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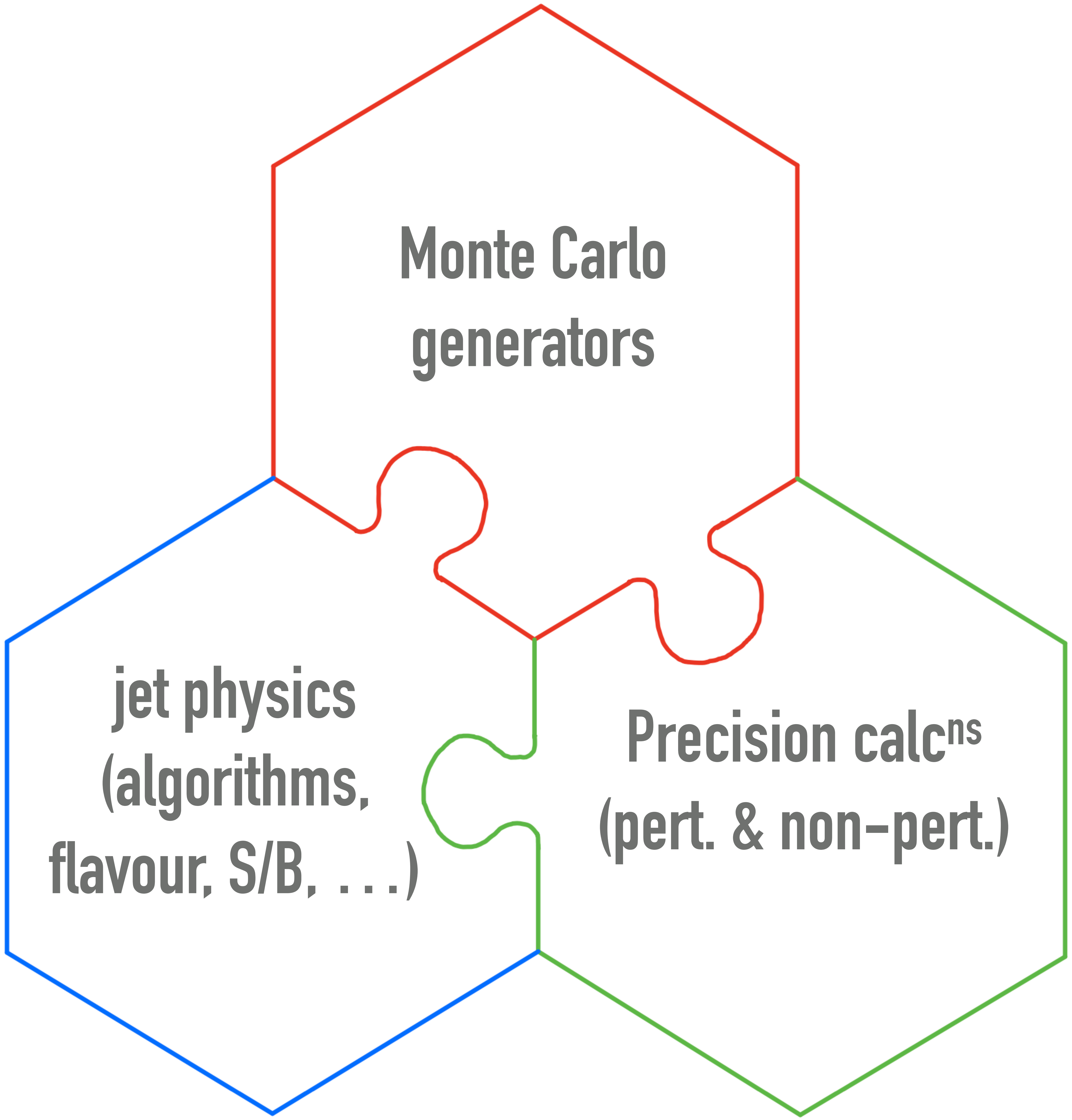
Precision (QCD) calculations for FCC-ee

P. Monni (CERN)

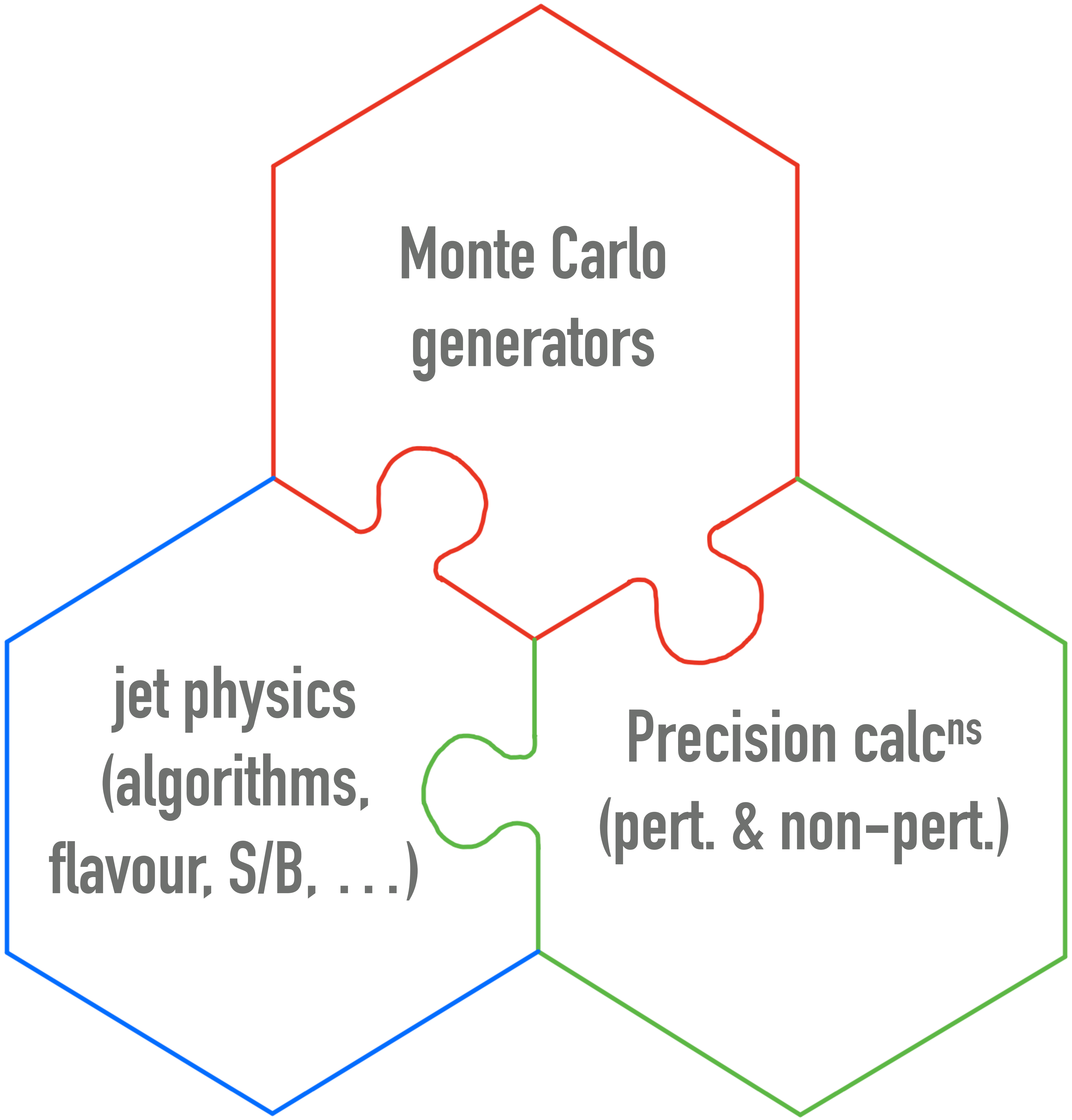
6th FCC Physics Workshop - 25 January 2023

Role of precision QCD at FCC-ee



Reaching the foreseen precision poses outstanding challenges on theory calculations. Evolution in many areas is required to meet the goals

Role of precision QCD at FCC-ee



This talk addresses mainly QCD aspects*, EW corrections will be discussed in detail in the EW sessions

* See also related talks in today's and tomorrow's session

Topical workshops at CERN TH

Precision calculations for future e+e− colliders: targets and tools

7–17 Jun 2022
CERN
Europe/Zurich timezone

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The main goal is to identify clear theoretical and computational targets for high-precision predictions of relevance to the programme of future e+e− colliders.

Parton Showers for future e+e- colliders

24–28 Apr 2023
CERN
Europe/Zurich timezone

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https://indico.cern.ch/e/PartonShowers2023

The unprecedented experimental performance expected by the next generation of lepton colliders poses an outstanding challenge for theoretical computations that must be pushed far beyond the current state of the art to guarantee an optimal exploitation of the data. Among the theoretical aspects of this programme, Monte Carlo event generators play a special role due to their versatility in bridging theoretical predictions and experimental measurements. The precision reached by current event generation algorithms is dramatically insufficient for this task, thus demanding a dedicated effort to improve their formal accuracy and achieve a higher precision in event simulations.

Physics at the Z pole

- **Numbers are given here for FCC-ee (best prospects)** [P. Janot's talk @ CERN FC workshop 2022]

Observables	Present value	FCC-ee stat.	FCC-ee current syst.	FCC-ee ultimate syst.	Theory input (not exhaustive)
m_Z (keV)	91187500 ± 2100	4	100	10 ?	Lineshape QED unfolding Relation to measured quantities
Γ_Z (keV)	2495500 ± 2300 [*]	4	25	5 ?	Lineshape QED unfolding Relation to measured quantities
σ^0_{had} (pb)	41480.2 ± 32.5 [*]	0.04	4	0.8	Bhabha cross section to 0.01% $e^+e^- \to \gamma\gamma$ cross section to 0.002%
N_ν ($\times 10^3$) from σ_{had}	2996.3 ± 7.4	0.007	1	0.2	Lineshape QED unfolding $(\Gamma_{\nu\nu}/\Gamma_{\ell\ell})_{SM}$
R_ℓ ($\times 10^3$)	20766.6 ± 24.7	0.04	1	0.2 ?	Lepton angular distribution (QED ISR/FSR/IFI, EW corrections)
$\alpha_s(m_Z)$ ($\times 10^4$) from R_ℓ	1196 ± 30	0.1	1.5	0.4 ?	Higher order QCD corrections for Γ_{had}
R_b ($\times 10^6$)	216290 ± 660	0.3	?	< 60 ?	QCD (gluon radiation, gluon splitting, fragmentation, decays, …)

- Theory crucial in 3 ways: measurement/calibration (e.g. QED ISR); interpretation of results (EWPO); parametric uncertainties (i.e. couplings, masses)

- QCD uncertainties concern all three categories

Precision physics in $Z/\gamma^* \to$ jets

- Main computational challenges from EW aspects:
  - EWPO $Z \to qq+X$ @ 3 loops EW and beyond
  - Beam calibration [$e^+e^- \to e^+e^-$, $\mu^+\mu^-$, $\gamma\,\gamma$ @ NNLO EW - still beyond reach]
- But **high potential for precision QCD** studies at the Z pole and above:
  - Strong coupling constant
  - Jet dynamics and substructure: spin correlations, fragmentation & track functions, multi-jet observables (global/non-global)
  - Non-perturbative effects & modelling
  - Heavy quarks (Q) studies (e.g. asymmetries, fragmentation) & jet tagging (e.g. q/Q vs. g jets)
  - τ decays (α_S)
  - Calibration/tuning of ML & MC models (instrumental for higher-energy runs)

