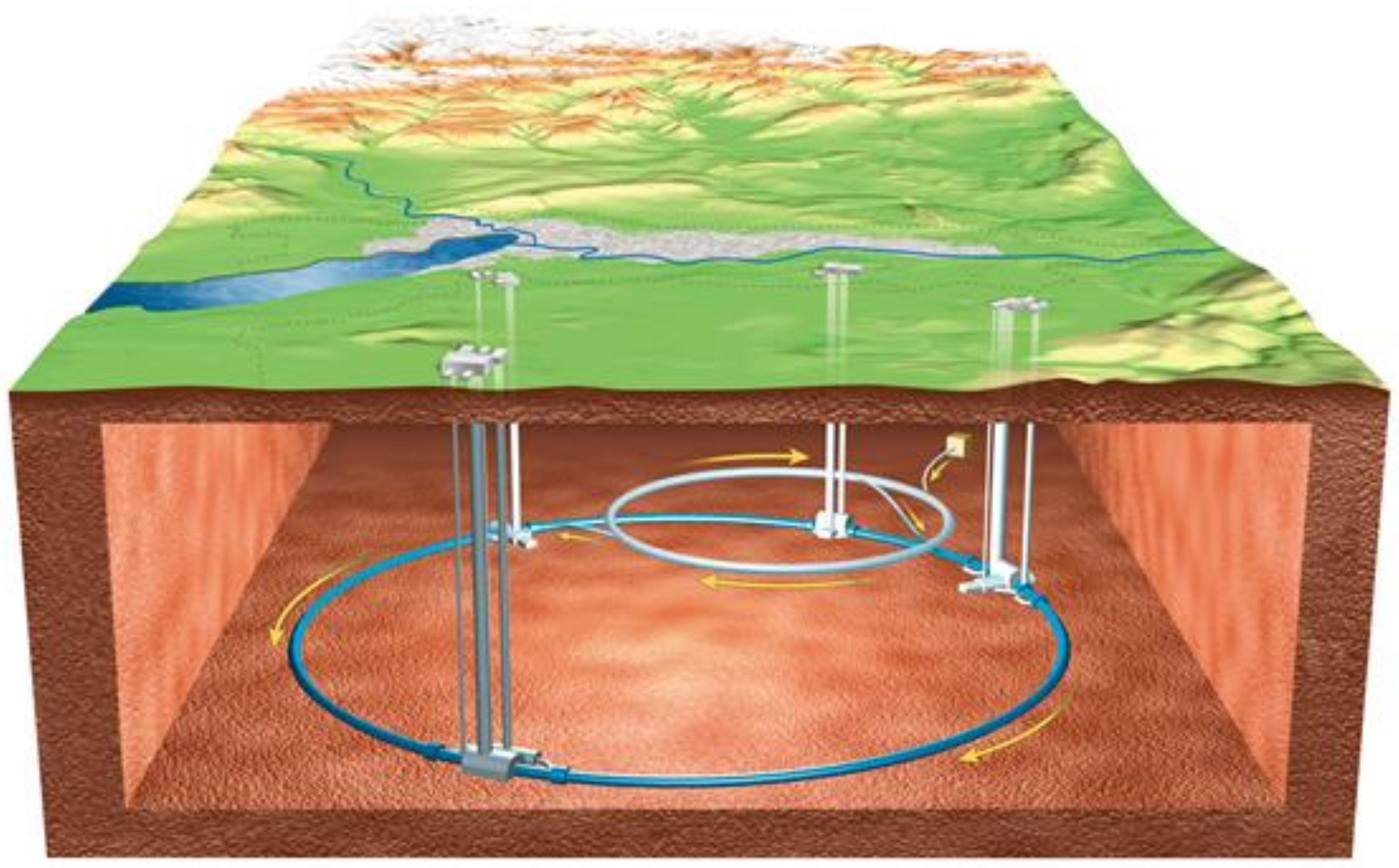
Taming the complex dynamics of scattering events

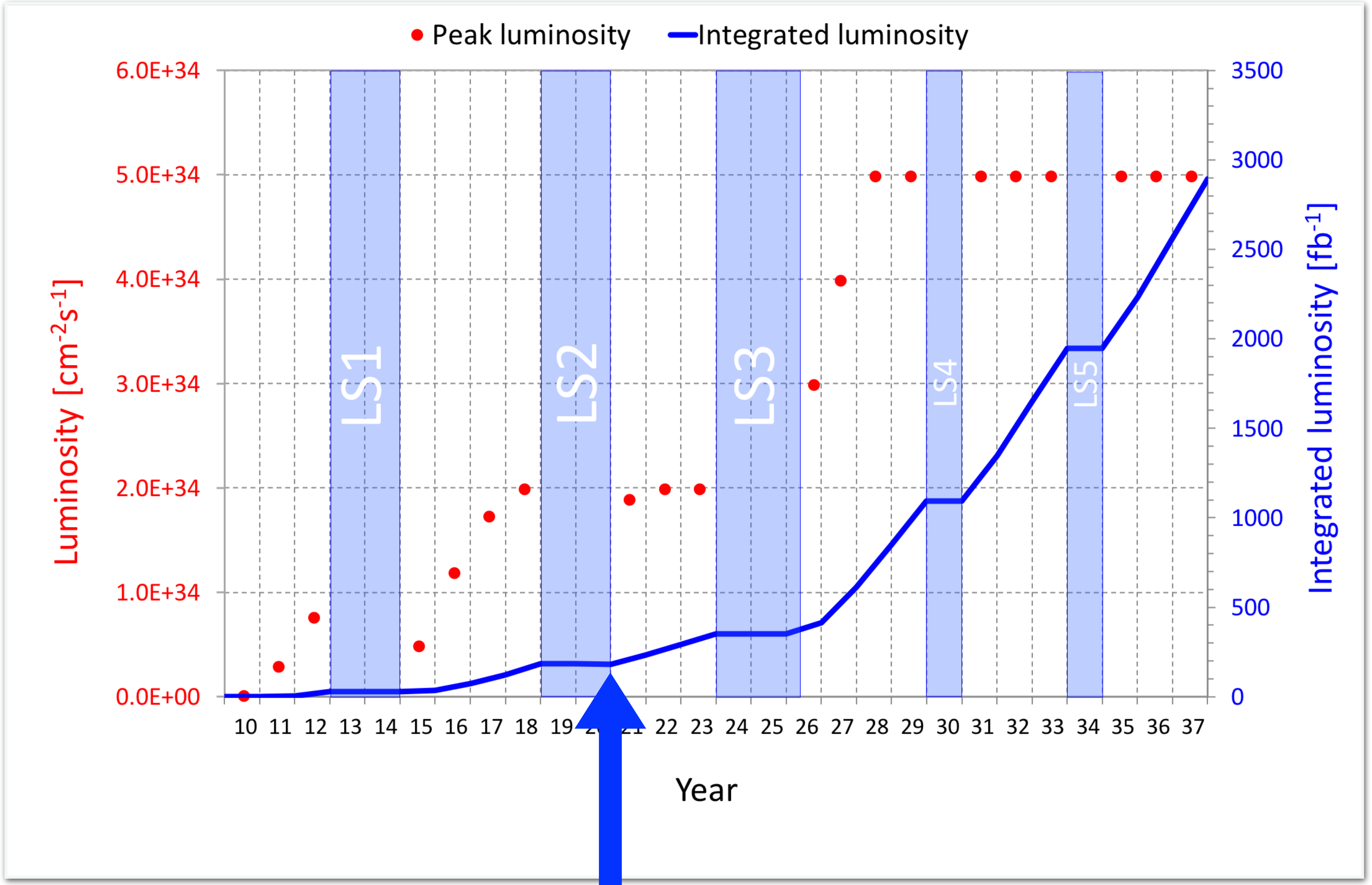
Pier Monni (CERN)

HET Seminar - BNL, June 2022

Particle physics at the Large Hadron Collider (LHC)

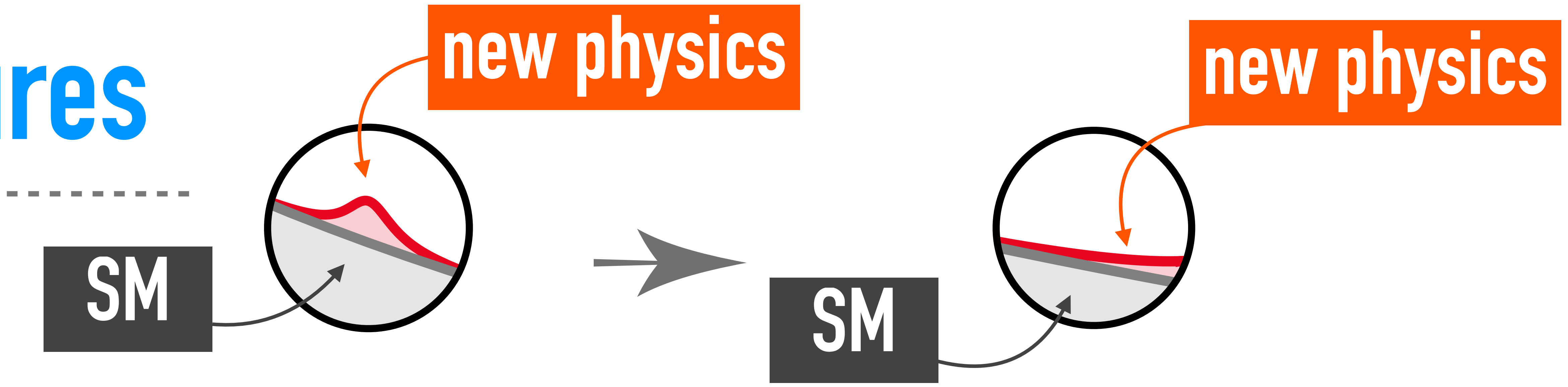
- LHC about to resume operations:
  - Huge boost in experimental precision foreseen (only ~5% of the total luminosity delivered so far)
- Key open questions to be addressed:
  - Establish the Higgs sector
  - Broad searches for New Physics (NP)
  - Stress test of the Standard Model (SM)





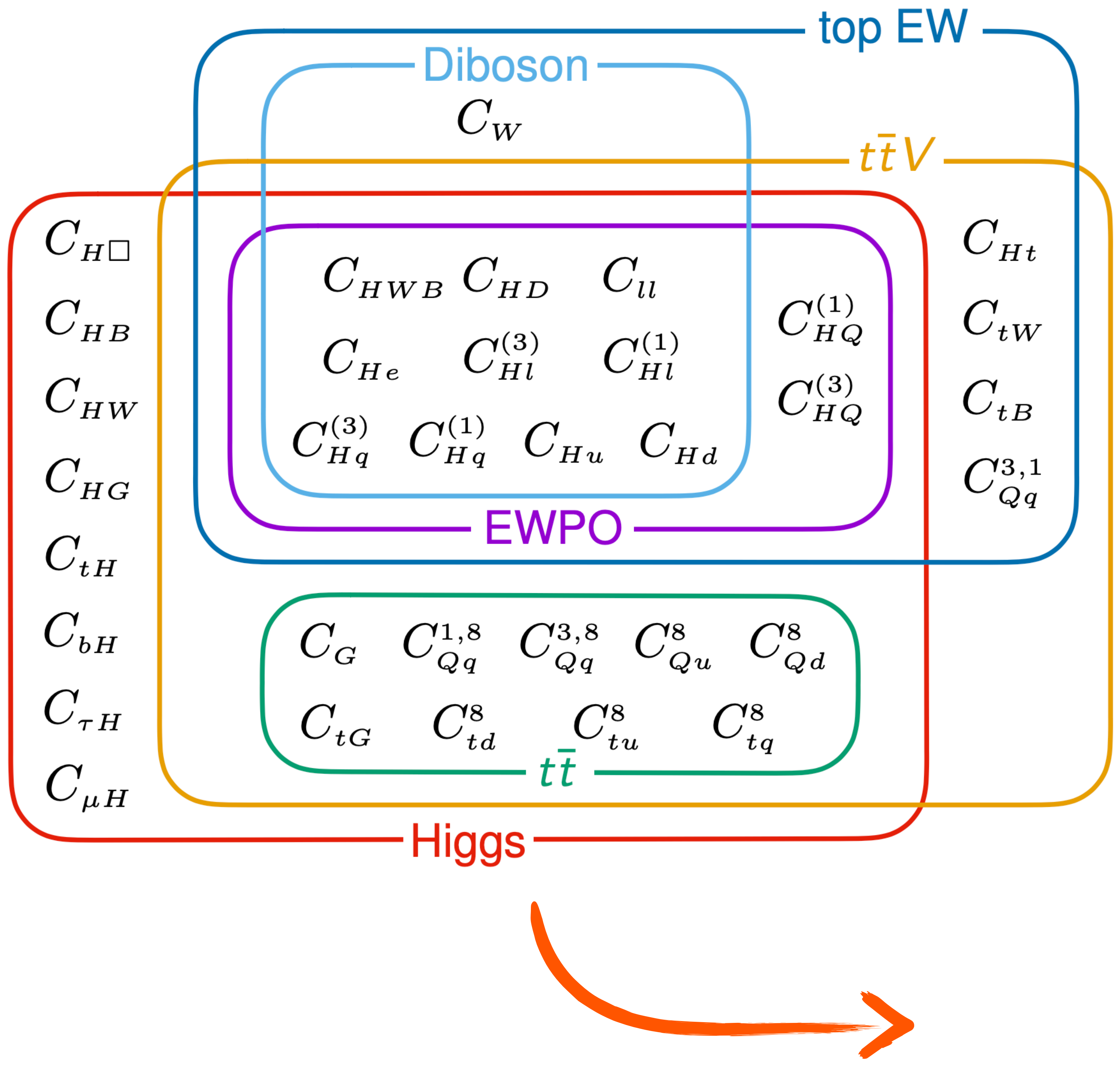
Current integrated luminosity

Broad spectrum searches for NP signatures

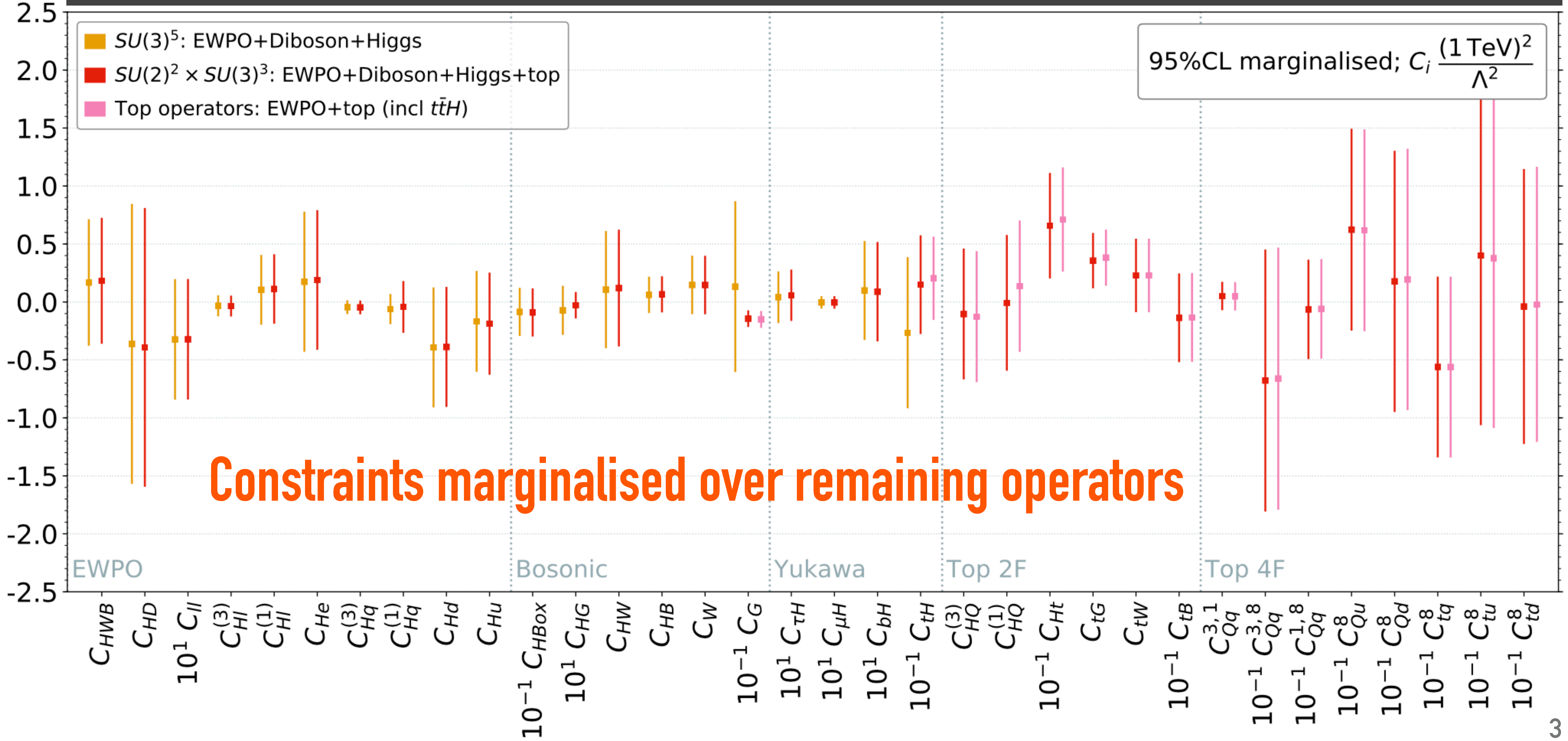


- Detailed scan of accessible regions parameter space
  - e.g. global EFT fits, dedicated searches & specific NP models
  - test of consistency structure of the theory (op. mixing and correlations)

[Ellis, Madigan, Mimasu, Sanz, You '21]



e.g. SMEFT global fit using LEP+SLC+Tevatron+LHC



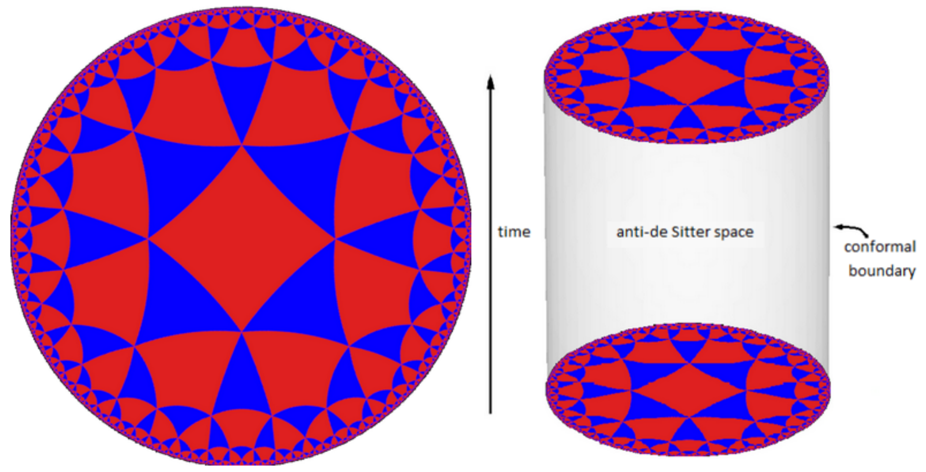
Main challenge: controlling the fine structure of collider events

Candidate H→γγ event at the LHC

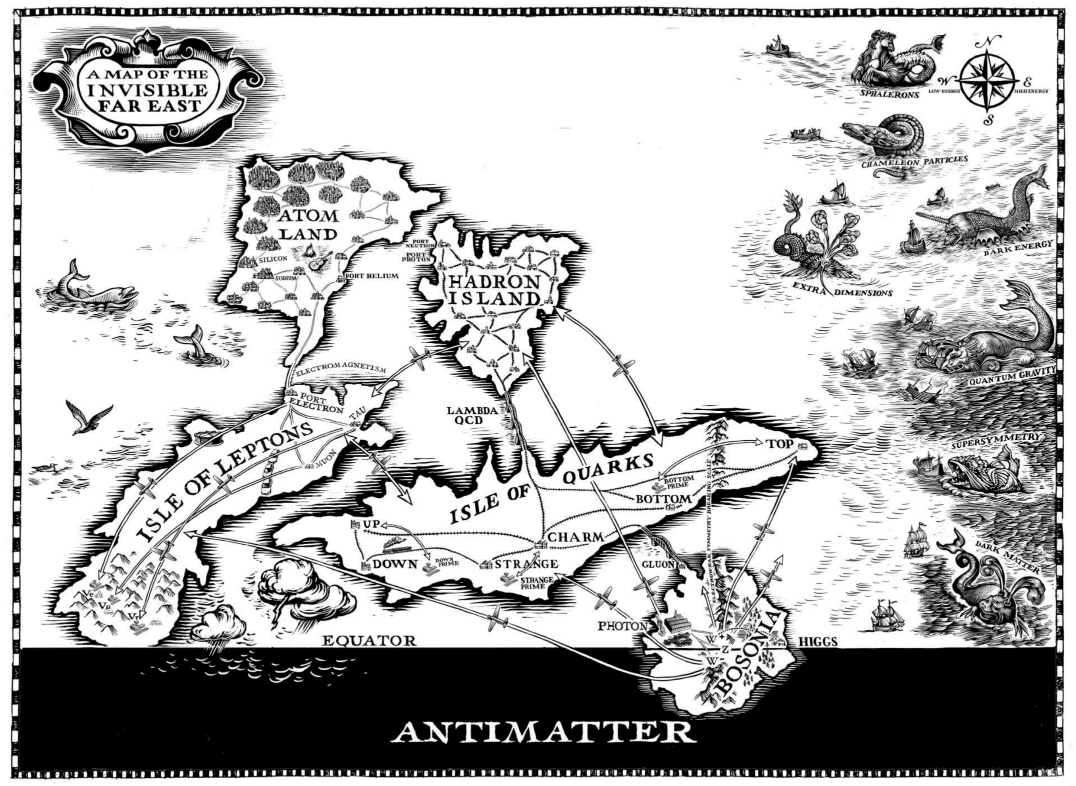
Vast technological progress (jointly Theory $\otimes$ Experiment)

Understanding of QFTs

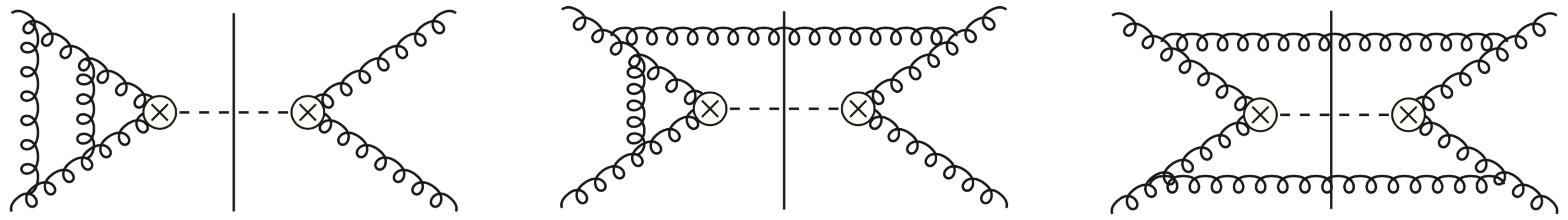
formal developments



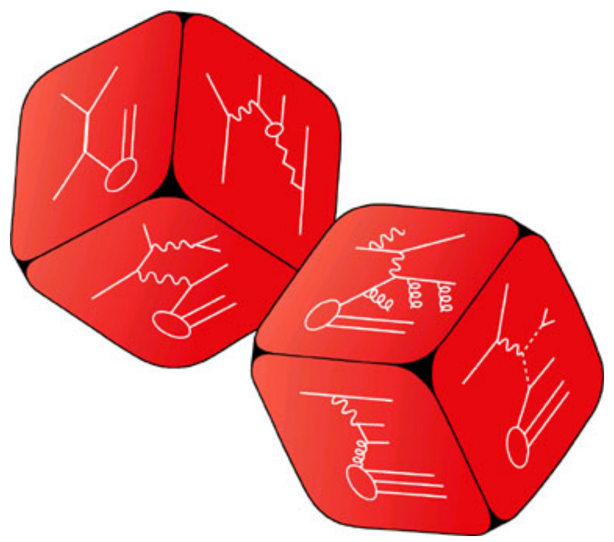
landscape of NP models



perturbative methods



event generators



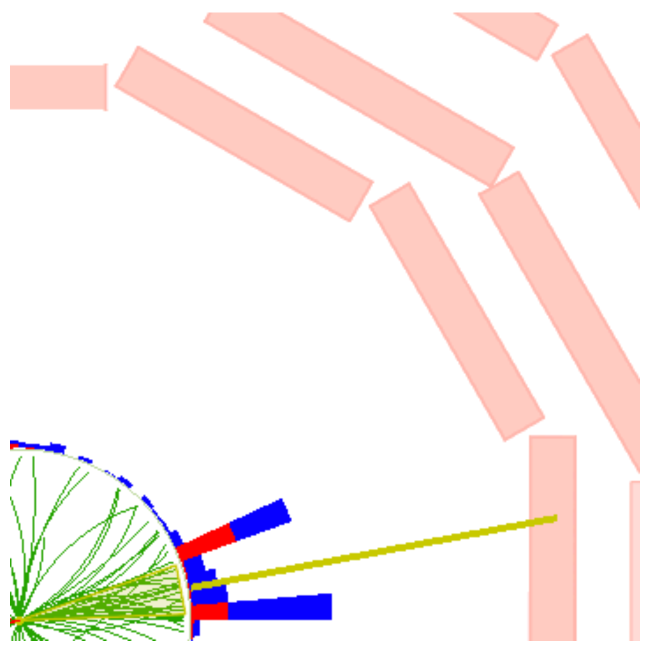
non-perturbative (QCD) corrections

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

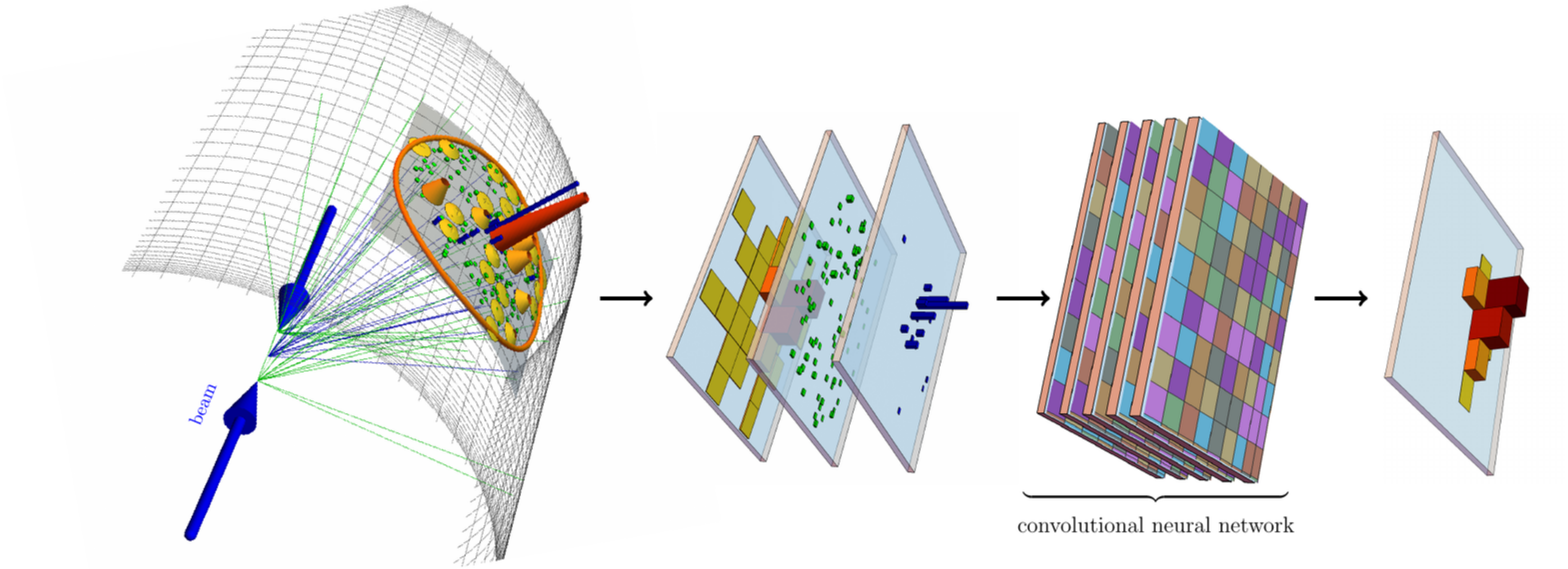
(. . .)

Experiment & pheno

exp. systematics



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



(. . .)

E.g. Impressive progress in theoretical calculations

formal developments

landscape of NP models

exp. systematics

Understanding of QFTs

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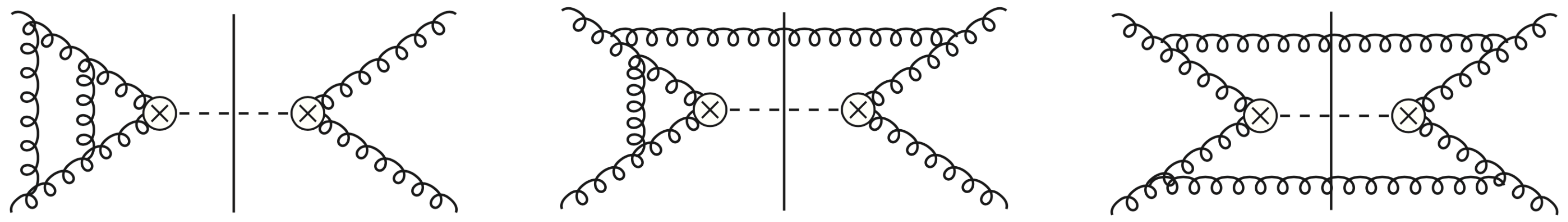

Experiment & pheno

(...)

(...)

