QCD

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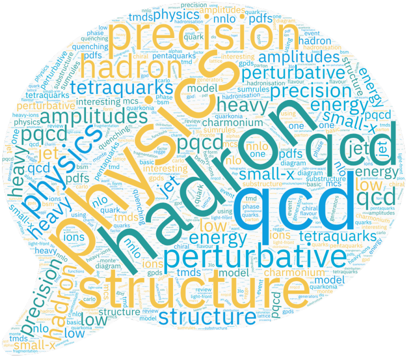
QCD in the particle-physics ecosystem



broad categories of
QCD-related papers
on arXiv:hep-ph
mid Jan-mid June 2025

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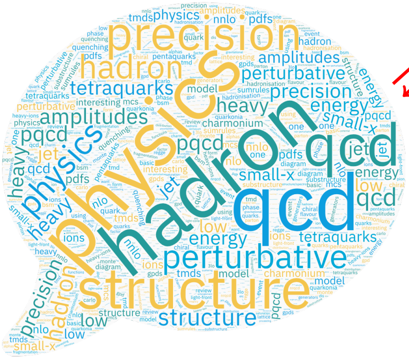

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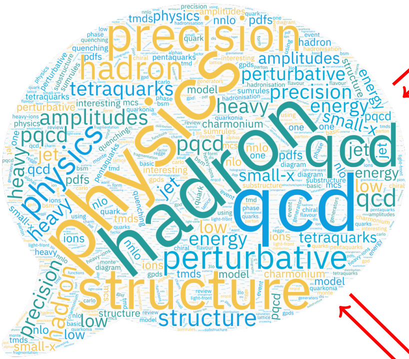
Searches

No BSM without understanding SM

Much of the "precision" era comes from here

Colliders

QCD in the particle-physics ecosystem



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Searches

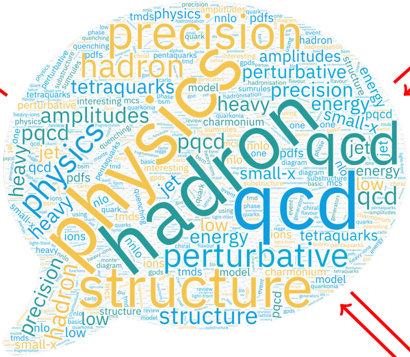
Colliders

Hold on until Urs' talk

Heavy-ions
(QCD matter)

QCD itself!

hadron spectra
hadron structure
amplitudes
confinement
precision physics
α_s determination
...



broad categories of QCD-related papers on arXiv:hep-ph mid Jan-mid June 2025

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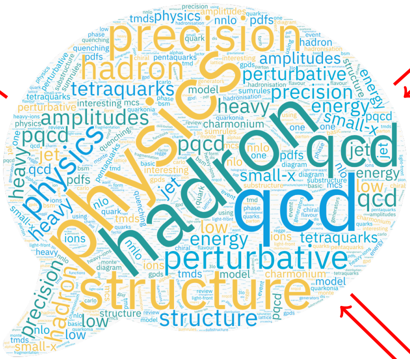

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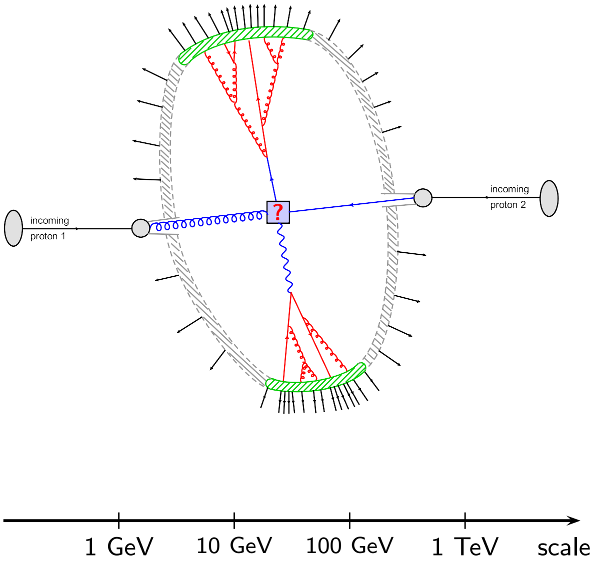
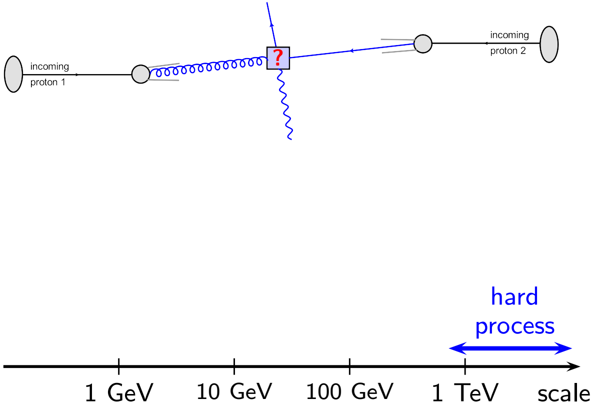
Main focus of this talk

