Parton Showers beyond leading logarithmic accuracy

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In collaboration with
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LTP Theory Seminar @ PSI - December 2 2020

Inspecting the structure of collider events

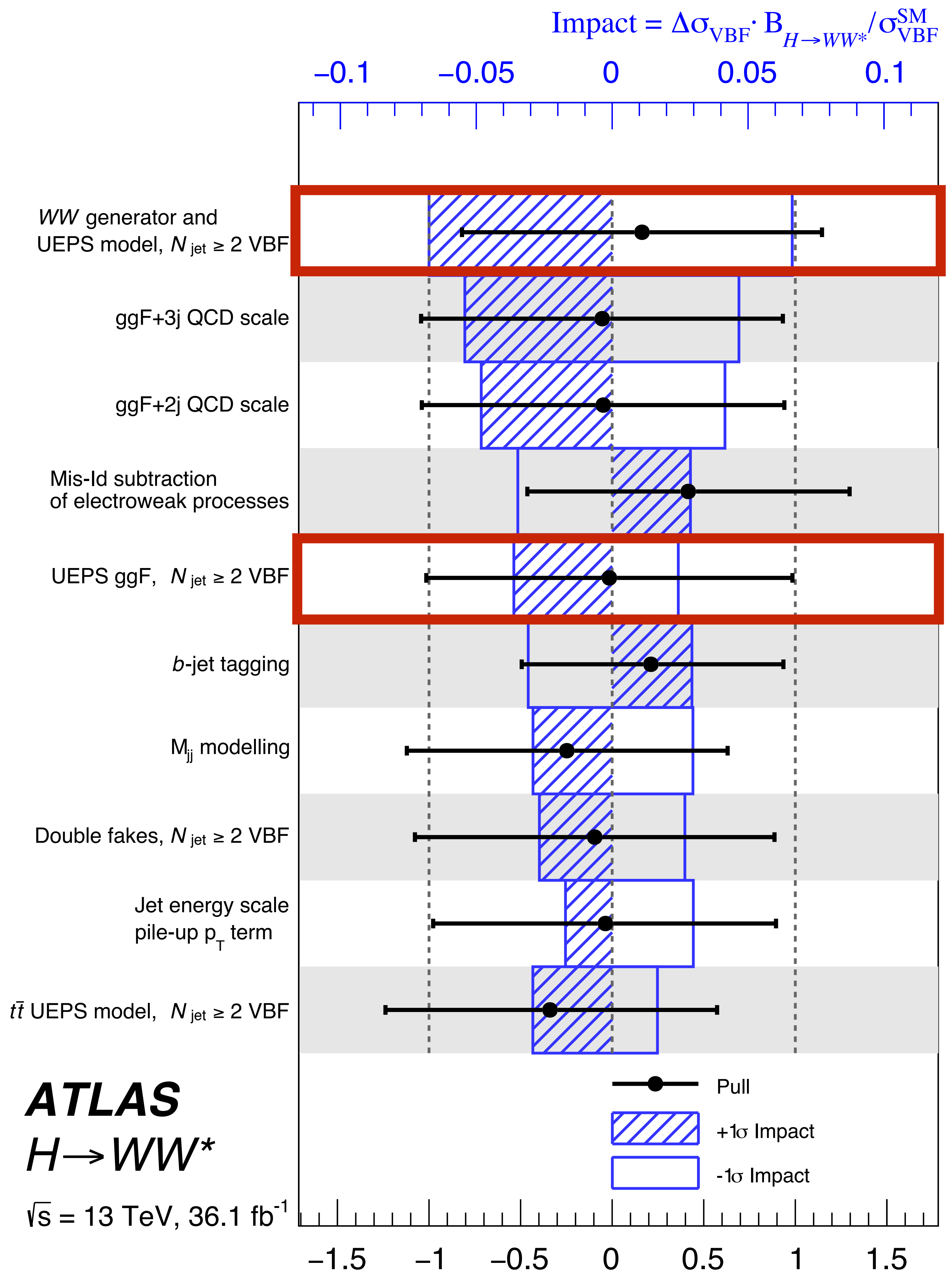
- Great advances in the exploration of perturbative calculations (fixed/all orders) in QFTs in the last decade, instrumental to exploit LHC data (new physics searches, Higgs sector, SM, …)

- However, more often than not the bridge between theory and experiments speaks the language of Monte Carlo (MC) parton showers … with considerable uncertainties

  e.g. Higgs prod^n in VBF:
  (N)NNLO QCD and NLO EW available,
  though Th. error dominates analyses

Large difference in the simulation of kinematic distributions with different MC tools

[Jaeger, Karlberg, Plaetzer, Scheller, Zaro '20]

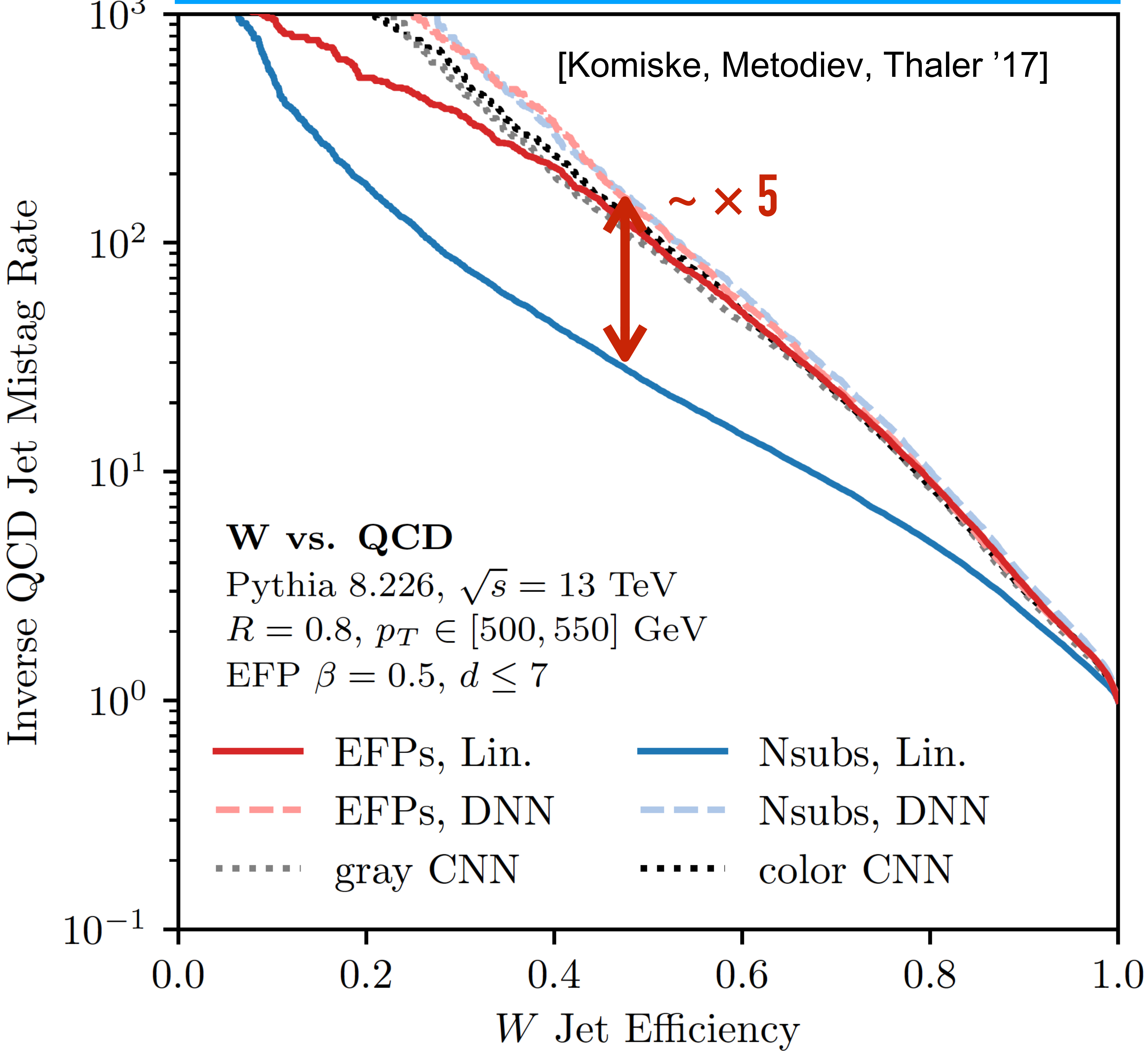


[ATLAS '19]

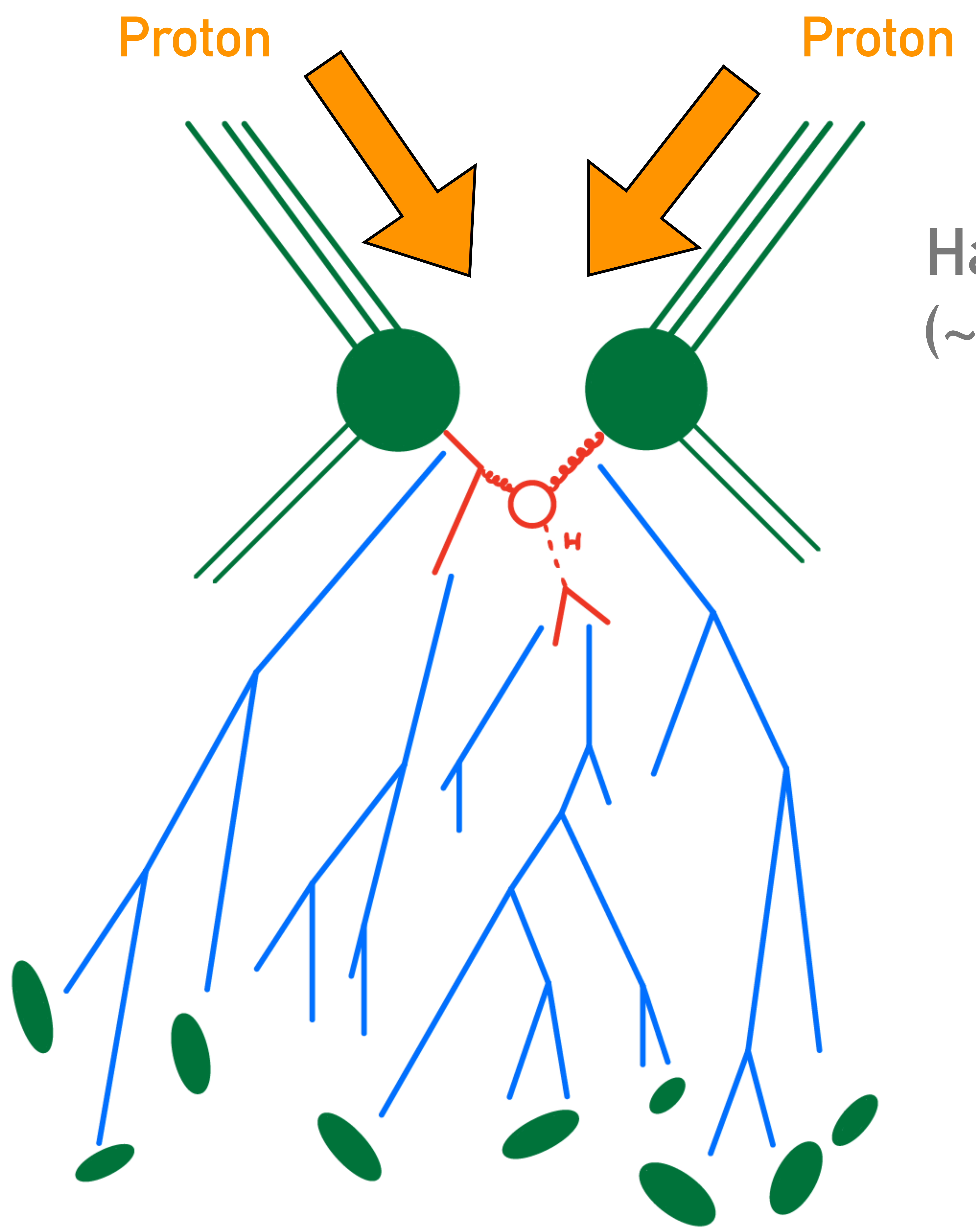
Inspecting the structure of collider events

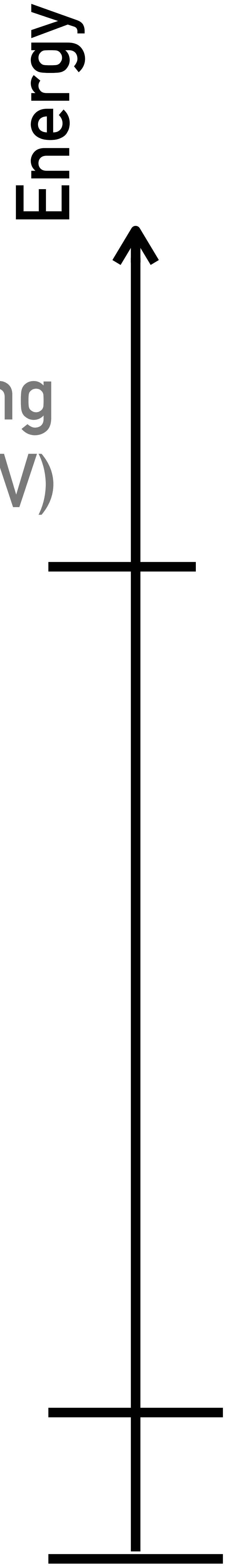
- Outstanding experimental performance at the LHC opens new avenues to test the SM and perform indirect searches (constraints) of New Physics models
  - In specific cases the sensitivity is augmented by Machine Learning technology: e.g. substructure of jets, tagging of heavy particles, q/g discrimination, …
  - Dependence on the training data (MC) may be substantial. Control over fine details needed !

e.g. N subjett. for W tag: linear vs. DNN



Monte Carlo Parton Showers





Hard scattering ($\sim 10^2$ - 10^3 GeV)

Fixed order perturbation theory: a lot of recent progress [e.g. N(N)LO+PS matching & multi-jet merging]

Parton Shower: multi-scale evolution & large hierarchy of scales: formal accuracy ??

Hadron formation (~ 1 GeV)

Modelling of non-perturbative dynamics

Observation

Perturbation theory in multi scale regimes

- When a hierarchy of scales is present

perturbative accuracy ≡ logarithmic accuracy (resummations)

- Two different (though perturbatively equivalent) definitions commonly used:

Perturbative order of EFT RGEs (anomalous dimensions & initial conditions)

Squared amplitudes in the relevant kinematic limits (ordering)

- e.g. cumulative distribution for an observable $v < e^{-L}$

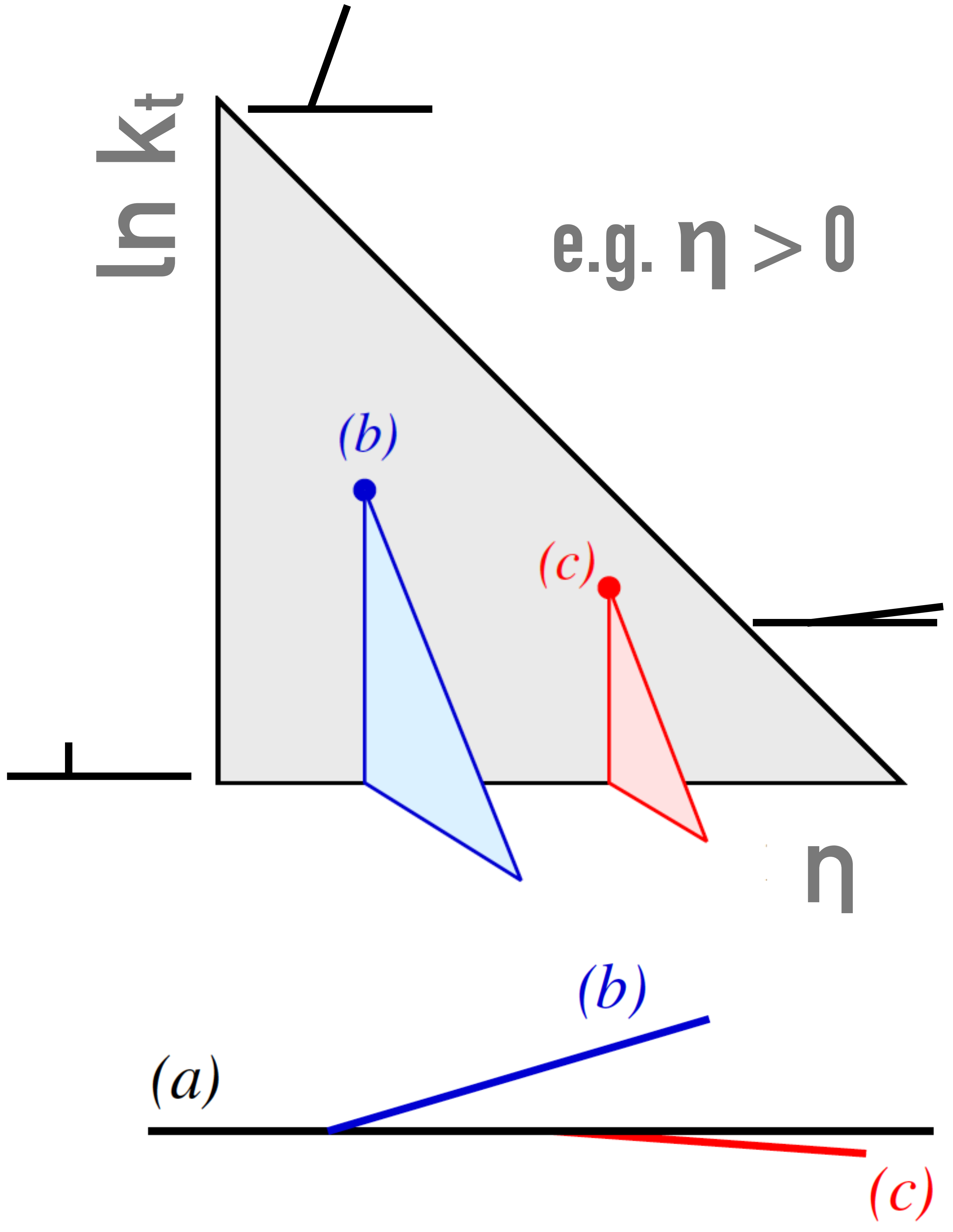
LL (=0 sometimes) NLL

$$\Sigma(\alpha_s, \alpha_s L) = \exp\left[\alpha_s^{-1} g_1(\alpha_s L) + g_2(\alpha_s L) + \mathcal{O}\left(\alpha_s^n L^{n-1}\right)\right]$$

A geometric criterion: the Lund plane

- 3 (phase space) variables per real radiation, two of which lead to logarithms, e.g. {k_T, η}; {E, θ}

- LL: reproduce correct squared amplitude in limits where both logarithmic variables are strongly ordered across emissions



Diagrams from [Dreyer, Salam, Soyez ’18]

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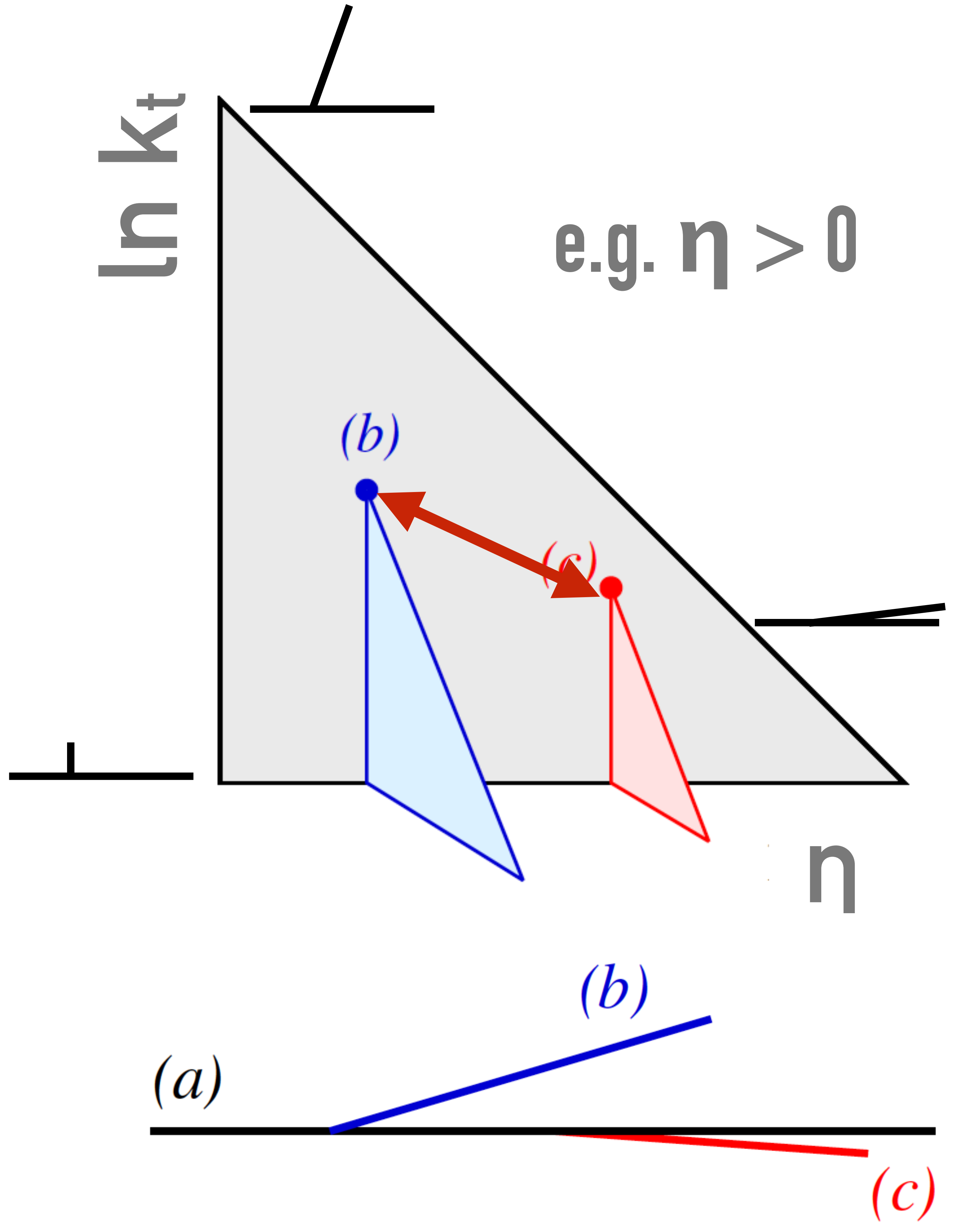
Strong ordering in one log variable ≡ large Lund plane distance



