European Research Council
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QCD challenges at FCC-ee

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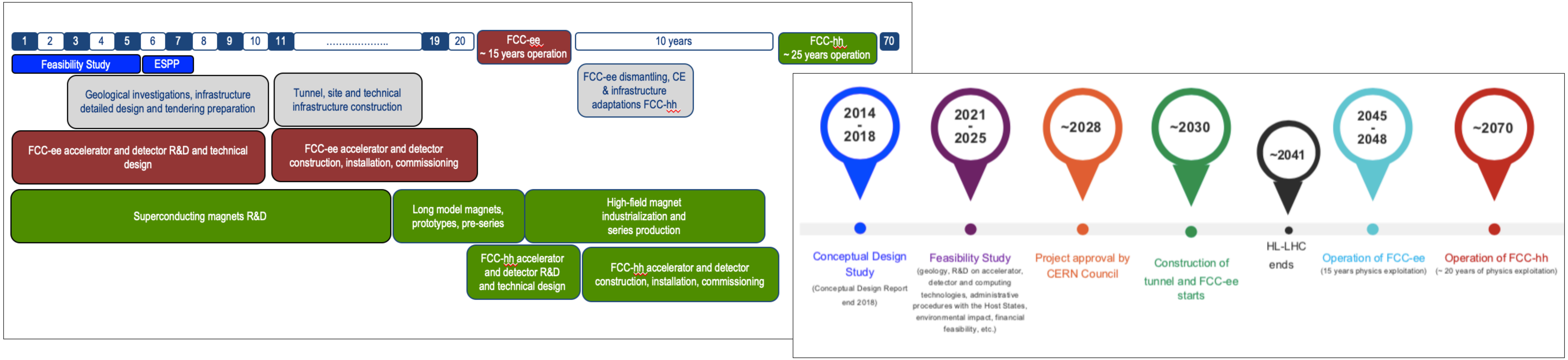
Zurich Phenomenology Workshop - 10 January 2024

FCC in the future collider landscape

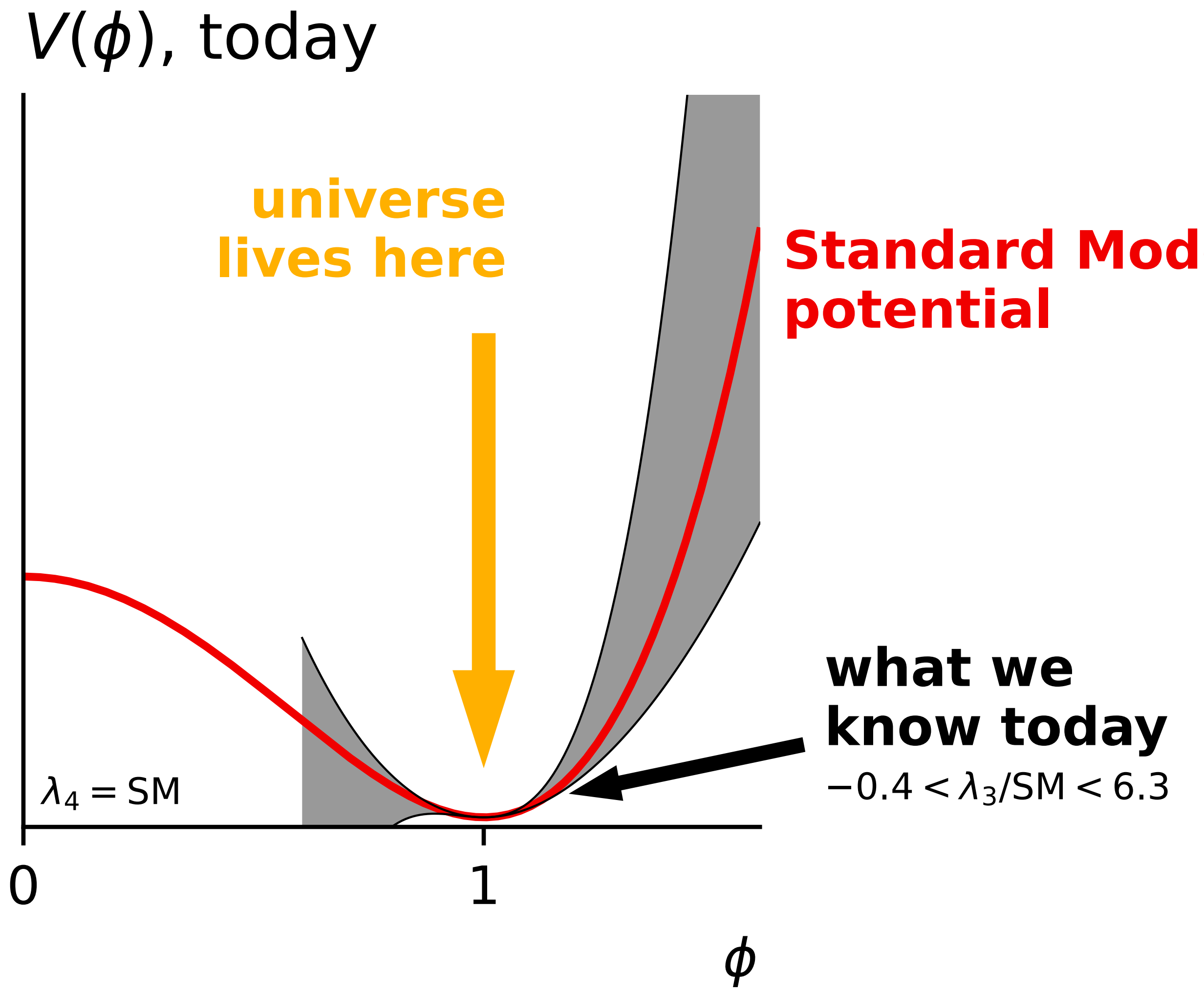
- Huge ongoing effort to figure out future directions after the great success of the LHC. Important lessons from this machine as to where to aim next: Higgs discovery, broad spectrum of SM measurements, refined understanding of QFT, constraints on BSM physics, …

- An ideal future collider should satisfy at least 3 criteria:
  - Guaranteed deliverables (e.g. Higgs)
  - Discovery reach (energy & intensity frontier)
  - Versatility ~ broad array of measurements and topics

Precision calculations crucially impact all three facets, placing this aspect at the core of the planning

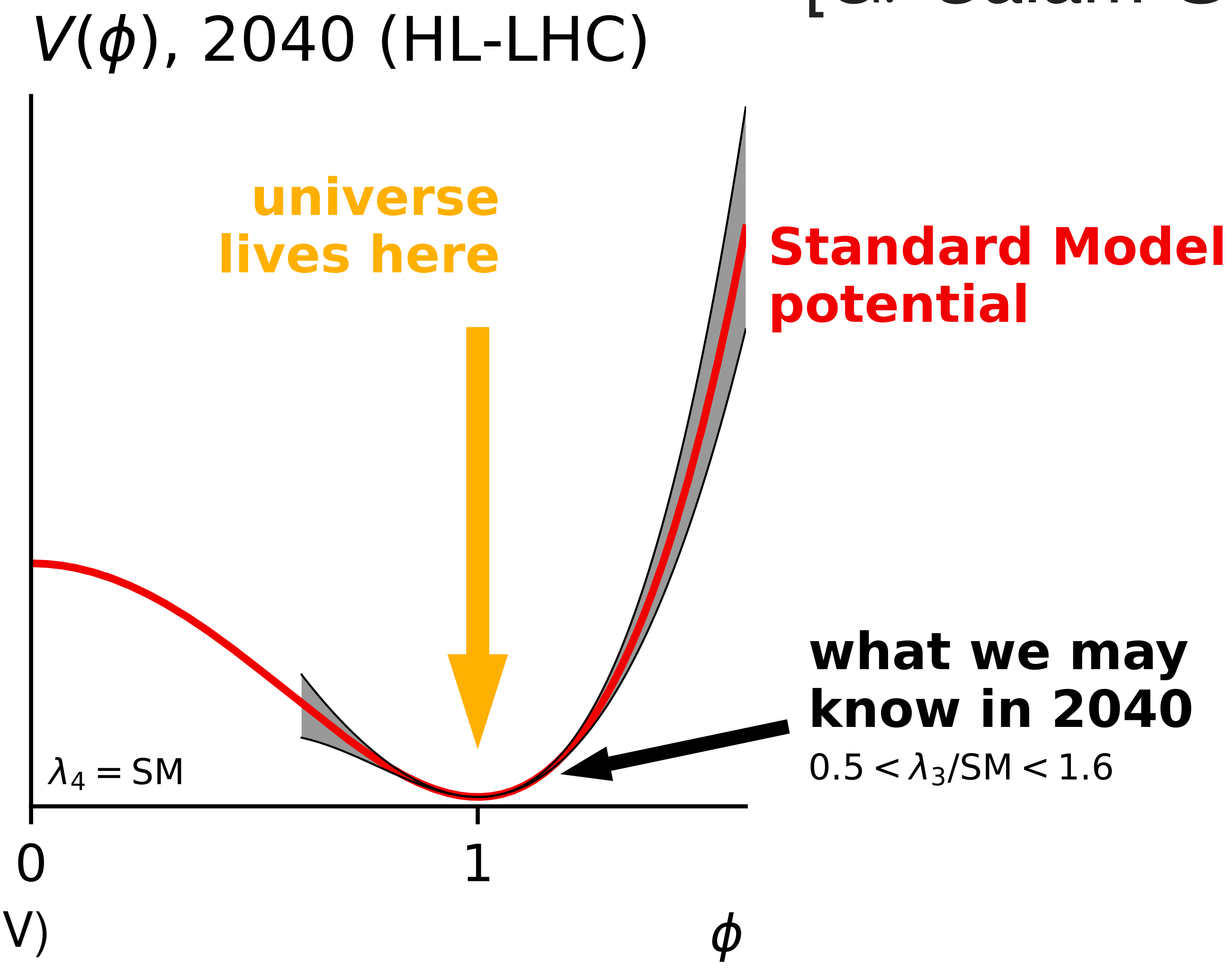


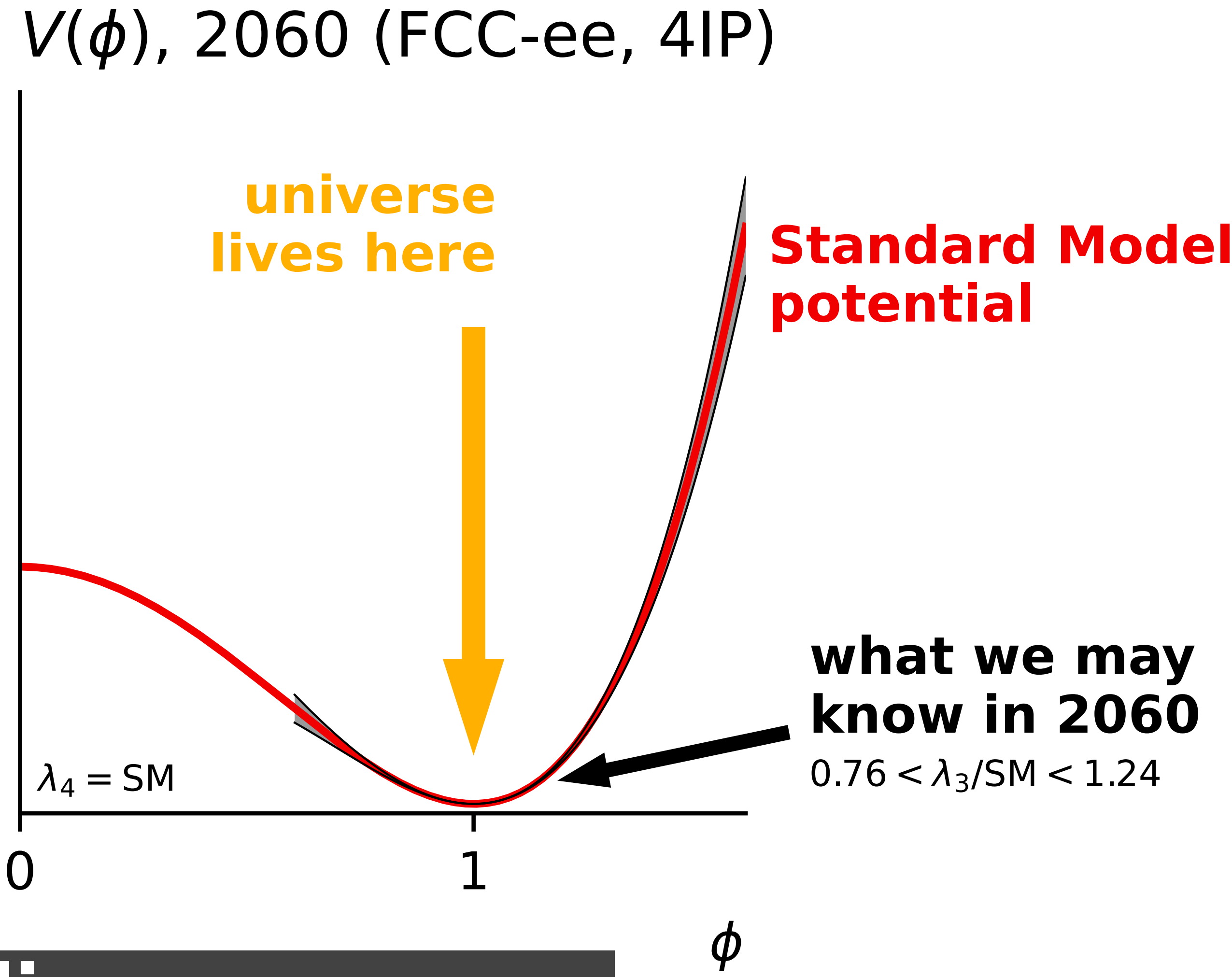
Guaranteed deliverable: exploration of the Higgs sector

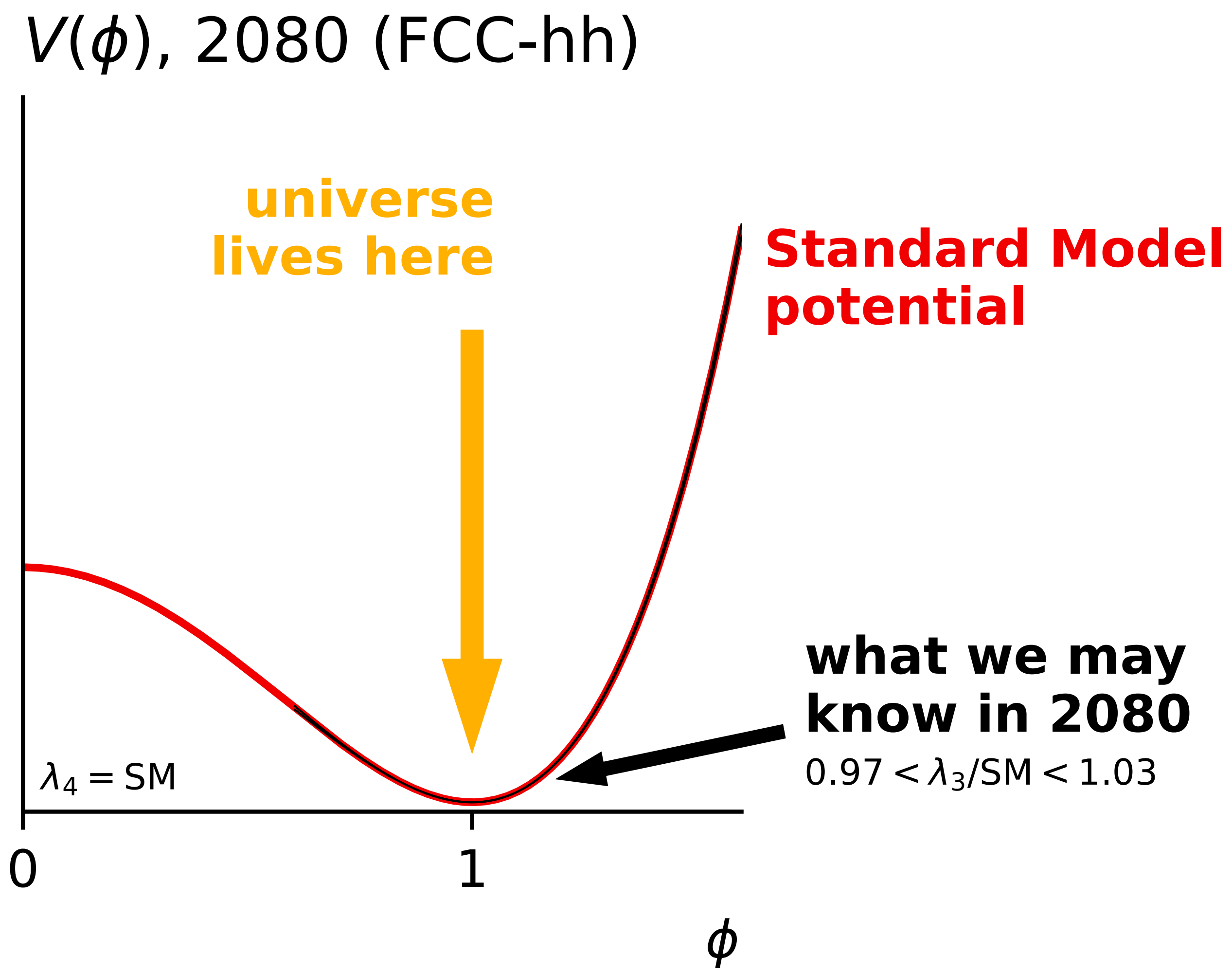


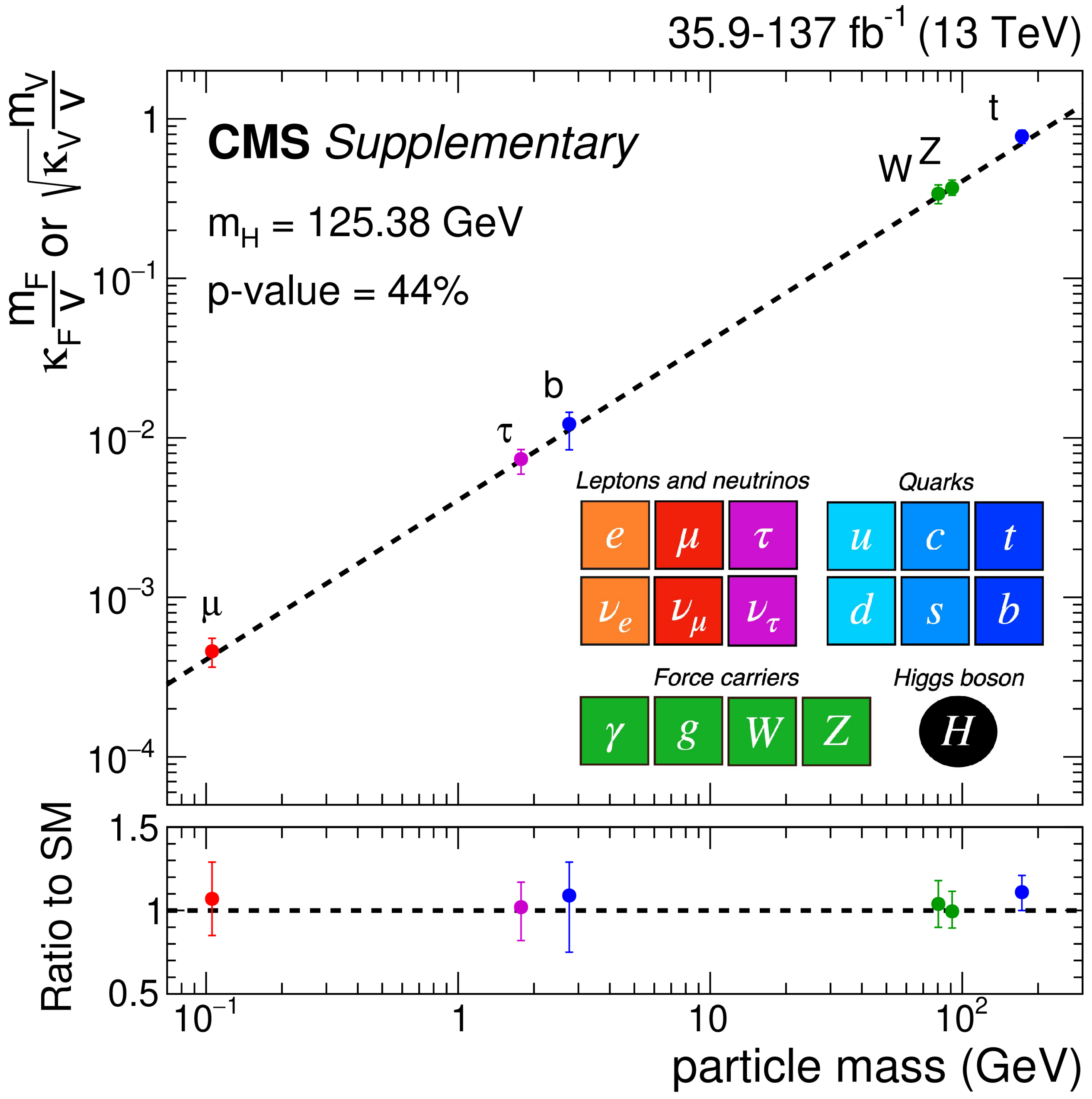
e.g. constraints on Higgs trilinear coupling

