



Challenges in theory predictions

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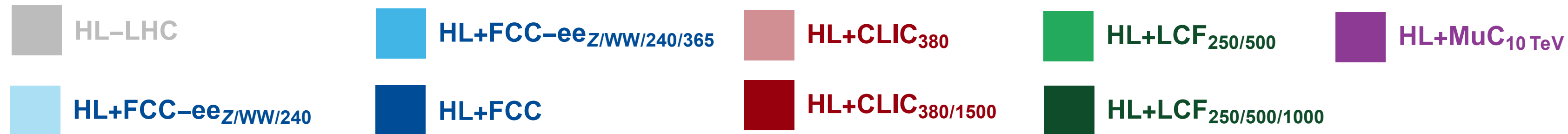


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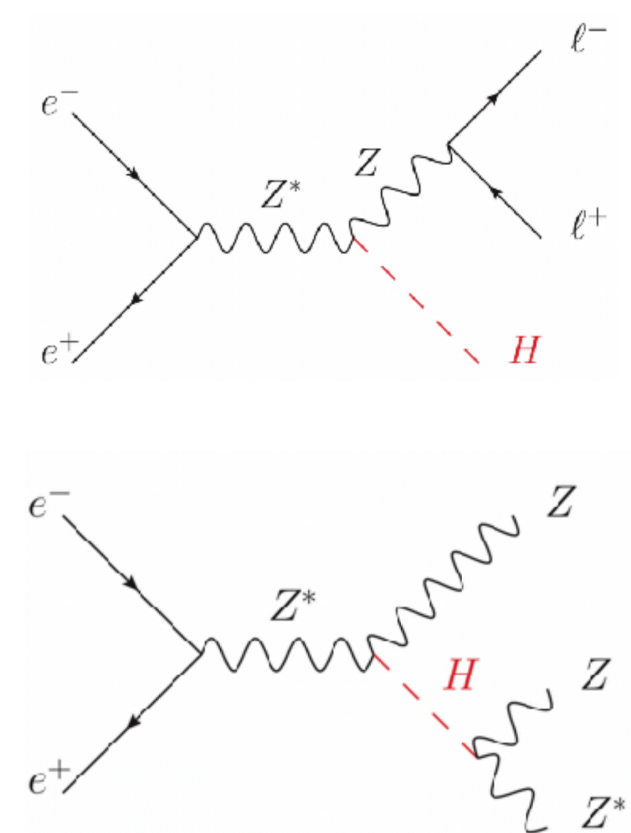
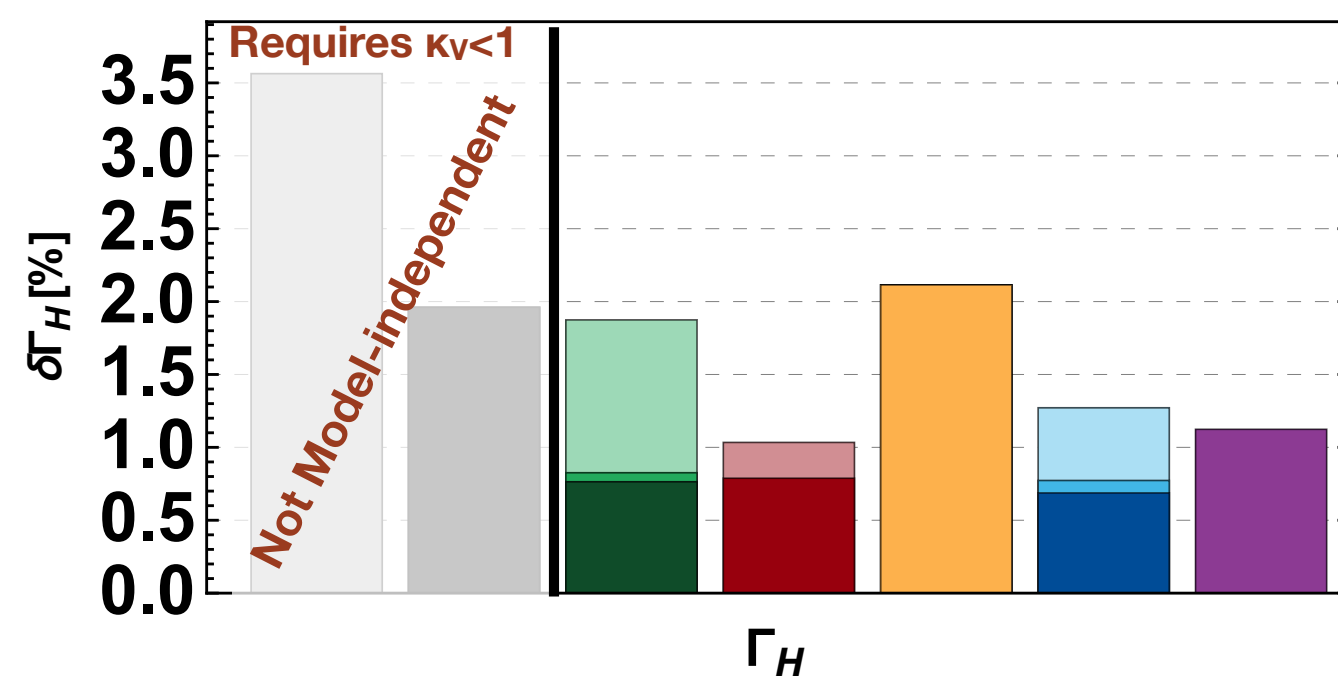
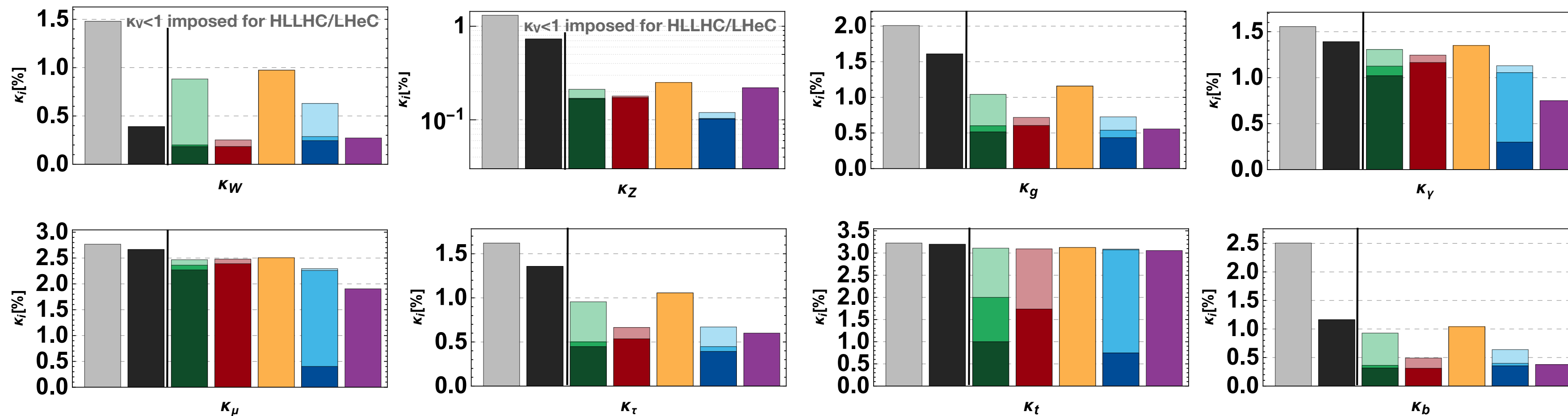
What to expect from this talk

- will not cover Physics cases of different incarnations of future colliders
- will not compare different neither colliders performances nor deliverables
- will refer to FCC-ee at times as a case study to showcase **general challenges**
- selection of topics might reflect personal bias + SM precision background
- main message: assuming an extreme precision era ahead of us
 - I. discuss **theory challenges/requirements**, and **highlight opportunities**
 - II. hopefully **spark excitement** and drive to start tackling such challenges

From (HL-)LHC to future colliders

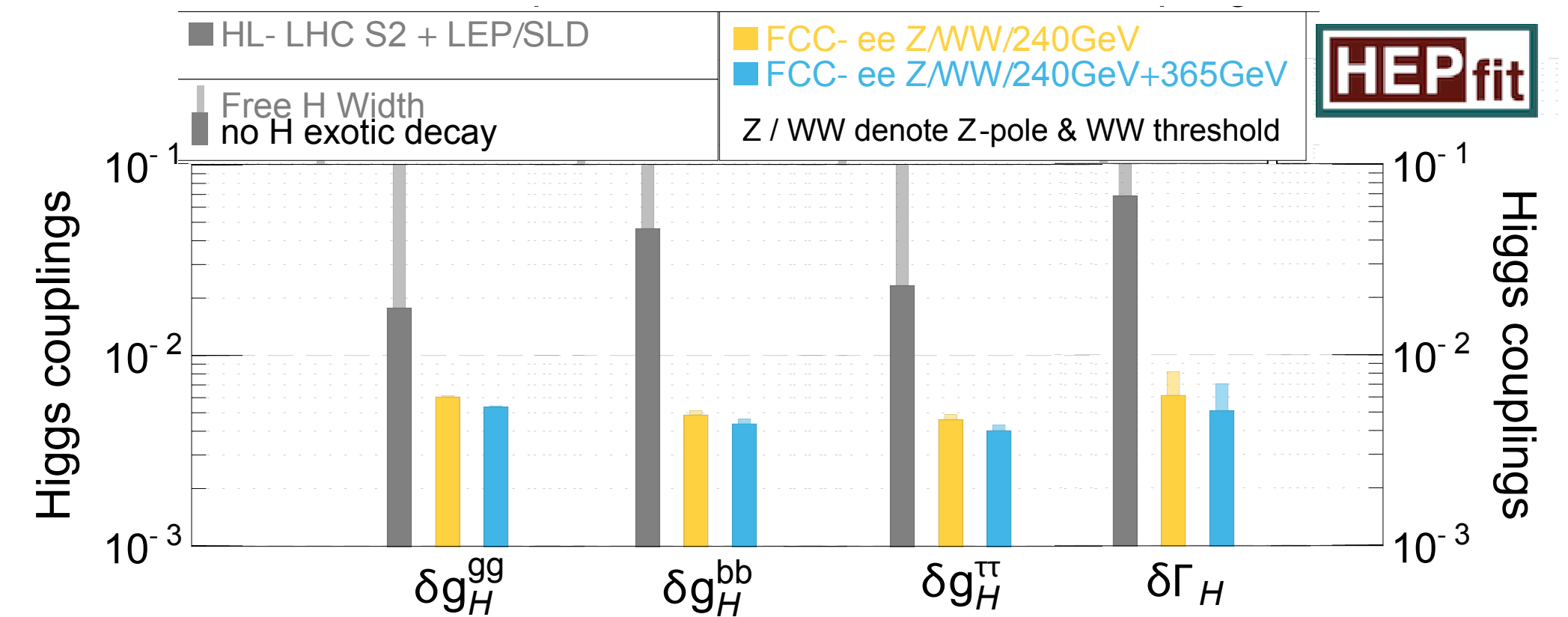


[adapted from J. de Blas, OS Venice 2025]



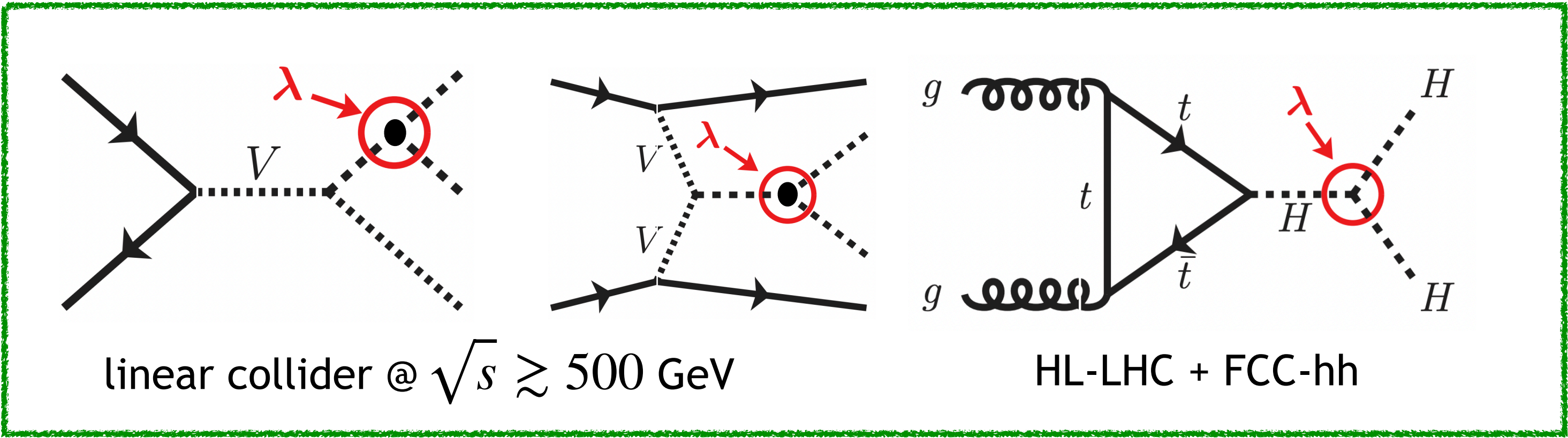
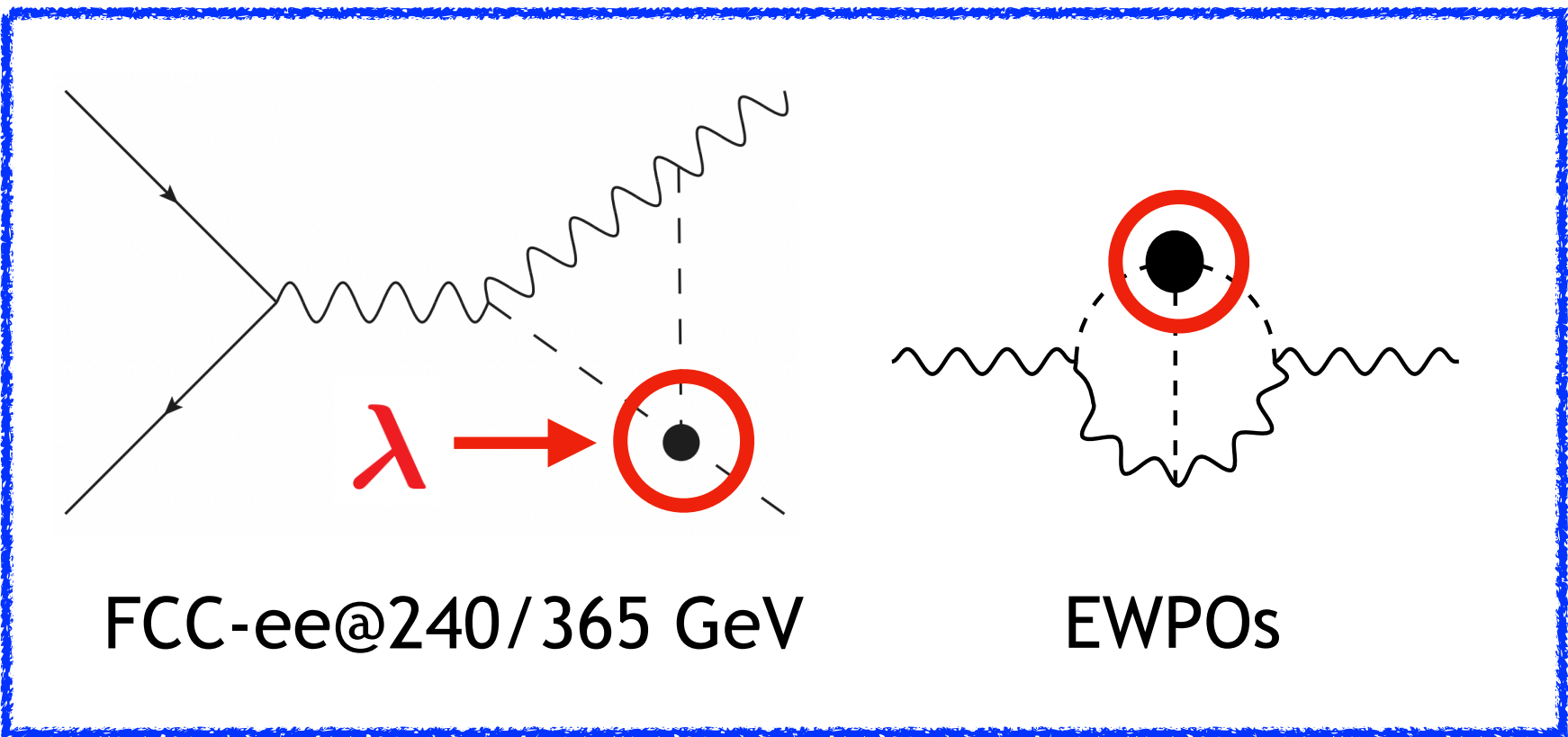
$$\propto g_{ZH}^2$$

$$\propto \frac{g_{ZH}^4}{\Gamma_H}$$



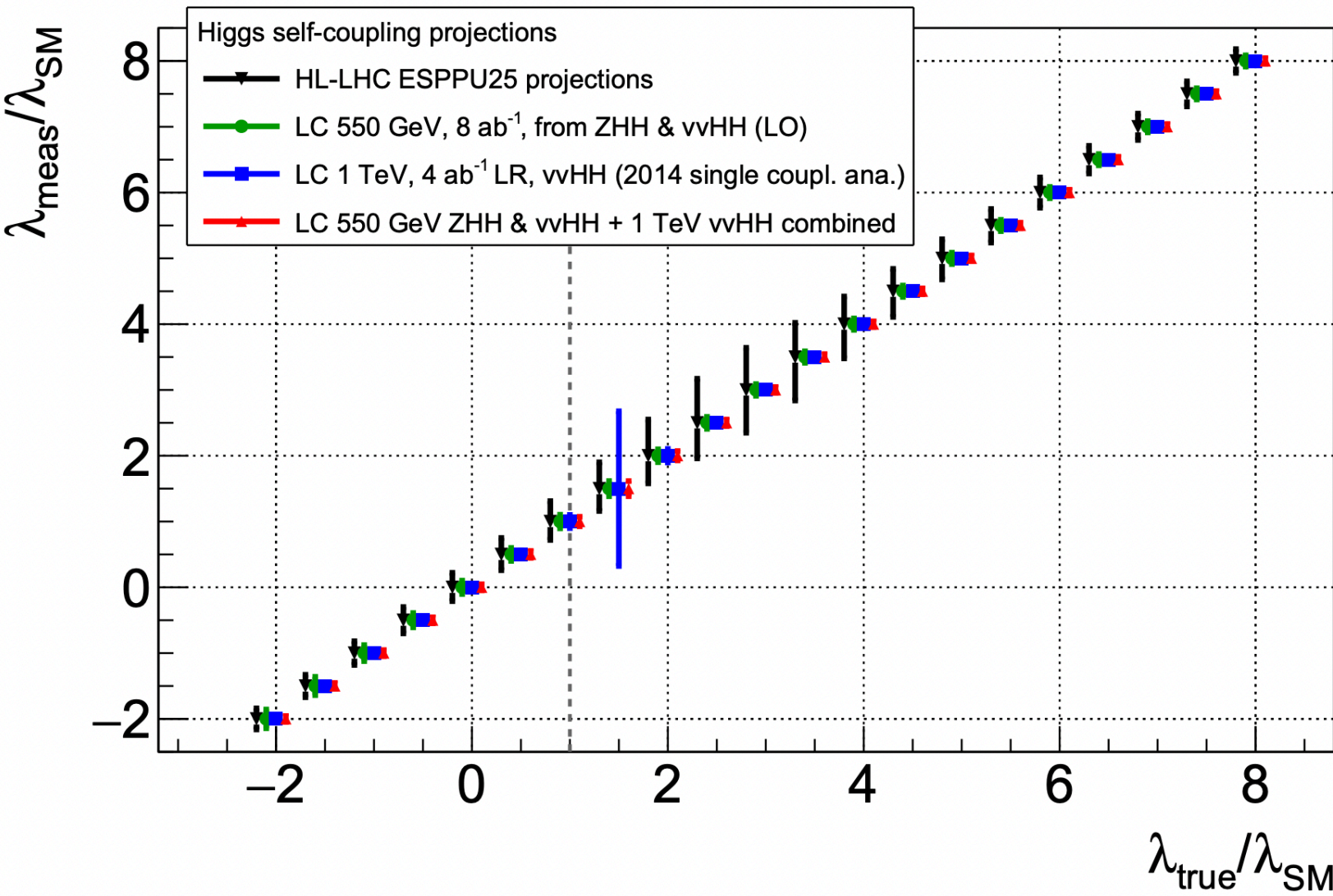
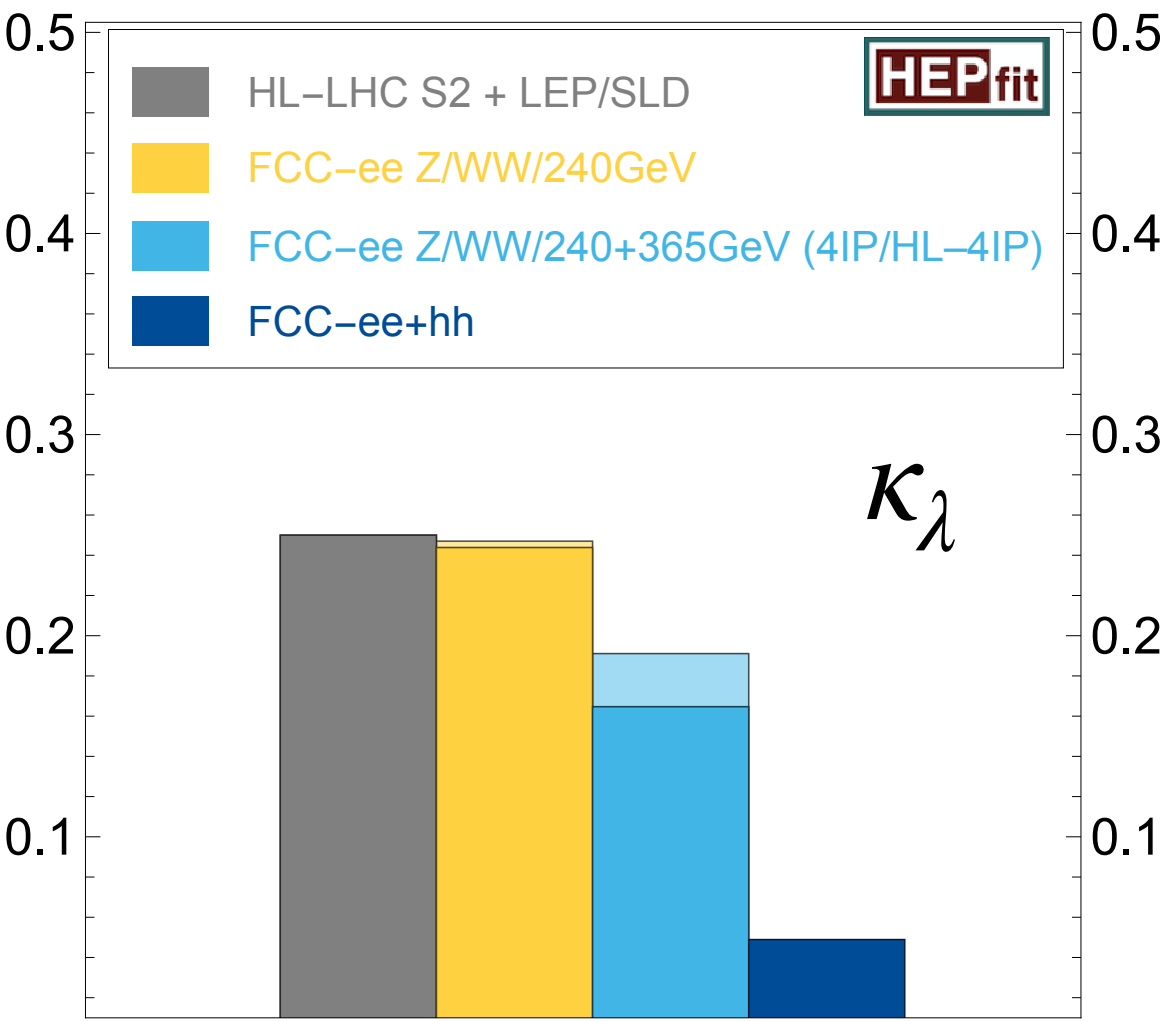
Higgs boson self-interaction

indirect determination o direct measurement of Higgs boson trilinear coupling (λ)



HL-LHC + FCC-ee/hh

LC@0.55/1 TeV. At 550 GeV, assuming $\kappa_\lambda = 1$, projection $\delta\lambda \simeq 15\%$ [LCV 2503.19983]



ideally: direct measurement

helps lifting possible flat directions in BSM interpretations

however:

realistic NP models: impact beyond just λ

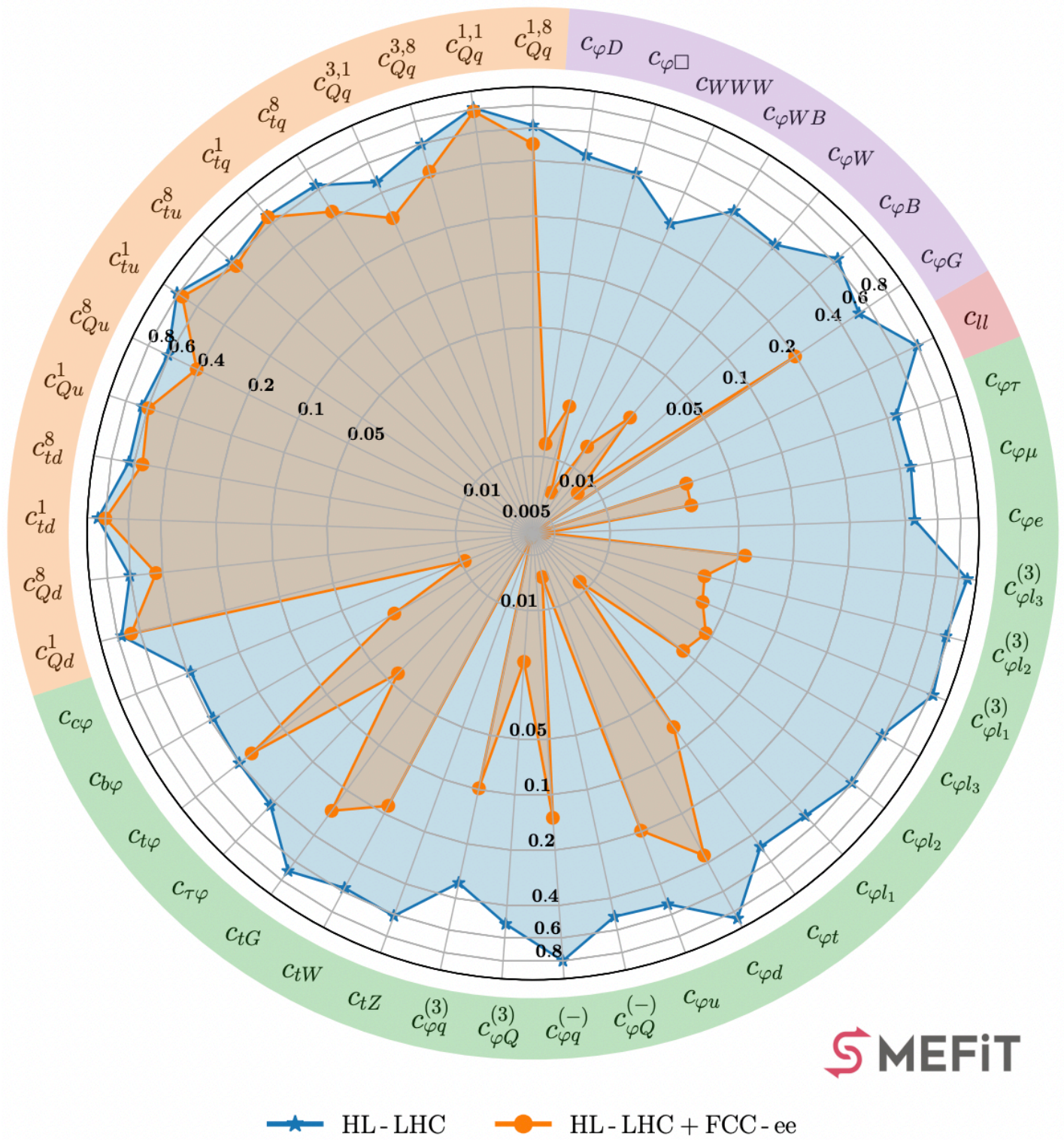
- searching broad and “globally”
- testing hypotheses

The discovery landscape

The SMEFT: a powerful framework to scan the landscape of NP theories

[see talk by Jose on Wed]

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{c_i^{[d]}}{\Lambda^{d-4}} \mathcal{O}_i^{[d]}[\mathcal{O}_{\text{SM}}]$$

