(Some) QCD aspects of FCC-ee

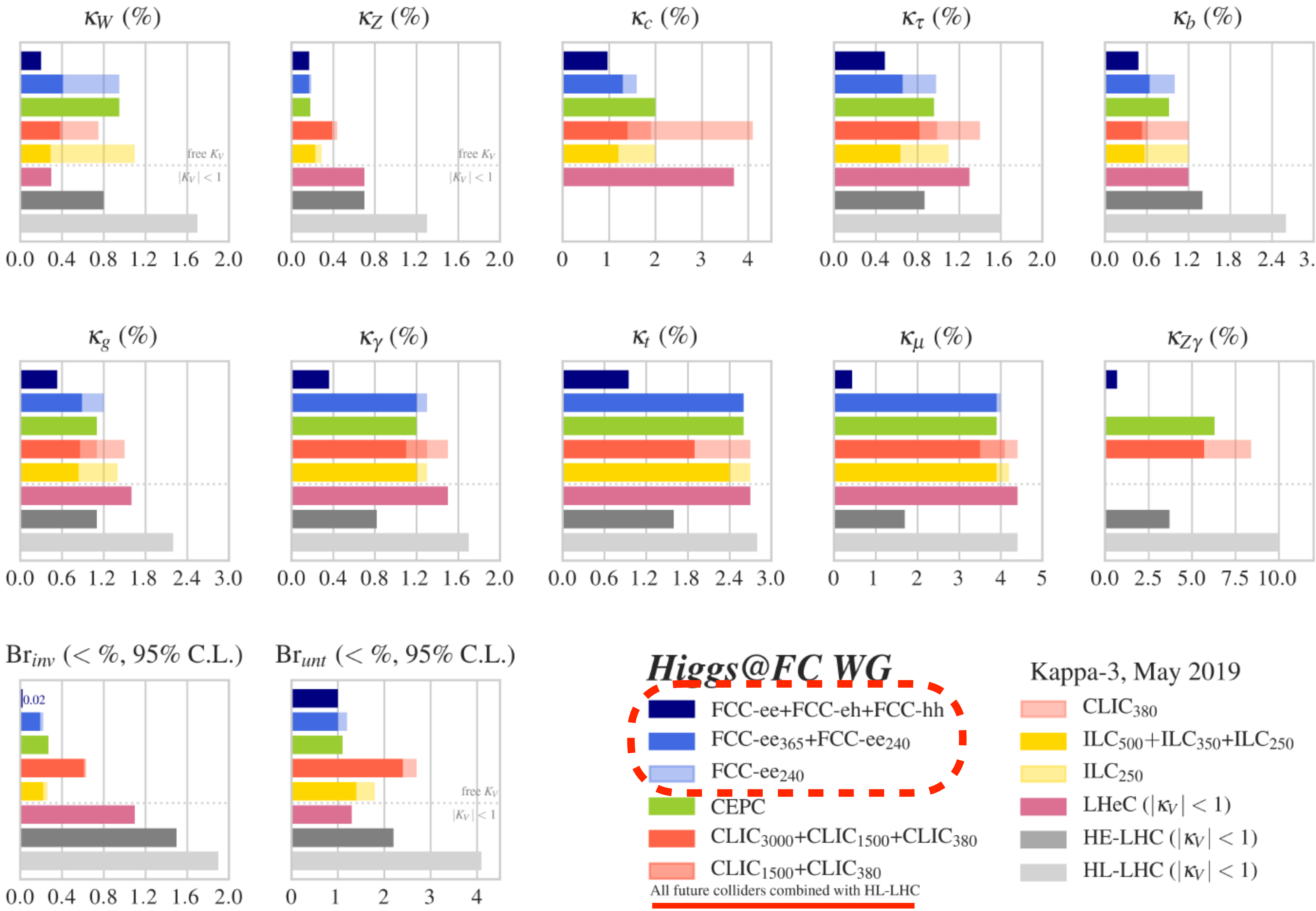
Pier Francesco Monni
CERN

3rd FCC Physics and Experiments Workshop - CERN, Jan 2020

FUTURE COLLIDERS: e.g. HIGGS

[de Blas et al. (1905.03764)]

Rich programme & extreme precision. High complementarity with HL-LHC



PRECISION THEORY

- **Technically non-trivial to reach desired precision in calculations [QCD $\oplus$ EW]: attractive challenge for TH in the coming decades**

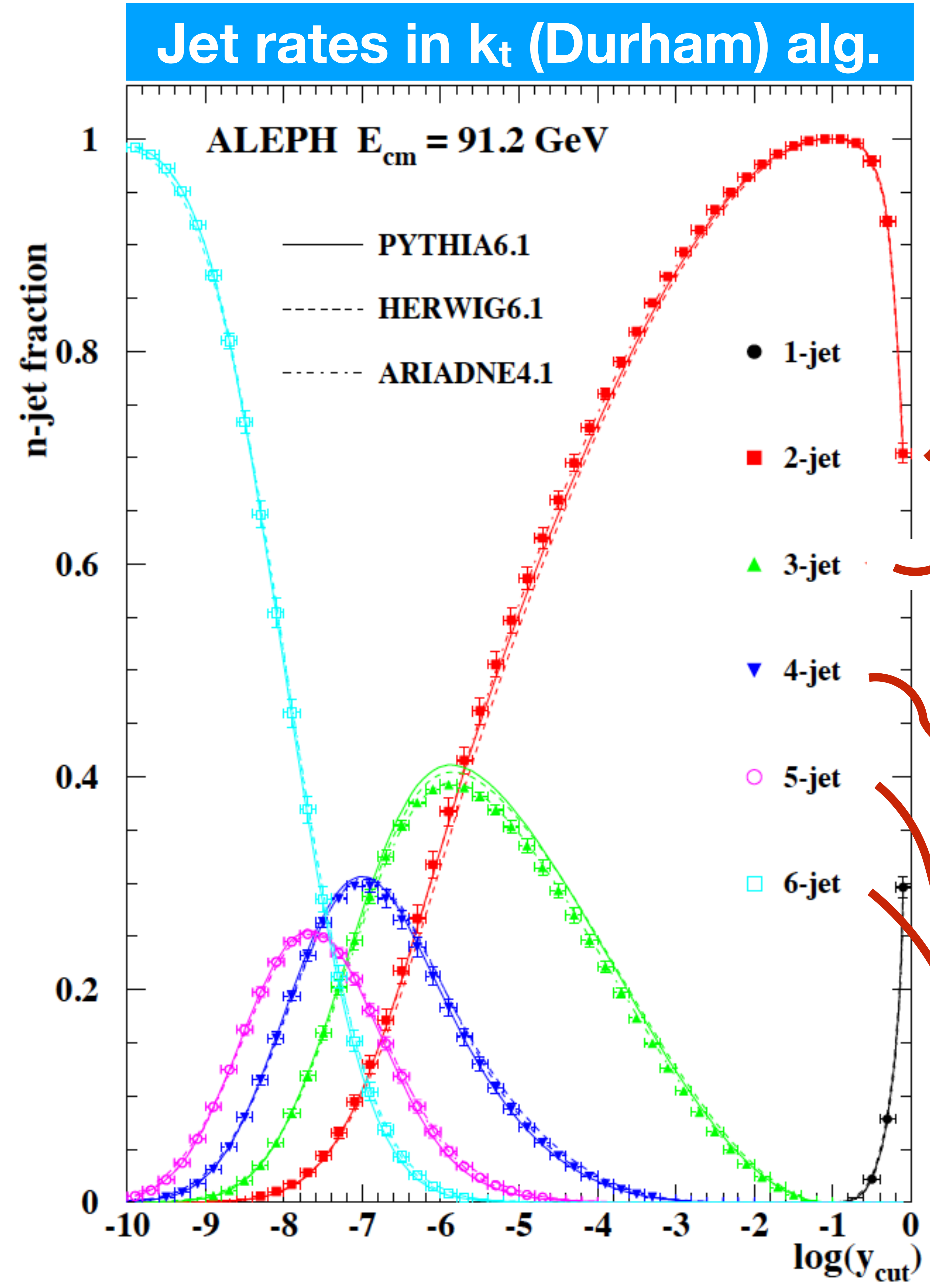
- **Extremely clean collider environment to *explore* certain aspects of the theory**

- **Crucial to *fully exploit* our TH knowledge to create new experimental opportunities (LHC docet)**

JET OBSERVABLES

- Final state hadronic observables (e.g. jet rates, event/jet shapes, …) are powerful probes of QCD dynamics from high to low energy scales
  - In a e^+e^- environment, perturbation theory allows for accurate predictions down to hadronic scales
  - Shape info (+ in some cases, q/g jet discrimination) allows one to disentangle final states with different multiplicity e.g.
    - e+e- → Z/γ* → qq +X: probe of coherent QCD dynamics & α_S fits
    - e+e- → WW / ZZ / ZH → 4 q + X: study of EW / Higgs couplings
    - e+e- → ZH → 6 q + X: study of HWW / HZZ couplings
    - …

e+e- → Z/γ* → jets: FIXED ORDER QCD



$N^3LO: 1 + \alpha_s + \alpha_s^2 + \alpha_s^3$

[Gorishnii, Kataev, Larin '91] +
[Gehrmann - De Ridder, Gehrmann, Glover, Heinrich '08] [Weinzierl '09]
[Del Duca, Duhr, Kardos, Somogyi, Szor, Trocsanyi, Tullipant '16]

$NNLO: \alpha_s + \alpha_s^2 + \alpha_s^3$

[Gehrmann - De Ridder, Gehrmann, Glover, Heinrich '08]
[Weinzierl '09]
[Del Duca, Duhr, Kardos, Somogyi, Szor, Trocsanyi, Tullipant '16]

Heavy-Quark mass effects known to NLO

[Nason, Oleari '98] [Brandenburg, Bernreuther, Uwer '97]

$NLO: \alpha_s^2 + \alpha_s^3$

[Nagy, Trocsanyi '99; Kosower, Weinzierl '99; Campbell, Cullen, Glover '99]

$NLO: \alpha_s^3 + \alpha_s^4$

[Frederix, Frixione, Melnikov, Zanderighi '10]

