PRECISION SM HIGGS PREDICTIONS AND FUTURE PROSPECTS

Higgs 2023

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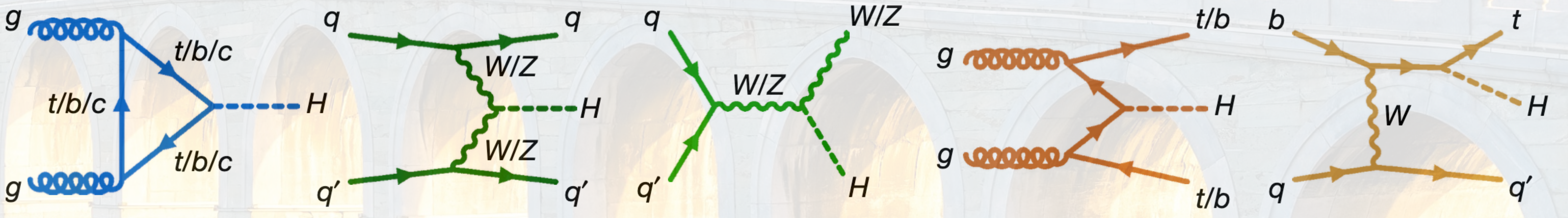
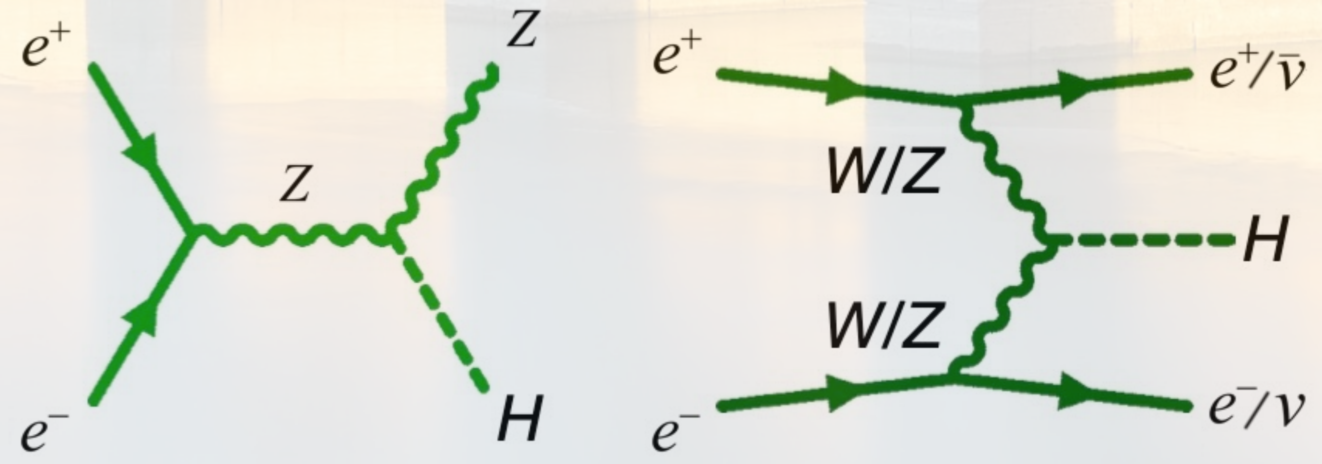
Standard Model Higgs Boson

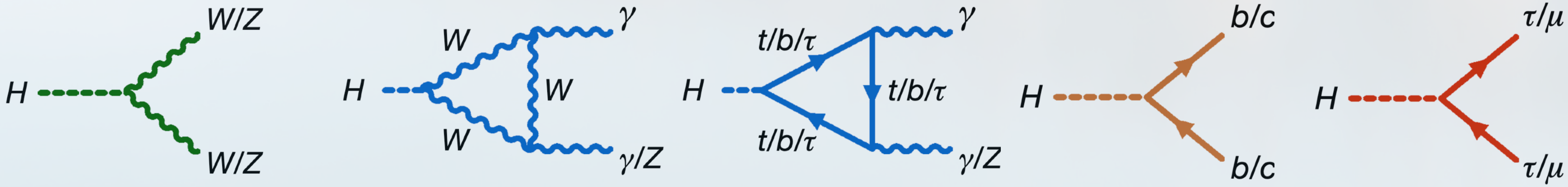
- SM Higgs properties
  - A fundamental scalar boson with spin zero, CP even, giving mass to SM massive particles (SSB)
  - $m_H \sim 125$ GeV leads metastable EW vacuum but all current data compatible with SM predictions
  - Higgs production channels at the LHC: (by cross sections)



- Higgs production channels at e^+e^- colliders: (by cross sections)



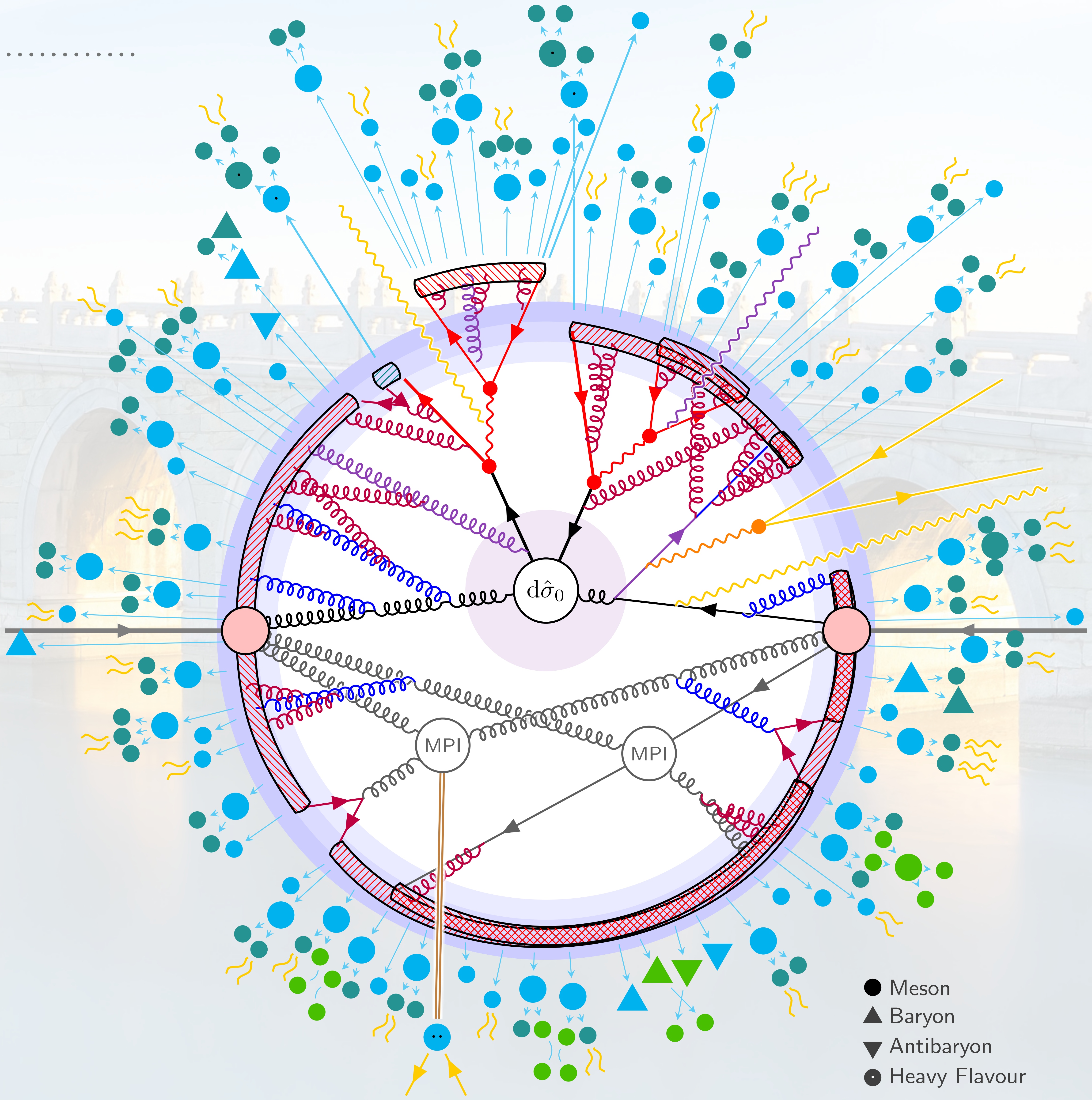
- Higgs decay channels:



Collider Event in Theorist's Eye

➤ For a scale of 100 GeV, the idea of factorisation in Quantum Field Theory plays important role to help understanding complex high energy processes:

Time ordering



PYTHIA 8.3

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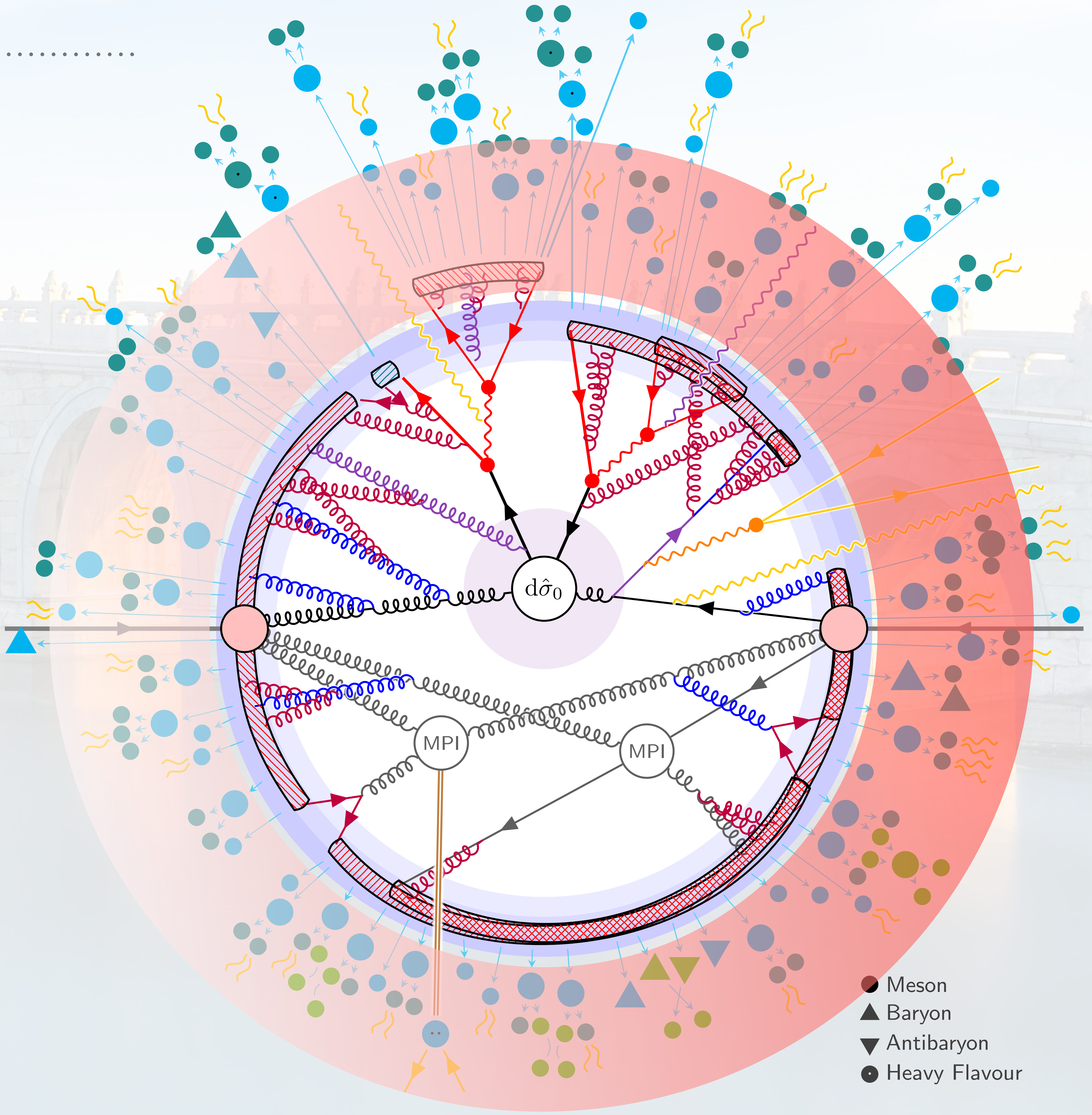
Hadronisation

Time ordering



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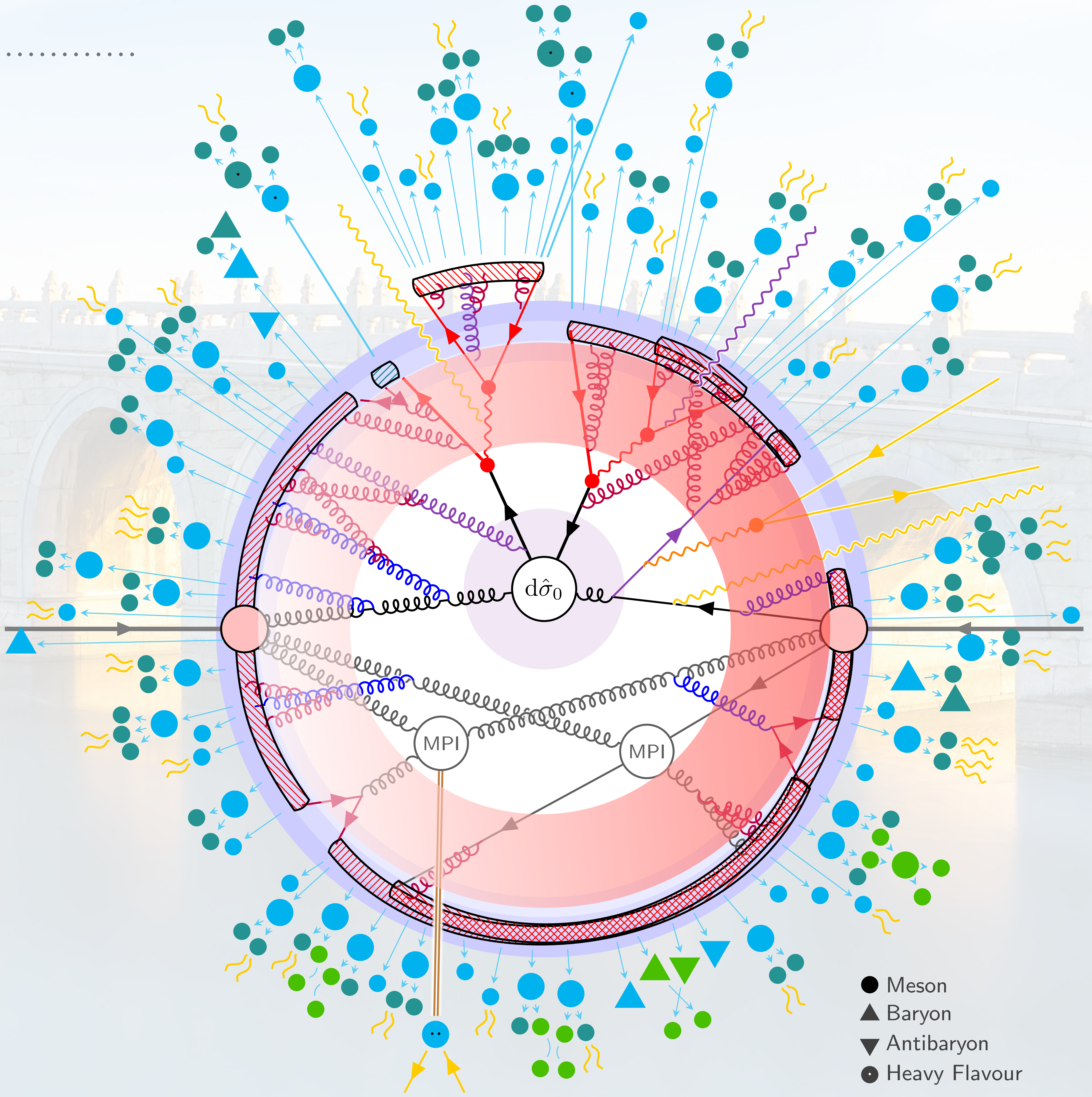
Hadronisation

Parton Shower



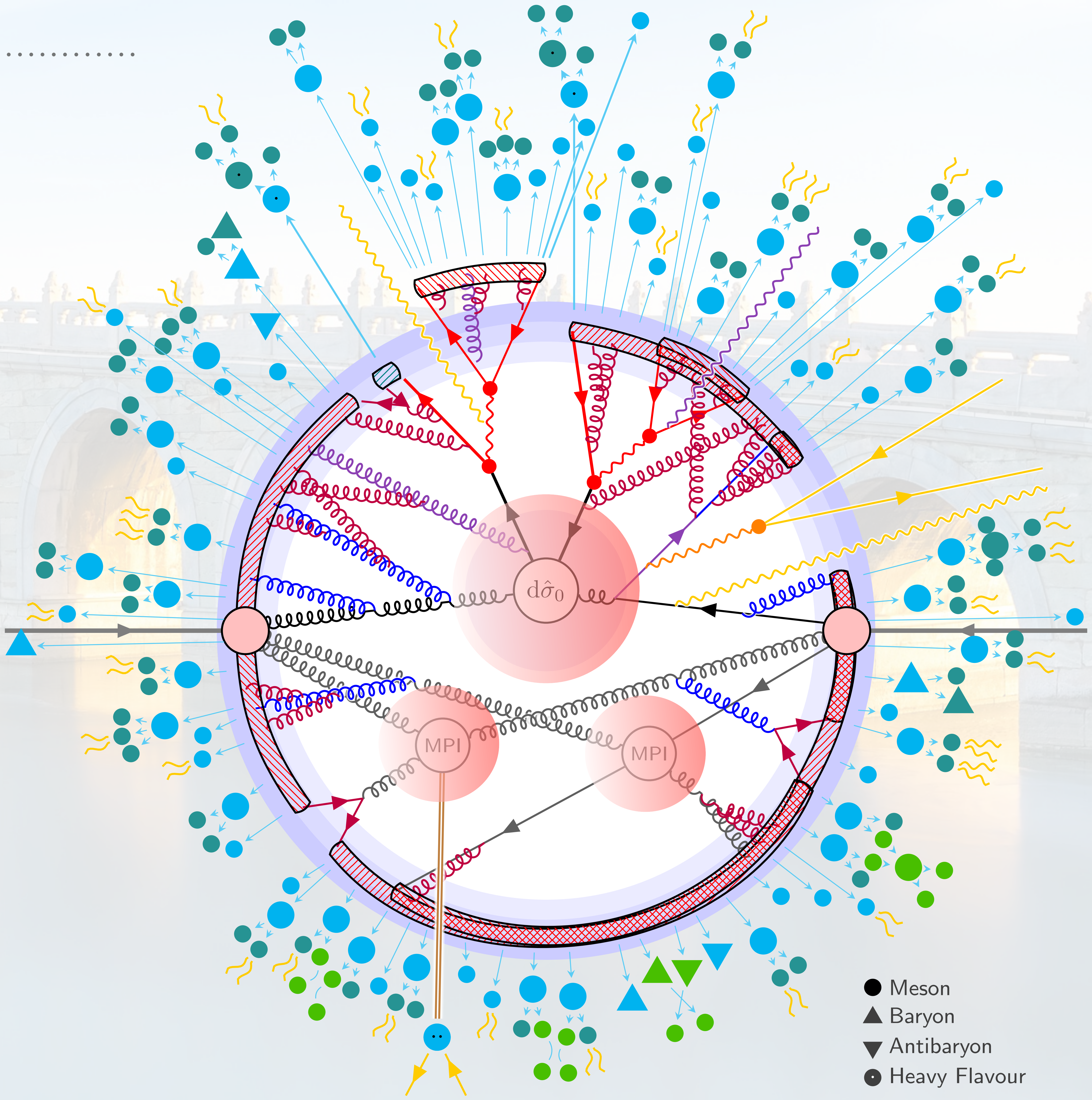
PYTHIA 8.3

Collider Event in Theorist's Eye

- For a scale of 100 GeV, the idea of factorisation in Quantum Field Theory plays important role to help understanding complex high energy processes:

Time ordering ↑

- Hadronisation
- Parton Shower
- Hard Scattering



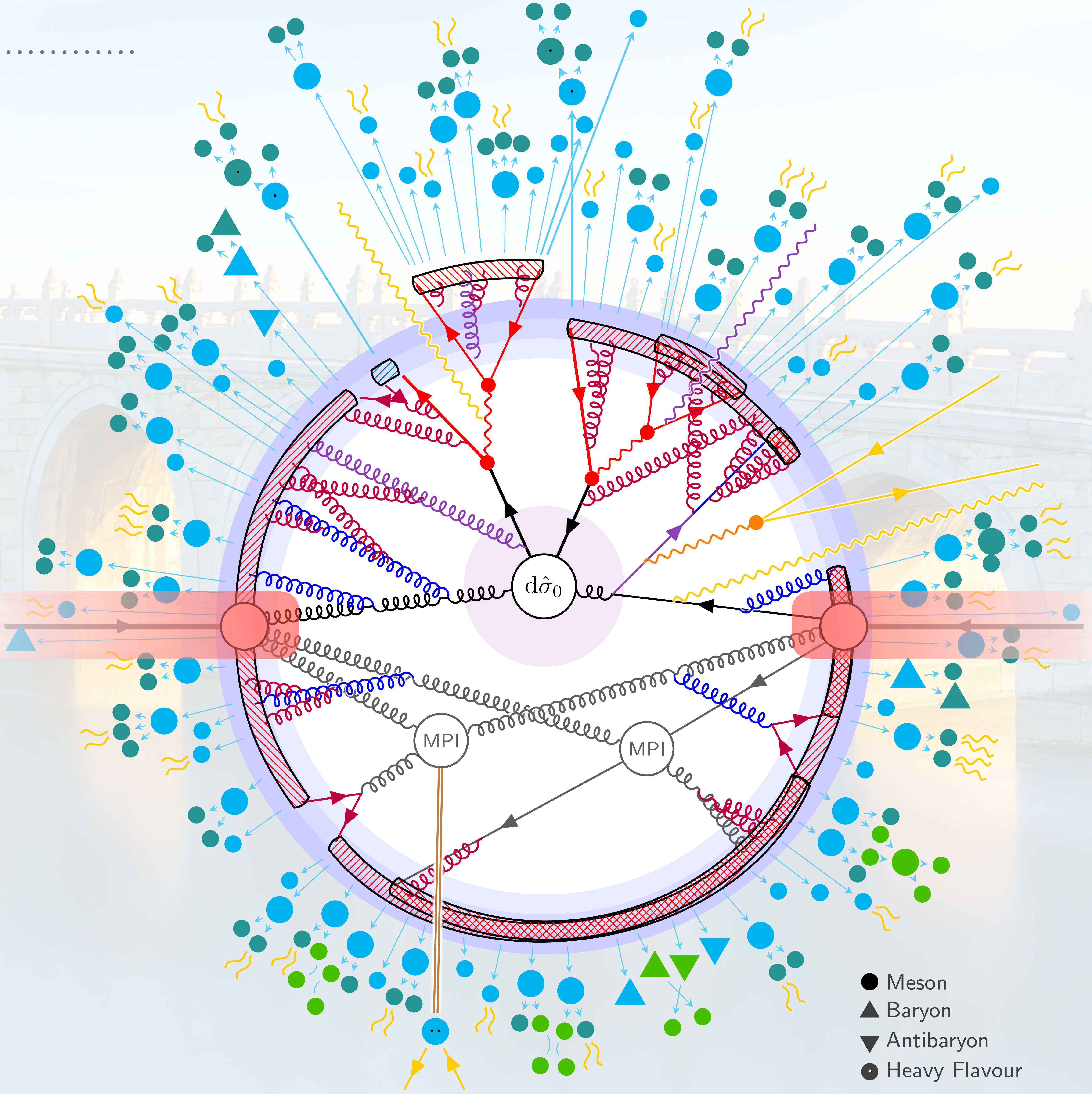
PYTHIA 8.3

Collider Event in Theorist's Eye

- For a scale of 100 GeV, the idea of factorisation in Quantum Field Theory plays important role to help understanding complex high energy processes:

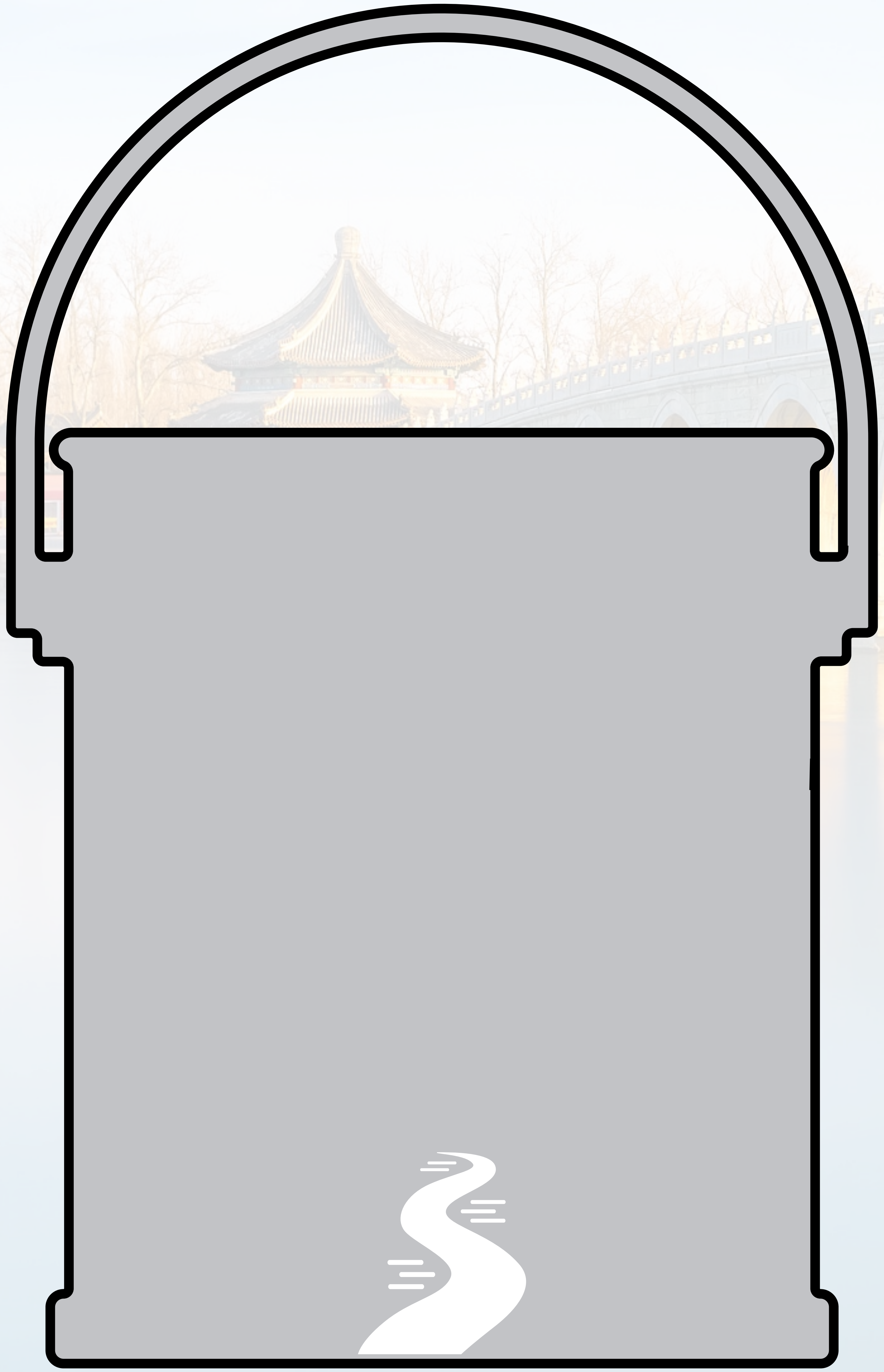
Time ordering ↑

- Hadronisation
- Parton Shower
- Hard Scattering
- Proton → Parton



PYTHIA 8.3

The Bucket Effect in Precision Predictions



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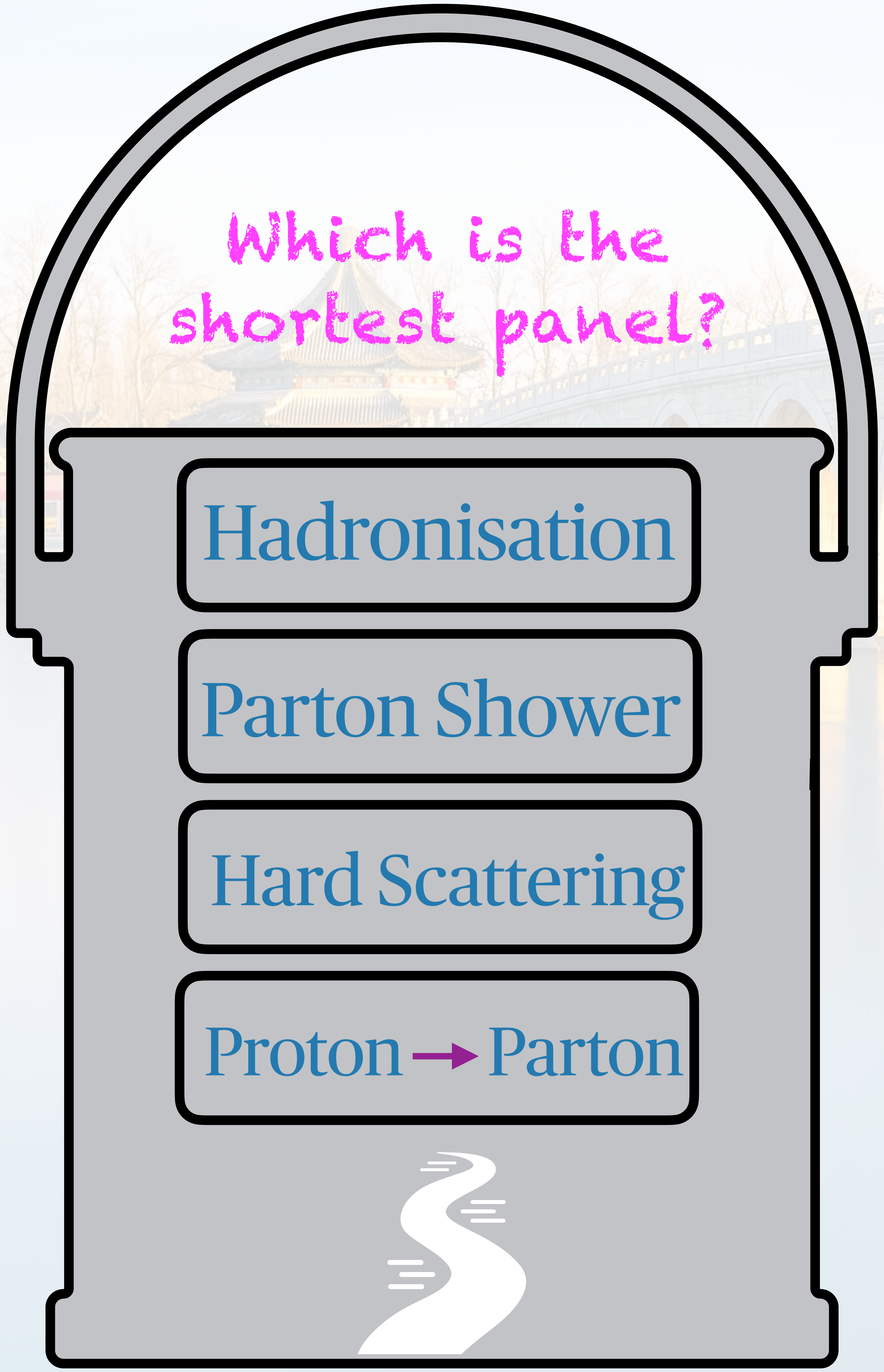
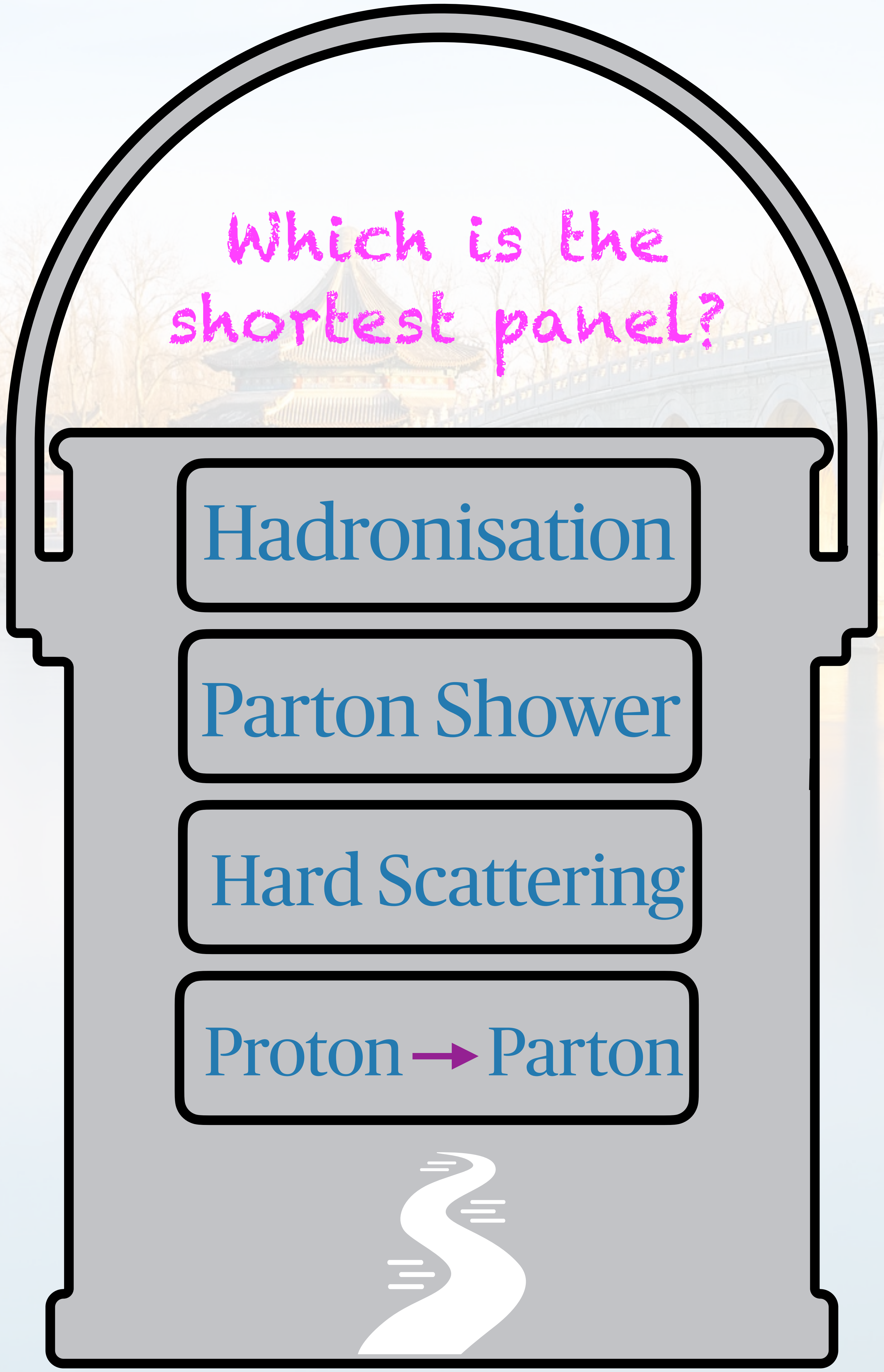
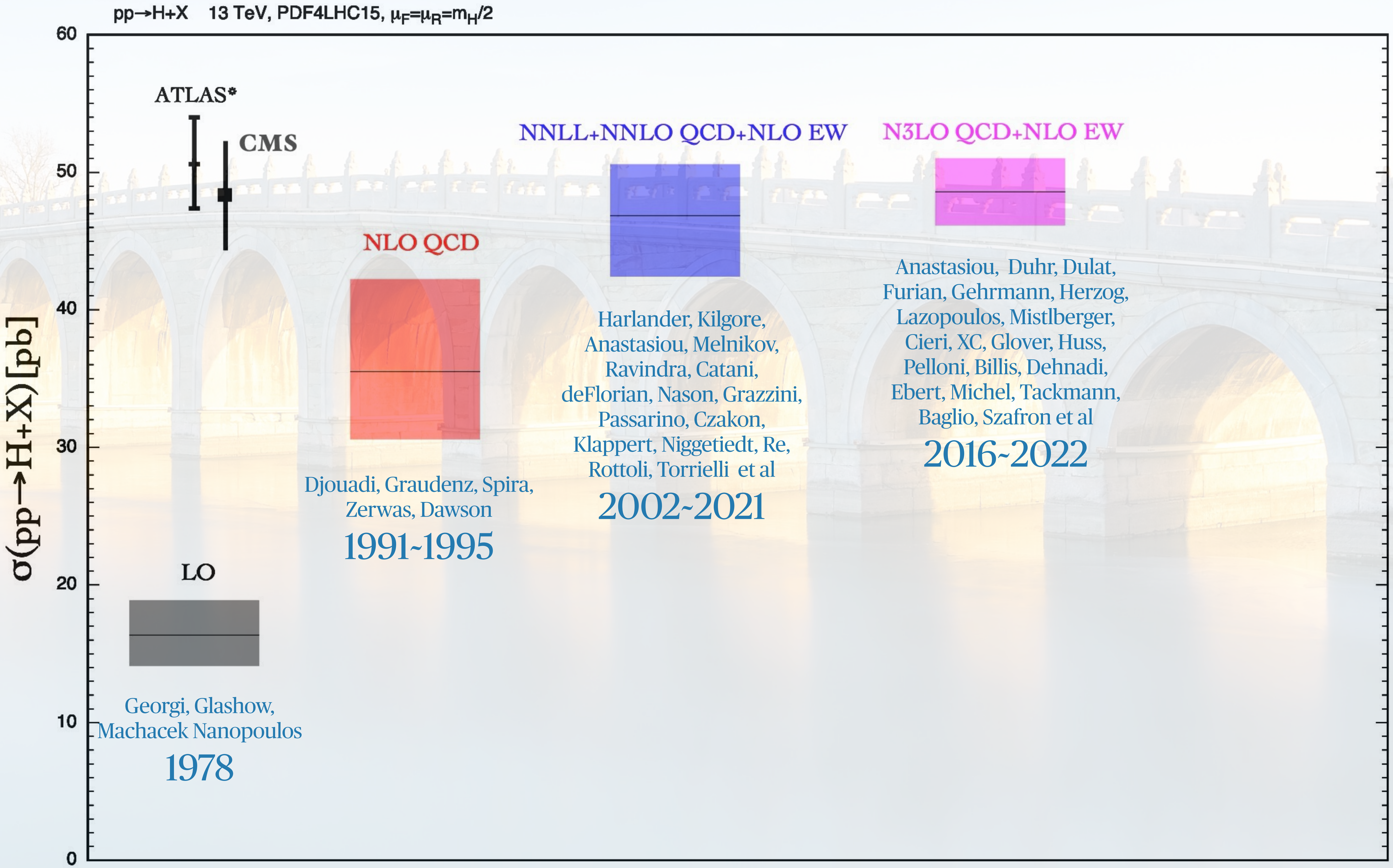


The Bucket Effect in $pp \to H + X$





Slide based on M. Grazzini's talk @ Higgs10

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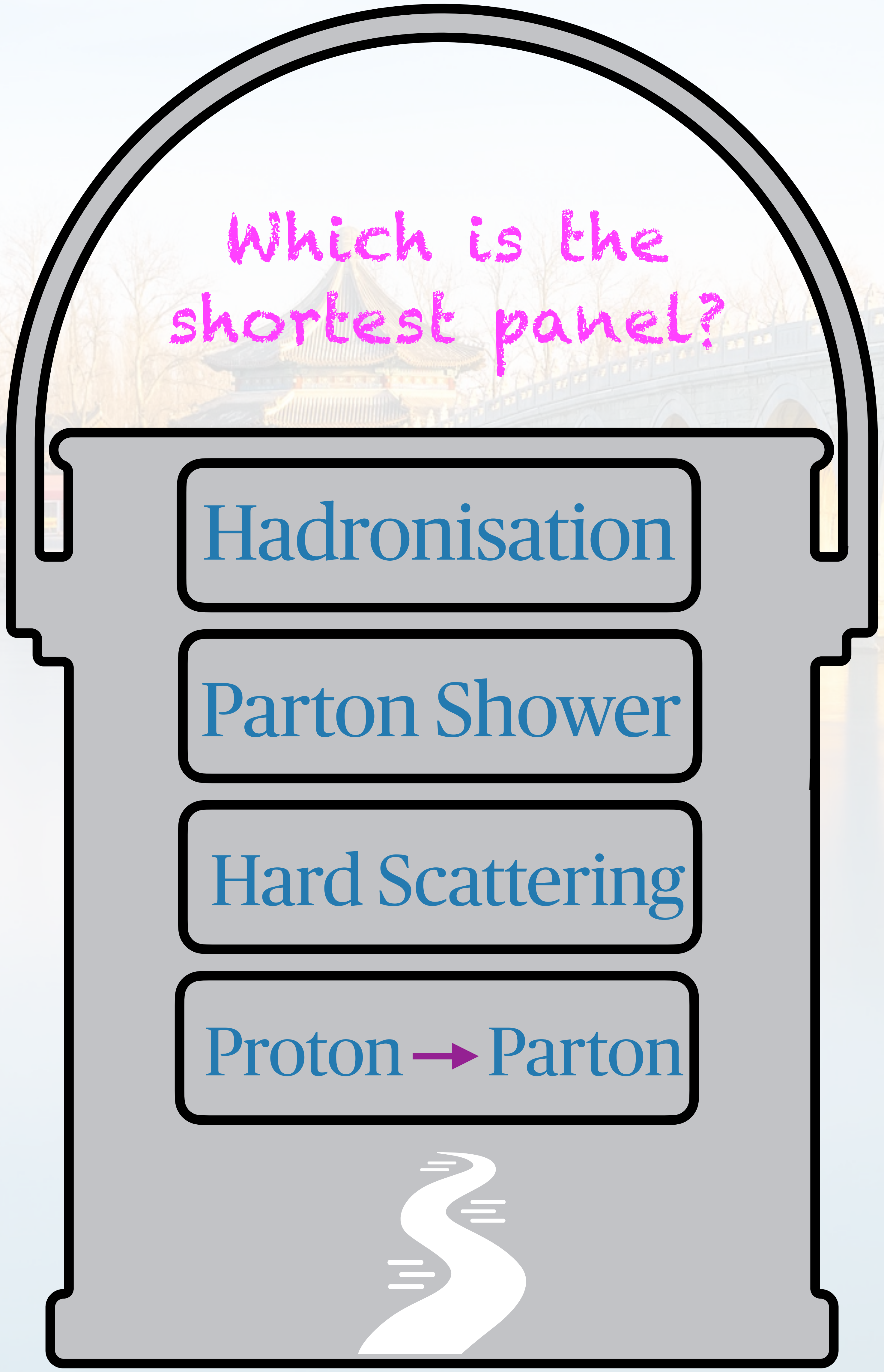

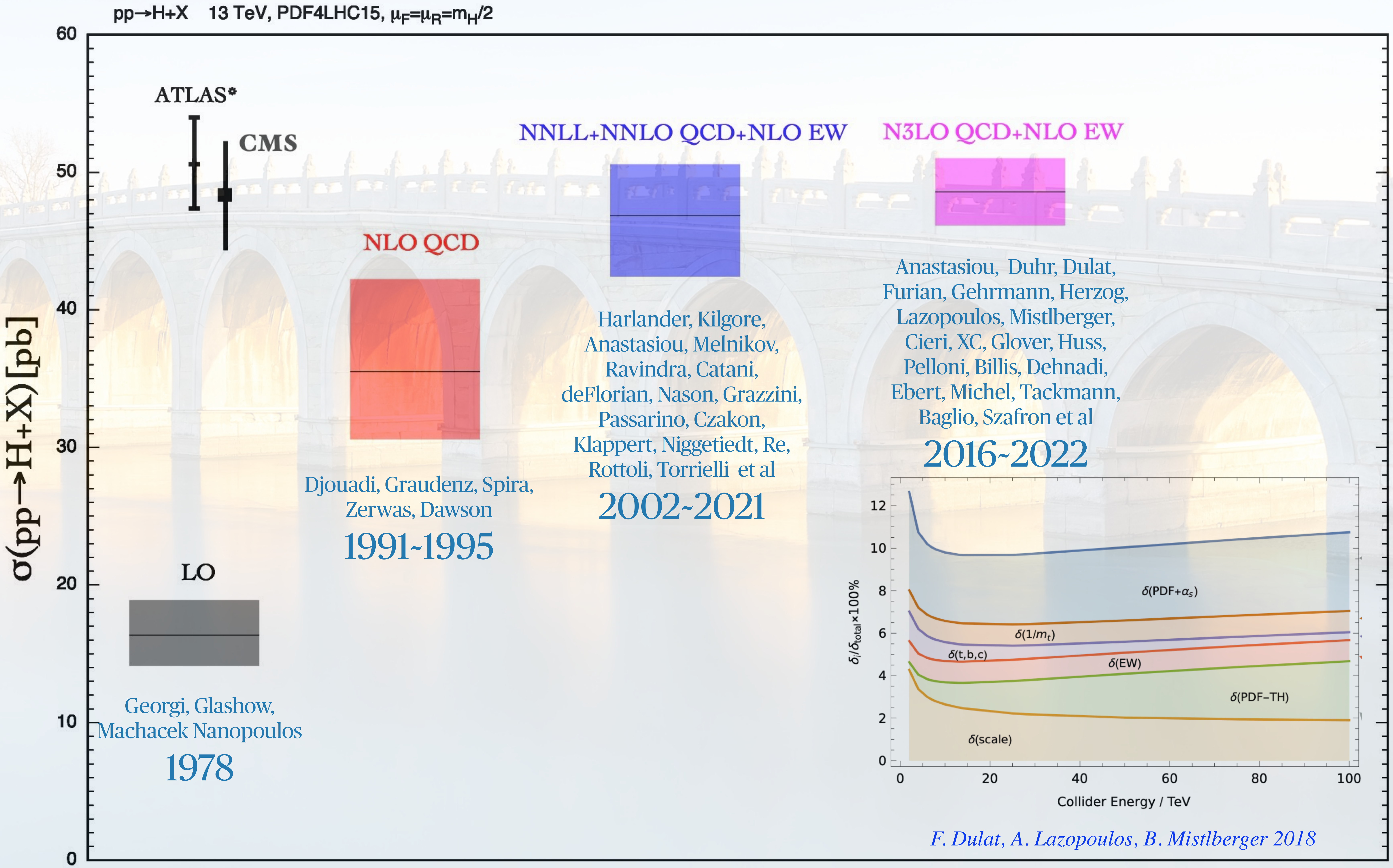

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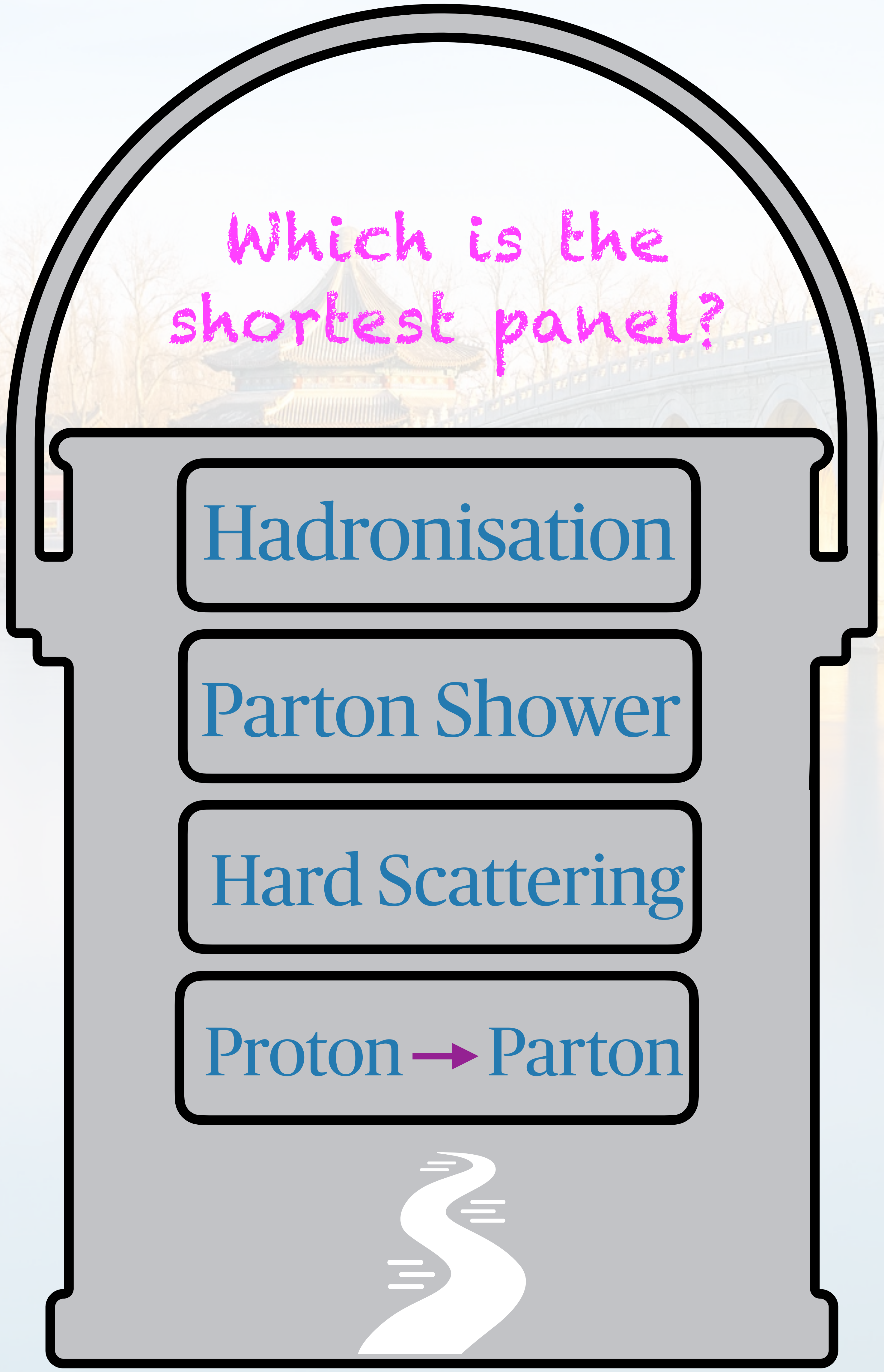

