MAX-PLANCK-INSTITUT
FÜR PHYSIK

Arts and craft of precision physics

Chiara Signorile-Signorile

On behalf of Director G. Zanderighi's group

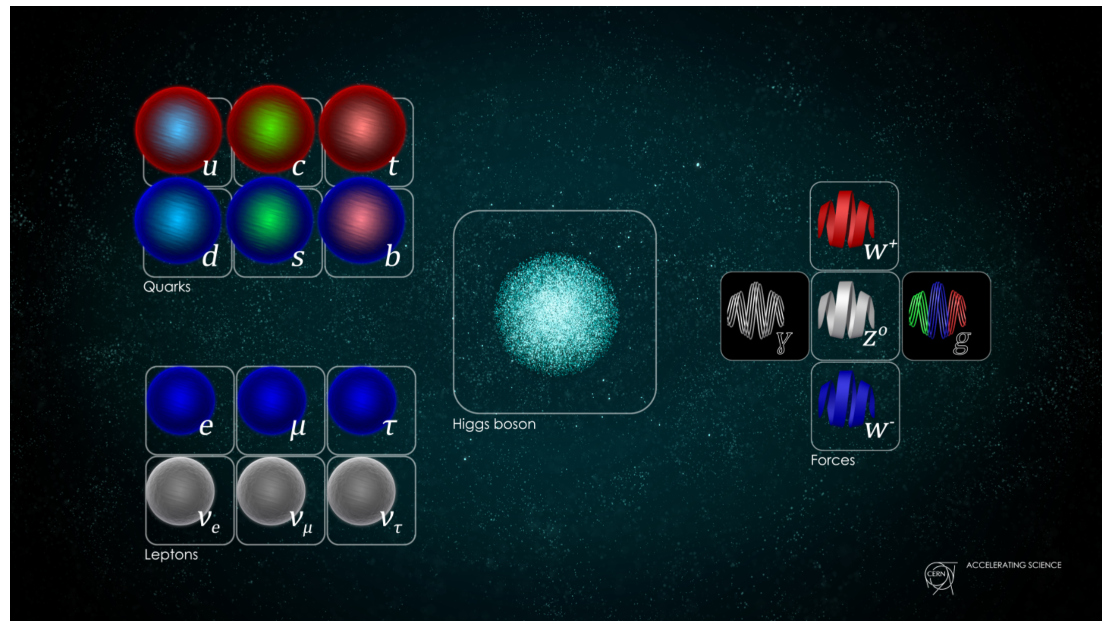
A universe in two lines

The Standard Model

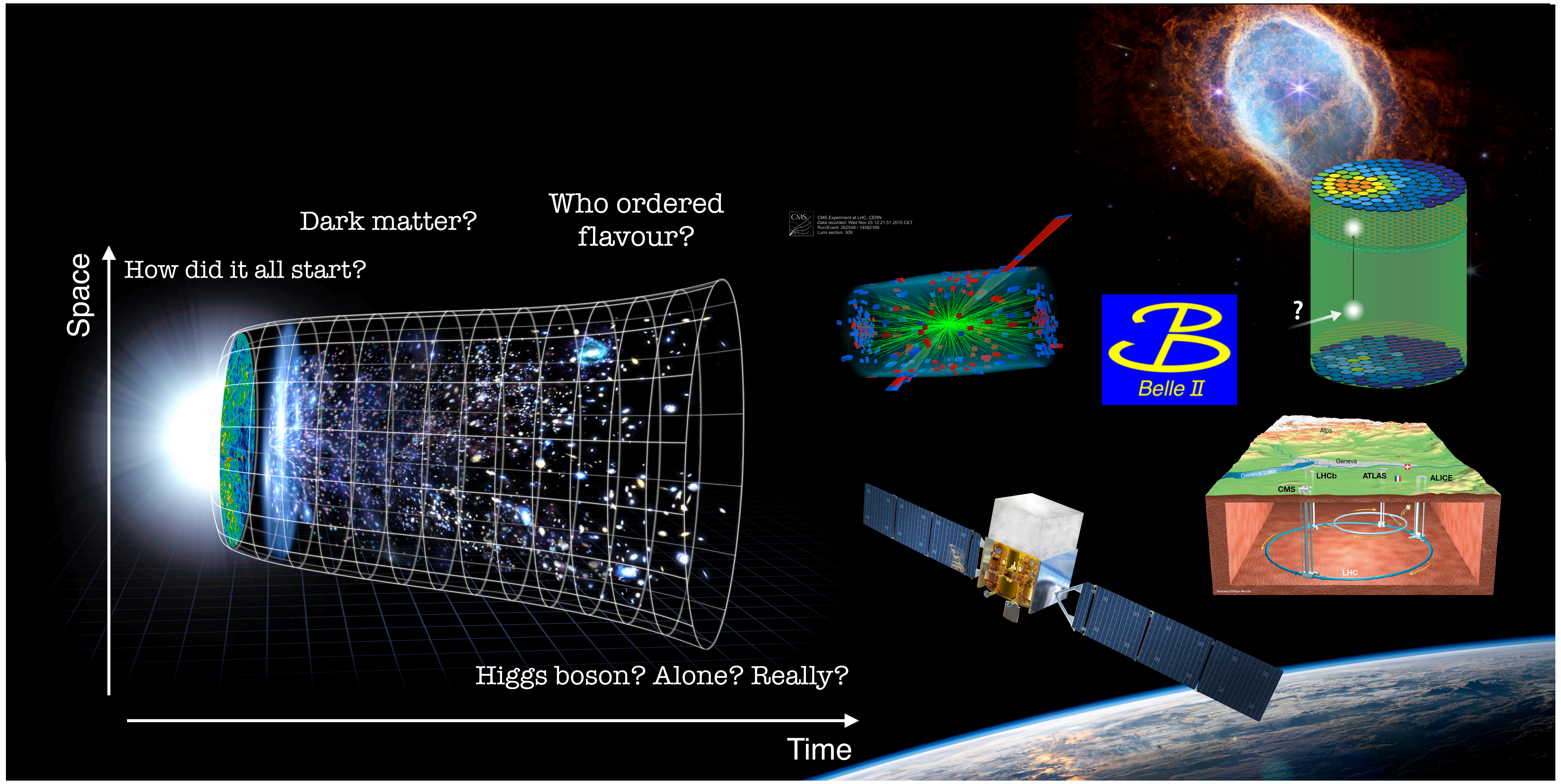
- **Standard Model** (SM) of particle physics gives us the **"code of the Universe"** through a compact formula

$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}W_{\mu\nu}\cdot W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^{\alpha}_{\mu\nu}G^{\mu\nu}_{\alpha}}_{\text{kinetic energies and self-interactions of the gauge bosons}} + \underbrace{\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)L + \bar{R}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g'YB_{\mu}\right)R}_{\text{kinetic energies and electroweak interactions of fermions}}$$

$$+ \underbrace{\frac{1}{2}\left|\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)\phi\right|^{2} - V(\phi)}_{W^{\pm},Z,\gamma \text{ and Higgs masses and couplings}} + \underbrace{g''\left(\bar{q}\gamma^{\mu}T_{a}q\right)G^{\alpha}_{\mu}}_{\text{interactions between quarks and gluons}} + \underbrace{\left(G_{1}\bar{L}\phi R + G_{2}\bar{L}\phi_{c}R + h.c.\right)}_{\text{fermion masses and couplings to Higgs}}$$



- The SM explains outcomes of most current terrestrial experiments and many aspects of the evolution of the Universe (add a grain of gravity!).
- However, many questions remain unresolved.
- **The main goal of the particle physics community is to test the SM as thoroughly as possible and, eventually, find physics beyond it.**

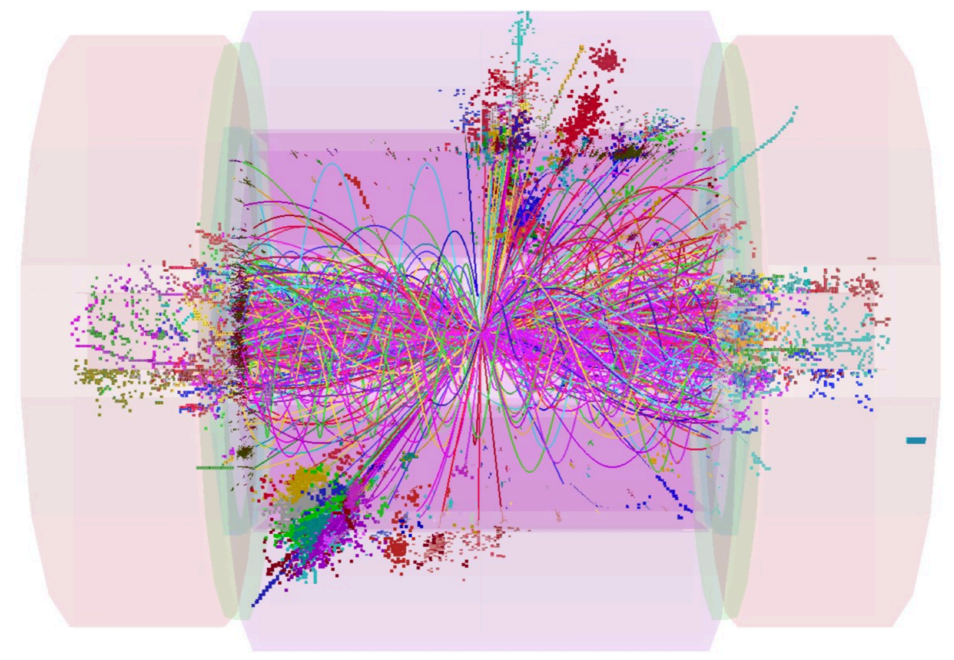


Being more realistic…

❖ One key aspect of this search is related to collider physics, where **increasing precision requires experimental improvements, but also advances in our understanding of the fundamental underlying theory.**

$$
\begin{aligned}
\mathcal{L} &= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
&+ i\bar{\psi}\not{D}\psi + h.c \\
&+ \psi_i y_{ij}\psi_j\phi + h.c \\
&+ |D_\mu\phi|^2 - V(\phi)
\end{aligned}
$$

Quantitative connections through a chain of experimental and theoretical links, based on a profound understanding of quantum fluctuations



❖ **The core idea behind our research:**

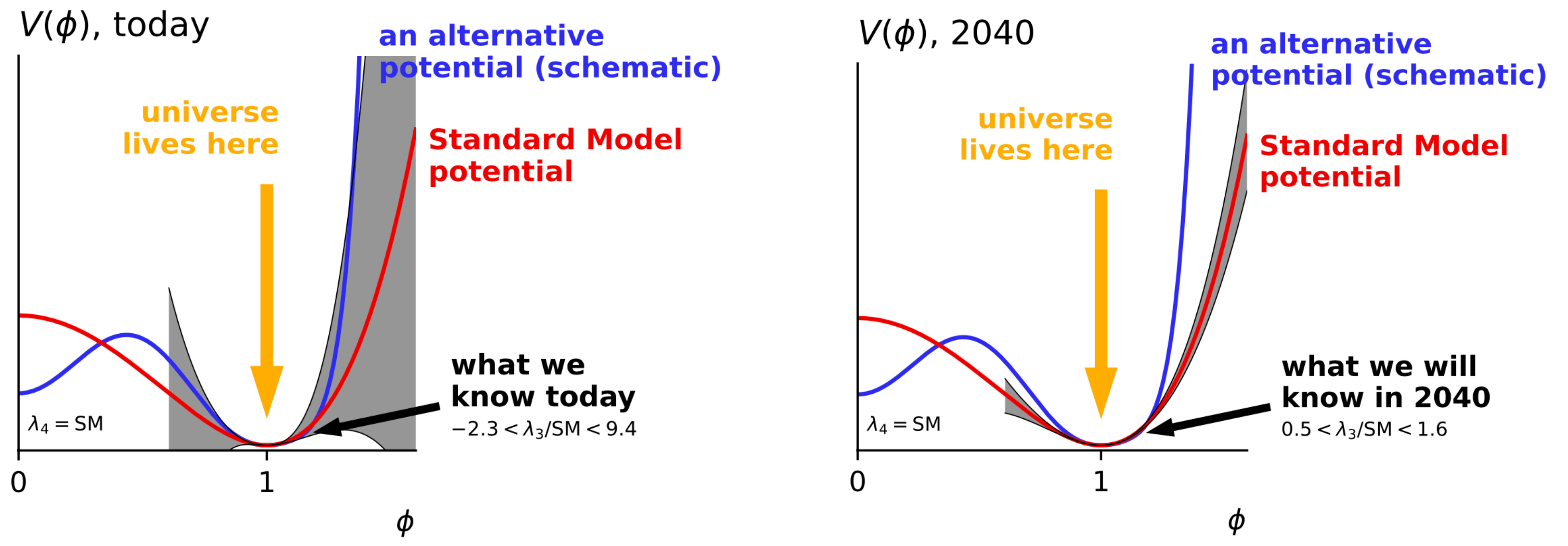
A. **Develop methods to obtain high precision* theoretical predictions.**

B. **Exploit these methods** for a wide range of **phenomenological studies** to improve our **knowledge of the SM (and its possible extensions).**

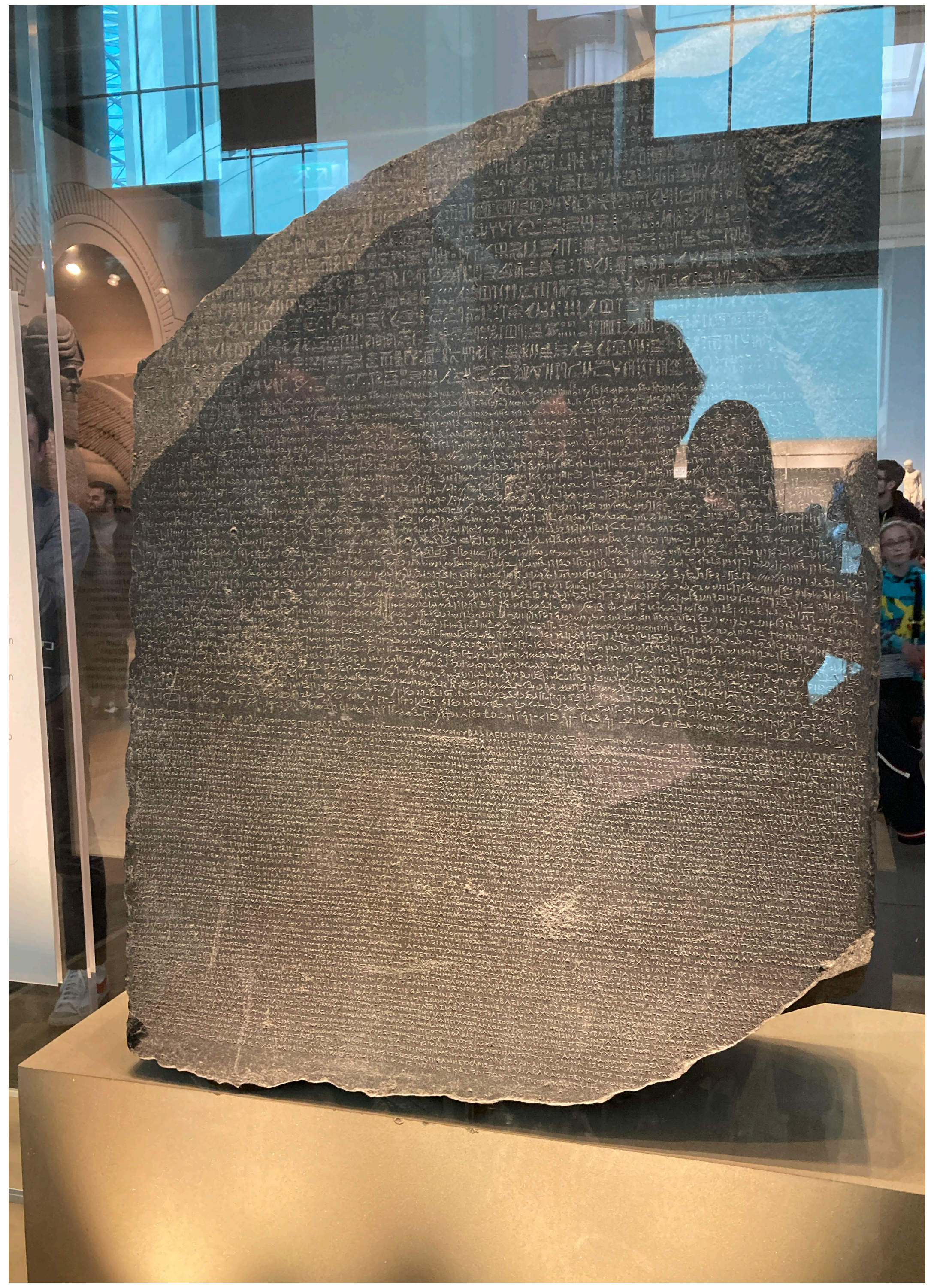
***precision is not simply an academic exercise, it can really change the game**

The Higgs potential may determine the fate of the universe!

Salam, Wang, Zanderighi [2207.00478]



With technical projects come technical notation



A. Expansion in the strong coupling constant (high energy scale effects)

$$d\sigma = d\sigma_{\mathrm{LO}} + \alpha_s\, d\sigma_{\mathrm{NLO}} + \alpha_s^2\, d\sigma_{\mathrm{N^2LO}} + \alpha_s^3\, d\sigma_{\mathrm{N^3LO}} + \dots$$

We refer to this kind of expansion as “fixed order calculation” at N^xLO

B. Joint expansion in strong coupling and logarithmic contributions (low energy scale effects)

$$\mathscr{P} \simeq -\#\alpha_s \ln^2 \frac{Q}{p_T} + \mathcal{O}(\alpha_s^2) \to \exp\left[-\sum_{n,m} \alpha_s^n \ln^m \frac{Q}{p_T}\right]$$

$m = n + 1$ → Leading Logs (LL)
$m = n$ → Next-To-LL (NLL)
$m = n - 1$ → Next-To-NLL (NNLL) . . .

We refer to this kind of expansion as N^yLL

NLO+PS$_{LL}$

NNLO+PS$_{LL}$

Problem: Match fixed-order predictions with parton shower avoiding an unphysical matching scale.

- **POWHEG** [0409146, 0709.2092, 1002.2581]
- **MiNLO’** [1212.4504]
- **MiNNLO$_{\mathrm{PS}}$** [1908.06987]
  - in the POWHEG framework

LHC

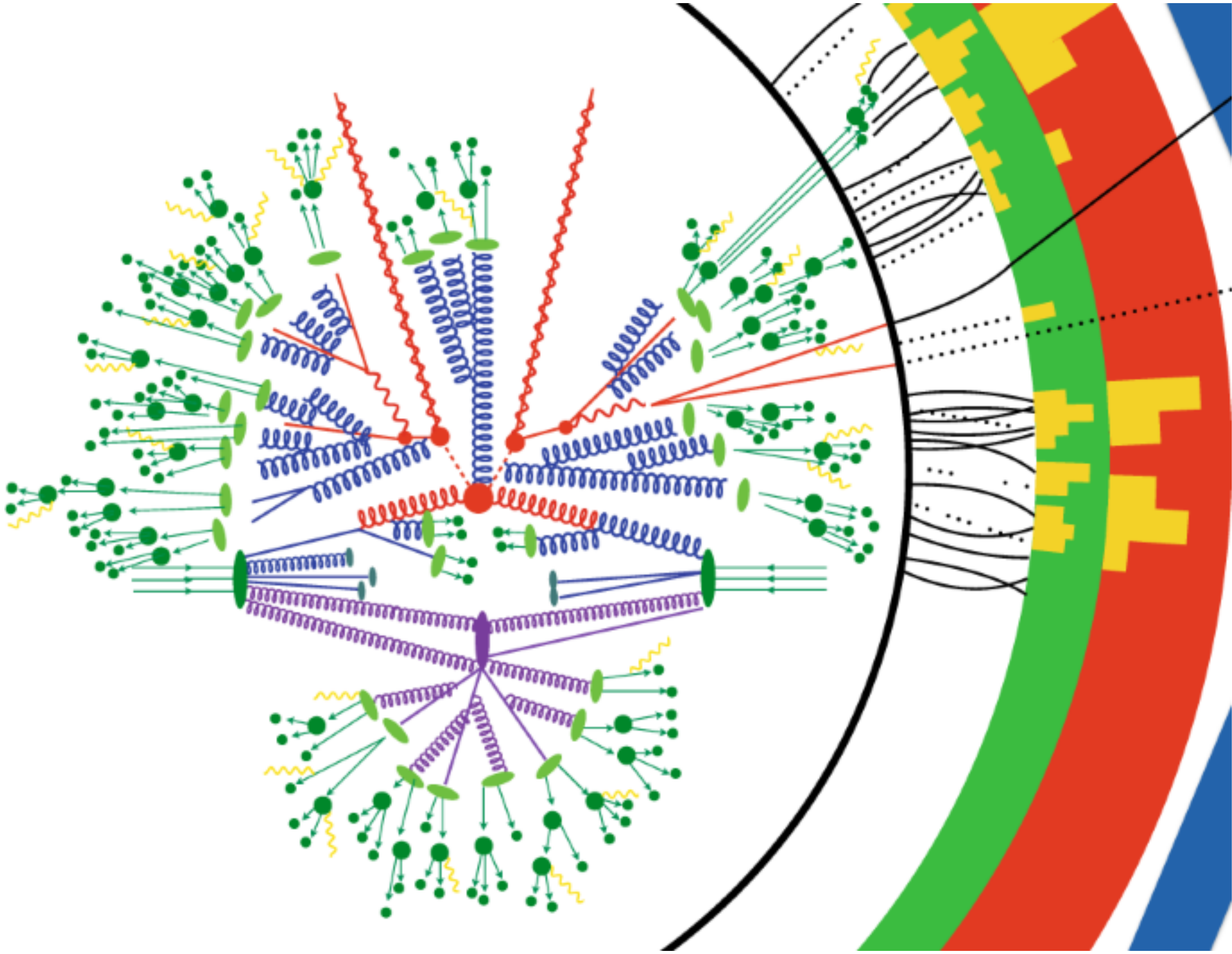


Image credit: Nature

LHC

$\alpha_s^n \log^{n-1}$	$NNLL$
$\alpha_s^n \log^{n}$	NLL
$\alpha_s^n \log^{n+1}$	LL