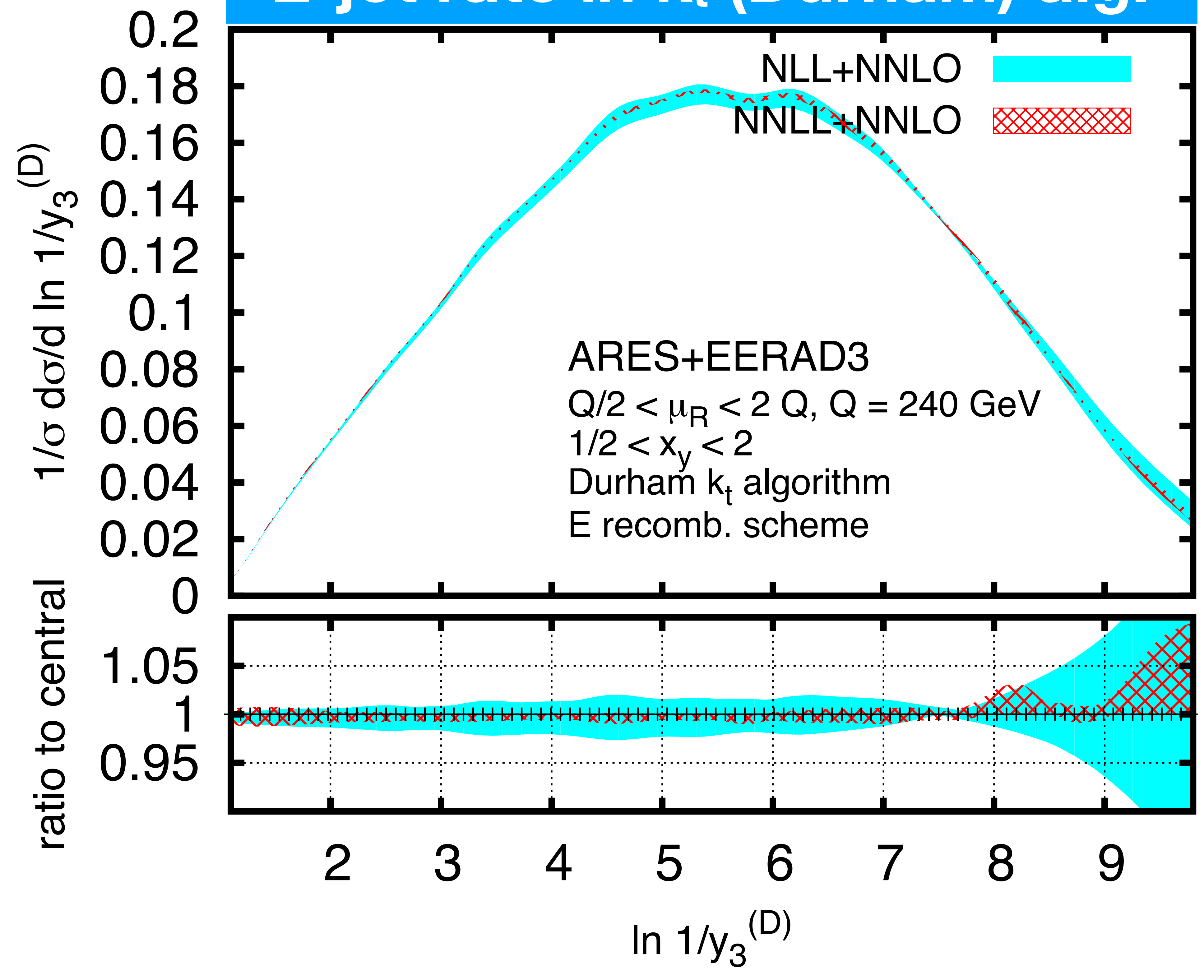
NLO for 6 & 7 jets (leading colour)

[Becker, Goetz, Reuschle, Schwan, Weinzierl '12]

e+e- → Z/γ* → jets: ALL ORDERS QCD

- Resummation for 2-jet *global* observables very well understood:
  - SCET provides a flexible tool for factorising observables (e.g. thrust @ N^3LL)
    [Becher, Schwartz ’08]
  - Numerical resummation for observables w/o a factorising measurement function (e.g. jet rates)
- Recent progress in the description of 3-jet *global* observables; **crucial to access gluon fragmentation**
  [D-param. @ NNLL: Arpino, Banfi, El-Menoufi ’19]
  [3-point EEC: Chen, Luo, Moult, Yang, Zhang, Zhu ’19]
- First steps towards formal understanding of *non-global* corrections beyond first order
  [Dasgupta, Salam ’01; Banfi, Marchesini, Smye ’02]
  [Caron-Huot ’15; Becher, Neubert, Shao et al. ’15-’19]

2-jet rate in k_t (Durham) alg.



[Banfi, McAslan, PM, Zanderighi ’16]

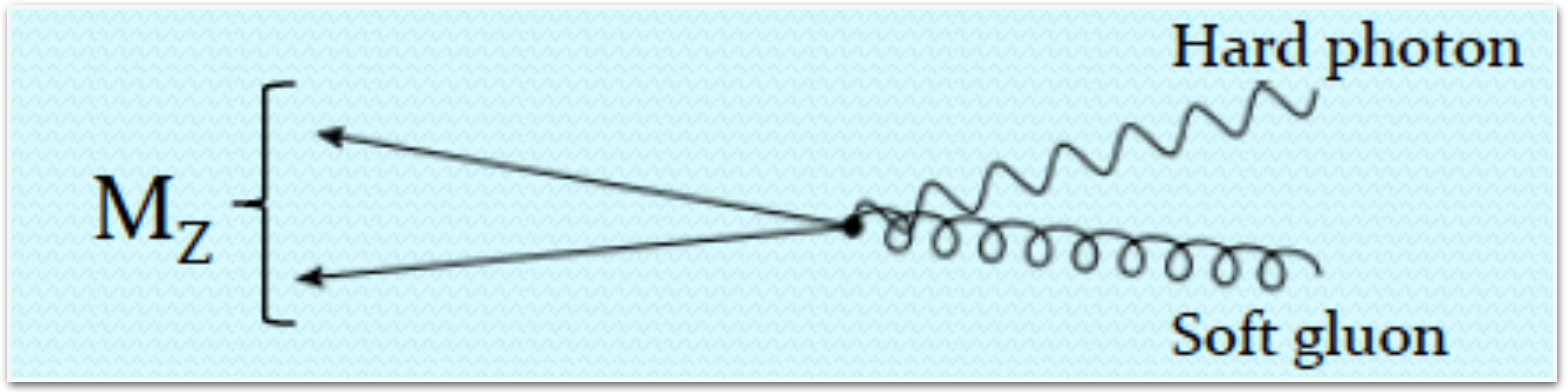
e+e- → Z/γ* → jets: EW CORRECTIONS

- NLO EW known for e+e- → Z/γ* → 3 jets:

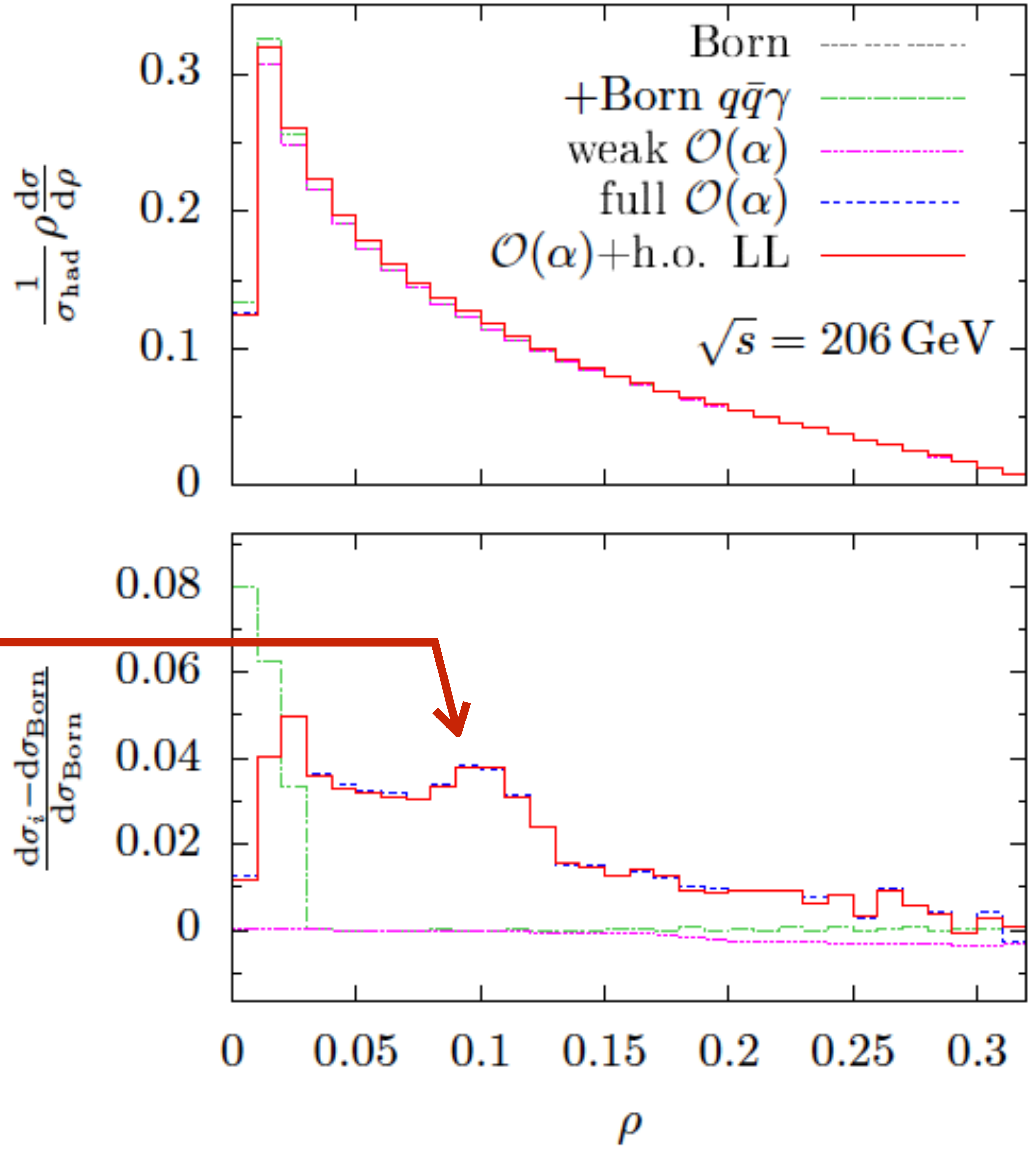
[Denner, Dittmaier, Gehrmann, Kurz ’10]

  - Weak corr. negligible, sizeable effects from photon radiation [mitigated by isolation]

  - Radiative return (Z peak) still moderately visible at high energies, shifting towards the IR region [accurate QED necessary at FCC-ee]



e.g. heavy-jet mass



STRONG COUPLING CONSTANT

- **World average 2019:**

$$\alpha_s(M_Z^2) = 0.1179 \pm 0.0010$$

- **Substantial tension among existing extractions (e.g. C-par. vs. ⟨lattice⟩)**

- **Compelling evidence that main source of discrepancy may be hadronisation dynamics**

