QCD & Heavy-Ion physics at the Future Circular Collider

QCD&HI workshop Comm. Workshop

(EU HEP Strategy Update)

Orsay, 19th Sept 2024

David d'Enterria

CERN

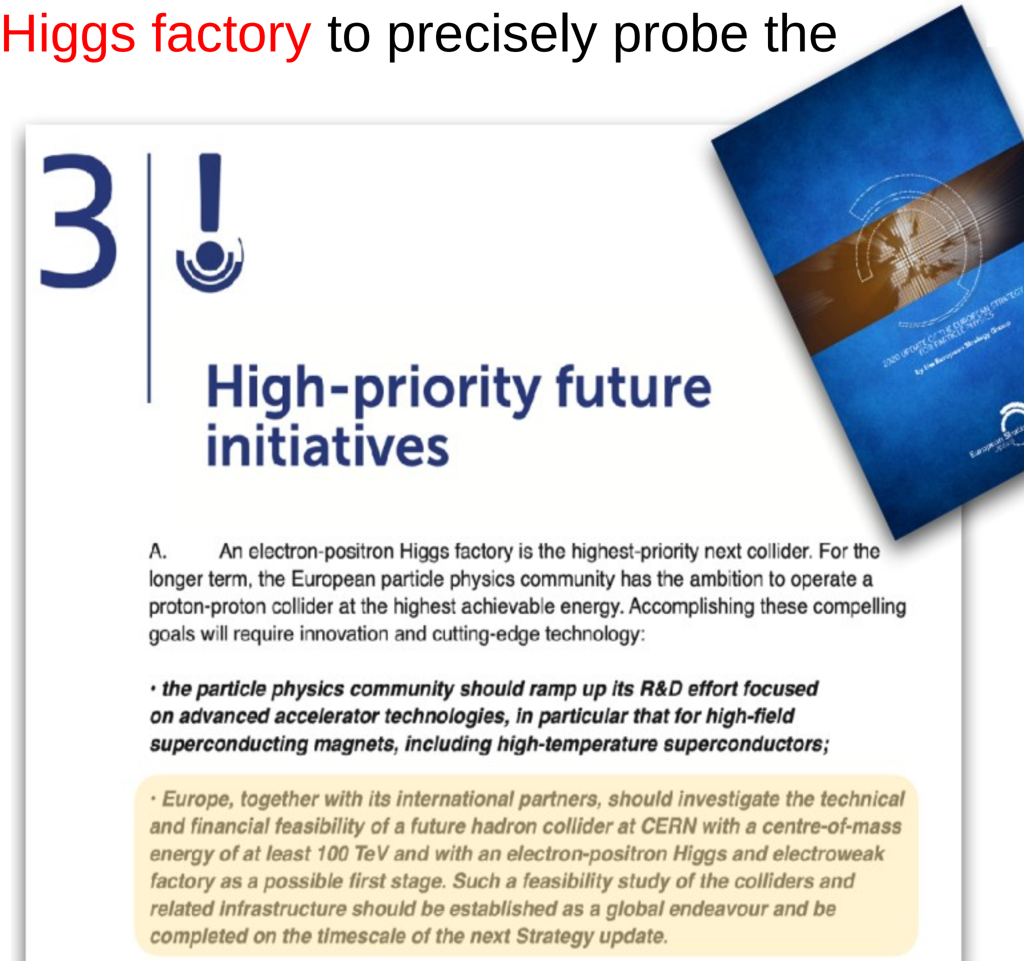
FUTURE CIRCULAR COLLIDER

Particle physics: World context

- Apart from the Higgs discovery, all fundamental questions that motivated the LHC still remain open! *DM, matter-antimatter asymm., EW-Planck hierarchy, nu masses, strong CP problem, DE, cosmol.const, inflation,...*

- World priority is a high-precision Higgs factory to precisely probe the crucial scalar sector of the SM:
  – Model-indep. Higgs couplings down to 0.1%: Indirect BSM up to $\Lambda \approx 7$ (70) TeV (+EW observ.)
  – Higgs Yukawa couplings to lightest fermions (u,d,s,e,nu?) Flavor-violating $H \rightarrow qq'$ decays?

- Followed by energy-frontier hadron collider (FCC-hh): H selfcoupling + direct BSM searches up to $\Lambda \approx 100$ TeV



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High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

• the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;

• Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

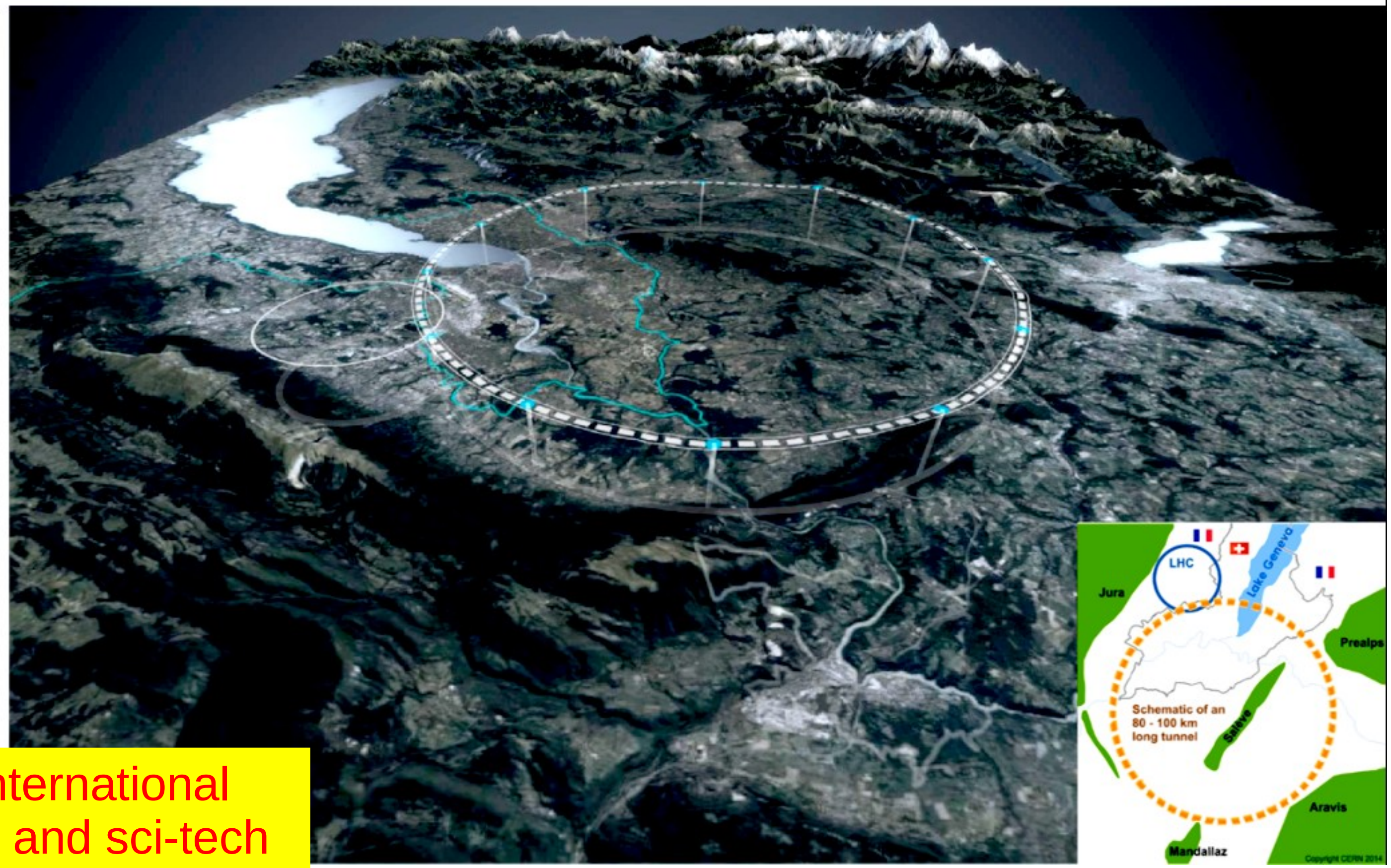
CERN Future Circular Collider (FCC)

FCC
hh ee he

- 90.7 km tunnel
- 4 experimental sites
- Deepest shaft 400 m, average 240 m

Two stages

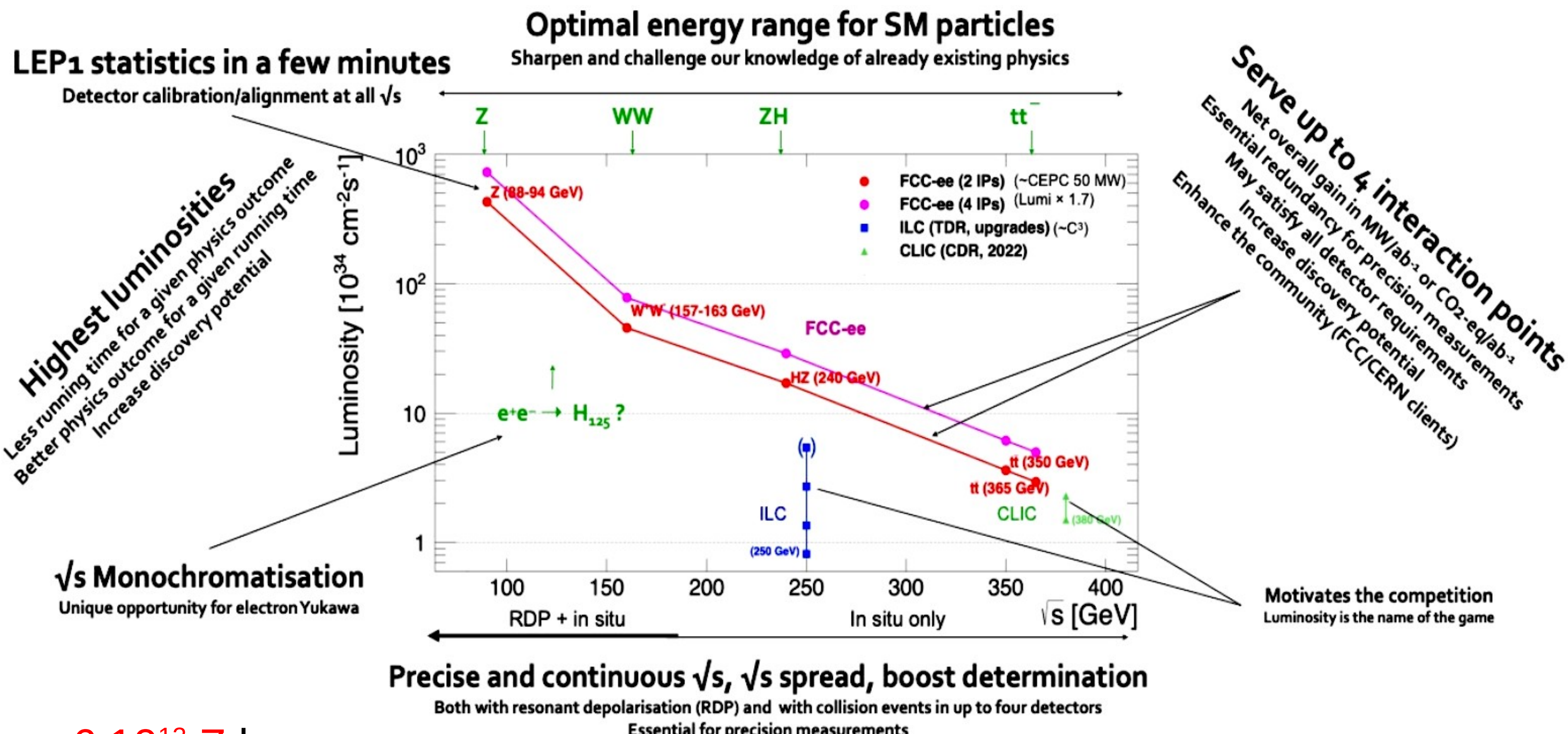
- FCC-ee (~15 years)
- FCC-hh (>20 years)



Exploit world-class international community, facilities, and sci-tech *savoir-faire* accumulated at CERN over the last 70 years!

"I believe FCC is the best project for CERN's future, we need to work together to make it happen"
- Fabiola Gianotti, FCC Week London, 5th June 2023

Impressive FCC-ee luminosities



$6{\cdot}10^{12}$ Z bosons

$5{\cdot}10^{8}$ W bosons

$2{\cdot}10^{6}$ Higgs bosons

$4{\cdot}10^{6}$ top quarks

H,Z,W,t (and u,d,s,c,b,g jets) probed in pristine conditions...

QCD is at the core of FCC-ee physics

- Though QCD is not per se the driving force for FCC-ee, it is crucial for a huge range of studies:

  70–80% of H, Z, W boson decays have fully hadronic final states!

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

2. Higher-order (N^nLO, N^nLL) calculations crucial to gain precise control over hadronic final states & jet dynamics.

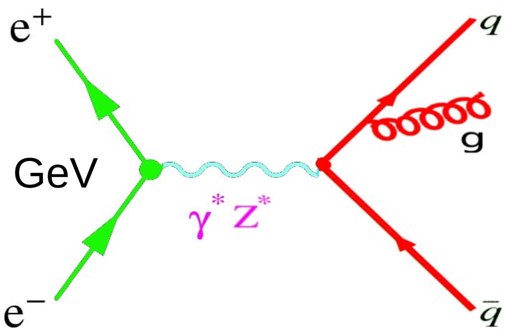
3. Heavy/light quark & gluon separation (flavour tagging, substructure,...) is key for multiple SM measurements (H Yukawas,...) and BSM searches ($X\to jj$ decays,...).

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

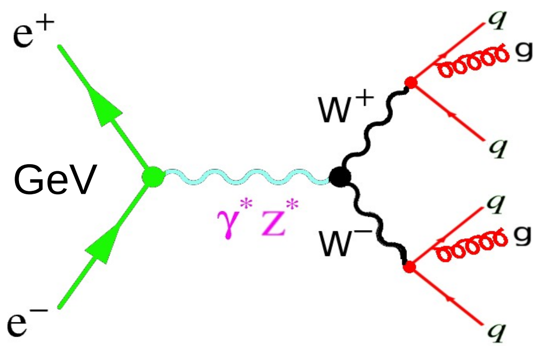
Precision QCD in e^+e^- collisions

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

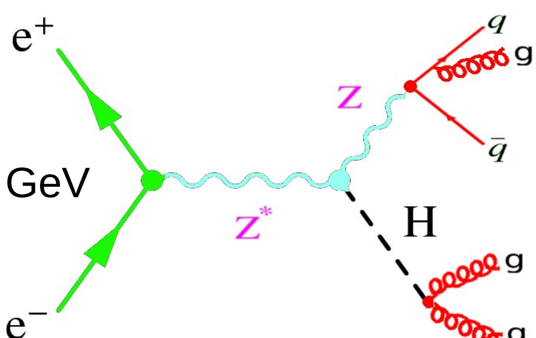
√s = 91 GeV



√s = 160 GeV



√s = 240 GeV



Advantages compared to p-p collisions:

1) QED initial-state with known kinematics

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

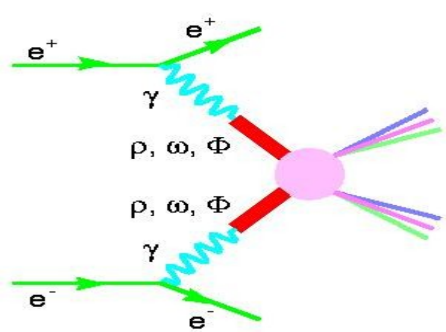
3) Well-defined heavy-Q, quark, gluon jets

4) Smaller non-pQCD uncertainties:

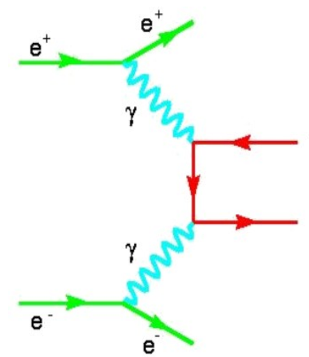
no PDFs, no QCD "underlying event",…

Direct clean parton fragmentation & hadroniz.

- Plus QCD physics in γγ (EPA) collisions:



(soft, VDM)



(direct)

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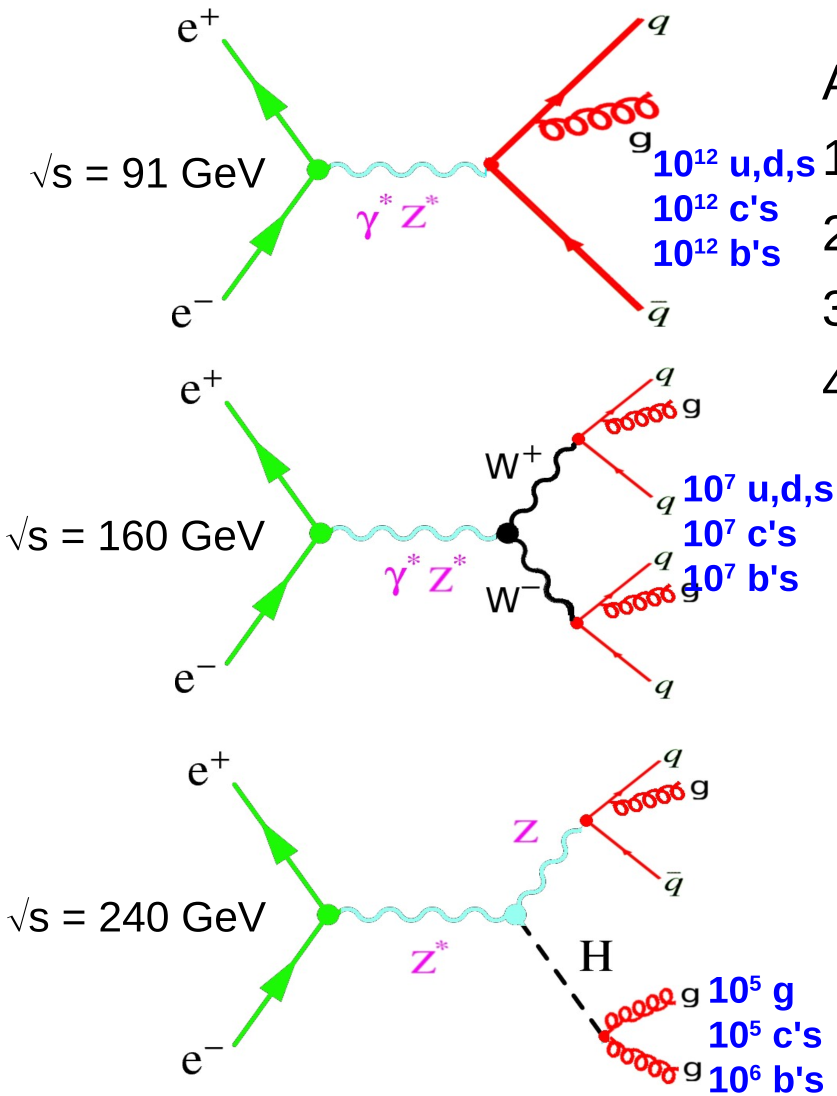

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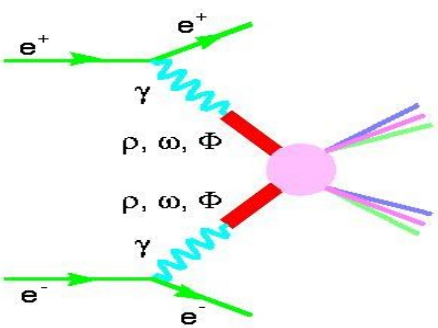

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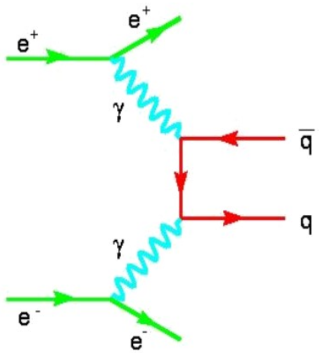


(direct)

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

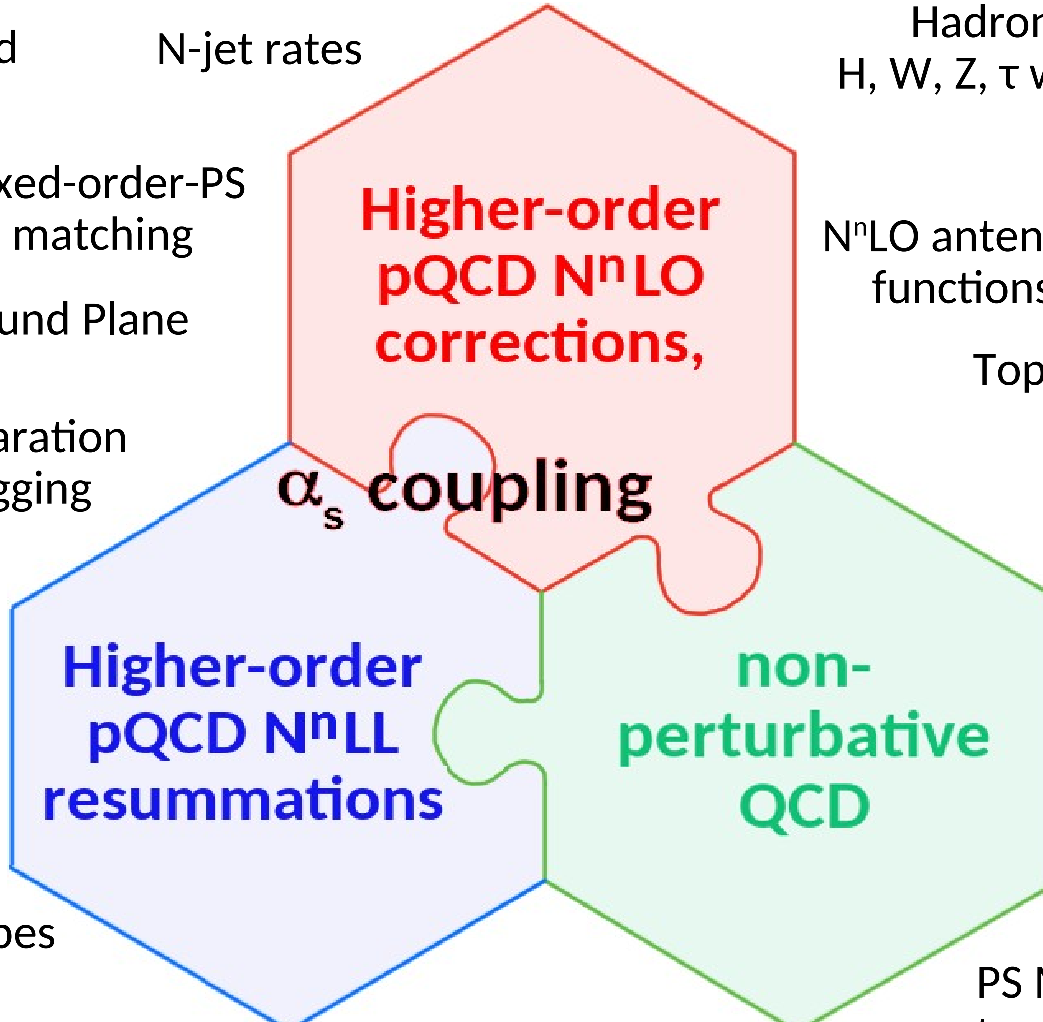
N^nLO antenna functions

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

N^nLL Parton Shower Monte Carlos

Fragmentation Functions

Spin correlations

$Q\bar{Q}$ transition probabs.