A geometric criterion: the Lund plane

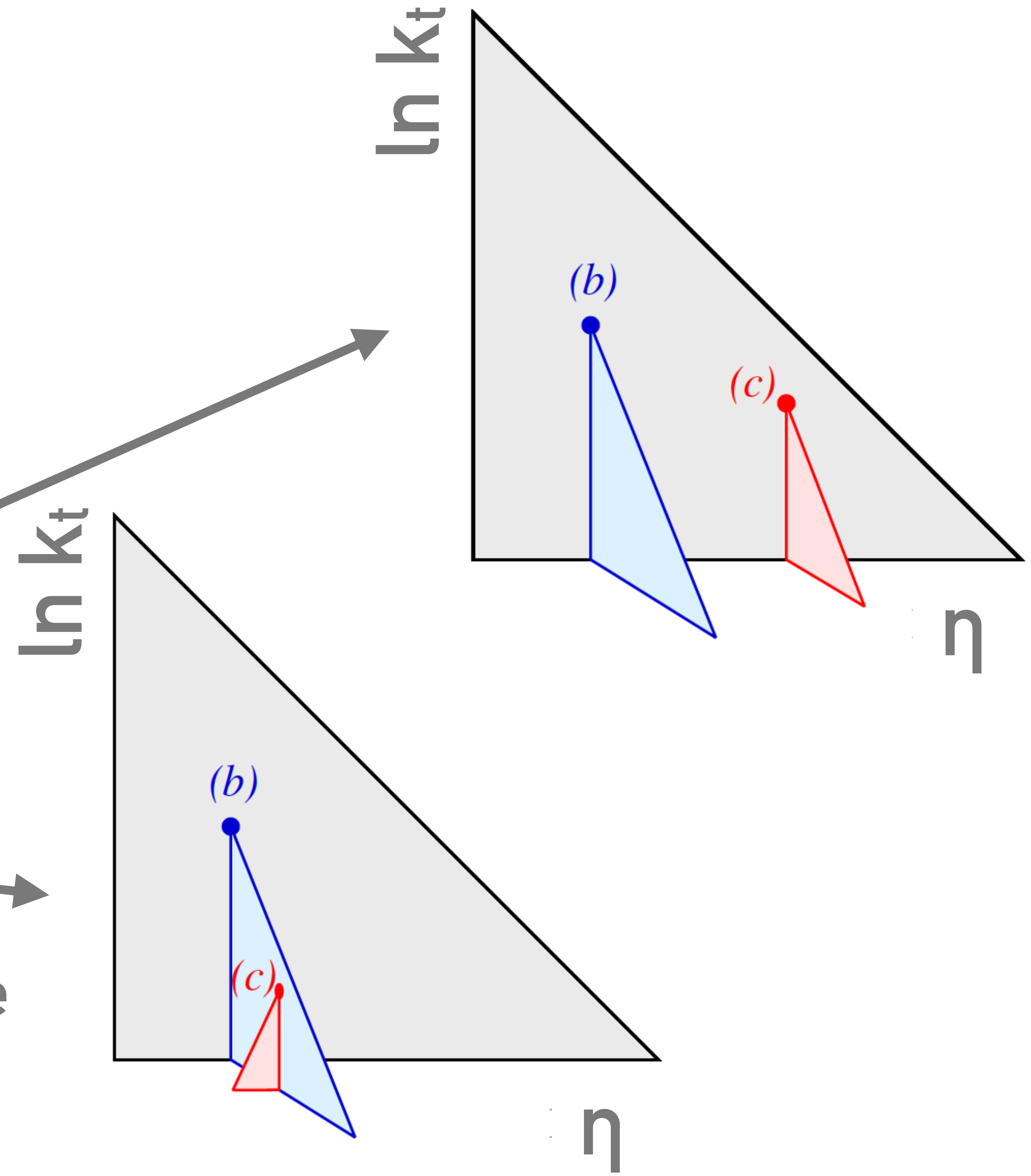
- 3 (phase space) variables per real radiation, two of which lead to logarithms, **e.g. {k_T, η}; {E, θ}**

- LL: reproduce correct squared amplitude in limits where **both logarithmic variables** are strongly ordered across emissions

Strong ordering in one log variable ≡ large Lund plane distance

- NLL: reproduce correct squared amplitude in limit where **at least one logarithmic variable** is strongly ordered across emissions. E.g.
  - Similar k_t and ordered in angle (or pseudo rapidity η)
  - Similar angle and ordered in k_t (or energy)

- When two emissions are close (in both variables), a mistake is allowed (NNLL)



Diagrams from [Dreyer, Salam, Soyez '18]

e.g. NLL: building blocks

- rIRC safe, global observables described by emissions strongly ordered in angle, but with commensurate transverse momenta (recoil effects are relevant)
  - realised, e.g., in angular ordered parton showers

e.g. e^+e^- -> q qbar + X at NLL

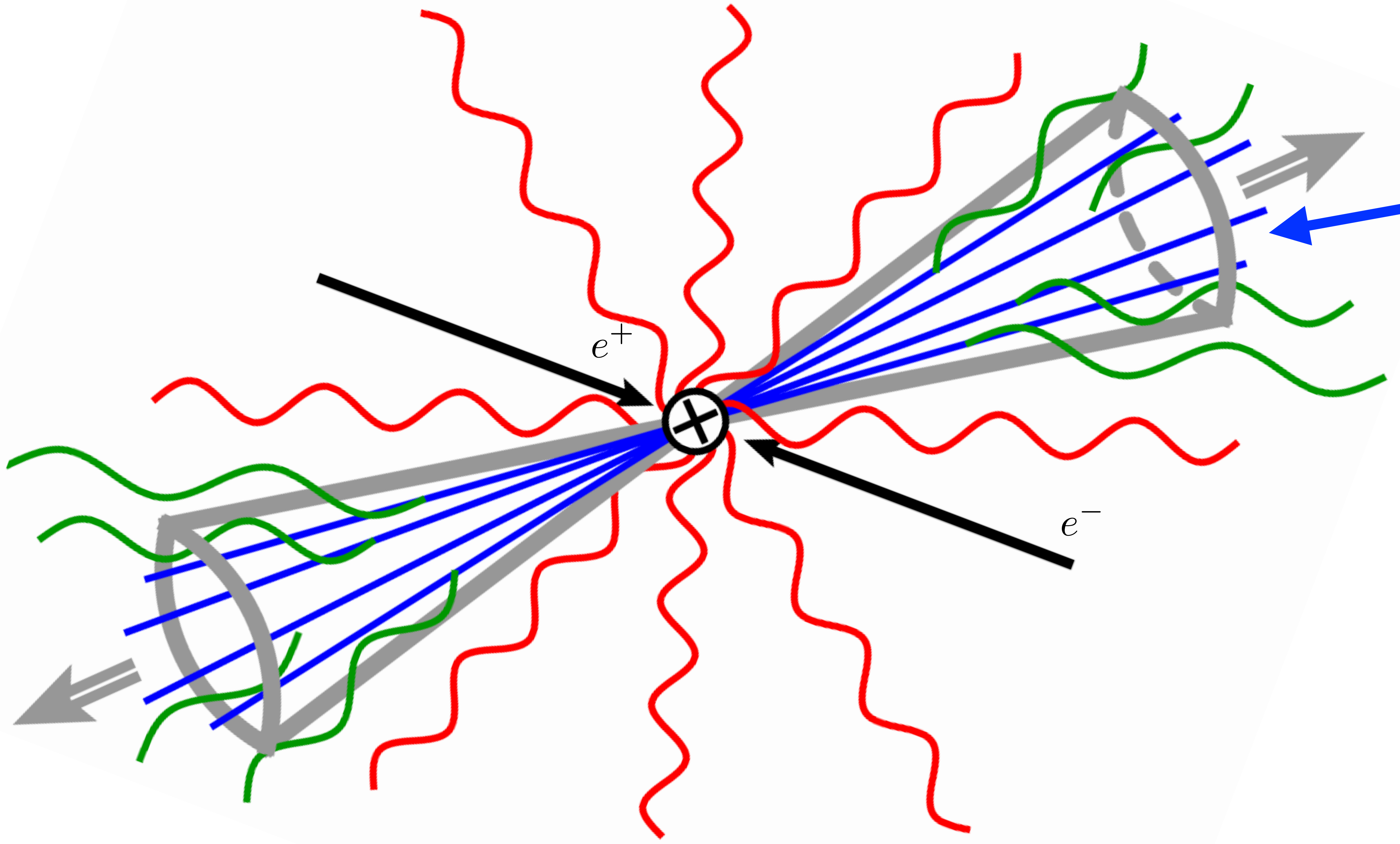


Image by T. Becher et al.

$$dP_n \simeq \frac{C_F^n}{n!} \prod_{i=1}^{n} \left(\frac{\alpha_s^{\mathrm{CMW}}(p_{\perp,i}^2)}{\pi} \frac{dp_{\perp,i}}{p_{\perp,i}} dz_i P_{q\to qg}(z_i) \frac{d\phi_i}{2\pi} \right)$$

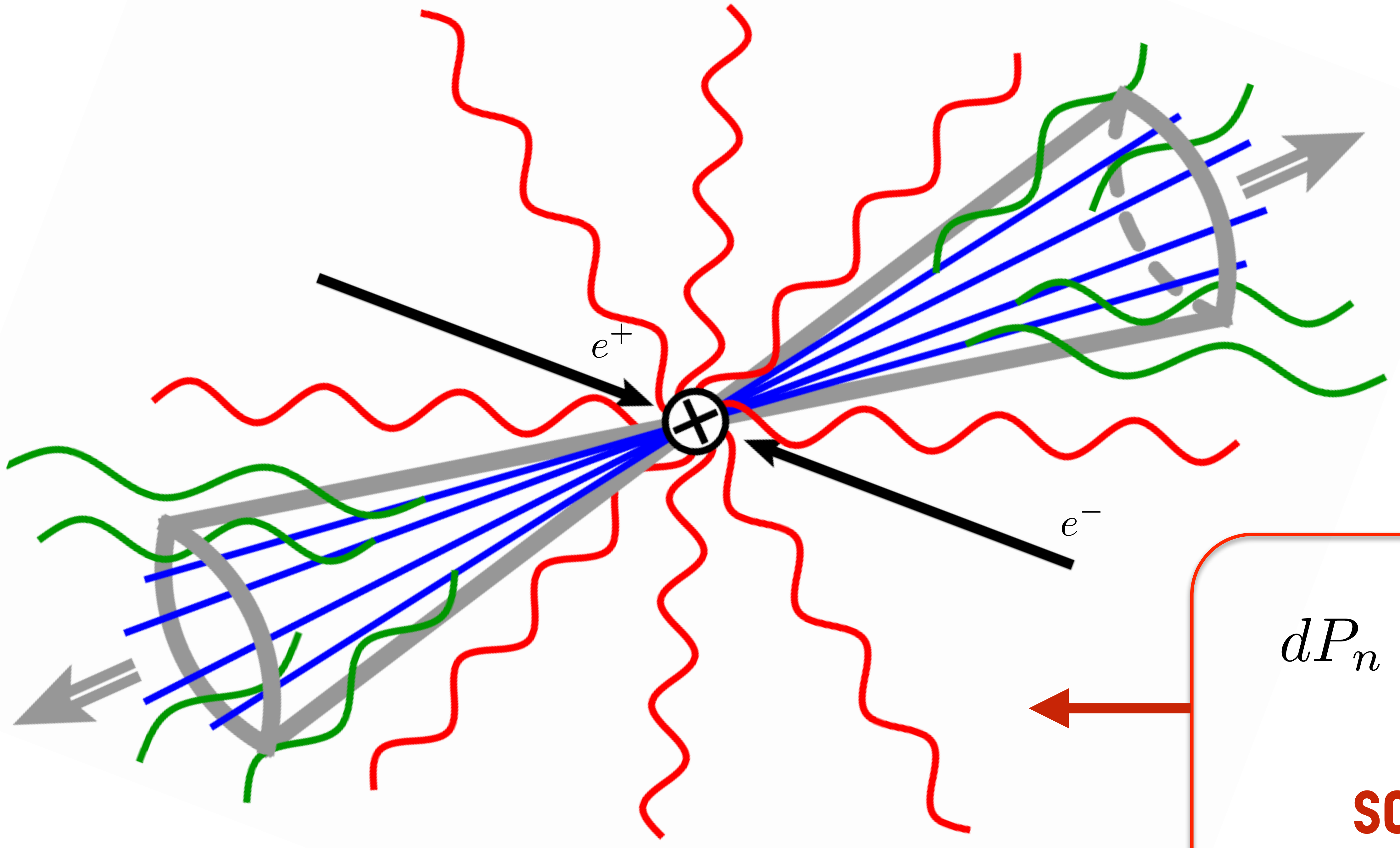
collinear limit described by independent emissions
strongly ordered in angle

e.g. NLL: building blocks

- non-global logarithms described radiation at similar angles, but strongly ordered energy / transverse momentum
  - angular ordering fails, dipole showers needed

[Banfi, Corcella, Dasgupta ’06]

e.g. e^+e^- -> q qbar + X at NLL



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$$dP_n \simeq \frac{1}{n!}\prod_{i=1}^{n}\frac{\alpha_s}{\pi}\frac{d\omega_i}{\omega_i}\frac{d^2\Omega}{4\pi}N_c\sum_{\pi_n}\frac{p_1\cdot p_2}{(p_1\cdot k_{i_1})(k_{i_1}\cdot k_{i_2})\dots(k_{i_n}\cdot p_2)}$$

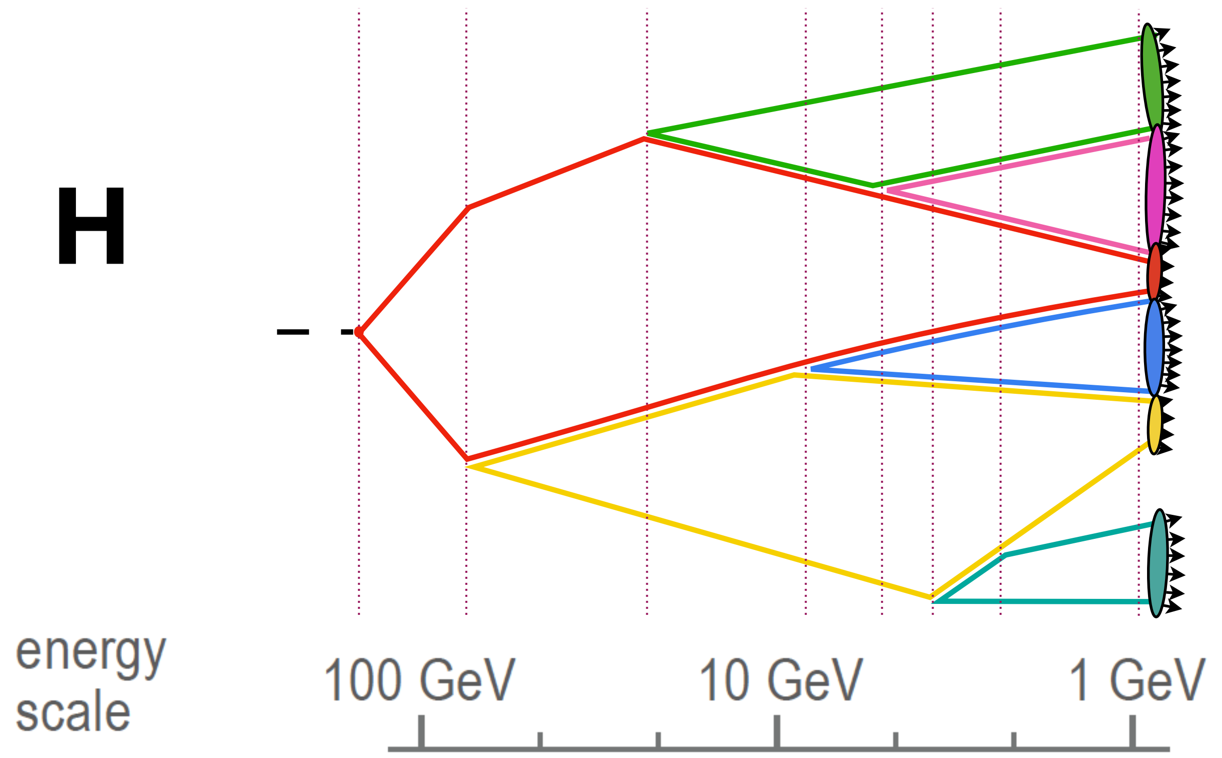
soft wide angle limit described by a collection of soft colour dipoles <u>strongly ordered in energy</u> (planar limit)

Dipole showers in a nutshell

- Squared amplitudes built recursively via a Markovian chain of emissions (planar limit). Virtual corrections strictly implemented through unitarity

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

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



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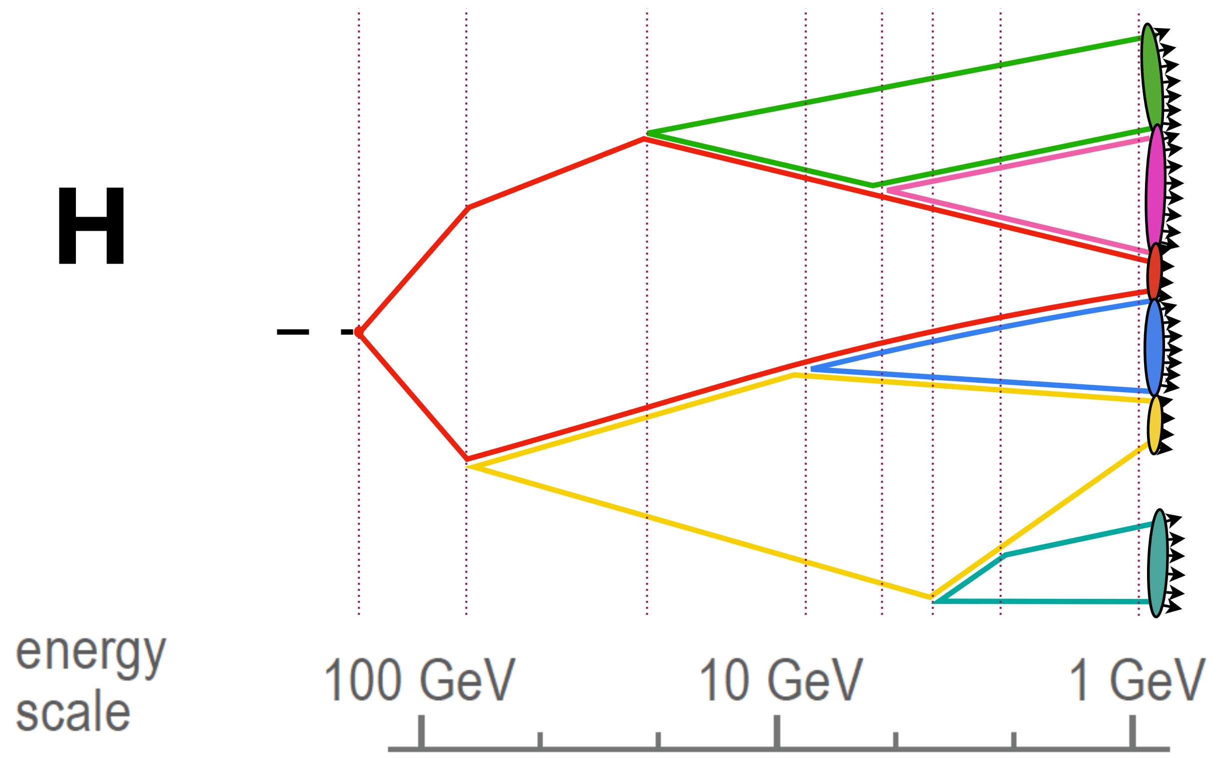
Evolution variable, e.g. k_T in the dipole c.o.m. frame