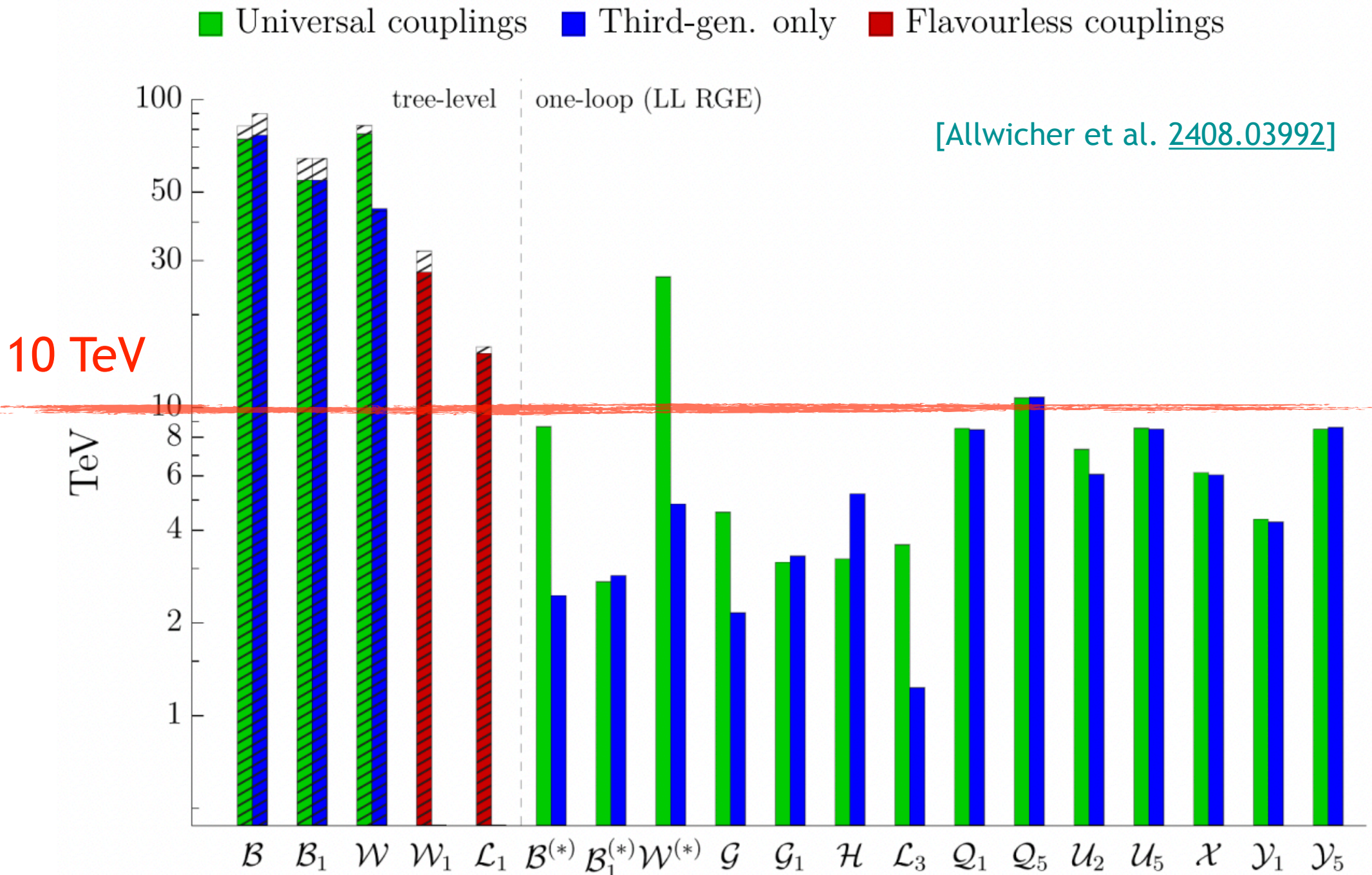


[Celada et al. 2404.12809]

$$R_{\delta c_i} = \frac{[c_i^{\min}, c_i^{\max}]^{95\% \text{ CI}} (\text{baseline} + \text{HL-LHC})}{[c_i^{\min}, c_i^{\max}]^{95\% \text{ CI}} (\text{baseline})}$$

Baseline: LEP + LHC

crucial role of Tera-Z programme at FCC-ee, in particular EWPOs



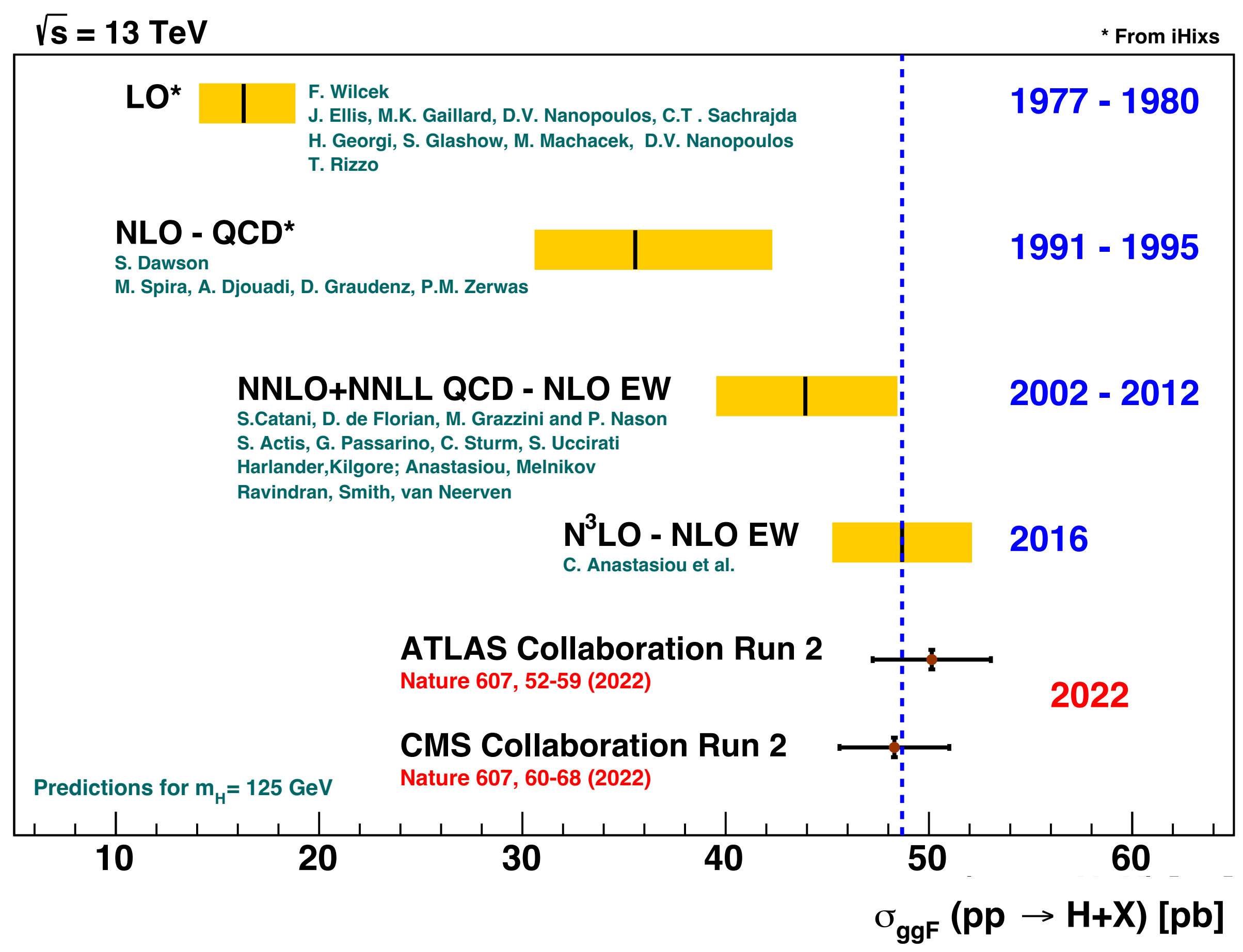
[Allwicher et al. 2408.03992]

(calculations ~ predictions ~ simulations)

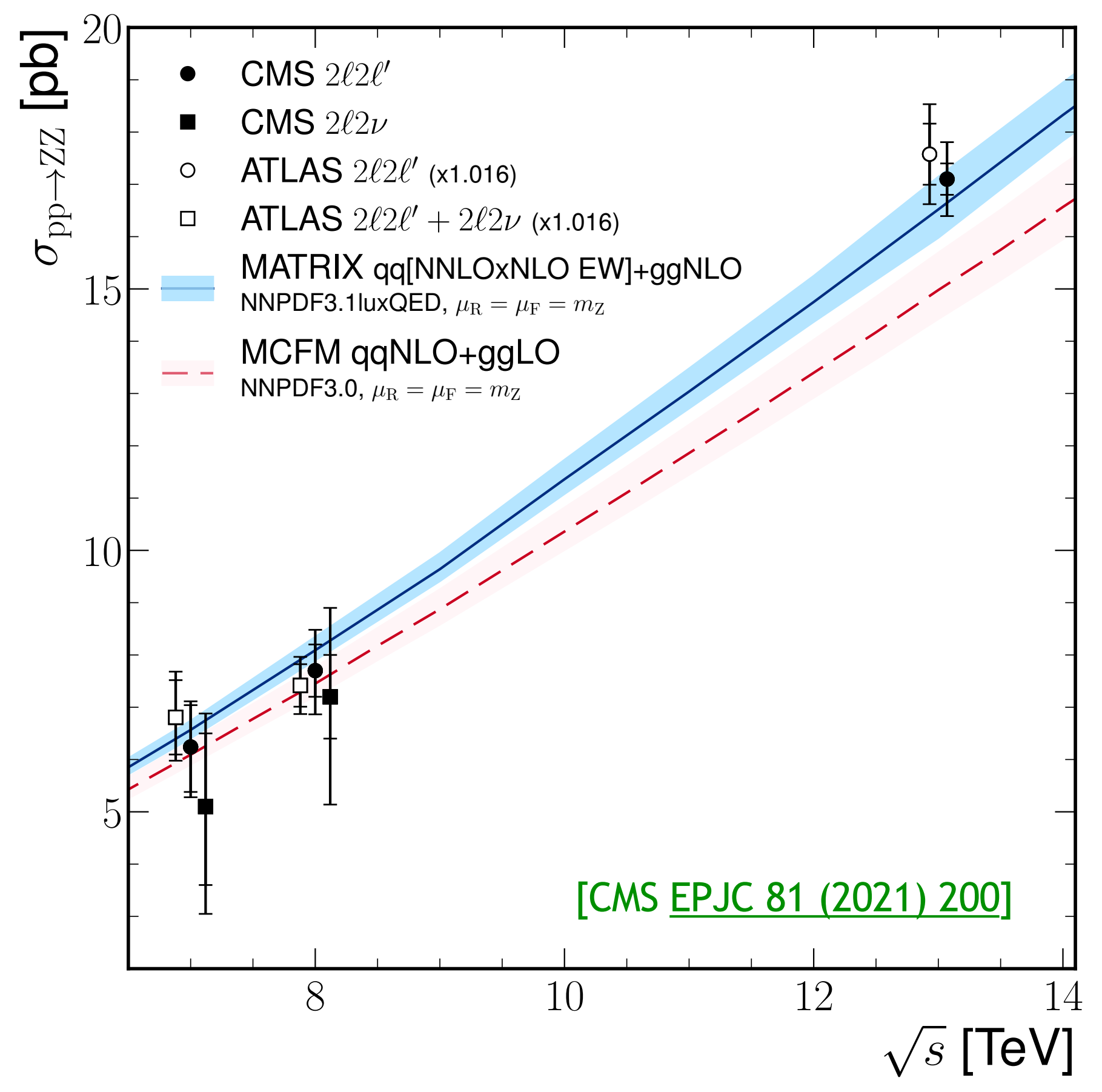
Precise theory predictions

their role, scope, and challenges

Theory predictions better be under control



Higgs-boson production



di-boson production

Role of precise theory predictions

“data-theory” (dis)agreement paradigm



input for meaningful interpretation of the data

prediction

vs

extraction

Theory uncertainties:

intrinsic

(eg missing higher orders)

parametric

(eg input parameters)

but there's more...

(Ex a) Electroweak Precision Observables (EWPOs)

(possibly need to go beyond? see eg discussion in [Frixione's talk](#))

(Ex b) Calibration/Interpretation of XS measurements

Delicate relation:

real observables



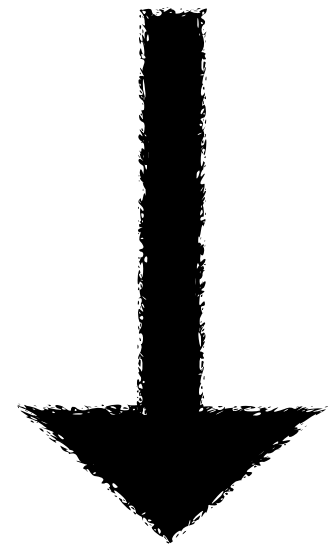
“pseudo observables”

critically hinges on accurate theory simulations

Inherent challenge in describing collider events

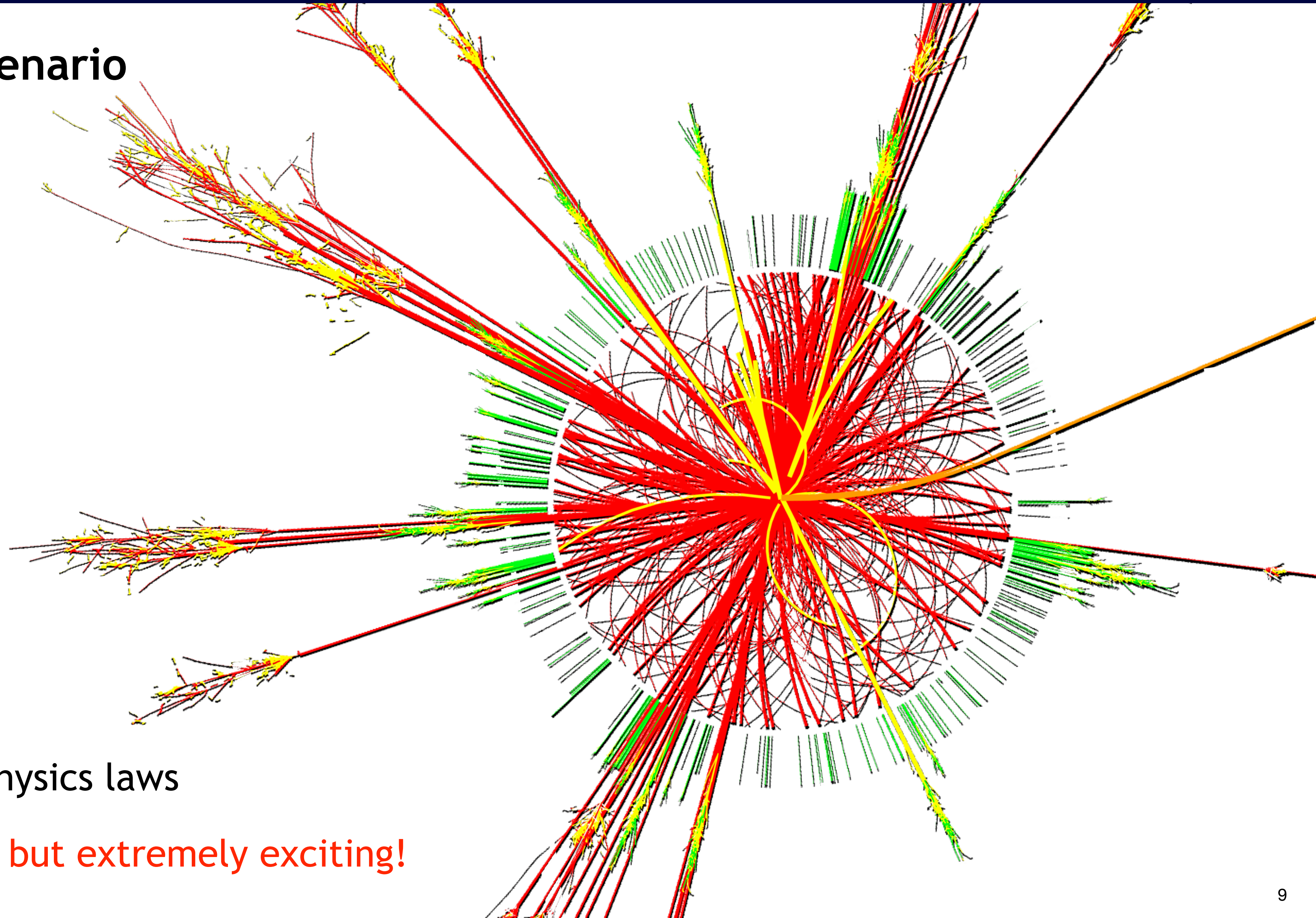
eg: potential FCC-hh scenario

partonic hard process
 $O(10 \text{ TeV})$



hadronisation phase
 $O(100 \text{ MeV})$

- in principle:
using a minimal set of Physics laws
- in practice: a lot harder, but extremely exciting!



Some “simple” guiding principles

Some “simple” guiding principles

$$Q \gg \Lambda_{\text{QCD}} \quad E \gg m_e$$

perturbative regime

$$\left(\frac{\alpha_s}{2\pi} \right)^n \quad \left(\frac{\alpha}{2\pi} \right)^\ell$$

QCD

EW

going $n \rightarrow n + 1$ enormous jump in complexity
(typically 10/20 years)

- $\ell = 2$ only for a couple of examples
- $n = 3$ for a handful of (simplest) reactions

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$$Q \gtrsim m_b$$

mass effects

$$\ln^k \left(\frac{m_b}{Q}\right) \quad \left(\frac{m_b}{Q}\right)^k$$

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mass contributions: additional scales in the problem

$$m_b \sim 4 \text{ GeV}, Q \sim 90 \text{ GeV} \Rightarrow m_b/Q \sim 4.5 \%$$

also related: heavy-flavour identification

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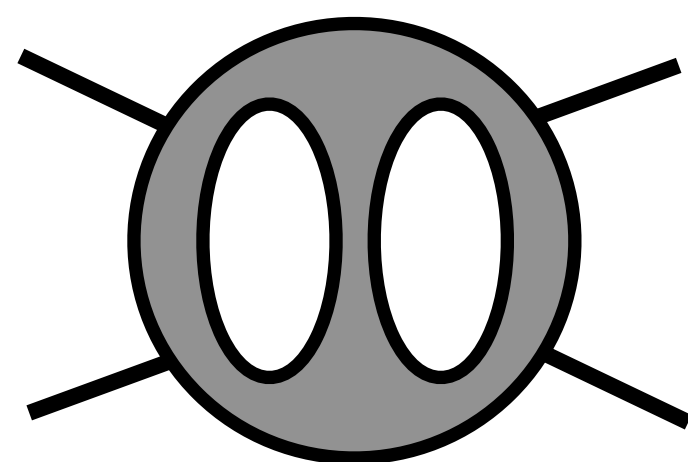
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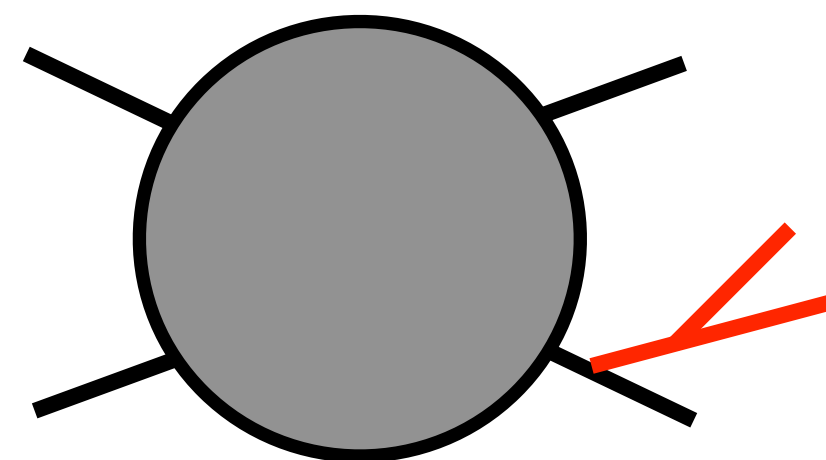
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also related: heavy-flavour identification

higher- (fixed-) order calculations



virtual/loop
corrections



real
corrections

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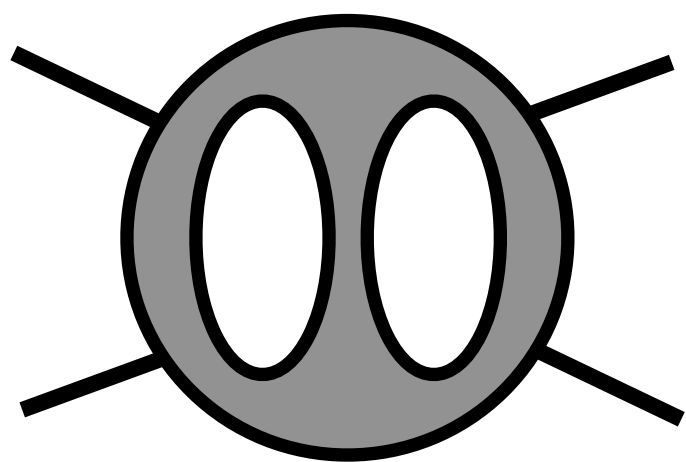
$$\ln^k\left(\frac{m_b}{Q}\right) \quad \left(\frac{m_b}{Q}\right)^k$$

x is some ratio of scales (eg $k_\perp/Q$)

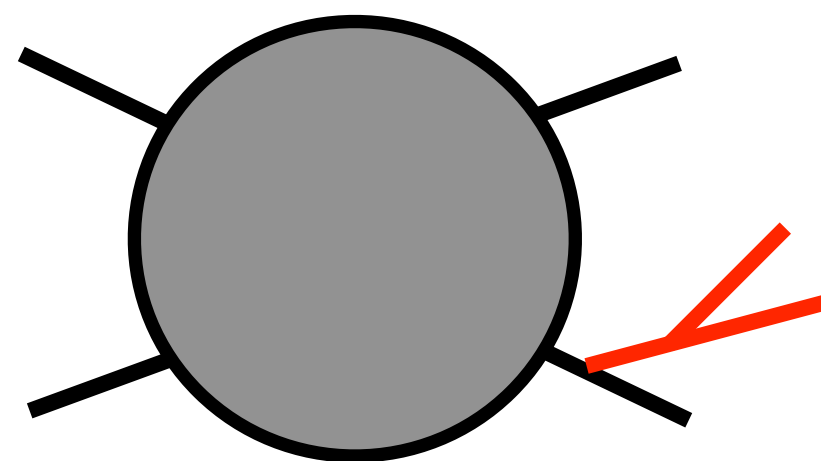
all-orders resummation needed

- achieving demanded accuracy highly complex

higher- (fixed-) order calculations



virtual/loop
corrections



real
corrections

in special kinematic configurations

$$\alpha_{(s)}^n \ln^k(x), \quad x \ll 1$$

logarithmically enhanced terms

resummation

Some “simple” guiding principles

Typical scenario of **threshold production** (“particles are slow”)

W^+W^- and $t\bar{t}$ threshold at FCC-ee

dominant physical effects can be very different from perturbative regime

need to devise/investigate the **appropriate theoretical framework**

$$v \ll 1$$

non-relativistic limit

$$m v < \mu < m$$

eg: NRQCD

$$\mu < m v$$

eg: pNRQCD

Some “simple” guiding principles

$$\Lambda_{\text{QCD}} \sim 200 \text{ MeV}$$

$$Q \sim m_Z \sim 91 \text{ GeV}$$

$$\longrightarrow \frac{\Lambda_{\text{QCD}}}{Q} \sim 0.2 \%$$

describing the non-perturbative regime is a **daunting but great conceptual challenge**

$$d\sigma \sim d\sigma^{(P)} + d\sigma^{(NP)} \quad d\sigma^{(NP)} \sim \left(\frac{\Lambda_{\text{QCD}}}{Q} \right)^p$$

- **reliable hadronisation models** are at the foundation of many (all?) future analysis

$$Q \sim \Lambda_{\text{QCD}}$$

non-perturbative phys.

$$\left(\Lambda_{\text{QCD}}/Q \right)^p$$

hadronisation

Some “simple” guiding principles

$$Q \gg \Lambda_{\text{QCD}} \quad E_V \gg m_e$$

perturbative regime

$$\left(\frac{\alpha_s}{2\pi}\right)^n \quad \left(\frac{\alpha}{2\pi}\right)^\ell$$

QCD

EW

$$Q \gtrsim m_b$$

mass effects

$$\ln^k\left(\frac{m_b}{Q}\right) \quad \left(\frac{m_b}{Q}\right)^k$$

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$$\mu < m v$$

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$$Q \sim \Lambda_{\text{QCD}}$$

non-perturbative phys.

$$\left(\Lambda_{\text{QCD}}/Q\right)^p$$

hadronisation

actually a very
complex and
exciting mosaic

in special kinematic configurations

$$\alpha_{(s)}^n \ln^k(x), \quad x \ll 1$$

logarithmically enhanced terms

Higgs boson characterisation

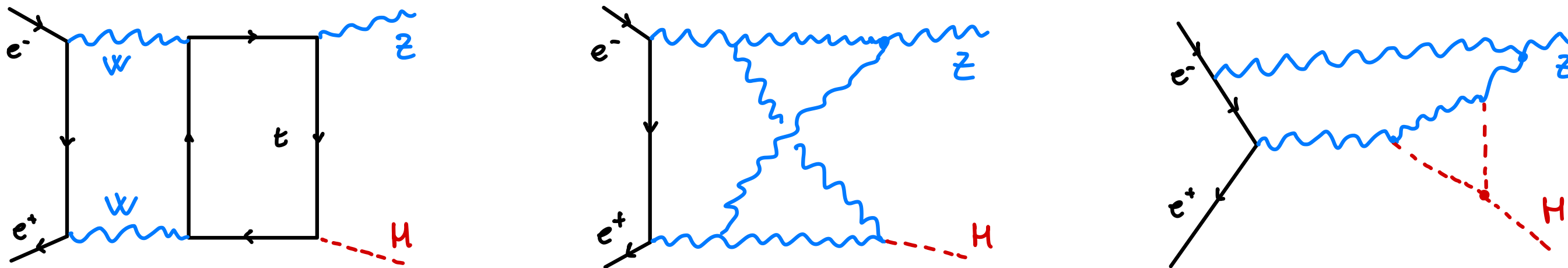
Higgs factories: $e^-e^+ \rightarrow ZH(H)$, cross section

1. single Higgs, eg FCC-ee: $10^6 ZH$ events $\rightarrow$ XS measurement with expected $\mathcal{O}(0.2\% - 0.5\%)$ accuracy

Technically extremely challenging

Perturbative second-order EW corrections are definitely in this ball park: mandatory

(multi-loop multi-scale problem)

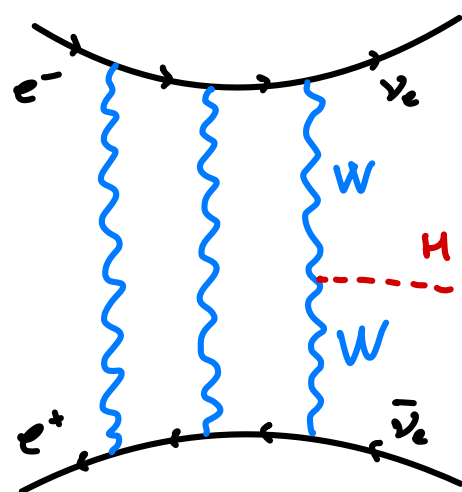
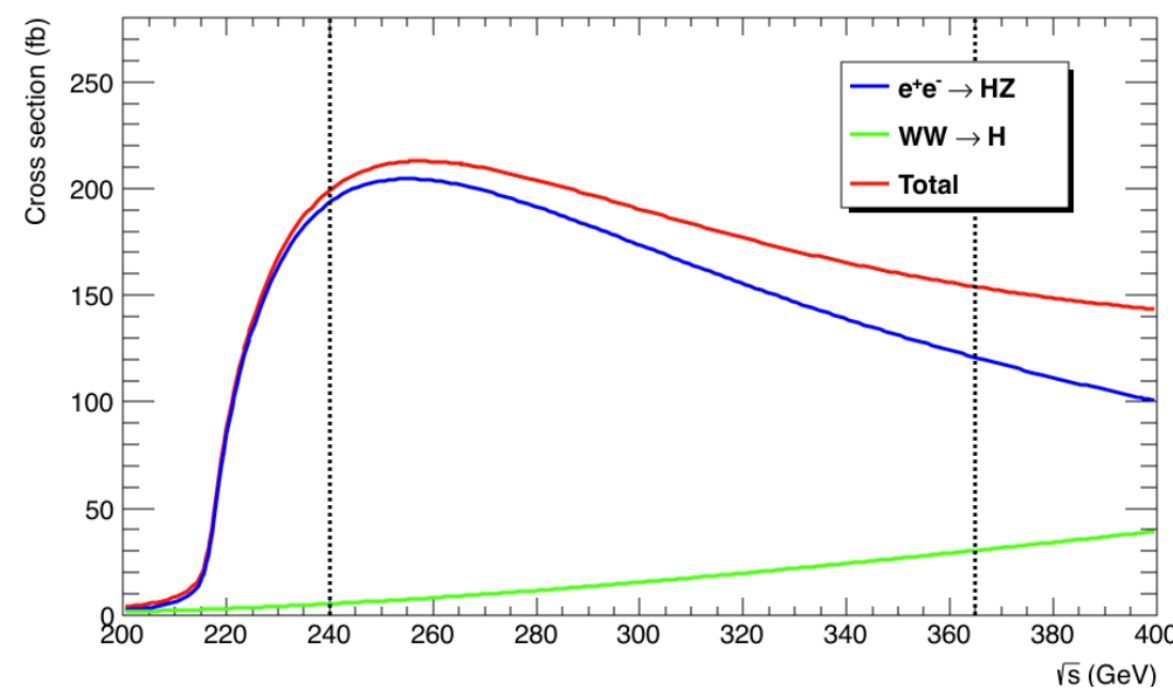


recent progress exploiting numerical approaches

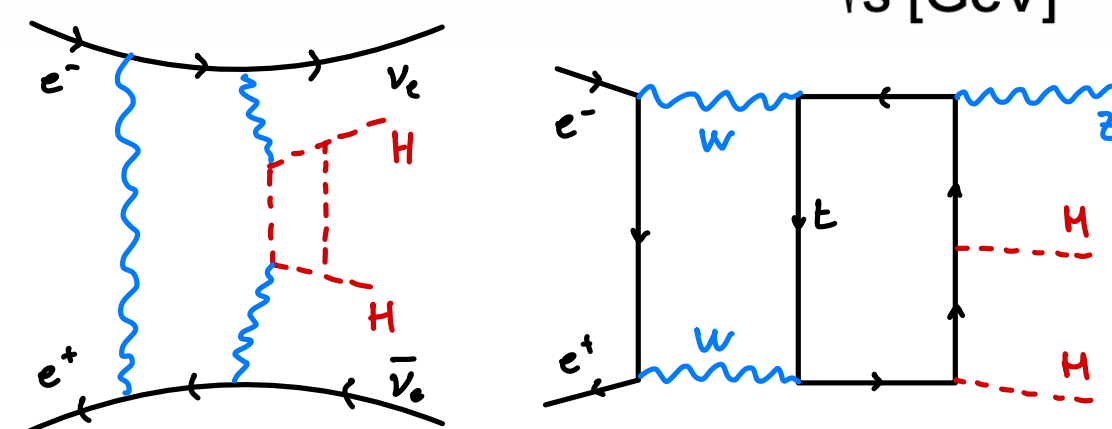
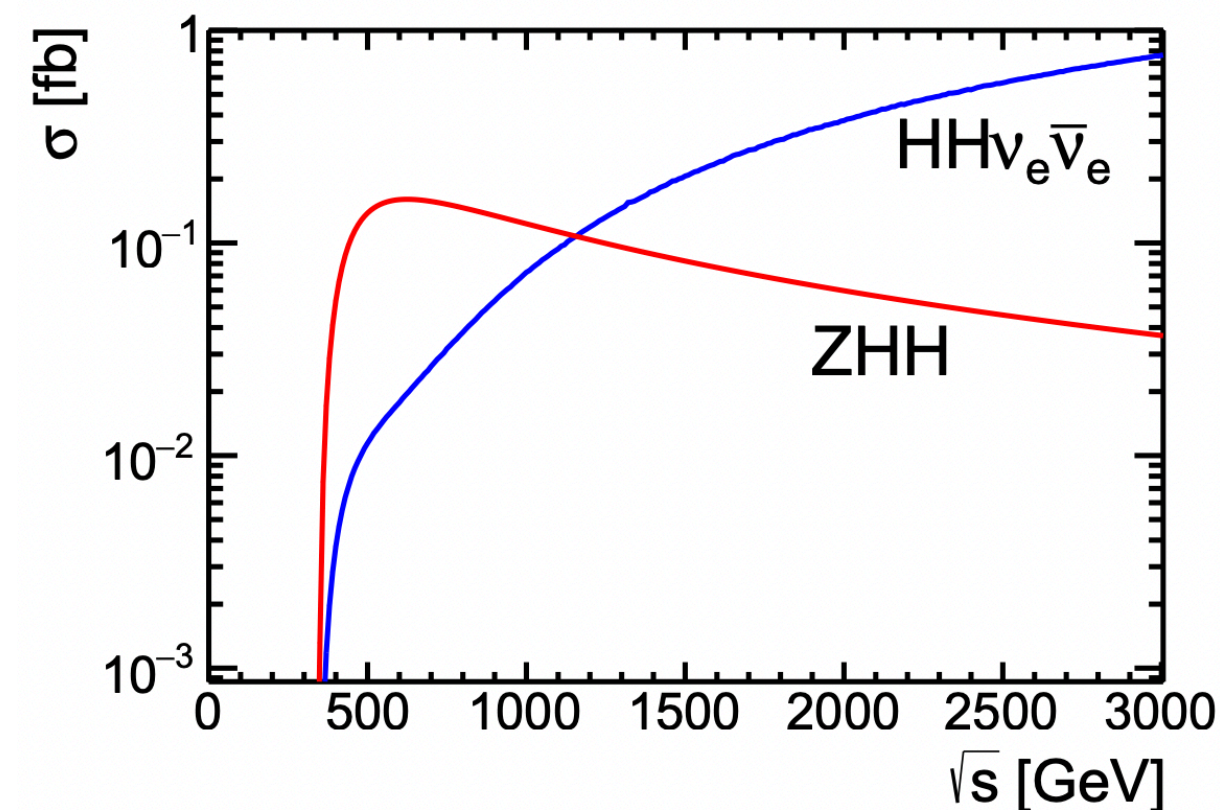
[Chen et al. 2209.14953, Freitas et al 2209.07612]

