Experimental QCD at future pp & e^+e^- colliders

“Strong interactions” ESPP Update

Granada, May 2019

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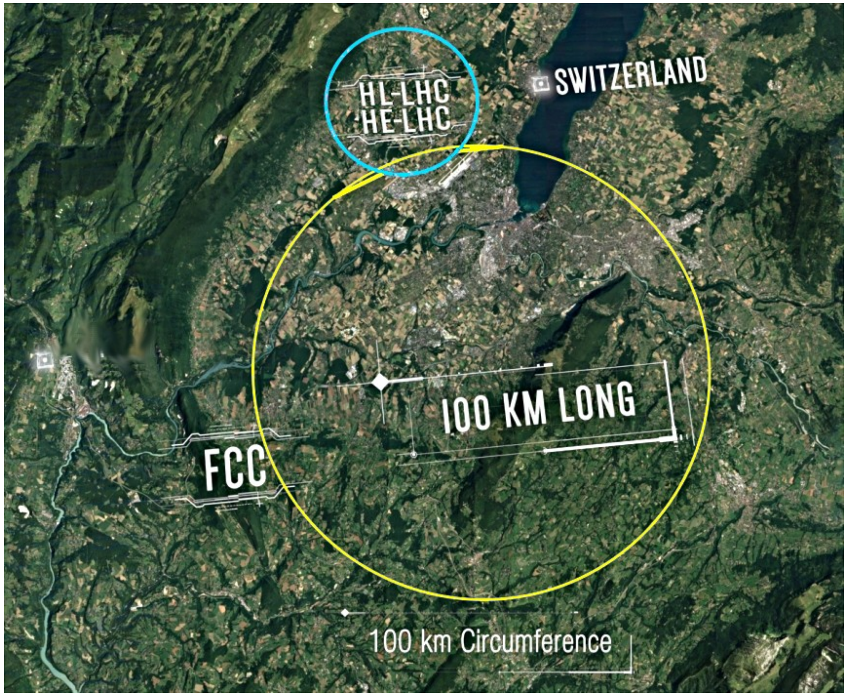
(CERN)

Future pp & e^+e^- colliders with QCD programme

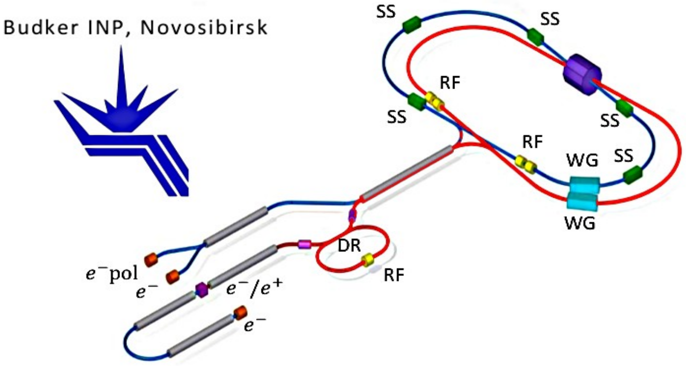
▶ Future proton-proton colliders:

1. HL-LHC: pp(14 TeV), 3 ab^{-1}
   ESPPU input #110, #152
2. HE-LHC: pp(27 TeV), 10–15 ab^{-1}
   ESPPU input #160
3. FCC-hh: pp(100 TeV), 20 ab^{-1}
   ESPPU input #135



▶ Future electron-positron colliders:

4. FCC-ee(*): e^+e^-(90,160,250,350 GeV), 1–100 ab^{-1}
   ESPPU input #160
5. SCT (Super Charm-Tau) Factory(**): e^+e^-(2–6 GeV), ~1 ab^{-1}
   ESPPU input #132



[Note: Other QCD machines: DIS, heavy-ions and/or fixed-target, covered by other talks].

[Note: Also in principle CEPC(*), BELLE-II(**) but to be developed]

QCD = Key piece at future ee, pp colliders

► Though QCD is *not per se* the main driving force behind future colliders, QCD is crucial for many pp, ee measurements (signals & backgrounds):

- High-precision α_s: Affects all x-sections & decays (esp. Higgs, top, EWPOs).
- N^nLO corrs., N^nLL resummations: For all precise pQCD x-sections & decays.
- High-precision PDFs: Affects all precision W,Z,H (mid-x) measurements & all searches (high-x) in pp collisions.
- Heavy-Quark/Quark/Gluon separation (subjet structure, boosted topologies..): Needed for all precision SM measurements & BSM searches with final jets.
- Semihard QCD (low-x gluon saturation, multiple hard parton interactions,…): Leading x-sections at FCC-pp (Note: Q_0~10 GeV at 100 TeV).
- Non-perturbative QCD: Colour reconnection affects e^+e^- jetty final-states: $e^+e^- \rightarrow WW \rightarrow 4j$, $Z \rightarrow 4j$, tt (m_{top} extraction). Parton hadronization, ...

QCD physics at future pp & e^+e^- machines

(1) QCD coupling
(FCC-ee, FCC-pp, SCT)

(2) Parton Distribution Functions
(HL-LHC, HE-LHC, FCC-hh)

(3) Jet substructure & flavour tagging
(FCC-ee, FCC-pp)

(4) Non-perturbative QCD
(FCC-ee, SCT, HL-LHC)

NOTE: Only UNIQUE QCD measurements, inaccessible at any current machine, are covered.

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Importance of the QCD coupling α_s

- Least-known of couplings: $\delta\alpha \sim 10^{-10} \ll \delta G_F \ll 10^{-7} \ll \delta G \sim 10^{-5} \ll \delta\alpha_s \sim 10^{-3}$
- Impacts all QCD x-sects.&decays. Leading param. uncert. H, t, EWPOs:

Process	σ (pb)	$\delta\alpha_s(\%)$	PDF $+\alpha_s(\%)$	Scale(%)
ggH	49.87	$\pm$ 3.7	-6.2 +7.4	-2.61 +0.32
ttH	0.611	$\pm$ 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	$\pm$ 7.1	$\pm$ 0.1%	$\pm$ 2.3 %
$H \to gg$	126	$\pm$ 4.1	$\pm$ 0.1%	$\pm$ 0 %

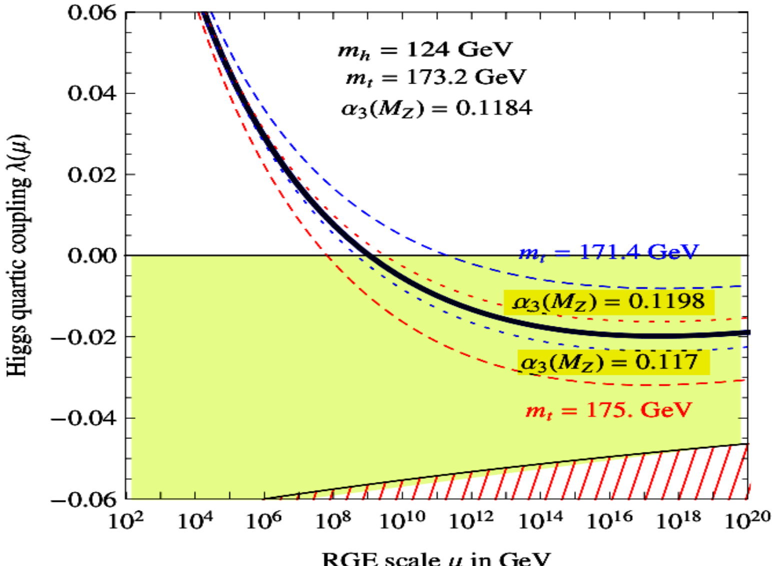
Msbar mass error budget (from threshold scan)

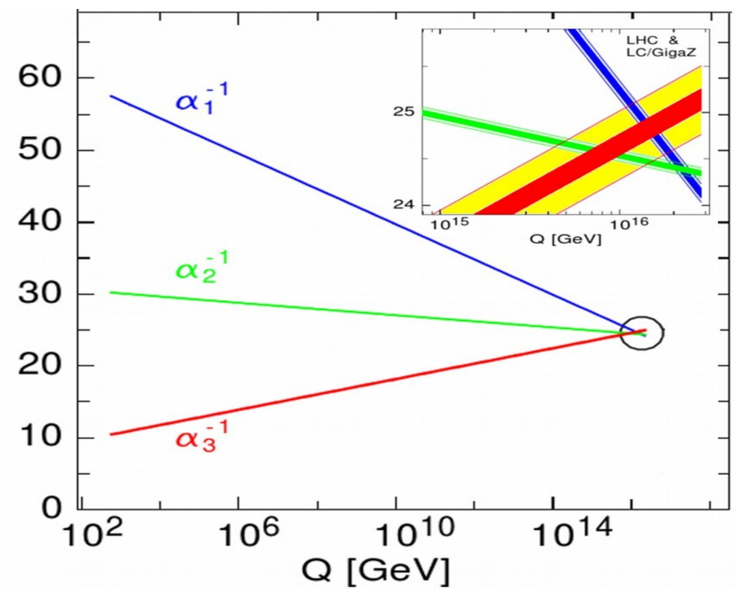
$(\delta M_t^{\text{SD-low}})^{\text{exp}}$	$(\delta M_t^{\text{SD-low}})^{\text{theo}}$	$(\delta\overline{m}_t(\overline{m}_t))^{\text{conversion}}$	$(\delta\overline{m}_t(\overline{m}_t))^{\alpha_s}$
40 MeV	50 MeV	7 – 23 MeV	70 MeV

$\Rightarrow$ improvement in α_s crucial $\qquad \delta\alpha_s(M_z) = 0.001$

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	$\delta\alpha_s$

- Impacts physics approaching Planck scale: EW vacuum stability, GUT

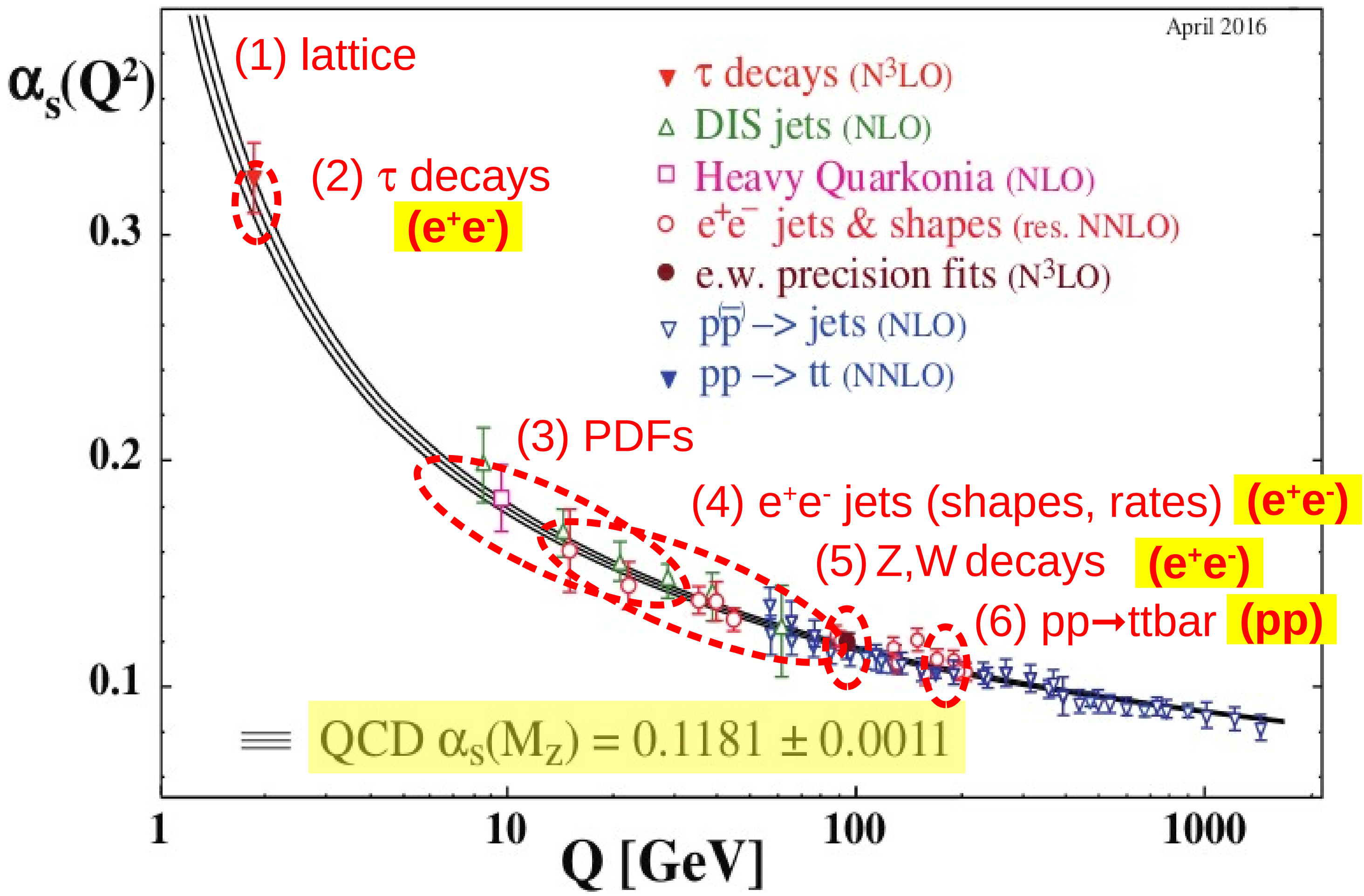




World α_s determination (PDG 2018)

- Determined today by comparing 6 experimental observables to pQCD NNLO,N^3LO predictions, plus global average at the Z pole scale:

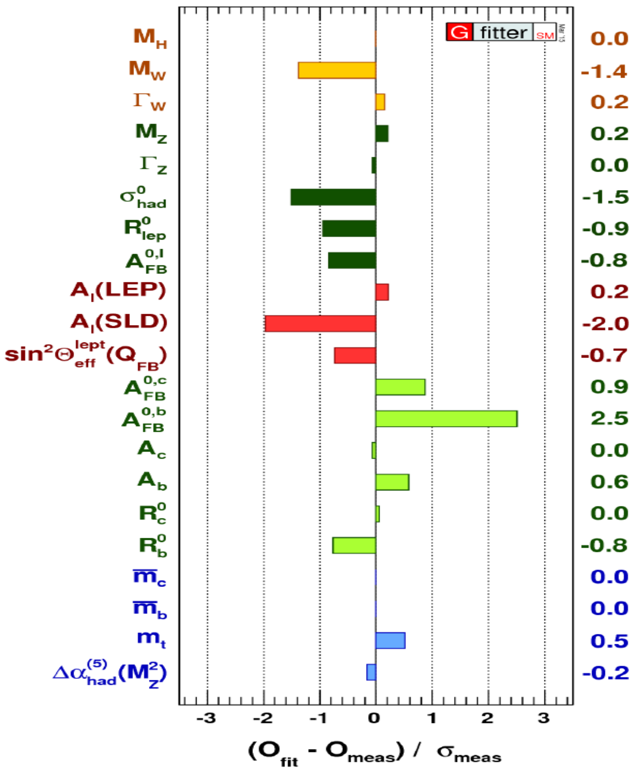
[Bethke/Dissertori/Salam]