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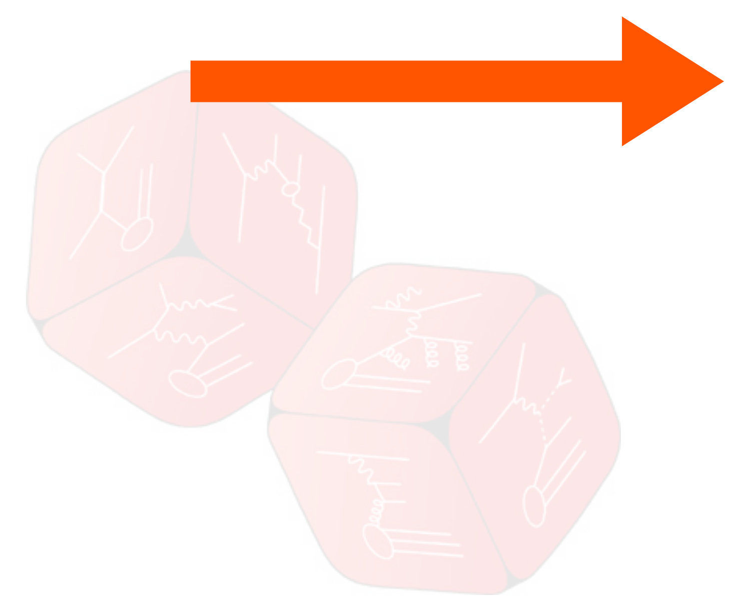
E.g. Impressive progress in theoretical calculations

[Chen, Gehrmann, Glover, Huss, PM, Re, Rottoli, Torrielli ’22]



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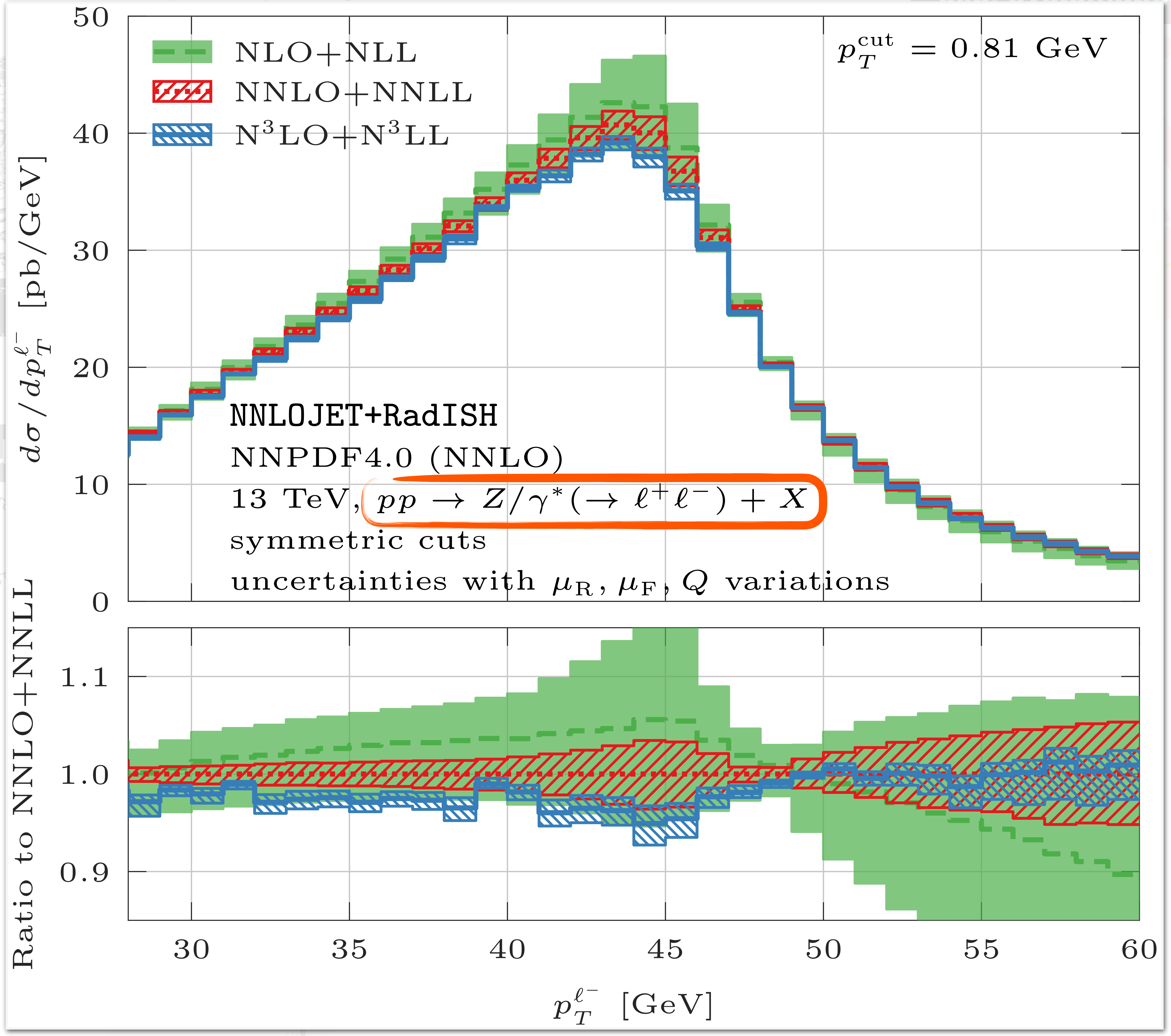
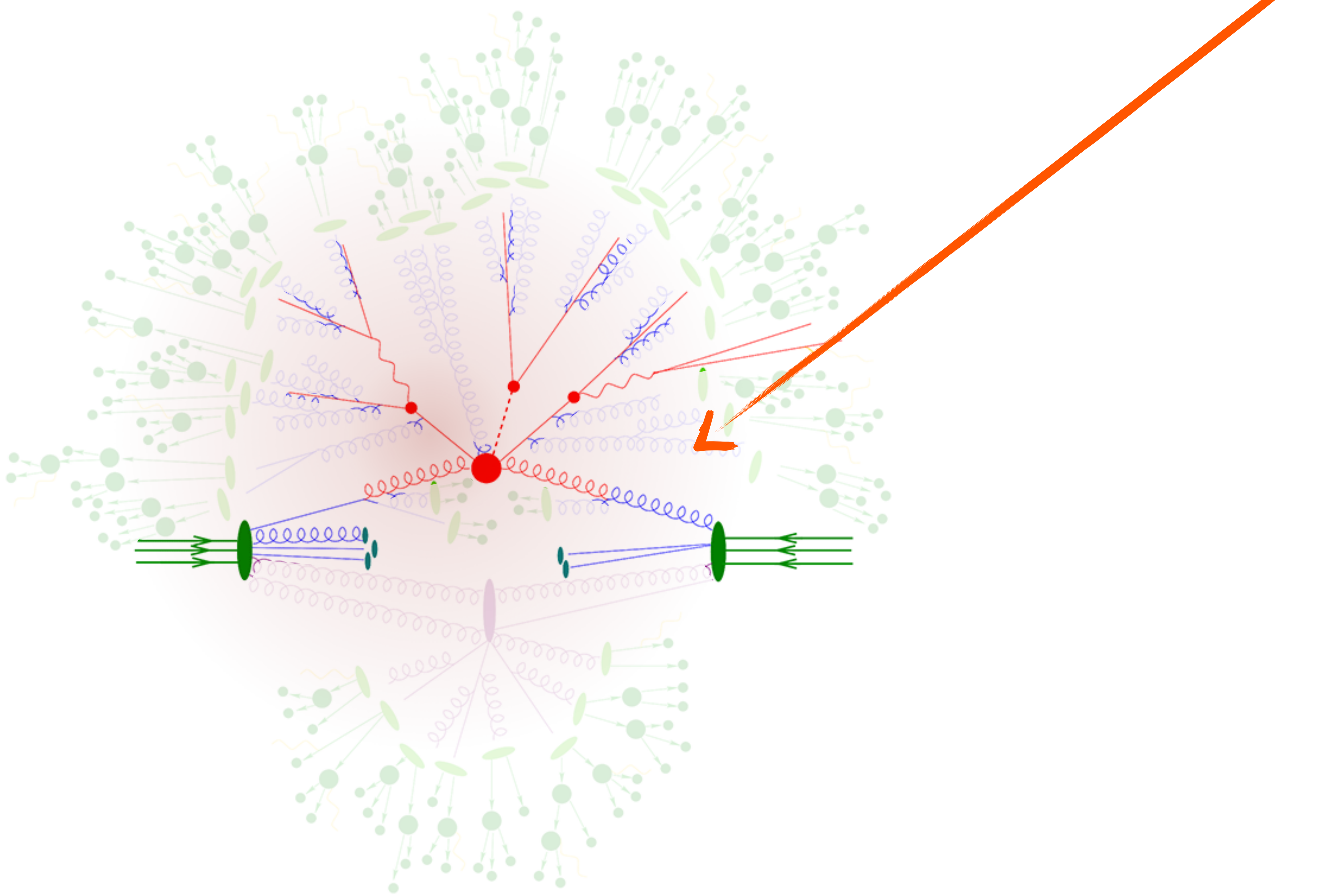
Fiducial Drell-Yan distributions at N3LO



This talk focuses on another crucial aspect: Event Generators

Anatomy of a scattering reaction at the LHC



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

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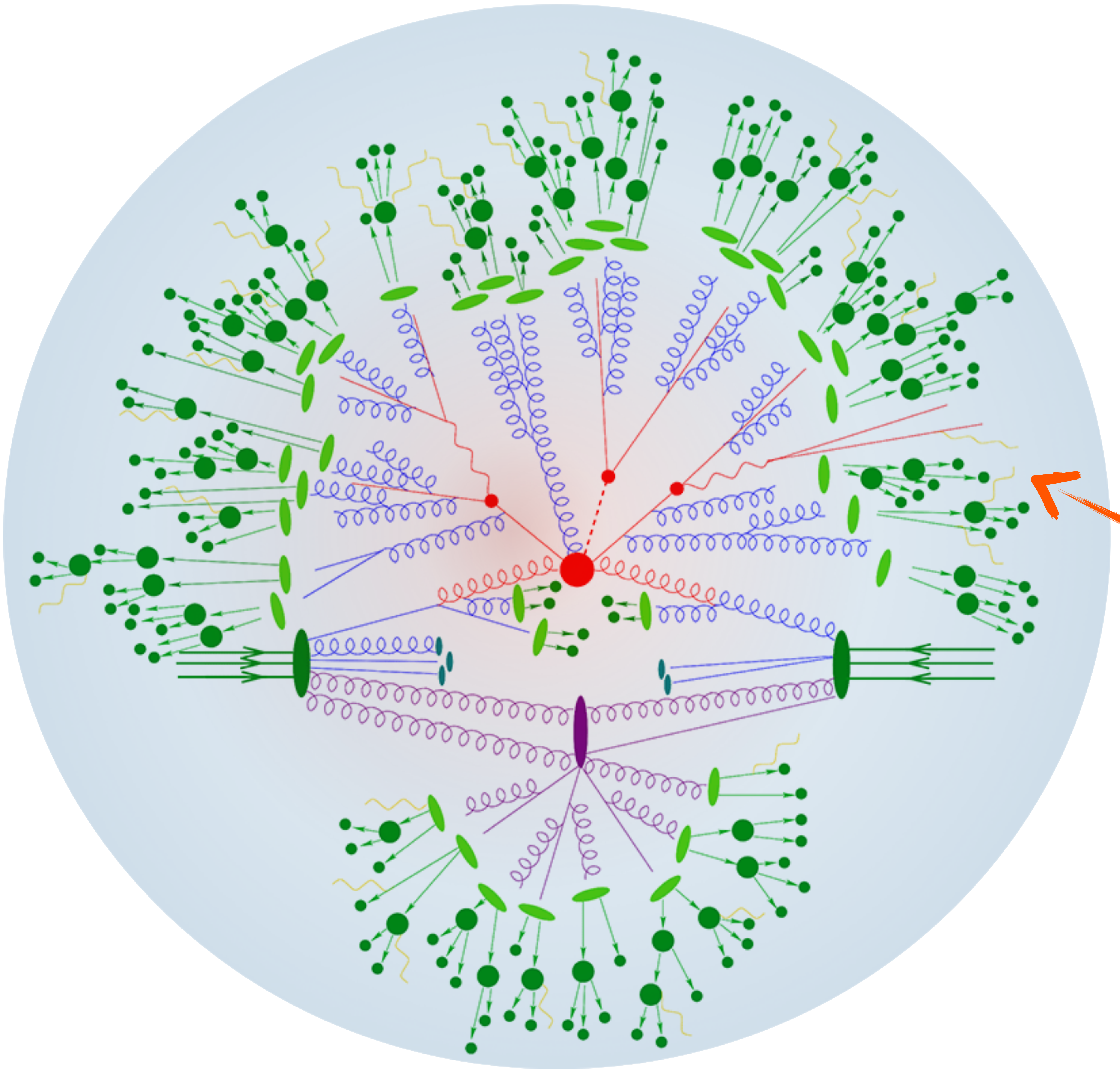


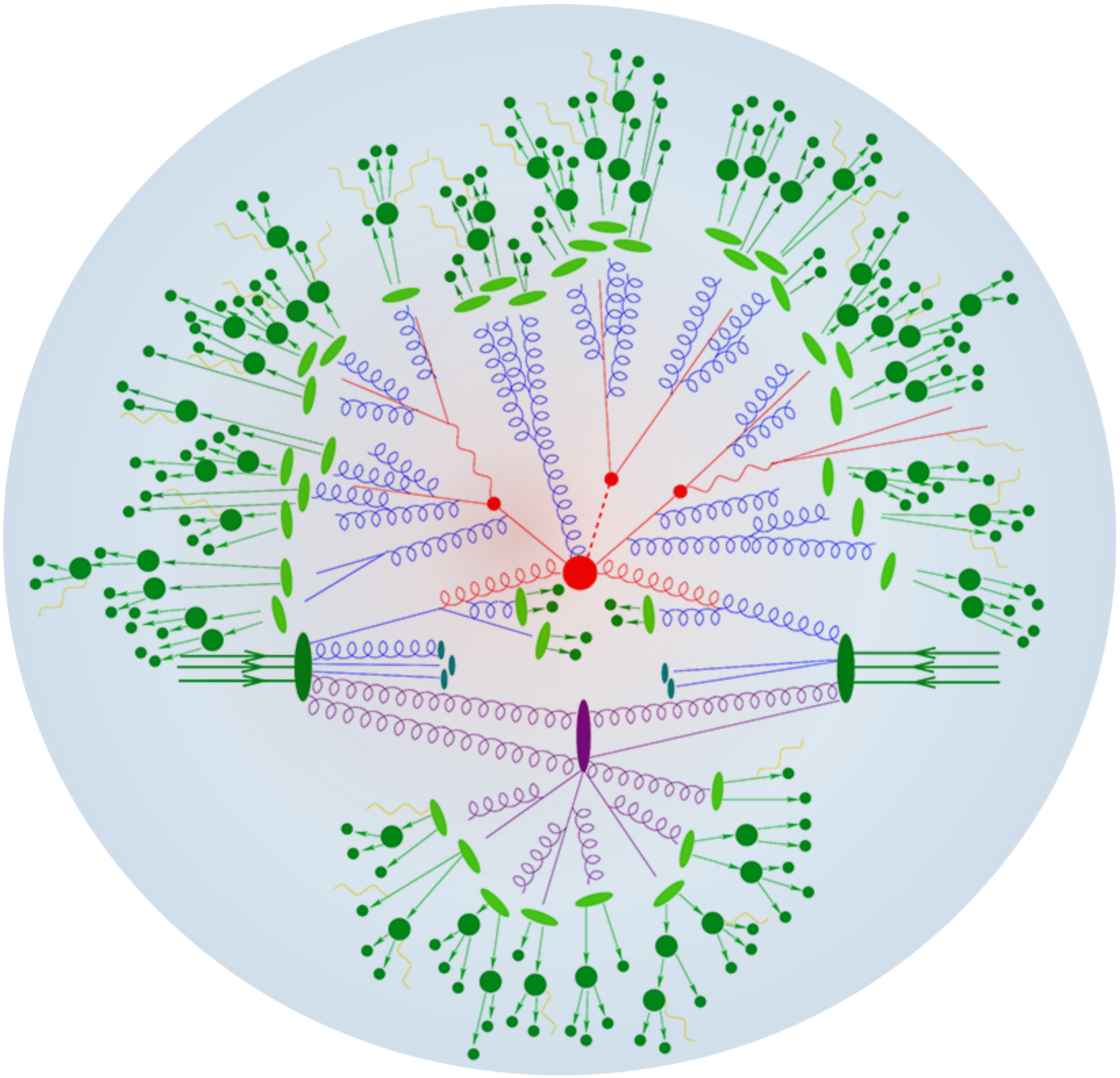
- Short distance (hard)
  - scales probed: $O(10^2)$-$O(10^3)$ GeV
  - stage sensitive to NP

evolution towards a physical observable state

(mainly QCD)

- Long distance (soft)
  - transition from $O(10^2)$-$O(10^3)$ GeV to $O(1)$ GeV
  - hard scattering gets "showered" with soft [and/or collinear] radiation
  - Output: what is actually measured

Event generators simulate all stages of the event formation



- Not a standard theory calculation:
  - ➡ return events, i.e. particle momenta with a physical probability distribution
  - ➡ allow the computation of many (~any) observables at once, as opposed to a few of them 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)

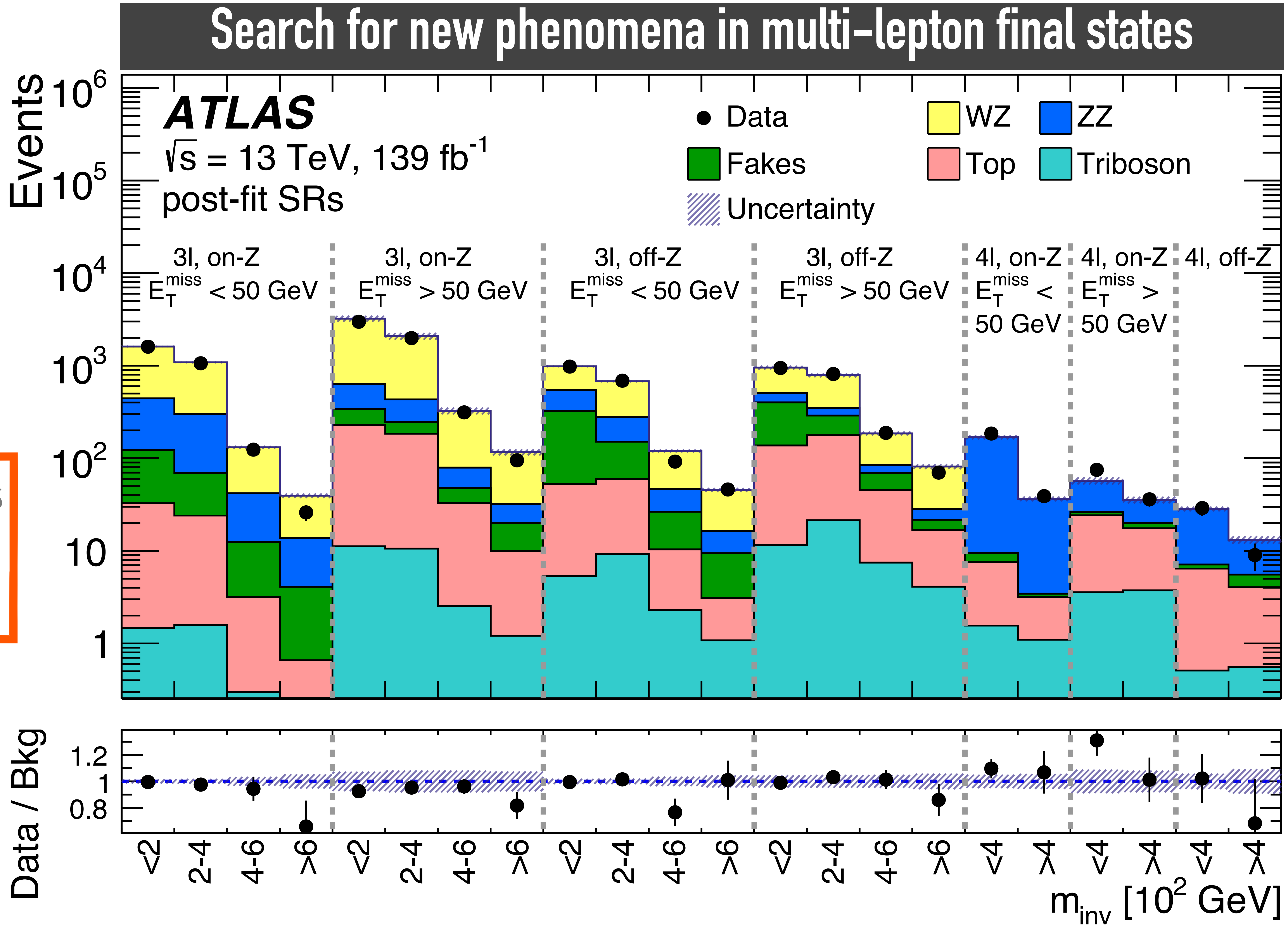
Strength: Back bone of nearly all LHC analyses

Herwig Pythia Sherpa

[+ POWHEG & MC@NLO]

Astonishing description of broad classes of collider reactions, with good accuracy (e.g. searches with rich background)

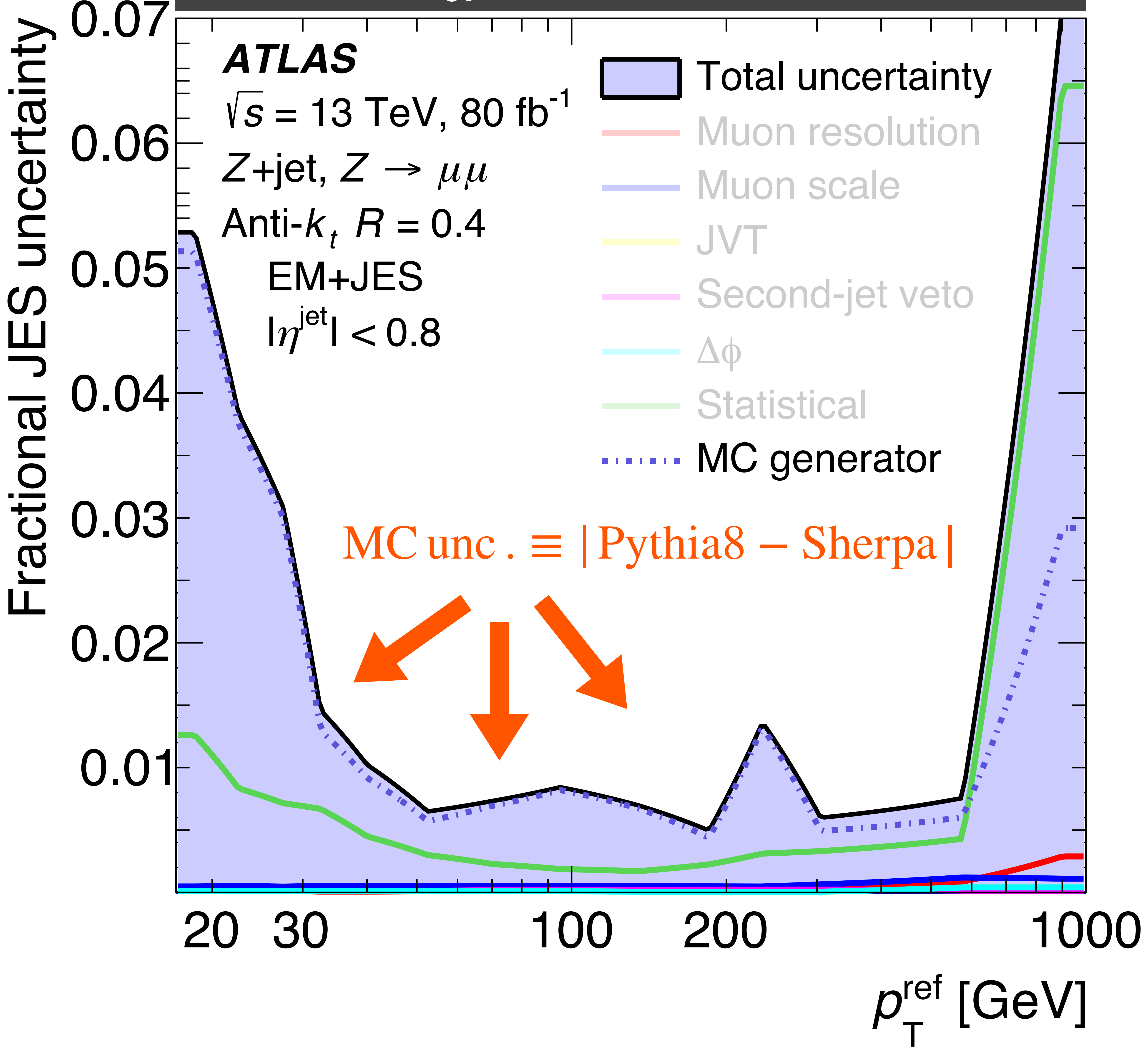
[ATLAS '22]



Weakness: Inaccuracies are now often the leading systematics

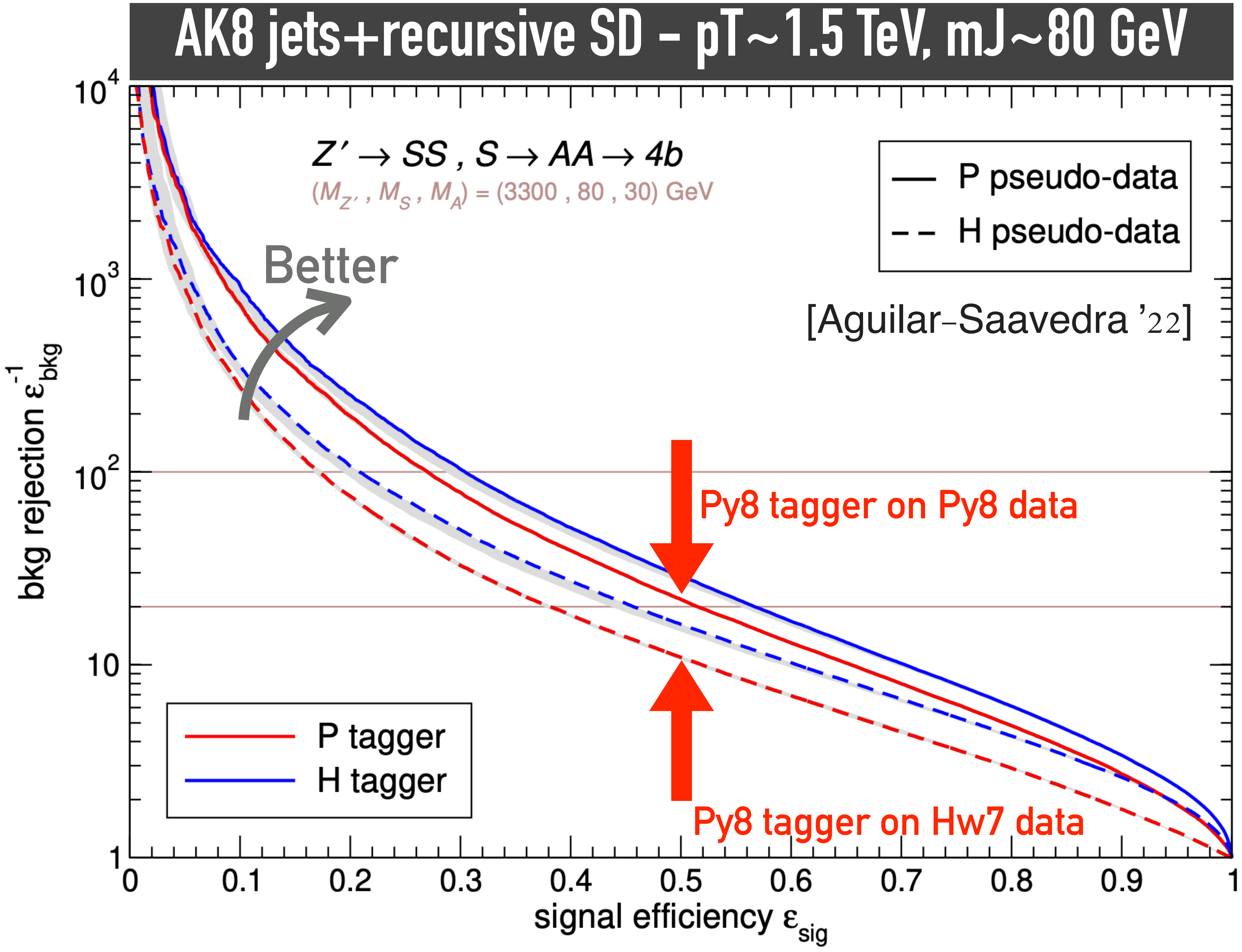
- The improving experimental performance highlights limitations of event generators
- Soon to be the bottleneck of LHC physics programme
  - Jet Energy Scale uncertainty (→ affecting many measurements)
  - … this is but one example

Jet energy scale (JES) measurement



Robust training of Machine Learning (ML) algorithms

- ML technology provides a great boost in sensitivity w.r.t. orthodox analysis techniques
- However, this comes often with a dependence on the modelling, i.e. Monte Carlo generator, raising the question of accuracy
  - e.g. dependence of 4-pronged tagger on training model & pseudo-data
- New generation of tools paramount to push this technology in the precision era of LHC

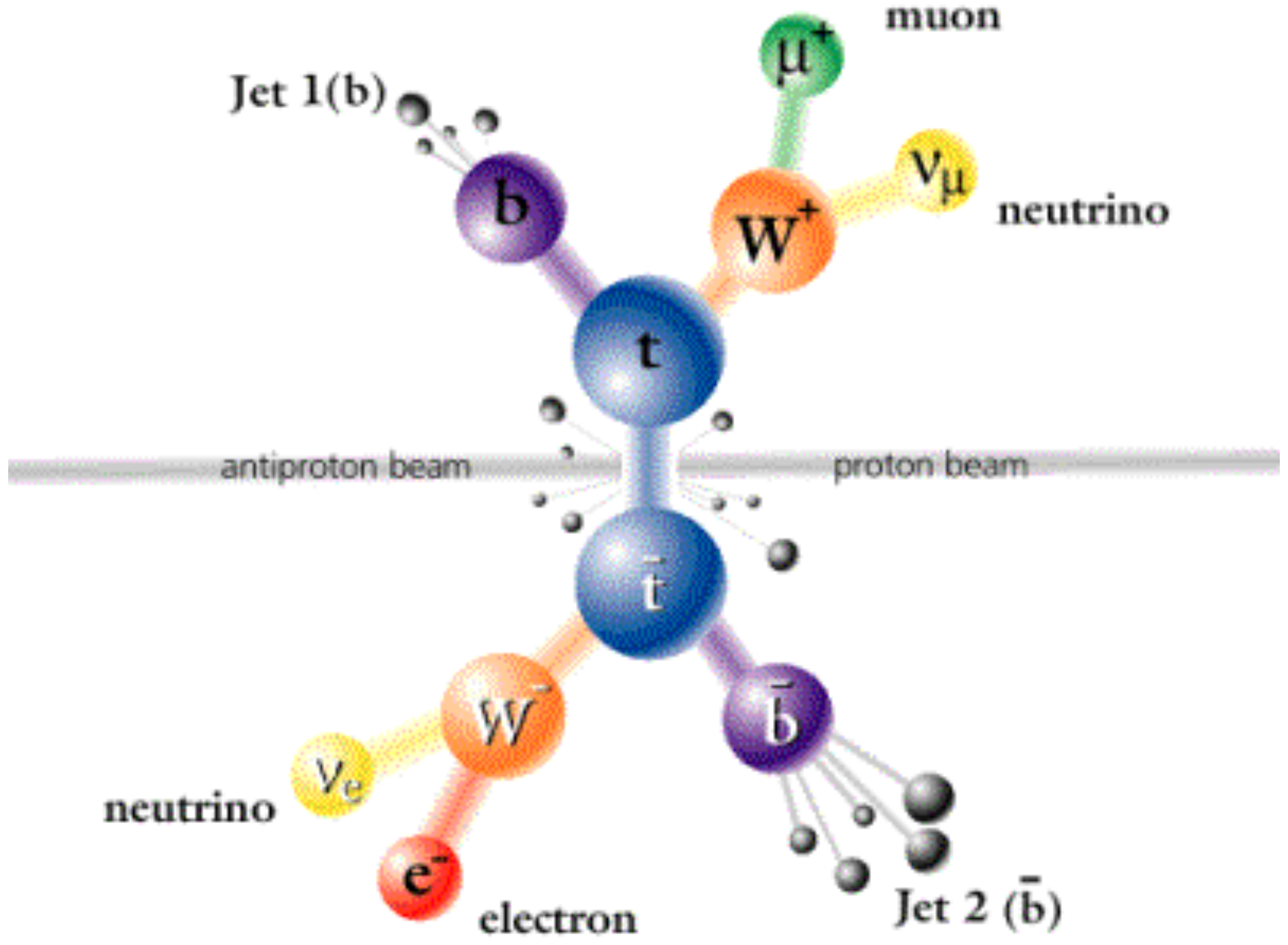


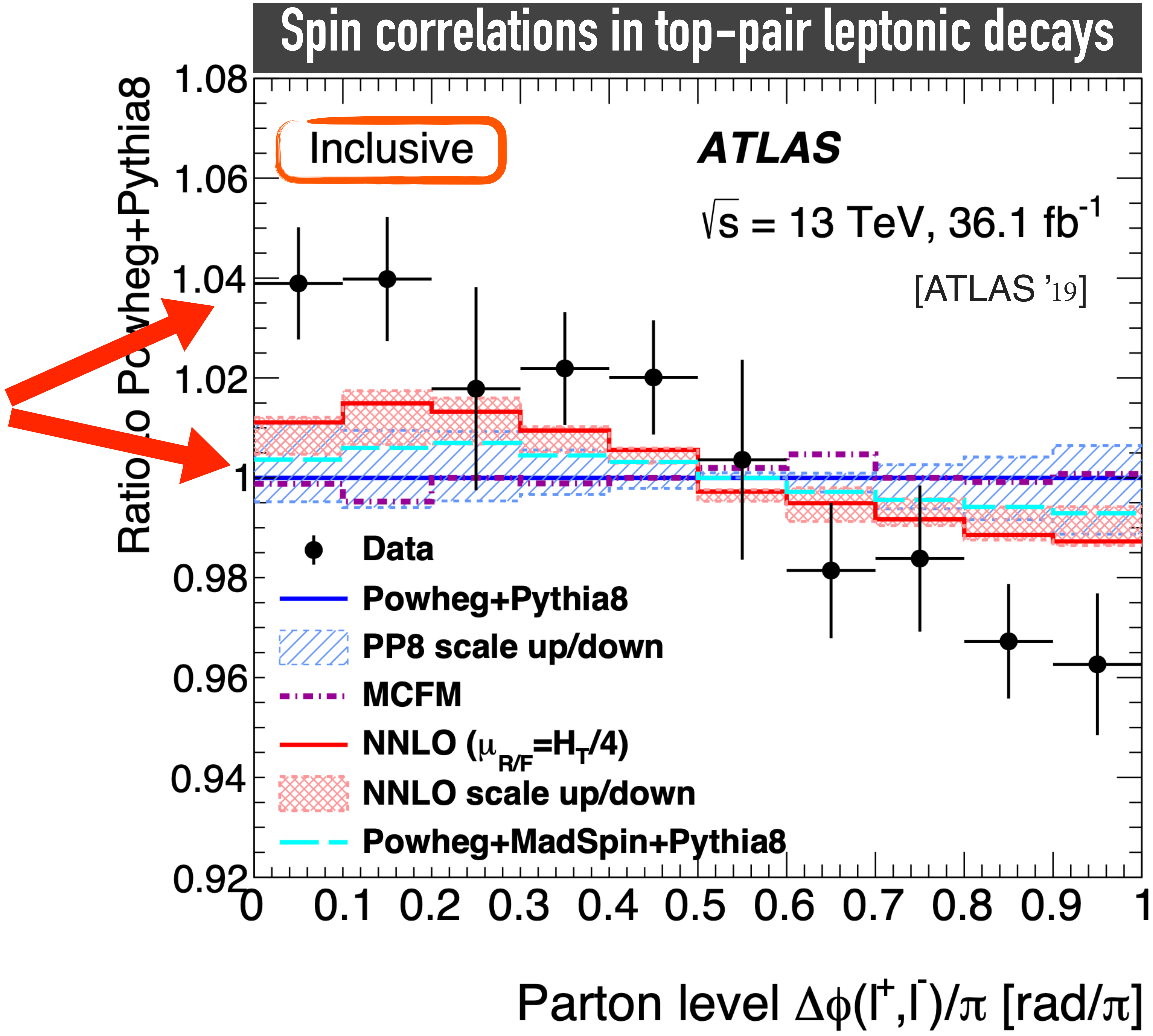
Extrapolation of experimental measurements

