International Committee on Future Accelerators, Toyama, 4th November 2026

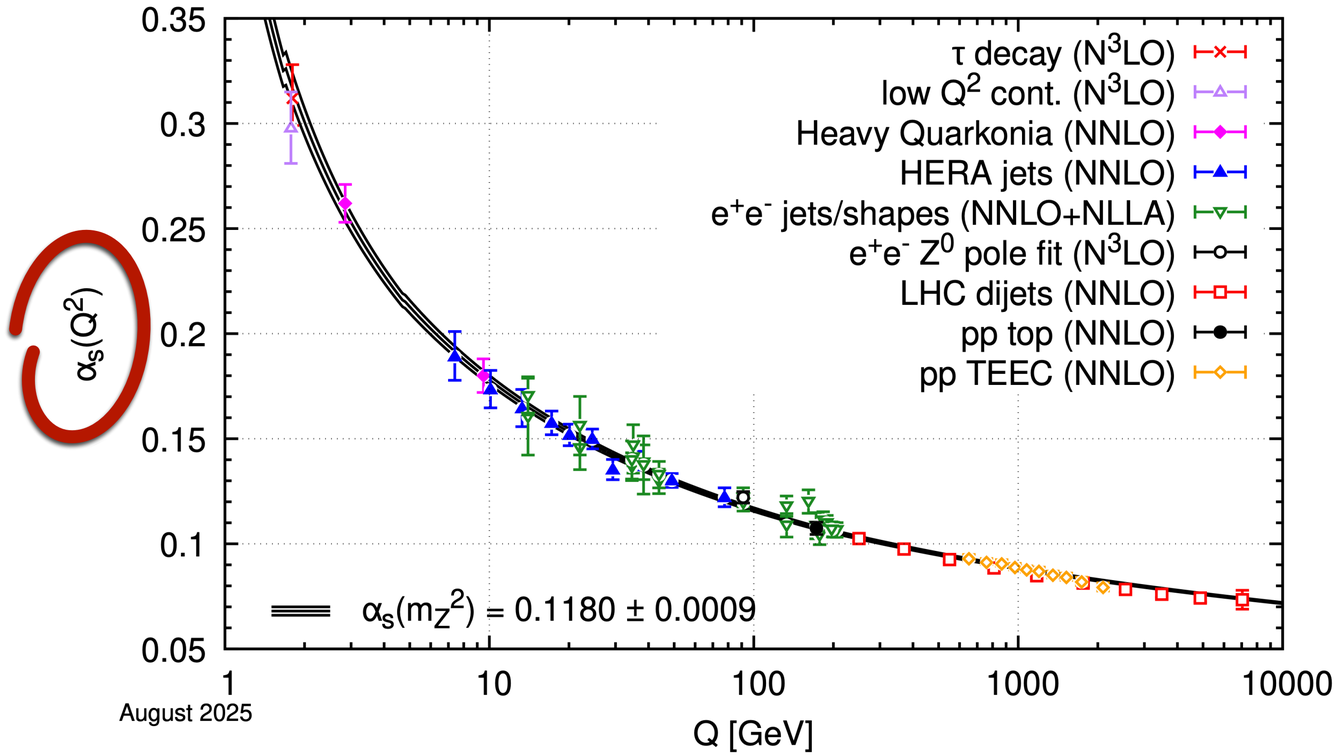


QCD at the Highest Energies

Garvita Agarwal
garvita.agarwal@cern.ch

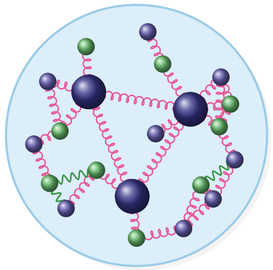
On behalf of ALICE, ATLAS, CMS and LHCb Collaborations

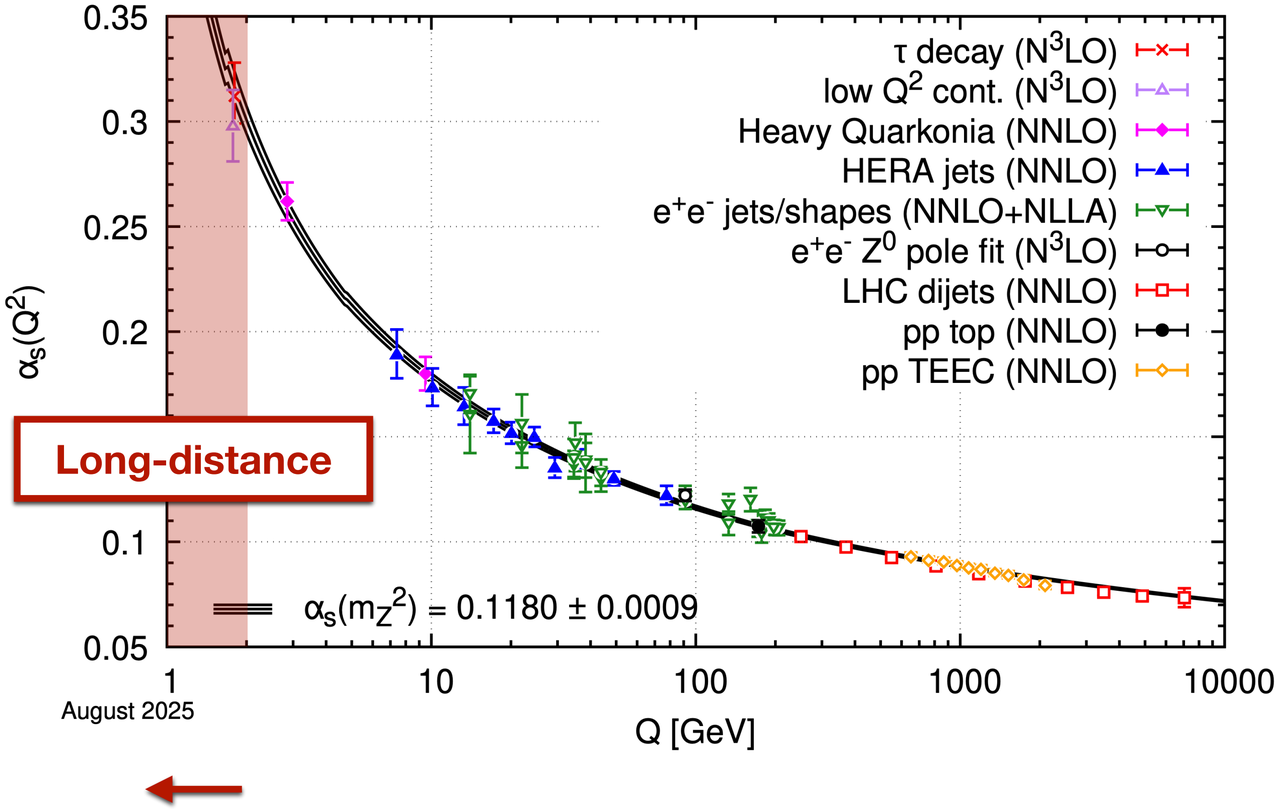
QCD: one parameter, and its running



One coupling, α_S, sets the dynamics; it runs with the momentum transfer Q.

Two regimes of QCD

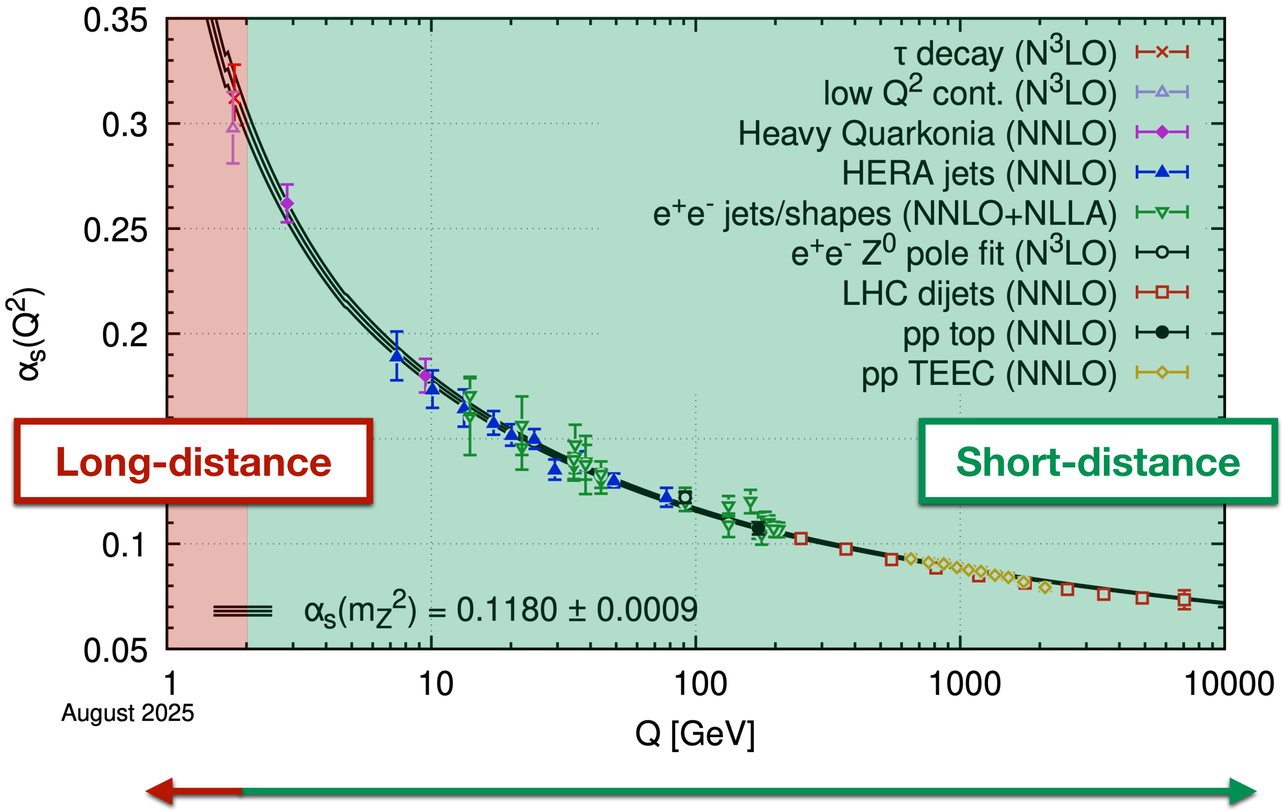




Non-perturbative

- **Strongly bound hadrons**: confinement; proton mass generated by QCD dynamics
- **PDFs and fragmentation functions**: fitted to data (their evolution is perturbative)
- **Color reconnection, underlying event, low p_T multi-parton interactions**: modeled and tuned

Two regimes of QCD



Modeled: a parametrization fitted to data whose uncertainty is the spread between models, and cannot be systematically reduced

Calculated: a perturbative expansion whose uncertainty is the next order, and can be reduced.

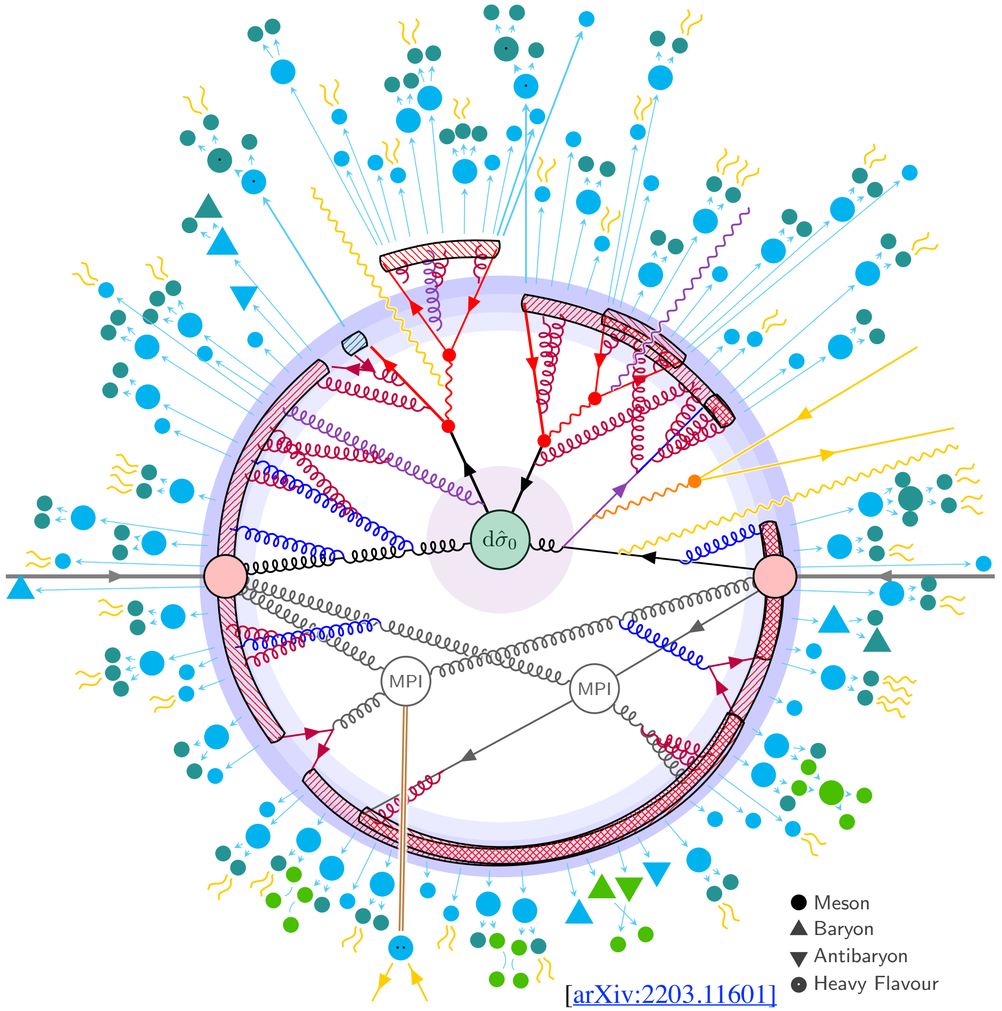
Non-perturbative ← → **Perturbative**

- **Strongly bound hadrons**: confinement; proton mass generated by QCD dynamics
- **PDFs and fragmentation functions**: fitted to data (their evolution is perturbative)
- **Color reconnection, underlying event, low p_T multi-parton interactions**: modeled and tuned

- **Asymptotically free partons** scattering off each other: high-order calculations in α_S (NNLO is the standard, N³LO for a few 2→1 processes)
- **Parton showers**; resummation of soft and collinear logarithms (LL → NLL → NNLL)
- heavy-quark production ($m_Q \gg \Lambda_{\text{QCD}}$)

One collision spans the whole Q-axis

$$\sigma_{pp\to X} = \sum_{i,j} \int_0^1 dx_1 dx_2 \; f_i(x_1, \mu_F^2)\, f_j(x_2, \mu_F^2) \times \hat{\sigma}_{ij\to X}(x_1, x_2, Q^2, \mu_R^2, \mu_F^2)$$



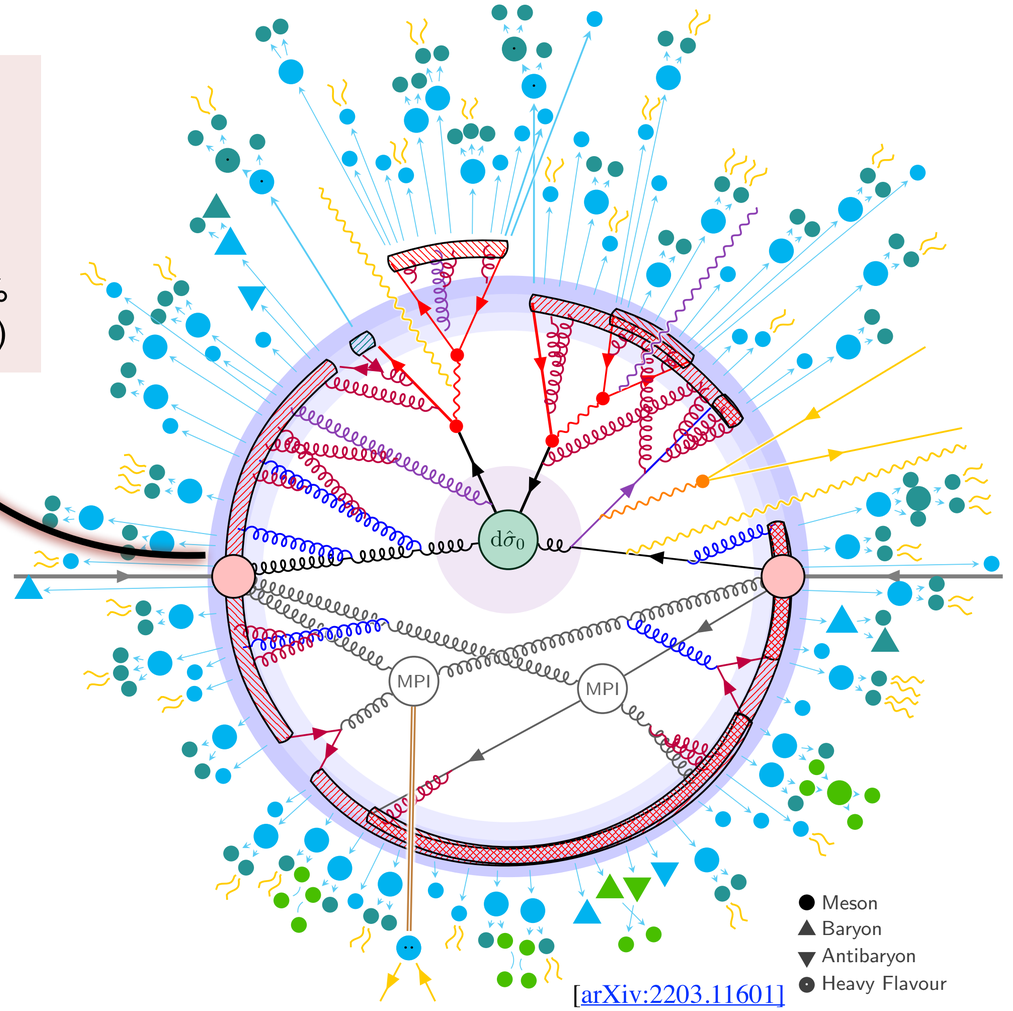
[arXiv:2203.11601]