Precision physics in $Z/\gamma^* \to$ jets

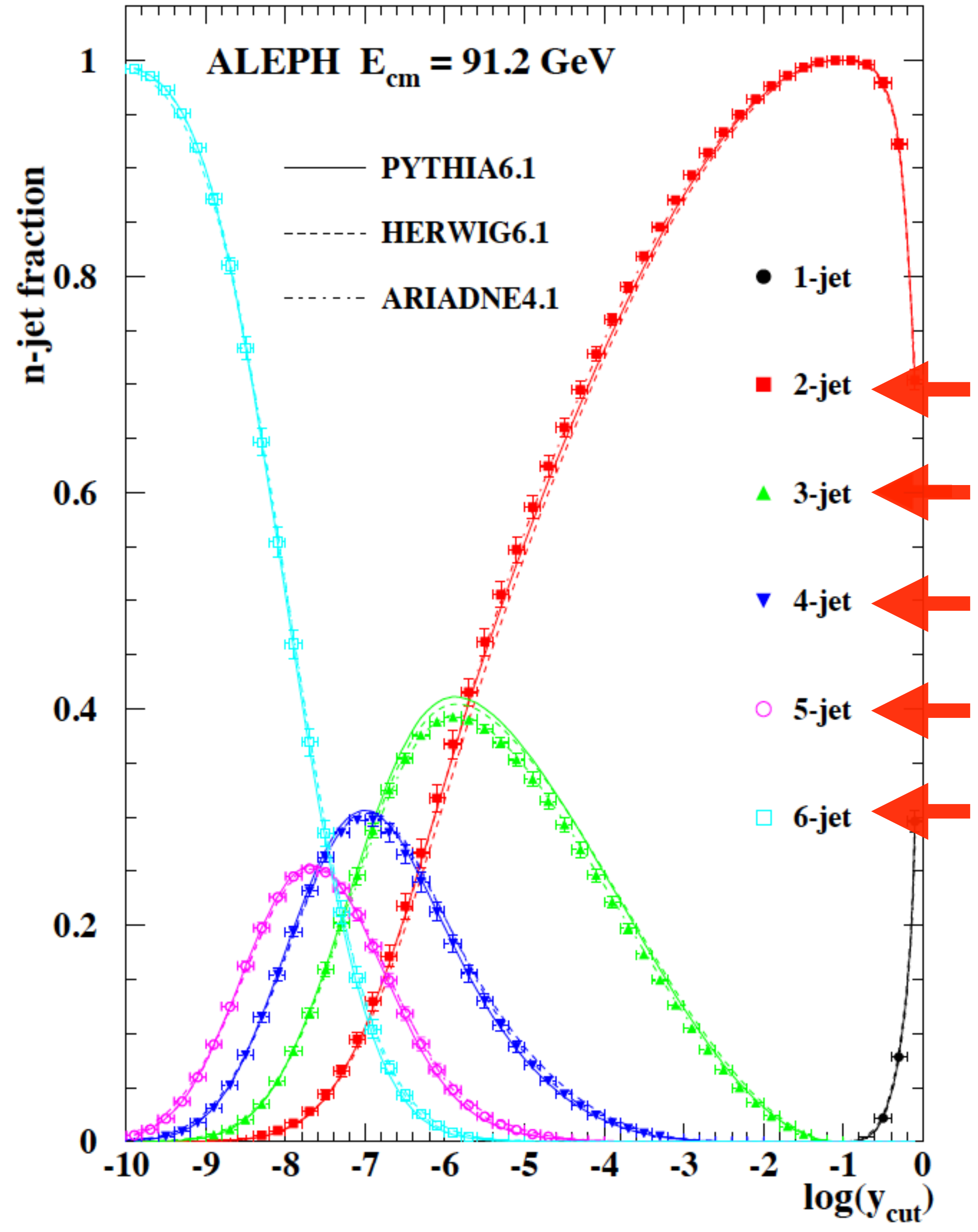
- Significant room for improvement for QCD calculations, e.g.

[Nason et al. ’98; Brandenburg et al. ’97]

- Heavy quarks: R_b, A_{FB} requires QQg and qqg(→ QQ) @ 2 loops with m_b dependence (NLO known)
- Fragmentation functions
- Multi-jet final states
  - 3 jets @ N^{3}LO QCD
  - 4 & 5 jets at NNLO QCD

Some of this is within the reach of technology developed at LHC (e.g. Z/γ^*+2 jets @ 2 loops, subtraction methods)

[e. g. five-point amplitudes in Abreu et al. ’18–’21; Badger et al ’19–’22; Chawdhry et al. ’20–‘21]



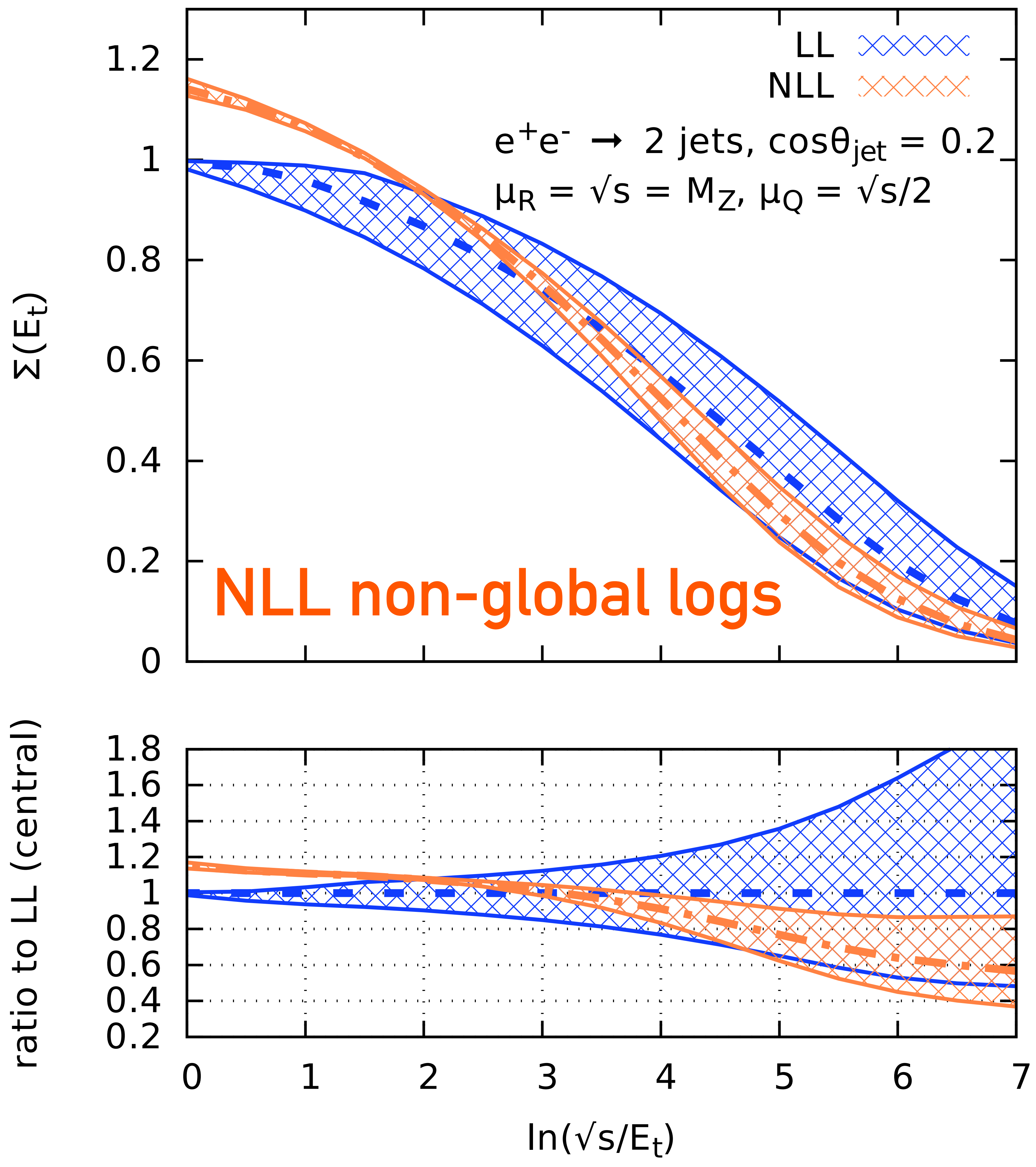
- 2-jet: N^{3}LO : $\mathcal{O}(\alpha_s^3)$
- 3-jet: NNLO : $\mathcal{O}(\alpha_s^3)$
- 4-jet: NLO : $\mathcal{O}(\alpha_s^3)$
- 5-jet: NLO : $\mathcal{O}(\alpha_s^4)$
- 6-jet: NLO for 6 & 7 jets (lead . colour)

- Promising new directions for loop calculations: e.g. numerical approaches for total rates at N$^{(2/3)}$LO (e.g. Feynman parameters, local unitarity, AMFlow, …), though further progress necessary for distributions