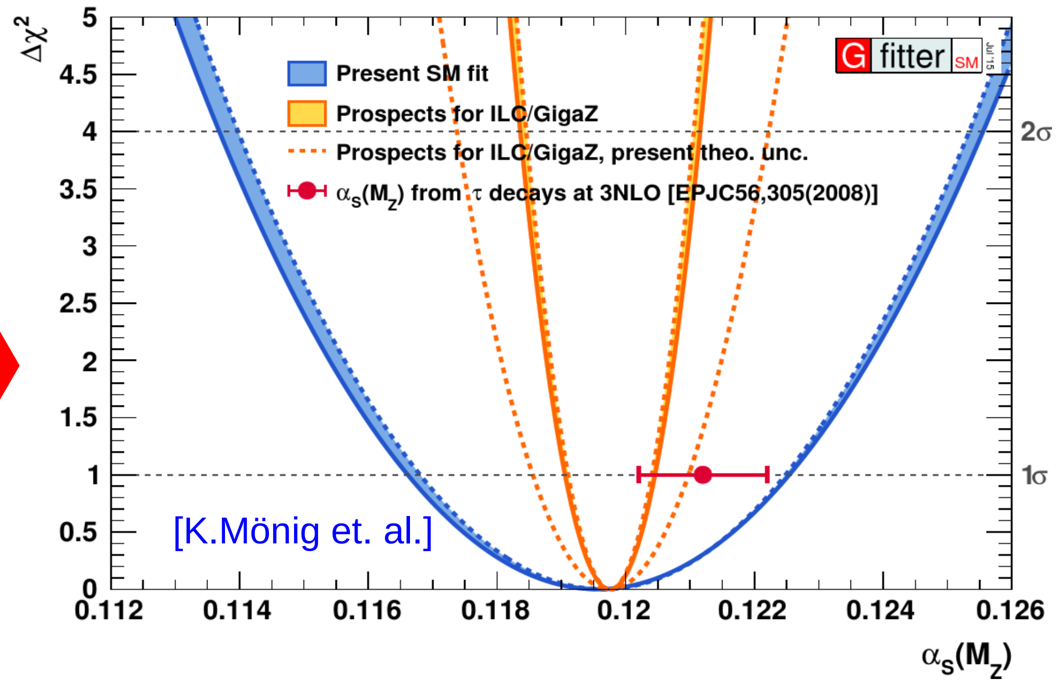


α_s via hadronic Z decays (FCC-ee)

- Computed at N^{3}LO: $R_Z \equiv \frac{\Gamma(Z\to h)}{\Gamma(Z\to l)} = R_Z^{EW} N_C (1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5)) + \delta_m + \delta_{np})$
- LEP Z pseudobservables: $R_\ell^0 = \frac{\Gamma_{had}}{\Gamma_\ell}$, $\sigma_{had}^0 = \frac{12\pi}{m_Z}\frac{\Gamma_e\Gamma_{had}}{\Gamma_Z^2}$, $\sigma_\ell^0 = \frac{12\pi}{m_Z}\frac{\Gamma_\ell^2}{\Gamma_Z^2}$ (exp. unc. <0.1%)

  Also after Higgs discovery, α_s can be directly determined from full fit of SM:





Today: α_s (M$_z$) = 0.1196 ± 0.0030 (±2.5%)

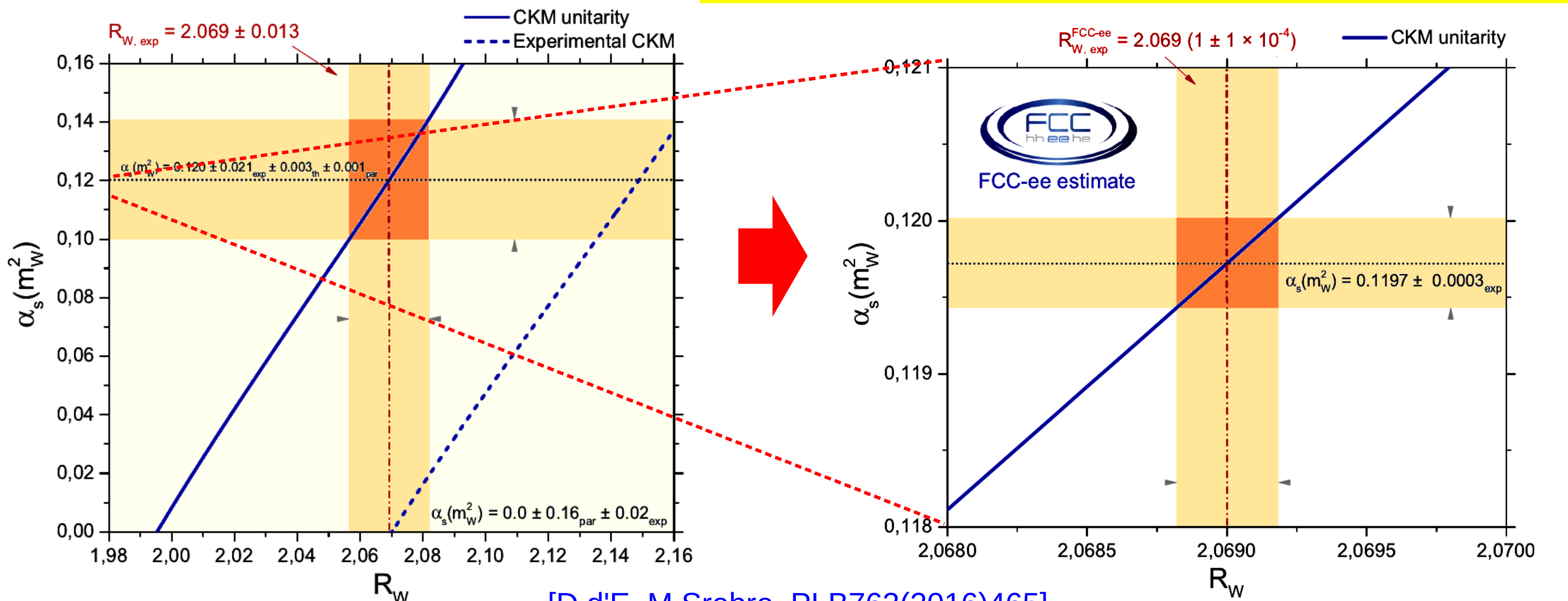
- FCC-ee: – Z stats (×10^5 LEP) will lead to: **$\delta\alpha_s$ < 0.15%**

  – TH (parametric) uncertainties: $\sin^2\theta_{eff}$, m_W, m_{top}

α_s via hadronic W decays (FCC-ee)

- Computed at N^{2,3}LO: $\Gamma_{\rm W,had} = \frac{\sqrt{2}}{4\pi} G_{\rm F} m_{\rm W}^3 \sum_{\rm quarks\ i,j} |V_{\rm i,j}|^2 \left[1 + \sum_{k=1}^{4} \left(\frac{\alpha_{\rm s}}{\pi}\right)^k + \delta_{\rm electroweak}(\alpha) + \delta_{\rm mixed}(\alpha\alpha_{\rm s})\right]$
- LEP: BR_W = 0.6741±0.0027 (±0.4%)
  Extraction with large exp. & parametric (CKM V_{cs}) uncertainties:

Today: α_s (M_z) = 0.117 ± 0.040 (±35%)

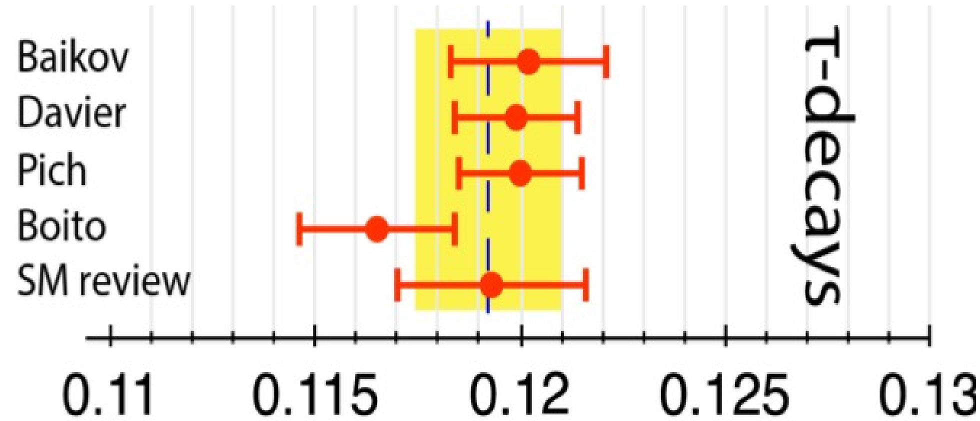


[D.d'E, M.Srebre, PLB763(2016)465]

- FCC-ee: – Huge W stats (×10⁴ LEP) will lead to: **$\delta\alpha_s$ < 0.2%**
  – TH (param.) uncertainty: $|\delta V_{cs}|$ to be significantly improved (10^{-4})

α_s from hadronic τ decays (SCT, FCC-ee)

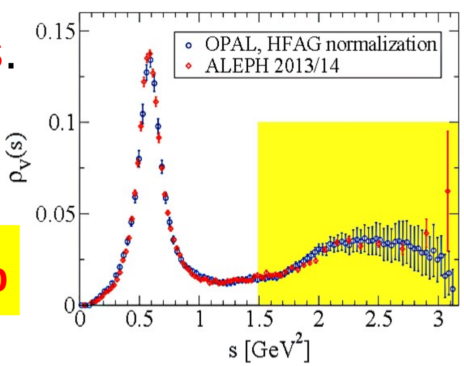
- Computed at N³LO: $R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = S_{\rm EW} N_C (1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\rm np})$
- Experimentally: $R_{\tau,exp}$ = 3.4697 ± 0.0080 (±0.23%)
- Various pQCD approaches (FOPT vs CIPT) & treatment of non-pQCD corrections (note: $(\Lambda/m_\tau)^2$ ~1%), yield different results.

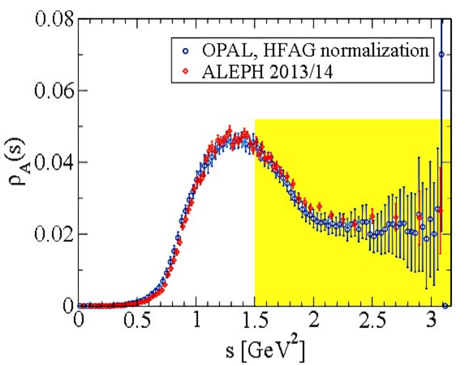


Today: $\alpha_s(M_Z)$= 0.1192 ± 0.0018 **(±1.5%)**

- Future prospects:
  - Understand FOPT vs CIPT differences.
  - Better exp. spectral functions needed (high stats & better precision):
    SCT: $\mathcal{O}(10^{10})$ $e^+e^- \to \tau\tau$
    FCC-ee: $\mathcal{O}(10^{11})$ from $Z(\tau\tau)$

$\delta\alpha_s$ < 1%





α_s running at the TeV scale (FCC-pp)

- Proton-proton collisions above LHC energies provide the only known means to test asymptotic freedom & new coloured sectors above ~3 TeV:

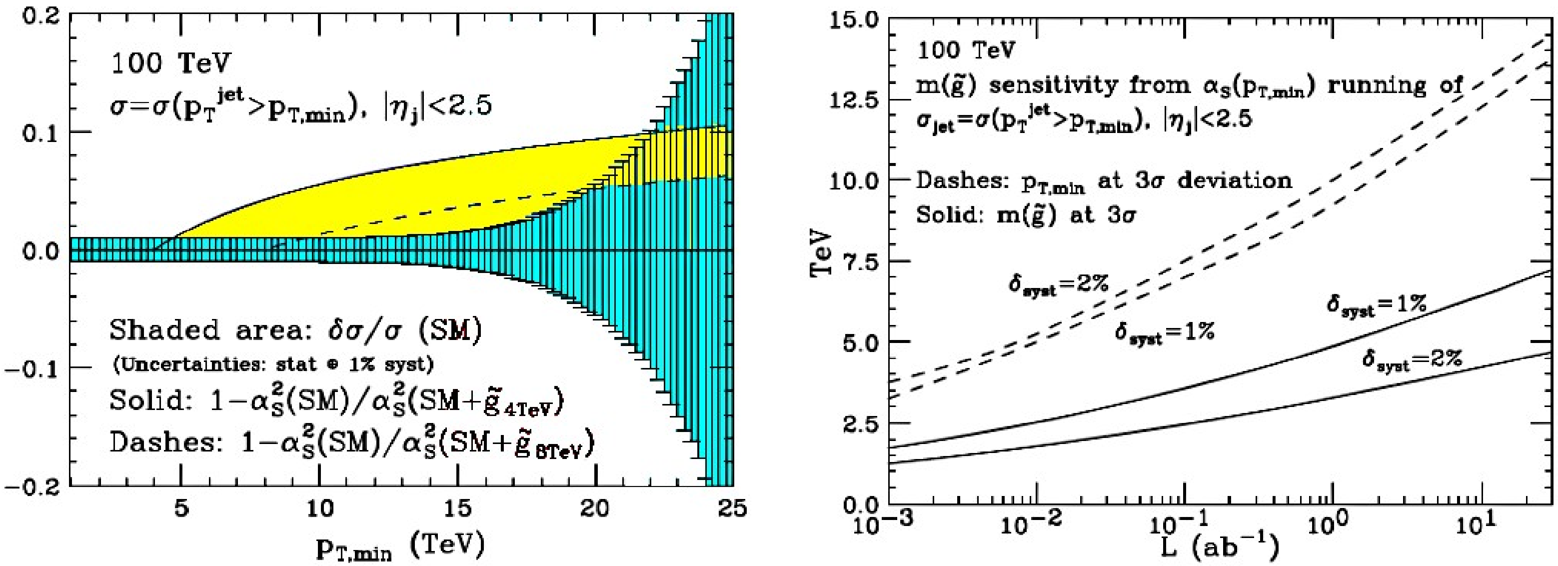


Figure 5.5: Left plot: combined statistical and 1% systematic uncertainties, at 30 ab^{-1}, vs p_T threshold; these are compared to the rate change induced by the presence of 4 or 8 TeV gluinos in the running of α_S. Right plot: the gluino mass that can be probed with a 3σ deviation from the SM jet rate (solid line), and the p_T scale at which the corresponding deviation is detected.