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PDFs ⇒ the proton

- non-perturbative input, perturbative evolution
- every cross section inherits them:
  - ggF prediction: **PDF ±1.9%** of ±5–7 %
  - m_W: **4.4 MeV** (CMS), **5.7 MeV** (ATLAS)



[arXiv:2203.11601]

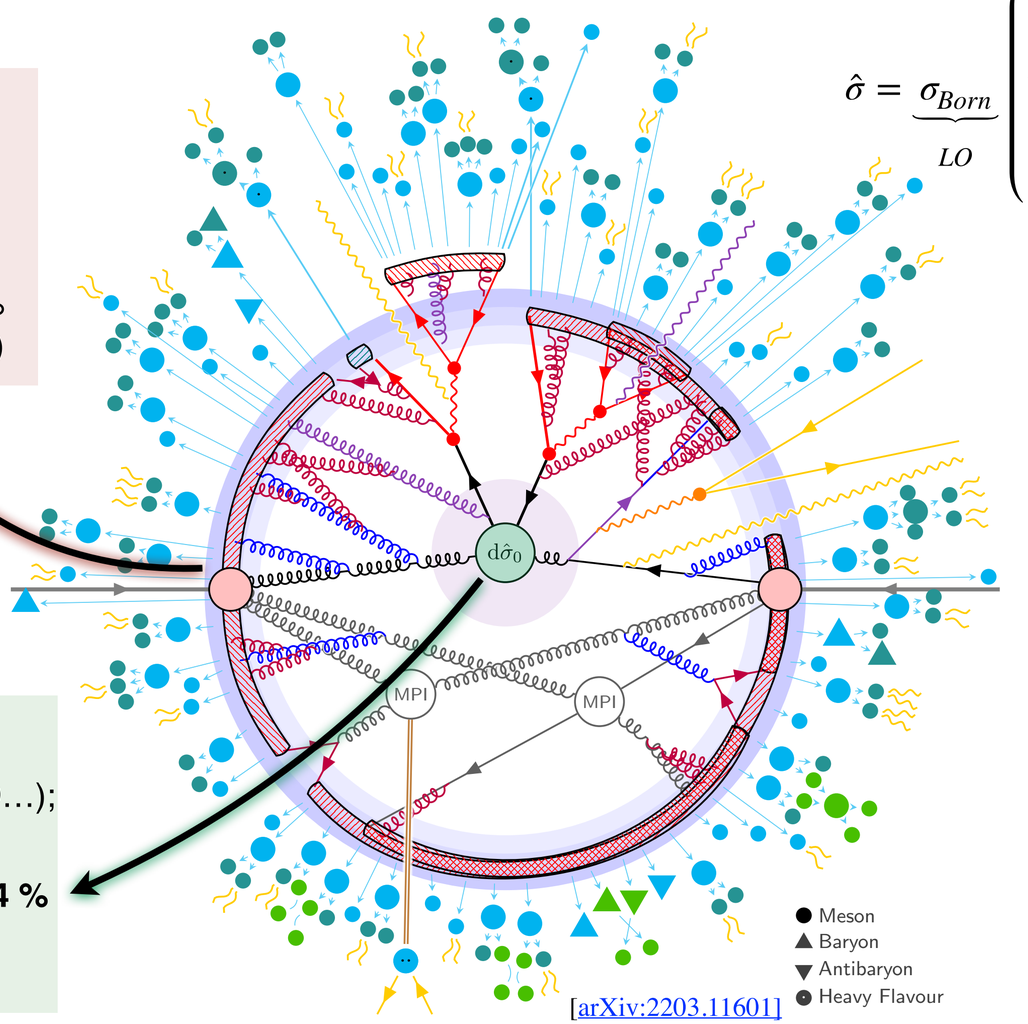
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$$\hat{\sigma} = \underbrace{\sigma_{Born}}_{LO}\left(1 + \underbrace{\left(\frac{\alpha_s}{2\pi}\right)}_{NLO}\sigma_1 + \underbrace{\left(\frac{\alpha_s}{2\pi}\right)^2}_{NNLO}\sigma_2 + \underbrace{\left(\frac{\alpha_s}{2\pi}\right)^3}_{N^3LO}\sigma_3 + \cdots\right)$$



[arXiv:2203.11601]

Hard Scatter ⇒ the coupling

- computed as a series in α_S (NNLO, N³LO…); α_S, known to 0.8%
- on ggF the **missing orders are +0.2/–2.4 %** and α_S **is ±2.6** % of ±5–7 % theory total [YR4]

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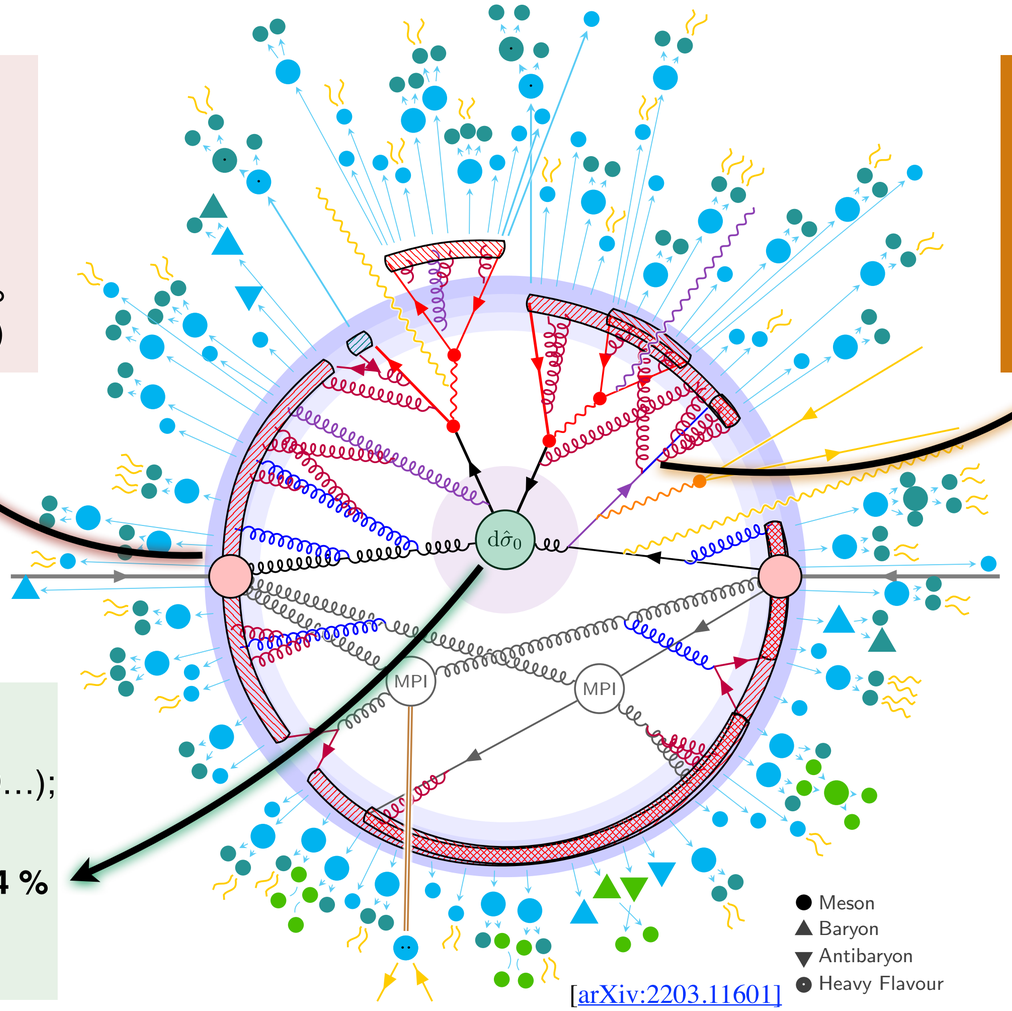
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Parton shower ⇒ jet evolution

- Evolves each parton from Q down to ≈1 GeV, resumming soft and collinear logarithms
- production **showers are formally LL** (NLL only for some observables)



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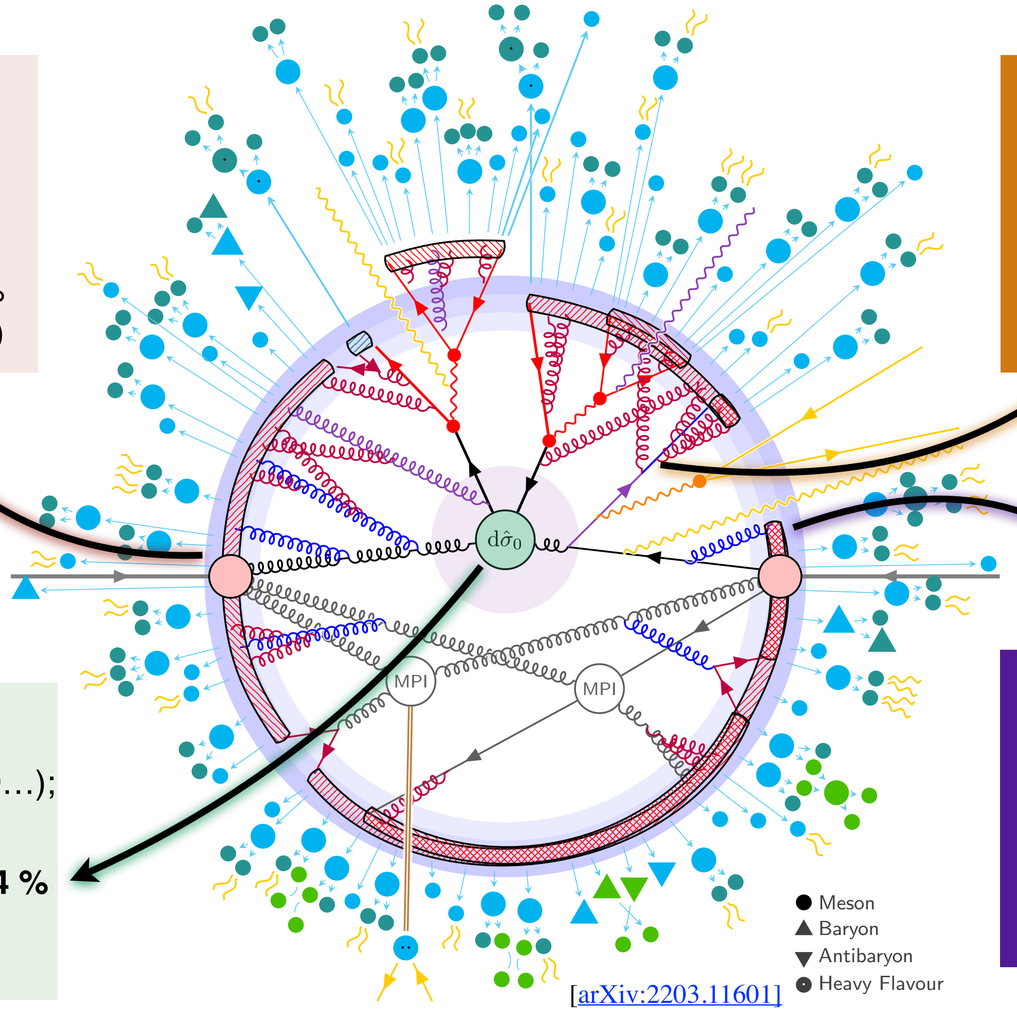
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Hadronisation ⇒ below 1 GeV

- At Q $\lesssim$ 1 GeV α_S is O(1): models tuned to e^+e^- and pp data.
- LHC m_t combination:
  - **0.02 GeV** (HAD) and **0.04 GeV** (CR)
  - **0.18 of 0.33 GeV** from b-jet scale

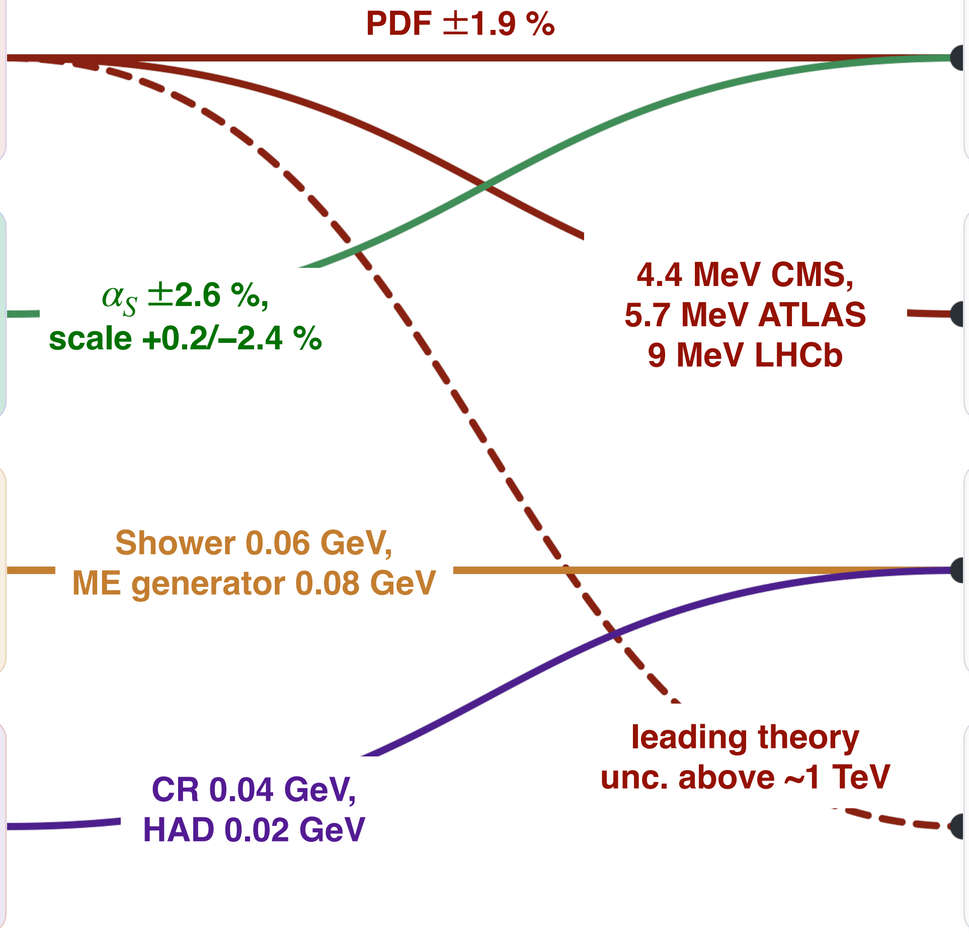
Why the last per cent?

THE PROTON
non-perturbative input, perturbative evolution: *every* cross section inherits the PDFs

STRONG COUPLING
one parameter; *every* hard process is a truncated series in it

PARTON SHOWER
a TeV down to a GeV, one log per emission; *still* leading-log

HADRONISATION
below 1 GeV: models tuned at LEP, *assumed* universal



Higgs couplings

σ(ggF) is predicted [YR4] at N³LO: PDF + α_S ±3.2 %, missing orders +0.2 / –2.4 %

W mass

measured to 9.9 (CMS), 15.9 (ATLAS), 32 MeV (LHCb); the PDF-induced uncertainty on each is 4.4 / 5.7 / 9 MeV
$\sin^2\theta_{\text{eff}}$: CMS 31×10^{-5}, PDF-dominated

Top mass

ATLAS + CMS 0.33 GeV; b-jet energy scale 0.18 GeV (exp.); shower and ME modeling 0.06 + 0.08; CR and hadronisation 0.04 + 0.02 (theory).

