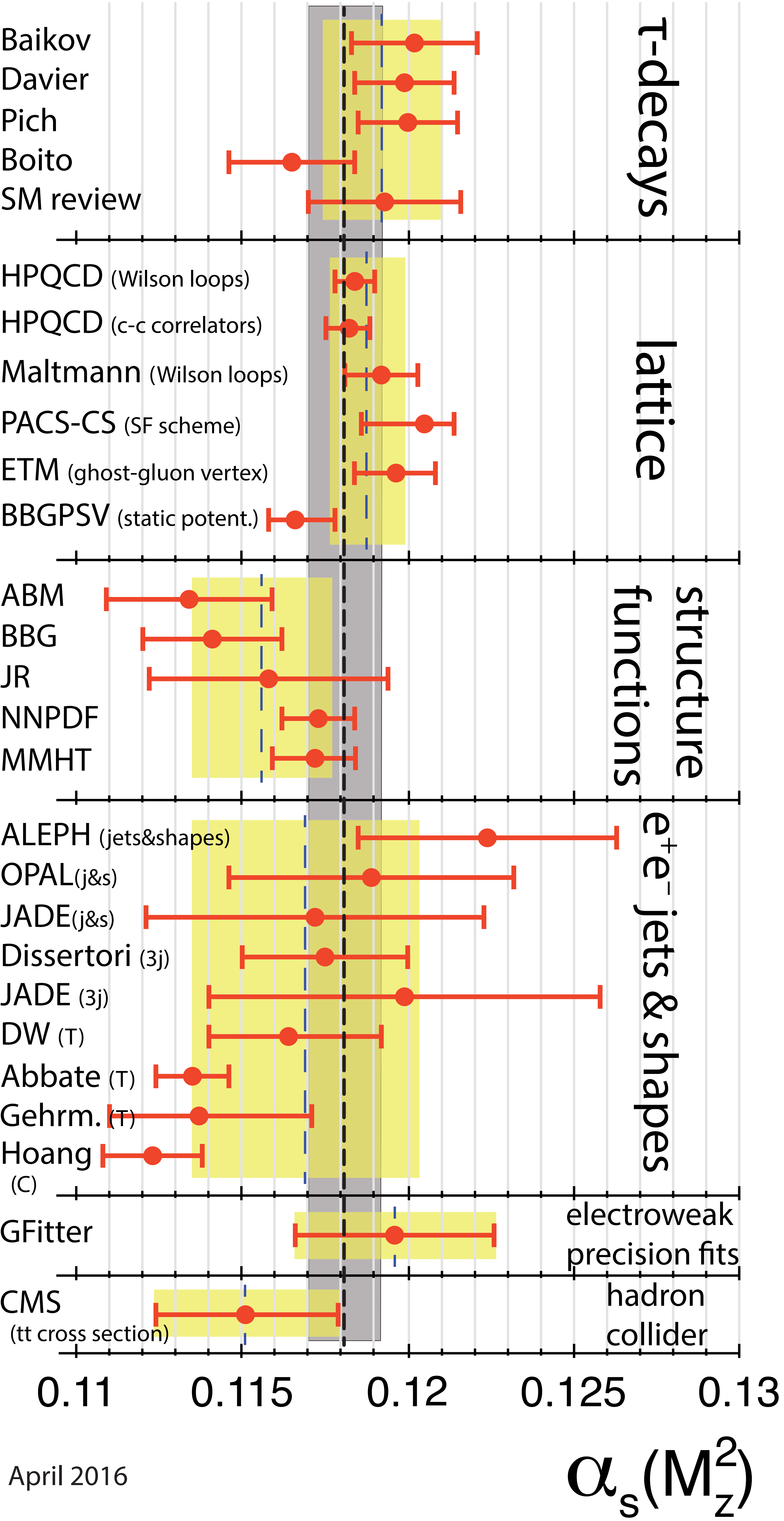
improvement needs N4LO (or new insight) i.e. unlikely to get better in next decade

progress requires N3LO PDF fits (may be possible in next years?)

likely to improve with new calculations in next years?

the inputs

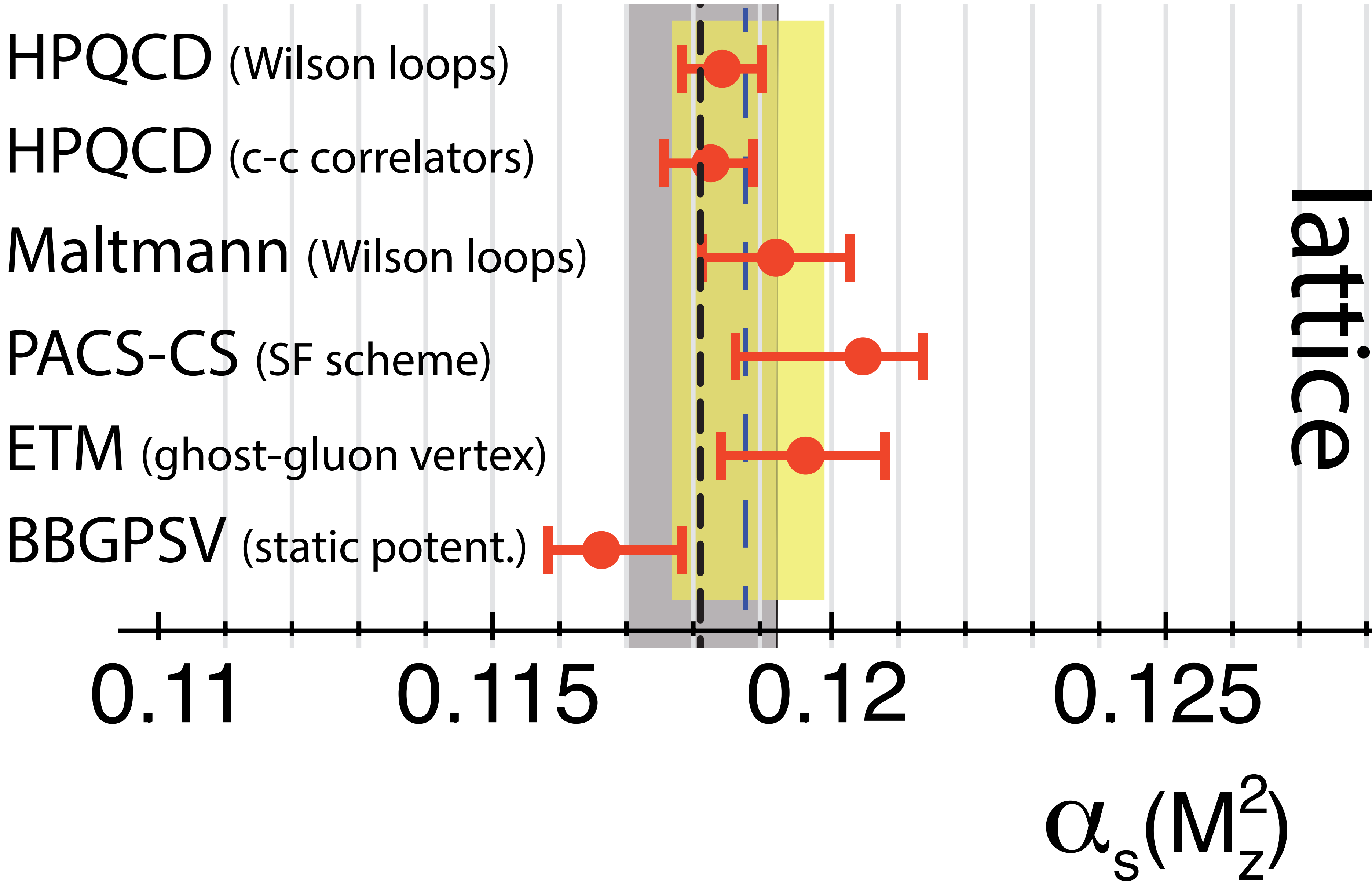
strong coupling (e.g. ±2.6% on ggF)
PDFs (e.g. ±1.9% on ggF)



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

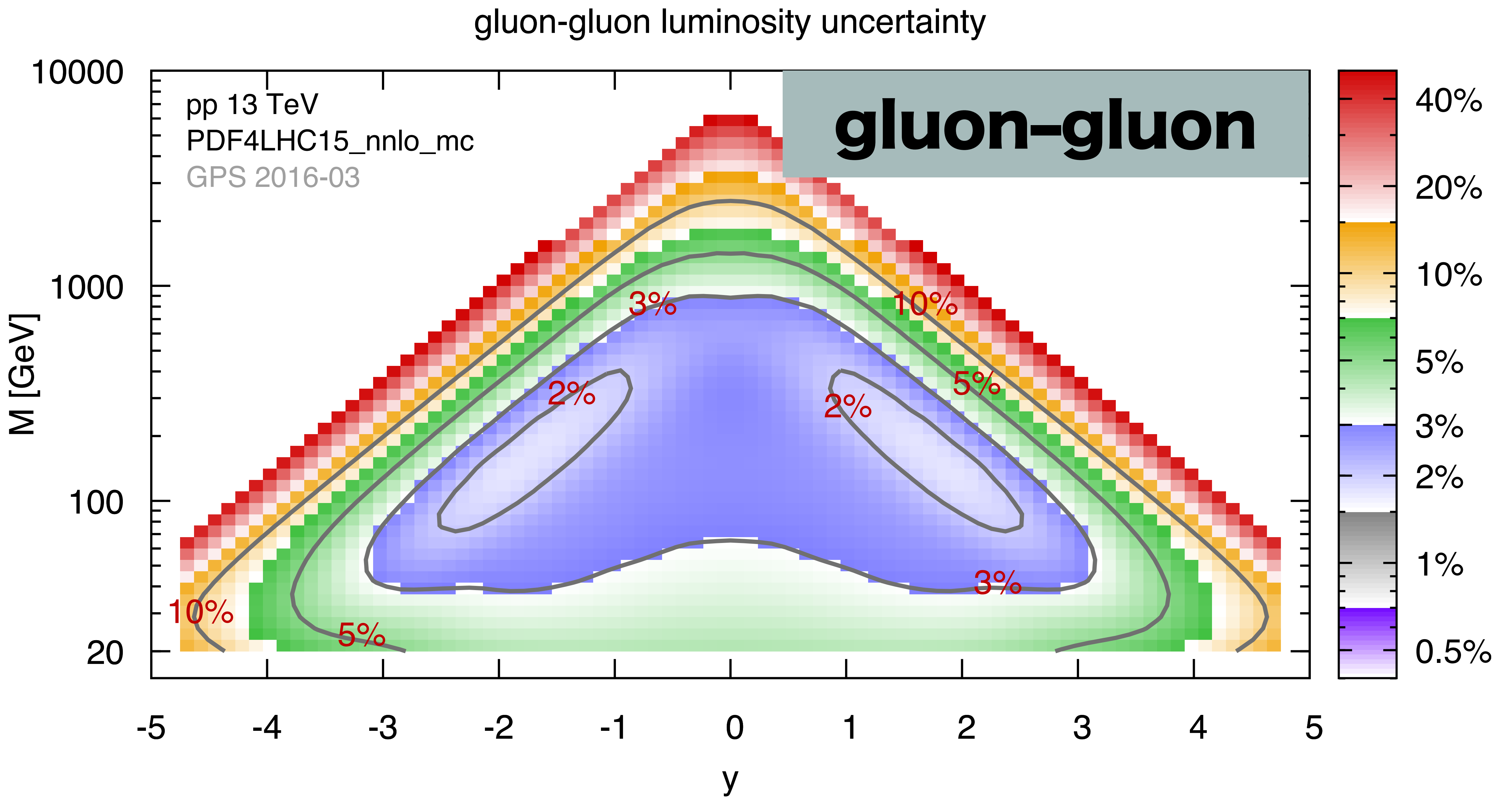
- For gluon-fusion & ttH, this comes in squared. It also correlates with the PDFs and affects backgrounds.

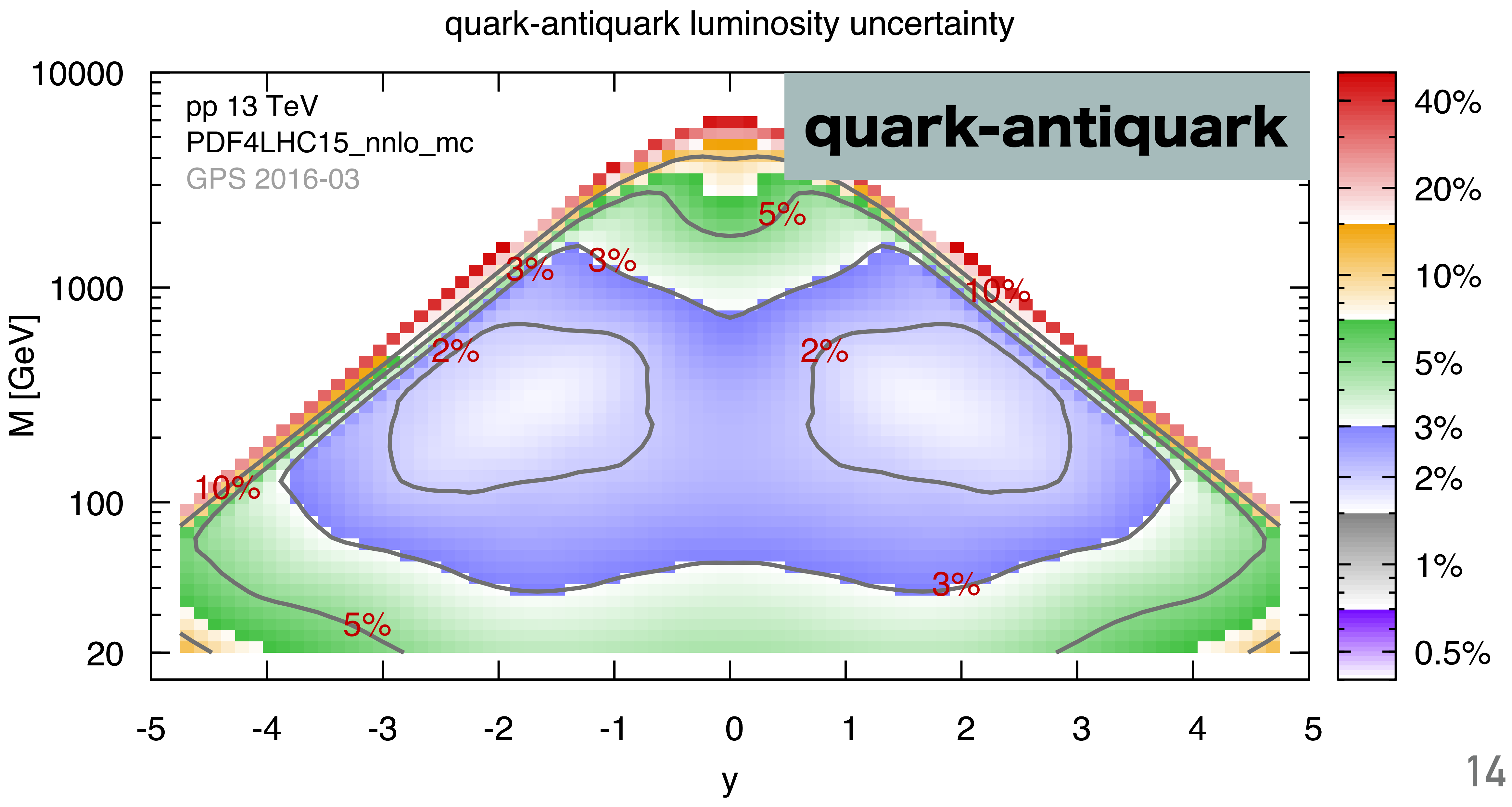
- To go beyond 1%, best hope is probably lattice QCD — on a 10-year timescale, there will likely be enough progress that multiple groups will have high-precision determinations



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%?**





data-driven workarounds?