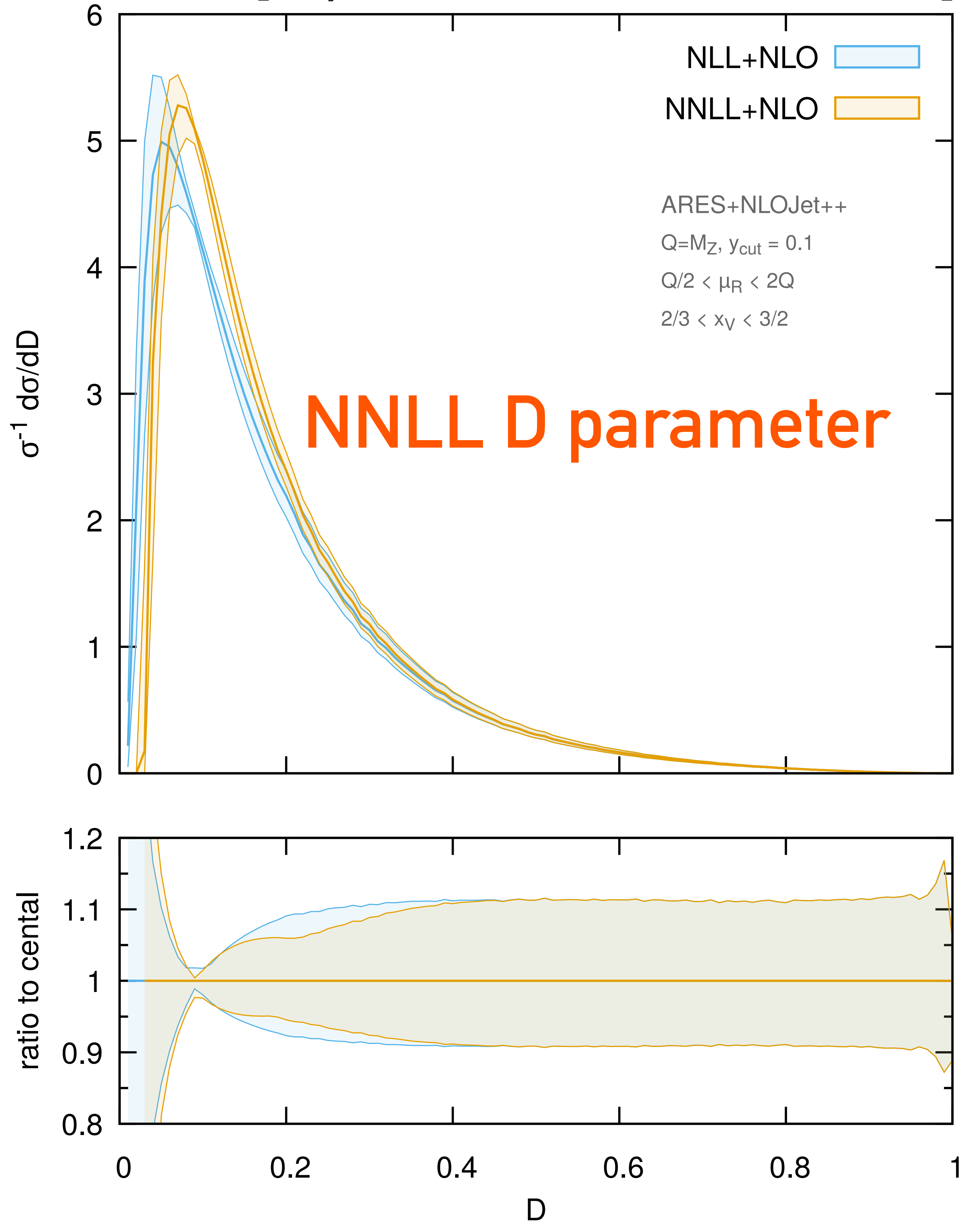
Precision physics in Z/γ* → jets

- All-order logarithmic corrections (resummations) desirable for phenomenology. A lot of new techniques refined in recent years for jet observables (SCET(s), numerical methods, generating functionals)

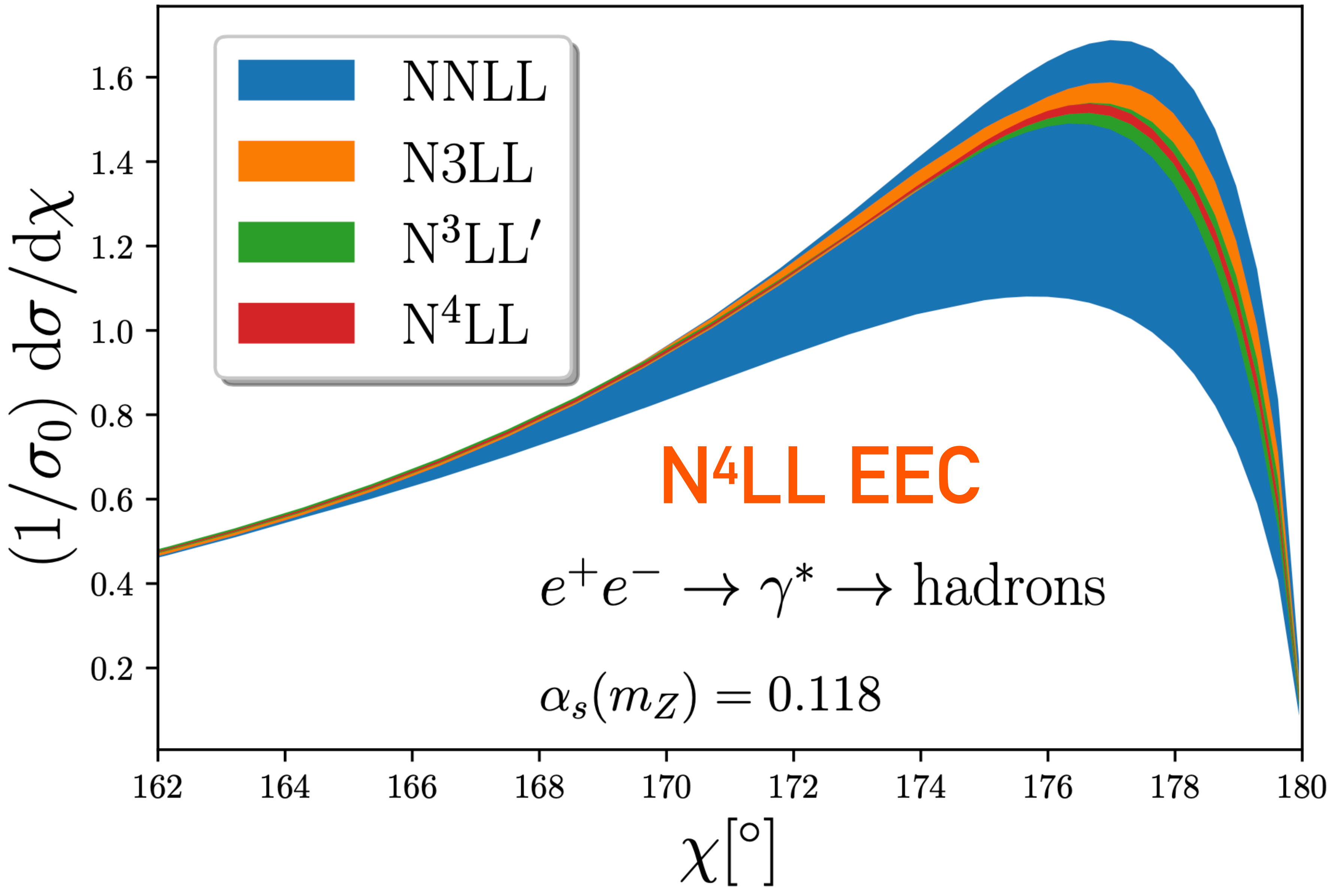
[Banfi, Dreyer, PM '21]



[Arpino, Banfi, El-Menoufi '19]



[Duhr, Mistlberger, Vita '22]



Room for improvement in high-multiplicity (≥ 3 jets) observables, possibly requires algorithmic methods

Non-perturbative QCD corrections

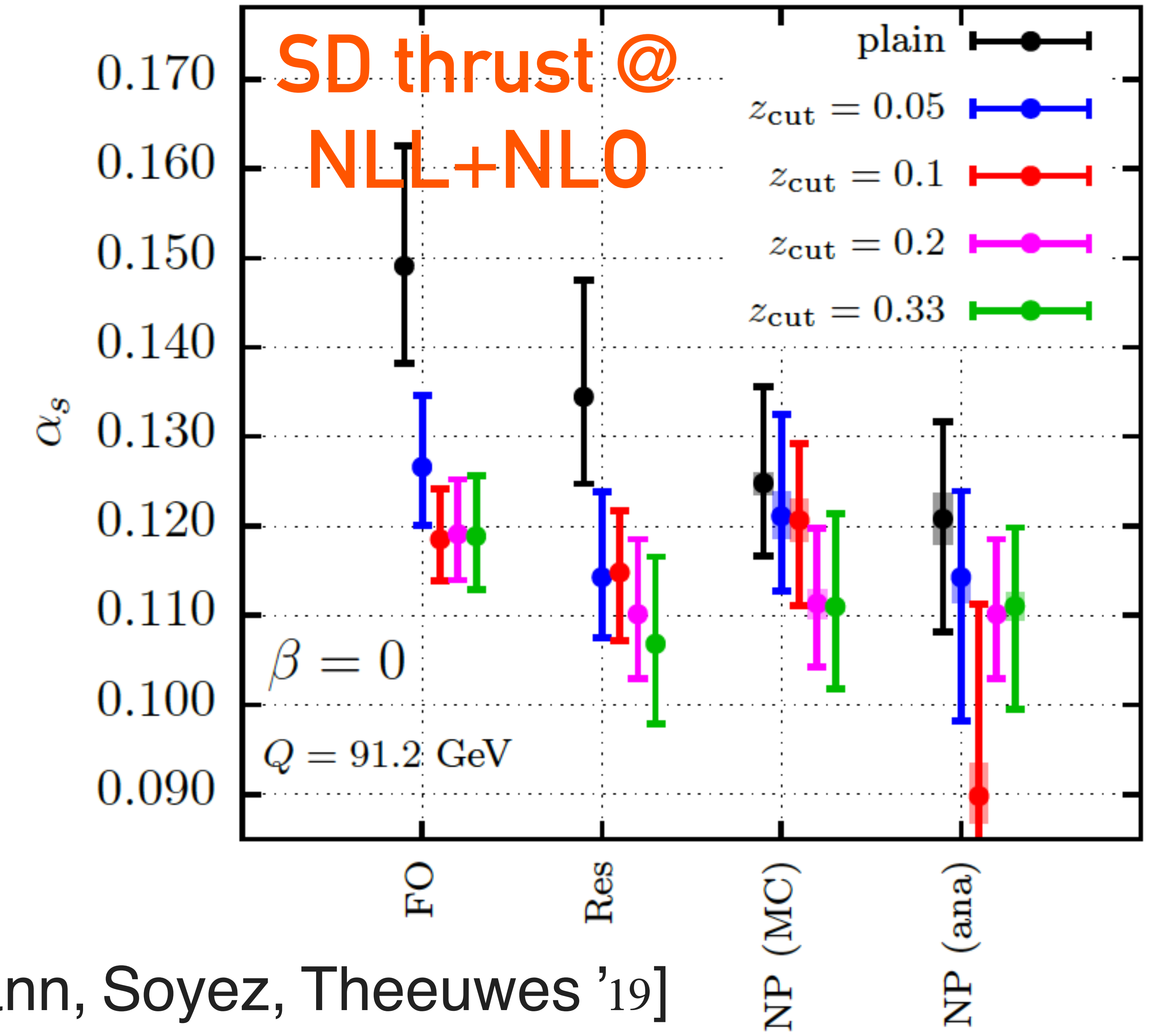
- **Better understanding of hadronisation in jet observables appears to be essential** (event shapes, jet rates, jet substructure); **serious limitation of TH accuracy.** Possible avenues (possibly in combination):

- Techniques to calculate leading corrections as $1/Q$ expansion, recently first important steps for 3-jet configurations (largely based on large-n_F approximation)

