STATUS AND OUTLOOK ON QCD PREDICTIONS

ICHEP 2022, Bologna

13 July 2022

Gavin Salam

Rudolf Peierls Centre for Theoretical Physics &

All Souls College, University of Oxford

European Research Council
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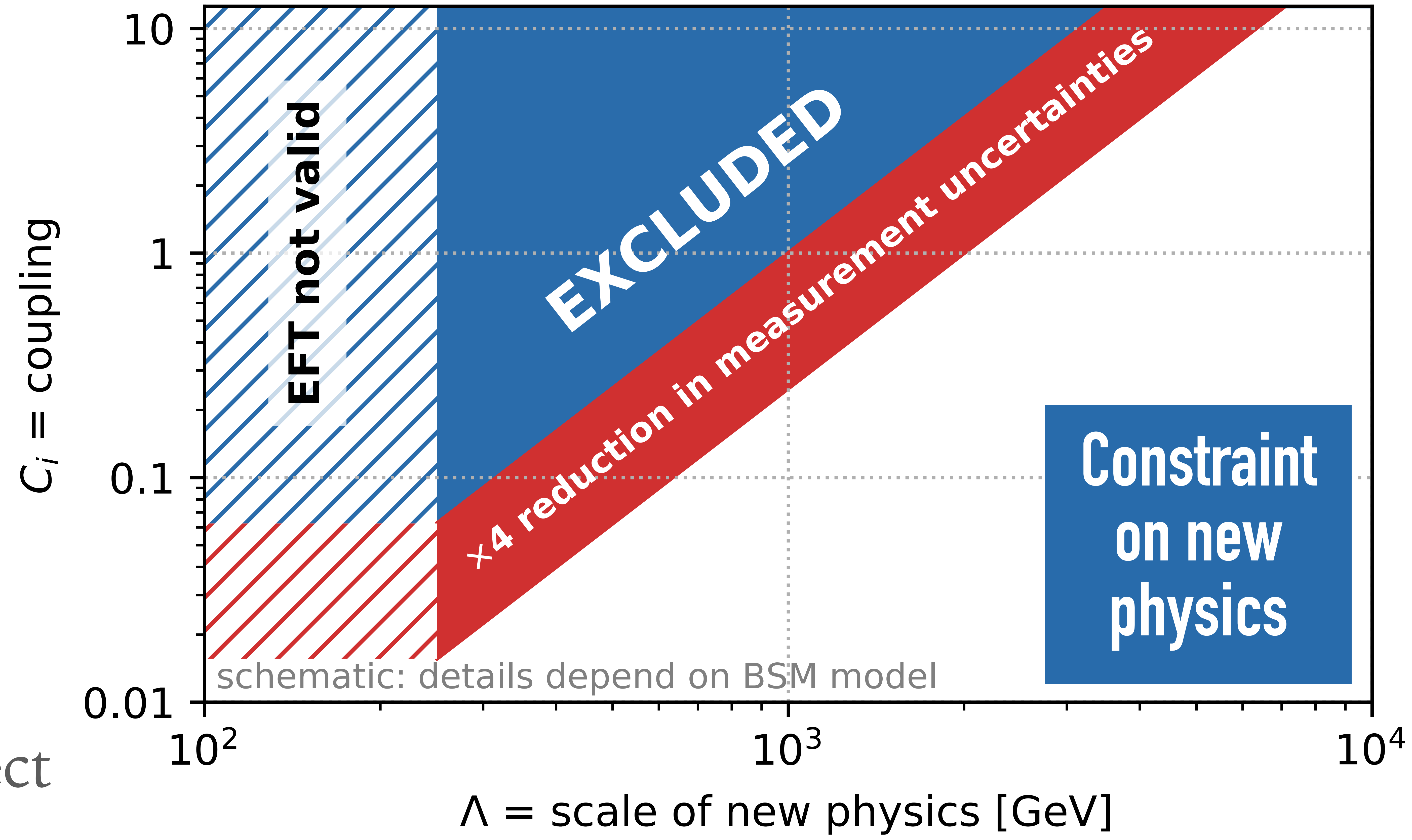
What are we aiming to achieve?

- We're trying to hone our understanding of strong interactions for its own sake
- We're trying to establish a new sector of the standard Model (Higgs)
- And we're trying to maximise sensitivity to new physics in precision measurements and direct searches



Fact II:

The SM cannot be the ultimate theory!

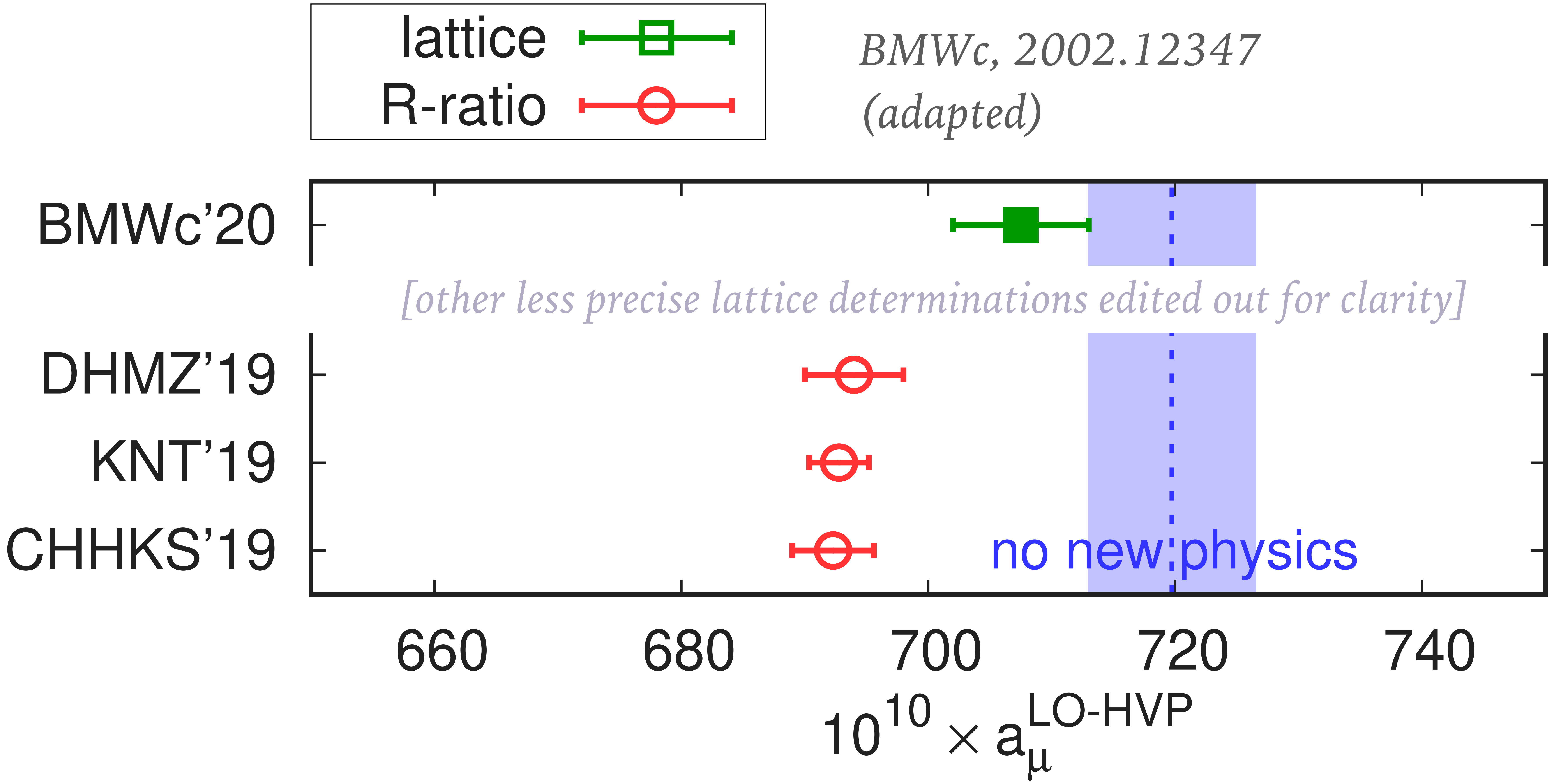
7. anomalous magnetic moment of the muon shows a $\sim 4\,\sigma$ discrepancy

Sven Heinemeyer, ICHEP 2022, Bologna, 12.07.2022 [adapted] 4

g_μ–2

the puzzle evolves

$g_\mu-2$: largest theory uncertainty is "HVP"



BMWc, 2002.12347 (adapted)

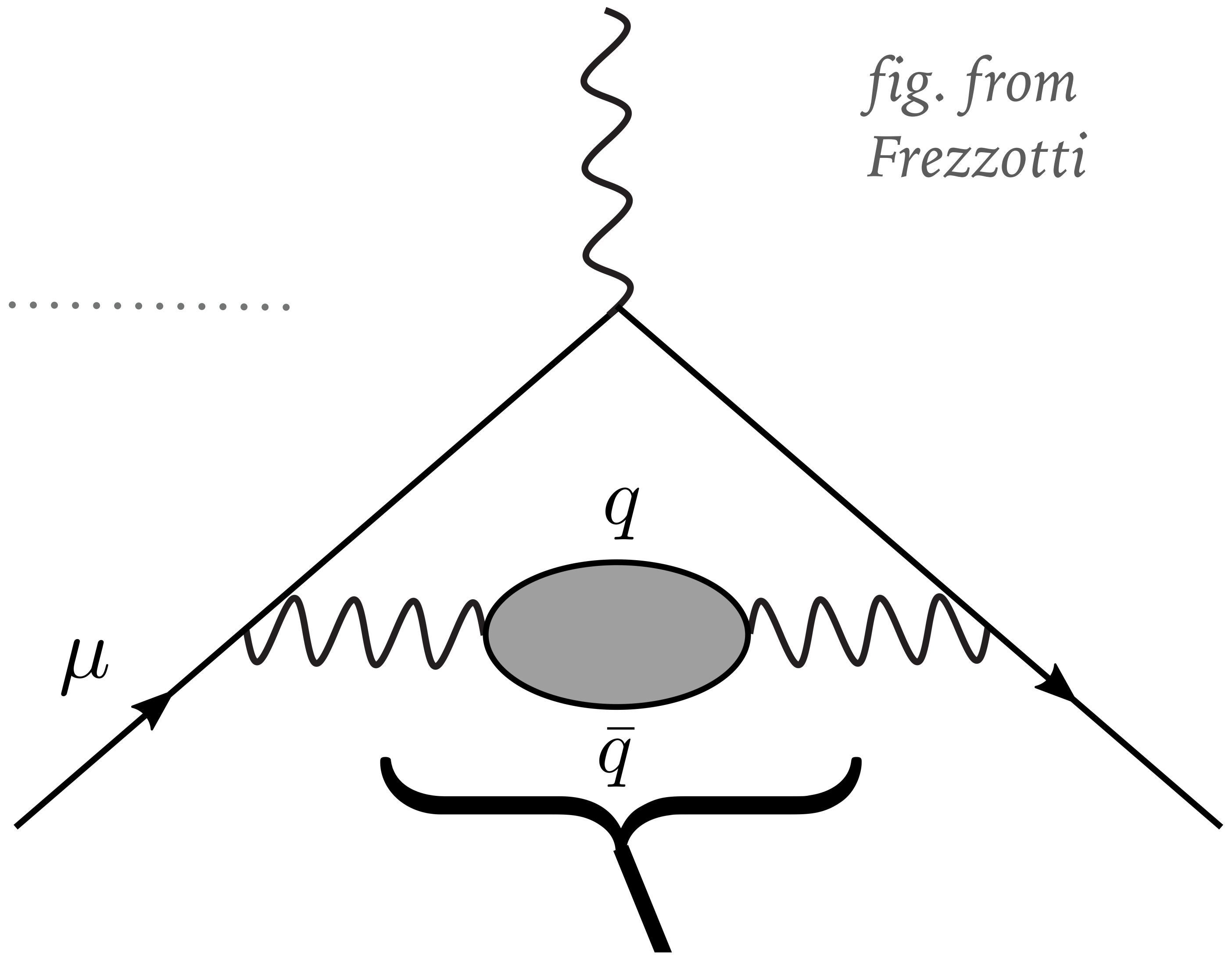
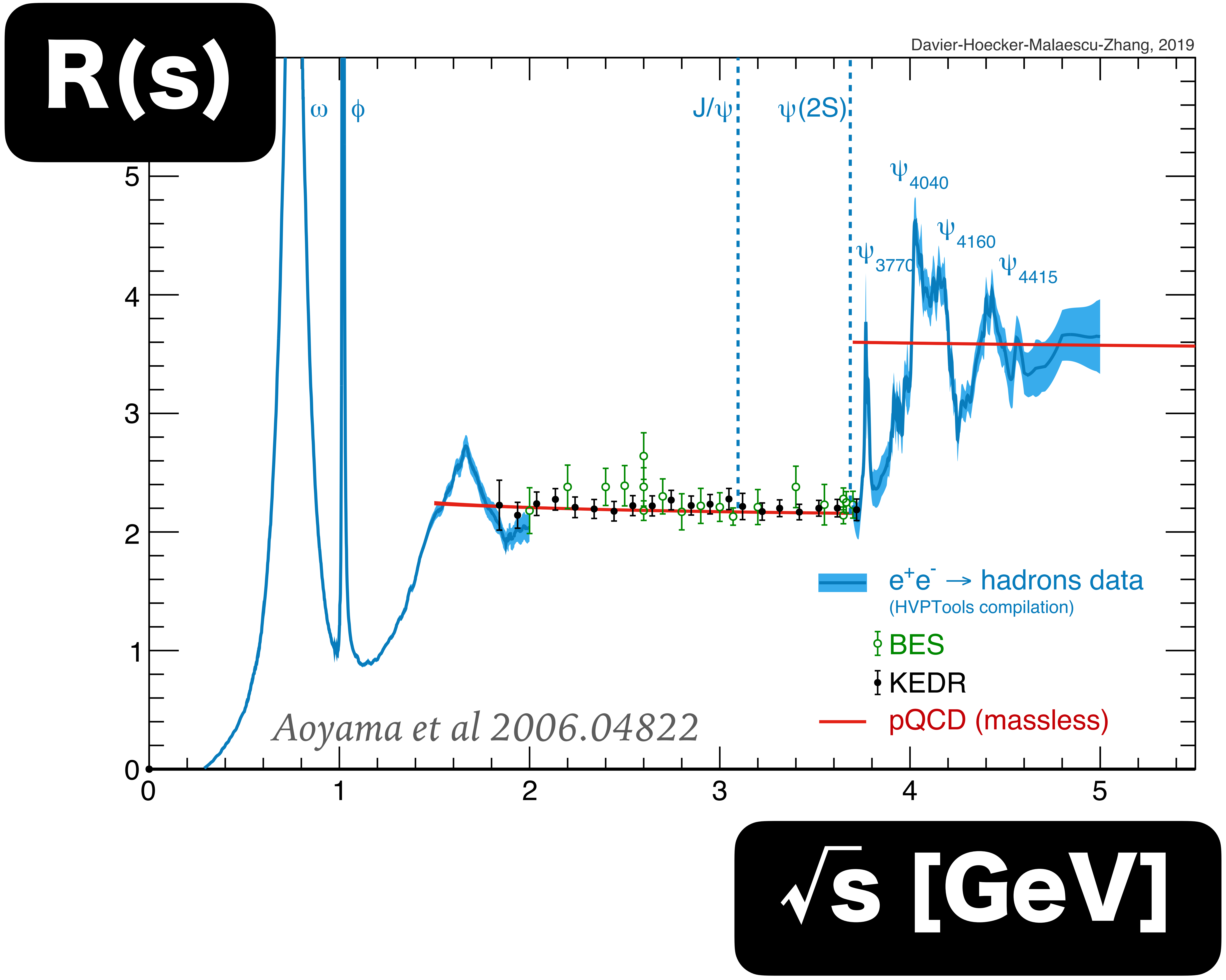


fig. from Frezzotti

Hadronic Vacuum Polarisation (HVP)

R-ratio method: re-interpret s-channel e+e− → hadrons data



$$a_\mu^{\mathrm{HVP,LO}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} \frac{\hat{K}(s)}{s^2} R(s)\, \mathrm{d}s$$

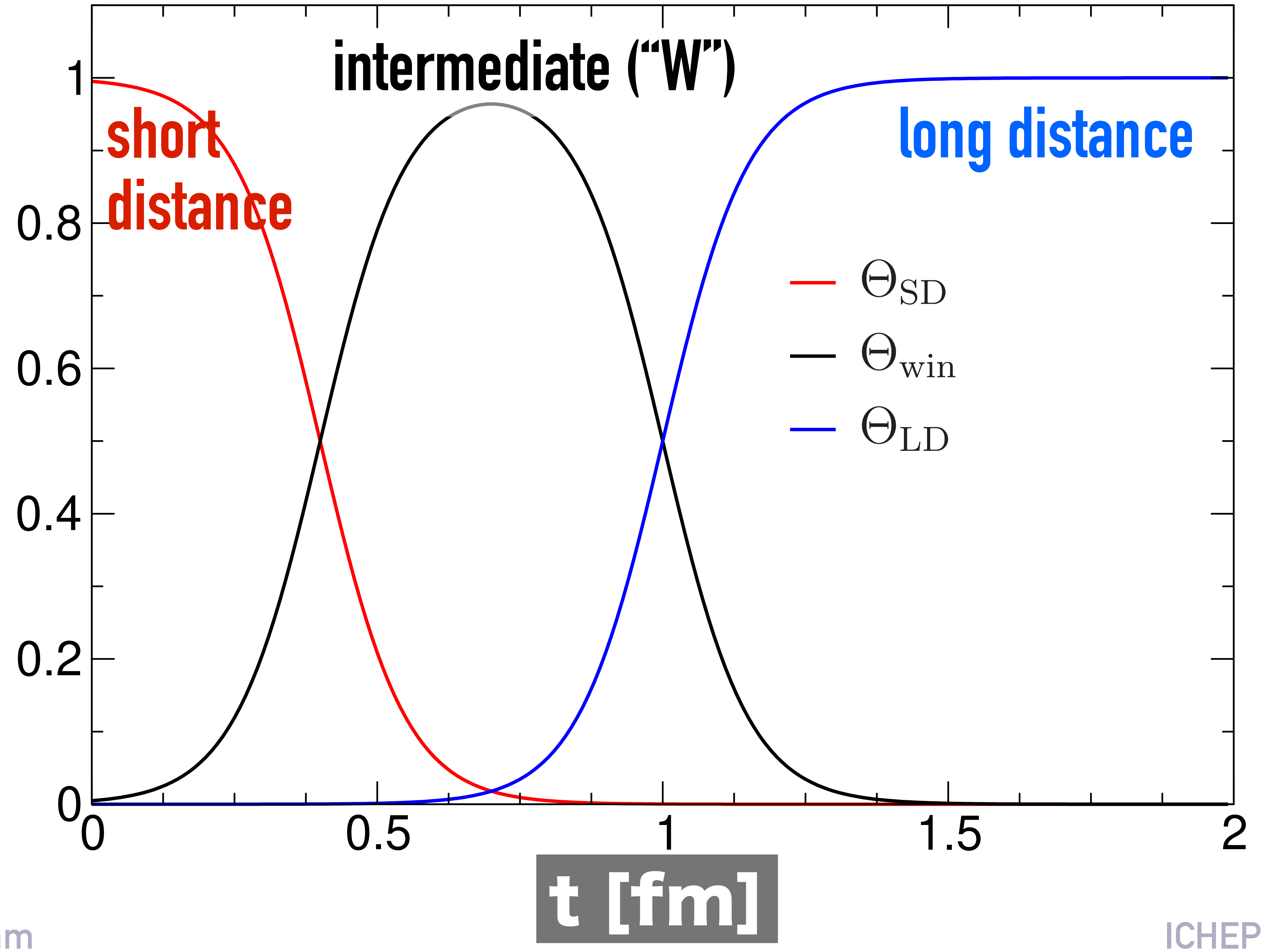
$$\hat{K}(4m_\pi^2) \approx 0.63, \qquad \lim_{s\to\infty} \hat{K}(s) = 1$$

