STANDARD MODEL PREDICTION UNCERTAINTIES

The 31st International Symposium on Lepton Photon Interactions at High Energies

Xuan Chen

Melbourne, Australia

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Schweizerischer Nationalfonds

Standard Model Prediction Uncertainties

➤SM has a wide range of theoretical uncertainties

$$a_\mu = 116591810(43) \times 10^{-11}$$

Phys. Reports 887 (2020) 1-116

$$a_e = 1159652180.252(95) \times 10^{-12}$$

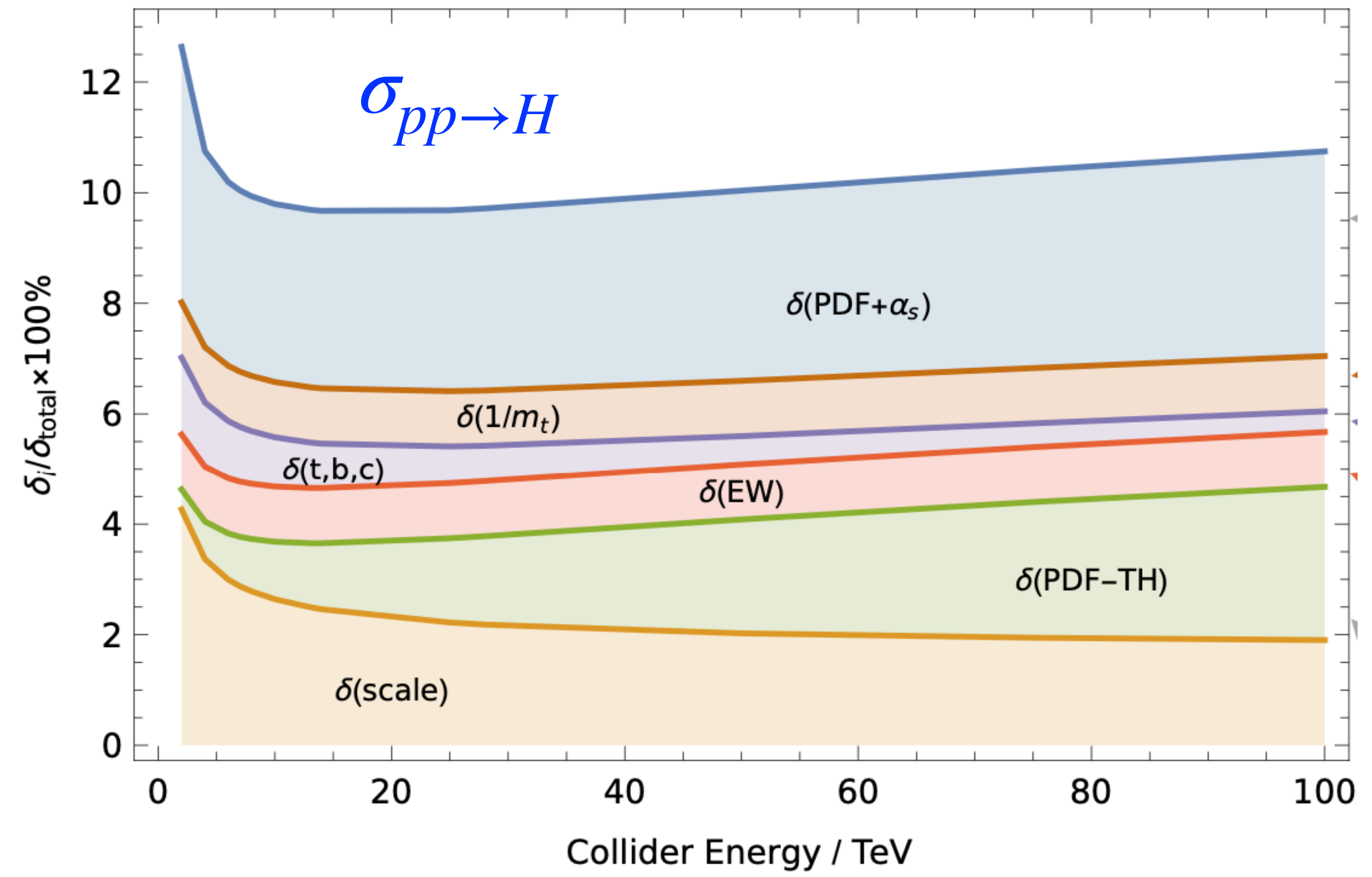
Nature (London) 588, 61 (2020)

$$\alpha^{-1} = 137.035999166(15)$$

Phys. Rev. Lett. 130, 071801 (2023)

0.1/billion ~ 10/cent

Uncertainties



F. Dulat, A. Lazopoulos, B. Mistlberger 2018

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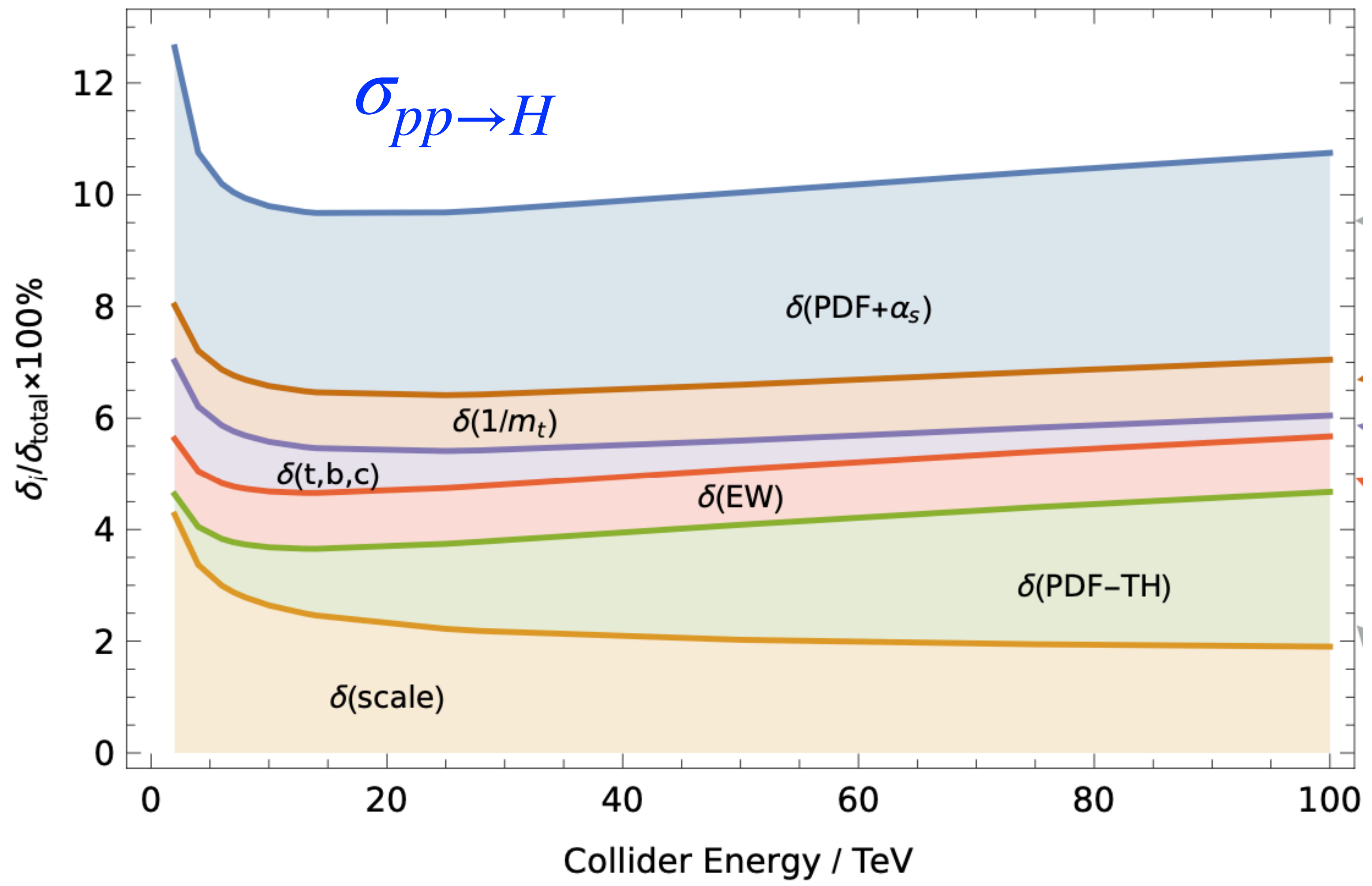
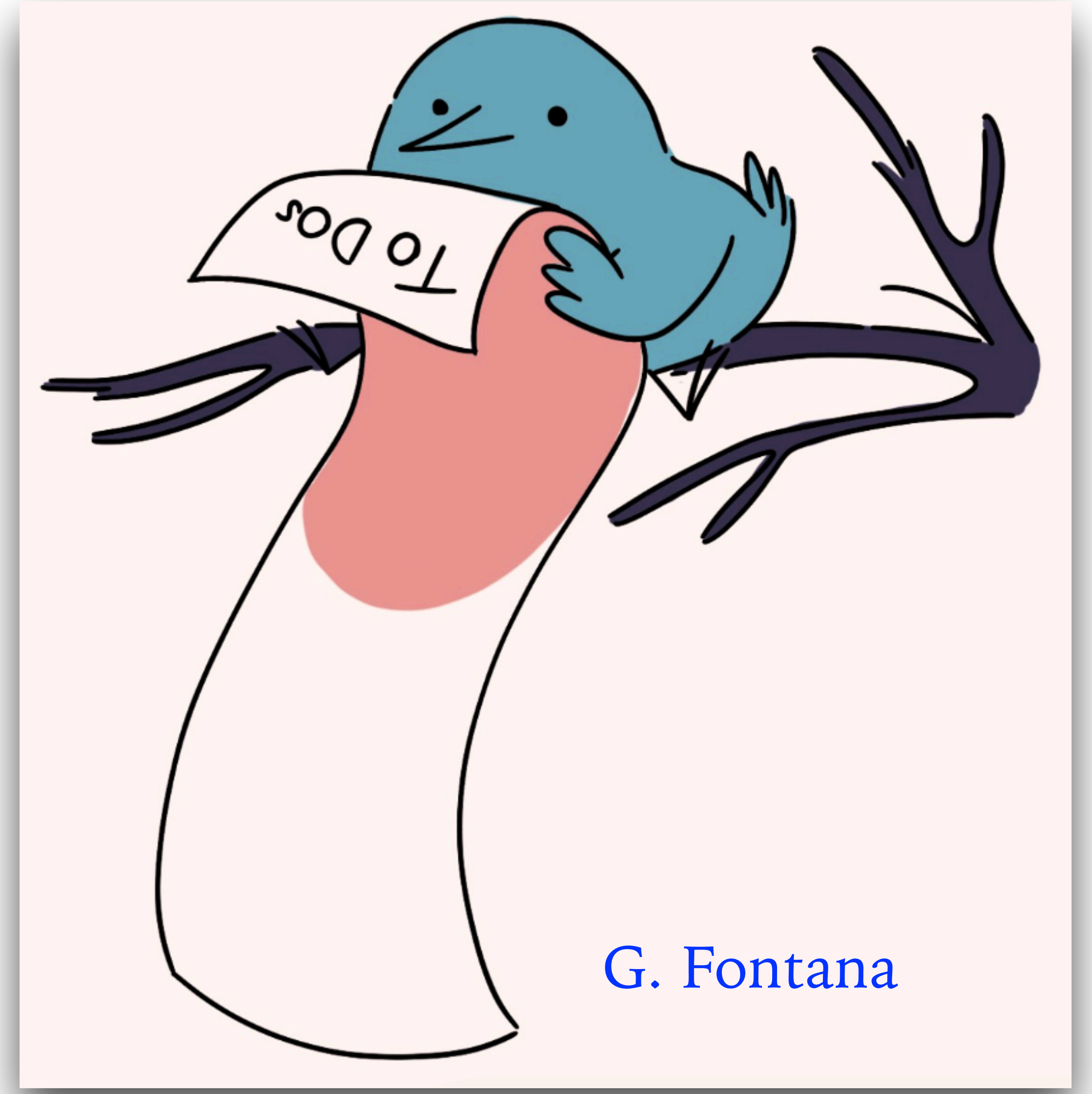


F. Dulat, A. Lazopoulos, B. Mistlberger 2018

- Motivations of scrutinisation:
  - To exercise our understanding of the Standard Model
  - To establish new sector of the Standard Model (Higgs)
  - To maximise sensitivity to new physics in measurements



G. Fontana

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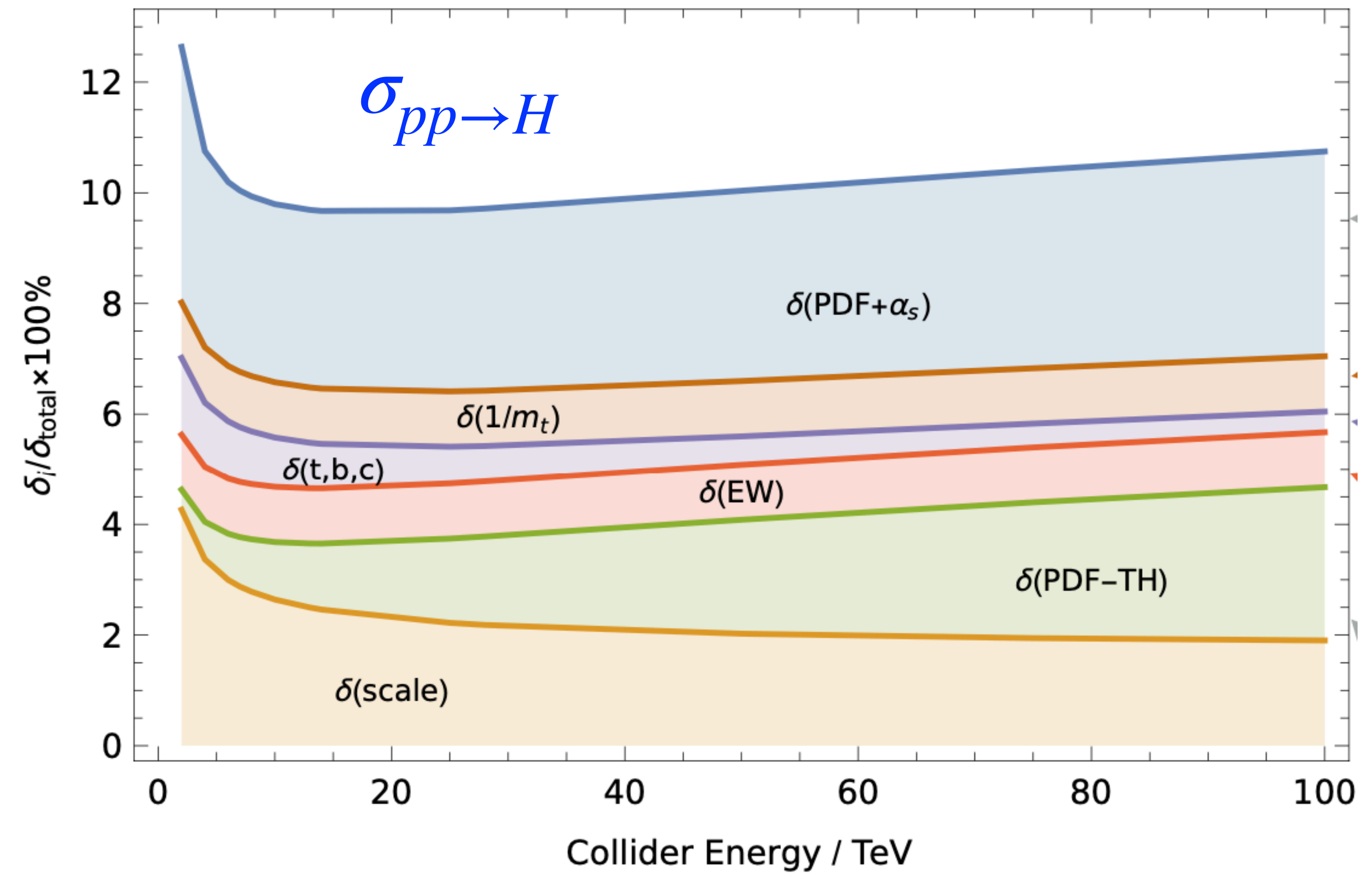
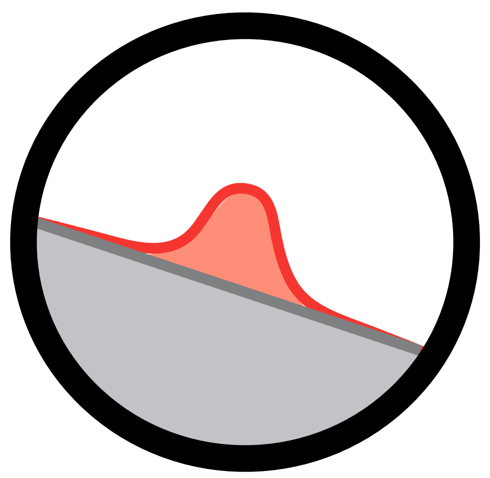
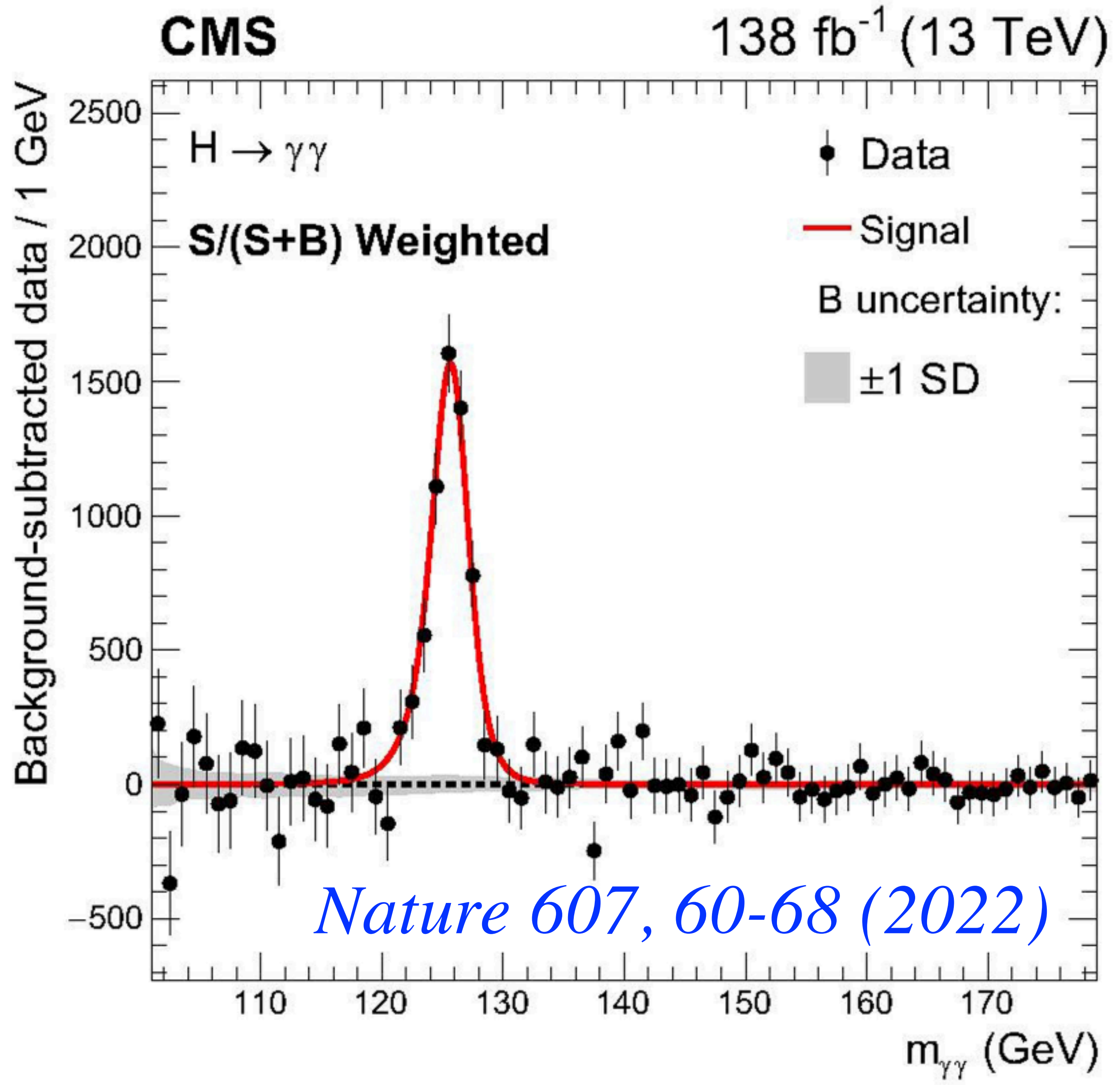


F. Dulat, A. Lazopoulos, B. Mistlberger 2018

➤Direct discovery for new channels and new resonants





Nature 607, 60-68 (2022)

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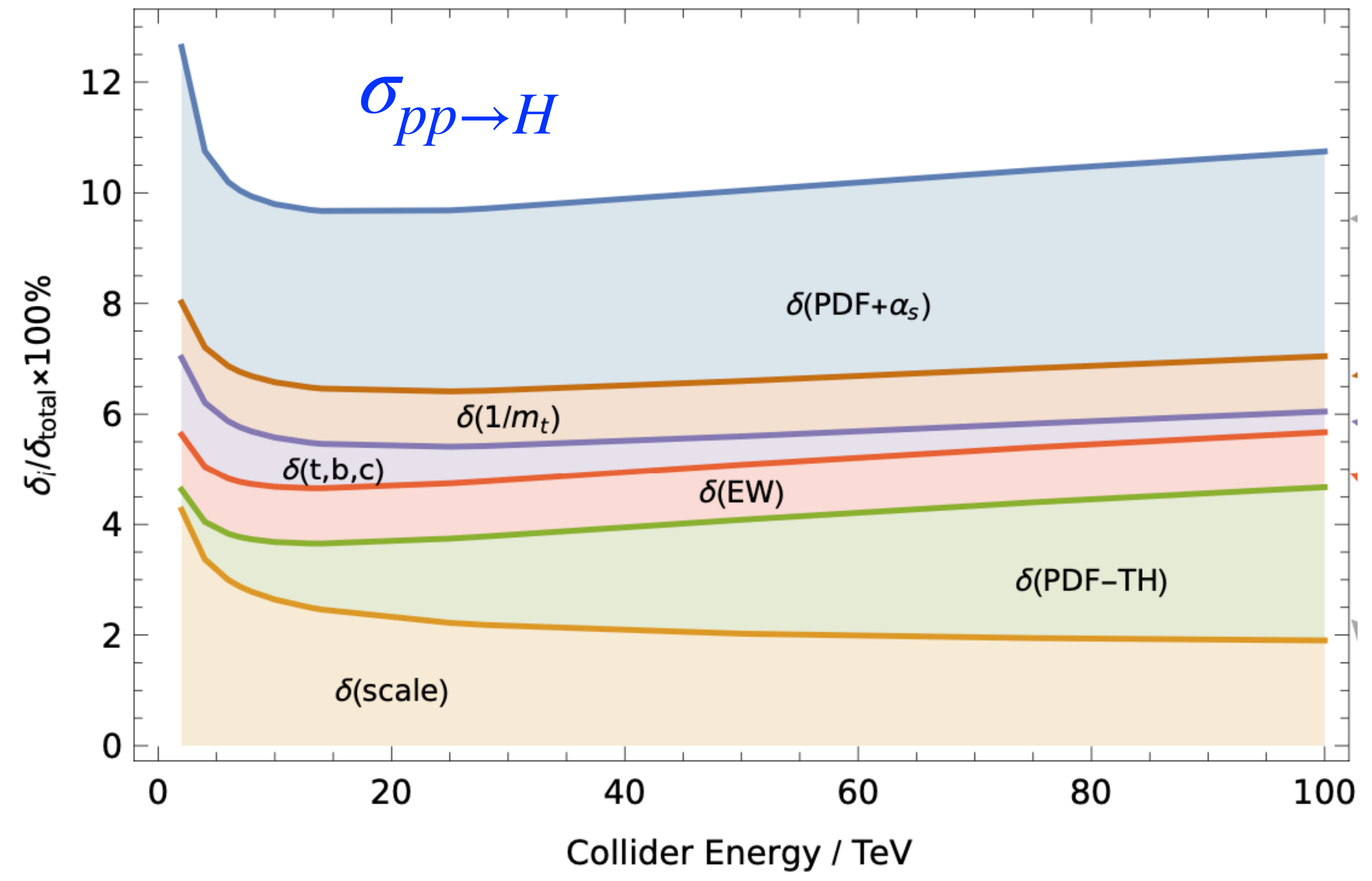
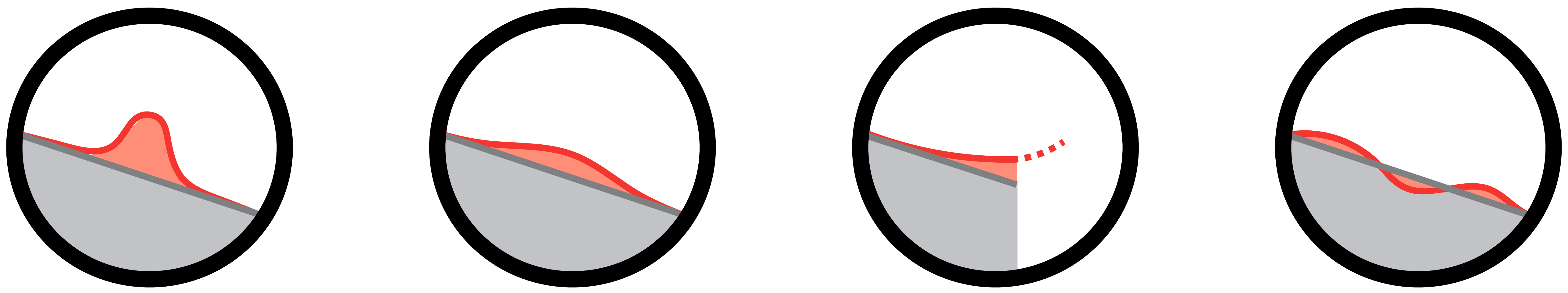


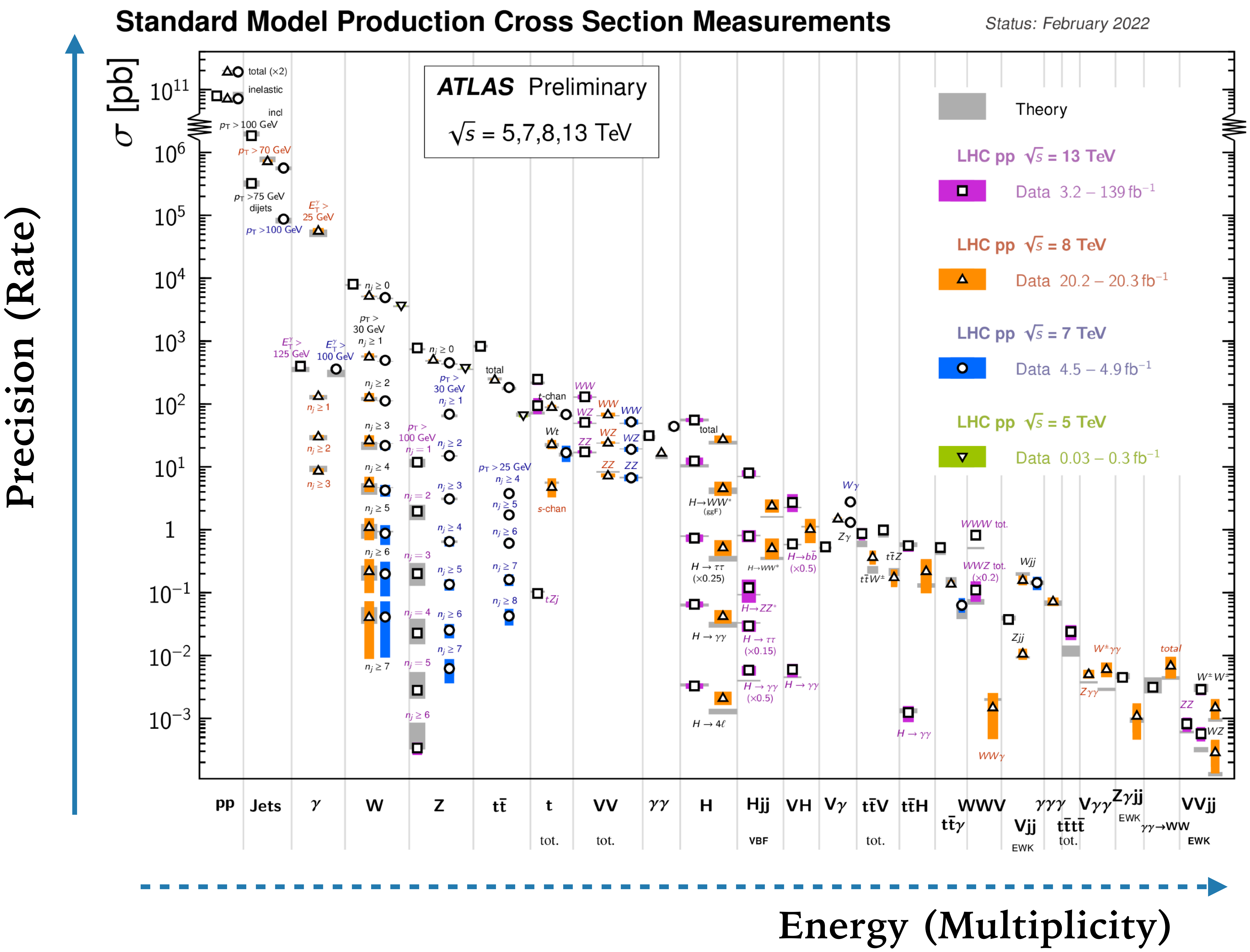
F. Dulat, A. Lazopoulos, B. Mistlberger 2018

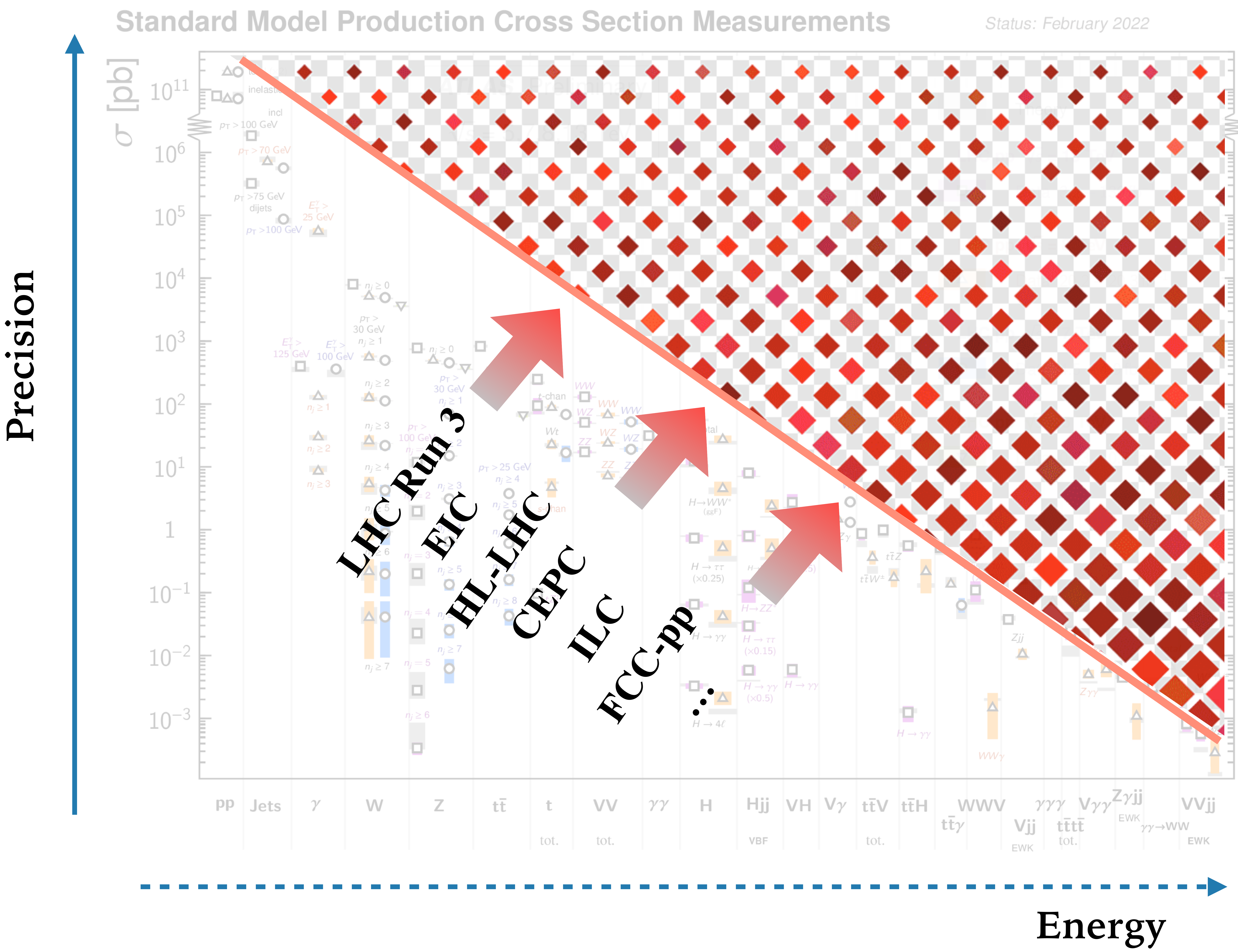
- Direct discovery for new channels and new resonants
- Indirect discovery with high precision
  - Wide resonance, Prepeak uptrend, Shape distortion

$$E - T_{SM} \propto \frac{1}{\Lambda_{BSM}^2}$$

$$(E \pm \delta E) - (T_{SM} \pm \delta T_{SM}) \propto \frac{1}{\Lambda_{BSM}^2}$$



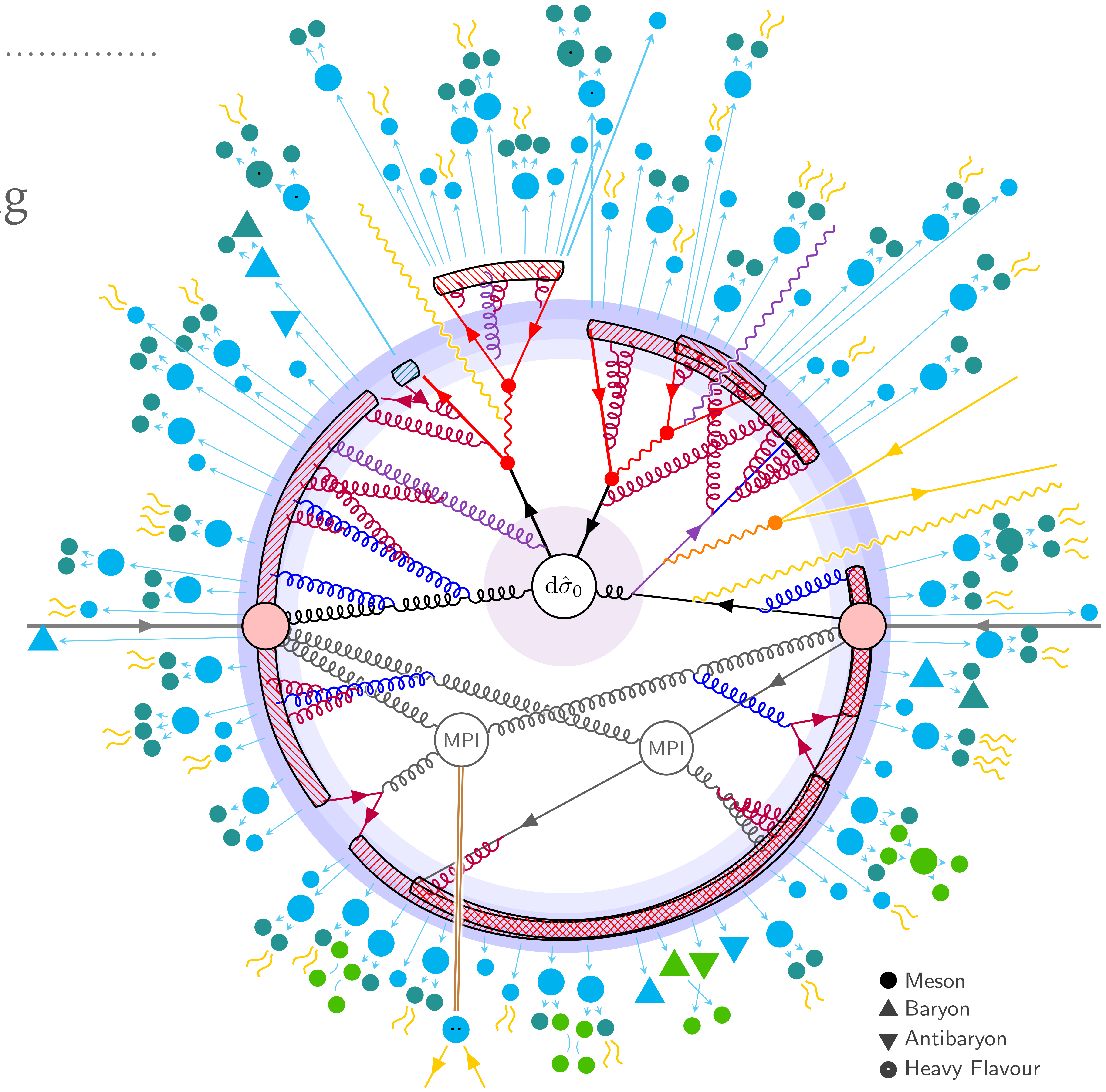

Standard Model Production Cross Section Measurements
Status: February 2022
ATLAS Preliminary
√s = 5,7,8,13 TeV
σ [pb]
Theory
LHC pp √s = 13 TeV
Data 3.2 – 139 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 5 TeV
Data 0.03 – 0.3 fb⁻¹
pp
Jets
γ
W
Z
tt̄
t
tot.
VV
tot.
γγ
H
Hjj
VBF
VH
Vγ
tt̄V
tot.
tt̄H
tt̄γ
WWV
Vjj
EWK
γγγ
tt̄tt̄
tot.
Vγγ
Zγjj
EWK
γγ→WW
VVjj
EWK
Precision (Rate)
Energy (Multiplicity)



Standard Model Production Cross Section Measurements
Status: February 2022
Precision
Energy
LHC Run 3
EIC
HL-LHC
CEPC
ILC
FCC-pp
...