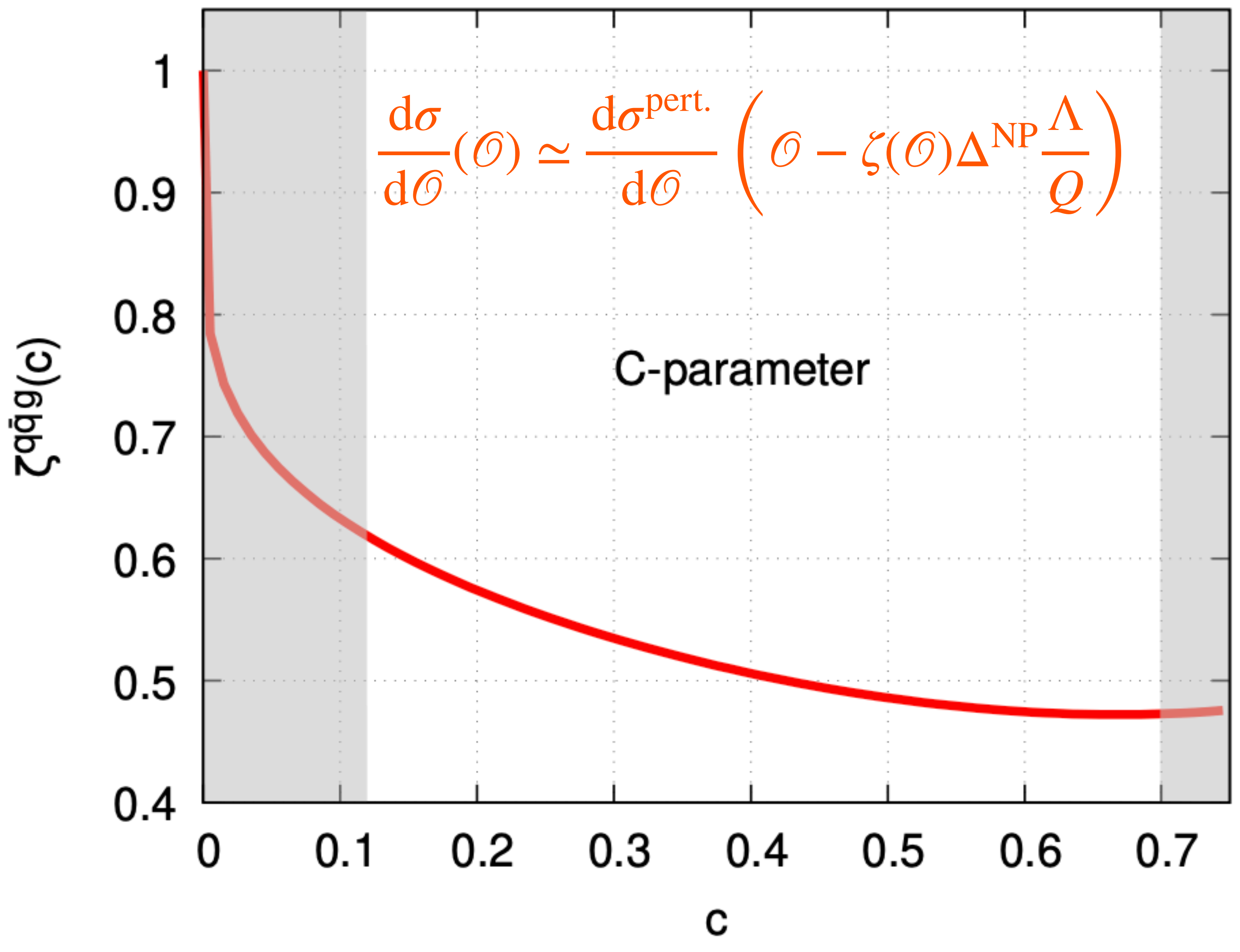
- New observables with reduced NP sensitivity, e.g. through jet grooming. Preliminary studies on strong coupling extractions

- Tuning of MC generators across $\sqrt{s}$ values (Q/q/g samples). High perturbative accuracy demanded, a lot of recent progress*

  * S. Plaetzer's and A. Siodmok's talks

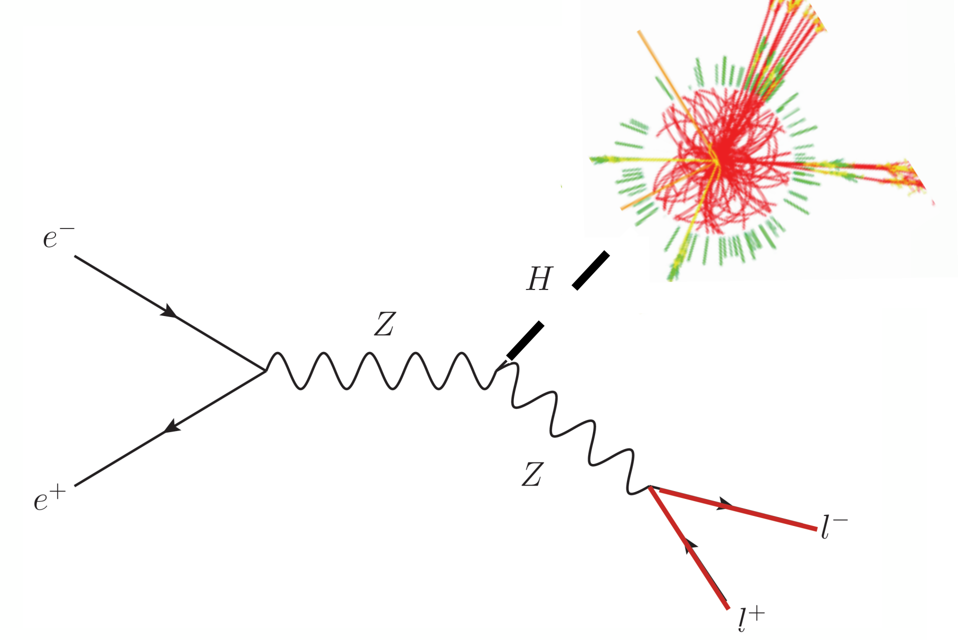


[Marzani, Reichelt, Schumann, Soyez, Theeuwes '19]



[Luisoni, PM, Salam '20]
[Caola, Ferrario Ravasio, Limatola, Melnikov, Nason '21+'22]
[Nason, Zanderighi '23]

ZH threshold



- Experimental precision approaching 0.1% in many cases at ZH threshold
- Example: **total cross section will be measured with precision in the range 0.2%-0.5%**. Necessary ingredients:
  - $e^+e^- \to Z\,H$ (now available), $H\,\nu\,\nu$ (e^+e^-) @ 2 loops EW (hard at the moment)

    [Chen, Guan, He, Liu, Ma '22; Freitas, Song '21–'22]
  - Mixed QCD⊗EW @ 2 loops under control

    [Gong et al. '17]
- Wealth of data in hadronic decays of the Higgs boson (demanding also excellent jet tagging performance*)

* See L. Gouskos' talk tomorrow

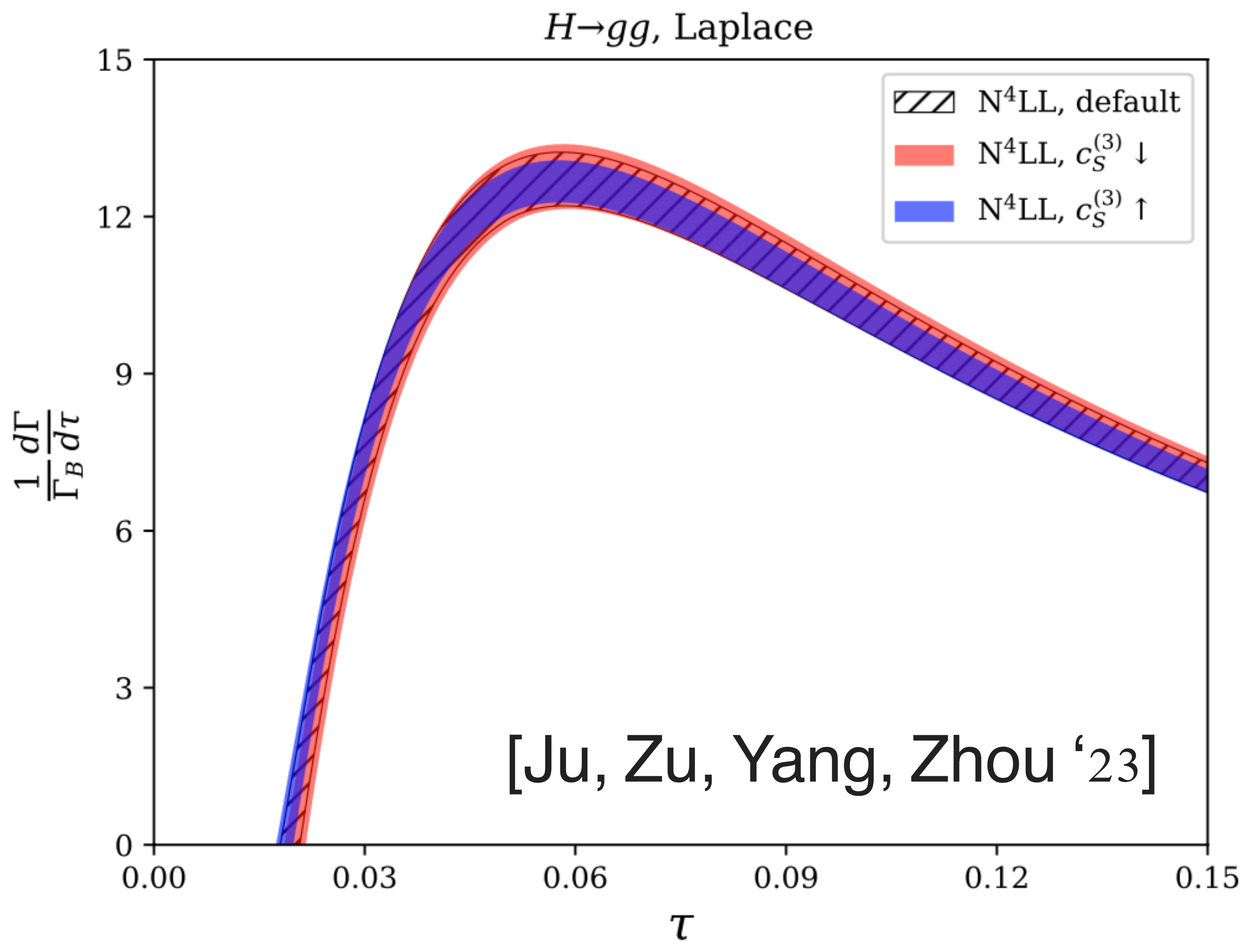
Decay	current unc. $\delta\Gamma$ [%]				future unc. $\delta\Gamma$ [%]			
	$\mathrm{Th}_{\mathrm{Intr}}$	$\mathrm{Th}_{\mathrm{Par}}^{m_q}$	$\mathrm{Th}_{\mathrm{Par}}^{\alpha_s}$	$\mathrm{Th}_{\mathrm{Par}}^{m_H}$	$\mathrm{Th}_{\mathrm{Intr}}$	$\mathrm{Th}_{\mathrm{Par}}^{m_q}$	$\mathrm{Th}_{\mathrm{Par}}^{\alpha_s}$	$\mathrm{Th}_{\mathrm{Par}}^{m_H}$
$H \to b\bar{b}$	< 0.4	1.4	0.4	–	0.2	0.6	< 0.1	–
$H \to \tau^+\tau^-$	< 0.3	–	–	–	< 0.1	–	–	–
$H \to c\bar{c}$	< 0.4	4.0	0.4	–	0.2	1.0	< 0.1	–
$H \to \mu^+\mu^-$	< 0.3	–	–	–	< 0.1	–	–	–
$H \to W^+W^-$	0.5	–	–	2.6	0.3	–	–	0.1
$H \to gg$	3.2	< 0.2	3.7	–	1.0	–	0.5	–
$H \to ZZ$	0.5	–	–	3.0	0.3	–	–	0.1
$H \to \gamma\gamma$	< 1.0	< 0.2	–	–	< 1.0	–	–	–
$H \to Z\gamma$	5.0	–	–	2.1	1.0	–	–	0.1