Lattice QCD

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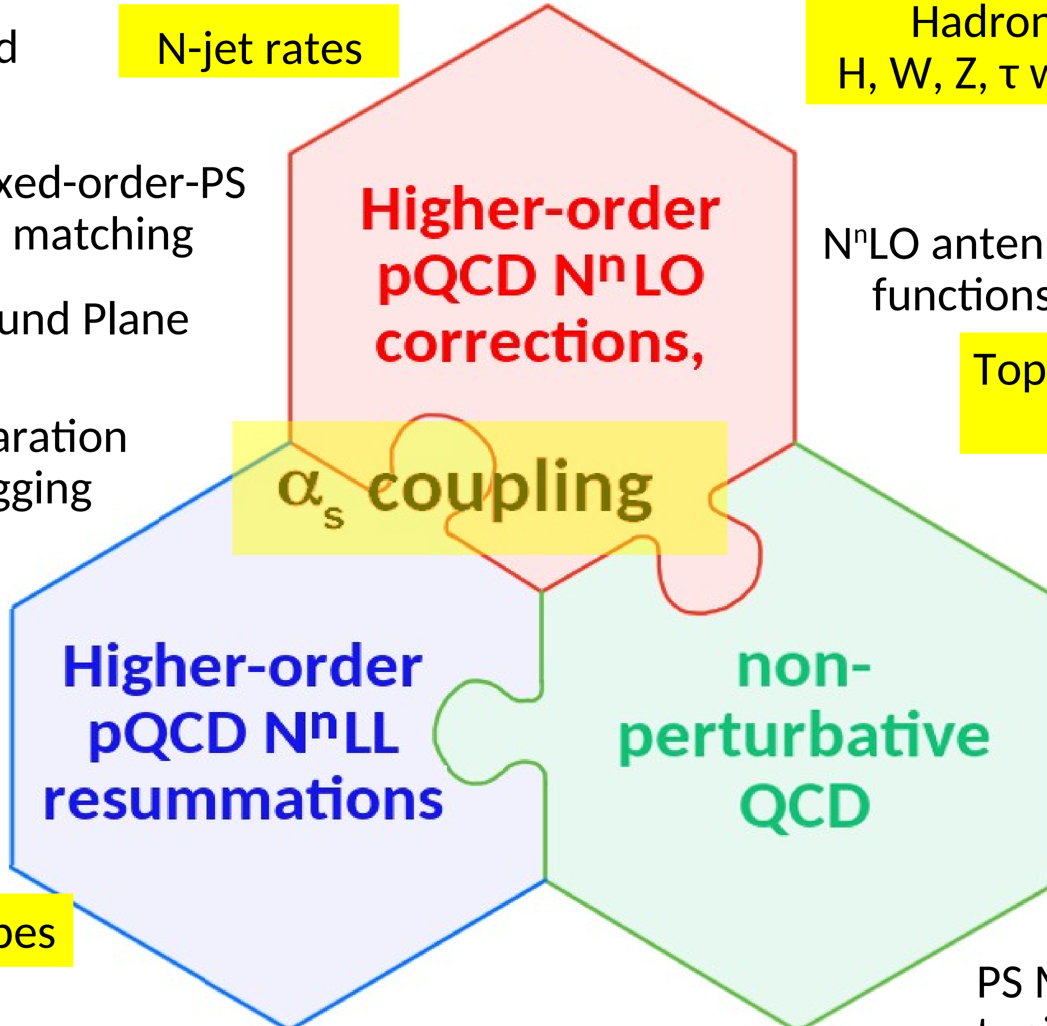

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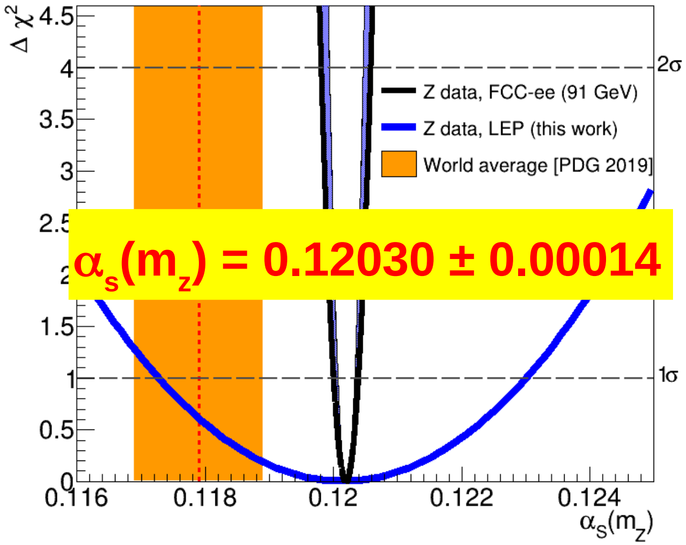
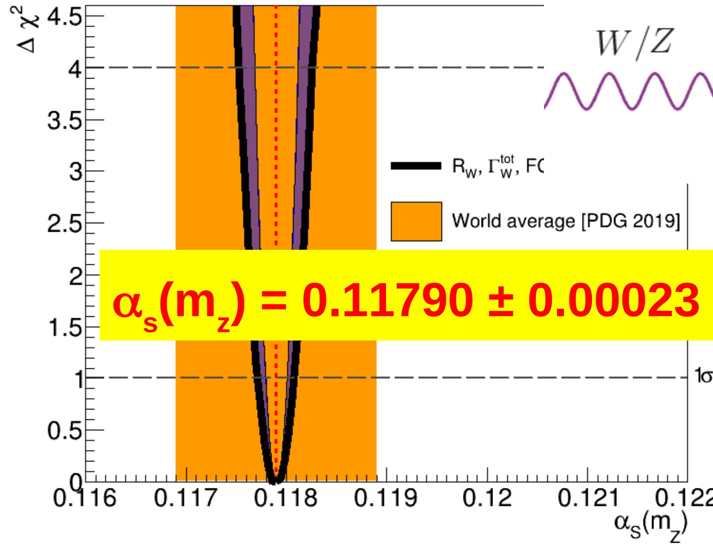
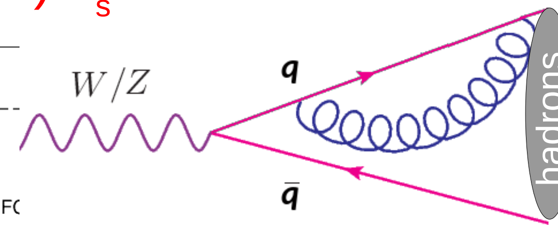
Example: QCD coupling α_s

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







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	± 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	± 0.1%	± 2.3 %
$H \to gg$	126	± 4.1	± 0.1%	± 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)

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

⇒ improvement in α_s crucial

$\delta\alpha_s(M_z) = 0.001$

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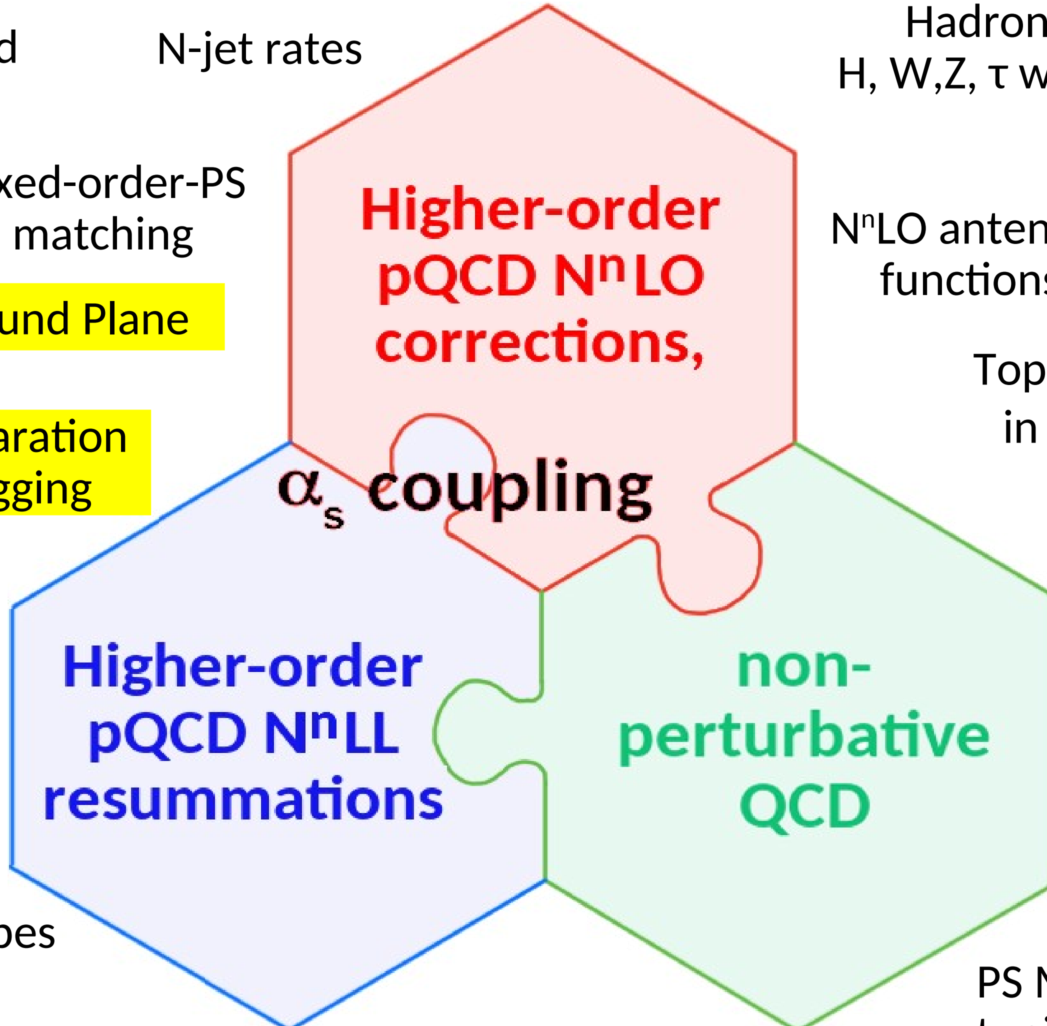

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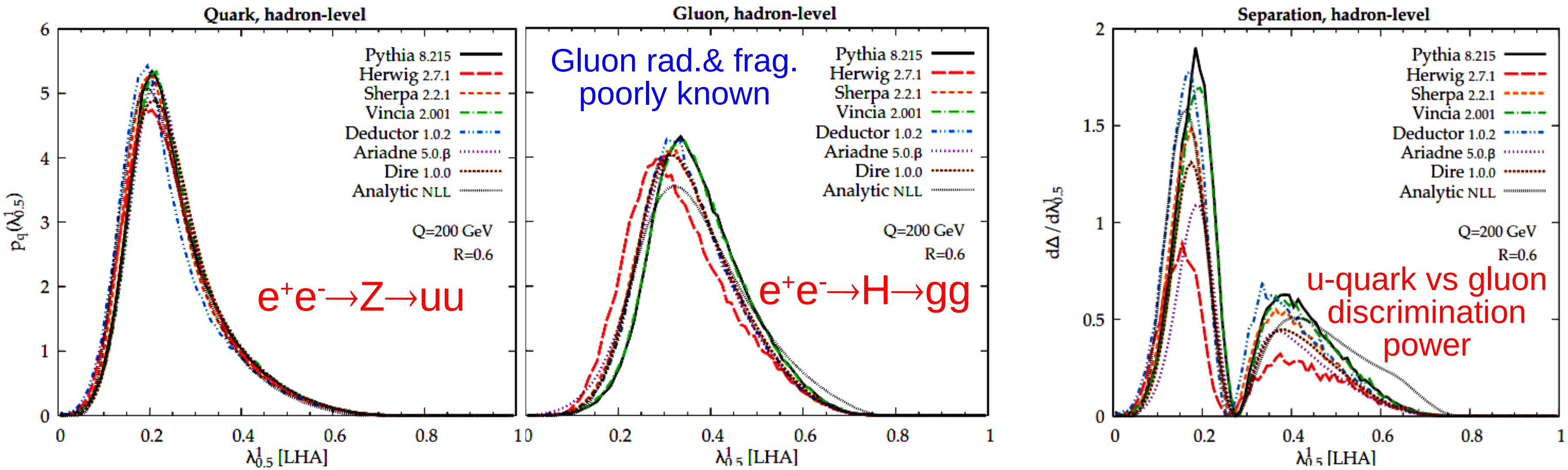
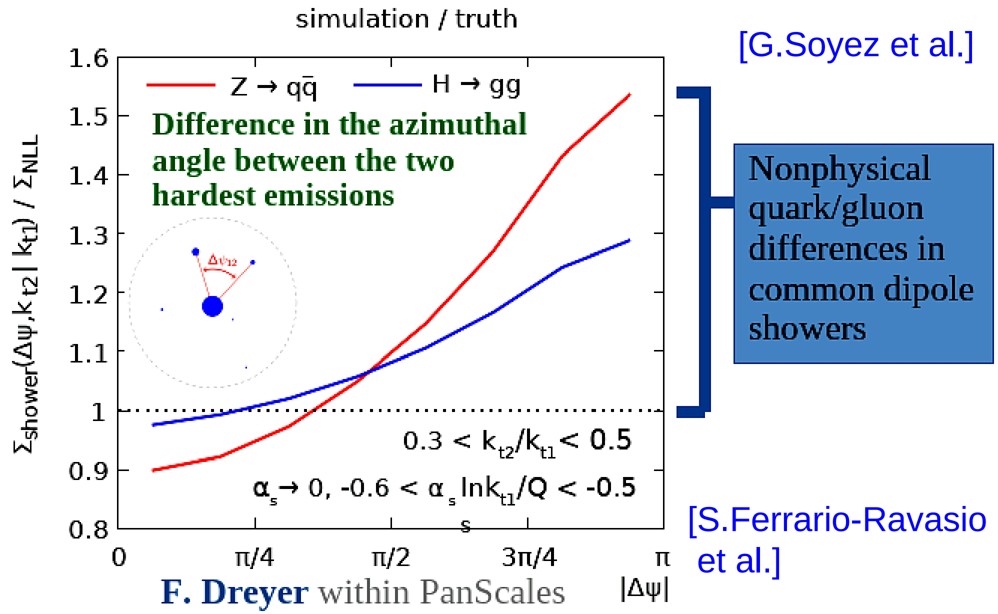
Gluon jets are badly known today

- MC LL parton showers differ vastly on gluon jet substructure properties:



- Unphysical differences in the radiation pattern of q & g jets in LL PS:
- NNLL PS + high-quality e^+e^- gluon jet data/tuning badly needed.

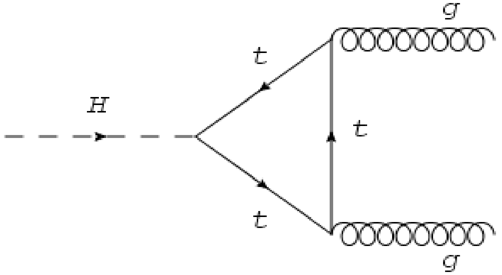
[G.Soyez et al.]



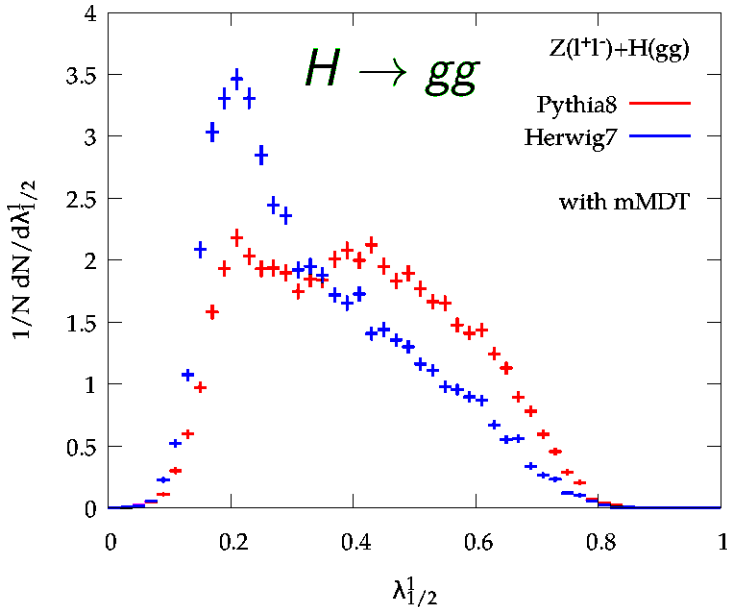
[S.Ferrario-Ravasio et al.]

Example: High-precision g & q jet studies

- Exploit FCC-ee H(gg) as a ”pure gluon” factory: H → gg provides $\mathcal{O}$(150.000) 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: $e^+e^- \rightarrow Z^*,\gamma^* \rightarrow jj(\gamma)$
  - Vary jet radius: small-R down to calo resol



- Multiple high-precision analyses at hand
  - – Jet tagging: ML training on <u>pure</u> samples: Improve q/g/Q discrimination
  - – pQCD: Improve/retune NNLL parton showers, Lund Plane, jet substructure...
  - – non-pQCD: Improved gluon hadronization: Leading η's ? Baryon junctions ? Octet neutralization? Colour reconnection? Glueballs ?