- MC generators used to extrapolate experimental data from fiducial to inclusive phase space (easy comparison with theory and interpretation)

- Inaccuracies may lead to dangerous biases

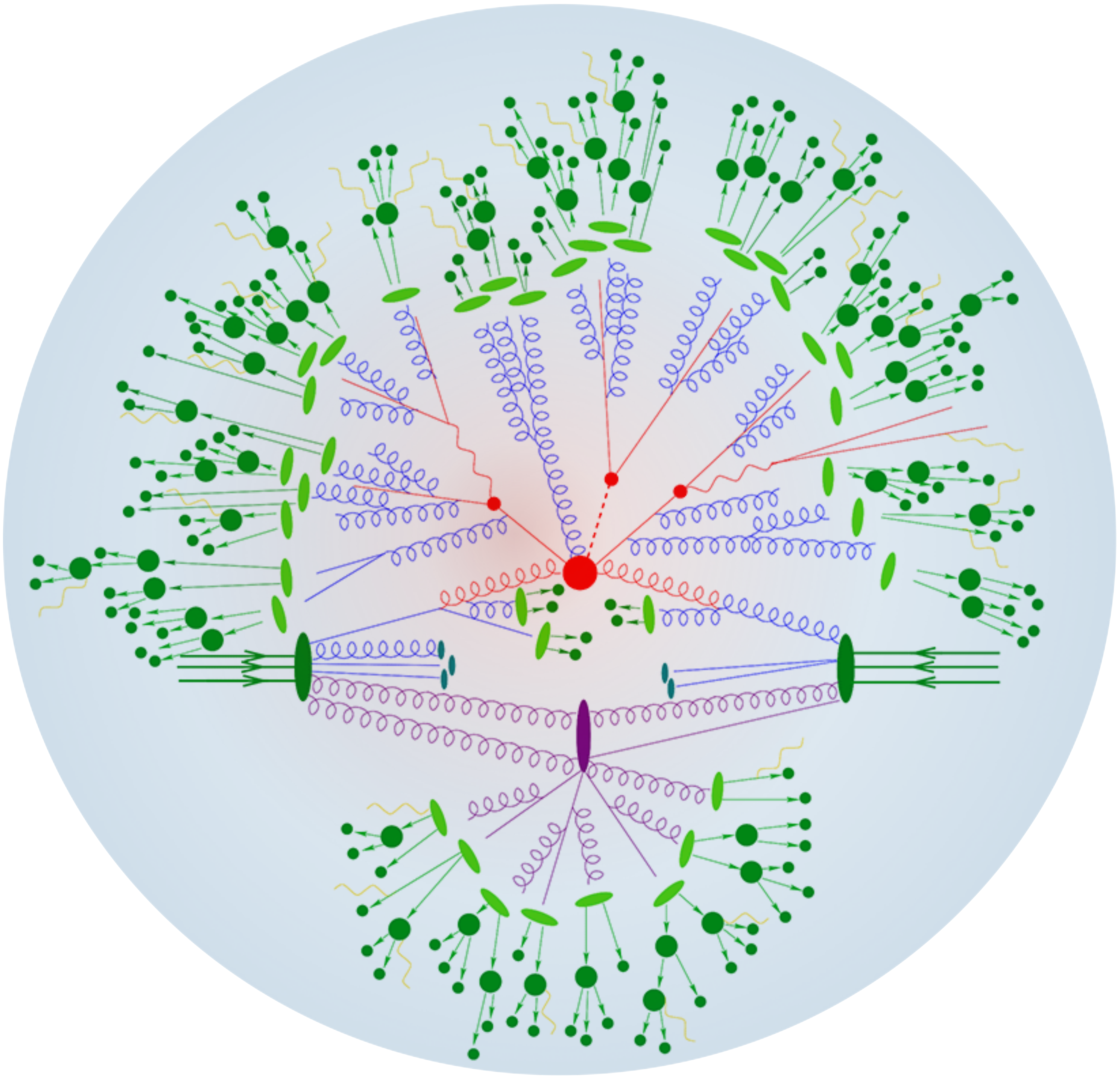
  ➡ e.g. discrepancy in $t\bar{t}$ spin-correlations: new physics or mis-modelling ? (more later)





The overarching question:
Can we do better?

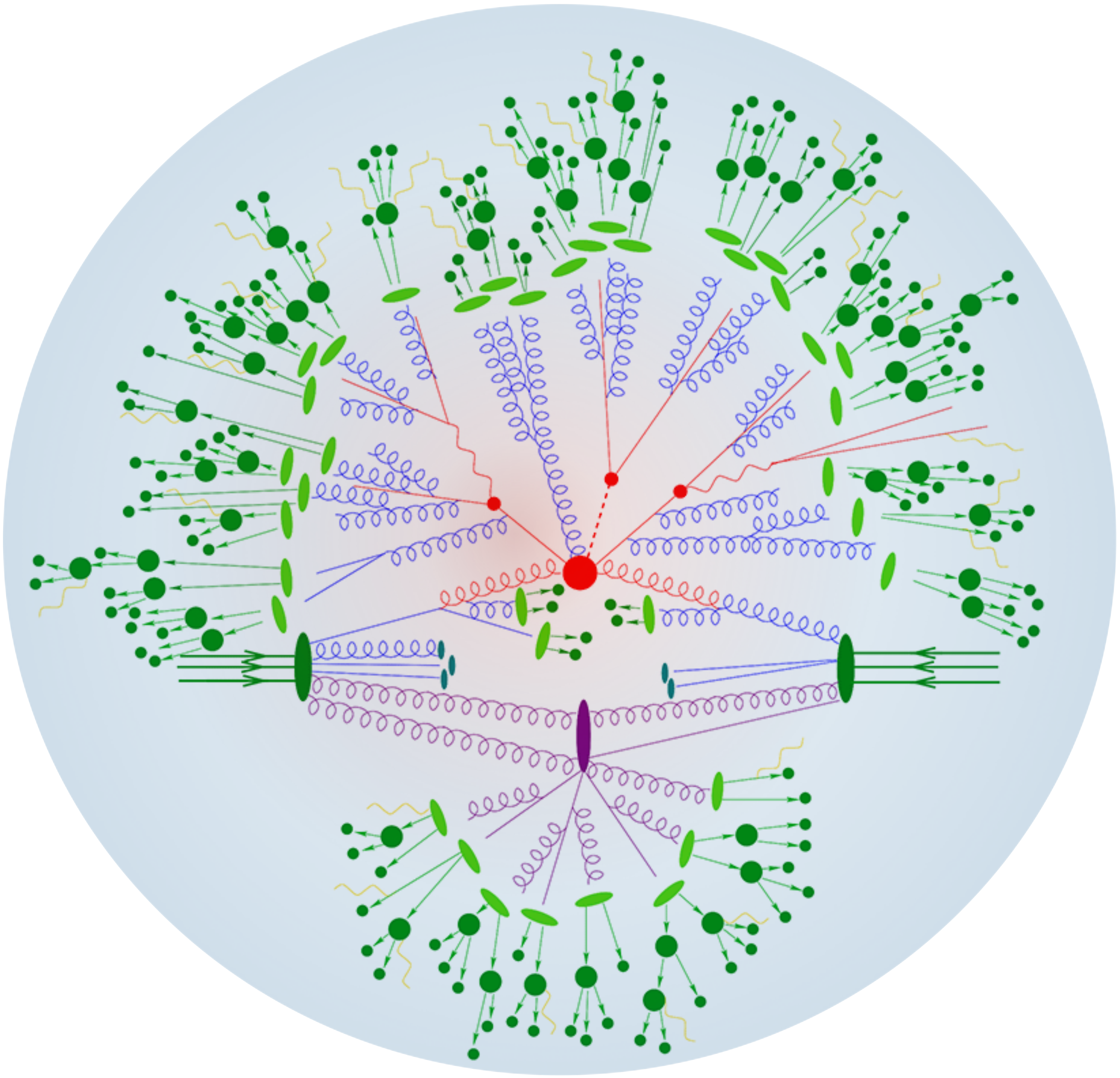
How do we even define the accuracy of event generators?



- Evolution spans several orders of magnitude in energy scale
  - Different perturbation theories needed in different regimes (e.g. fixed-order, logarithmic power counting, subleading power corr.^{ns})
  - We should demand that event generators reproduce these limits correctly
    - This talk addresses the two main elements: the hard scattering & the parton shower

The parton shower stage

The parton shower component



- Large hierarchy of scales ($\mu_{\text{hard}} \gg \mu_{\text{soft}}$)
  - Yet, fully perturbative regime ($\mu_{\text{soft}} \gg \Lambda_{\text{QCD}}$)
  - Initial conditions for hadronisation
- Several successful public tools:

Herwig   Pythia   Sherpa

[also DiRe, Deductor]

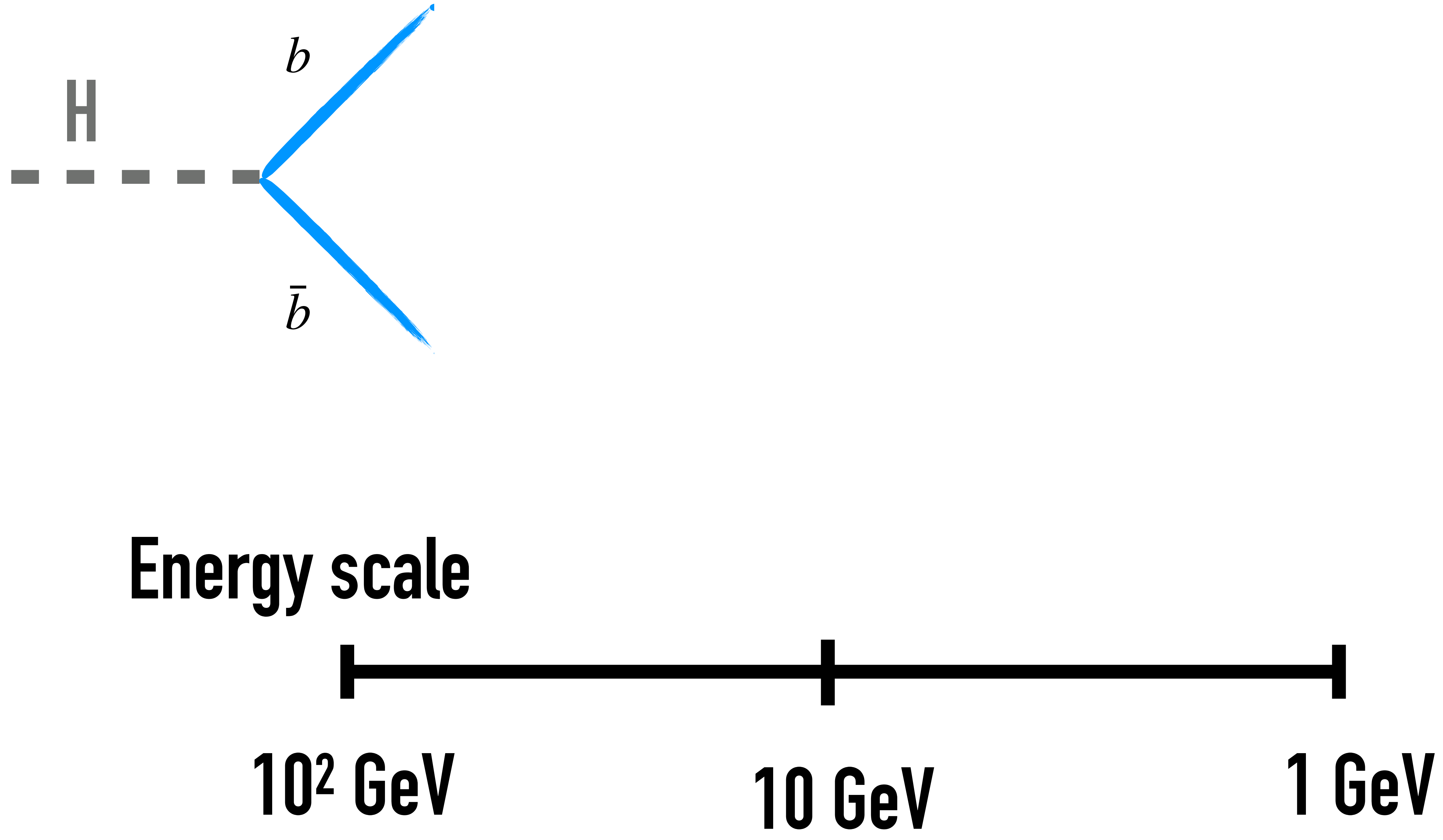
How do they work? [dipole shower case]

- Algorithms based on concepts invented in the mid ‘80s. Many variants built across the years

e. g. [Sjostrand ’85; Marchesini, Webber ’88; Lonnblad ’89]

e.g. H→bb decay

- Schematically [non-linear evolution]:
  - →Recursive iteration of 2→3 branching probabilities [i.e. LO splitting functions]
  - → Evolve towards smaller values of a resolution variable [e.g. dipole transverse momentum]
  - → Kinematic map to restore on-shellness [i.e. recoil scheme]
  - → Iterate until hadronisation scale is reached



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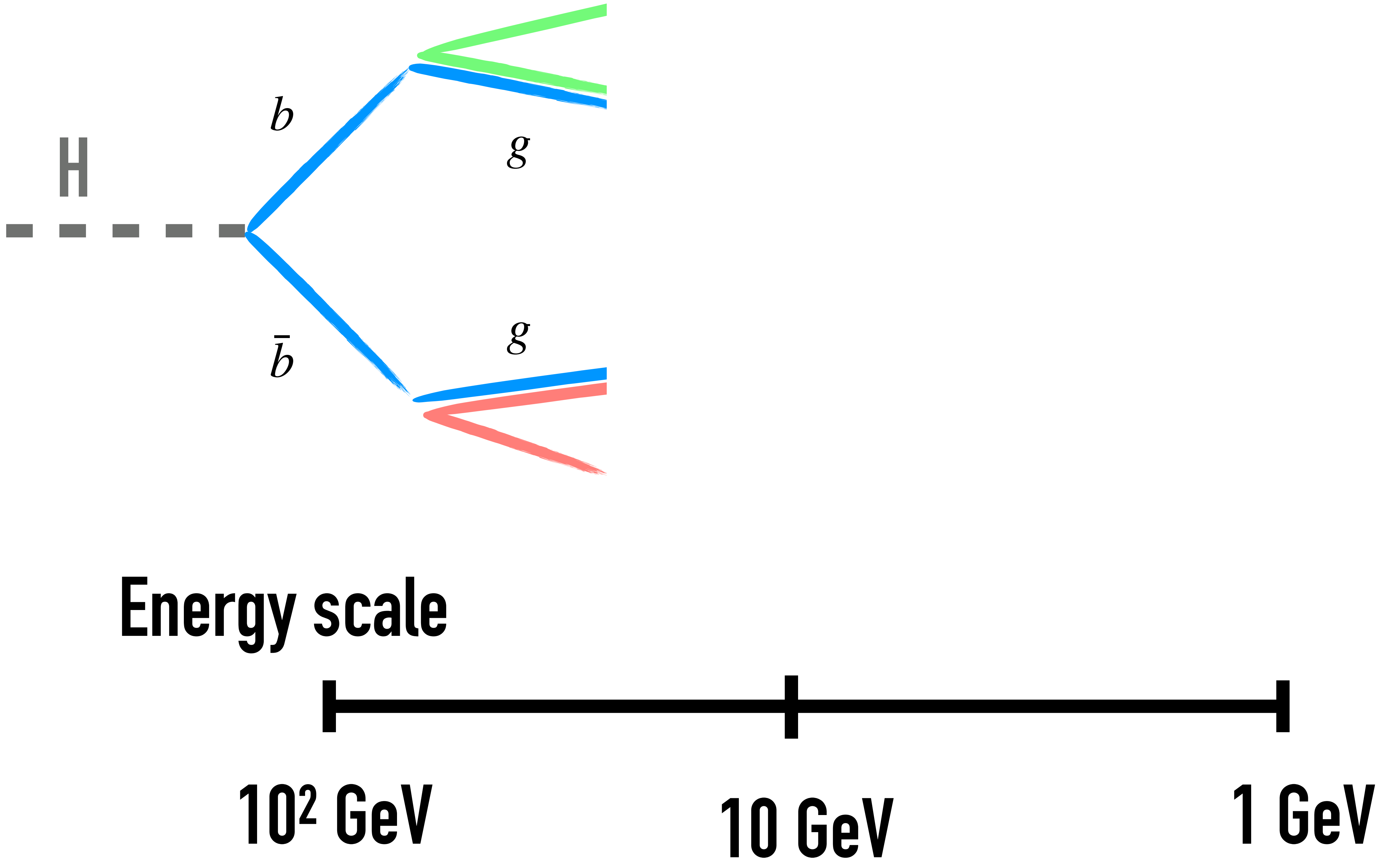

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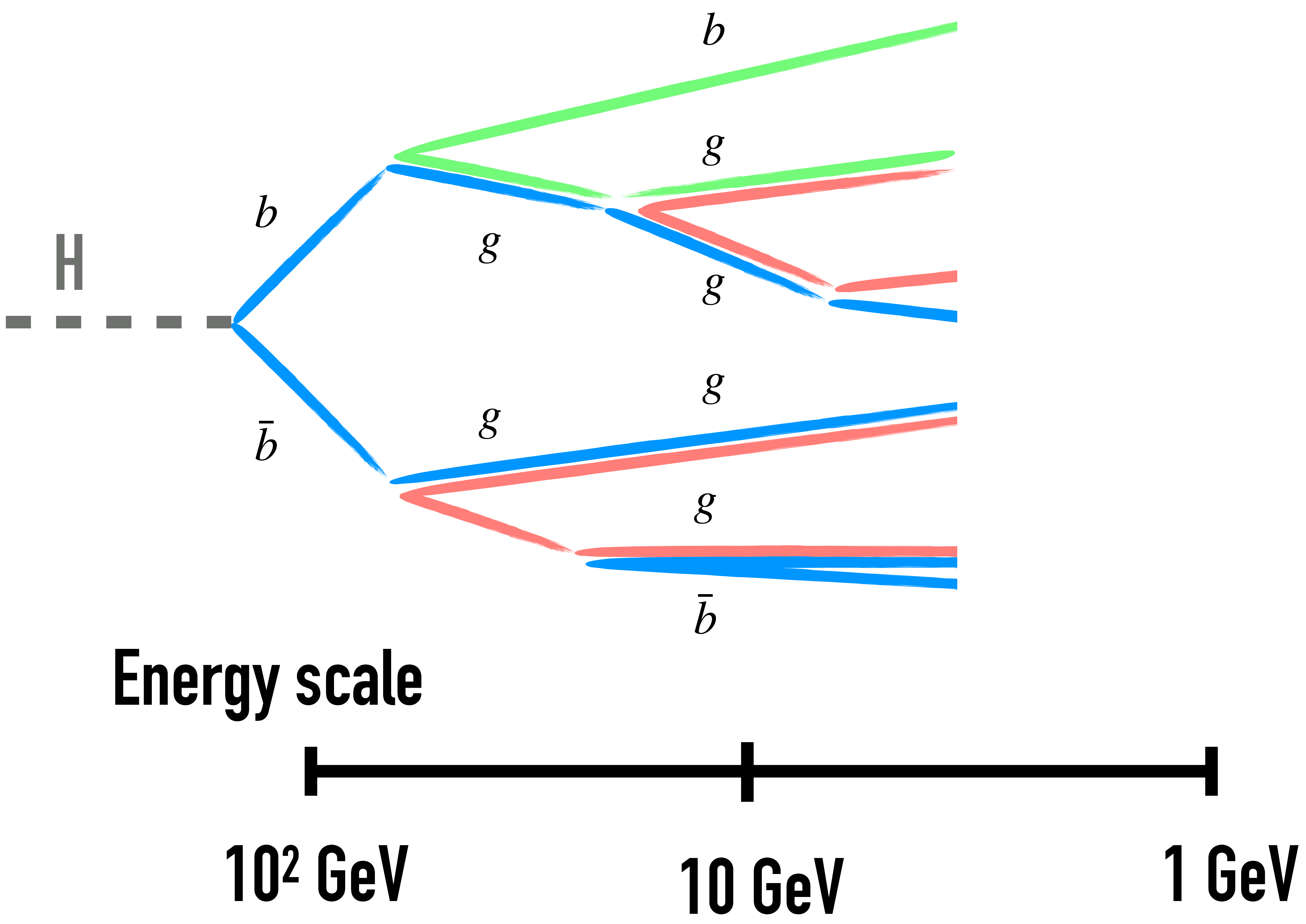

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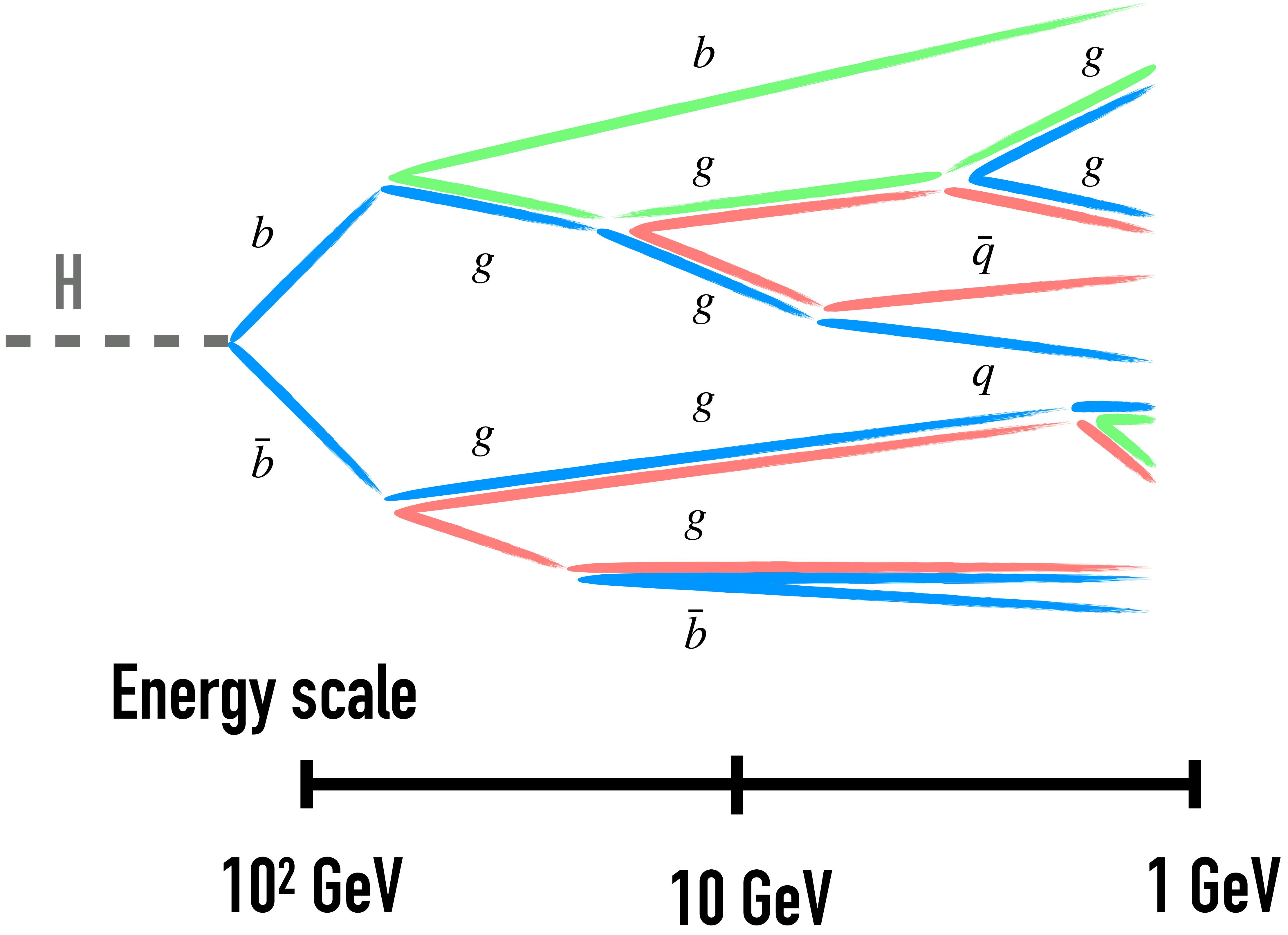

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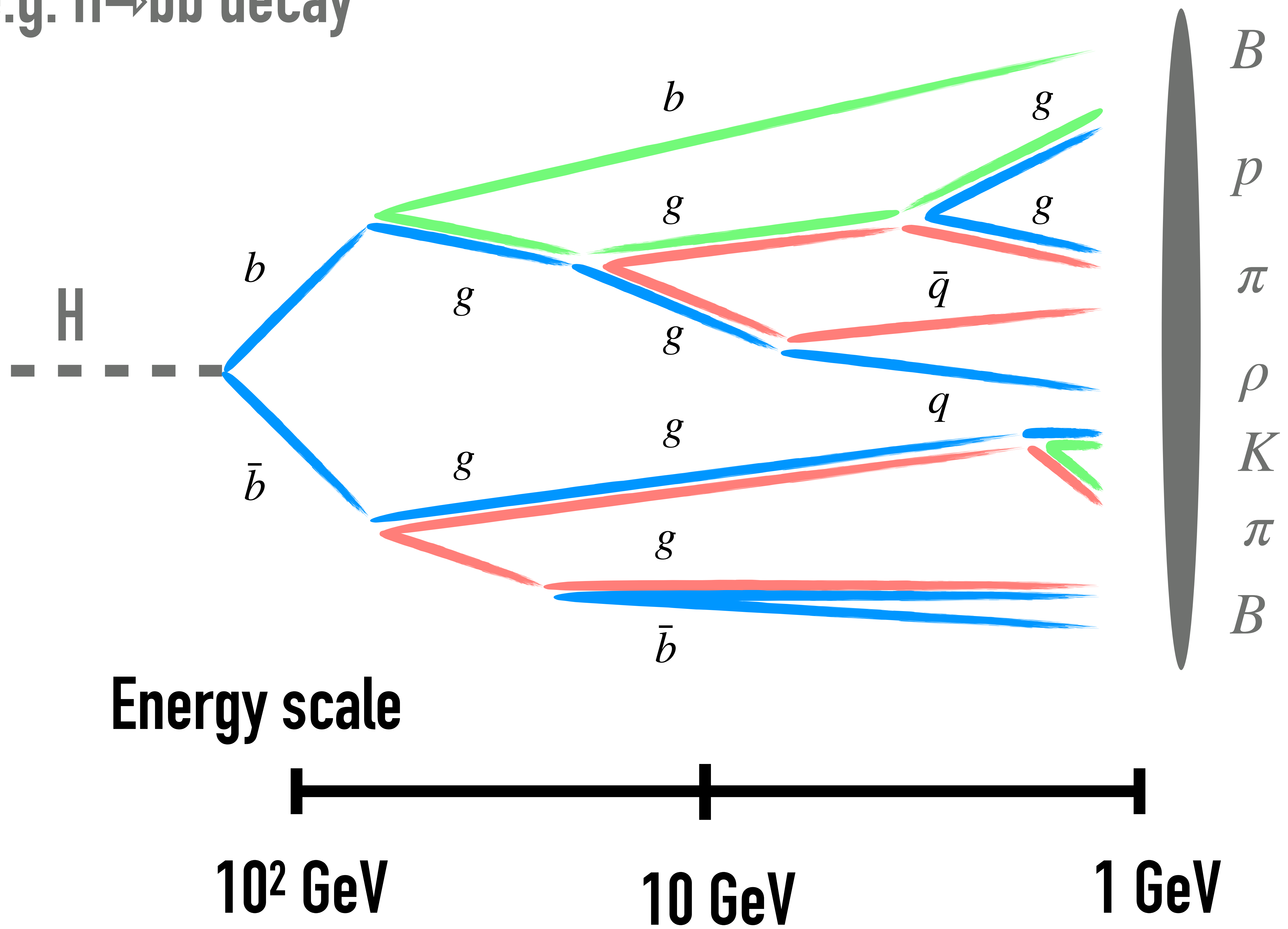


What's the logarithmic accuracy of a PS?

- Identify the appropriate QCD perturbative expansion in the multi-scale regime

Perturbation theory: small coupling, large scale hierarchy [logarithmic counting]

- How can we formulate the concept of accuracy for whole classes of observables at once? e.g. for
  - fraction of events passing a jet veto in a rapidity window?
  - azimuthal correlation between two sub-jets?
  - event shapes?
  - ...