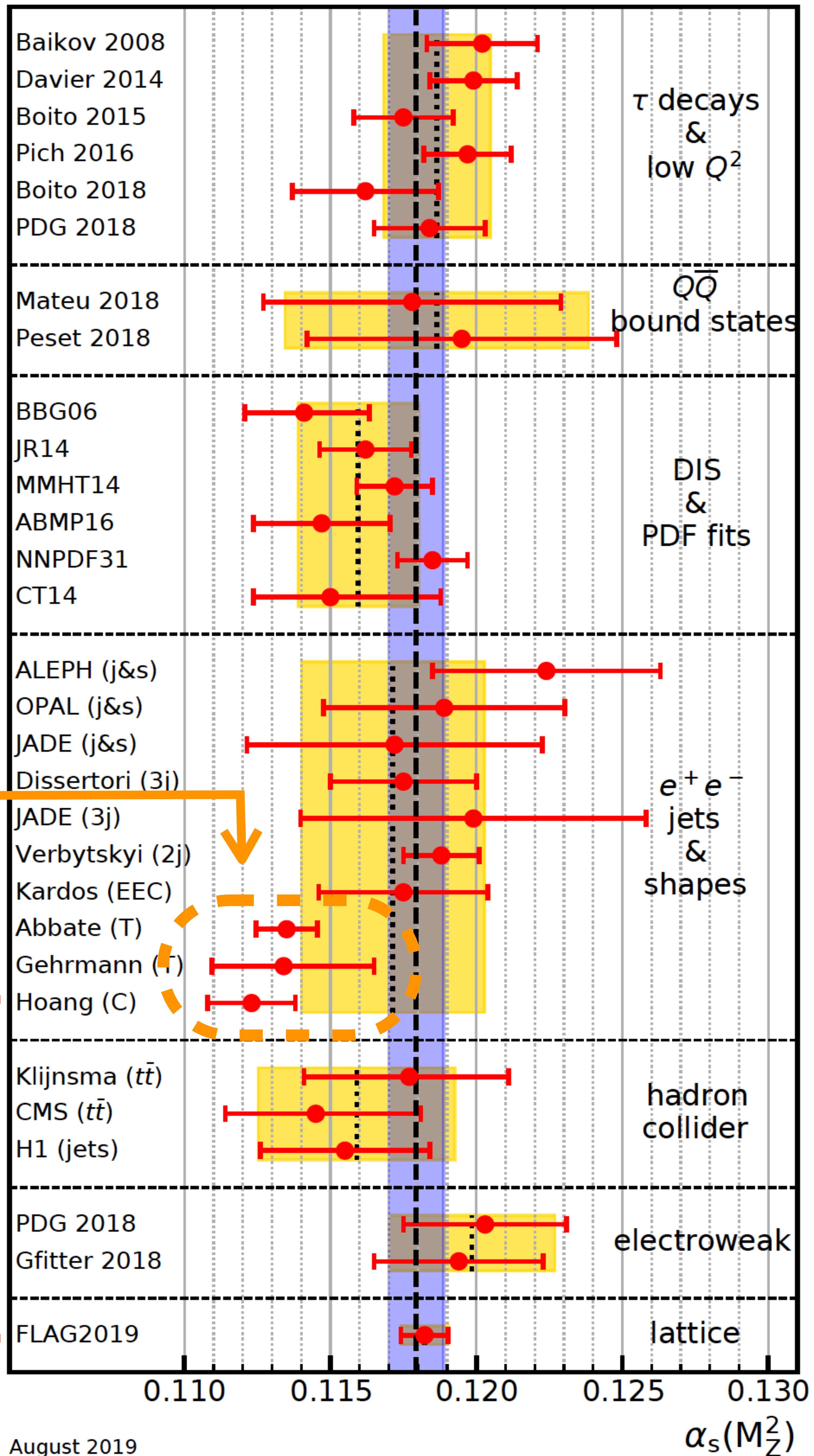
Analytic hadronisation models lead to smaller couplings in e+e- fits

$$\alpha_s(M_Z^2) = 0.1123 \pm 0.0015$$

~ 3.5 σ

$$\alpha_s(M_Z^2) = 0.1182 \pm 0.0008$$

PDG 2019 - online update



HADRONISATION: ANALYTIC vs. MC ?

- An important difference between e^+e^- fits is the modelling of non-perturbative corrections. Two options available:

- **Extract correction from Monte Carlo generators**, e.g.
  - Build bin-by-bin hadron/parton level migration matrix for an observable $\mathcal{O}$

$$\mathcal{M}_{ij}(d\sigma_{\mathrm{MC}}^{\mathrm{parton}}(\mathcal{O}) \to d\sigma_{\mathrm{MC}}^{\mathrm{hadron}}(\mathcal{O})), \qquad \text{total XS unchanged}$$

[Kardos et al. ‘19]
[Verbytskyi et al. ‘19]

  - Fold it with the higher-order perturbative calculation

☑ **PROS:**
accurate description of event kinematics

☒ **CONS:**
tuning of hadr. models performed with lower-accuracy MC generators

HADRONISATION: ANALYTIC vs. MC ?

- An important difference between e^+e^- fits is the modelling of non-perturbative corrections. Two options available:

- **Estimate leading $1/Q^p$ correction from analytic models and fit to data**, i.e.

Extract from data

$$d\sigma_{\mathrm{MC}}^{\mathrm{hadron}}(\mathcal{O}) \simeq d\sigma_{\mathrm{MC}}^{\mathrm{parton}}\left(\mathcal{O} - \frac{\alpha_0}{Q}\Delta(\mathcal{O})\right)$$

observable dependent & calculable in PT

☑ **PROS:**
usable with state of the art perturbative calculations

☒ **CONS:**
shift assumed to be constant, observable dependence poorly described

$$\text{i.e. } \Delta(\mathcal{O}) = \text{constant}^{*}$$

* **At least for thrust and C-parameter**

AN EXAMPLE: C PARAMETER

$$C = 3 - \frac{3}{2}\sum_{i,j}\frac{(p_i \cdot p_j)^2}{(p_i \cdot Q)(p_j \cdot Q)}$$

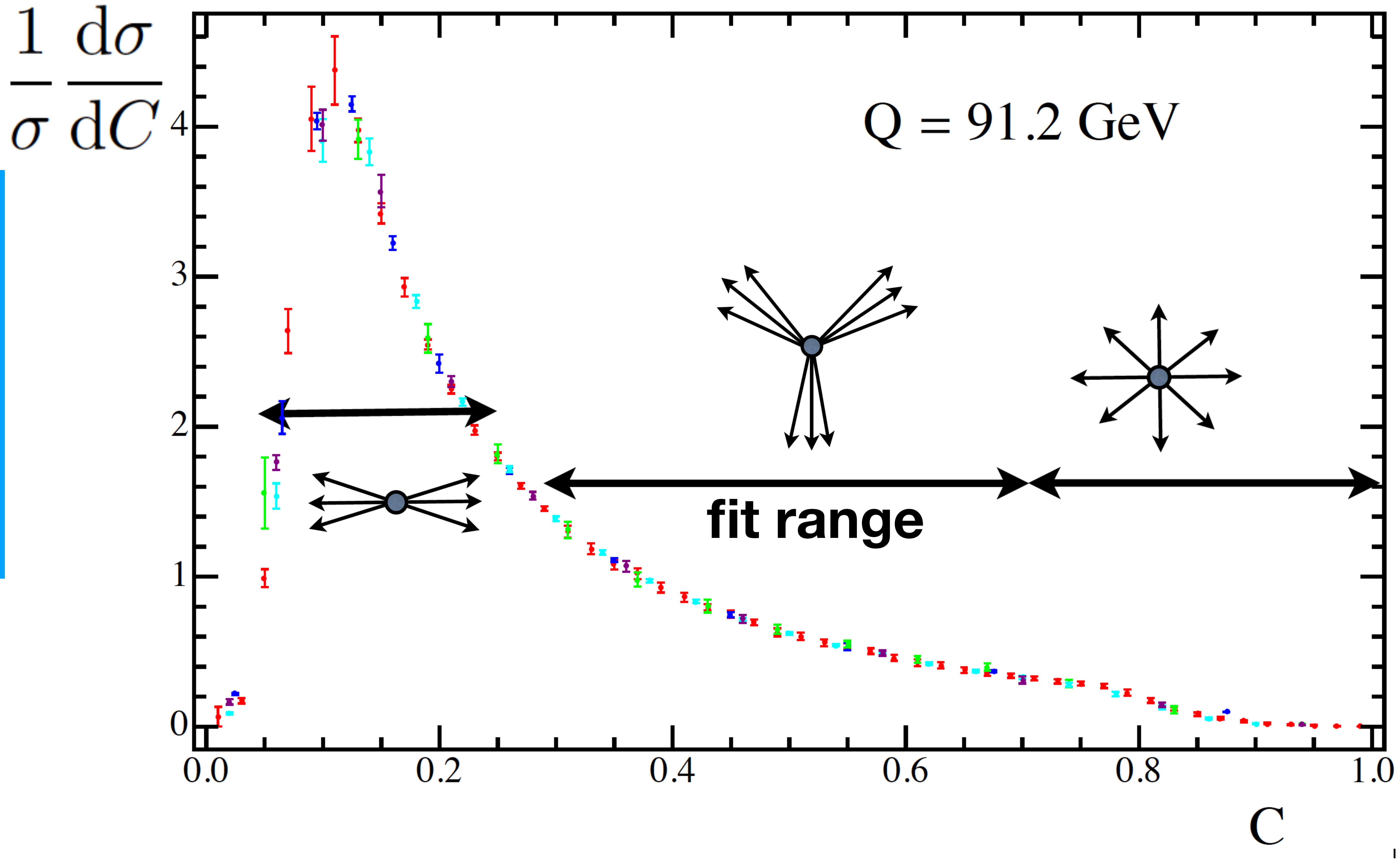
- Analytic power correction coefficient calculated in the 2-jet limit
- Fit of the coupling performed in the 3-jet regime (contribution from gluon jet substantial)

Fit performed with state of the art PT (N³LL+NNLO) returns a low value for the coupling, with small error

$$\alpha_s(M_Z^2) = 0.1123 \pm 0.0015$$

[Hoang, Kolodrubetz, Mateu, Stewart '15]

[Plot by V. Mateu]



AN EXAMPLE: C PARAMETER

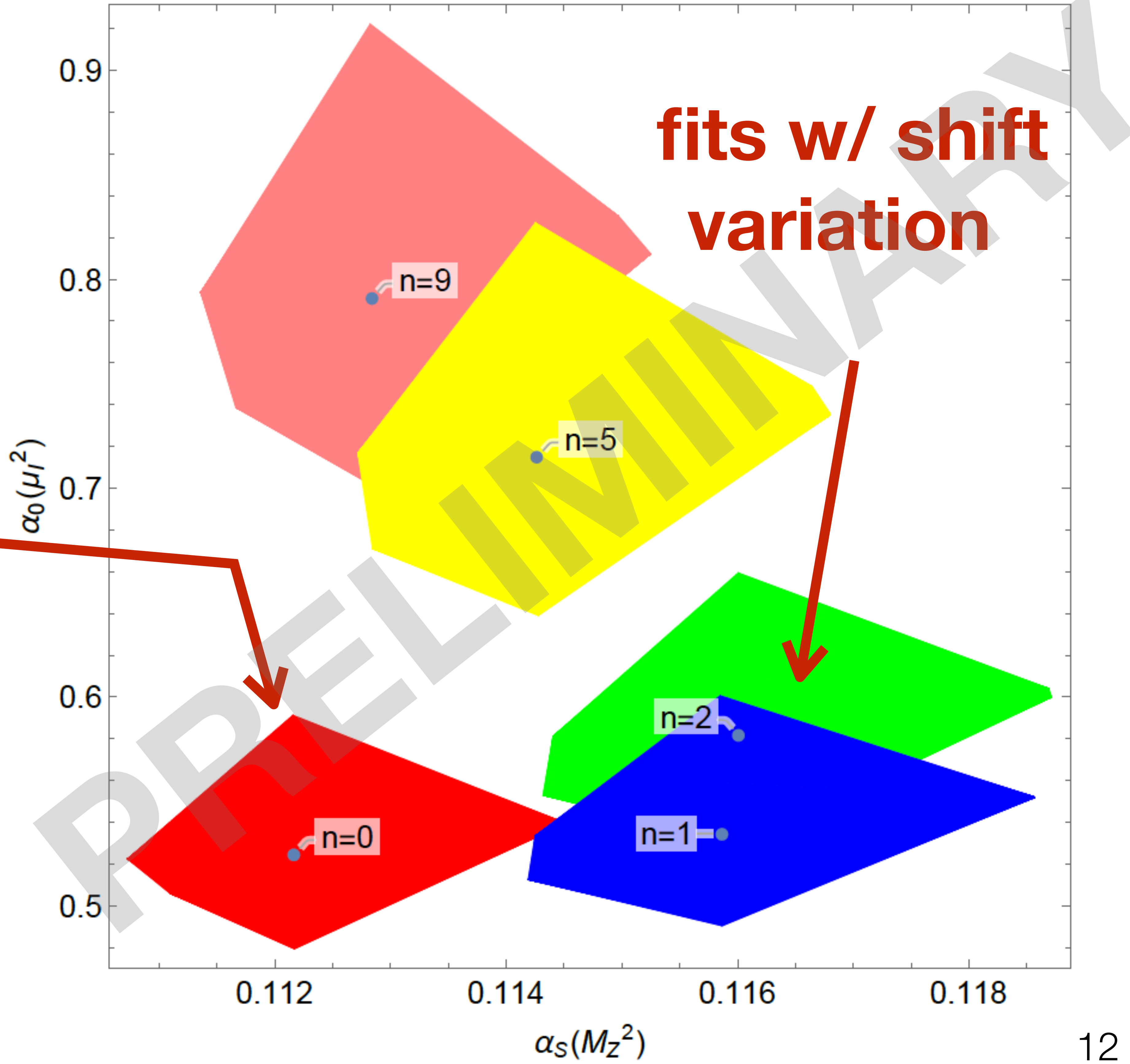
$$d\sigma_{\rm MC}^{\rm hadron}(\mathcal{O}) \simeq d\sigma_{\rm MC}^{\rm parton}(\mathcal{O} - \frac{\alpha_0}{Q}\Delta(\mathcal{O}))$$

