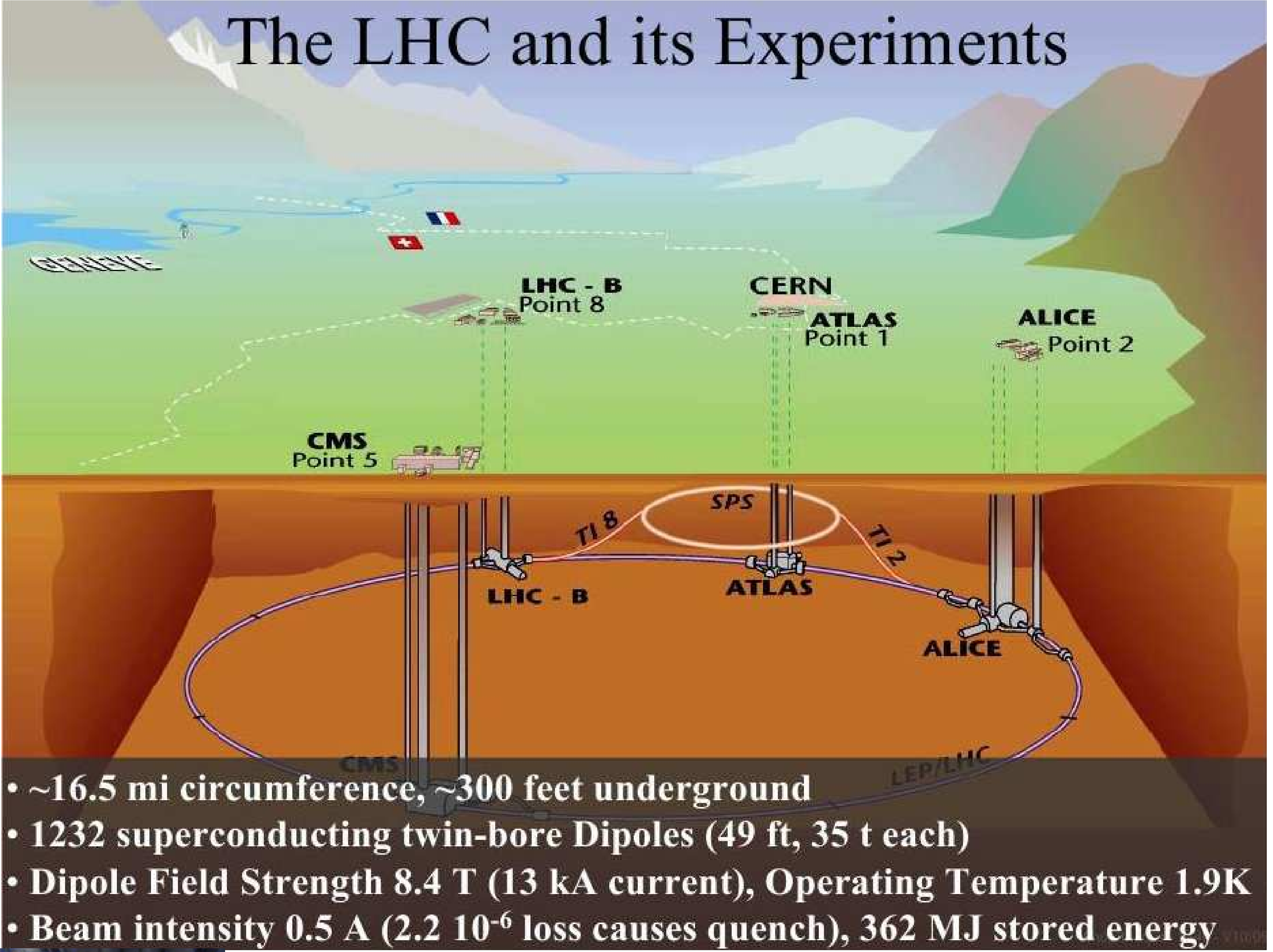
LHC THEORY — TOWARDS 1% PRECISION?

Gavin P. Salam, CERN

Joint CTEQ Meeting and 7th International Conference on Physics Opportunities at an EIC (POETIC 7)

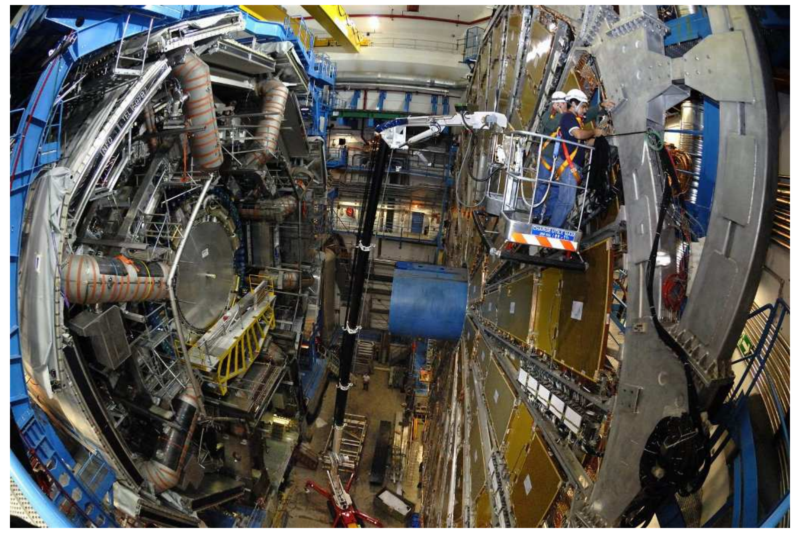
Talk in part inspired by discussions at KITP Santa Barbara
& for ECFA HL-LHC workshop

LHC – TWO ROLES – A DISCOVERY MACHINE AND A PRECISION MACHINE

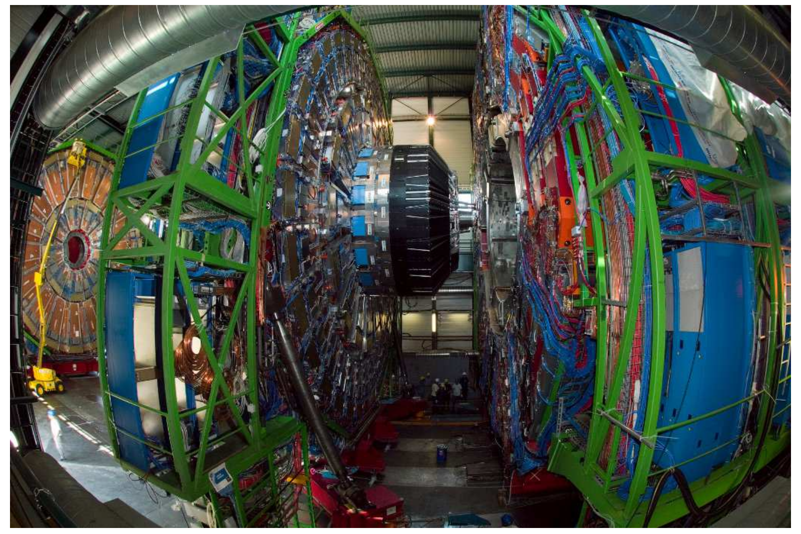


- ~16.5 mi circumference, ~300 feet underground
- 1232 superconducting twin-bore Dipoles (49 ft, 35 t each)
- Dipole Field Strength 8.4 T (13 kA current), Operating Temperature 1.9K
- Beam intensity 0.5 A (2.2 10^{-6} loss causes quench), 362 MJ stored energy

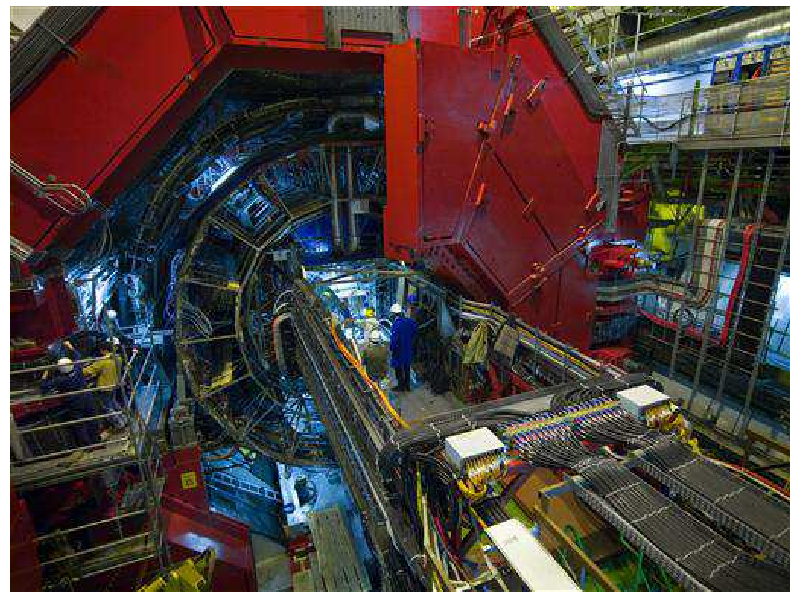
ATLAS: general purpose



CMS: general purpose



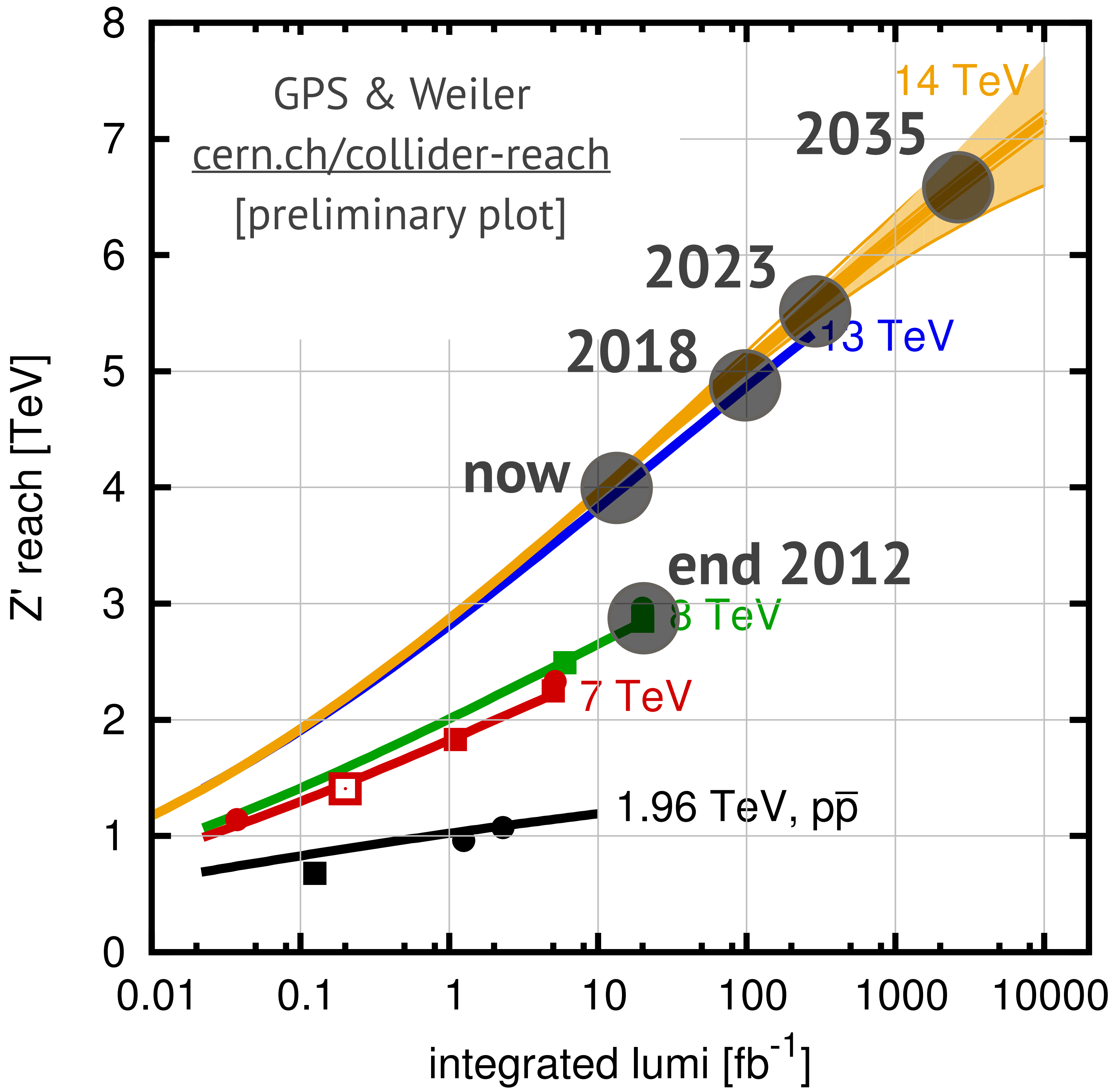
ALICE: heavy-ion physics



LHCb: B-physics

+ TOTEM, LHCf

Z' exclusion reach v. lumi



Today

- 20 fb^{-1} @ 8 TeV
- 13 fb^{-1} @ 13 TeV (analysed)

Future

- 2018: 100 fb^{-1} @ 13 TeV
- 2023: 300 fb^{-1} @ 1? TeV
- 2035: 3000 fb^{-1} @ 14 TeV

1 fb^{-1} = 10^{14} collisions

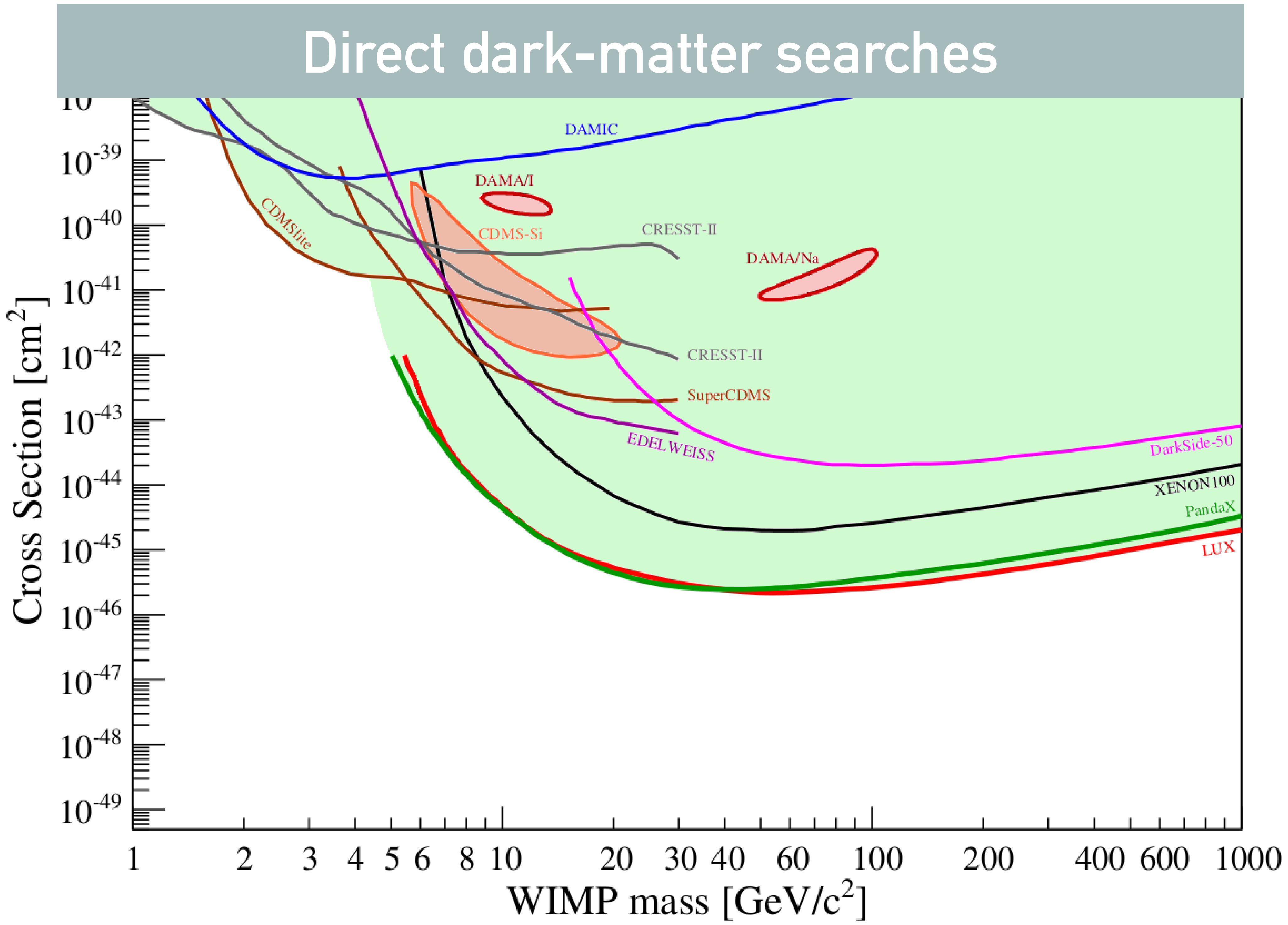
Increase in luminosity brings discovery reach and precision

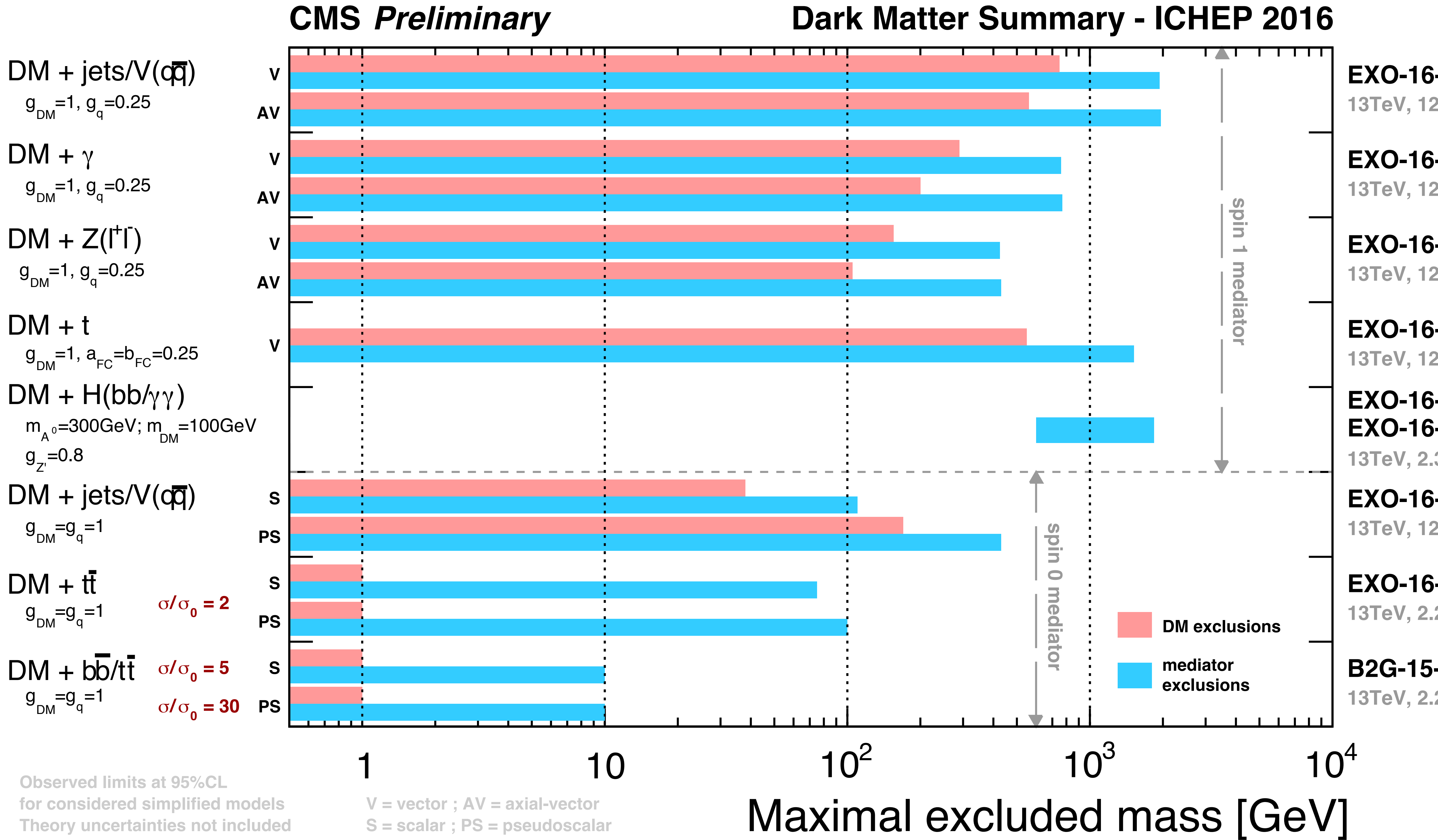
KEY UNRESOLVED PROBLEMS

- nature of dark matter
- nature of dark energy
- origin of matter-antimatter asymmetry
- …

The field has made enormous progress in excluding regions of parameter space for new physics models that resolve some of these problems.

But we need new clues.


Direct dark-matter searches

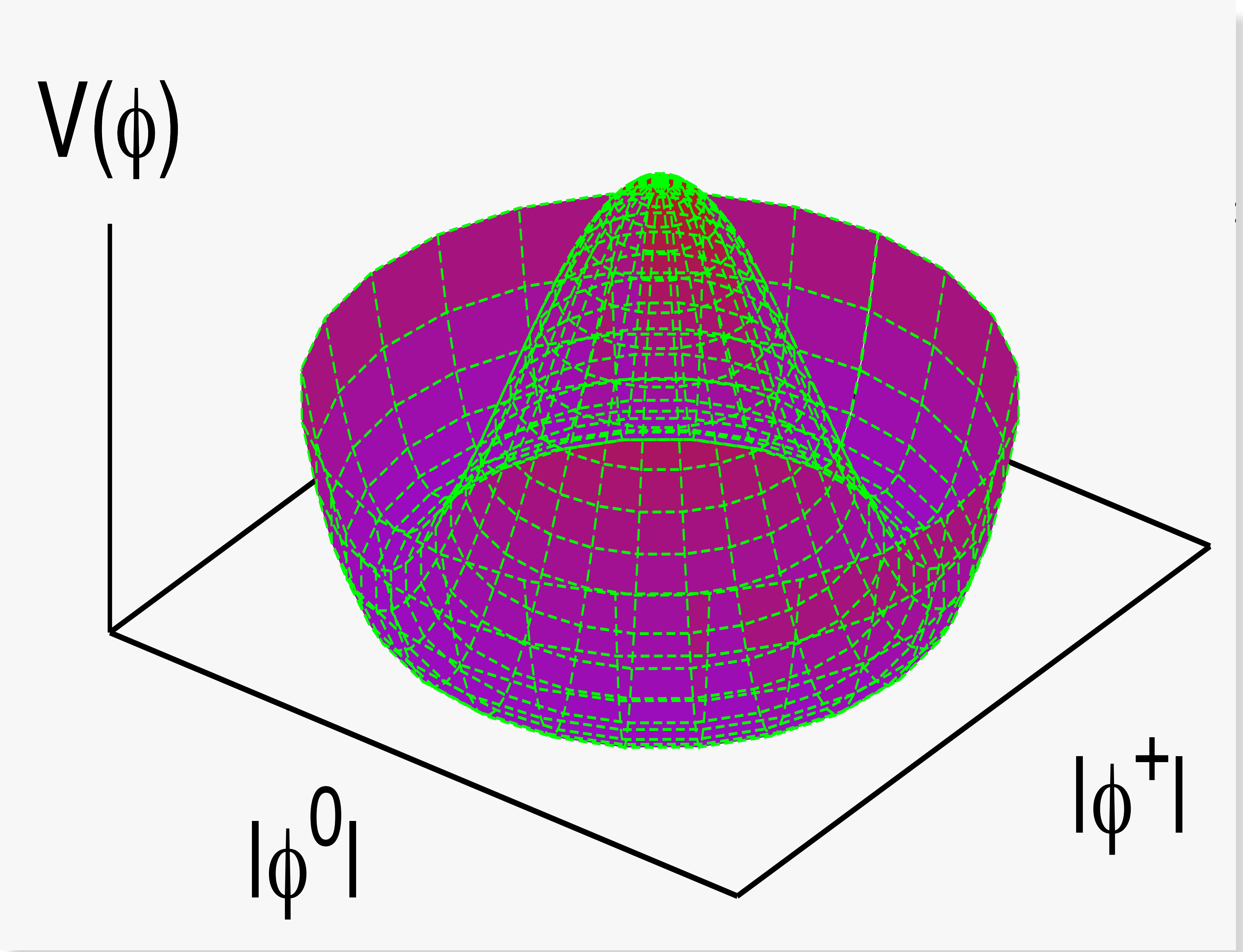


A PLACE TO LOOK: THE HIGGS-BOSON SECTOR

The theory is old (1960s-70s).

But the particle and it's theory are unlike anything we've seen in nature.

- A fundamental scalar φ, i.e. spin 0 (all other particles are spin 1 or 1/2)
- A potential $V(\varphi) \sim -\mu^2(\varphi\varphi^\dagger) + \lambda(\varphi\varphi^\dagger)^2$, which until now was limited to being theorists' "toy model" (φ^4)
- "Yukawa" interactions responsible for fermion masses, $y_i \phi \bar{\psi}\psi$, with couplings (y_i) spanning 5 orders of magnitude



Higgs sector needs stress-testing

Is Higgs fundamental or composite?
If fundamental, is it "minimal"?
Is it really φ^4?
Are Yukawa couplings responsible for all fermion masses?

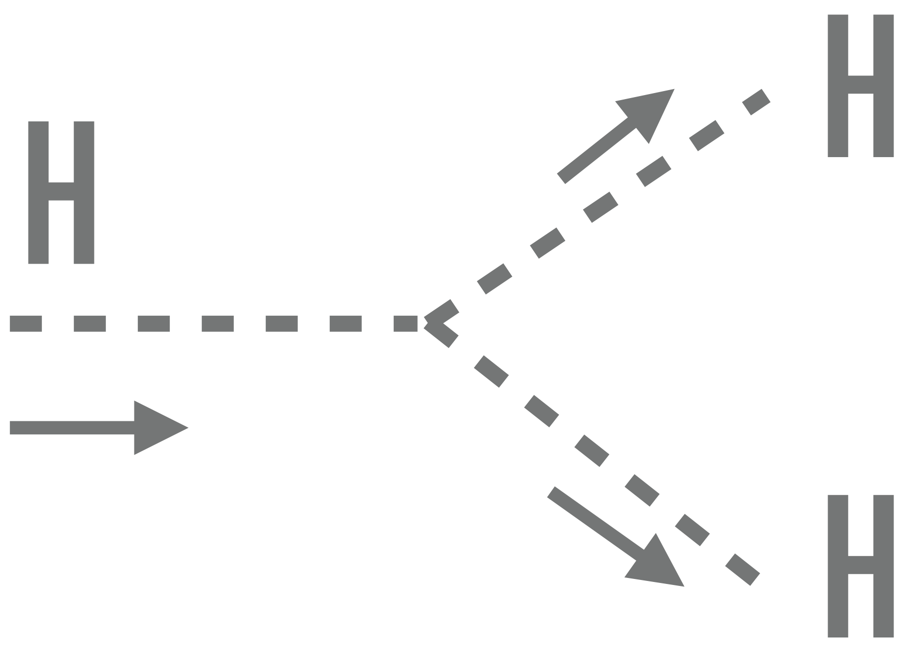
HOW DO WE STRESS-TEST THE HIGGS SECTOR?

By looking for deviations from Higgs-sector standard-model (SM) predictions

$$g = g_{\mathrm{SM}}\left[1+\Delta\right] \quad : \quad \Delta = \mathcal{O}(v^2/\Lambda^2)$$

Sensitivity to small deviations Δ ↔ probe large scales Λ where theory is not SM-like.
Higher precision → sensitivity to higher scales.

There could also be LARGE deviations in rare processes, e.g. those with couplings to second generation, or double Higgs production.

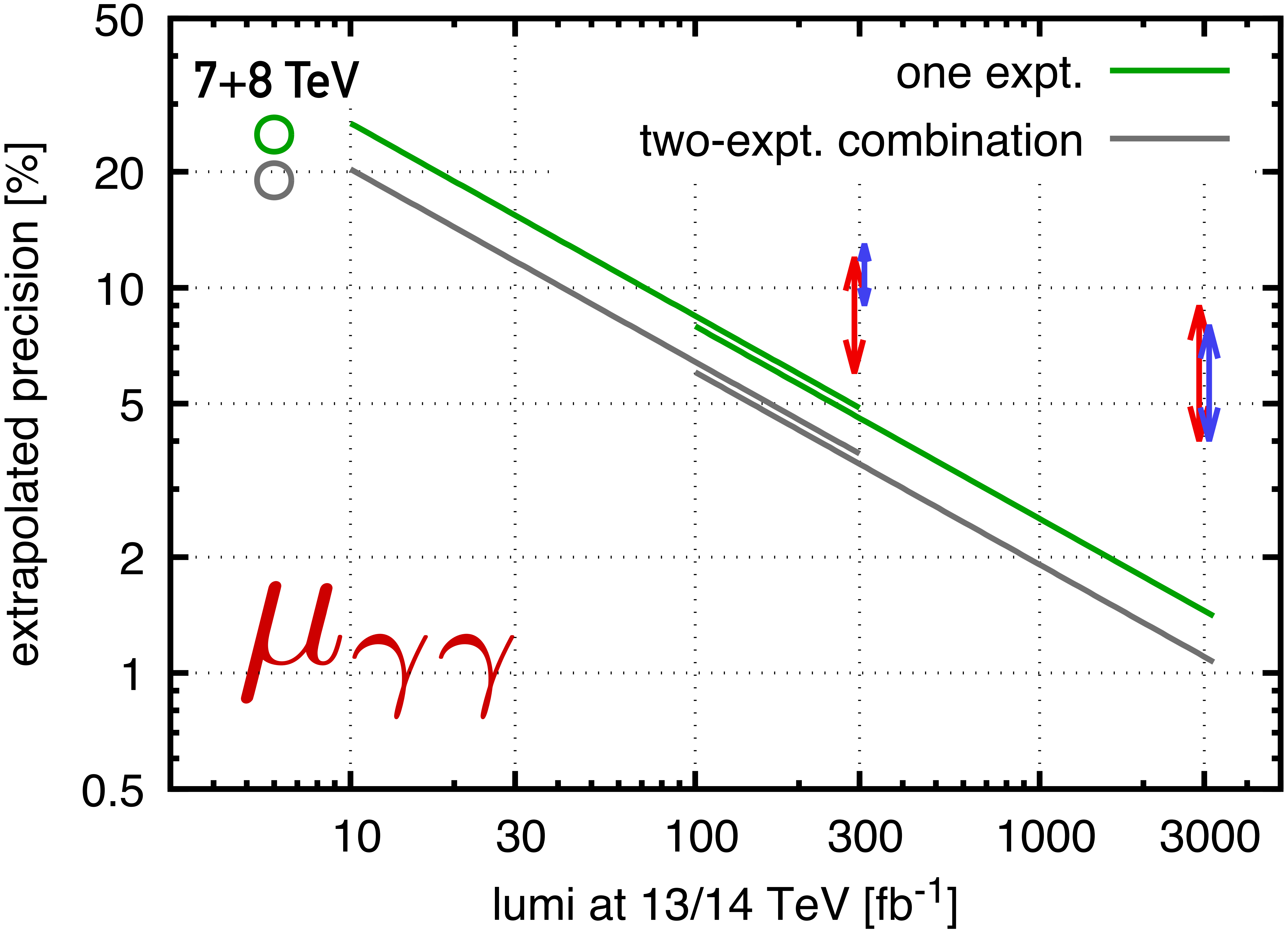


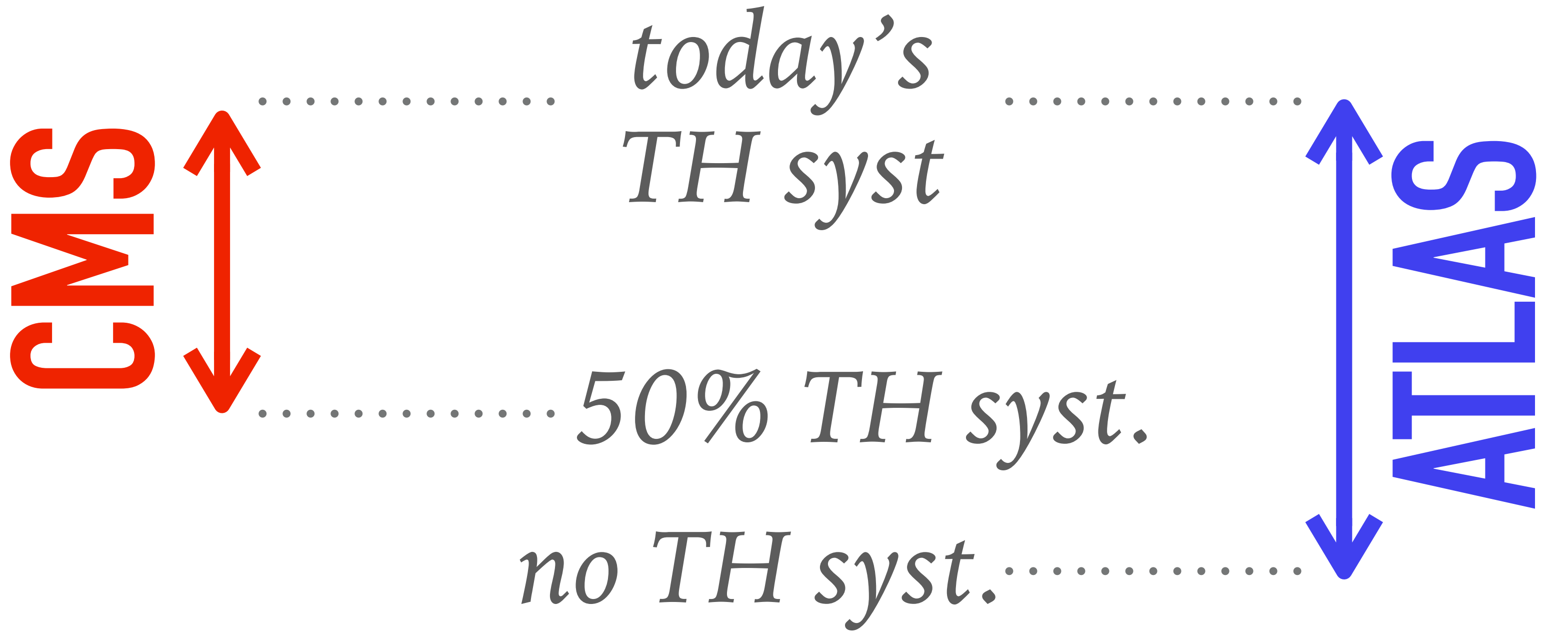
controlled by third derivative of Higgs potential at its minimum

What precision should LHC have as a target?

my personal point of view, not official LHC statements

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





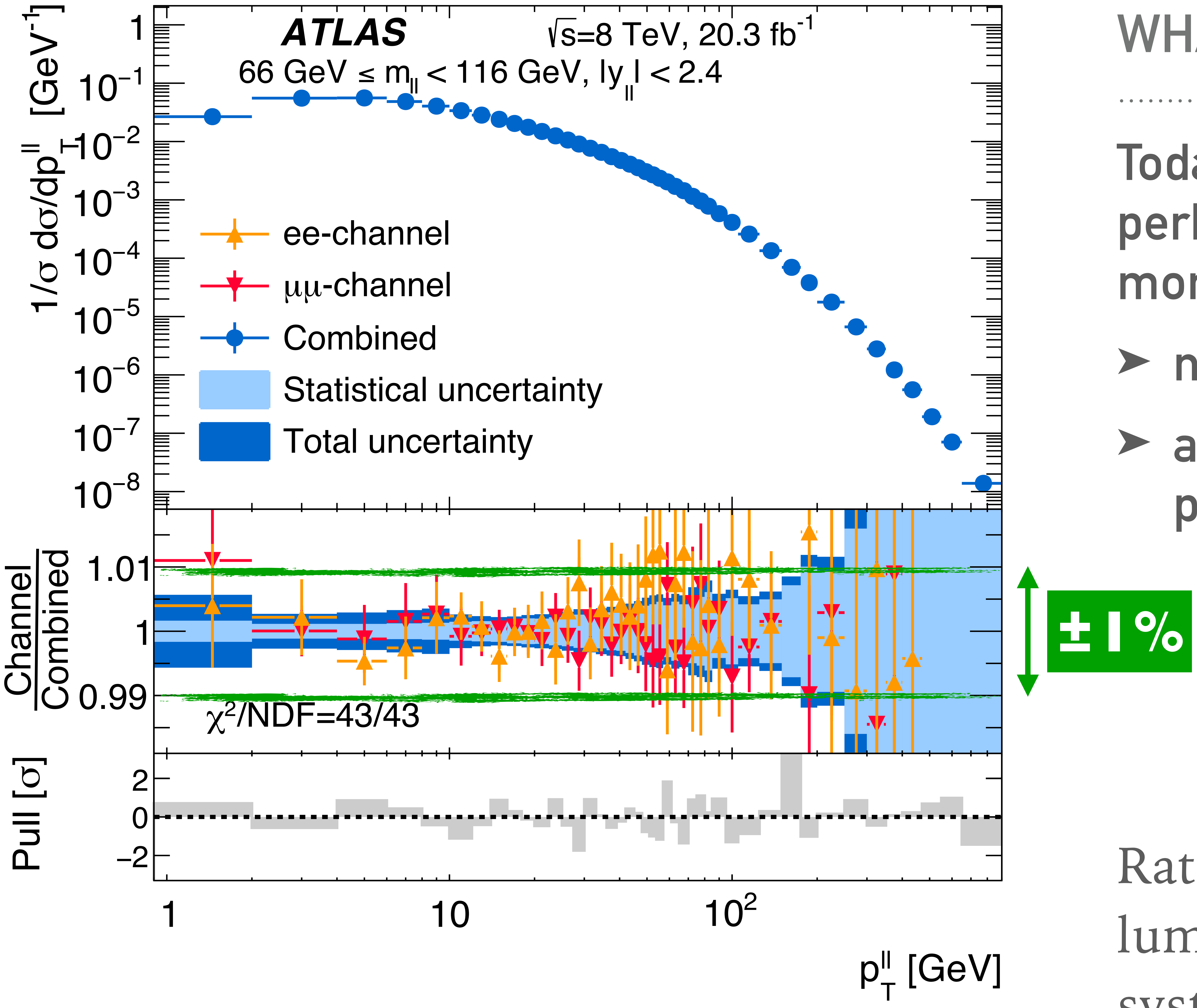
today's TH syst

50% TH syst.

no TH syst.