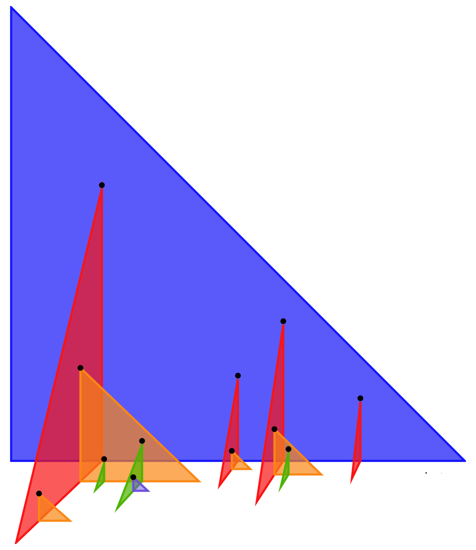
A geometric definition of leading-logarithmic (LL) accuracy

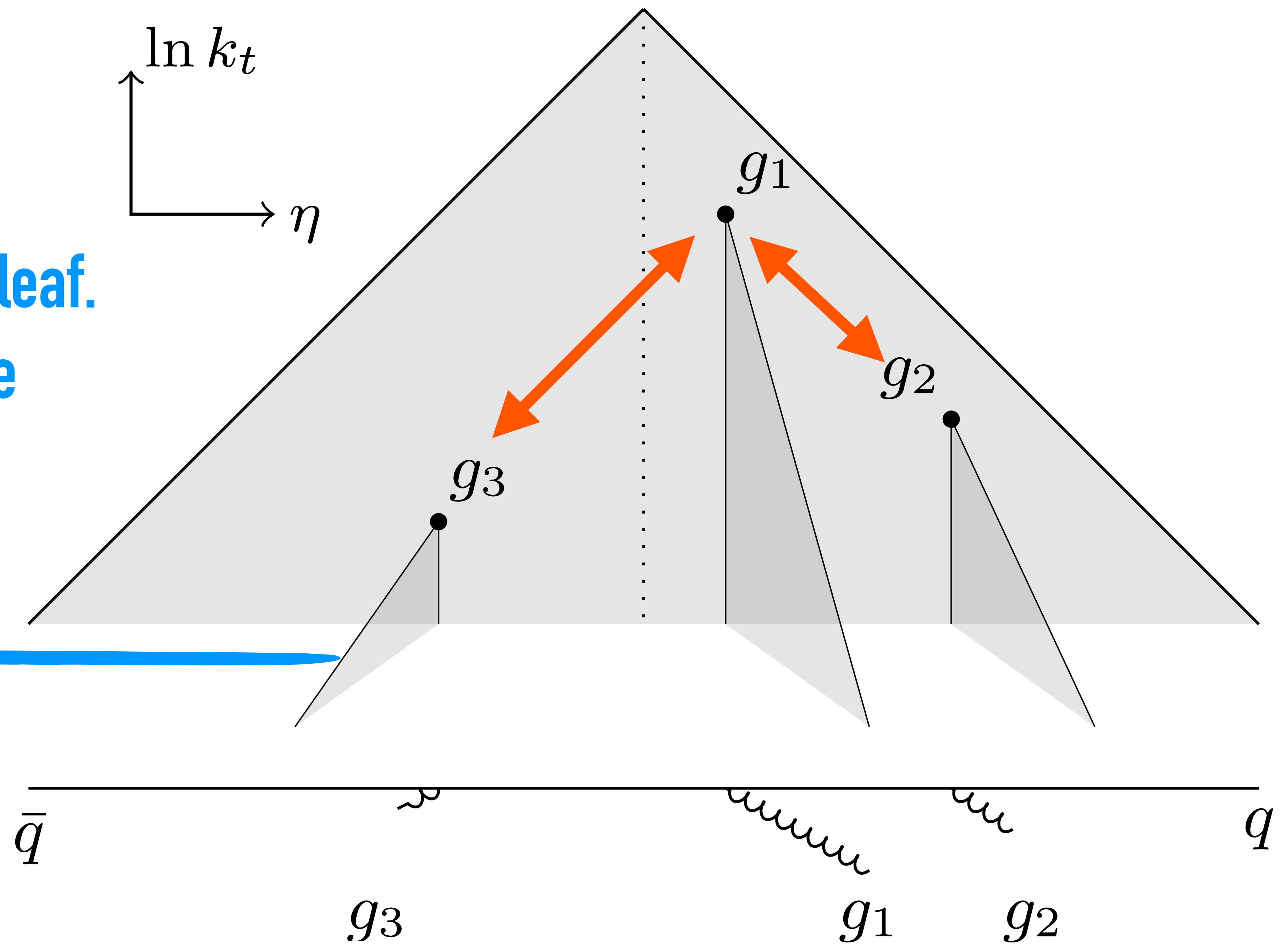
- Radiation phase space conveniently organised in the Lund Plane (LP)

[Anderson, Gustafson, Lonnblad, Pettersson ’89]

- LL → emissions widely separated in both directions of the LP → $\mathcal{O}(50 - 100\%)$ uncertainties

Each new emission is parametrised by a new leaf.
Event has an self-similar origami structure





$$k_t = E \sin\theta\,; \quad \eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

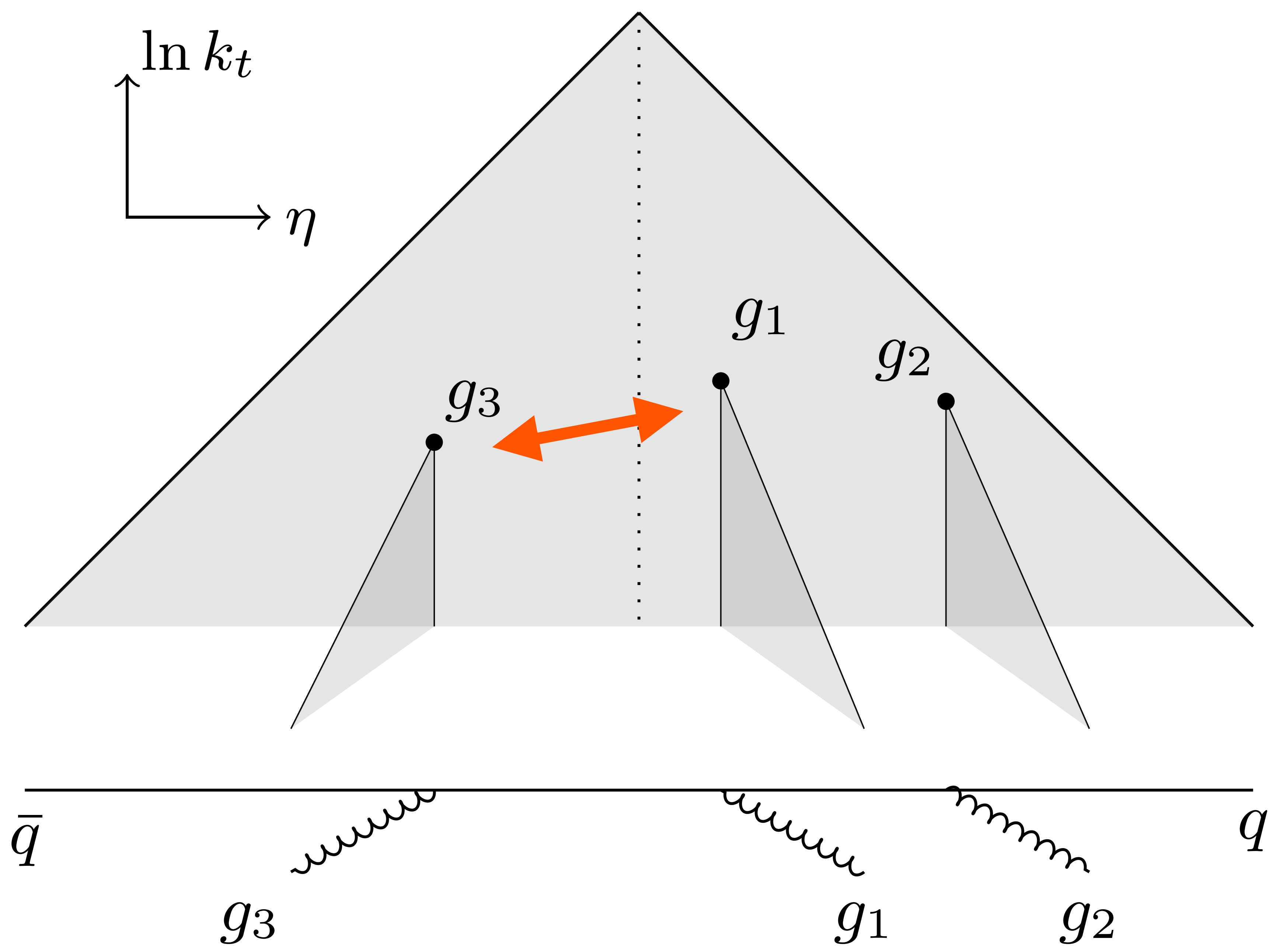
$$\text{Area} \longrightarrow \int \mathrm{d}\ln k_t\, \mathrm{d}\eta \sim L^2/\text{emission}$$

Definition used in QCD resummations, e. g.
[Banfi, Salam, Zanderighi ’04; Banfi, McAslan, PM, Zanderighi (JHEP 2015)]

A geometric definition of NLL accuracy

- NLL → emissions **strongly separated in a single direction of the LP** → $\mathcal{O}(10\%)$ **uncertainties**

e.g. in rapidity at similar transverse momentum



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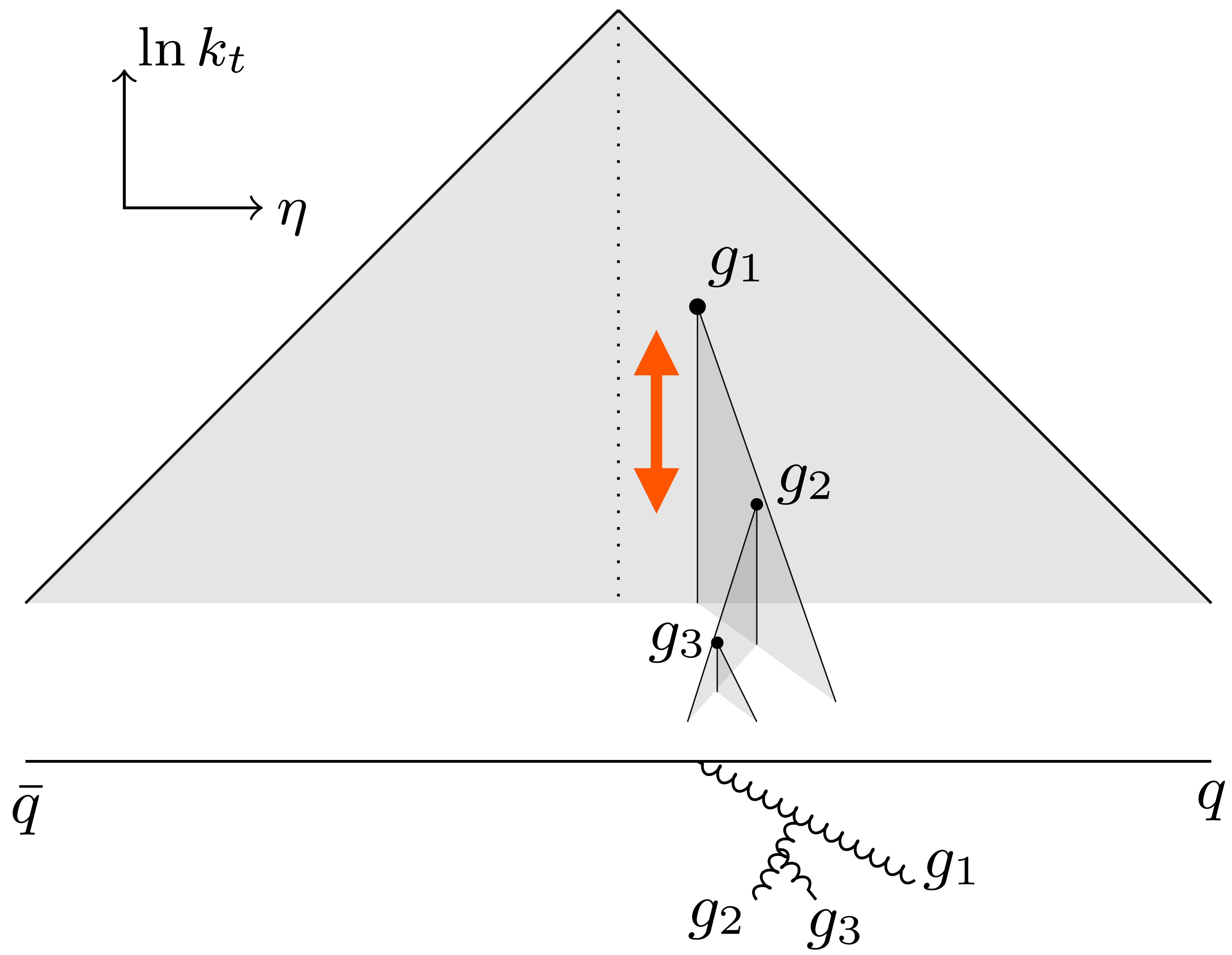

$$\text{Line} \longrightarrow \int d\ln k_t \sim \int d\eta \sim L/\text{emission}$$

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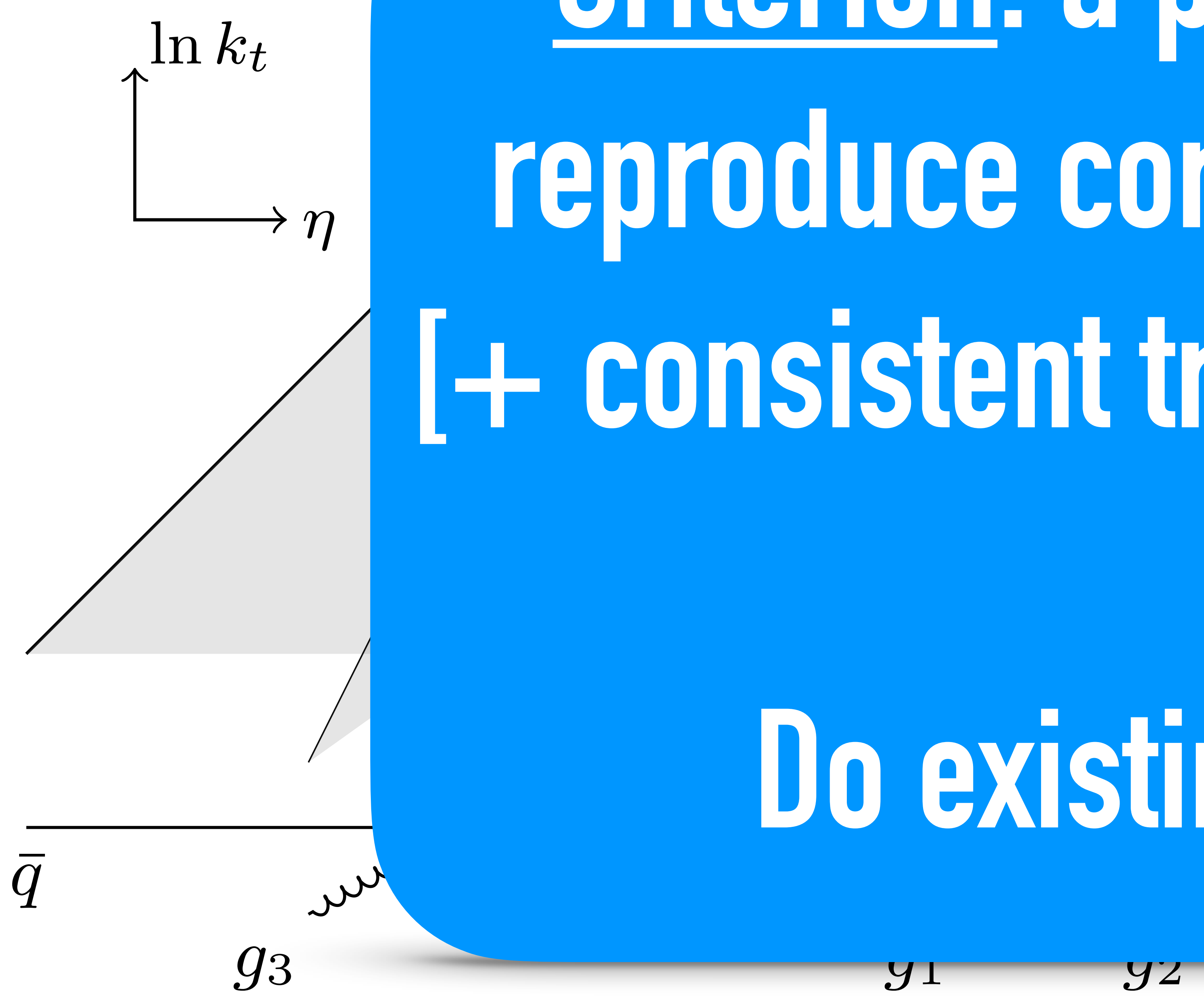

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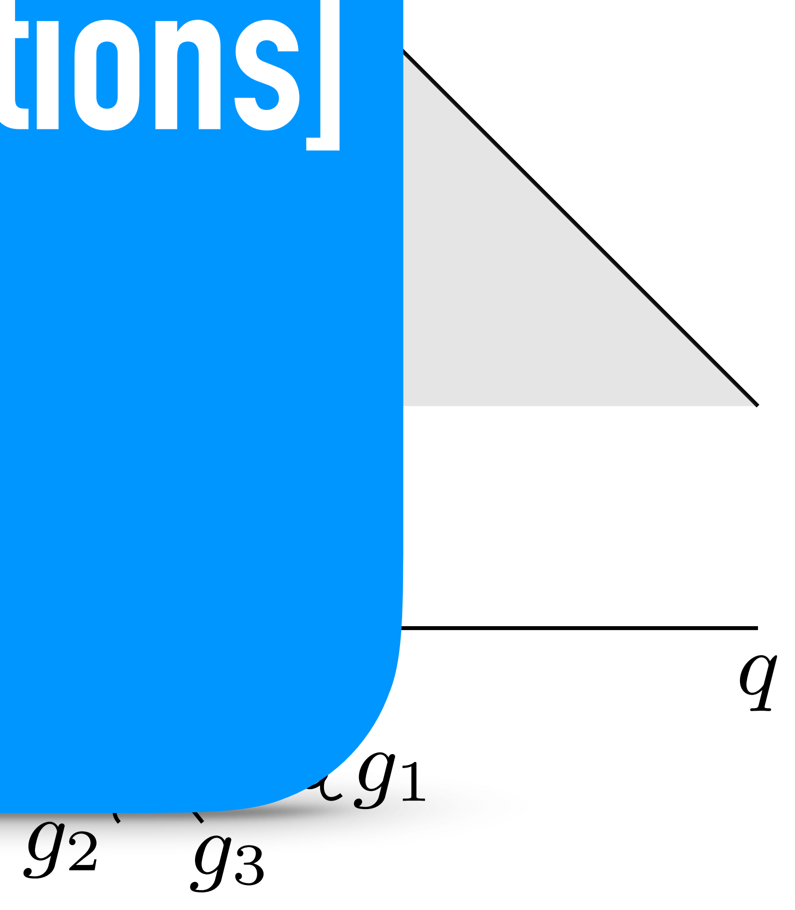


Criterion: a parton shower is expected to reproduce correctly all these limits at once [+ consistent treatment of virtual corrections]

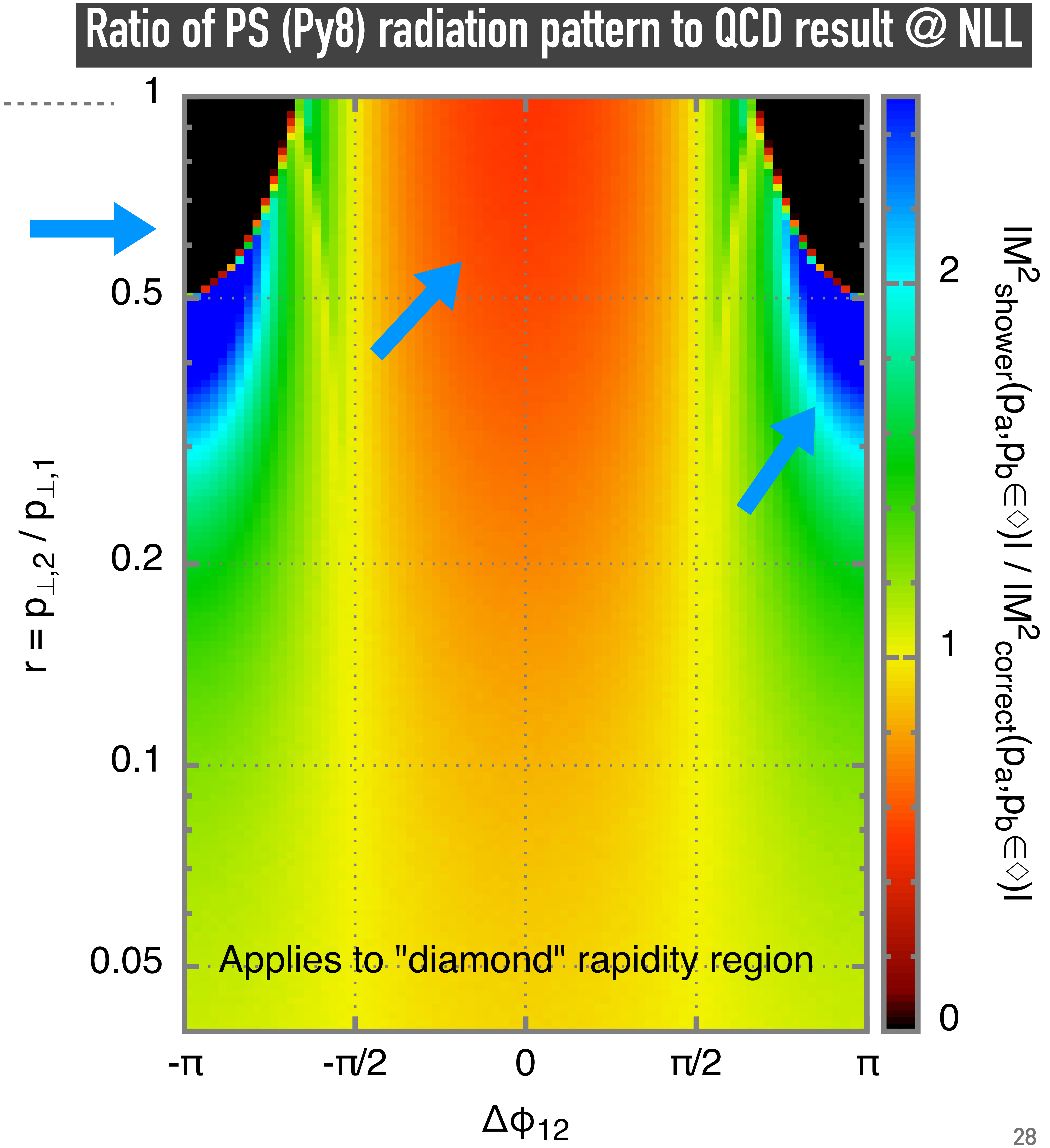
Do existing showers satisfy this?

$$\text{Line} \longrightarrow \int d\ln k_t \sim \int d\eta \sim L/\text{emission}$$

Definition used in QCD resummations, e. g.
[Banfi, Salam, Zanderighi ’04; Banfi, McAslan, PM, Zanderighi (JHEP 2015)]

The double-emission matrix element

- Simplest check: **probability density for radiating two (soft) gluons**
- Compare the result of common showers (e.g. Pythia8, DiRE) to that of a QCD calculation
- **Ratio is expected to be = 1** for NLL showers
  [Dasgupta, Dreyer, Hamilton, PM, Salam (JHEP 2018)]



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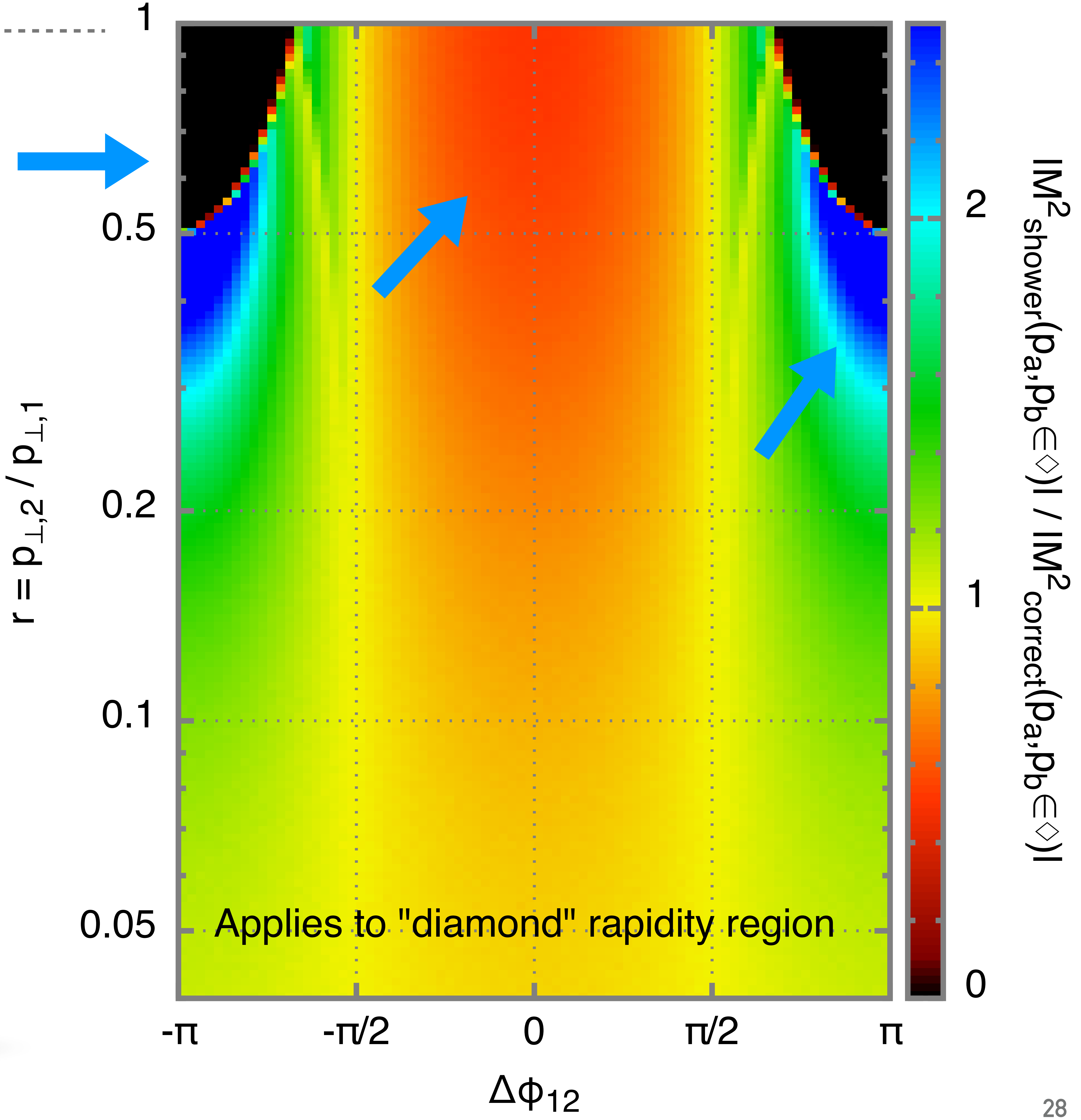
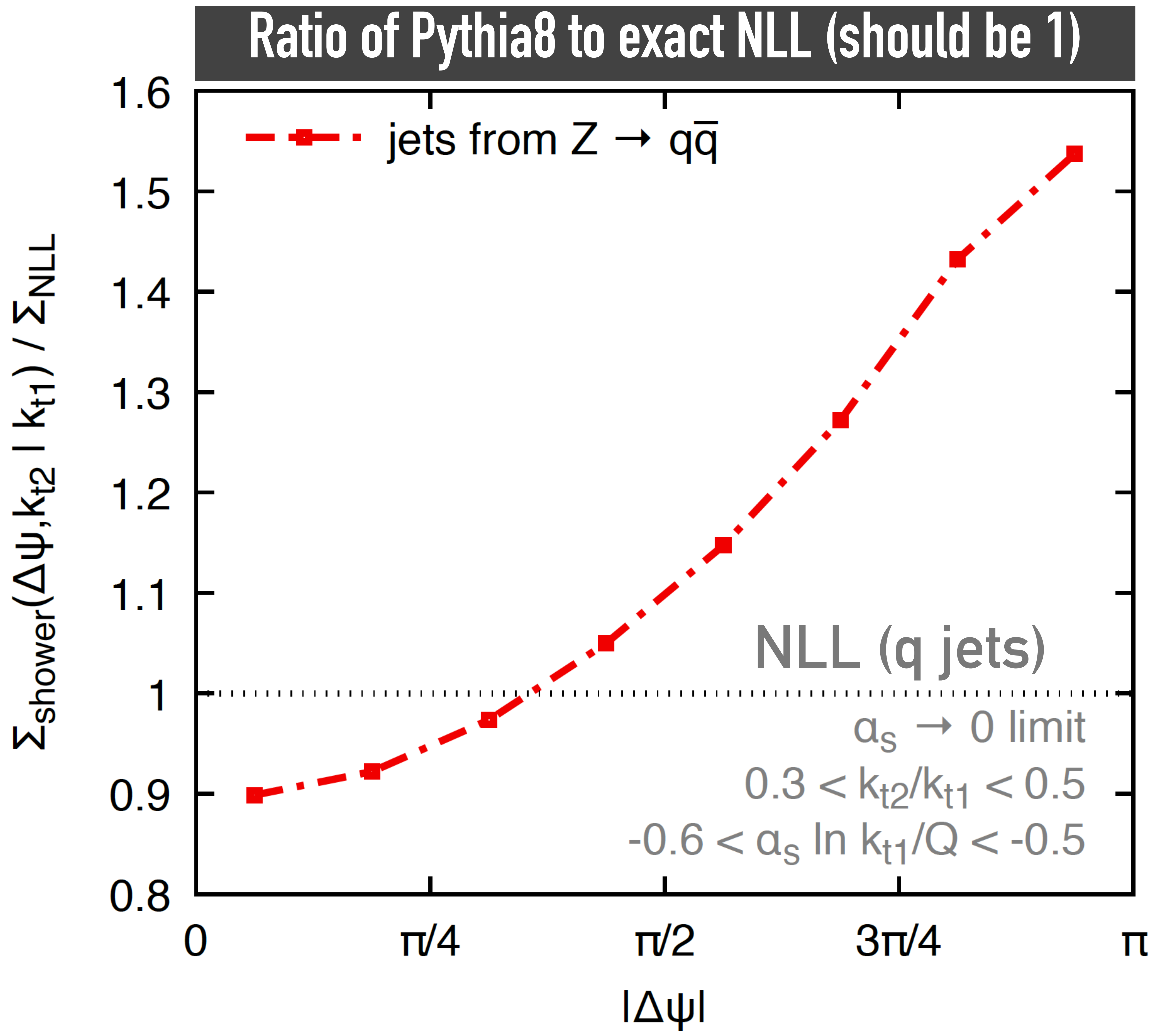
Common parton showers are only LL accurate