- FCC-pp: – Jet cross sections with <10% stat. uncert. up to p_T~25 TeV
  – Sensitivity to m_g=4–8 GeV gluinos in α_s running.

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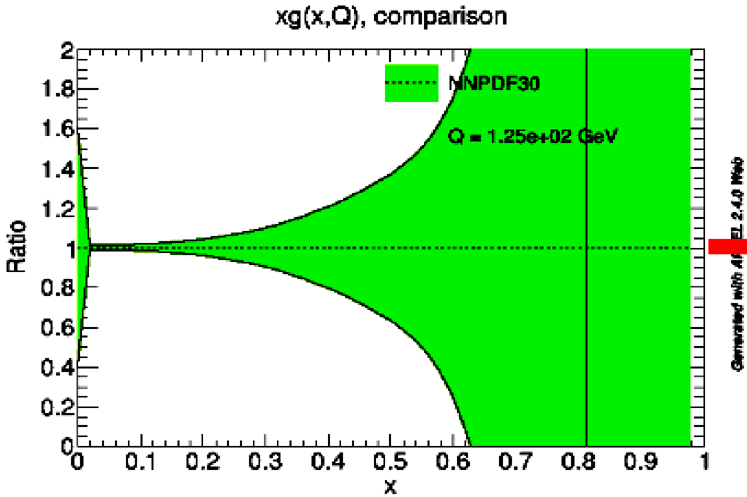
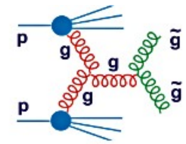
PDFs impact on new BSM / QCD physics

New physics at high-x?



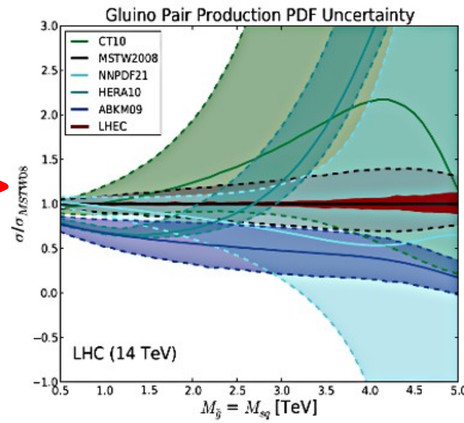
GLUON

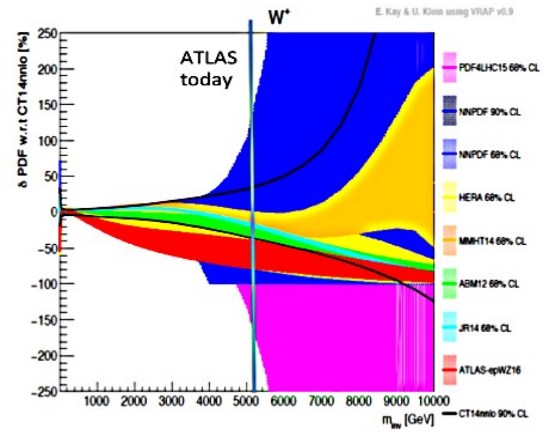
SUSY, RPC, RPV, LQS..



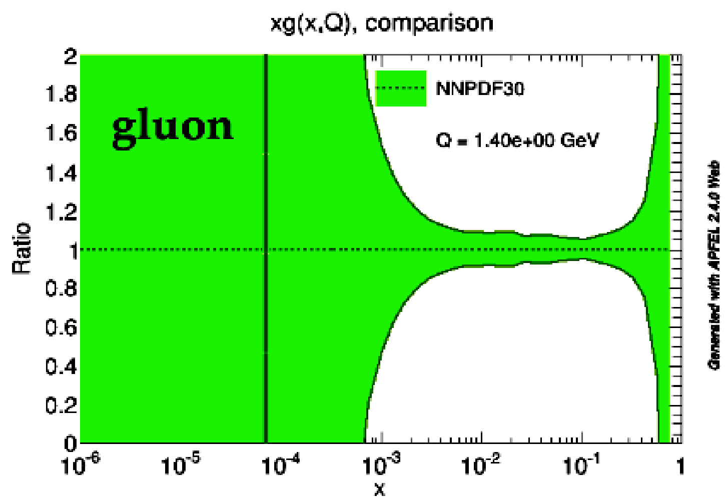
QUARKS

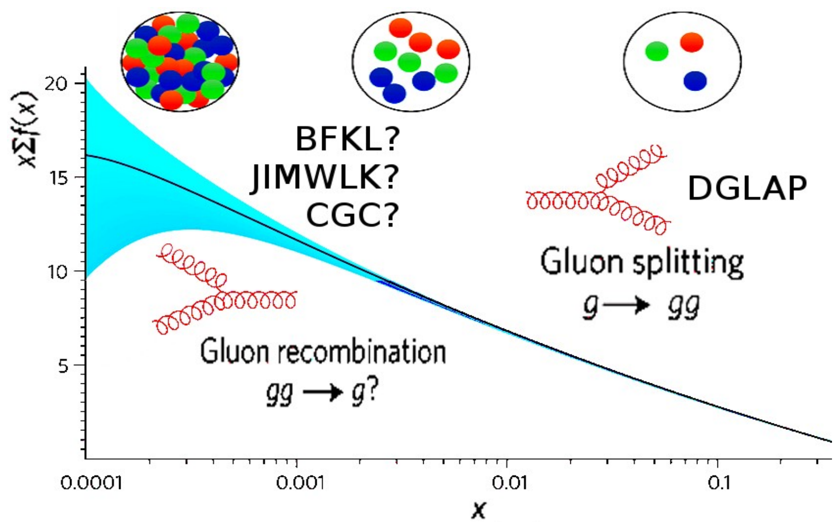
Exotic+ Extra boson searches at high mass





New QCD evolution at low-x?

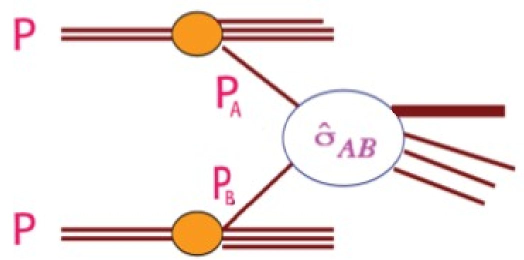


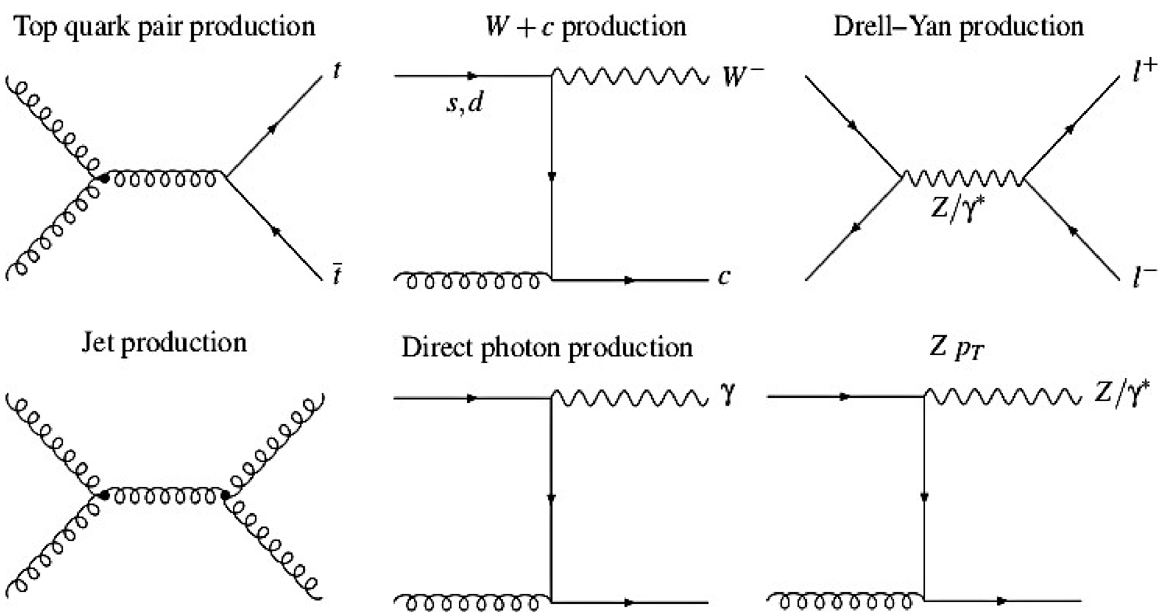


Improving PDFs with proton-proton data

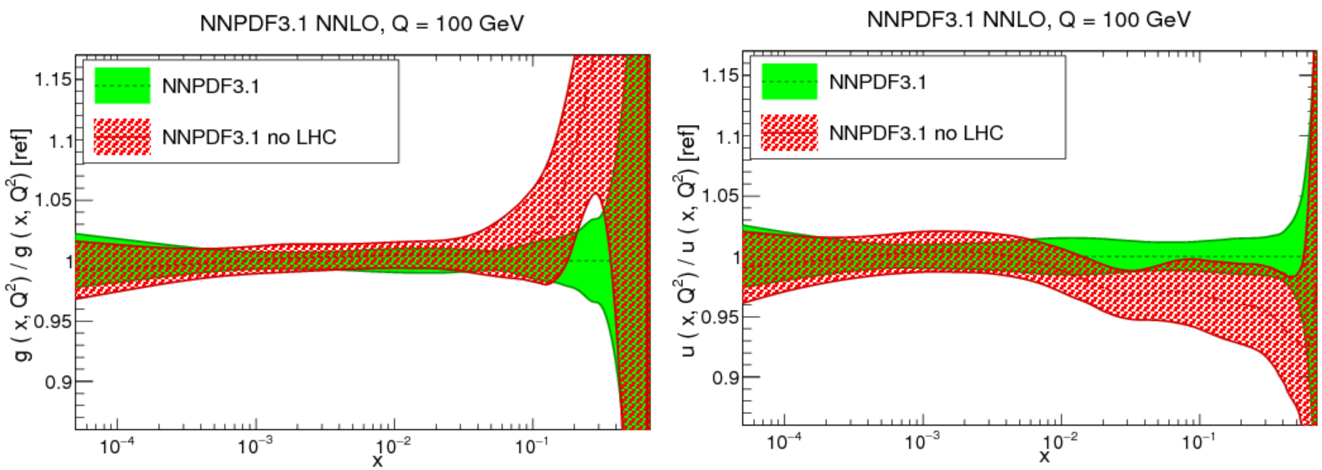
- 6 partonic processes in pp at the LHC have provided key PDF constraints:

$\sigma = \hat{\sigma} \otimes PDF$



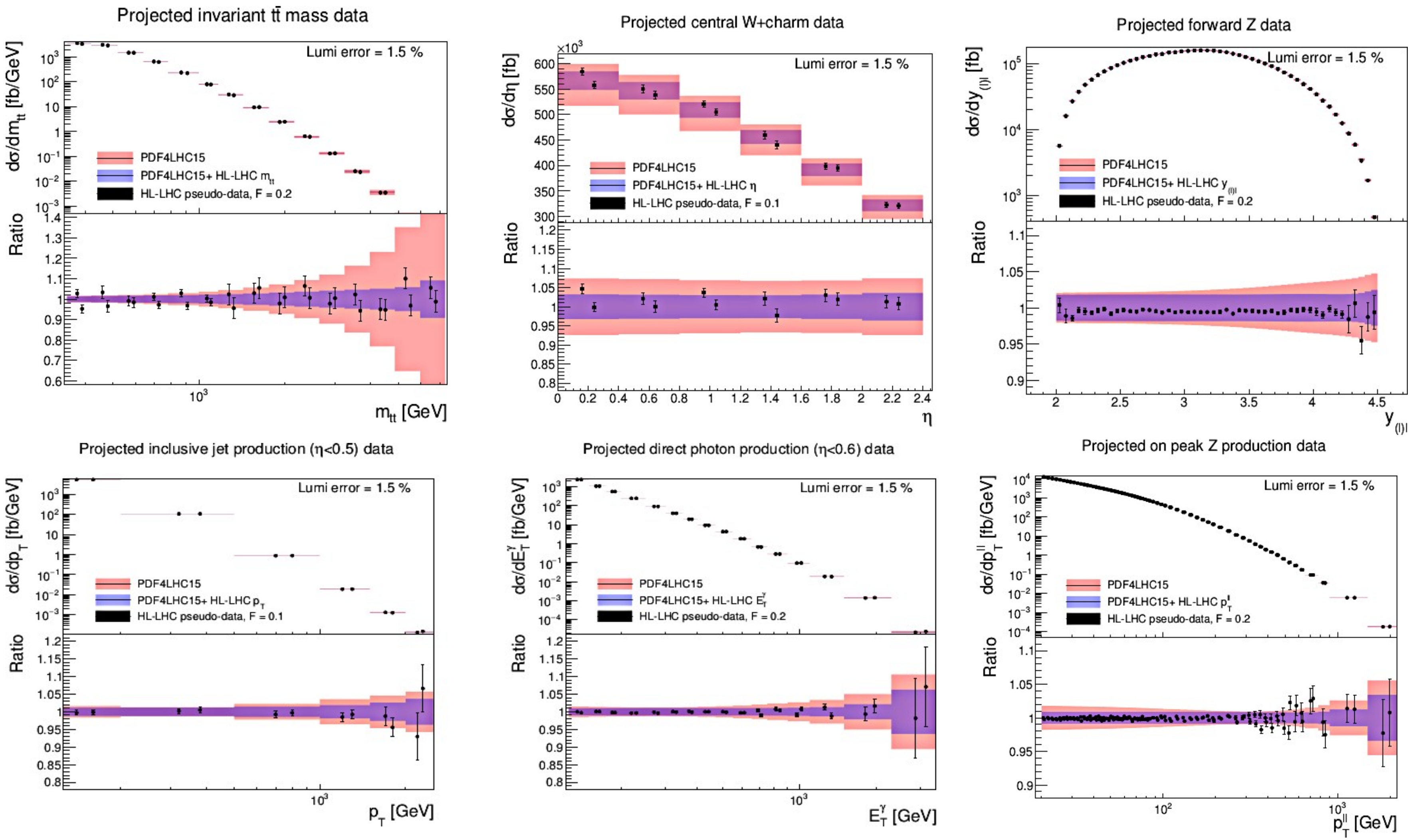


- Improved NNLO g, u, ... PDFs already today using LHC data:



Improved PDFs with pp data (HL-LHC)

