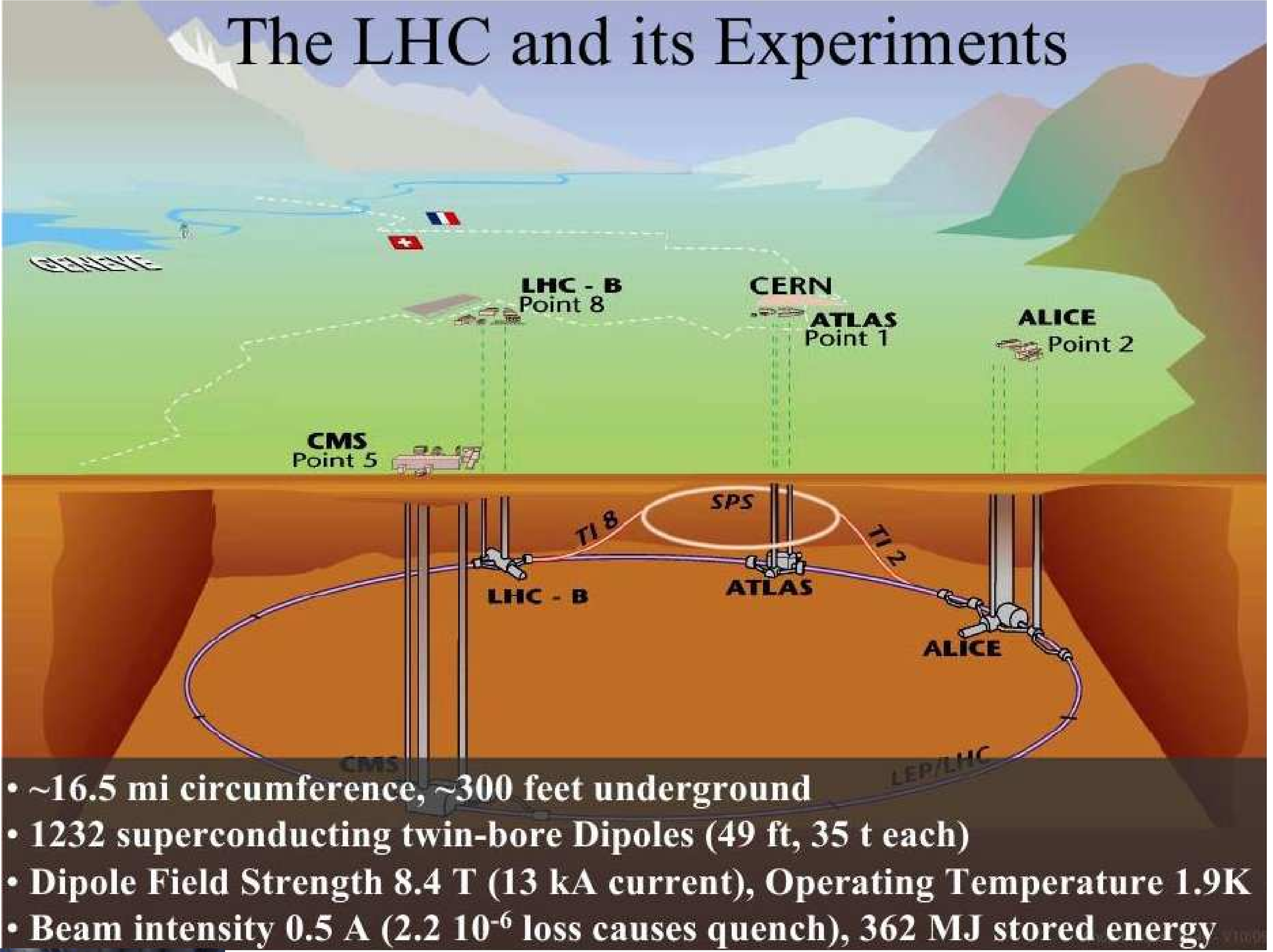
TOWARDS 1% PRECISION AT THE LHC?

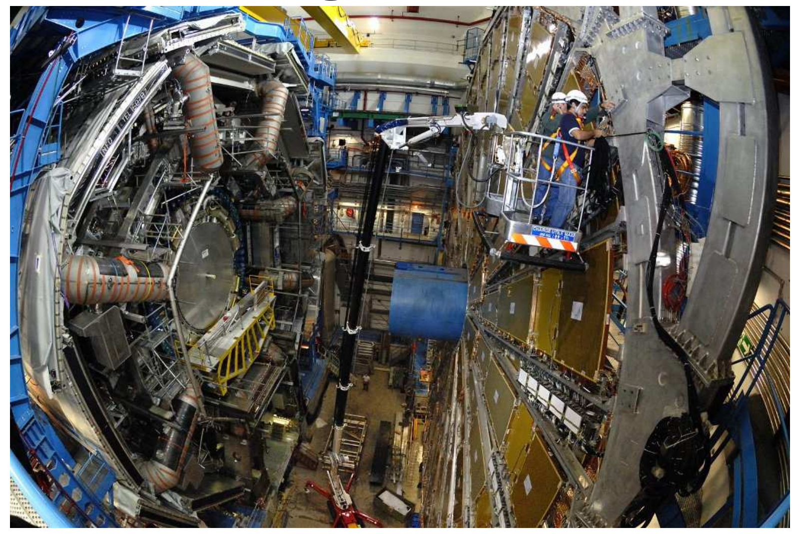
Gavin Salam, CERN

PSR16
Paris, France, 4–6 July, 2016

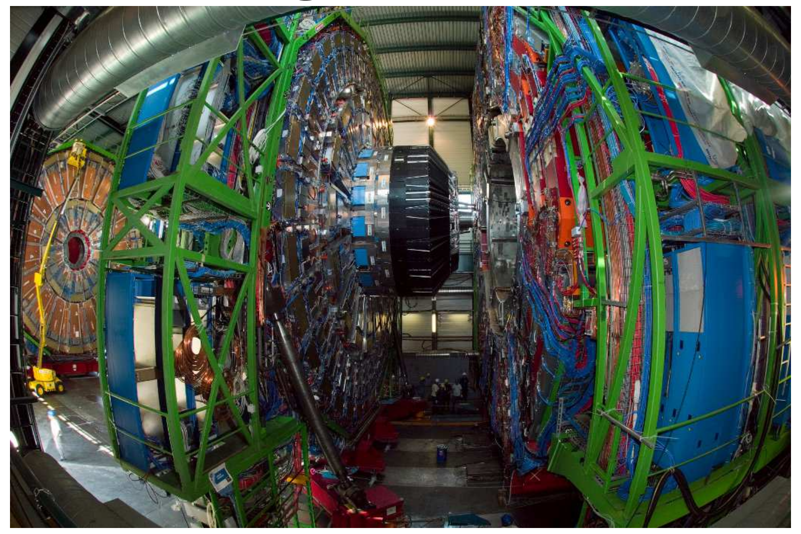
Talk in part inspired by discussions at KITP Santa Barbara



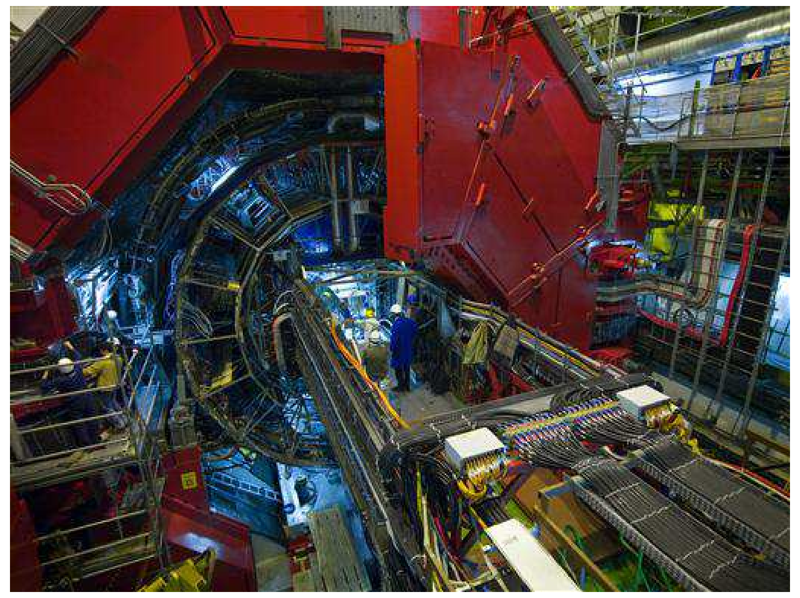
ATLAS: general purpose



CMS: general purpose



ALICE: heavy-ion physics

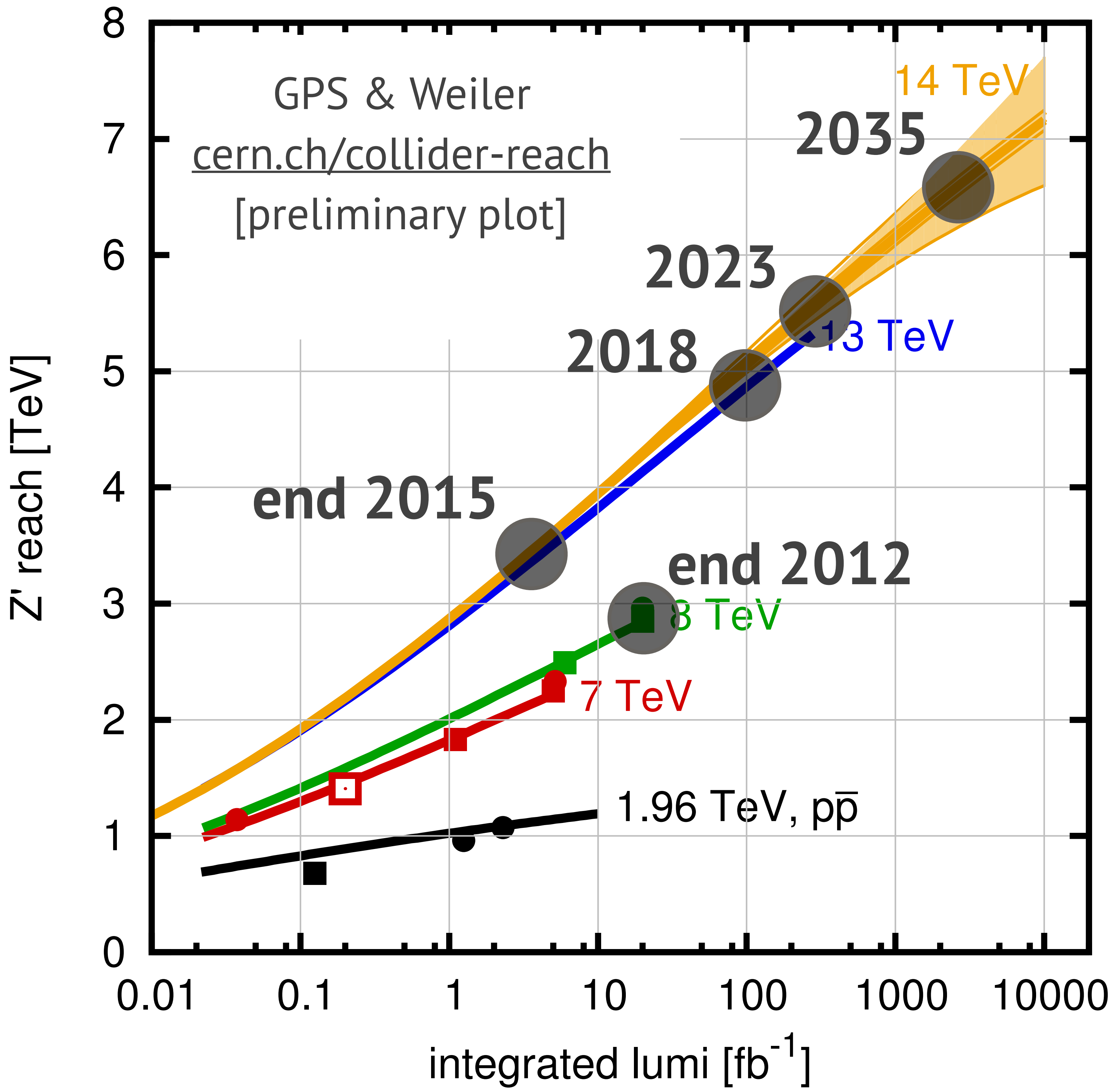


LHCb: B-physics

+ TOTEM, LHCf

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

Z' exclusion reach v. lumi



Today

- 20 fb^{-1} at 8 TeV
- 3–4 fb^{-1} at 13 TeV

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

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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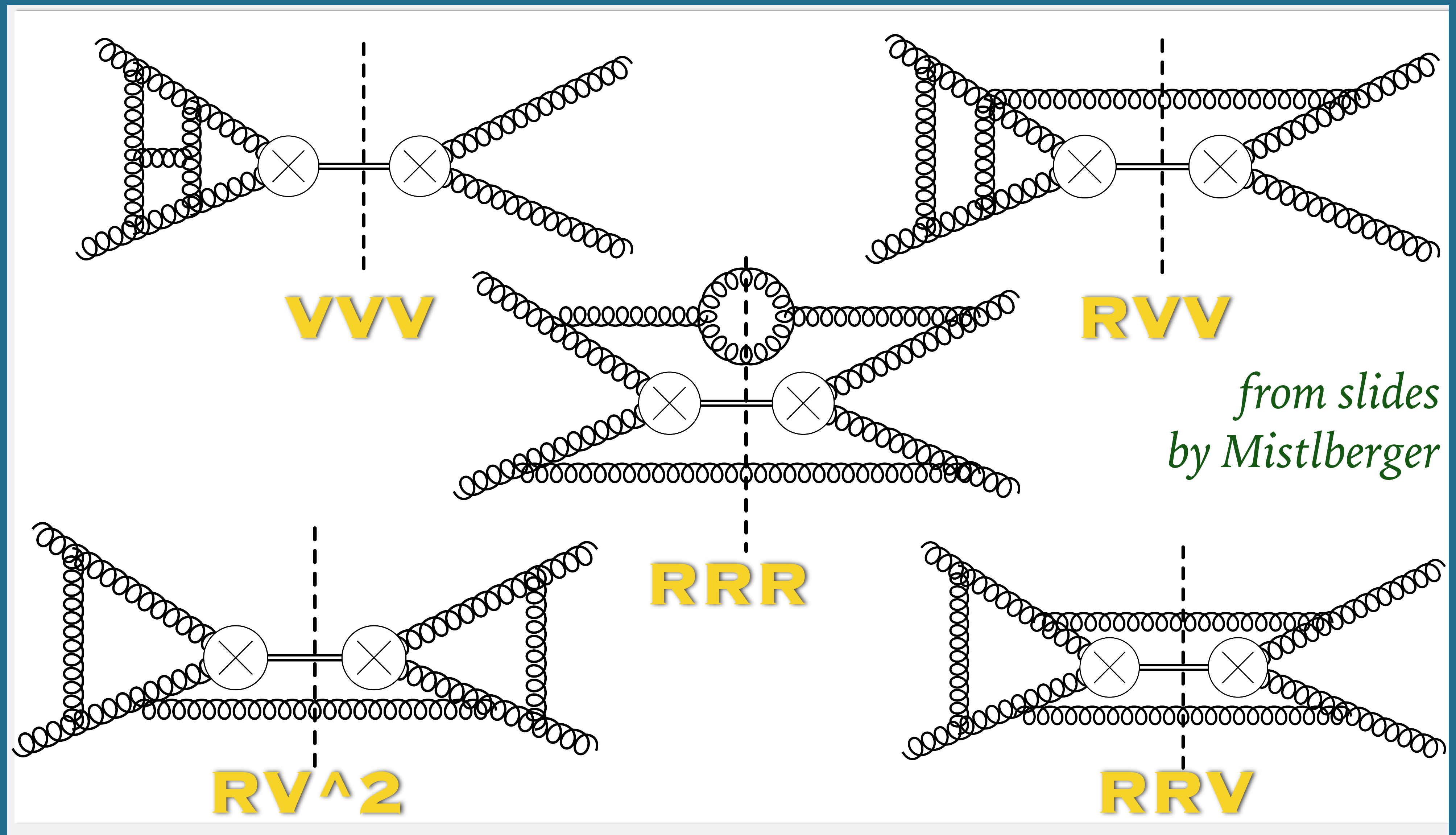
N3LO Higgs production

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

100,000 diagrams



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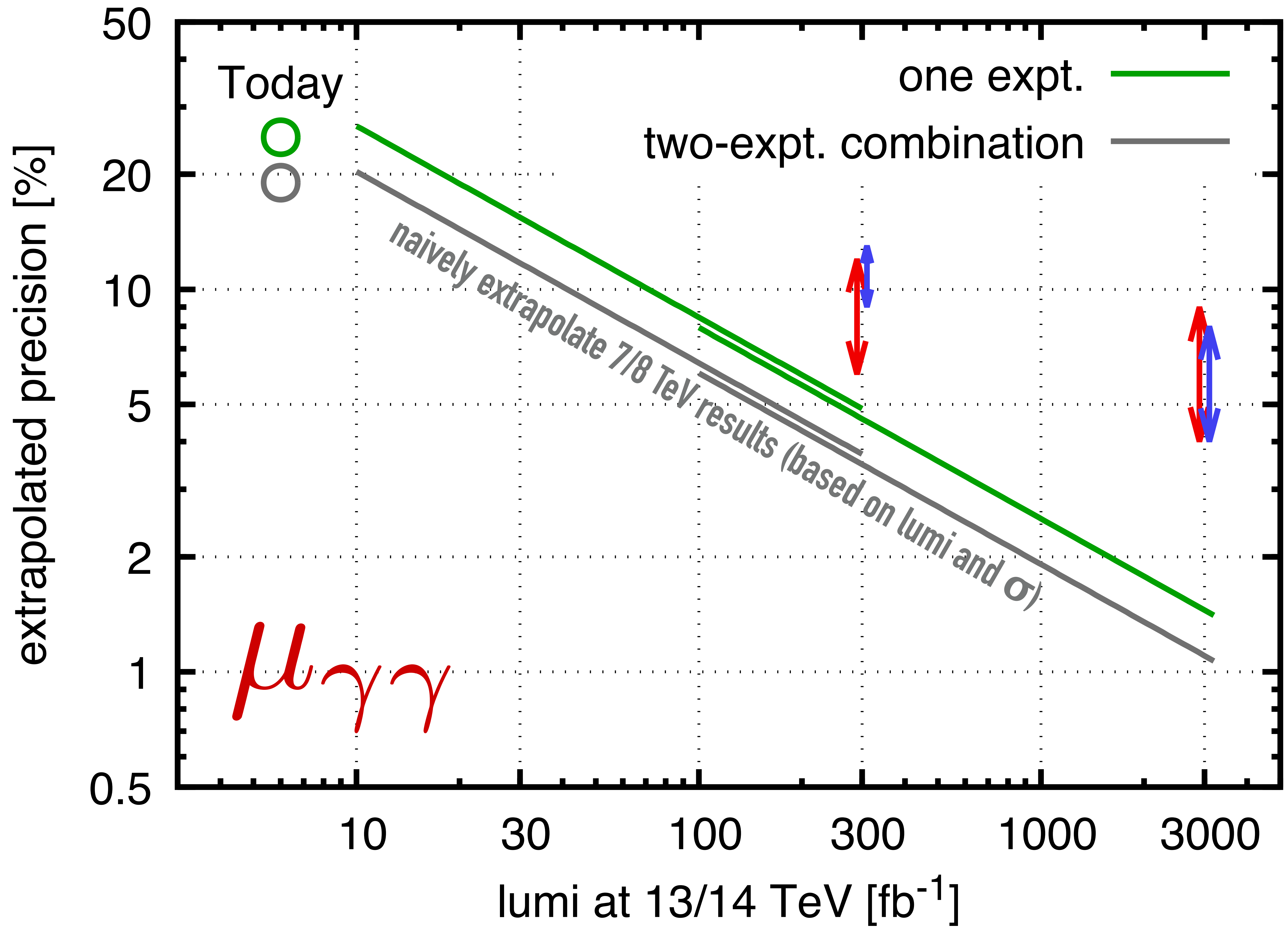
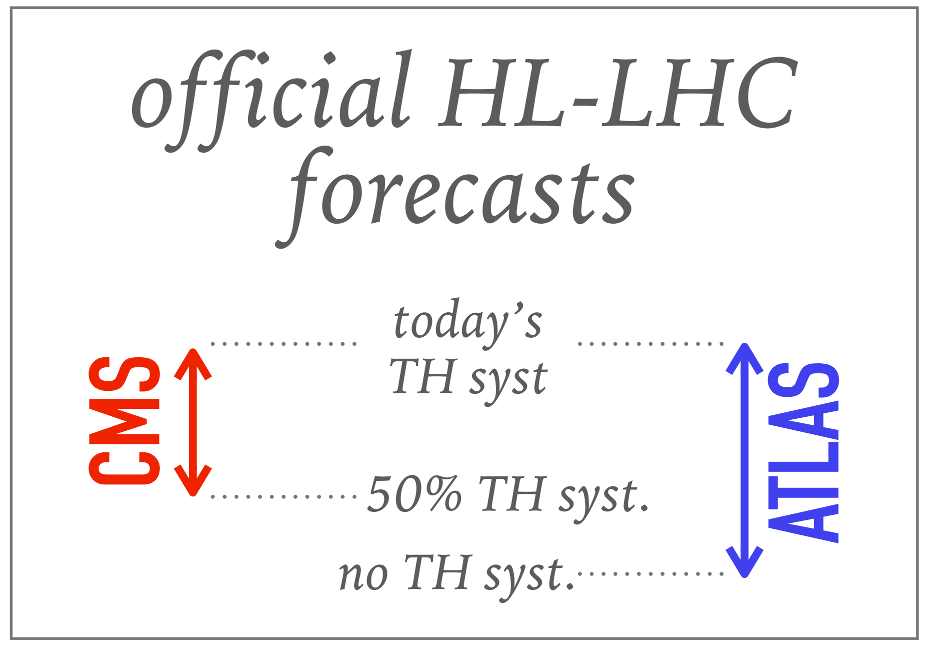
The intention with this talk?

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

What precision should we have as a target?

HIGGS TODAY & TOMORROW





HL-LHC prospects?

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

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

DI-HIGGS PRODUCTION AT HL-LHC ($HH \to 4b$, $3ab^{-1}$)

Behr, Bortoletto, Frost, Hartland, Issever & Rojo, 1512.08928

Category		signal N_{ev}	background N_{ev}^{tot}	N_{ev}^{4b}	$S/\sqrt{B_{tot}}$	$S/\sqrt{B_{4b}}$	S/B_{tot}	S/B_{4b}
Boosted	no PU	290	$1.2 \cdot 10^4$	$8.0 \cdot 10^3$	2.7	3.2	0.03	0.04
	PU80+SK+Trim	290	$3.7 \cdot 10^4$	$1.2 \cdot 10^4$	1.5	2.7	0.01	0.02
Intermediate	no PU	130	$3.1 \cdot 10^3$	$1.5 \cdot 10^3$	2.3	3.3	0.04	0.08
	PU80+SK+Trim	140	$5.6 \cdot 10^3$	$2.4 \cdot 10^3$	1.9	2.9	0.03	0.06
Resolved	no PU	630	$1.1 \cdot 10^5$	$5.8 \cdot 10^4$	1.9	2.7	0.01	0.01
	PU80+SK	640	$1.0 \cdot 10^5$	$7.0 \cdot 10^4$	2.0	2.6	0.01	0.01
Combined	no PU				4.0	5.3		
	PU80+SK+Trim				3.1	4.7		

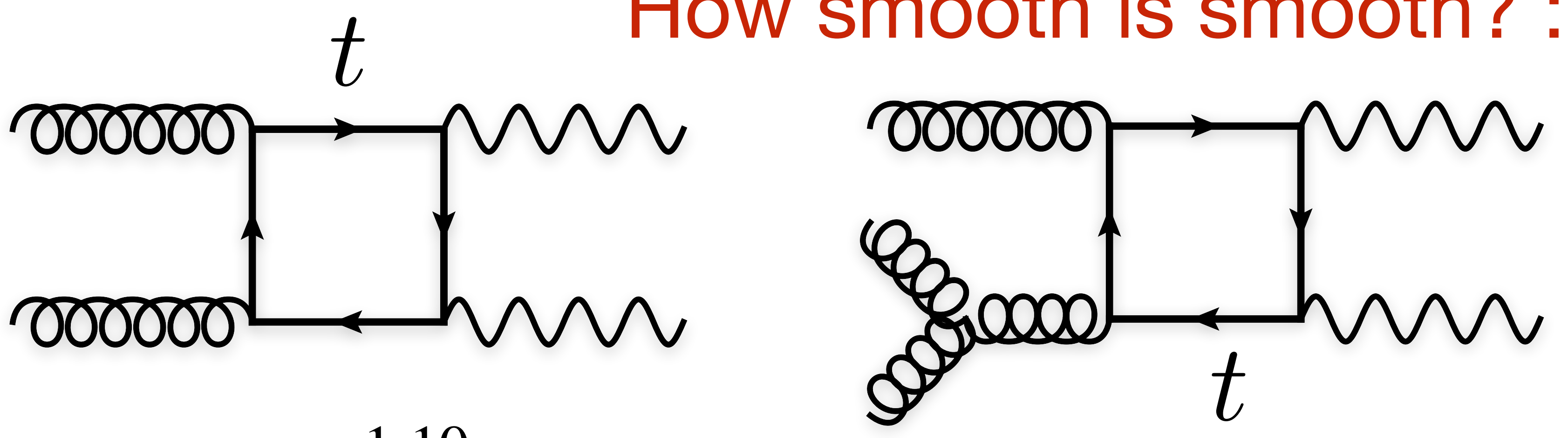
Key signal channels will need ~1% control of complex bkgds

DATA-DRIVEN BKGD ESTIMATES: NON-SMOOTHNESS AT 1% LEVEL

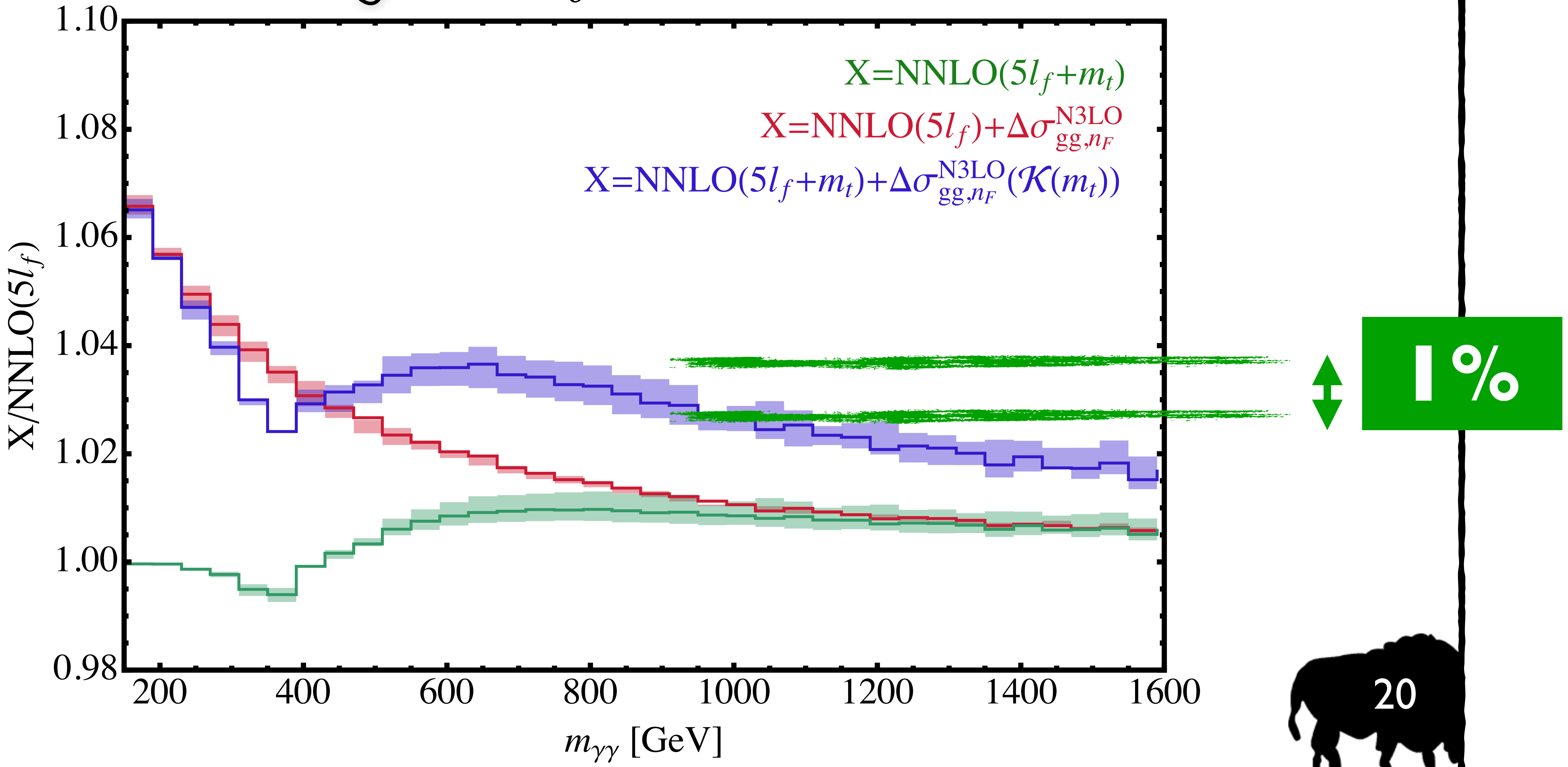
Predictions at high invariant masses.

As we all know, bump hunts in the diphoton system assume a smooth function which can be fitted to the data. Begging the question,

How smooth is smooth? :-)



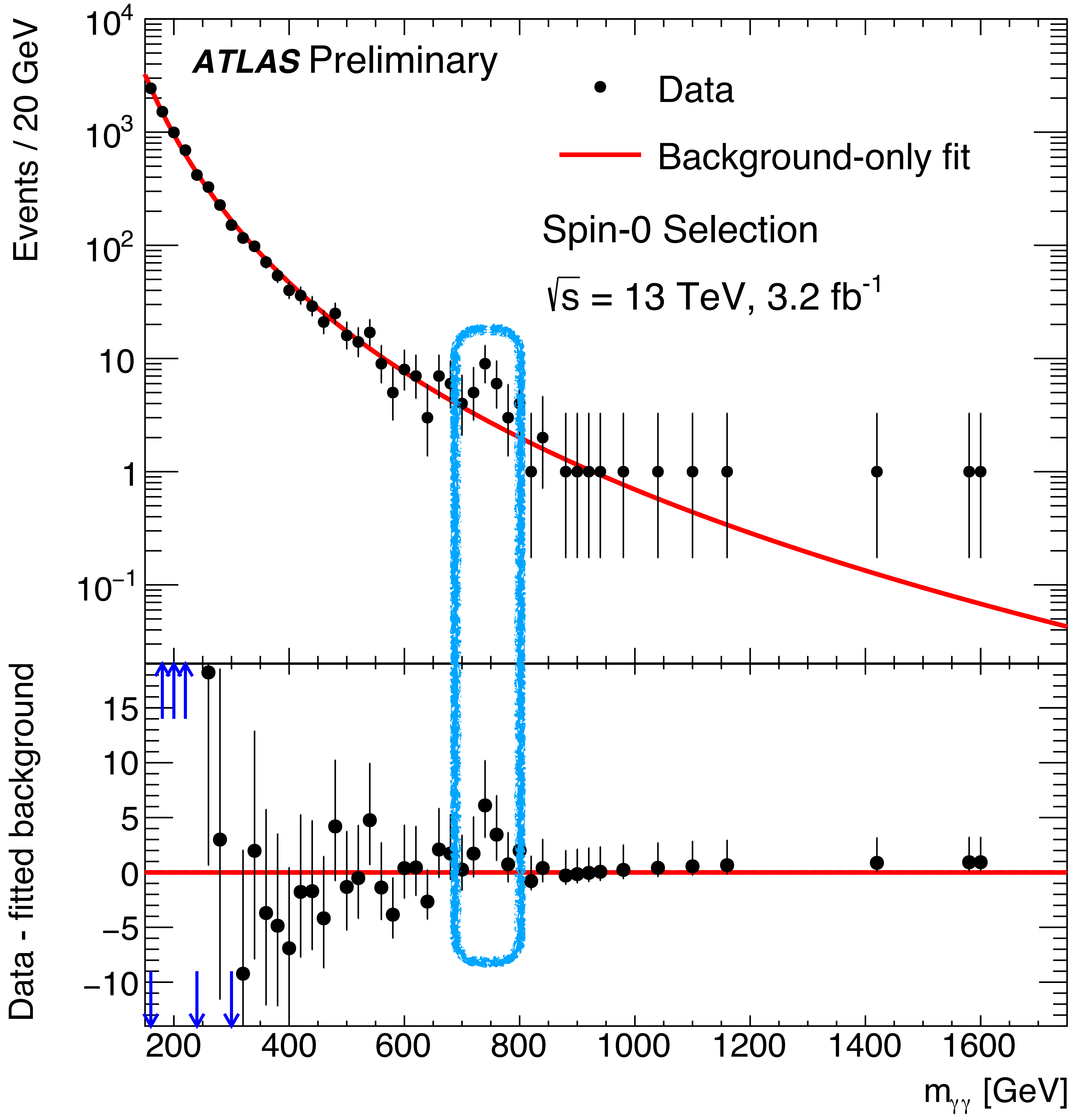
C. Williams
Moriond QCD ‘16

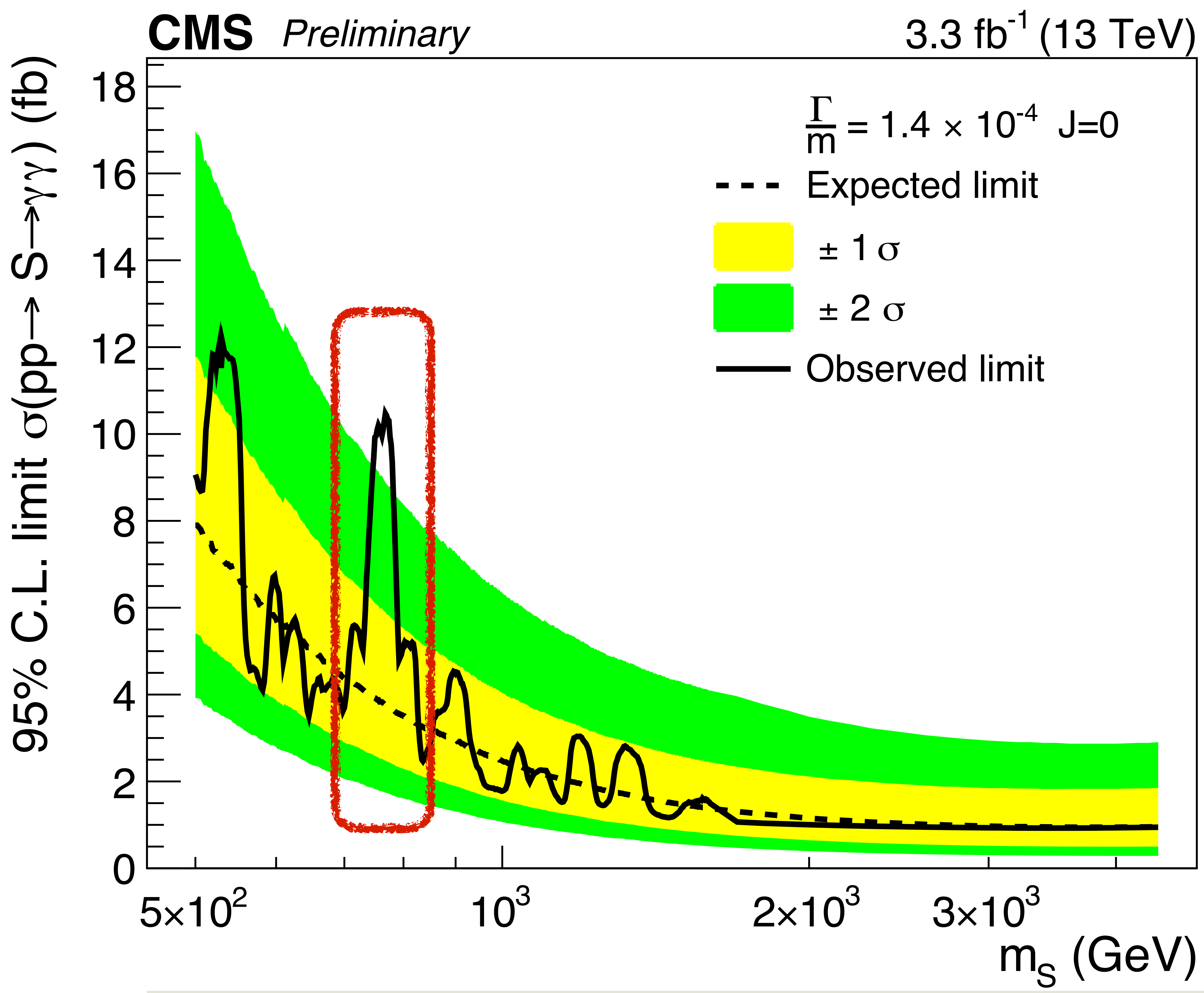


20

Standard experimental techniques, like data-driven bkgd estimates, can be skewed by O(1%) theoretical subtleties.