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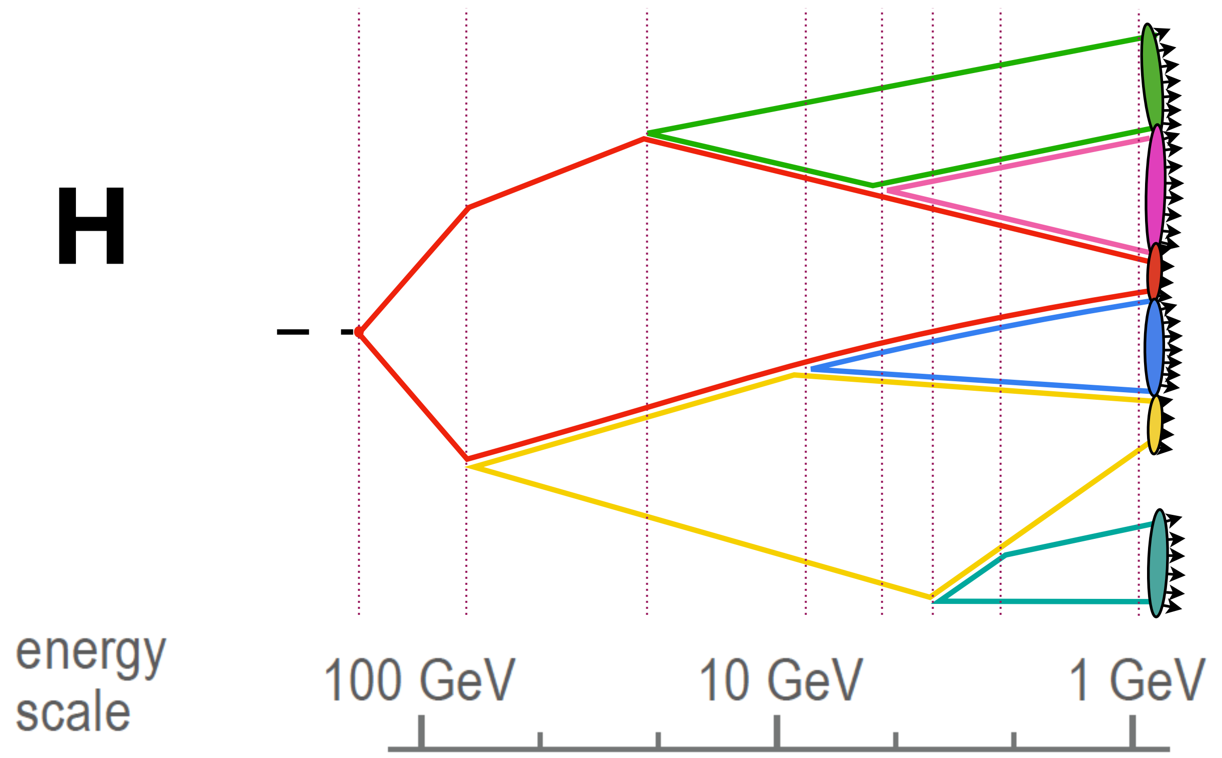

Some notion of rapidity of the emission within the dipole, deciding how the dipole is partitioned.

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

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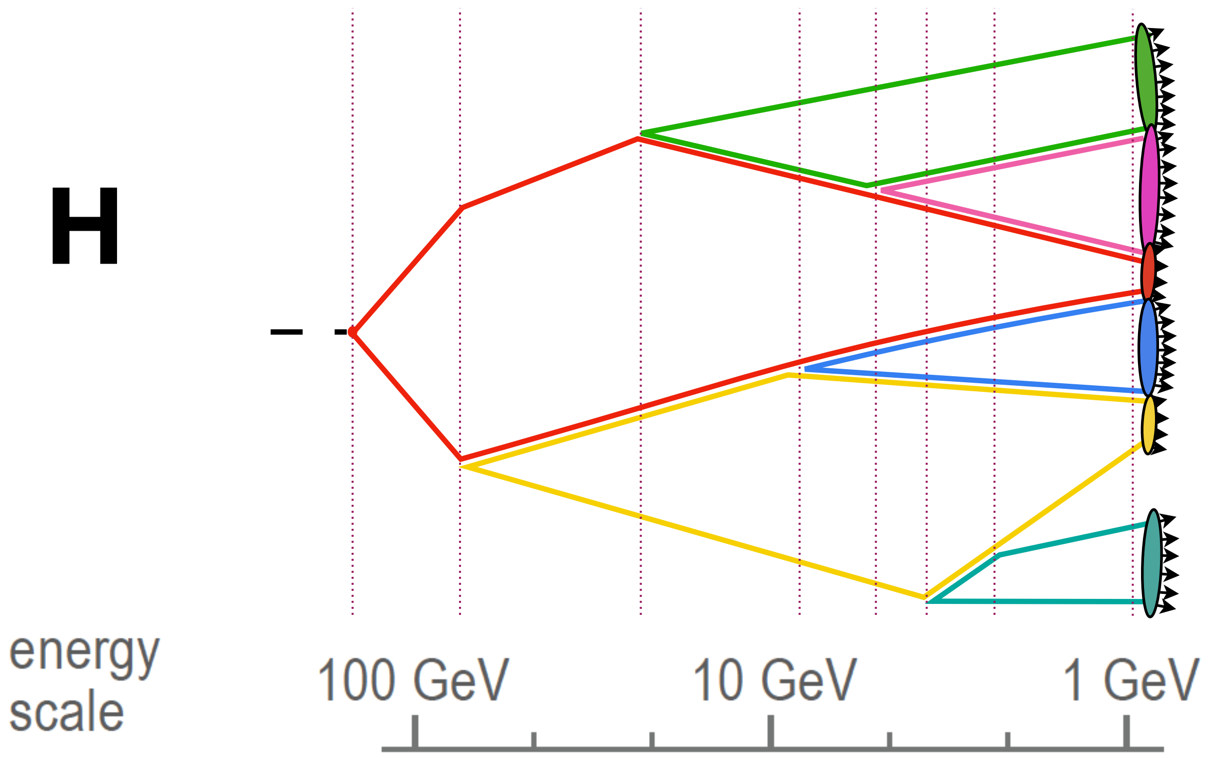
LO Splitting functions



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CMW scheme, consistent inclusion of $O(\alpha_s^2)$ soft current up to NLL

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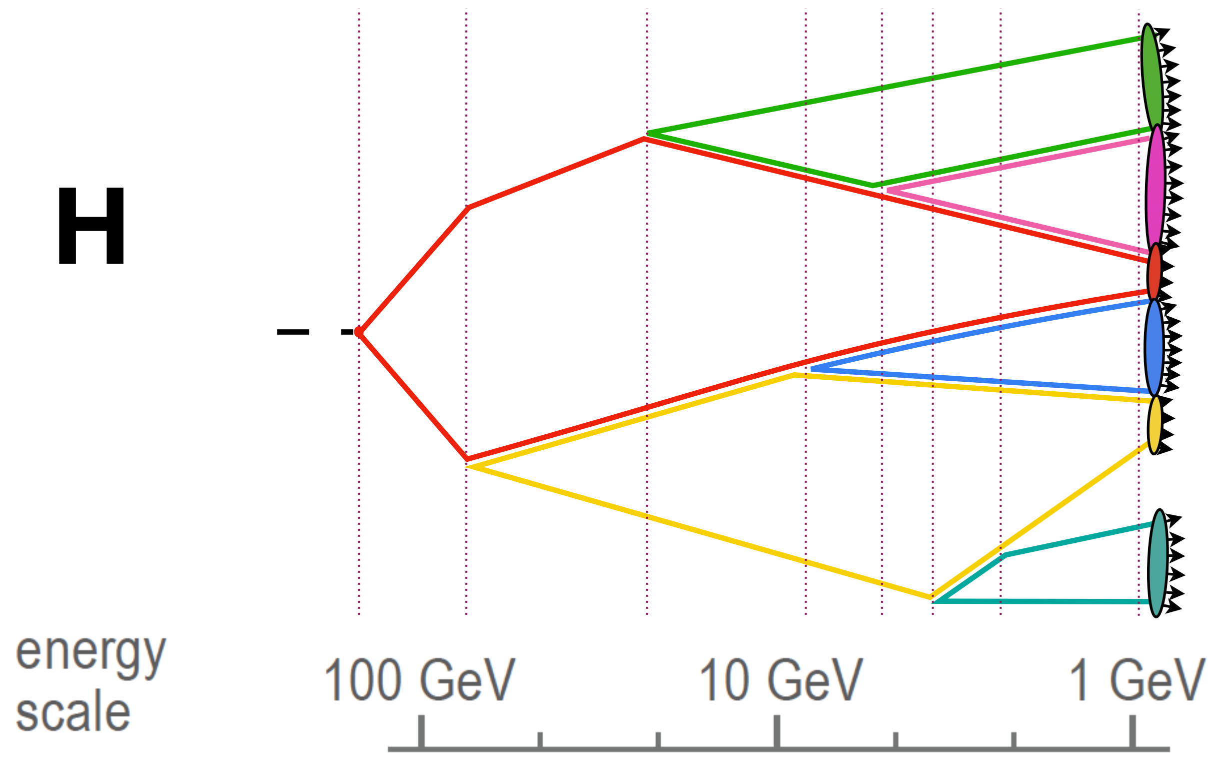

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Recoil assigned according to a **map $S_n \to S_{n+1}$**

A case study: k_t ordering & local recoil

(e.g. Pythia8, Dire$_{v1}$, CS dipole shower are of this type)

A case study: k_t ordering & local recoil

- As an example, let us consider the $O(\alpha_s^2)$ soft emission off a fermion line. In the (NLL) limit of strong angular ordering, similar transverse momenta, one expects the emission probability (**squared amplitude x phase space**) to be

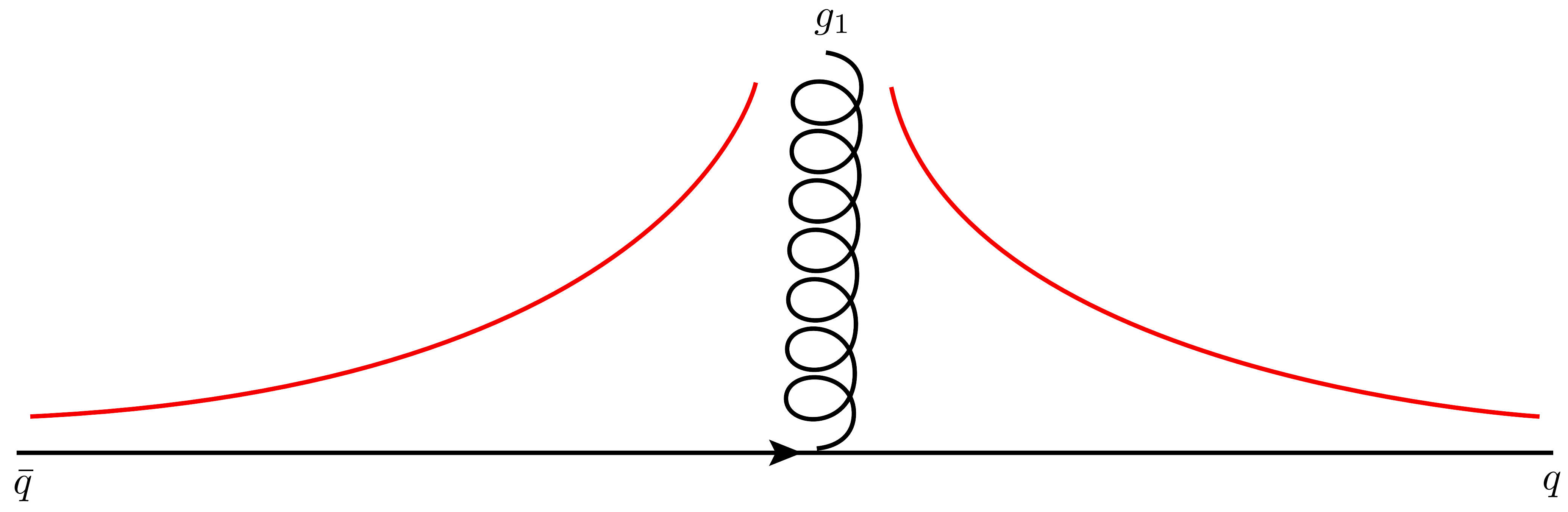
$$dP_2 = \frac{C_F^2}{2!} \prod_{i=1,2} \left(\frac{2\alpha_s(p_{\perp,i}^2)}{\pi} \frac{dp_{\perp,i}}{p_{\perp,i}} d\eta_i \frac{d\phi_i}{2\pi} \right)$$

i.e. recoil taken from the quark

- Instead, dipole local showers assign the recoil to either of the emitting dipole ends, according to the rapidity of the emission in the dipole centre-of-mass frame

- e.g.

- Start with an emission g_1



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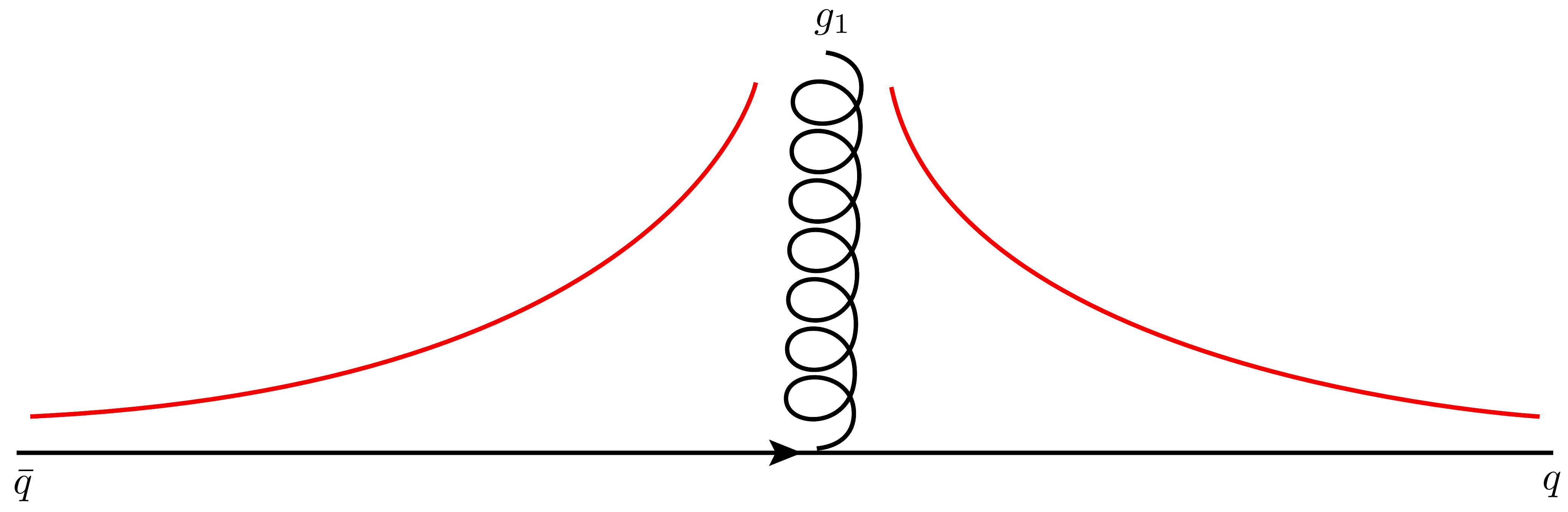
- Add a branching q g_1 -> q g_1 g_2 (right dipole)



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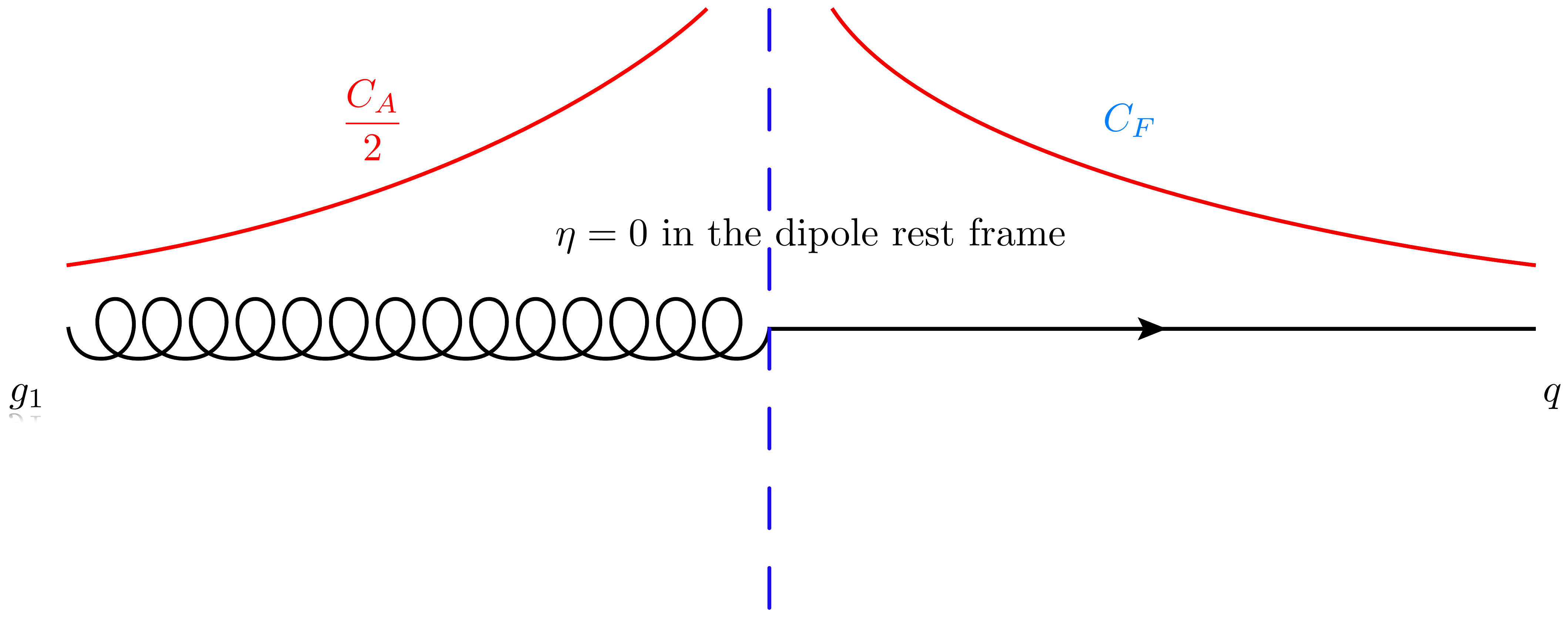

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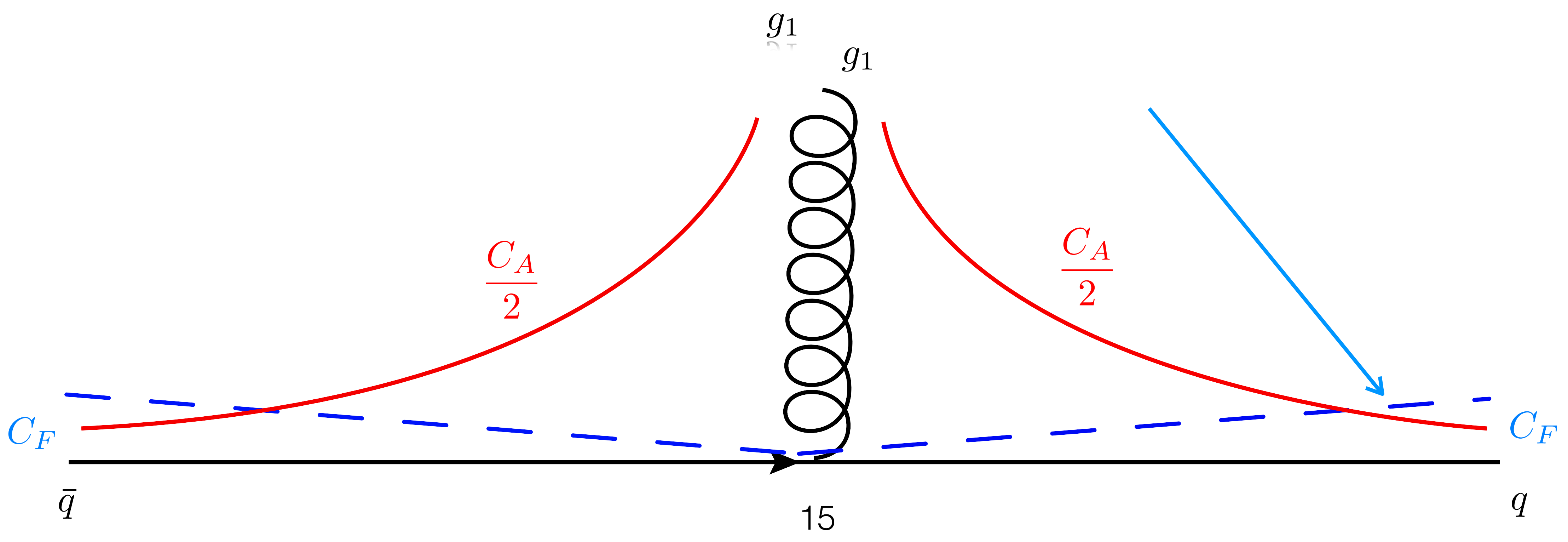
- e.g.
- Start with an emission g_1
- Add a branching $q\,g_1 \to q\,g_1\,g_2$ (right dipole)
- <u>Recoil & color</u> taken from g1 even if the second emission is collinear to the quark: **breakdown of the independent emission picture**

