Standard Model, Flavour & Collider Physics

CERN TH retreat - Les Houches 2022

Our group at CERN TH




Staff

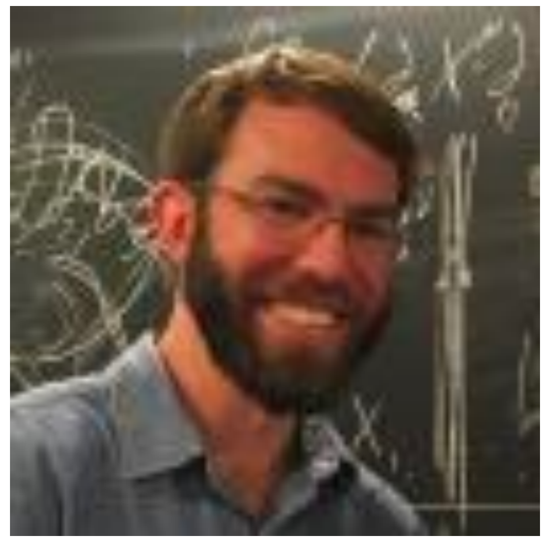
New New New New







New

Fellows

Associates & Visitors + Student



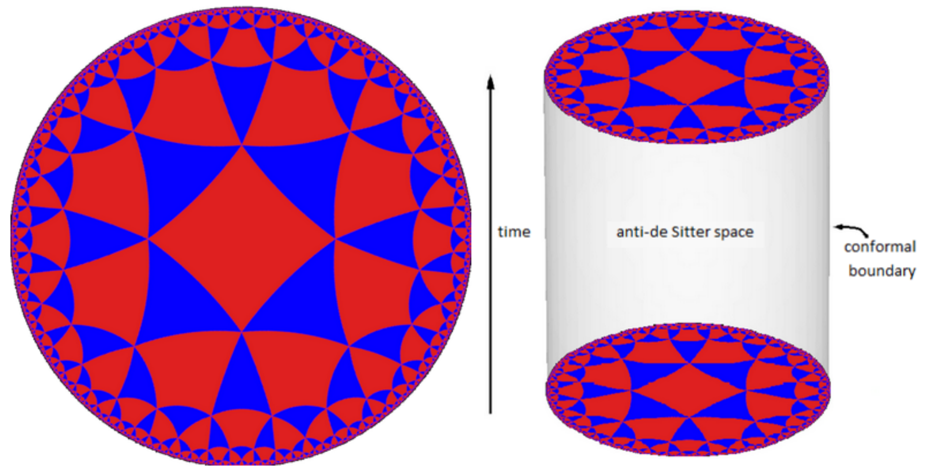




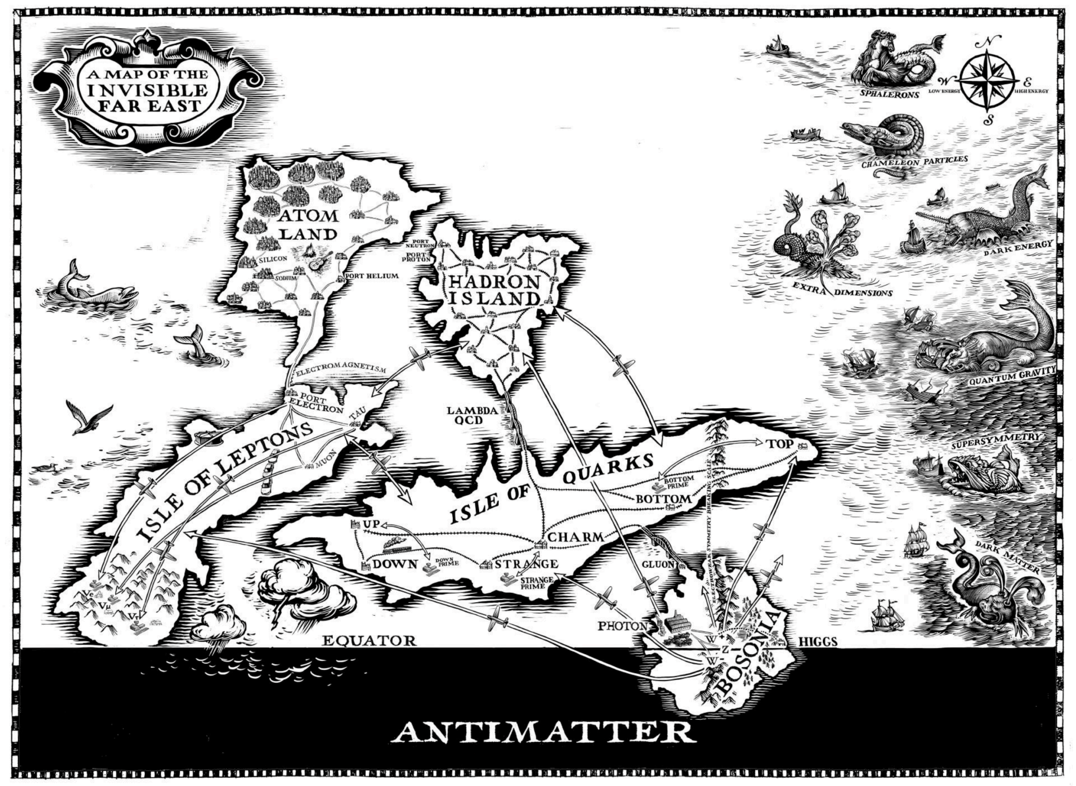
The collider physics landscape

Understanding of QFTs

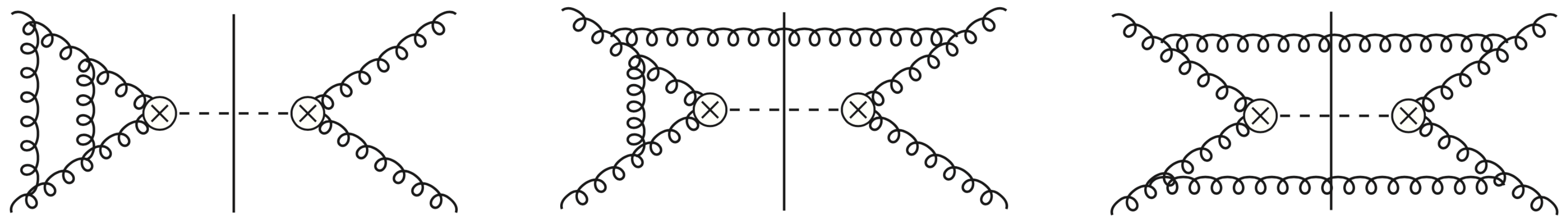
formal developments



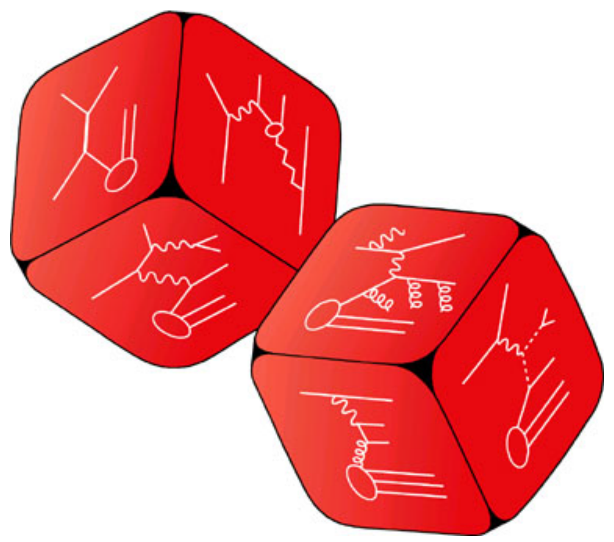
landscape of NP models



perturbative methods



event generators



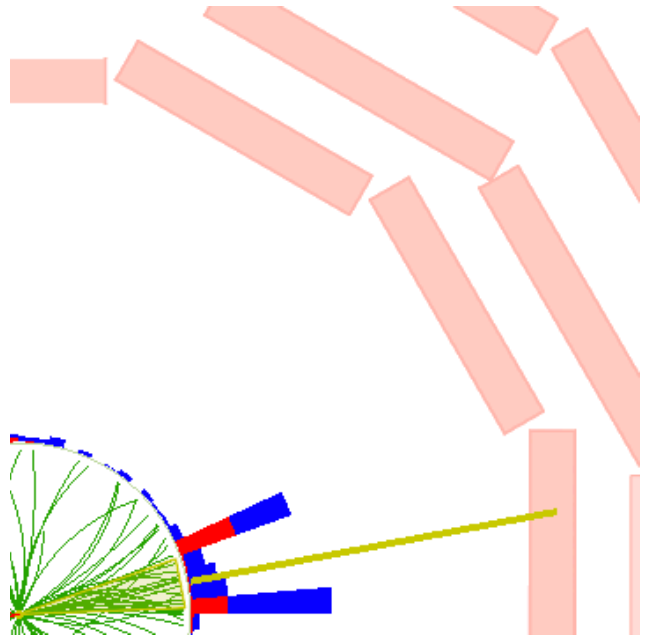
non-perturbative (QCD) corrections

$$\tilde{\alpha}_s(\mu^2) \equiv \tilde{\alpha}_s(0) + \int_0^\infty \mathrm{d}m^2 \frac{\mu^2}{m^2+\mu^2} \frac{\mathrm{d}\alpha_{\mathrm{eff}}(m^2)}{\mathrm{d}m^2}$$

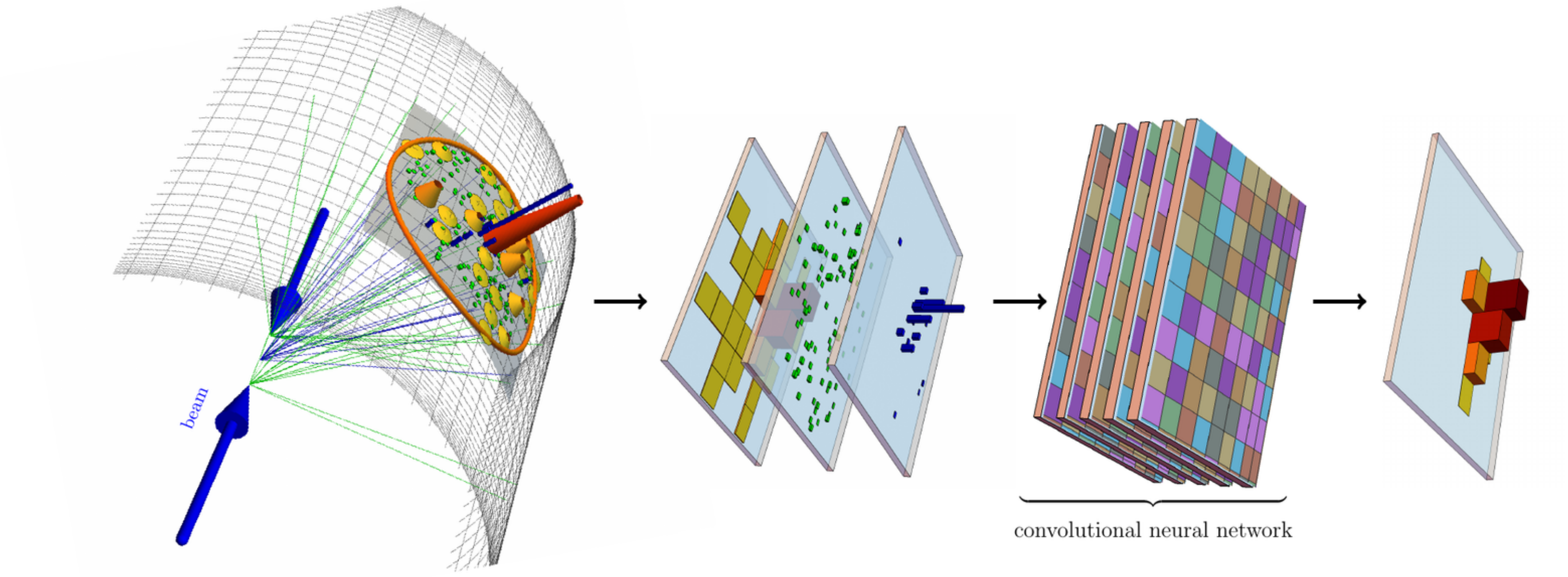
(...)