theory may have a hard limit

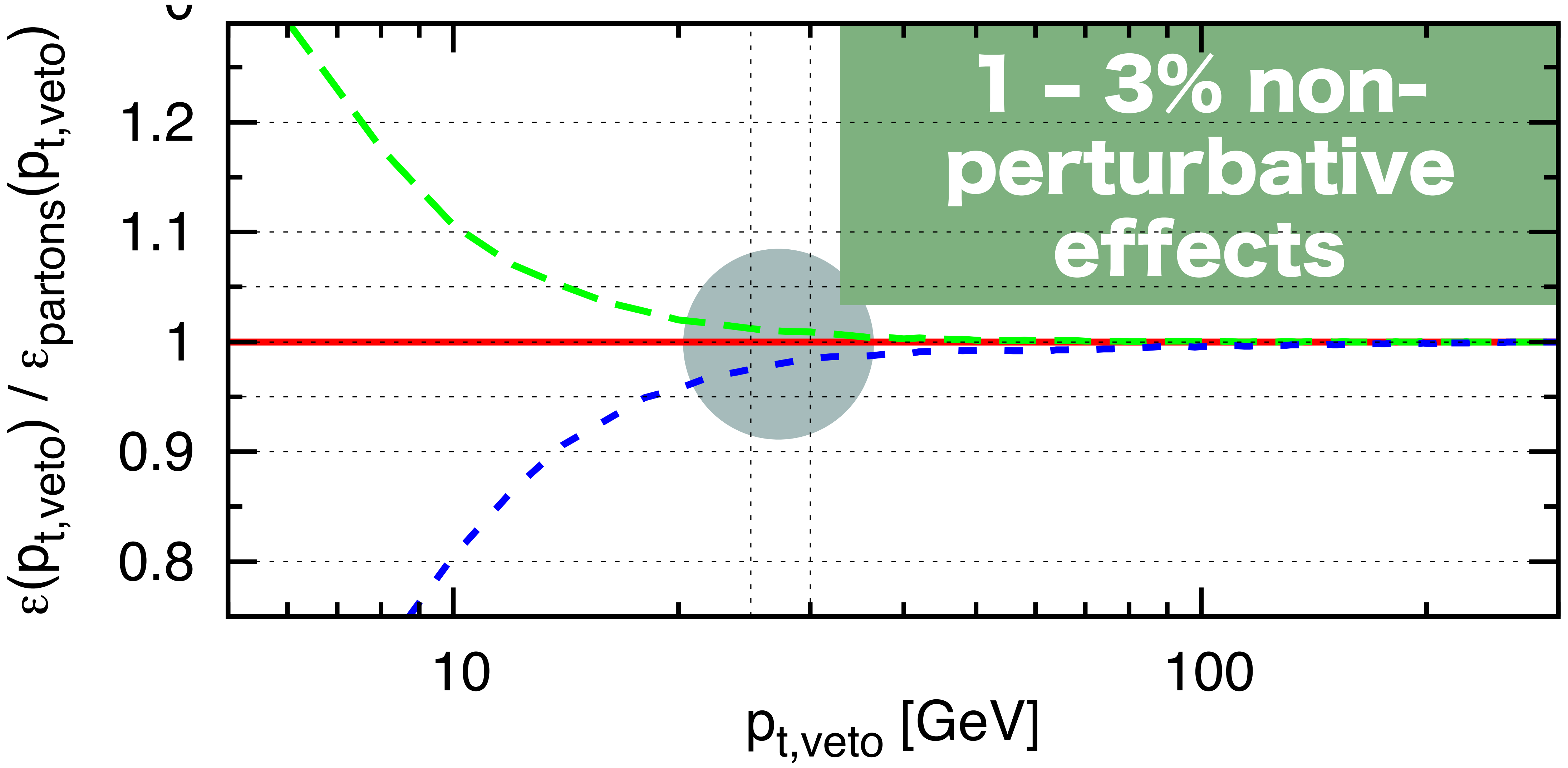
e.g. non-perturbative effects for cuts on jets

E.g. jet veto efficiency for H → WW*

LHC 13 TeV	$\epsilon^{\mathrm{N^3LO+NNLL+LL_R}}$
$p_{t,\mathrm{veto}} = 25\,\mathrm{GeV}$	$0.539^{+0.017}_{-0.008}$
$p_{t,\mathrm{veto}} = 30\,\mathrm{GeV}$	$0.608^{+0.016}_{-0.007}$

perturbative uncert: 1.5-3%

Anastasiou, Duhr, Dulat, Herzog & Mistlberger 1503.06056
Boughezal, Caola, Melnikov, Petriello & Schulze 1504.07922
Banfi, Caola, Dreyer, Monni, GPS, Zanderighi & Dulat 1511.02886



Banfi, GPS, Zanderighi 1203.5773

Measurements of H→ZZ* and γγ can constrain this directly.

Today: ~ 40 evts. equiv.

HL-LHC: ~ 15k events equiv.

→ 1% uncertainties?

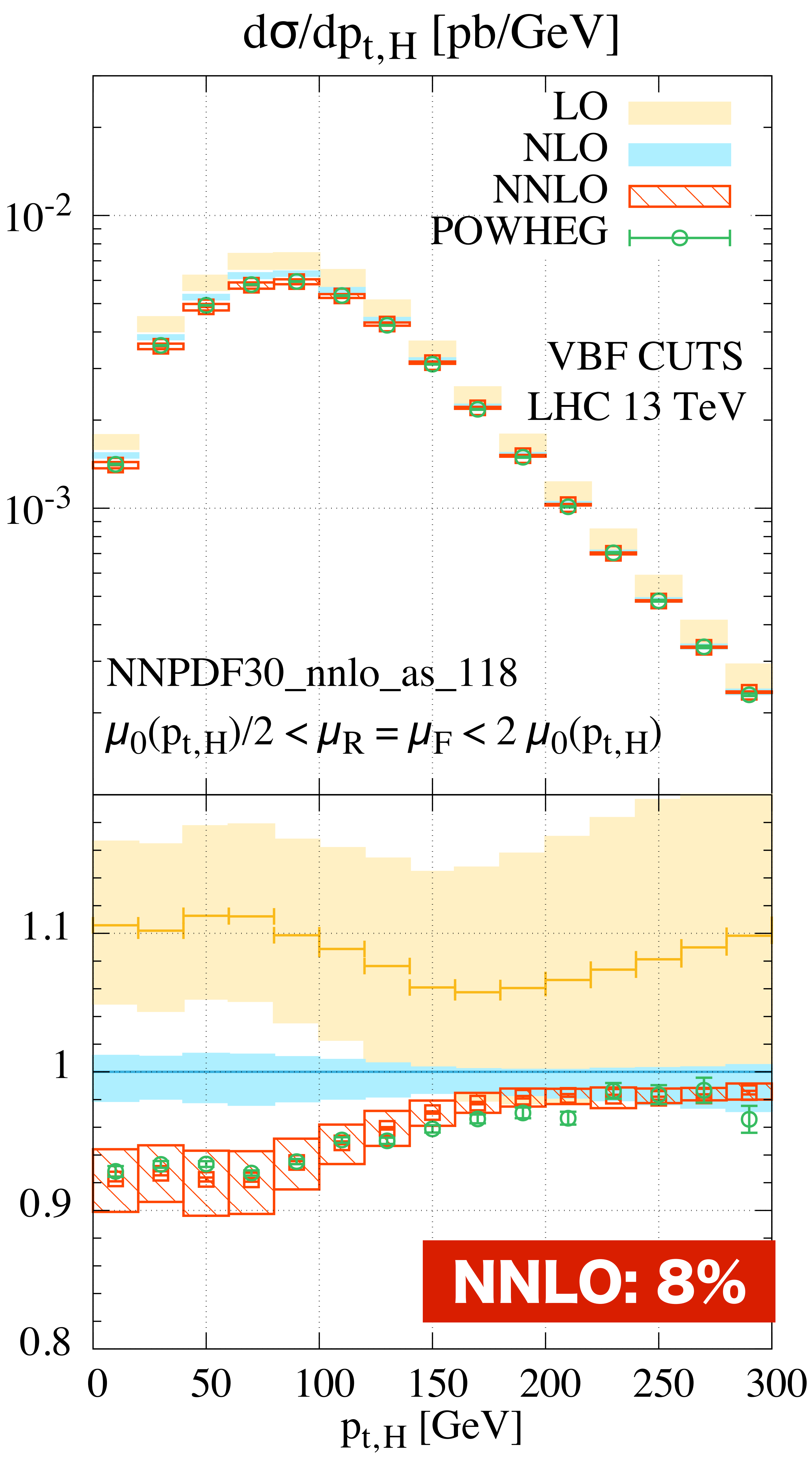
advocated notably by Michelangelo

VECTOR-BOSON FUSION

- NNLO (with cuts) is 8%
- UE/MPI is up to 5%
- all due to jets

At high Higgs p_T, impact of NNLO vanishes, because both jets always above p_T cuts.

Could this be exploited, e.g. with cuts just on jet rapidities? Where is tradeoff between data loss & improvement in systematics?



Differential VBF calculation (with cuts)

NNLO is up to 8% effect

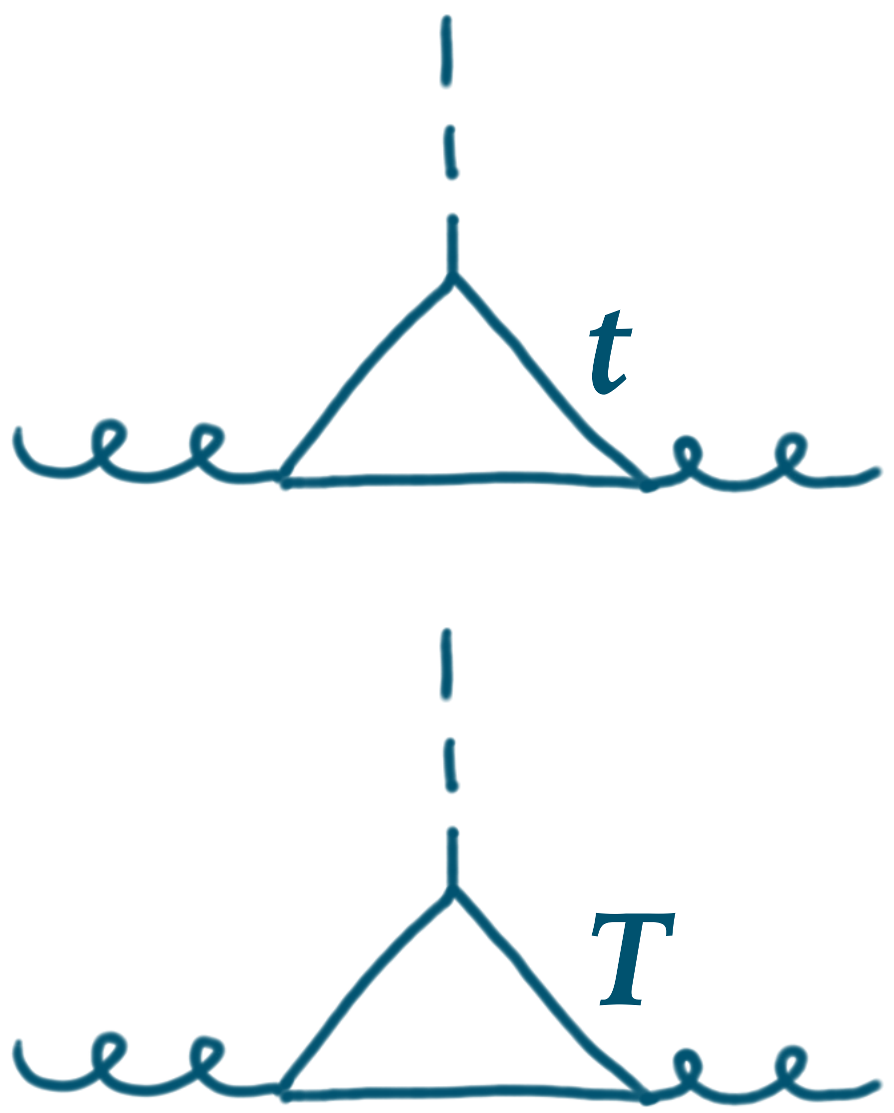
Almost all of which comes from jet fragmentation