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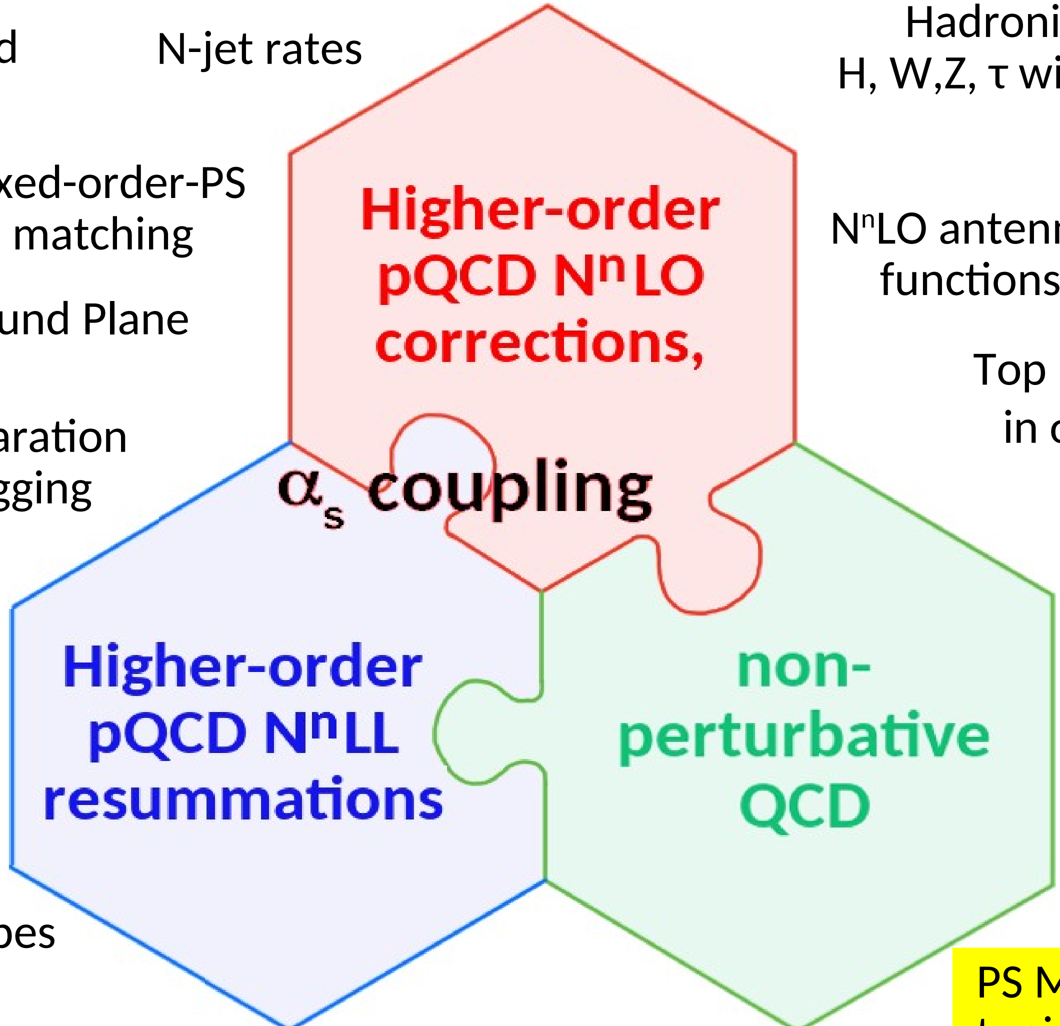

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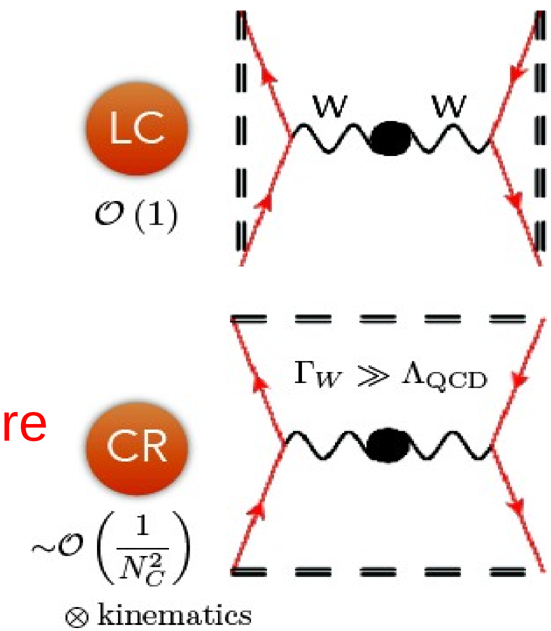
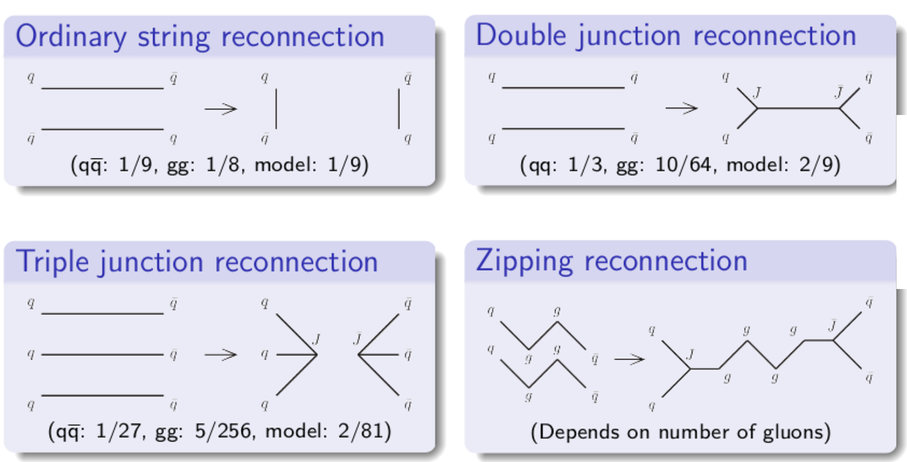
Non-pQCD example: Colour reconnection

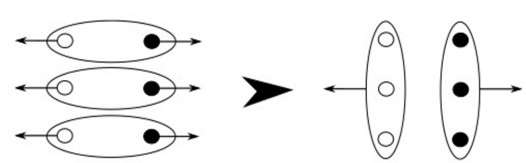
- Colour reconnection among partons is source of uncertainty in m_W, m_{top}, aGC extractions in multijet final-states. Especially in pp (MPI cross-talk).
- CR "string drag" effect impacts all FCC-ee multi-jet final-states: $e^+e^- \to WW(4j)$, H(2j,4j), ttbar,…
  - Shifted masses & angular correlations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



- Exploit huge stat WW at rest (×10^4 LEP) to measure m_W leptonically & hadronically and constrain CR:

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

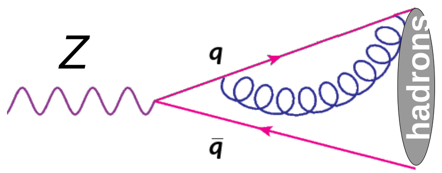


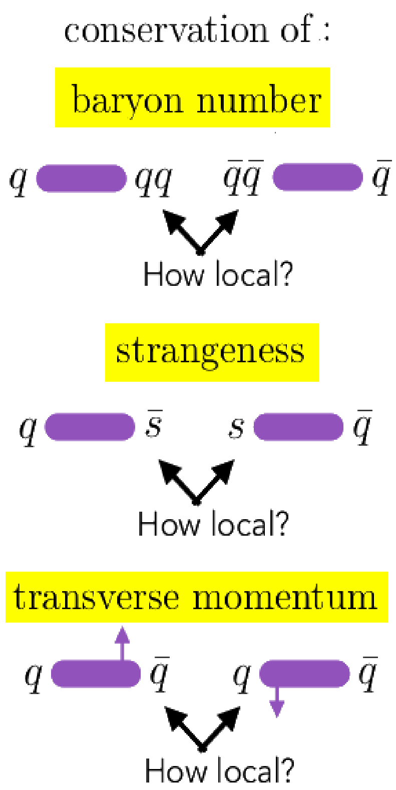


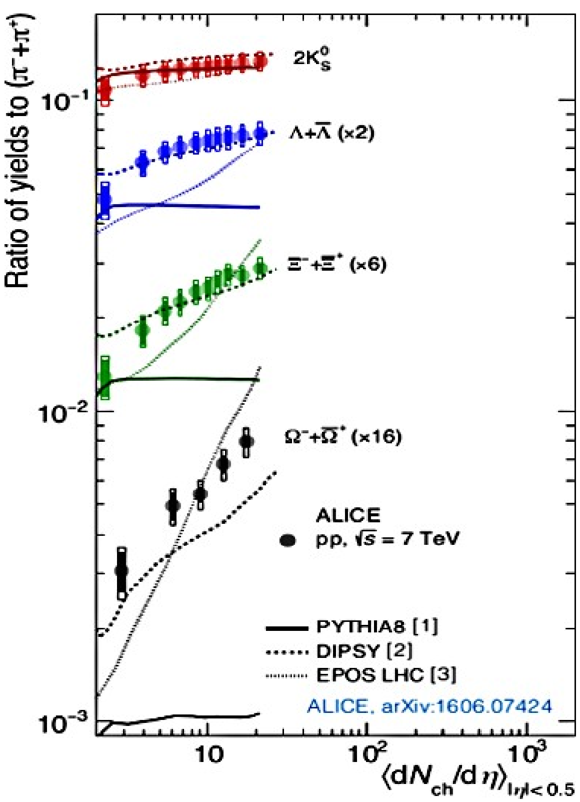
Triple-junction also in HERWIG cluster model. (1710.10906)

Non-pQCD example: Vacuum hadronization

- Precision low-p_T PID hadrons in 10^{12} $e^+e^- \rightarrow Z \rightarrow (10^{14}$ hadrons) for studies:
  - Baryon & strangeness prod. Colour string dynamics
  - Final-state correlations: space-time, spin (BE, FD)
  - Exotic BR(10^{-12}) bound-states: Onia, multi-quark states, glueballs, ...







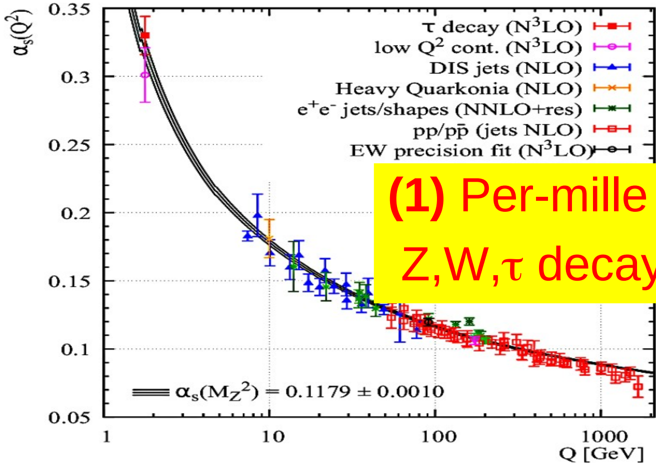
▶ Understand breakdown of universality of parton hadronization with system size observed at LHC.

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

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

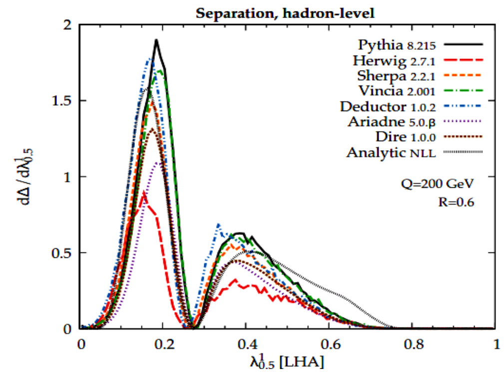
Summary (1): High-precision QCD at FCC-ee

- ☛ 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:

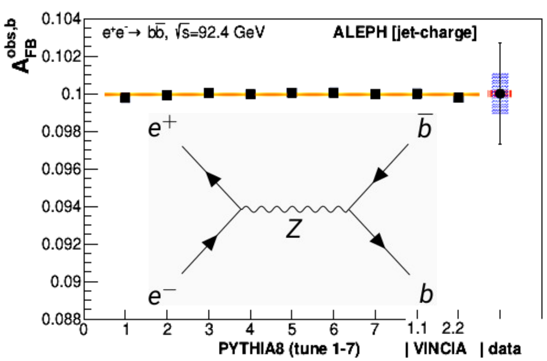


(1) Per-mille α_s via hadronic Z,W,τ decays, evt shapes...

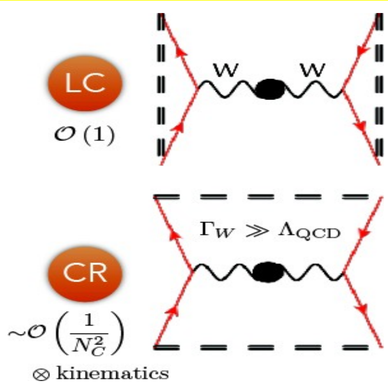
(2) N^nLO+N^nLL parton showers
Ultimate g/q/Q discrimination



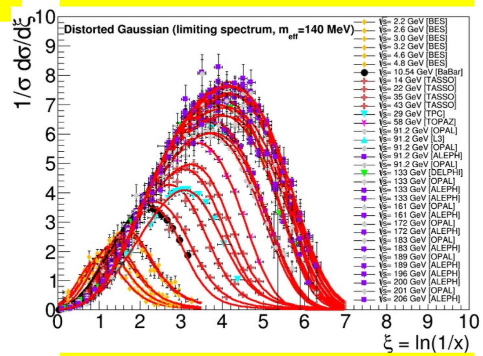
(3) <0.1% PS+hadroniz. uncert. for EWPOs

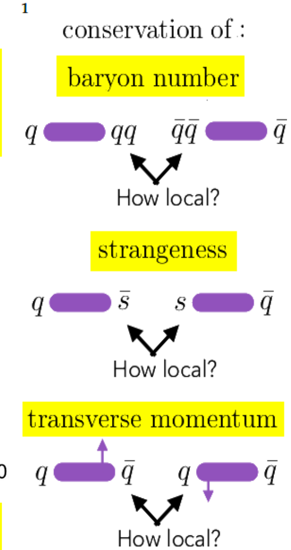


(4) <<1% control of colour reconnection



(5) High-precision hadronization:





(6) Ultra-rare QCD bound states

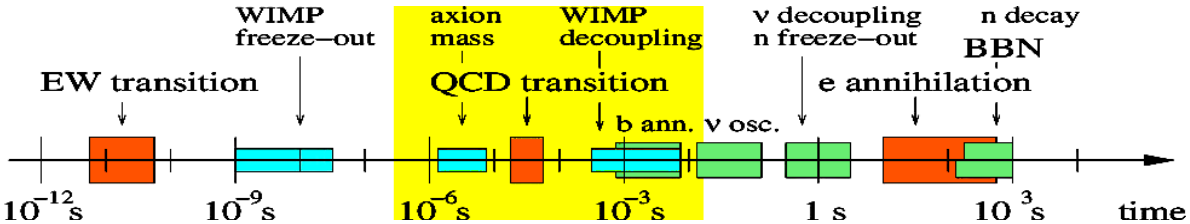
Heavy-ions at the FCC energy frontier

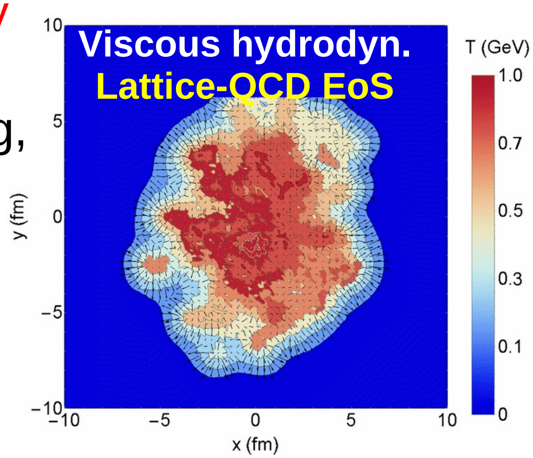
■ Central (hadronic) heavy-ion collisions:

1) ONLY way known to experimentally study the thermodynamics & phase transitions of a non-Abelian quantum-field theory. Collective ✔ QCD, ✖ EWK in the lab.

☞ QGP = Least viscous fluid known. Test-bed for string theory applications via AdS/CFT duality.

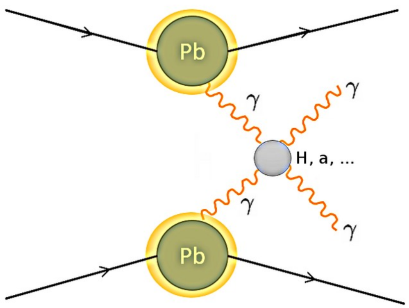
☞ Understand early Universe "bath" (~1 μs): WIMP decoupling, axion mass, imprints on gravitational wave spectrum? ...





■ Ultraperipheral (electromagnetic) heavy-ion collisions:

☞ Strongest electromagnetic fields in the Universe (~10^{15} T).



2) Unique SM & BSM studies via photon-photon collisions: light-by-light, axion-like particles, magn. monopoles, Higgs,...

Note: Likely, no other place in Universe produces Pb-Pb collisions at multi-TeV c.m. energies (heaviest cosmic-rays colls.: Fe-Air up to $\sqrt{s}_{max} \approx 400$ TeV).

Heavy-ion collisions at the FCC-hh

- CM energy $\sqrt{s}$ = 100 TeV for pp means: $\sqrt{s_{NN}} = \sqrt{s}\sqrt{Z_1 Z_2/A_1 A_2}$ for A-A colls.

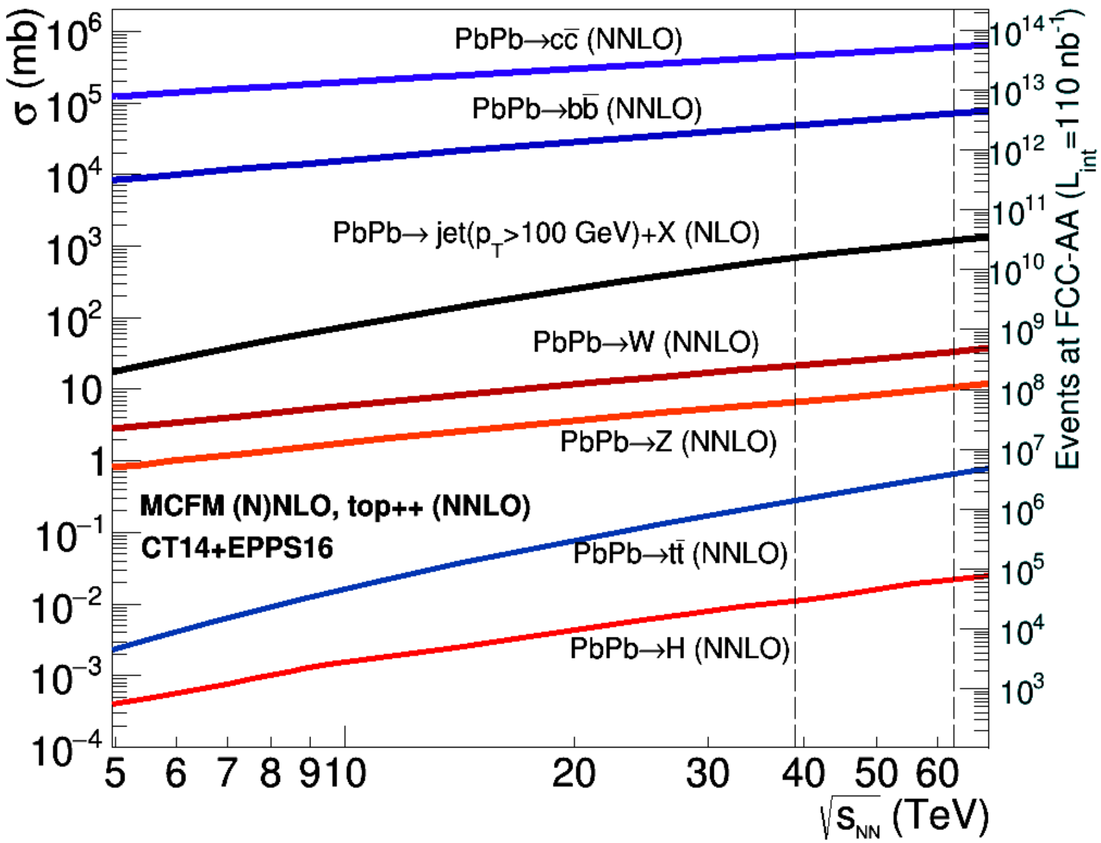
  PbPb: $\sqrt{s_{NN}}$ = 39 TeV, $\mathcal{L}_{int}$ = 110 nb^{-1}/month

  pPb: $\sqrt{s_{NN}}$ = 63 TeV, $\mathcal{L}_{int}$ = 29 pb^{-1}/month

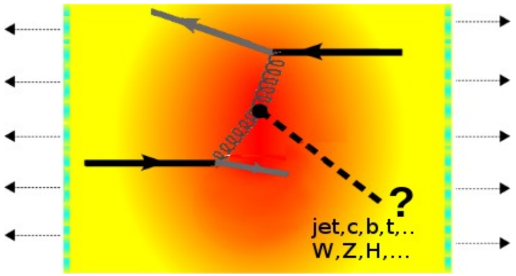
  $\sqrt{s_{NN}}$: ×7 larger than LHC

  $\mathcal{L}_{int}$: ×10–30 larger than LHC

- Huge increase in pQCD cross sections (yields) to probe QGP:

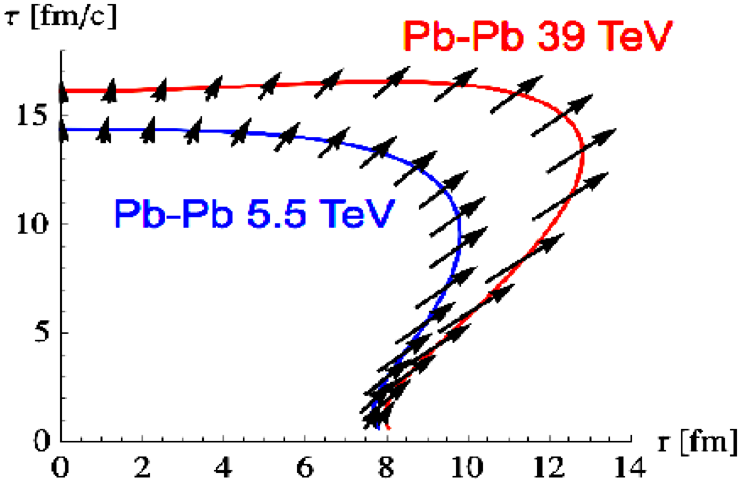


- ☞ Charm: ×4 (40) LHC
- ☞ Bottom: ×6 (60) LHC
- ☞ 100-GeV jets: ×30 (300) LHC
- ☞ W: ×7 (70) LHC
- ☞ Z : ×7 (70) LHC
- ☞ Top: ×80 (800) LHC
- ☞ Higgs: ×20 (200) LHC



PbPb(39 TeV): Bulk QGP properties

Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$dE_T/d\eta$ at $\eta = 0$	1.8–2.0 TeV	2.3–2.6 TeV	5.2–5.8 TeV
Homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
Decoupling time	10 fm/c	11 fm/c	13 fm/c
ε at $\tau = 1$ fm/c	12–13 GeV/fm^3	16–17 GeV/fm^3	35–40 GeV/fm^3



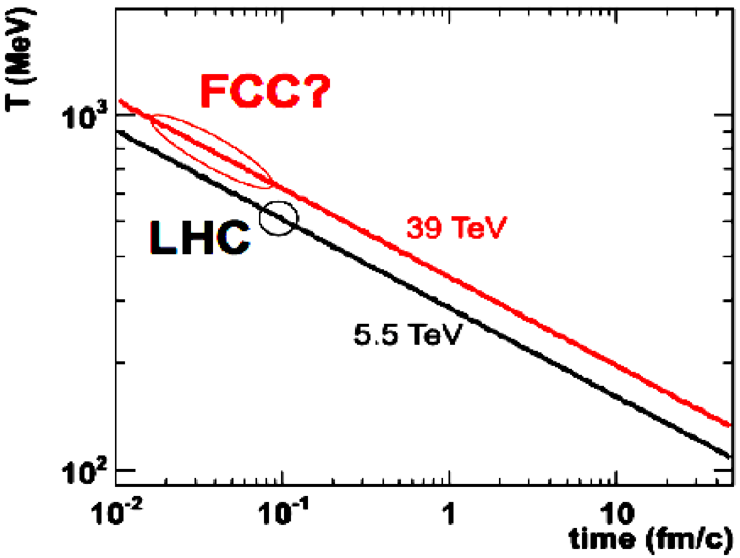
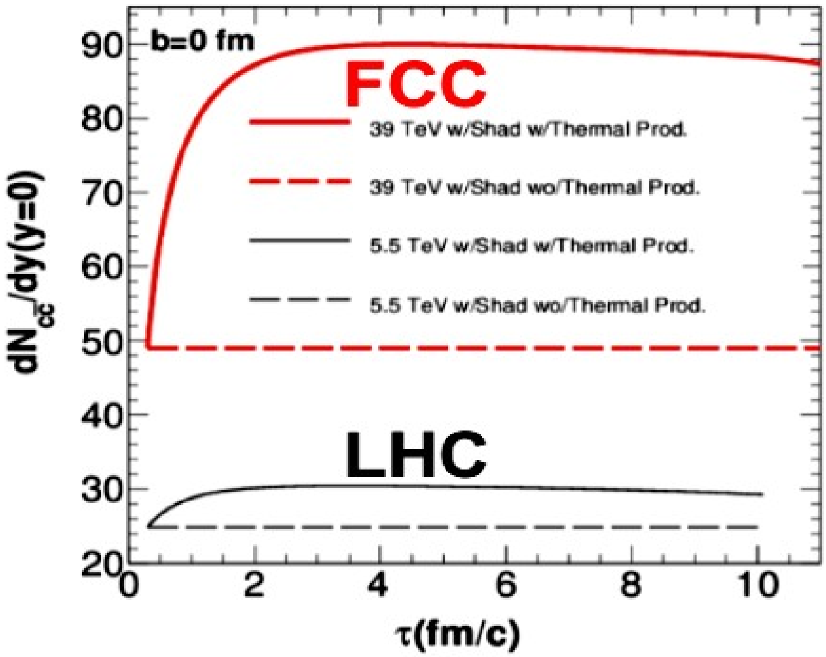


Fig. 2: Left: space-time profile at freeze-out from hydrodynamical calculations for central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV and 39 TeV. Right: time evolution of the QGP temperature as estimated on the basis of the Bjorken relation and the Stefan-Boltzmann equation (see text for details).