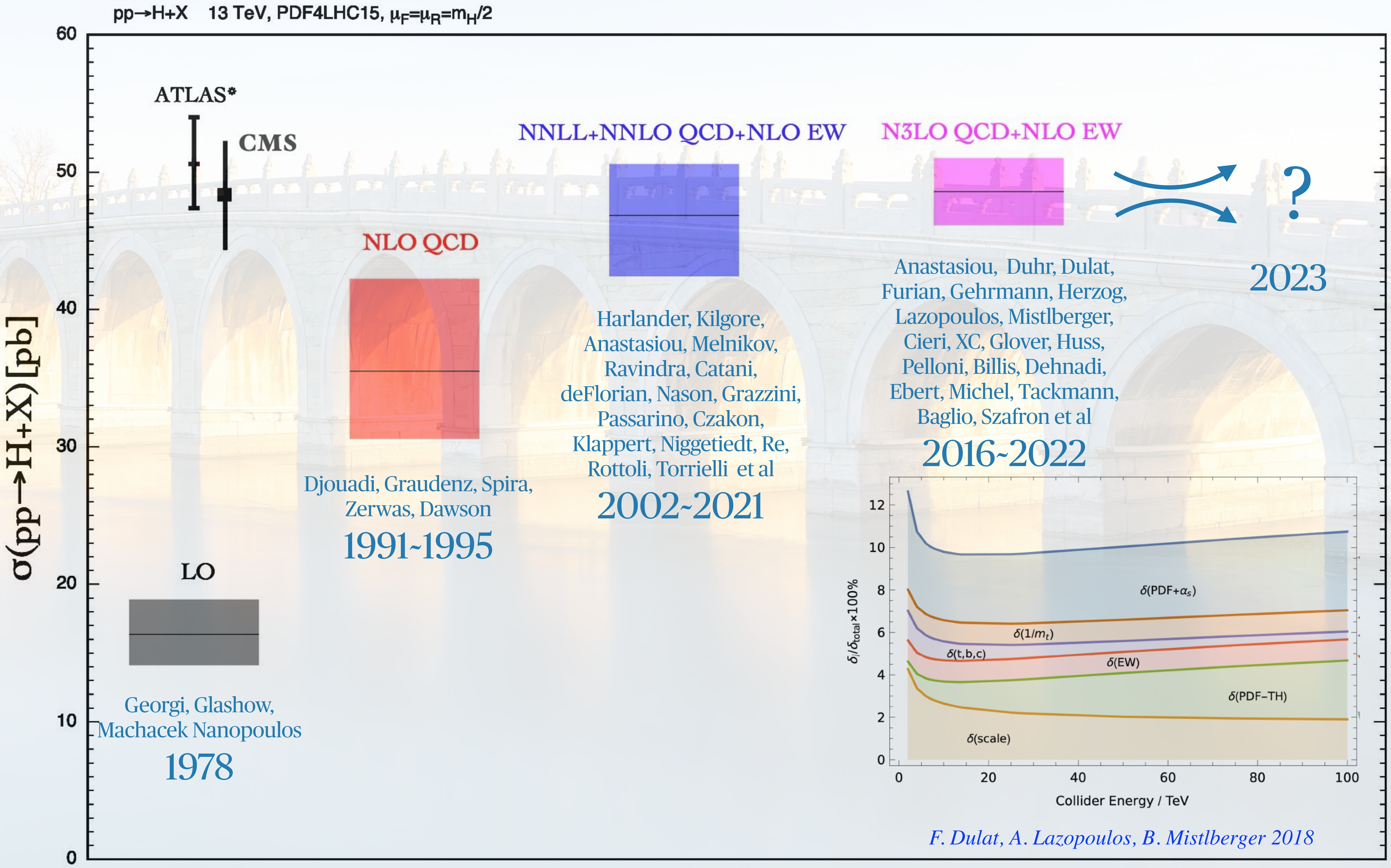

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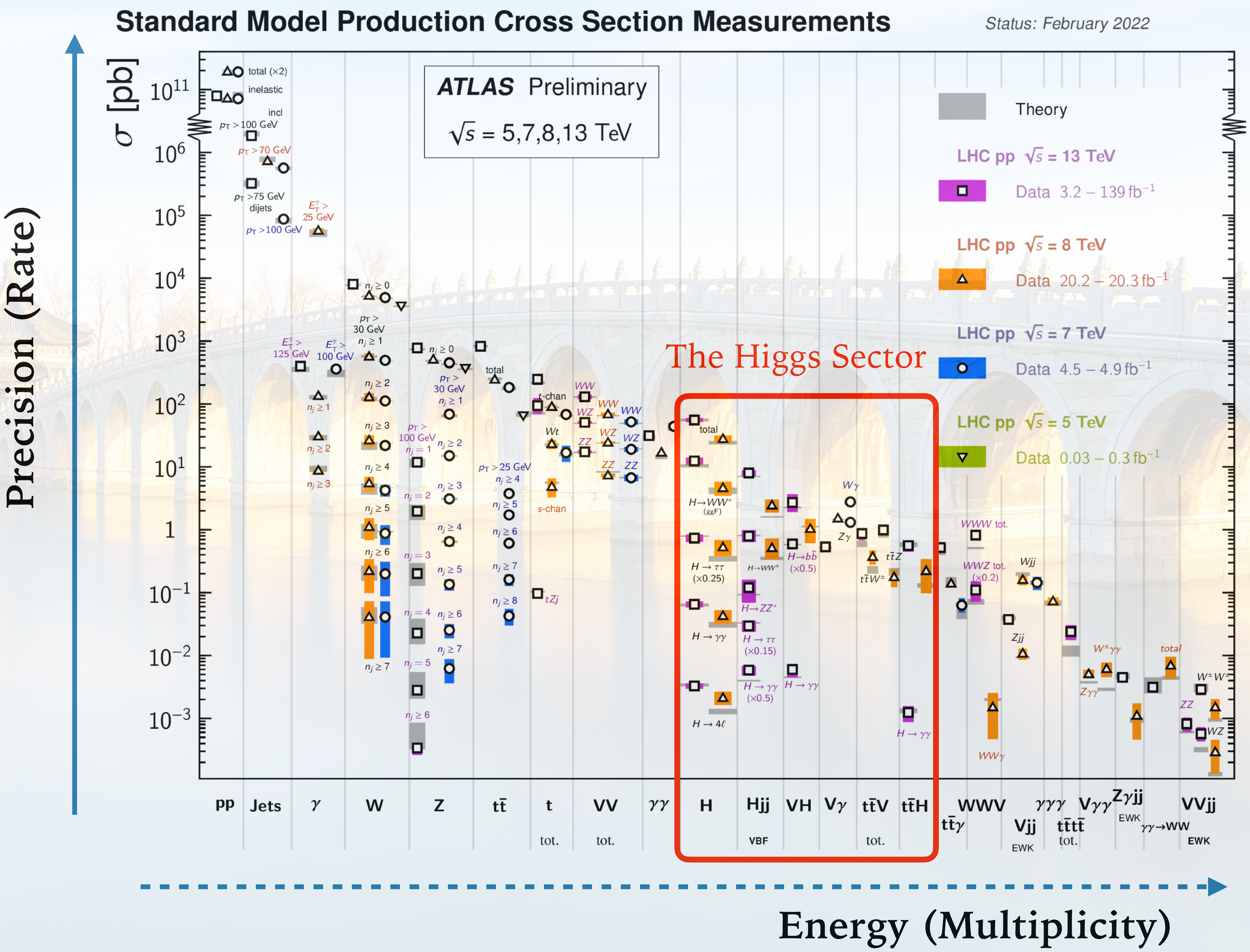
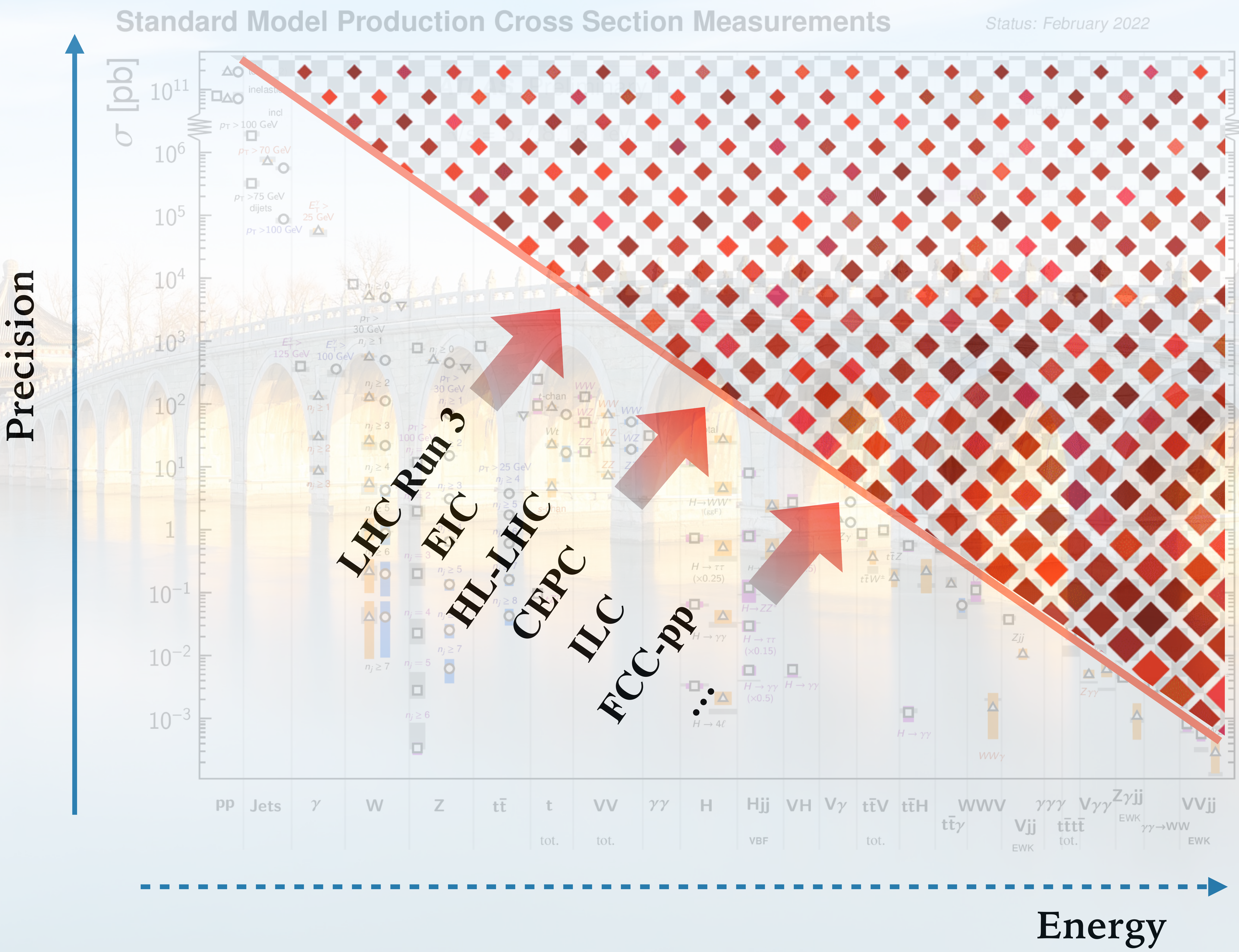
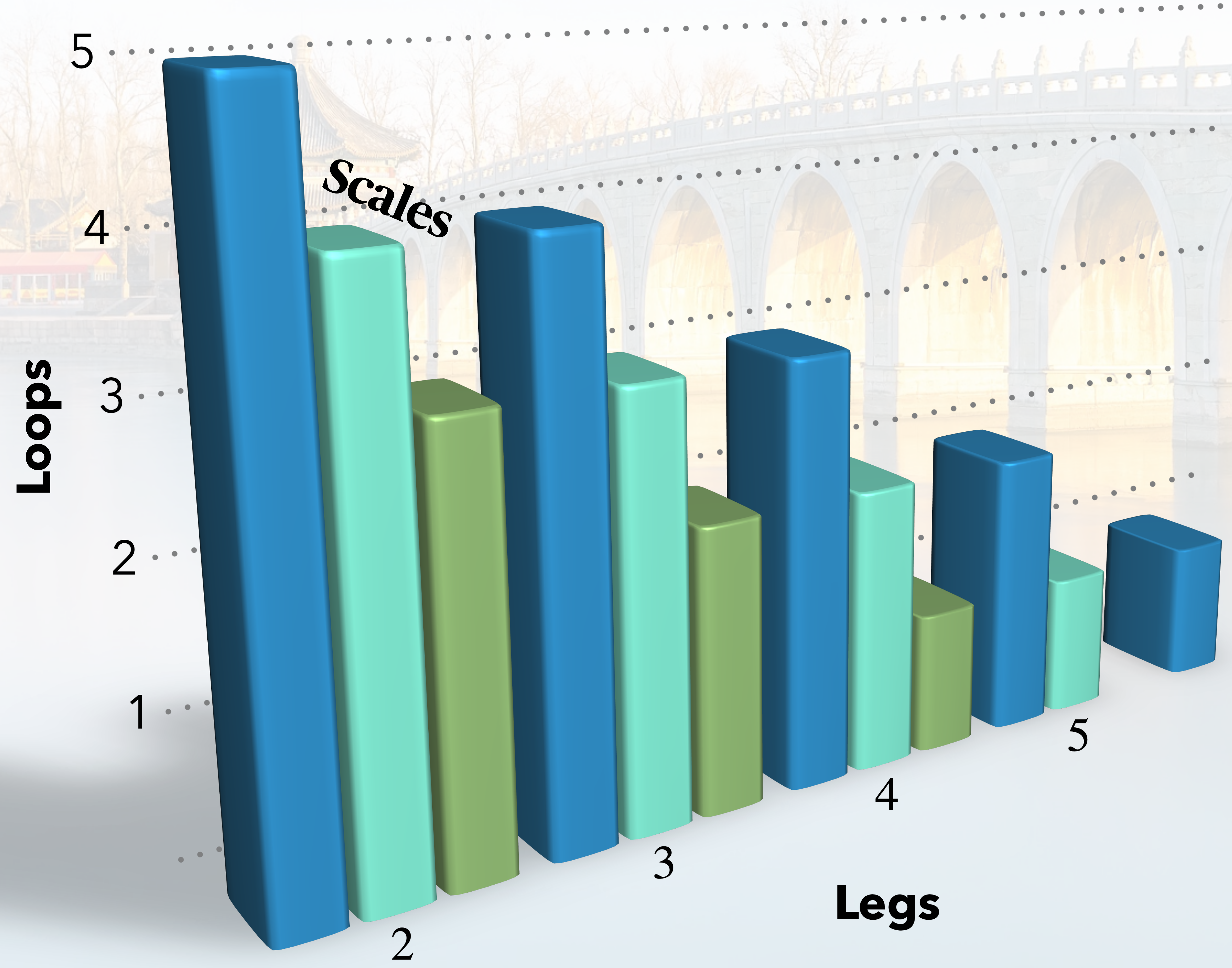
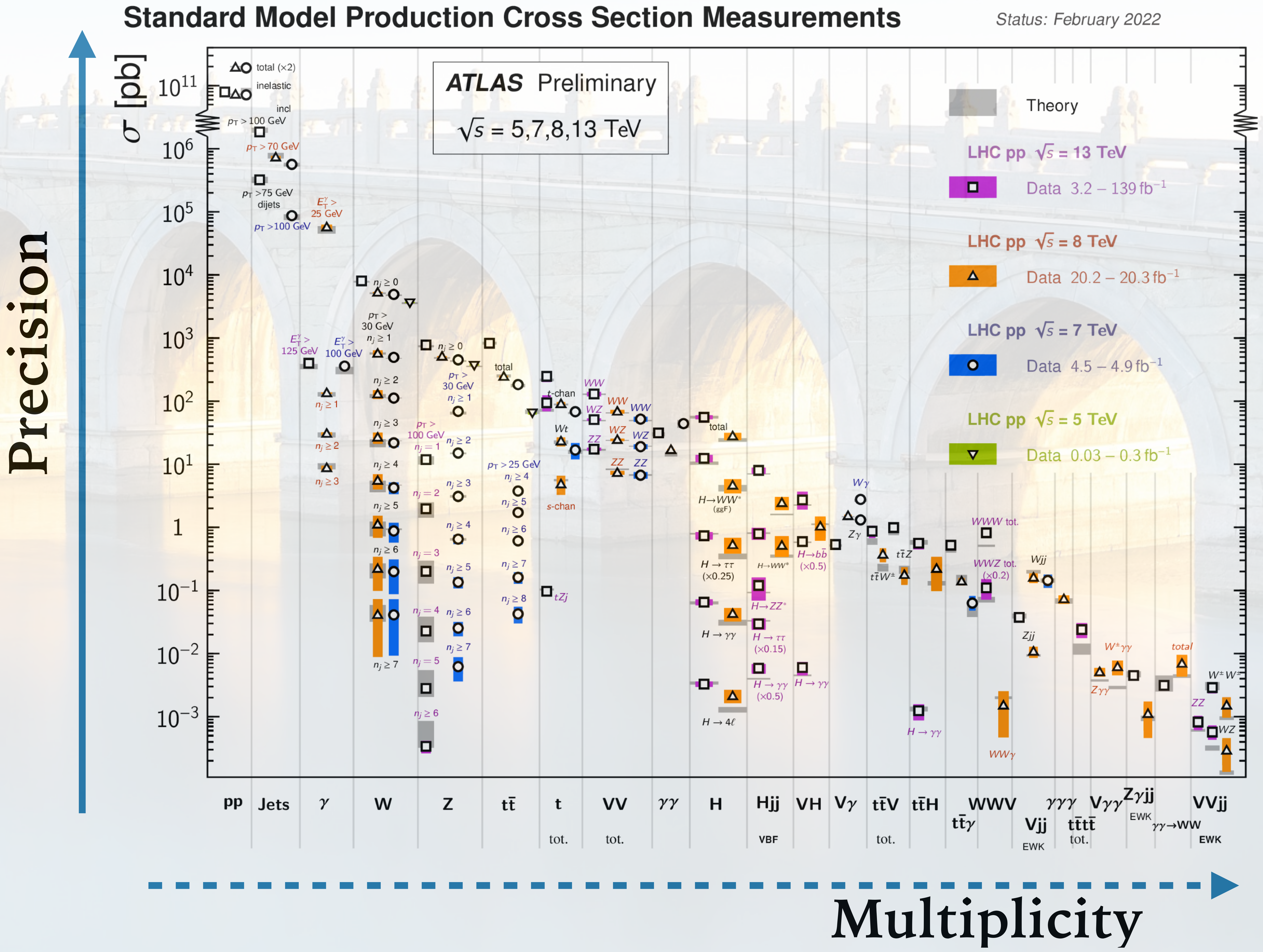

Standard Model Production Cross Section Measurements
Status: February 2022
ATLAS Preliminary
√s = 5,7,8,13 TeV
σ [pb]
Theory
LHC pp √s = 13 TeV
Data 3.2 – 139 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 5 TeV
Data 0.03 – 0.3 fb⁻¹
The Higgs Sector
pp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

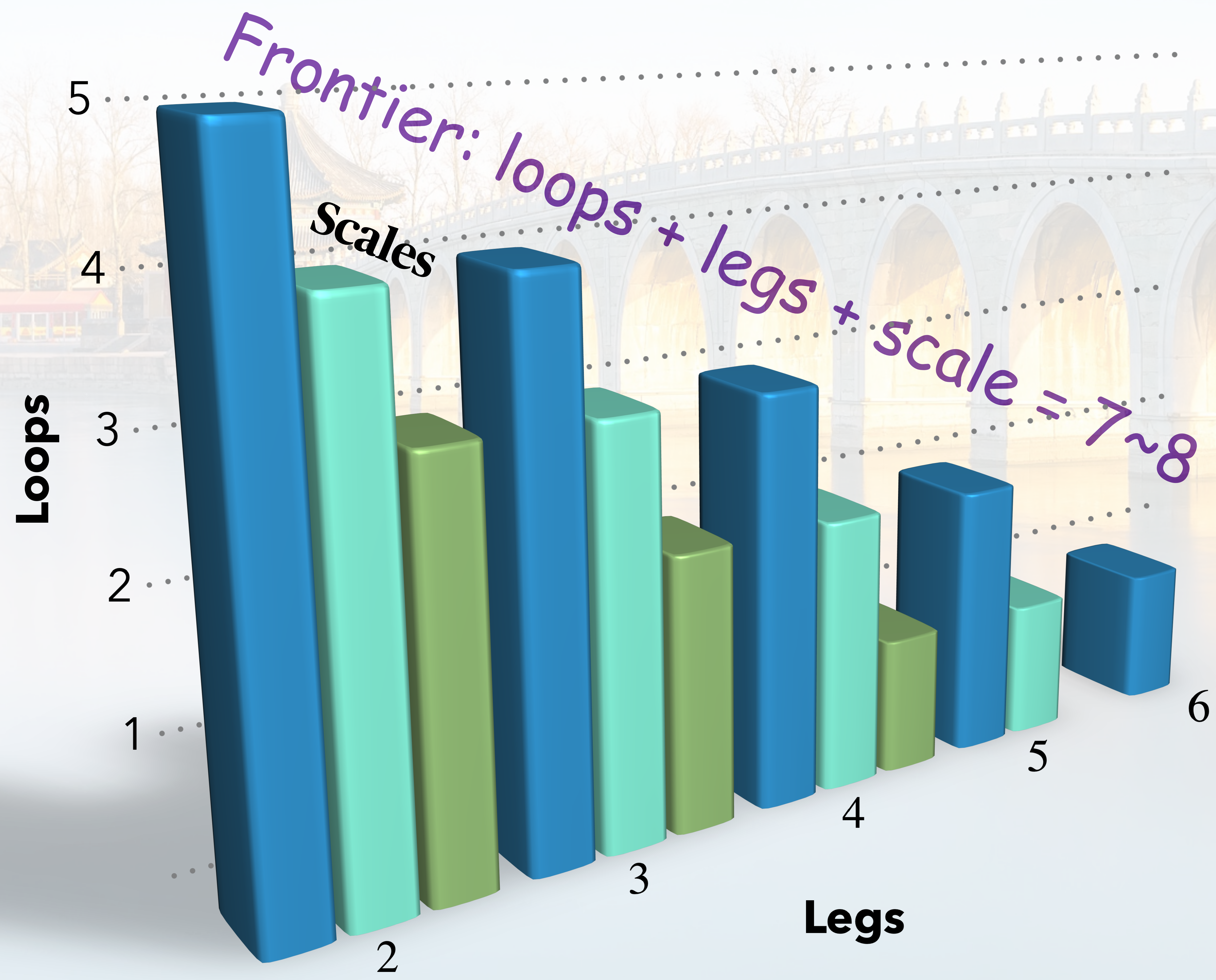

Standard Model Production Cross Section Measurements
Status: February 2022
σ [pb]
Precision
Energy
LHC Run 3
EIC
HL-LHC
CEPC
ILC
FCC-pp
...
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
Hjj
VH
Vγ
tt̄V
tt̄H
tt̄γ
WWV
Vjj
γγγ
tt̄tt̄
Vγγ
Zγjj
γγ→WW
VVjj

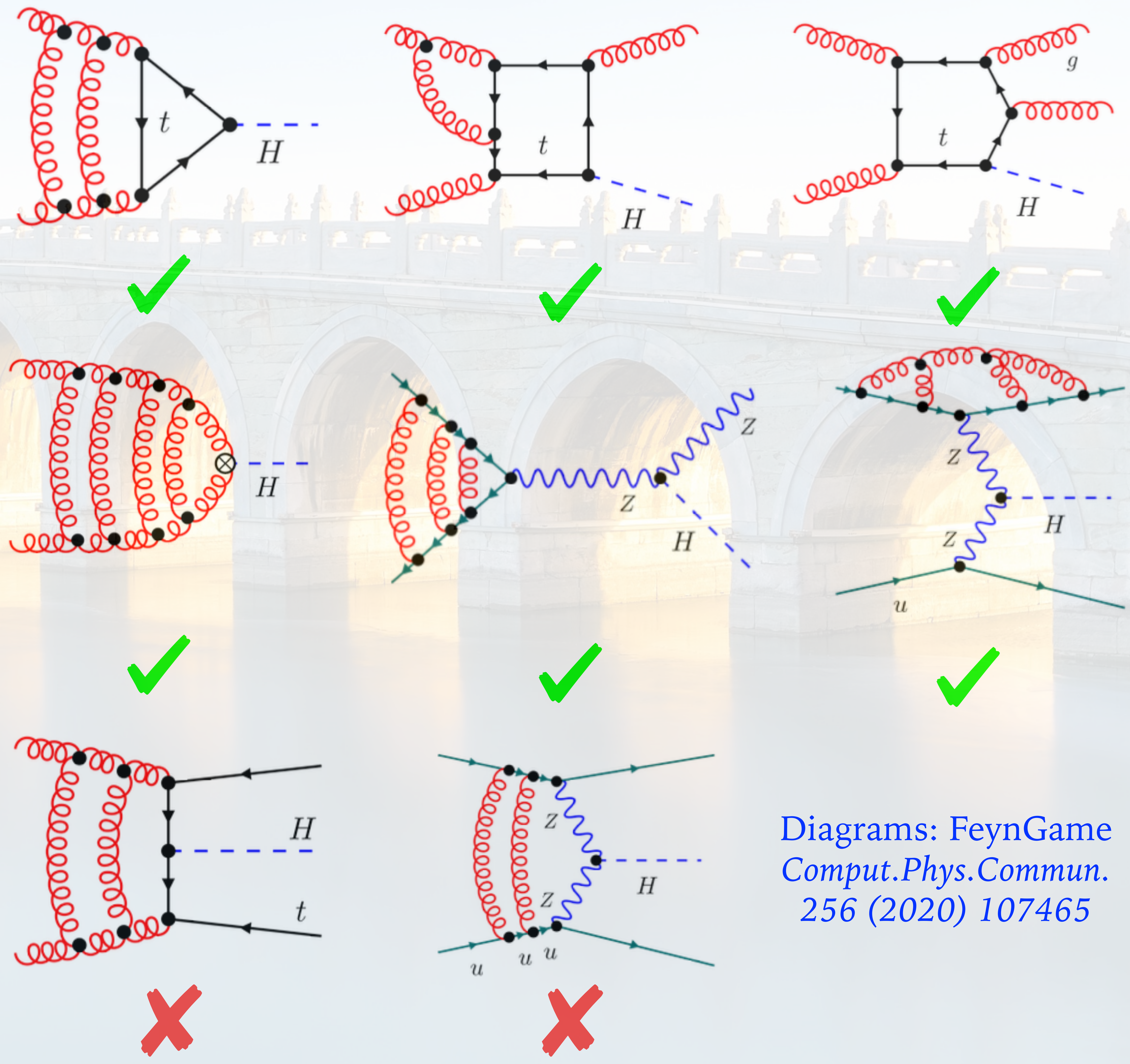
Perturbative QFT for Precision Predictions





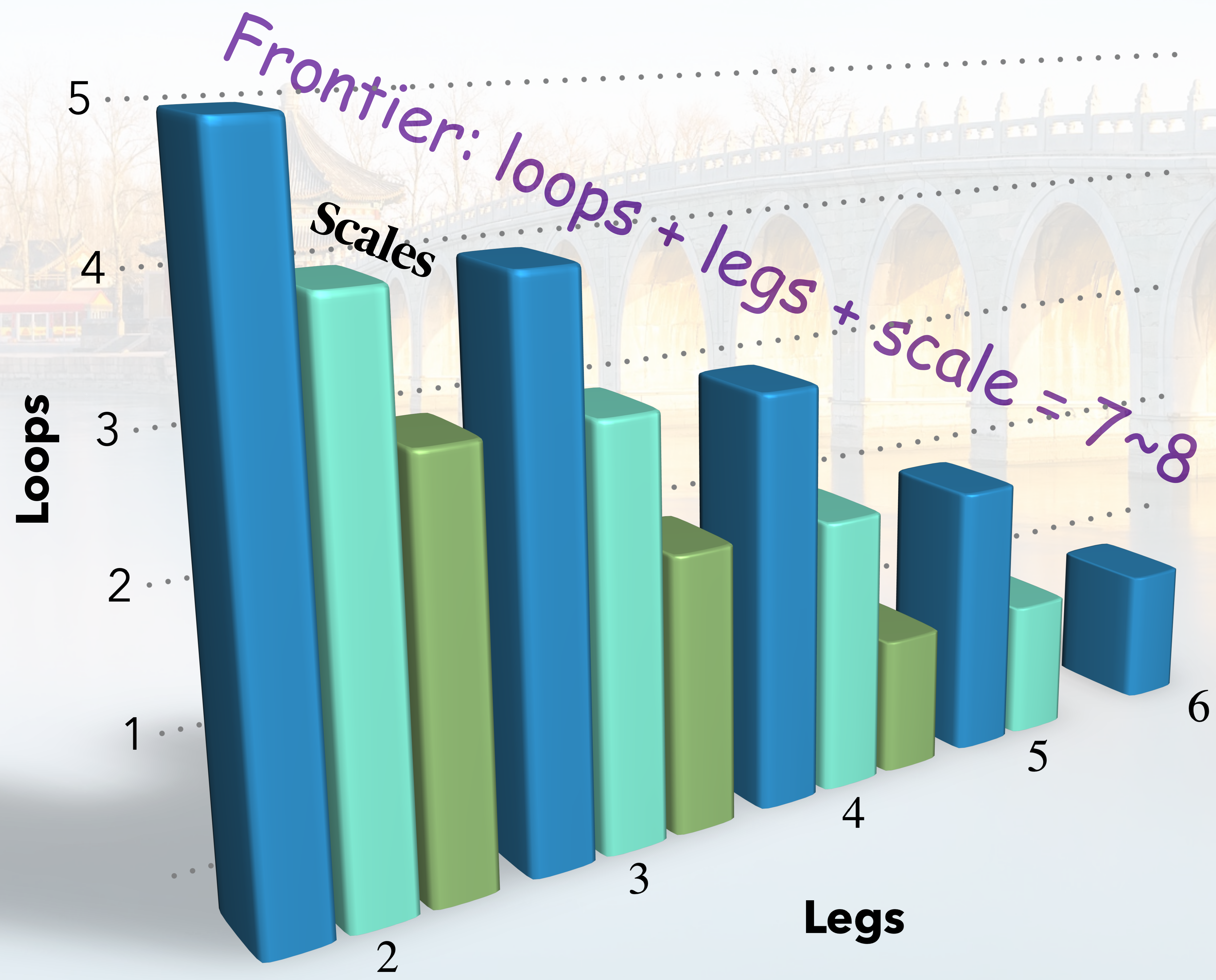
Perturbative QFT for Precision Predictions





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

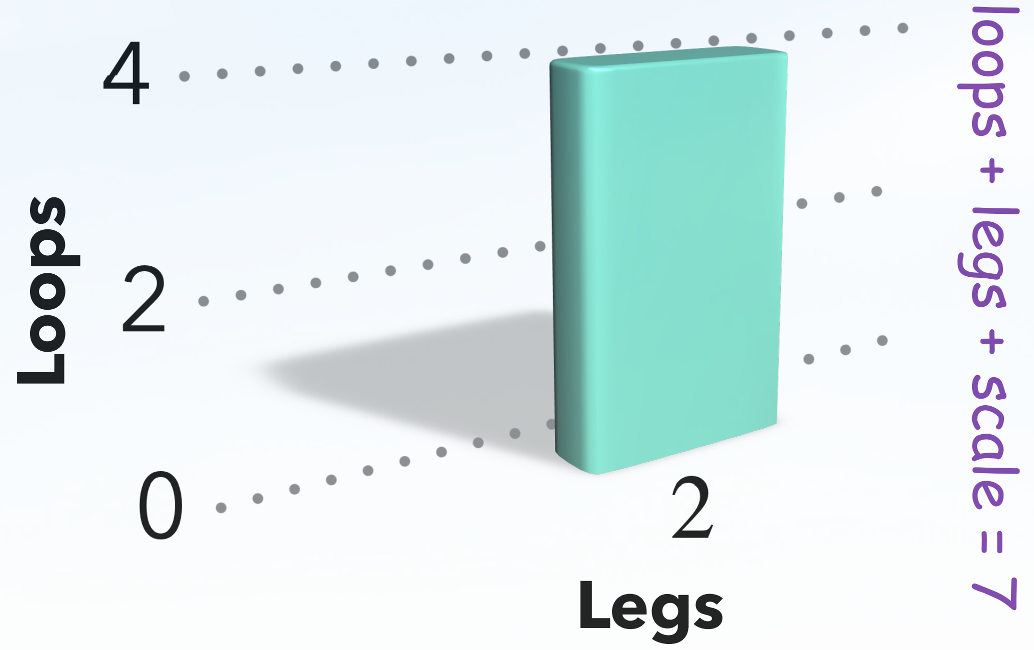
Finite field

Auxiliary mass flow

Neural network amplitude

…

Parton Distributions @ approximated N3LO



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

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

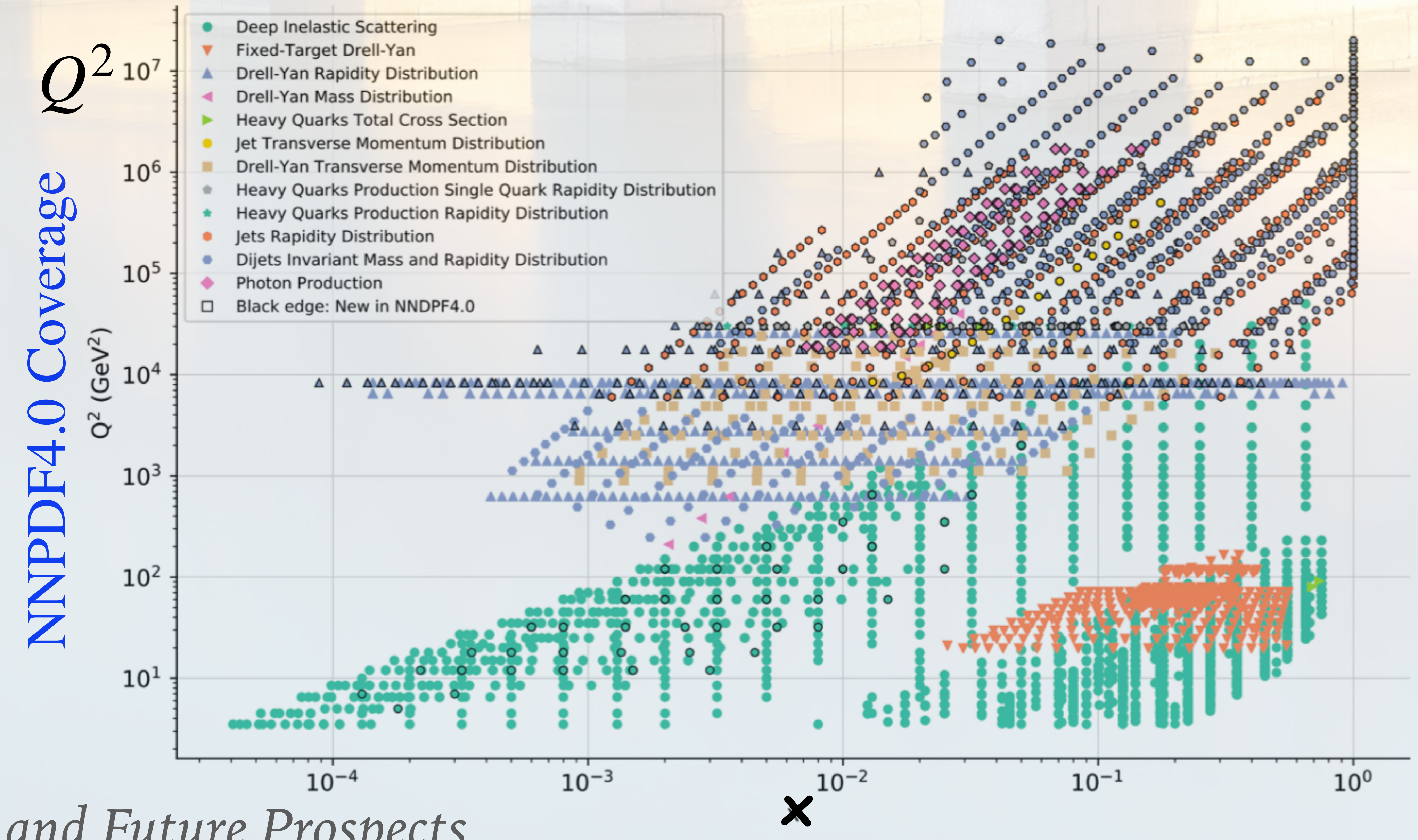
1970's 1980 2004

$$\gamma^{(3)}_{q\leftarrow q}(N) = -\int_0^1 \mathrm{d}x x^{N-1} P^{(3)}_{q\leftarrow q}(x)$$ *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.