other observables

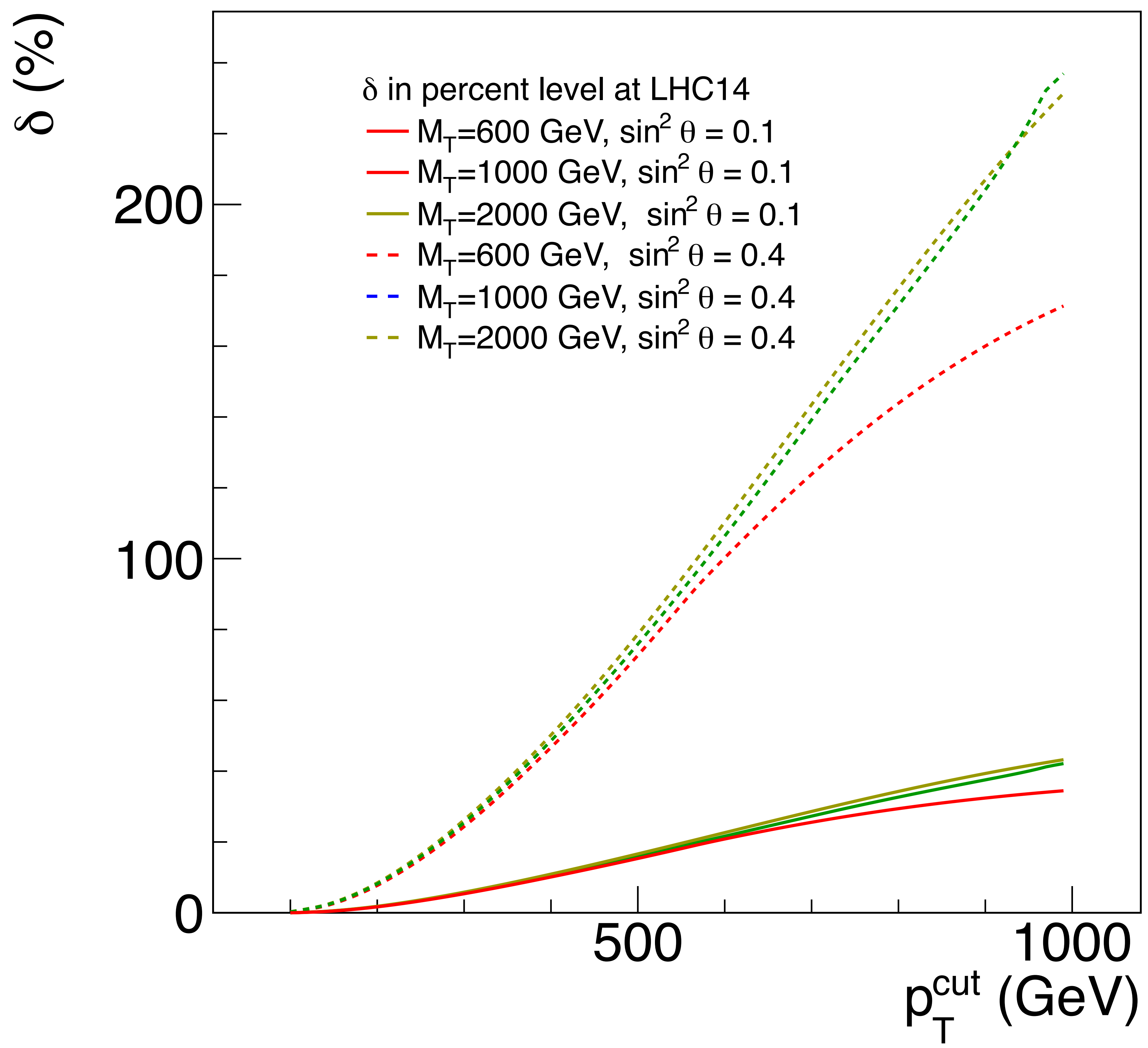
high-pT Higgs production

Higgs width constraints

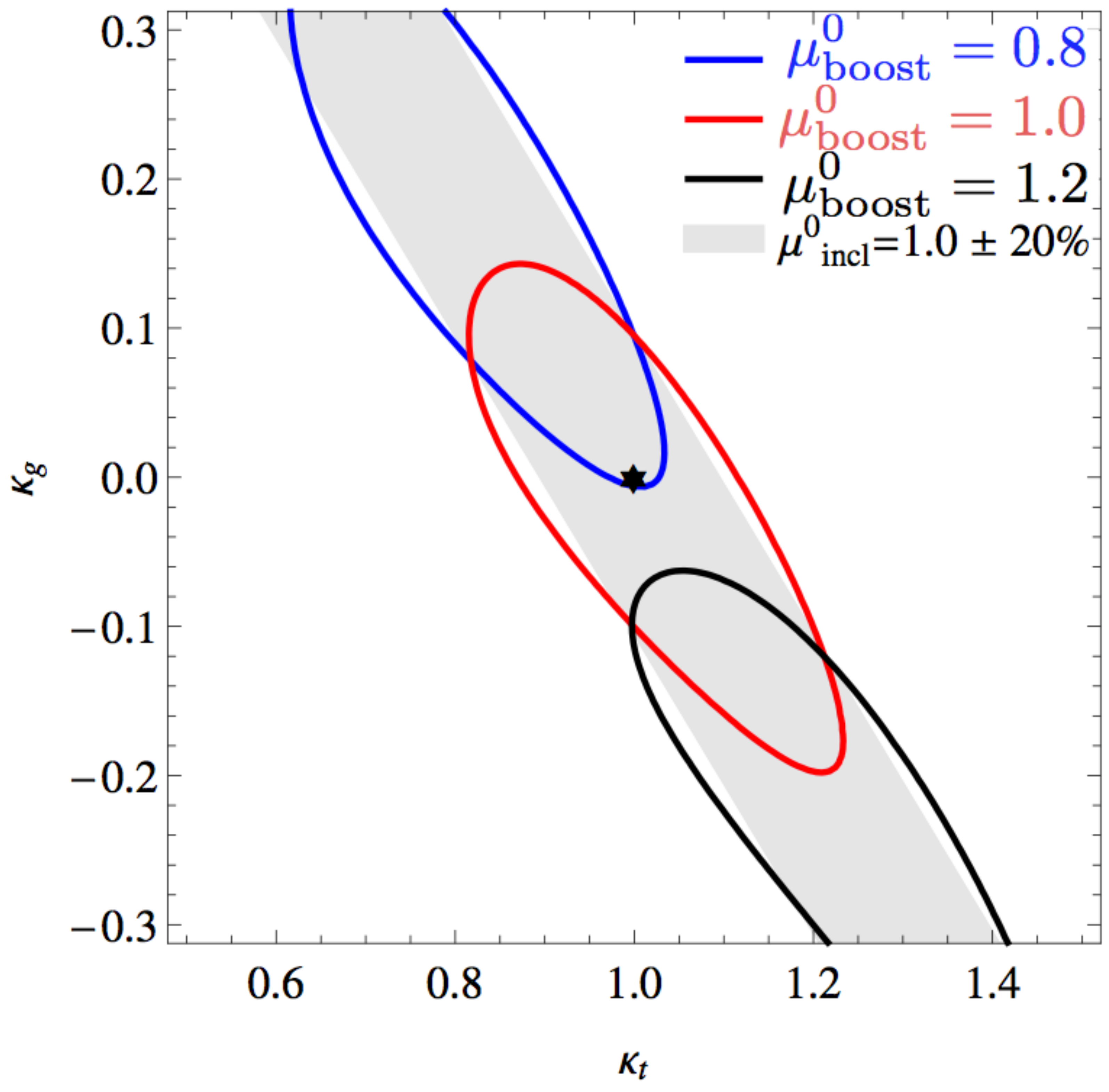
High-pt Higgs (e.g. to distinguish κ_g and κ_t)



Structure of loops is best probed by going to high p_T



A.Banfi, A.Martin, V.Sanz (2013)

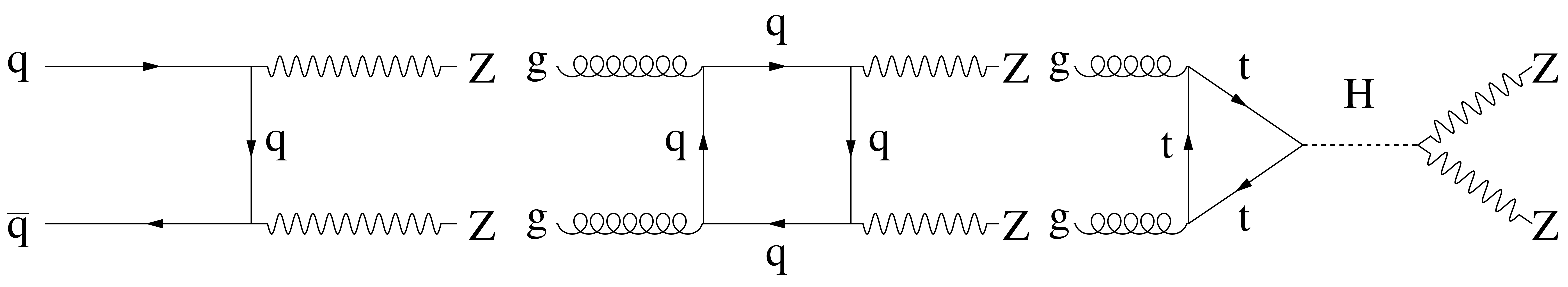


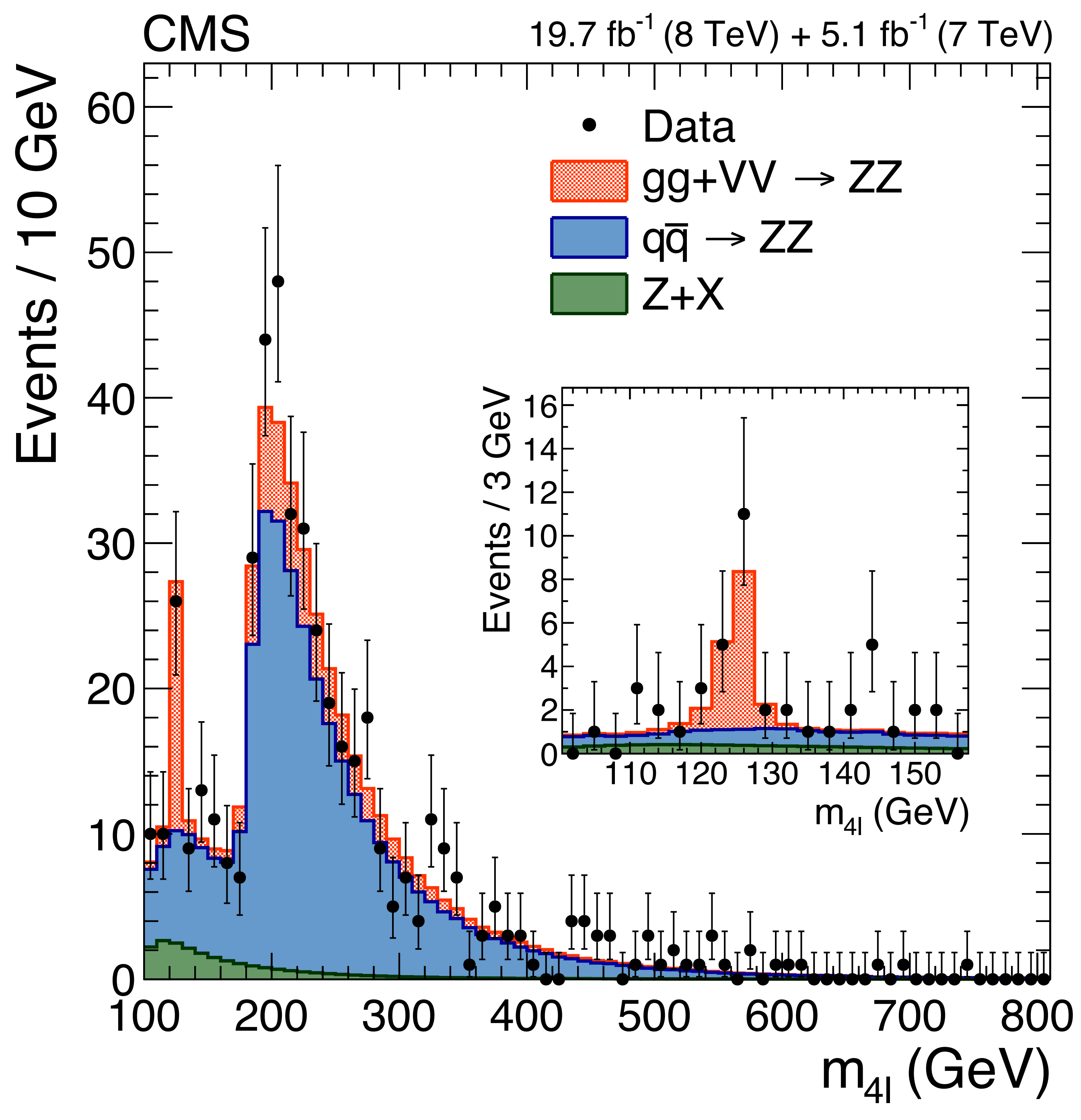
C.Grojean et al. (2013)

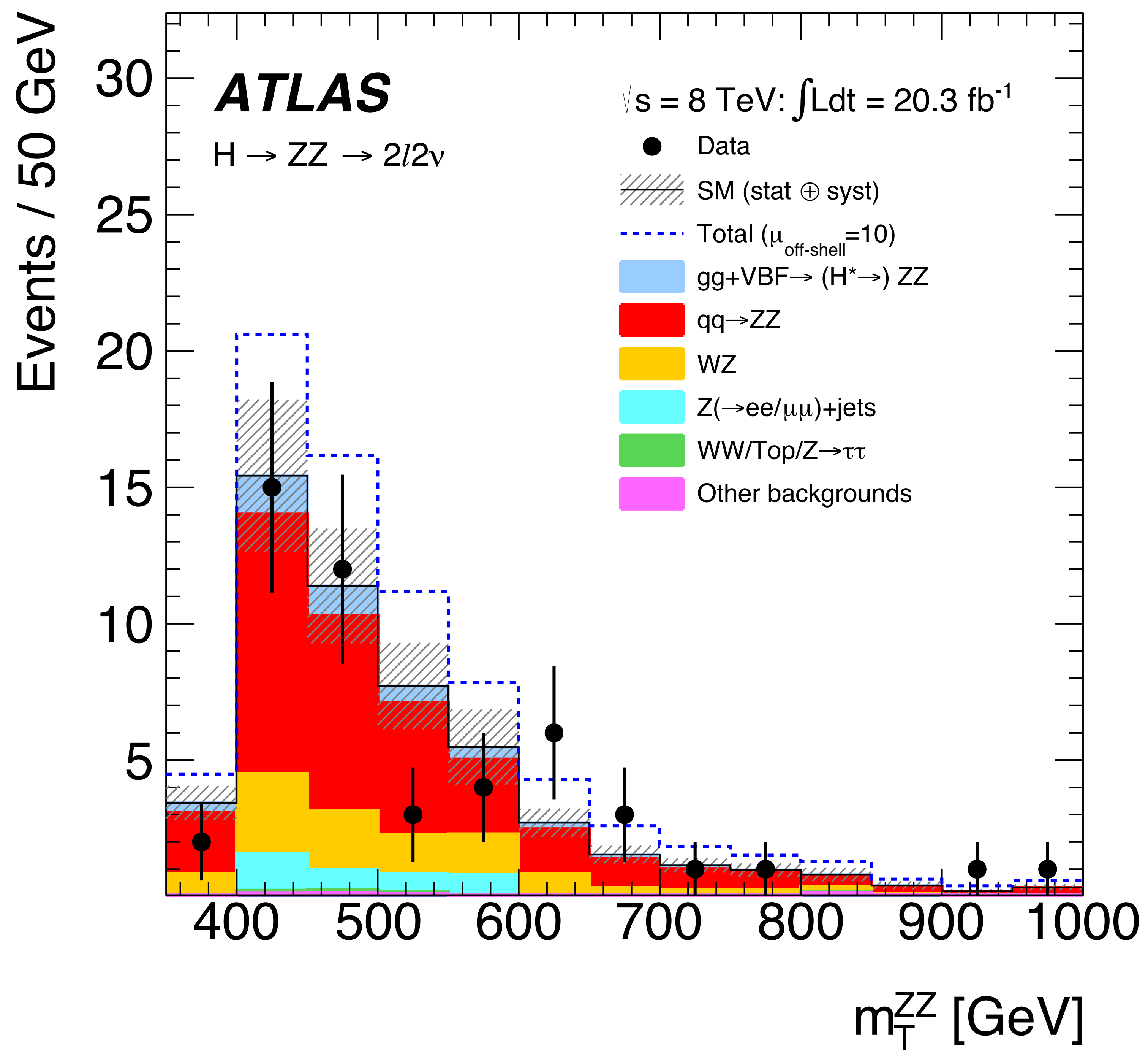
see also Azatov, Paul (2013)
S.Dawson,I.Lewis,M.Zeng (2014)

what are experimental prospects?
are there any theory-issues to be solved?

Higgs width constraints from off-shell production







What are HL-LHC prospects for this measurement?

What will the limiting systematics be?

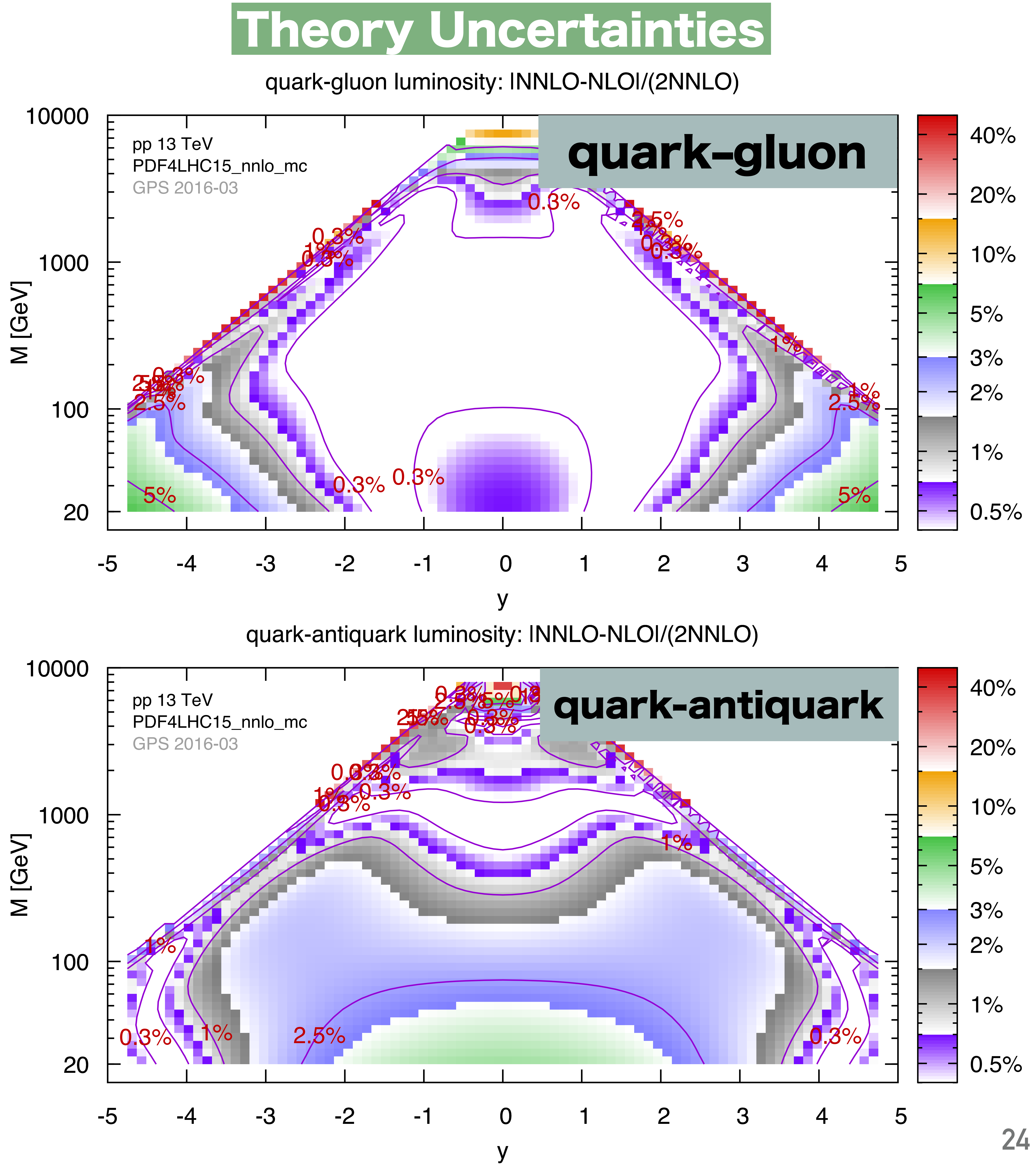
outlook

OUTLOOK

- What is real experimental reach on precision? I.e. can we get full advantage of 3000fb^{-1}? I.e. 1%.
- Can we establish a comprehensive list of “theory roadblocks” along the way? E.g. a table, for each process, with an ordered list of limiting theory uncertainties.
- From that, can we establish a theory roadmap (some things are obvious already now, but maybe not all)
- I haven’t talked about MC generators? How do their characteristics fold into the issue of theory uncertainties?