- **Analytic power correction coefficient calculated in the 2-jet limit**
- **Fit of the coupling performed in the 3-jet regime (contribution from gluon jet substantial)**
  - **[NEW] direct calculation of leading power correction in the 3-jet symmetric limit reveals that $\Delta(\mathcal{O})$ is not constant & hadronisation is overestimated in the fit region**

$$\Delta_{3-\rm jet}^{\rm symm.}(\mathcal{O}) \lesssim \frac{\Delta_{2-\rm jet}(\mathcal{O})}{2}$$

[Luisoni, PM, Salam (in preparation)]

Impact on α_s fits



Variation of non-perturbative shift impacts α_s fits by 3%-4% (becomes compatible with WA)

HADRONISATION AT FCC-ee

- A precise control of distributions requires a better modelling of hadronisation
- FCC-ee can be instrumental in this task [a lot of TH work required - much in common with HL-LHC and other future colliders]

  - Collect data (e.g. event shapes) in IR regimes where factorisation theorems apply & perform full fits of non-perturbative models (e.g. soft factors)

    - exploit known universality across observables to constrain models with data

  - Tune complete hadronisation models with more accurate Monte Carlo (e.g. NNLL+N(N)LO) - exploit data collected at different c.o.m. energies

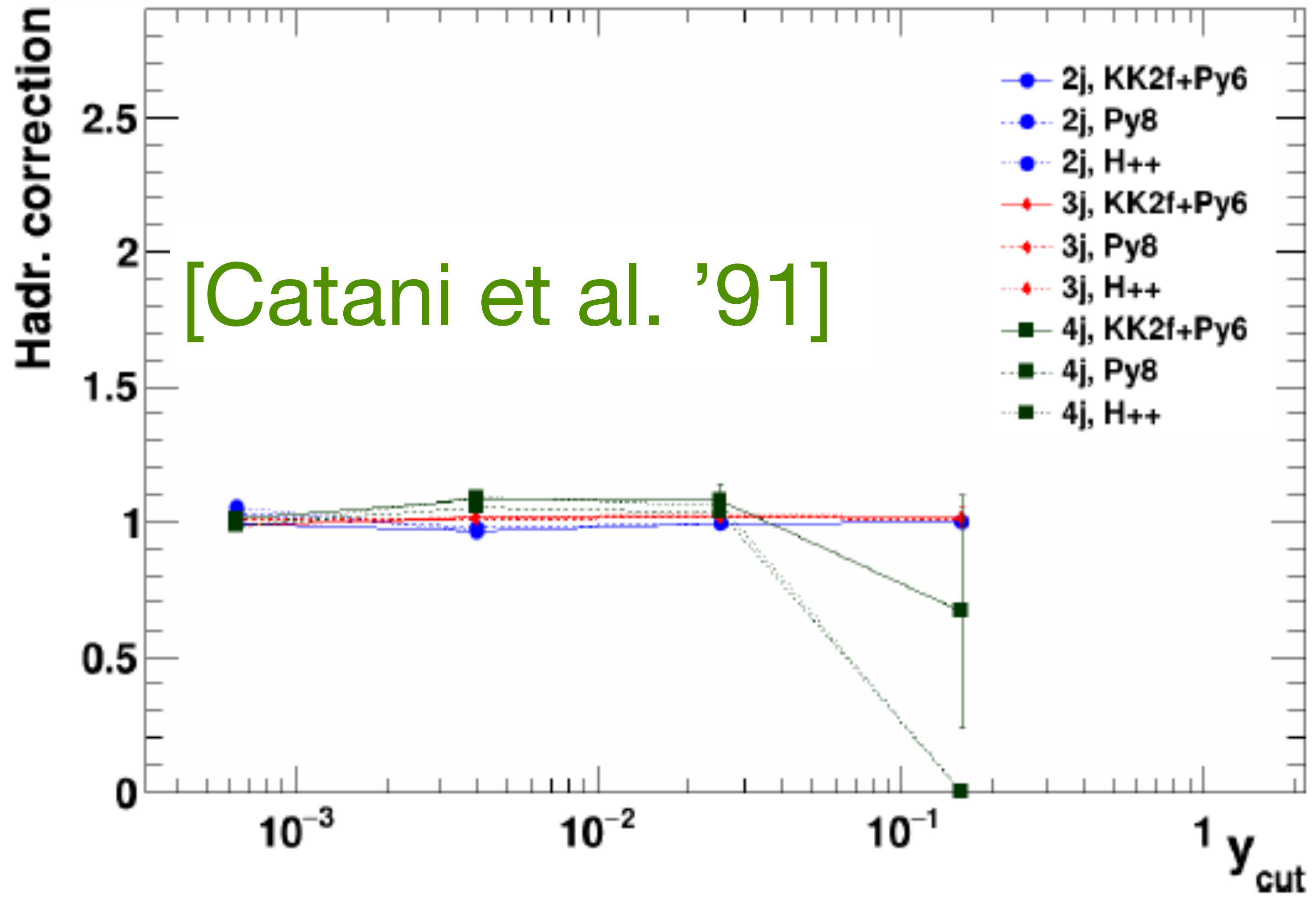
HADRONISATION AT FCC-ee

- **Exploit better observables (i.e. less sensitive to hadronisation):**
  - **use jet algorithms [better understanding of scaling of hadronisation corrections necessary in these observables]. Monte Carlo studies ongoing:**

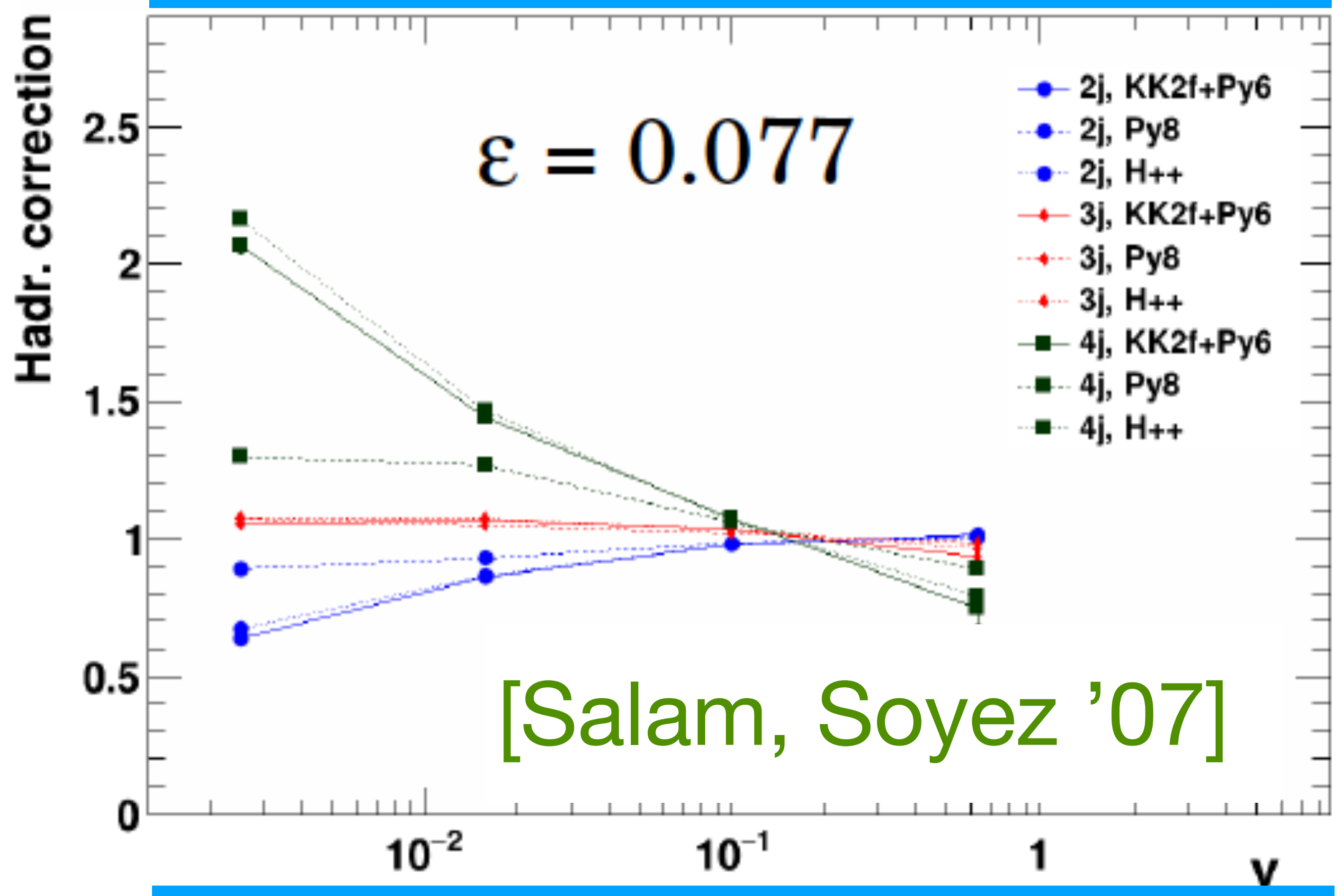
e.g. size of hadronisation corrections for different jet algorithms at LEP2 energies Q = 207 GeV

[Kluth, Verbytskyi @ ISMD2016]