Line of zero rapidity in the dipole's rest frame, boosted into the event frame



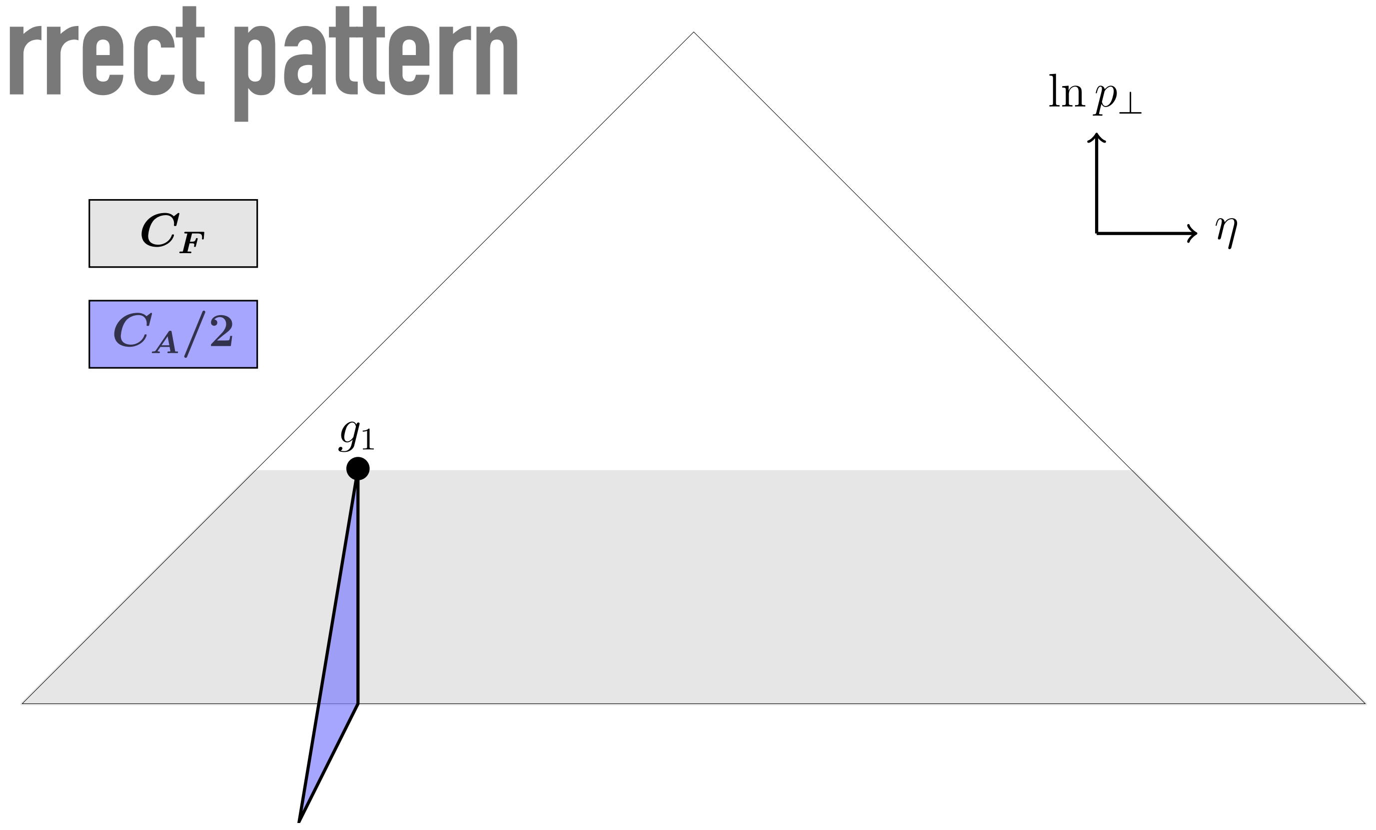
A case study: k_t ordering & local recoil

[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez ’18; see also Bewick, Ferrario Ravasio, Richardson, Seymour ’19]

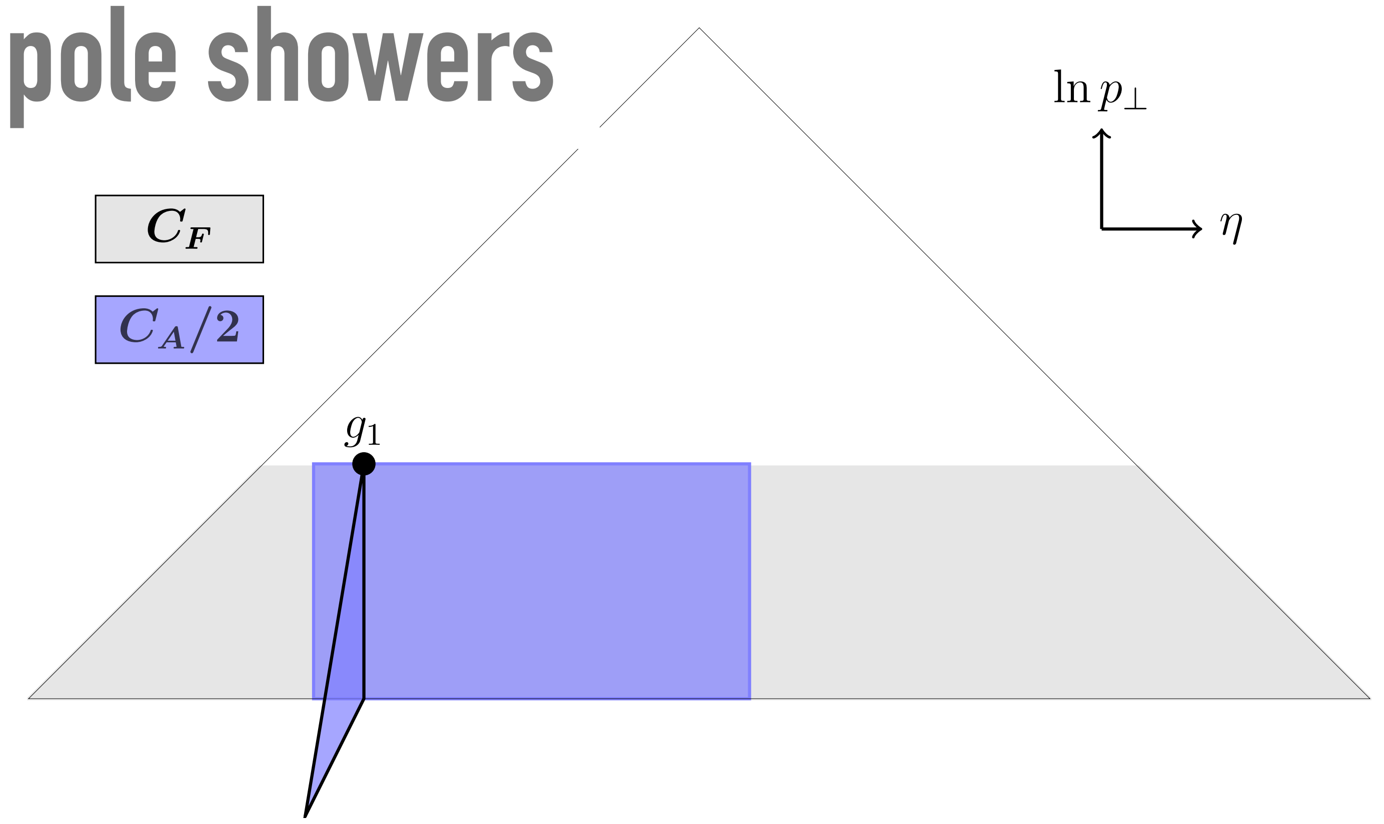
- Problems start at LL: even with strong k_T ordering (i.e. no kinematic recoil), the colour factors are assigned incorrectly, leading to a $1/N_c^2$ - suppressed mistake for specific observables

  e.g. Double logarithmic difference from correct result for the Thrust

Correct pattern



Dipole showers

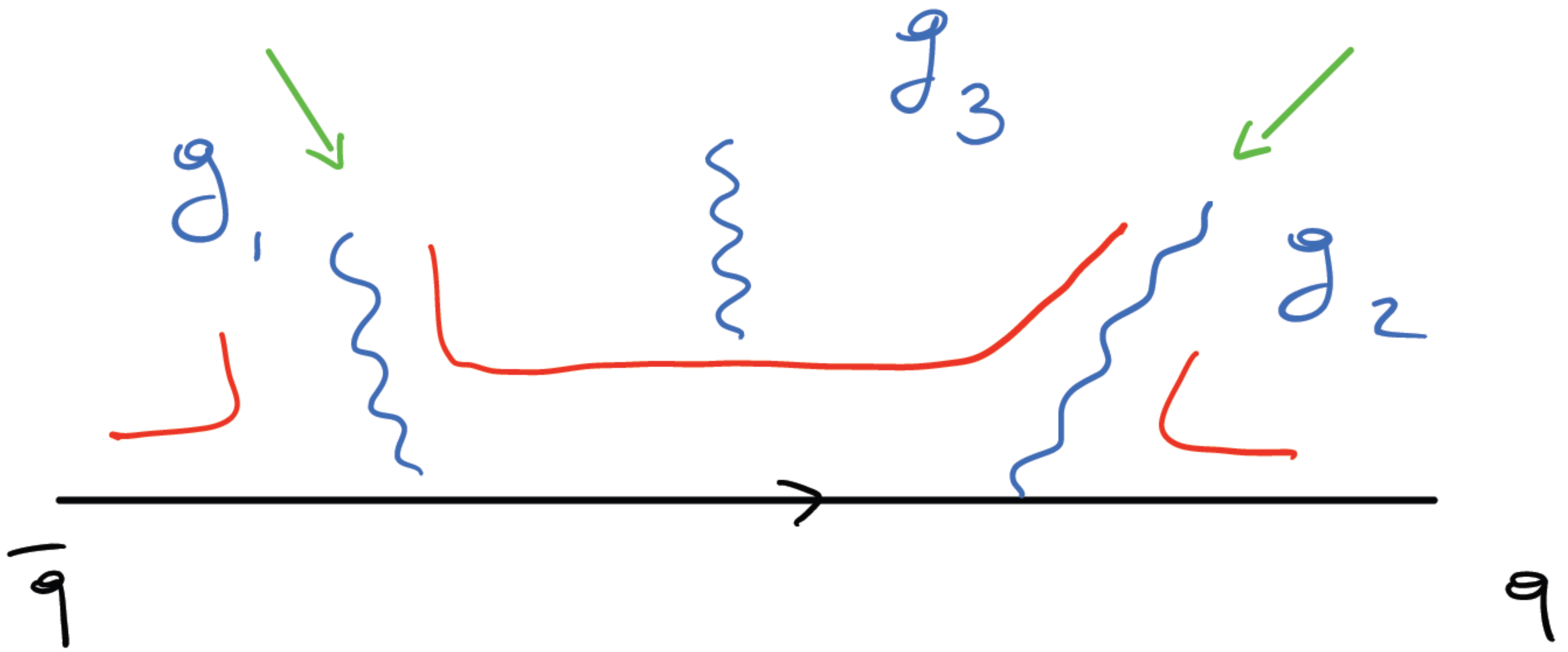


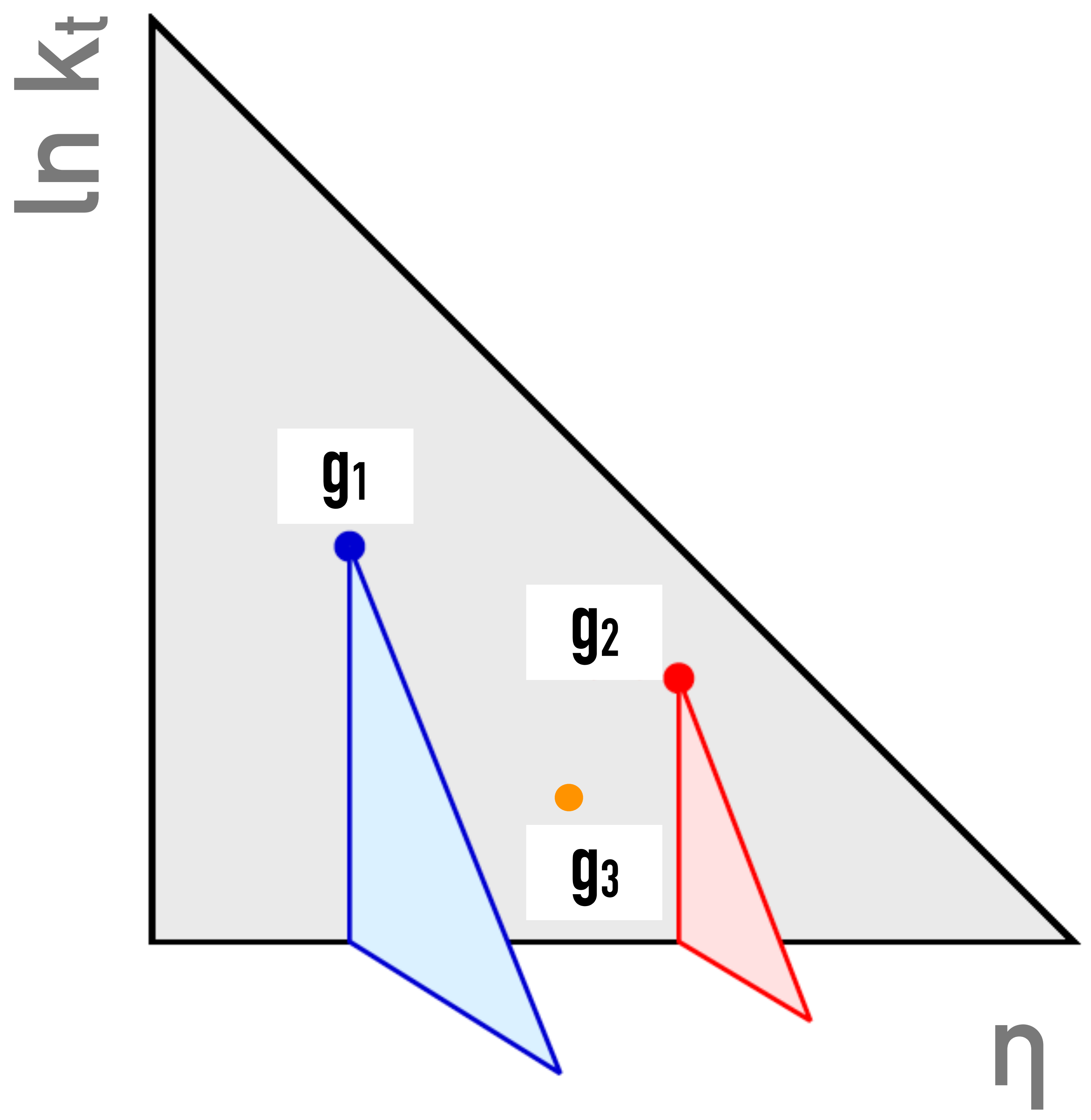
$$\delta\Sigma(L) = -\frac{1}{64}\left(\frac{2\alpha_s C_F}{\pi}\right)^2 L^4 \left(\frac{C_A}{2C_F} - 1\right)$$

- At NLL the kinematic recoil plays a role, and all global observables formally have a problem originating from the above mechanism: $\alpha_s^n L^n$ terms wrong (see later)

A case study: k_t ordering & local recoil

- Beyond α_s^2 the independent emission picture is further violated by emissions from soft {gg} dipoles, for which the recoil is necessarily taken from one of the two soft ends rather than from the hard fermion line





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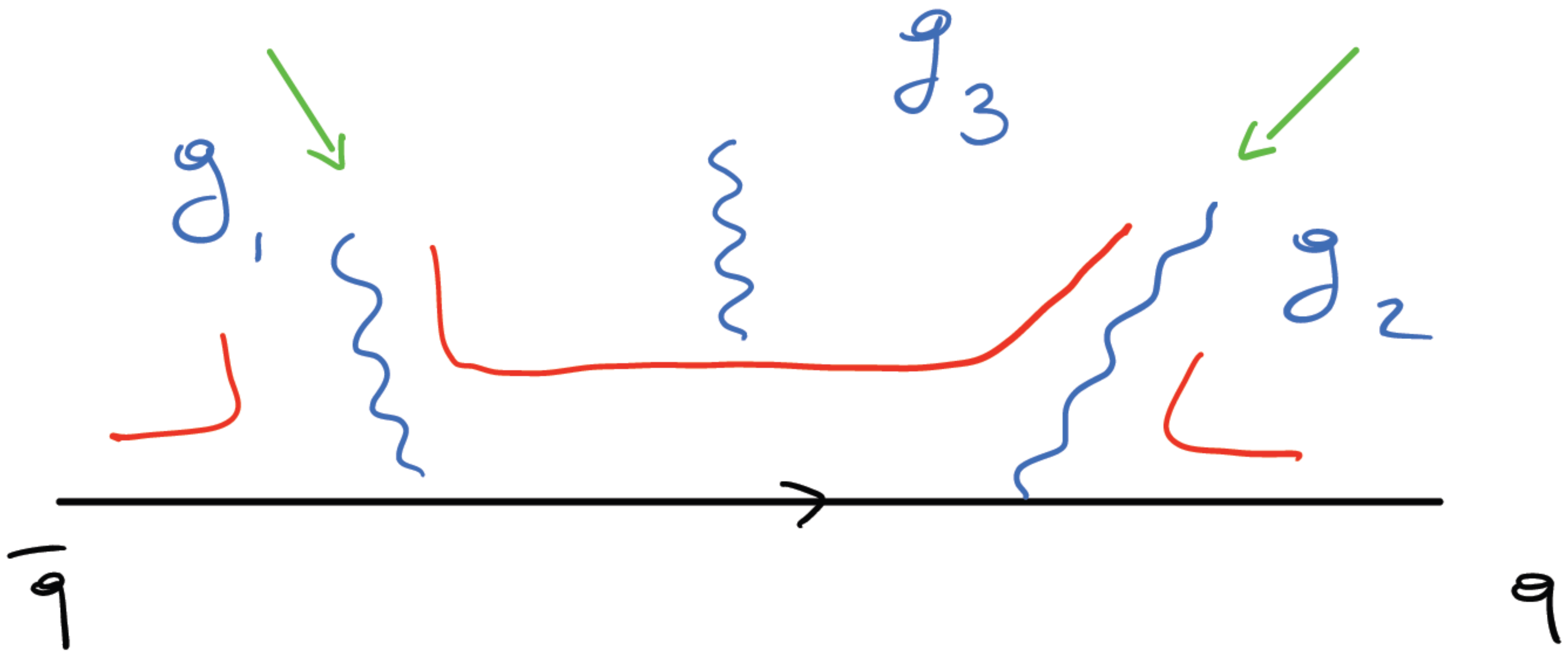