[Table from J. de Blas' talk]

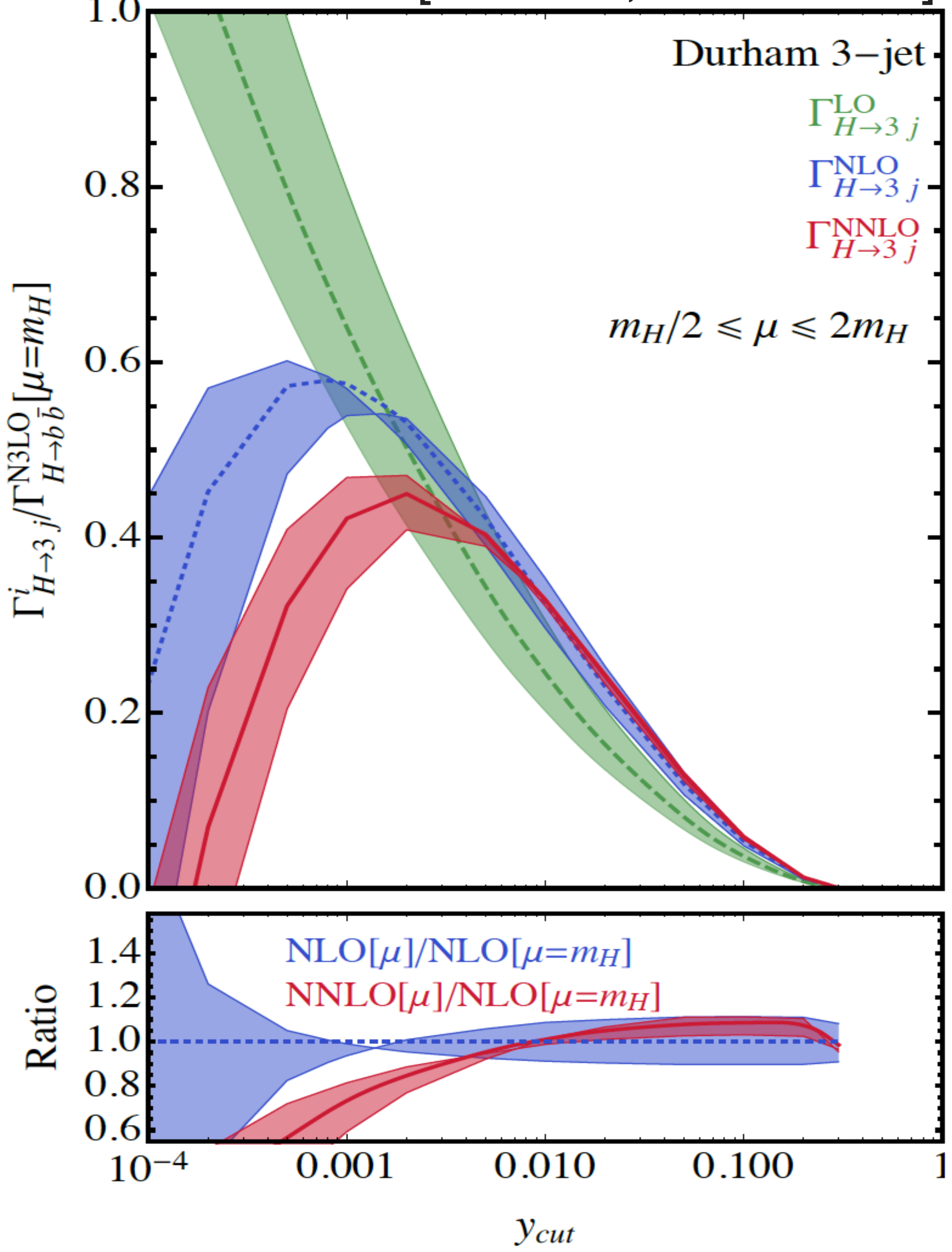
Projected reduction of intrinsic TH uncertainties in line with what can be achieved with future calculations (total rates); improvement needed in parametric unc.

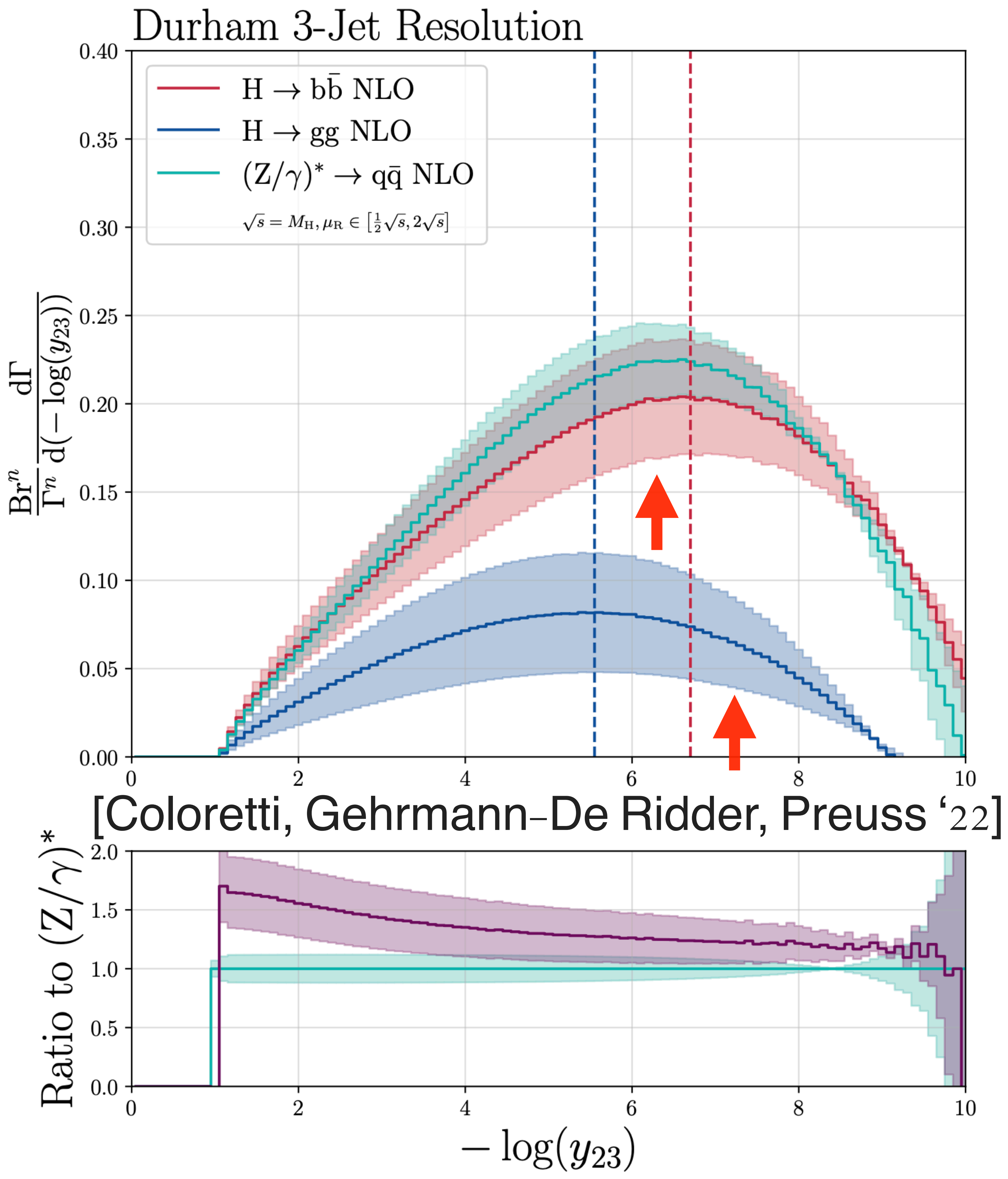
Hadronic Higgs decays

- Accuracy significantly lower for differential distributions (e.g. potential sensitivity to light-quarks Yukawa)
- NNLO (+resummations) achievable in the coming years (already available in H→bb and partly H→gg*); sufficient for several-% precision (3loops needed for few-% level)



[Mondini, Williams '21]

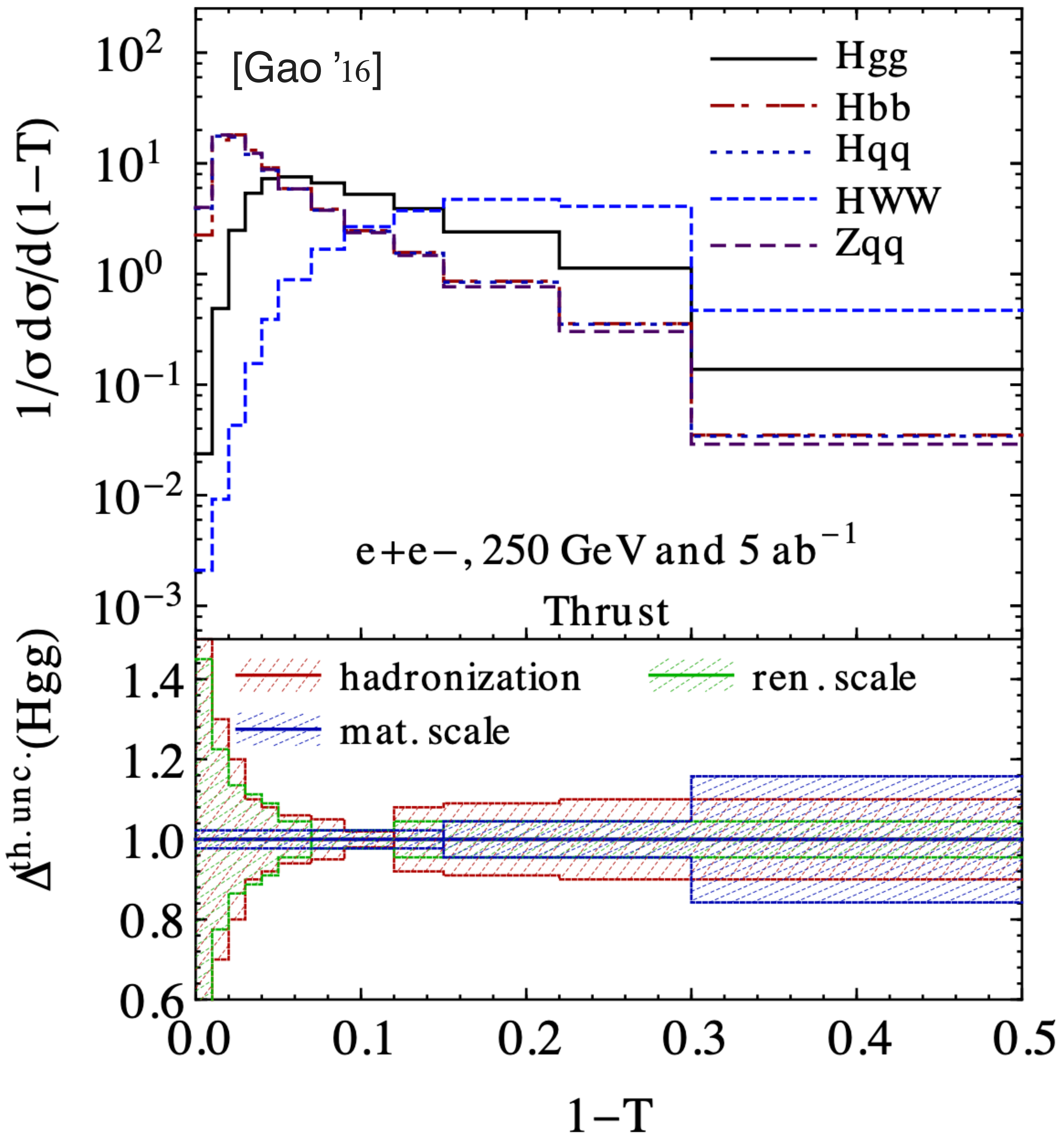




* All ingredients for HO in H→gg known (with full mass dependence)
[Czakon et al. '20; Bonciani et al. '22
Melnikov, Penin '16; Liu, Penin '17–'19;
Anastasiou, Penin '20, …]