from Marco Cè@ICHEP

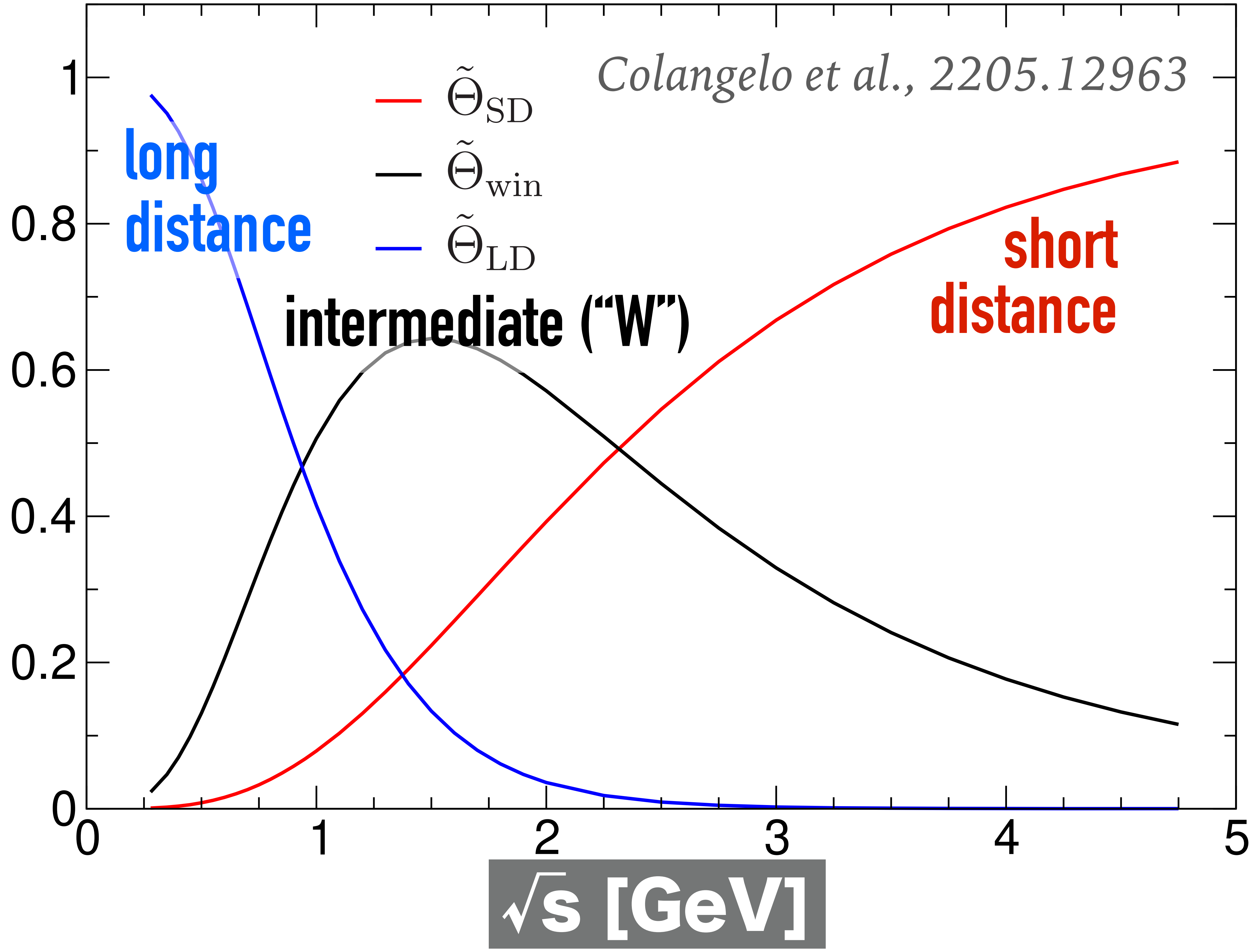
2022 news: lattice & R-ratio results in time/energy **windows**

Covering whole region at high precision is challenging for lattice calculations
→ but individual time/energy regions are more accessible

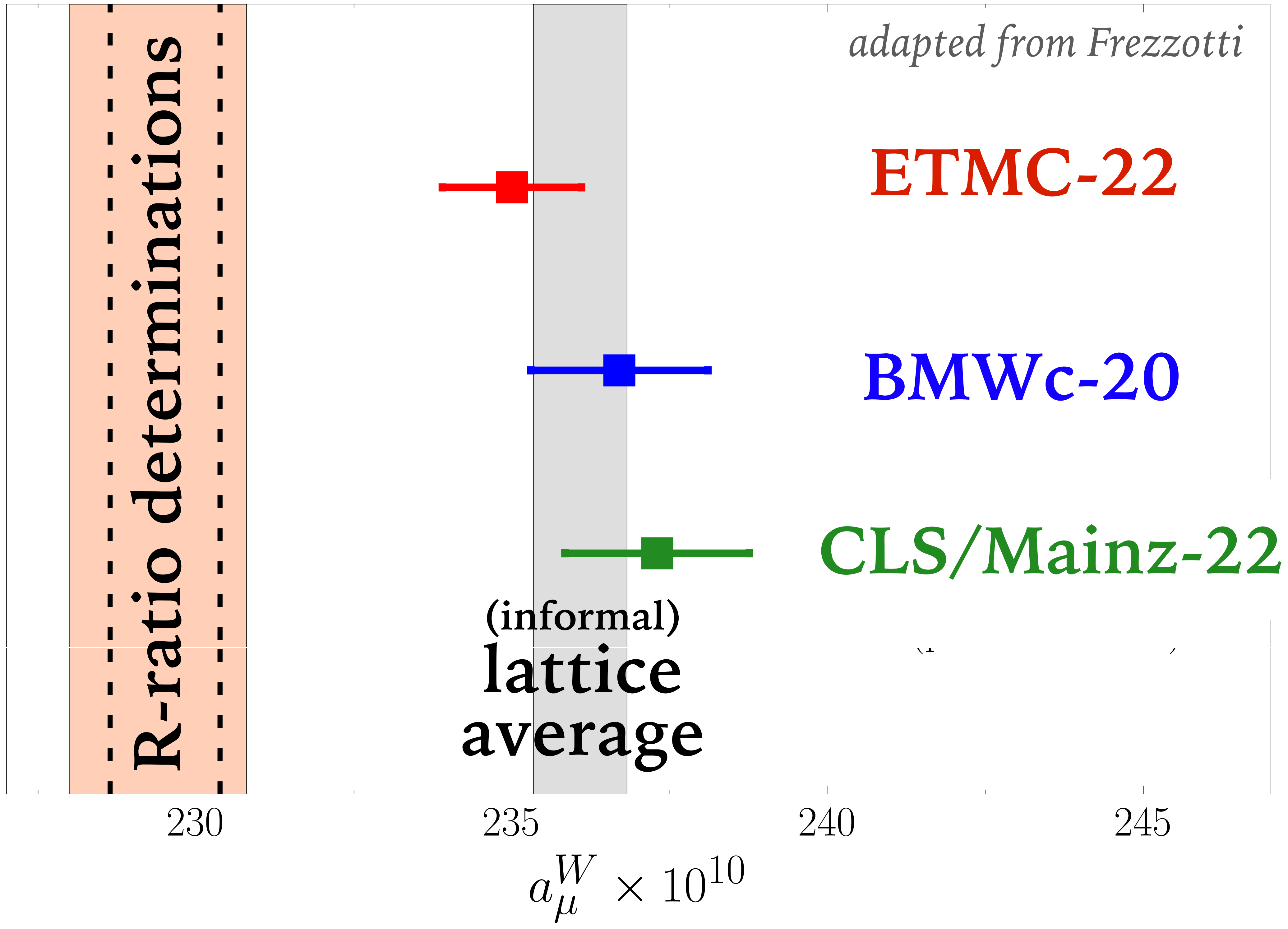
lattice: time windows



R-ratio: energy windows



intermediate window: 2 new lattice results (ETMC-22 & CLS/Mainz-22)



- Highest precision lattice results mutually consistent (more to come soon)
- Difference in this window alone (~7) not enough to explain g_μ-2 (~25), but enhances credibility of full BMWc-20 result
- Tension between lattice & e^+e^- data clearly needs to be understood

- strong tension with a_μ^W (HVP-LO) results driven by experimental e^+e^- data :

  at $\sim 4.2\sigma_{combined}$ if WP-proc.('22) (2205.12963, Colangelo et al.), see *light-red band*, is used

  at $\sim 5.8\sigma_{combined}$ if KNT('19-'22) (1911.00367 + private comm.), see *dashed lines*, is used

a_μ^{HVP} window observables: SM (lattice) vs. experiment (R^{had})

SM predictions from lattice QCD + QED (col. 2,3,4) against R^{had} data driven results (col. 5, 6)

latt. "aver." $\leftrightarrow$ our average of the "independent" results from ETMC-22, CLS-22 and BMW-20

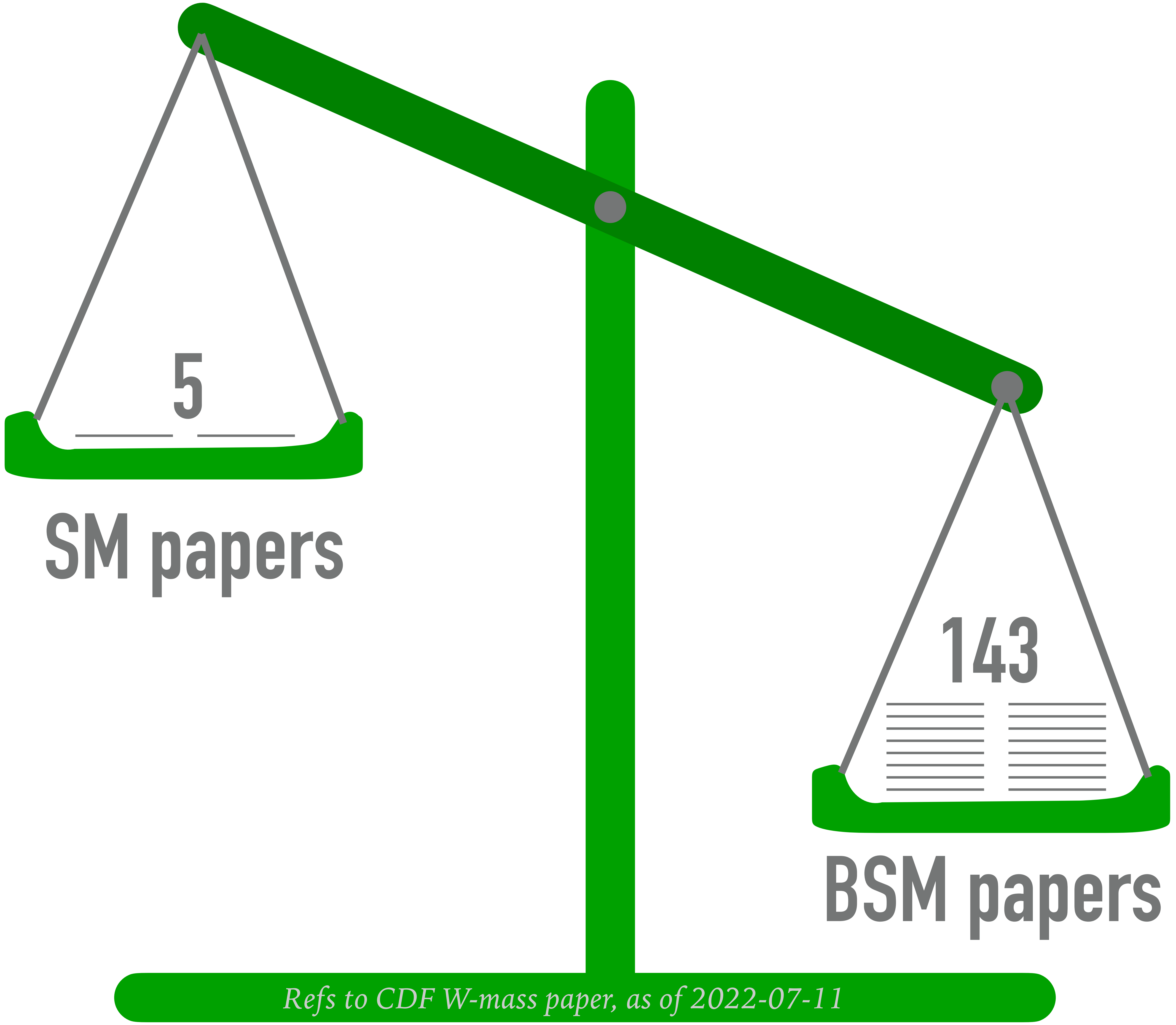
WP-proc.('22) $\leftrightarrow$ 2205.12963 (Colangelo et al.) with merging procedure of 2006.04822 (WP)

KNT('19-'22) $\leftrightarrow$ Keshavarzi, Nomura, Teubner: 1911.00367 + private communication (2022)

obs.(HVP-LO)	ETMC-22	BMW-20	latt. "aver."	WP-proc.('22)	KNT('19-'22)
a) $a_\mu^{\mathrm{SD}}\,10^{10}$	69.33(29)	–	–	68.4(5)	*68.44(48)*
b) $a_\mu^{\mathrm{W}}\,10^{10}$	235.0(1.1)	236.7(1.4)	236.08(74)	229.4(1.4)	*229.51(87)*
c) $a_\mu^{\mathrm{HVP}}\,10^{10}$	–	707.5(5.5)	–	693.0(3.9)	*692.78(2.42)*

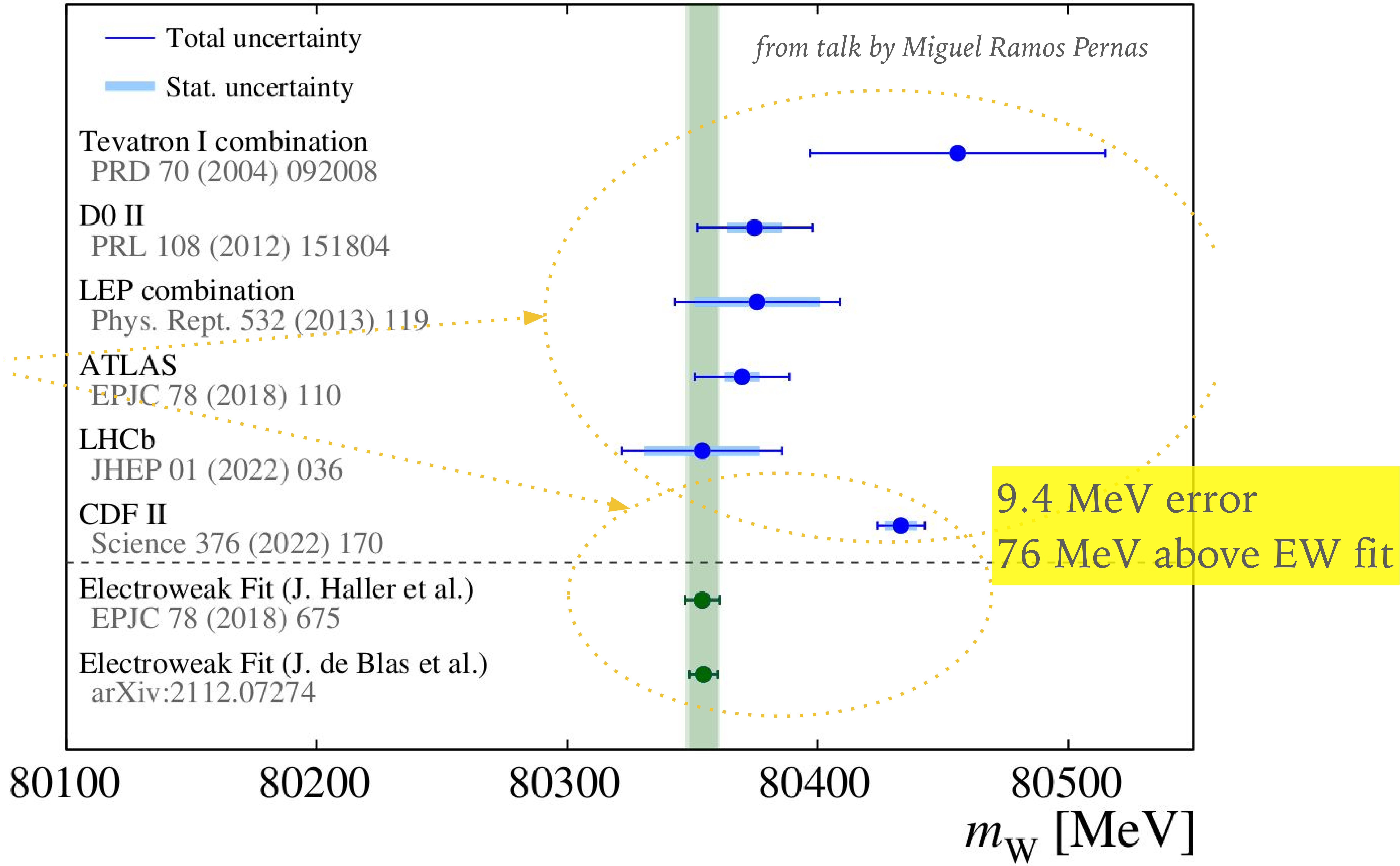
stop press: 2207.04765 Fermilab Lattice/HPQCD/MILC also consistent with ETMC-22 SD+W