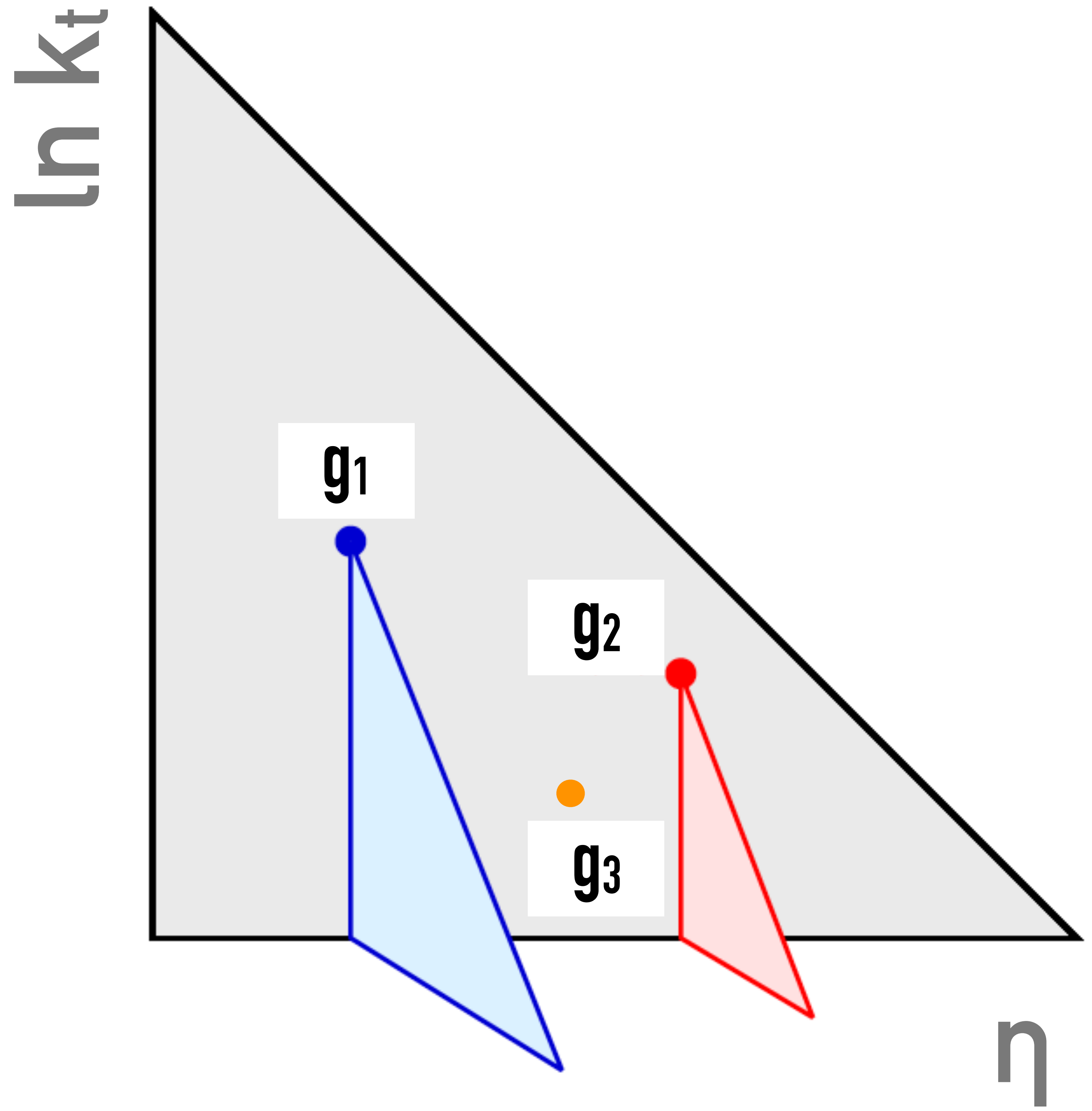

- Additional problems are discovered for classes of observables for which the recoil mechanism leads to a violation of coherence and the appearance of **super leading logarithms (SLL) starting at $O(\alpha_s^3)$ or $O(\alpha_s^4)$**, not predicted by QCD (cf. paper appendix).

Design of NLL parton showers

Some remarks

- Solving these problem demands a fundamental redesign of the dipole shower

- Ultimately, we want to achieve a parton shower that is NLL accurate simultaneously for rIRC safe global, and for non-global observables across many collider processes. Crucial to build a framework to **demonstrate the formal accuracy** in a solid manner

- Let's start from a clear theoretical environment: **e^+e^- collisions, large N_c limit**. Also, neglect for now azimuthal (spin) correlations, which are known at this order

[Collins '88; Knowles '90; Super '08; Richardson & Webster '18]

- NB: QCD resummation provides us with guidelines, therefore **more than one solution is possible**. Difference between various NLL accurate solutions gives us a way to estimate the size of genuine subleading (NNLL) logarithmic corrections

The PanLocal shower (local recoil)

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

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

- Novel element #1: partitioning of the dipole (at $\bar{\eta} = 0$) occurs at equal angles between the emission and the dipole ends in the event c.o.m. frame

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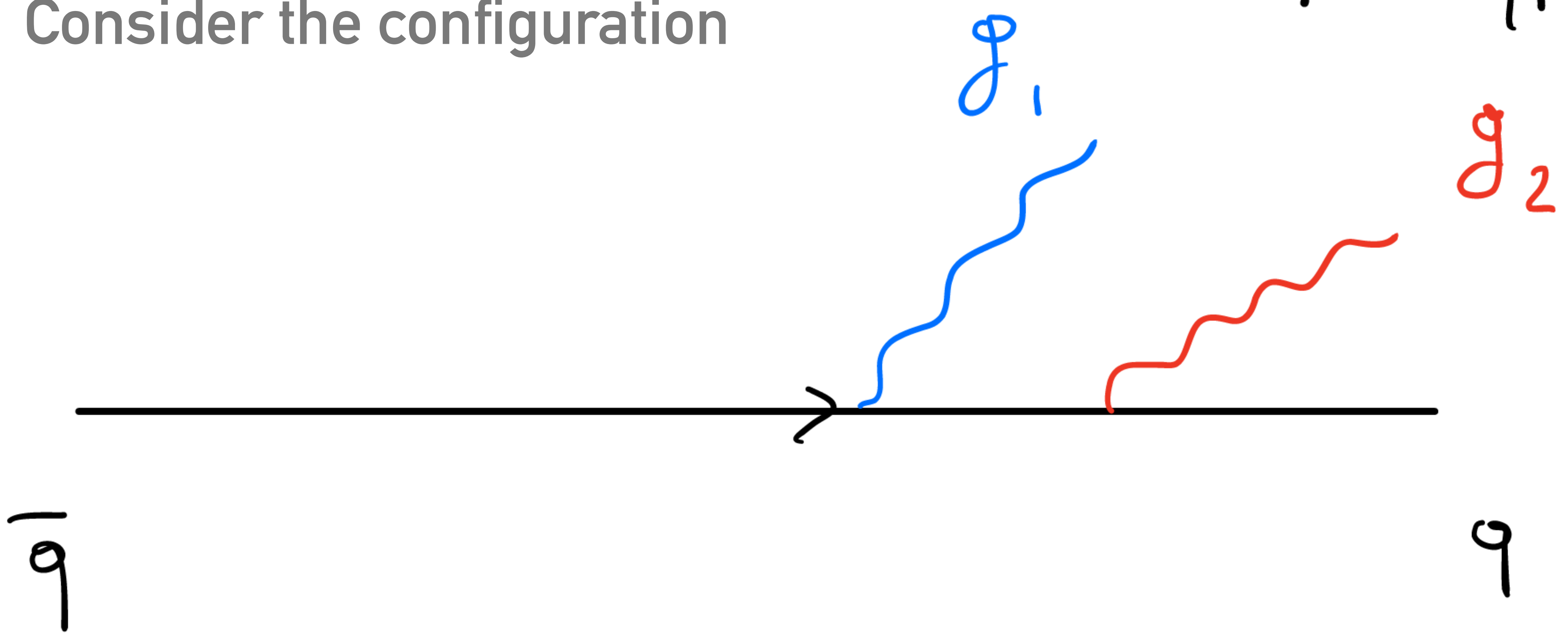
- **Novel element #1**: partitioning of the dipole (at $\bar{\eta} = 0$) occurs at equal angles between the emission and the dipole ends in the **event c.o.m. frame**

e.g.
Consider the configuration

$$|\eta_{2q}| >> |\eta_{1q}|$$



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

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dipole $\{\tilde{p}_i, \tilde{p}_j\}$ $\longrightarrow$

$$
\begin{aligned}
p_k &= a_k \tilde{p}_i + b_k \tilde{p}_j + k_\perp\,, \\
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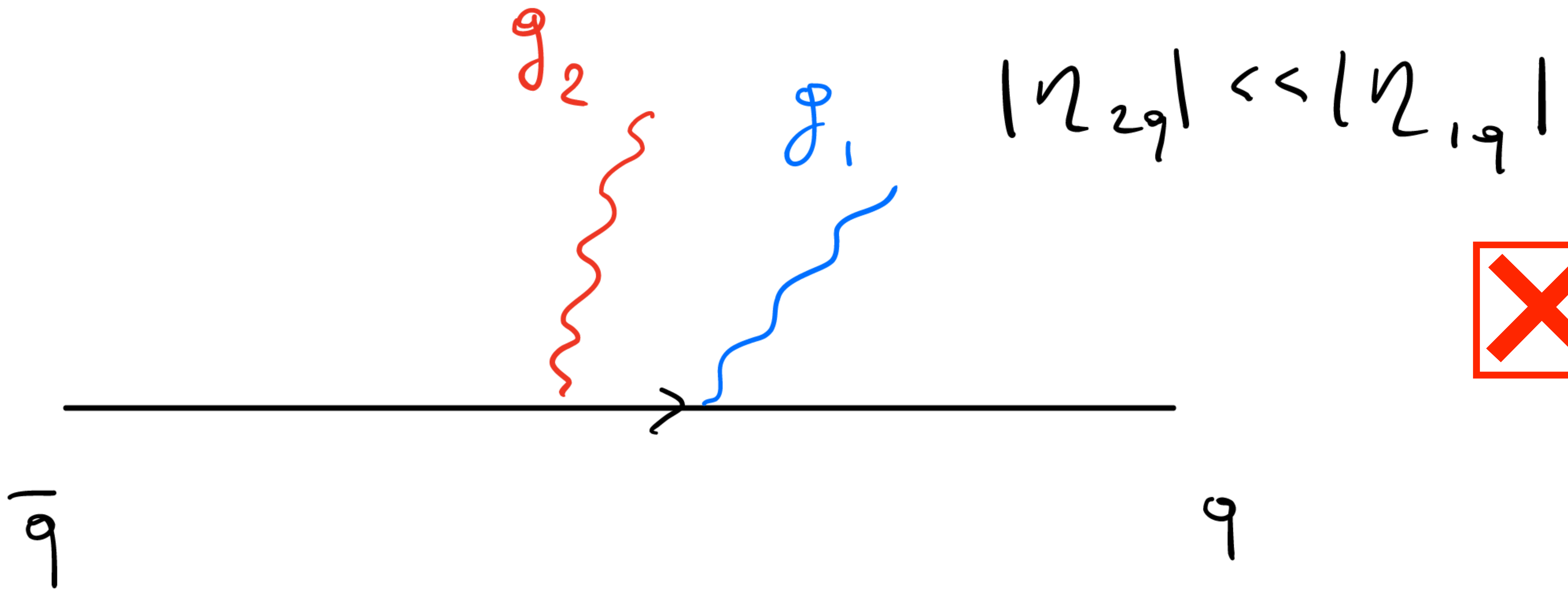


Instead, if g_2 is produced at larger rapidities than g_1, and they are both collinear to the quark, the recoil is still taken from g_1 in a logarithmic (NLL) region of phase space

The PanLocal shower (local recoil)

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

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

- Novel element #2: use an evolution variable v defined as ($\beta < 1$)

$$k_t = \rho v e^{\beta|\bar{\eta}|} \sim v e^{\beta|\eta^{\text{w.r.t. emitter}}|} \qquad \rho = \left(\frac{s_{\tilde{\imath}} s_{\tilde{\jmath}}}{Q^2 s_{\tilde{\imath}\tilde{\jmath}}}\right)^{\frac{\beta}{2}}$$

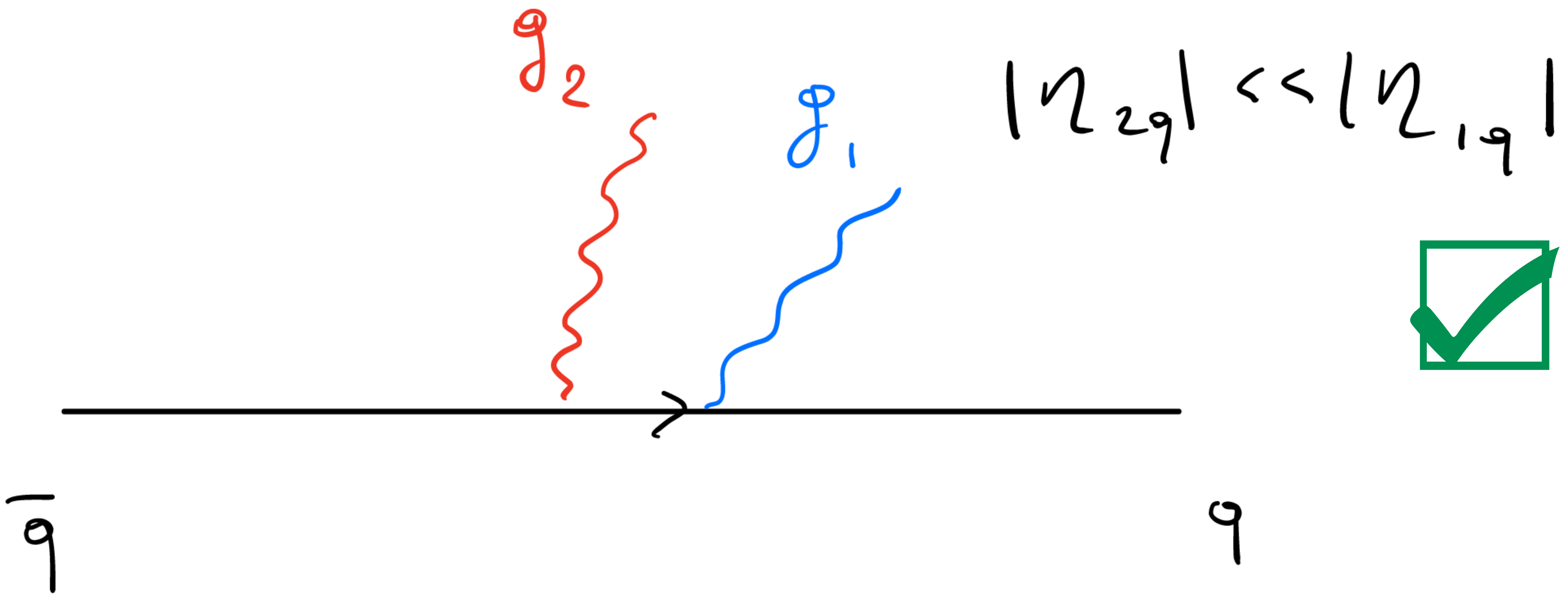
- Choosing $\beta > 0$ effectively reproduces angular ordering in the limit of commensurate k_t's and strong angular separation (NB: k_t ordering not allowed in local recoil scheme)

The PanLocal shower (local recoil)

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

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

- **Novel element #2**: use an evolution variable v defined as ($\beta < 1$)



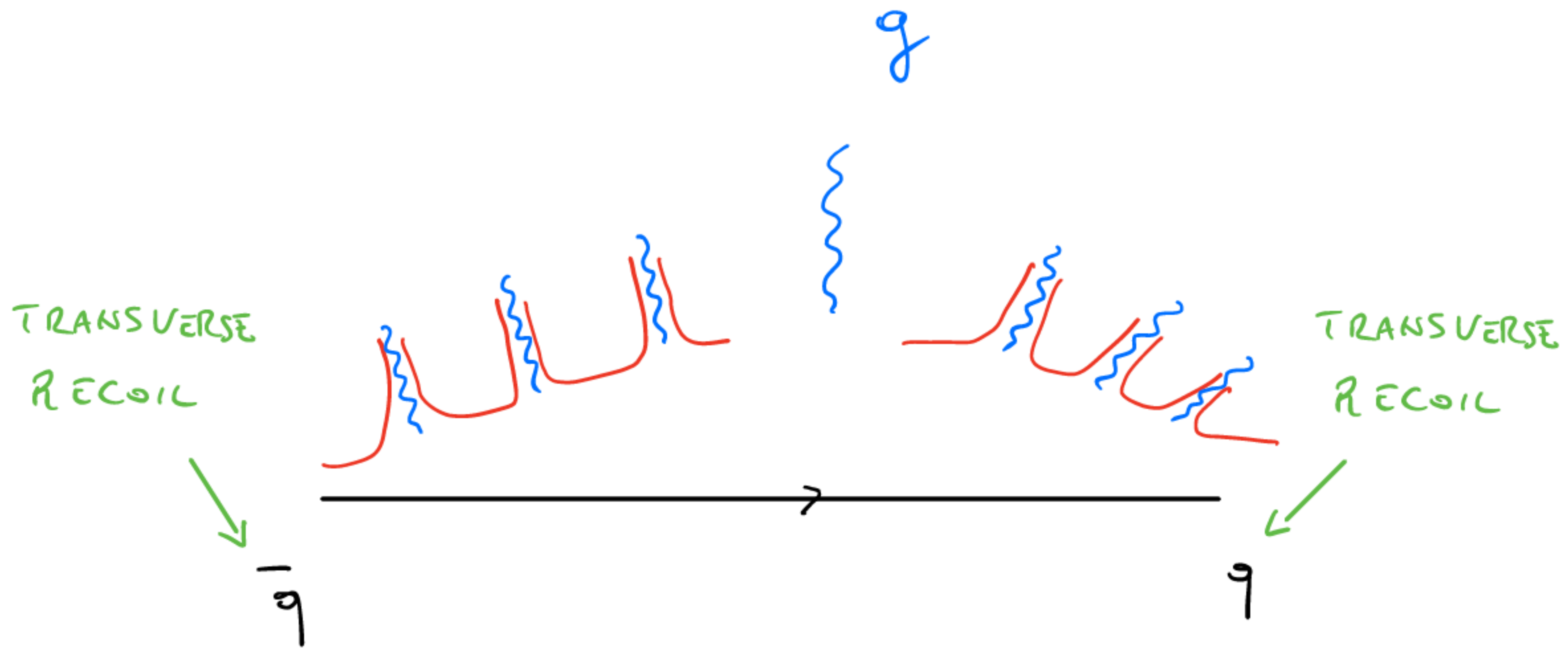
- Ordering in v now implies that $k_{t2} << k_{t1}$ [i.e. no recoil]
- The combination of partition⊕ordering creates a mechanism in which the recoil is always taken from the hard extremities of the dipole chain [correct at NLL]

The PanGlobal shower (local recoil)

- Longitudinal recoil is kept dipole local

$$\text{dipole}\ \{\widetilde{p}_i, \widetilde{p}_j\} \longrightarrow \begin{aligned} \bar{p}_k &= a_k \tilde{p}_i + b_k \tilde{p}_j + k_\perp\,, \\ \bar{p}_i &= (1-a_k)\tilde{p}_i\,, \\ \bar{p}_j &= (1-b_k)\tilde{p}_j\,. \end{aligned}$$

- Transverse recoil is distributed globally across the event via a Lorentz boost + rescaling i.e. recoil is taken from (and shared among) the hard extremities of the dipole string



- With this scheme, also k_t ordering is now a viable option

Testing the logarithmic accuracy of a parton shower

- Definition of observables (sometimes new) sensitive to different aspects of QCD radiation

- Formulation of a toy model of each shower algorithm
  (soft limit, fixed coupling, simplified kinematics, primary radiation only):
  - All-order numerical tests against NLL calculation in the same toy model
  - Fixed order calculations up to $O(\alpha_s^4)$, numerical and analytic.
    - reveal issues that give small effects when resummed
      (e.g. spurious super-leading logarithms)