α_s^3	N^3LO
α_s^2	$NNLO$
α_s^1	NLO
α_s^0	LO

Parton shower PS_{N^yLL} and hadronisation

- ☑ Realistic description
- ☑ N^yLL resummation

Hard Process N^xLO

- ☑ High precision

Matching

$N^xLO + PS_{N^yLL}$

- ☑ High precision
- ☑ Realistic simulation of LHC events
- ☑ Resummation

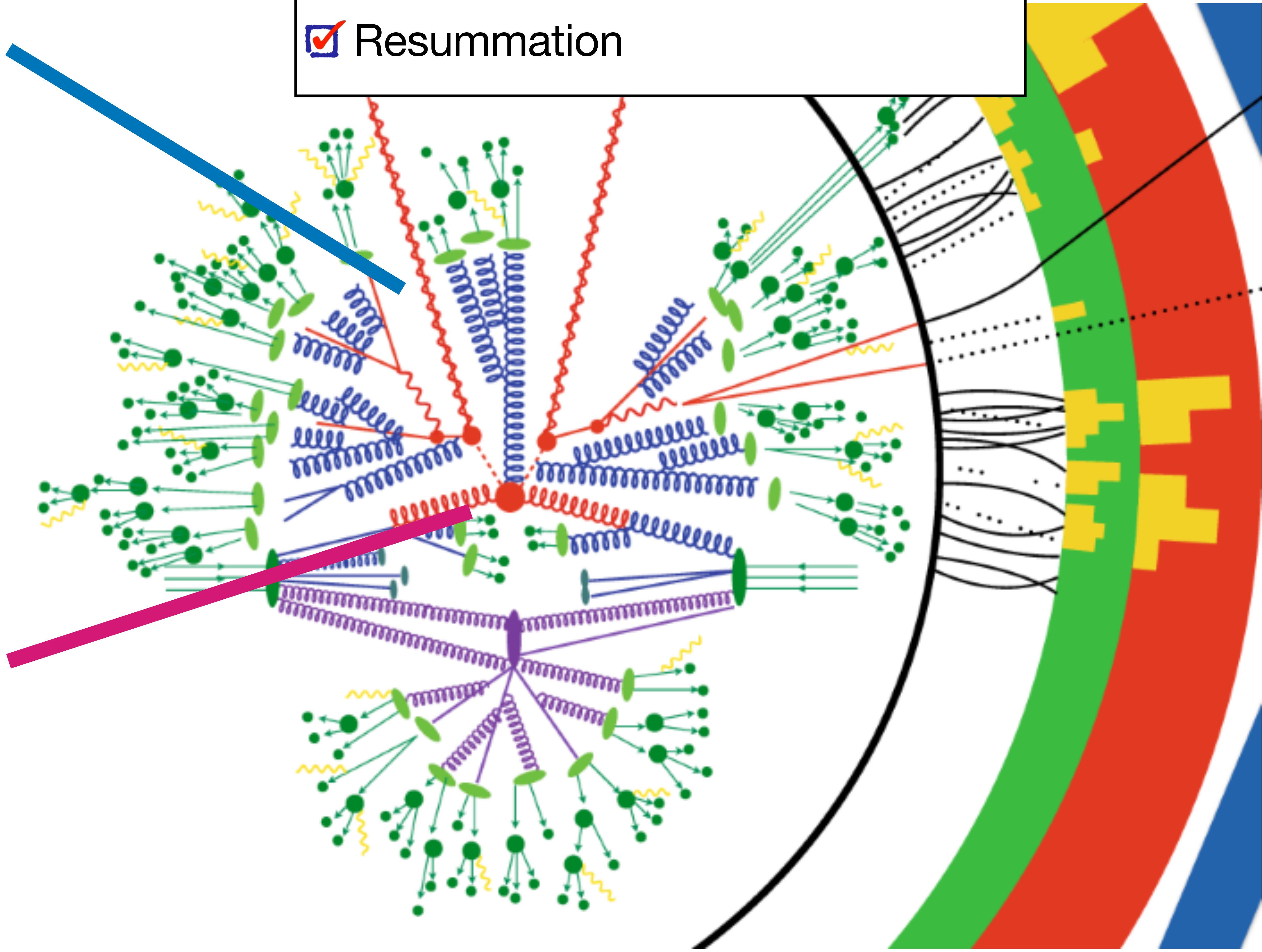
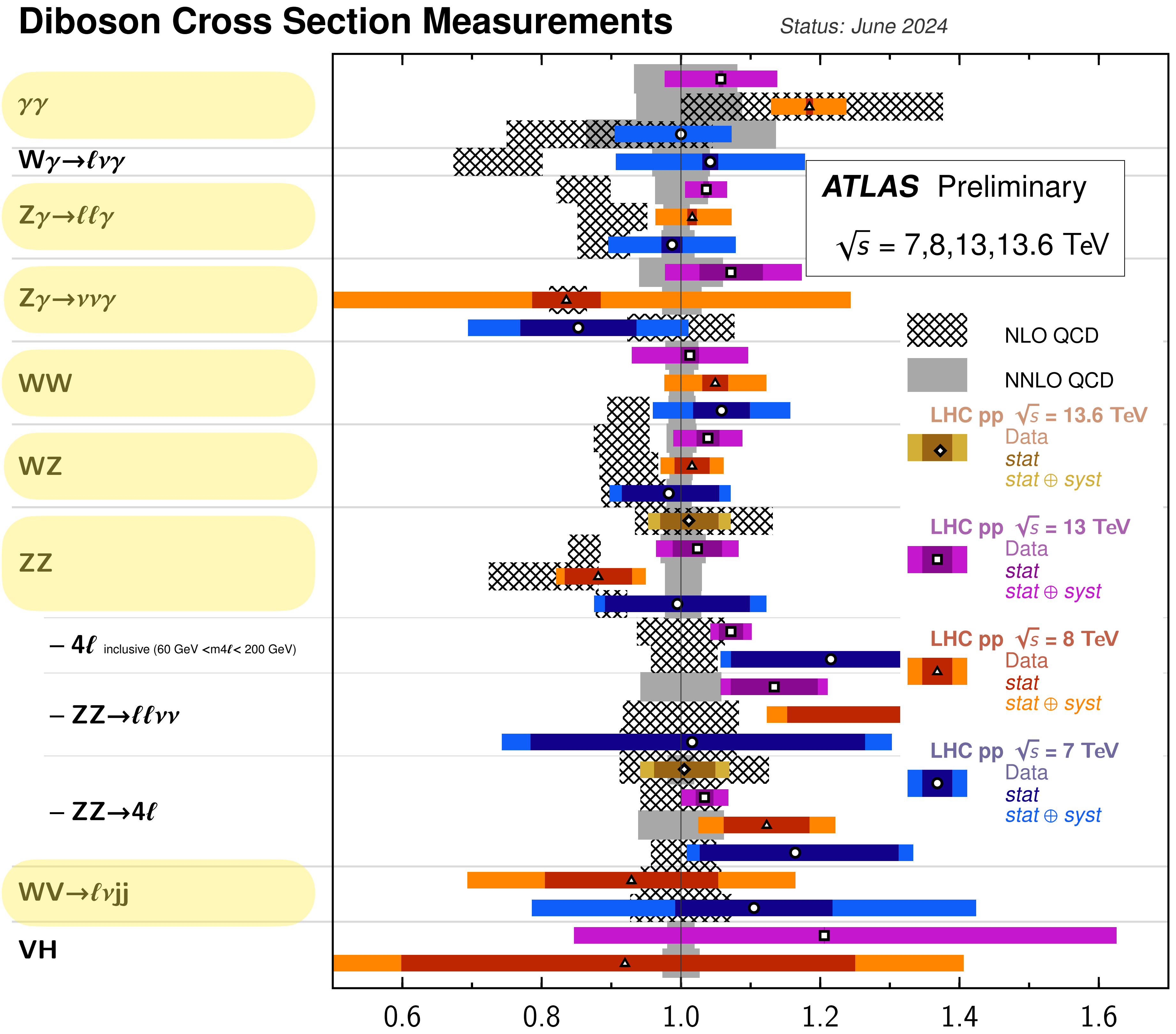
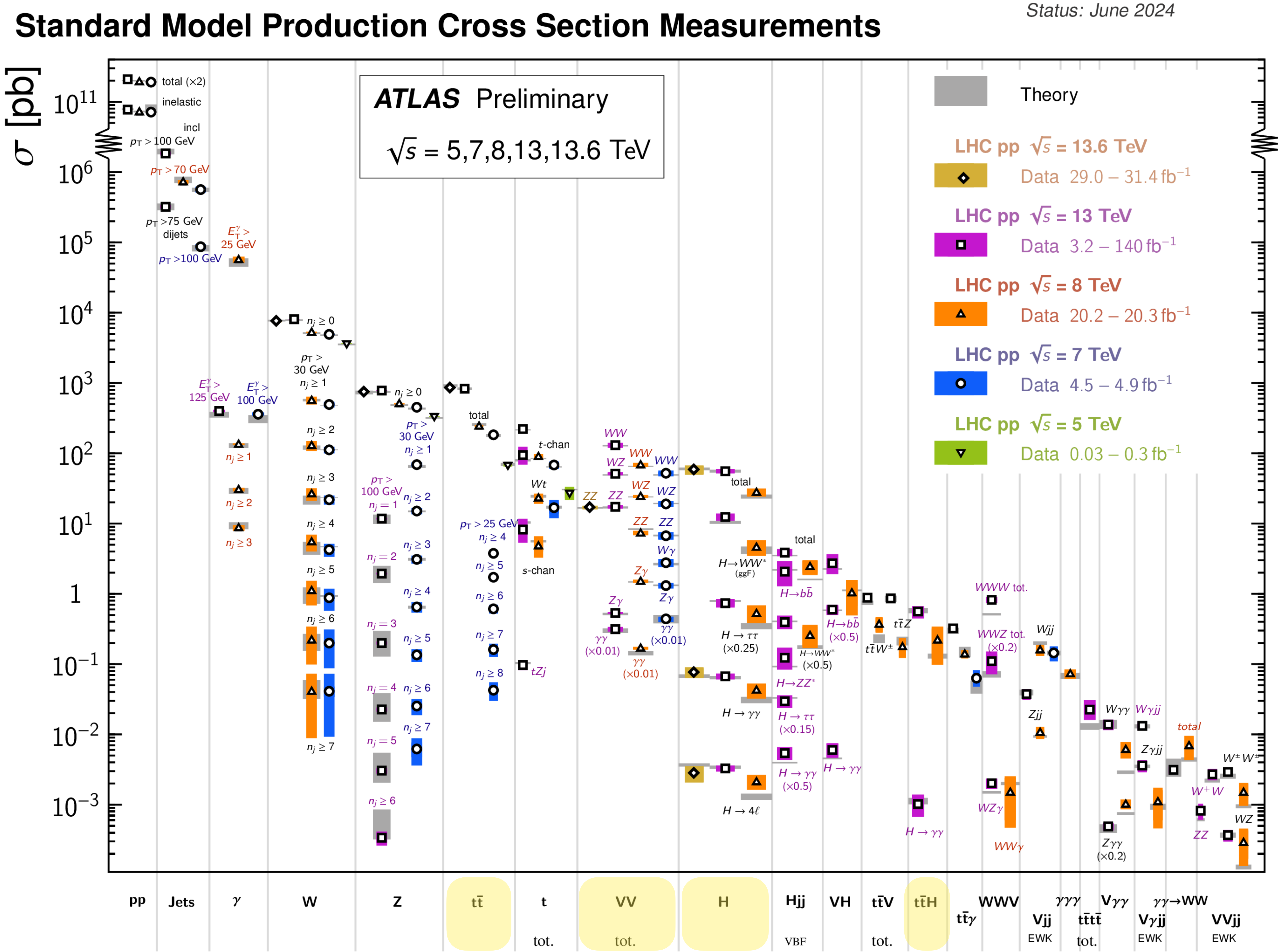


Image credit: Nature

LHC

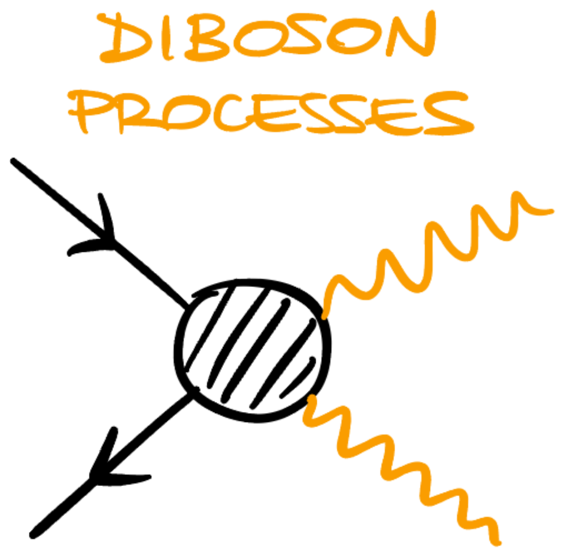


Diboson Cross Section Measurements
Status: June 2024
γγ
Wγ→ℓνγ
Zγ→ℓℓγ
Zγ→ννγ
WW
WZ
ZZ
– 4ℓ inclusive (60 GeV <m4ℓ< 200 GeV)
– ZZ→ℓℓνν
– ZZ→4ℓ
WV→ℓνjj
VH
ATLAS Preliminary
√s = 7,8,13,13.6 TeV
NLO QCD
NNLO QCD
LHC pp √s = 13.6 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
0.6
0.8
1.0
1.2
1.4
1.6

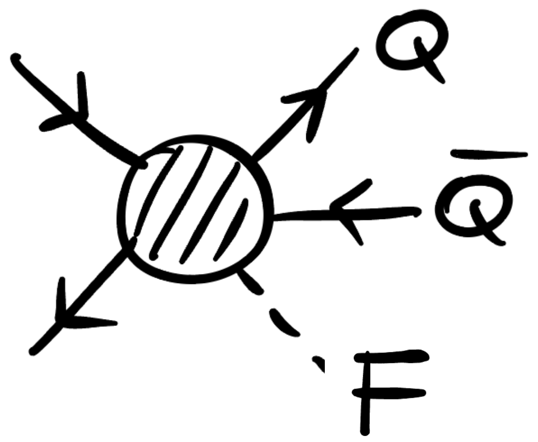


Standard Model Production Cross Section Measurements
Status: June 2024
σ [pb]
ATLAS Preliminary
√s = 5,7,8,13,13.6 TeV
Theory
LHC pp √s = 13.6 TeV
Data 29.0 – 31.4 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 140 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 5 TeV
Data 0.03 – 0.3 fb⁻¹
pp
Jets
γ
W
Z
tt̄
t
tot.
VV
tot.
H
Hjj
VBF
VH
tt̄V
tot.
tt̄H
tt̄γ
WWW
Vjj
EWK
γγγ
tt̄tt̄
tot.
Vγγ
Vγjj
EWK
γγ→WW
VVjj
EWK

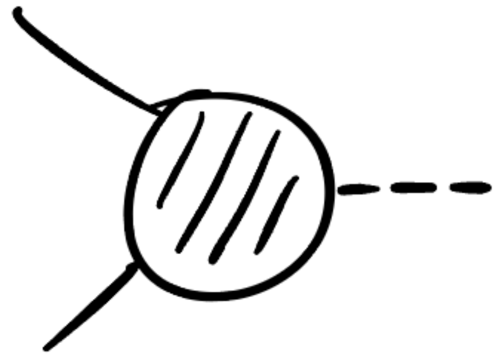
Recent progresses in MiNNLO$_{PS}$



	$Z\gamma$	[2010.10478, 2108.11315]
(1)	WW	[2103.12077, in progress]
	ZZ	[2108.05337, in progress]
	$WH/ZH(H \to b\bar{b})$	[2112.04168]
	$\gamma\gamma$	[2204.12602]
	WZ	[2208.12660]
(5)	SMEFT	[2204.00663, 2311.06107, in progress]

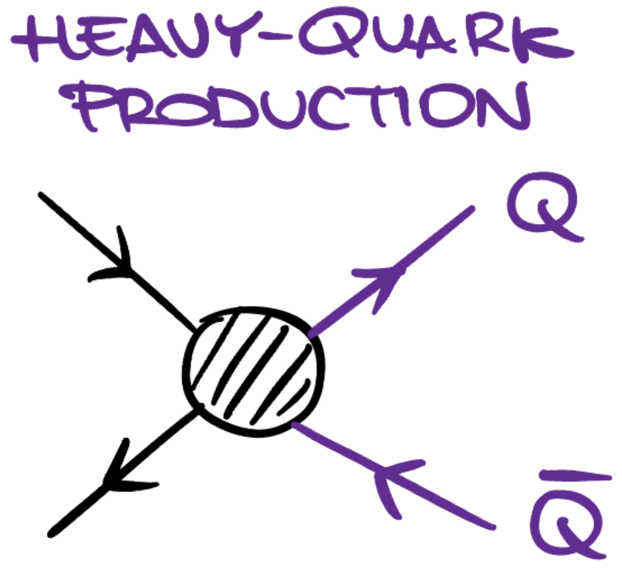


(3)	$b\bar{b}H$	[in progress]
	$b\bar{b}Z$	[2404.08598]
(4)	$t\bar{t}H$	[in progress]
	$b\bar{b}\ell\nu\ell\nu$	[in progress]



(1)	$gg \to H$, W/Z	[1908.06987, 2006.04133, 2402.00596, 2407.01354]
(3)	$b\bar{b} \to H$	[2402.04025]

first (and currently only) NNLO+PS method for heavy-quark final states



(2)	$t\bar{t}$	[2012.14267, 2112.12135]
	$b\bar{b}$	[2302.01645, in progress]

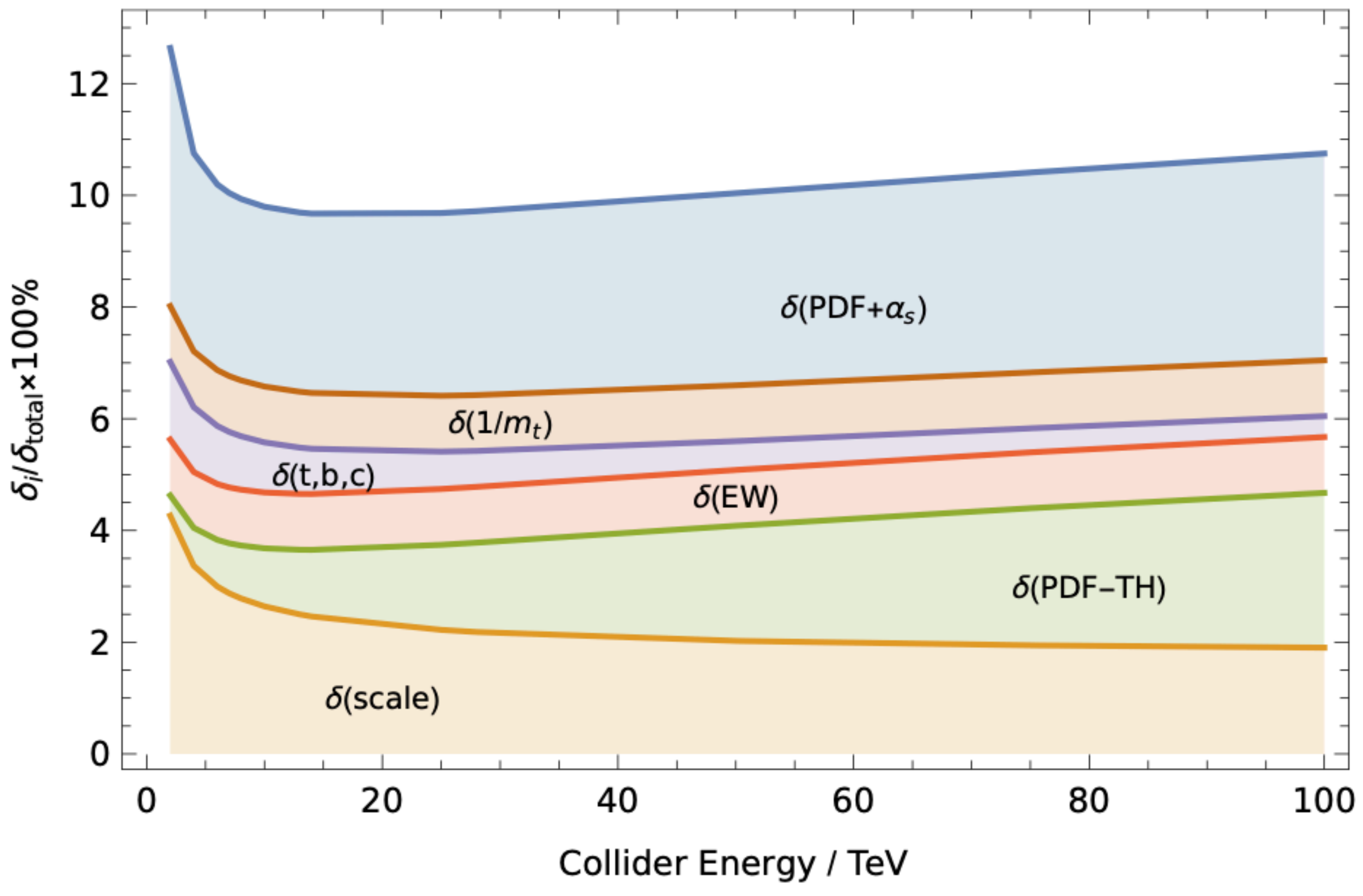
Top-mass effects in color-singlet production

- **Goal: account for exact top-quark mass dependence**

- **Motivation: increasing precision calls for including previously neglected subleading effects.** This might require, in turn to develop new computational techniques

Higgs production via gluon fusion: $gg \to H$

Missing mass-effects are one of the main sources of uncertainties



Dulat, Lazopoulos, Mistlberger [1802.00827]

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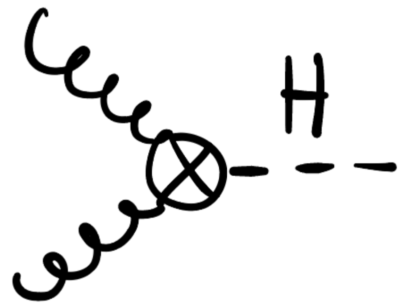
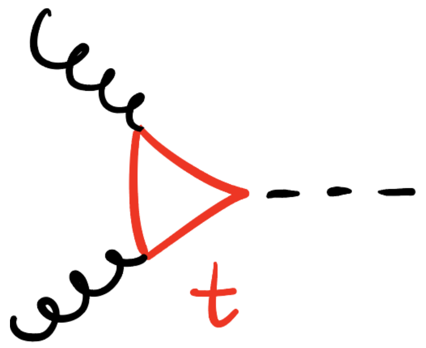
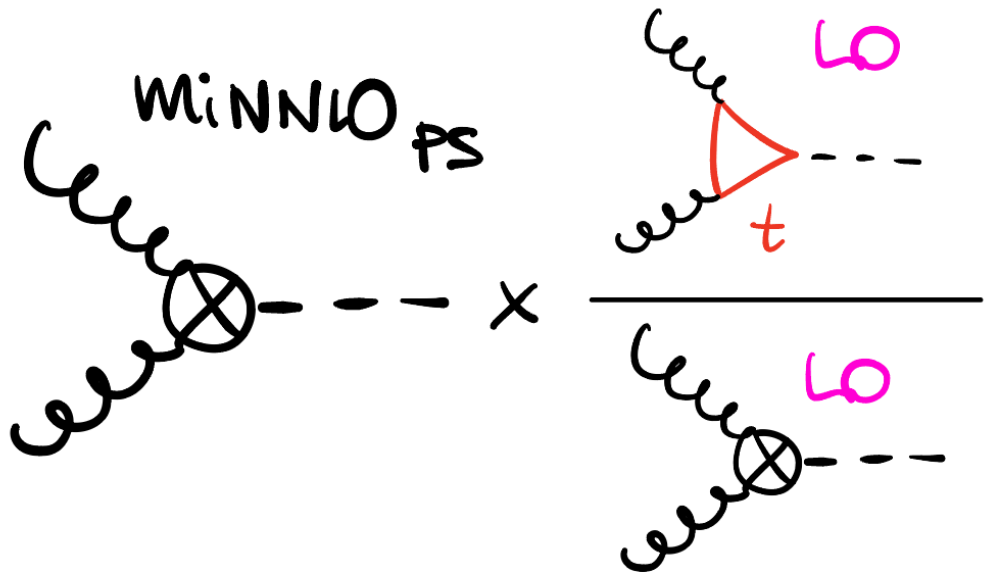
Higgs production via gluon fusion: $gg \to H$



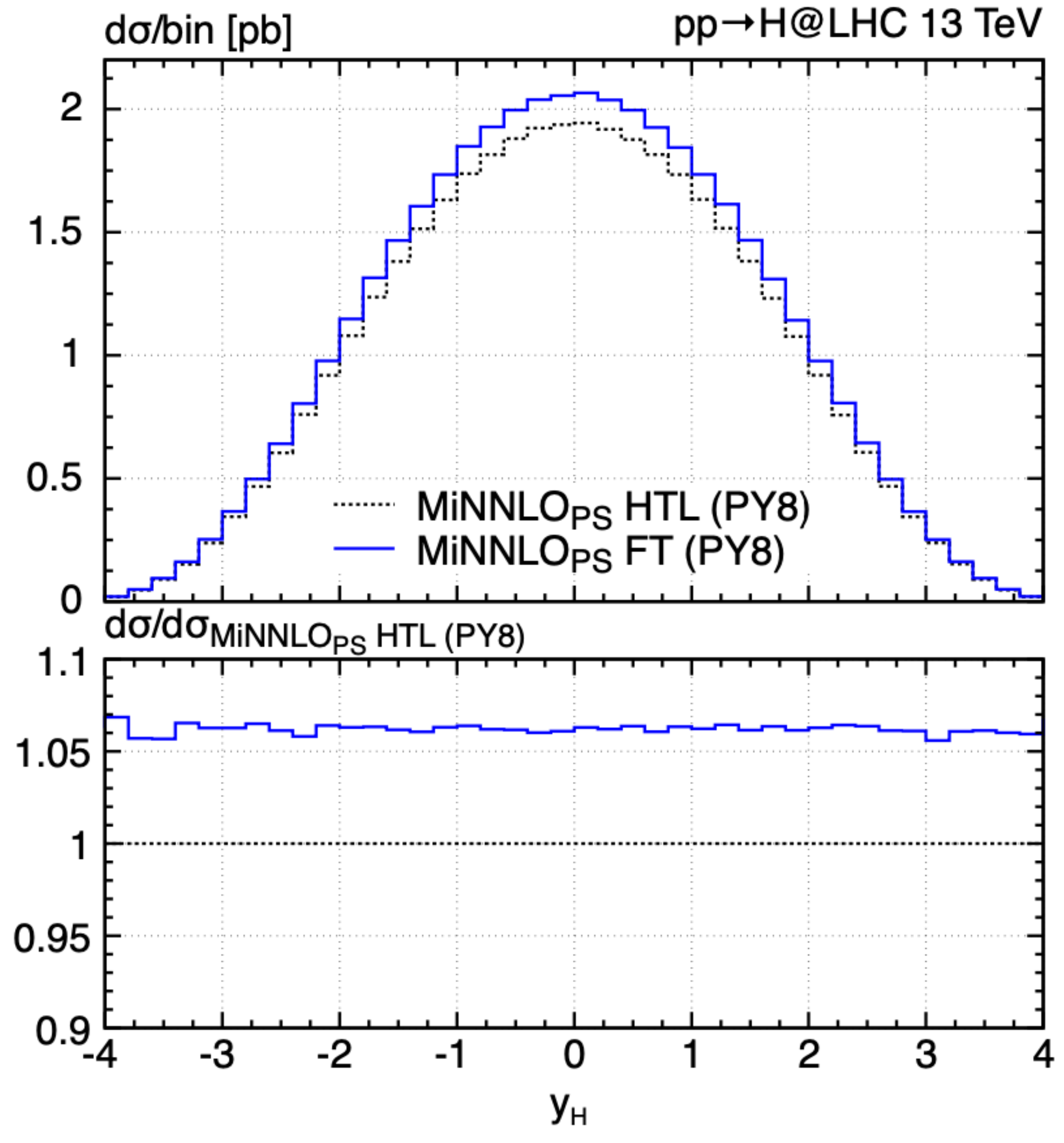
MiNNLO$_{PS}$ HTL $39.55(1)^{+11.0\%}_{-10.5\%}\,pb$