EXTRA SLIDES

PDF THEORY UNCERTAINTIES



REFS

- ATLAS projections ATL-PHYS-PUB-2014-016
- CMS projections (snowmass): 1307.7135

- Current status — ATLAS/CMS combination note

- YR4 14 TeV numbers: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt14TeV
- YR3 14 TeV numbers: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt1314TeV2014#s_14_0_TeV
- new ggF https://arxiv.org/abs/1602.00695
- ATLAS differential 1504.05833, CMS differential: ZZ 1512.08377 & gg 1508.07819

PRECISION LHC PHYSICS NEEDS PRECISION THEORY

Progress on calculations has been stunning in the past years

- N3LO Higgs
- Many processes at NNLO
- NLO + PS automation
- First NNLO + PS
- NNLL Resummations
- EW + QCD, etc.

This progress is essential for LHC precision physics, but also only part of the story.

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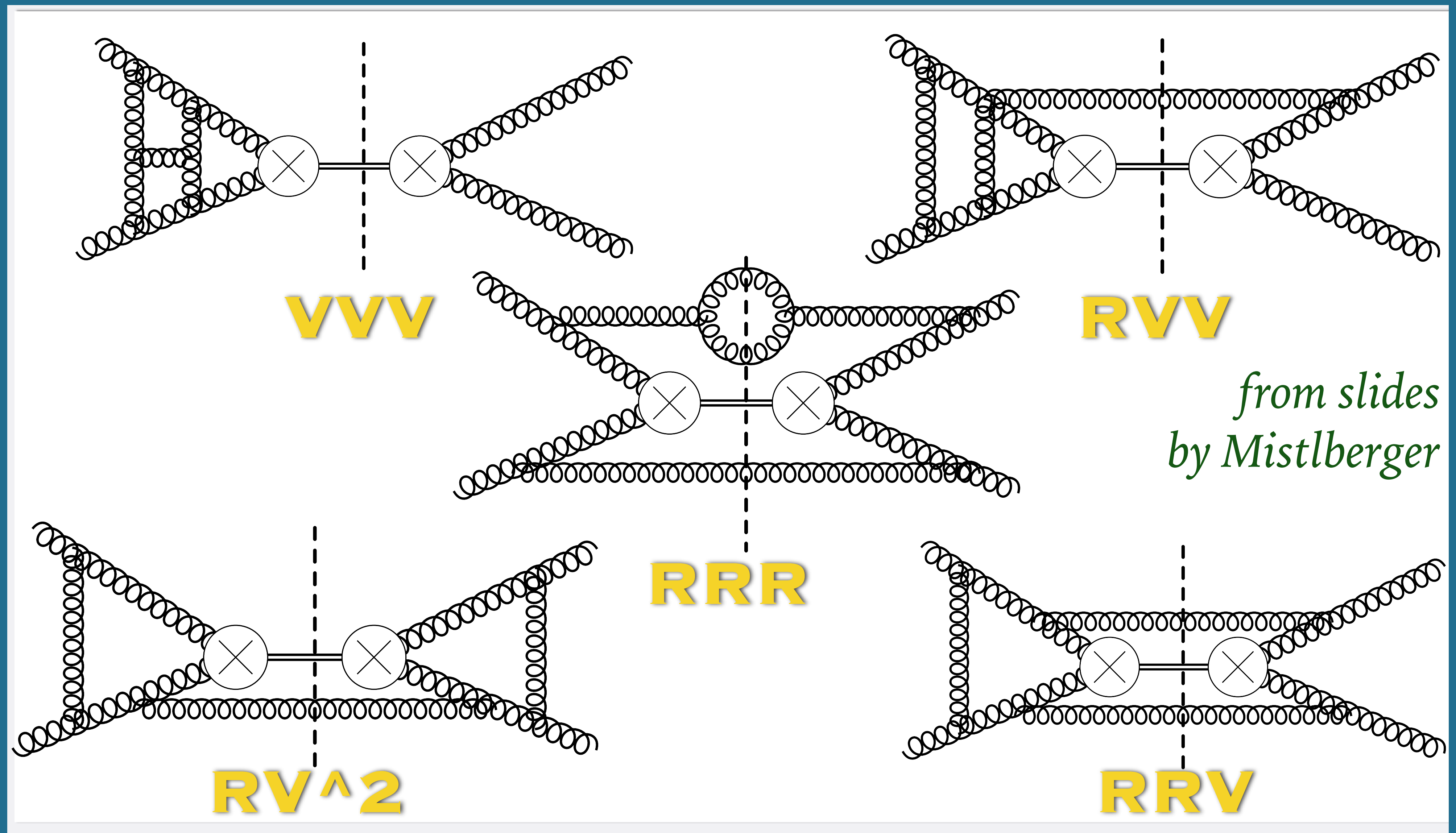
N3LO Higgs production

Anastasiou, Duhr, Dulat, Herzog, Mistlberger ’15-16

100,000 diagrams



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This progress is essential for LHC precision physics, but also only part of the story.

The intention with this talk?

Start asking questions about what precision goals we might set ourselves, what obstacles we will meet, what techniques and measurements might help us progress

HIGGS TODAY & TOMORROW

Production process	ATLAS+CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$

Decay channel	ATLAS+CMS
$\mu^{\gamma\gamma}$	$1.16^{+0.20}_{-0.18}$
μ^{ZZ}	$1.31^{+0.27}_{-0.24}$
μ^{WW}	$1.11^{+0.18}_{-0.17}$
$\mu^{\tau\tau}$	$1.12^{+0.25}_{-0.23}$
μ^{bb}	$0.69^{+0.29}_{-0.27}$

ATLAS-CMS Run I combination

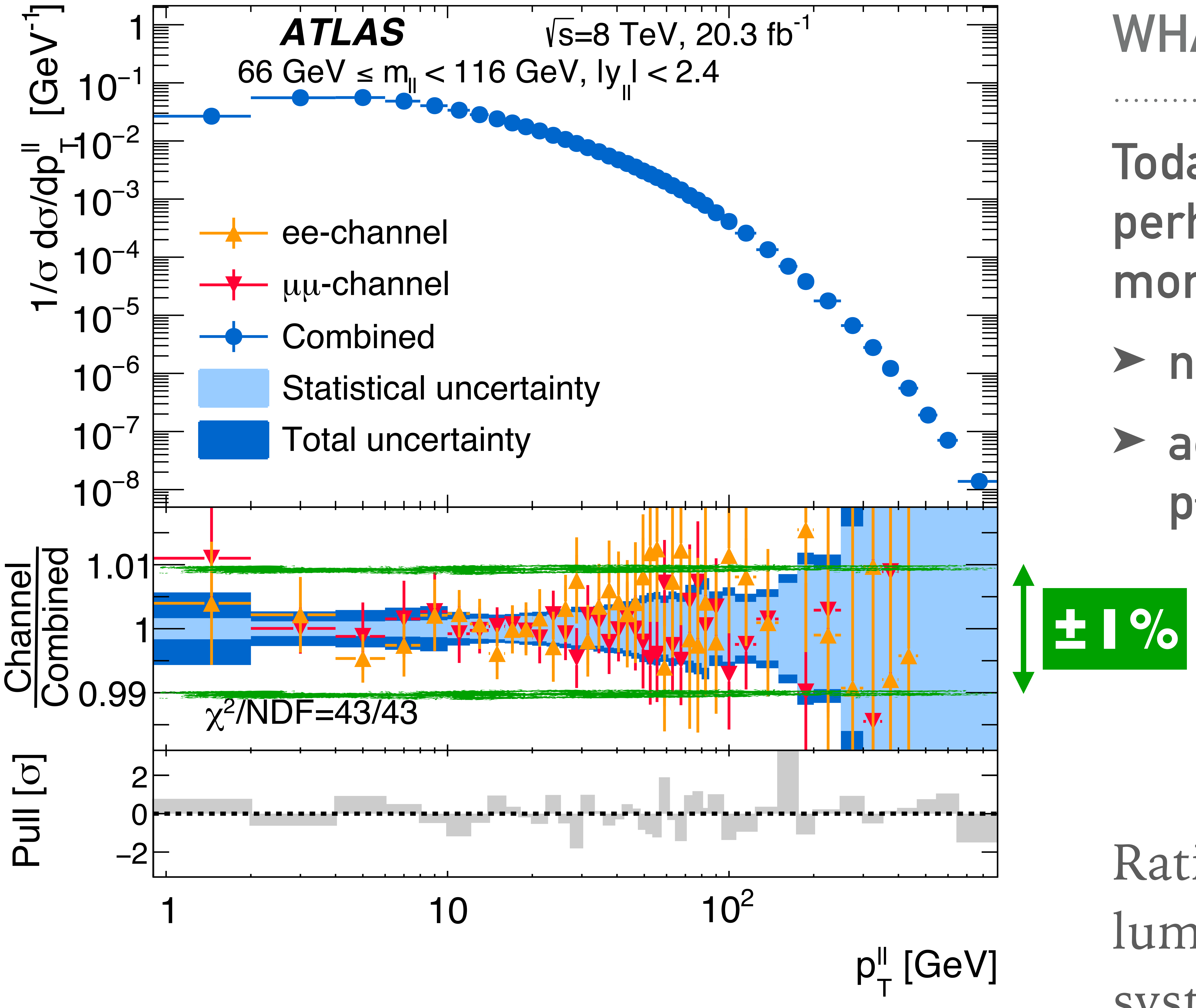
In most cases, stat. errors are largest single source

Best channels $\sim\pm 20\%$

HL-LHC prospects?

x2.5 in cross section
x150 in luminosity (→ 3000 fb^{-1})
~ 400 times more events

⇒ stat. errors in 1-2% range

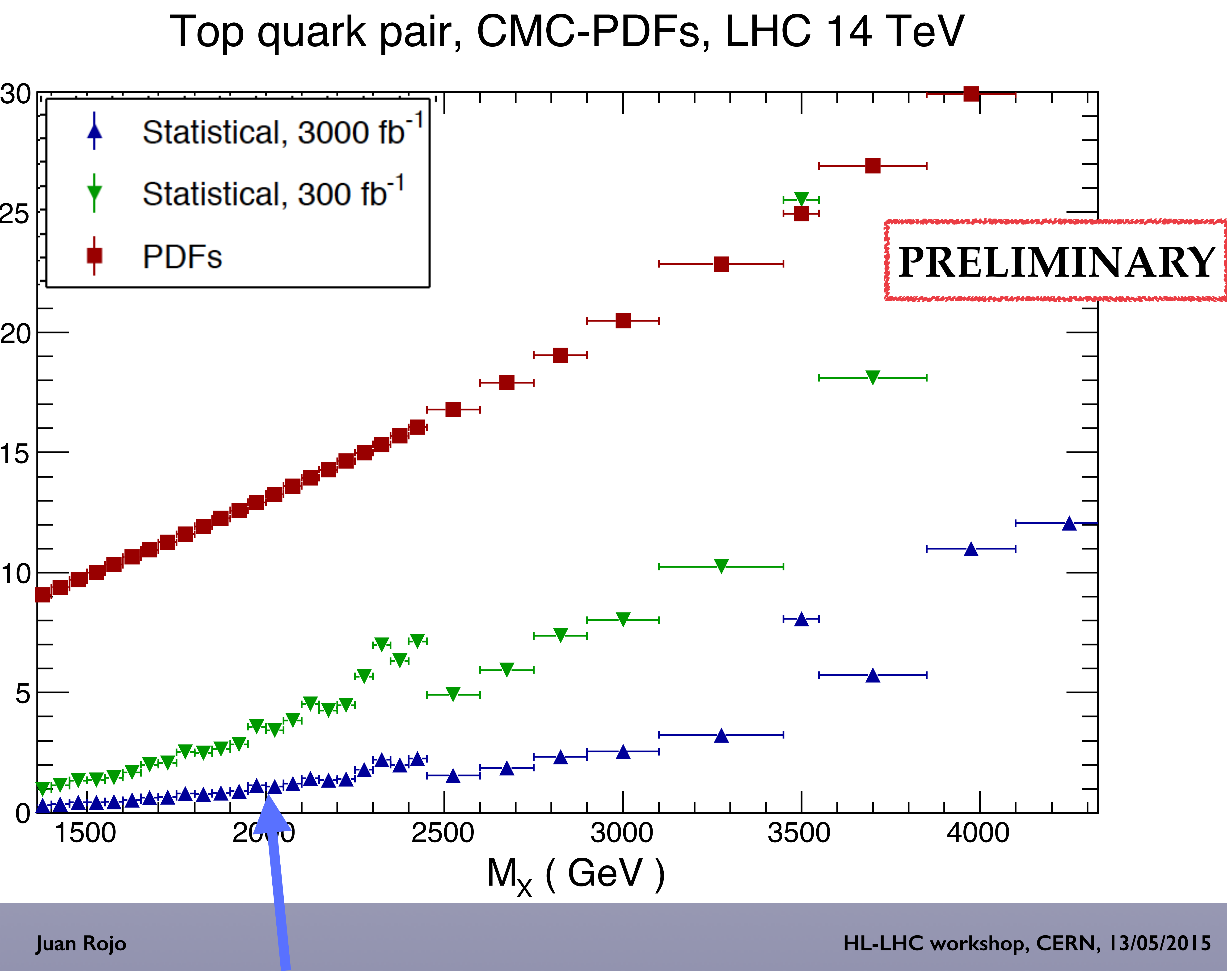


WHAT'S POSSIBLE EXPERIMENTALLY?

Today's most precise results are perhaps for the Z transverse momentum

- normalised to Z fiducal σ
- achieves <1%, from p_T = 1 to 200 GeV

Ratio to total cross section cancels lumi & some lepton-efficiency systematics.