[G. Salam @ ICFA 2023] (λ3 only)









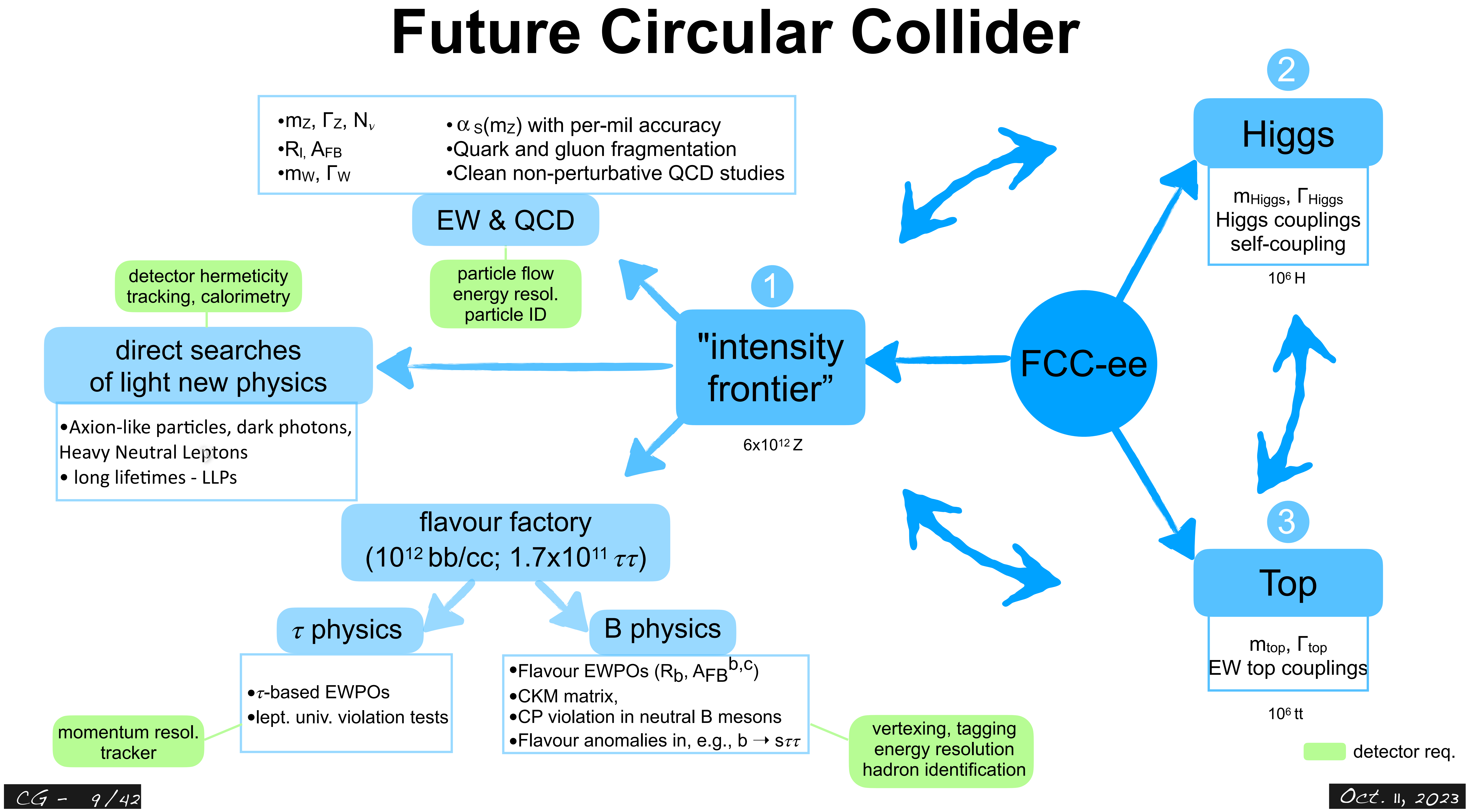
e.g. Yukawa couplings

- 3rd gen: established at LHC (with higher precision from lepton colliders)
- 2nd gen: Y_μ will likely be measured at LHC; Y_c constrained at LHC / guaranteed at FCC-ee. Prospects for Y_s at FCC-ee
- 1st gen: prospects for Y_e at FCC-ee; some ideas to (loosely) constrain $Y_{u,d}$

Breadth & diversity of the scientific programme

[C. Grojean's CERN TH colloquium 2023]

Broad array of physics measurements on several areas of fundamental physics



Future Circular Collider

FCC-ee

1 "intensity frontier"

6×10^{12} Z

EW & QCD

- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W
- $\alpha_S(m_Z)$ with per-mil accuracy
- Quark and gluon fragmentation
- Clean non-perturbative QCD studies

particle flow
energy resol.
particle ID

direct searches of light new physics

- Axion-like particles, dark photons, Heavy Neutral Leptons
- long lifetimes - LLPs

detector hermeticity
tracking, calorimetry

flavour factory (10^{12} bb/cc; 1.7×10^{11} $\tau\tau$)

τ physics

- τ-based EWPOs
- lept. univ. violation tests

momentum resol.
tracker

B physics

- Flavour EWPOs (R_b, $A_{FB}{}^{b,c}$)
- CKM matrix,
- CP violation in neutral B mesons
- Flavour anomalies in, e.g., b → s$\tau\tau$

vertexing, tagging
energy resolution
hadron identification

2 Higgs

m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

10^6 H

3 Top

m_{top}, Γ_{top}
EW top couplings

10^6 tt

🟩 detector req.

CG - 9/42

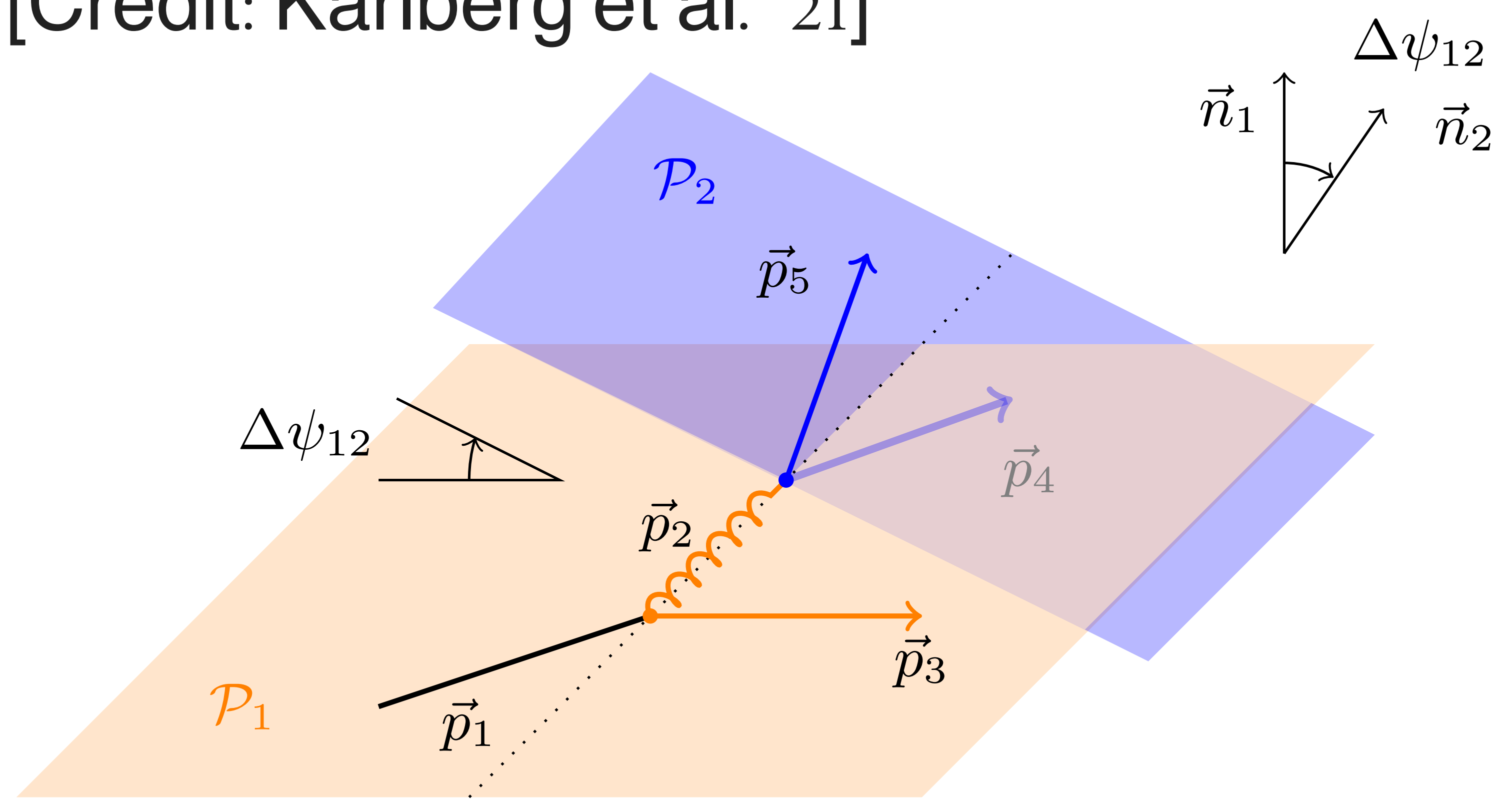
Oct. 11, 2023

Exploration of QFT structure

- The LHC taught us much more than the Higgs boson, what more can we learn from FCC(-ee)?

e.g. spin correlations & entanglement

[Credit: Karlberg et al. '21]



e.g. structure of fragmentation

[Credit: Lee et al. '22]

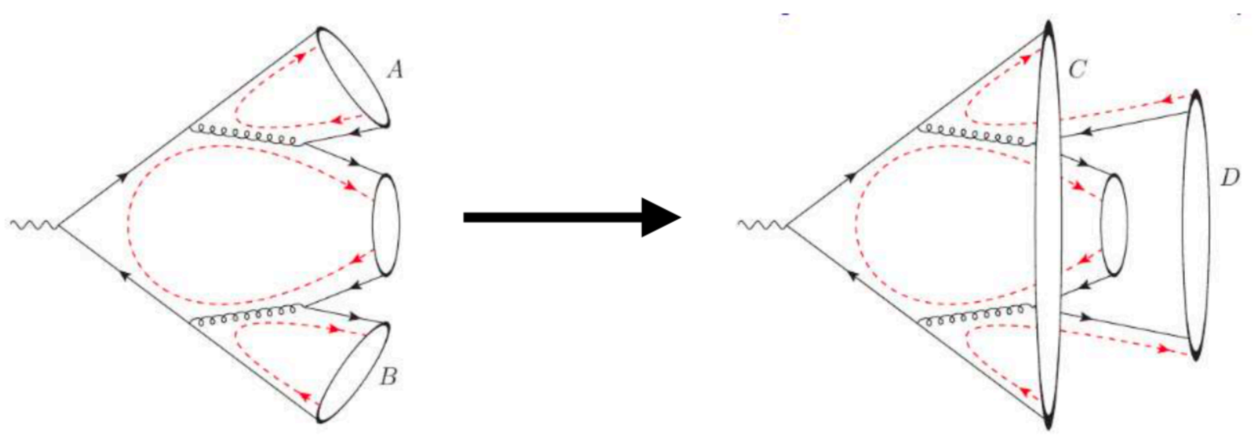
$$\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\cdots\mathcal{E}(\vec{n}_k) = \frac{1}{R_L^2}\left\{f_q^{[k]}(u_i,v_i)\mathbb{O}_q^{[k+1]}(\vec{n}_1) + f_g^{[k]}(u_i,v_i)\mathbb{O}_g^{[k+1]}(\vec{n}_1)\right\} + \mathcal{O}(R_L^0)$$

$$\mathcal{O}_q^{[J]} = \frac{1}{2^J}\bar{\psi}\gamma^+(iD^+)^{J-1}\psi\,,$$

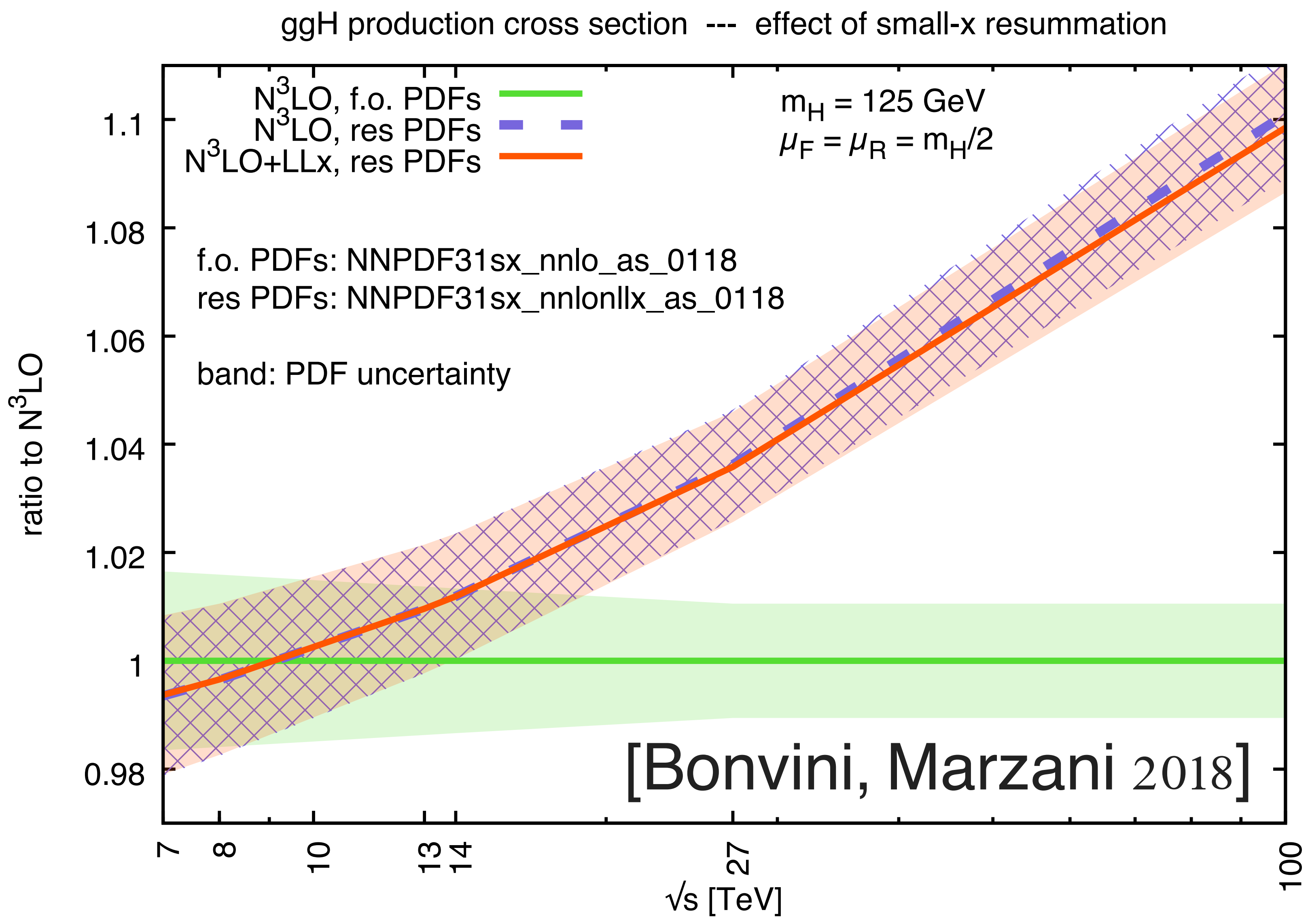
$$\mathcal{O}_g^{[J]} = -\frac{1}{2^J}F_a^{\mu+}(iD^+)^{J-2}F_a^{\mu+}$$

e.g. non-perturbative QCD

[Credit: Plaetzer et al. '23]