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

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.

OVERALL, 1% SEEMS AN INTERESTING FIGURE TO HAVE IN MIND

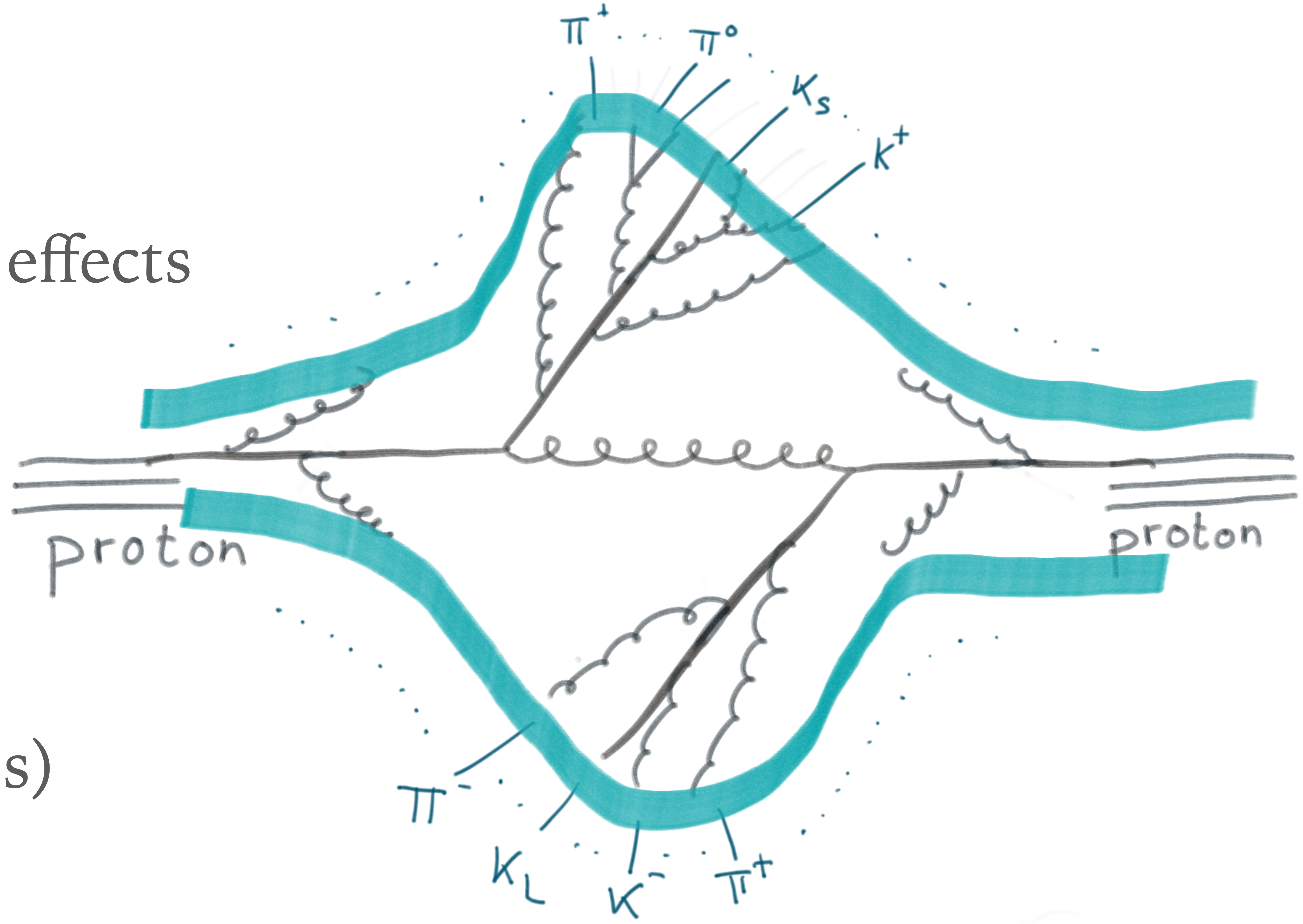
What do we need to get there?

Theory:

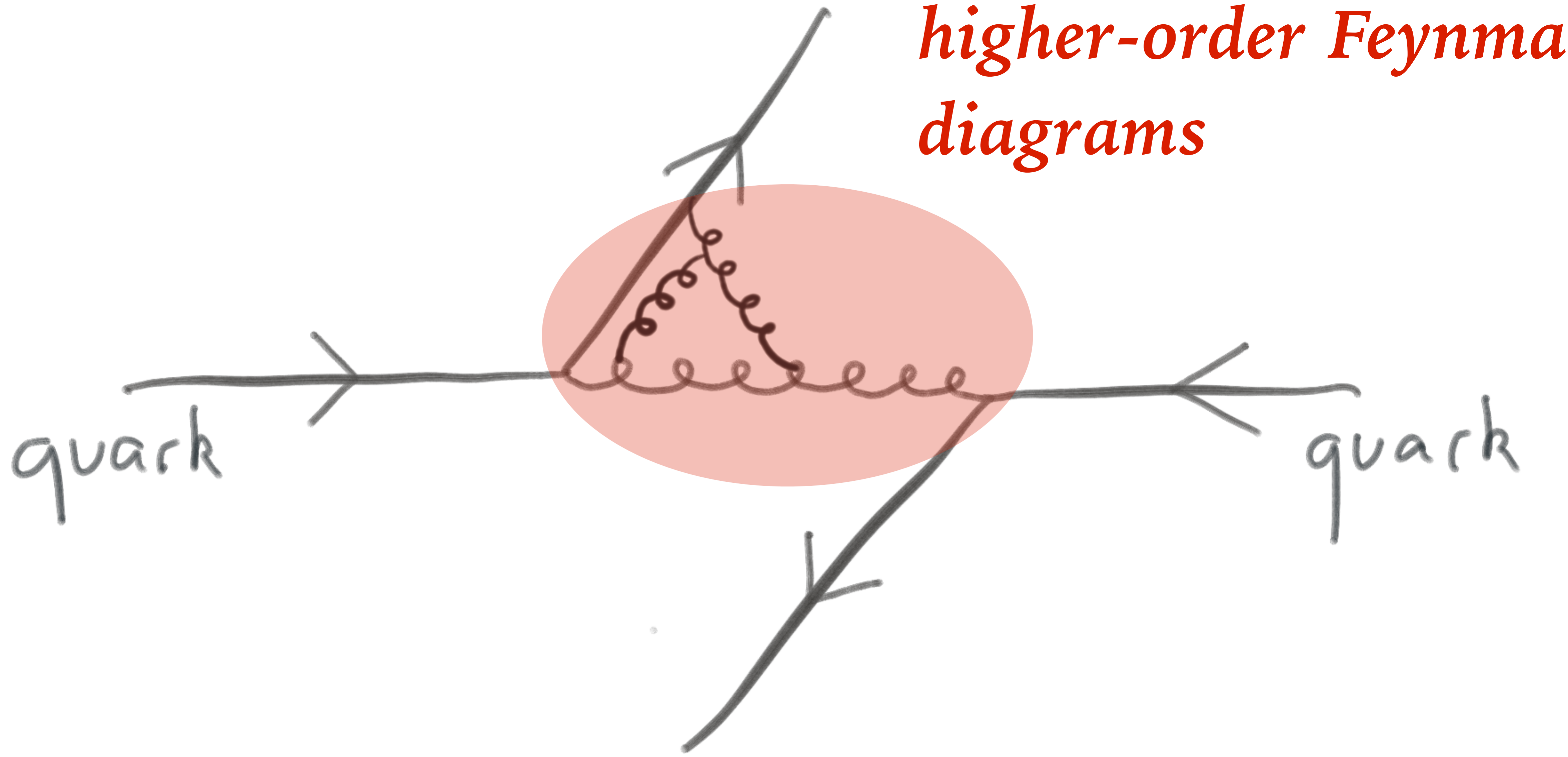
- perturbative calculations
- understanding of non-perturbative effects

Inputs

- the strong coupling
- parton distribution functions (PDFs)



Perturbative calculations



higher-order Feynman diagrams

(almost) all theory predictions for LHC are based on perturbation theory, e.g.

$$\sigma = a_s \sigma_1 + a_s^2 \sigma_2 + \ldots$$

PRECISION LHC PHYSICS RELIES ON PRECISION THEORY

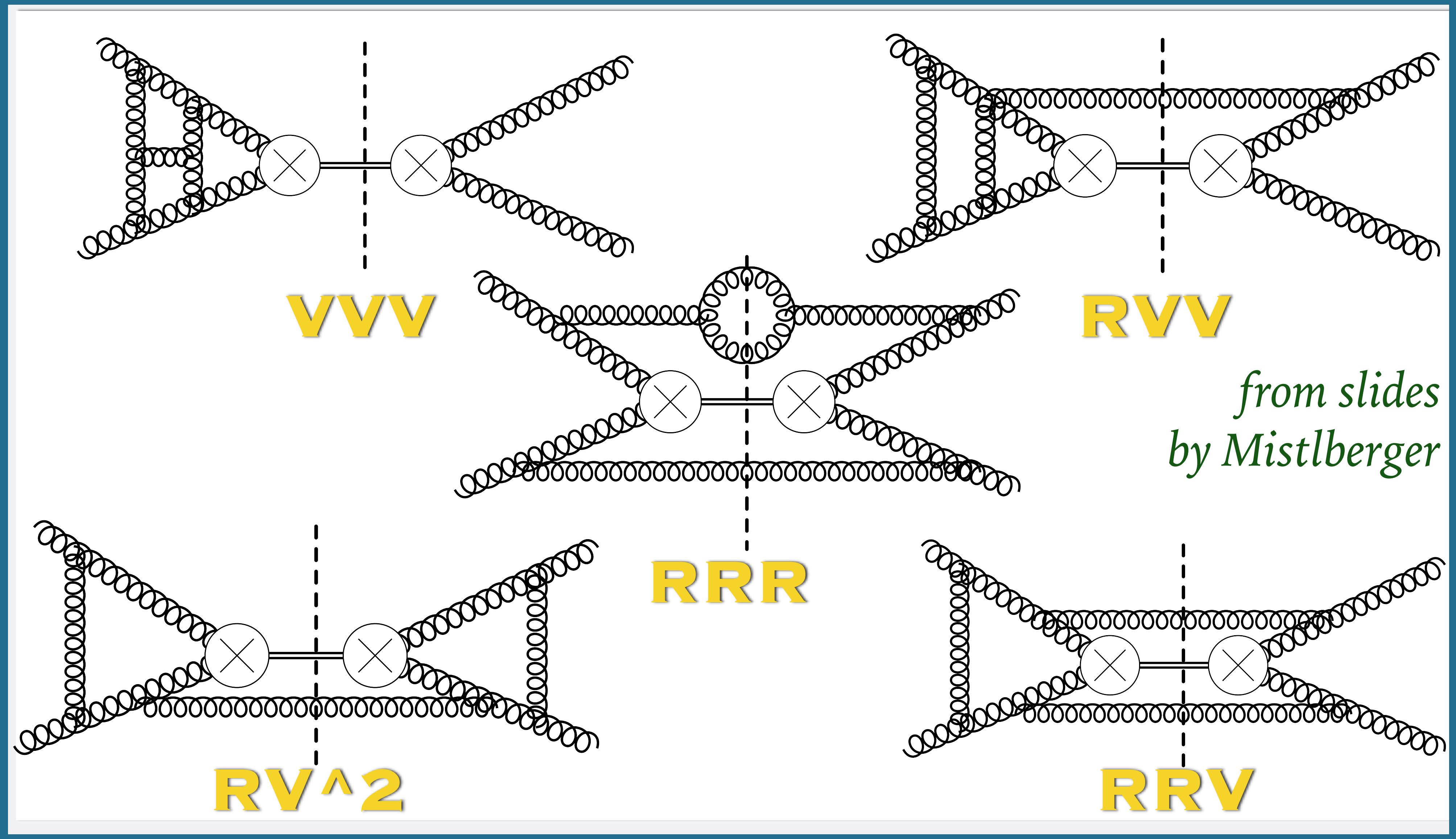
Progress on calculations has been stunning in the past years

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

N3LO Higgs production

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

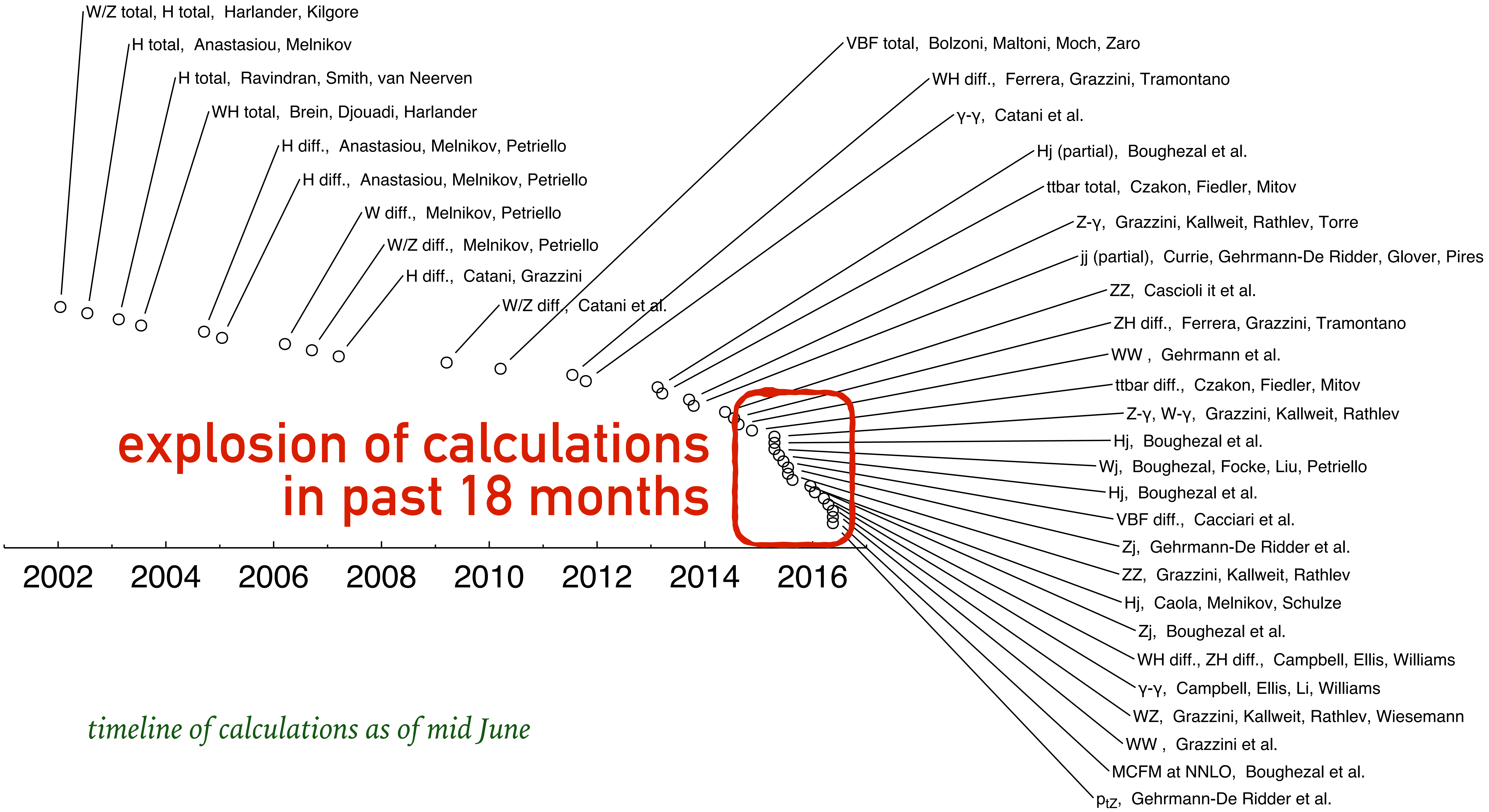
100,000 diagrams



from slides by Mistlberger

gives a few % precision for Higgs cross section

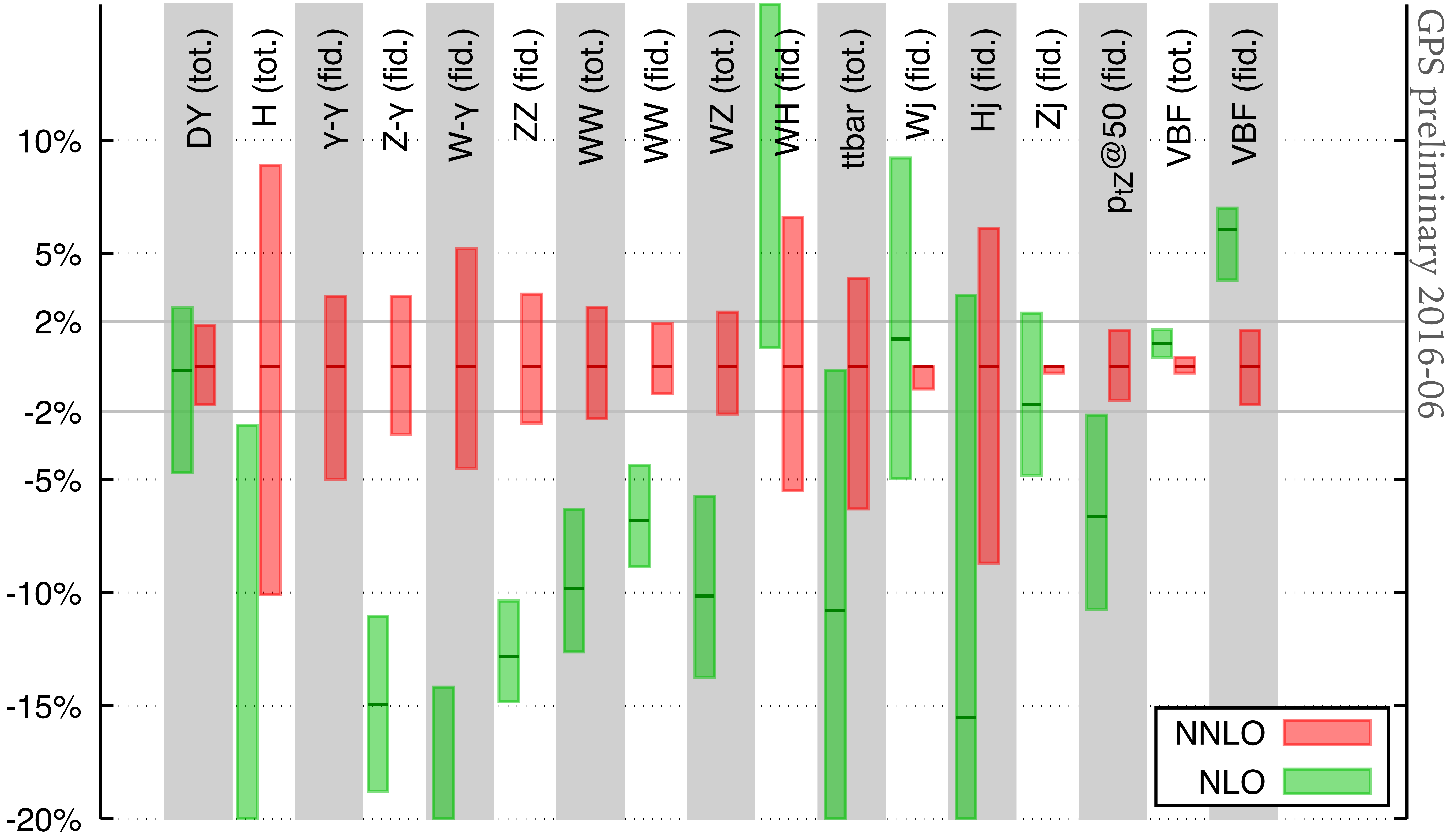
NNLO (relative α_s^2) is becoming today's state of the art



explosion of calculations in past 18 months

timeline of calculations as of mid June

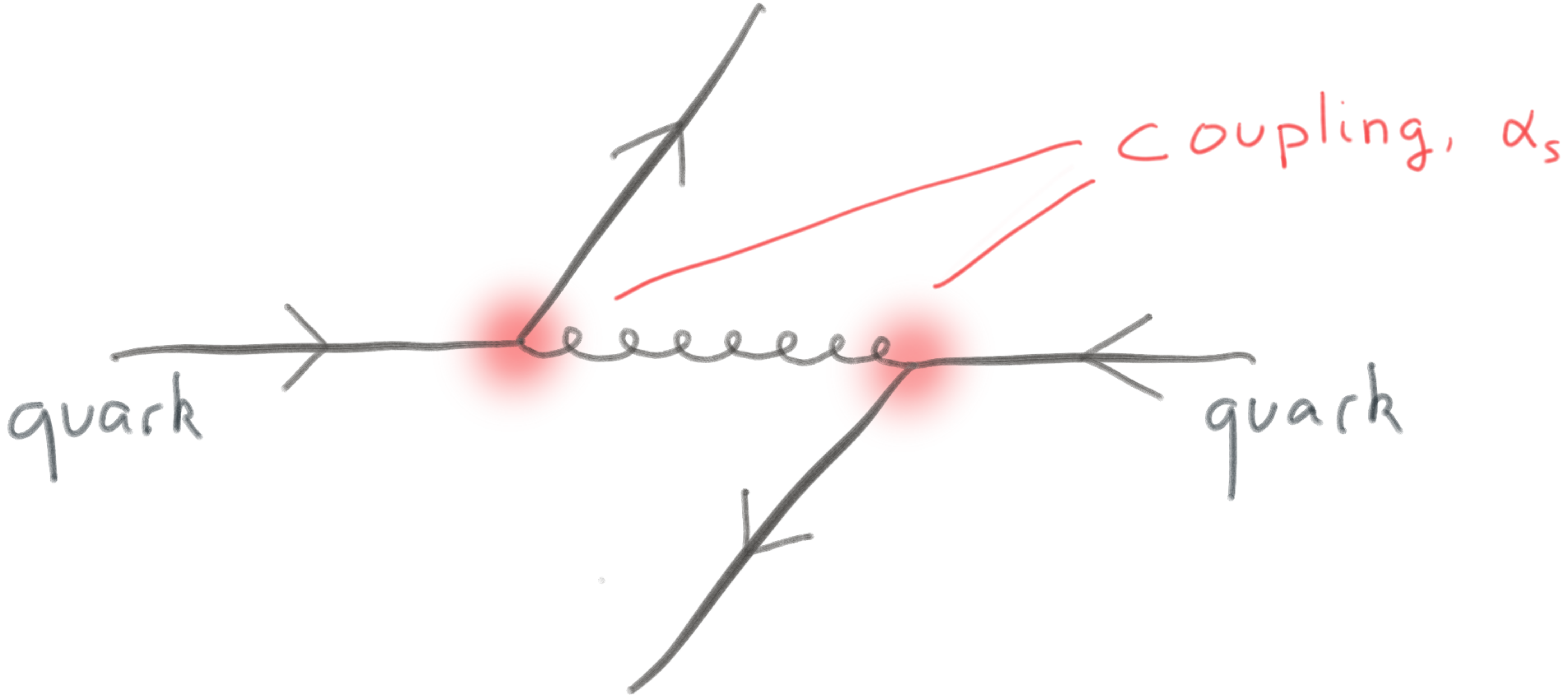
WHAT PRECISION AT NNLO?



For many processes NNLO scale band is ~±2%

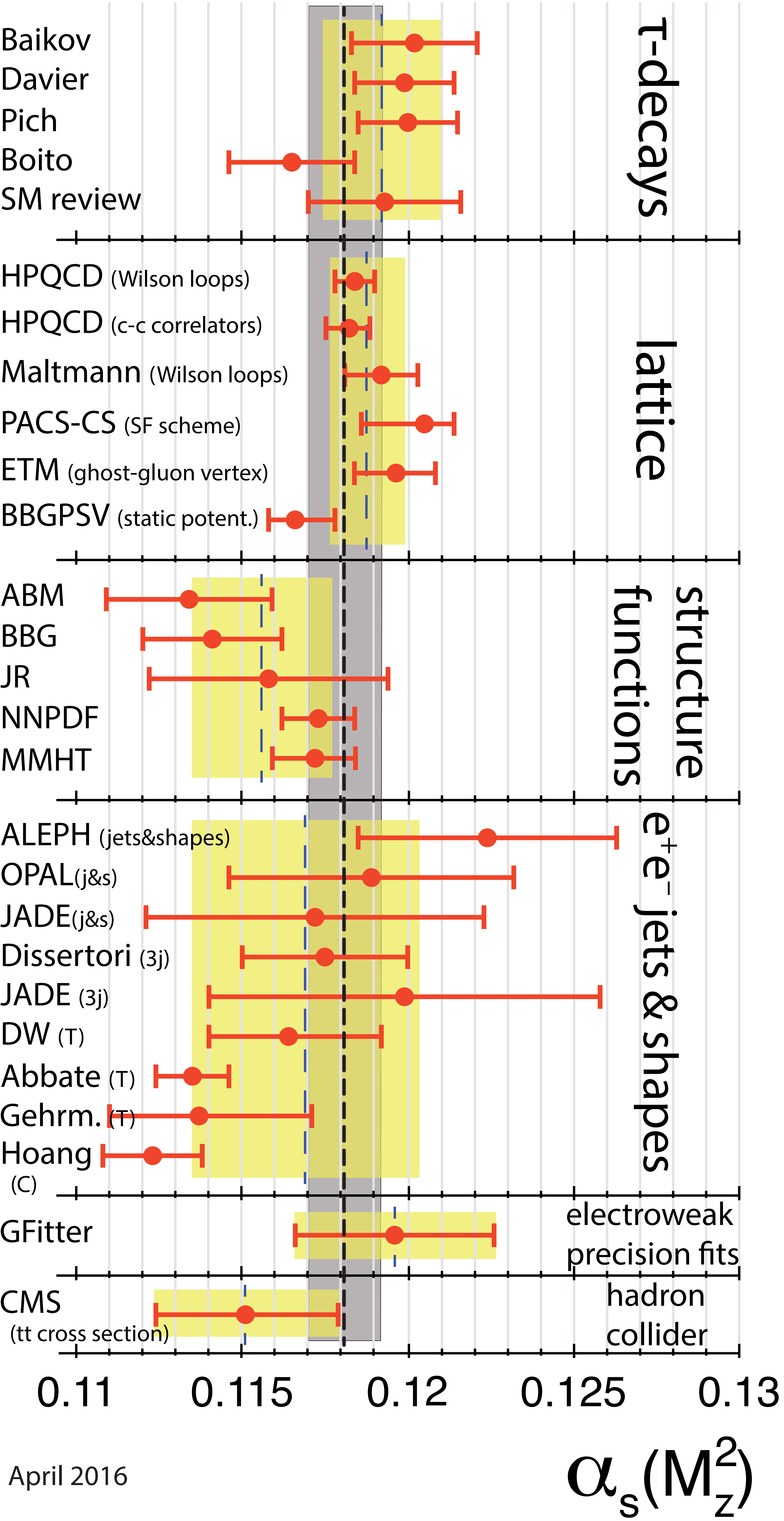
Though only in 3/17 cases is NNLO (central) within NLO scale band…

The strong coupling: α_s



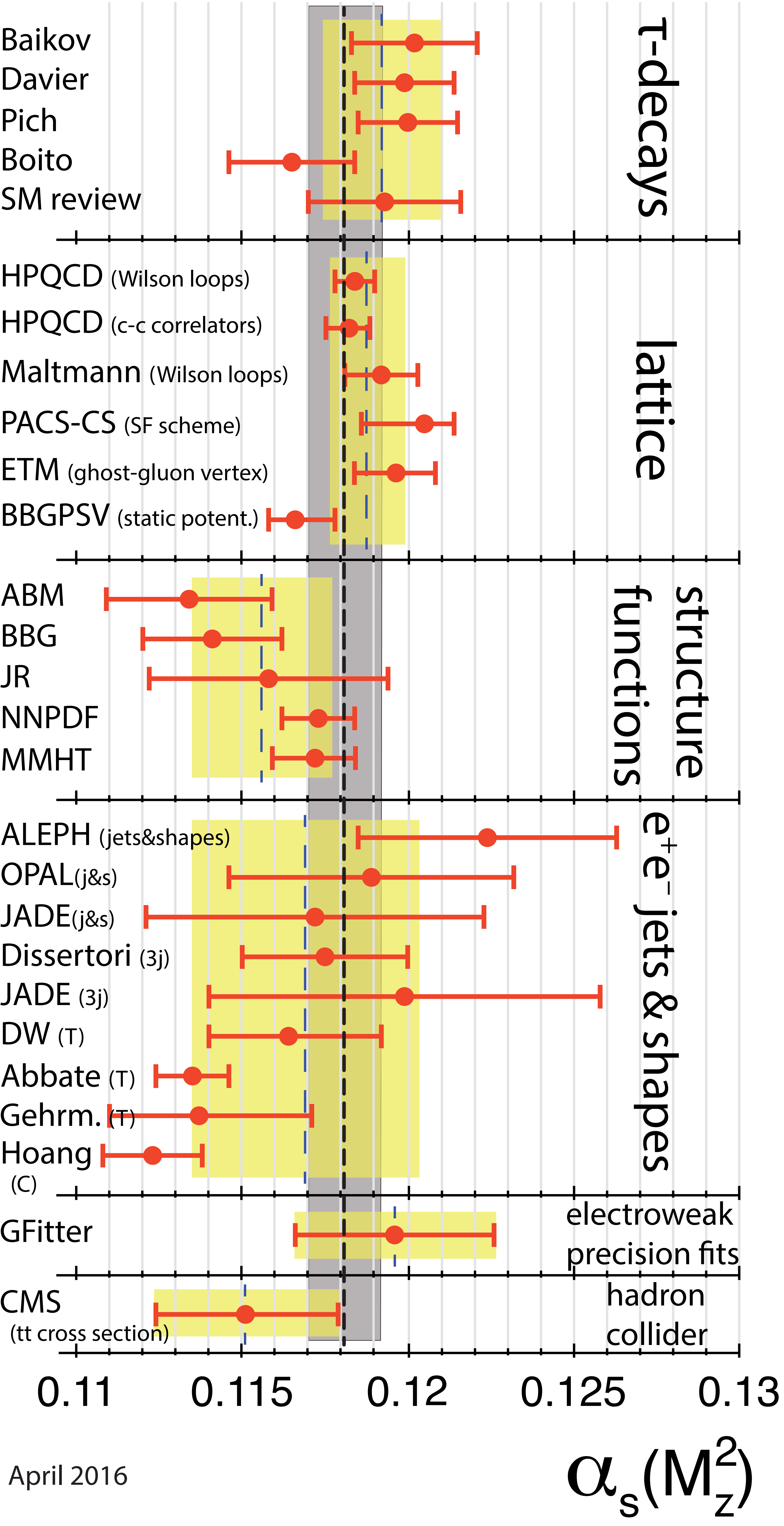
(almost) all theory predictions for LHC are based on perturbation theory, e.g.

$$\sigma = a_s\sigma_1 + a_s{}^2\sigma_2 + \dots$$



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

Bethke, Dissertori & GPS in PDG '16



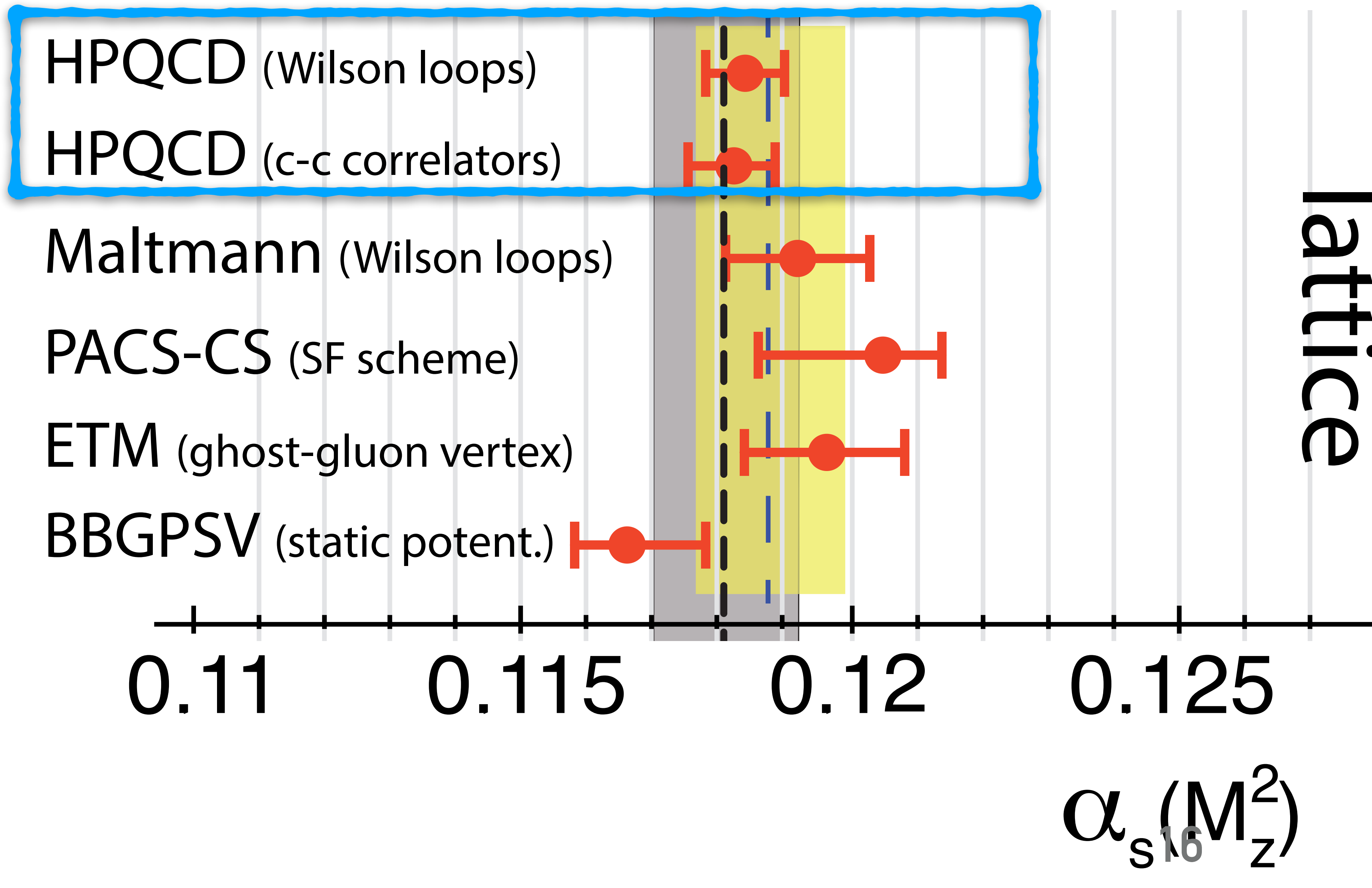
April 2016

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

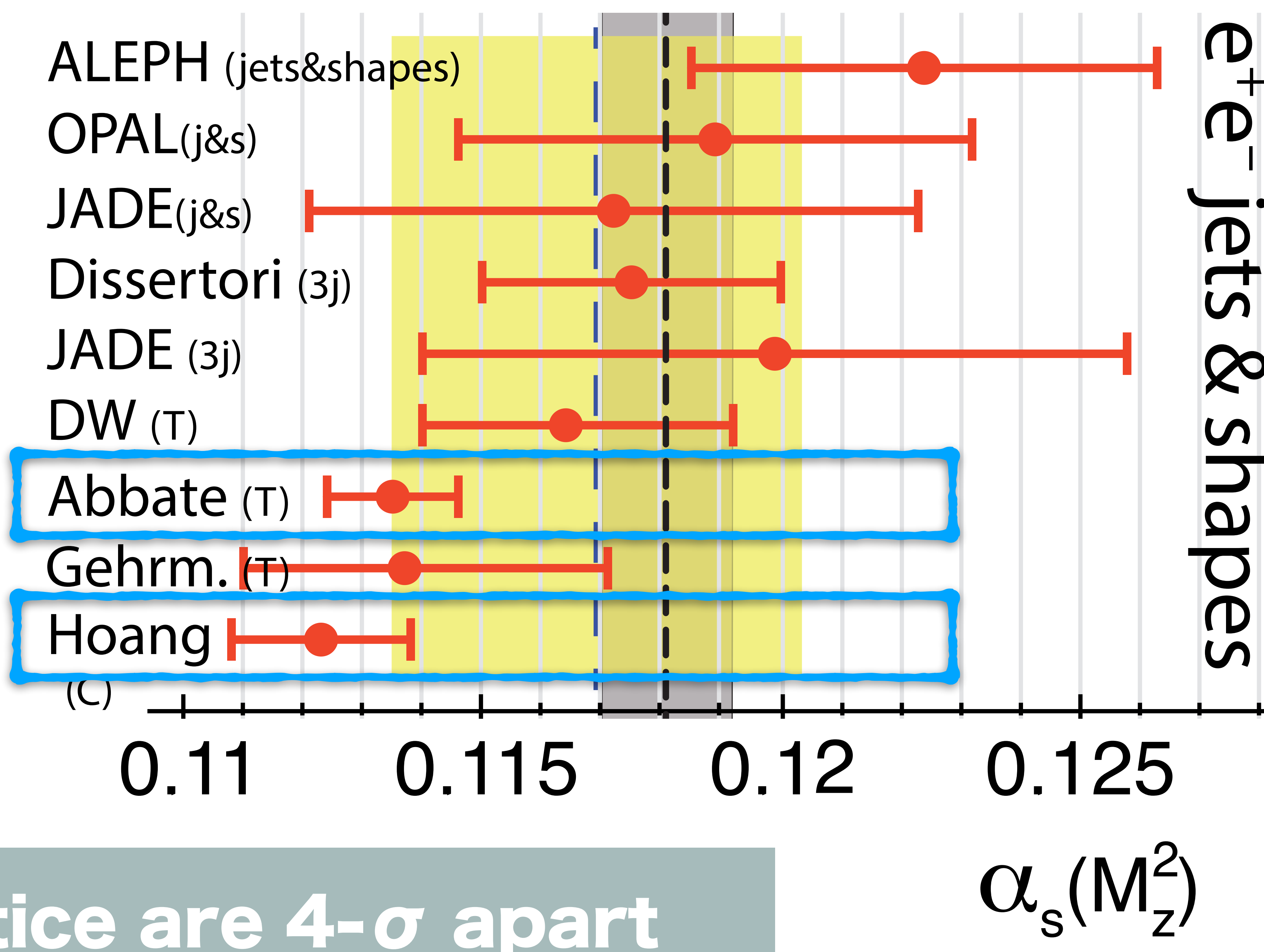
$\alpha_s(M_Z) = 0.1184 \pm 0.0012$(1%)