Parton Distributions @ approximated N3LO

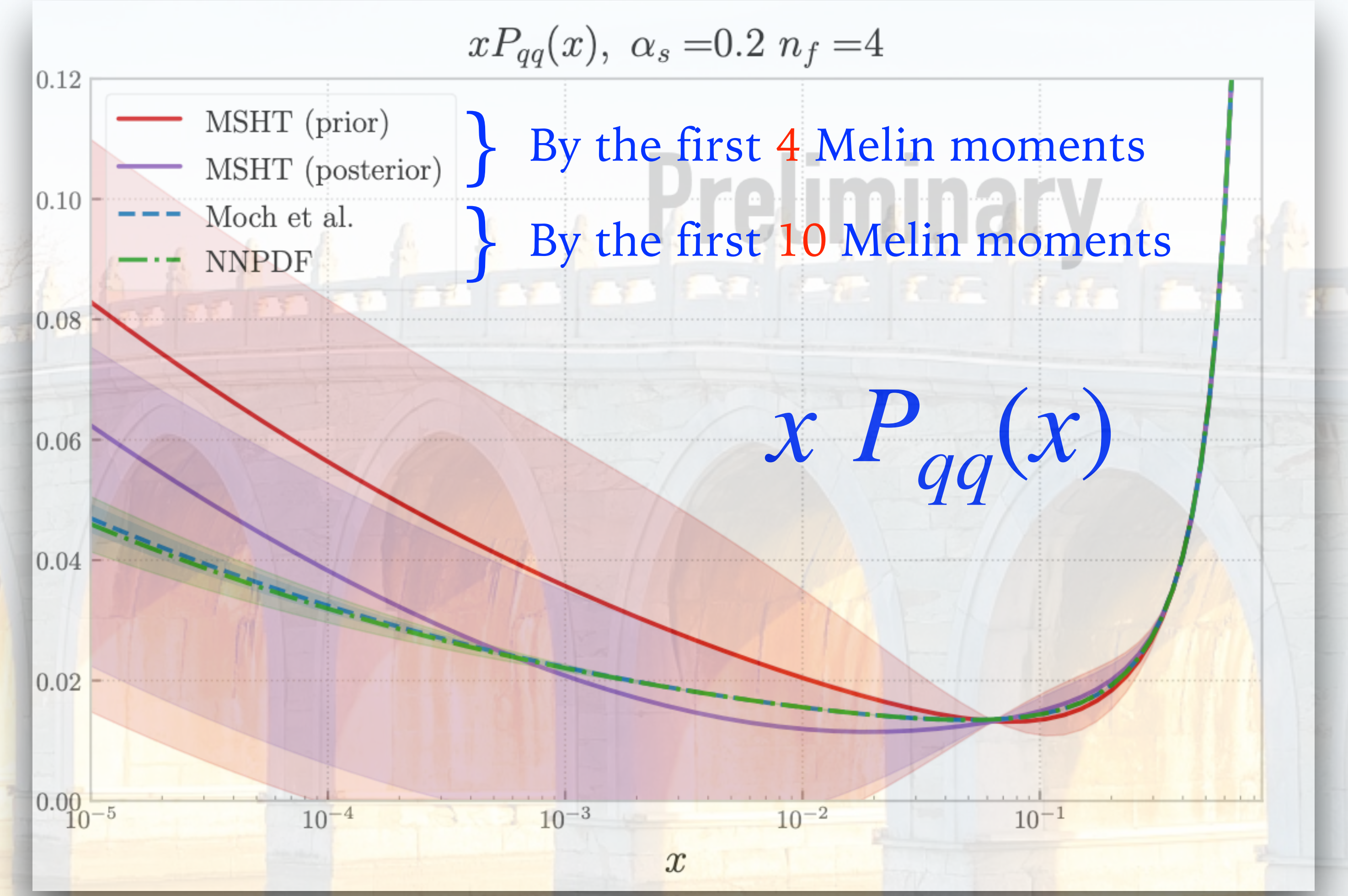
State-of-the-art Parton Distribution Functions

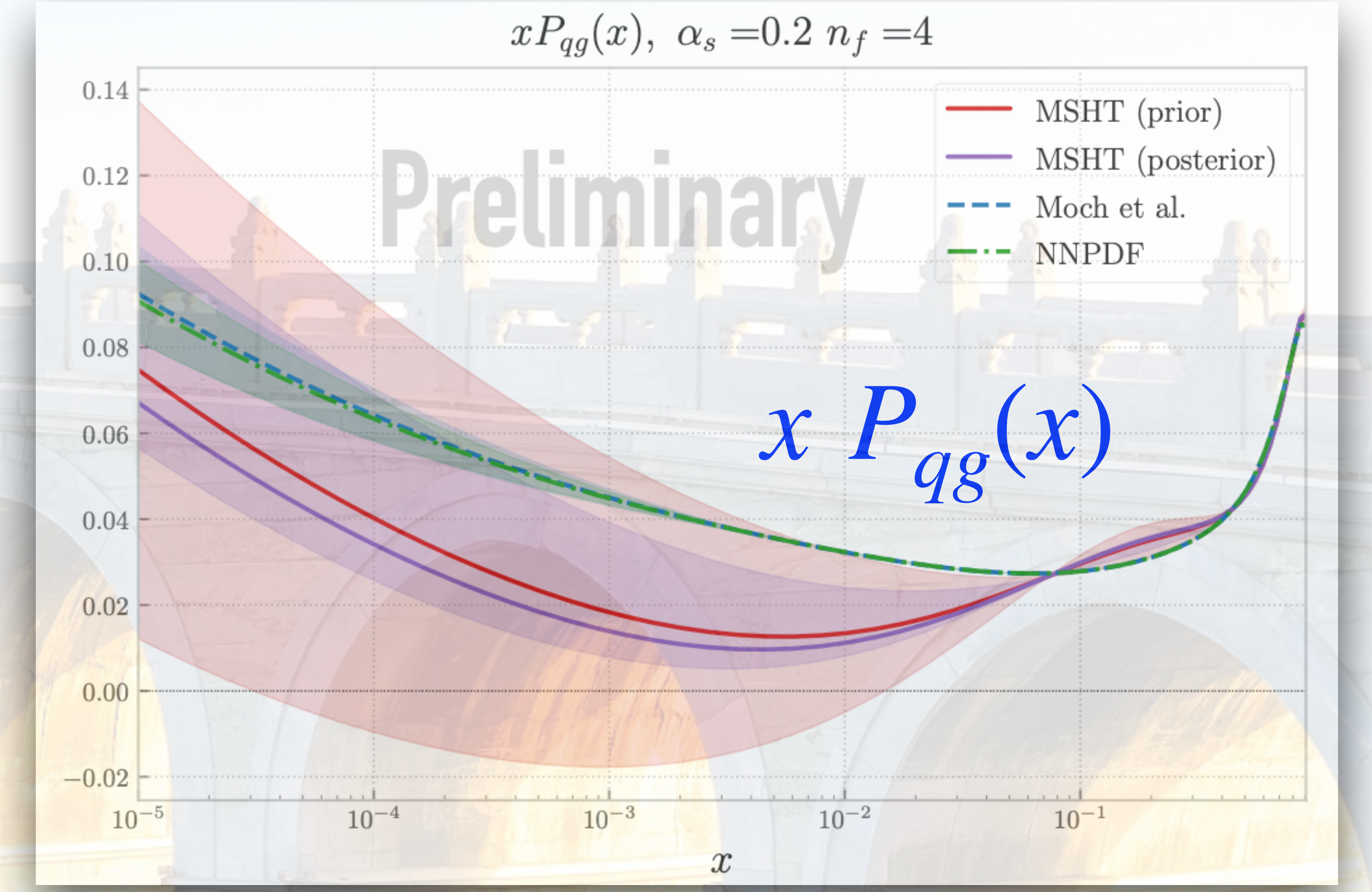
- Approximated N3LO PDF available:

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

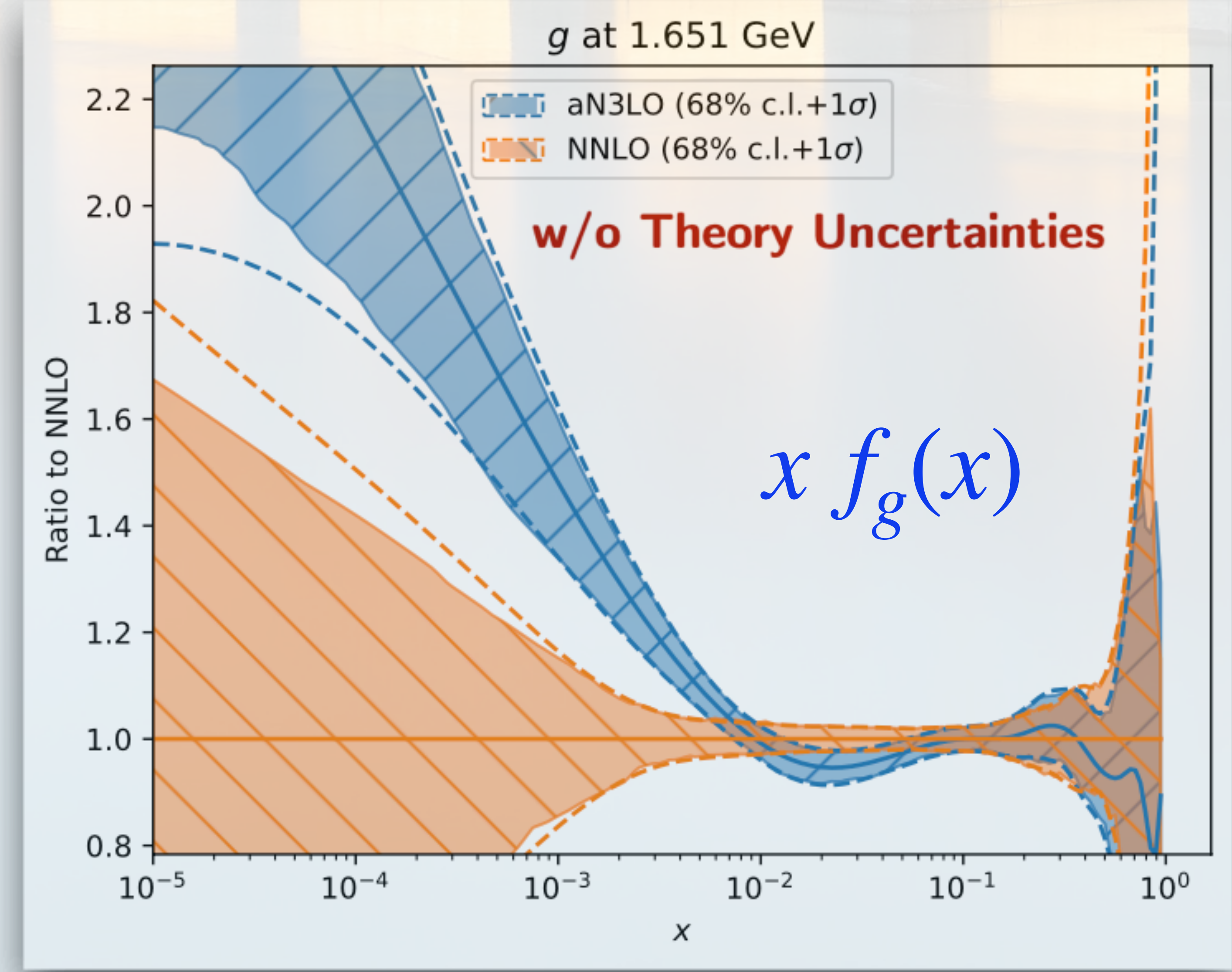
  NNPDFaN3LO *NNPDF preliminary*

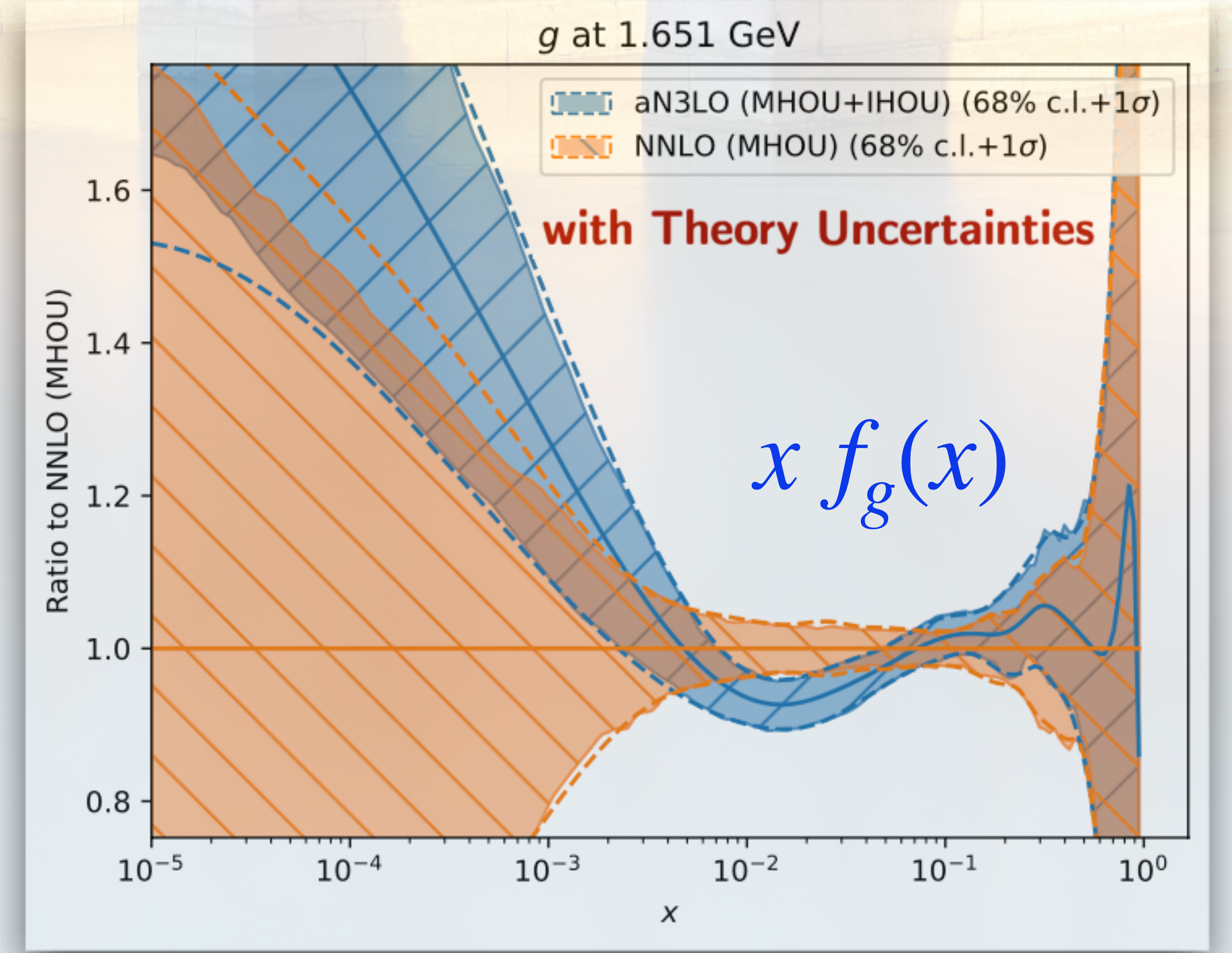
- More precise 4-loop splitting functions affect small x region.
- Large correction at aN3LO at small x region outside 68% c.l. region.
- Missing Higher Order Uncertainty (MHOU) not included in standard NNLO PDF.
- Crucial to consider MHOU and IHOU to understand consistency between NNLO and N3LO PDF.





M. Ubiali @ HWG 23





G. Magni @ Les Houches 23

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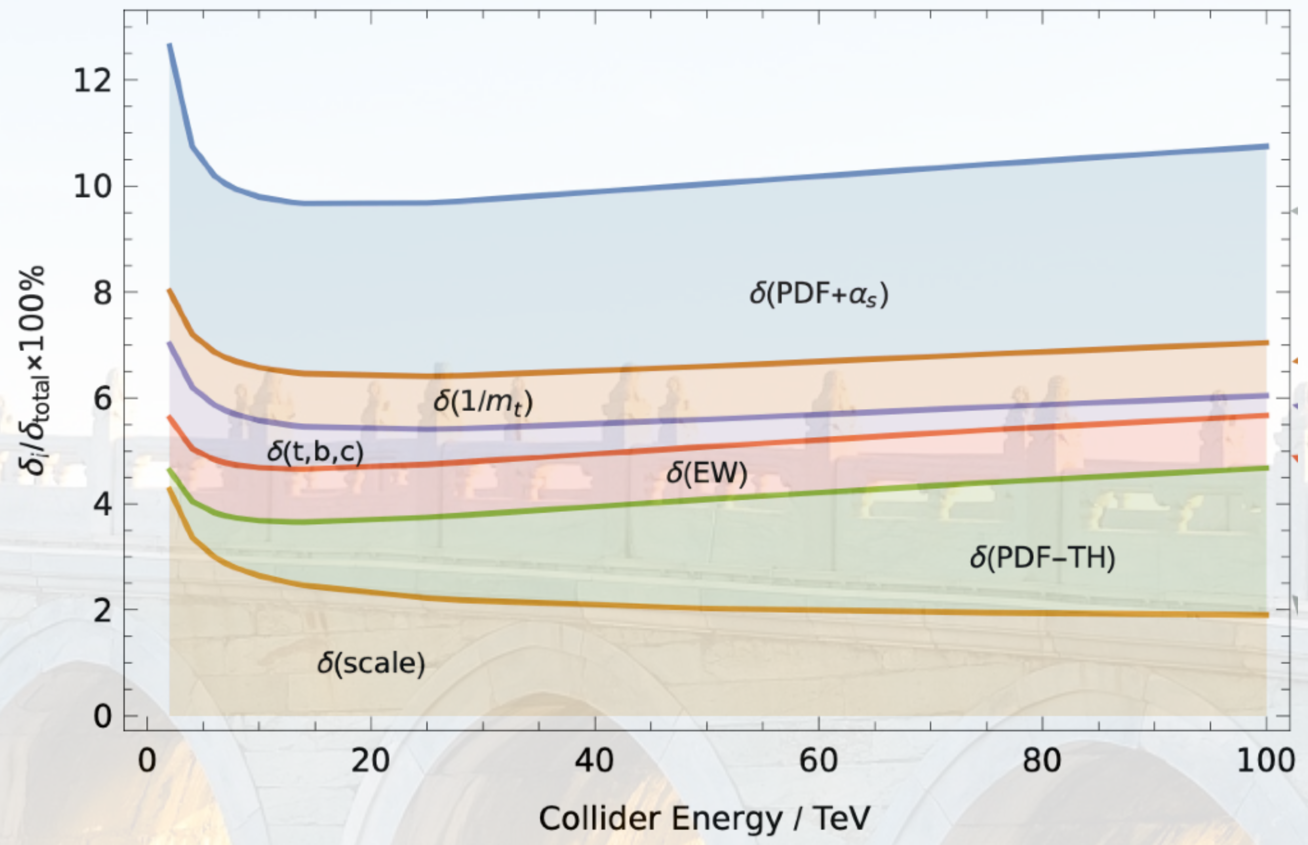

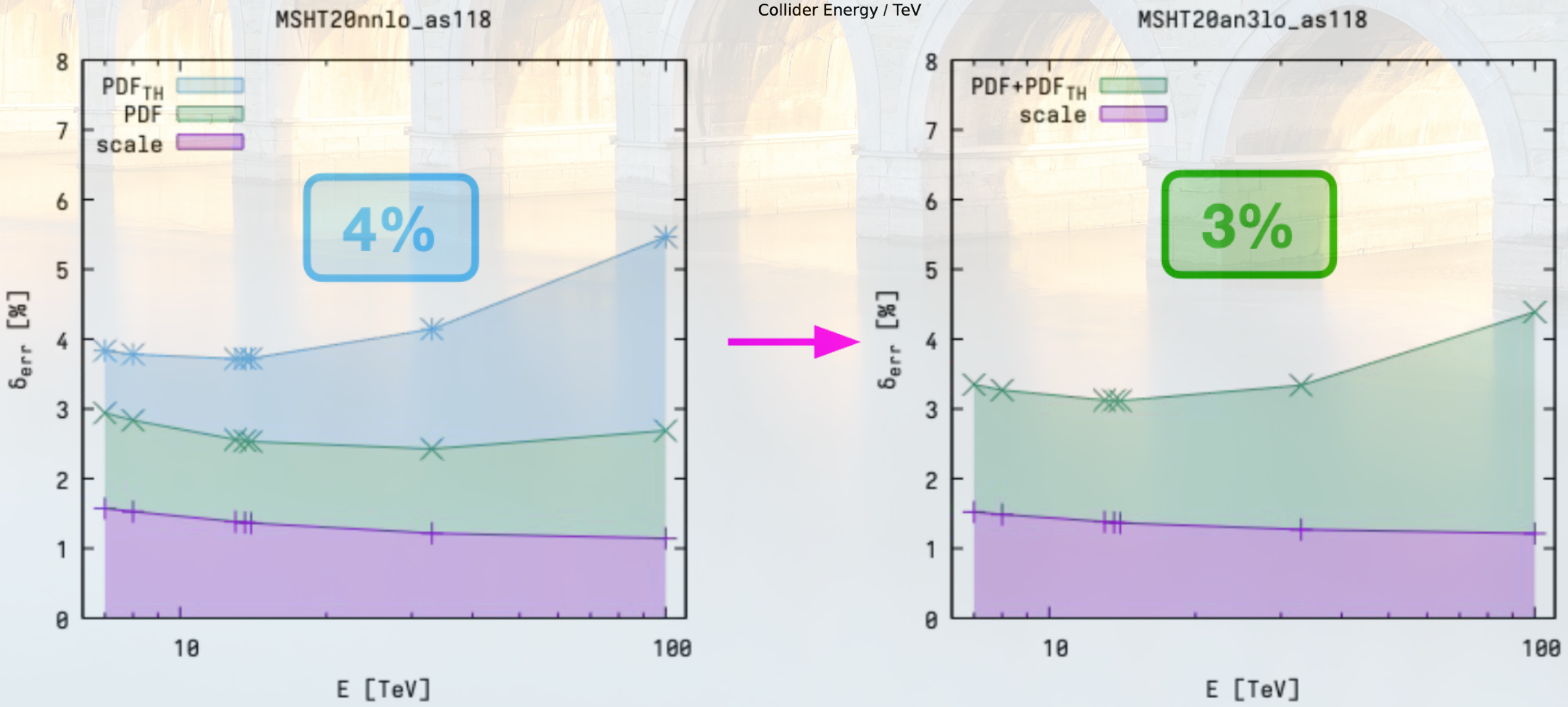

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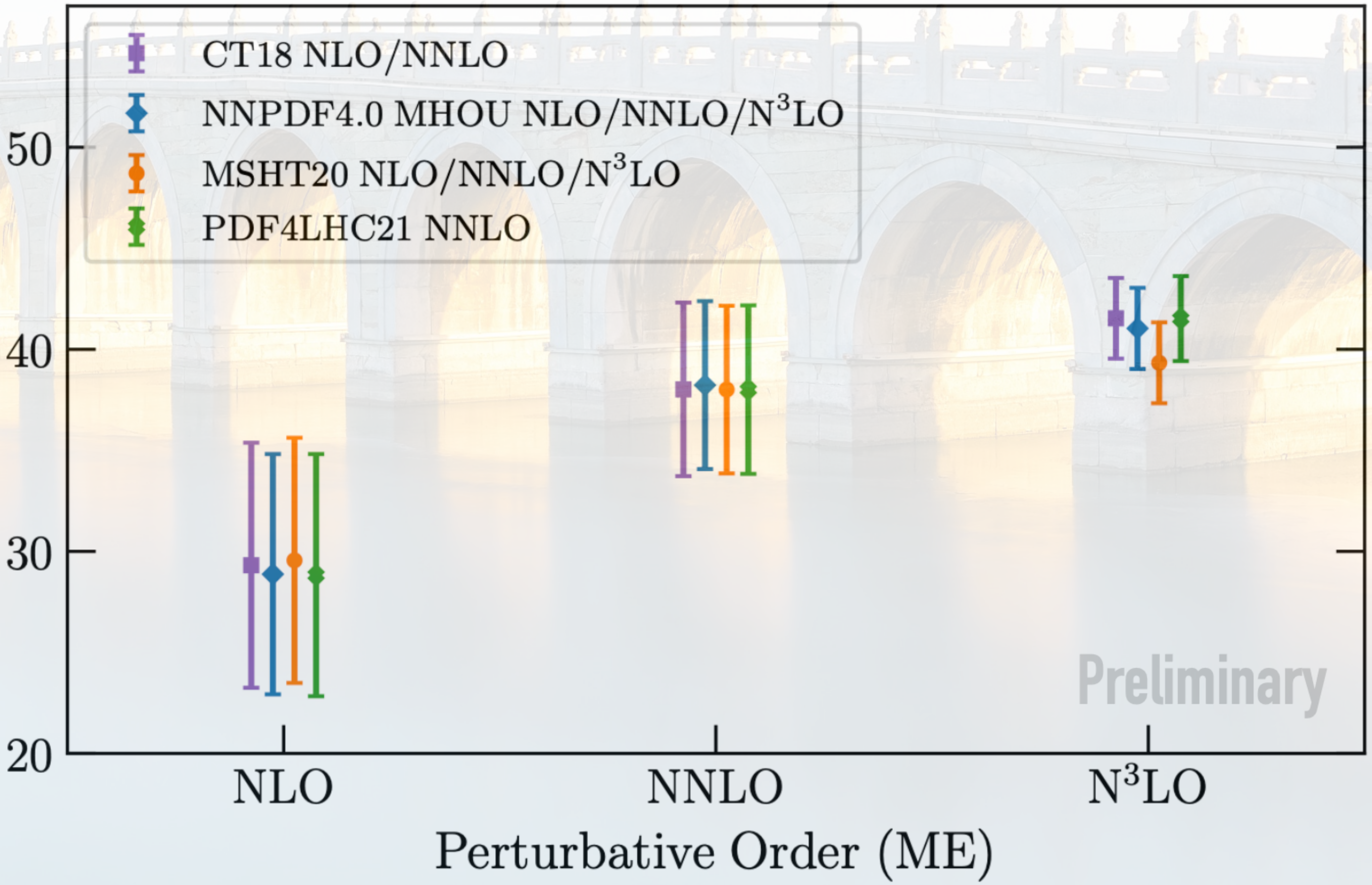
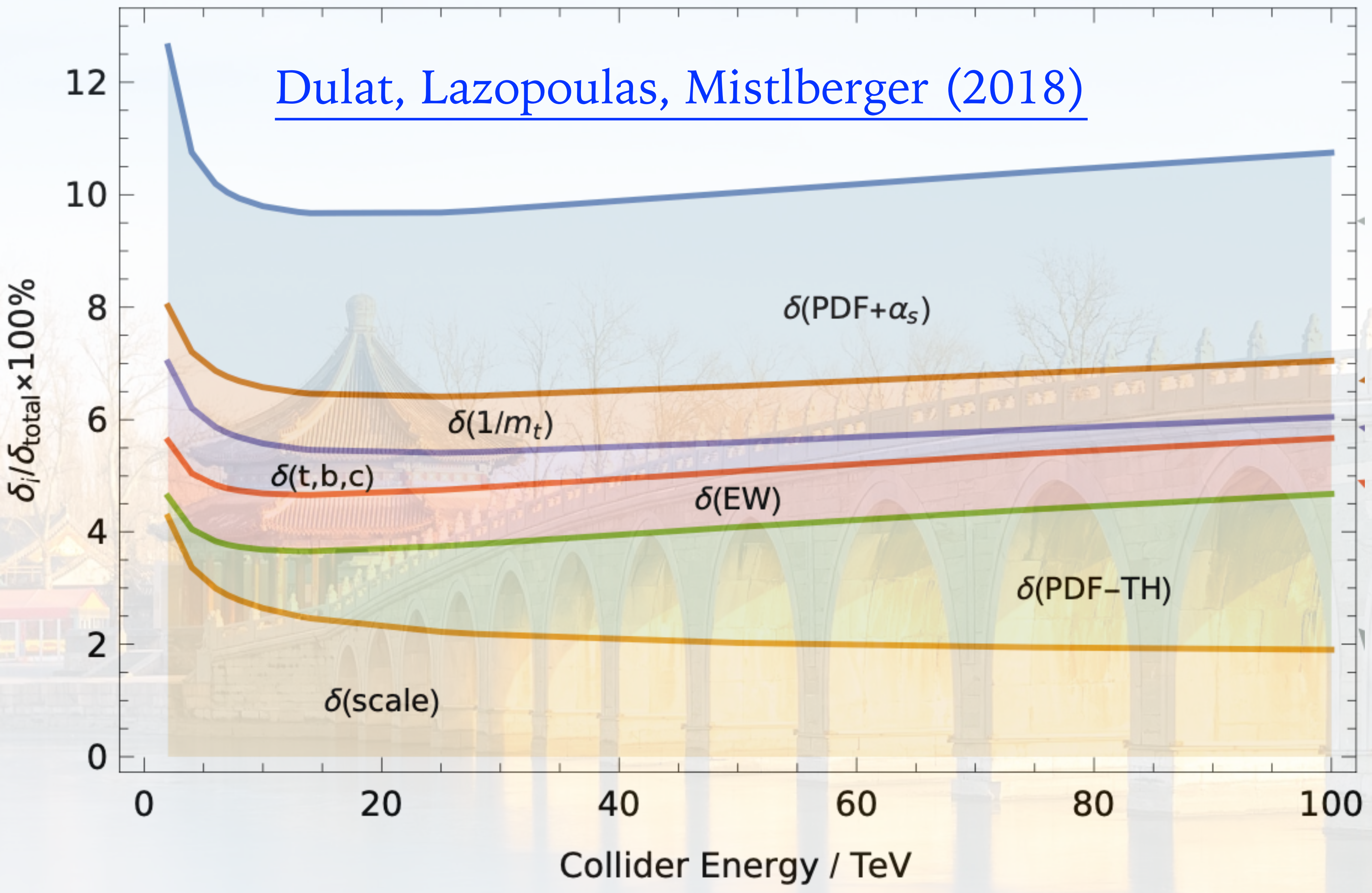
Higgs production in gluon fusion (PDF + MHOUs)



