QCD physics at FCC-ee: Intro

6th FCC Physics Workshop

Krakow, Jan. 24th 2023

David d'Enterria 

Pier F. Monni

(CERN)

QCD at the core of FCC physics programs

- Though QCD is not per se the driving force for FCC-ee,hh, it is crucial for a vast range of studies (signals & backgrounds):

1. Precise α_s determination is needed to accurately & precisely predict all SM x-sections & decay rates (Higgs, top, EWPOs,...)

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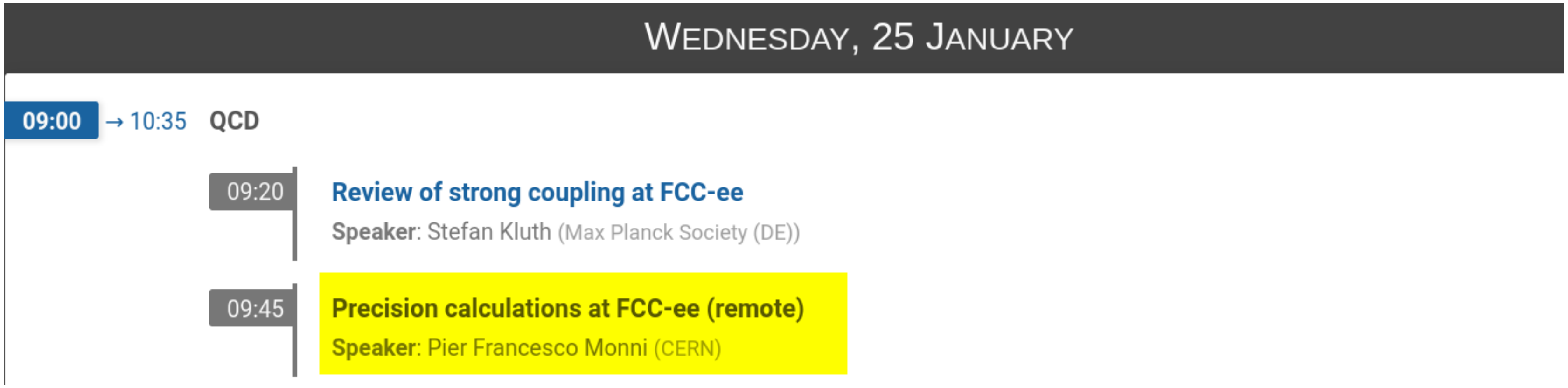

WEDNESDAY, 25 JANUARY

09:00 → 10:35 QCD

09:20 **Review of strong coupling at FCC-ee**
Speaker: Stefan Kluth (Max Planck Society (DE))

09:45 **Precision calculations at FCC-ee (remote)**
Speaker: Pier Francesco Monni (CERN)

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10:10 **Monte Carlo challenges for FCC-ee and progress**
Speaker: Simon Plaetzer (U. of Graz)

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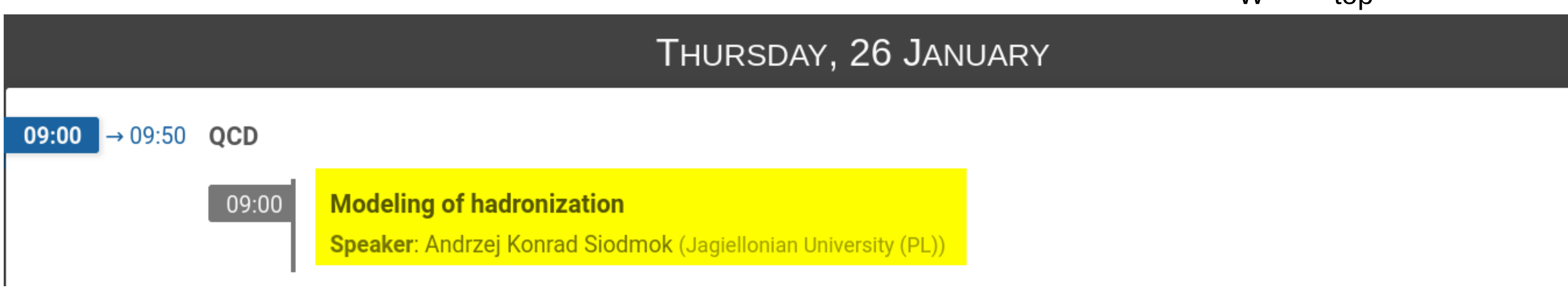
4. Non-perturbative QCD (hadronisation, colour reconnection,...) impacts studies w/ hadronic final states: $e^+e^-\to WW,tt$ ($\to$jets), m_W, m_{top} extractions



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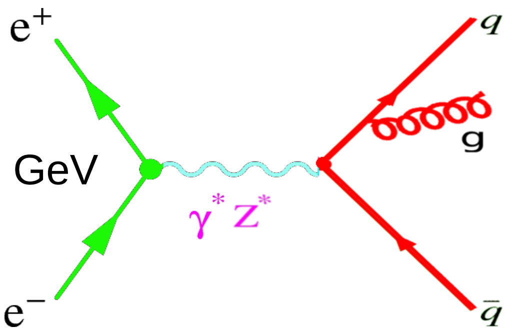
5. @ FCC-hh, accurate knowledge of parton densities at high-*x* (BSM) and saturation dynamics at small-*x*, MPI dynamics,… is fundamental.

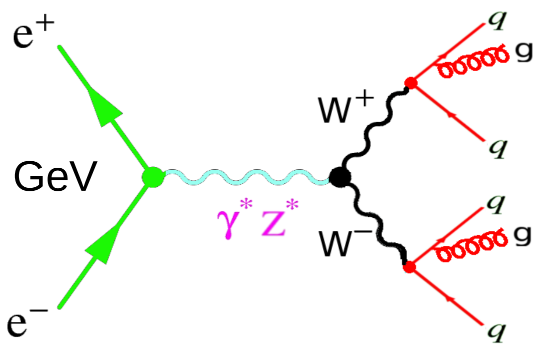
Precision QCD in e^+e^- collisions

- e^+e^- collisions provide an extremely clean environment with fully-controlled initial-state to probe very precisely q,g dynamics:

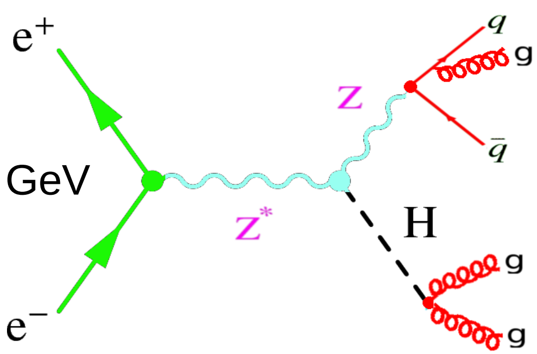
$\sqrt{s}$ = 91 GeV



$\sqrt{s}$ = 160 GeV



$\sqrt{s}$ = 240 GeV



Advantages compared to p-p collisions:

1) QED initial-state with known kinematics

2) Controlled QCD radiation (only in final-state)

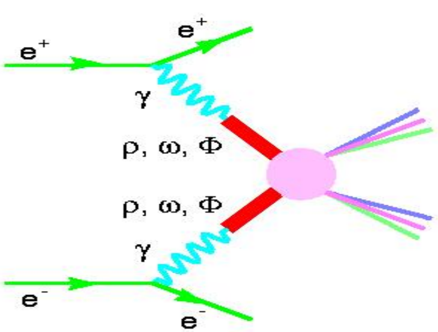
3) Well-defined heavy-Q, quark, gluon jets

4) Smaller non-pQCD uncertainties:

no PDFs, no QCD "underlying event",…

Direct clean parton fragmentation & hadroniz.