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

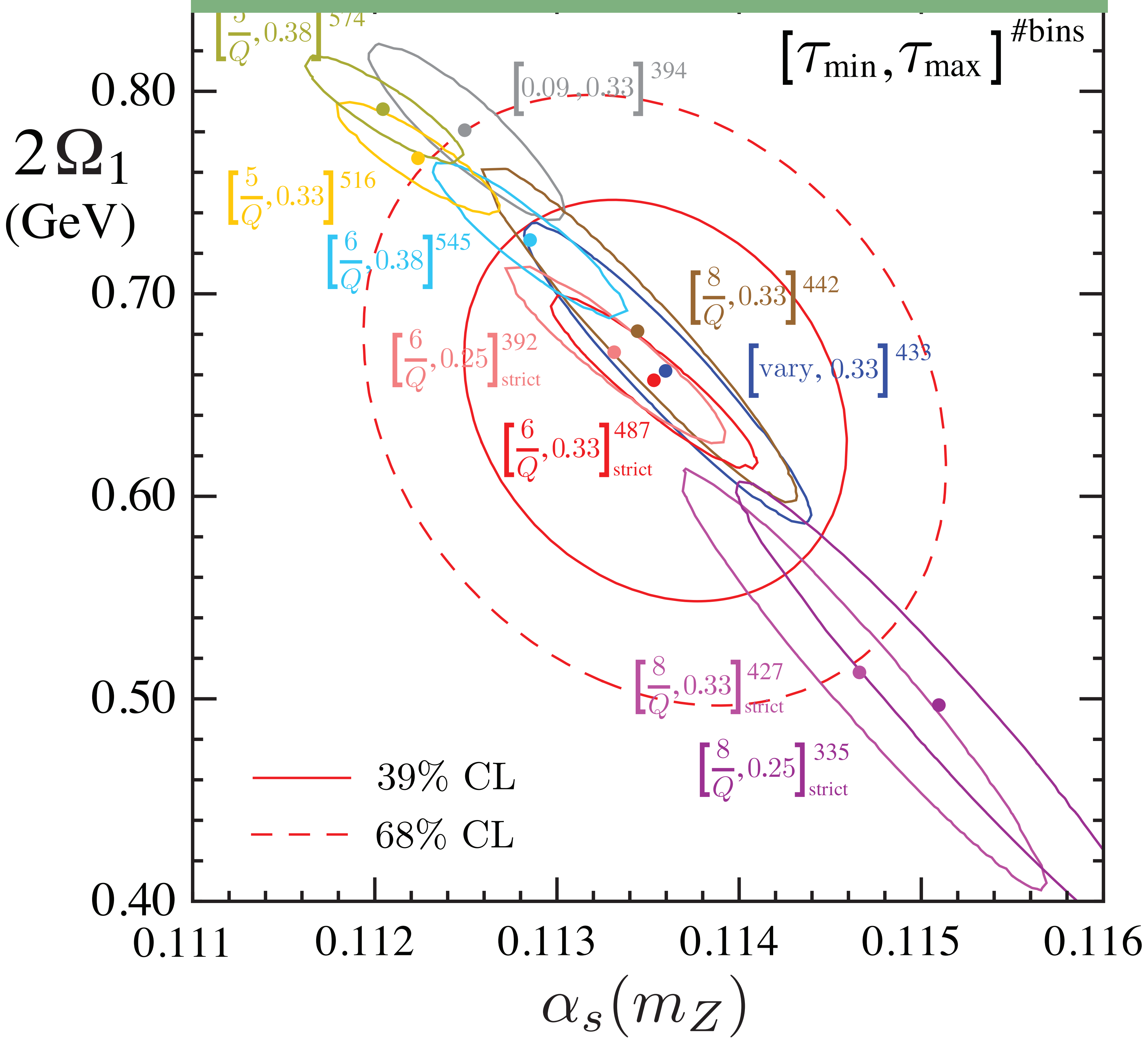


E+E- EVENT SHAPES AND JET RATES

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



dependence on fit range



thrust & “best” lattice are 4-σ apart

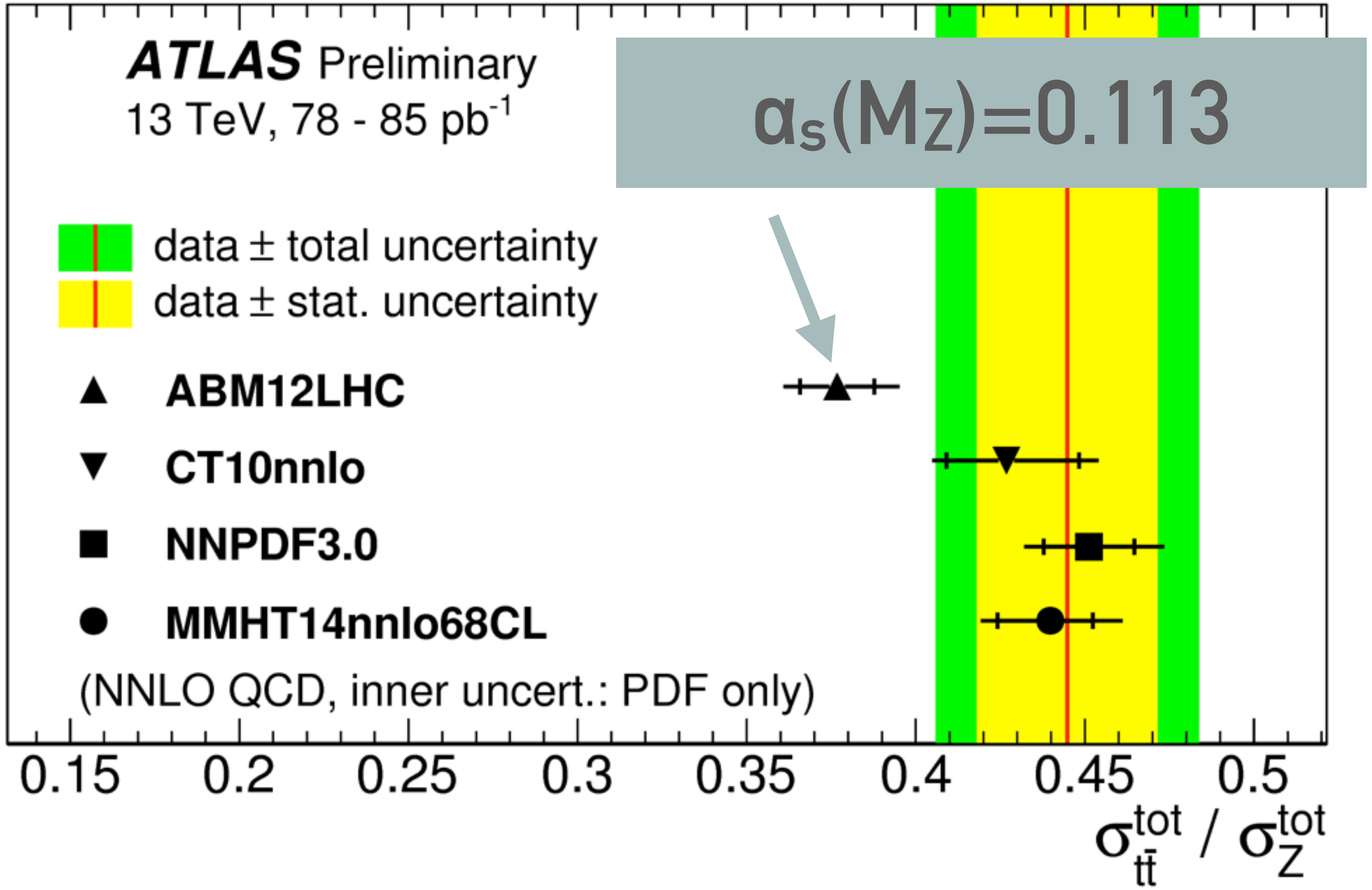
Comments:

- thrust & C-parameter are highly correlated observables
- event-shapes subject to large non-perturbative effects, and precision relies on accurate understanding of them (no consensus in the field that that’s been reached)
- some groups also find small $\alpha_s(M_Z)$ from DIS (but many argue this is an artefact of the fit procedure)

WHAT WAY FORWARD FOR α_s?

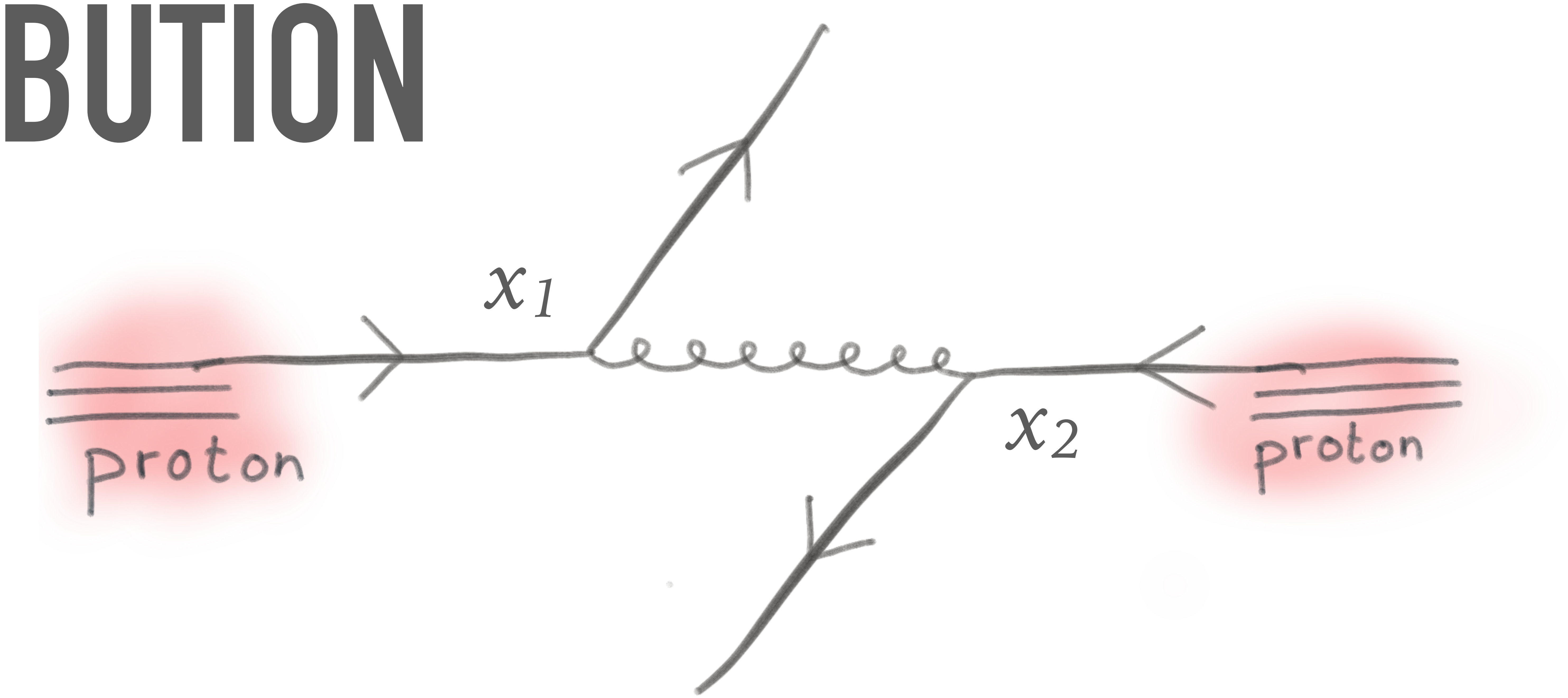
- We need to settle question of whether "small" (0.113) α_s is possible. LHC data already weighing in on this (top data), further info in near future (Z p_T?)?
- To go beyond 1%, best hope is probably lattice QCD — on a 10-year timescale, there will likely be enough progress that multiple groups will have high-precision determinations

ATLAS-CONF-2015-049



NB: top-quark mass choice affects this plot

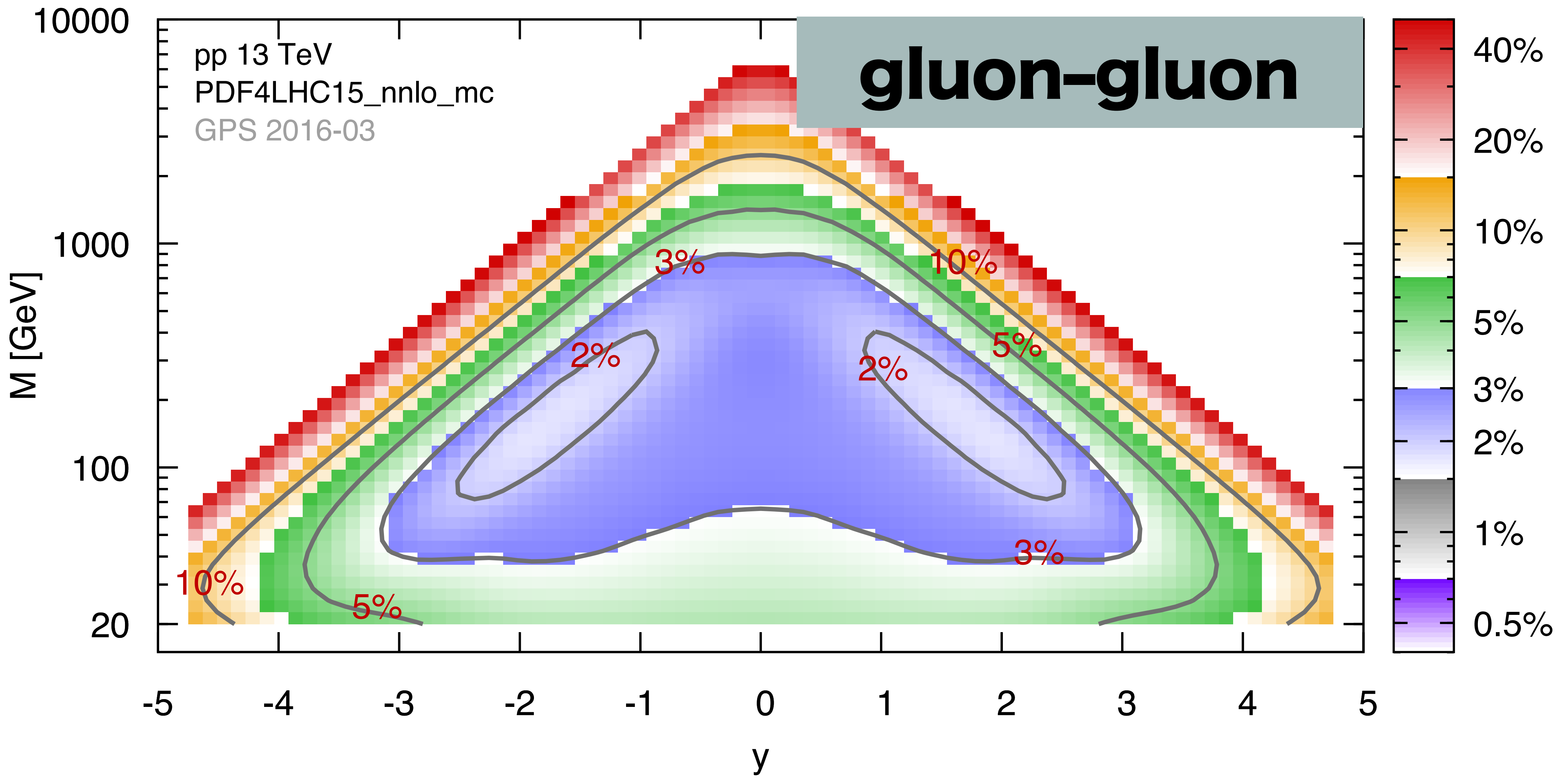
PARTON DISTRIBUTION FUNCTIONS (PDFs)



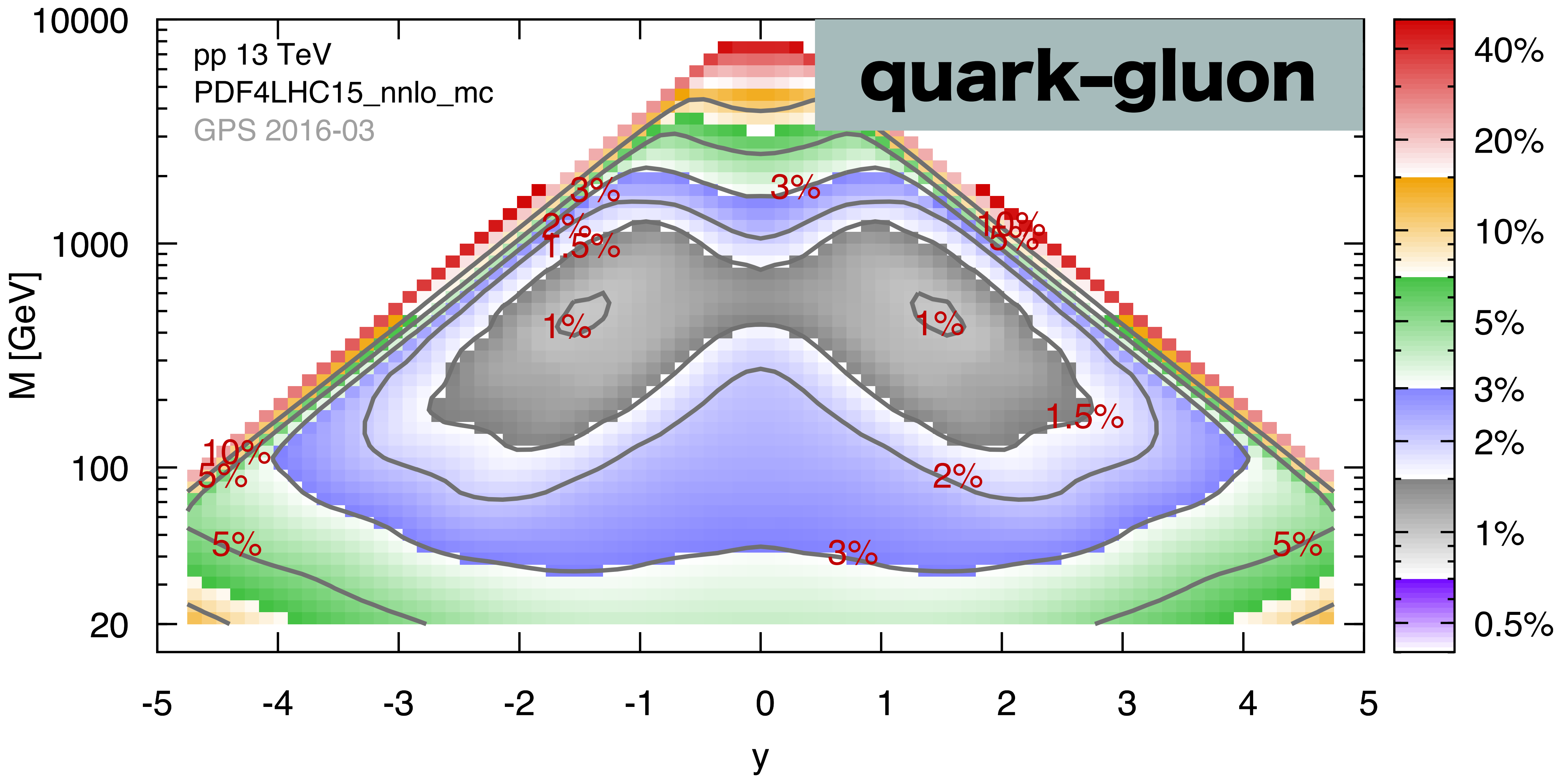
how many quarks and gluons are there
carrying a fraction x of the proton's momentum?

$$\sigma \propto f_{q/p}(x_1,\mu^2)\ f_{q/p}(x_2,\mu^2)$$

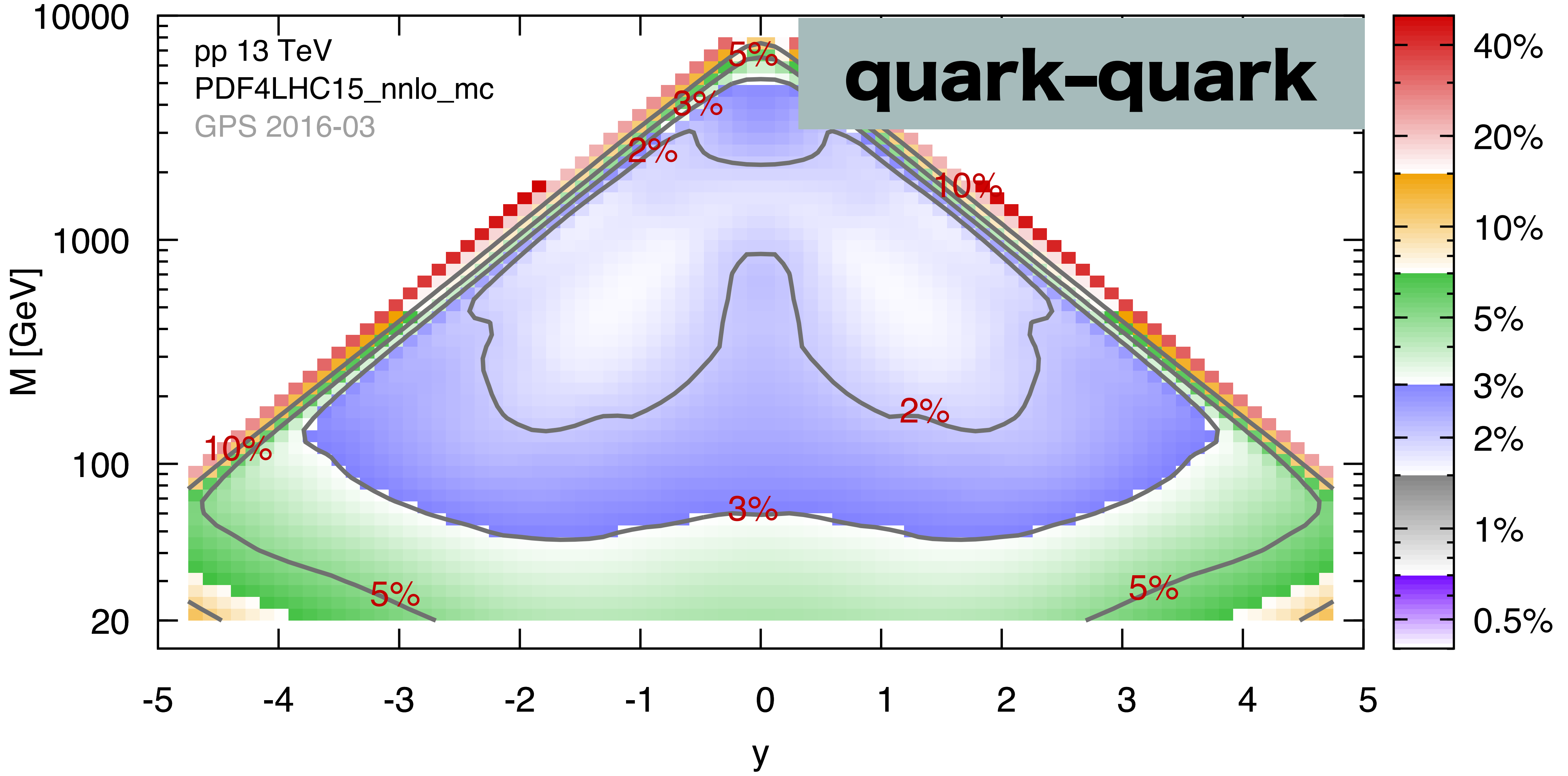
UNCERTAINTIES ON PARTONIC LUMINOSITIES — V. RAPIDITY(Y) AND MASS



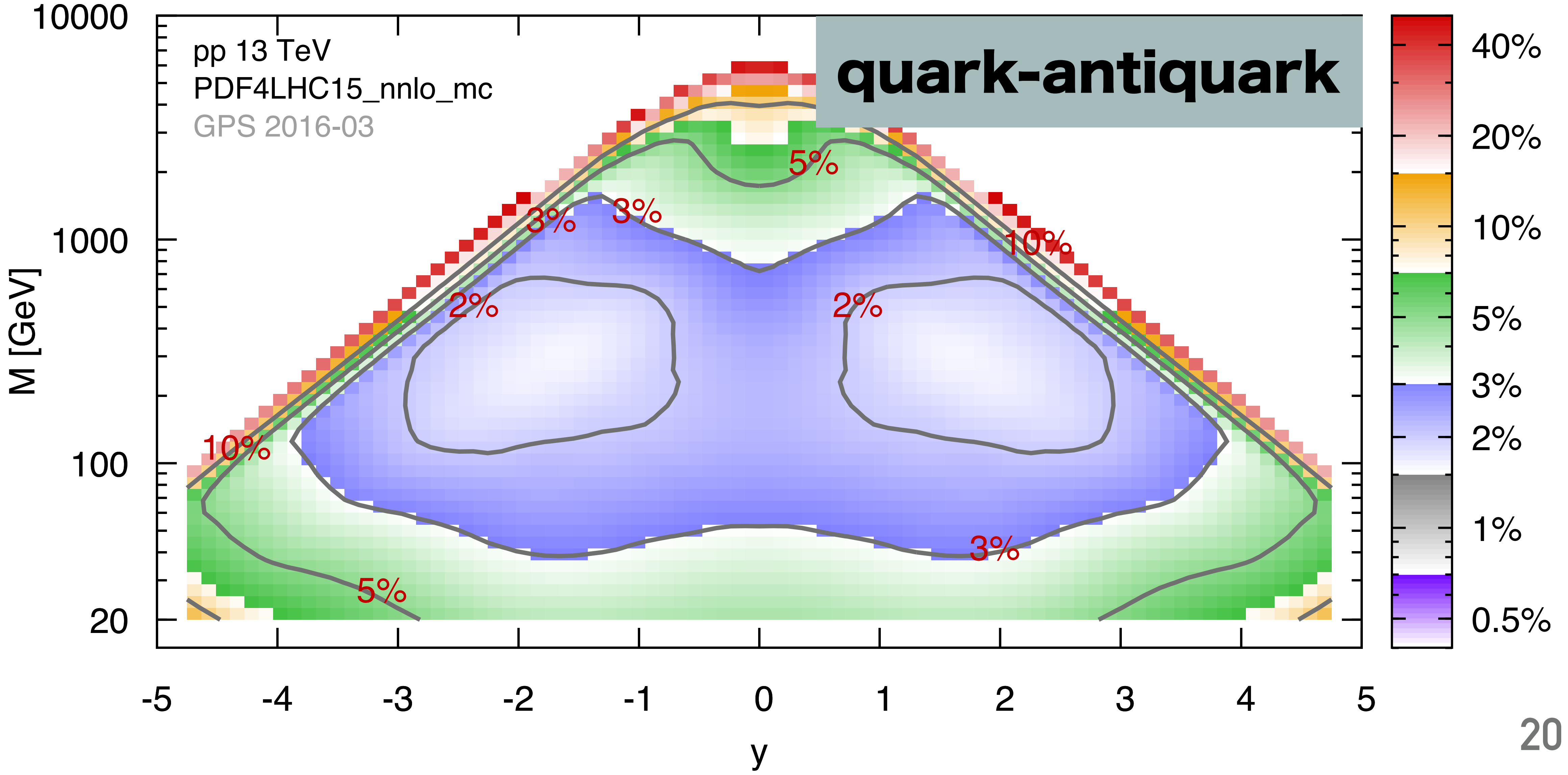
gluon-gluon luminosity uncertainty



quark-gluon luminosity uncertainty



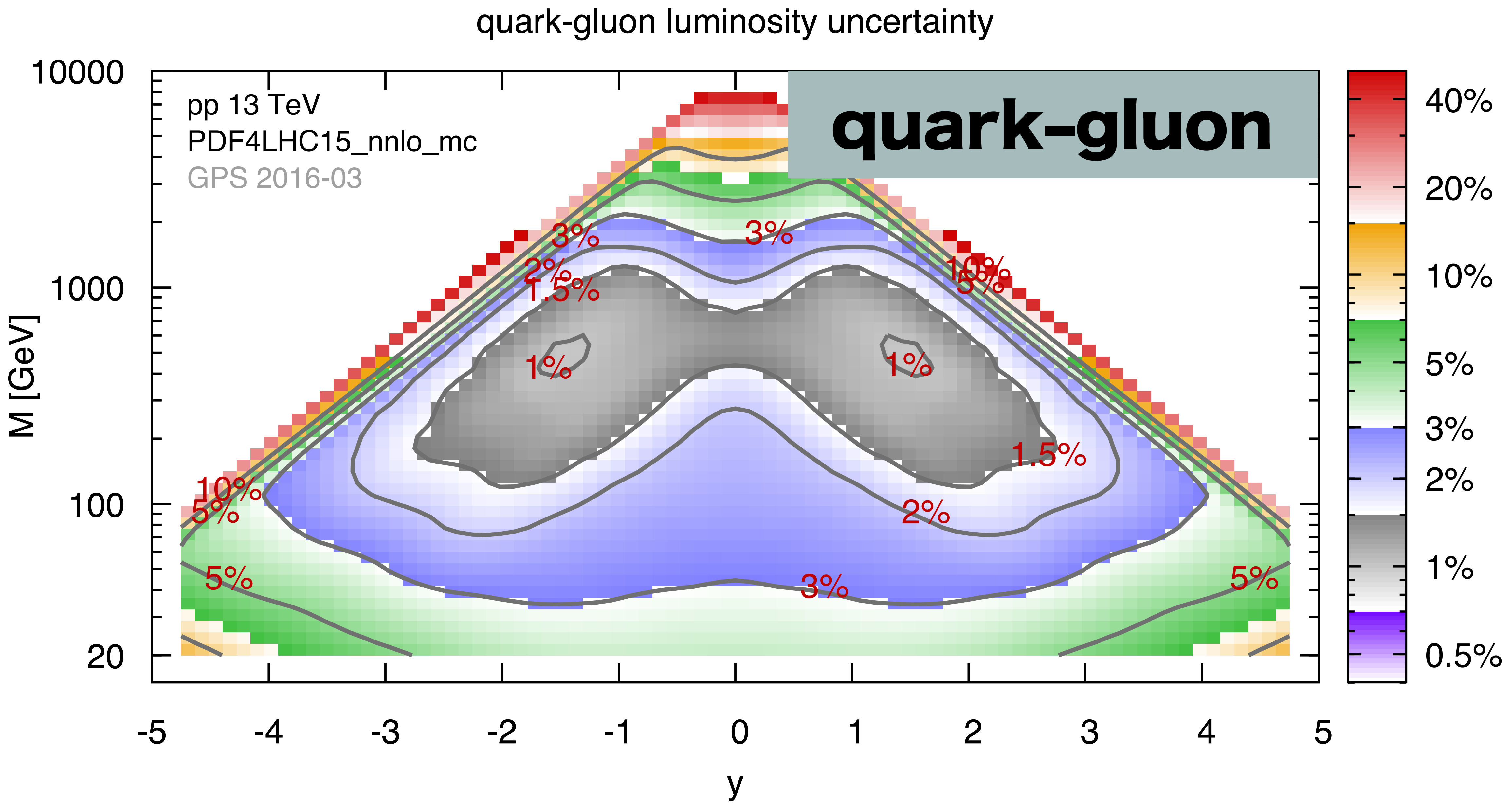
quark-quark luminosity uncertainty

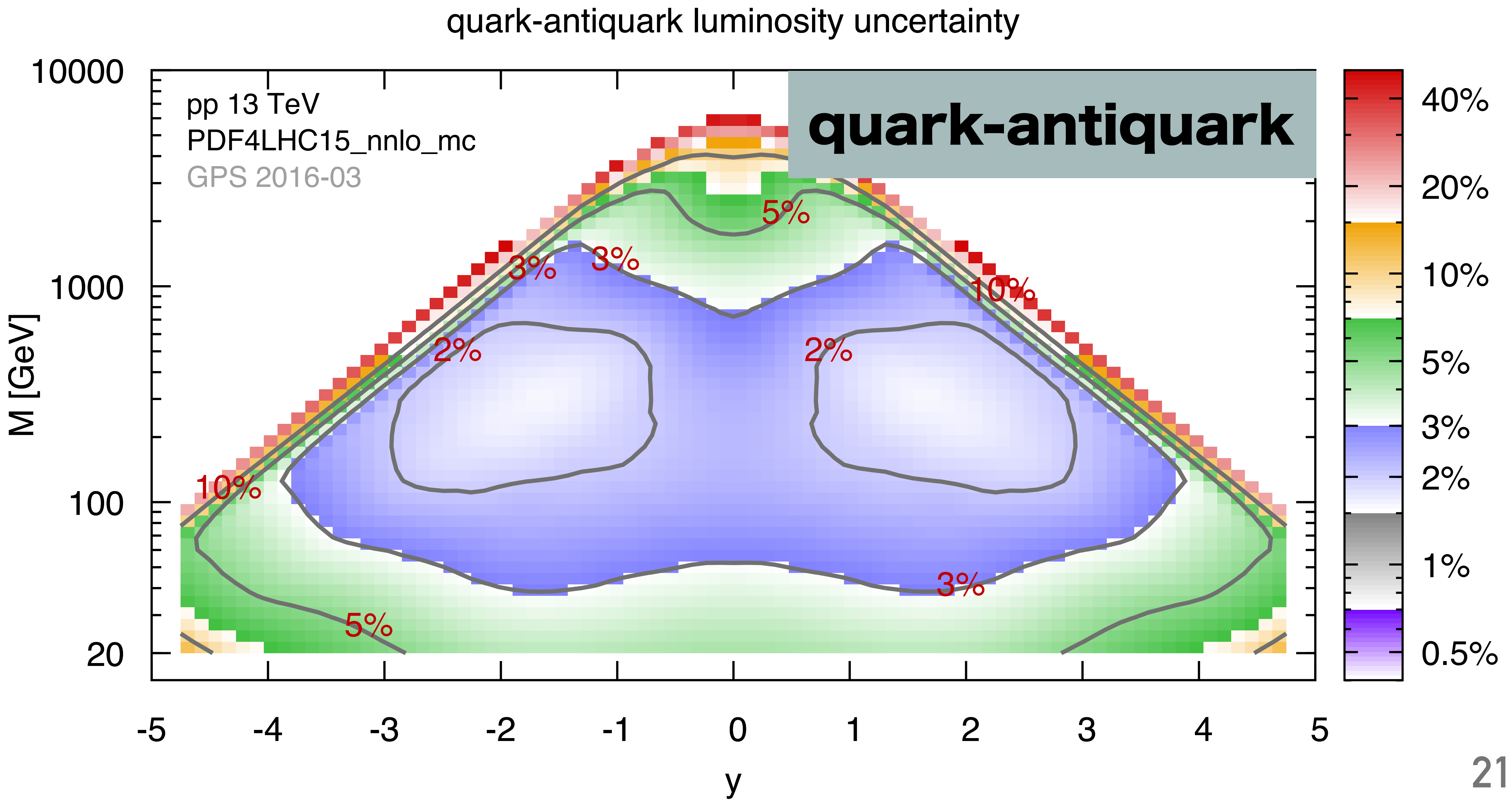


quark-antiquark luminosity uncertainty

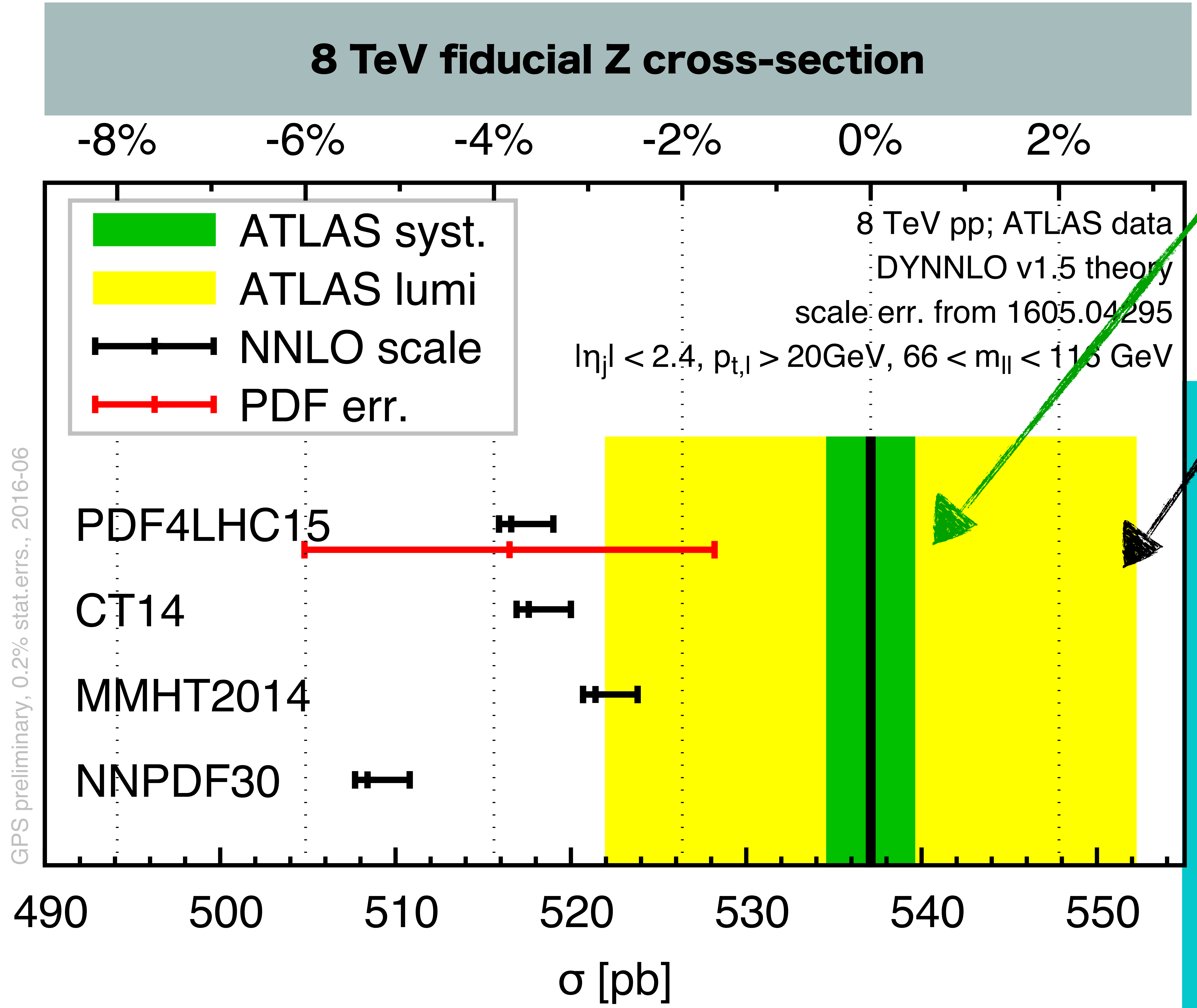
WHAT ROUTE FOR PROGRESS?