Collider pheno

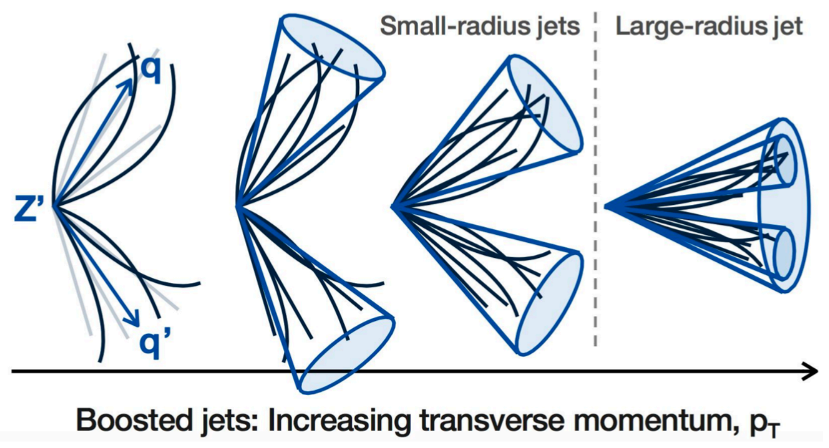
Future colliders



novel strategies (e.g. ML, new observables)

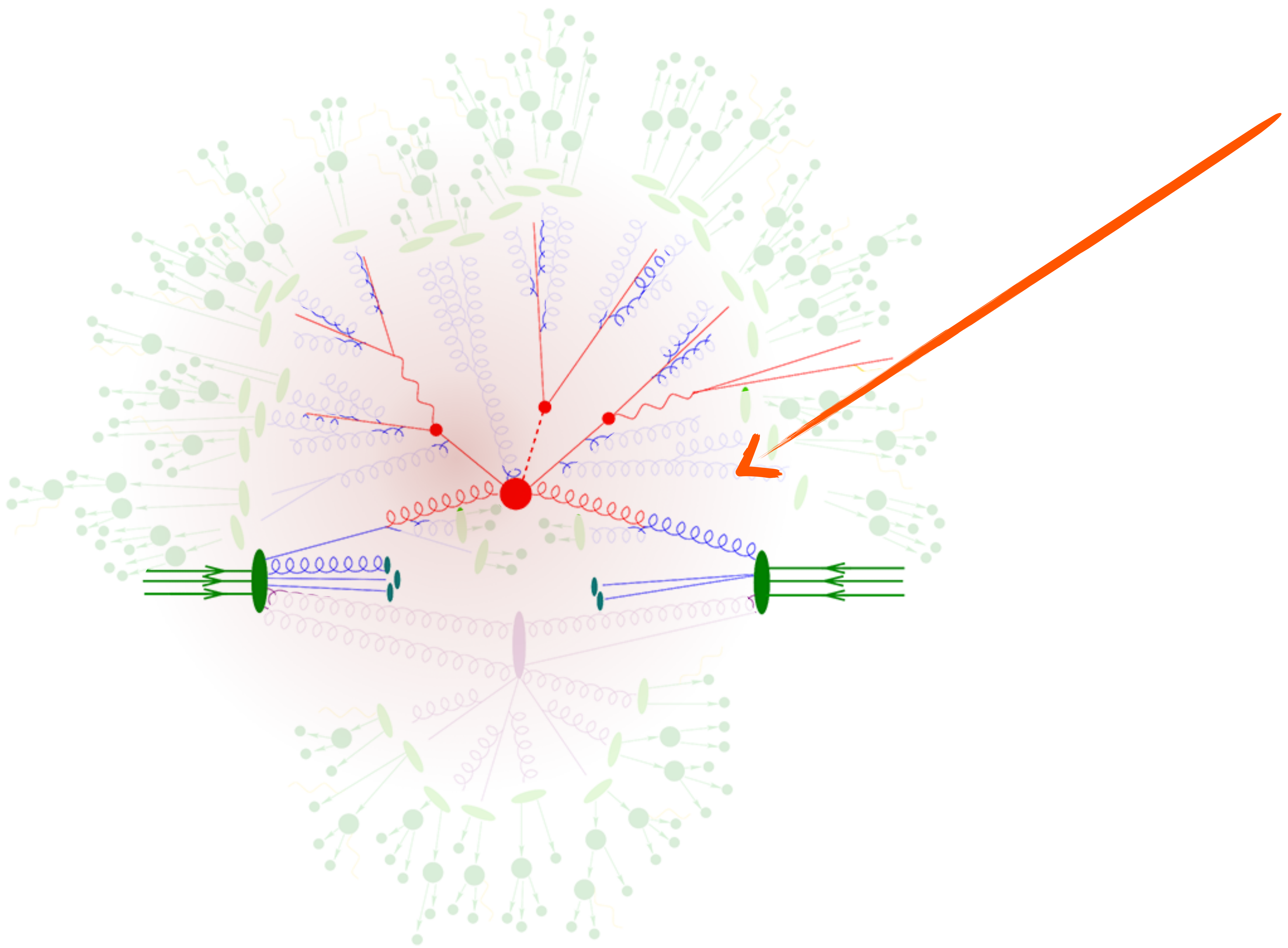


BSM searches & jets



The collider physics landscape

$$d\sigma = \sum_{a,b} f_{a/A}(x_a) f_{b/B}(x_b)\, d\hat{\sigma}_{ab} \left(1 + \mathcal{O}\left(\frac{\Lambda}{Q}\right)^p\right)$$



- Short distance (hard)
  - ➡ scales probed: $O(10^2)$-$O(10^3)$ GeV
  - ➡ stage sensitive to New Physics

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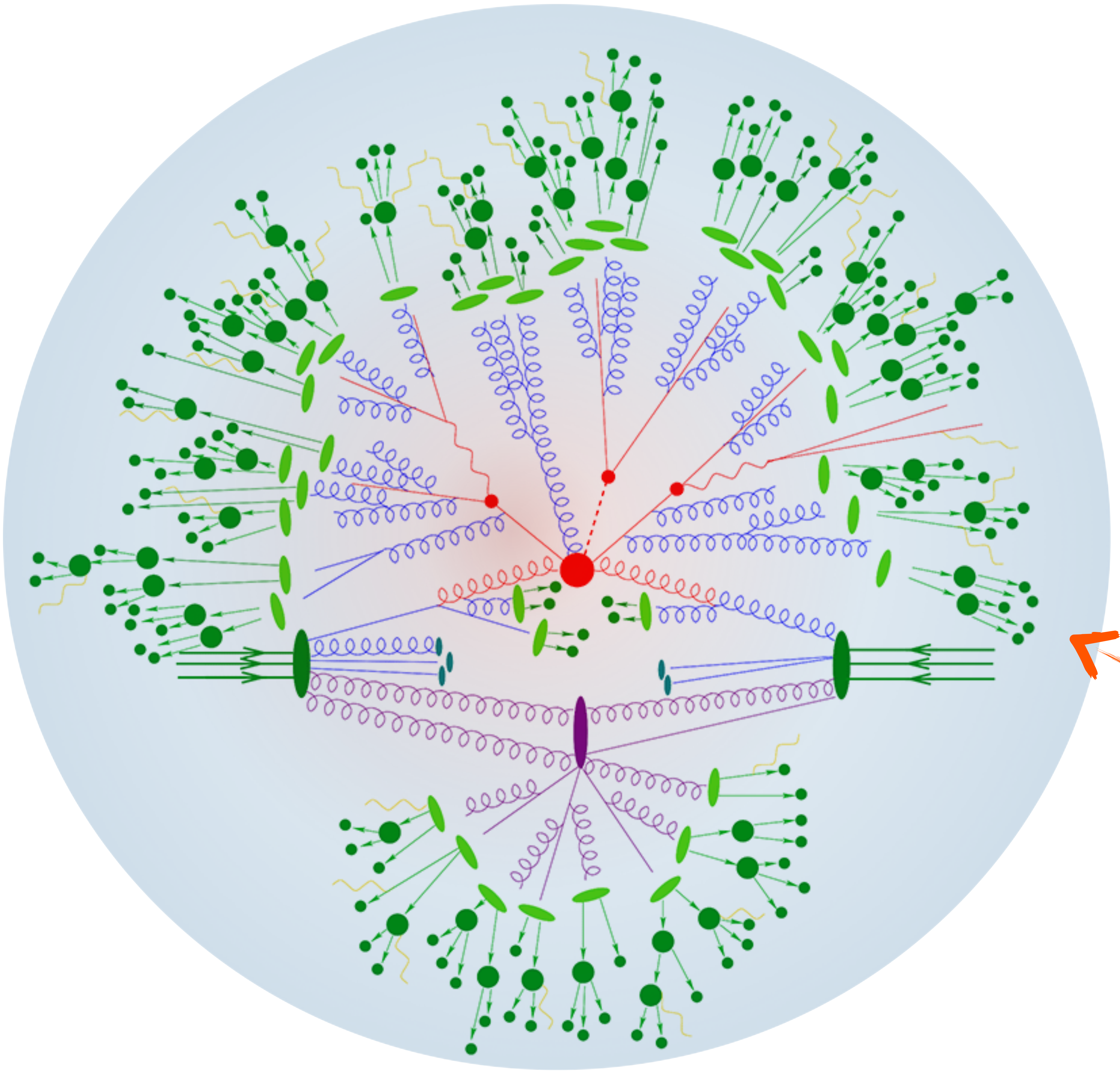
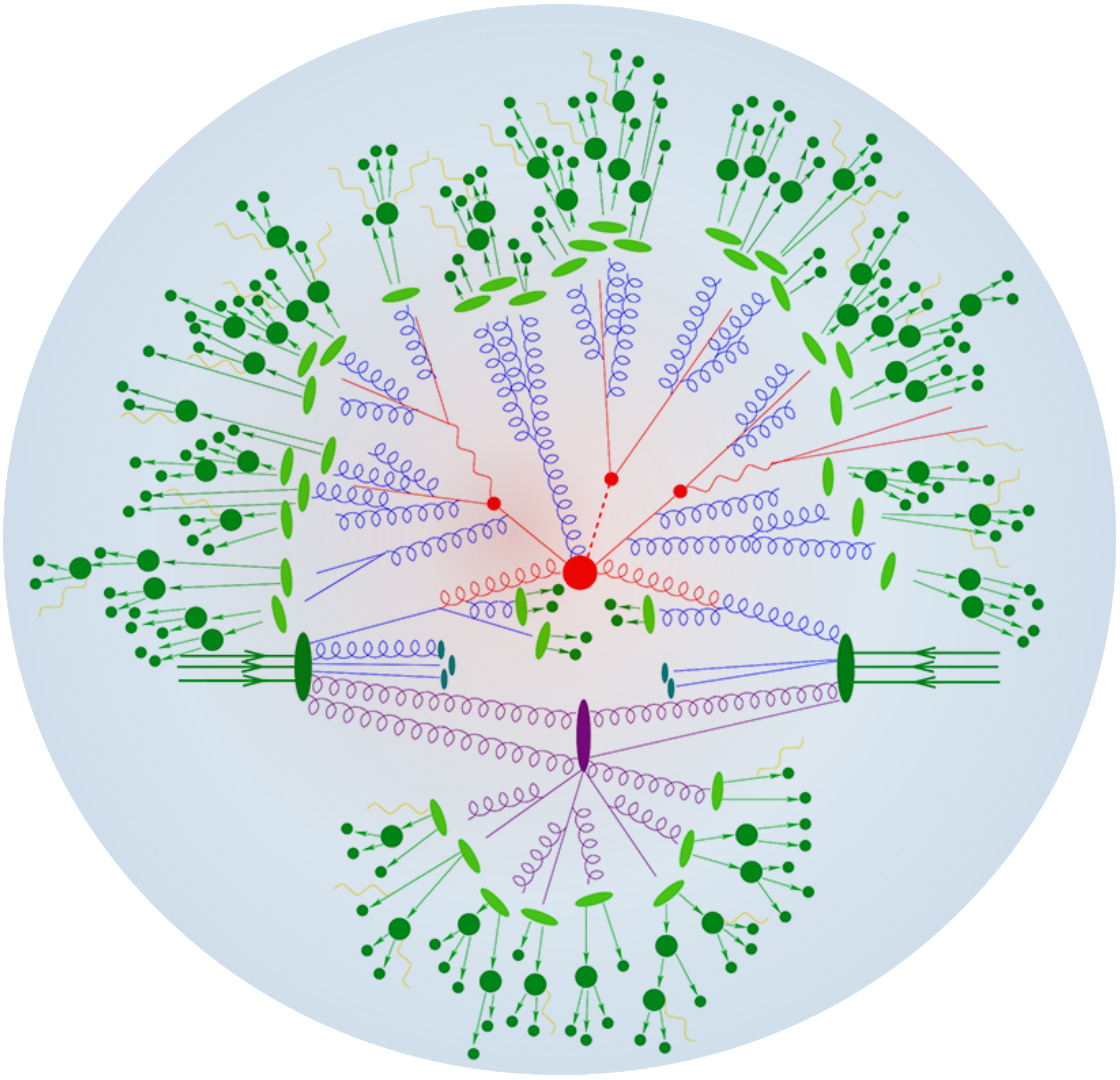