Collider Event in Theorist's Eye

➤ The idea of factorisation in Quantum Field Theory plays important role to help theorists understanding complex high energy processes:



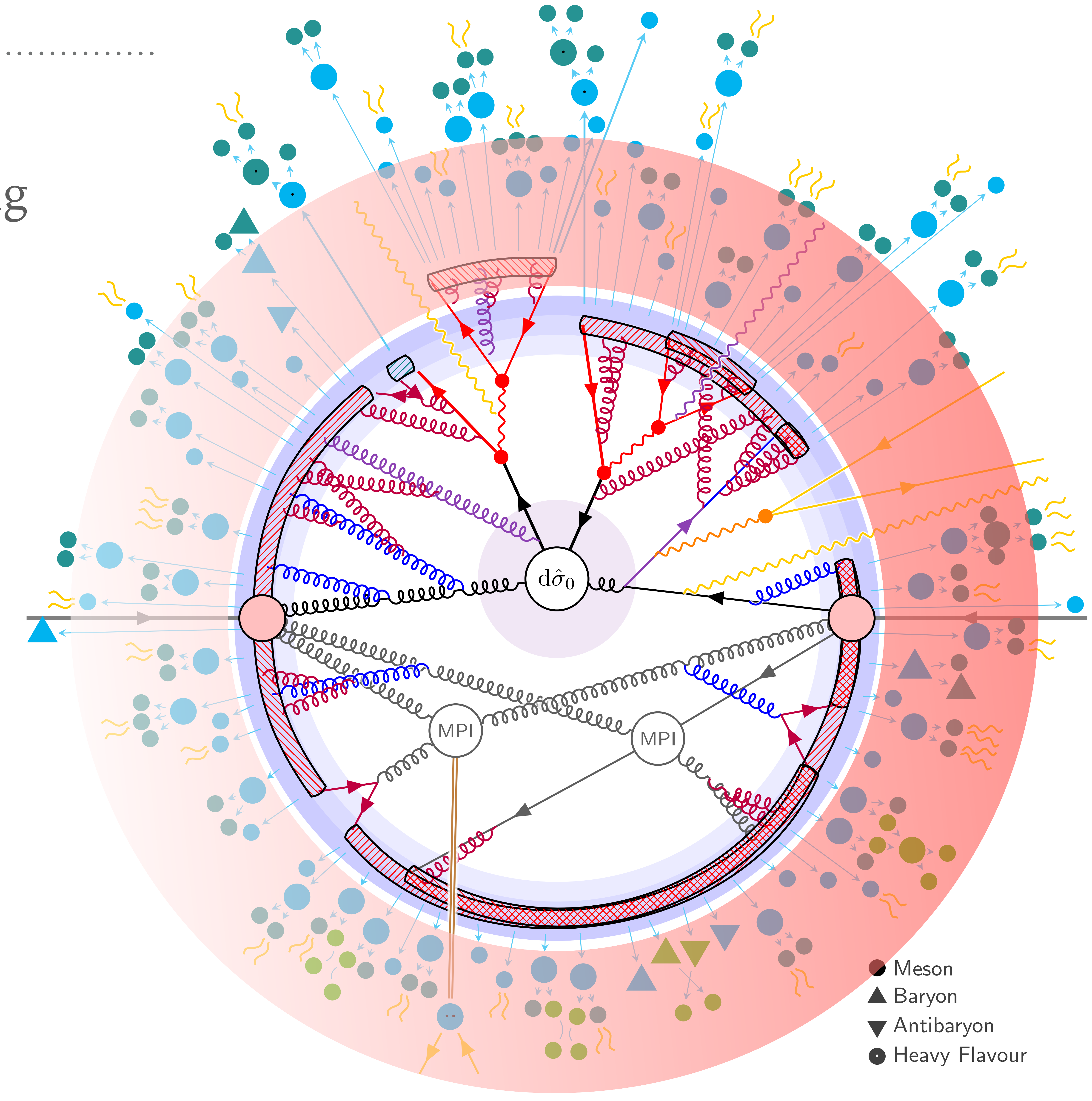
PYTHIA 8.3

Collider Event in Theorist's Eye

➤ The idea of factorisation in Quantum Field Theory plays important role to help theorists understanding complex high energy processes:

Time ordering

Hadronisation



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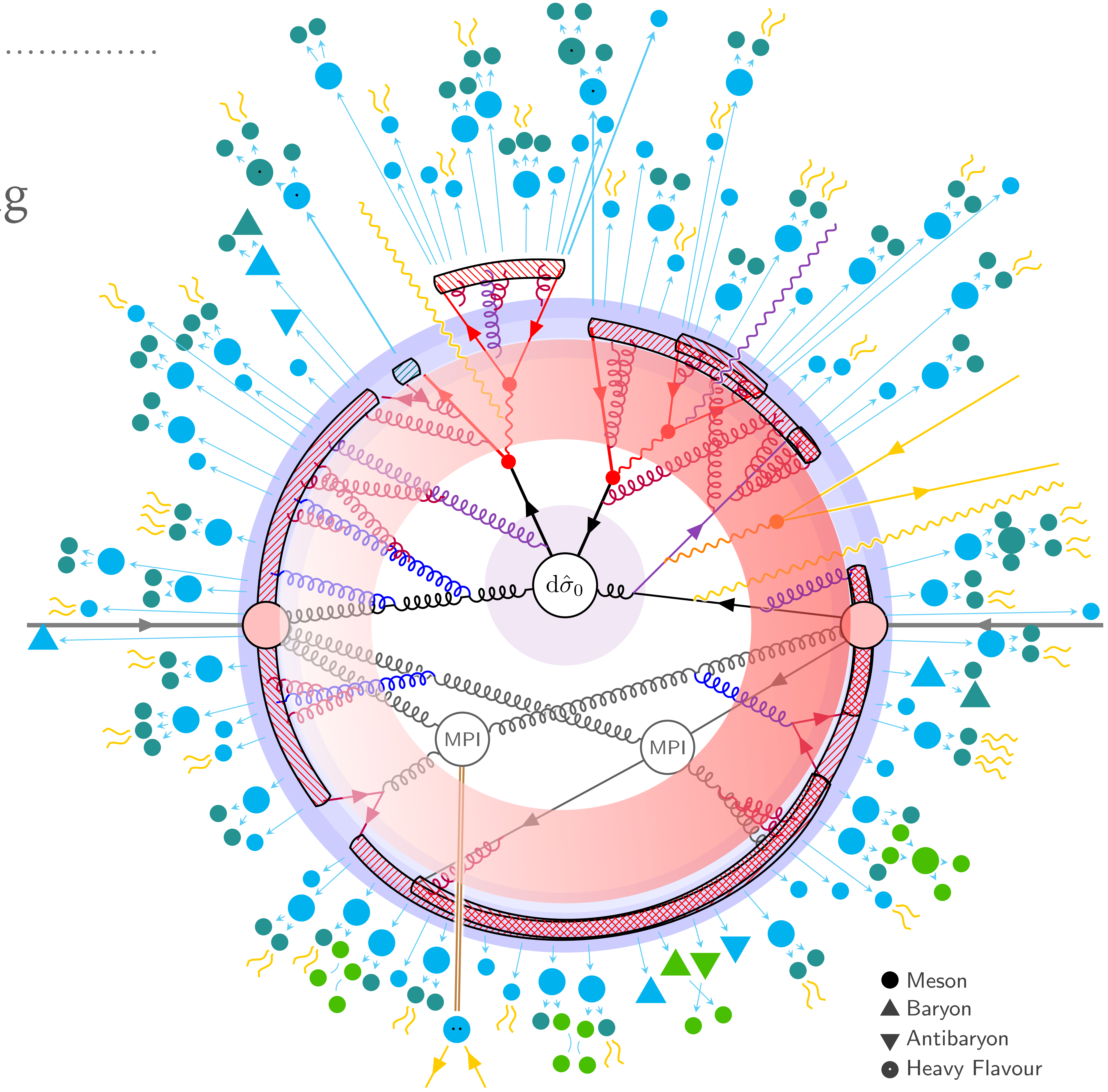

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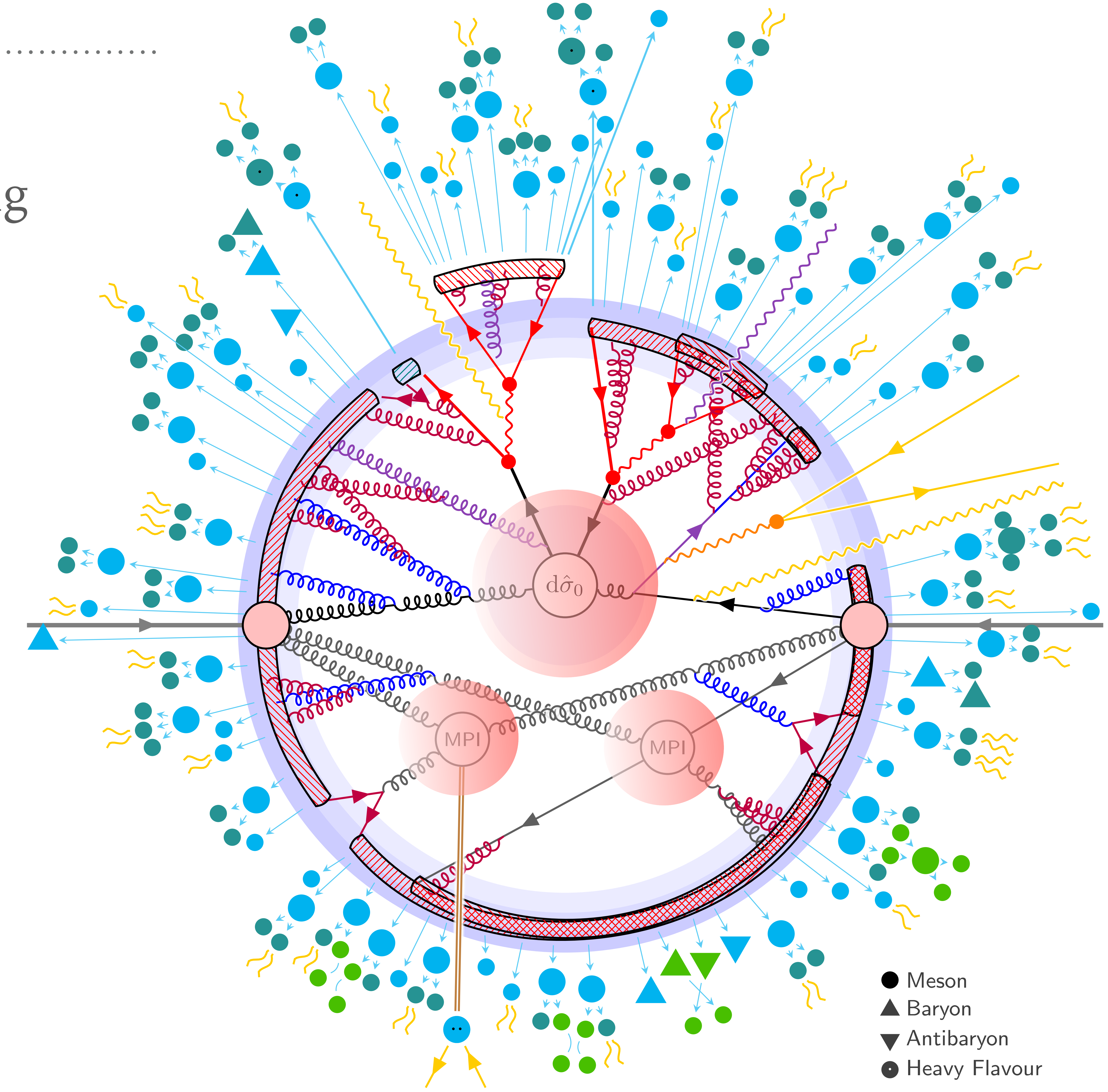

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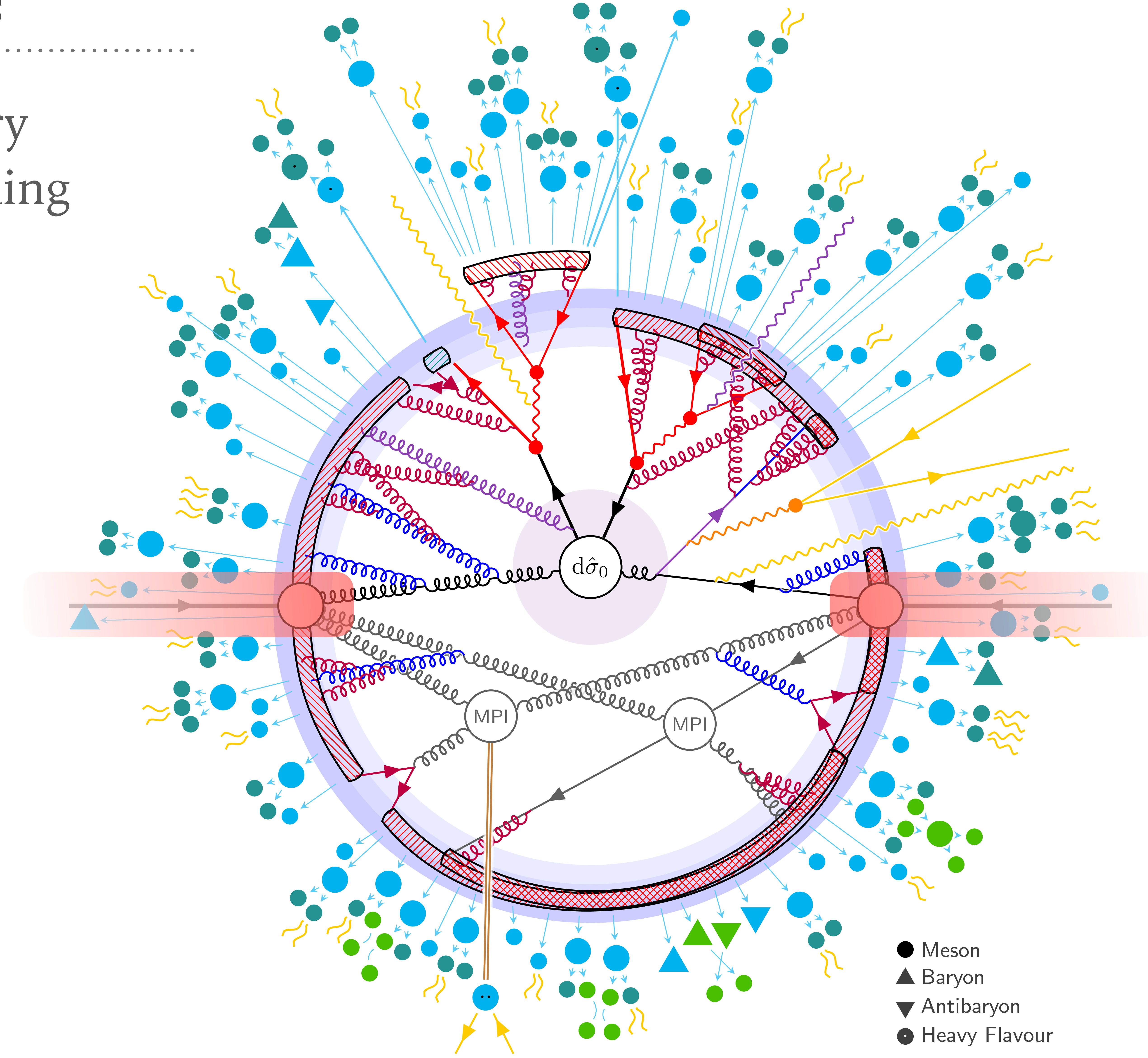
Hard Scattering

Proton→Parton



PYTHIA 8.3

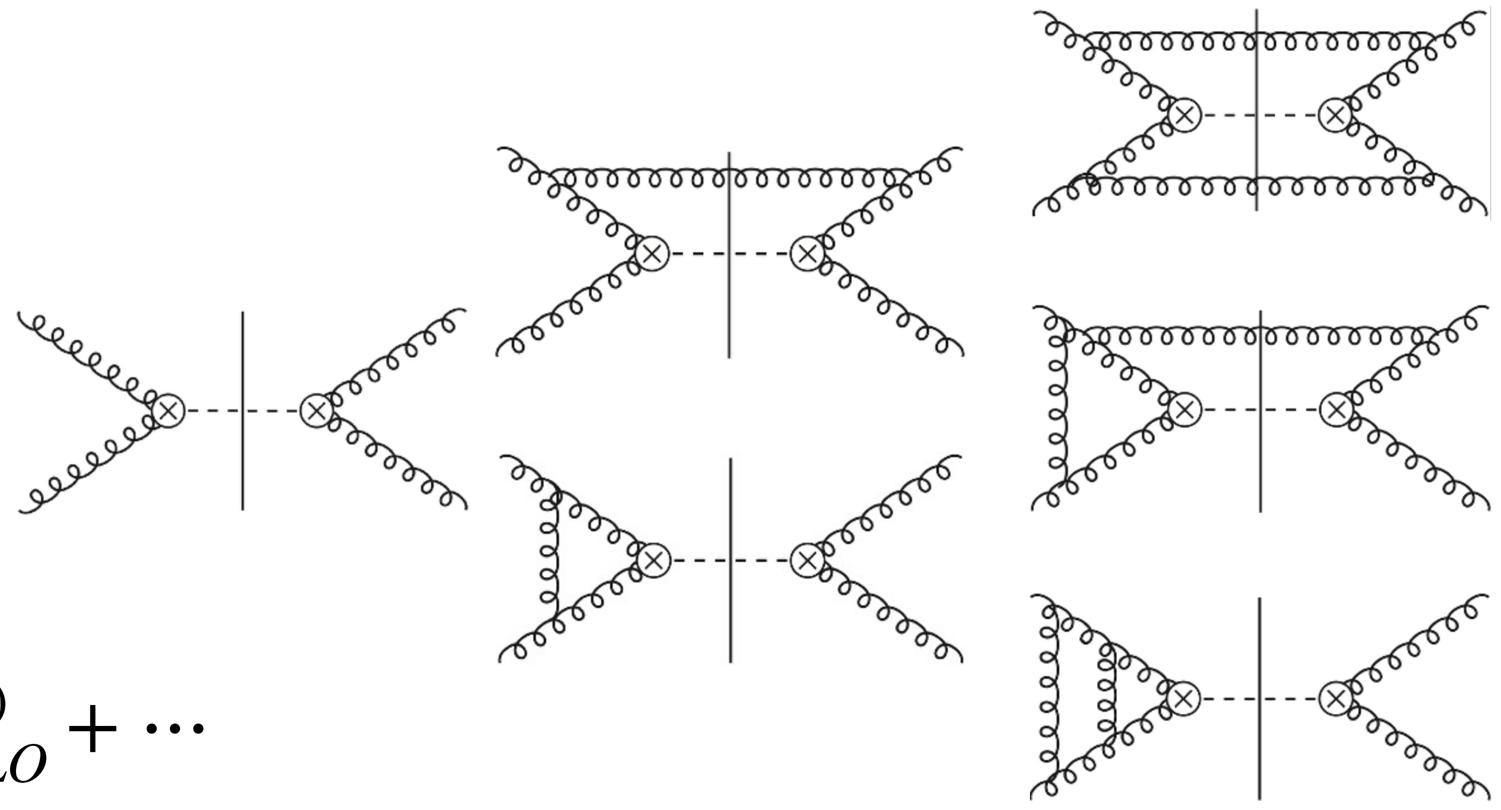
Theory Tools for Precision Predictions

General Tools (perturbative-QFT)

$m|_{\geq 1} \rightarrow n|_{\geq 1}$

Hard Scattering

Parton Shower



$$Q^2 \frac{\mathrm{d}\alpha_S}{\mathrm{d}Q^2} = \beta(\alpha_S) = -\alpha_S^2 \left(b_0 + b_1 \alpha_S + \cdots\right)$$

$$\hat{\sigma} = \hat{\sigma}_{LO}^{(0,0)} + \left(\frac{\alpha}{2\pi}\right)\hat{\sigma}_{NLO}^{(0,1)} + \left(\frac{\alpha_S}{2\pi}\right)\hat{\sigma}_{NLO}^{(1,0)} + \left(\frac{\alpha_S}{2\pi}\right)^2 \hat{\sigma}_{NNLO}^{(2,0)} + \cdots$$

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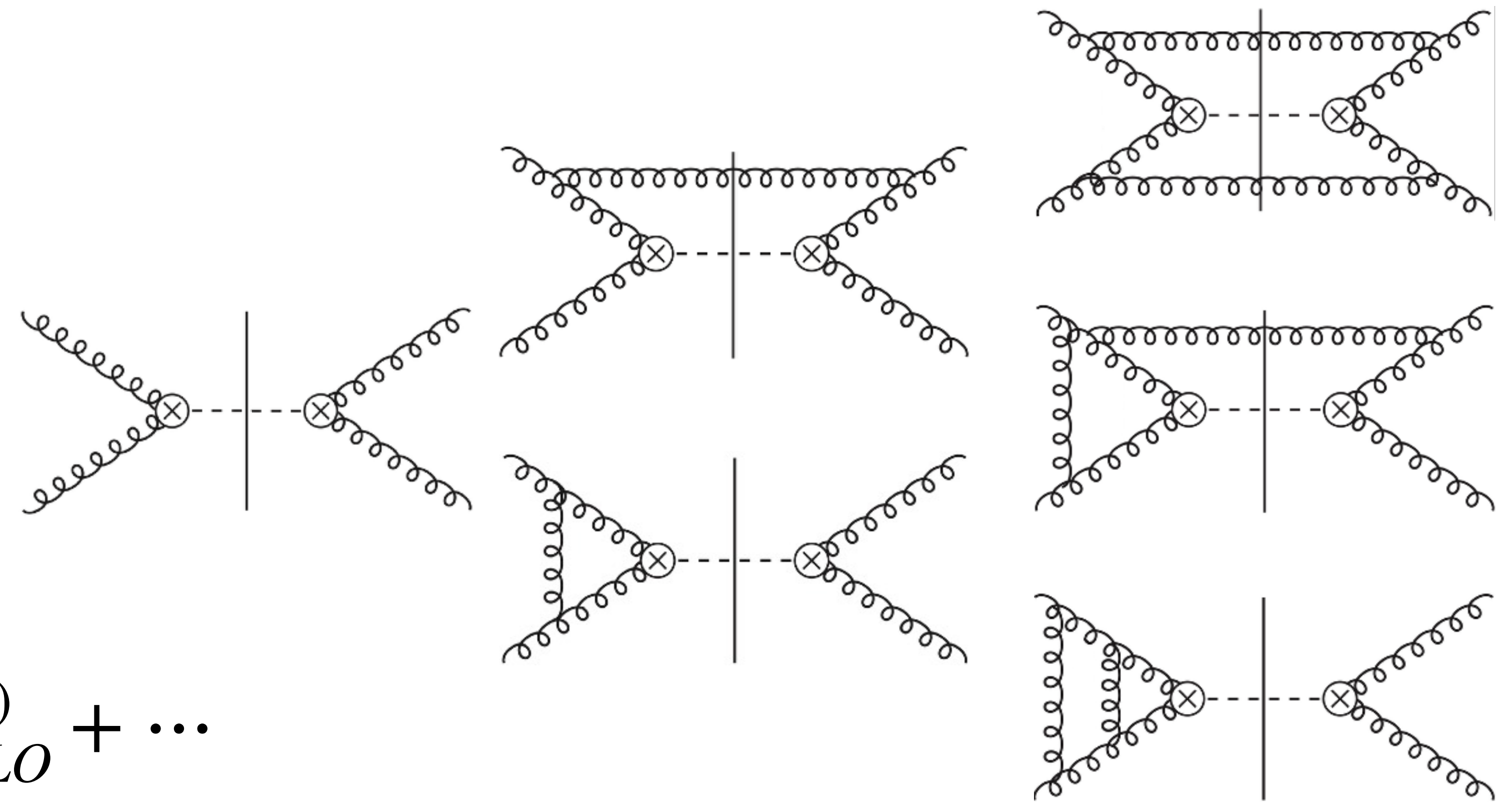

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Special Tools (non-perturbative-QFT)

m_q

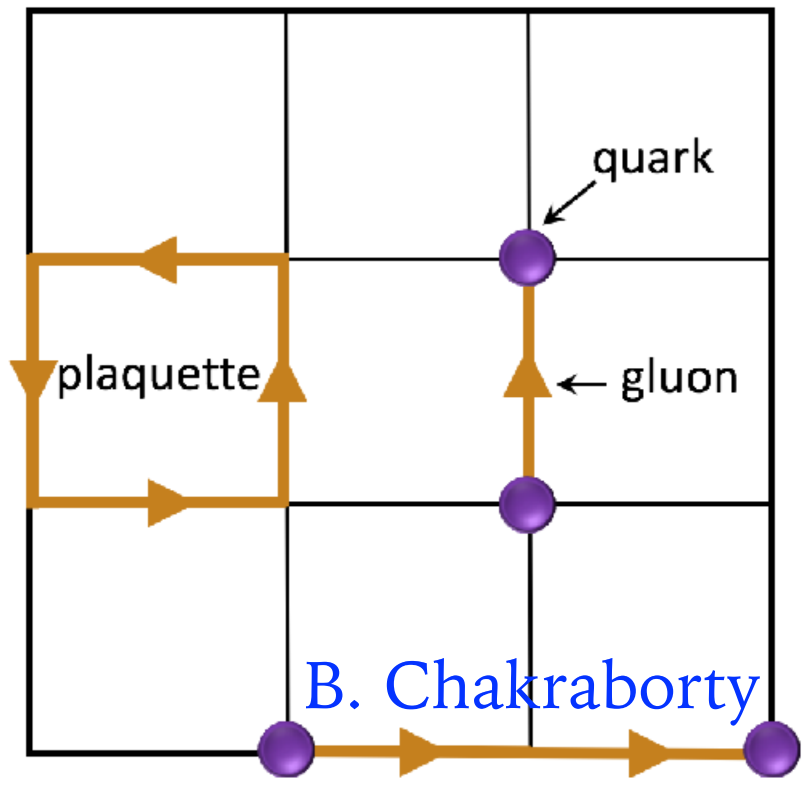
Proton → Parton

a_μ^{HVP}

α_S

CKM

$(\Lambda/Q)^n$



Theory Tools for Precision Predictions

General Tools (perturbative-QFT)

$m|_{\geq 1} \to n|_{\geq 1}$

Hard Scattering

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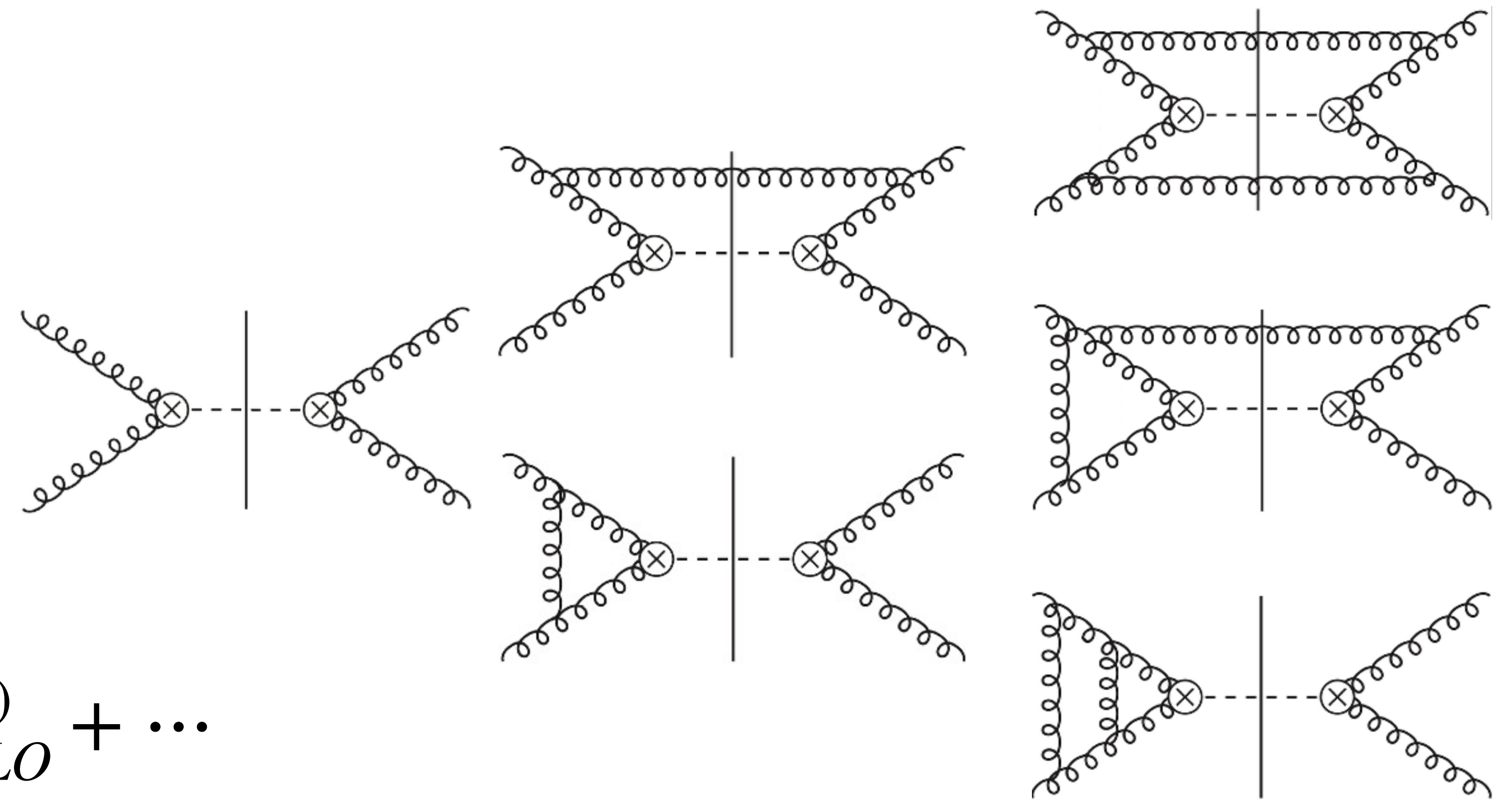

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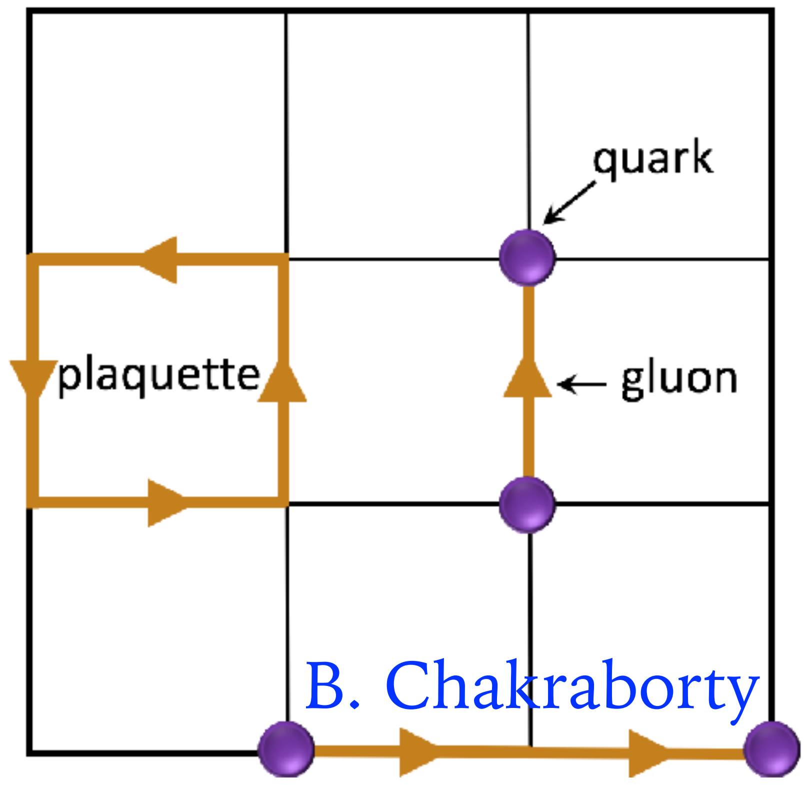


Dedicate Tools (fitting)

Theory + Experiment

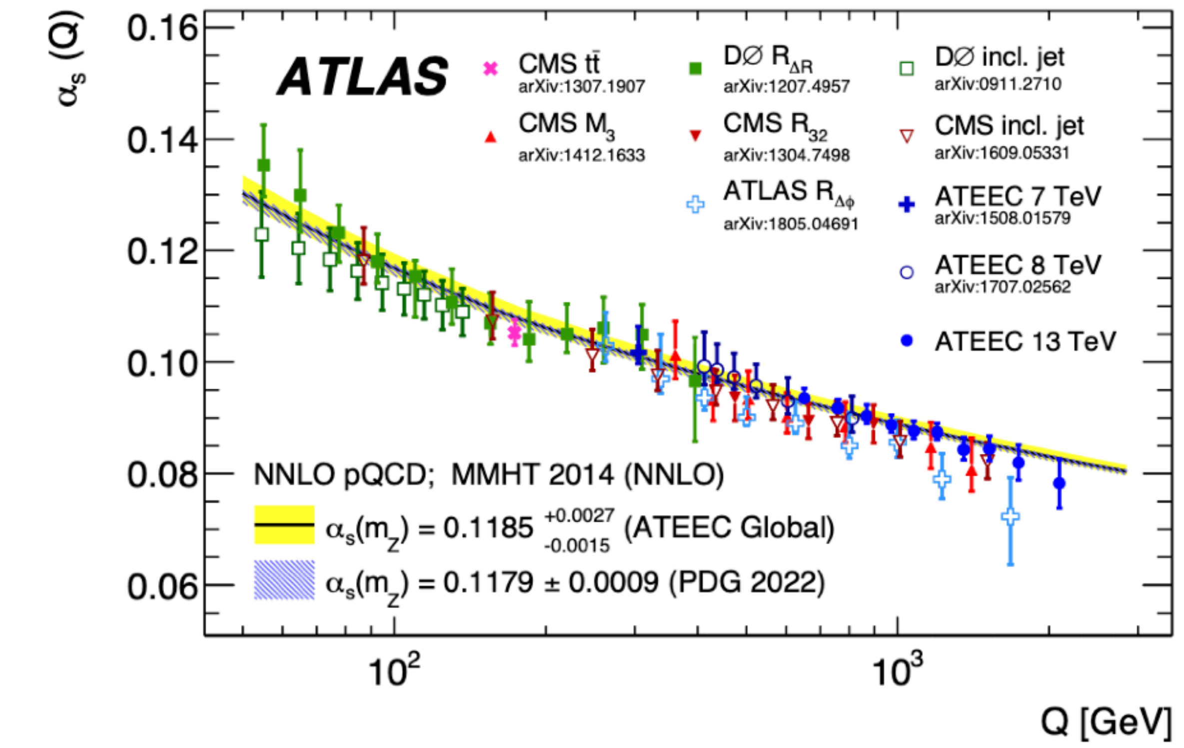
To fit NP model

α_S

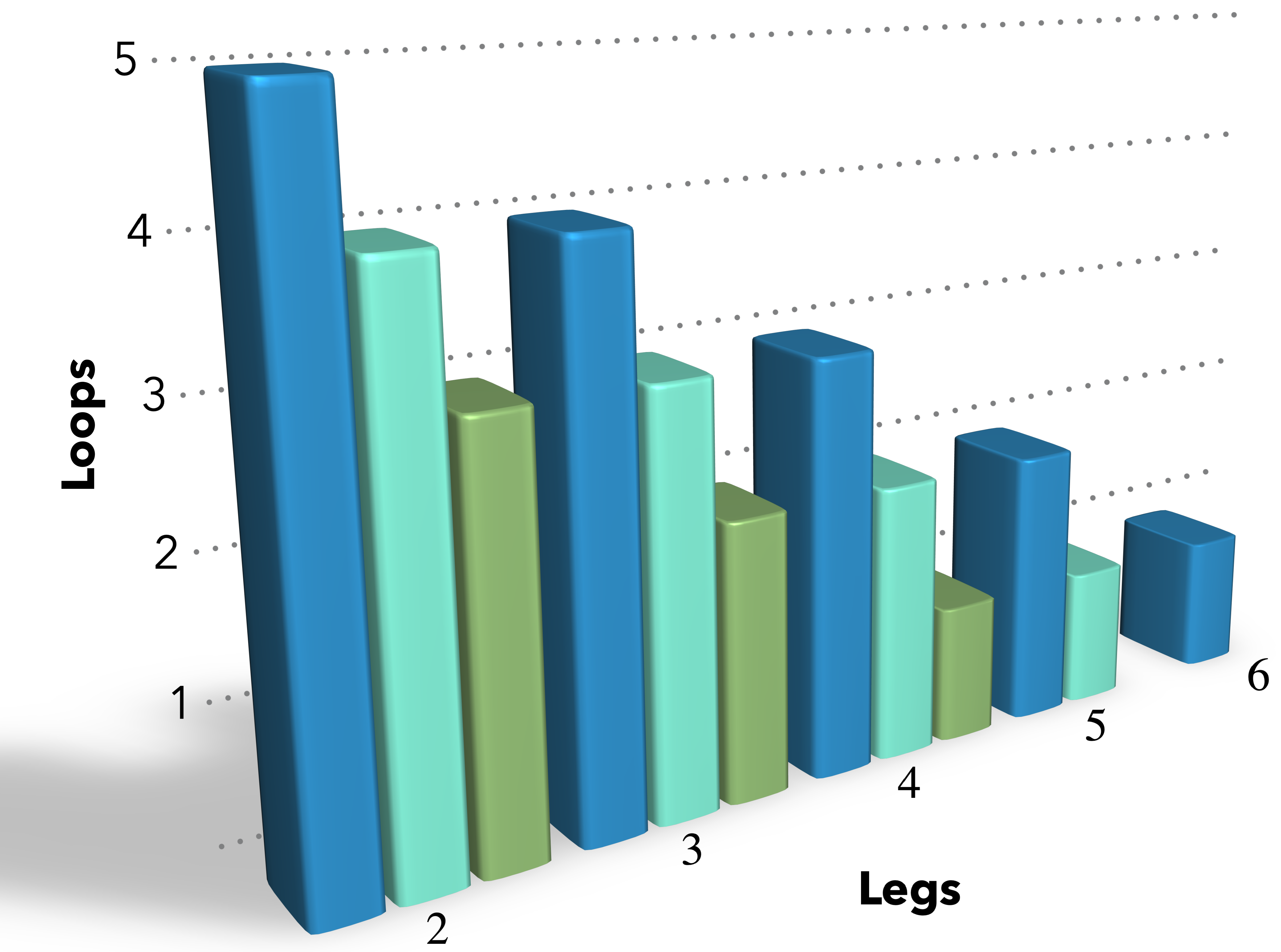
Proton → Parton

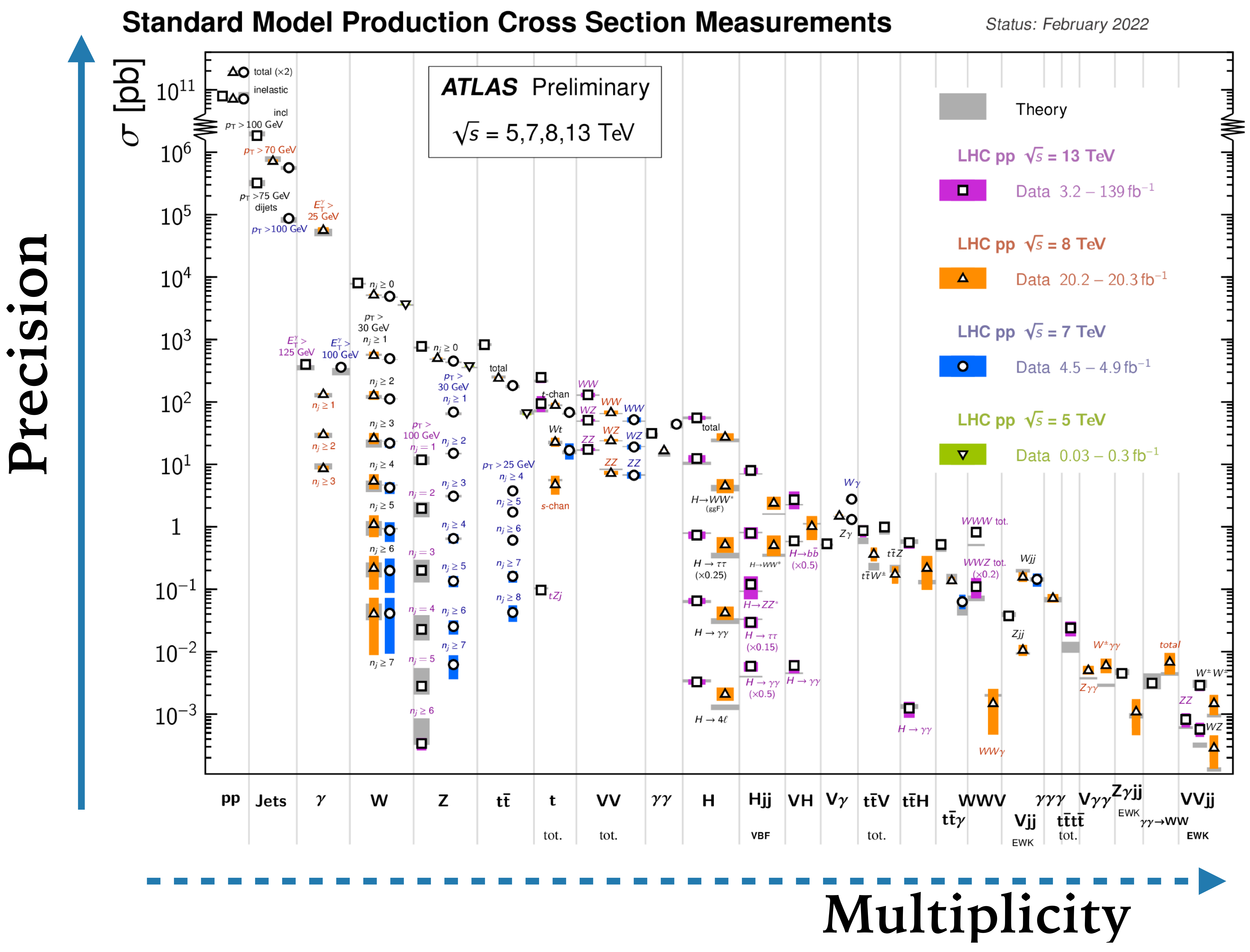
Hadronisation

Fragmentation



Perturbative QFT for Precision Predictions





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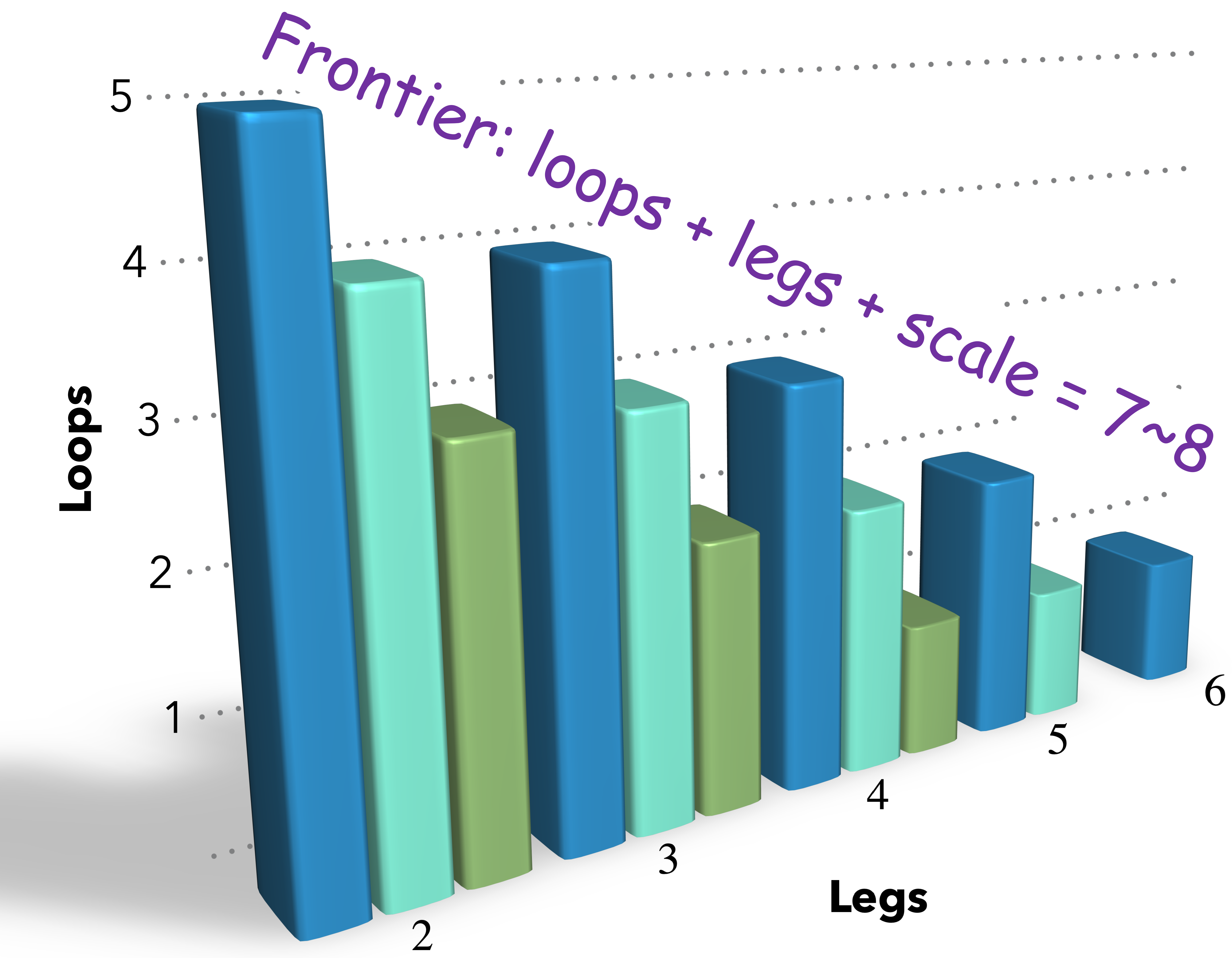
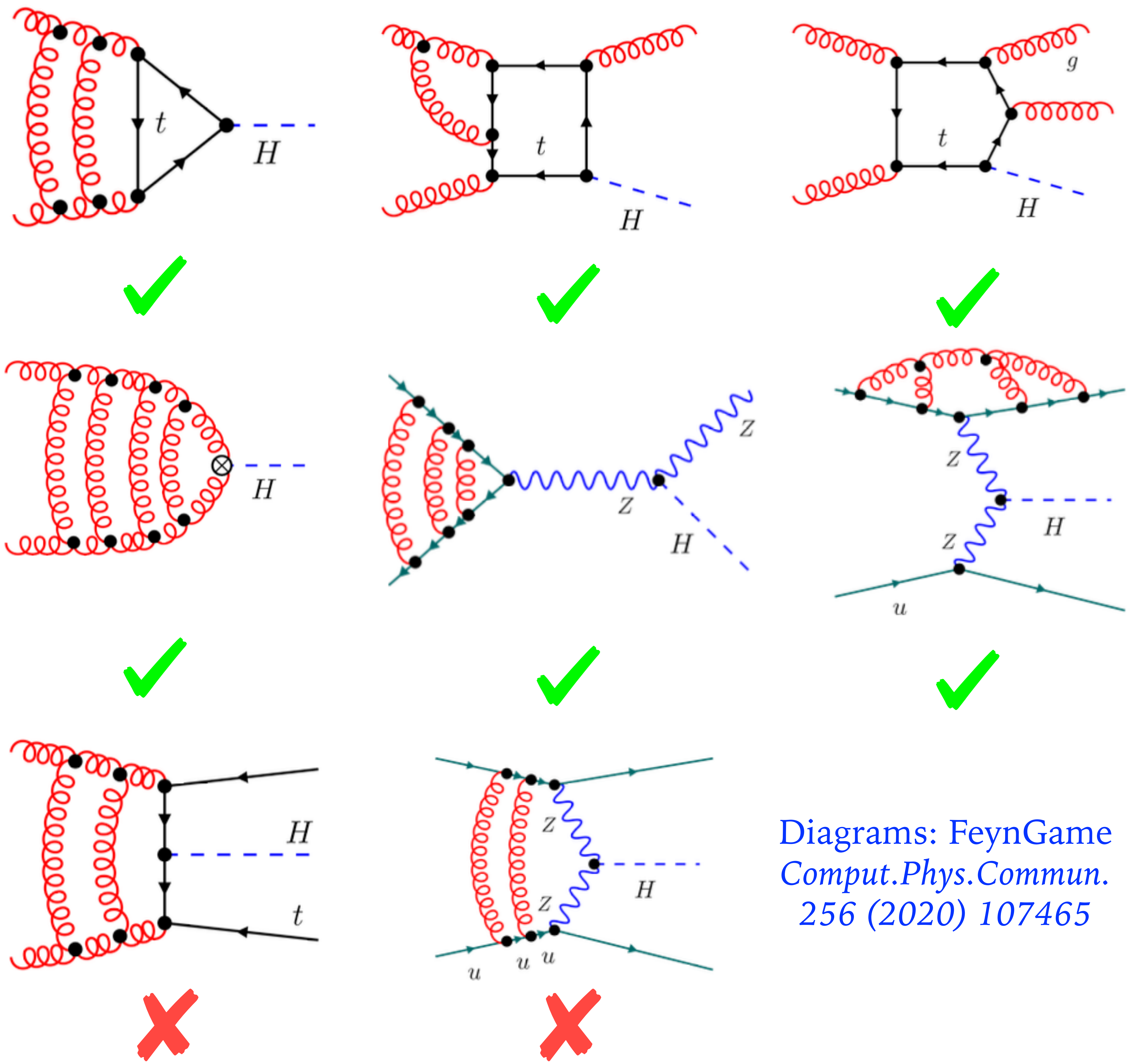
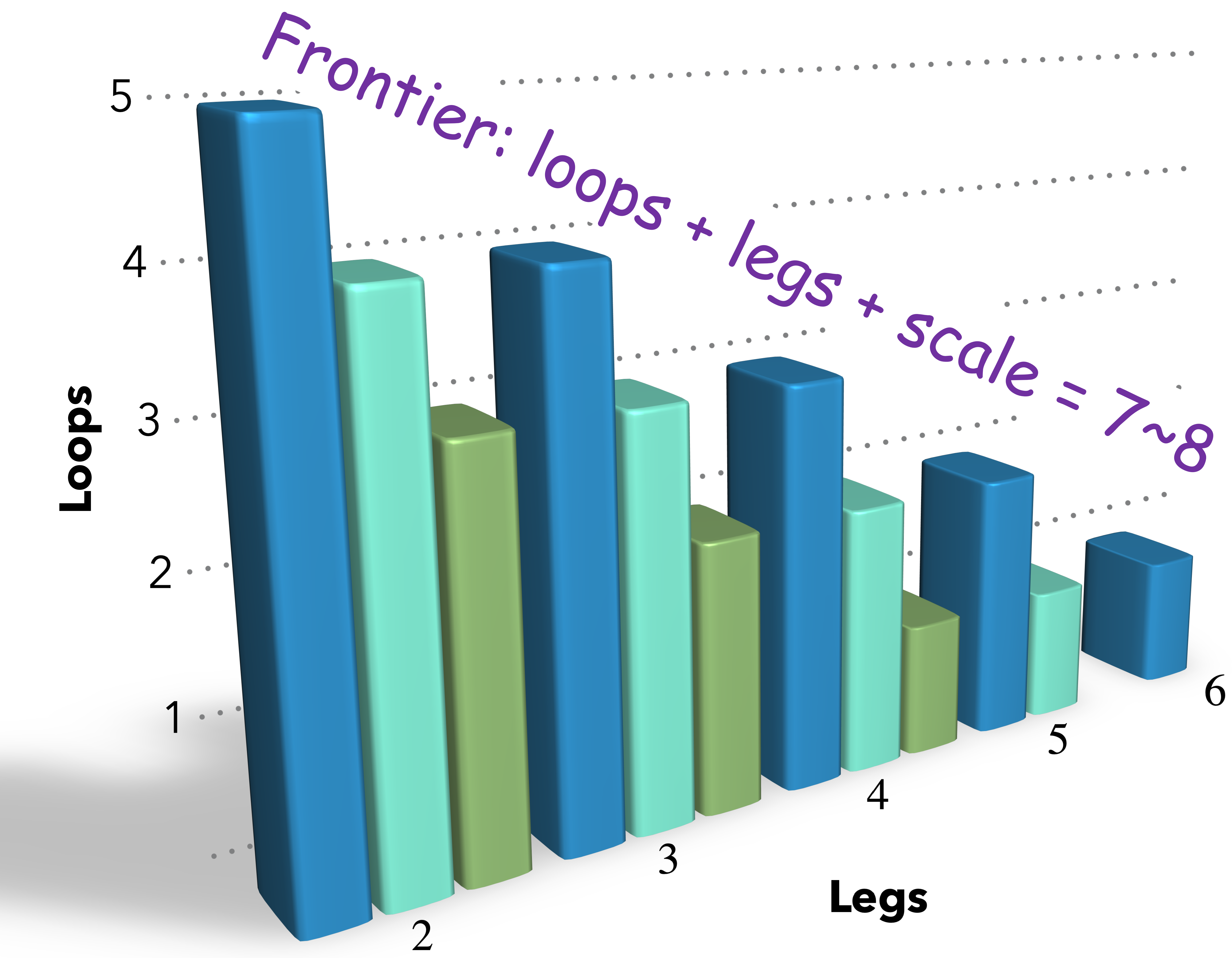