Theorist view of a collision

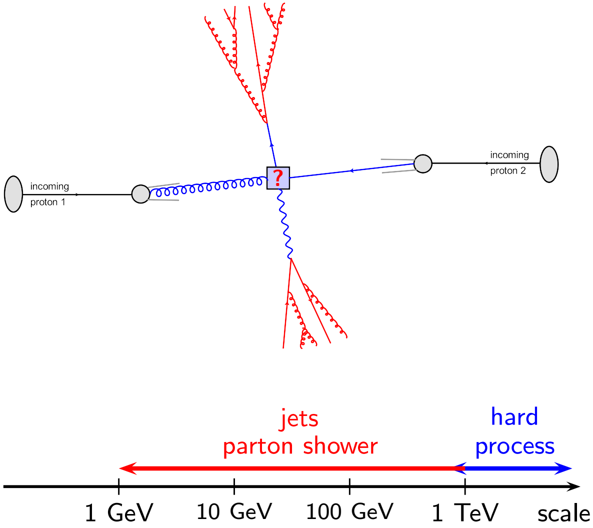


High-energy collision have several steps/ingredients



High-energy collision have several steps/ingredients

- A hard process



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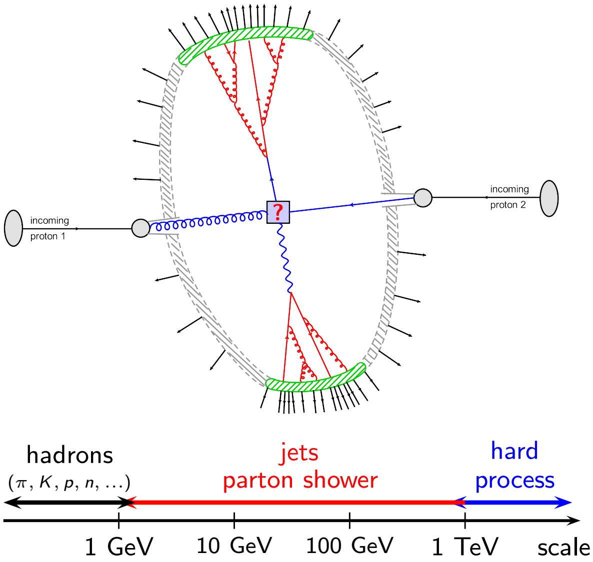
- A hard process
- Parton shower (initial and final-state)

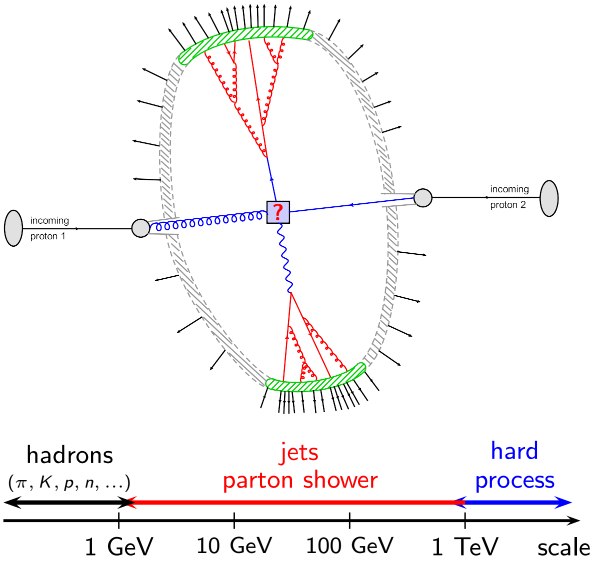
Theorist view of a collision



High-energy collision have several steps/ingredients

- A hard process
- Parton shower (initial and final-state)
- Hadronisation
- Multi-parton interactions
- Hadron decays