2. (DH) double Higgs and (SH) single Higgs at higher energies: high-multiplicity processes

SH: $e^-e^+ \rightarrow H\ell^-\ell^+ (\nu\bar{\nu})$



DH: $e^-e^+ \rightarrow ZHH$



Open (technical) issues:

- reduction to minimal set of integrals
- implementation for real-events simulation

more conceptually:

- complex-mass scheme @NNLO EW
- mathematical structure of amplitudes

Hadronic Higgs decays

Hadronic decays (~ 80% of total rate)

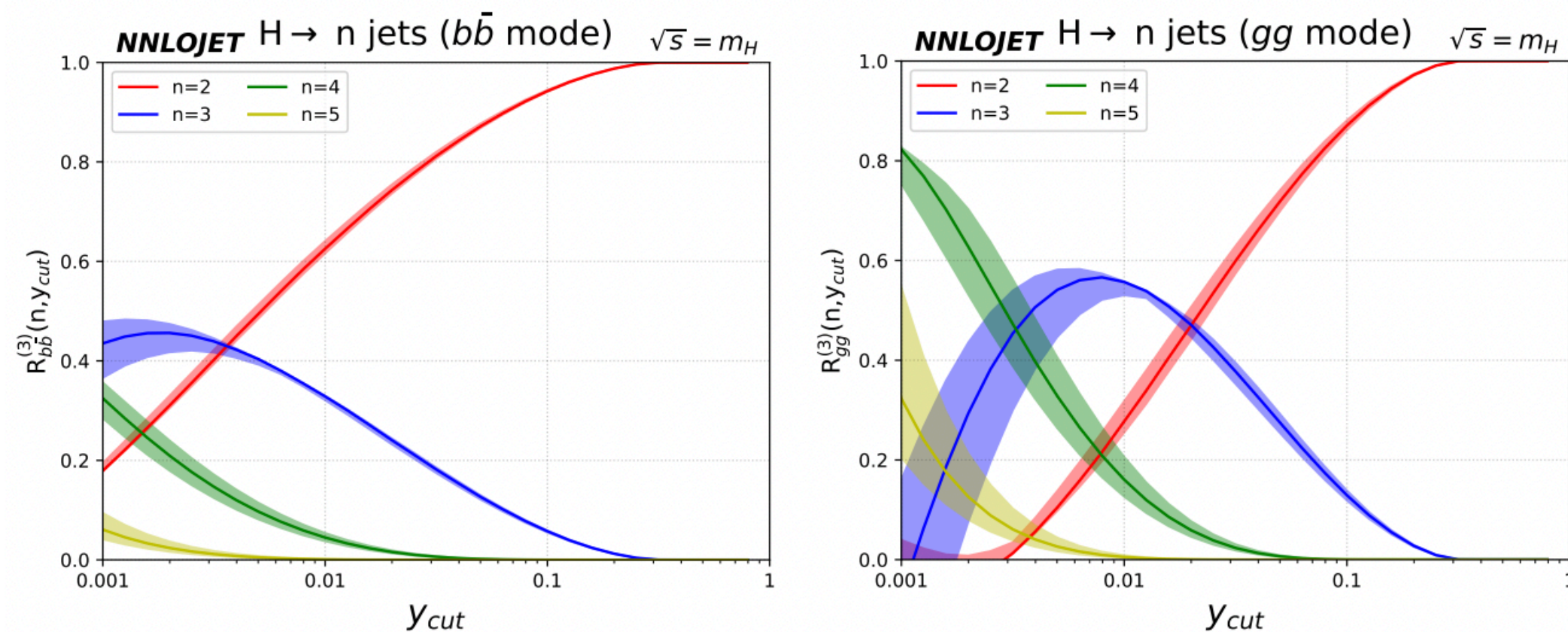
Inclusive calculations in good shape (even fourth order in pert. QCD in some cases)

However: **differential calculations absolutely crucial, theory accuracy significantly lower**

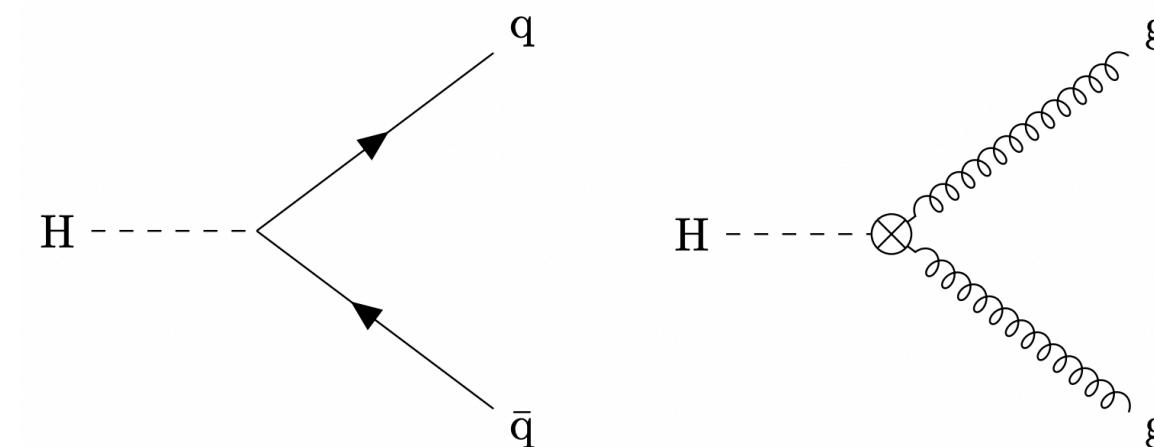
- correcting for fiducial acceptance of experiments
- kinematic distributions of decay products and **jet observables**

N3LO QCD corrections for $H \rightarrow b\bar{b}$ with $m_b = 0$ [Mondini et al 1904.08960]

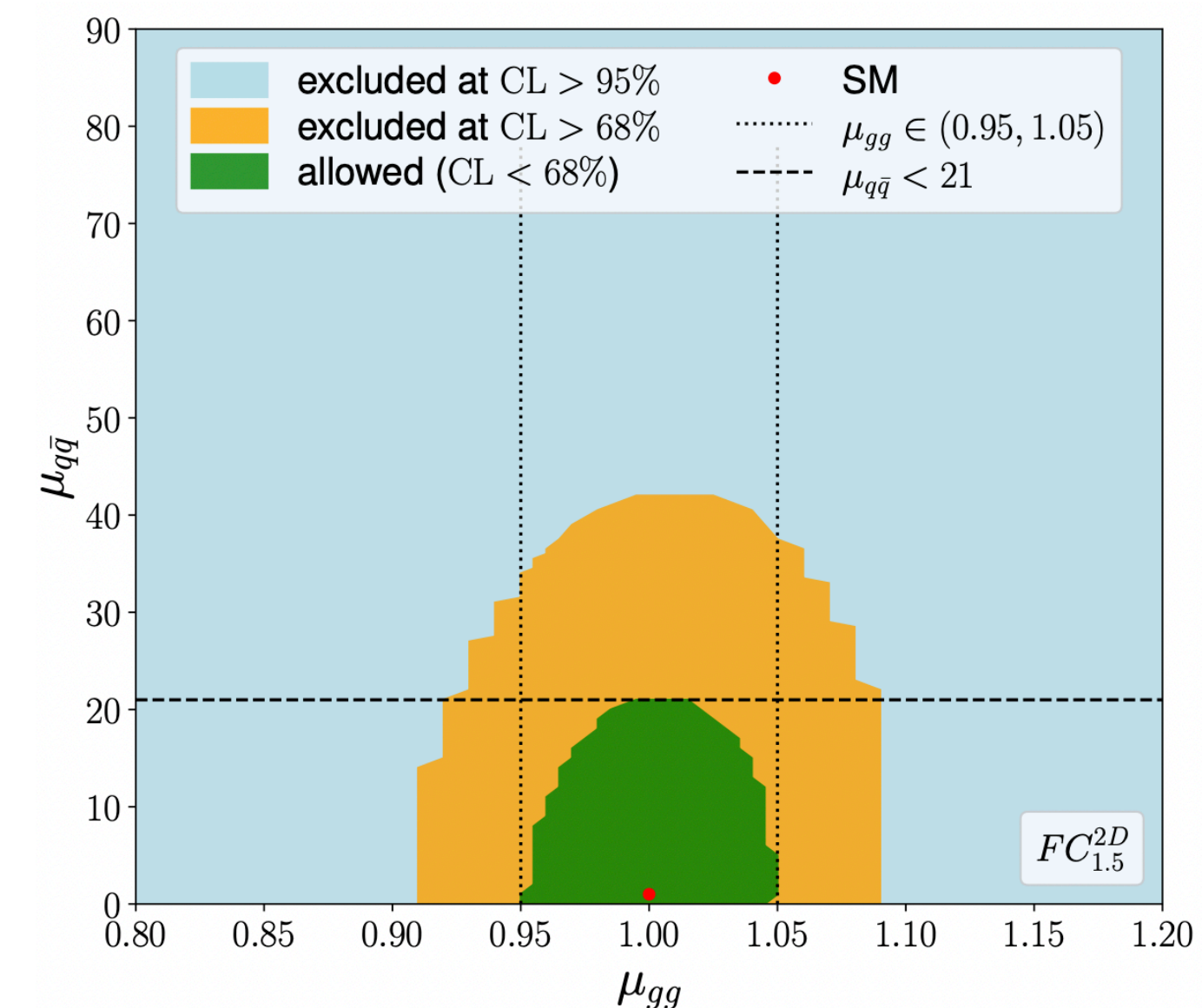
recently: N3LO QCD corrections for all hadronic decay modes [Fox et al 2502.17333]



Potential and power of QCD observables in discriminating Higgs hadronic decays



[Knobbe et al 2306.03682]



Jet rates in Higgs hadronic decays

[Fox et al 2502.17333]

desirable for the future:

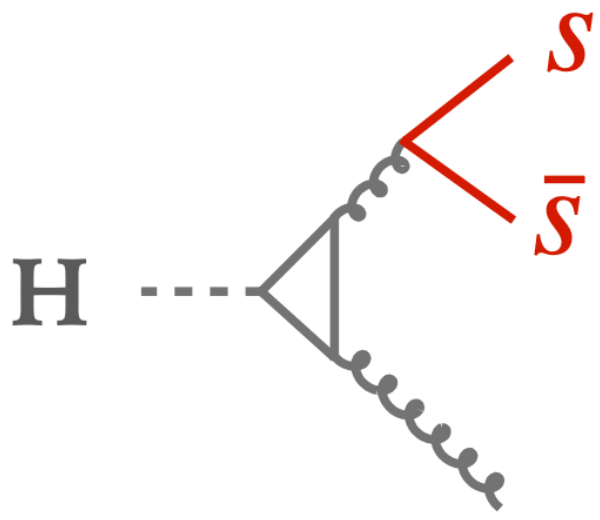
$H \rightarrow q\bar{q}$ with $m_q \neq 0$ and mass effects

sensitivity of event shapes to radiation pattern from gg, qq, heavy-q

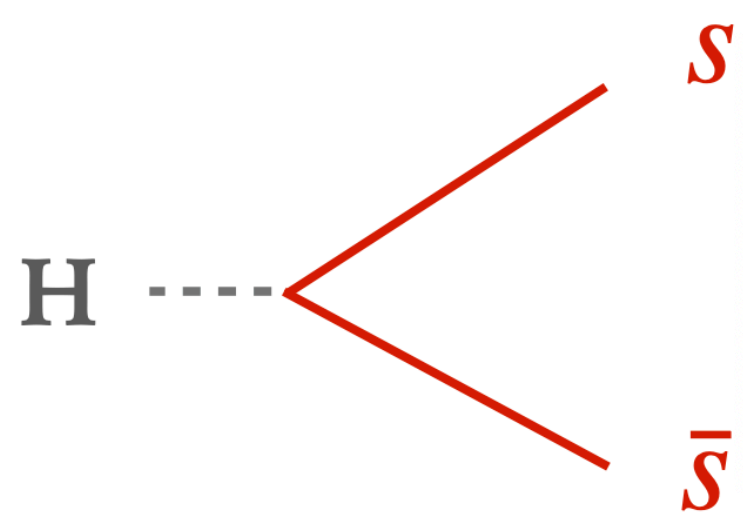
overarching challenge: heavy (jet) flavour at high orders

Light-quark Yukawas: $H \rightarrow s\bar{s}$

New ideas/explorations in $H \rightarrow s\bar{s}$: disentangling $H \rightarrow s\bar{s}$ from $H \rightarrow gg(\rightarrow s\bar{s})$ (aka Dalitz decay)



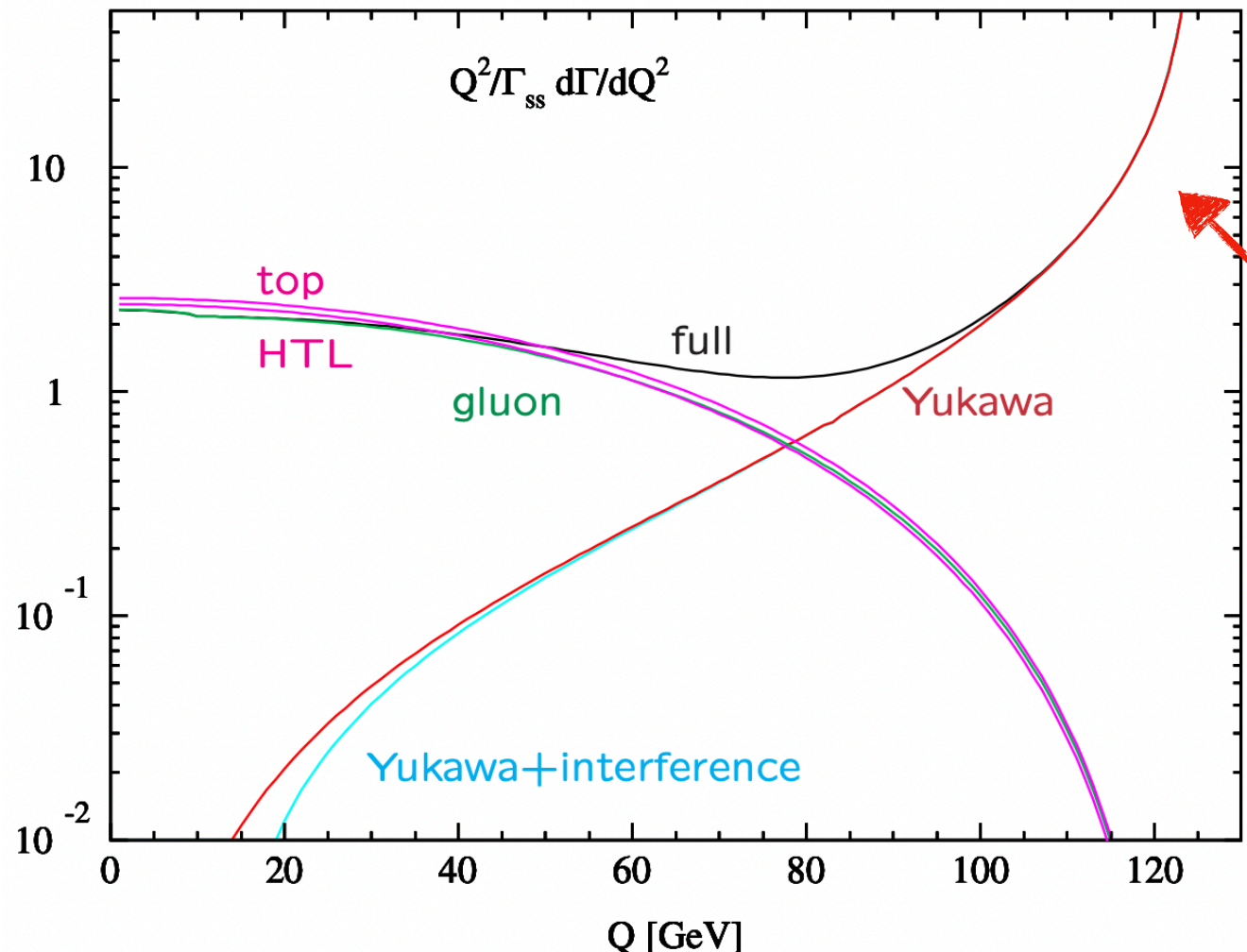
Dalitz decay ($\alpha_s^3 y_t^2$)



Yukawa decay (y_s^2)

	BR
$H \rightarrow gg$	8.1×10^{-2}
$H \rightarrow ss$	$\sim 2 \times 10^{-4}$

Ratio is ~ 400



Exp. tagging based on machine learning

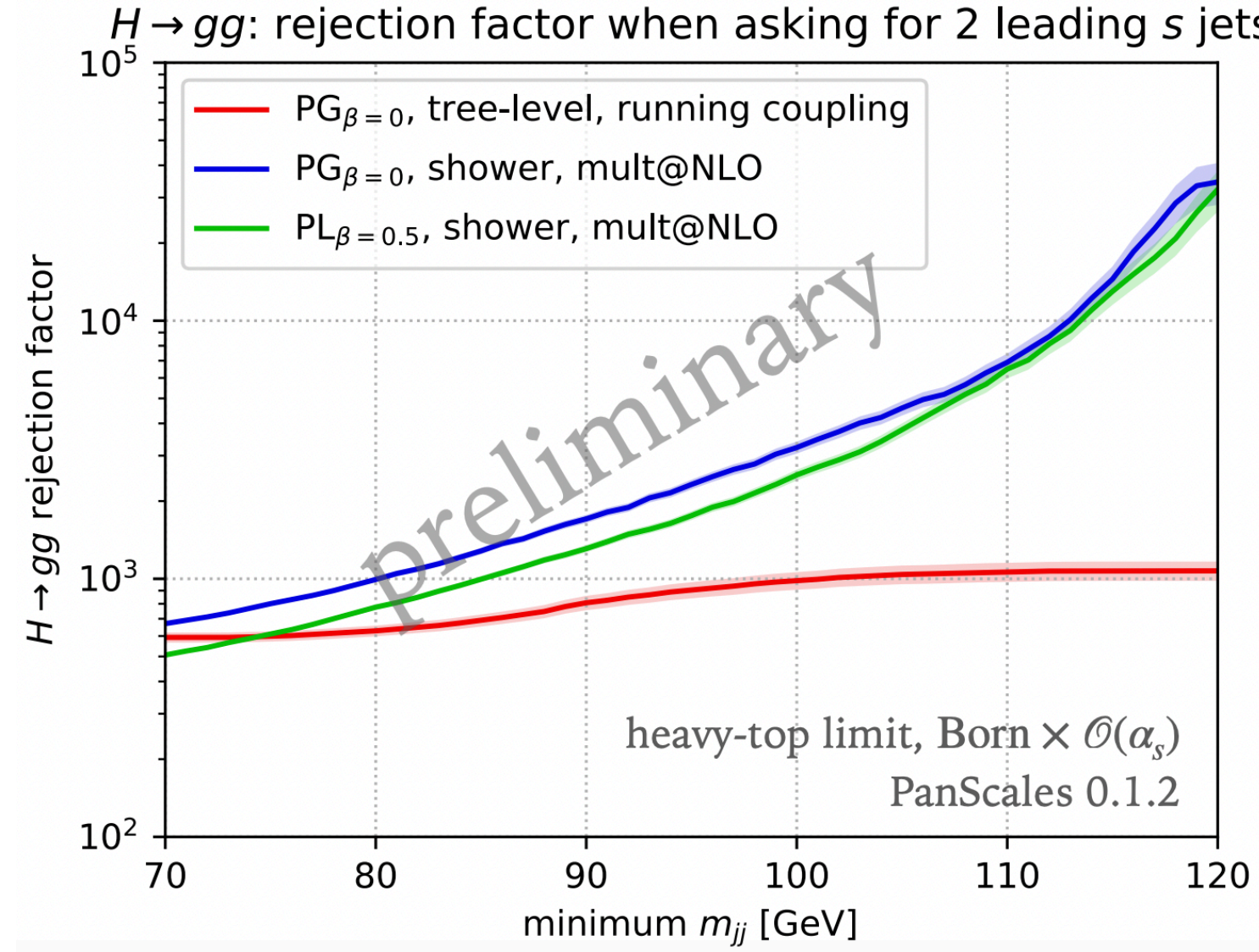
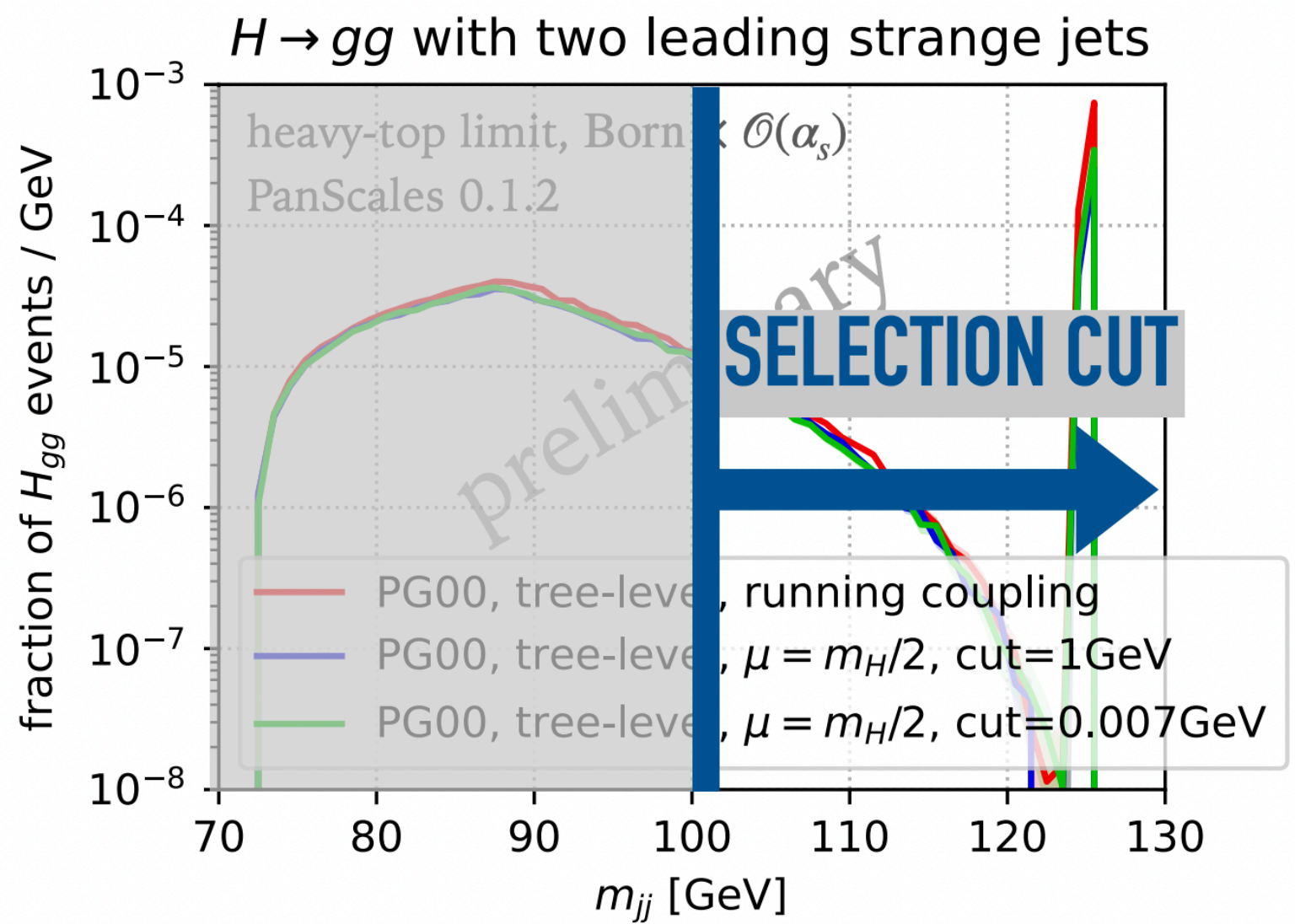


importance of accurate **resummation/parton shower** in training

[see talk by M. Spira]

preliminary study [credits to Gavin Salam, see [talk](#)]:

invariant mass cut to suppress Dalitz decay background



For more:

ECFA H->ss Focus Group - Open Meeting

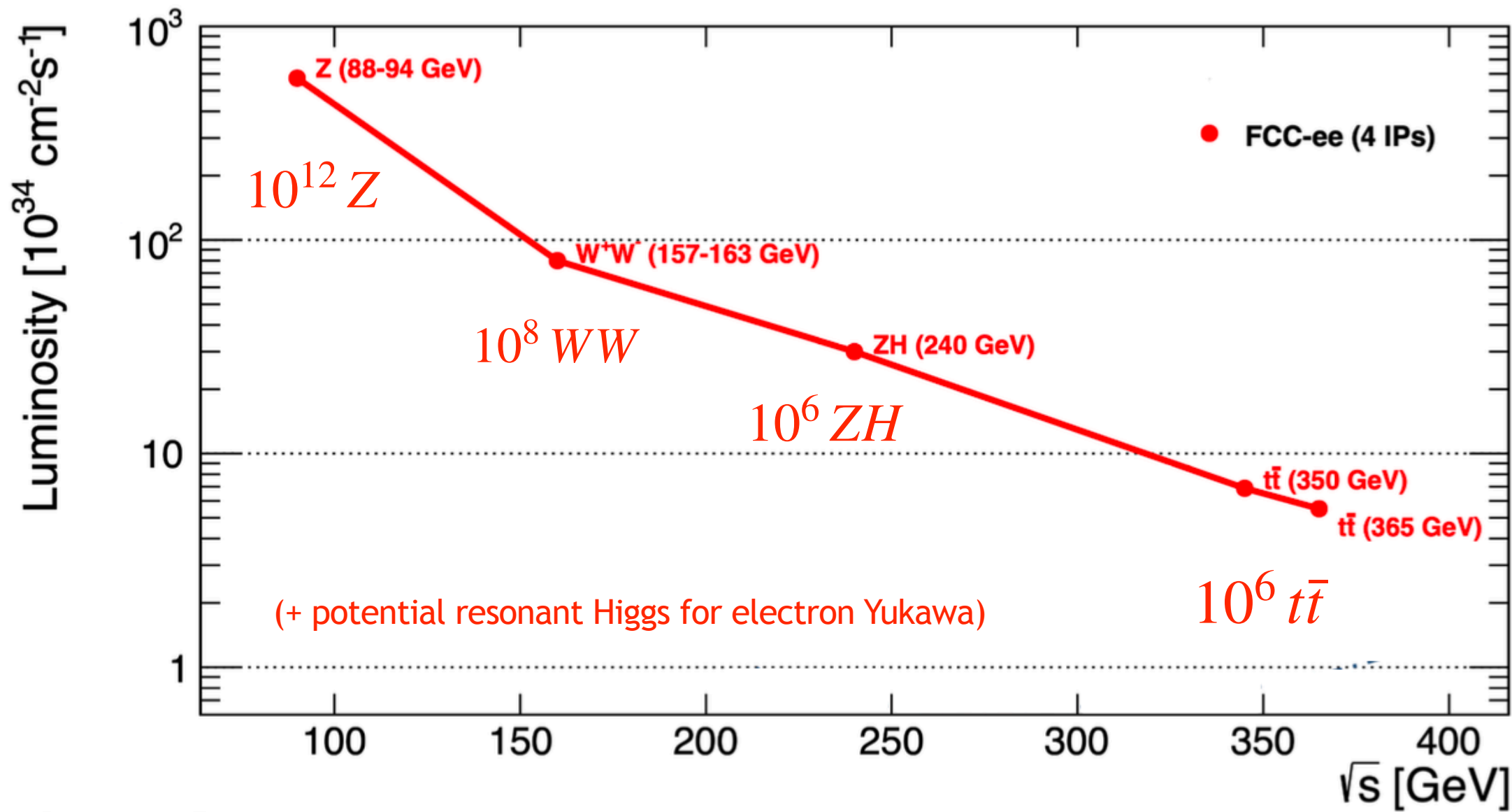
[visit [here](#)]