Diagrams: FeynGame
Comput.Phys.Commun. 256 (2020) 107465

Perturbative QFT for Precision Predictions



Generalised polylogarithms

Riemann zeta values

Elliptic functions

…

Unitarity

Generalised Unitarity

Recursion

Twistors

Differential equations

Integrand/Integral

Sector decomposition

Numerical unitarity

Finite field

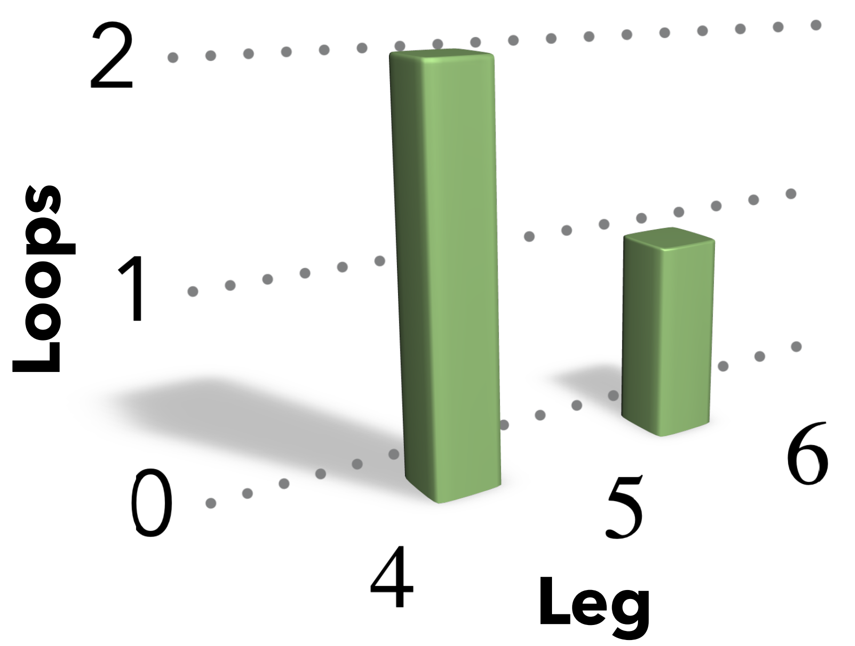
Auxiliary mass flow

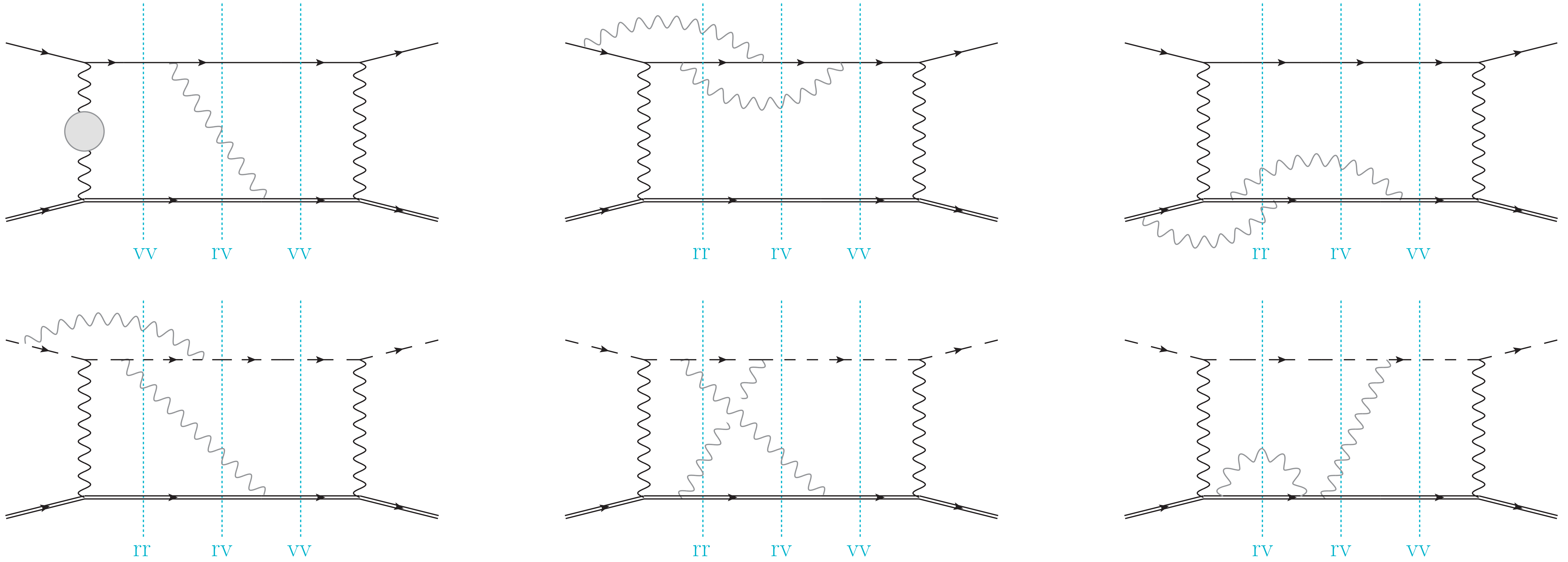
Neural network amplitude

…

Perturbative QFT for Precision Predictions

$e\mu \to e\mu$ @NNLO QED





- Complete NNLO photon corrections via McMule framework
  - Full m_e and m_μ dependence of RR, RV and factorisable VV (top).
  - m_e effects in mixed VV (bottom) estimated via massification.
  - IR divergence handled by FKS^2 subtraction method.
  - Fully differential MC tool for MUonE experiment.
  - Key input to extract $\Delta\alpha_{\rm had}(Q^2)$ for $Q^2 < 0$.
  - Alternative dispersive approach from R-ratio to calculate a_μ^{HVP}.

A. Broggio, T. Engel, A. Ferroglia et. al. JHEP 01 (2023) 112

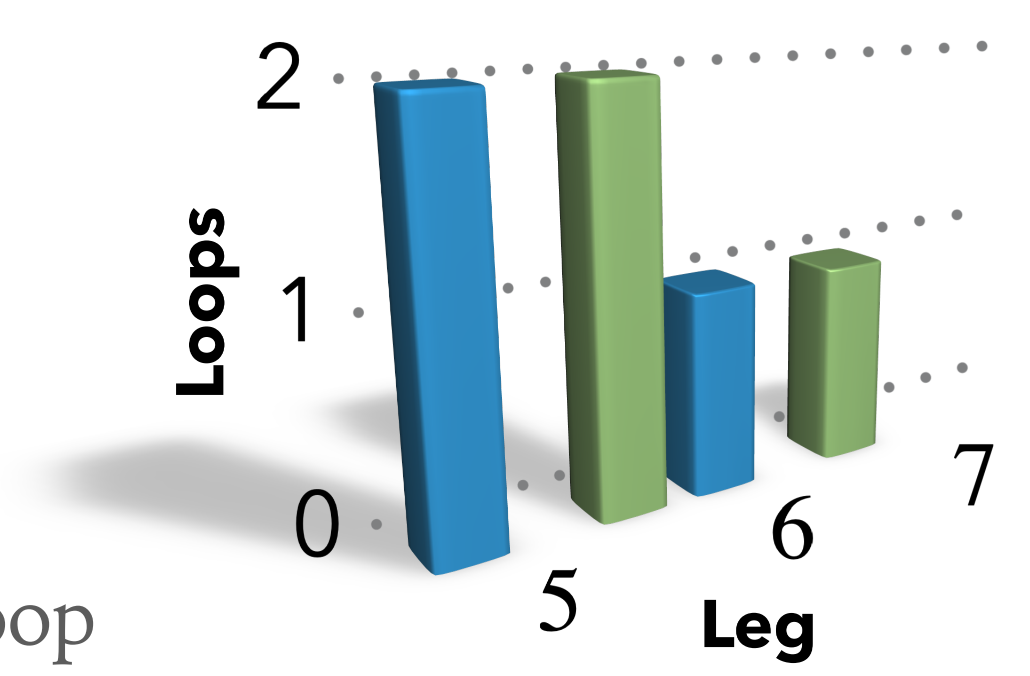
MUonE Fiducial	$\sigma/\mu b$ S1	$\sigma/\mu b$ S2	$\delta K^{(i)}/\%$ S1	$\delta K^{(i)}/\%$ S2
σ_0	106.44356	106.44356		
σ_1 −	106.99038(3)	102.86304(3)	0.51372(3)	−3.36377(3)
σ_1 +	107.41847(3)	103.18338(3)	0.91589(3)	−3.06283(3)
σ_2 −	106.97977(3)	102.88154(3)	−0.00992(4)	0.01799(4)
σ_2 +	107.41832(3)	103.19386(3)	−0.00013(4)	0.01016(4)

Perturbative QFT for Precision Predictions

$pp \to t\bar{t}W,\ \gamma JJ,\ t\bar{t}H$ @NNLO QCD

- Rapid progress of NNLO QCD corrections to $2 \to 3$ scattering at the LHC
  - Automation of tree and 1-loop scattering ME with OpenLoops.
  - Processes dependent calculation/approximation for 2-loop-5-leg ME:
    - Complete analytical amplitudes for $\gamma q\bar{q}gg$, $\gamma q\bar{q}Q\bar{Q}$ at 2-loop
    - Eikonal or massification approximation to estimate $Vt\bar{t}gg$, $Vt\bar{t}q\bar{q}$ @ 2-loop
  - Mature machinery of NNLO subtraction methods for event generator:
    - STRIPPER (Sector-improved), MATRIX (qT-slicing)

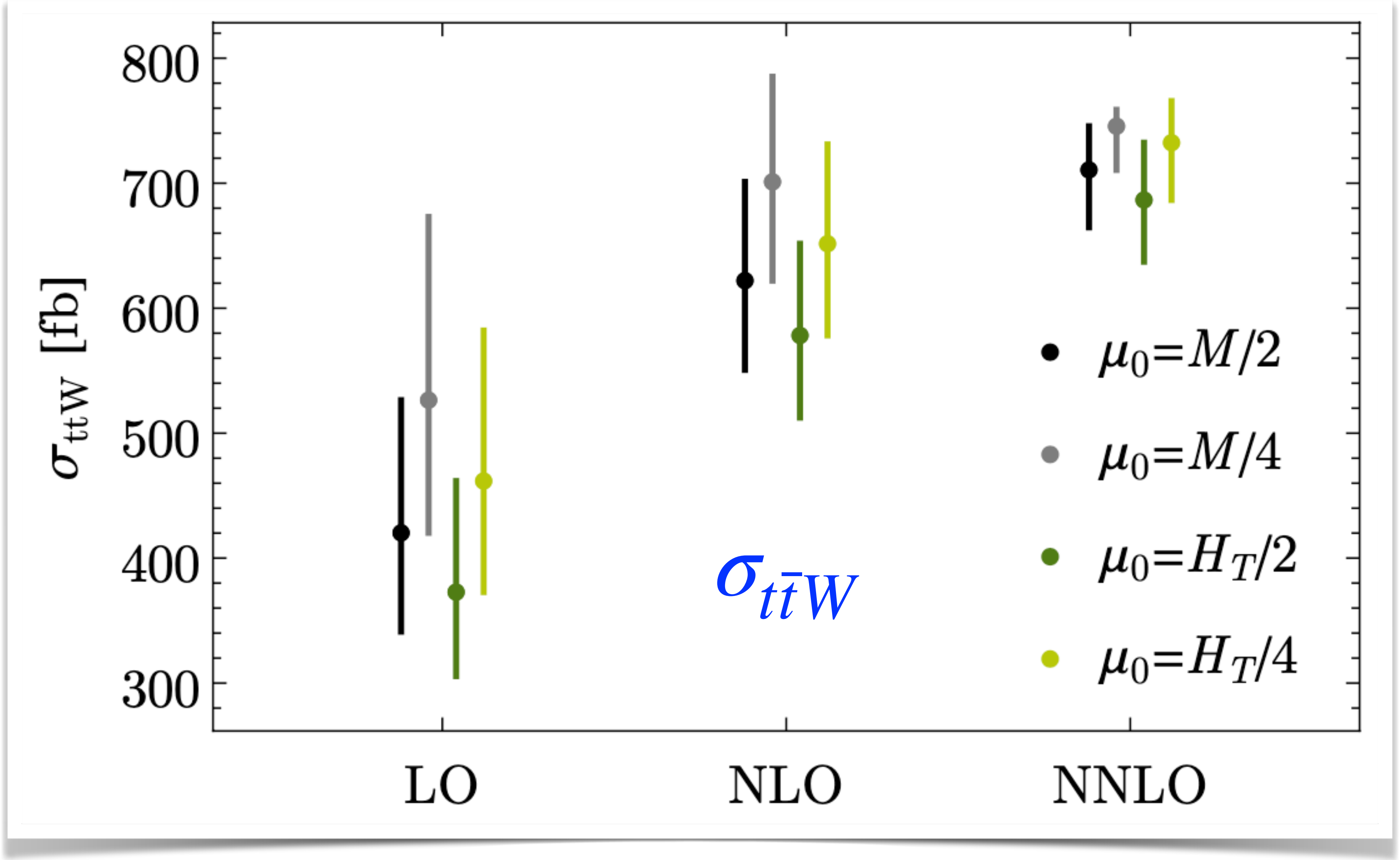
loops + legs + scale = 7~8



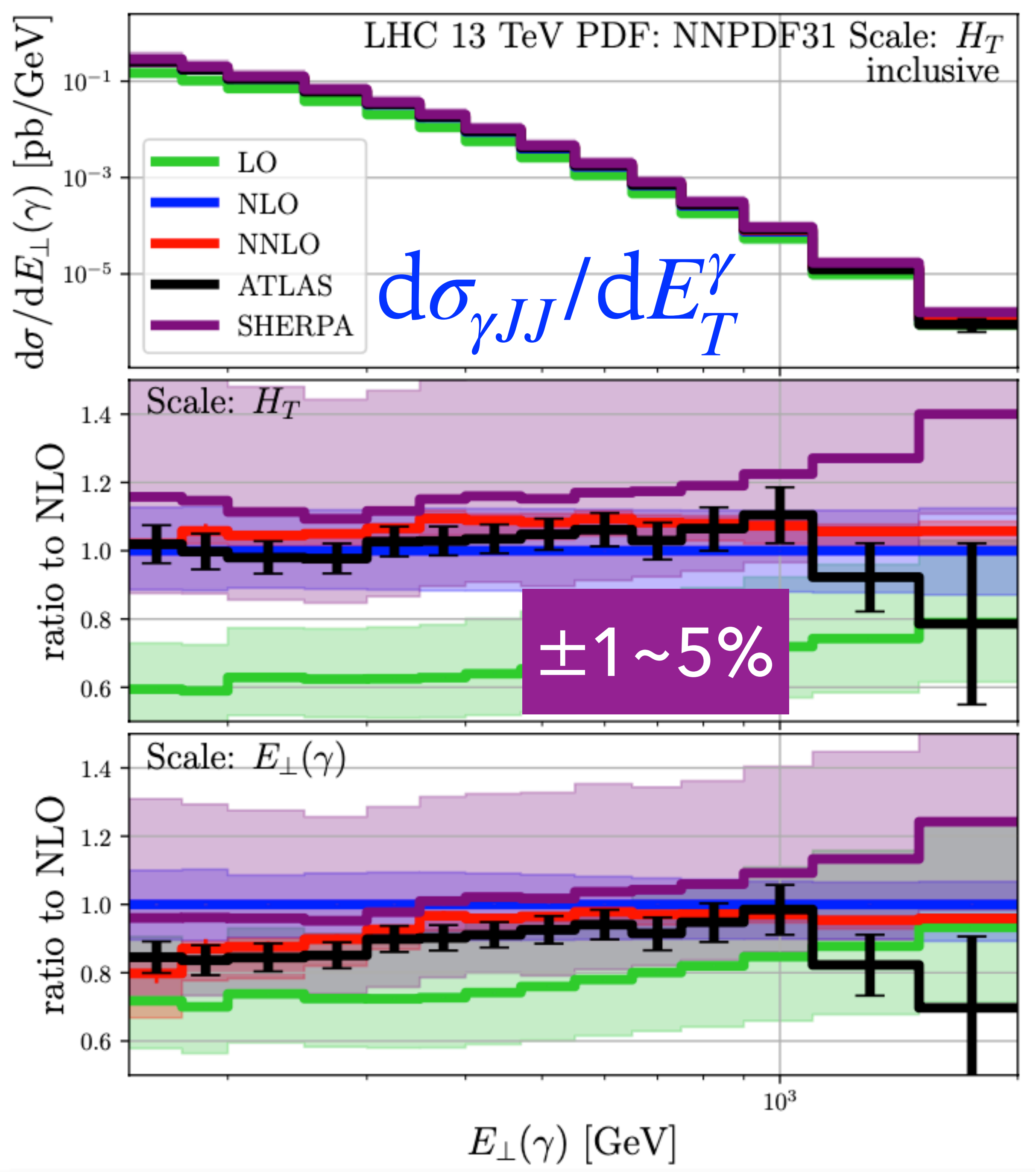
Also available @ NNLO

- $pp \to \gamma\gamma J$ ✓
- $pp \to JJJ$ ✓
- $pp \to \gamma\gamma\gamma$ ✓
- $pp \to Wb\bar{b}$ ✓

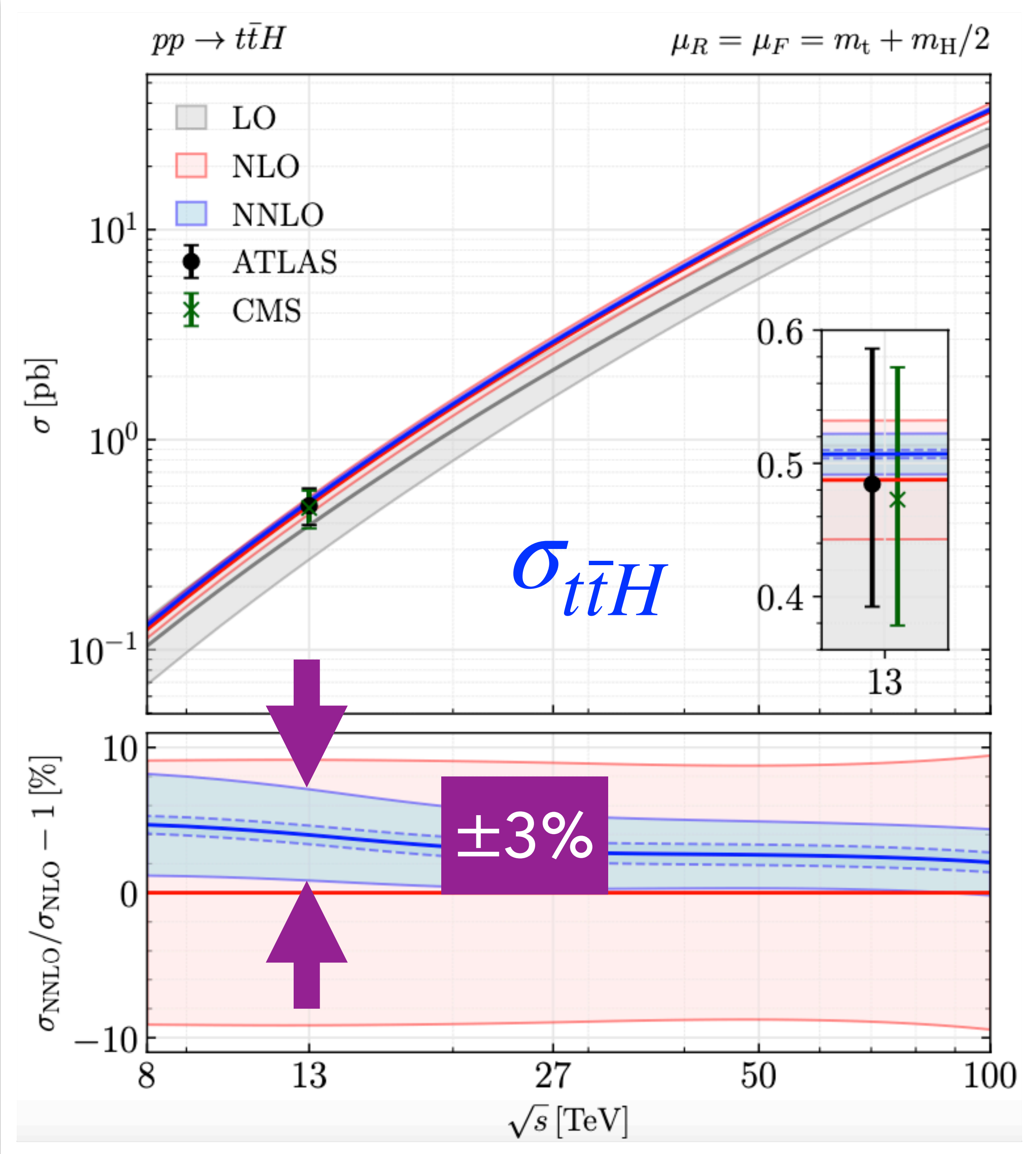
L. Buonocore et. al. 2306.16311



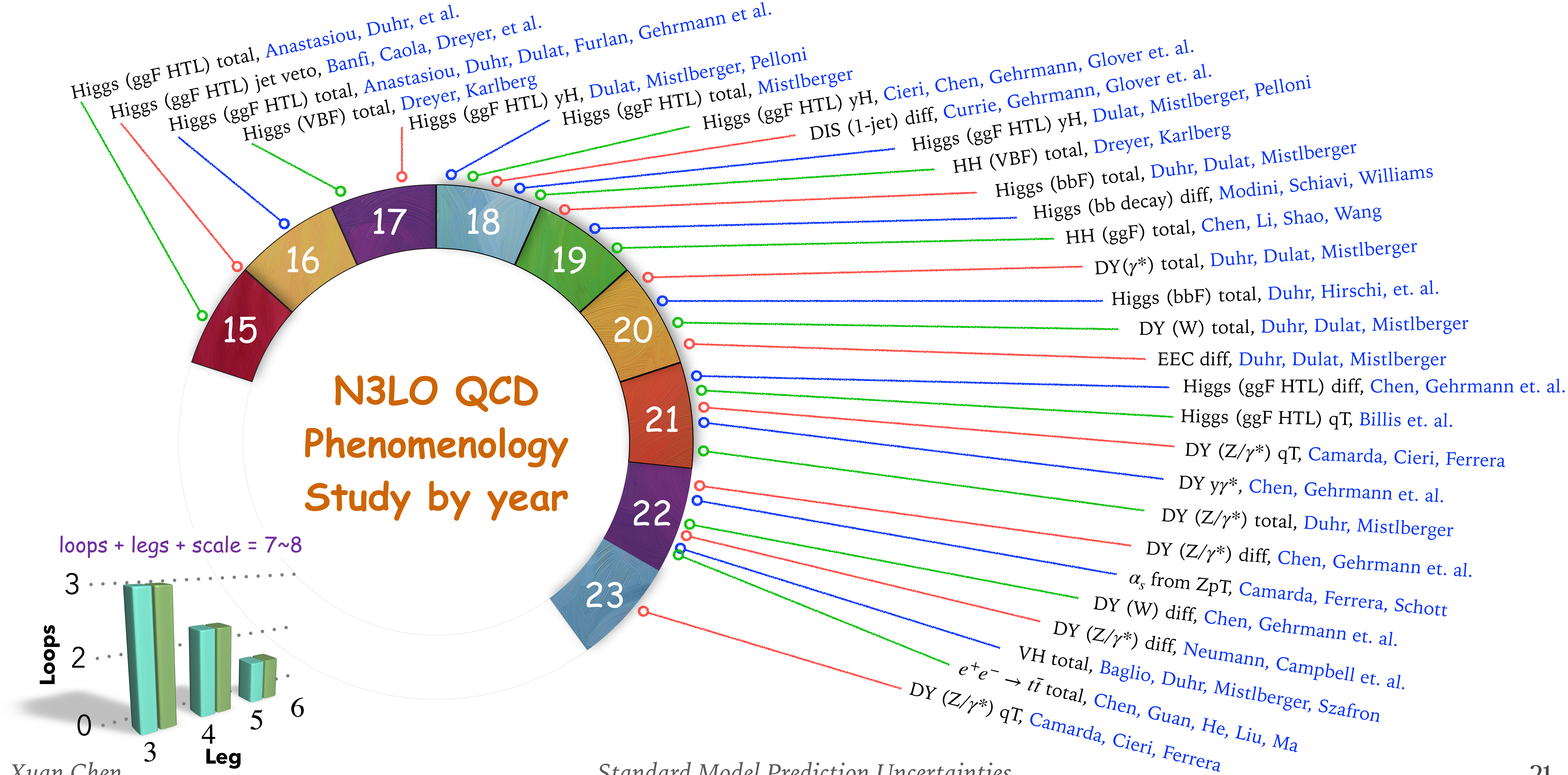
S. Badger, M Czakon et. al. 2304.06682



S. Catani et. al. PRL 130, 111902 (2023)



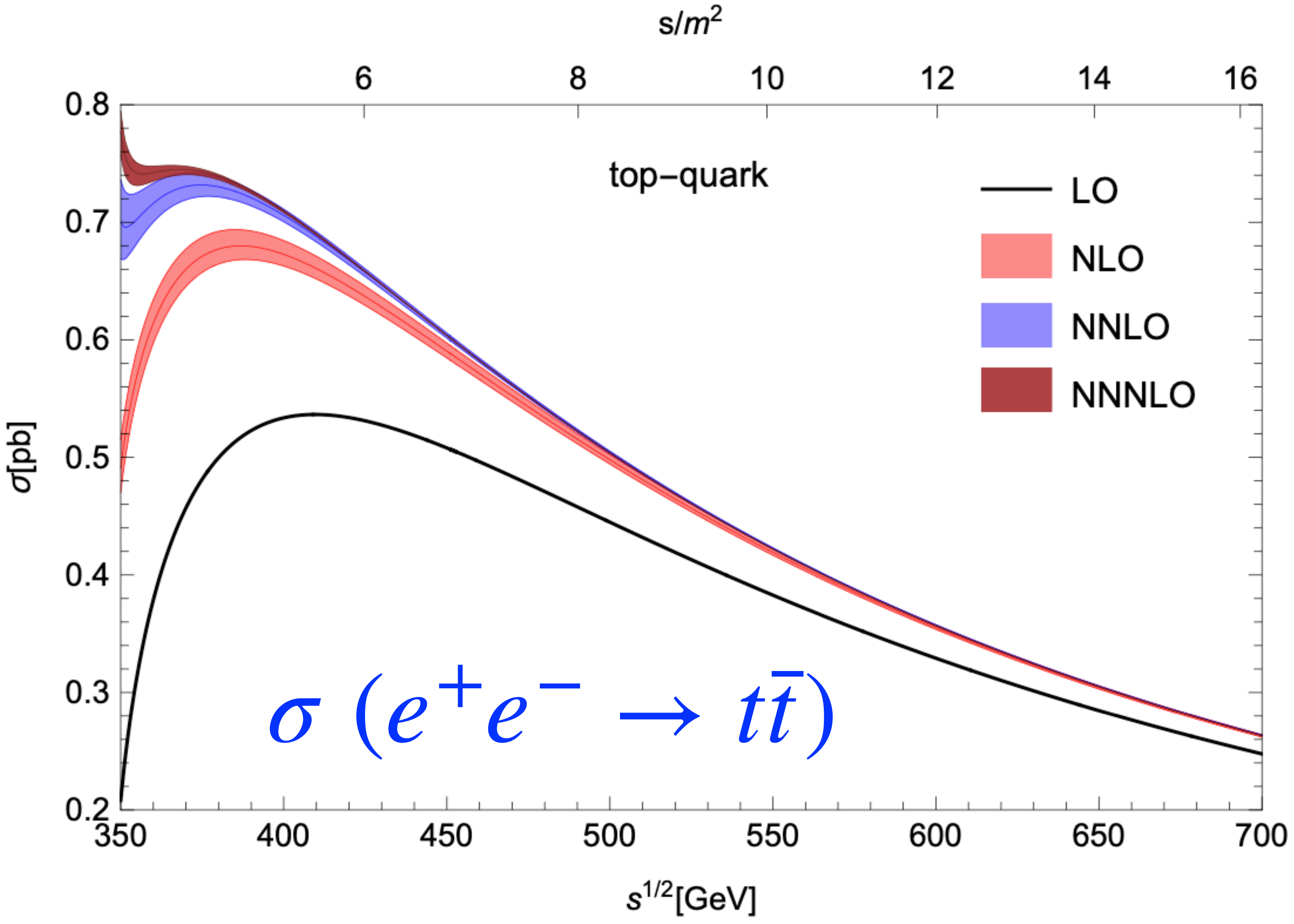
Perturbative QFT for Precision Predictions



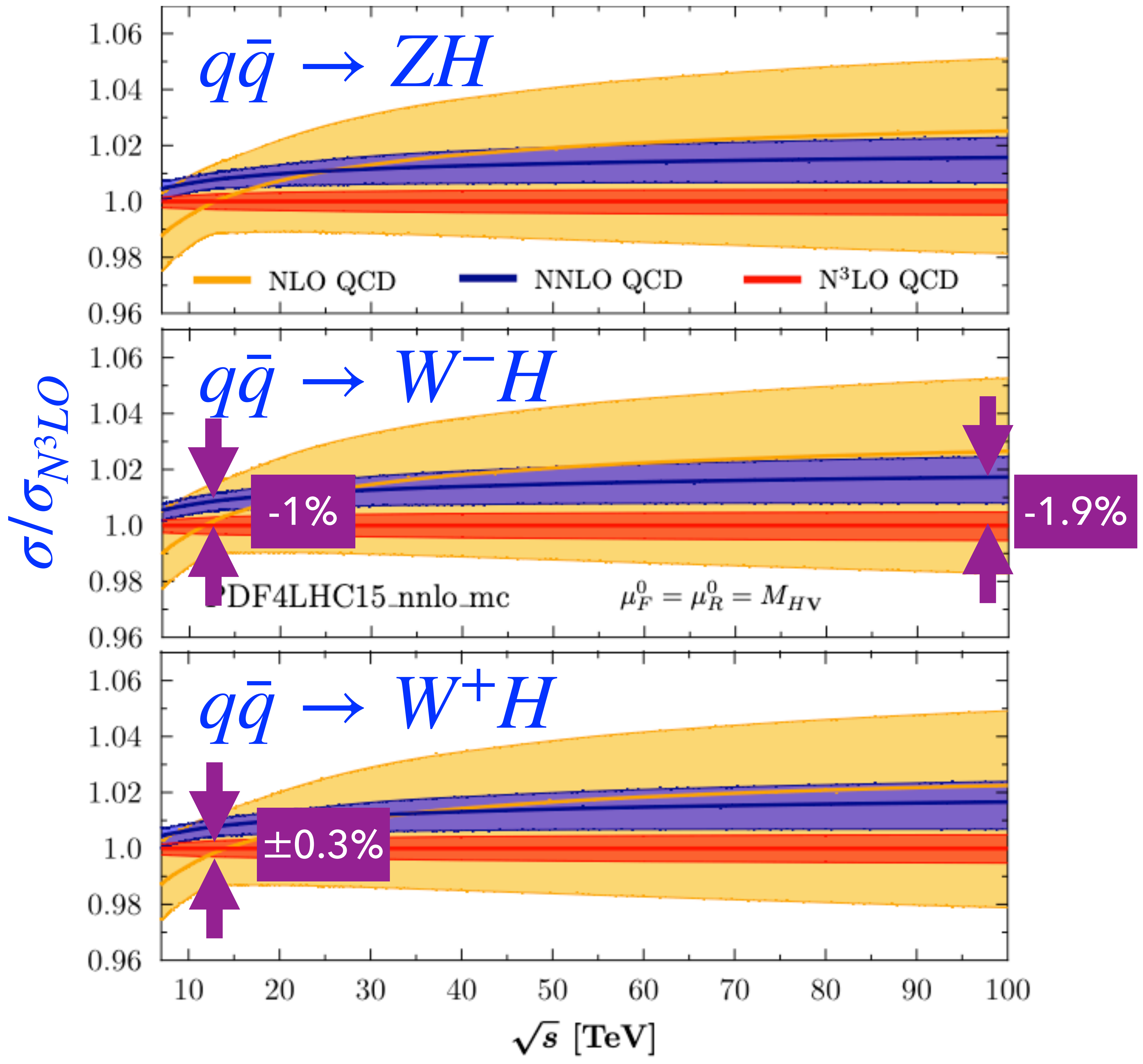
Perturbative QFT for Precision Predictions

$2 \to 2$ @N3LO QCD

- Total cross section for pp and epem collider
  - ME from $2 \to 3$ @ NNLO + ME @ 3-loop.
  - Use reverse unitarity for IR pole cancellation.
  - Different perturbative-series convergent behaviour



X. Chen, X. Guan, C.-Q. He, X. Liu, Y.-Q. Ma 2209.14259



J. Baglio, C. Duhr, B. Mistlberger, R. Szafron JHEP 12 (2022) 066

Perturbative QFT for Precision Predictions

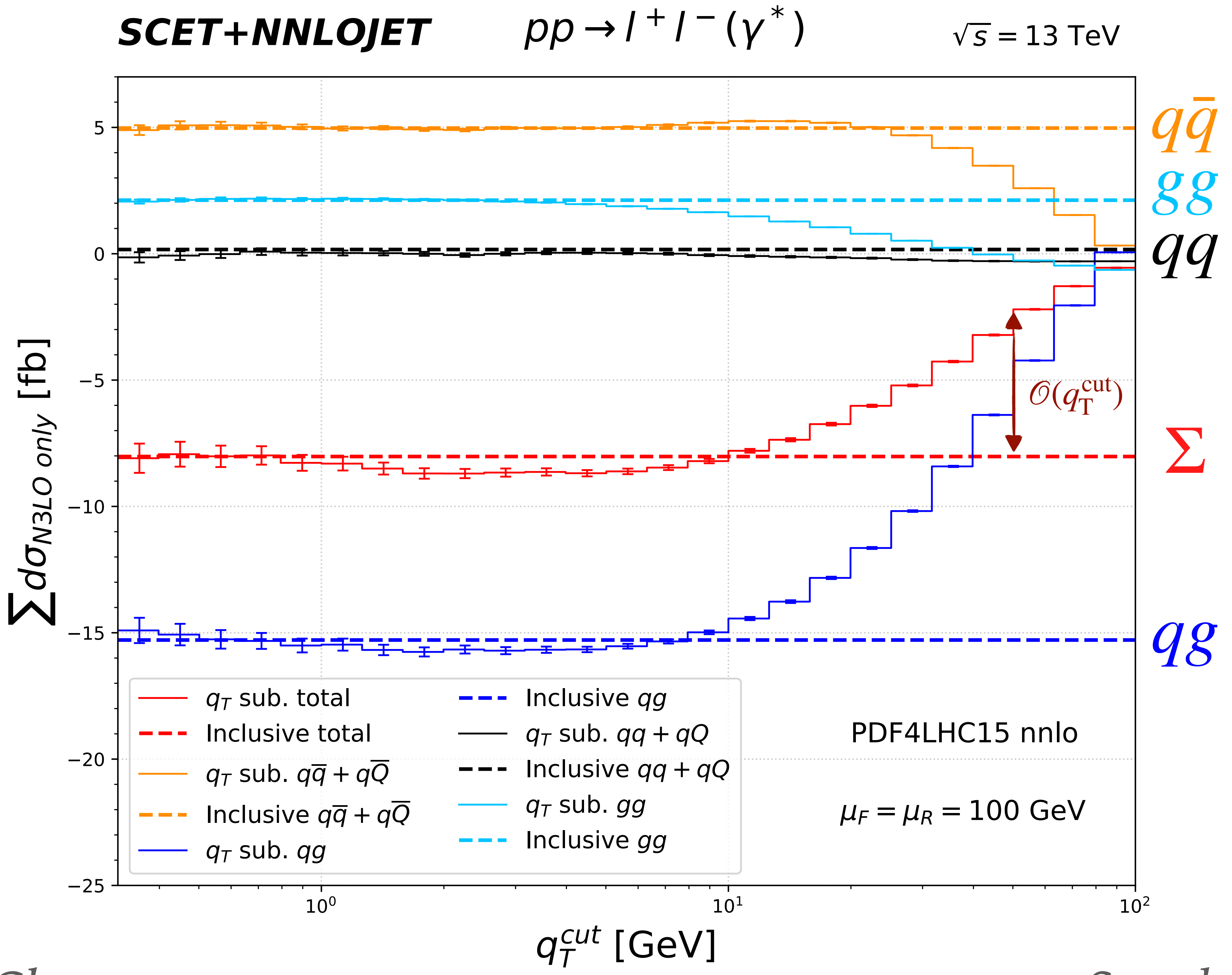
$2 \to 1$ @ N3LO (+ N3LL) QCD

- Fully differential N3LO correction in event generator
  - Recycle $pp \to V+J$ @ NNLO with τ_{cut} slicing

$$\mathrm{d}\sigma^{F}_{N^kLO} = \mathscr{H}^{F}_{N^kLO} \otimes \mathrm{d}\sigma^{F}_{LO}\Big|_{\delta(\tau)} + \left[\mathrm{d}\sigma^{F+jet}_{N^{k-1}LO} - \mathrm{d}\sigma^{F\ CT}_{N^kLO}\right]_{\tau>\tau_{cut}} + \mathcal{O}(\tau^2_{cut}/Q^2)$$

  - Fiducial power correction removed via MC recoil technique.
- Small p_T resummation at N3LL and partial N4LL

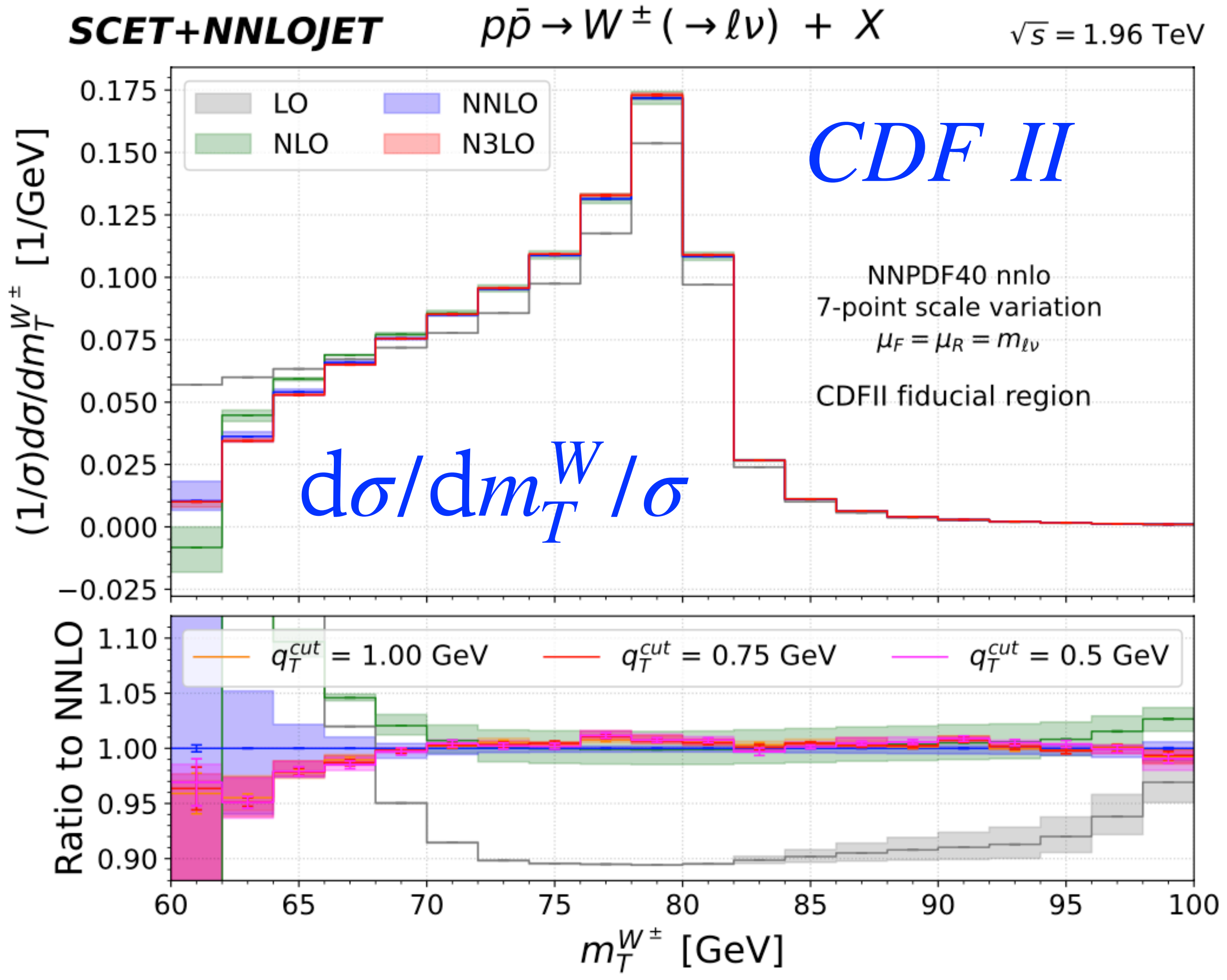
XC, T. Gehrmann, et. al. PRL. 128, 052001 (2022)

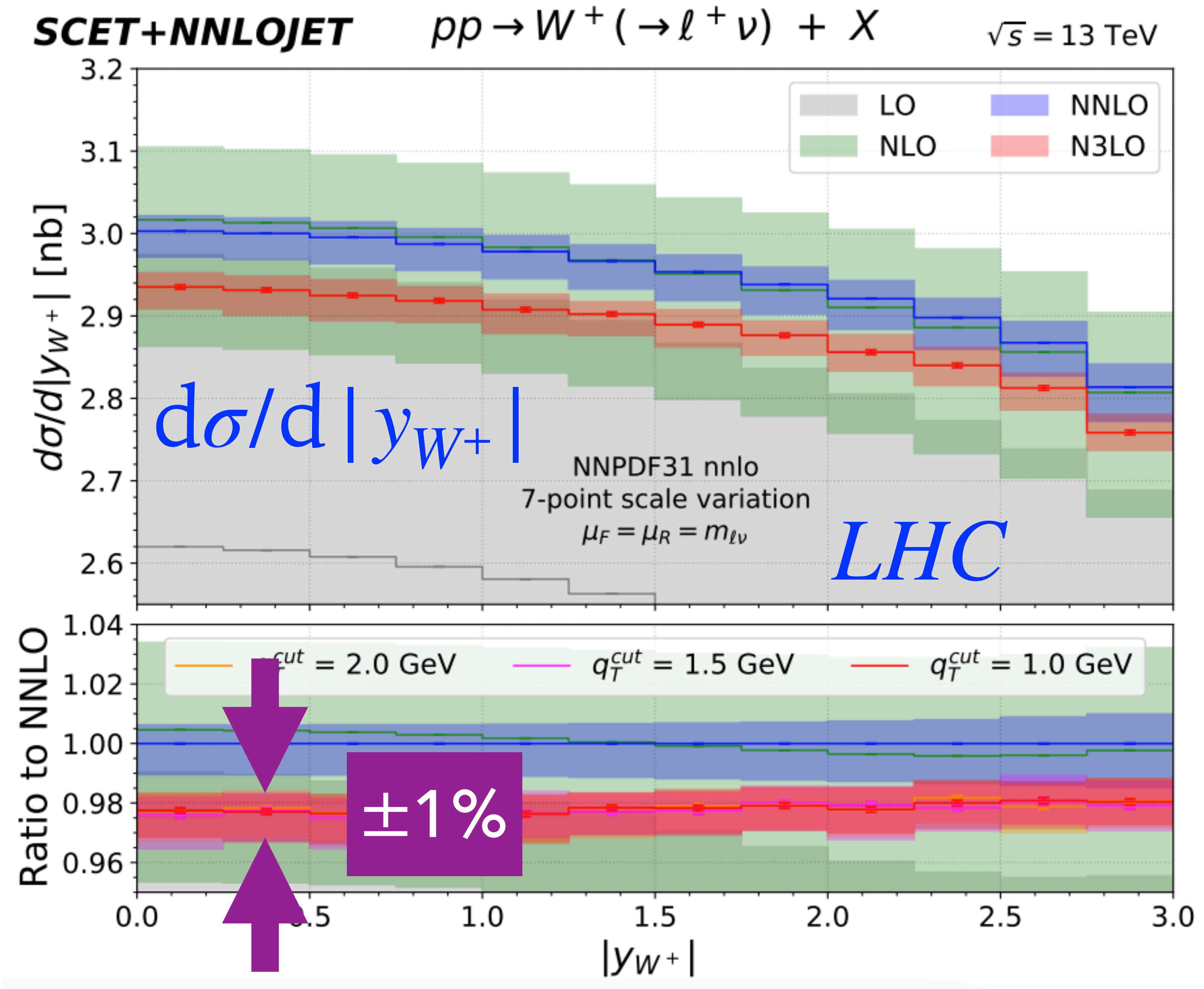


- Validation of inclusive total cross section for $q_T^{cut} < 1$ GeV.