Hadronic Higgs decays

- Accuracy significantly lower for differential distributions (e.g. potential sensitivity to light-quarks Yukawa)
- However, hadronisation remains the main bottleneck
  - e.g. thrust in Higgs decays (MC variation in plot)
- Increase in energy insufficient for suppression ($Q \sim m_H$)
- Runs at lower energies are essential for a robust tuning of NP models in MCs
  - Also crucial for training of ML algorithms for jet tagging, instrumental in extraction of Higgs couplings



WW threshold scan and W mass and width

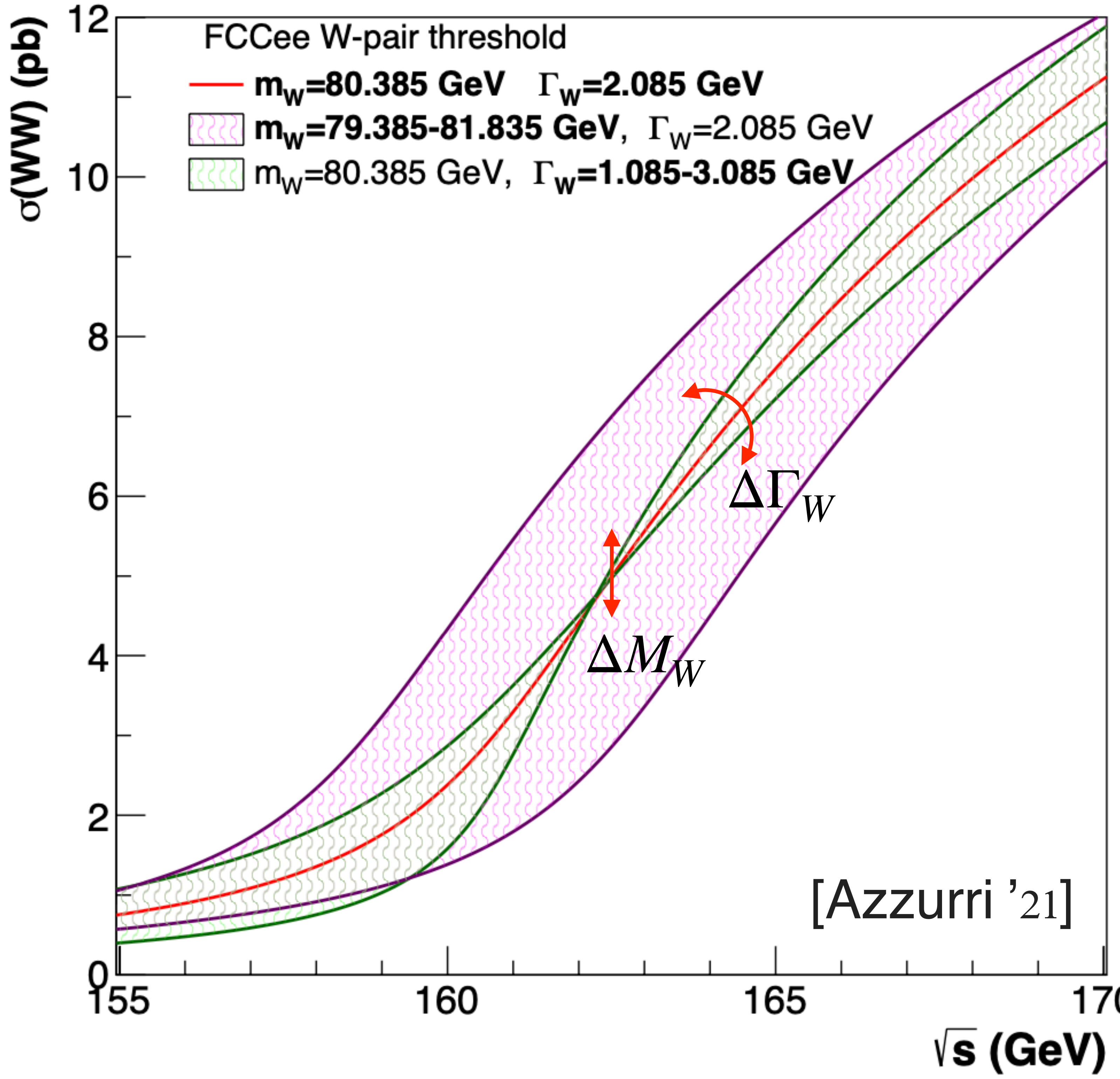
- TH cross section currently known accurately at NLO (EW) + NNLO (unstable particles EFT) sufficient for $\delta m_W \sim$ 5-6 MeV

[Actis, Beneke, Falgari, Schwinn '08]

	$\sigma(e^-e^+ \to \mu^-\bar{\nu}_\mu u\bar{d}X)$(fb)				
$\sqrt{s}$ [GeV]	Born	Born (ISR)	NLO	$\hat{\sigma}^{(3/2)}$	$\sigma^{(3/2)}_{\rm ISR}$
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‰]

- Can be further improved using NLL ISR

- Effect of tight selection cuts in the EFT to be understood



Reaching the stat. uncertainty of 0.3–0.5 MeV is very demanding

$$\Delta m_{\rm W}({\rm T}) = \left(\frac{d\sigma_{\rm WW}}{dm_{\rm W}}\right)^{-1} \Delta\sigma_{\rm WW}({\rm T})$$

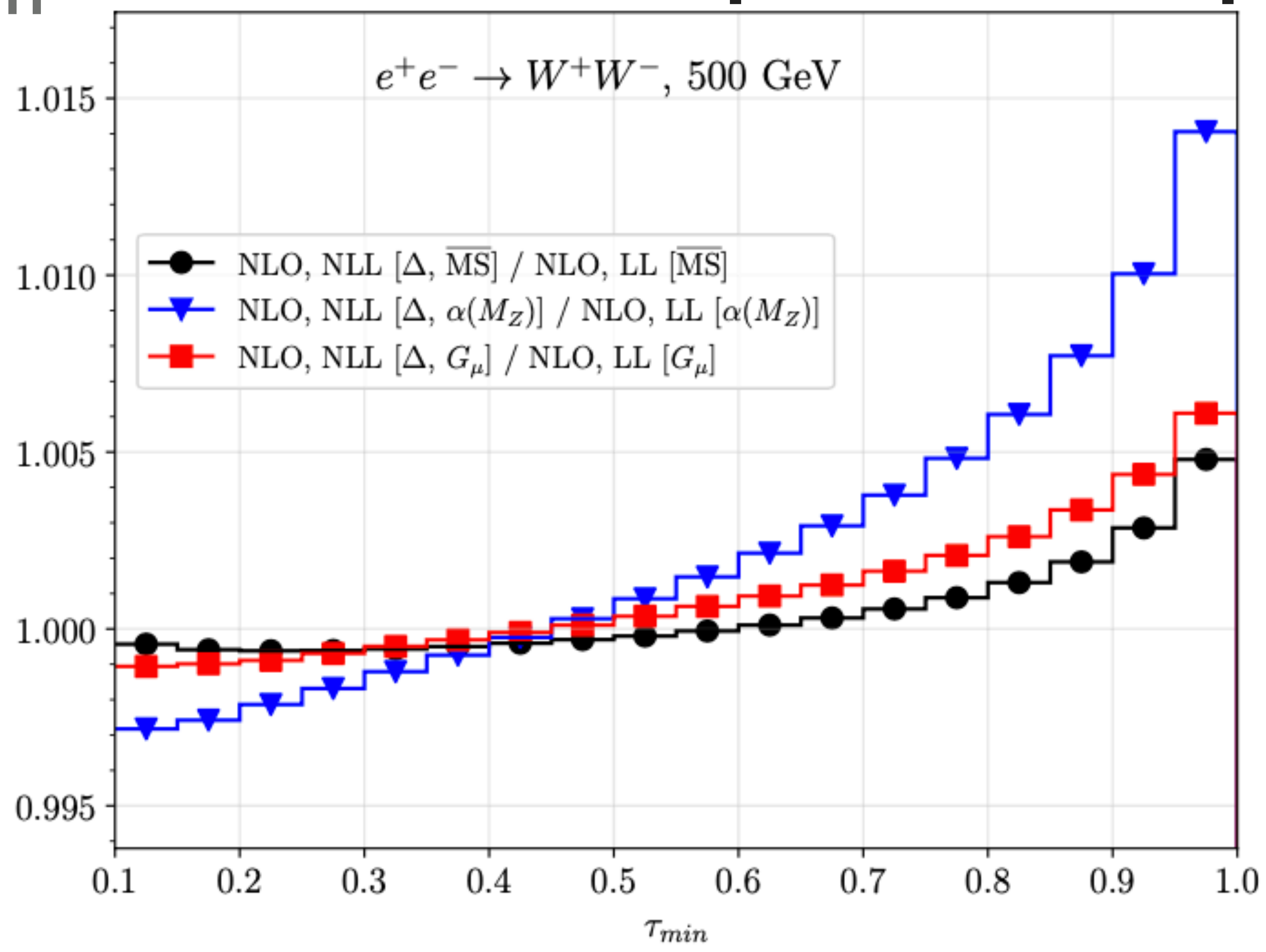
$$\Delta\sigma_{\rm WW}({\rm T}) < 0.8 \text{ fb}$$

Intermezzo: ISR and collinear factorisation

- Central component in FCCee precision phenomenology (Z, WW, tt, ZH,…)
- Recently important progress in formulating collinear factorisation (as opposed to YFS) beyond LO/LL. NLL sizeable (% level) and process/observable dependent. E.g. corrections to total rates ($\tau_{\rm min} = \frac{M^2}{s}$)
  - NNLL hard but within reach of modern perturbative techniques

    e. g. [Bluemlein et al. '12–'21] (talk on Monday)
  - Ongoing discussions as to whether a simultaneous resummation of soft and collinear corrections is necessary

[Bertone et al. 2022]