Theorist view of a collision

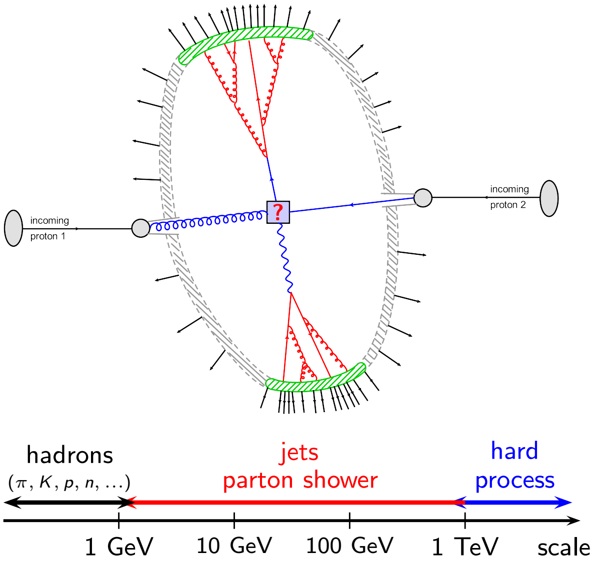


High-energy collision have several steps/ingredients

perturbative "calculable"
- A hard process
- Parton shower (initial and final-state)

non-pert. "modelled"
- Hadronisation
- Multi-parton interactions

various approaches
- Hadron decays



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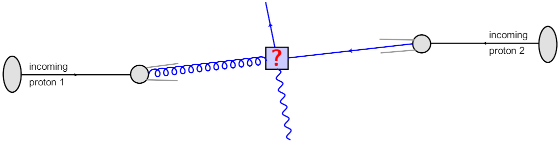
progress at each step

Organisation of this talk

For each step of this collision "steps":

1. Describe the underlying physics/interest
2. Highlight recent/ongoing progress
    - analytic viewpoint (most precise for a given observable)
    - Monte Carlo generator viewpoint (4-vectors give flexibility + usage in exp software)
3. Give a (tentative) view into the future

Usual caveat: incomplete and biased... but hopefully enough to give you the gist



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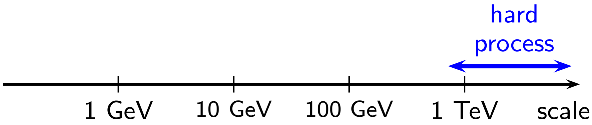


Core factorisation for hard processes

Write hard processes as "$\text{PDF}_a \otimes \text{PDF}_b \otimes \text{ME}_{\text{partonic}}$":

$$\frac{d\sigma(Q)}{dv} = \int dx_a dx_b\, f_a(x_a, Q)\, f_b(x_b, Q)\, |\mathcal{M}(Q, x_a, x_b)|^2\, \delta_{\text{observable}}(v)$$

$$|\mathcal{M}(Q, x_a, x_b)|^2 = |\mathcal{M}(Q, x_a, x_b)|^2_{\text{LO}} + \alpha_s |\mathcal{M}(Q, x_a, x_b)|^2_{\text{NLO}} + \alpha_s^2 |\mathcal{M}(Q, x_a, x_b)|^2_{\text{NNLO}} + \cdots$$

- This is the core of the "precision-era" effort
- Crucial for LHC today and forthcoming high-lumi LHC
  Mandatory for future colliders
- Note: known cases where the above factorisation is violated (super leading logs)

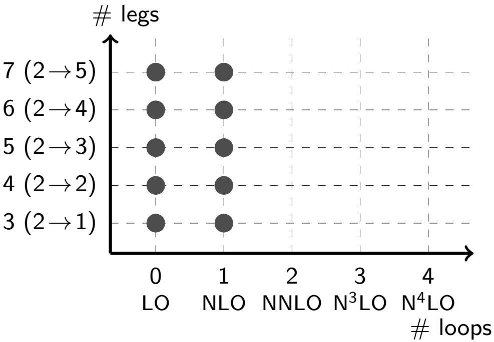
Fixed-order expansion

Two core components:

- amplitudes calculation: heavily connected with fundamental properties of gauge theories
- from amplitudes to (differential) cross-sections ("subtraction", connected to Monte Carlo)

Status and recent progress:

- LO, NLO mostly "solved"



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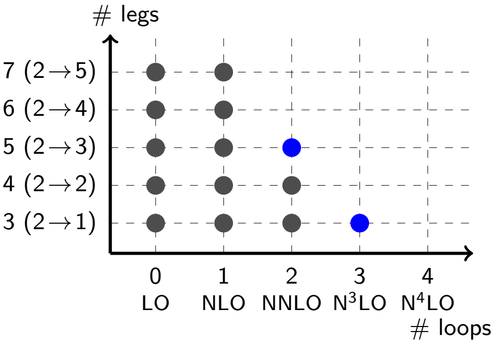
- NNLO: $2 \to 3$ massless with full colour [2311.09870]
  NNLO becomes the standard
- N^3LO: $2 \to 1$ known
- + mixed QCD/EW + applications to gravity [1811.10950]



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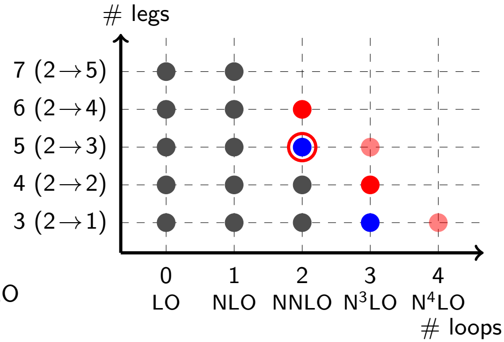


many ongoing efforts:

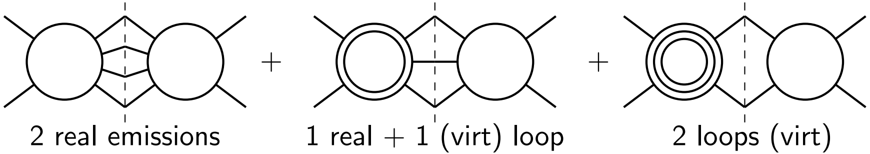
$2 \to 4$ NNLO (+ massive $2 \to 3$), $2 \to 2$ N^3LO, $2 \to 3$ N^3LO

see e.g. [2504.13011] [2412.19884] [2307.15405] [2504.06490] [2411.18697]

Timescales for extra leg/loop $\mathcal{O}(5-10)$ year $\Rightarrow$ future OK

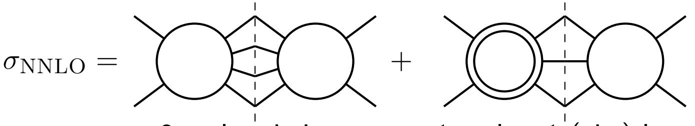
Subtraction

$\sigma_{\rm NNLO} =$



Fine cancellations between terms $\longrightarrow$ insert counterterms so that each term is now finite

Subtraction



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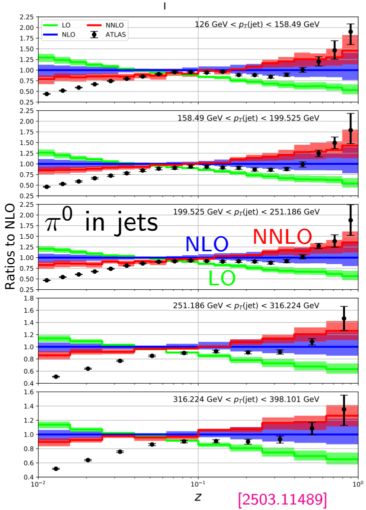
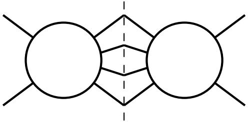


Status and recent progress:

- many methods: antenna sub [0505111], q_t subt [0703012], sector decomp [0305234], N-jettiness [1505.04794], proj2Born [1506.02660], ...
- recent progress examples: NNLOJet code public [2503.22804], $ee \to$jets N^{3}LO [2505.10618], Geneva $V\&V+j$ NNLO [2504.11357]

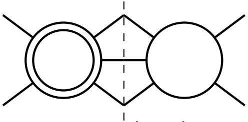
Subtraction

$\sigma_{\text{NNLO}} =$



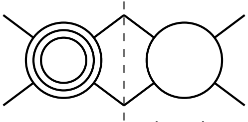
2 real emissions

$+$



1 real + 1 (virt) loop

$+$



2 loops (virt)

Fine cancellations between terms $\longrightarrow$ insert counterterms so that each term is now finite

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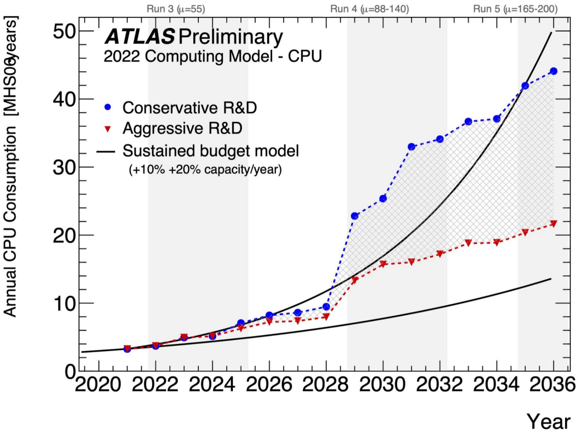
Future challenges:

- improvements needed as NNLO becomes standard
- e.g. computing resources
- theory uncertainties?

Example: projected ATLAS CPU usage

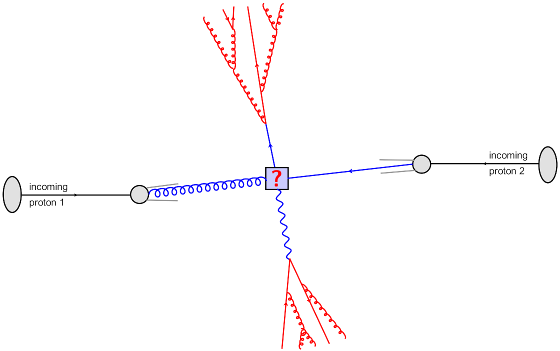


[ATLAS Software and Computing HL-LHC Roadmap, 2022]

Improved simulations would be very much appreciated

This covers many aspects on top of HPC/GPU/...:

- amplitudes/integrals evaluation
- subtraction schemes
- matching (see later)
- ...



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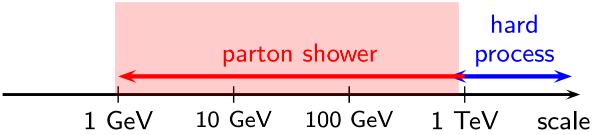

Approaches to connect widely disparate scales

All-order resummations: N^{k}LL resums $(\alpha_s L)^n \alpha_s^{k-1}$ for all n (limit $\alpha_s L \sim 1$, $\alpha_s \ll 1$)

Option 1: analytic

High-accuracy but usually done observable per observable. Two main approaches:

1. SCET (effective theory): routinely NNLL; some observables (almost) up to N^{4}LL
   Recent progress: super-leading logs [2107.01212], heavy quarks [2412.06881], energy correlators [2506.09119], links with TMDs and NRQCD, ...
   Looking forwards: core (QFT-based) analytic approach to resummation with many applications and clear path towards precision
2. "direct QCD": NNLL frequent as well (automatised for simple processes), N^{3}LL sometimes

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Option 2: parton shower (core of general-purpose Monte Carlo generators)

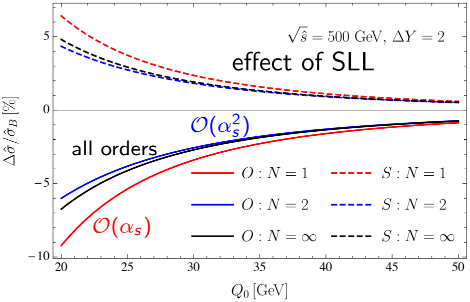
Full kinematics, and (roughly) any observable but limited in accuracy (LL until $\sim$ 2019)