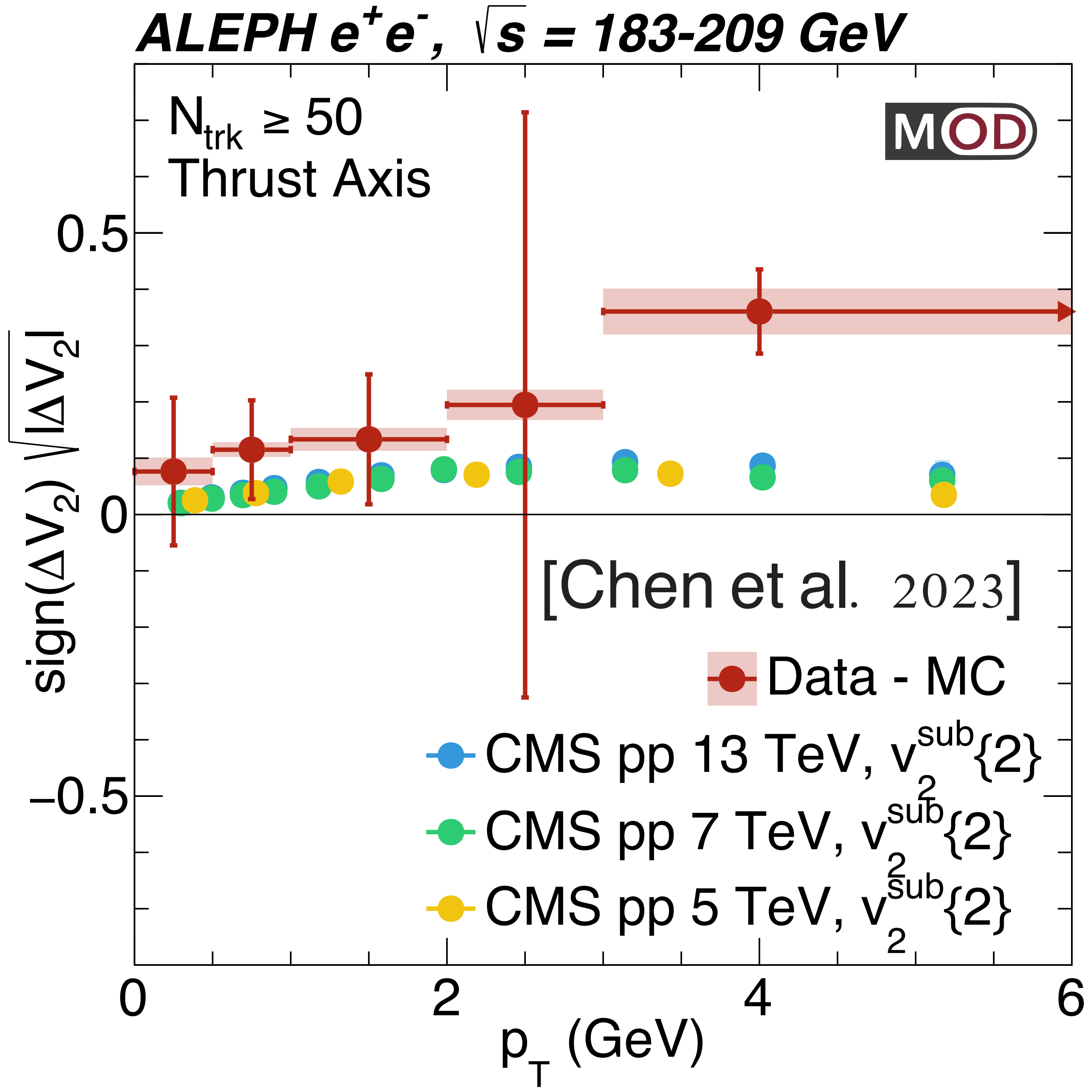


e.g. BFKL dynamics (hh)



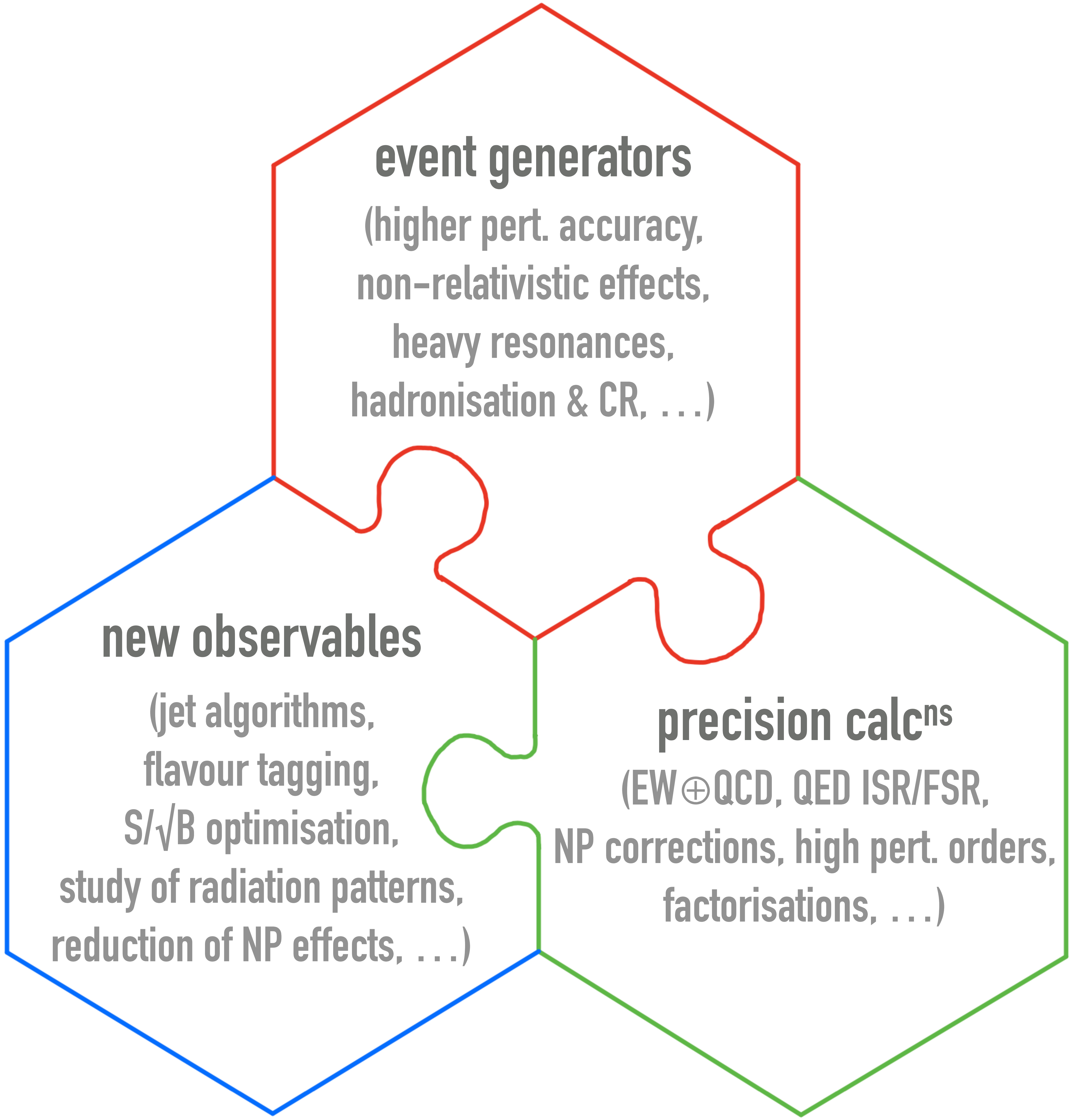
[Bonvini, Marzani 2018]

e.g. collective effects?



[Chen et al. 2023]

Theory challenges (in this talk mainly QCD)



event generators

(higher pert. accuracy,
non-relativistic effects,
heavy resonances,
hadronisation & CR, . . .)

new observables

(jet algorithms,
flavour tagging,
S/$\sqrt{B}$ optimisation,
study of radiation patterns,
reduction of NP effects, . . .)

precision calc^{ns}

(EW$\oplus$QCD, QED ISR/FSR,
NP corrections, high pert. orders,
factorisations, . . .)

- Reaching the foreseen performance poses outstanding challenges on TH. Evolution in many areas is demanded‡
  - NB: cross-pollination across fields essential, global progress is required to match astonishing experimental precision

‡ I will focus on some of the next steps in this direction. Monte Carlo generators covered in Silvia, Peter and Stefano’s talks

QCD studies in $Z/\gamma^* \to$ jets

Physics at the Z pole

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

❑ **Numbers are given here for FCC-ee (best prospects)**

[P. Janot's talk @ CERN FC workshop 2022]

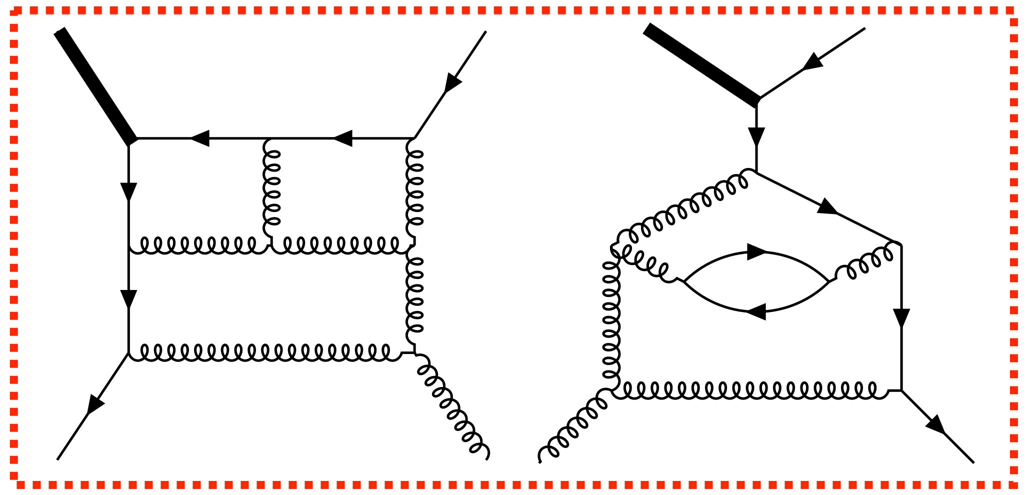
Observables	Present value	FCC-ee stat.	FCC-ee current syst.	FCC-ee ultimate syst.	Theory input (not exhaustive)
m_Z (keV)	**91187500 ± 2100**	**4**	**100**	**10 ?**	Lineshape QED unfolding Relation to measured quantities
Γ_Z (keV)	**2495500 ± 2300 [*]**	**4**	**25**	**5 ?**	Lineshape QED unfolding Relation 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, …)

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

- Main challenges from EW aspects:
  - EWPO $Z \to qq+X$ @ 3 loops EW (with 4 loop arguably necessary in some cases)
  - 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 from R_ℓ (4 loop QCD known, $1/Q^6$ hadronisation corrections)
  - Jet dynamics and substructure: spin correlations, fragmentation & track functions, (multi-)jet observables
  - Study of non-perturbative effects & their modelling
  - Heavy quarks (Q) studies (e.g. asymmetries, fragmentation functions) & flavour tagging (e.g. q/Q vs. g jets)
  - τ decays
  - Calibration/tuning of ML & MC tools (instrumental for higher-energy runs)

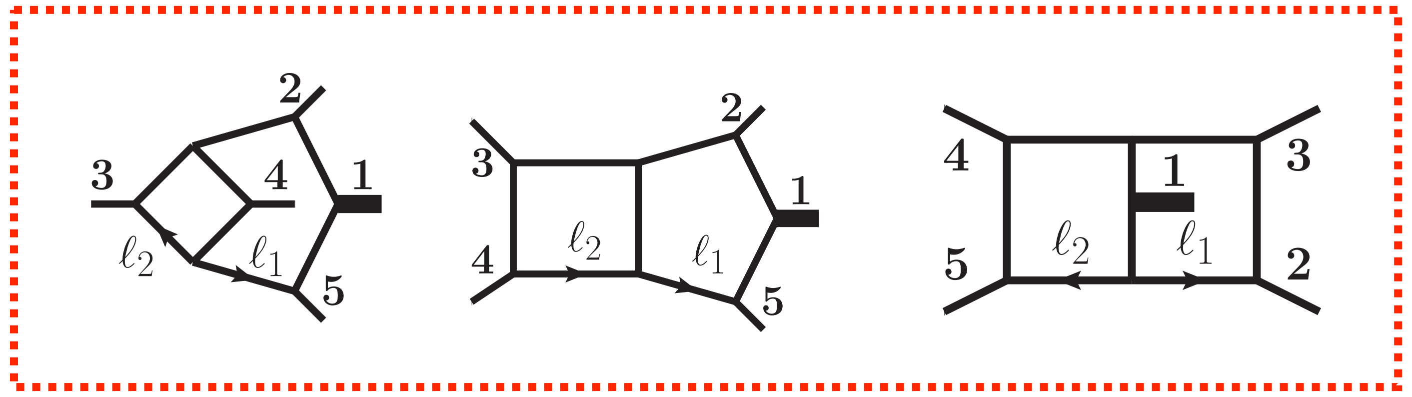
Precision physics in $Z/\gamma^* \to$ jets

- Significant improvement needed for QCD calculations
  - 3 jets @ N^3LO QCD: amplitudes in the making (planar limit), but IR subtraction is an open challenge



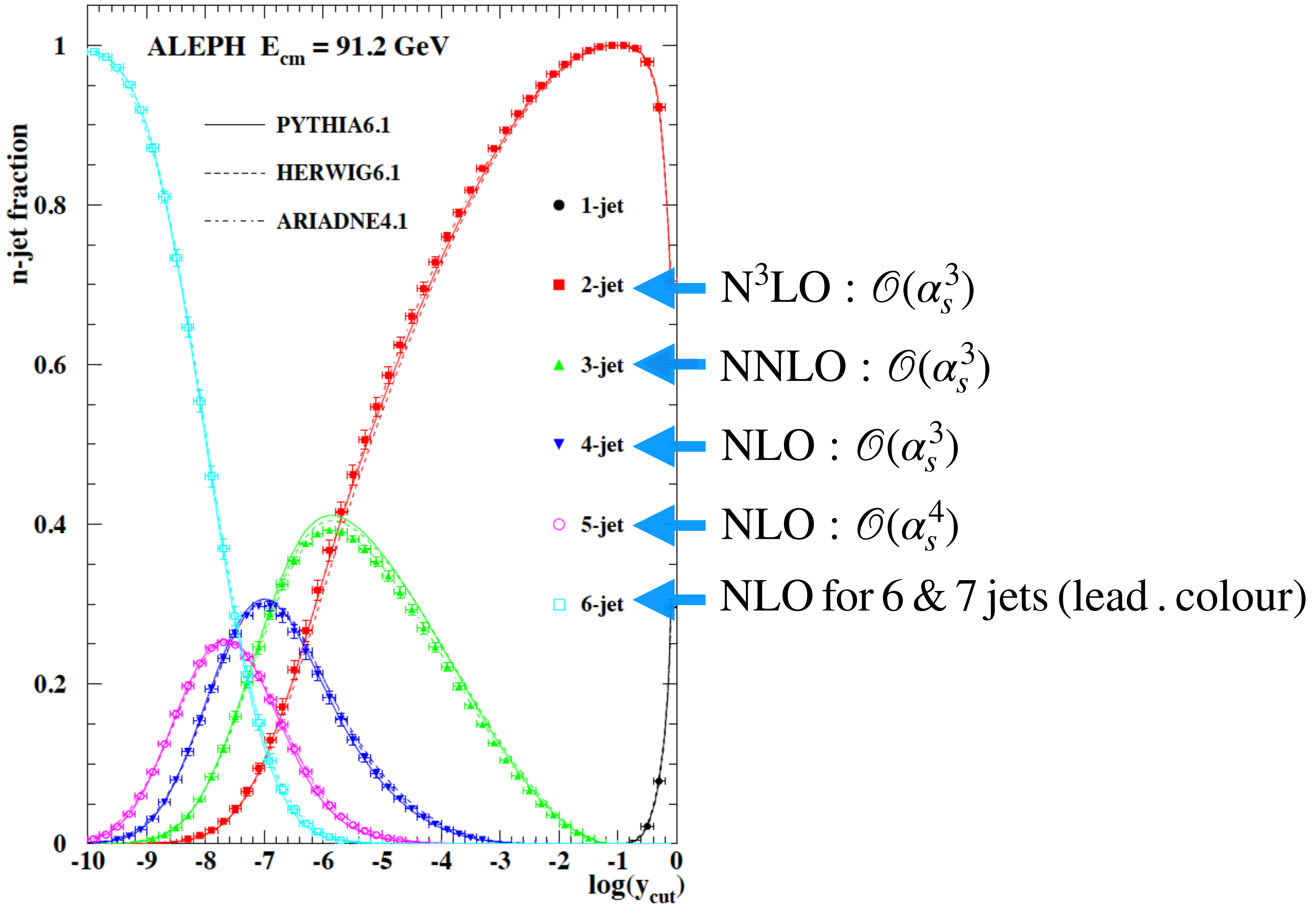
[Gehrmann et al. 2023]

  - 4 jets @ NNLO QCD: likely within reach in next O(few) years



[Abreu et al. 2023]

Current state of the art



  - Higher orders/jet multiplicities are more ambitious and require a breakthrough. Crucial bottlenecks are amplitudes & how to handle the overwhelming complexity (e.g. N^3LO subtraction) in efficient numerical codes

Precision physics in $Z/\gamma^* \to$ jets (heavy quarks)

- Heavy quarks challenges: let's consider A_{FB} as an example

[Blondel, Janot 2021]

Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^{b}, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge

[Bernreuther et al. 2016]

Of this, the current QCD error is

$$\Delta A_{FB}/A_{FB} \sim \pm\, 0.003$$

May become a bottleneck at FCC-ee

- N^3LO quite hard at the moment (QQg @ 2L, QQ @ 3L): possible workaround with series expansions (e.g. R_b currently known to N^3LO up to $O(m_b^4/Q^4)$, "massification" of massless amps, …) or numerical methods
- Explore fiducial selections to improve perturbative convergence (e.g. cut on acollinearity angle to suppress g → QQ reduces the size of QCD corrections/uncertainties)