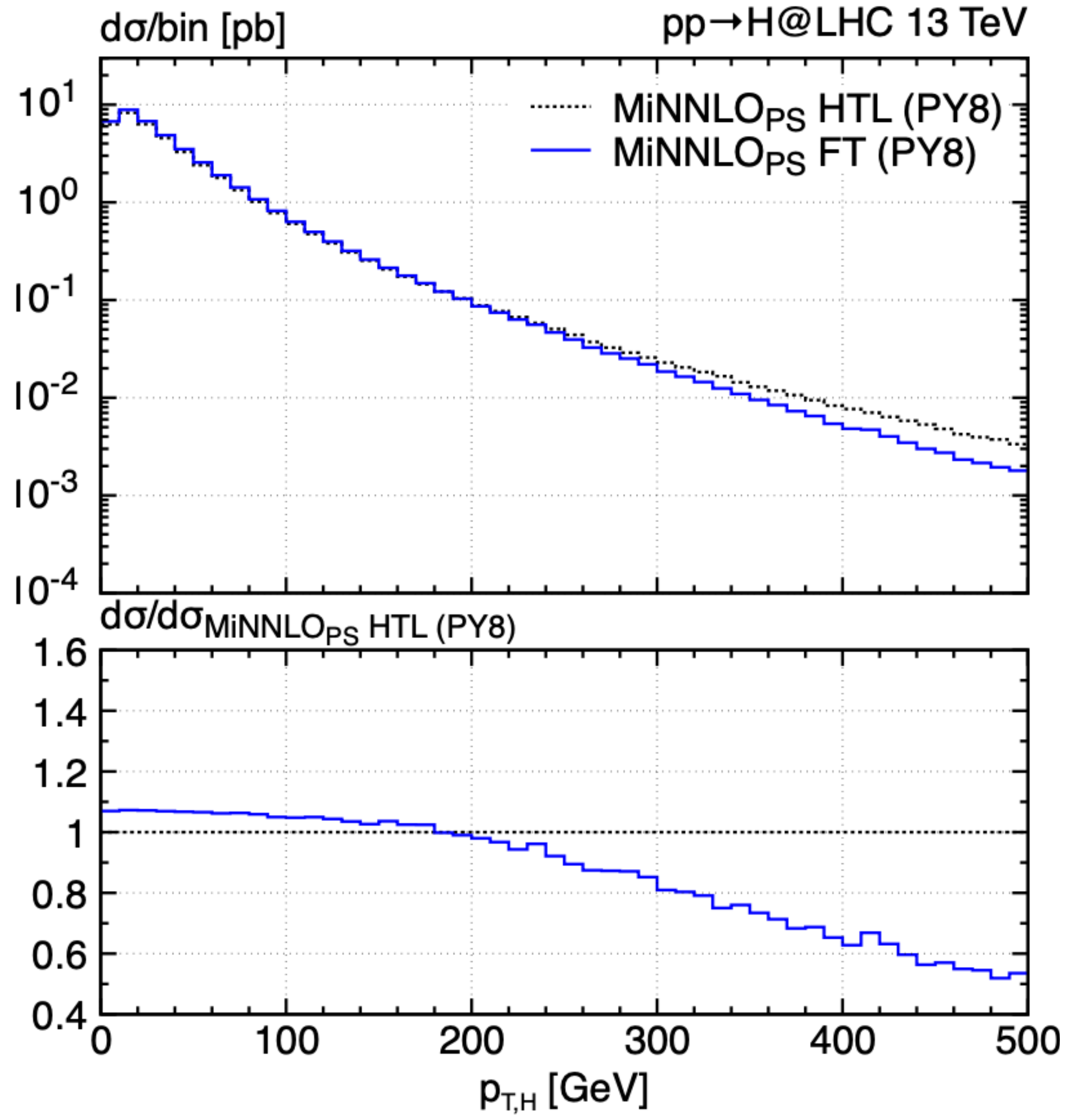


MiNNLO$_{PS}$ FT $42.01(1)^{+11.2\%}_{-10.6\%}\,pb$



$42.13(1)^{+11.0\%}_{-10.5\%}\,pb$





Niggetiedt, Wiesemann [2407.01354]

Ongoing efforts to include b/c-quarks effects! *Niggetiedt, Wiesemann [in progress]*

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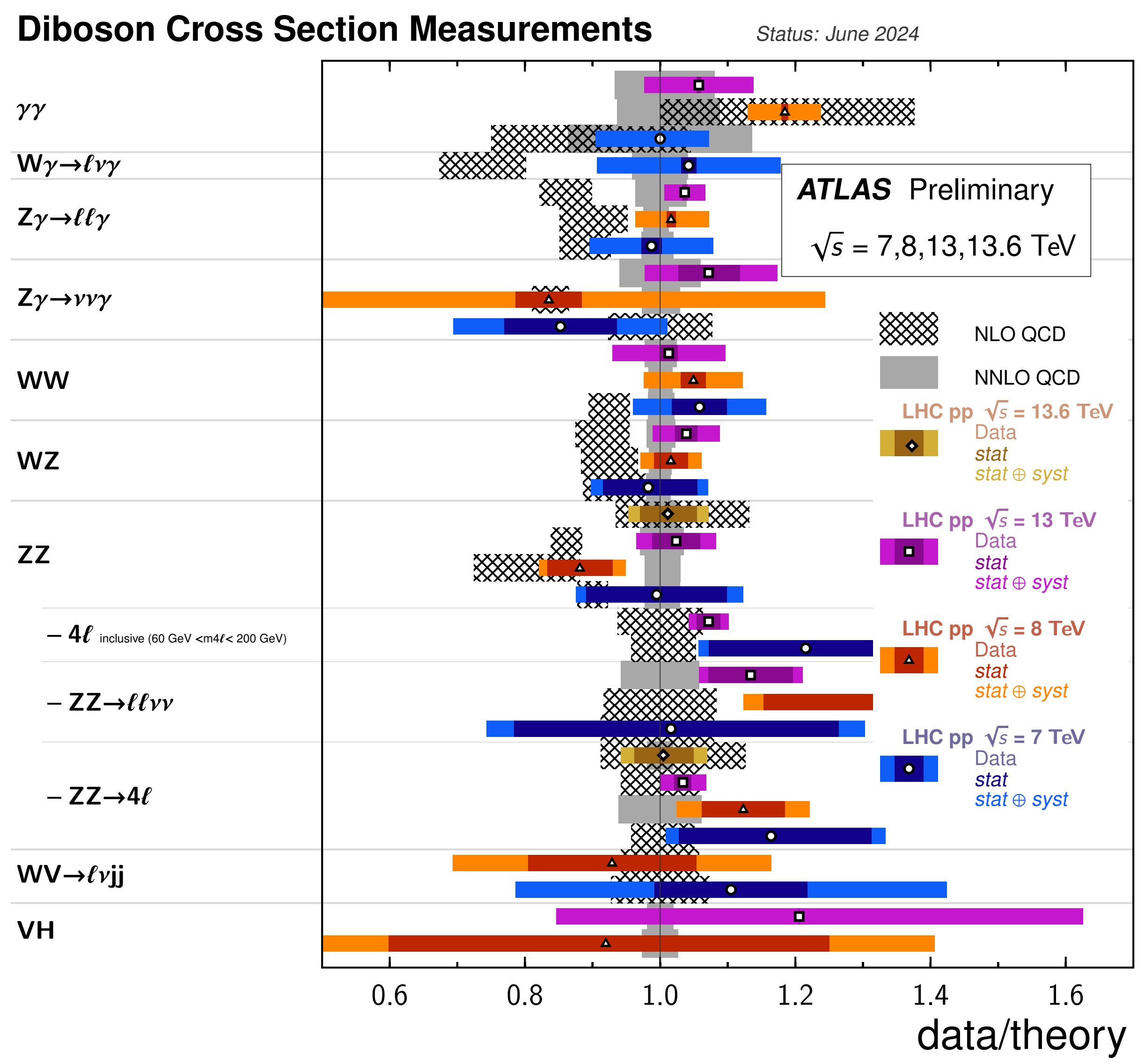
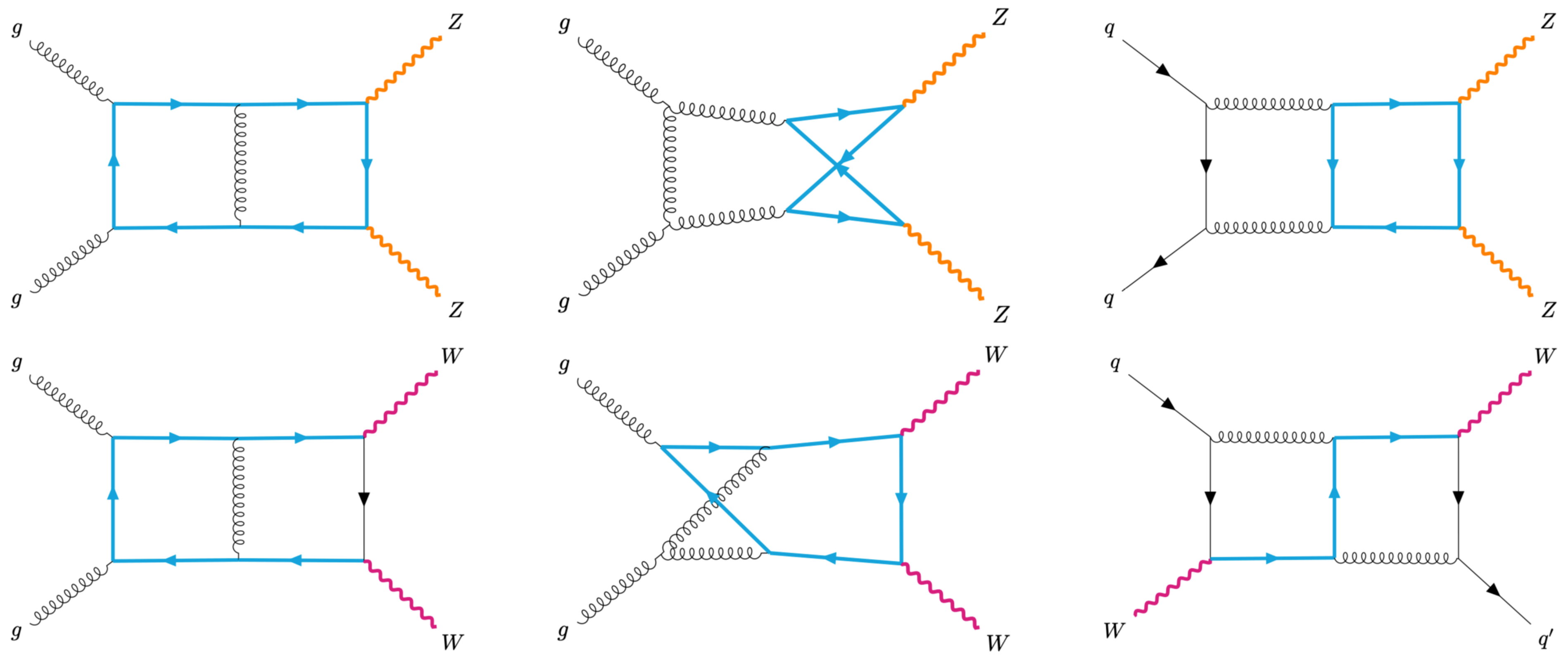


Double boson production: WW, ZZ

- **Interesting applications:**
  1. Irreducible background to $H^* \to WW/ZZ \implies$ constrain Higgs width
  2. Probing anomalous W/Z coupling to quarks
  3. Mass effects tend to increase at high energy (Goldstone equivalence)

- **Work in progress:** 4-scale integrals@2loop → beyond current analytic technology
  - ✓ numerical IBP + numerical DE
  - ✓ loop integrals evaluated numerically



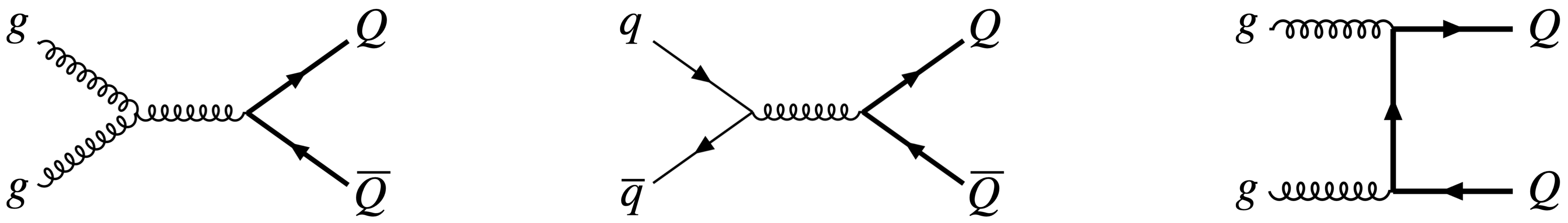
Ongoing efforts!
Wang, Wiesemann, Zanderighi, … [in progress]

Heavy-quark pair production in MiNNLO$_{PS}$

❖ **Goal: access processes with massive final states → first NNLO+PS implementation of $Q\bar{Q}$ hadroproduction within MiNNLO$_{PS}$**

❖ **Motivation: multi-purpose studies,** from top-quark mass determination, to estimate of backgrounds for cosmic neutrino searches, including B-hadron production and flavoured-jet definition impact.

LO: $Q = t, b, c$



Small natural scale of the process ($m_b, m_c < 5\text{GeV}$)

Slow convergence of perturbative series: sizeable NNLO corrections.

$$pp \to t\bar{t} + X$$

- High precision needed for determination of top-quark mass m_t.
- Interplay with EW sector (**EW decay**).

[Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi '20]

$$pp \to b\bar{b} + X$$

- Main channel for inclusive **B-hadron** production at LHC.
- Predictions for **b-jet** with finite m_b.

[Mazzitelli, Ratti, Wiesemann, Zanderighi '23]

$$pp \to c\bar{c} + X$$

- Constrain gluon PDF at low x.
- Study **prompt atmospheric neutrino** background in cosmic neutrino searches.

Ongoing efforts!

Gauld, Giani, Ratti, Wiesemann, Zanderighi, … [in progress]

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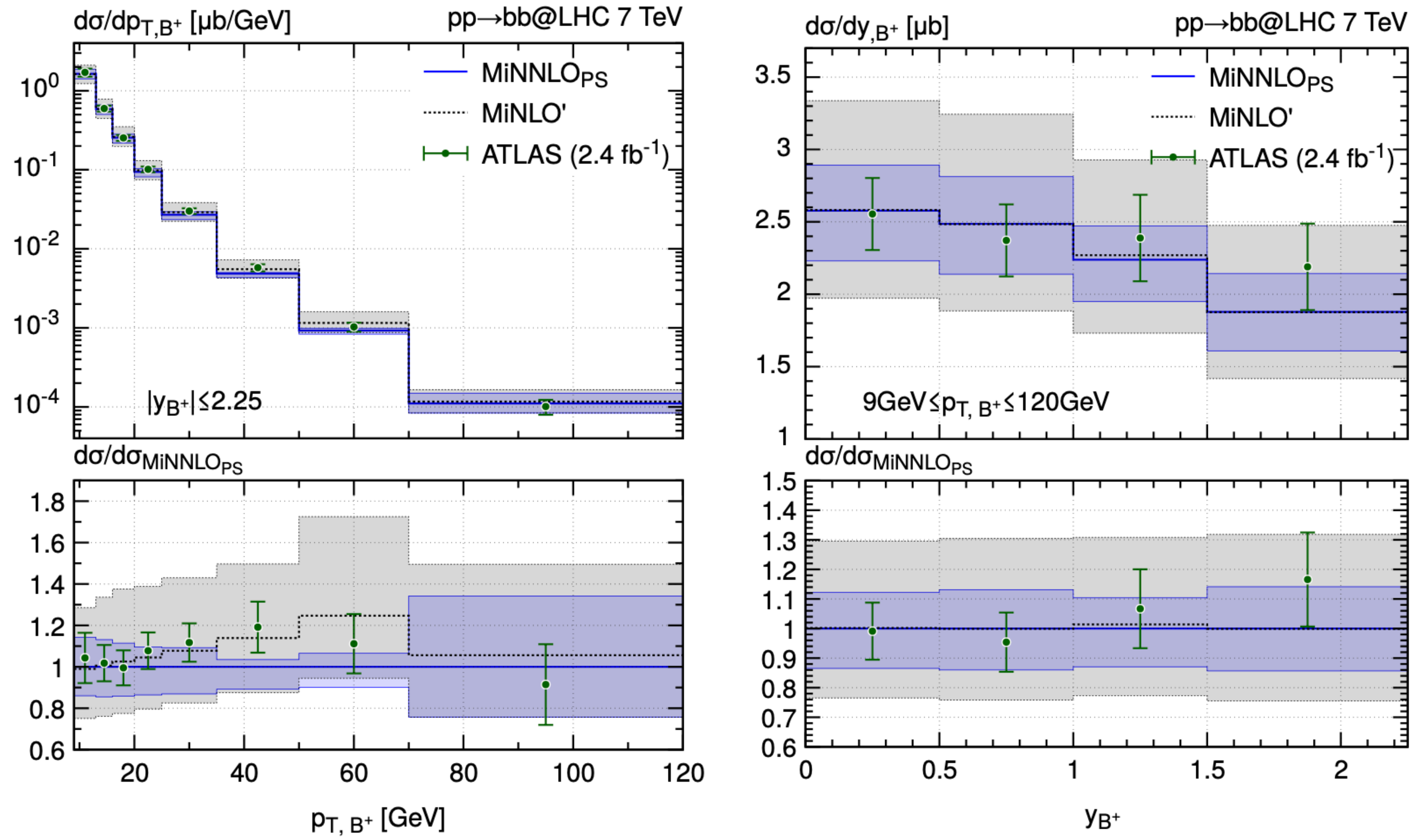
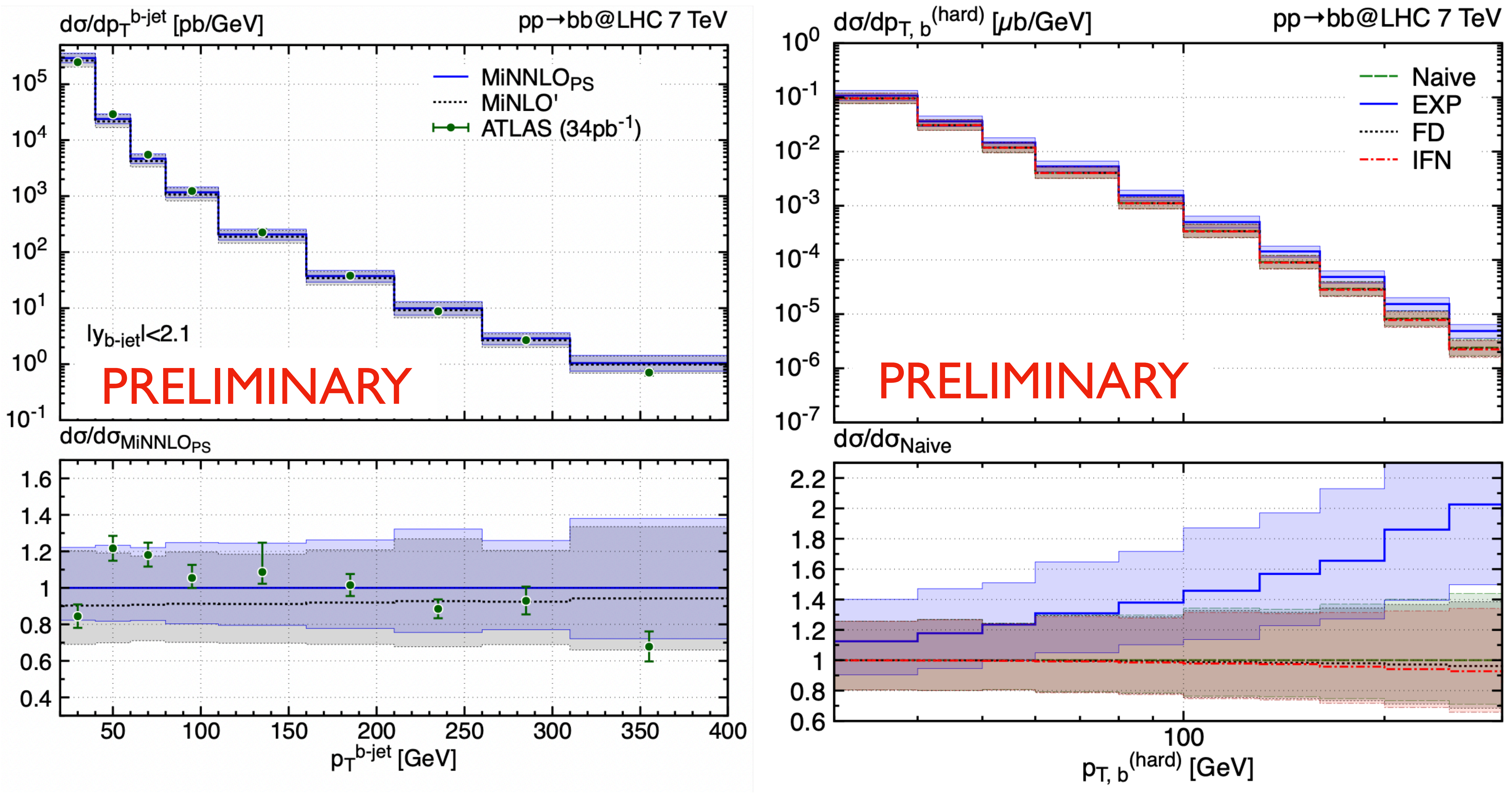
$$pp \;\to\; b\bar{b} + X \;\to\; B + X'$$
$$B \;=\; \{B^+, B^-, B^0, \bar{B}^0, B^0_s, \bar{B}^0_s, \dots\}$$



First NNLO+PS predictions for inclusive B-hadron production at the LHC.

[Mazzitelli, Ratti, Wiesemann, Zanderighi '23]

Study of flavoured-jet definition impact



Comparison of different b-jet definitions ongoing!