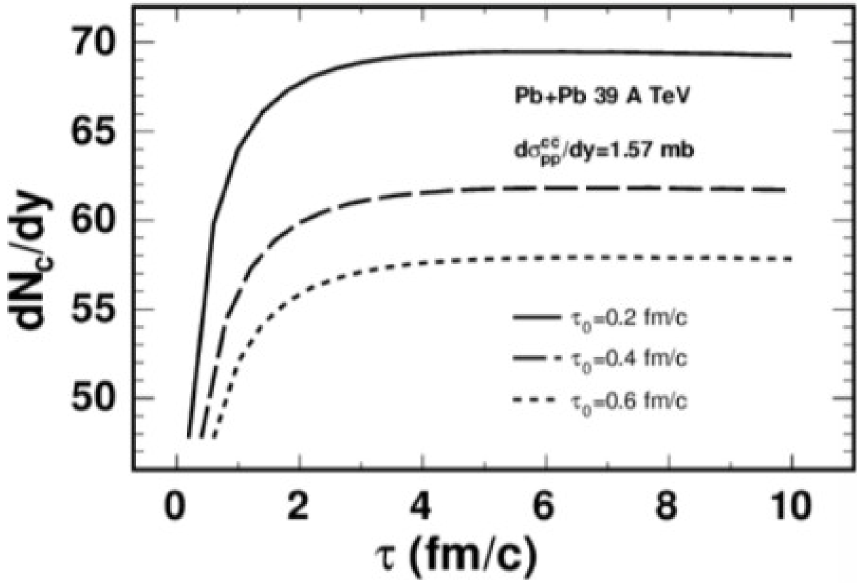
×2–2.5 larger particle & energy densities (~40 GeV/fm^3) than LHC

PbPb(39 TeV): Thermalized charm in QGP

- Expect abundant secondary production of $c\bar{c}$ pairs in the medium from $gg \to c\bar{c}$, $q\bar{q} \to c\bar{c}$ + NLO … **(~500 $c\bar{c}$ pairs!)**



K. Zhou et al., arXiv:1602.01667
C.M. Ko, Y. Liu, arXiv:1604.01207

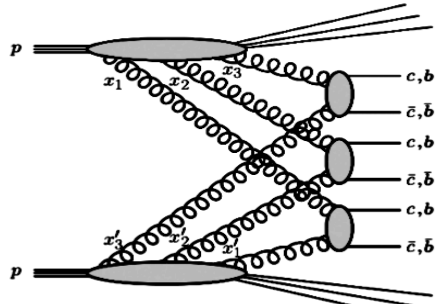


- Up to 50-100% "enhancement" wrt primary charm
- Sensitive to QGP properties: T vs τ, and τ_0 **(active *ndof* in QCD EoS)**

×3 larger charm-anticharm densities than at the LHC

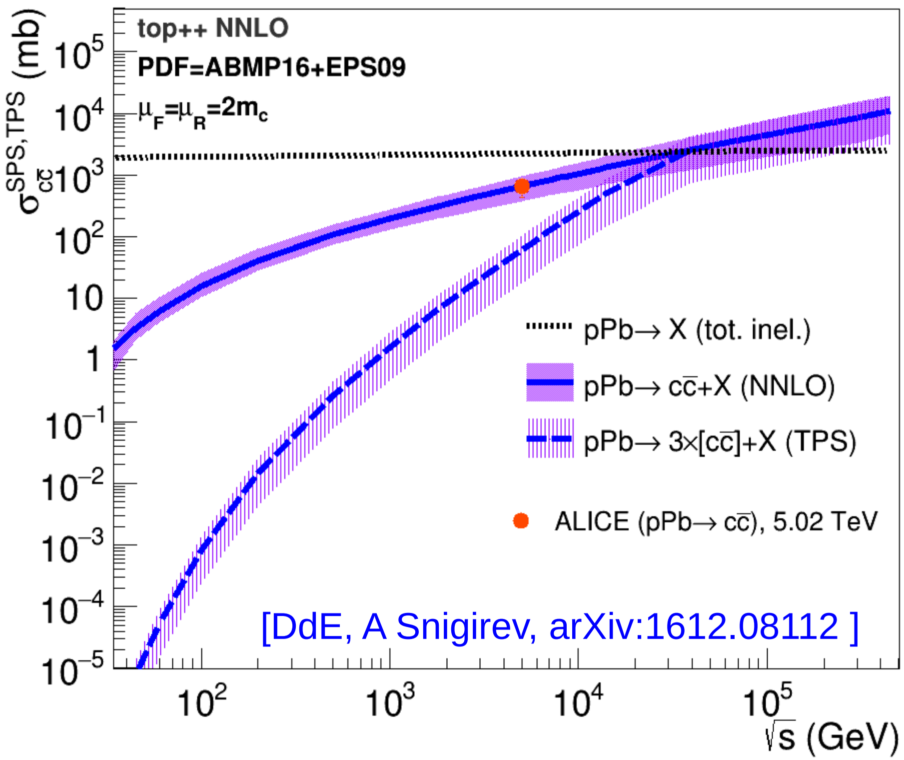
pPb(63 TeV): Triple-parton scatterings

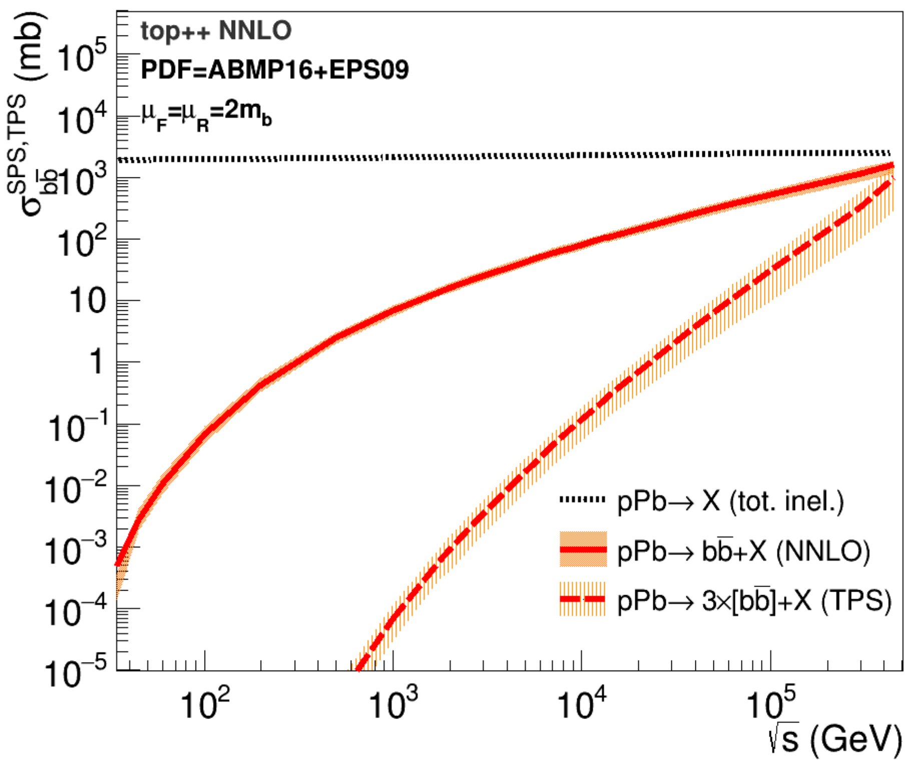
- Huge triple-parton-scattering (TPS) x-sections for charm & bottom derived from σ(NNLO) SPS plus "pocket formula" and p-A Glauber:



$$\sigma^{\rm TPS}_{hh'\to abc} = \left(\frac{m}{3!}\right)\frac{\sigma^{\rm SPS}_{hh'\to a}\cdot\sigma^{\rm SPS}_{hh'\to b}\cdot\sigma^{\rm SPS}_{hh'\to c}}{\sigma^2_{\rm eff,TPS}},$$

Energy evolution of proton transv. profile?

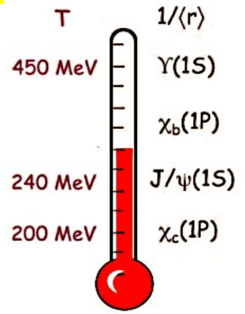


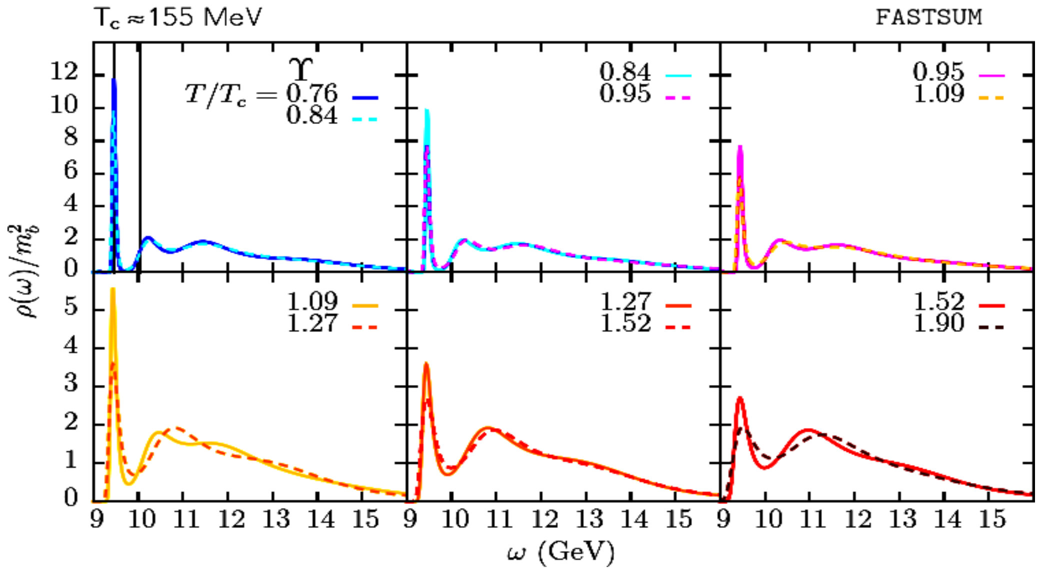


- At $\sqrt{s_{NN}}$ = 63 TeV: σ(triple-charm) ≈ 8.6 b, σ(triple-J/ψ),σ(triple-bb) ≈ 1,10 mb

PbPb(39 TeV): $Q\bar{Q}$ melting & recombination in QGP

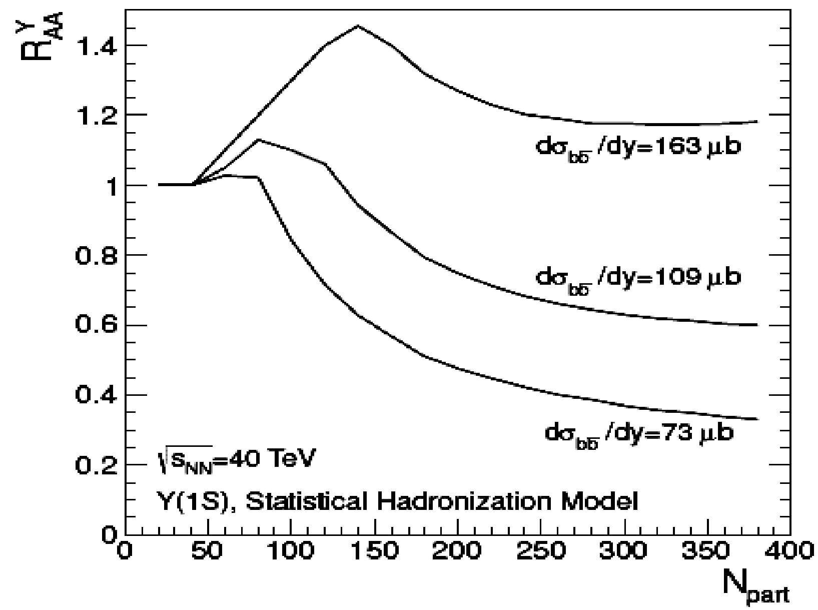
- FCC (T_0~1GeV) can probe QGP temperature through Υ(1S) "melting" expected by lattice-QCD at T = 4–5 T_c





[G. Aarts et al, JHEP 07 (2014) 097]

- Melting compensated by b-$\bar{b}$ recombination? Density of bottom pairs large enough for Υ(1S) recombination?



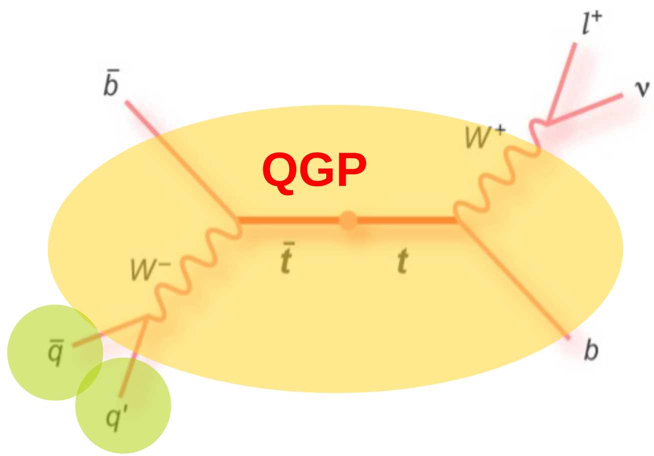
[A.Andronic, et al., JPG38 (2011) 124081]

PbPb(39 TeV): Boosted-top quark in QGP

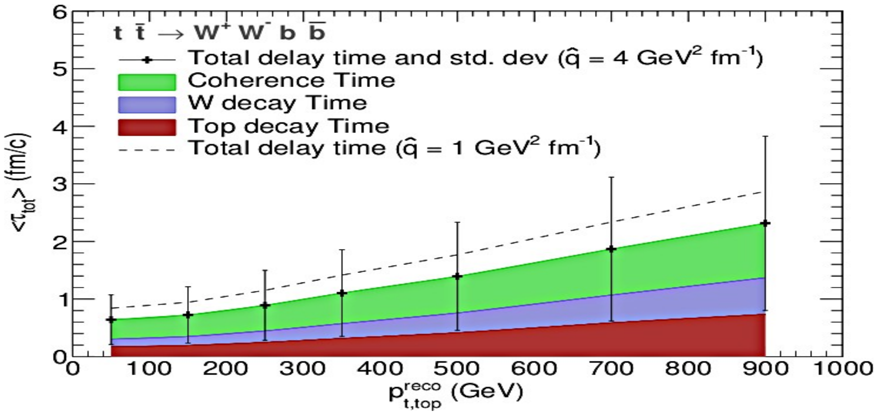
- Top-quark decays (t~0.1 fm/c) before hadronization into W+b. But, boosted t→W→ qq' traverses QGP:

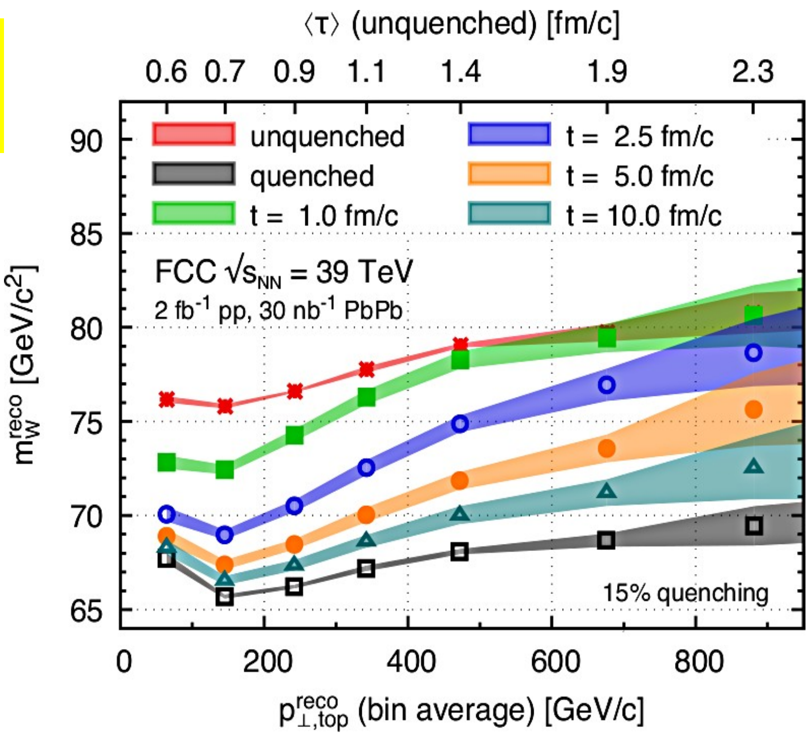
  t → b + 2jets (66%)
  ttbar → bbar + 2jets + 1ℓ + MET(n) (45%)

→ Colour reconnection of decay b,q,q'?
→ Enhanced gluon radiation in QGP?
→ Boosted t-tbar = Color-singlets probe medium opacity at diff. time scales:



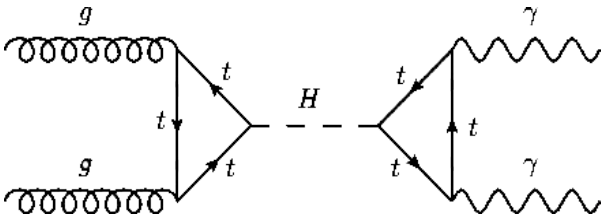
- Reconstructed m_W(qq) vs p_T(t) provides space-time QGP tomography:





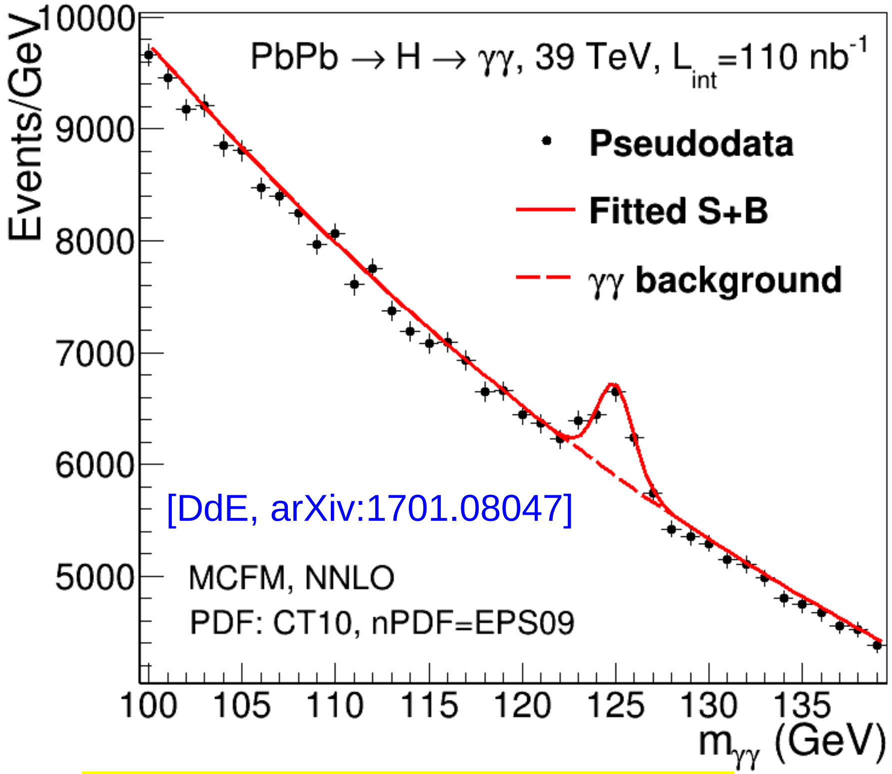
[Apolinaro et al, PRL (2018); 1711.03105]

PbPb(39 TeV): H → γγ in the QGP



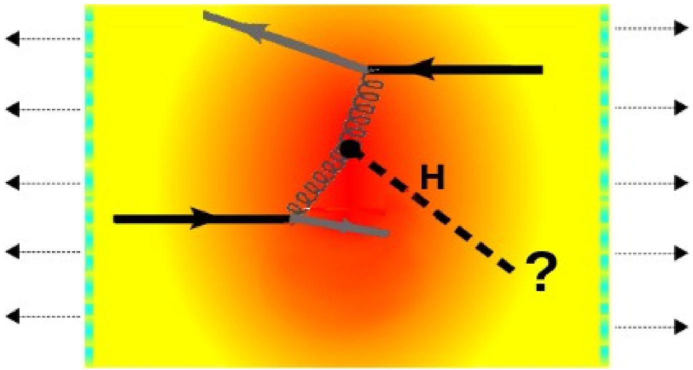
Analysis based on NNLO MCFM cross sections.
Pseudo-data for H(γγ) and γγ backgrounds
after typical CMS/ATLAS cuts

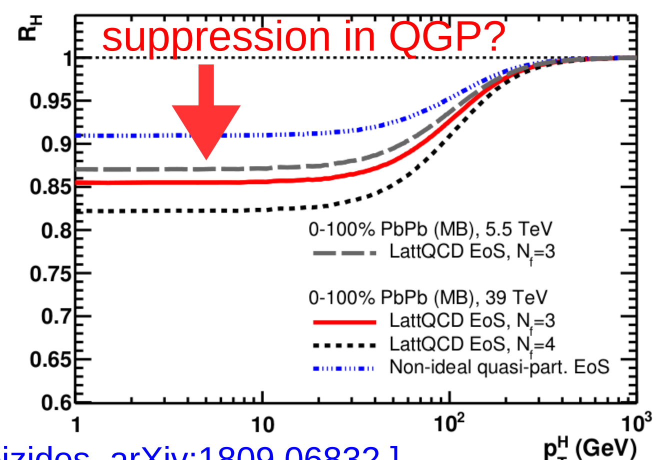
- Pb-Pb @ 39 TeV (L_{int}= 110 nb^{-1})



- S/√B~5.7σ observation in just 1st month

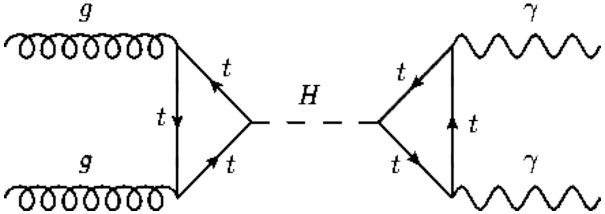
- Higgs boson (τ~50 fm) final-state interaction in QGP?