- $\sqrt{Q^2} = 500$ GeV

$$\ell = \log \frac{Q^2}{\langle E_\gamma \rangle^2}\,, \qquad L = \log \frac{Q^2}{m^2}$$

[Example from S. Frixione 2022]

$$L = 24.59 \implies \frac{\alpha}{\pi} L = 0.068$$

$$0 \leq m_{ll} \leq m_Z\,, \quad \ell = 1.46 \implies \frac{\alpha}{\pi}\ell = 0.0036$$

$$m_Z - 1 \text{ GeV} \leq m_{ll} \leq m_Z\,, \quad \ell = 4.51 \implies \frac{\alpha}{\pi}\ell = 0.01$$

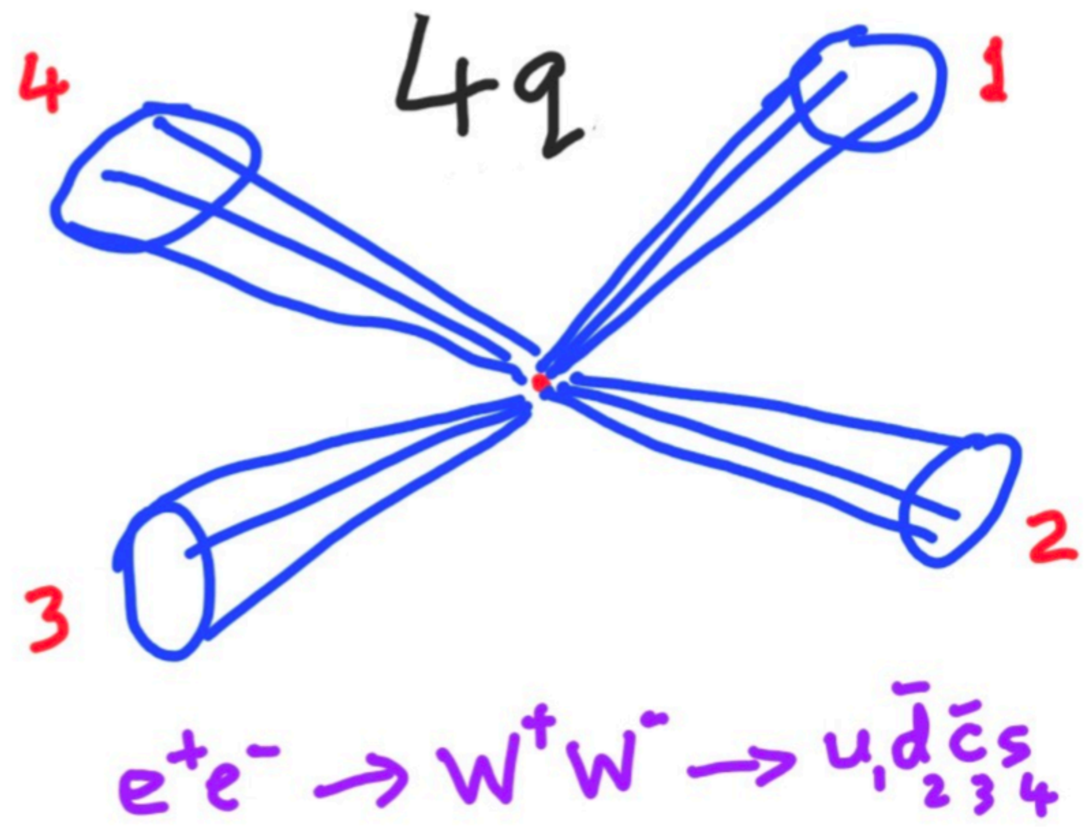
W mass extraction from hadronic and semi-leptonic decays

- Very good experimental resolution with momentum conservation fit (4C or 5C), competitive with threshold scan

- Theory modelling harder, with systematics yet to be precisely assessed
  - Control over QED ISR (NLL available)
  - EFT resonant aspects near threshold
  - Backgrounds: 2f & 4f final states
  - Colour reconnection in hadronic channels (A. Siodmok's talk)

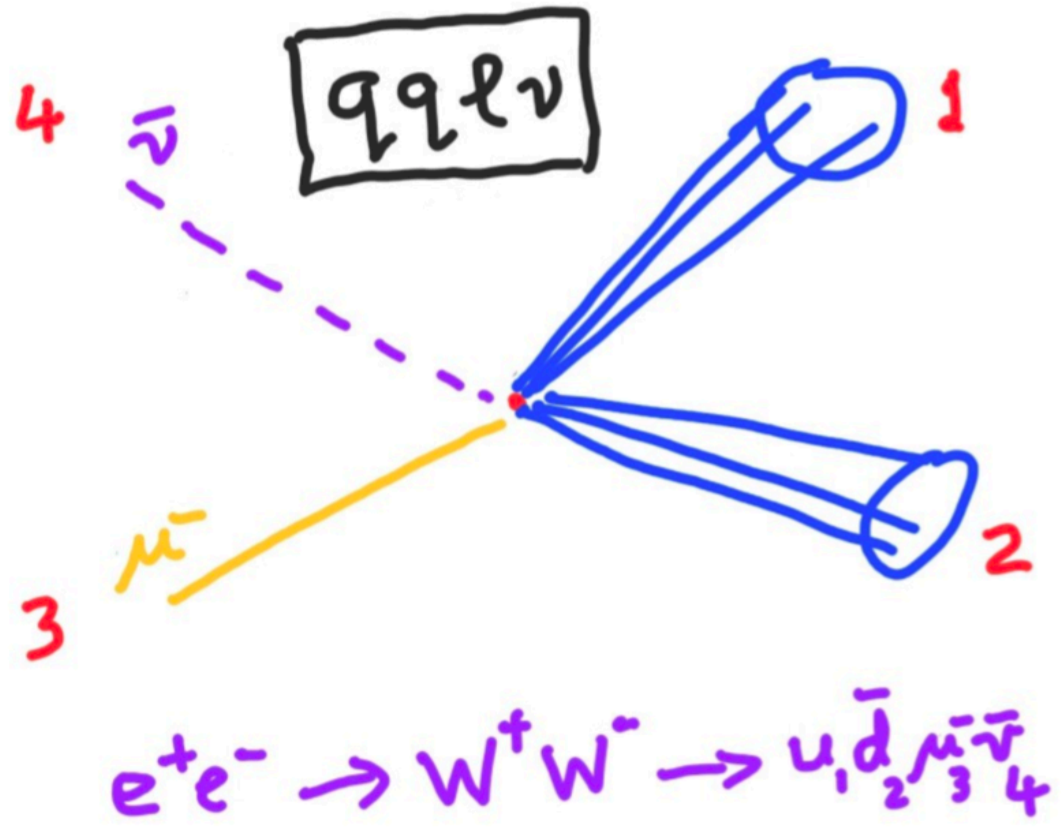
[G. Wilson's talk @ CERN FC workshop 2022]

fully hadronic $q\bar{q}q\bar{q}$



$B_h^2 = 45.4\%$

semi-leptonic $q\bar{q}\ell\nu_\ell$

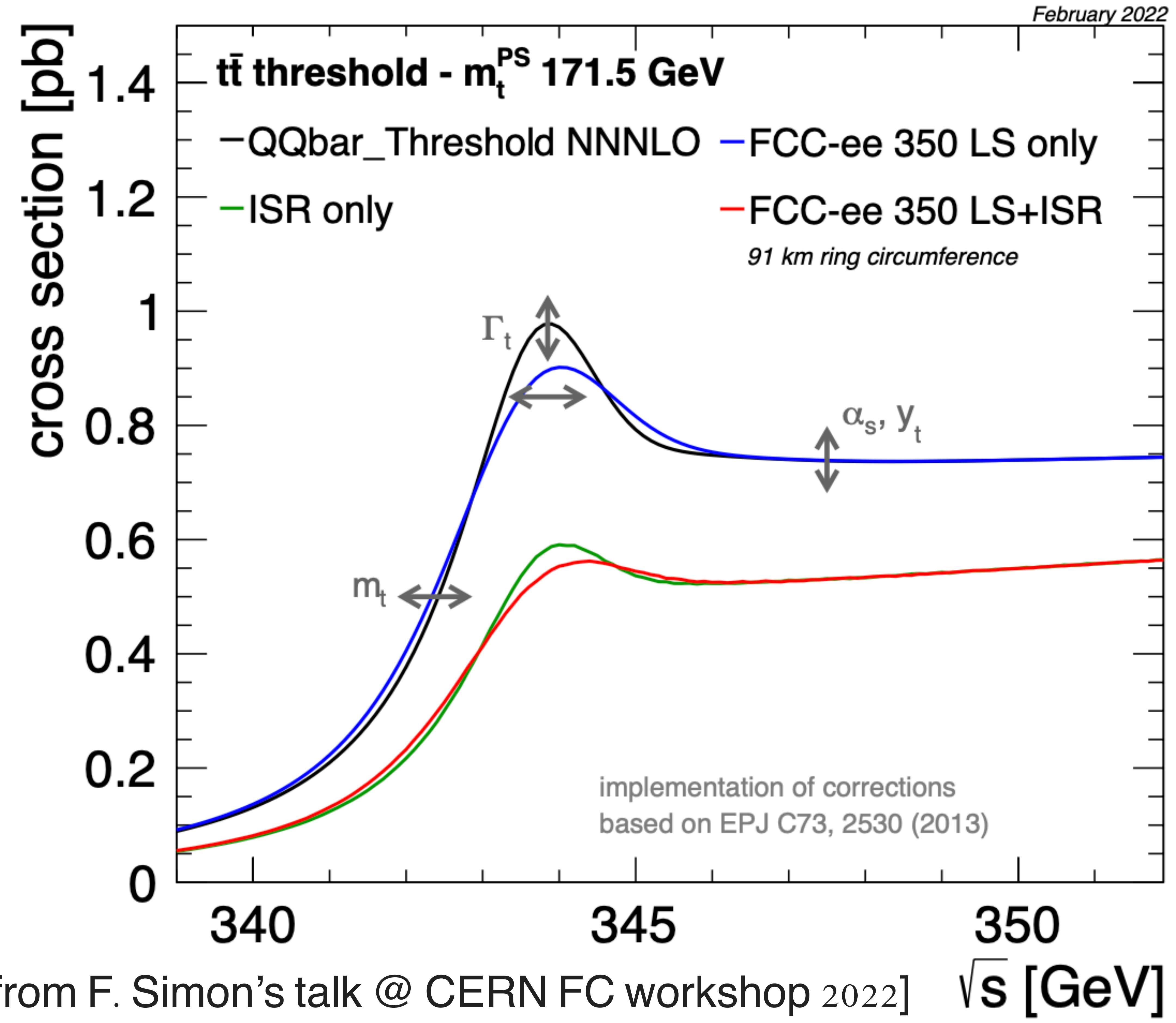


$6B_\ell B_h = 43.9\%$

Top physics

- Huge potential from threshold scan: up to per-mille accuracy on cross section & asymmetries
- Access to top mass and width, as well as strong coupling and top Yukawa coupling
- e.g. projected exp. target for top mass **$\delta m_t \sim 20$ MeV**