- Plus QCD physics in $\gamma\gamma$ (EPA) collisions:



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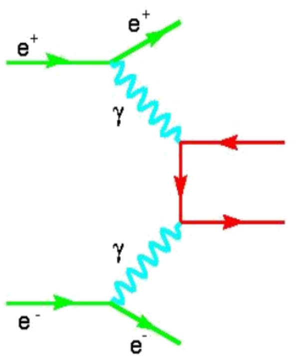

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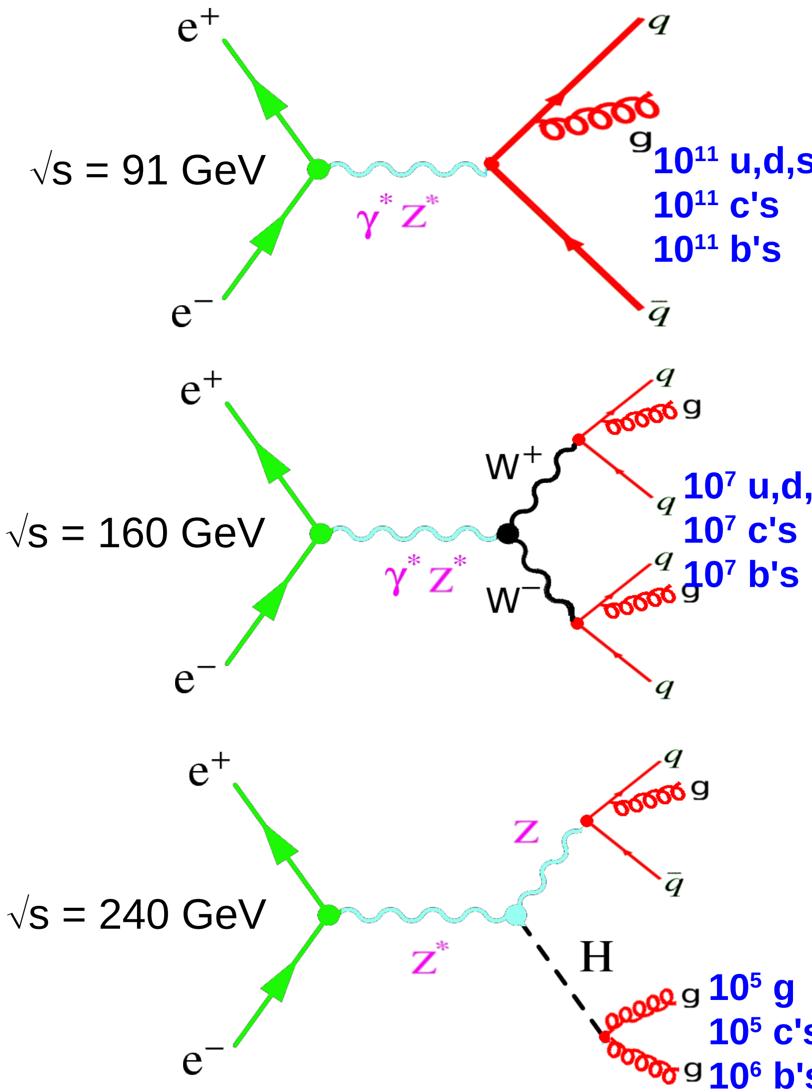

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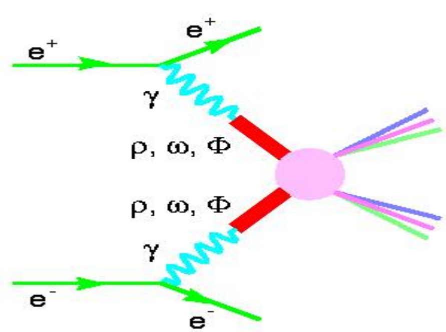

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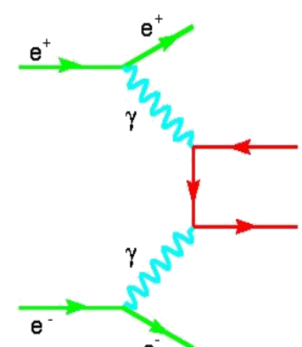


(direct)

Very rich QCD physics at FCC-ee

$\sin^2\theta_W$ via Fwd-Bckwd asymm. in $Z \to q\bar{q}$

N-jet rates

Hadronic H, W, Z, τ widths

Mixed QCD-EW corrections

$g \to c\bar{c}, b\bar{b}$ splitting

Fixed-order-PS matching

N^nLO antenna functions

Lund Plane

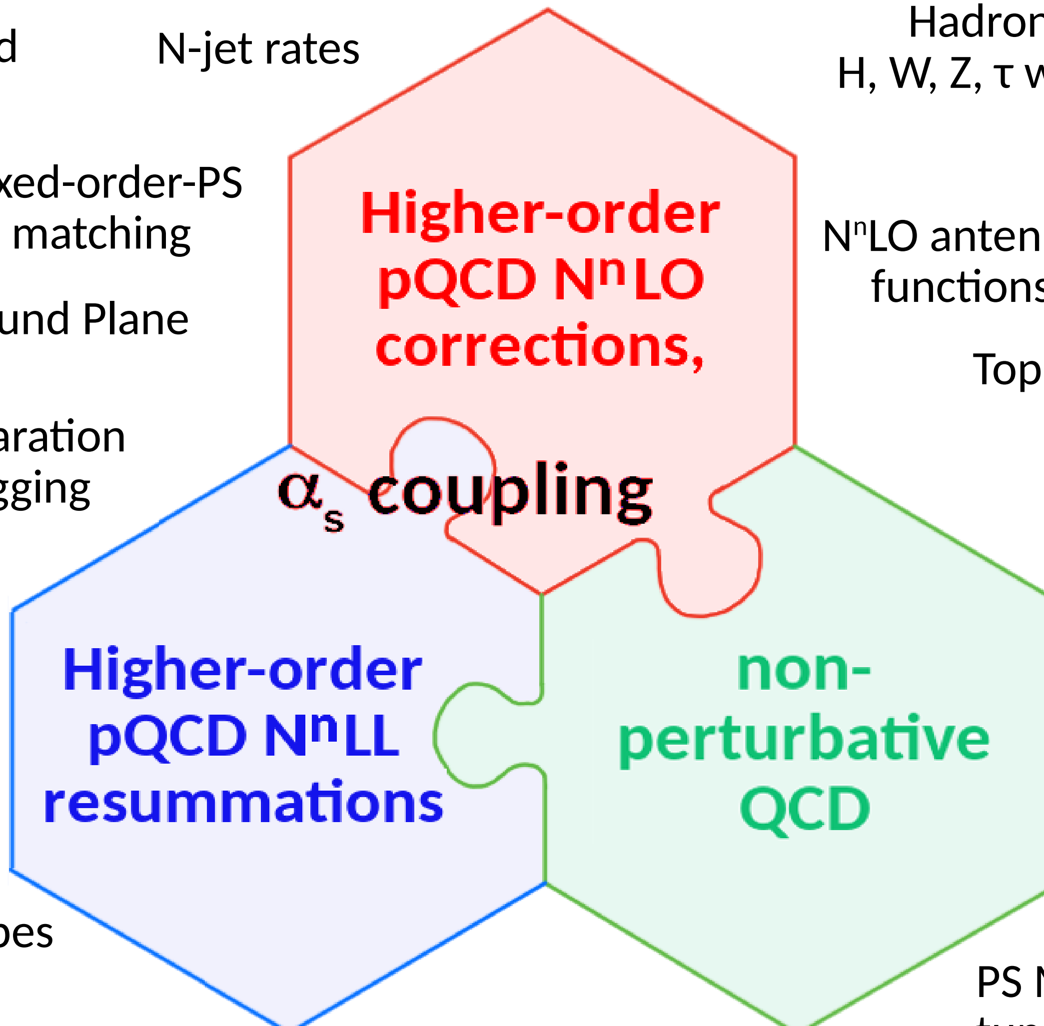
Jet substructure

Top mass extraction via $e^+e^- \to t\bar{t}$

q-g separation Jet tagging

Heavy-Q rad. dead-cone

Colour reconnection



Jet reco/flavour algorithms

Parton hadronization

Non-Global Logs

Final-state correlations

Event shapes

Beyond Leading Color

PS MC tuning

Spin correlations

N^nLL Parton Shower Monte Carlos

Fragmentation Functions

$Q\bar{Q}$ transition probabs.