A γγ RESONANCE?





3σ ~ 30%

if it's real, then by 2018: 5%

& by 2035: 1%

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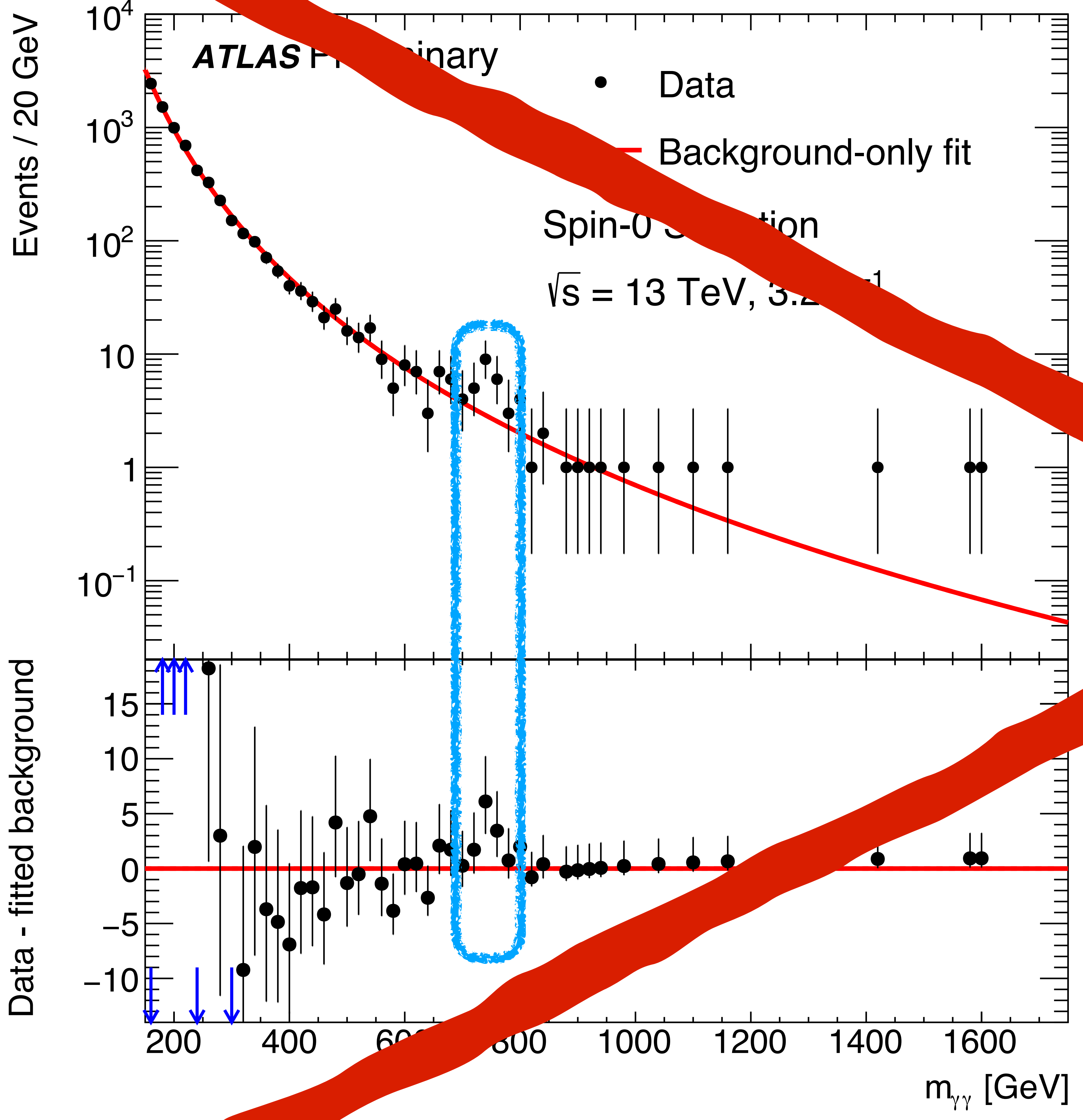

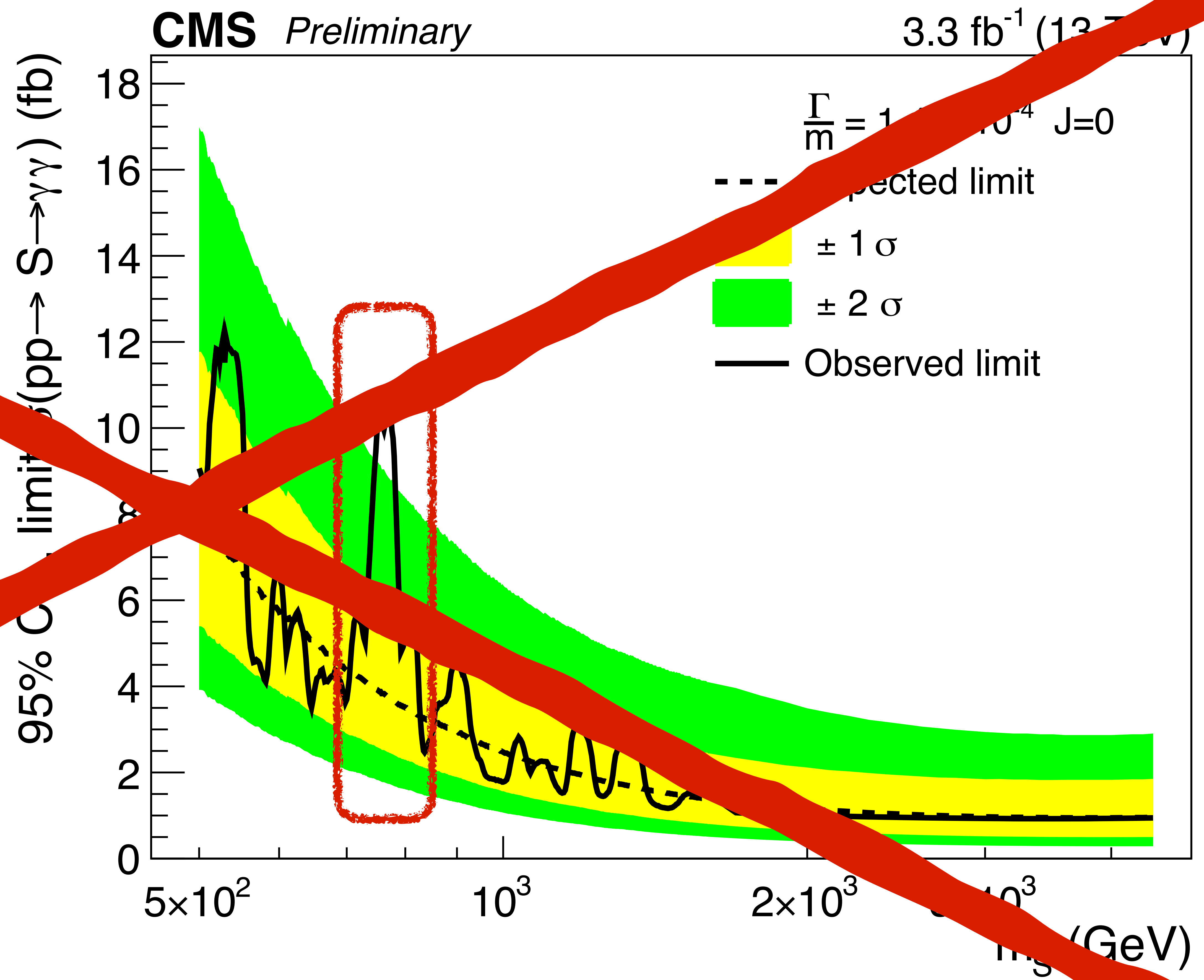

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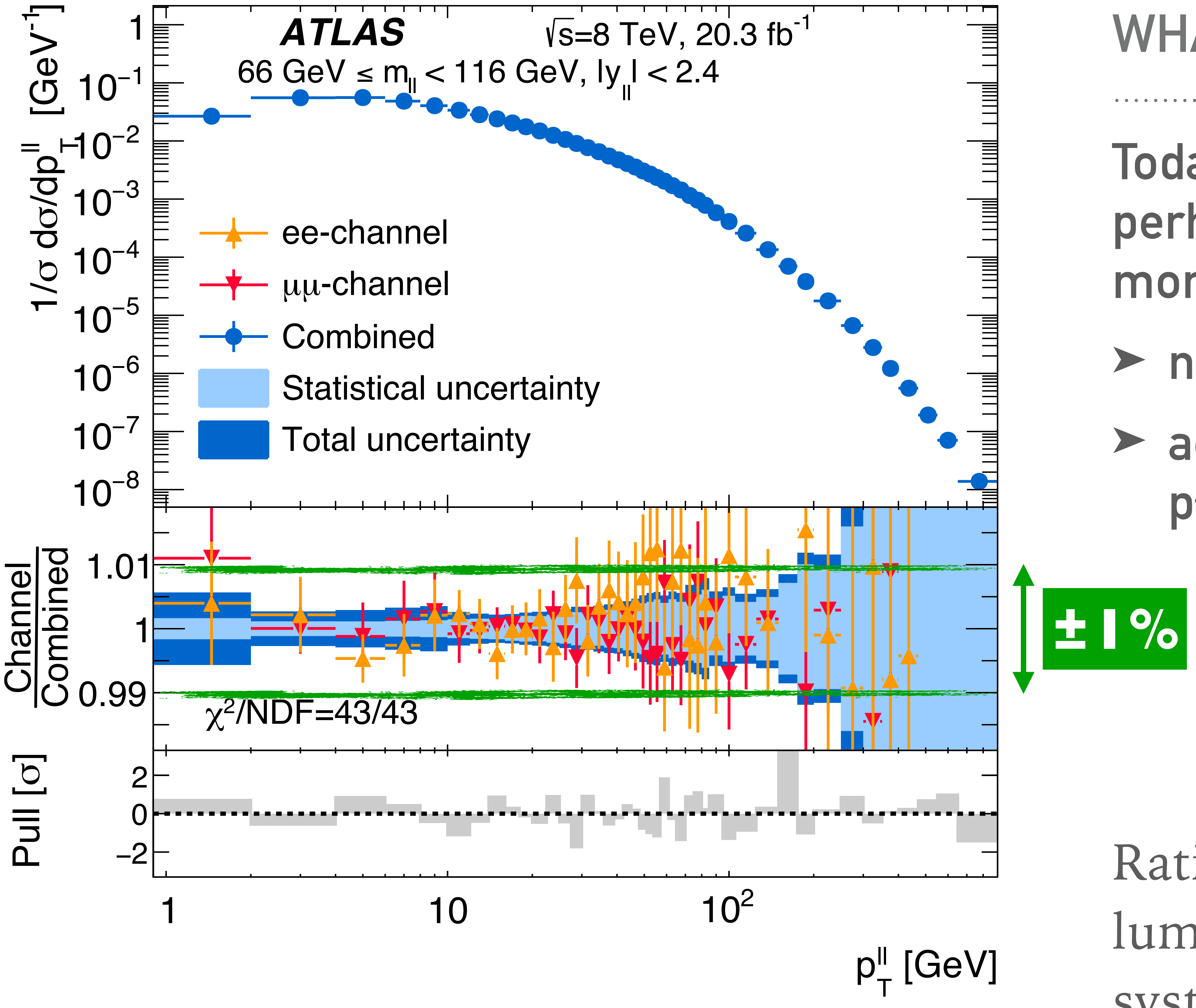


WHAT'S POSSIBLE EXPERIMENTALLY?

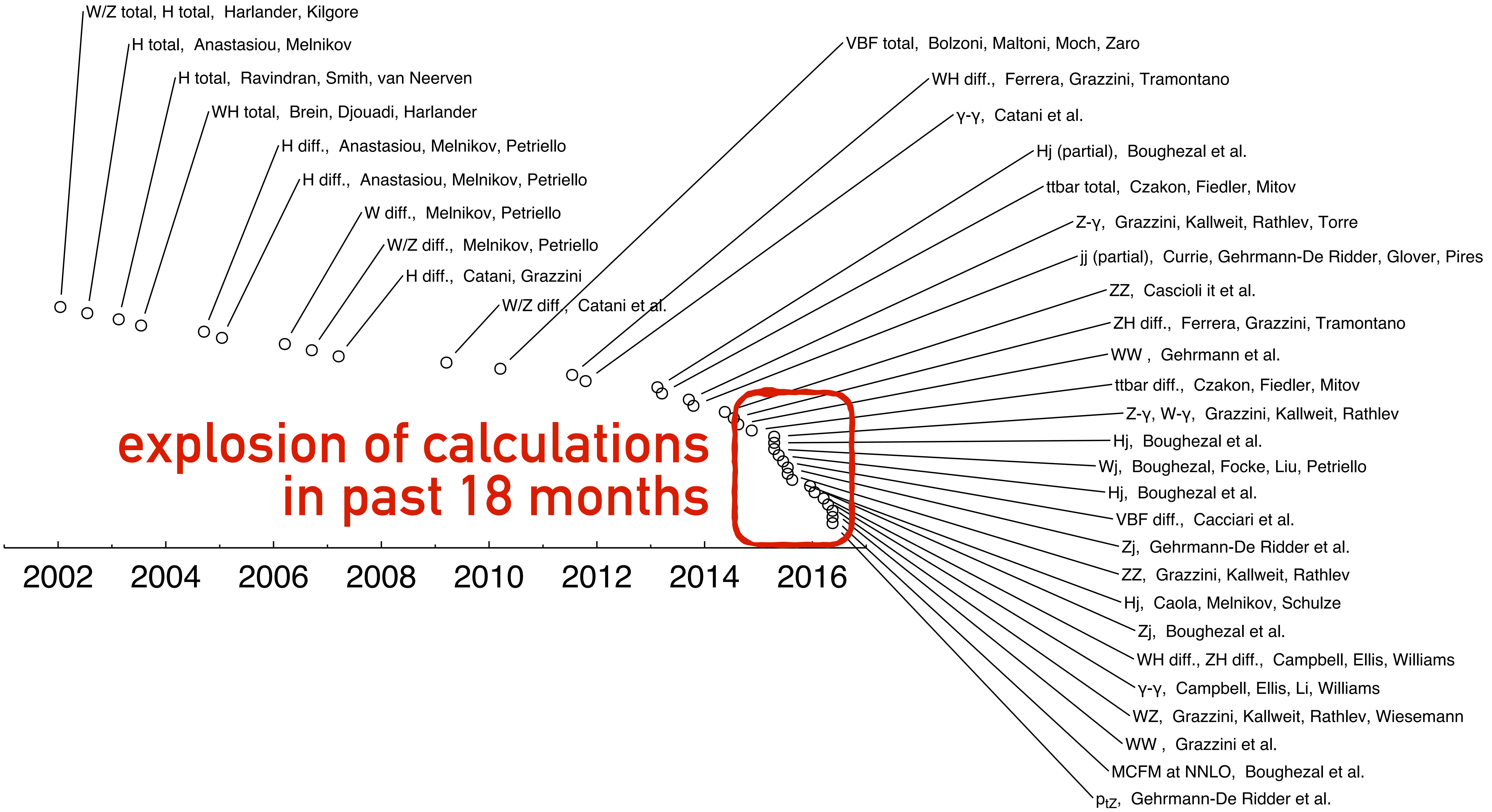
Today's most precise results are perhaps for the Z transverse momentum

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

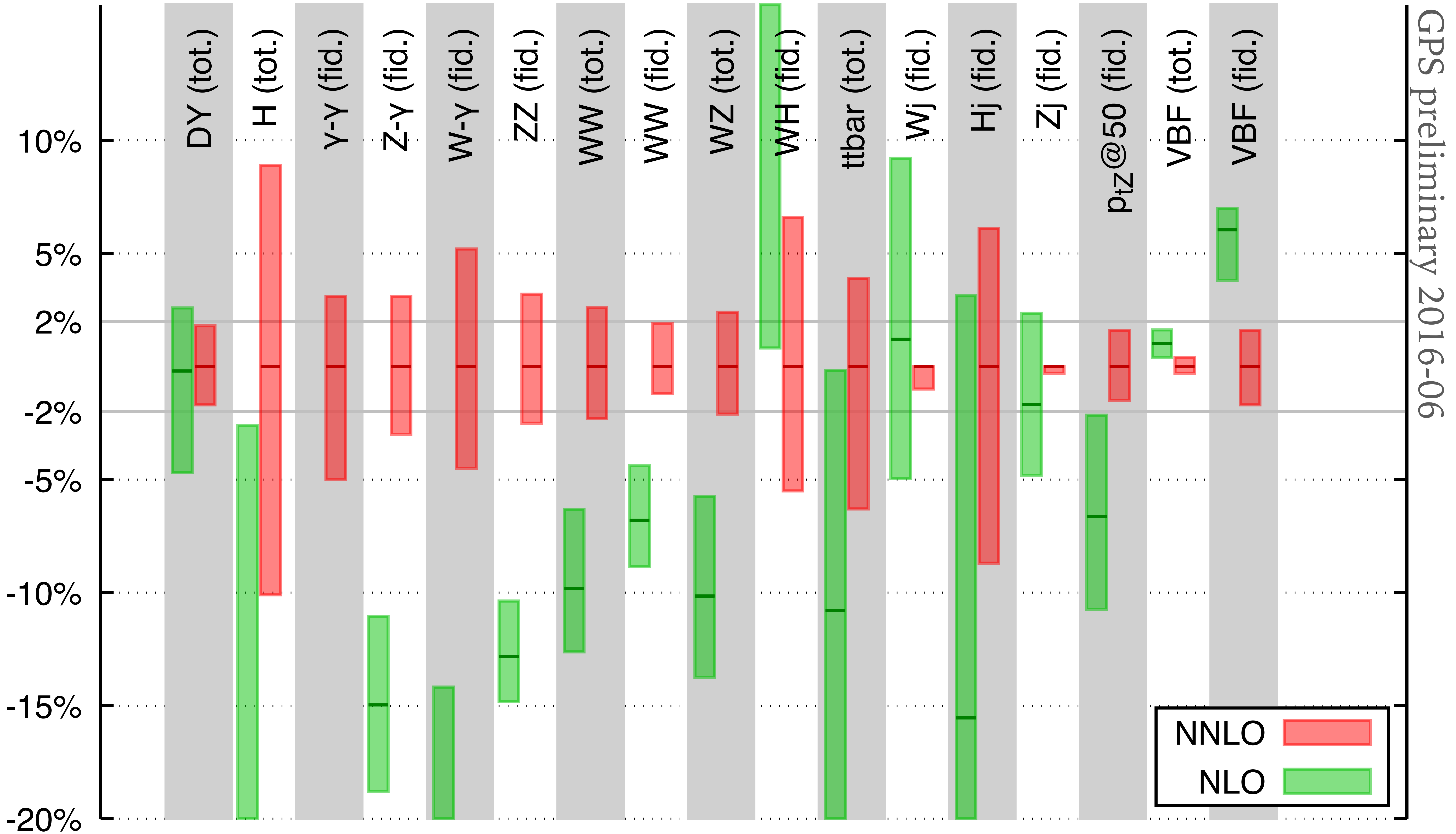
Ratio to total cross section cancels lumi & some lepton-efficiency systematics.

NNLO hadron-collider calculations v. time

as of mid June



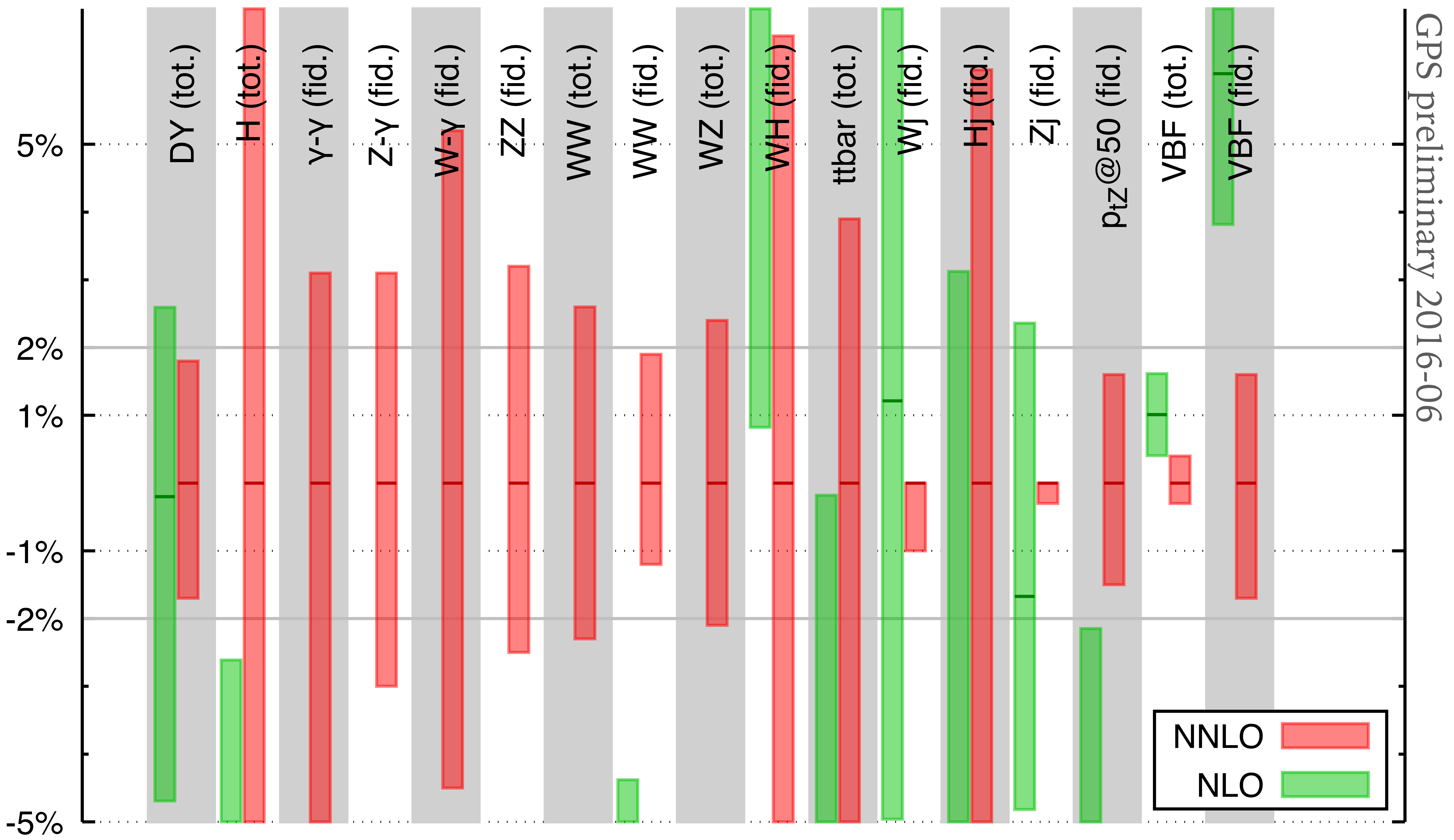
WHAT PRECISION AT NNLO?



For many processes NNLO scale band is ~±2%

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

WHAT PRECISION AT NNLO?



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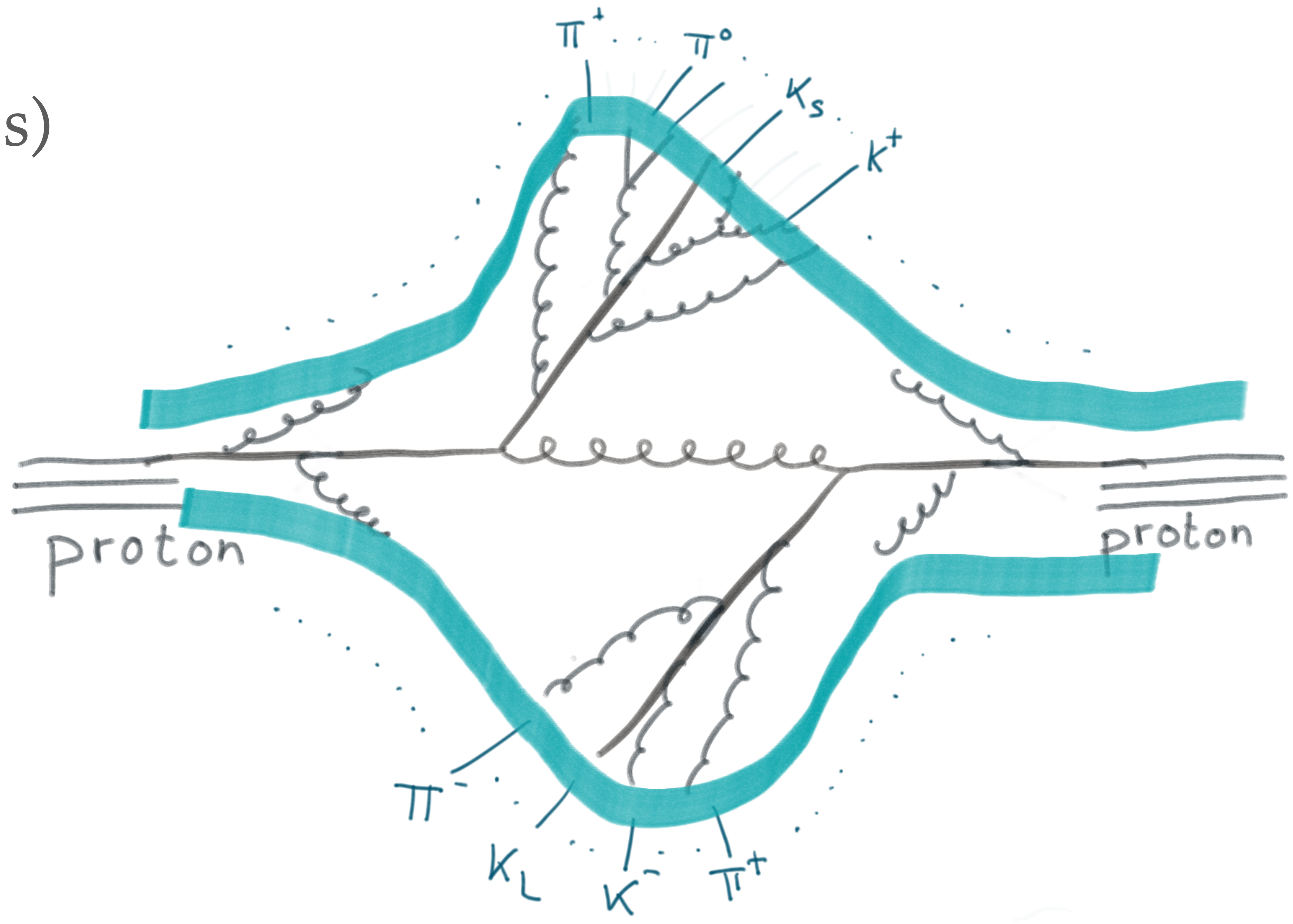
OVERALL, 1% SEEMS AN INTERESTING FIGURE TO HAVE IN MIND

To start thinking about getting there, let's work through the **"inputs"**:

- the strong coupling
- parton distribution functions (PDFs)

And the **types of process:**

- inclusive / purely leptonic
- processes with jets



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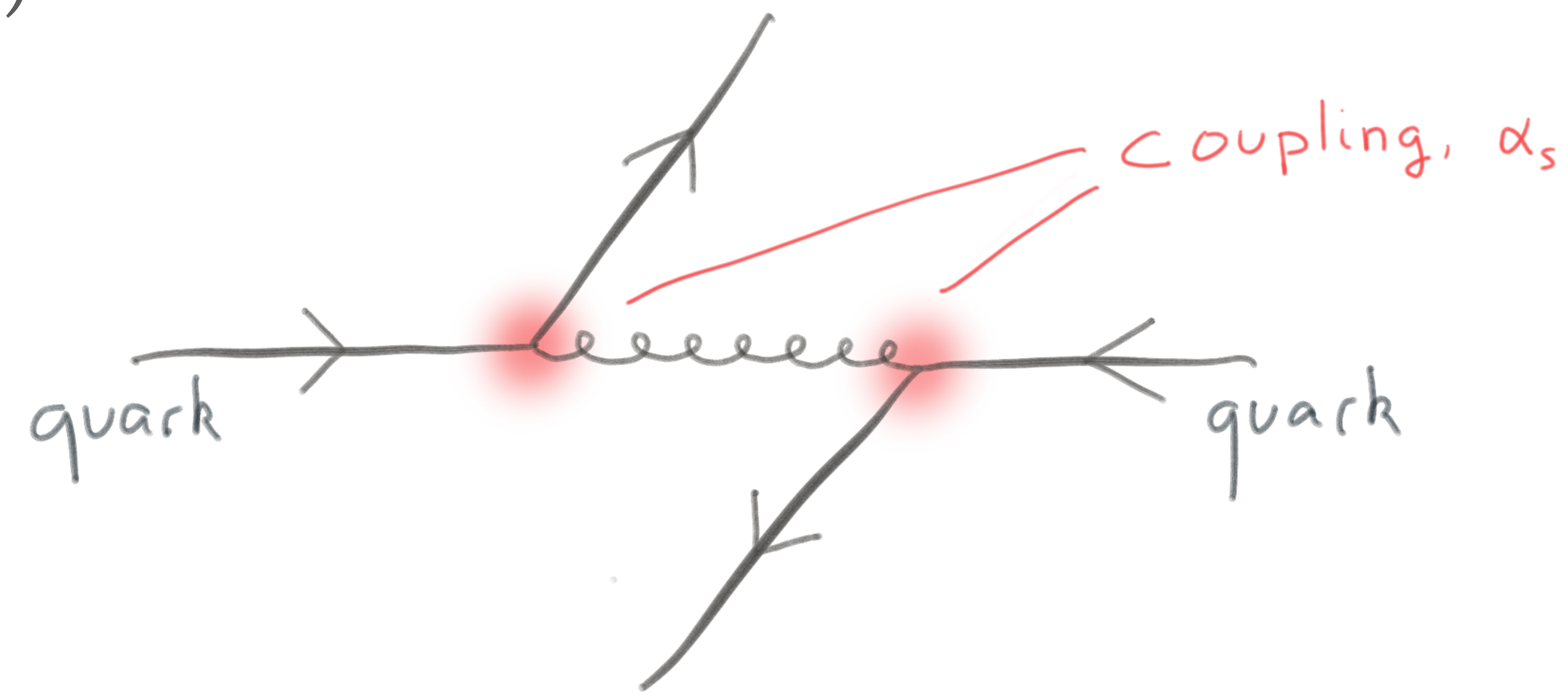
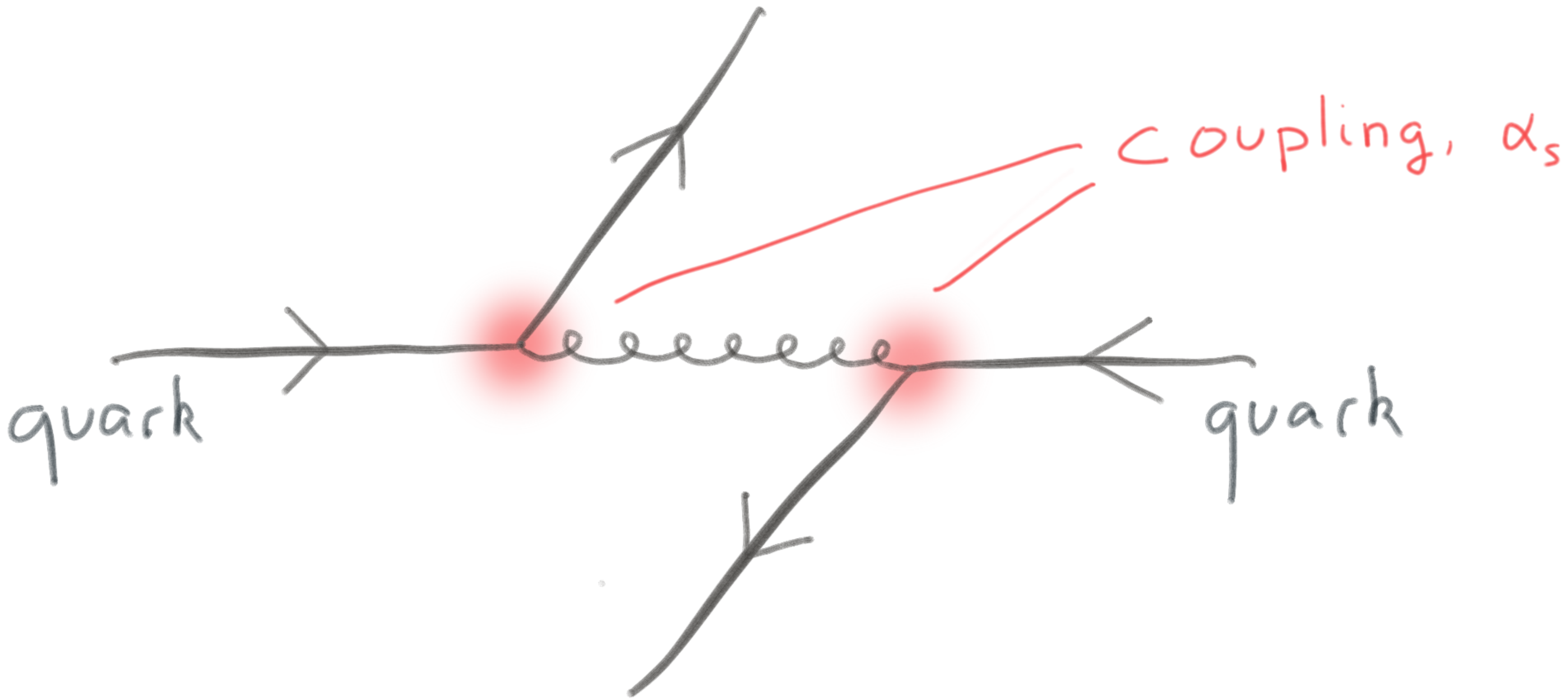
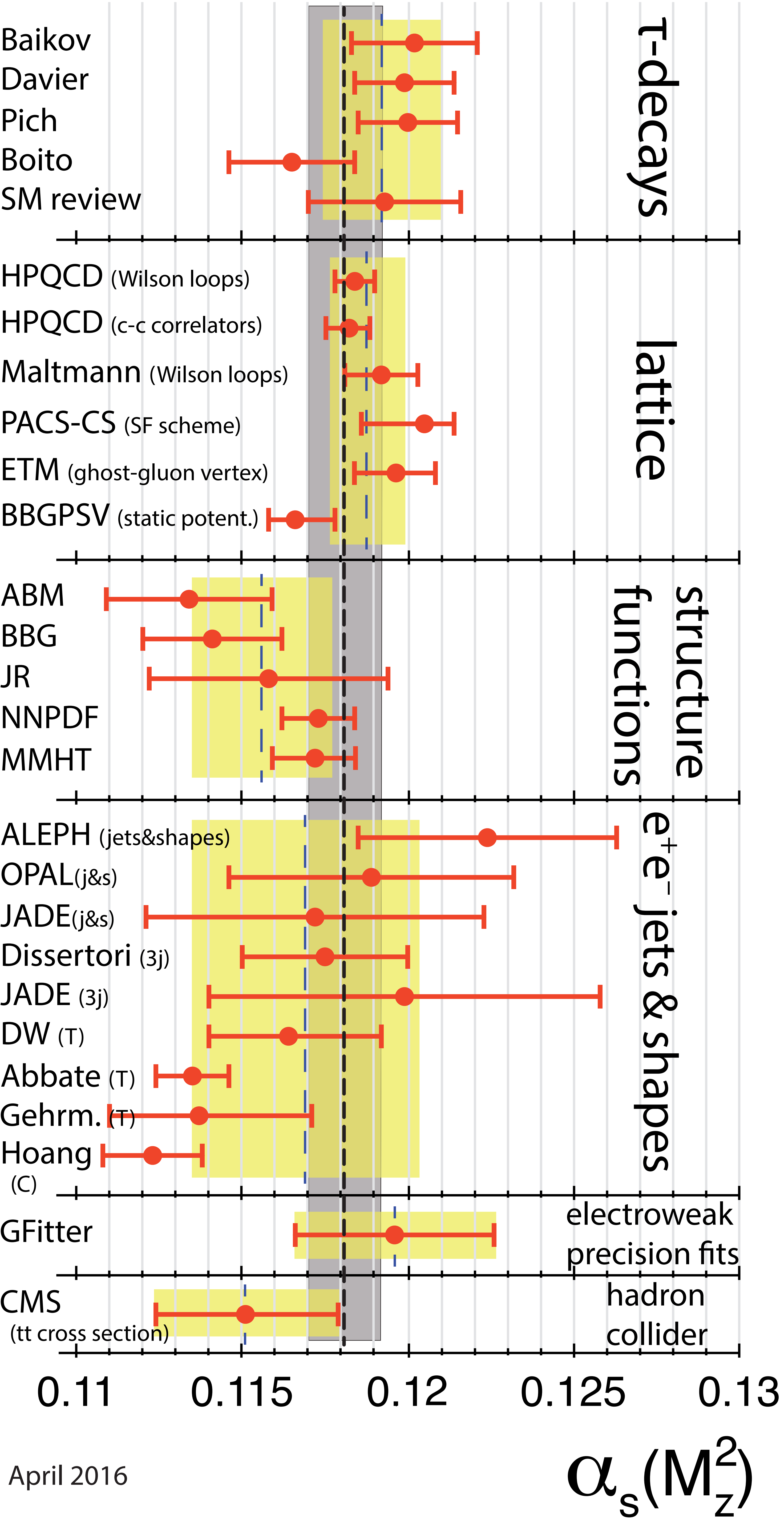