Gauld, Mazzitelli, Ratti, Wiesemann, Zanderighi [in progress]

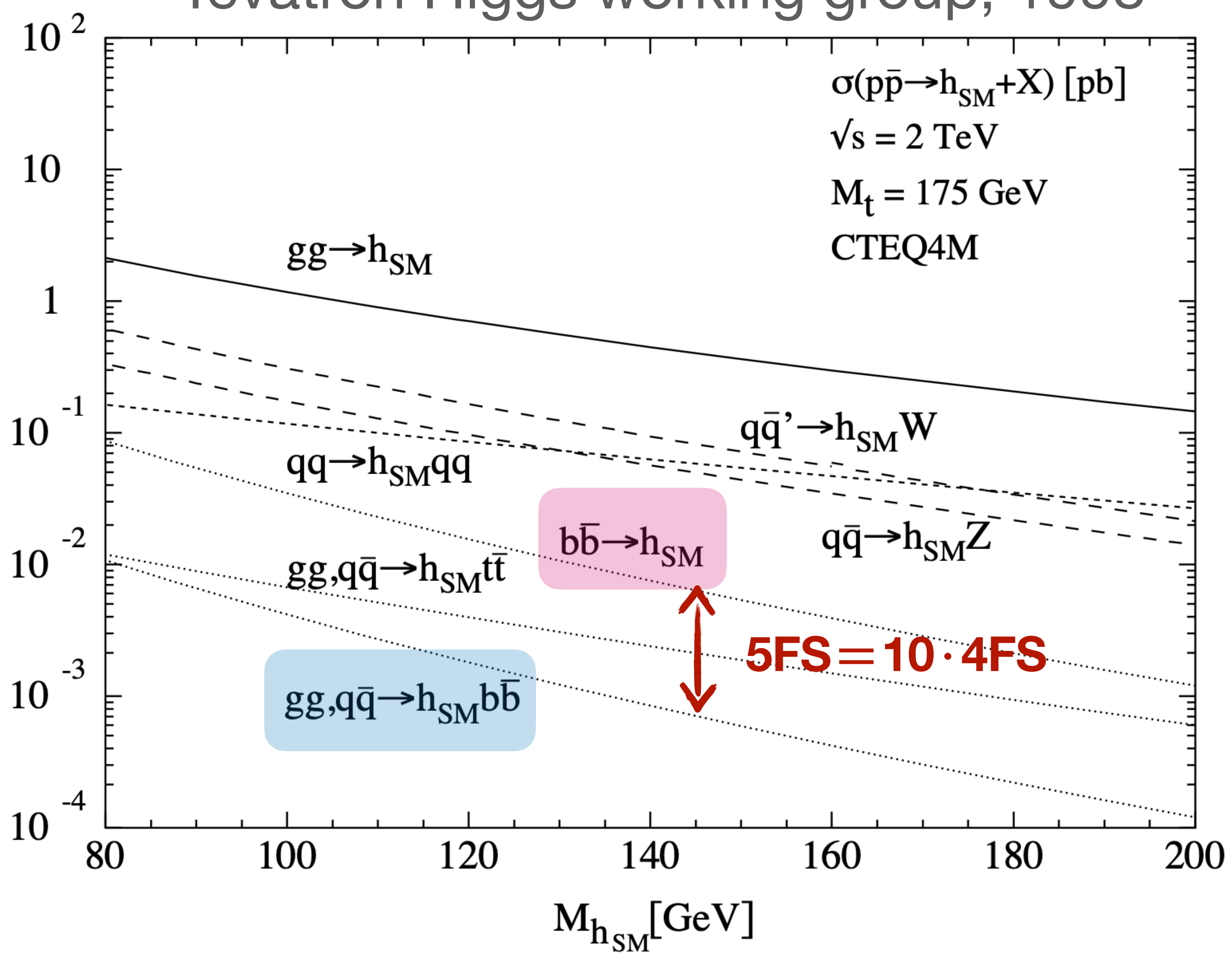
Flavour scheme effects in Higgs production: $b\bar{b} \to H$ vs $b\bar{b}H$

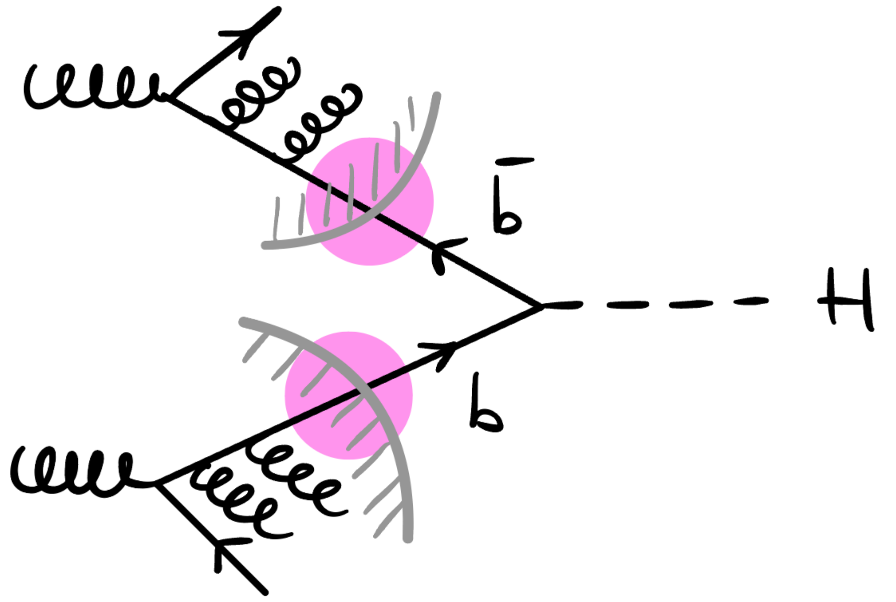
❖ **Goal: account for massless-bottom Higgs production and associated H production with massive bottom at NNLO+PS**

❖ **Motivation:**

1. Strong control on major background for HH searches
2. Solving long-standing theoretical issues: significant differences have been observed in predictions in different schemes

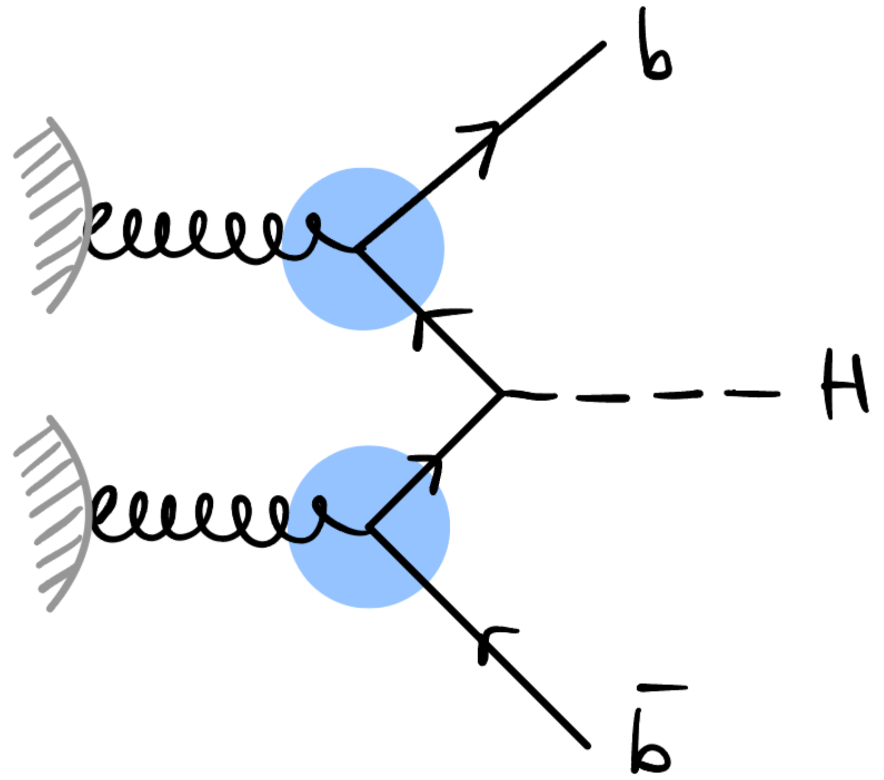
Tevatron Higgs working group, 1998





Massless bottoms (5FS)

Biello, Sankar, Wiesemann, Zanderighi [2402.04025]



Massive bottoms (4FS)

Biello, Mazzitelli, Sankar, Wiesemann, Zanderighi [to appear]

Flavour scheme effects in Higgs production: $b\bar{b} \to H$ vs $b\bar{b}H$

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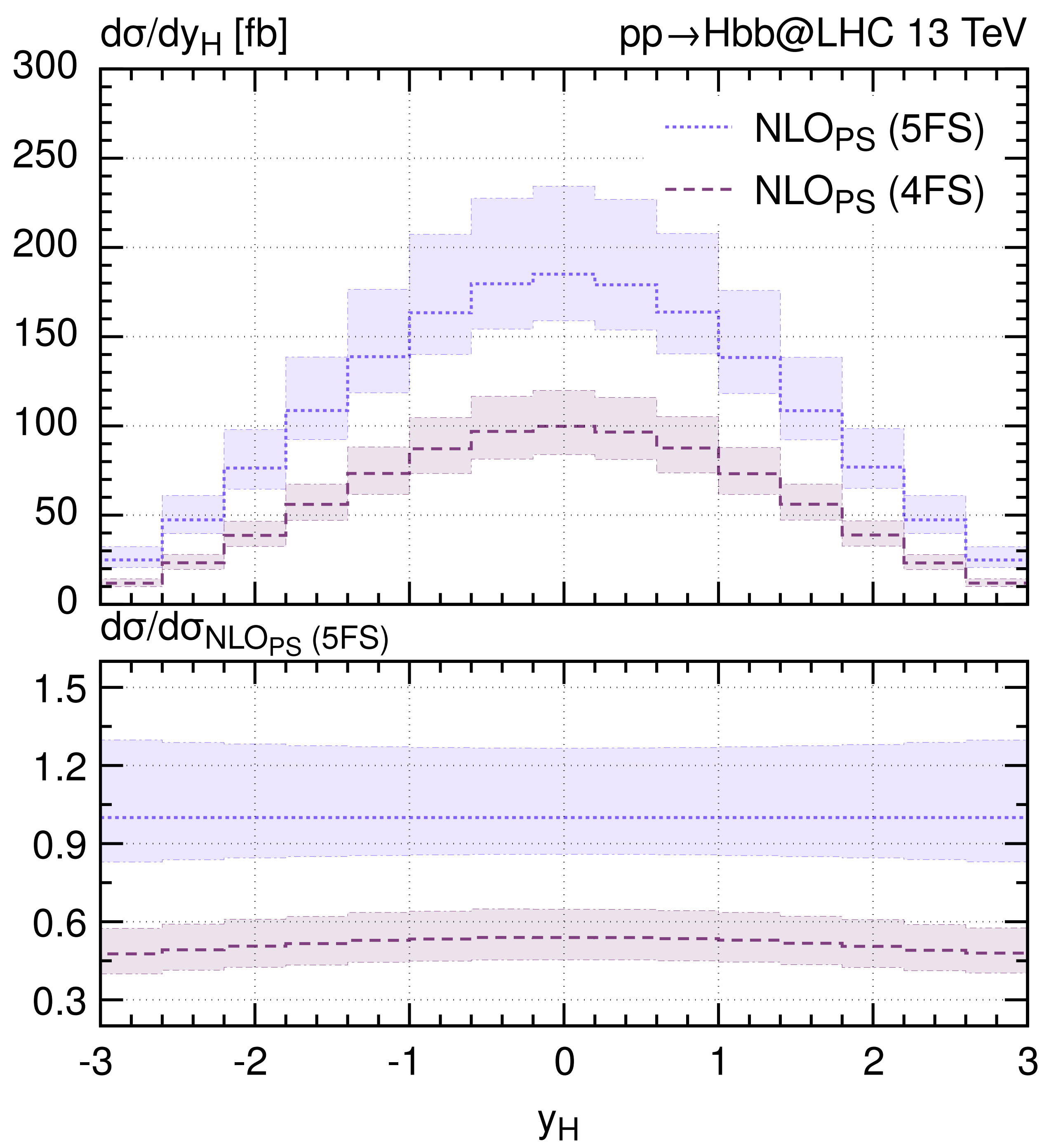


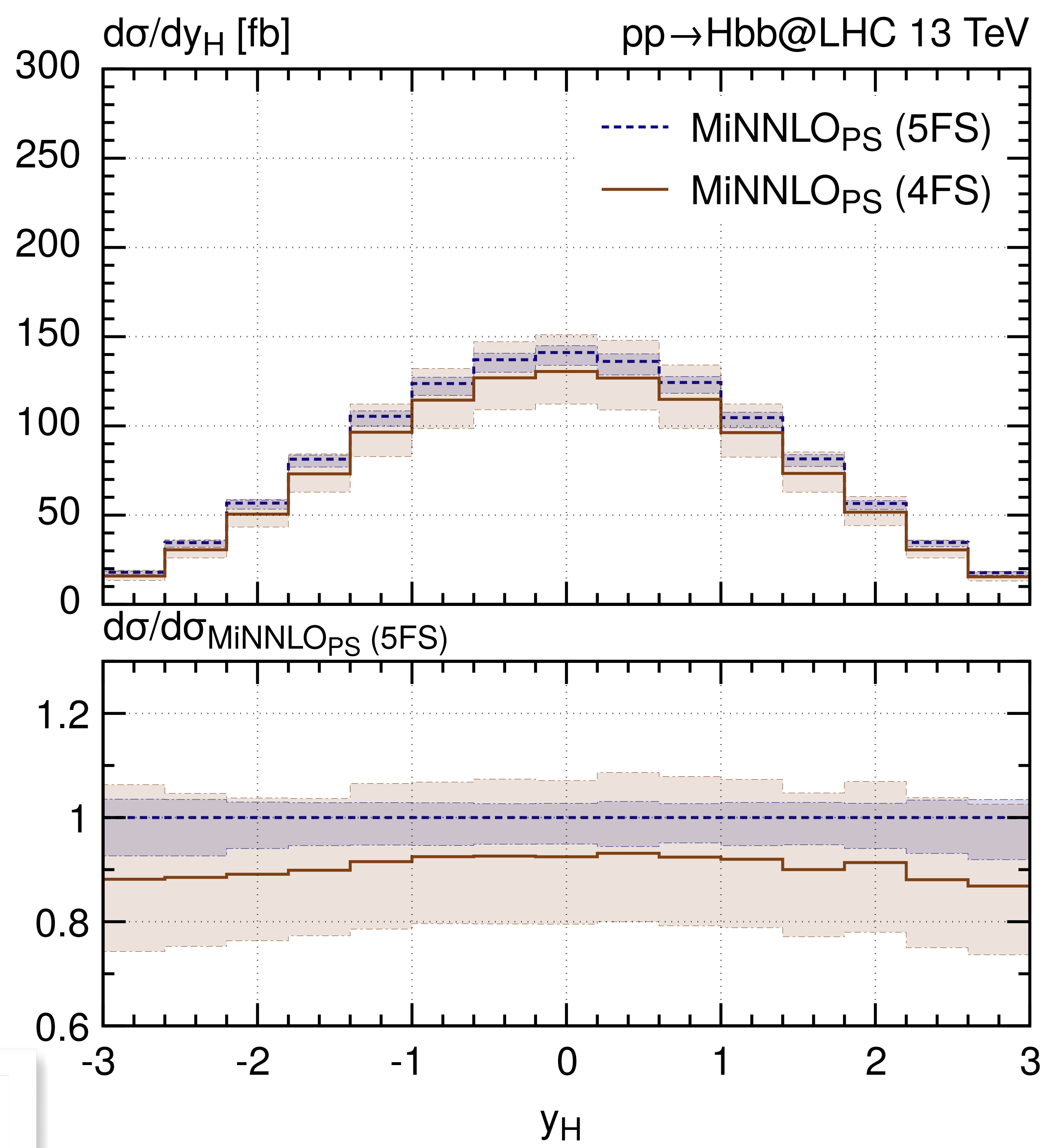
5FS NLO$_{\rm PS}(m_H)$	$0.676(6)^{+27\%}_{-15\%}$ pb
4FS NLO$_{\rm PS}(m_H)$	$0.354(6)^{+20\%}_{-16\%}$ pb
4FS NLO$_{\rm PS}(\frac{H_T}{4})$	$0.385(3)^{+16\%}_{-14\%}$ pb

Problem solved with natural scale choices at NNLO!

5FS MiNNLO$_{\rm PS}$ (m_H)	$0.509(1)^{+2.9\%}_{-5.3\%}$ pb
4FS MiNNLO$_{\rm PS}$ (m_H)	$0.465(9)^{+16\%}_{-14\%}$ pb
4FS MiNNLO$_{\rm PS}$ $(\frac{H_T}{4})$	$0.496(6)^{+16\%}_{-14\%}$ pb

Ongoing efforts to combine 4FS and 5FS

Biello, Gauld, Sankar, Wiesemann, Zanderighi [in progress]



Biello, Sankar, Mazzitelli, Wiesemann, Zanderighi [to appear]

Flavour scheme effects in Higgs production: $b\bar{b} \to H$ vs $b\bar{b}H$

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Ongoing efforts to obtain predictions for HH production in MiNNLO$_{PS}$

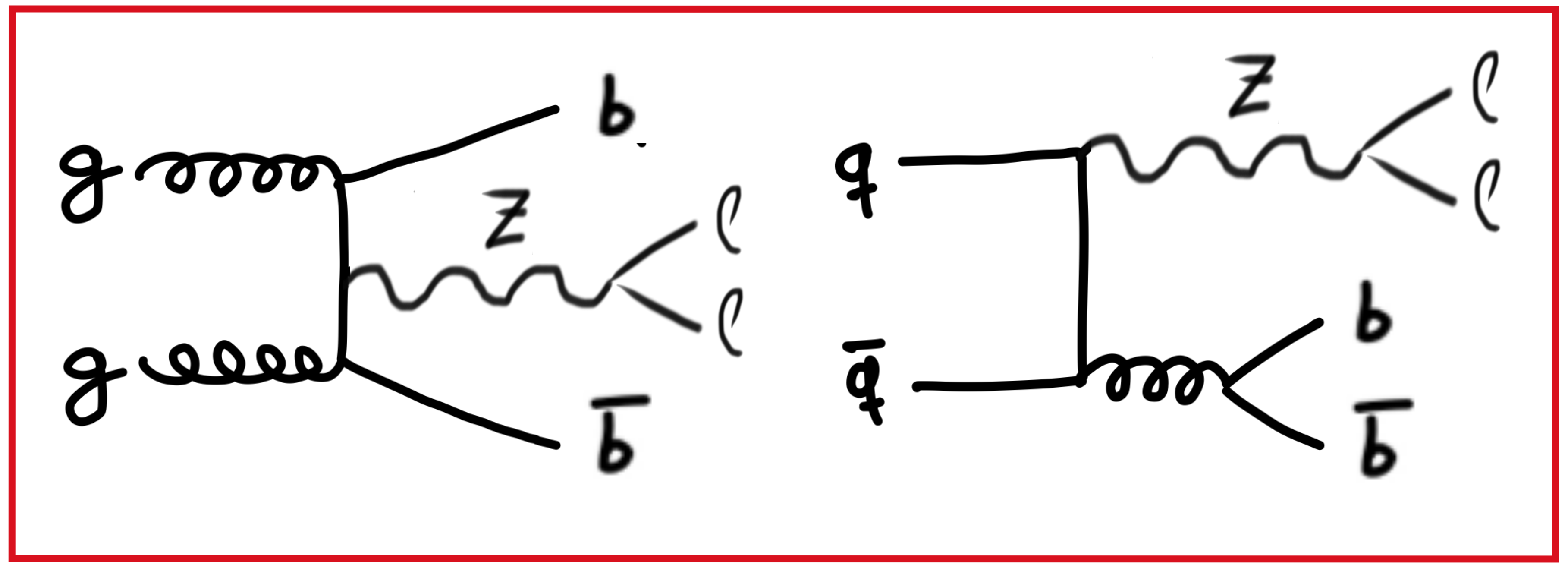
Garosi, Wiesemann, Zanderighi [to begin]

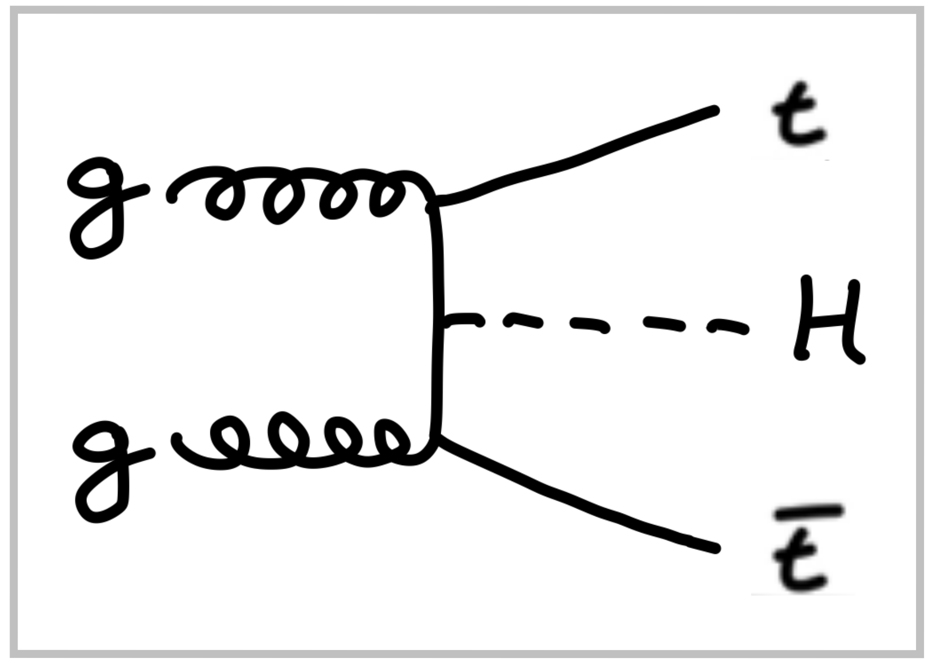
Ongoing efforts to obtain predictions for VBF Higgs production with $H \to b\bar{b}$ decays in MiNNLO$_{PS}$

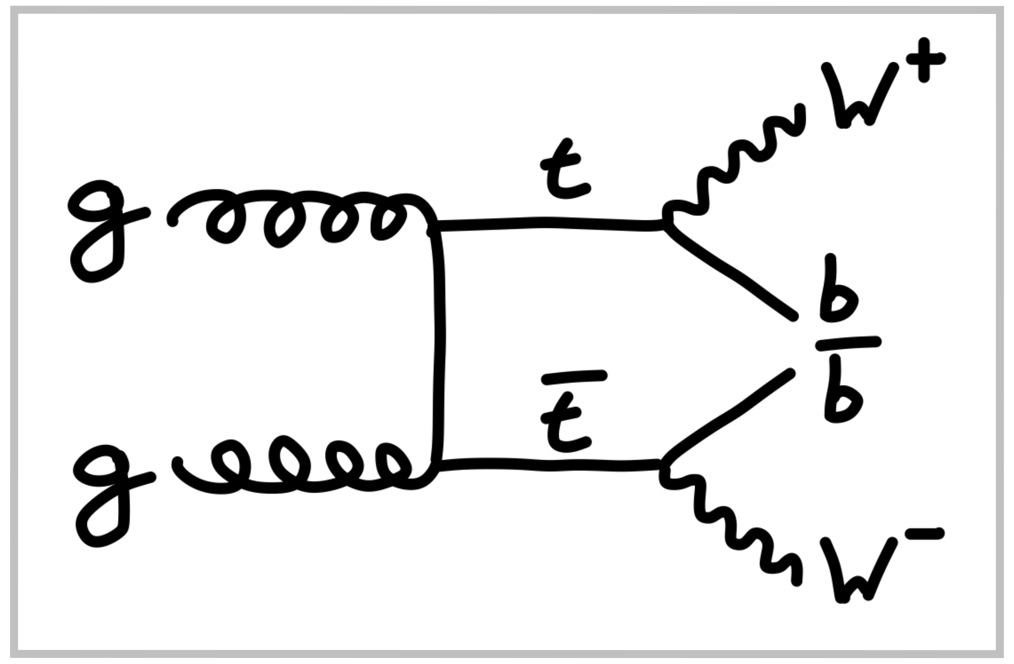
Behring, Zanderighi, … [to begin]

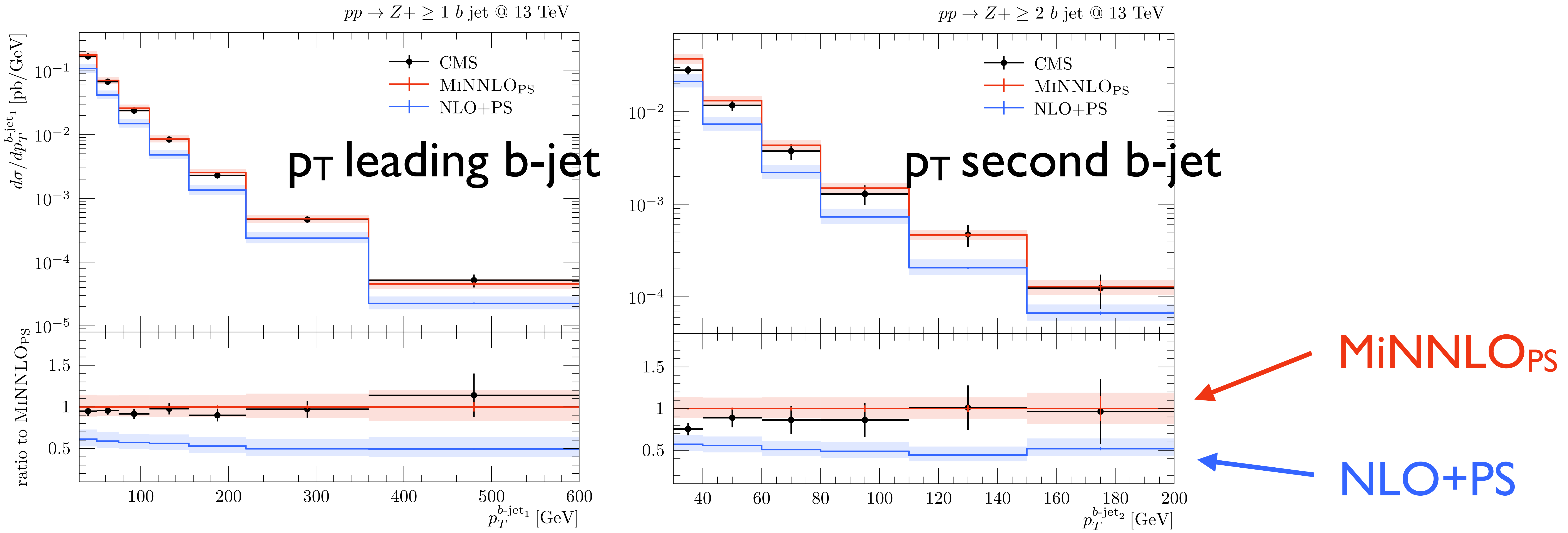
High multiplicity final state and heavy partons at NNLO+PS