Lattice QCD

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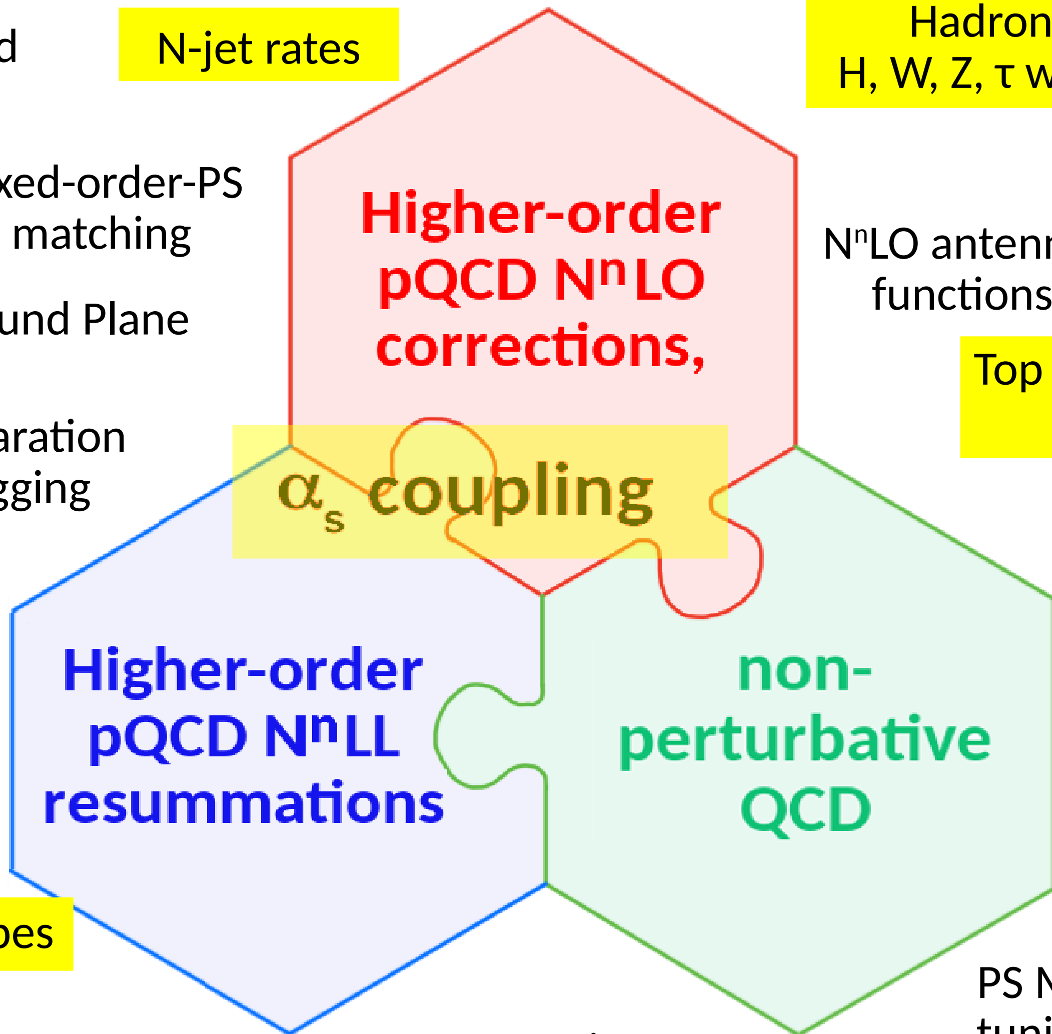

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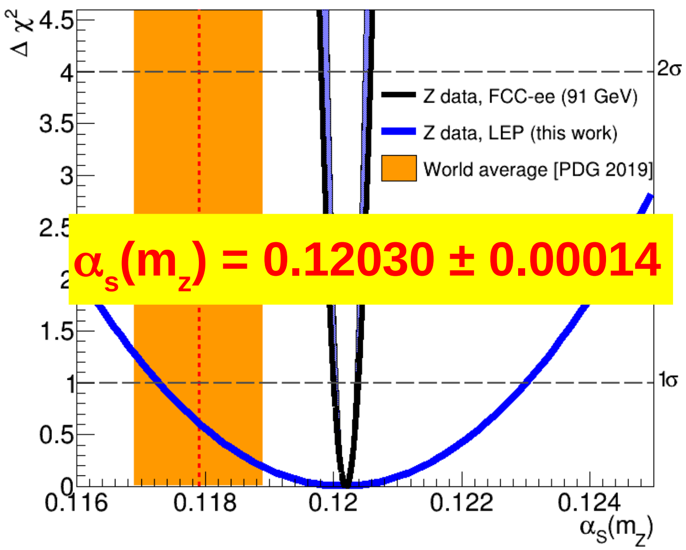
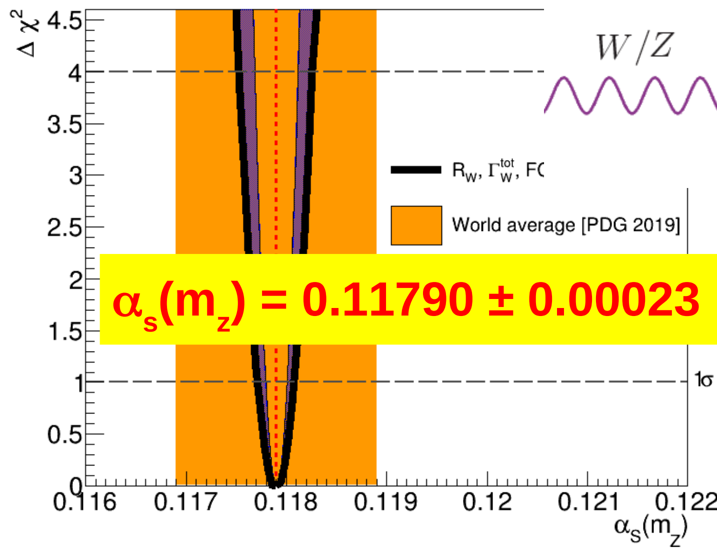
Example: QCD coupling α_s

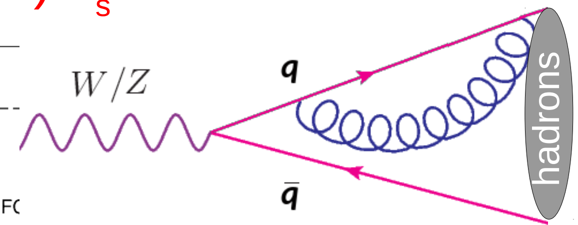
- Z,W hadronic widths provide the most precise (0.1%) α_s extraction:



$\alpha_s(m_z) = 0.12030 \pm 0.00014$



$\alpha_s(m_z) = 0.11790 \pm 0.00023$



Strong (B)SM consistency test

- Reduced parametric uncertainties: Higgs, EWPO, top… x-sections & decays

Process	σ (pb)	$\delta\alpha_s(\%)$	PDF $+\alpha_s(\%)$	Scale(%)
ggH	49.87	± 3.7	-6.2 +7.4	-2.61 +0.32
ttH	0.611	± 3.0	$\pm$ 8.9	-9.3 +5.9