  C. Duhr, F. Dulat, B. Mistlberger. PRL. **125**, 172001 (2020)

- Separated in parton channels
- Foundation of numerical Monte Carlo setup for differential predictions.





XC, T. Gehrmann, N. Glover, et. al. Phys.Lett.B 840 (2023) 137876

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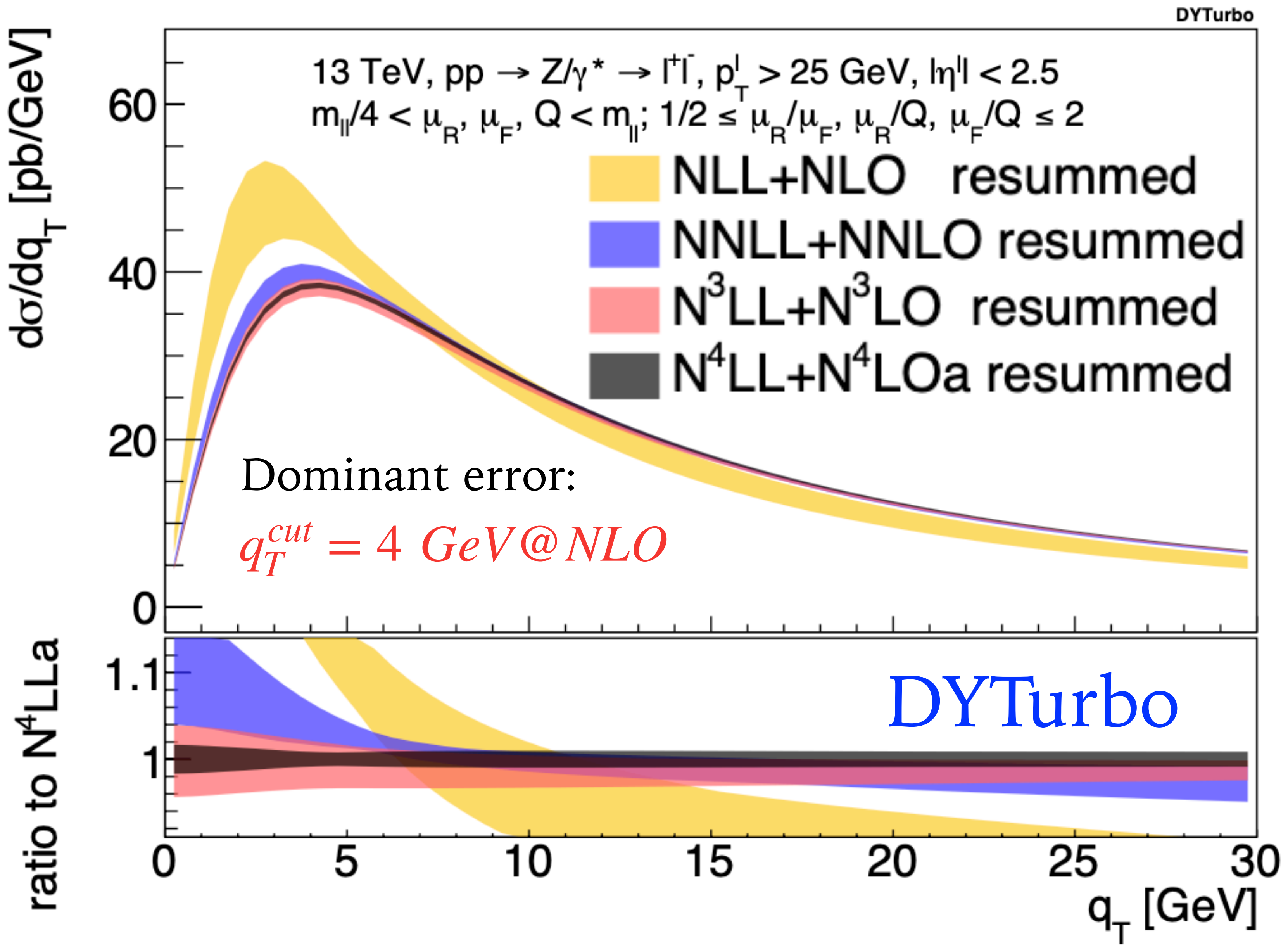
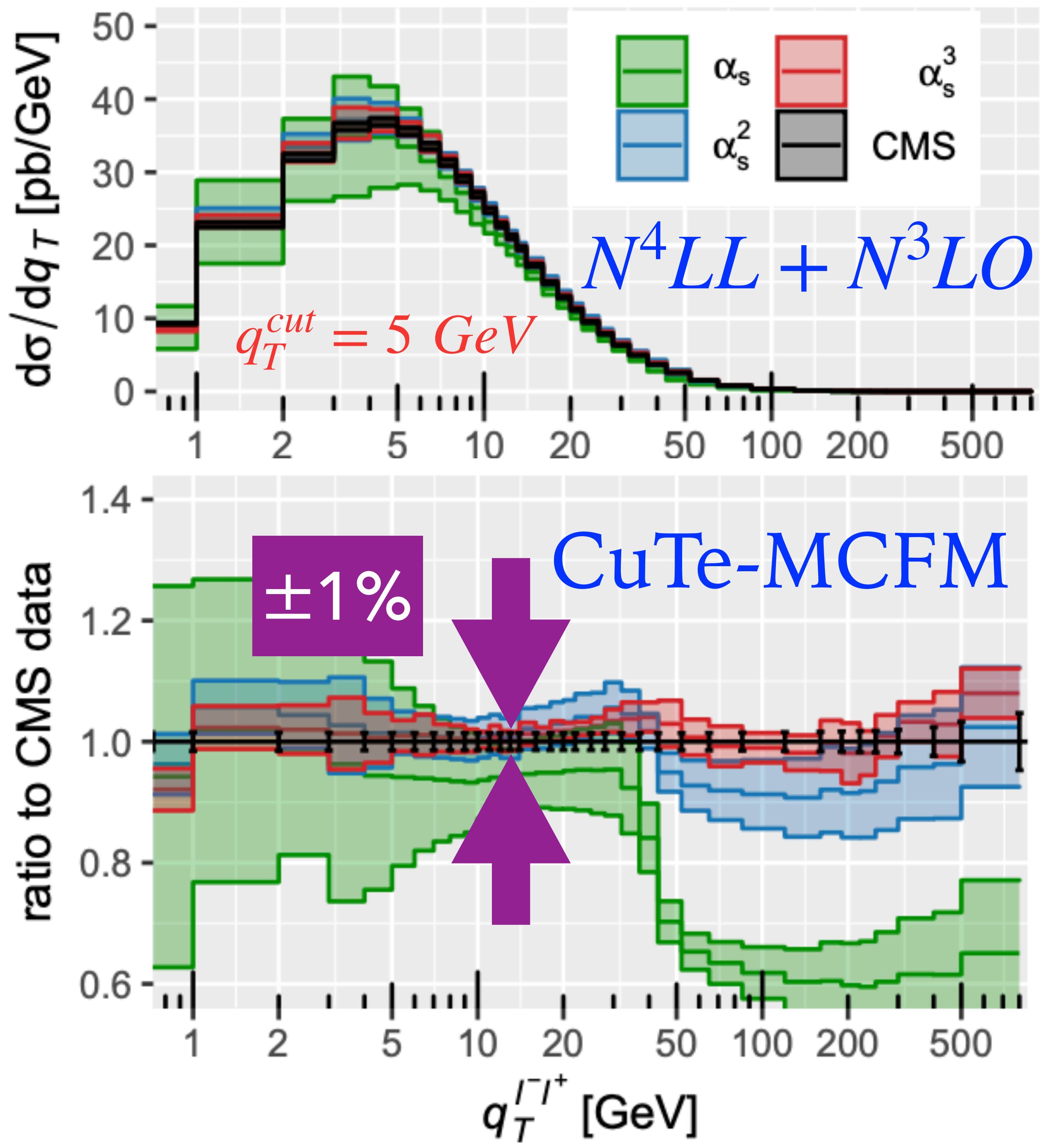
  - Fiducial power correction removed via MC recoil technique.
- Small p_T resummation at N3LL and partial N4LL

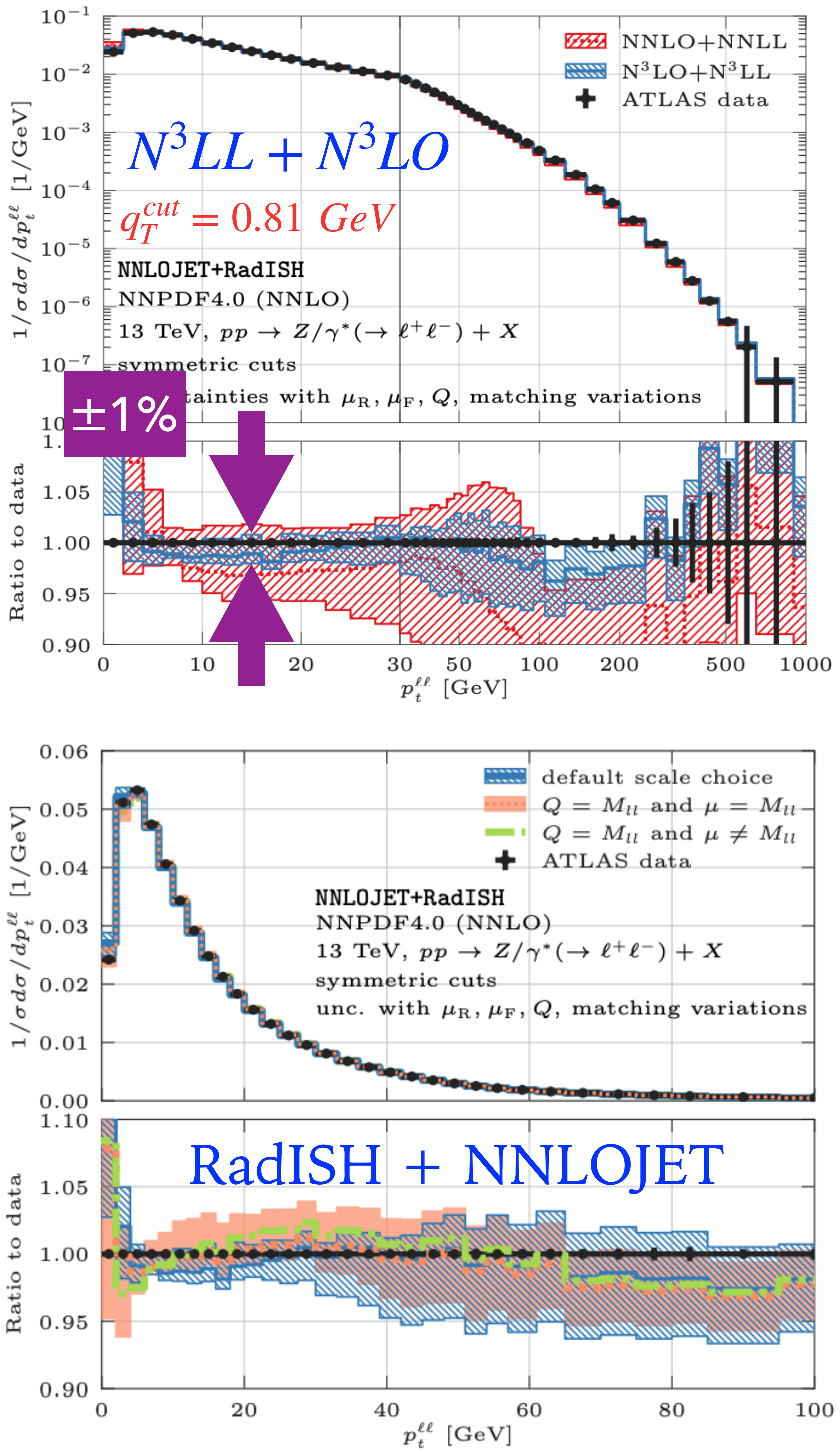
$d\sigma/dp_T^Z$



S. Camarda, L. Cieri, G. Ferrera 2303.12781



T. Neumann, J. Campbell PRD 107, L011506 (2023)



XC, T. Gehrmann, N. Glover, et. al. PRL 128, 252001 (2022)

Perturbative QFT for Precision Predictions

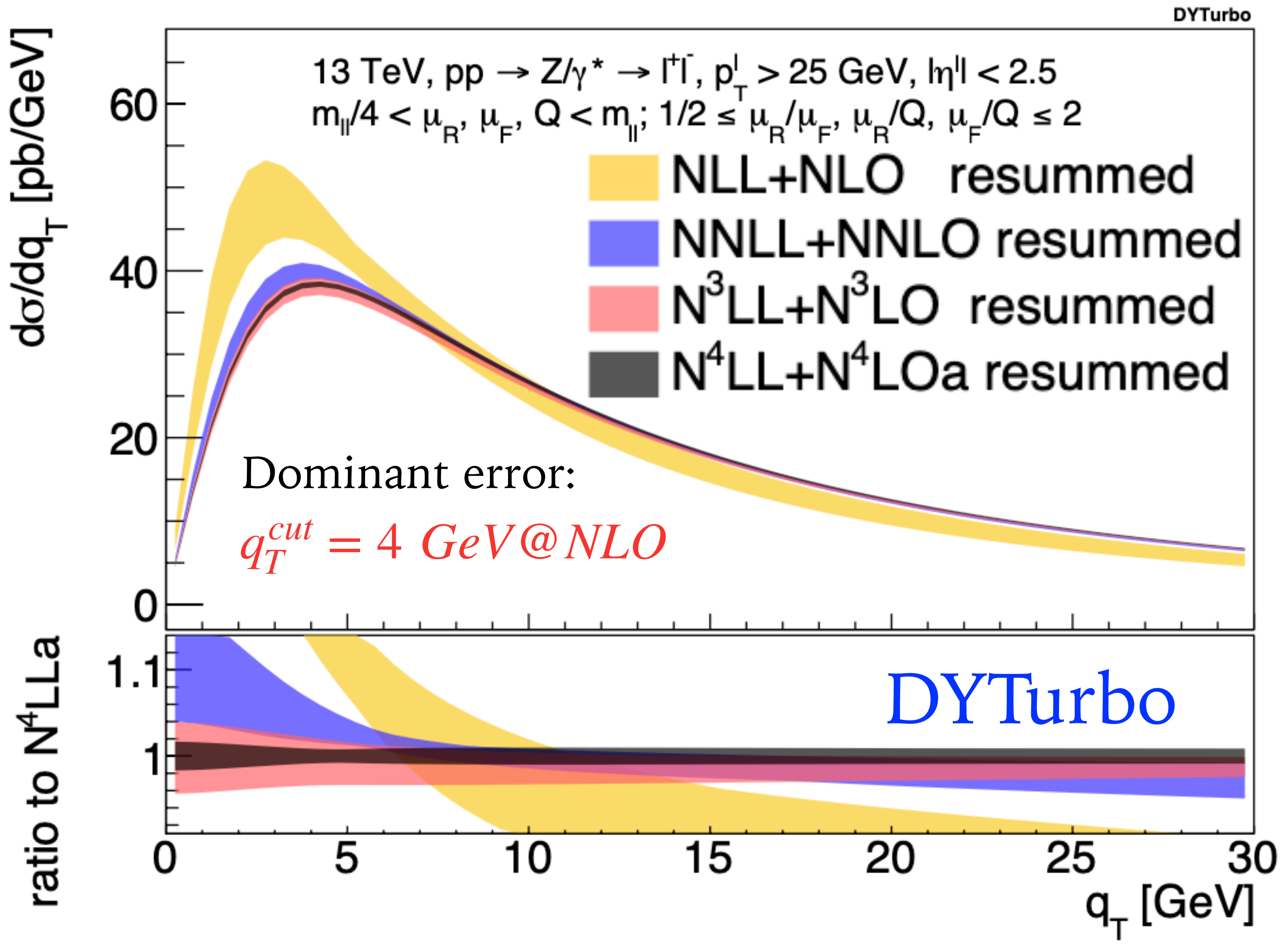
$2 \to 1$ @ N3LO (+ N3LL) QCD

- Fully differential N3LO correction in event generator
  - Recycle $pp \to V + J$ @ NNLO with $\tau_{\rm cut}$ slicing

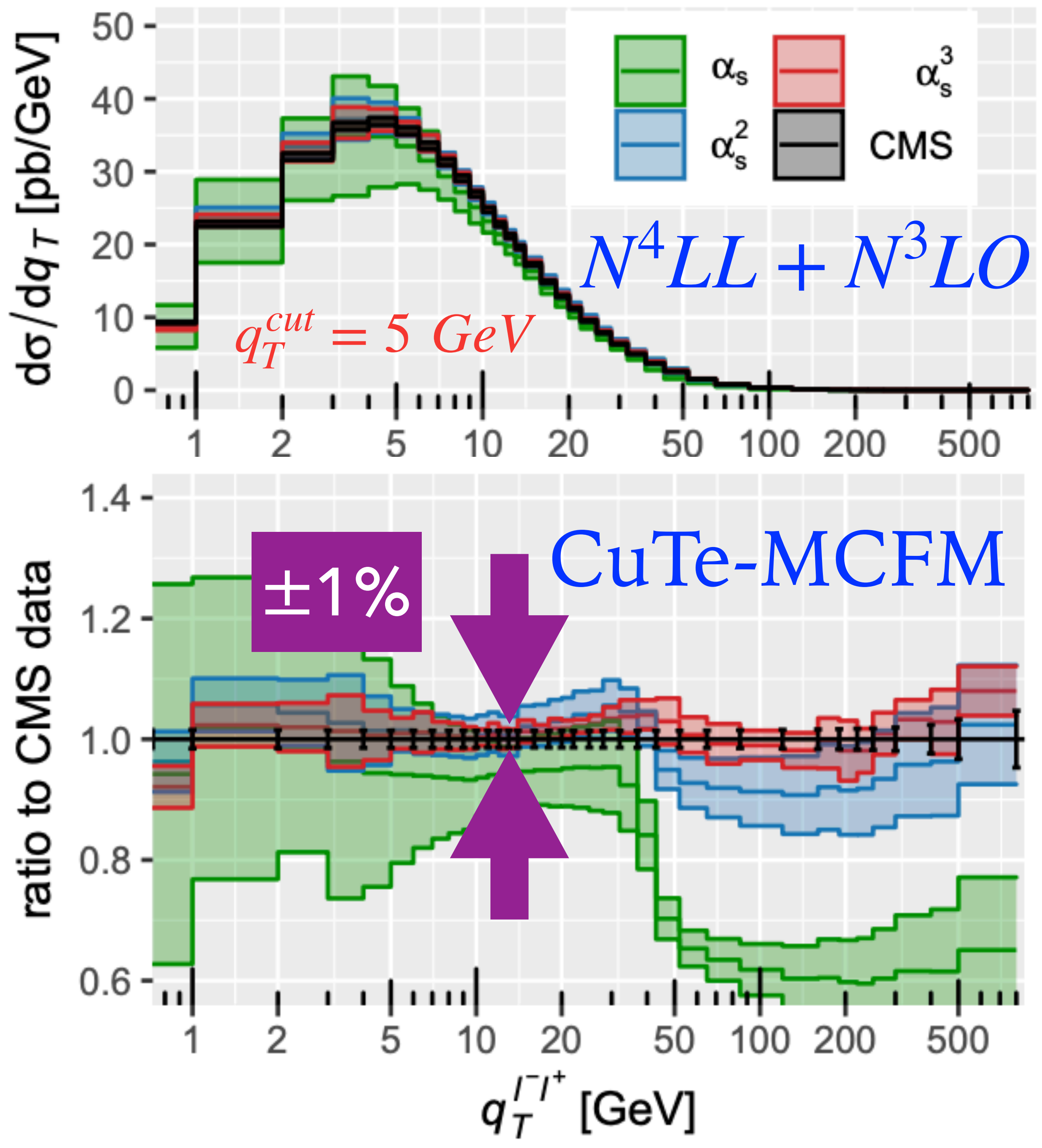
$$d\sigma^F_{N^kLO} = \mathscr{H}^F_{N^kLO} \otimes d\sigma^F_{LO}\Big|_{\delta(\tau)} + \left[d\sigma^{F+jet}_{N^{k-1}LO} - d\sigma^{F\ CT}_{N^kLO}\right]_{\tau>\tau_{cut}} + \mathcal{O}(\tau^2_{cut}/Q^2)$$

  - Fiducial power correction removed via MC recoil technique.
- Small p_T resummation at N3LL and partial N4LL

$d\sigma/dp_T^Z$



S. Camarda, L. Cieri, G. Ferrera 2303.12781



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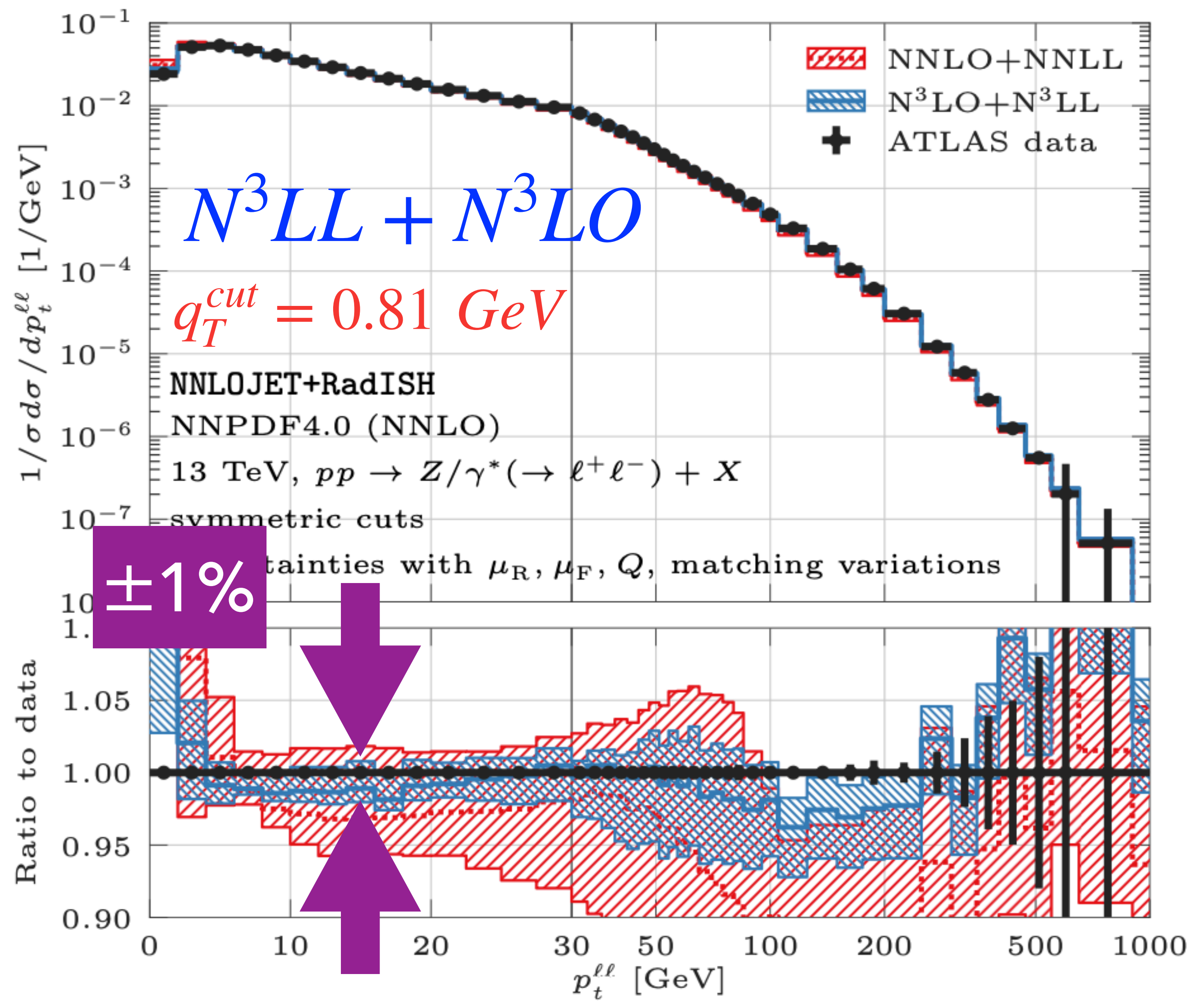

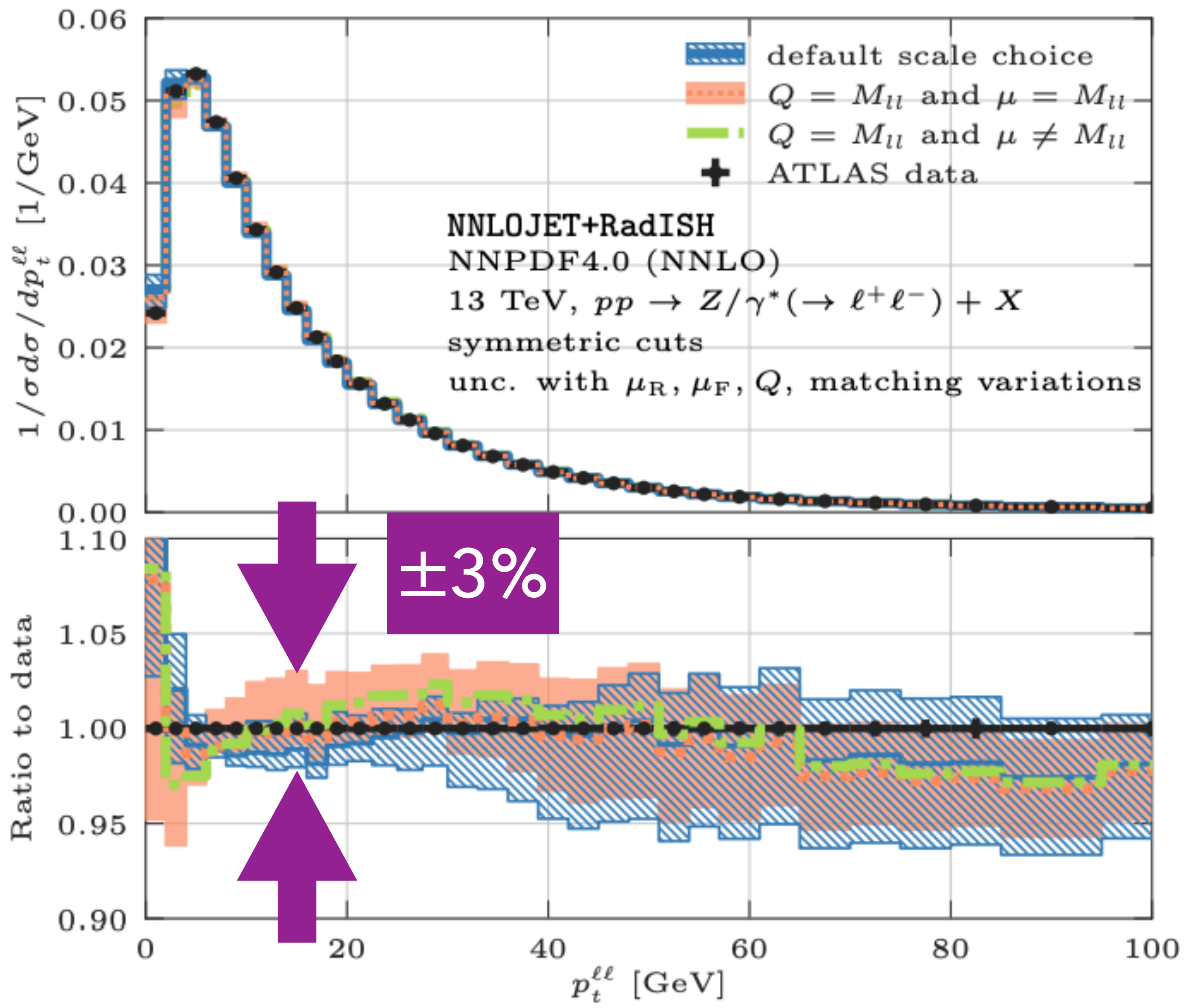

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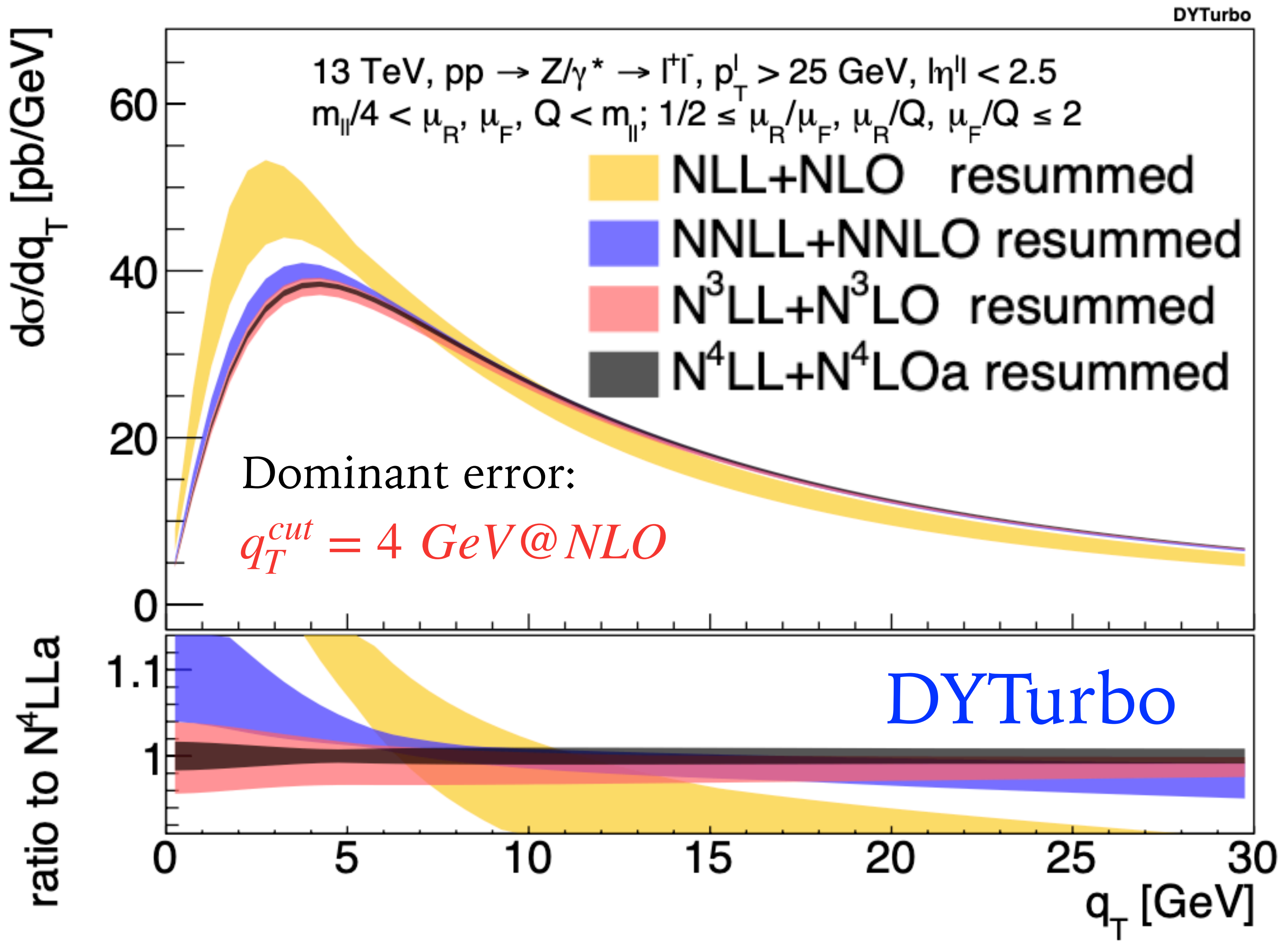
G. Fontana



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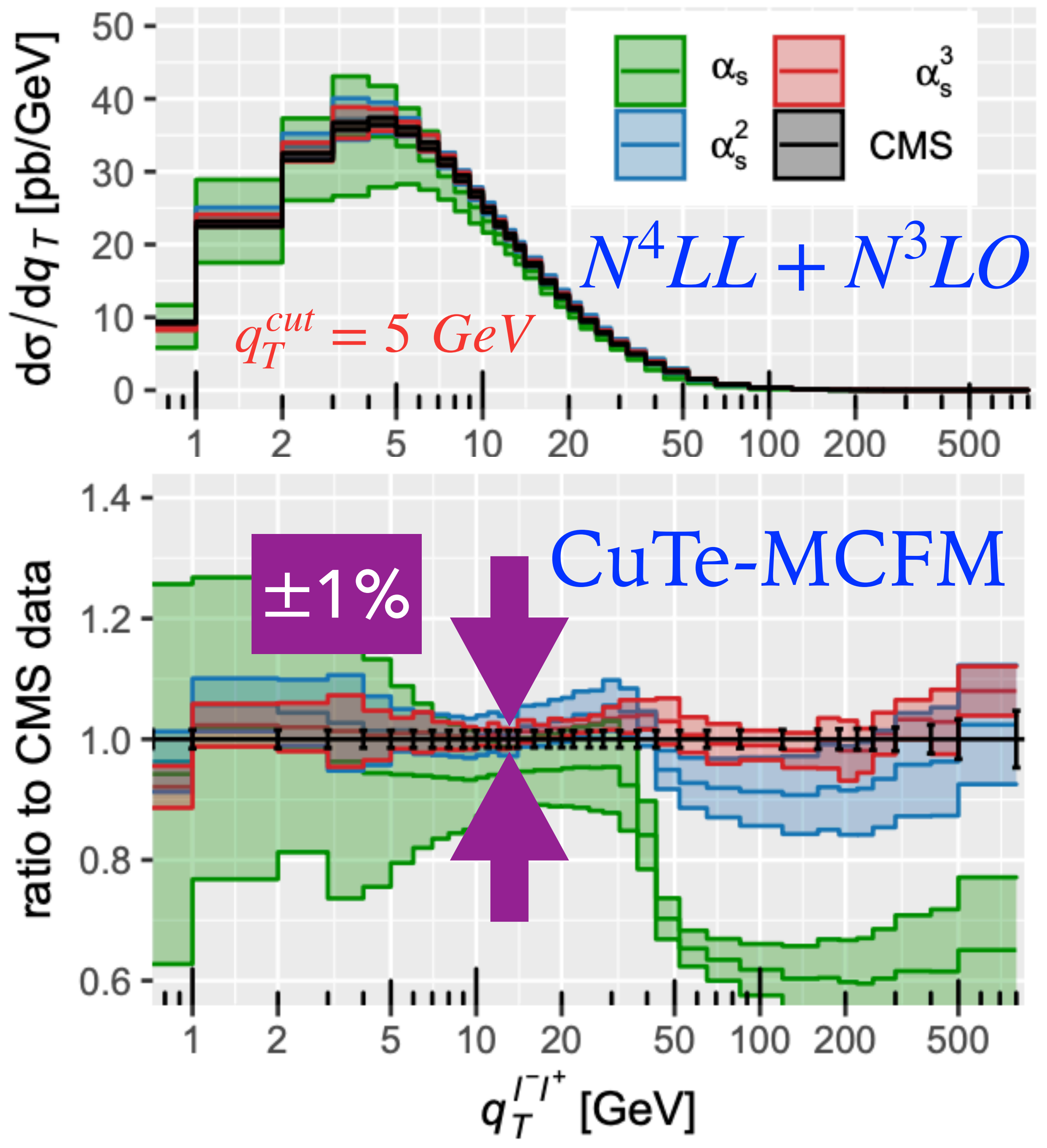

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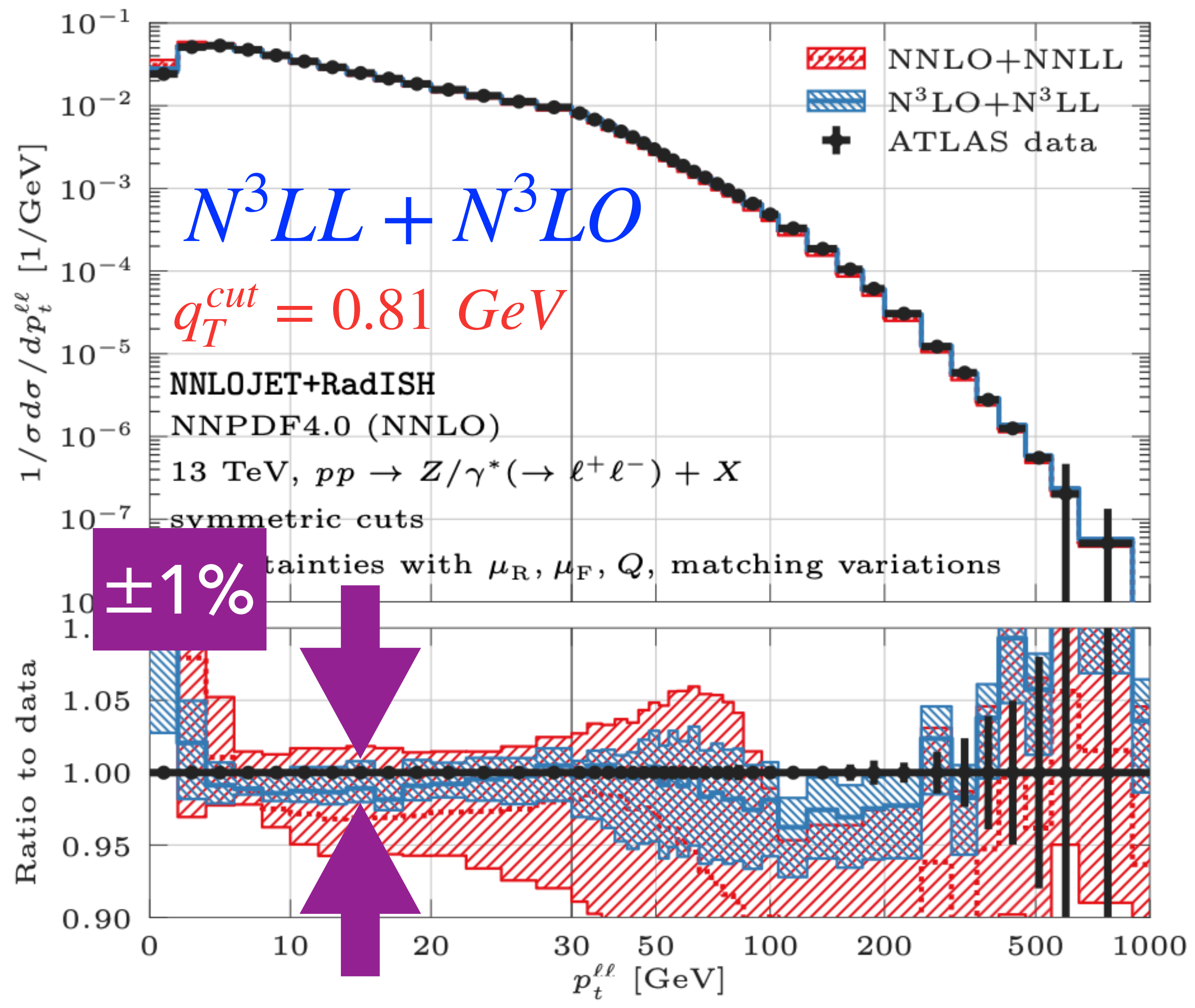