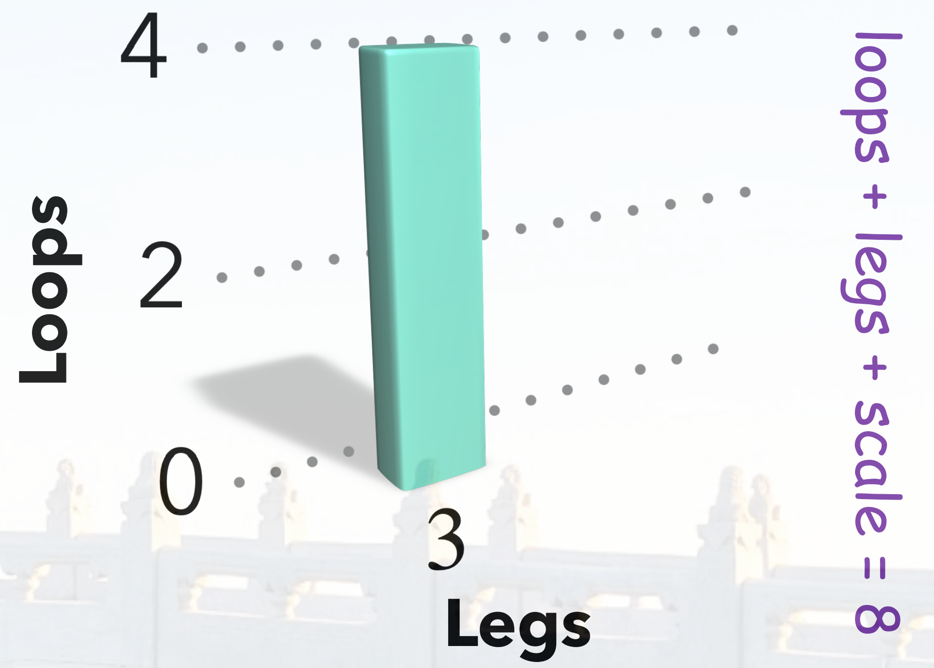
M. Ubiali @ HWG 23

Gluon Fusion Channel Uncertainties



➤ δ(Scale) : 4-loop QCD form factors

von Manteuffel, Schabinger(2019), Das, Moch, Vogt (2020), Lee, von Manteuffel, Schabinger et al (2022)

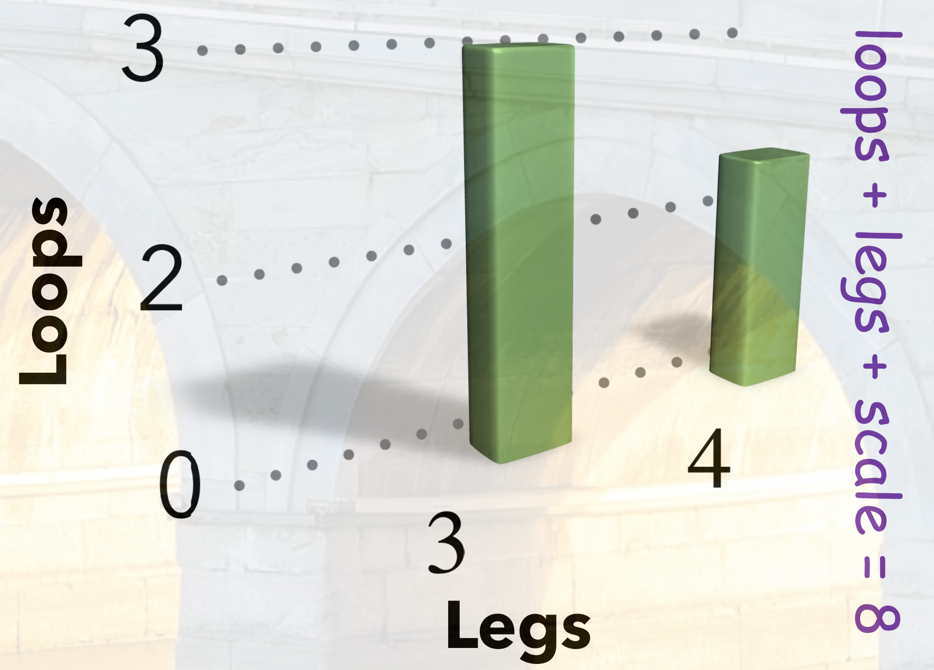


➤ δ(Scale) : Diff. N3LO(+N3LL) QCD

Cieri, XC et al (2018), XC, Gehrmann et al (2021), Billis, Dehnadi et al (2021),

➤ $\delta(EW)$: NLO mixed QCD-EW ~ 0.5%

Bonetti, Panzer et al (2020), Becchetti, Bonciani et al (2020), Becchetti, Moriello, Schweitzer (2021), Bonetti, Panzer, Tancredi (2022)



➤ $\delta(1/m_t)$: 3 and 4-loop QCD form factors

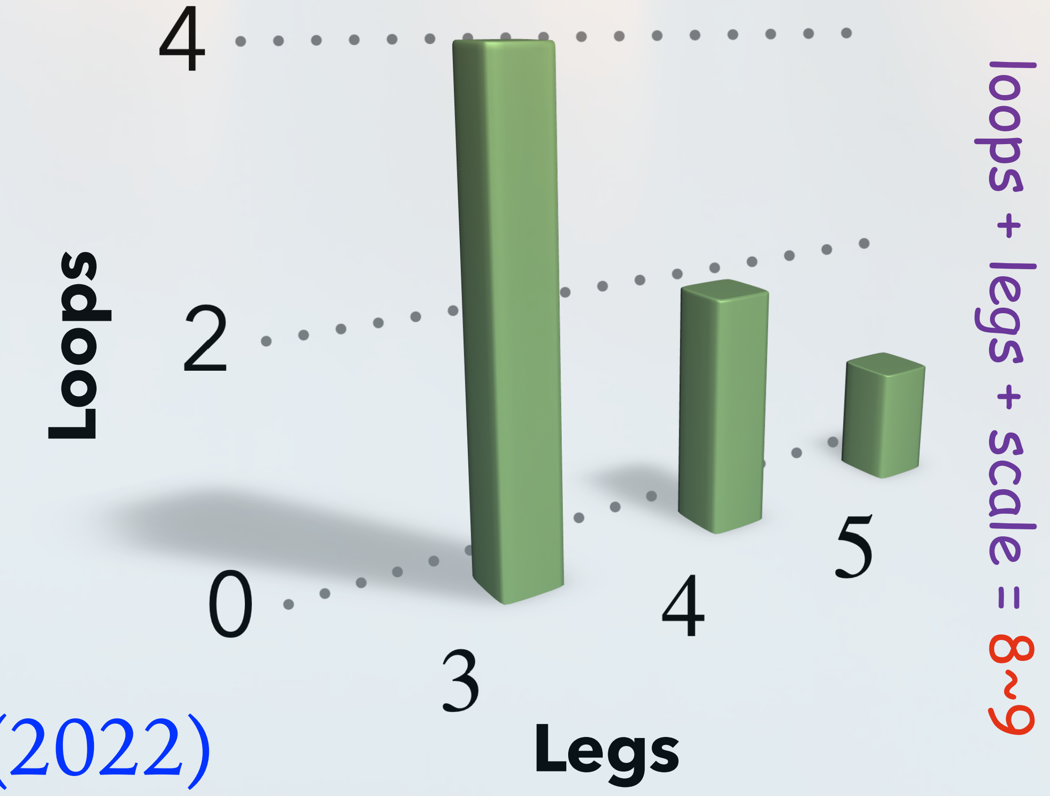
Davies, Gröber et al (2019), Davies, Herren, Steinhauser (2019)

➤ $\delta(1/m_t)$: H@NNLO QCD ~ 0.3%

Czakon, Niggetiedt (2020), Czakon, Harlander et al (2021)

➤ $\delta(1/m_t)$: H+J(J)@NLO QCD

XC, Huss, Jones et al (2020), Bonciani, Del Duca, Frellesvig et al (2022)



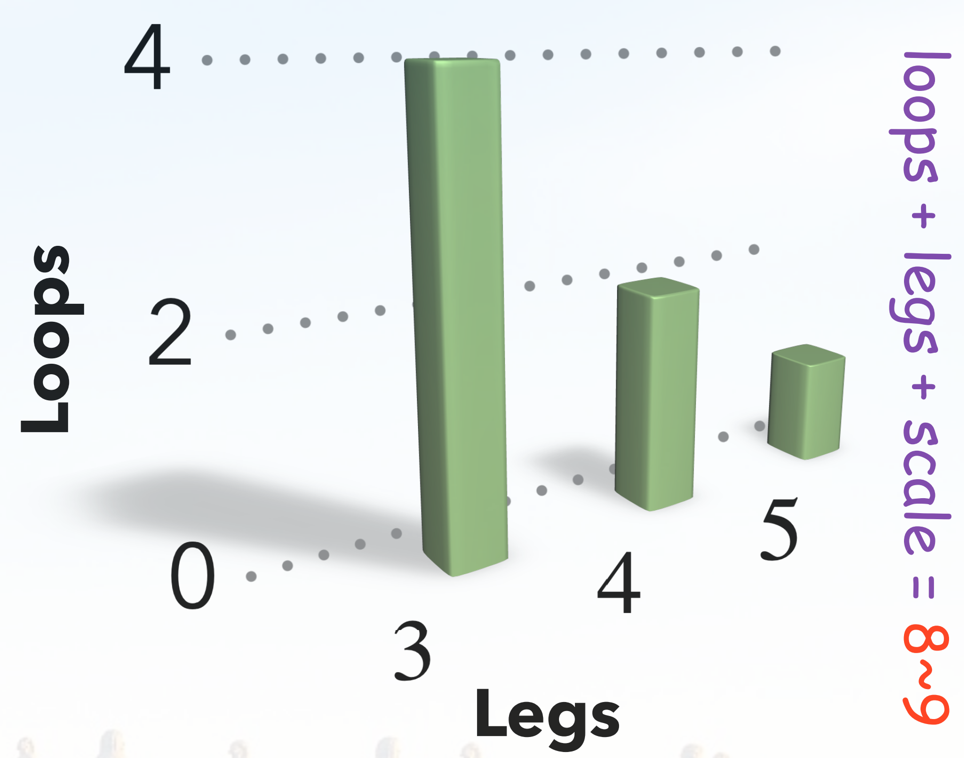
➤ δ(t,b,c) : NLO+NNLL QCD

Caola, Lindert, Melnikov et al (2018), Anastasiou, Penin (2020),

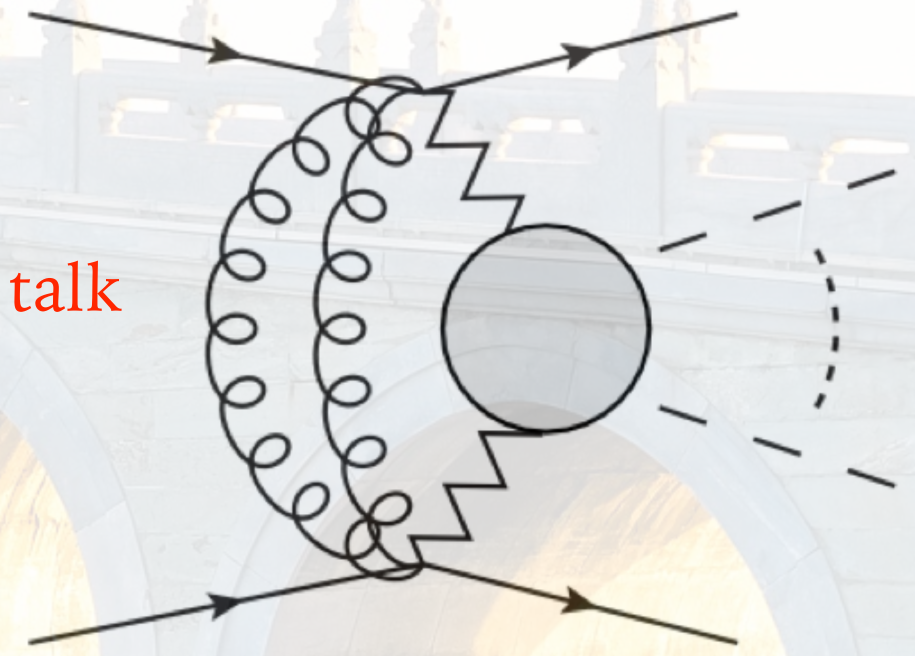
➤ δ(t,b,c) : 3-loop form factor

Harlander, Prausa Usovitsch (2019)

Vector Boson Fusion to Higgs



- Double DIS approx. @ inclusive N3LO with ~ ± 0.2% scale uncertainty Dreyer, Karlberg (2016)
- Fully differential predictions @ NNLO (DDIS approx.) with ~ ± 1% scale uncertainty:
  Cacciari, Dreyer, Salam, Zanderighi (2015), Cruz-Martinez, Gehrmann et al (2018), Asteriadis, Caola et al (2021)
- Non-factorizable corrections @ NNLO (eikonal approx.) ~0.4%:
  Liu, Melnikov, Penin (2019), Dreyer, Karlberg, Tancredi (2020), Long, Melnikov, Quarroz (2023) More details in M.M. Long's talk
  Partial N3LO ($\beta_0 \alpha_s^3$) corrections ~ 0.2% : Brønnum-Hansen, Long, Melnikov (2023)
- EW and QCD showers @ NLOPS (Powheg): Jäger, Scheller (2022)



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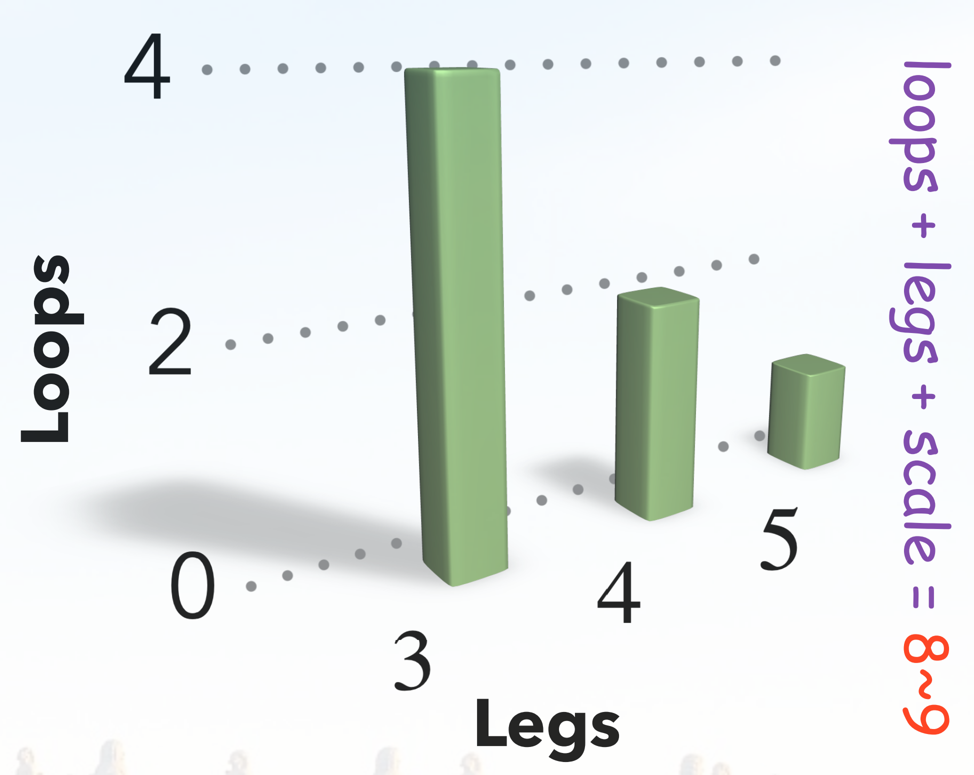

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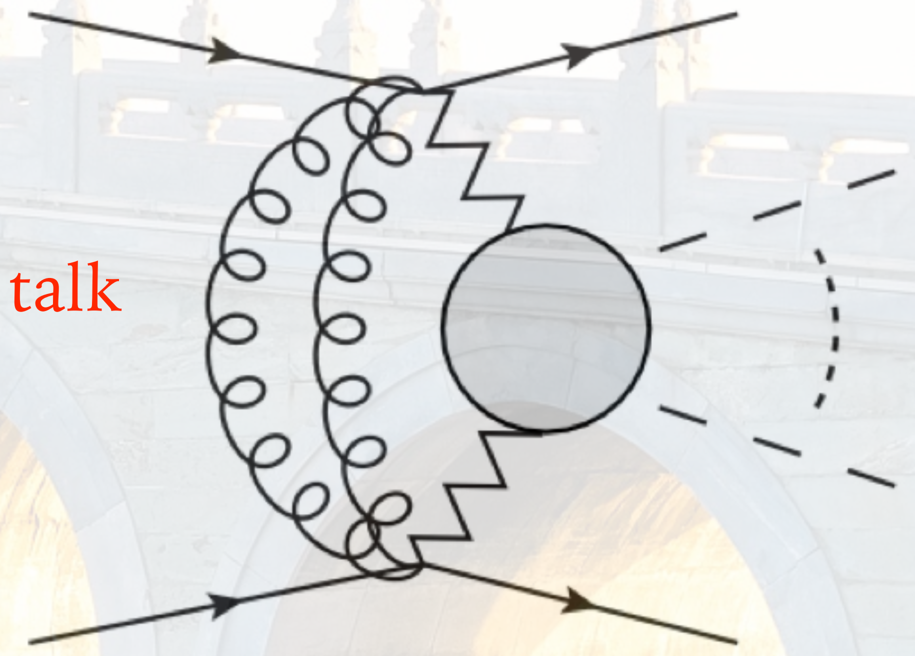


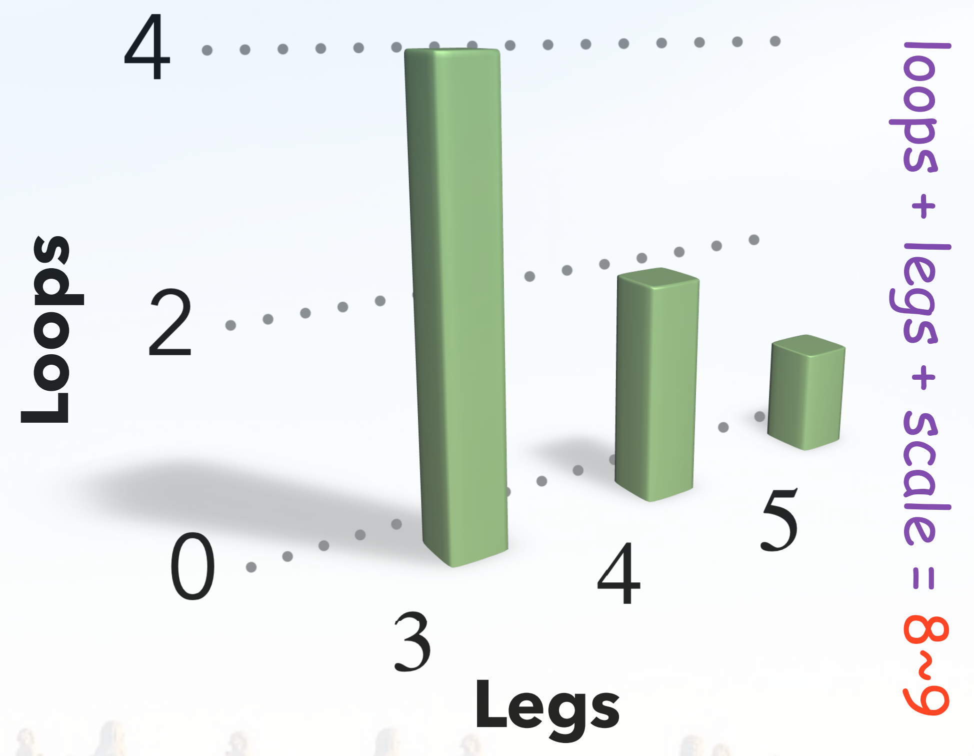
- EW and QCD showers @ NLOPS (Powheg): Jäger, Scheller (2022)

Source of systematic uncertainty	Impact on signal strength [%]
VBF parton shower	13.0
Jet energy scale	7.7
Trigger efficiency	6.7
Parton shower (final-state radiation)	5.6
b jet regression smearing	3.3
b tagging efficiency	3.0
Pileup modeling	2.3
b jet regression scale	2.0
Jet energy resolution	1.5

CMS 2308.01253

- What is the shortest panel of the bucket?
- CMS and ATLAS measurement in 2023 indicates parton shower uncertainties.

Vector Boson Fusion to Higgs



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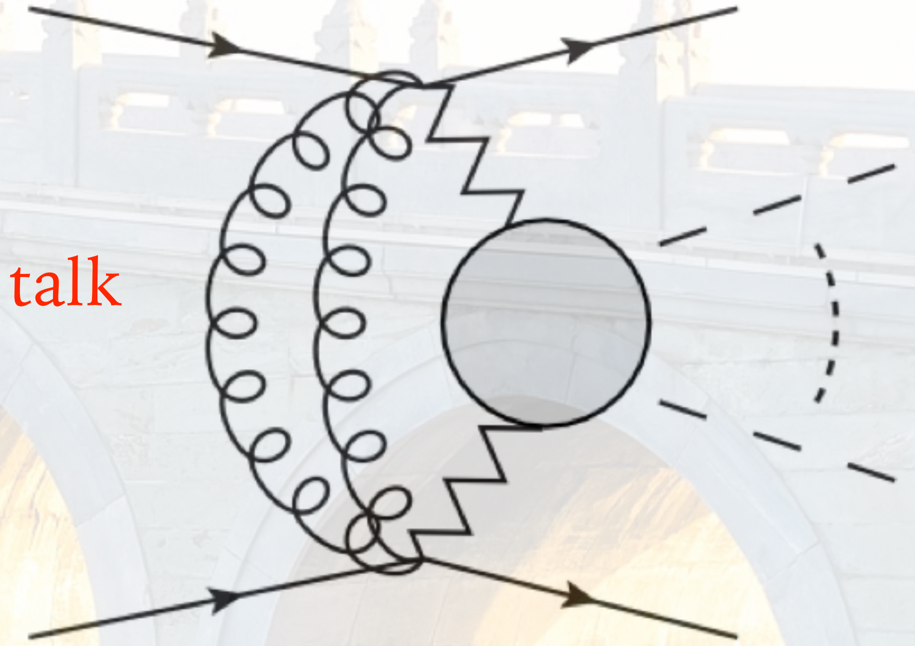
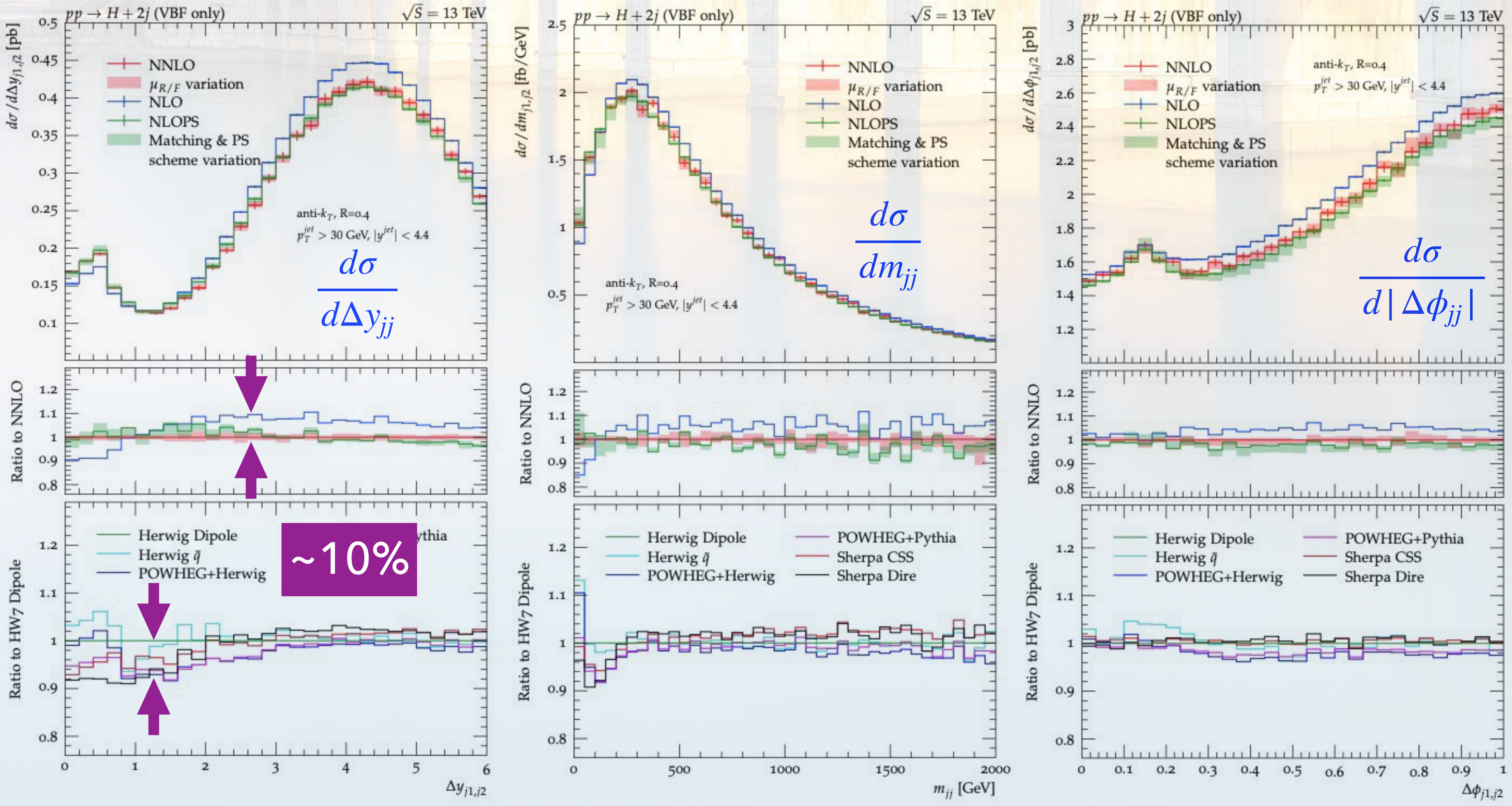




- What is the shortest panel of the bucket?
- CMS and ATLAS measurement in 2023 indicates parton shower uncertainties.
- Comparative study of VBF with different parton showers (NLO+LL accuracy):

  Jäger, Karlberg, Plätzer, Scheller, Zaro (2022)

  Buckley, XC, Cruz-Martinez et al (2021)
- Can we Improve the PS accuracy?