Moderate cuts seem to reduce the QCD error by an order of magnitude

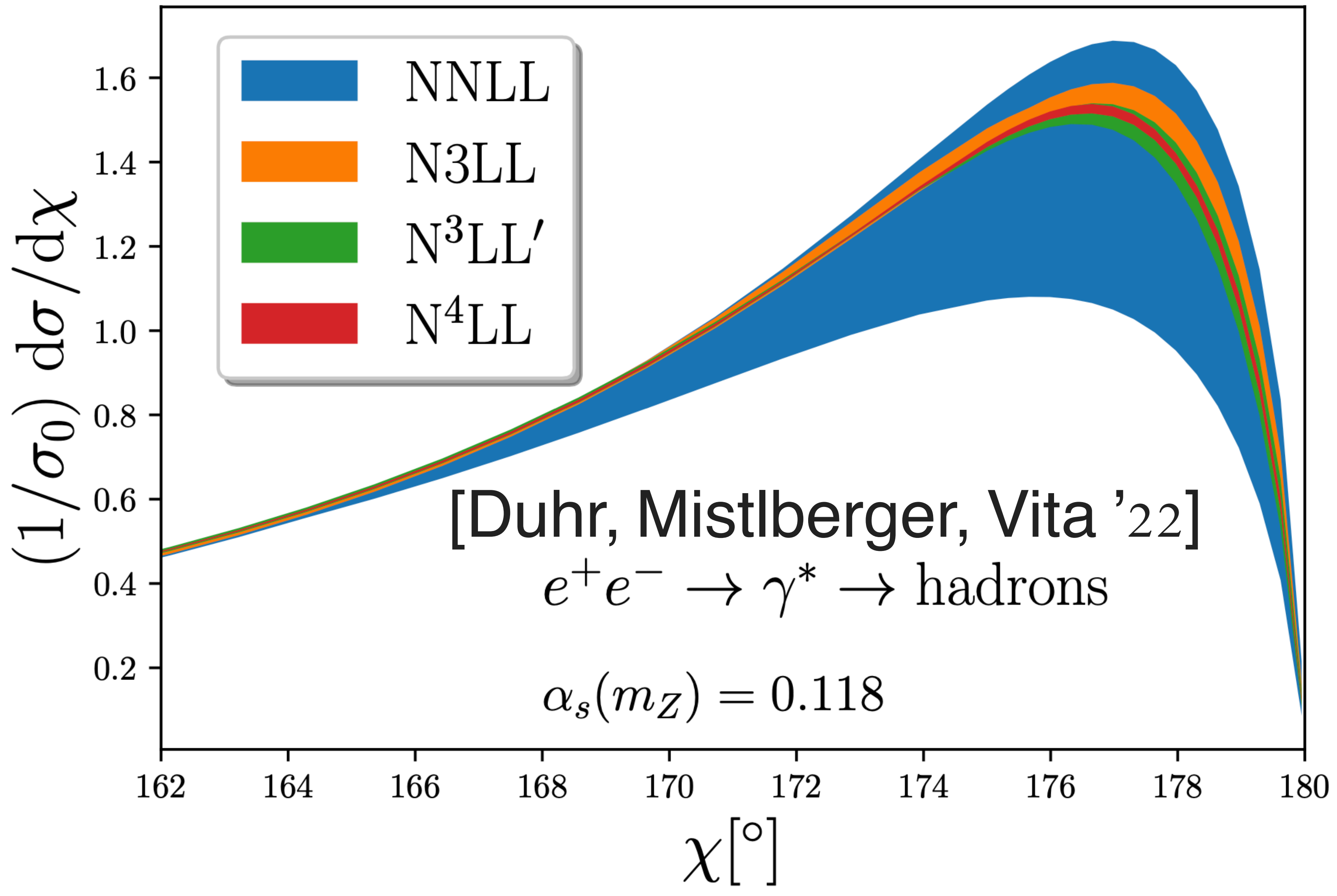
ξ_0 cut	Measured A_{FB}	ΔA_{FB}(stat)	ΔA_{FB}(tune)	ΔA_{FB}(theo. QCD corr)
No cut	0.0998 ± 0.0004	0.00008	0.00014	0.00033
1.50	0.1003 ± 0.0003	0.00011	0.00014	0.00023
1.00	0.1011 ± 0.0002	0.00011	0.00010	0.00016
0.50	0.1023 ± 0.0002	0.00011	0.00010	0.00007
0.30	0.1030 ± 0.0002	0.00011	0.00010	0.00003
0.20	0.1033 ± 0.0001	0.00011	0.00005	0.00002
0.10	0.1035 ± 0.0002	0.00016	0.00005	0.00001

[Alcaraz Mestre 2020]

Precision physics in Z/γ* → jets (resummations)

- Resummation techniques refined at the LHC (SCET, numerical methods, generating functionals, higher-order parton showers, …)
  - Ongoing effort to push standard for 2-leg observables to N^{3}LL (even N^{4}LL in some cases). Progress needed for n-jet case (some NNLL, e.g. D parameter)
  - Exploit LHC-gained expertise in designing new observables (e.g. w/o NGLs); balance performance (e.g. small NP corr.^{ns}) and calculability (e.g. correlators, Lund jet plane, grooming, …)

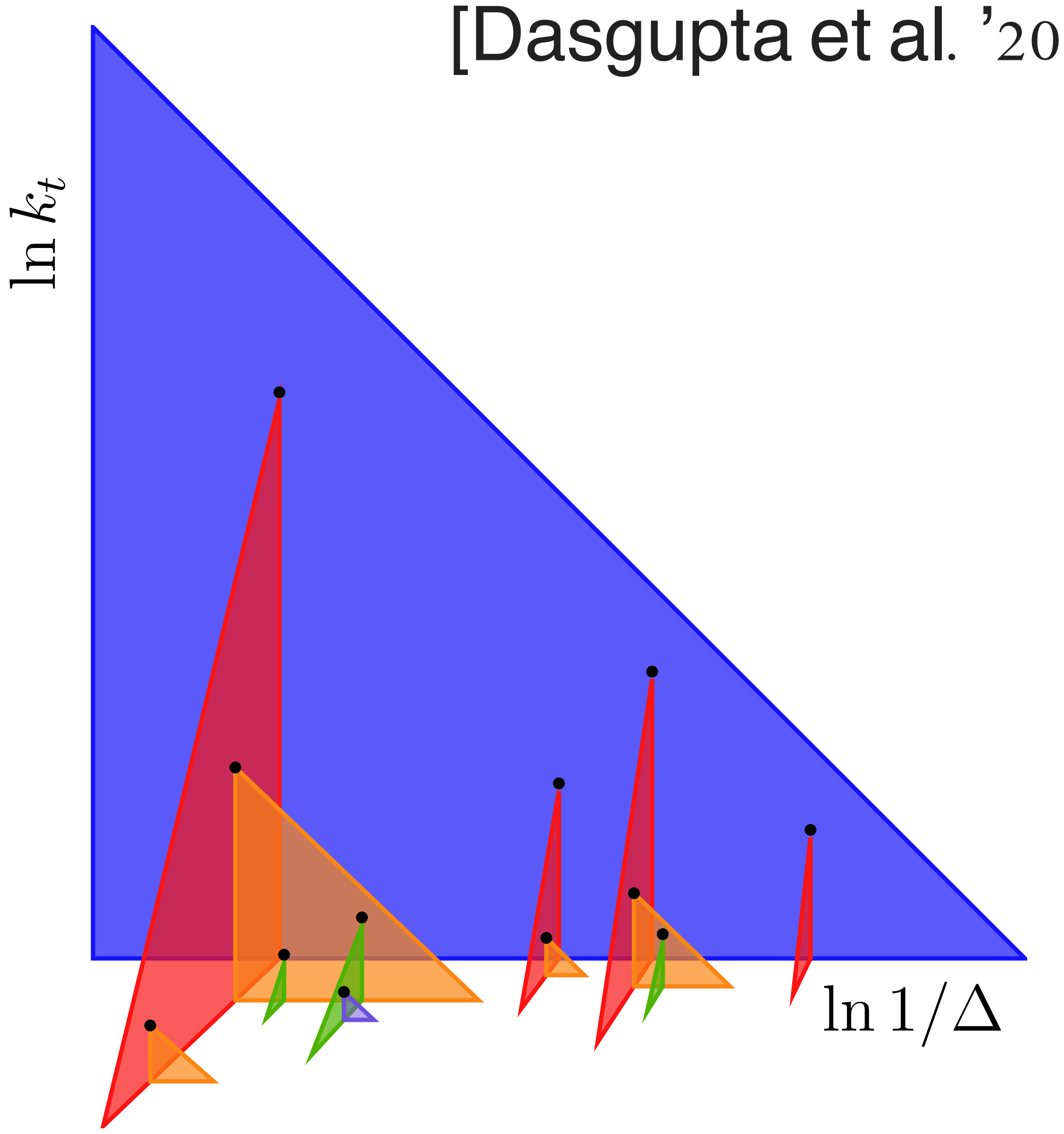
e.g. EEC in back-to-back limit



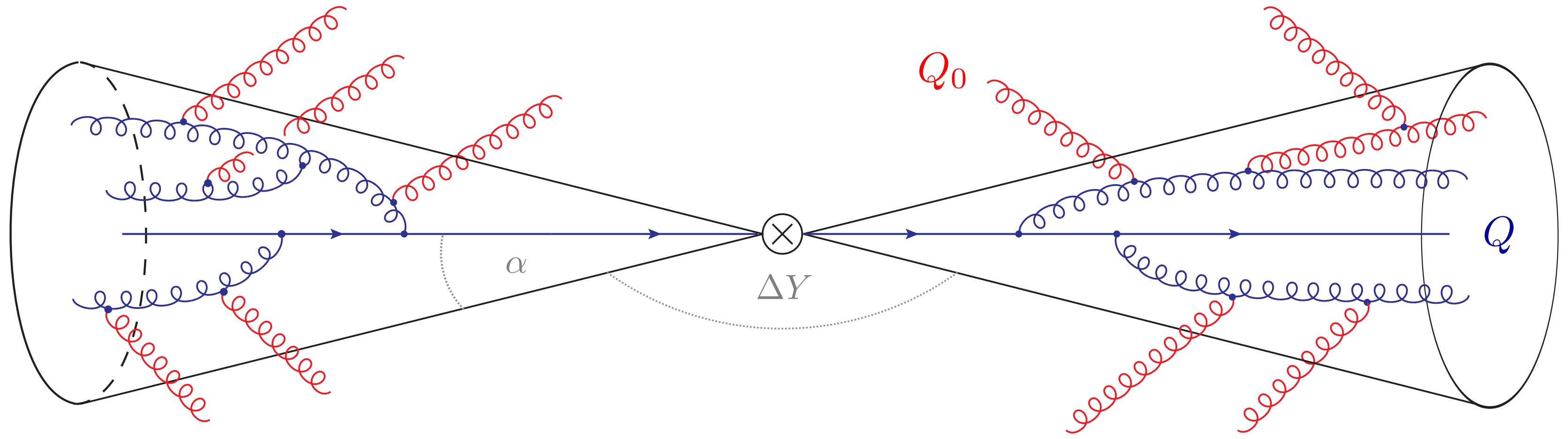
[Duhr, Mistlberger, Vita ’22]

e.g. Lund event shapes

[Dasgupta et al. ’20]



e.g. NGLs in jet cross sections (planar)



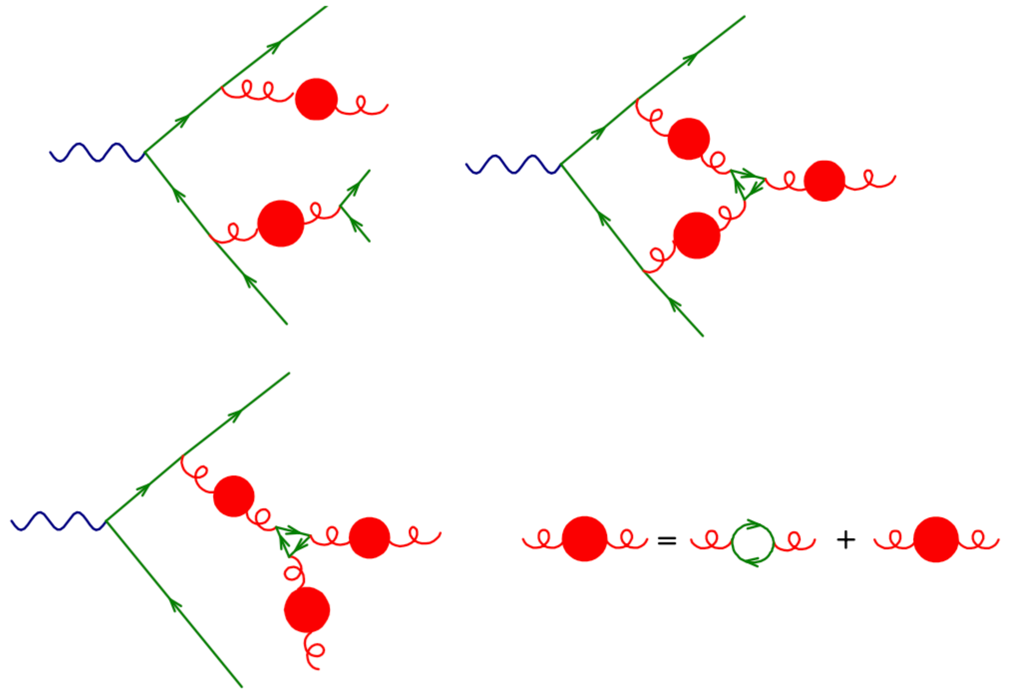
[Banfi, Dreyer, PM ’21]

[Becher, Rauh, Xu ’21, + Becher, Schalch, Xu ‘23]

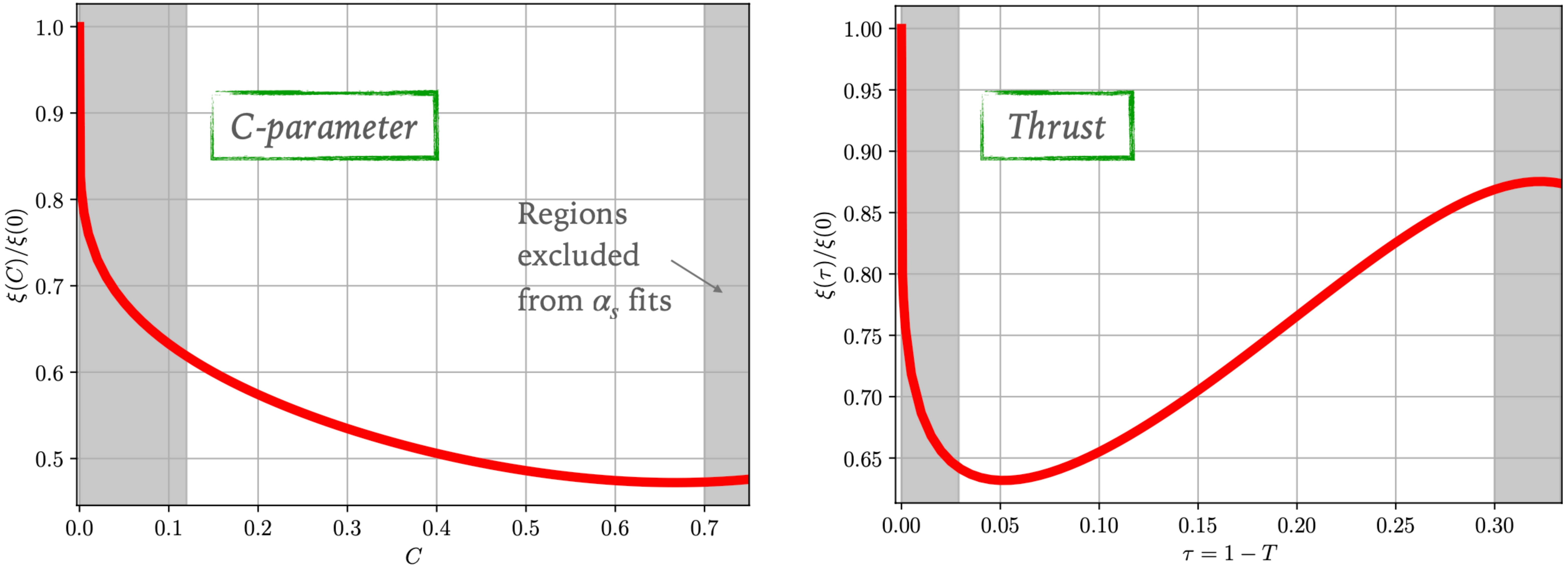
[Ferrario Ravasio et al. ’23]

Non-perturbative QCD corrections

- Large hadronization corrections are a limiting factor (e.g. up to ~15% for event shapes/jet rates)
- Recent work revealed flaws in analytic models, with uncertainties arguably under-estimated (?)
  - Leading corrections ($\sim 1/Q$) varies with kinematics across the spectrum, and can become much smaller than assumed in 3-configurations
  - Current observations largely based on large-n_F calculations, still far from QCD (except around Sudakov shoulders). Interplay with resummations currently unknown
  - NP scale Λ could itself vary across the spectrum (i.e. $\langle O \rangle$ of different EFT ops.)



e.g. 1/Q correction relative to the 2-jet approximation



$$\frac{d\sigma}{d\mathcal{O}}(\mathcal{O}) \simeq \frac{d\sigma^{\text{pert.}}}{d\mathcal{O}}\left(\mathcal{O} - \zeta(\mathcal{O})\alpha_0(\Lambda)\frac{\Lambda}{Q}\right)$$

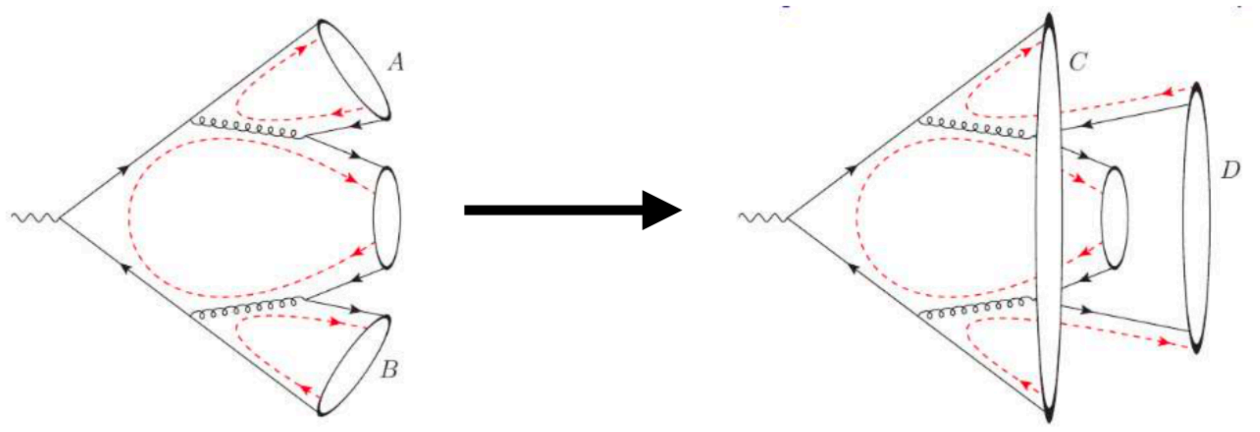
[Luisoni, PM, Salam ’20; Caola, Ferrario Ravasio, Limatola, Melnikov, Nason ’21+’22; Nason, Zanderighi ’23]

Non-perturbative QCD: possible avenues

- Better MC models/tuning
  - Span of c.o.m. energies crucial for tuning, jointly w/ higher order PSMCs [High-purity samples of g/q/Q jets beneficial]
  - Cross-benefit between stages of FCCee (e.g. Z → jets useful for ZH, CR at WW → jets, …)
- Observables with smaller sensitivity to soft physics
  - e.g. grooming, albeit unclear whether effective at FCC-ee due to limited phase space
- Factorisation theorems and data driven extraction
  - Constrain NP parameters/operators across energies (use of lattice also shows promising prospects)
  - Idea to run below the Z peak might be beneficial
  - Further progress in analytic methods very desirable