[DdE,C.Loizides, arXiv:1809.06832]

PbPb(39 TeV): H→γγ in the QGP



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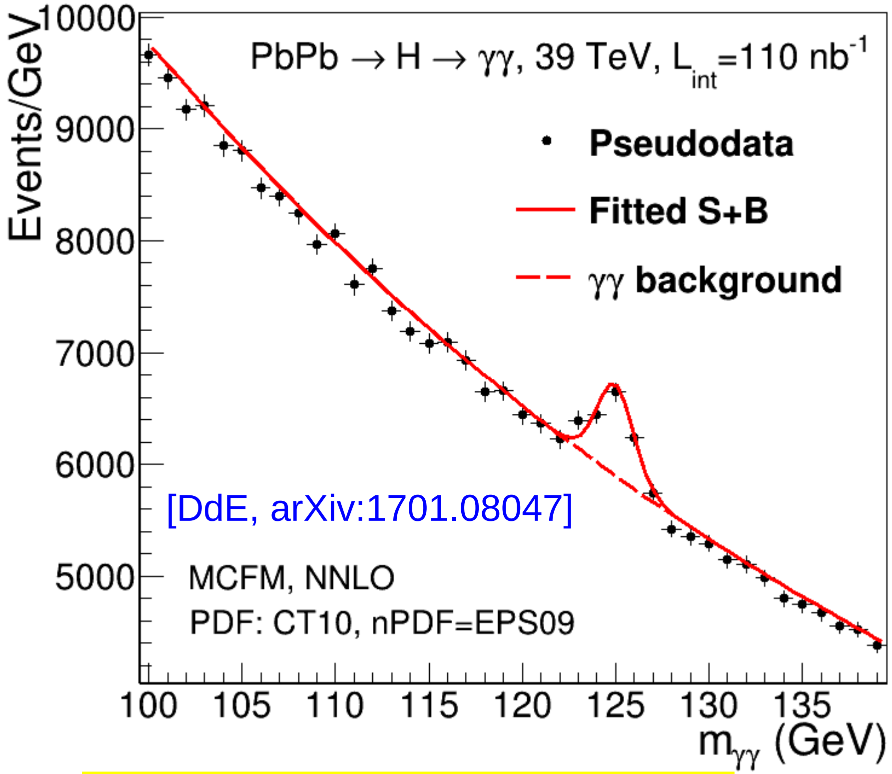

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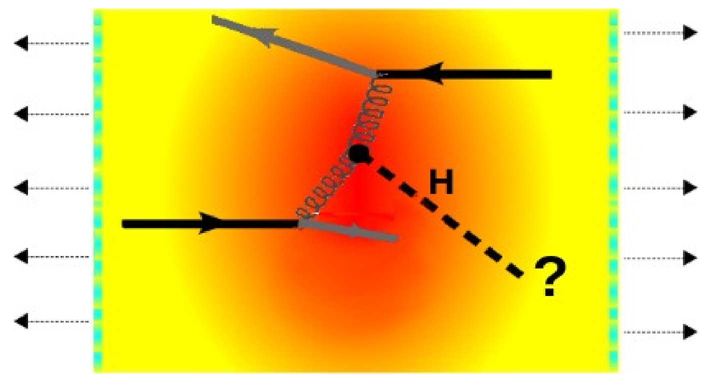


[Ghiglieri & Wiedemann, arXiv:1901.04503]

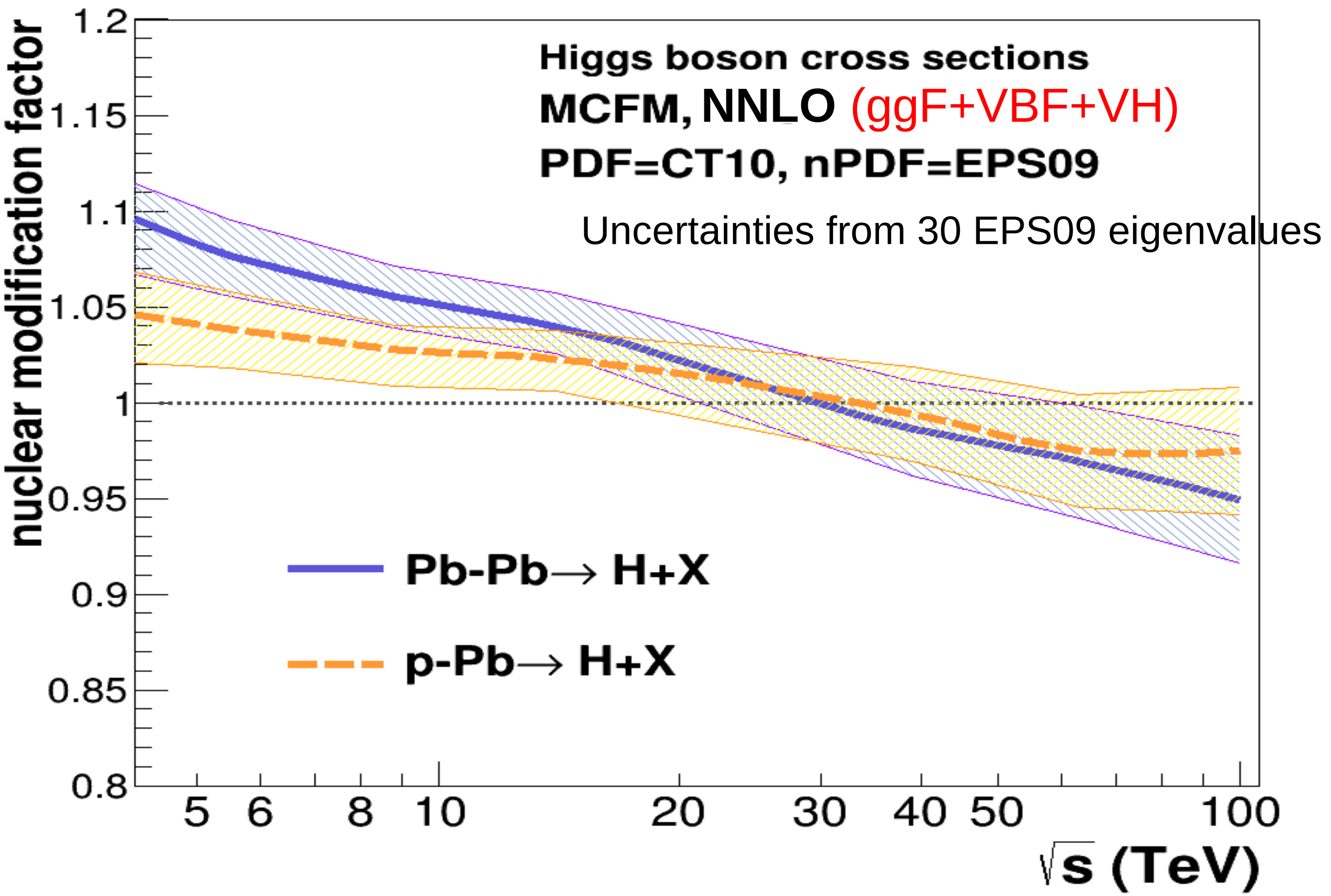
$$\delta\Gamma_{H\to gg} = -\Gamma^{\rm vac}_{H\to gg}\alpha_s \frac{T^4}{M_H^4}\frac{112\,\pi^3}{45}\left(8-n_f^T\right)$$

for H-decay in the plasma rest frame.

- Negligible modification of Higgs decay width in QGP ~ $(T/m_H)^4$~10^{-6}...

nPDF (anti)shadowing via Higgs boson

- EPS09 nuclear PDFs modify slightly x-sections wrt. pp PDFs:



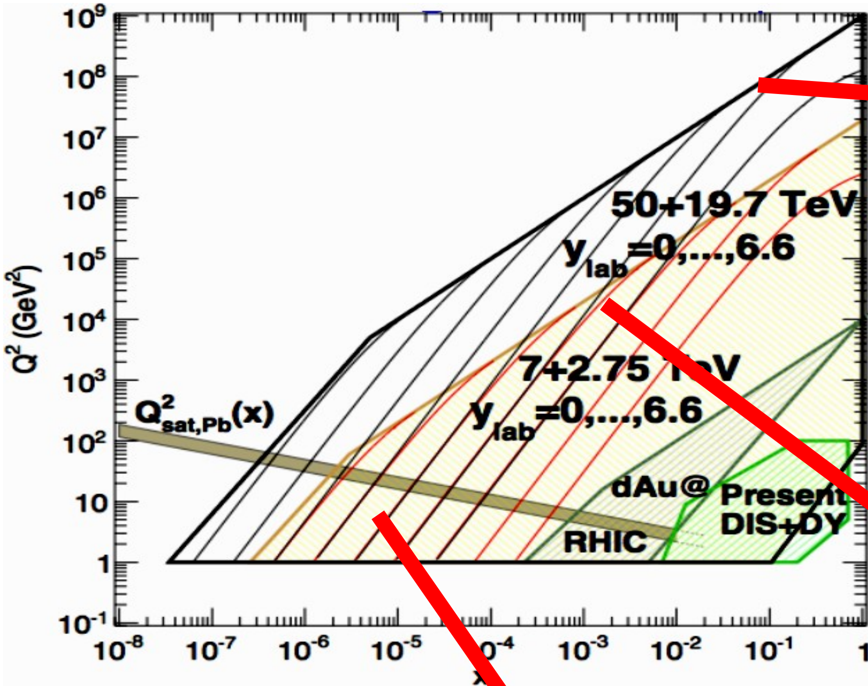
→ LHC: Small antishadowing: R_{AA}~ 1.07, R_{pA}~1.03

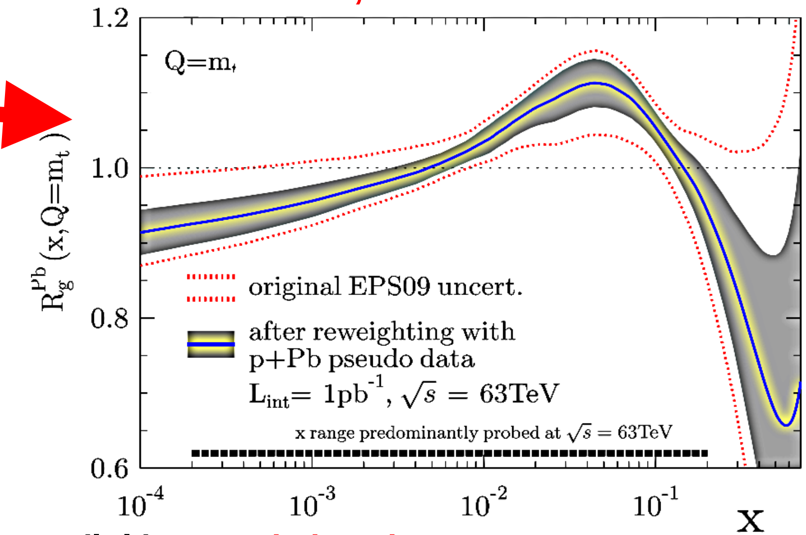
→ FCC: Mild shadowing: R_{AA}~ R_{pA}~ 0.97

[DdE arXiv:1701.08047]

pPb(63 TeV): Nuclear parton distrib. functions

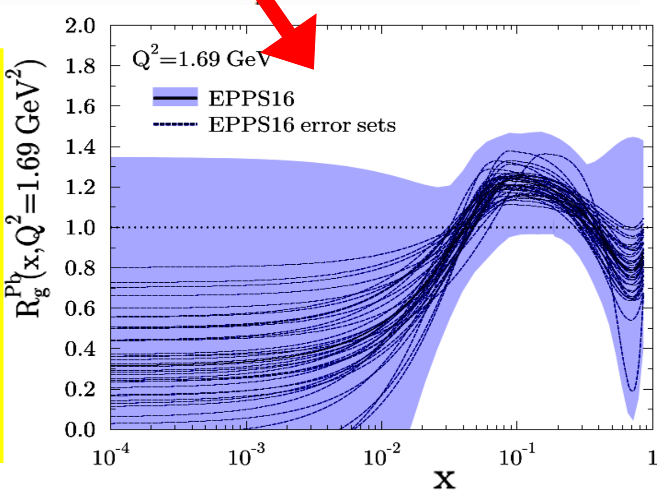
- Huge nPDF kinematical reach: $Q^2 \approx 2\text{–}4\cdot 10^8\ \mathrm{GeV}^2$, $x \approx 1\text{–}10^{-7}$

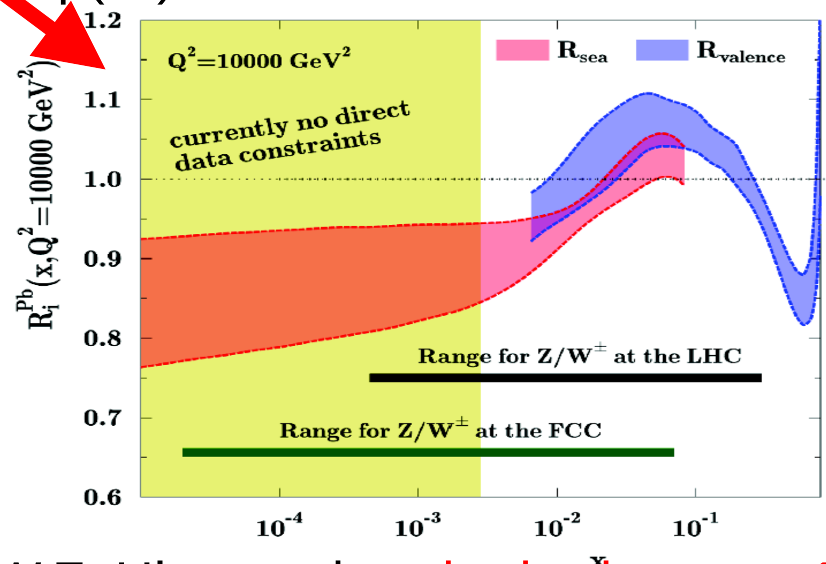




top(l^+l^-): Antishadow.&EMC at x > 0.1

Unknown nuclear gluon at $x<10^{-4}$ (saturation?)





W,Z: Ultraprecise shadowing at $x \approx 10^{-3}$

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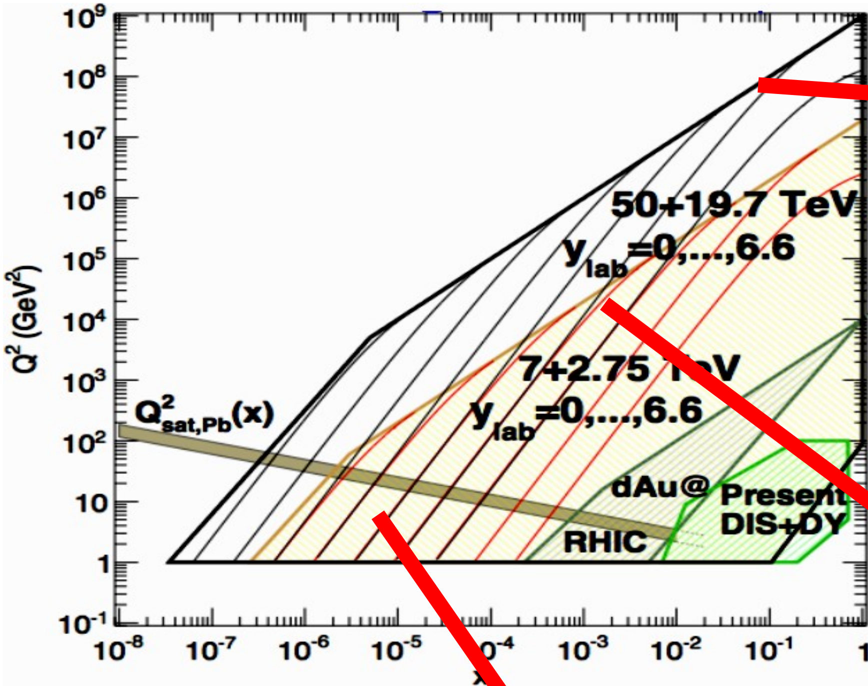

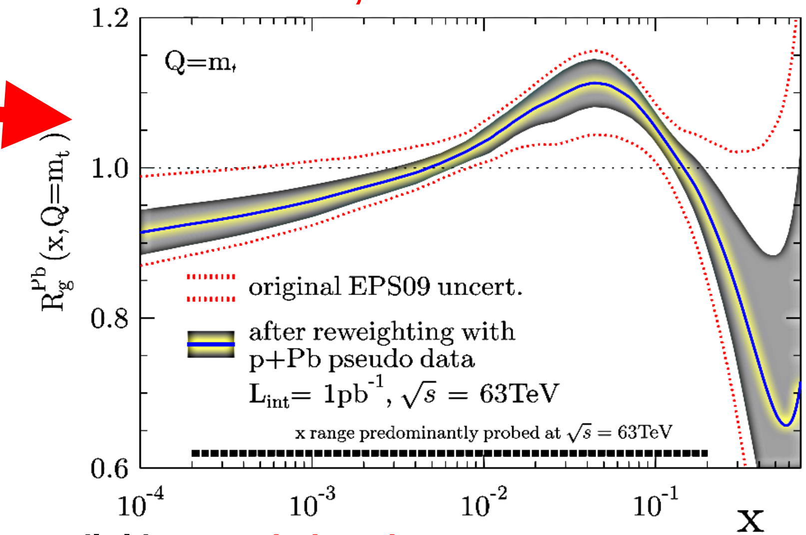

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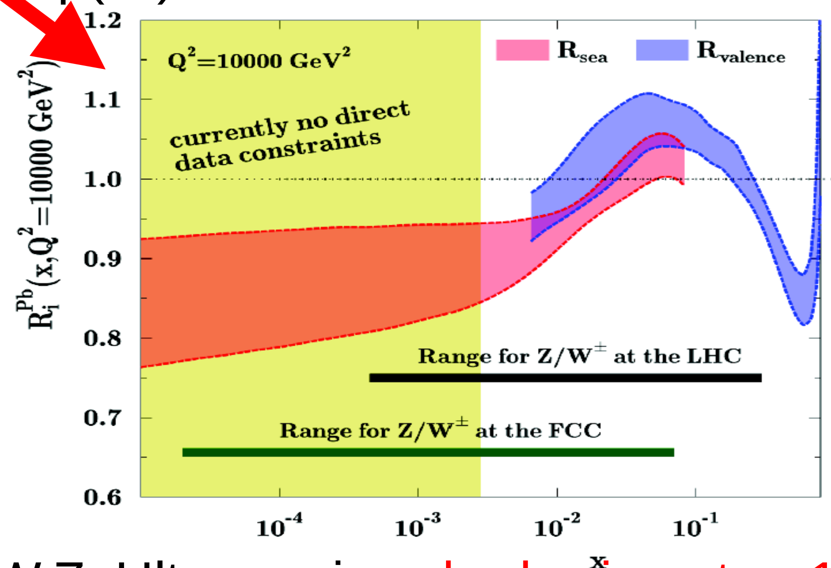
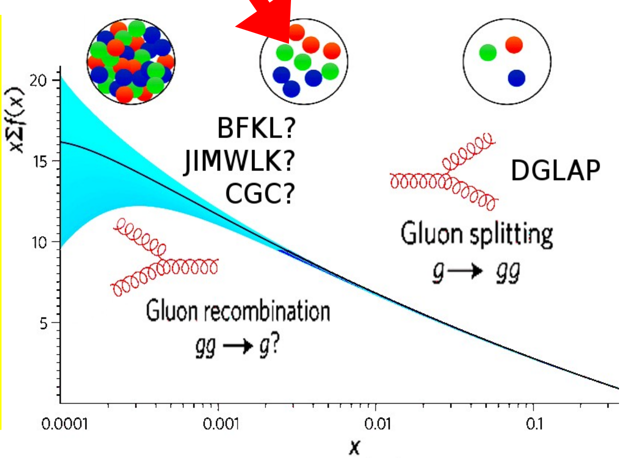


DGLAP breakdown below $x<10^{-4}$ (CCG?)