More details in Simone Alioli's talk

Vector Boson Fusion to Higgs

More details in Simone Alioli's talk

State-of-the-art Parton Shower accuracy

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

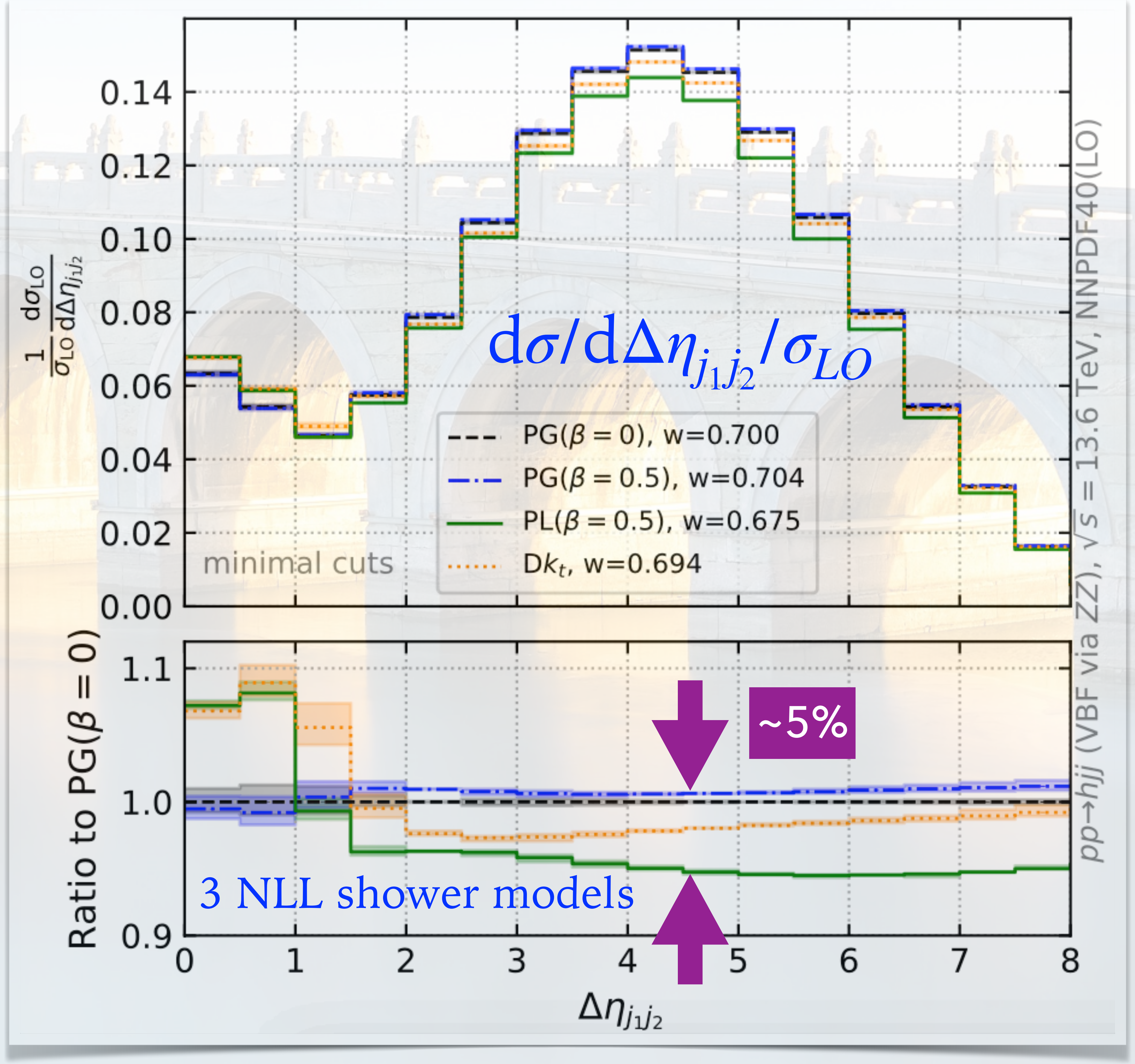
- Standard parton showers are Leading Logarithmic (LL) accurate. (SHERPA, PYTHIA, DIRE, GENEVA, HERWIG, VINCIA etc.)
- NNLO + LL PS established for $2 \to 2$ colour singlet and $t\bar{t}$.
  - $pp \to W^{\pm}Z \to l^{+}l^{-}l'^{\pm}\nu_{l}' +$ [QCD, QED] shower

  J. M. Lindert, D. Lombardi, M. Wiesemann et al (2022)
- 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):

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

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

Alaric Collaboration (2022), *B. Assi, S. Höche (2023)*

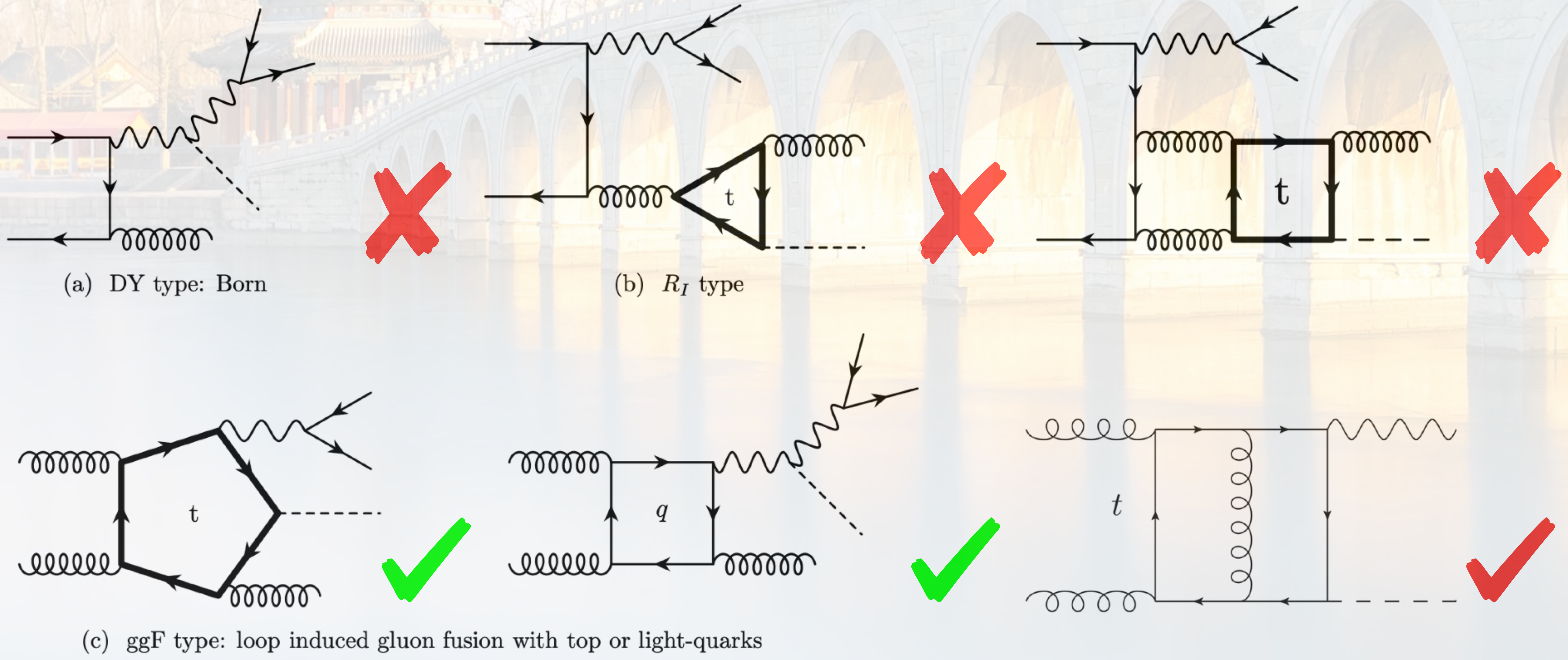


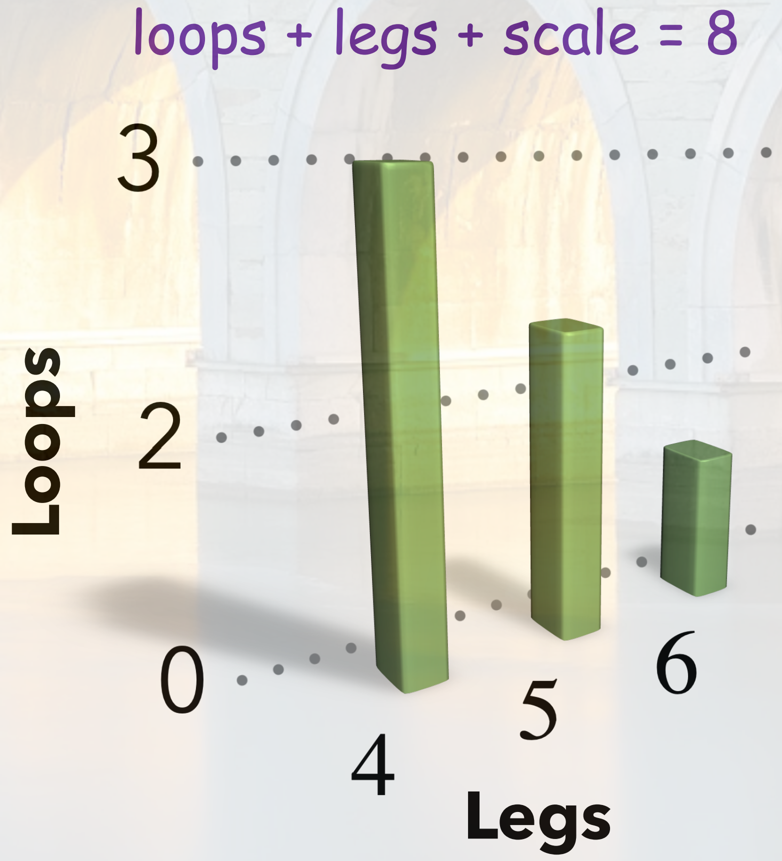
Beekveld, Ferrario Ravasio (2023)

VH Production

- $q\bar{q} \to VH$ @ NNLO contribute ~ 4% to Higgs XS with ± 5% error
- $gg \to VH$ @ NLO contribute ~ 0.5% to Higgs XS:

  Wang, Xu et al (2021), Chen, Davies et al (2022), Degrassi, Gröber, et al (2022)





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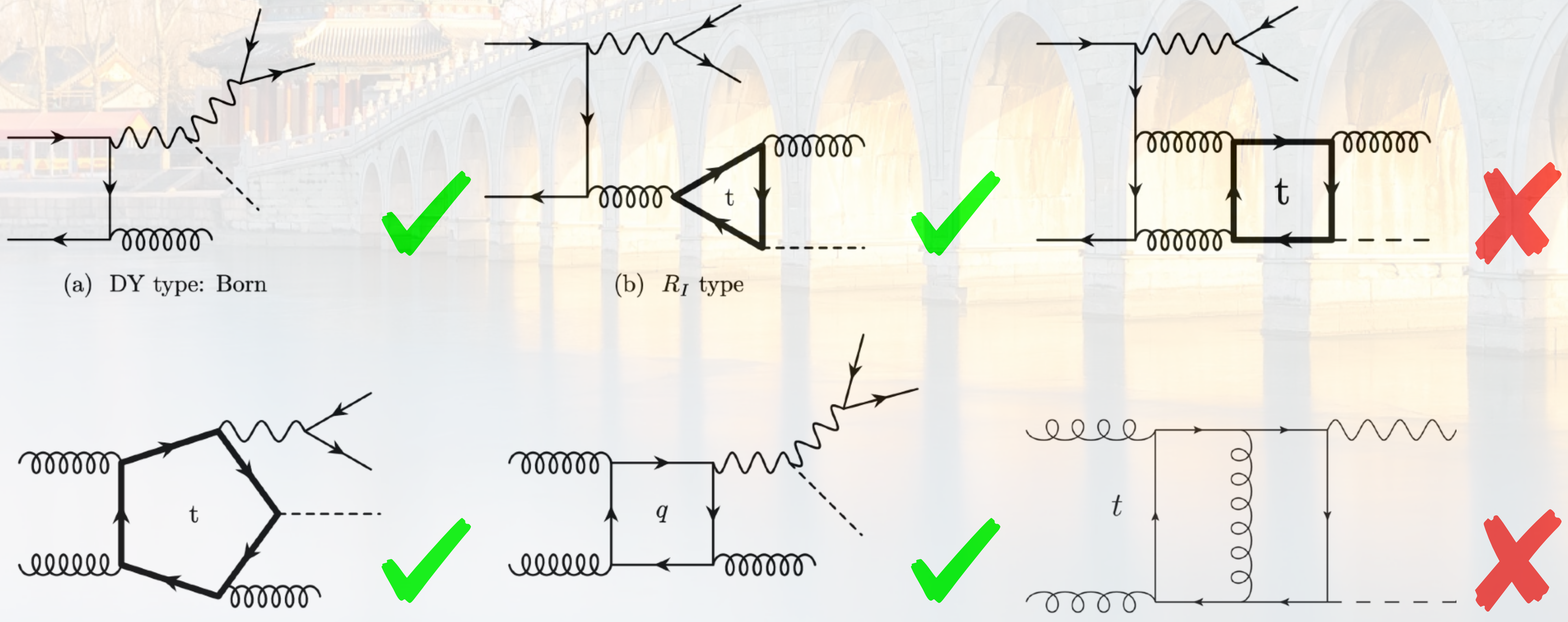
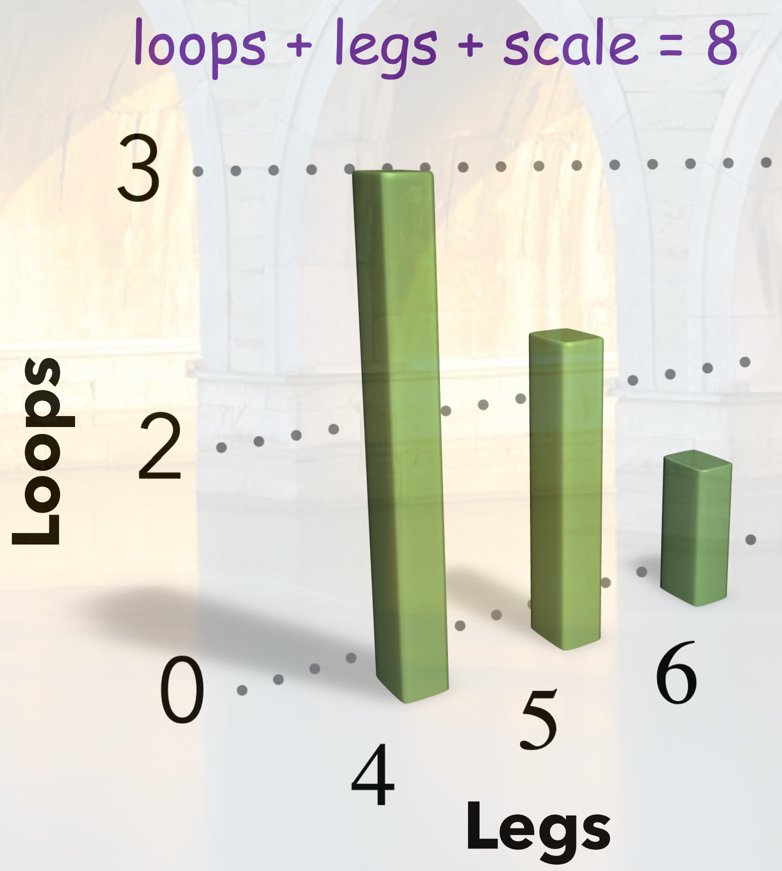
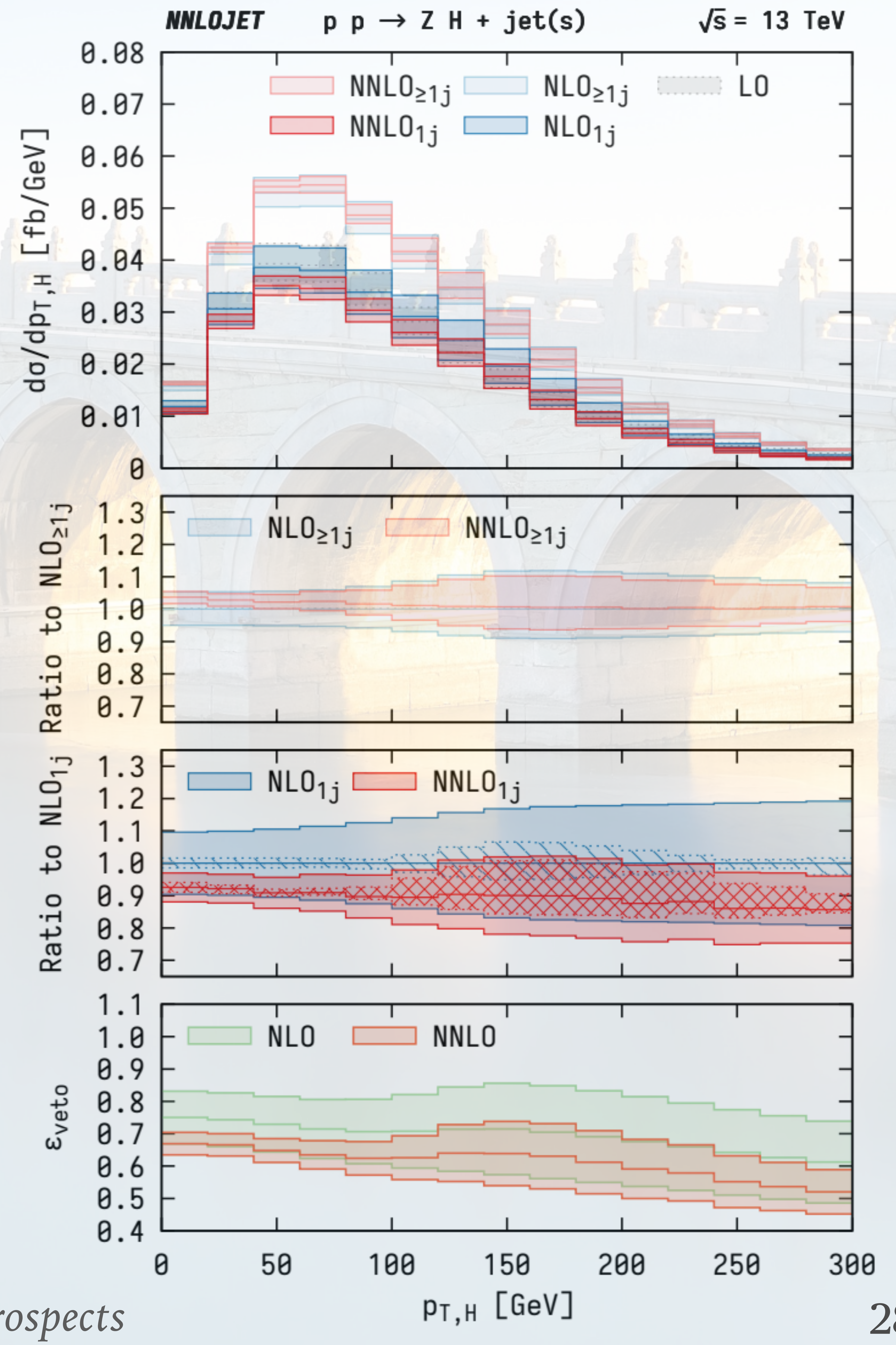


(a) DY type: Born

(b) R_I type

(c) ggF type: loop induced gluon fusion with top or light-quarks





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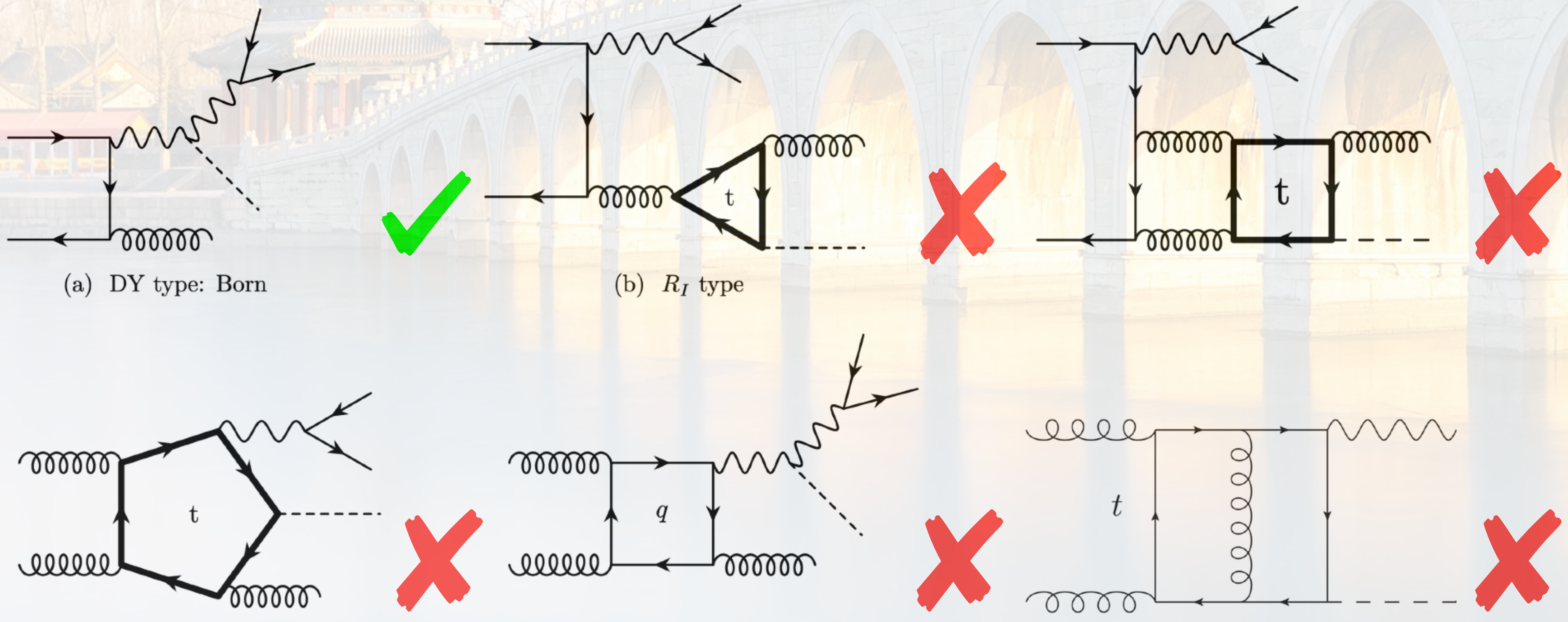

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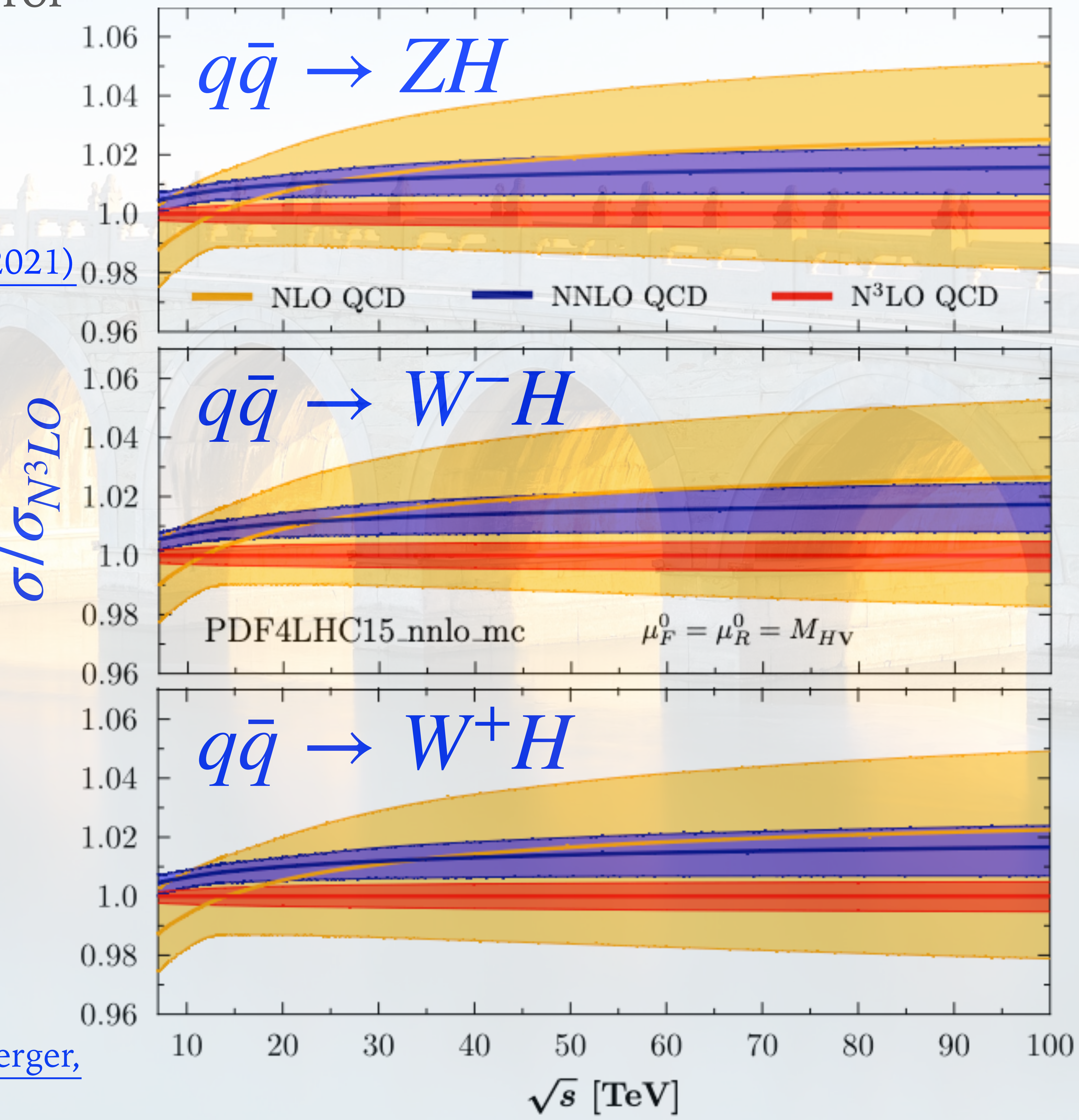

- VH @ N3LO (DY type contribution) ± 0.5% error
  - ME from 2 → 3 @ NNLO + ME @ 3-loop.
  - Use reverse unitarity for IR pole cancellation.
  - Different perturbative-series convergent behaviour

Baglio, Duhr, Mistlberger, Szafron (2022)

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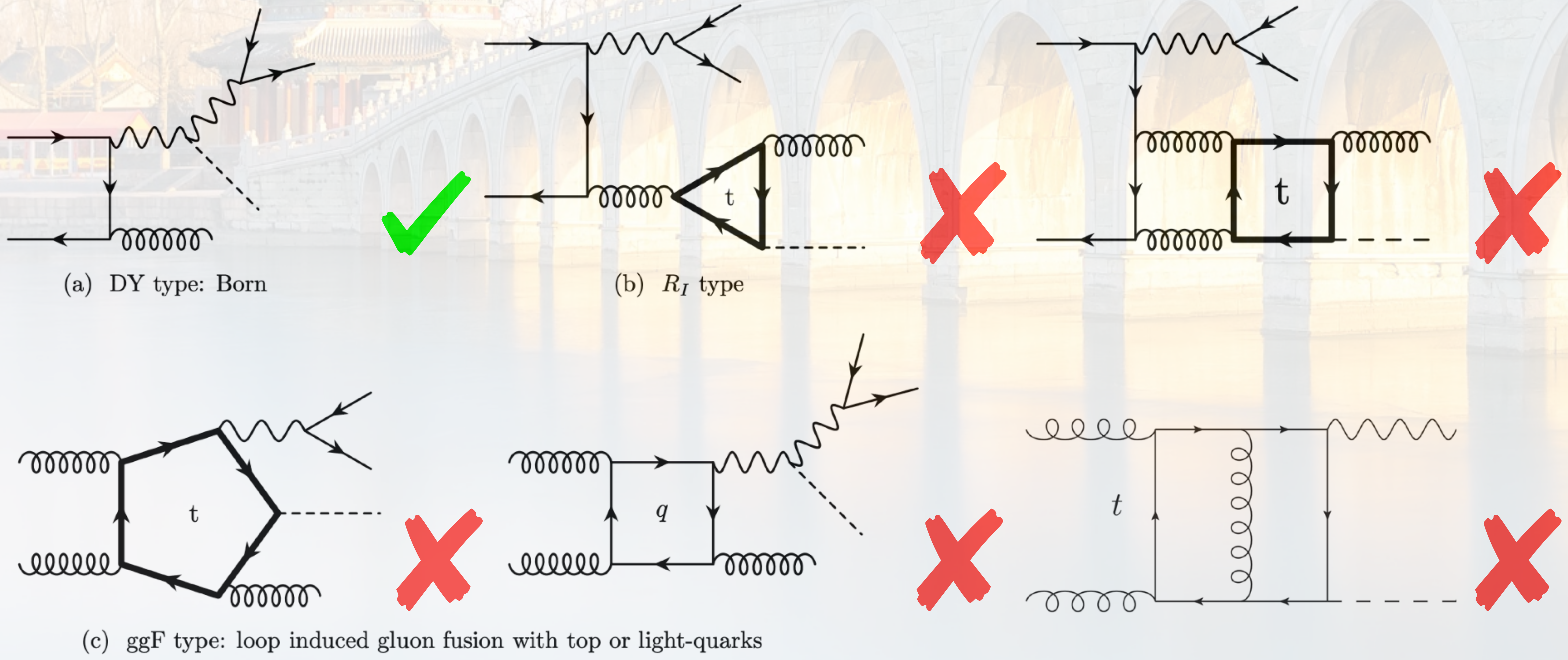