- 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?
- [is it time for PDFs to include theory uncertainties?]


quark-gluon luminosity uncertainty


quark-antiquark luminosity uncertainty

There are, however, issues. Notably in Z production



±0.45% syst.

×6

±2.8% lumi

Up to 5% discrepancy with data

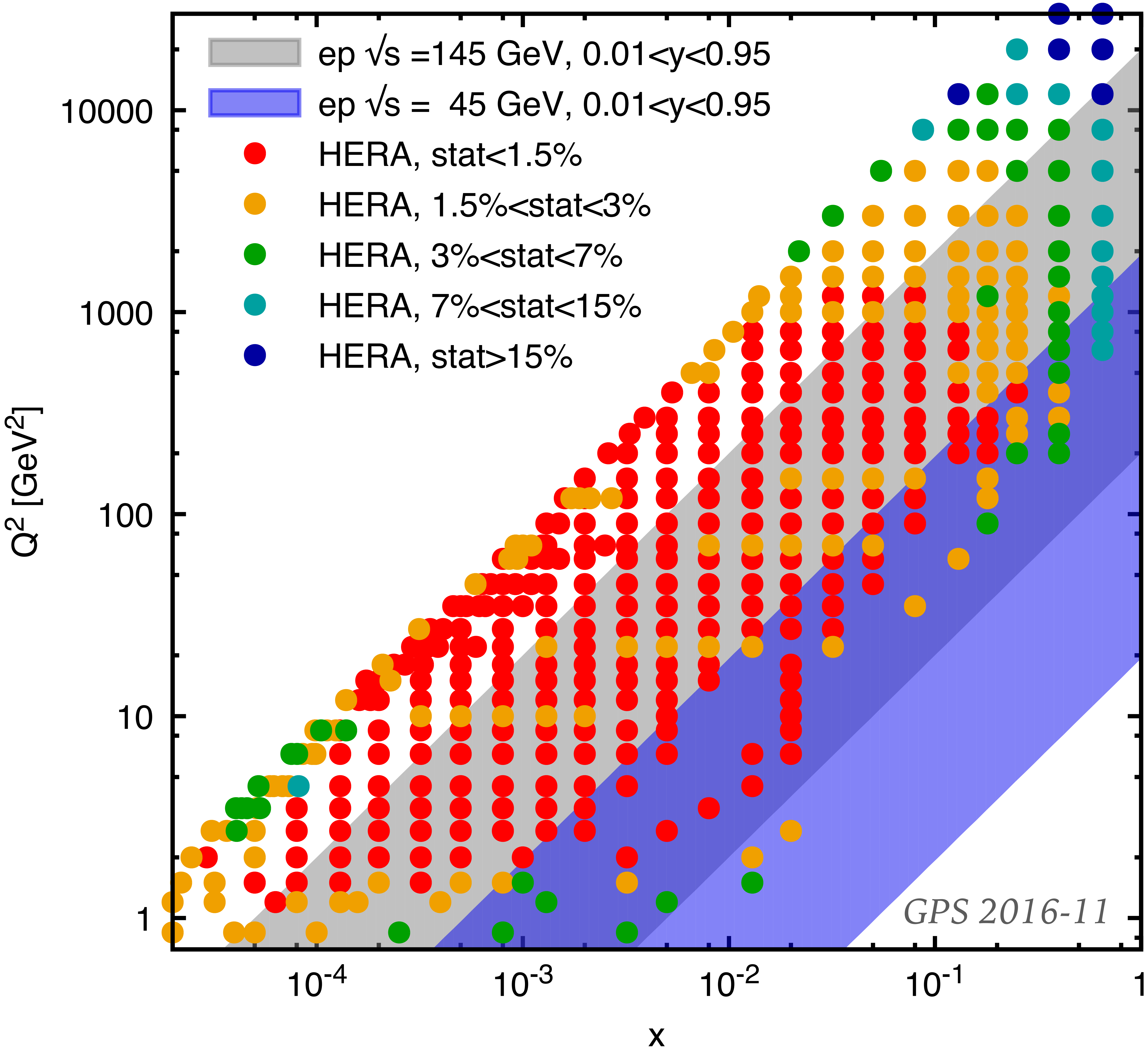
Experimental progress on luminosity determination may be the **keystone** for precision physics at LHC.

Are there hardware changes to HL-LHC that could help with lumi determination?

unpolarized PDF opportunities at EIC?

especially at high Q^2, large-x

cf. also the talks by Nocera, Klein



EIC & high-x parton distributions

PDF4LHC15_nnlo_100	uncertainty at x = 0.5 Q = 100 GeV
up	2.4%
down	12%
strange	140%
gluon	34%

- today's high-x partons largely constrained from low-Q^2 data, where higher-twist effects may be a concern
- down/strange/gluon poorly known at large x, and LHC prospects for improvement not clear
- could high-statistics large-x large-Q^2 data from EIC bring significant improvement?
  - by rigorously eliminating higher-twist effects
  - by comparing high-precision electron-proton with electron-deuteron data
  - Charged-current (especially positron) data

Detailed projections of EIC potential for PDF improvements
v. LHC physics programme would be valuable.

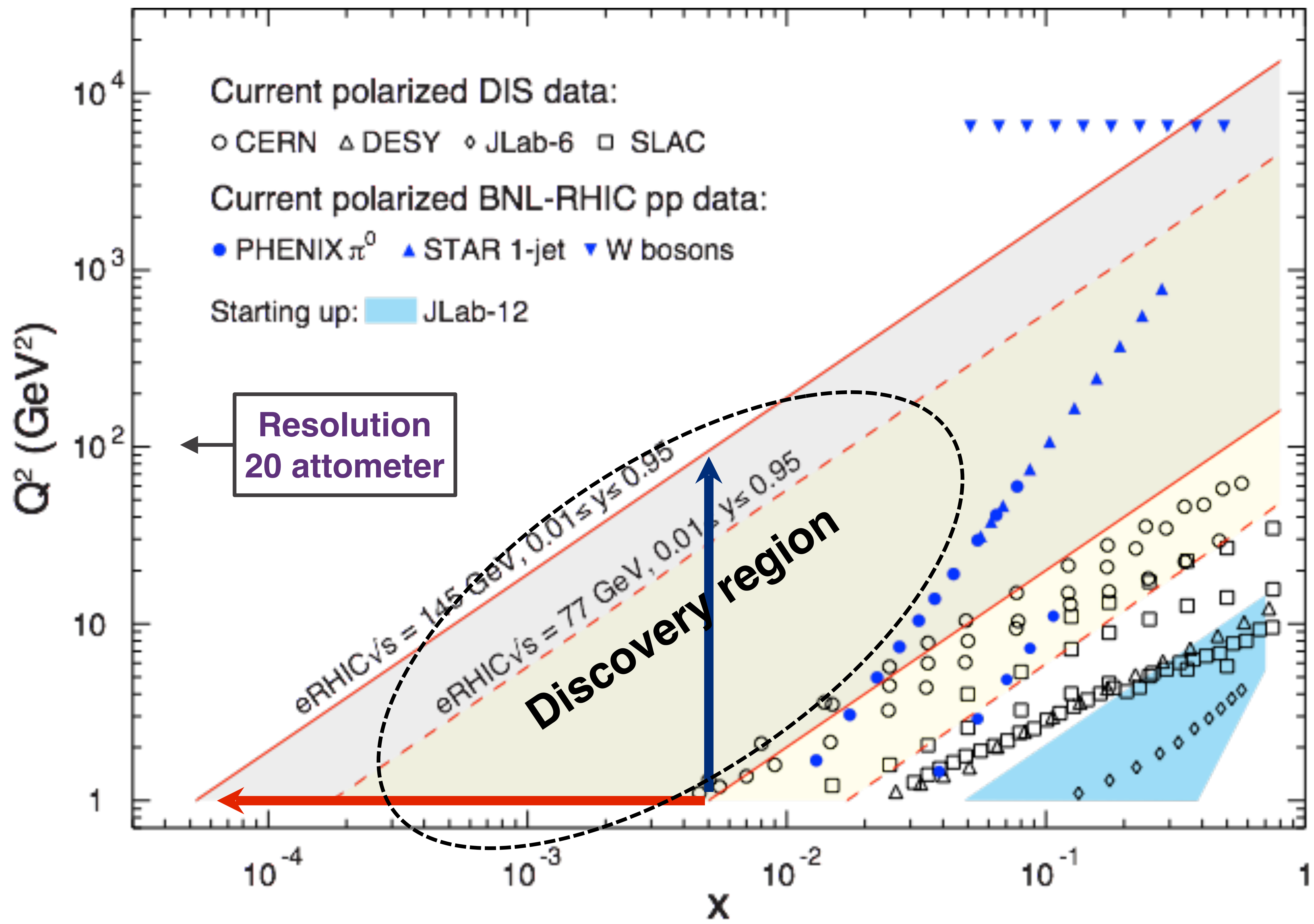
COMMENTS / CONCLUSIONS

- A big part of LHC's physics programme (Higgs, top, dilepton, …) will involve precision physics
- 1% is a target to keep in mind, at the edge of what is realistic today (recall: LHC has another 20 years to go)
- Perturbative calculations are making huge progress (though much still to be done)
- Some problems remain to be solved:
  - consensus on PDFs (& path to 1%), strong coupling
  - non-perturbative effects
- Can EIC bring constraints on PDFs beyond what we have already from HERA? Perhaps at large-*x*? It would be good to have a clearer answer on this.

BACKUP

Requirements: √s and Polarization

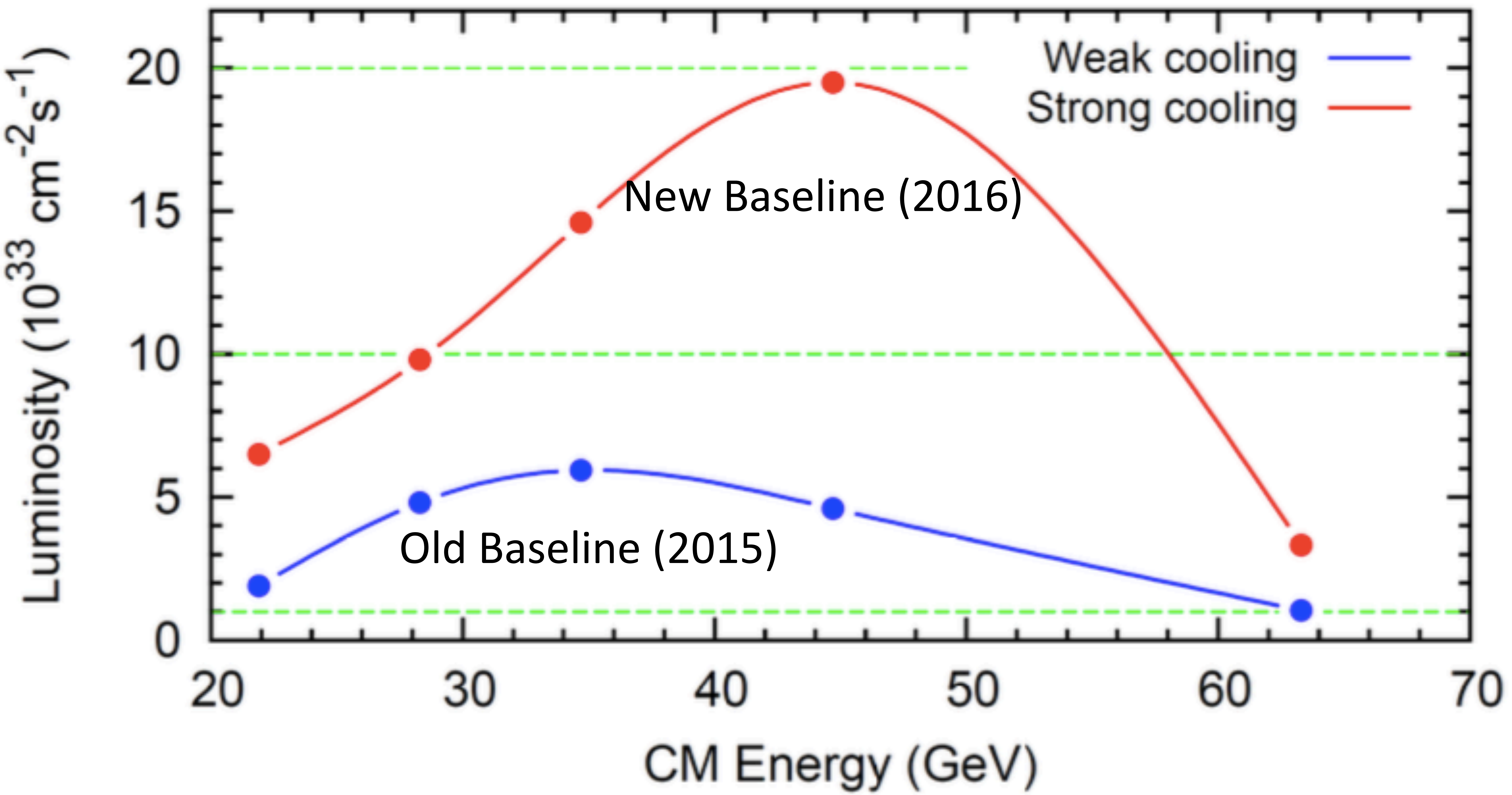
From Berndt Mueller’s talk



polarized
ep, μp, pp

$$Q^2 \approx s \cdot x \cdot y$$

- ✳ Need to reach low-x where gluons dominate (ΔG, ΔΣ range!)
- ✳ Flexible energies (see also structure functions later)
- ✳ Need sufficient lever arm in Q^2 at **fixed** x (evolution along Q^2 or x)
- ✳ Electrons and protons/light nuclei (p, ^{3}He, d) highly polarized (70%)

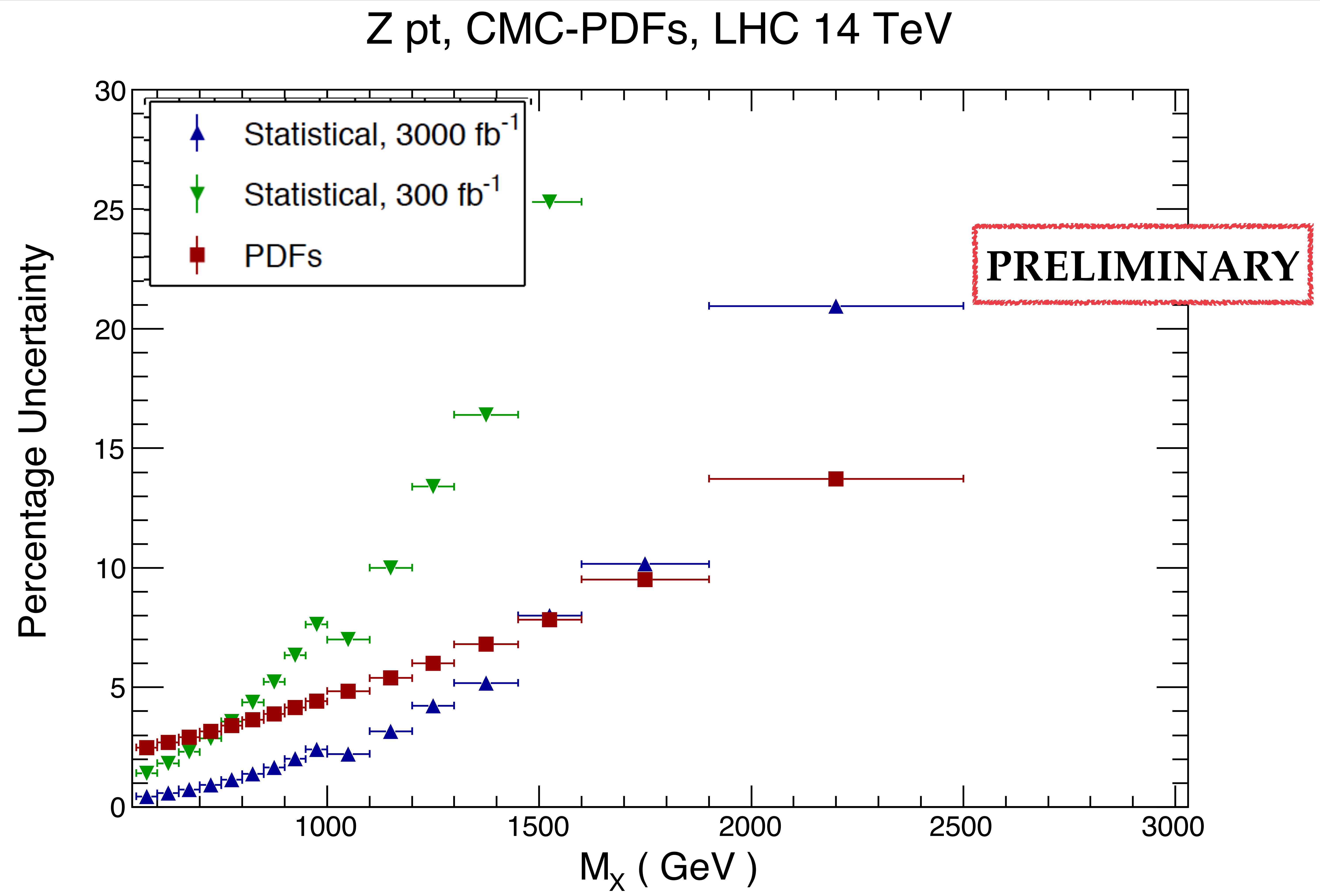


From Rik Yoshida's talk

EXPERIMENTAL PERSPECTIVES

Generation of pseudo-data: the Z pt

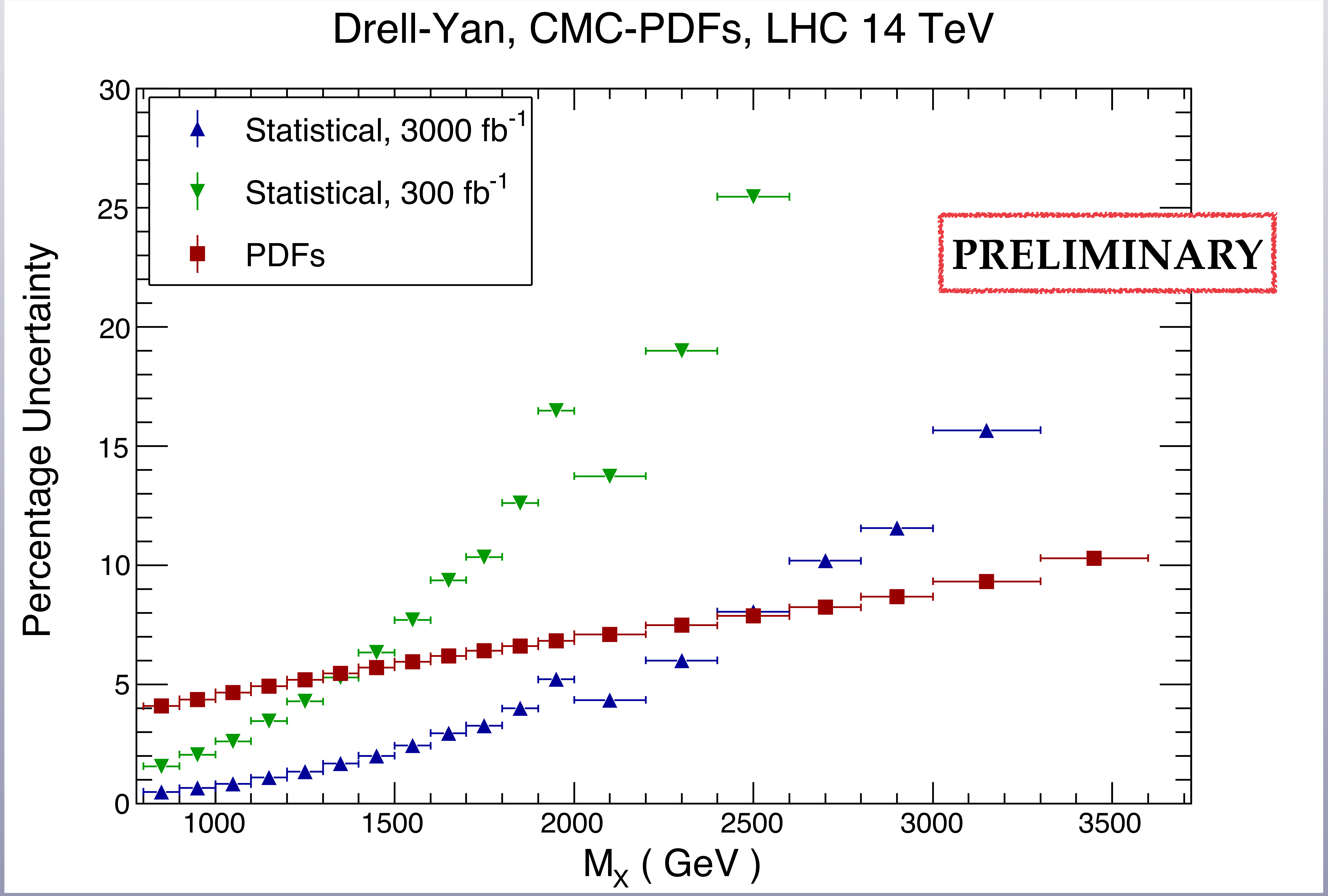
- Generate pseudo-data for the **transverse momentum distribution** of **Z bosons decaying into leptons**
- Statistical uncertainties determined from **number of events per bin**, after a binning optimisation
- Added a **2% systematic uncertainty** to the statistical uncertainty



PRELIMINARY

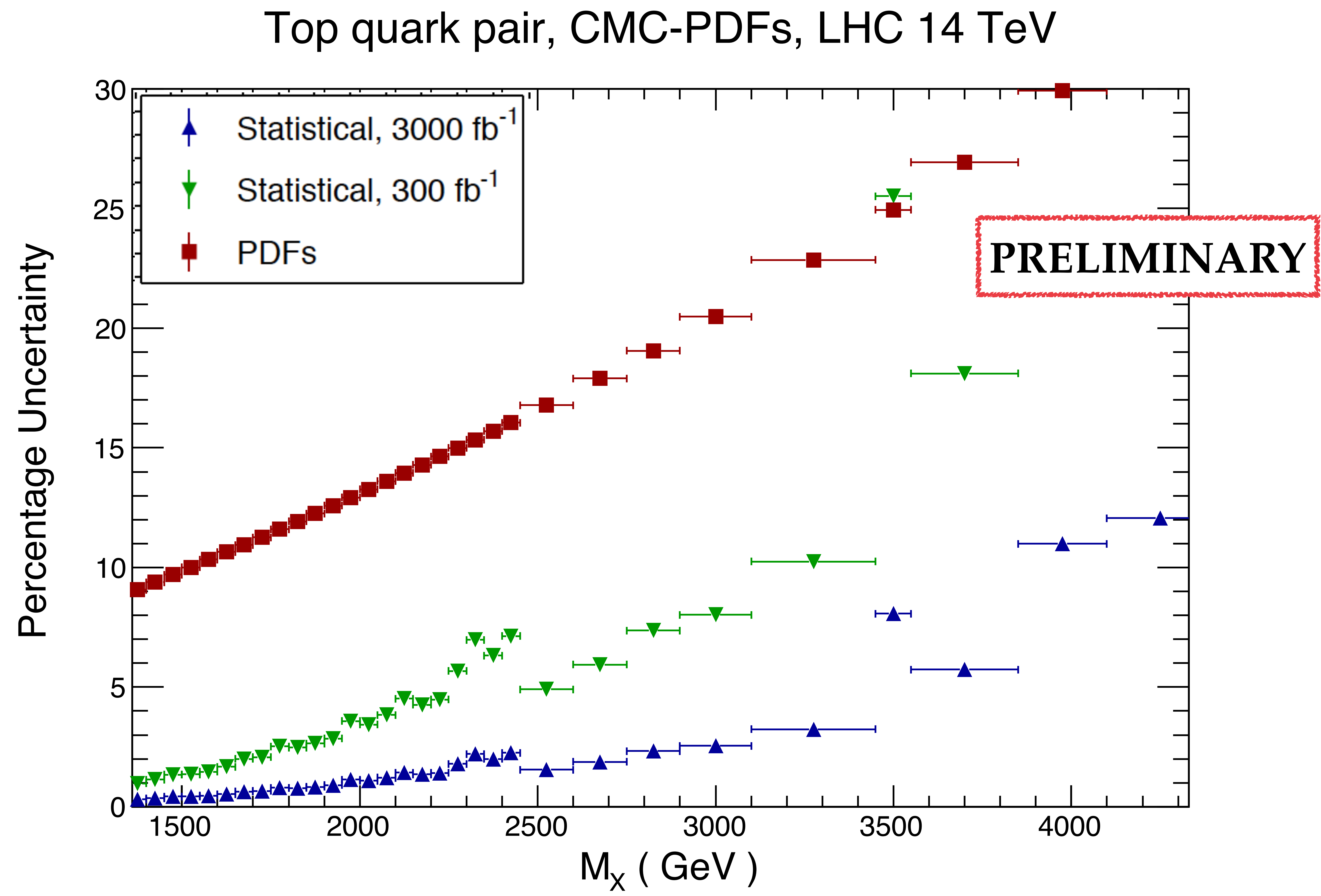
Generation of pseudo-data: high-mass Drell-Yan

- Generate pseudo-data for the **invariant mass distribution** of **di-electrons** and **di-muons**
- Statistical uncertainties determined from **number of events per bin**, after a binning optimisation
- Added a **2% systematic uncertainty** to the statistical uncertainty

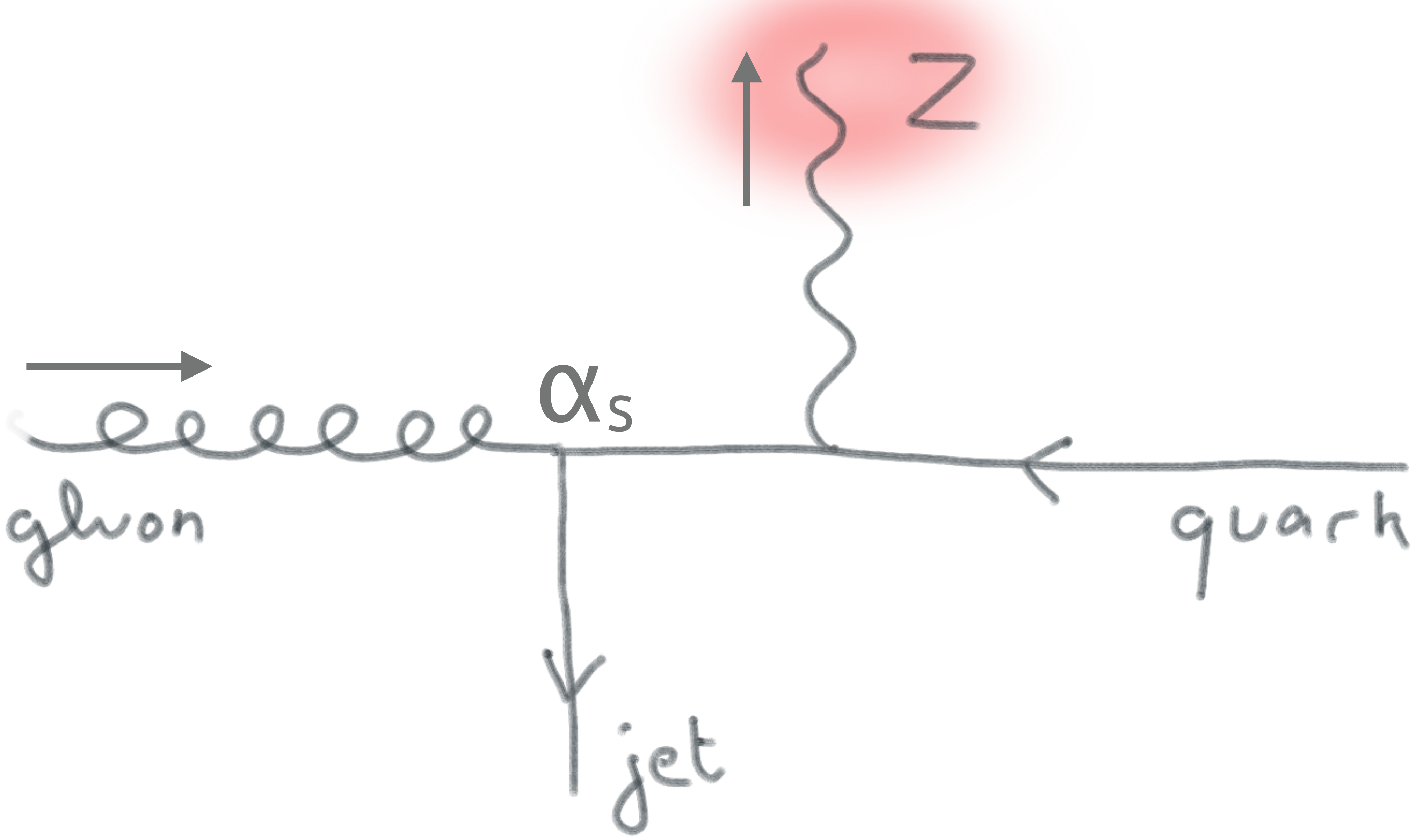


Generation of pseudo-data: top quark pair

- Generate pseudo-data for the **invariant mass distribution** in the **leptonic final state**
- Statistical uncertainties determined from **number of events per bin**, after a binning optimisation
- Added a **3% systematic uncertainty** to the statistical uncertainty



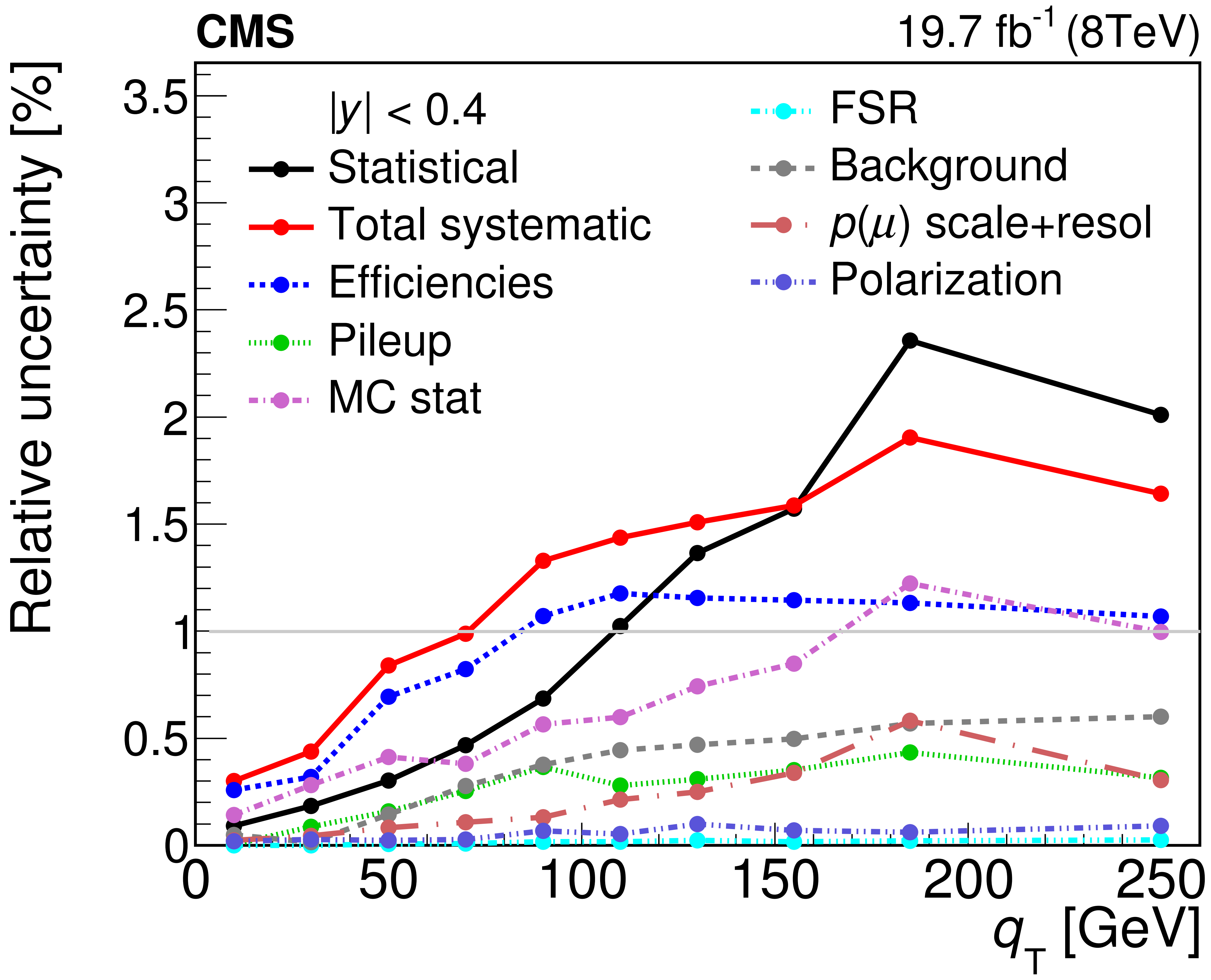
Z P_T: the "ideal" hard process?

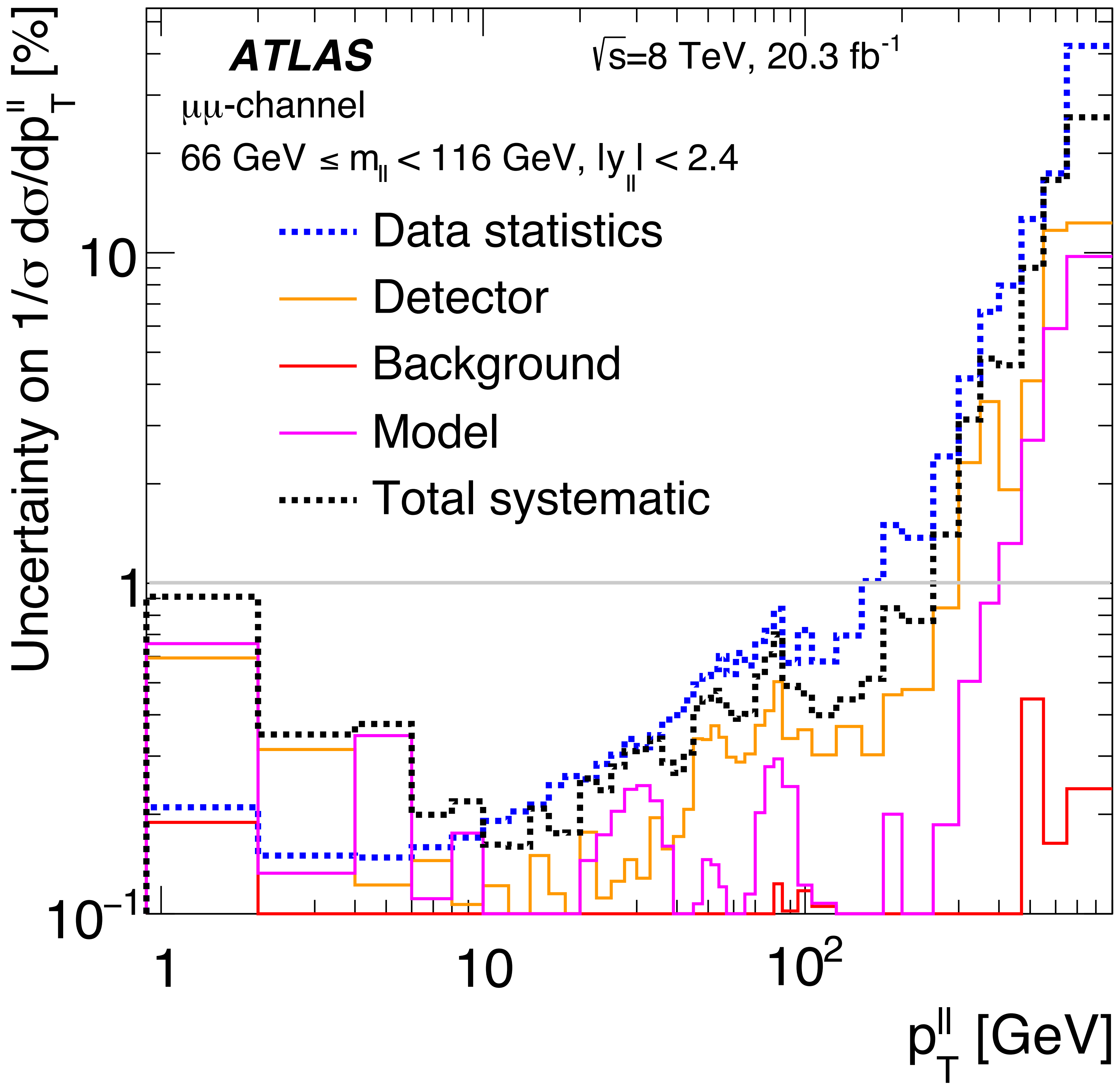


For both data and theory, Z p_T is an immediate testing ground for 1% effects.