- Short distance (hard)
  - scales probed: $O(10^2)$-$O(10^3)$ GeV
  - stage sensitive to New Physics

evolution (radiation) towards observable state

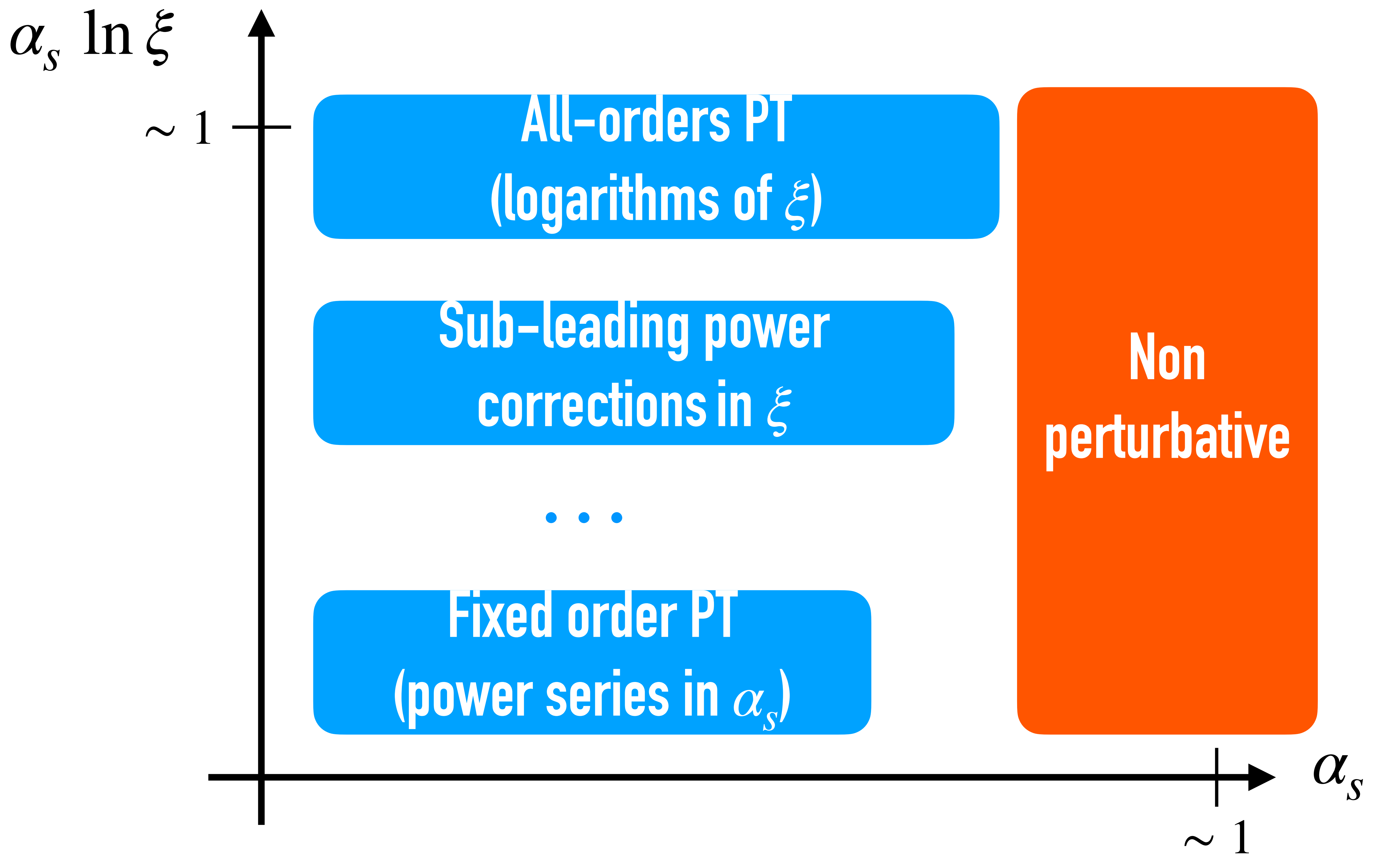
- Long distance (soft)
  - transition from $O(10^2)$-$O(10^3)$ GeV to $O(1)$ GeV
  - Initial condition for hadronisation (observation)

$$\mathrm{d}\sigma = \sum_{a,b} f_{a/A}(x_a) f_{b/B}(x_b)\, \mathrm{d}\hat{\sigma}_{ab} \left(1 + \mathcal{O}\left(\frac{\Lambda}{Q}\right)^p\right)$$



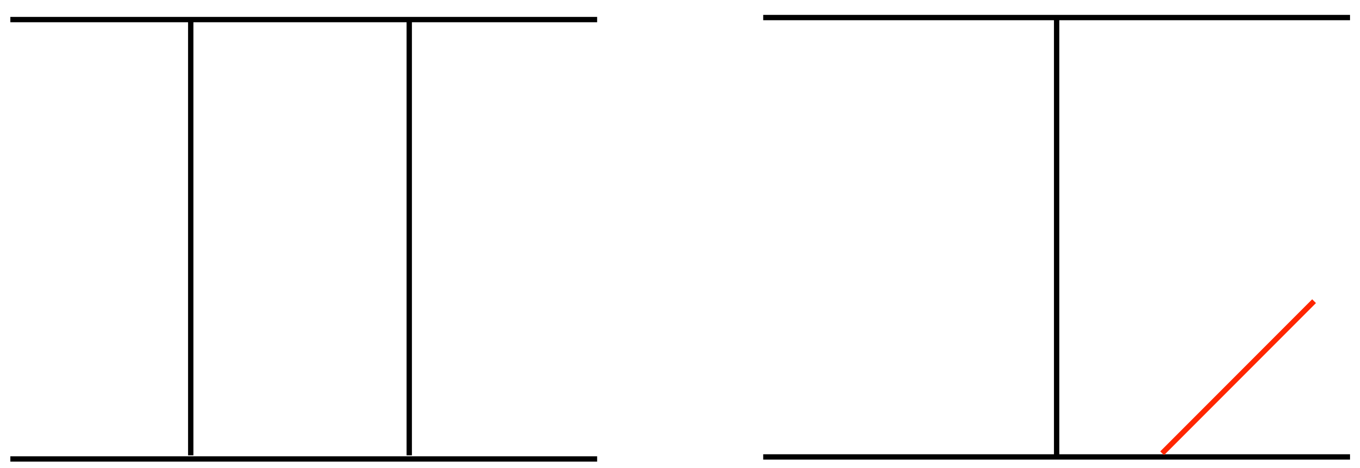
- Perturbation theory: figure of merit is the value of couplings (QCD, EW) and scale ratio(s) ξ (e.g. of external invariants, particle virtualities, …)

e.g. single scale ratio & coupling constant

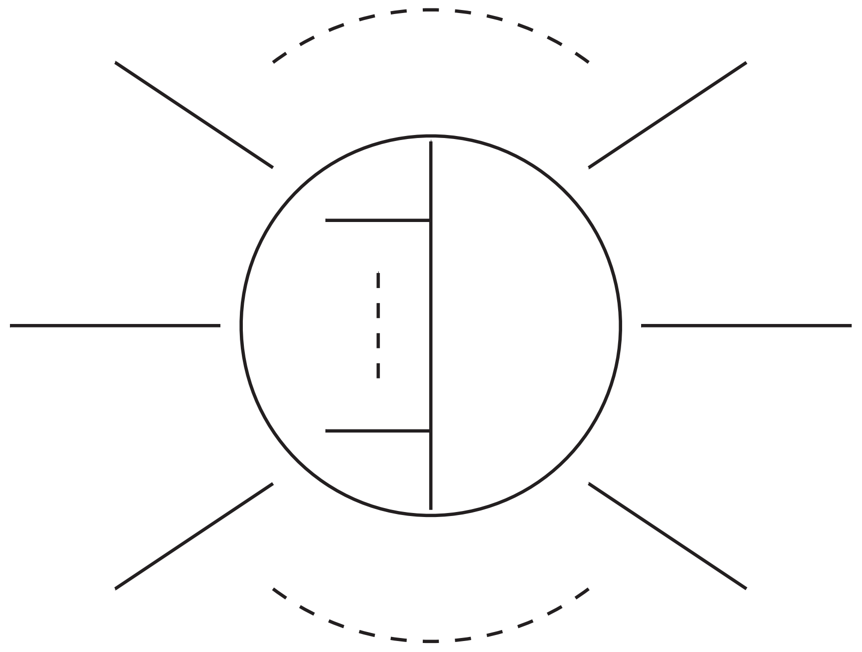


Fixed order perturbation theory

$$d\sigma \sim \int [d\Phi_n] \, |A_{2\to n}|^2$$



- Cancellation of IR singularities at the integrand level
  - subtractions/slicing + numerical integration
  - realistic observables (e.g. cuts, kinematic distributions)



$$\mathcal{I} = \int \prod_{l=1}^{L} \frac{d^D k_l}{(2\pi)^D} \frac{S_1^{b_1} \dots S_m^{b_m}}{D_1^{a_1} \dots D_n^{a_n}}$$

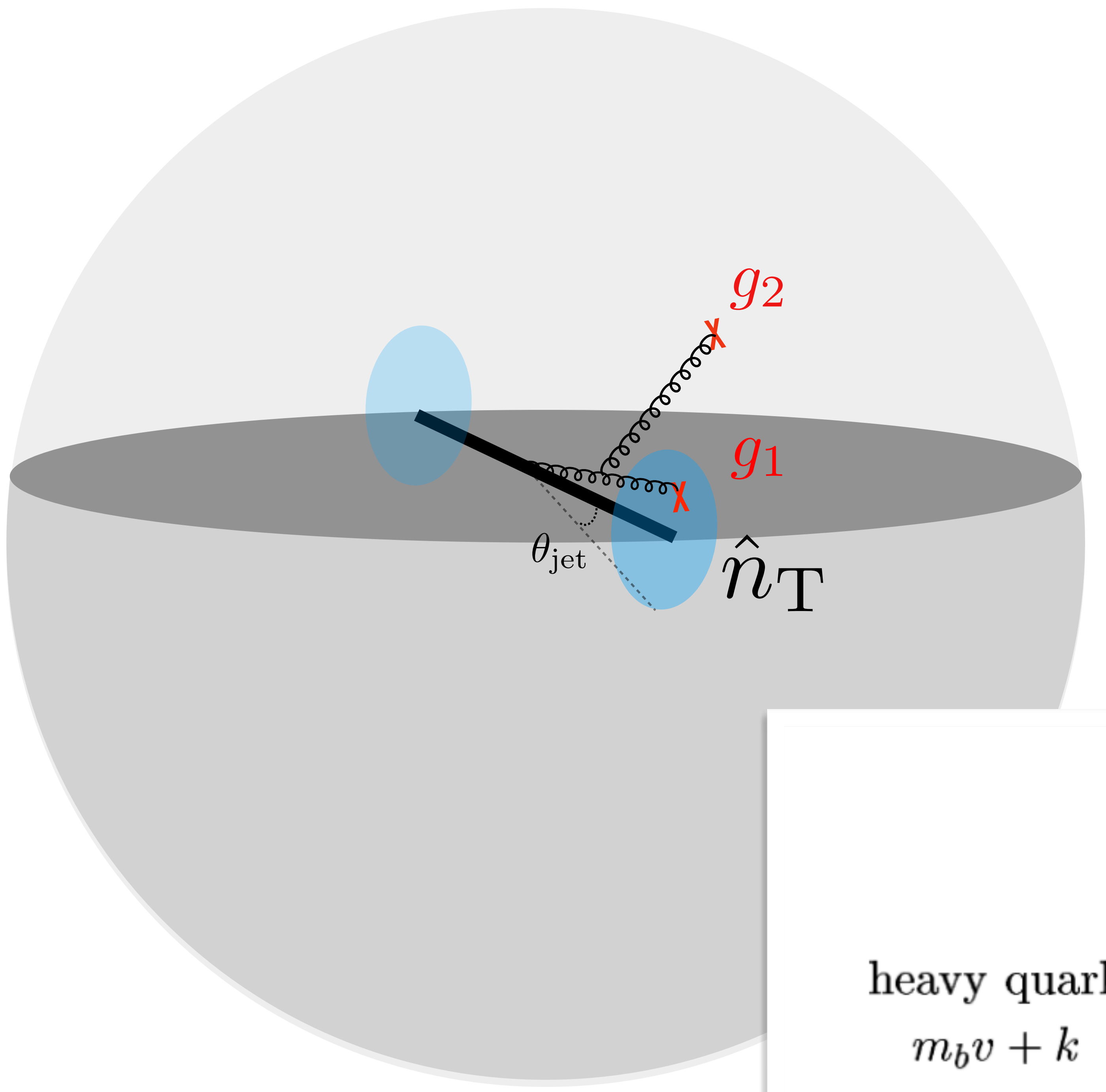
with $S_i \in \{k_i \cdot k_j, \dots, k_i \cdot p_j\}$

$$\sim \quad \mathcal{A} = \epsilon_1^{\mu_1} \cdots \epsilon_n^{\mu_n} \, \bar{v}(q) \, \Gamma_{\mu_1,\dots,\mu_n} \, u(p)$$

- Large expressions (algebraic complexity) & special functions with complicated properties (analytic complexity)
- Study of more formal aspects of structure of scattering amplitudes, e.g. discontinuities, Landau eqs, bootstrap, supersymmetric theories & gravity