QCD for Higgs physics at FCC-ee

[visit [here](#)]

Precision program beyond the Higgs boson

Challenges + opportunities



The foreseen precision is staggering!
astounding challenges on theory predictions

- SM predictions of equivalent accuracy to exploit discovery/exclusion power
- practically all aspects of theoretical investigations/ predictions pushed far beyond the current edge

[FCC feasibility study report Vol 1, 2505.00272]

Observable	value	present ±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	4	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	4	12	From Z line shape scan Beam energy calibration
$\sin^2 \theta_W^{\text{eff}} (\times 10^6)$	231,480	±	160	1.2	1.2	From $A_{\text{FB}}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\text{QED}}(m_Z^2) (\times 10^3)$	128 952	±	14	3.9 0.8	small tbc	From $A_{\text{FB}}^{\mu\mu}$ off peak From $A_{\text{FB}}^{\mu\mu}$ on peak QED&EW uncert. dominate
$R_\ell^Z (\times 10^3)$	20 767	±	25	0.05	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2) (\times 10^4)$	1 196	±	30	0.1	1	Combined $R_\ell^Z, \Gamma_{\text{tot}}^Z, \sigma_{\text{had}}^0$ fit
$R_b (\times 10^6)$	216 290	±	660	0.25	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{\text{FB}}^{b,0} (\times 10^4)$	992	±	16	0.04	0.04	b-quark asymmetry at Z pole From jet charge
m_W (MeV)	80 360.2	±	9.9	0.18	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	0.27	0.2	From WW threshold scan Beam energy calibration
m_{top} (MeV)	172 570	±	290	4.2	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	±	190	10	6	From $t\bar{t}$ threshold scan QCD uncert. dominate

Electroweak Physics at the Z-pole

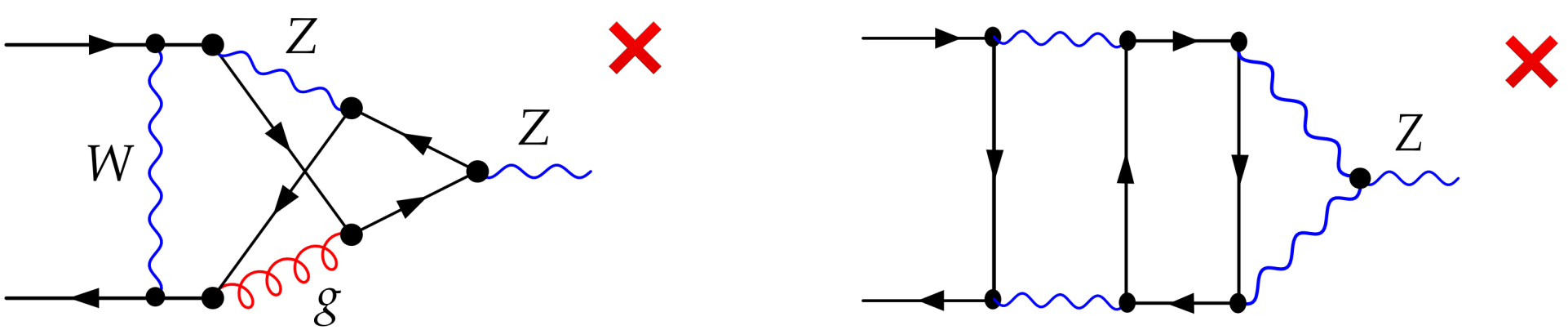
[Table 11 of 2505.00272]

Delicate relation EWPOs $\leftrightarrow$ real observables

quantities of interest are defined in terms of a resonant (on-shell) Z boson

Quantity	Required theory input	Theory status as of today	Needed theory improvement [‡]
Γ_Z $\sin^2 \theta_{\text{eff}}^\ell$	vertex corrections for $Z \rightarrow f\bar{f}$	NNLO + partial higher orders	N ³ LO EW + partial higher orders

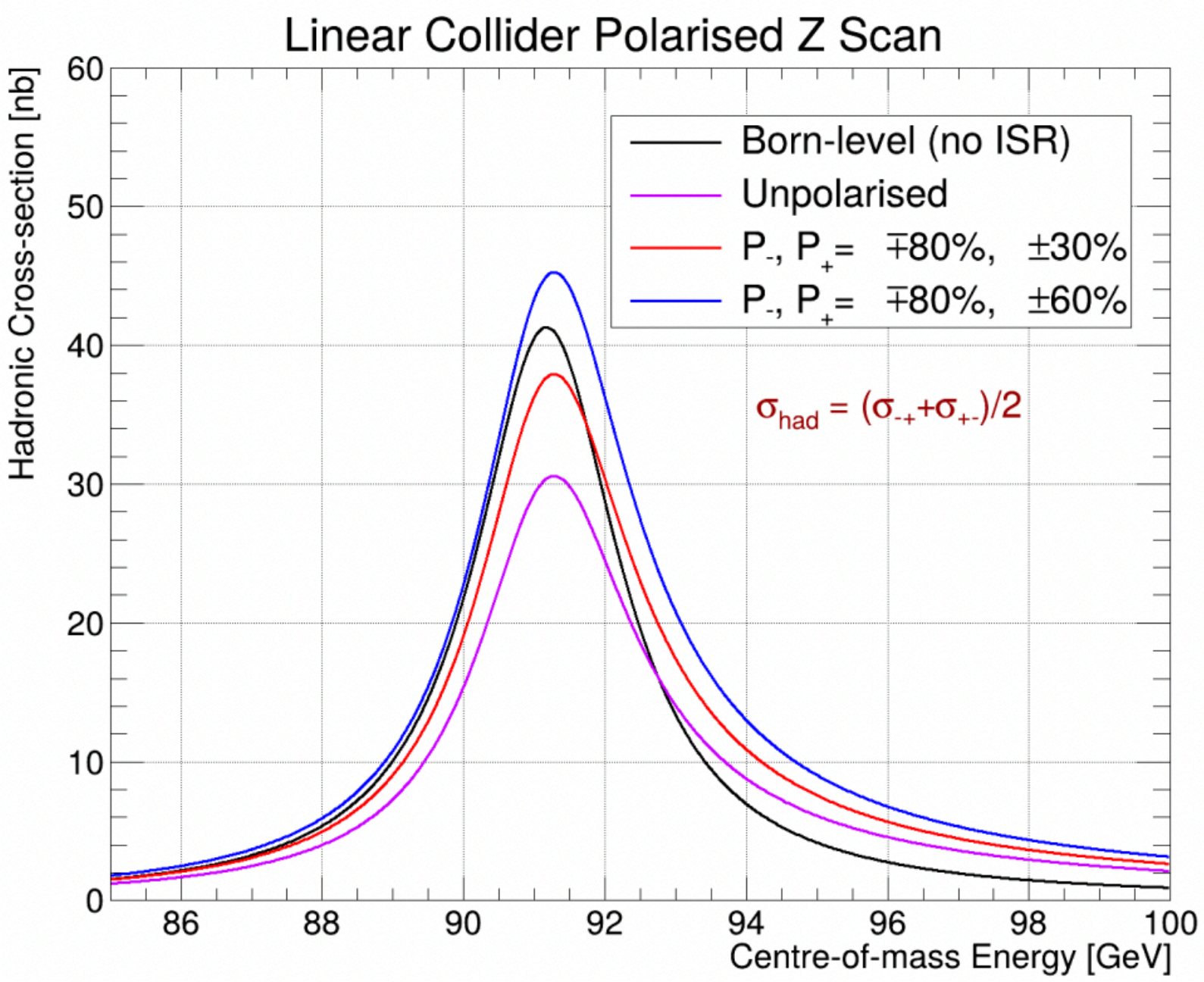
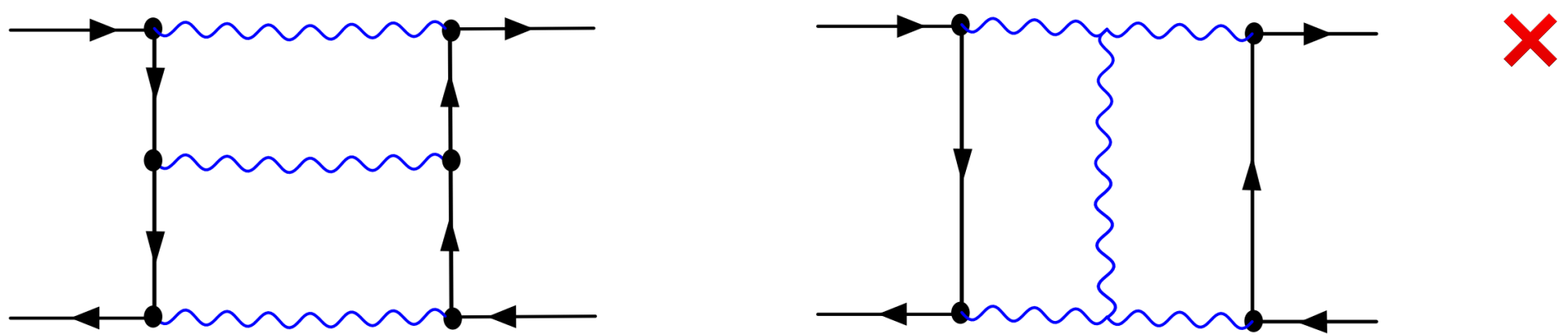
Higher-order EW and QCD x EW corrections to $Z \rightarrow f\bar{f}$ vertex required



beyond state-of-the-art technology required

The complete $e^-e^+ \rightarrow f\bar{f}$ process receives also non-resonant contributions, eg.
(need to be properly taken into account)

- $\gamma^* - Z$ interference
- box diagrams



Highly challenging multiloop-multiscale calculation

QCD at the Z-pole and beyond

1. Ultra-precise extraction of $\alpha_s(m_Z^2)$. Expected: $\delta\alpha_s \sim 0.1\%$

- $\delta\alpha_s$ will enter as a **parametric uncertainty** practically everywhere
- $\alpha_s(m_Z^2)$ extracted from **inclusive EWPOs** (small non-pert hadronisation corrections) $\longrightarrow$ theory predictions in good shape
- 2-jet production at N3LO QCD [\[Chen et al 2505.10618\]](#) $\longrightarrow$ crucial to assess impact of cuts

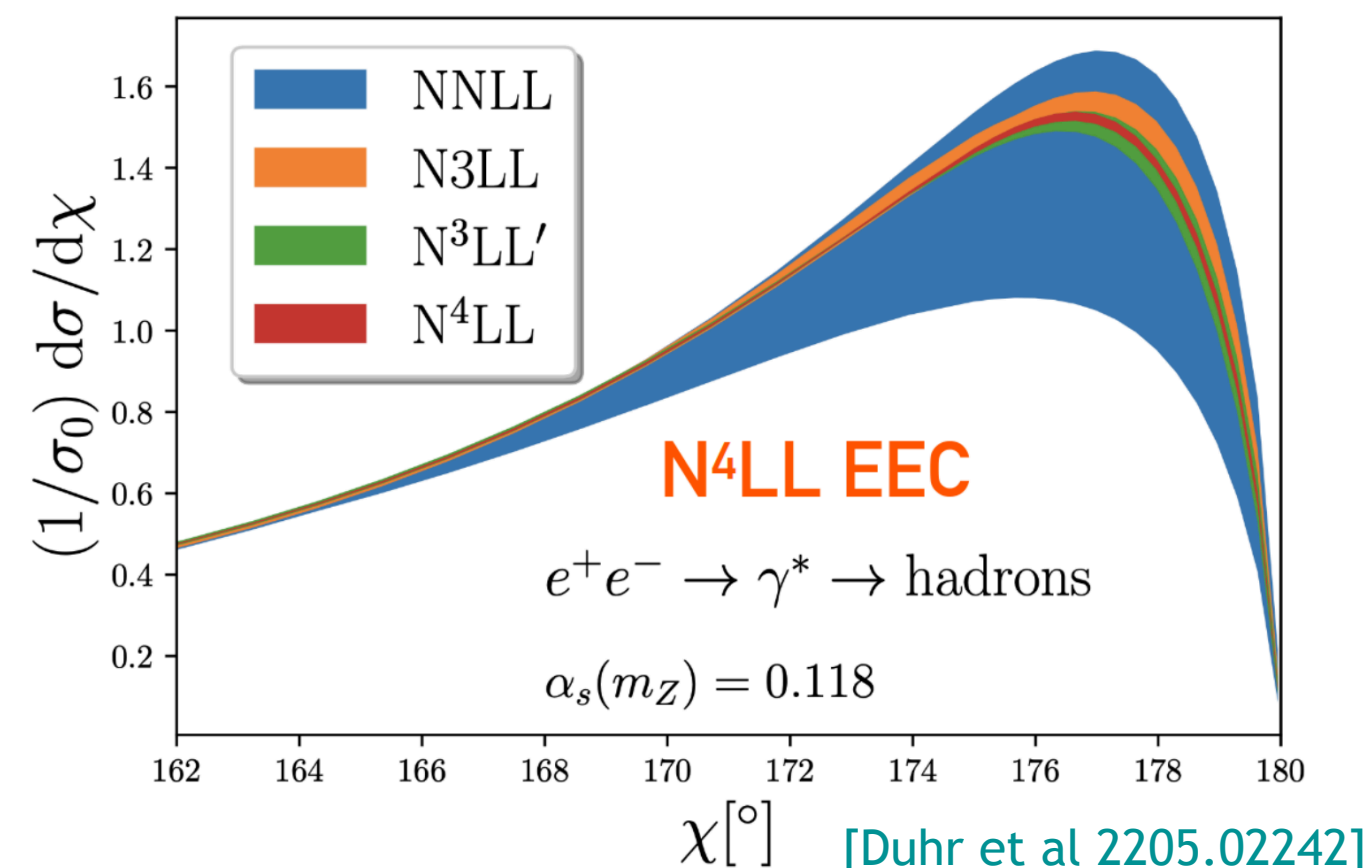
2. Deep characterisation of QCD $\rightarrow$ Jets (dynamics and substructure) $\rightarrow$ high-multiplicity (>2 jets)

Multi-jet cross-section in perturbative QCD extremely challenging:

- no results available beyond N(N)LO QCD order for > 4 (3) jets

scattering amplitudes + IR dynamics (subtraction schemes)

3. significantly advance resummation program



- 3rd/4th logarithmic order to a wider set of 2-jet obs.
- 2nd/3rd logarithmic order to general n-jet case
- devise new observables to enhance:
calculability and performance

will require breakthroughs
in several directions

Non-perturbative corrections, hadronisation

Elephant in the room in precision jet physics

Mis modeling of non-perturbative/hadronisation effects potential serious limitation

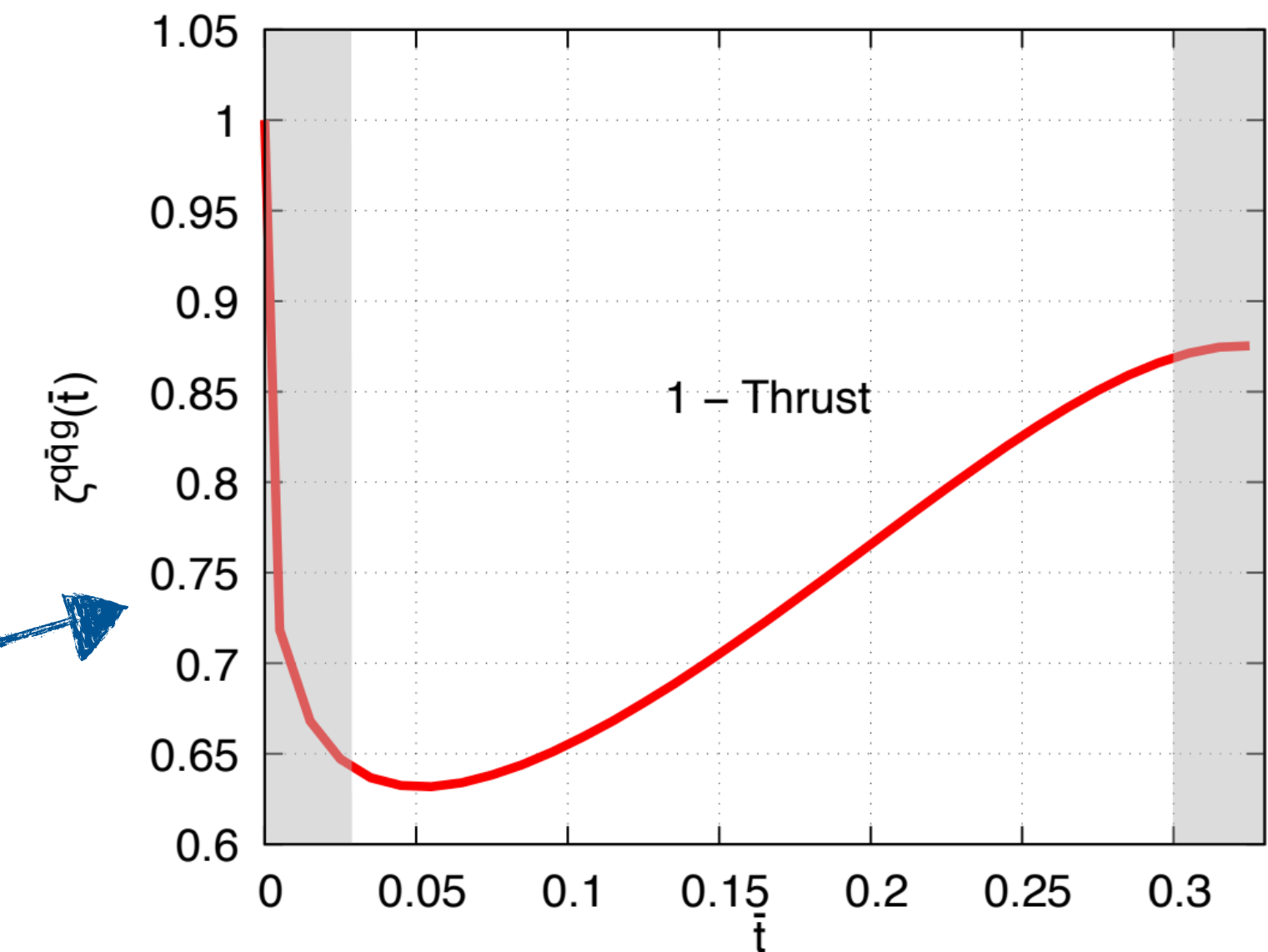
- interplay with Monte Carlo generators: tuning of hadronisation models
- analytic results typically derived in simple scenarios (then extrapolated)

Ways forward and challenges (**possibly a breakthrough**):

- examples of first analytical studies:
 - I. **(linear)** power corrections in shape observables [\[Luisoni et al 2012.00622\]](#) [\[Caola et al 2204.02247\]](#)
 - II. soft anomalous dimension for $1/Q$ power corrections [\[Dasgupta et al 2411.16867\]](#)
- analytic approaches in their infancy (relation to full QCD not yet robust)

refined analytic methods highly desirable

- devise observables with reduced sensitivity

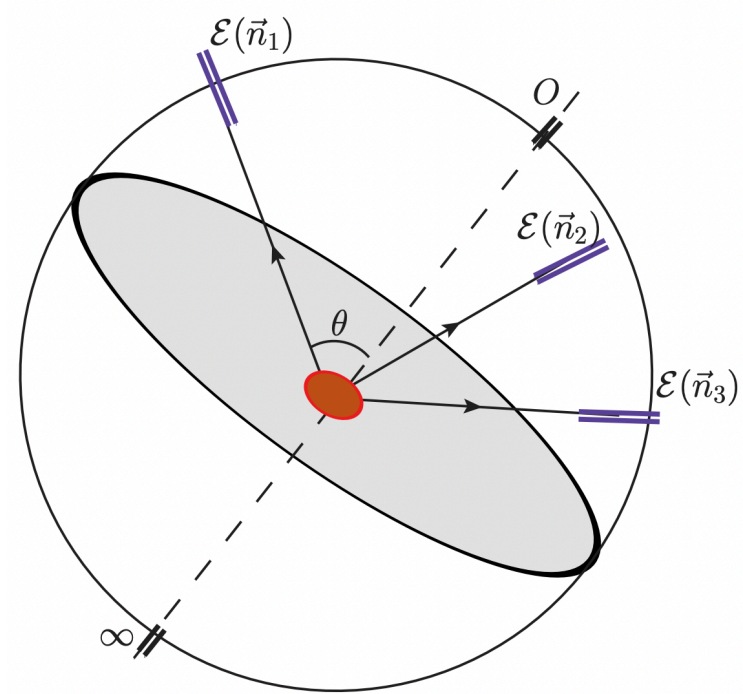


Thanks to accuracy at e^+e^- colliders, we have a **unique opportunity!**
profound investigation of (arguably) the least understood regime of QCD

“New” avenues to QCD across all regimes

Emergence of novel ideas, inspired by formal QFT/CFTs

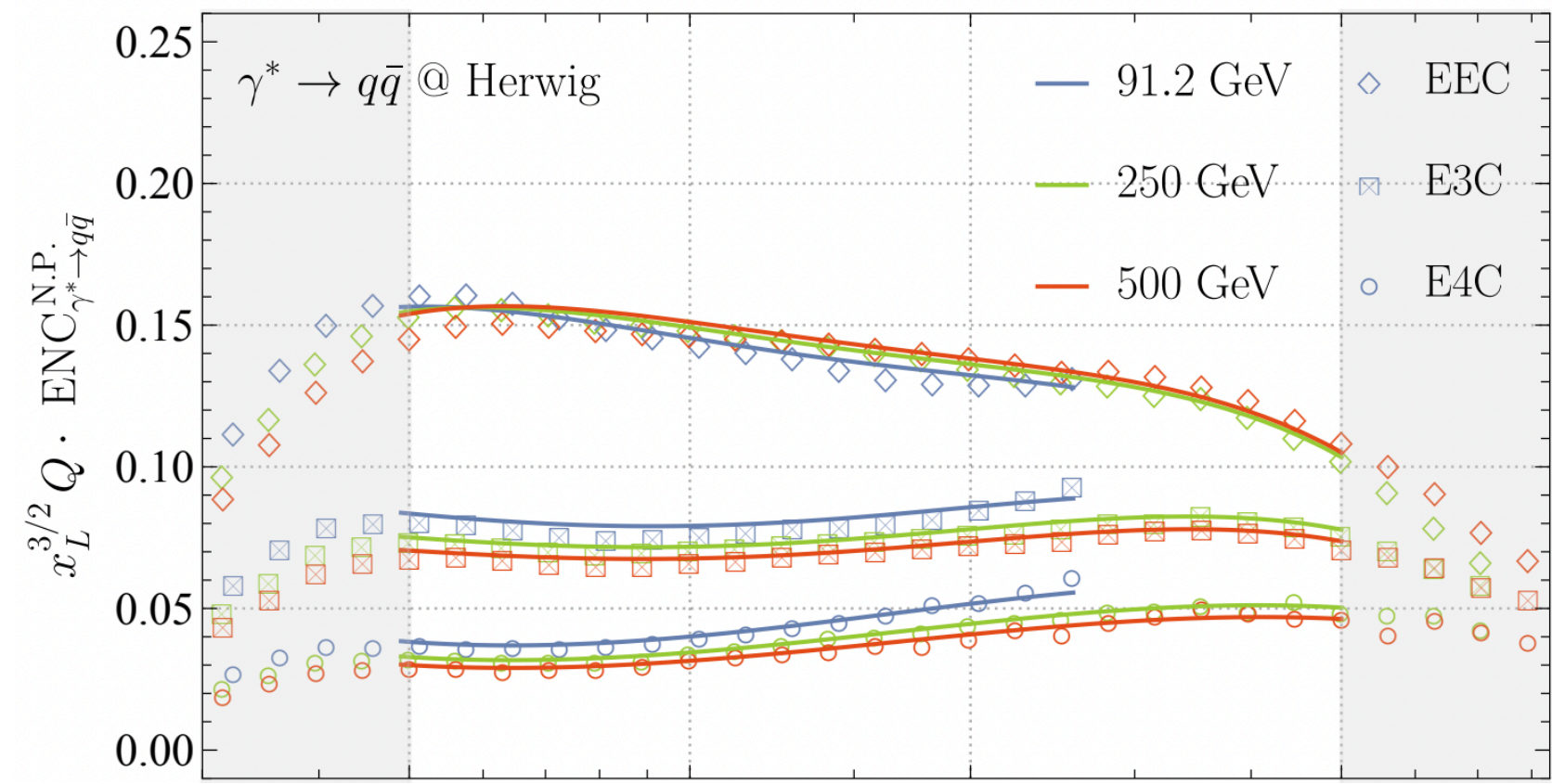
energy flow operator (~ “**detector operators**”)



$$\mathcal{E}(\hat{n}) = \lim_{r \rightarrow \infty} \int_0^\infty dt r^2 n_i T_{0i}(t, r \hat{n})$$

detector operator observables via **light-ray OPE**
in the **collinear limit**

$$\lim_{n_1 \rightarrow n_2} \mathcal{E}(n_1) \mathcal{E}(n_2) = \frac{1}{x_L} \vec{C} \cdot \vec{O}_{\tau=2}^{[J=3]}(n_2) + \frac{\Lambda_{\text{QCD}}}{x_L^{3/2}} \vec{D} \cdot \vec{O}_{\tau=2}^{[J=2]}(n_2) + \dots$$



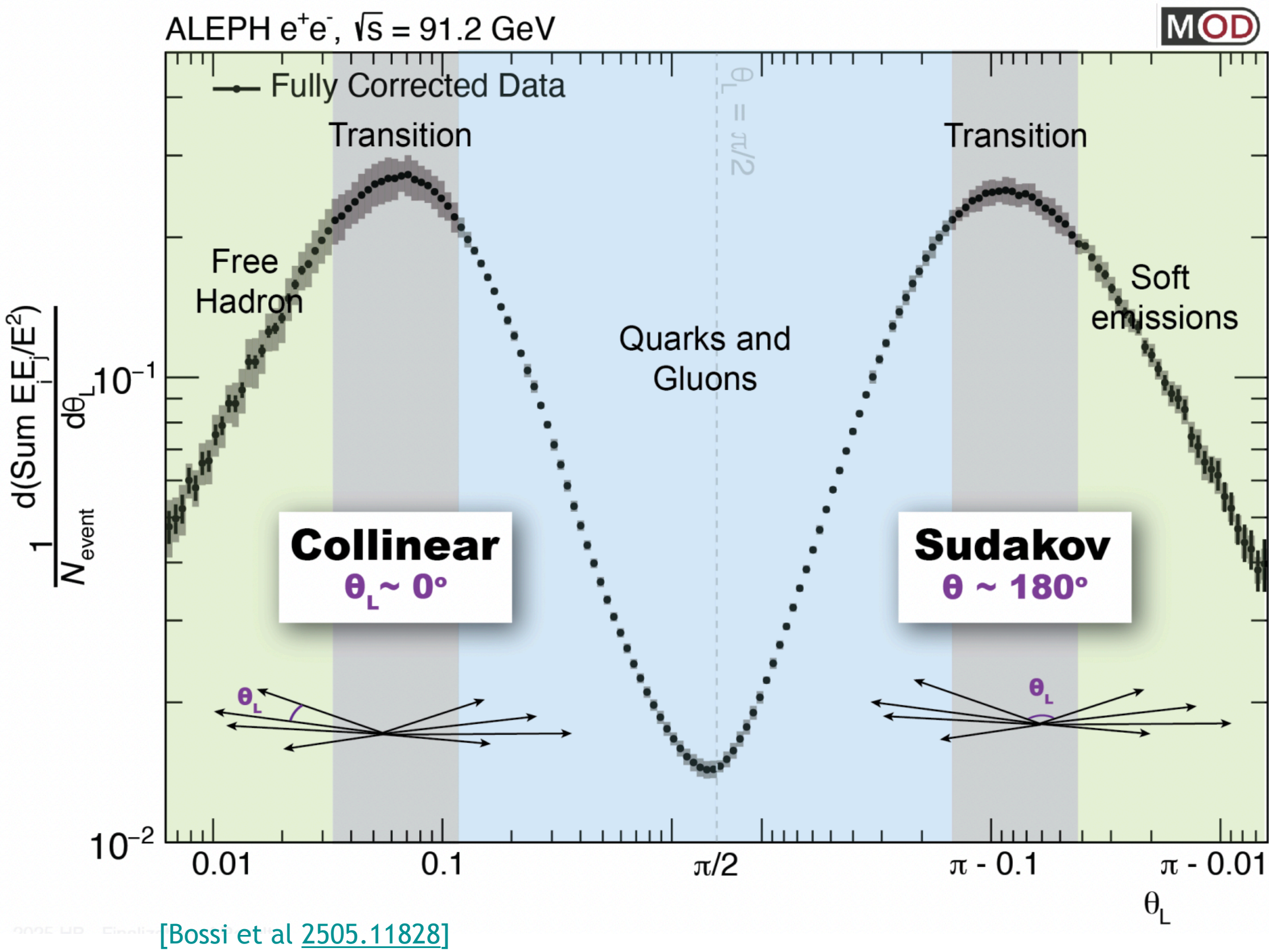
analytic vs Monte Carlo predictions

Scaling violation in
power corrections to
energy correlators

[Chen et al [2406.06668](#)]