The strong coupling: α_s



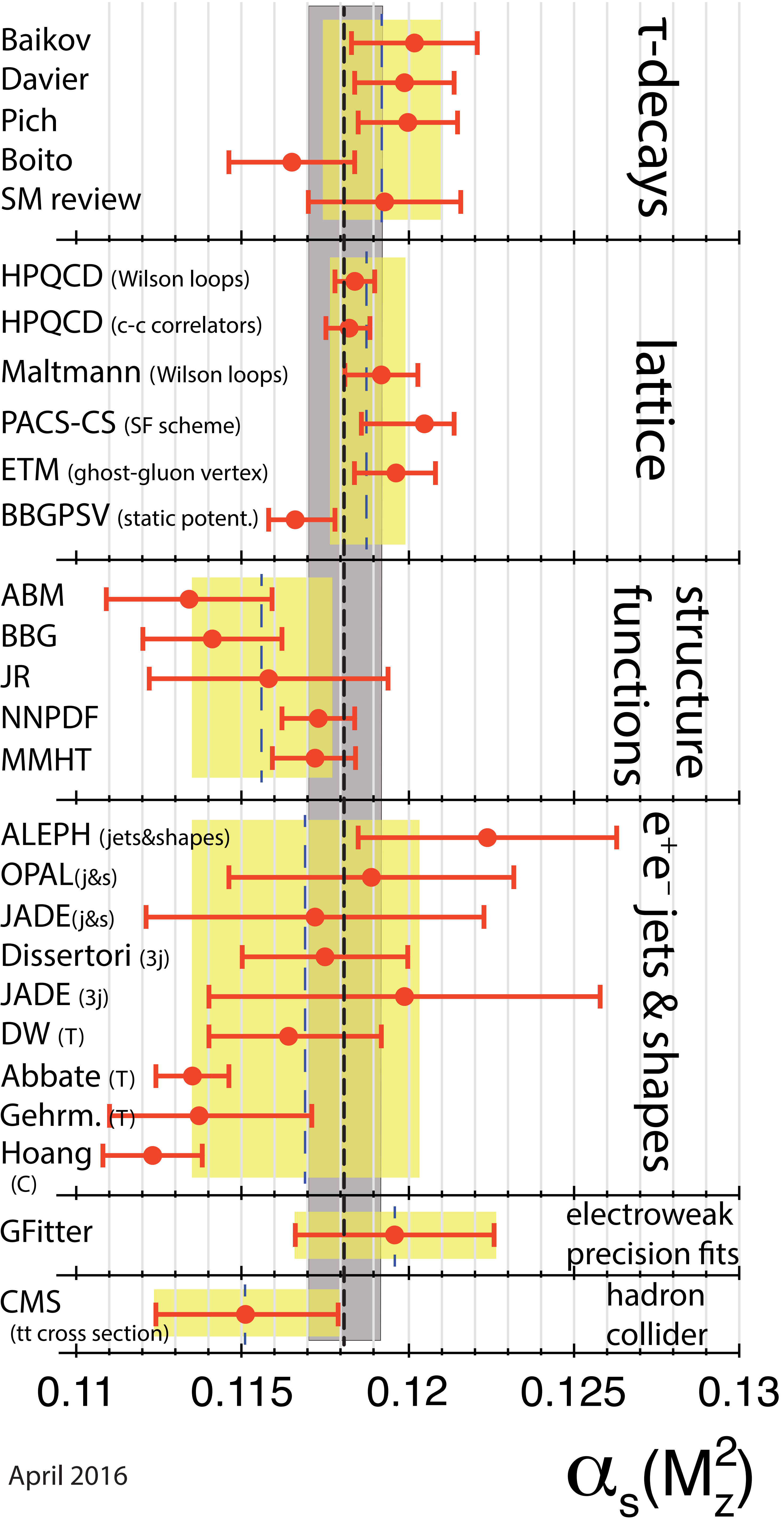
(almost) all theory predictions for LHC are based on perturbation theory, e.g.

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



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

Bethke, Dissertori & GPS in PDG '16

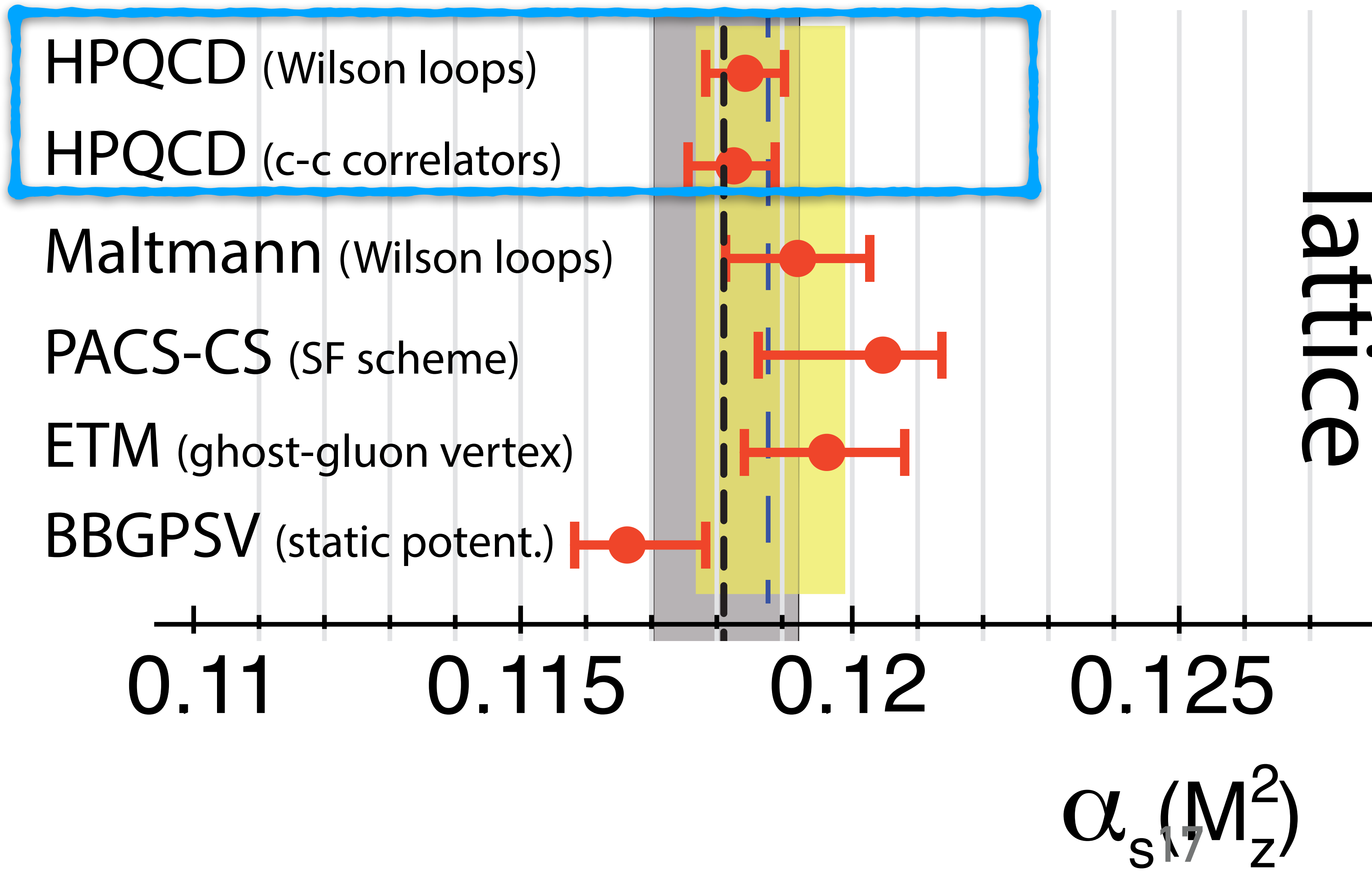


PDG World Average: $\alpha_s(M_Z) = 0.1181 \pm 0.0011$ (0.9%)

- 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

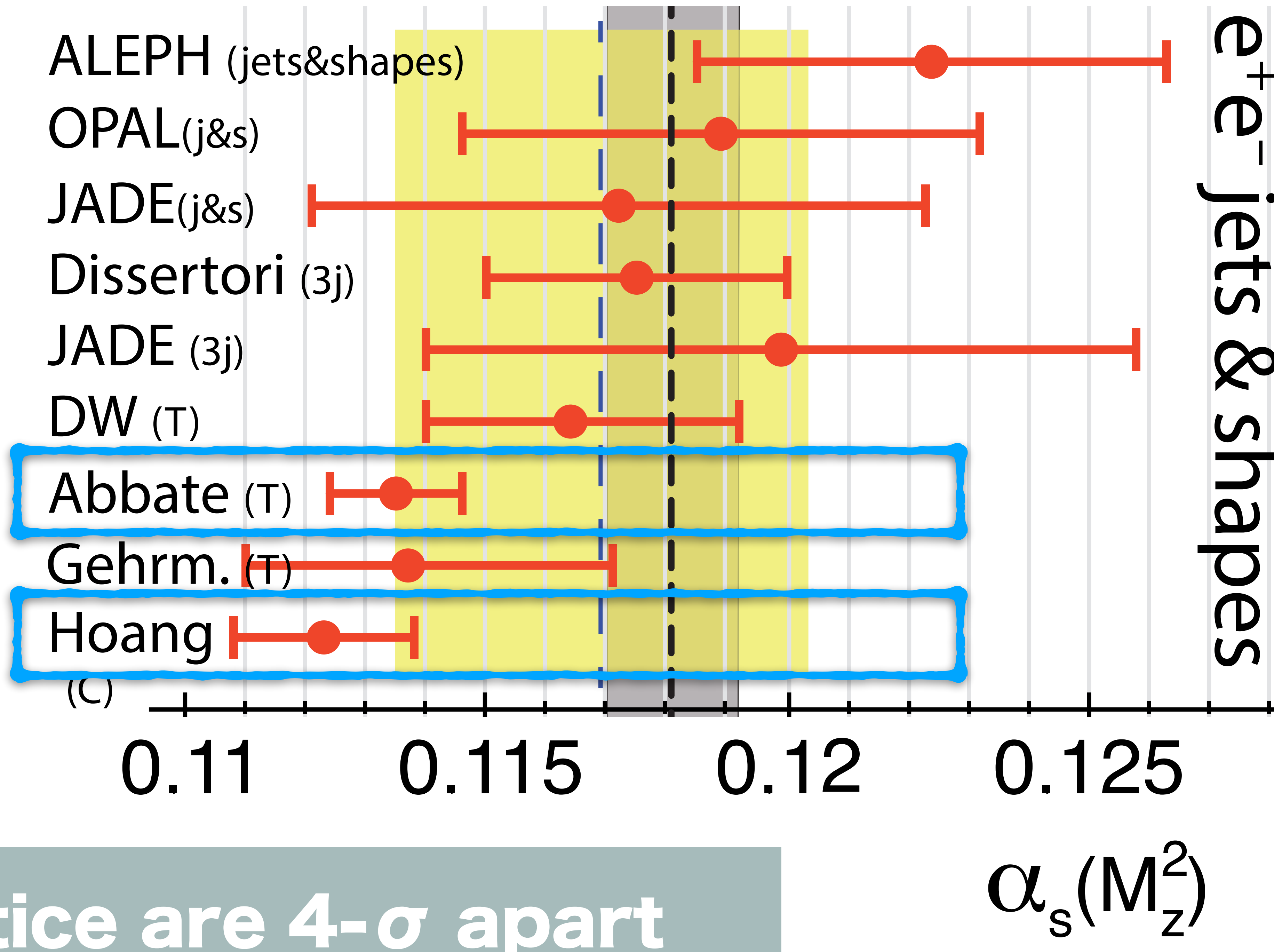
$\alpha_s(M_Z) = 0.1184 \pm 0.0012$(1%)

- 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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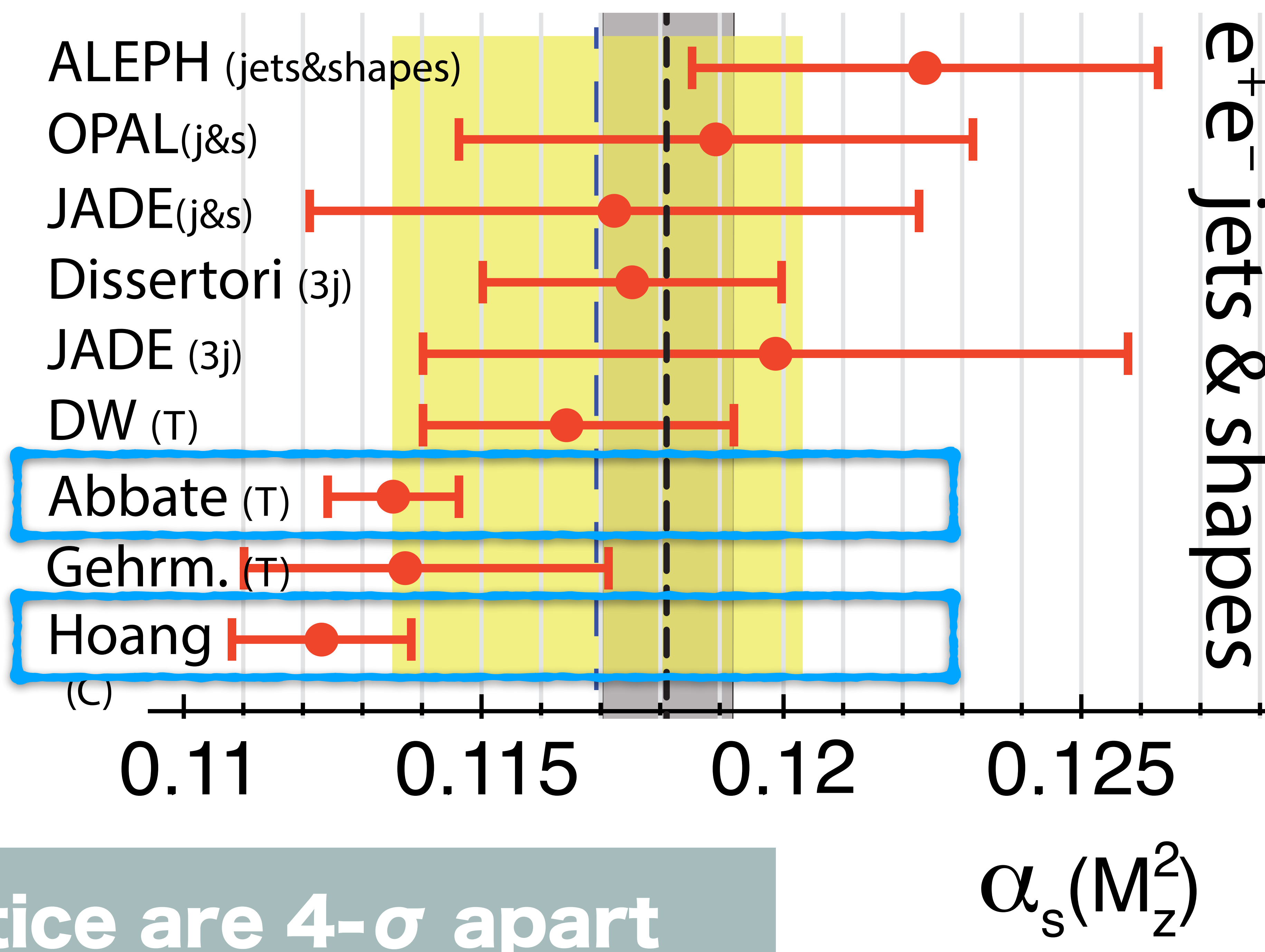
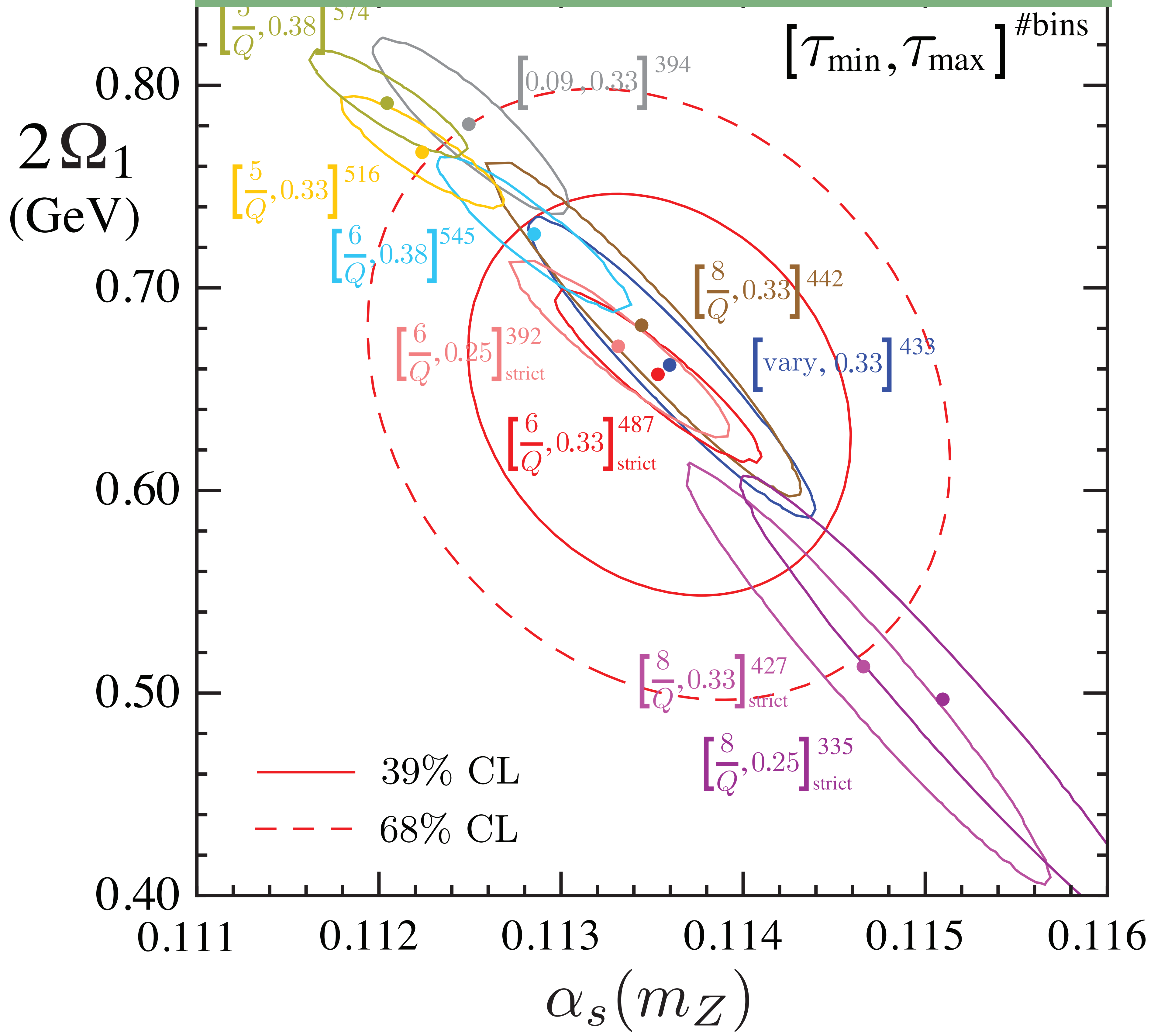


dependence on fit range



thrust & "best" lattice are 4-σ apart

Comments:

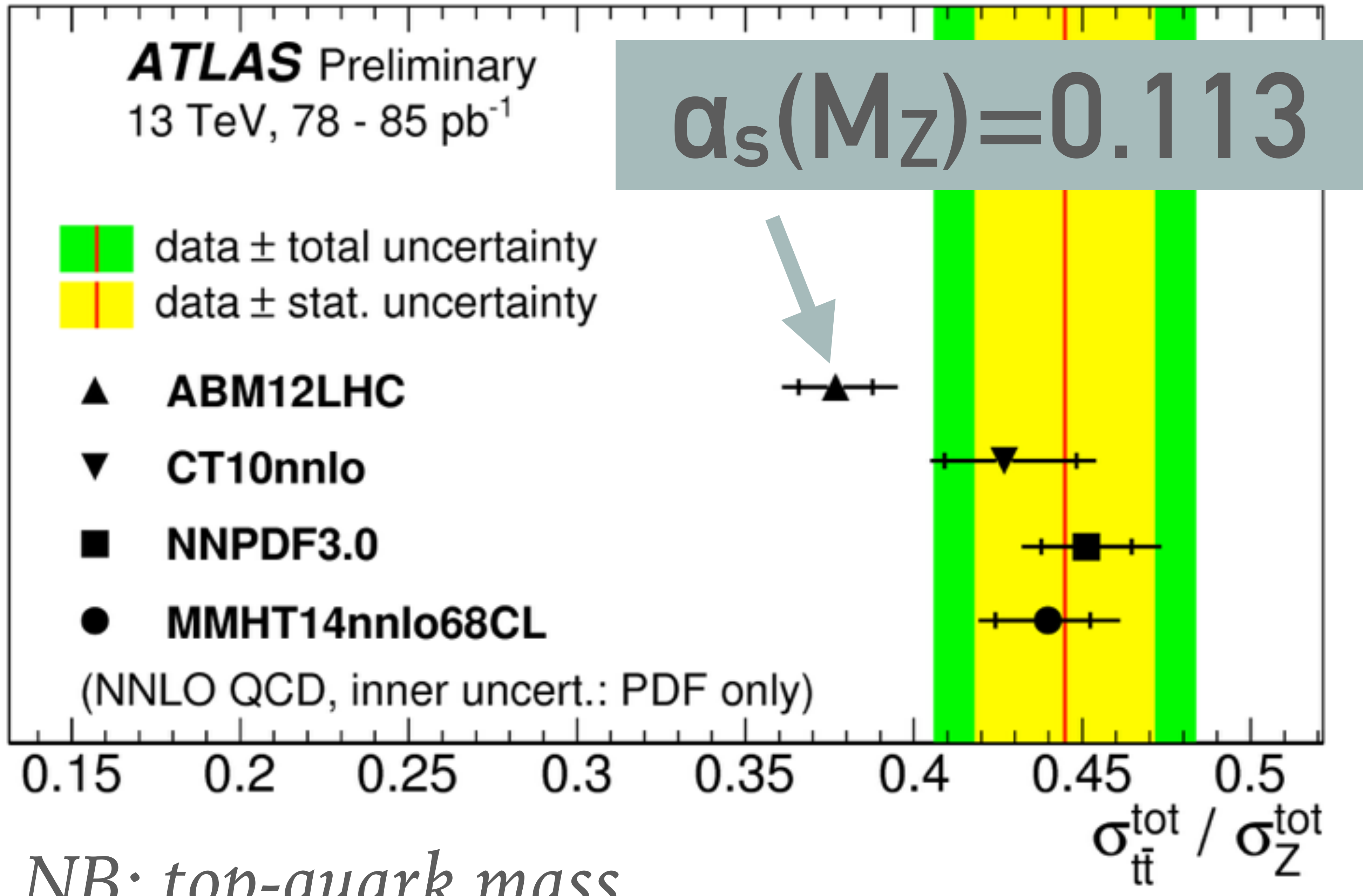
- thrust & C-parameter are highly correlated observables
- Analysis valid far from 3-jet region, but not too deep into 2-jet region — at LEP, not clear how much of distribution satisfies this requirement
- thrust fit shows noticeable sensitivity to fit region (C-parameter doesn't)

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, *cf.* later slides)

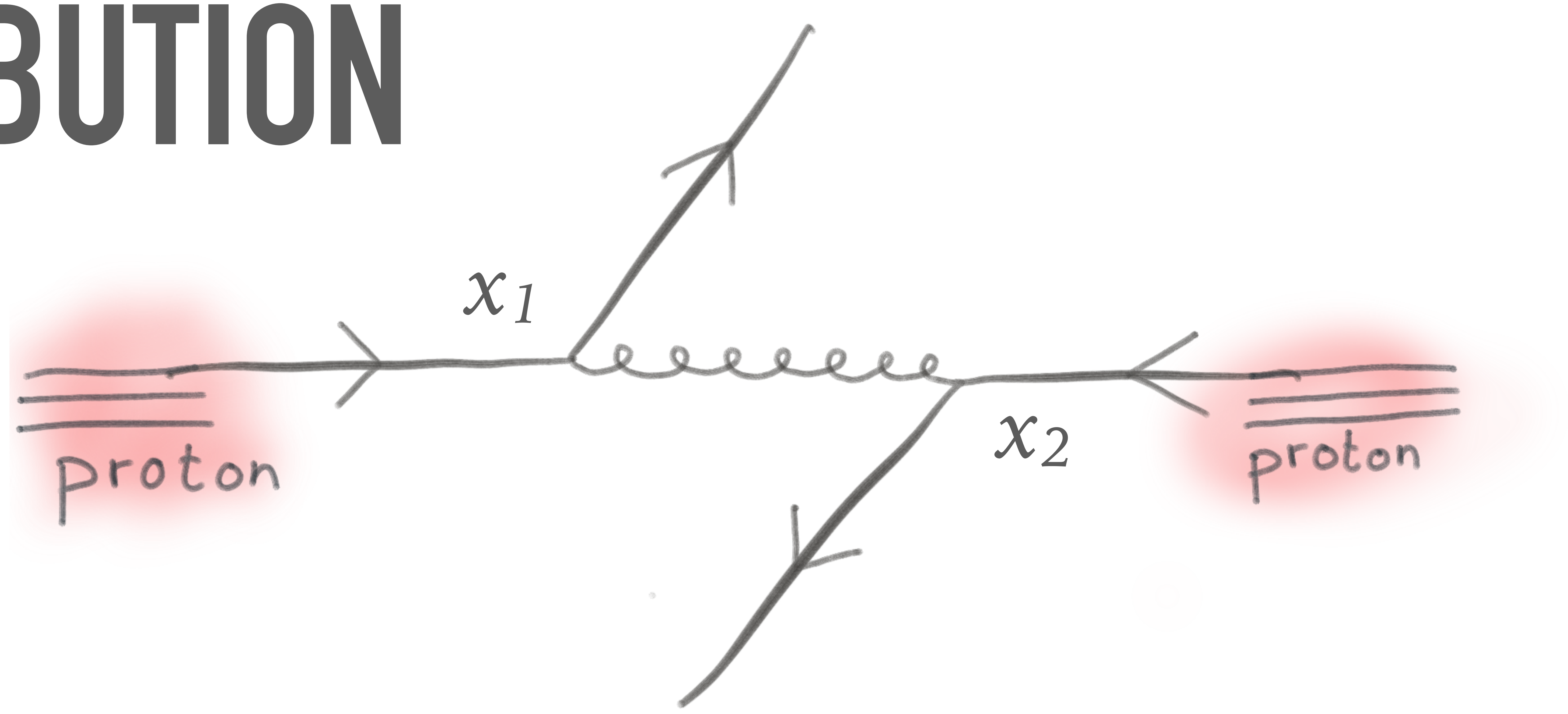
- To go beyond 1%, best hope is probably lattice QCD — on a 10-year timescale, there will likely be enough progress that multiple groups will have high-precision determinations

ATLAS-CONF-2015-049



NB: top-quark mass choice affects this plot

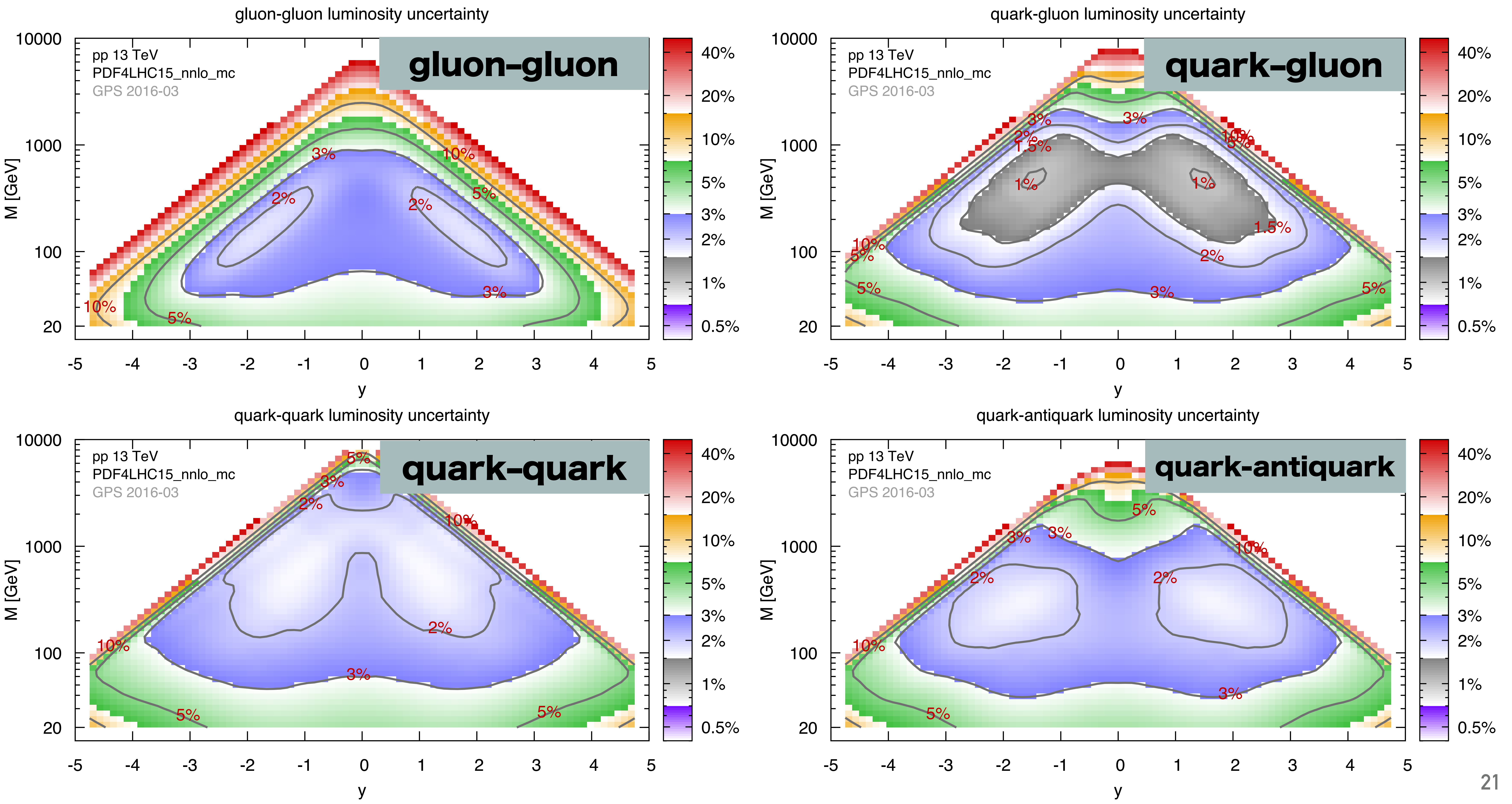
Parton Distribution Functions (PDFs)