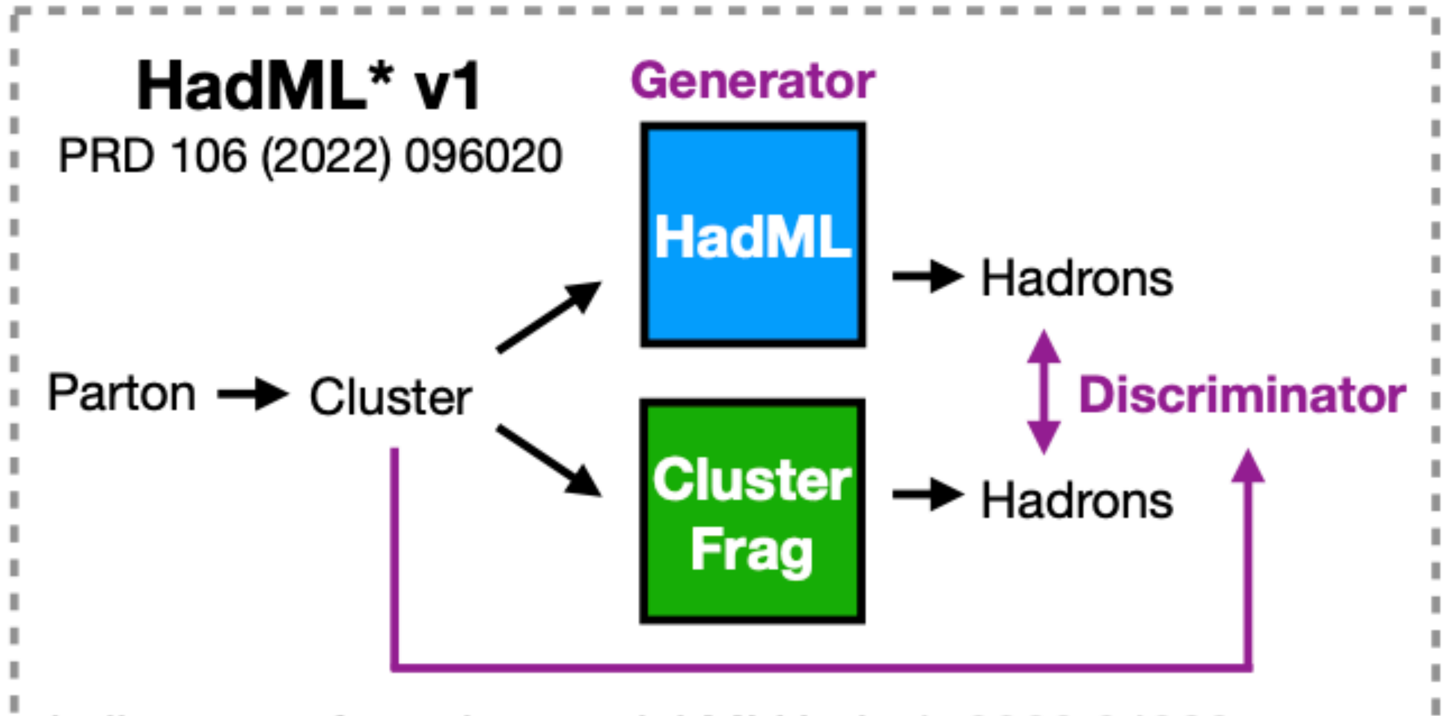
e.g. CR inspired by amplitude-level evolution

[S. Plaetzer et al. 2023]



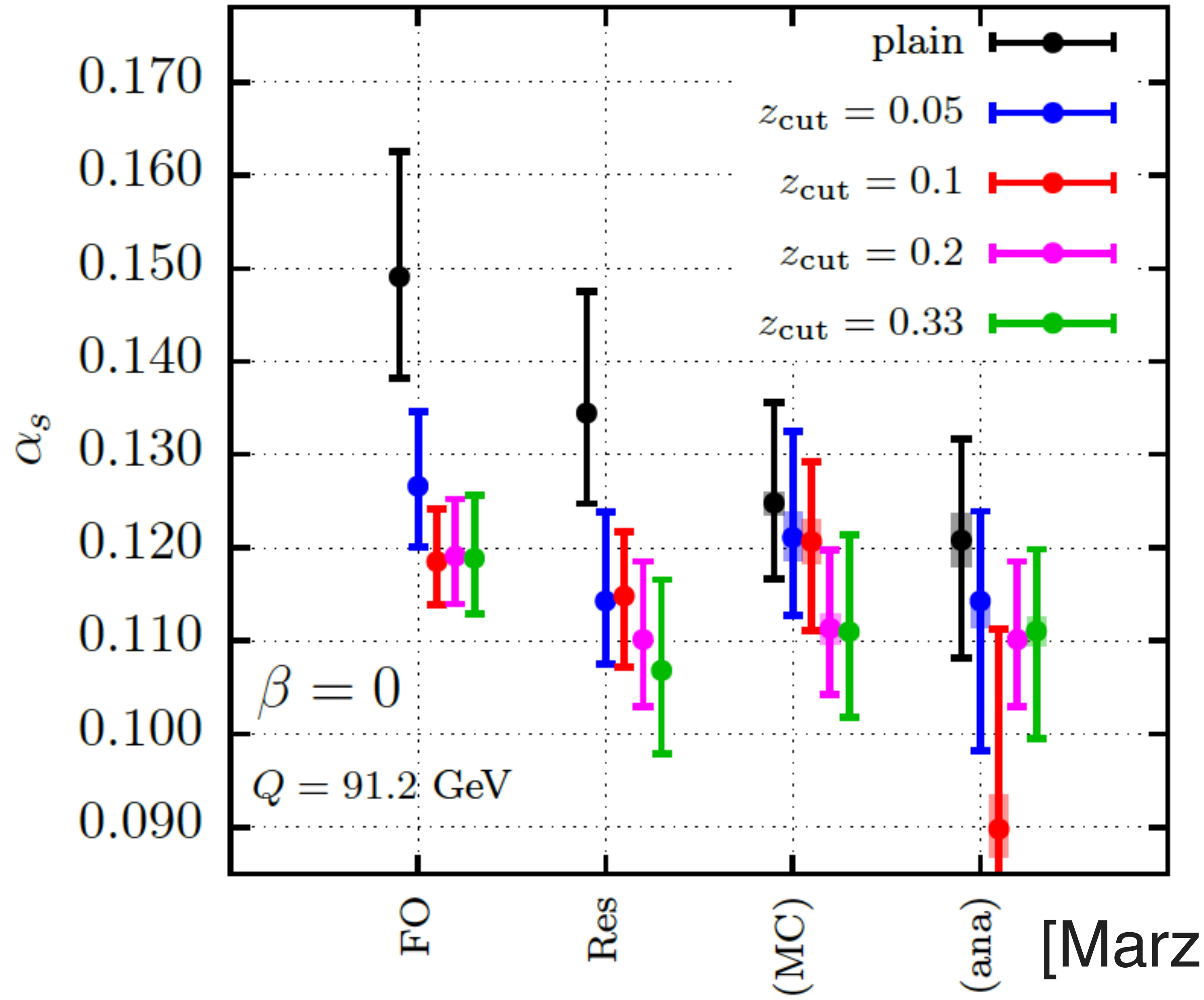
[J. Chan et al. '22–'23]

e.g. GANs as hadronisation model



similar setup for string model MLHad v1: 2203.04983

e.g. α_S from SD thrust



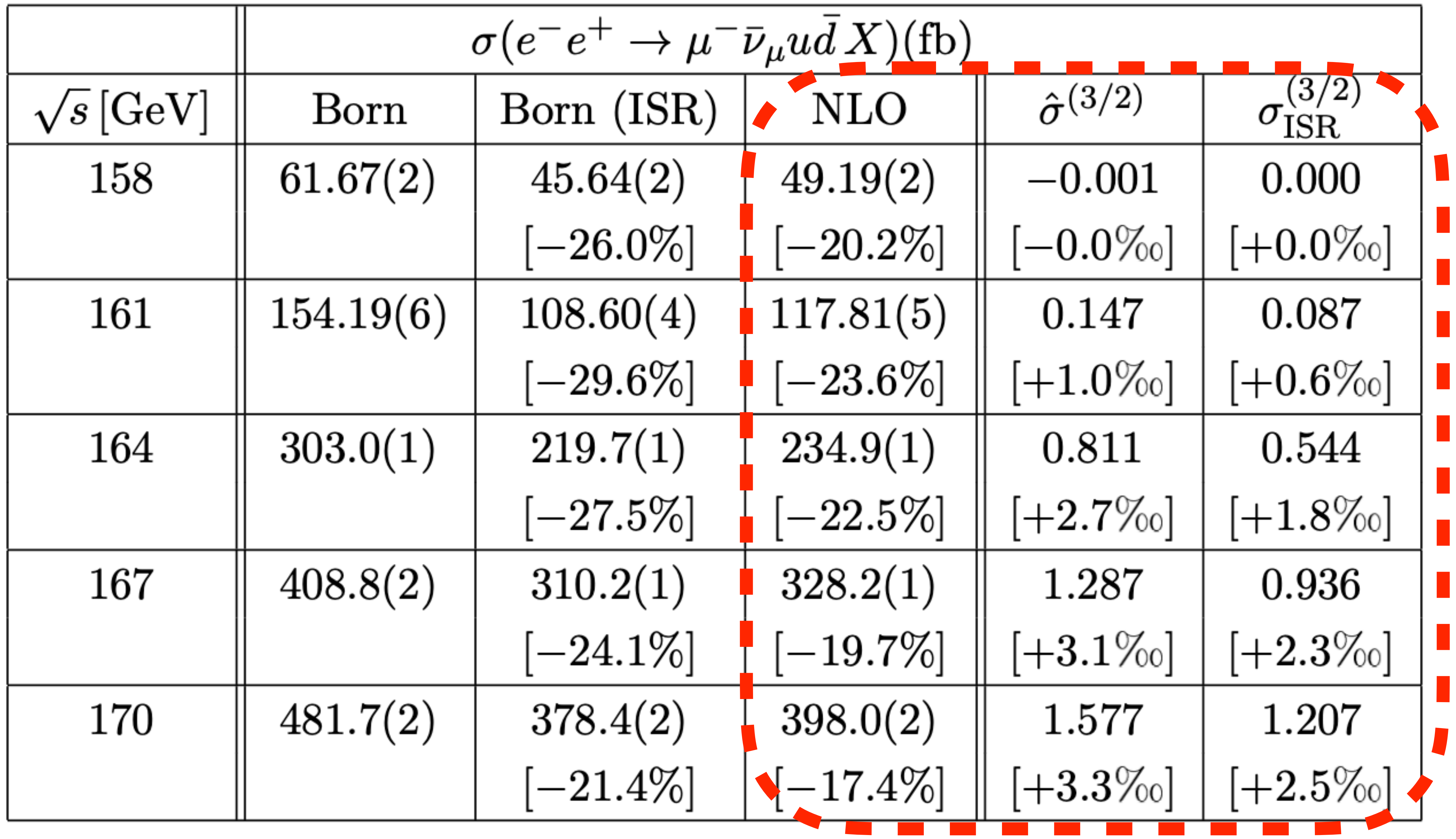
[Marzani et al. 2019]

WW threshold

WW threshold scan and W mass and width

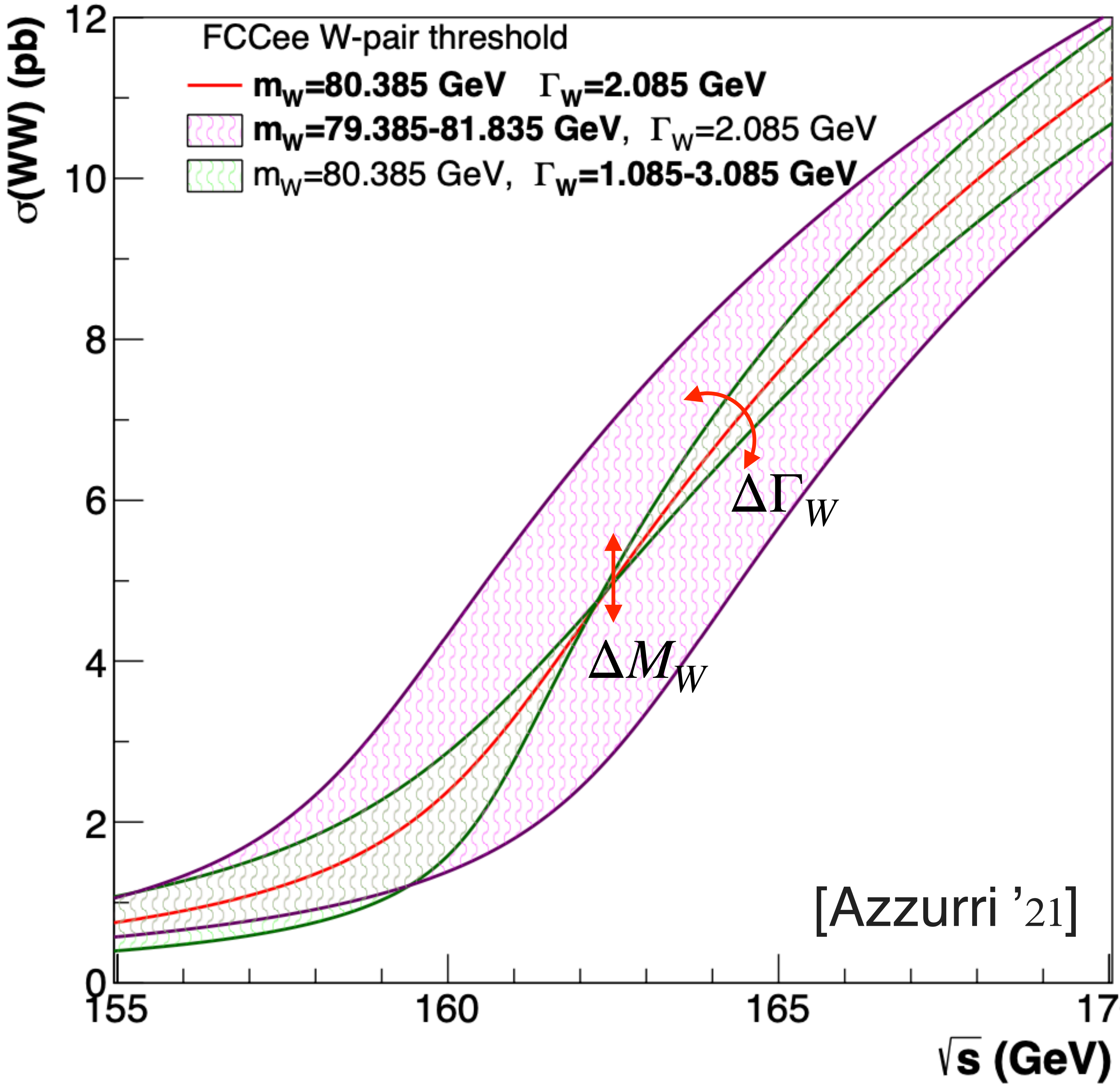
- TH cross section currently known accurately at NLO (EW) + NNLO (unstable particles EFT) sufficient for $\delta m_W \sim$ 5-6 MeV

[Denner, Dittmaier, Roth, Wieders '05; 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



[Azzurri '21]

Reaching the stat. uncertainty of 0.3-0.5 MeV (lep. channel) is very demanding

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

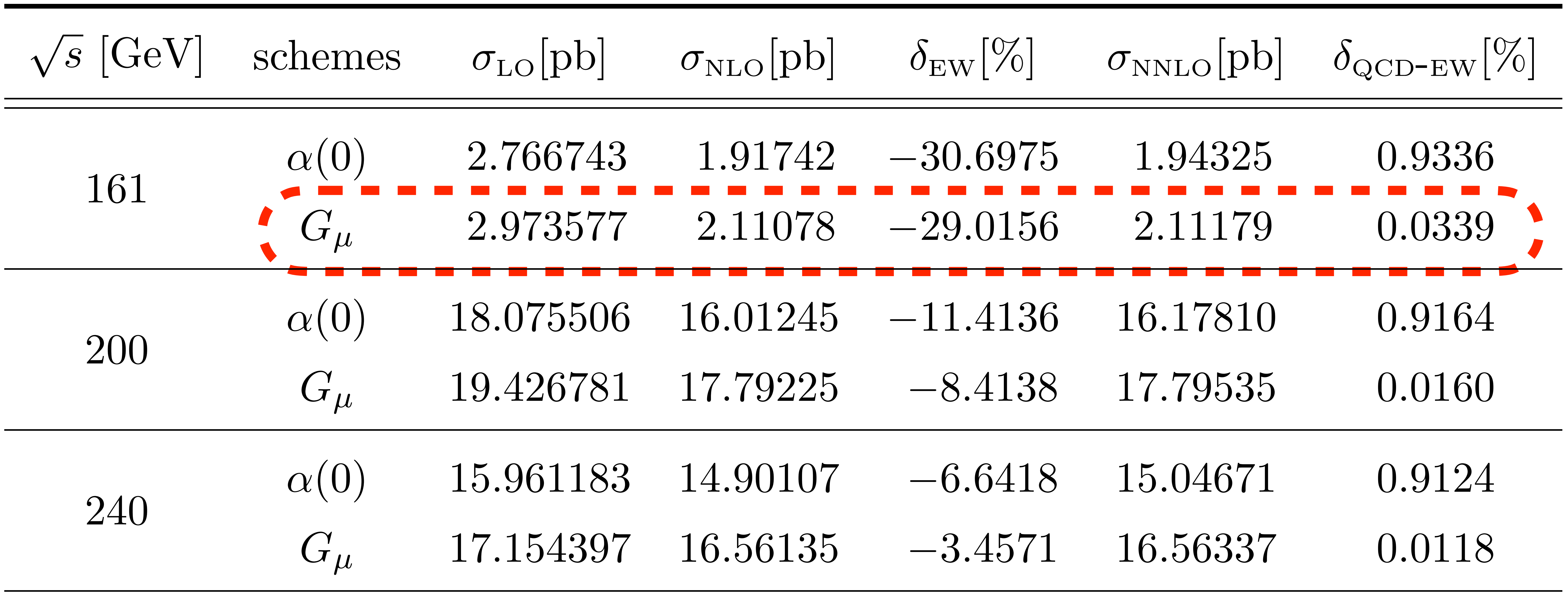
$$\Delta\sigma_{\rm WW}({\rm T}) < 0.8 \text{ fb}$$

(NB: no W BRs [~0.04% in table units])

WW threshold scan and W mass and width

- Recent computation of $\mathcal{O}(\alpha_s\alpha)$ terms to WW production
  - Corrections of O(0.034%) (G_μ scheme)
  - Suggests that full NNLO (EW) may likely be necessary [out of reach at the moment]

[Li et al. 2024]



$\sqrt{s}$ [GeV]	schemes	σ_{LO}[pb]	σ_{NLO}[pb]	δ_{EW}[%]	σ_{NNLO}[pb]	$\delta_{\text{QCD-EW}}$[%]
161	$\alpha(0)$	2.766743	1.91742	−30.6975	1.94325	0.9336
	G_μ	2.973577	2.11078	−29.0156	2.11179	0.0339
200	$\alpha(0)$	18.075506	16.01245	−11.4136	16.17810	0.9164
	G_μ	19.426781	17.79225	−8.4138	17.79535	0.0160
240	$\alpha(0)$	15.961183	14.90107	−6.6418	15.04671	0.9124
	G_μ	17.154397	16.56135	−3.4571	16.56337	0.0118