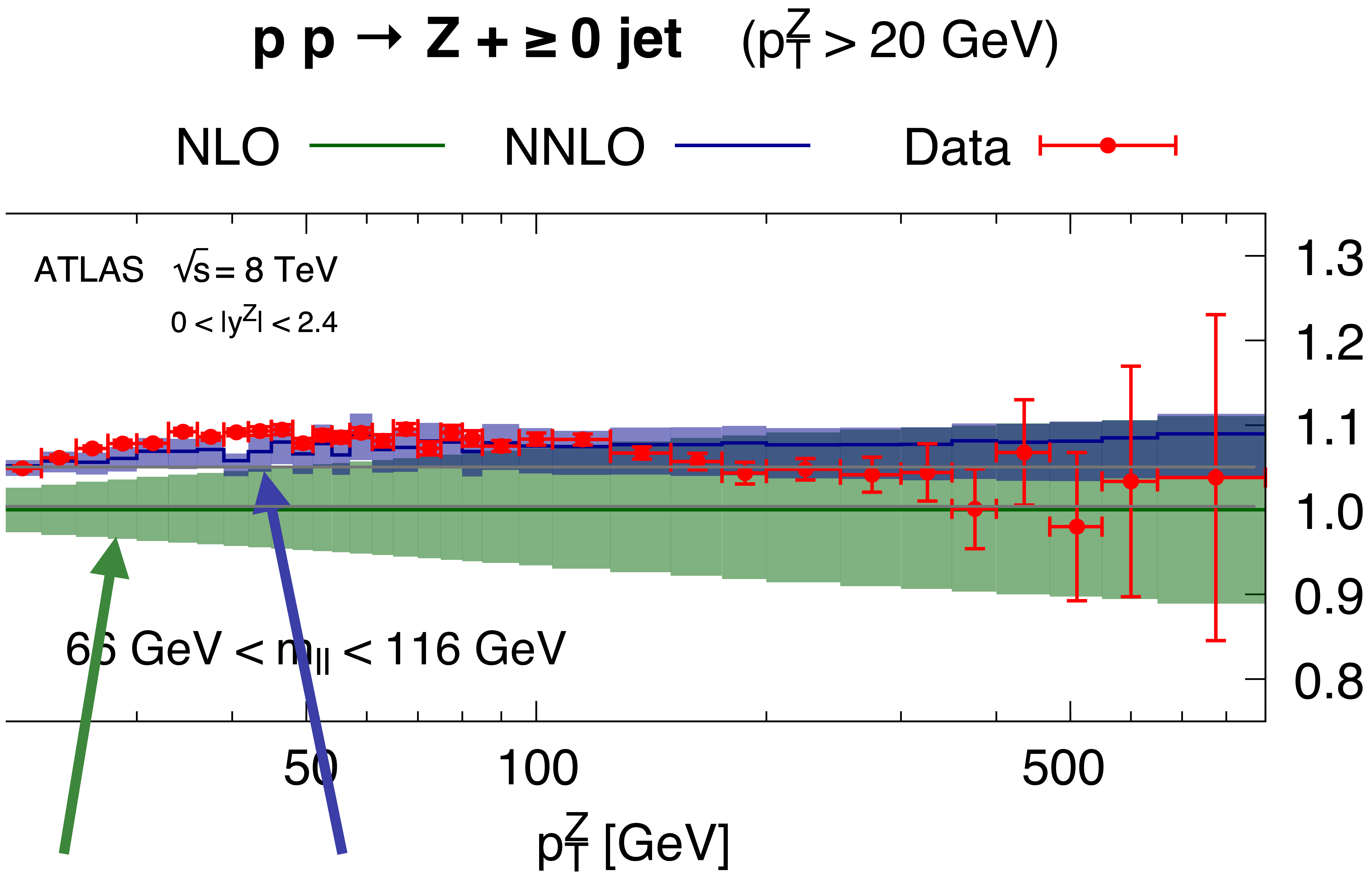
(& unlike Z & W prod^n it's sensitive to α_s)

Z p_T: uncertainties somewhat smaller for ATLAS than CMS





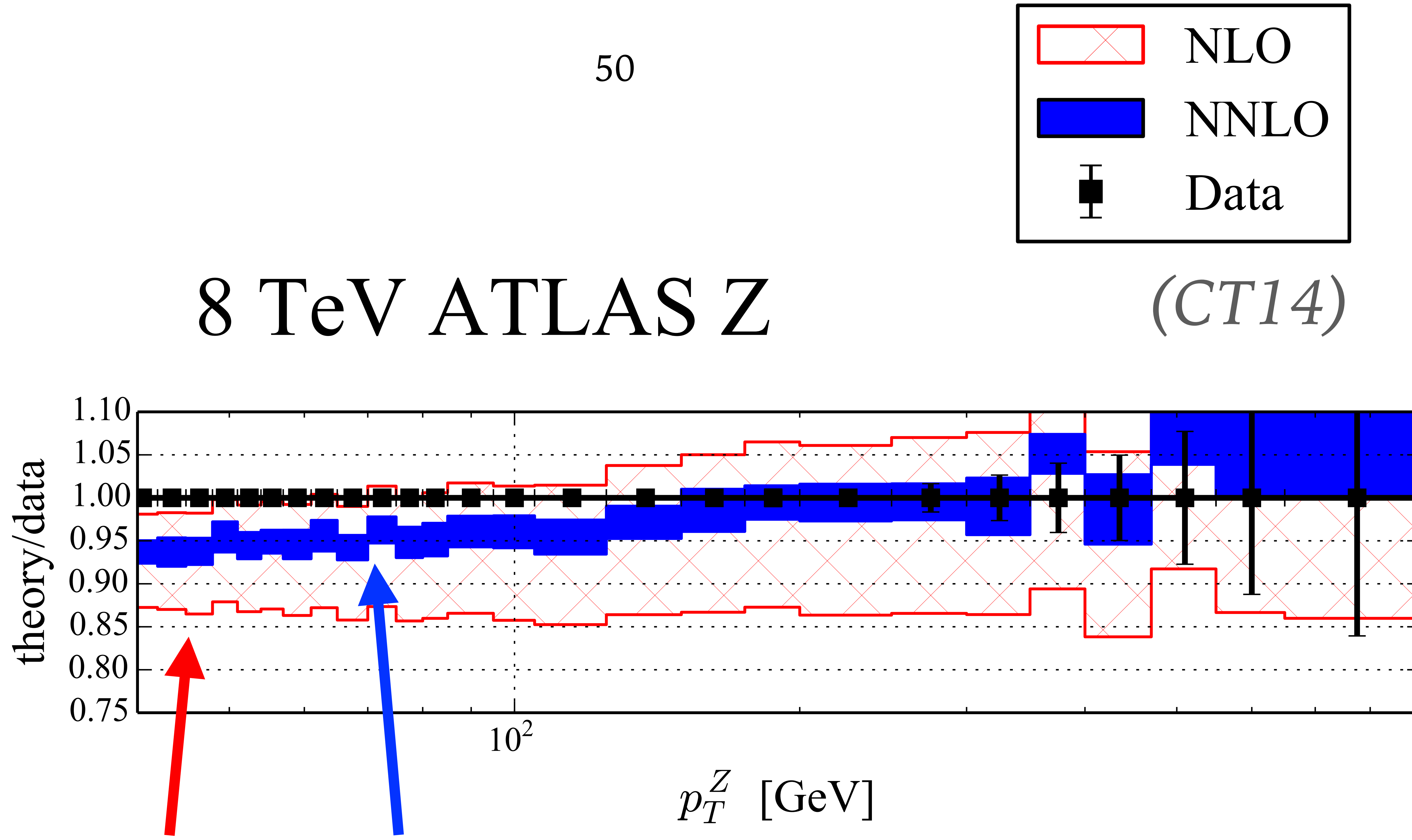
Z p_T: Data v. two theory calculations



NLO **NNLO**

Gehrmann-de Ridder, Gehrmann
Glover, Huss & Morgan

arXiv:1605.04295



NLO **NNLO**

Boughezal, Liu & Petriello
’16 preliminary

NNLO ~ ±1.5 %

REMARKS

- ➤ Looks like scale uncertainties are ±1–2% (but how well does series converge?)
- ➤ In key 50–100 GeV region, data seem ~4% higher than NNLO theory
- ➤ This could have important implications for α_s and PDFs (smaller α_s will not help!)
- ➤ What about non-perturbative effects?

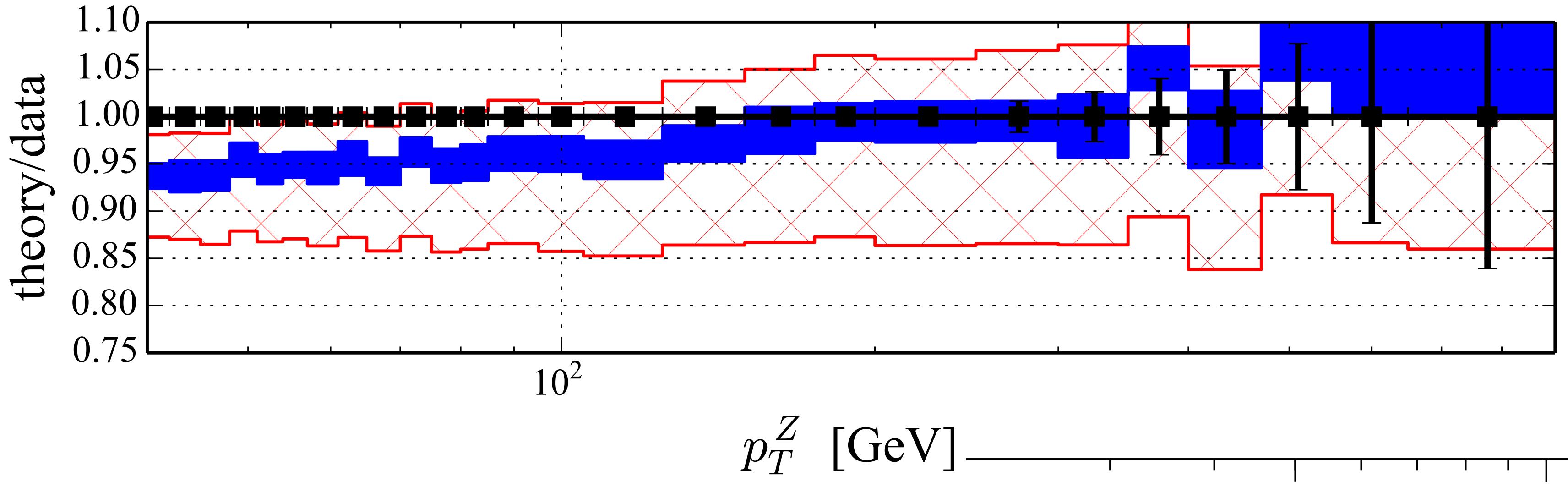
NB: both calc^n use a central scale

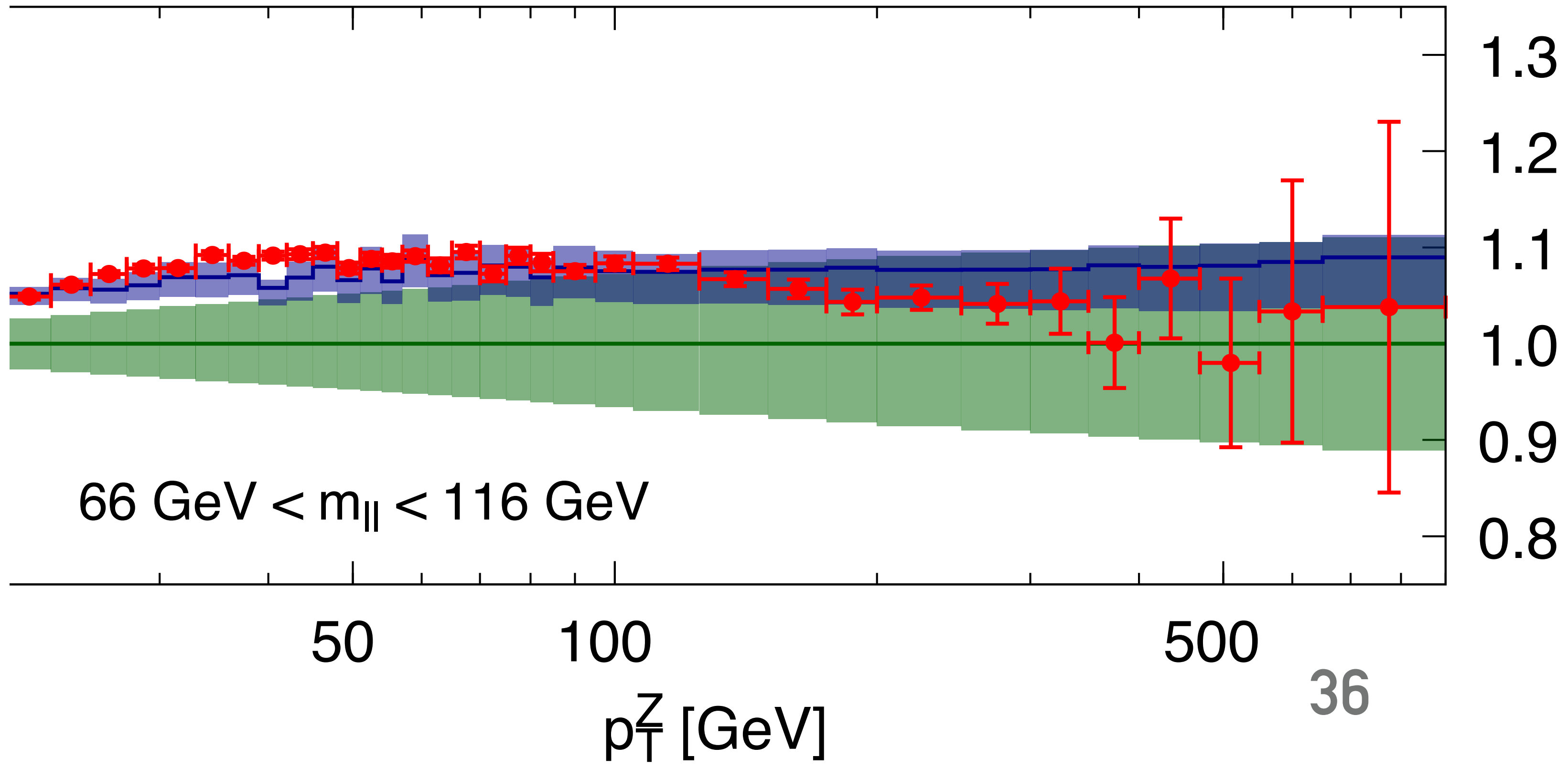
$$\mu = \sqrt{m_Z^2 + p_{T,Z}^2}$$

An alternative

$$\mu = \frac{1}{2}\left(p_{T,Z} + \sqrt{m_Z^2 + p_{T,Z}^2}\right)$$

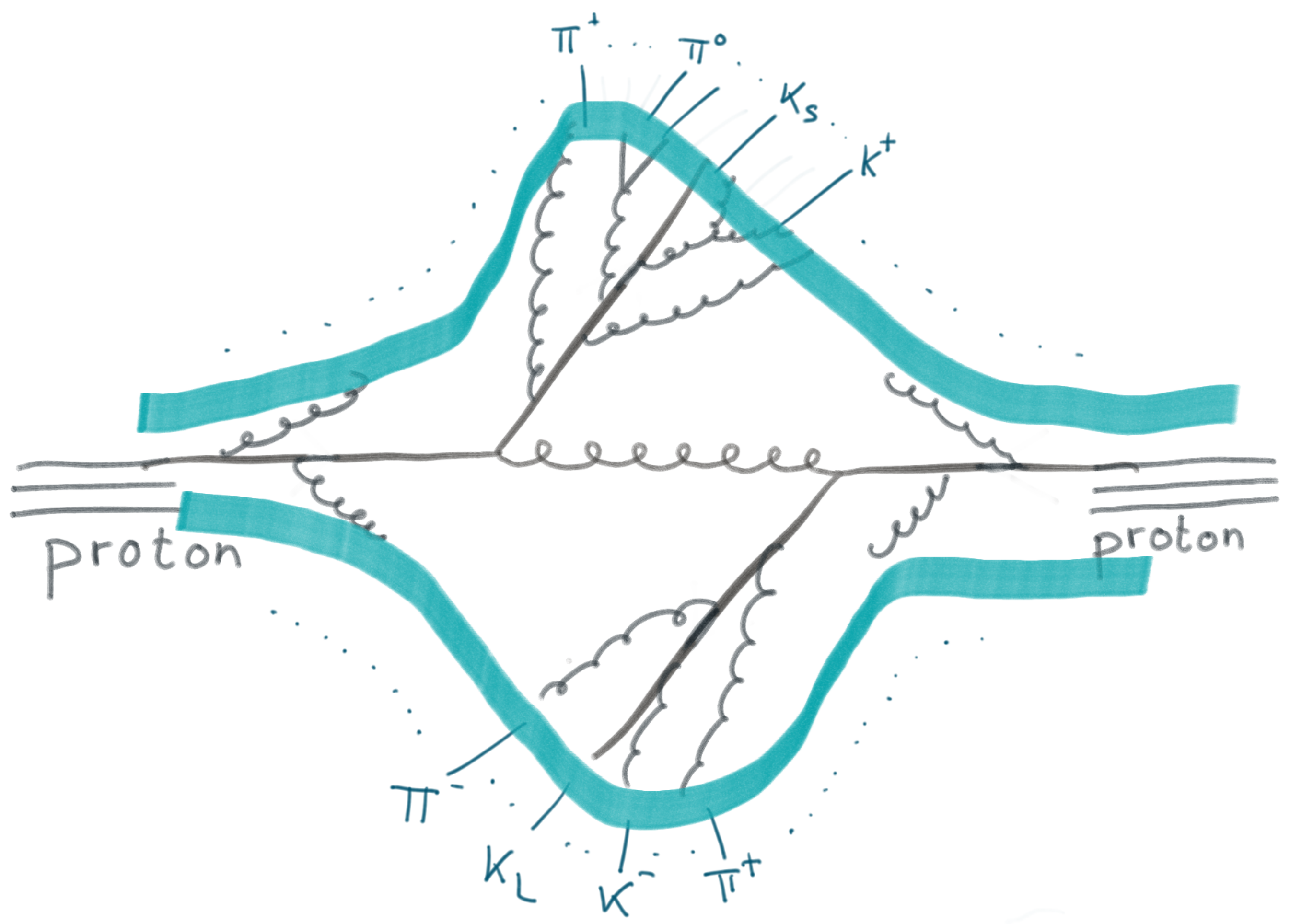
would seem more consistent with choices being made elsewhere (and might show better convergence?)



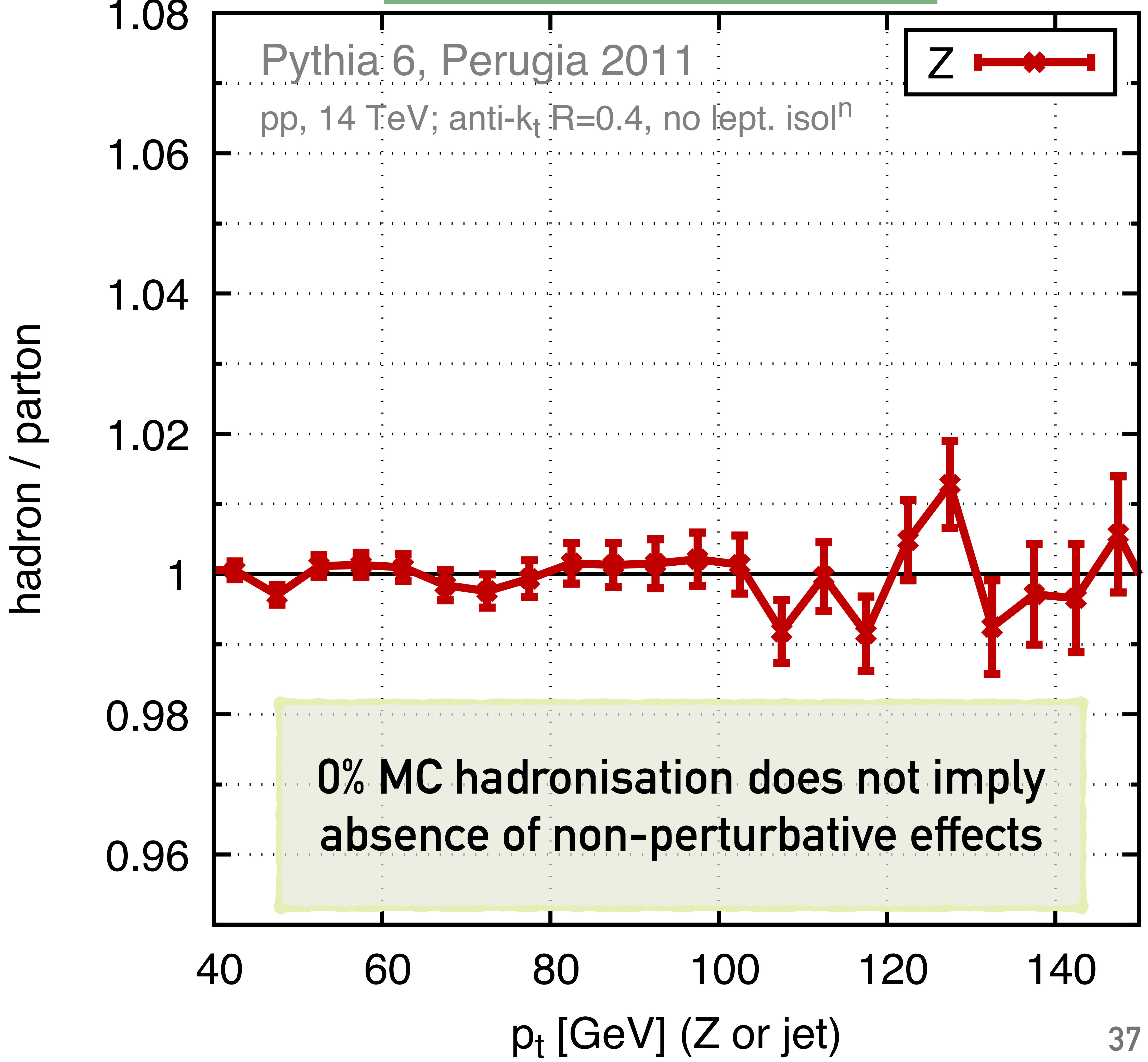


Non-perturbative effects in Z p_T

- Inclusive Z cross section should have $\sim\Lambda^2/M^2$ corrections ($\sim10^{-4}$?)
- 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?]

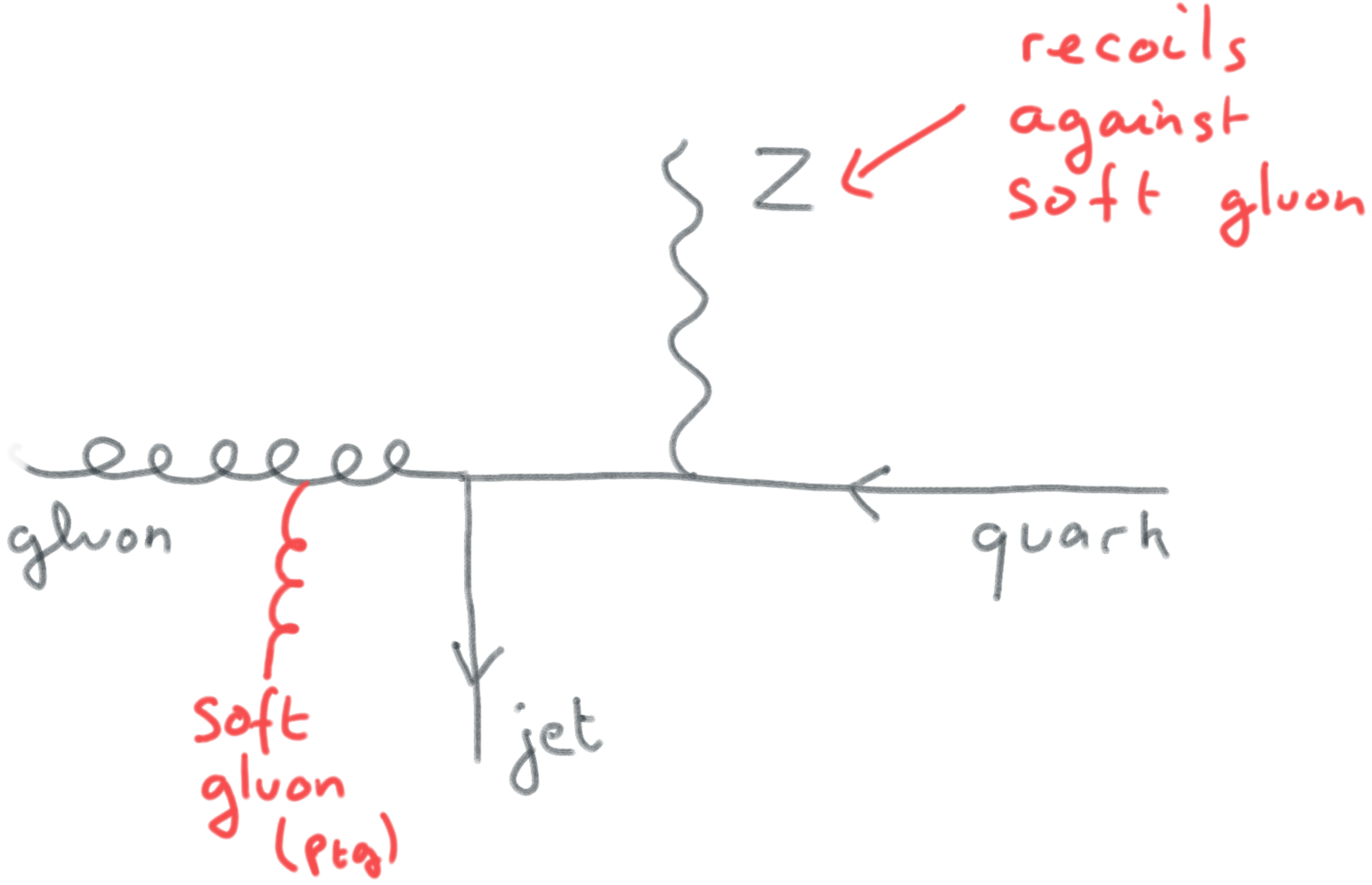


MC hadronisation

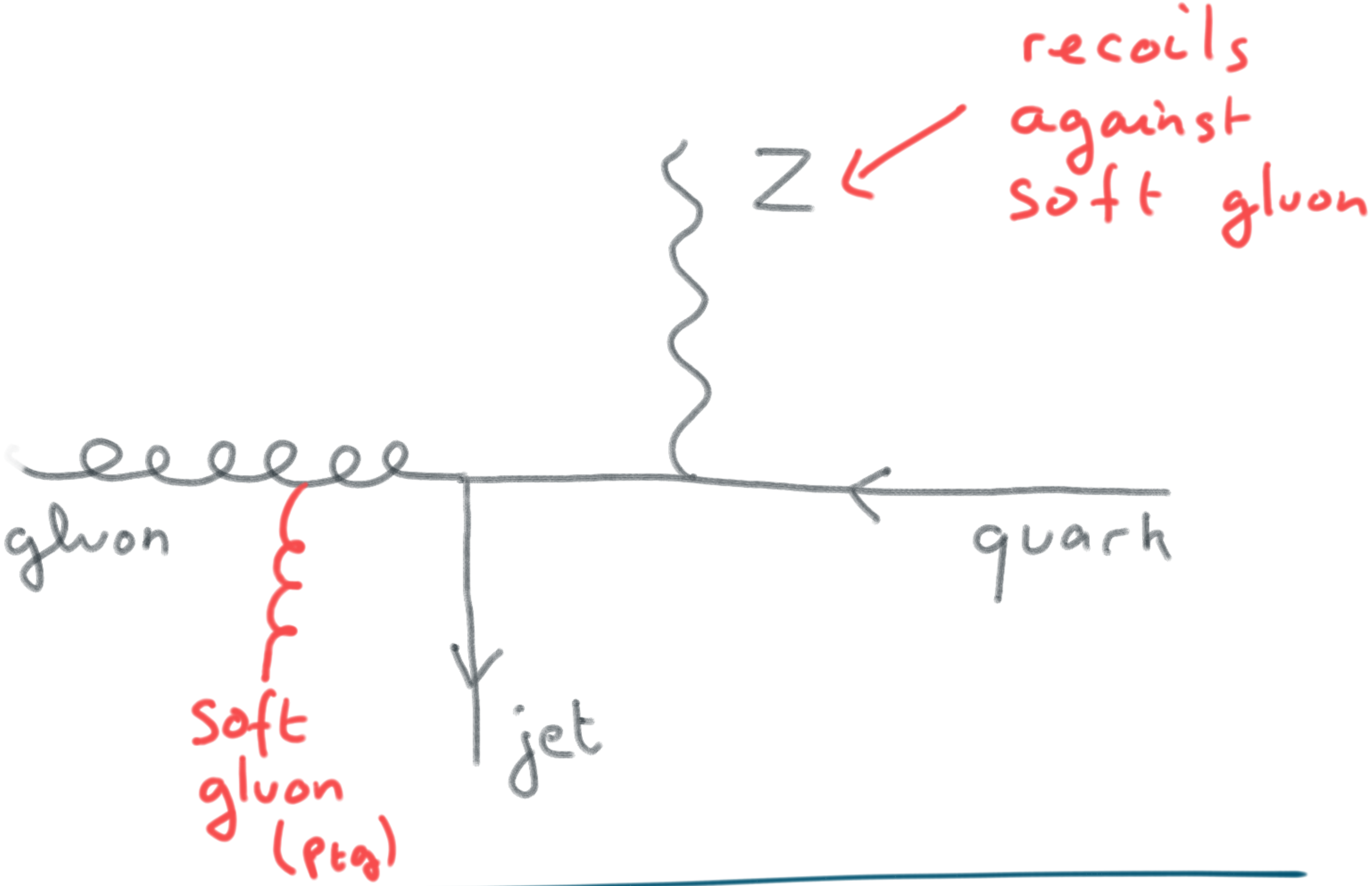


0% MC hadronisation does not imply absence of non-perturbative effects

Non-perturbative effects in Z p_T



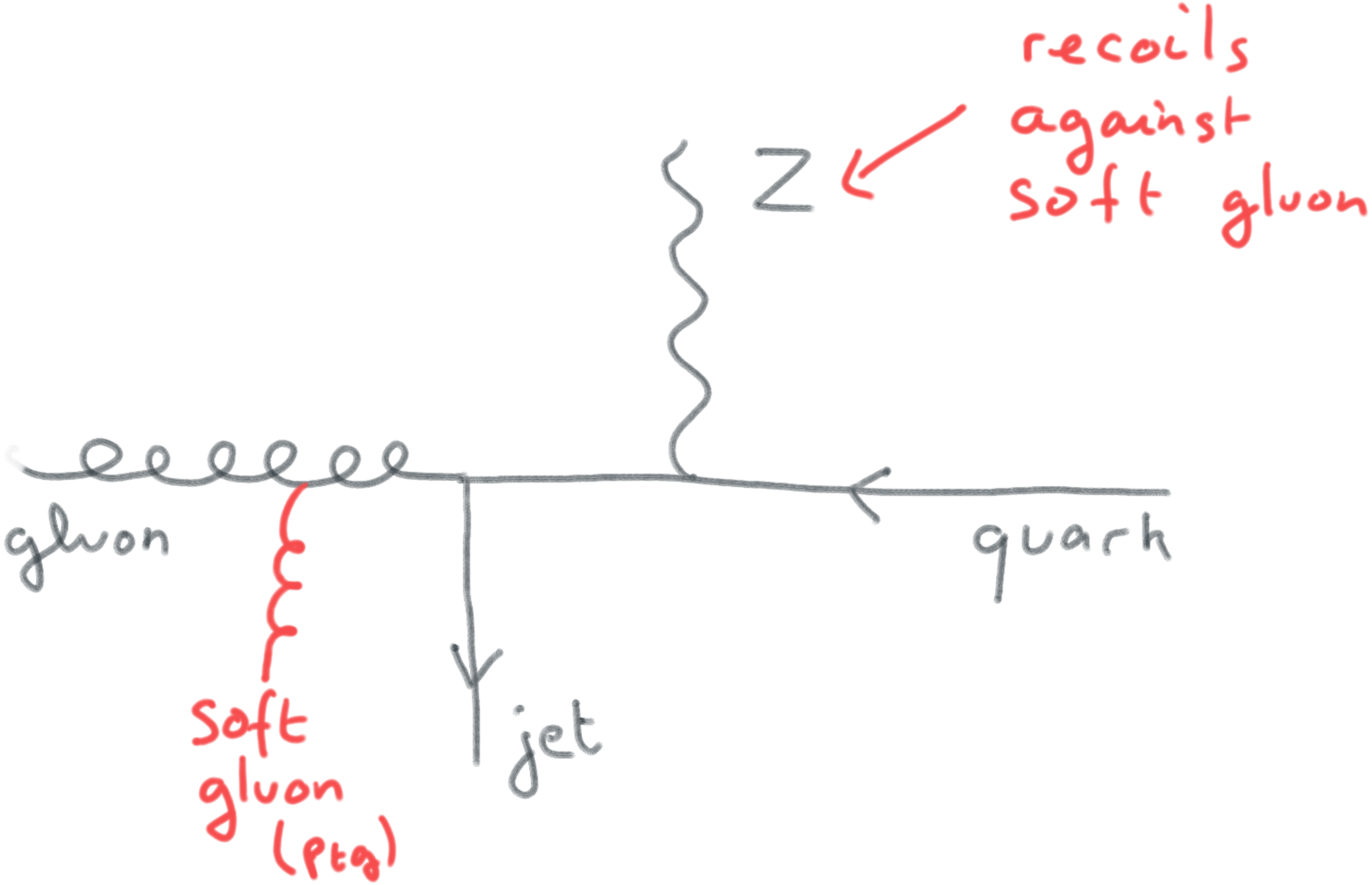
Non-perturbative effects in Z p_T



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

integral over low p_t emissions is non-perturbative

Non-perturbative effects in Z p_T

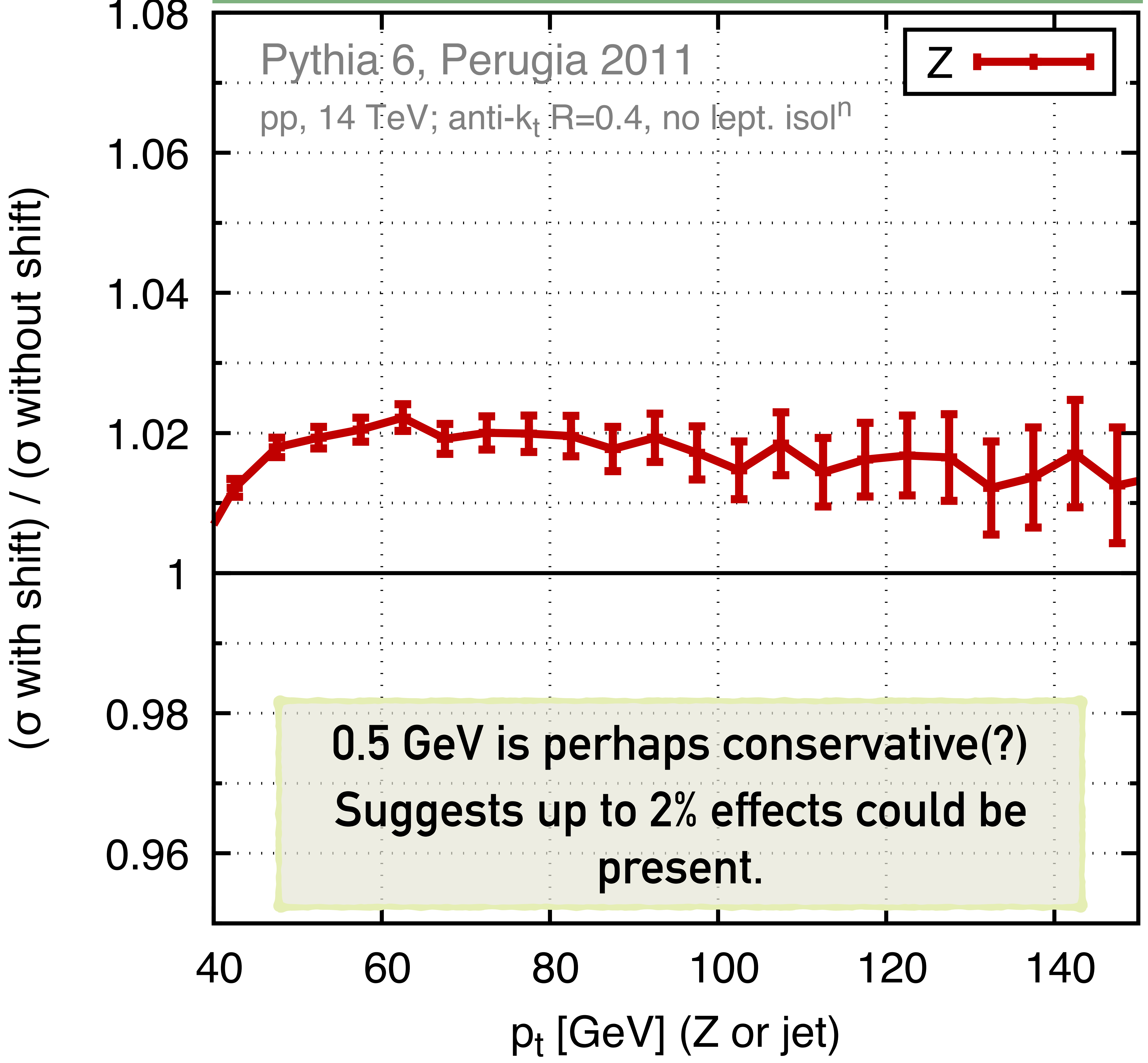


model non-perturbative effect by shifting Z p_t by e.g. 0.5 GeV

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 $\sim\Lambda/M$.
- 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

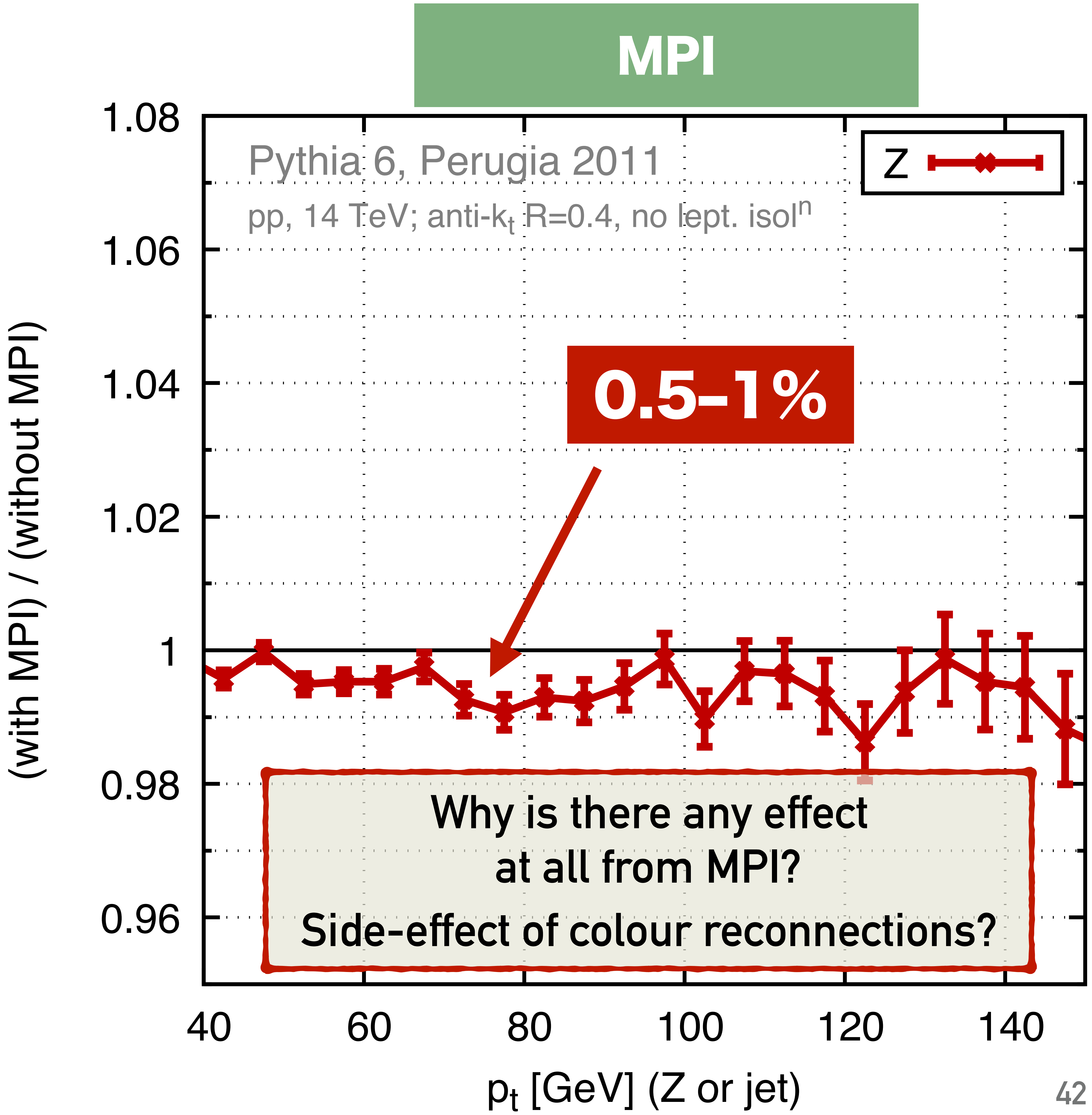


0.5 GeV is perhaps conservative(?)
Suggests up to 2% effects could be present.

A conceptually similar problem is present for the W momentum in top decays

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%)



0.5–1%

Why is there any effect at all from MPI?