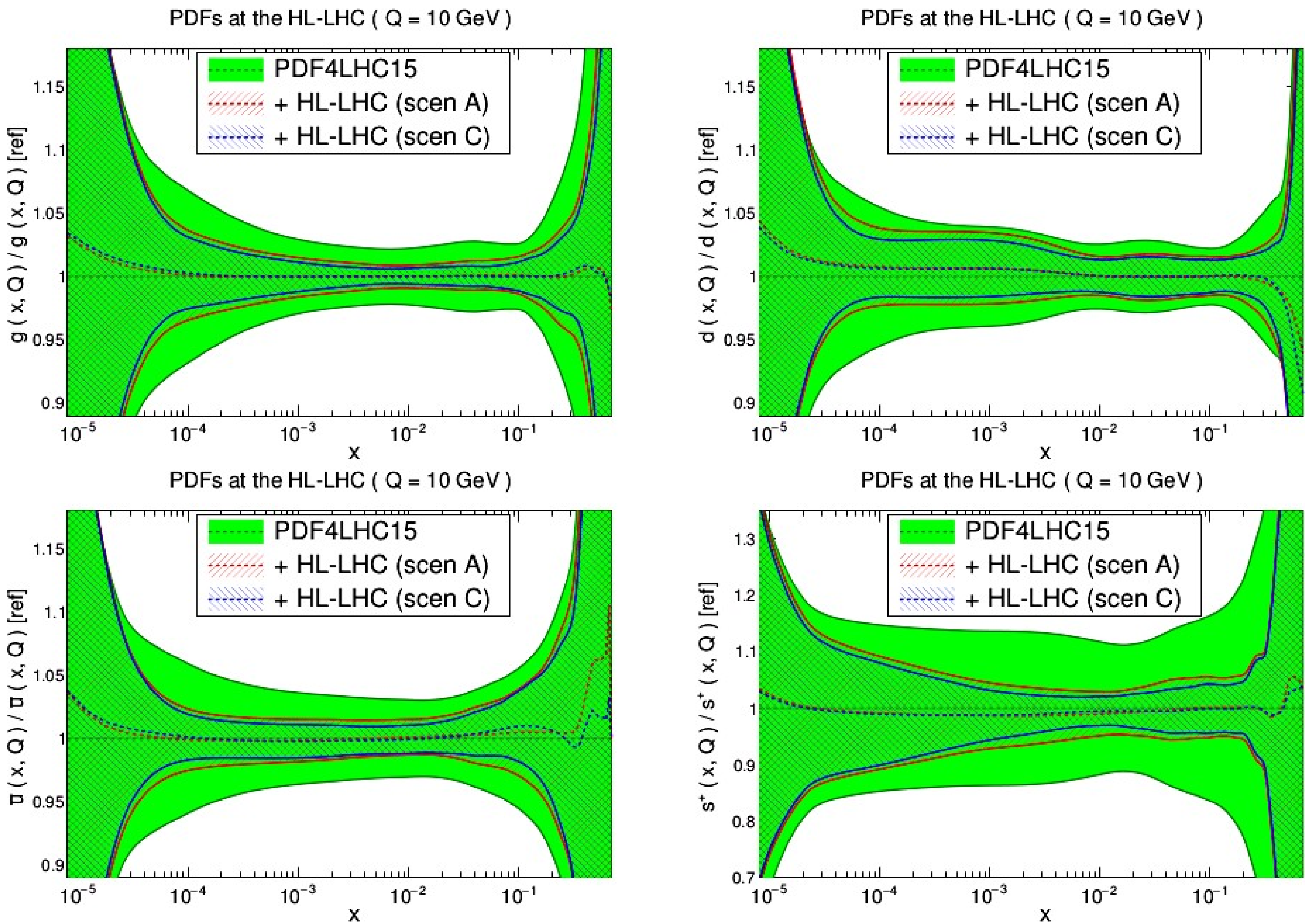
- Generation of HL-LHC pQCD pseudo-data (pp, 3 ab^{-1}):



[R.A. Khalek et al. arXiv:1810.03639]

- Significant constraining power in many phase space regions.

Improved PDFs with pp data (HL-LHC)

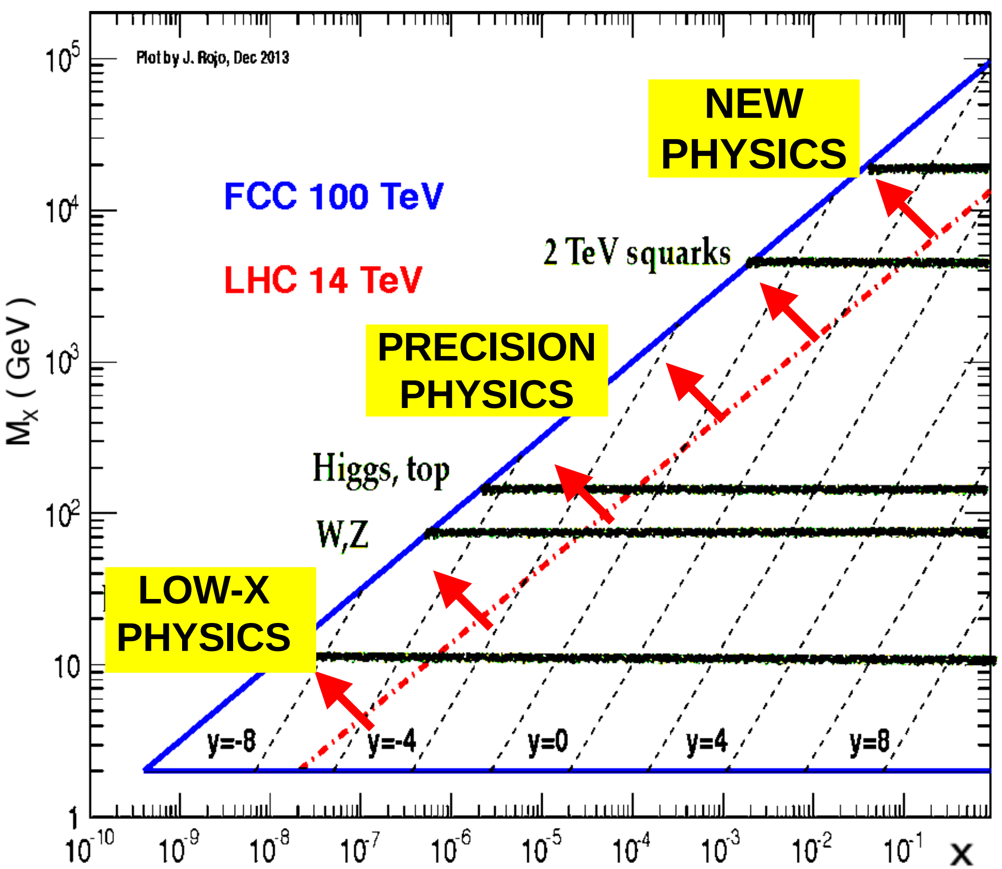


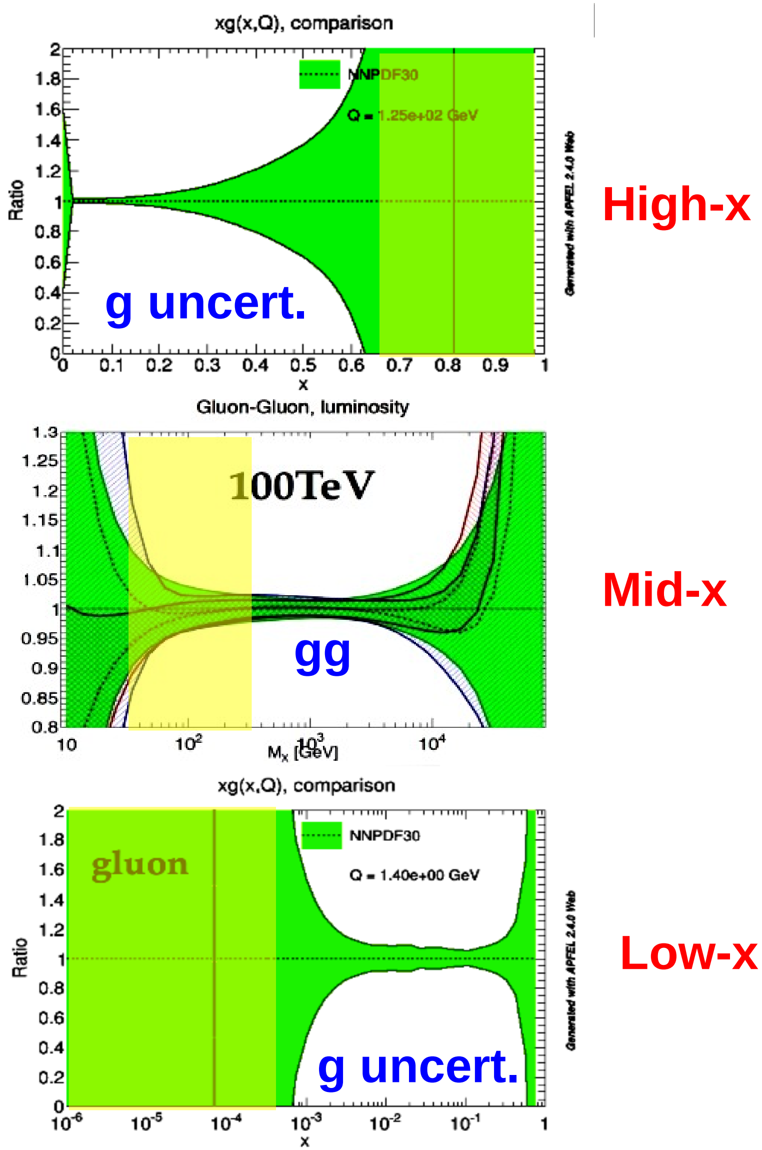
[R.A. Khalek et al. arXiv:1810.03639]

- Significant (factor ~2) PDF uncertainty reduction (with little dependence on projected systematics). But not at very low-,high-x...

PDFs: Still work to do for FCC...

- Still large PDF uncertainties in pp at 100 TeV in key (x,Q^2) regions:





- FCC-ep required to reach O(1%) uncertainty for σ(W,Z,H) at FCC-pp

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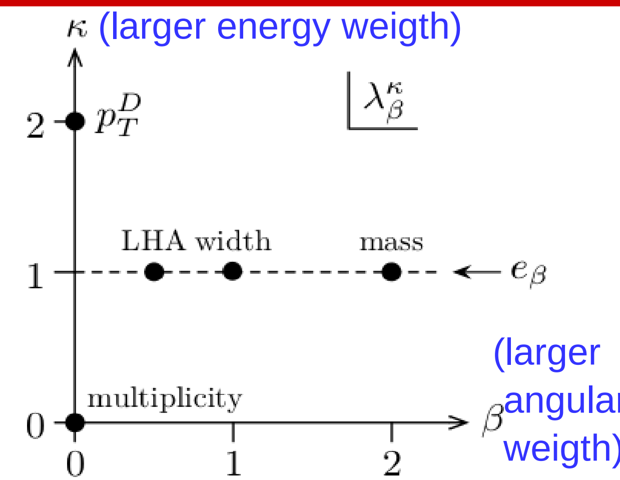
Precise jet substruct. & flavour tagging (FCC-ee)

- State-of-the-art jet substructure studies based on angularities ("Sudakov"-safe) variables of jet constituents: multiplicity, LHA, width/broadening, mass/thrust, C-parameter,...

$$\lambda_\beta^\kappa = \sum_{i\in \text{jet}} z_i^\kappa \theta_i^\beta ,$$

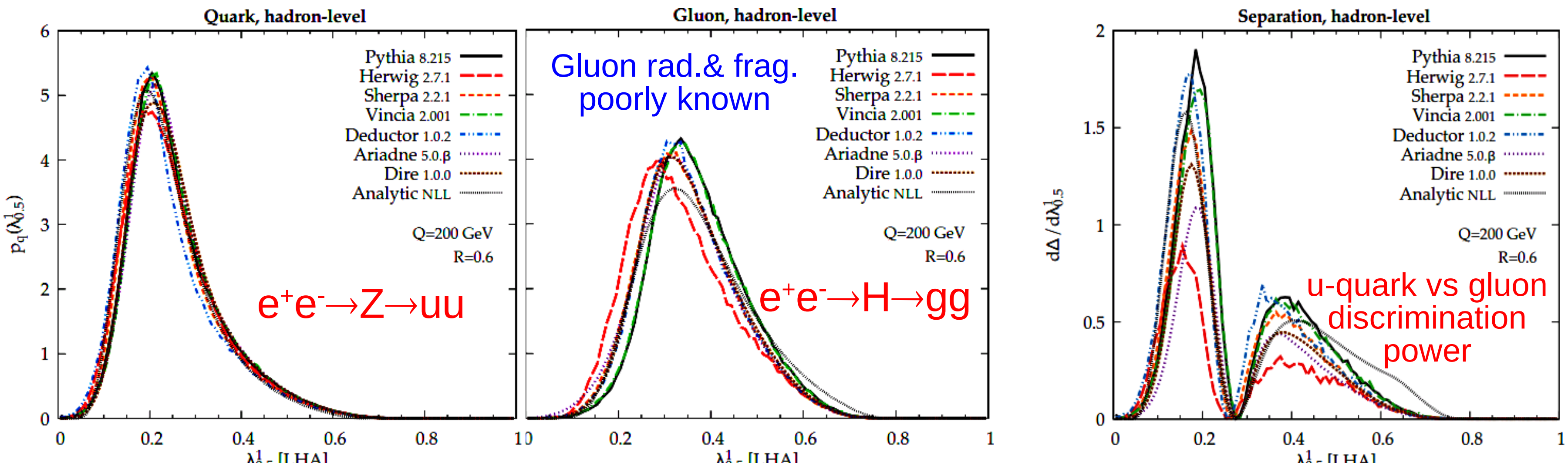
(normalized $E^n \times \theta^n$ products)



- k=1: IRC-safe computable (N^nLO+N^nLL) via SCET (but uncertainties from non-pQCD effects)

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

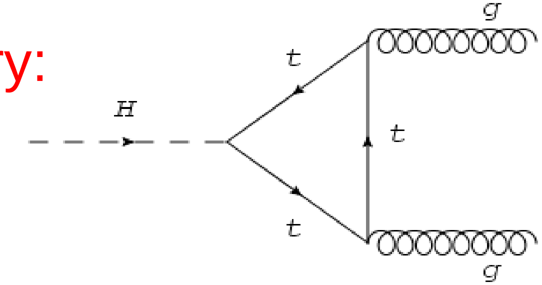
- MC parton showers differ on gluon (less so quark) radiation patterns:



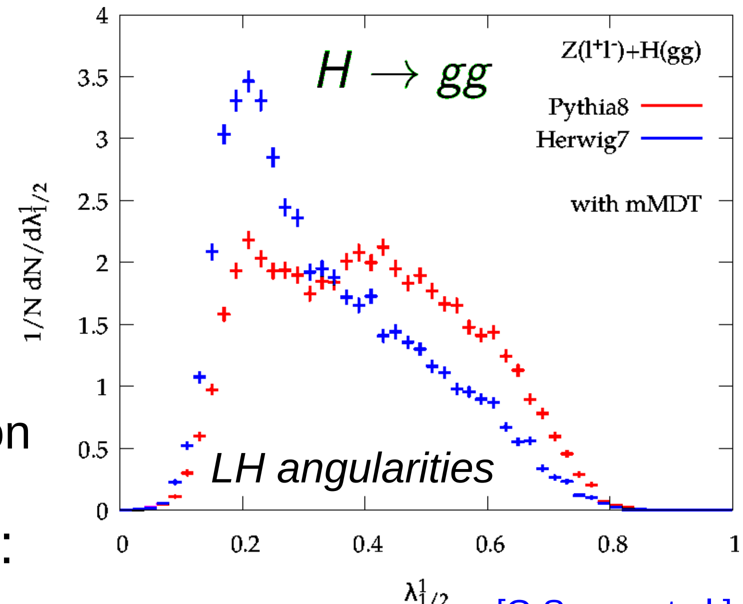
[G.Soyez et al.]