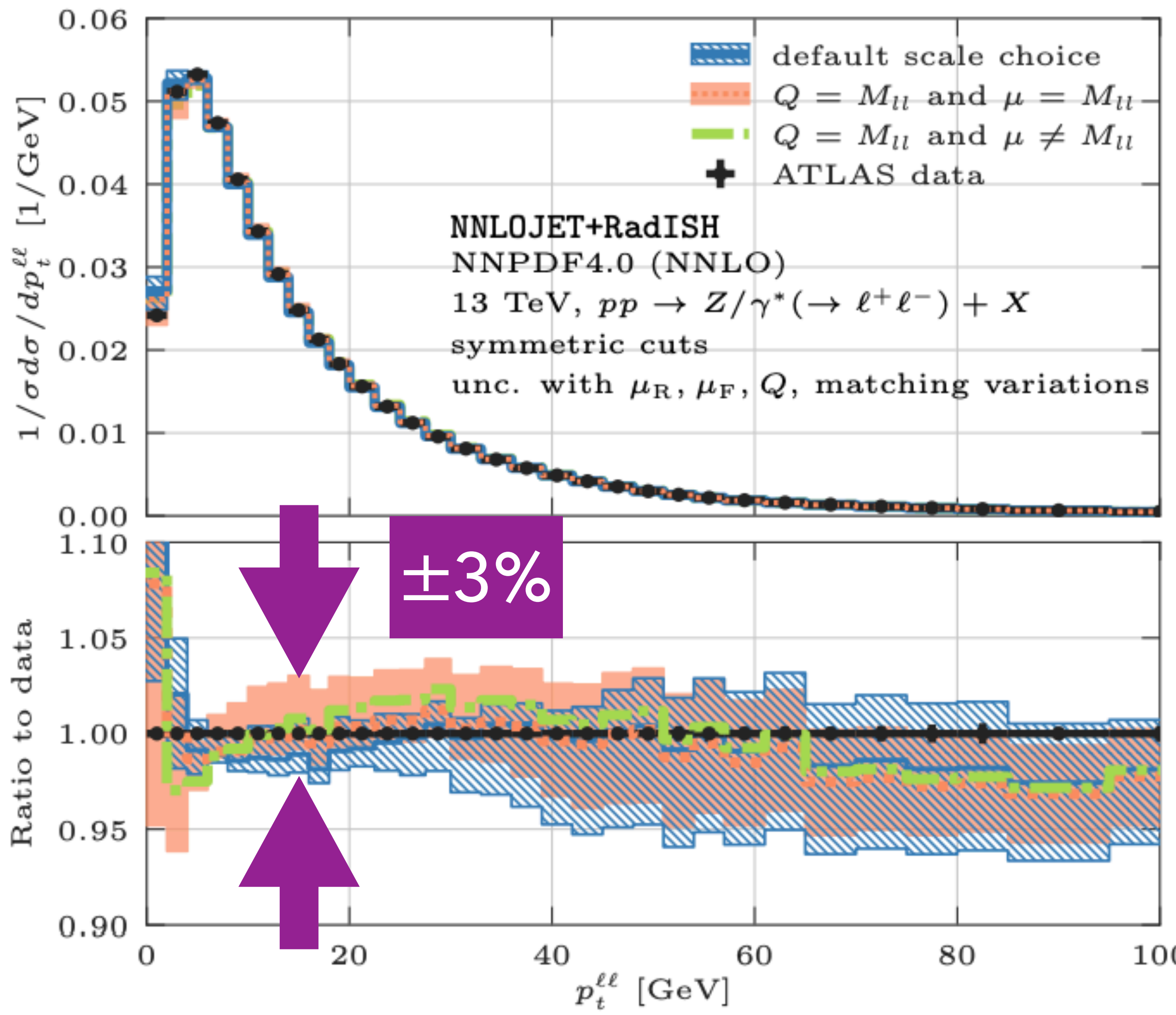

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Perturbative QFT for Precision Predictions

State-of-the-art Parton Shower accuracy

- Standard parton showers are Leading Logarithmic (LL) accurate. (SHERPA, PYTHIA, DIRE, GENEVA, HERWIG, VINCIA etc.)
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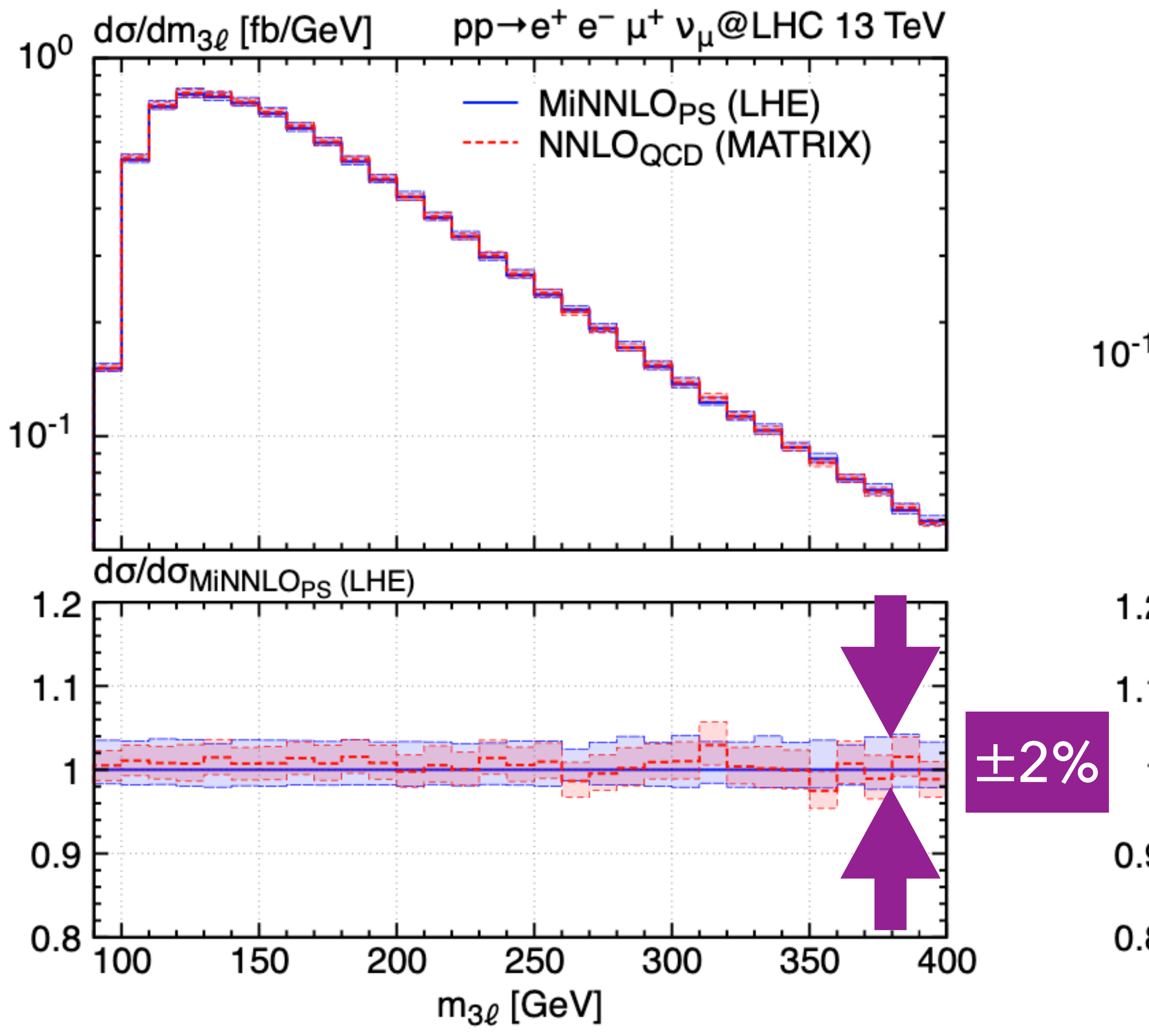
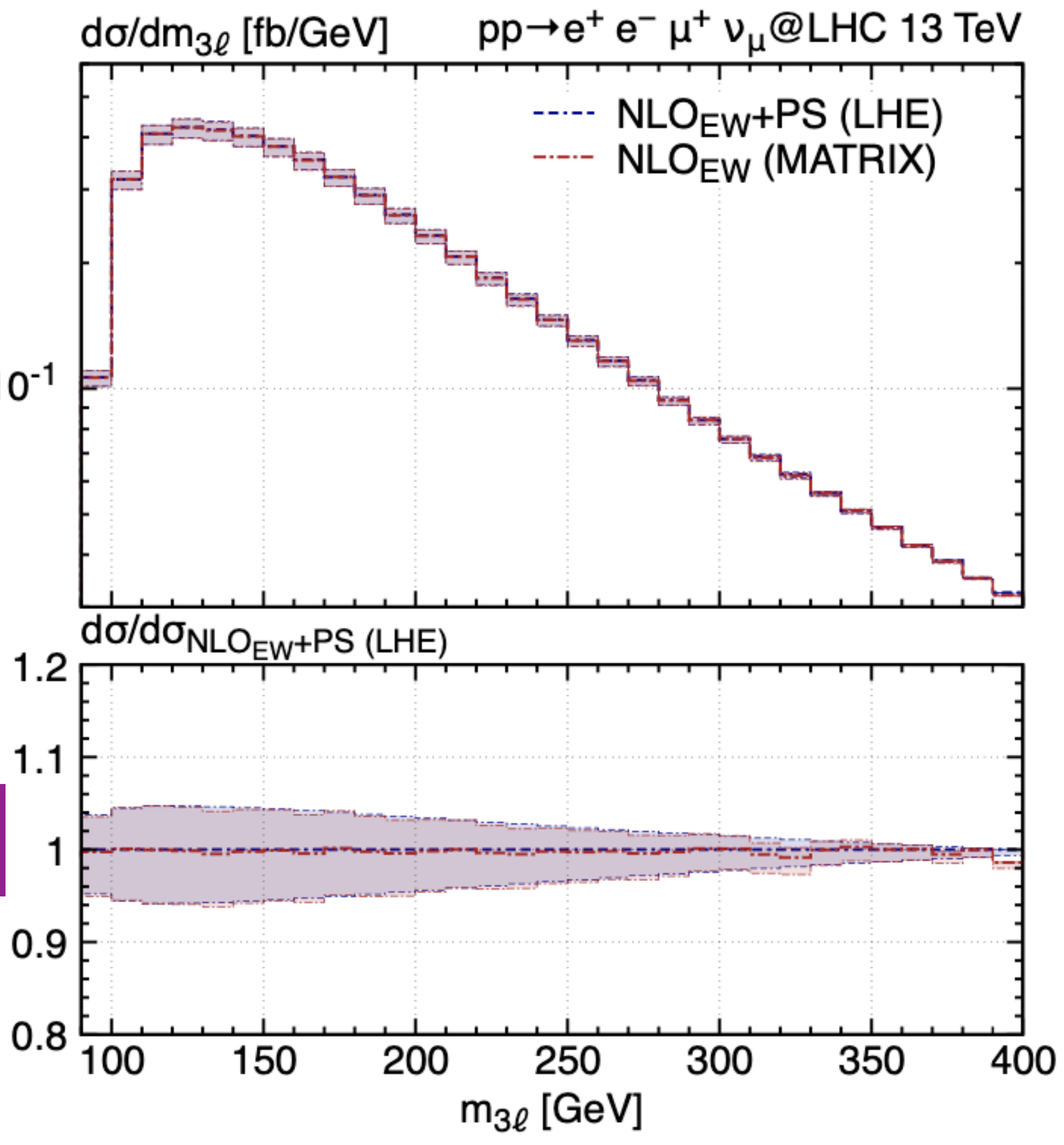
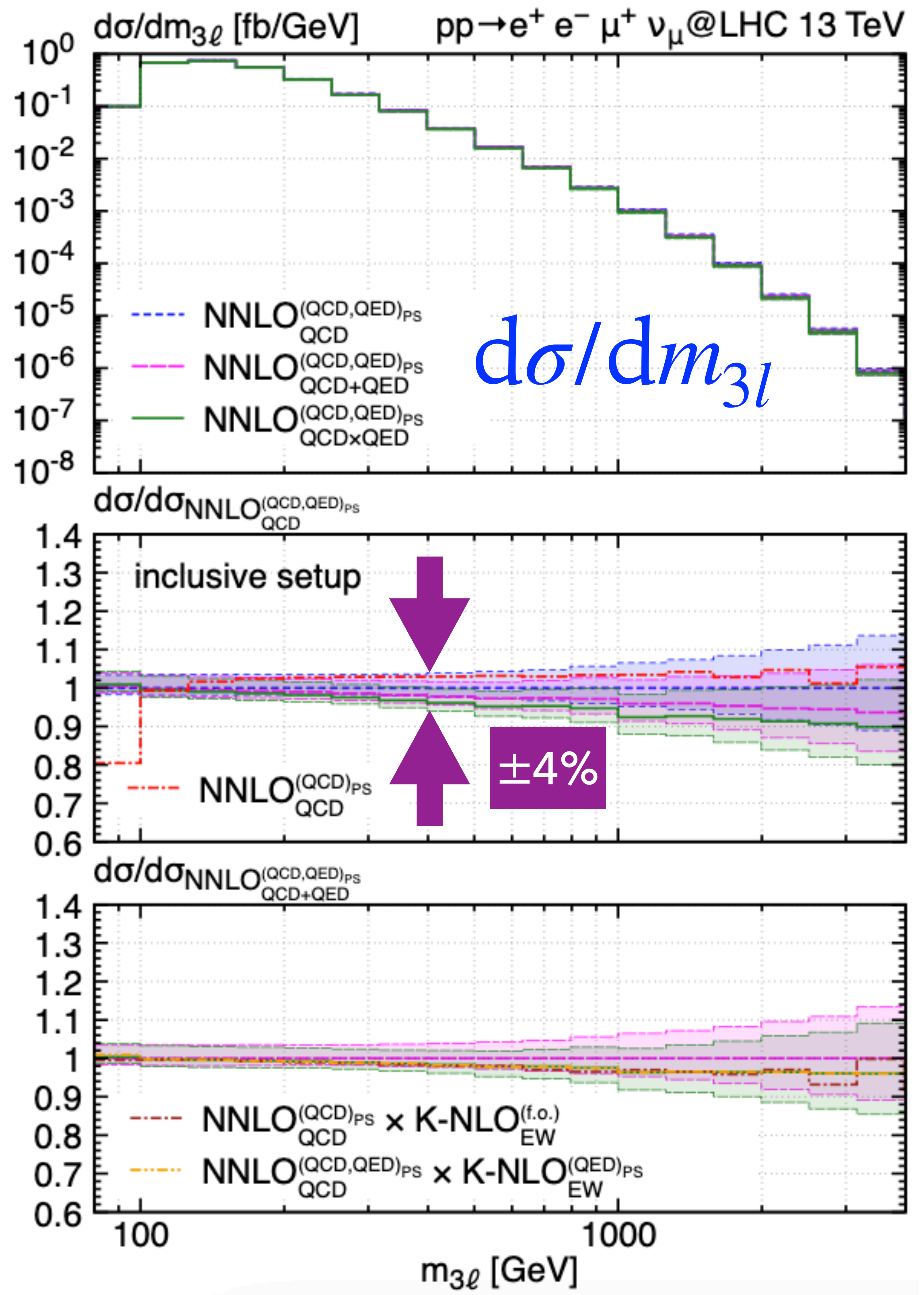
    J. M. Lindert, D. Lombardi, M. Wiesemann et. al. JHEP 11 (2022) 036







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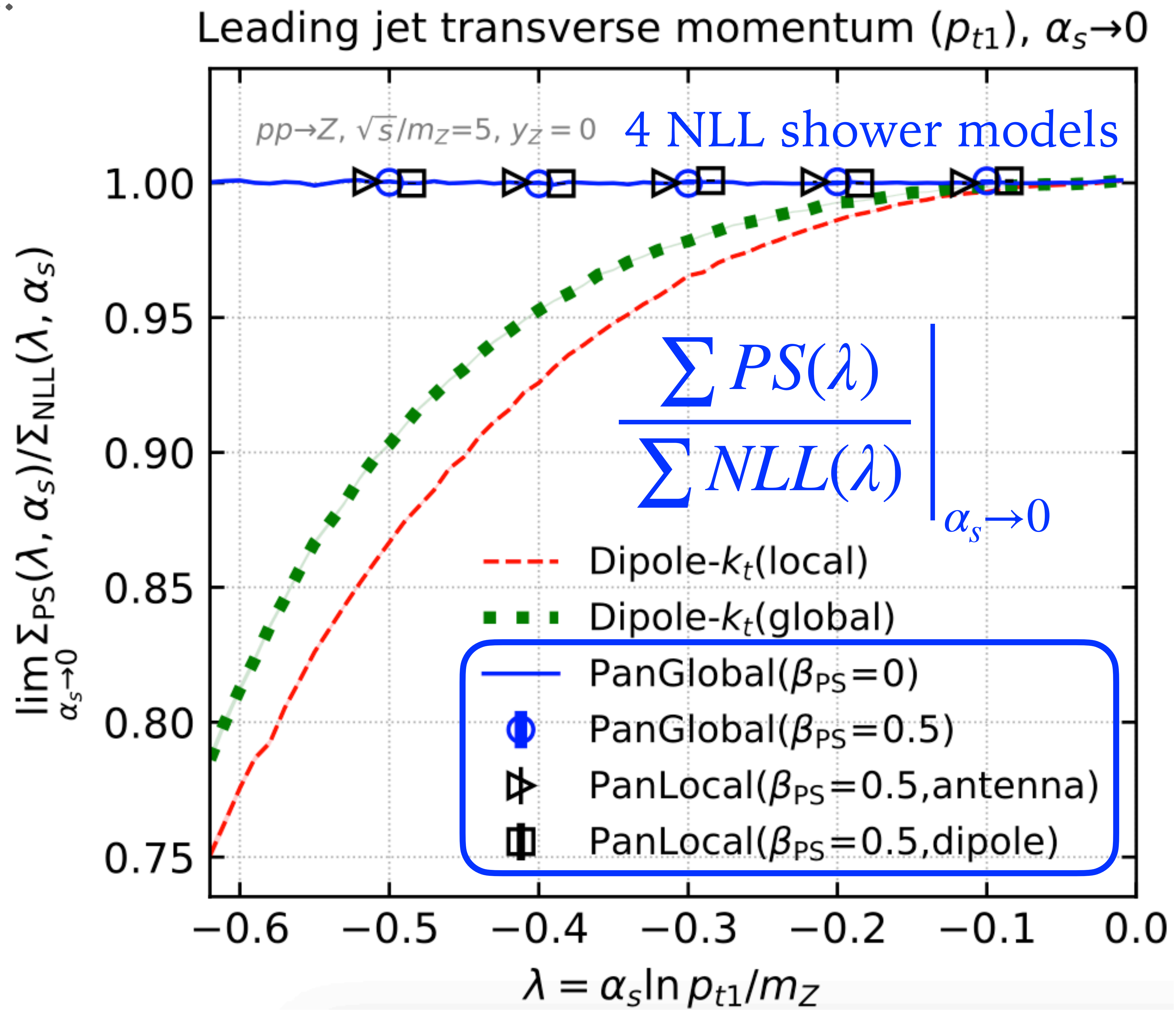
    J. M. Lindert, D. Lombardi, M. Wiesemann et. al. JHEP 11 (2022) 036
- Several groups working on new PS framework aiming for NLL:
  - CVOLVER: Forshaw, Holguin, Plätzer DEDUCTOR: Nagy, Soper ALARIC: Assi, Herren, Höche, Krauss, Reichelt, Schönherr PANSCALES: van Beekveld, Ferrario Ravasio, Hamilton, Salam, Soto-Ontoso, Soyez, Verheyen, Halliwell, Medves, Dreyer, Scyboz, Karlberg, Monni, El-Menoufi
- Test of shower accuracy (PANSCALES):

$$\lim_{\alpha_s \to 0} \frac{\Sigma_{\mathrm{PS}}(\lambda) - \Sigma_{\mathrm{NLL}}(\lambda)}{\Sigma_{\mathrm{NLL}}(\lambda)}, \quad \lambda = \alpha_s L$$

- PANSCALES: VBFH (initial and final NLL shower)
  - First NLL shower uncertainty estimation at $\sim$10%
- ALARIC: massive shower (final NLL shower)

Alaric Collaboration 2208.06057, B. Assi, S. Höche 2307.00728

$pp \to Z + PS$



More validations in:
PanScales Collaboration JHEP 11 (2022) 020

Perturbative QFT for Precision Predictions

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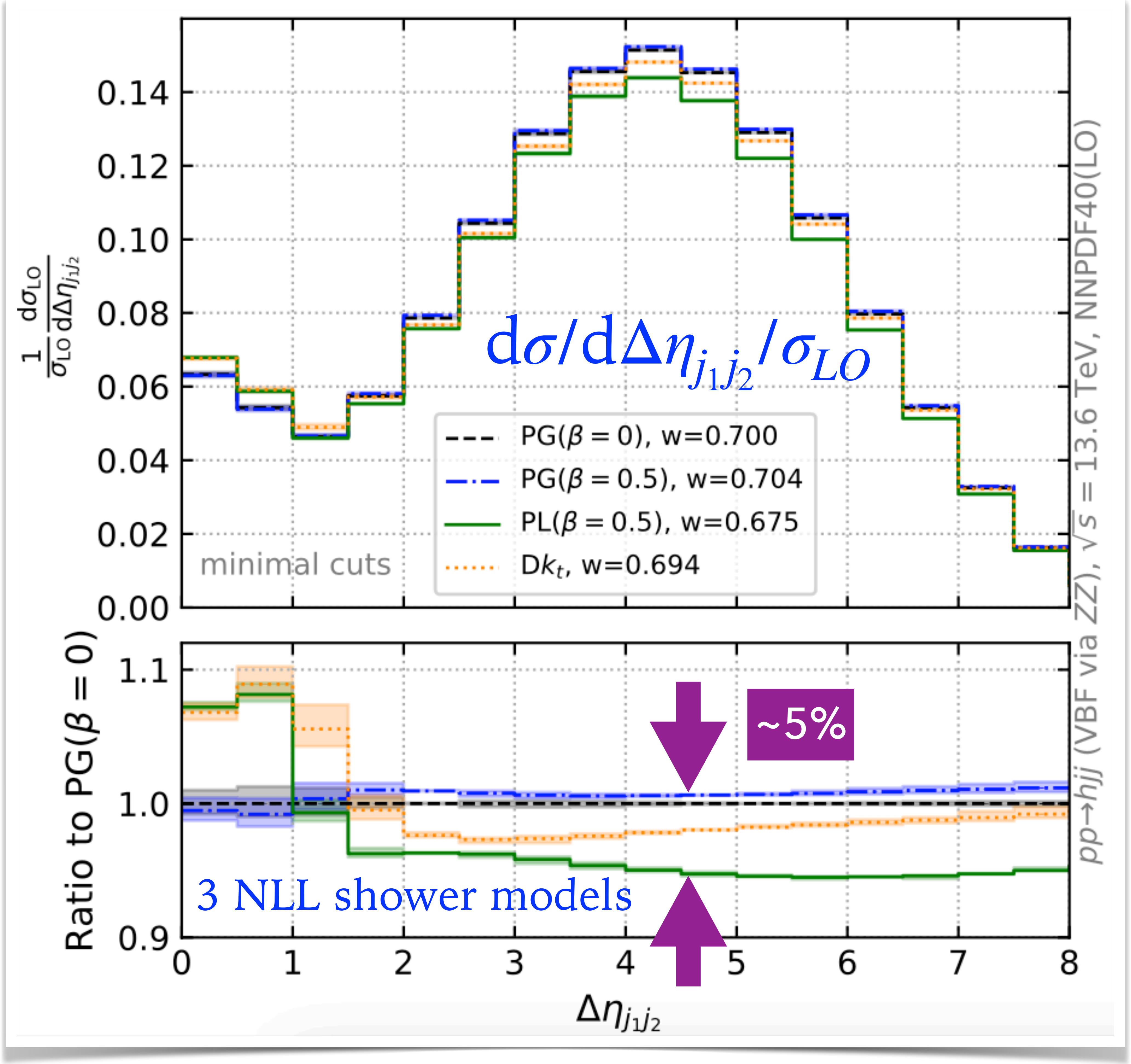
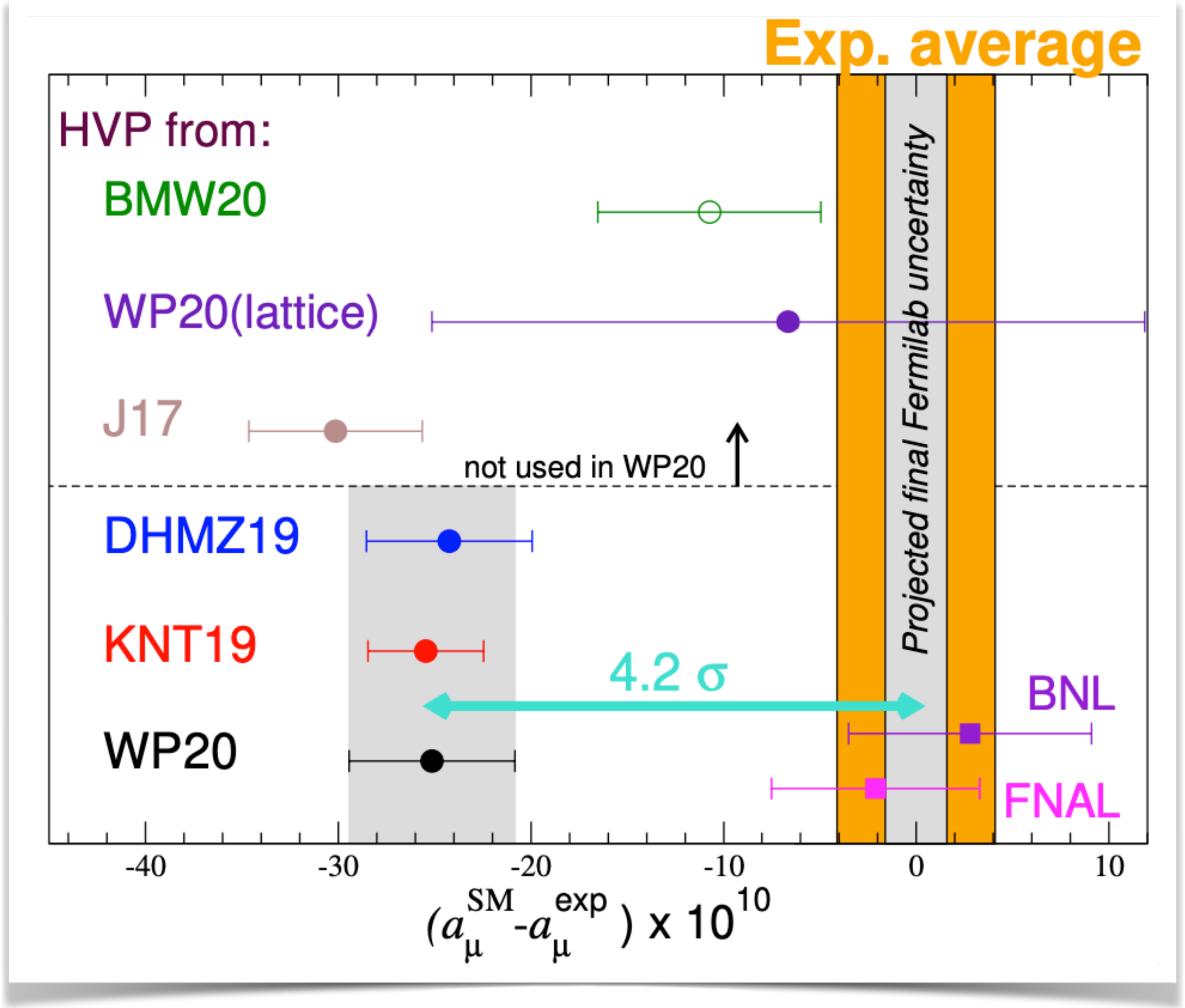
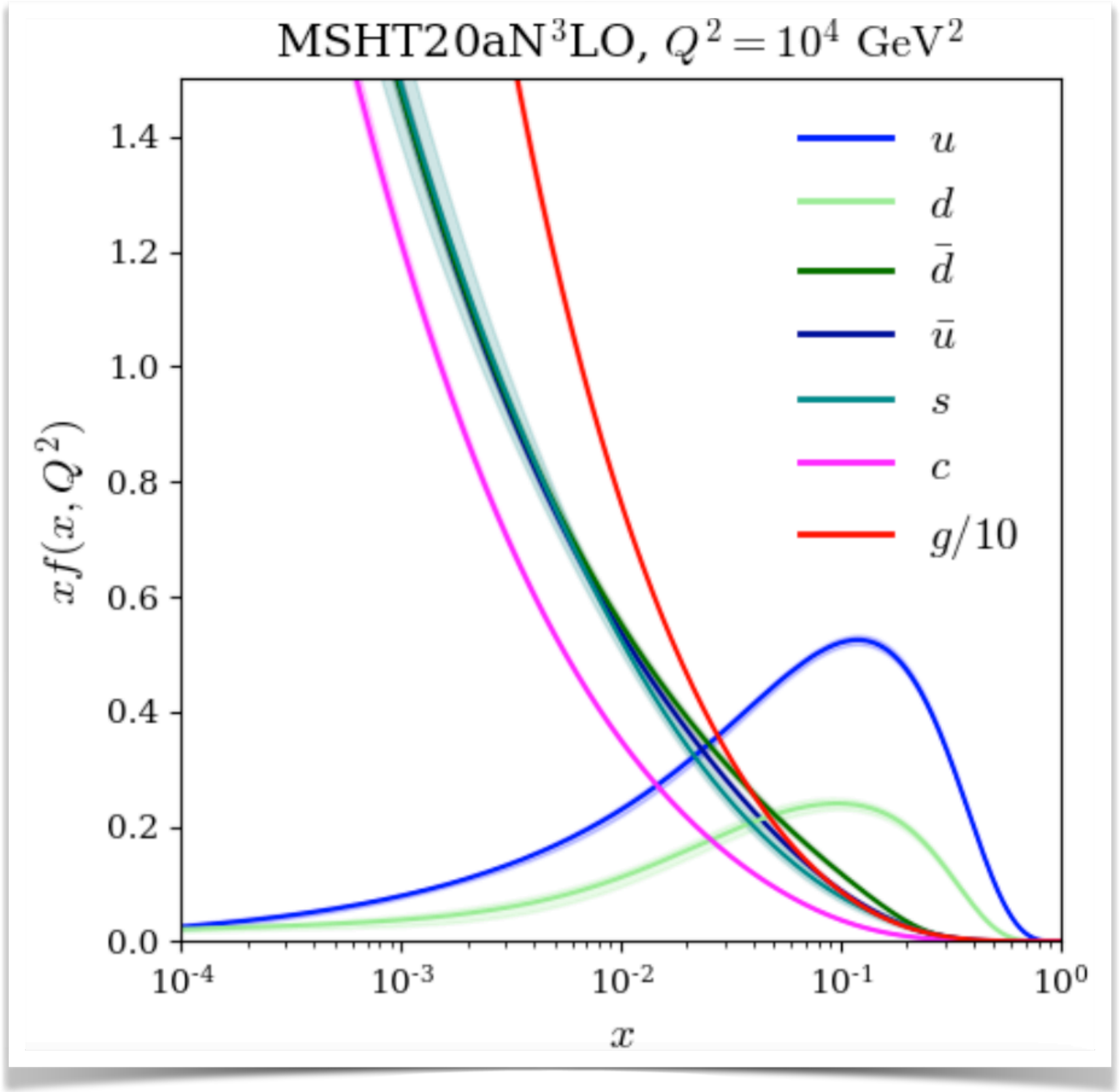
$pp \to H\ (VBF) + PS$

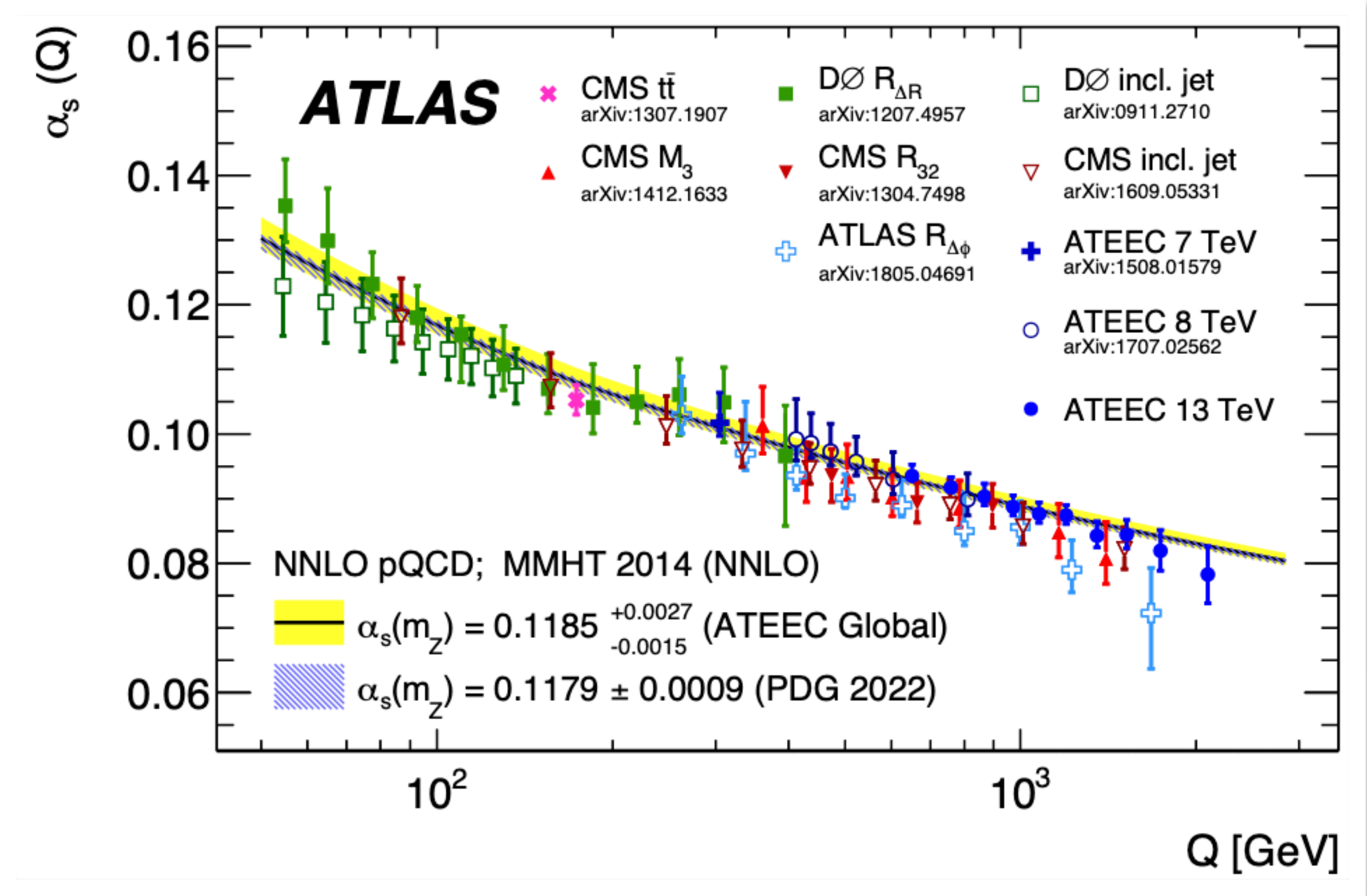


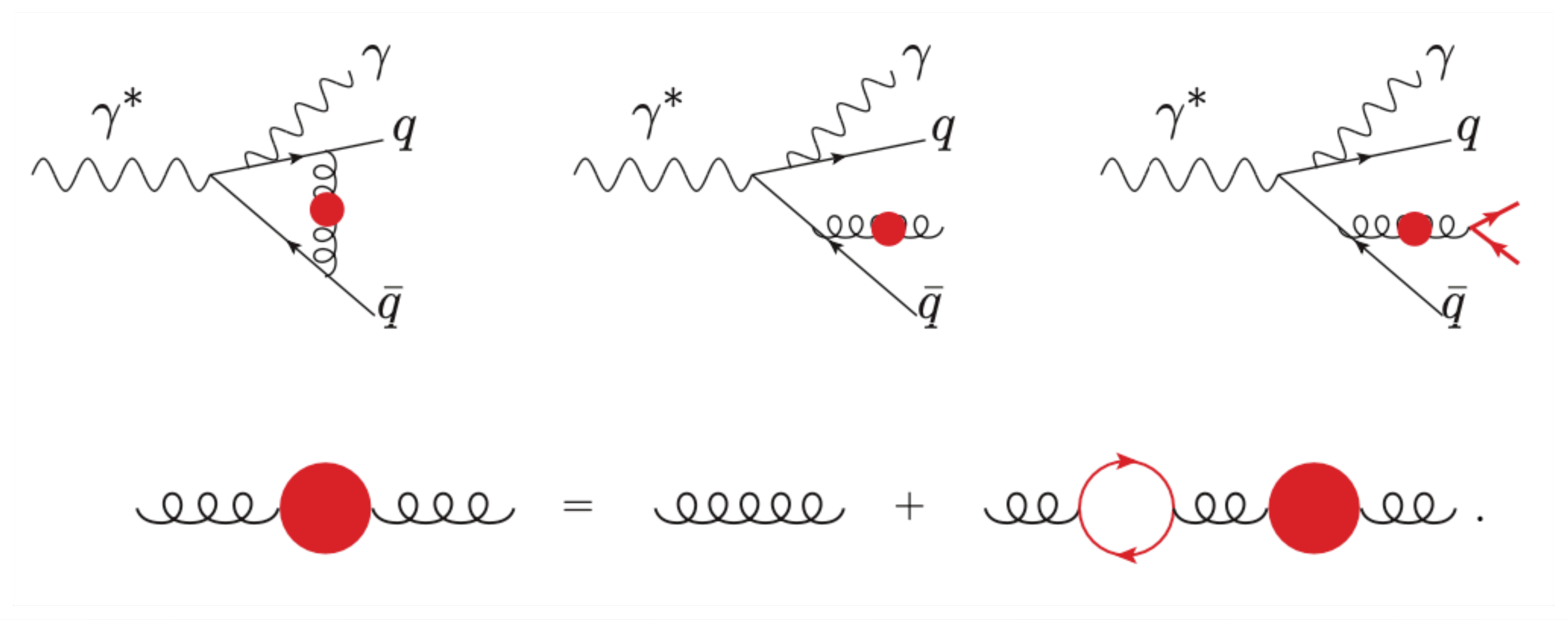
M. van Beekveld, S. Ferrario Ravasio 2305.08645

Non-Perturbative QFT for Precision Predictions









Non-Perturbative QFT for Precision Predictions

a_μ^{HVP} Data driven vs. Lattice QCD

Data from SM White Paper Phys.Rept. 887 (2020)

SM contrib.	$a_\mu^{contrib.} \times 10^{10}$	
HVP-LO (e^+e^-)	693.1	± 4.0
HVP-NLO (e^+e^-)	-9.83	± 0.07
HVP-NNLO (e^+e^-)	1.24	± 0.01
HLbL-LO (pheno)	9.2	± 1.9
HLbL (lattice *usd*)	7.8	± 3.4
HLbL (pheno+lattice)	9.0	± 1.7
HLbL-NLO (pheno)	0.2	± 0.1
QED (5 loops)	11 658 471.8931	± 0.0104
EW (2 loops)	15.36	± 0.10
HVP (e^+e^-, LO + N(N)LO)	684.5	± 4.0
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SM Total	11 659 181.0	± 4.3