Searches at the TeV scale

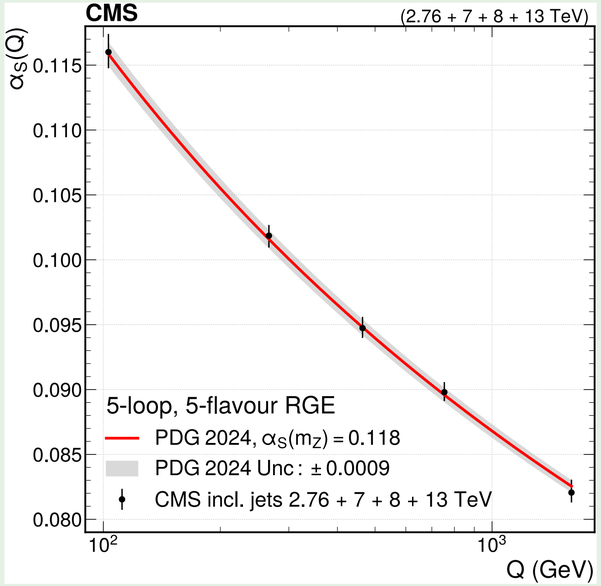
above ~1 TeV the PDF uncertainty is the leading theory uncertainty on every SM prediction

HL-LHC projections assume theory uncertainties halved and PDF uncertainties 2-4× smaller.

Three ways to measure the coupling

Cross sections

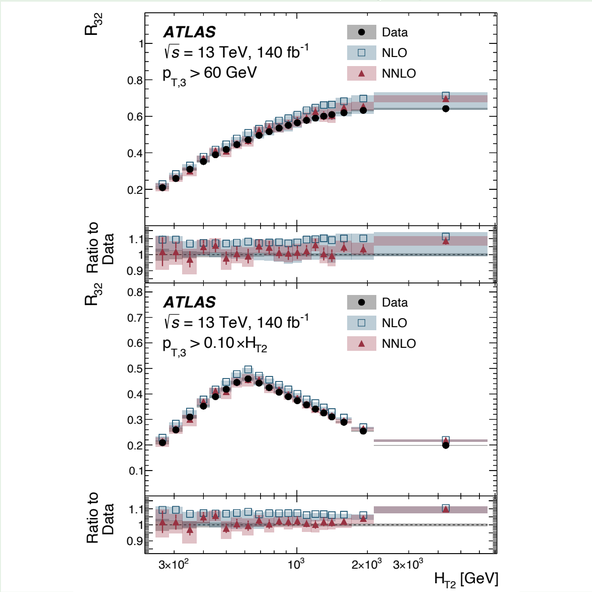
$$\sigma_{\text{jet}} \propto \alpha_S^2 \otimes f_g(x)$$



- carries the gluon PDF: fit α_S and the PDFs together; four $\sqrt{s}$ reduce the α_S-gluon correlation
- **CMS inclusive jets:** 2.76–13 TeV: 1.3%; running follows the 5-loop RGE to 1.6 TeV [arXiv:2412.16665]
- **CMS dijets in 3D**: the pair boost measures the patron momentum fraction, the rapidity separation angle measures the ME [arXiv:2312.16669]

Ratios

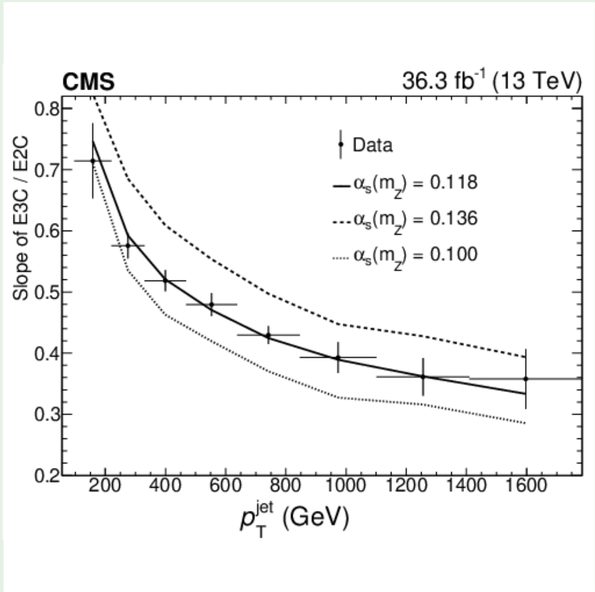
$R_{32} = \sigma(\geq 3 \text{ jets})/\sigma(\geq 2 \text{ jets})$;
$R_{\Delta\phi}$ = fraction of events with a neighboring jet within $\Delta\phi$ of the leading jet;
TEEC = transverse-energy-weighted angular correlation between jet pairs



- PDFs and the JES **largely cancel**; limited only by the theory order
- ATLAS R_{32} at 13 TeV: **NNLO describes it better than NLO** [arXiv:2405.20206]
- CMS $R_{\Delta\phi}$: running to 2 TeV; NNLO three-jet now exists [arXiv:2404.16082, arXiv:2106.05331]

Jet substructure

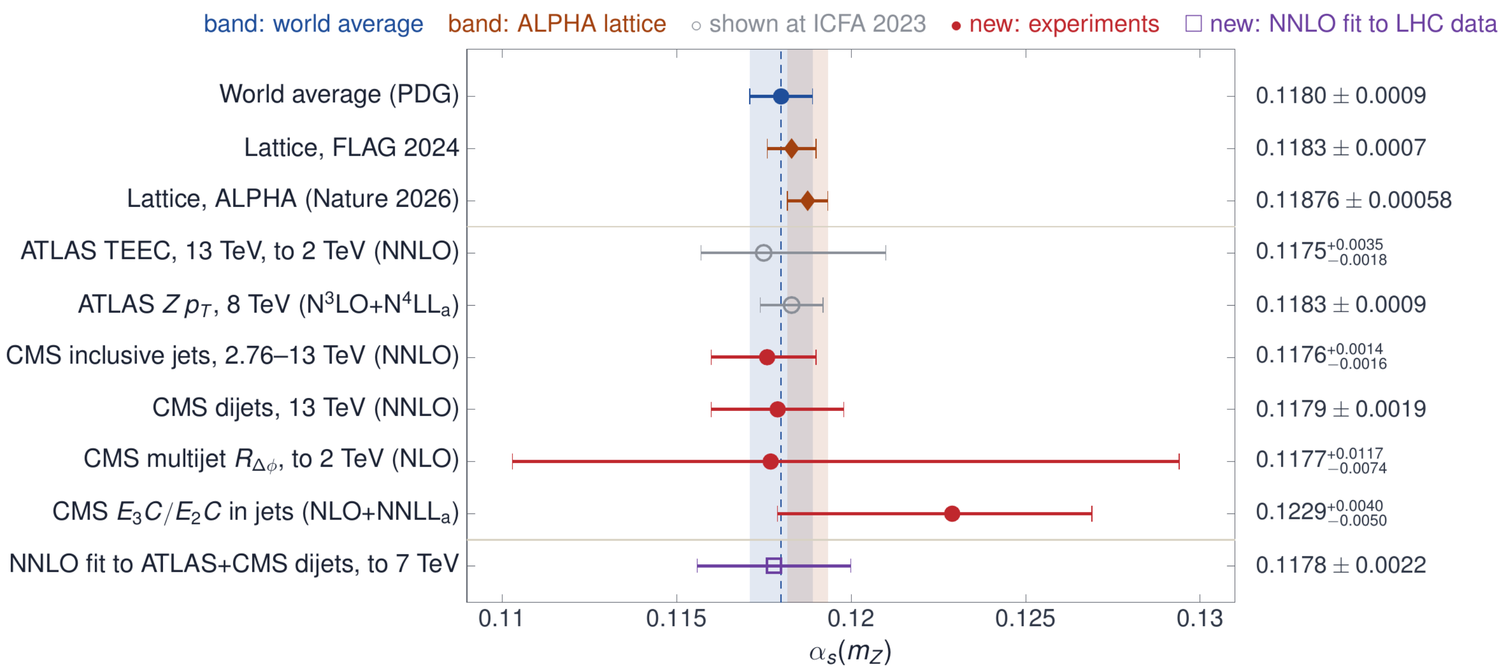
three-point over two-point energy correlator inside a jet, vs angle



- non-perturbative effects largely cancel; **most precise α_S from substructure**
- CMS: $\alpha_S(m_Z) = 0.1229^{+0.0040}_{-0.0050}$; 4% today, limited by NNLL and non-perturbative corrections [arXiv:2402.13864]
- the slope of the correlator *is* the running

STRONG COUPLING

α_S: 0.8% from colliders, 0.5% from the lattice



$$\alpha_S(m_Z) = 0.1178 \pm 0.0022$$

NNLO fit to ATLAS + CMS dijets; the running tested up to 7 TeV [arXiv:2412.21165]

$$\alpha_S(m_Z) = 0.11876 \pm 0.00058$$

ALPHA lattice, from hadron masses and decay constants. [Nature 652 (2026) 328]

$$\alpha_S(m_Z) = 0.1180 \pm 0.0009$$

world average, PDG 2025 (**0.76%**)

- limited by missing higher orders and non-perturbative corrections, not by statistics
- the target of the field is **per mille** [arXiv:2203.08271]

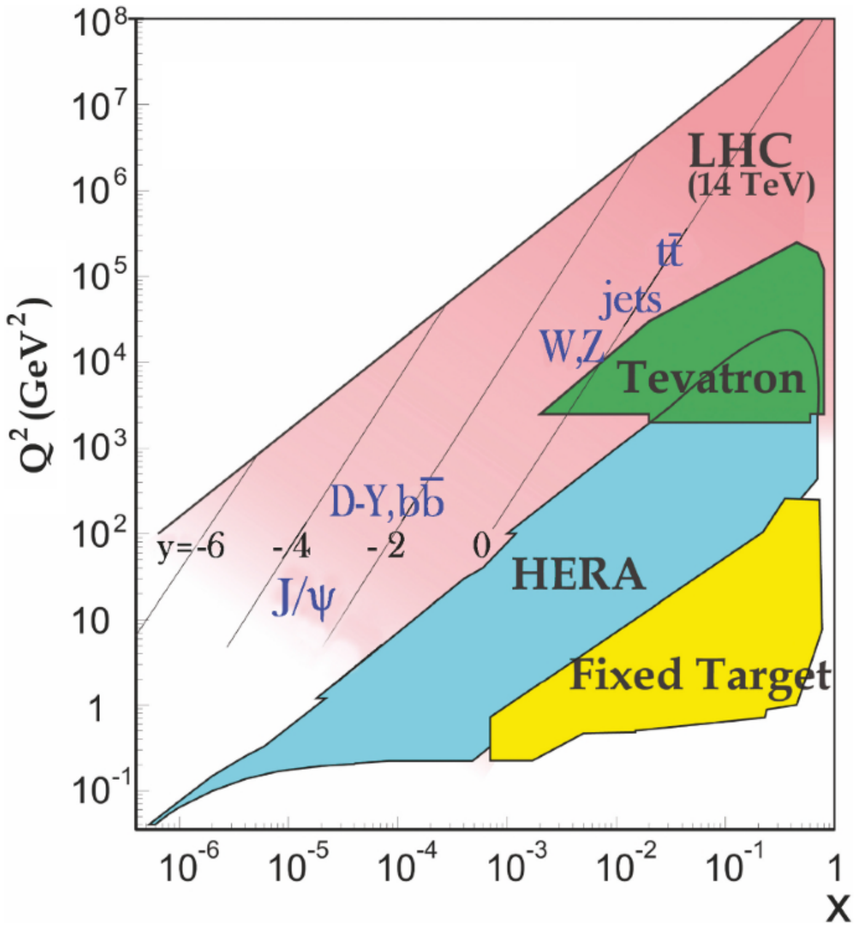
The most precise collider determinations are limited by theory i.e. missing orders and non-perturbative corrections

STRONG COUPLING

The proton is a fit, its evolution a calculation

$$\sigma_{pp\to X} = \sum_{i,j} \int_0^1 dx_1 dx_2 \; f_i(x_1, \mu_F^2)\, f_j(x_2, \mu_F^2) \times \hat{\sigma}_{ij\to X}(x_1, x_2, Q^2, \mu_R^2, \mu_F^2)$$

- $f_i(x, \mu_F^2)$: the probability of finding parton i with momentum fraction x when the proton is resolved at scale μ_F.
- the **DGLAP evolution** in μ_F is perturbative (splitting functions now at approximate N³LO), so one measurement at one scale constrains every other scale
- the LHC measures the proton at the highest Q^2 ever, at high x: dijets to $m_{jj} \approx 10$ TeV, W bosons to $m_T = 5$ TeV
- every flagship number inherits the PDF uncertainty: ggF Higgs is predicted **PDF ±1.9 %**, m_W measured to **4.4 MeV CMS, 5.7 MeV ATLAS**



Measurements at many scales, one set of PDFs:
DGLAP evolution connects them and the fit must describe them all.

THE PROTON

Run 3 standard candles at 13.6 TeV

$$W^{\pm}/Z = 10.288 \pm 0.007 \pm 0.066 \pm 0.037$$

CMS, 5.0 fb^{-1}: NNLO+NNLL agrees; luminosity (1.4%) dominates on the absolute XS
[JHEP 01 (2026) 047]

$$t\bar{t}/Z = 1.145 \pm 0.003 \pm 0.021 \pm 0.002$$

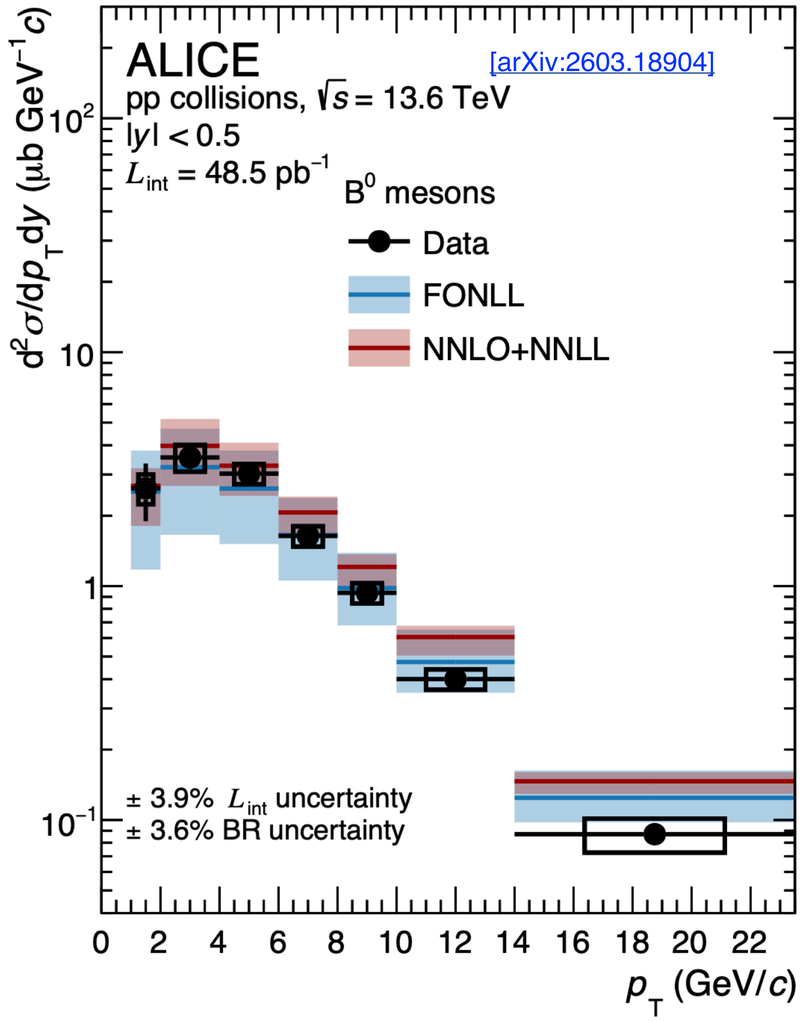
ATLAS, 29 fb^{-1}: luminosity cancels; a 2% test of the gg vs $q\bar{q}$ luminosities
[PLB 848 (2024) 138376]

$$\mathrm{d}\sigma/\mathrm{d}y(B^0) = 24.2 \pm 1.4 \pm 2.6\ \mu b$$

ALICE: first mid-rapidity B^0 at 13.6 TeV, down to 1 GeV; pQCD describes it
[arXiv:2603.18904]

$$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta = 7.10 \pm 0.18$$

ALICE: first 13.6 TeV charged-particle density ($|\eta| < 0.5$, INEL > 0)
[arXiv:2602.10658]