W mass

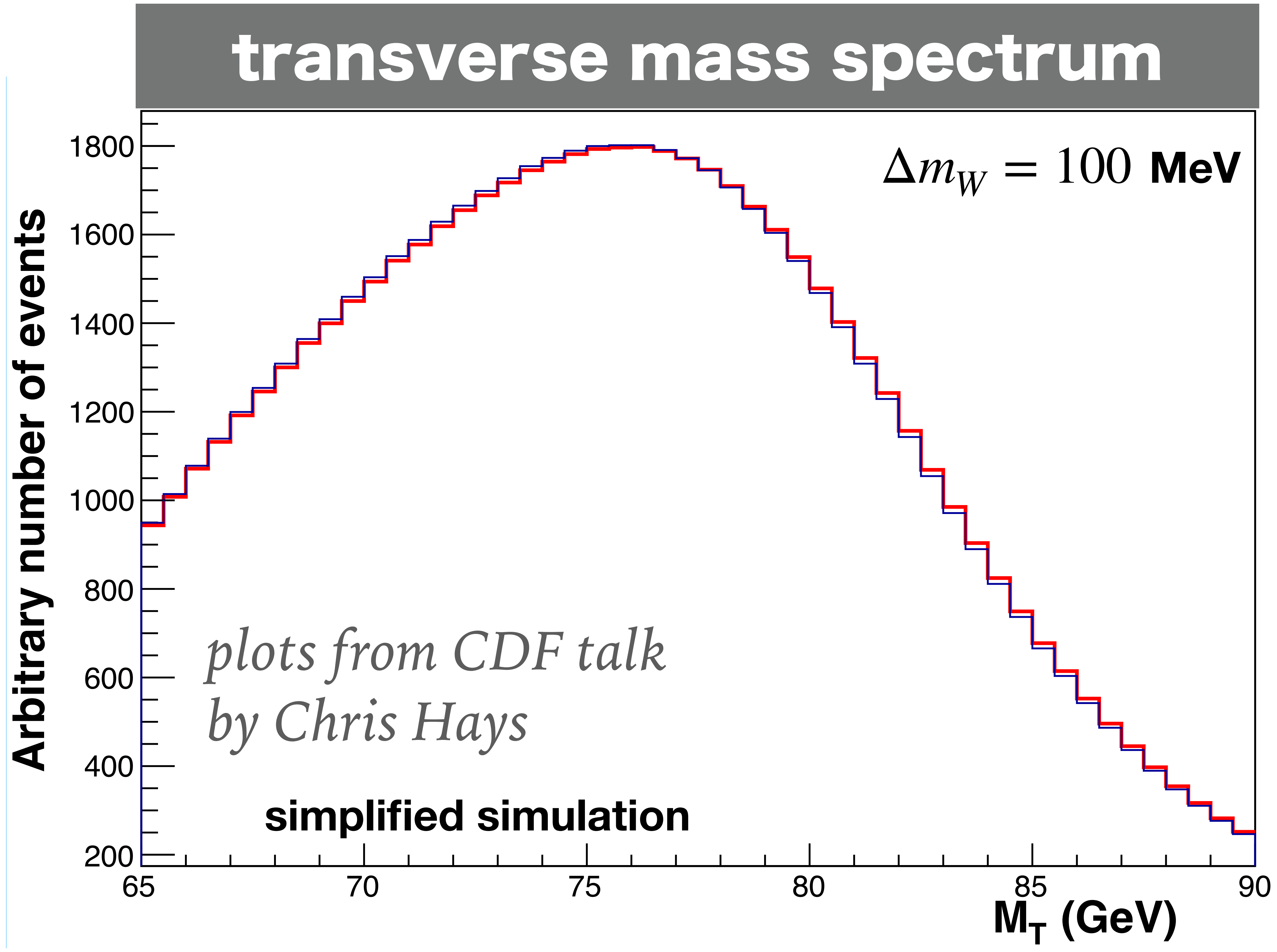


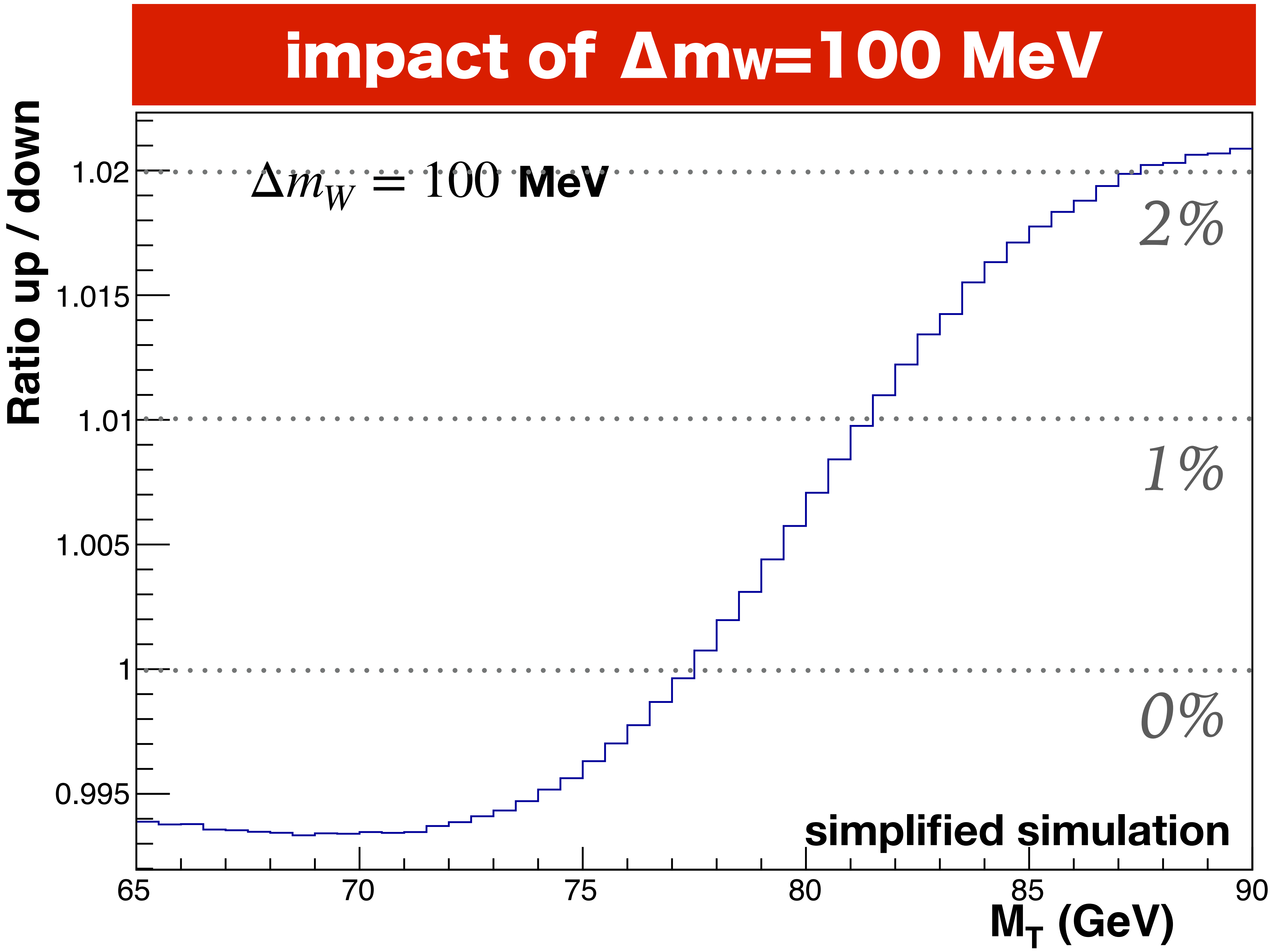
5
SM papers
143
BSM papers
Refs to CDF W-mass paper, as of 2022-07-11

[LHCB-FIGURE-2022-003]



Δm_W of 100 MeV → 0.5 – 2% change in spectrum

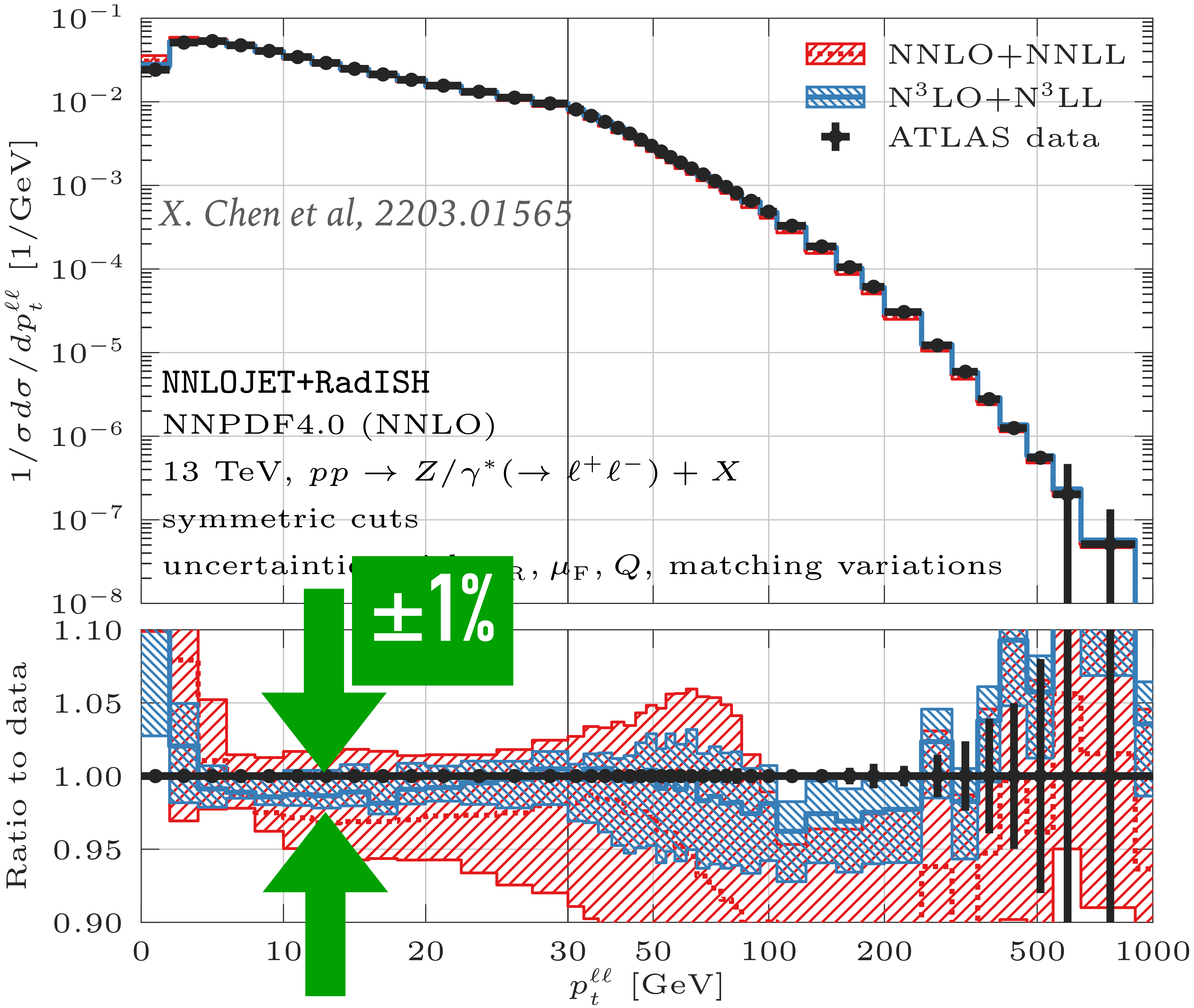




10 MeV precision requires ~0.1% control on kinematic distributions

Best QCD predictions (N3LL + N3LO) for W/Z processes reach ~ 1%

- naively that would translate to 50-200 MeV on m_W
- instead actual experimental analyses exploit (assumptions about?) similarity between W & Z distributions
- requires deep understanding of small differences between W & Z-boson production



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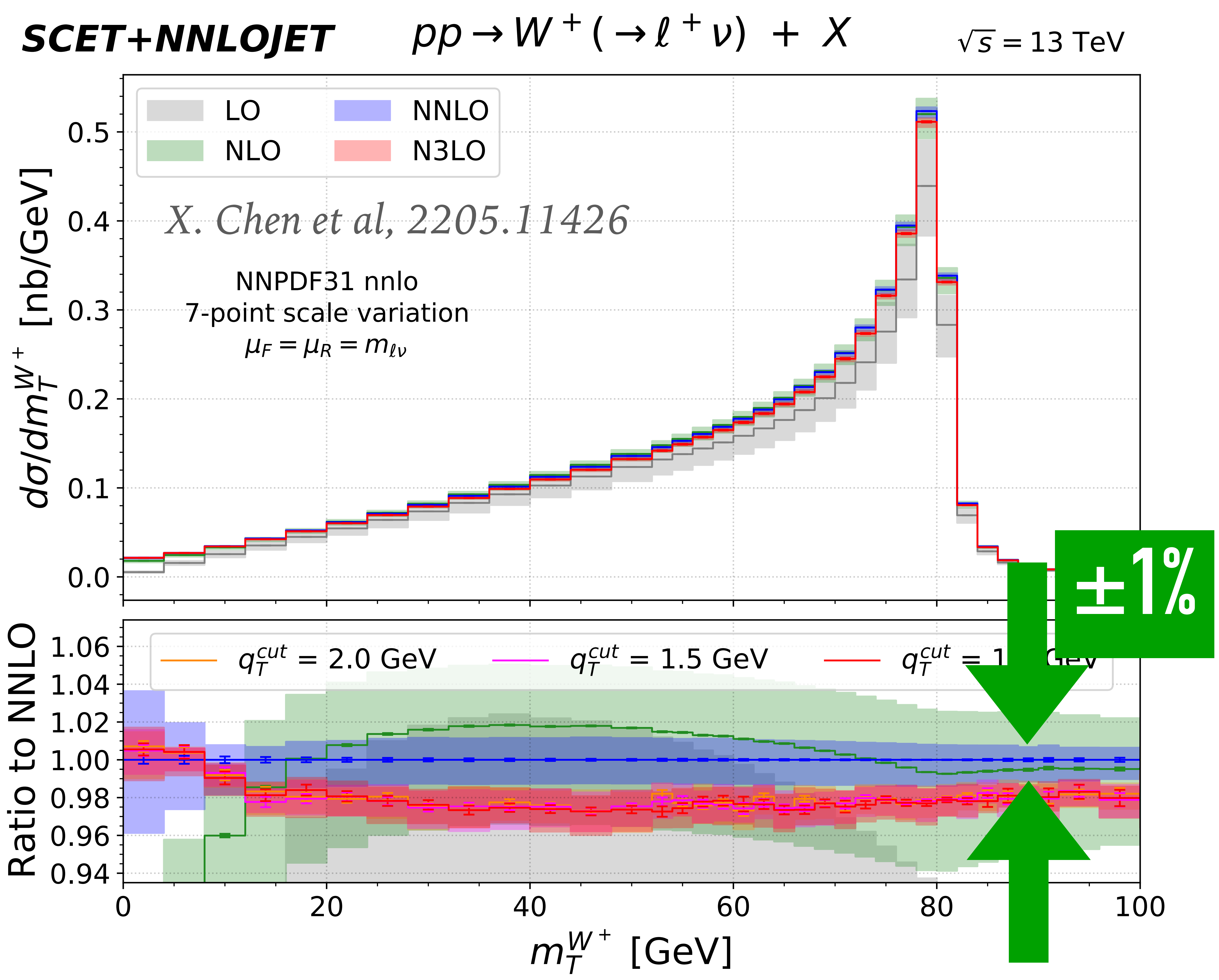


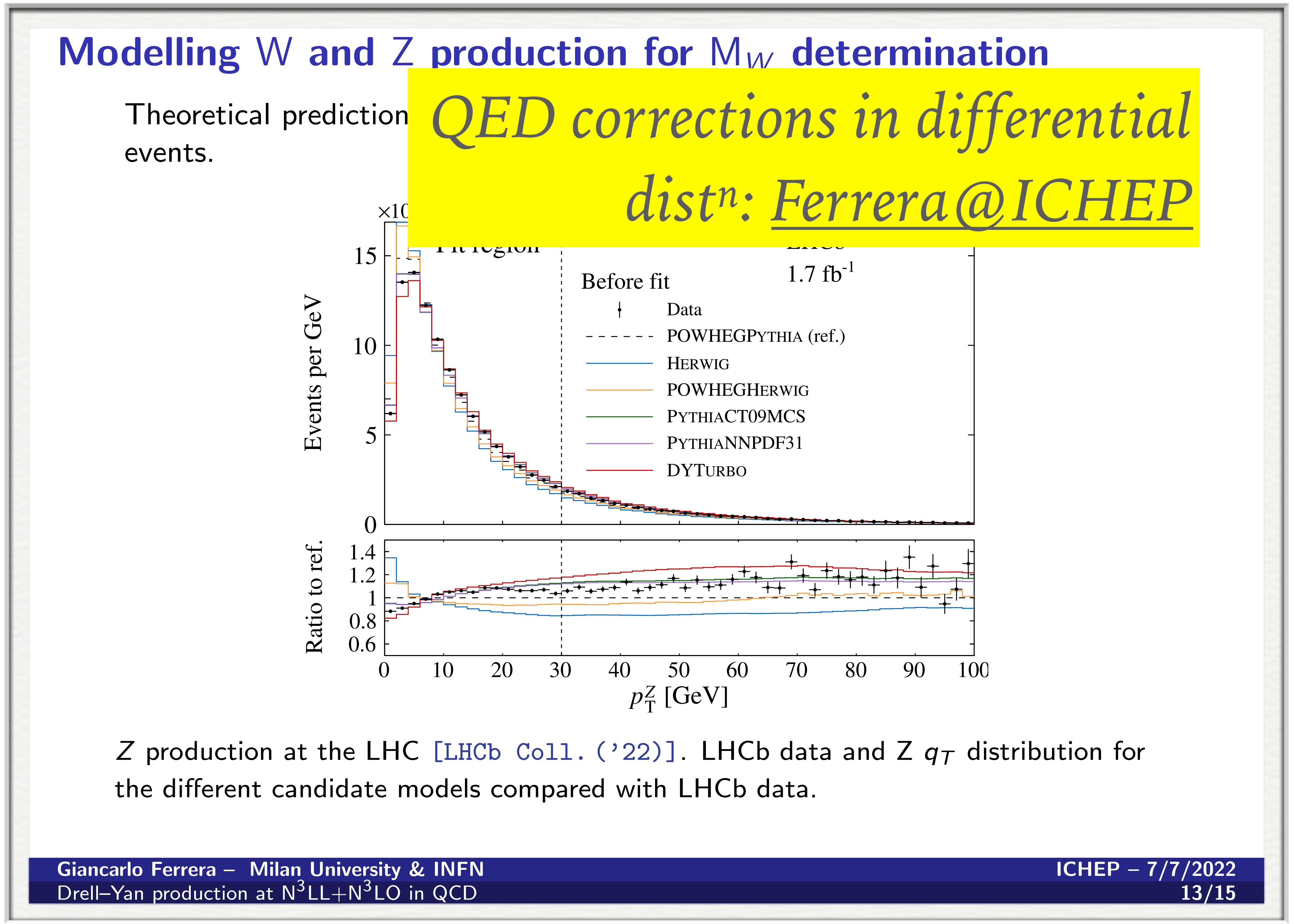
Studies specific to CDF analysis: no signs of obvious big trouble

δM_W in MeV	sta.	NNPDF3.1	CT18	MMHT14	NNPDF4.0	MSHT20
$\langle M_T \rangle$(LO)	–	$0^{+8.3}_{-8.3}$	$-1.0^{+8.3}_{-11.4}$	$-3.3^{+7.4}_{-4.2}$	$+7.8^{+5.1}_{-5.1}$	$-3.1^{+6.7}_{-5.7}$
χ^2 fit (LO)	8.0	$0^{+7.6}_{-7.6}$	$-1.0^{+5.4}_{-8.6}$	$-3.3^{+6.1}_{-3.0}$	$+8.0^{+3.7}_{-3.7}$	$-3.0^{+5.0}_{-4.0}$
$\langle M_T \rangle$(NLO)	–	$0^{+5.9}_{-5.9}$	$-4.2^{+8.8}_{-13.3}$	$-5.0^{+6.7}_{-5.3}$	$+6.9^{+6.2}_{-6.2}$	$-7.6^{+7.9}_{-6.7}$
χ^2 fit (NLO)	8.0	$0^{+4.2}_{-4.2}$	$-4.3^{+5.4}_{-10.1}$	$-5.1^{+4.8}_{-3.4}$	$+7.1^{+4.5}_{-4.5}$	$-7.8^{+5.7}_{-4.5}$
CDF	9.2	$0^{+3.9}_{-3.9}$	–	–	–	–

Impact of PDFs: Gao, Liu & Xie, 2205.03942

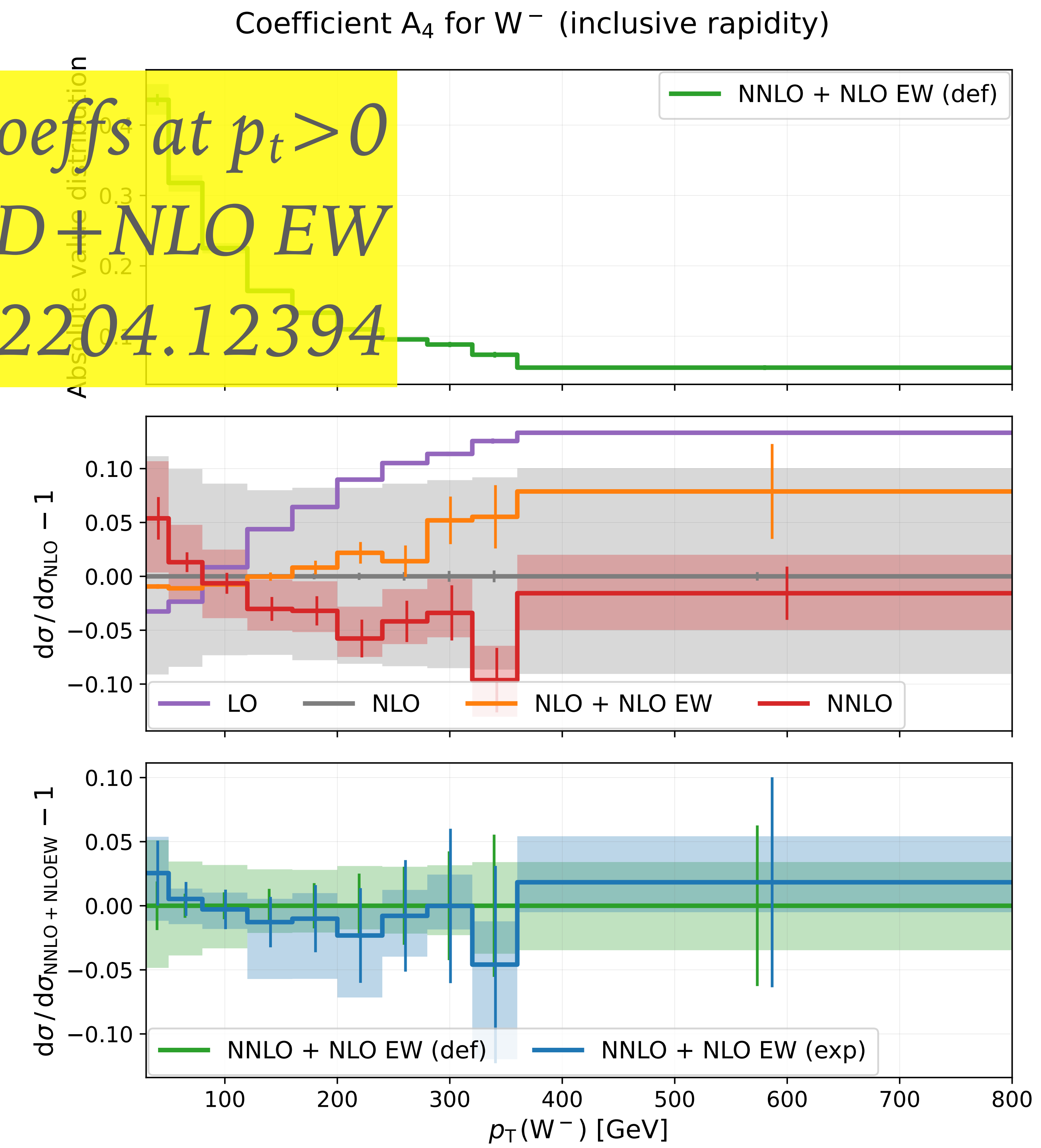
7σ. The CDF experiment used an older version of the ResBos code that was only accurate at NNLL+NLO, while the ResBos2 code is able to make predictions at N^{3}LL+NNLO accuracy. We determine that the data-driven techniques used by CDF capture most of the higher order corrections, and using higher order corrections would result in a decrease in the value reported by CDF by at most 10 MeV.