Recent progress: NLL revolution in the past $\sim$ 5 years, starting to get NNLL (+ heavy progress on colour)

Looking forwards: will hopefully become competitive in the precision business

example: super-leading logs

- Nasty logs discovered in 2006 [0604094]
  non-global, subleading-N_c, pp only, start at $\alpha_s^4 L^5$
- First (SCET) resum in 2021 [2107.01212]



Showers 2019-2024: many now achieve NLL

- PanScales [2002.11114] [2011.10054] [2103.16526] [2111.01161] [2205.02237] [2207.09467] [2305.08645] [2312.13275]
- Deductor [2011.04773] [2011.04777]
- CVolver [1905.08686] [2003.06400] [2011.15087]
- Alaric [2208.06057] [2307.00728] [2404.14360]
- Apollo [2403.19452]

NLL is becoming the new standard

Examples of recent progress

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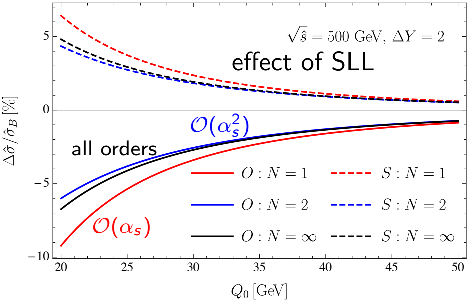
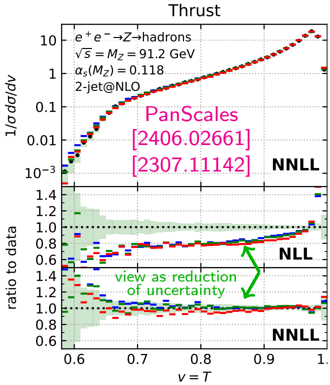


Showers 2024-now: progress towards NNLL



so far only *ee*, large-N_c and not all obs

but promising for precise all-purpose MC generators in coming years

PDFs

Basic concepts:

- PDFs appear "core factorisation formula"
- Technically, resum collinear $\log(Q/m_p)$
- Fundamental QCD factorisation theorem: $f_i(x, Q > Q_0)$ from $f_i(x, Q_0)$ input ($Q_0 \sim 1$ GeV) and pQCD evolution

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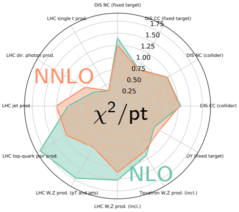
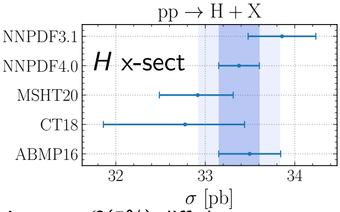
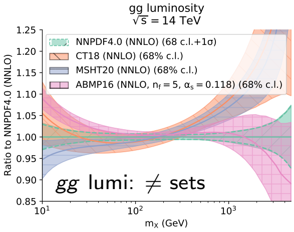
- All (main) PDF sets are NNLO ([CTEQ], [MSHT], [NNPDF], ...)
- approximate N^{3}LO start to appear Needed for 1%-level (still differences between sets)



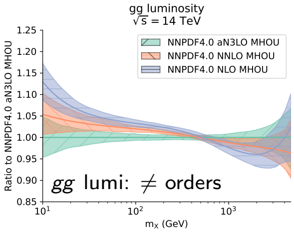
NNLO improves data description



$\mathcal{O}(5\%)$ diffs between sets



$\mathcal{O}(5-10\%)$ uncert



sizeable aN^{3}LO effects

PDFs

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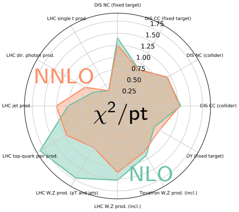
Looking forwards: PDFs will improve!
e.g. need more N^{3}LO x-sections (only DIS now)
Recall: interplay w data through fit!