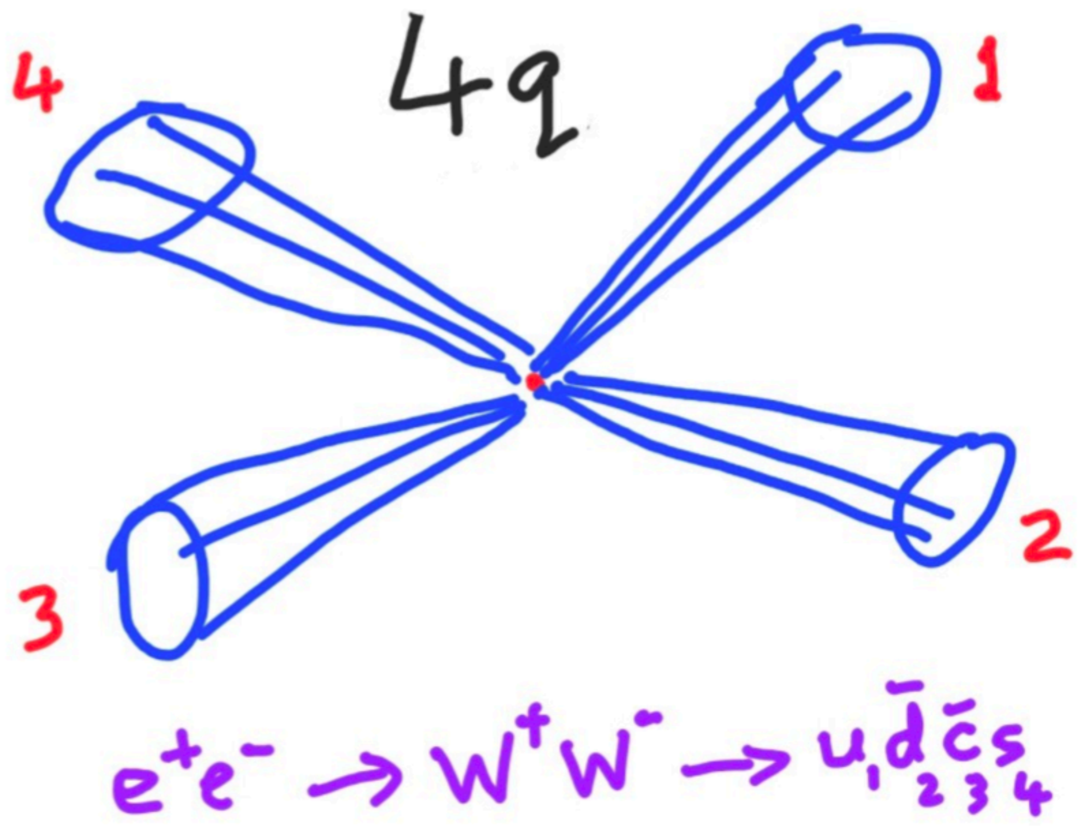
W mass extraction from hadronic and semi-leptonic decays

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

- Theory modelling harder, with systematics yet to be precisely assessed
  - Control over QED ISR
  - EFT resonant aspects near threshold
  - Backgrounds: 2f & 4f final states
  - Colour reconnection in hadronic channels

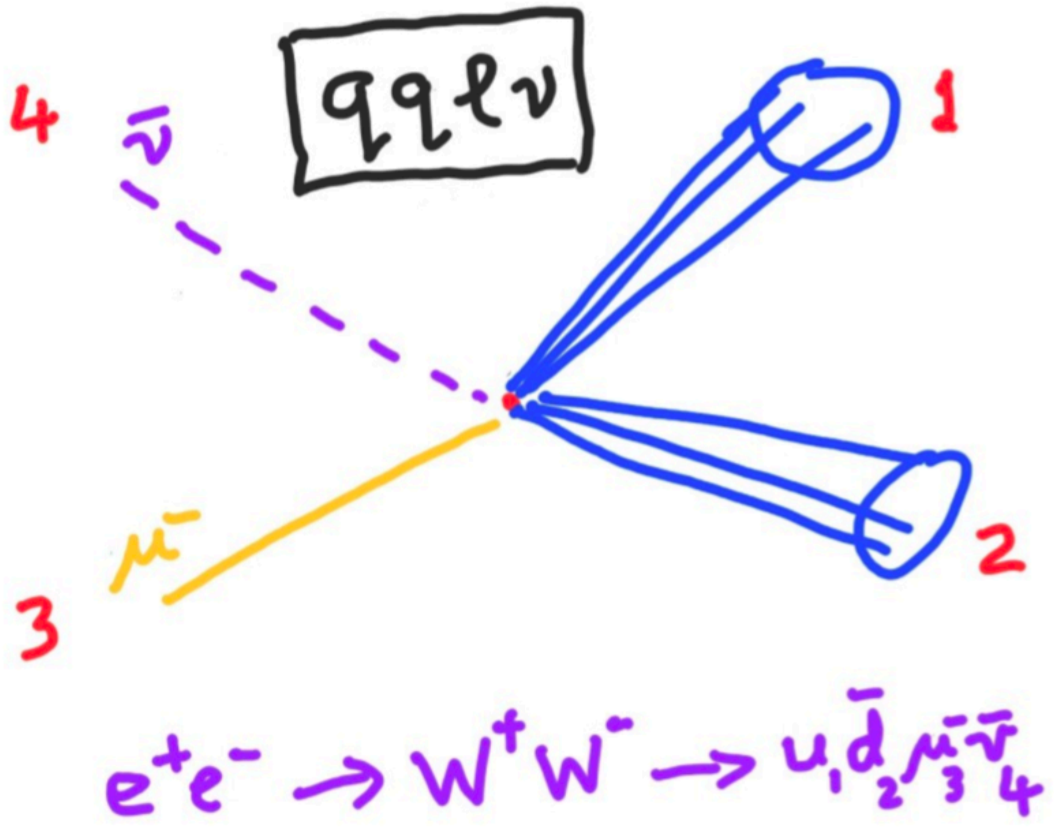
[G. Wilson's talk @ CERN FC workshop 2022]

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



$B_h^2 = 45.4\%$

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



$6B_\ell B_h = 43.9\%$

Intermezzo: QED aspects & ISR

QED collinear factorisation

- Central component in across whole FCCee programme (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; NNLL needed (hard but within reach with modern methods)
  - Implementation in fully differential PSMCs essential
  - Collinear factorisation probably insufficient in some cases (e.g. tt), simultaneous treatment of soft and collinear corrections necessary

[from S. Frixione's talk]

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

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

soft

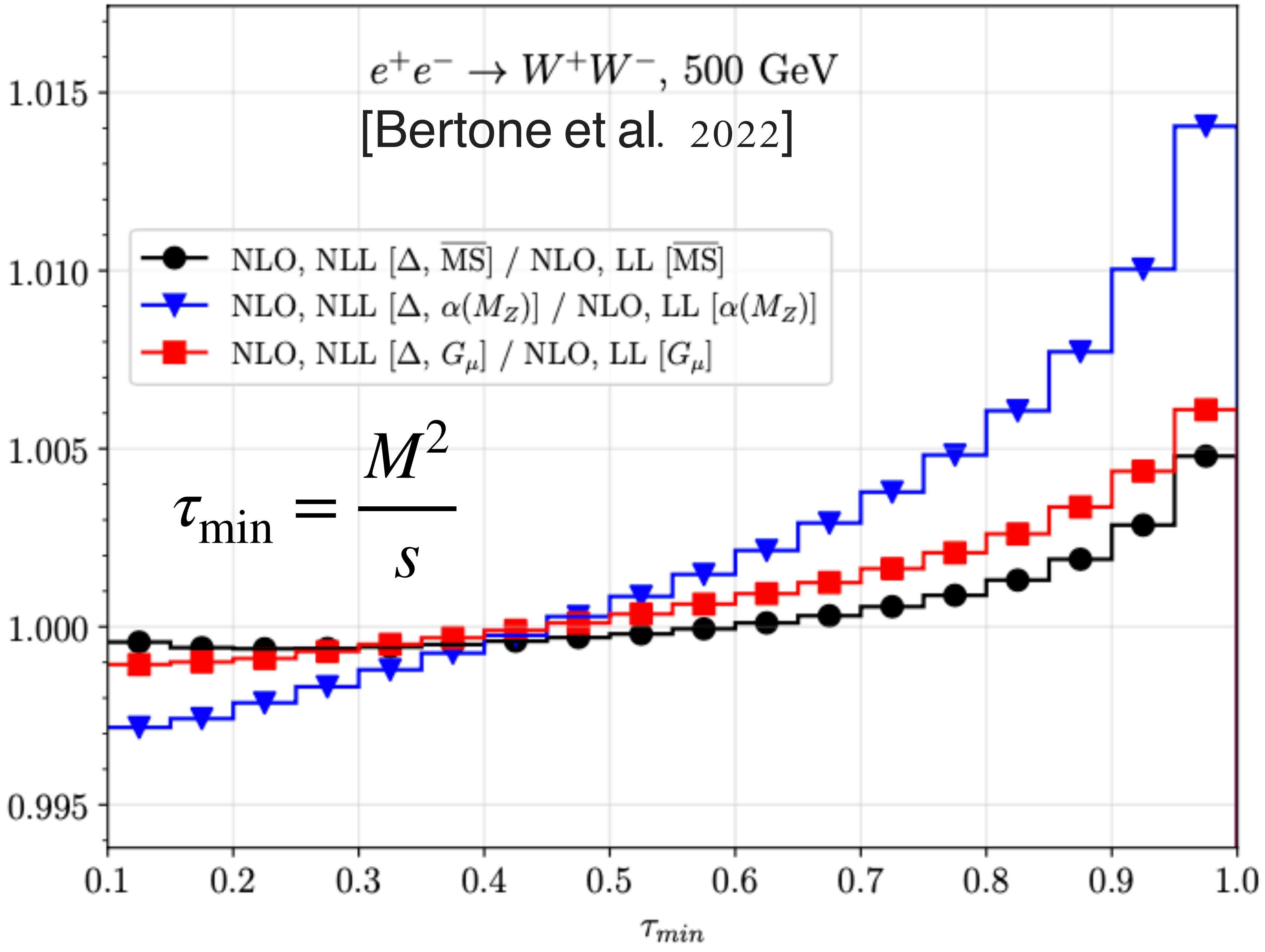
collinear

$$L = 24.59 \quad \Longrightarrow \quad \frac{\alpha}{\pi} L = 0.068$$

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

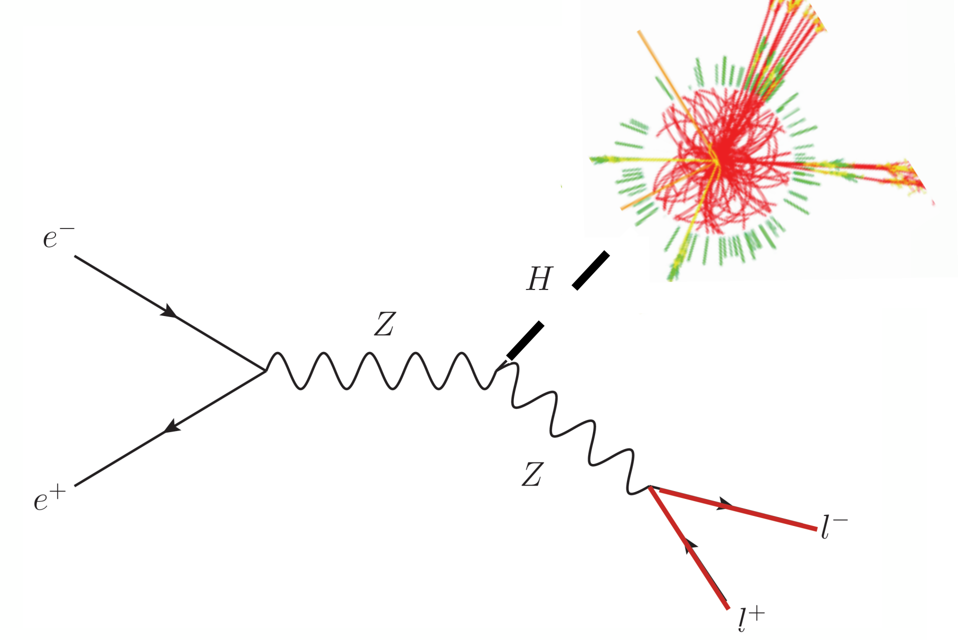
$$m_Z - 1\ \text{GeV} \leq m_{ll} \leq m_Z\,, \quad \ell = 4.51 \quad \Longrightarrow \quad \frac{\alpha}{\pi} \ell = 0.01$$

Size of NLL correction to total rates

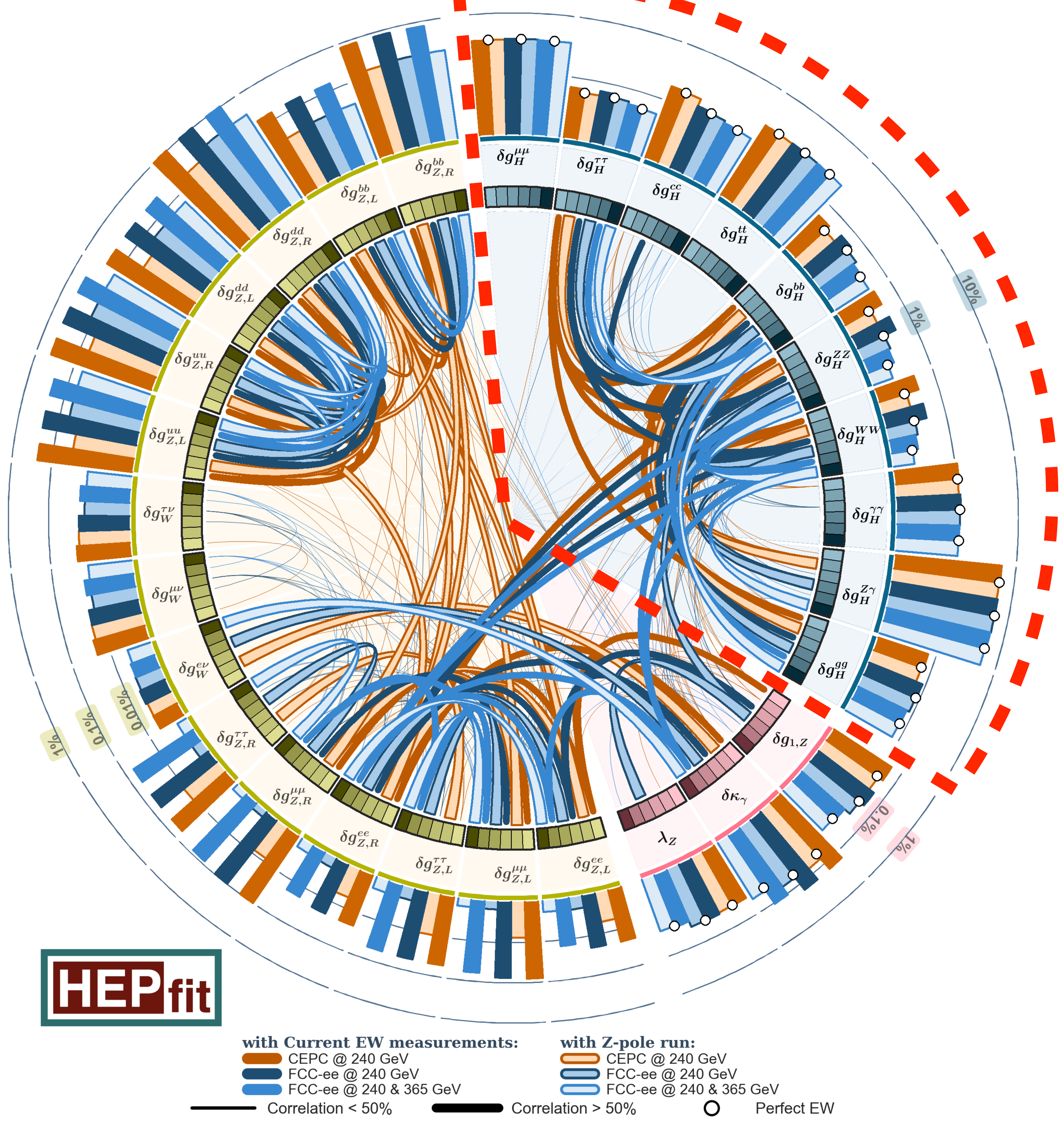


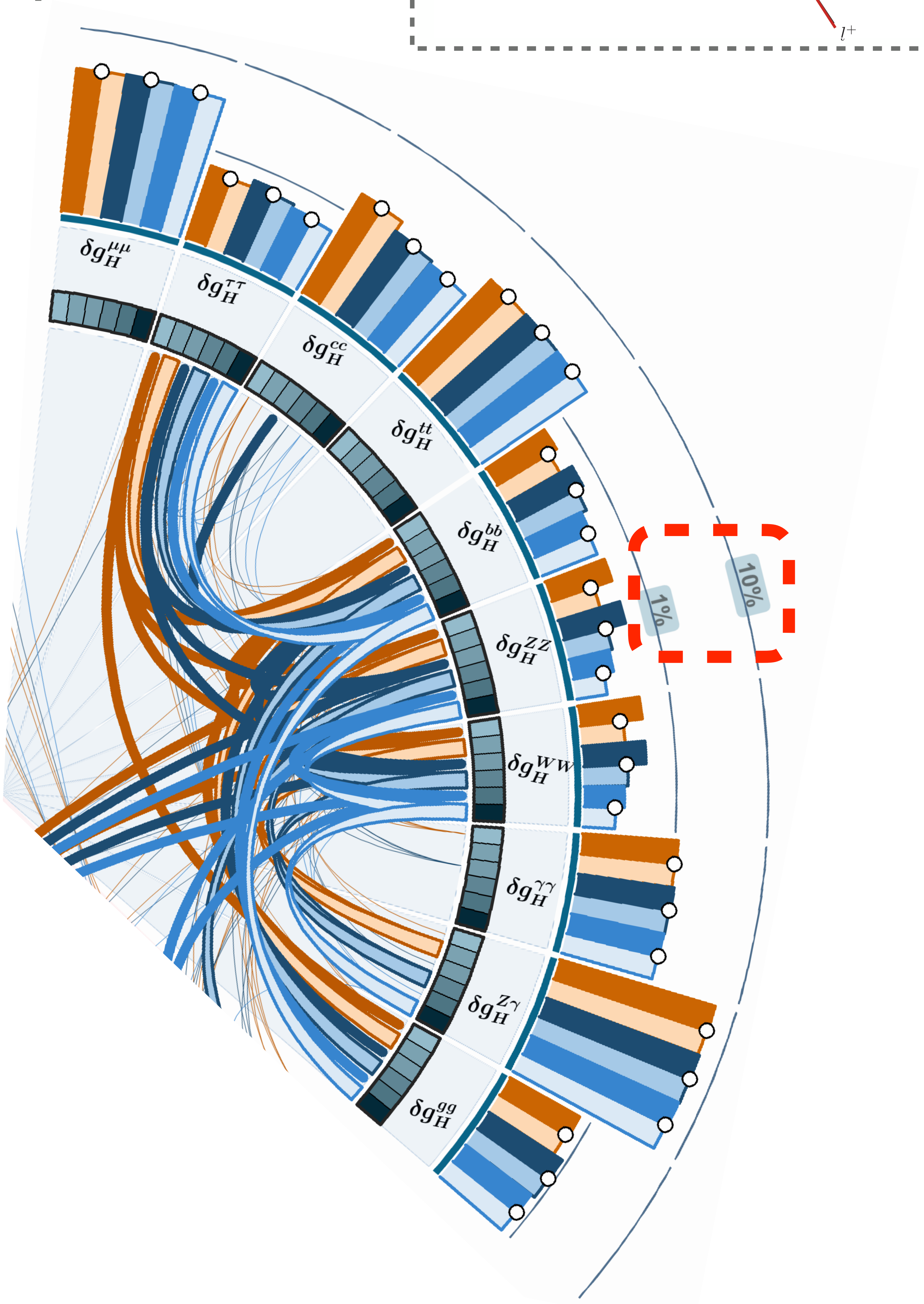
FCC-ee as a Higgs factory

Higgs at FCC-ee



- Experimental precision (approaching 0.1% level in many cases) enables precise extraction of Higgs properties