Impact of Resbos → Resbos2: Isaacson, Fu & Yuan, 2205.02788

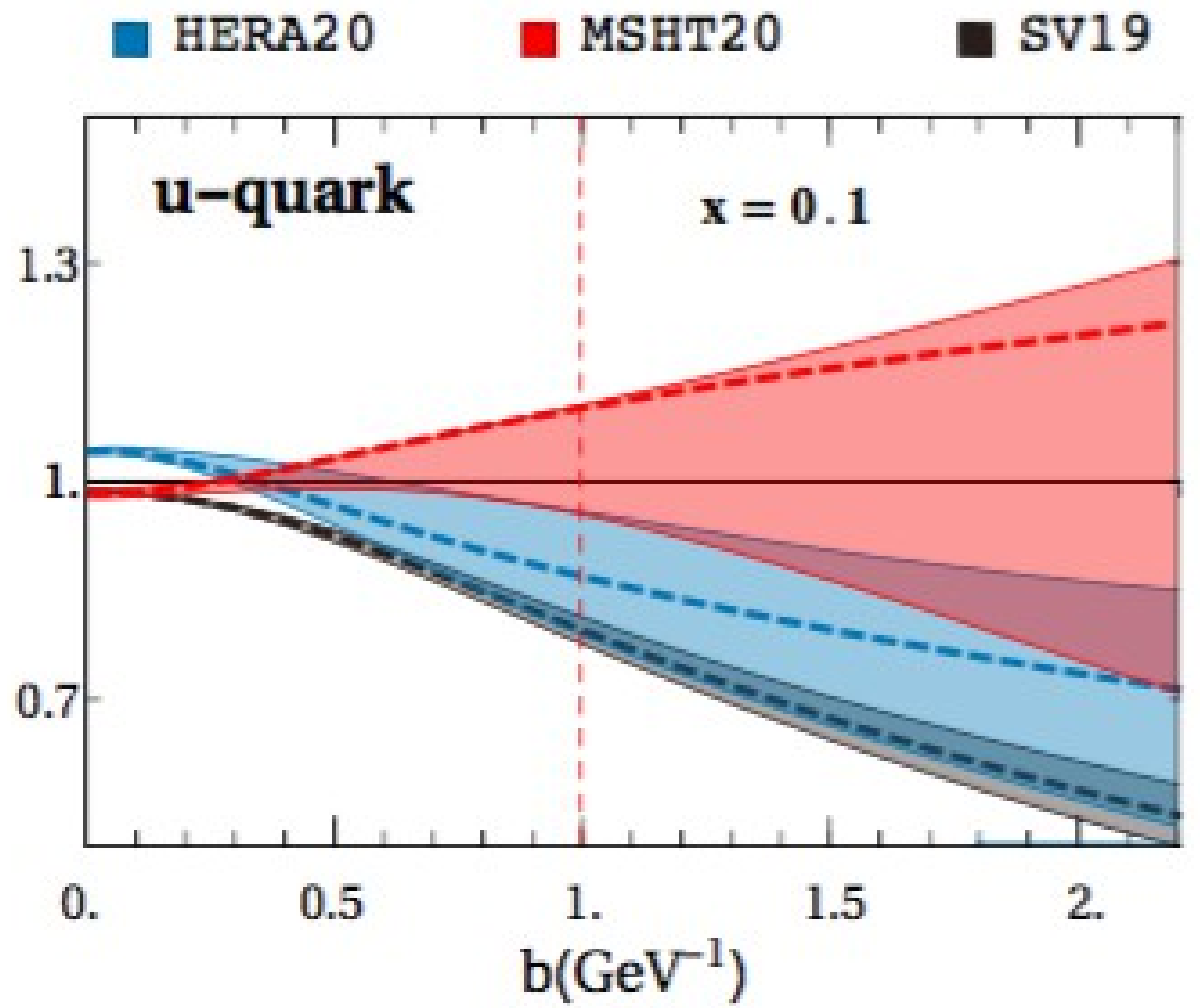


QED corrections in differential dist^n: [Ferrera@ICHEP](#)

angular coeffs at $p_t > 0$
NNLO QCD+NLO EW
Pellen et al, 2204.12394



TMD-PDFs & non-perturbative effects in pT distributions: [Bozzi@ICHEP](#), [Hautmann@ICHEP](#) (cf plot), [Keersmakers@ICHEP](#)



impact of mixed QCD–EW corrections: $\alpha_{EW} \times \alpha_s$

Behring et al, 2103.02671
see also differential QED: Ferrera@ICHEP
high-mass: talk by Signorile-Signorile
& Armadillo et al, 2201.01754

- full study of fit to distribution not easy at fixed order
- instead study **mass determination from mean lepton p_t**, inclusive or fiducial (here just the **production corrections**; decay corrections should factorise)

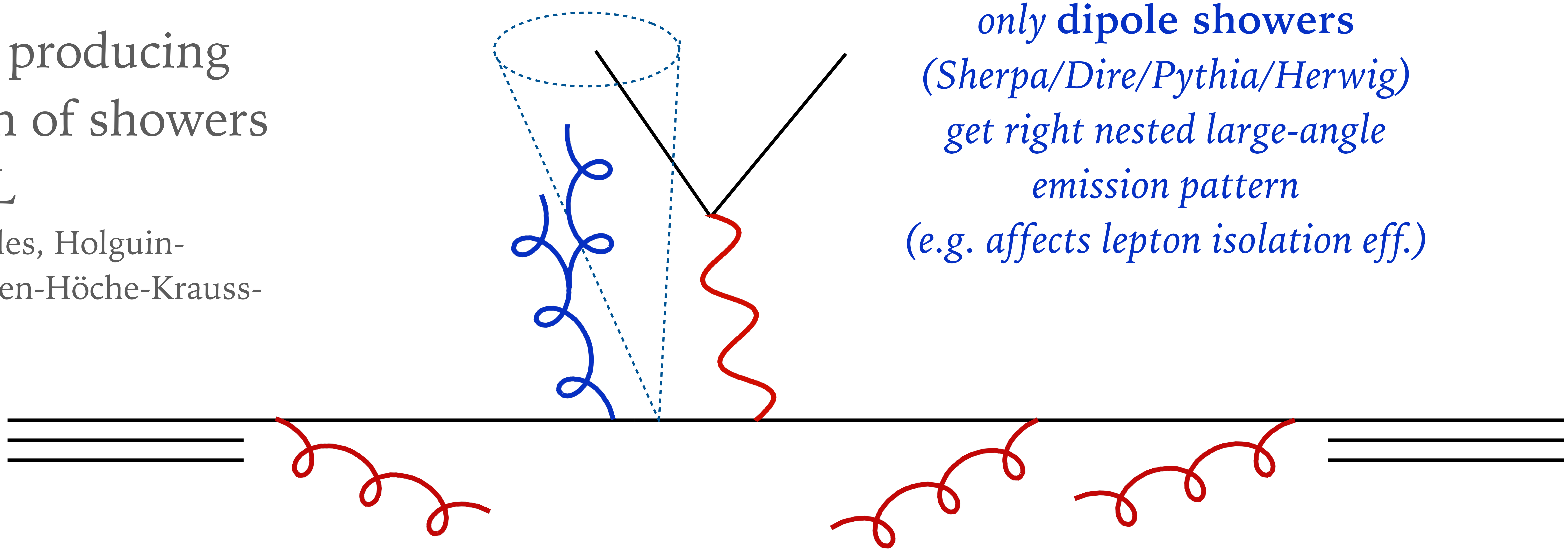
	δm_Z (scaled by m_W/m_Z)	δm_W	difference
inclusive $\langle p_{t\ell} \rangle$ @ α_{EW}	–32 MeV	–32 MeV	0.3 MeV
inclusive $\langle p_{t\ell} \rangle$ @ $\alpha_{EW}\,\alpha_s$	+62 MeV	+55 MeV	–7 MeV
fiducial $\langle p_{t\ell} \rangle$ @ $\alpha_{EW}\,\alpha_s$	[ATLAS cuts]		–17±2 MeV

LHC 13 TeV
my adaptation of their numbers

- relevant for both Z-calibrated methods (impact may be moderated by tuned fiducial cuts) & standalone W methods. **Needs more study (e.g. differential)**

Parton Shower accuracy — can affect m_W & 1000's of other studies

- standard parton showers are Leading Logarithmic (LL), increasingly a limitation
- several groups producing new generation of showers aiming for NLL
  [Nagy&Soper, PanScales, Holguin-Forshaw-Platzer, Herren-Höche-Krauss-Reichelt-Schönherr]

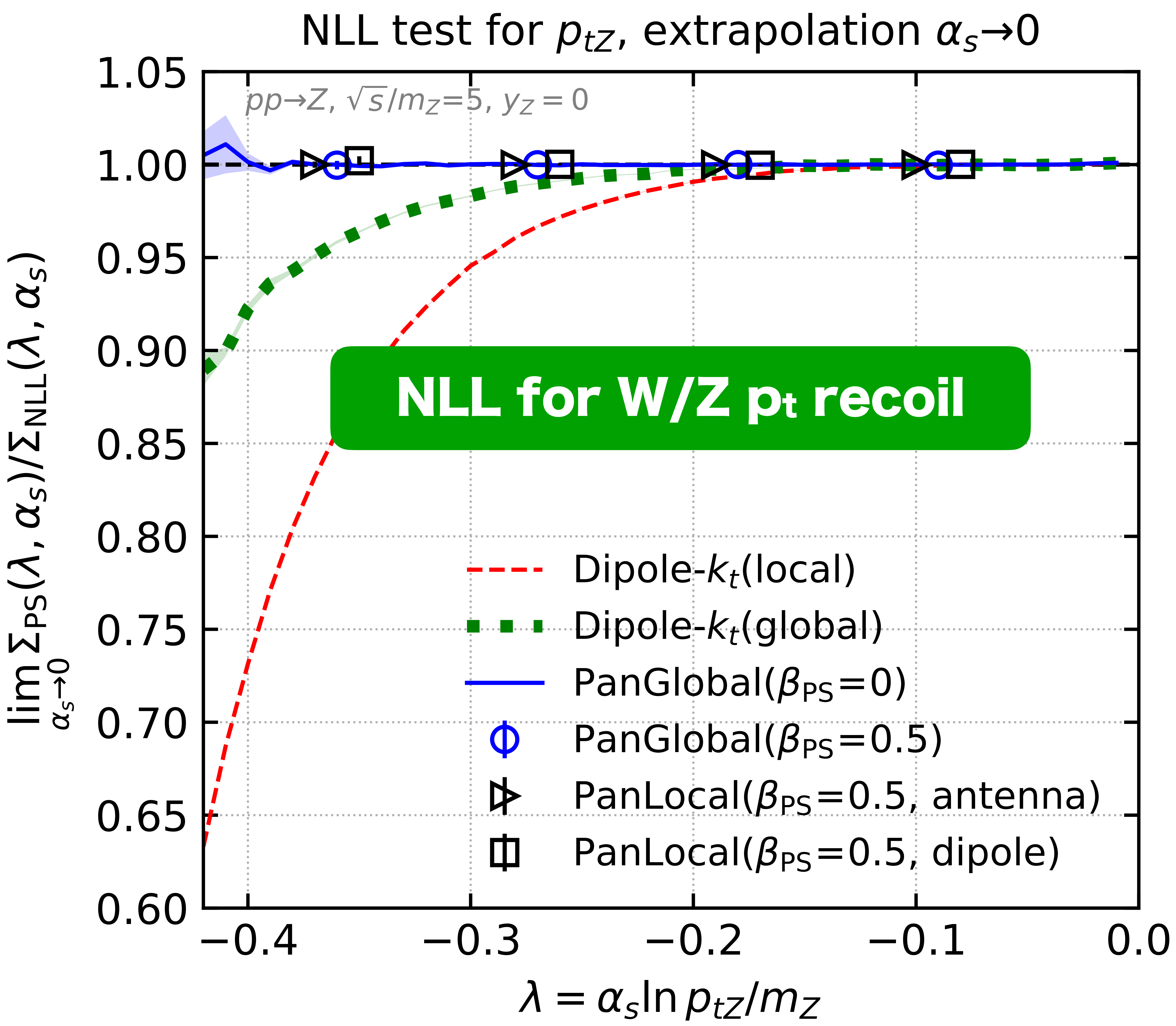


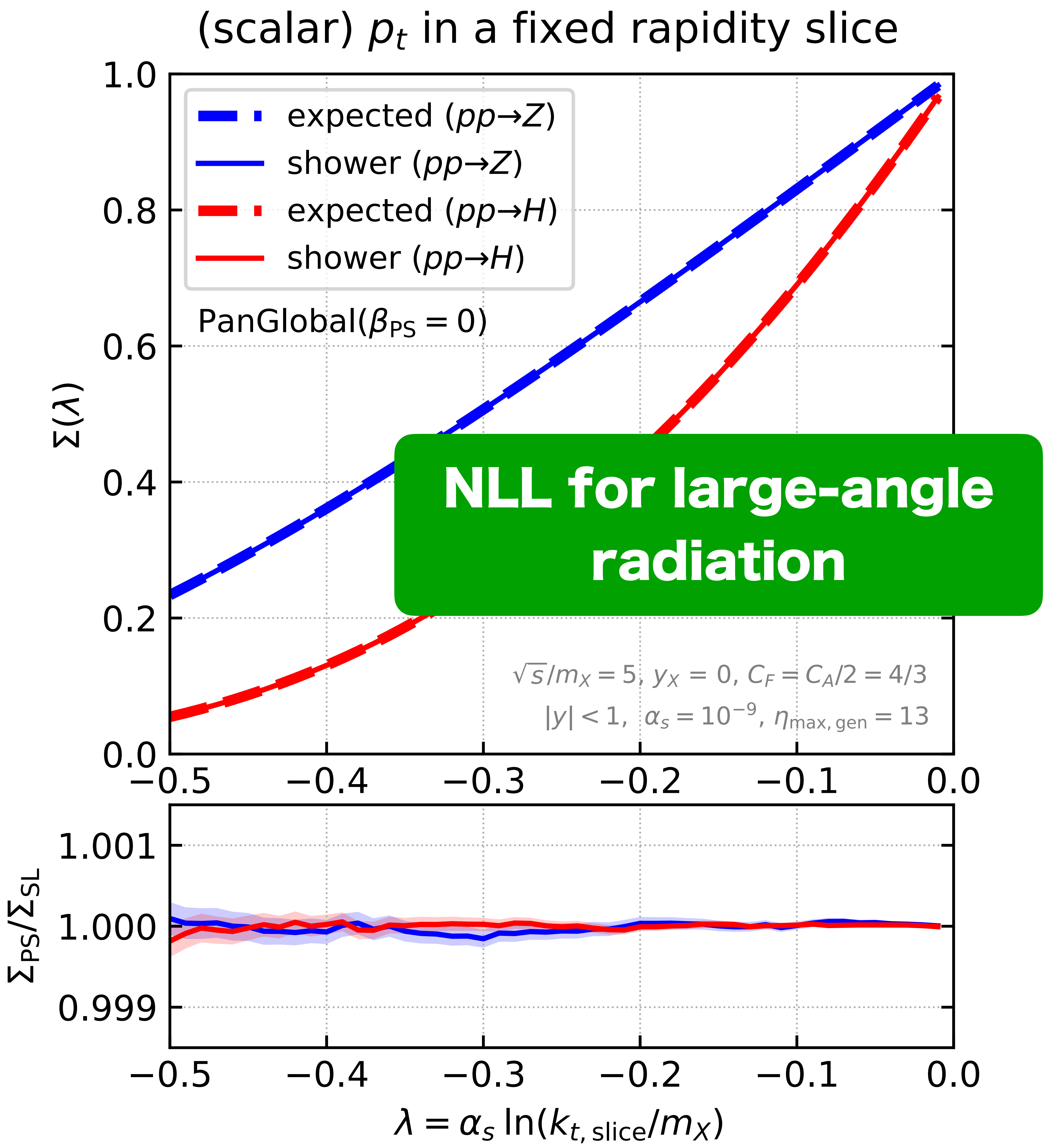
only **dipole showers**
(Sherpa/Dire/Pythia/Herwig)
get right nested large-angle emission pattern
(e.g. affects lepton isolation eff.)

only **angular-ordered showers** *(e.g. Herwig)*
get right pattern of W/Z recoil & associated radiation

van Beekveld, Ferrario Ravasio, GPS, Soyez, Soto Ontoso, Soyez, Verheyen, 2205.02237
idem + Hamilton to appear, Ferrario Ravasio @ ICHEP