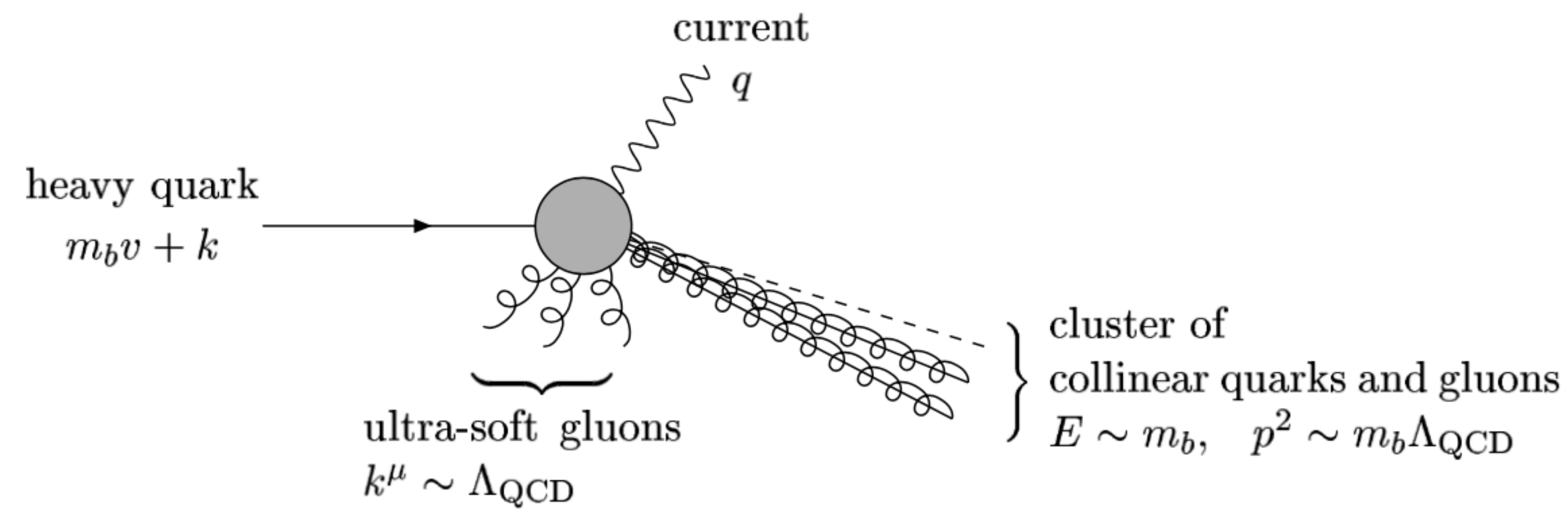
All-order perturbation theory & factorisation

$$Z_{12}[Q;\{u\}] = \Delta_{12}(Q) + \int [dk_a]\bar{\alpha}(k_{ta}) w_{12}^{(0)}(k_a)\,\frac{\Delta_{12}(Q)}{\Delta_{12}(k_{ta})}$$
$$\times Z_{1a}[k_{ta};\{u\}] Z_{a2}[k_{ta};\{u\}] u(k_a)\Theta(Q - k_{ta})$$

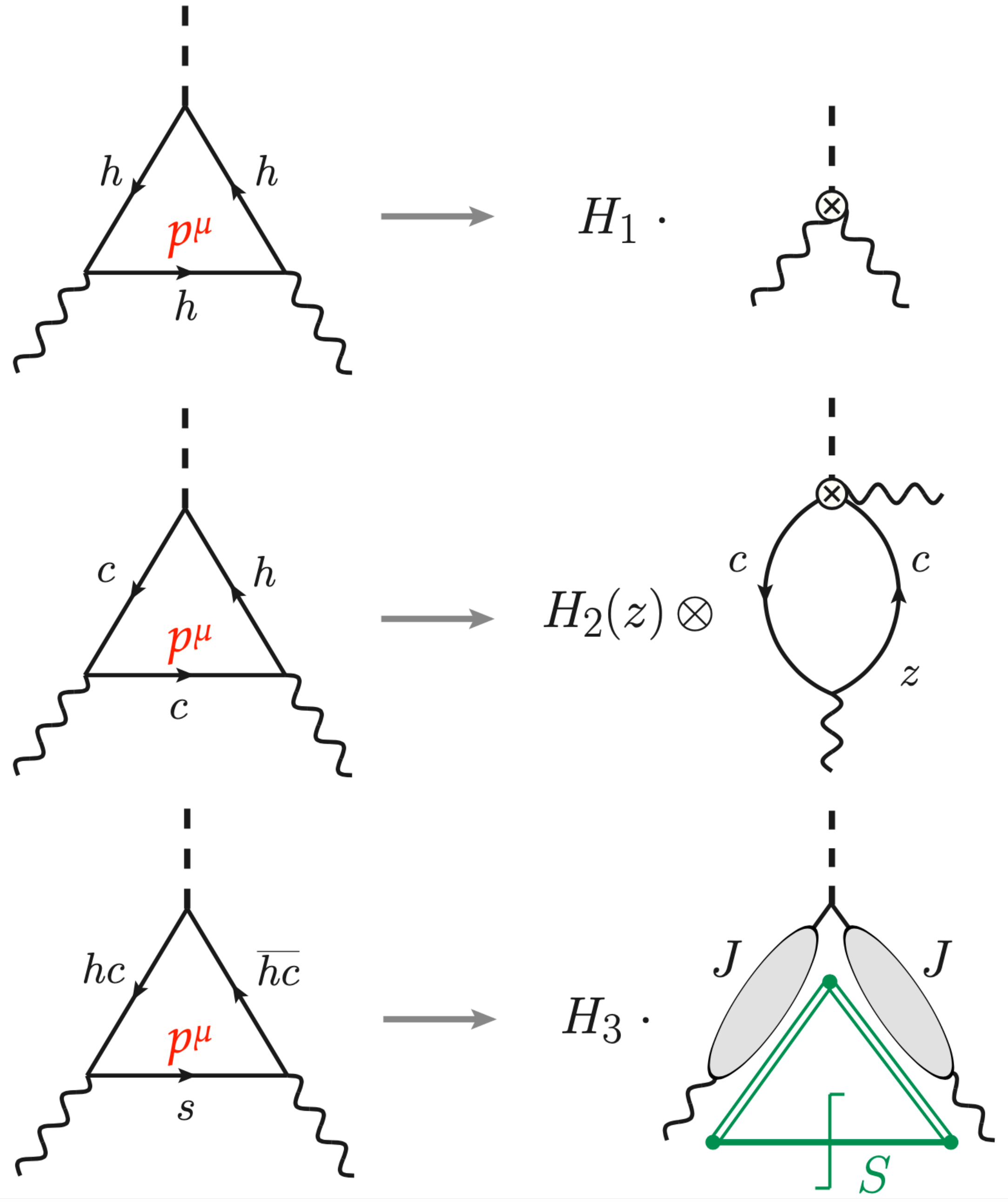


Perturbative solution in regimes with large scale gaps

- Factorisation of amplitudes ⊕ evolution equations: EFTs, generating functionals, numerical methods & Monte Carlo
  - e.g. distribution of soft gluons on celestial sphere; power expansion of amplitudes w.r.t. invariants; kinematic distributions near singular limits, HQ decays, …



$$\mathscr{L}_{\rm QCD} = \mathscr{L}_{\rm SCET}^{\rm (LP)} + \mathcal{O}(\lambda)$$



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Future colliders

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perturbative methods

Collider phenomen.

(...)

event generators

novel strategies (e.g. ML, new observables)

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non-perturbative (QCD) corrections

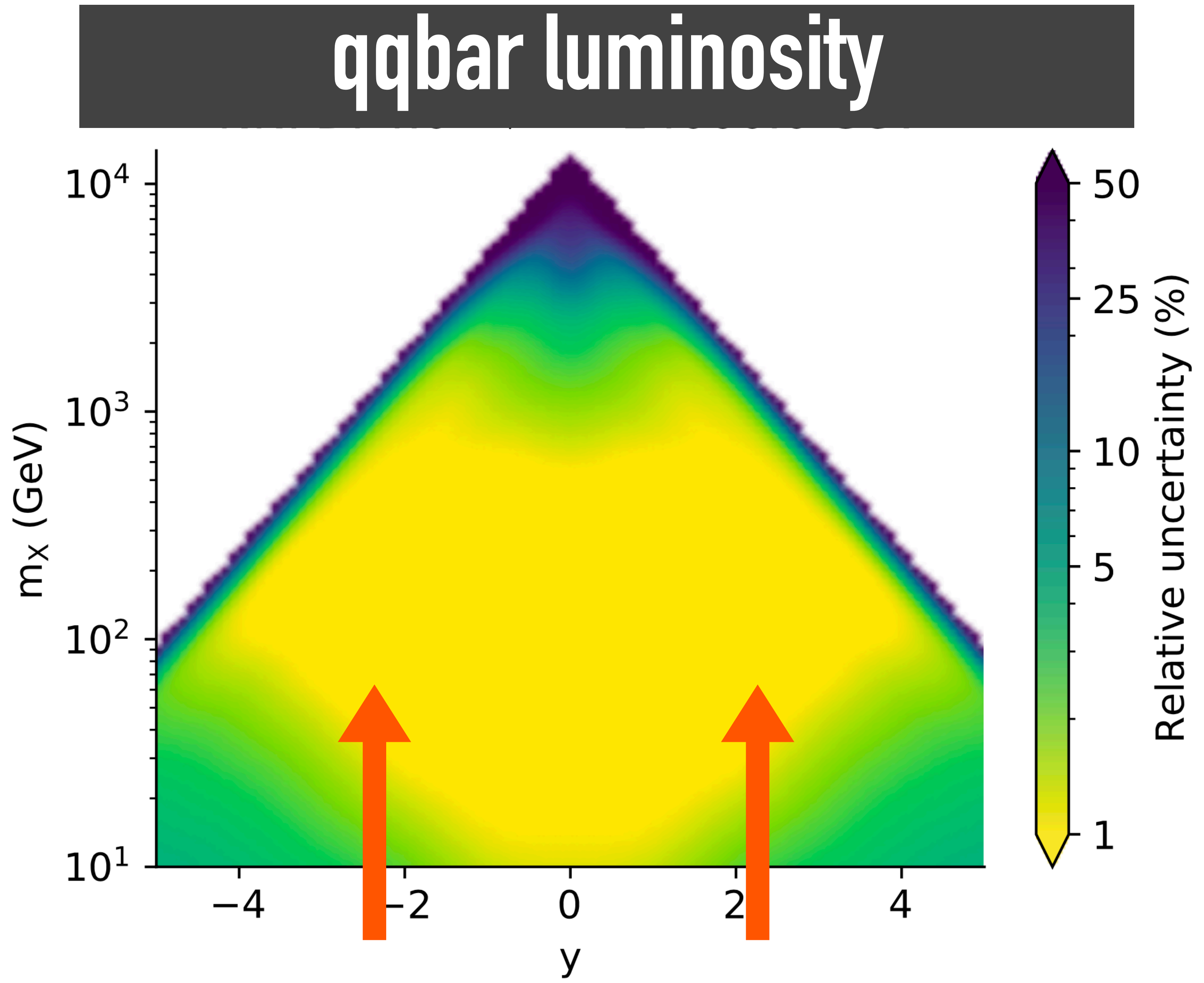
$$\tilde{\alpha}_s(\mu^2) \equiv \tilde{\alpha}_s(0) + \int_0^\infty \mathrm{d}m^2 \frac{\mu^2}{m^2+\mu^2} \frac{\mathrm{d}\alpha_{\mathrm{eff}}(m^2)}{\mathrm{d}m^2}$$

Non-perturbative dynamics & higher twist corrections

$$d\sigma = \sum_{a,b} f_{a/A}(x_a) f_{b/B}(x_b)\, d\hat{\sigma}_{ab} \left(1 + \mathcal{O}\left(\left(\frac{\Lambda}{Q}\right)^p\right)\right)$$

Parton densities (PDFs):

- Extracted from data at low (NP) scales
- Accuracy now approaching % level; some caveats (e.g. theory uncertainties, fit methods)



Higher-twist corrections ($\Lambda \sim 1$ GeV):