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

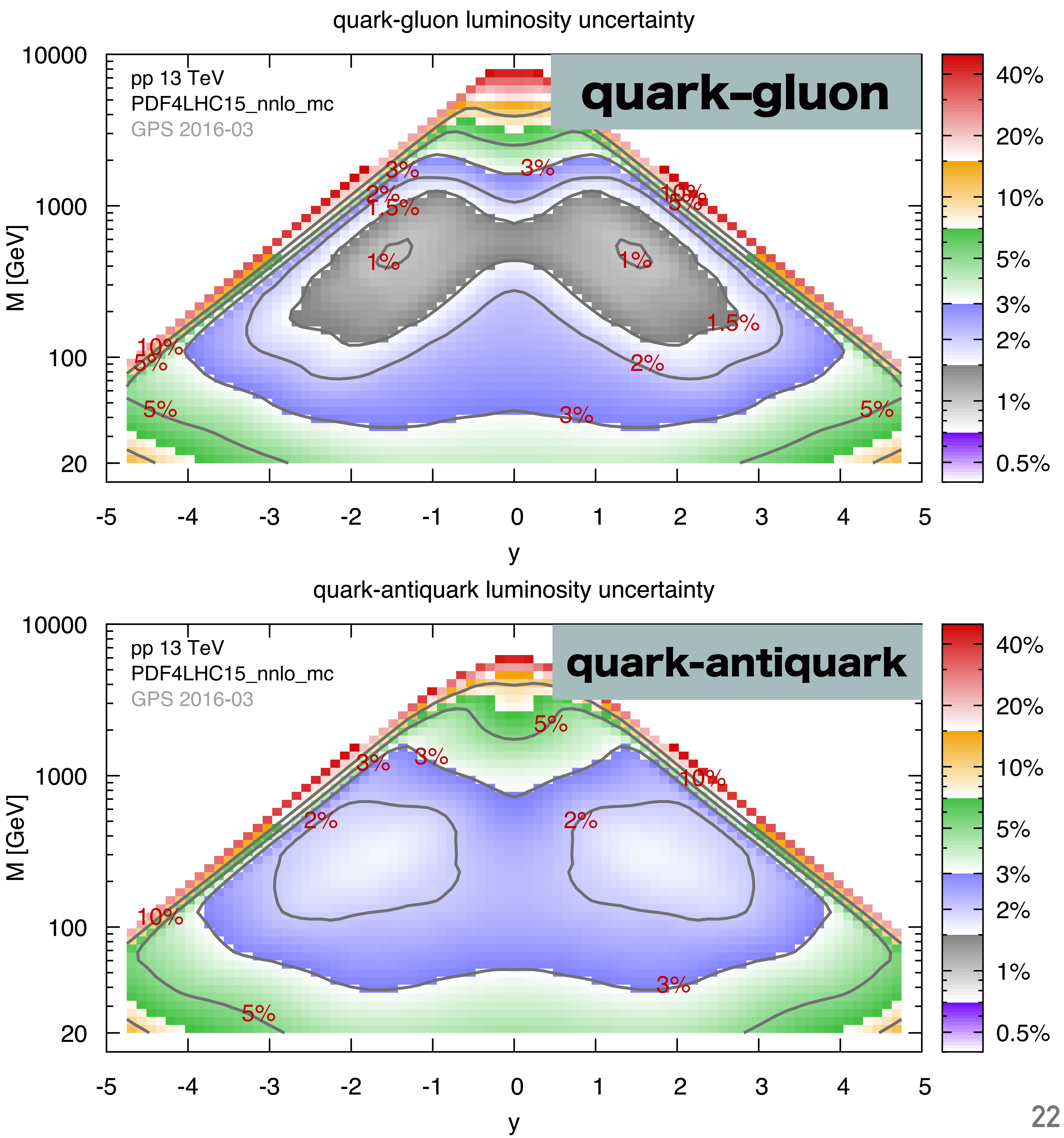
$$\sigma \propto f_{q/p}(x_1,\mu^2)\, f_{q/p}(x_2,\mu^2)$$

Uncertainties on partonic luminosities — v. rapidity(y) and mass

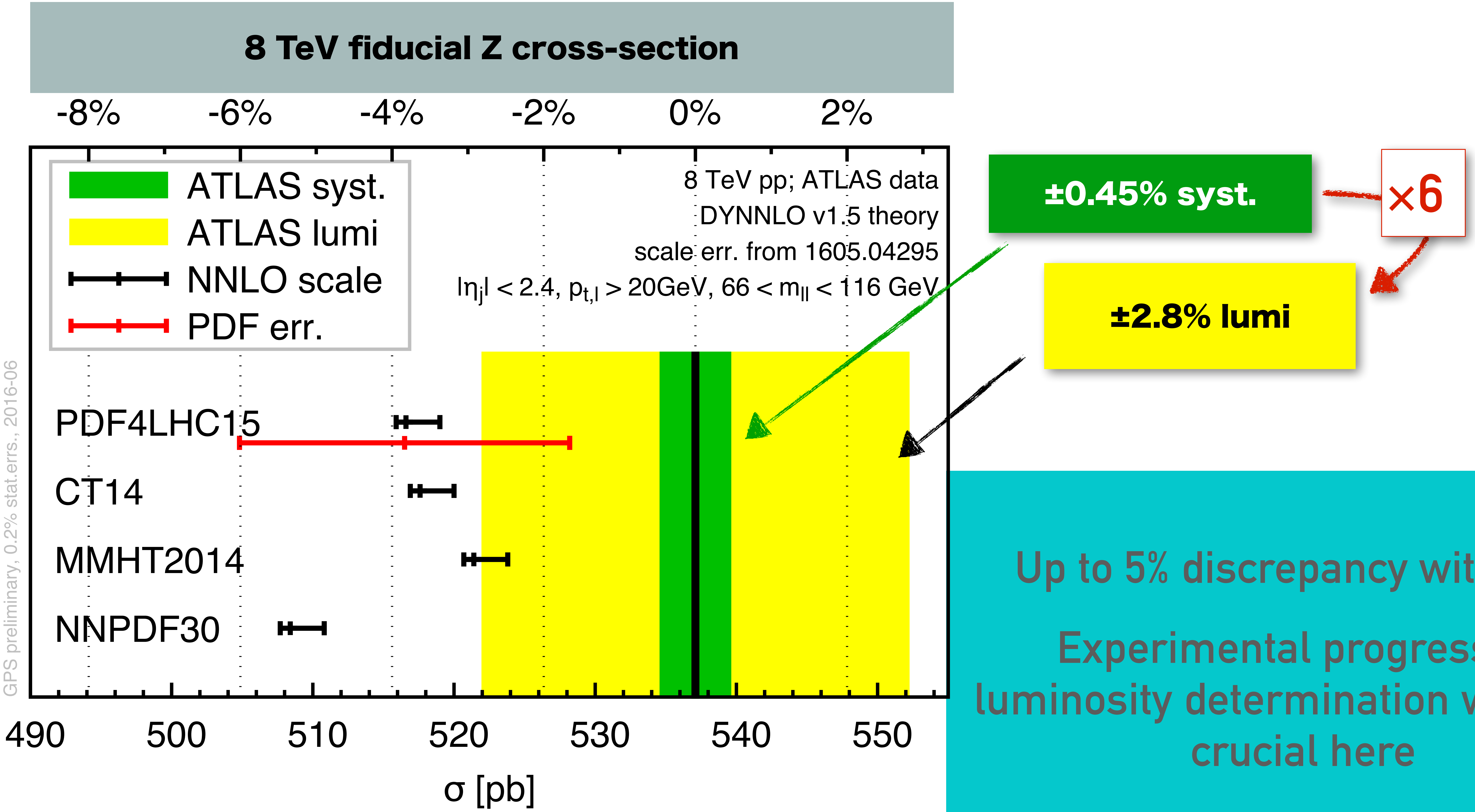


What route for progress?

- 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?]



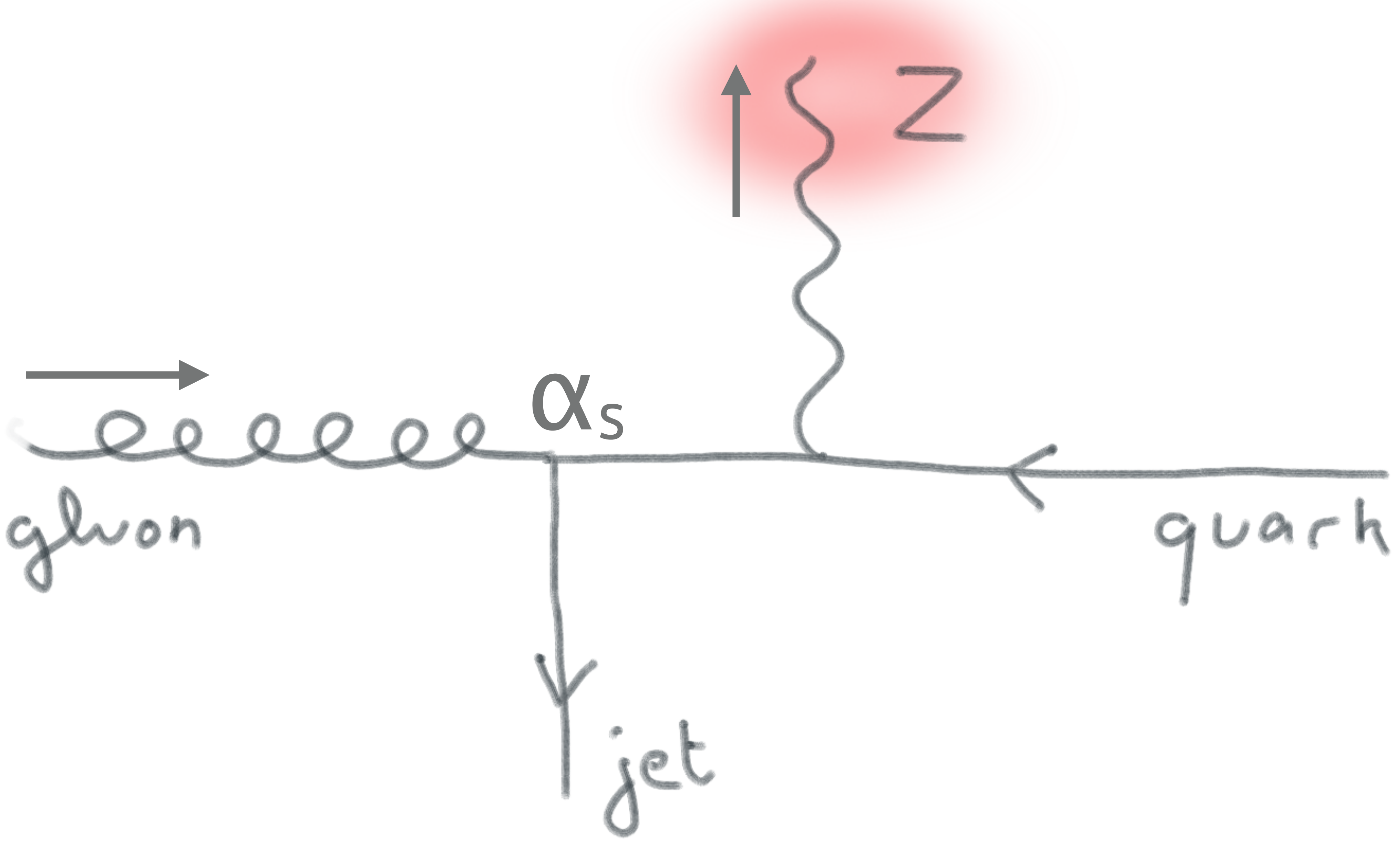
There are, however, issues. Notably in Z production



Up to 5% discrepancy with data

Experimental progress on luminosity determination would be crucial here

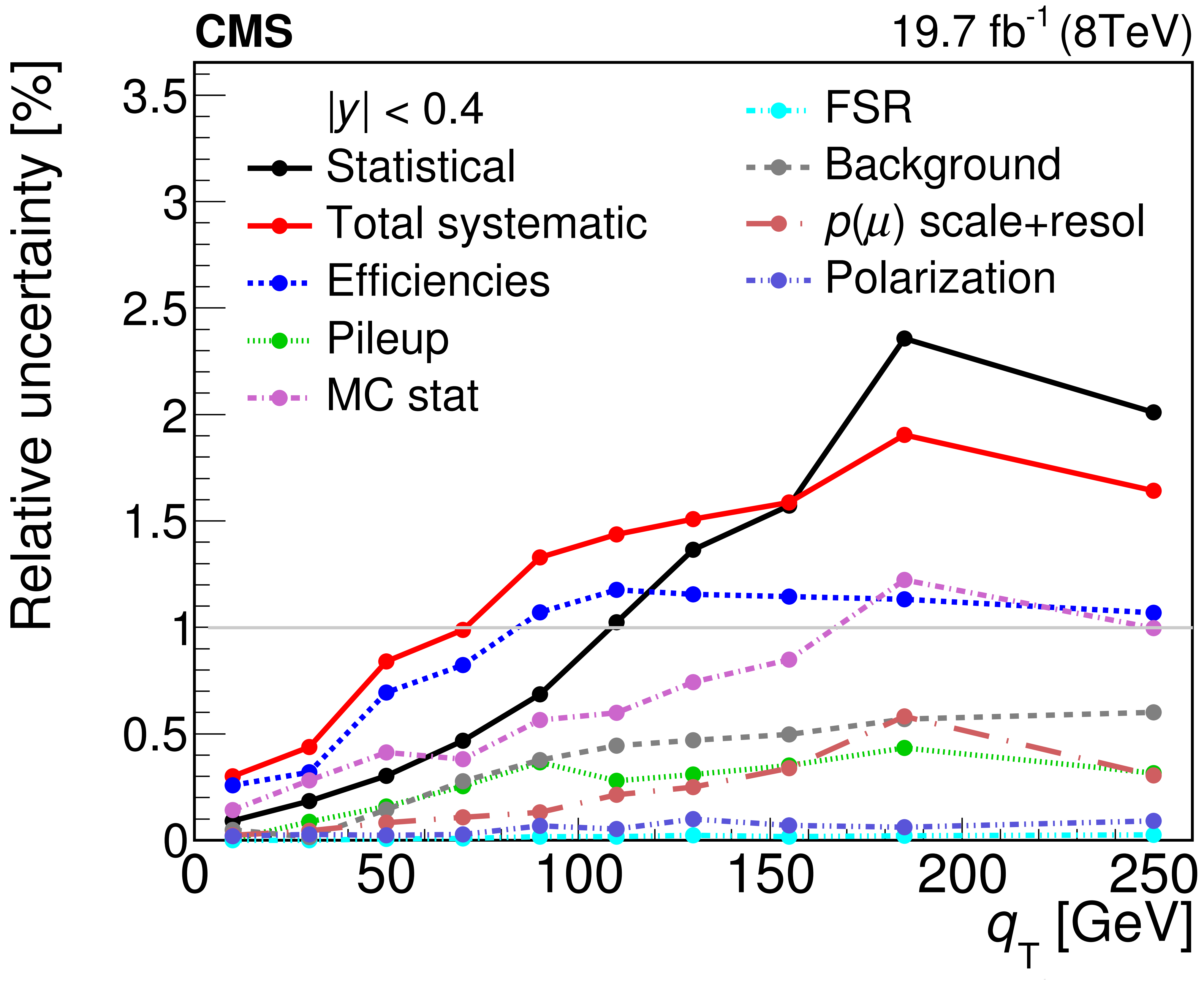
Z P_T: the "ideal" hard process?

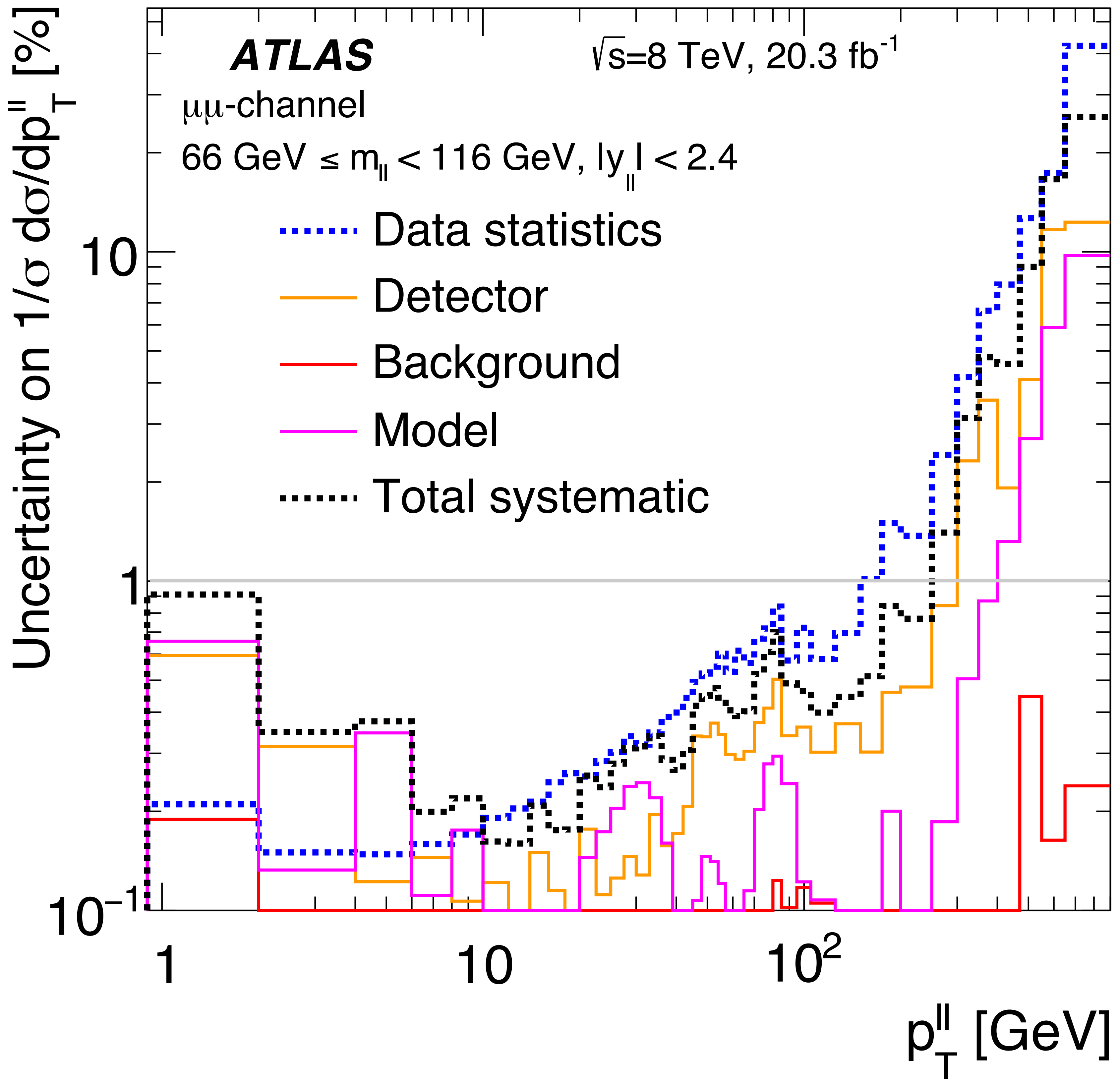


For both data and theory, Z p_T is an immediate testing ground for 1% effects.

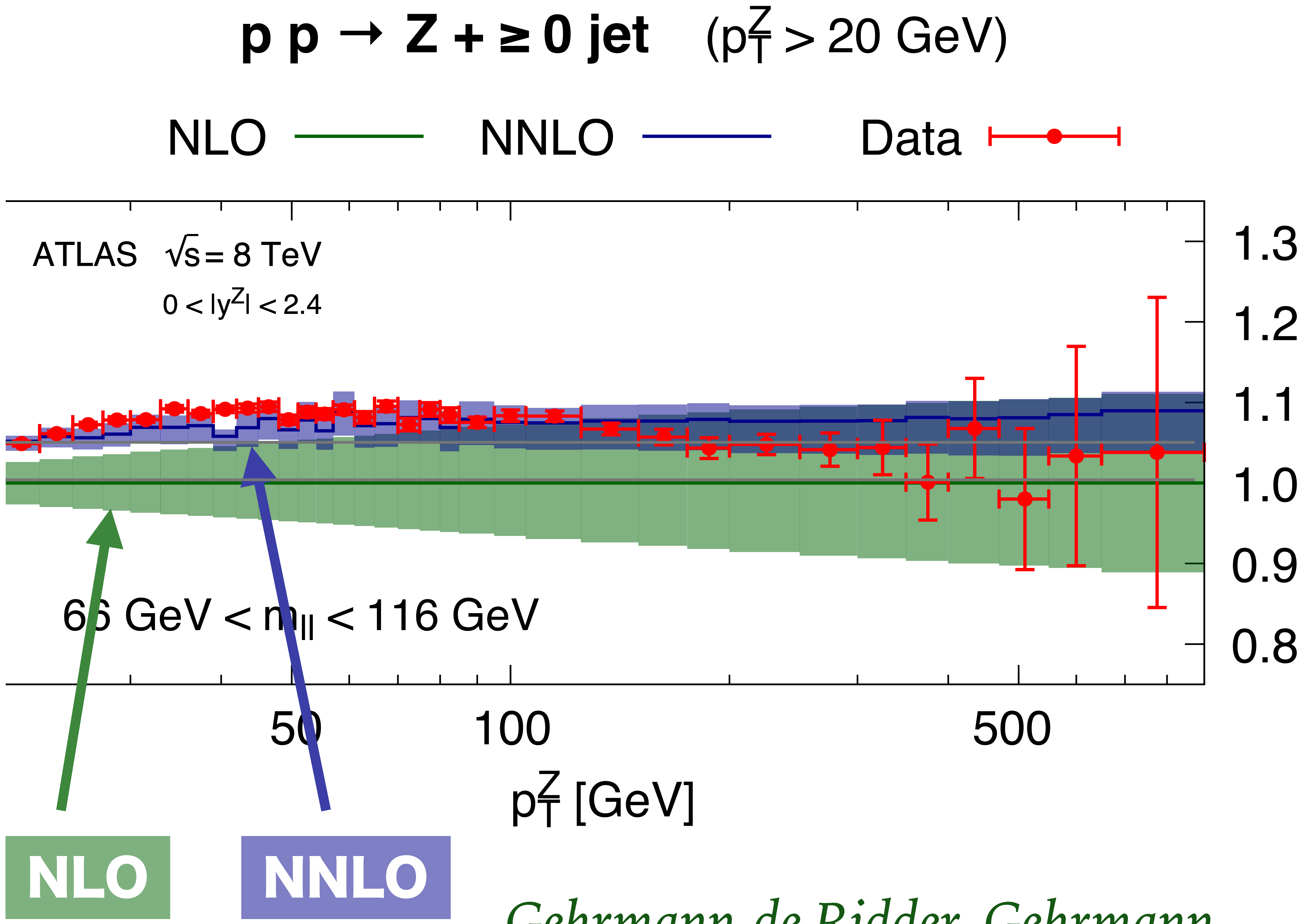
(& unlike Z & W prod[n] it's sensitive to α_s)

Z p_T: uncertainties somewhat smaller for ATLAS than CMS



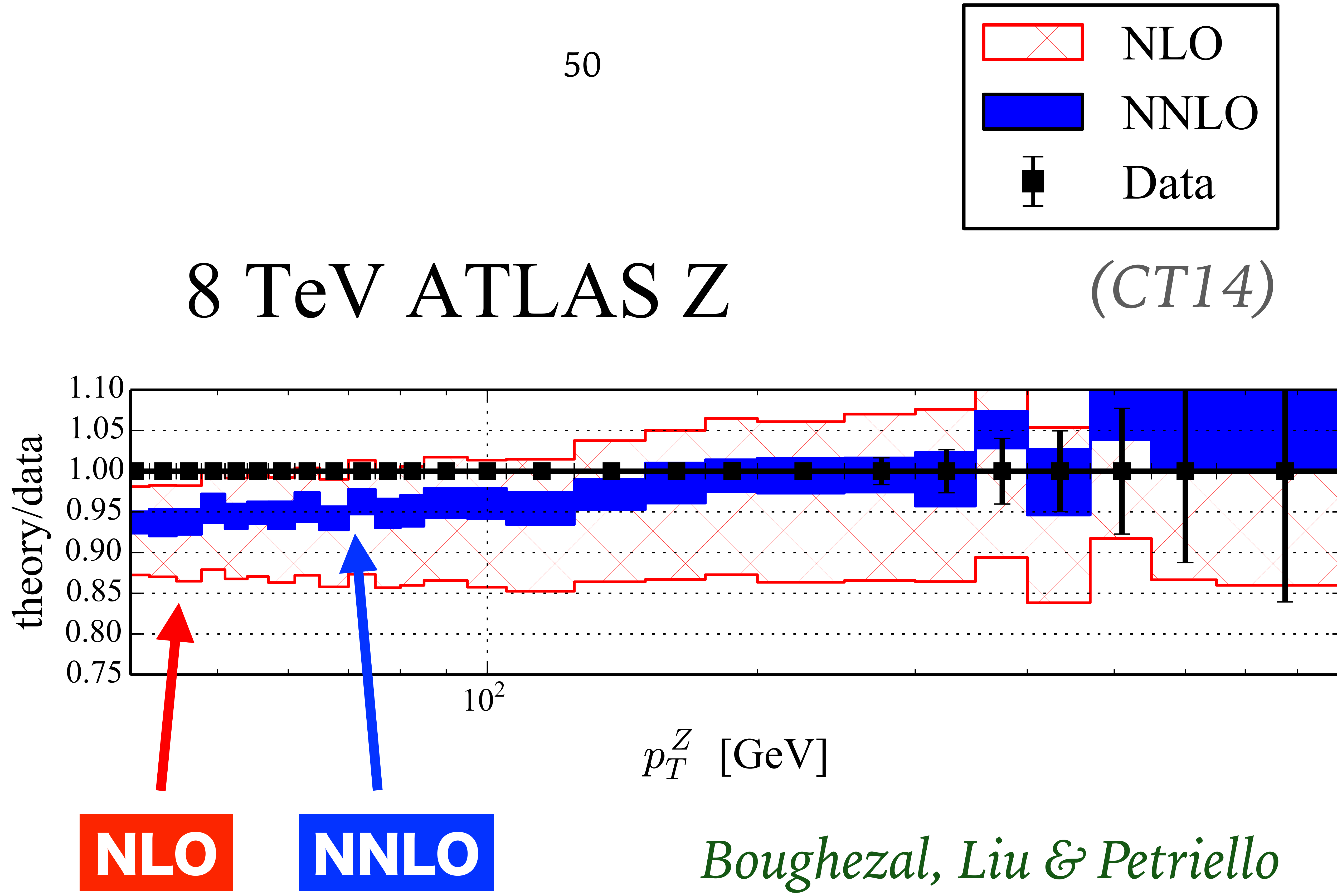


Z pT: Data v. two theory calculations



Gehrmann-de Ridder, Gehrmann Glover, Huss & Morgan

arXiv:1605.04295



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?

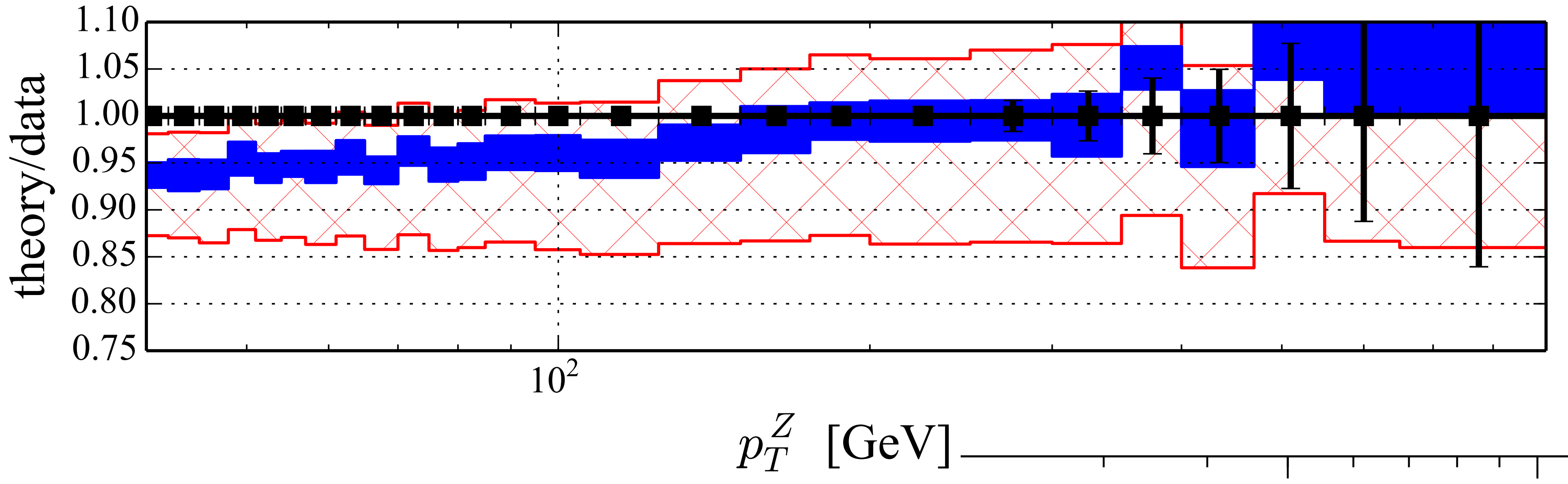
NB: both calc^n use a central scale

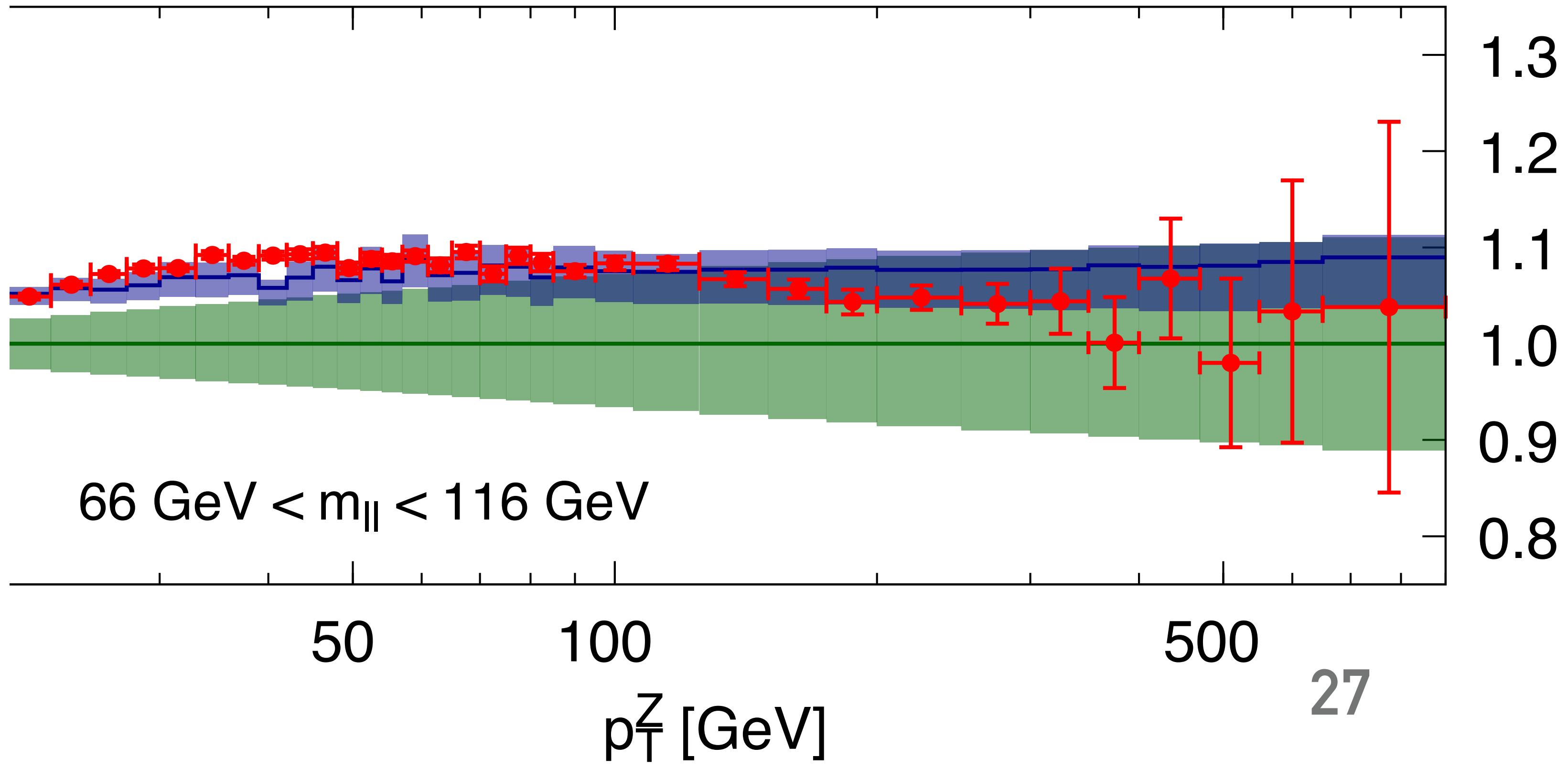
$$\mu = \sqrt{m_Z^2 + p_{T,Z}^2}$$

An alternative

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

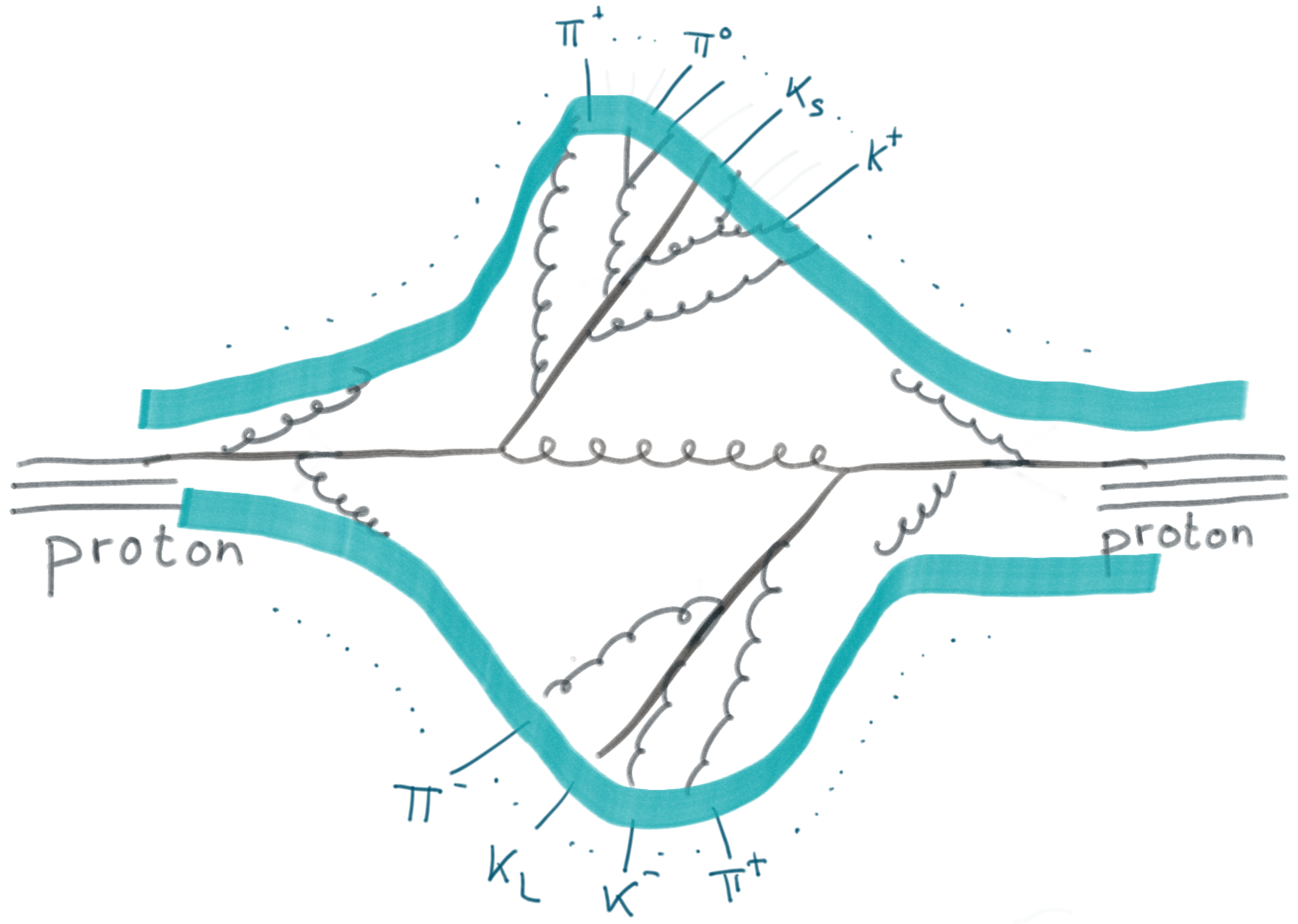
would seem more consistent with choices being made elsewhere (and might show better convergence)