Mazzitelli, Sotnikov, Wiesemann [2404.08598]



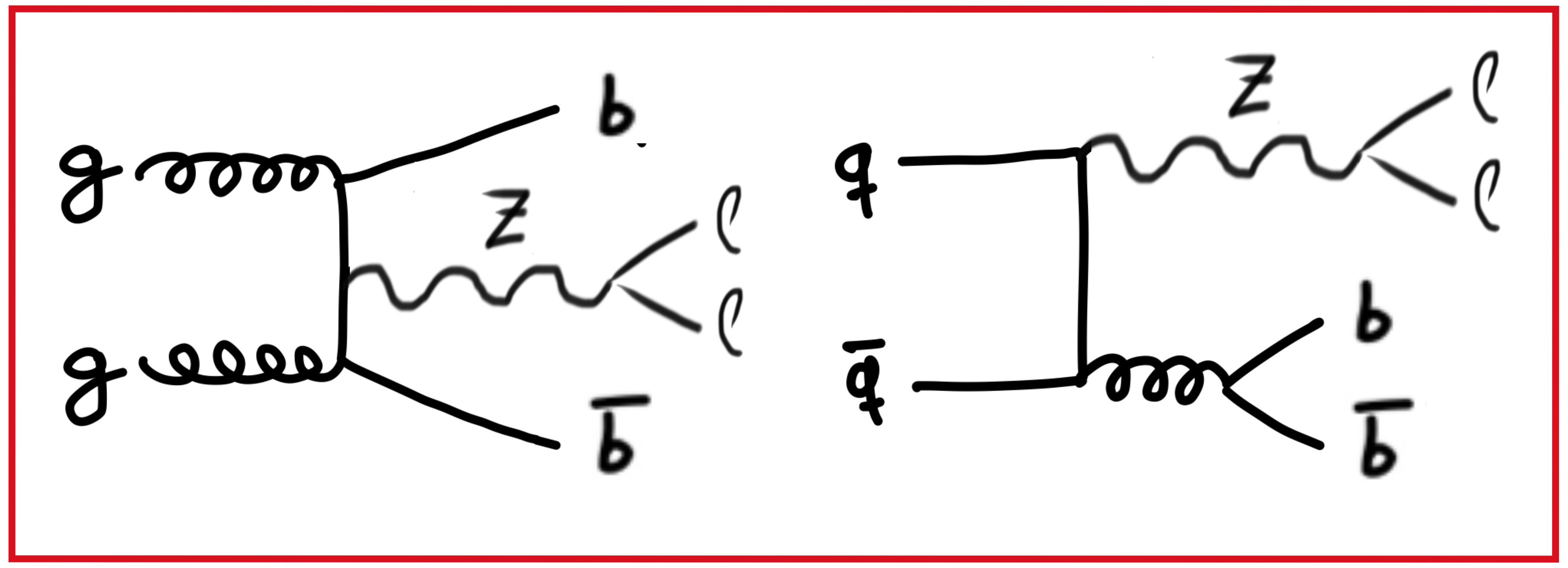


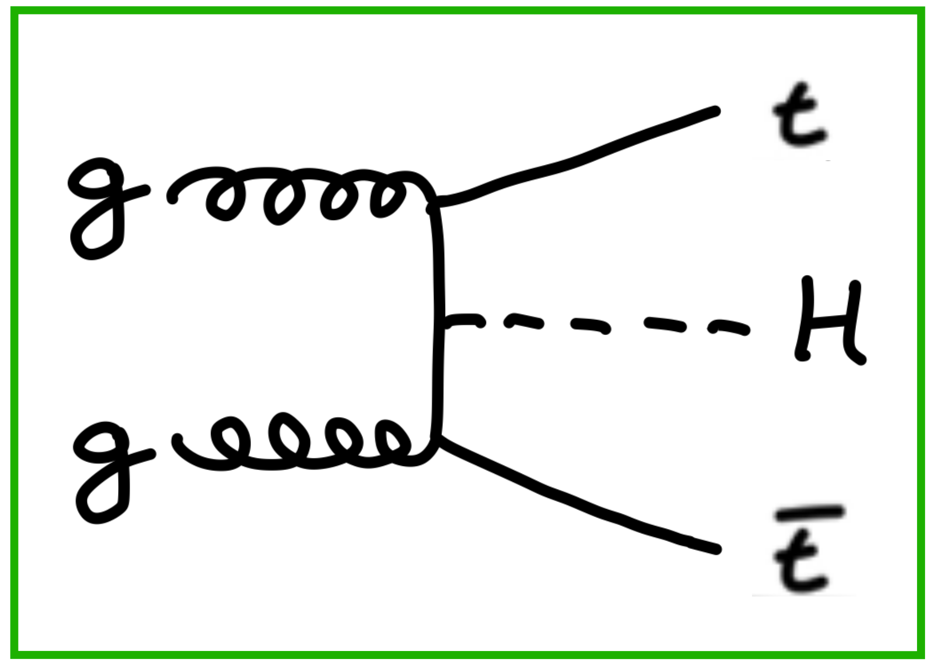


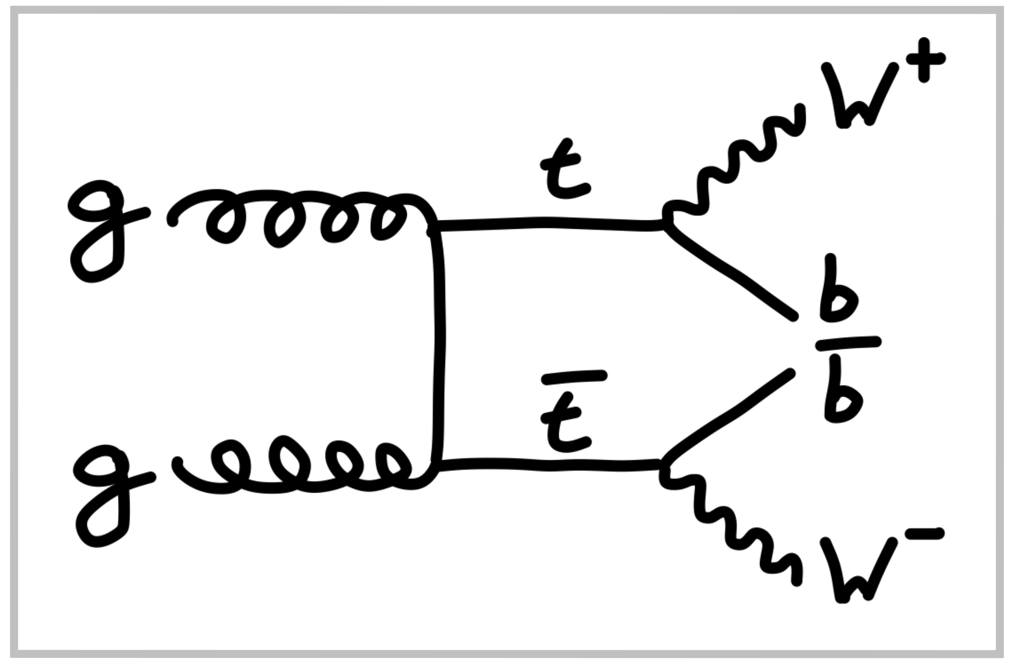


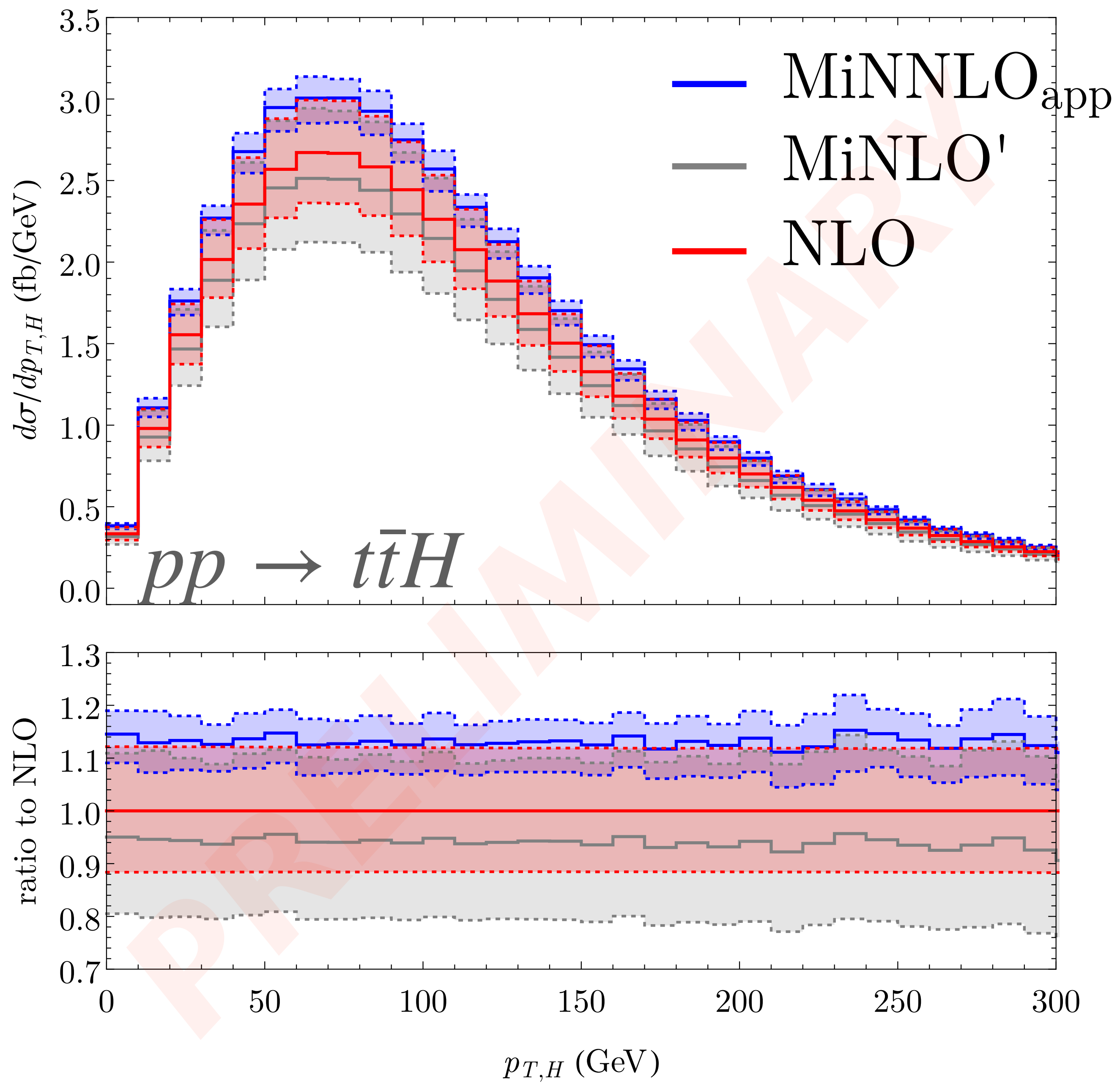
High multiplicity final state and heavy partons at NNLO+PS

Ongoing efforts!
Mazzitelli, Wiesemann [in progress]



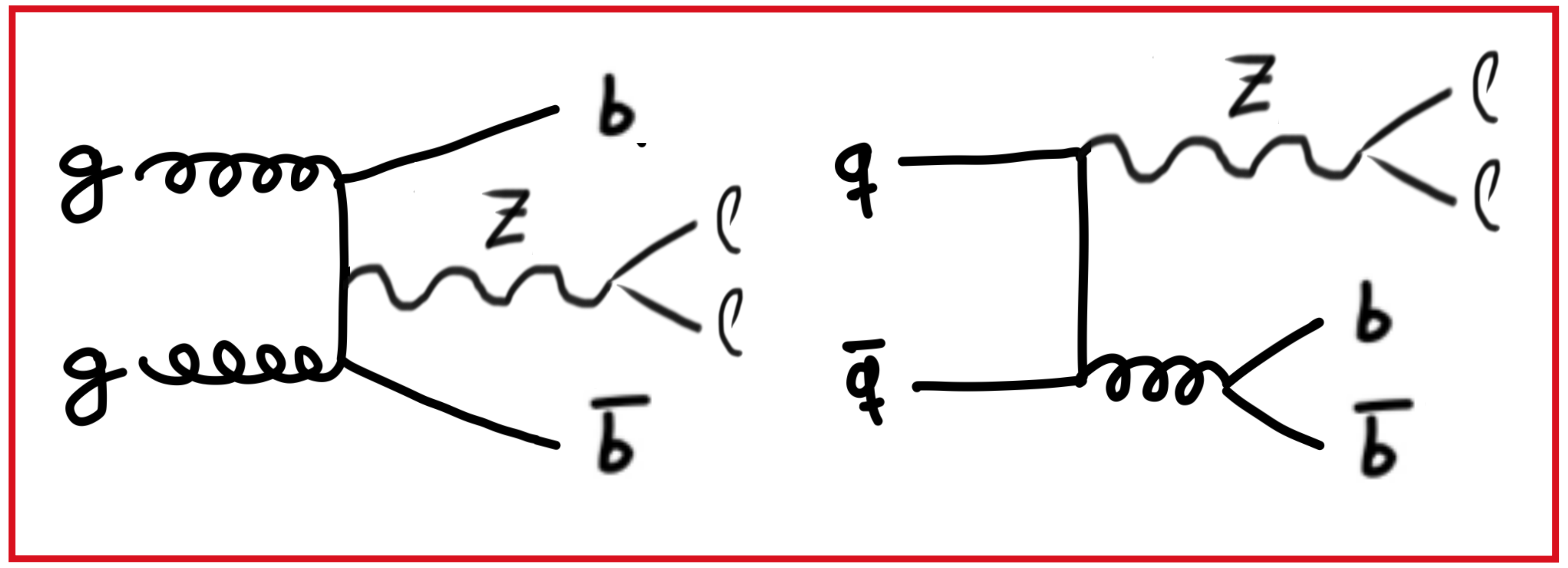


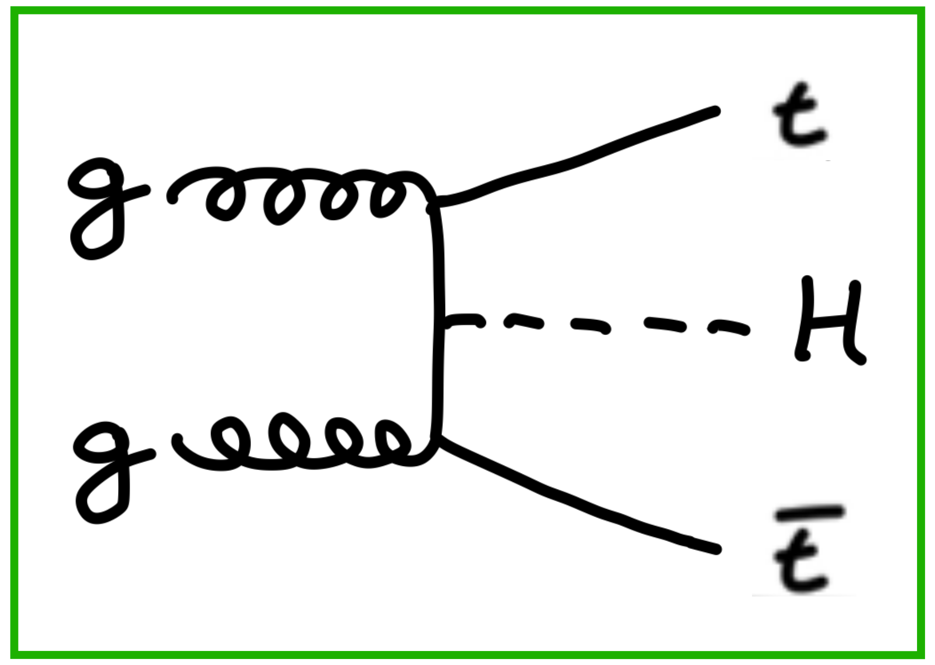


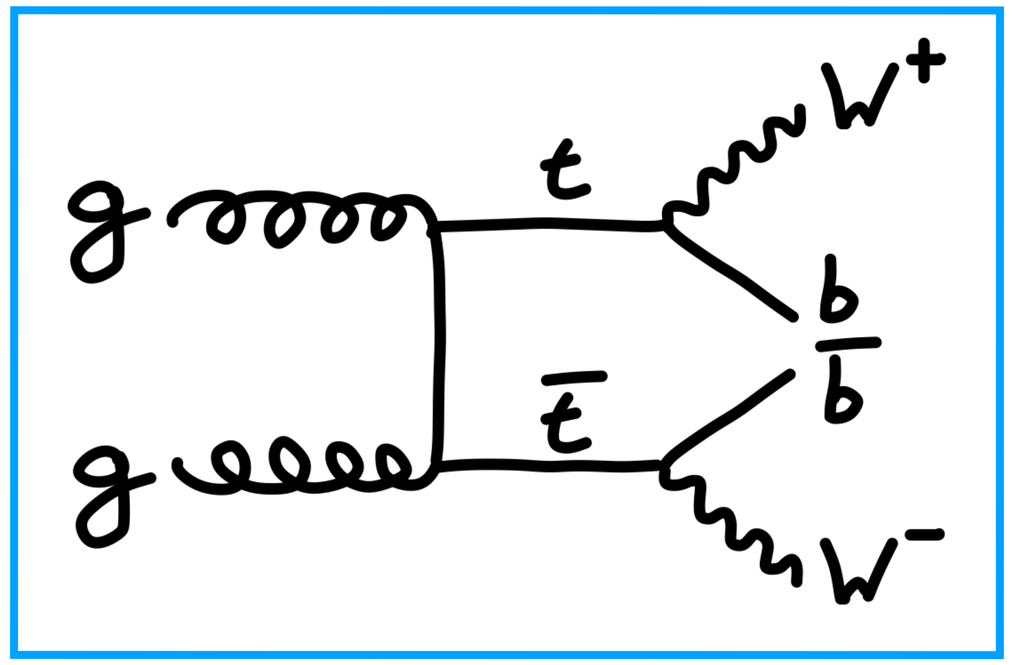


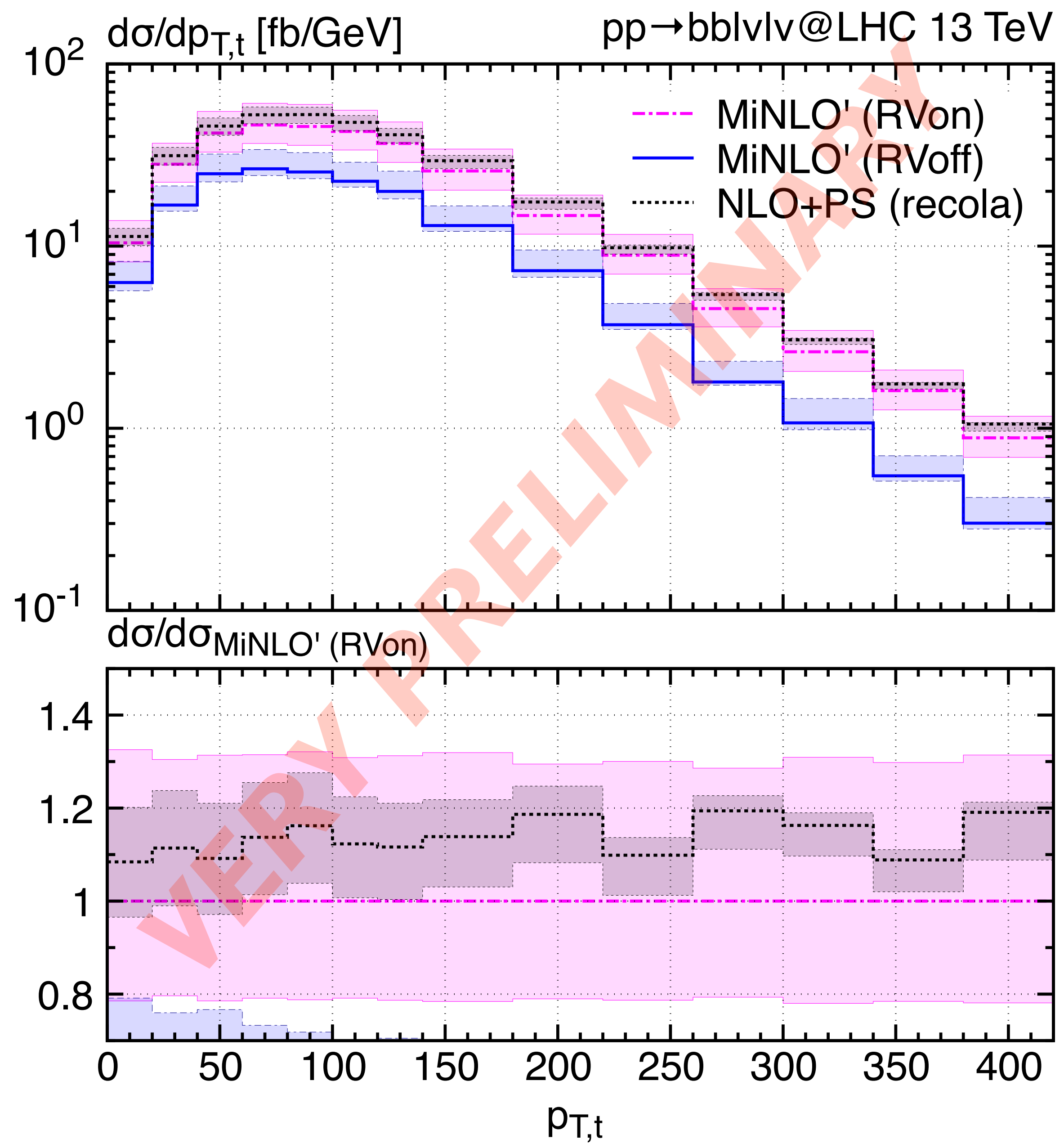
High multiplicity final state and heavy partons at NNLO+PS

Ongoing efforts!
Biello, Mazzitelli, Signorile-Signorile, Wiesemann, Zanderighi [in progress]