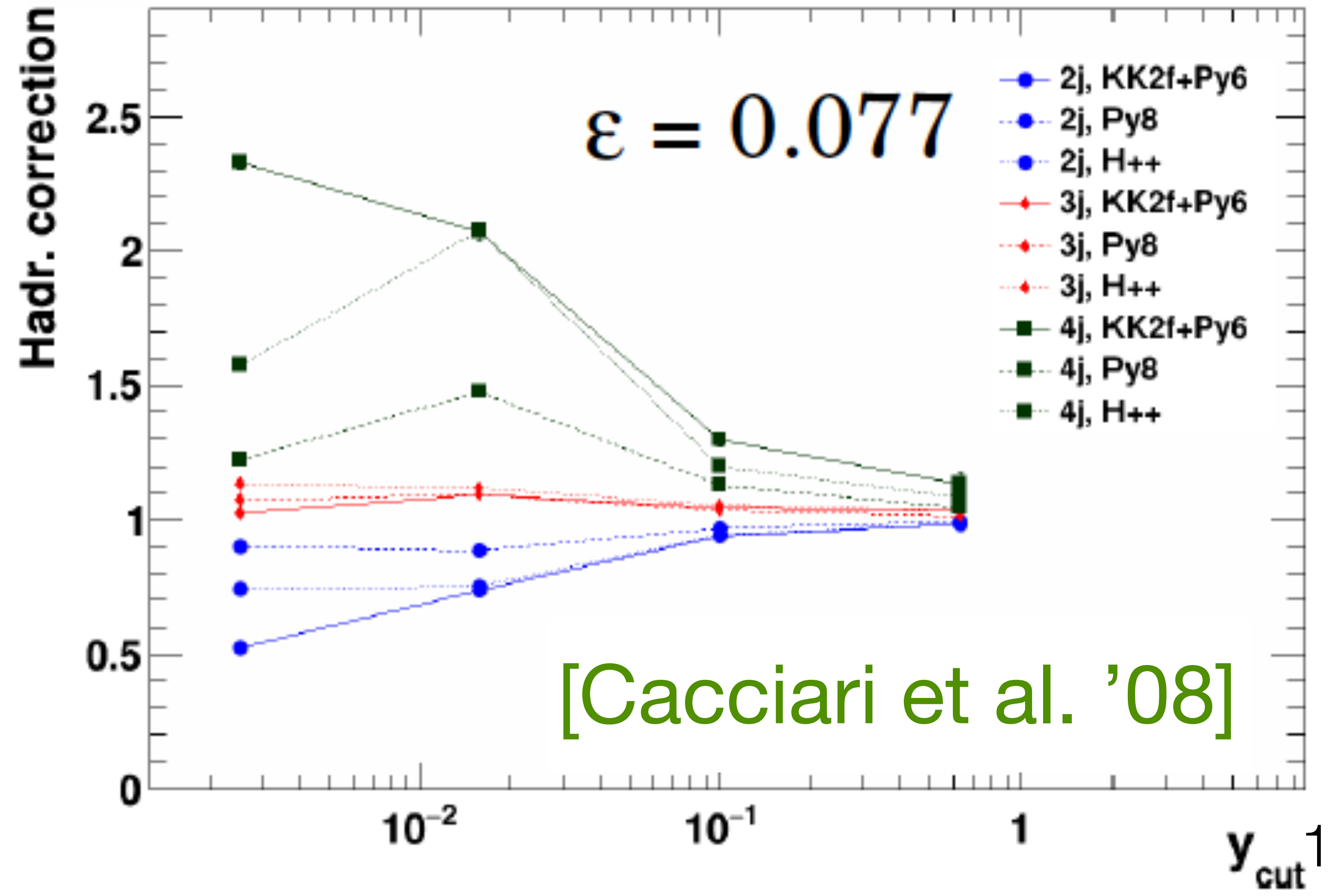
Durham k_t



SISCone*



anti-k_t*



***For anti-kt and SISCone:**

$$y = 1 - \cos(R)$$

$$\varepsilon = \frac{E_{\rm cut}}{Q}$$

See also talks by Gabor Somogyi and Andrii Verbytskyi on Wednesday

HADRONISATION AT FCC-ee

- **Exploit better observables (i.e. less sensitive to hadronisation):**
  - **use jet substructure to get rid of soft physics**

e.g. soft-drop Thrust:
[Marzani, Reichelt, Schumann, Soyez, Theeuwes '19]

$$\tau \equiv 1 - T = \min_{\vec{n}} \left(1 - \frac{\sum_{i \in \mathcal{E}} |\vec{n} \cdot \vec{p}_i|}{\sum_{i \in \mathcal{E}} |\vec{p}_i|} \right)$$

↓

$$\tau_{\mathrm{SD}} = \frac{\sum_{i \in \mathcal{E}_{\mathrm{SD}}} |\vec{p}_i|}{\sum_{i \in \mathcal{E}} |\vec{p}_i|} \left[1 - \frac{\sum_{i \in \mathcal{H}^L_{\mathrm{SD}}} |\vec{n}_L \cdot \vec{p}_i| + \sum_{i \in \mathcal{H}^R_{\mathrm{SD}}} |\vec{n}_R \cdot \vec{p}_i|}{\sum_{i \in \mathcal{E}_{\mathrm{SD}}} |\vec{p}_i|} \right]$$

See also talk by Zoltan Trocsanyi on Monday

HADRONISATION AT FCC-ee

- **Exploit better observables (i.e. less sensitive to hadronisation):**
  - **use jet substructure to get rid of soft physics**

e.g. soft-drop Thrust:
[Marzani, Reichelt, Schumann, Soyez, Theeuwes ’19]

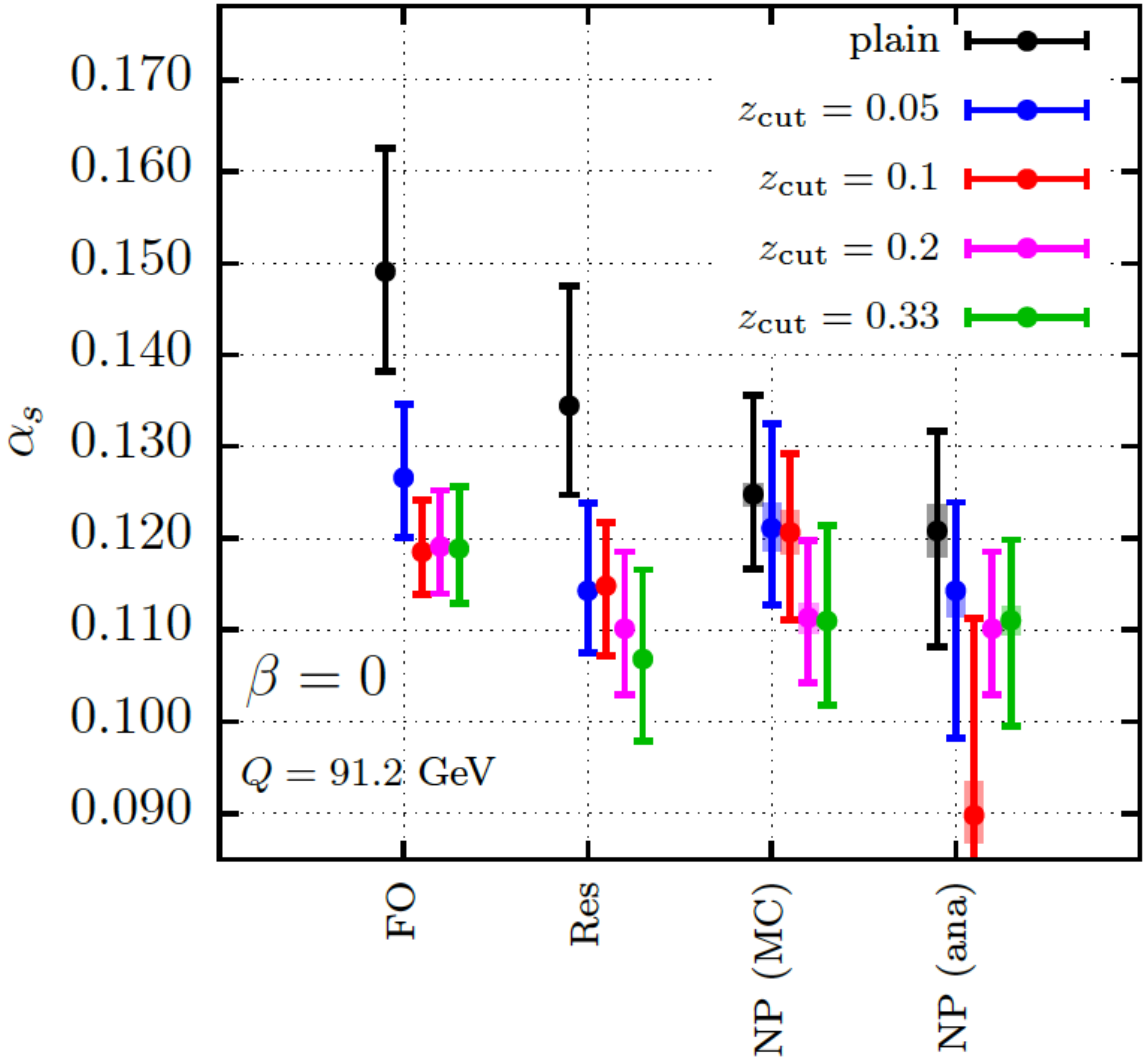
- **Less discrepancy between analytic and MC models, but not enough phase space for grooming at LEP - better at FCCee ?**

i.e. soft drop condition to each hemisphere

$$\frac{\min[E_i, E_j]}{E_i + E_j} > z_{\rm cut}(1 - \cos\theta_{ij})^{\beta/2}$$

- **Calculation of higher orders desirable …**

Groomed thrust at NLL+NLO



HIGGS PHYSICS

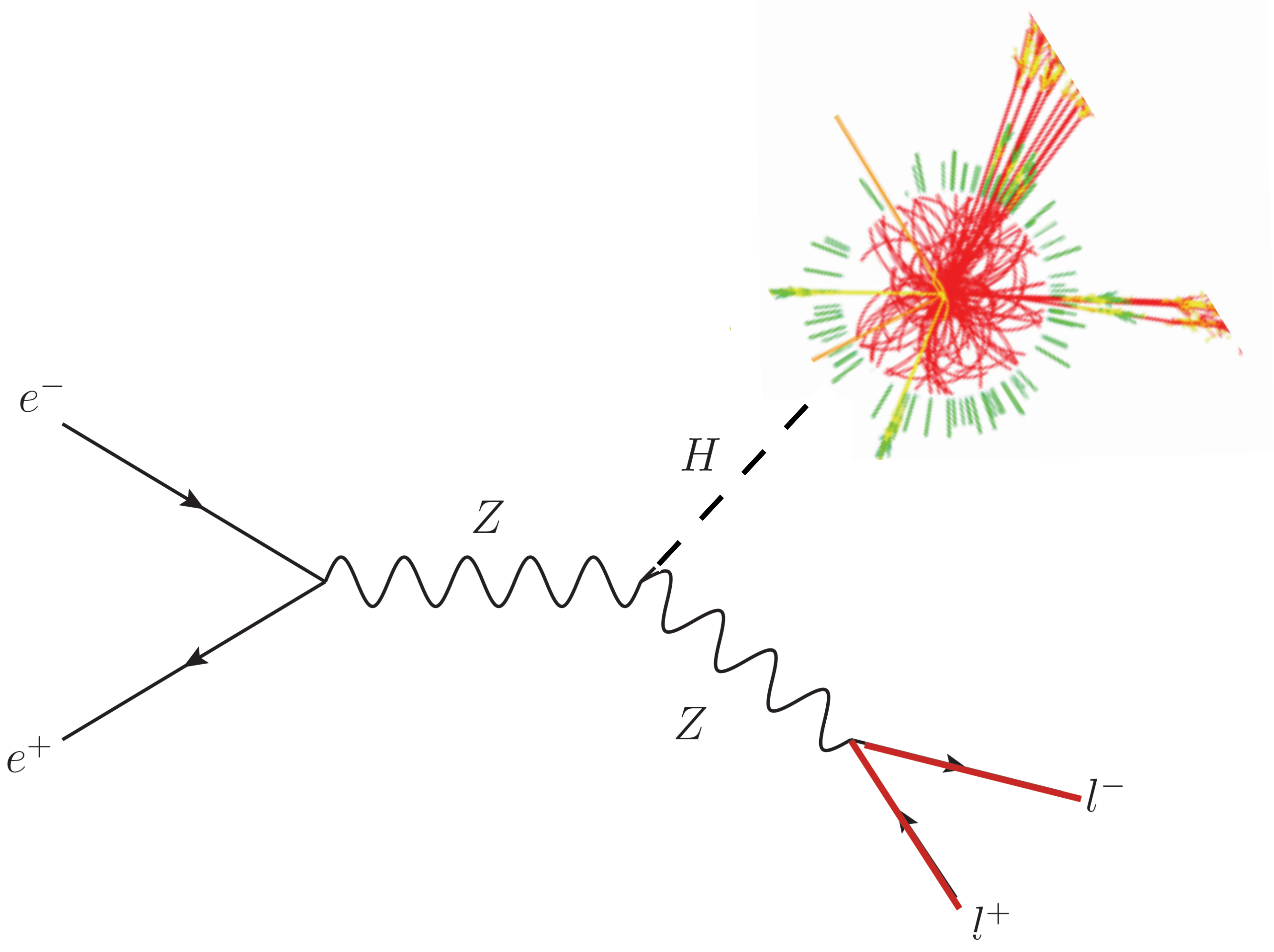
Precision in Higgs couplings in κ framework / EFT fits