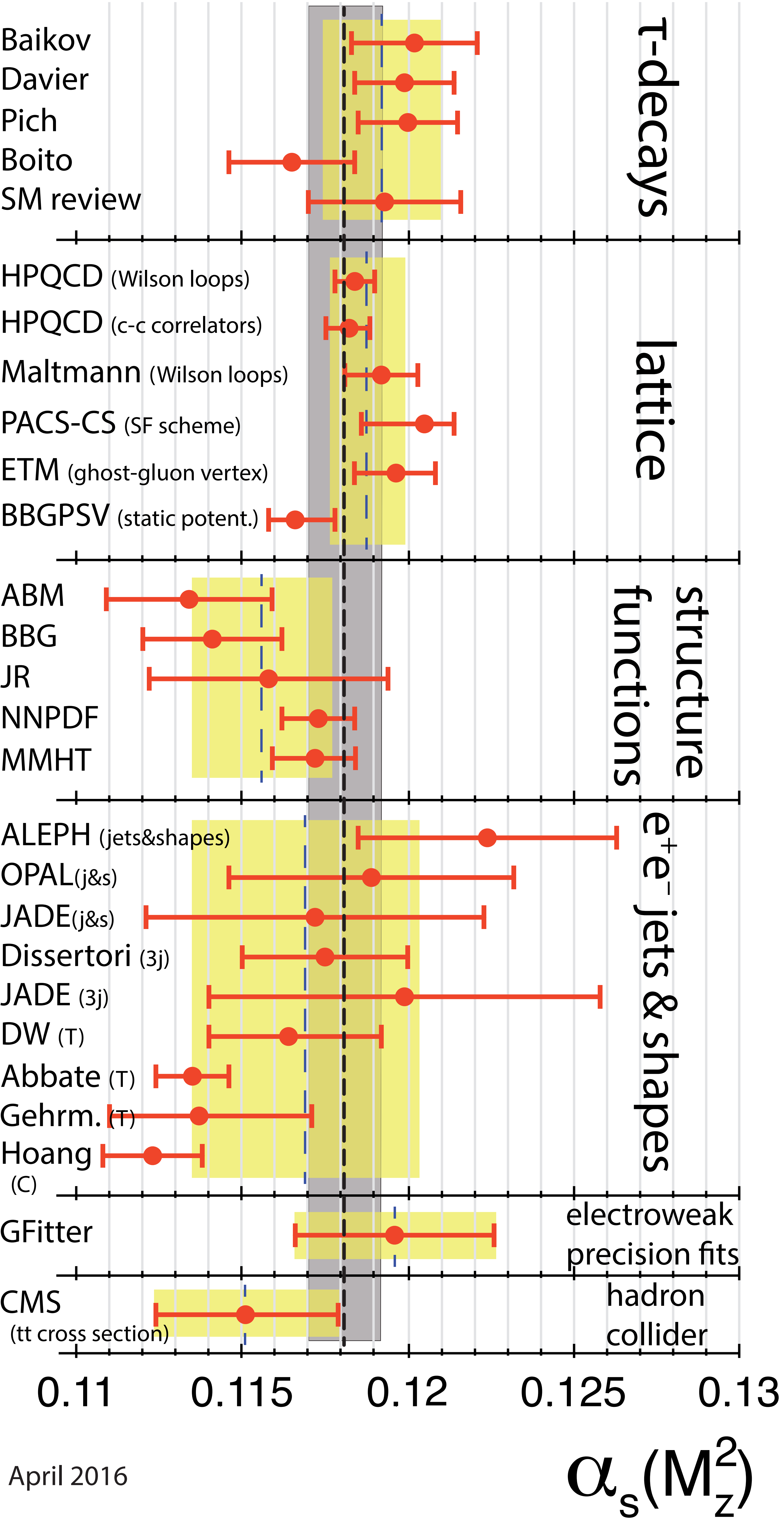
At HL-LHC, Statistical errors on ttbar production will be < 1% up to Mtt ~ 2 TeV

IN THE FUTURE?

- high-pt W, Z
- high-mass Drell-Yan
- high-mass ttbar

Will all be at ~1% statistical level up to and even beyond the TeV scale.

With leptonic final states, there's a chance systematic errors may also be < 1%.



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)

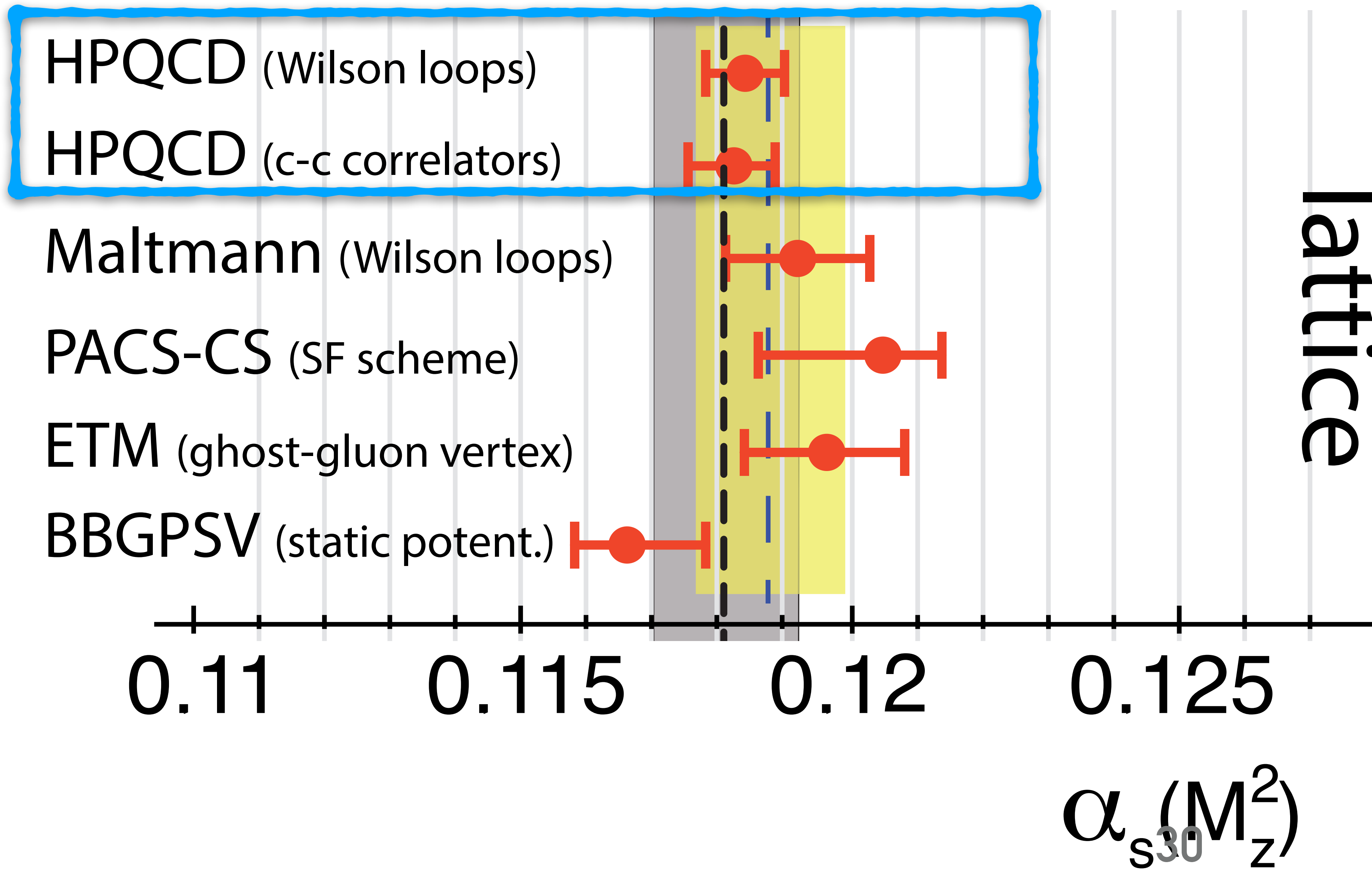
  $\alpha_s(M_Z) = 0.1183 \pm 0.0007$ (0.6%) [heavy-quark correlators]

  $\alpha_s(M_Z) = 0.1183 \pm 0.0007$ (0.6%) [Wilson loops]

- Error criticised by FLAG, who suggest

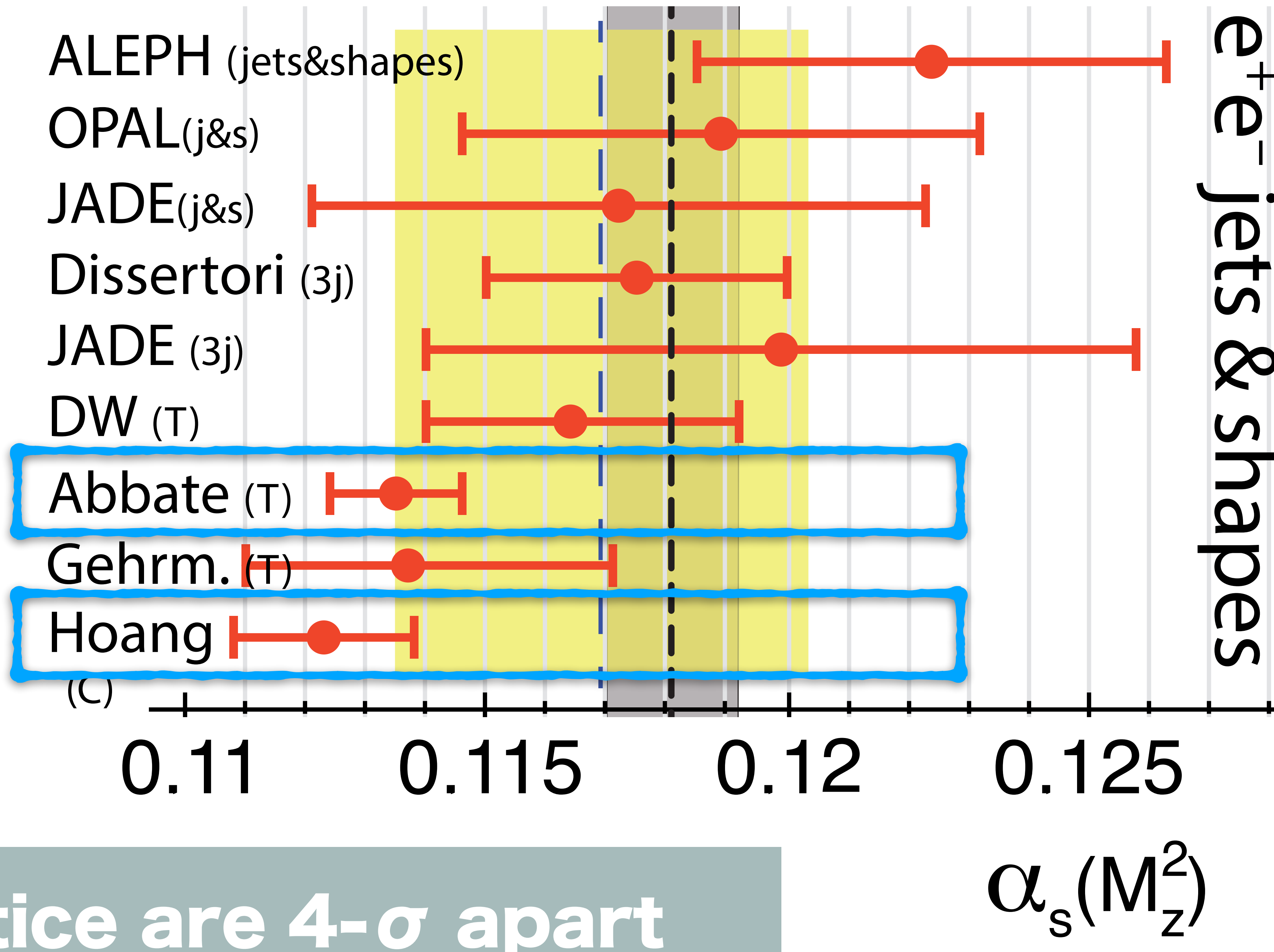
$\alpha_s(M_Z) = 0.1184 \pm 0.0012$(1%)

- 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 apart

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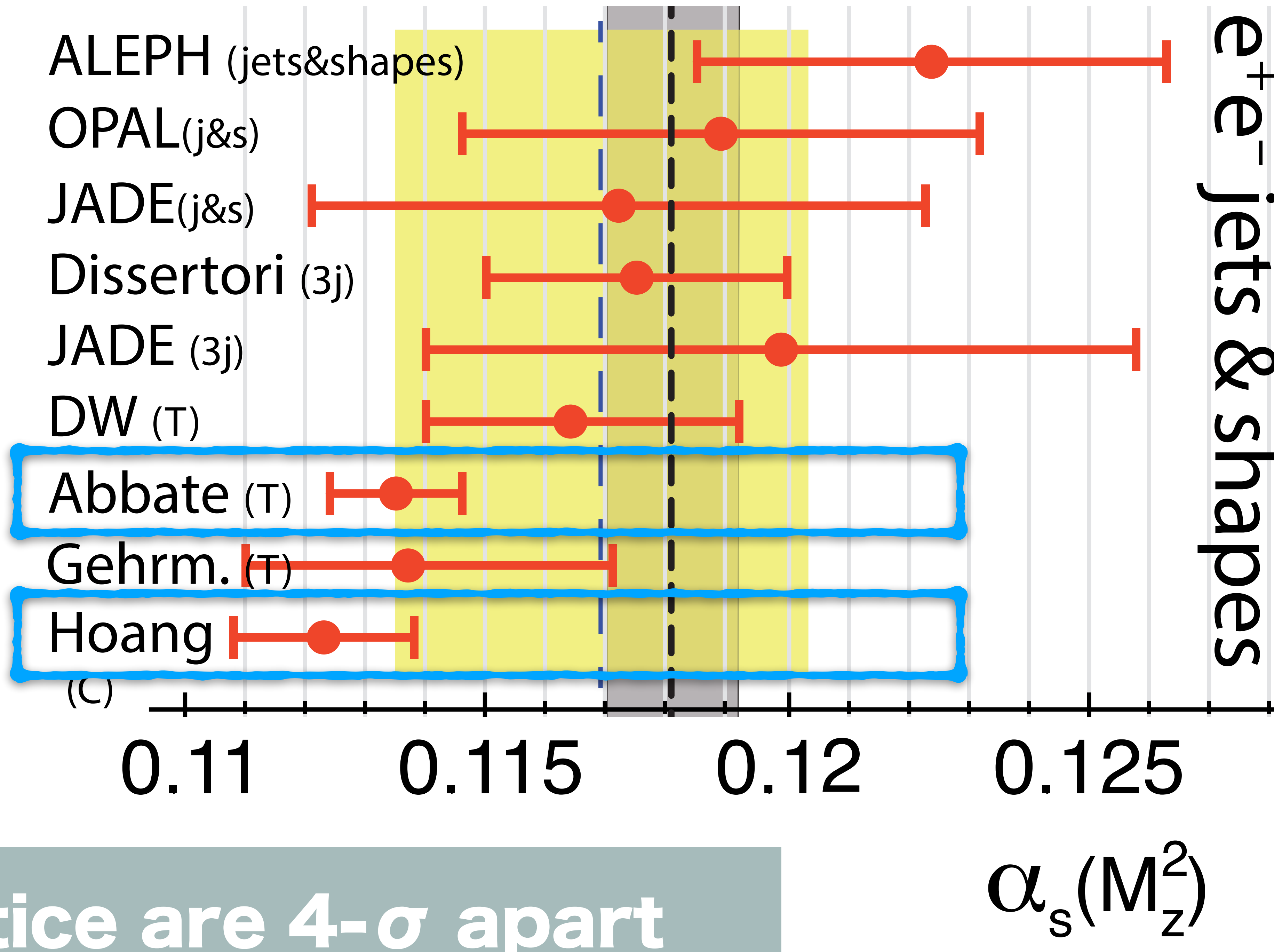
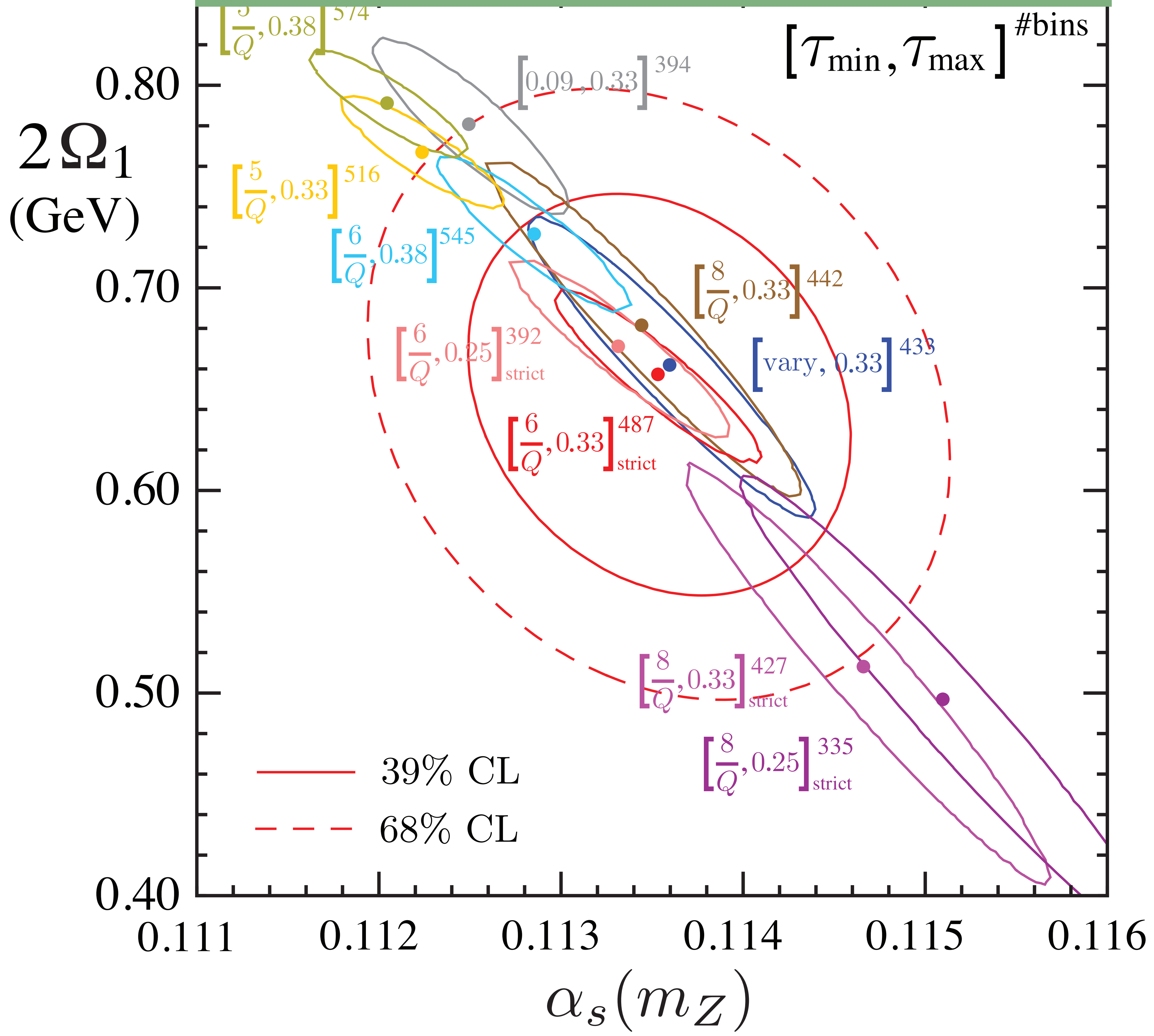