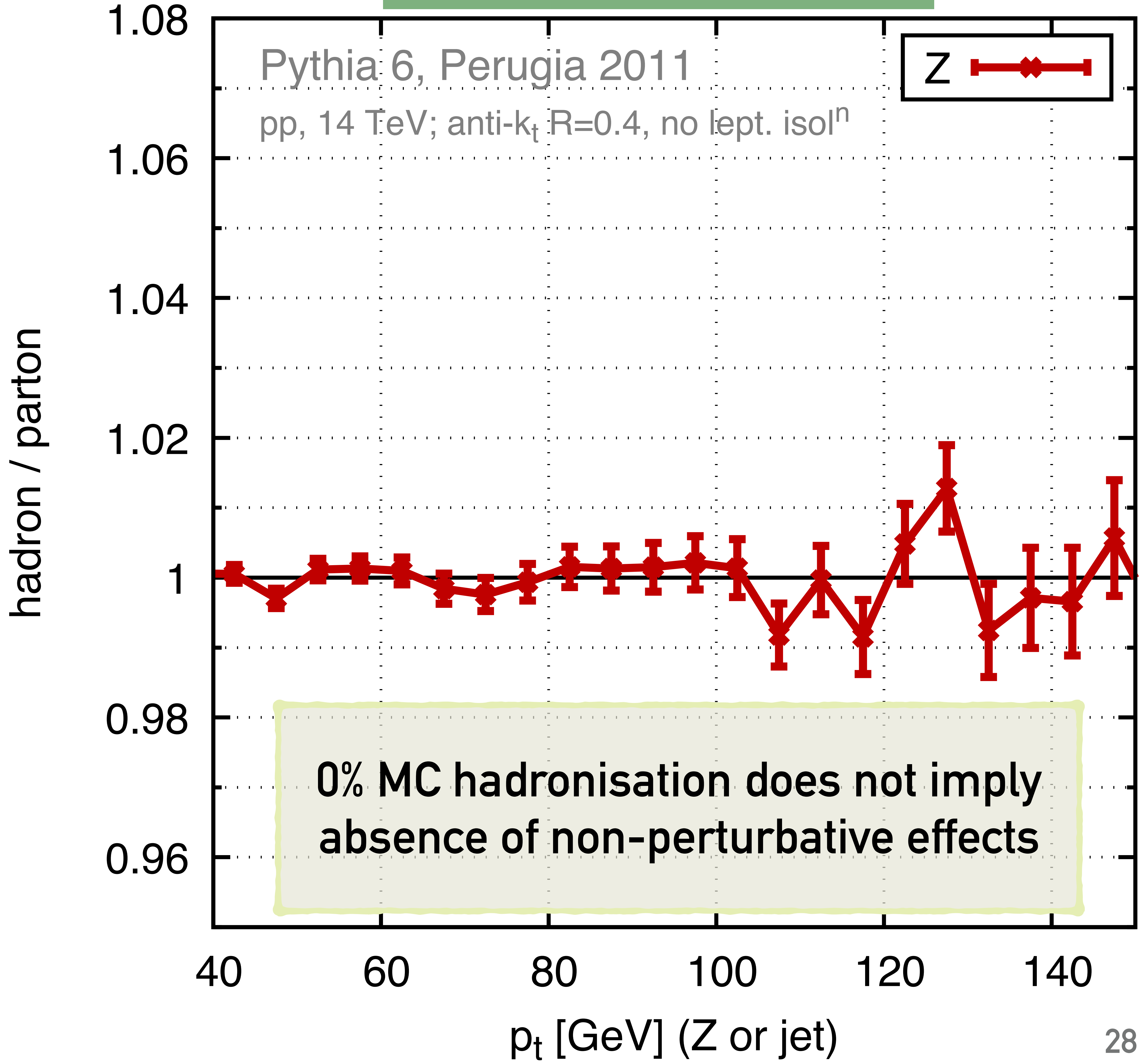


Non-perturbative effects in Z p_T

- Inclusive Z cross section should have $\sim\Lambda^2/M^2$ corrections ($\sim 10^{-4}$?)
- 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



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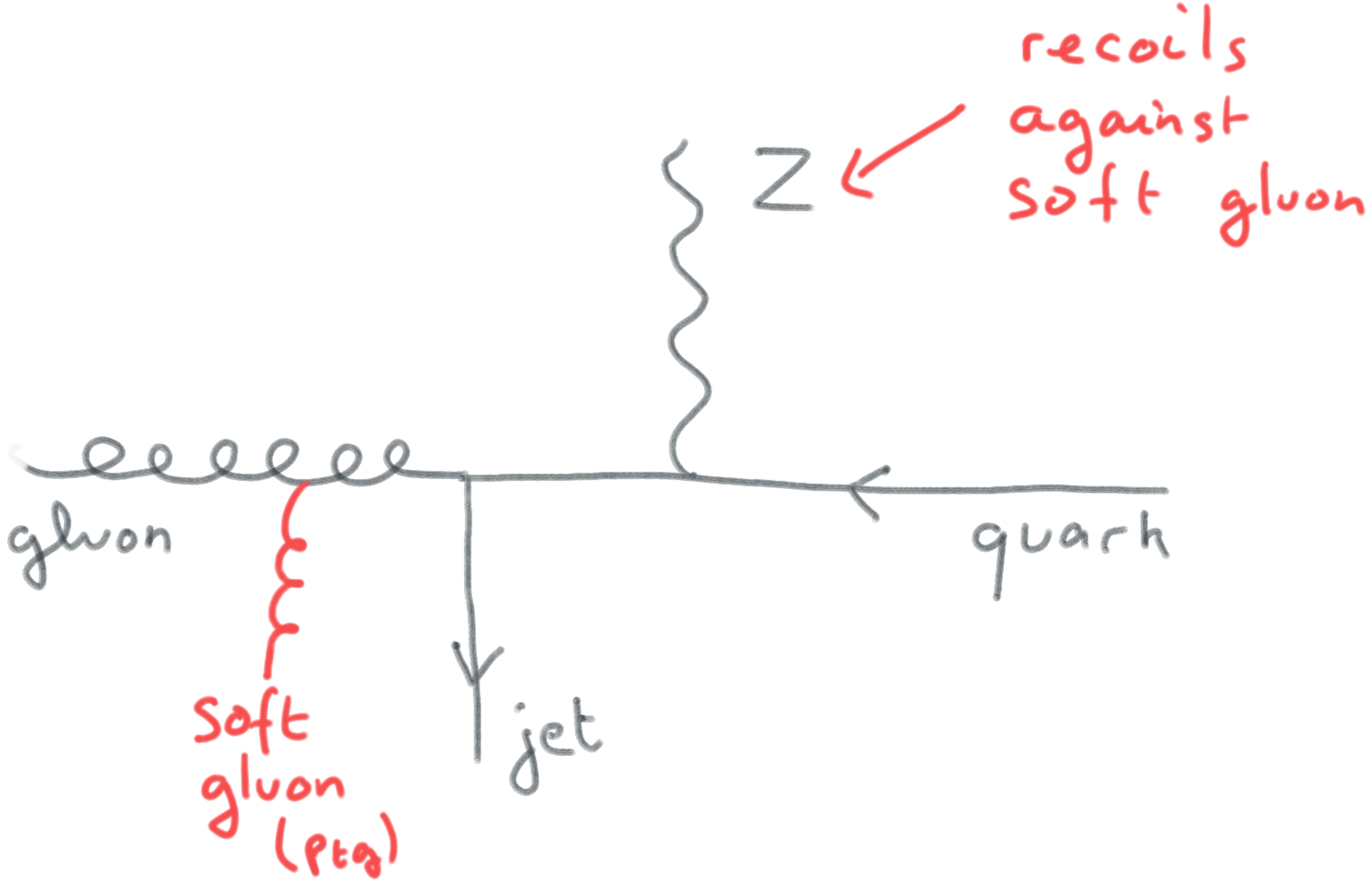
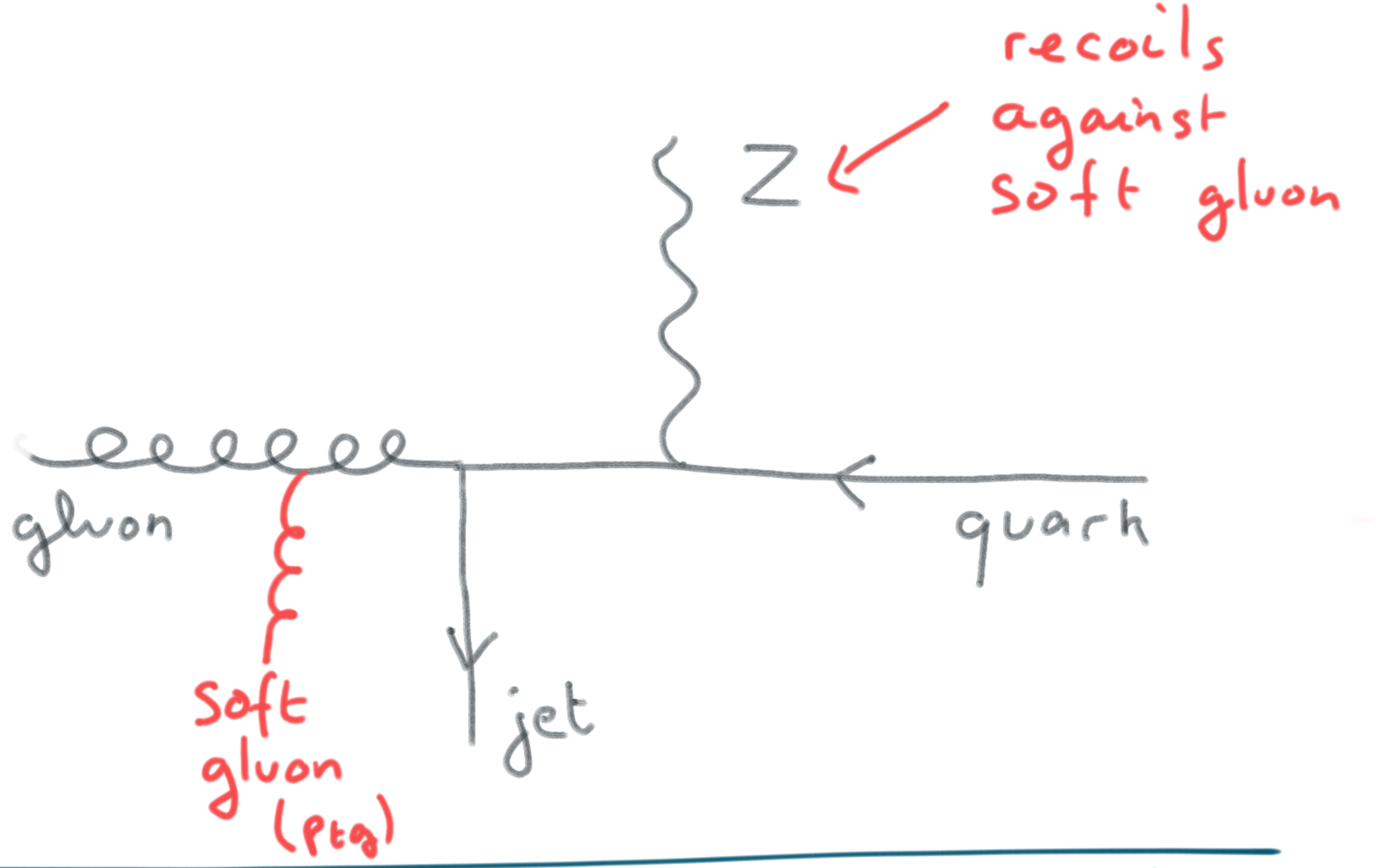


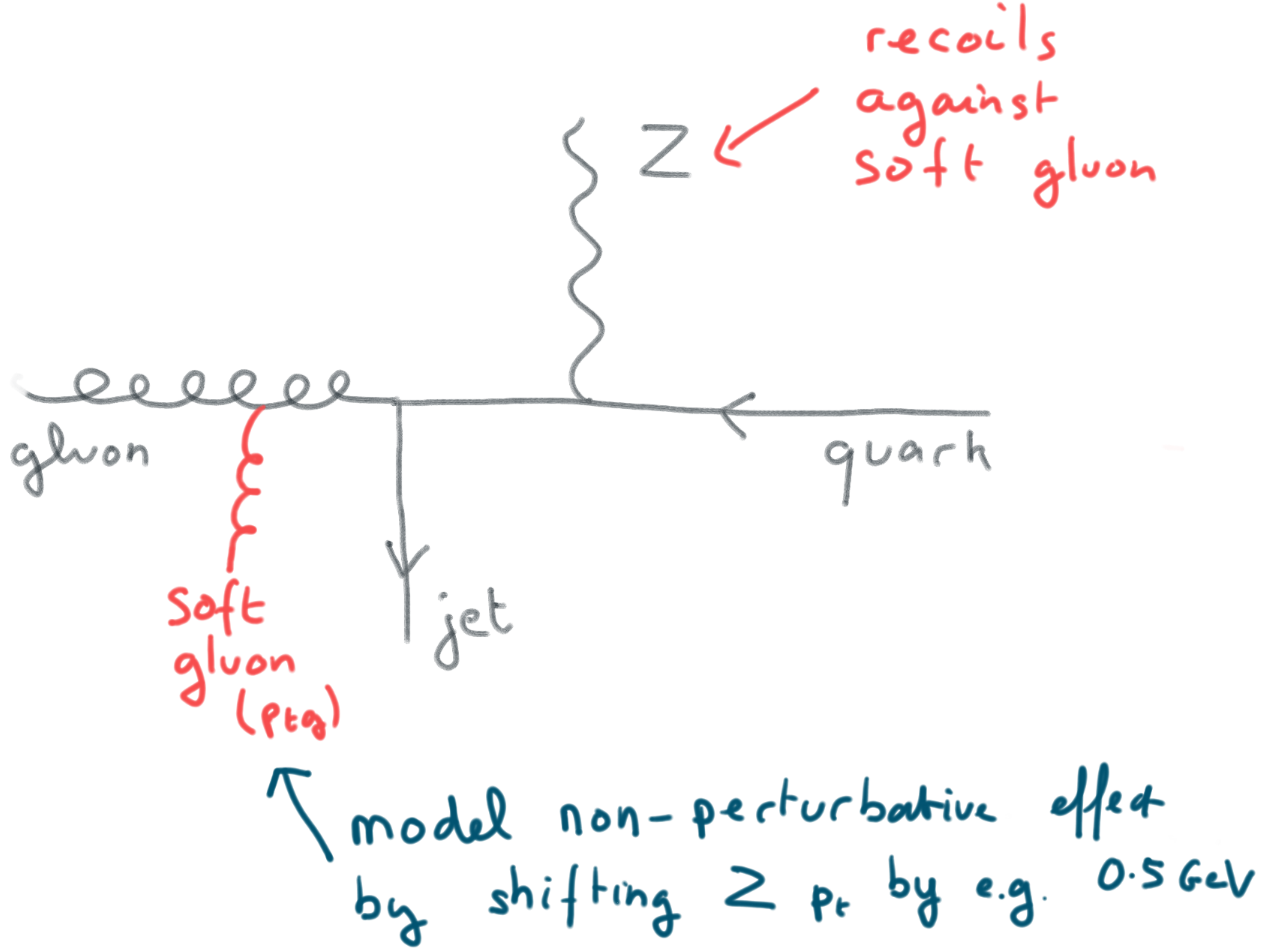
Non-perturbative effects in Z p_T



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

integral over low p_t emissions is non-perturbative

Non-perturbative effects in Z p_T



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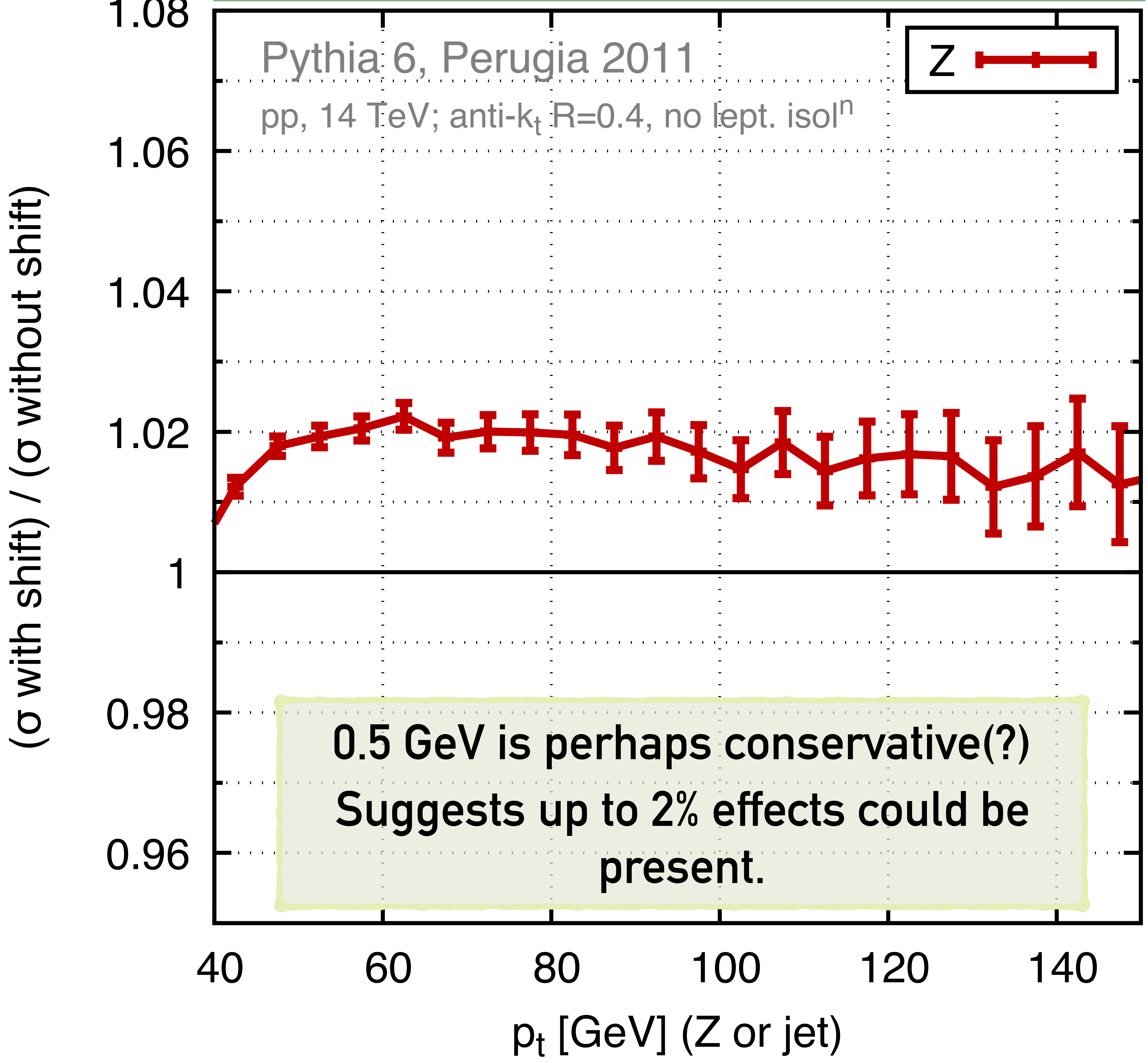
- Z p_T is **not inclusive** so corrections can be $\sim\Lambda/M$.
- Size of effect can't be probed by turning MC hadronisation on/off
  [maybe by modifying underlying MC parameters?]
- Shifting Z p_T by a finite amount illustrates what could happen

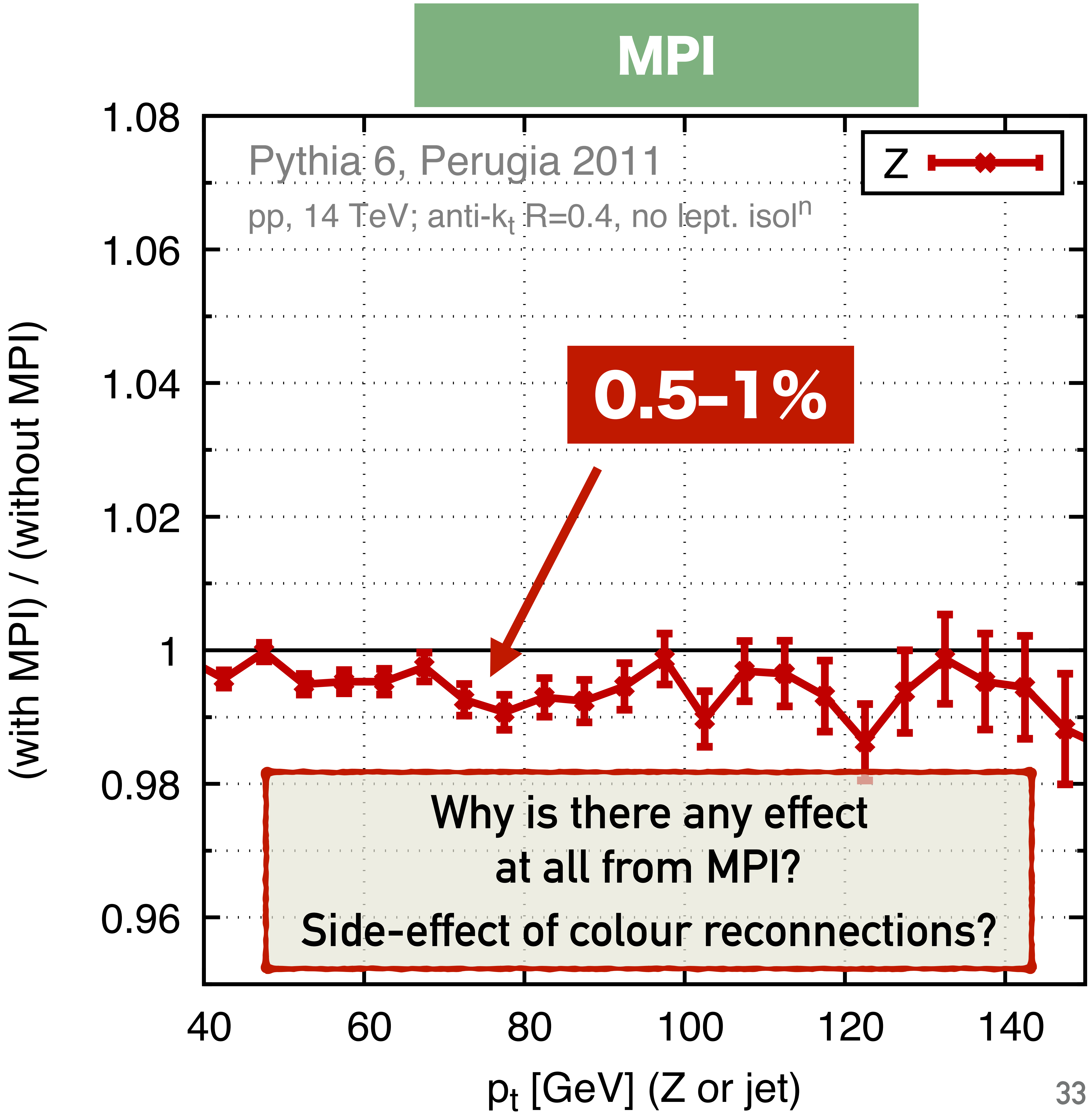
impact of 0.5 GeV shift of Z p_T



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

Multi-Parton Interactions?

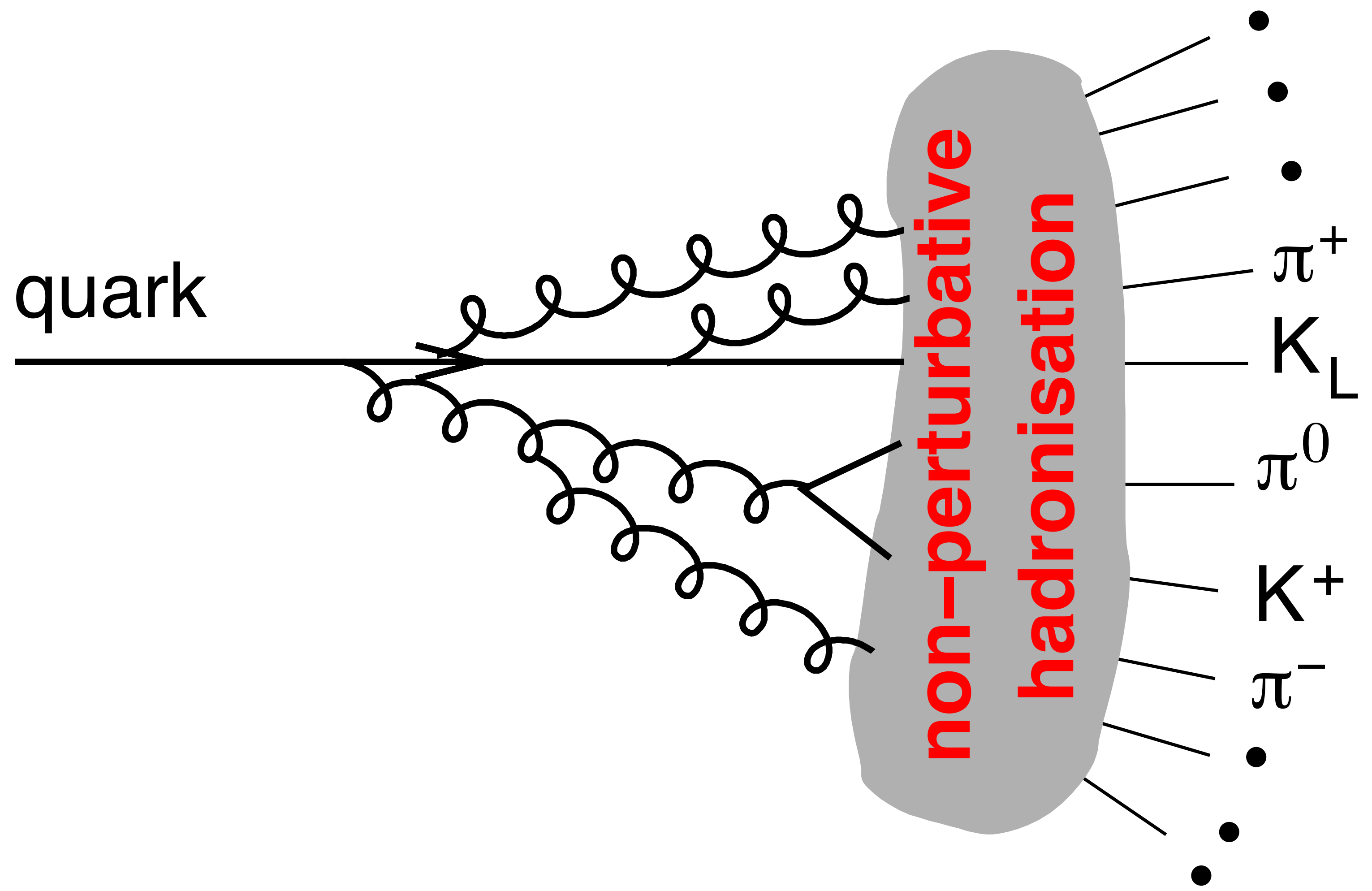
- Naively, you'd expect these are not correlated with Z p_T — but in at least one MC (Pythia 6) switching them on/off changes distribution by O(1%)