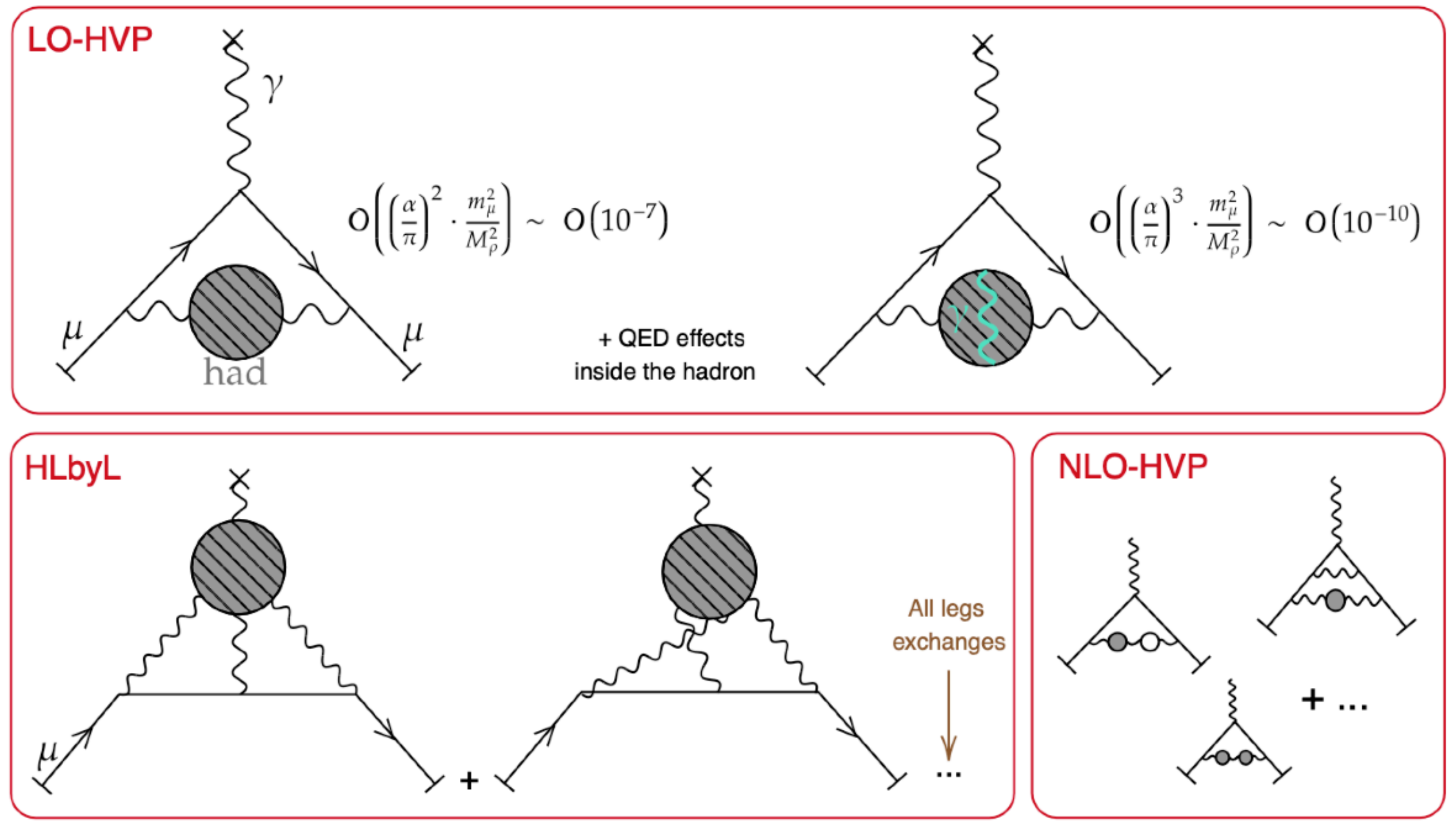

Table and diagram by L. Pareao at Zurich Workshop in June 2023

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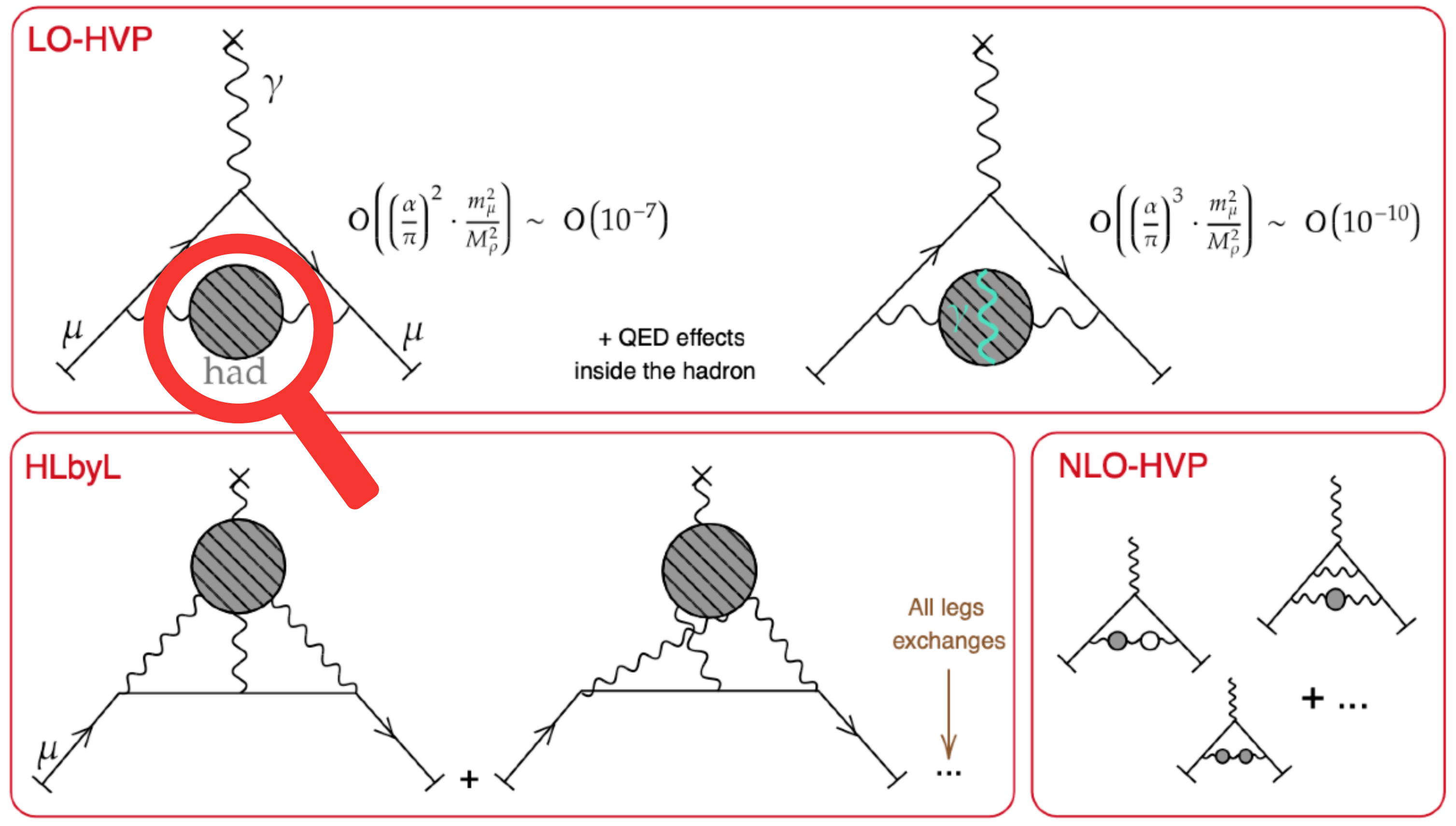

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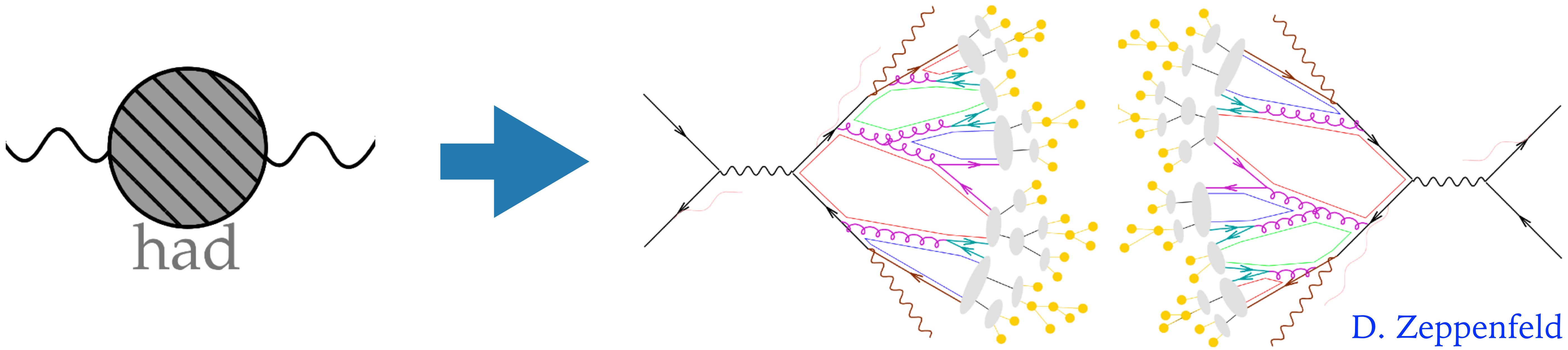
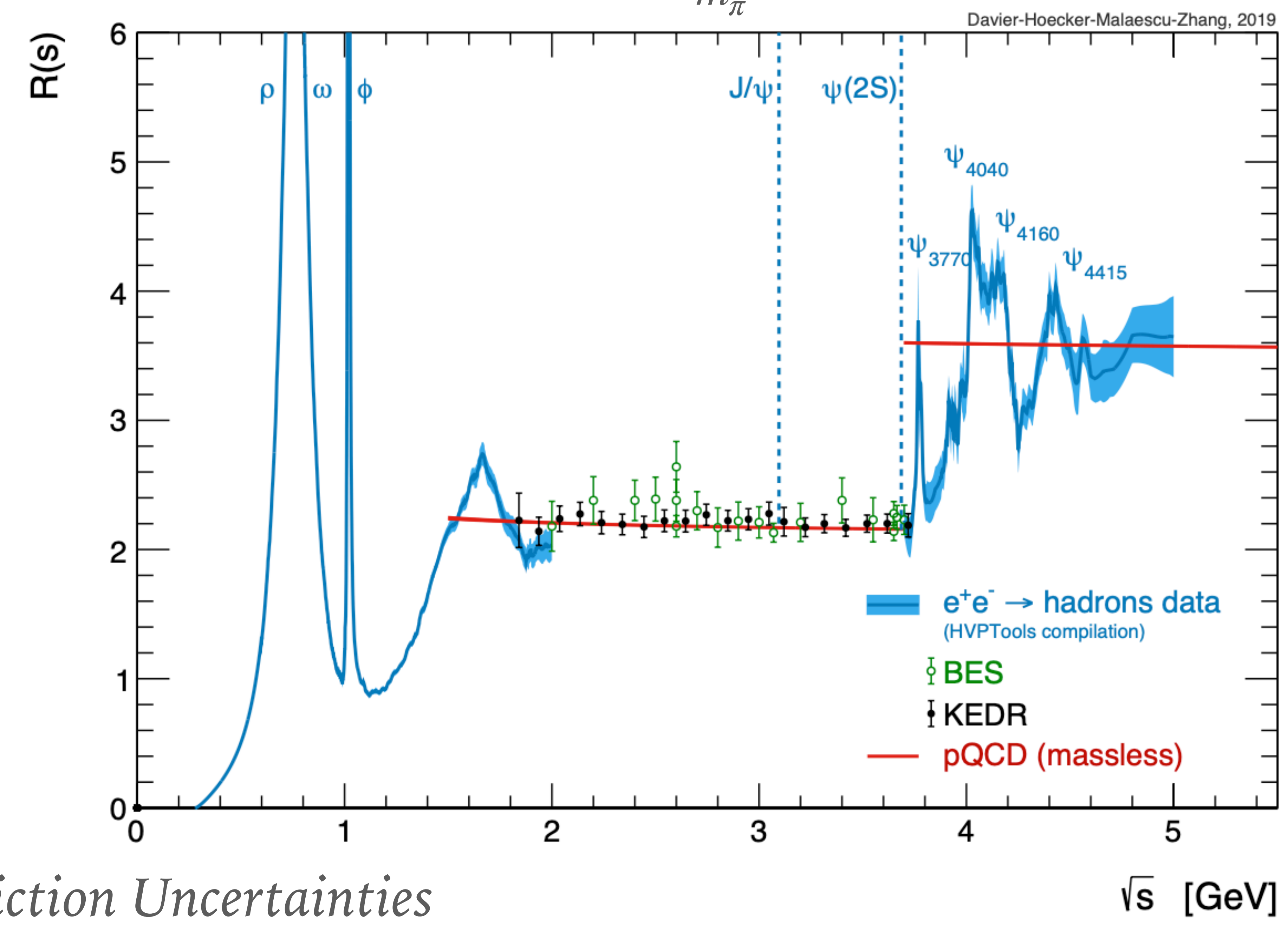


- Perturbative QCD is not valid for $\Lambda = m_\mu \ll \Lambda_{QCD}$
- Use dispersive approach to include $e^+e^- \rightarrow$ Hadron data via R-ratio:

$$a_{\mu,DA}^{LO-HVP} = \frac{\alpha^2}{3\pi^3}\int_{m_\pi^2}^{\infty}\frac{ds}{s}K(s)R(s)$$



M. Davier et. al. Eur.Phys.J.C 80 (2020) 5

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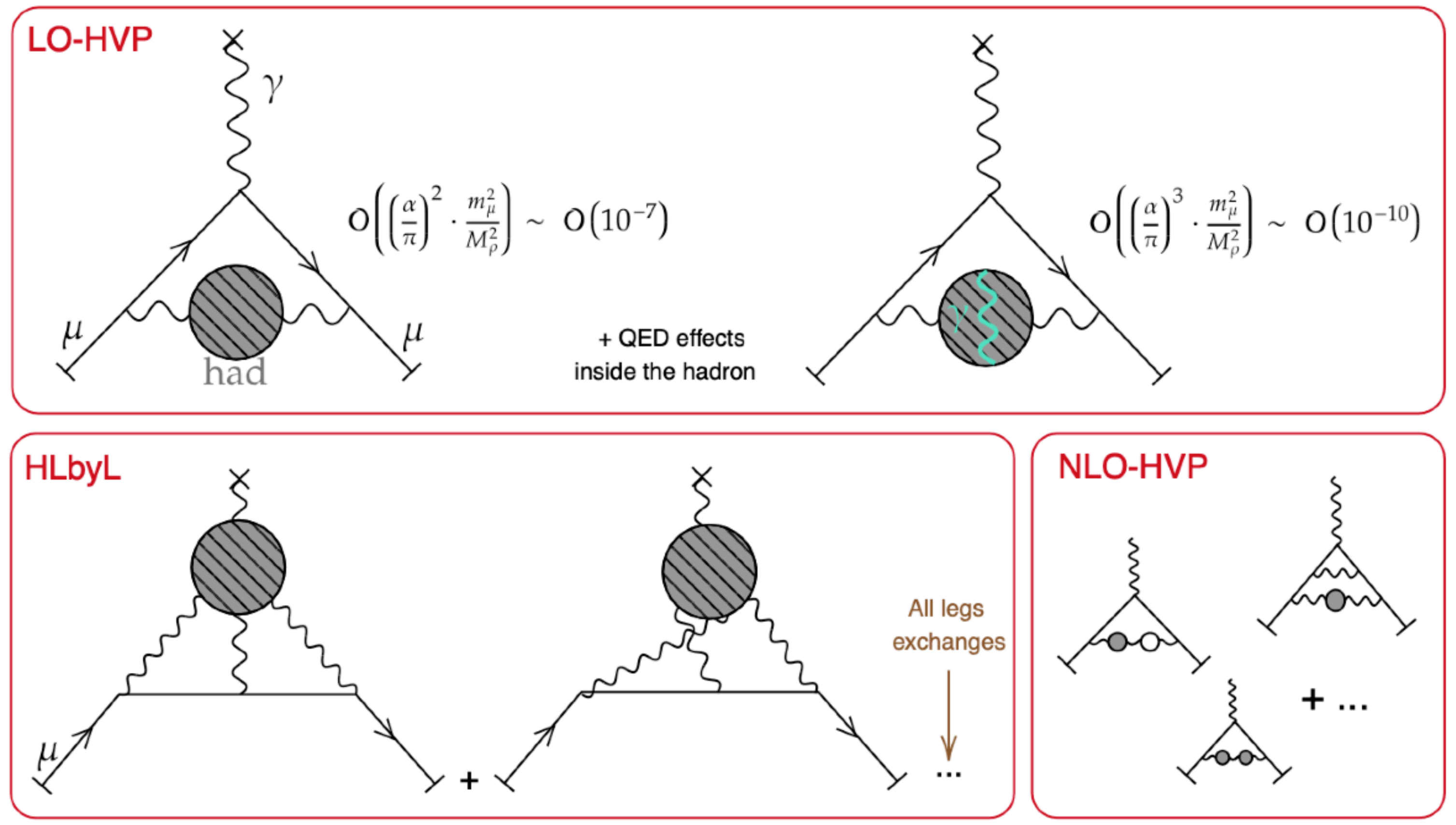

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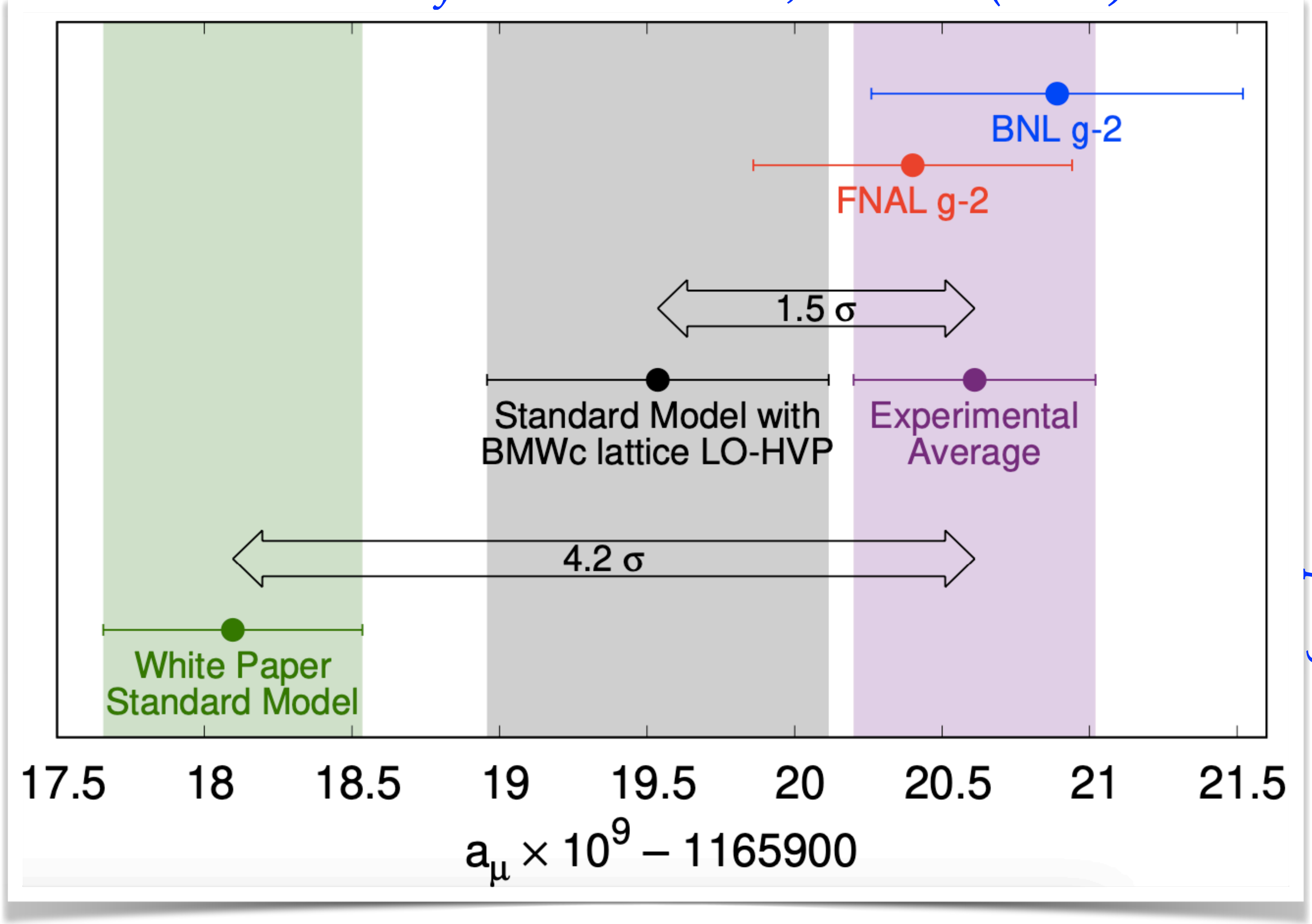
*FNAL Phys. Rev. Lett. **126**, 141801 (2021)*



L. Pareao at Zurich Workshop in June

Non-Perturbative QFT for Precision Predictions

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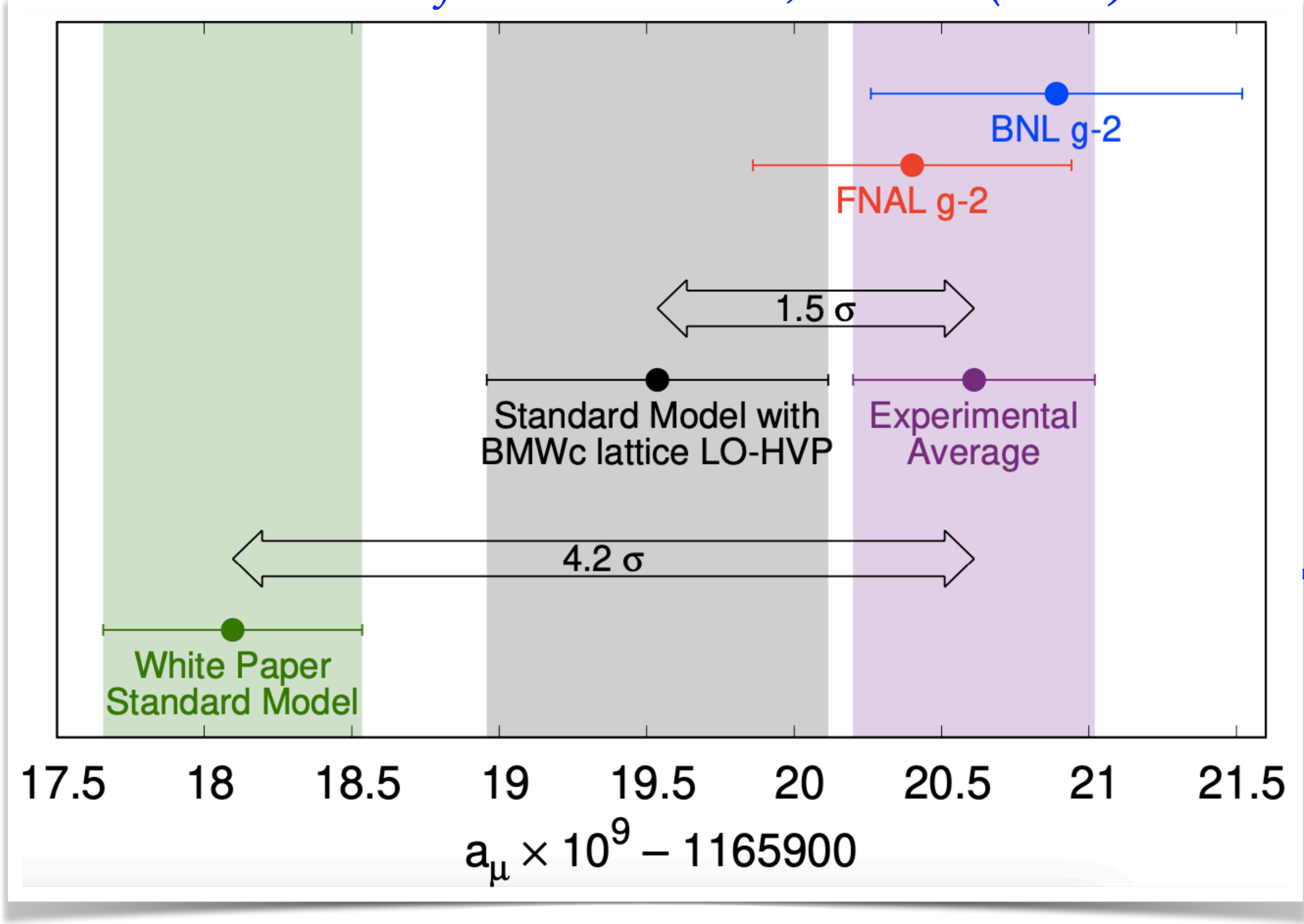
$$a_{\mu,DA}^{LO-HVP} = \frac{\alpha^2}{3\pi^3}\int_{m_\pi^2}^{\infty}\frac{ds}{s}K(s)R(s) \qquad a_{\mu,LQCD}^{LO-HVP} = 2\alpha^2\int_0^{\infty} t^2 dt K(m_\mu t)V(t)$$

$$a_{\mu,LQCD}^{LO-HVP,\omega} = 2\alpha^2\int_0^{\infty} t^2 dt K(m_\mu t)\Theta^\omega(t)V(t)$$

- Time ↔ Energy Window
  - $[0,\ t_0] \oplus [t_0,\ t_1] \oplus [t_1, +\infty]$ for SD, W, LD.
  - SD and W precisely predicted by Lattice QCD in continuum.
  - SD and W energy windows with precise e^+e^- EXP data.
  - a_μ^W (intermediate window) has 3.7 σ tension for DA vs. LQCD

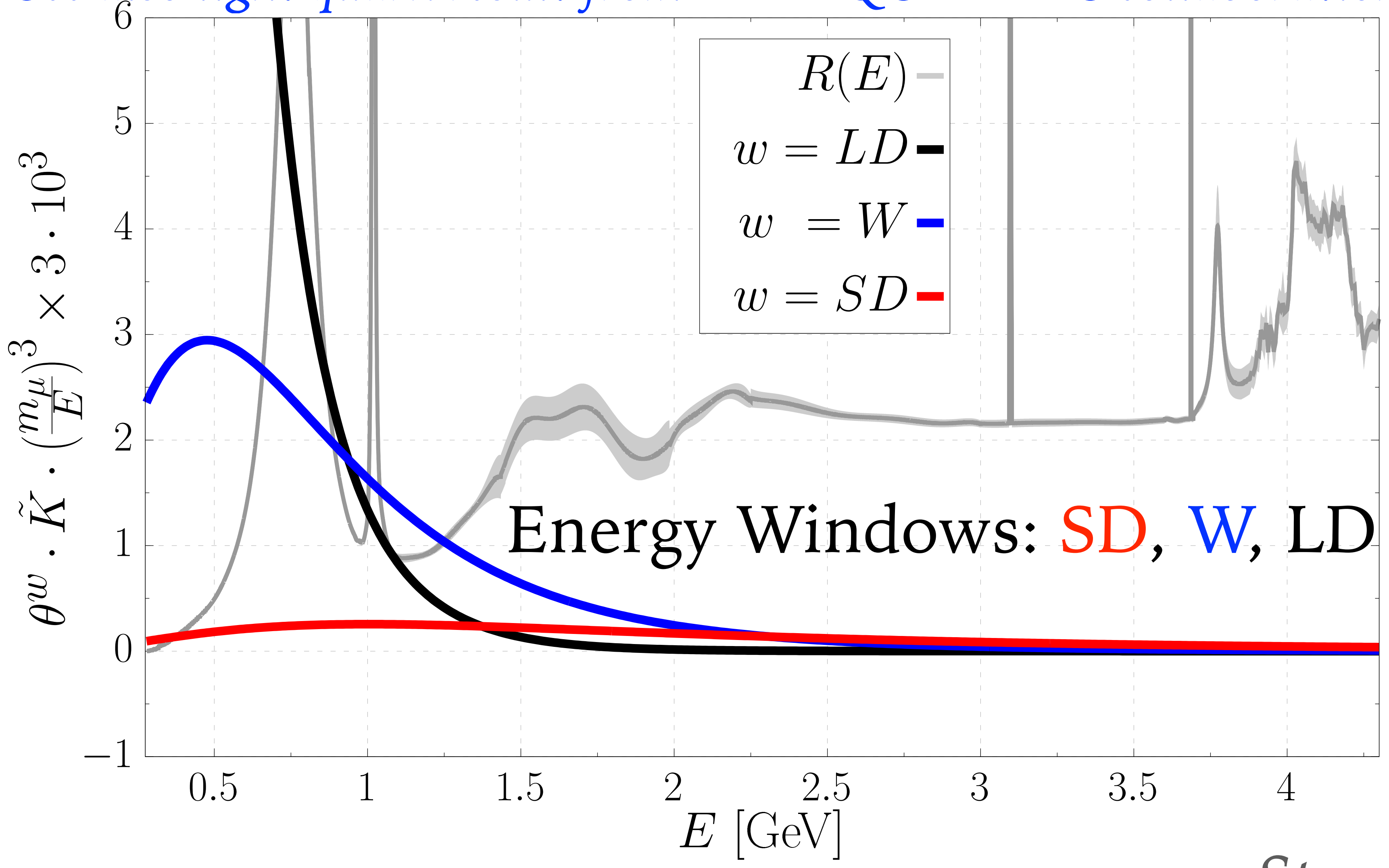
*FNAL Phys. Rev. Lett. **126**, 141801 (2021)*

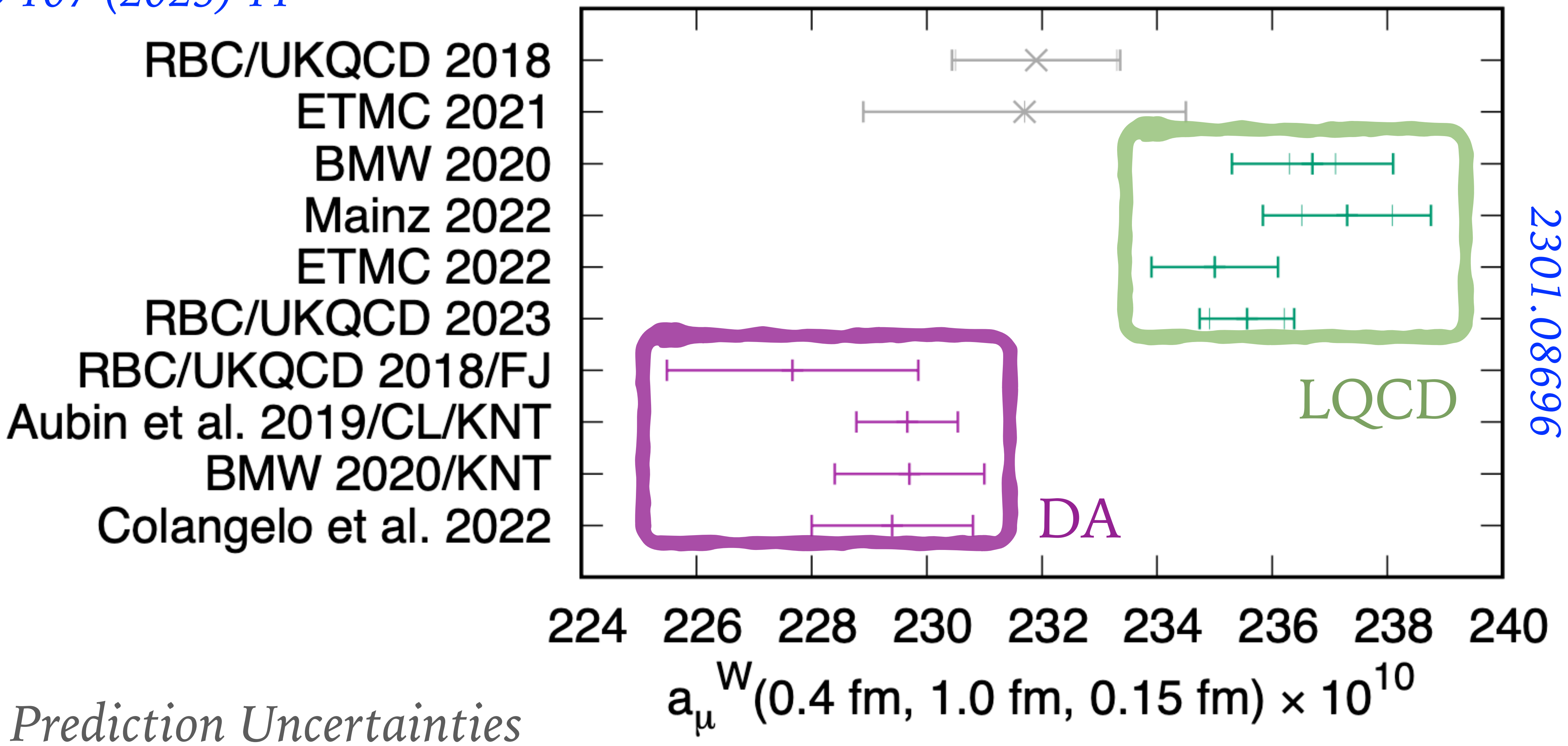


L. Pareao at Zurich Workshop in June

See also light quark result from FL-HPQCD-MILC collaboration, Phys.Rev.D 107 (2023) 11

ETM Collaboration, 2212.10490





RBC/UKQCD Collaboration 2301.08696

Parton Distributions and α_s

State-of-the-art Parton Distribution Functions

- Theory input
  - Option A: solve proton wave function with Lattice QCD *Recent progress in D. Chakrabarti, P. Choudhary et. al. 2304.09908*
  - Option B: collinear factorisation $f_a \to f_a(x,\mu)$ with p-QCD evolution of factorisation scale

$$\frac{d}{d\ln\mu^2}\begin{pmatrix} f_q \\ f_g \end{pmatrix} = \begin{pmatrix} P_{q\leftarrow q} & P_{q\leftarrow g} \\ P_{g\leftarrow q} & P_{g\leftarrow g} \end{pmatrix} \otimes \begin{pmatrix} f_q \\ f_g \end{pmatrix}$$

DGLAP evolution with

$$p_{a\leftarrow b} = \frac{\alpha_s}{\pi}P^{(0)}_{a\leftarrow b} + \frac{\alpha_s^2}{\pi^2}P^{(1)}_{a\leftarrow b} + \frac{\alpha_s^3}{\pi^3}P^{(2)}_{a\leftarrow b} + \cdots$$

1970's 1980 2004

$$\gamma^{(3)}_{q\leftarrow q}(N) = -\int_0^1 \mathrm{d}x x^{N-1} P^{(3)}_{q\leftarrow q}(x)$$ *G. Falcioni, F. Herzog et. al. Phys.Lett.B 842 (2023)*

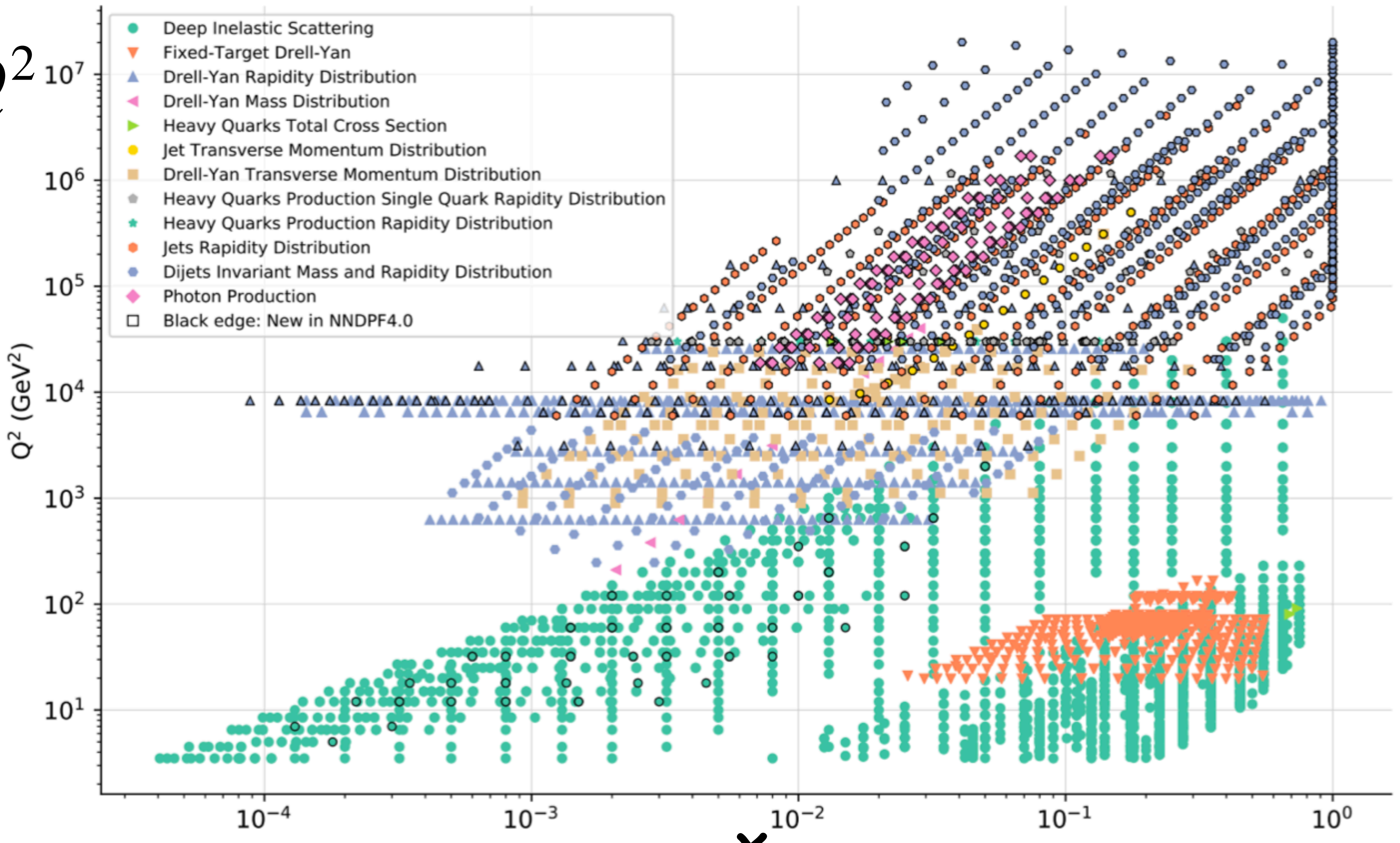
$$\gamma^{(3)}_{q\leftarrow g}(N) = -\int_0^1 \mathrm{d}x x^{N-1} P^{(3)}_{q\leftarrow g}(x)$$ *G. Falcioni, F. Herzog, S. Moch, A. Vogt 2307.04158*

For $N = 2,4,\cdots 20$

- Experiment input
  - All past and current measurements of DIS, DY, jets etc. provide fitting targets of $f_a(x,Q)$
  - Differential and total cross sections provide sensitivity in different regions of $x \in [0,1]$
  - Various technology for fitting: functional form, neural network, fast evaluation grids etc.

Q^2

NNPDF4.0 Coverage



x

Parton Distributions and α_s

State-of-the-art Parton Distribution Functions

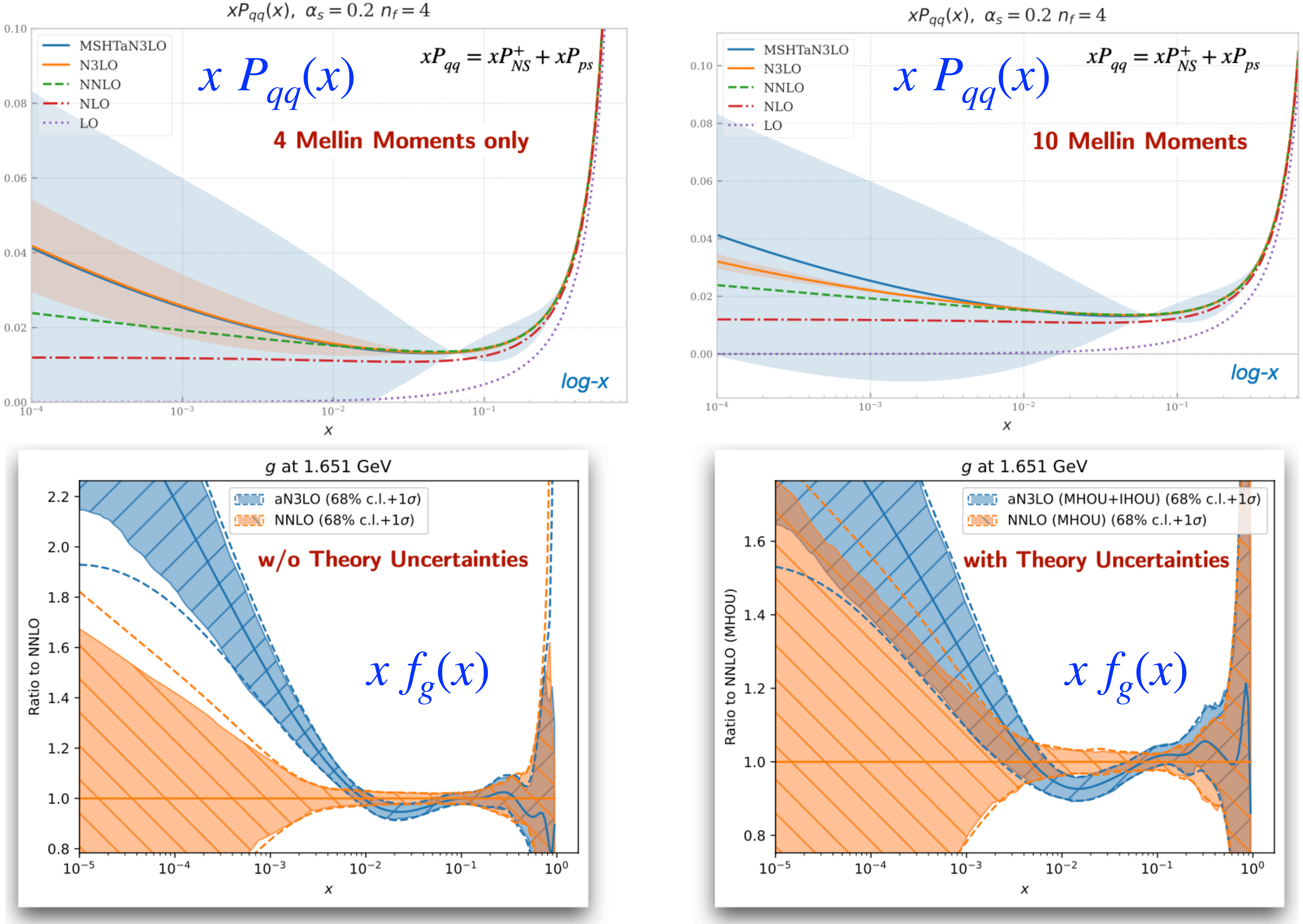
G. Magni (NNPDF) @ Les Houches 23

- Approximated N3LO PDF available:

  MSHT20aN3LO *Eur.Phys.J.C 83 (2023) 4*

  NNPDFaN3LO *NNPDF preliminary*

- More precise 4-loop splitting functions affect small x region.
- Large correction at aN3LO at small x region outside 68% c.l. region.
- Missing Higher Order Uncertainty (MHOU) not included in standard NNLO PDF.
- Crucial to consider MHOU and IHOU to understand consistency between NNLO and N3LO PDF.