Measurement of EEC with archived ALEPH data

$$\text{EEC}(\theta_L) = \sum_{i,j=1}^n \int d\sigma \frac{E_i E_j}{E^2} \delta(\theta_{ij} - \theta_L)$$



[Bossi et al [2505.11828](#)]

Opportunities at low $\sqrt{s}$ -QCD

[Discussion on FCC-ee case based on [D. d'Enterria et al 2503.23855](#)]

Q: interested in non-perturbative QCD? **A:** better look at lower energies

data collected at different (hadronic) energies can help **disentangling effects of hadronisation** corrections, **refine modelling**
stress-test theoretical **understanding**, **validate analytic approaches**

$$d\sigma \sim d\sigma^{(P)} + d\sigma^{(NP)} \xrightarrow{\text{non-perturbative component}} d\sigma^{(NP)} \sim \Omega(\nu) \left(\frac{\Lambda_{\text{QCD}}}{\sqrt{s_{\text{had}}}} \right) + \mathcal{O} \left(\frac{\Lambda_{\text{QCD}}^2}{s_{\text{had}}} \right)$$

great [advantages/opportunities](#):

- clean scenario, highly reduced background
- study quark-mass effects
- test/investigate/explore non-perturbative dynamics
- extremely valuable input for hadronisation models

W^+W^- threshold scan at FCC-ee

Observable	value	present		FCC-ee Stat.	FCC-ee Syst.
		$\pm$	uncertainty		
m_W (MeV)	80 360.2	$\pm$	9.9	0.18	0.16
Γ_W (MeV)	2 085	$\pm$	42	0.27	0.2

$\delta m_W / m_W \simeq 3 \times 10^{-6}$

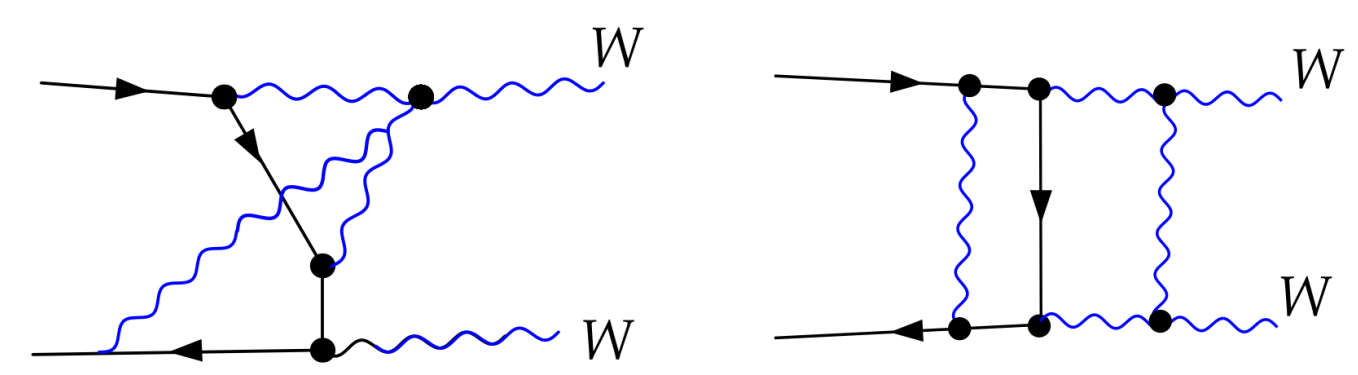
EFT approach for unstable particles, i.e. $v^2 \sim \alpha \sim \frac{\Gamma_W}{M_W} \ll 1$
[\[Actis et al hep-ph/0807.0102\]](#)

1. missing relevant contributions:

- residual uncert. on resonant part $\approx 0.1\% \times \sigma_{\text{Born}}$
- non-resonant effects and kinematic corrections $\approx 0.02\% \times \sigma_{\text{Born}}$

2. in order to address both:

2-loop EW effects to WW production



3. hadronic W decays:

QCD corrections and effects of colour reconnection

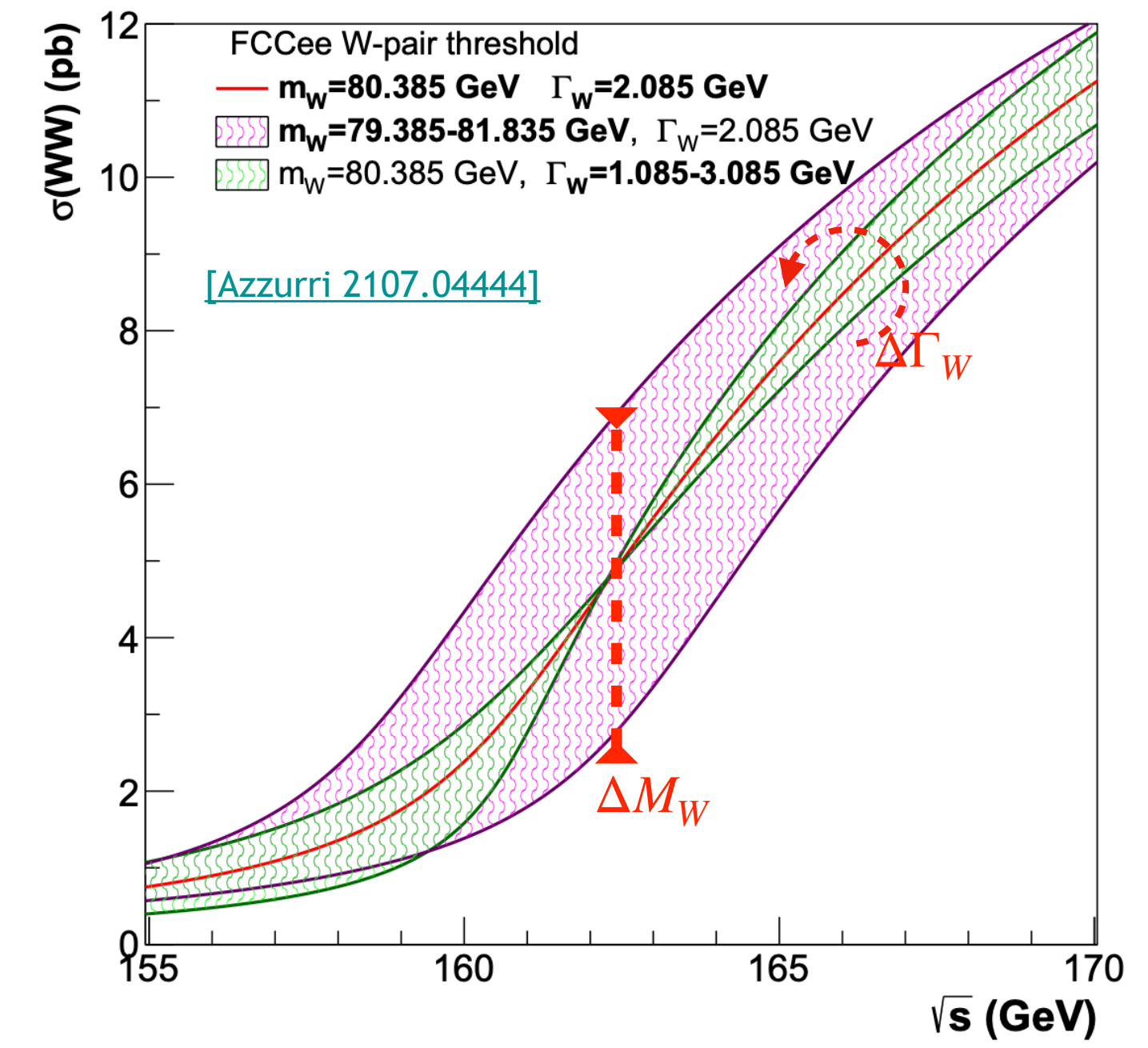
$\delta\sigma \simeq 0.1\% \Rightarrow \delta m_W \simeq 1.5 \text{ MeV}$
theory control on XS at threshold well below permille

mandatory

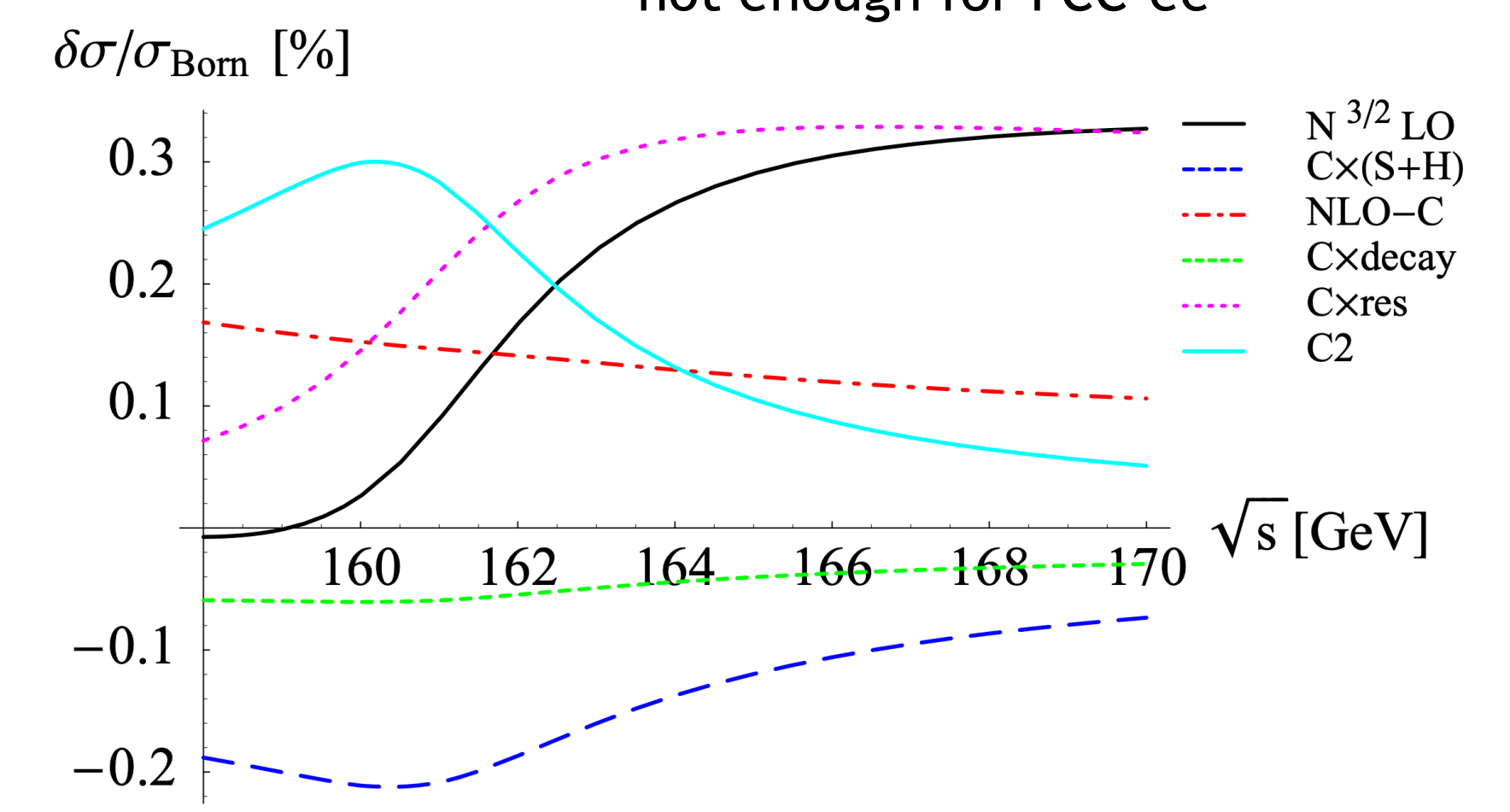
[\[Schwinn in 1905.05078\]](#)

must be under control

extremely challenging



$\mathcal{O}(0.3\%)$ uncertainty on XS:
not enough for FCC-ee



$t\bar{t}$ threshold production: state of the art

Ultra-precise measurement of top-quark mass from threshold scan

Observable	value	present		FCC-ee Stat.	FCC-ee Syst.
		$\pm$	uncertainty		
m_{top} (MeV)	172 570	$\pm$	290	4.2	4.9
Γ_{top} (MeV)	1 420	$\pm$	190	10	6

Same considerations apply to a linear collider [see Defranchis et al 2503.18713]

Two main crucial features:

- production of a resonant, non-relativistic, $t\bar{t}$ pair
- possibility of a rigorous definition of a short-distance mass scheme
cancellation of potentially large renormalon ambiguity [see also talk by M. Beneke]

Accurate description via non-relativistic (QCD) EFT: $v \sim \alpha_s$

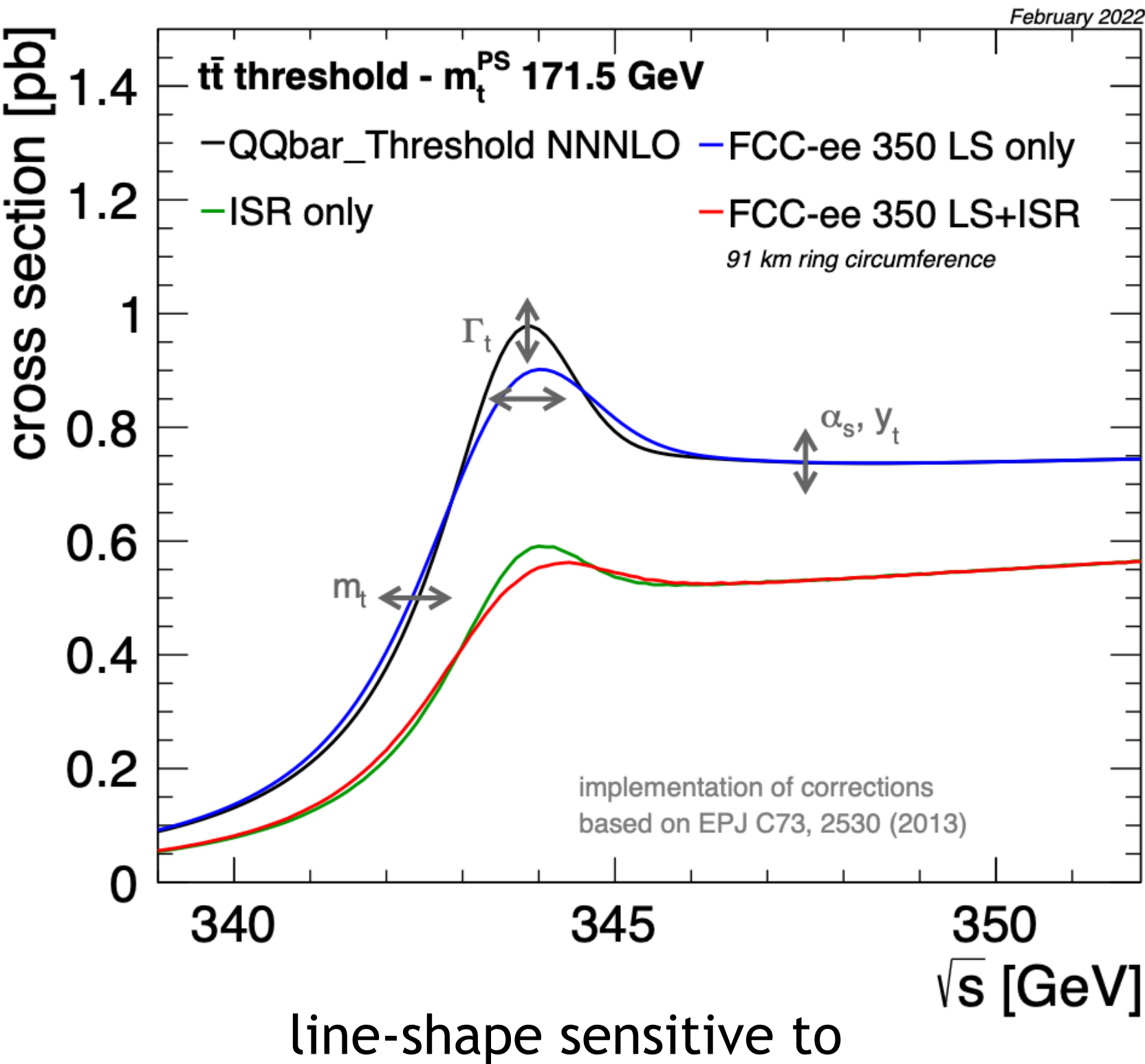


Theoretical control at third order. i.e.

$$\alpha_s^n v^m, \quad m + n = 3 \quad \text{[Beneke et al. 1506.06864]}$$

$$\delta m_t \simeq 35 \text{ MeV (MHO)}$$

$$\delta m_t \simeq 10/20 \text{ MeV } (\overline{\text{MS}} \leftrightarrow \text{PS})$$



$t\bar{t}$ threshold and continuum

Even at threshold: ultimately interested in $e^-e^+ \rightarrow W^+W^-b\bar{b}$

$$\sigma(s) = \sigma_{\text{res}}(s) + \sigma_{\text{non-res}}(s)$$

EW and Higgs effects in good shape

[Beneke et al. 1711.10429](#)

What we need (**beyond reach now**):

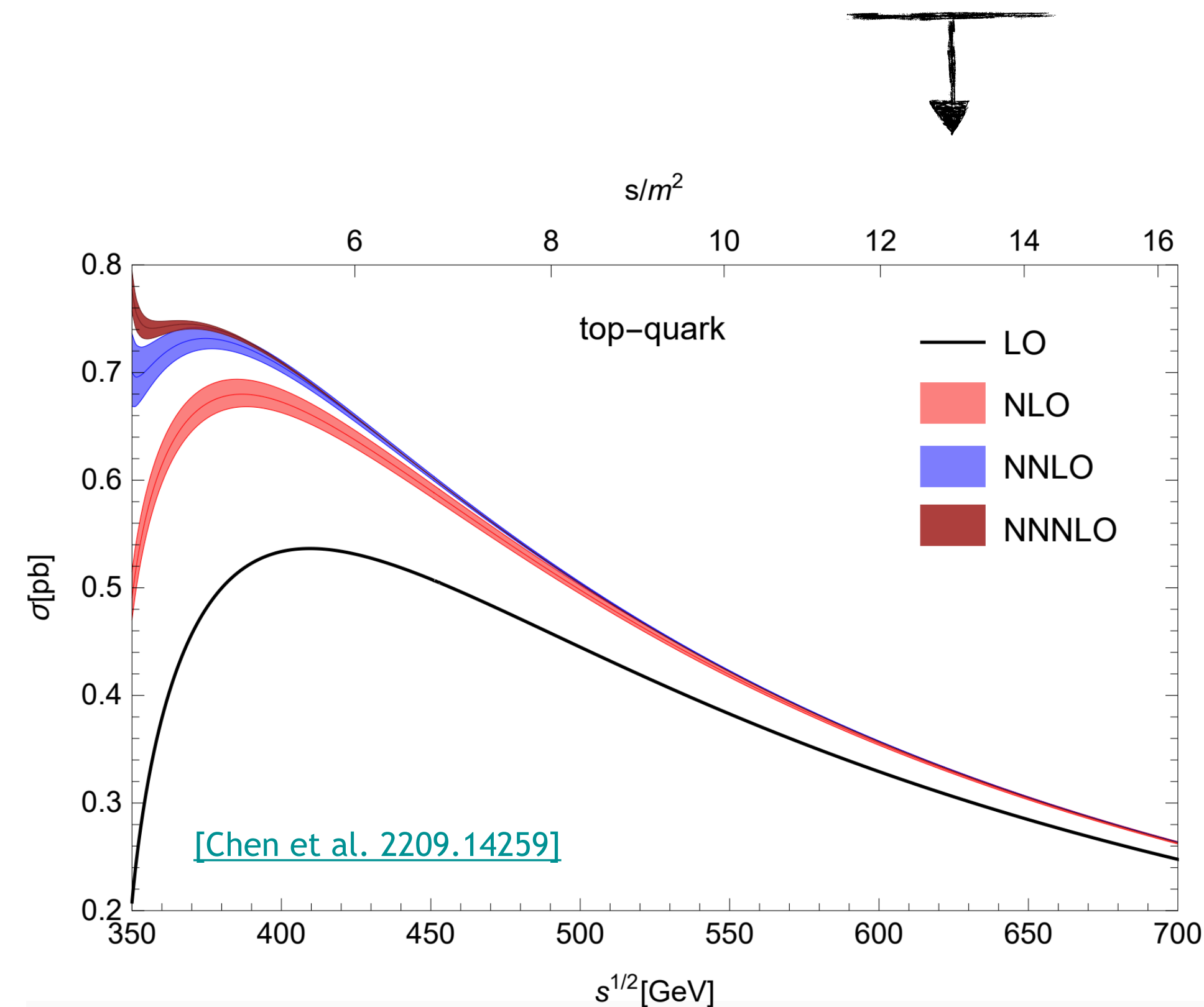
- fourth-order QCD corrections to **resonant contribution** (4-loop QCD calculation)
- third-order effects in **non-resonant contributions**

Beyond total rates/EFT

- **differential predictions** in non-relativistic limit: effects of cuts
- how to assess **off-shell effects** at higher orders and have them under control
- embedding all in **Monte Carlo generators** (QCD/QED resonance aware)
- need to include **NLL ISR resummation**

above the threshold:

Total inclusive rate computed to N3LO in QCD



$\mathcal{O}(0.15\%)$ at $\sqrt{s} = 500$ GeV

General topic: PSMCs

Parton **S**hower **M**onte **C**arlo Generators**s**

Parton-shower Monte Carlo generators (PSMCs)

The **accuracy of current generators insufficient** to match foreseen experimental precision

a topic which deserves an entire workshop, not making justice in one slide!

MC generators are at the heart of arguably any analysis (future and present colliders)

Key topics/aspects/ways forward:

I. **Formal** (logarithmic) **accuracy**

II. **Matching** to higher-order calculations (log-accuracy compliant)

III. **Non-perturbative QCD** effects

hadronisation models, colour reconnect. → relevant eg in m_t , m_W measur.

IV. **Electroweak corrections**

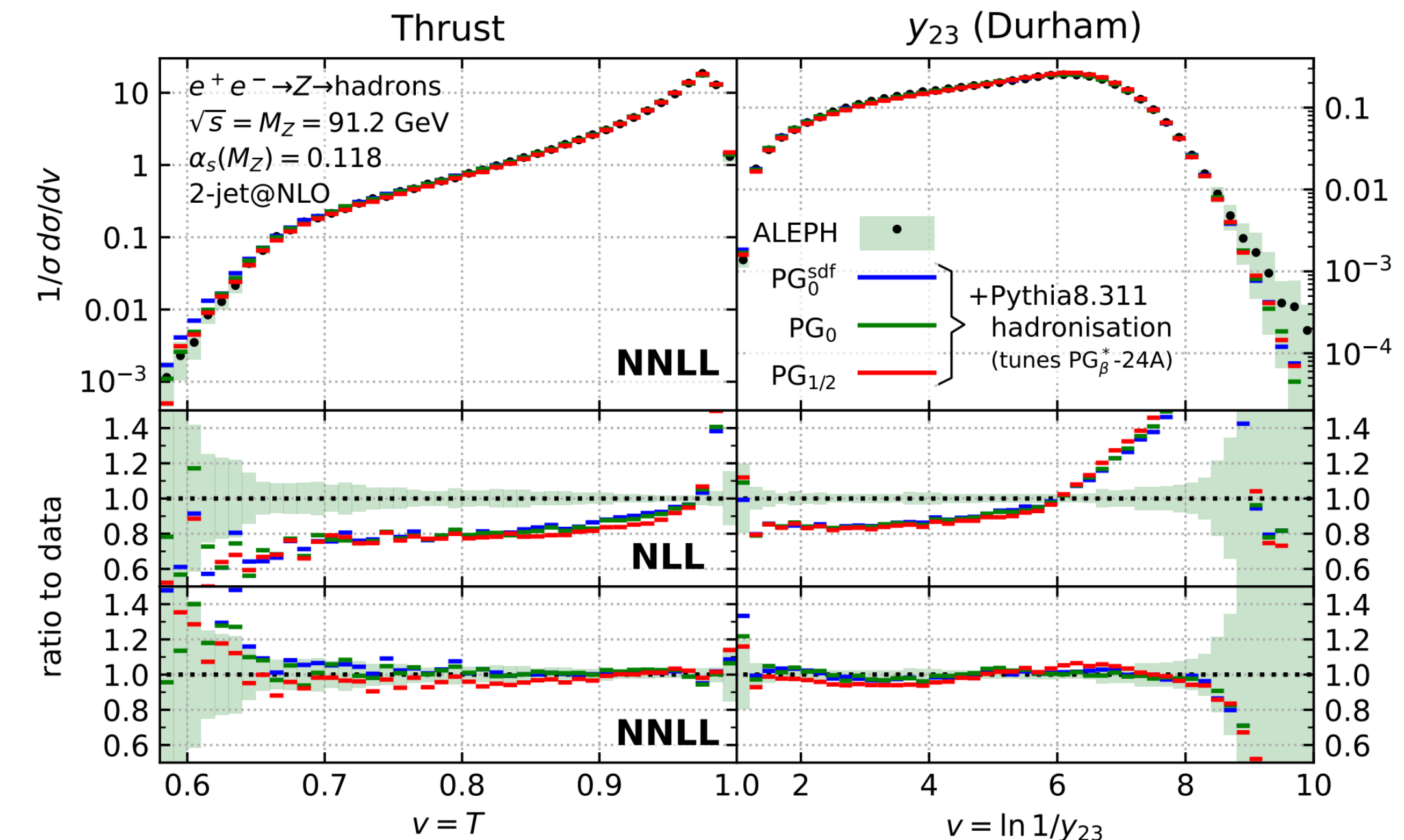
QCD + QED showers, resonance-aware showers

V. **Possible alternative avenues/rethinking**

eg. amplitudes/colour evolution [see eg Forshaw et al 2502.12133]

VI. **Theory uncertainties**

Extrapolation from fiducial to inclusive (typically in much better control)



Recent milestone result: NNLL accurate PS for e+e-

[[van Beekveld et al. 2406.02661](#)]

Parton Showers for future e+e- colliders

[please visit [here](#) for more]

Concluding remarks

More challenges (not covered so far)

Higgs-related:

- non-hadronic Higgs decays and higher-order corrections
- progress and status of Higgs cross sections, eg $H+J@N^3LO\text{-QCD}$, $gg\rightarrow H@N^4LO\text{-QCD}$

Lepton colliders:

- Multiple photons emission from incoming lepton beam, i.e. **Initial-State Radiation (ISR)**: YFS vs Coll.Fact.
- precise determination of **fine-structure constant** α
- beam polarisation and related challenges

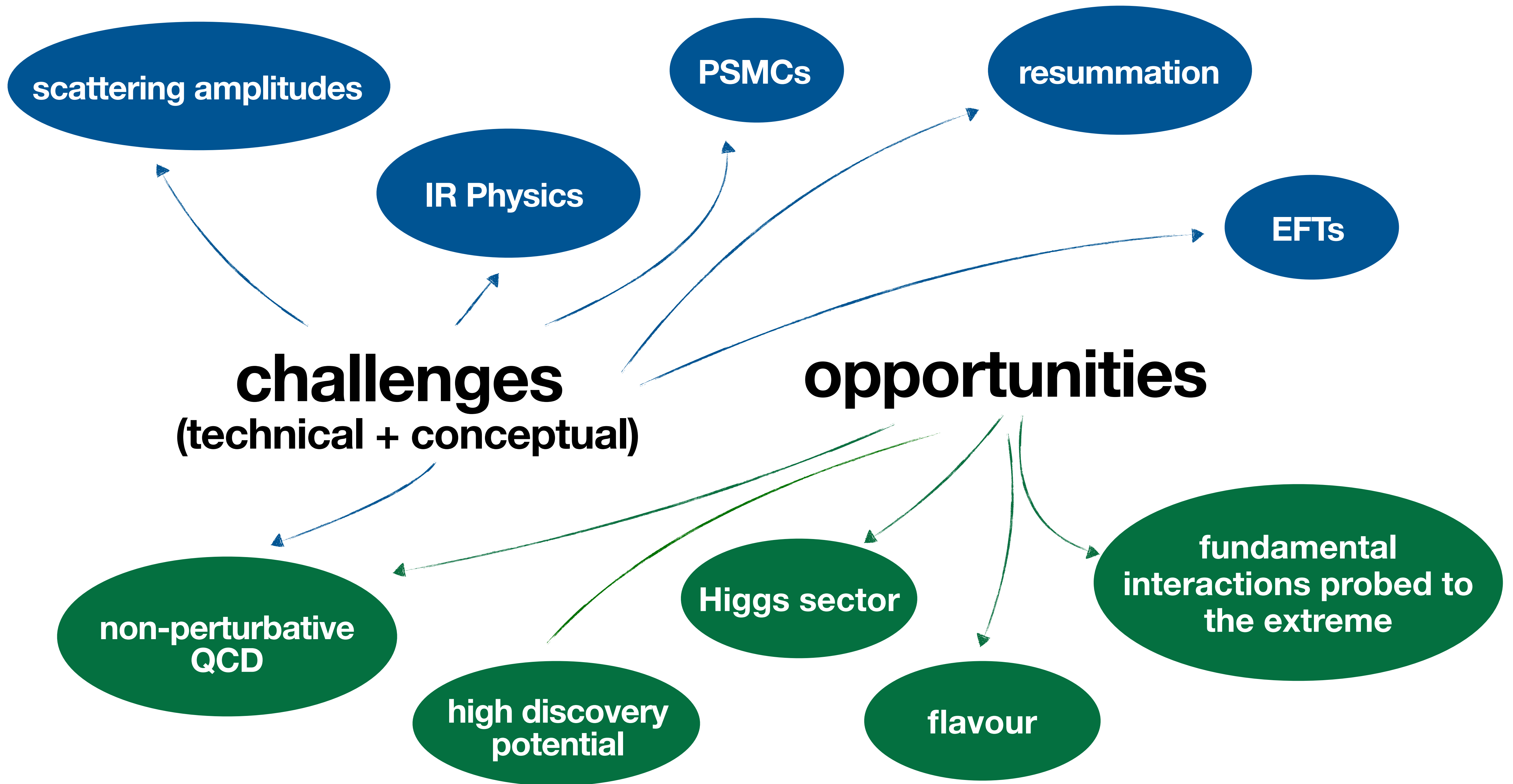
Hadron colliders (eg LHeC and FCC-hh):

- parton distribution functions (**PDFs**) at hadron colliders (see talk by Juan on Tue)
- Challenges in heavy-ion Physics and **QCD in dense media**

General topics:

- role and impact of **Machine-Learning** and their training, eg. jet taggers
- status, projections and challenges in **lattice calculations**

certainly infinitely many more that I am neglecting...