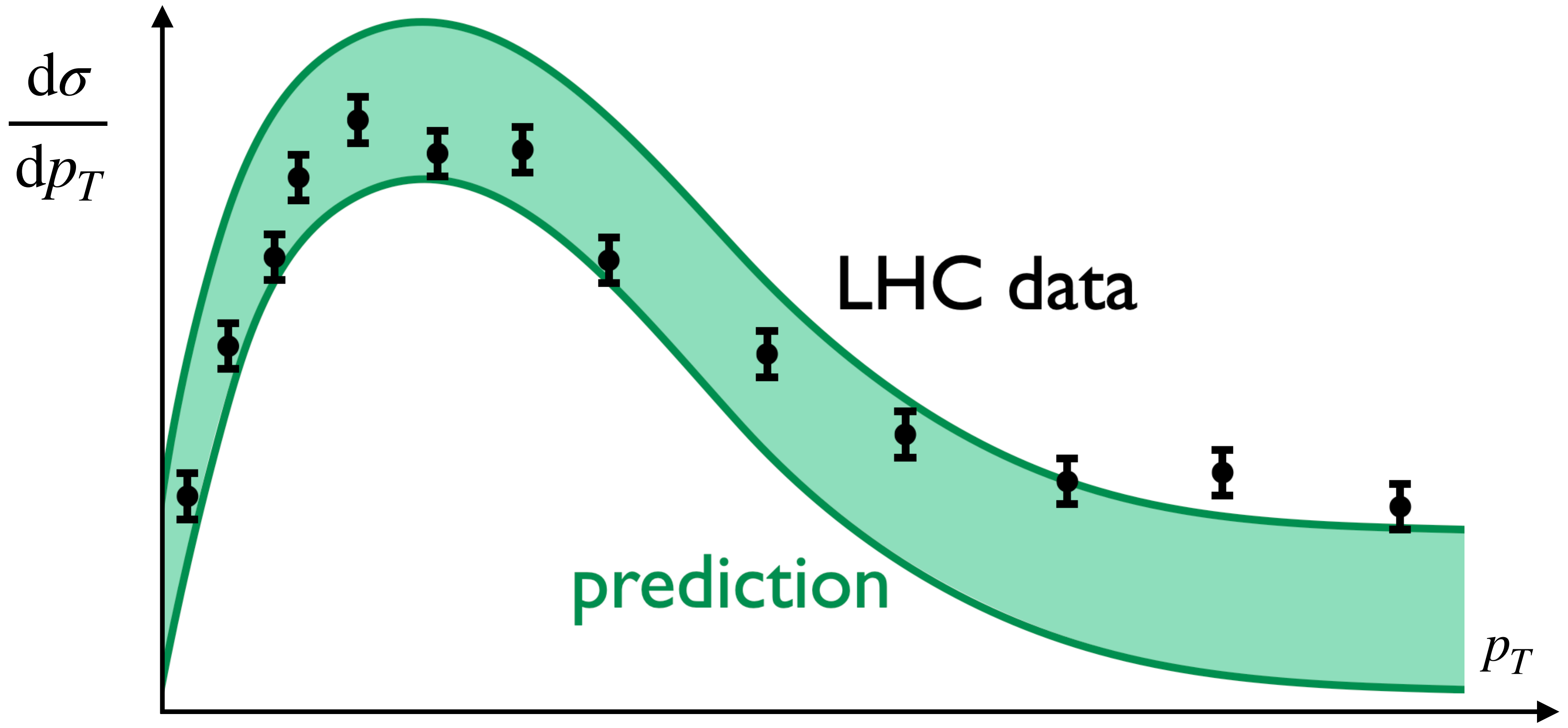


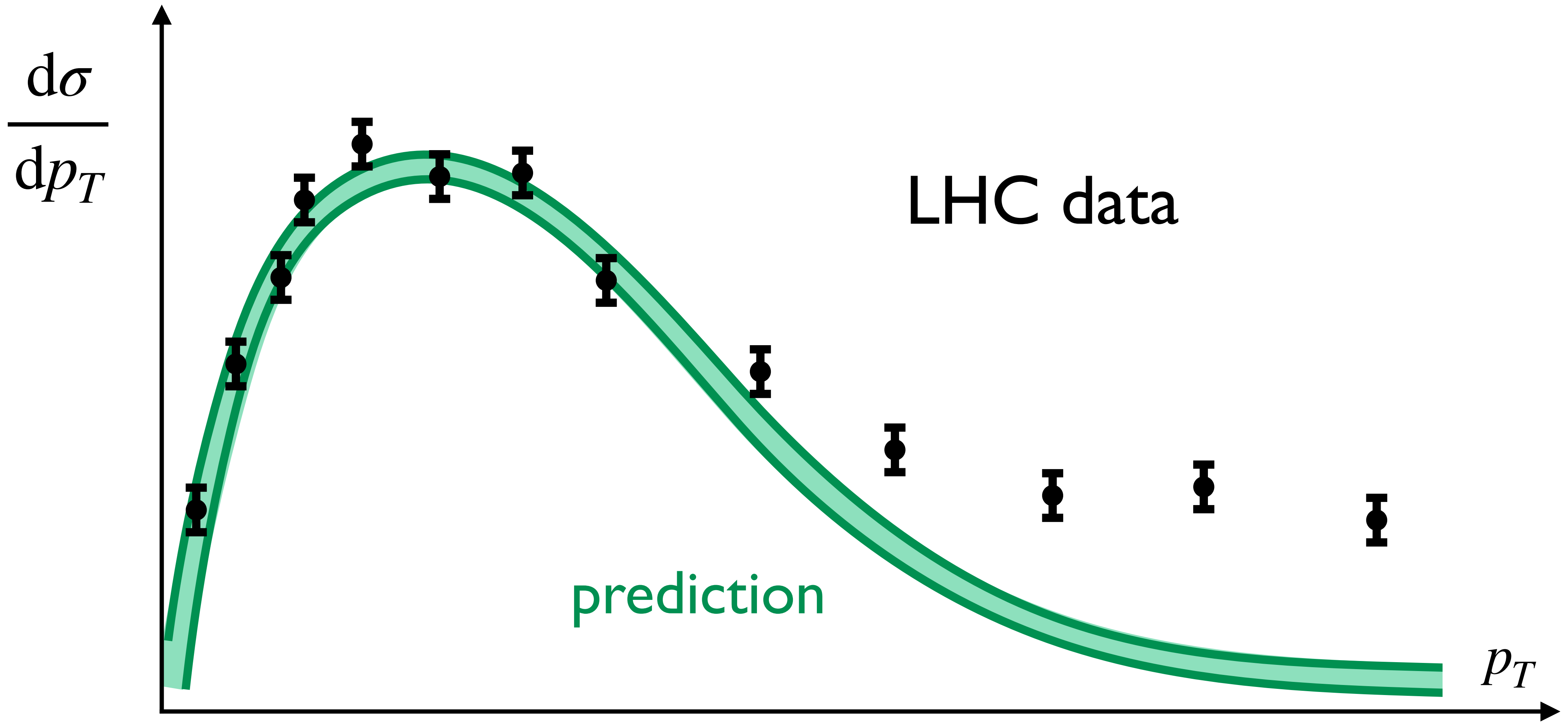


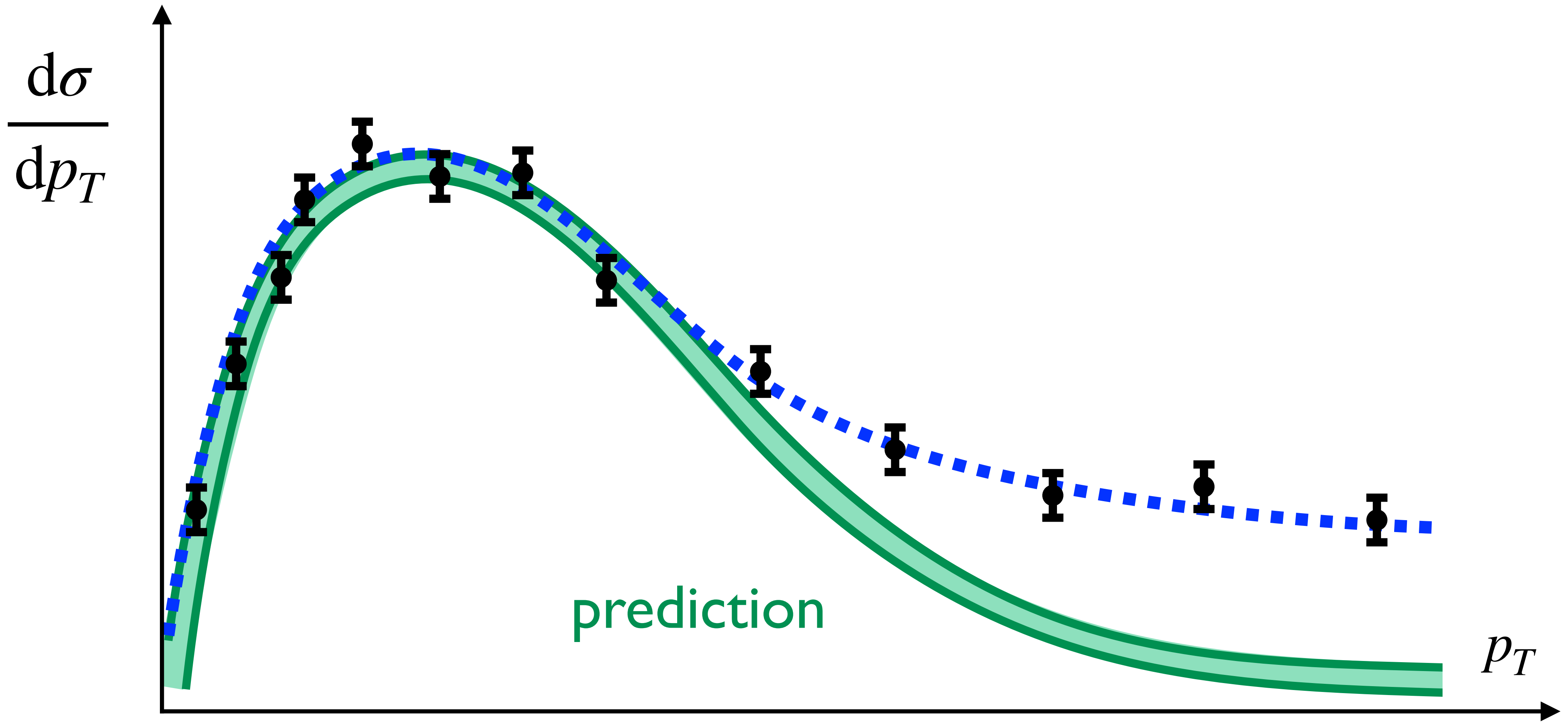


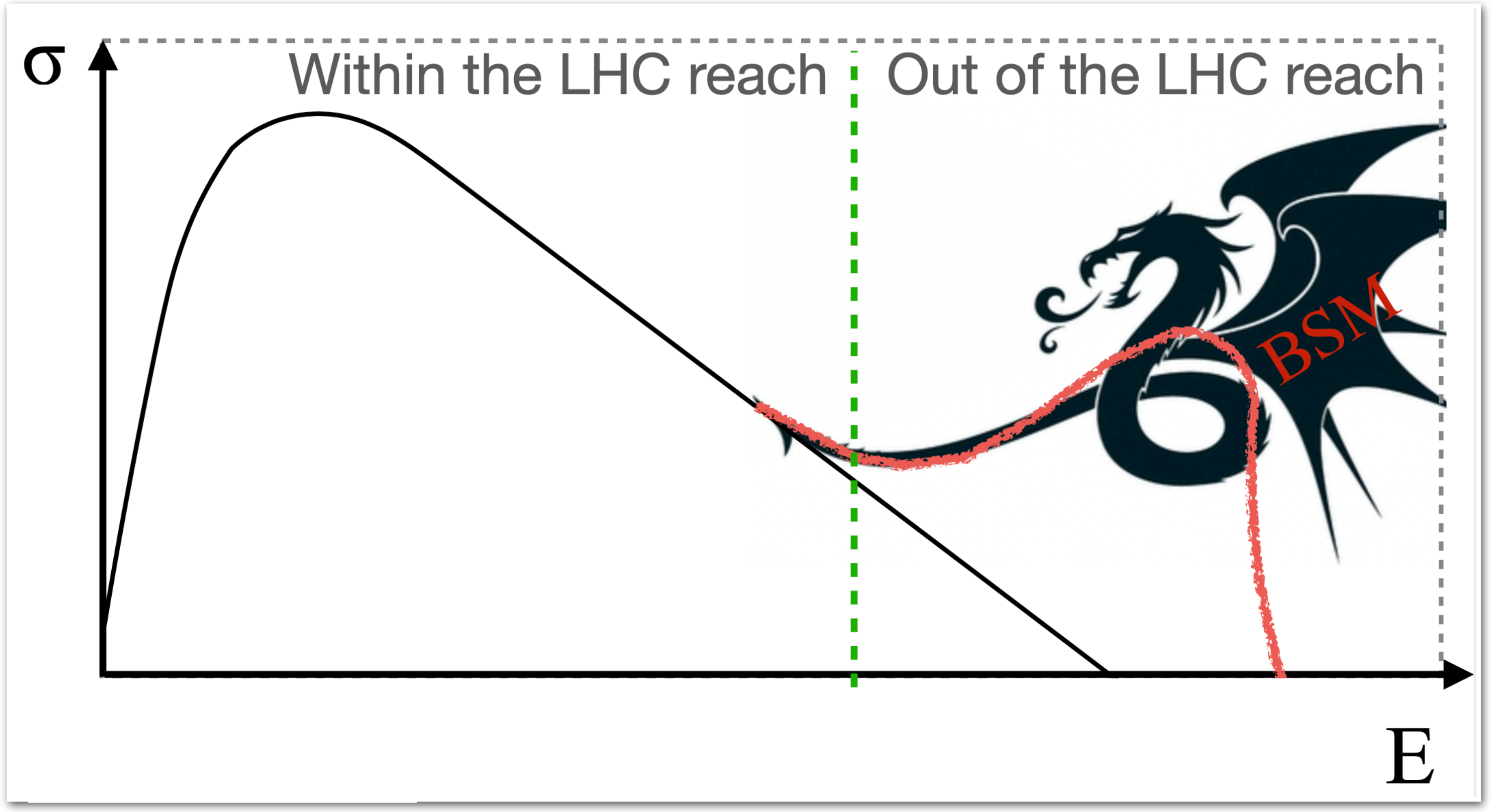


Not only standard model…









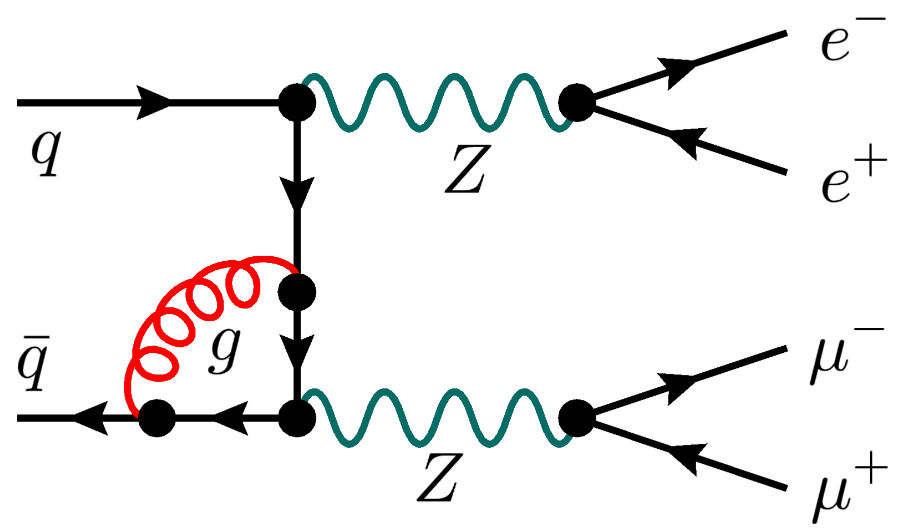
[D. Pagani]

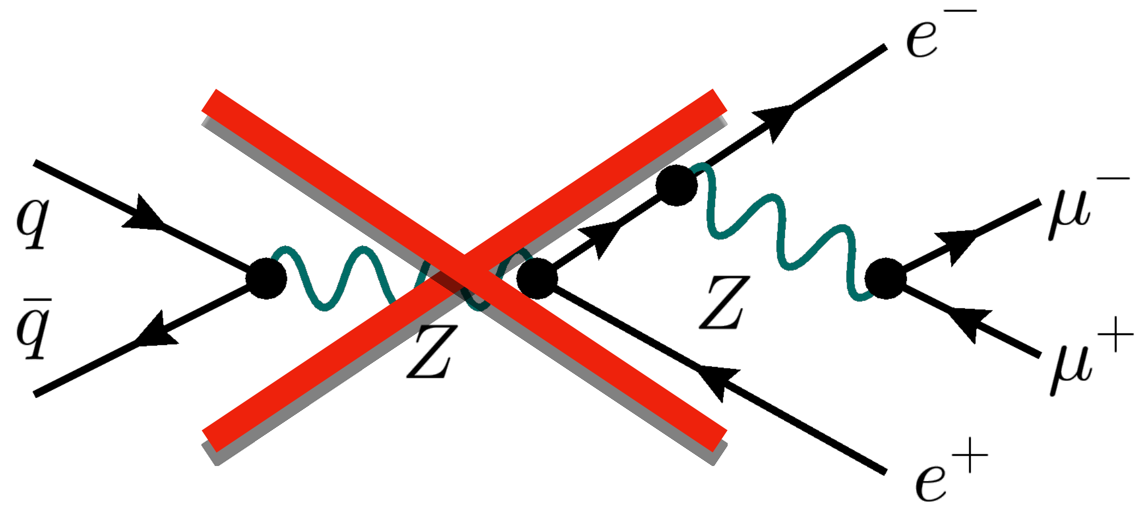
SMEFT effects in polarised diboson production

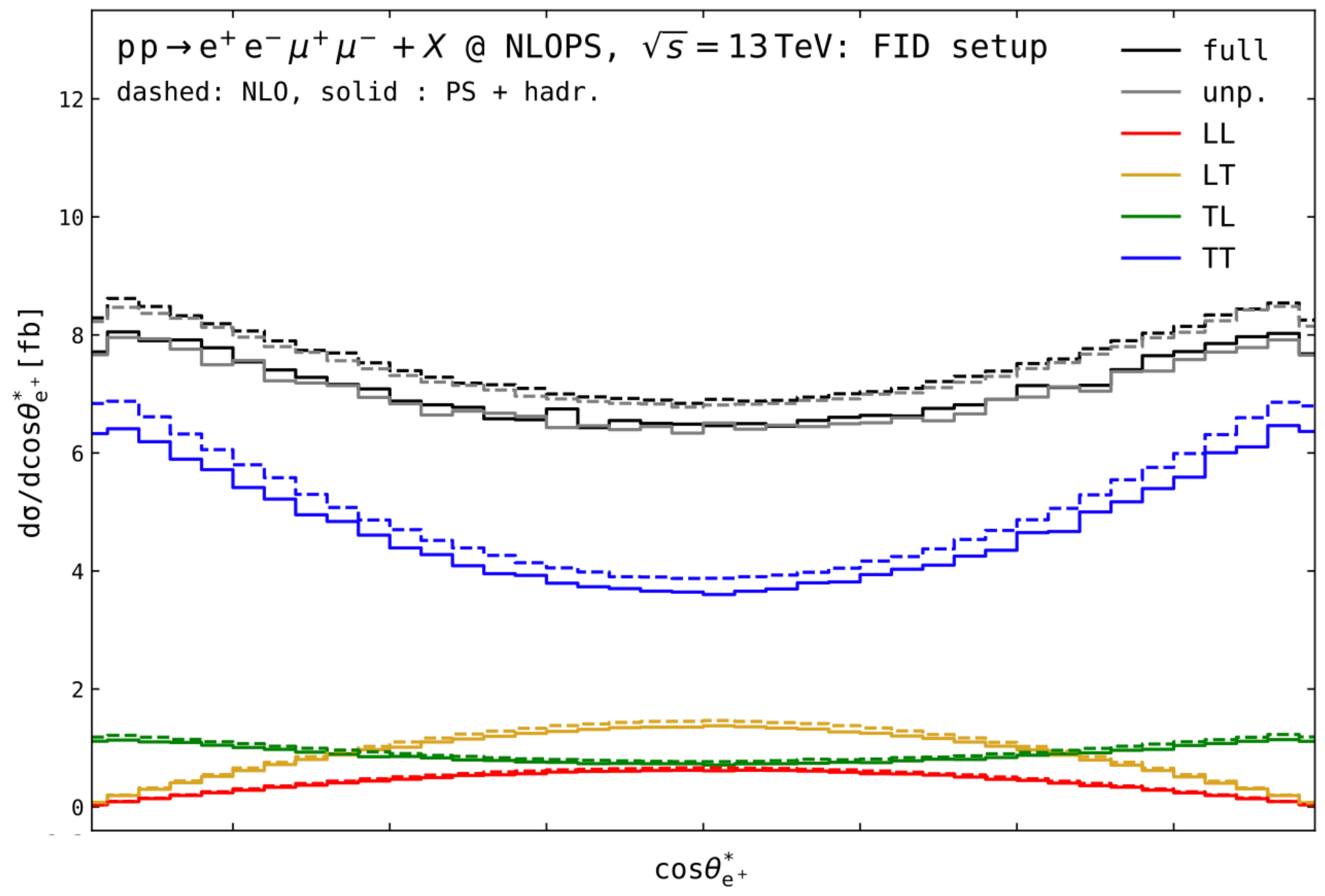
❖ **Goal: model the production and decay of polarised bosons including SMEFT effects**

❖ **Motivation:**

1. Probe Standard Model gauge and Higgs sectors → SMEFT effects can be enhanced in some polarisation configurations
2. Develop/test new techniques to isolate polarisation effects (double-pole approximation)







Decay angle of e^+ in the Z boson rest frame, w.r.t. the direction of the Z in the VV-CM

❖ **Work in progress/done:**

✔ Modelling of polarised dibosons in SM

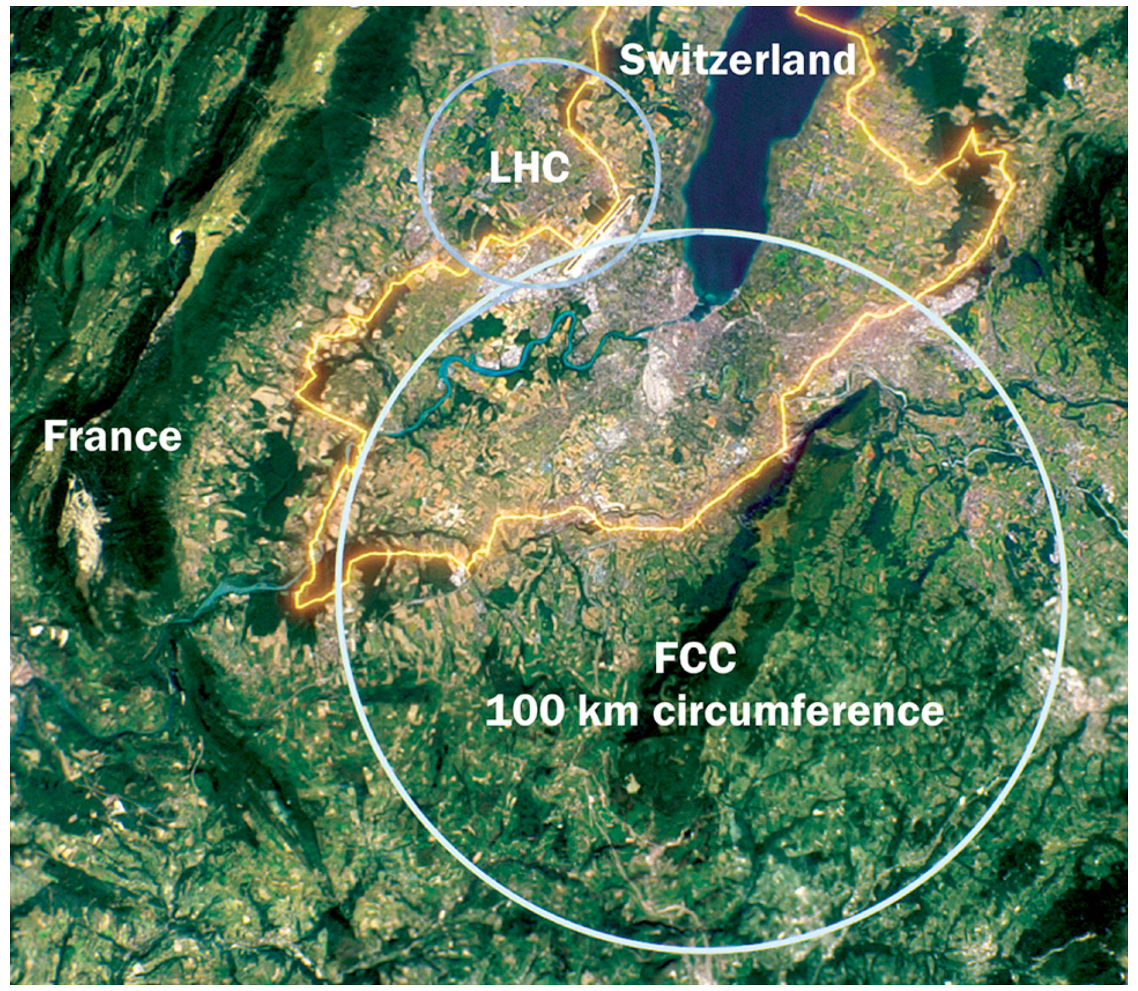
Pellicciolі, Zanderighi [2311.05220]