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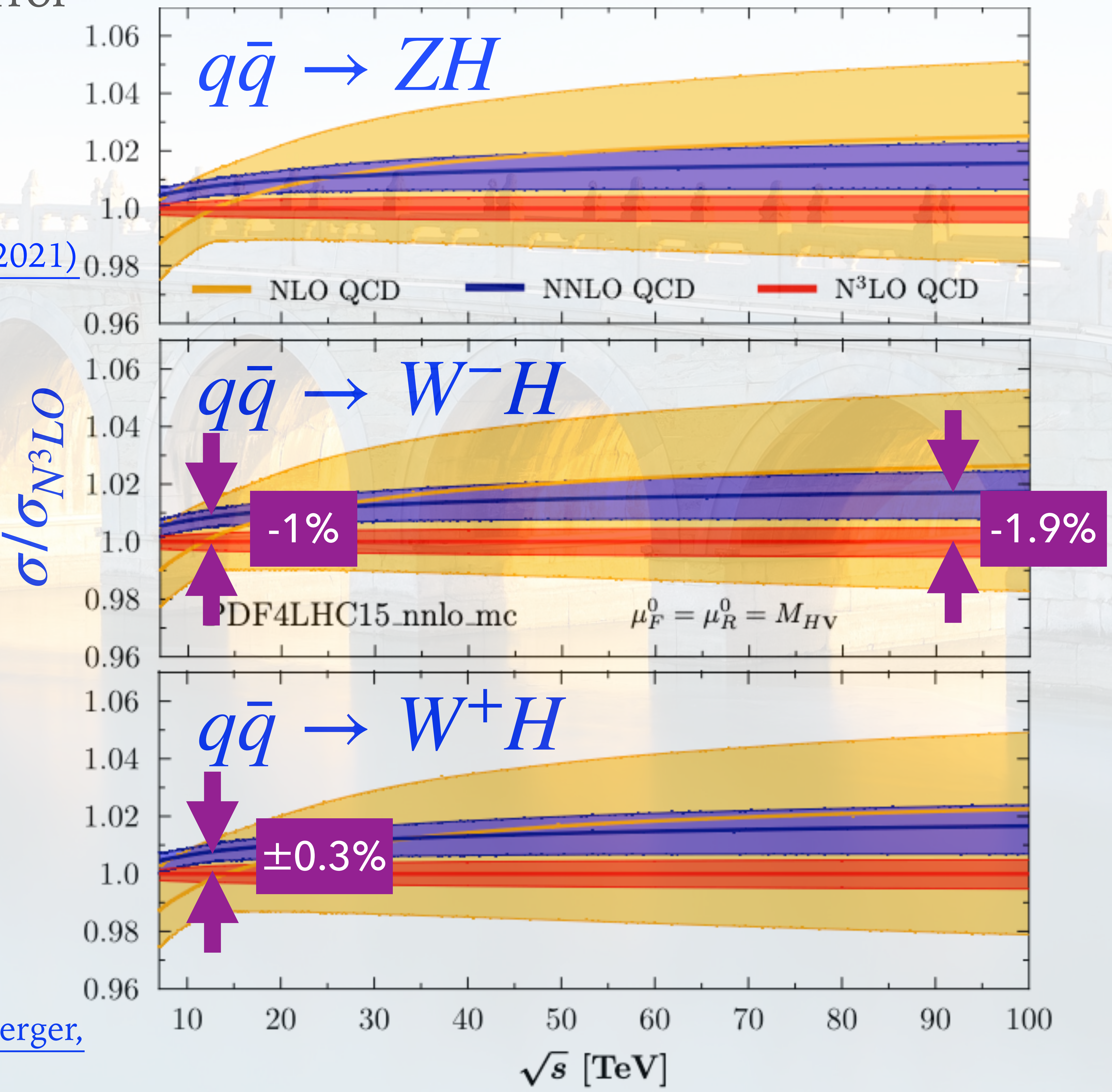

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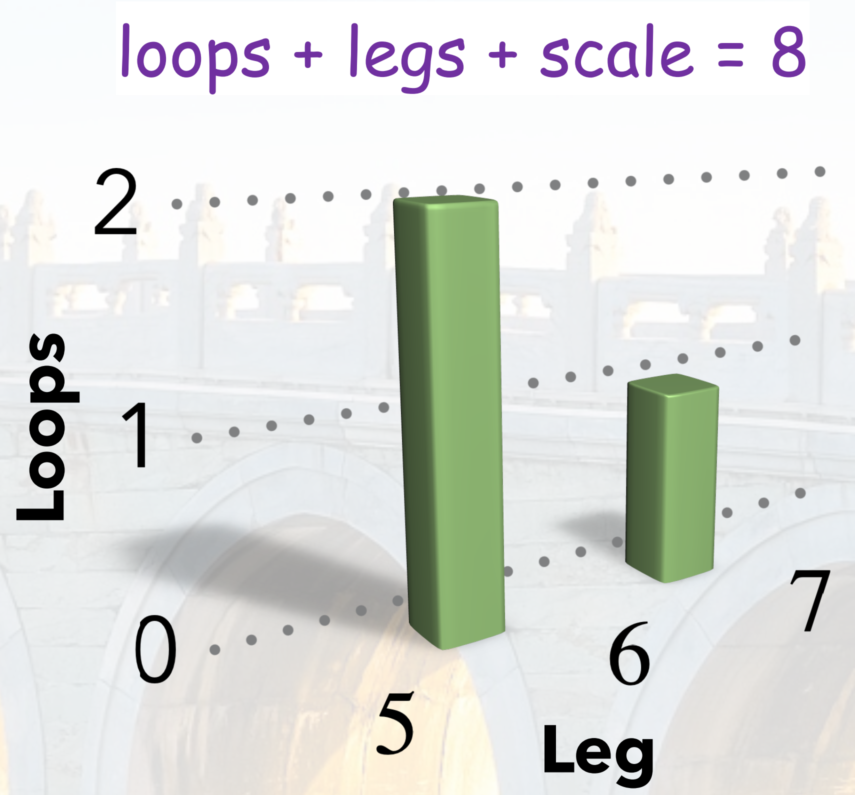
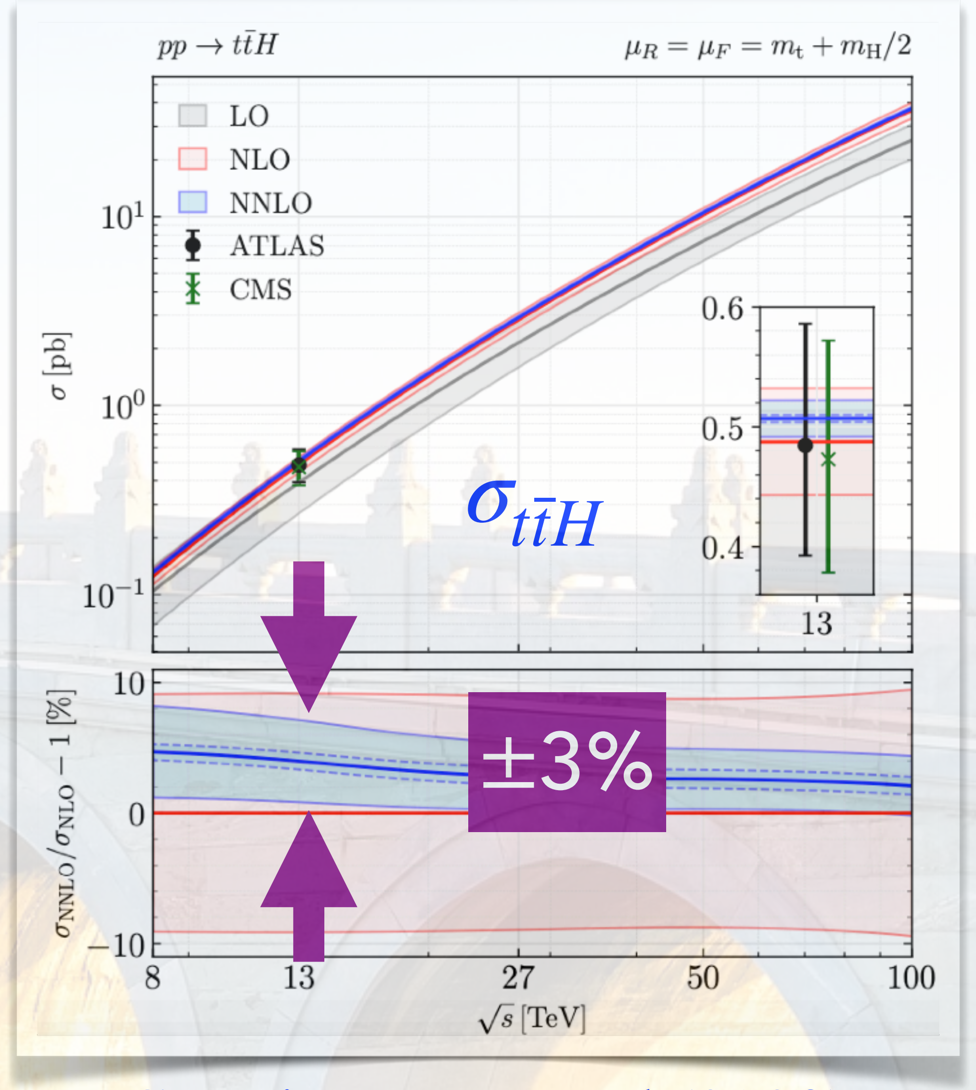
ttH Production

$pp \to \; t\bar{t}H$ @NNLO + NNLL QCD + NLO EW

More details in Simone Devoto's talk

- Rapid progress of NNLO QCD corrections to $2 \to 3$ scattering at the LHC
  - Automation of tree and 1-loop scattering ME with OpenLoops.
  - IR pole structure at 2-loop: Chen, Ma, Wang, Yang, Ye (2022)
  - Processes dependent approximation for 2-loop-5-leg ME with 1 mass scale:
    - Soft approximation to estimate $Ht\bar{t}gg$, $Ht\bar{t}q\bar{q}$ @ 2-loop
  - Mature machinery of NNLO qT-slicing in MATRIX Catani, Devoto et al (2023)





Catani, Devoto et al (2023)

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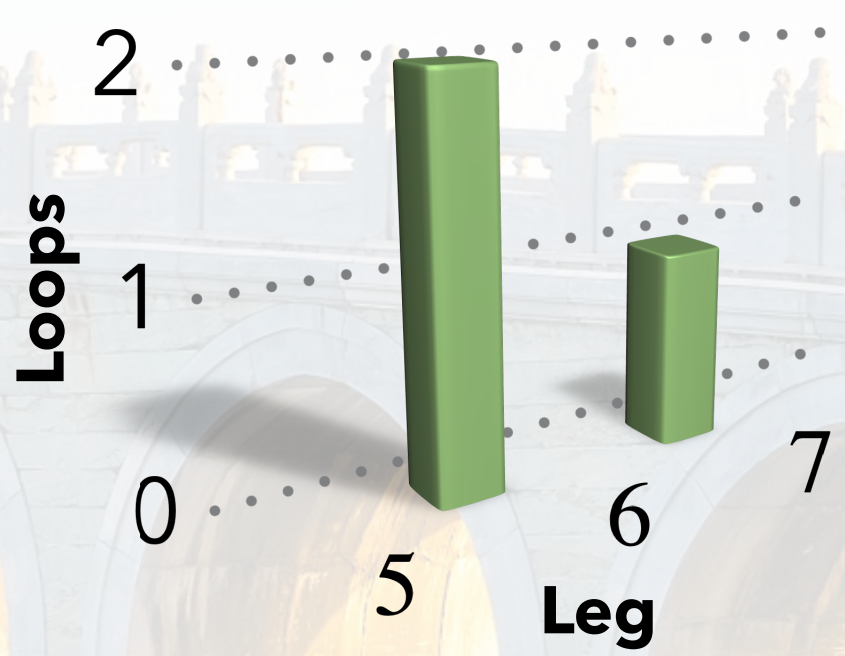
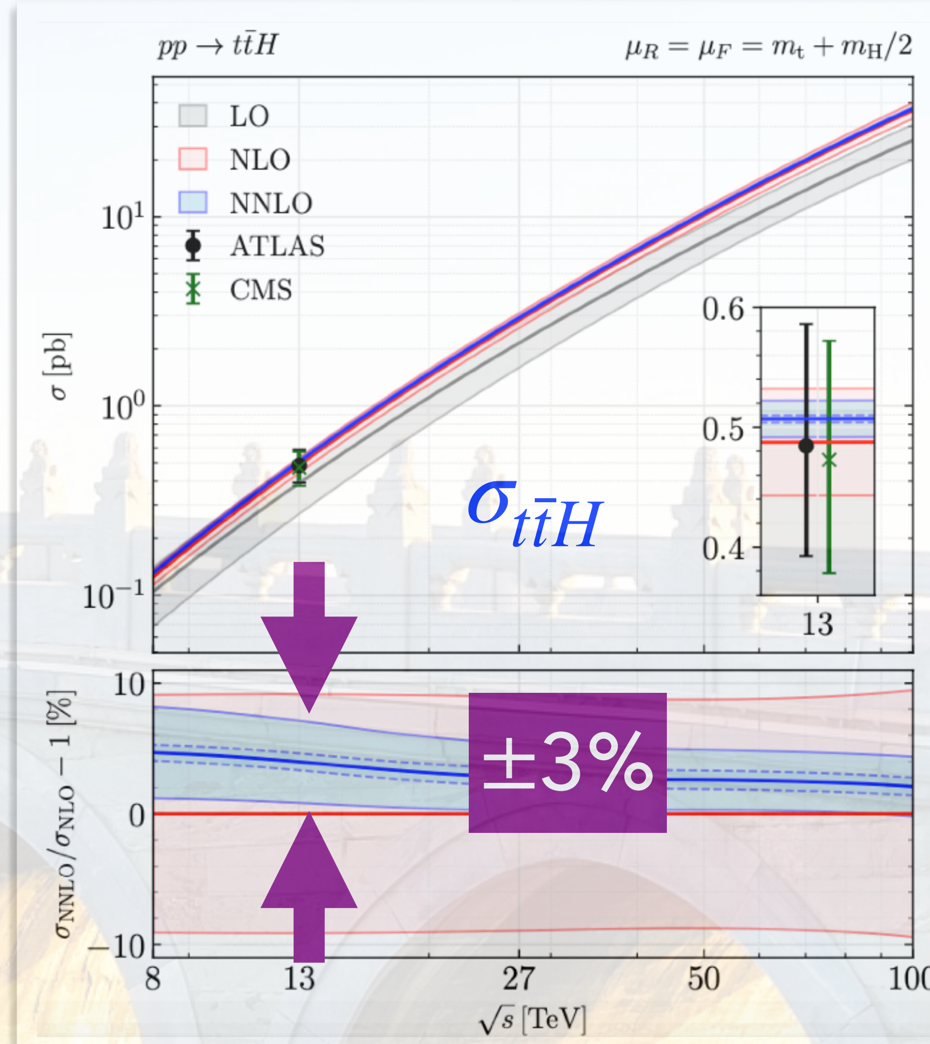
loops + legs + scale = 8





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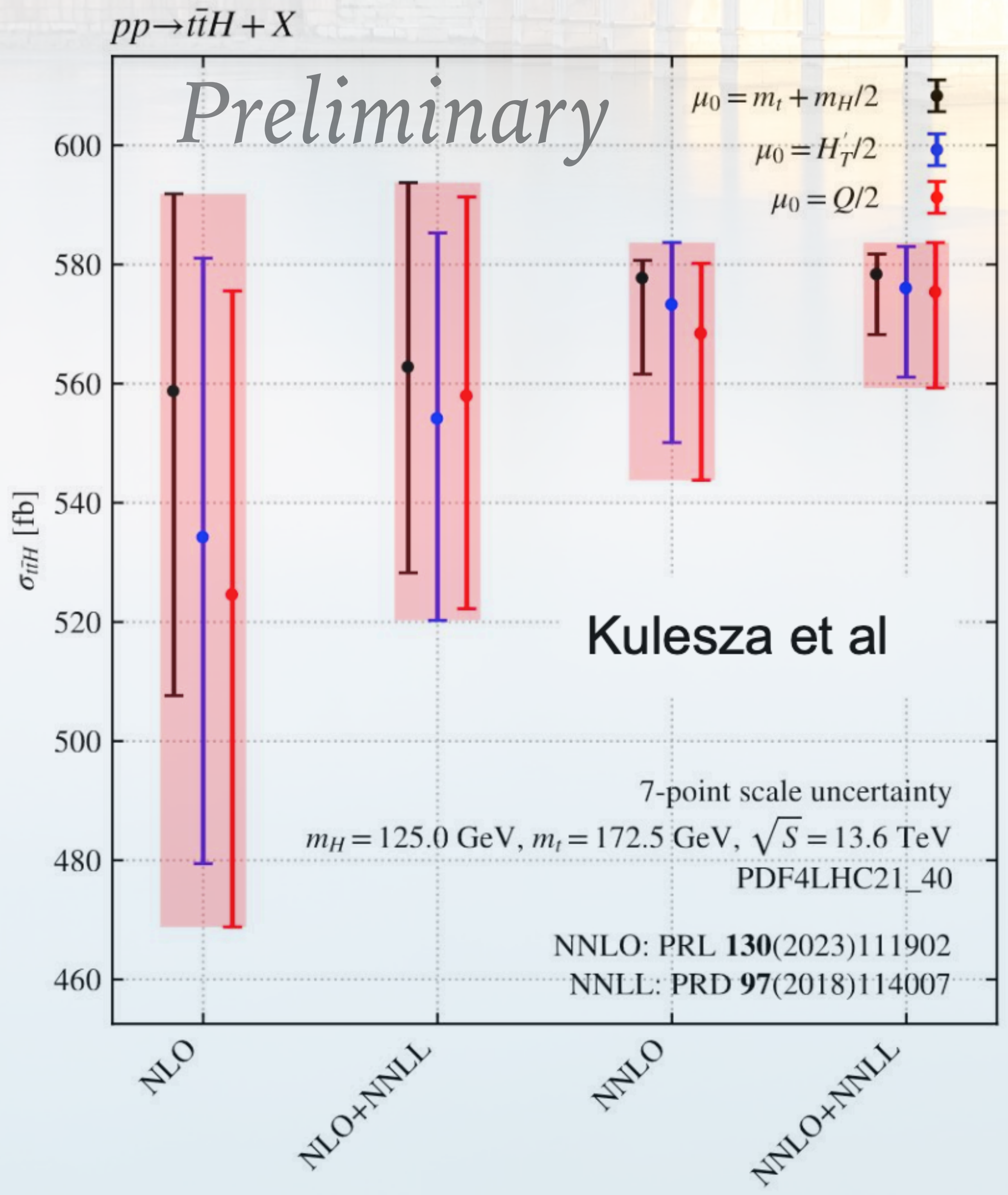
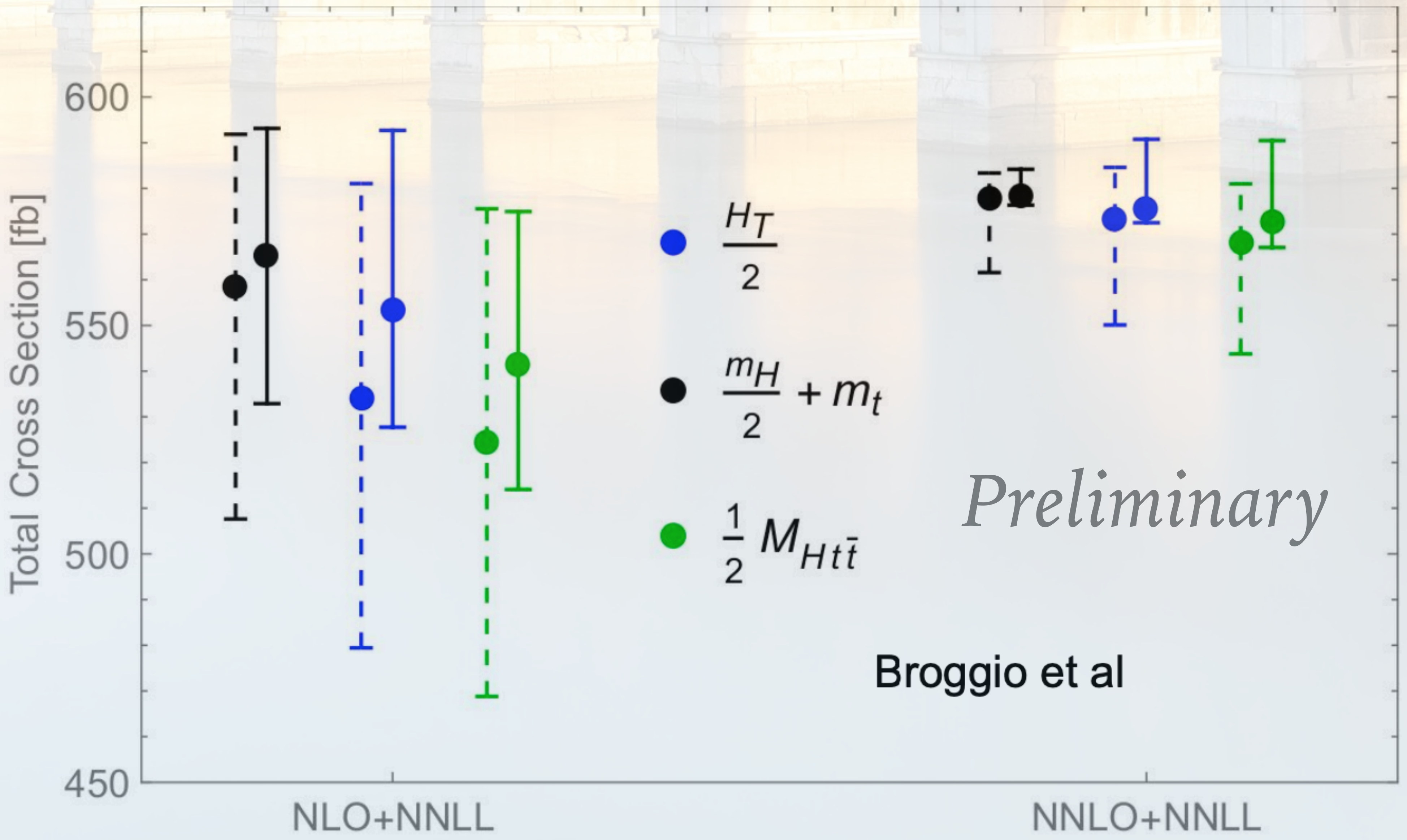




S. Sánchez Cruz @ HWG 23

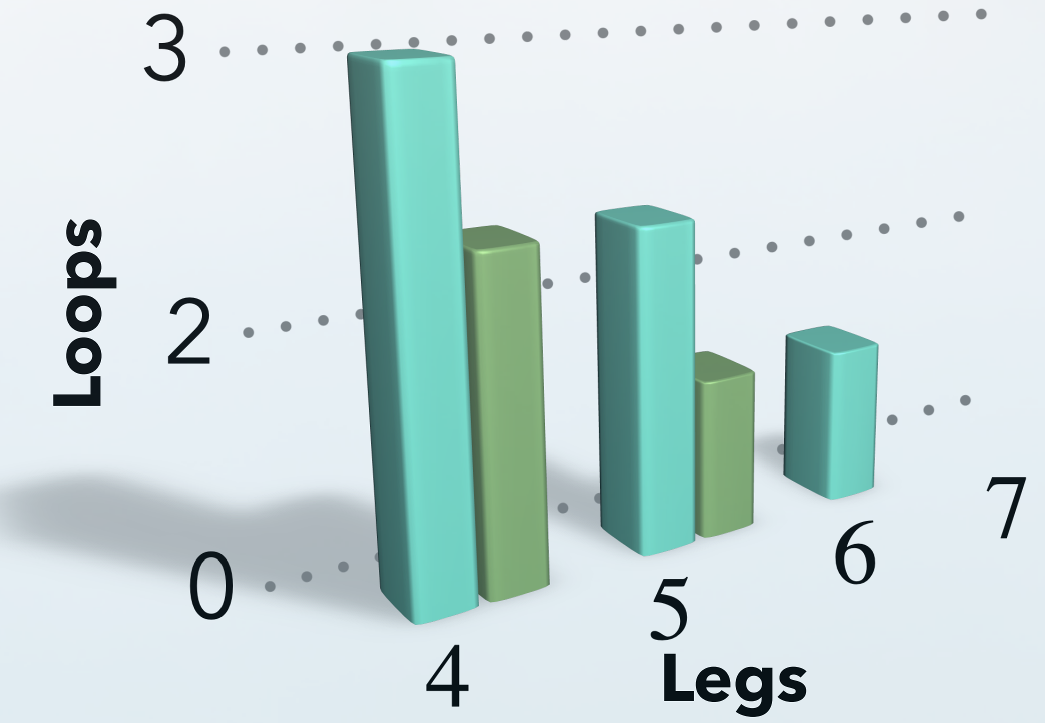
- Combined with NNLL QCD + NLO EW: Broggio, Ferroglia et al (2019), Kulesza, Motyka et al (2020)
  - see also high energy EW correction in Pagani et al (2023)
- Combined effort at 13.6 TeV in HWG:
  - Two resummation collaborations
  - Three different central scales
  - Contribute 0.58 pb ~ 1% to Higgs XS

HH Production

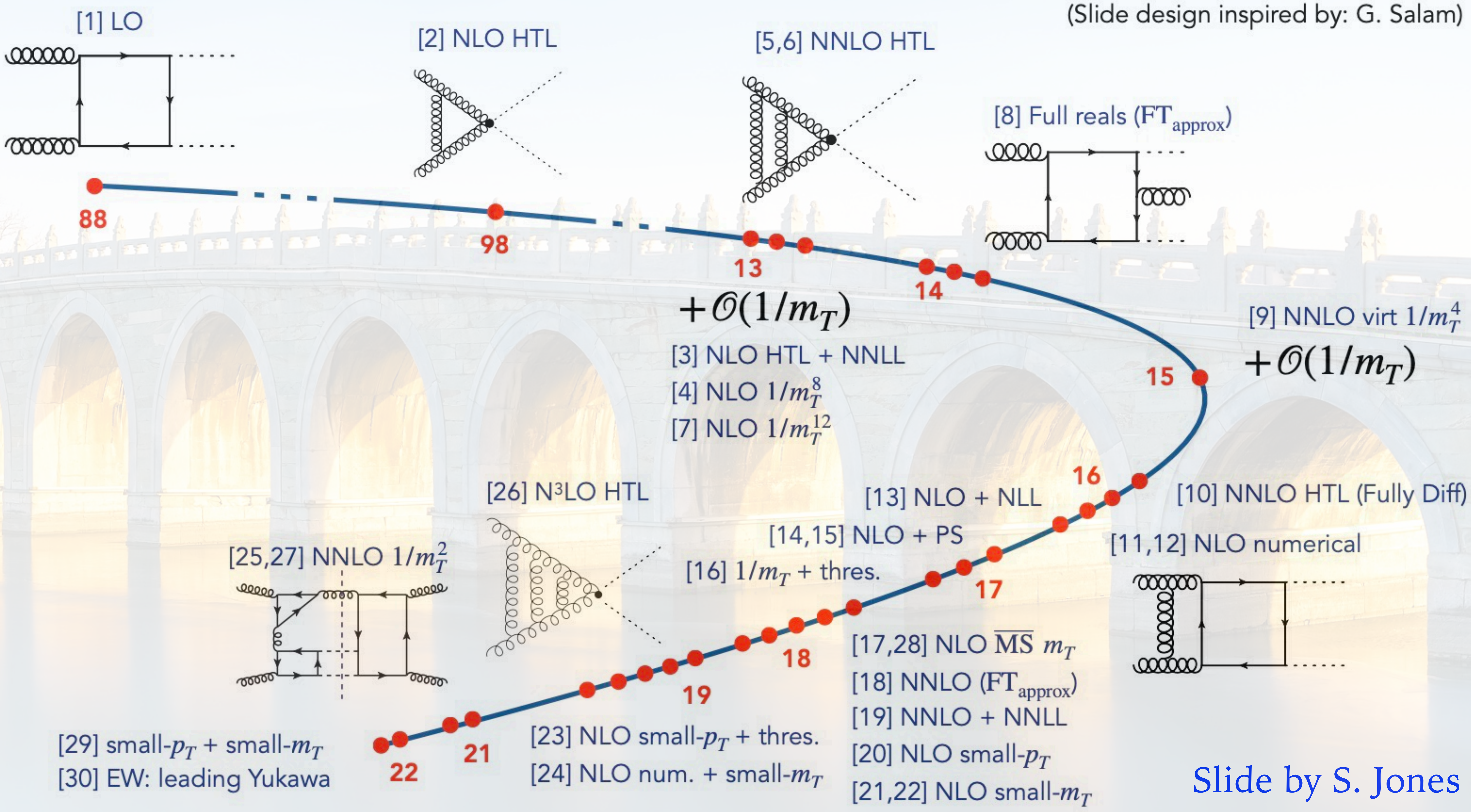
- $pp \to HH$ theory history in 35 years
  - LLS complexity from 6 to 9
  - State-of-the-art accuracy at 13 TeV:
    - NNLO QCD $\mathrm{FT}_{\mathrm{approx.}}$ fiducial $\sim 5\%$
    - N3LO QCD HTL total $\sim 3\%$
    - Large NLO m_T scheme dependence
    - Partial NNLO QCD ME know: Davies, Schönwald, Steinhauser (2023)
    - NLO EW corrections: Davies, Schönwald, Steinhauser, Zhang (2023)