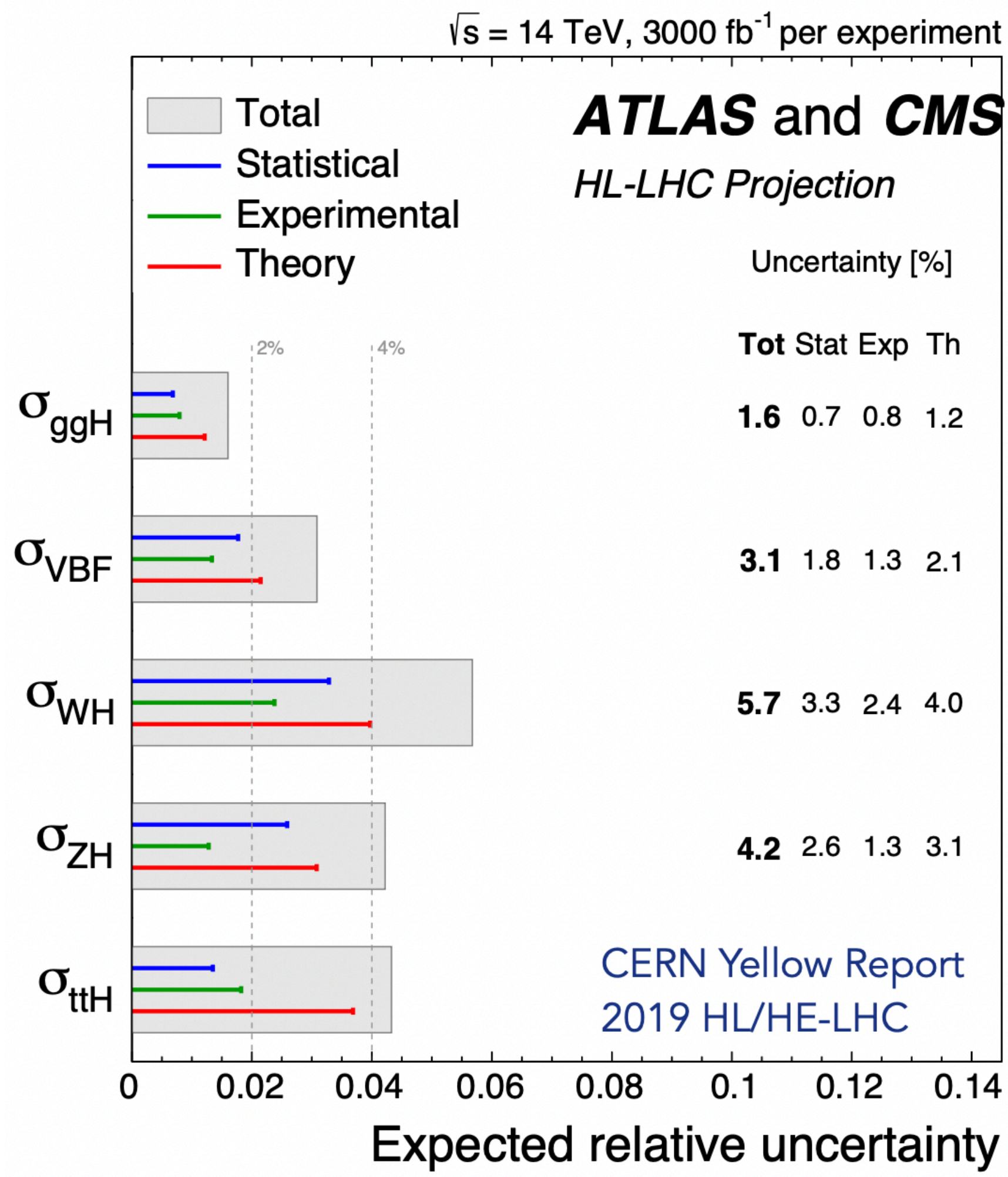
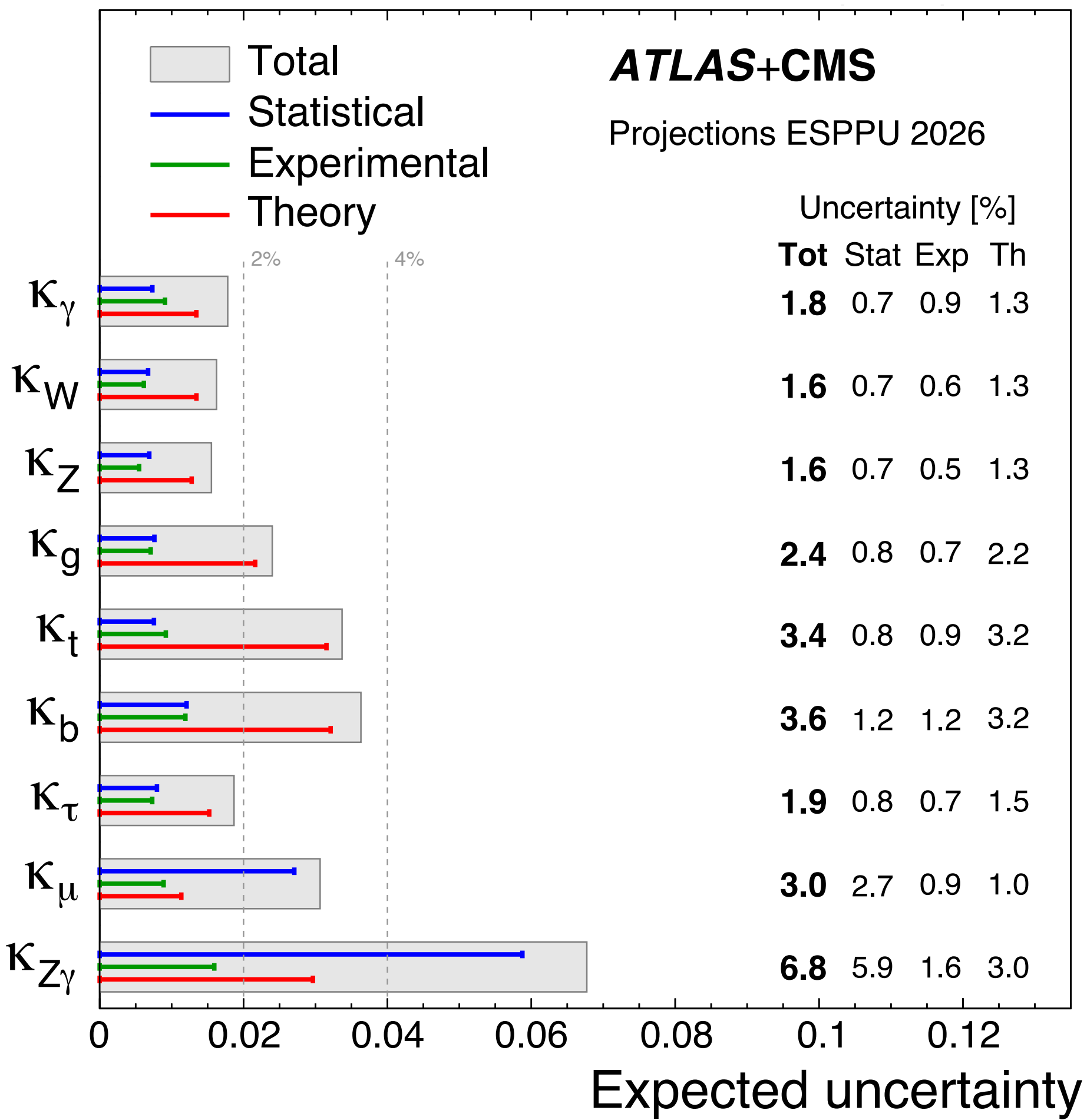
Thanks! (for bearing with me)

I gratefully acknowledge M. Beneke, F. Caola, P.F. Monni, T. Gehrmann and G. Zanderighi for many interesting discussions during the preparation of this talk

Backup slides

Higgs at HL-LHC

- I. approaching few % precision target
- II. theory most often limiting factor



Priorities from the ESPP



High-priority future initiatives (I): future colliders

[Fabiola Gianotti, Open Symposium ESPP Venice 2025]

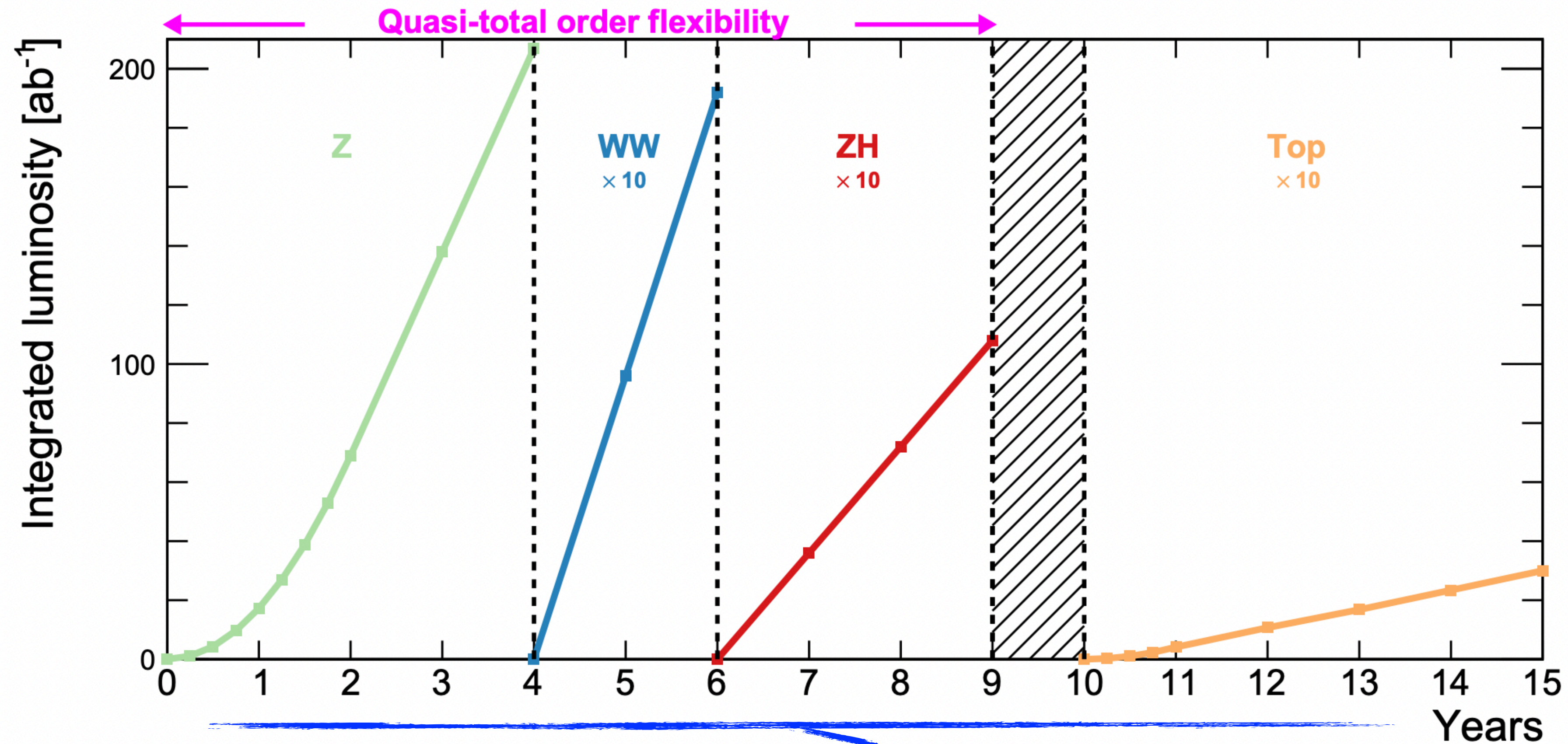
An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.

Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

As I will try to argue: the array of searches and studies extends far beyond just the Higgs sector

The FCC-ee timeline

Baseline operation mode: four main interaction points (IPs)



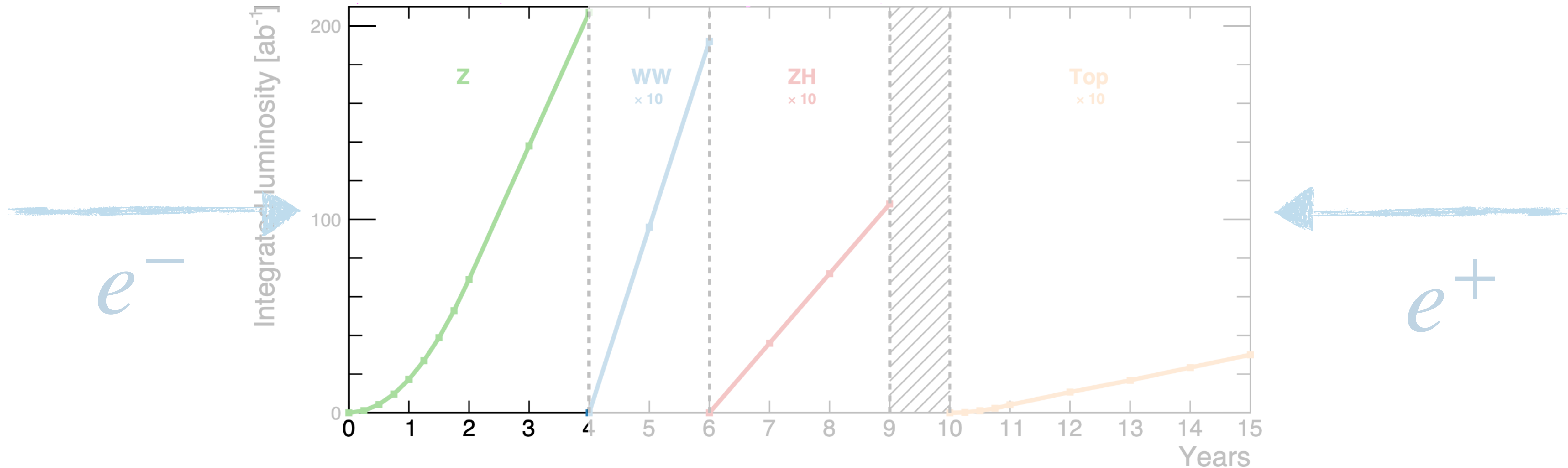
+ potentially (eg):

- dedicated runs at lower energies for QCD studies (below Z pole)
- runs at Higgs pole (electron Yukawa measurement)

interconnected crucial
input/studies from all IPs

FCC-ee timeline as a guideline

Let us discuss in more concrete terms: using FCC-ee timeline to showcase common challenges faced by theory predictions

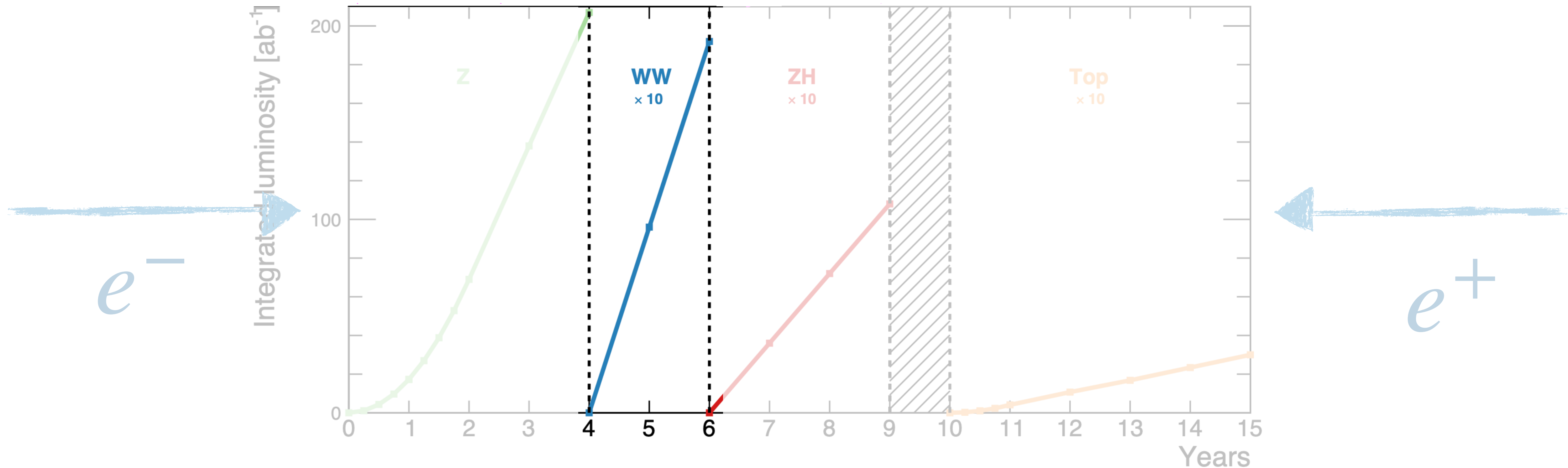


Physics at the Z pole

- precision observables and perturbative corrections (**QCD** and **EW**)
- **jets** and **QCD studies**
- hadronisation and non-perturbative effects

FCC-ee timeline as a guideline

Let us discuss in more concrete terms: using FCC-ee timeline to showcase common challenges faced by theory predictions

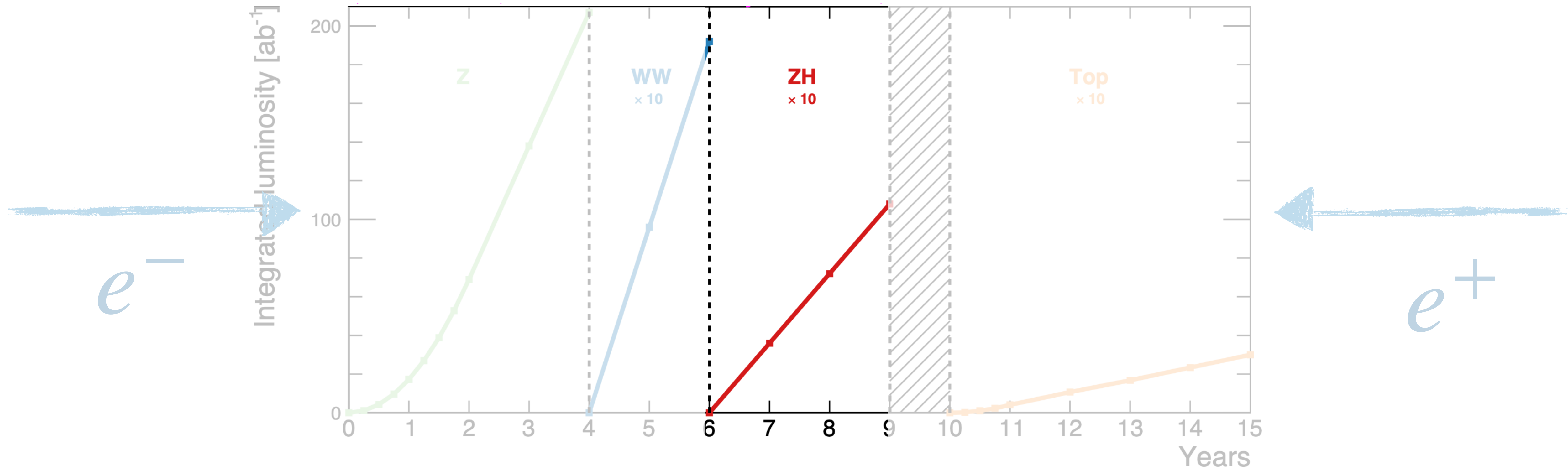


W^-W^+ threshold scan

- perturbative corrections (**EW**)
- **theoretical framework**: future challenges and limitations

FCC-ee timeline as a guideline

Let us discuss in more concrete terms: using FCC-ee timeline to showcase common challenges faced by theory predictions

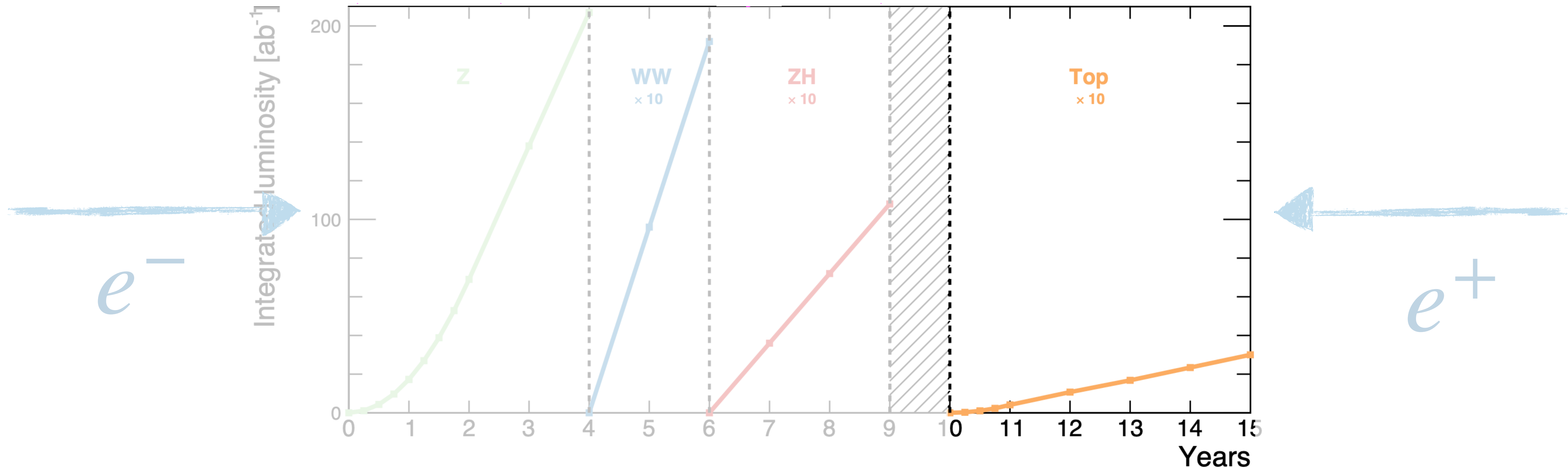


Higgs factory

- perturbative corrections in XS (**EW**)
- Higgs hadronic decays → **pert.** and **non-pert. QCD**

FCC-ee timeline as a guideline

Let us discuss in more concrete terms: using FCC-ee timeline to showcase common challenges faced by theory predictions



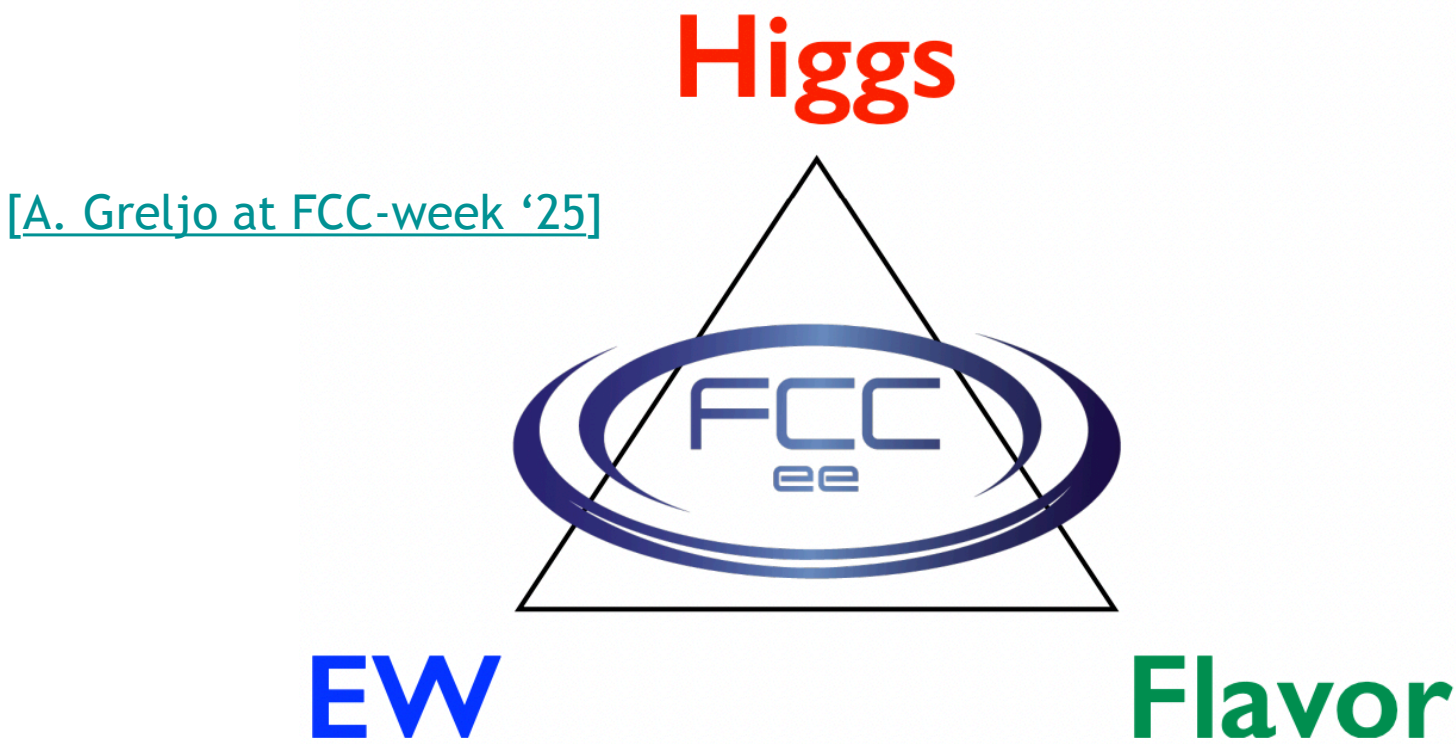
$t\bar{t}$ threshold scan

- pert. and non-pert. **QCD**, **EW** effects
- **theoretical framework**: future challenges and limitations

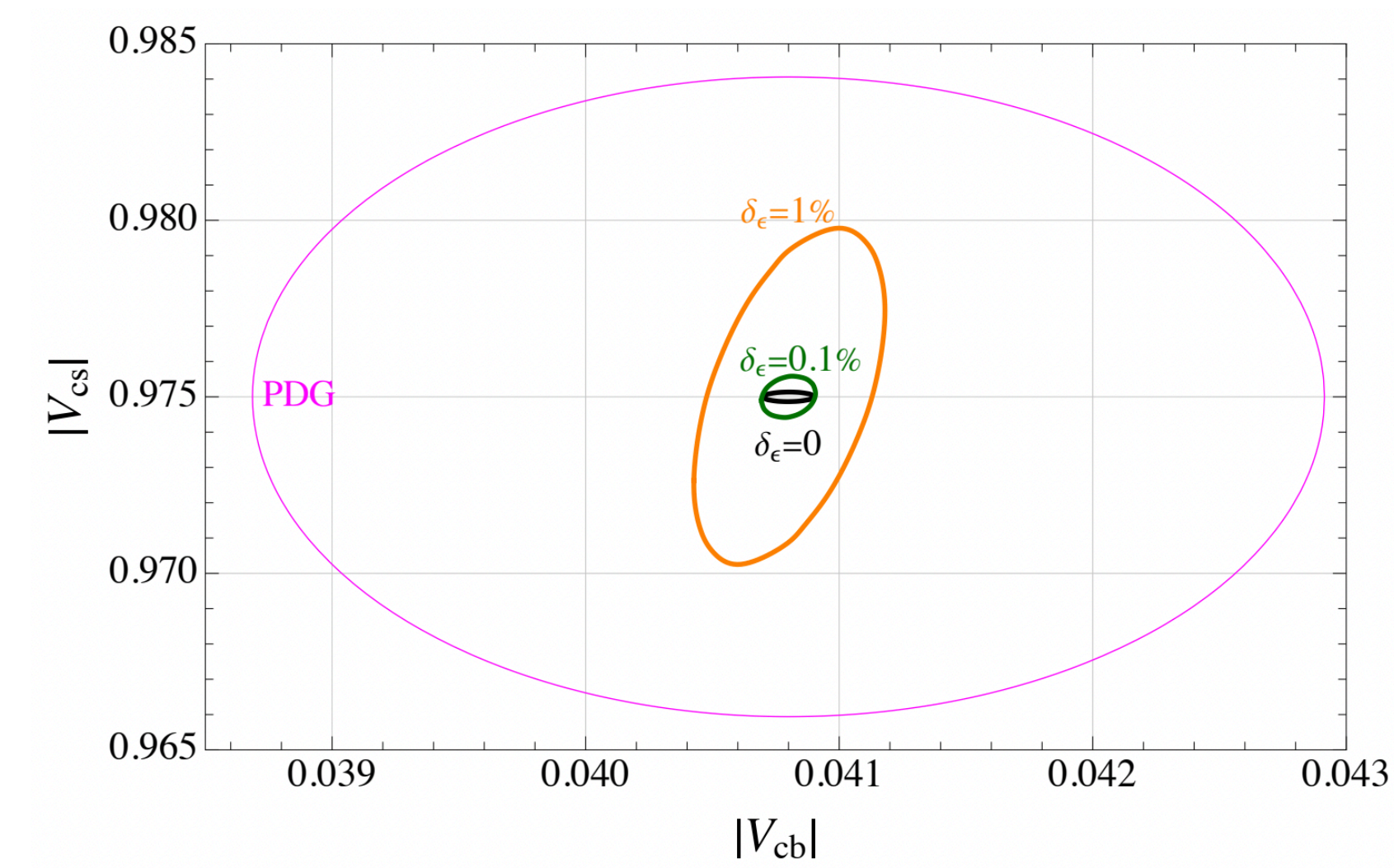
Flavour opportunities, FCC-ee case study

Intimate connection between flavour and Higgs physics

- Tera Z

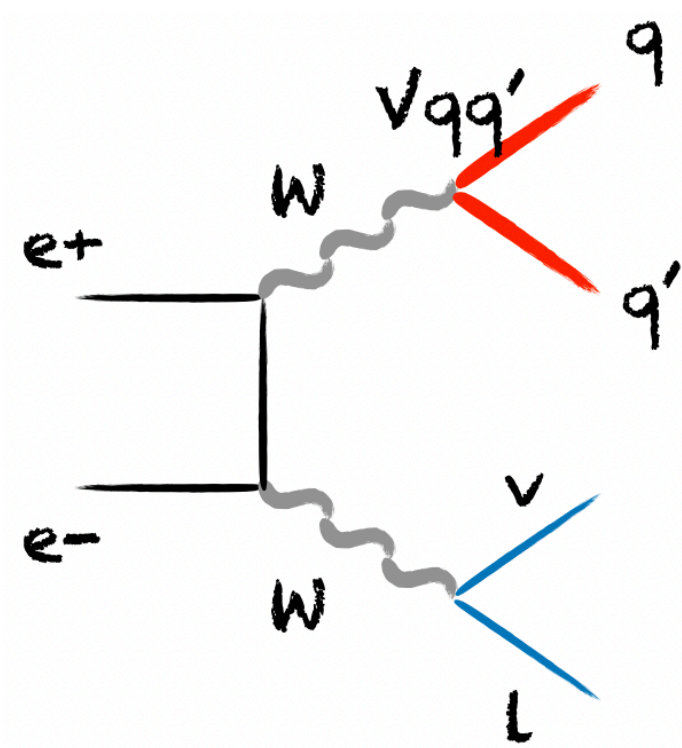


- WW



[Marzocca et al, 2405.08880]

[credit to L. Buonocore for pic]



Exploit 10^8 W^+W^- events to significantly improve $|V_{cb}|, |V_{cs}|$ determination

critical dependence on **jet taggers efficiency**/uncertainties

heavy-flavour identification

[Kamenik et al.]