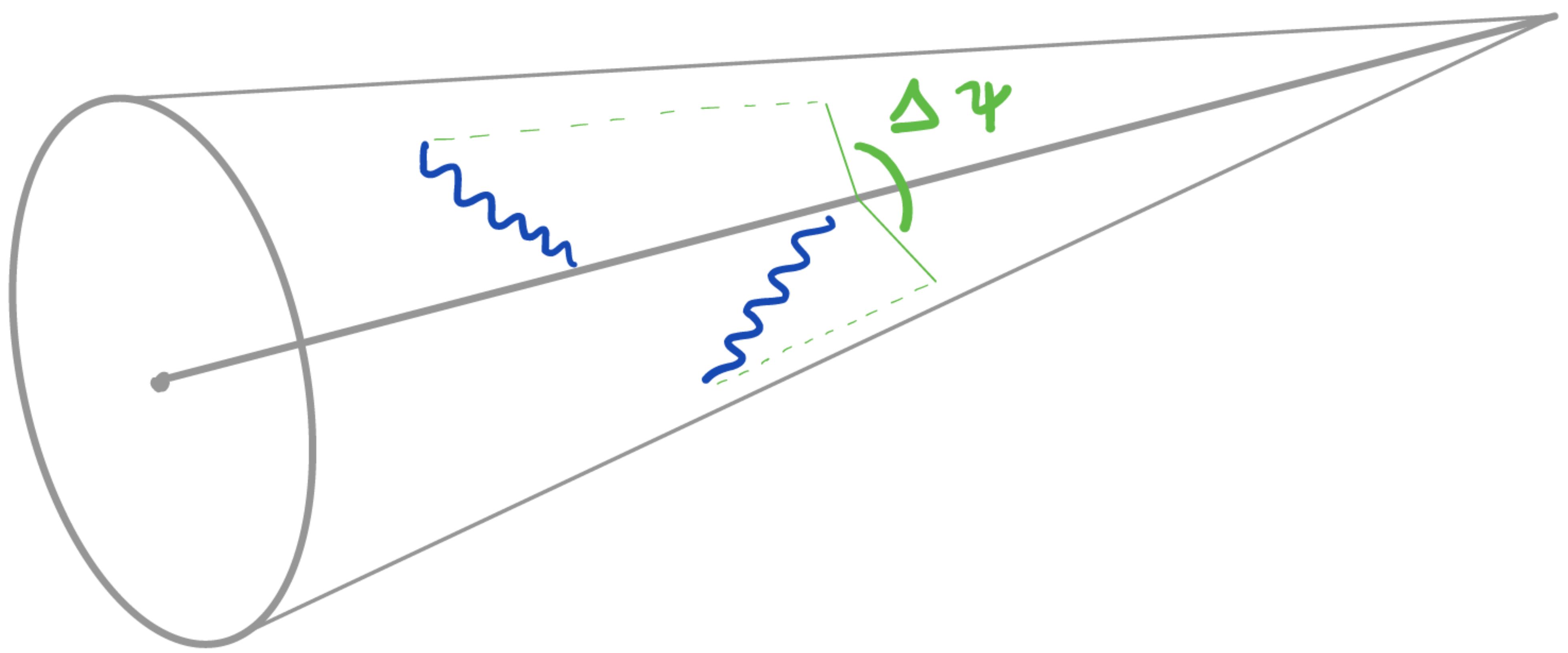
→ large uncertainties $\mathcal{O}(50-100\%)$

Ratio of PS (Py8) radiation pattern to QCD result @ NLL



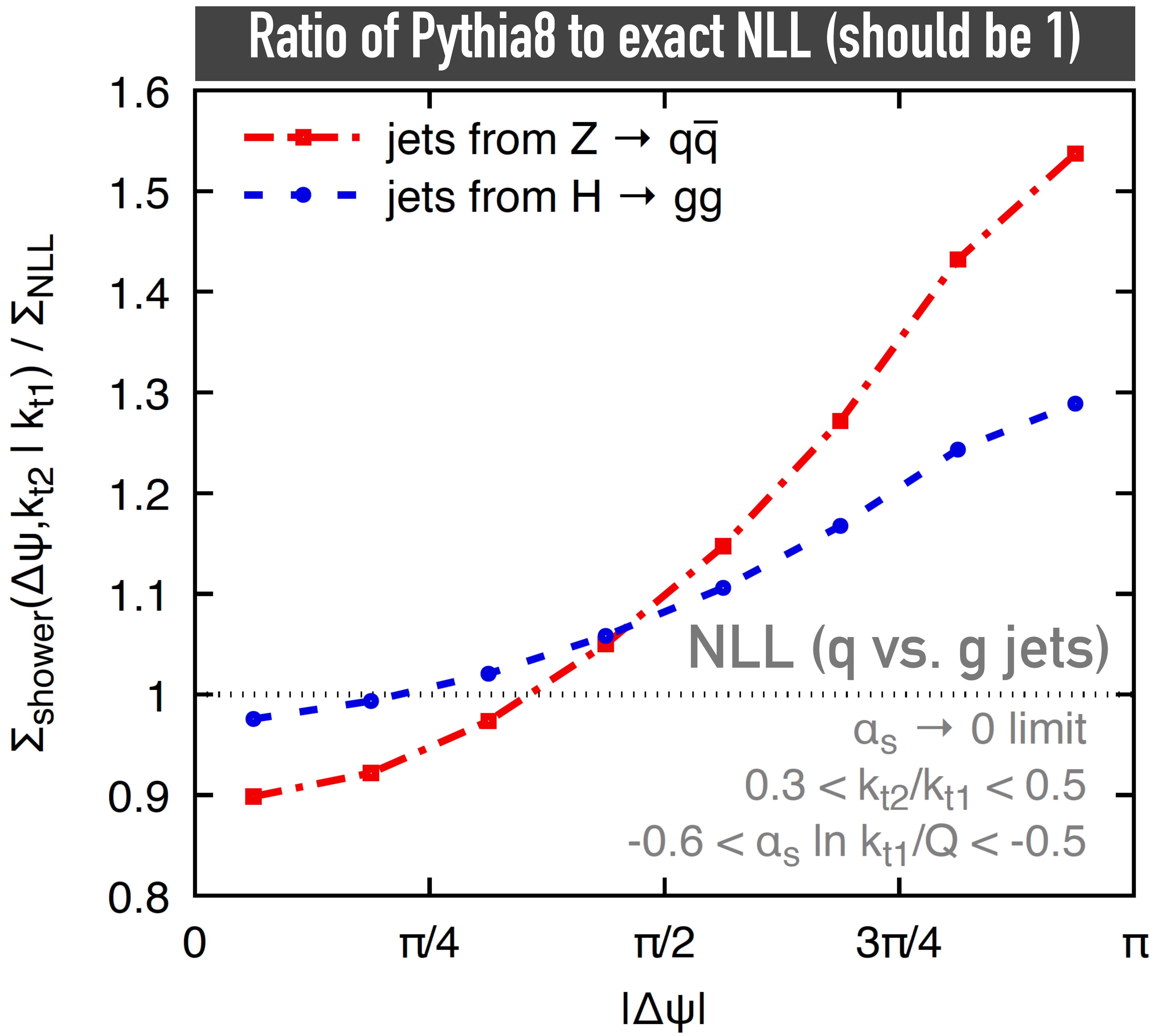
Consequences for accuracy: a jet substructure example

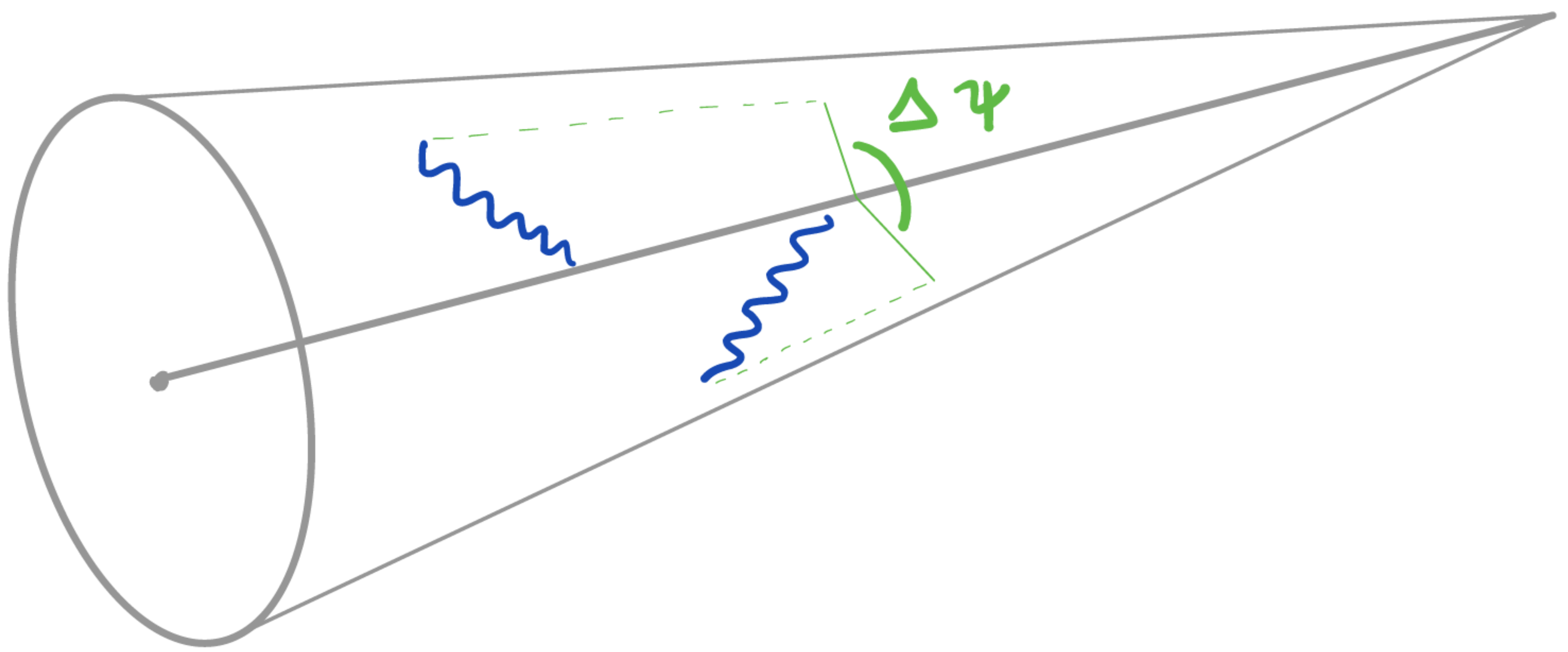




- Consider azimuthal distance between two hardest sub-jets
  - e.g. Z-boson decay: “quark” jets
  - O(60%) differences with NLL result (large theory uncertainty)

Consequences for accuracy: a jet substructure example

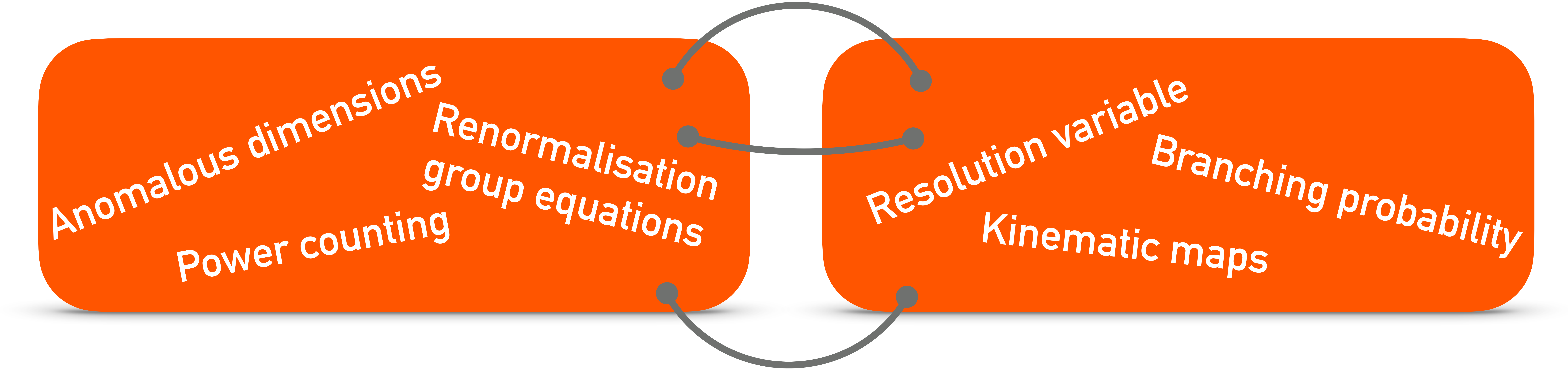




- Consider azimuthal distance between two hardest sub-jets
  - e.g. H-boson decay: "gluon" jets
  - unphysical dependence on jet flavour (potential bias for machine learning)

Formulating NLL parton showers

- Connection between parton showers and perturbative calculations (i.e. resummation) has been an open problem for the past 30 years, i.e. different mathematical language



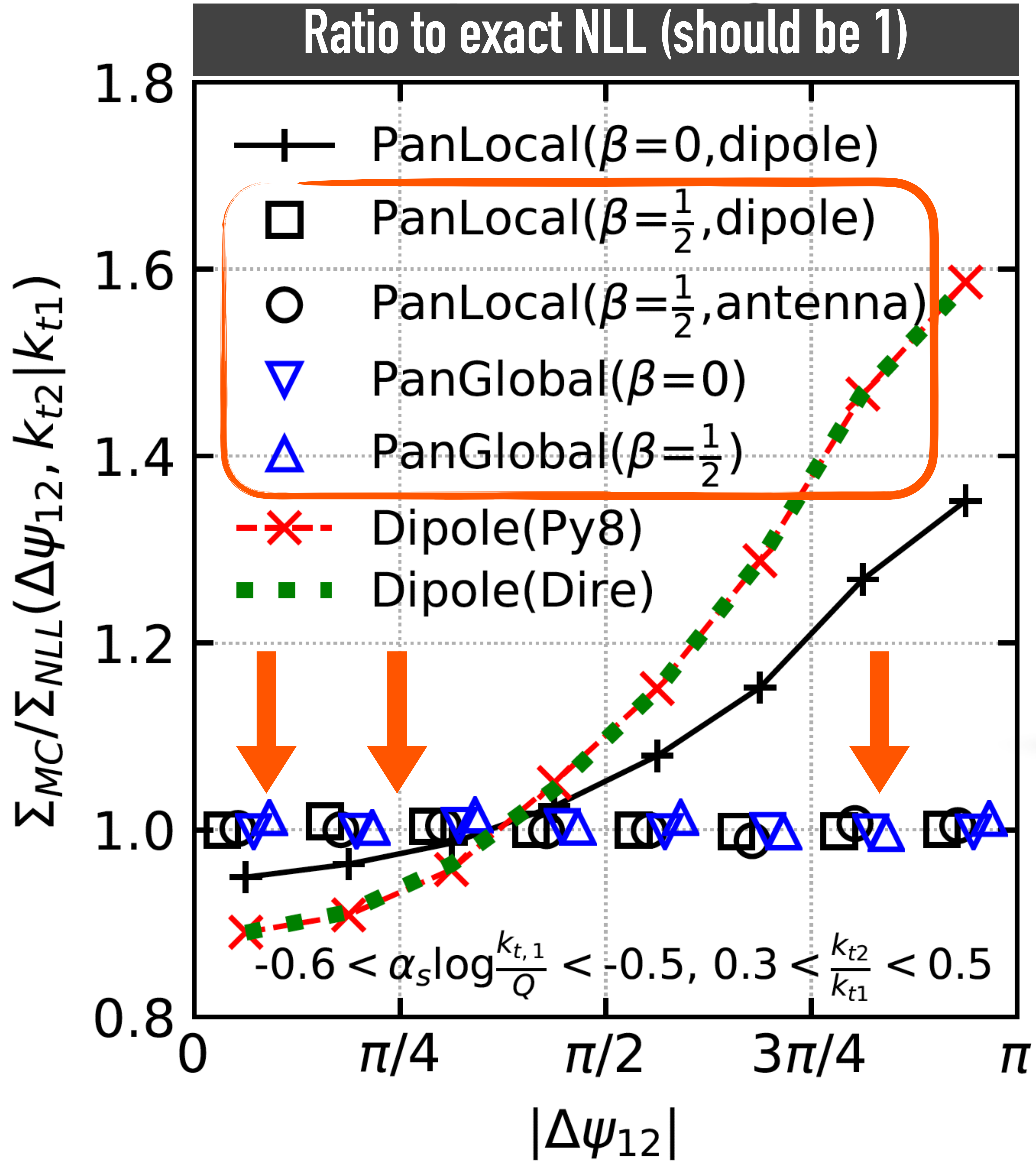
- Mapping of one field into another leads to criteria (e.g. backup) for the building blocks of a PS‡

- Methods to create novel algorithms with higher formal accuracy: the PanScales showers

[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez (PRL 2020)]

‡ QCD resummation provides guidelines, more than one architecture is possible

Back to sub-jet's azimuthal correlations

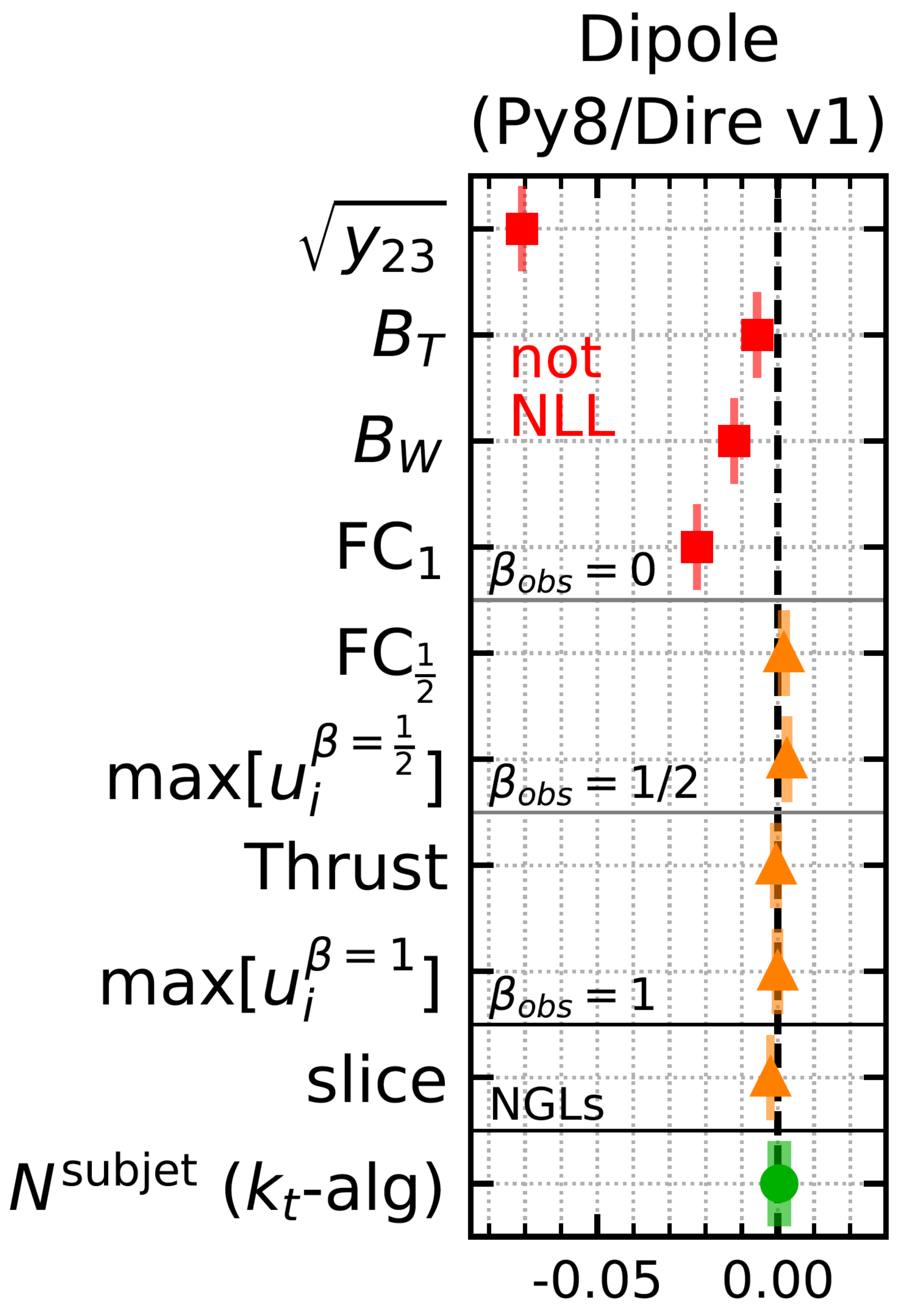


PanScales showers perfectly agree with NLL, while Pythia/Dire do not

[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez (PRL 2020)]

Repeat the test across several collider observables (e+e- collider case)

[Sjostrand et al. (2020); Hoeche, Prestel (2015)]



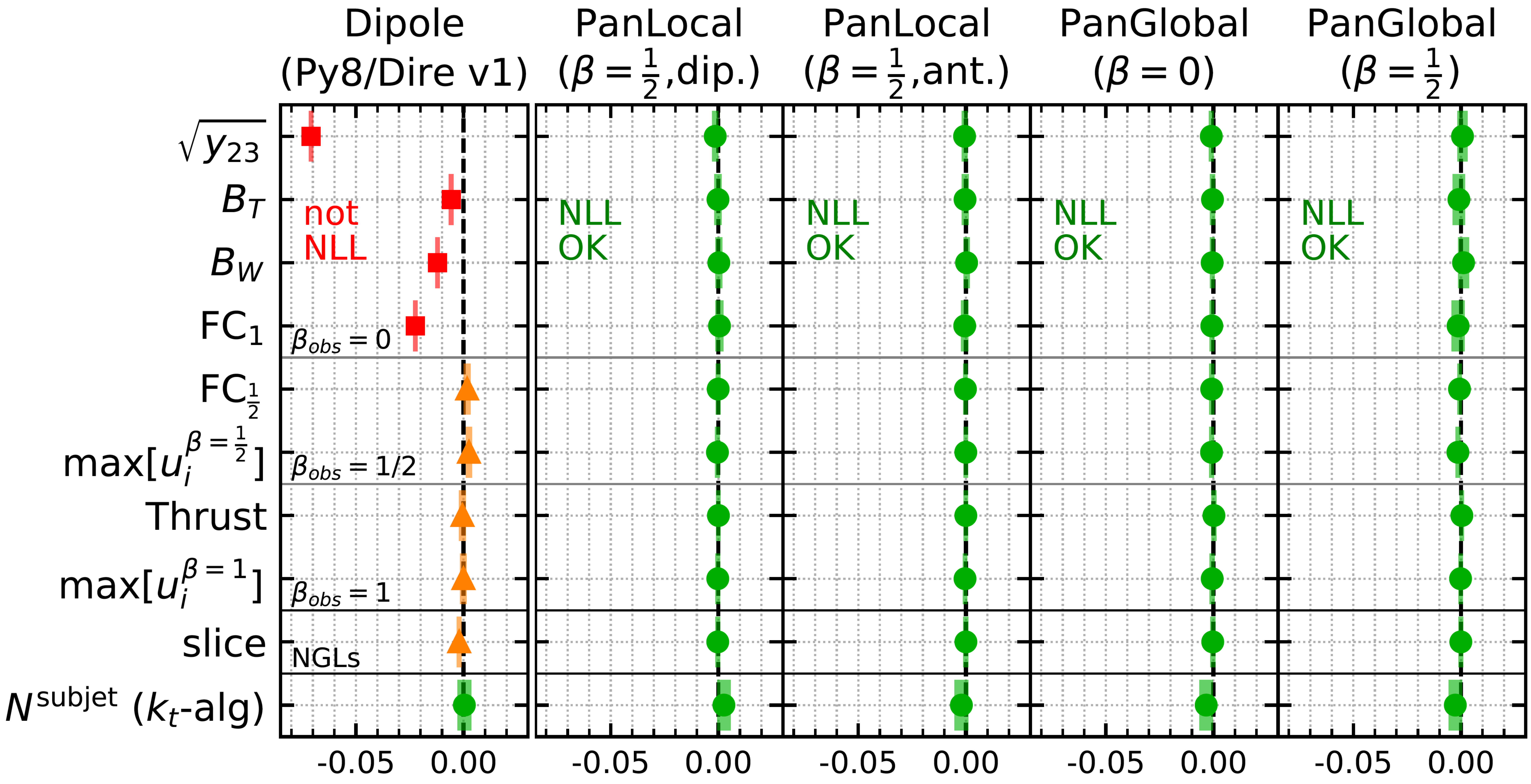
Plot: relative deviations from exact NLL [taken in the relevant kinematic limit]

Only LL accurate

NLL accurate

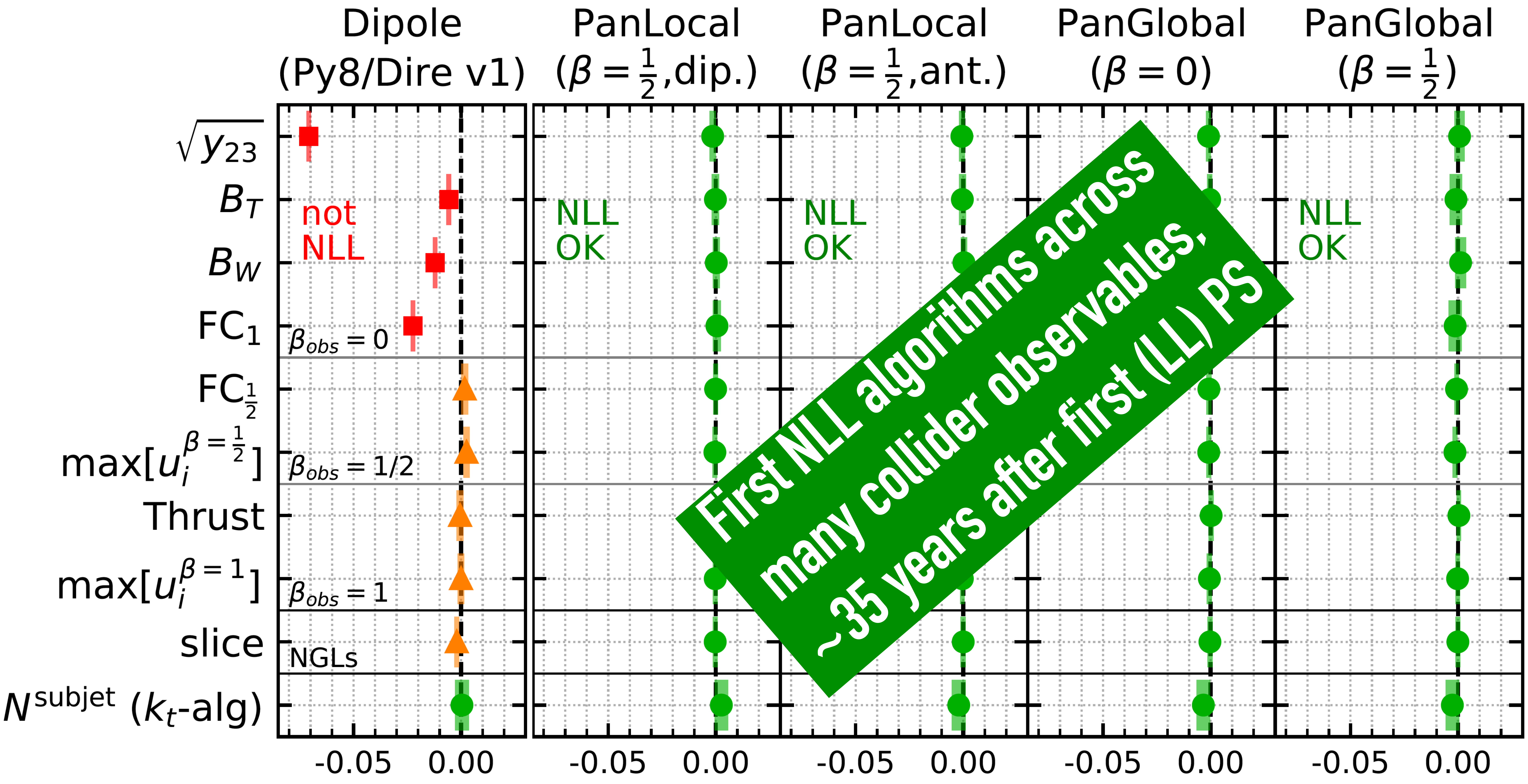
[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez (PRL 2020)]

A new generation of NLL showers: PanScales



[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez (PRL 2020)]

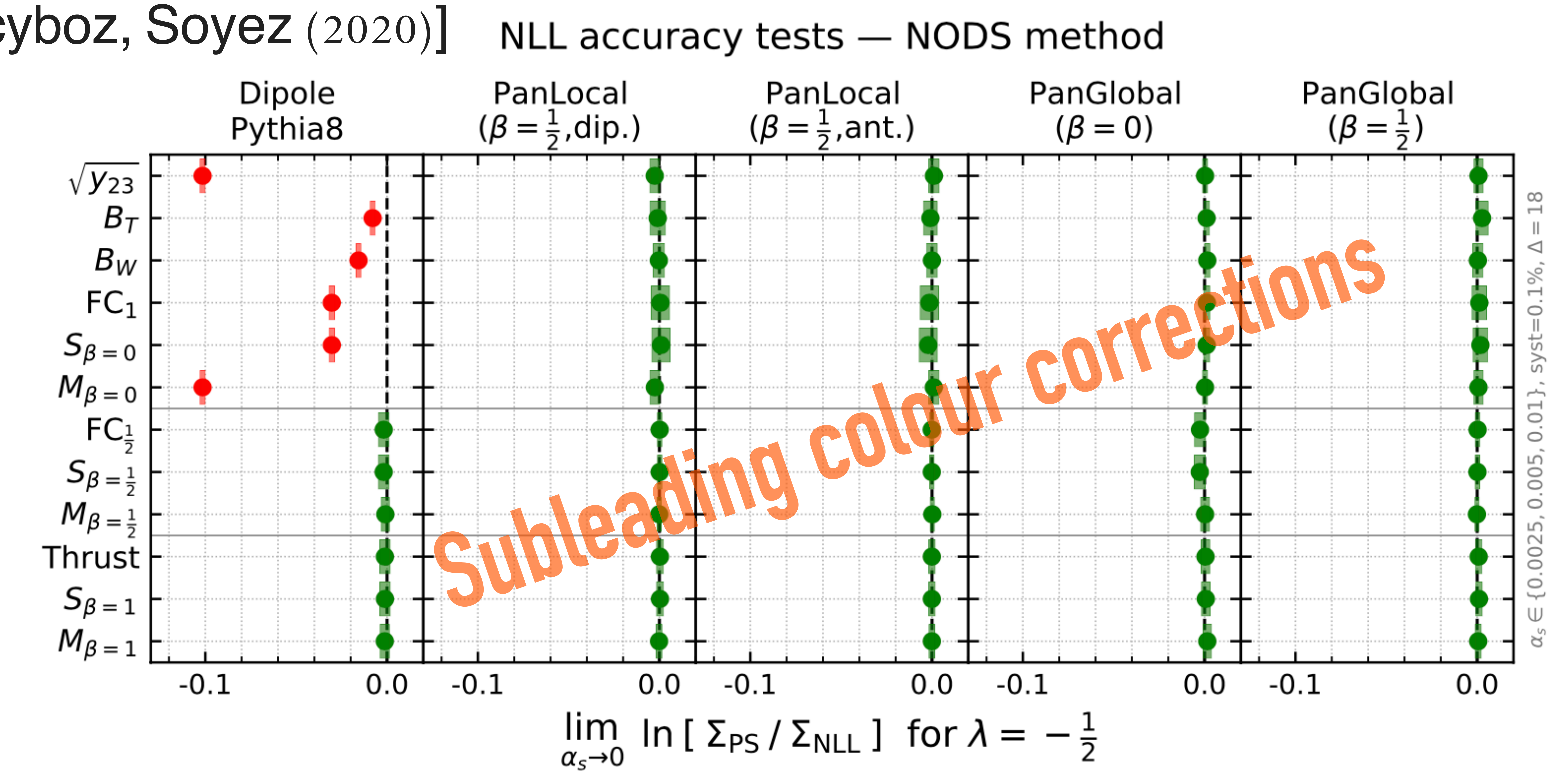
A new generation of NLL showers: PanScales