- Accuracy tests in the full shower, algorithmic optimisation necessary

➥ Discussed in the following

Testing the logarithmic accuracy of a parton shower

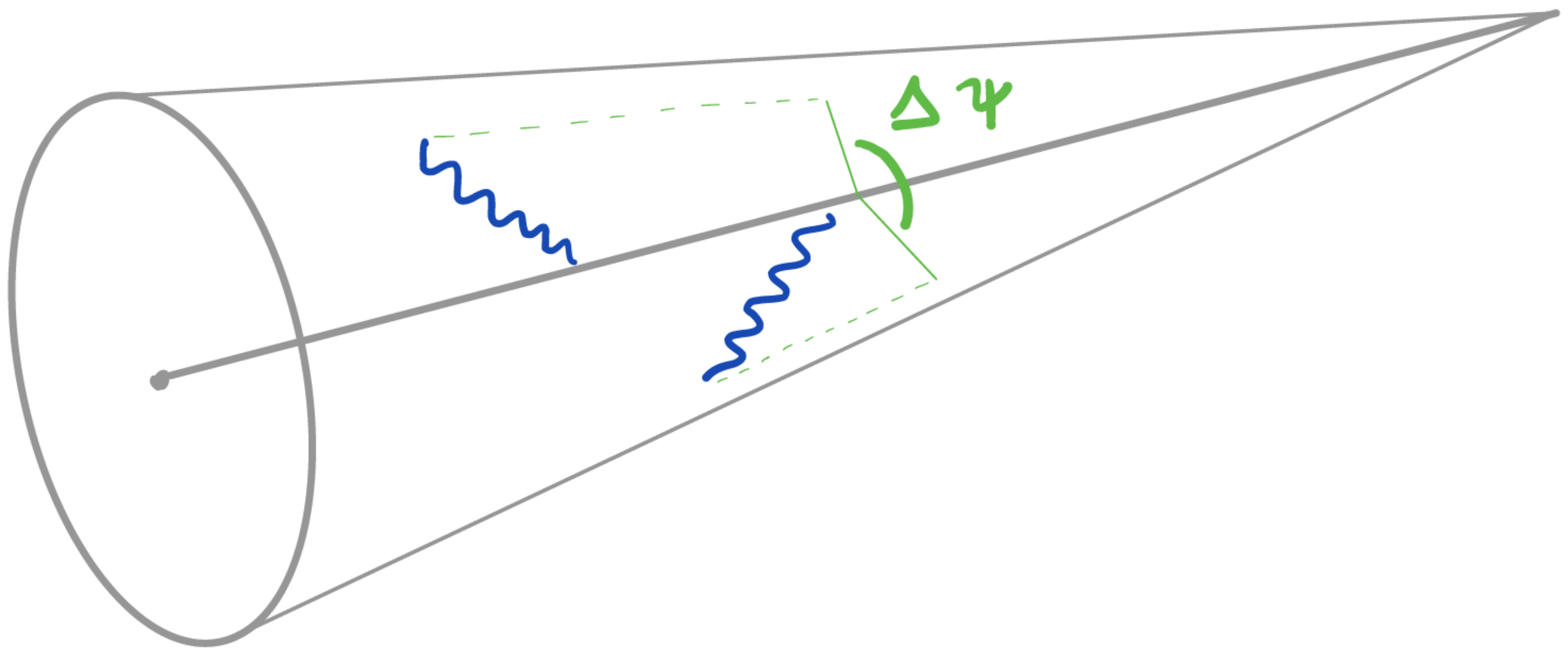
- Tests of logarithmic accuracy in the full shower against NLL resummations:
  - Consider cumulative distributions for an observable (e.g. jet rate, event shapes, …) in the limit **$\alpha_s |L| \sim 1$, and $|L| \gg 1$**

LL (=0 sometimes) NLL

$$\Sigma(\alpha_s, \alpha_s L) = \exp\left[\alpha_s^{-1} g_1(\alpha_s L) + g_2(\alpha_s L) + \mathcal{O}\left(\alpha_s^n L^{n-1}\right)\right]$$

  - Compute the ratio $\frac{\Sigma_{\rm PS}}{\Sigma_{\rm NLL}}$
    - PS is LL: Σ_{PS} misses **O(1)** corrections, i.e. $\lim_{\alpha_s \to 0} \frac{\Sigma_{\rm PS}}{\Sigma_{\rm NLL}} \neq 1$
    - PS is NLL: Σ_{PS} misses **O(α_s)** corrections, i.e. $\lim_{\alpha_s \to 0} \frac{\Sigma_{\rm PS}}{\Sigma_{\rm NLL}} = 1$

An example: azimuthal substructure of jets



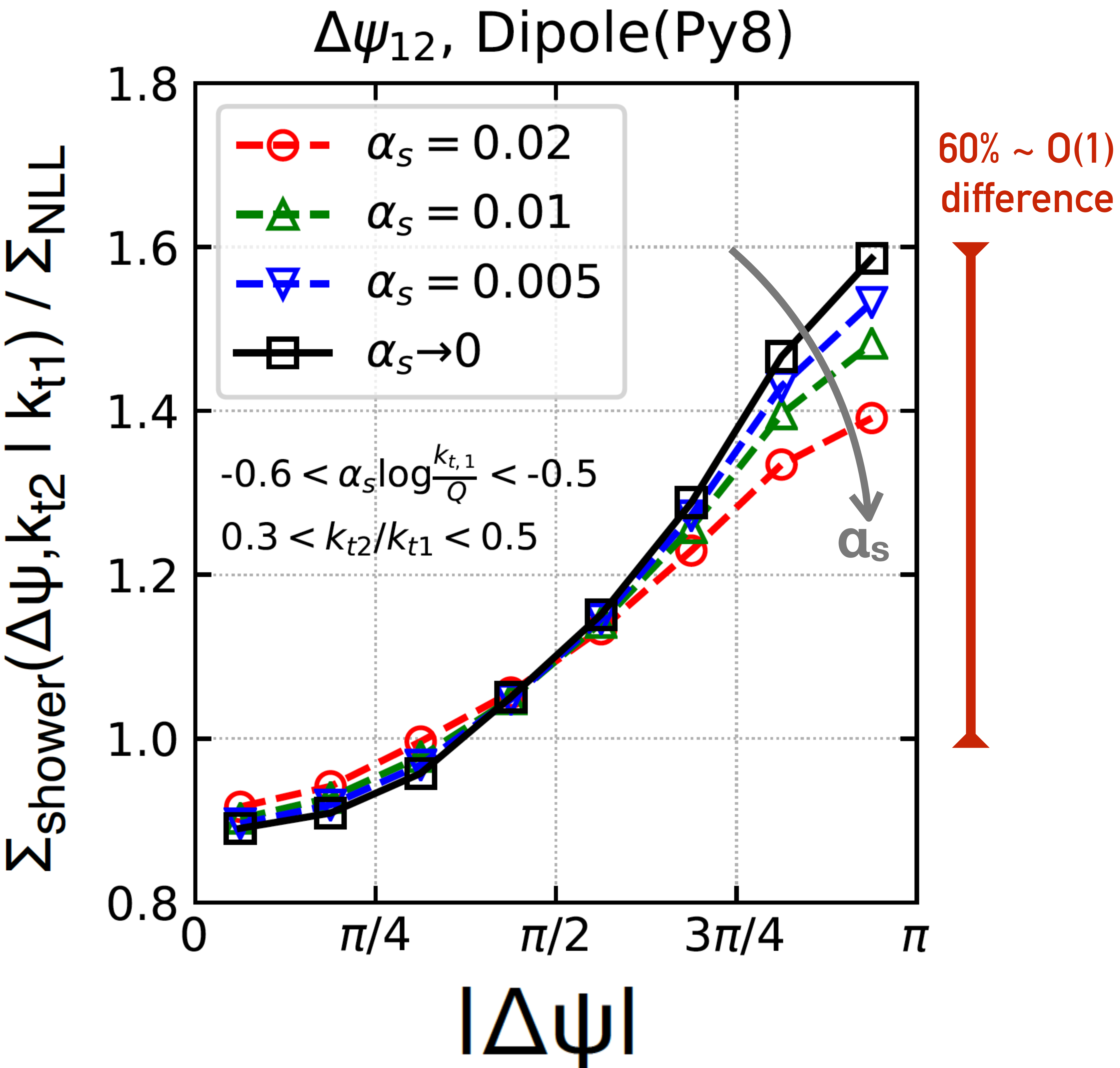
- Definition of Lund Jet Plane (LJP) based azimuthal angle between two leading primary declusterings [actual definition involves a dynamical frame]

[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez ’20]
cf. [Dreyer, Salam, Soyez ’18] for construction of the Lund Jet Plane

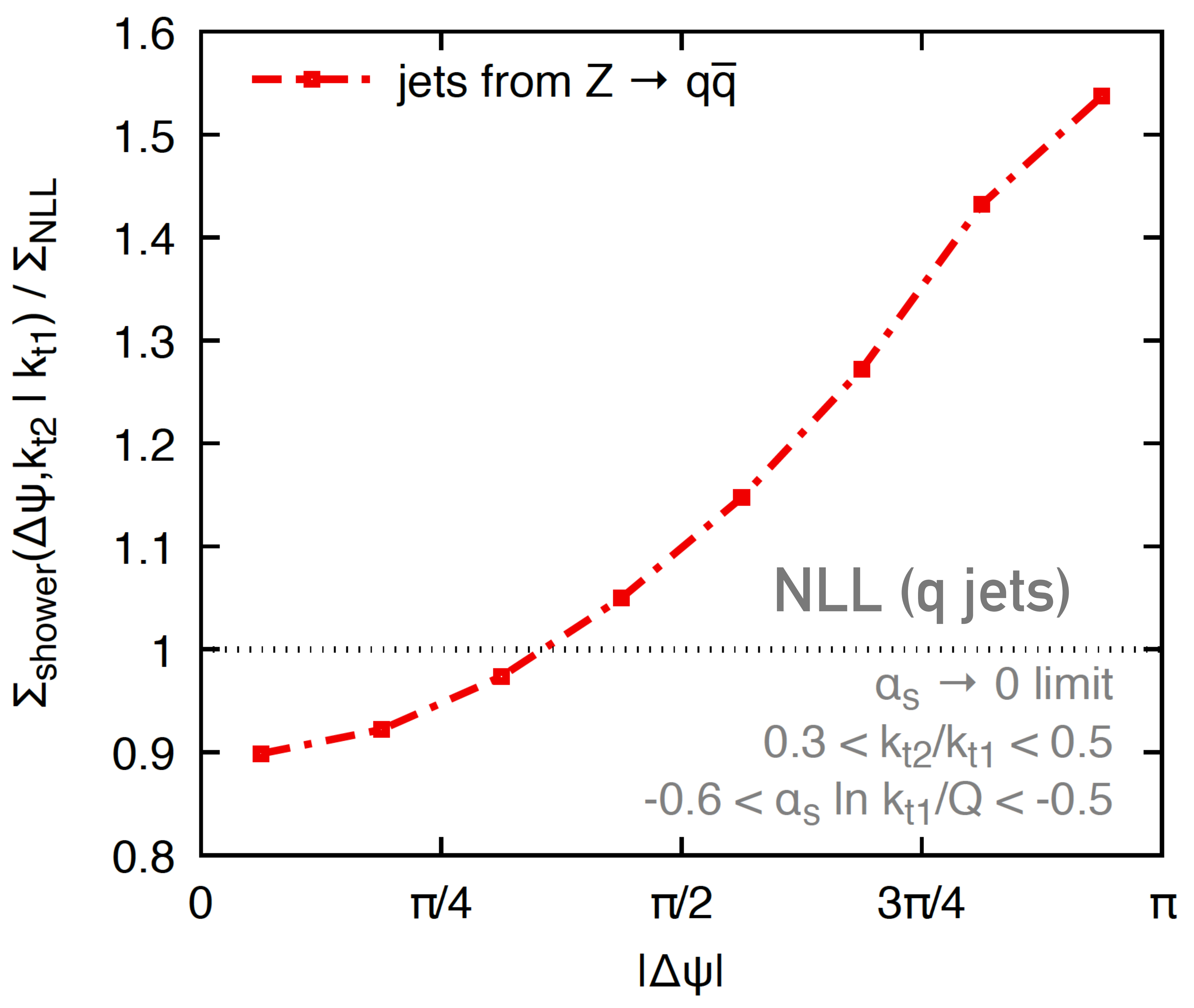
An example: azimuthal substructure of jets

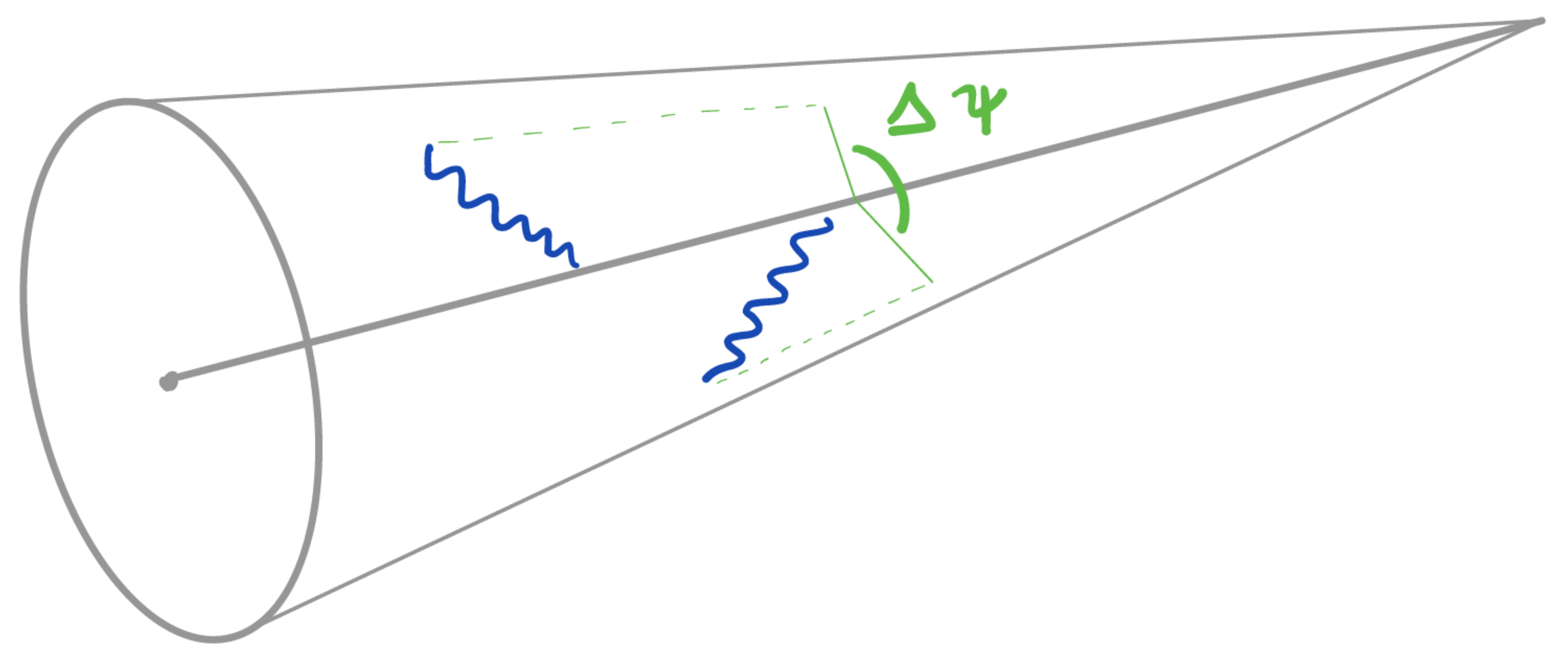
e.g. let's consider the ΔΨ distribution given earlier. Ratio to NLL shows a residual & non-trivial shape difference in the limit $\alpha_s \to 0$.

➥ The observed discrepancy is due to the unphysical features in the (transverse) recoil assignment which fails to reproduce the correct NLL matrix elements. This translates into a breaking of NLL accuracy



An example: azimuthal substructure of jets

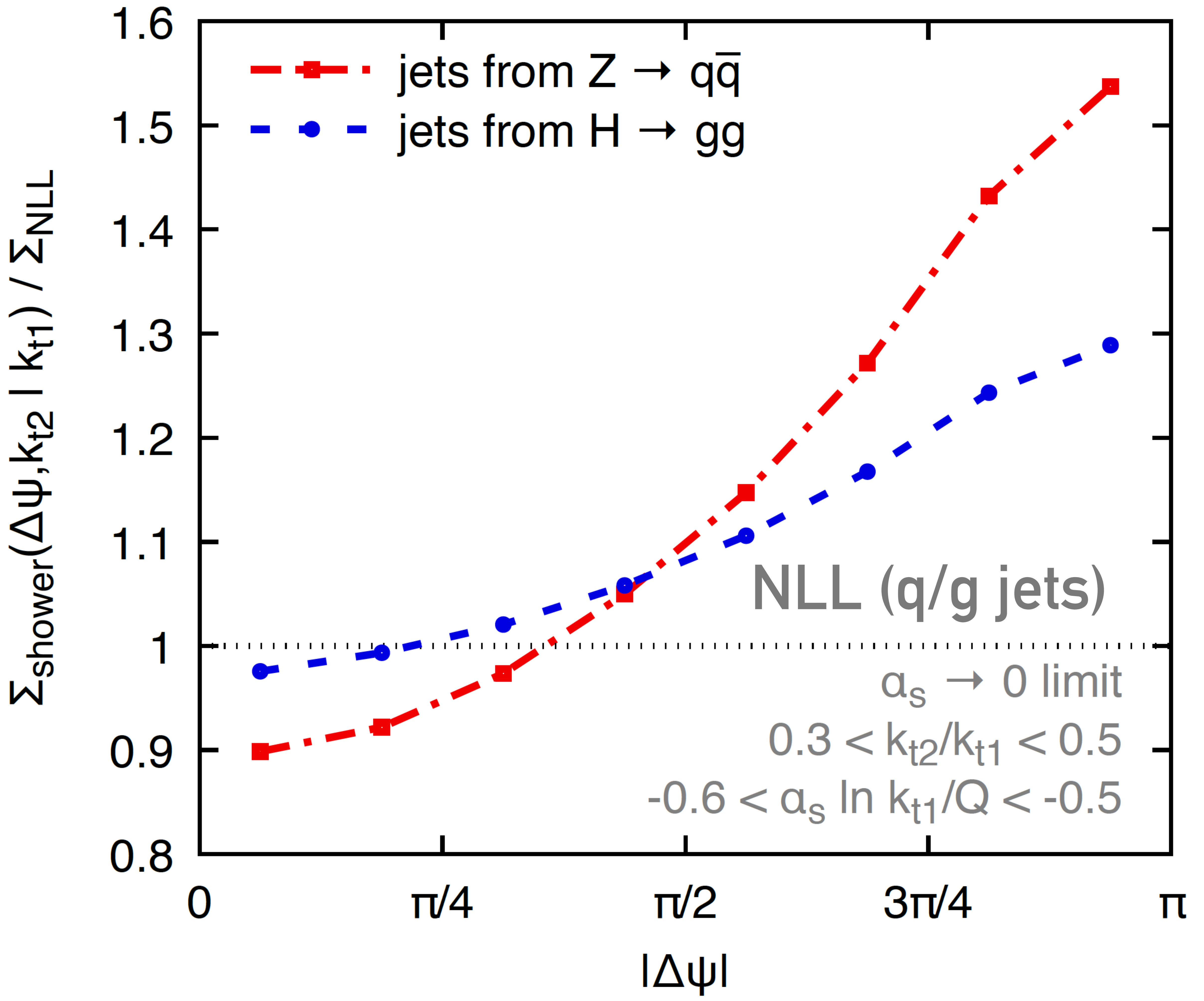


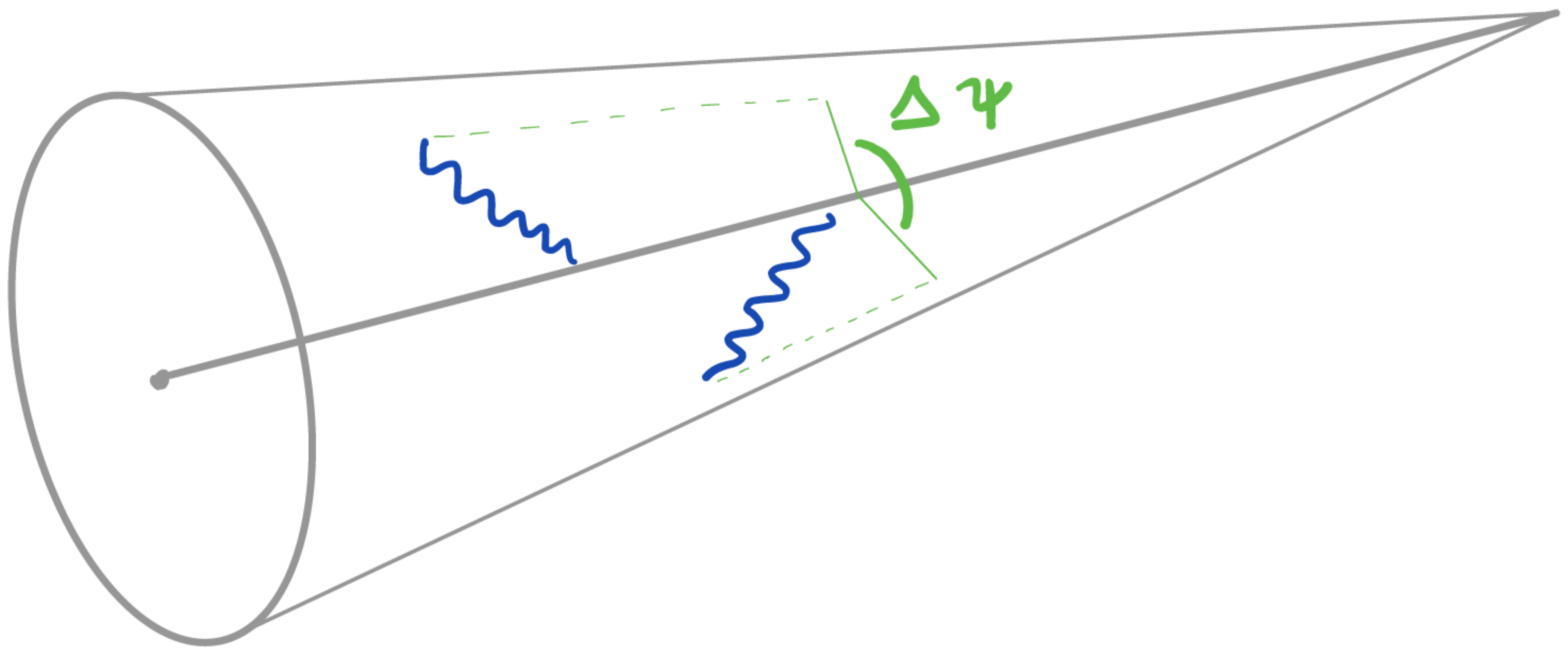


- ΔΨ distribution is uniform at NLL, while modern dipole showers (e.g. Pythia8 / Dire) predict a non-trivial shape

[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez ’20]
cf. [Dreyer, Salam, Soyez ’18] for construction of the Lund Jet Plane

An example: azimuthal substructure of jets





- ΔΨ distribution is uniform at NLL, while modern dipole showers (e.g. Pythia8 / Dire) predict a non-trivial shape
- Unphysical dependence on jet flavour, with implications for q/g jet discrimination if Machine Learning tools learn these features.