New PanScales NLL hadron-collider showers





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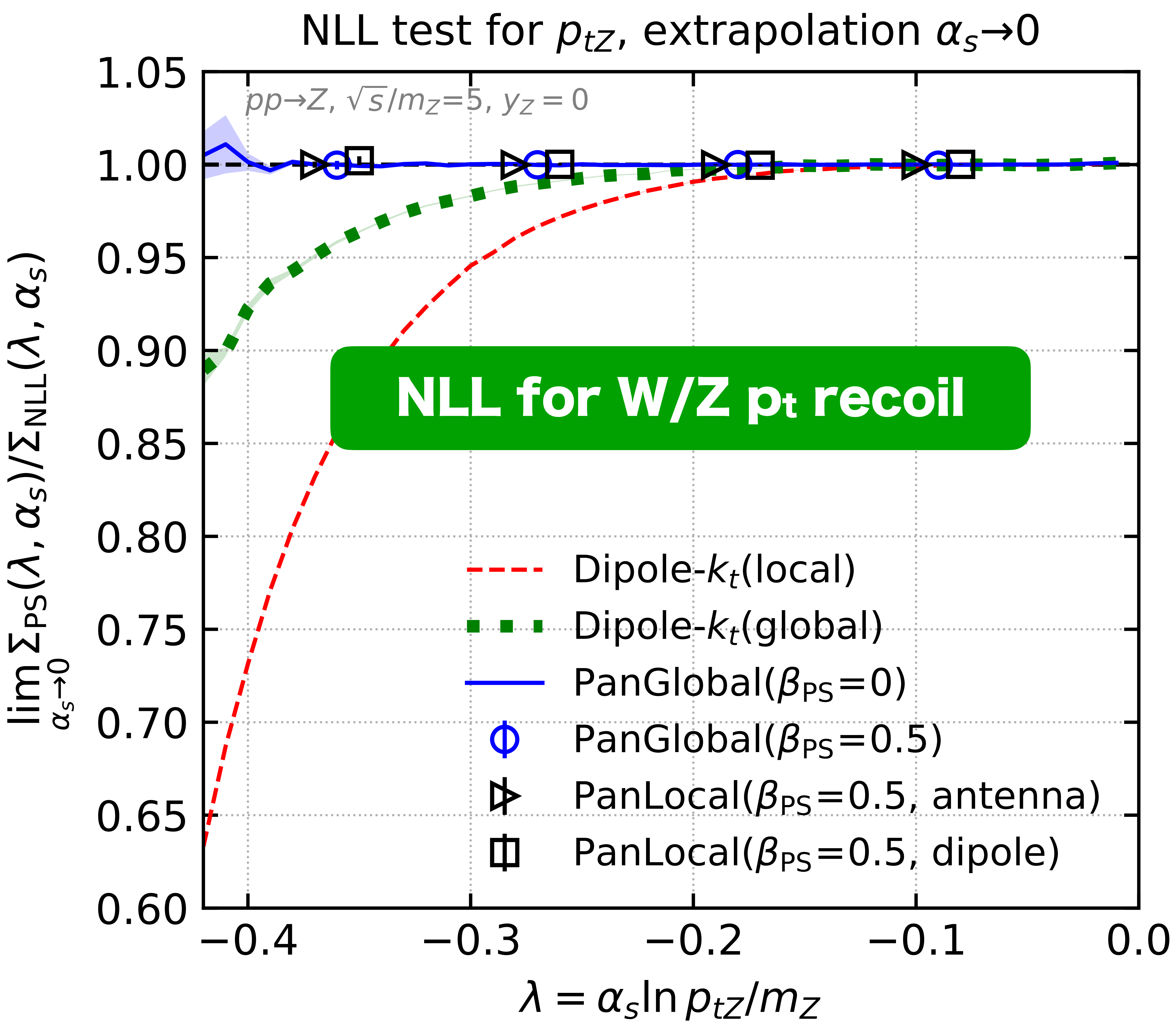


and much more, e.g.

- conceptually, practically simple soft spin correlations (Hamilton, Karlberg, GPS, Scyboz, Verheyen 2111.01161)
- calculations for steps beyond NLL
  - collinear splitting: Dasgupta, El Menoufi@ICHEP, 2109.07496;
  - subleading non-global logs: Banfi, Dreyer, Monni, 2111.02413; NNDL
  - multiplicity at NNDL: Medves@ICHEP, Soto-Ontoso, Soyez, 2111.02413
- phenomenological use (a year or two away)

10 years HIGGS boson discovery

theory systematics dominate

$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.}).$$

ATLAS

$$\mu = 1.002 \pm 0.057 = 1.002 \pm 0.036\,(\text{theory}) \pm 0.033\,(\text{exp.}) \pm 0.029\,(\text{stat.})$$

CMS

the master formula

$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

PDFs

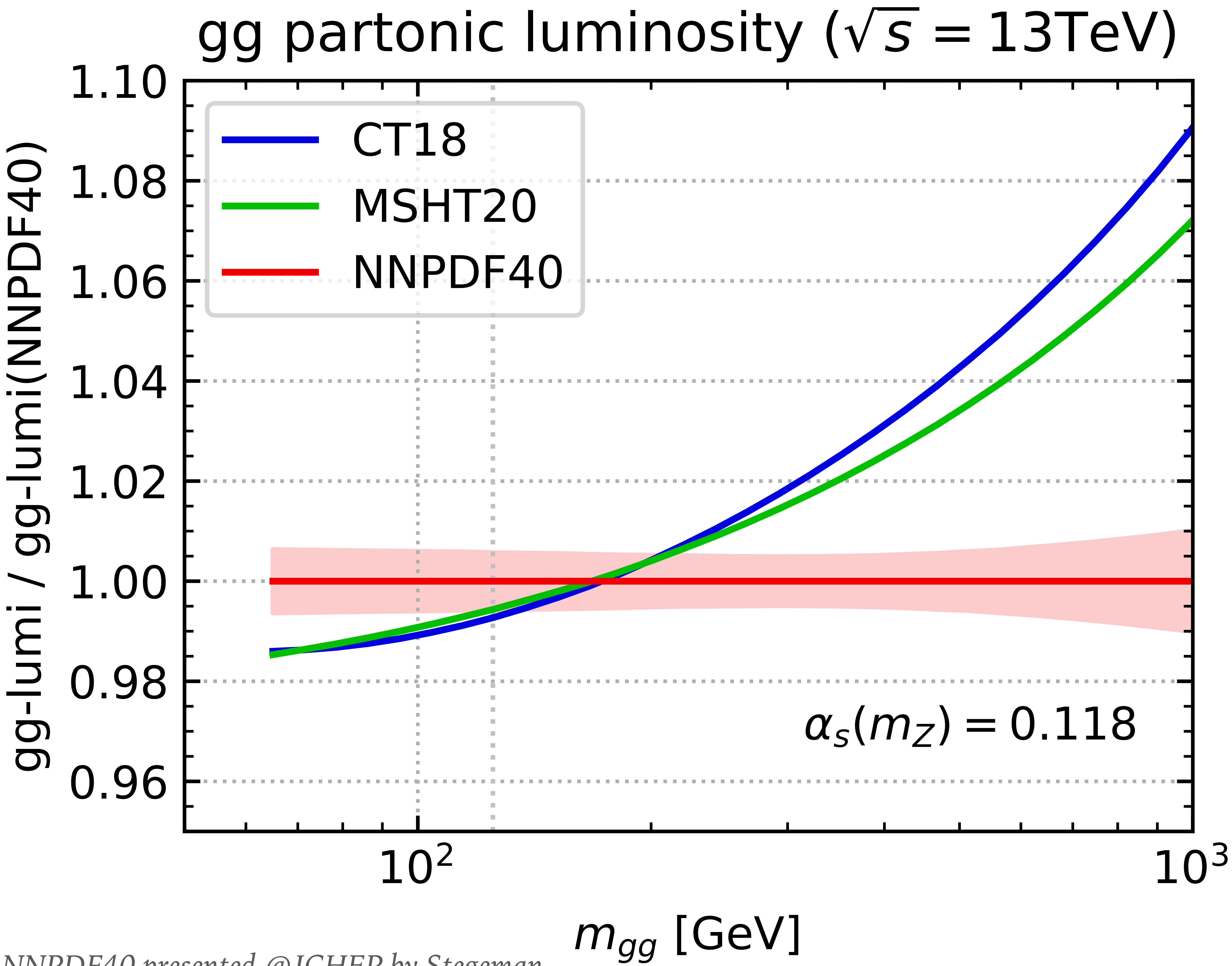
m_H (GeV)	Cross Section (pb)	TH Gaussian %	±PDF %	$\pm\alpha_s$ %
125.00	4.858E+01	±3.9	±1.9	±2.6

$$\sigma = \sum_{i,j} \int dx_1 dx_2 f_{i/p}(x_1) f_{j/p}(x_2) \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

Several major updates in past two years

- PDF4LHC21: 2203.05506 (based on CT18, MSHT20, NNPDF31)
- NNPDF40: 2109.02653
- MSHT20QED: 2111.05357
- MSHT20: 2012.04684
- …

Comparing modern PDF sets



NNPDF40 presented @ICHEP by Stegeman
NB: PDF4LHC21 uses CT18/MSHT20/NNPDF31

gg-lumi, ratio to PDF4LHC15 @ m_H

PDF4LHC15	1.0000	±	0.0184
PDF4LHC21	0.9930	±	0.0155
CT18	0.9914	±	0.0180
MSHT20	0.9930	±	0.0108
NNPDF40	0.9986	±	0.0058

$\times 3$

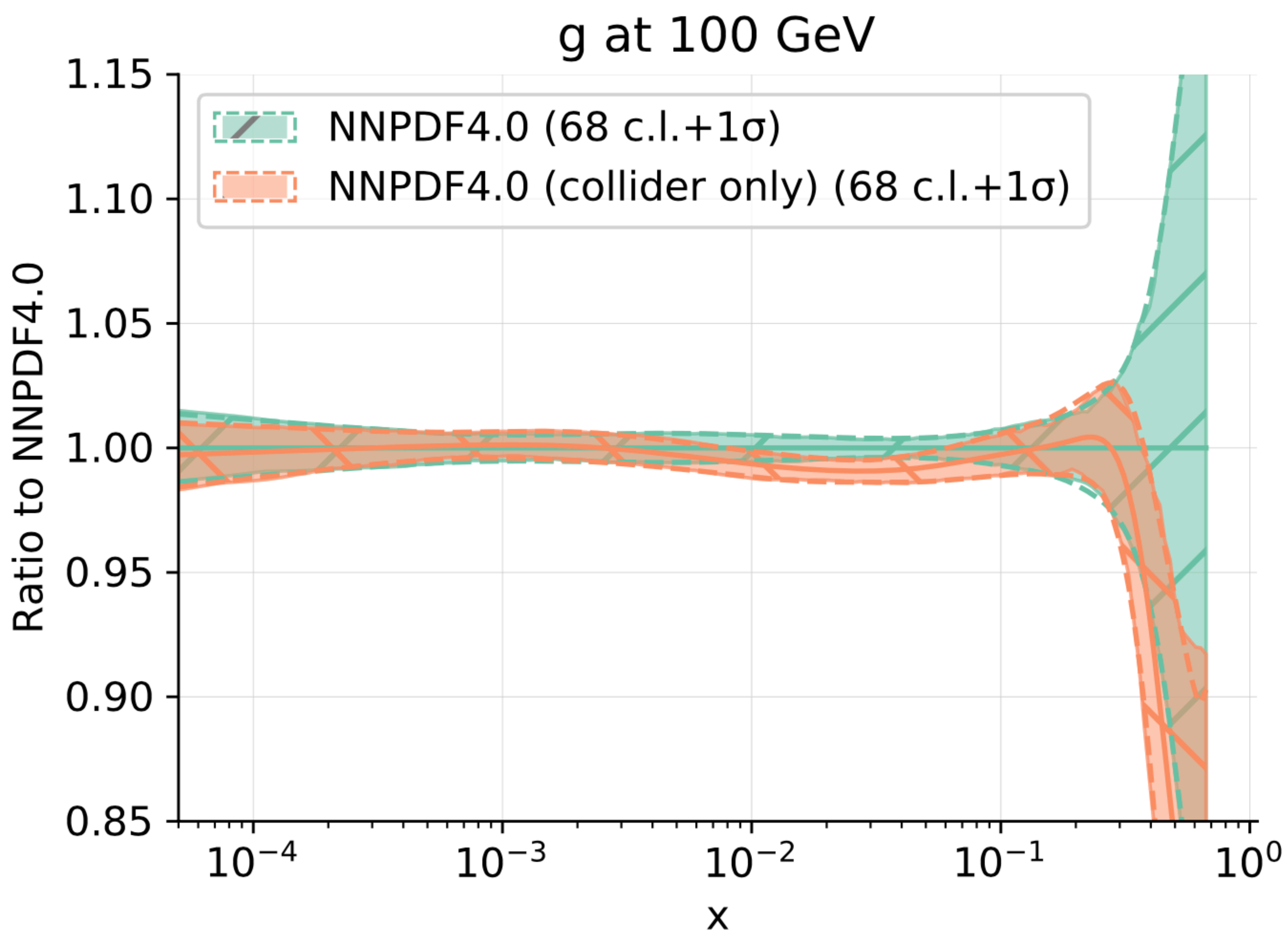
Amazing that MSHT20 & NNPDF40 are reaching %-level precision

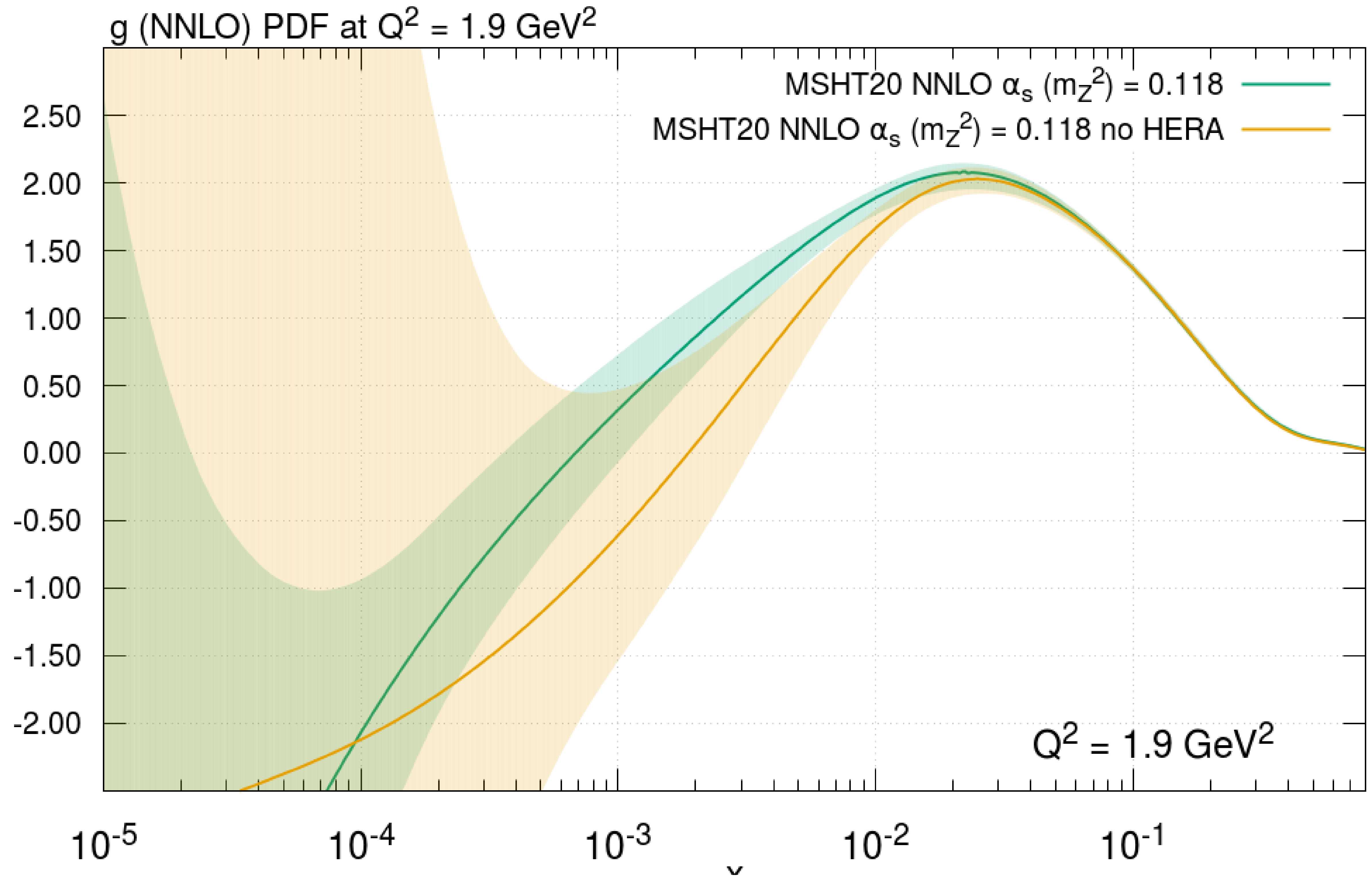
Differences include

- methodology (replicas & NN fits, tolerance factors, etc.)
- data inputs
- treatment of charm

At this level, QED effects probably no longer optional (MSHT20QED: 0.9870)

NNPDF40 has many checks: e.g. removing DIS data (and associated worries about sizeable Λ^2/Q^2 corrections)

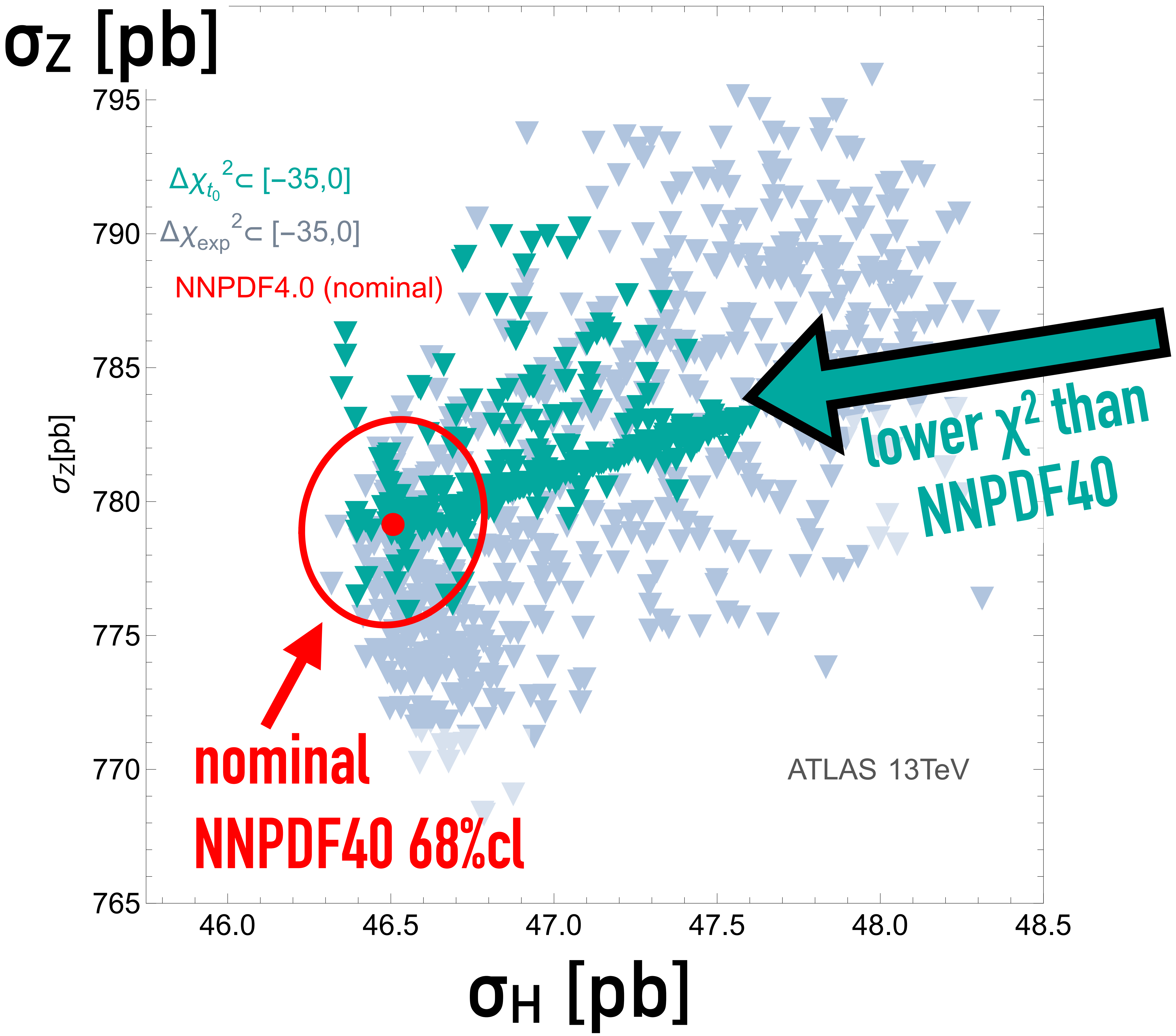




Reassuring indications that results are not (substantially) affected by Λ^2/Q^2 corrections from low-Q^2 DIS part of fit