Theory challenges at the ZH threshold

- Example: total cross section will be measured with 0.2%-0.5% accuracy. Necessary TH for (EW) production:
  - $e^+e^- \to$ Z H (available), H v v (e^+e^-) @ 2 loops EW (beyond reach at the moment)

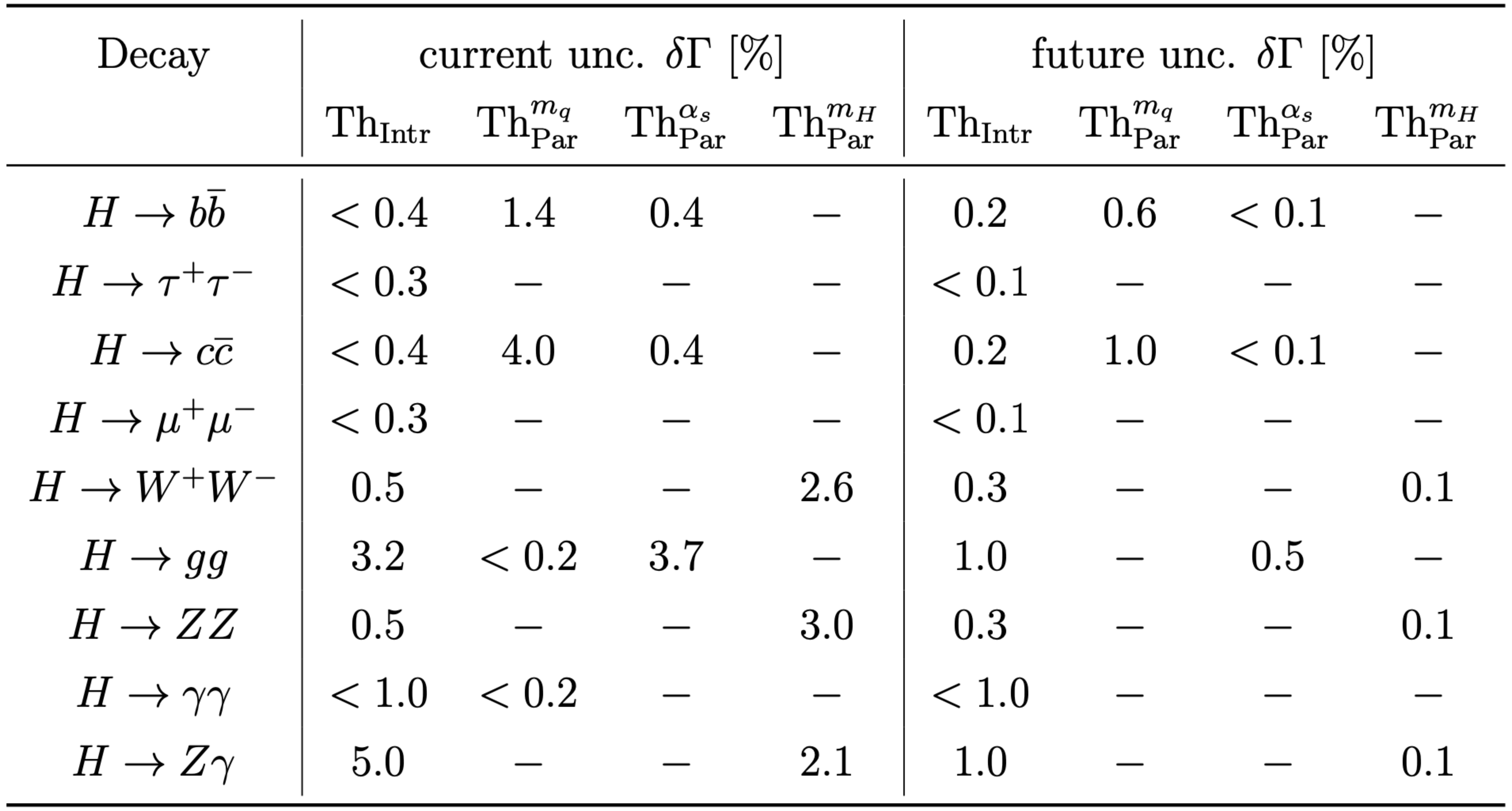
[Chen, Guan, He, Liu, Ma '22; Freitas, Song '21–'22]

  - Mixed QCD⊗EW @ 2 loops under control

[Gong et al. '17]

- Wealth of data in hadronic decays relies on QCD input

Current and future uncertainties in total Higgs decay rates



Decay	current unc. $\delta\Gamma$ [%]				future unc. $\delta\Gamma$ [%]			
	$\mathrm{Th}_{\mathrm{Intr}}$	$\mathrm{Th}^{m_q}_{\mathrm{Par}}$	$\mathrm{Th}^{\alpha_s}_{\mathrm{Par}}$	$\mathrm{Th}^{m_H}_{\mathrm{Par}}$	$\mathrm{Th}_{\mathrm{Intr}}$	$\mathrm{Th}^{m_q}_{\mathrm{Par}}$	$\mathrm{Th}^{\alpha_s}_{\mathrm{Par}}$	$\mathrm{Th}^{m_H}_{\mathrm{Par}}$
$H \to b\bar{b}$	< 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

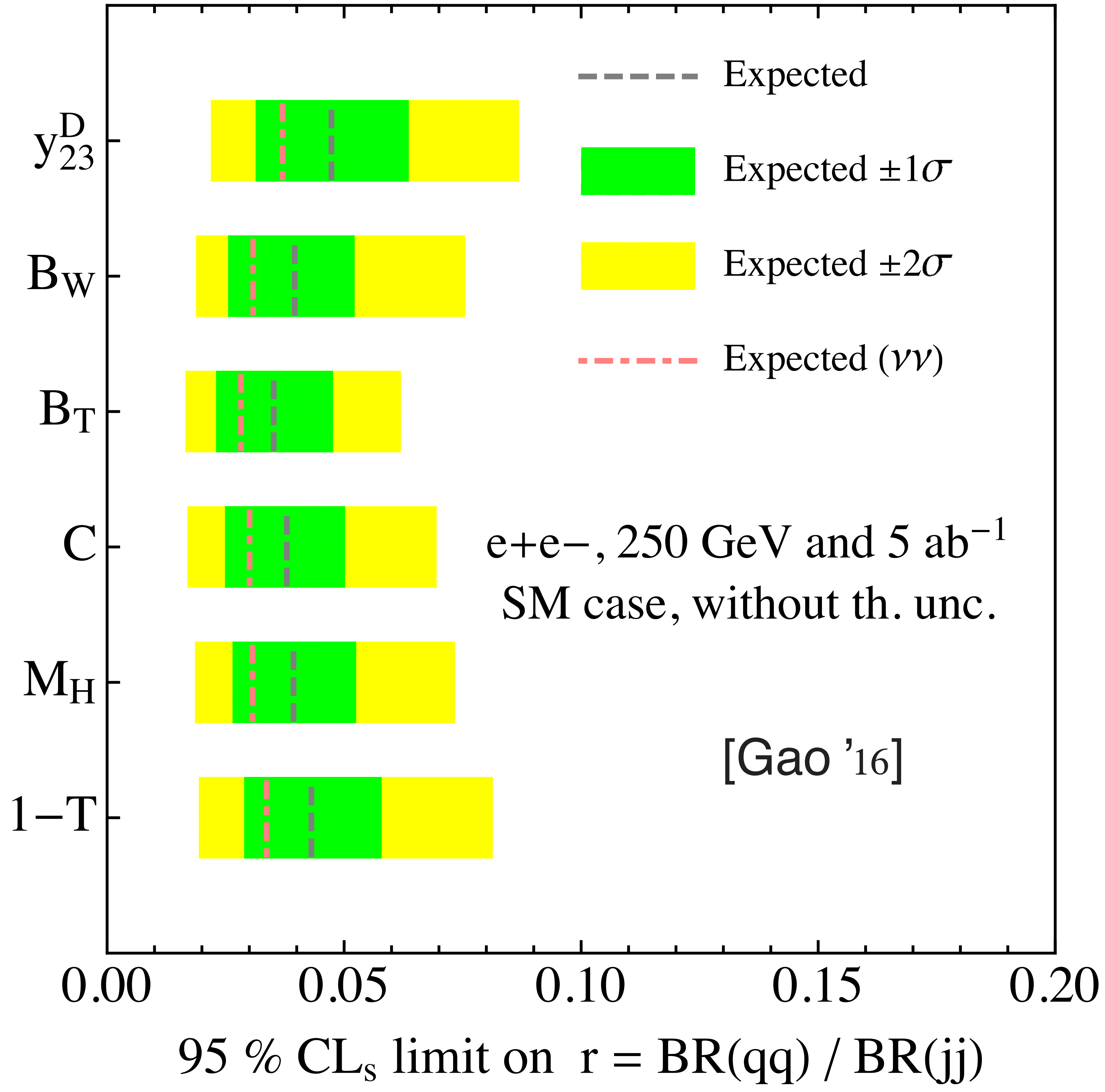
[Table from J. de Blas' talk at FCC week 2023]

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

Hadronic Higgs decays

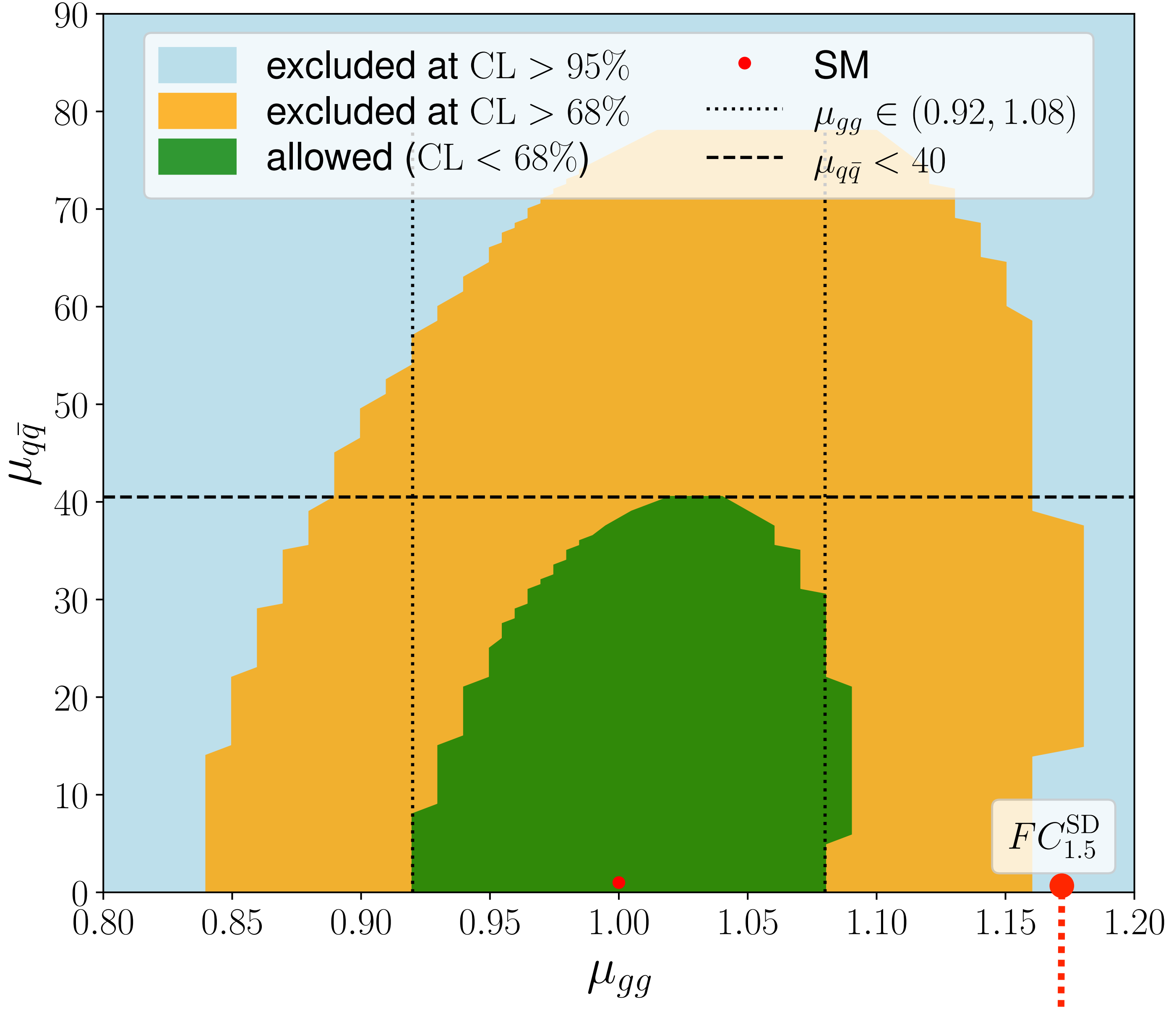
- New opportunities in differential distributions: e.g. strange (light quarks?) Yukawa/Higgs BRs from shapes
  - ➡ Standard event shapes sensitive to hadronization, likely necessary to rely on new observables or tuning from lower √s

e.g. H → qq BRs from event shapes

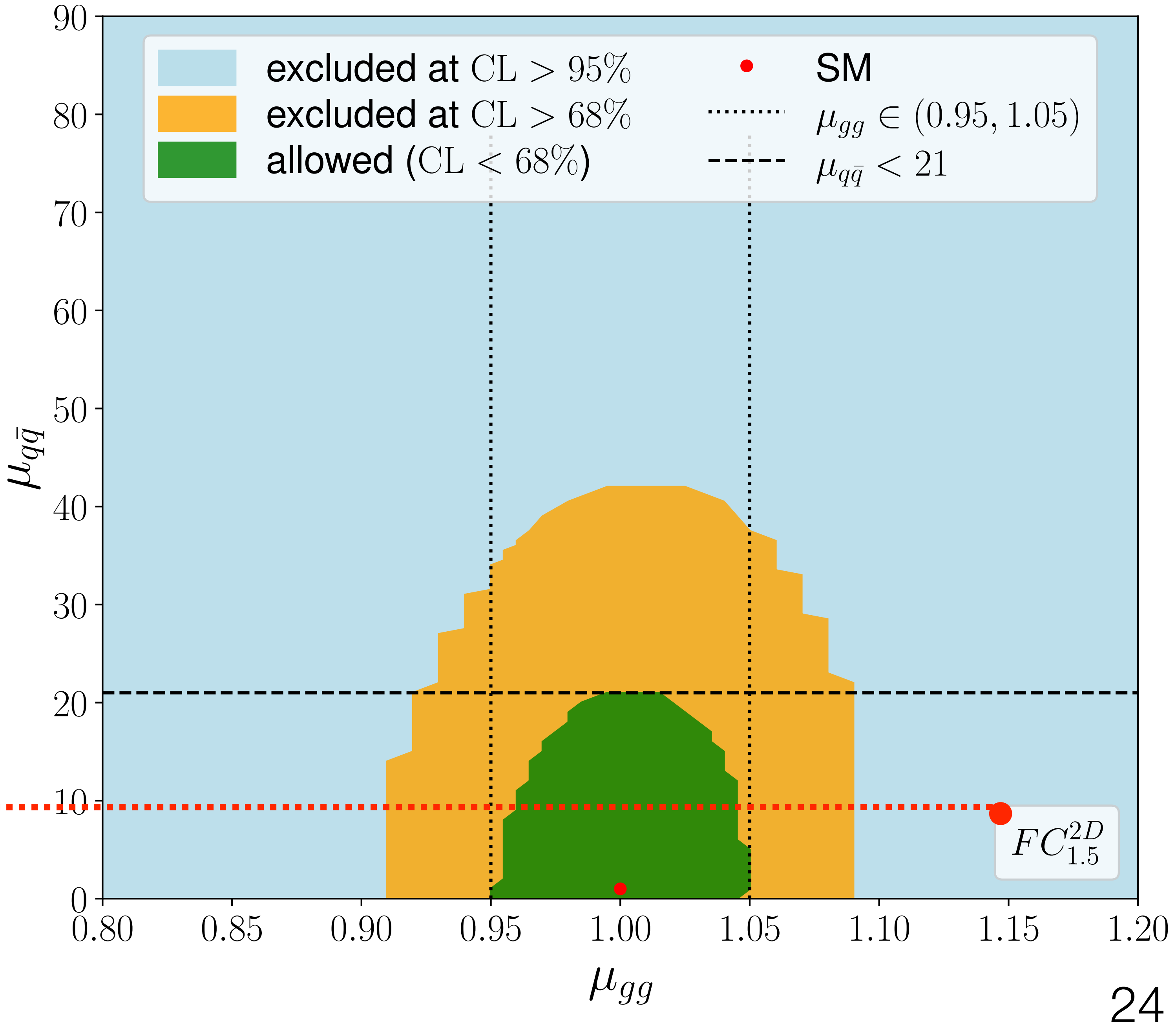


e.g. H → gg & H → qq BRs from fractional moments of EEC

[Knobbe, Krauss, Reichelt, Schumann '23]



with Soft Drop

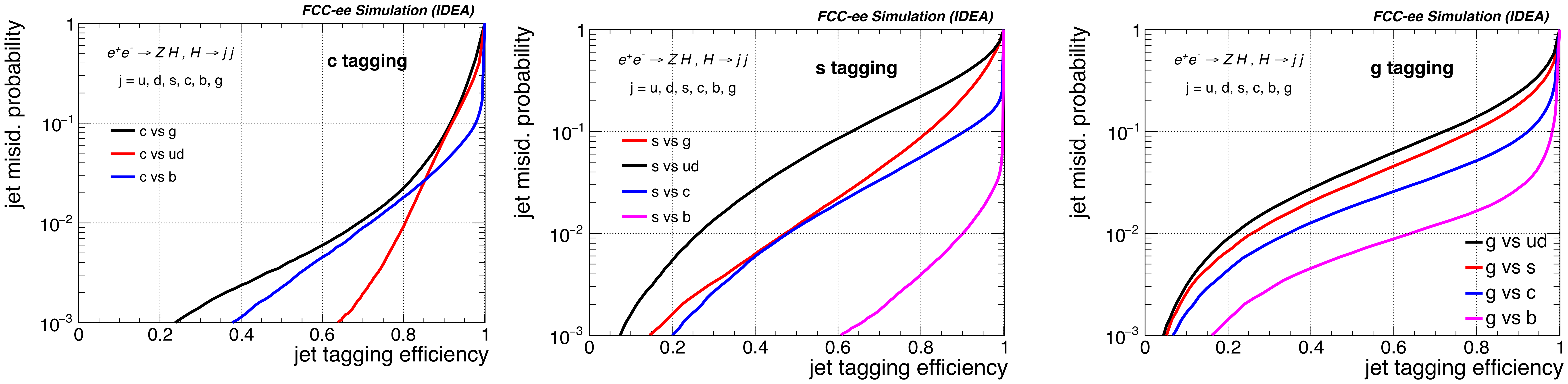


constraints from two independent hemispheres

Hadronic Higgs decays

- Much room for improvement on the QCD front
  - NNLO & resummations within reach (already available in H→bb and partly H→gg‡); N^3LO needed for few-% accuracy (~ available for 2-jet observables)
  - Very promising prospects from ML taggers to constrain Y_s (better understanding of theory uncertainties desirable)