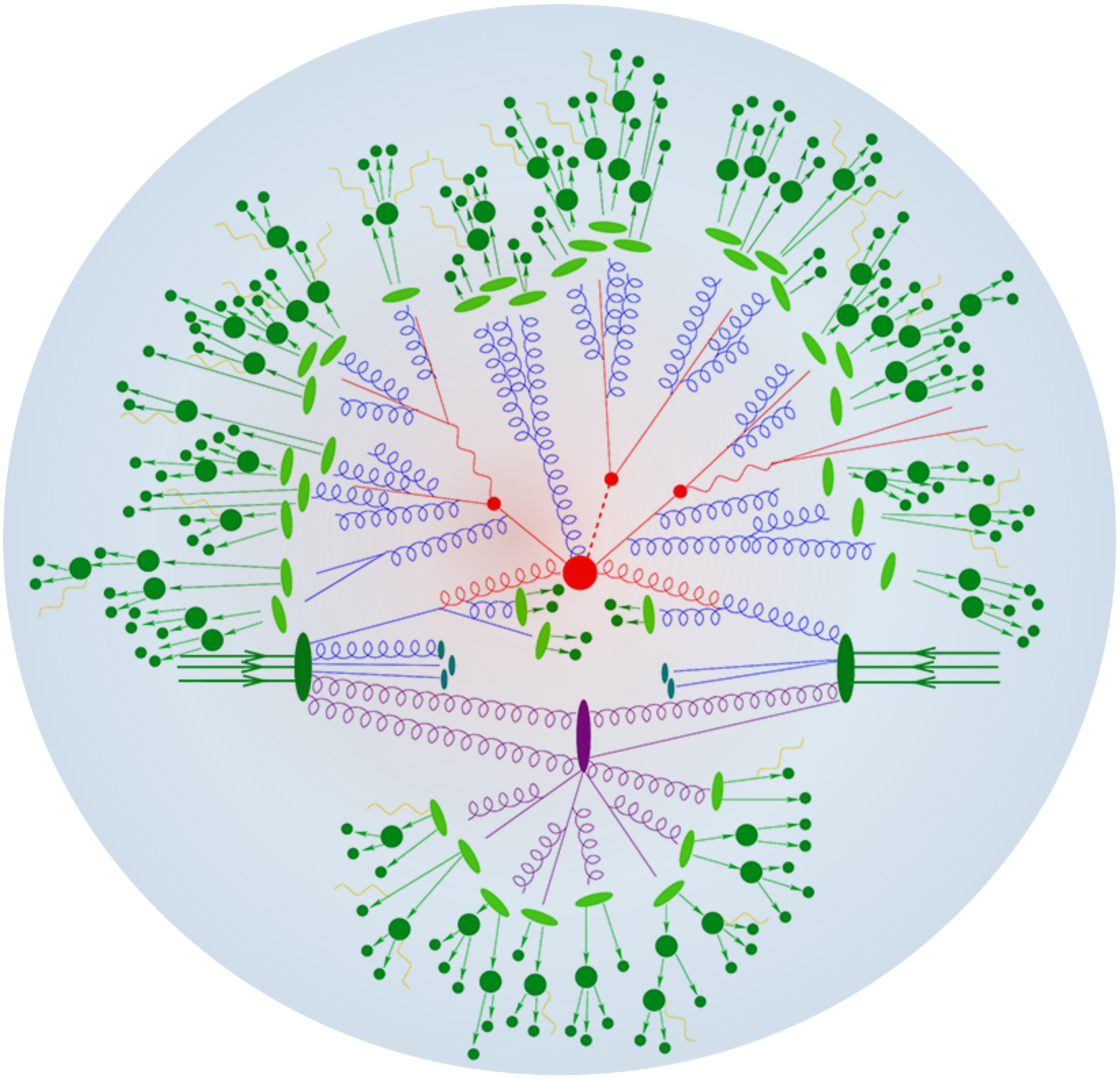
- Power p depends on observable (e.g. p=2 for inclusive p_T distributions, p=1 for jets)

  ➡ if Q~100 GeV: $\frac{\Lambda}{Q} \sim \mathcal{O}(1\%)\,,\ \left(\frac{\Lambda}{Q}\right)^2 \sim \mathcal{O}(0.1\%)$

- Partially accessible with perturbative techniques (e.g. IR renormalons, multi-parton scattering)
- Otherwise non-perturbative physics (e.g. hadronisation, intrinsic partonic k_t)

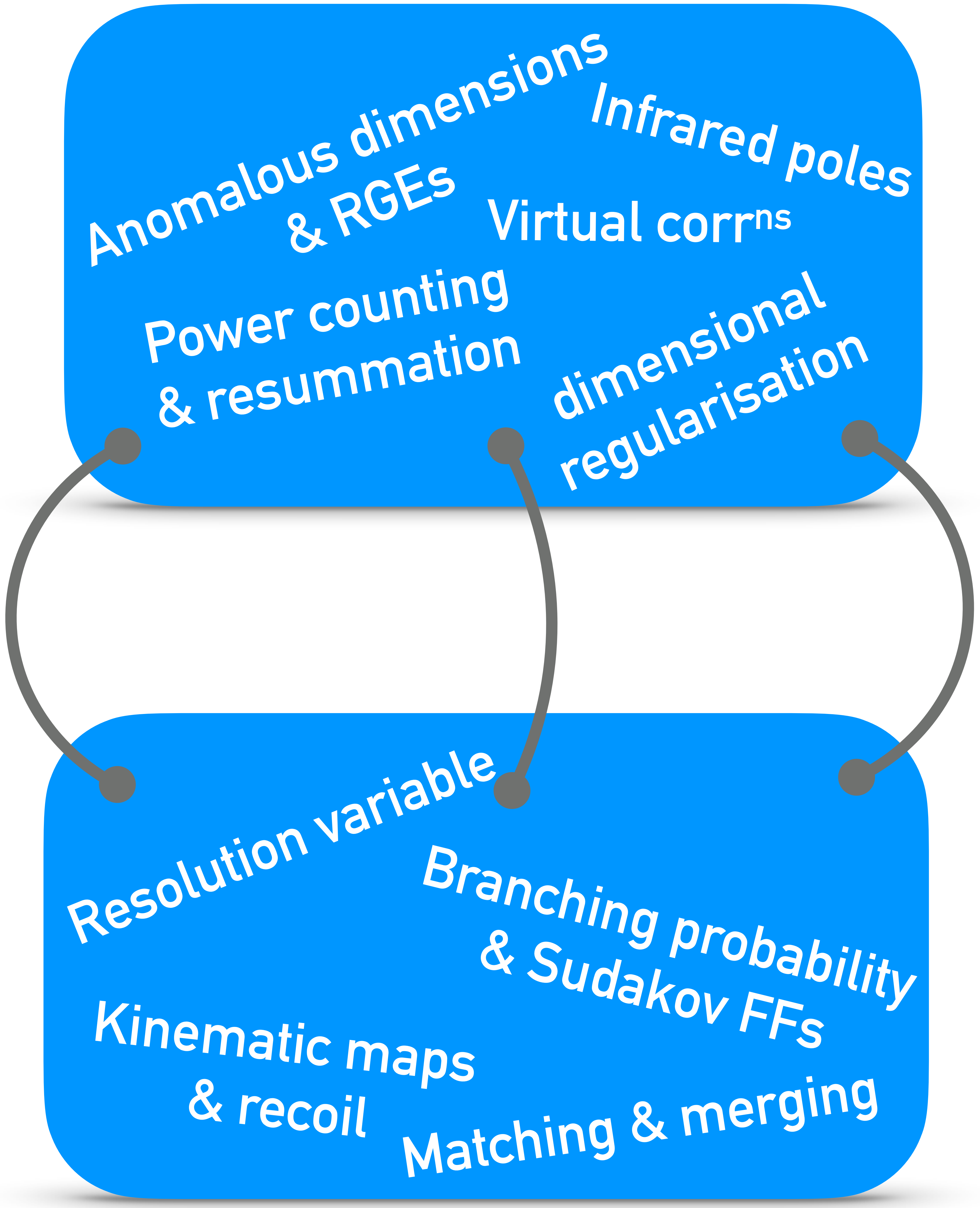
The collider physics landscape

Event generators simulate all stages of the event formation

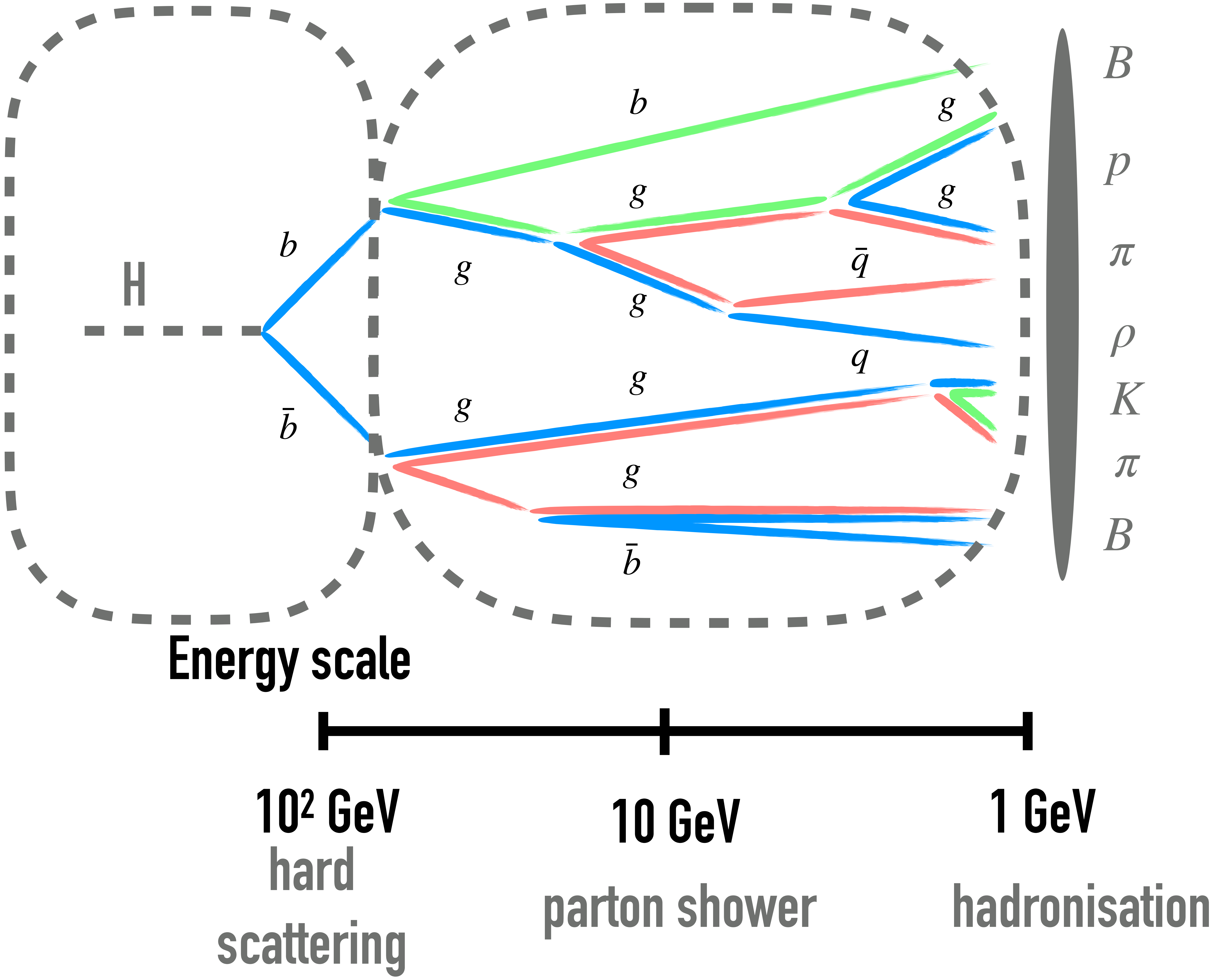


- Not a standard theory calculation:
  - ➡ simulate events, i.e. particle momenta with a physical probability distribution
  - ➡ allow the computation of many (any) observables at once, as opposed to a few in perturbative calculations
  - ➡ deeply different mathematical formulation, difficult to exploit state of the art QFT technology
- Crucial pillar of modern collider physics, e.g. full simulation of experimental analysis, phase-space extrapolation, training of tools (e.g. Machine Learning)