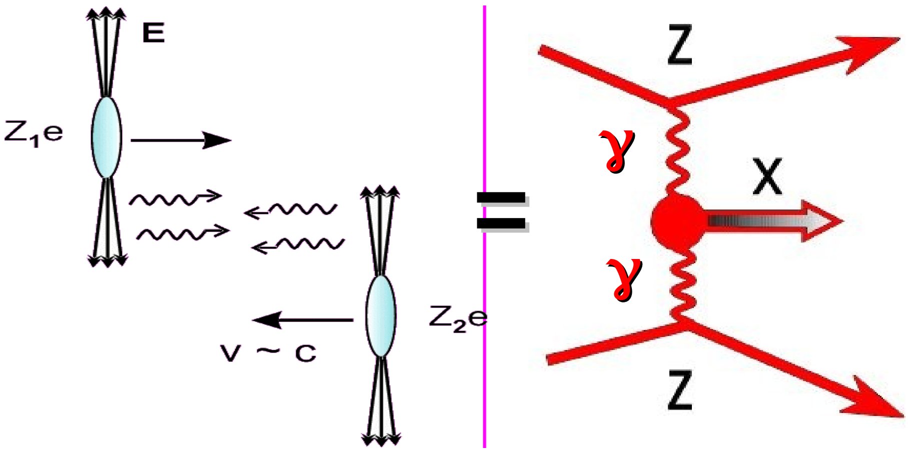


W,Z: Ultraprecise shadowing at $x \approx 10^{-3}$

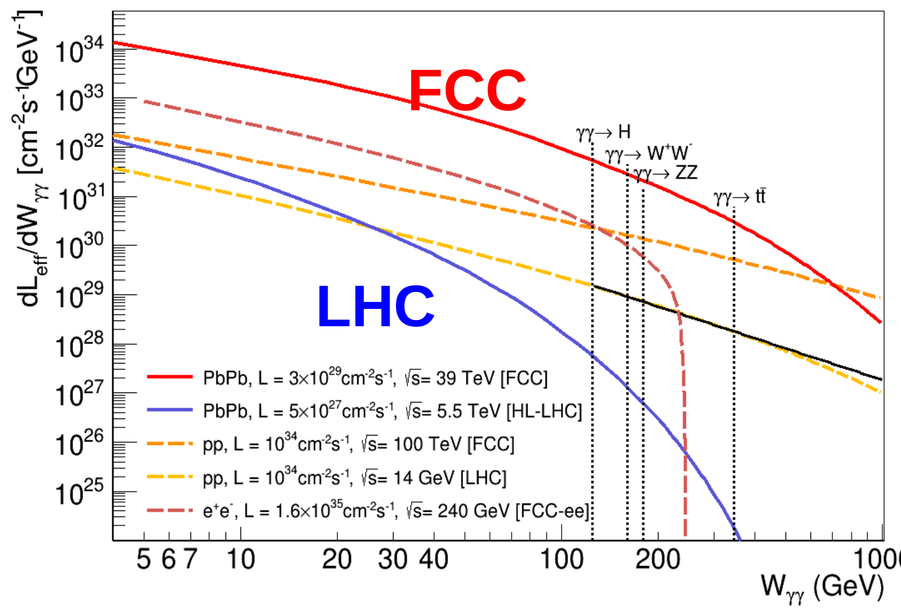
PbPb(39 TeV): SM & BSM via γγ collisions

- Huge γγ luminosities in AA thanks to collective action of Z=82 charges:

$\sigma_{PbPb\to\gamma\gamma\to X} \approx Z^4 \times \sigma_{pp\to H} = 5\cdot 10^7 \times \sigma_{pp\to\gamma\gamma\to X}$

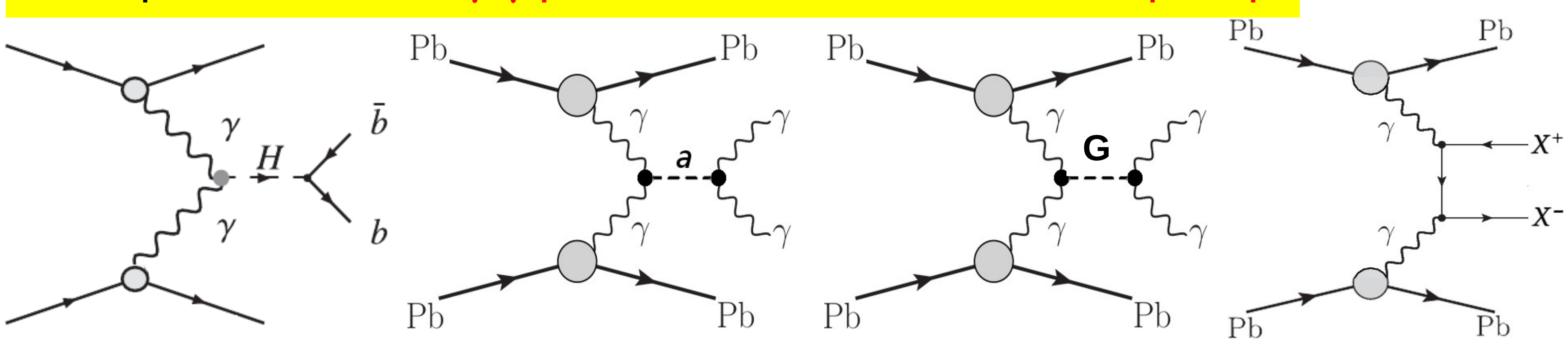


- Large eff. lumi up to $\sqrt{s_{\gamma\gamma}} \approx 1$ TeV



Ultraperipheral interactions: Nuclei survive.

- Unique SM & BSM γ-γ processes acessible without pileup:



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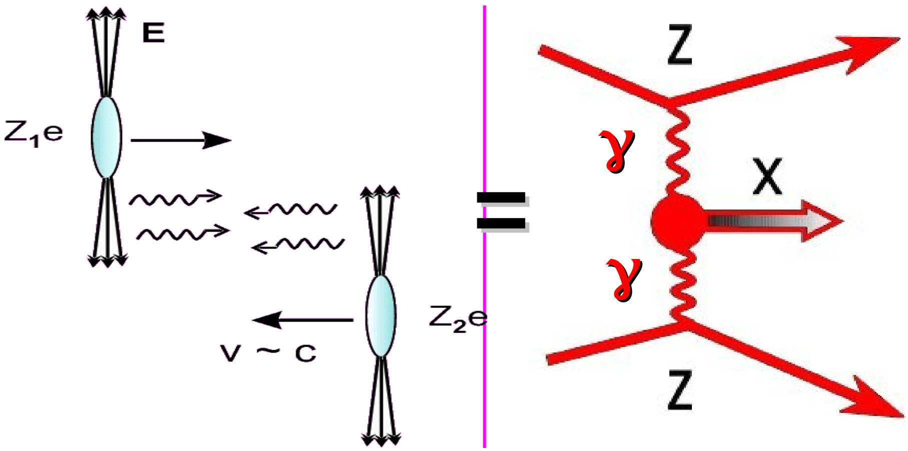
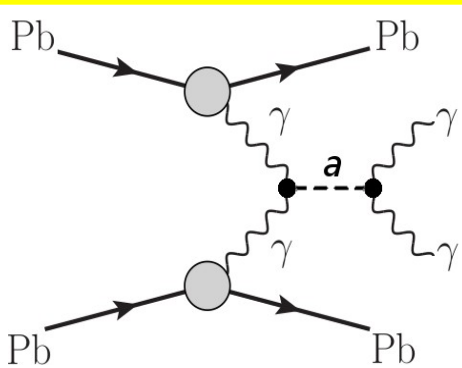
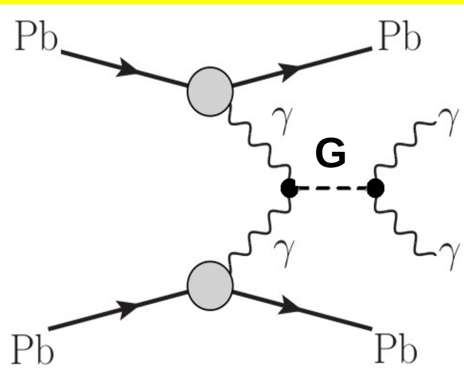


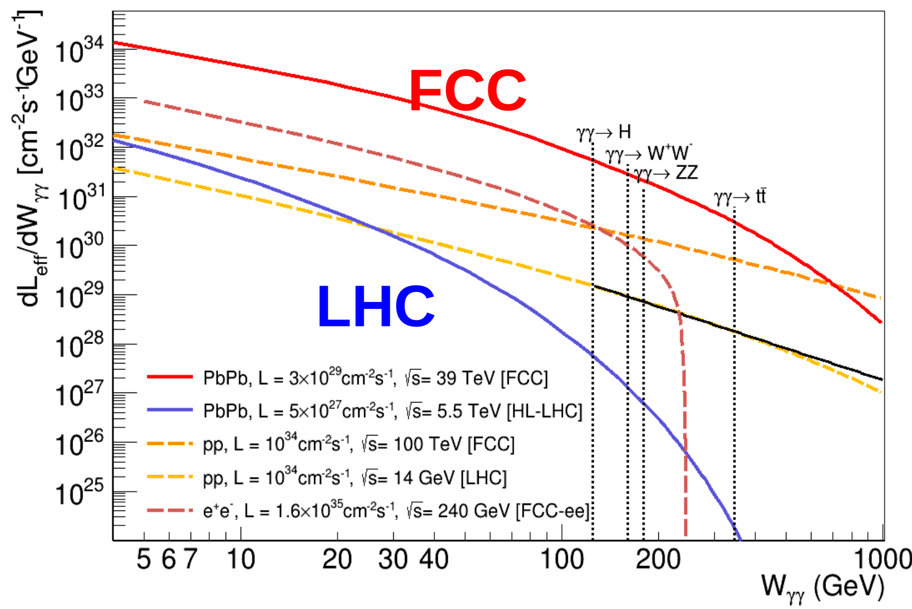
Ultraperipheral interactions: Nuclei survive.

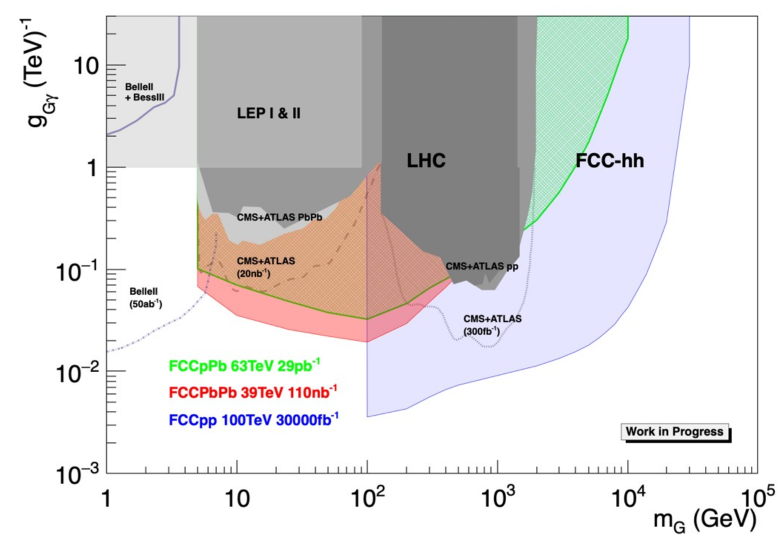
■ Competitive ALPs, GRAVs searches:





■ Large eff. lumi up to $\sqrt{s}_{\gamma\gamma}\approx$1 TeV

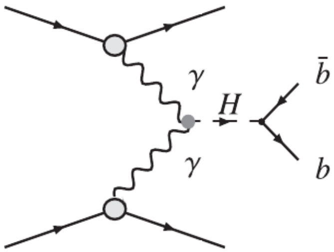




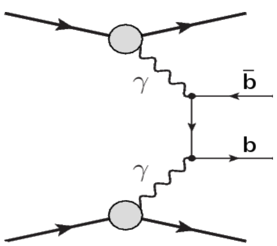
PbPb(39 TeV): Higgs boson via γγ → H → bb

- Expected exclusive Higgs over bb background after cuts:

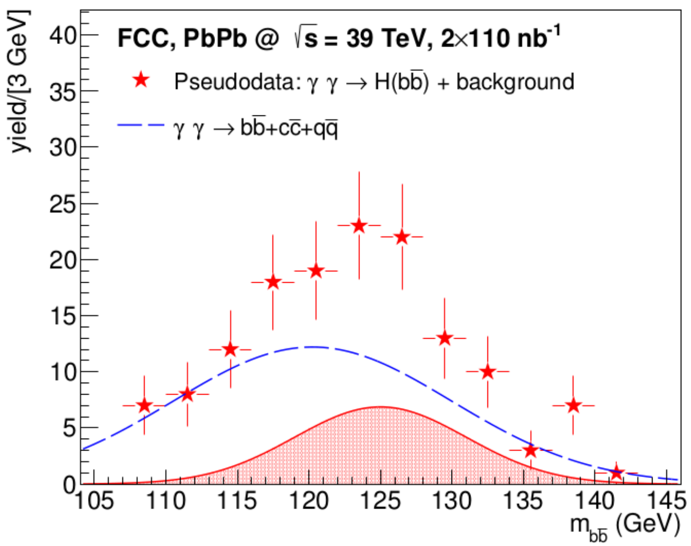
System	Nominal runs: $\mathcal{L}_{AB}$ (cm^{-2} s^{-1})	Nominal runs: Δt (s)	Nominal runs: $\langle N_{\text{pileup}}\rangle$	Nominal runs: N_{Higgs} total ($H \to b\bar{b}$)	Upgraded pA scenario: $\mathcal{L}_{AB}$ (cm^{-2} s^{-1})	Upgraded pA scenario: Δt (s)	Upgraded pA scenario: $\langle N_{\text{pileup}}\rangle$	Upgraded pA scenario: N_{Higgs} total ($H \to b\bar{b}$)
pp (14 TeV)	10^{34}	10^7	25	77 (55)	10^{34}	10^7	25	77 (55)
pPb (8.8 TeV)	$1.5 \cdot 10^{29}$	10^6	0.05	0.050 (0.035)	$1 \cdot 10^{31}$	10^7	1	34 (25)
PbPb (5.5 TeV)	$5 \cdot 10^{26}$	10^6	$5 \cdot 10^{-4}$	0.009 (0.007)	$5 \cdot 10^{26}$	10^7	$5 \cdot 10^{-4}$	0.15 (0.1)

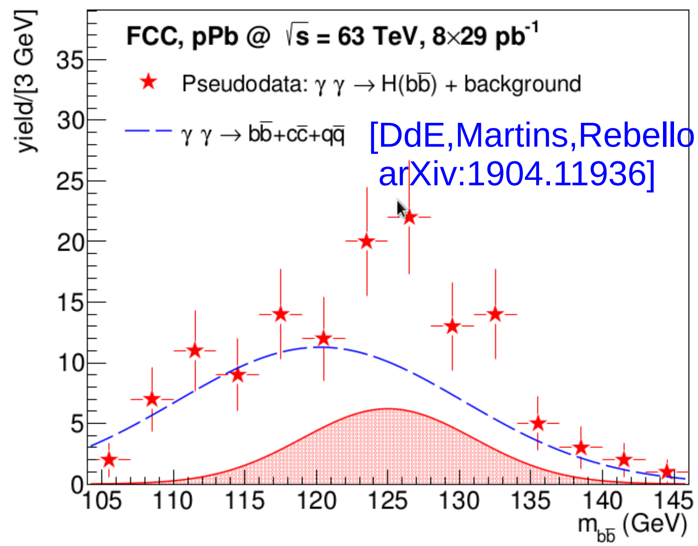


PbPb at $\sqrt{s_{\text{NN}}}$ = 39 TeV	cross section (b-jet (mis)tag efficiency)	visible cross section after p_T^j, $\cos\theta_{jj}$, m_{jj} cuts	N_{evts} ($\mathcal{L}_{\text{int}} = 110$ nb^{-1})
$\gamma\gamma \to \text{H} \to b\bar{b}$	1.02 nb (0.50 nb)	0.19 nb	21.1
$\gamma\gamma \to b\bar{b}$ [$m_{b\bar{b}}$=100−150 GeV]	24.3 nb (11.9 nb)	0.23 nb	25.7
$\gamma\gamma \to c\bar{c}$ [$m_{c\bar{c}}$=100−150 GeV]	525 nb (1.31 nb)	0.02 nb	2.3
$\gamma\gamma \to q\bar{q}$ [$m_{q\bar{q}}$=100−150 GeV]	590 nb (0.13 nb)	0.002 nb	0.25



- 5σ significance in first PbPb (pPb) month (year):





[DdE,Martins,Rebello, arXiv:1904.11936]

→ Measurement of H-γ coupling not based on decay but s-channel prod.

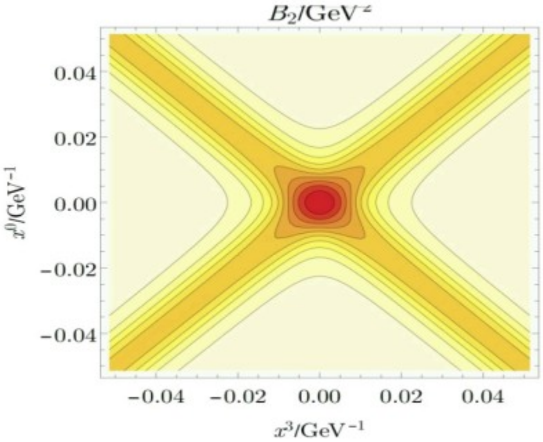
→ Total Higgs width via:

$$\Gamma_H^{\text{tot}} = \Gamma(\text{H} \to \gamma\gamma)/\mathcal{B}(\text{H} \to \gamma\gamma)$$

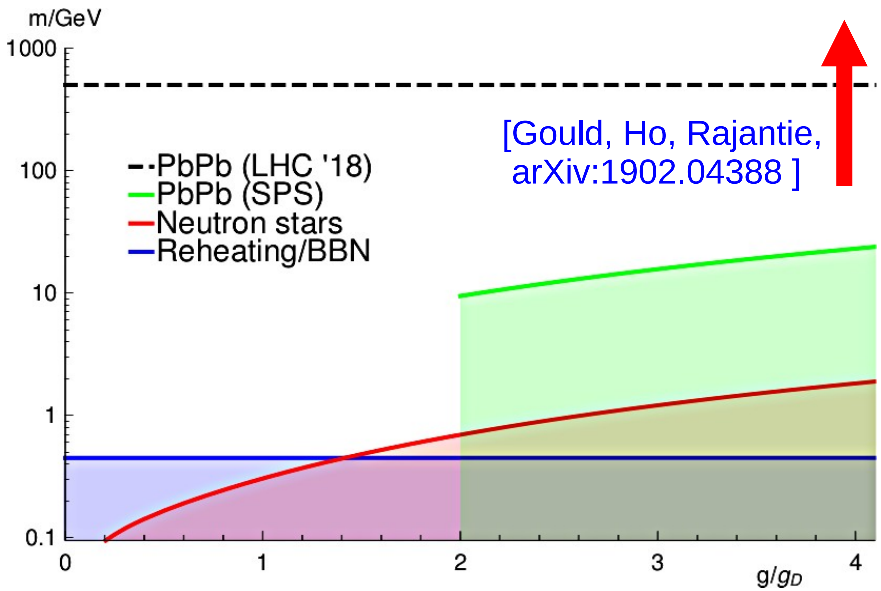
PbPb(39 TeV): BSM searches (e.g. magnetic mopoles)

- Heavy-ion collisions at the LHC generate the largest B-fields in the universe $B \sim 10^{16}$ T, i.e. $\times 10^5$ magnetar fields (albeit over ~10 fm for ~1 fm/c):

LHC magnets	$\lvert\vec{B}\rvert \sim 8.3\ \mathrm{T} \sim 1.6\times10^{-15}\ \mathrm{GeV}^2$
Magnetars	$\lvert\vec{B}\rvert \sim 2\times10^{11}\ \mathrm{T} \sim 4\times10^{-5}\ \mathrm{GeV}^2$
Fixed-target Pb collisions at SPS	$\lvert\vec{B}\rvert \sim 5\times10^{13}\ \mathrm{T} \sim 10^{-2}\ \mathrm{GeV}^2$
5.02 TeV Pb-Pb collisions at LHC	$\lvert\vec{B}\rvert \sim 4\times10^{16}\ \mathrm{T} \sim 7\ \mathrm{GeV}^2$



FCC: B-fields further increased by ×10



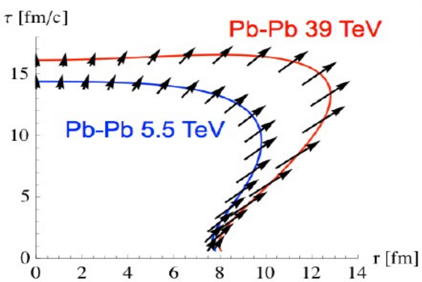
- Magnetic monopoles:
  - Explain charge quantization.
  - Predicted by GUT/string theory.
- B-monopoles via Schwinger mechn. not accesible in p-p,e^+e^- collisions (pair prod. expon. suppressed), but x-section $\sigma \sim \exp(-m^2/(gB))$:

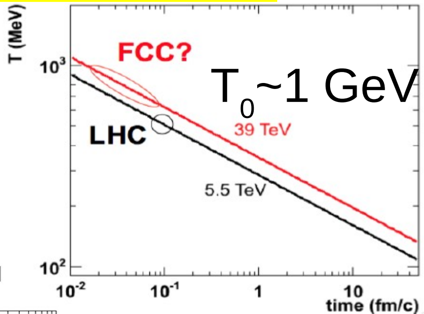
Unique FCC mass bounds m>1 TeV

Summary (2): Unique heavy-ion physics at FCC-hh

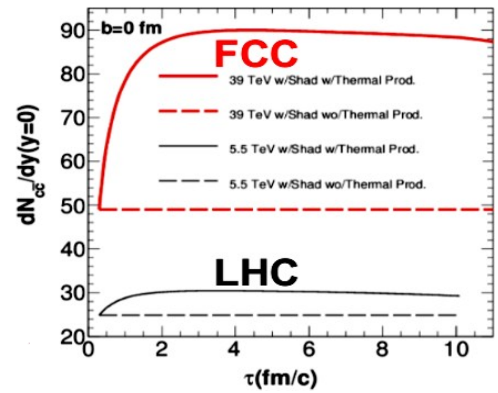
- Unparalleled HI physics with ×7, ×10 larger $\sqrt{s}$ and $\mathcal{L}_{int}$ than LHC:

energy densities: ~40 GeV/fm³

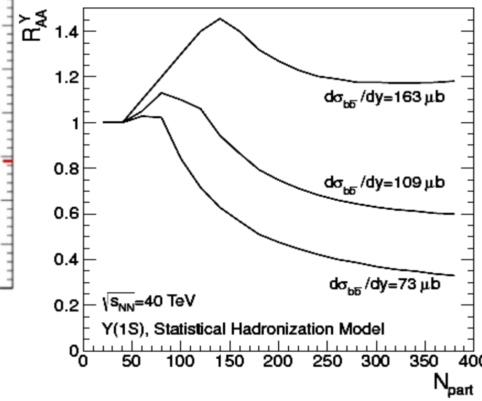


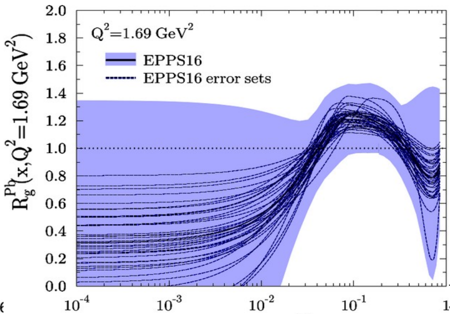


~500 charm pairs in QGP

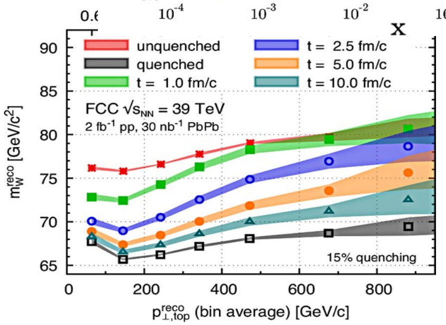


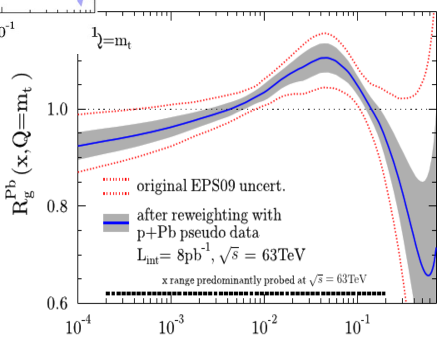
Υ(1S) melt.+recomb.?





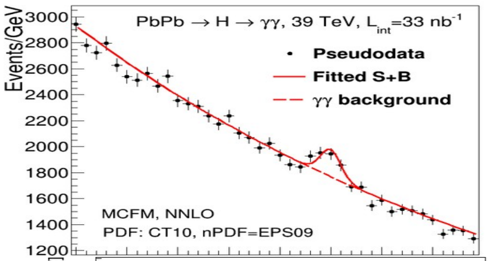
Gluon saturation down to x~10⁻⁷

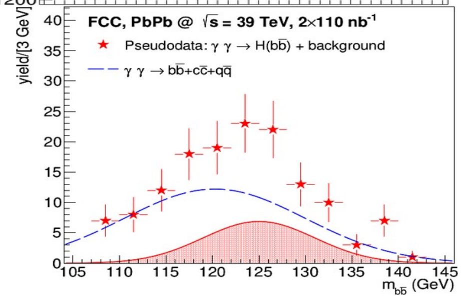




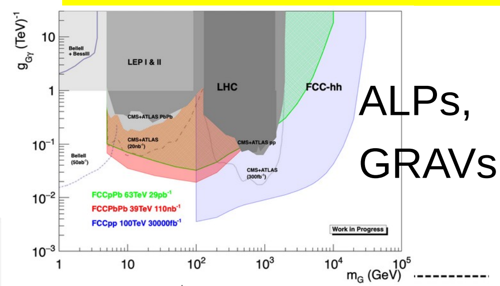
Top quark = Parton rad. "chrono-fmeter" & high-x gluon nPDF probe

Higgs in QGP & via γγ



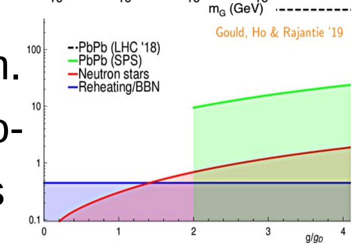


BSM via γγ colls.



ALPs, GRAVs

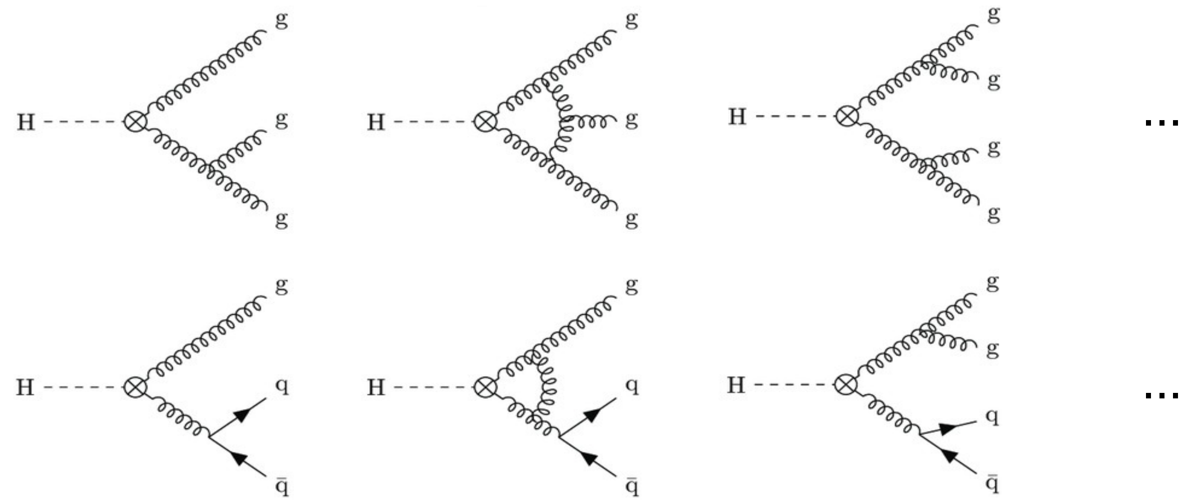
Magn. mono-poles



Back-up slides

Higgs → gg decay and BSM

- H → gg partial width known today theoretically at N[4]LO (approx) accuracy



- Percent deviations on Higgs-gluon coupling in BSM models:

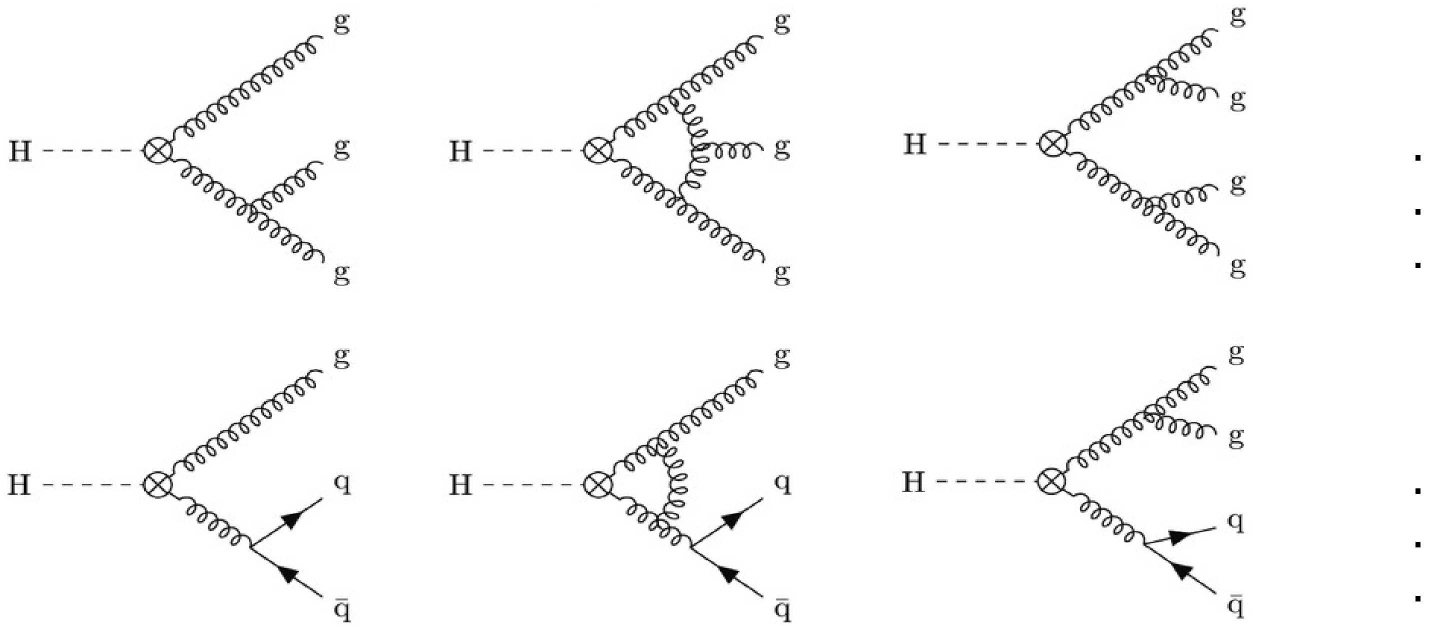
Table 5: Deviations from the Standard Model predictions for the Higgs boson couplings in %

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [40]	+4.8	-0.8	-0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [42]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [42]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [42]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [44]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [45]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [46]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [47]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [48]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

[T. Barklow et al. arXiv:1708.08912]

Higgs decays widths & QCD coupling

- $H \to gg$ partial width known today theoretically at N^4LO (approx) accuracy



Uncertainties: O(3%) TH + O(4%) parametric from $\alpha_s(m_Z)=0.118\pm1\%$ (today):

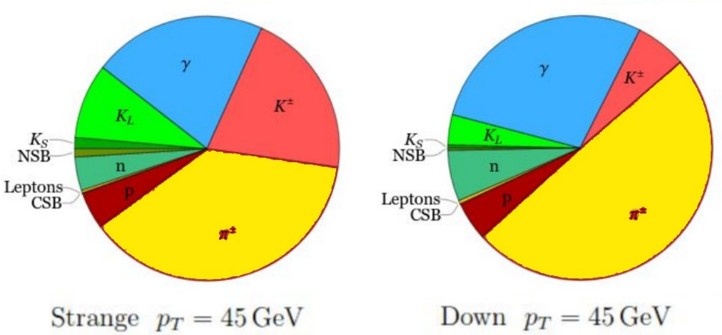
Partial width	intr. QCD	intr. electroweak	total	para. m_q	para. α_s
$H \to b\bar{b}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	1.4%	0.4%
$H \to c\bar{c}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	4.0%	0.4%
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3.2\%$	$< 0.2\%$	3.7%

- FCC-ee will need a much more precise $\alpha_s(m_Z)$ to constrain κ_g at $\pm$0.7% (exp

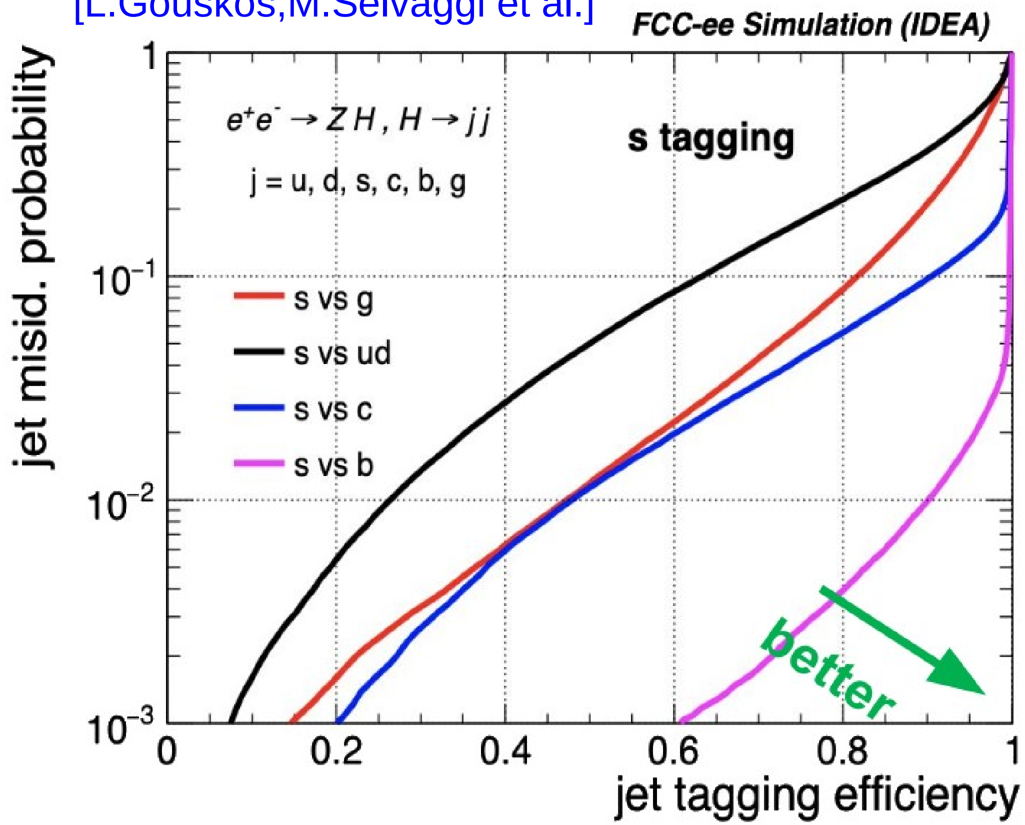
Strange-quark jet tagging at FCC-ee

- FCC-ee will produce O(400) H→ssbar decays. Can we measure y_s?
- ParticleNet jet tagger exploiting hadron PID (via dE/dx, ToF, RICH):

[2003.09517] Momentum weighted fraction:



[L.Gouskos,M.Selvaggi et al.]



Tagger exploits directly full list of jet constituents (ReconstructedParticles):

[O(50) properties/particle]

× [~50-100 particles/jet]

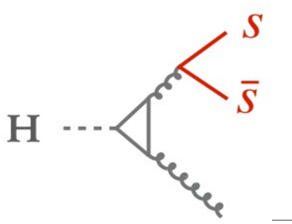
~ O(1000) inputs/jet

- Analysis $e^+e^- \to$ HZ, H→qq with N=2j exclusive jet algorithm:
  Backgds: WW/ZZ/Z, qqH, HWW, HZZ
  Combined jj (Hbb, Hcc, Hss, Hbb) fit yields: H→ss with O(80%) uncertainty

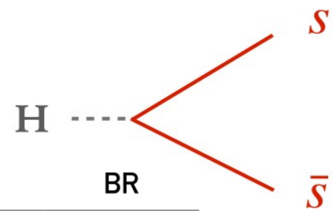
Separating H→ ss and H→ gg

- Does the H→ gg(ss) Dalitz decay jeopardize the H→ ss measurement?

Dalitz decay ($\alpha_s^3 y_t^2$)

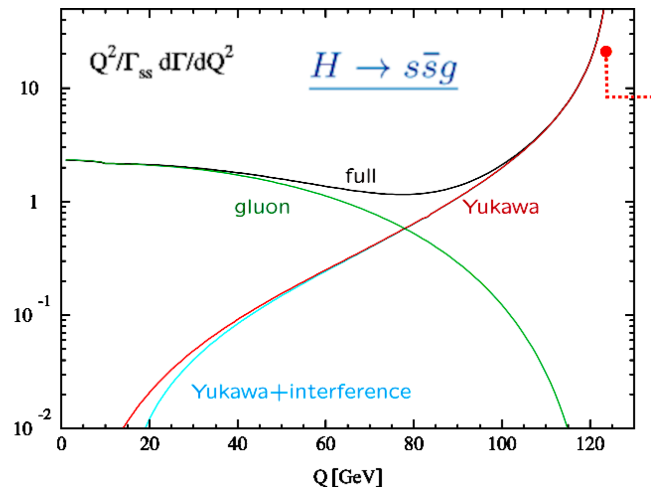


Yukawa decay (y_s^2)



	BR
H → gg	8.1×10^{-2}
H → ss	$\sim 2 \times 10^{-4}$

Ratio is ~ 400

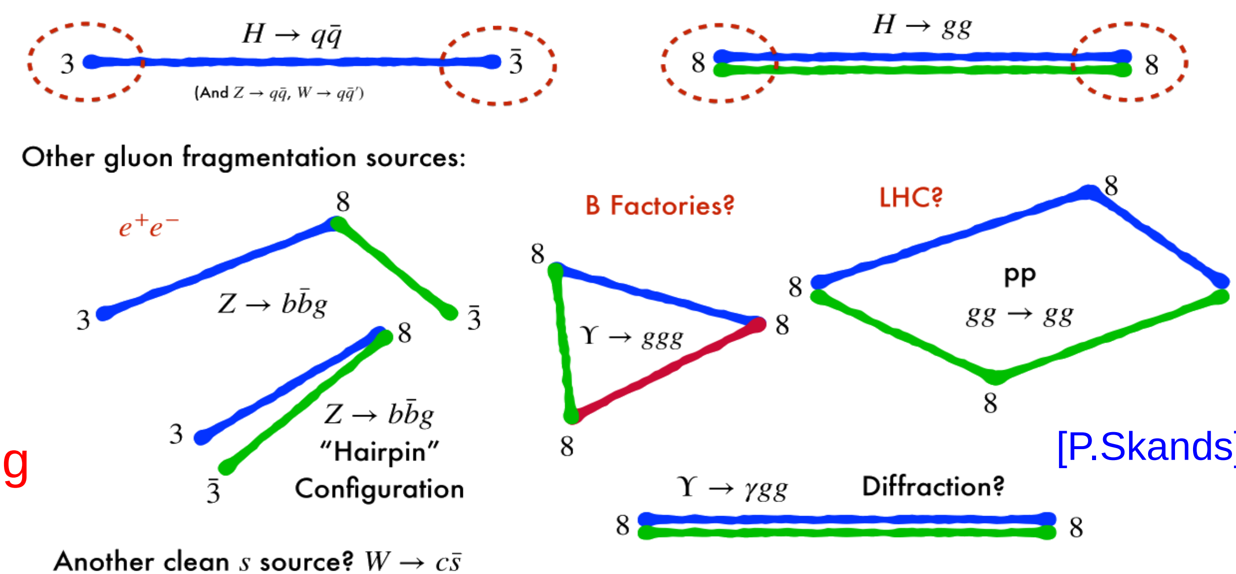


For m_{jj}>100 GeV: Dalitz ssg decays are no bottleneck to the y_s extraction (high mass resum. needed)

[M.Spira; G. Salam]

- Need also NNLL parton showers (matched to NNLO) and accurate/precise s, g (string, cluster) hadronization:

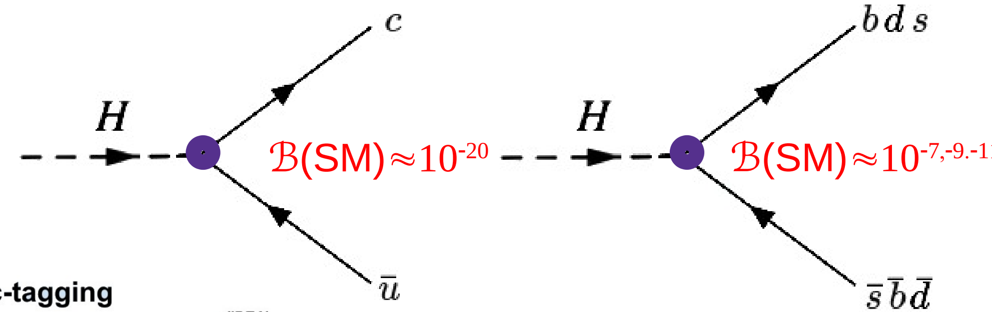
High-precision hadron data (FCC-ee, B-factories?) needed to reliably distinguish leading s, u,d,g fragmentation hadrons



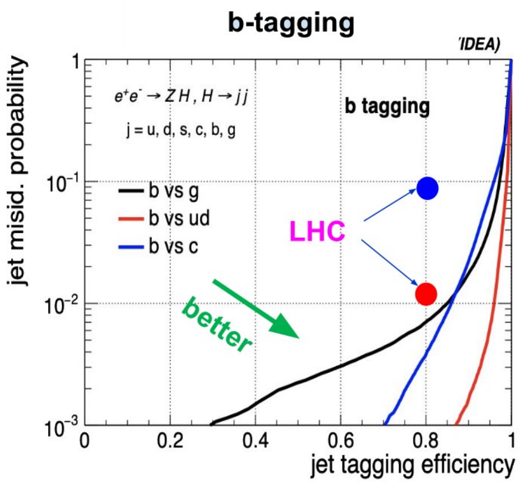
[P.Skands]

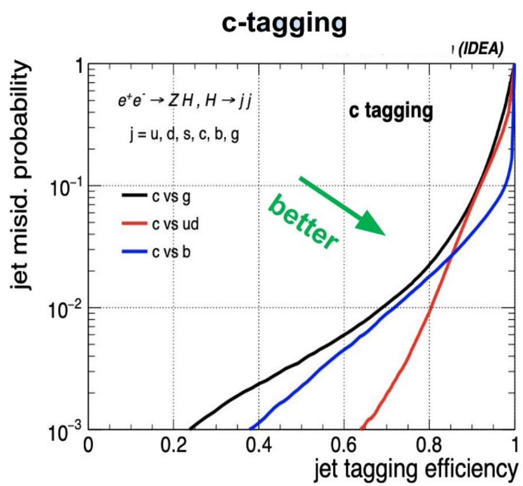
Flavor-violating Higgs decays at FCC-ee

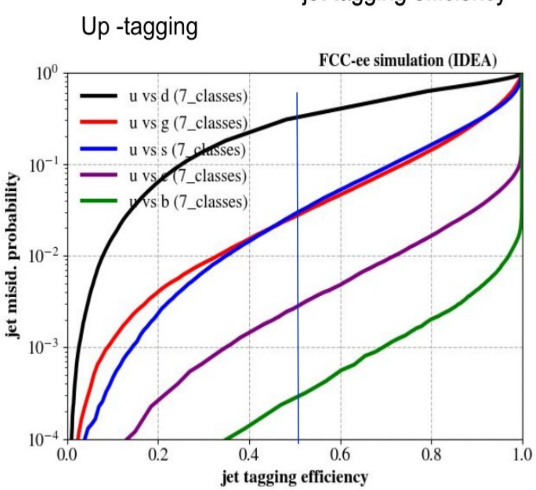
- Are there flavour-violating Higgs decays $H \to qq'$?