Side-effect of colour reconnections?

THE JET IN Z+JET @ NNLO

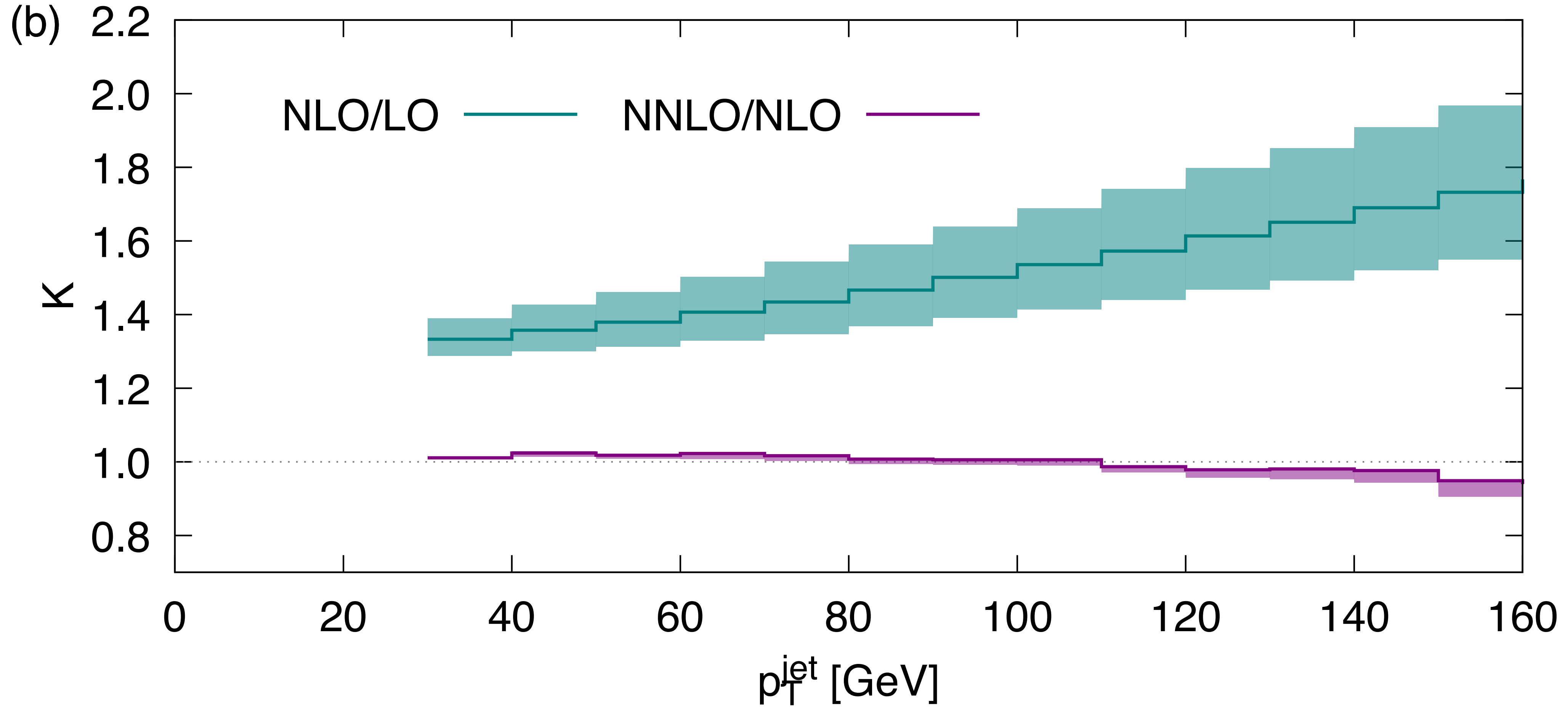
Boughezal, Liu & Petriello, 1602.08140

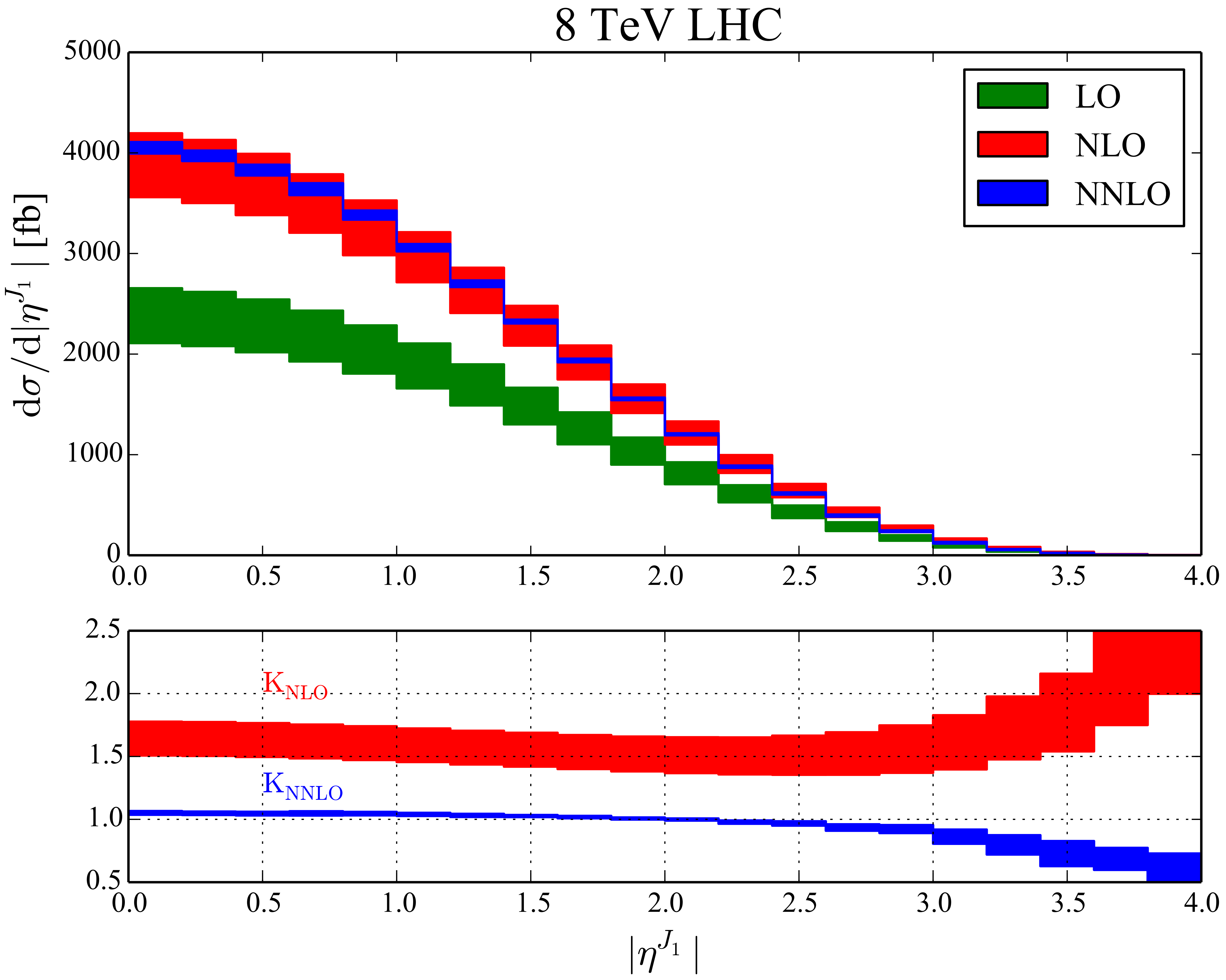
1-jet cross sections

	$\sigma_{\rm LO}$ (pb)	$\sigma_{\rm NLO}$ (pb)	$\sigma_{\rm NNLO}$ (pb)	$K_{\rm NLO}$	$K_{\rm NNLO}$
8 TeV	$4.17^{+0.55}_{-0.47}$	$6.59^{+0.62}_{-0.53}$	$6.86^{+0.01}_{-0.13}$	1.58	1.04
13 TeV	$9.12^{+0.88}_{-0.79}$	$14.90^{+1.29}_{-1.06}$	$15.54^{+0.01}_{-0.24}$	1.63	1.04

➤ NNLO K-factor is a few%

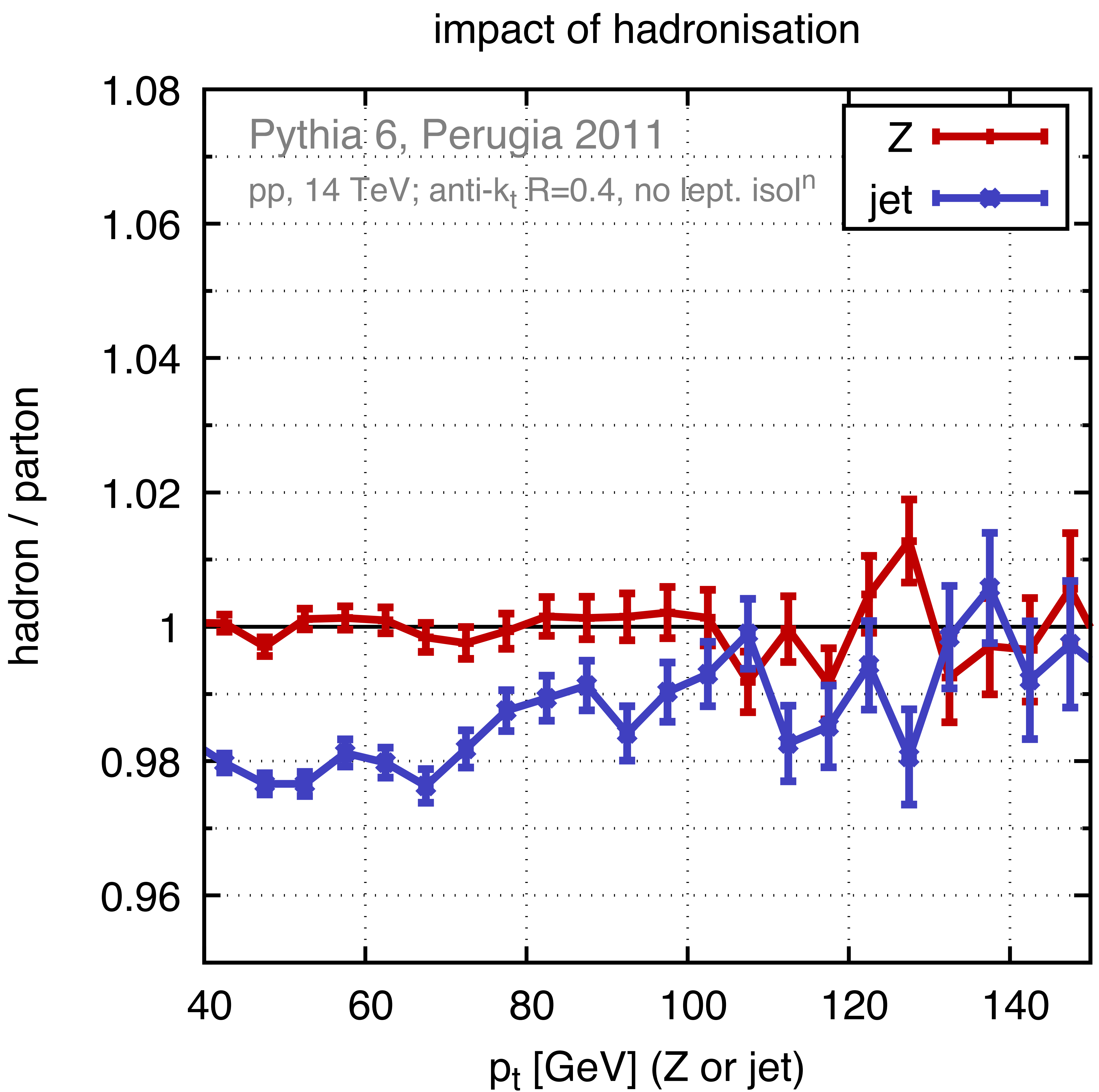
➤ Residual scale uncertainty <2%

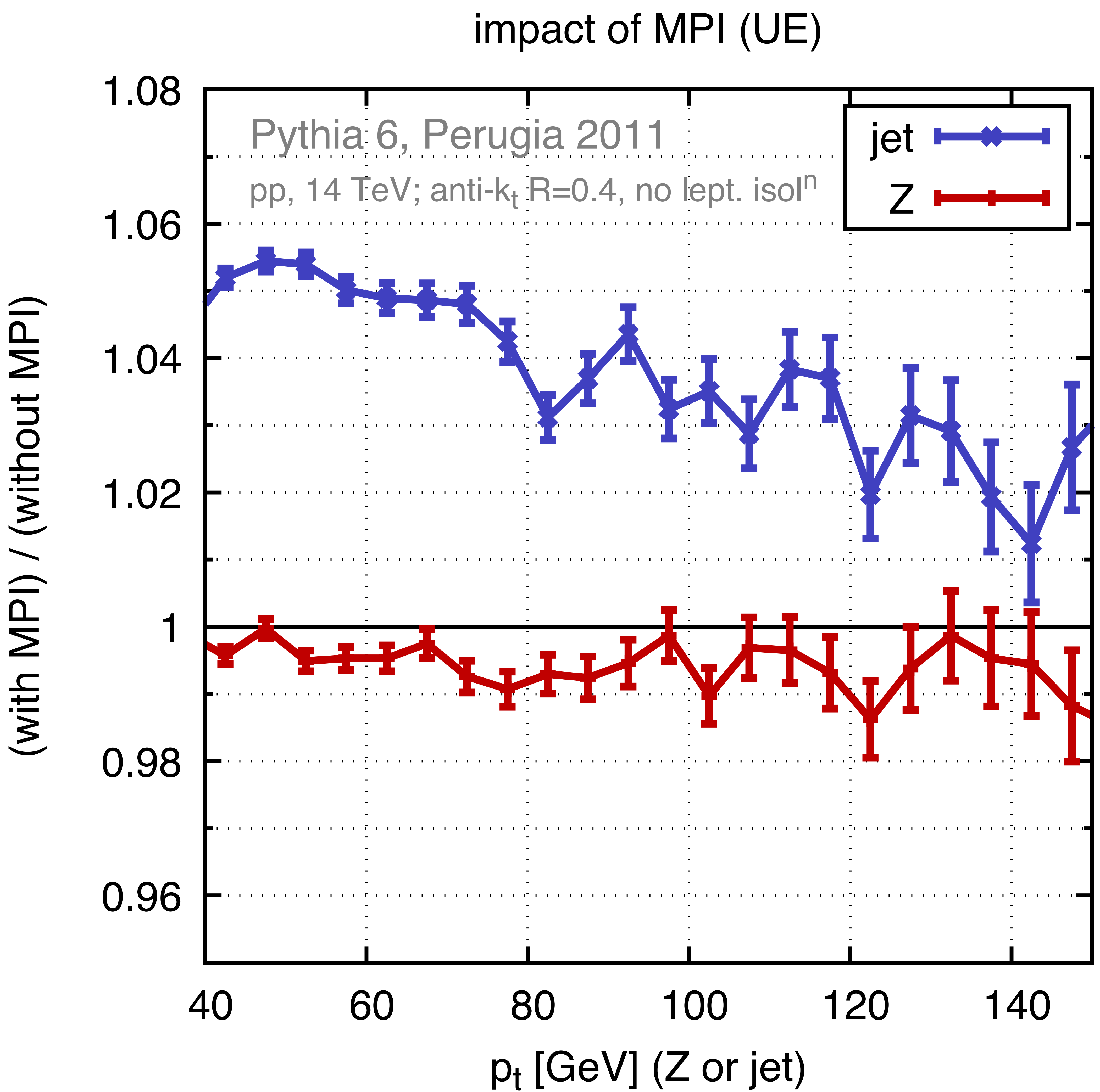




Gehrmann-De Ridder et al, 1607.01749

Hadronisation: Jet v. Z in Z+jet process





2 – 5% effects for jets

POWERFUL HANDLE: EXPLORE A RANGE OF JET RADII

Dasgupta, Dreyer, GPS & Soyez, 1602.01110

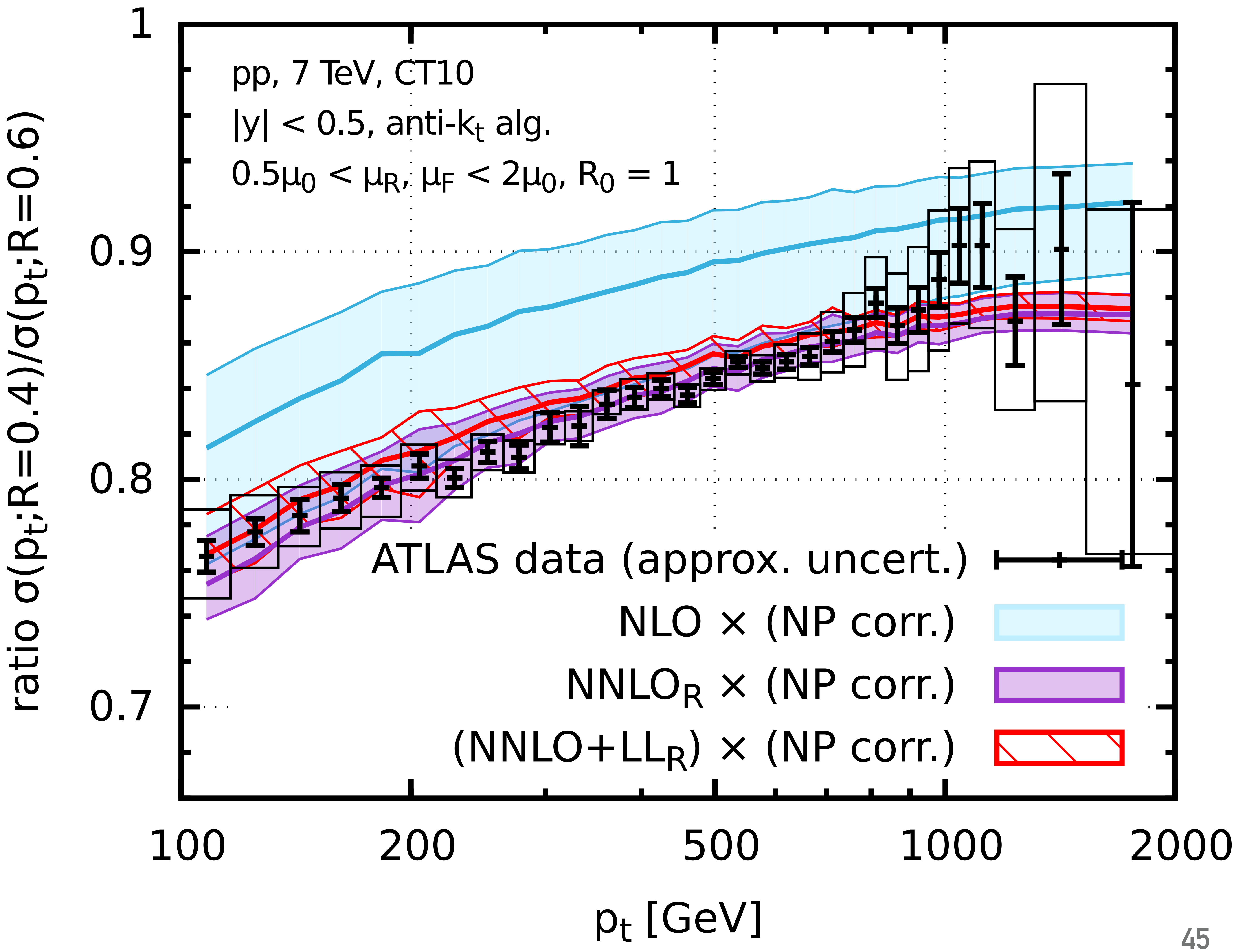
3 effects:

- ➤ perturbative (~ ln R)
- ➤ hadronisation (~ 1/R)
- ➤ MPI/UE (~ R^2)

To disentangle them, need ≥3 R values:

- ➤ 0.6–0.7: large MPI/UE
- ➤ 0.4: non-pert. effects cancel?
- ➤ 0.2–0.3: large hadronisation

ratio of inclusive jet spectra at R=0.4 and 0.6



NNLO$_R$ & small-R resummation

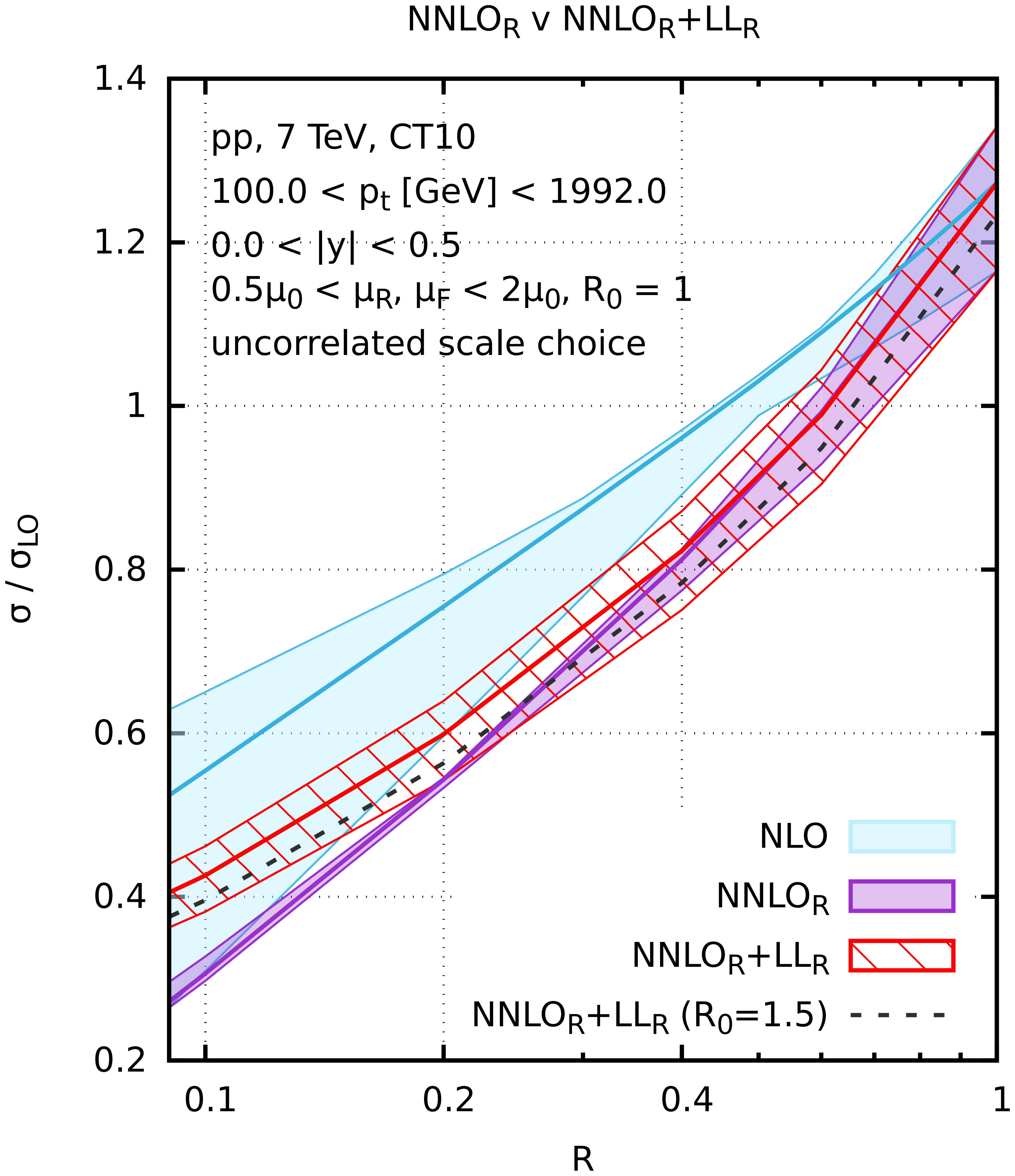
- to explore full R-range, need resummation as well

$$\sigma(R) = \sigma(R_0 = 1) \times \text{ratio}(R, R_0)_{\text{fixed-order} + \text{LL}_R}$$

At R=0.4, NNLO corrections are 15%

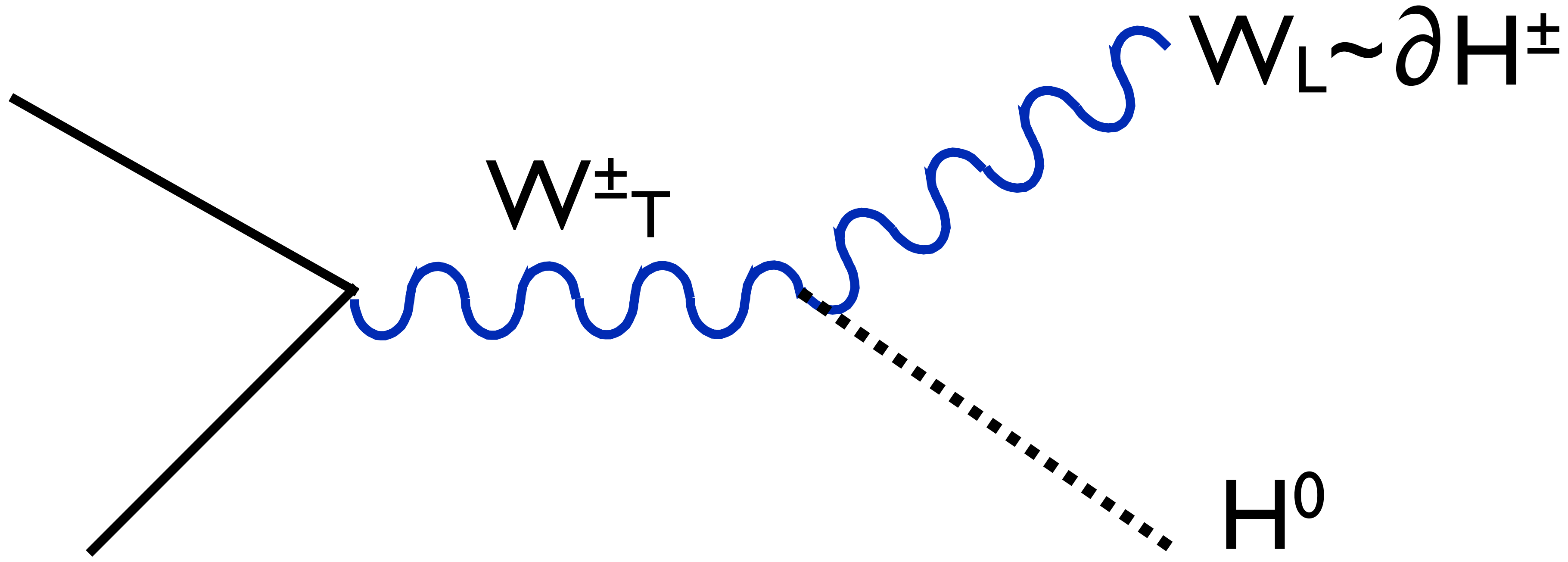
(up to 30% for R=0.2, where resummation also needed)

If we're to reach 1% accuracy for jet processes, NNLO may not be enough



VH prodution at large m(VH)

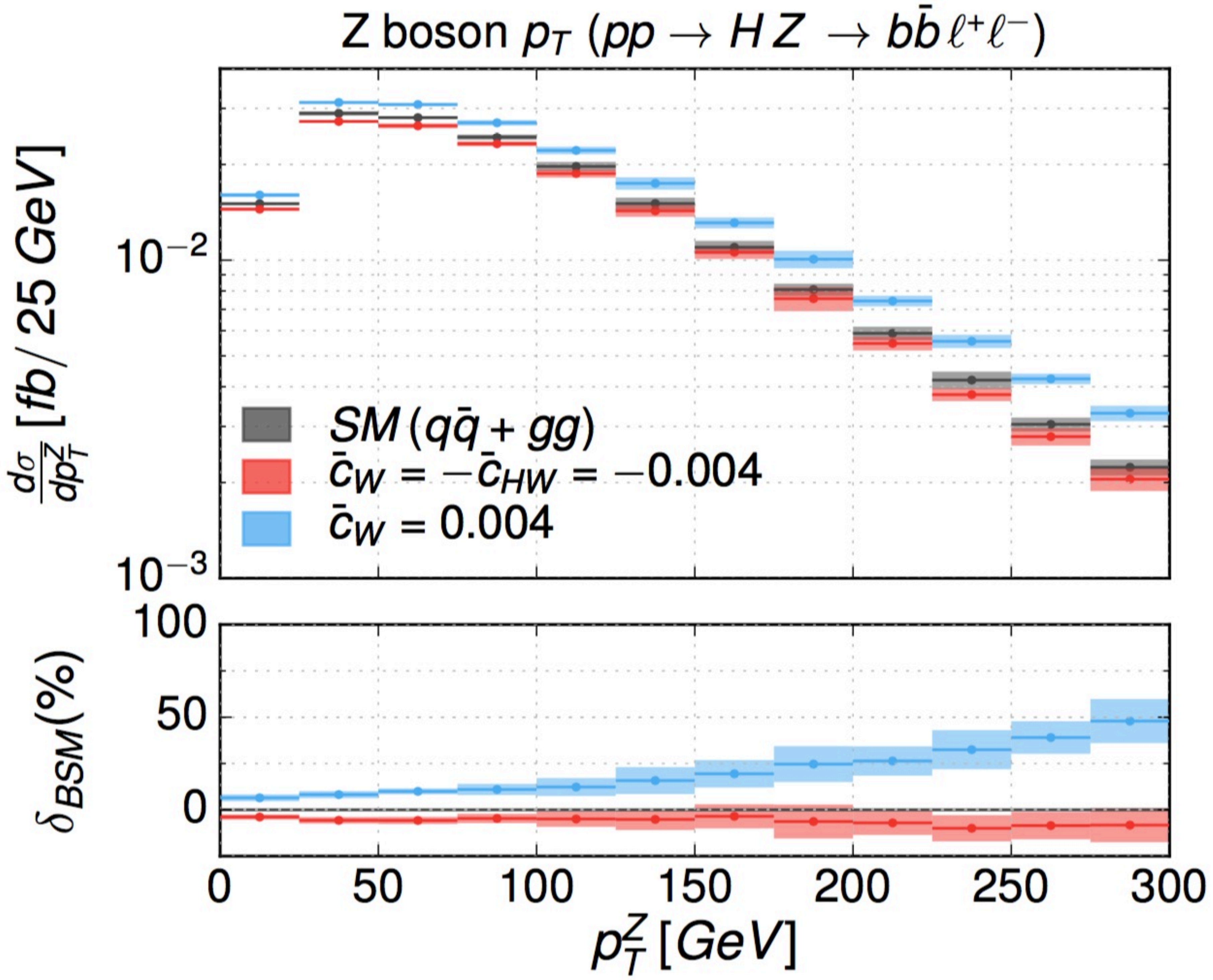
See e.g.
Biekötter, Knochel, Krämer, Liu, Riva,
arXiv:1406.7320



In presence of a higher-dim op such as:

$$L_{D=6} = \frac{ig}{2}\frac{c_W}{\Lambda^2}\left(H^\dagger \sigma^a D^\mu H\right) D^\nu V^a_{\mu\nu}$$