Monte Carlo generators & perturbative accuracy



e.g. H→bb decay



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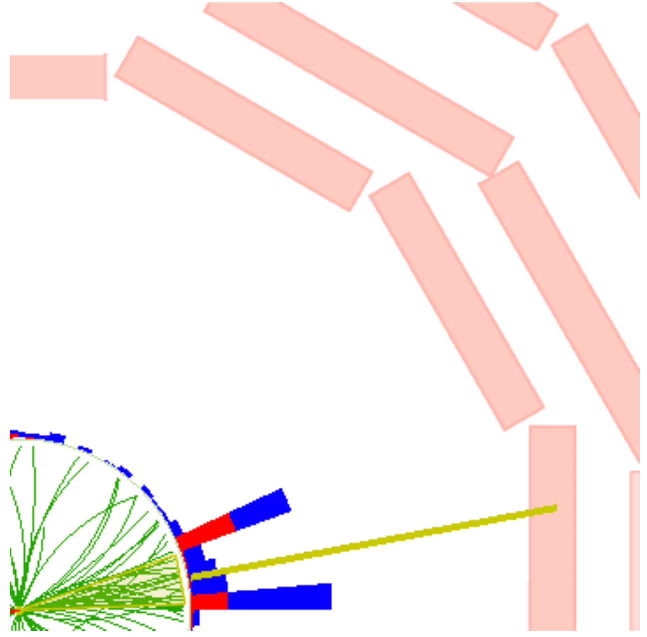
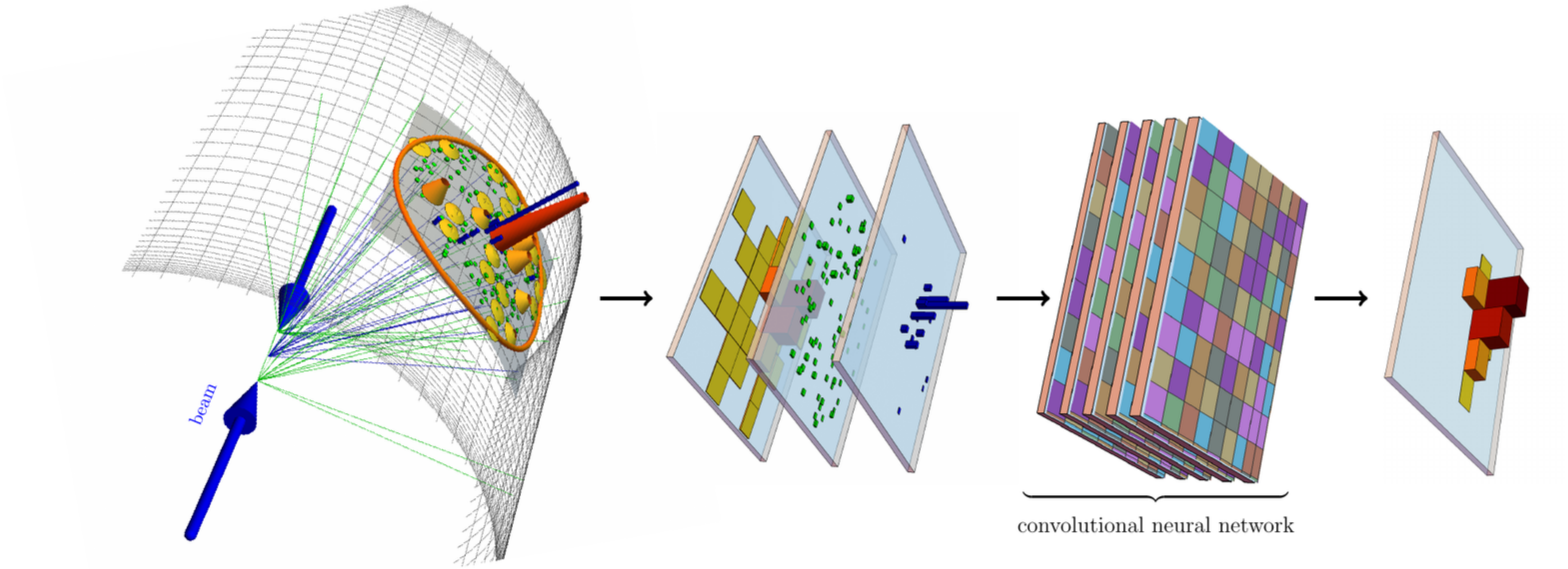
$$\tilde{\alpha}_s(\mu^2) \equiv \tilde{\alpha}_s(0) + \int_0^\infty dm^2 \frac{\mu^2}{m^2+\mu^2} \frac{d\alpha_{\text{eff}}(m^2)}{dm^2}$$

Future colliders

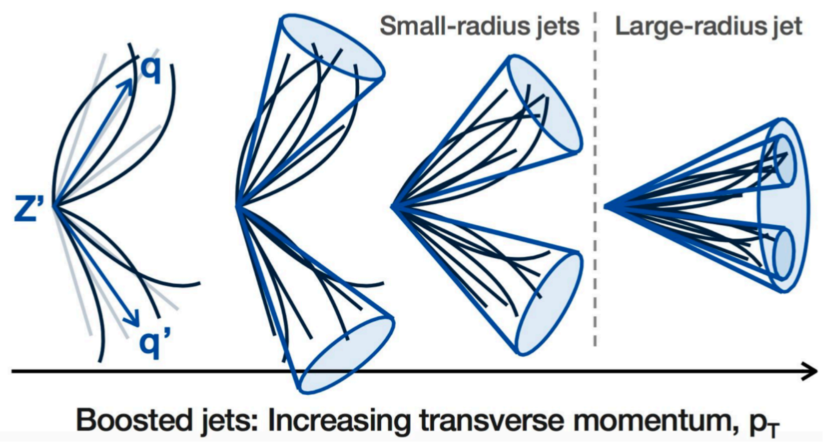


Collider phenomen.

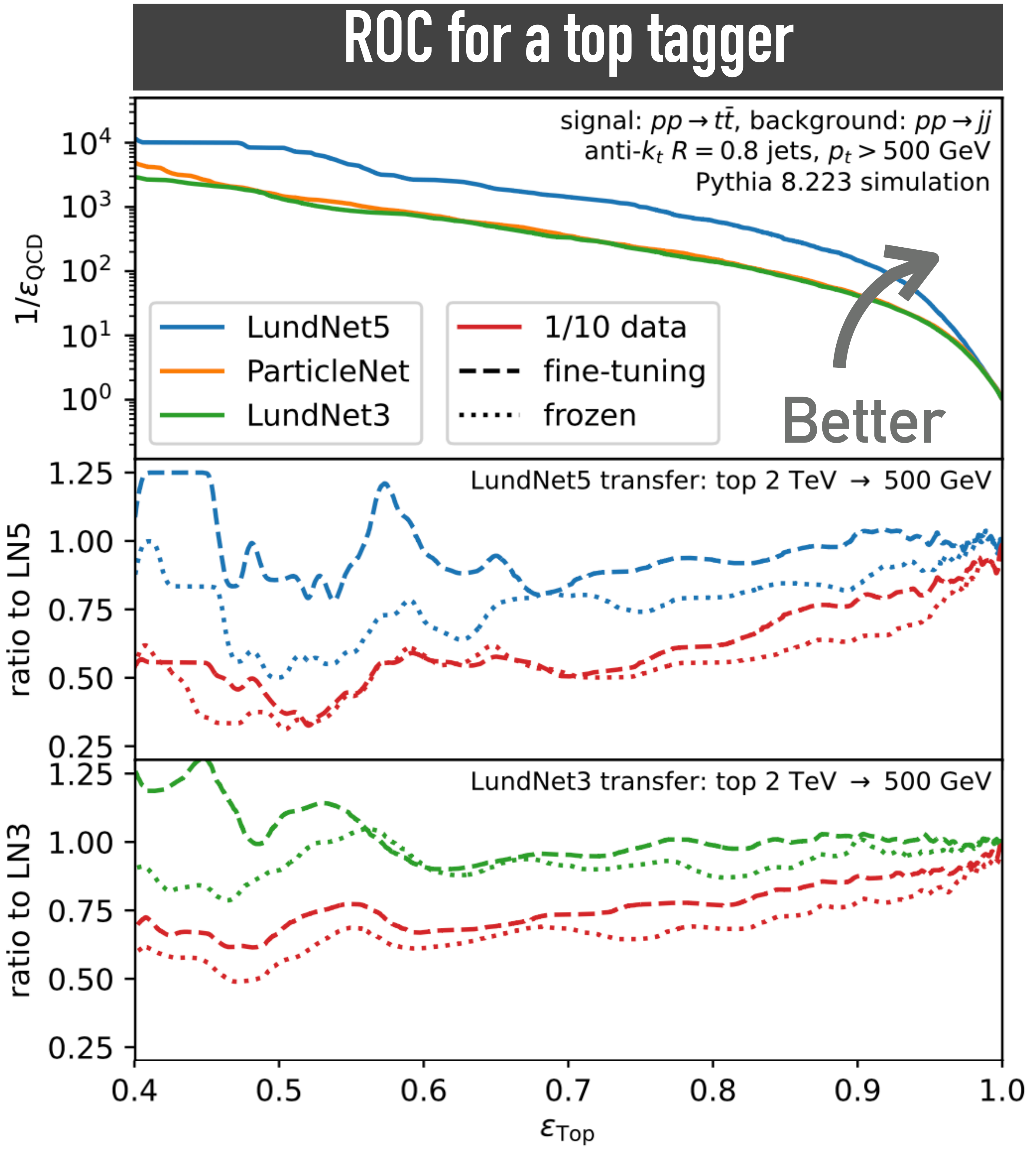
novel strategies (e.g. ML, new observables)

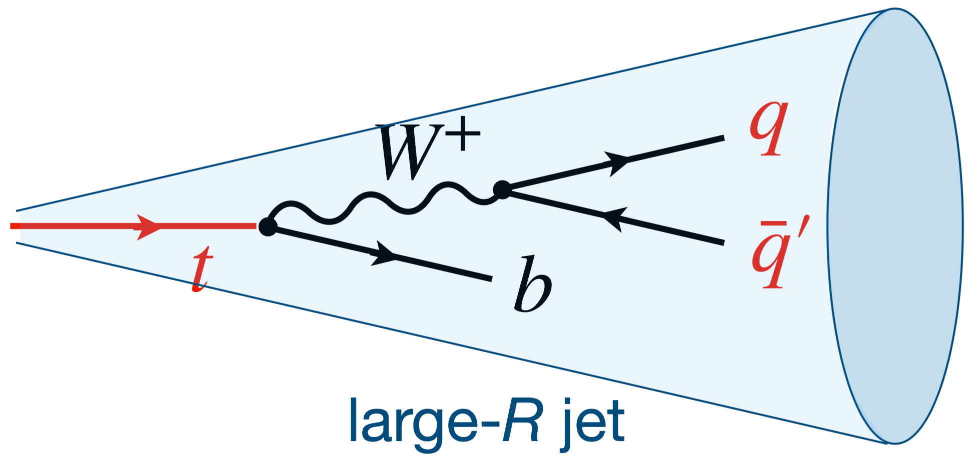


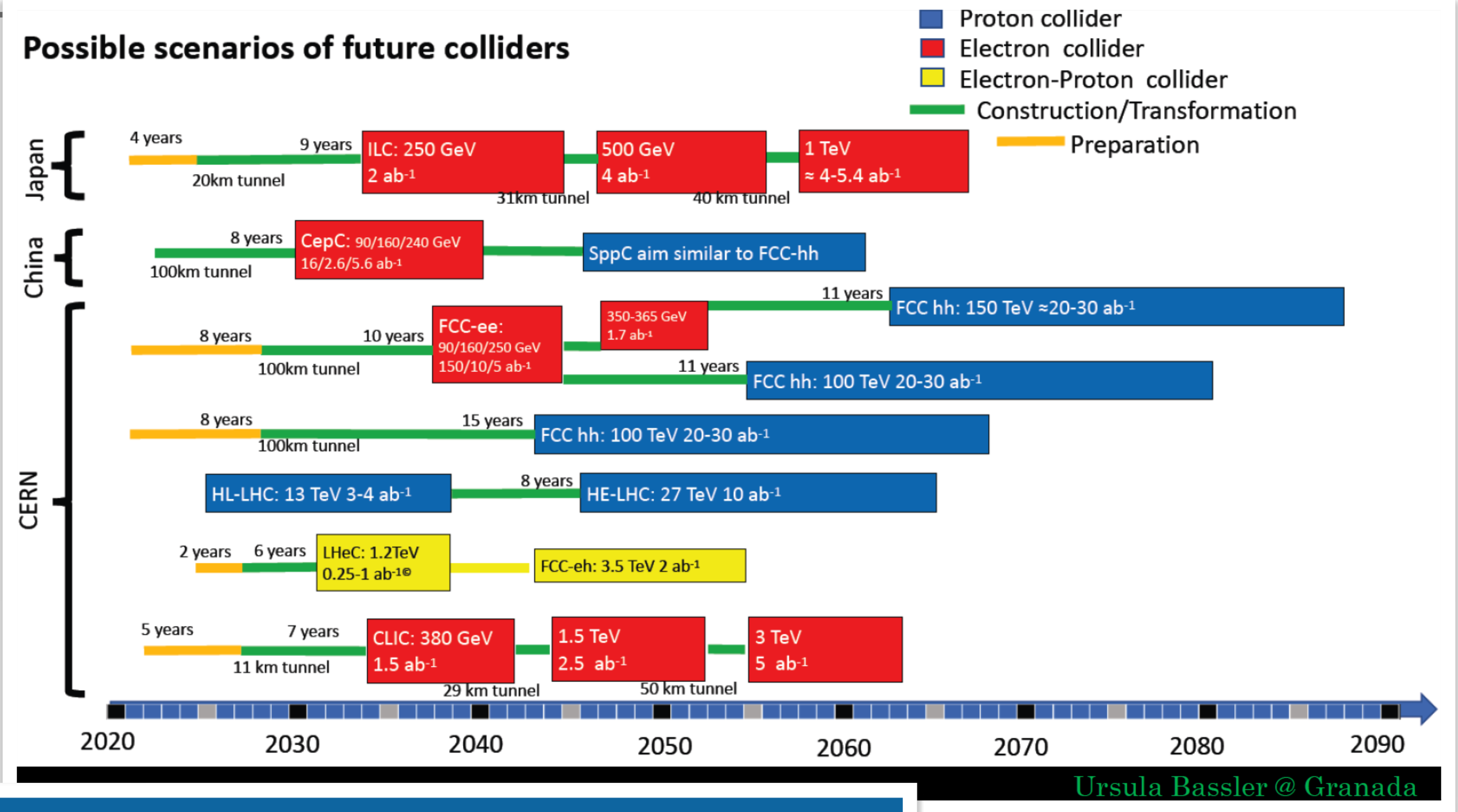
BSM searches & jets



Phenomenology at present & future colliders







Precision calculations for future e+e− colliders: targets and tools

7–17 Jun 2022
CERN
Europe/Zurich timezone

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- Programme Committee
- Timetable
- Application Form
- Participant List
- Health insurance and visa
- Accommodation
- Directions to and inside CERN
- Computing access

Programme Committee

Samuel Abreu
Juan Alcaraz
Juliette Alimena
Patrizia Azzi
David D'Enterria
Ayres Freitas
Gudrun Heinrich
Alex Huss
Michelangelo Mangano
Matthew McCullough
Pier Monni
Johann Usovitsch
Marcel Vos