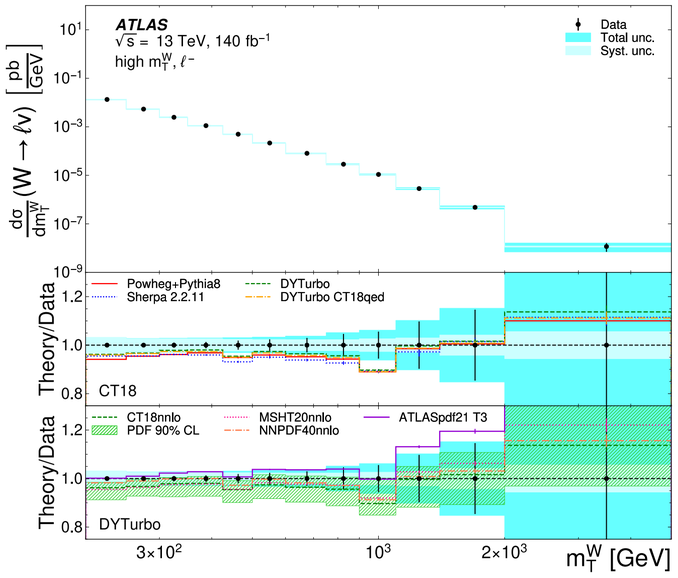
- Run 3 ended in 2026: **355 fb^{-1}** delivered to each CMS and ATLAS, (Total ≈ 540 fb^{-1} over 3 Runs)
- The candles **test PDF predictions at the 2% level**; ATLAS $t\bar{t}/W$ sits slightly **below** most sets [arXiv:2403.12902]
- CMS isolated photons, 13.6 TeV: the gluon probed without a jet energy scale; compared to NLO only; disagreement at the highest p_T [CMS-PAS-SMP-25-004]

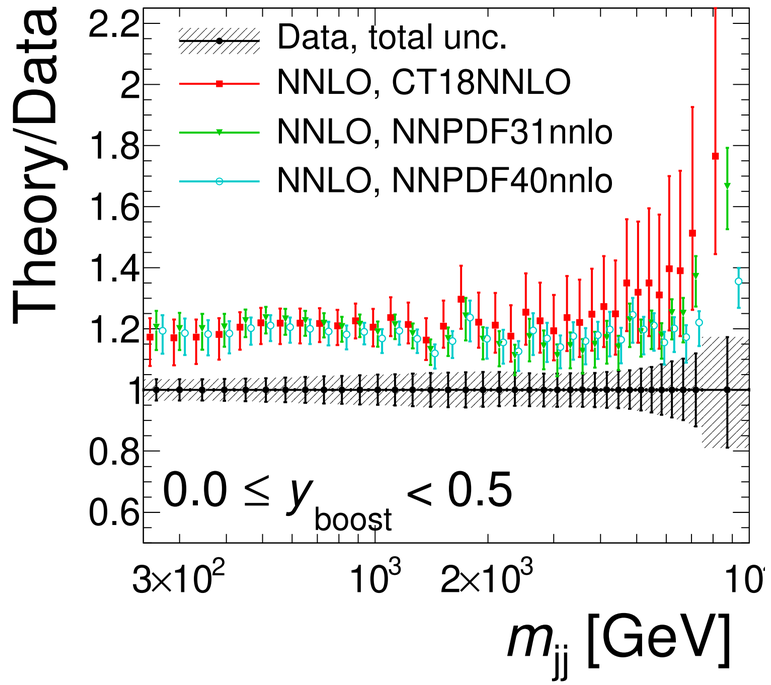
The proton at 13.6 TeV is the proton the fits predicted, at the 2 per cent level

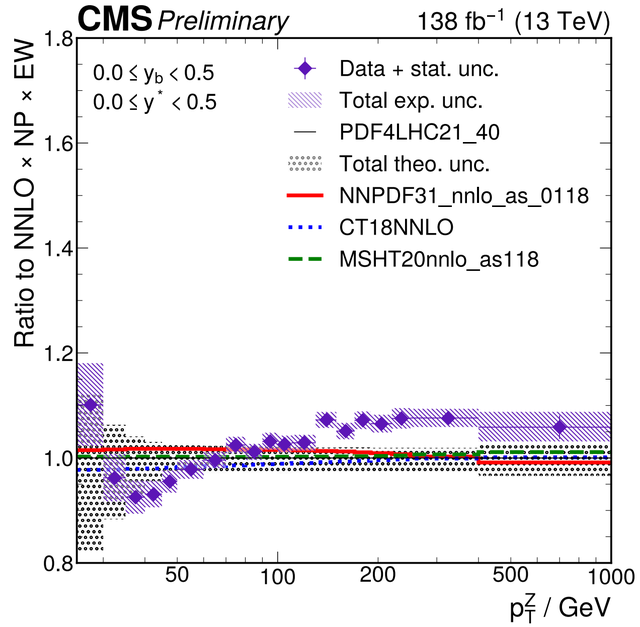
THE PROTON

The proton at high x: jets to 10 TeV, W to 5 TeV

- **ATLAS dijets**, m_{jj} 240 GeV to ~10 TeV: NNLO ⊗ EW ⊗ NP lies **15–20% above data,** a normalization offset (NLO too); jet energy scale is the dominant uncertainty; NNPDF4.0 best shape [arXiv:2512.19073]
- **ATLAS W** $\rightarrow \ell\nu$ at m_T 200 GeV to 5 TeV: first above the resonance; 3% precision at upto $m_T \approx 600$ GeV; NNLO ⊗ NLO EW; PDF uncertainty is the **largest theory uncertainty** at high m_T limiting sensitivity to new physics [arXiv:2502.21088]
- **CMS Z+jet triple-differential**: 1.5–5% in the central region, $p_{T,Z}$ to 1 TeV, **good agreement with NNLO** [CMS-PAS-SMP-24-010]

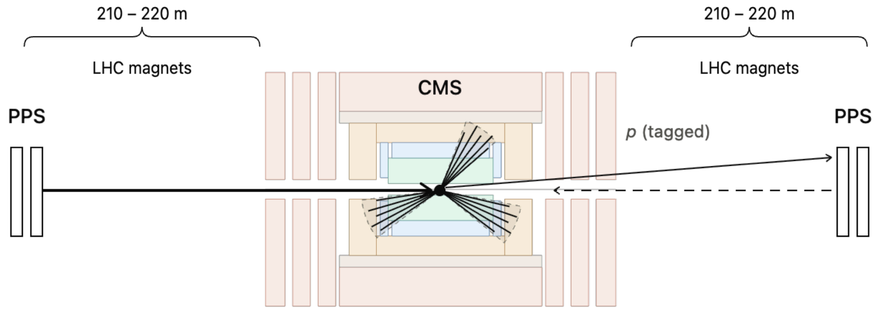






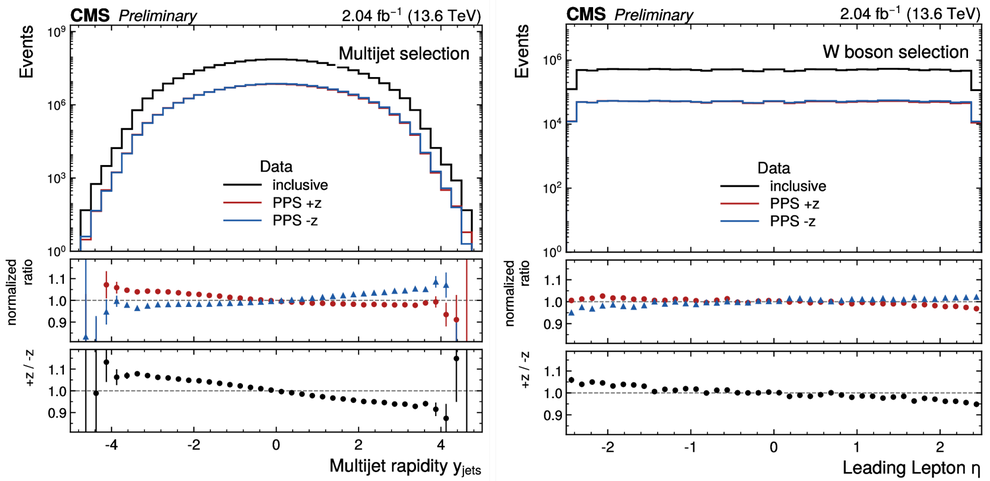
Above ~1 TeV the PDF uncertainty is the leading theory uncertainty in every tail, and a PDF fitted to those tails can absorb a new-physics signal

Photons, leptons and what survives



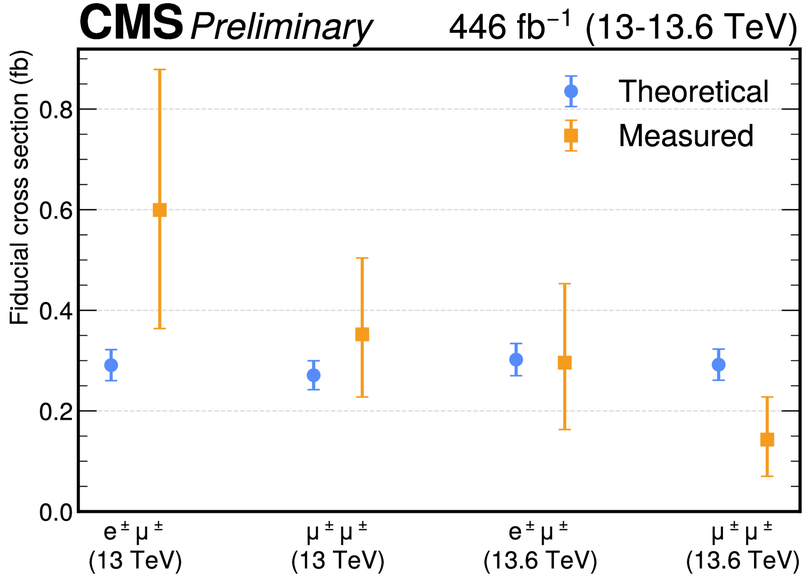
Diffractive events:

- In ~1 % of W, Z and dijet events the **proton stays intact**; hard diffractive **factorization fails** in pp (it holds in ep), so the rapidity-gap survival probability is model-dependent.
- **Proton-tagged W, Z and multijets in the 2026 special runs at 13.6 TeV**: 1.0%, 1.1%, 0.44% with a proton in PPS acceptance (lower limits); first proton-tagged W [CMS-PAS-SMP-26-015]



Photons and leptons inside proton:

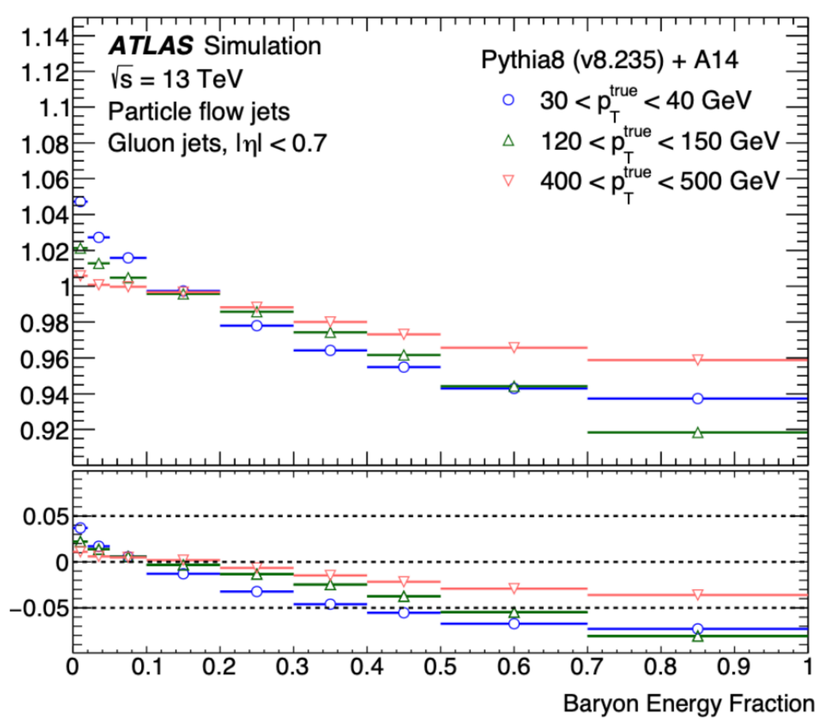
- Photon PDF determined from data via QED to 1–2% (LUXqed [arXiv:1607.04266]) ⇒ lepton PDFs follow from it at NLO [arXiv:2005.06477]
- **First observation of lepton–lepton scattering** in pp: **5.4**σ ($\mu\mu$ alone 4.0σ) using 13 + 13.6 TeV — leptons inside the proton via its photon content [CMS-PAS-SMP-26-008]

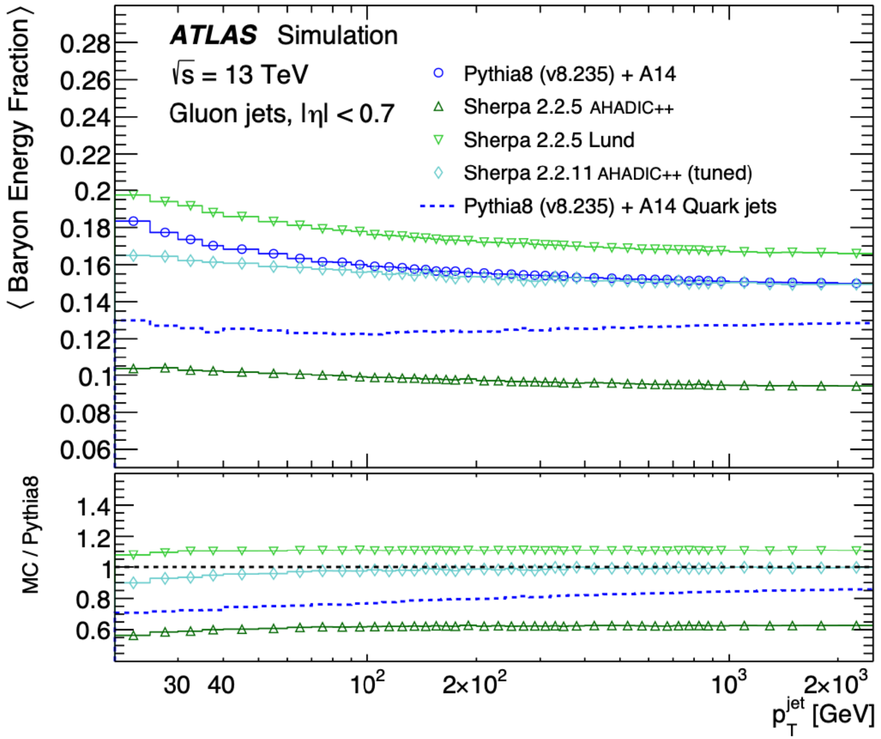


The photon content is known to 1–2 % from ep data; the proton's survival probability is model-dependent.

The jet energy scale: below 1%

- **ATLAS JES (R = 0.4, central)**: < 1% at 100 GeV, 0.3% at 300 GeV, 0.6% at 4 TeV (single-particle + in situ); the Pythia–Herwig response difference is explained by the baryon fraction (protons ≈ 10 % lower than pions for 1–7 GeV, from Λ decays) [arXiv:2407.15627, EPJC 85 (2025) 927]
- **ATLAS in-situ from the W mass in $t\bar{t}$, Run 2 + Run 3:** JES 0.93–1.7% for 35–200 GeV [arXiv:2512.17482]
- **ATLAS multijet ratios**: flavor-response term made subdominant; gluon-jet response spread between generators 2.5% at 60 GeV, quark jets < 1% [arXiv:2405.20206]
- **CMS Run 3**: residual non-closure ~0.8% for $|\eta| < 2.4$ [CMS-DP-2024-039]





At the sub-per-cent level, the JES depends on the hadronisation model.