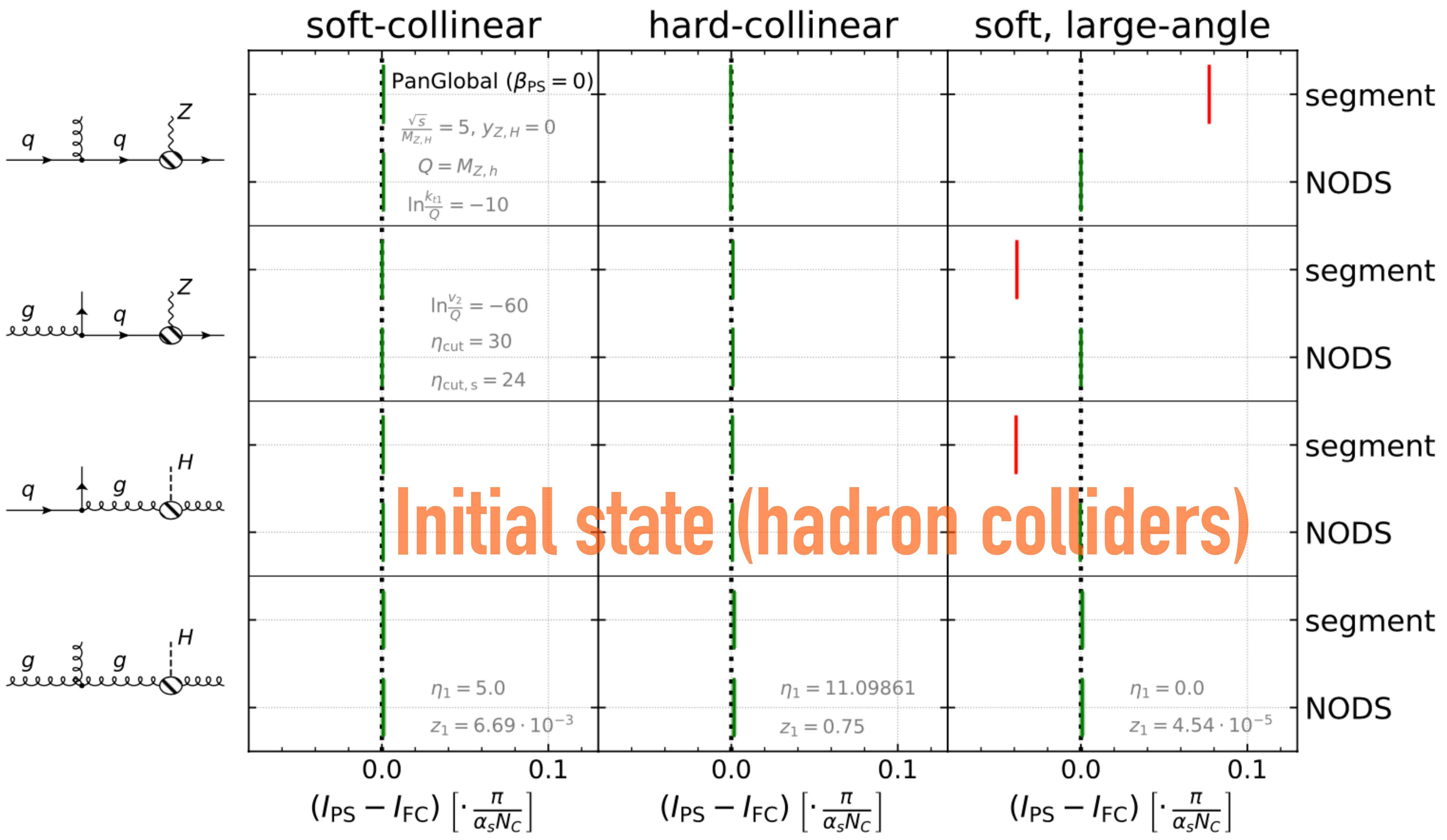


[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez (PRL 2020)]

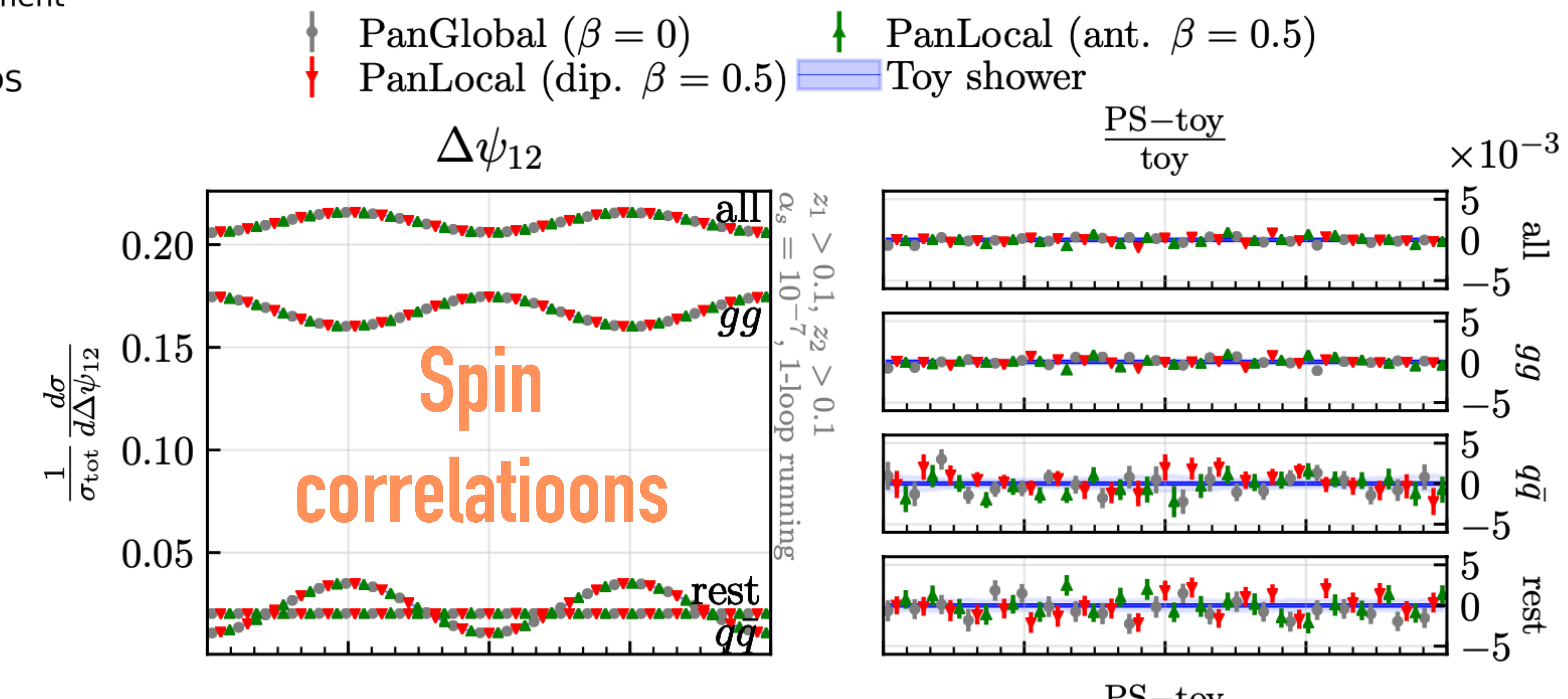
Further developments: towards a full NLL PanScales shower

[Hamilton, Medves, Salam, Scyboz, Soyez (2020)]





[van Beekveld, Ferrario Ravasio, Salam, Soto-Ontoso, Soyez (2022)]

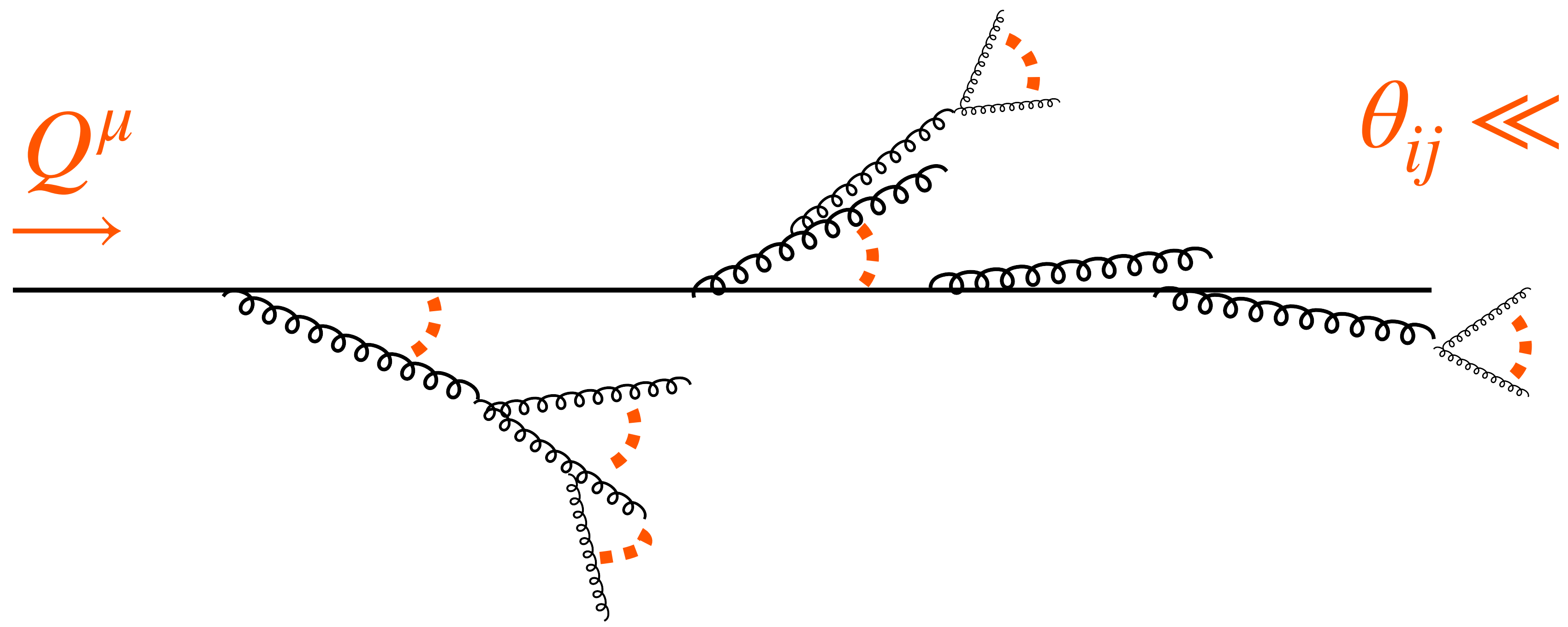


Related work on log accuracy in:
[Bewick, Ferrario Ravasio, Richardson, Seymour (2019);
Forshaw, Holguin, Plaetzer (2020); Nagy, Soper (2020)]

[Karlberg, Salam, Scyboz, Verheyen (2021)] EEEC

Towards few-percent accuracy: NNLL building blocks

differential collinear fragmentation

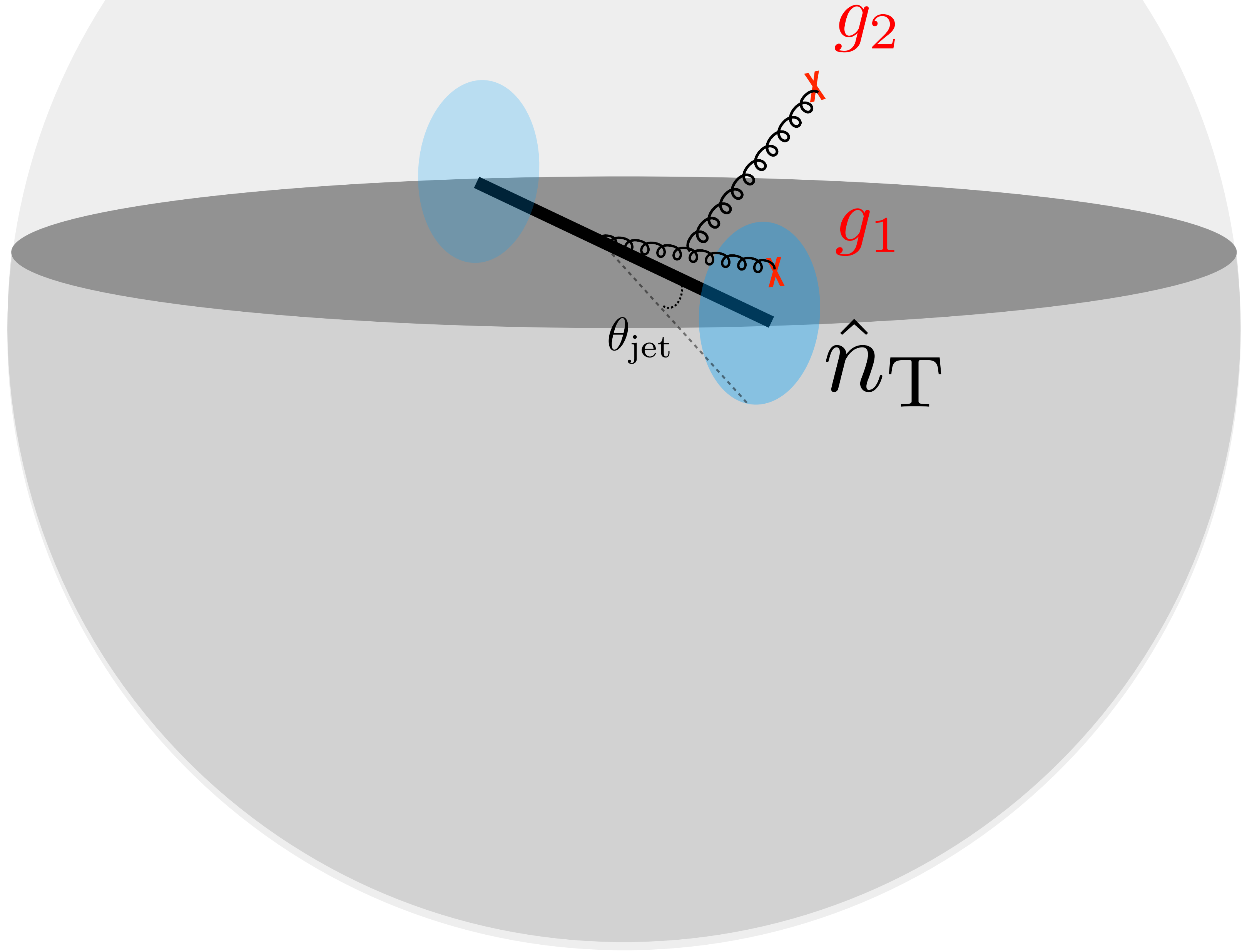


$$\theta_{ij} \ll 1\,, \quad \frac{E_i^2}{Q^2} \sim 1$$

[Dasgupta, El-Menoufi (2021); van Beekveld, Dasgupta, El-Menoufi , PM, Salam (in progress)]

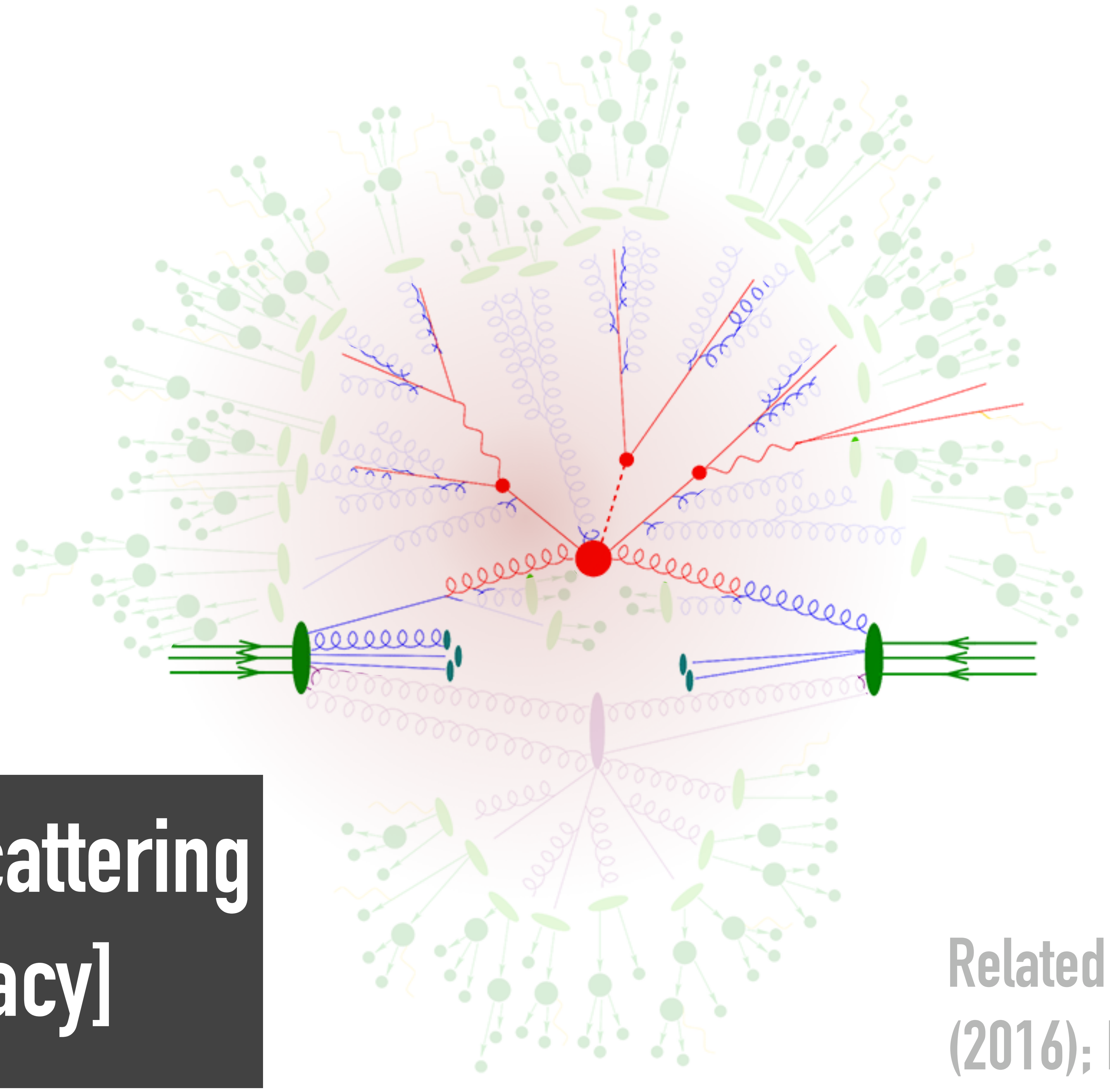
NNLL soft (non-global) evolution [a 20 years old problem]

$$\theta_{ij} \sim 1\,, \quad \frac{E_i^2}{Q^2} \ll 1$$



[Banfi, Dreyer, PM (JHEP 2021 + JHEP 2022)]

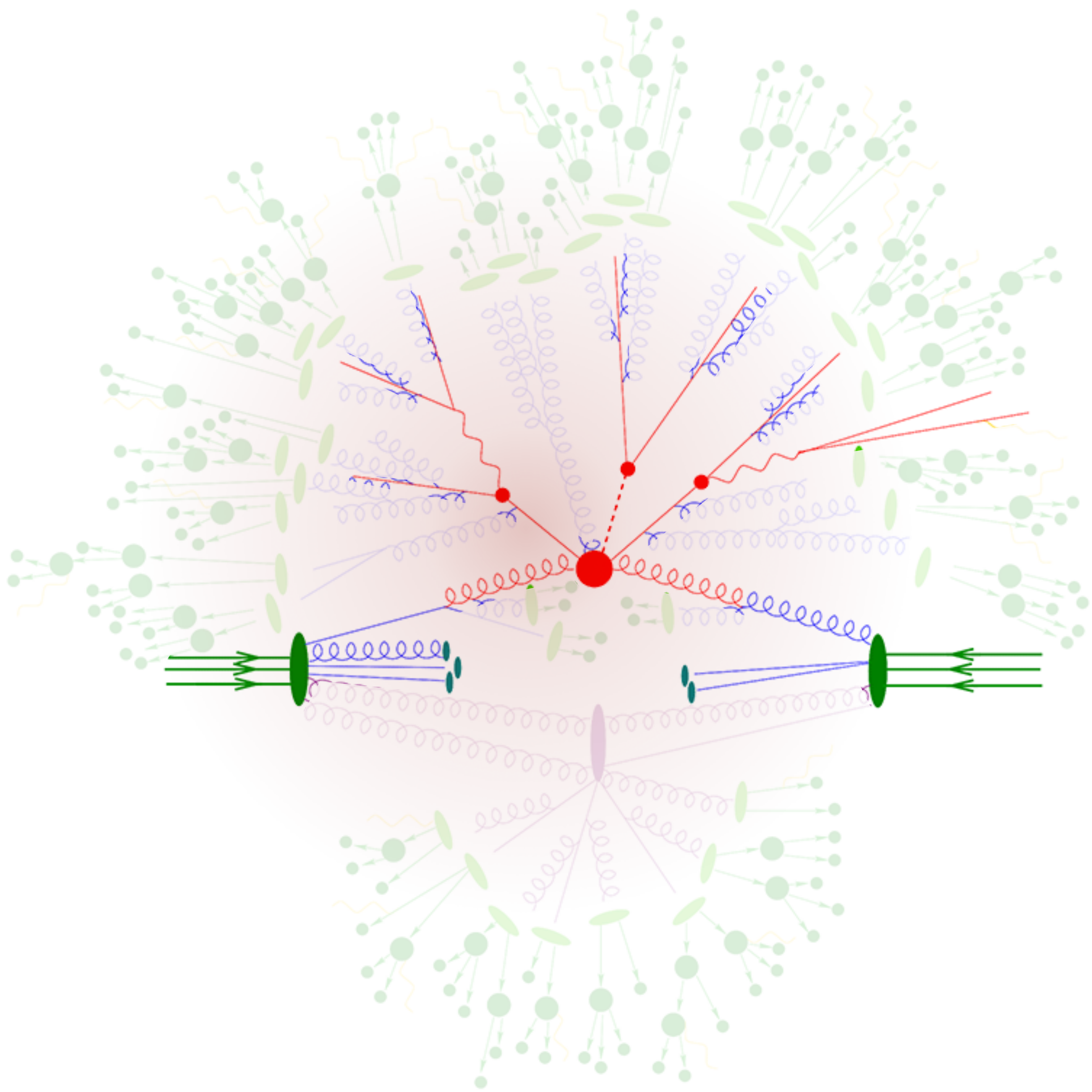
Related work by several groups: [Jadach et al. (2015); Li, Skands (2016); Hoeche, Prestel+Krauss+Dulat+Gellersen (2017-2021)]



Radiative corr^{ns} to hard scattering [preserving PS accuracy]

The hard scattering

The hard partonic scattering

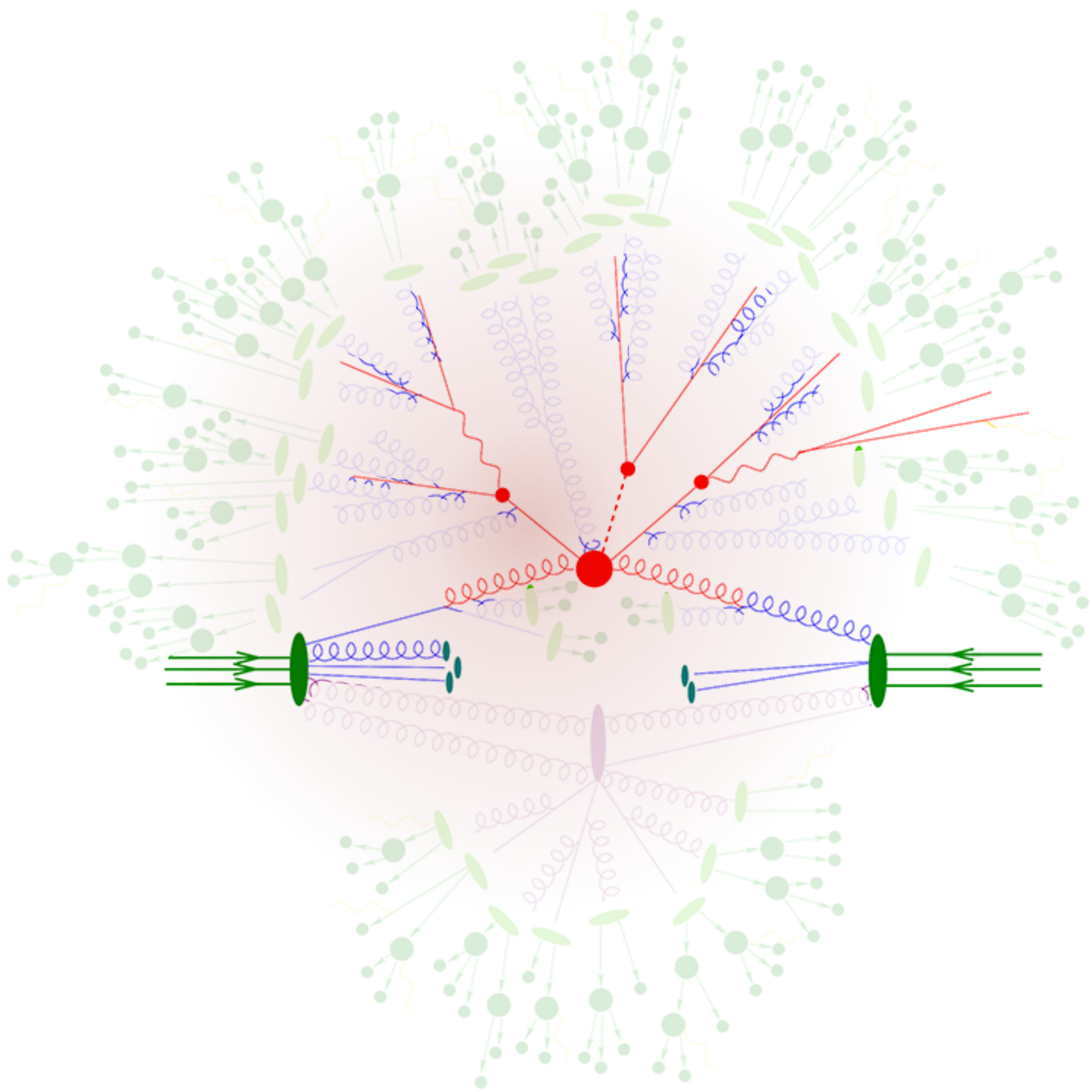


- QCD well described by the radiation of a fixed number of partons (quarks & gluons) [and corresponding virtual corrections]

Perturbation theory: [fixed-order]

$$\alpha_s(M_Z) \sim 0.118 \longrightarrow \begin{cases} \text{NLO} & \sim 10\,\% \\ \text{NNLO} & \sim 1\,\% \\ \dots & \end{cases}$$

The hard partonic scattering



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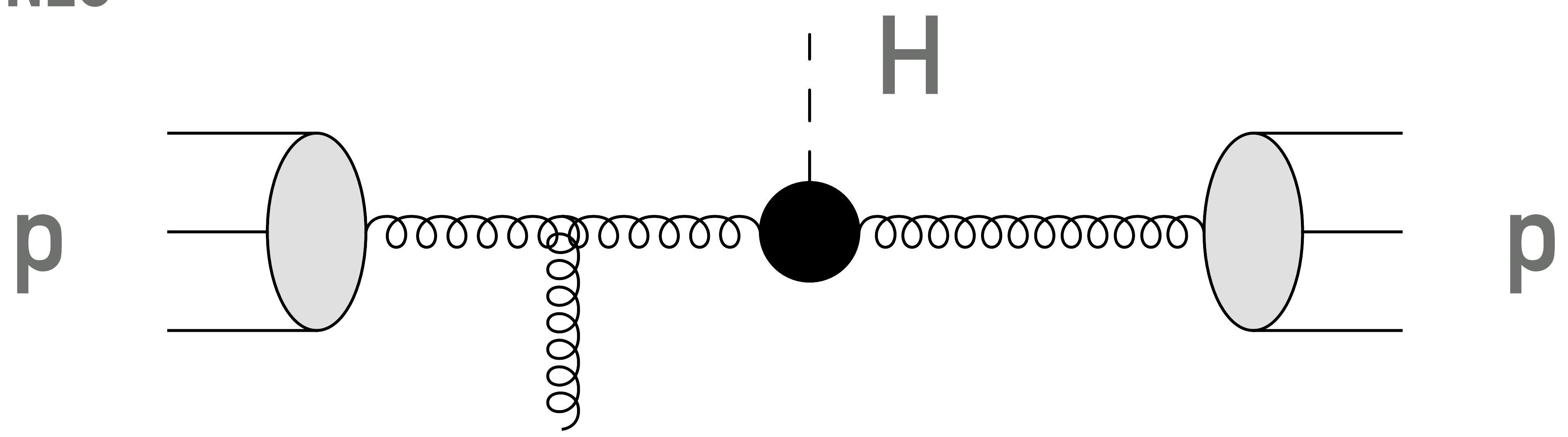
Target: (At least!) Next-to-next-to-leading order corrections with respect to Born approximation: up to two extra emissions

Radiative corrections & interplay with parton showering

- Computation of radiative corrections to the hard process, while
  - Avoiding double-counting with parton shower [PS emits further radiation]

e.g. illustration for Higgs+jet production at NLO
(one order less than our target)



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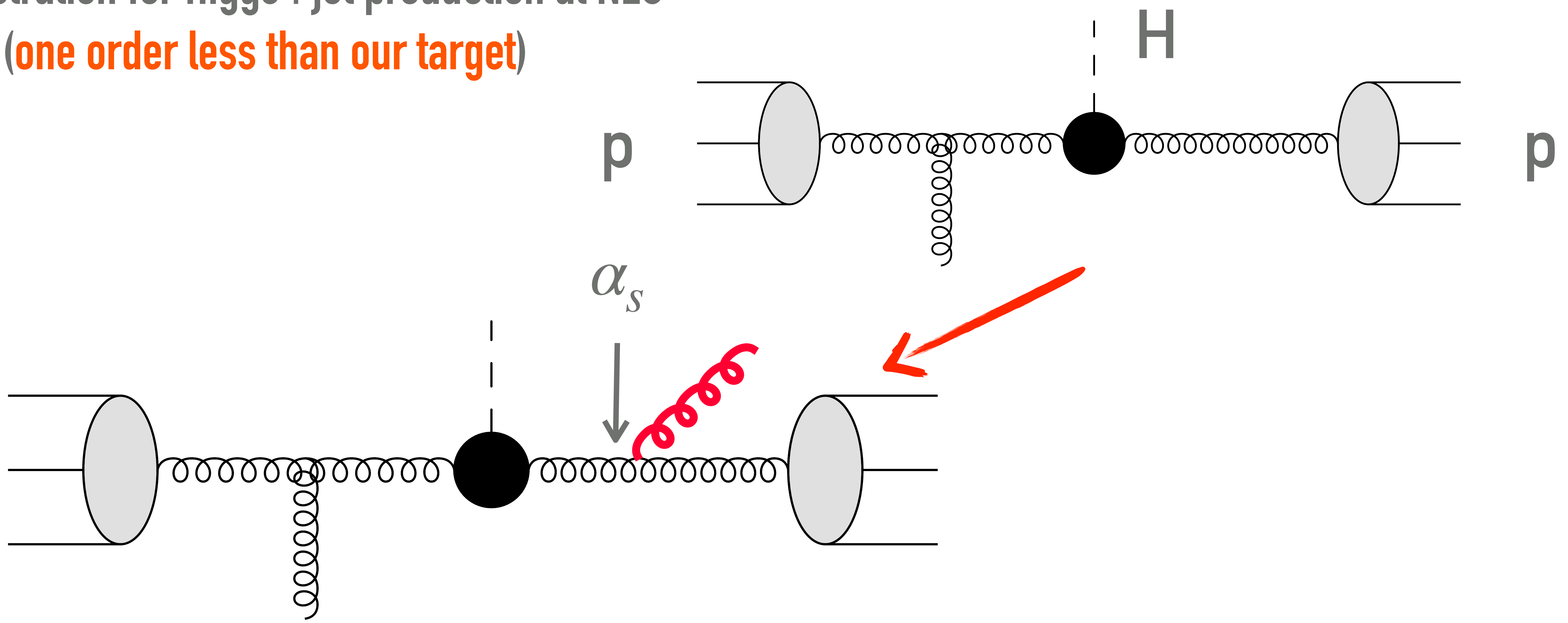