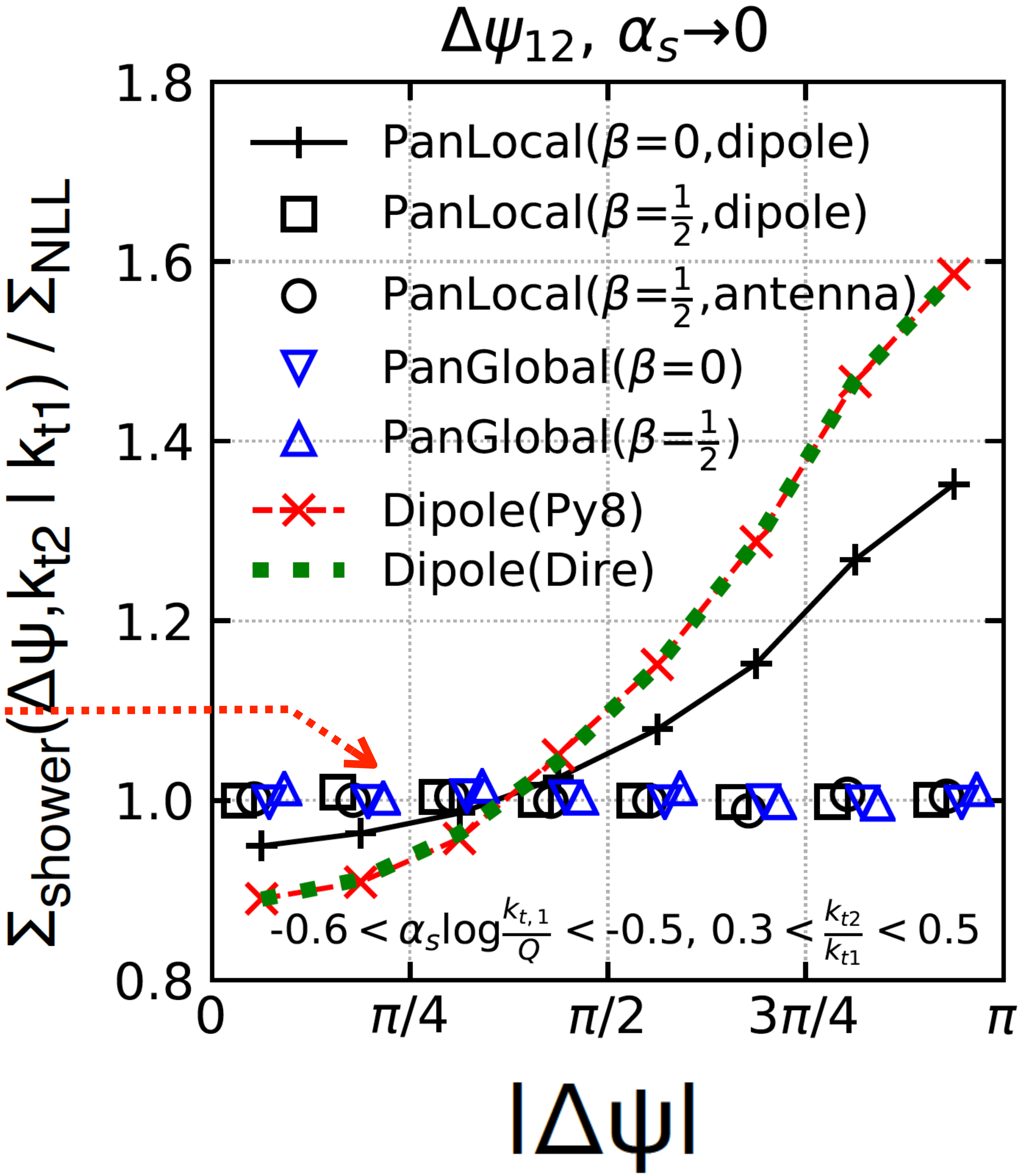
[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez '20]
cf. [Dreyer, Salam, Soyez '18] for construction of the Lund Jet Plane

An example: azimuthal substructure of jets

- Use input from NLL resummations to construct a parton shower alg. that constructs the correct multiparton squared amplitudes in the relevant kinematic limits

➥ New classes of NLL shower algorithms (PanLocal = local recoil map; PanGlobal = global recoil map) reproduce correct NLL results as expected

[Dasgupta, Dreyer, Hamilton, PM, Salam ’18]
[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez ’20]
See also [Forhsaw, Holguin, Plaetzer ’20]

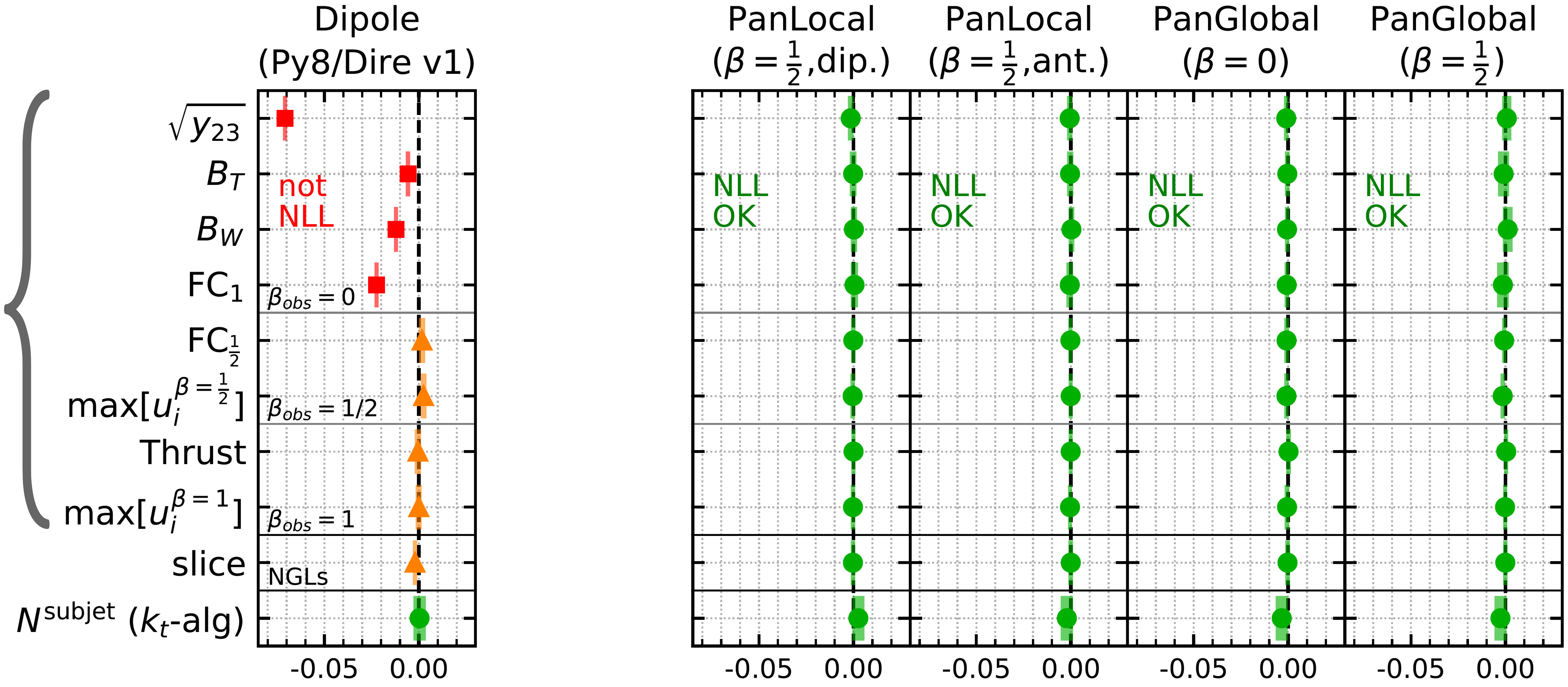


Accuracy across many observables

[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez '20]

Plots: relative deviation from exact NLL
[in $\alpha_s \to 0$ limit at fixed α_s L]

Global observables: sensitive to strong η (θ) separation at NLL



e.g.

$$\mathrm{T} = \max_{\hat{n}} \frac{\sum_i |\mathbf{p}_i \cdot \hat{n}|}{\sum_i |\mathbf{p}_i|}$$ [Thrust]

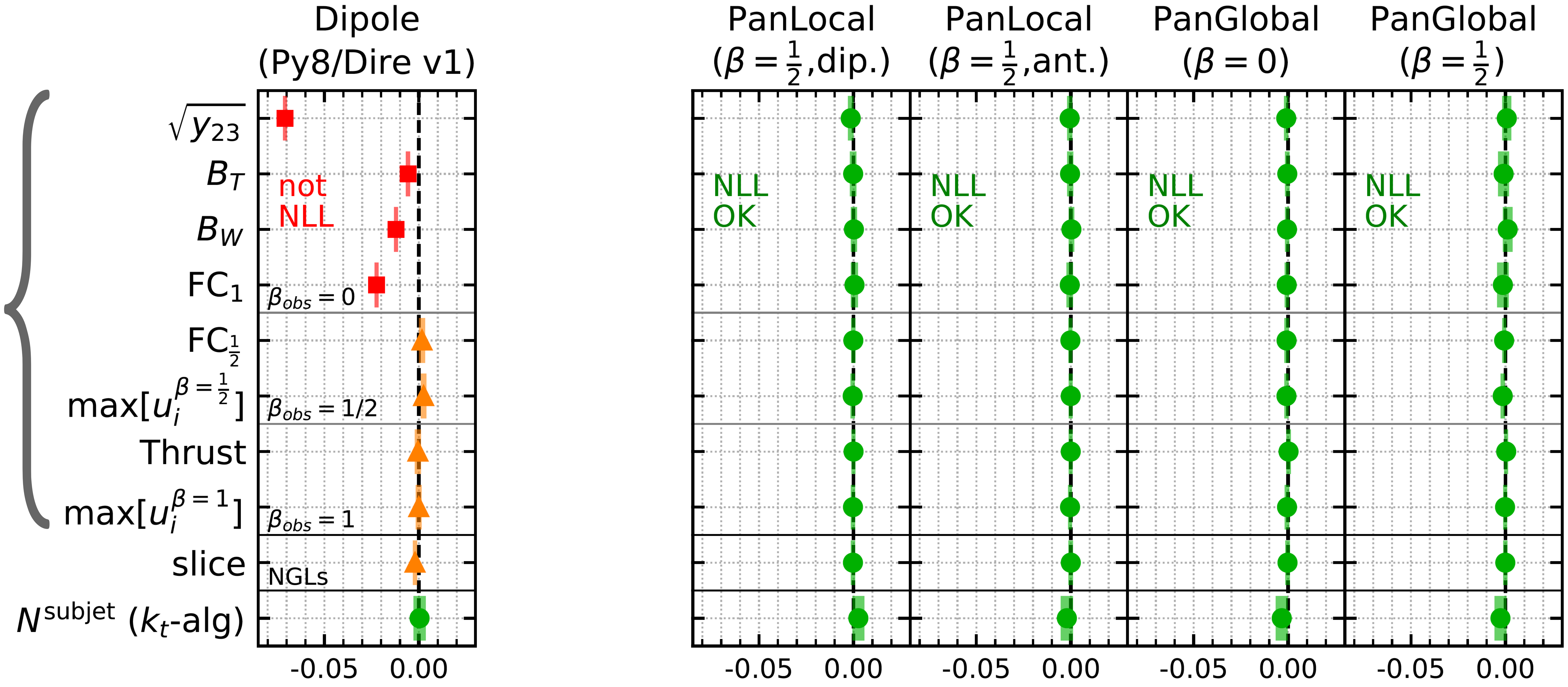
$$\mathrm{FC}_x = \sum_{i \neq j} \frac{E_i E_j}{(\sum_i E_i)^2} |\sin\theta_{ij}|^x (1 - |\cos\theta_{ij}|)^{1-x} \Theta((\mathbf{p}_i \cdot \hat{n})(\mathbf{p}_j \cdot \hat{n}))$$ [Moment of Energy-Energy correlation]

Accuracy across many observables

[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez '20]

Plots: relative deviation from exact NLL [in $\alpha_s \to 0$ limit at fixed $\alpha_s L$]

[Sjostrand et al. '15]
[Hoeche, Prestel '15]



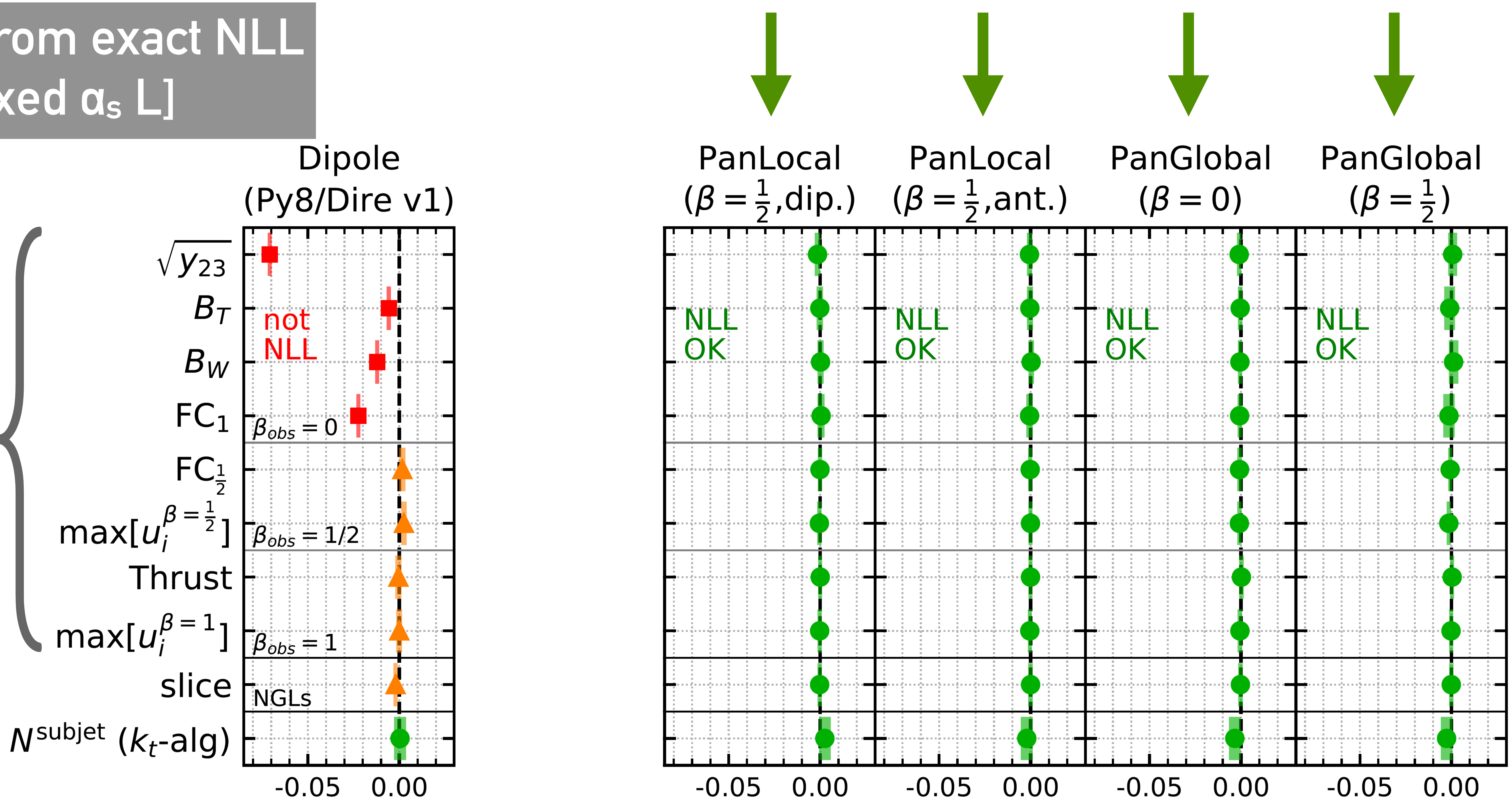
Global observables: sensitive to strong η (θ) separation at NLL

Orange triangles indicate spurious terms (either NLL or SLL) at fixed order, that become small when resummed

Accuracy across many observables

[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez '20]

Plots: relative deviation from exact NLL
[in $\alpha_s \to 0$ limit at fixed $\alpha_s L$]