PARTON SHOWER

The Lund plane maps every emission in a jet

- Lund planes are a **2D representation** of the phase-space of **1→2 splittings**
- Decluster the jet, one dot per emission goes onto the plane

WHAT THE MAP TELLS US

density $\approx 2C_R\alpha_S(k_T)/\pi$

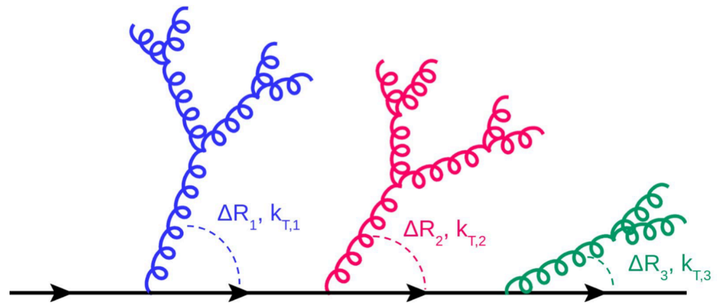
The showers' radiation pattern comparable generator by generator

dead cone

Gluon emissions suppressed for heavy quarks (LHCb, CMS: b-jets ALICE: charm jets)

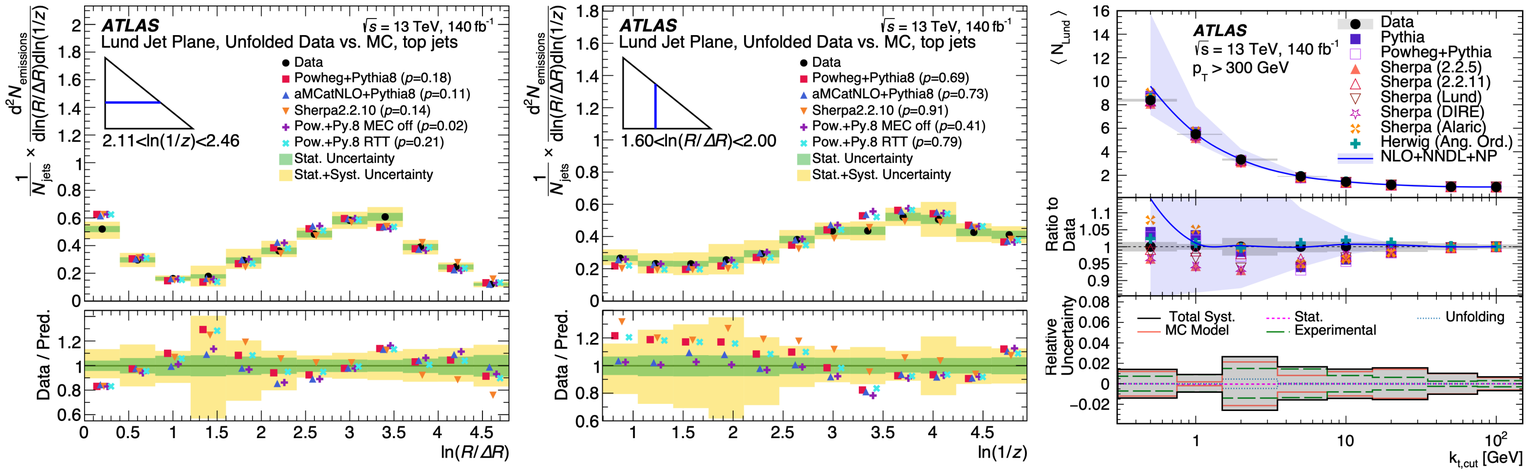
the bottom edge

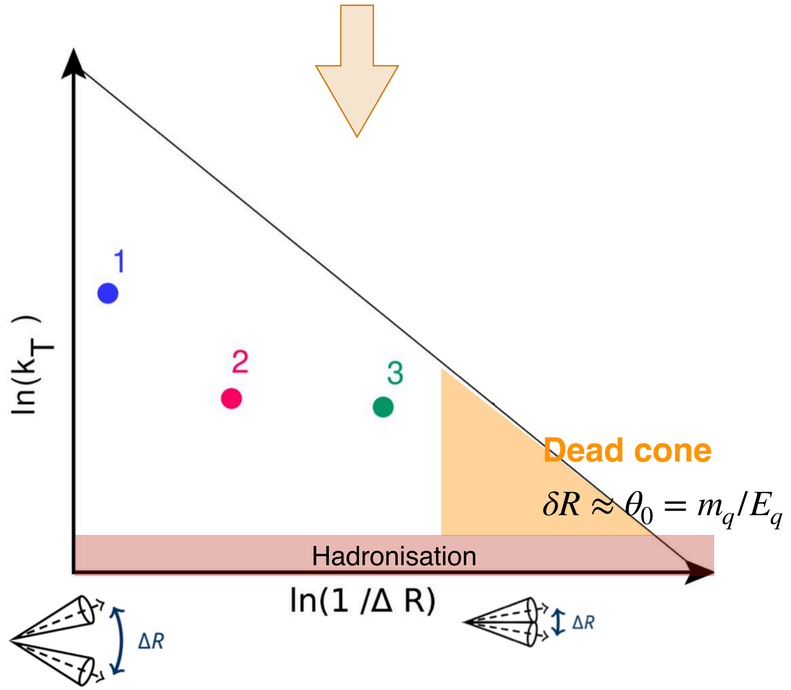
Where the shower hands over to hadronisation



k_T:relative transverse momentum of emission
ΔR: angular opening of emission and core

- **ATLAS Lund plane of W and top jets**: "*all the predictions are incompatible*" for W jets [arXiv:2407.10879, EPJC 85 (2025) 416]; **Lund subjet multiplicities**: most predictions fail at high pT, Herwig angle-ordered best [arXiv:2402.13052]

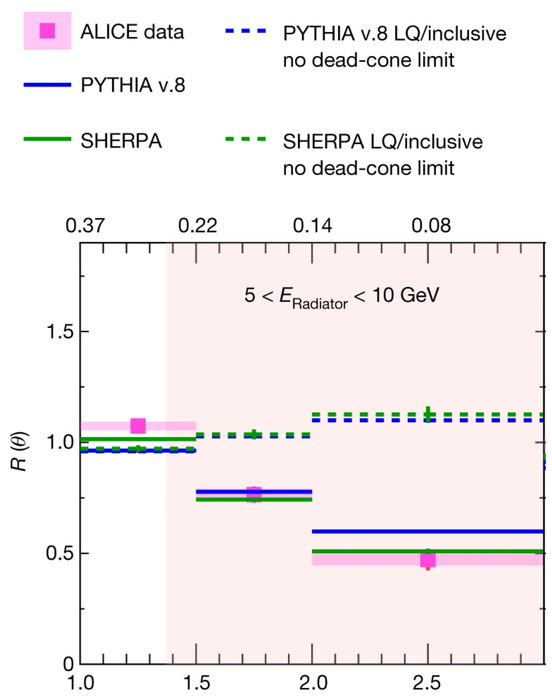


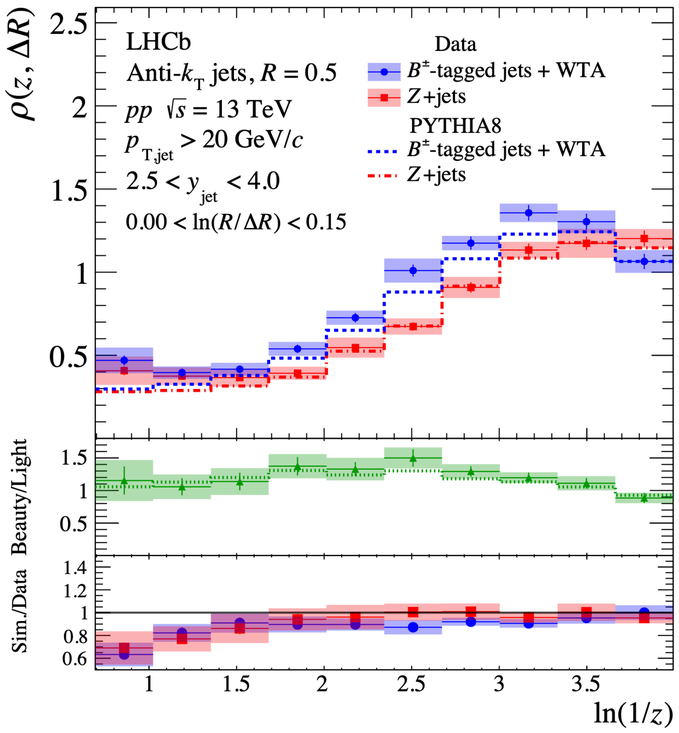


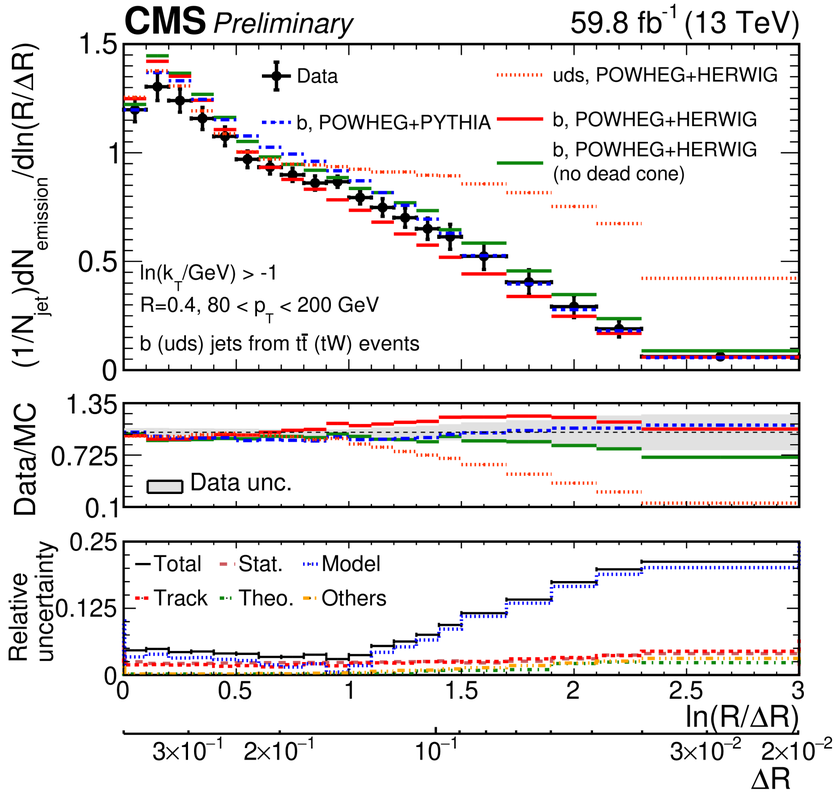
PARTON SHOWER

The dead cone, measured three ways

- **ALICE**: Direct observation of the dead-cone effect in quantum chromodynamics [Nature 605 (2022) 440]
- **LHCb:** Lund plane of B±-tagged vs light jets; first direct observation of the dead cone in beauty jets; **Pythia under-predicts b-jet emissions by up to 25%** [arXiv:2505.23530, PRD 112 (2025) 072015]
- **CMS:** b-jets from $t\bar{t}$; no-dead-cone model disfavored at 4.3σ [arXiv:2608.29412]



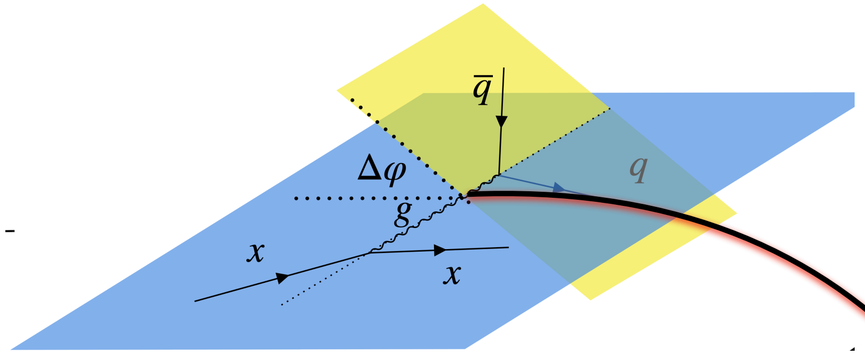




Three experiments, two quark flavors, one QCD prediction from 1991; now measured at the LHC.

PARTON SHOWER

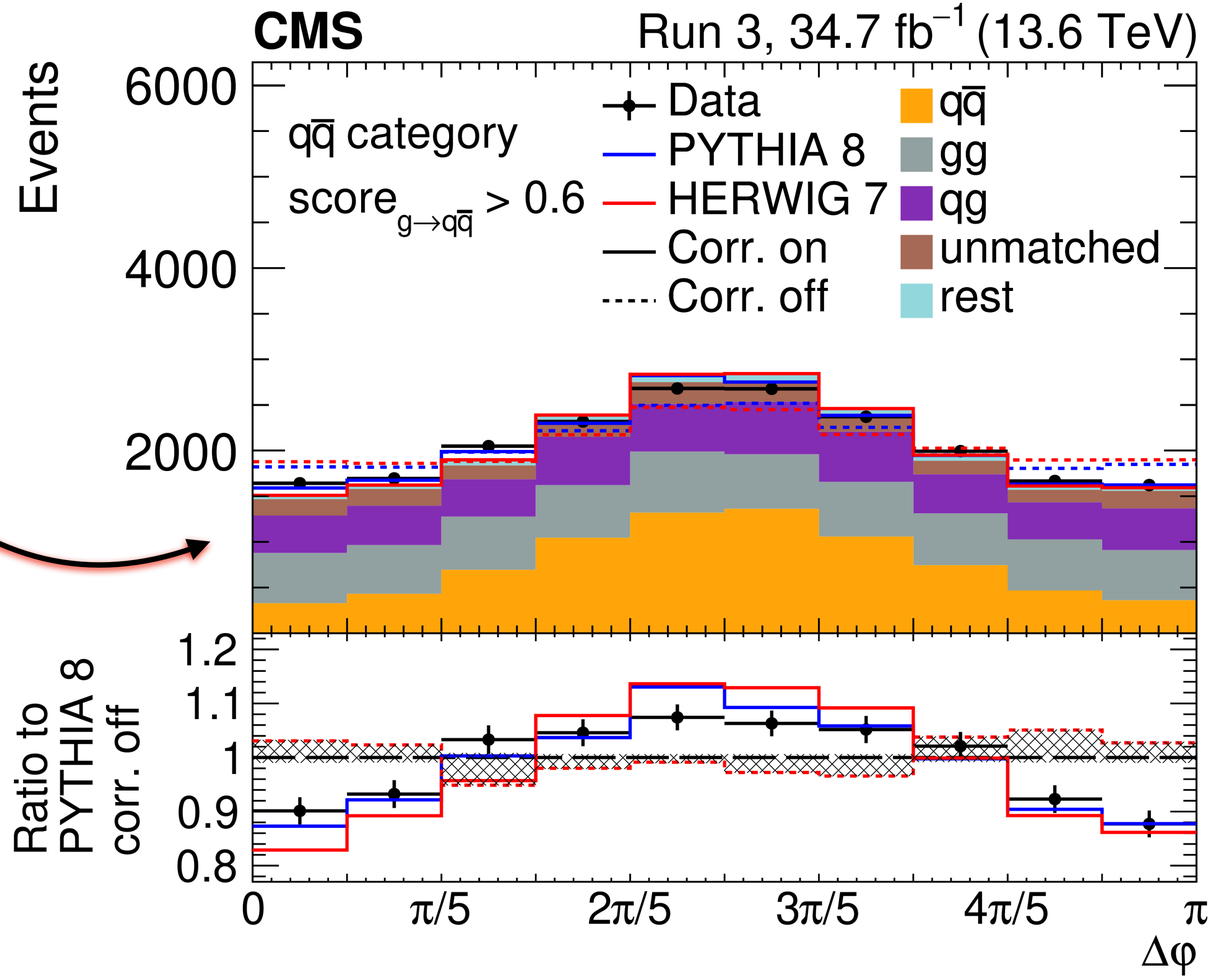
Accounting for gluon spin in shower evolution



$$|M_+ + M_-|^2 = |M_+|^2 + |M_-|^2 + 2|M_+||M_-|cos2\Delta\phi$$

Splitting functions $P_{ij}(z)$ are spin-averaged;
the azimuthal correlation has to be put back by hand

- CMS, Run 3 jets above 700 GeV: a gluon from the first splitting is linearly polarized, and its decay $g \to qq$ prefers a plane
  - a $\cos(2\Delta\phi)$ modulation between the two splitting planes
- The generators differ:
  - Herwig tracks the full spin-density matrices
  - Pythia and Sherpa add an approximate azimuthal modulation



no spin correlation excluded at 6.8σ

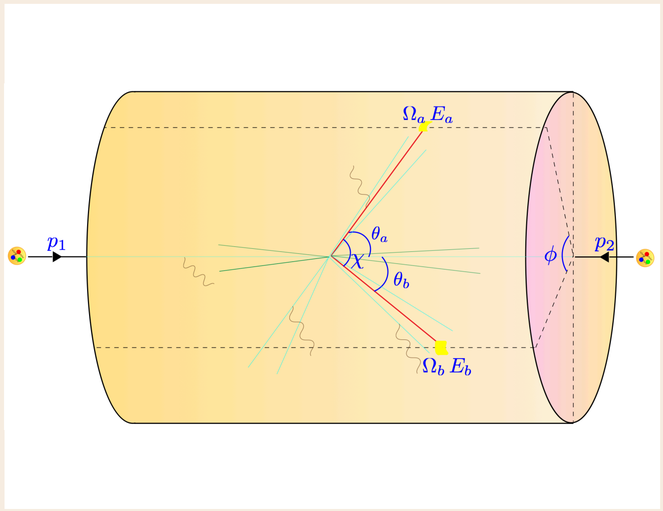
1.9σ from the spin-correlated prediction [arXiv:2603.03689]

PARTON SHOWER

Energy correlators

Measures the angular correlations between the energy flows of particles produced in a collision; no clustering inside the jet, calculable directly in field theory.

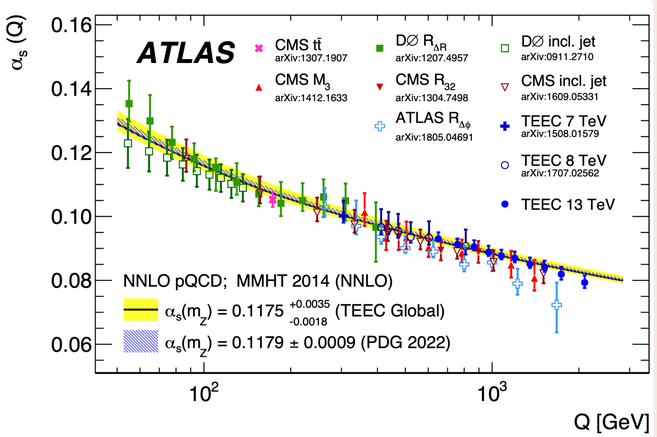
$$\mathrm{EEC}(\theta) \propto \sum_{a,b}^{n} \frac{E_a E_b}{Q^2} \delta(\theta - \hat{n}_a \cdot \hat{n}_b)$$



- the angular scale θ selects the stage of the shower: large θ = early, small θ = late.