NNPDF40 query: sampling quality

Courtoy et al, 2205.10444
using NNPDF public code



Construct new replicas as linear combinations of NNPDF replicas

Some of them (cyan points) have lower χ^2 than NNPDF central PDF

Many of those lie well outside nominal NNPDF40 68%cl region

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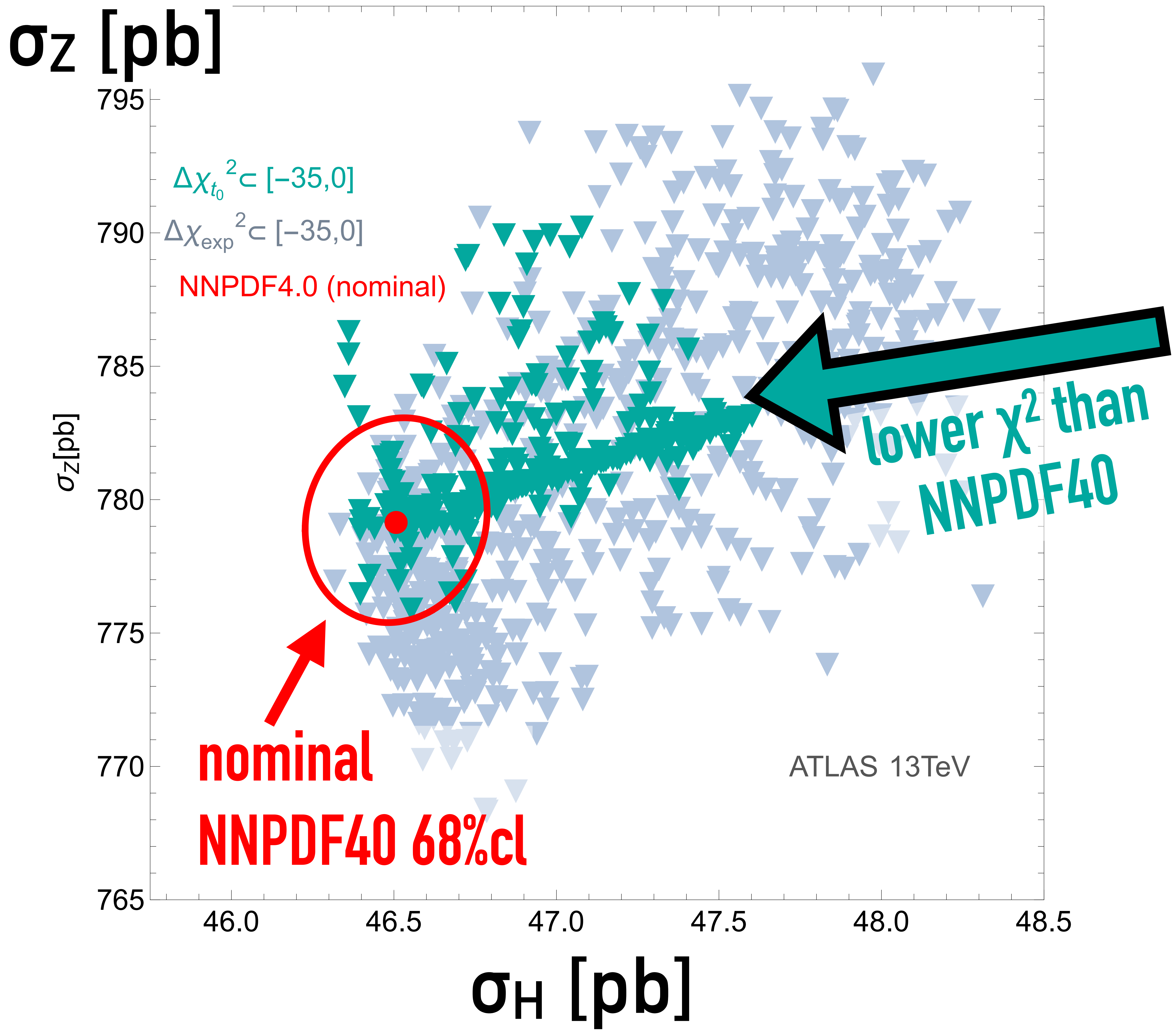

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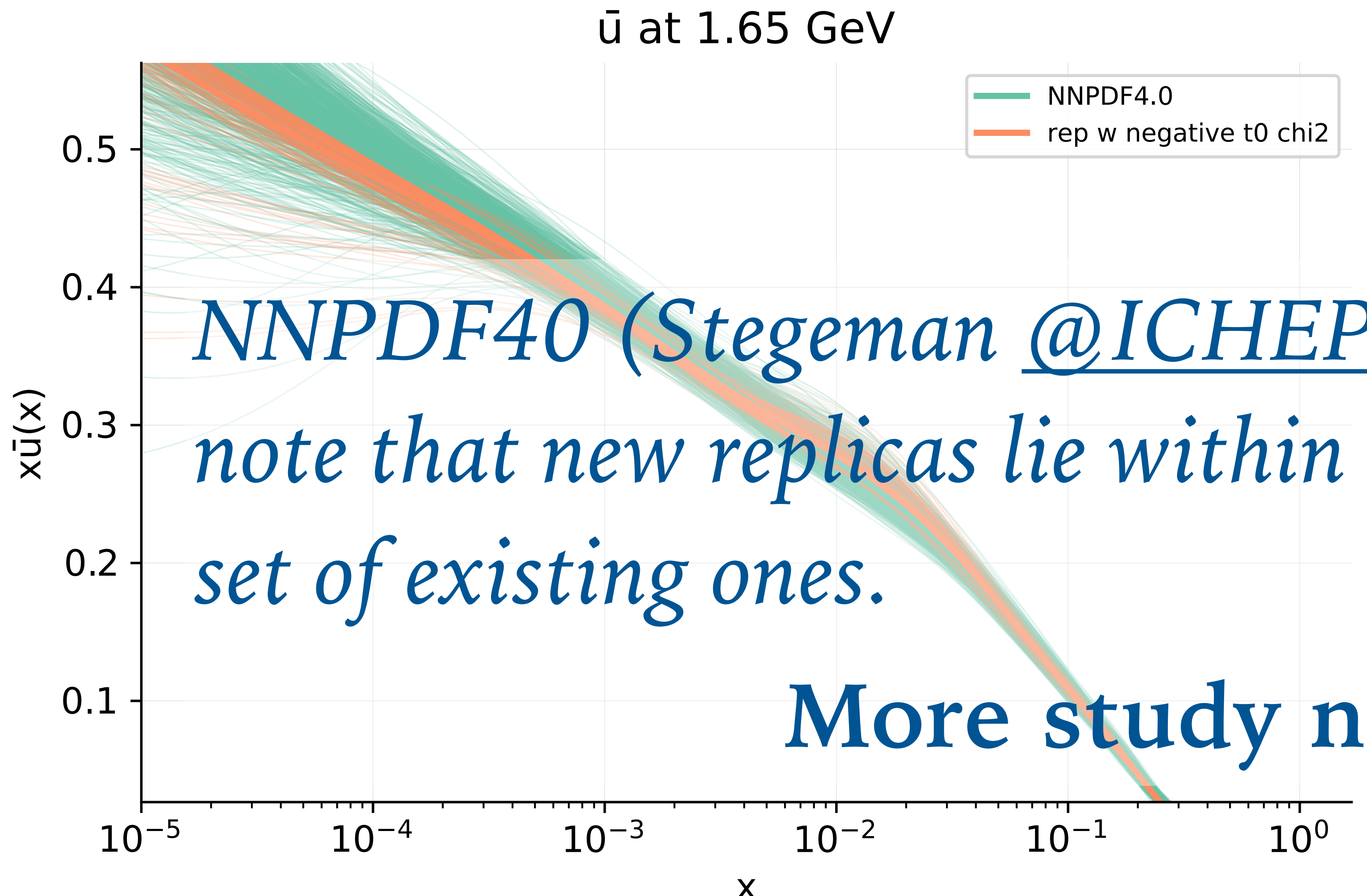


NNPDF40 (Stegeman @ICHEP) note that new replicas lie within set of existing ones.

More study needed

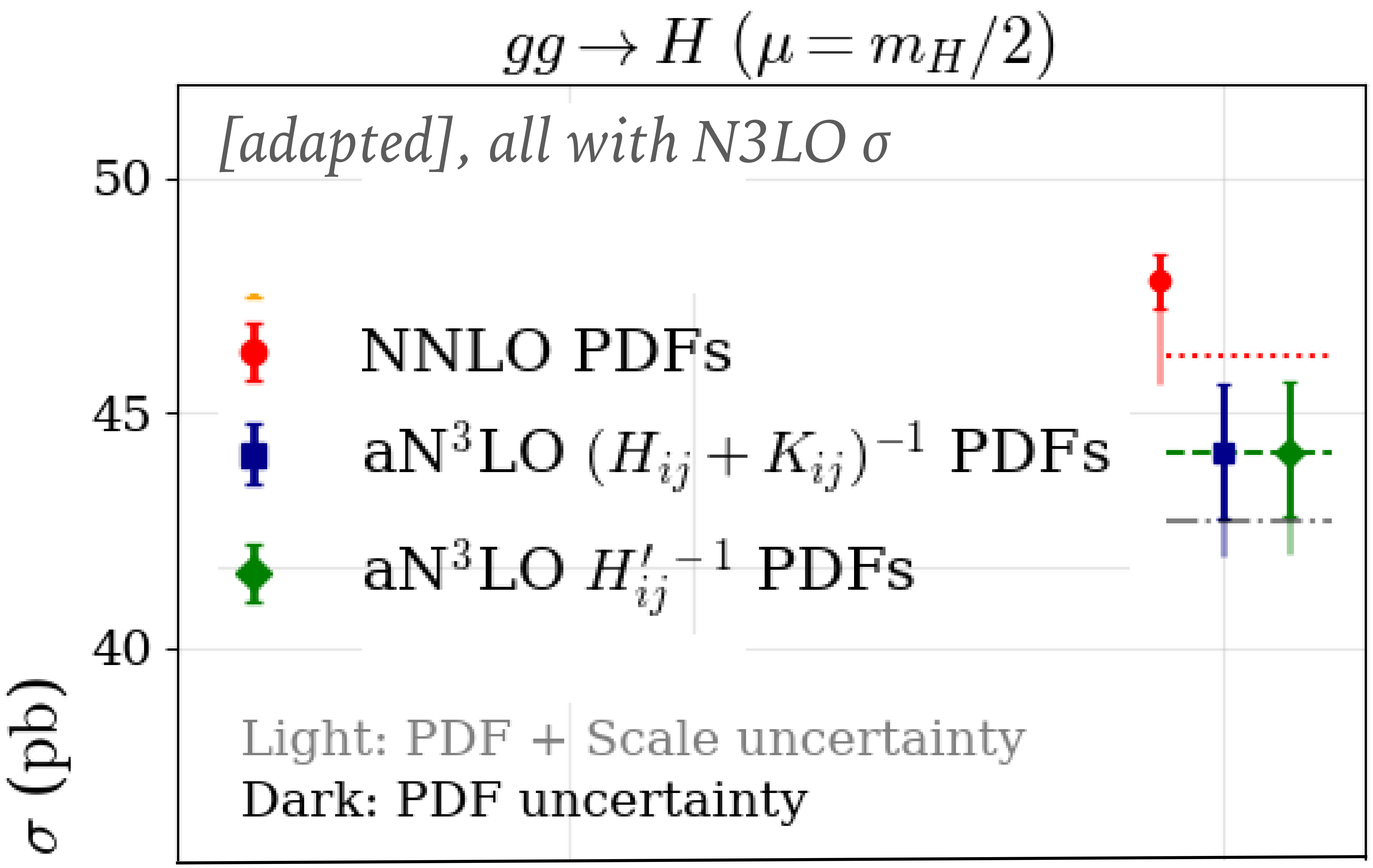
stop press first approx N3LO PDFs

Approximate N^{3}LO Parton Distribution Functions with Theoretical Uncertainties:

MSHT20aN^{3}LO PDFs

arXiv:2207.04739v1

J. McGowan[a], T. Cridge[a], L. A. Harland-Lang[b], and R.S. Thorne[a]



σ order	PDF order	σ (pb) + $\Delta\sigma_+$ − $\Delta\sigma_-$ (%)
		PDF uncertainties
N^{3}LO	aN^{3}LO (no theory unc.)	44.164 + 3.03% - 3.13%
	aN^{3}LO ($H_{ij} + K_{ij}$)	44.164 + 3.34% - 3.15%
	aN^{3}LO (H'_{ij})	44.164 + 3.43% - 3.07%
	NNLO	47.817 + 1.17% - 1.22%

- includes approximations & data-driven fits to parts of N3LO currently unknown
- **7.6% decrease in Higgs cross section** (w. N3LO σ)
- PDF part of **uncertainty goes up by ×2.5–3**
- fairly surprising; starting point for many future investigations

the perturbative part

m_H (GeV)	Cross Section (pb)	TH Gaussian %	±PDF %	$\pm\alpha_s$ %
125.00	4.858E+01	±3.9	±1.9	±2.6

$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

Standard QCD+EW perturbation theory

GLUON FUSION — THE ERROR BUDGET

[adapted from Alexander Huss @ Higgs 2021 see his slides & Tancredi@ICHEP for more]

[Czakon, Harlander, Klappert, Niggetiedt '20]

Remove one source of uncertainty!

Future:

- light-quark mass effects
  - large logs to resum?

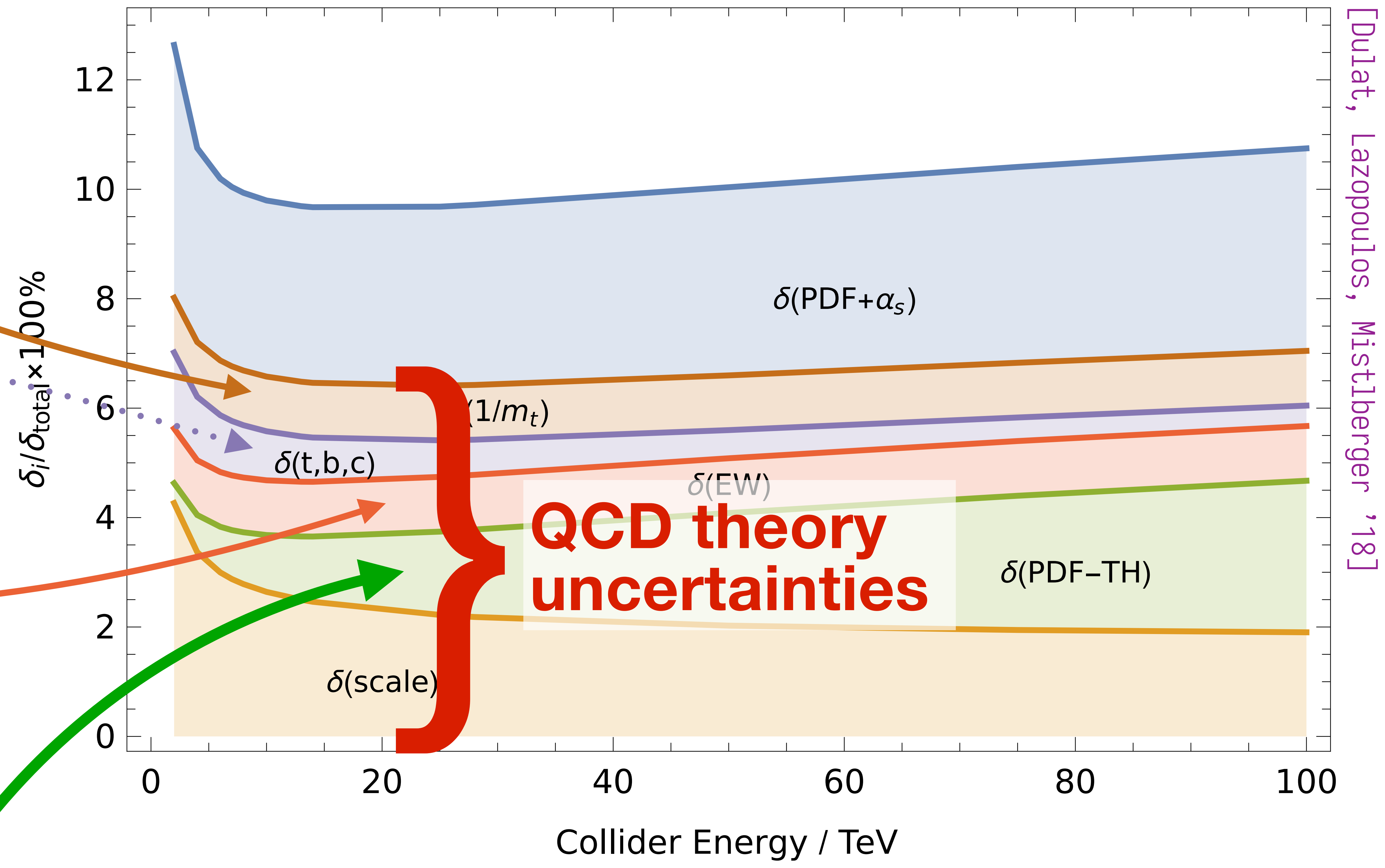
[Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer '20]

Reduce uncertainty: $\sim 1\,\% \to 0.6\,\%$

Future:

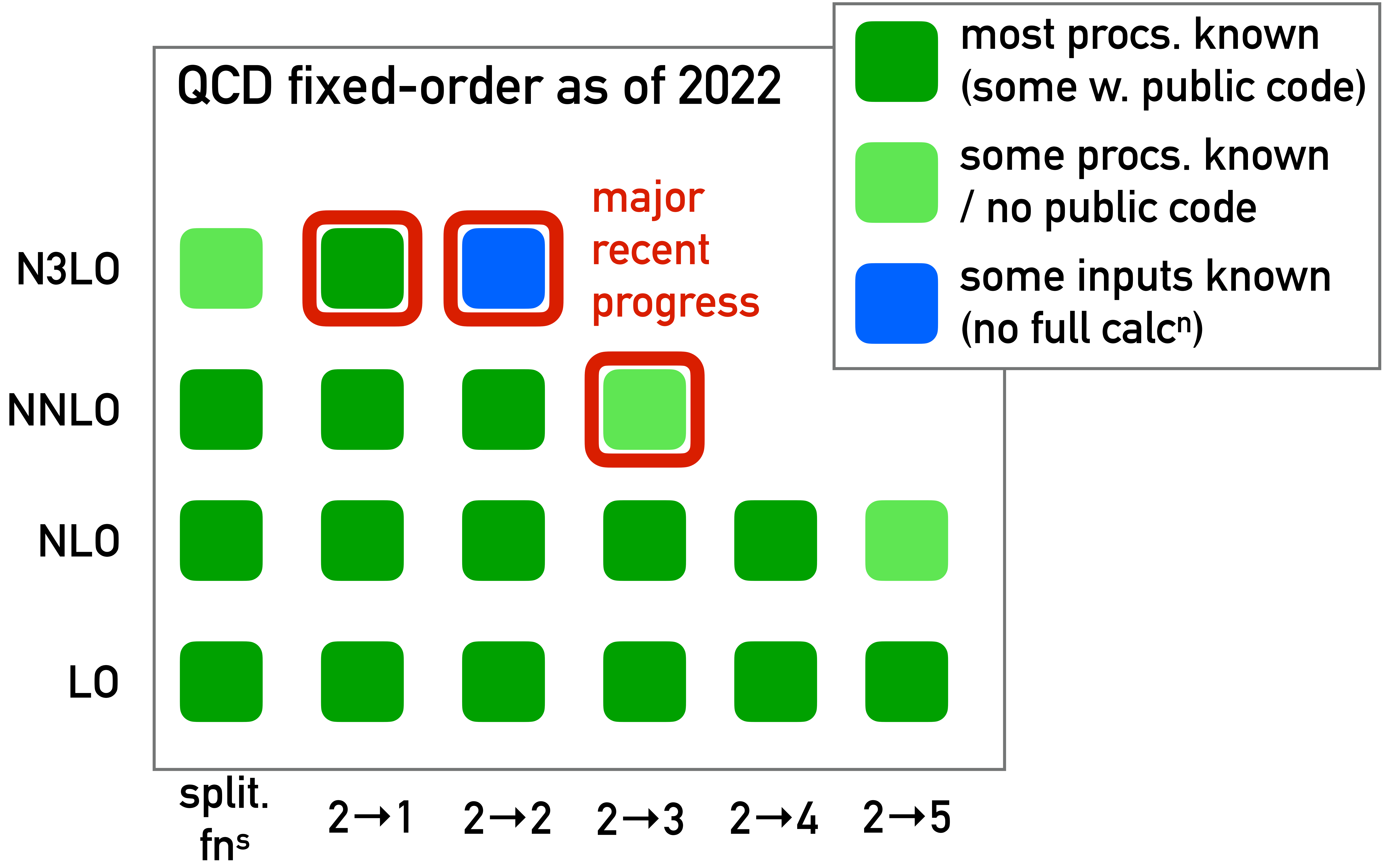
- quark-induced EW contributions
- large p_T^H?
- m_t dependence in QCD amplitude?