Attribute	$\Upsilon(4S)$	pp	Z
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
High geometrical acceptance	✓		✓
Low backgrounds	✓		✓
Flavour-tagging power	✓		✓
Initial-energy constraint	✓		(✓)

at FCC-ee, 15 times more $b\bar{b}$ pairs than at Belle II

Initial-State Radiation (QED effects)

Multiple photons emission from incoming beam: Initial-state-radiation (ISR)

I. Yennie-Frautschi-Suura (YFS):

- soft photon effects resummed to infinite orders (collinear not!)
- well-established framework, implemented already in several Monte Carlo gen.

logarithmic enhancement from

soft and collinear emissions

must be resummed

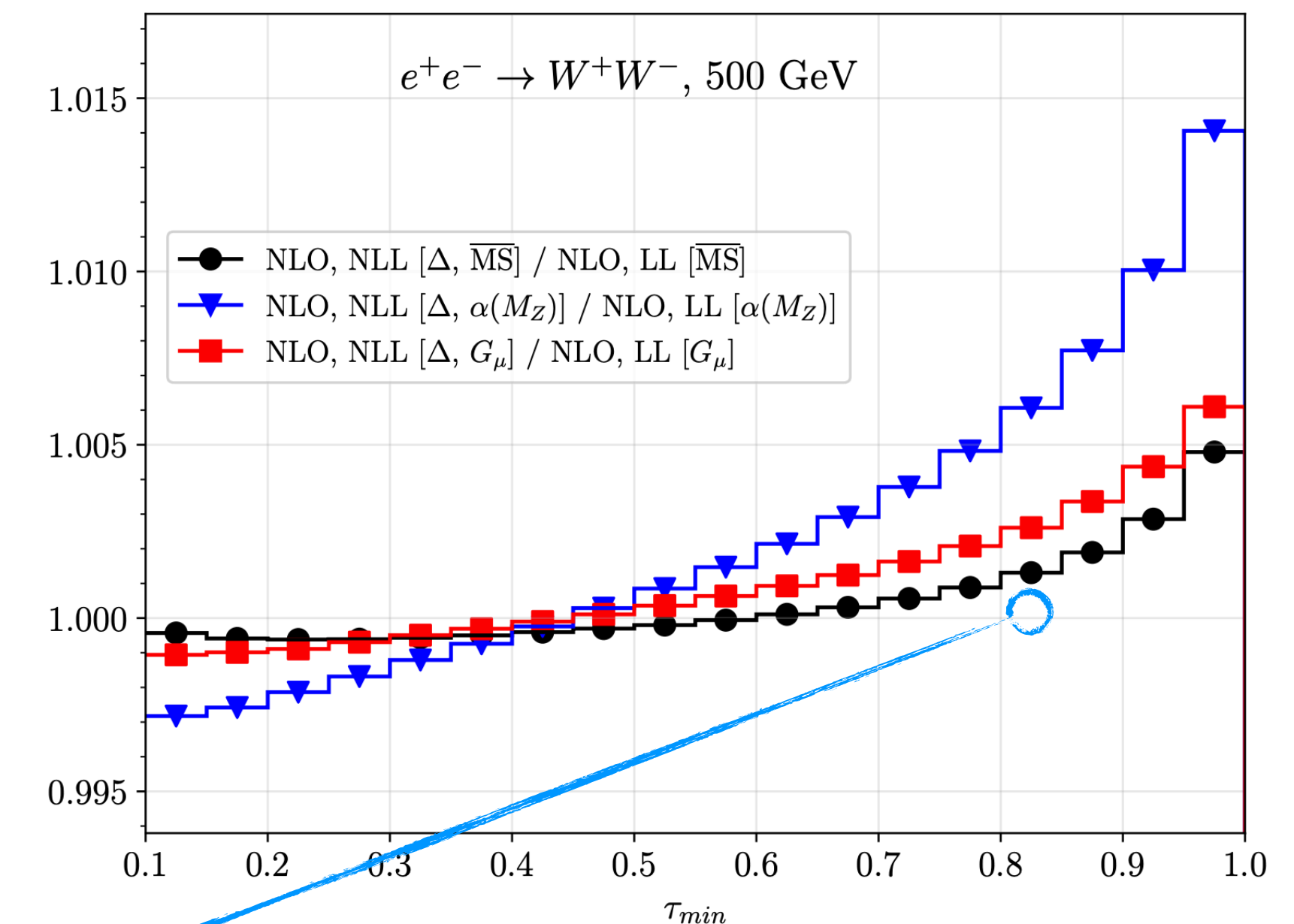
II. Collinear factorisation:

- resummation of collinear emissions ~ electron Parton Distr. Funct. (ePDF)
- great recent progress to go to Next-to Leading logarithmic accuracy (NLL)
[\[Frixione 1909.03886, 2105.06688; Bertone et al 1911.12040, 2207.03265\]](#)
- impact of higher-log sizeable and observable dependent

III. Future challenges:

- extend coll. factorisation to NNLL (needed for FCC-ee)
- Q: combined soft + collinear resummation?

[\[Bertone et al. 2207.03265\]](#)



0(1%) level
effects from NLL

$$y \equiv (\sigma^{\text{NLO}} + \text{NLL ISR}) / (\sigma^{\text{NLO}} + \text{LL ISR})$$

Determination of α_s at FCC-ee

Current world average: $\alpha_s(m_Z) = 0.1180 \pm 0.0009$, value and uncertainty largely dominated by lattice

Foreseen α_s extraction at FCC-ee:

[QCD physics at FCC, d’Enterria and Monni]

Category	present $\alpha_s(m_Z^2)$ ($\times 10^4$) value $\pm$ uncertainty	FCC-ee Stat. Syst.		Extraction method Theory developments needed
Z hadronic decays	1 208 $\pm$ 28	0.1	1	Combined $R_\ell^Z, \Gamma_Z, \sigma_{\text{had}}^0$ fit $\mathcal{O}(\alpha_s^5), \mathcal{O}(\alpha^3), \mathcal{O}(\alpha_s, \alpha^3), \mathcal{O}(\alpha_s^2, \alpha^2)$ corrs.
W hadronic decays	1 070 $\pm$ 350	2	2	Combined R_ℓ^W, Γ_W fit $\mathcal{O}(\alpha_s^5), \mathcal{O}(\alpha^2), \mathcal{O}(\alpha^3), \mathcal{O}(\alpha_s, \alpha^3), \mathcal{O}(\alpha_s^2, \alpha^2)$ corrs.
τ hadronic decays	1 178 $\pm$ 19	$\ll 1$	< 10	Combined $\Gamma^{\tau, \text{had}}$ and τ lifetime fit $\mathcal{O}(\alpha_s^5)$, hadronisation corrections
Event shapes & jet rates	1 171 $\pm$ 31	$\ll 1$	< 10	Combination of event shapes and jet rates $\mathcal{O}(\alpha_s^4)$, hadronisation corrections

$\mathcal{O}(2 \times 10^{11})$ τ leptons from $Z \rightarrow \tau^+ \tau^-$ decays (α_s extraction from hadronic to leptonic branching fractions)

Precise extraction $\alpha_s(m_Z)$ from inclusive EWPOs, essential input to investigate hadronisation models via event shapes and jet rates

W^+W^- : status and more challenges

Improvements due to LL collinear ISR resummation

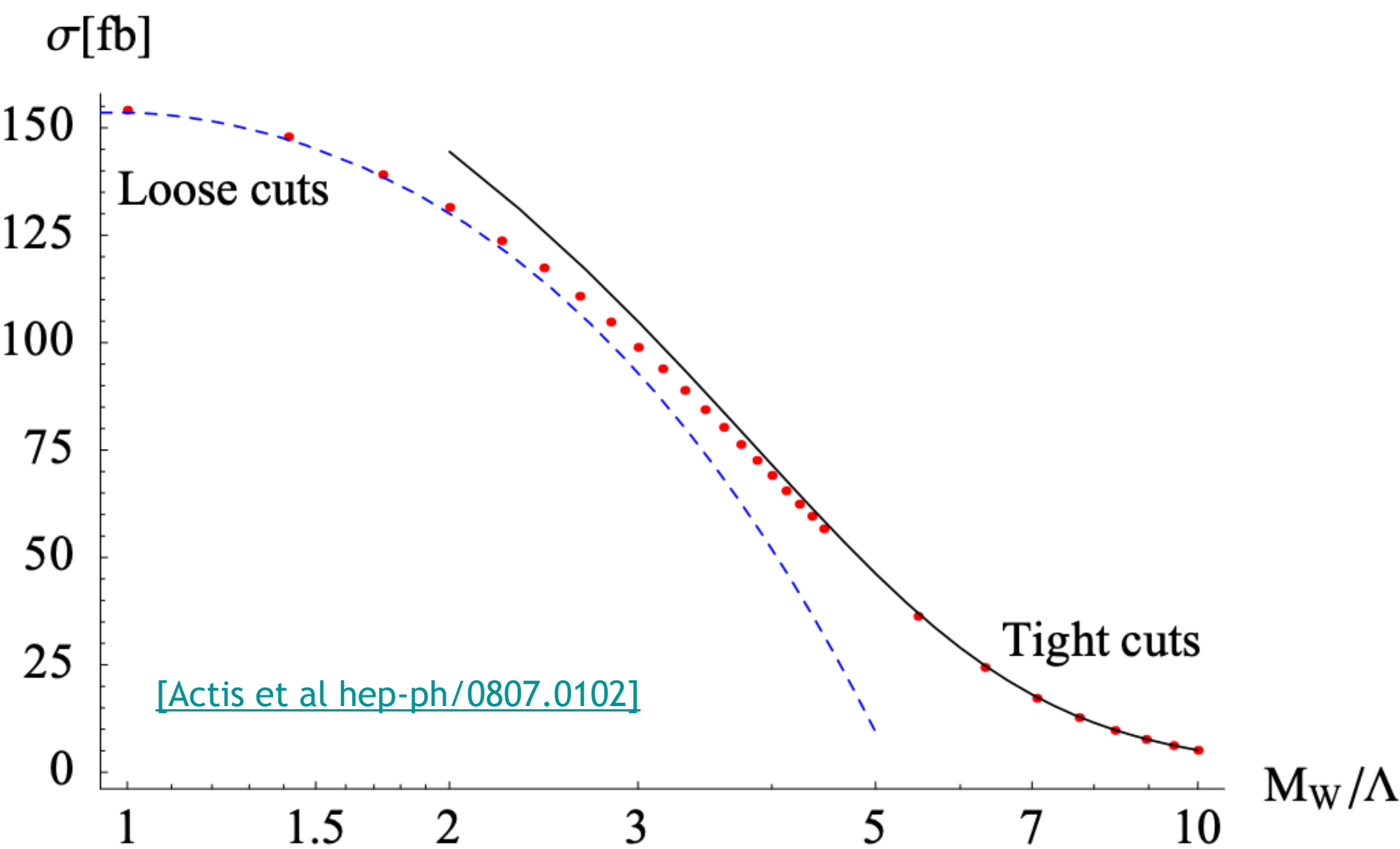
$\sqrt{s}$ [GeV]	$\sigma(e^-e^+ \rightarrow \mu^- \bar{\nu}_\mu u \bar{d} X)(\text{fb})$				
	Born	Born (ISR)	NLO	$\hat{\sigma}^{(3/2)}$	$\sigma_{\text{ISR}}^{(3/2)}$
158	61.67(2)	45.64(2) [−26.0%]	49.19(2) [−20.2%]	−0.001 [−0.0‰]	0.000 [+0.0‰]
161	154.19(6)	108.60(4) [−29.6%]	117.81(5) [−23.6%]	0.147 [+1.0‰]	0.087 [+0.6‰]
164	303.0(1)	219.7(1) [−27.5%]	234.9(1) [−22.5%]	0.811 [+2.7‰]	0.544 [+1.8‰]
167	408.8(2)	310.2(1) [−24.1%]	328.2(1) [−19.7%]	1.287 [+3.1‰]	0.936 [+2.3‰]
170	481.7(2)	378.4(2) [−21.4%]	398.0(2) [−17.4%]	1.577 [+3.3‰]	1.207 [+2.5‰]

Readily improvable including NLL ISR (ideally beyond)

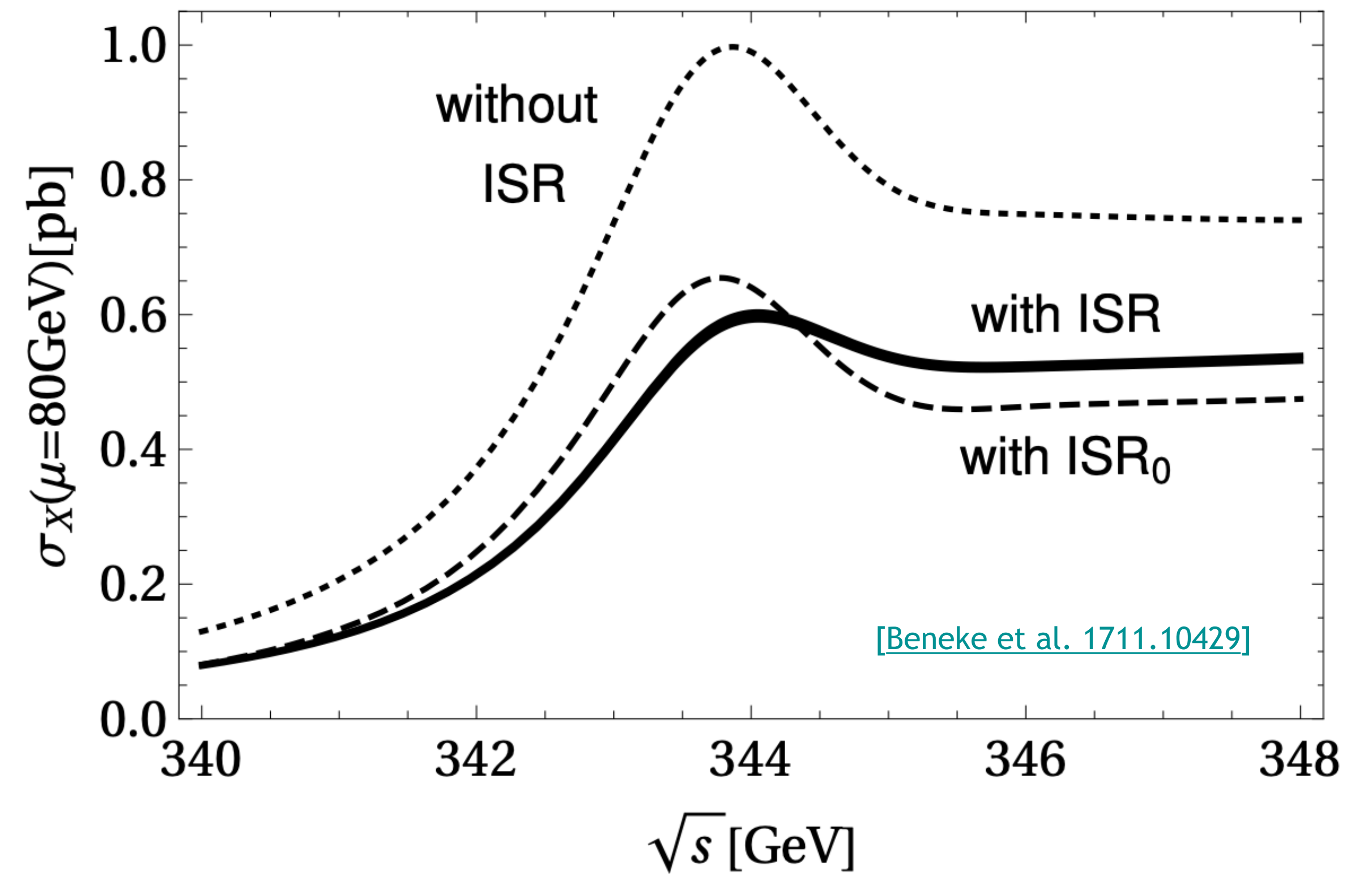
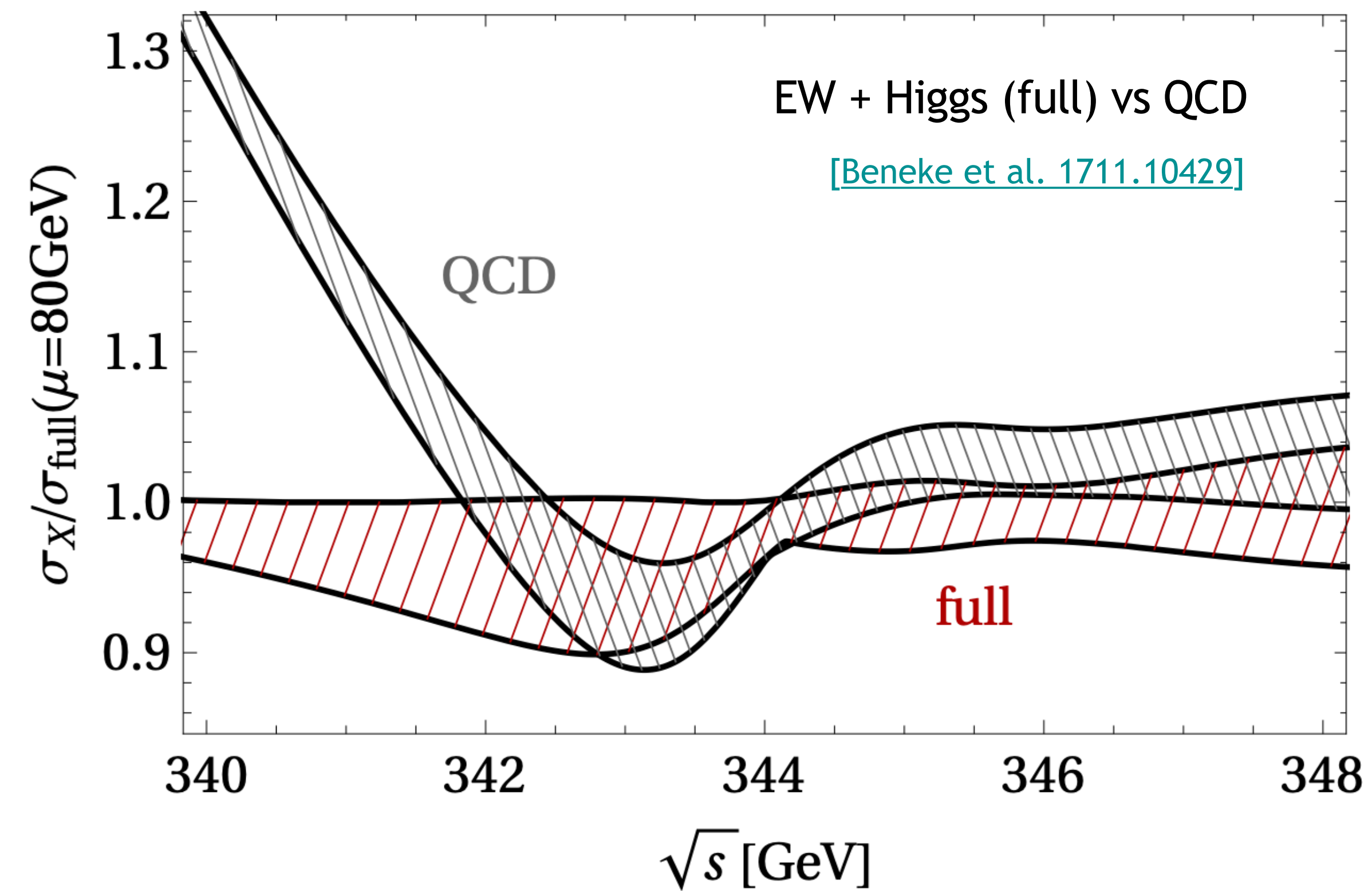
Questions/open problems/challenges:

- do we really need full-fledged $e^-e^+ \rightarrow 4f$ @ NNLO EW?
given current estimates: most likely not
- thorough assessment of impact of selection cuts in EFT

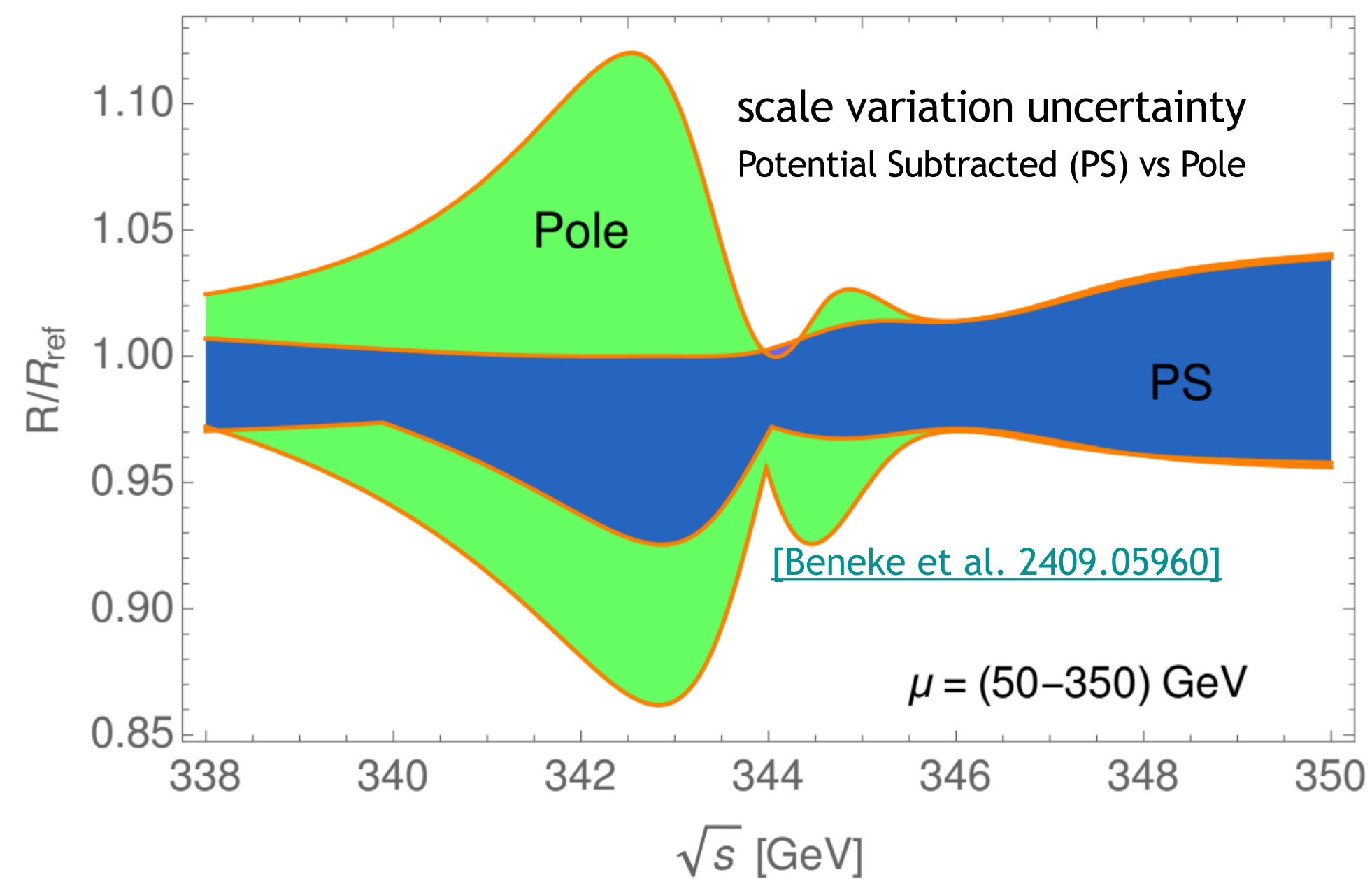
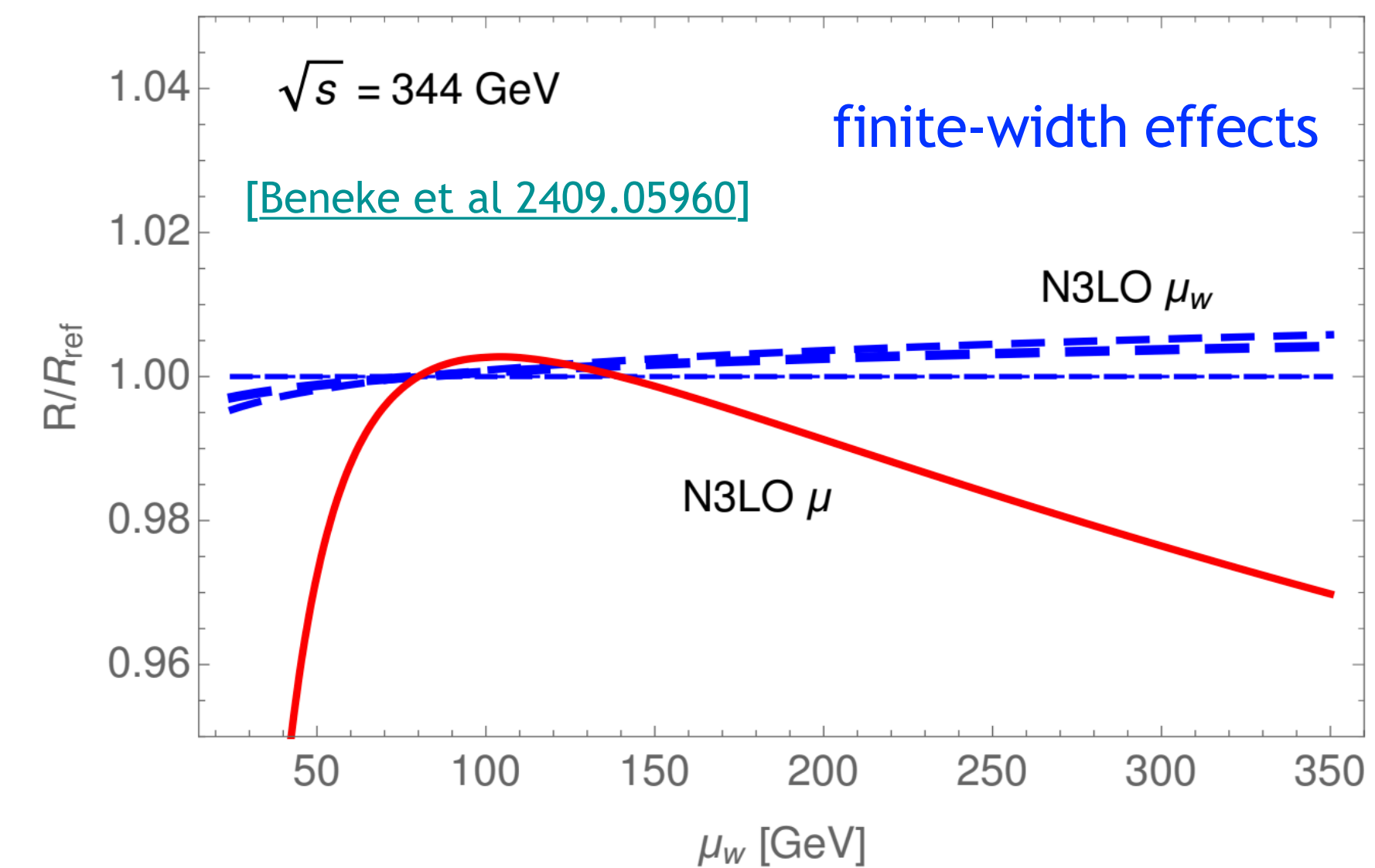
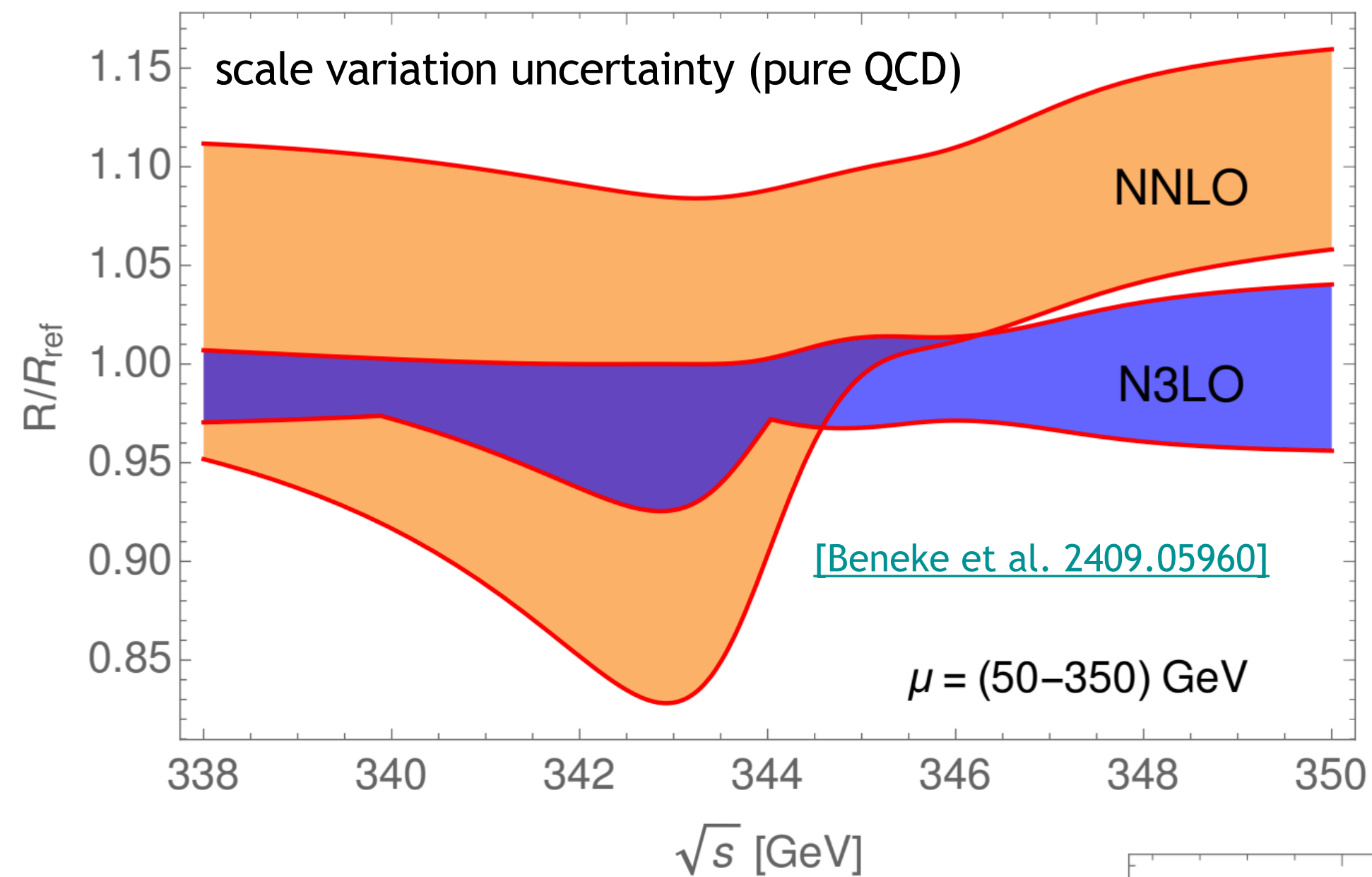
impact of invariant-mass cuts in EFT framework