Between the jets — the event

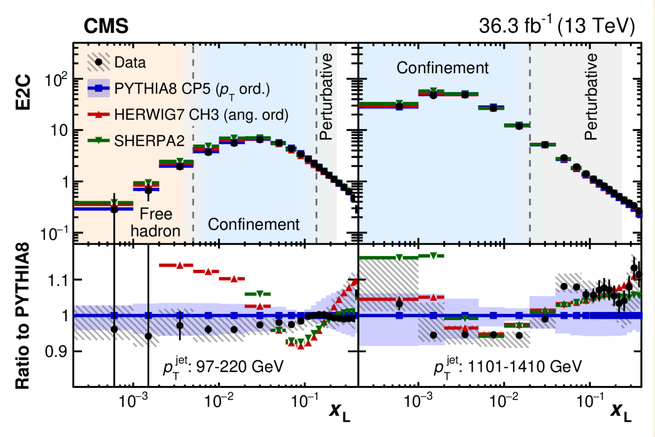
TEEC: the azimuthal angle ϕ between pairs of jets, weighted by their transverse energies [arXiv:2301.09351]



ATLAS, 7 / 8 / 13 TeV with NNLO: $\alpha_S(m_Z) = 0.1175^{+0.0035}_{-0.0018}$; the running probed to Q ≈ 2 TeV

Inside a jet — 2 point EECs

E2C: every pair of particles, weighted by energies, vs their angle xL = ΔR [PRL 133 (2024) 071903]

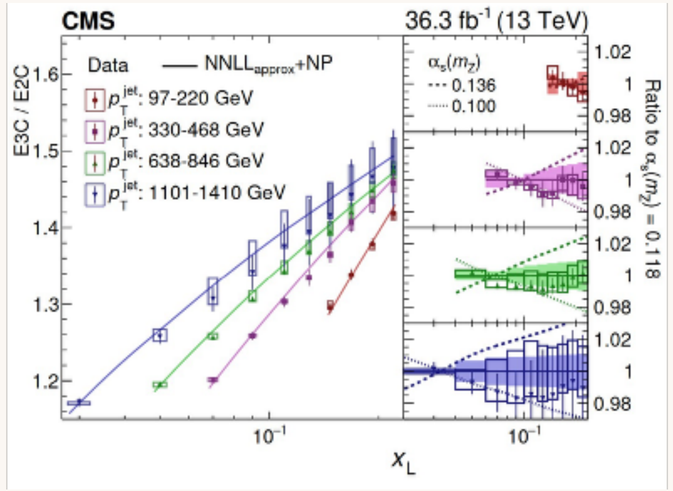


CMS, 13 TeV: three regions in one plot: a perturbative power law, a confinement turnover, flat free hadrons

PARTON SHOWER

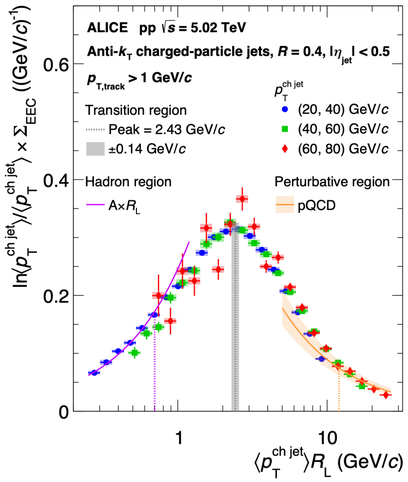
What the EECs can measure

The slope is the coupling



CMS, 13 TeV: E3C/E2C largely cancels hadronisation and the energy scale. The **most precise α_S from substructure**; 4 % today, limited by NNLL. [PRL 133 (2024) 071903]

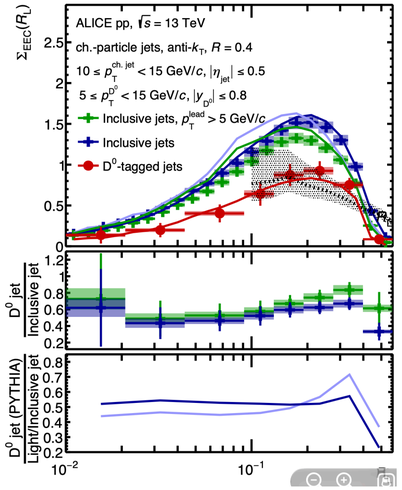
Confinement has a universal peak



ALICE, 5.02 TeV: scale the angle by jet pT and 20–80 GeV jets fall on one curve. The parton→**hadron transition at a common scale**, $R_L \approx \Lambda/p_T$. [PRD 114 (2026) 032002]

LHCb: first EECs in **Z-tagged jets**, light-quark enriched, Transition at 2.74 ± 0.25, 2.71 ± 0.50, 2.67 ± 0.22 GeV for the three pT bins [CERN-EP-2026-257]

A heavy quark changes the shape



ALICE, 13 TeV: D^0-tagged jets **suppressed at small angles.** The dead cone as a correlator; the peak in tension with the expected mass-dependent shift. [arXiv:2504.03431]

PARTON SHOWER

Parton showers: the next order exists, unused

LL

Production showers

- Pythia 8, Herwig 7, Sherpa: every LHC analysis
- tuned to data; the ~10–25% generator spread seen on the previous slides

NLL

Exists, validated

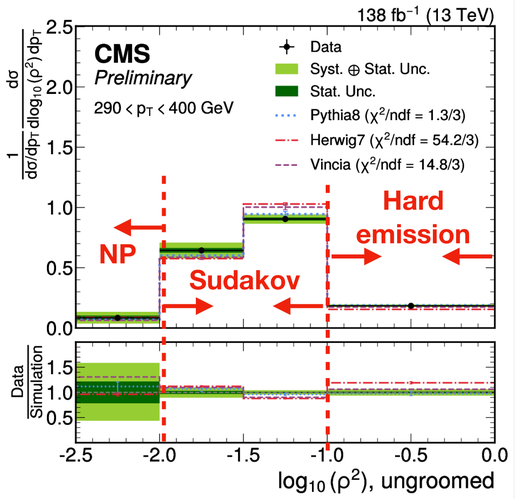
- PanScales; Alaric in Sherpa; Apollo in Pythia [JHEP 11 (2022) 019, JHEP 11 (2022) 020]
- validated for colour-singlet pp [JHEP 11 (2022) 020]
- quark masses at NLL arrived in 2026, for e^+e^- [arXiv:2605.13953]

NNLL

First steps

- first NNLL shower, e^+e^- [PRL 134 (2025) 011901]
- not yet at a hadron collider

- the jet calibration, the dead cone, the spin correlation and the correlators all **compare data to LL showers** → the generator spread is the floor of every substructure measurement
- **CMS** groomed/ungroomed jet mass in Z+jet: Pythia 8 describes it, Herwig 7 and Vincia do not. [CMS-PAS-SMP-25-010]
- IRC-safe **flavored-jet algorithms** now let theory and experiment define a "b jet" the same way [arXiv:2506.13449]



NLL showers exist and are validated for colour-singlet pp; none is yet usable in production analyses.

PARTON SHOWER

Below 1 GeV, hadronisation is a model

Lund string

Pythia

color flux tube between quarks breaks into hadrons; parameters tuned to e^+e^-(LEP) and pp underlying-event data

Cluster

Herwig, Sherpa

gluons split, color-singlet clusters decay; Herwig 7.3 adds baryonic clusters [arXiv:2312.05175]

Coalescence

EPOS4HQ, hydro-coalescence

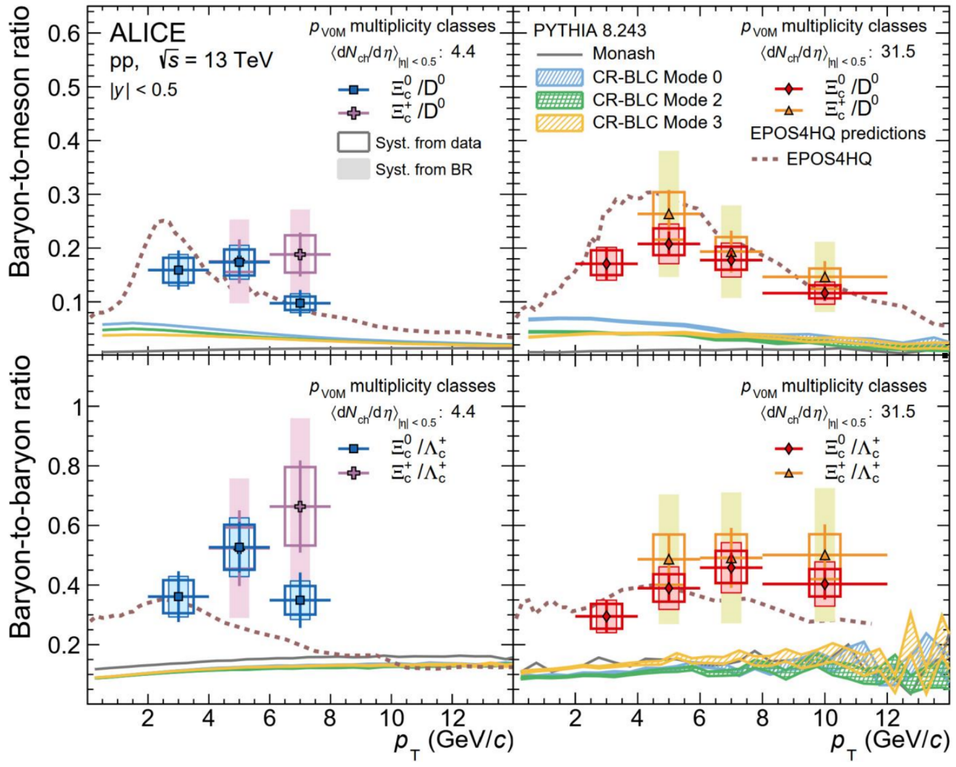
quarks nearby in phase space combine; built for heavy ions, now also applied to pp

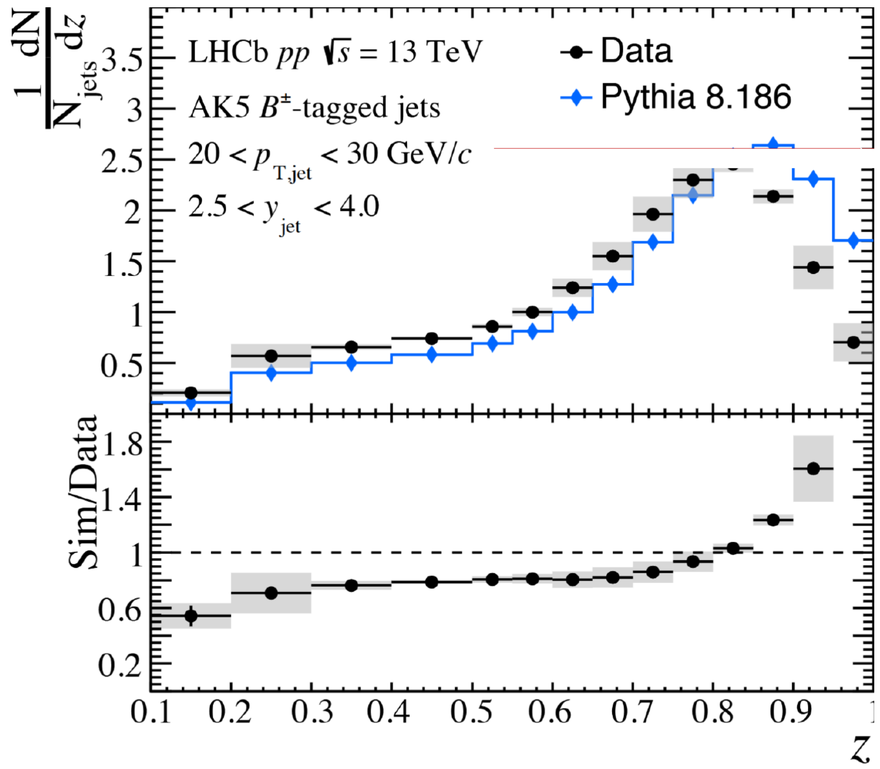
- none is derived from QCD: below 1 GeV α_S is O(1) and **there is no expansion parameter**
  - the lattice computes static properties, not fragmentation
- parameters tuned mostly to LEP are assumed to transfer to pp
- it enters the flagships directly: **the jet and b-jet response, CR in m_t**
- the question for the next slide: **is it universal**?

Below 1 GeV there is no expansion parameter: hadronisation is tuned, not derived.

Hadronisation is not universal

- **ALICE** Ξ_c: ratios to D^0 and Λ_c **above every** e^+e^-**or** ep**-tuned prediction**; EPOS4HQ (coalescence) describes it; Pythia CR-BLC improves on Monash but undershoots; no significant multiplicity dependence [arXiv:2508.09955]
- **LHCb** B± in jets: **Pythia overpredicts isolated B mesons**, worse at high p_T [arXiv:2603.23663]; Λ_b^0/B^0 doubles with multiplicity at low p_T, returns to the e^+e^-value at high p_T [PRL 132 (2024) 081901]
- **CMS** Υ(1S) in jets: too isolated in every generator [arXiv:2607.25653]



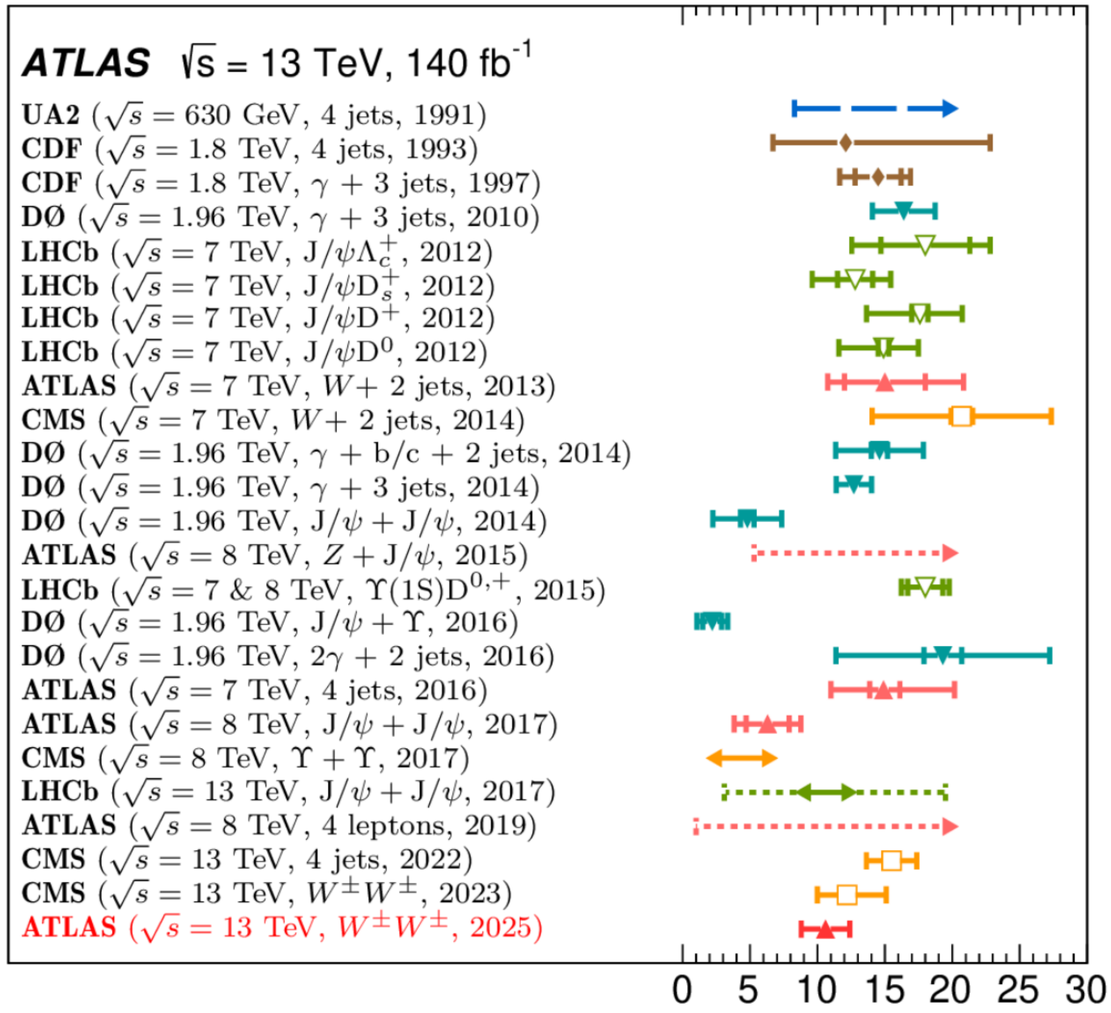


Hadronisation tuned in e^+e^- does not directly transfer to pp

BELOW 1 GeV

One collision, many parton interactions

- **ATLAS**: **two W bosons from two separate parton interactions**, 8.8σ; $\sigma_{\text{eff}} = 10.6 \pm 1.8$ mb, $\sigma_{\text{DPS}} = 4.59 \pm 0.64$ fb [arXiv:2505.08313, PLB 870 (2025) 139892]
- new σ_{eff} values:
  - **LHCb:** J/ψ J/ψ 13.1 ± 1.8 ± 2.3 mb [JHEP 03 (2024) 088];
  - **LHCb:** Z + J/ψ 16.6 ± 4.7 mb [arXiv:2606.05786];
  - **CMS:** Υ + Z $13.0^{+7.7}_{-3.4}$ mb, observed at 5.3σ [arXiv:2602.02770]
  - **CMS:** same-sign WW $12.2^{+2.9}_{-2.2}$ mb, 6.2σ [PRL 131 (2023) 091803]
- a global fit **rejects a constant σ_{eff} at > 6σ** [arXiv:2506.05337, JHEP 10 (2025) 163]: the transverse structure of the proton depends on the process
- the same physics is the **underlying event** under every jet and every Higgs: modeled by the same tunes