About myself

- LD Staff since 2019
- Current duties: CERN ECFA representative
- Involvement in FCC WG (QCD convener) & Higgs cross section WG (marginal at the moment)
- Interests: perturbative methods/computations, event generators, collider phenomenology

An example: a quasi-pure route to multiple scatterings

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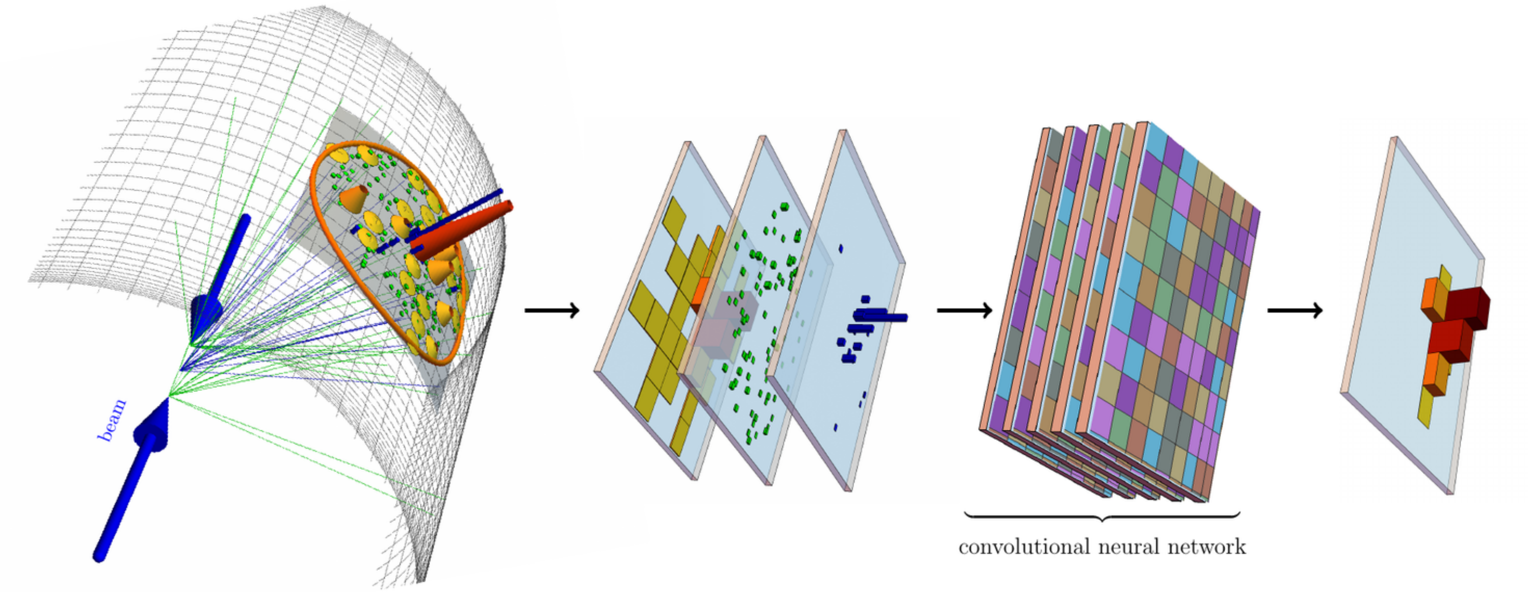

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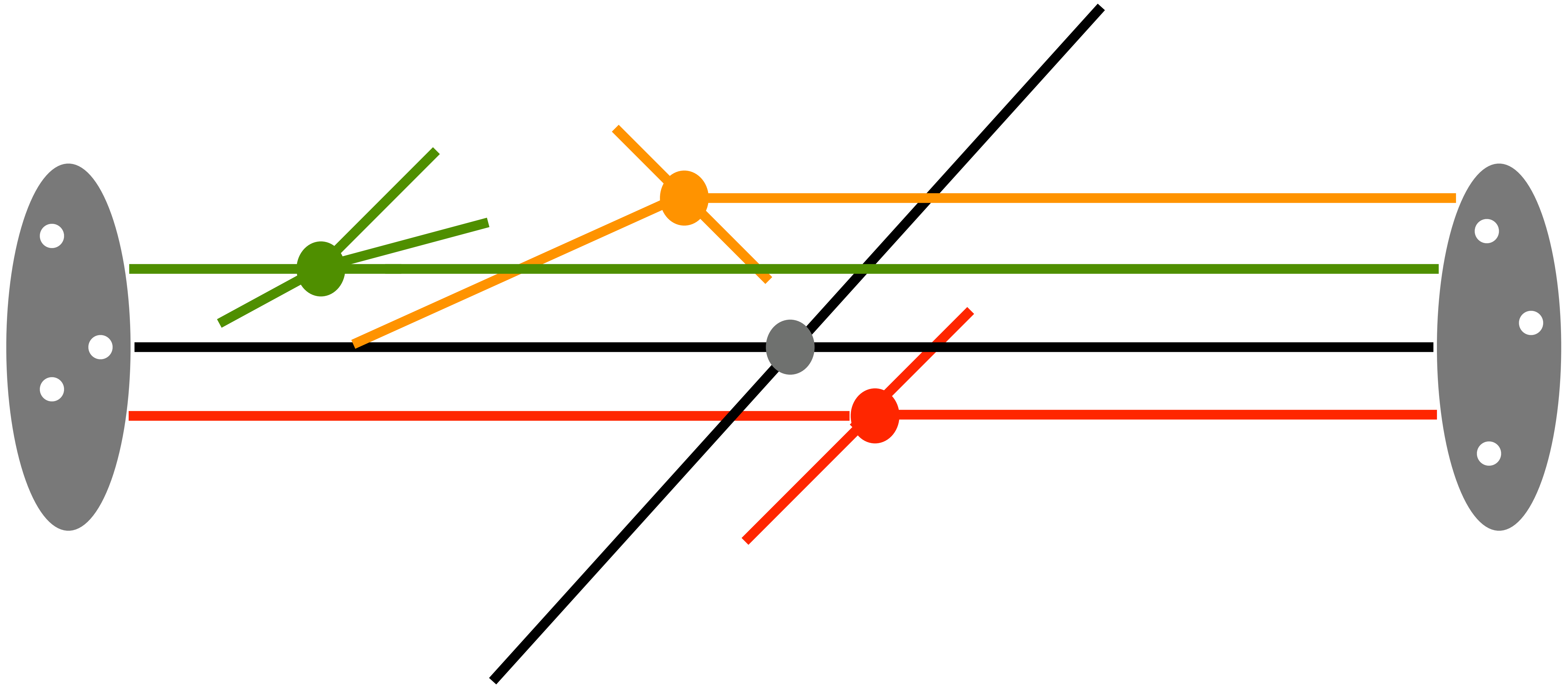
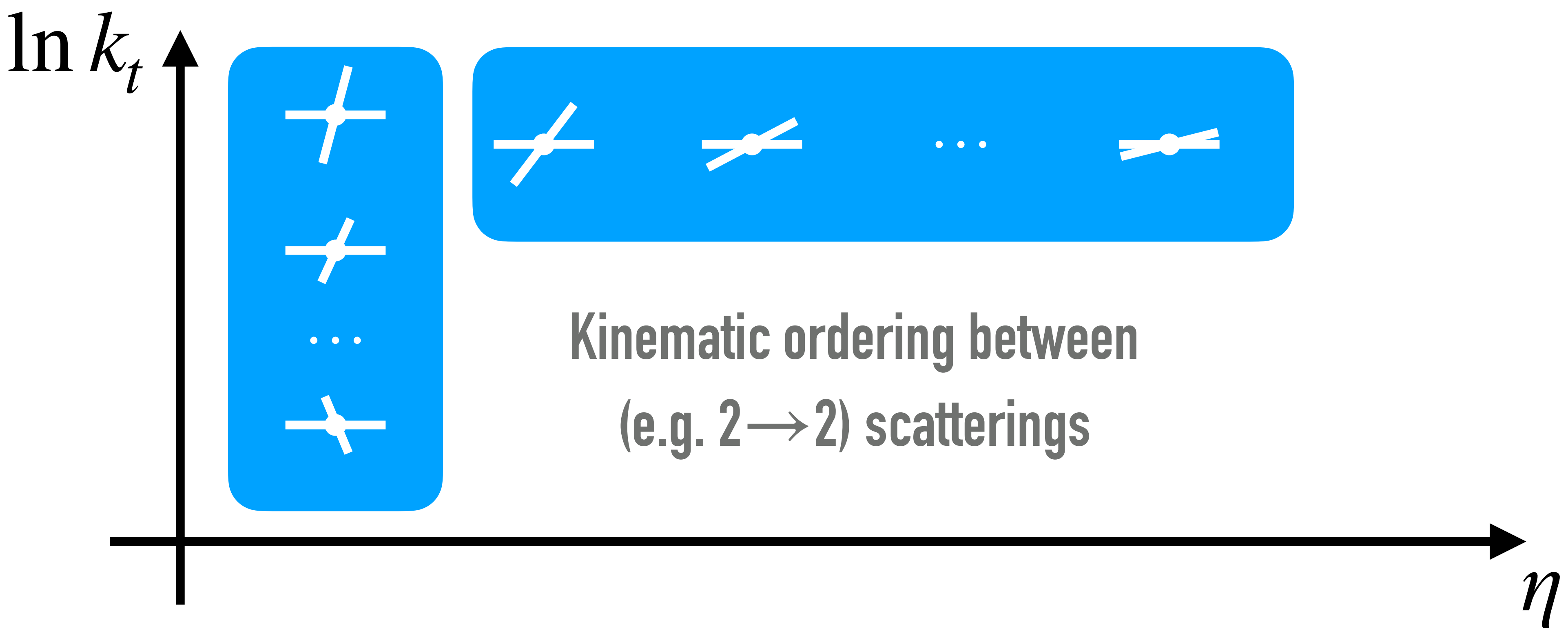
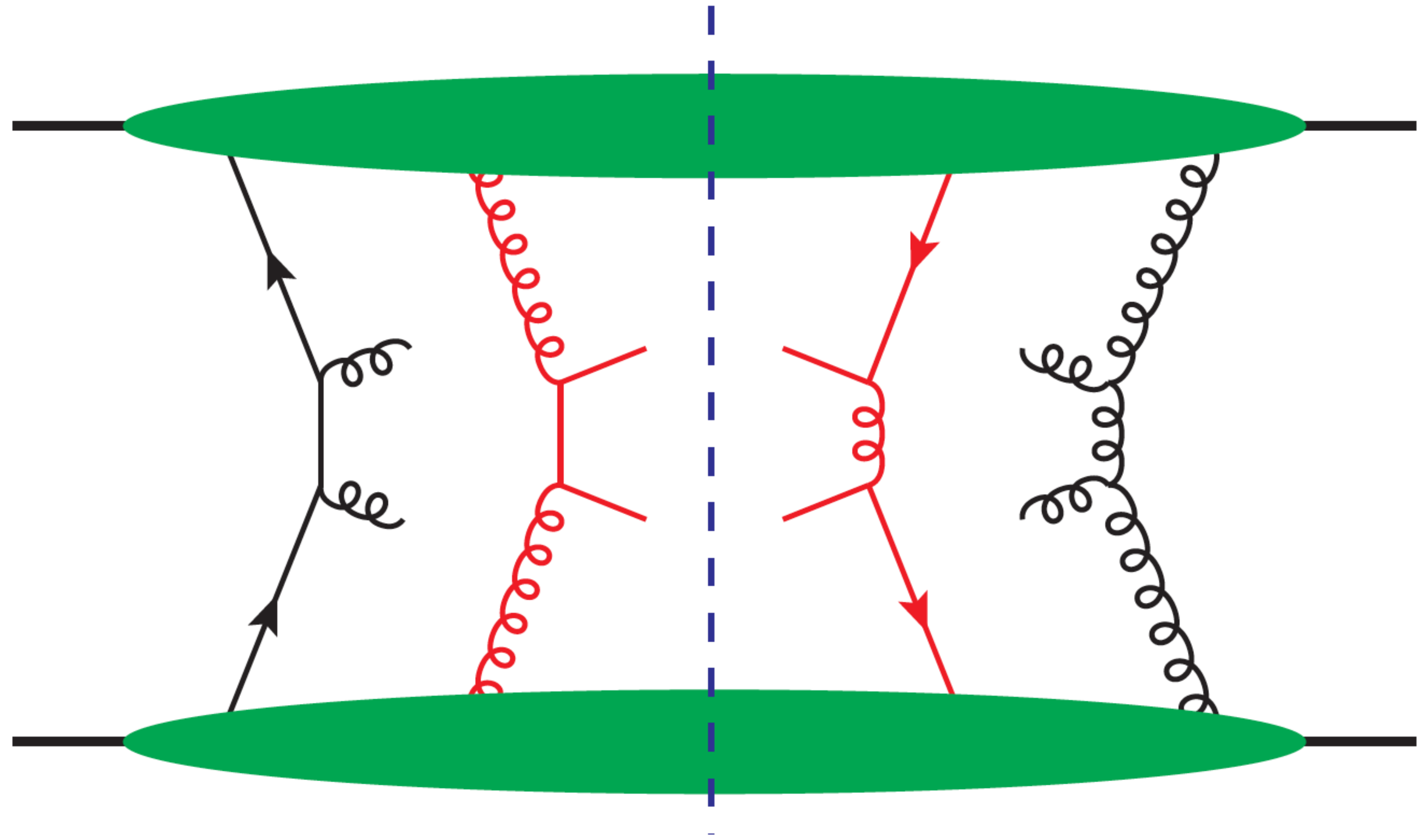
$$d\sigma = \sum_{a,b} f_{a/A}(x_a) f_{b/B}(x_b)\, d\hat{\sigma}_{ab} \left(1 + \mathcal{O}\left(\frac{\Lambda}{Q}\right)^p\right)$$

with J. Andersen, L. Rottoli, A. Soto Ontoso, G. Salam (in preparation)



- Open questions: composition of MPIs?
  - Average transverse momentum? Correlators? Impact parameter dependence?
  - Separation between subsequent scatterings?