Channel	M_H[GeV]	$\delta\alpha_s(\%)$	Δm_b	Δm_c
$H \to c\bar{c}$	126	± 7.1	$\pm 0.1\%$	$\pm 2.3\ \%$
$H \to gg$	126	± 4.1	$\pm 0.1\%$	$\pm 0\ \%$

Summary of future parametric uncertainties:

Quantity	FCC-ee	future param.unc.	Main source
Γ_Z [MeV]	0.1	0.1	$\delta\alpha_s$
R_b [10^{-5}]	6	< 1	$\delta\alpha_s$
R_ℓ [10^{-3}]	1	1.3	$\delta\alpha_s$

Msbar mass error budget (from threshold scan)

$(\delta M_t^{\text{SD-low}})^{\text{exp}}$	$(\delta M_t^{\text{SD-low}})^{\text{theo}}$	$(\delta\overline{m}_t(\overline{m}_t))^{\text{conversion}}$	$(\delta\overline{m}_t(\overline{m}_t))^{\alpha_s}$
40 MeV	50 MeV	7 – 23 MeV	70 MeV

$\Rightarrow$ improvement in α_s crucial

$\delta\alpha_s(M_z) = 0.001$

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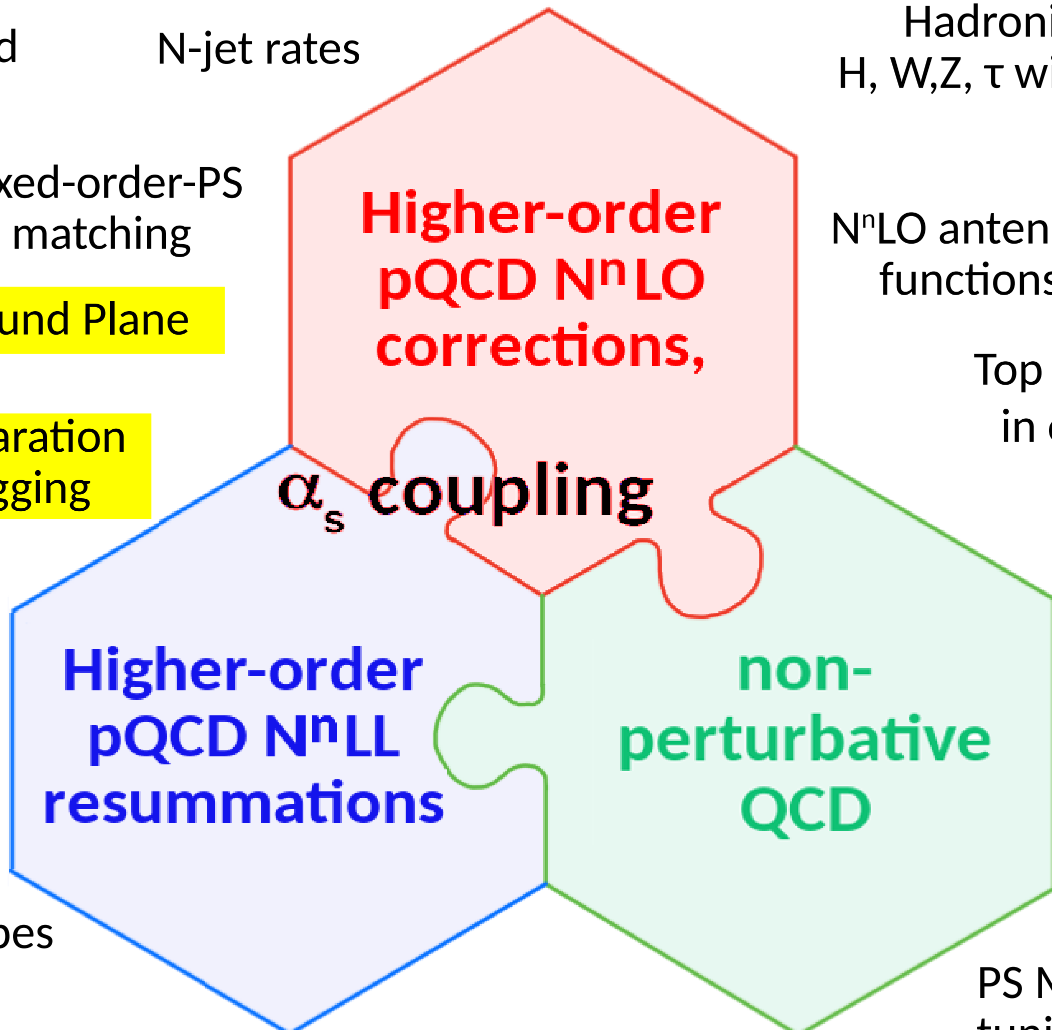

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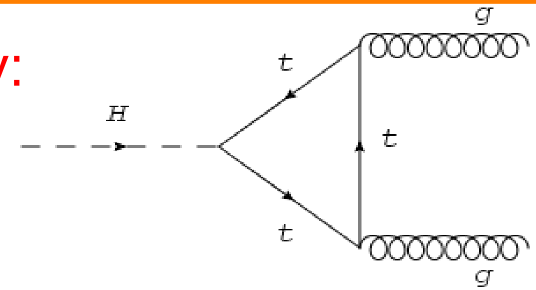
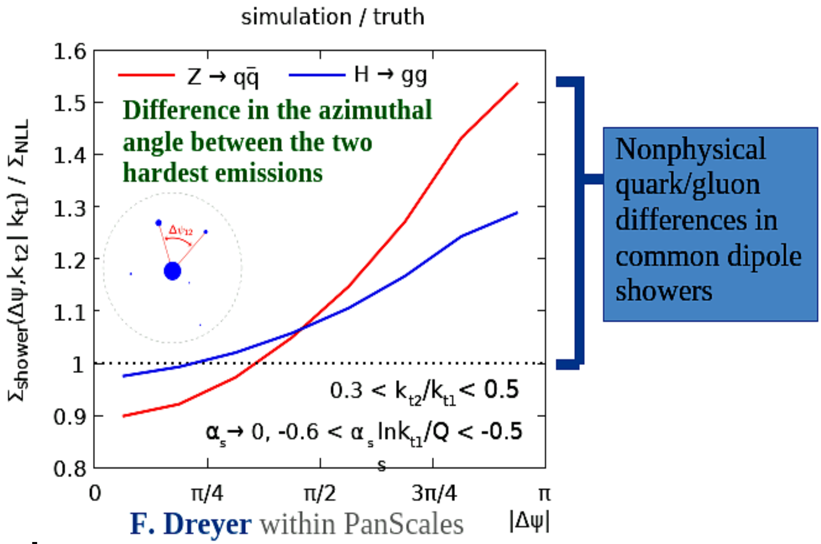
Example: High-precision g & q jet studies

- Exploit FCC-ee H(gg) as a "pure gluon" factory: H→gg (BR~8% accurately known) provides $\mathcal{O}$(100.000) extra-clean digluon events.



- Compare to Z→qq(g): Multiple handles to study g rad./jet properties:
  - Gluon vs. quark via H→gg vs. Z→qq (Profit from excellent g,b separation)
  - Gluon vs. quark via Z→bbg vs. Z→qq(g) (g in one hemisphere recoiling against 2-b-jets in the other).
  - Vary E_{jet} range via ISR: $e^+e^- \to Z^*,\gamma^* \to jj(\gamma)$
  - Vary jet radius: small-R down to calo resol



- Multiple high-precision analyses at hand:
  - Higgs/BSM/flavour: Improve q/g/Q discrimin. tools: ML training on pure samples
  - pQCD: Check N^nLO antenna functions. High-precision QCD coupling.
  - non-pQCD: Gluon fragmentation: Octet neutralization? (zero-charge gluon jet with rap gaps). Colour reconnection? Glueballs ? Leading η's,baryons?