Parton Distributions and α_s

The running strong coupling

- Both non-perturbative and perturbative α_s determination depend on the beta-function.
- More and more precision predictions and measurements across 10^3 magnitude.

$$Q^2 \frac{\mathrm{d}\alpha_s}{\mathrm{d}Q^2} = \beta(\alpha_s) = -\,\alpha_s^2\left(\underset{1973}{b_0} + \underset{1979}{b_1\alpha_s} + \underset{1993}{b_2\alpha_s^2} + \underset{1997}{b_3\alpha_s^3} + \underset{2017}{b_4\alpha_s^4} + \cdots\right)$$

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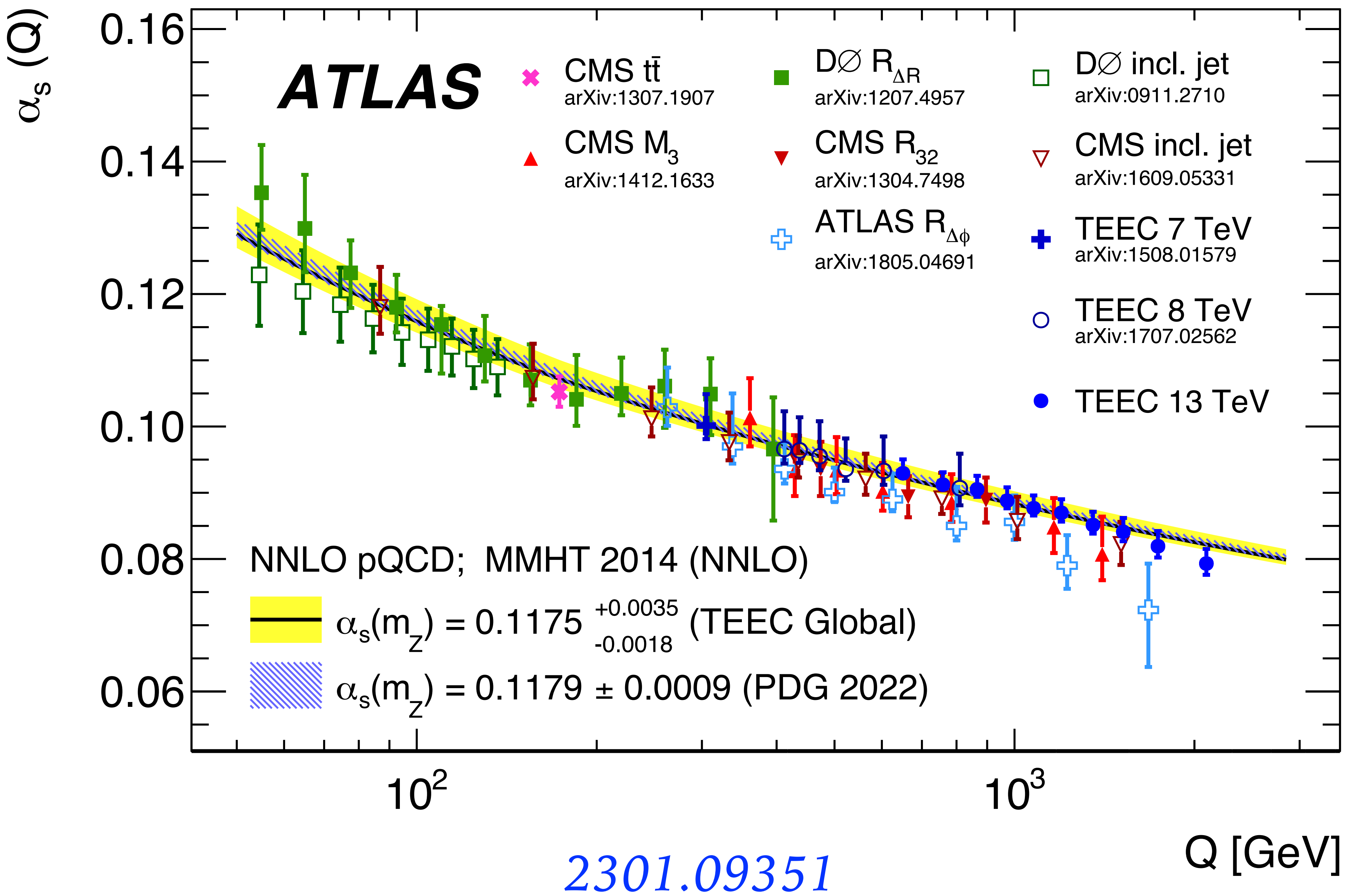
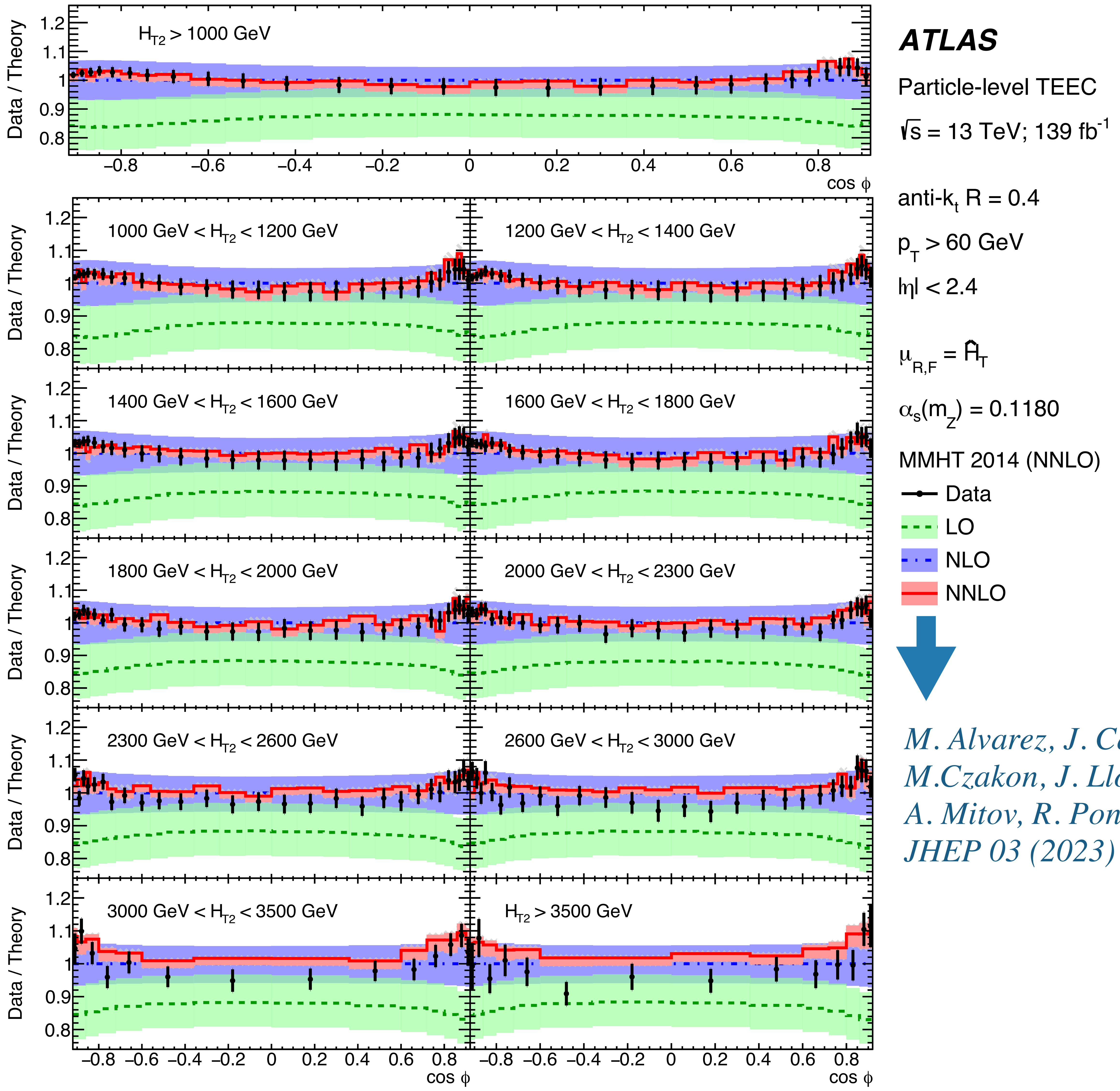
$$\text{TEEC:}\quad \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{\mathrm{T}i}E^A_{\mathrm{T}j}}{\left(\sum_k E^A_{\mathrm{T}k}\right)^2}\delta(\cos\phi - \cos\varphi_{ij})$$



2301.09351



M. Alvarez, J. Cantero, M.Czakon, J. Llorente, A. Mitov, R. Poncelet JHEP 03 (2023) 129

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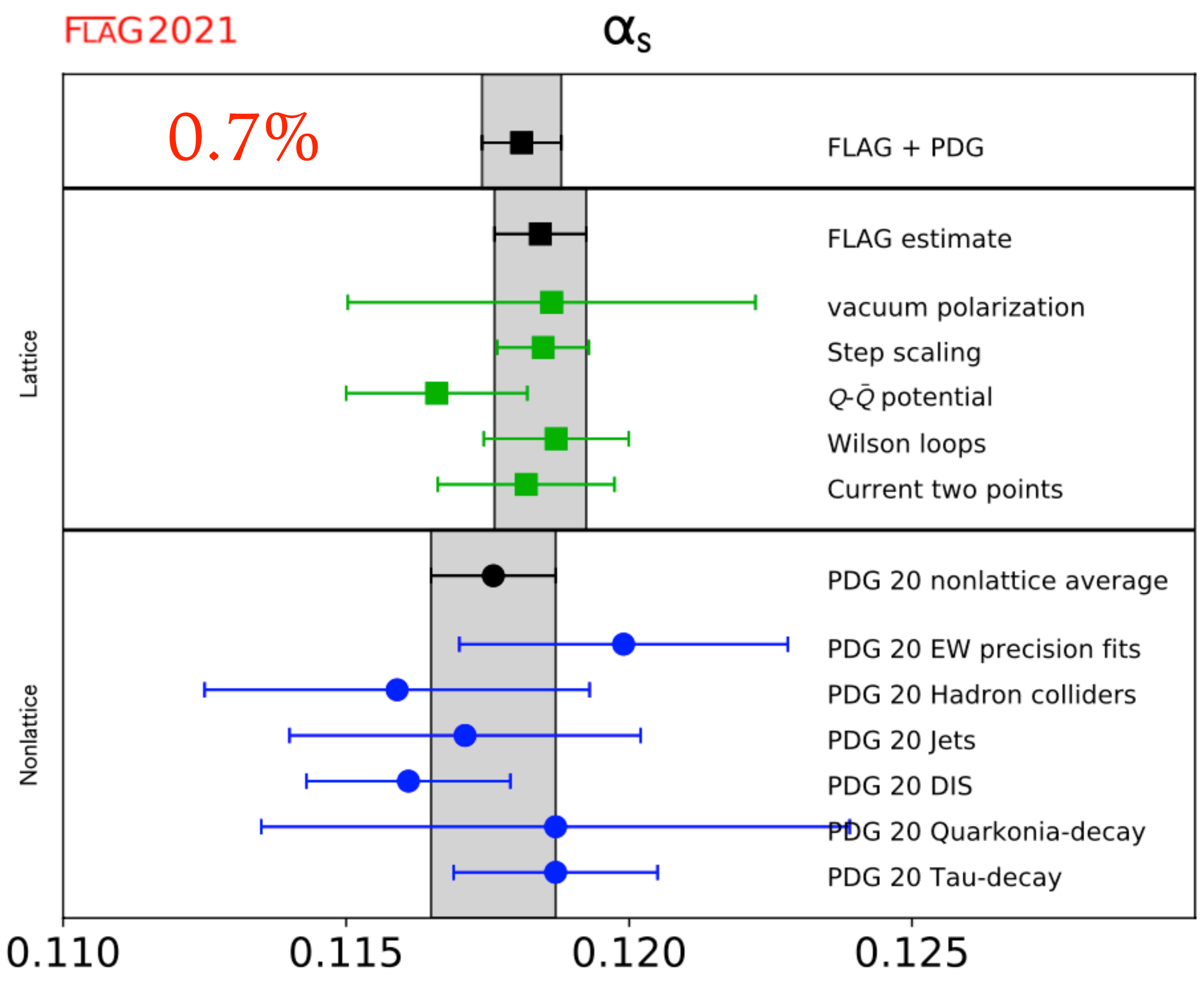

Flavour Lattice Averaging Group Eur.Phys.J.C 82 (2022) 10

Parton Distributions and α_s

The running strong coupling

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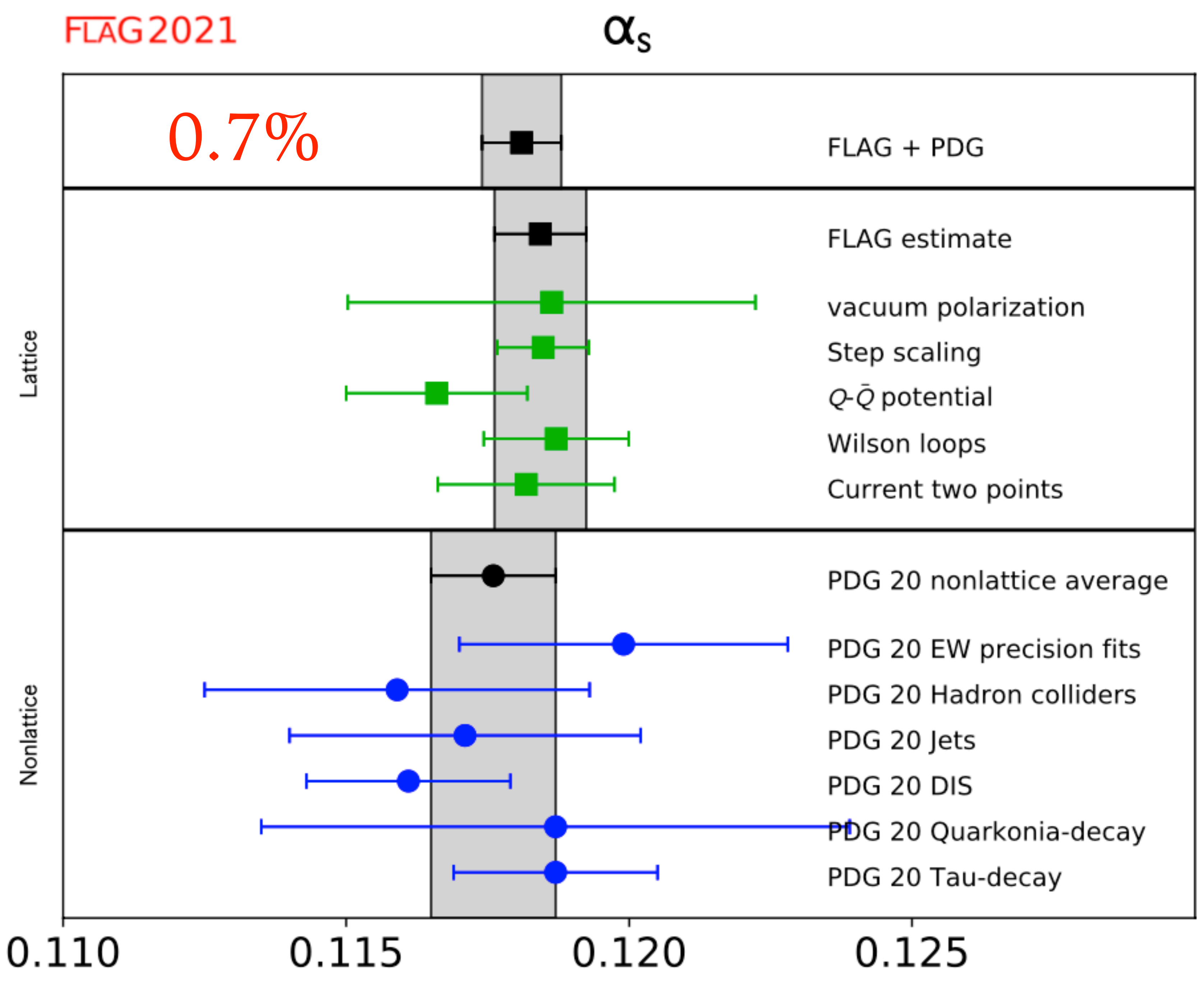
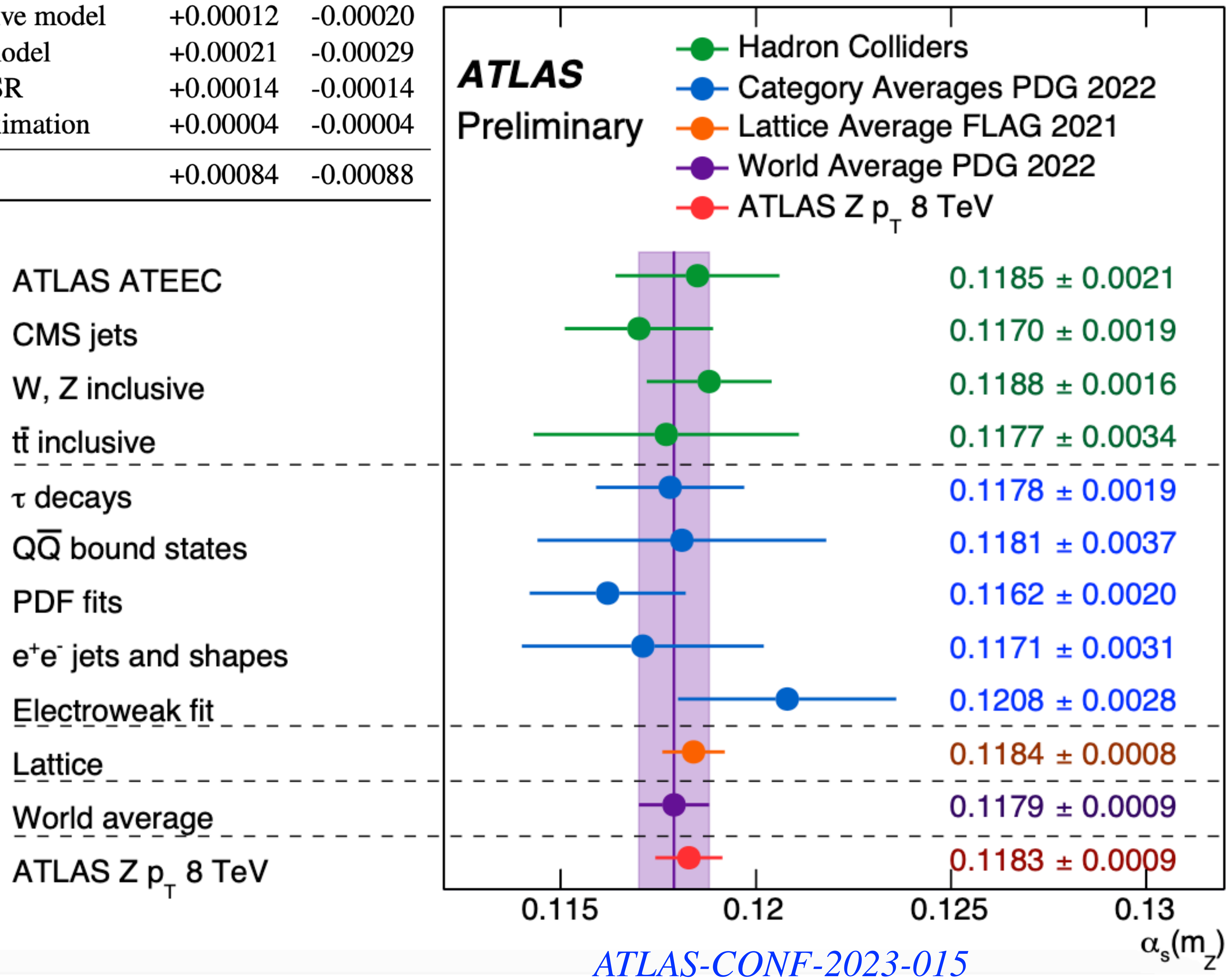


Flavour Lattice Averaging Group Eur.Phys.J.C 82 (2022) 10

Error budget of ATLAS Z p_T 8 TeV

Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088

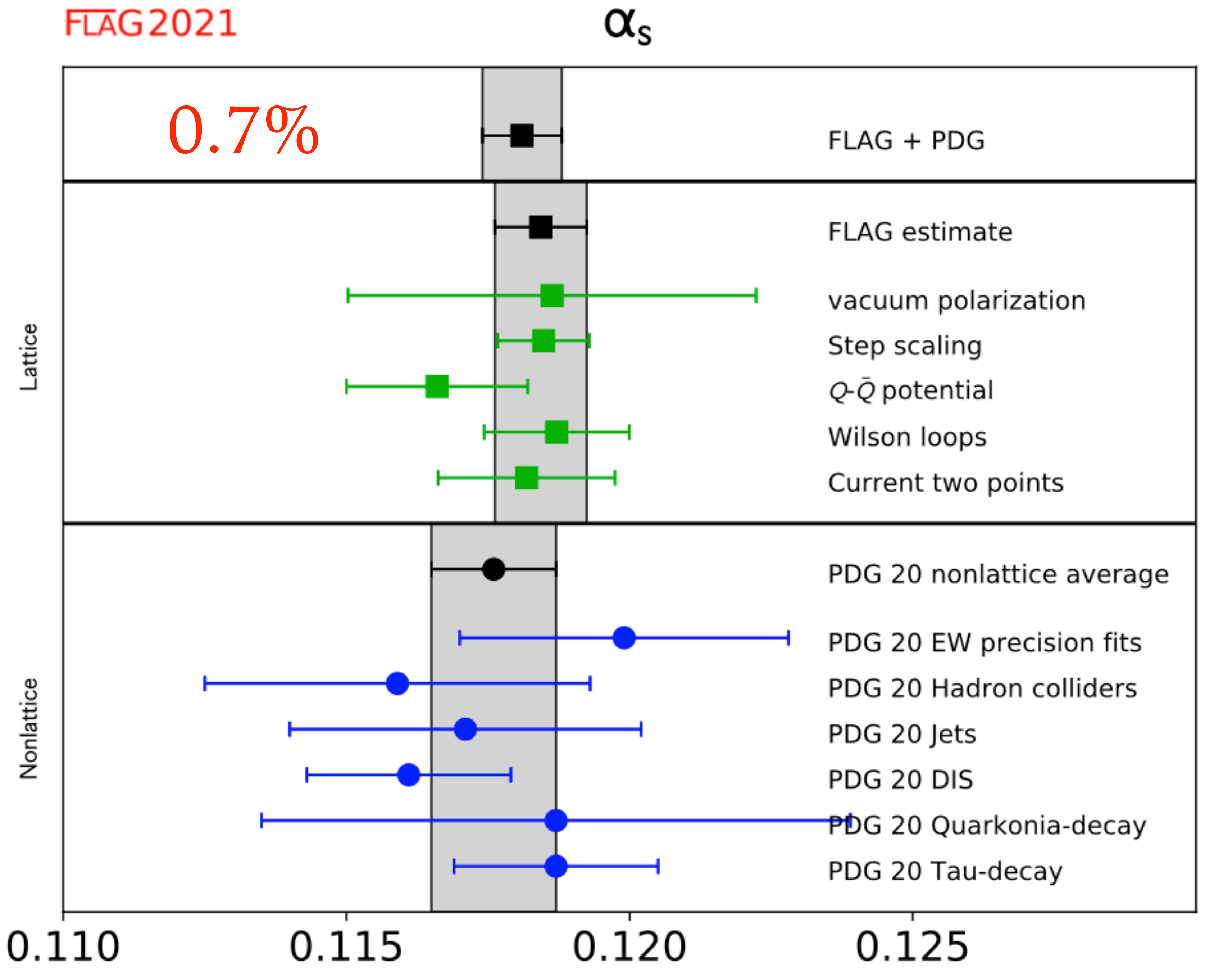


ATLAS-CONF-2023-015

Parton Distributions and α_s

The running strong coupling

- Both non-perturbative and perturbative α_s determination depend on the beta-function.
- More and more precision predictions and measurements across 10^3 magnitude.



Flavour Lattice Averaging Group Eur.Phys.J.C 82 (2022) 10

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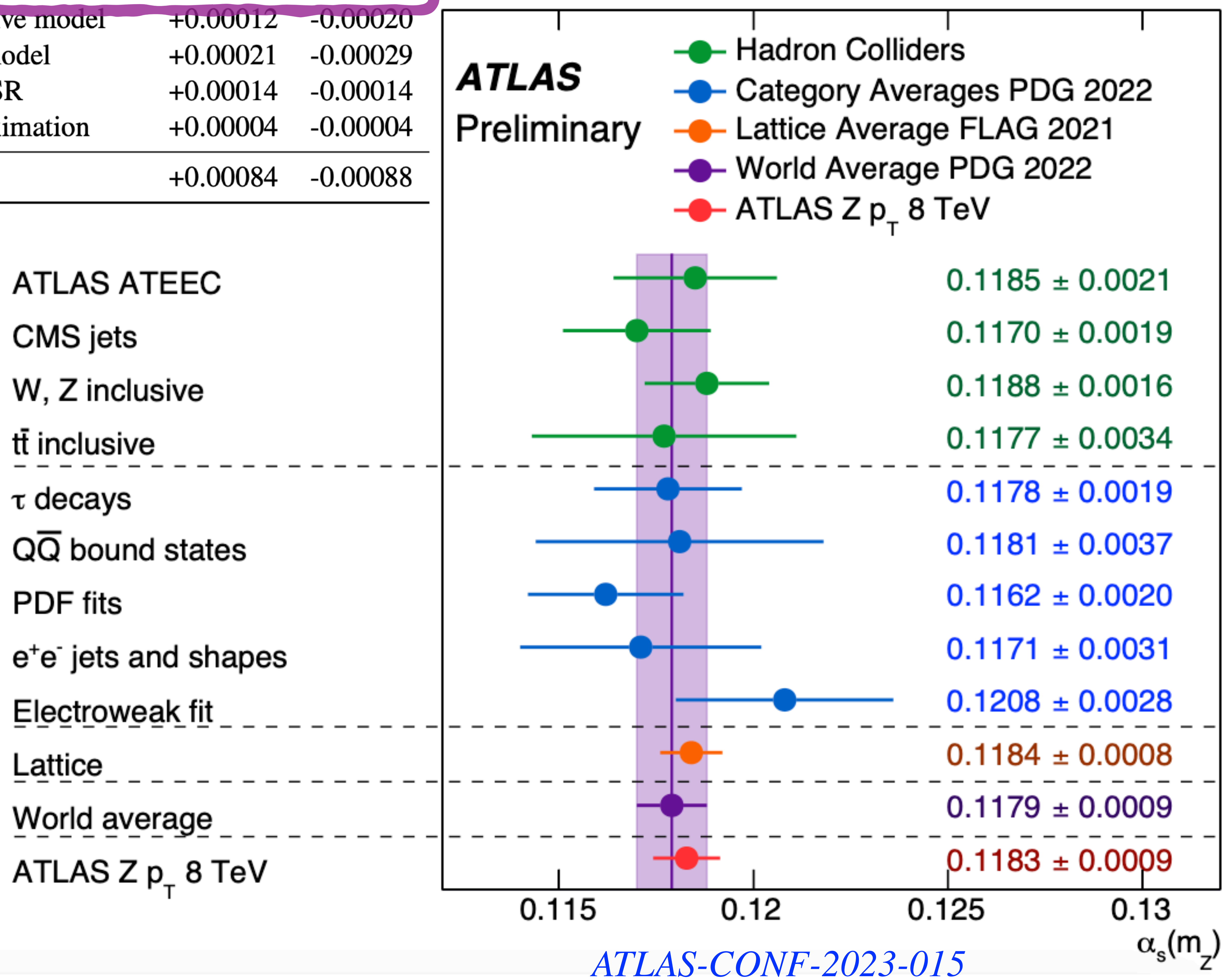
Missing: MHOU from aN3LOPDF; Dominant matching error; Systematic slicing error in DYTurbo and MCFM (double slicing);

→ Optimistic uncertainty estimation



ATLAS-CONF-2023-015

Parton Distributions and α_s

The running strong coupling

- Both non-perturbative and perturbative α_s determination depend on the beta-function.
- More and more precision predictions and measurements across 10^3 magnitude.
- To understand the NP power correction in collinear factorisation (hadron collider):
  - n=2 for inclusive DY, n=1 for hadronisation
  - What about Z/W at large p_T ?

$$\left(\frac{1\ \mathrm{GeV}}{30\ \mathrm{GeV}}\right)^{\mathrm{n}} \approx 3\,\%\ (0.1\%)\ \text{for n=1 (n=2)}$$

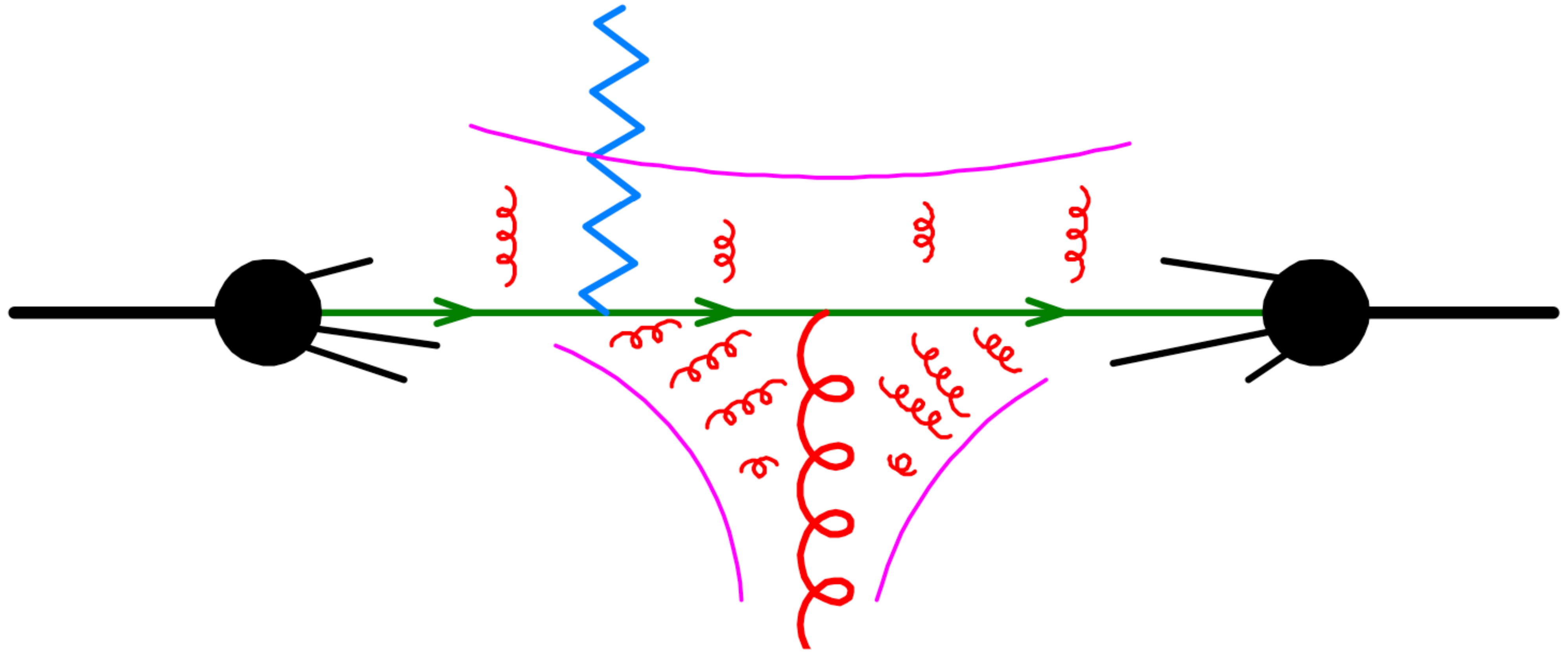
- MC framework to estimate renormalon corrections:

Ferraro Ravasio, Limatola, Nason JHEP 06 (2021) 018

Carla, Ferrario Ravviso, et. al. JHEP 01 (2022) 093, JHEP 12 (2022) 062

- Confirm n=2 for p_T^Z at hadron colliders → no need to update α_s fitting related to DY data.

$$\sigma = \sum_{i,j} \int \mathrm{d}x_1 \mathrm{d}x_2 f_i(x_1) f_j(x_2) \hat{\sigma}(\hat{s}) \times \left[1 + \mathcal{O}\left(\Lambda/Q\right)^n\right]$$



- Linear NP corrections in $e^+e^- \to 3$ jets ease the tension in α_s fitting from C-parameter and thrust.

P. Nason, G. Zanderighi JHEP 06 (2023) 058

CONCLUSION AND OUTLOOK

- Reducing and understanding the Standard Model uncertainties is indispensable for future high energy experiment.
- It is about finding the shortest panel of a bucket rather than boosting the longest.
- Multiple solutions work together to test our understand of the Standard Model: perturbative and non-perturbative QFT, specialised fitting etc.
- There is rapid progress in the complexity of amplitudes, NNLO and N3LO phenomenology, parton shower framework, lattice QCD and machine learning technology etc.
- It is not only to predict a more precise number but to be confronted by conceptual problems that we previously ignored.

[Apologies for the personal selection of topics, and for the many interesting results not covered here]

CONCLUSION AND OUTLOOK

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Thank You for Your Attention

BACK UP SLIDES

STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO+N^{3(4)}LL}$

FO	α_s^n	$P^{(n)}_{ab}(x)$	$\ln W(x_a, x_b, m_V, \vec{b}, \mu = b_0/b) \sim \int_{\mu_h}^{\mu} d\bar{\mu}/\bar{\mu}\left(A(\alpha_s(\bar{\mu}))\ln\frac{m_V^2}{\bar{\mu}^2} + B(\alpha_s(\bar{\mu}))\right)$						
$\frac{d\hat{\sigma}^V_{NLO}}{dq_T}$	1	✓	$\ln^2(b^2m_V^2)$	$\ln(b^2m_V^2)$	1				
$\frac{d\hat{\sigma}^V_{NNLO}}{dq_T}$	2	✓	$\ln^3(b^2m_V^2)$	$\ln^2(b^2m_V^2)$	$\ln(b^2m_V^2)$	1			
$\frac{d\hat{\sigma}^V_{N^3LO}}{dq_T}$	3	✓	$\ln^4(b^2m_V^2)$	$\ln^3(b^2m_V^2)$	$\ln^2(b^2m_V^2)$	$\ln(b^2m_V^2)$	1		
$\frac{d\hat{\sigma}^V_{N^4LO}}{dq_T}$	4	✗	$\ln^5(b^2m_V^2)$	$\ln^4(b^2m_V^2)$	$\ln^3(b^2m_V^2)$	$\ln^2(b^2m_V^2)$	$\ln(b^2m_V^2)$	1	
…	…		…	…	…	…		…	…
$\frac{d\hat{\sigma}^V_{N^kLO}}{dq_T}$	K		$\ln^{k+1}(b^2m_V^2)$	$\ln^{k}(b^2m_V^2)$	$\ln^{k-1}(b^2m_V^2)$	$\ln^{k-2}(b^2m_V^2)$	$\ln^{k-3}(b^2m_V^2)$	…	…
…	…		…	…	…	…		…	…
	Resum		LL	NLL	NNLL	N3LL	N4LL	…	$N^{k+1}LL$
	A		A1 ✓	A2 ✓	A3 ✓	A4 ✓	A5 ✗	…	A_{k+2}
	B			B1 ✓	B2 ✓	B3 ✓	B4 ✓	…	B_{k+1}

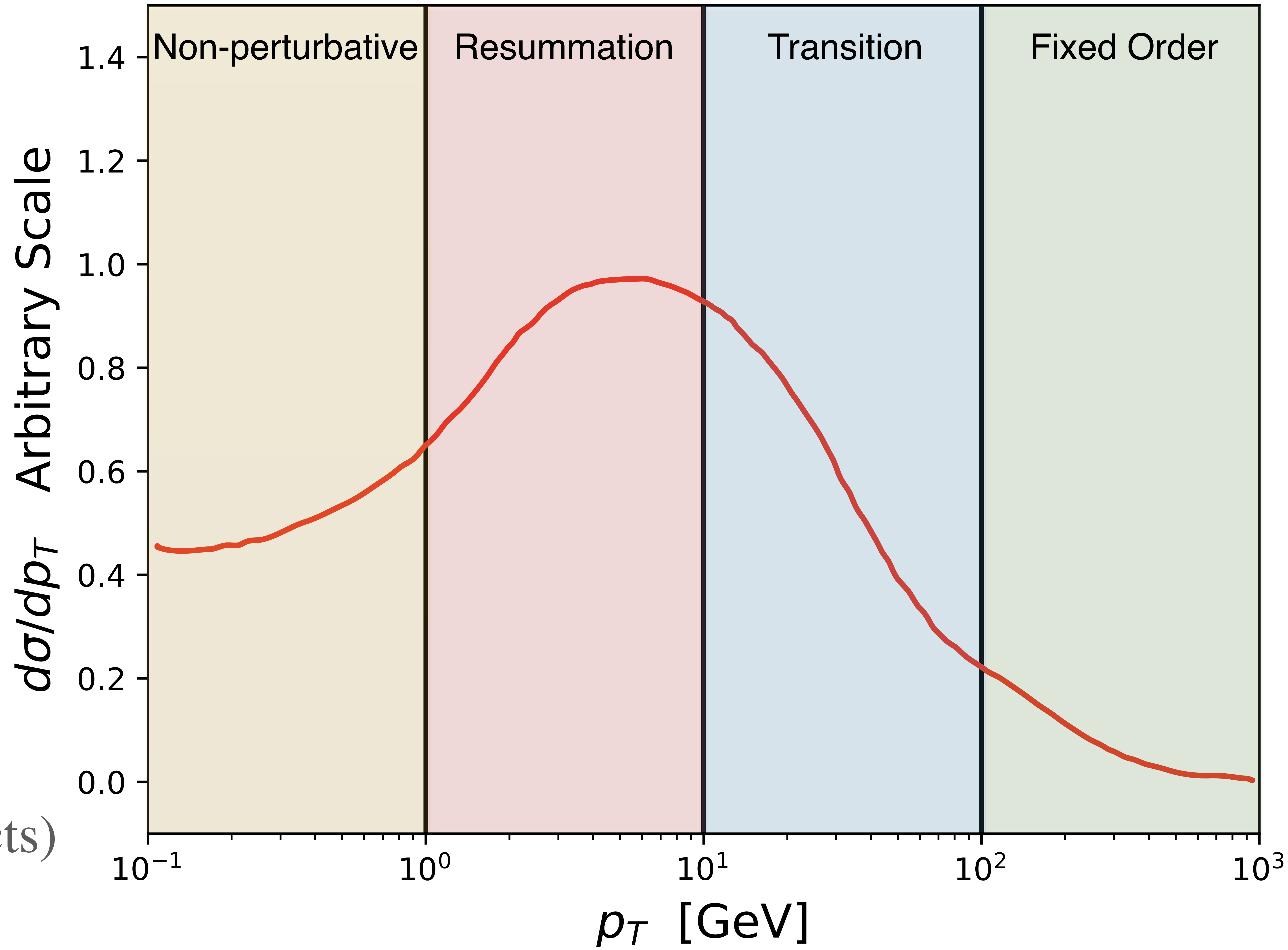
Predictions of Colourless pT at Hadron Collider

- Beyond QCD improved parton model
  - pQCD describes the tail of spectrum
  - Large logarithmic divergence

$$\ln\frac{p_T}{Q} \text{ as } p_T \to 1 \text{ GeV}$$

  - Various LP resummation schemes
  - Multiple solutions in transition region
  - Non-perturbative effects ~ 1 GeV
    (Short distance and long distance effects)

p_T Spectrum = multi-scale problem



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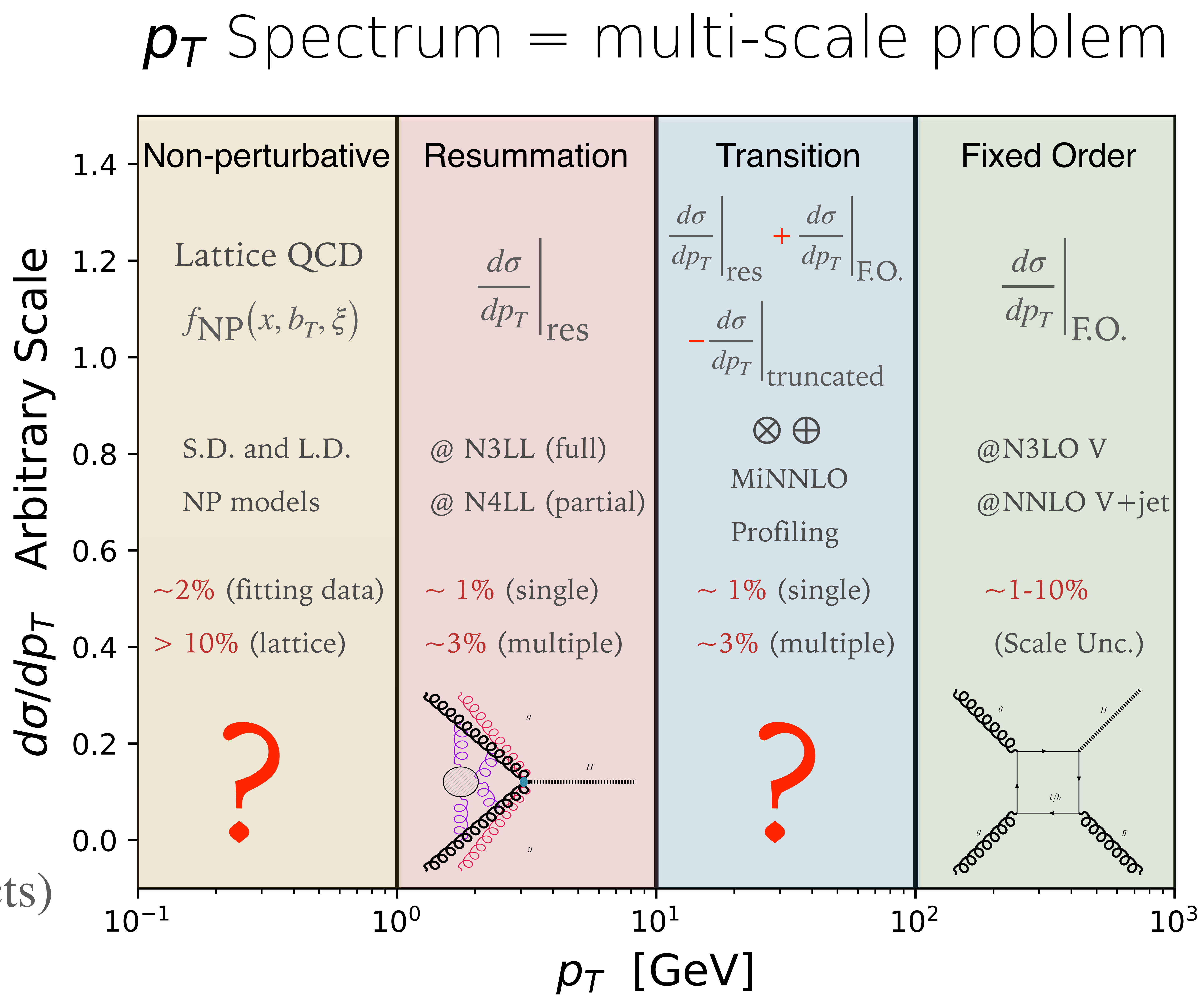


Anatomy of differential cross sections $d\hat{\sigma}_{ab}$

➤ State-of-the-art differential N3LO predictions

- Fully differential N3LO Drell-Yan production (via γ^*) (XC, T. Gehrmann, N. Glover, A. Huss, T.-Z. Yang, H. X. Zhu 2021)
- Apply qt-slicing at N3LO with SCET factorisation and expand to N3LO:

$$\frac{d^3\sigma}{dQ^2 d^2\vec{q}_T dy} = \int \frac{d^2 b_\perp}{(2\pi)^2} e^{-iq_\perp \cdot b_\perp} \sum_q \sigma_{\text{LO}}^{\gamma^*} H_{q\bar{q}} \Bigg[\sum_k \int_{x_1}^1 \frac{dz_1}{z_1} \mathcal{I}_{qk}\left(z_1, b_T^2, \mu\right) f_{k/h_1}(x_1/z_1, \mu)$$
$$\times \sum_j \int_{x_2}^1 \frac{dz_2}{x_2} \mathcal{I}_{\bar{q}j}\left(z_2, b_T^2, \mu\right) f_{j/h_2}(x_2/z_2, \mu) \mathcal{S}\left(b_\perp, \mu\right) + (q \leftrightarrow \bar{q}) \Bigg] + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$

- All factorised functions are recently known up to N3LO:

  1) 3-loop hard function $H_{q\bar{q}}^{(3)}$ (T. Gehrmann, E.W.N. Glover, T. Huber, N. Ikizlerli, C. Studerus 2010)

  2) Transverse-momentum-dependent (TMD) soft function $S(b_\perp, \mu)$ at α_s^3 (Y. Li, H.X. Zhu 2016)

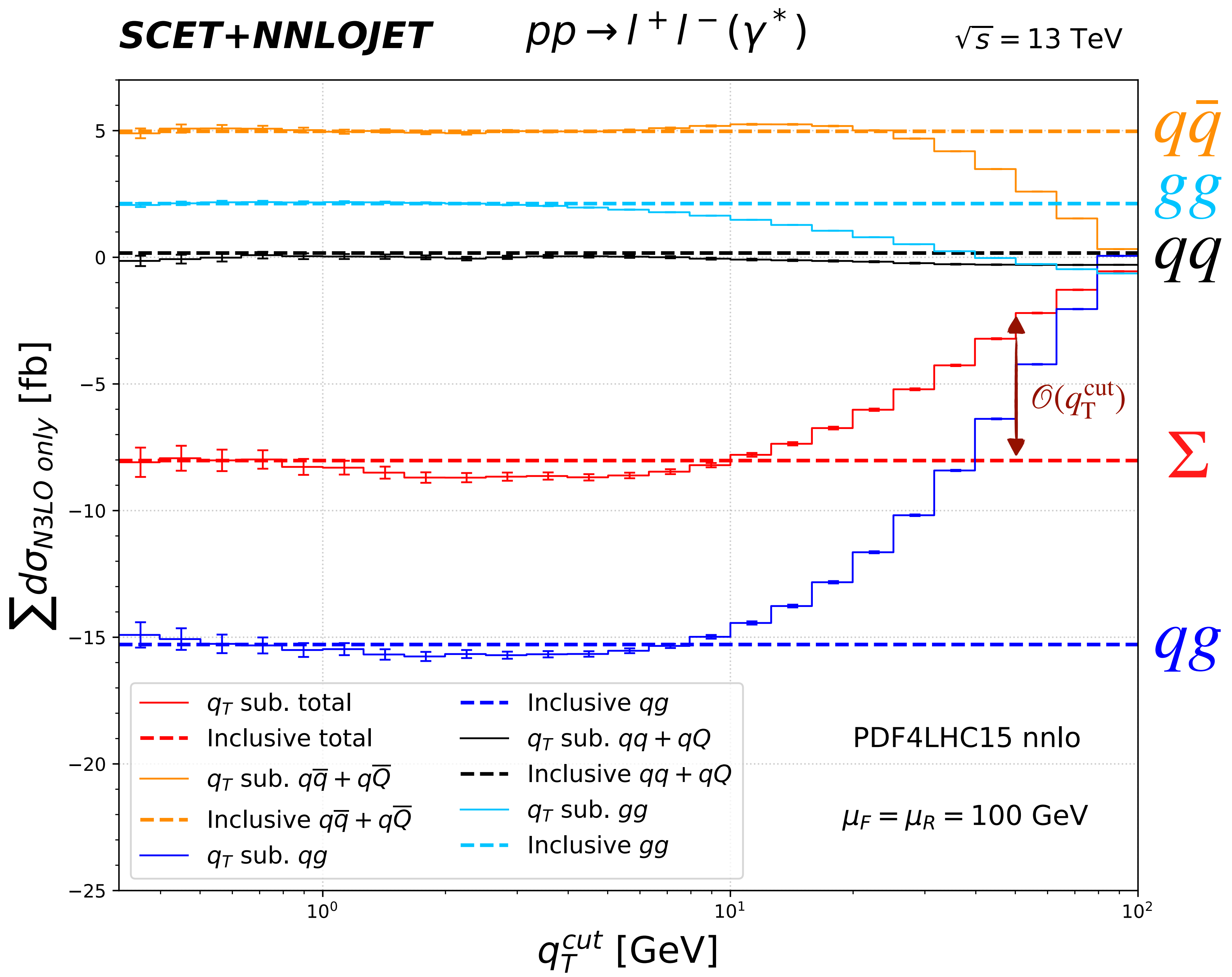
  3) Matching kernel of TMD beam function I_{qk} at α_s^3 (M.-X. Luo, T.-Z. Yang, H. X. Zhu, Y. J. Zhu 2019, M. A. Ebert, B. Mistlberger, G. Vita 2020)