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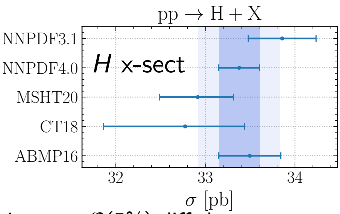

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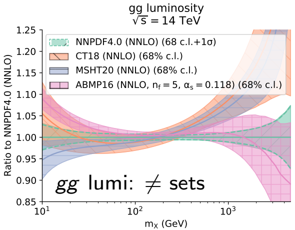
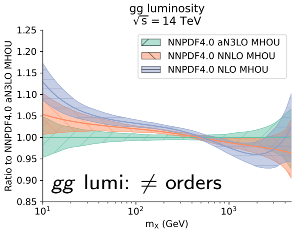
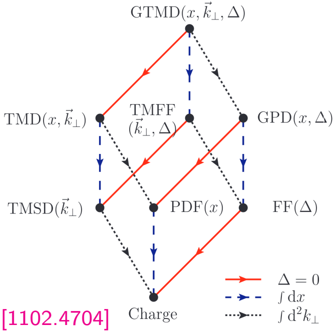


$\mathcal{O}(5-10\%)$ uncert



sizeable aN^{3}LO effects

Fundamental question: what is the partonic contents of a proton?



[1102.4704]

interesting at many levels

- Additional degrees of freedon
  - transverse momentum, $\vec{k}_t$
  - momentum transfer Δ
  - + potential polarisation info
- Gaining in precision: e.g. TMDs at N^{4}LL [2305.07473]
- Not only for the proton:
  - nuclear PDFs relevant for heavy-ion collisions
  - other hadrons (like pions)
- Links to lattice determinations: e.g. [2412.01750]
- Links to small-x/saturation physics: e.g. [2503.16162]
- Relevance for pheno: DY, SIDIS, Diffractive DIS

  Looking forwards to the EIC!

Pheno interlude: matching fixed-order and parton shower

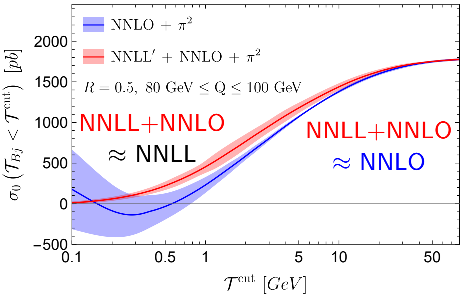
Idea:

Build a prediction that works both in the fixed-order and resummation regimes
e.g. NNLO+NNLL p_{tZ} spectrum would have NNLO for $p_{tZ} \gtrsim M_Z$ and NNLL for $p_{tZ} \ll M_Z$

Analytic viewpoint

almost systematic for pheno predictions

Right: Drell-Yan with veto on additional jets [2504.06353]



Several other (recent) examples:

- Soft log resummations in VH, $t\bar{t}$, $t\bar{t}H$ or $t\bar{t}t\bar{t}$ [2502.20331] [2503.18713] [2503.15043] [2505.10381]
- DIS Thrust [2504.05234]
- Small-R jet resummations [2503.21866] [2402.05170]
- TMDs for J/Ψ [2504.19617]

Future: multi-scale processes?

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In Monte Carlo generators

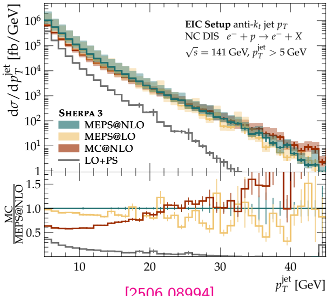
NLO+PS matching is standard
[POWHEG] [aMCNLO] [MEPSNLO]

Progressively getting NNLO+PS
e.g. MiNNLO [1908.06987] [2108.05337] [2112.12135]

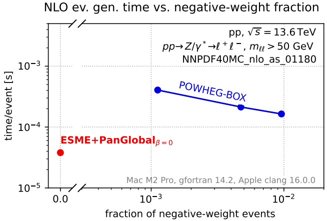
Looking forwards:

- interplay with shower accuracy
- avoiding negative weights
- CPU budget

NLO+PS matching in DIS



[2506.08994]