High-precision gluon & quark jet studies (FCC-ee)

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



- Multiple handles to study gluon radiation & g-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 resolution

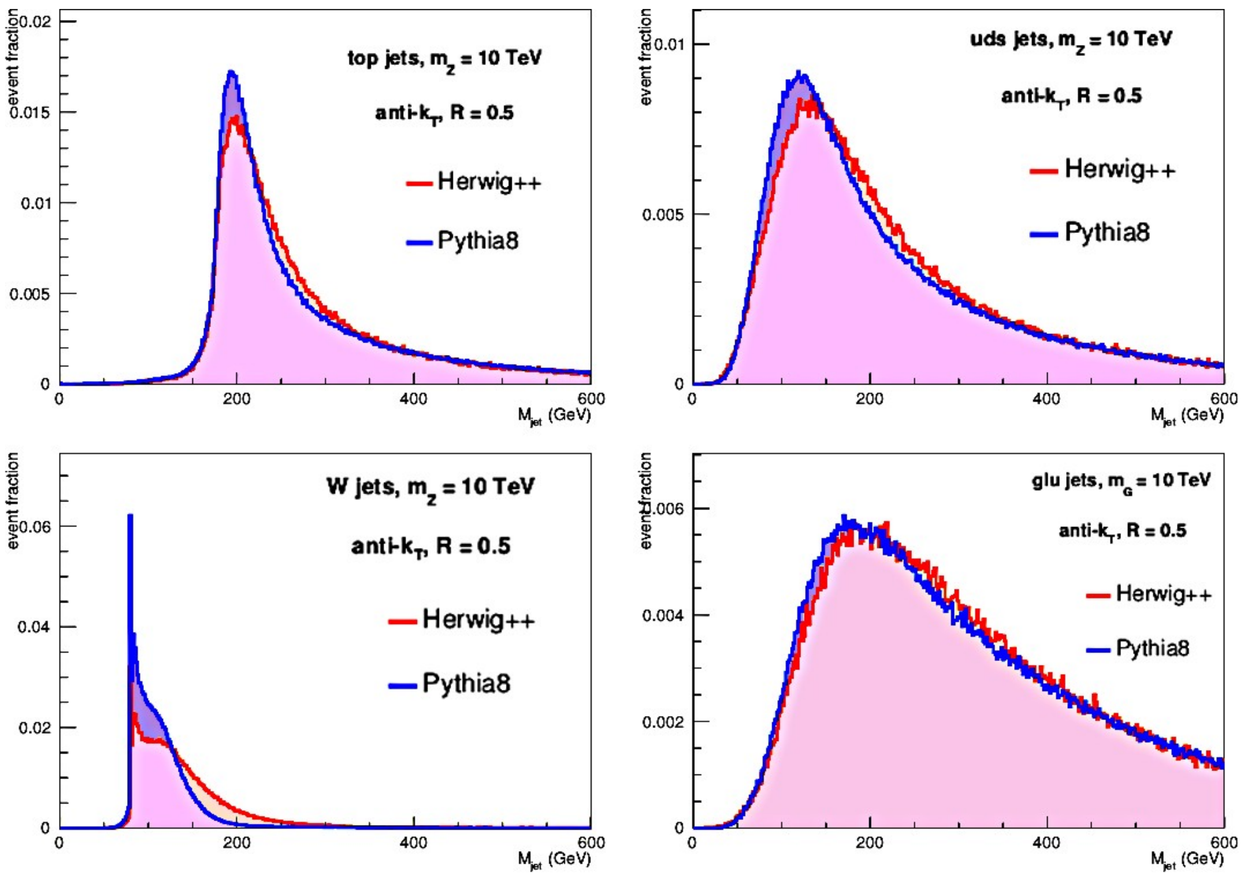


[G.Soyez et al.]

- Multiple high-precision analyses at hand:
  – BSM: Improve q/g/Q discrimination tools
  – 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?

Highly-boosted partons (FCC-pp)

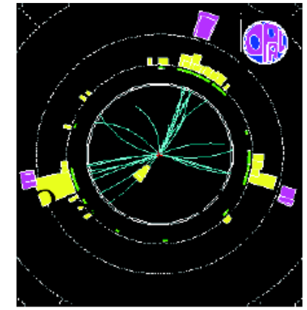
- Proton-proton collisions at 100 TeV provide uninque conditions to produce & study highly-boosted objects ($\theta<E_j/m_{jj}$): boosted tops, $R_{BSM} \rightarrow jj$, high-p_T Higgs studies,...
- MC-dependent quark vs. gluon jet (& jet radius) differences:



α_s via e^+e^- event shapes & jet rates (FCC-ee)

- Computed at $N^{2,3}LO+N^{(2)}LL$ accuracy.
- LEP data for thrust, C-parameter, jet shapes, 3-jet x-sections

$$\tau = 1 - \max_{\hat{n}} \frac{\sum |\vec{p}_i \cdot \hat{n}|}{\sum |\vec{p}_i|}$$

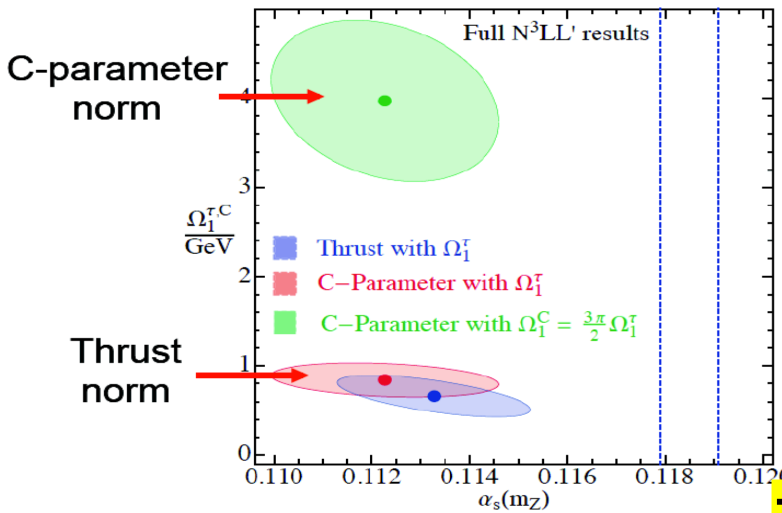


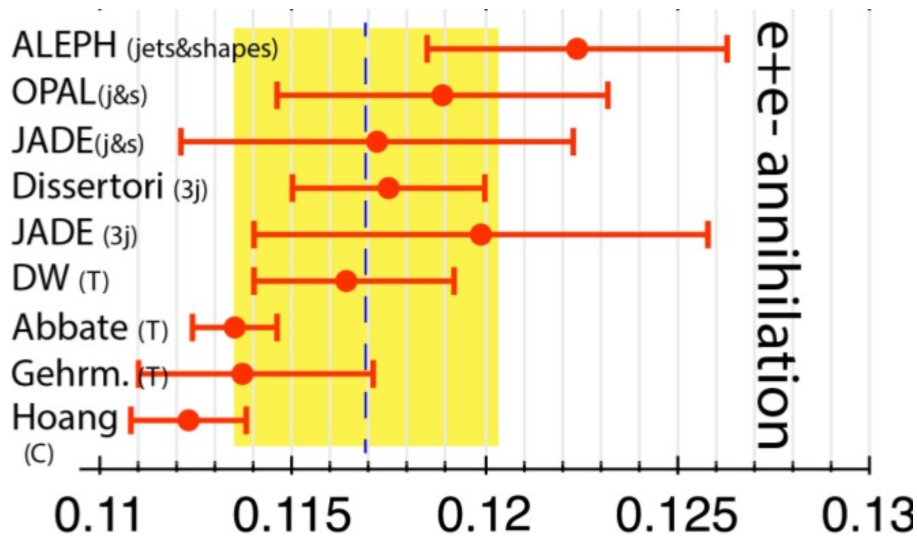
OPAL 3 jet event

Results sensitive to resummation & non-pQCD (hadronization) accounted for via MCs or analytically:

$$C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2\theta_{ij}}{(\sum_i |\vec{p}_i|)^2}$$

[S.Kluth et al., A.Hoang et. al.]





Today: $\alpha_s(M_Z) = 0.1169 \pm 0.0034$ **(±2.9%)**

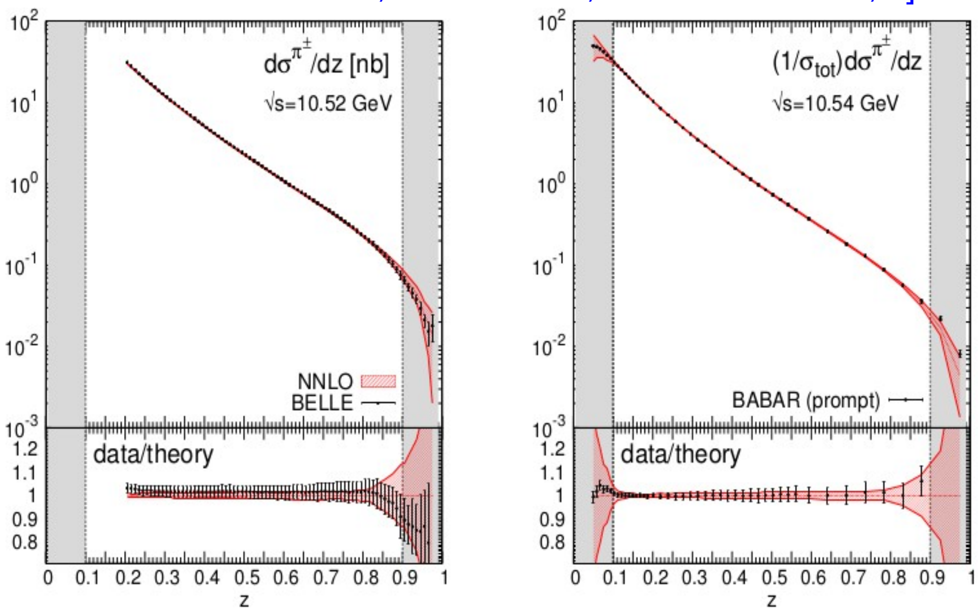
- FCC-ee:
  - Provides higher-√s data for rates & lower-√s for shapes: **$\delta\alpha_s < 1\%$**
  - TH: Improved $(N^{2,3}LL)$ resummation for rates & hadroniz. for shapes

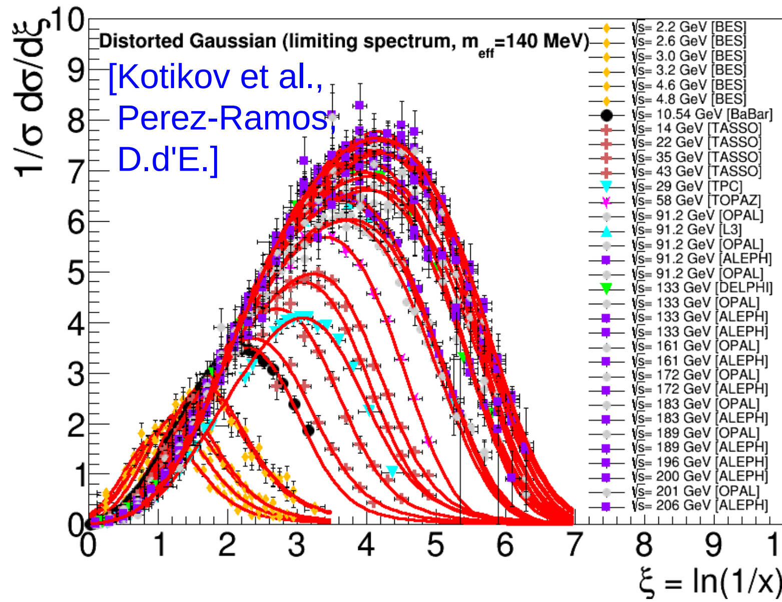
High-precision parton FFs (FCC-ee)

- Parton-to-hadron fragment. functions evolution known at NNLO at high-z &

[D.Anderle et al., A.Vossen et al., B.Kniehl et al., V.Bertone et al., N.Sato et al., D.deFlorian et al.,...]

at NNLO*+NNLL at low-z:





Method	Current $\delta\alpha_s(m_Z^2)/\alpha_s(m_Z^2)$ uncertainty (theory & experiment state-of-the-art)	Future $\delta\alpha_s(m_Z^2)/\alpha_s(m_Z^2)$ uncertainty (theory & experiment progress)
soft FFs	$1.8\%_{th} \oplus 0.7\%_{exp} \approx 2\%$ (NNLO* only (+NNLL), npQCD small)	$0.7\%_{th} \oplus 0.7\%_{exp} \approx 1\%$ (∼2 yrs), <1% (FCC-ee) (NNLO+NNLL. More precise e^+e^- data: 90–350 GeV)
hard FFs	$1\%_{th} \oplus 5\%_{exp} \approx 5\%$ (NLO only. LEP data only)	$0.7\%_{th} \oplus 2\%_{exp} \approx 2\%$ (+B-factories), <1% (FCC-ee) (NNLO. More precise e^+e^- data)

- FCC-ee (much broader z range) allows for α_s extraction with **$\delta\alpha_s$ < 1%**

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(FCC-ee, FCC-pp, SCT)

(2) Parton Distribution Functions
(HL-LHC, HE-LHC, FCC-hh)

(3) Jet substructure & flavour tagging
(FCC-ee, FCC-pp)

(4) Non-perturbative QCD
(FCC-ee, SCT, HL-LHC)

NOTE: Only UNIQUE QCD measurements, inaccessible at any current machine, are covered.