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	$FCC\text{-}ee_{240\to365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years		11.5 [5]	8	7	3 + 1 + 4
g_{HZZ} (%)	1.5 / 3.6	0.29 / 0.47	0.44 / 0.66	0.18 / 0.52	**0.17 / 0.26**
g_{HWW} (%)	1.7 / 3.2	1.1 / 0.48	0.75 / 0.65	0.95 / 0.51	**0.41 / 0.27**
g_{Hbb} (%)	3.7 / 5.1	1.2 / 0.83	1.2 / 1.0	0.92 / 0.67	**0.64 / 0.56**
g_{Hcc} (%)	SM / SM	2.0 / 1.8	4.1 / 4.0	2.0 / 1.9	**1.3 / 1.3**
g_{Hgg} (%)	2.5 / 2.2	1.4 / 1.1	1.5 / 1.3	1.1 / 0.79	**0.89 / 0.82**
$g_{H\tau\tau}$ (%)	1.9 / 3.5	1.1 / 0.85	1.4 / 1.3	1.0 / 0.70	**0.66 / 0.57**
$g_{H\mu\mu}$ (%)	4.3 / 5.5	4.2 / 4.1	4.4 / 4.3	3.9 / 3.8	**3.9 / 3.8**
$g_{H\gamma\gamma}$ (%)	1.8 / 3.7	1.3 / 1.3	1.5 / 1.4	1.2 / 1.2	**1.2 / 1.2**
$g_{HZ\gamma}$ (%)	11. / 11.	11. / 10.	11. / 9.8	6.3 / 6.3	**10. / 9.4**
g_{Htt} (%)	3.4 / 2.9	2.7 / 2.6	2.7 / 2.7	2.6 / 2.6	**2.6 / 2.6**
g_{HHH} (%)	50. / 52.	28. / 49.	45. / 50.	17. / 49.	**19. / 34.**
Γ_H (%)	SM	2.4	2.6	1.9	**1.2**
BR_{inv} (%)	1.9	0.26	0.63	0.27	**0.19**
BR_{EXO} (%)	SM (0.0)	1.8	2.7	1.1	**1.0**

[de Blas et al. '19]

Astonishing precision for Higgs couplings. Can we achieve more by looking at differential distributions ?

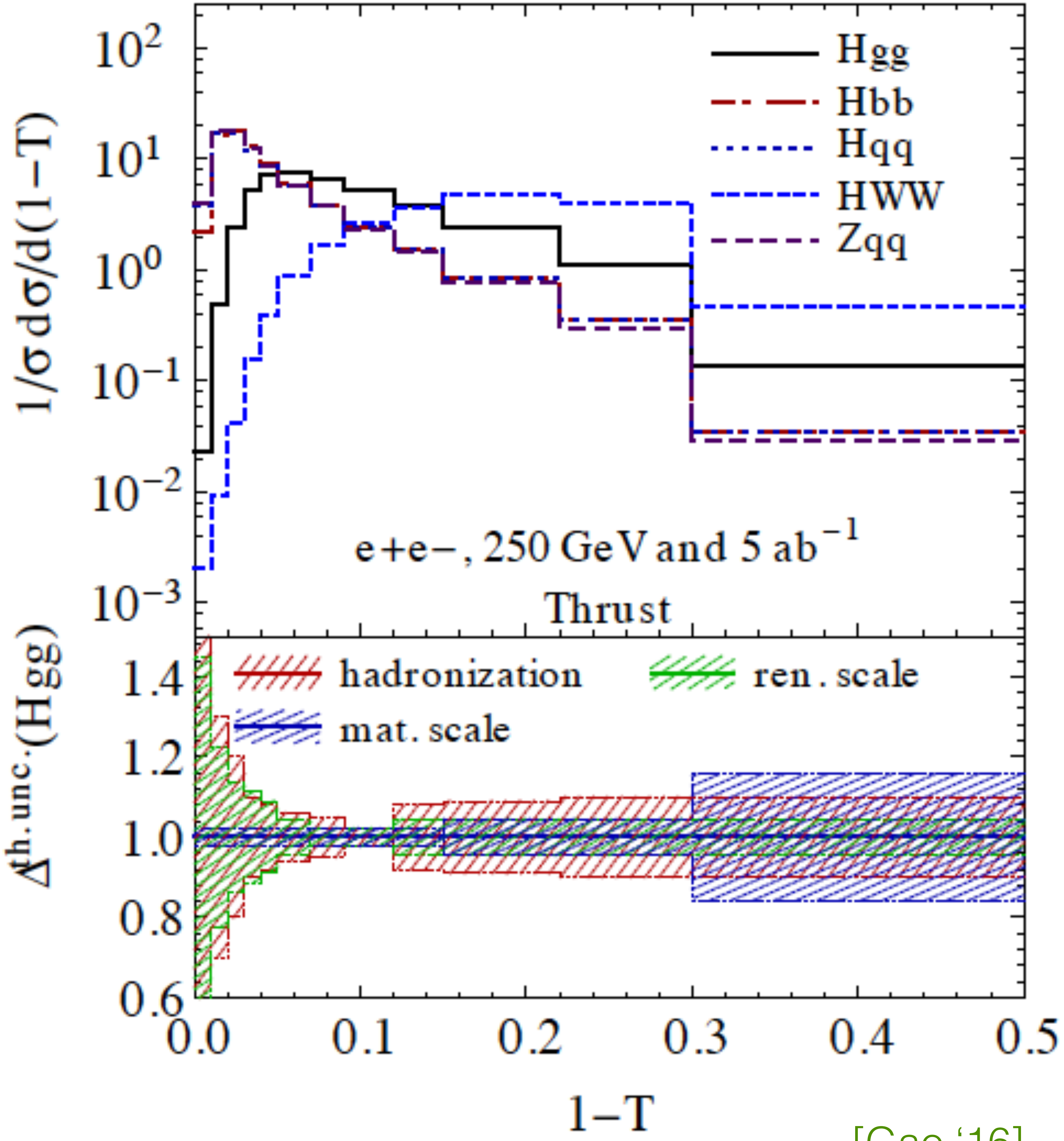
HIGGS JET OBSERVABLES



Differential shapes rich of information due to different final states

Access to light quark Yukawa couplings, but precision TH necessary

e.g. Thrust distribution

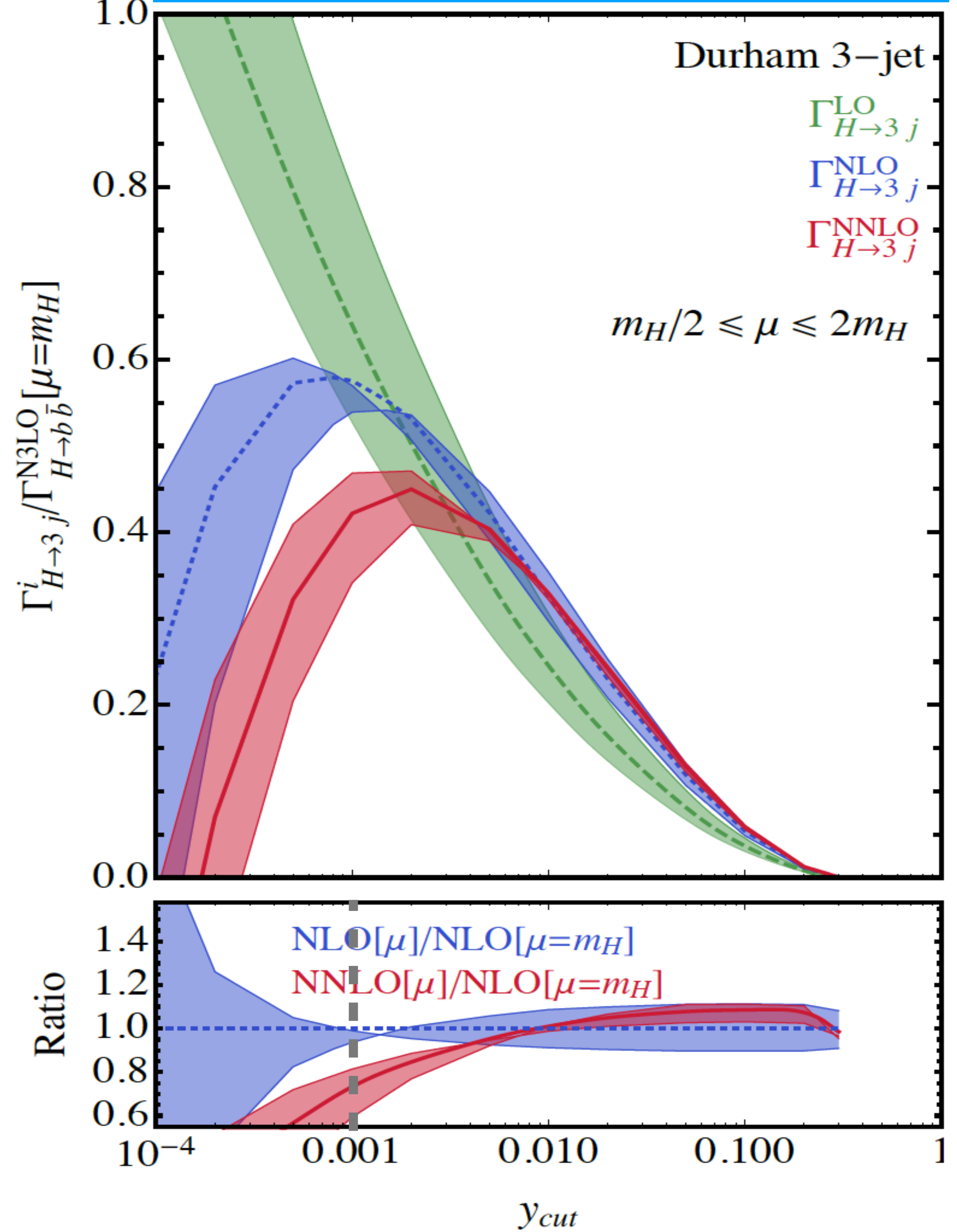


[Gao '16]