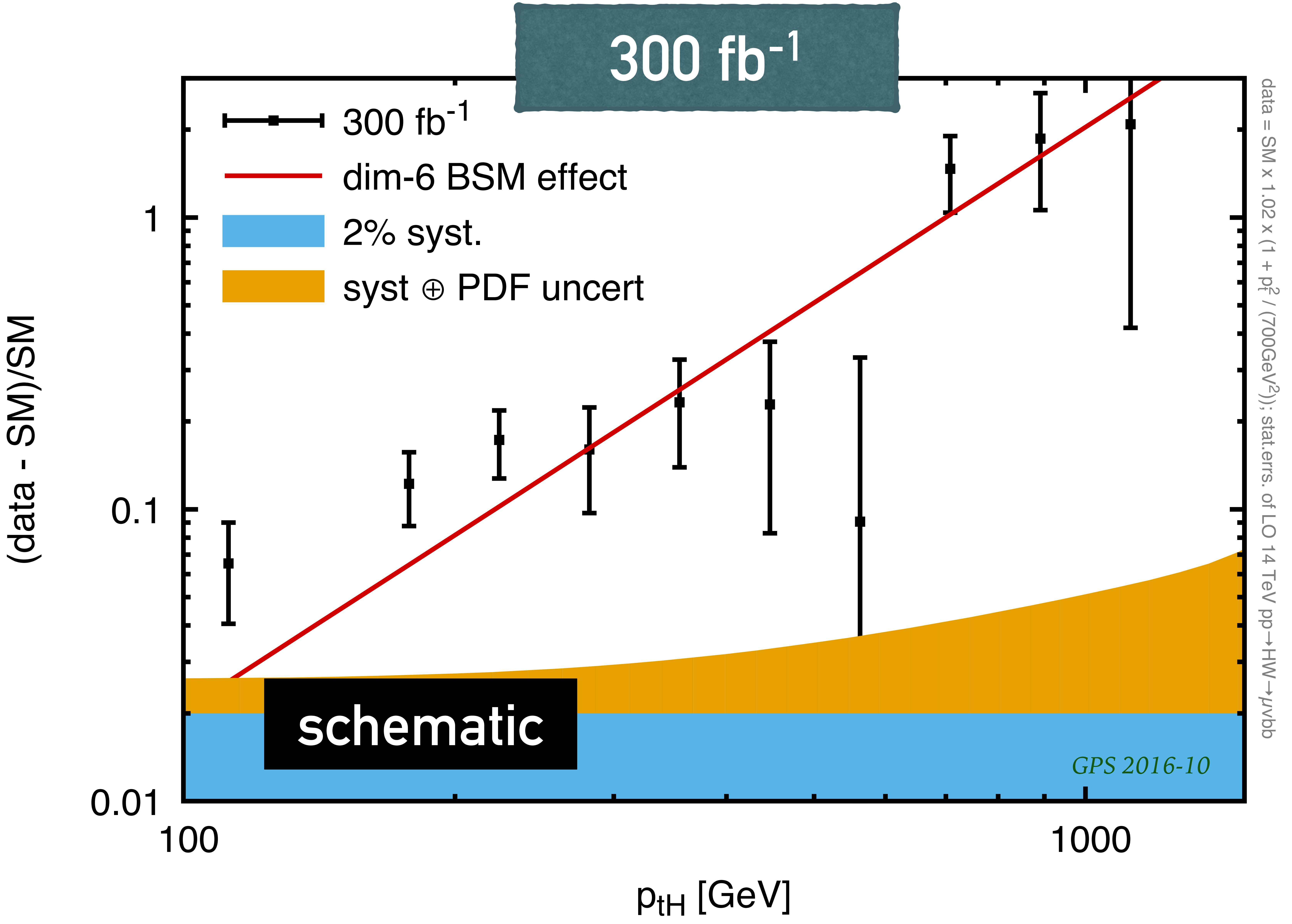
$$\frac{\sigma}{\sigma_{SM}} \sim \left(1 + c_W \frac{\hat{s}}{\Lambda^2}\right)^2$$



Mimasu, Sanz, Williams, arXiv:1512.02572v

Slide from Michelangelo

WH at large Q^2 with dim-6 BSM effect



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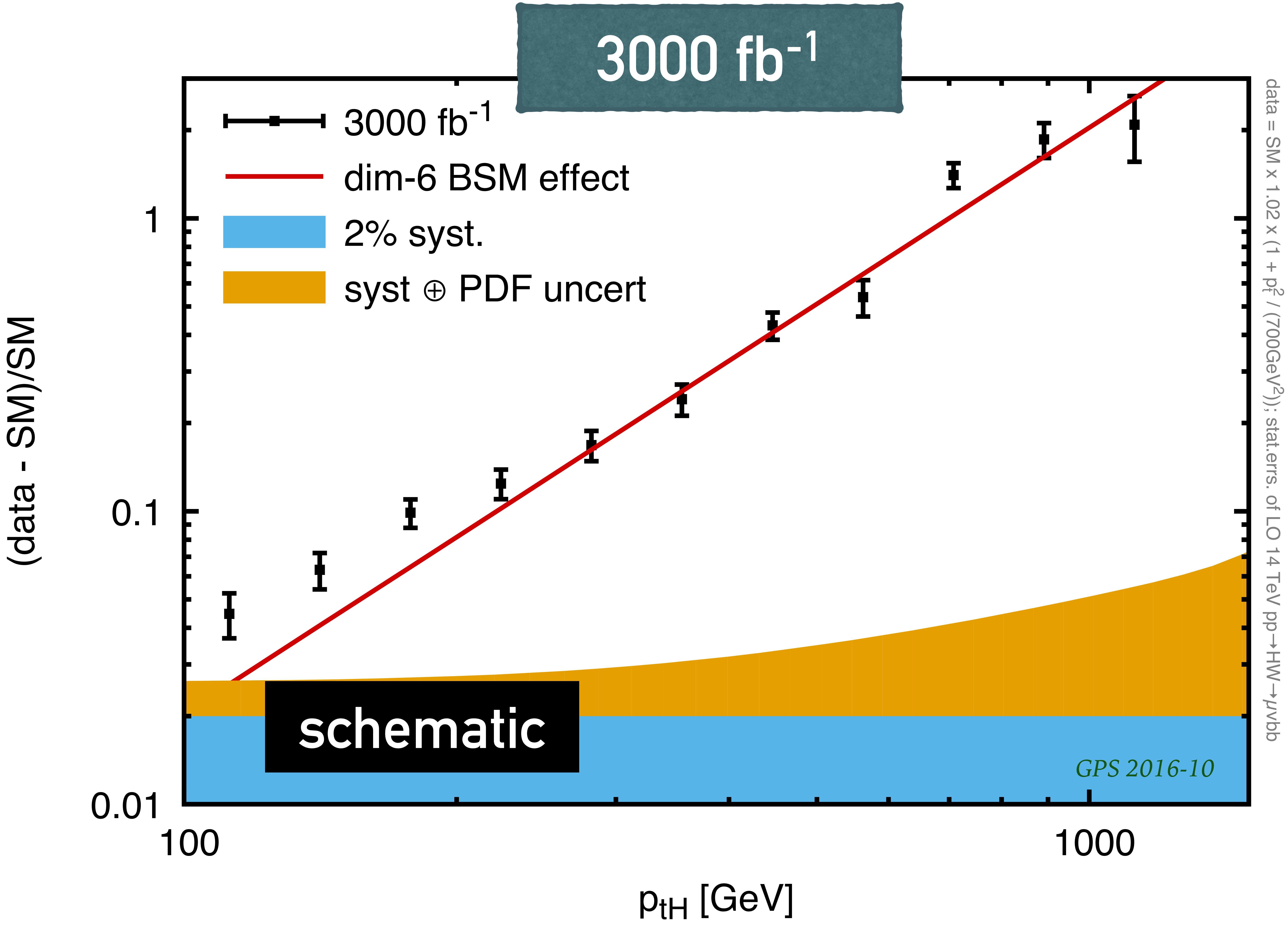


cf also Wulzer et al, arXiv:1609.08157

new physics isn't just a single number that's wrong (think g-2)

but rather a distinct scaling pattern of deviation (~ p_T^2)

moderate and high p_T's have similar statistical significance — so it's useful to understand whole p_T range

Precision buys us kinematic reach to establish scaling pattern of any deviation

CMS Z p_T uncertainties (normalised to total fiducial)

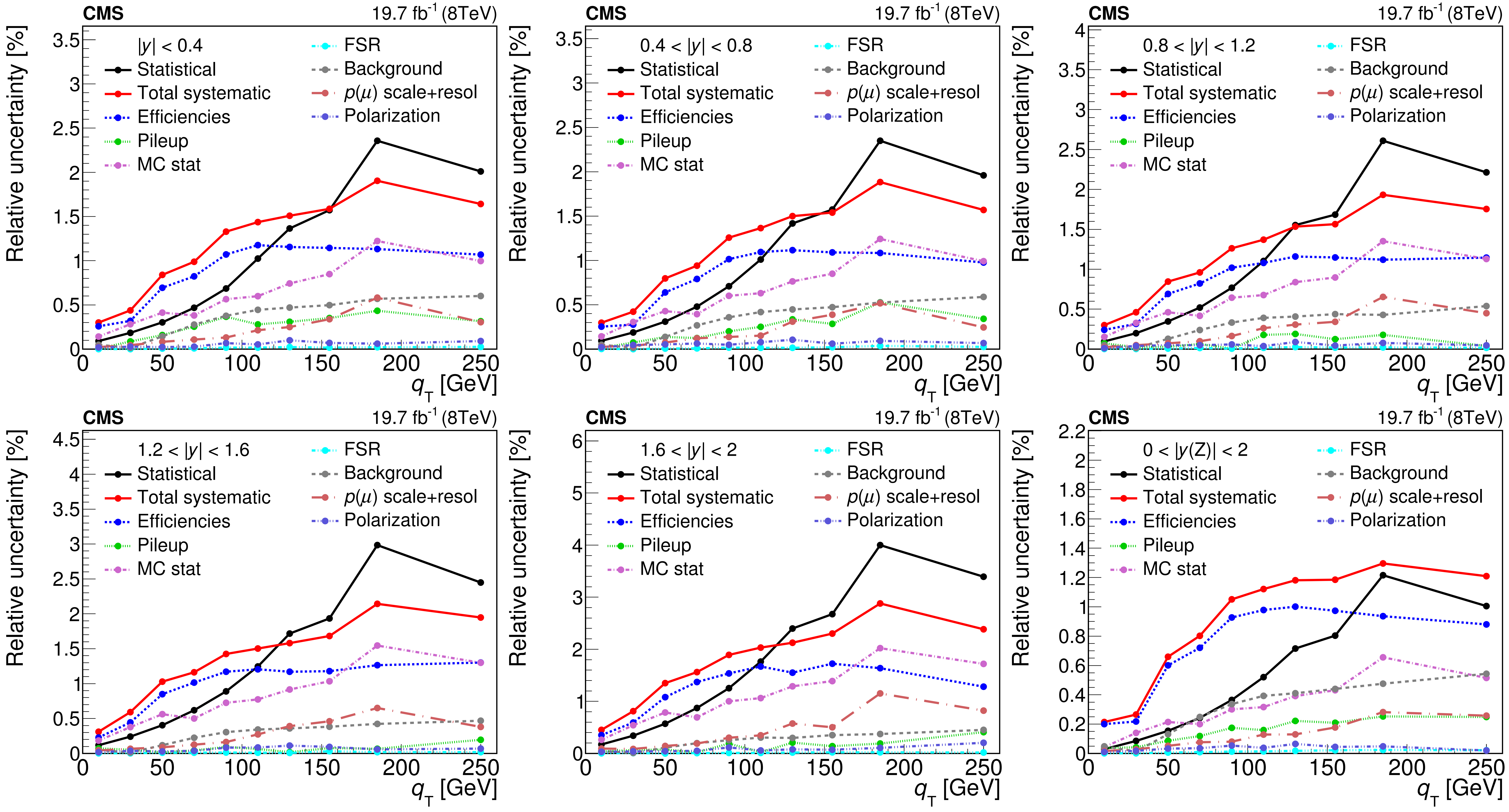


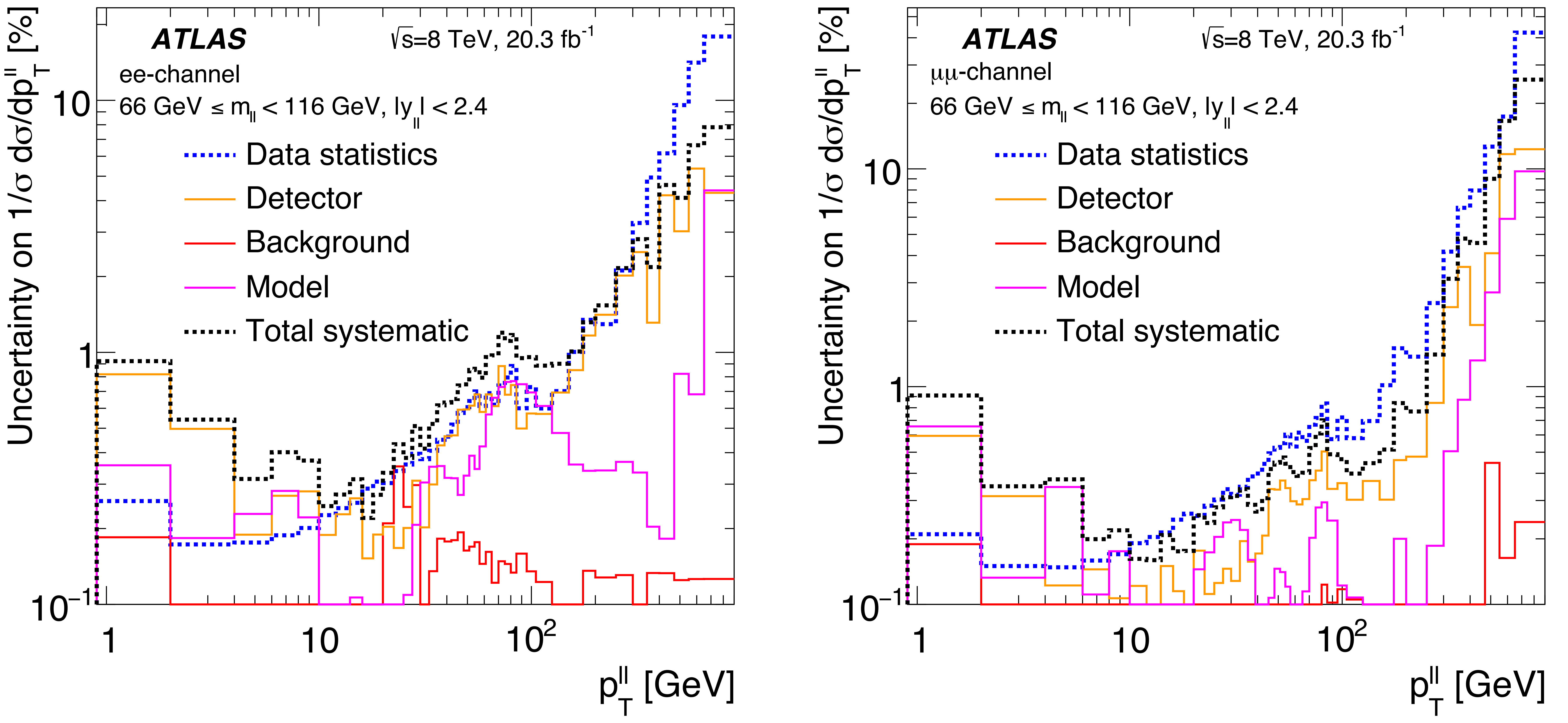
Figure 1: Relative uncertainties in percent of the normalised fiducial cross section measurement. Each plot shows the q_T dependence in the indicated ranges of $|y|$.

Uncertainties seem significantly larger for CMS.

Where are the differences wrt ATLAS?

1504.03511

ATLAS Z p_T uncertainties (normalised to total fiducial)



Uncertainties seem significantly larger for CMS.

Where are the differences wrt ATLAS?

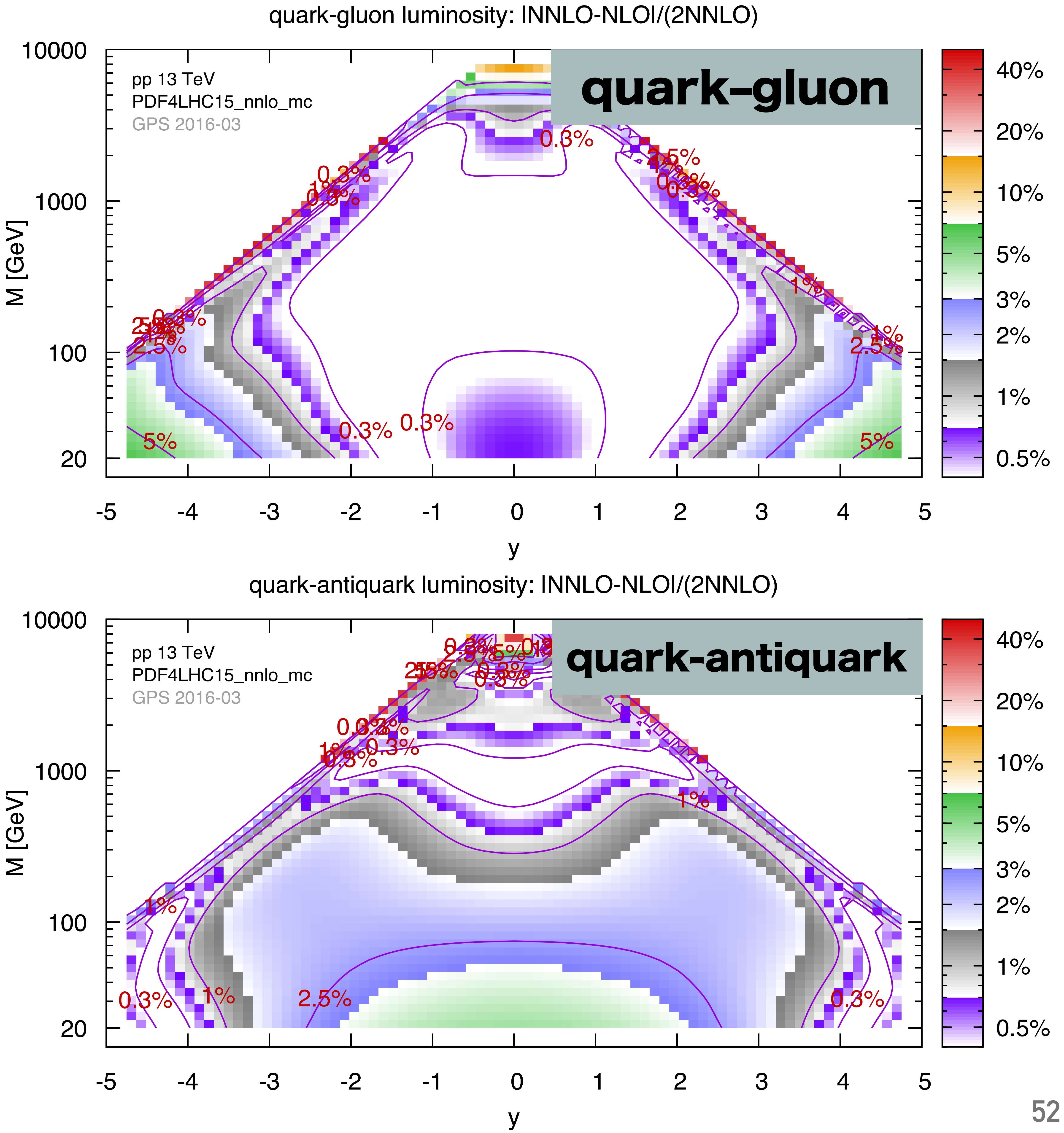
1512.02912

Figure 4: Uncertainty from various sources on $(1/\sigma)\,\mathrm{d}\sigma/\mathrm{d}\phi^*_\eta$ (top) and $(1/\sigma)\,\mathrm{d}\sigma/\mathrm{d}p_\mathrm{T}^{\ell\ell}$ (bottom) for events with 66 GeV < $m_{\ell\ell}$ < 116 GeV and $|y_{\ell\ell}|$ < 2.4. Left: electron-pair channel at dressed level. Right: muon-pair channel at bare level.

WHAT ROUTE FOR PROGRESS?

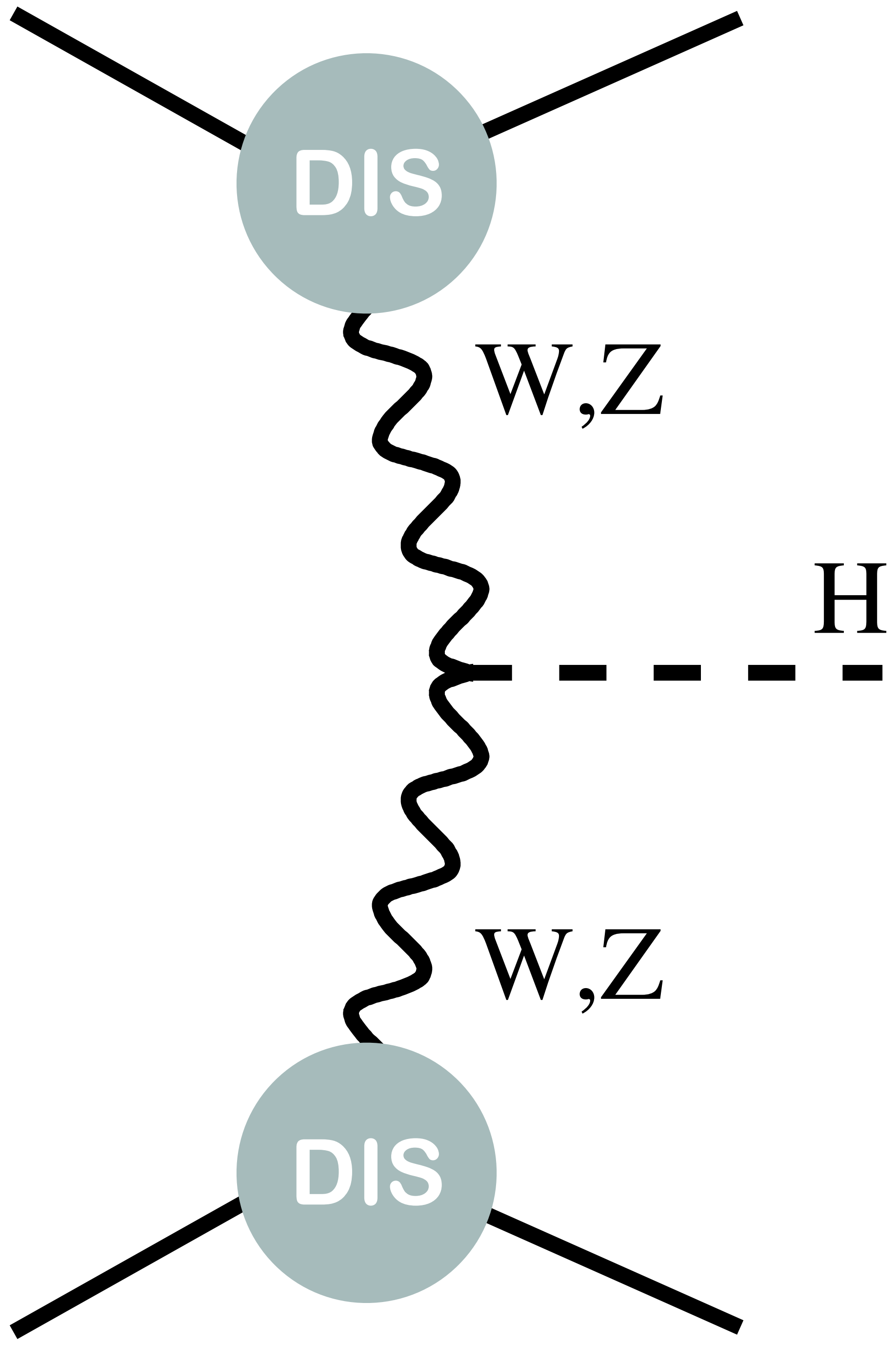
- Current status is 2–3% for core "precision" region
- Path to 1% is not clear — e.g. Z p_T's strongest constraint is on qg lumi, which is already best known (why?)
- It'll be interesting to revisit the question once ttbar, incl. jets, Z p_T, etc. have all been incorporated at NNLO
- Can expts. get better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

Theory Uncertainties



VECTOR-BOSON FUSION → HIGGS

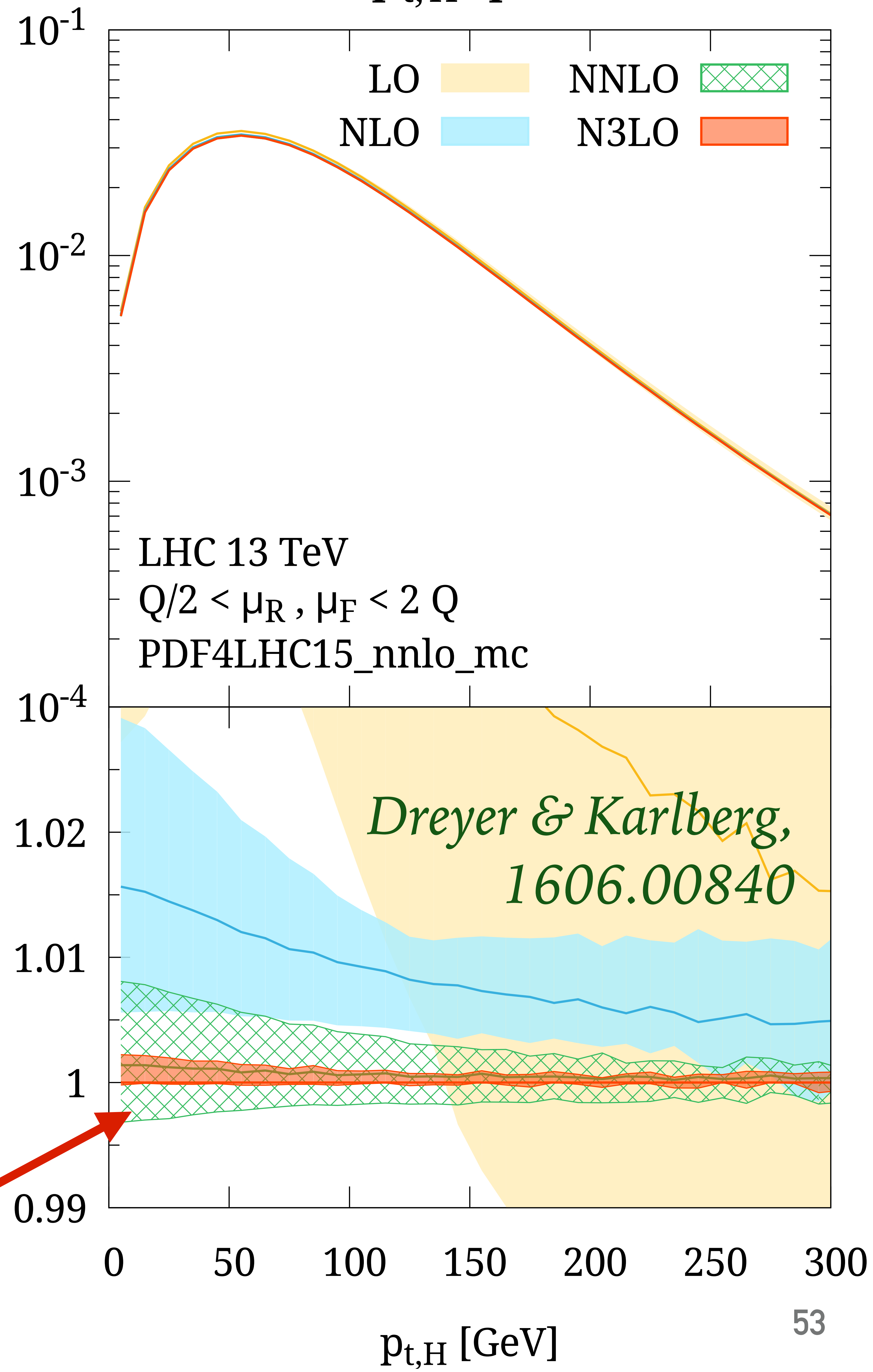
- double DIS approximation is powerful tool for VBF, using structure functions for the W/Z production (Han, Valencia & Willenbrock 1992, NNLO by Bolzoni et al 1003.4451)



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

N3LO

N3LO VBF (no cuts)



Dreyer & Karlberg, 1606.00840

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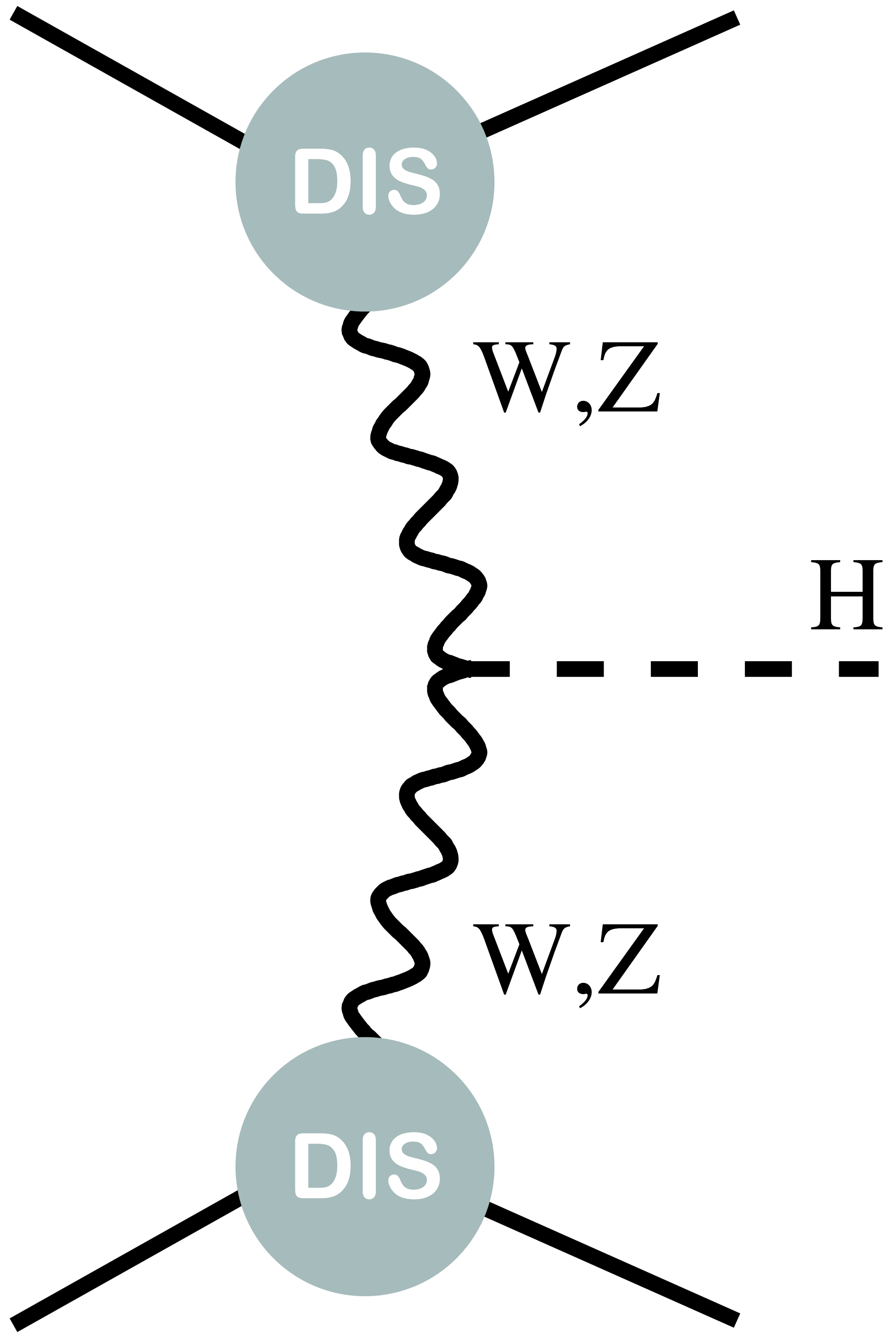

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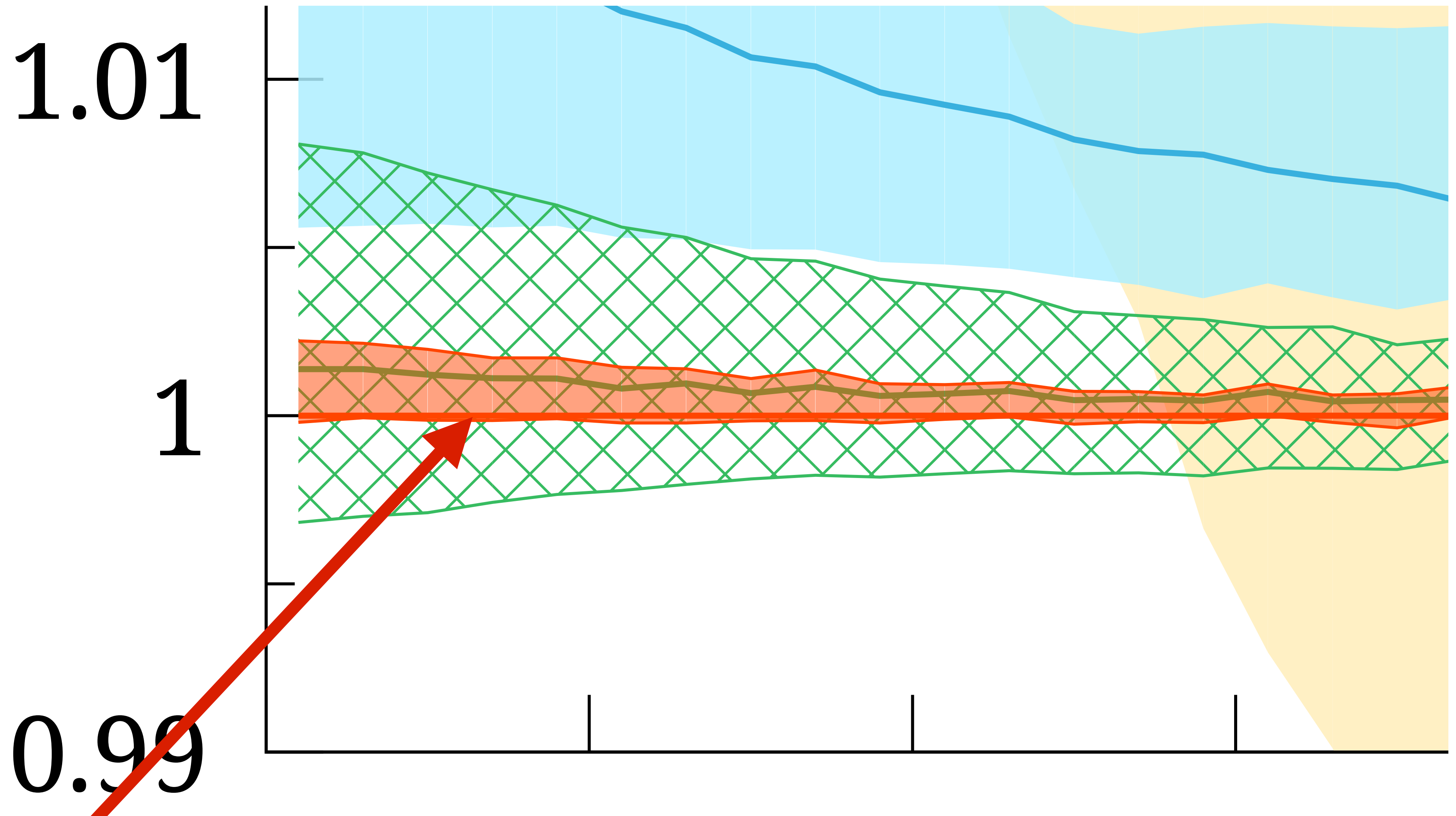


Dreyer & Karlberg, 1606.00840

N3LO

Exact in "QCD$_1$ ⊗ QCD$_2$"
Non-trivial real-world corrections believed < 1%

VBF with cuts on jets: Projection to Born method

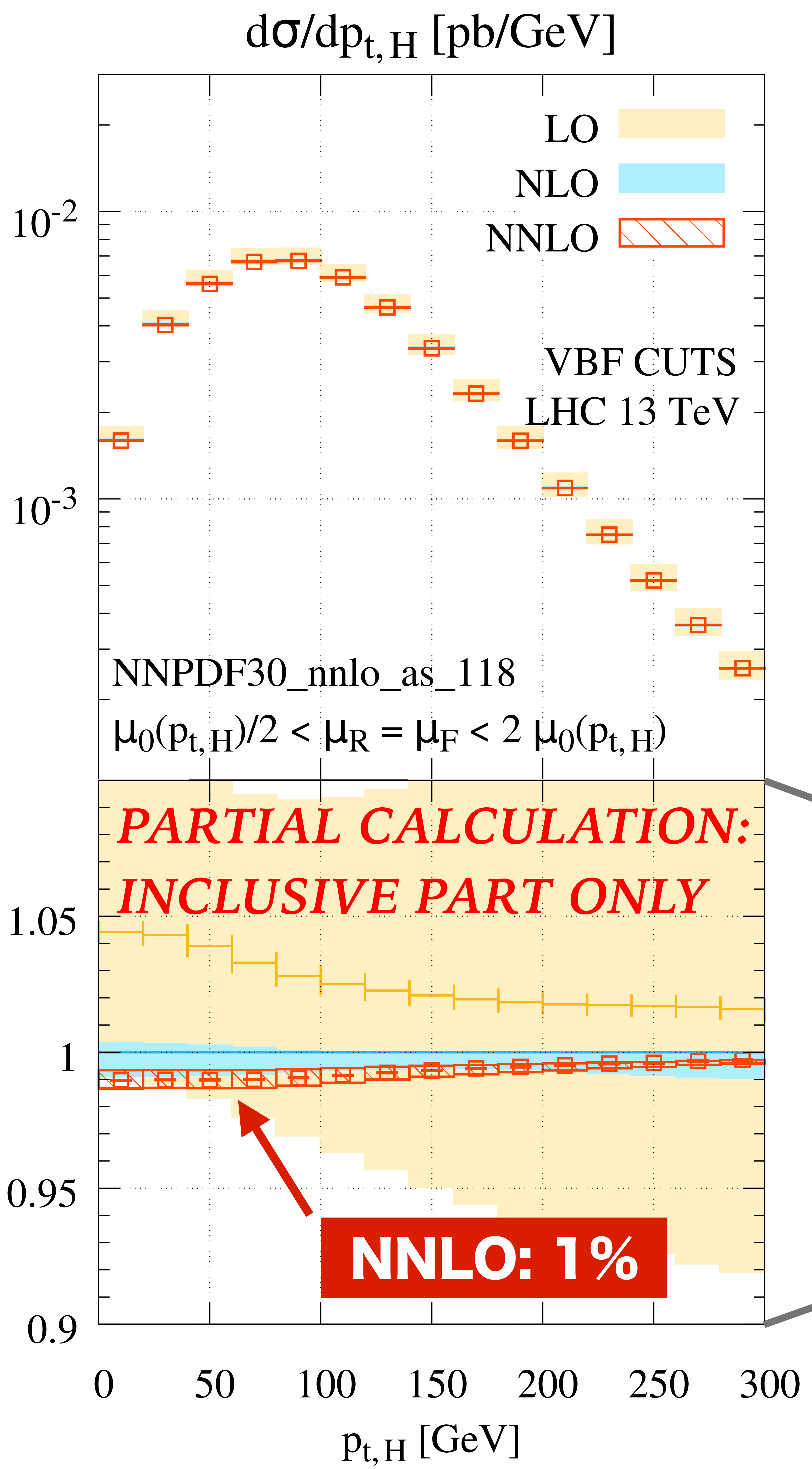
Cacciari, Dreyer, Karlberg, GPS & Zanderighi, 1506.02660

Exact in "$QCD_1 \otimes QCD_2$"

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

Inclusive part only (with VBF cuts)

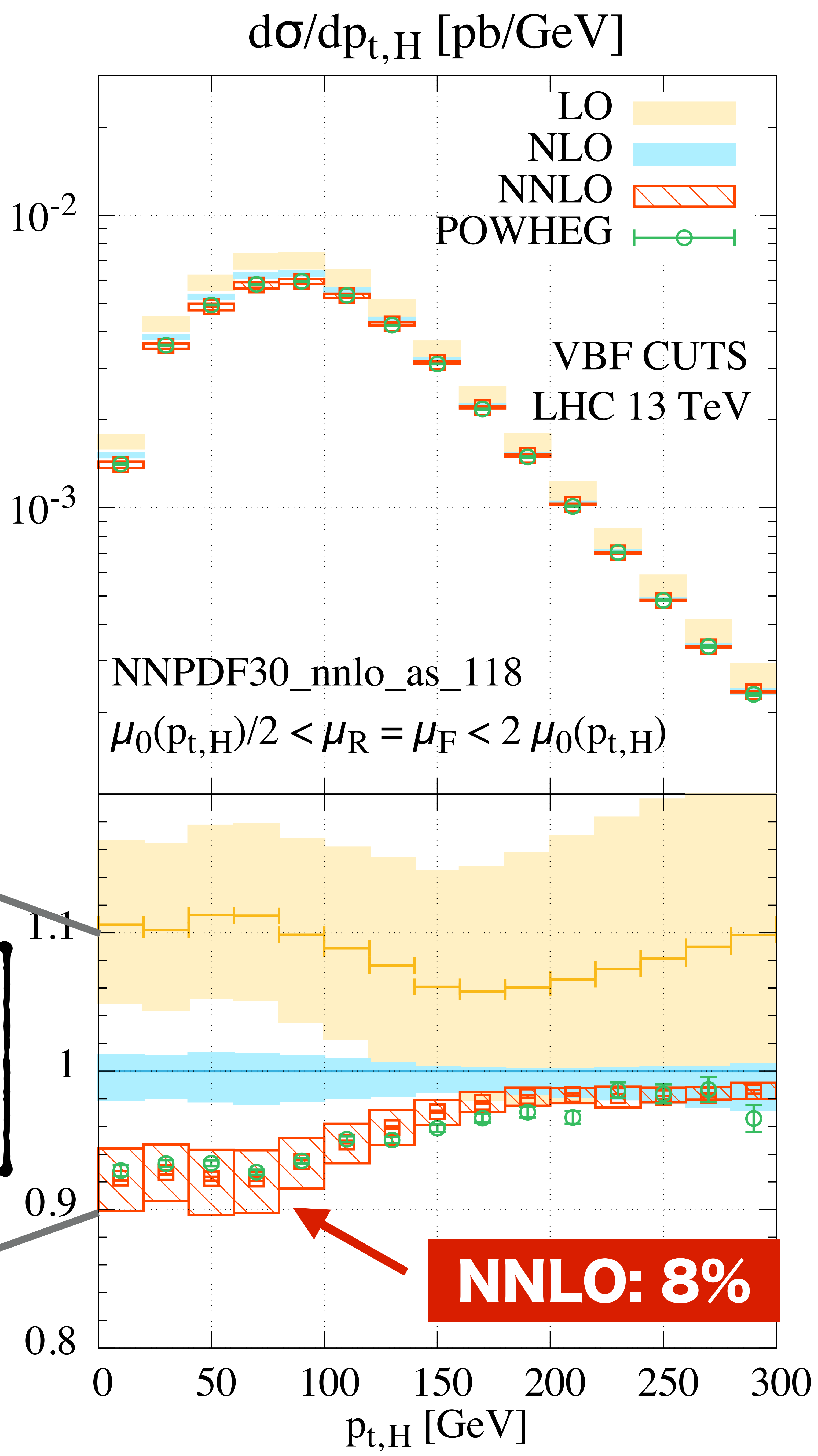
NNLO is 1% effect



PARTIAL CALCULATION: INCLUSIVE PART ONLY

NNLO: 1%

note different scales



NNLO: 8%

Full calculation (with VBF cuts)

NNLO is up to 8% effect

Almost all of which comes from jet fragmentation

2 KINDS OF EFFECT IN SUCH PROCESSES ?

- “Inclusive” correction to process as a whole (insofar as this is meaningful)
- corrections related to jet fragmentation

Can we make such a distinction meaningful?