Radiation included by radiative corrections

Radiative corrections & interplay with parton showering

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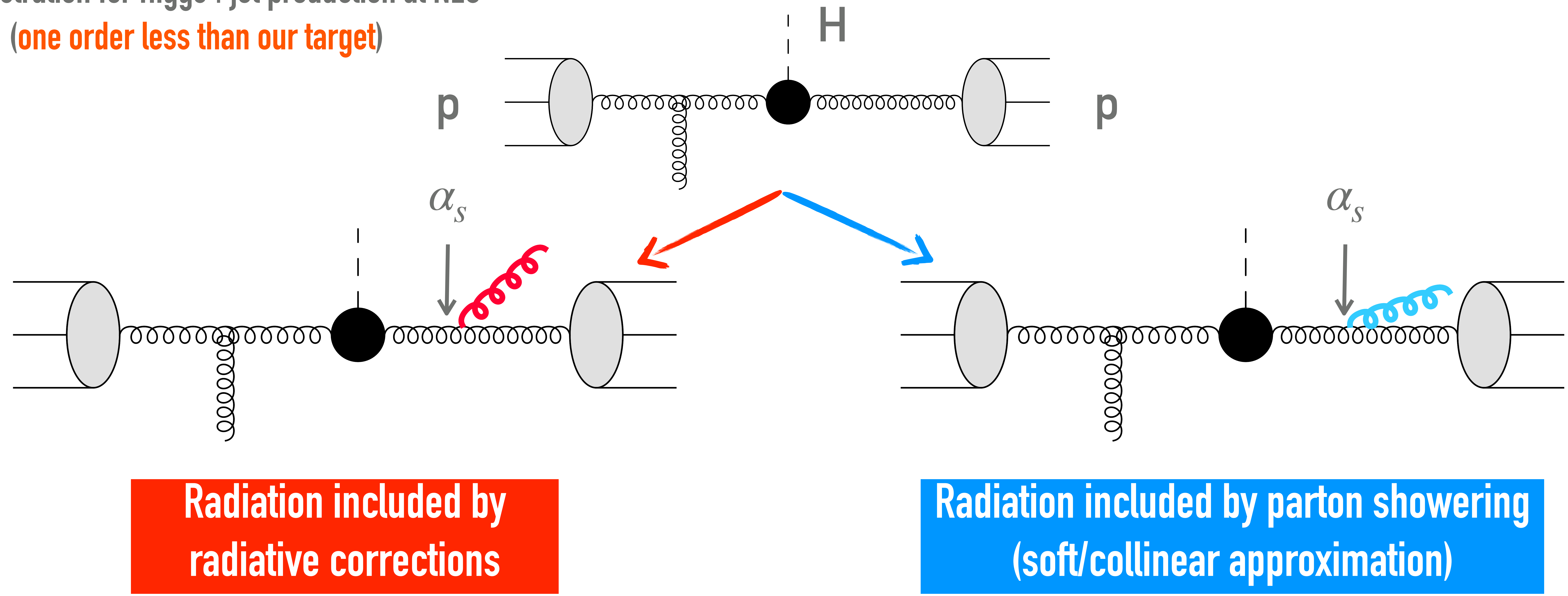

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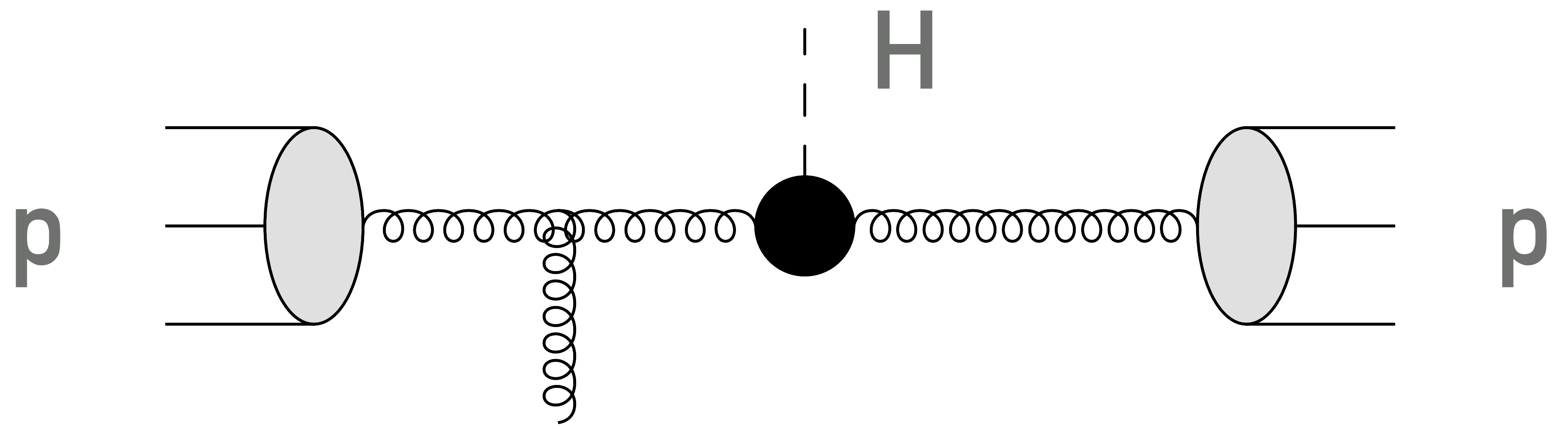

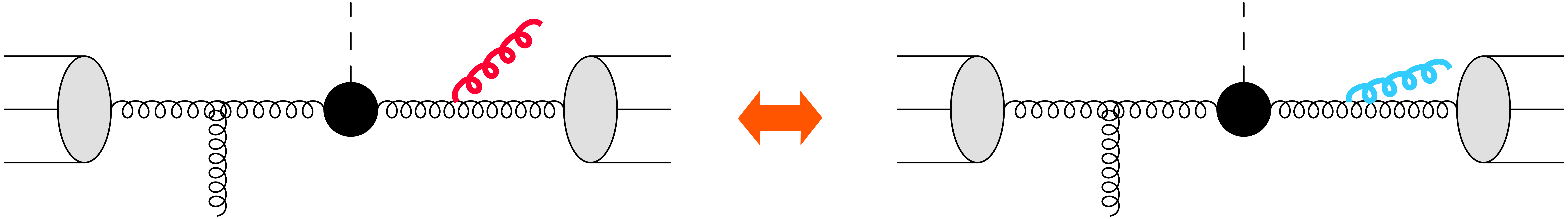

Accuracy broken by double counting across radiation phase space [and virtual corrections]

NLO solutions: [Frixione, Webber ’02; Nason ‘04; Jadach et al. ‘15; Nason, Salam ‘22]

Radiative corrections & interplay with parton showering

- Computation of radiative corrections to the hard process, while
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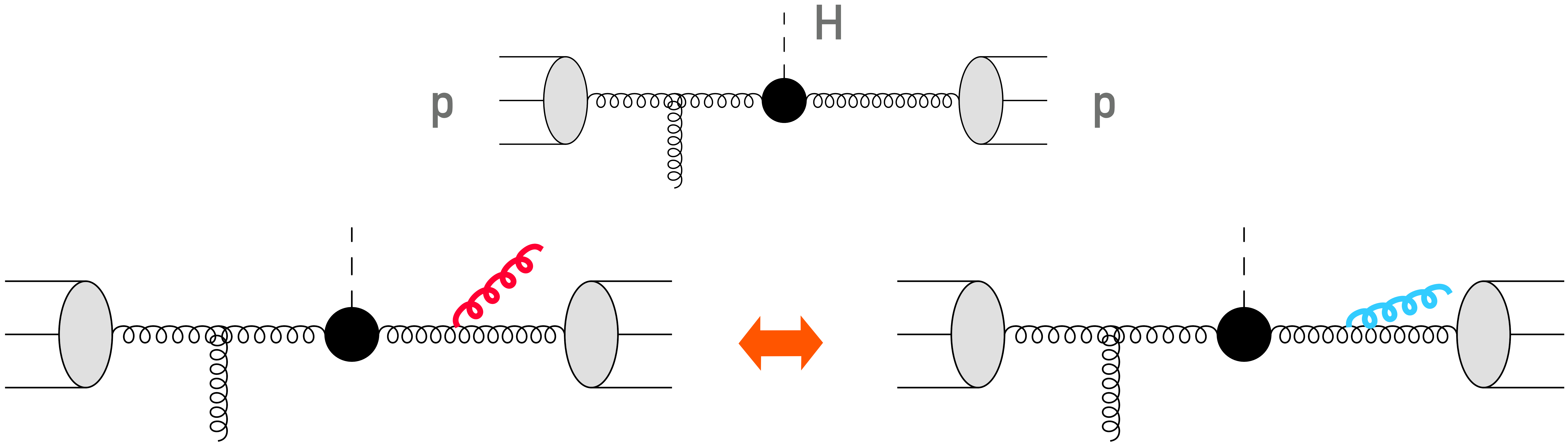

  - Not tampering "too much" with the parton shower [i.e. without spoiling its accuracy, so far LL]

At the same time, we want to keep computational aspects under control [e.g. fraction of negative weights, stability, ...]

Radiative corrections & interplay with parton showering

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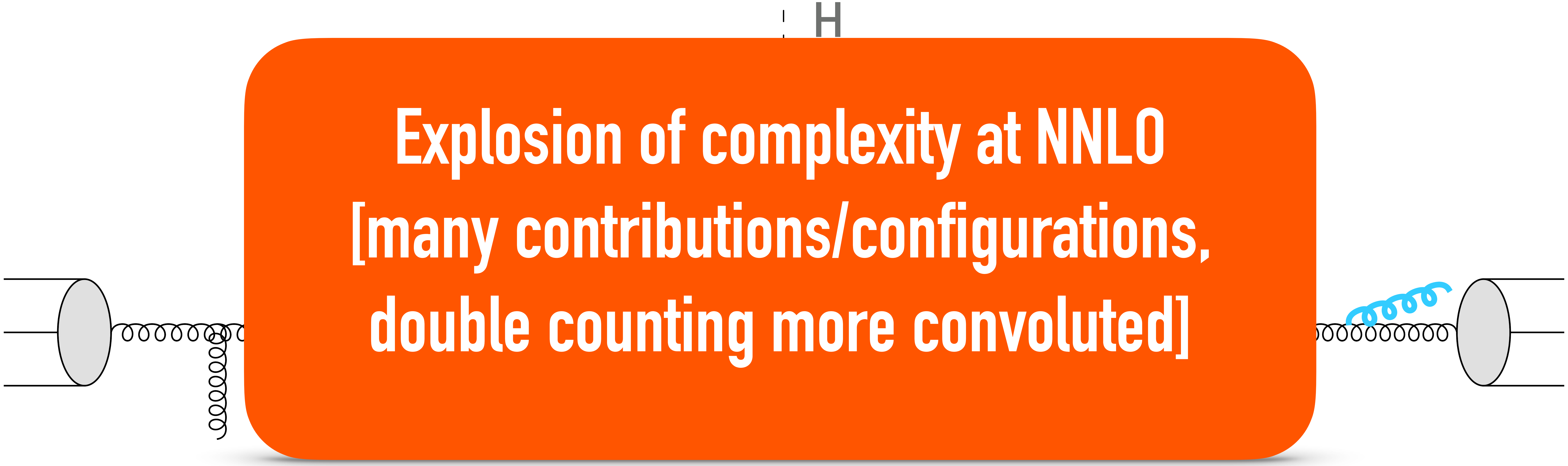


Explosion of complexity at NNLO [many contributions/configurations, double counting more convoluted]

  - Not tampering “too much” with the parton shower [i.e. without spoiling its accuracy, so far LL]

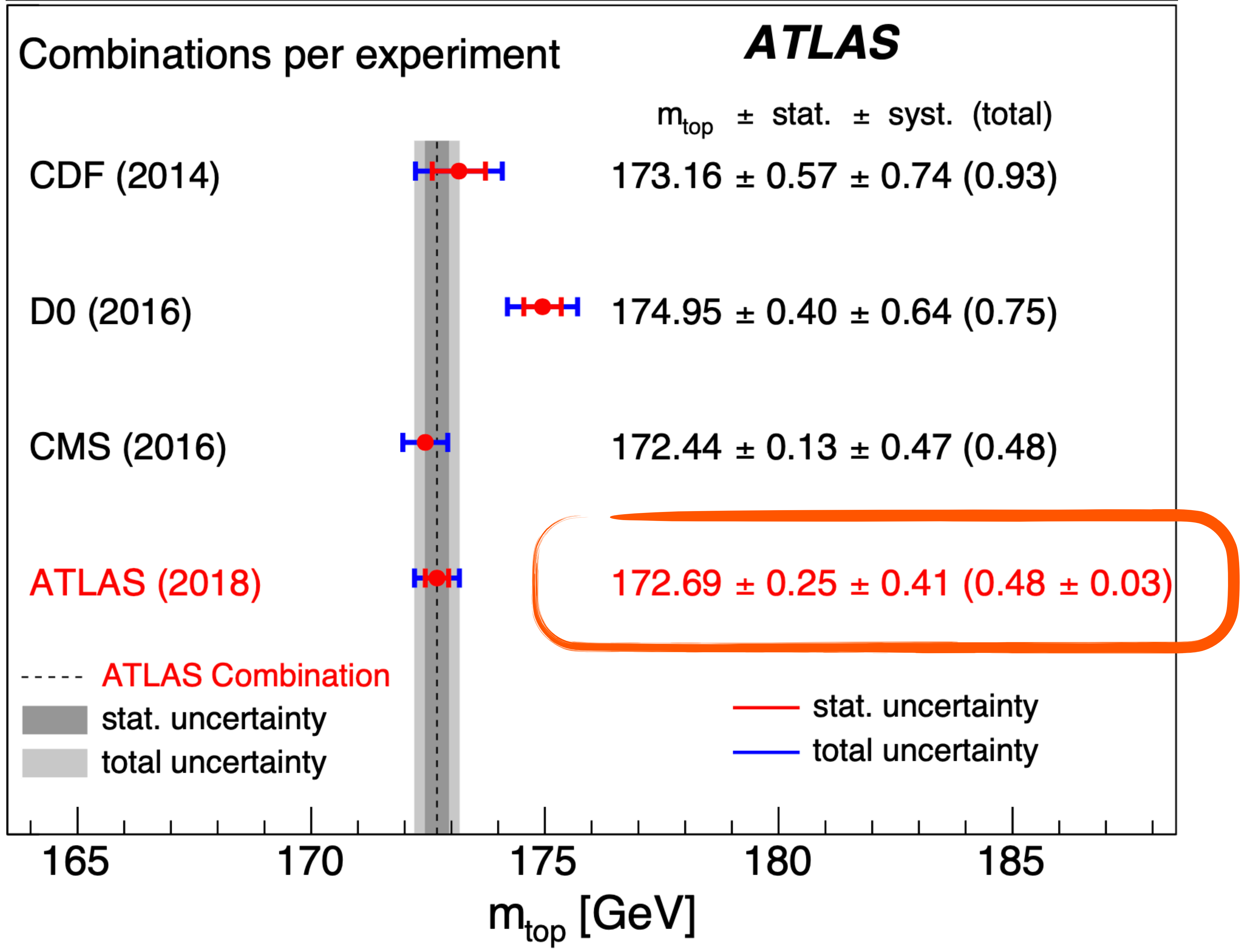
At the same time, we want to keep computational aspects under control [e.g. fraction of negative weights, stability, . . .]

An LHC example: top-quark pair production

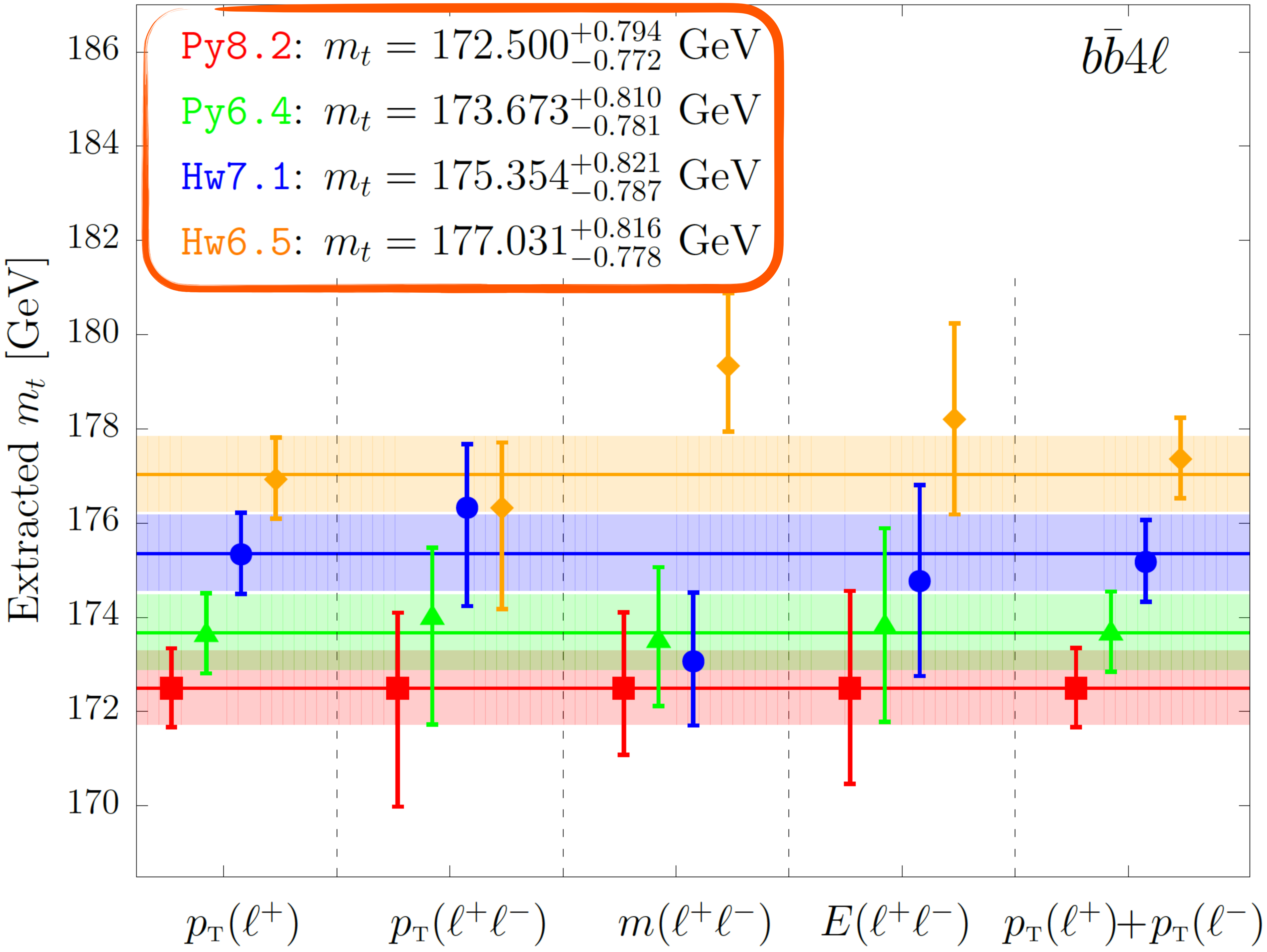
- Main top-quark production mechanism at LHC
  - Several NP scenarios couple to top quark. Important ingredient of EFT fits
- Inaccuracy of generators already a nuisance

[Ferrario Ravasio, Jezo, Nason, Oleari '18]

e.g. Extraction of top pole mass



m_t dependence on parton shower



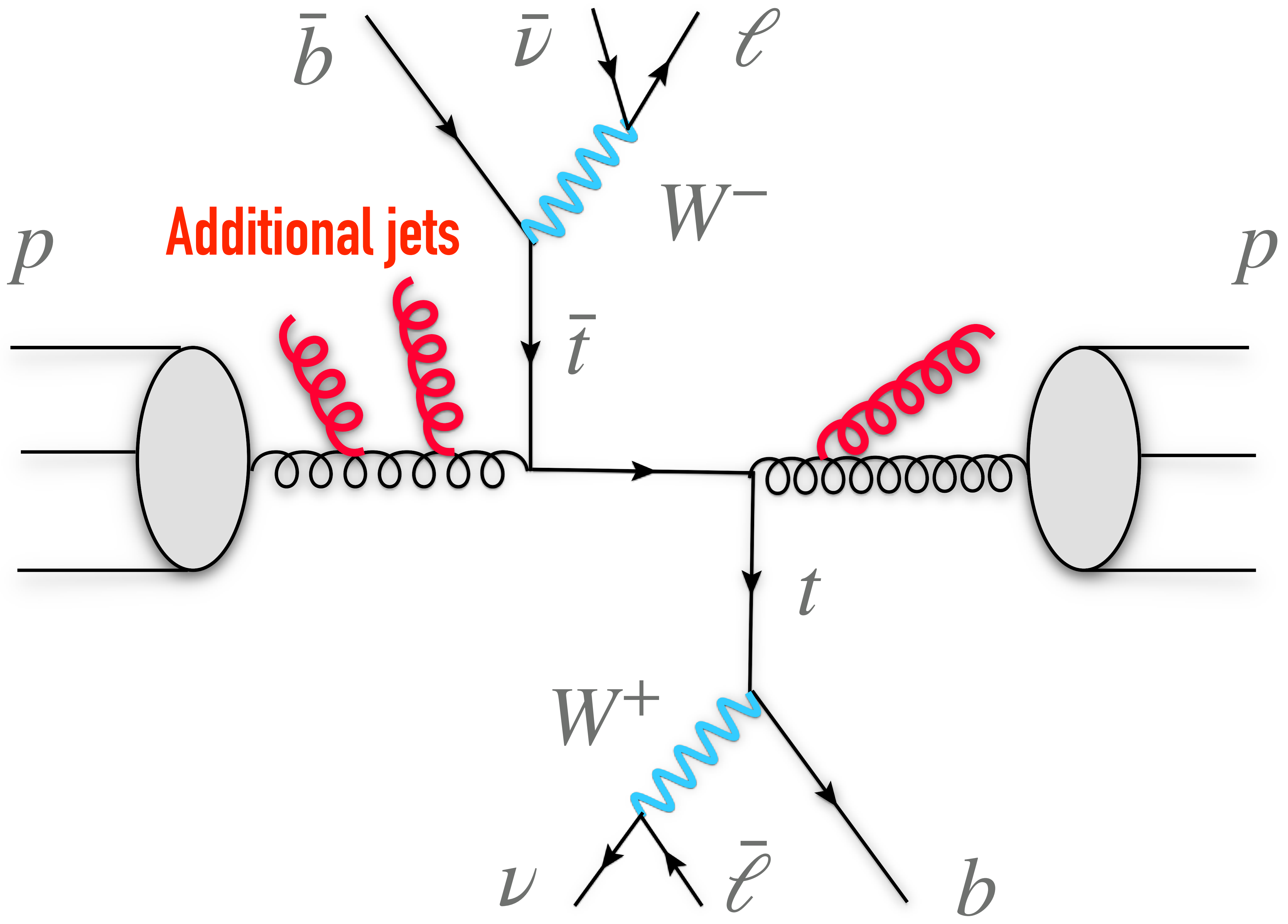
NNLO event generation

- Variety of methods to handle the production of colourless systems (e.g. EW bosons, Higgs boson)

  [Hamilton, Nason, Re, Zanderighi '13; Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi '13; Hoeche, Li, Prestel '14; PM, Nason, Re, Wiesemann, Zanderighi '19; PM, Re, Wiesemann '20; Campbell, Hoeche, Li, Preuss, Skands '21]

- NNLO event generator for top-pair production has remained a challenge for many years
  - Colour charges in initial and final state: involved quantum interference
  - Interplay with parton shower highly non trivial
  - Many body decays: computationally hard

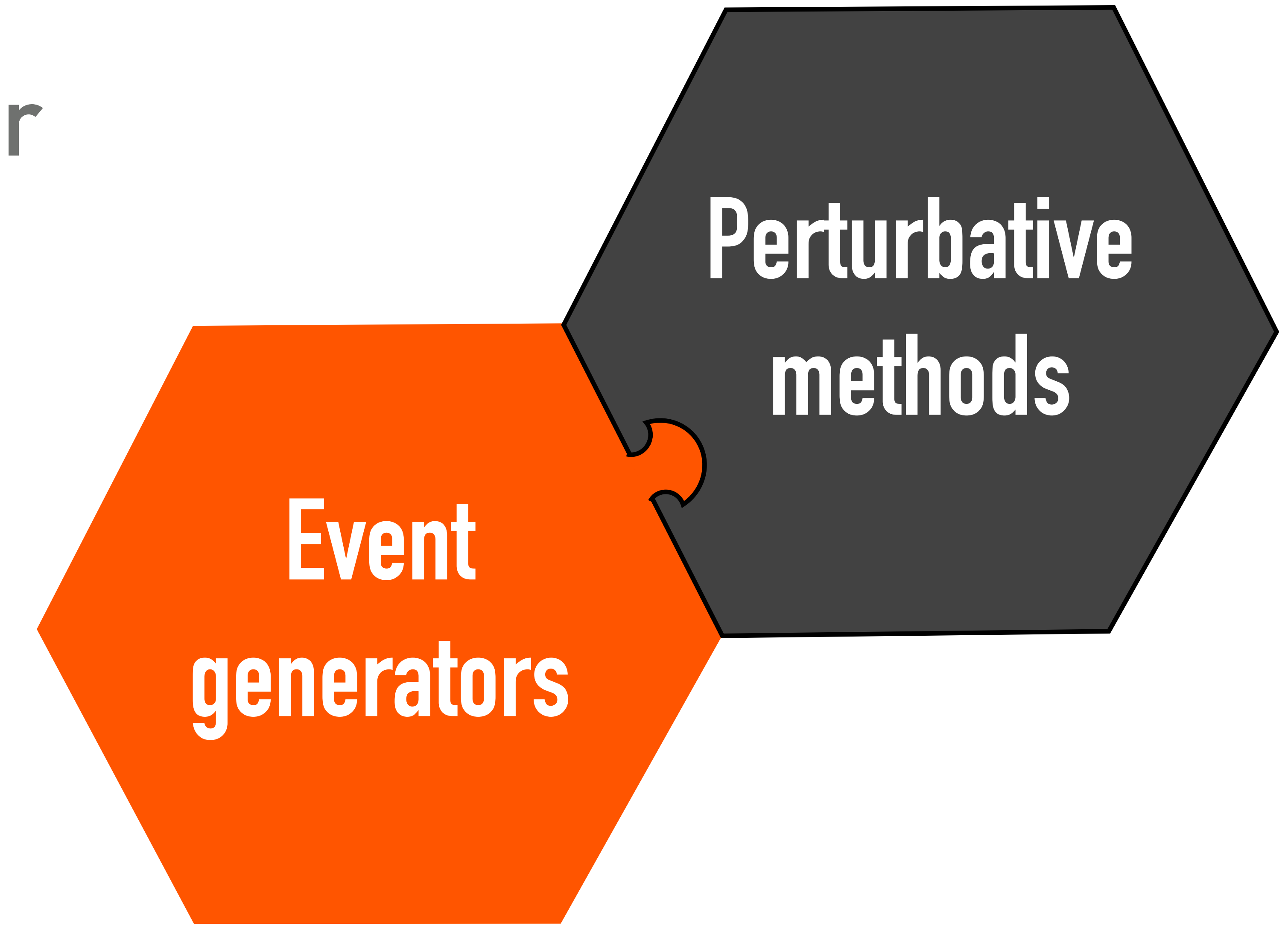
E.g. first NLO generator for $t\bar{t}$ formulated in 2003, it took more than 17 years to achieve NNLO!