$t\bar{t}$ threshold production: status



$t\bar{t}$ threshold production: status



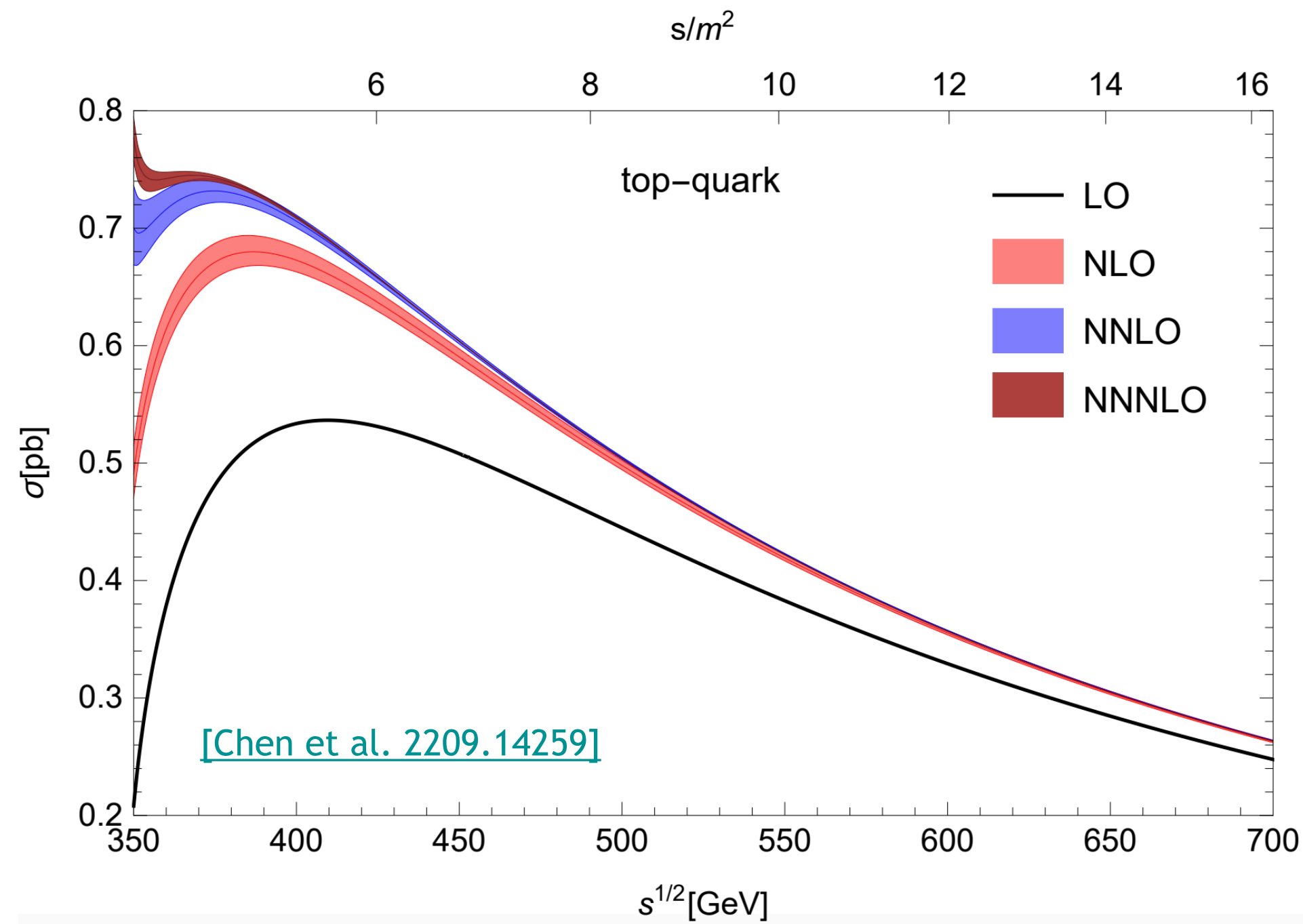
$t\bar{t}$ production above threshold and continuum

Precision target: $\mathcal{O}(0.1\%)$ on cross-section measurements

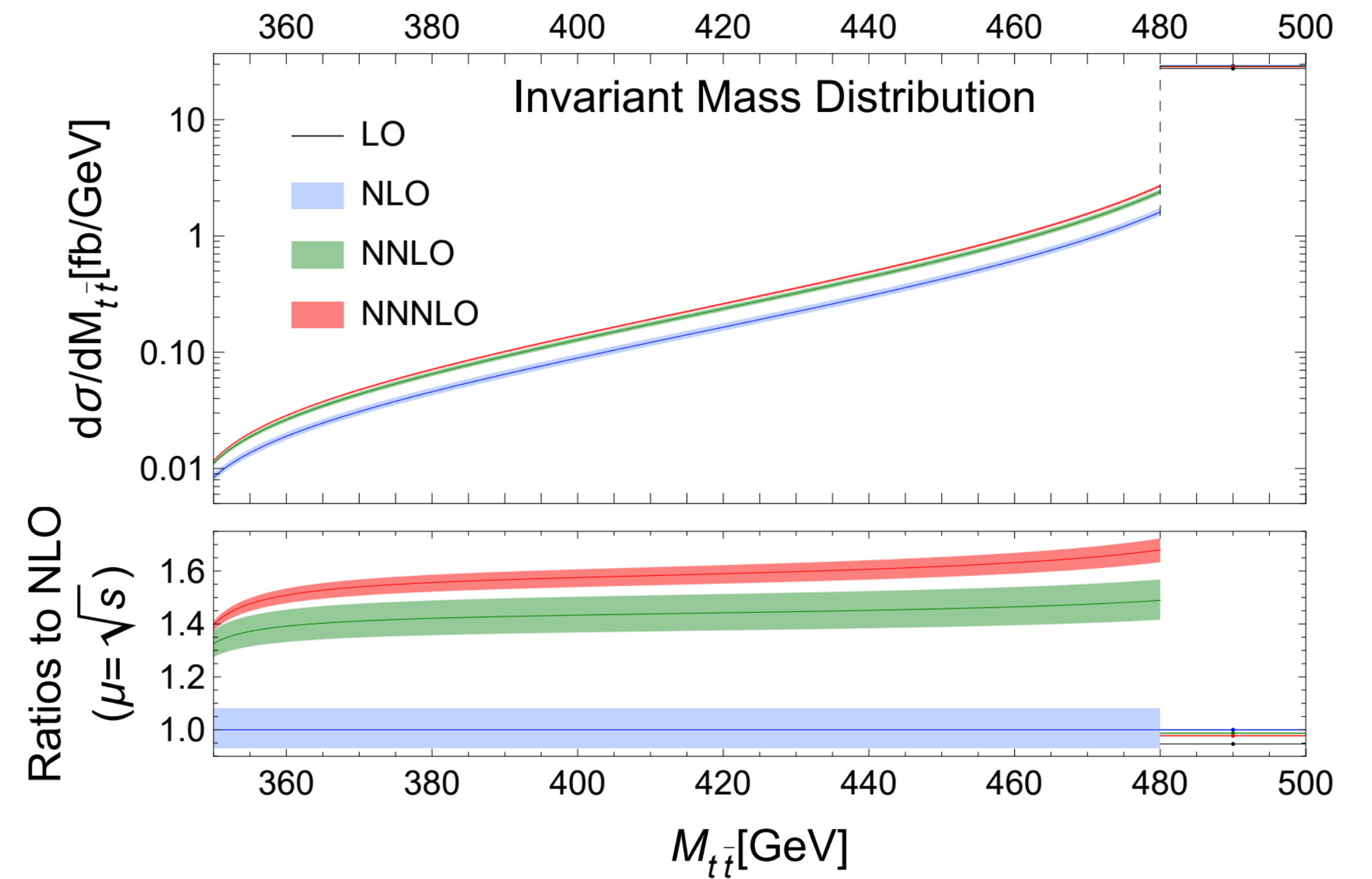
Requires N3LO QCD and NNLO EW (not available)



Total rate, ie fully inclusive XS



$\mathcal{O}(0.15\%)$ at $\sqrt{s} = 500$ GeV

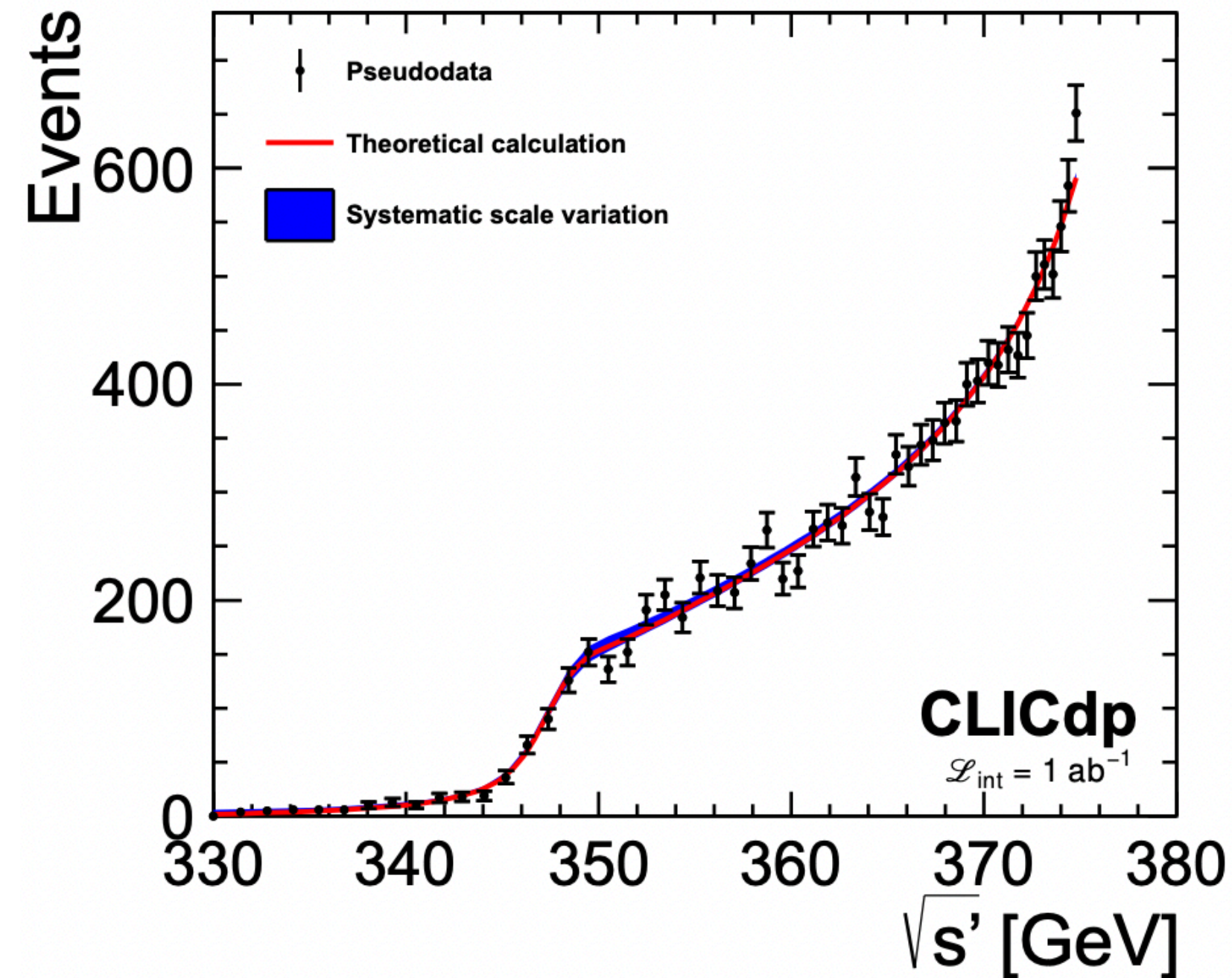
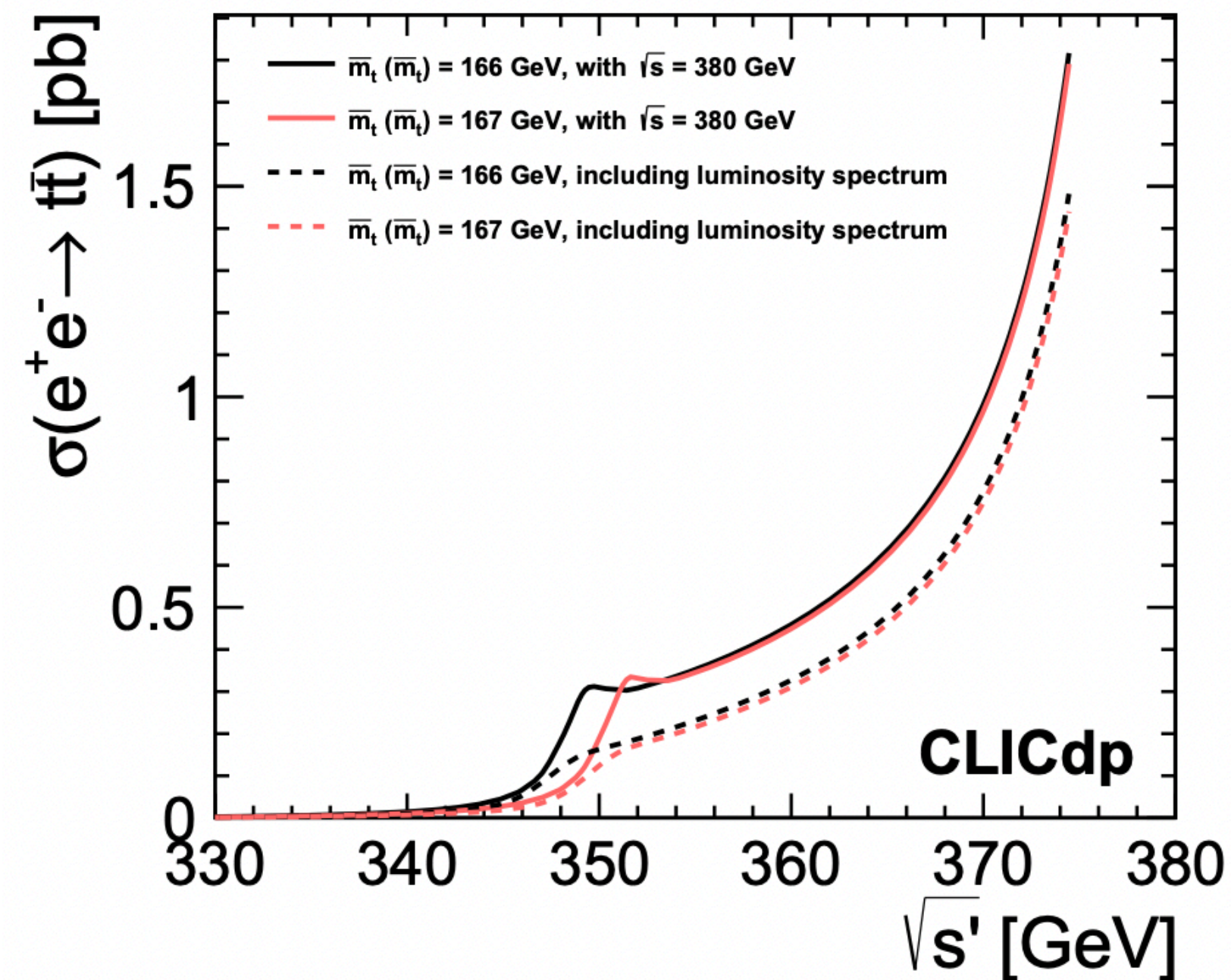


m_t via radiative return and in the continuum

m_t extracted from cross section in radiative events $e^-e^+ \rightarrow t\bar{t}\gamma$

$$\text{measure} \longrightarrow \frac{d\sigma_{t\bar{t}\gamma}}{d\cos\theta d\sqrt{s'}} = \frac{\alpha}{\pi^2} g(x, \theta) \sigma_{t\bar{t}}(s') \longrightarrow \text{fit templates}$$

$$s' = s \left(1 - \frac{2E_\gamma}{\sqrt{s}} \right)$$



Estimates: $\delta m_t \simeq 150 \text{ MeV}$ using 4 ab^{-1} of data at $\sqrt{s} = 500 \text{ GeV}$ [Boronat et al [1912.01275](#)]

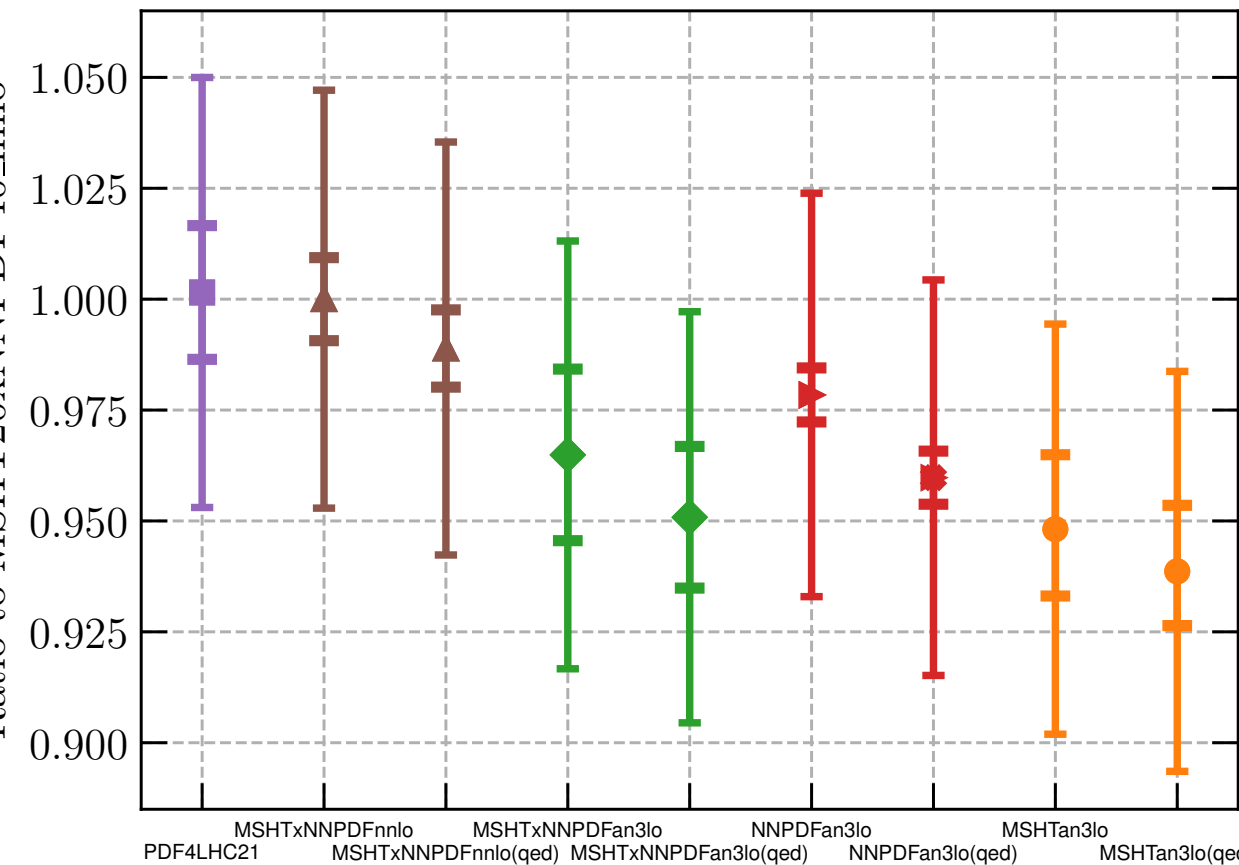
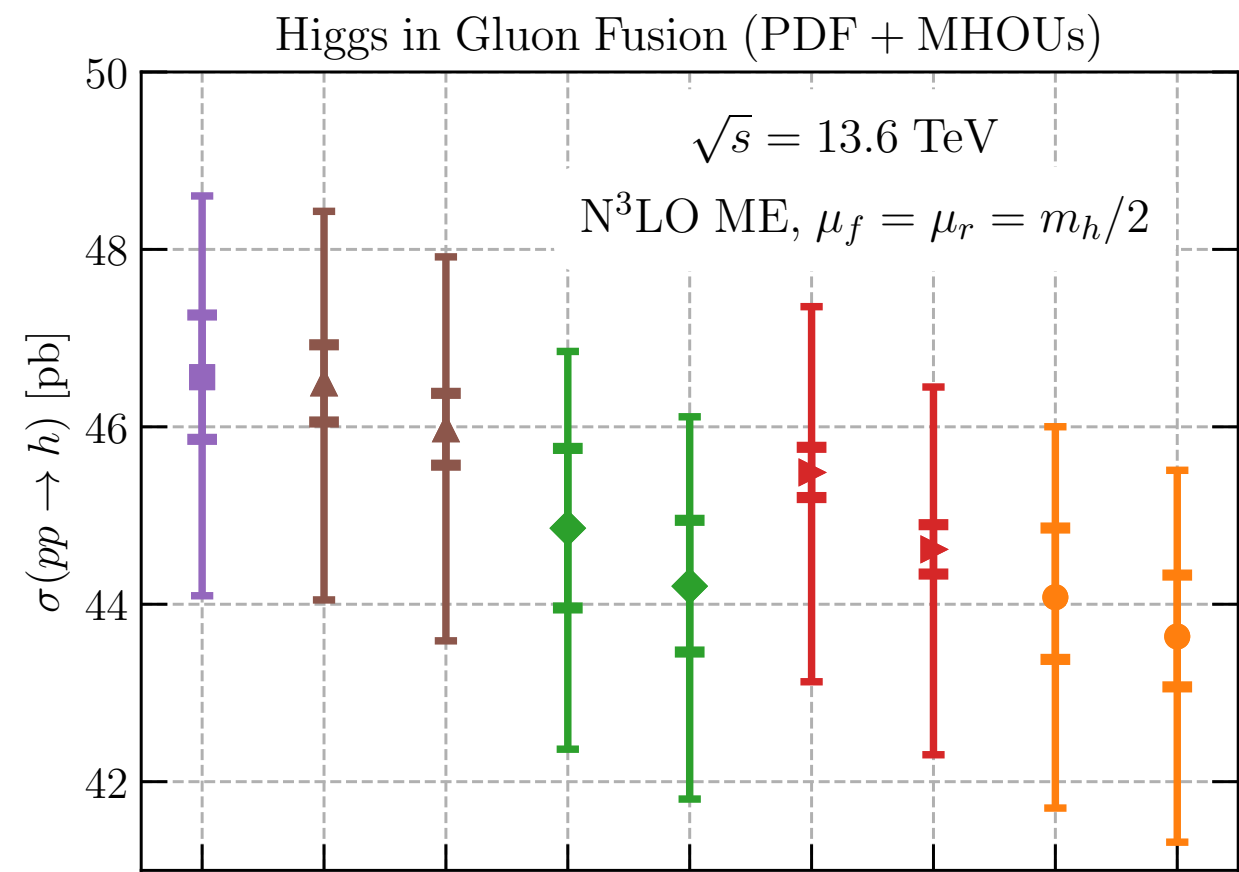
FCC-hh, selected topic: PDFs

Theory requirements strongly motivated already by LHC and HL-LHC scenarios

PDF at the core of any hadron-collider study. Absolutely crucial piece

1. aN3LO PDFs and implications on Higgs XS

[MSHT+NNPDF 2411.05373]



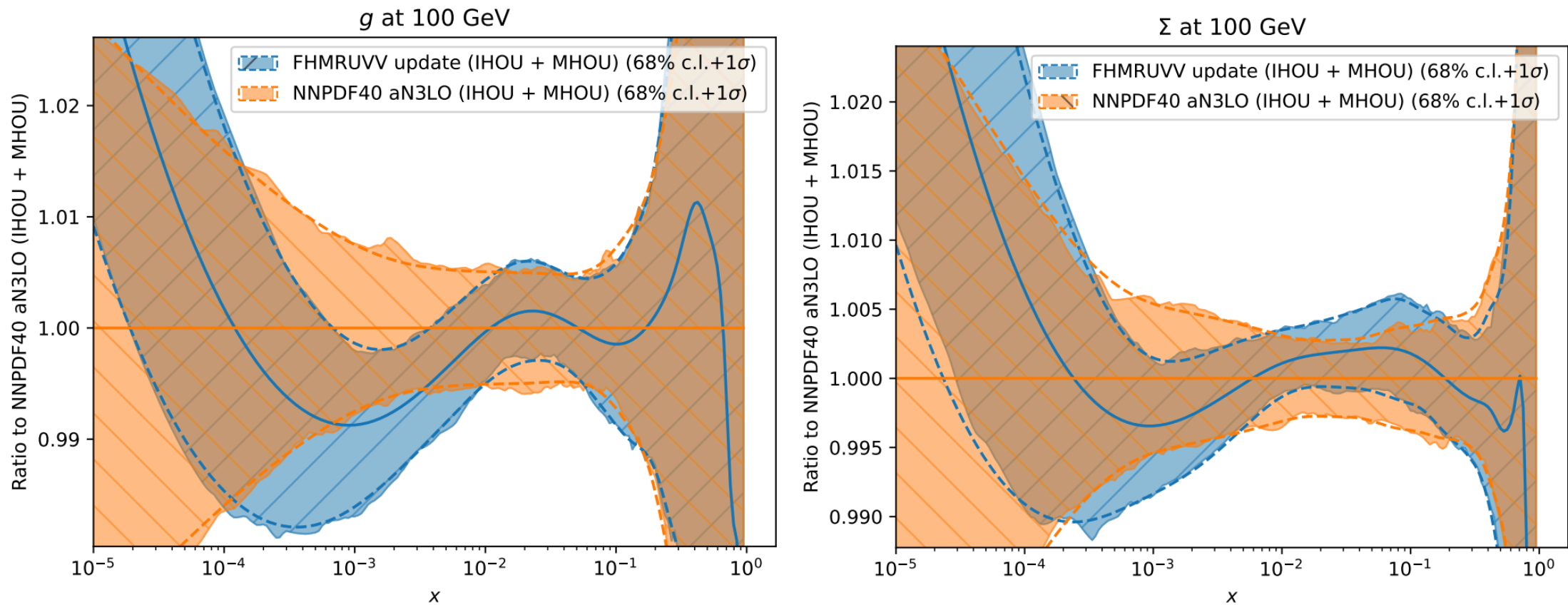
2. CMS m_W measurement, PDFs in the top 3 uncertainties

Source of uncertainty	Impact (MeV)			
	Nominal		Global	
	in m_Z	in m_W	in m_Z	in m_W
Muon momentum scale	5.6	4.8	5.3	4.4
Muon reco. efficiency	3.8	3.0	3.0	2.3
W and Z angular coeffs.	4.9	3.3	4.5	3.0
Higher-order EW	2.2	2.0	2.2	1.9
p_T^V modeling	1.7	2.0	1.0	0.8
PDF	2.4	4.4	1.9	2.8
Nonprompt-muon background	—	3.2	—	1.7
Integrated luminosity	0.3	0.1	0.2	0.1
MC sample size	2.5	1.5	3.6	3.8
Data sample size	6.9	2.4	10.1	6.0
Total uncertainty	13.5	9.9	13.5	9.9

(some) Future avenues/challenges:

- Complete N3LO QCD PDFs
- Systematic inclusion of EW effects
- small-x studies
- Lattice PDFs

[see 1711.07916 or talk by Constantinou QCD@LHC 2024]



[Towards N3LO PDF, Hekhorn]