- Apply qt cut to factorise N3LO contribution into two parts:

$$\mathrm{d}\sigma^{\gamma^*}_{N^3LO} = \left[\mathscr{H}^{\gamma^*} \otimes \mathrm{d}\sigma^{\gamma^*}\right]_{N^3LO}\Big|_{\delta(p_{T,\gamma^*})} + \left[\mathrm{d}\sigma^{\gamma^*+jet}_{NNLO} - \mathrm{d}\sigma^{\gamma^*\ CT}_{N^3LO}\right]_{p_{T,\gamma^*} > qt_{cut}} + \mathcal{O}(qt_{cut}^2/Q^2)$$

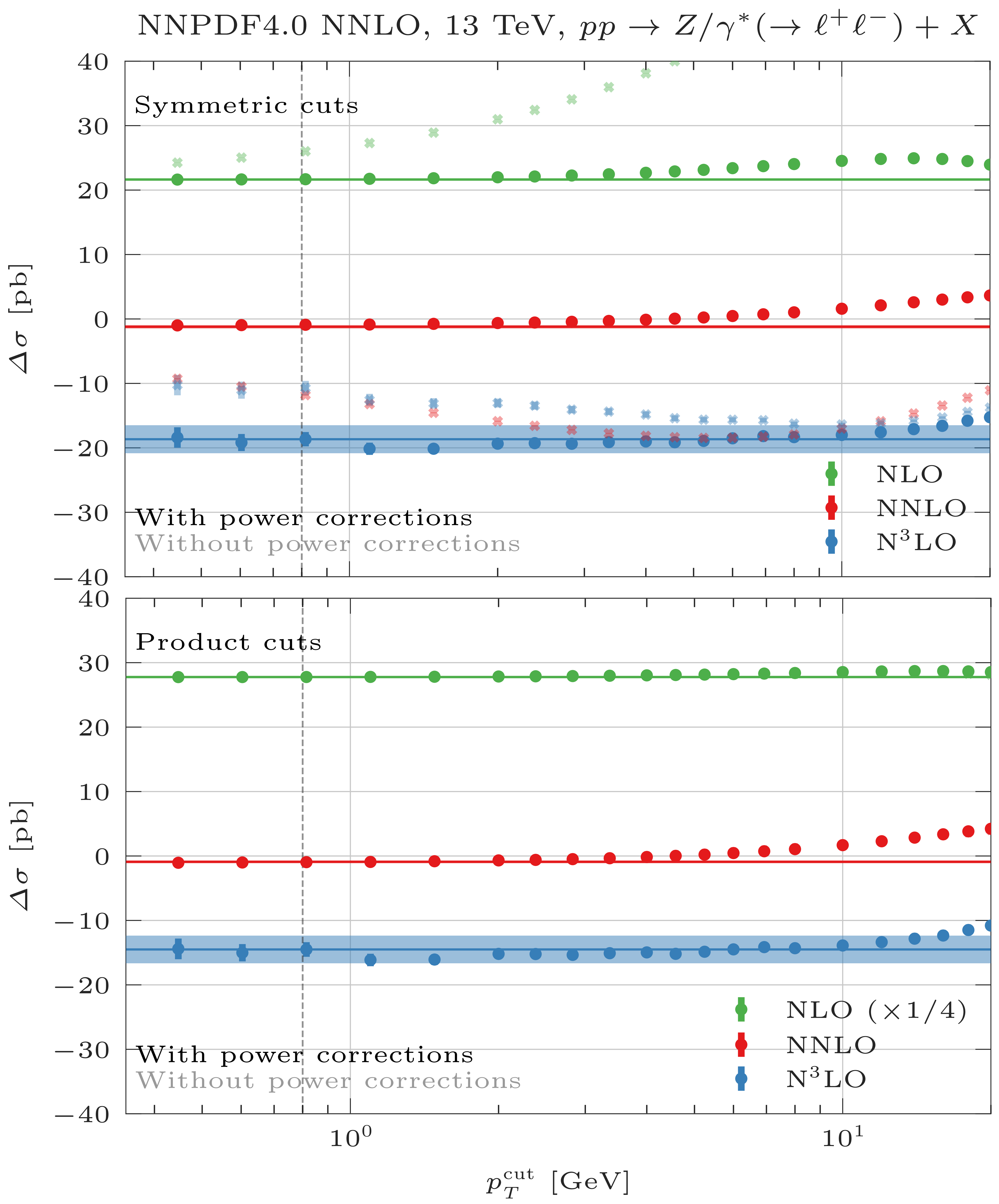
$pp \to \gamma^*/Z$ @ N^{3}LO

XC, T. Gehrmann, et. al. PRL. 128, 052001 (2022)



Fixed order	$\sigma_{pp\to\gamma^*}$ (fb)		
LO	$339.62^{+34.06}_{-37.48}$		
NLO	$391.25^{+10.84}_{-16.62}$		
NNLO	$390.09^{+3.06}_{-4.11}$		
N^{3}LO	$382.08^{+2.64}_{-3.09}$ [14]		
N^{3}LO only	$q_T^{\rm cut} = 0.63$ GeV	$q_T^{\rm cut} \to 0$ fit	[14]
qg	$-15.32(32)$	$-15.34(54)$	-15.29
$q\bar{q}+q\bar{Q}$	$+5.06(12)$	$+5.05(12)$	$+4.97$
gg	$+2.17(6)$	$+2.19(6)$	$+2.12$
$qq+qQ$	$+0.09(13)$	$+0.09(17)$	$+0.17$
Total	$-7.98(36)$	$-8.01(58)$	-8.03

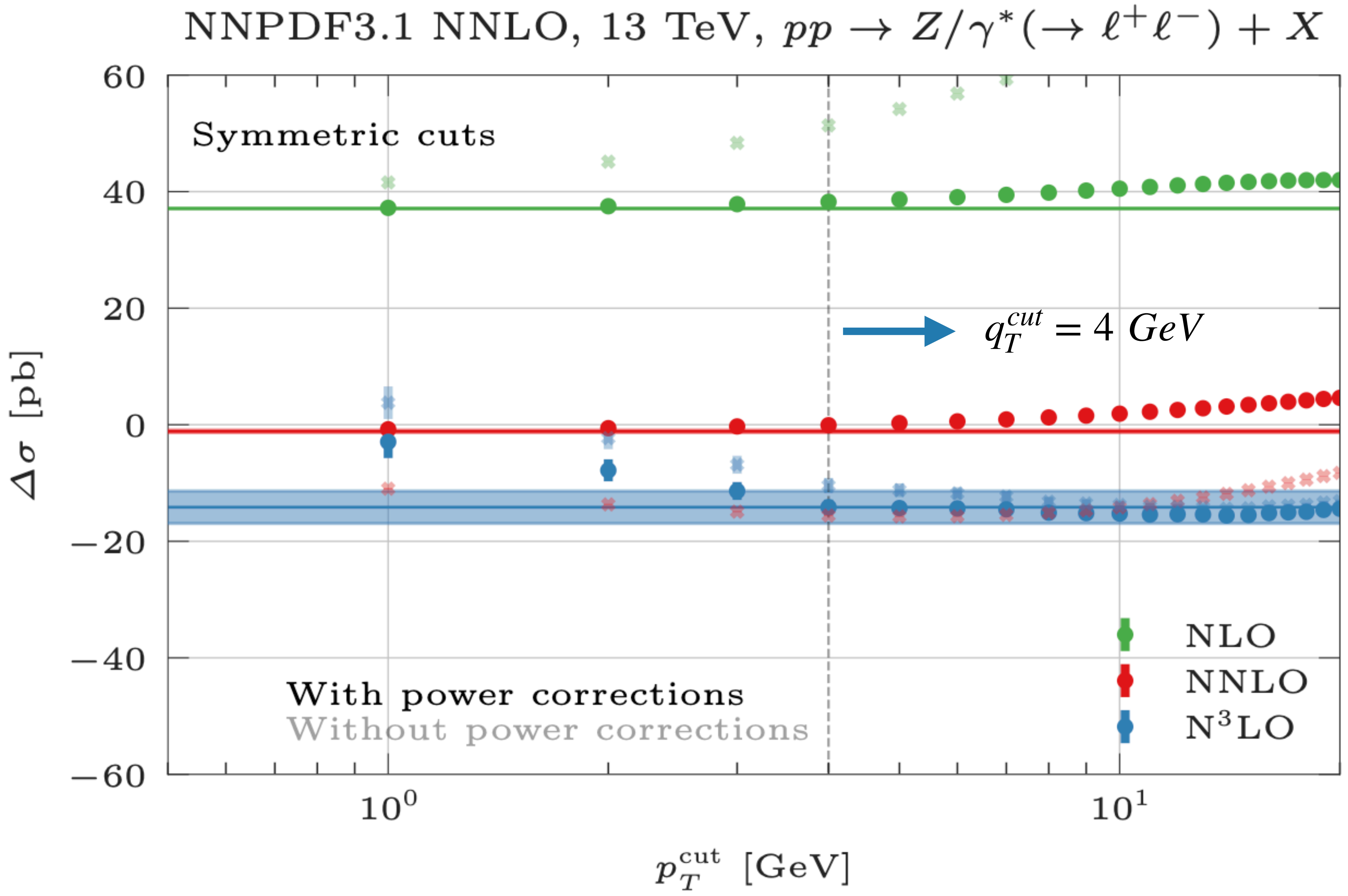
C. Duhr, F. Dulat, B. Mistlberger. PRL. **125**, 172001 (2020)



XC, T. Gehrmann, N. Glover, et. al. PRL 128, 252001 (2022)

Precision Predictions at Hadron Collider

$2 \to 1$ @ N3LO (+ N3LL) QCD



XC, T. Gehrmann, N. Glover, et. al. PRL 128, 252001 (2022)

- Solid horizontal lines: NLO, NNLO at 1 GeV, N3LO at 4 GeV with MC error.
  - N3LO shows no plateau in 1905.05171
- Pale dots are values used by DYTurbo in 2103.04974 and 2303.12781 (taken from 1905.05171).
  - Fiducial power corrections are not included.
  - Leads to 30% difference of N3LO coefficients at $q_T^{cut} = 4\ GeV$.
- Solid dots are corrected values with fiducial power correction.
  - Central value shifts 2 pb starting from NLO (the dominant error).
  - ±2.1 pb uncertainty from MC and q_T^{cut} (estimated from [3,5] GeV region).
  - Not included in DYTurbo update result with ±0.7 pb uncertainty.

DYTurbo result with fiducial power correction

Order	N^{3}LO
q_T subtr. ($q_T^{\rm cut} = 4\,$GeV)	$747.1 \pm 0.7\,$pb
recoil q_T subtr.	$745.7 \pm 0.7\,$pb

S. Camarda, L. Cieri, G. Ferrera Eur.Phys.J.C 82 (2022) 6

DYTurbo result without fiducial power correction cited in ATLAS α_s fitting

Order	NLO	NNLO	N^{3}LO
$\sigma(pp \to Z/\gamma^* \to l^+l^-)$ [pb]	766.3 ± 1	757.4 ± 2	746.1 ± 2.5
Order	NLL+NLO	NNLL+NNLO	N^{3}LL+N^{3}LO
$\sigma(pp \to Z/\gamma^* \to l^+l^-)$ [pb]	773.7 ± 1	759.8 ± 2	749.6 ± 2.5

S. Camarda, L. Cieri, G. Ferrera Eur.Phys.J.C 82 (2022) 6

Non-Perturbative QFT for precision predictions

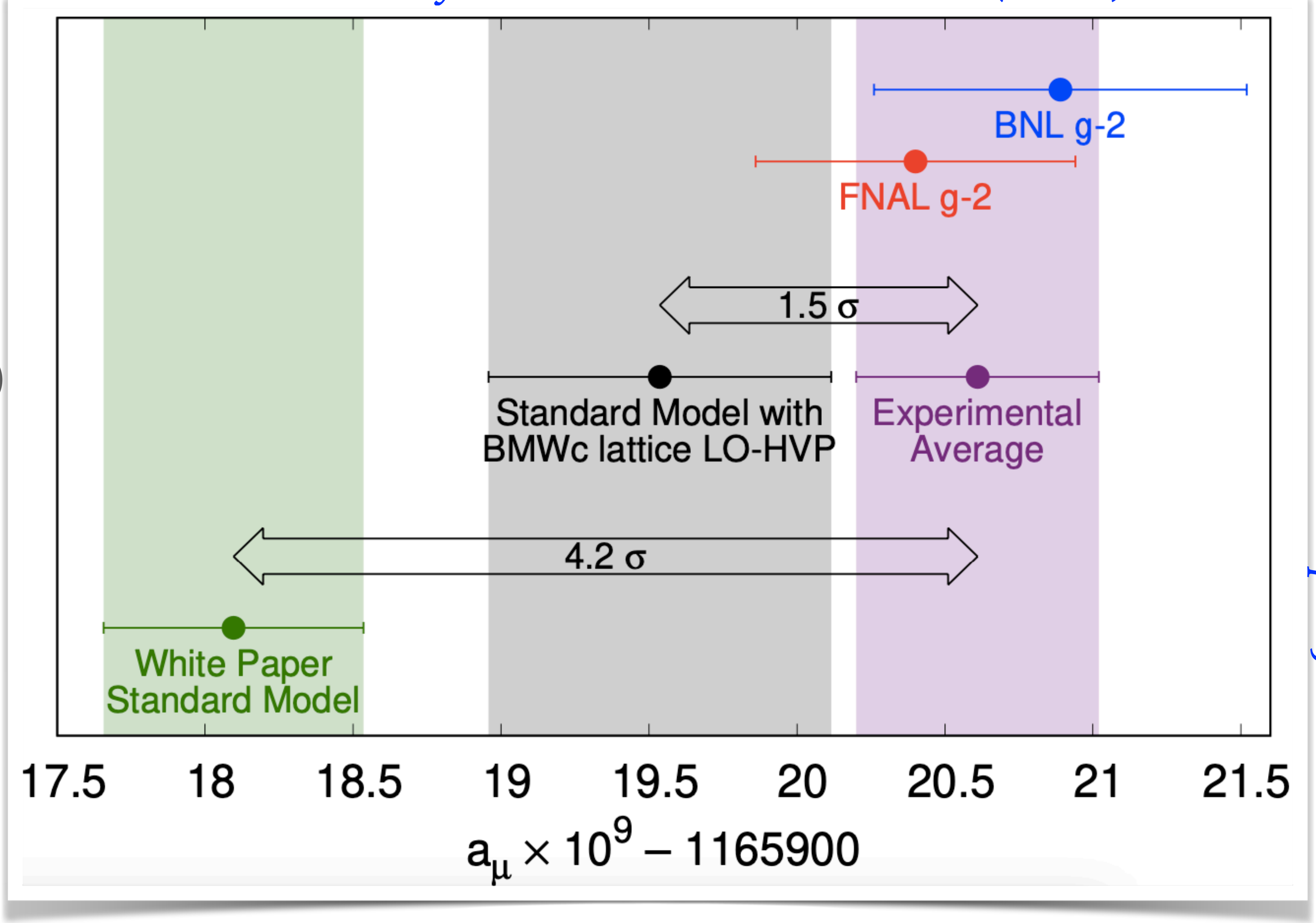
a_μ^{HVP} Data driven vs. Lattice QCD

$$a_{\mu,DA}^{LO-HVP} = \frac{\alpha^2}{3\pi^3}\int_{m_\pi^2}^{\infty}\frac{ds}{s}K(s)R(s) \qquad a_{\mu,LQCD}^{LO-HVP} = 2\alpha^2\int_0^{\infty} t^2 dt K(m_\mu t)V(t)$$

$$a_{\mu,LQCD}^{LO-HVP,\omega} = 2\alpha^2\int_0^{\infty} t^2 dt K(m_\mu t)\Theta^{\omega}(t)V(t)$$

- Time ↔ Energy Window
  - $[0, t_0] \oplus [t_0, t_1] \oplus [t_1, +\infty]$ for SD, W, LD.
  - SD and W precisely predicted by Lattice QCD in continuum.
  - SD and W energy windows with precise e^+e^- EXP data.
  - a_μ^W (intermediate window) has 3.7 σ tension for DA vs. LQCD

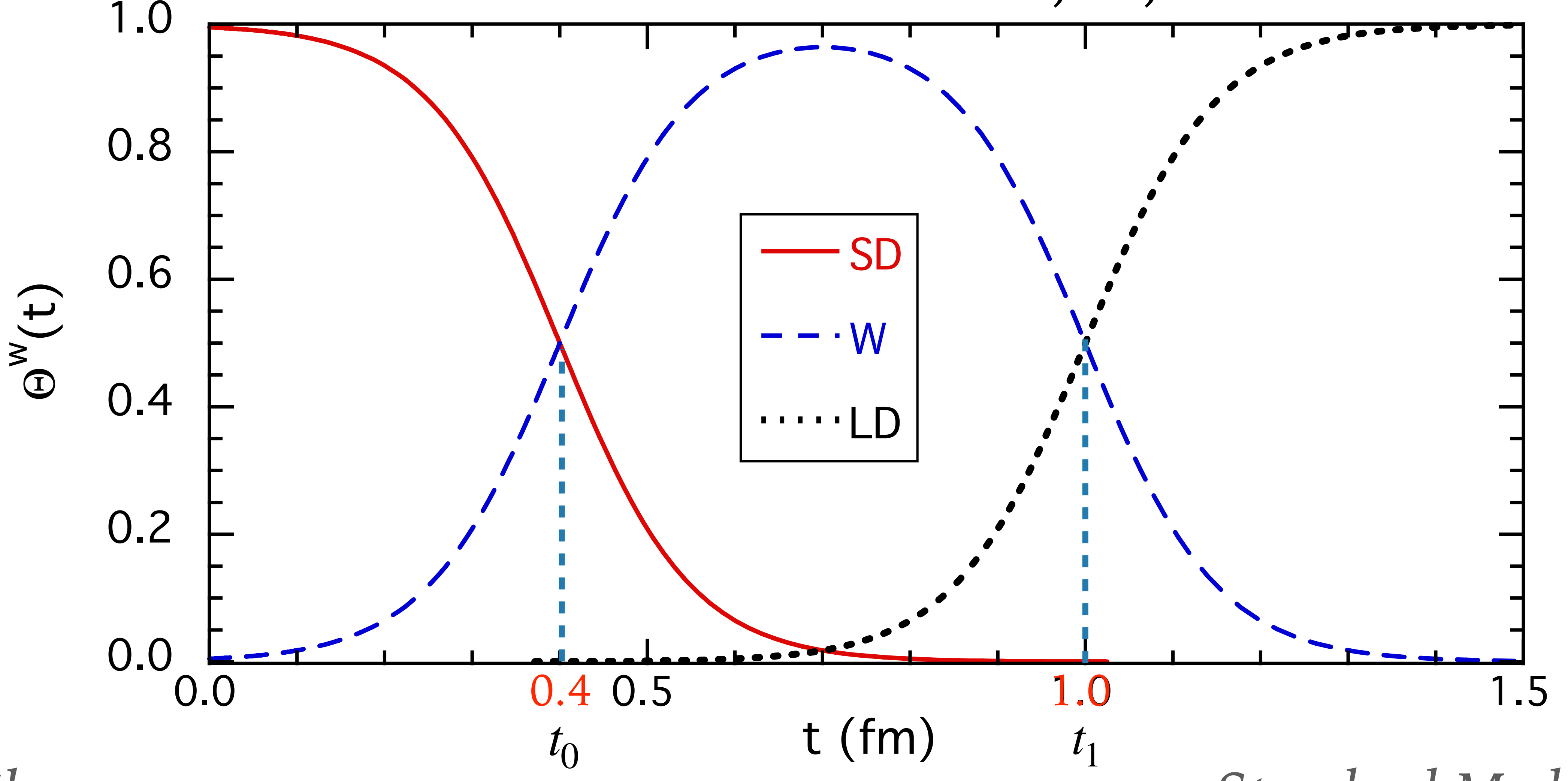
*FNAL Phys. Rev. Lett. **126**, 141801 (2021)*

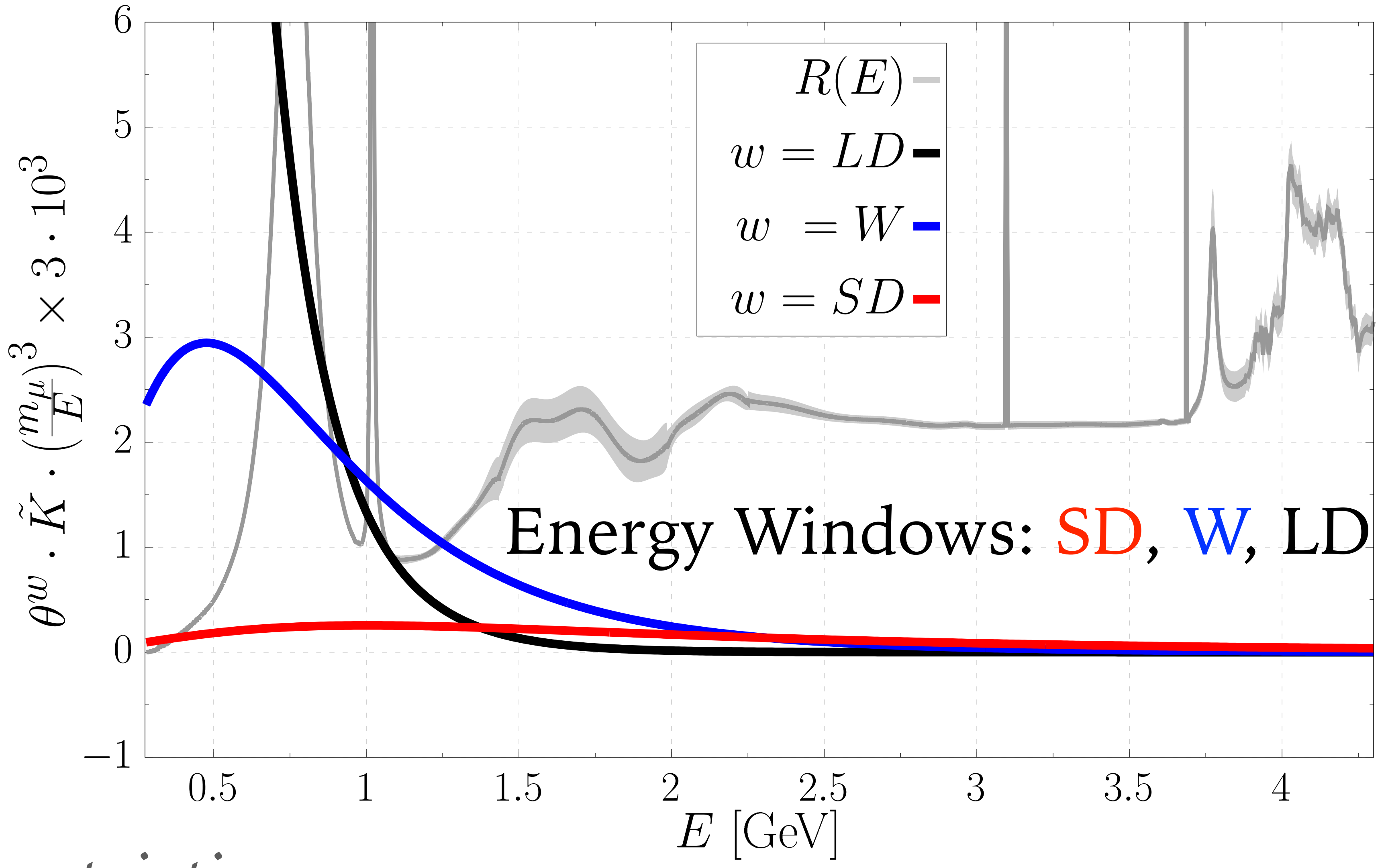


L. Pareao at Zurich Workshop in June

Distance Windows: SD, W, LD

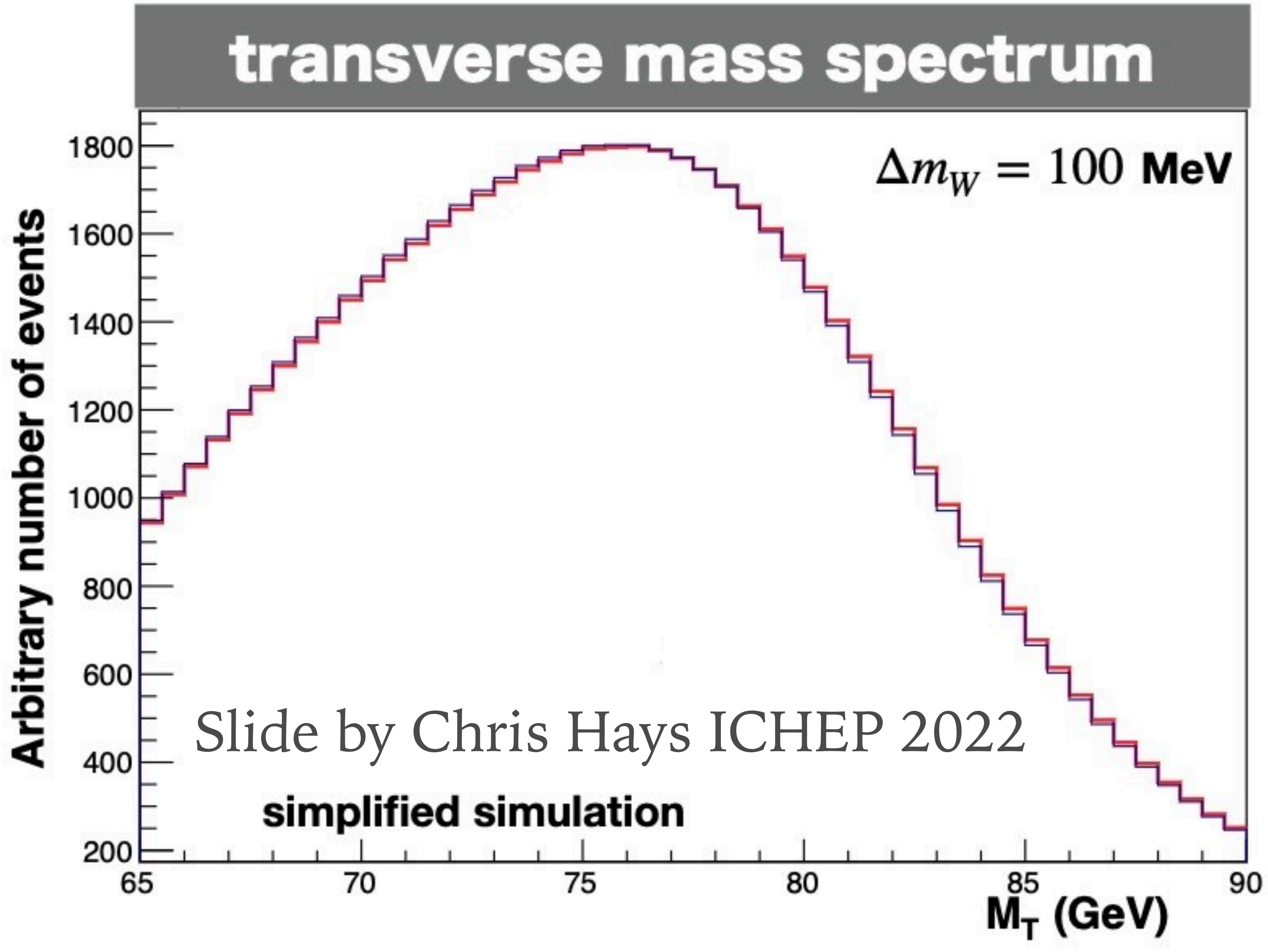
ETM Collaboration, 2212.10490

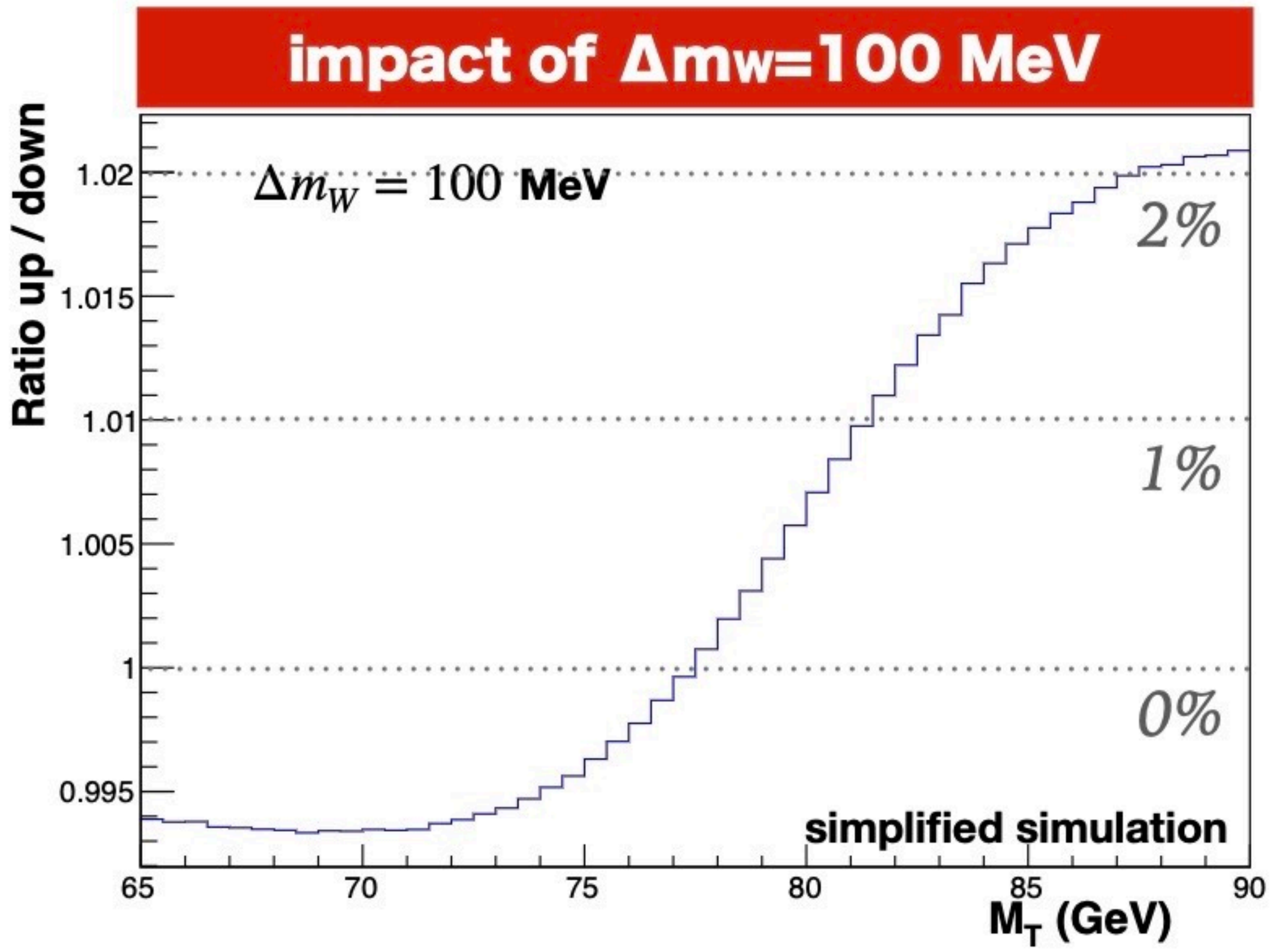




W mass in CDFII measurement

➤$d\sigma/dm_T^W$ two templates with $\Delta m_W = 100$ MeV





$\Delta m_W =$ 100 MeV ~ 0.5-2% change in $d\sigma/dm_T^W$ → $\Delta m_W =$ 10 MeV ~ 0.1% precision in $d\sigma/dm_T^W$

Precision predictions in CDF II

➤CDF II use ResBos to generate theory templates

➤NLO+NNLL accuracy for W/Z production

Balazs, Brock, Landry, Nadolsky and Yuan`97 to`03

➤CSS factorisation and resummation of p_T in b space:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2\,\mathrm{d}^2\vec{p}_T\,\mathrm{d}y\,\mathrm{d}\cos\theta\,\mathrm{d}\phi} = \sigma_0 \int \frac{\mathrm{d}^2 b}{(2\pi)^2} e^{i\vec{p}_T\cdot\vec{b}} e^{-S(b)}$$

$$\times\, C\otimes f(x_1,\mu)\, C\otimes f(x_2,\mu) + Y(Q,\vec{p}_T,x_1,x_2,\mu_R,\mu_F)$$

Collins, Soper and Sterman`85

➤Non-perturbative effects at $\alpha_s(\Lambda)$ and large b:

$$S(b) = S_{\mathrm{NP}} S_{\mathrm{Pert}}\,,$$

Collins and Soper `77

$$S_{\mathrm{Pert}}(b) = \int_{C_1^2/(b^*)^2}^{C_2^2 Q^2} \frac{\mathrm{d}\bar{\mu}^2}{\bar{\mu}^2}\left[\ln\left(\frac{C_2^2 Q^2}{\bar{\mu}^2}\right) A(\bar{\mu},C_1) + B(\bar{\mu},C_1,C_2)\right]$$

$$S_{\mathrm{NP}} = \left[-g_1 - g_2 \ln\left(\frac{Q}{2Q_0}\right) - g_1 g_3 \ln(100 x_1 x_2)\right] b^2$$

S_{NP} assumes the BLNY functional form

Brock, Landry, Nadolsky and Yuan `02

➤Use data driven method:

Fix	g1	g2	g3	α_s
p_T^Z	Global fit `03	CDFII fit	Global fit `03	CDFII fit
p_T^Z/p_T^W			Global fit `03	

Global fit by Brock, Landry, Nadolsky and Yuan `03

$m_T^W \sim 0.7$ MeV, $p_T^l \sim 2.3$ MeV, $p_T^\nu \sim 0.9$ MeV

CDF supplementary materials `22

➤Scale uncertainty of p_T^Z/p_T^W by DYQT

Bozzi, Catani, Ferrera, de Florian, Grazzini `09 `11

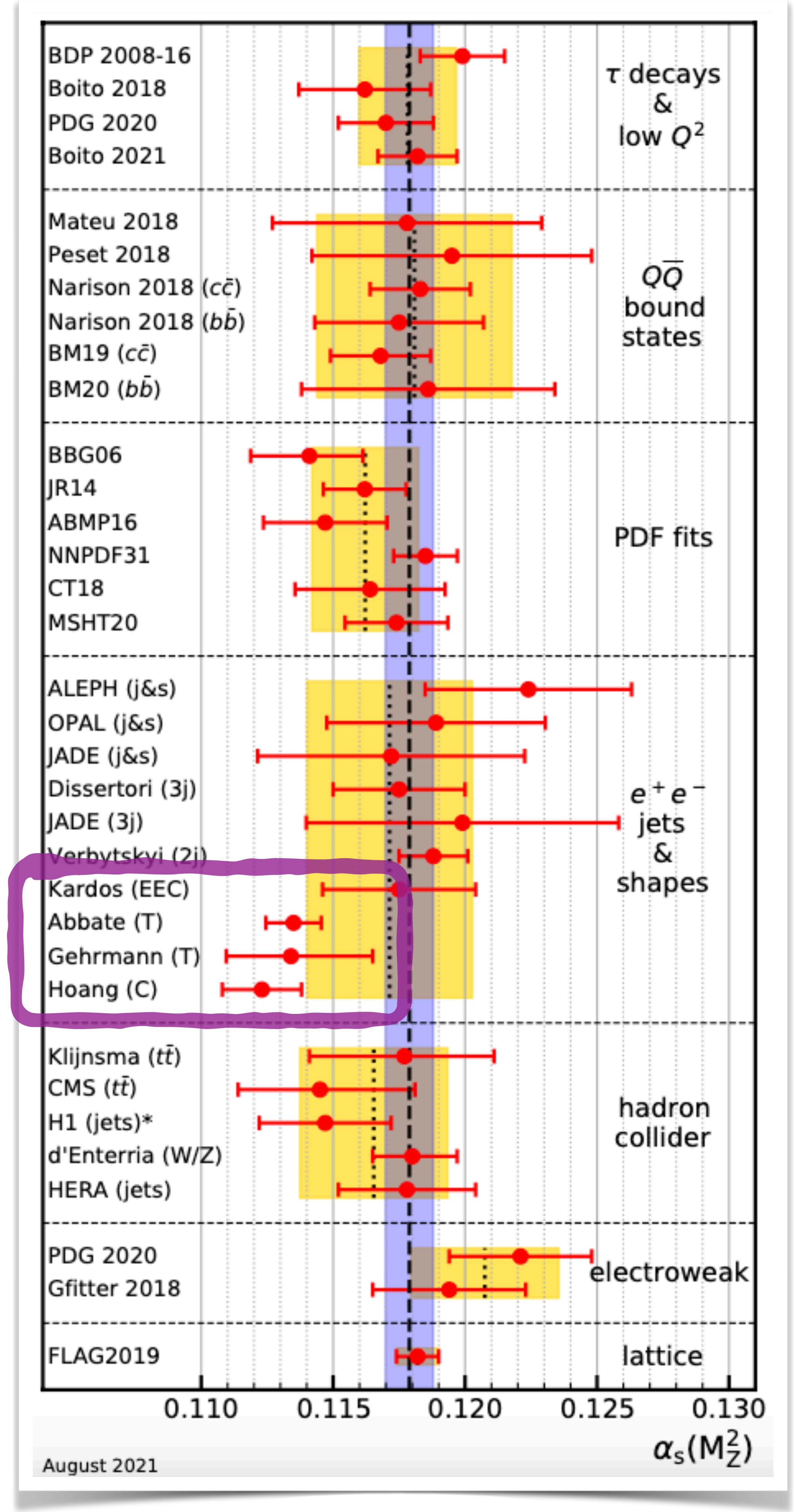
$m_T^W \sim 3.5$ MeV, $p_T^l \sim 10.1$ MeV, $p_T^\nu \sim 3.9$ MeV

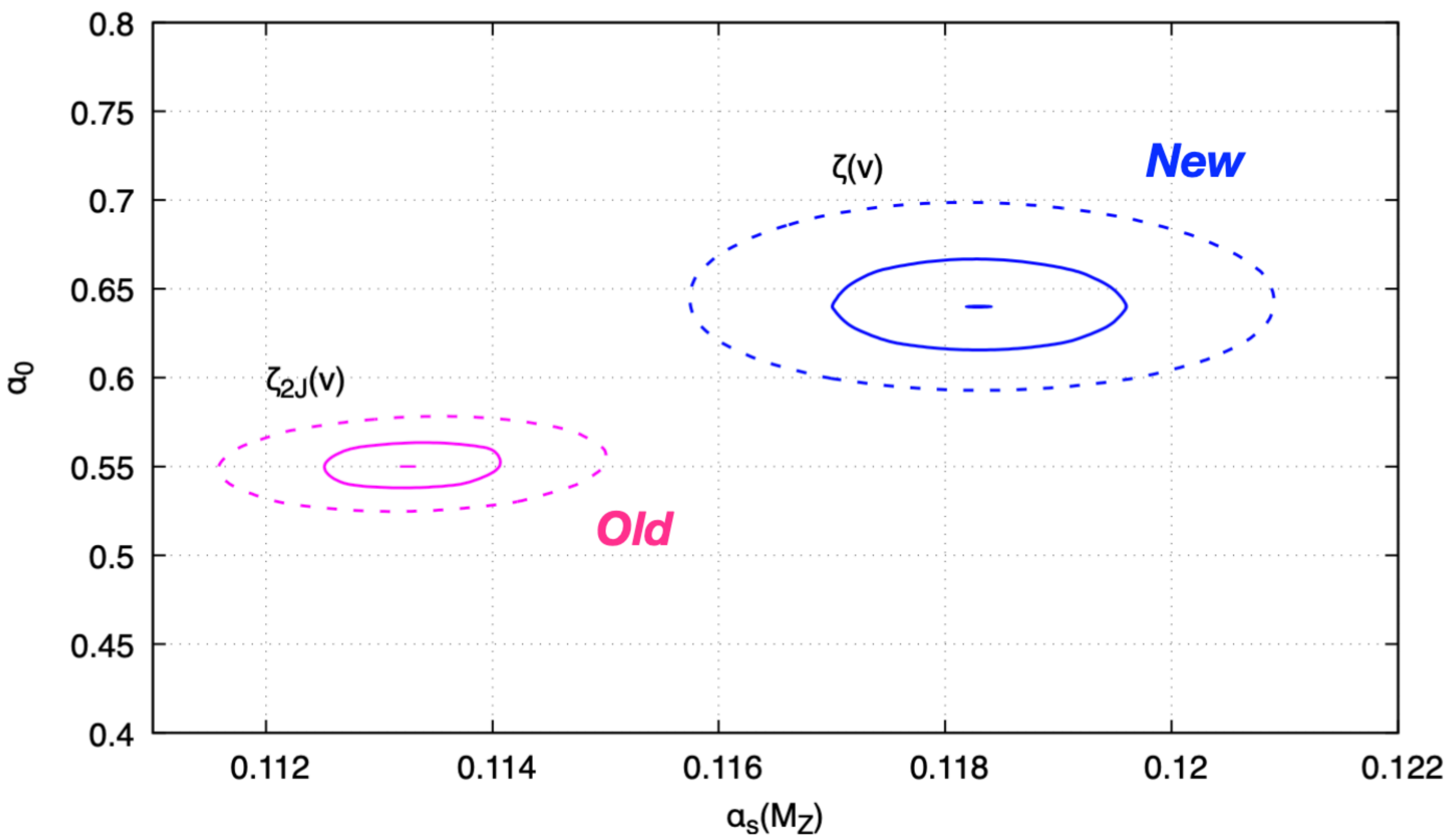
Not included in final result CDF sm`22

α_s Fitting With NP Corrections

➤ Linear NP corrections in $e^+e^- \to 3$ jets ease the tension in α_s fitting from C-parameter and thrust.

J. Huston, K. Rabbertz, G. Zanderighi PDG 2021





P. Nason, G. Zanderighi JHEP 06 (2023) 058