The MiNNLO$_{PS}$ method

[PM, Nason, Re, Wiesemann, Zanderighi (JHEP 2019); PM, Re, Wiesemann (EPJC 2020)]

- Main observation: exploit link between perturbative methods and Monte Carlo language
  - Recast NNLO calculation as the first two steps of a parton shower
    [i.e. radiation ordered in resolution variable, Sudakov factors]
  - Fix d.o.f. by matching it to a NNLO perturbative calculation
    [i.e. resummation properties of q_T as a resolution variable]



- Advantages:
  - ☑ Accurate: Fully differential NNLO QCD
  - ☑ Fast: Marginal loss in complexity w.r.t. NLO computation
  - ☑ Flexible: Possible to tackle complex reactions

MiNNLO$_{PS}$: NNLO generator for $t\bar{t}$ production

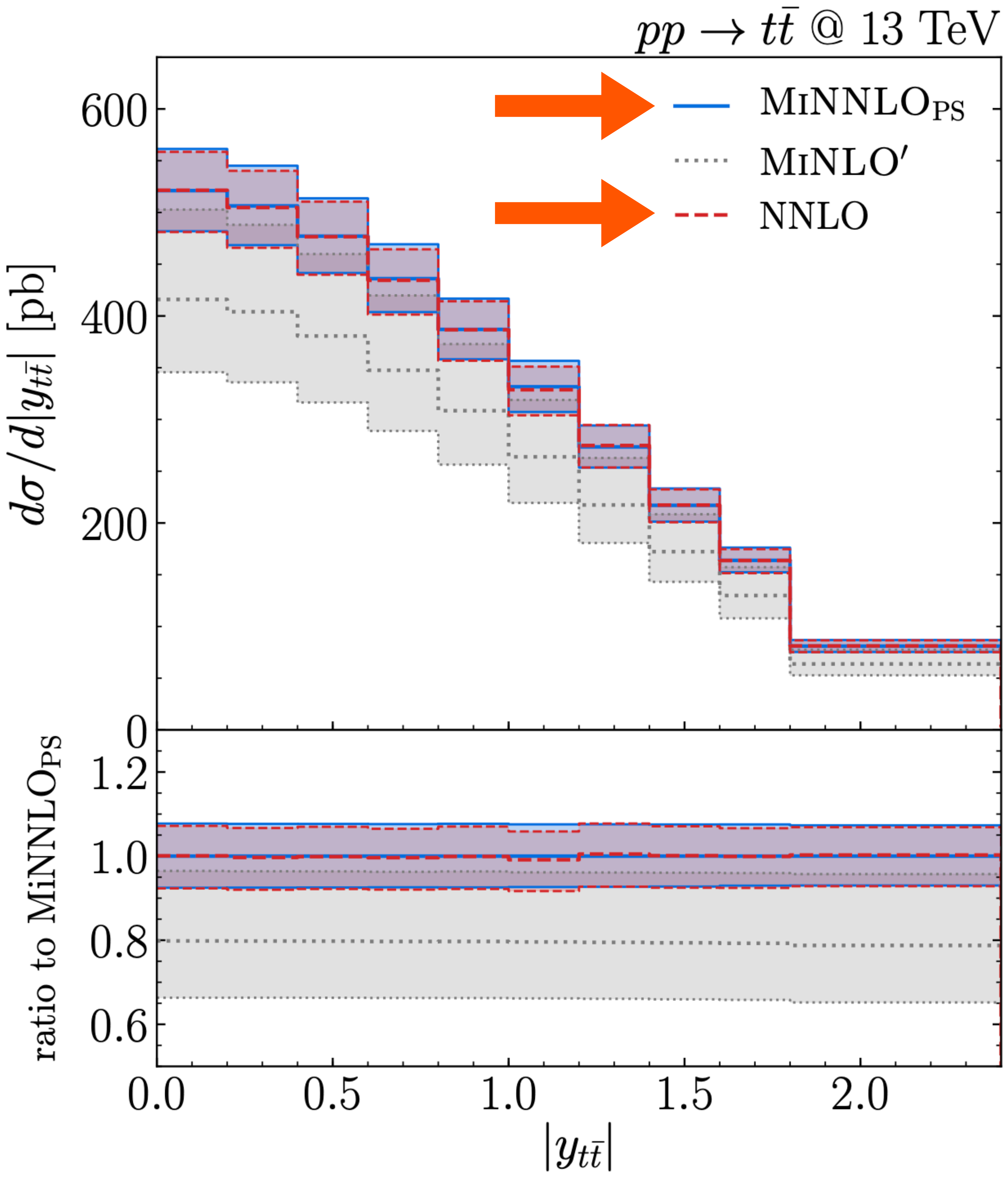
[Mazzitelli, PM, Nason, Re, Wiesemann, Zanderighi (PRL 2021 + JHEP 2022)]

- Validation: verify agreement with perturbative QCD calculations for inclusive observables (i.e. without experimental selection cuts)
  - total cross section:

MiNLO′	NNLO	MiNNLO$_{PS}$
$572.9(2)^{+21\%}_{-17\%}$ pb	$719.1(8)^{+7.0\%}_{-7.6\%}$ pb	$719.8(2)^{+7.6\%}_{-7.4\%}$ pb

  - rapidity distribution of the top pair

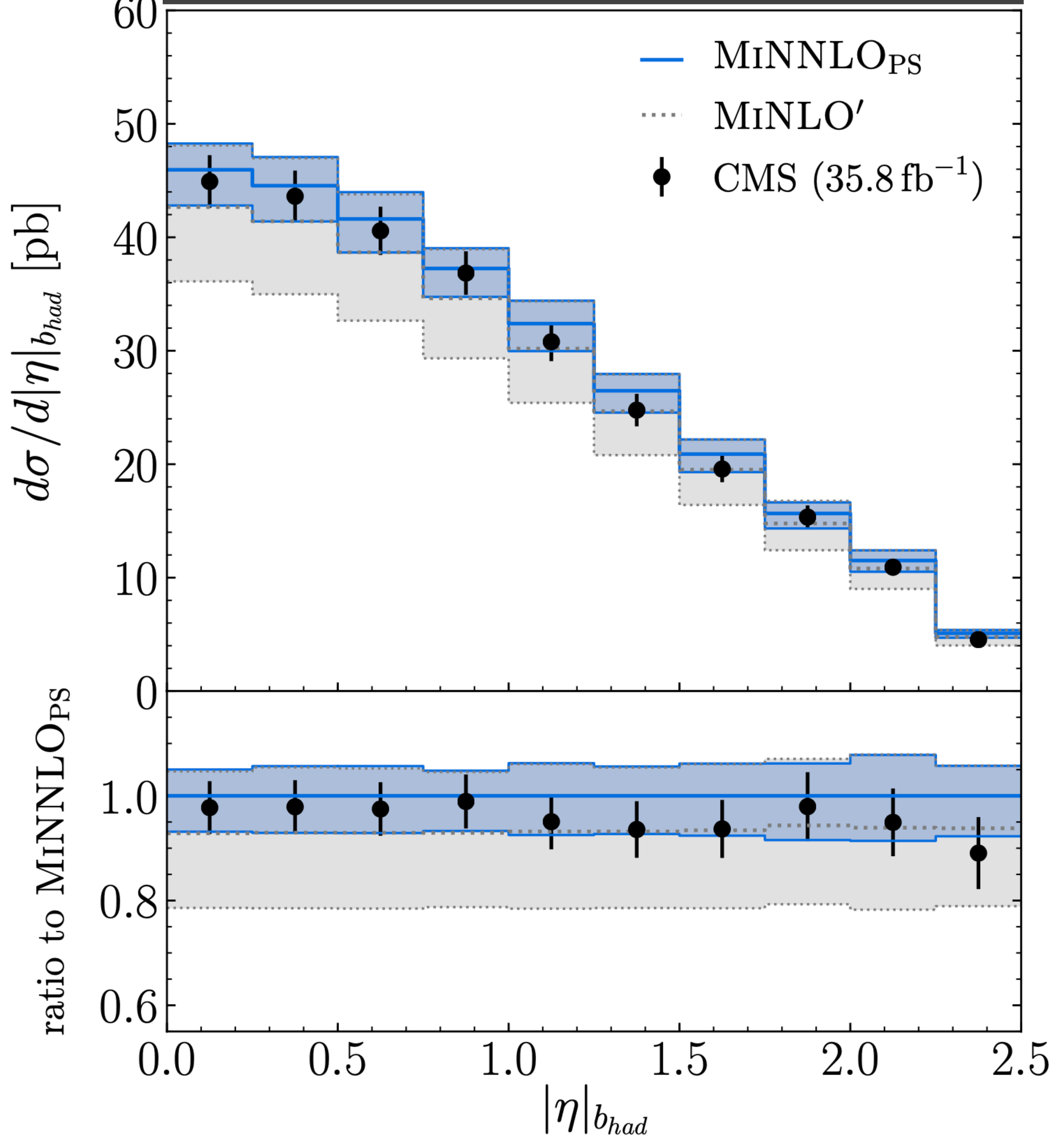
Excellent agreement with pQCD, drastic reduction of theory uncertainties w.r.t. NLO!



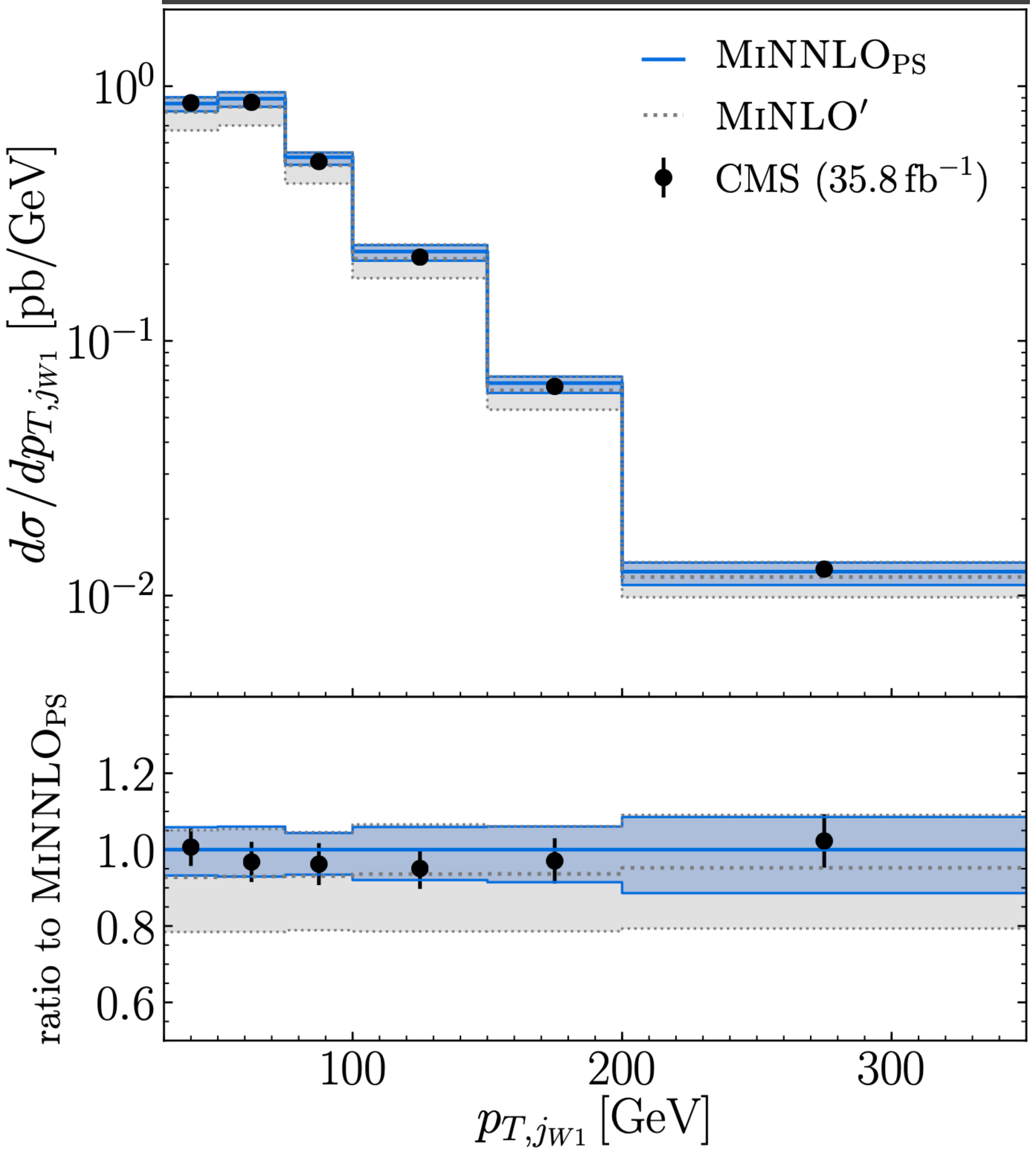
MiNNLO$_{PS}$: broad comparison to experimental data

[Mazzitelli, PM, Nason, Re, Wiesemann, Zanderighi (JHEP 2022)]

e.g. rapidity of b-flavoured jet



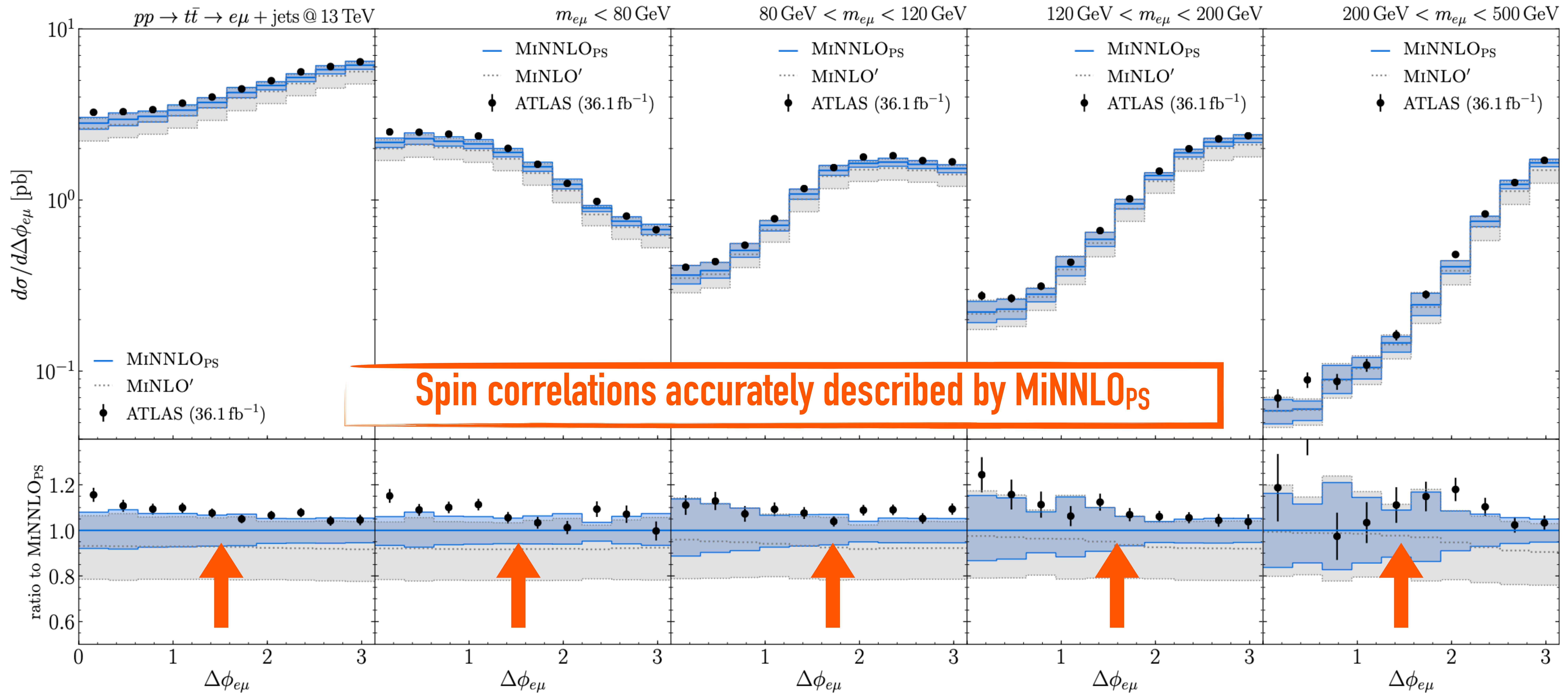
e.g. p_T of hadronic W decay's jet



Possible resolution of a long-standing tension in spin correlations?

- Ongoing studies show good theory/data agreement for correlations

[Mazzitelli, PM, Nason, Re, Wiesemann, Zanderighi (JHEP 2022)]



Conclusions and Outlook

- Modern problems in collider physics demand rethinking the approach to a crucial bridge between theory and experiment: Monte Carlo event generators

- Novel ideas are paving the way to a new generation of tools with a higher and controllable formal accuracy, led by powerful techniques in connection with perturbative QCD:

  - New methods to diagnose parton-shower (PS) accuracy and design NLL algorithms

  - PS@NLL is today a nearly-solved problem, accessible via public tools in the future. Gearing up for higher orders (NNLL) corrections requires tackling many intriguing conceptual challenges

- Considerable progress in the matching of PS to NNLO calc^n for coloured final states. Open problems ahead:

  - Consistently preserve higher-order PS accuracy (e.g. matching to PanScales showers)

  - First considerations about higher (N^{3}LO) orders matching have started to emerge

Backup

An example: local-recoil dipole showers

- (planar) squared amplitudes built recursively via a Markovian chain of emissions (& virtuals via unitarity)

CMW scheme
(cusp anom. dim^n)

Evolution from a state with n particles S_n to S_{n+1}

$$\frac{d\mathcal{P}_{n\to n+1}}{d\ln v} = \sum_{\text{dipoles }\{\tilde{\imath},\tilde{\jmath}\}} \int d\bar{\eta}\frac{d\phi}{2\pi}\frac{\alpha_s(k_t)+K\alpha_s^2(k_t)}{\pi} \times \left[g(\bar{\eta})a_k P_{\tilde{\imath}\to ik}(a_k) + g(-\bar{\eta})b_k P_{\tilde{\jmath}\to jk}(b_k)\right],$$

LO splitting functions

Evolution variable,
e.g. k_T in the dipole
c.o.m. frame

Dipole partitioning (rapidity within the dipole)

Recoil assigned according to a map $S_n \to S_{n+1}$

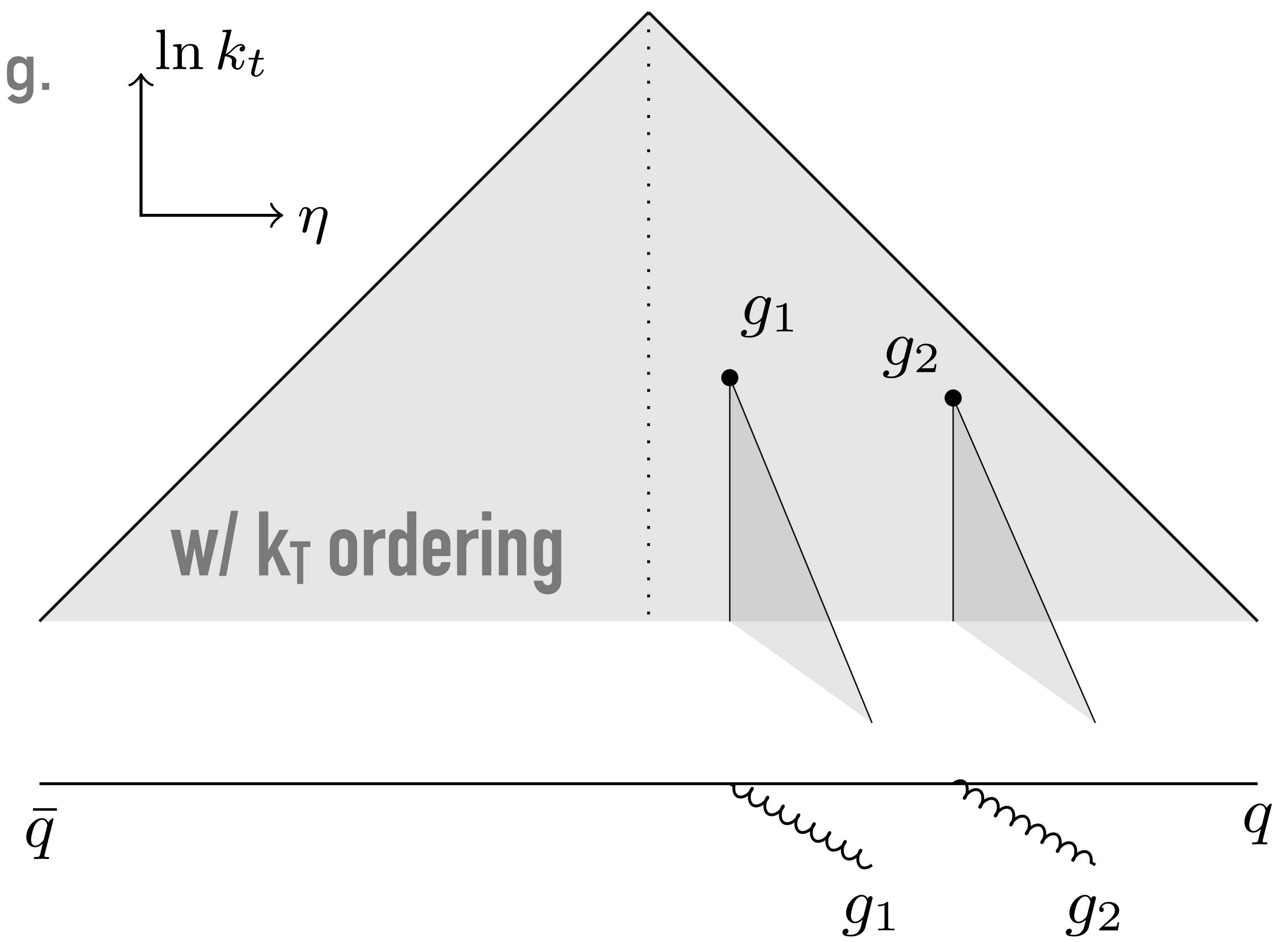
An example: local-recoil dipole showers

- Keep the recoil local, i.e. for each new emission use the map

$$\text{dipole } \{\tilde{p}_i, \tilde{p}_j\} \longrightarrow \begin{aligned} p_k &= a_k \tilde{p}_i + b_k \tilde{p}_j + k_\perp\,, \\ p_i &= a_i \tilde{p}_i + b_i \tilde{p}_j - f k_\perp\,, \\ p_j &= a_j \tilde{p}_i + b_j \tilde{p}_j - (1-f) k_\perp \end{aligned}$$

- Typical problem (source of the issues in the heat plot): dipole partitioned in the dipole c.o.m. frame

e.g.



e. g. Pythia8 / DiRE

❌

- In the limit of strong angular ordering and commensurate k_T's, g_2 can still take the recoil from g_1

➡ i.e. violation of locality in the LP

The PanLocal algorithm

[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez (PRL 2020)]

- Keep the recoil **local**, i.e. for each new emission use the map

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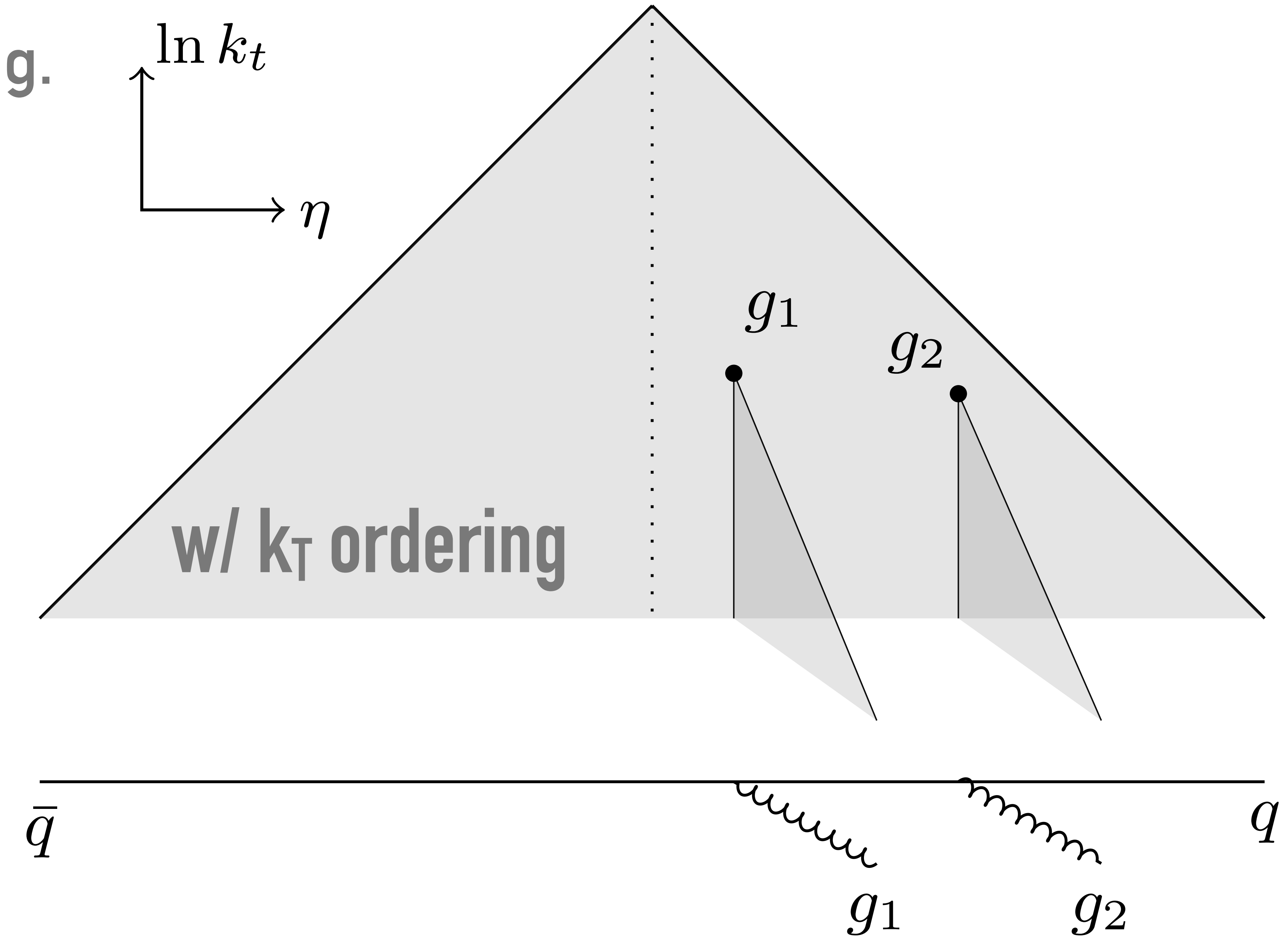
- **Key element #1**: partitioning ($\bar{\eta}$=0) occurs at equal angles to the dipole ends in the **event c.o.m. frame**

e.g.



- In the limit of strong angular ordering and commensurate k_T's, **g_2 takes the recoil from the hard quark**

The PanLocal algorithm

[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez (PRL 2020)]

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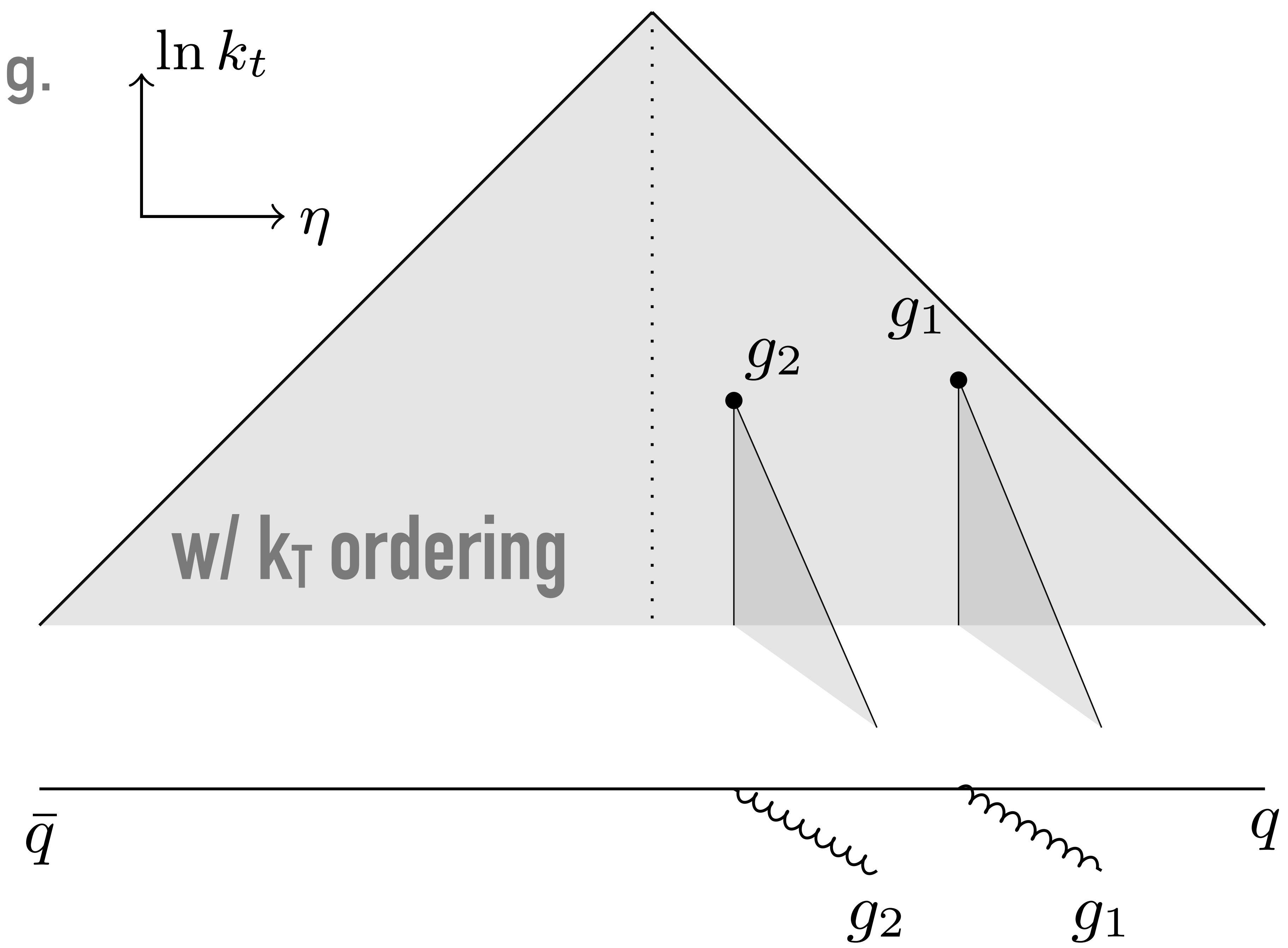

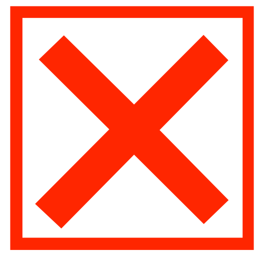

- However, if g_2 is produced at larger angles than g_1, the recoil is still taken from g_1 in a logarithmic (NLL) region of phase space

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[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez (PRL 2020)]

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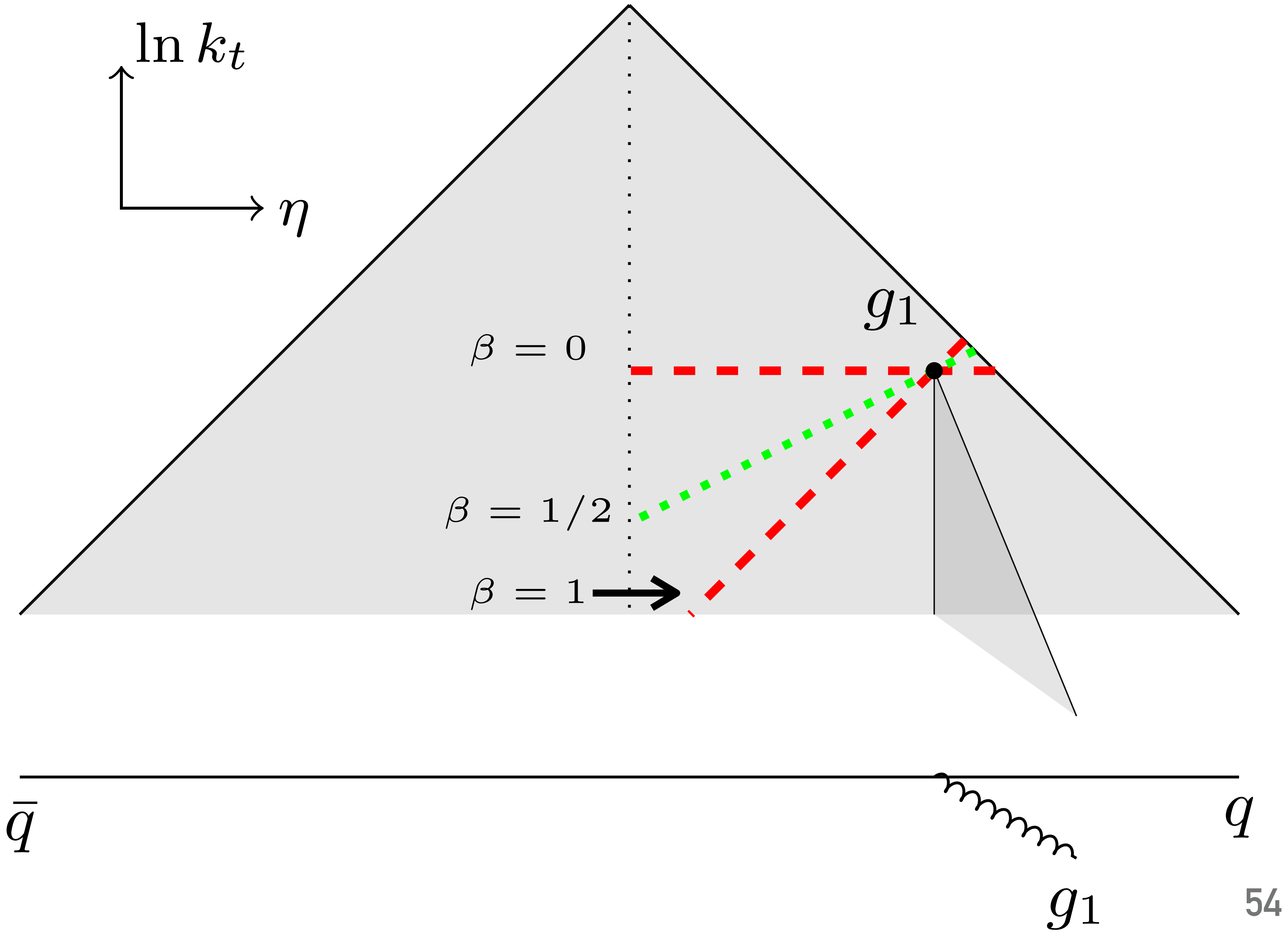
- **Key element #2**: modify the evolution variable (instead of dipole k_T)

$$k_t = \rho v e^{\beta|\bar{\eta}|} \sim v e^{\beta|\eta^{\text{w.r.t. emitter}}|}$$

$$\rho = \left(\frac{s_{\tilde{\imath}} s_{\tilde{\jmath}}}{Q^2 s_{\tilde{\imath}\tilde{\jmath}}}\right)^{\frac{\beta}{2}}$$



k_T ordering corresponds to $\beta=0$

The PanLocal algorithm

[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez (PRL 2020)]

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- **Key element #2**: modify the evolution variable (instead of dipole k_T)

    - Ordering in v now implies that $k_{t2} << k_{t1}$ [i.e. no recoil]
    - Interplay of partition⊕ordering ensures that the recoil is always taken from the hard extremities **[OK at NLL]**

✅