PROCESSES WITH (MEASURED) JETS

much less inclusive wrt QCD radiation

subject to larger hadronisation effects



THE JET IN Z+JET @ NNLO

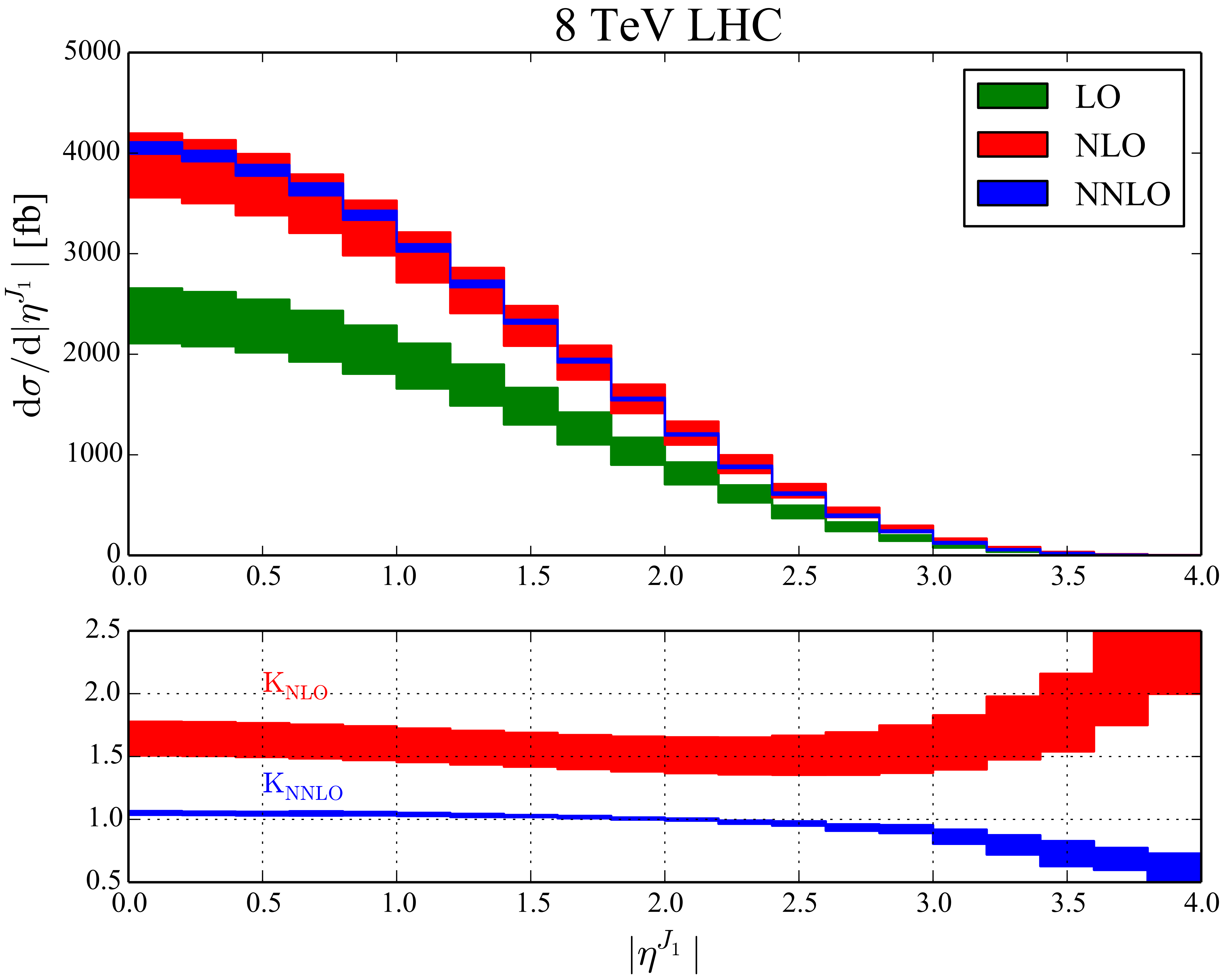
Boughezal, Liu & Petriello, 1602.08140

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%

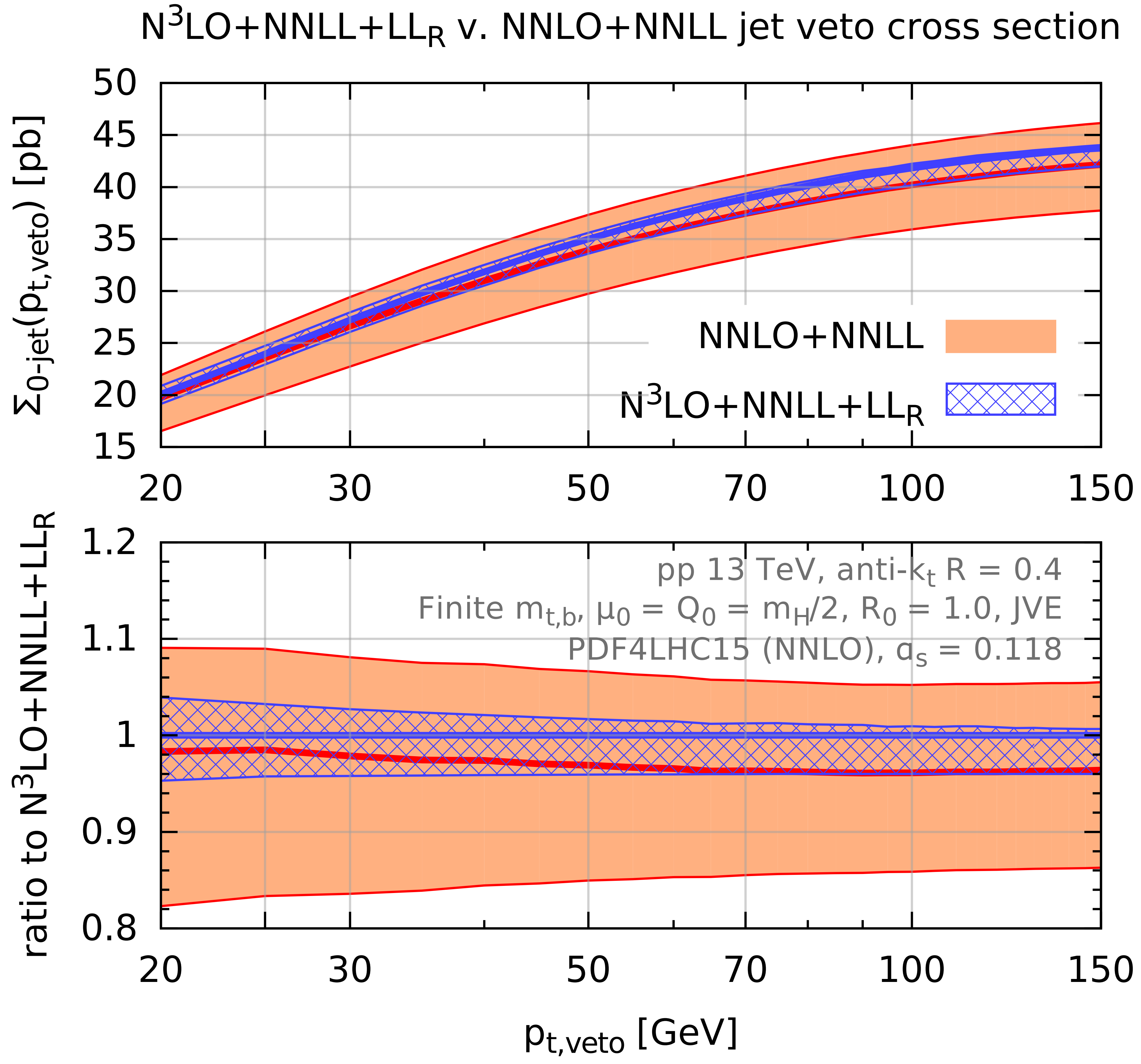


HIGGS JET VETO @ N3LO + NNLL

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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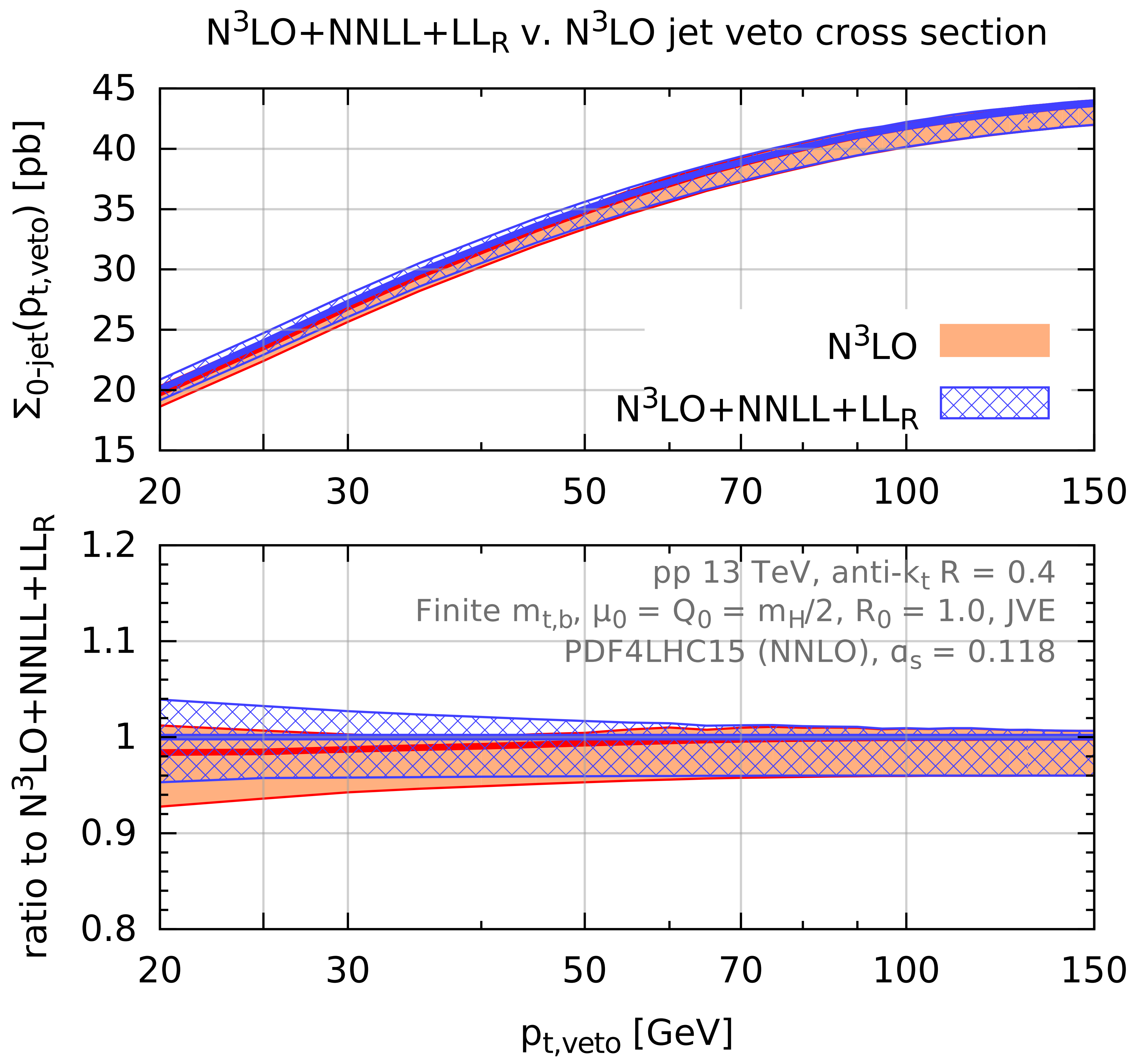
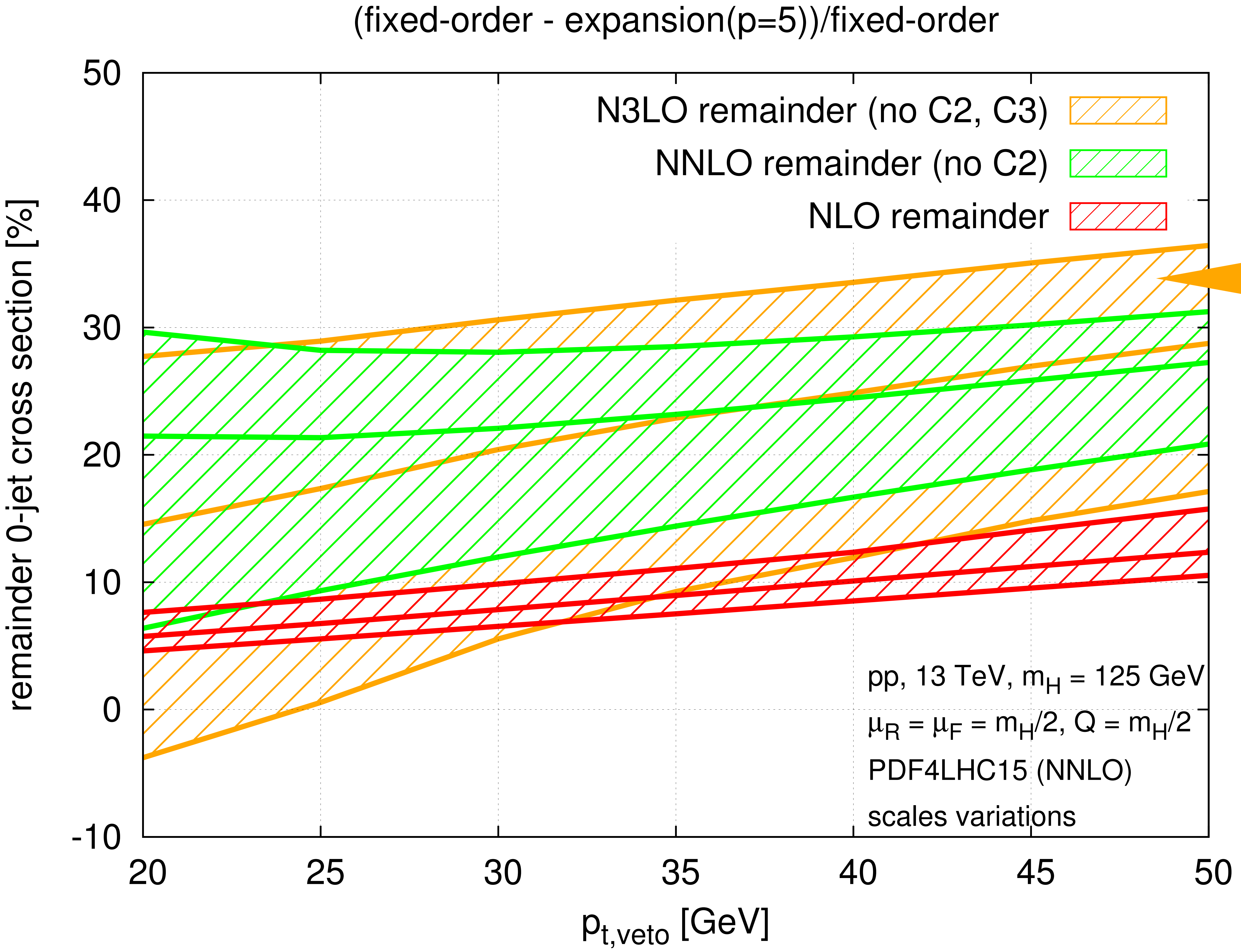
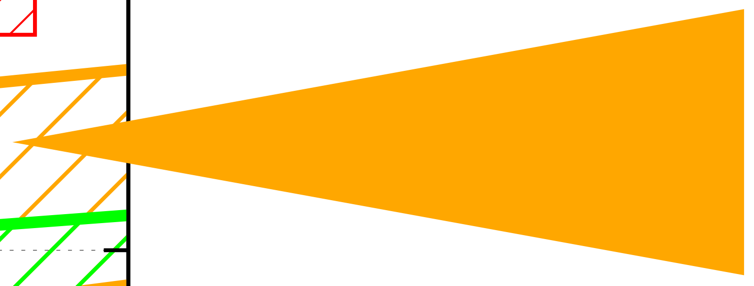


- N3LO effects at 2–4%
- Residual uncertainty up to 4% (fairly conservative)
- rather stable (~2%) wrt jet-p_T resummation effects

how good is resummation at finite p_t?



thanks to P. Monni for producing this plot



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

- 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

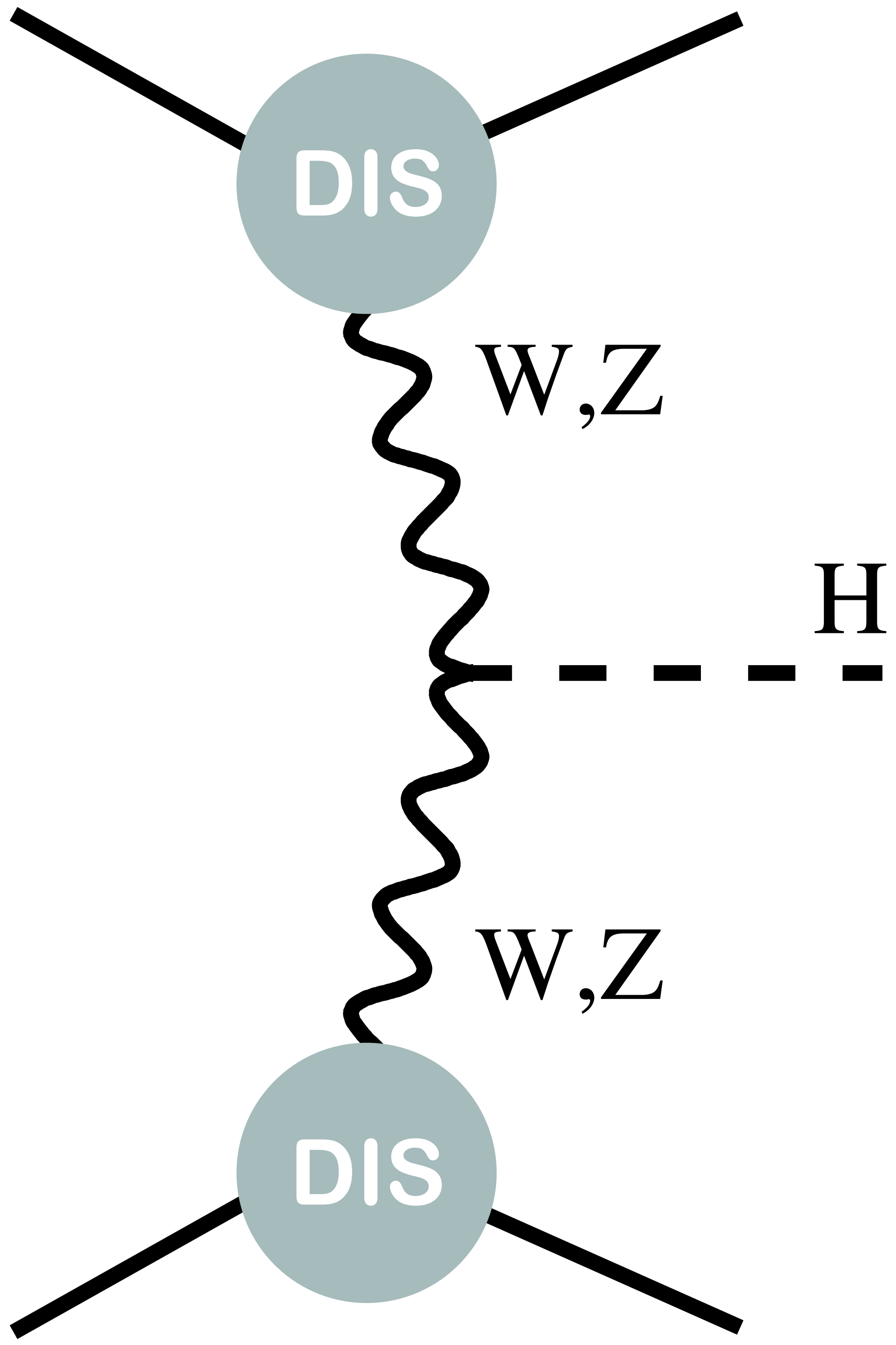
2 KINDS OF EFFECT IN SUCH PROCESSES ?

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

Can we make such a distinction meaningful?

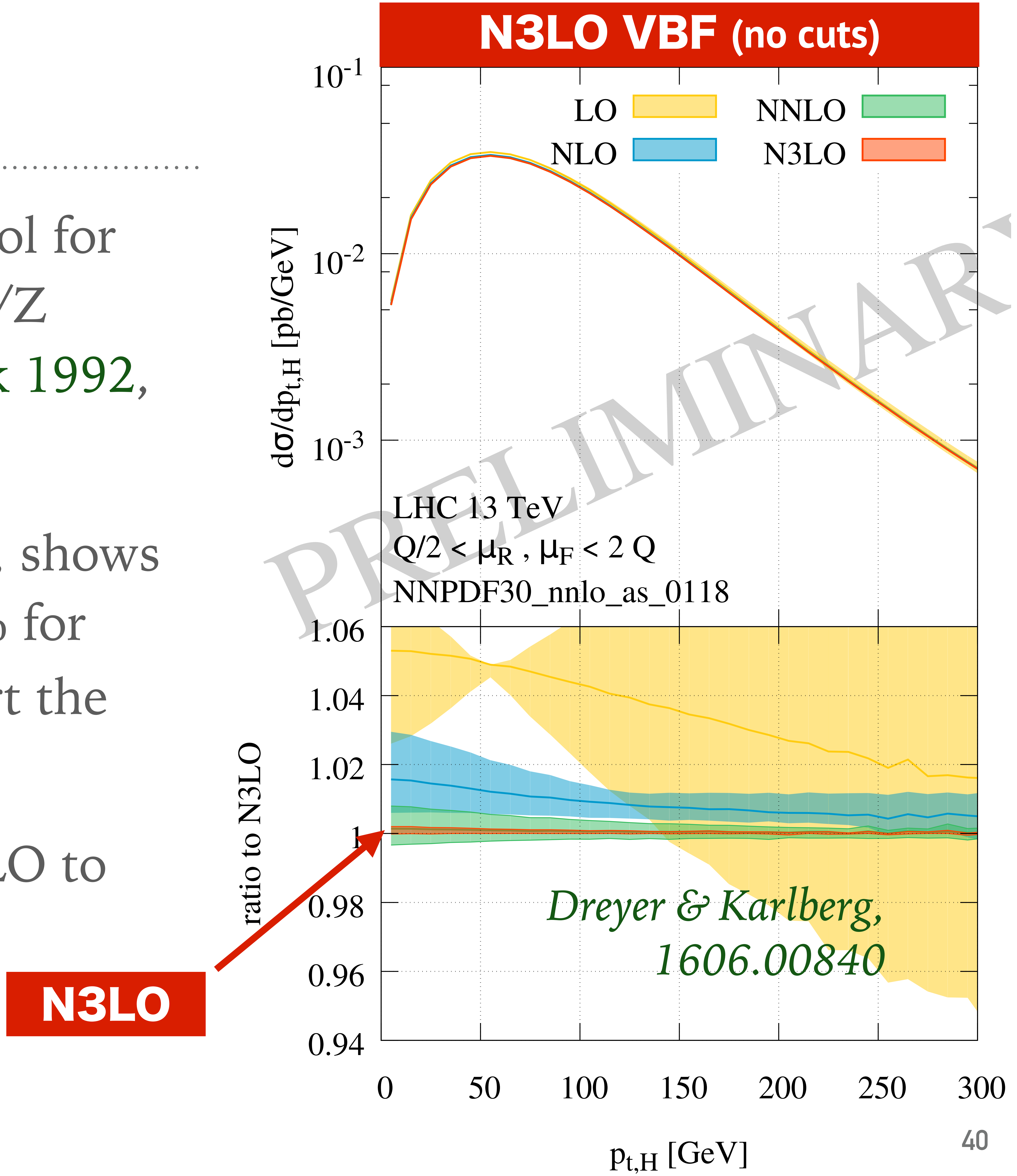
VECTOR-BOSON FUSION → HIGGS

- 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 VBF (no cuts)

VECTOR-BOSON FUSION → HIGGS

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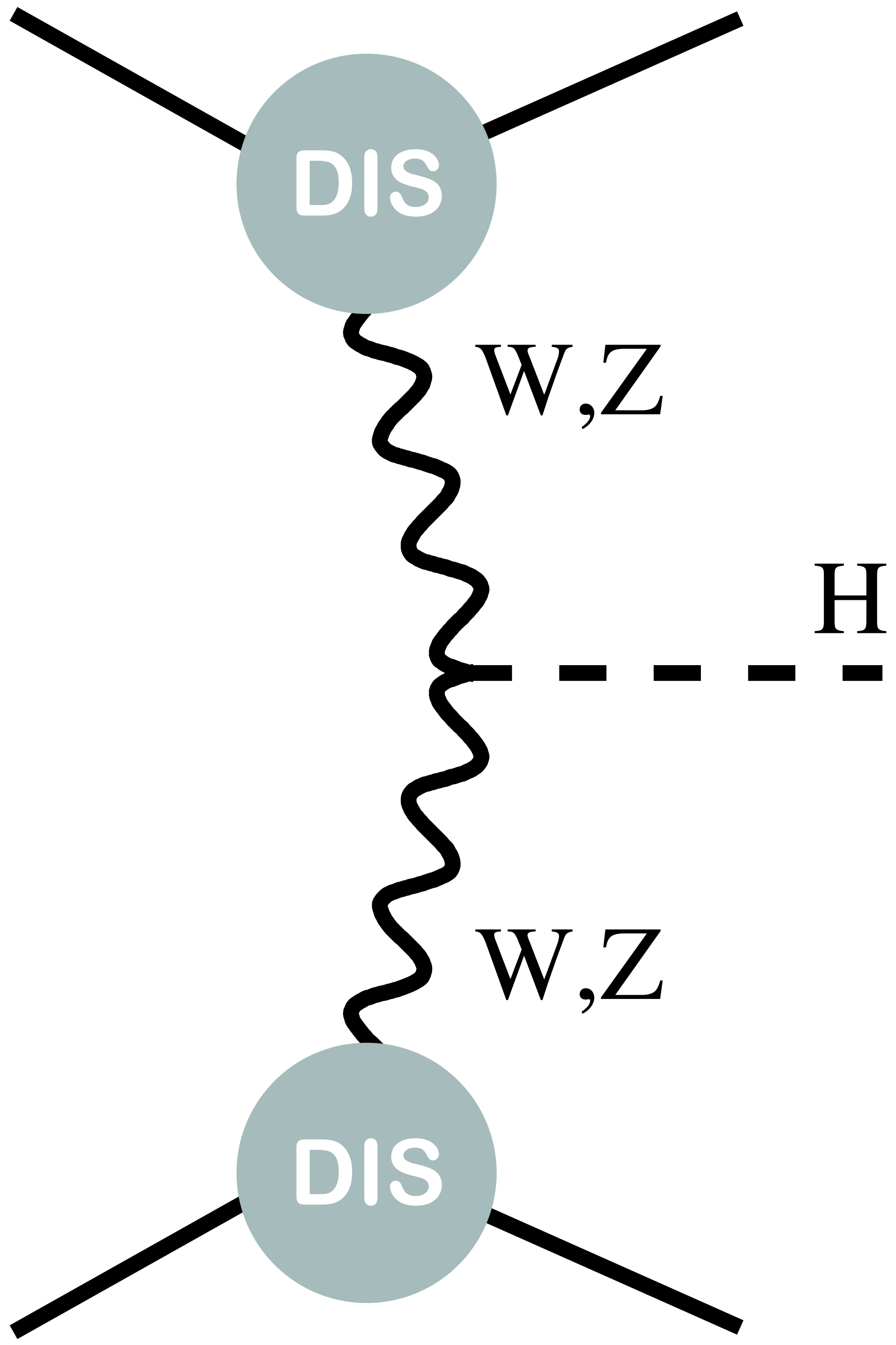

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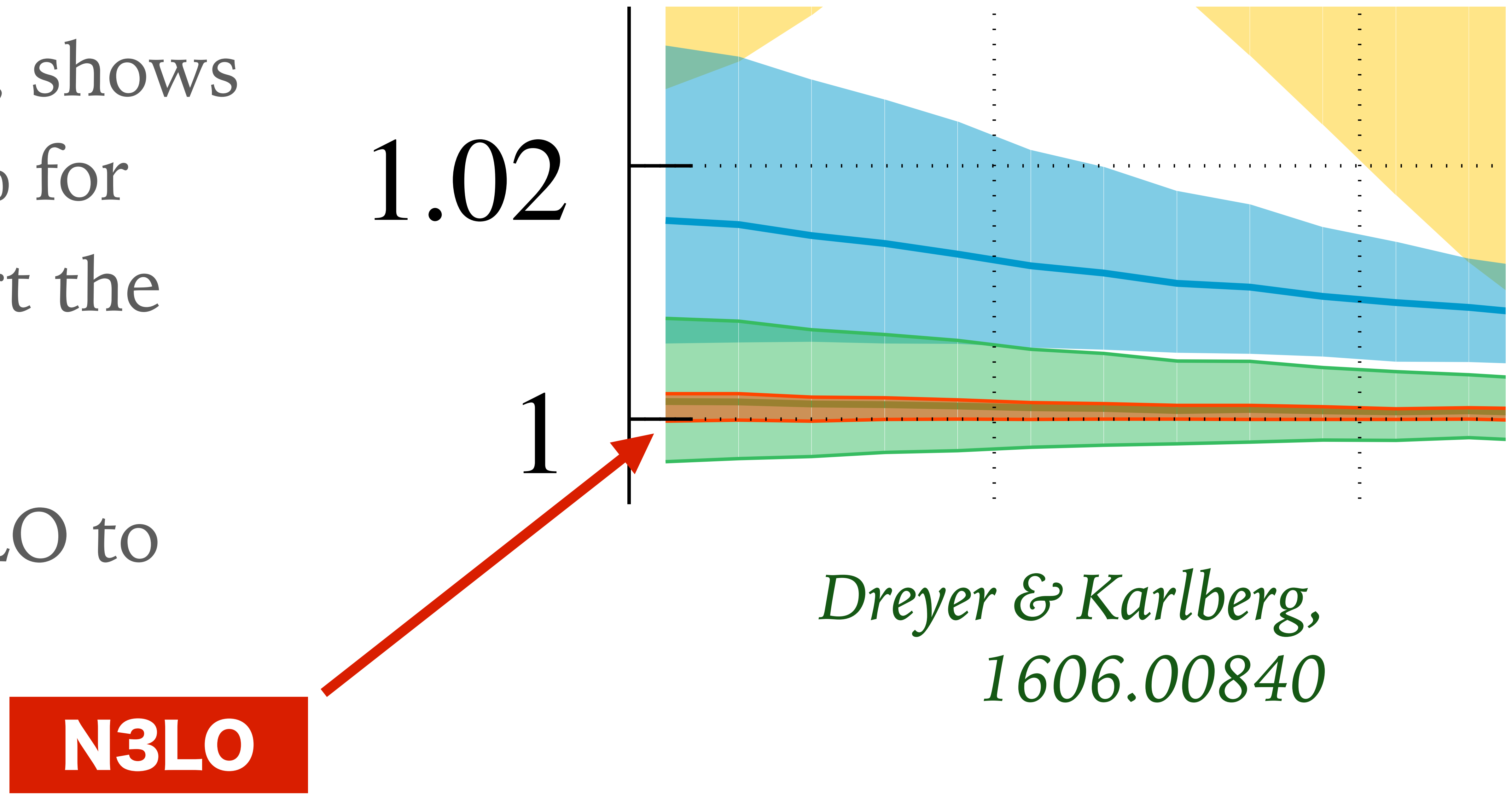


Dreyer & Karlberg, 1606.00840

Exact in "QCD₁ ⊗ QCD₂"

Non-trivial real-world corrections believed < 1%

VBF with cuts on jets: Projection to Born method

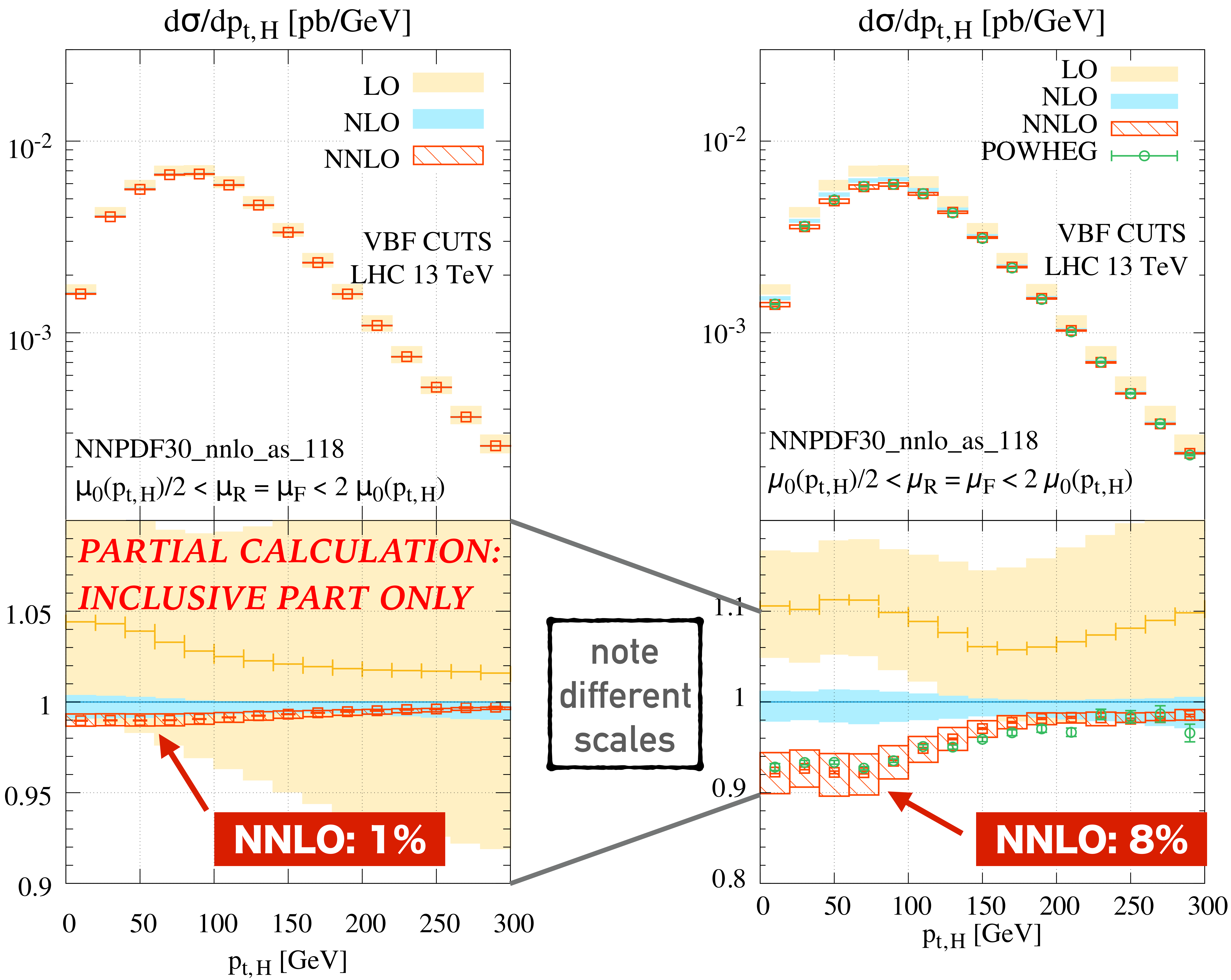
Cacciari, Dreyer, Karlberg, GPS & Zanderighi, 1506.02660

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



Full calculation (with VBF cuts)

NNLO is up to 8% effect

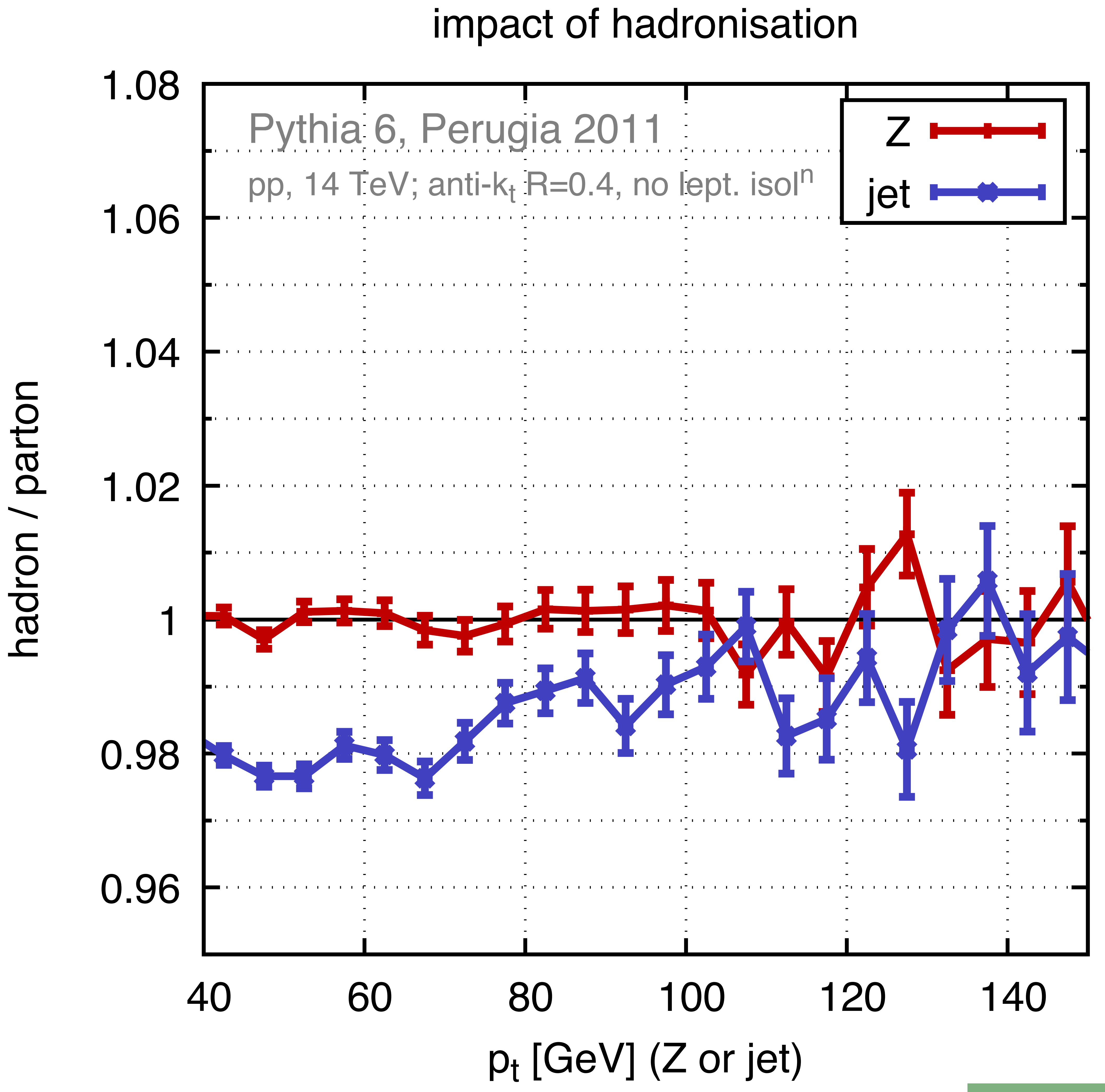
Almost all of which comes from jet fragmentation