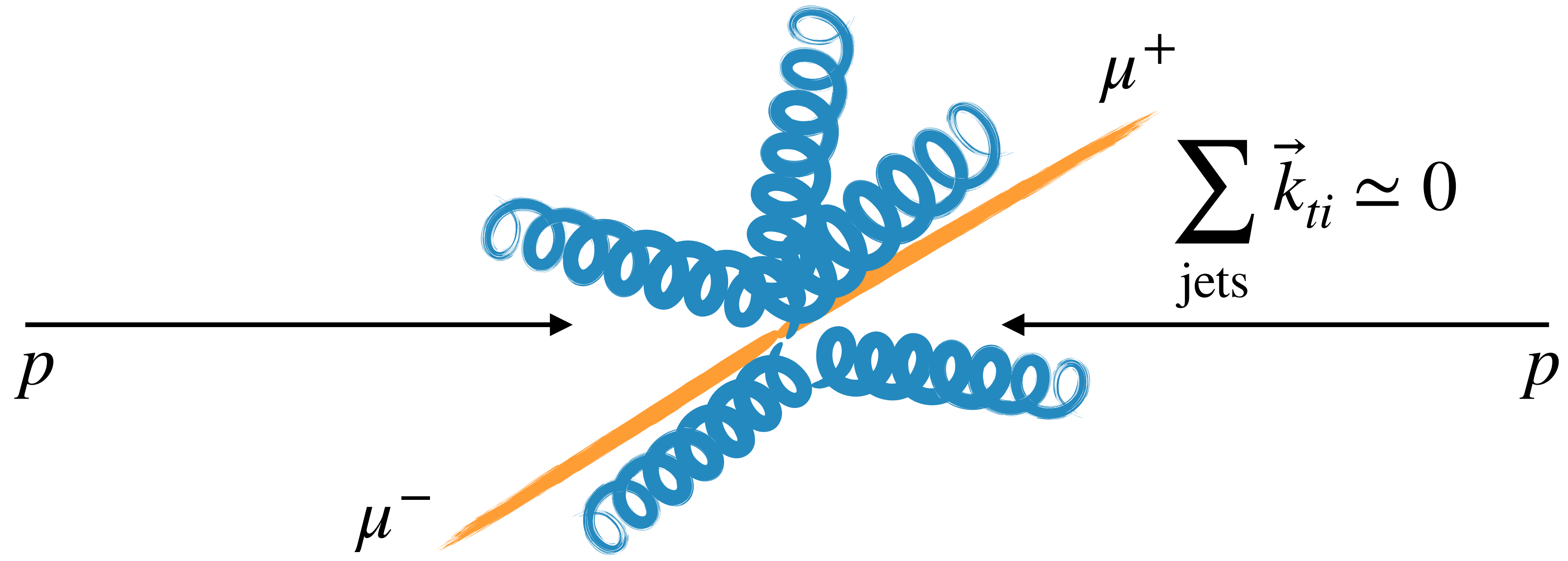
  - Testing of QFT formulations (higher twist expansion, mainly DPS)

Tone down the primary scattering using Drell-Yan events

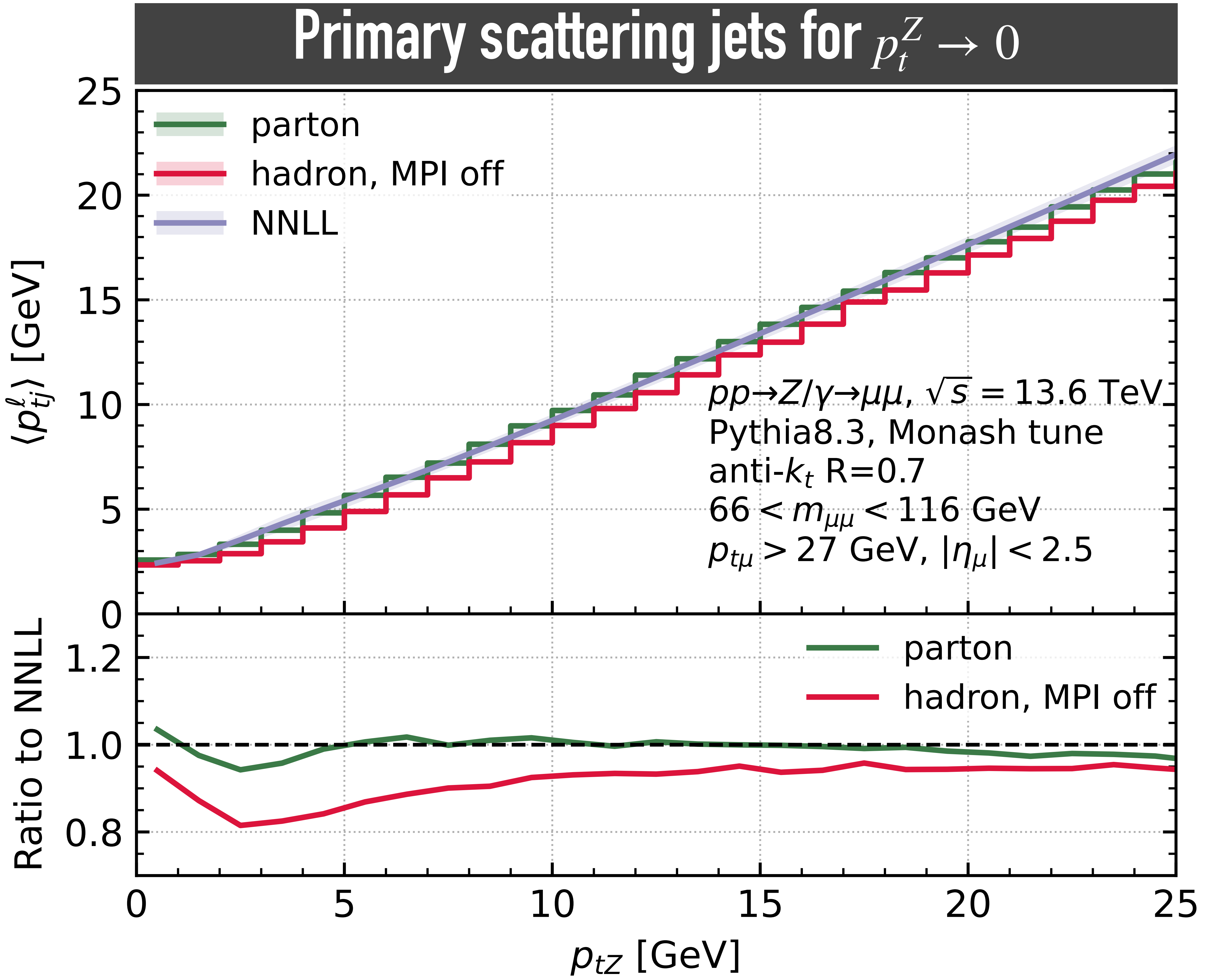
- Hard to disentangle neatly primary and secondary scatterings: usually very exclusive observables, hard to reach solid TH control

- New route:
  - measure DY events & require $p_t^Z \to 0$
  - Dynamics of recoiling (~soft) jets can be robustly described within perturbation theory

$$< p_{tj}^{\ell} > \sim \Lambda \left(\frac{m_{\mu\mu}}{\Lambda} \right)^{\eta}, \quad \eta > 0$$



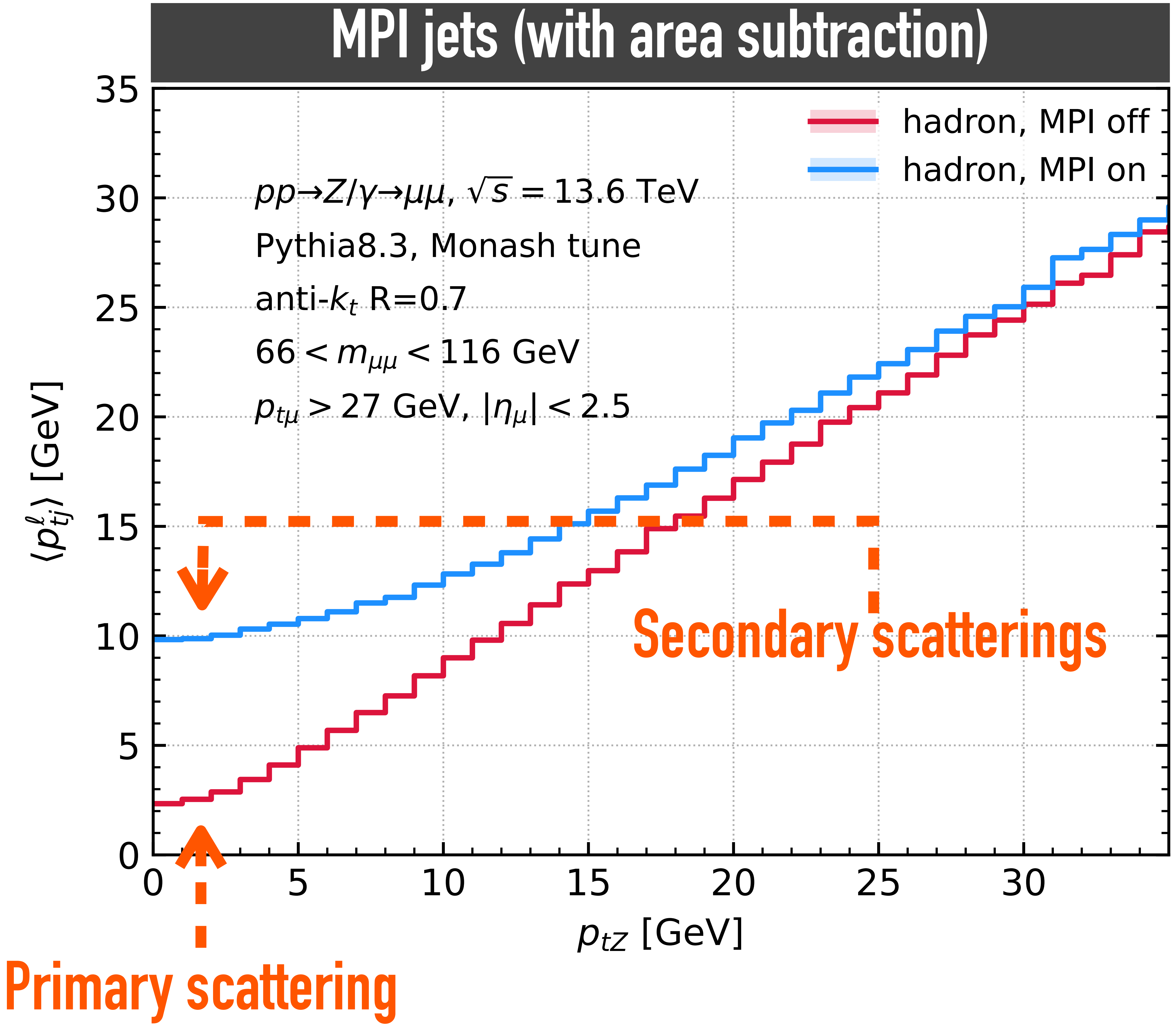
Many thanks to Alba for the plots



Tone down the primary scattering using Drell-Yan events

- Primary scattering is now a (mild) background to MPI, and known with high TH precision
- Use the quasi-pure MPI sample to answer questions about composition of Underlying Event (e.g. azimuthal correlations, jet spectrum, rapidity separations, ...)
- Synergy of advances in TH (e.g. multi-differential resummations) and EXP (e.g. good resolution of track jets at small p_T)

Many thanks to Alba for the plots



Outlook

- Large and dynamical group covering main TH areas of collider physics.
- Constant interactions with CERN EP community and involvement in Working Groups
- Our weekly activities (if interested, sign up to the e-group!)
  - QCD lunch (Johann): Tuesdays at 12:15pm
  - QCD seminar (Andrew & Ben): Fridays at 2pm
  - Collider Cross Talk (Emanuele): next seminar on November 10th
- Interests overlapping with neighbouring fields in TH:
  - Heavy Ion (jets, event generators), Lattice (strong coupling constant, (q/p)PDFs), BSM (collider phenomenology, EFTs), String/QFT (scattering amplitudes, formal QFT, gravity)