dependence on fit range



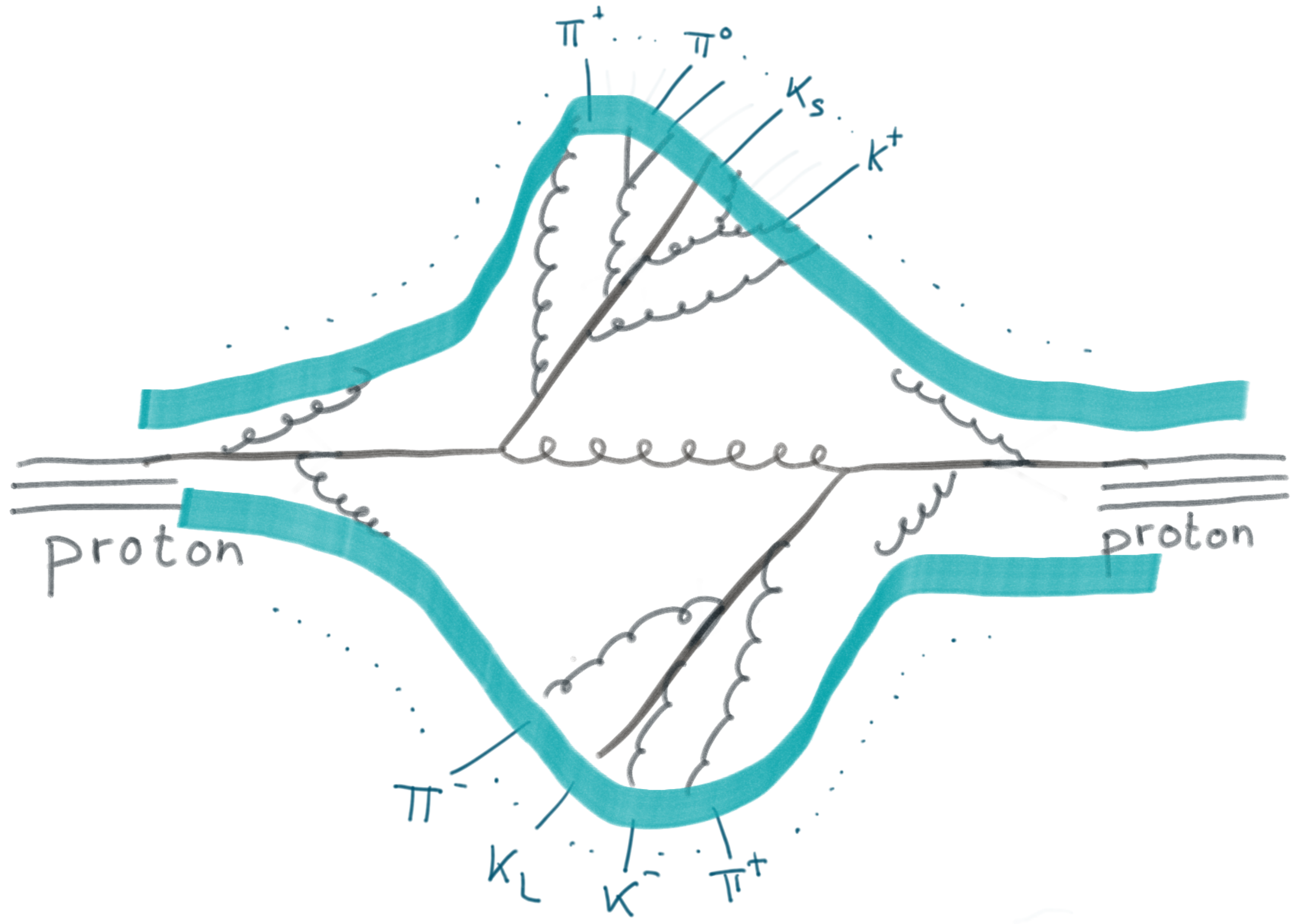
thrust & "best" lattice are 4-σ apart

Comments:

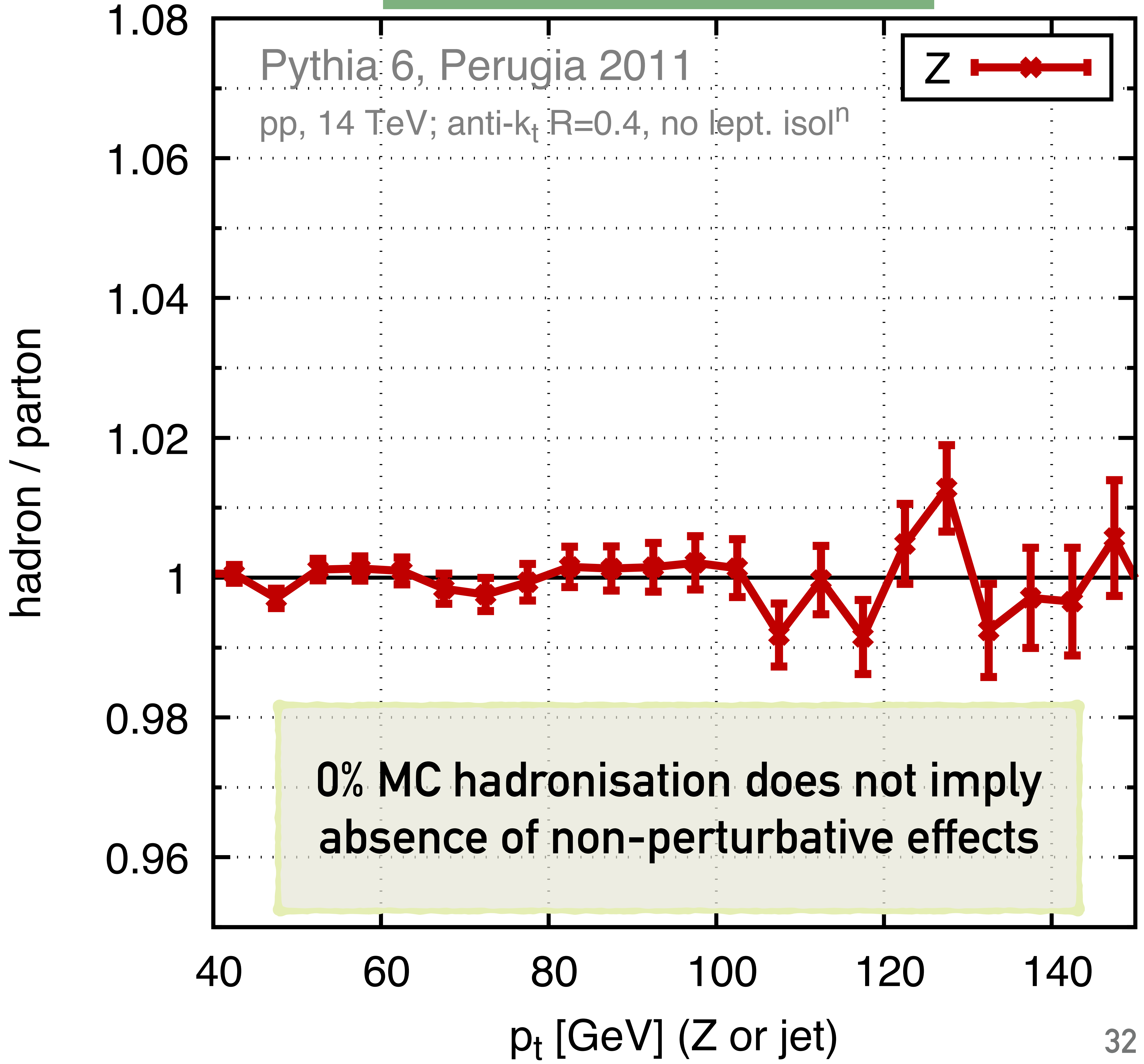
- thrust & C-parameter are highly correlated observables
- Analysis valid far from 3-jet region, but not too deep into 2-jet region — at LEP, not clear how much of distribution satisfies this requirement
- thrust fit shows noticeable sensitivity to fit region (C-parameter doesn't)

Non-perturbative effects in Z p_T

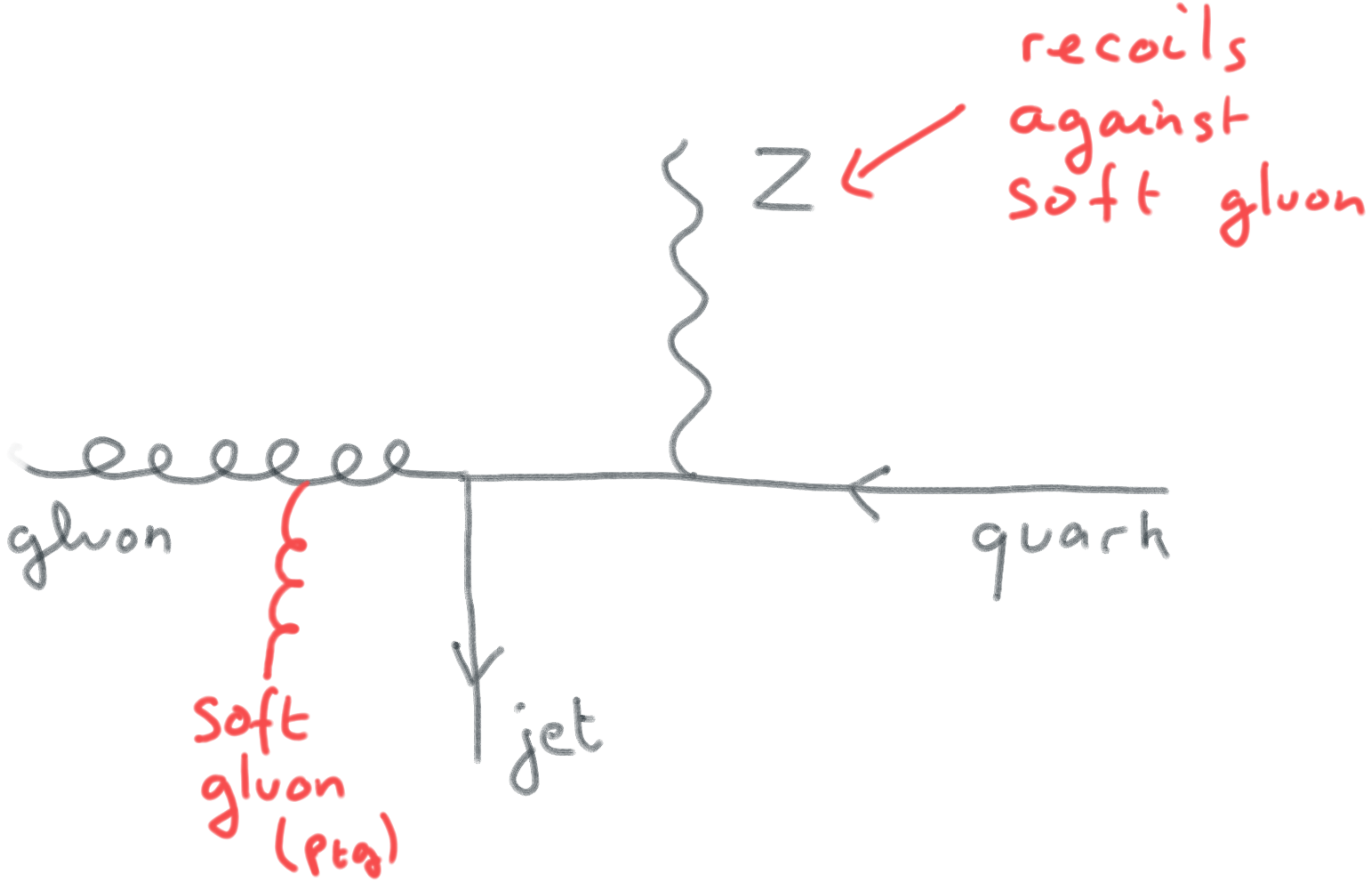
- Inclusive Z cross section should have $\sim\Lambda^2/M^2$ corrections ($\sim 10^{-4}$?)
- Z p_T is **not inclusive** so corrections can be $\sim\Lambda/M$.
- It seems size of effect can't be probed by turning MC hadronisation on/off [maybe by modifying underlying MC parameters?]