HIGGS JET OBSERVABLES

- **Existing technology developed in recent years instrumental to achieve this precision**
  - **e.g. exclusive H → bb + X at N3LO (massless b quarks)** [Mondini, Schiavi, Williams '19]
  - **b-mass effects relevant at scales** $y_{cut} \sim \frac{m_b^2}{m_H^2}$ **(known to NNLO for H → bb)**
    [Bernreuther, Chen, Si '18]
    [Primo, Sasso, Somogyi, Tramontano '18]
    [Behring, Bizon '19]
  - **Calculation of all-order corrections for 2/3 jet observables very desirable (partly easy with existing technology)**

Durham alg. 3-jet rate



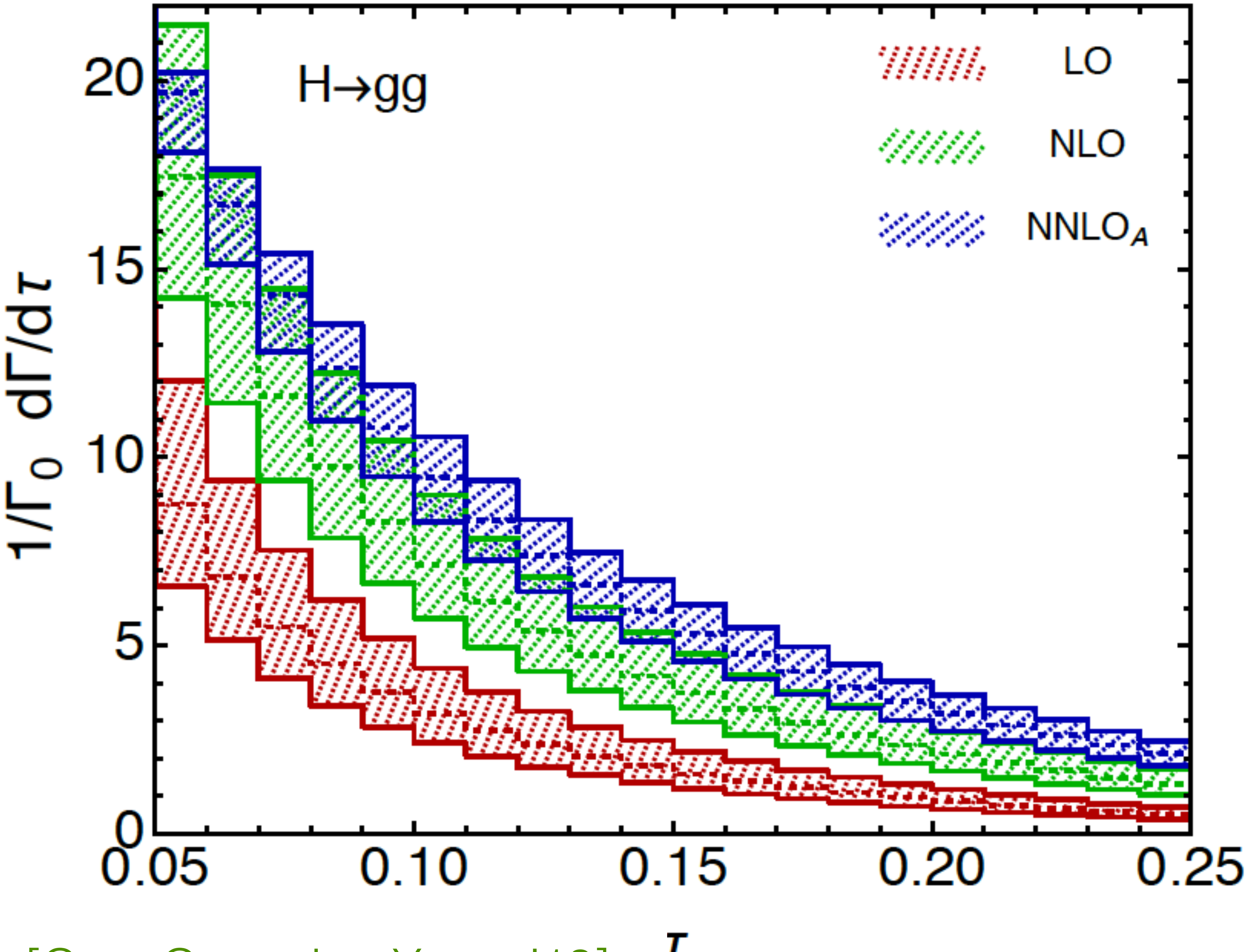
HIGGS JET OBSERVABLES

- **Existing technology developed in recent years instrumental to achieve this precision**
  - **e.g. Higgs event shapes in H → gg (large - m_t limit)**
  - **corrections to HEFT important to be sensitive to light-quark Yukawas - much progress recently in H → gg**

[Davies et al. ’19] [Harlander ’19] [Czakon, Niggetiedt ’20]
[Bonciani et al. ’19; Frellesvig et al. ’19]
[Melnikov, Penin ’16; Liu, Penin ’17-’18]
[Liu, Neubert ’19; Wang ’19]

  - **bottleneck once again seems to be non-perturbative corrections (Q~125 GeV, gluon jets,…)**

Thrust distribution in HEFT

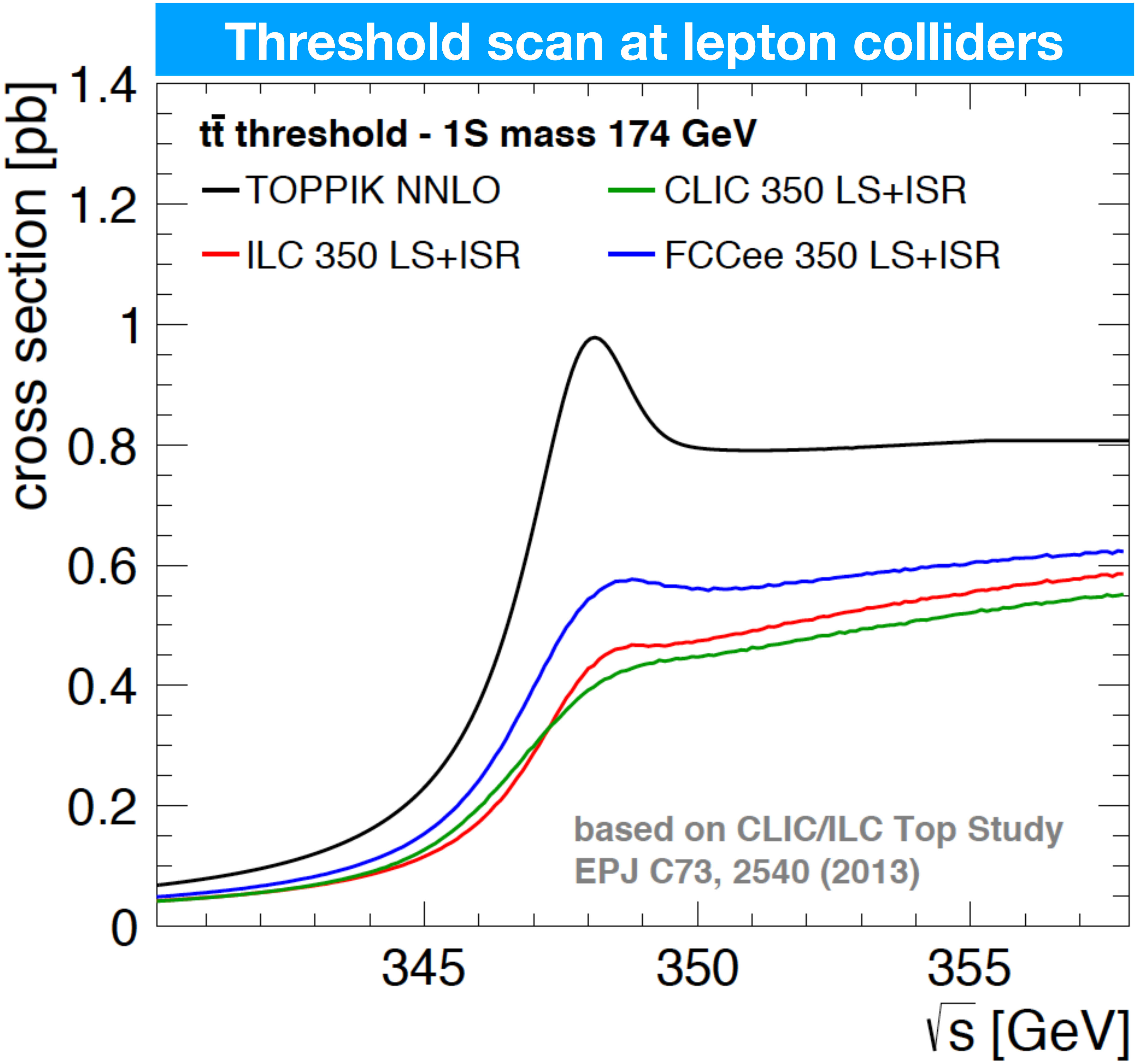


[Gao, Gong, Lu, Yang ’19]

TOP MASS AT FUTURE LEPTON COLLIDERS

- FCC-ee offers extremely precise access to the top mass
  - threshold scan: $\Delta m_t \sim 50\ \mathrm{MeV}$ or better
  - from ttγ (rad. return): $\Delta m_t \sim 110 - 150\ \mathrm{MeV}$
    [Boronat et al. '19]
- complex QCD theory near threshold, but in excellent shape (NRQCD, resummation of velocity sing., …)
  [Hoang, Stahlhofen '12; Beneke et al. '15, …]
  - some technical aspects of matching (also incl. EW corrections) to be sorted out

[Vos et al. 1604.08122]