Colour reconnection (FCC-ee)

- Colour reconnection among partons in e^+e^- = Source of uncertainty in m_W, m_{top}, CP-violating Higgs in multijet final-states: $e^+e^- \rightarrow$ WW(4j), Z(4j), tt
- Use e^+e^- leptonic final-states to learn about CR:

At LEP 2: hot topic (by QCD standards)**: 'string drag' effect on W mass**

Non-zero effect convincingly demonstrated at LEP-2

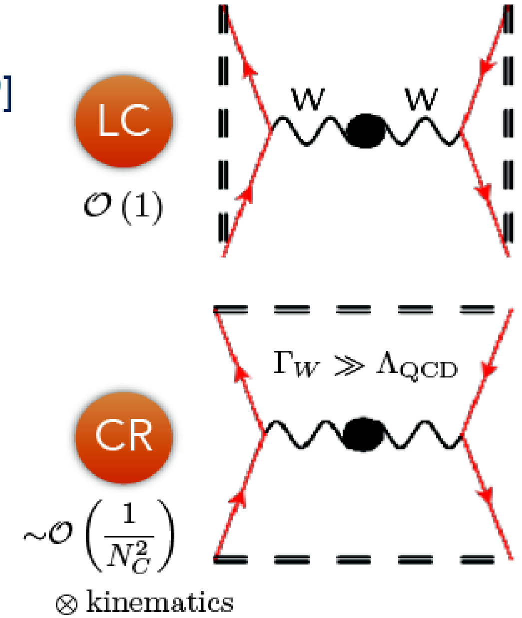
No-CR excluded at 99.5% CL [Phys.Rept. 532 (2013) 119]

But not much detailed (differential) information

Thousand times more WW at FCC-ee

Sjöstrand: turn the W mass problem around; use huge sample of semi-leptonic events to measure m_W

→ use as constraint to measure CR in hadronic WW



Has become even hotter topic at LHC

It appears jet universality is under heavy attack.
Fundamental to understanding & modeling hadronisation

Follow-up studies now underway at LHC.

T. Sjöstrand, W. Metzger, S. Kluth, C. Bierlich

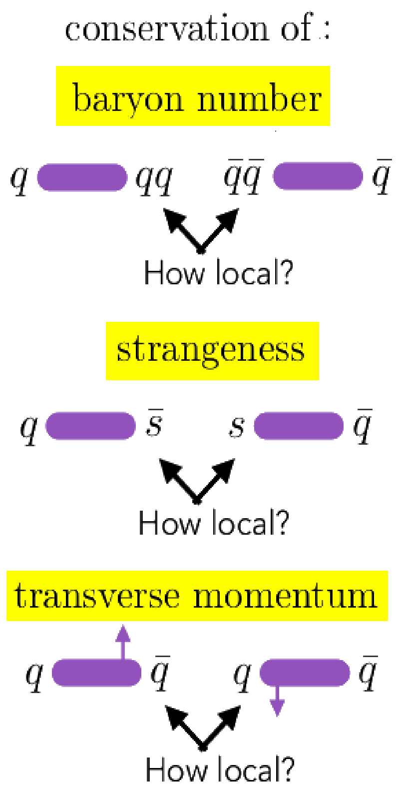
High-stats ee → other side of story

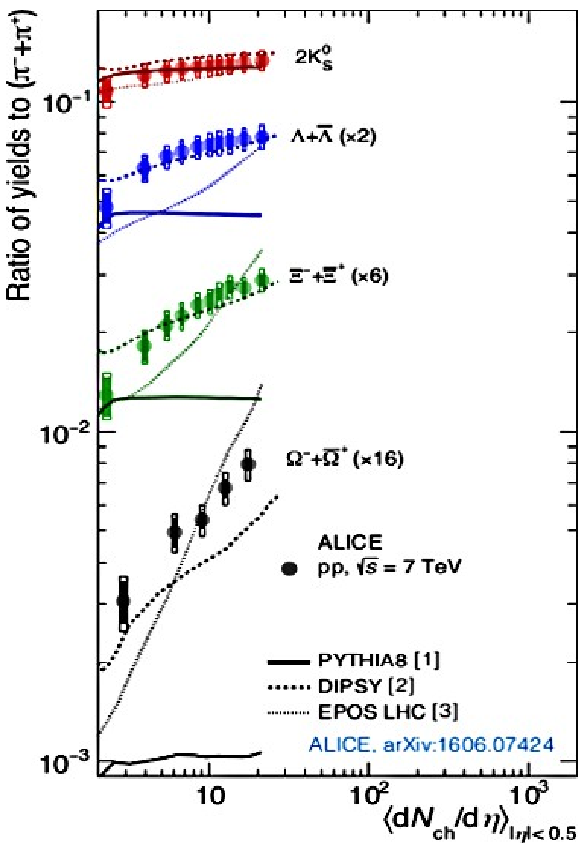
Also relevant in (hadronic) ee→tt, and Z→4 jets

+ Overlaps → interactions?
increased tensions (strangeness)?
breakdown of string picture?

Other Non-pQCD (SCT, FCC-ee, HL-LHC)

- High-precision low-p_T PID hadrons in e^+e^- allow for detailed studies:
  - Baryon & strangeness production. Colour string dynamics.
  - Final-state correlations (spin: BE, FD; momenta; space)
  - Bound state formation: Onia, multiquark states, glueballs, ...





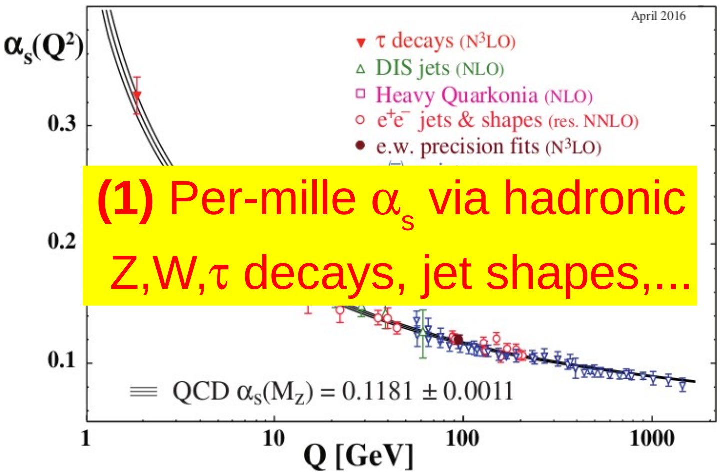
- ▶ Key test of universality of parton hadronization.

- Baseline studies for high-density QCD in small and large systems.

  [Ultra-thin ALICE proposal beyond 2030].

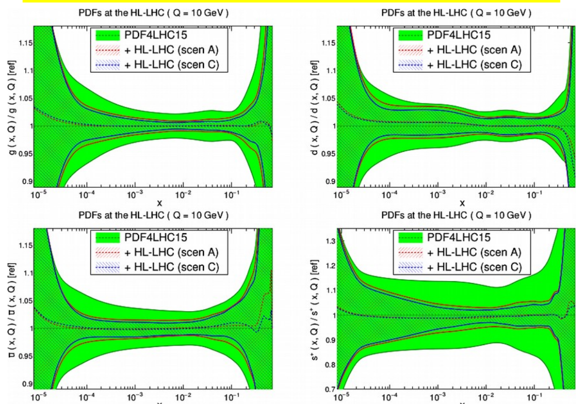
Summary: QCD at future pp & e^+e^- colliders

☛ The precision needed to fully exploit the future ee/pp/ep/eA/AA SM & BSM programs requires exquisite control of (n)pQCD, accessible in multiple, unique, high-stats, clean e^+e^- & pp measurements:

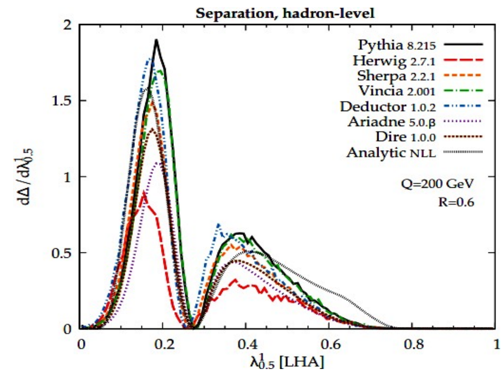


(1) Per-mille α_s via hadronic Z,W,τ decays, jet shapes,...

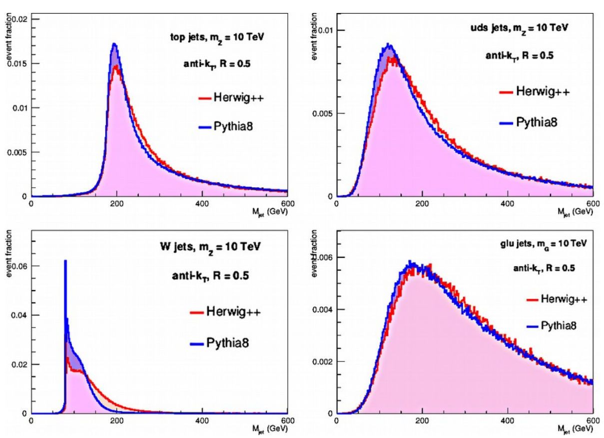
(2) High-precision PDFs



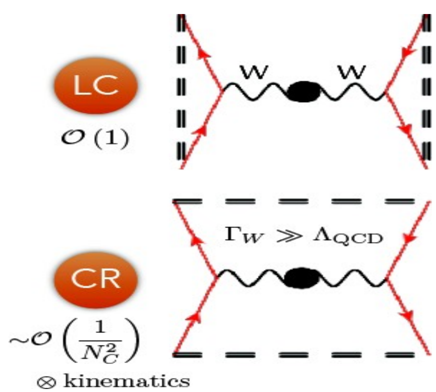
(3) N^nLO+N^nLL jet struct. High g/q/Q discrimination



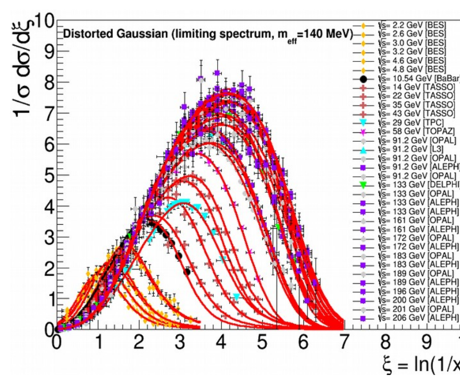
(4) Unique studies of highly-boosted dijet objects

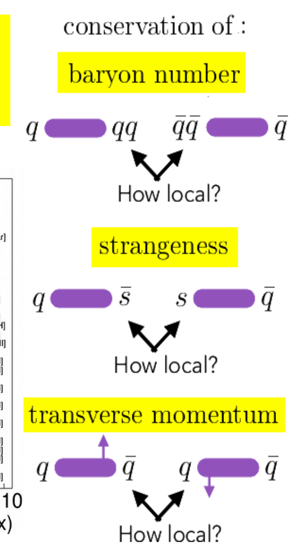


(5) <1% control of colour reconnection



(6) High-precision hadronization:





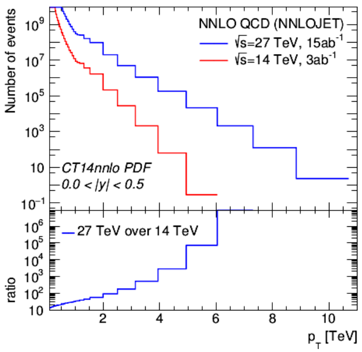
Backup slides

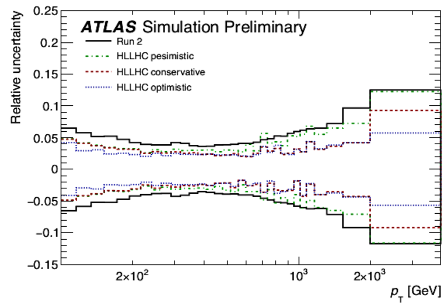
HL-LHC QCD performances: jets, γ

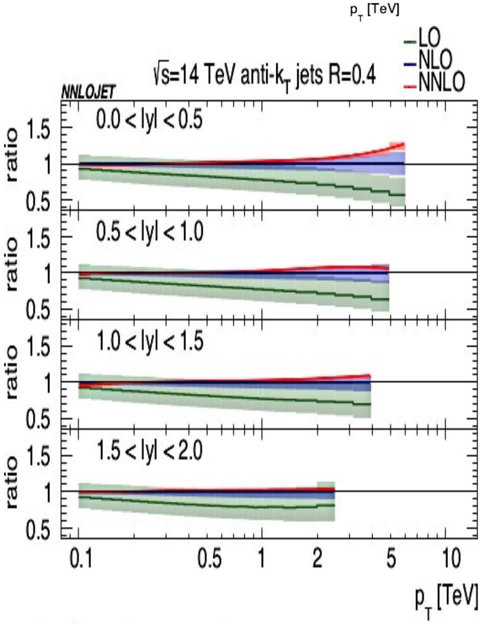
- **ATLAS** projections for inclusive jet production at **HL** and **HE-LHC**, including detailed study of systematic uncertainties:

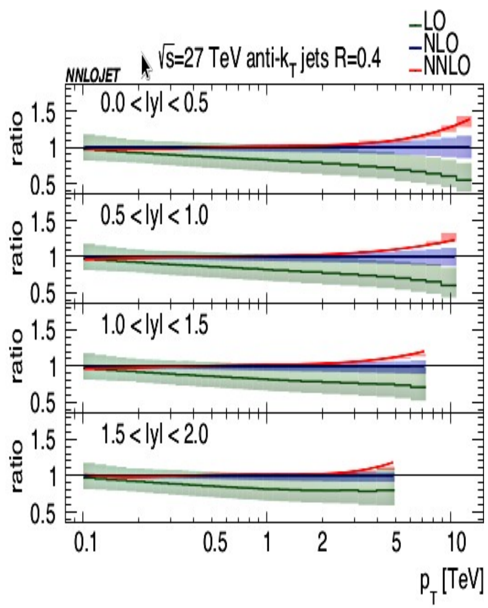
  ★ Potentially significant improvement in uncertainties at both low and high jet $p_\perp$ demonstrated, depending on scenario considered.

  ★ Extensive jet $p_\perp$ reach: ~ 5 (9) TeV at HL (HE) LHC.





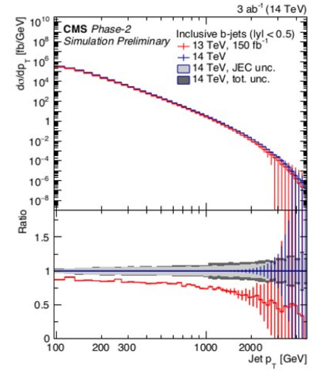


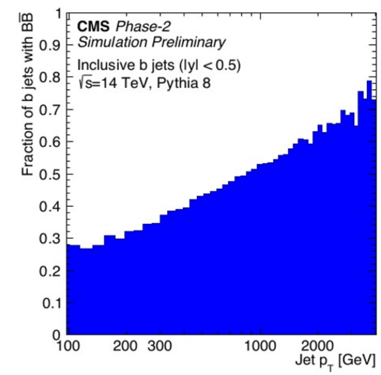


- **CMS** projections for b-jet production at **HL-LHC**:

  ★ Increased b-jet reach: $p_\perp \sim 3$ TeV.