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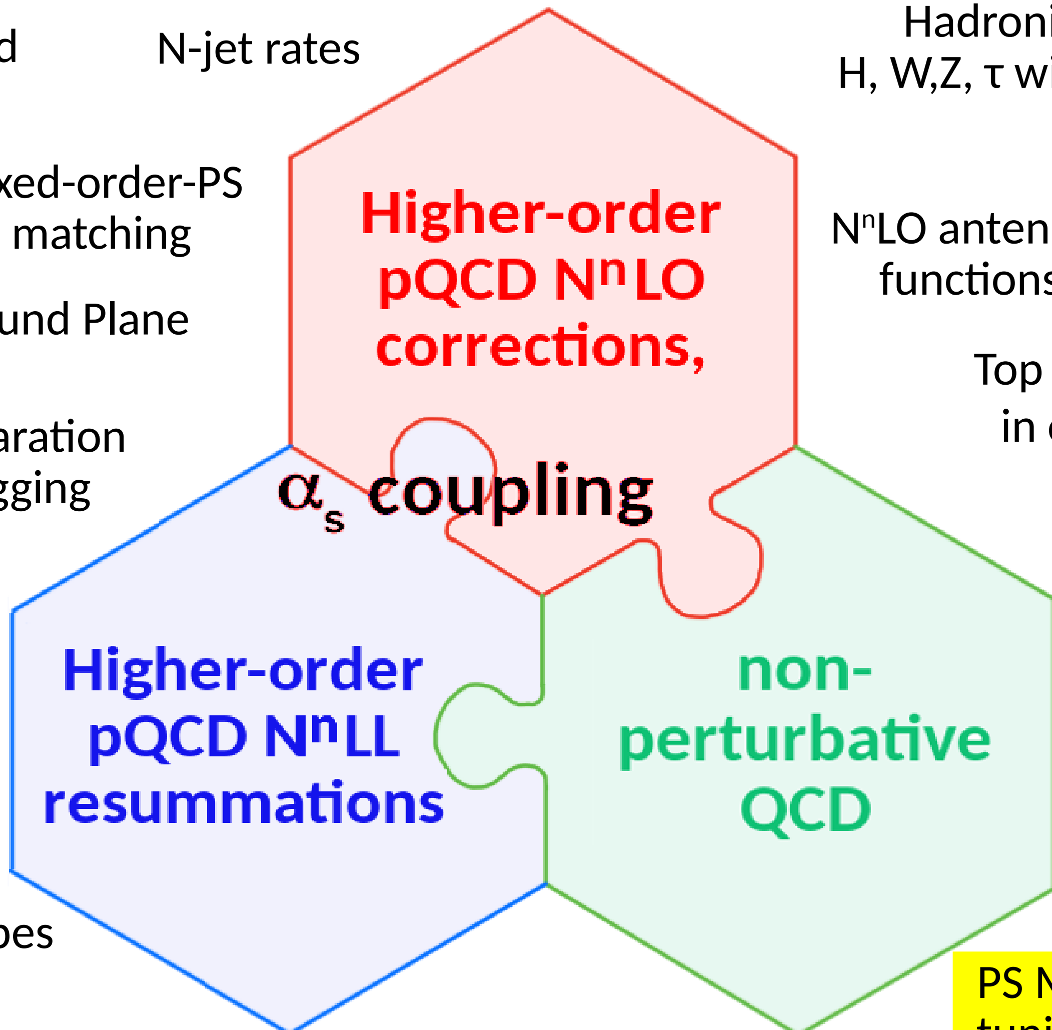

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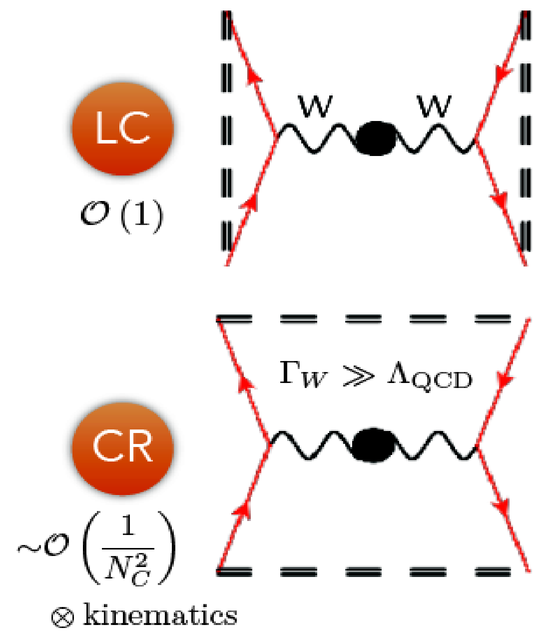
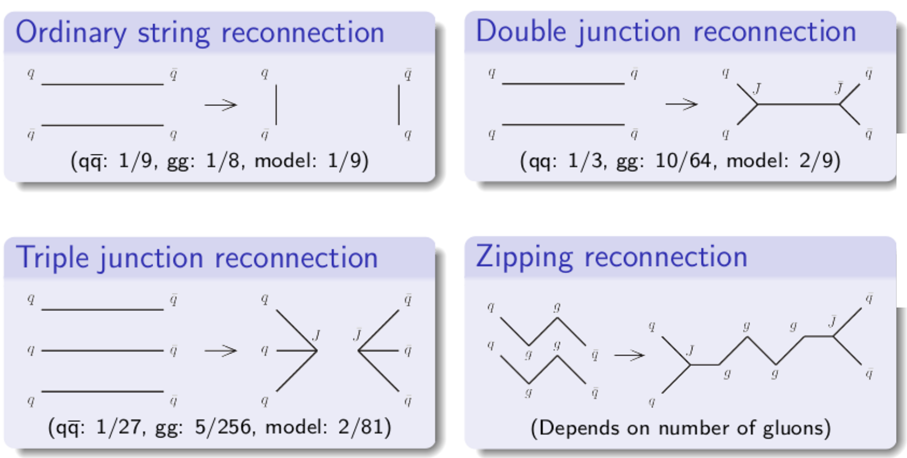
Non-pQCD example: Colour reconnection

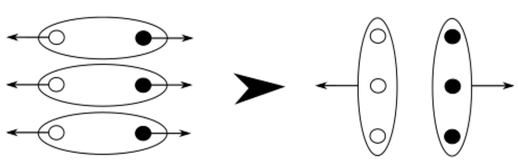
- Colour reconnection among partons is source of uncertainty in m_W, m_{top}, aGC extractions in multijet final-states. Especially in pp (MPI cross-talk).
- CR "string drag" effect impacts all FCC-ee multi-jet final-states: $e^+e^- \to$ WW(4j), H(2j,4j), ttbar,…
  - Shifted masses & angular correlations (CP studies).
  - Combined LEP $e^+e^- \to$ WW(4j) data best described with 49% CR, 2.2σ away from no-CR.