Sources of Uncertainties:



- $\delta(\mathrm{PDF} + \alpha_s)$ — more data & accurate determinations
- $\delta(\mathrm{PDF} - \mathrm{TH})$ — missing N³LO PDFs (AP kernels)

4-loop splitting (low moments): Moch, Rujil, Ueda, Vermaseren & Vogt '21
Drell-Yan @ N3LO: Duhr, Dulat & Mistlberger, '20, '21
still to be incorporated into PDF fits


QCD fixed-order as of 2022
N3LO
NNLO
NLO
LO
split. fn^s
2→1
2→2
2→3
2→4
2→5
major recent progress
most procs. known (some w. public code)
some procs. known / no public code
some inputs known (no full calc^n)

Wbb @ NNLO

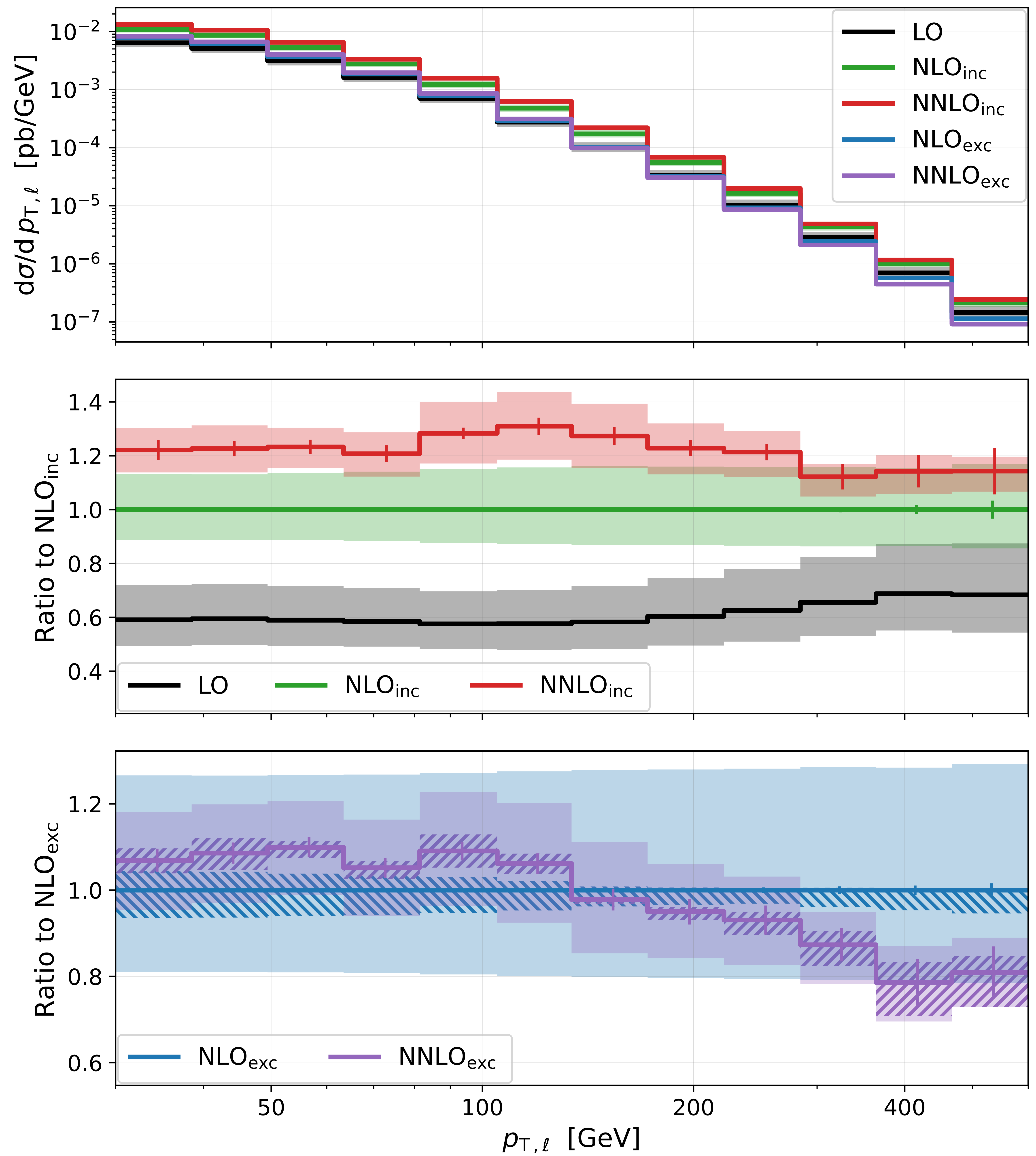
crucial background to

- $pp \to WH(\to b\bar{b})$
- single top, $pp \to \bar{b}t(\to bW)$

Done with massless b-quarks

First 2→3 NNLO calculations with massive final-state particle (i.e. W)

Bayu Hartanto @ ICHEP, with Poncelet, Popescu, Zoia, 2205.01687



3-loop amplitudes for 2→2 processes (crucial part of N3LO 2→2)

Bargiela @ ICHEP

Towards 3-loop revolution

3-loop amplitude milestones

- 1→1 QCD [Tarasov et al. PRLB 1980]
- 2→1 QCD [Moch et al. arXiv:0508055]
- 2→2 SYM [Henn, Mistlberger arXiv:1608.00850]

first 3-loop 2→2 QCD results

- $q\bar{q} \to \gamma\gamma$ [Caola, Manteuffel, Tancredi arXiv:2011.13946]
- $q\bar{q} \to q\bar{q}$ [Caola, Chakraborty, Gambuti, Manteuffel, Tancredi arXiv:2108.00055]
- $gg \to \gamma\gamma$ [PB, Caola, Manteuffel, Tancredi arXiv:2111.13595]
- $gg \to gg$ [Caola, Chakraborty, Gambuti, Manteuffel, Tancredi arXiv:2112.11097]

challenge = **complexity**

# diagrams	0L	1L	2L	3L
$q\bar{q} \to \gamma\gamma$	2	10	143	2922
$q\bar{q} \to q\bar{q}$	1	9	158	3584
$gg \to \gamma\gamma$	0	6	138	3299
$gg \to gg$	4	81	1771	**48723**

3-loop amplitudes for 2→2 processes (crucial part of N3LO 2→2)

Bargiela @ ICHEP

Towards 3-loop revolution

3-loop amp

- 1→1 QCD [*Tarasov et al.*
- 2→1 QCD [*Moch et al. ar*
- 2→2 SYM [*Henn, Mistlberg*

first 3-loop

- $q\bar{q} \to \gamma\gamma$ [*Caola, Manteuffel*
- $q\bar{q} \to q\bar{q}$ [*Caola, Chakrabort*
- $gg \to \gamma\gamma$ [*PB, Caola, Mante*
- $gg \to gg$ [*Caola, Chakrabort*

challenge

# diagrams	0L
$q\bar{q} \to \gamma\gamma$	2
$q\bar{q} \to q\bar{q}$	1
$gg \to \gamma\gamma$	0
$gg \to gg$	4

compact *result* even for the most complicated helicity configuration

$$f^{(3,\text{fin})}_{--++} =$$

the non-perturbative part at hadron colliders

$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

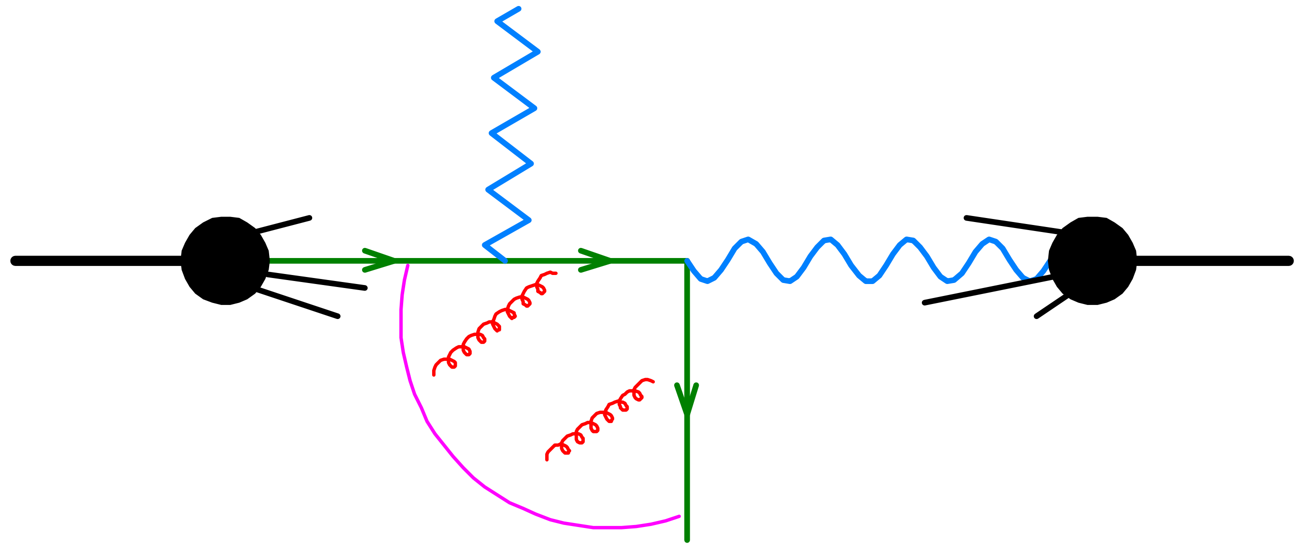
What is value of p in $(\Lambda/Q)^p$? [Λ ~ 1 GeV]

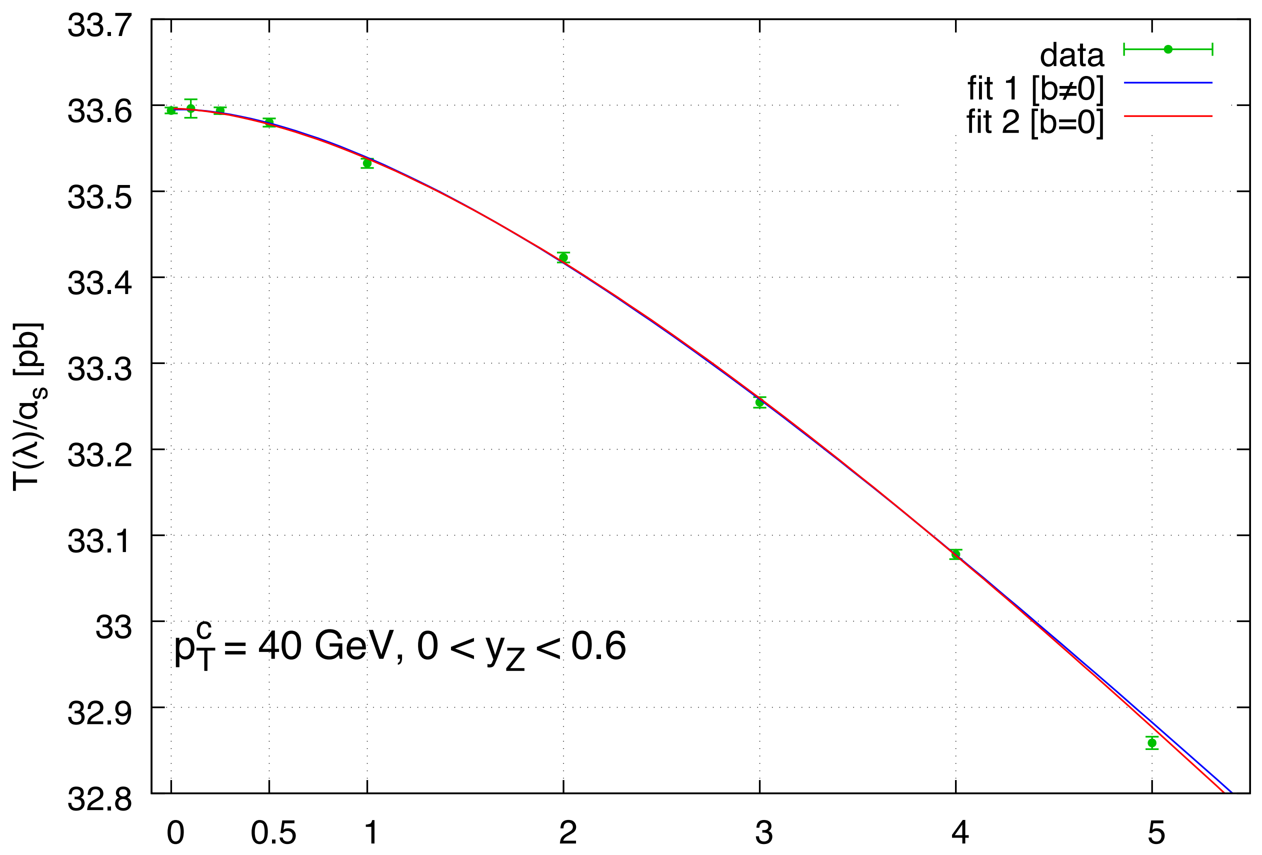
- Jet physics at LHC is dirty because $p = 1$ (hadronisation & MPI)
- LEP event-shape (C-parameter, thrust) α_s fit troubles are complex about because $p = 1$ $\Lambda \sim 0.5\,\mathrm{GeV} \to (\Lambda/20\mathrm{GeV}) \sim 2.5\,\%$
- Hadron-collider inclusive and rapidity-differential Drell-Yan cross sections are believed to have $p = 2$ (Higgs hopefully also), so leptonic / photonic decays should be clean, aside from isolation.
  $\Lambda \sim 0.5\,\mathrm{GeV} \to (\Lambda/125\mathrm{GeV})^2 \sim 0.002\,\%$
  [Beneke & Braun, hep-ph/9506452; Dasgupta, hep-ph/9911391]
- But at LHC, we're also interested in Z, W and Higgs production with non-zero p_T
  Nobody knew if we have $(\Lambda/p_T)^p$ with $p = 1$ (a disaster) or $p = 2$ (all is fine)

What is value of p in $(\Lambda/Q)^p$? → answer appears to be 2

Limatola @ ICHEP
(see also Ozcelik @ ICHEP)

- We consider the process $d(p_1)\gamma(p_2) \to Z(p_3)d(p_4)$ to work in the *Large-n_f* limit and to preserve the azimuthal color asymmetry ($E_{CM} = 300$ GeV)





We (Ferrario Ravasio, GL, Nason ('20)) found

$$\langle O \rangle_\lambda^{(1)} \sim \left(\frac{\lambda}{p_T^c}\right)^2 \log\left(\frac{\lambda}{p_T^c}\right)$$

No numeric evidence of a IR linear renormalon for the transverse momentum of the Z boson!

critical for viability of LHC precision programme, especially highest-precision leptonic measurements

Ferraro Ravasio, Limatola & Nason, 2011.14114

+ analytic demonstration in Caola, Ferrario Ravasio, Limatola, Melnikov & Nason, 2108.08897 , idem + Ozcelik 2204.02247

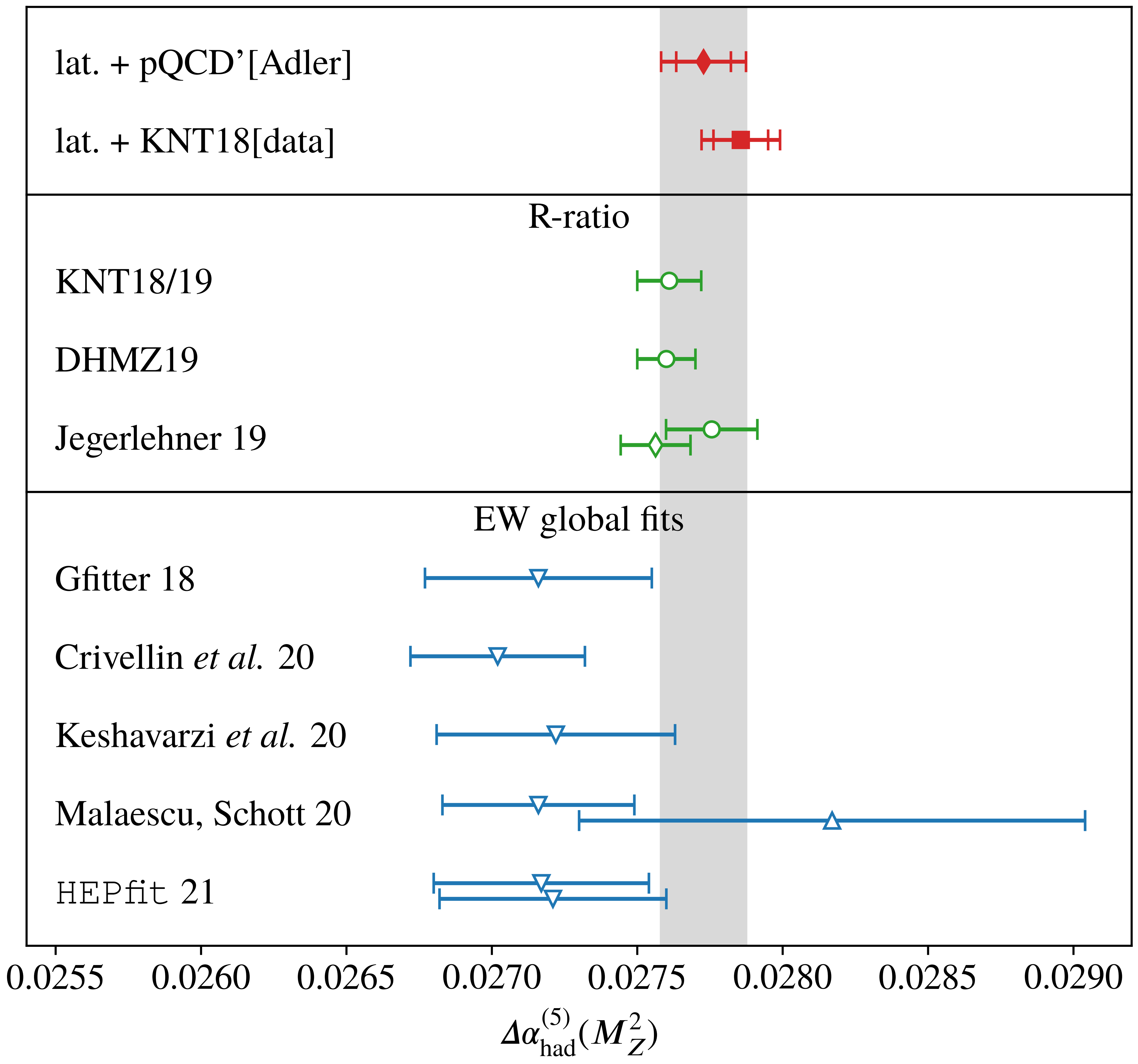
outlook

Concluding remarks

- impact of strong interactions stretches from 0.1 GeV to highest energy scales we can probe
- understanding QCD (& EW) corrections is crucial for drawing conclusions from precision measurements and direct searches for new physics
- as we approach high-precision, we should expect to be confronted by conceptual problems that we could, so far, ignore
- diversity of approaches likely to be crucial to make sense of next decades' data