$\sigma_{\text{eff}} = 10.6 \pm 1.8$ **mb**

ATLAS same-sign WW, 8.8σ

> 6σ

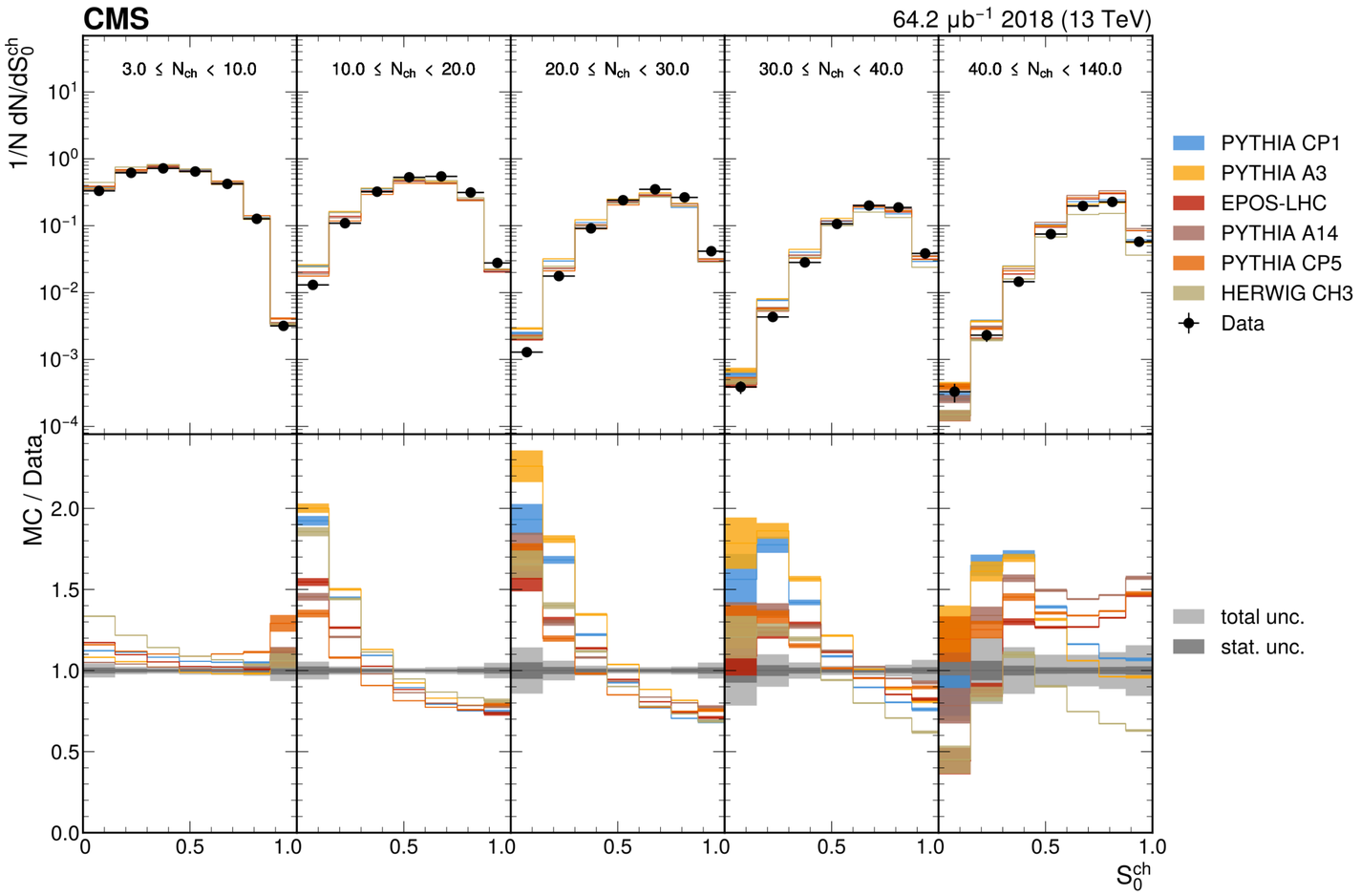
a constant σ_{eff} rejected, global fit of all channels

σ_{eff} is process-dependent: partons in the proton are correlated, not independent.

BELOW 1 GeV

No generator describes the soft event

- **CMS** minimum-bias event shapes at 13 TeV**: no model describes the data**; data are more isotropic; all generators overpopulate $N_{ch} \leq 10$
  [arXiv:2505.17850, PRD 112 (2025) 112006]
- **ATLAS** underlying event with strange hadrons: **no model describes the full range**; Λ/K^0_S nearly flat vs transverse-region multiplicity [arXiv:2405.05048]
- the tunes that fix this: **MPI/UE parameters are tuned to minimum-bias and UE data** (ATLAS A14/A3, CMS CP5/CH3) and extrapolated to other processes and energies.
- this is the floor under the jet calibration and every "non-perturbative correction" at the per-cent level.



The soft event enters every measurement through tunes; its uncertainty is a spread between models.

BELOW 1 GeV

The same four pieces: what 2024–26 delivered

What Run 2 and Run 3 delivered on each piece, and what the flagship still needs

THE PROTON

13.6 TeV candles test PDFs at 2 %; jets to 10 TeV, W to 5 TeV; CT25 moved the high-x gluon

STRONG COUPLING

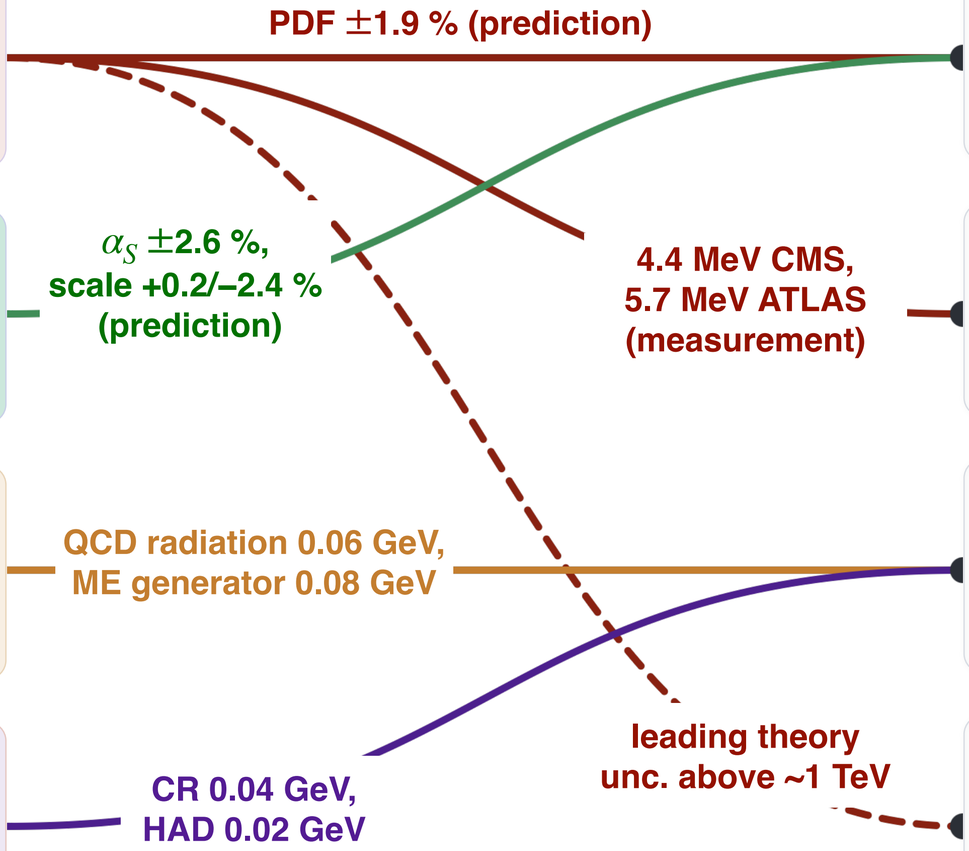
1.3 % from jets, 0.5 % from the lattice; most precise α_S from substructure; no 13.6 TeV value yet

PARTON SHOWER

dead cone, gluon spin, correlators all measured against LL showers; NLL exists, not yet in production

HADRONISATION

pp makes more baryons than LEP tunes predict; heavy flavor and quarkonia depend on the environment



Higgs couplings

Needs: 1/2 × theory

W mass

Needs: 2-4 times smaller PDF

Top mass

Assumed: reduced modeling uncertainties

Searches at the TeV scale

Assumed: PDFs fitted without the tails they test

Each line has a measurement behind it and a known next step.

Three ways to probe QCD

RESOLVE IT — this talk

No longer whether QCD works: below $\alpha_S \approx 0.3$ it works to the per cent. The question is how precisely, set by: the proton we start from, the hadrons we end up with.

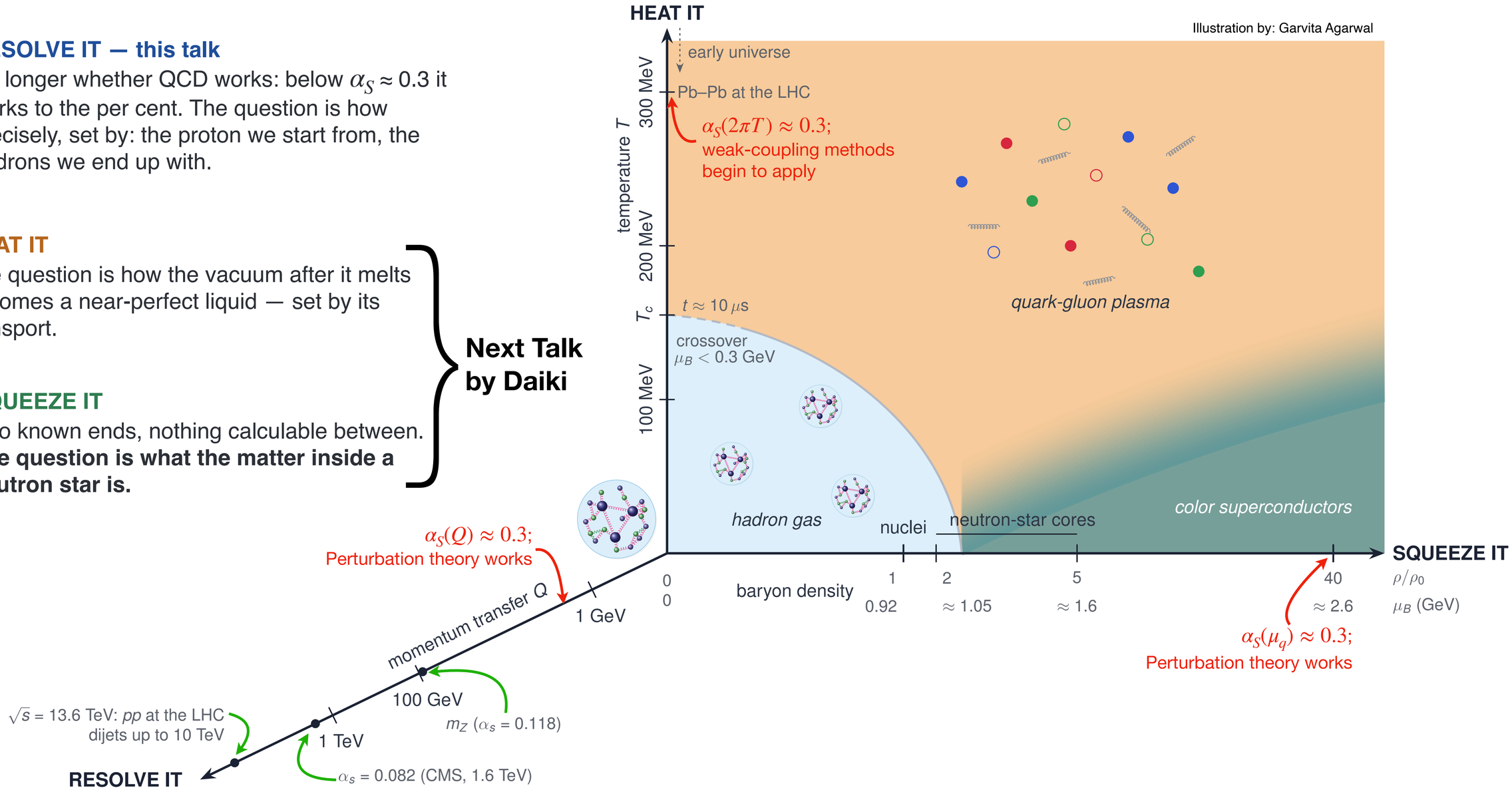
HEAT IT

The question is how the vacuum after it melts becomes a near-perfect liquid — set by its transport.

SQUEEZE IT

Two known ends, nothing calculable between. **The question is what the matter inside a neutron star is.**

Next Talk by Daiki



“Sometimes when I go to bed I wake up and think it's new physics, and sometimes I wake up and think it is just QCD!”

— Giorgio Bellettini

CDF co-spokesperson, 1996

[article]

Backup Slides

Which facility buys which per cent

What each piece still needs, and where it can be bought

THE PROTON

fitted, not calculated: every cross section inherits the PDFs

STRONG COUPLING

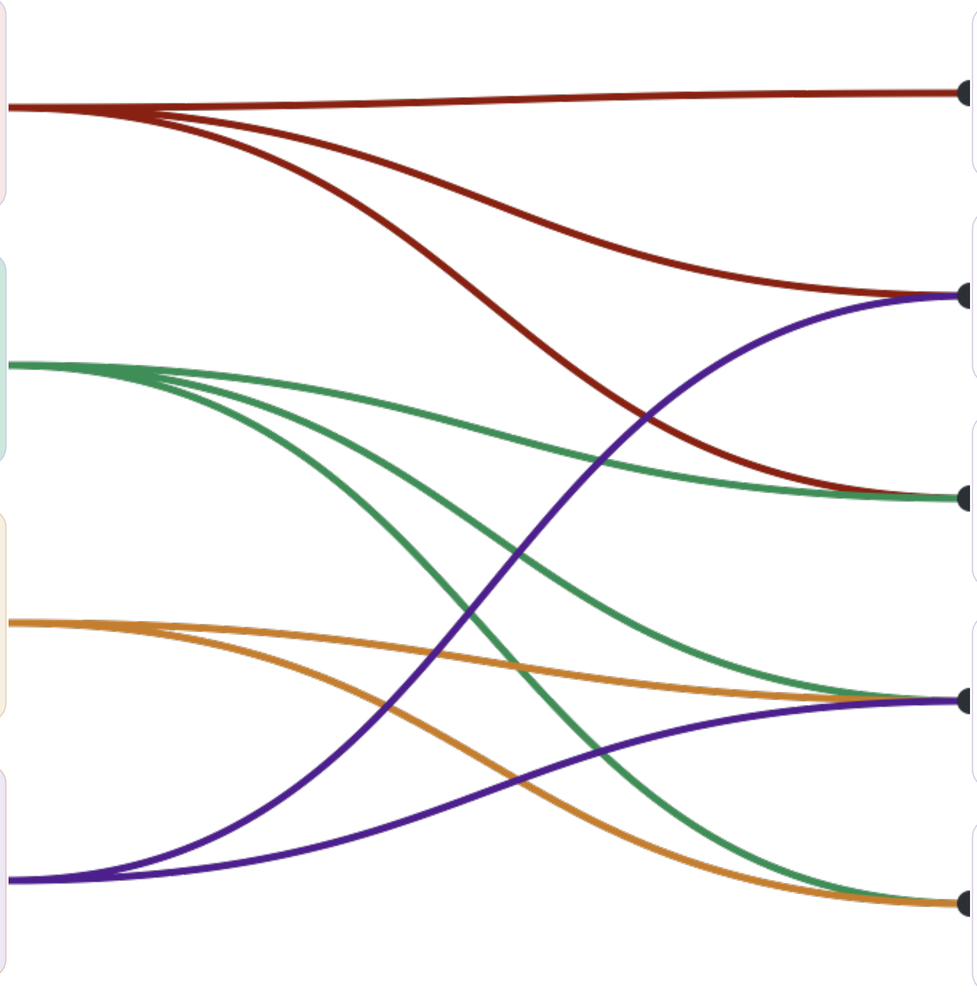
one parameter; every hard process is a truncated series in it