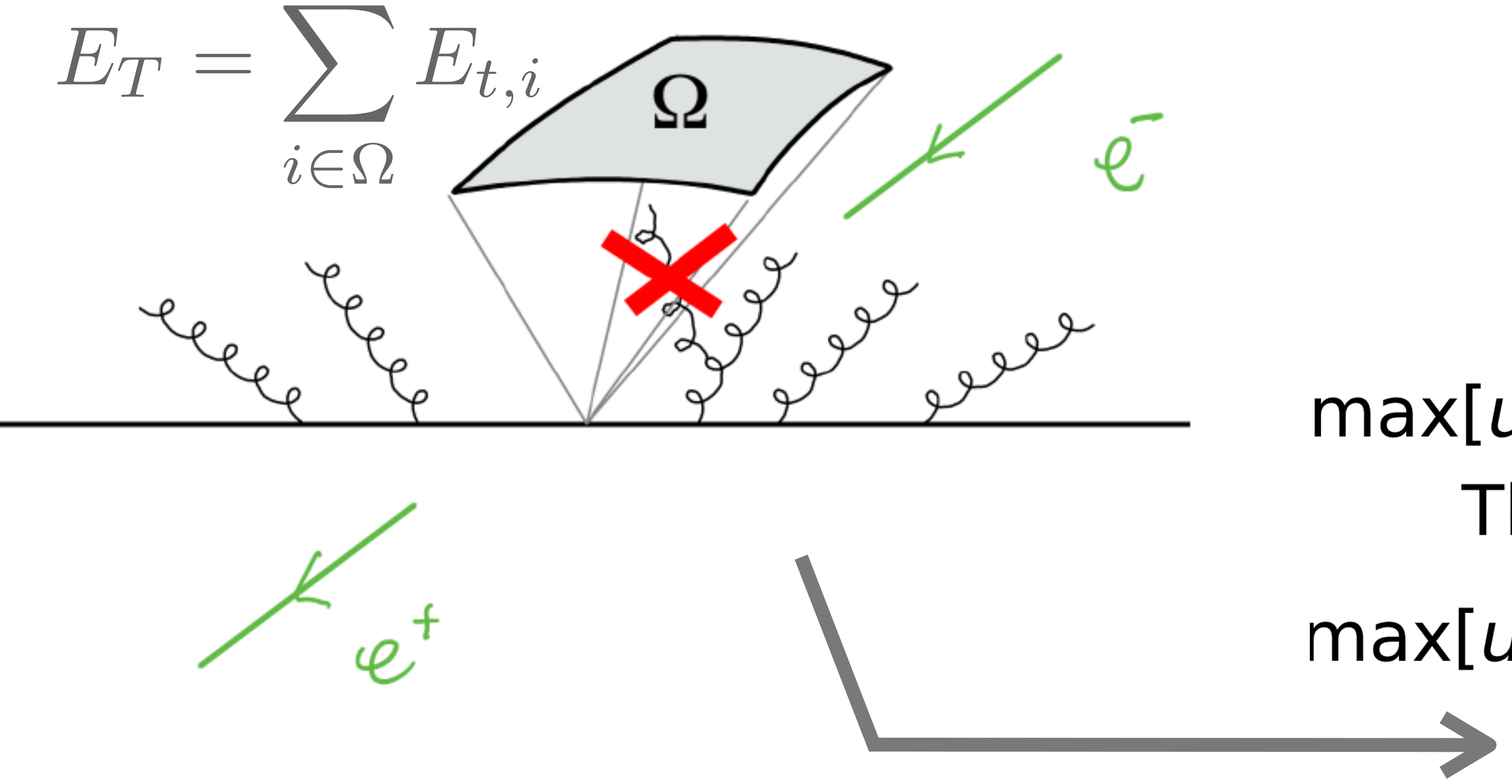


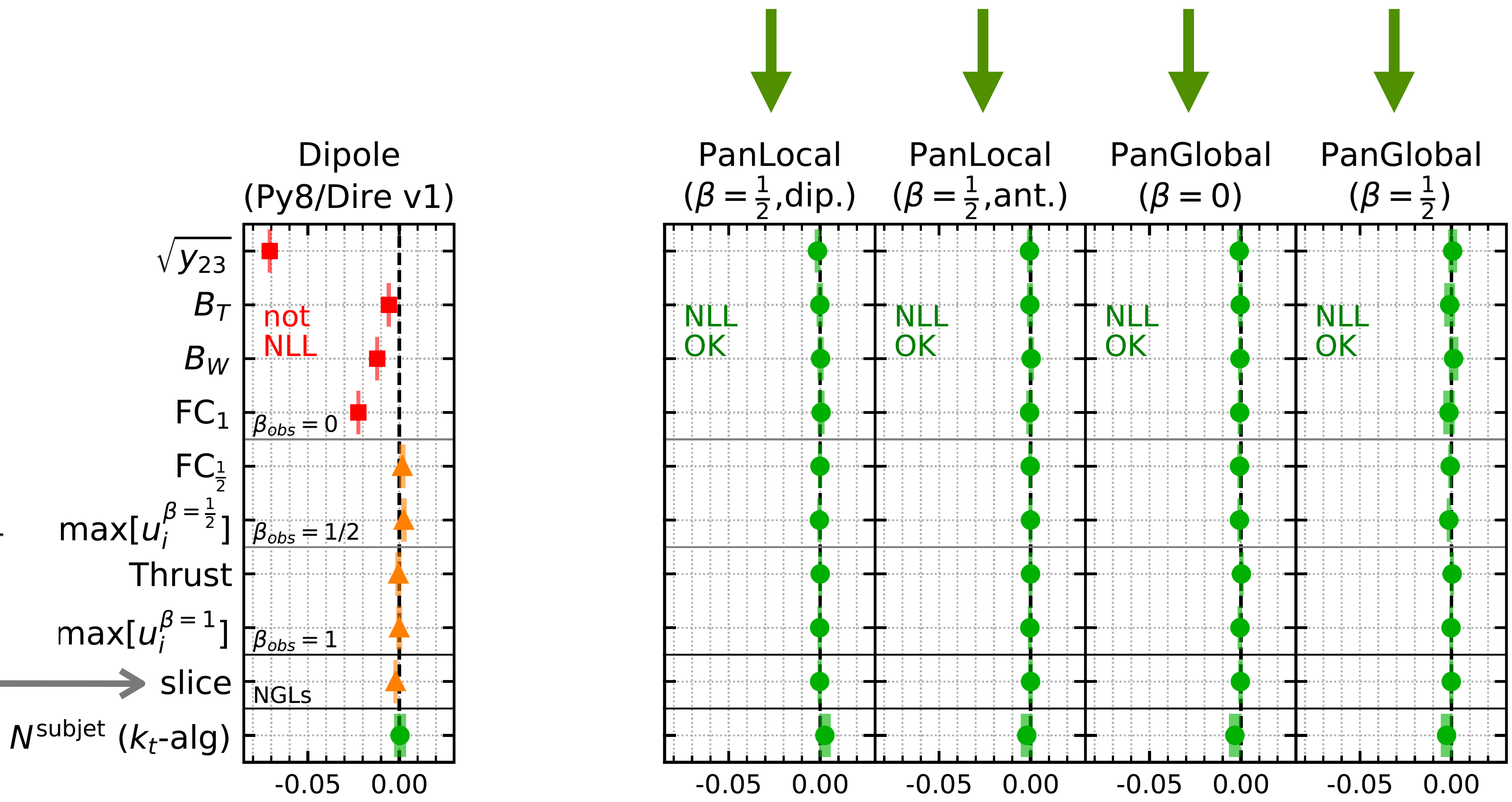
Global observables:
sensitive to strong η (θ)
separation at NLL

Accuracy across many observables

[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez '20]

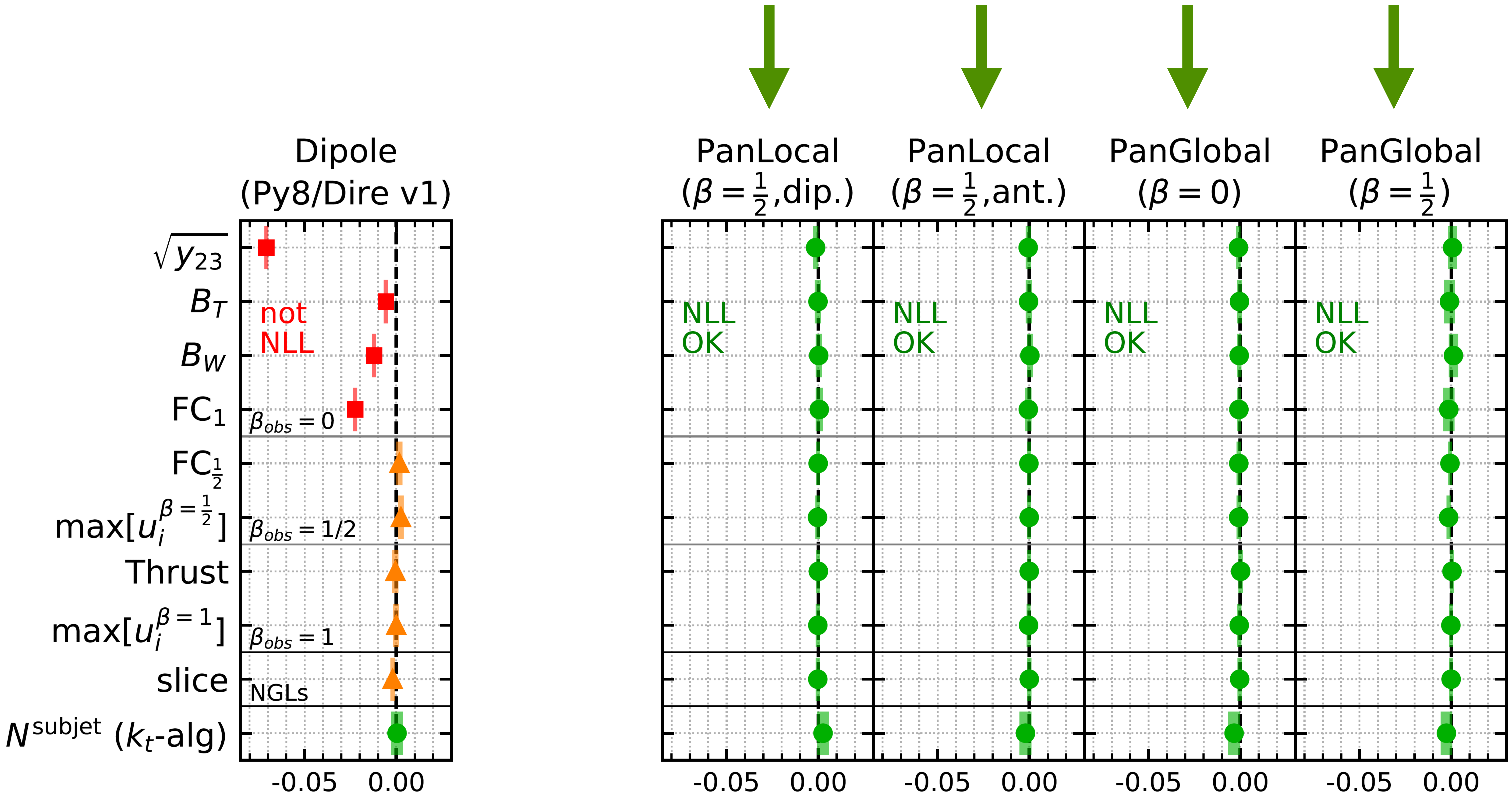
Non-global observables: sensitive to strong kt (E) separation at NLL
e.g.





Accuracy across many observables

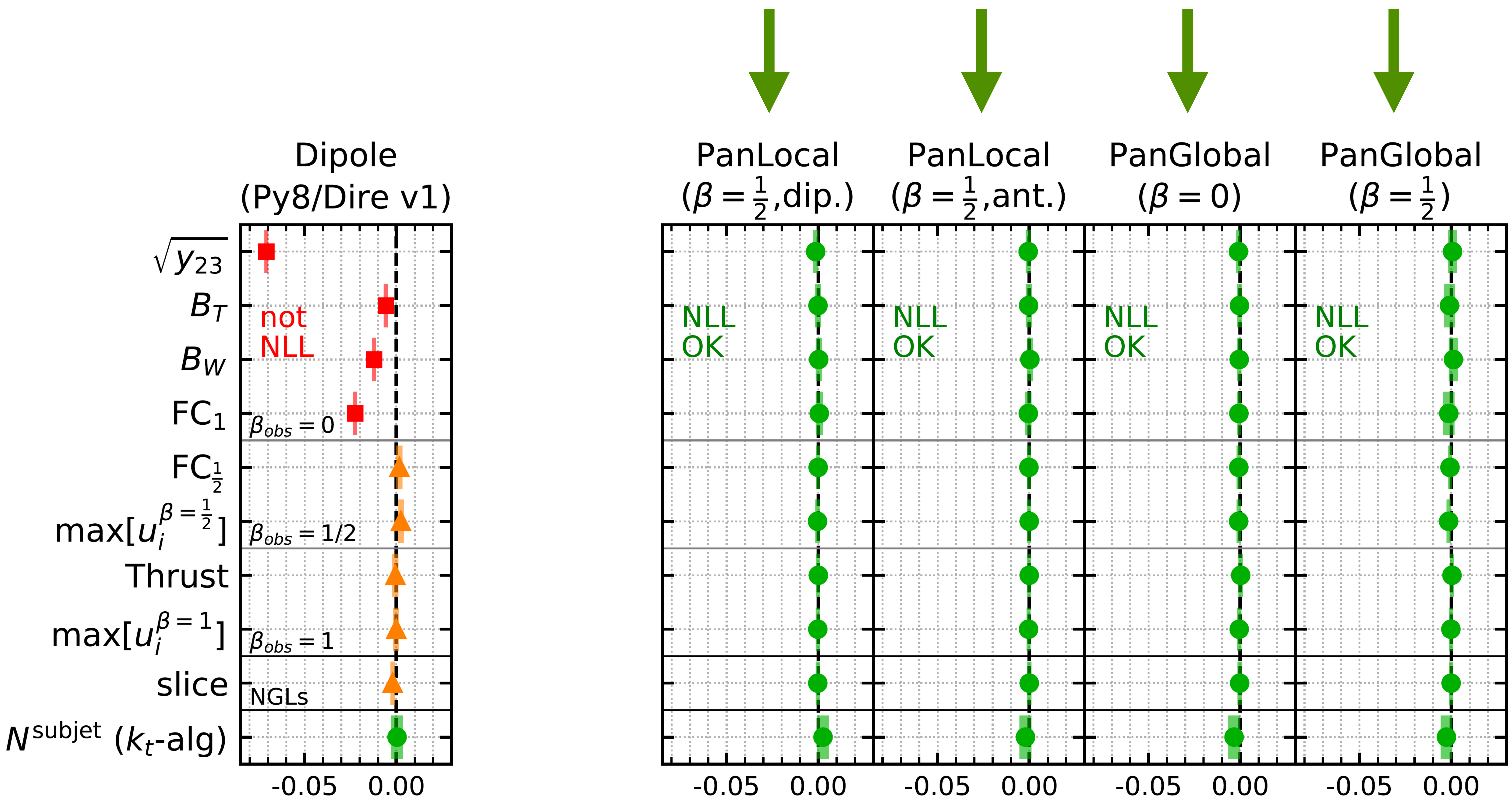
[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez '20]



Subjet particle multiplicity in the k_T algorithm: sensitive to full recursive shower structure

Accuracy across many observables

[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez '20]

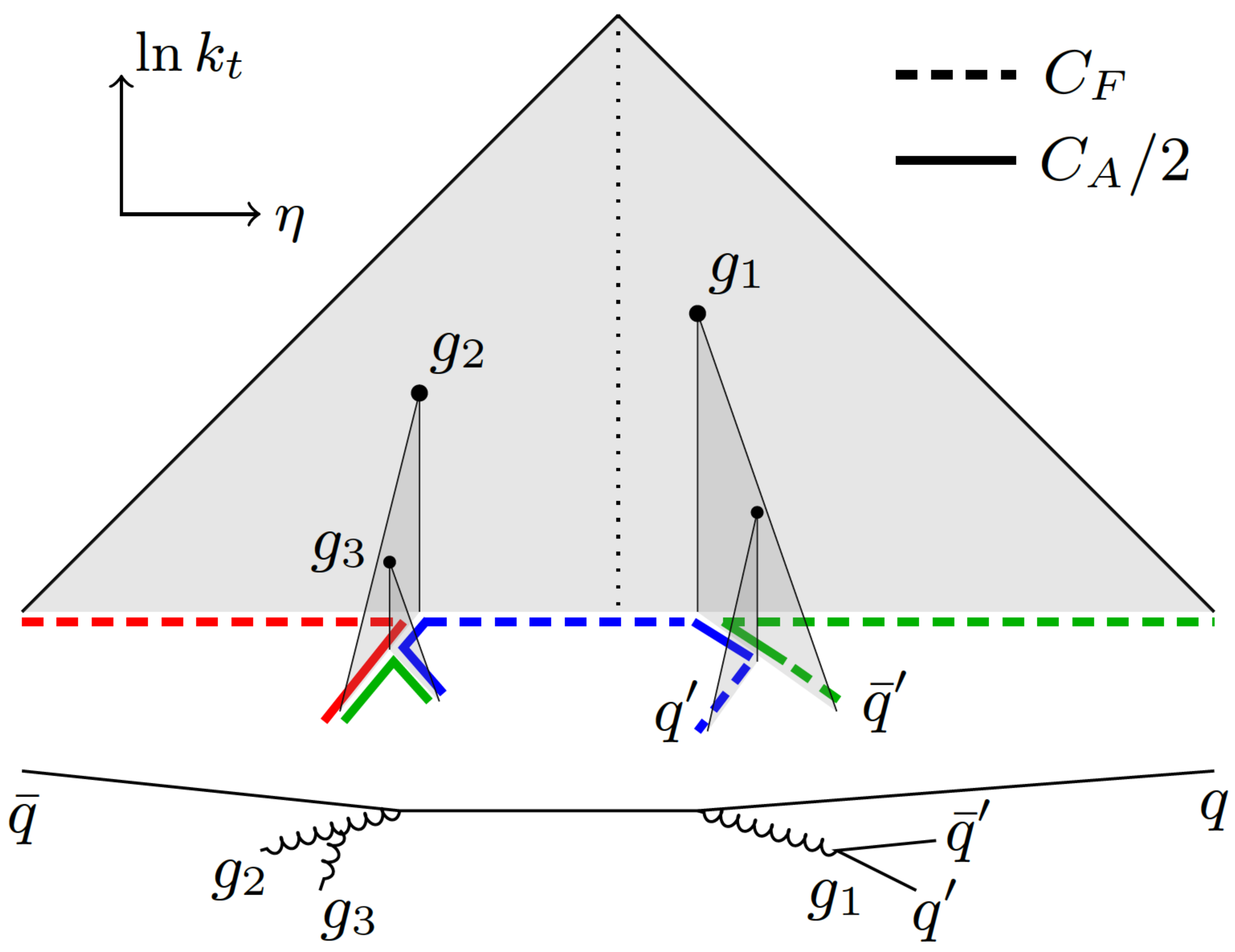


Subjet particle multiplicity in the k_T algorithm: sensitive to full recursive shower structure

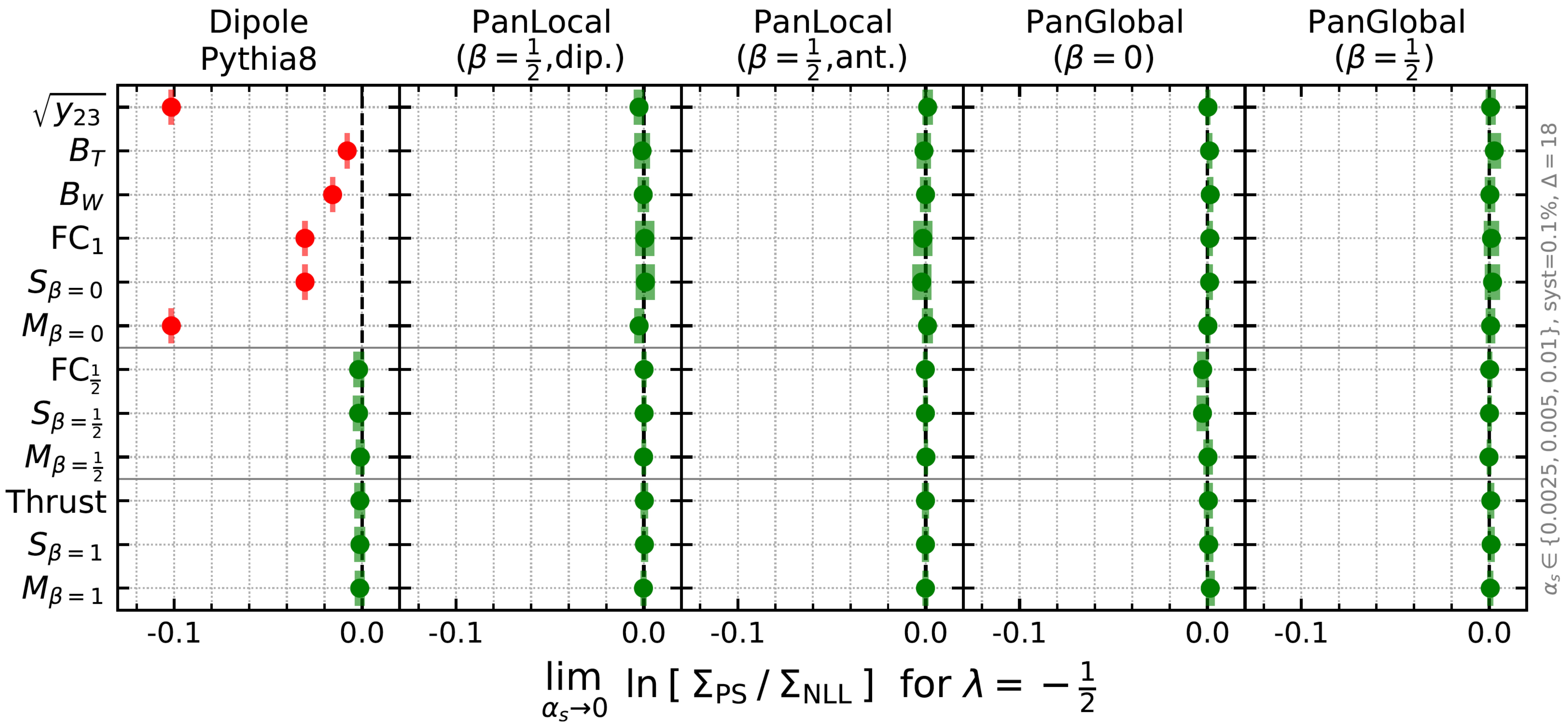
New classes of shower: NLL for all observables considered [global & non-global at once]

Beyond the planar limit: subleading N_c

- Same guiding principles can be used to include some information about subleading colour corrections
- Full colour accuracy can be achieved for global observables in processes with up to three coloured legs



NLL accuracy test – NODS procedure



[Hamilton, Medves, Salam, Scyboz, Soyez '20]
see also related work by
[Plaetzer, Sjodahl '12 + Thoren '18; Nagy, Soper '12-'19; Hoeche, Reichelt '20; De Angelis, Forhsaw, Plaetzer '20; Forshaw, Holguin, Plaetzer '20]

Conclusions and Outlook

- Formulation of accuracy criteria for parton showers guided by principles of QCD resummations
  - Testing framework for algorithms based on comparison to all order calculations
- With seemingly simple methods, one can engineer new PS algorithms that are NLL accurate for global & non-global observables at once
  - Demonstration of NLL accuracy both at fixed order and all orders
- Some aspects remain to be addressed (initial state radiation, spin correlations) but the proposed algorithms and techniques can incorporate solutions to the above problems
- This approach offers a powerful avenue to look beyond NLL, and take the first steps towards a new generation of accurate parton shower algorithms

see also related work by
[Hoeche, Prestel, + Krauss ’17; Dulat, Hoeche, Prestel ’18]