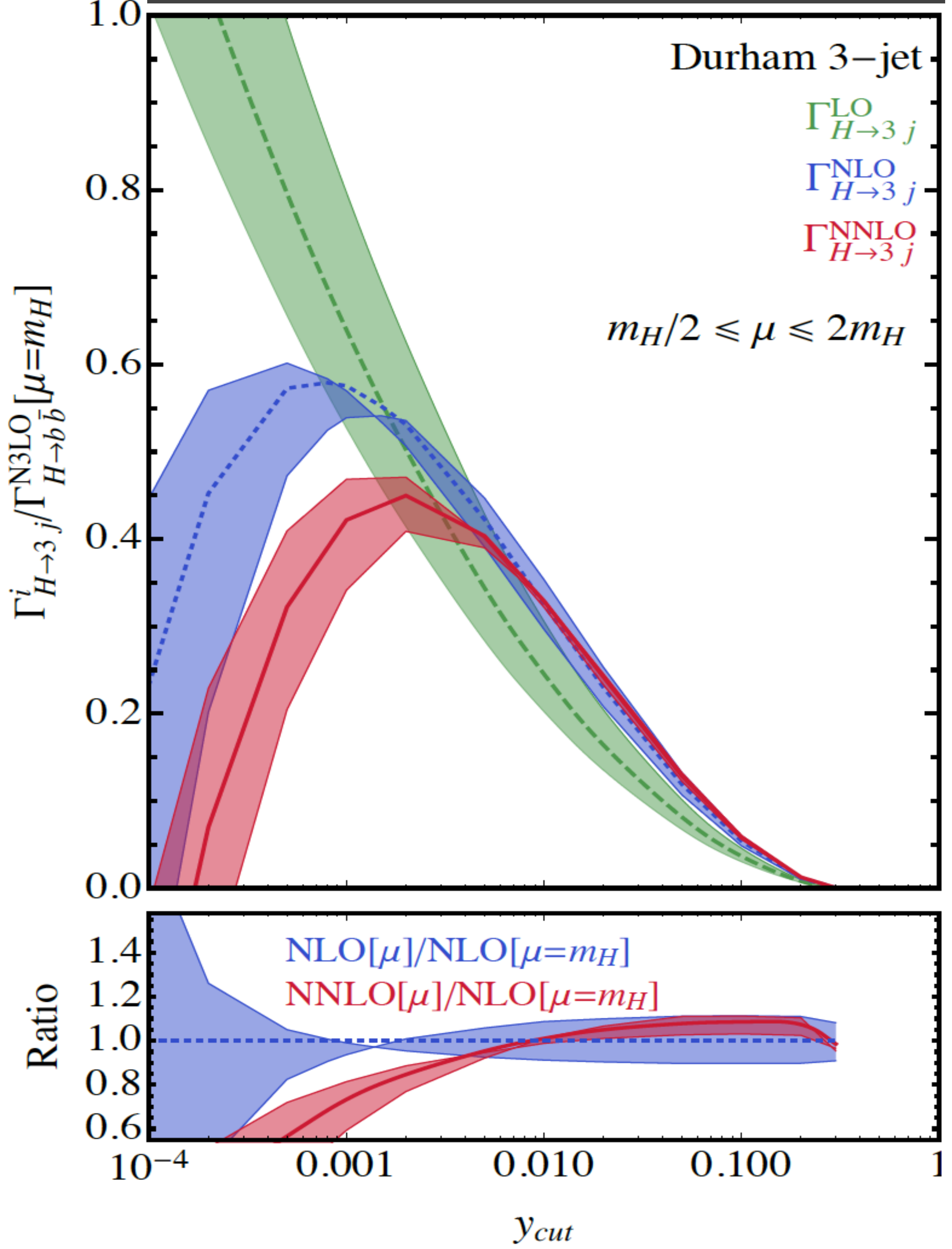
e.g. flavour tagging with graph neural networks (ParticleNet)



[Bedeschi, Gouskos, Selvaggi '22]

[Mondini, Williams '21]

e.g. jet rates in H → bb



‡ All ingredients for HO in H→gg known including quark-mass dependence

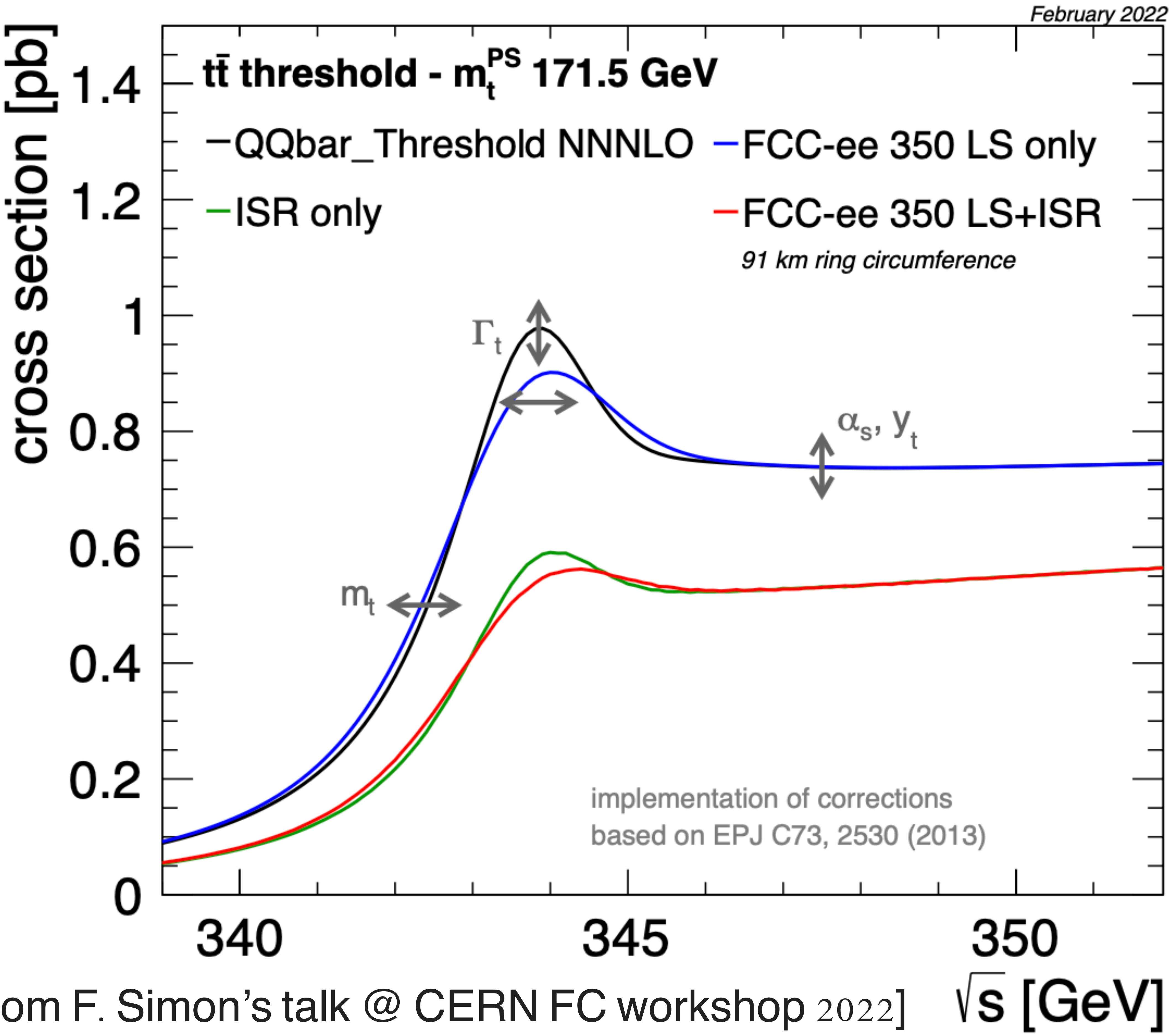
[Czakon et al. '20; Bonciani et al. '22; Melnikov, Penin '16; Liu, Penin 17–'19; Anastasiou, Penin '20; Coloretti et al '22; Chen, Jakubcik, Marcoli, Stagnitto '23; Gehrmann-De Ridder et al. '23]

tt threshold scan

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]

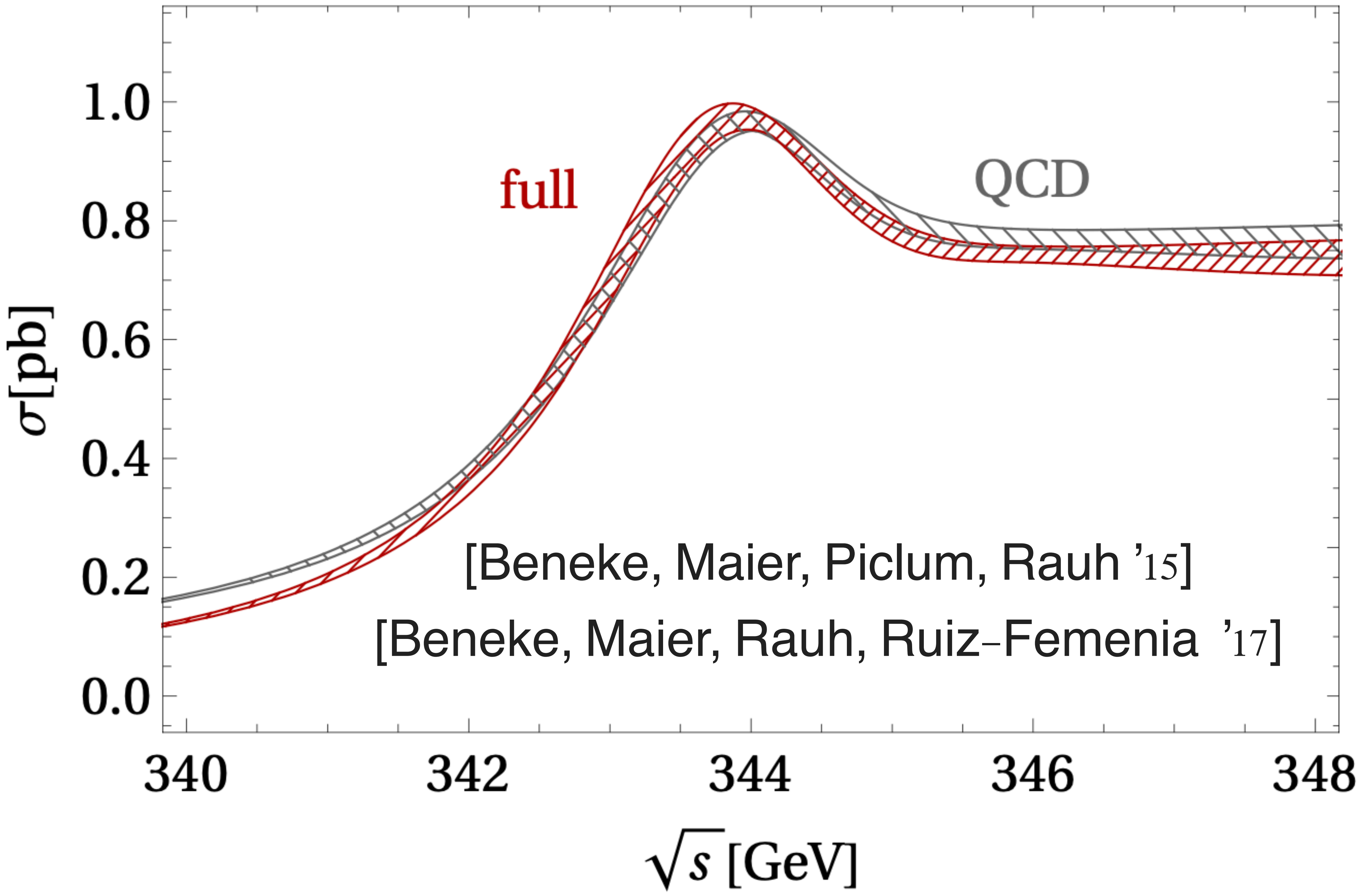
Top physics: theory for threshold scan

- PNRQCD predictions known to N^3LO (also including EW+non-resonant effects @ NNLO)

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

[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 will come from matching of N^3LO+NNLL (ingredients available)
  - Needs NLL ISR (possibly including soft modes)
  - Ultimately might require N^4LO in PNRQCD needed (currently out of reach)

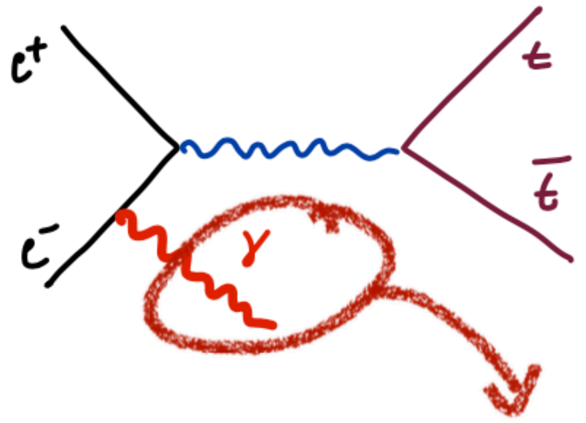


[Beneke, Maier, Piclum, Rauh ’15]

[Beneke, Maier, Rauh, Ruiz-Femenia ’17]

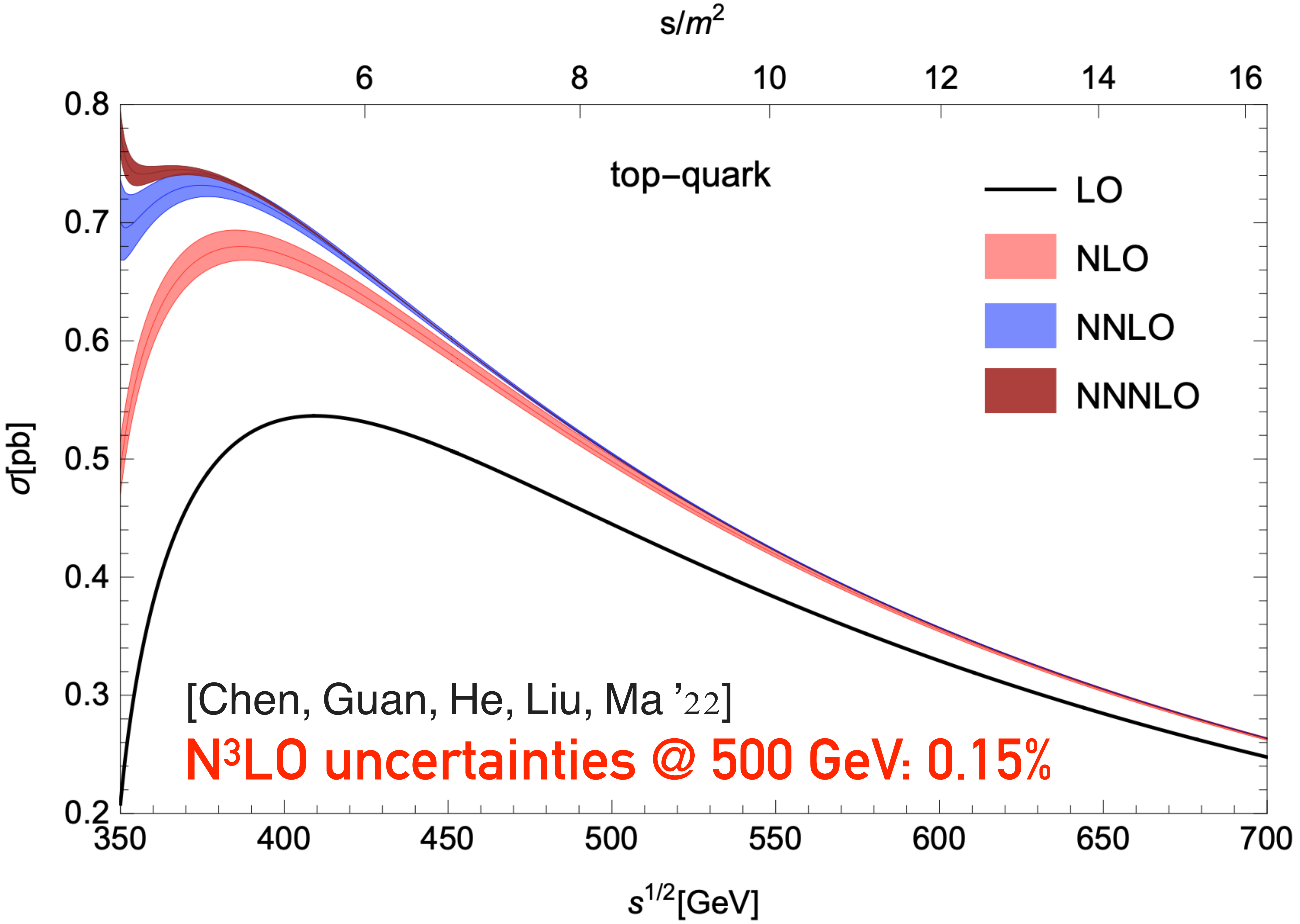
Top physics: above threshold & continuum (mainly ILC/CLIC)

- Continuum: **target is 0.1% on cross section**. N^{3}LO QCD recently calculated but NNLO EW necessary
- Top mass from radiative return from ISR photon: required matching of continuum and threshold calc^{ns}
  - 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 $[\text{fb}^{-1}]$	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



[Chen, Guan, He, Liu, Ma '22]

N^{3}LO uncertainties @ 500 GeV: 0.15%

Concluding remarks

- Astounding physics programme at FCCee, drastic reduction of experimental 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, new observables,…)

  - ➡ Many challenges are technical in nature: hard calculations, currently beyond reach but likely to become achievable with the evolution of the field in the coming decades, and substantial work

  - ➡ Also deep conceptual questions, which need significant breakthroughs to improve their understanding: e.g. non-perturbative QCD (hadronisation, CR, EFT calculations, high-order QCD+EW MCs) currently a bottleneck in several studies

  - ➡ New opportunities from data-driven approaches, crucial to think of how to exploit it for modelling aspects and theory uncertainties (e.g. heavy flavour & gluon fragmentation, hadronisation modelling, …)

  - ➡ Huge step forward demanded for MCs (QCD/EW, ISR, HO for jet processes, NR QCD, resonances)