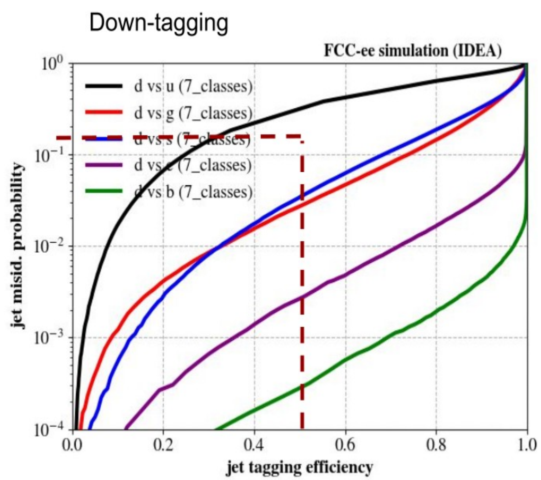


[Kamenik et al. arXiv:2306.17520]









– Projected sensitivities: $y_{bs,bd,cu} \sim 3{\cdot}10^{-4}$, $y_{sd} \sim 8{\cdot}10^{-4}$ well beyond current indirect constraints (B_s and D meson oscillations)

– Expected reach strongly depend on the performance of jet flavor taggers:

Tunable (tag&probe) with ultra-pure $Z \to qq$, $W \to qq'$ samples

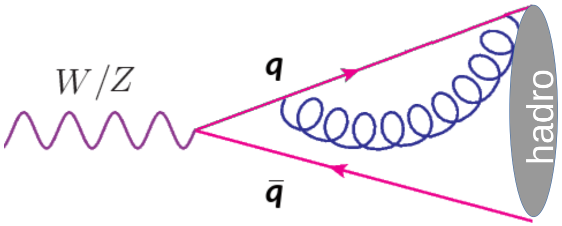
Qu/Gouskos: arXiv:1902.08570
Bedeschi/Gouskos/Selvaggi, arXiv:2202.03285

QCD coupling at FCC-ee (Tera-Z)

- EW boson pseudoobservables known at N^3LO in pQCD:

• The W and Z hadronic widths :

$$\Gamma^{\rm had}_{\rm W,Z}(Q) = \Gamma^{\rm Born}_{\rm W,Z}\left(1 + \sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\rm EW} + \delta_{\rm mix} + \delta_{\rm np}\right)$$



• The ratio of W, Z hadronic-to-leptonic widths :

$$R_{\rm W,Z}(Q) = \frac{\Gamma^{\rm had}_{\rm W,Z}(Q)}{\Gamma^{\rm lep}_{\rm W,Z}(Q)} = R^{\rm EW}_{\rm W,Z}\left(1 + \sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\rm mix} + \delta_{\rm np}\right)$$

• In the Z boson case, the hadronic cross section at the resonance peak in e^+e^-:

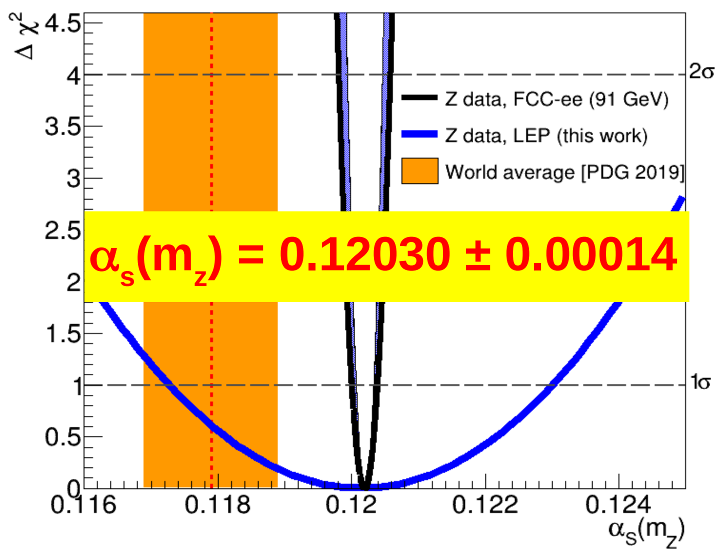
$$\sigma^{\rm had}_{\rm Z} = \frac{12\pi}{m_{\rm Z}} \cdot \frac{\Gamma^e_{\rm Z}\Gamma^{\rm had}_{\rm Z}}{(\Gamma^{\rm tot}_{\rm Z})^2}$$

Note: Sensitivity to $\alpha_s(m_Z)$ from O(4%) virtual corrs.

[DdE, Jacobsen: arXiv:2005.04545]

- FCC-ee will reach 0.1% precision on $\alpha_s(m_Z)$ ($\times$20 better than LEP results):
  - Huge Z pole stats. ($\times 10^5$ LEP):
  - Exquisite syst./parametric precision:

$$\Delta R_Z = 10^{-3}, \quad R_Z = 20.7500 \pm 0.0010$$
$$\Delta\Gamma^{\rm tot}_Z = 0.1\ \text{MeV}, \quad \Gamma^{\rm tot}_Z = 2495.2 \pm 0.1\ \text{MeV}$$
$$\Delta\sigma^{\rm had}_Z = 4.0\ \text{pb}, \quad \sigma^{\rm had}_Z = 41\,494 \pm 4\ \text{pb}$$
$$\Delta m_Z = 0.1\ \text{MeV}, \quad m_Z = 91.18760 \pm 0.00001\ \text{GeV}$$
$$\Delta\alpha = 3\cdot 10^{-5}, \quad \Delta\alpha^{(5)}_{\rm had}(m_Z) = 0.0275300 \pm 0.0000009$$



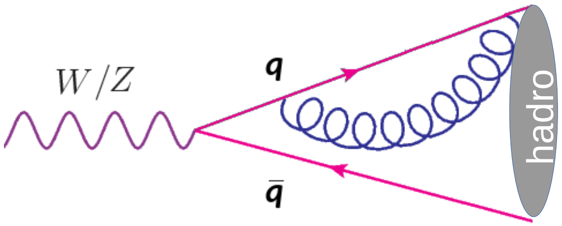
  - TH uncertainty to be reduced by $\times$4 from missing α_s^5, α^3, $\alpha\alpha_s^2$, $\alpha\alpha_s^2$, $\alpha^2\alpha_s$ terms

QCD coupling at FCC-ee (Oku-W)

- EW boson pseudoobservables known at N^{3}LO in pQCD:

• The W and Z hadronic widths :

$$\Gamma^{\rm had}_{\rm W,Z}(Q) = \Gamma^{\rm Born}_{\rm W,Z}\left(1+\sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\rm EW} + \delta_{\rm mix} + \delta_{\rm np}\right)$$



• The ratio of W, Z hadronic-to-leptonic widths :

$$\mathrm{R}_{\rm W,Z}(Q) = \frac{\Gamma^{\rm had}_{\rm W,Z}(Q)}{\Gamma^{\rm lep}_{\rm W,Z}(Q)} = \mathrm{R}^{\rm EW}_{\rm W,Z}\left(1+\sum_{i=1}^{4} a_i(Q)\left(\frac{\alpha_S(Q)}{\pi}\right)^i + \mathcal{O}(\alpha_S^5) + \delta_{\rm mix} + \delta_{\rm np}\right)$$

Note: Sensitivity to $\alpha_s(m_Z)$ from O(4%) virtual corrs.

[DdE, Jacobsen: arXiv:2005.04545]

- FCC-ee will reach 0.2% precision on $\alpha_s(m_W)$ ($\times$300 better than LEP results):
  - Huge W pole stats. ($\times 10^4$ LEP-2).
  - Exquisite syst./parametric precision:

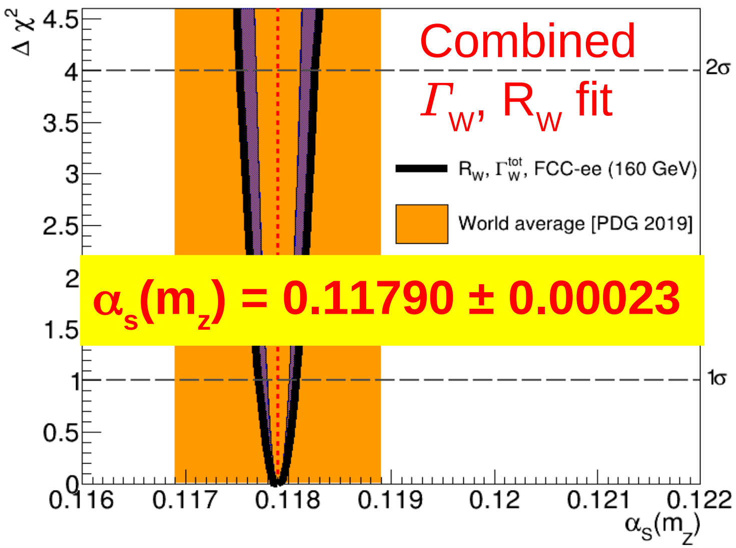
$$\Gamma^{\rm tot}_{\rm W} = 2088.0 \pm 1.2 \text{ MeV}$$

$$\mathrm{R}_{\rm W} = 2.08000 \pm 0.00008$$

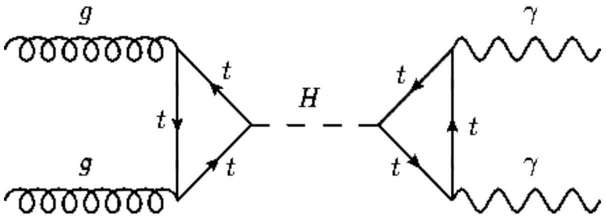
$$m_{\rm W} = 80.3800 \pm 0.0005 \text{ GeV}$$

$$|V_{cs}| = 0.97359 \pm 0.00010$$ ← *O(10^{12}) D mesons*

  - TH uncertainty to be reduced by $\times$10 from missing α_s^5, α^2, α^3, $\alpha\alpha_s^2$, $\alpha\alpha_s^2$, $\alpha^2\alpha_s$ terms



$H \rightarrow \gamma\gamma$ counts after cuts



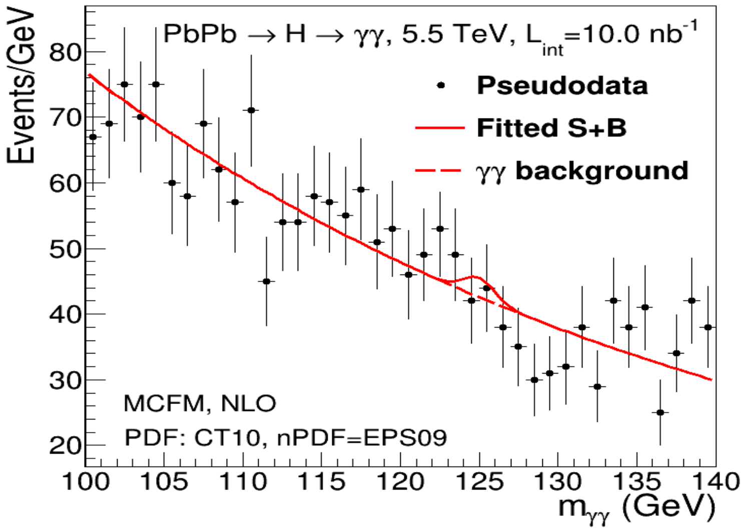
Analysis based on NNLO MCFM v.8.0 pseudo-data for H(γγ) plus γγ backgrounds after typical CMS/ATLAS cuts

System	$\sqrt{s_{NN}}$ (TeV)	$\mathcal{L}_{int}$	H σ_{tot}	$\rightarrow \gamma\gamma$ yields	$\rightarrow ZZ^*(4\ell)$ yields
PbPb	5.5	10 nb^{-1}	500 nb	6	0.3
pPb	8.8	1 pb^{-1}	6.0 nb	7	0.4
PbPb	39	33 nb^{-1}	11.5 μb	450	25
pPb	63	8 pb^{-1}	115 nb	950	50

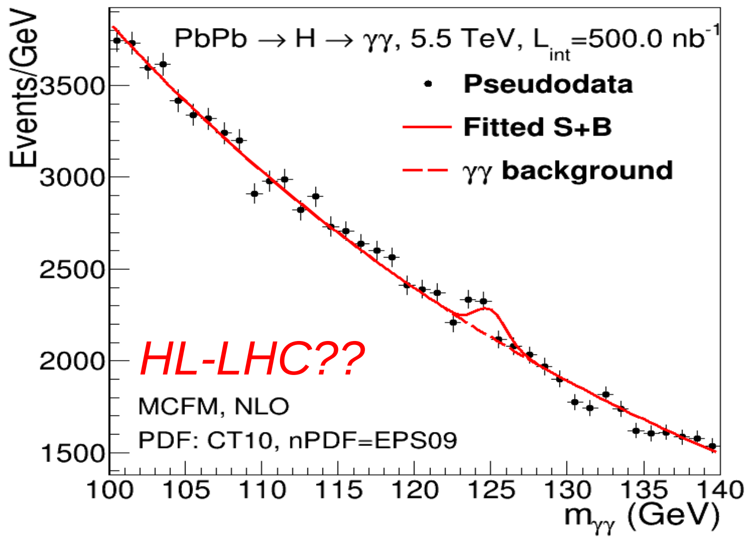
- LHC (nominal L_{int}): ~2 Higgs bosons/month in Pb-Pb
- HE-LHC (nominal L_{int}): ~10 Higgs bosons/month in Pb-Pb
- FCC (nominal L_{int}): ~500 H bosons/month in Pb-Pb

H → γγ observation in Pb-Pb (LHC, FCC)

- Pb-Pb @ 5.5 TeV (L_{int}= 10 nb^{-1})



- Pb-Pb @ 5.5 TeV (*L_{int}=500 nb^{-1}*)



➜ LHC (5.5 TeV, 10 nb^{-1}):

Nomin. lumi: $S/\sqrt{B}$~0.36 (0.5, adding 4*l*)

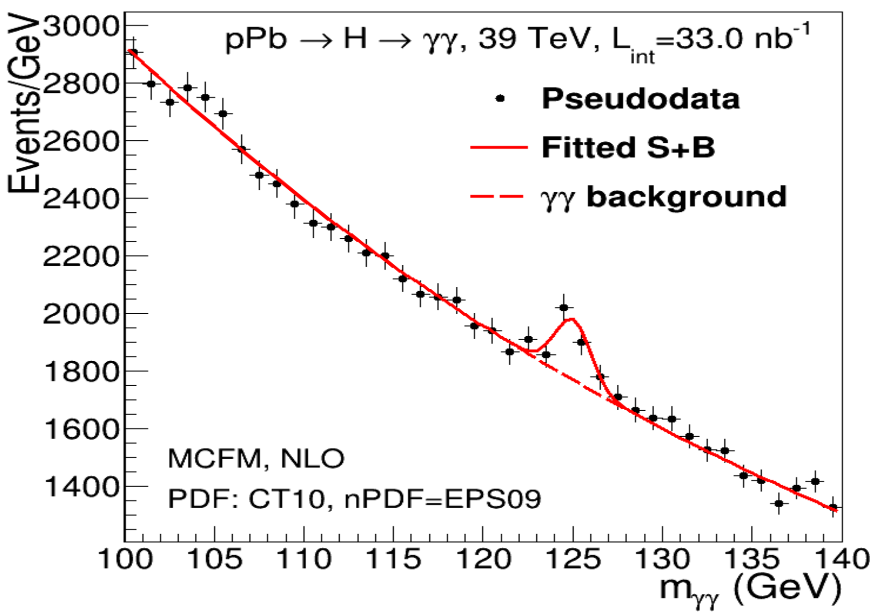
L_{int}= 500 nb^{-1}: 3s evidence

4.2s combined with H(4*l*)

➜ FCC (39 TeV, 33 nb^{-1}):

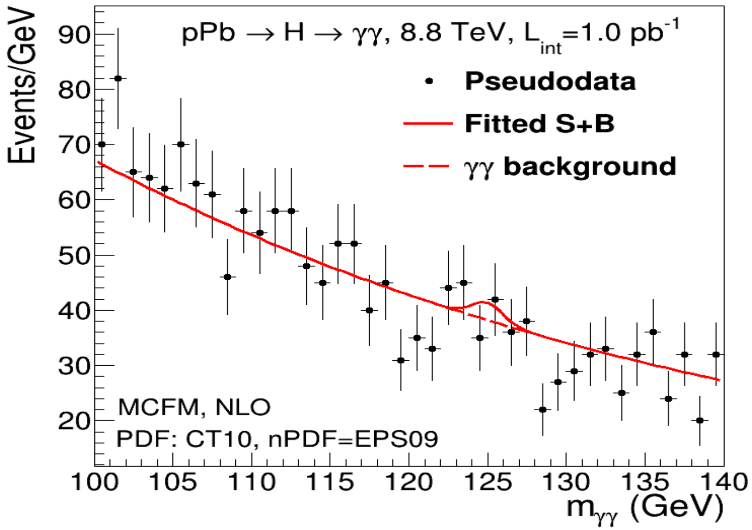
Nominal lumi: $S/\sqrt{B}$~5.2s observation

- Pb-Pb @ 39 TeV (L_{int}= 33 nb^{-1})



H → γγ observation in p-Pb (LHC, FCC)

- p-Pb @ 8.8 TeV (L_{int}= 1 pb^{-1})



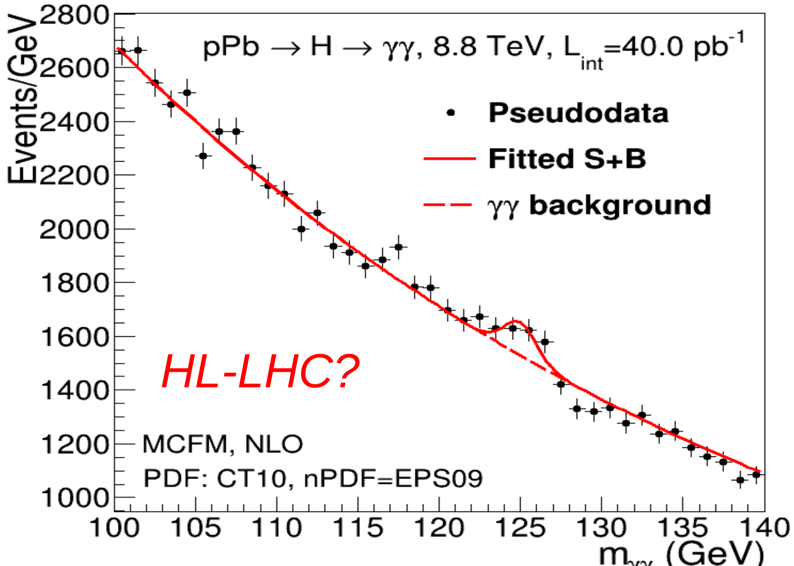
➜ LHC (8.8 TeV, 1 pb^{-1}):

Nominal lumi: S/√B~0.4 (0.6, adding 4*l*)

L_{int}= 40 pb^{-1}: 3s evidence

4.2s combined with H(4*l*)

- p-Pb @ 8.8 TeV (*L_{int}= 40 pb^{-1}*)



➜ FCC (63 TeV, 8 pb^{-1}):

Nominal lumi: S/√B~7.7s observation

- p-Pb @ 63 TeV (L_{int}= 8 pb^{-1})