- Exploit huge W stats (×10[4] LEP) to measure m_W leptonically & hadronically and constrain CR:

"Recent" PYTHIA option: QCD-inspired CR (QCDCR) (1505.01681):





Triple-junction also in HERWIG cluster model. (1710.10906)

FCC QCD working group activities

- Join our monthly meetings:

https://indico.cern.ch/category/5662/

QCD and γγ physics

April 2023

24 Apr - 28 Apr Parton Showers for future e+e- colliders NEW

December 2022

13 Dec FCC-ee QCD Physics -- jet flavour & tagging

October 2022

03 Oct FCC-ee QCD Physics -- jet physics and fragmentation functions

July 2022

27 Jul FCC-ee QCD Physics -- Kickoff Meeting (ZOOM only)

January 2022

31 Jan - 04 Feb alpha_s(2022)

- Join our e-groups mailing:

FCC-PED-PhysicsGroup-QCD
https://e-groups.cern.ch/e-groups

- Contact the conveners:

FCC-PED-PhysicsGroup-QCD-admin@cern.ch

- “Parton showers for FCC-ee” workshop

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

CERN, 24th–28th April 2023

Parton Showers for future e+e- colliders

24–28 Apr 2023
CERN
Europe/Zurich timezone

Enter your search term

Overview
Timetable
Registration
Participant List
Videoconference
Accommodation
Directions to and inside CERN
Computer Access
Child Care
Health insurance, VISA
Code of Conduct

TH secretariat
thworkshops.secretariat...
PartonShowers-2023-or...

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. The goal of this workshop is to bring together many of the world leading experts in the field to discuss recent developments and main obstacles on path to precision, as well as encourage new collaborations to tackle big open questions such as:

- **Perturbative accuracy of parton showers (PS)**: logarithmic accuracy; treatment of colour & spin; amplitude-level evolution; heavy quarks & resonances.
- **Non perturbative QCD**: tuning observables at the future lepton colliders; hadronisation & colour reconnection.
- **Matching to hard scattering**: N(N)LO QCD and beyond; production of resonant final states.

The workshop will consist of one or two talks a day, leaving most of the time for discussions among the participants and collaboration work.

Organising committee:
- Samuel Abreu (CERN)
- Mrinal Dasgupta (University of Manchester)
- David d'Enterria (CERN)
- Silvia Ferrario Ravasio (CERN)
- Alexander Huss (CERN)
- Alexander Karlberg (CERN)
- Michelangelo Mangano (CERN)
- Pier Monni (CERN)
- Simon Plätzer (University of Graz)
- Alba Soto Ontoso (CERN)
- Gregory Soyez (IPhT Saclay)
- Robert Szafron (BNL)
- Johann Usovitsch (CERN)

Starts 24 Apr 2023, 09:00
Ends 28 Apr 2023, 17:00
Europe/Zurich

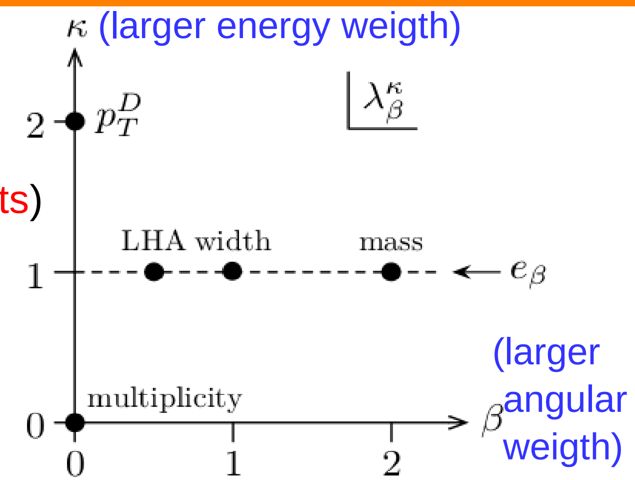
CERN
4/3-006 - TH Conference Room
Go to map

There are no materials yet.

Backup slides

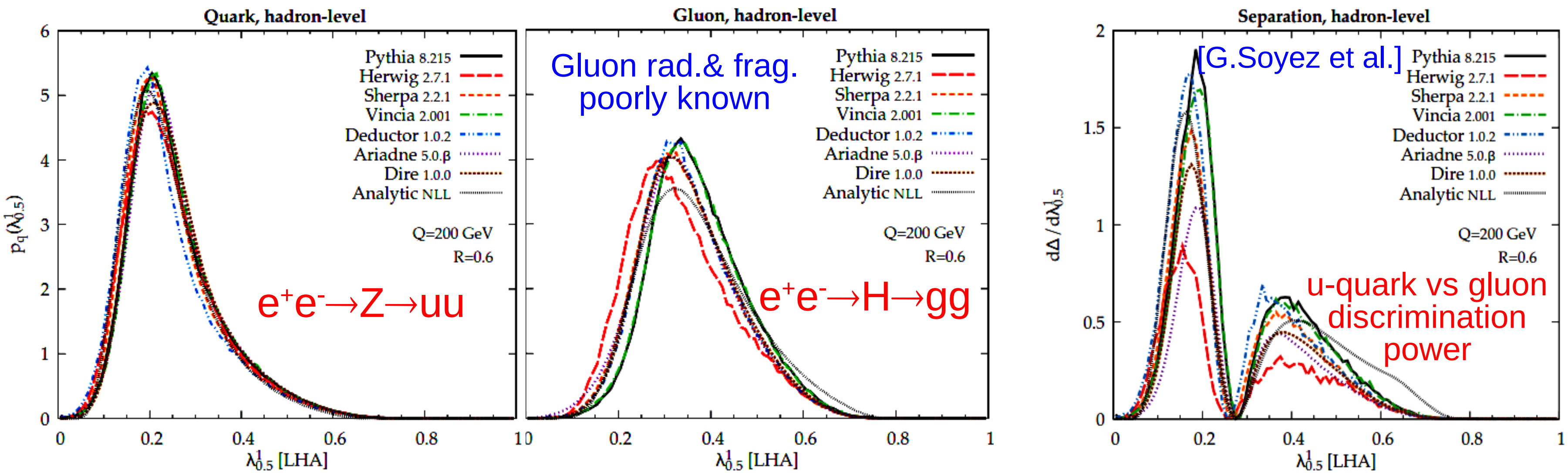
Jet substructure & flavour tagging

- State-of-the-art jet substructure based on Lund Plane & angularities: $\lambda_\beta^\kappa = \sum_{i\in\text{jet}} z_i^\kappa \theta_i^\beta$, (normalized $E^n \times \theta^n$ products)
- "Sudakov"-safe variables of jet constituents: multiplicity, LHA, width/broadening, mass/thrust, C-parameter,...



[Larkoski,Salam,Thaler,13]
[Larkoski,Thaler,Waalewijn,14]

- k=1: IRC-safe computable (N^nLO+N^nLL) via SCET (but uncertainties from non-pQCD effects)
- MC parton showers differ on gluon (less so quark) radiation patterns:



Jet substructure & flavour tagging

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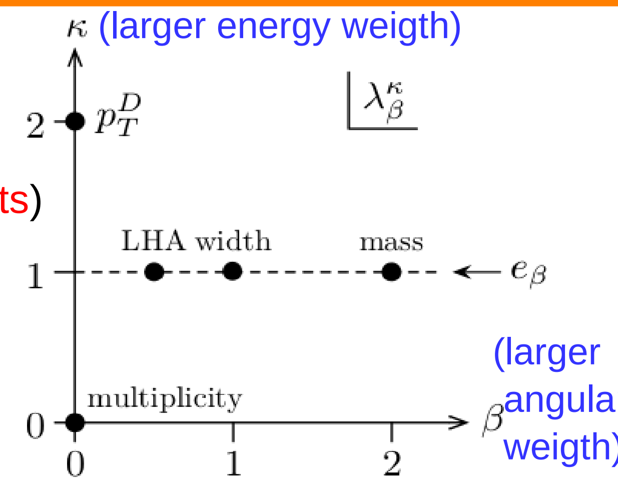