MC hadronisation



Non-perturbative effects in Z p_T



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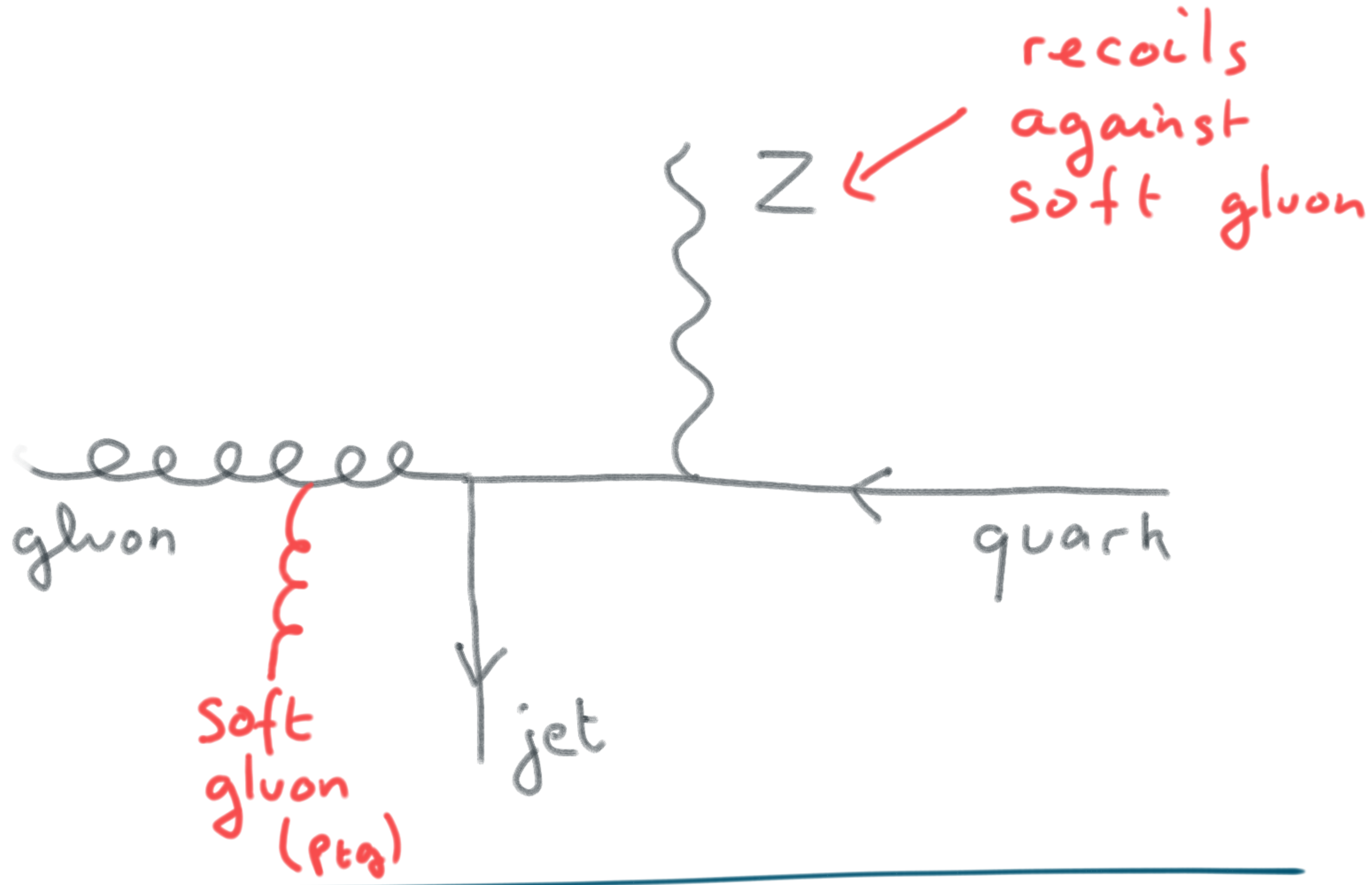
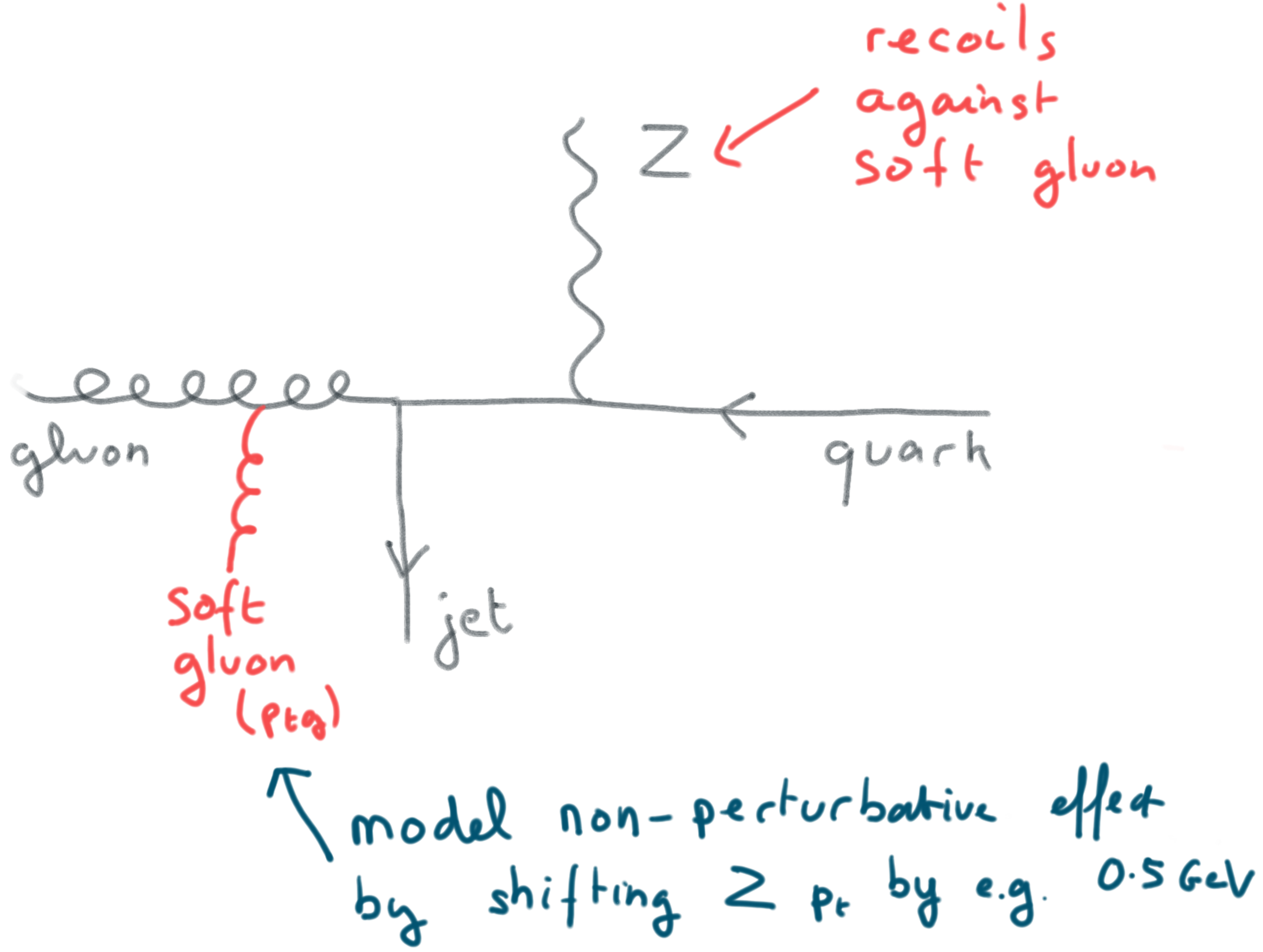


$$\text{recoil} \sim \int_0 \frac{dp_{tg}}{p_{tg}} \alpha_s(p_{tg})$$

integral over low p_t emissions is non-perturbative

Non-perturbative effects in Z p_T



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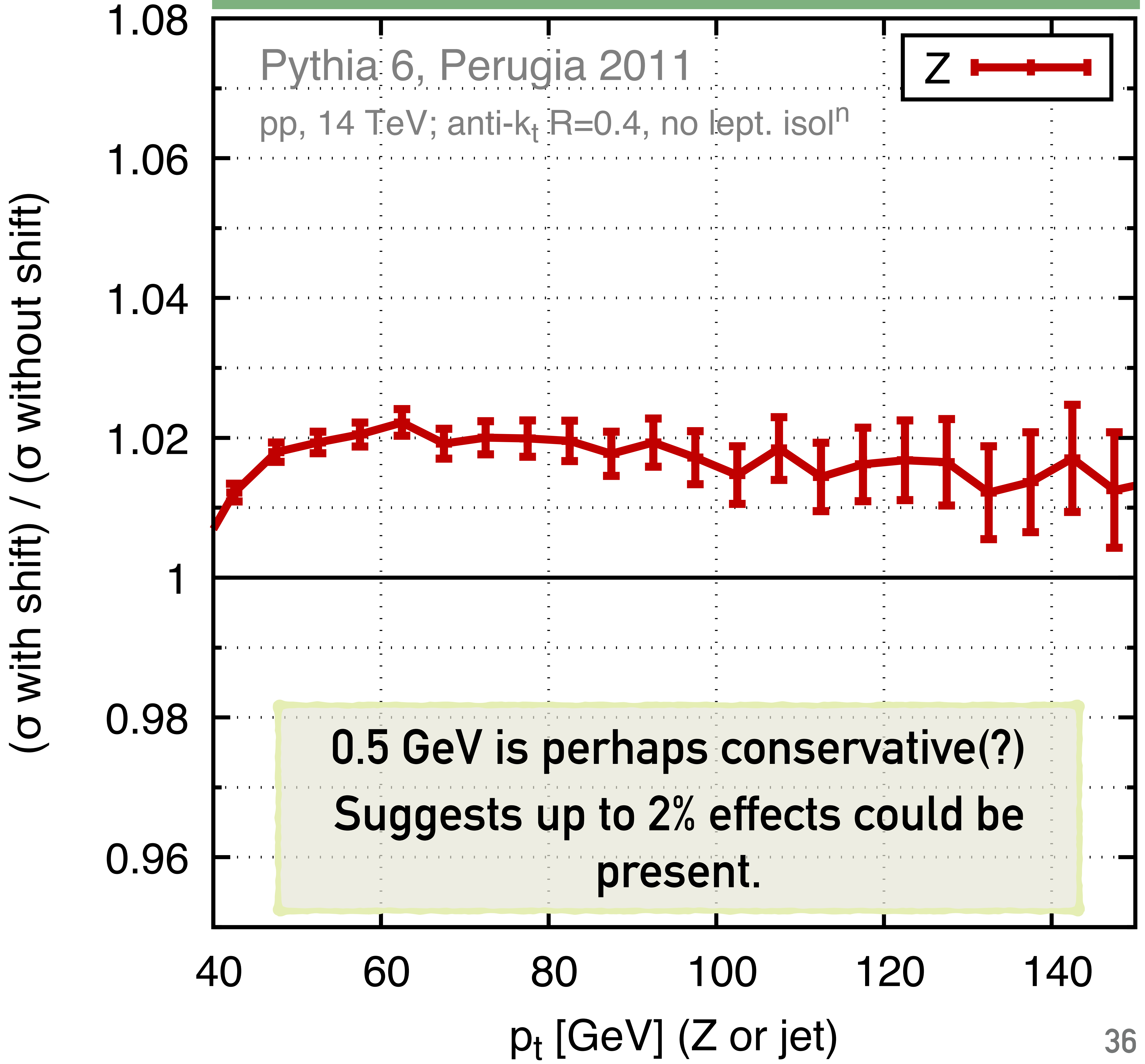
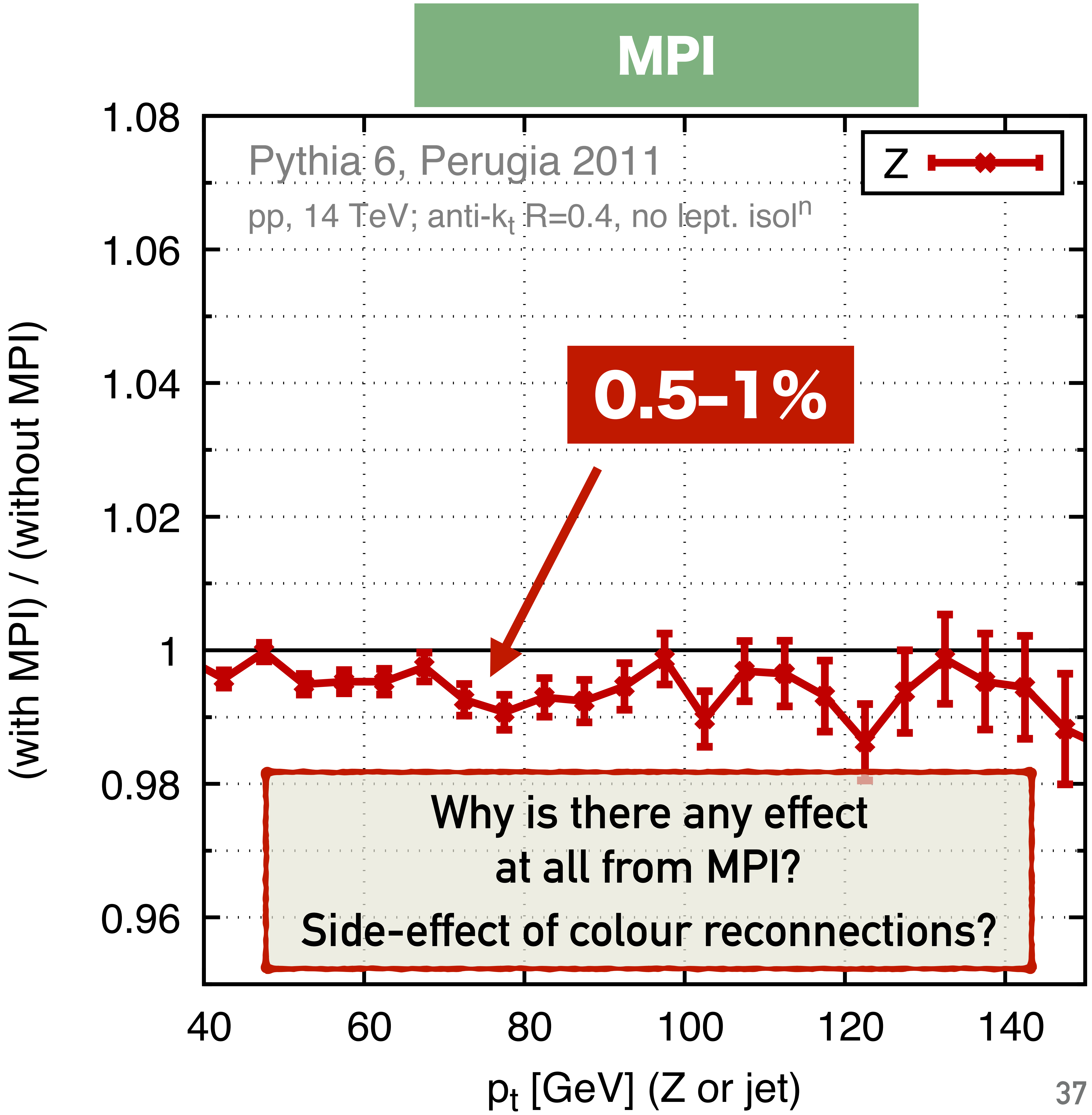
impact of 0.5 GeV shift of Z p_T