Can we examine same idea in other contexts? E.g. inclusive jet spectrum

Dasgupta, Dreyer, GPS & Soyez, 1602.01110

- There is no way of defining the "inclusive" part in most cases
- But there are arguments that for a jet radius $R_\mathrm{m} \simeq 1$, ISR and FSR effects mostly cancel each other *[Soyez, 1006.3634]*
- So try looking at effect of NNLO corrections relative to $R_\mathrm{m} = 1$
  [can be done with NLO 3-jet calc^n from NLOJET++]

$$\sigma^{\mathrm{NNLO}_R}(R, R_m) \equiv \underbrace{\sigma_0 + \sigma_1(R)}_{\text{NLO}} + \underbrace{[\sigma_2(R) - \sigma_2(R_m)]}_{\text{R-dependent piece of NNLO, relative to } R_m}$$

- Full NNLO will have an additional NNLO term associated with the effective K-factor for the "inclusive" piece — we miss that part (and unlike VBF, it may not be small)

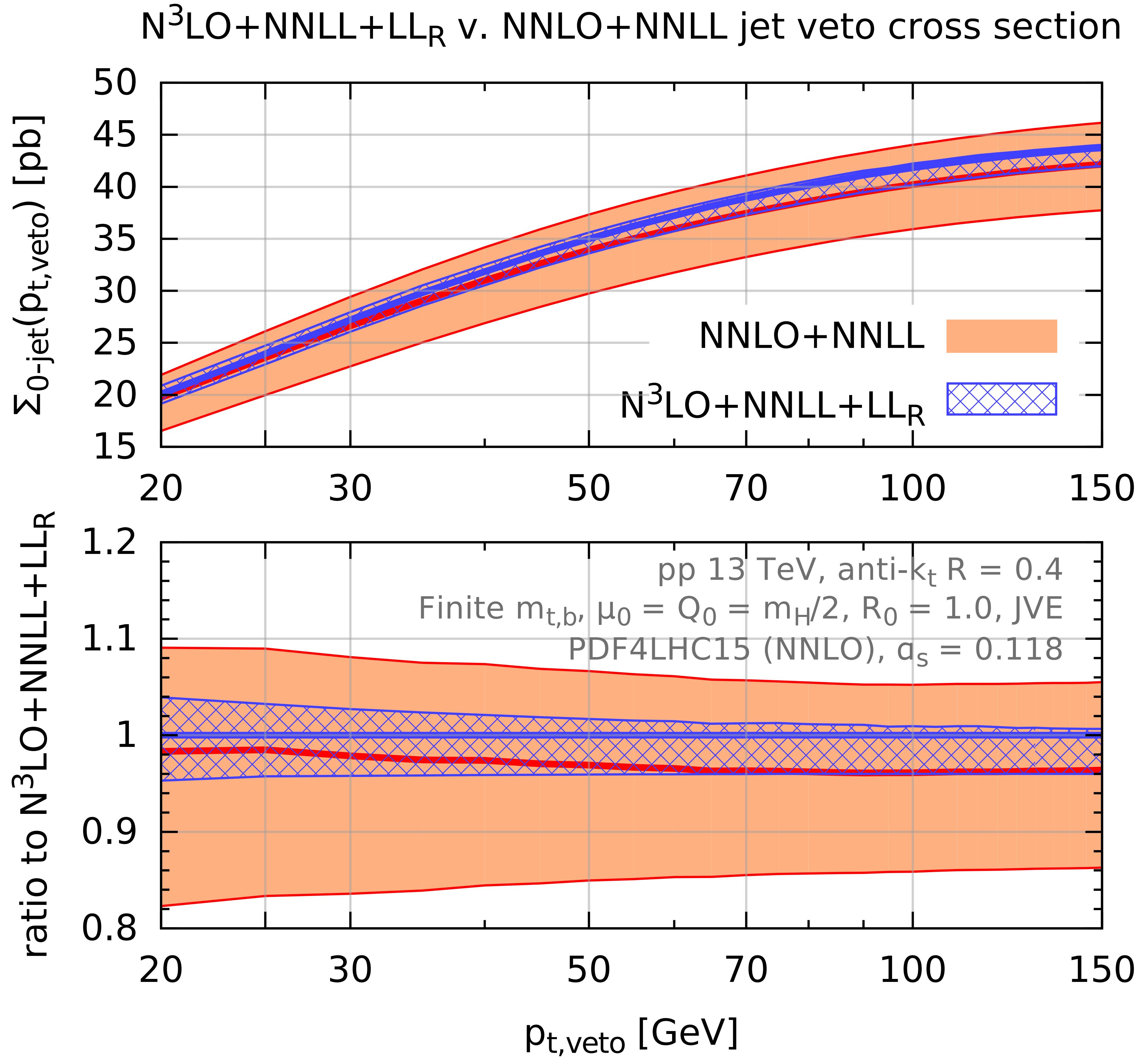
HIGGS JET VETO @ N3LO + NNLL

Anastasiou, Duhr, Dulat, Herzog & Mistlberger 1503.06056

Boughezal, Caola, Melnikov, Petriello & Schulze 1504.07922

Banfi, Caola, Dreyer, Monni, GPS, Zanderighi & Dulat 1511.02886

- N3LO effects at 2–4%
- Residual uncertainty up to 4% (fairly conservative estimate)



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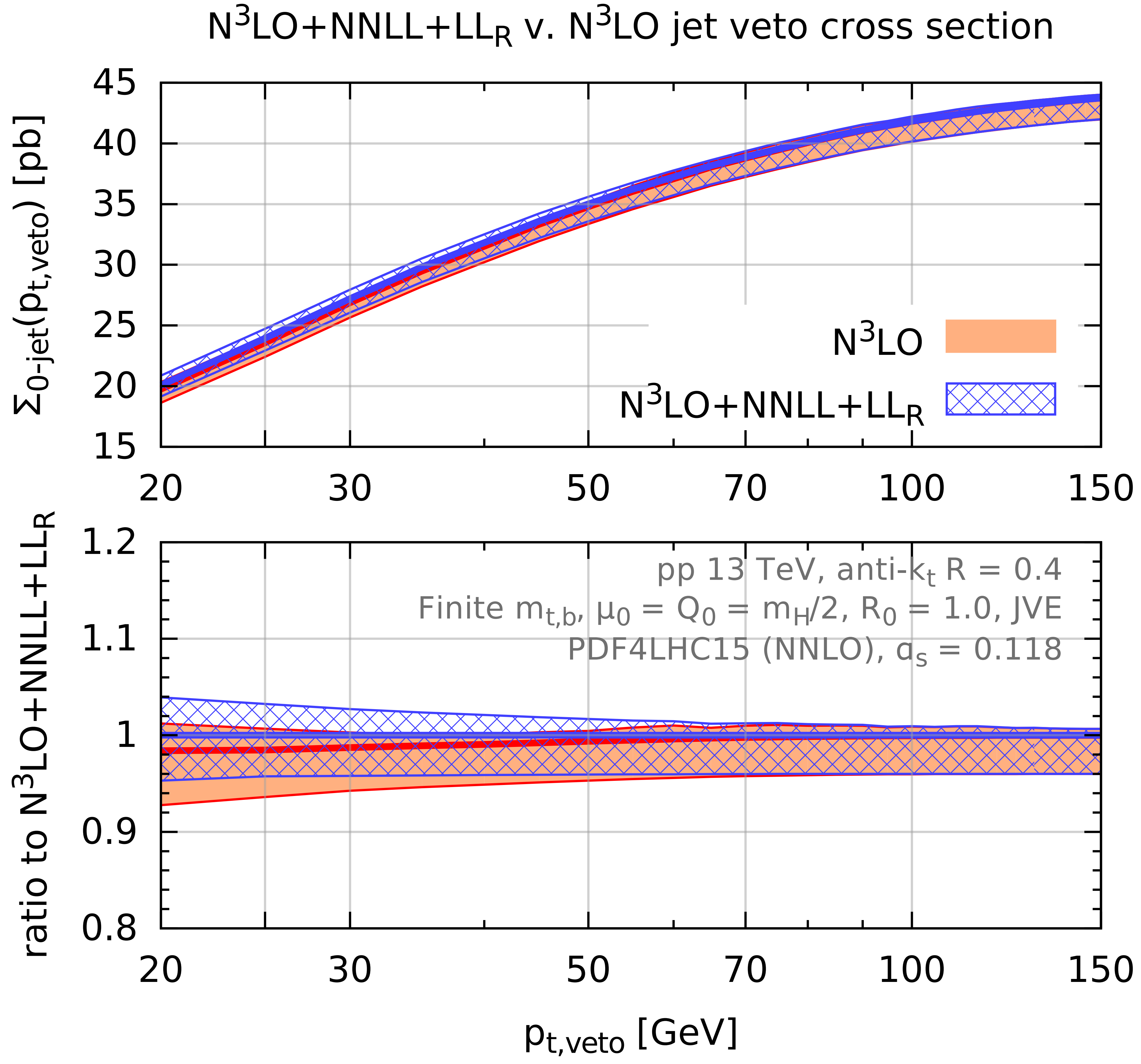
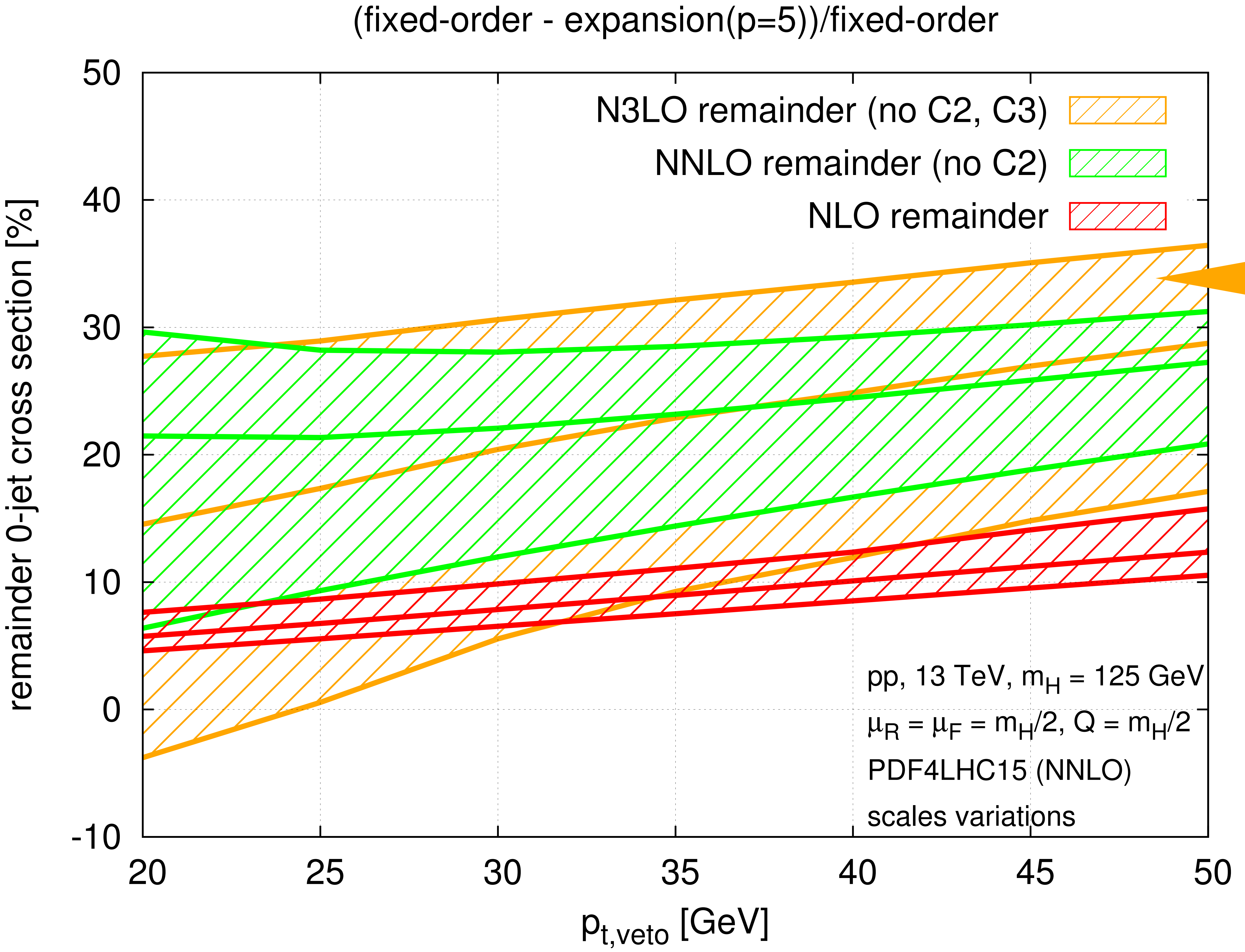
- rather stable (~2%) wrt jet-p_T resummation effects



how good is resummation at finite p_t?



(fixed-order - expansion(p=5))/fixed-order

pp, 13 TeV, m_H = 125 GeV

$\mu_R = \mu_F = m_H/2$, $Q = m_H/2$

PDF4LHC15 (NNLO)

scales variations

$$\frac{\text{N3LO-NNLL@N3LO}}{\text{N3LO}}$$

- Resummation is designed for $p_t \ll m_H$,
- At what point does it actually become relevant?
- From figure, for $p_t/m_H \sim 0.4$ it already captures 70% of fixed order

thanks to P. Monni for producing this plot

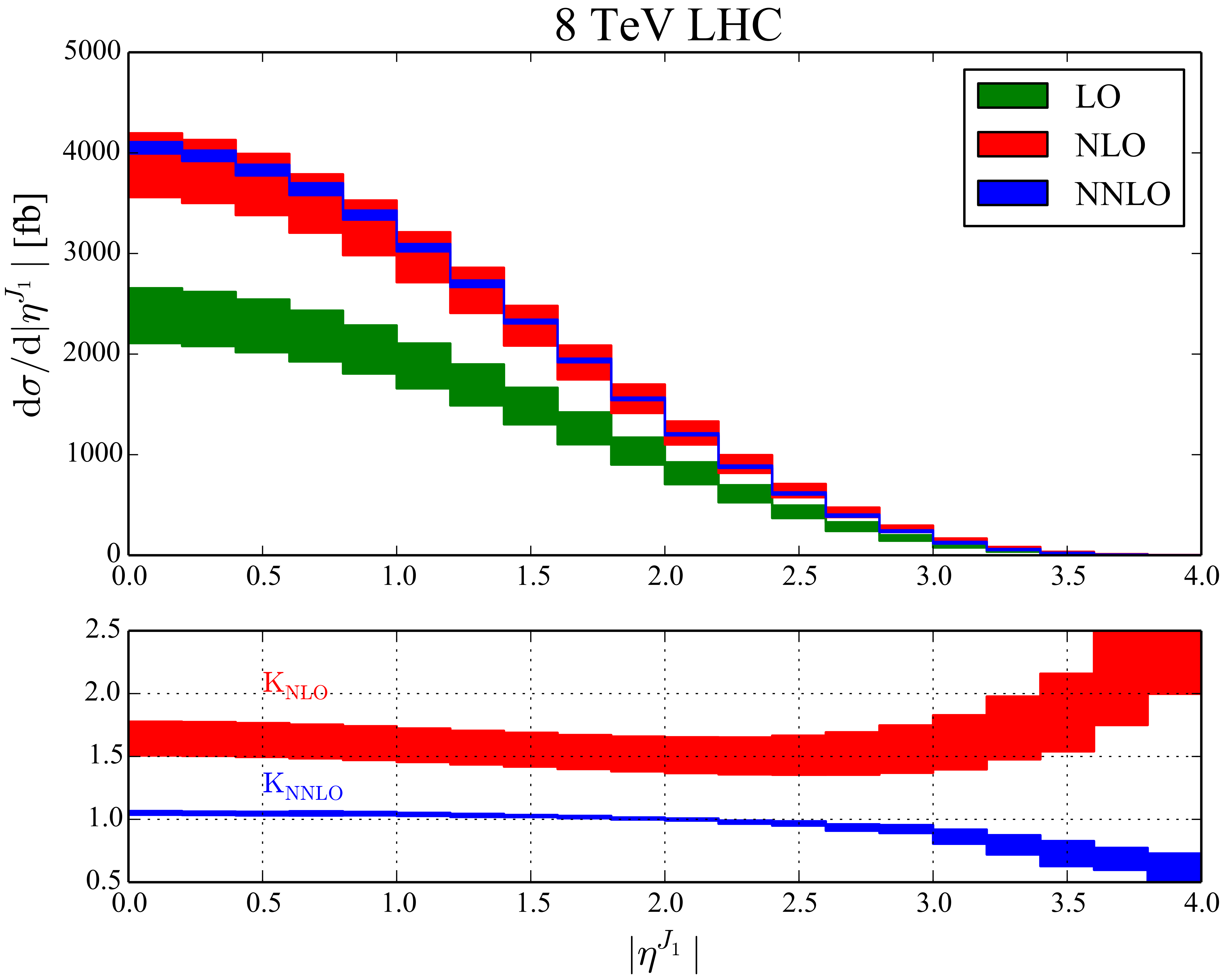
THE JET IN Z+JET @ NNLO

Boughezal, Liu & Petriello, 1602.08140

1-jet cross sections

	σ_{LO} (pb)	σ_{NLO} (pb)	σ_{NNLO} (pb)	K_{NLO}	K_{NNLO}
8 TeV	$4.17^{+0.55}_{-0.47}$	$6.59^{+0.62}_{-0.53}$	$6.86^{+0.01}_{-0.13}$	1.58	1.04
13 TeV	$9.12^{+0.88}_{-0.79}$	$14.90^{+1.29}_{-1.06}$	$15.54^{+0.01}_{-0.24}$	1.63	1.04

- NNLO K-factor is 4%
- Residual scale uncertainty <2%



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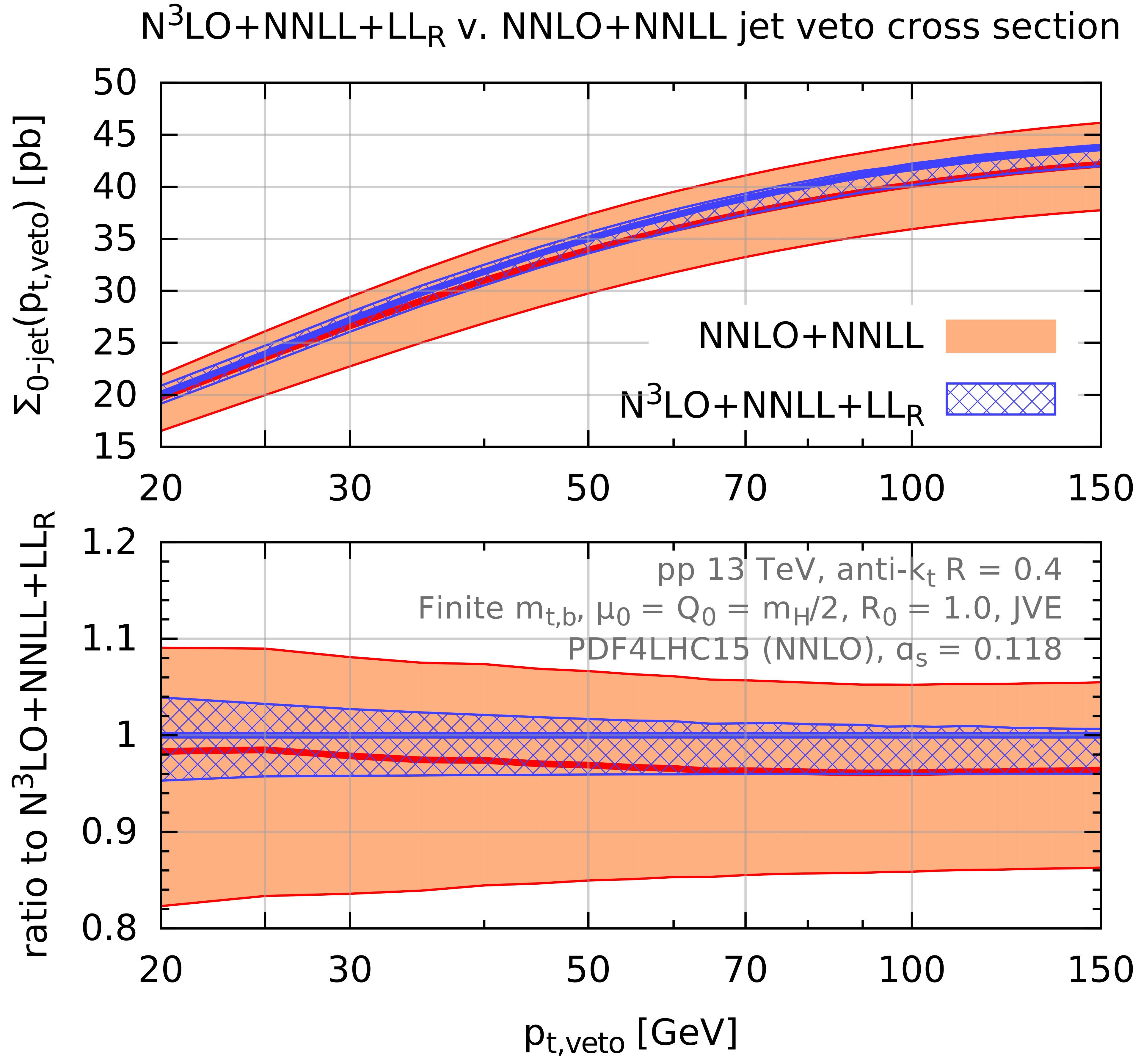

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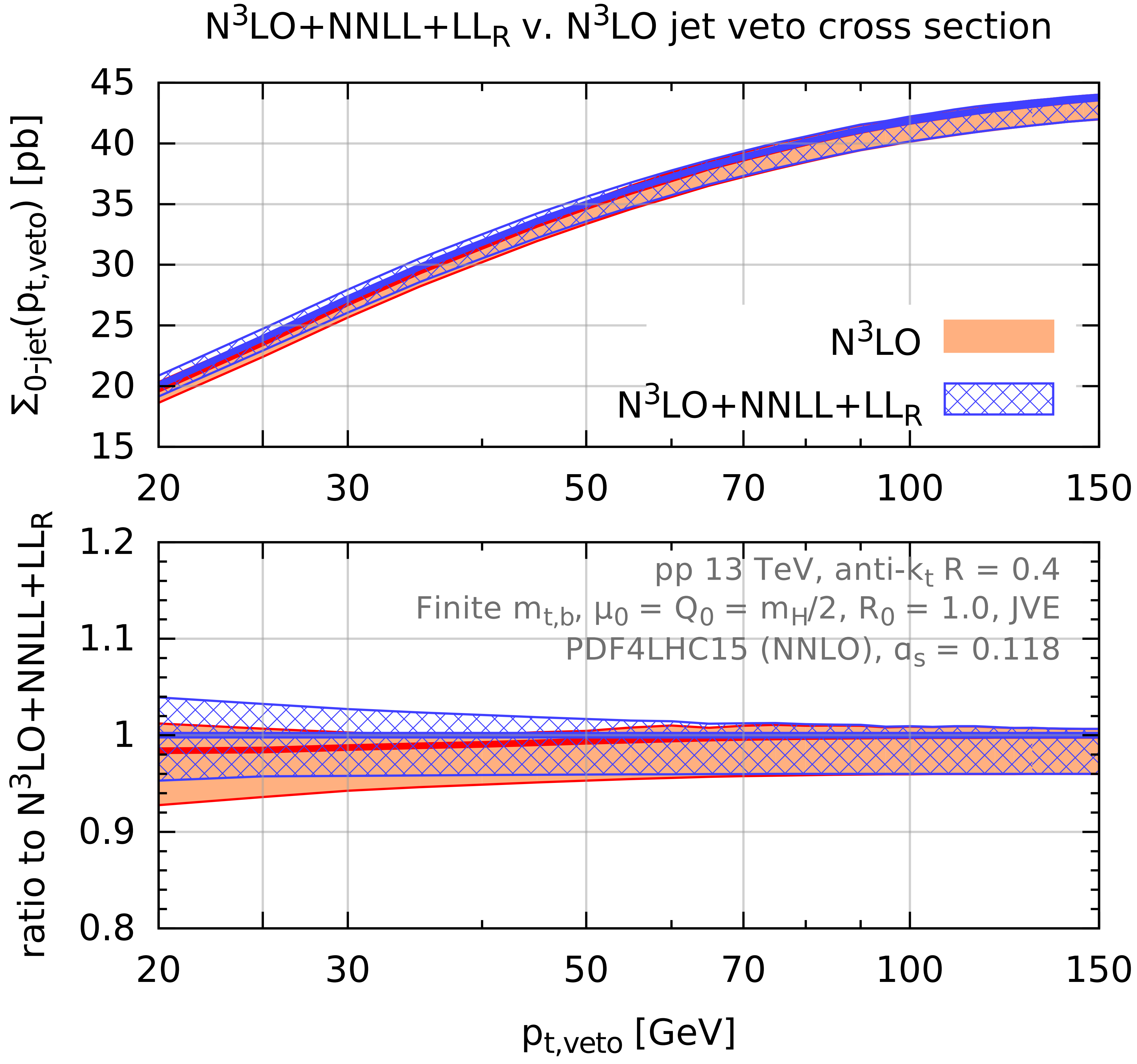
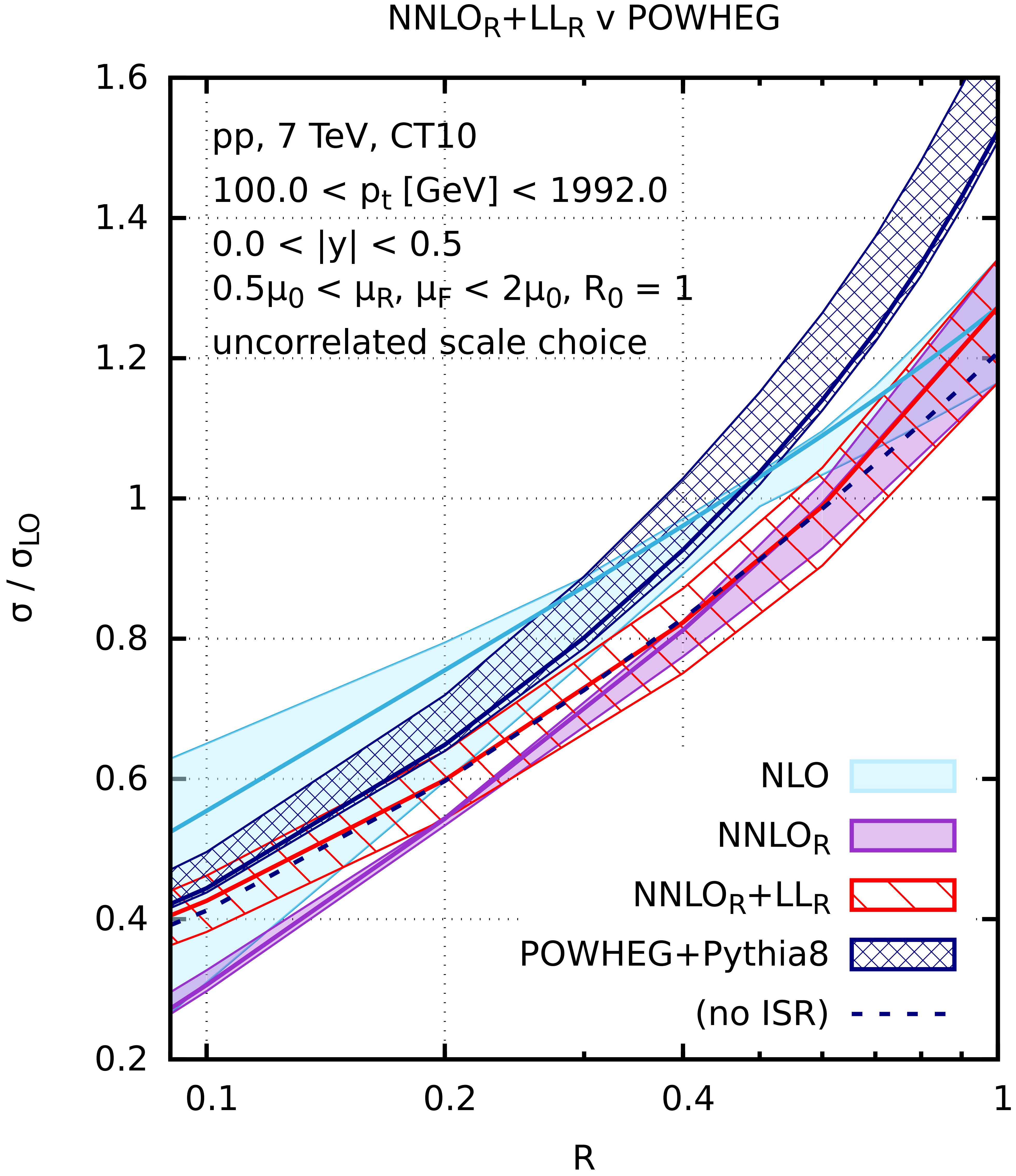


NNLO$_R$ & small-R resummation

- to explore full R-range, need resummation as well

$$\sigma(R) = \sigma(R_0 = 1) \times \text{ratio}(R, R_0)_{\text{fixed-order} + \text{LL}_R}$$



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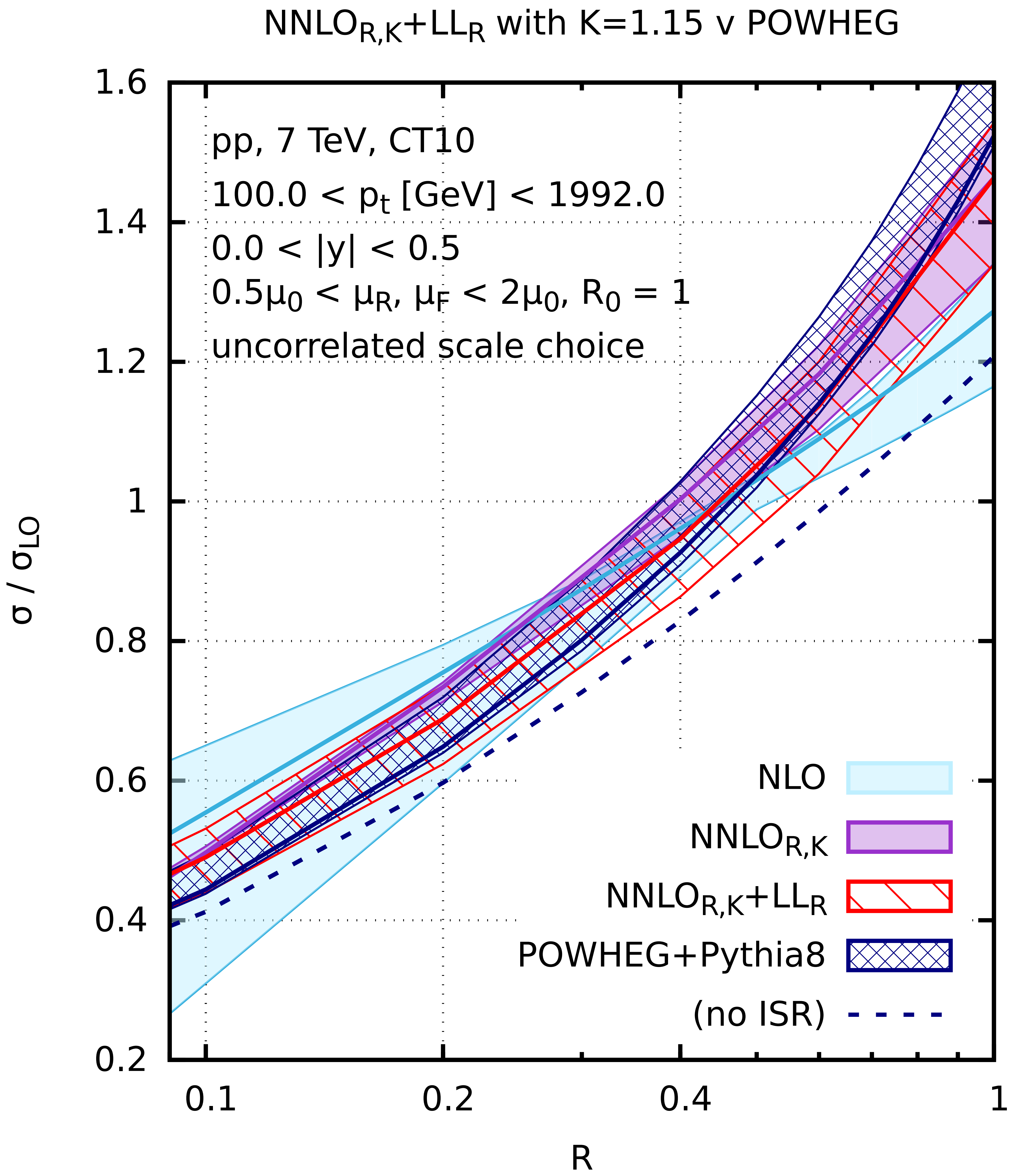

NLL SMALL-R TERMS