BACKUP

running to Z pole – results and comparison



CLS/Mainz results show consistency of QED coupling running to Z pole with R-data & EW precision results arXiv:2207.04765v1

Windows on the hadronic vacuum polarisation contribution to the muon anomalous magnetic moment

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(Fermilab Lattice, HPQCD, and MILC Collaborations)[‡]

$$\Theta(t, t_1, \Delta t) = \frac{1}{2}\left[1 - \tanh\left(\frac{t - t_1}{\Delta t}\right)\right] . \tag{3}$$

The contribution to a_μ from this window is then

$$a_\mu^w(t_1, \Delta t) = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dt\, G_{ff'}(t) K_G^w(t)\, , \tag{4}$$

with a modified kernel,

$$K_G^w(t) \equiv K_G(t)\Theta(t, t_1, \Delta t). \tag{5}$$

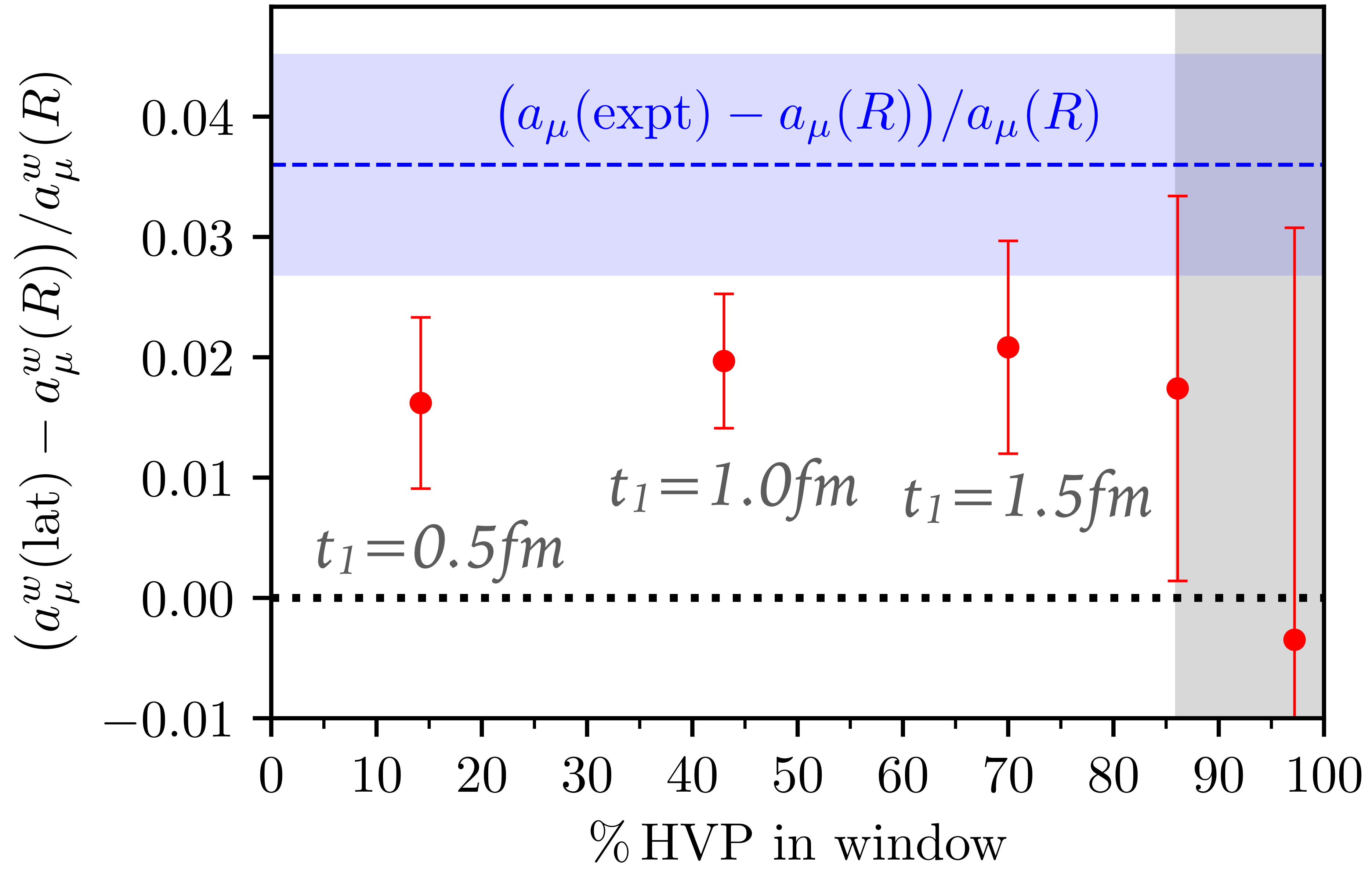

FIG. 11. Fractional difference between determinations of a_μ^w from the lattice and from $R_{e^+e^-}$ with one-sided windows for different values of t_1. The differences are plotted versus the fraction of the total HVP included in the window. We have insufficient statistics to give reliable results for $t_1 > 2$ fm (grey shading). For comparison, the current difference between the experimental average for a_μ and the SM a_μ using the data-driven HVP contribution divided by the SM a_μ is 0.036(9) (blue band).

The muon g-2 anomaly confronts new physics in $e^\pm$ and $\mu^\pm$ final states scattering

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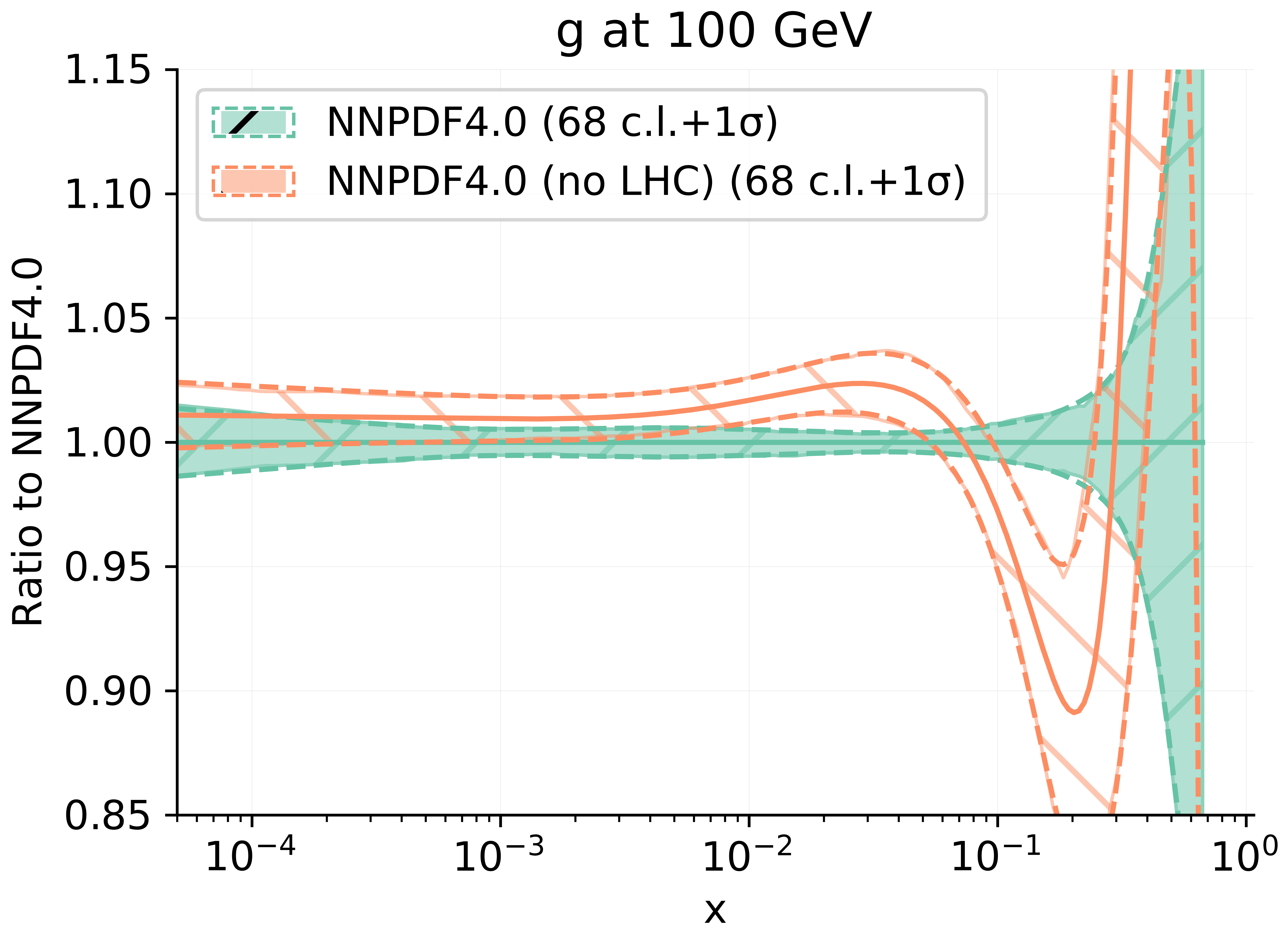
arXiv:2112.09139v2 [hep-ph] 21 Feb 2022

ABSTRACT: The 4.2σ discrepancy between the standard model prediction for the muon anomalous magnetic moment a_μ and the experimental result is accompanied by other anomalies. A crucial input for the prediction is the hadronic vacuum polarization $a_\mu^{\rm HVP}$ inferred from $\sigma_{\rm had} = \sigma(e^+e^- \to {\rm hadrons})$ data. However, the two most accurate determinations of $\sigma_{\rm had}$ from KLOE and BaBar disagree by almost $3\,\sigma$. Additionally, the combined data-driven result disagrees with the most precise lattice determination of $a_\mu^{\rm HVP}$ by $2.1\,\sigma$. We show that all these discrepancies could be accounted for by a new boson produced resonantly around the KLOE centre of mass energy and decaying promptly yielding e^+e^- and $\mu^+\mu^-$ pairs in the final states. This gives rise to three different effects: (i) the additional e^+e^- events will affect the KLOE luminosity determination based on measurements of the Bhabha cross section, and in turn the inferred value of $\sigma_{\rm had}$; (ii) the additional $\mu^+\mu^-$ events will affect the determination of $\sigma_{\rm had}$ via the (luminosity independent) measurement of the ratio of $\pi^+\pi^-\gamma$ versus $\mu^+\mu^-\gamma$ events; (iii) loops involving the new boson would contribute directly to the prediction for a_μ. We discuss in detail this possibility, and we present a simple model that can reconcile the KLOE and BaBar results for $\sigma_{\rm had}$, the data-driven and the lattice determinations of $a_\mu^{\rm HVP}$, the predicted and measured values of a_μ, while complying with all phenomenological constraints.

Removing LHC data

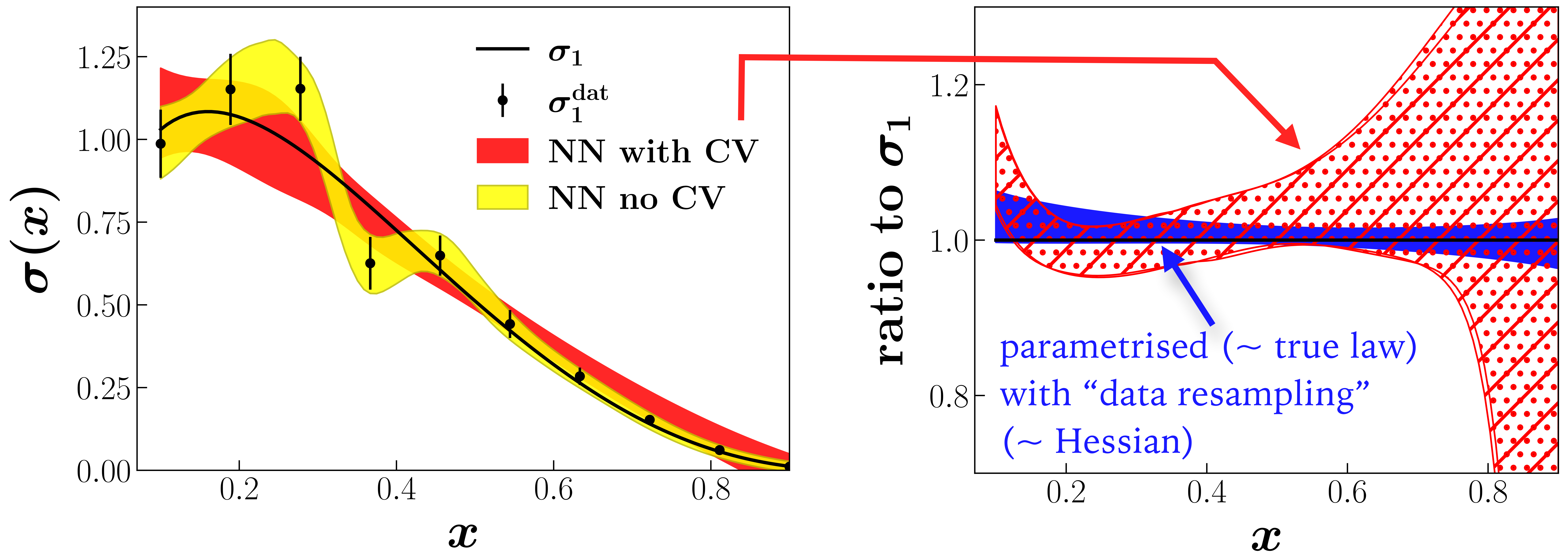


- LHC data appears to be dominant in constraining the gluon
- One clear question is how to interpret gg-lumi uncertainties $\lesssim 1\,\%$ when all input cross sections at hadron colliders have larger theory uncertainties.

NN (PDFs), cross validation & uncertainty biases?

Hunt-Smith et al, 2206.10782

a toy model test of NN PDF fitting procedure



NNPDF closure tests are designed to reveal any bias of this kind in full fit (none seen).
But this toy-model test raises question of interplay between priors (parametrisation) & result

2207.02122 LH Wishlist

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO^{(t)}_{QCD}}$ $\mathrm{N^{(1,1)}LO^{(HTL)}_{QCD\otimes EW}}$	$\mathrm{N^4LO_{HTL}}$ (incl.) $\mathrm{NNLO^{(b,c)}_{QCD}}$
$pp \to H + j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$
$pp \to H + 2j$	$\mathrm{NLO_{HTL} \otimes LO_{QCD}}$ $\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ (incl.) $\mathrm{NNLO^{(VBF^*)}_{QCD}}$ $\mathrm{NLO^{(VBF)}_{EW}}$	$\mathrm{NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$ $\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ $\mathrm{NNLO^{(VBF)}_{QCD}}$
$pp \to H + 3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO^{(VBF)}_{QCD}}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to VH$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$ $\mathrm{NLO^{(t,b)}_{gg\to HZ}}$	
$pp \to VH + j$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD} + NLO_{EW}}$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$
$pp \to HH$	$\mathrm{N^3LO_{HTL} \otimes NLO_{QCD}}$	$\mathrm{NLO_{EW}}$
$pp \to HH + 2j$	$\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ (incl.) $\mathrm{NNLO^{(VBF^*)}_{QCD}}$ $\mathrm{NLO^{(VBF)}_{EW}}$	
$pp \to HHH$	$\mathrm{NNLO_{HTL}}$	
$pp \to H + t\bar{t}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ $\mathrm{NNLO_{QCD}}$ (off-diag.)	$\mathrm{NNLO_{QCD}}$
$pp \to H + t/\bar{t}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD} + NLO_{EW}}$

Table 1: Precision wish list: Higgs boson final states. $\mathrm{N^xLO^{(VBF^*)}_{QCD}}$ means a calculation using the structure function approximation. $V = W, Z$.

process	known	desired
$pp \to V$	$\mathrm{N^3LO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$ $\mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD} + N^{(1,1)}LO_{QCD\otimes EW}}$ $\mathrm{N^2LO_{EW}}$
$pp \to VV'$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$ $\mathrm{+ NLO_{QCD}}$ (gg channel)	$\mathrm{NLO_{QCD}}$ (gg channel, w/ massive loops) $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to V + j$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$	hadronic decays
$pp \to V + 2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (QCD component) $\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW component)	$\mathrm{NNLO_{QCD}}$
$pp \to V + b\bar{b}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$
$pp \to VV' + 1j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to VV' + 2j$	$\mathrm{NLO_{QCD}}$ (QCD component) $\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW component)	Full $\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to W^+W^+ + 2j$	Full $\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to W^+W^- + 2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW component)	
$pp \to W^+Z + 2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW component)	
$pp \to ZZ + 2j$	Full $\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to VV'V''$	$\mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to W^\pm W^+ W^-$	$\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to \gamma\gamma$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma + j$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma\gamma + j$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$ $\mathrm{+ NLO_{QCD}}$ (gg channel)	
$pp \to \gamma\gamma\gamma$	$\mathrm{NNLO_{QCD}}$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$

Table 3: Precision wish list: vector boson final states. $V = W, Z$ and $V', V'' = W, Z, \gamma$. Full leptonic decays are understood if not stated otherwise.

process	known	desired
$pp \to V$	$\mathrm{N^3LO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$ $\mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD} + N^{(1,1)}LO_{QCD\otimes EW}}$ $\mathrm{N^2LO_{EW}}$
$pp \to VV'$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$ $\mathrm{+ NLO_{QCD}}$ (gg channel)	$\mathrm{NLO_{QCD}}$ (gg channel, w/ massive loops) $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to V + j$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$	hadronic decays
$pp \to V + 2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (QCD component) $\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW component)	$\mathrm{NNLO_{QCD}}$
$pp \to V + b\bar{b}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$
$pp \to VV' + 1j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to VV' + 2j$	$\mathrm{NLO_{QCD}}$ (QCD component) $\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW component)	Full $\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to W^+W^+ + 2j$	Full $\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to W^+W^- + 2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW component)	
$pp \to W^+Z + 2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ (EW component)	
$pp \to ZZ + 2j$	Full $\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to VV'V''$	$\mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to W^\pm W^+ W^-$	$\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to \gamma\gamma$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma + j$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma\gamma + j$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$ $\mathrm{+ NLO_{QCD}}$ (gg channel)	
$pp \to \gamma\gamma\gamma$	$\mathrm{NNLO_{QCD}}$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$

Table 3: Precision wish list: vector boson final states. $V = W, Z$ and $V', V'' = W, Z, \gamma$. Full leptonic decays are understood if not stated otherwise.

modifications to these slides since original talk

- slide 23: fixed typo (the NNPDF input to PDF4LHC21 is NNPDF31, not NNPDF40)
- slide 35: fixed missing author in ref