More details in H.T. Zhang's talk

loops + legs + scale = 8-9



(Slide design inspired by: G. Salam)

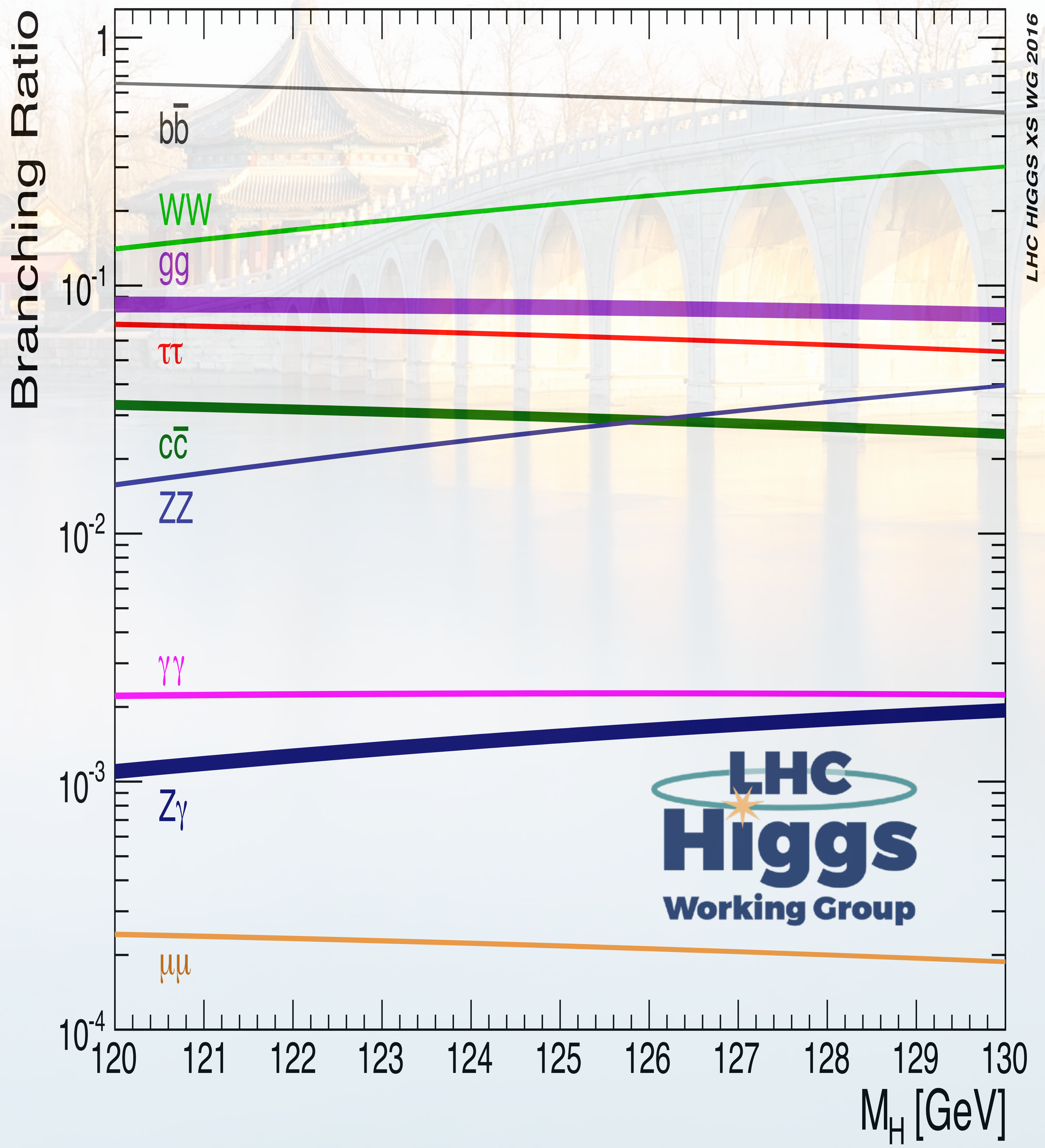


Slide by S. Jones

[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22; [30] Davies, Mishima, Schönwald, Steinhauser, Zhang 22;

Higgs Boson Decay

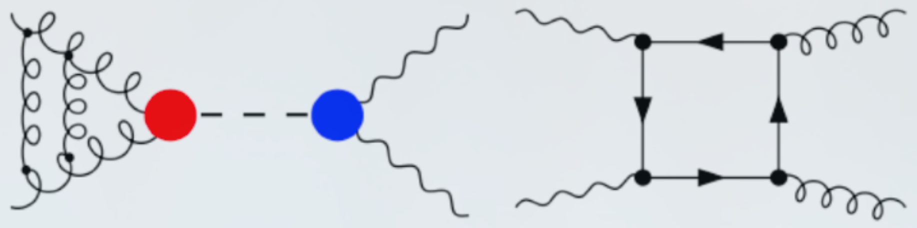
- Higgs decay branch ratio (YR4):
  - $\Gamma_H^{tot} \sim$ 4 MeV for all Higgs Factories



- Dominant $H \to b\bar{b}$
  - Inclusive BR known at N4LO: Baikov, Chetykin, Kuhn (2005), Herzog et al (2017), Davies et al (2017)
    $\sim \pm 0.15\%$ scale error for $\mu \in [0.1,10] \times m_H$
  - Differential BR known at N3LO $\sim \pm 0.7\%$: Mondini, Schiavi, Williams (2019)
  - Additional 1% (15%) contribution for top induced $b\bar{b}$ ($c\bar{c}$) decay at N3LO: Mondini, Schubert, Williams (2020)
  - Need IR safe flavour tagging (anti-kT is NOT)
- $H \to gg$ BR known at N4LO $\sim \pm$ 3%: Davies et al (2017), Herzog et al (2017)

More details in L. Chen's talk

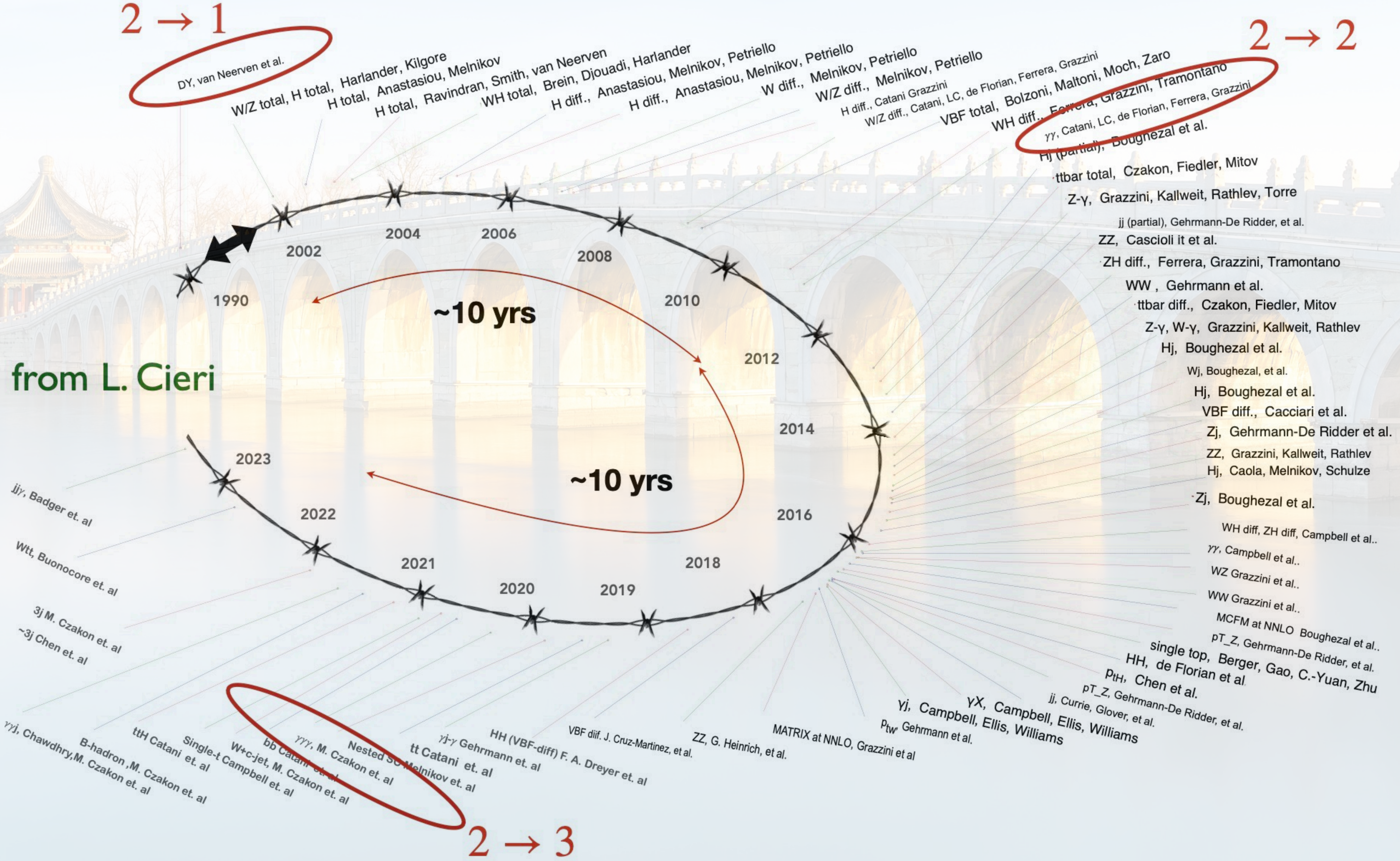
- $H \to W^+W^-$
  - Mixed QCD-EW at 2-loop contribute 0.2~1% depending on EW schemes: Ma, Wang, Xu, Yang, Zhou (2021)
- $H \to Z\gamma, ZZ$
  - Mixed QCD-EW correction (2-loop triangle) Wang, Xu, Yang (2019)
- $H \to \gamma\gamma$ interference at NNLO$_{SV}$
  - $gg \to H \to \gamma\gamma \times gg \to \gamma\gamma$ background
  - -2% destructive contribution to $\sigma_{H\to\gamma\gamma}$



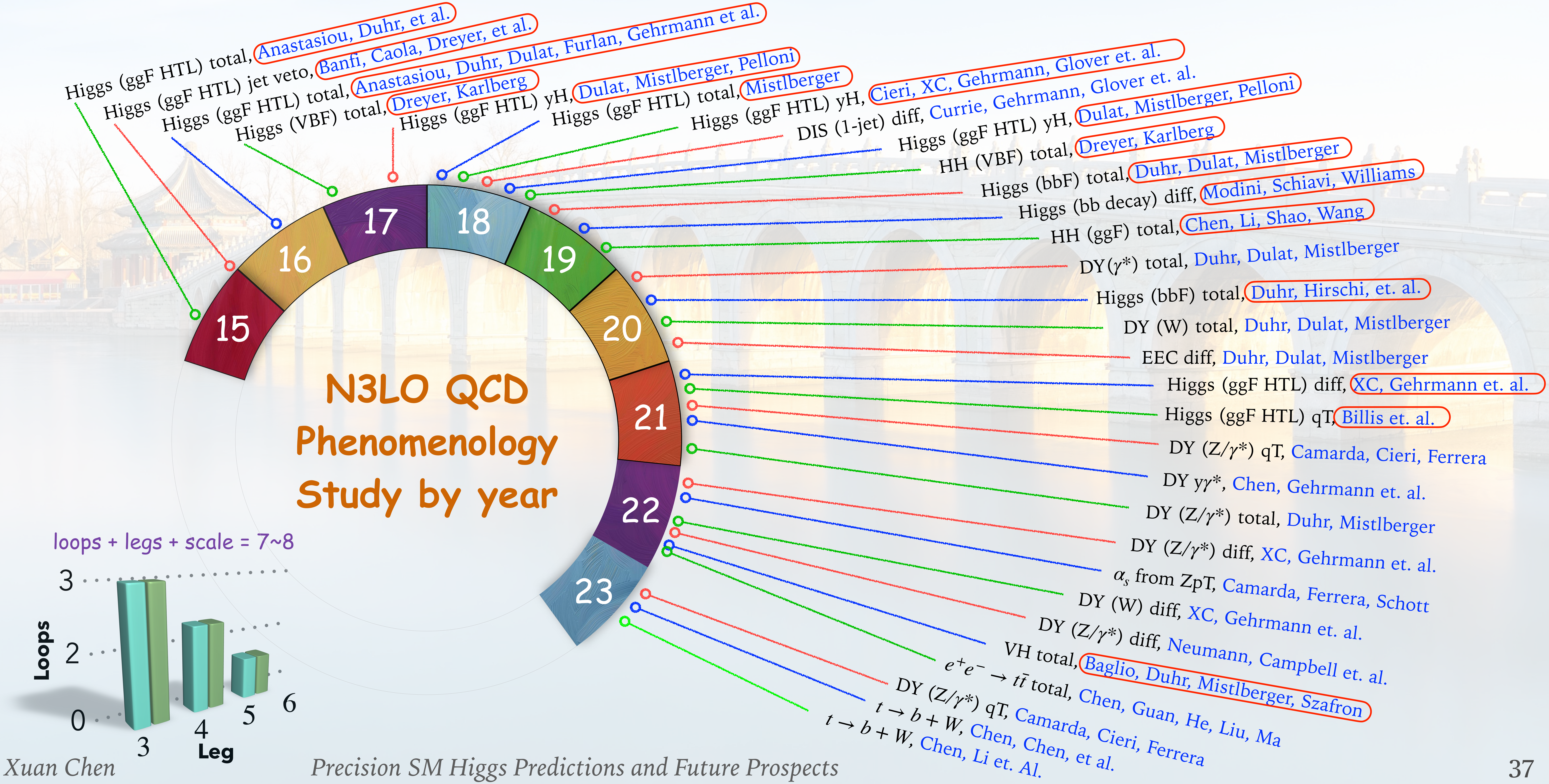
Bargiela, Buccioni et al (2022)

Future Prospects

Perturbative QCD @ NNLO



Perturbative QCD @ N3LO



FUTURE PROSPECTS

- Precision is not the ultimate goal → identify anomaly then understand
- The most famous **failed experiment**: Michelson–Morley in 1887,  foundation of special relativity. → 1907 Nobel Prize to Albert A. Michelson .
- "… it seems probable that **most of the grand underlying principles have been firmly established** and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice. … An eminent physicist remarked that **the future truths of physical science are to be looked for in the sixth place of decimals.**" —— Albert A. Michelson, 1894 University of Chicago
- Mass origin, Higgs potential, EW vacuum metastability etc.

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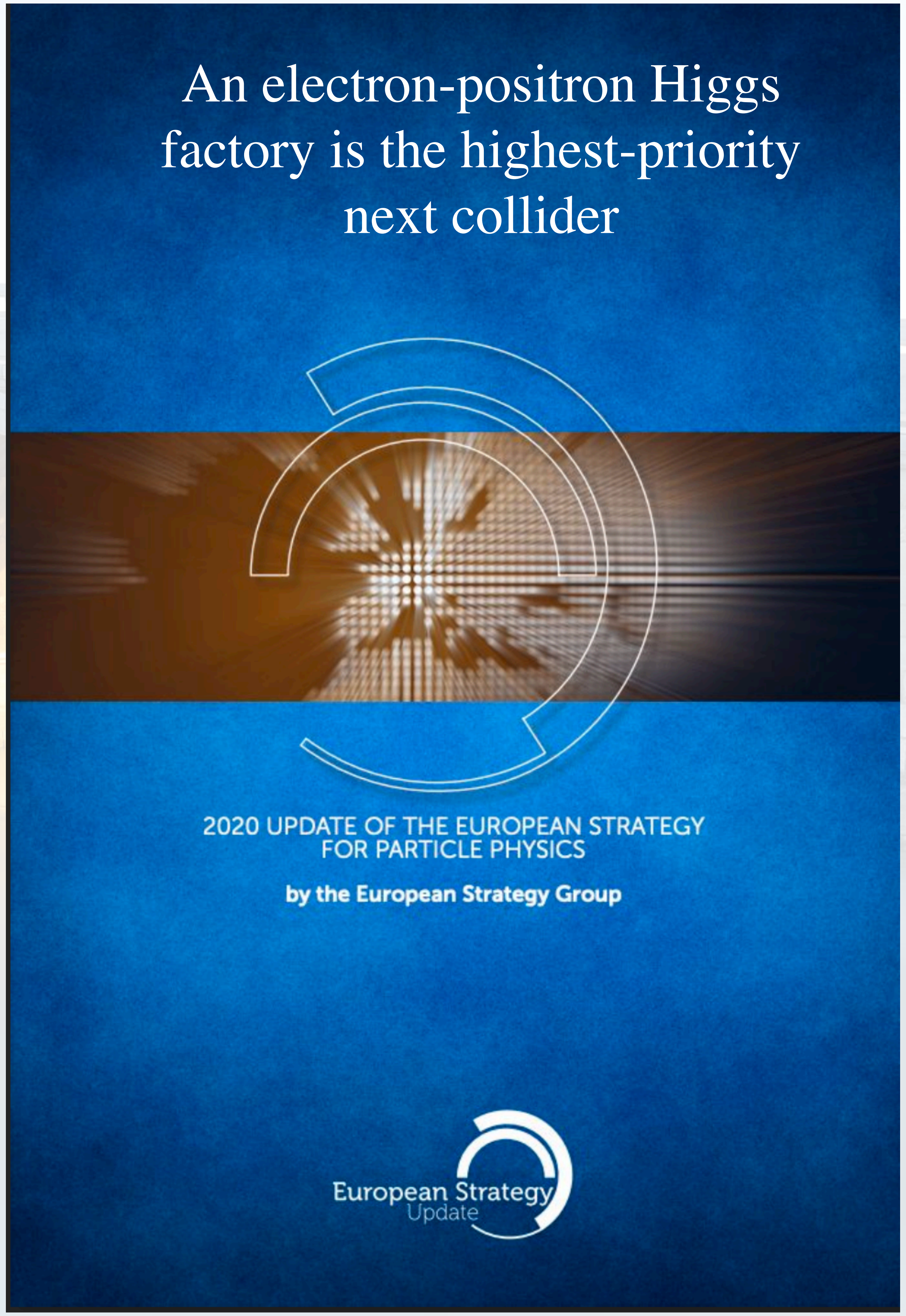

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- Higgs Yellow Report 5 planned at 2025, publication style, not monolithic

Yellow Report 5

- Four Yellow Reports produced by the LHC Higgs WG over its lifetime:
  - *'Inclusive Observables'* [CERN-2011- 002]
  - *'Differential Distributions'* [CERN-2012-002]
  - *'Higgs Properties'* [CERN-2013-004]
  - *'Deciphering the Nature of the Higgs Sector'* [CERN-2017-002]
- HL-LHC data-taking will start in 2029. Aim to collect 1000 fb^{-1} data during Run 4 (2029–2032).
  - What can we achieve with this dataset?
  - What recommendations are needed for analyses?
  - **Plan to collect this information in a new Yellow Report 5.**

Towards Yellow Report 5

- YR5 preferably not monolithic, rather many separate reports; could be published in a dedicated *SciPost Physics Community Reports* Volume
- Time scale ~2025, focus on Run 4 of HL-LHC (1000 fb^{-1}) and include Run 3 results as far as available
- Predictions should be reproducible (ideally provide runcards)
- Initial brainstorming for experimental wishlist with ATLAS and CMS Higgs/HDBS convenors in July 2023

G. Heinrich @ HWG 23

Thank You for Your Attention

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

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

FO	α_s^n	$P_{ab}^{(n)}(x)$	$\ln W(x_a, x_b, m_V, \vec{b}, \mu = b_0/b) \sim \int_{\mu_h}^{\mu} d\bar{\mu}/\bar{\mu}\left(A(\alpha_s(\bar{\mu}))\ln\frac{m_V^2}{\bar{\mu}^2} + B(\alpha_s(\bar{\mu}))\right)$						
$\frac{d\hat{\sigma}^V_{NLO}}{dq_T}$	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

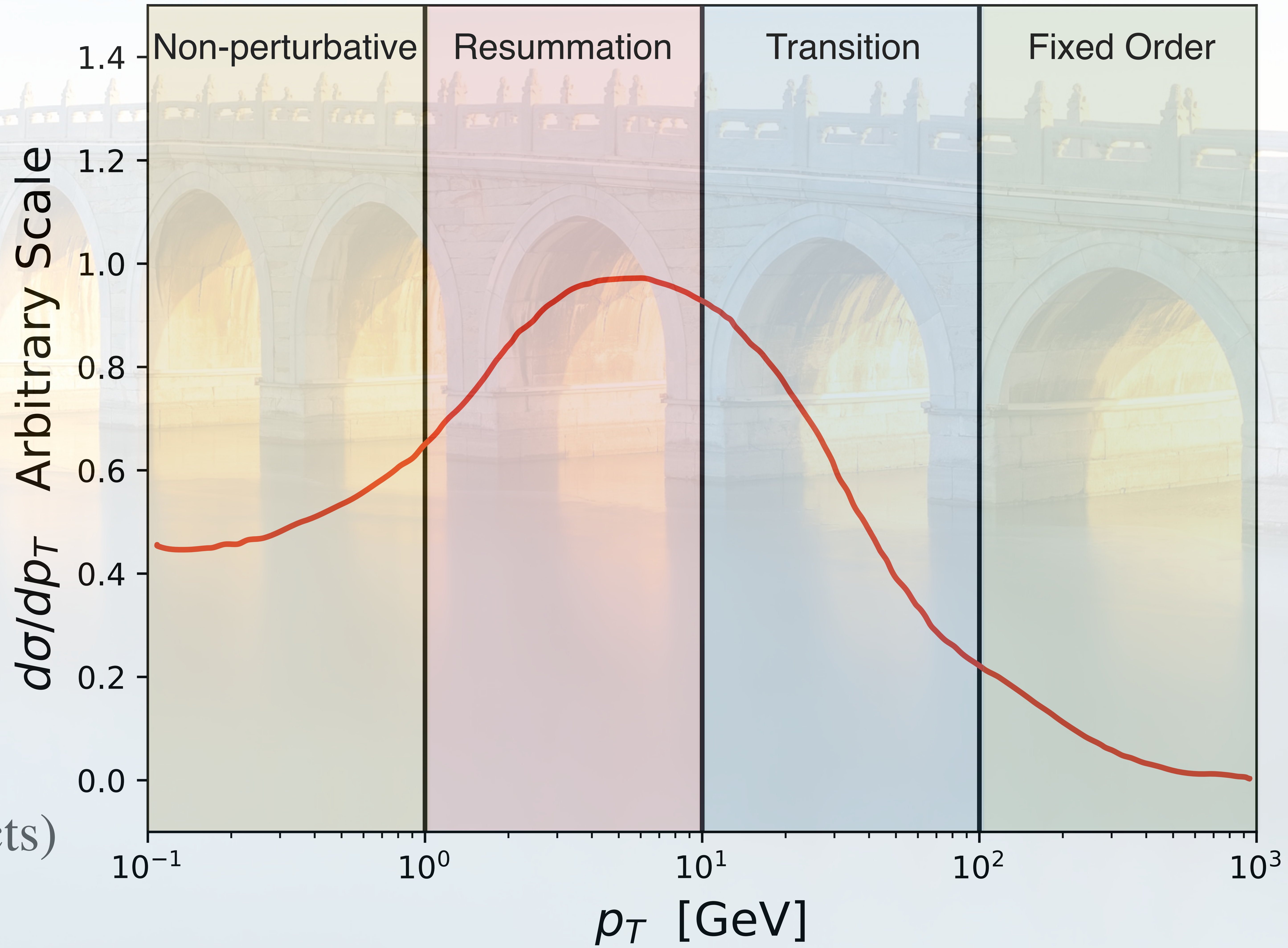
$$\ln\frac{p_T}{Q} \text{ as } p_T \to 1 \text{ GeV}$$

➤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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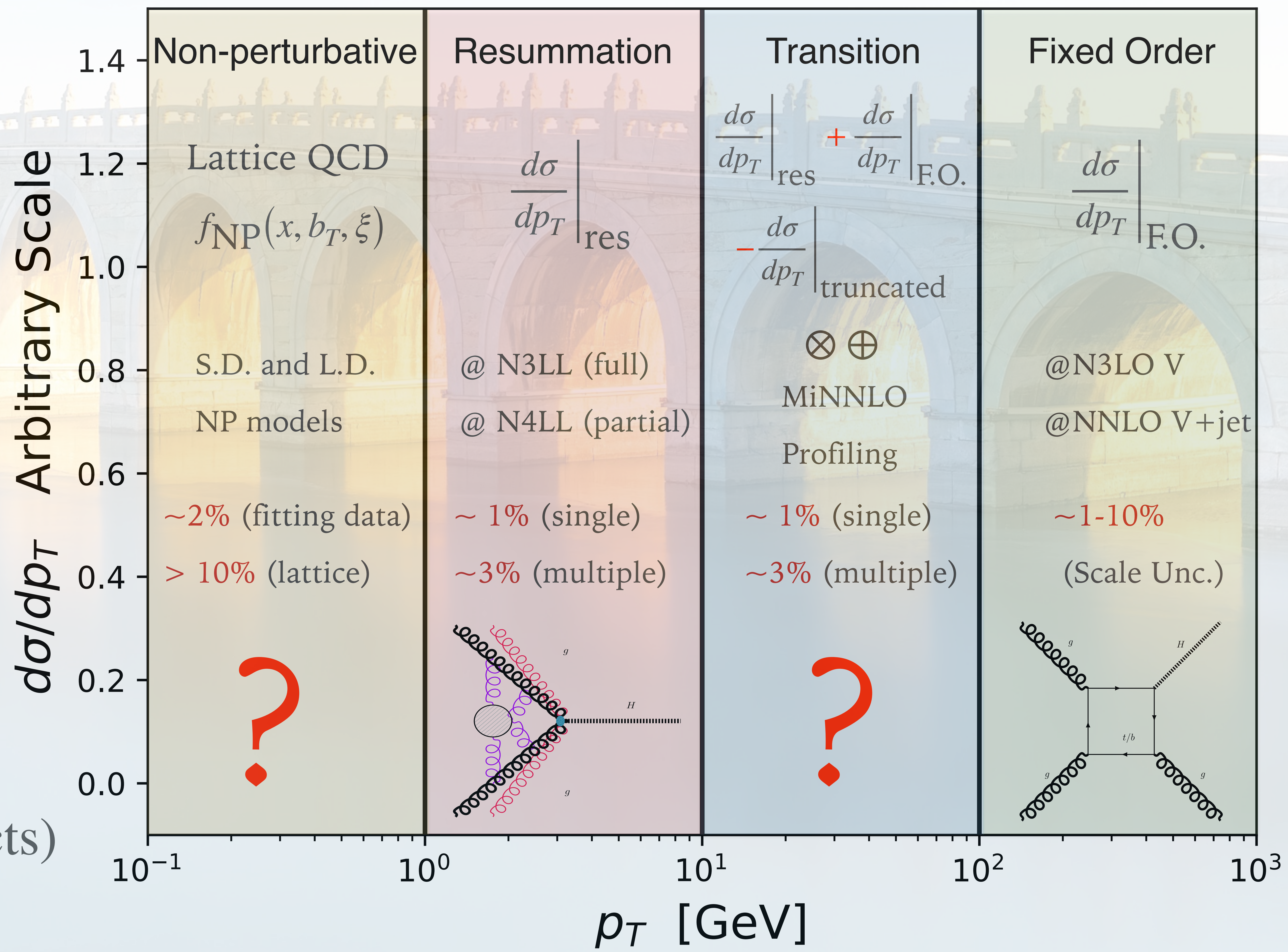

Anatomy of differential cross sections $d\hat{\sigma}_{ab}$

- 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:

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

  - 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:

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