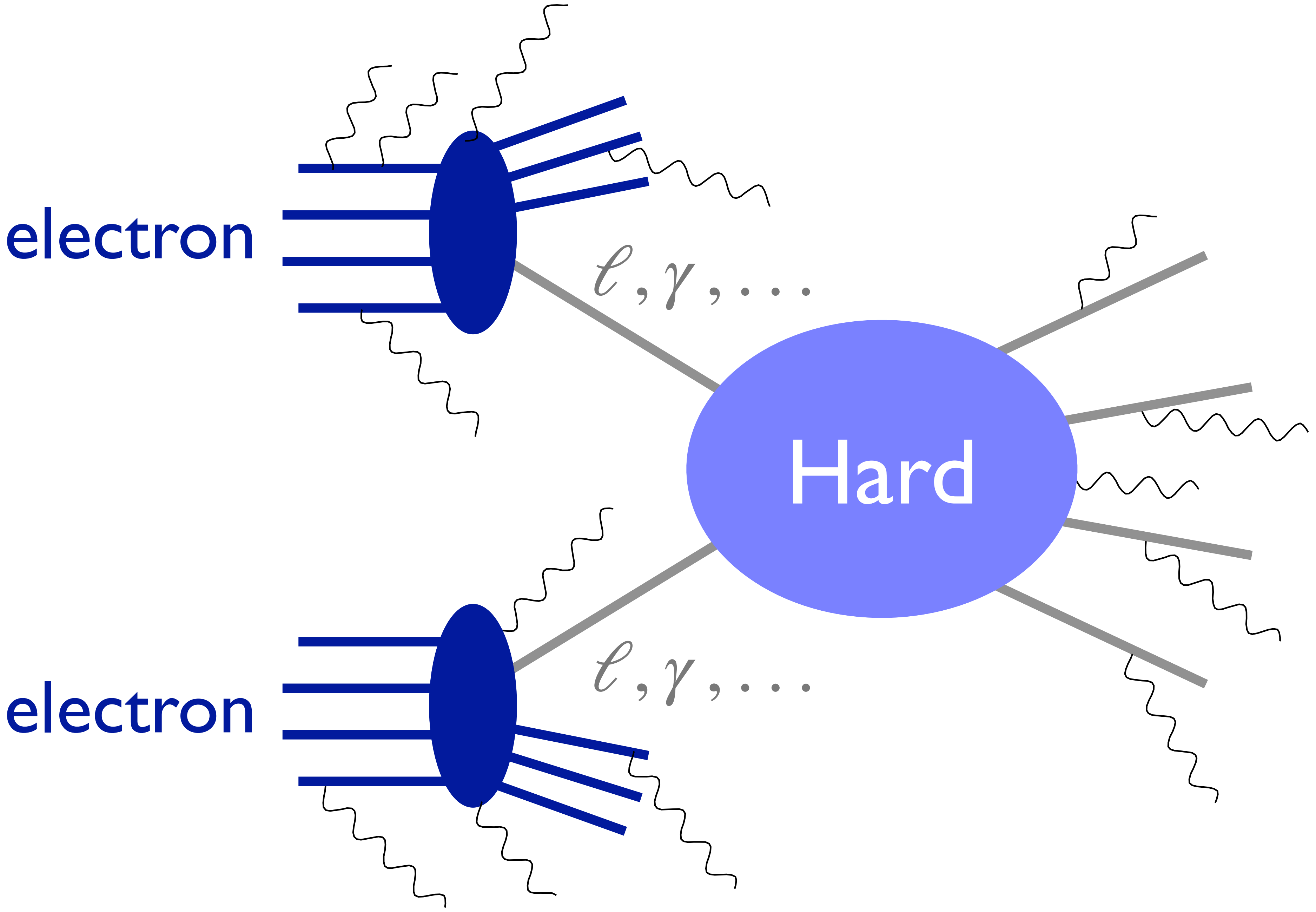
✔ Modelling of polarised dibosons in SMEFT

✔ Implementation in the **POWHEG-BOX-RES** framework

Ongoing efforts!
Haisch, Linder, Pellicciolі, Zanderighi [in progress]

… not only hadron collisions…



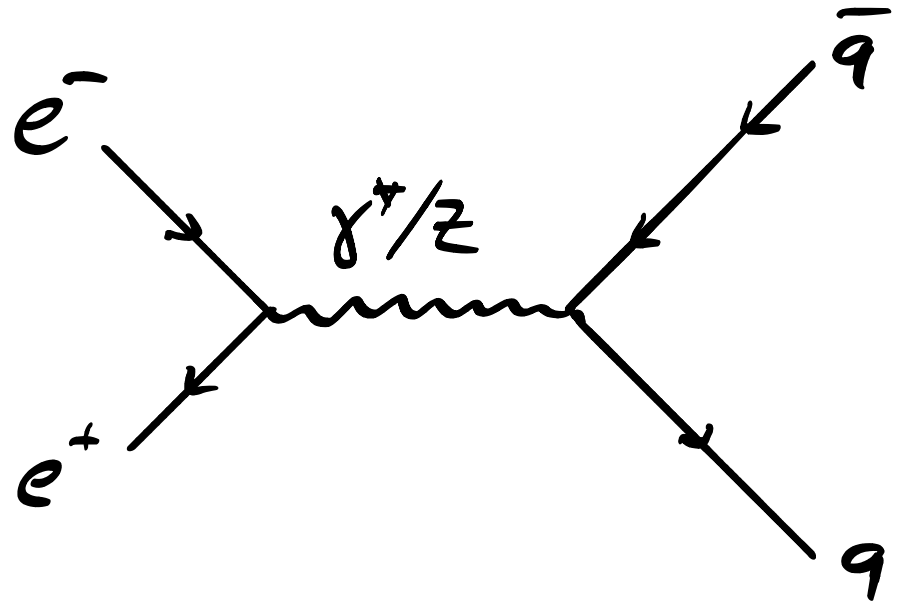


Predictions for lepton colliders

❖ **Goal: accurate event generator lepton collisions [crucial in view of future colliders]**

❖ **Motivation:**

1. Lepton collider phenomenology, quark mass effects, electroweak corrections
2. Improving our understanding of heavy-flavour hadron production



Light jet production in e^+e^- collisions with MiNNLO$_{PS}$

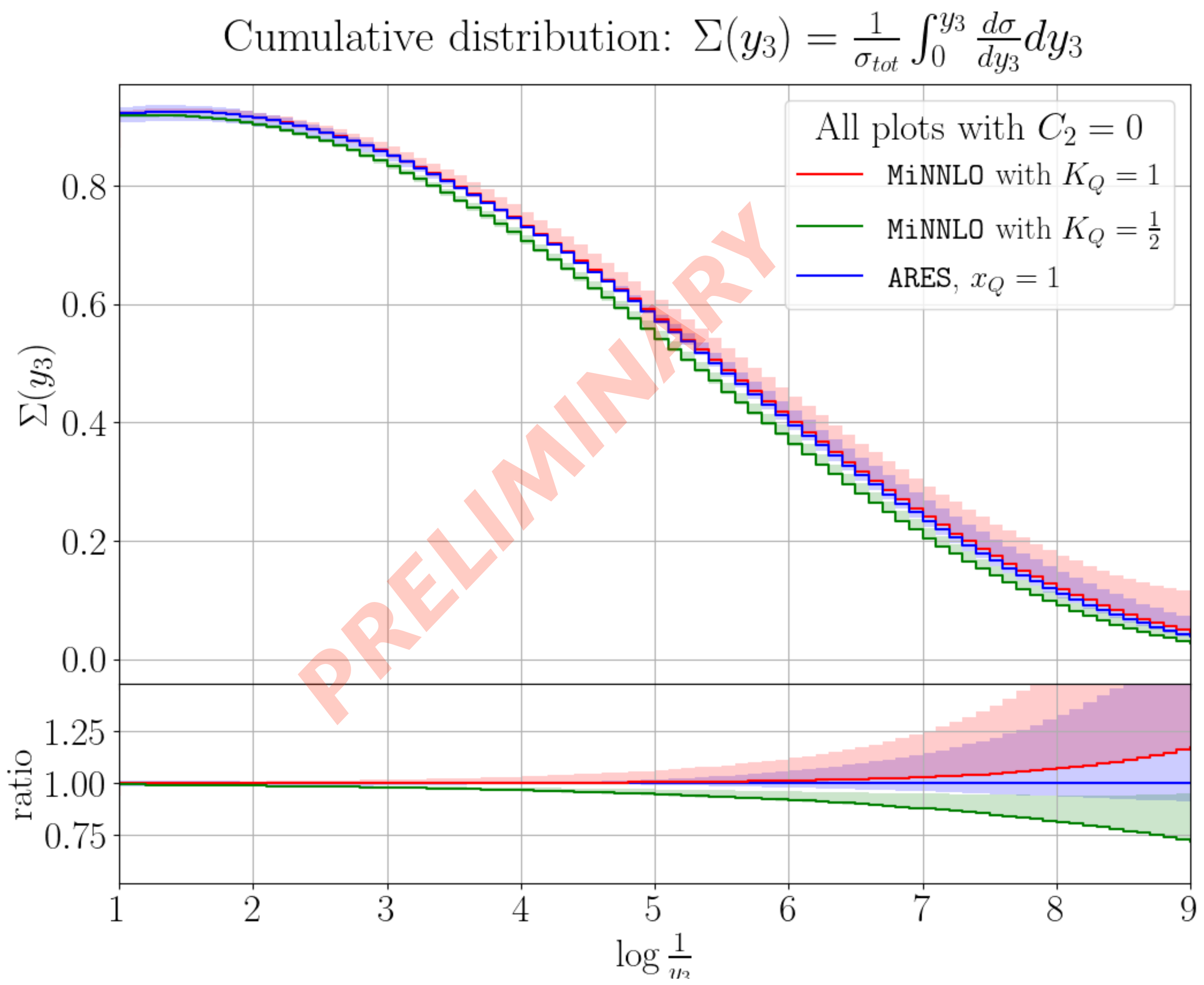
❖ **Work in progress:** many non-trivial steps required, both from the technical and the conceptual point of view:

✓ Requires a resummation formula for a reference observable

✓ Combine fixed order + resummation

Ongoing efforts!
König, Schorer, Wiesemann, Zanderighi [in progress]

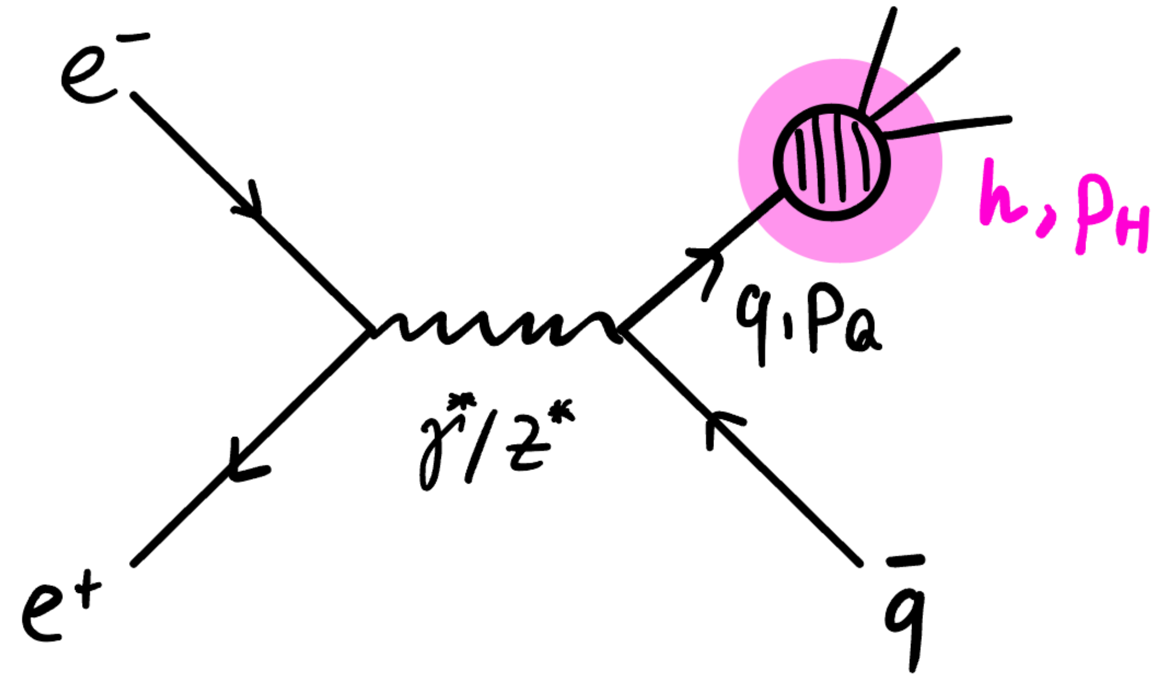
Comparison of resummation contributions



y_3= 3jet resolution parameter

Predictions for lepton colliders

❖ **Goal: accurate event generator lepton collisions [crucial in view of future colliders]**



❖ **Motivation:**

1. Lepton collider phenomenology, quark mass effects, electroweak corrections
2. Improving our understanding of heavy-flavour hadron production

Heavy-flavour hadron production

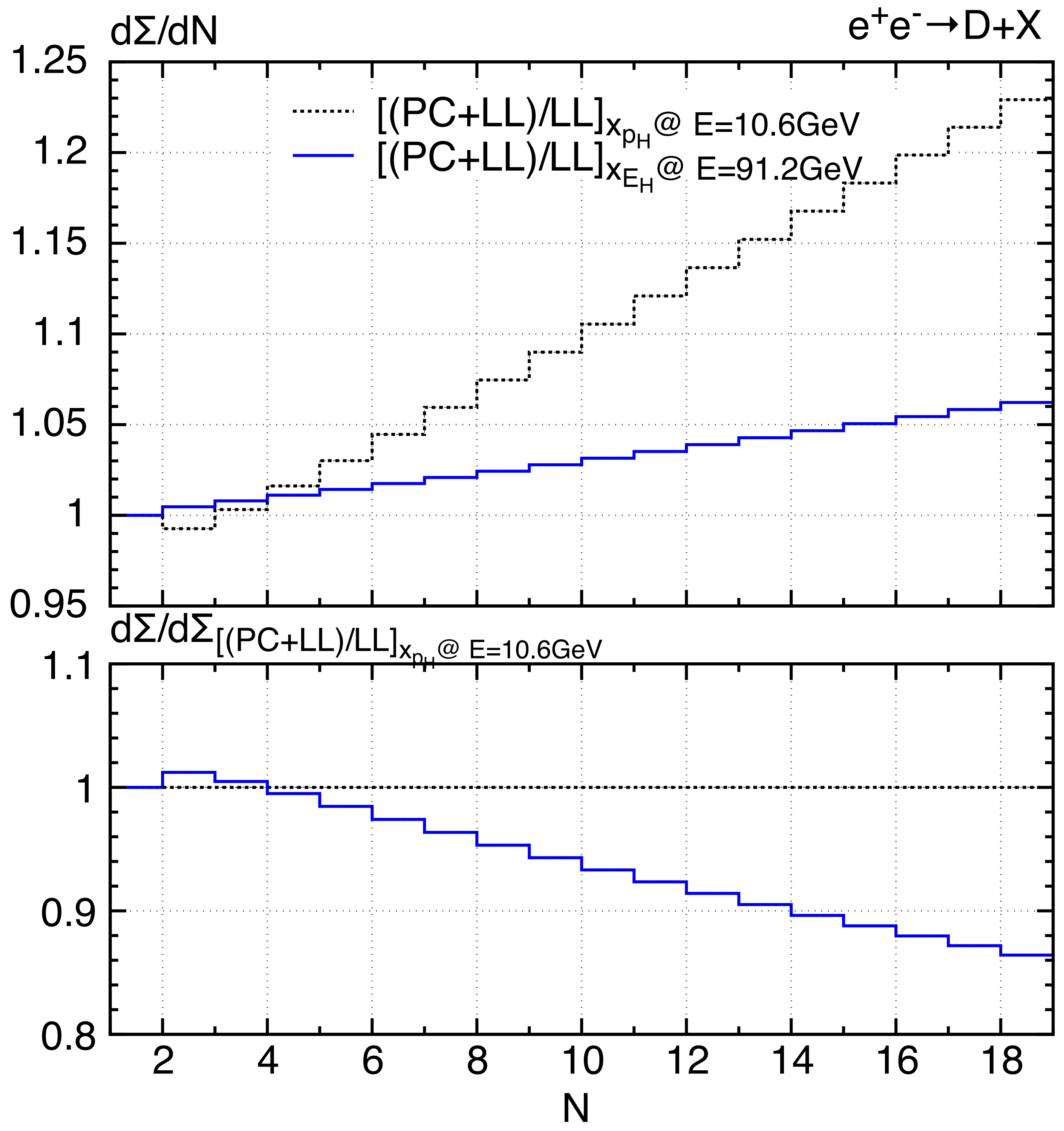
❖ **Work in progress:**

✓ A technique to combine massive and massless fragmentation approaches

✓ As a test case, applied to differential quantities in $e^+ + e^- \to H_Q + X$

✓ Results for D-hadron production at different CoM energies (large N = large $|p_H|$)

Ongoing efforts!
Ahmadova, Gauld [in progress]



Belle vs LEP

Large effects

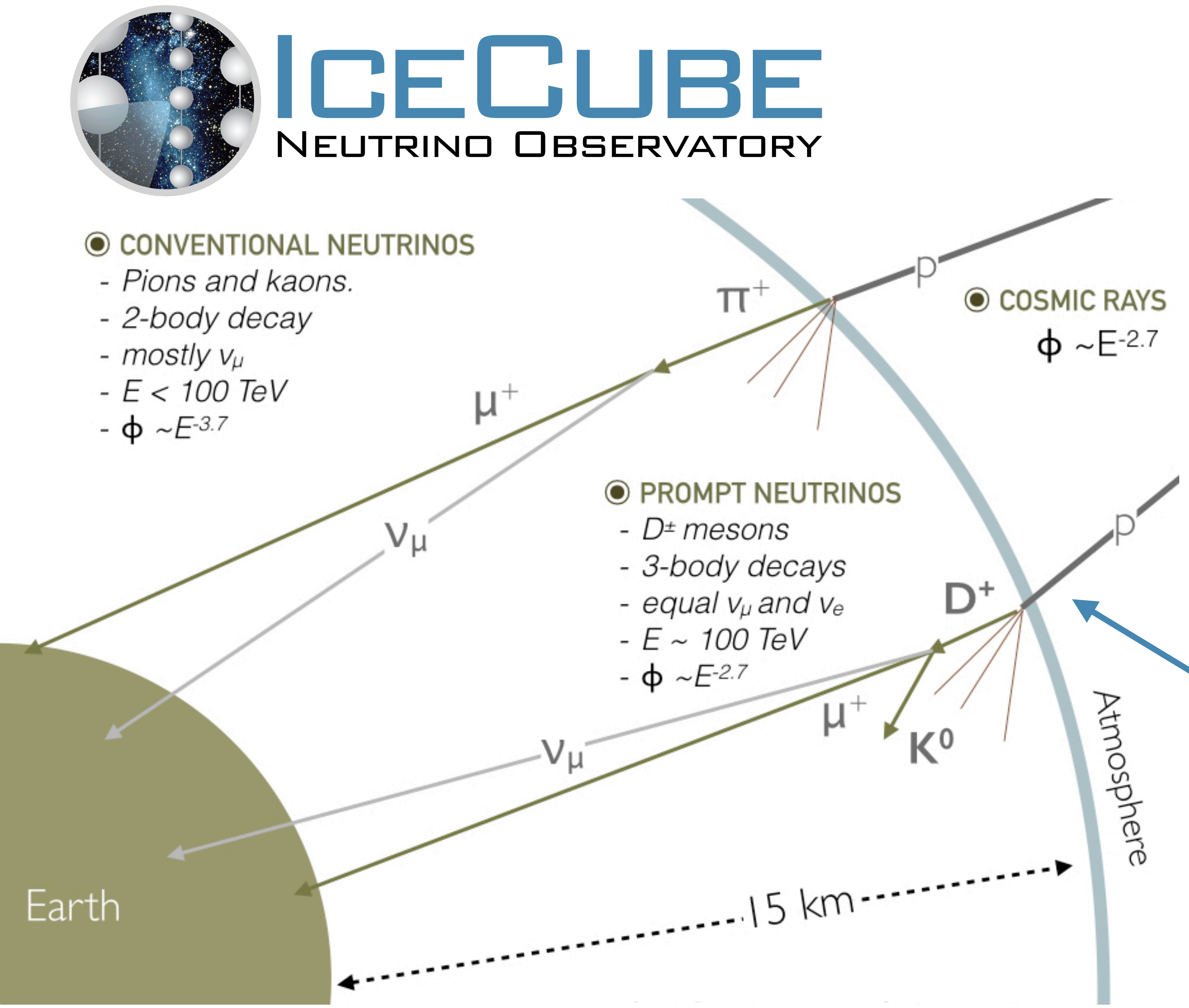
$$|p_H| \sim \frac{1}{2} E_{\rm cms}$$

combined approach
Mass corrections ~15%

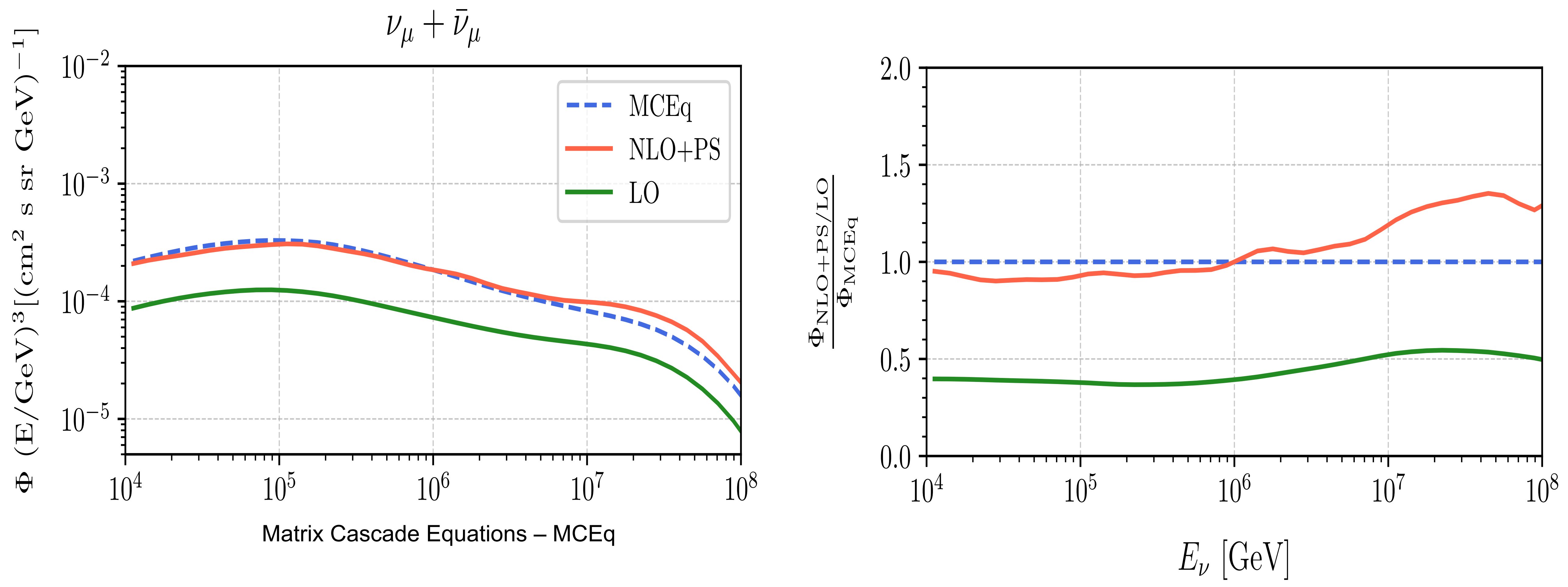
Applications beyond the LHC

- **Goal: prompt neutrino flux @ LO/NLO+PS**

- **Motivation:** Astrophysical neutrinos are important cosmic messengers. Atmospheric neutrinos form a significant background to the signal of astrophysical neutrinos



Particle propagation in the atmosphere



Ongoing efforts!
Mahr, Gauld, Wiesemann [in progress]

simulate prompt atmospheric neutrino flux (dominant background) with NNLO+PS for $pH \to c\bar{c}\ (\to D^+ + X)$

Conclusions:

- ✓ **I have presented a very limited number of studies that are carried out by the group. The general picture is way more extended**
- ✓ **Incredibly rich research program**
- ✓ Cutting edge results in a large variety of processes, accounting for different aspects of physics at colliders and beyond

An event generator for neutrino-induced Deep Inelastic Scattering and applications to neutrino astronomy

Silvia Ferrario Ravasio[1,a], Rhorry Gauld[2,b], Barbara Jäger[3,c], Alexander Karlberg[1,d], Giulia Zanderighi[2,4,e]

[arXiv: 2407.03894]

Zero-jettiness soft function to third order in perturbative QCD

Daniel Baranowski,[1,*] Maximilian Delto,[2,†] Kirill Melnikov,[3,‡] Andrey Pikelner,[3,§] and Chen-Yu Wang[4,¶]

[arXiv: 2409.11042]

Time-Like Heavy-Flavour Thresholds for Fragmentation Functions: the Light-Quark Matching Condition at NNLO

Christian Biello[a,1], Leonardo Bonino[b,2]

[arXiv: 2407.07623]

Status of QCD precision predictions for Drell-Yan processes

[arXiv: 2405.19714]

S. Alekhin[a], S. Amoroso[b], L. Buonocore[c], A. Huss[c], S. Kallweit[d], A. Kardos[e,f], J. Michel[g,h], S. Moch[a], F. Petriello[i,j], L. Rottoli[d], Z. Trócsányi[f,e], and M. Wiesemann[k]

The photon parton distribution function: updates and applications

Aneesh Manohar, Paolo Nason, Gavin Salam, and Giulia Zanderighi[1]

[arXiv: 2408.12719]

Testing the Neutrino Content of the Muon at Muon Colliders

[arXiv: 2410.21383]

Rodolfo Capdevilla,[1] Francesco Garosi,[2,3,4] David Marzocca,[4] Bernd Stechauner[5,6]

Renormalization of the pseudoscalar operator at four loops in QCD

[arXiv: 2410.18674]

Long Chen[a], Michał Czakon[b], Marco Niggetiedt[c]

Mapping the SMEFT at High-Energy Colliders: from LEP and the (HL-)LHC to the FCC-ee

[arXiv: 2404.12809]

Eugenia Celada,[a] Tommaso Giani,[b,c] Jaco ter Hoeve,[b,c] Luca Mantani,[d] Juan Rojo,[b,c] Alejo N. Rossia,[a] Marion O. A. Thomas,[a] and Eleni Vryonidou[a]

Next-to-soft threshold effects on Higgs boson production via bottom quark annihilation

[arXiv: 2409.01553]

Goutam Das[a] and Aparna Sankar[b,c]

The list of collaborators can't fit a page...