[Larkoski,Salam,Thaler,13]
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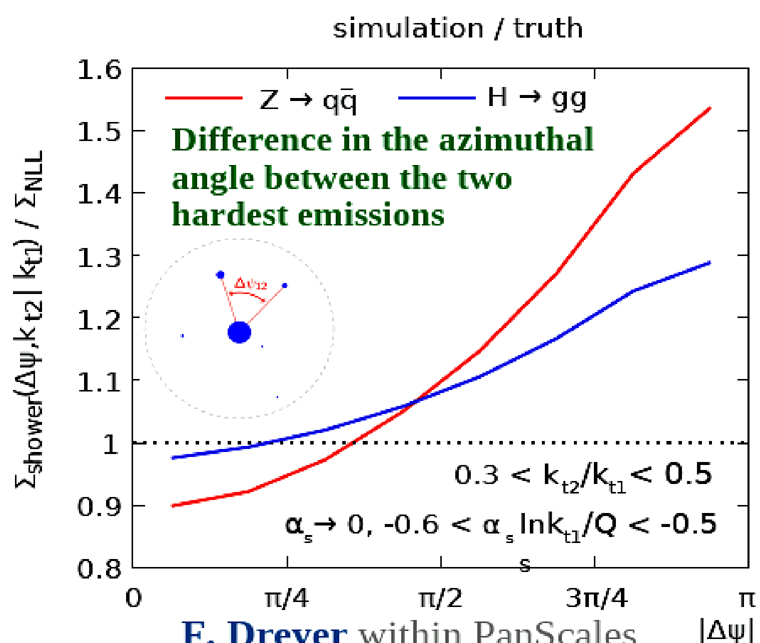
- "Sudakov"-safe variables of jet constituents: multiplicity, LHA, width/broadening, mass/thrust, C-parameter,...
- k=1: IRC-safe computable (N^nLO+N^nLL) via SCET (but uncertainties from non-pQCD effects)

- MC parton showers feature unphysical differences in the radiation pattern of quark & gluon jets



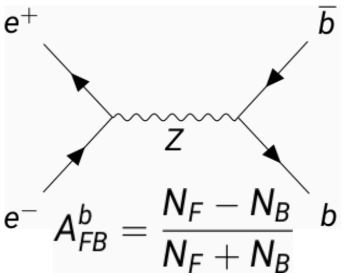
F. Dreyer within PanScales

Nonphysical quark/gluon differences in common dipole showers

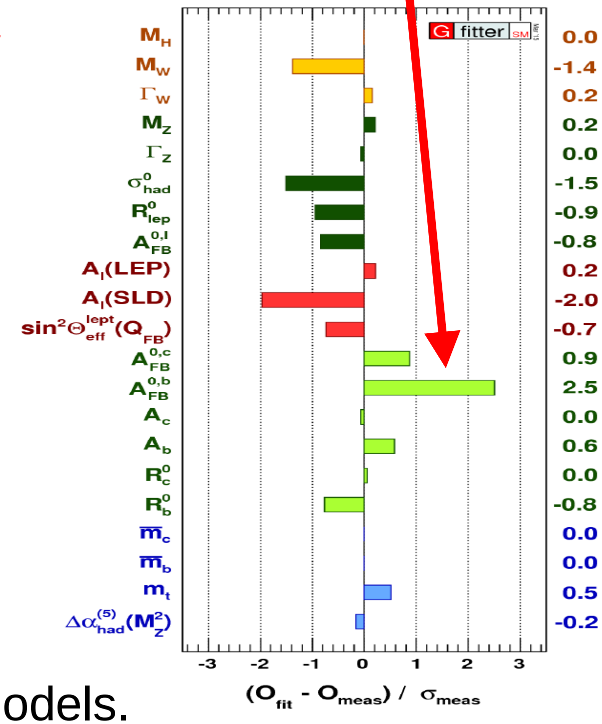
[S.Ferrario-Ravasio]

QCD uncertainties on EWK observables

- With ×10⁵ more Z's than LEP, some EWPO uncerts at FCC-ee will be dominated by QCD syst.
  Example: $e^+e^- \rightarrow b\bar{b}$ forward–backward asymmetry
  – 8 measurements at LEP: 4 lepton-, 4 jet-charge-based
  – Largest EWPO discrepancy today wrt. the SM: 2.8σ



- Exp. uncertainties of $A_{FB}^{0,b}$ at LEP: ~1.6%
  – Statistical: ±1.5% (~0.05% at FCC-ee)
  – Systematics: ±0.6% (QCD-related: ±0.4%)

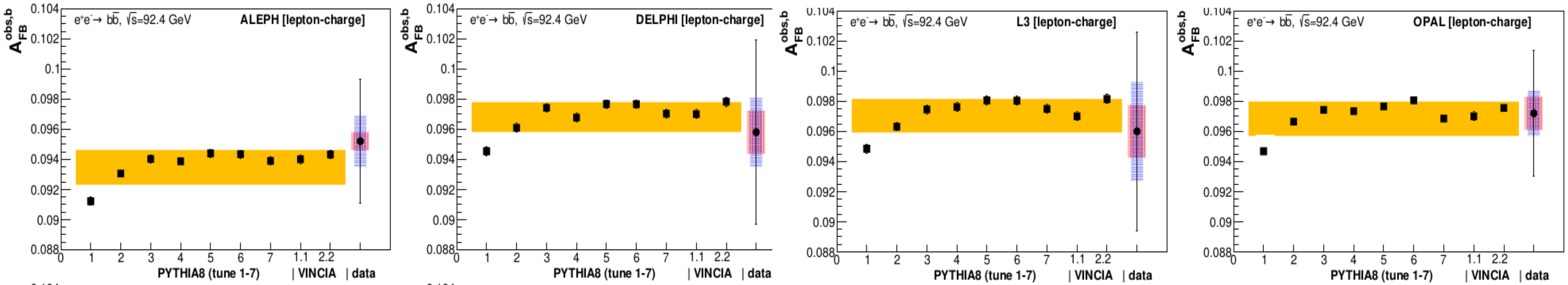


- QCD effects on $A_{FB}^{0,b}$ (depending strongly on exp. selection procedure):
  – Gluon splitting (TH control: α_s^2 corrections)
  – Smearing of b-jet/thrust axis
  – b and c radiation & fragmentation. B and D decay models.
  [Uncertanties estimated by Abbaneo et al., EPJC 4 (1998)]

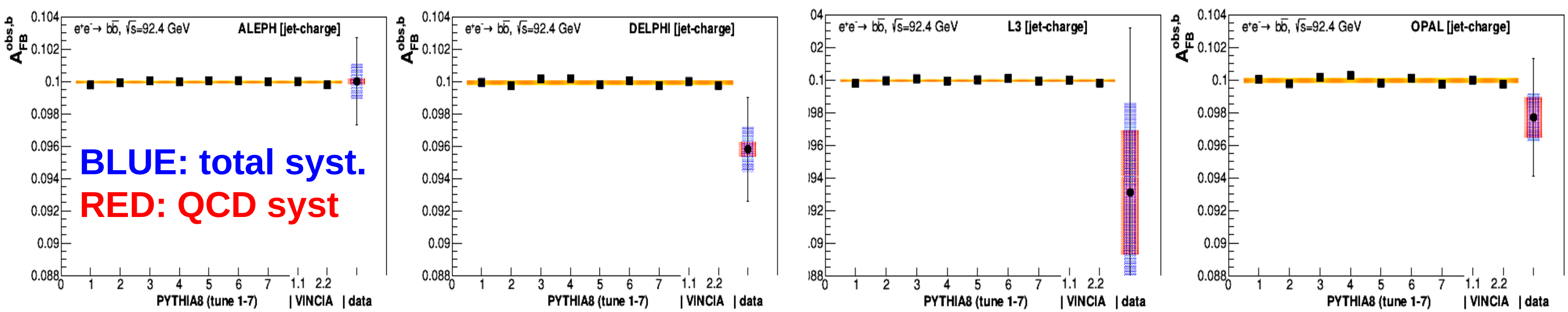
- Impact of QCD effects on $A_{FB}^{0,b}$ revisited by implementing original analyses in up-to-date retuned parton-shower+hadronization MCs