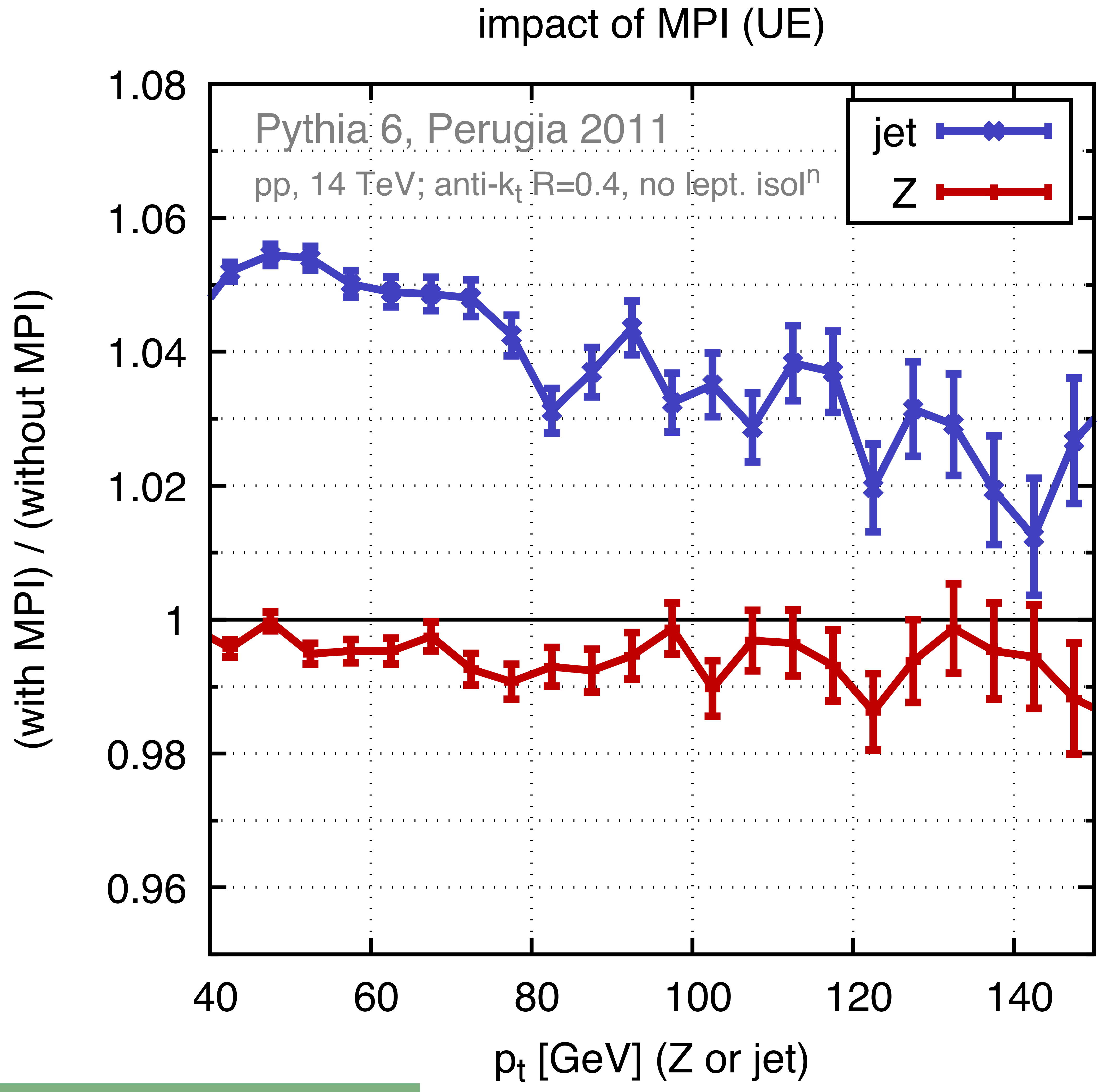
Non-perturbative effects & jets

Often discussed for inclusive jet spectrum

But relevant for any process involving jets

Jet v. Z in Z+jet process

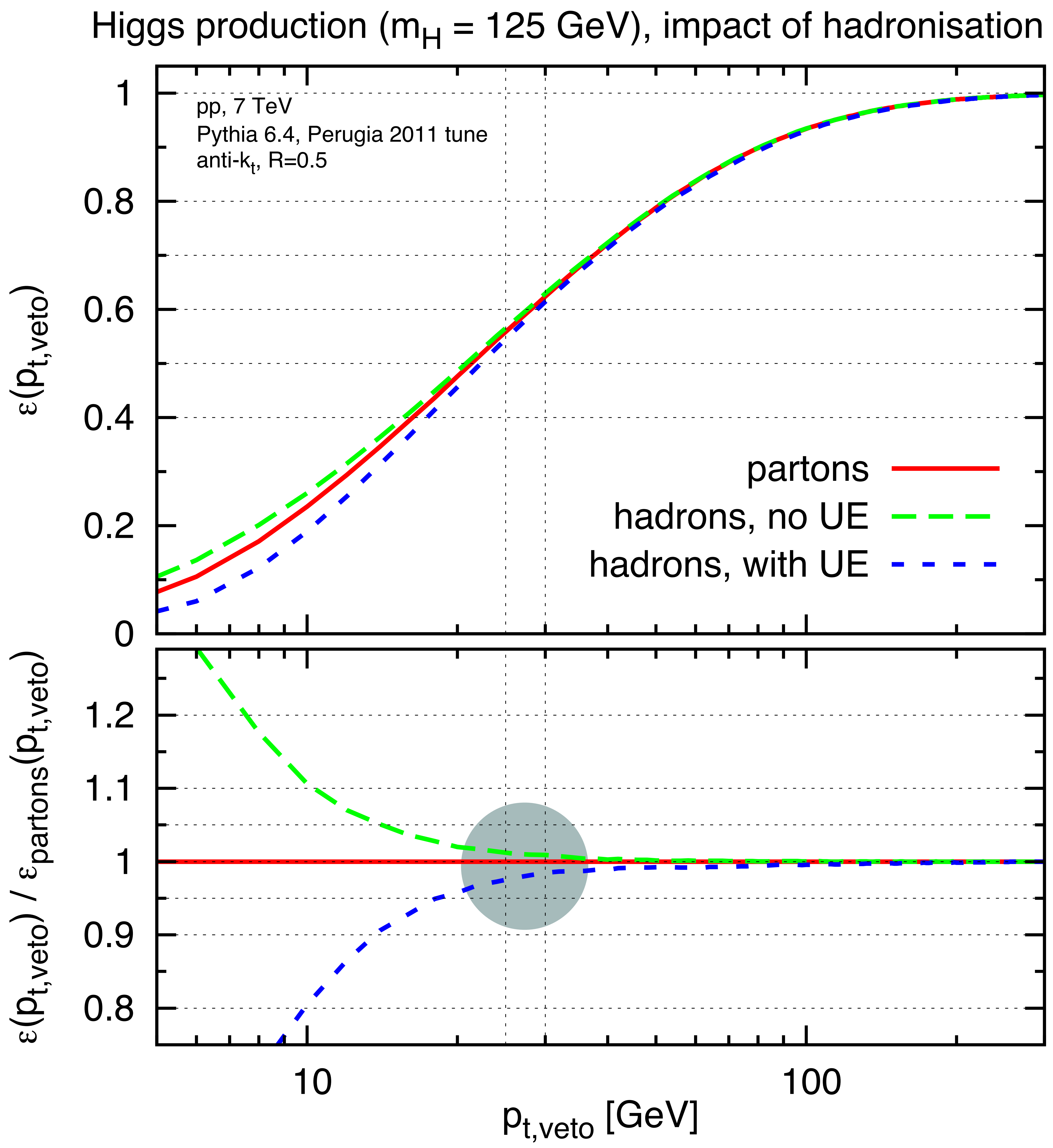




2 – 5% effects for jets

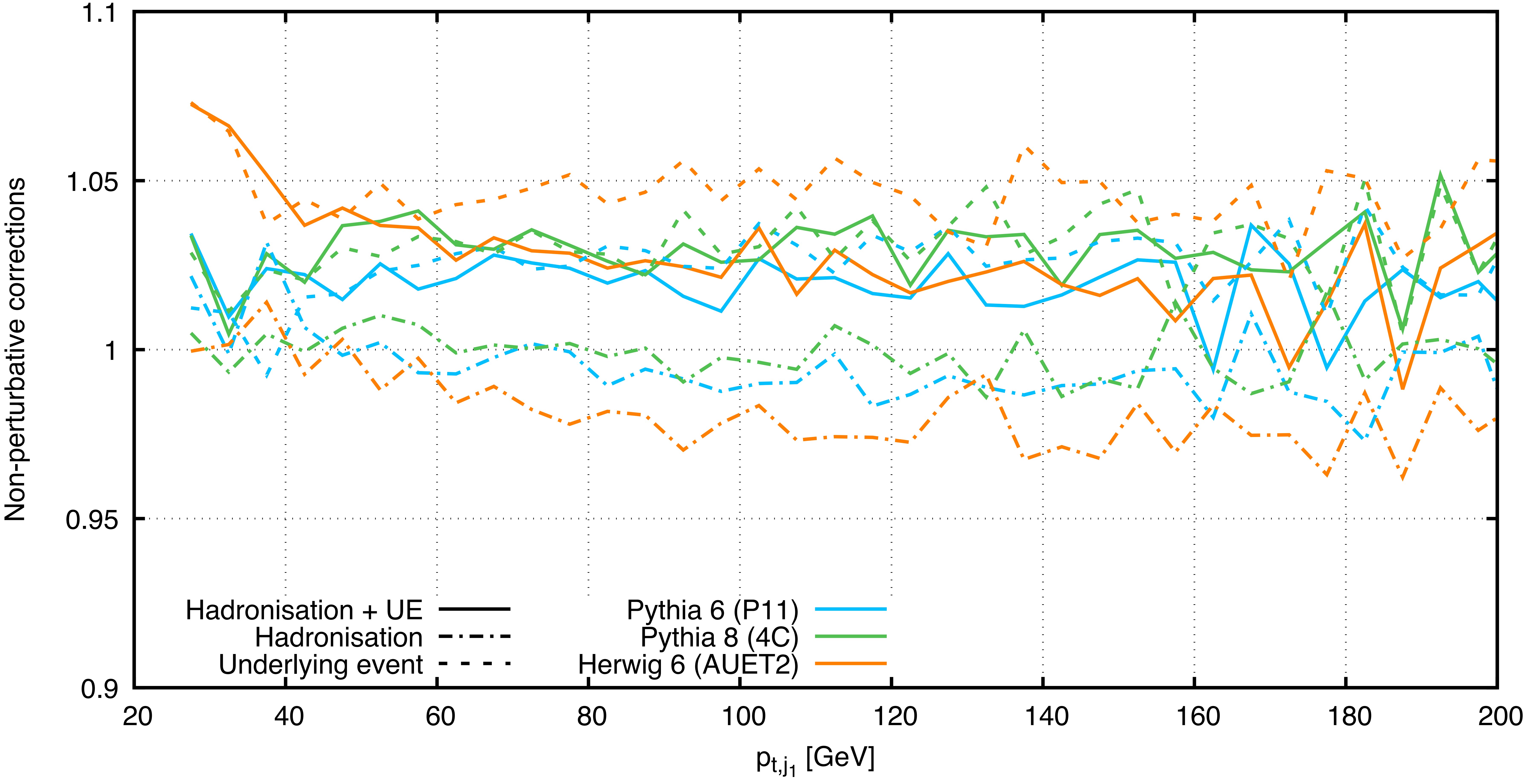
Higgs jet veto

1 – 3% effects for jets



Banfi, GPS, Zanderighi 1203.5773

VBF (leading jet)



3 - 5% effects

Cacciari, Dreyer, Karlberg, GPS & Zanderighi, 1506.02660 [unpublished backup plots]

POWERFUL HANDLE: EXPLORE A RANGE OF JET RADII

Dasgupta, Dreyer, GPS & Soyez, 1602.01110

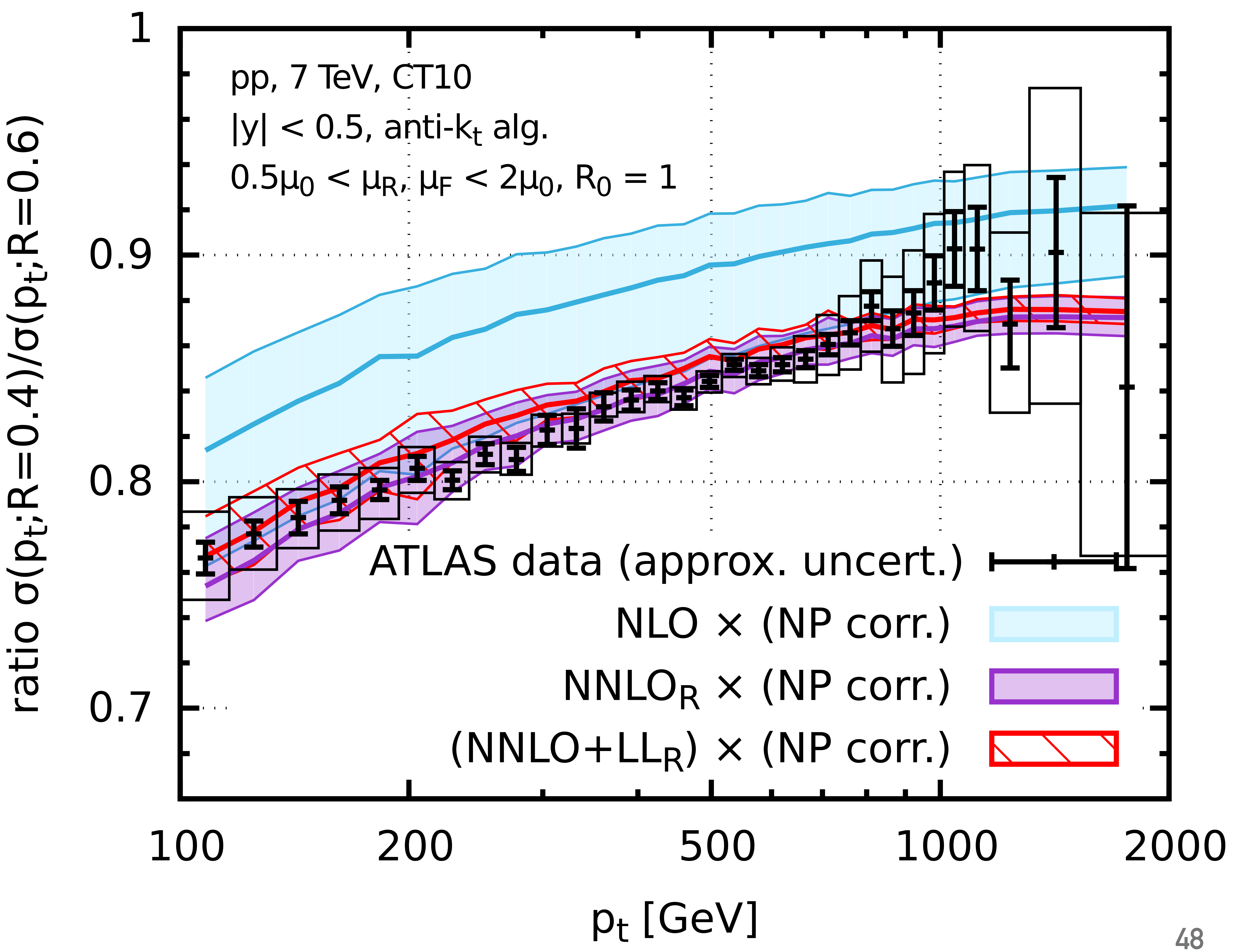
3 effects:

- ➤ 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



COMMENTS / CONCLUSIONS

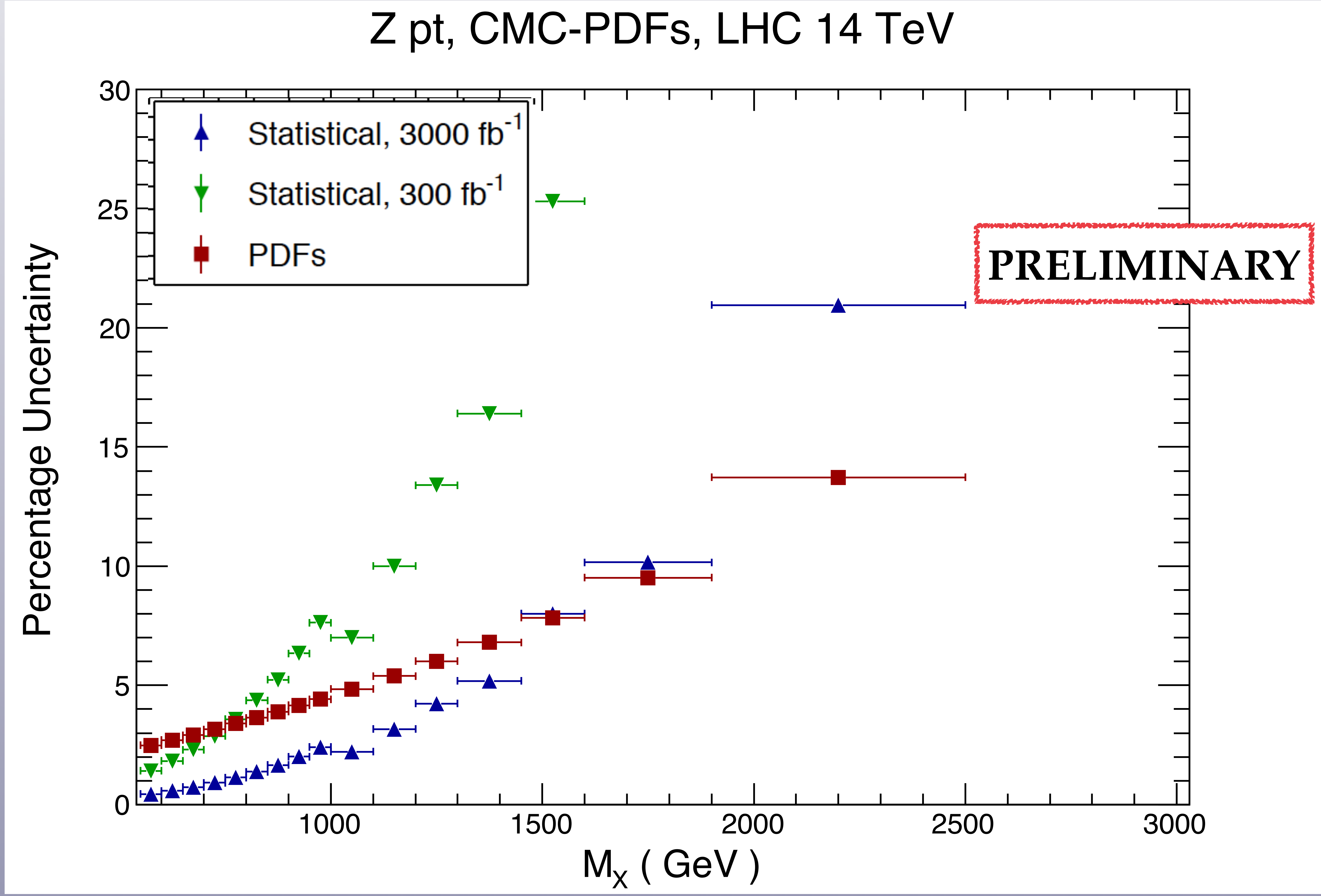
- 1% precision is something that we will want to reach for a range of processes to get full value out of the "precision" part of LHC's programme (Higgs, top, dilepton, …)
- We're entering the precision era today, notably with 1% Z p_T distribution (first hadron-collider process $\propto \alpha_s$ known with this precision)
- Where do resummation and parton showers fit into this?
  - Better insight into non-perturbative effects will be crucial
  - Need to understand boundary of where resummation and fixed order are reliable (e.g. sub-Eikonal contributions in resummation?)

BACKUP

EXPERIMENTAL PERSPECTIVES

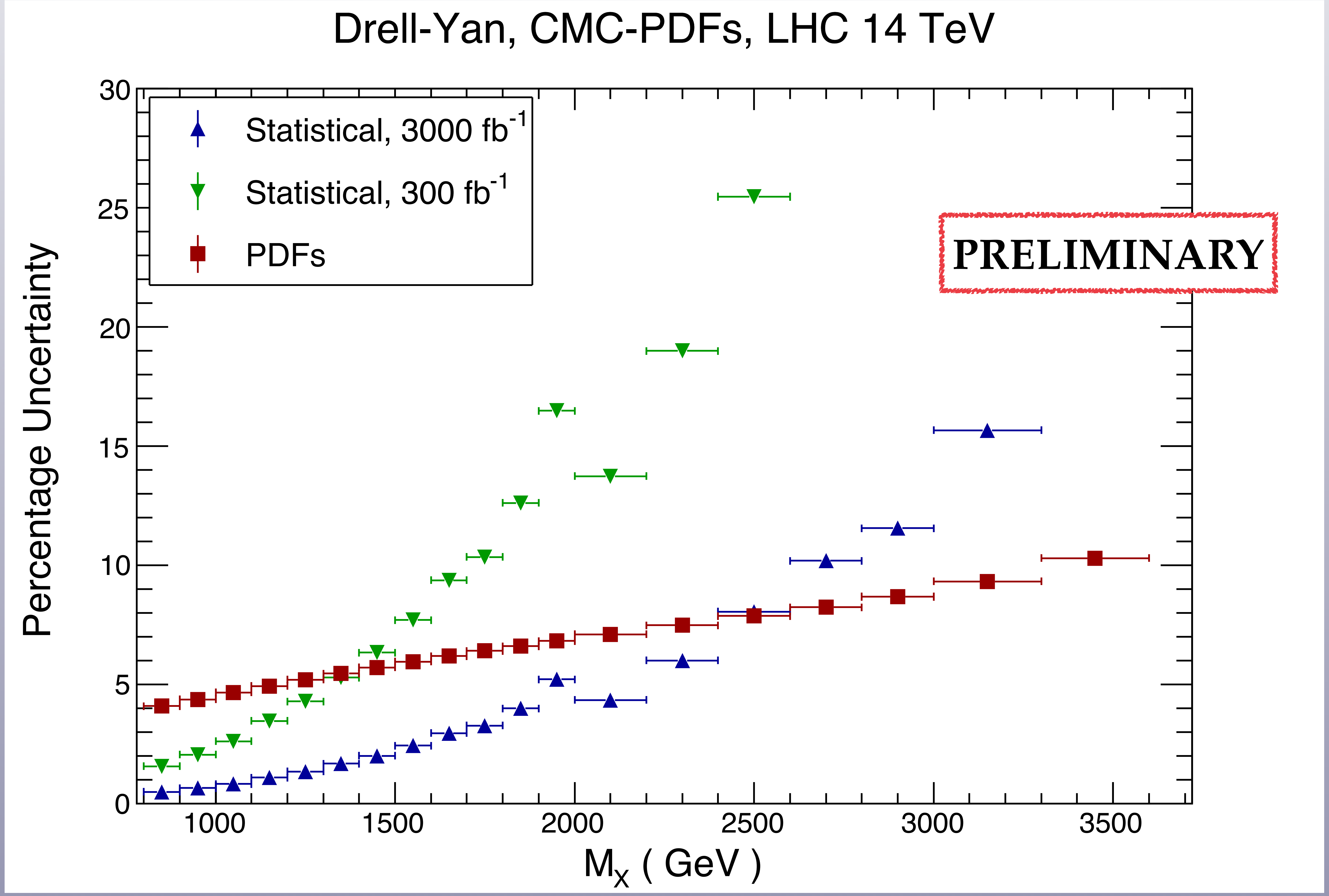
Generation of pseudo-data: the Z pt

- 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



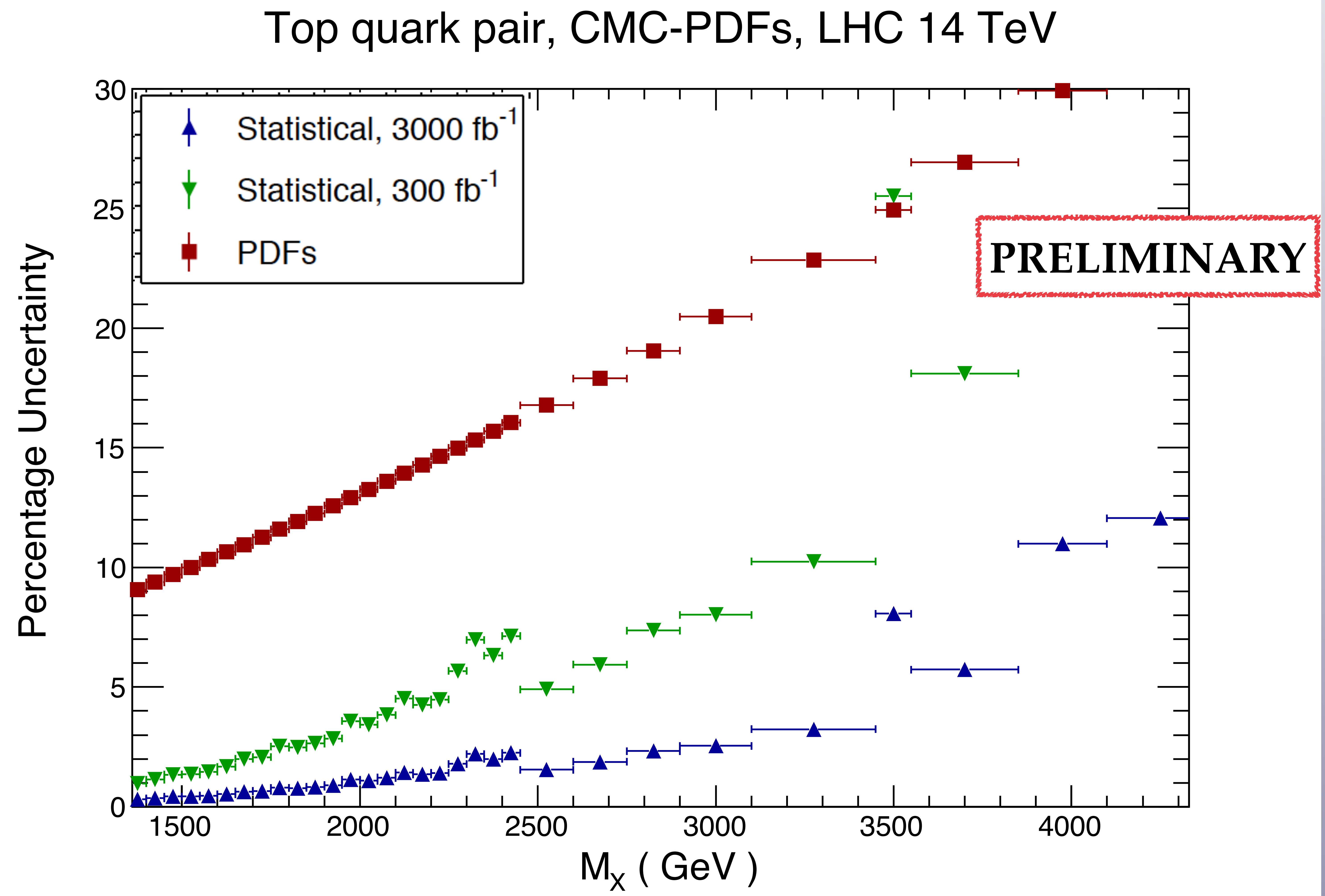
Generation of pseudo-data: high-mass Drell-Yan

- 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



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%.

$Z\ P_T$

CMS Z p_T uncertainties (normalised to total fiducial)

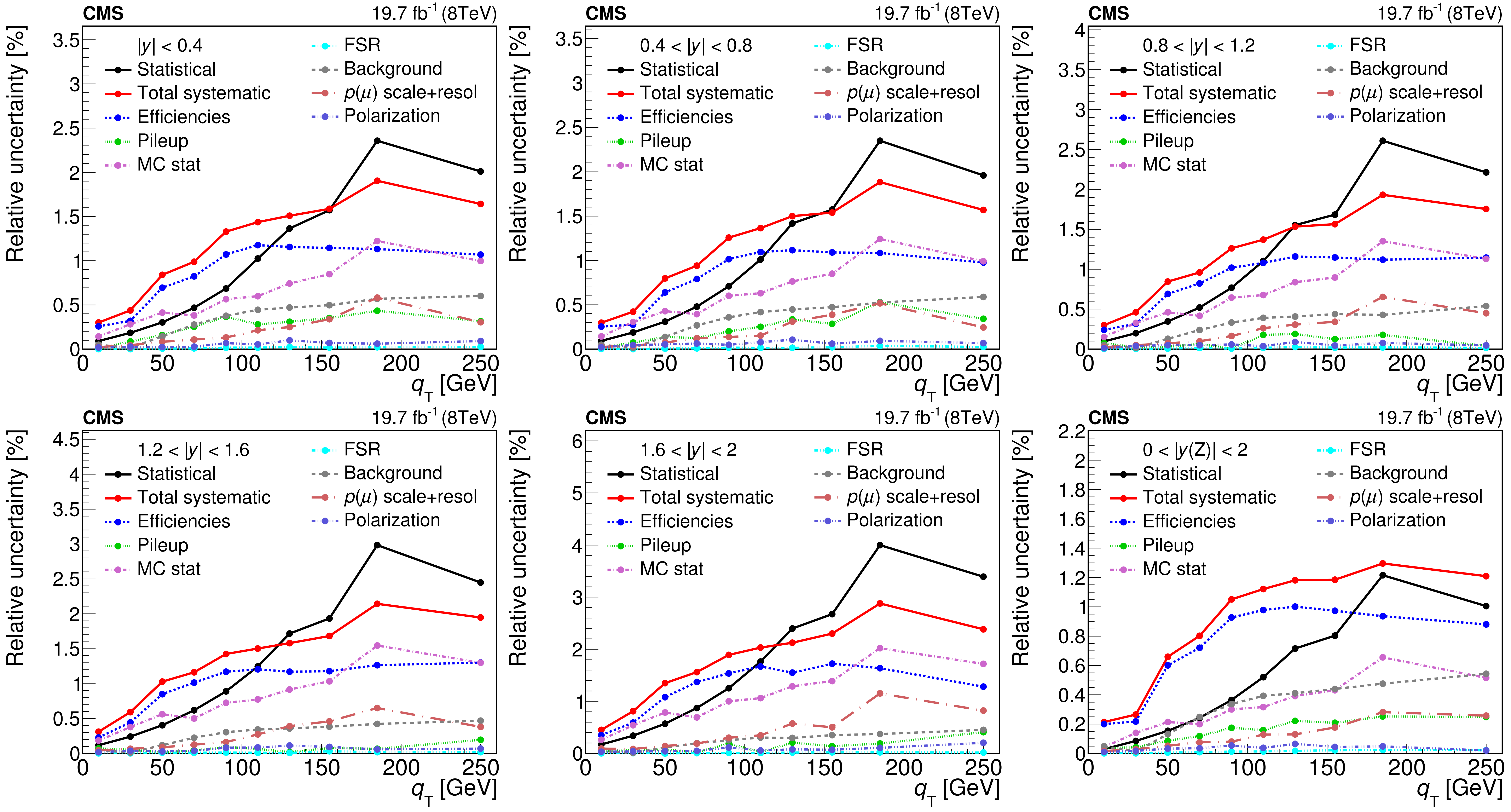


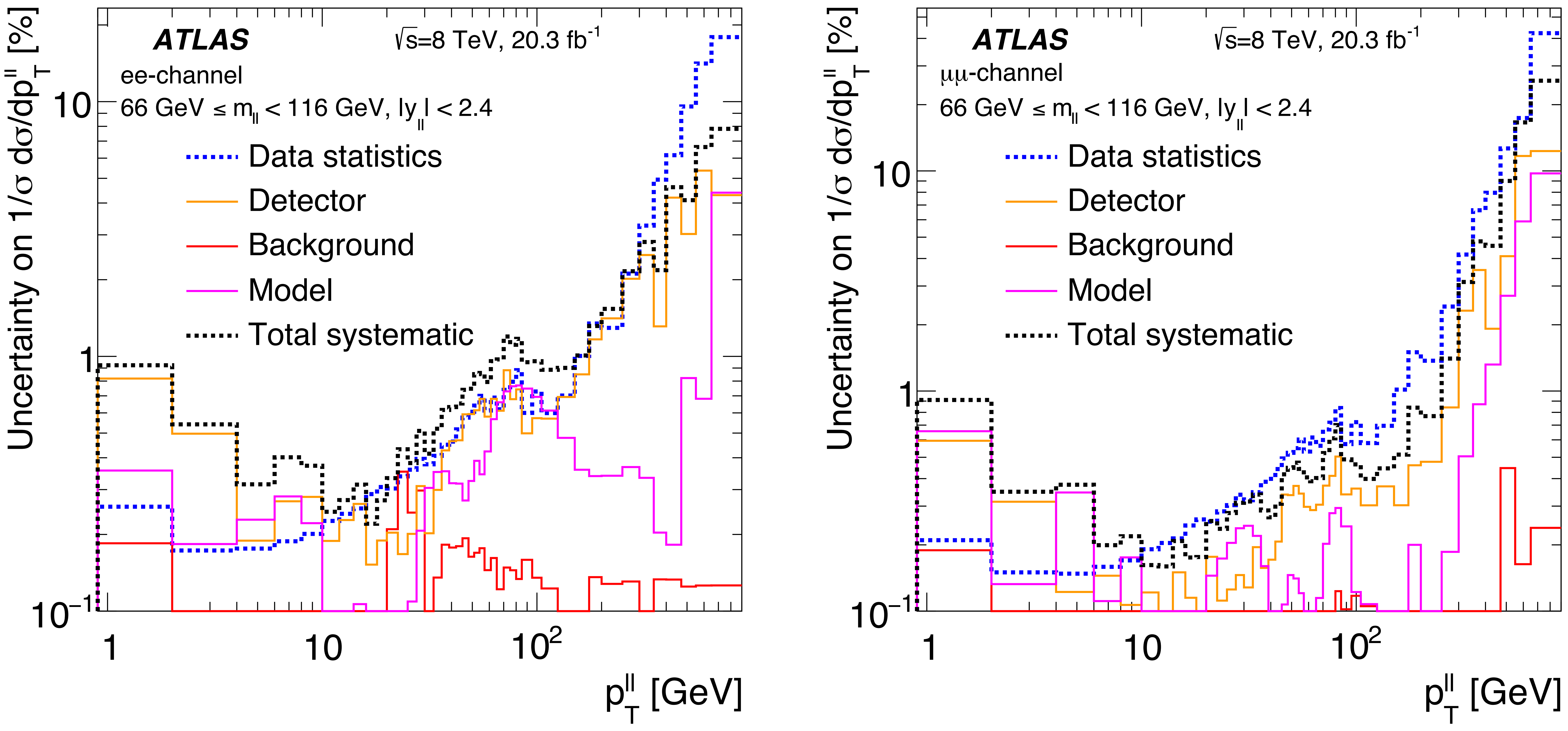
Figure 1: Relative uncertainties in percent of the normalised fiducial cross section measurement. Each plot shows the q_T dependence in the indicated ranges of $|y|$.

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

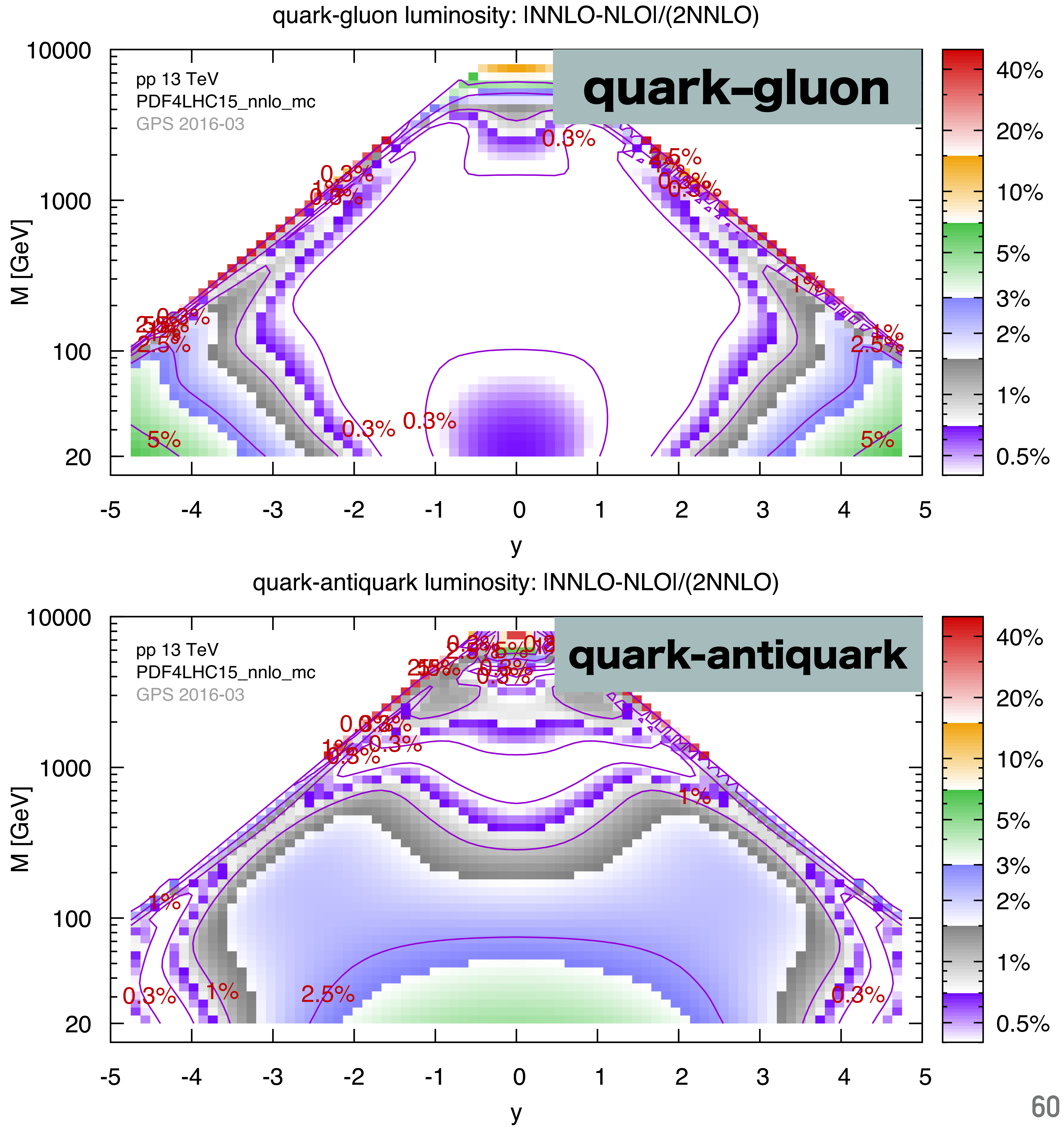
Figure 4: Uncertainty from various sources on $(1/\sigma)\,\mathrm{d}\sigma/\mathrm{d}\phi^*_\eta$ (top) and $(1/\sigma)\,\mathrm{d}\sigma/\mathrm{d}p_T^{\ell\ell}$ (bottom) for events with 66 GeV $< m_{\ell\ell} <$ 116 GeV and $|y_{\ell\ell}| < 2.4$. Left: electron-pair channel at dressed level. Right: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

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

Theory Uncertainties



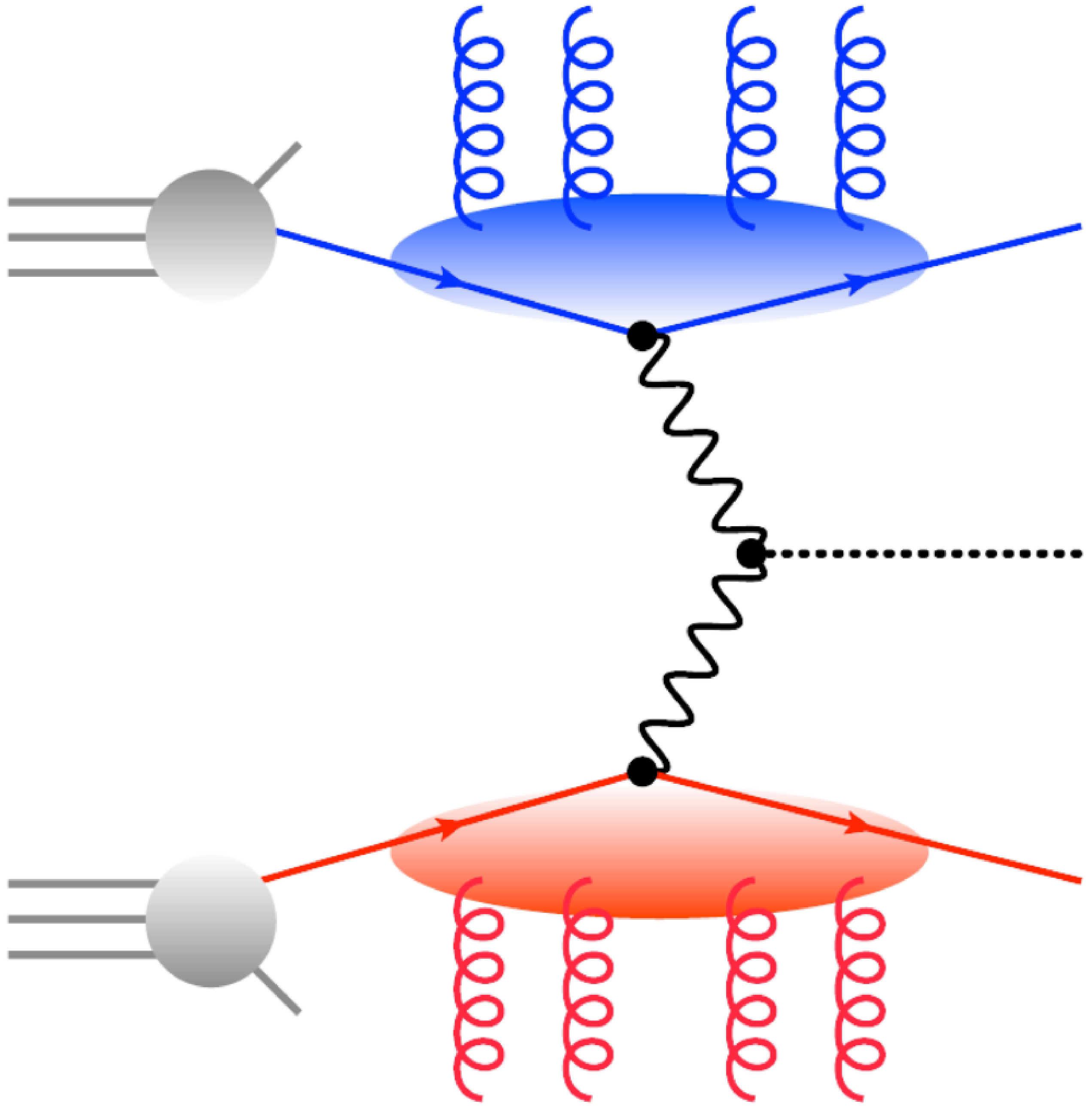
VBF HIGGS PRODUCTION

Structure Function Approach

One can think of VBF Higgs production as a double Deep Inelastic Scattering (DIS×DIS) with no cross-talk between the upper and lower sectors. [Han, Valencia, Willenbrock (1992)]

- this picture is accurate to more than 1%

[Bolzoni et al. (2012)], [Ciccolini, Denner, Dittmaier (2008)], [Andersen et al. (2008)]



- the factorisation of the two sectors is exact if one imagines two copies of QCD, QCD_1 and QCD_2 , respectively for the upper and lower sectors.
- all DIS coefficients are known to NNLO and almost all to N^3LO.
- as the DIS coefficients are inclusive over the hadronic final state, the calculation cannot provide differential results.