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Backup

Interdisciplinary applications of NLO+PS matching: neutrino astronomy

An event generator for neutrino-induced Deep Inelastic Scattering and applications to neutrino astronomy

Silvia Ferrario Ravasio[1,a], **Rhorry Gauld**[2,b], **Barbara Jäger**[3,c], **Alexander Karlberg**[1,d], **Giulia Zanderighi**[2,4,e]

[1]Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland
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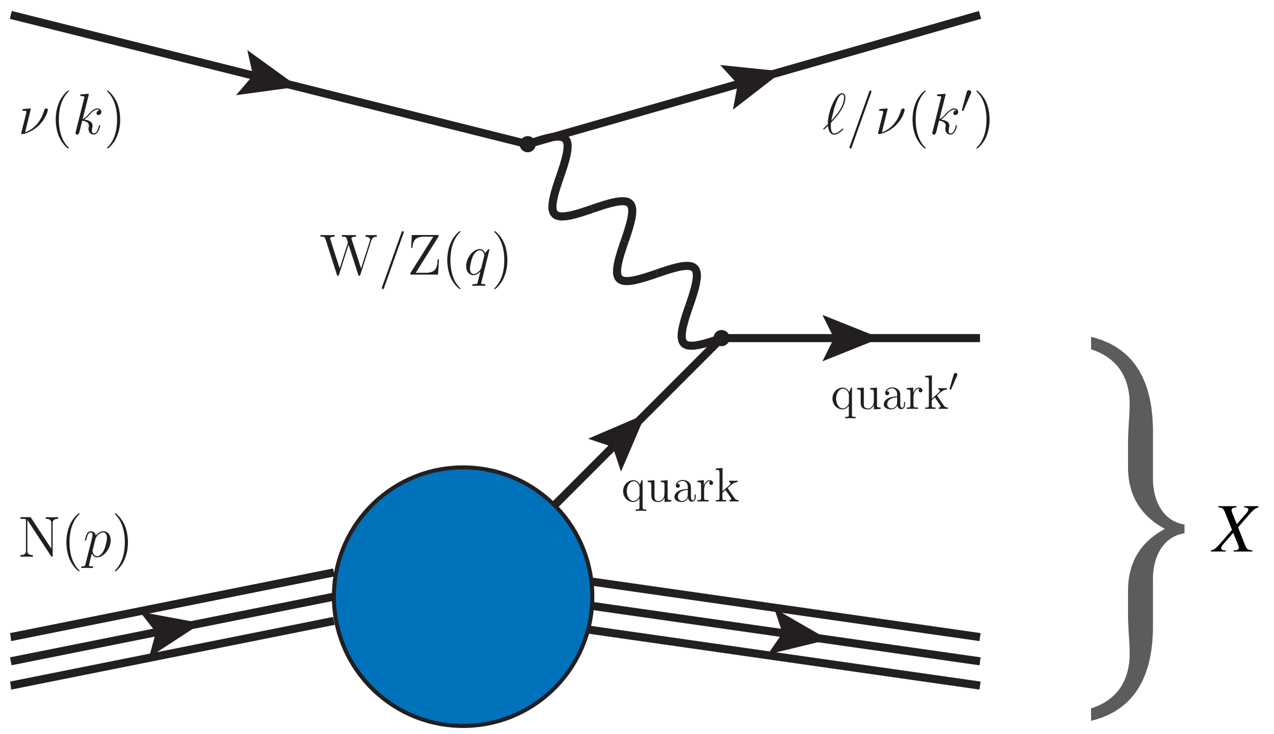
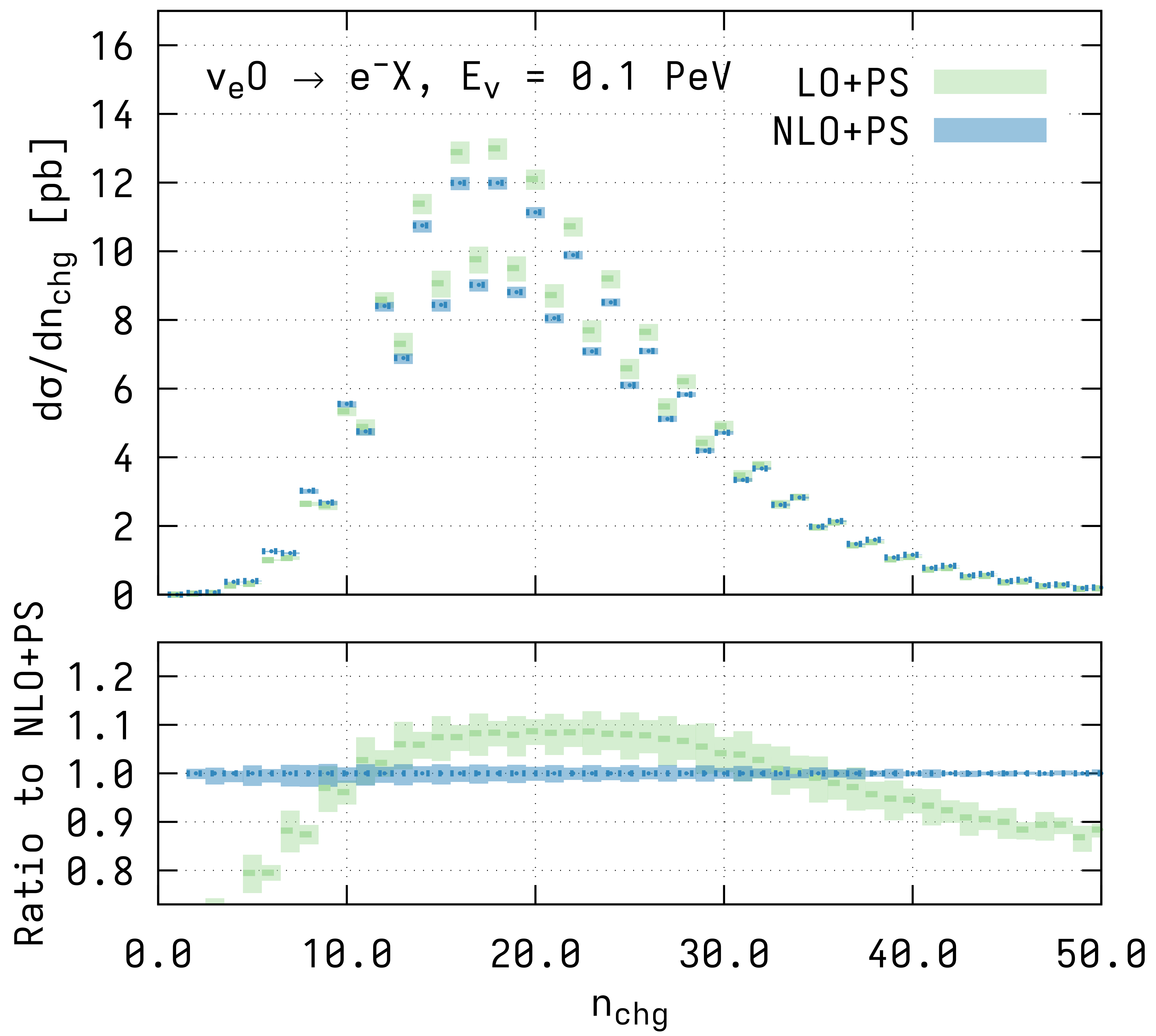
arXiv: 2407.03894



fully exclusive description



charged particle distribution

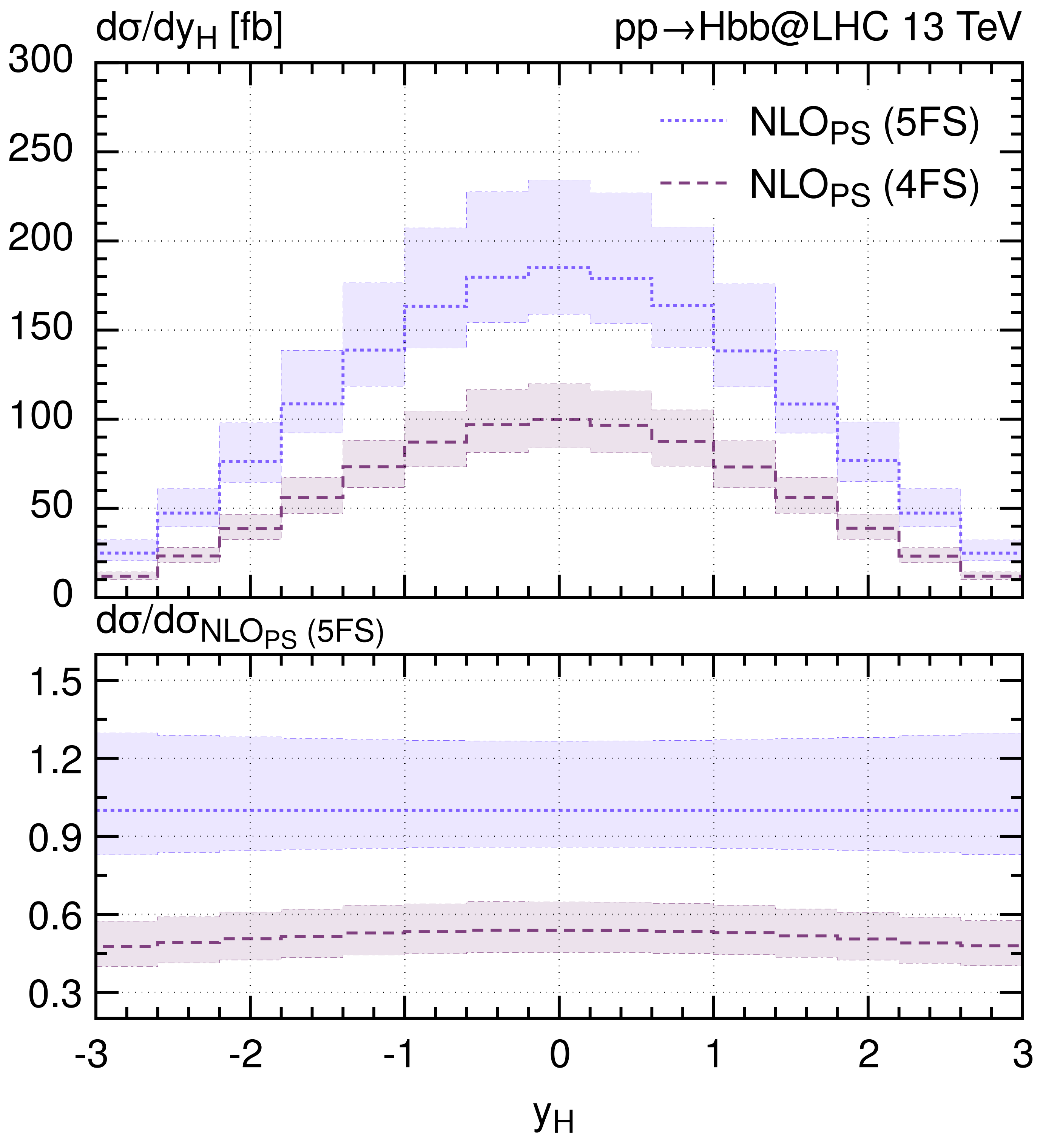
Applied to the case of PeV neutrino interactions with ice/water nuclei

Here the 'oscillating' behaviour due to scattering on either neutron / proton (charge conservation)

Bottom-mass effects in Higgs production: $b\bar{b} \to H$ vs $b\bar{b}H$

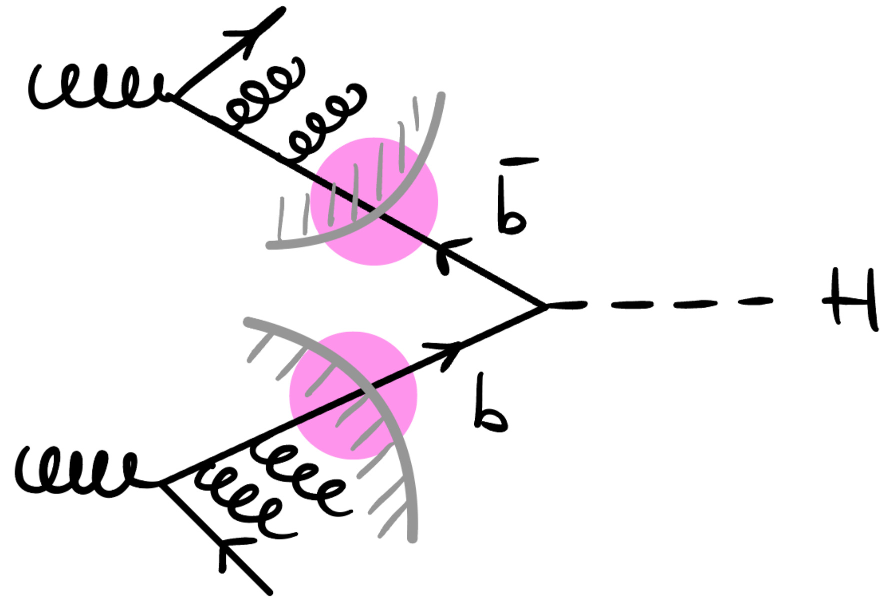
- **Goal: account for massless-bottom Higgs production and associated H production with massive bottom at NNLO+PS**

- **Motivation:**
  1. Strong control on major background for HH searches
  2. Solving long-standing theoretical issues: significant differences have been observed in predictions in different schemes



5FS $\mathrm{NLO_{PS}}(m_H)$	$0.676(6)^{+27\%}_{-15\%}$ pb
4FS $\mathrm{NLO_{PS}}(m_H)$	$0.354(6)^{+20\%}_{-16\%}$ pb
4FS $\mathrm{NLO_{PS}}(\frac{H_T}{4})$	$0.385(3)^{+16\%}_{-14\%}$ pb

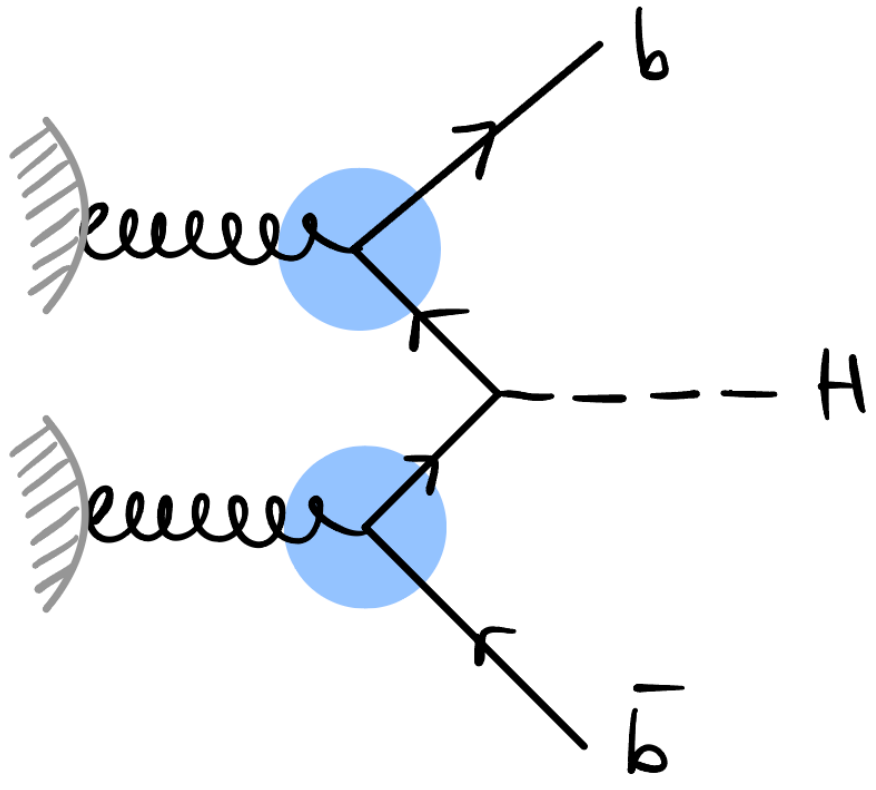
Wiesemann et al. ['14]
Jäger, Reina, Wackeroth ['15]



NLO improvement, but still not sufficient

NLO predictions have improved the agreement by 40%. The discrepancy has been artificially mitigated by tuning the renormalisation and, notably, the factorisation scale factors.

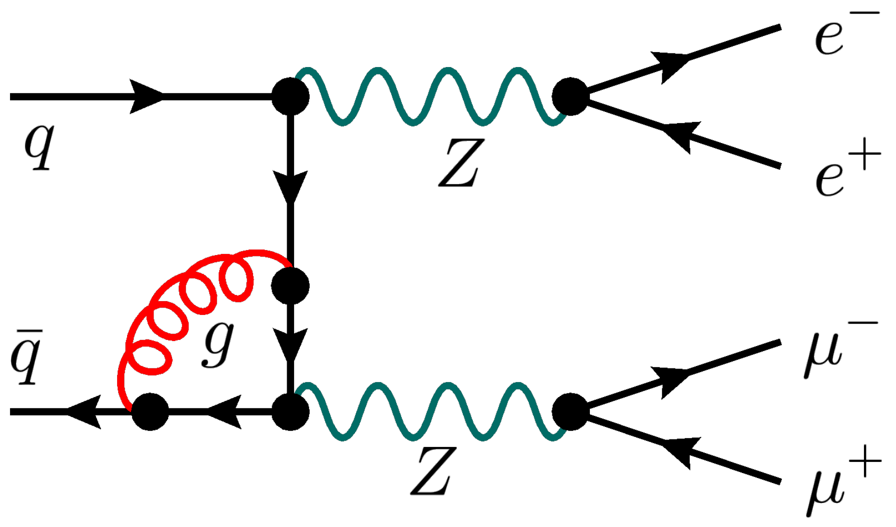
Our group performed the first NNLO comparison (matched with PS)

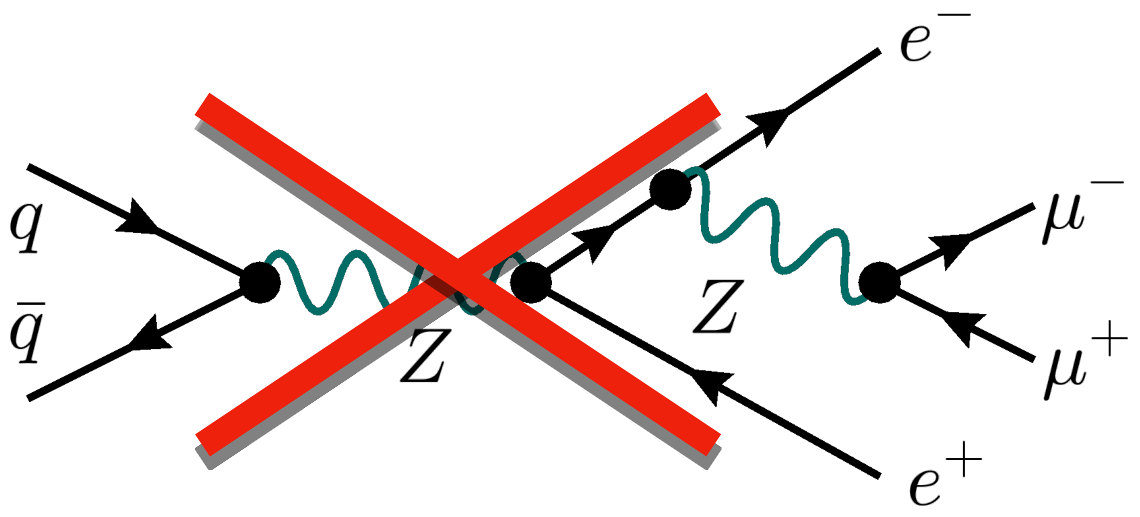


SMEFT effects in polarised diboson production

Uli Haisch, Jakob Linder, Giovanni Pelliccioli & Giulia Zanderighi

- **Goal**:
  - Production and decay of 2 polarised bosons including SMEFT effects in the POWHEG-BOX-RES framework
  - Probe the SM gauge and Higgs sectors
- Use the **Double pole approximation** to extract the polarised parts of the propagator

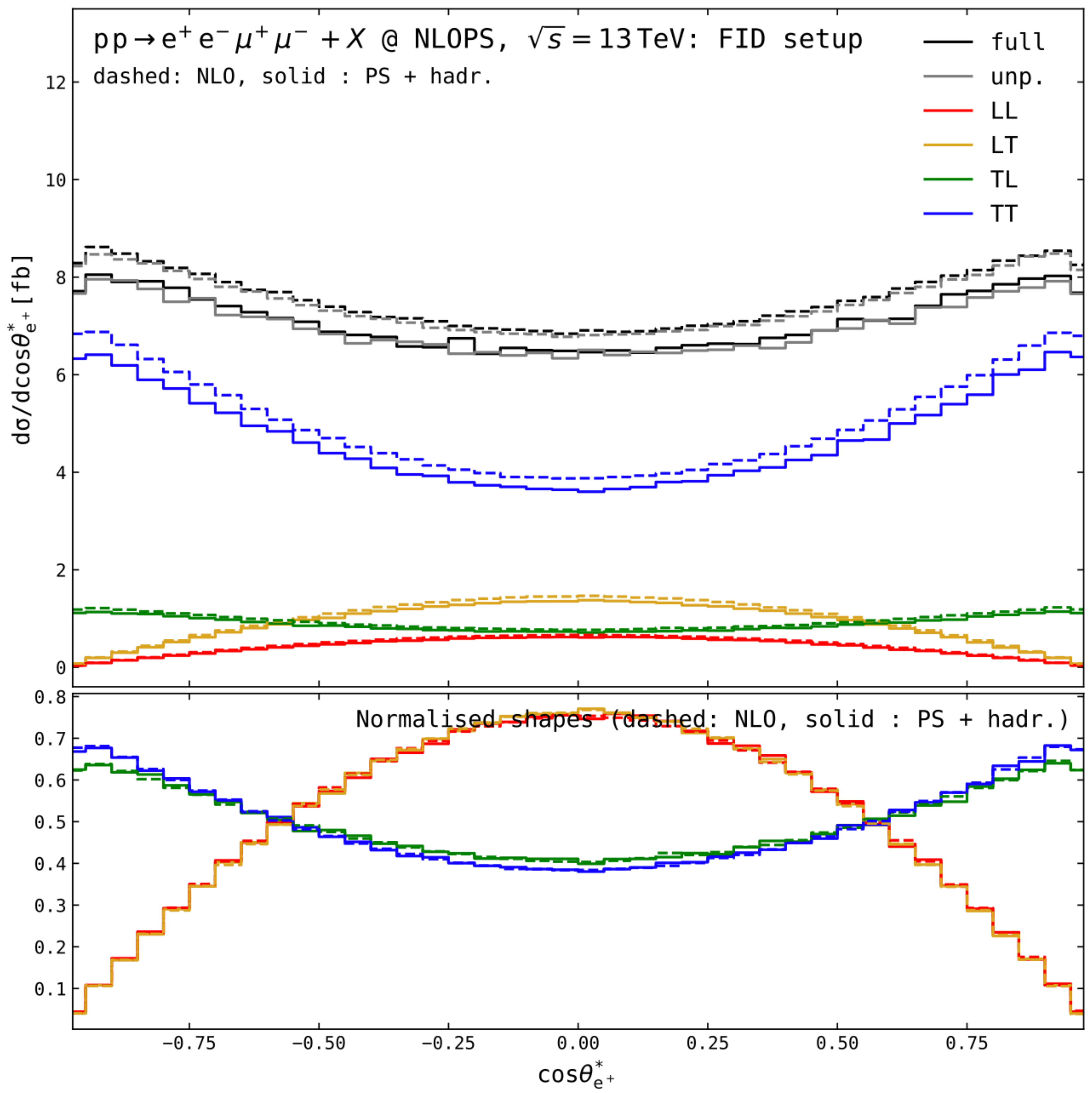




- Replace the Z propagators:

$$\frac{-g^{\mu\nu}}{k^2 - m_Z^2 + i\Gamma_Z m_Z} = \frac{\sum_\lambda \epsilon^{\mu}_{\lambda}(k)\epsilon^{*\nu}_{\lambda}(k)}{k^2 - m_Z^2 + i\Gamma_Z m_Z} \to \frac{\epsilon^{\mu}_{\lambda}(k)\epsilon^{*\nu}_{\lambda}(k)}{k^2 - m_Z^2 + i\Gamma_Z m_Z}$$

- **Status**:
  - Polarised dibosons in SM
  - Polarised dibosons including SMEFT
    - Implemented and currently being tested.



Decay angle of e^+ in the Z boson rest frame, w.r.t. the direction of the Z in the VV-CM