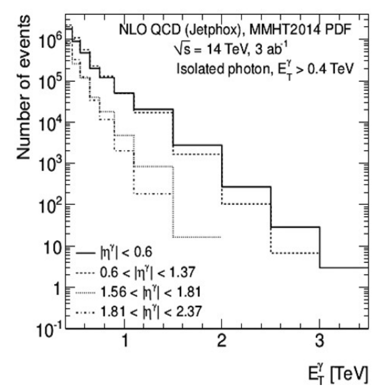
  ★ New regime: b-quark ~ massless w.r.t. high $p_\perp$ jet large fraction of jets with $B + \overline{B}$ due to PS ($g \to b\bar{b}$): important to disentangle from b-quarks produced in hard subprocess.

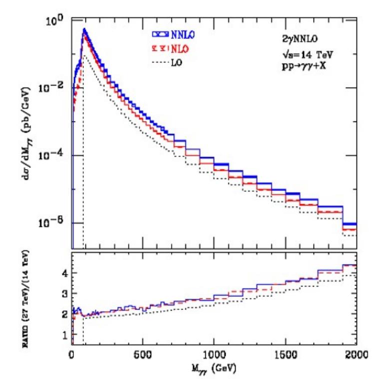




★ **Isolated photon**: **CMS** projections show extensive reach, $E_\perp^\gamma \sim 3(5)$ TeV for the HL(HE)-LHC. Increase by ~ 2-3 w.r.t. existing data.

★ **Diphoton** production: predictions with cutting-edge **NNLO** theory. Significant increase in reach with HE-LHC again shown.



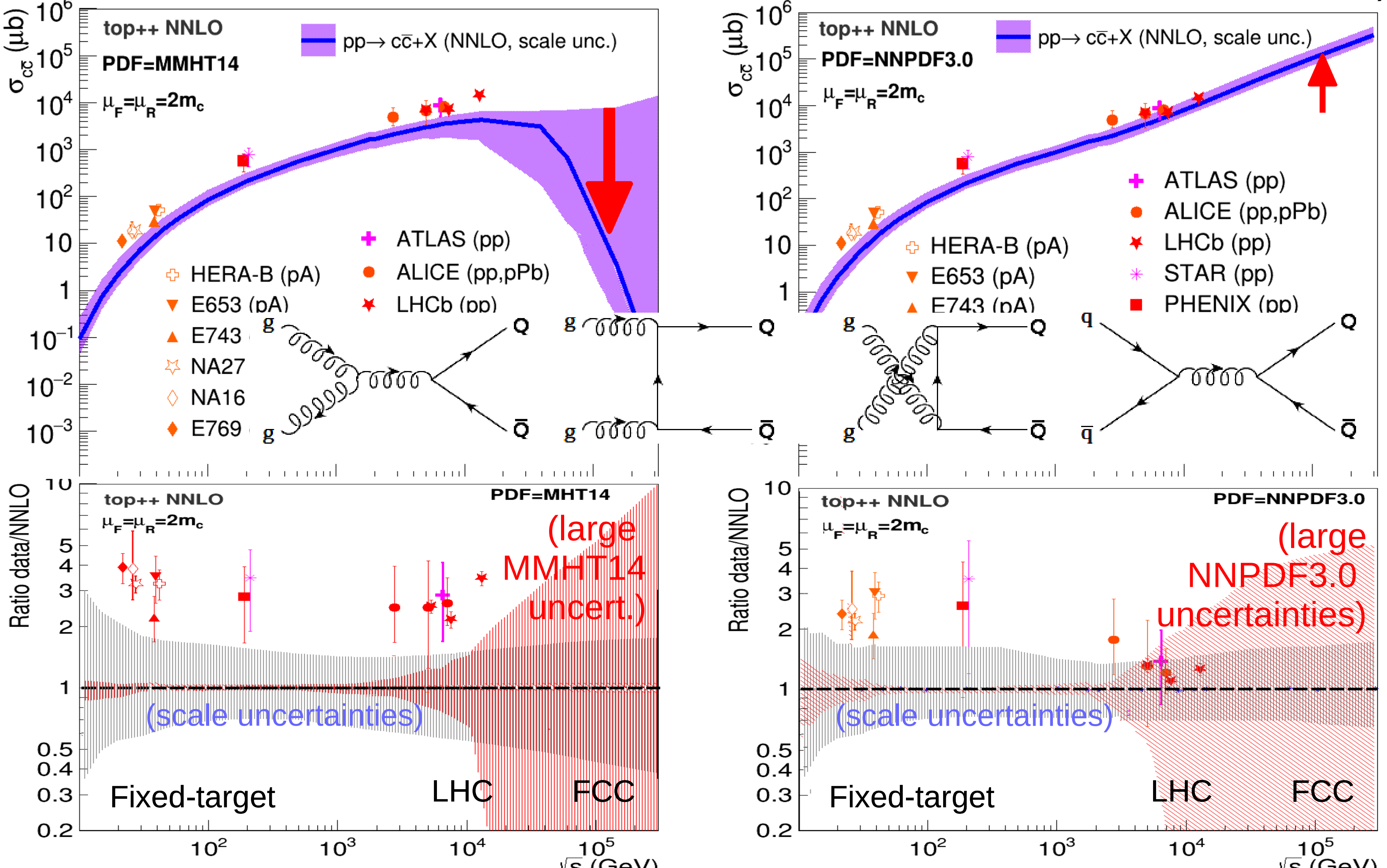


QCD physics at future pp & e^+e^- machines

1. High-precision α_s (parametric uncertainty on BSM via "SM stress tests"):
   - Via σ(ttbar), σ(W,Z) in p-p at HL-LHC, HE-LHC, FCC-hh
   - Via $BR_{had}(\tau$,W,Z) and jets shapes/rates/FFs in e^+e^- at FCC-ee (via tau at SCT)
2. High-precision PDFs (impact on precision SM & high-x BSM searches):
   - Via dσ(W,Z,jets,ttbar,γ) in p-p at HL-LHC, HE-LHC, FCC-hh
3. Heavy-Q/quark/gluon separation, jet substructure:
   - Via jet observables in p-p at HL-LHC, HE-LHC, FCC-hh (boosted topologies)
   - Via jet observables in e^+e^- at FCC-ee
4. Soft gluon resummations (improvements of MC parton showers):
   - Via dσ/dp_T(ttbar,Z,W,H) in p-p at HL-LHC, HE-LHC, FCC-hh
   - Via various jet observables in e^+e^- at FCC-ee
5. Semi-hard QCD (low-x gluon saturation, multiple hard parton interactions,…):
   - Via various observables in p-p at HL-LHC, HE-LHC, FCC-hh
6. Non-perturbative QCD (hadronization, onia bound states, colour reconnection):
   - Via multiple observables in p-p at HL-LHC, HE-LHC, FCC-hh
   - Via jet FFs, CR via $e^+e^- \rightarrow WW \rightarrow 4j$ at FCC-ee

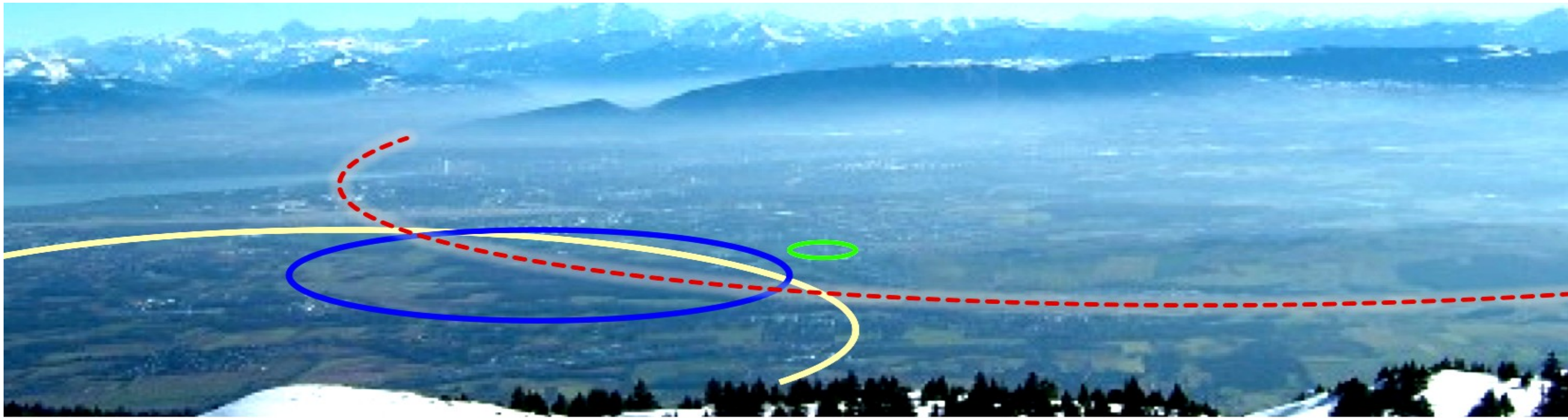
σ(cc̄): Data vs. NNLO (MMHT14, NNPDF3.0)

- Charm: Data ×2.5 theory (negative gluon at very low x, √s>30 TeV)
- Charm: Data ×2 theory (agreement within uncert. but "kink" at √s>10 TeV)



CERN FCC-ee project

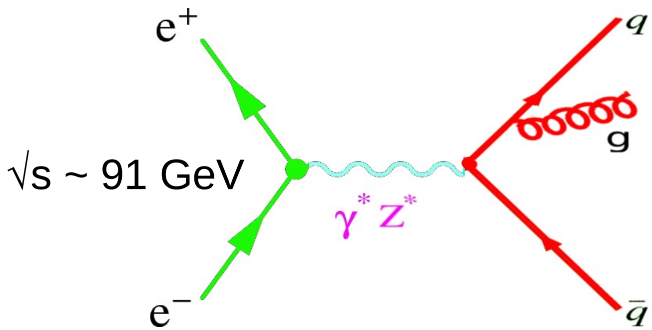
- e^+e^- option (before pp) at $\sqrt{s}$ = **90**, (125), 160, **240**, 350 GeV

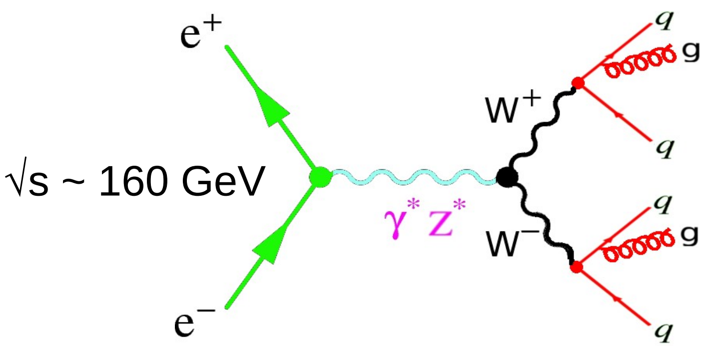


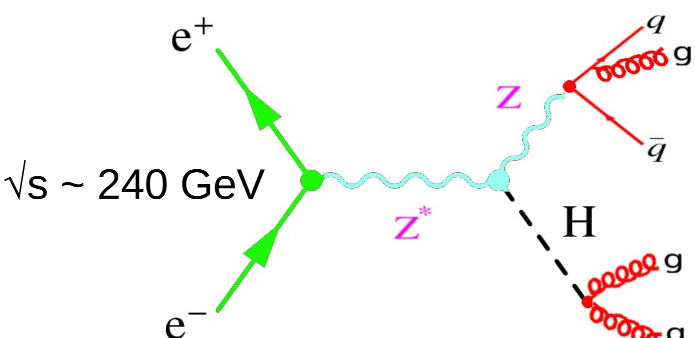
$\sqrt{s}$ (GeV):	90 (Z)	125 (eeH)	160 (WW)	240 (HZ)	350 ($t\bar{t}$)	350 (WW→H)
σ	43 nb	290 ab	4 pb	200 fb	0.5 pb	25 fb
$\mathcal{L}$/IP (cm^{-2} s^{-1})	10^{36}	$5{\cdot}10^{35}$	10^{35}	$7 \cdot 10^{34}$	$1.5{\cdot}10^{34}$	$1.5{\cdot}10^{34}$
$\mathcal{L}_{\rm int}$ (ab^{-1}/yr, 2 IPs)	50	10	8	1.8	0.5	0.35
Events/year (2 IPs)	10^{12}	$3{\cdot}10^{3}$	$3{\cdot}10^{7}$	$3 \cdot 10^{5}$	$2.5{\cdot}10^{5}$	10^{4}
Years needed (2 IPs)	4	1.5	1	3	0.5	4
# of light-q jets/year:	$\mathcal{O}(10^{12})$	–	$\mathcal{O}(10^{7})$	$\mathcal{O}(10^{5})$	–	–
# of gluon-jets/year:	$\mathcal{O}(10^{11})$	$\mathcal{O}(10^{2})$	$\mathcal{O}(10^{6})$	$\mathcal{O}(10^{4})$	–	$\mathcal{O}(10^{3})$
# of heavy-Q jets/yr:	$\mathcal{O}(10^{12})$	$\mathcal{O}(10^{3})$	$\mathcal{O}(10^{7})$	$\mathcal{O}(10^{5})$	$\mathcal{O}(10^{5})$	$\mathcal{O}(10^{4})$

QCD in e⁺e⁻ collisions

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



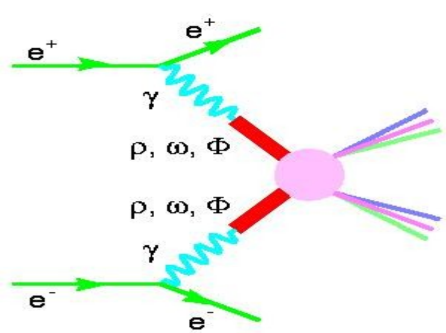




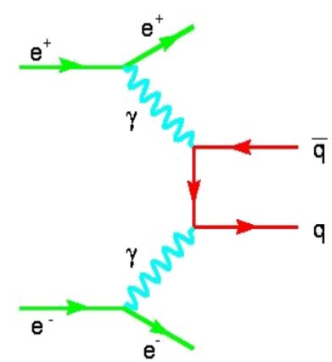
Advantages compared to p-p collisions:

- QED initial-state with known kinematics
- Controlled QCD radiation (only in final-state)
- Well-defined heavy-Q, quark, gluon jets
- Smaller non-pQCD uncertainties:
  no PDFs, no QCD "underlying event",…
  Direct clean parton fragmentation & hadroniz.