Great challenge for theory to match this precision: intrinsic (e.g. higher order) & parametric (e.g. strong coupling from Z pole) uncertainties



[Plot from F. Simon's talk @ CERN FC workshop 2022]

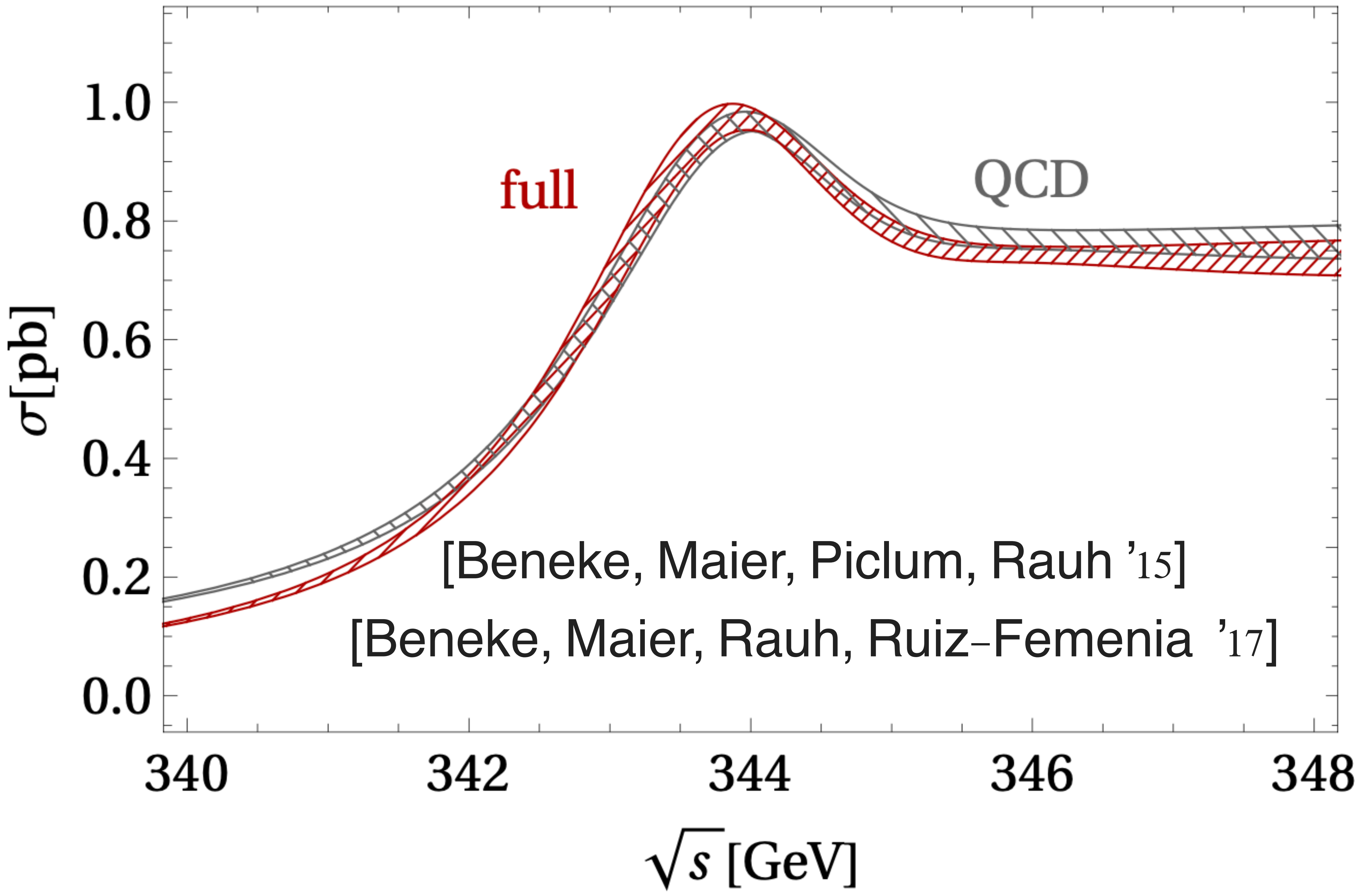
Top physics: theory for threshold scan

- PNRQCD predictions known to N³LO (also including EW+non-resonant effects @ NNLO)

$$R \sim v \sum_k \left(\frac{\alpha_s}{v}\right)^k \cdot \{ \underbrace{1\,(\text{LO})}\ ; \underbrace{\alpha_s, v\,(\text{NLO})}; \underbrace{\alpha_s^2, \alpha_s v, v^2\,(\text{NNLO})}; \underbrace{\alpha_s^3, \alpha_s^2 v, \alpha_s v^2, v^3\,(\text{N3LO})}; \ldots \}$$

[Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser '15]

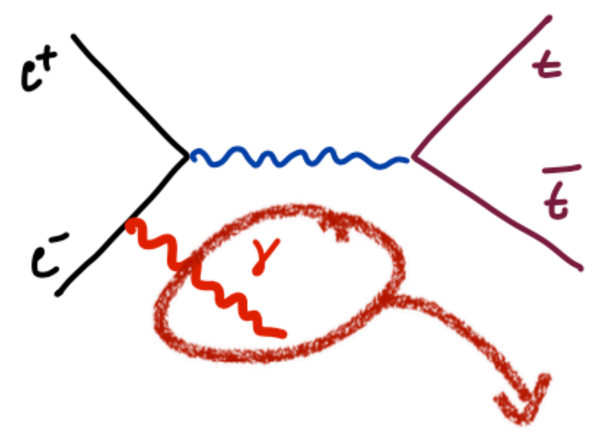
- Uncertainty in top mass (potential subtracted) **$\delta m_t \sim$ 40 MeV.** Towards exp. target (20 MeV):
  - Some improvements already from **matching of N³LO+NNLL** (NNLL from Hoang et al.)
  - Needs **NLL ISR (possibly including soft modes)**
  - Ultimately might require **N⁴LO in PNRQCD needed** (currently out of reach)



[Beneke, Maier, Piclum, Rauh '15]
[Beneke, Maier, Rauh, Ruiz-Femenia '17]

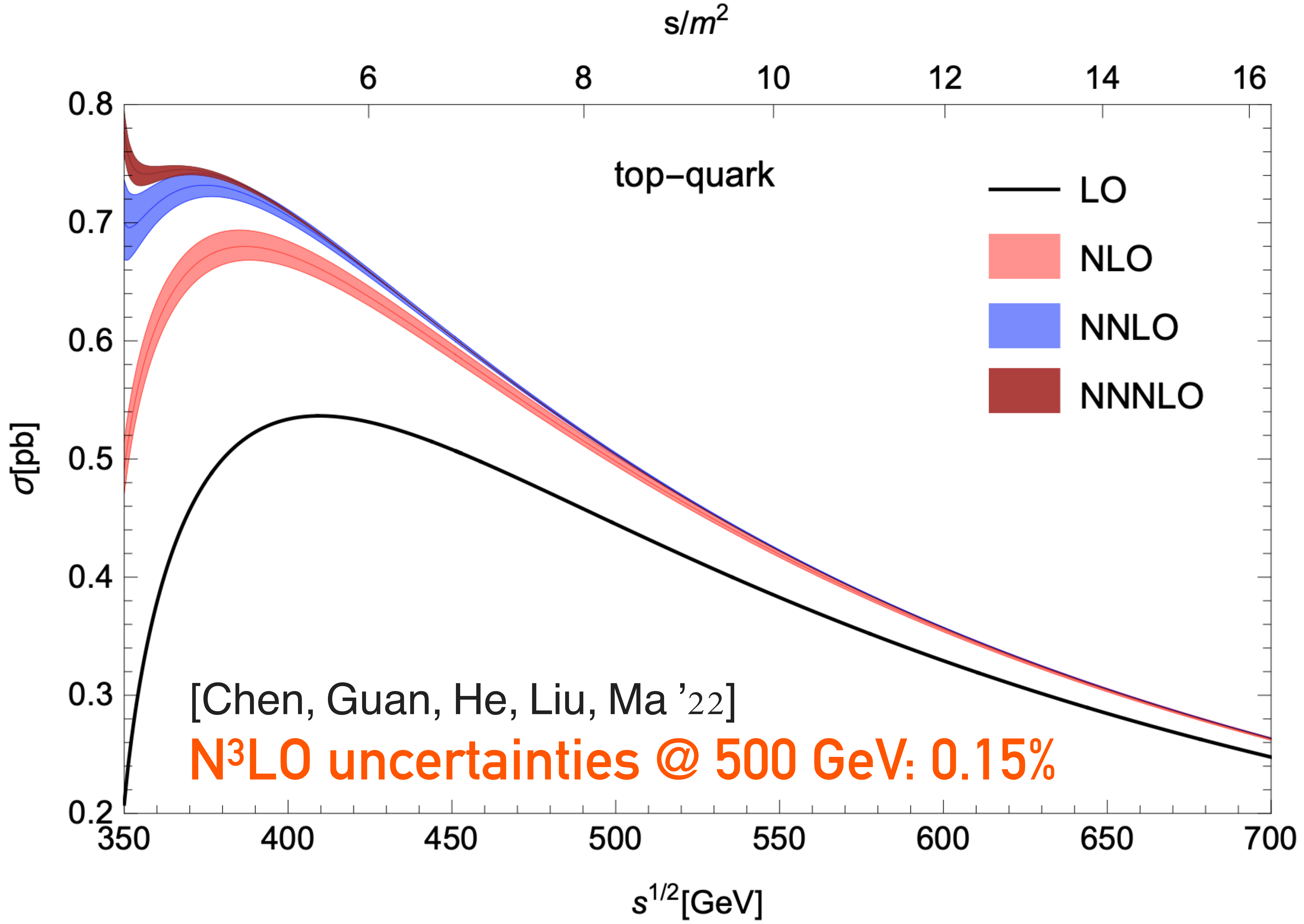
Top physics: above threshold & continuum (mainly ILC/CLIC)

- Continuum: **target is 0.1% on cross section**. N³LO QCD recently calculated but NNLO EW is necessary
- Top mass from radiative return from ISR photon: required matching of continuum and threshold calcns
  - TH unc. doesn't seem to be dominant source of unc.
  - Possible access to running of (MSR) mass



[Boronat, et al. '19]

cms energy	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
luminosity [fb^{-1}]	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV



Outlook

- Astounding experimental programme at FCCee, drastic reduction of statistical (and systematic) uncertainties: theory precision likely to be among the main bottlenecks

- Many (if not all) areas of theory calculations need to be involved (fixed order QCD + EW, resummations in QCD & QED, effective field theories, non-perturbative QCD, event generators , …)

  - Most challenges are technical in nature: hard calculations, currently beyond reach but likely to become achievable with the evolution of the field at the LHC in the coming decade(s), and a lot of work

  - Some deep conceptual issues, which need significant breakthroughs to improve their understanding: e.g. non-perturbative QCD (hadronisation, colour reconnection), currently a bottleneck in several studies

  - Not covered here, but quite essential: issues related to MC generators (e.g. accurate simulation of Coulomb effects, resonances), pushing accuracy of parton showers (interleaved QCD $\oplus$ QED) & matching to NN(N)LO QCD $\oplus$ EW, …