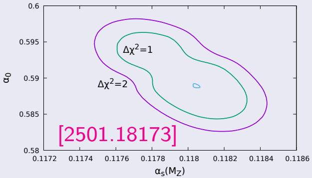
NLO+NLL with positive weights

[2504.05377]

fundamental param & impacts many things (e.g. if we are stable)

ee event shapes

3-jet non-pert corrections

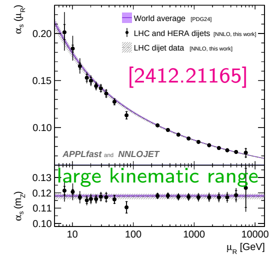


$$\alpha_s(M_Z) = 0.1181^{+0.0018}_{-0.0022}$$

NNLO+N^{3}LL thrust: 0.1181 ± 0.0018 [2502.01570]

Heavy jet mass: $0.1145^{+0.0021}_{-0.0019}$ [2502.12253]

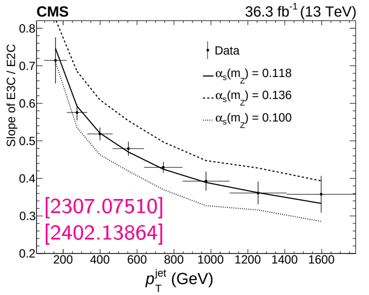
LHC dijets & PDFs



$$\alpha_s(M_Z) = 0.1178 \pm 0.0022$$

aN^{3}LO PDFs: $0.1194^{+0.0007}_{-0.0014}$ [2506.13871]

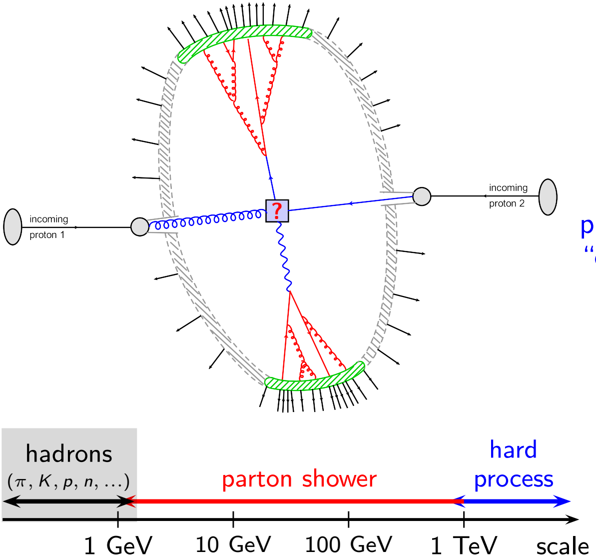
EEC (jet substructure)



$$\alpha_s(M_Z) = 0.1229^{+0.0040}_{-0.0050}$$

Latest lattice result: $\alpha_s(M_Z) = 0.11873 \pm 0.00056$ [2501.06633]

Theorist view of a collision: focus on hadronic physics



High-energy collision have several steps/ingredients

perturbative "calculable"
- A hard process
- Parton shower (initial and final-state)

non-pert. "modelled"
- Hadronisation
- Multi-parton interactions

various approaches
- Hadron decays

Physics of hadrons

This is where QCD is getting the most complicated! So I will only give a few pointers...

Many systems

- Hadrons/mesons with heavy quarks
- Tetraquarks
- Pentaquarks
- Even hexa/octaquarks

Many questions

- spectrum
- nature
- (rare) decays
- structure/fragmentation

Many approaches

- B physics tentatively perturbative
- light-cone wave-functions
- NRQCD
- EFTs (chiral PT, HQET, SCET, ...)
- sumrules
- potential models
- lattice QCD

Exprimental relevance

LHC, Belle, BESIII, ...

Modelling in MC

Trying to better understand/constraint the Lund string and cluster hadronisation models

Large activity
($\sim$300 papers from mid-Jan to mid-June)

data and lots of unkonwn
$\Rightarrow$ work for the future

Conclusions

QCD is a fundamental component of the standard model
at the core of the (past,) current (and future) particle-physics program

Tremendous progress

After 50 years: we have reached a phenomenal degree of understanding of the theory:

- structure and properties of hadrons
- control over the perturbative properties (fixed and all-order)
- development of tools (Monte-Carlo generators, jets, AI, ...)

Exciting challenges ahead

Challenges & bright future await:

- more fundamental aspects to be learned
- connection with rich pheno/exp program

Thank you!

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