PARTON SHOWER

a TeV down to a GeV, one log per emission; still leading-log

HADRONISATION

below 1 GeV: models tuned at LEP, assumed universal



HL-LHC — 2030, 3 ab^{-1}

PDFs ×2–4 smaller from its own data; substructure at TeV scales; $t\bar{t}$ × 10 for b-fragmentation and CR

EIC — first collisions ≈ 2035

nucleon and nuclear PDFs, spin, 3D imaging; identified hadrons with full PID

LHeC — proposed ep bridge

parton luminosities ≥ 5× better than PDF4LHC21; $\delta\alpha_S$ = 0.00022 (DIS), 0.00013 (jets)

FCC-ee — decision 2028

α_S ±0.2 % from Z and W widths (6×10^{12} Z); 10^5 $H \to gg$; 2.4×10^8 WW for CR

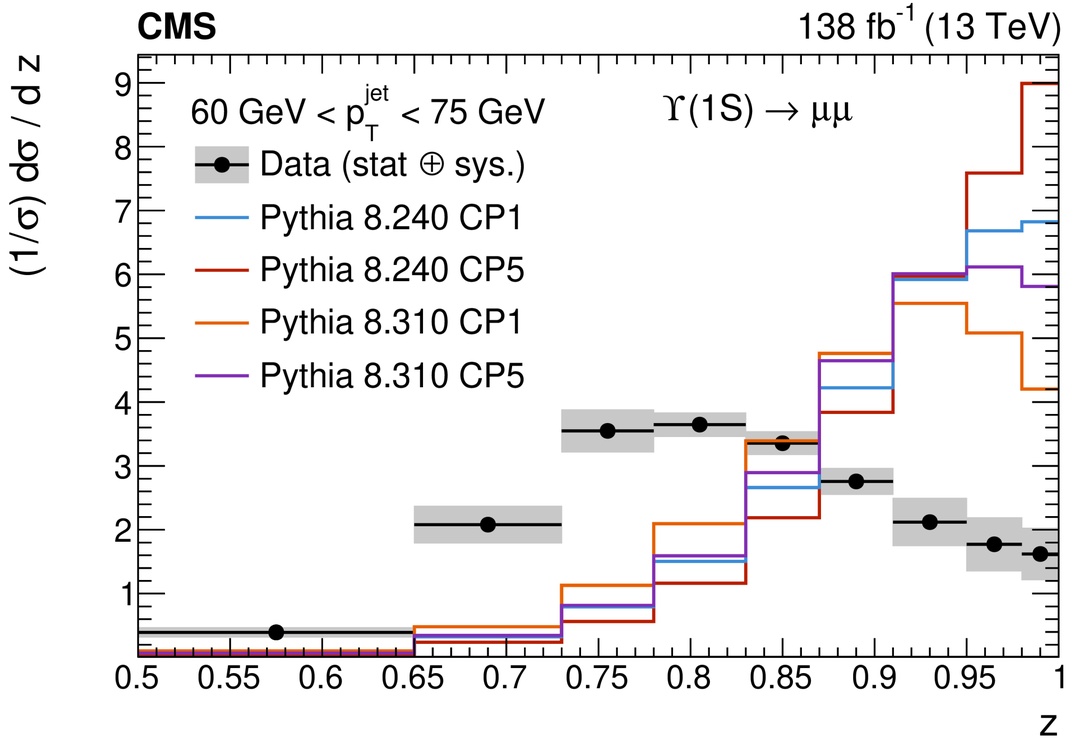
Theory and lattice

α_S from 0.5 % today to per mille within a decade; static hadron properties, not fragmentation

THEORY: N^{3}LO 2→2 and splitting functions · NLL showers into production, NNLL matched to NNLO · hadronisation beyond tuning

The complete event: many parton collisions in one crossing

- **ATLAS: two W bosons from two parton collisions**, 8.8σ; σ_eff = 10.6 ± 1.8 mb; σ_DPS = 4.59 ± 0.64 fb [arXiv:2505.08313, PLB 870 (2025) 139892]; new σ_eff values: LHCb J/ψJ/ψ 13.1 ± 1.8 ± 2.3 mb [JHEP 03 (2024) 088], LHCb Z+J/ψ 16.6 ± 4.7 mb [arXiv:2606.05786], CMS Y+Z 13.0 +7.7/–3.4 mb (5.3σ) [arXiv:2602.02770]; a global fit rejects a constant σ_eff at > 6σ [arXiv:2506.05337, JHEP 10 (2025) 163]
- **ATLAS underlying event with strange hadrons**: no model describes the full range; Λ/K⁰S nearly flat vs transverse multiplicity [arXiv:2405.05048]
- **CMS minimum-bias event shapes**: no model describes the data; all generators overpopulate N_ch ≲ 10 [arXiv:2505.17850, PRD 112 (2025) 112006]; ALICE: a long-range ridge even at mean N_ch ≈ 9, above e+e– limits by 3.8–6.3σ [PRL 132 (2024) 172302]
- **CMS tunes CP5, CH3 and the colour-reconnection tunes fit underlying-event data**; a 2025 intrinsic-kT tune fits Drell–Yan pT [EPJC 80 (2020) 4; EPJC 81 (2021) 312; EPJC 83 (2023) 587; PRD 111 (2025) 072003]

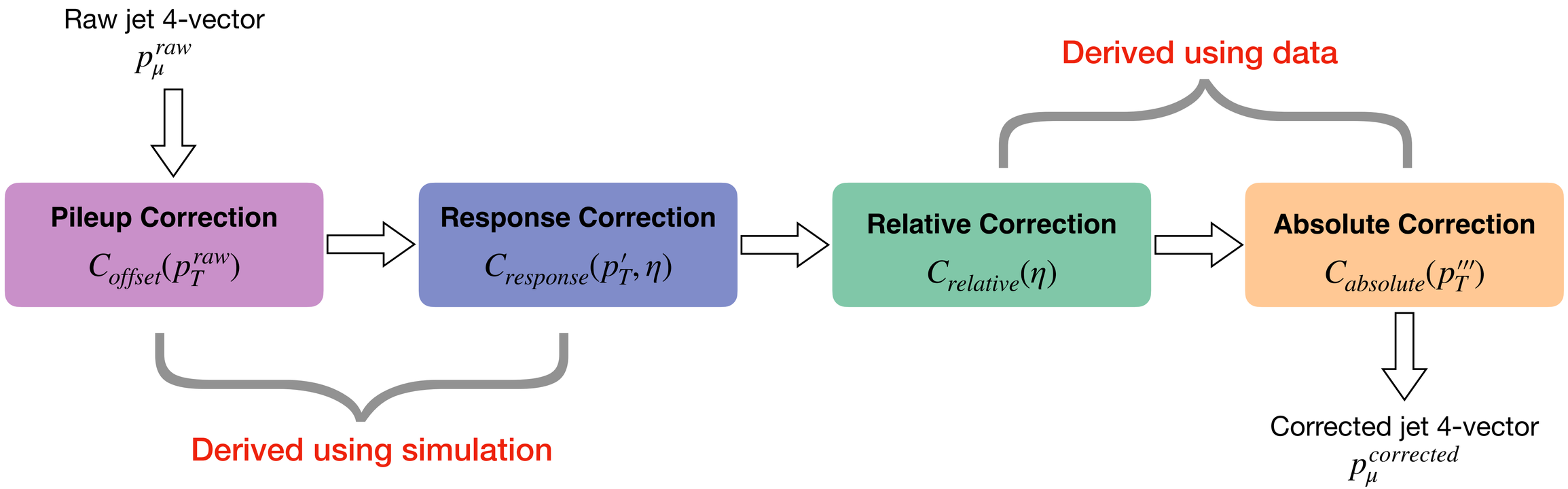


WHERE THEORY STANDS

No first-principles hadronisation. String and cluster models tuned at LEP are assumed universal; pp data say they are not. Beyond-leading-colour reconnection, Herwig 7.3 baryonic clusters [arXiv:2312.05175], coalescence (EPOS4HQ) each describe part of the data, none all of it.

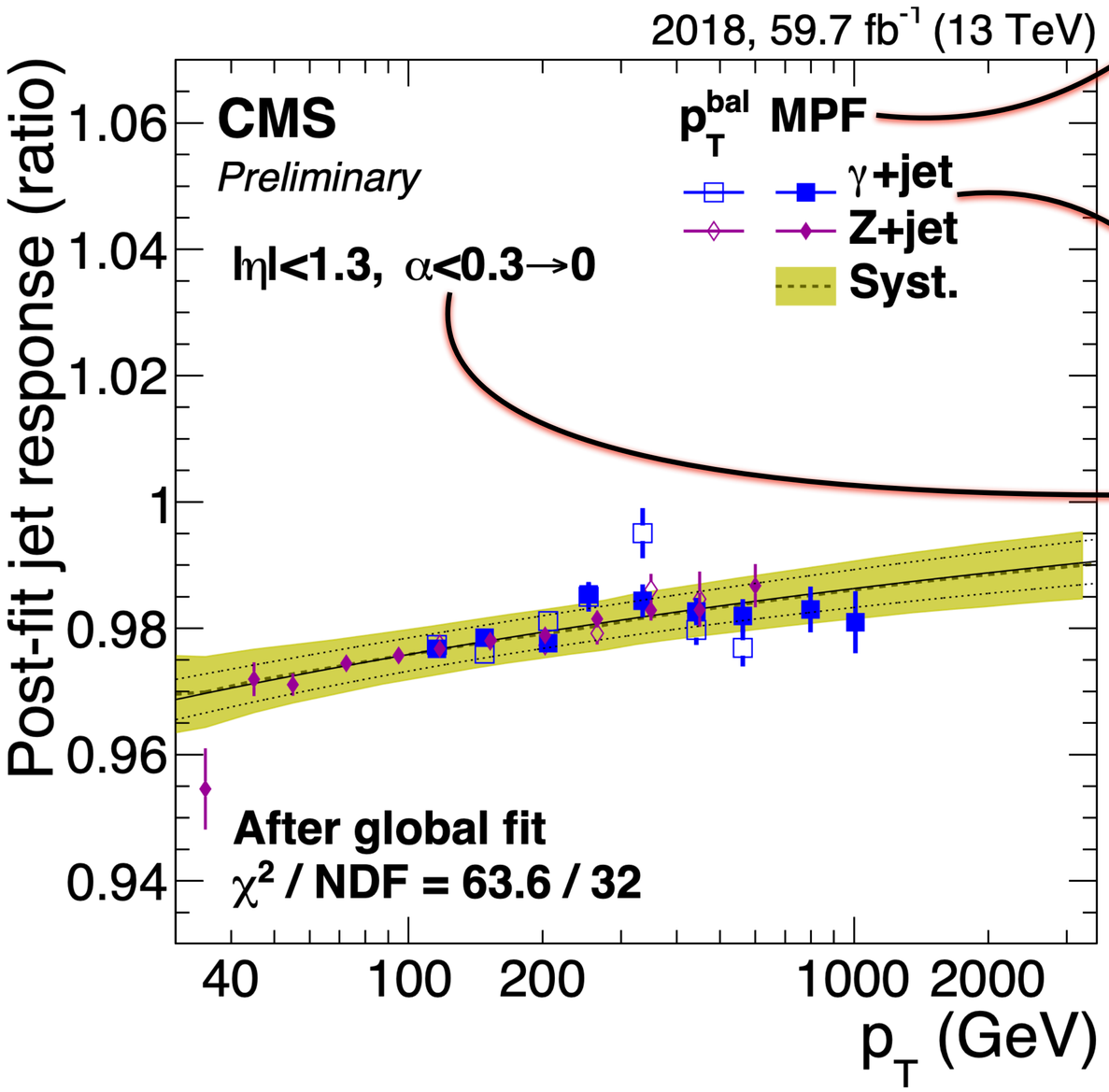
BELOW 1 GeV

Jet Scale Calibration



$$p_\mu^{corrected} = \underbrace{C_{absolute}(p_T'') \cdot C_{relative}(\eta) \cdot C_{response}(p_T', \eta) \cdot \underbrace{C_{offset}(p_T^{raw}) \cdot p_\mu^{raw}}_{p_\mu'}}_{p_\mu''}$$

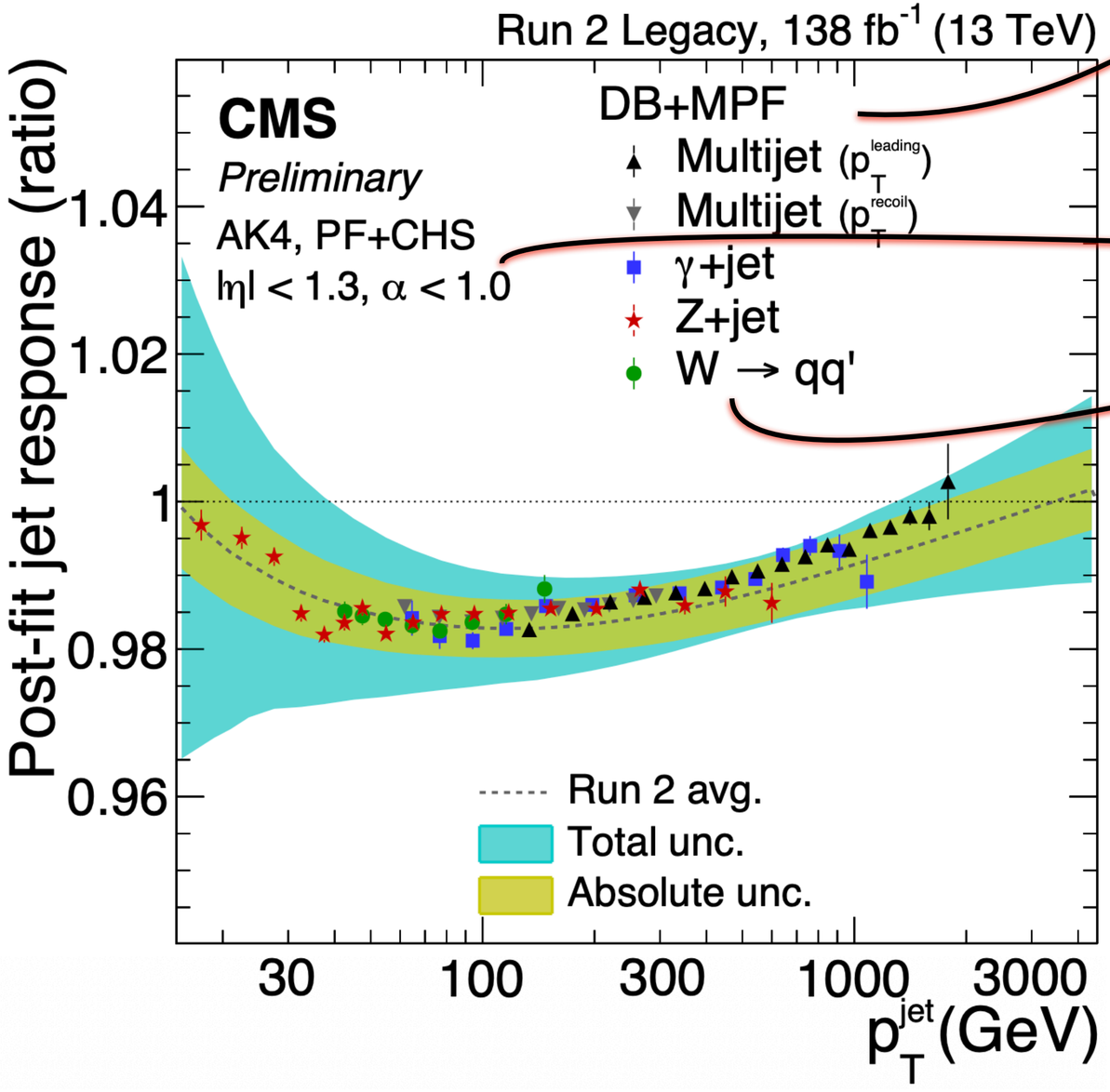
Residual corrections: End-of-year



- **Using two established methods**:
  - *pT-balance (DB)*: highly sensitive to FSR from the jets
  - *MPF*: practically immune to FSR but sensitive to unclustered energy
- **Using Z+jet and γ+jet events**
  - *Z+jet*: lacks in high-pT coverage
  - *γ+jet*: limited at low pT due to trigger
- **Limit additional radiation in the event**

The jet scale is anchored to the electroweak sector!

Residual corrections: Legacy



- **Updated method combining DB and MPF**
  - additional jets and unclustered energy factored into the momentum balance equation
- **Relaxed additional-activity requirement**
  - More events, smaller extrapolation to the two-body limit
- **Many more channels accessible**
  - *Multijet (leading and recoil pT):* carries the scale to the TeV
  - *W→qq′ from $t\bar{t}$:* anchors 40–200 GeV on the W mass
  - *Inclusive jets:* constrains time dependence
- **PF composition as a fit input**
  - constrains degenerate fit parameters

Fit anchored with data across the pT range!