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



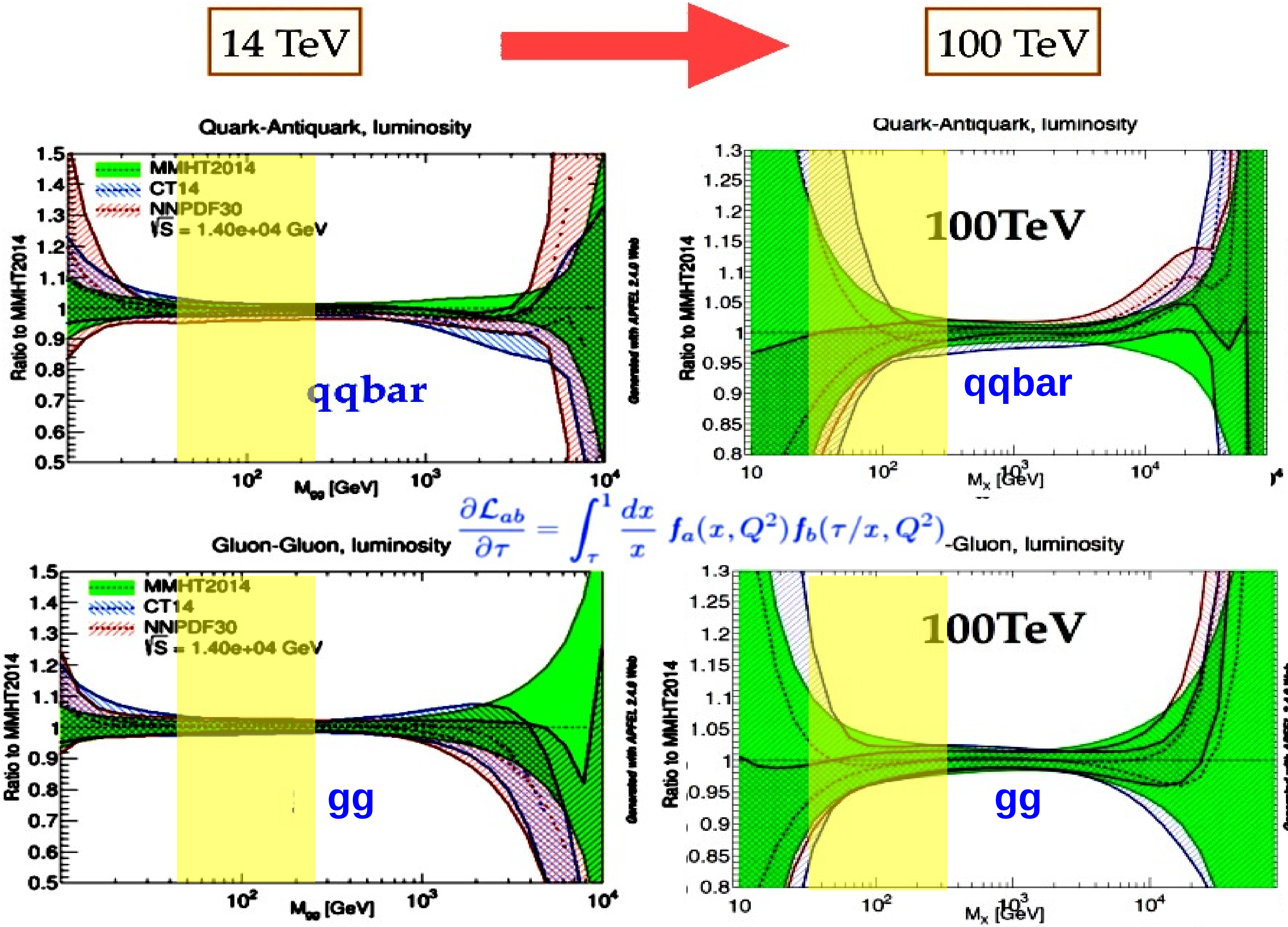
(soft, VDM)



(direct)

Parton lumis at FCC "precision" region

- "Precision" region at FCC-pp: **5–7%** PDF uncertainty for σ(W,Z,H)



$$\frac{\partial \mathcal{L}_{ab}}{\partial \tau} = \int_{\tau}^{1} \frac{dx}{x} \, f_a(x, Q^2) f_b(\tau/x, Q^2)$$

QCD physics at future pp & e^+e^- machines

(1) QCD coupling (FCC-ee, FCC-pp, SCT)

(2) PDFs (HL-LHC, HE-LHC, FCC-hh)

(3) Jet substructure & flavour tagging
(FCC-ee, FCC-pp)

(4) Beyond DGLAP (FCC-pp, FCC-hh)

(5) Non-perturbative QCD (FCC-ee, FCC-hh)

NOTE: Only UNIQUE QCD measurements, not accessible at any current machine, are covered.

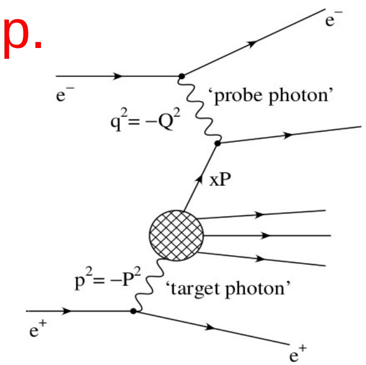
α_s from γ QCD structure function

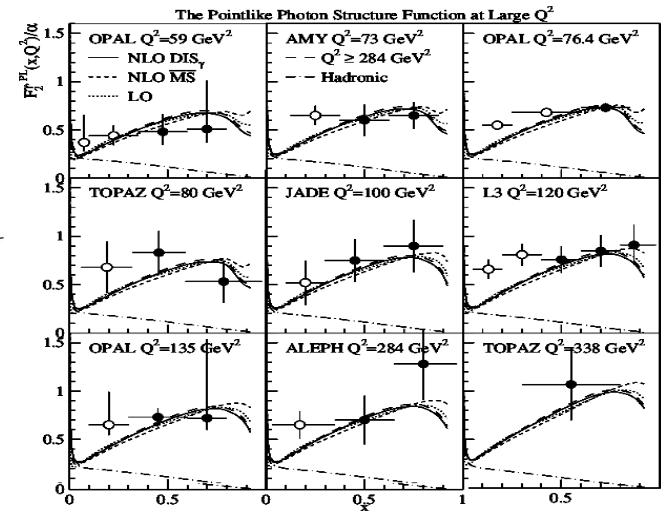
- Computed at NNLO: $\int_0^1 dx F_2^\gamma(x,Q^2,P^2) = \frac{\alpha}{4\pi}\frac{1}{2\beta_0}\left\{\frac{4\pi}{\alpha_s(Q^2)}c_{LO} + c_{NLO} + \frac{\alpha_s(Q^2)}{4\pi}c_{NNLO} + \mathcal{O}(\alpha_s^2)\right\}$
- Poor $F^2_\gamma(x,Q^2)$ experimental measurements:
- Extraction (NLO) with large exp. uncertainties today:

α_s (M_z) = 0.1198 ± 0.0054

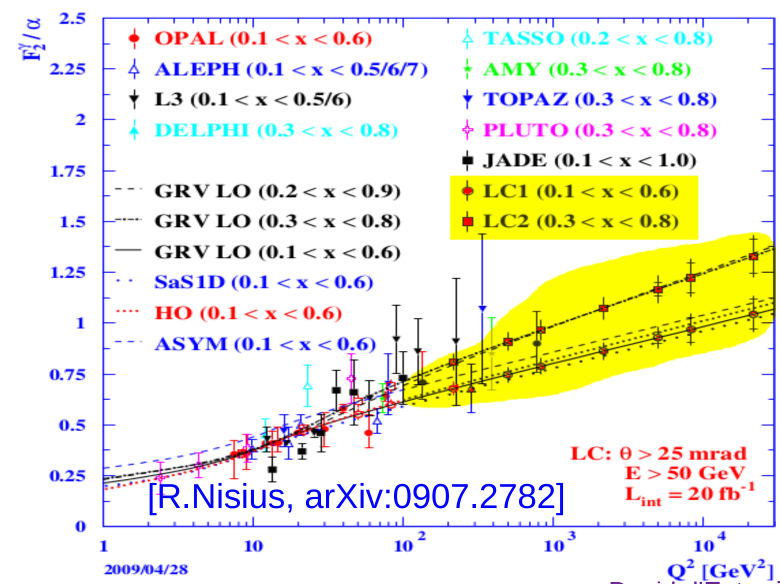
(±4.5%)

[M.Klasen et al. PRL89 (2002)122004]





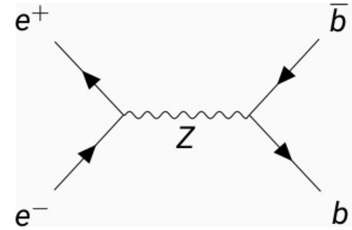
- Future prospects:
  - Better data badly needed.
  - Belle-II ?
  - Dedicated studies at ILC exist:
  - Huge $\gamma\gamma$ (EPA) stats at FCC-ee will lead to: **$\delta\alpha_s$ < 1%**



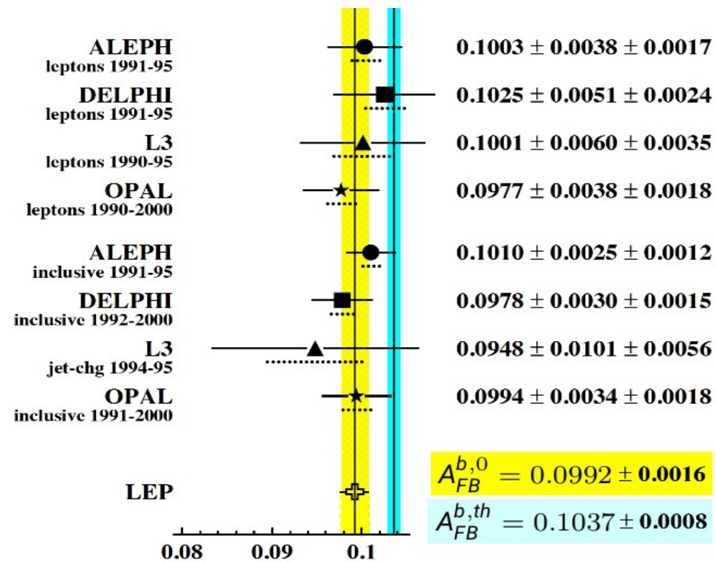
Reduced QCD uncertainties on EWK observables

- With $\times10^5$ more Z's than LEP, EWK uncertainties at FCC-ee will be dominated by syst. (QCD). Example: $e^+e^-\to b\bar{b}$ forward–backward asymmetry
  - – 8 measurements at LEP: 4 lepton-based, 4 jet-charge-based
  - – Exp. observable with largest discrepancy today wrt. the SM: 2.8σ
- Exp. Uncertainties: ~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)]
- We have revisited the impact of QCD effects on $A_{FB}^{0,b}$ implementing original analyses in up-to-date retuned parton-shower+hadronization MCs

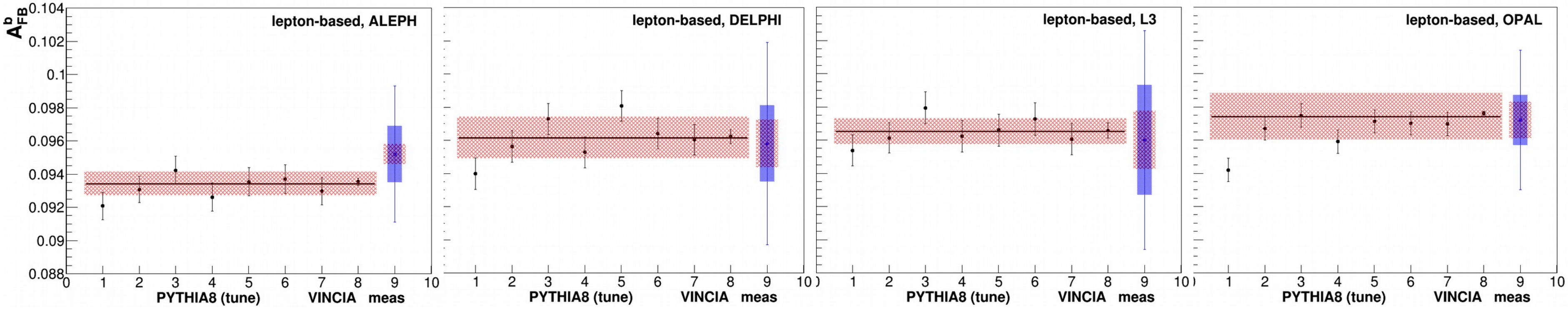


$$A_{FB}^{b} = \frac{N_F - N_B}{N_F + N_B} \qquad A_{\rm FB} = \frac{\sigma_{\rm A}}{\sigma_{\rm S}} \propto \frac{-g_{\mu\nu}T^{\mu\nu}}{i\epsilon_{\mu\nu\lambda\rho}\frac{n^\lambda Q^\rho}{n\cdot Q}T^{\mu\nu}}$$

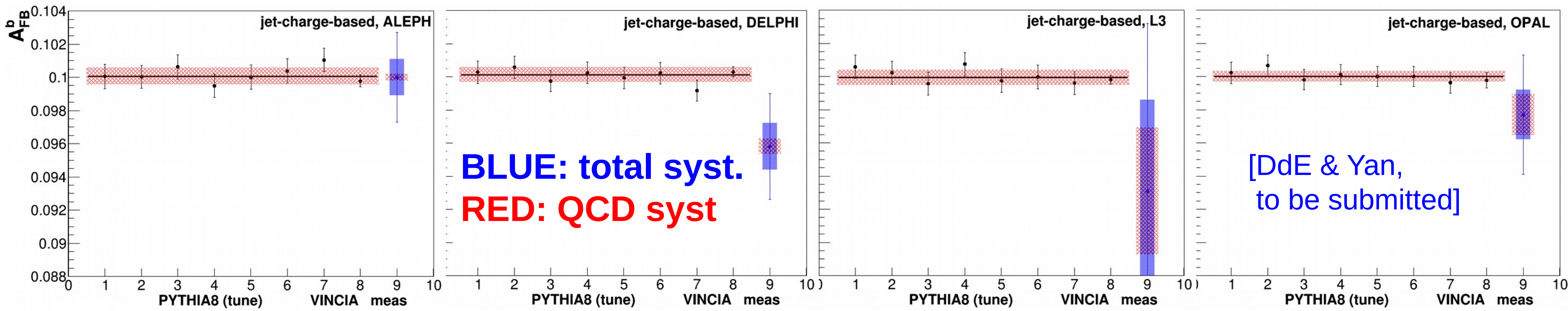


Reduced QCD uncertainties on A_{FB} at Z pole

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



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



- 2018 vs. 1998 PS+hadronization uncertainties:
  – Lepton-based: Consistent for ALEPH/DELPHI, smaller for L3, larger for OPAL.
  – Jet-charge-based: Consistent for DELPHI, smaller for ALEPH/L3/OPAL.
- LEP average to be recomputed (likely no change as stat.unc. dominates)