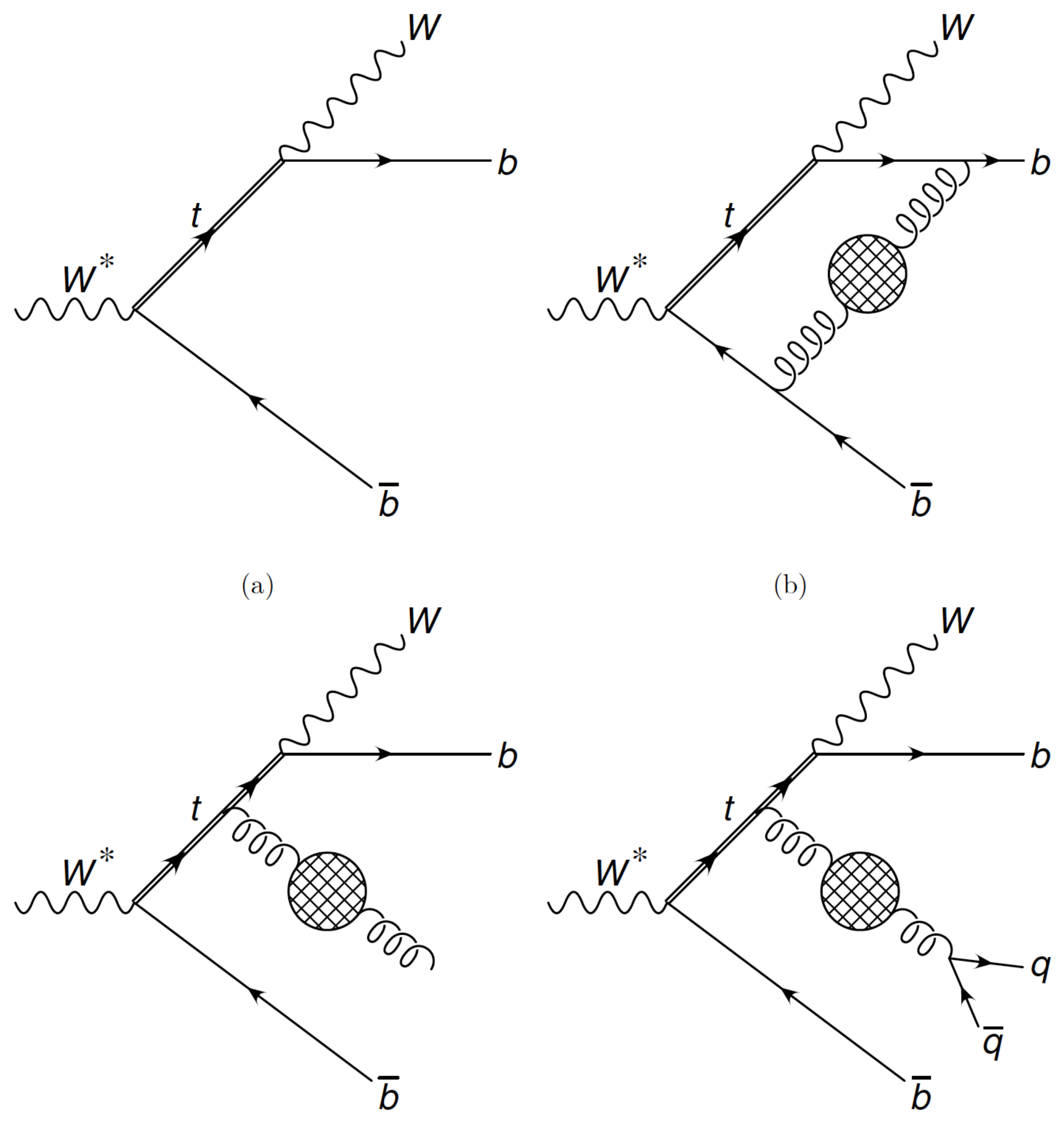


See also talk by Andre Hoang on Wednesday

TOP MASS AT FUTURE LEPTON COLLIDERS

- The top mass measured this way can be used as input to explore important aspects of infrared physics that are hard to access in hadronic collisions
  - Linear renormalons in short-distance top-mass: m_t-sensitive jet observables are affected by a $O(\Lambda_{QCD})$ ambiguity due to infrared physics.

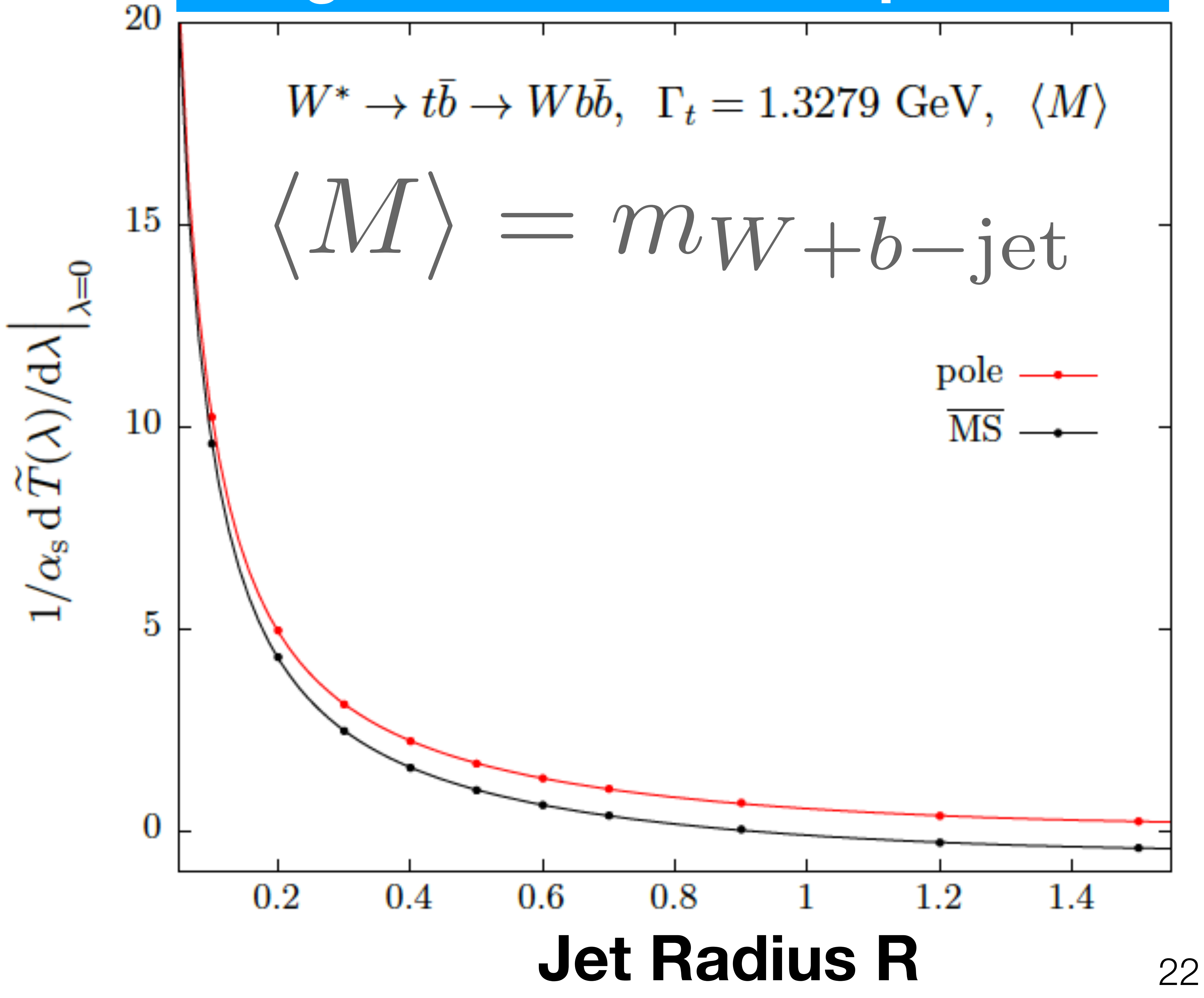
e.g. W* decay



Proportional to the coefficient of the linear renormalon

[Ferrario-Ravasio, Nason, Oleari '18]

e.g. reconstructed top mass

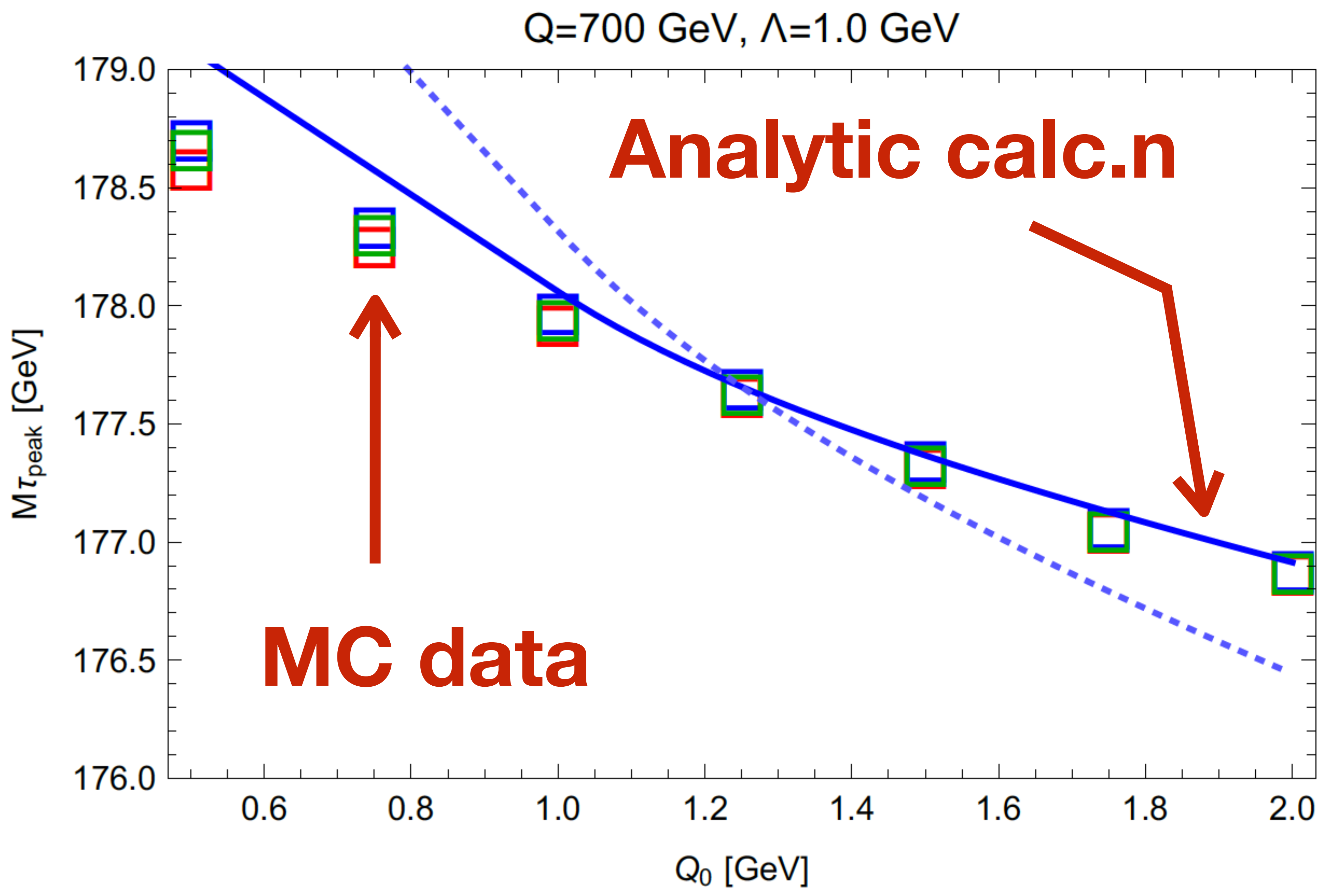


TOP MASS AT FUTURE LEPTON COLLIDERS

- The top mass measured this way can be used as input to explore important aspects of infrared physics that are hard to access in hadronic collisions
  - <u>Monte Carlo top mass</u>:

[Hoang, Plaetzer, Samitz '18]

for MC based on angular ordering, the top pole mass receives a correction proportional to the shower cutoff scale Q_0



$$m^{(\mathrm{MC})} = m^{\mathrm{pole}} - \frac{2}{3}\alpha_s(Q_0)Q_0 + \mathcal{O}(\alpha_s^2)$$

Position of the (hemisphere) mass peak in boosted tt production can be related to the shift. Better understanding crucial for direct reconstruction, e.g. effect of MC tuning, finite width, …

CONCLUSIONS

- FCC has huge physics potential with its very rich and diversified program
- Achieving the expected precision in many collider observables constitutes a massive challenge for the whole TH community
  - Accurate control over a broad range of TH elements (QCD, EW - not mentioned much in this talk) is necessary; great opportunity to use data to explore aspects which are still poorly known (e.g. infrared dynamics, couplings/masses, …)
  - Crucial to think of new ways to exploit the modern knowledge of QFT and its tools to devise new measurements that will help exploit future collider machines effectively