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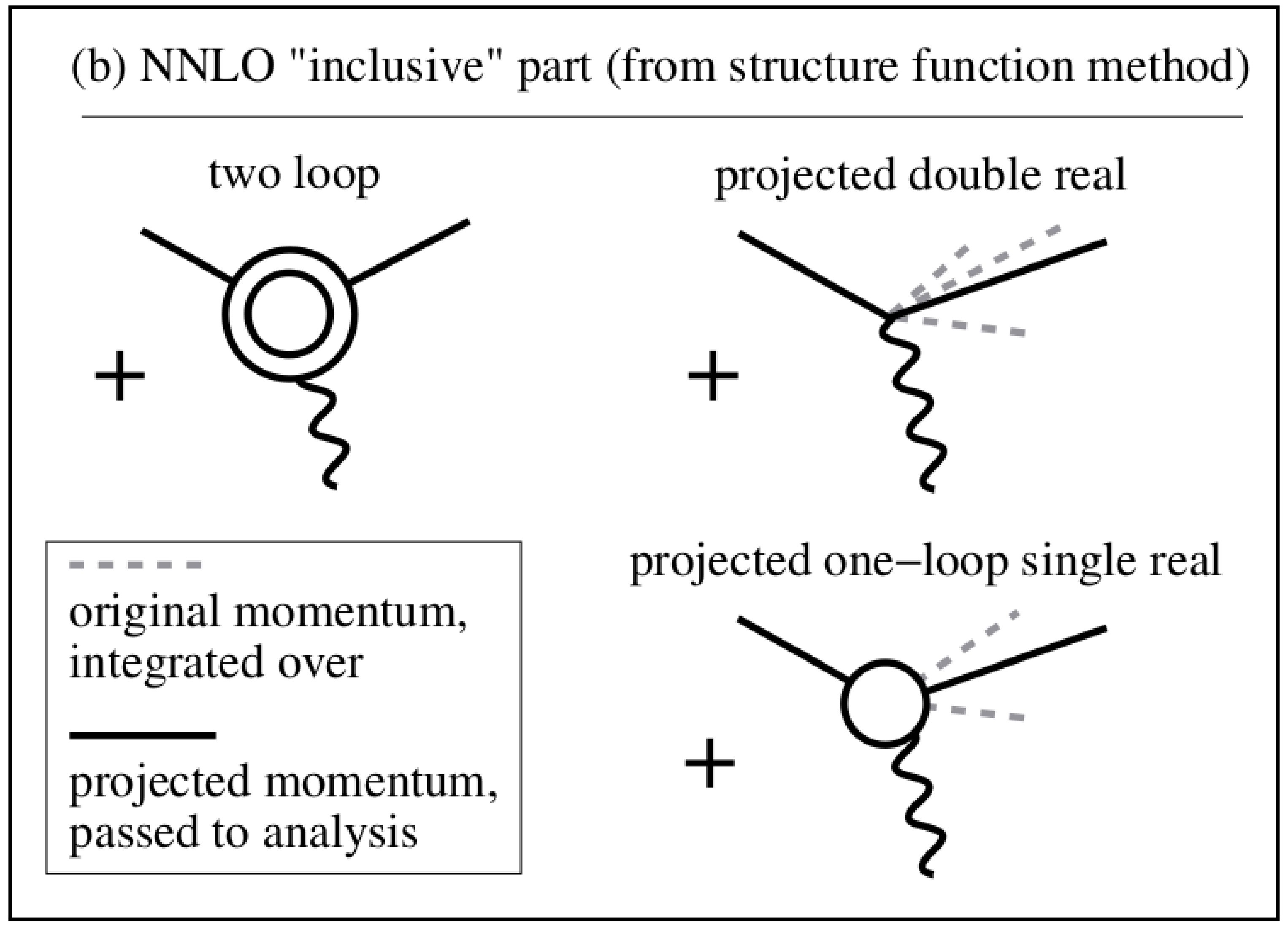
Beyond the Structure Function Approach

The calculation is based on two ingredients:

1. *An "inclusive" contribution*
   - use the Structure Function Approach and use four-vectors q_1, q_2 to assign Born-like kinematics using the equations below
   - use the projected Born-like momenta to compute differential distributions



$$p_{in,i} = x_i P_i$$

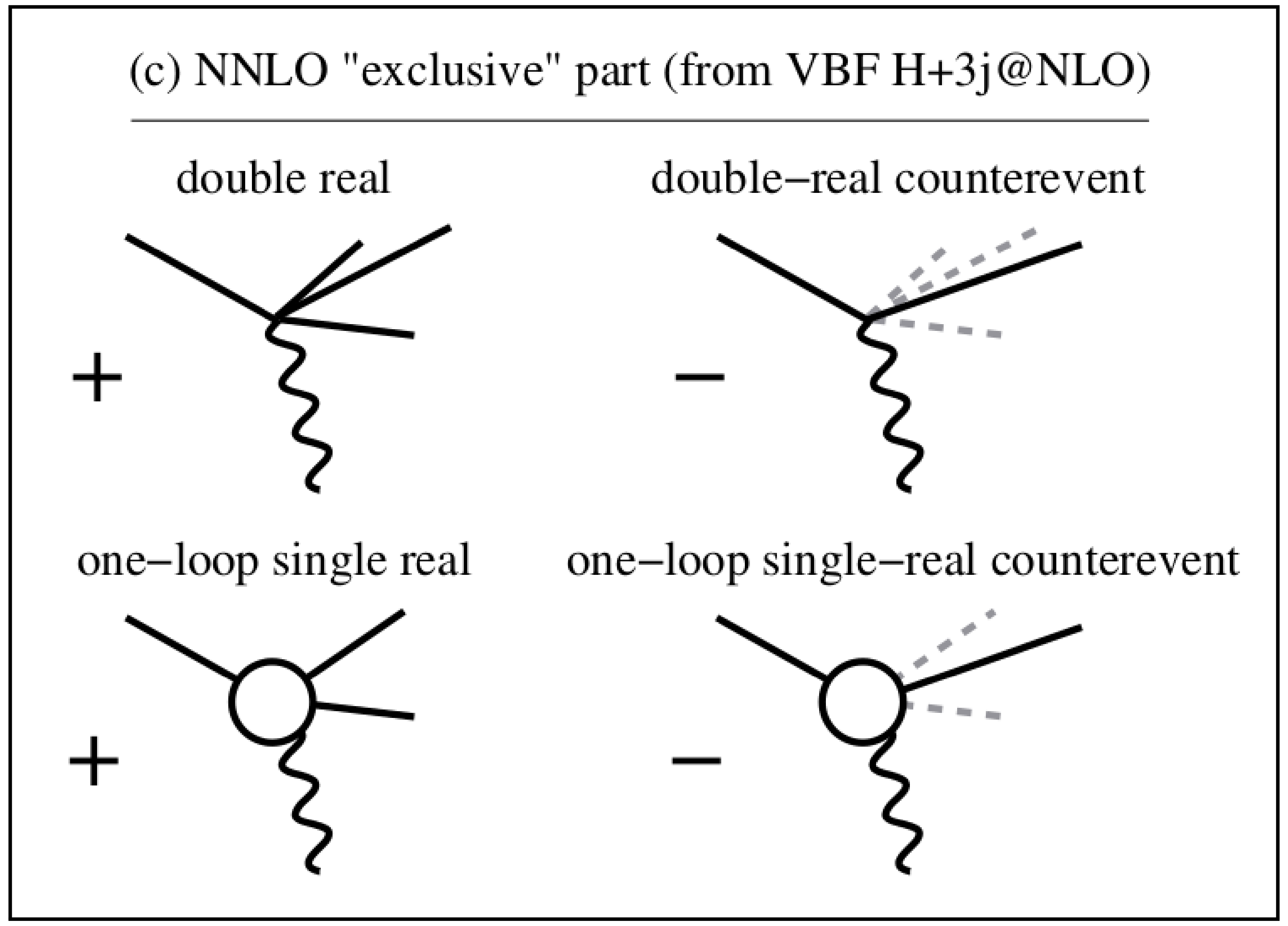
$$p_{out,i} = x_i P_i - q_i$$

$$x_i = \frac{q_i^2}{2 q_i P_i}$$

Beyond the Structure Function Approach

The calculation is based on two ingredients:

2. *An "exclusive" contribution*
   - use the electroweak $H+jjj$ NLO calculation in the factorized approximation [Figy et al. (2007)], [Jäger et al. (2014)]



- for each parton, keep track of whether it belongs to the upper or lower sector, and compute vector-boson momenta q_1, q_2
- for each event add counter-event with projected Born kinematics and opposite weight

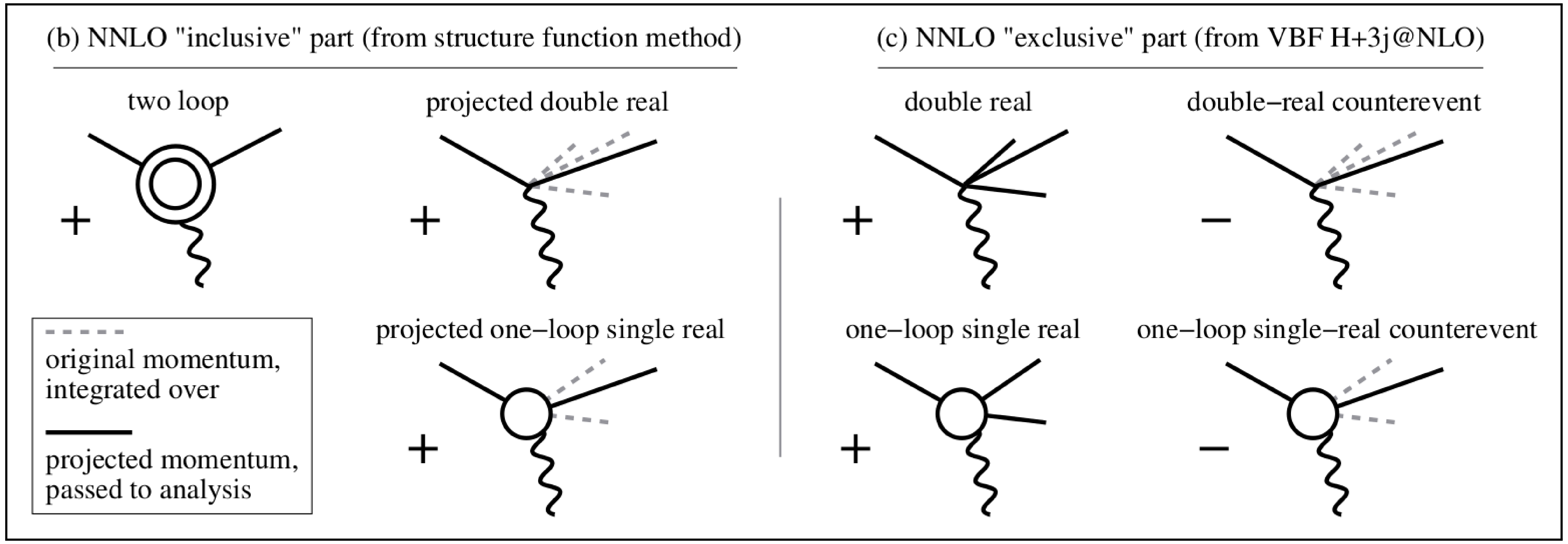
The counter-events cancel identically with the projected terms from the "inclusive" contribution.

Beyond the Structure Function Approach

Schematically we express the "projection-to-Born" (P2B) method as

$$\mathrm{d}\sigma = \int \mathrm{d}\Phi_B (B+V) + \int \mathrm{d}\Phi_R R$$

$$= \underbrace{\int \mathrm{d}\Phi_B (B+V) + \int \mathrm{d}\Phi_R R_{P2B}}_{\text{“inclusive” contribution}} + \underbrace{\int \mathrm{d}\Phi_R R - \int \mathrm{d}\Phi_R R_{P2B}}_{\text{“exclusive” contribution}}$$



Phenomenology

We study 13 TeV LHC collisions with $M_H = 125$ GeV and NNPDF3.0_nnlo_as118. We use the following VBF cuts:

- Jets defined with anti-k_t, $R = 0.4$ and $p_t > 25$ GeV
- Two hardest jets within $|y| < 4.5$
- High dijet invariant mass, $M_{j_1 j_2} > 600$ GeV, and separation, $\Delta y_{j_1 j_2} > 4.5$
- Hardest jets in opposite hemispheres, $y_{j_1} y_{j_2} < 0$

We choose a central scale which approximates well $\sqrt{Q_1 Q_2}$ and symmetrically vary by a factor 2 up and down

$$\mu_0^2(p_{t,H}) = \frac{M_H}{2}\sqrt{\left(\frac{M_H}{2}\right)^2 + p_{t,H}^2}$$

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JETS

THE JET IN Z+JET @ NNLO

Boughezal, Liu & Petriello, 1602.08140

1-jet cross sections

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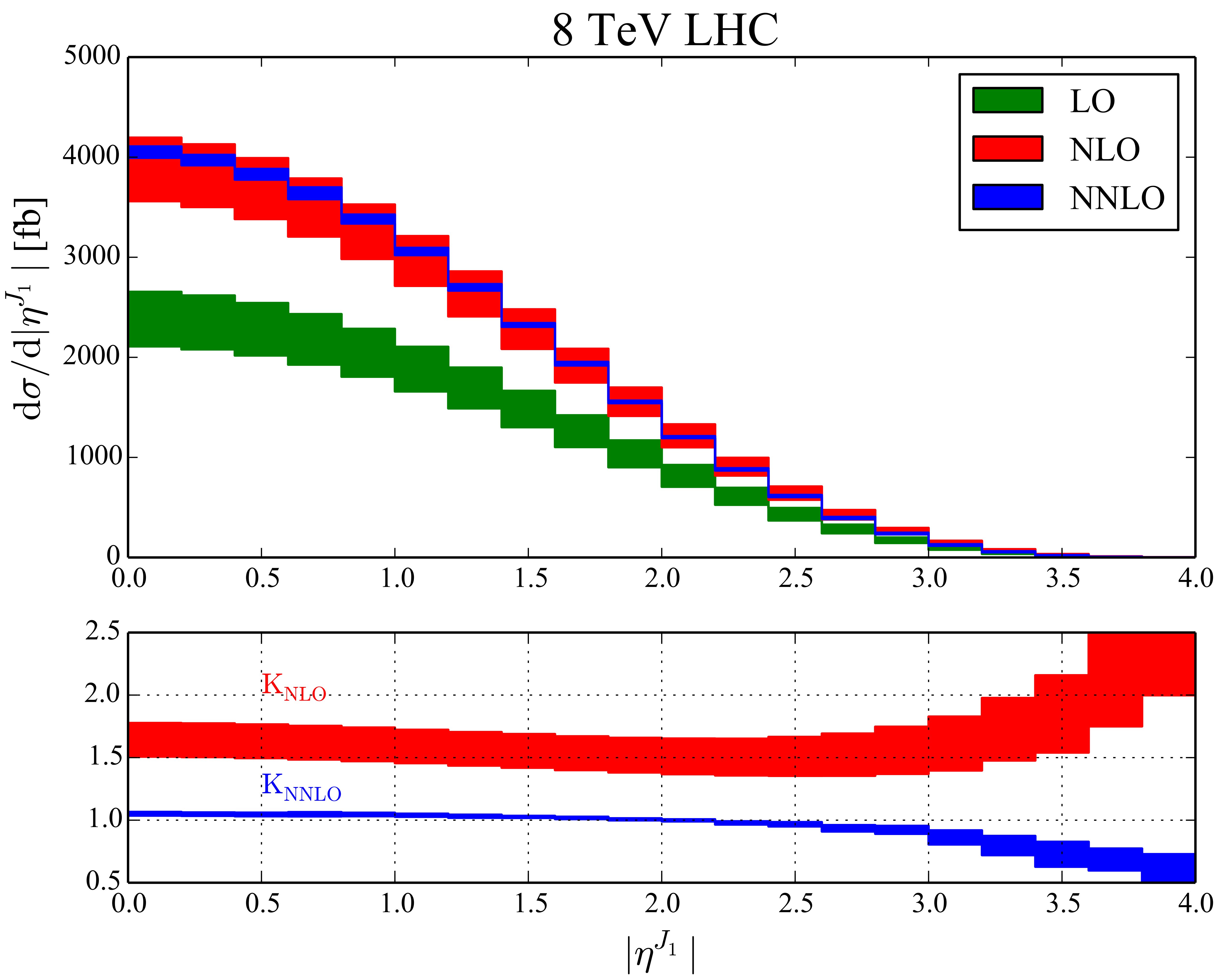

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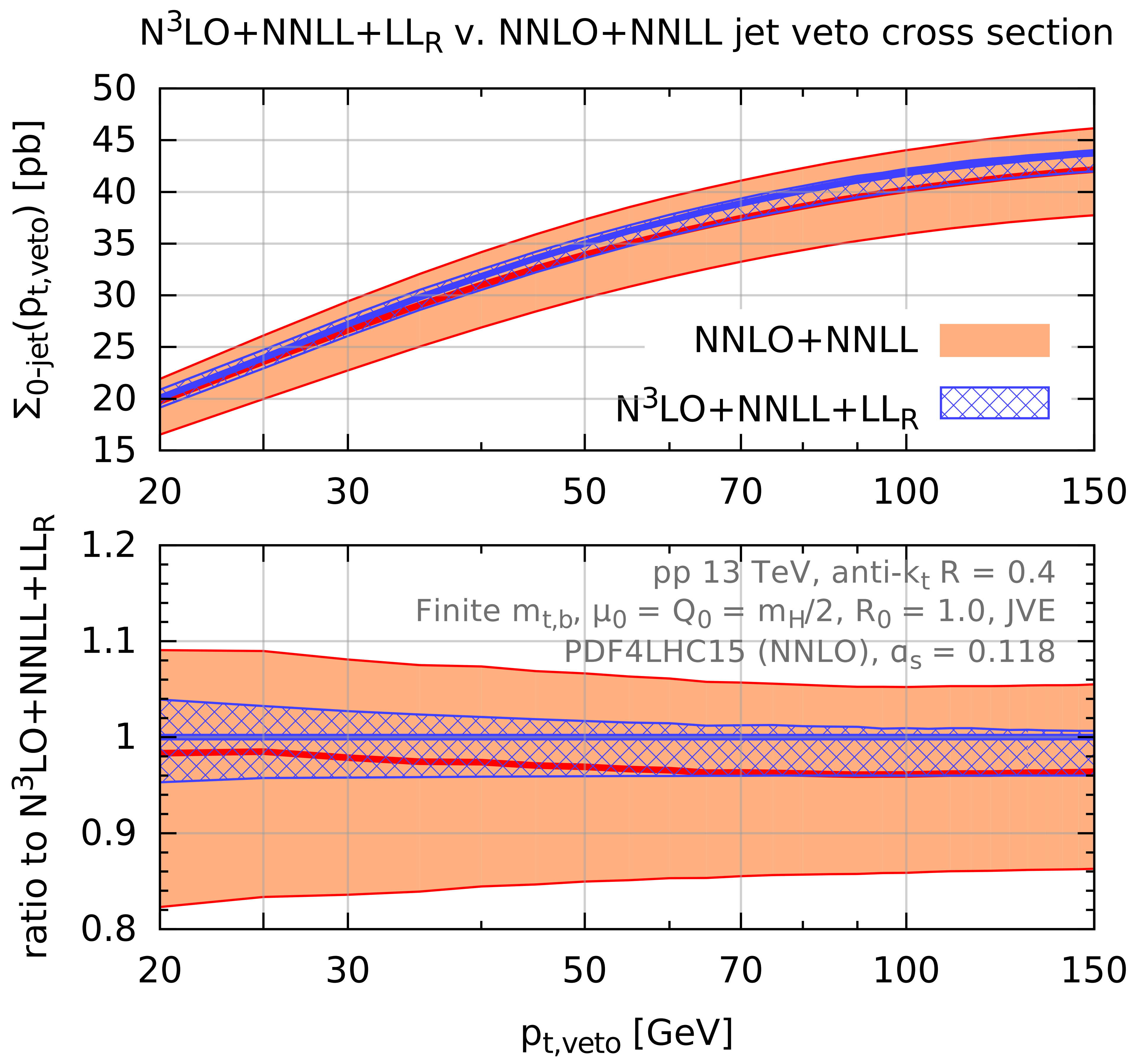

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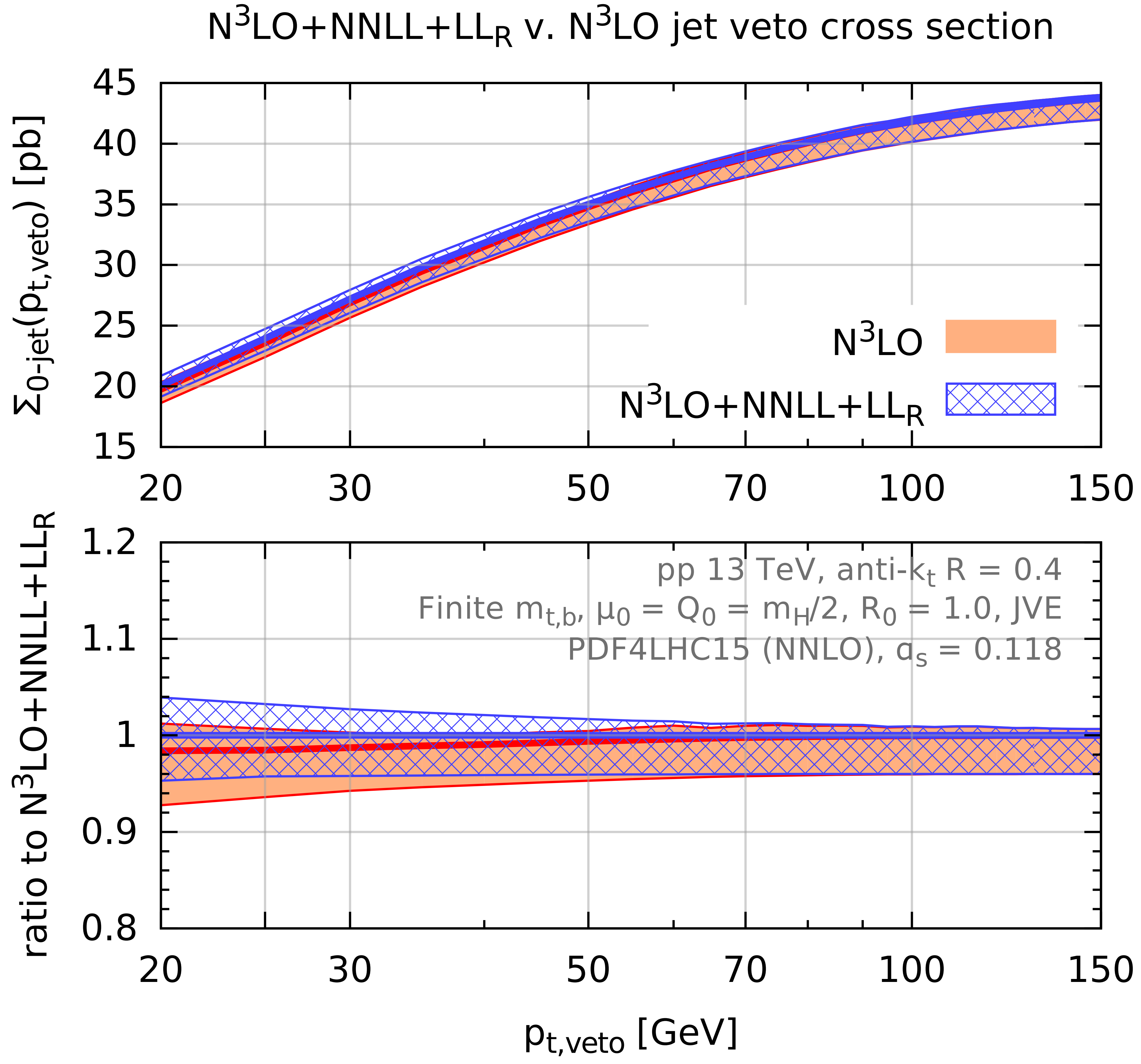
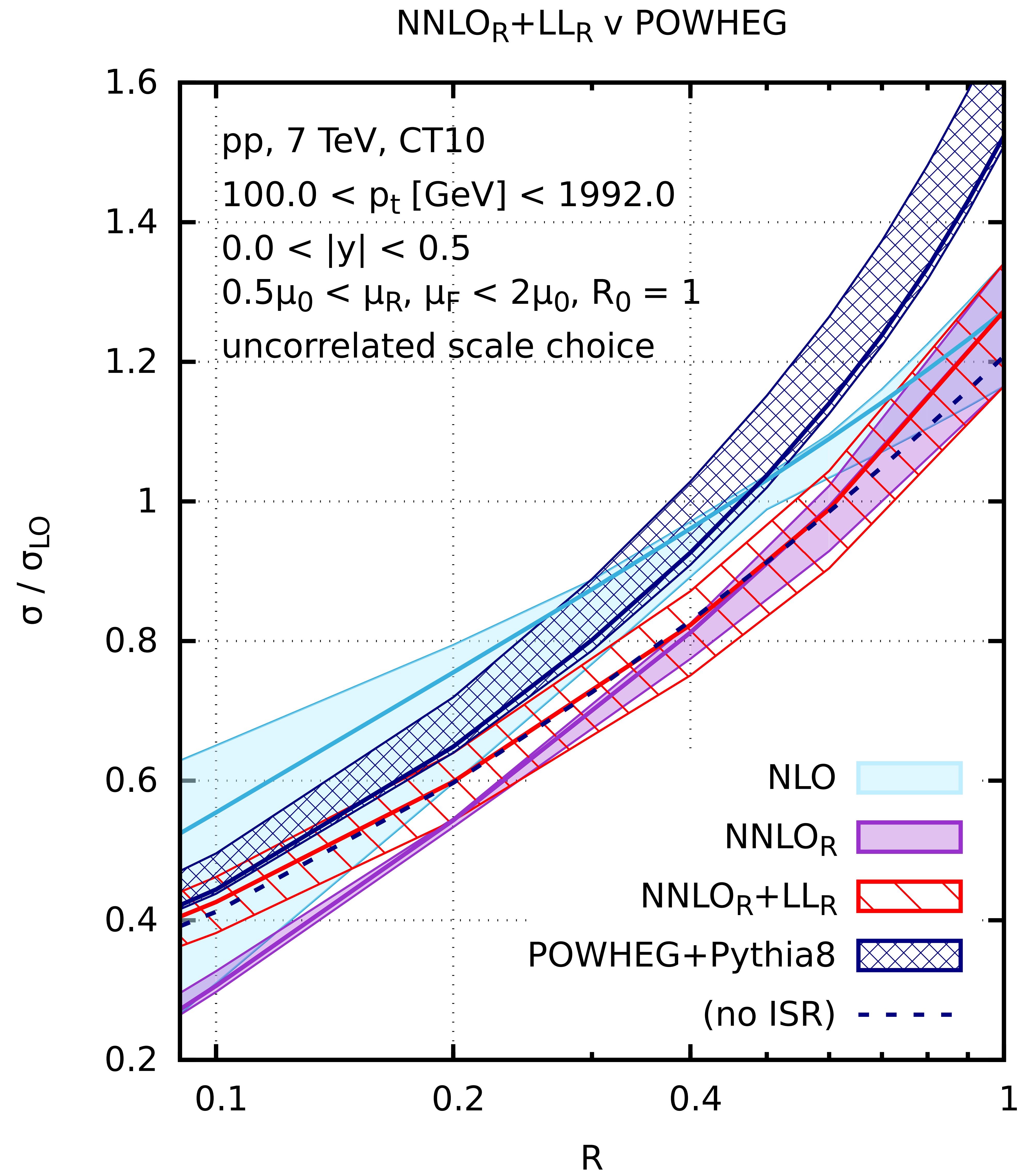


- N3LO effects at 2–4%
- Residual uncertainty up to 4% (fairly conservative)
- rather stable (~2%) wrt jet-p_T resummation effects

NNLO_R & small-R resummation

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

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



$NNLO_R$ & small-R resummation

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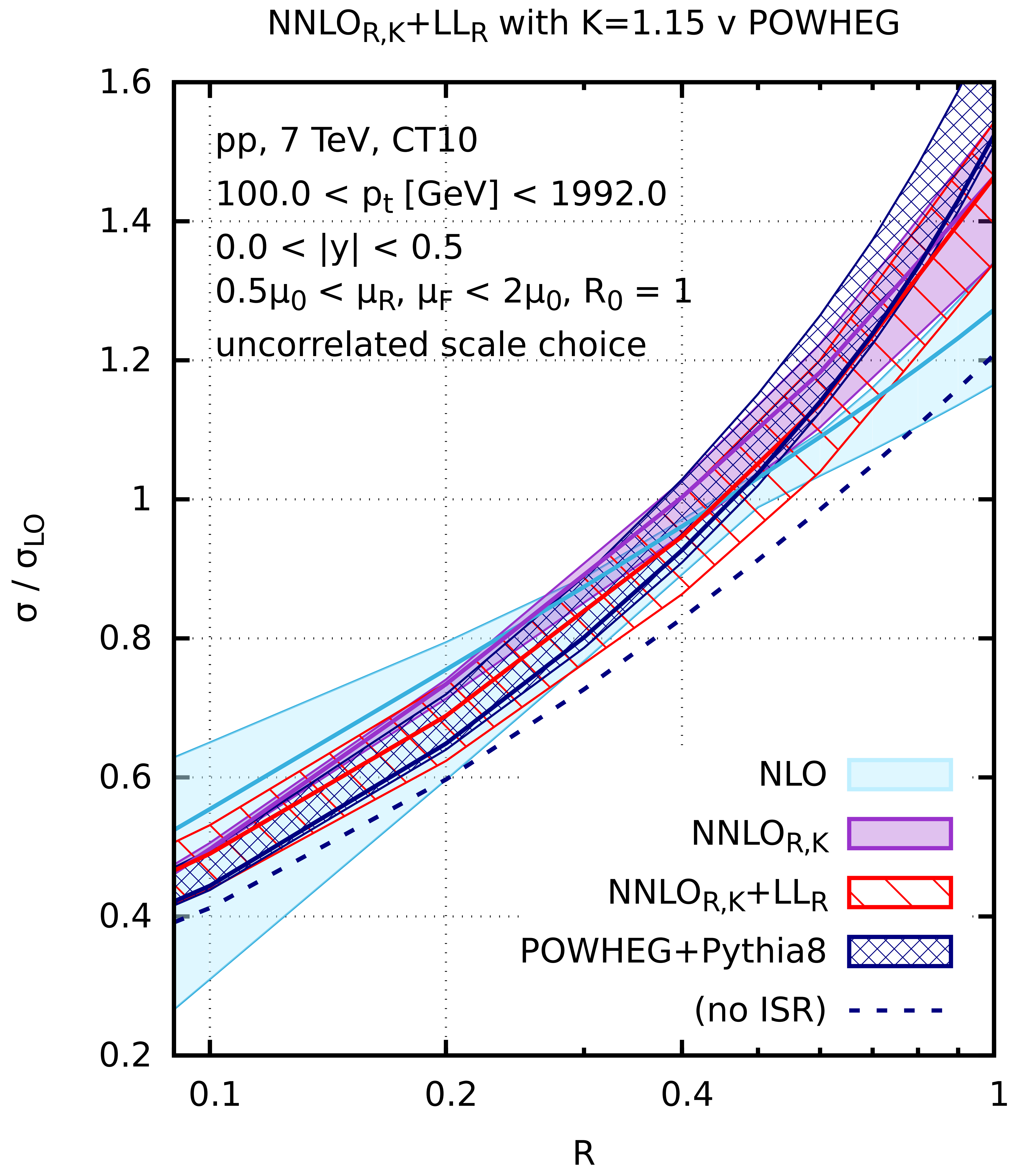

SMALL-R APPROX.

NLL SMALL-R TERMS