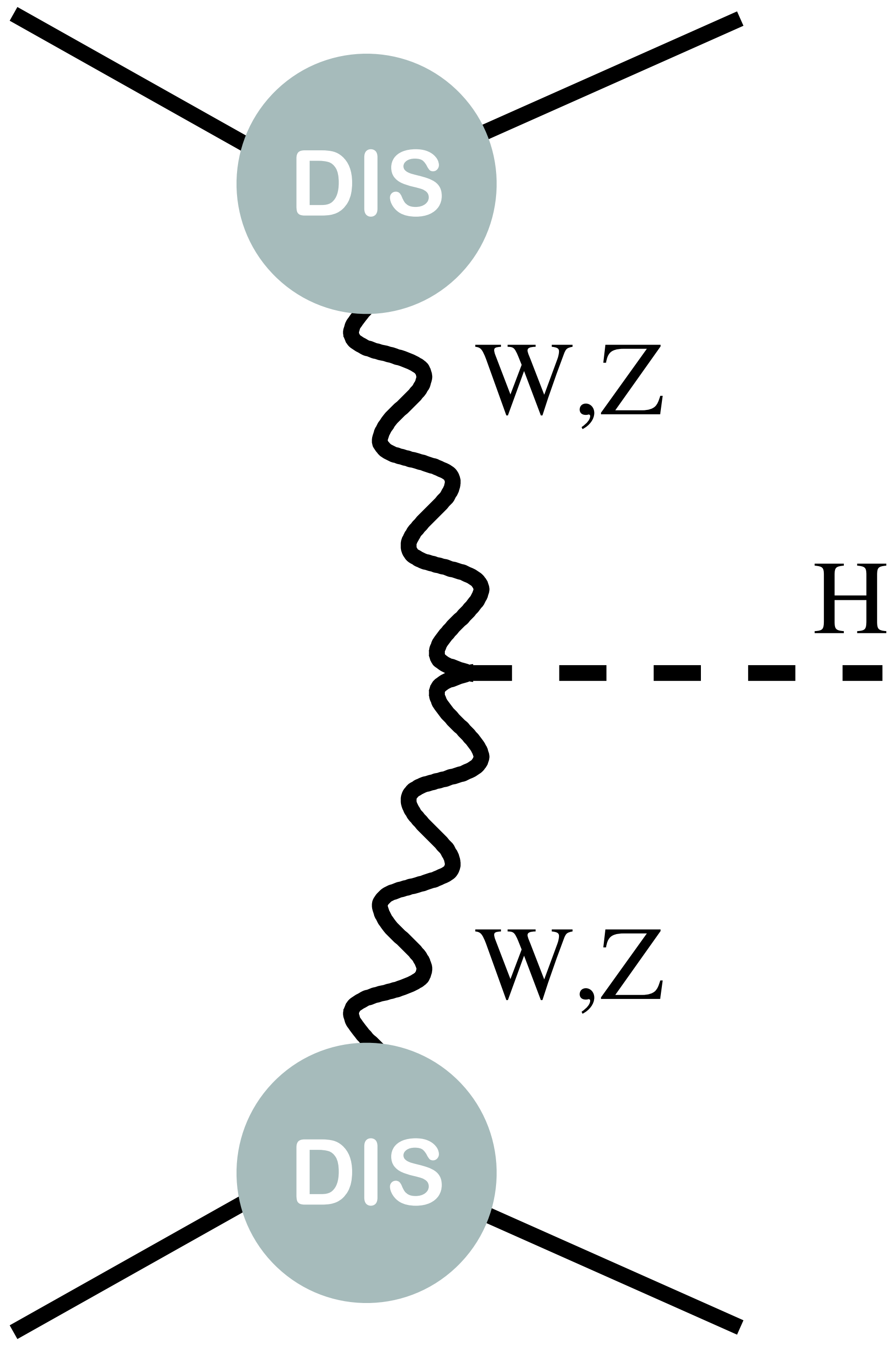
Multi-Parton Interactions?

- Naively, you'd expect these are not correlated with Z p_T — but in at least one MC (Pythia 6) switching them on/off changes distribution by O(1%)



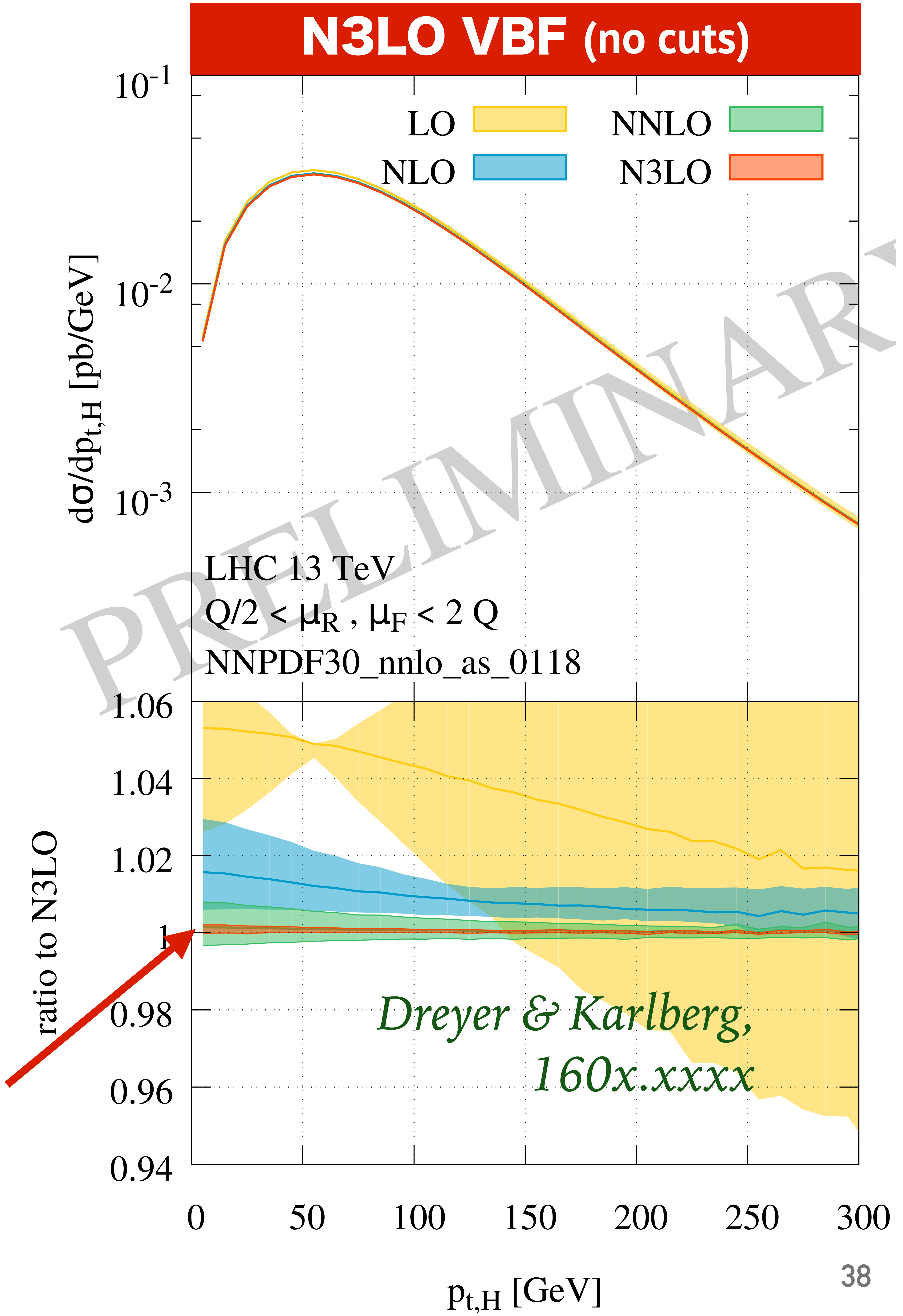
VECTOR-BOSON FUSION → HIGGS

- double DIS approximation is powerful tool for VBF, using structure functions for the W/Z production (Han, Valencia & Willenbrock 1992, NNLO by Bolzoni et al 1003.4451)



- Now being extended to N3LO, shows scale uncertainties « 1% for observables inclusive wrt the jets
- good stability from NNLO to N3LO

N3LO



N3LO VBF (no cuts)

VECTOR-BOSON FUSION → HIGGS

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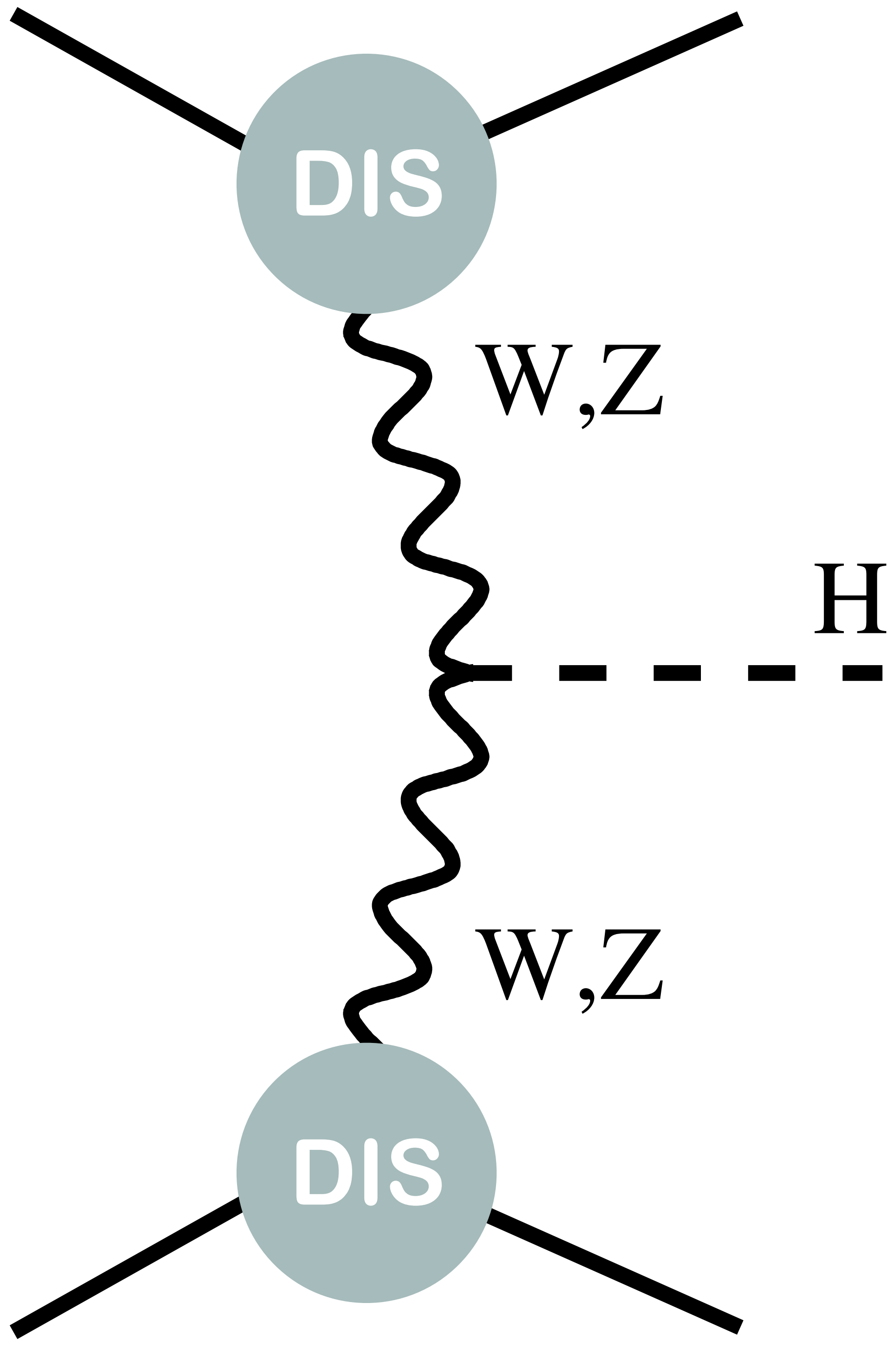
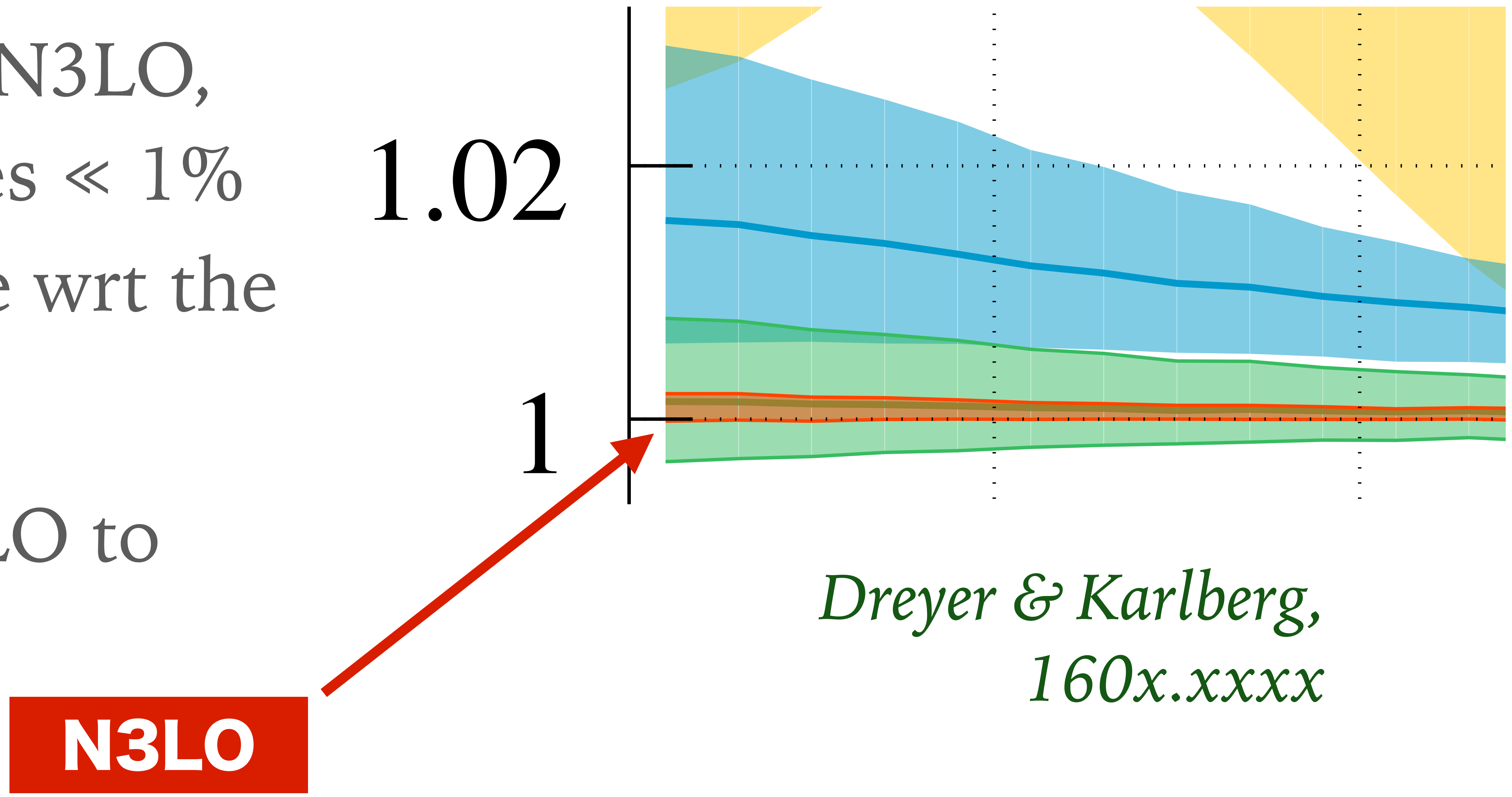


- Now being extended to N3LO, shows scale uncertainties ≪ 1% for observables inclusive wrt the jets
- good stability from NNLO to N3LO



Dreyer & Karlberg, 160x.xxxx

Exact in "$QCD_1 \otimes QCD_2$"

Non-trivial real-world corrections believed < 1%

VBF with cuts on jets: Projection to Born method

Cacciari, Dreyer, Karlberg, GPS & Zanderighi, 1506.02660

Exact in "$QCD_1 \otimes QCD_2$"

using VBF 3-jet @ NLO from Jäger, Schissler & Zeppenfeld, 1405.6950

ABSOLUTE CROSS-SECTIONS MEASURED TO ~ 1%?

Beam Imaging and Luminosity Calibration

arXiv:1603.03566v1 [hep-ex]

March 14, 2016

Markus Klute, Catherine Medlock, Jakob Salfeld-Nebgen
Massachusettes Institute of Technology

We discuss a method to reconstruct two-dimensional proton bunch densities using vertex distributions accumulated during LHC beam-beam scans. The x-y correlations in the beam shapes are studied and an alternative luminosity calibration technique is introduced. We demonstrate the method on simulated beam-beam scans and estimate the uncertainty on the luminosity calibration associated to the beam-shape reconstruction to be below 1%.