Reduced QCD uncertainties on A_{FB} at Z pole

- QCD uncertainties recomputed from PYTHIA8.226 (7 tunes) & VINCIA2.2
- $e^+e^- \rightarrow b\bar{b}$ forward–backward asymmetry for lepton-based analyses:



- $e^+e^- \rightarrow b\bar{b}$ forward–backward asymmetry for jet-charge-based analyses:



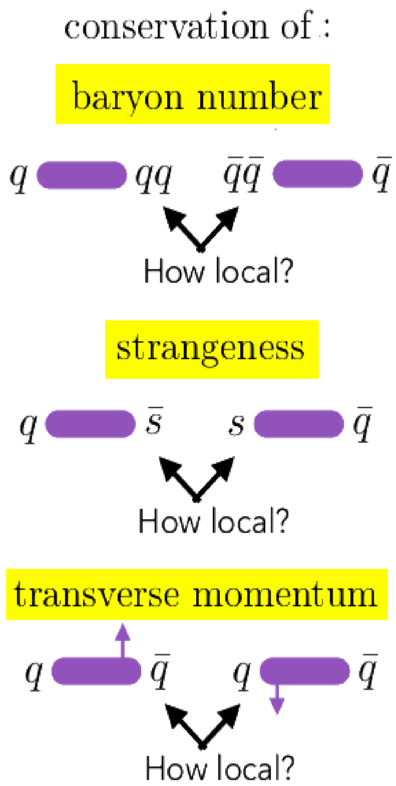
- 2020 vs. 1998 parton shower+hadronization uncertainties halved:
  – Lepton-based analyses: ~1.4% → ~0.7%
  – Jet-charge-based analyses: ~0.7% → ~0.3%

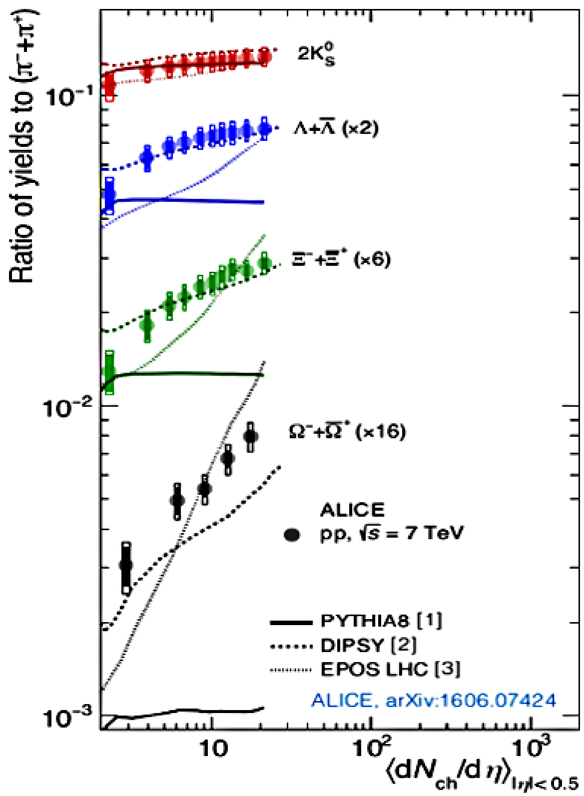
[DdE & Yan, 2011.00530 [hep-ph]]

- FCC-ee data will significantly improve PS & non-pQCD syst. uncert.

Non-pQCD: Detailed hadronization studies

- Precision low-p_T PID hadrons in 10^{12} $e^+e^- \to (10^{14}$ hadrons) for studies:
  - Baryon & strangeness production. Colour string dynamics.
  - Final-state correlations (spin: Bose-Einstein, Fermi-Dirac; momenta; space)
  - Bound state formation: Onia, multi-quark states, glueballs, ...





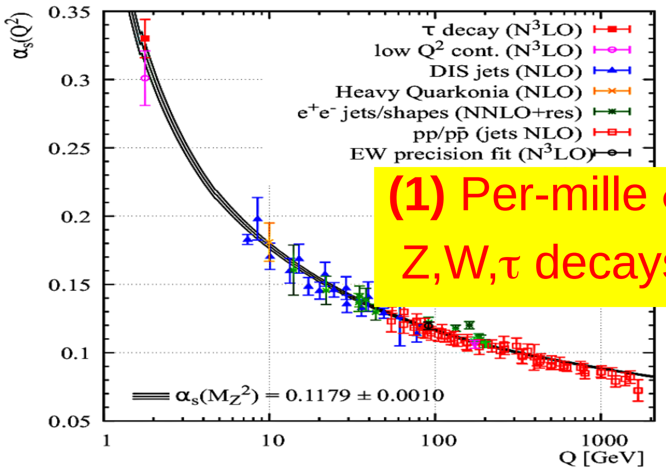
- ► Understand breakdown of universality of parton hadronization with system size observed at LHC.

- Baseline vacuum e^+e^- studies for high-density QCD in small & large systems.

Also impact e.g. ultra-high-energy cosmic-ray MCs (muon puzzle)

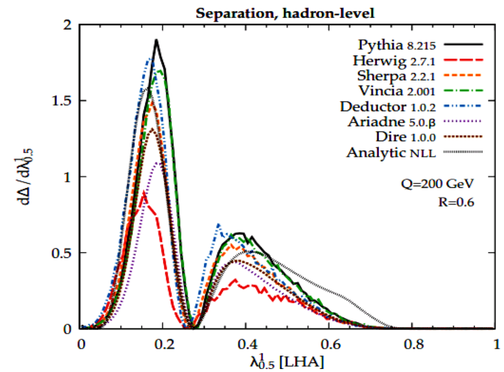
Summary: High-precision QCD at FCC-ee

- ☛ The precision needed to fully exploit all future ee/pp/ep/eA/AA SM & BSM programs requires exquisite control of pQCD & non-pQCD physics.
- ☛ Unique QCD precision studies accessible at FCC-ee:

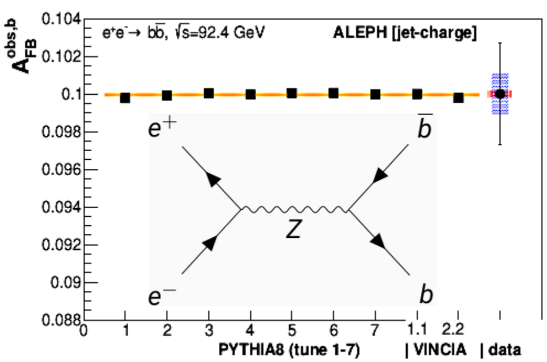


(1) Per-mille α_s via hadronic Z,W,τ decays, evt shapes...

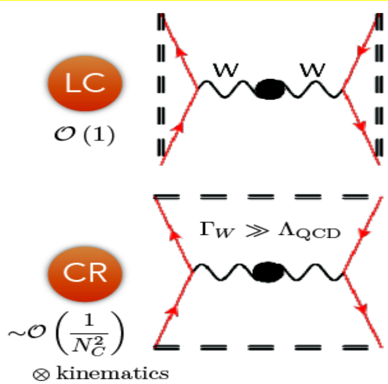
(2) N^nLO+N^nLL parton showers
Ultimate g/q/Q discrimination



(3) <0.1% PS+hadroniz. uncert. for EWPOs



(4) <<1% control of colour reconnection



(5) High-precision hadronization: