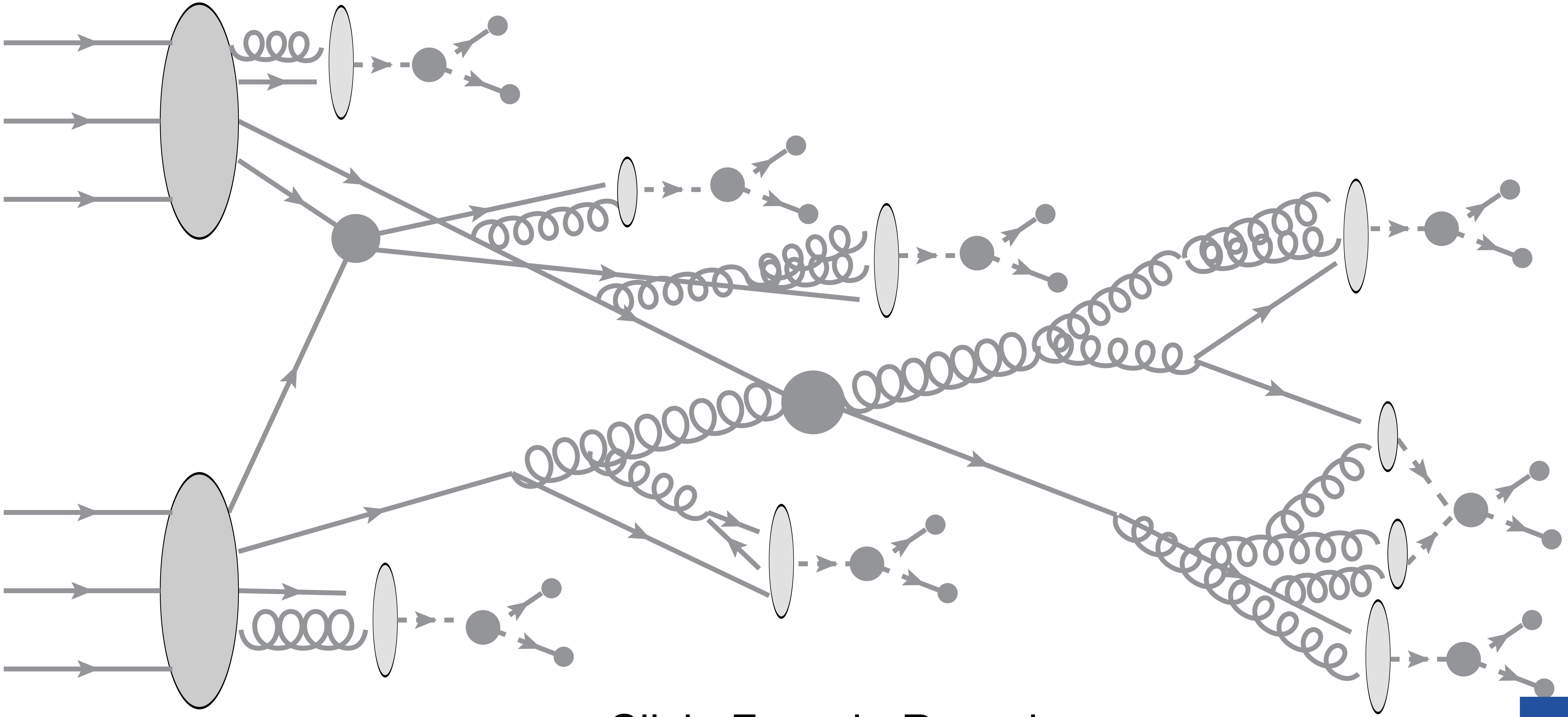
Overview on Parton Shower Developments

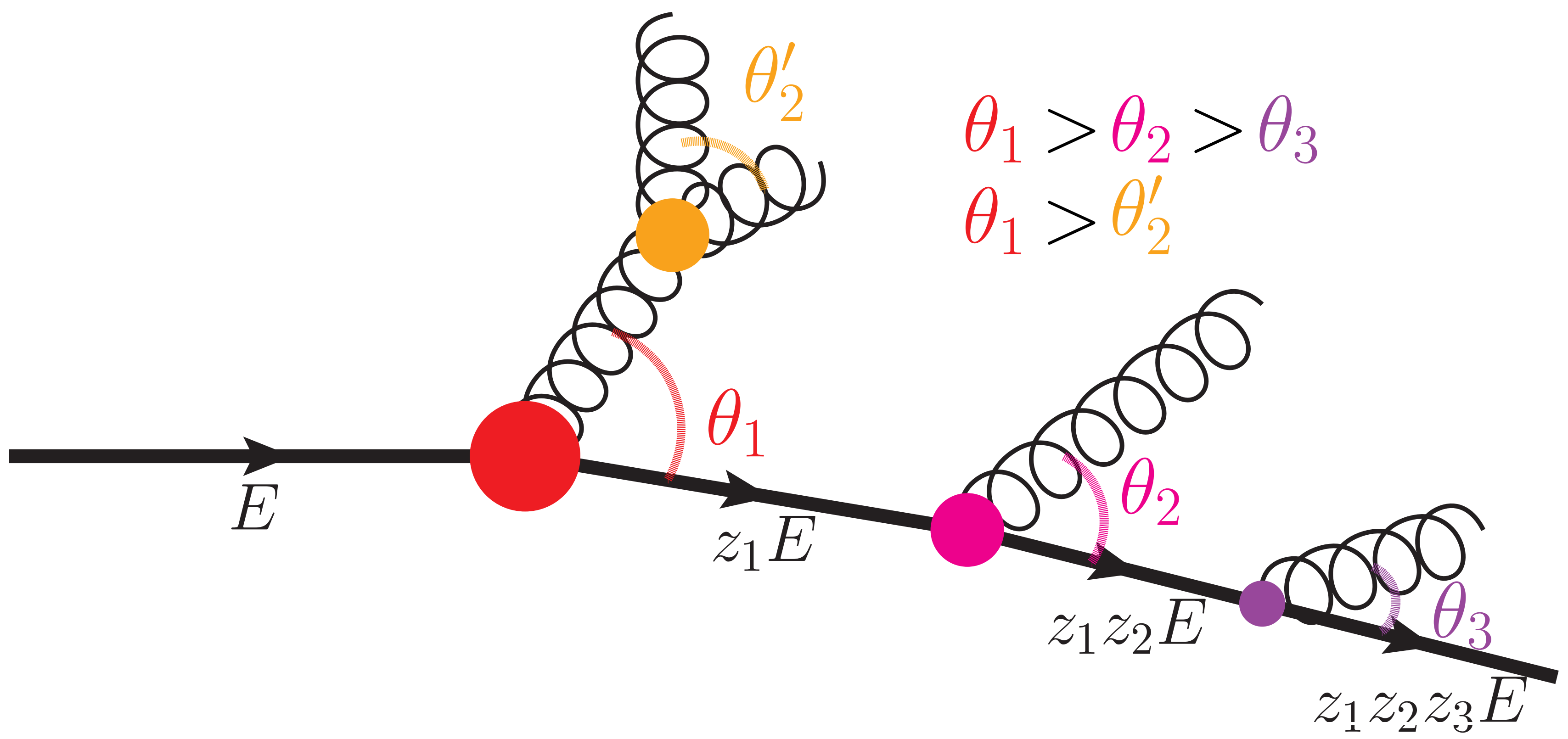


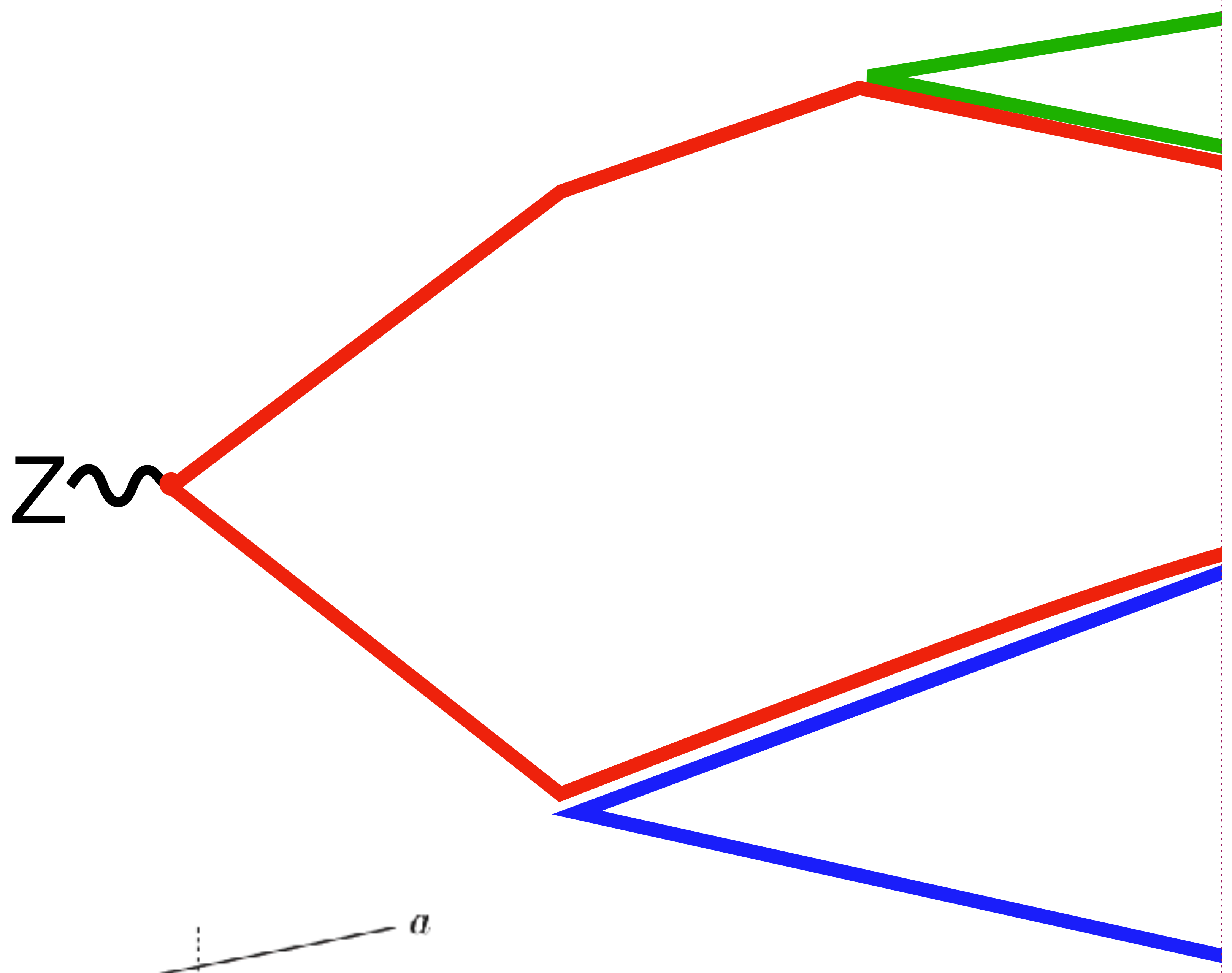
Silvia Ferrario Ravasio

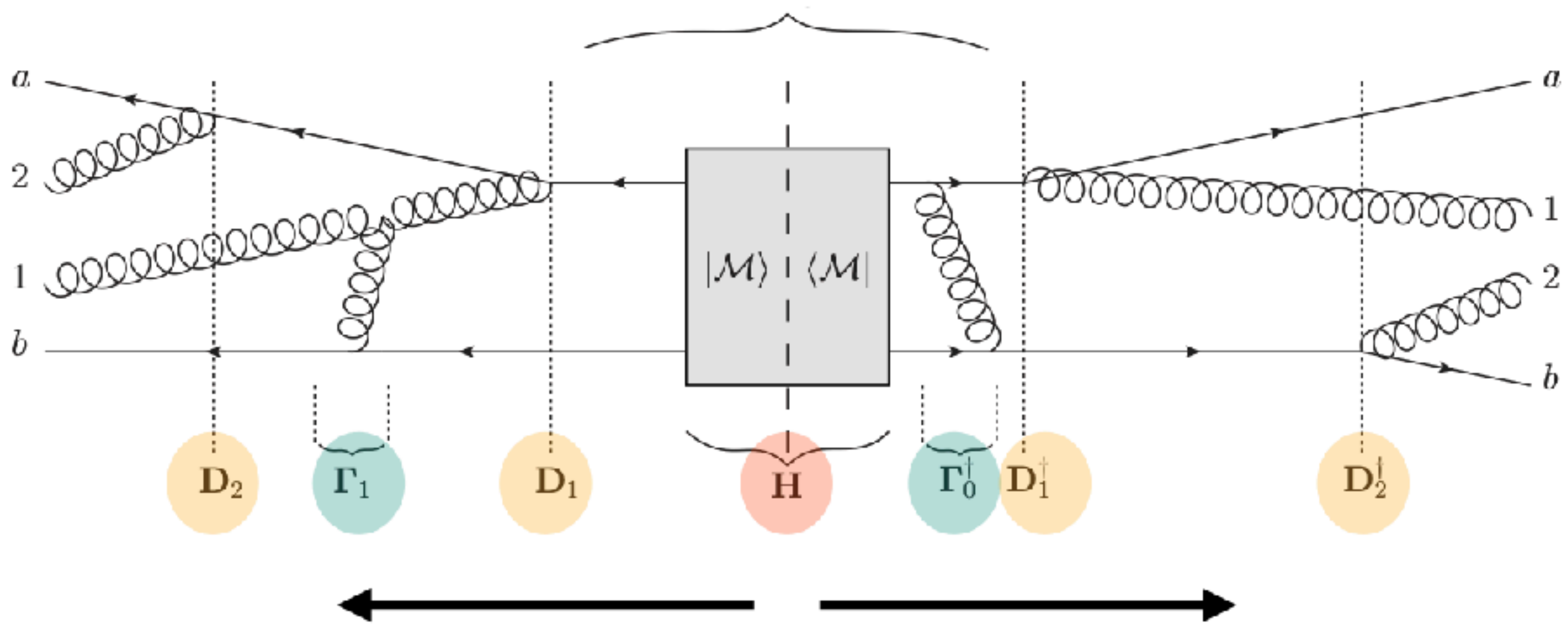
Parton Showers and Resummation 2024

2nd July 2024, Universität Graz

What is a parton shower?

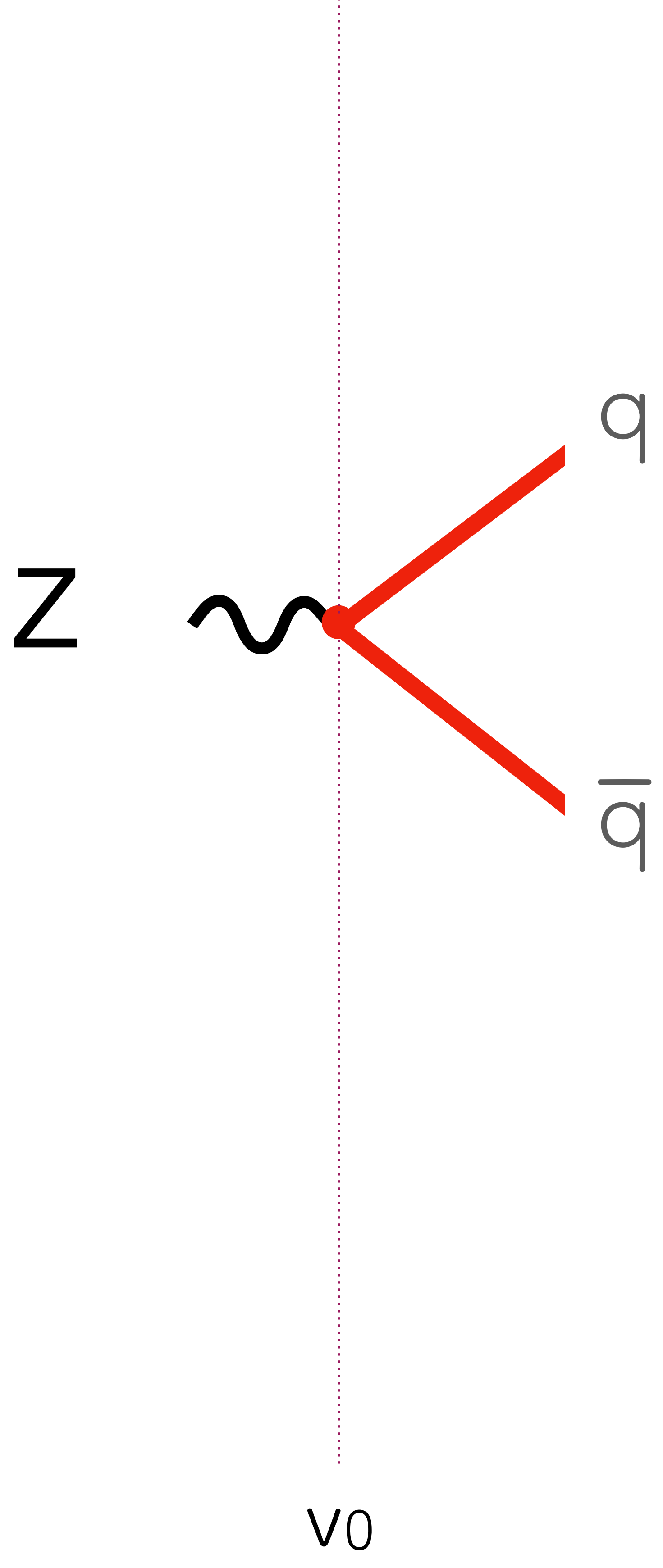






Dipole Showers in a nutshell

Dipole showers [Gustafson, Pettersson, '88] are the most used shower paradigm



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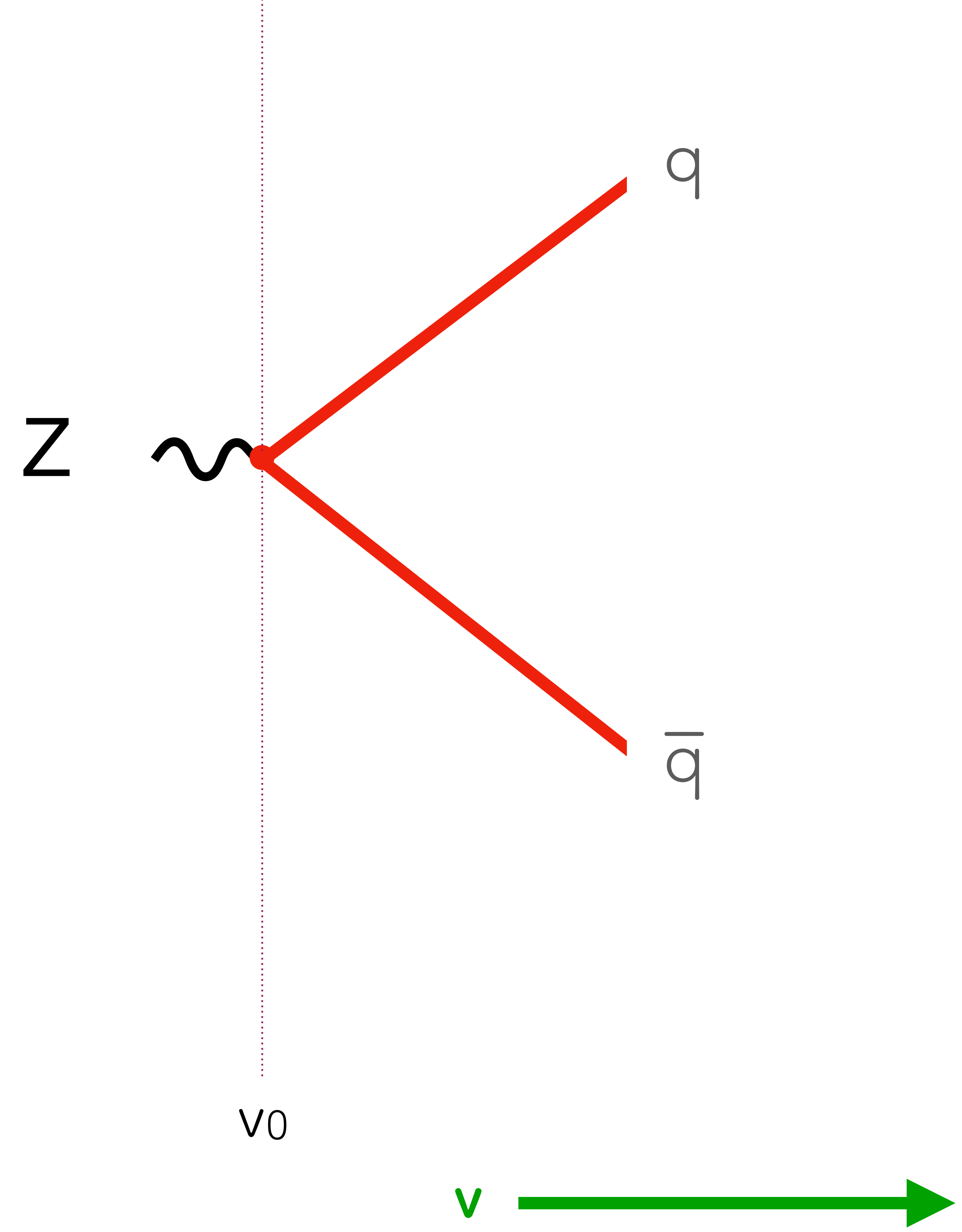

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Throw a random number to determine down to what **scale** state persists unchanged

$$\Delta(v_0, v) = \exp\left(-\int_{v}^{v_0} dP_{q\bar{q}}(\Phi) \right)$$

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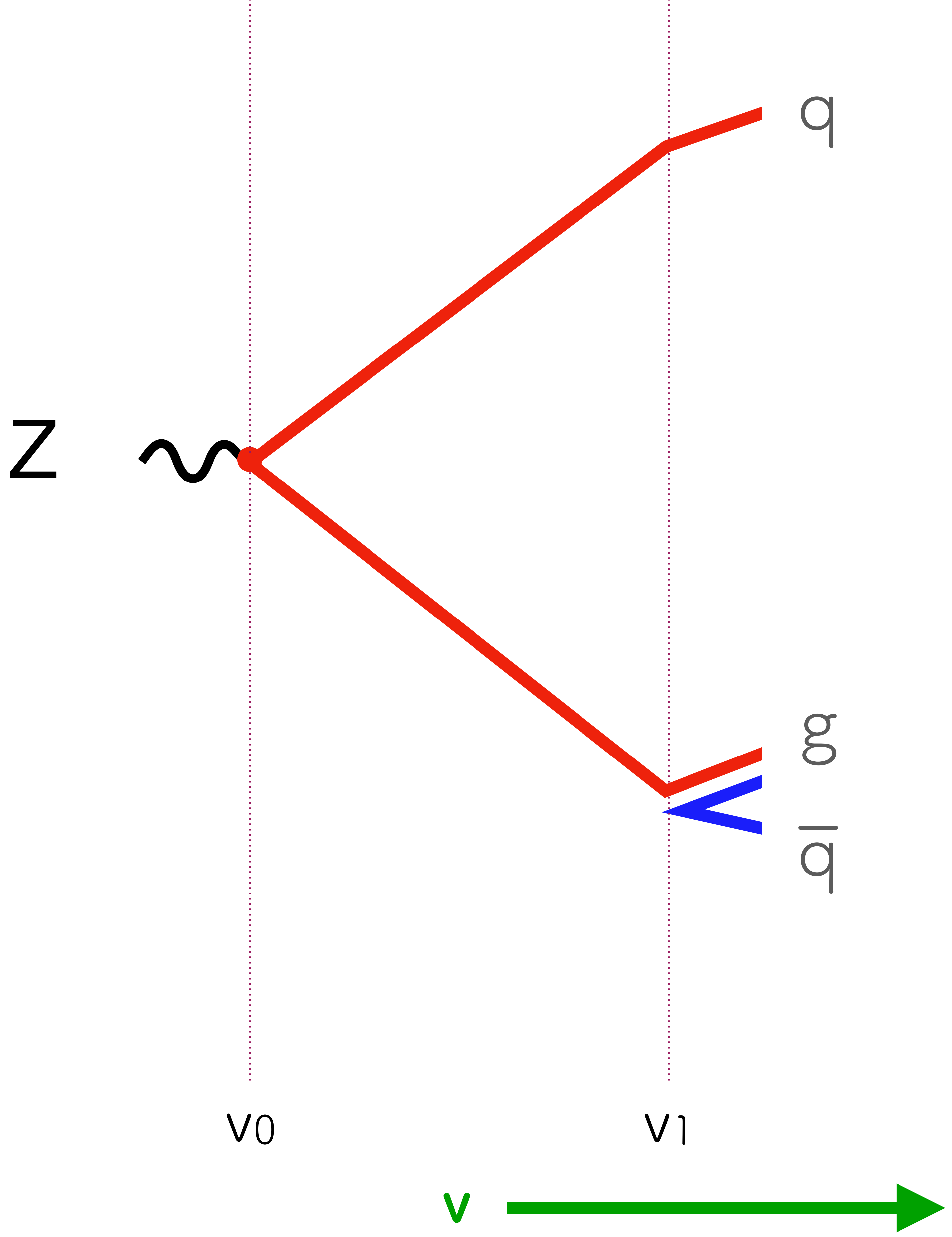

Start with $q\bar{q}$ state produced at a hard scale v_0.

Throw a random number to determine down to what **scale** state persists unchanged

At some point, **state splits** (2→3, i.e. emits gluon) at a scale $v_1 < v_0$. The kinematic (rapidity and azimuth) of the gluon is chosen according to

$$dP_{q\bar{q}}(\Phi(v_1)) \qquad \Phi = \{v, \eta, \varphi\}$$

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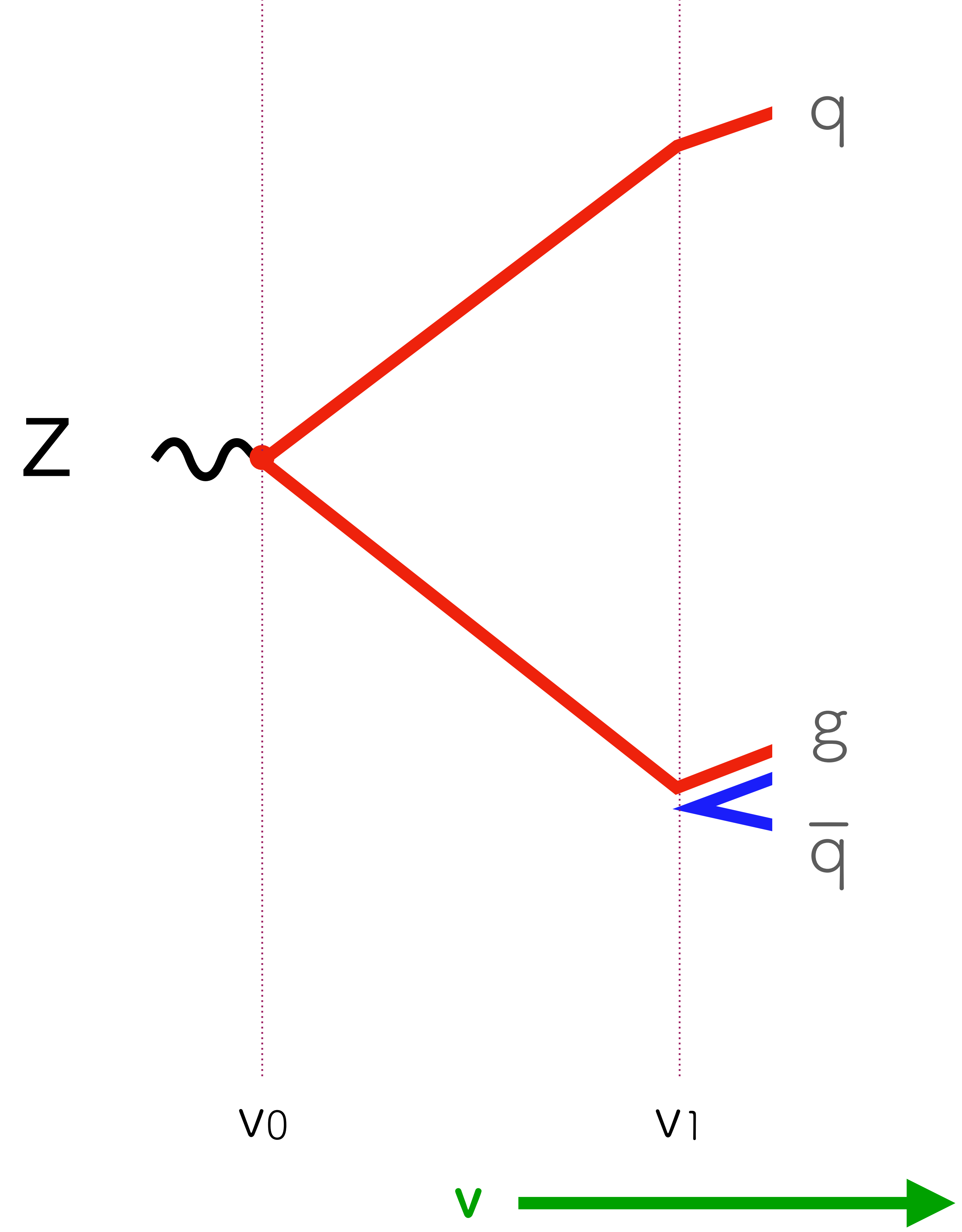


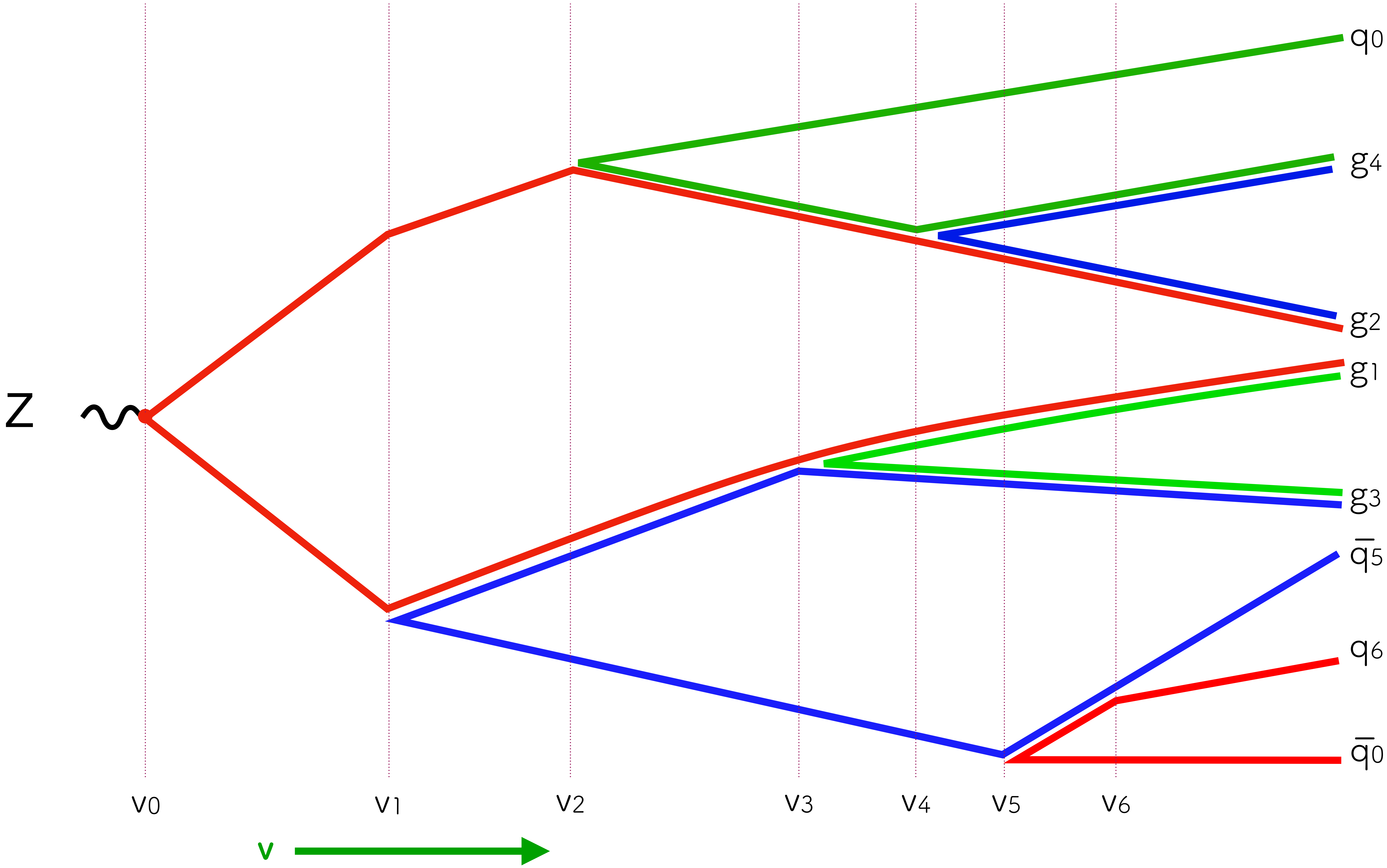
Start with $q\bar{q}$ state produced at a hard scale v_0.

Throw a random number to determine down to what **scale** state persists unchanged

At some point, **state splits** (2→3, i.e. emits gluon) at a scale $v_1 < v_0$.

The gluon is part of two dipoles (qg), $(g\bar{q})$.

Iterate the above procedure for both dipoles independently, using v_1 as starting scale.

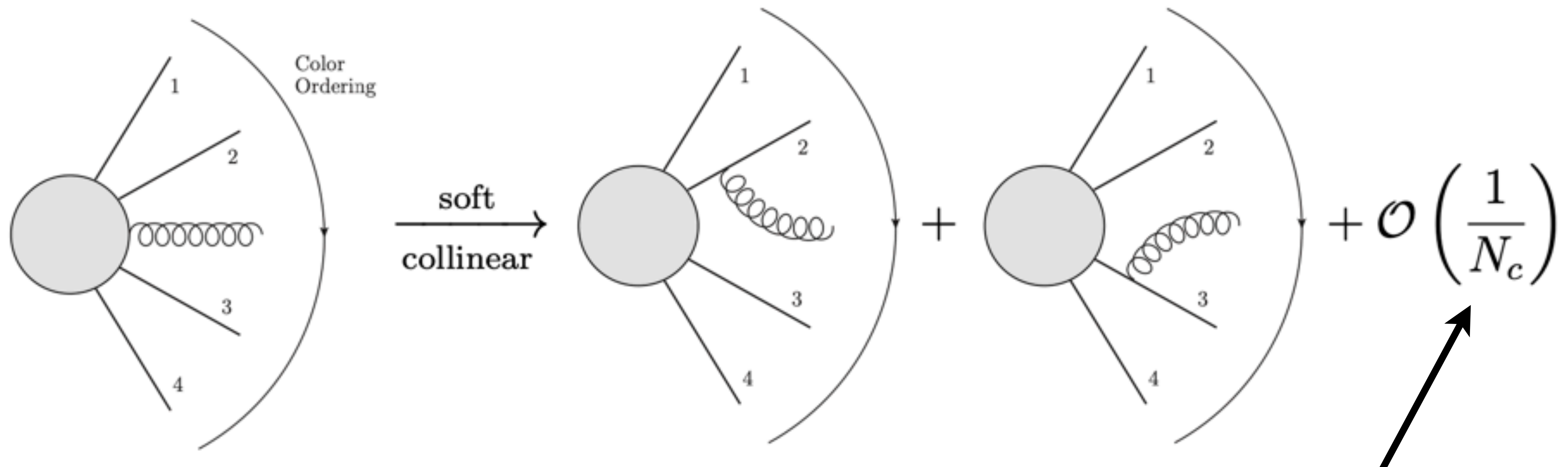


self-similar evolution continues until it reaches a non-perturbative scale

Adding QED and EW interactions in dipole showers: the Vincia solution

Plots from Verheyn PhD thesis

➤ Dipole showers reproduce the soft **QCD** radiation pattern, exploting the large number of colour approximation



For the inclusion of **subleading N_c corrections** in a dipole shower see 1202.4496 +1501.00778 (**Deductor**), 2011.10054 (**PanScales**), 2011.15087 (**FHP**)

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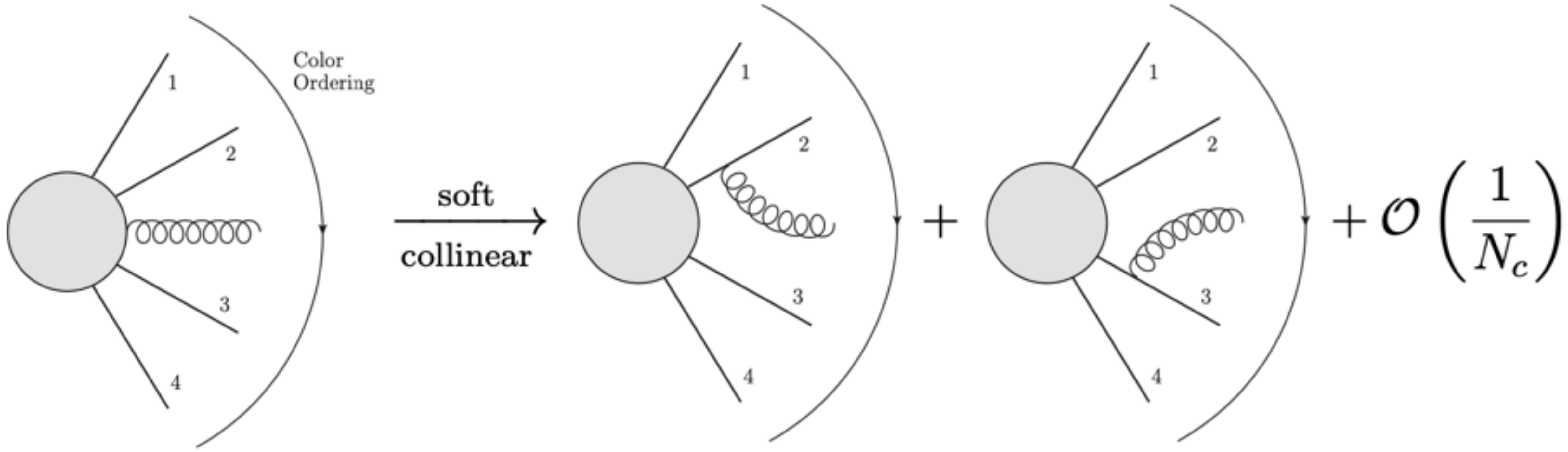

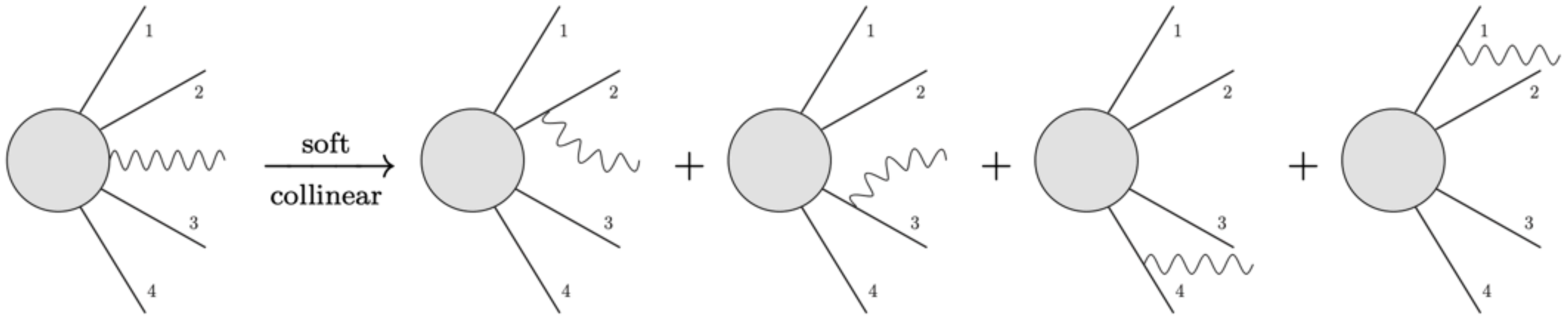

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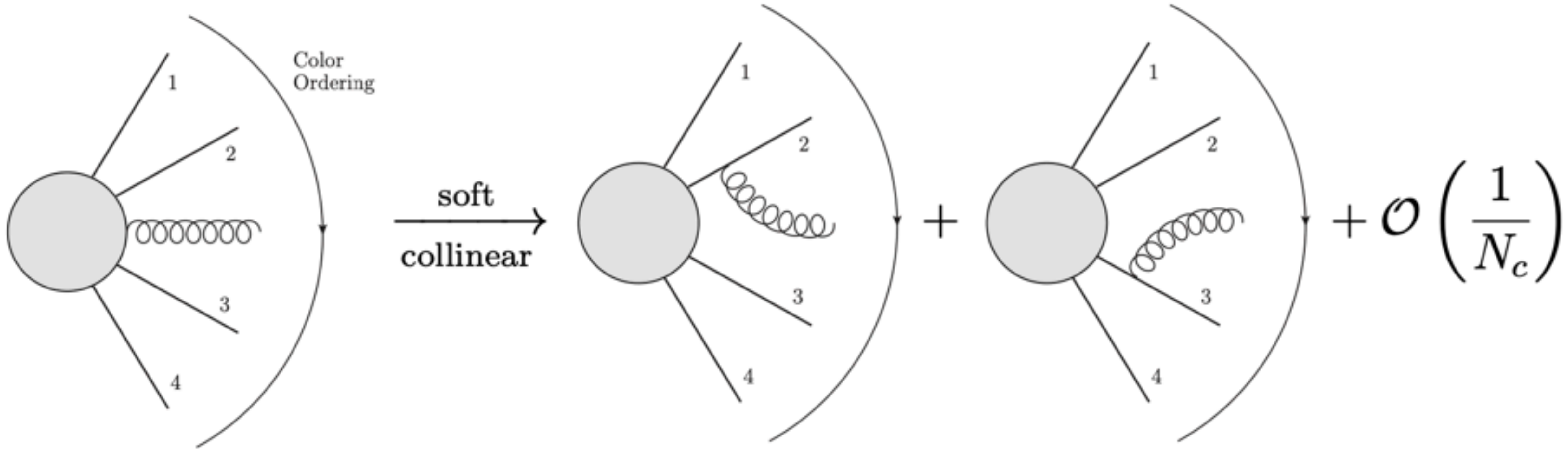

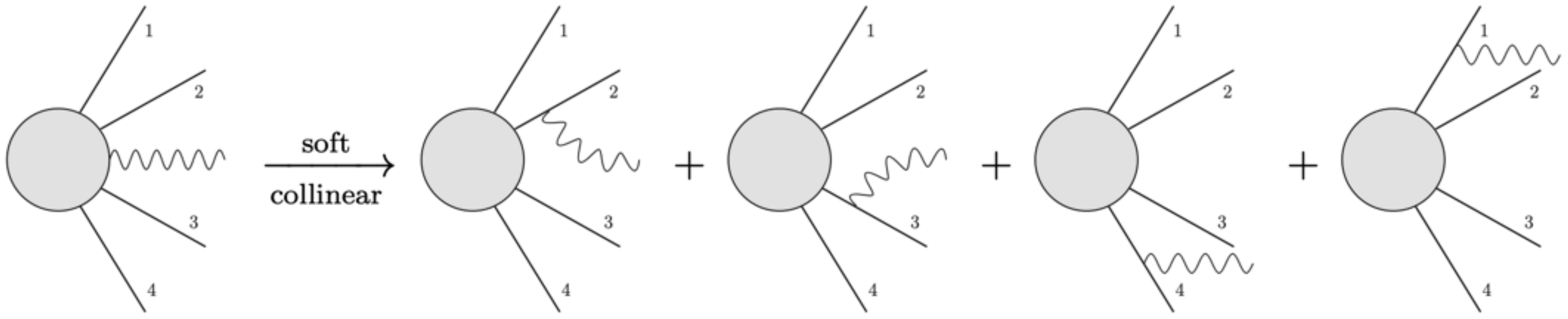

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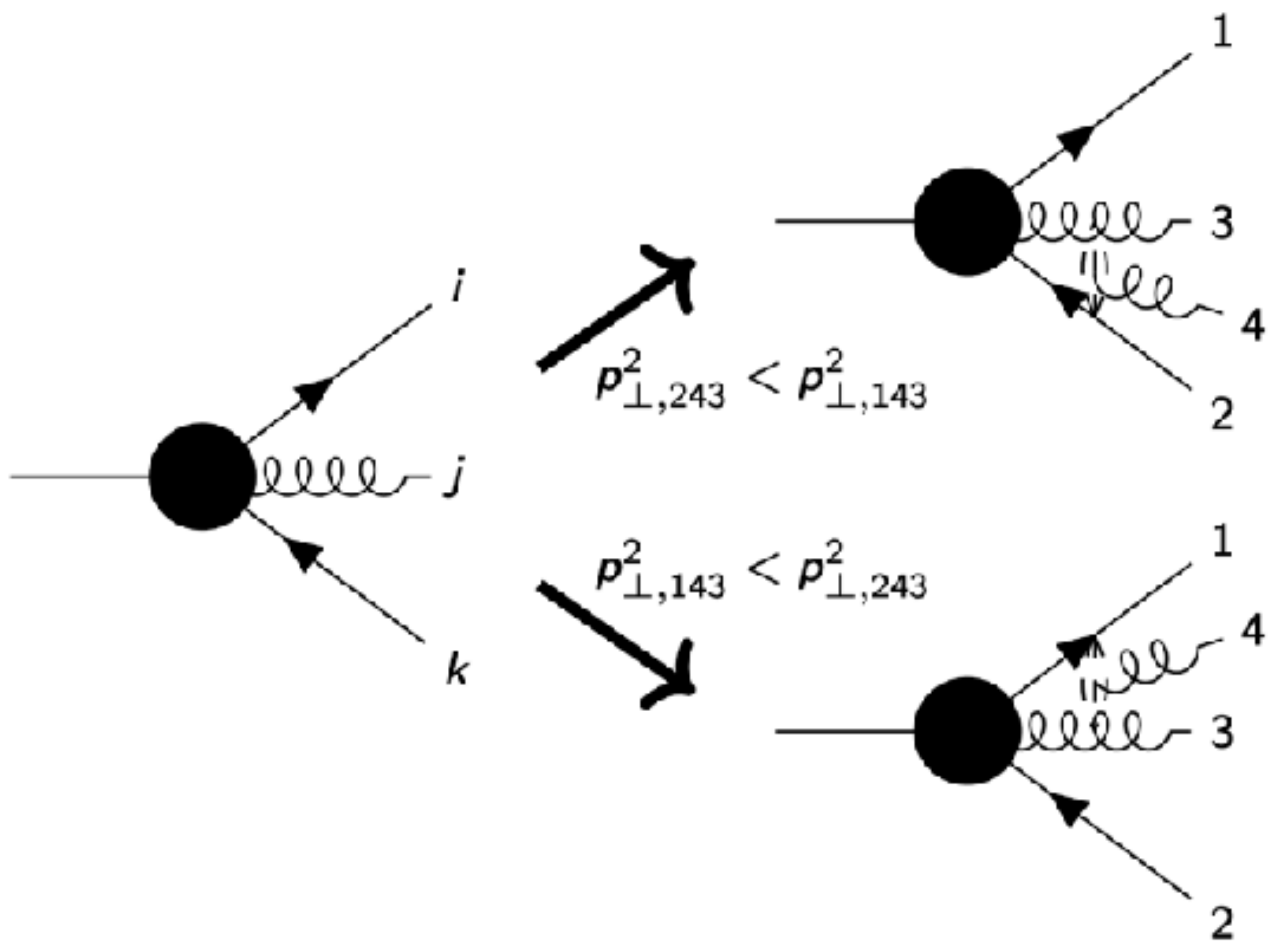
- **VINCIA** is a **sector shower**: **phase space** available for an emission **sectorised** with Θ mimicking jet clustering [Brooks, Preuss, Skands 2003.00702; Lopez-Villarejo, Skands 1109.3608]
- Apply a similar factorisation to break the giant **QED multipole** [Verheyen, Skands 2002.04939]



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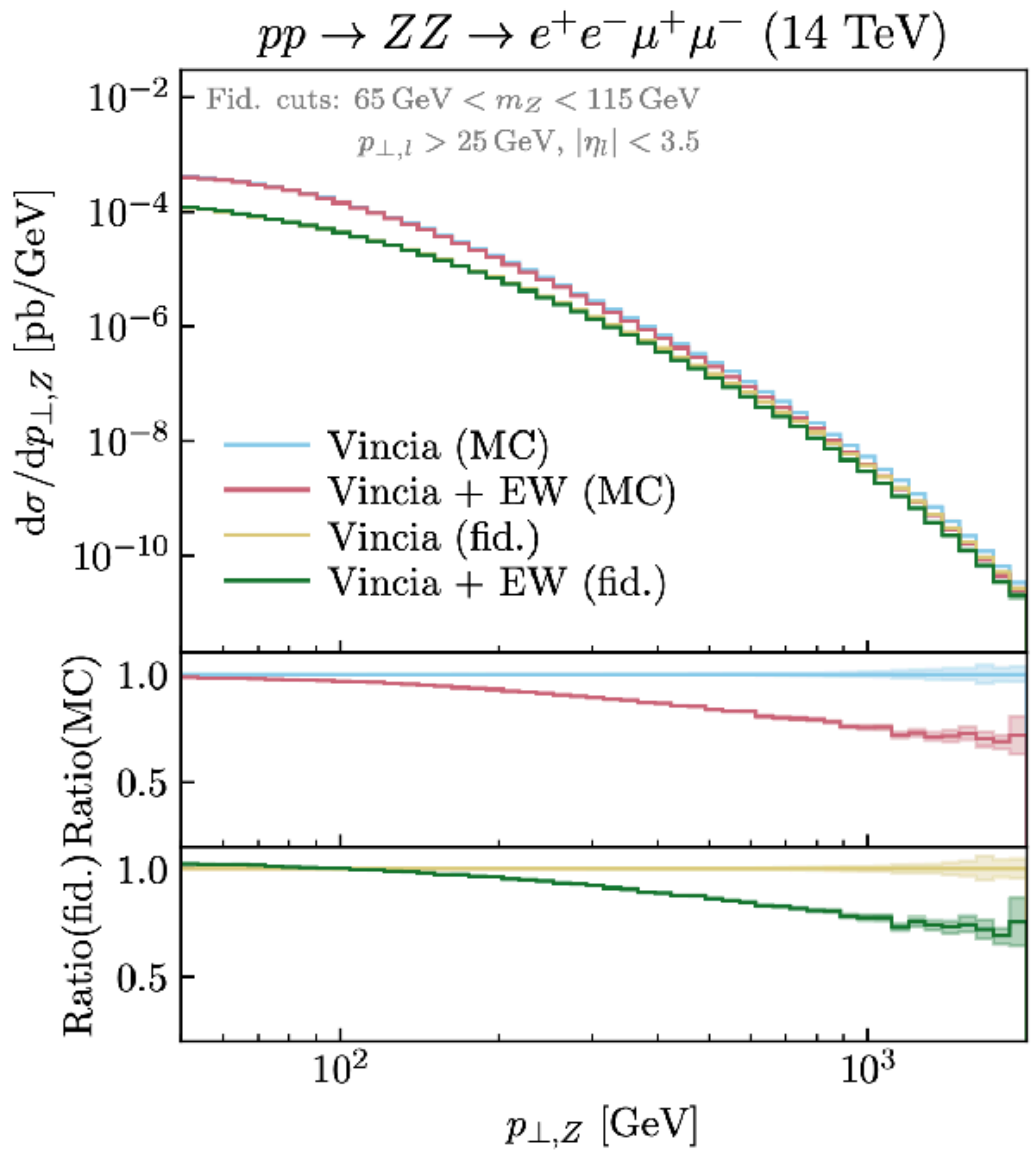

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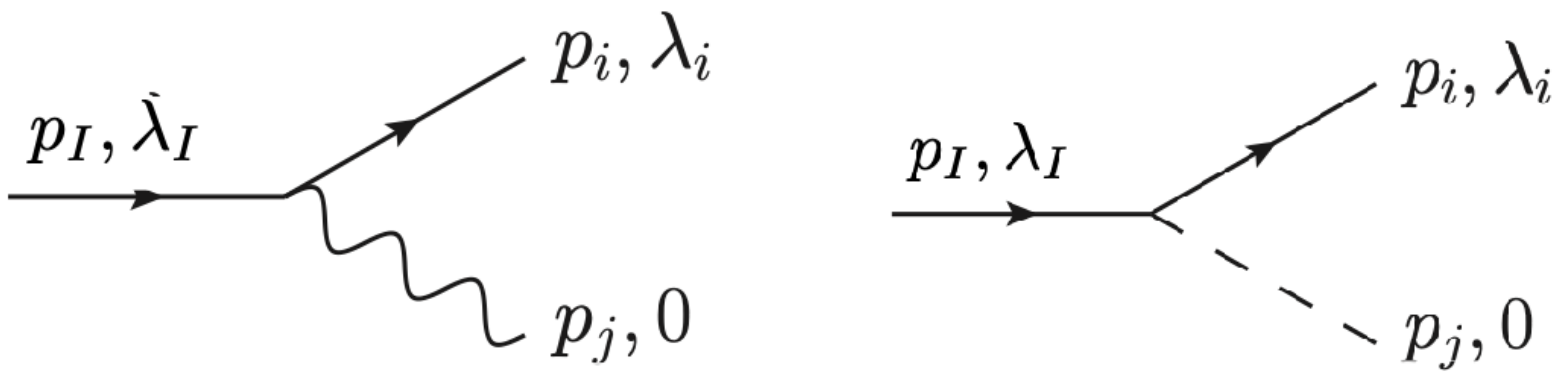
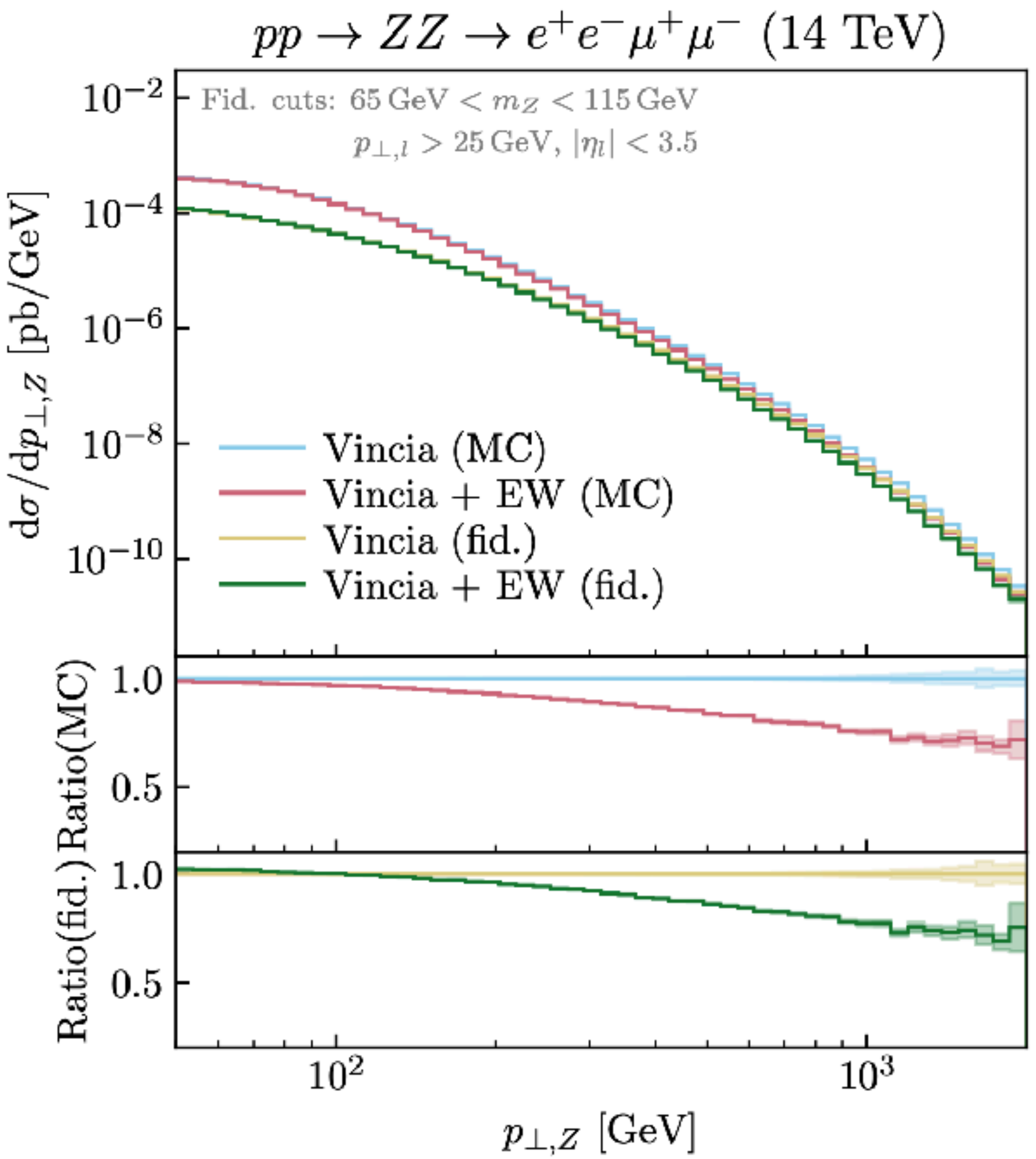
- ➤ … and also include **EW splittings** [Verheyen, Skands 2002.04939]
- ➤ EW showers critically are **helicity showers** [1301.0933, Larkoski, Lopez-Villarejo, Skands]



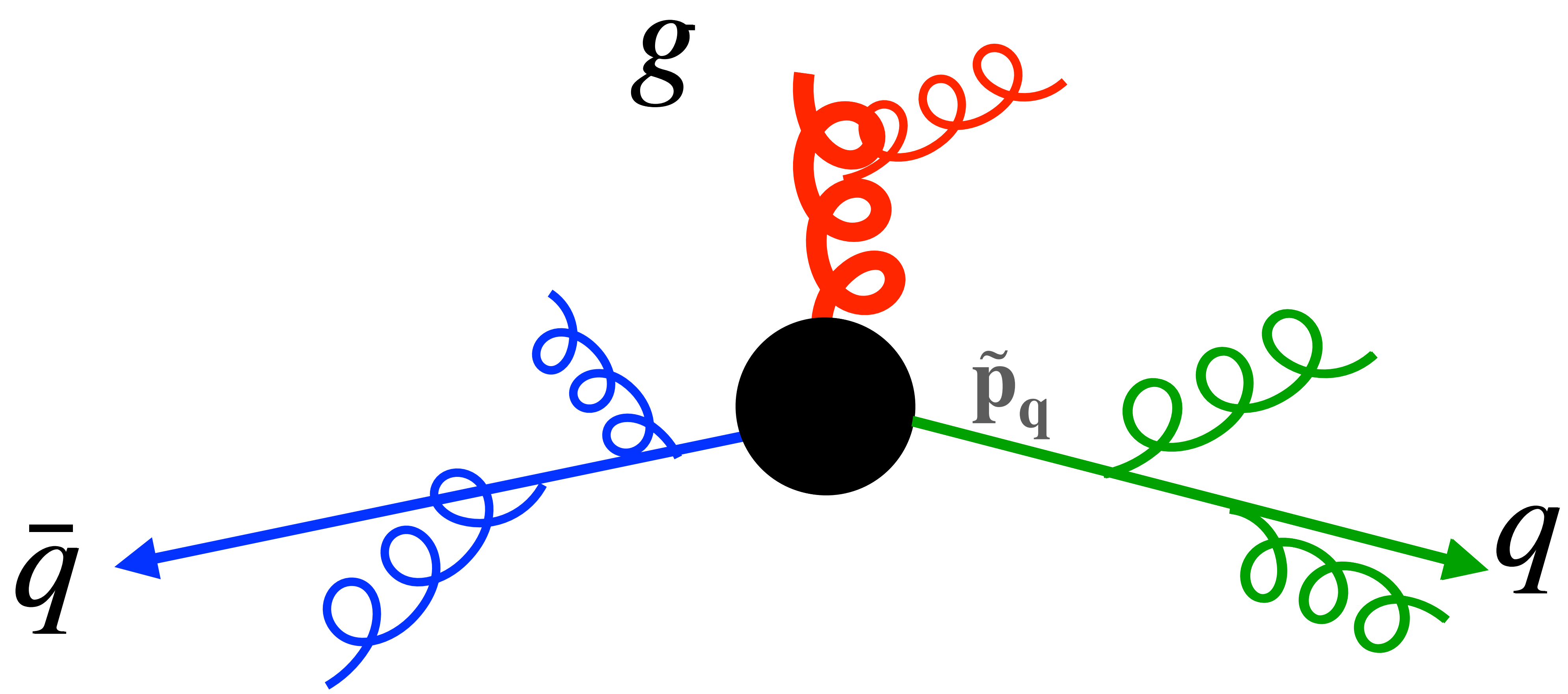


For handling of **spin correlations** in (QCD) dipole showers, see also 1807.01955 (**Herwig**) and 2103.16526, 2111.01161 (**PanScales**)

Herwig7 Angular-Orderd **parton** shower

[Marchesini, Webber '88;
Gieseke, Stephens, Webber hep-ph/0310083]

- ➤ Each **parton** produced in the hard scattering showers independently



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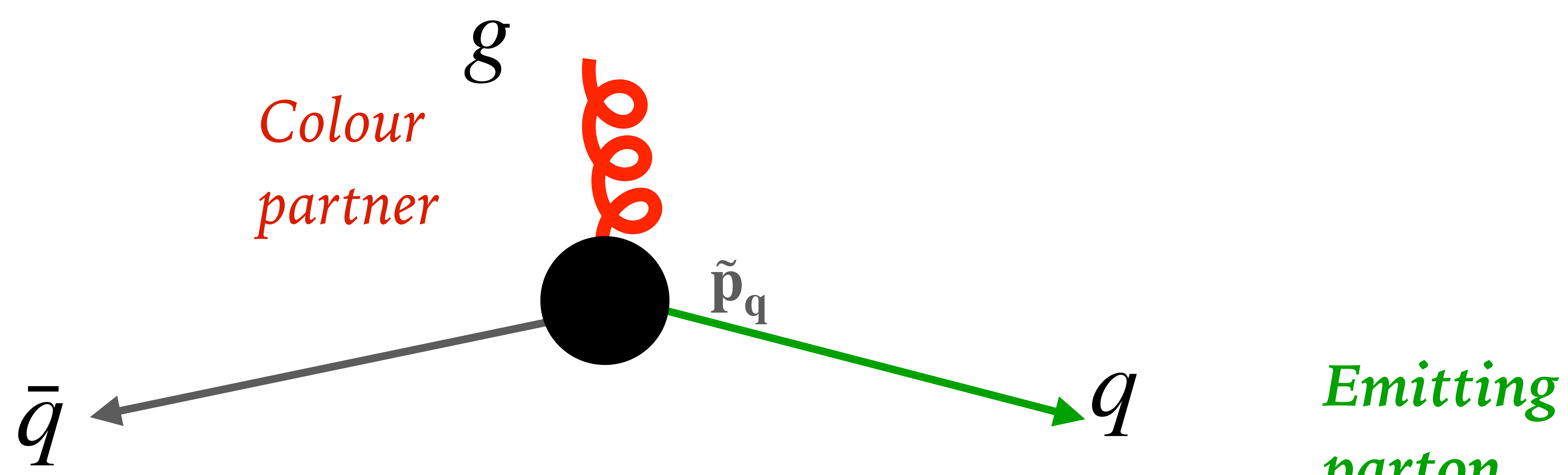

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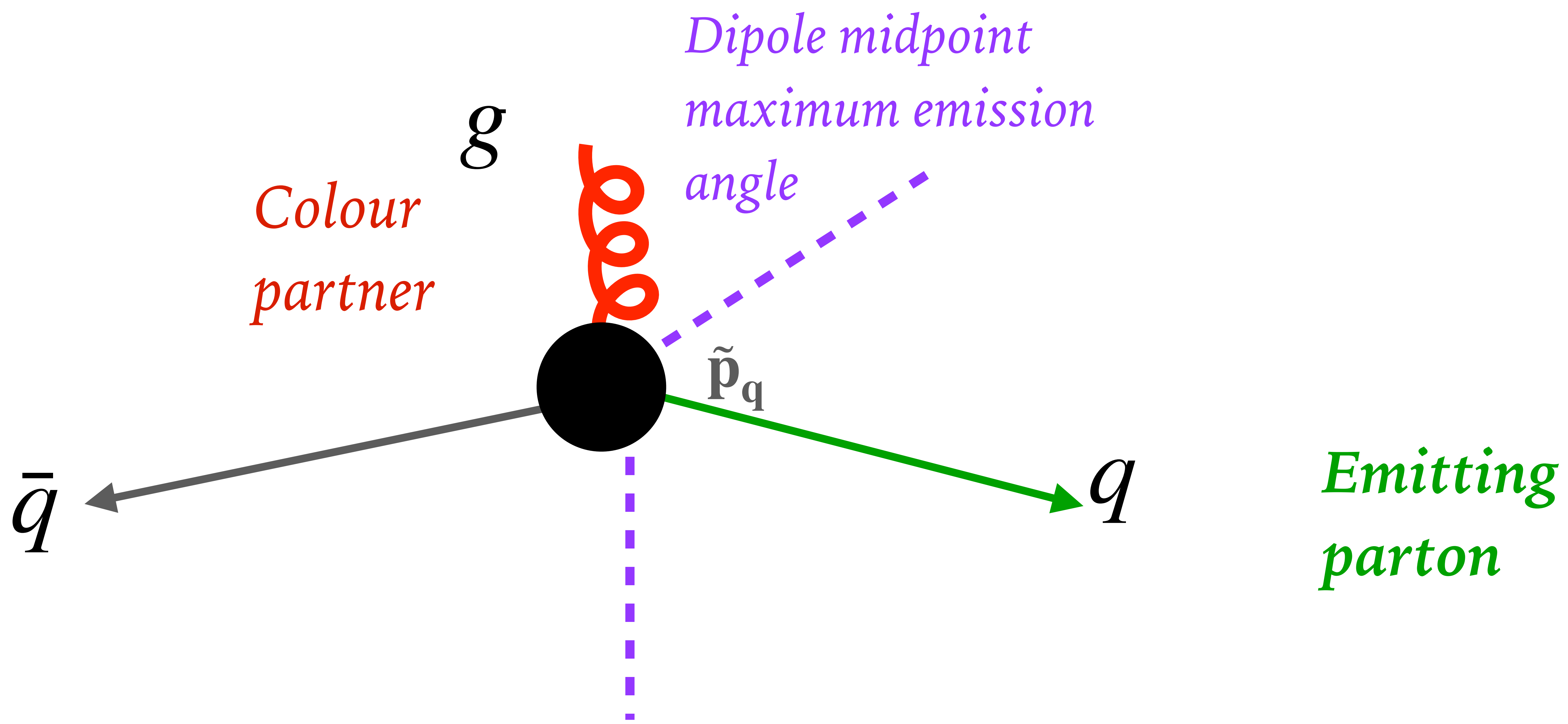

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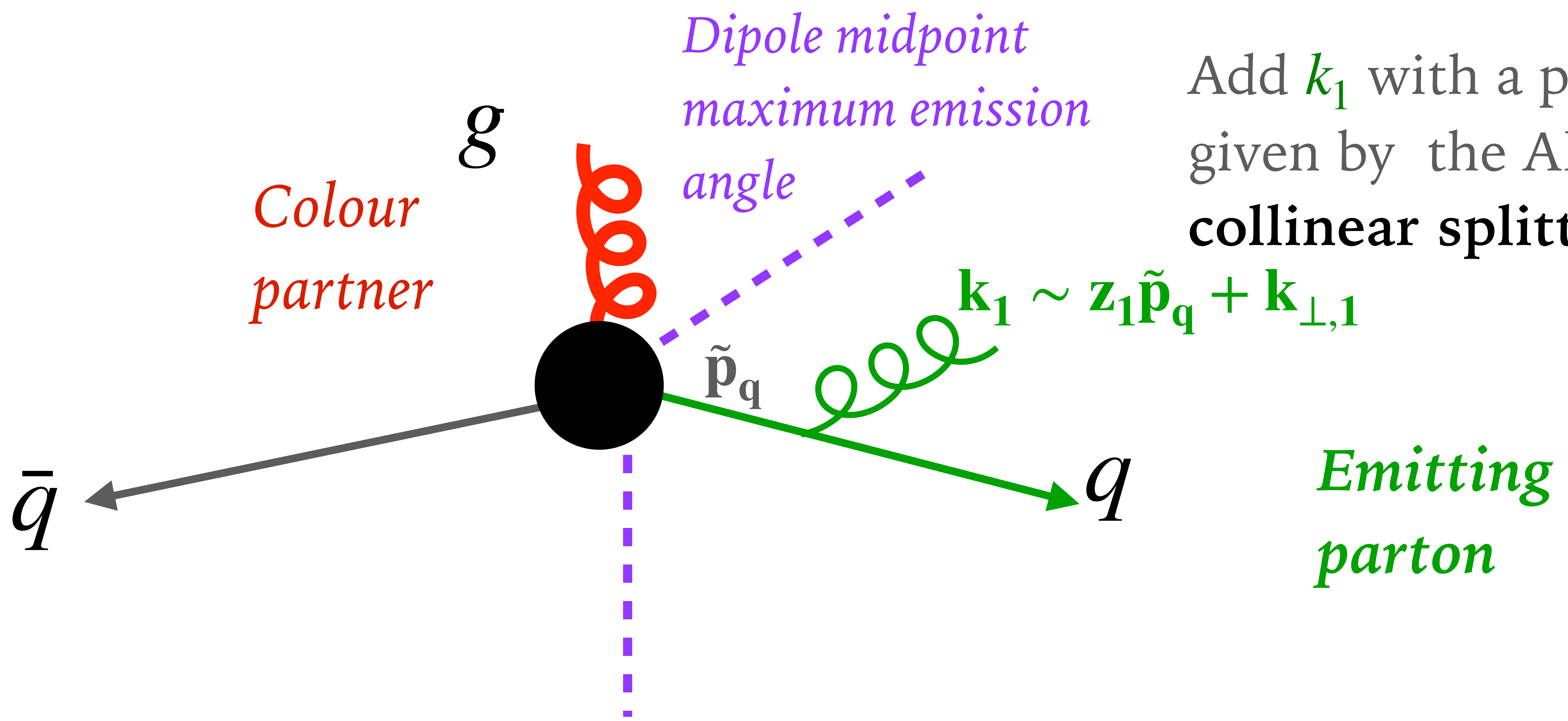

Add k_1 with a probability given by the Altarelli-Parisi **collinear splitting function**

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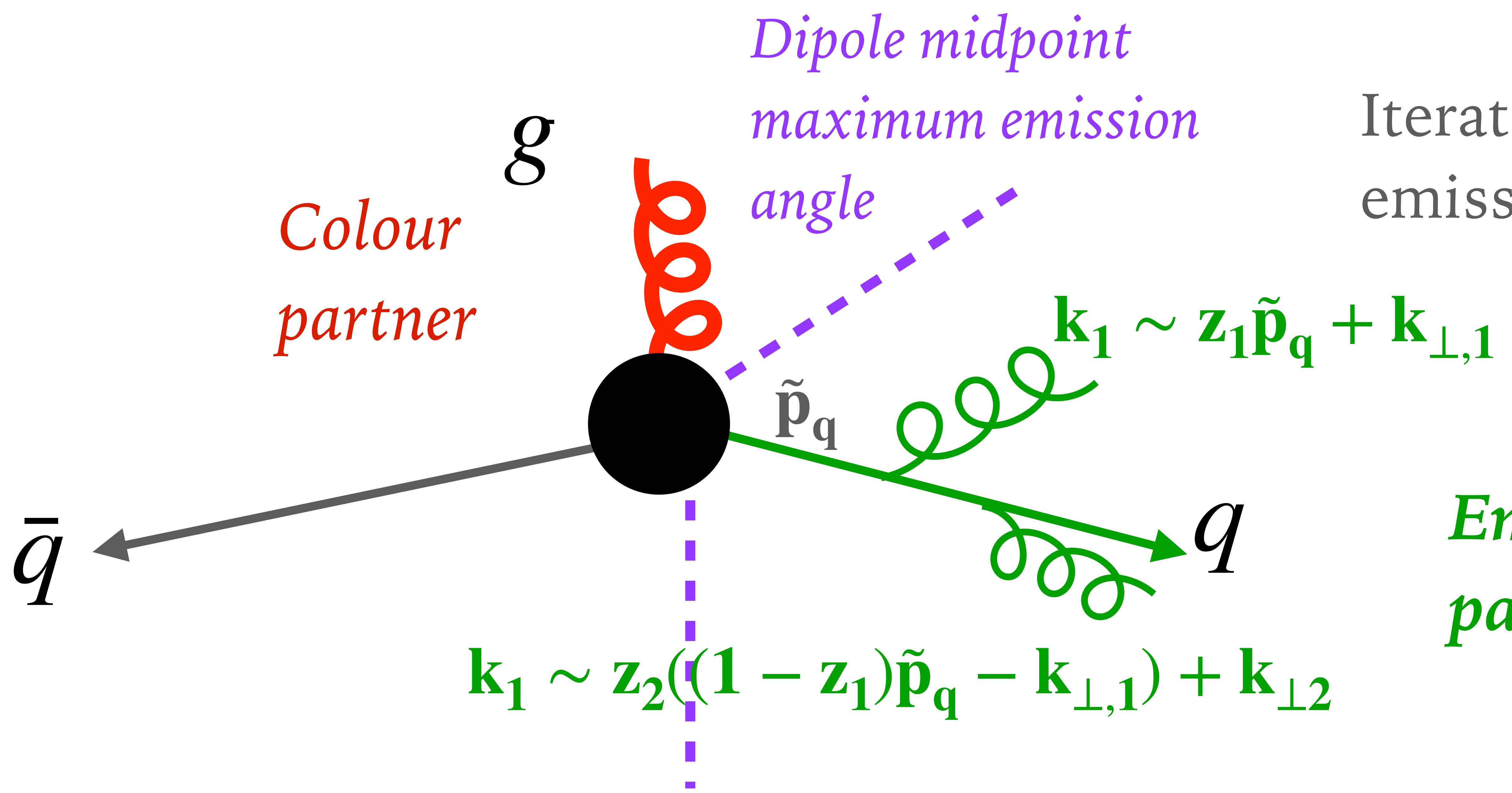


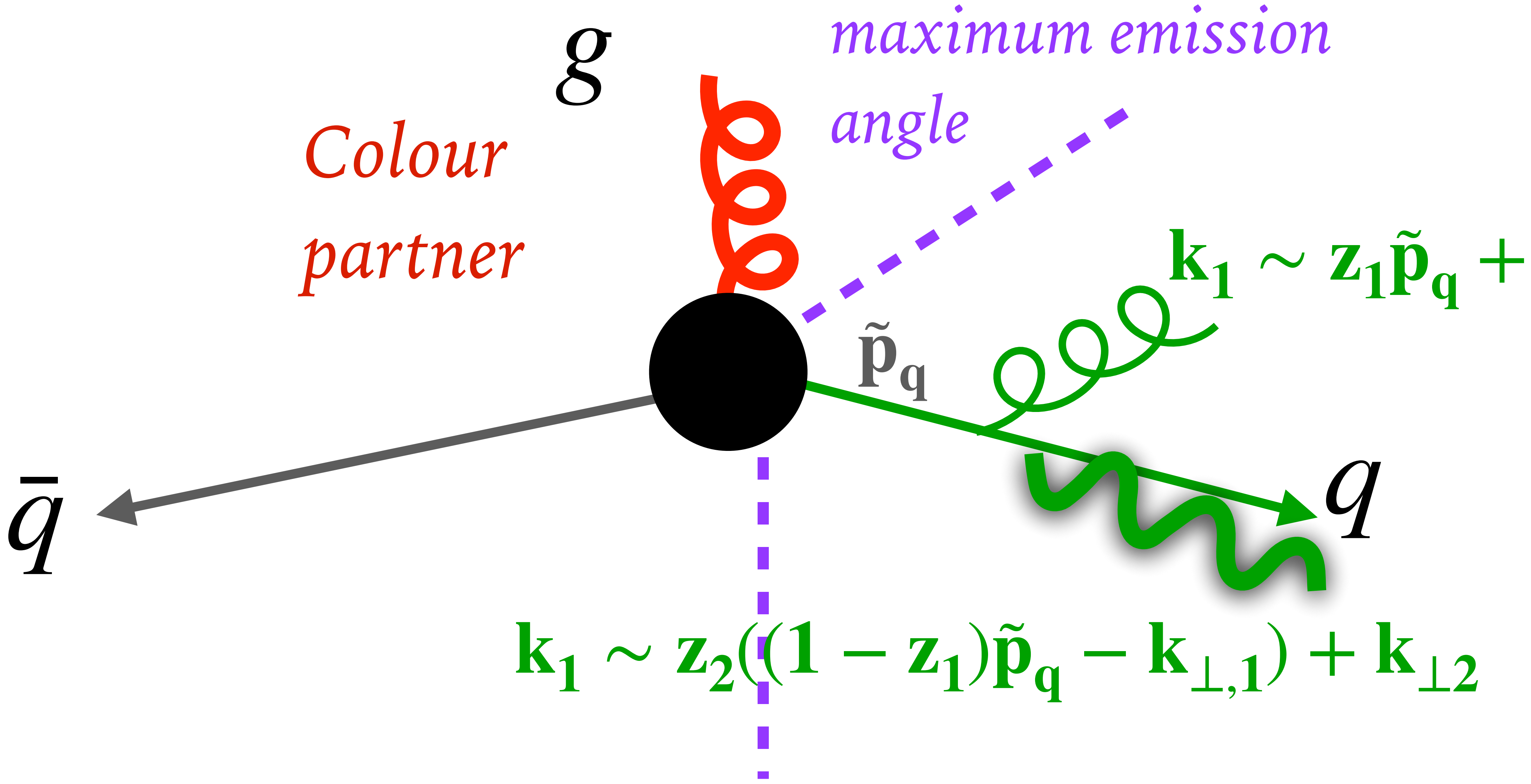
Iterate considering **smaller** emissions **angles**

Emitting parton

Herwig7 Angular-Orderd generalised shower

- Each **parton** produced in the hard scattering showers independently

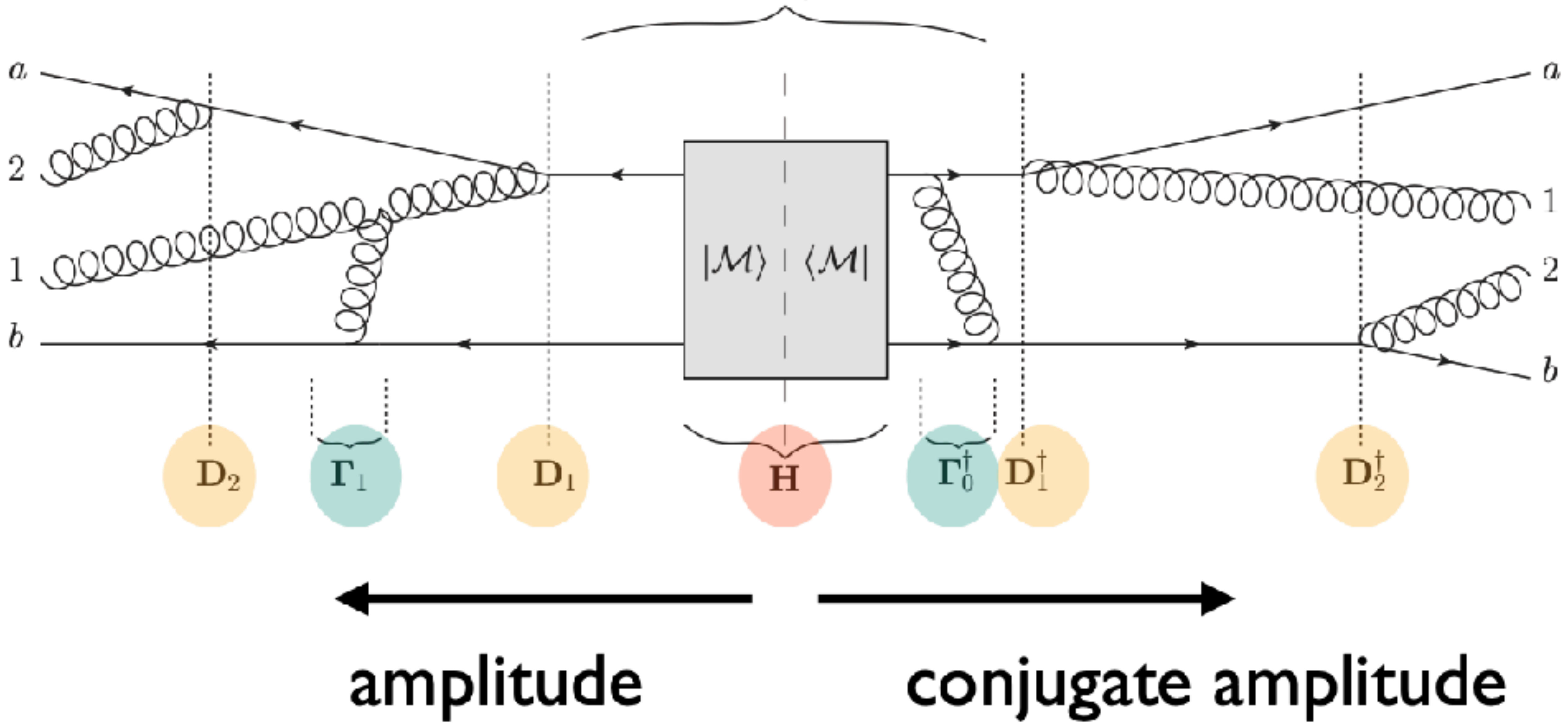
Spin correlations
hep-ph/0110108, 1807.01955
(based on ***Collins-Soper*** *'88)*



It is straighforward to include **QED** [since v 7.0 1512.01178], **Electro-Weak** [Masoumnia, Richardson, 2108.10817; available since v 7.3 2312.05175], **BSM** [Lee, Masouminia, Seymour, Yang, 2312.13125; will be available in v 7.4]

Amplitude-level evolution

- **CVolver** =evolve separately **amplitude** and **conjugate amplitude**: subleading **colour**, **spin** correlations, **Glauber** phases taken into account
  [Plätzer, Sjodahl, De Angelis, Forshaw, Holguin, see 2210.09178 and refs therein]
  + **EW** interactions [Plätzer, Sjodahl 2204.03258]



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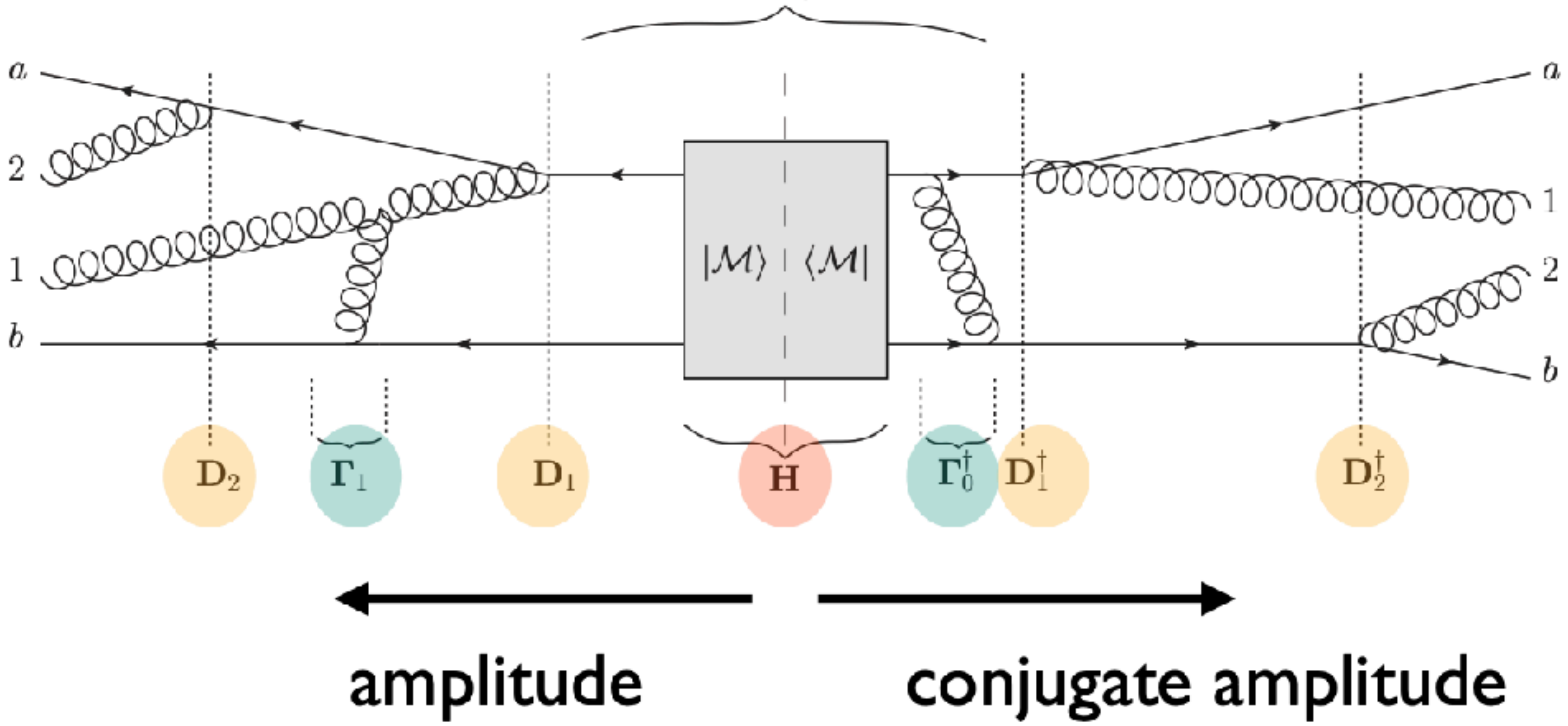

- ➤ Deductor =density matrix in **colour** [Nagy, Soper 0805.0216, 1202.4496, 1401.6364, 1501.00778, 1902.02105, 1905.07176, 1908.11420] to resum "**nasty soft & Glauber contributions**" [and more]

Are current showers good enough?

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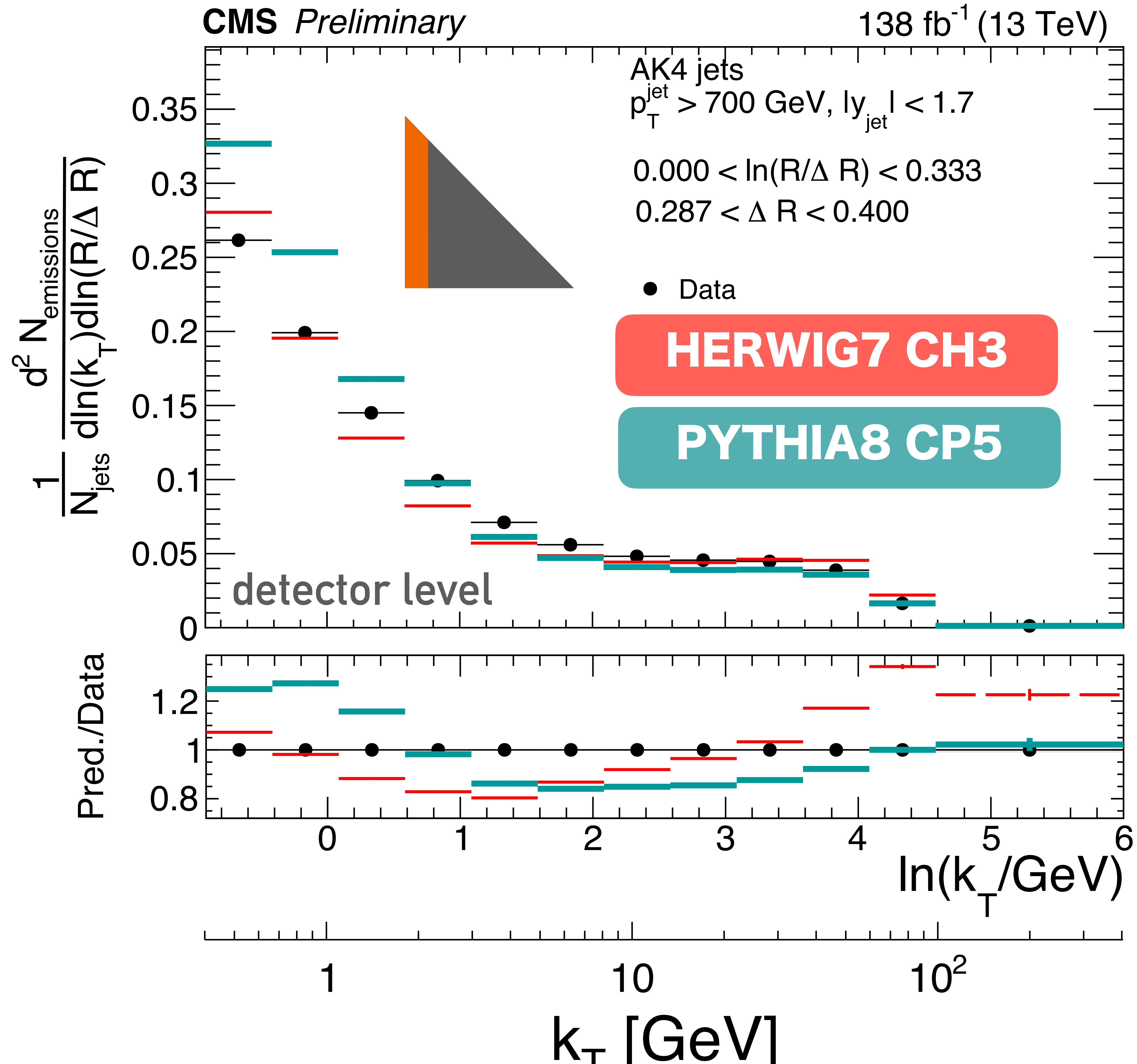
What does good shower mean?

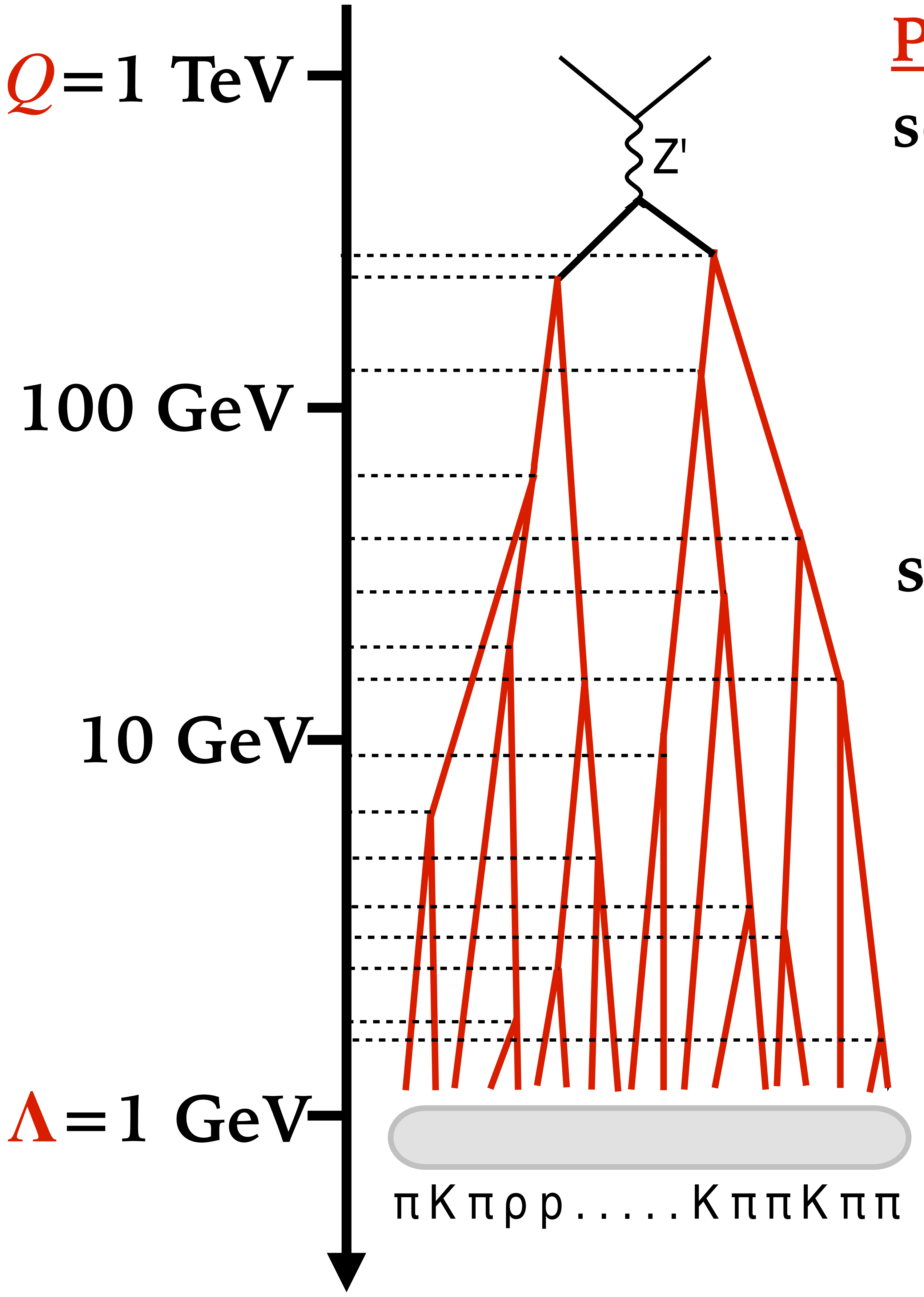
Are current showers good enough?

- showers do an amazing job on many observables for **LHC**
- various places see **10–30% discrepancies** between showers and data
- A lot of work is required to reach the **percent precision target**!

Lund Plane



Logarithmically-accurate Parton Showers



PARTON SHOWERS = energy degradation via an iterated sequence of **softer and softer** emissions

$$L = \ln \frac{Q}{\Lambda} \gg 1$$

simple algorithm to include the **dominant radiative corrections** at all orders for **any observable**!

$$\Sigma(O < e^{-L}) = \exp\left(-L g_{\mathrm{LL}}(\beta_0 \alpha_s L) + \ldots\right)$$

LL = leading logs

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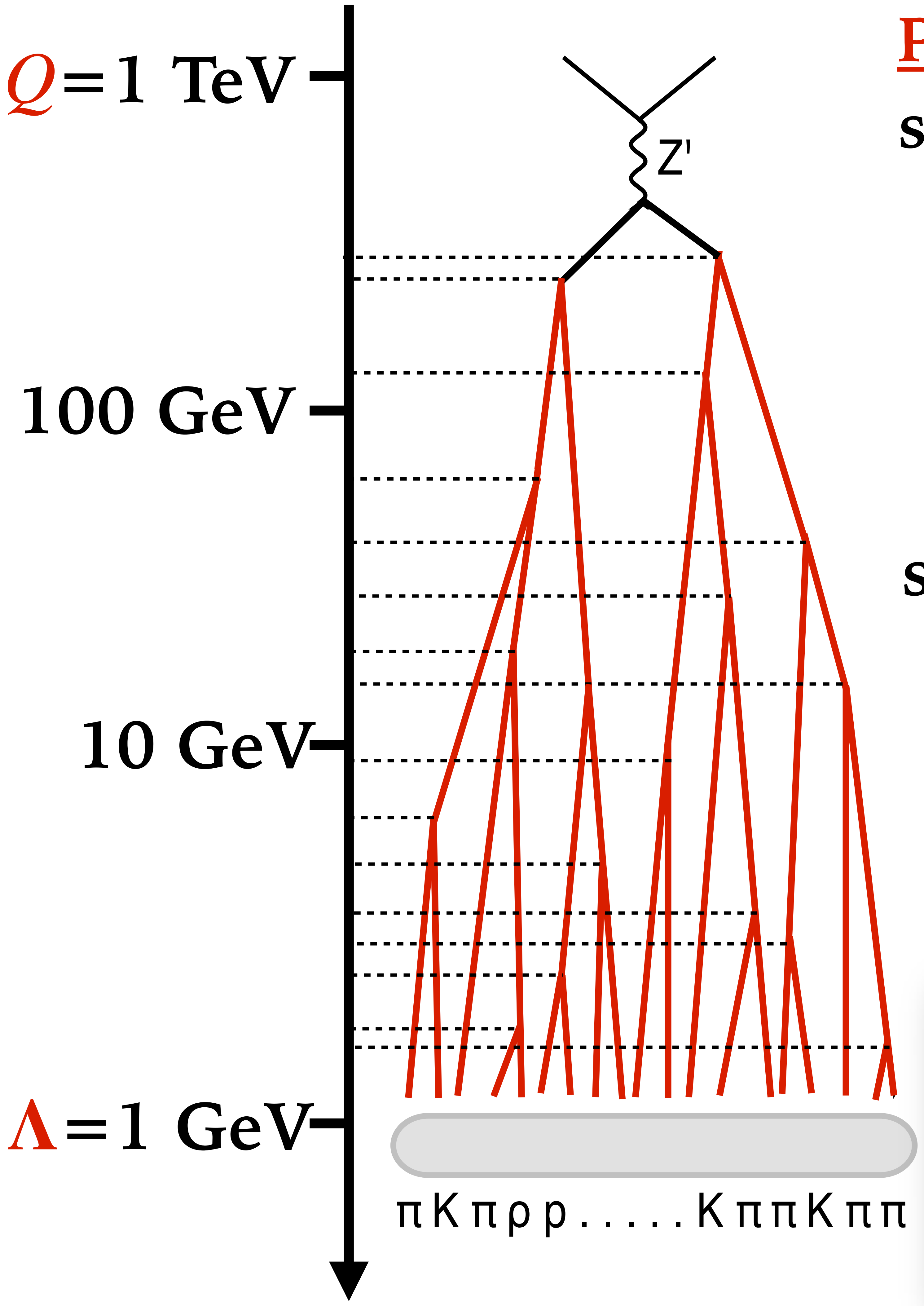

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??

$$\Sigma(O < e^{-L}) = \exp\left(-L g_{\mathrm{LL}}(\beta_0 \alpha_s L) + g_{\mathrm{NLL}}(\beta_0 \alpha_s L) + \ldots\right)$$

For $Q \sim 50 - 10000\,\mathrm{GeV}$, $\beta_0 \alpha_s L \sim 0.3 - 0.5$:
Next-to-Leading Logarithms needed for quantitative predictions!

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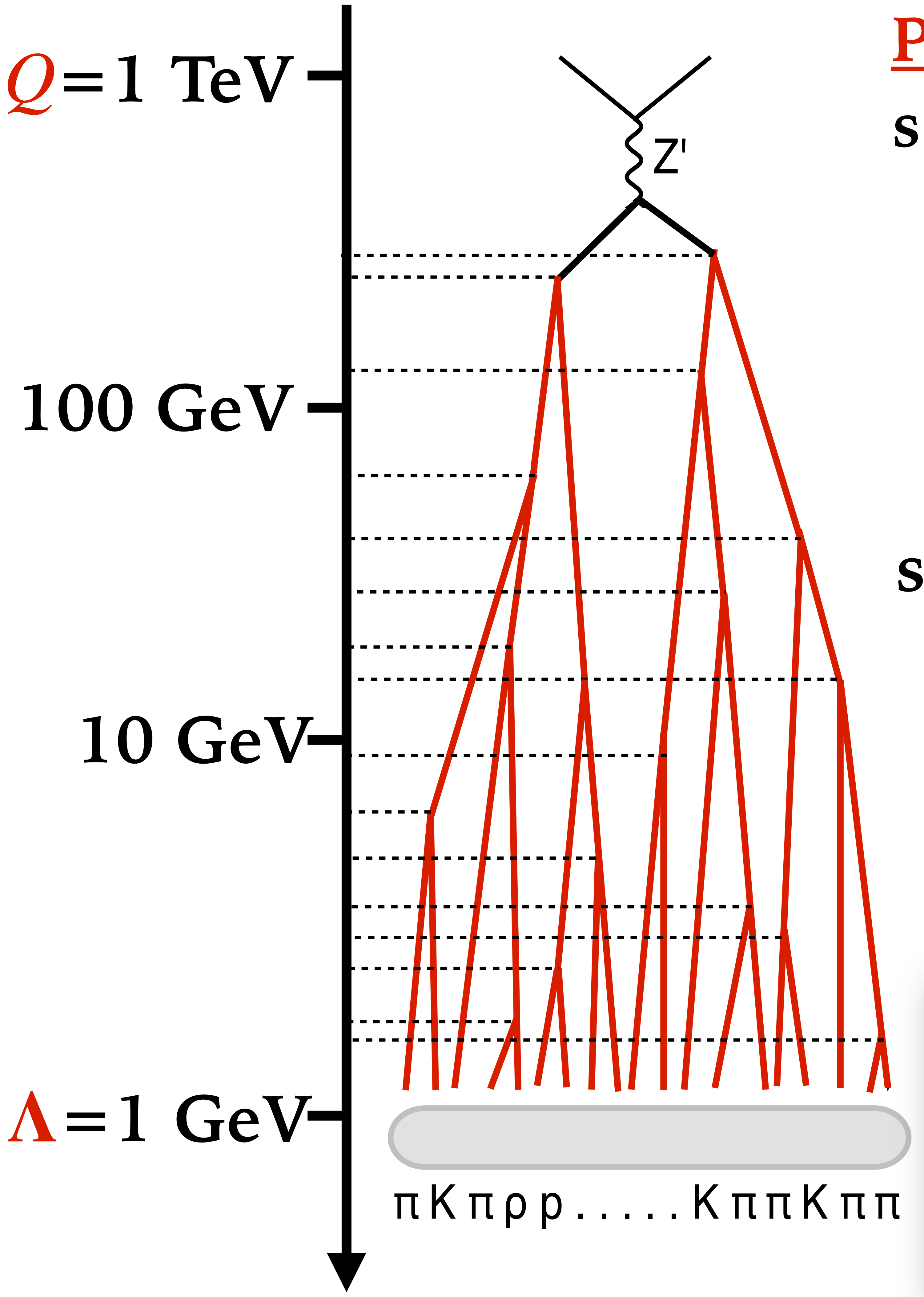

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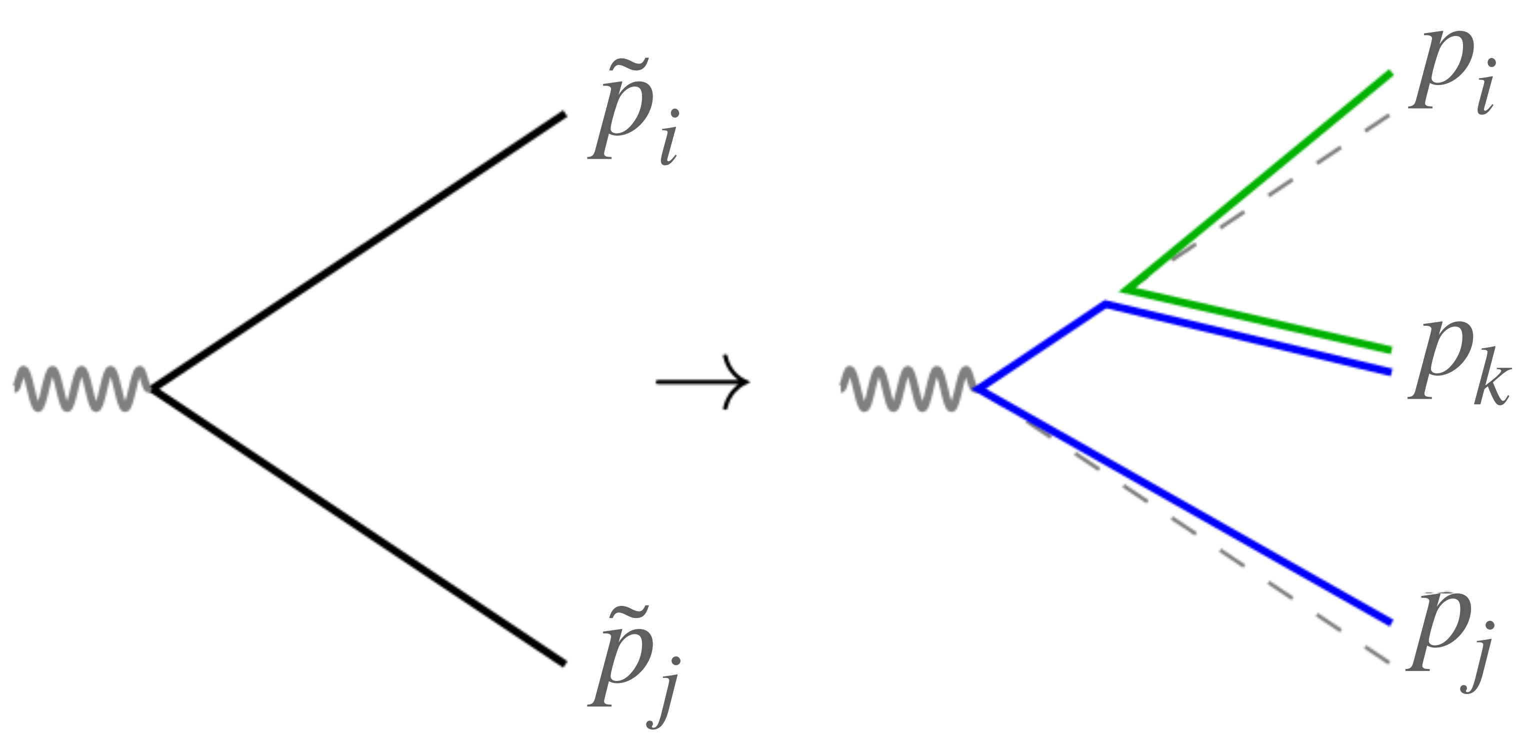
Dissecting the parton shower emission probability

Starting from a $e^+e^- \to Z^* \to q\bar{q}$ system, what is the splitting probability?



$$\mathrm{d}\mathscr{P}_{\tilde{i}\tilde{j}\to ijk} \sim \frac{\mathrm{d}v^2}{v^2}\mathrm{d}\bar{\eta}\,\frac{\mathrm{d}\varphi}{2\pi}\;P_{\tilde{i},\tilde{j}\to i,j,k}(v,\bar{\eta},\varphi)$$

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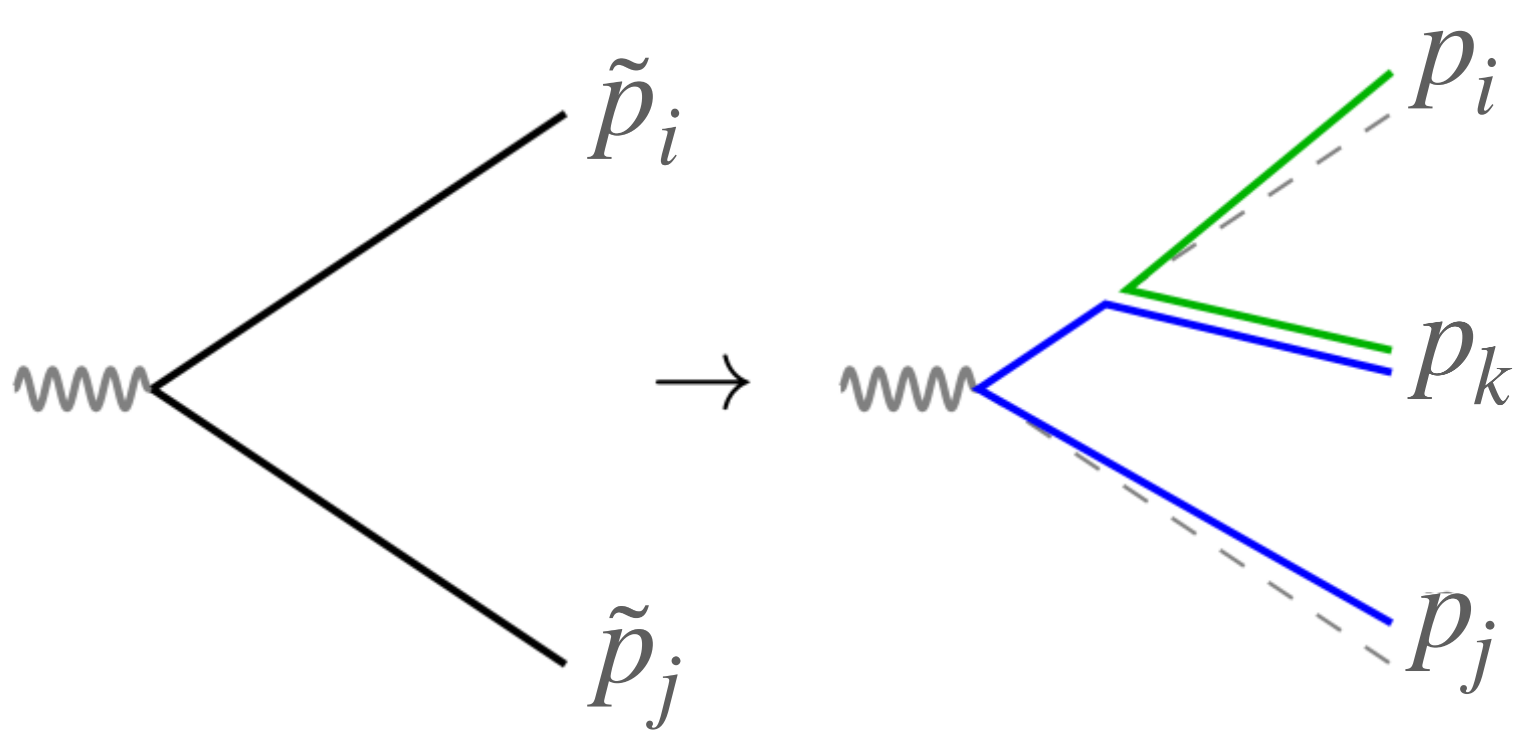

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Matrix element for emitting a parton k from a parton i (or j)

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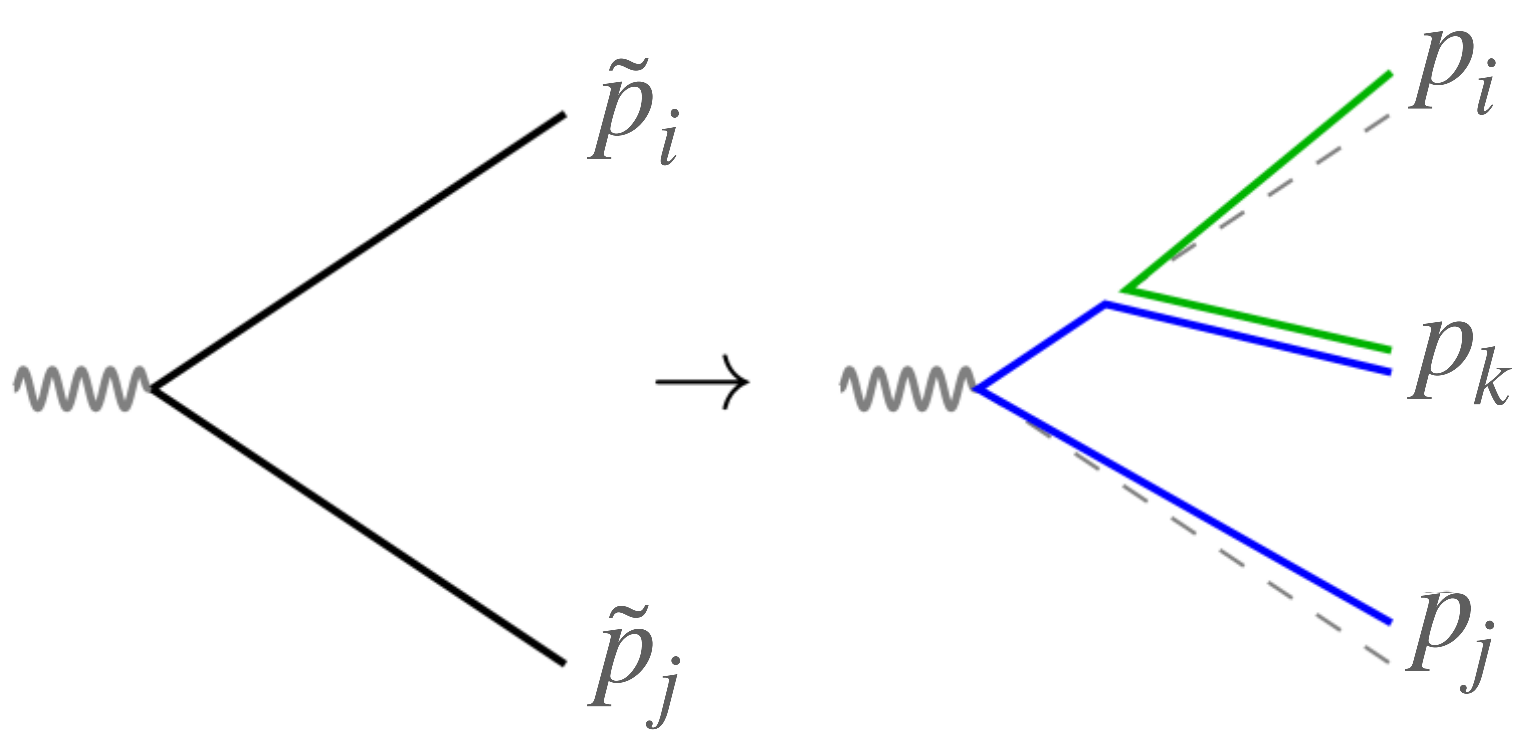

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Evolution variable:
emissions are ordered
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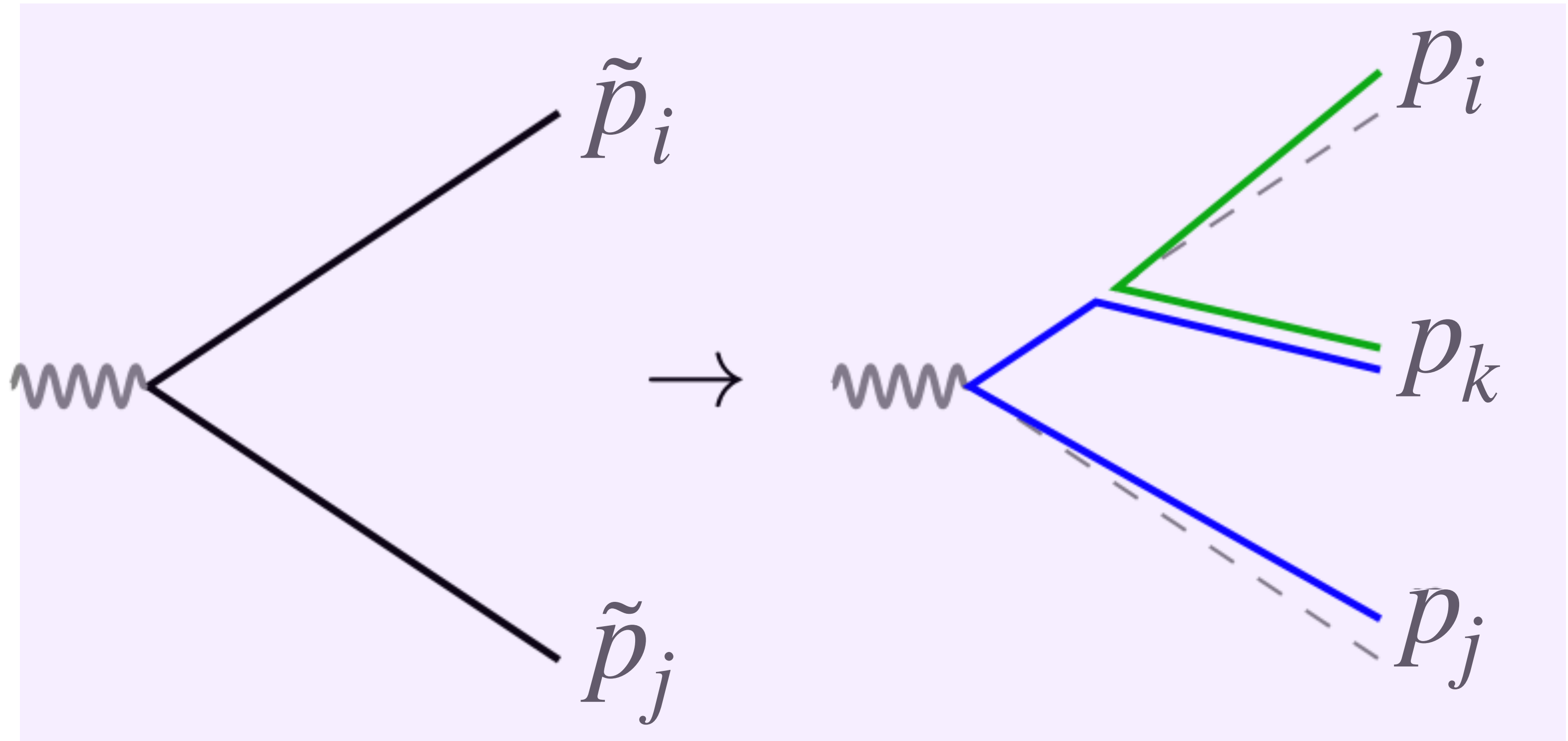

Kinematic mapping: how to reshuffle the momenta of i and j after the emission takes place

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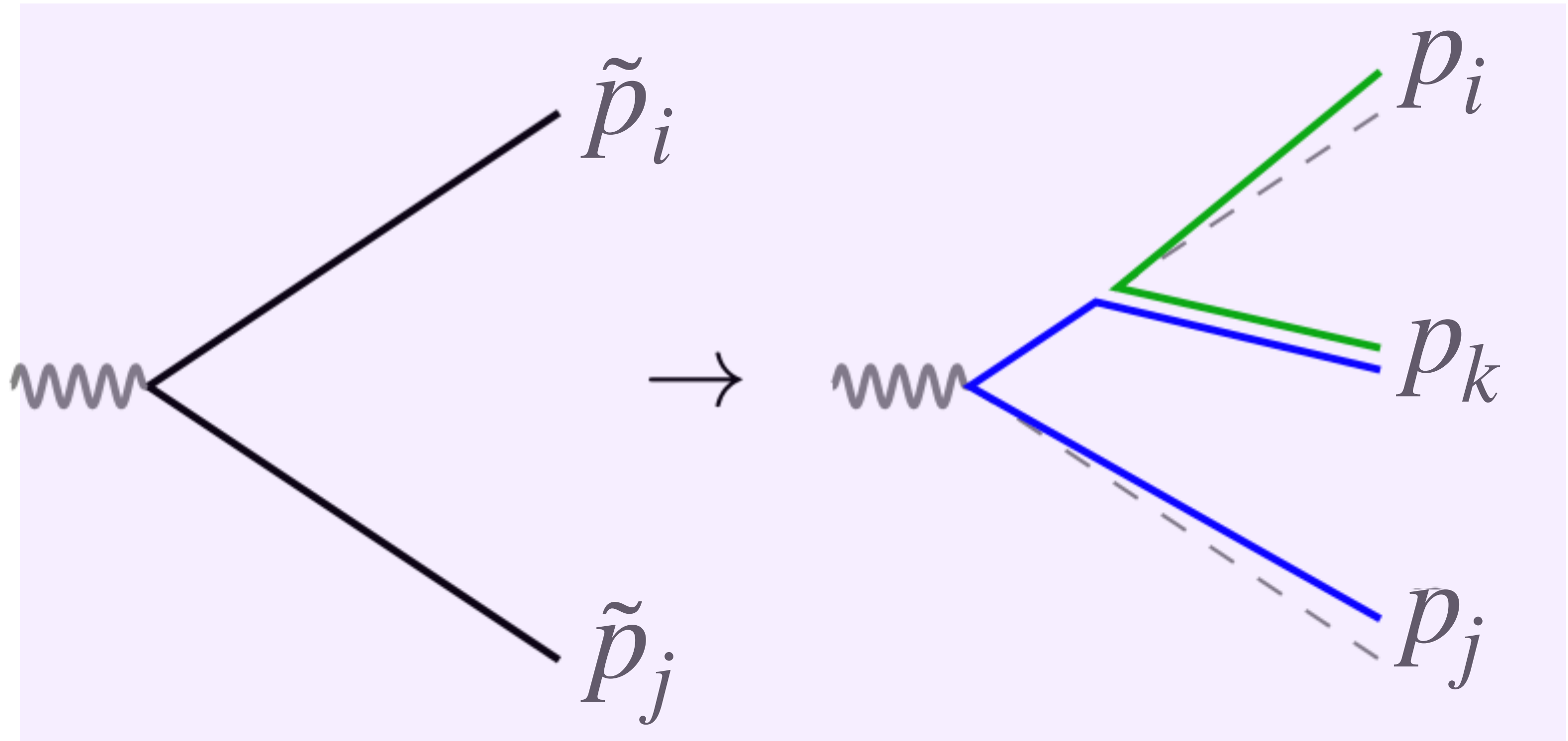
Starting from a $e^+e^- \to Z^* \to q\bar{q}$ system, what is the splitting probability?

Their inteplay determines the shower logarithmic accuracy



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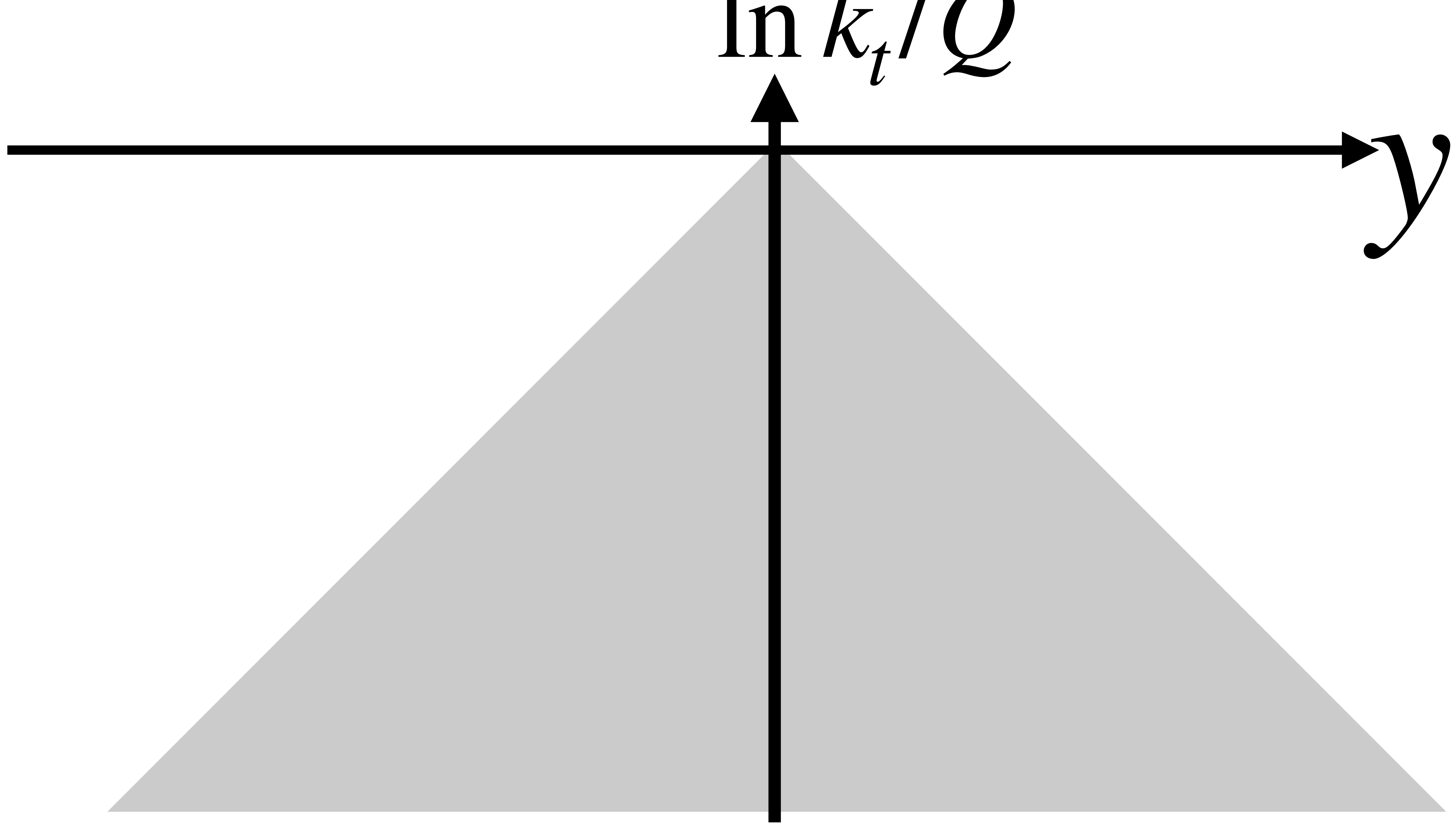
How to build a logarithmically-accurate parton shower?

- **<u>The Lund plane:</u>** diagnostic tools for resummation and parton showers



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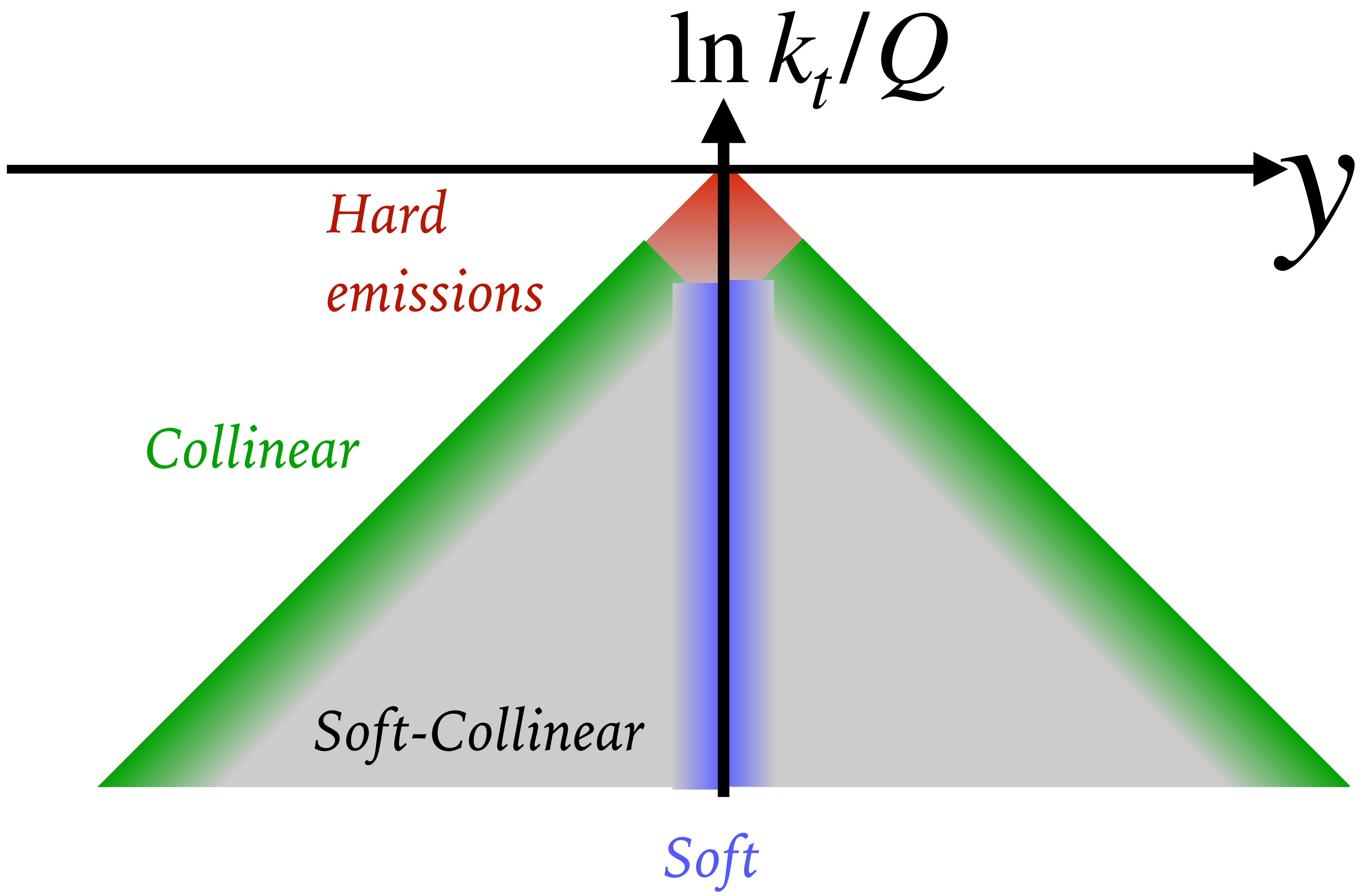


How to build a **LL** parton shower?

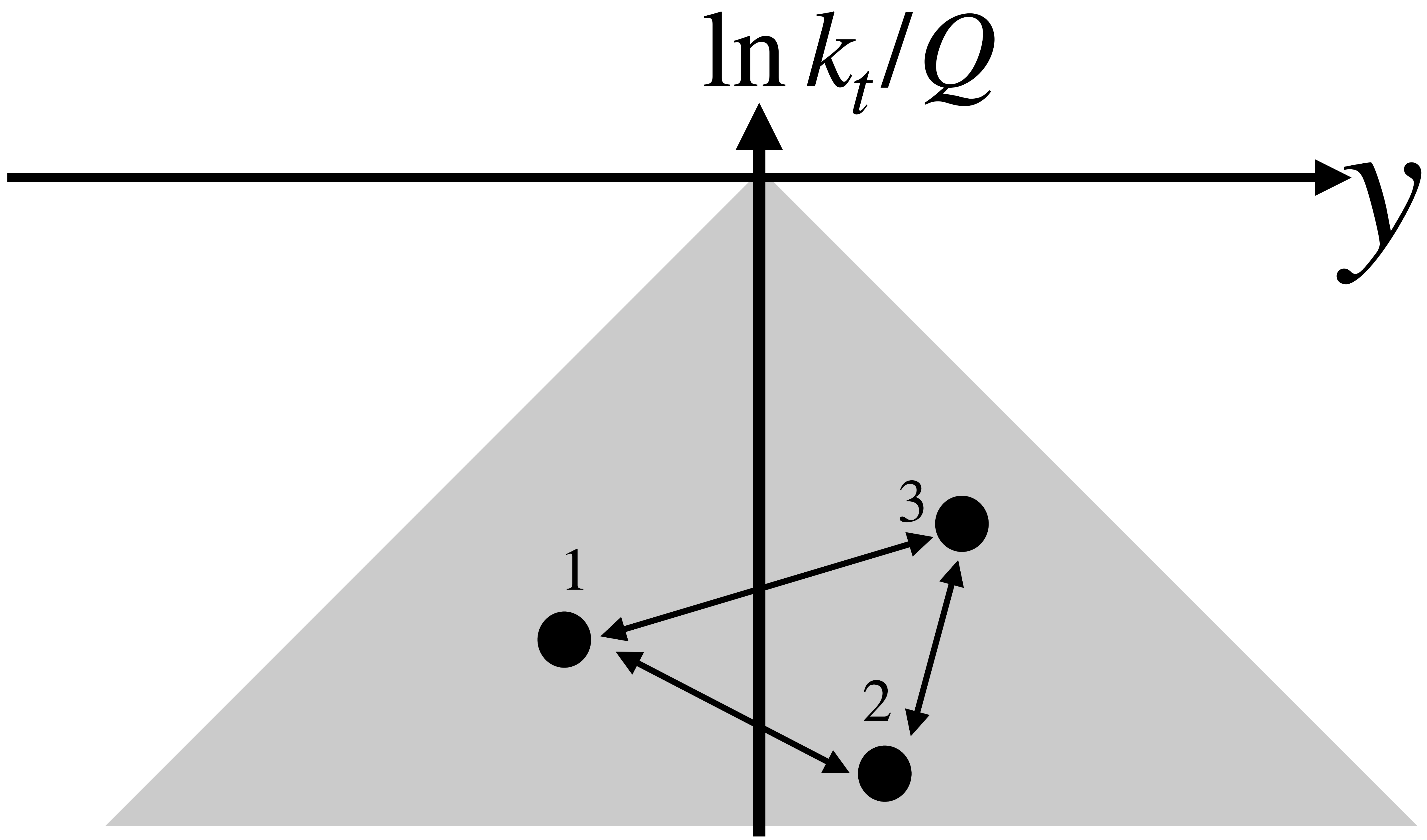
- **The Lund plane:** diagnostic tools for resummation and parton showers

- At **Leading Logarithmic accuracy** we only care about **soft-collinear emissions** very separated between each others

$$dP_i = \frac{\alpha_s(k_t)}{\pi}\frac{2C_F}{z}dz\, d\ln k_t$$

One-loop QCD coupling constant at $\mu_R = k_t$

LO soft splitting function



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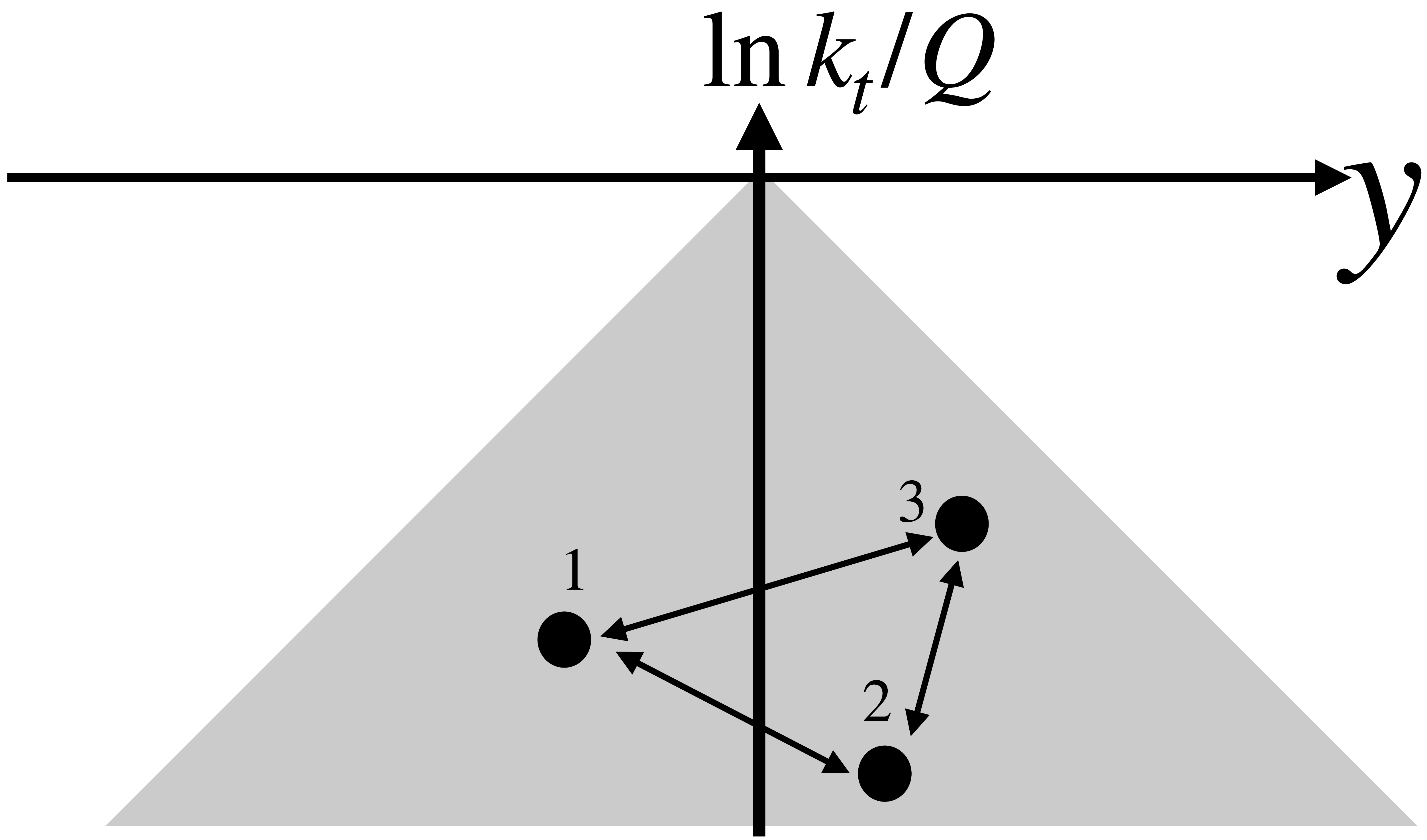

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LO soft splitting function

This tells us what **matrix element** should we use to generate a new emission

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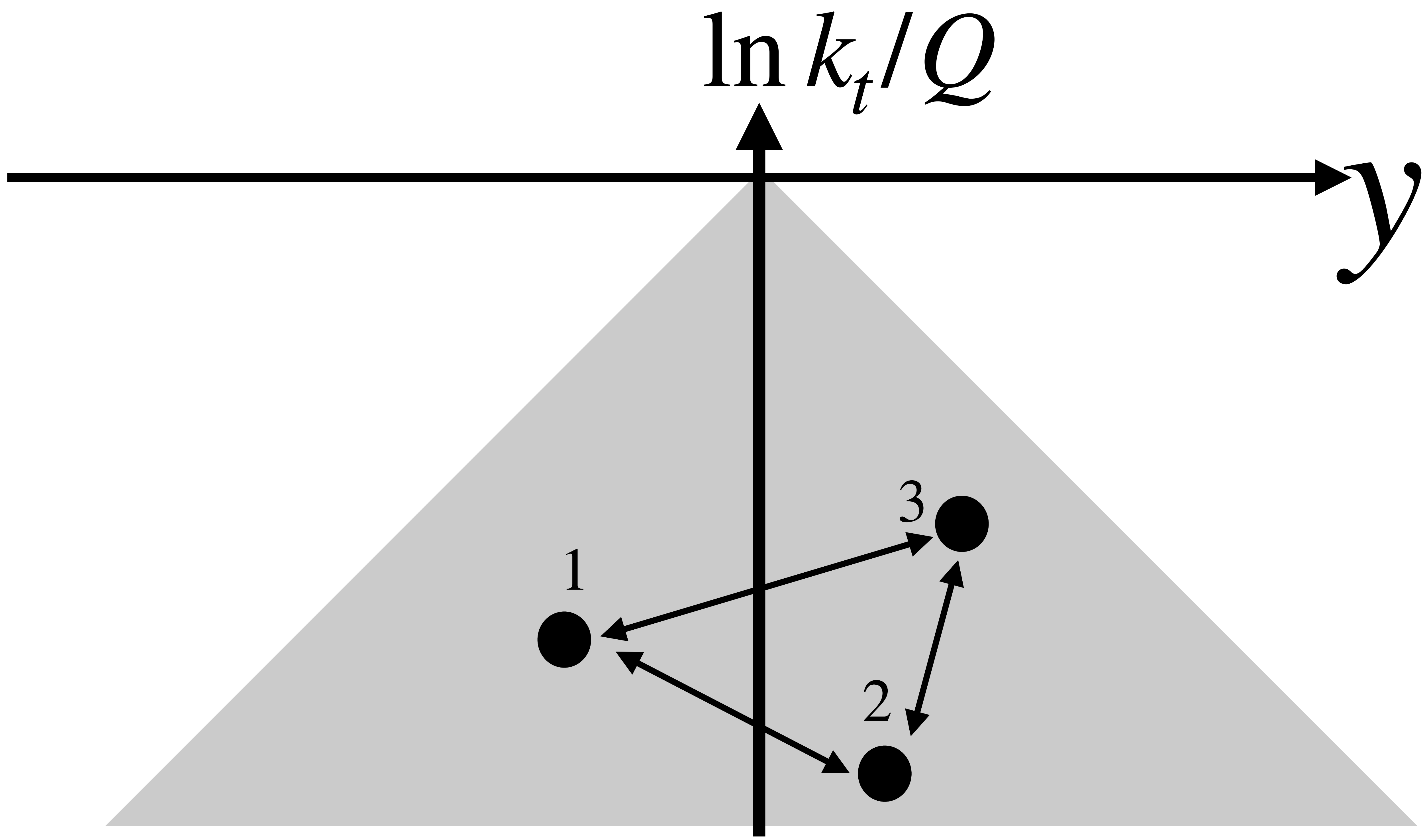

This constrains the **kinematic mapping** $\Phi_n \to \Phi_{n+1}$ and the **ordering variable** choice: **emissions well separated in rapidity and transverse momentum are independent from each other**

How to build a **NLL** parton shower?

At **NLL accuracy:**

- The rate for **soft-collinear emissions** must be correct at NLO

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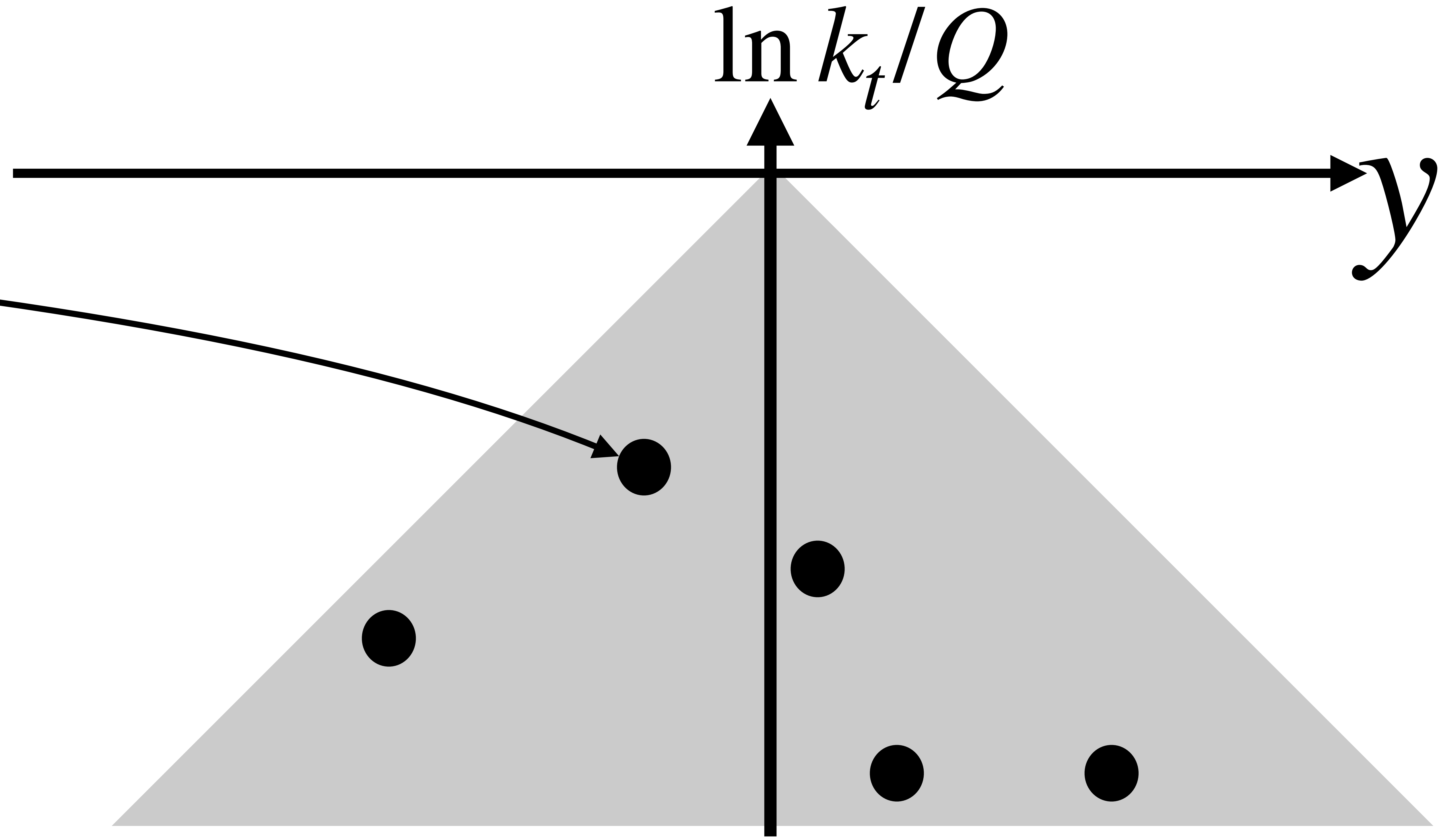

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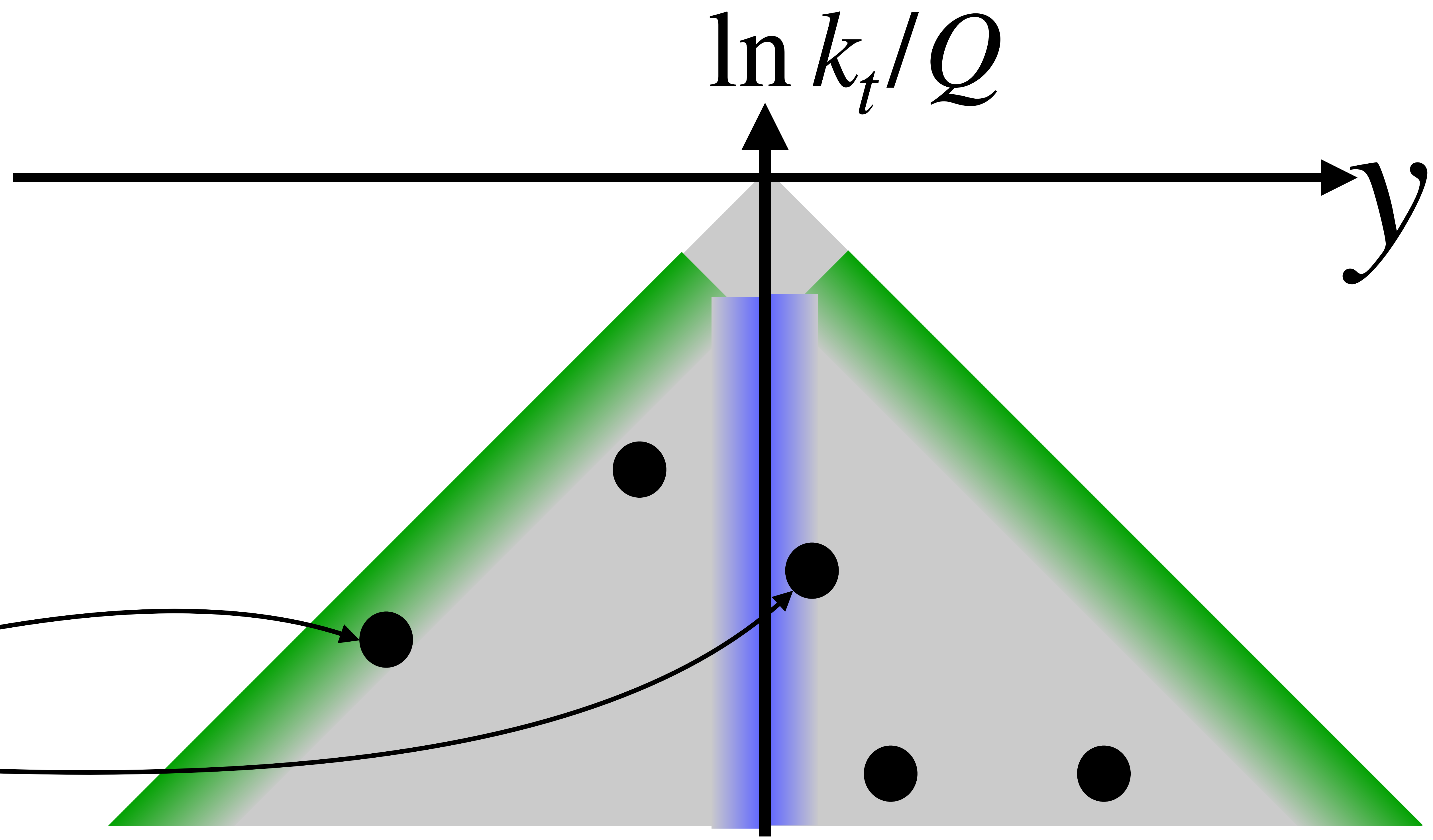

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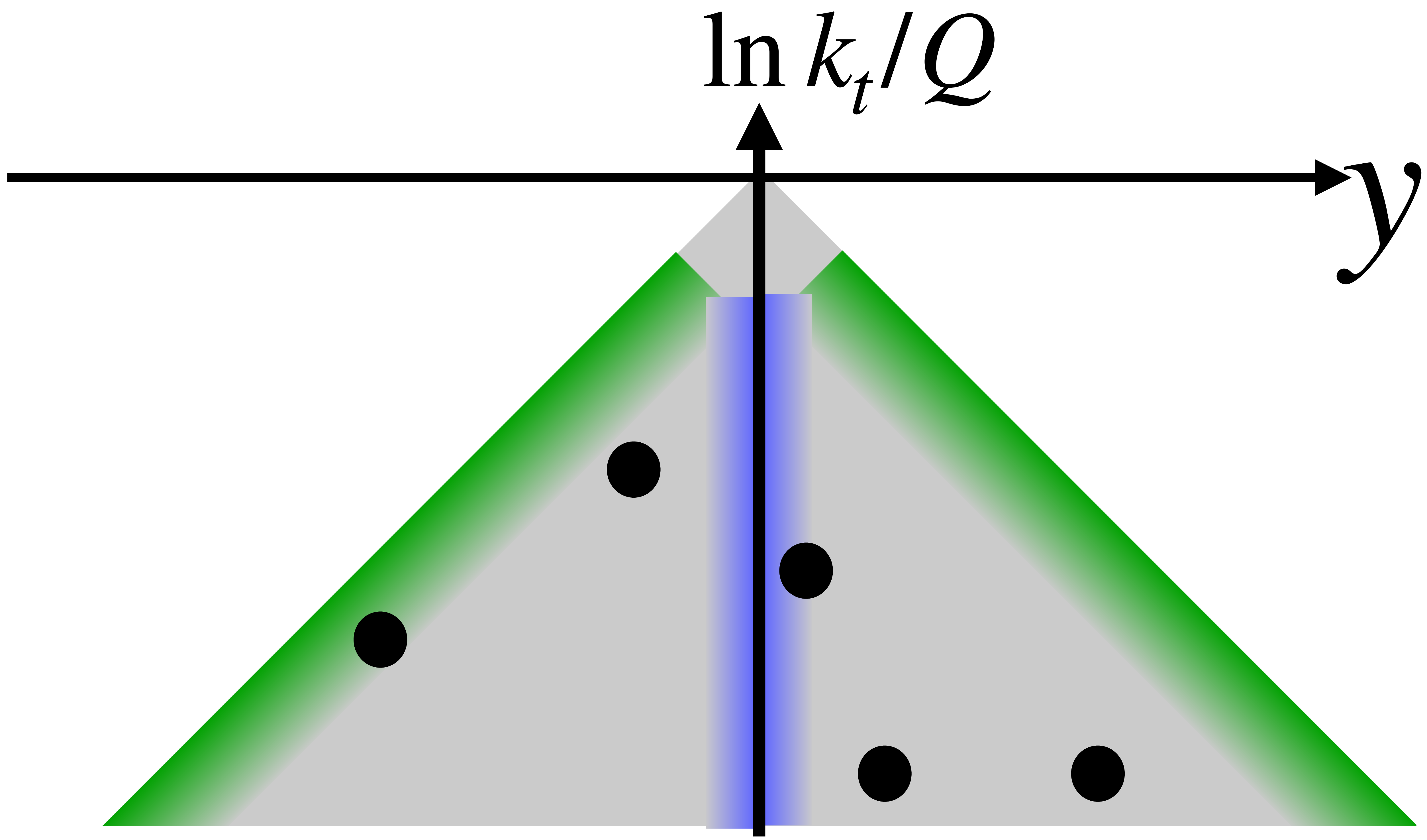

This tells us what **matrix element** we ned to use to generate a new emission

Catani, Marchesini, Webber '91

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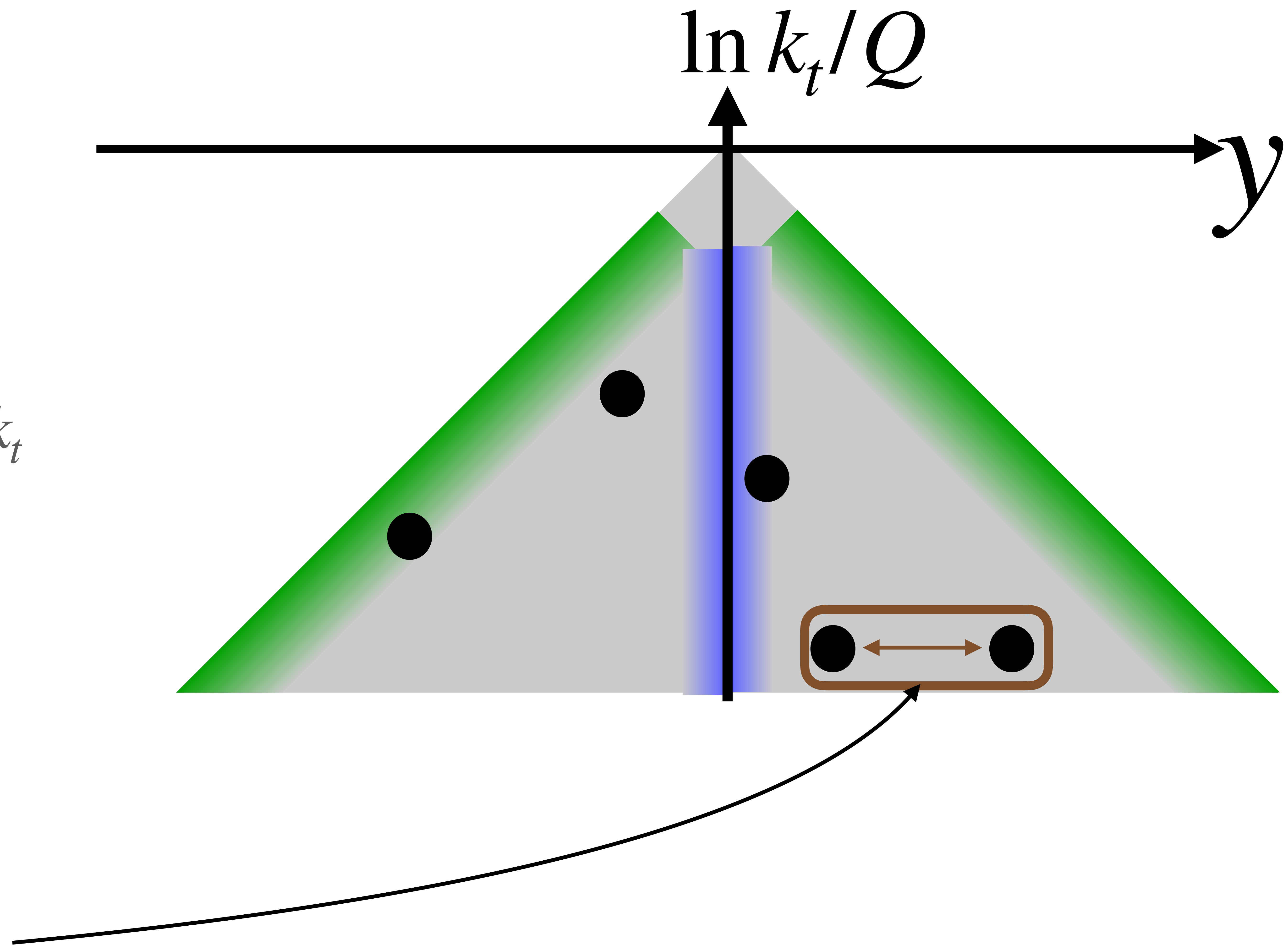

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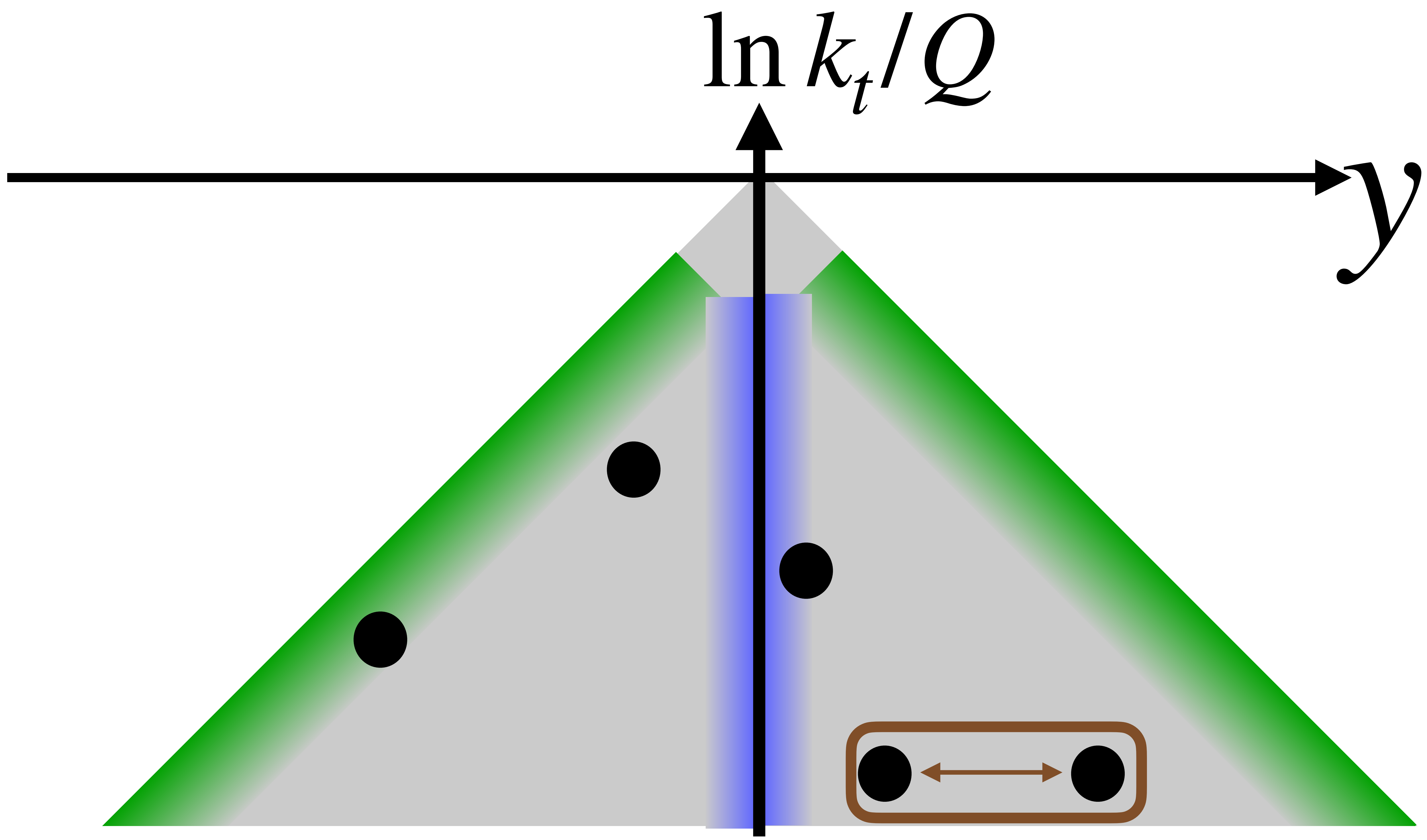
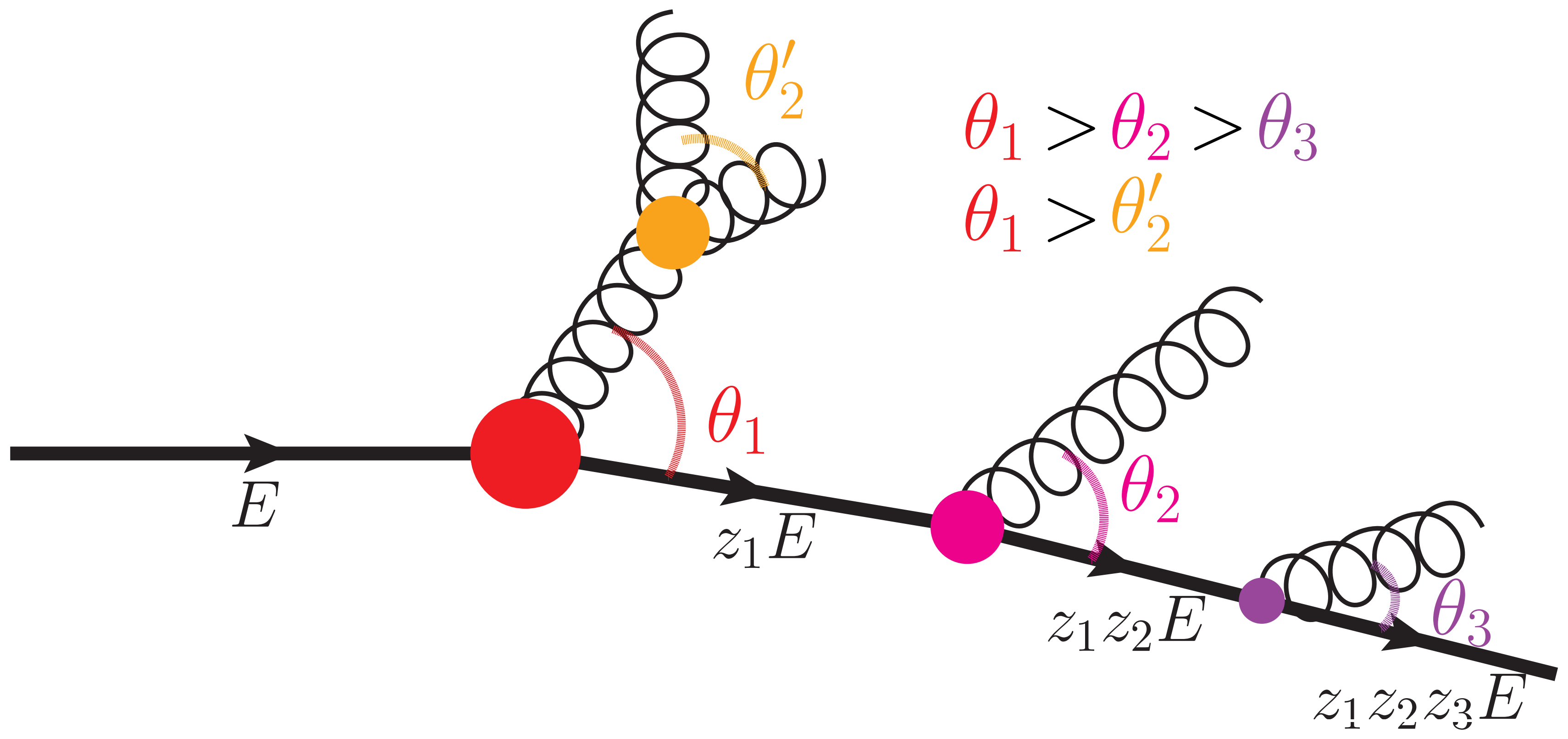


Constrains **kinematic mapping $\Phi_n \to \Phi_{n+1}$** and **ordering variable**: **emissions well separated in rapidity are independent from each other, even if they have similar transverse momentum**

Parton Showers in a nutshell

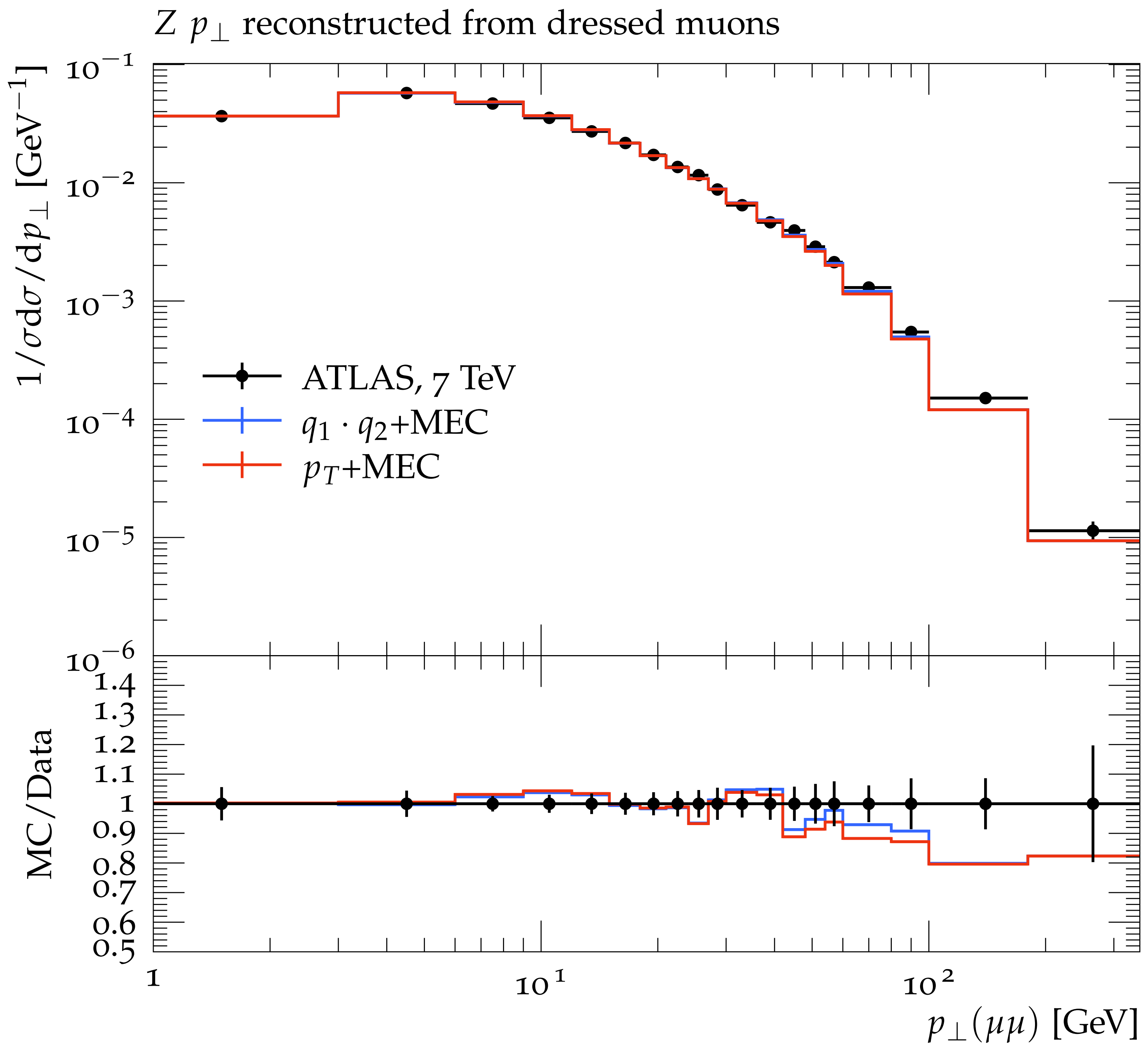
Angular-ordered shower (Herwig)



➤ Designed to achieve **NLL** for many observables

[Marchesini, Webber '88]

$p_\perp$ of the Z at LHC



2 recoil schemes that achieve NLL accuracy for global event shapes

(difference can be used to estimate shower uncertainties)

[Bewick, SFR, Richardson, Seymour; 1904.11866, 2107.04051]

Parton Showers in a nutshell

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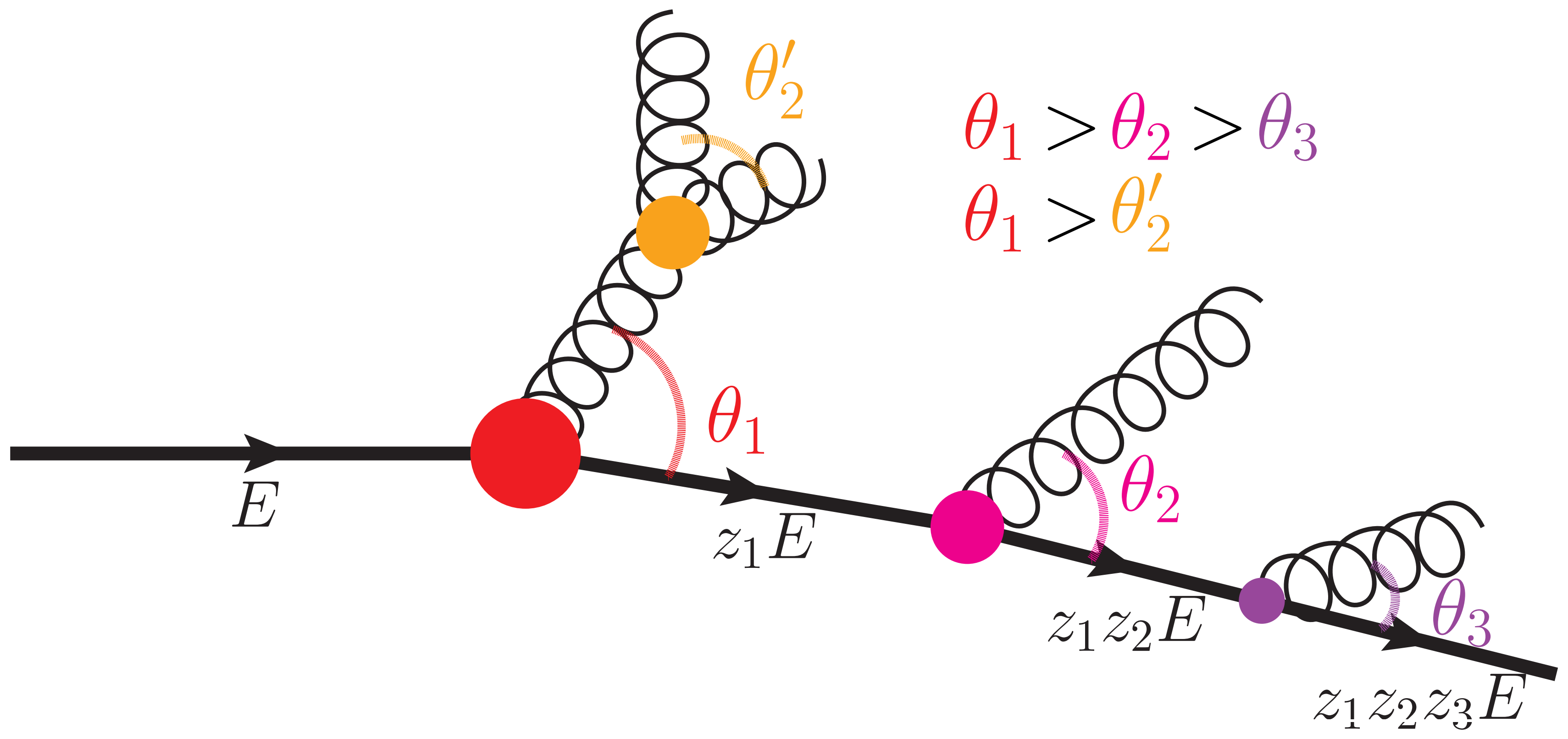

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BUT

- **Matching** with fixed-order calculations **beyond NLO** is painful (and not available)
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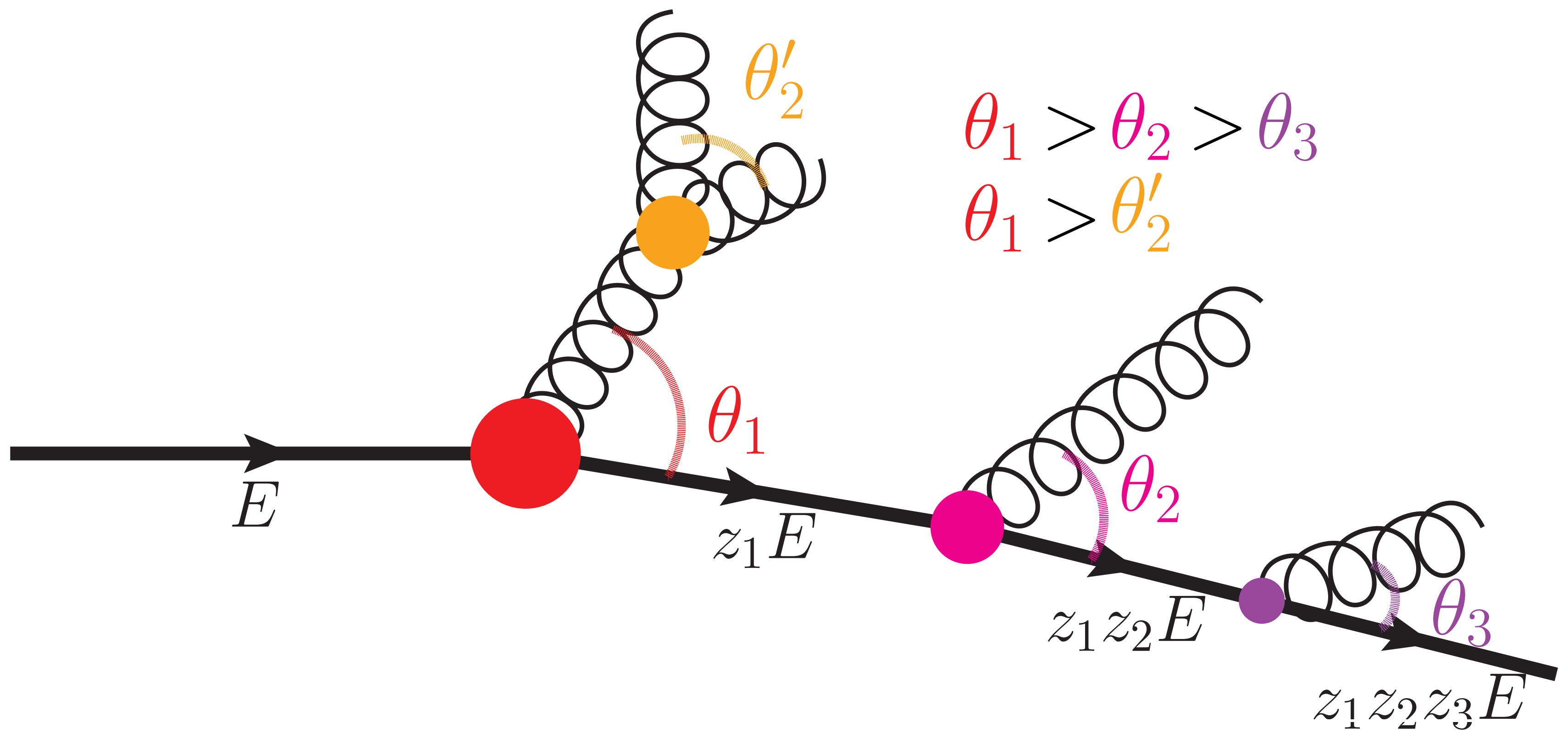

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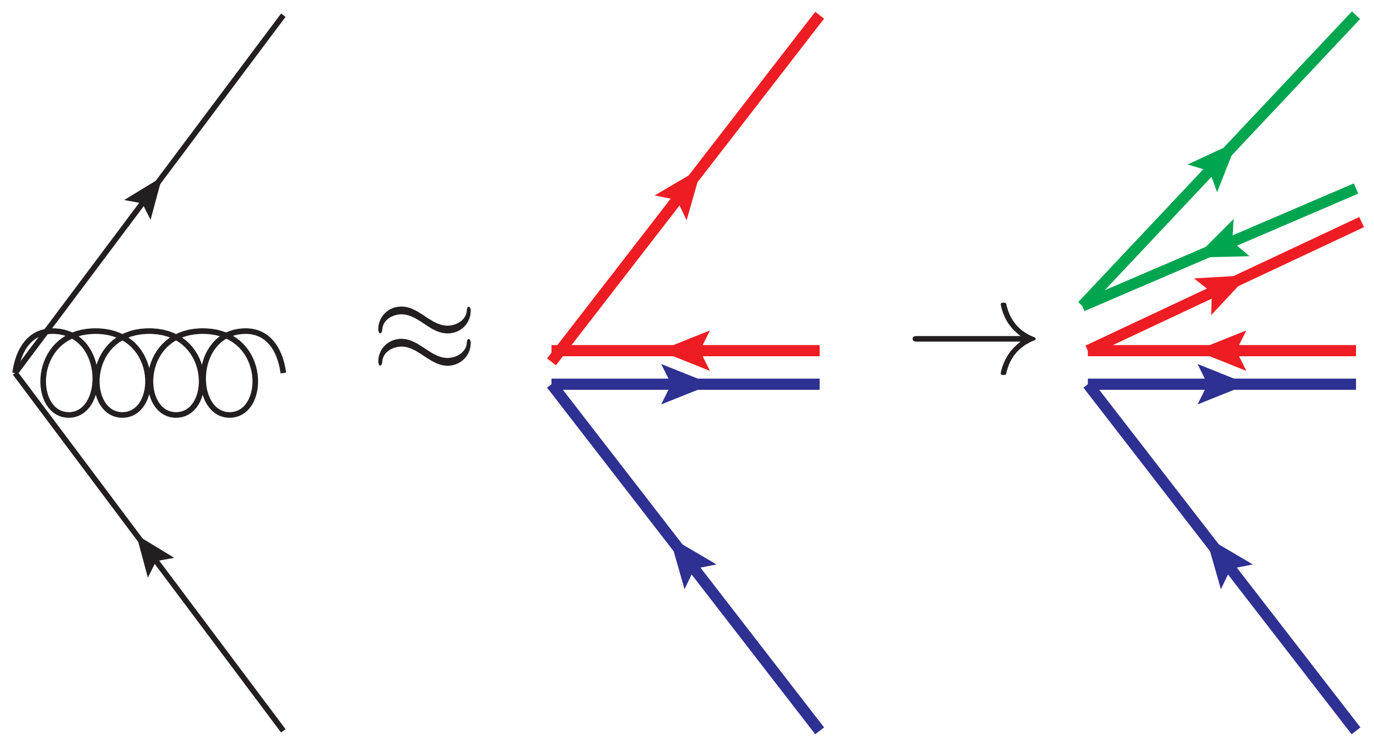
Dipole shower (Pythia, Sherpa, Herwig)



➤ Dipole showers are the more popular alternative to angular-ordered showers

[Gustafson, Pettersson '88]

➤ **Matching beyond NLO and multi-jet merging** much simpler as hardest emissions come first

➤ Azimuthal dependendece of soft emission necessary for **non-global logs**

BUT THEY ARE <u>NOT YET</u> (N)NLL!

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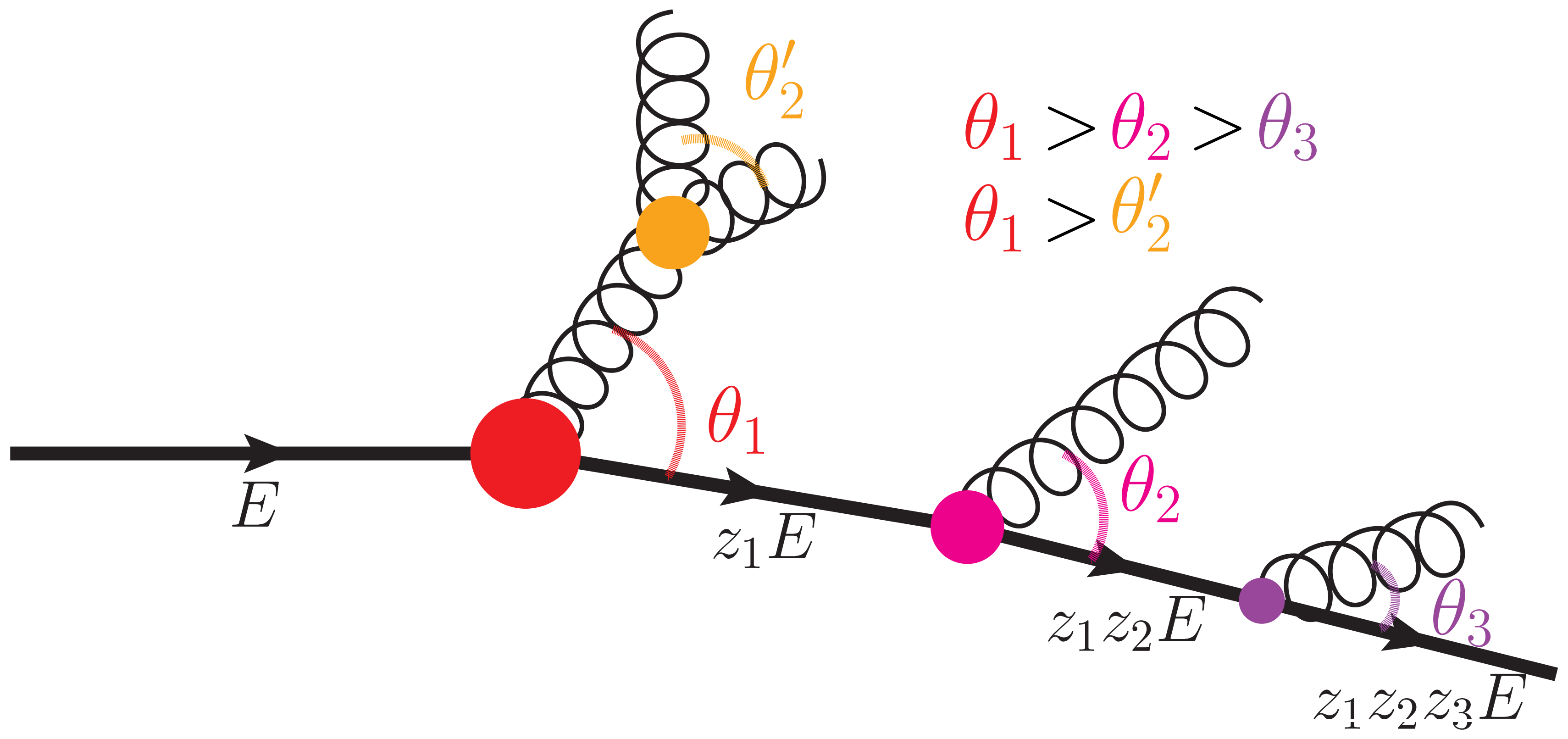

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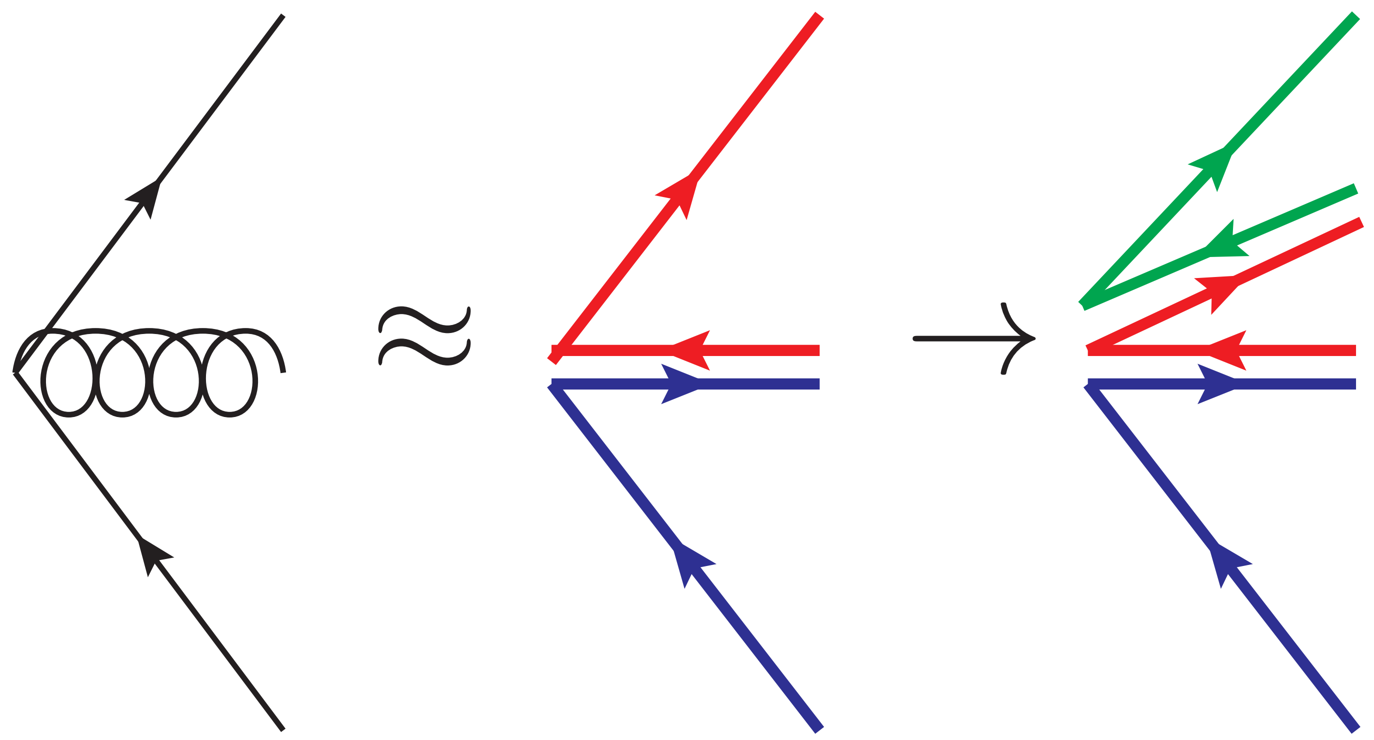

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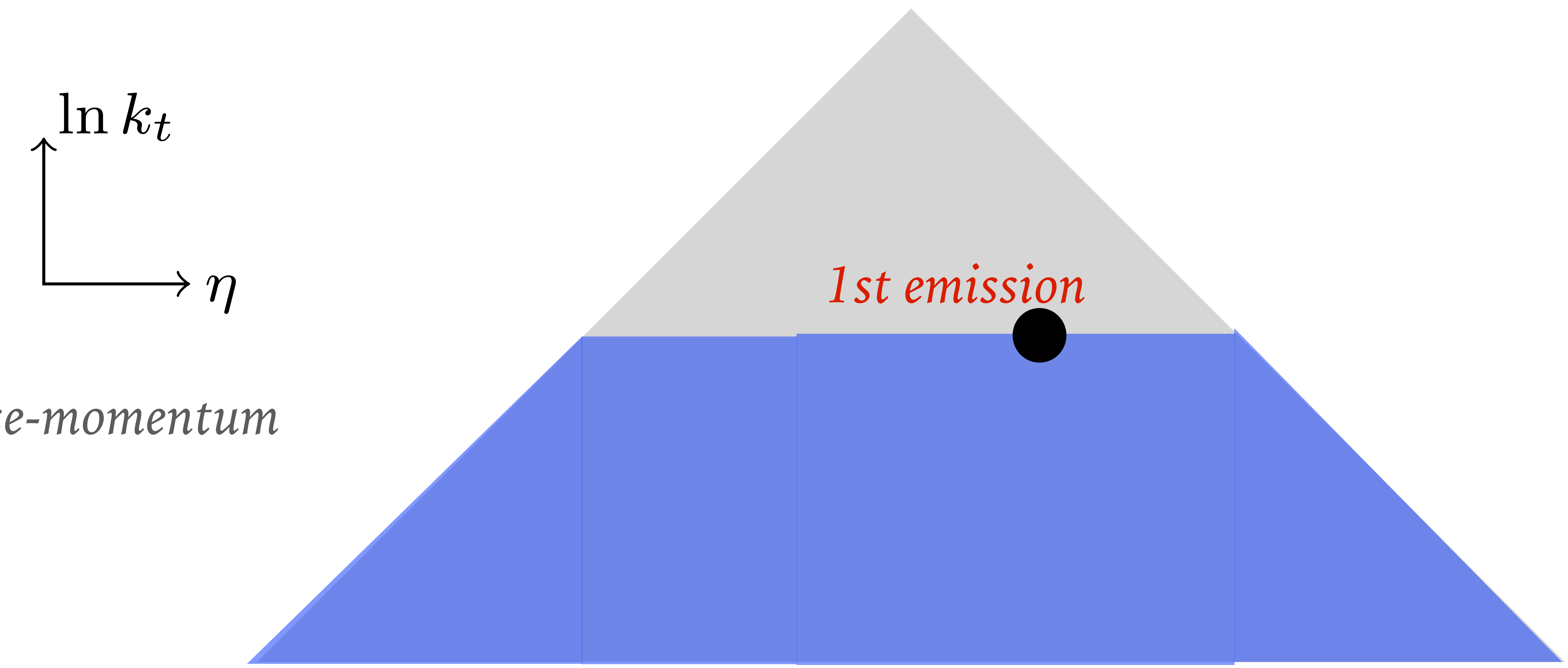
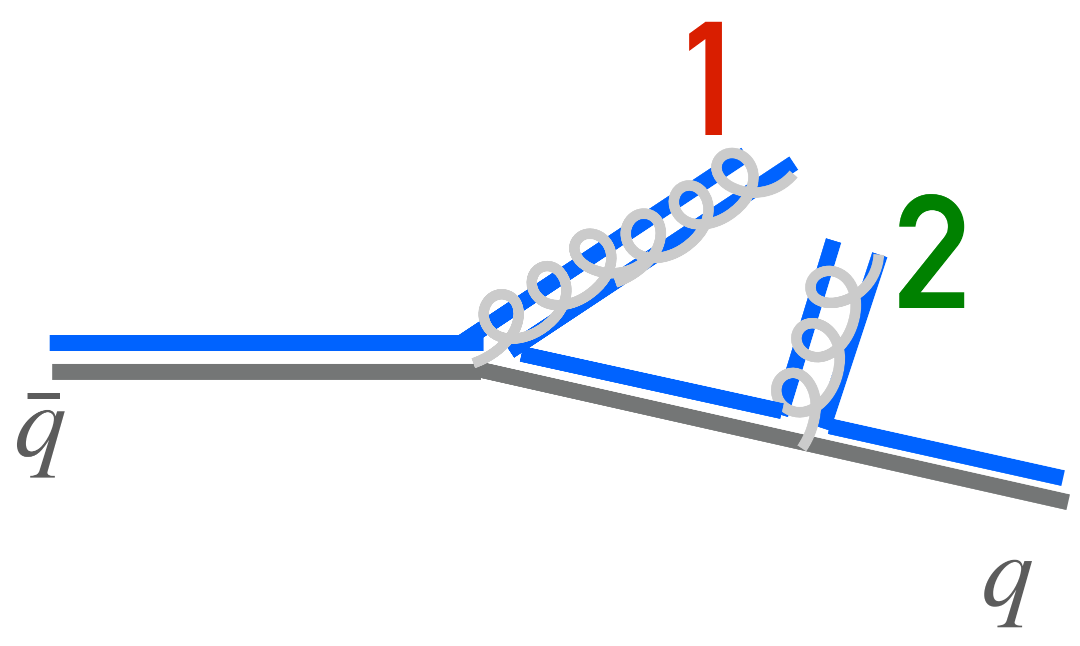
Steady progresses in building (N)NLL

Why are "standard" dipole showers not NLL?

Emission of a **soft-collinear gluon** g_2, from a $q\bar{q}g_1$ final-state, where g_1 is soft-collinear as well



Transverse-momentum ordering



1805.09327 Dasgupta, Dreyer, Hamilton, Monni, Salam

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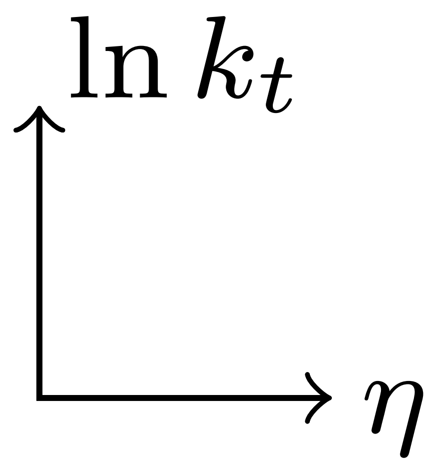

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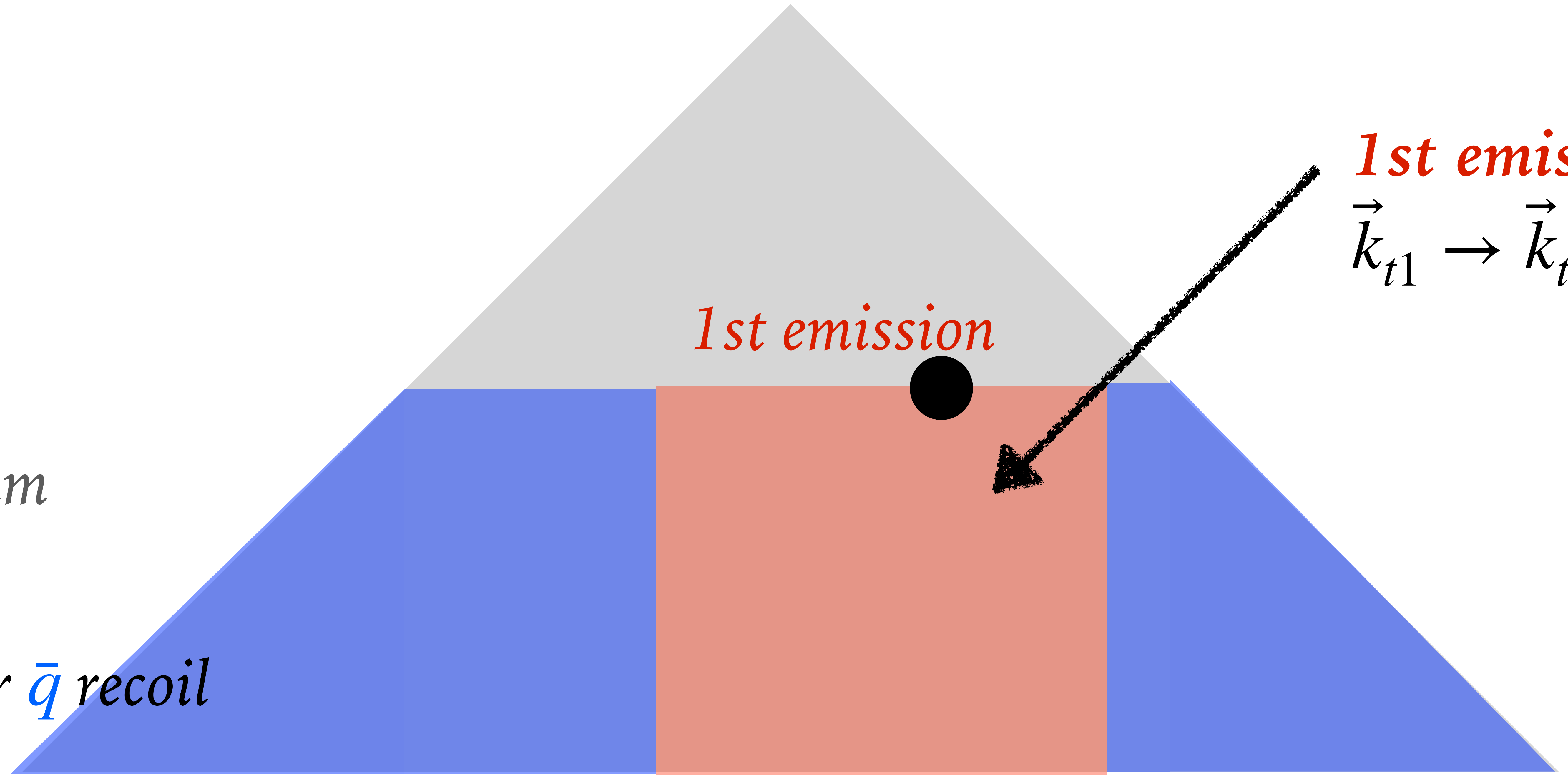
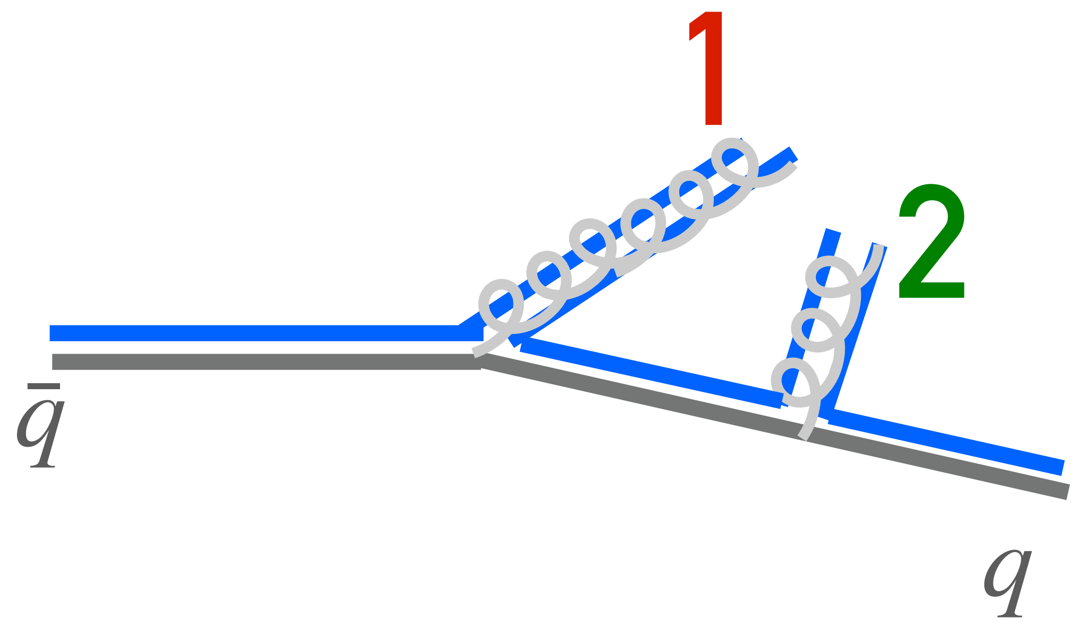


The q or $\bar{q}$ recoil

1st emission *recoils*

$\vec{k}_{t1} \to \vec{k}_{t1} - \vec{k}_{t2}$

Who takes the $k_\perp$ recoil of the new emission?



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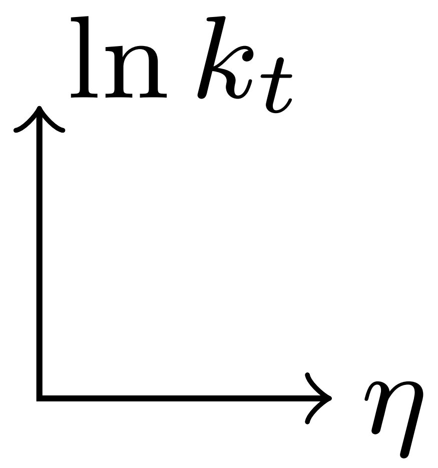

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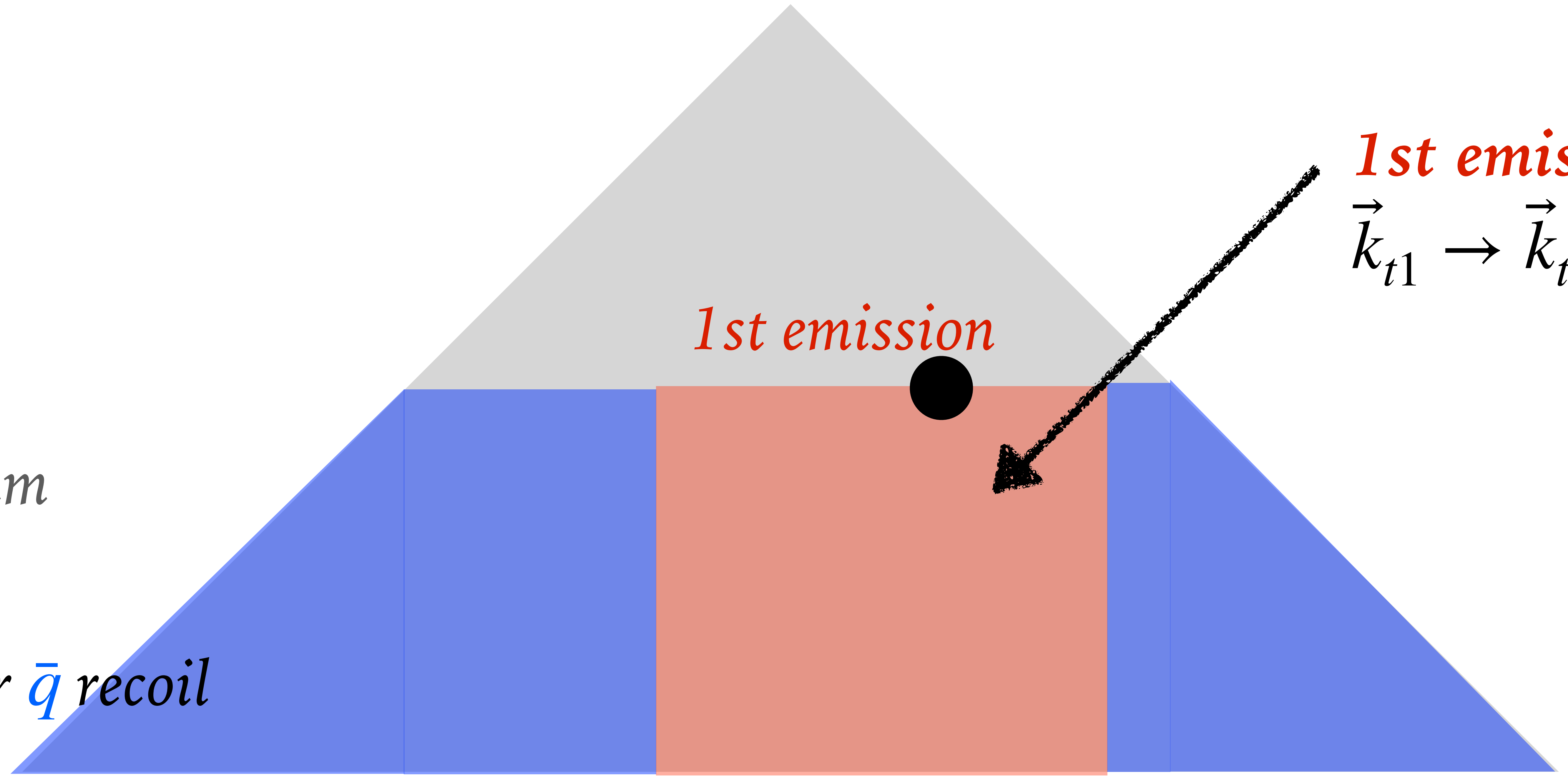

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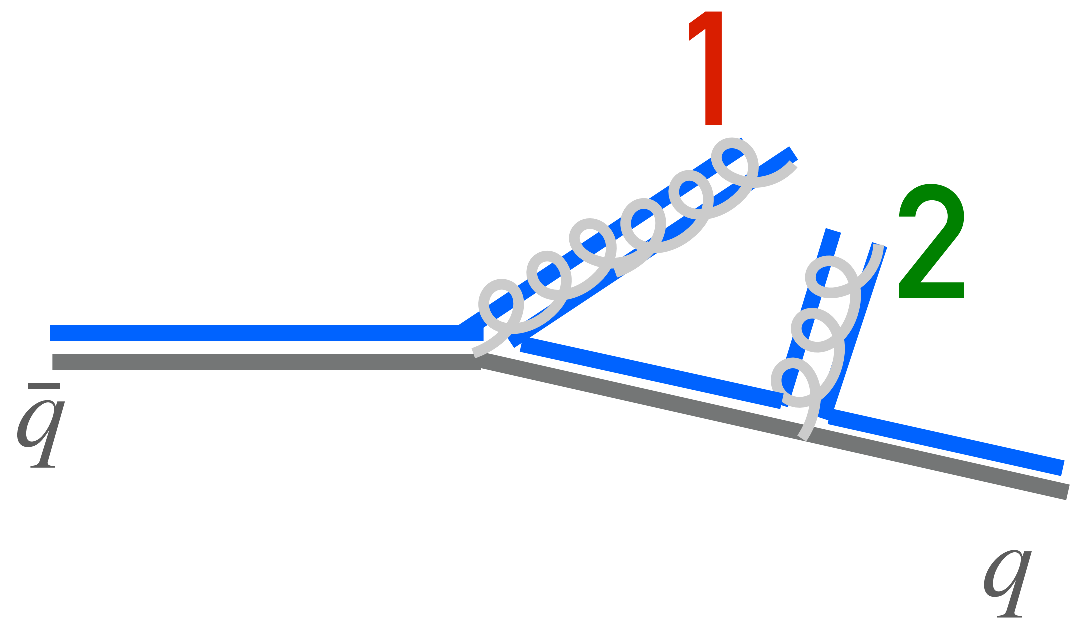
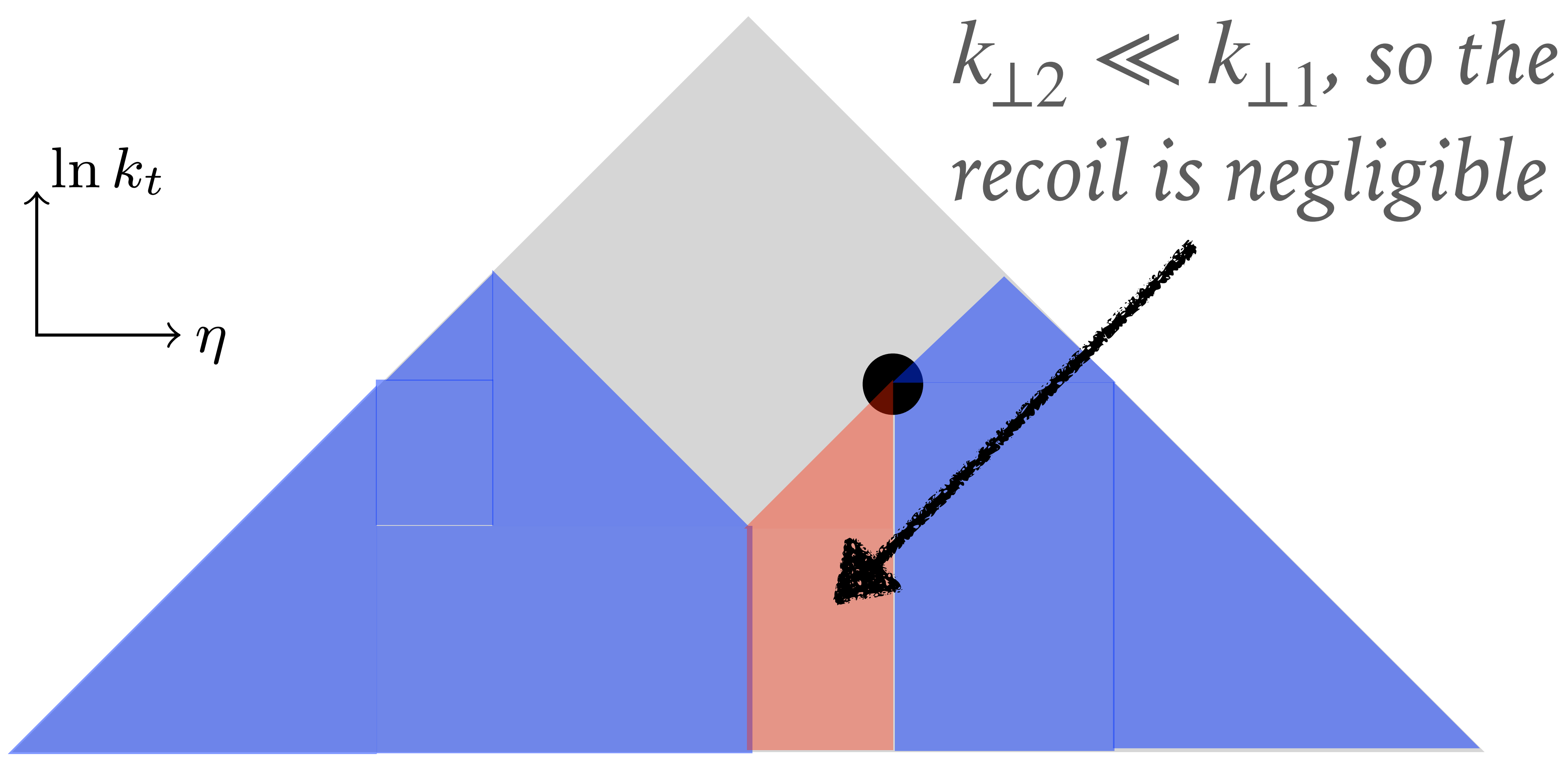


For $|\eta_1 - \eta_2| \gg 1$ but $k_{t,1} \sim k_{t,2}$, the 1st emission is affected by the 2nd: ***NLL is not OK***!

1805.09327 Dasgupta, Dreyer, Hamilton, Monni, Salam

Building a NLL shower



Local recoil

Evolution variable: $v \sim k_\perp e^{-\beta|y|}$

Deductor by Nagy & Soper 0912.4534

PanScales (local variant), Dasgupta et al. 2002.11114

+angles in the event frame

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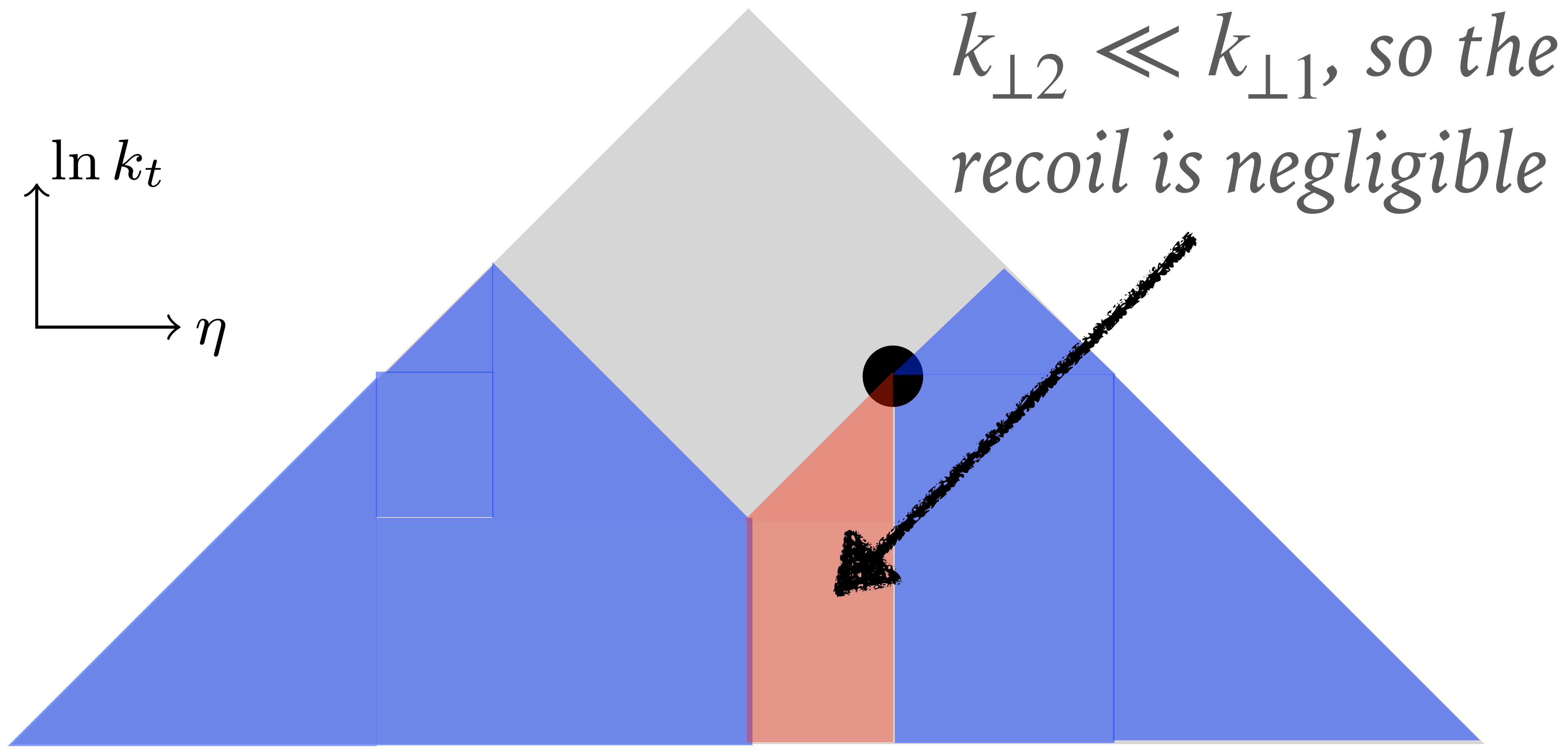

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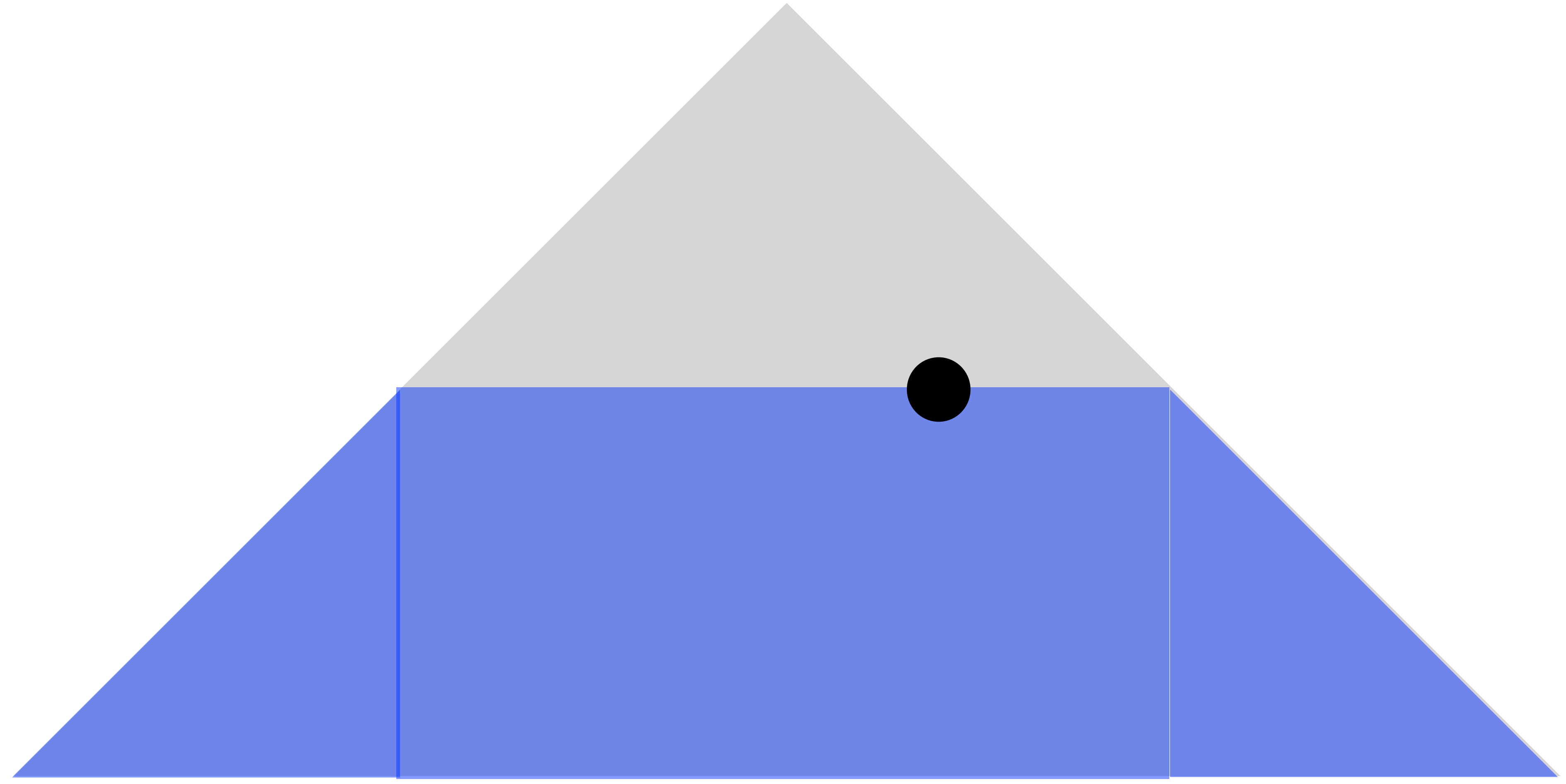


Global recoil: $k_\perp$ is redistributed among all the partons in the event (mainly the hardest)

Deductor by Nagy & Soper 0912.4534

PanScales (local variant), Dasgupta et al. 2002.11114

+angles in the event frame

PanScales (global variant), Dasgupta et al. 2002.11114

Forshaw, **H**olguin, and **P**lätzer 2003.06400

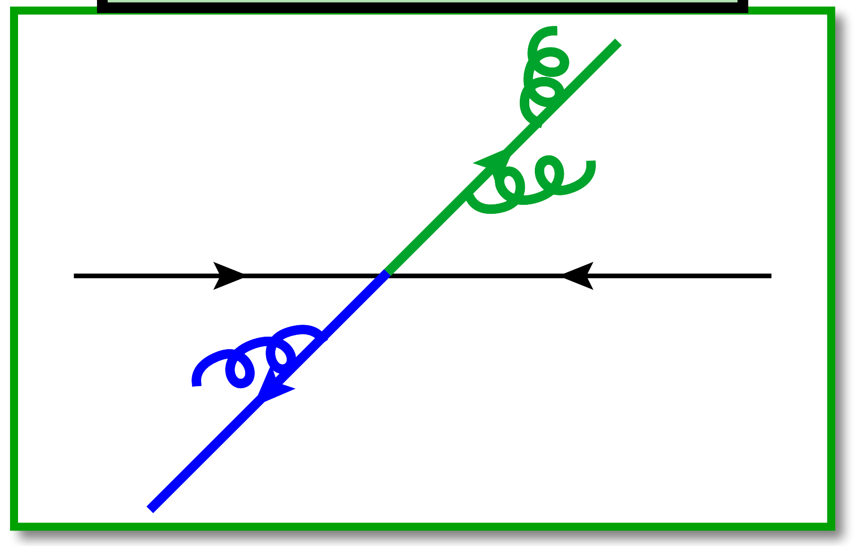
Alaric by Herren et al. 2208.06057

Apollo by Preuss 2403.19452

Status of **NLL PanScales** showers

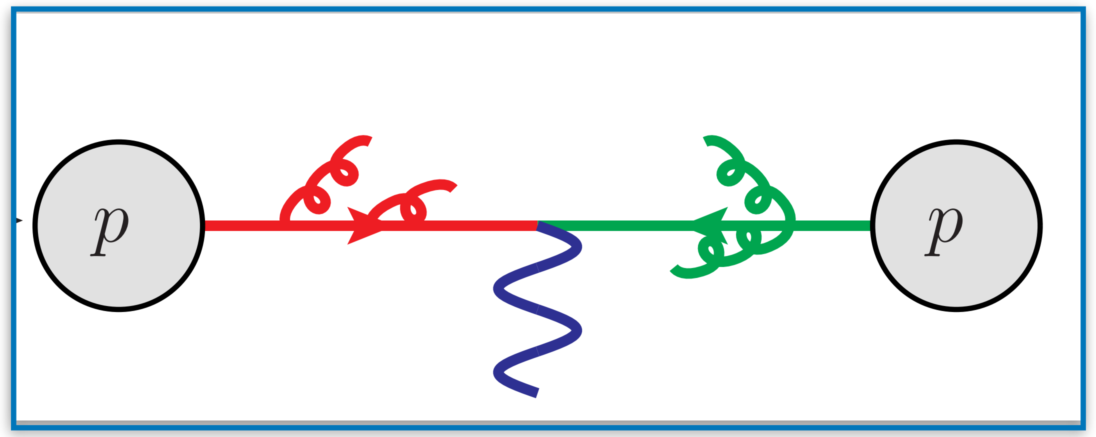
- **PanScales** is the **first** shower with **general** NLL accuracy for

$e^+e^- \to j_1 j_2$



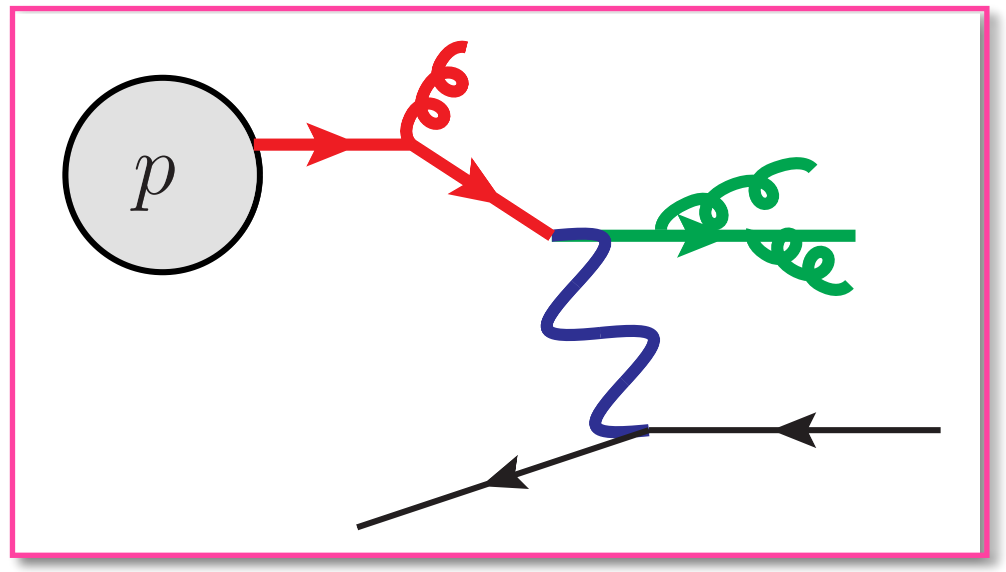
Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez, 2002.11114

$pp \to$ ***colour singlet***



van Beekveld, **SFR**, Soto-Ontoso, Salam, Soyez, Verheyen, 2205.02237, + Hamilton 2207.09467

DIS & VBF



van Beekveld, **SFR**, 2305.08645

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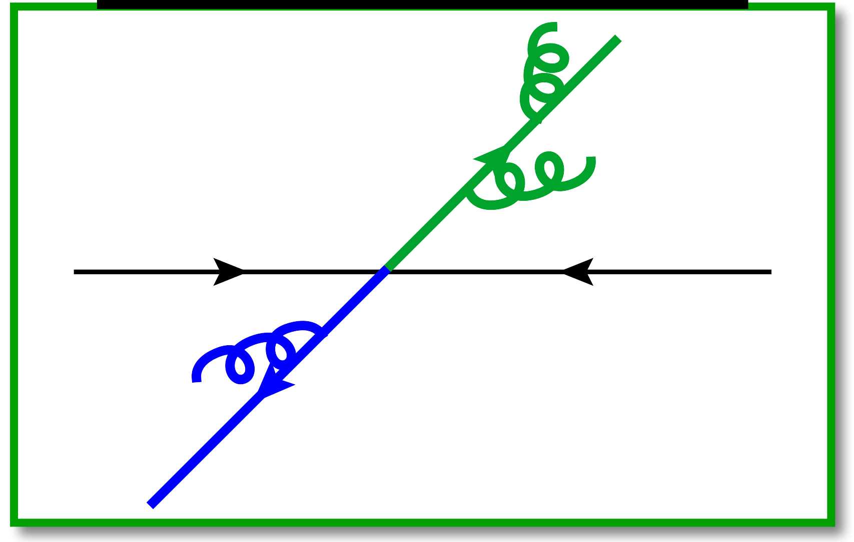

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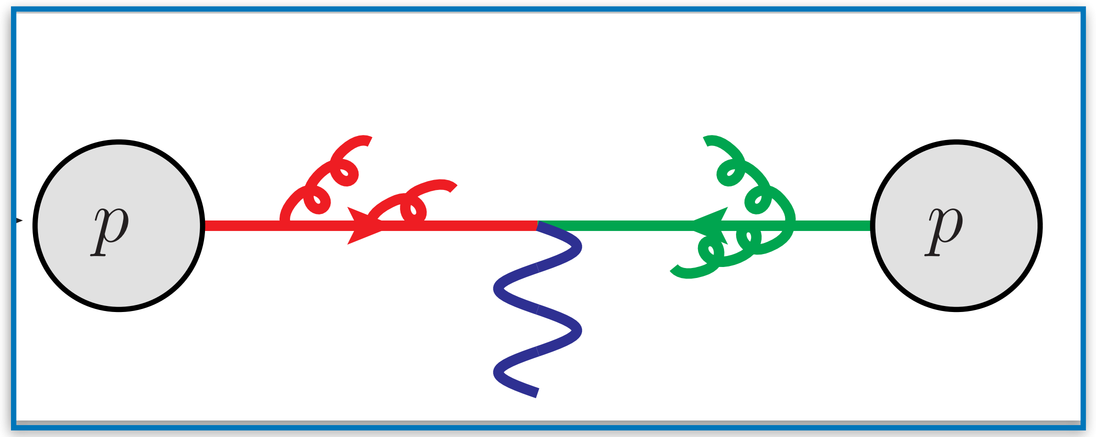

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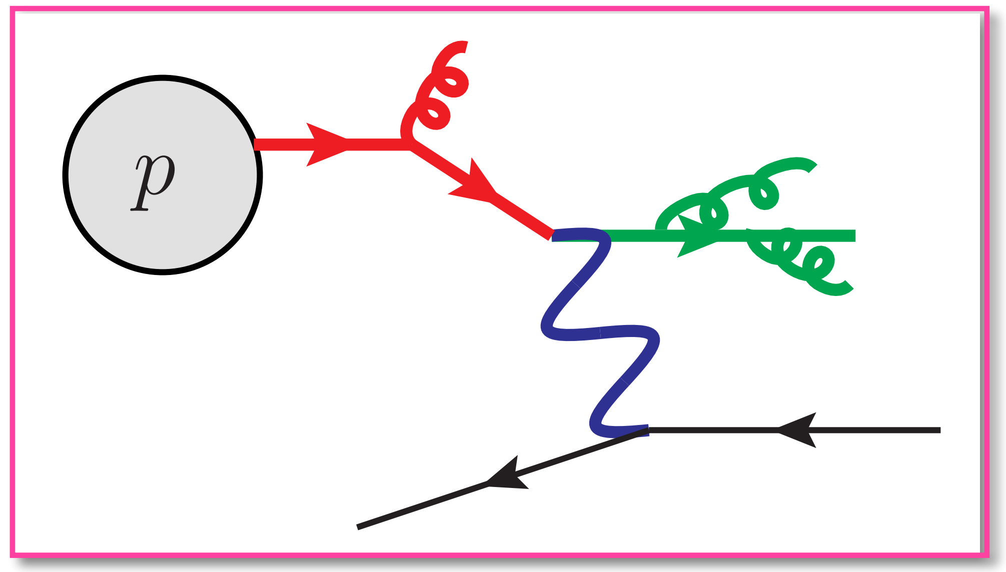

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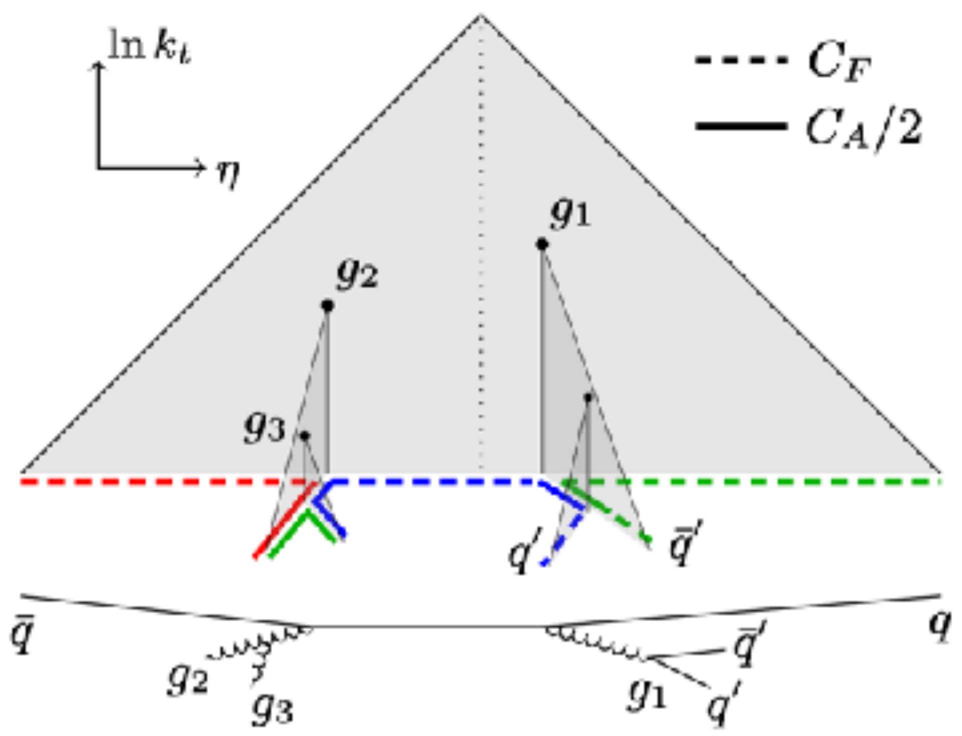
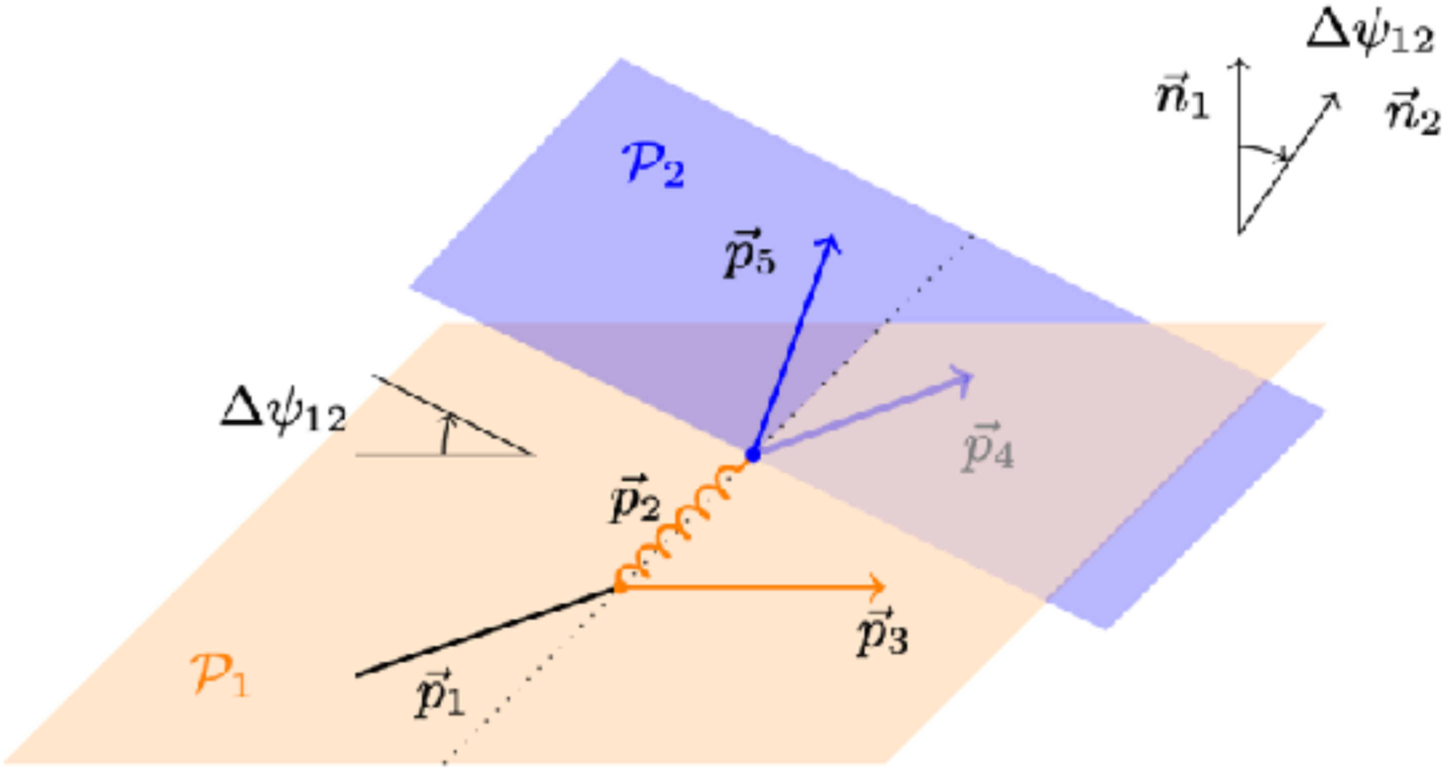


…with **subleading colour** (Hamilton, Medves, Salam, Scyboz, Soyez 2011.10054) and **spin correlations** (Karlberg, Salam, Scyboz, Verheyen 2103.16526, + Hamilton 2111.01161)



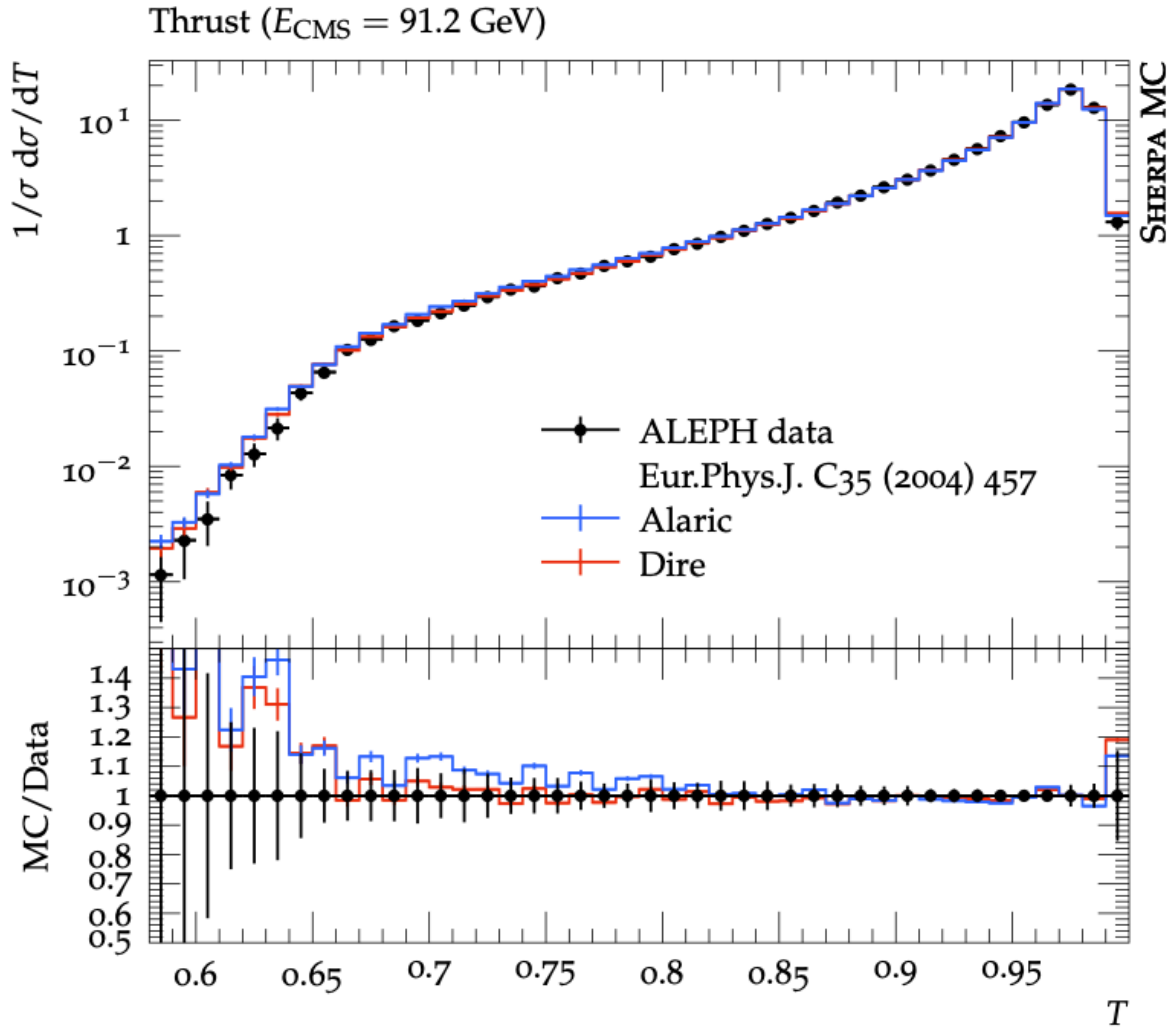
Alaric highlights

NLL shower for e^+e^- in 2208.06057
[Herren, Höche, Krauss, Reichelt, Shönherr]

- The **anti-collinear** component is conserved globally in the map: the colour partner is not used as recoiler (as in Deductor and FHP)
- Separate soft from collinear evolution e.g.

$$\frac{P_{q\to qg}}{C_F} = \frac{2z}{1-z} + 1 - z$$

(similar proposal by Nagy and Soper in 2204.05631)



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With mass effects 2307.00728 [Assi, Höche]

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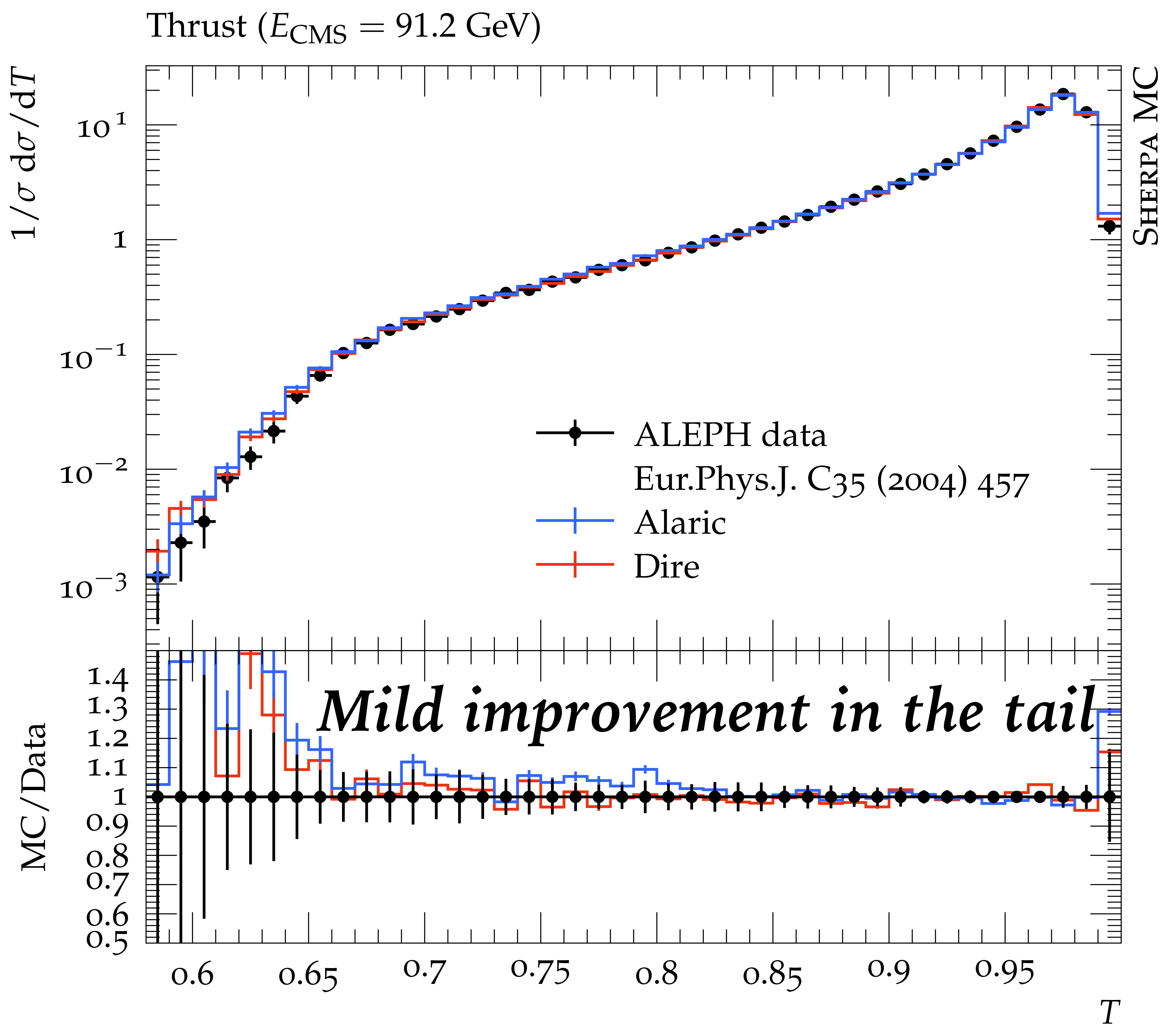

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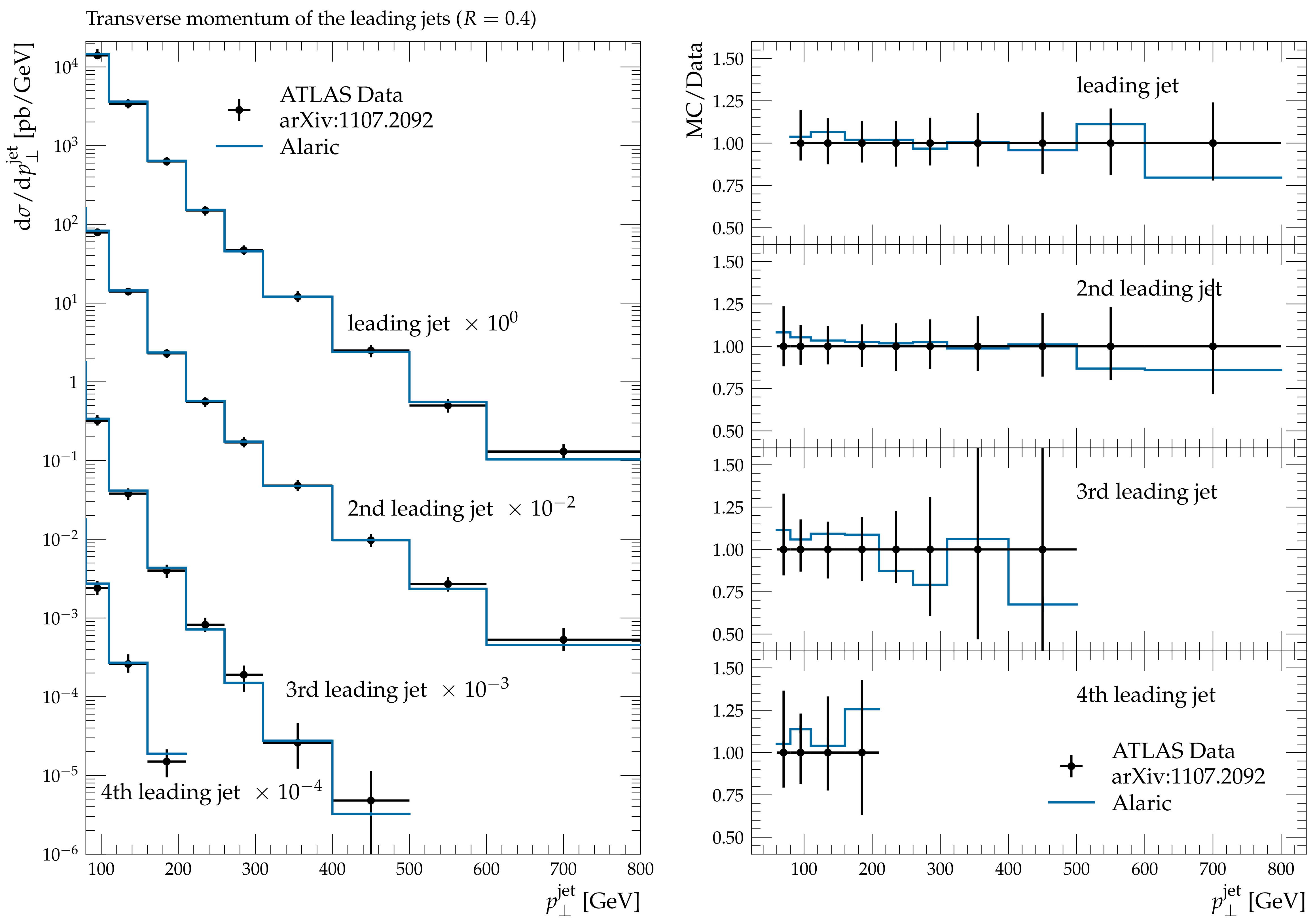
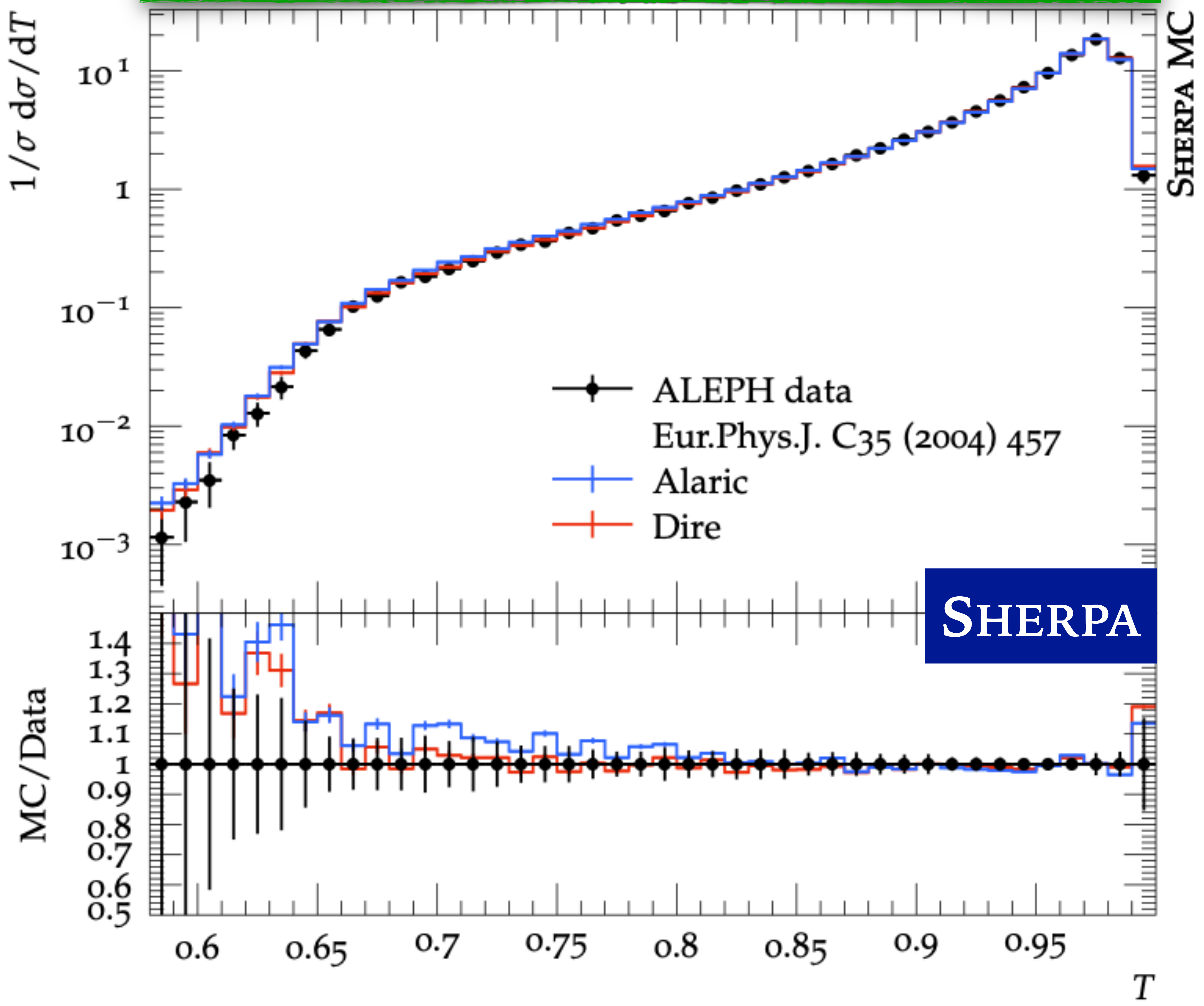
pp colliders and multi-jet merging 2404.14360
[Höche, Krauss, Reichelt]

- Global $k_\perp$ conservation for **ISR**

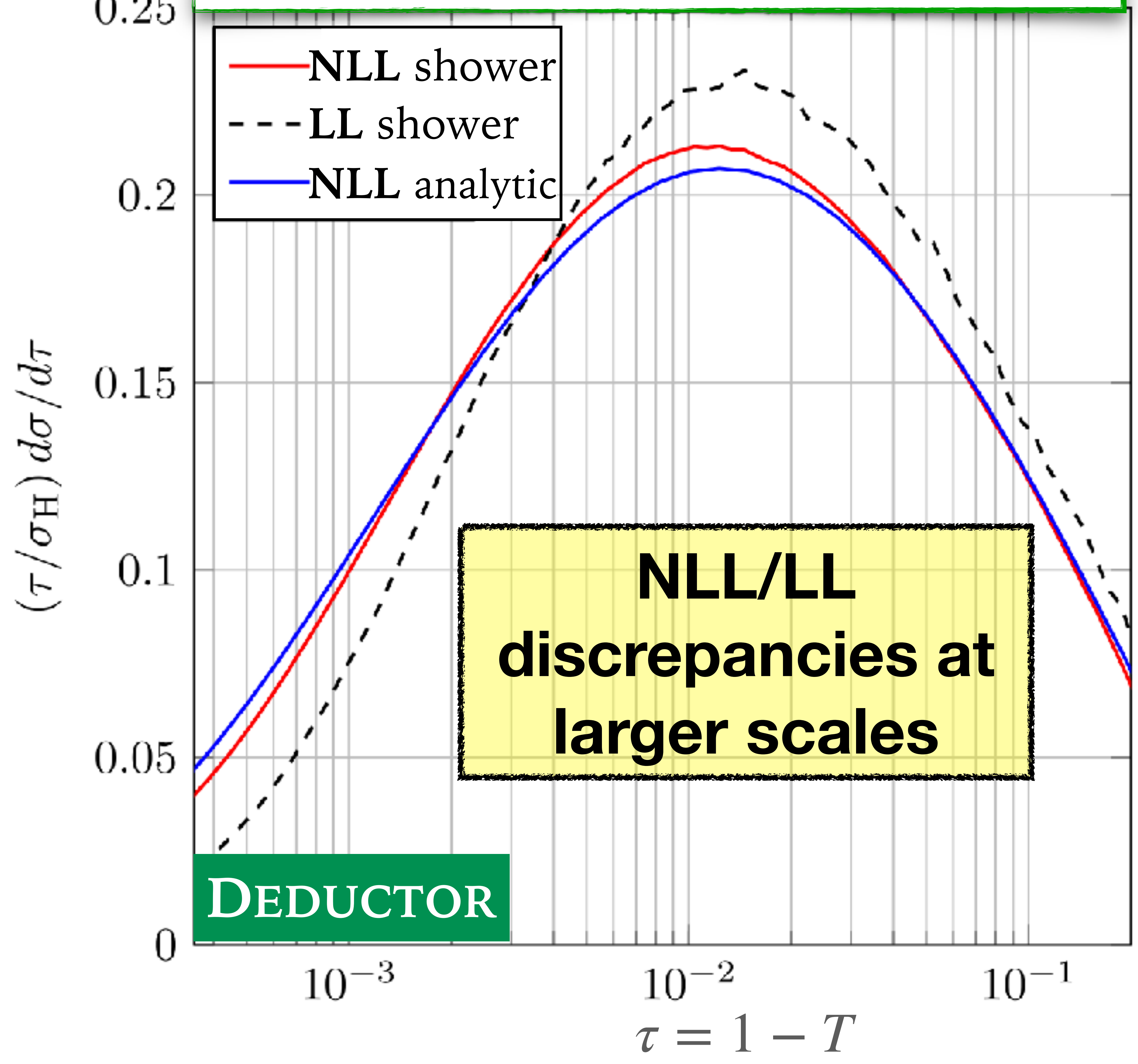


LEP: when is NLL important?

$\sqrt{s}$=91 GeV



$\sqrt{s}$=10 TeV



NLL/LL discrepancies at larger scales

The (Panscales) route to NNLL

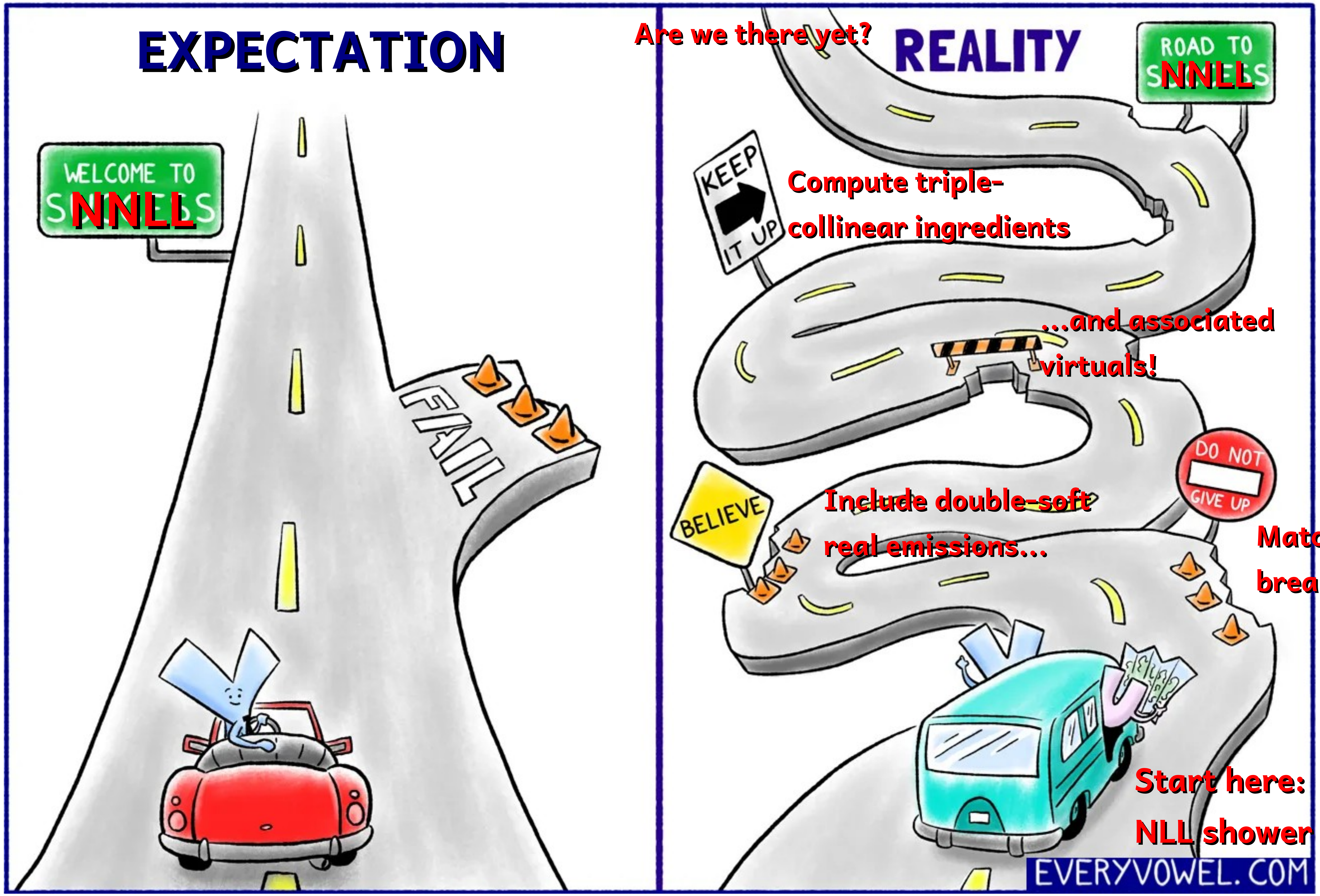


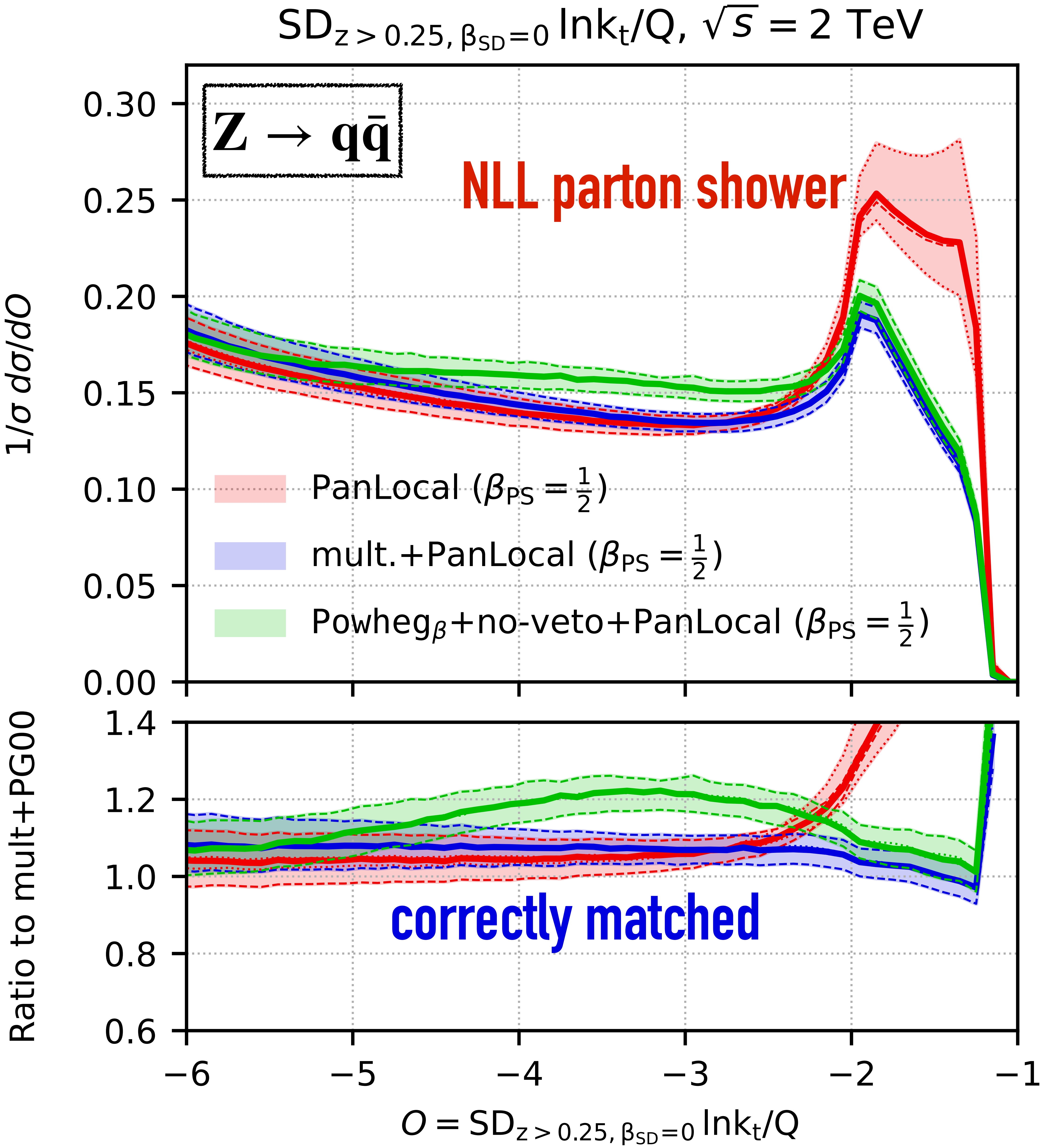
Figure from Alexander Karlberg

Matching and Logarithmic Accuracy

➤ **NLO matching** is necessary for NNLL accuracy

$$\Sigma_{\text{NLO}} = \Sigma_{\text{LO}}(1 + \alpha_s \Delta_{\text{NLO}} + \ldots)$$

$$\Sigma_{\text{NNLL}} = \exp\left(L g_{\text{LL}}(\alpha_s L) + g_{\text{NLL}}(\alpha_s L) + \alpha_s g_{\text{NNLL}}(\alpha_s L)\right)$$



[Hamilton, Karlberg, Salam, Scyboz, Verheyen, 2301.09645]

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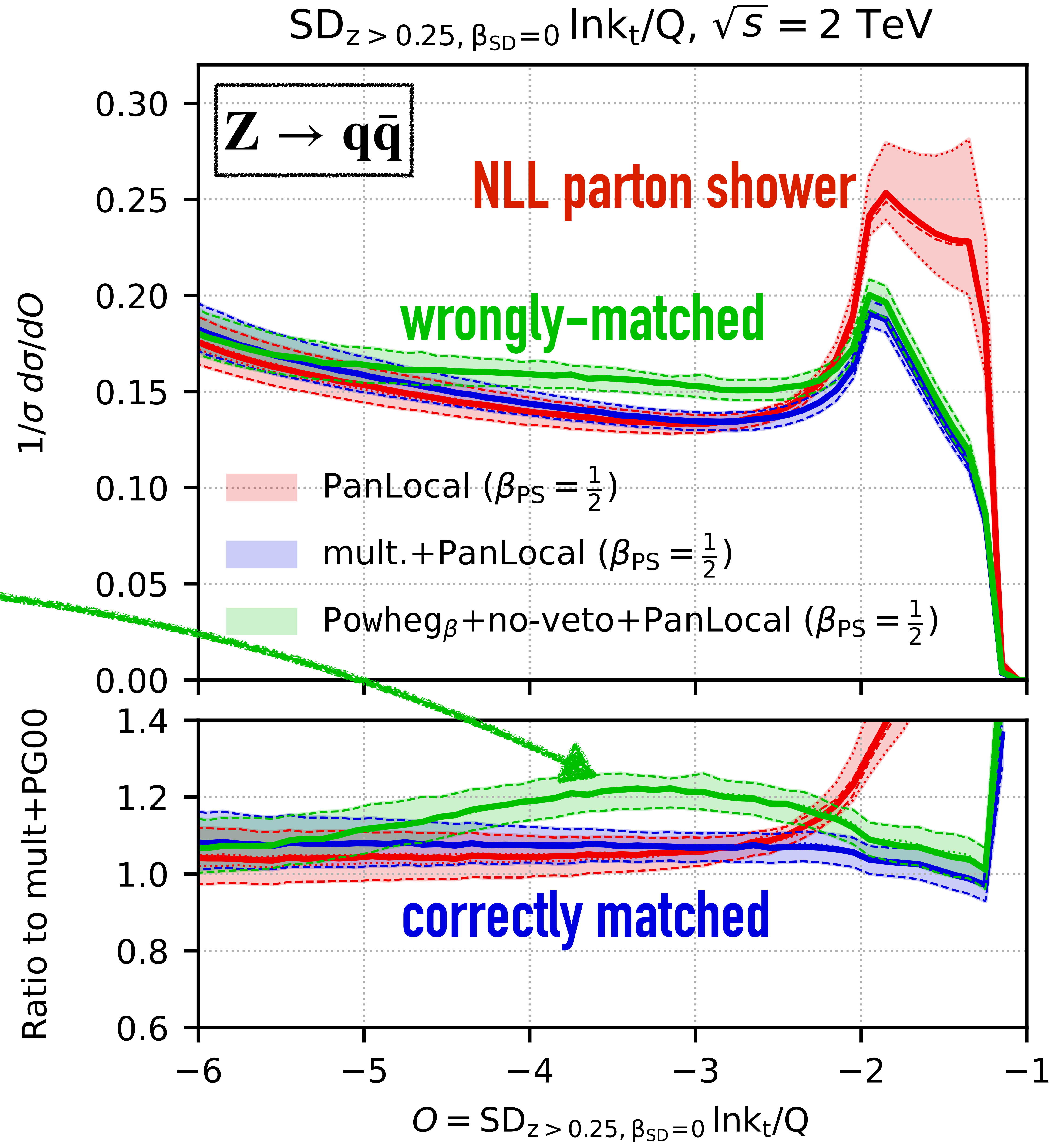
➤ But it could instead **downgrade the NLL accuracy** of the shower

e.g. Soft Drop

$$\partial_L \Sigma_{\rm SD}(L) = \bar\alpha c\, e^{\bar\alpha c L - \bar\alpha \Delta} - 2\bar\alpha L e^{-\bar\alpha L^2}(1 - e^{-\bar\alpha \Delta})$$



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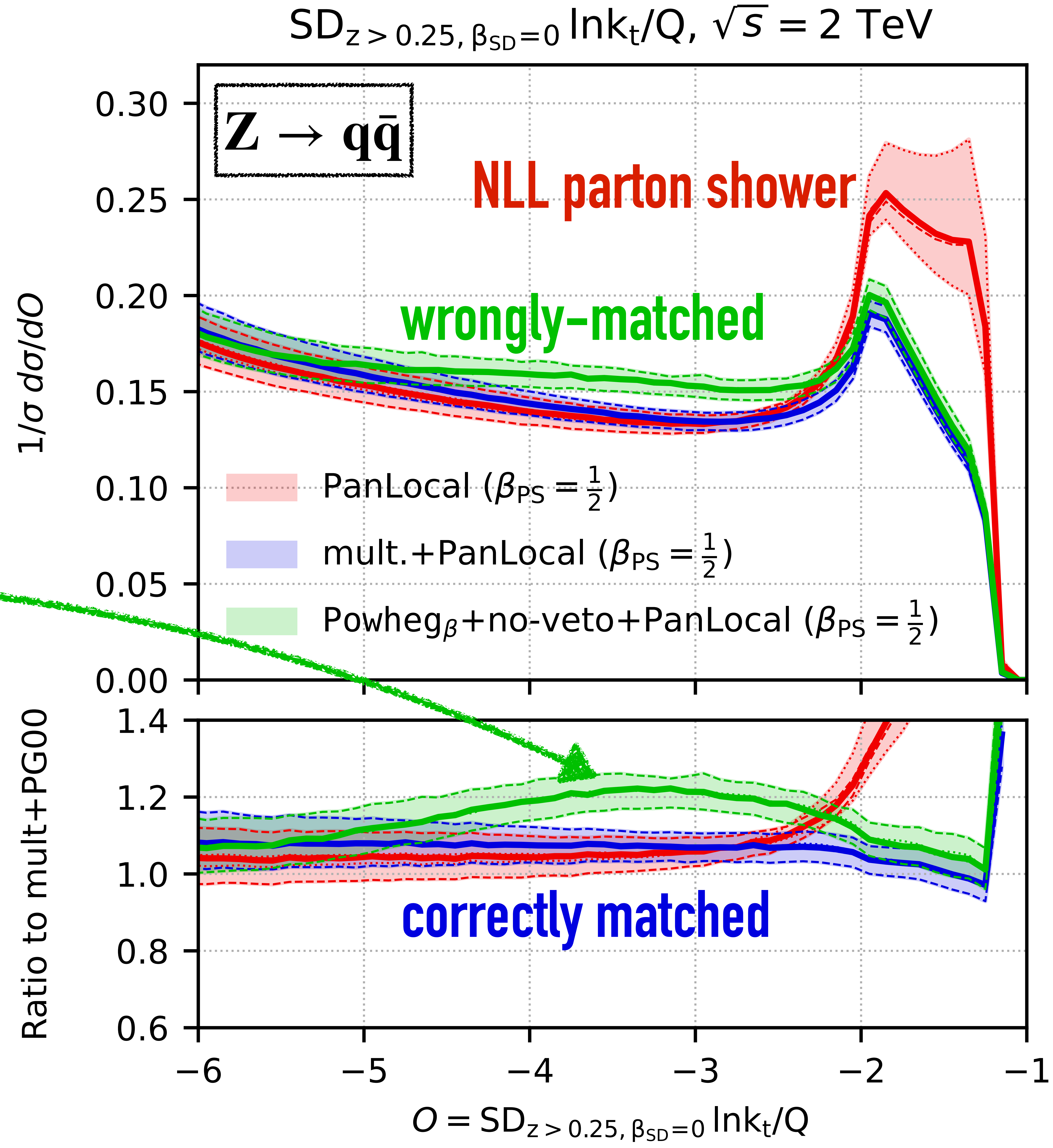
General strategy for NLO matching with NLL showers for generic processes **still missing**!



[Hamilton, Karlberg, Salam, Scyboz, Verheyen, 2301.09645]

How to go **beyond NLL** in a parton shower?

[**SFR**, Hamilton, Karlberg, Salam, Scyboz, Soyez 2307.11142]

Focus on soft emissions

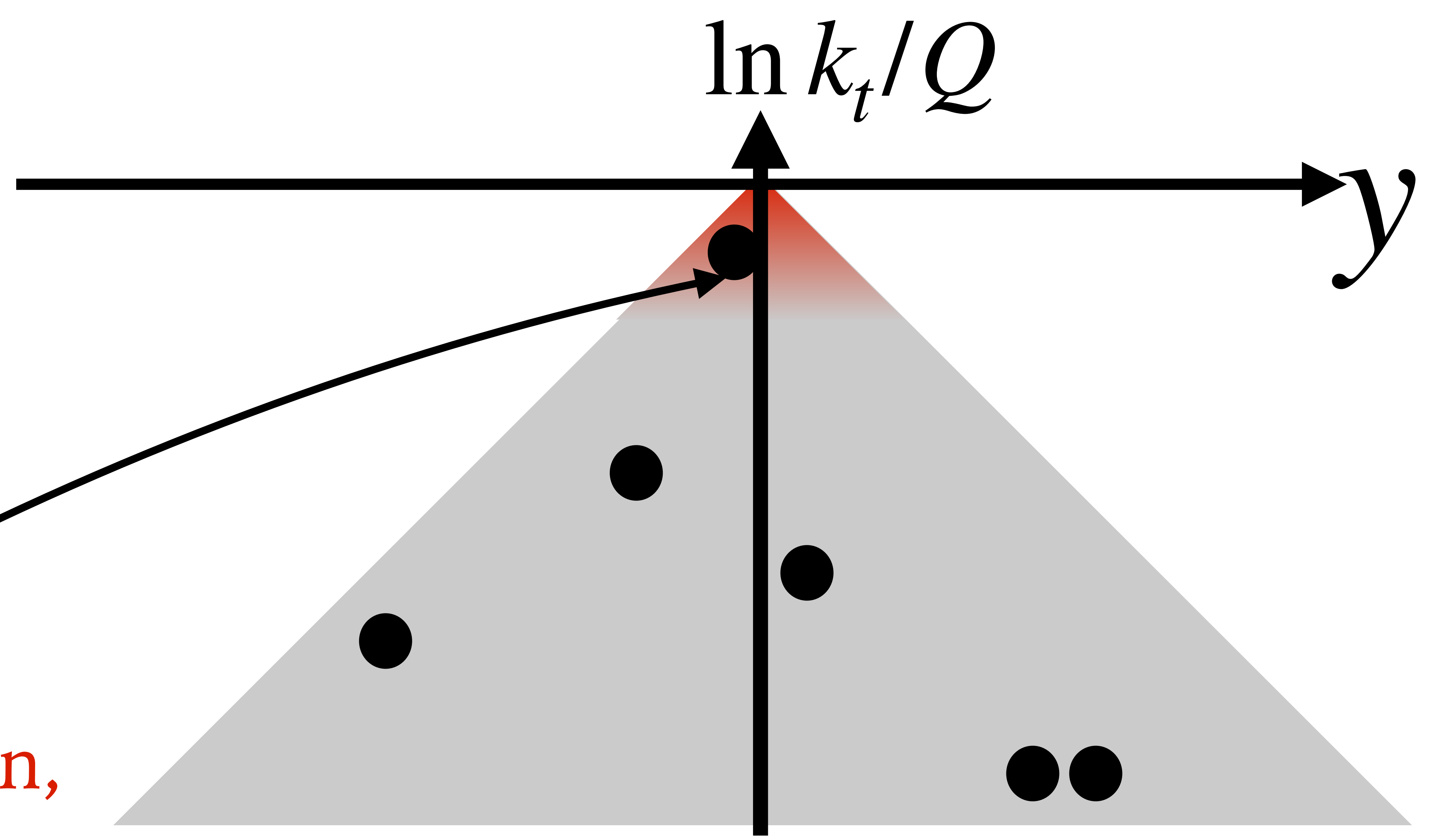
NLL

- ✓ **Soft-collinear** emsns at **NLO**
- ✓ **Soft** (large angle) emsns at **LO**
- ✓ Correct rate for **pair of emsns** separated only in **one Lund coordinate**

NNLL

- ✓ **Hard** emissions at **LO**

[Hamilton, Karlberg, Scyboz, Salam, Verheyen, 2301.09645]



How to go **beyond NLL** in a parton shower?

[**SFR**, Hamilton, Karlberg, Salam, Scyboz, Soyez 2307.11142]

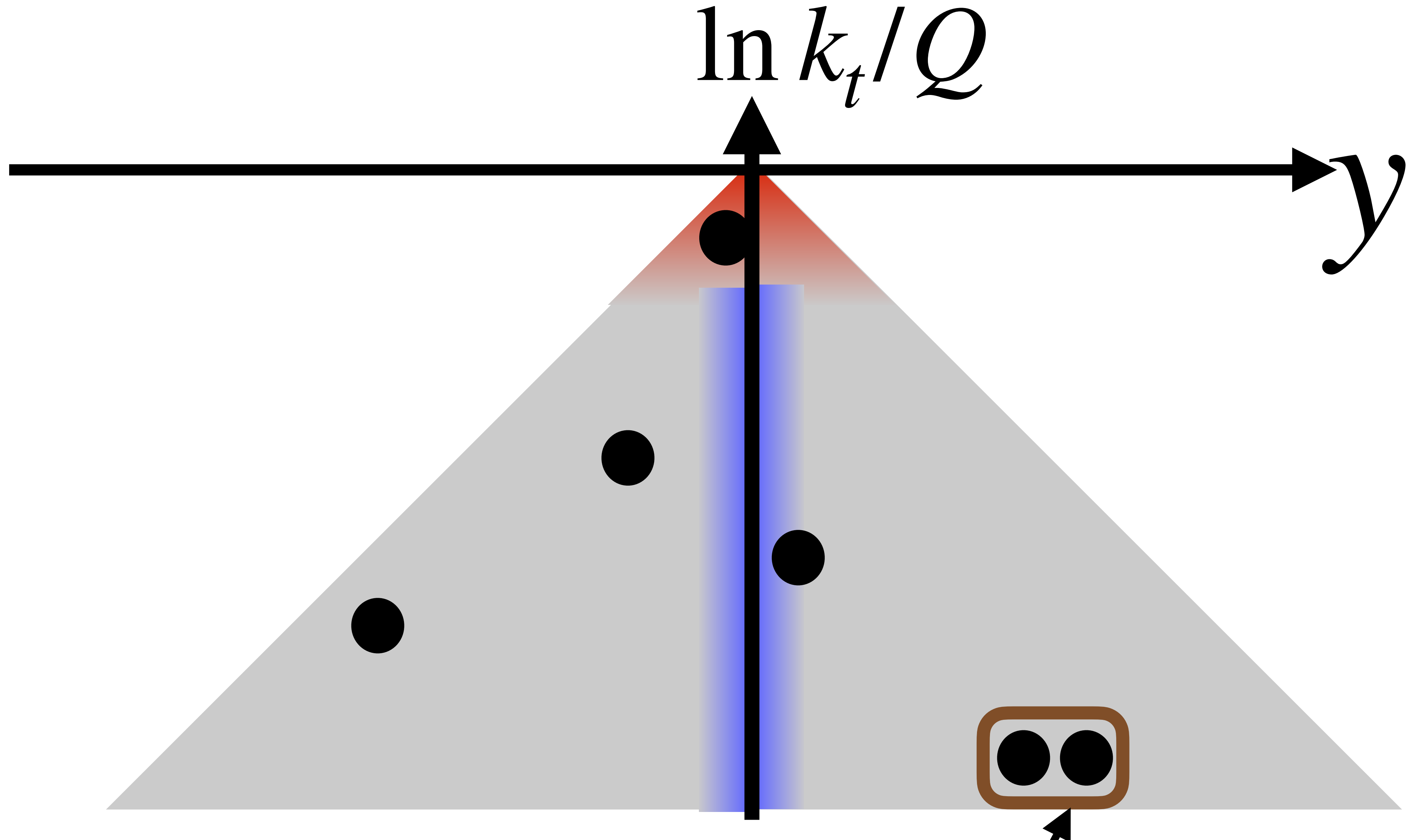
Focus on soft emissions

NLL

- ✓ Soft-collinear emsns at NLO
- ✓ Soft (large angle) emsns at LO
- ✓ Correct rate for pair of emsns separated only in **one Lund coordinate**

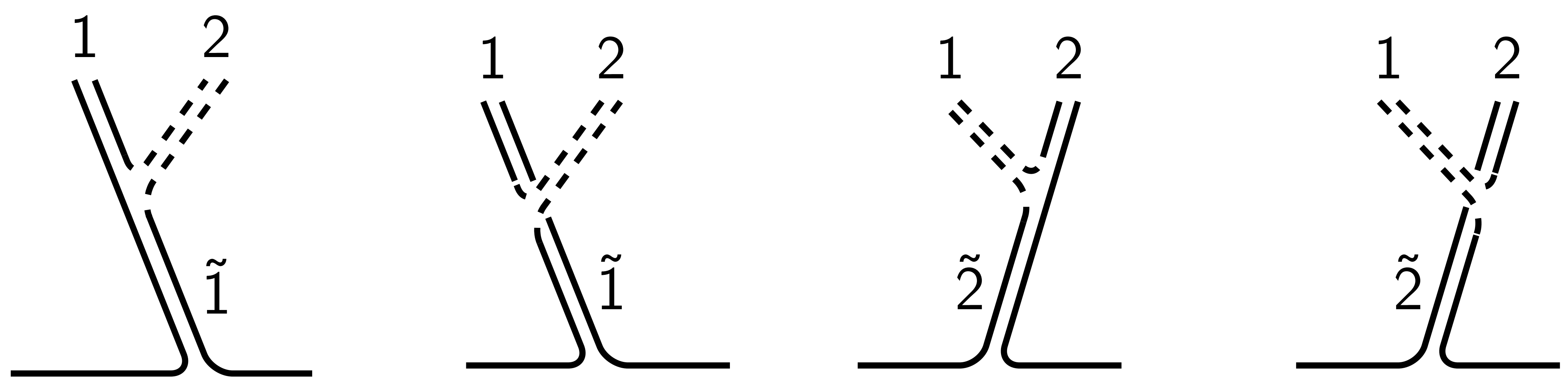
NNLL

- ✓ Hard emissions at LO
- ✓ Soft (large angle) emsns at NLO
- ✓ Correct rate for pair of emsns **close in the Lund plane**



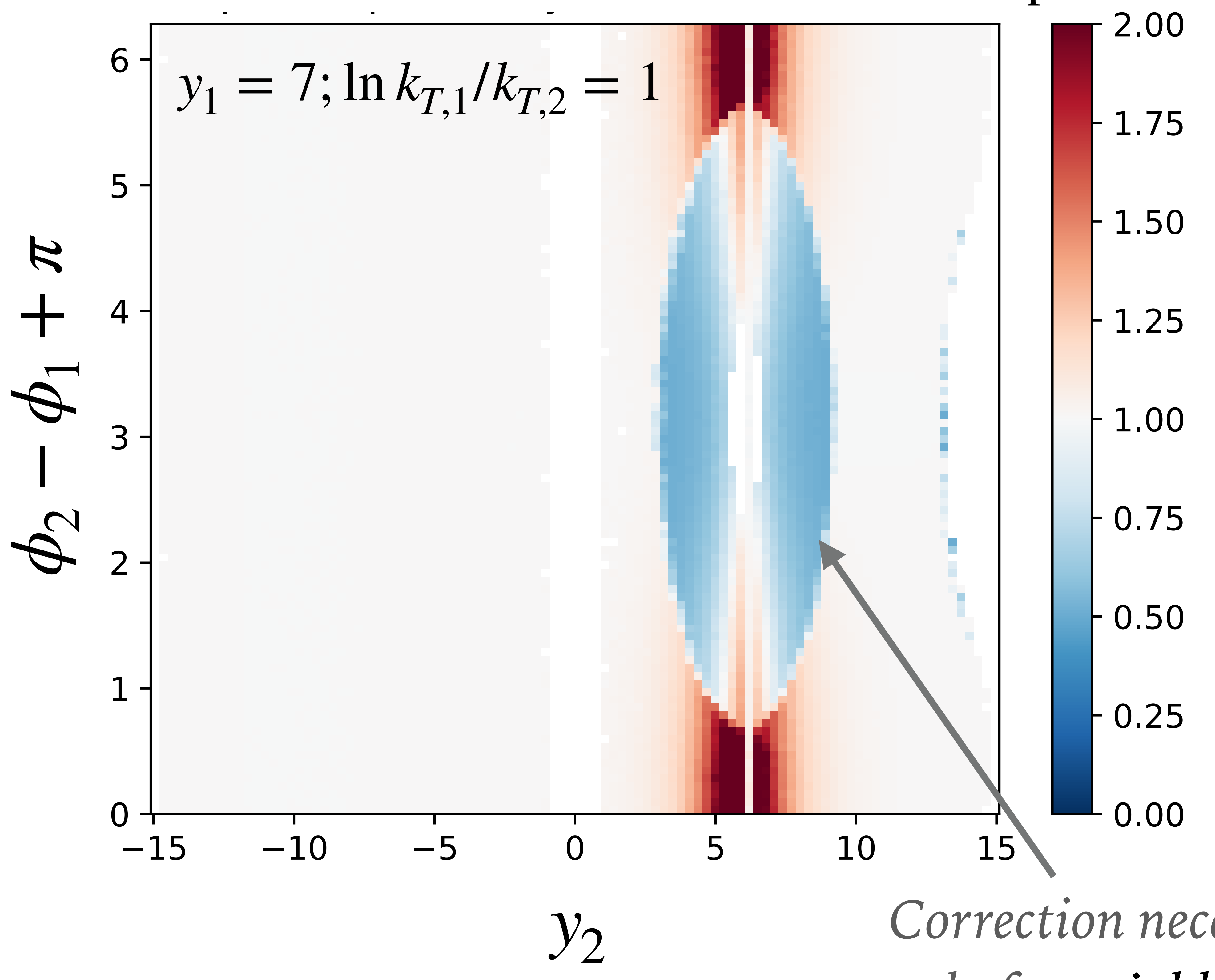
NB: **Vincia** and **Sherpa** groups have also explored inclusion of the double-soft current; novelty here is doing so to reach NNLL

Correct rate for **pairs** or soft emissions



- a given two-emission configuration can come from several shower histories
- **accept a given emission with exact double-soft $M^{(\mathrm{DS})}_{\mathrm{exact}}$ divided by shower's effective double-soft matrix element** summed over the histories h that could have produced that configuration

Double-soft acceptance P_{accept}



Correction necessary only for **neighbouring emsn** *as the shower is already NLL*

$$P_{\mathrm{accept}} = \frac{M^{(\mathrm{DS})}_{\mathrm{exact}}}{\sum_h M^{(\mathrm{DS})}_{h,\mathrm{PS}}}$$

How to go **beyond NLL** in a parton shower?

[**SFR**, Hamilton, Karlberg, Salam, Scyboz, Soyez 2307.11142]

Focus on soft emissions

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- ✓ **Soft-collinear** emsns at **NLO**
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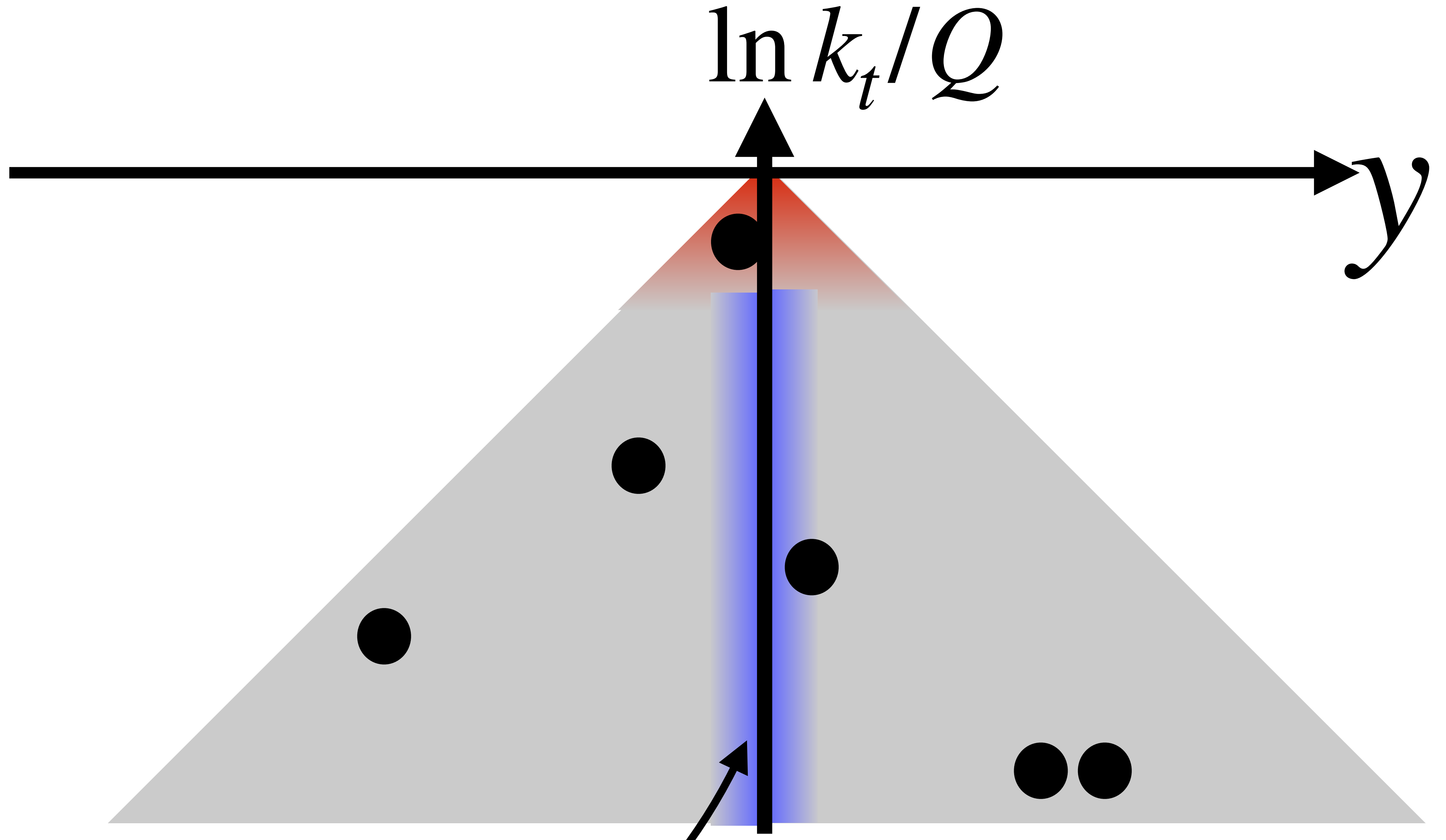
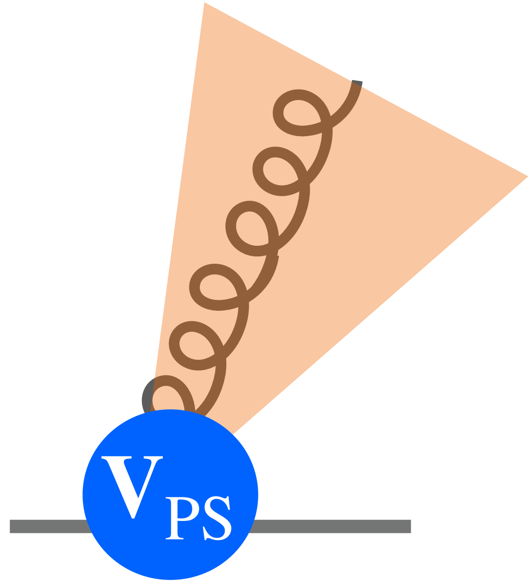
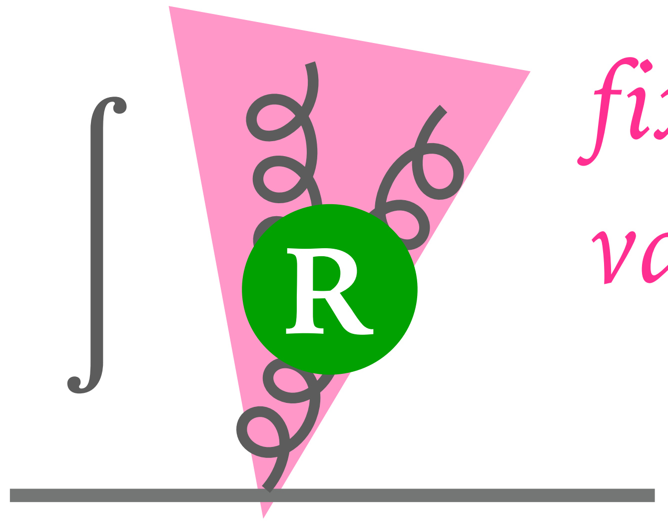


Virtual corrections for soft emissions

Parton shower unitarity ensures



$$= \frac{\alpha_s}{2\pi} K_1 \; - \int$$

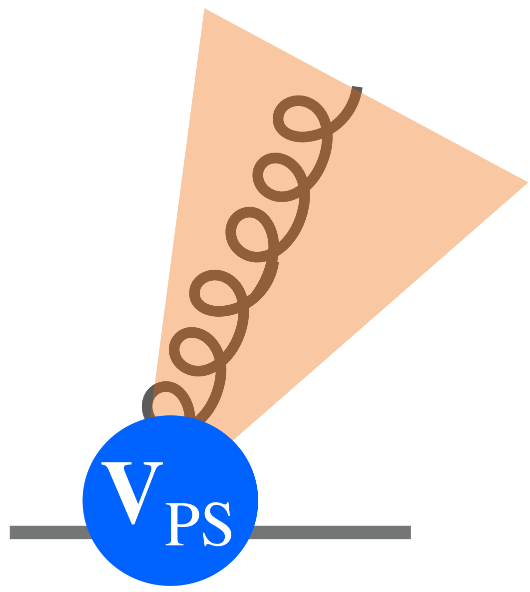


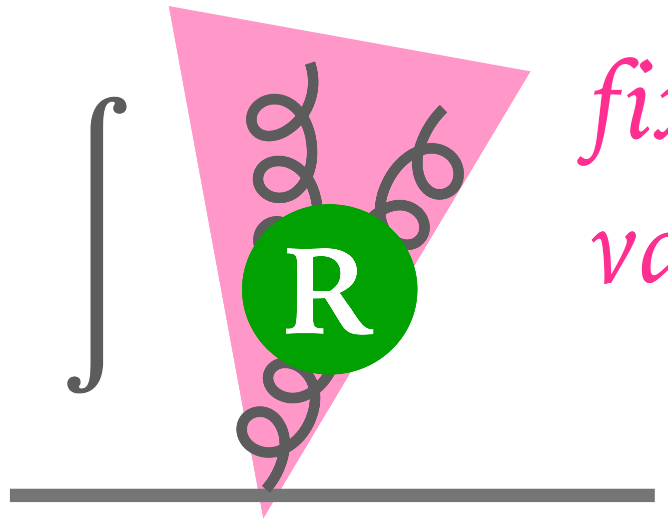
fixed "shower variables"

but analytic resummation tells we need the integral at **fixed rapidity and k_t**!

Virtual corrections for soft emissions

Parton shower unitarity ensures



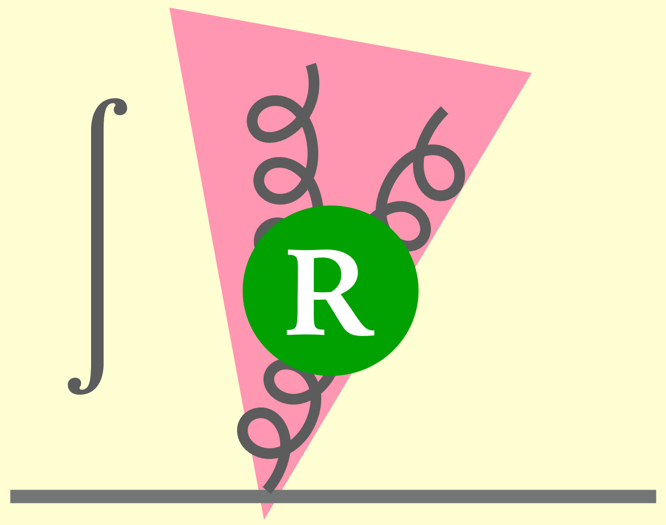
$= \frac{\alpha_s}{2\pi} K_1 \; - \int$


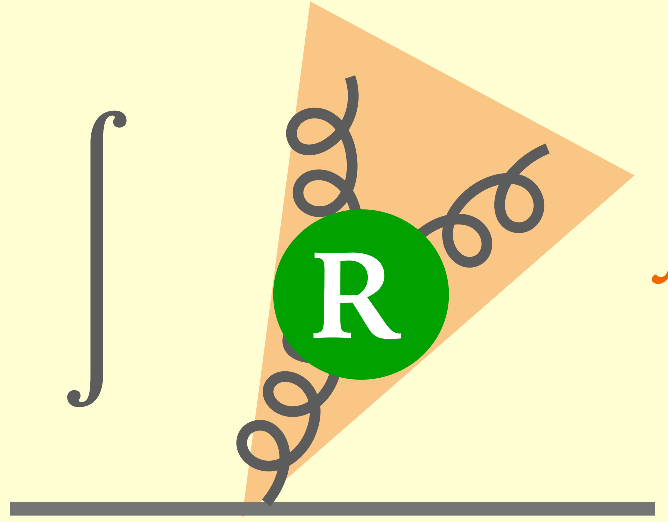
fixed "shower variables"

but analytic resummation tells we need the integral at **fixed rapidity and k_t**!

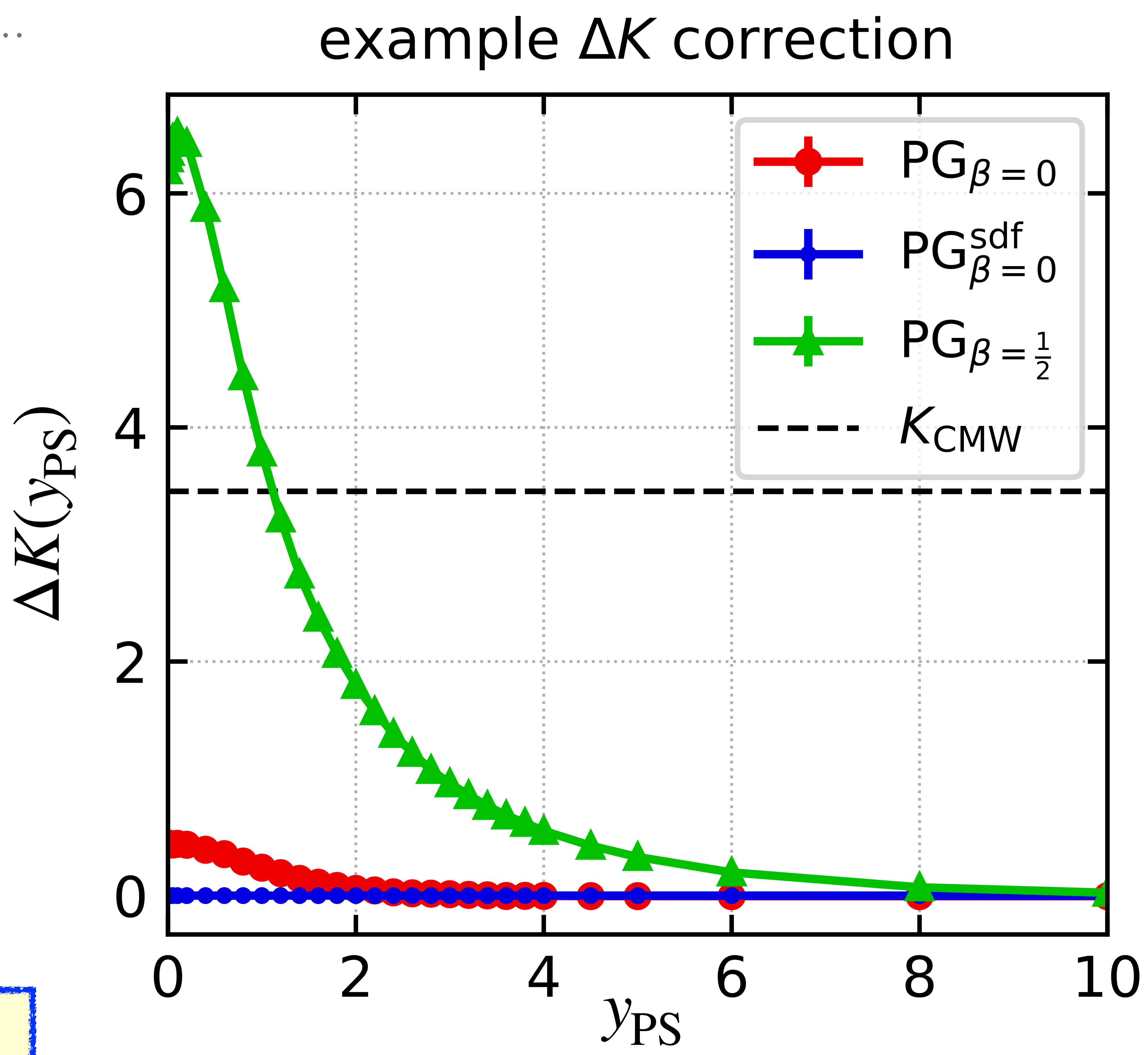
$$K_1^{PS} = K_1 + \Delta K(\Phi_{PS}^{(1)})$$

fixed "shower variables"

$\frac{\alpha_s}{2\pi} \Delta K(\Phi_{PS}^{(1)}) = \int$


$- \int$


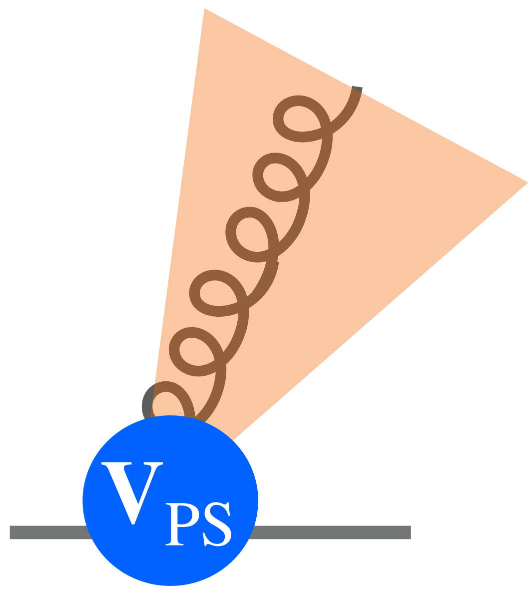
$y, p_\perp$ fixed



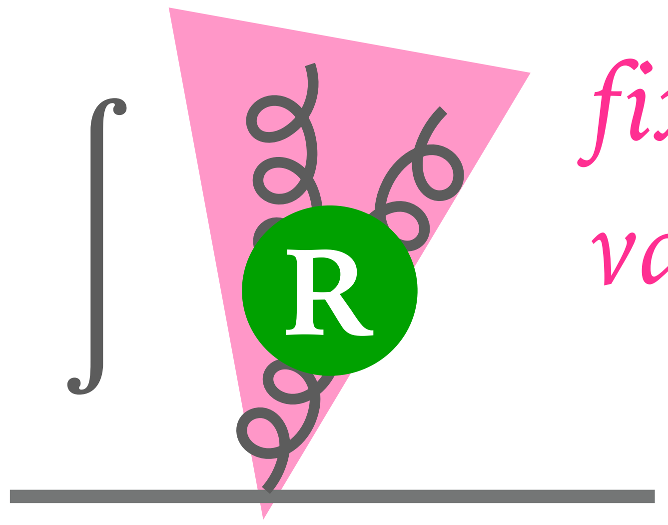
ΔK vanishes for large rapidities since virtual corrections to soft-collinear emissions are OK for NLL showers

Virtual corrections for soft emissions

Parton shower unitarity ensures



$= \frac{\alpha_s}{2\pi} K_1 - \int$



fixed "shower variables"

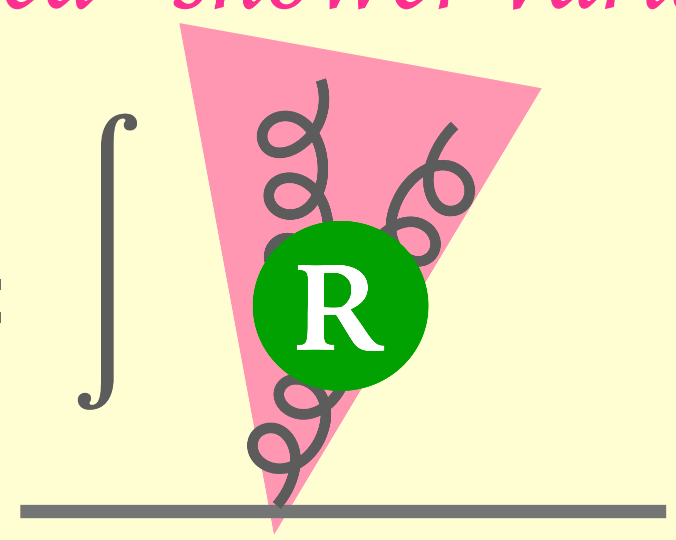
but a

integ

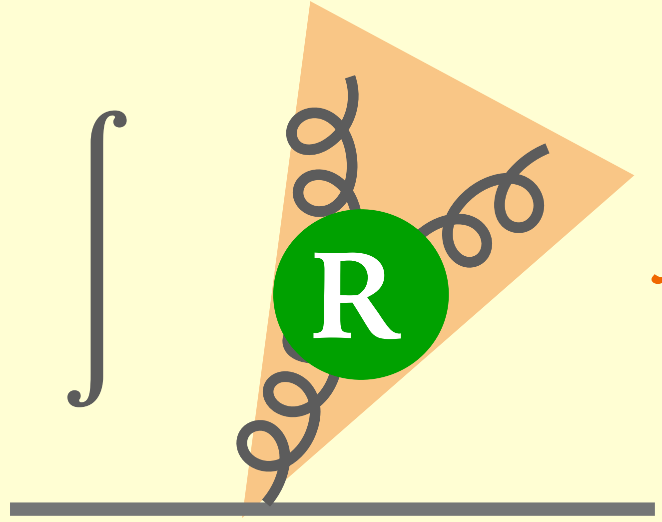
Augmenting the order of the splitting function used is not sufficient to achieve superior logarithmic accuracy: one first needs to remove the mistakes a shower is making at a given order!

fixed "shower variables"

$$\frac{\alpha_s}{2\pi}\Delta K(\Phi^{(1)}_{PS}) = \int$$

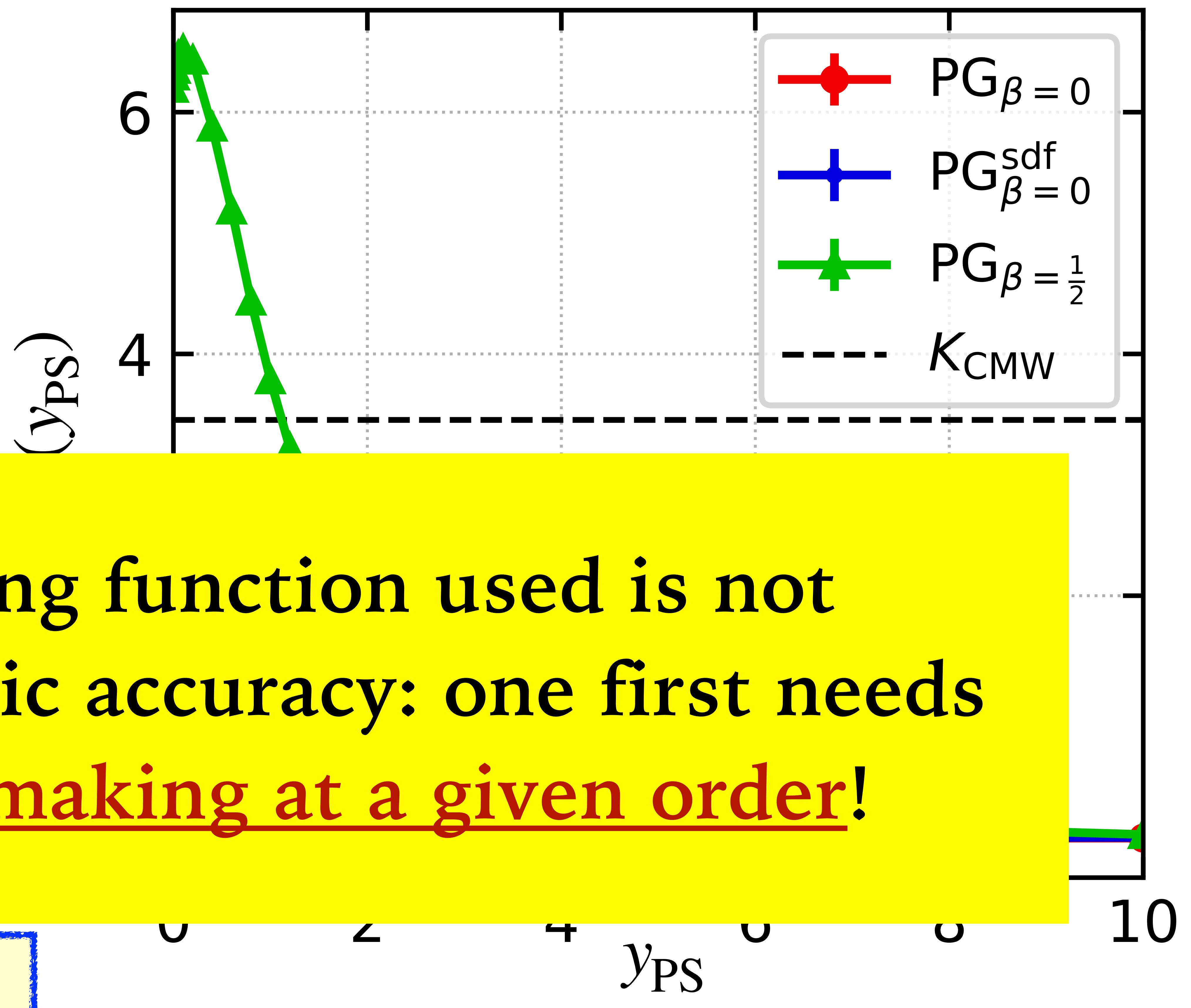


$- \int$



$y, p_\perp$ fixed

example ΔK correction

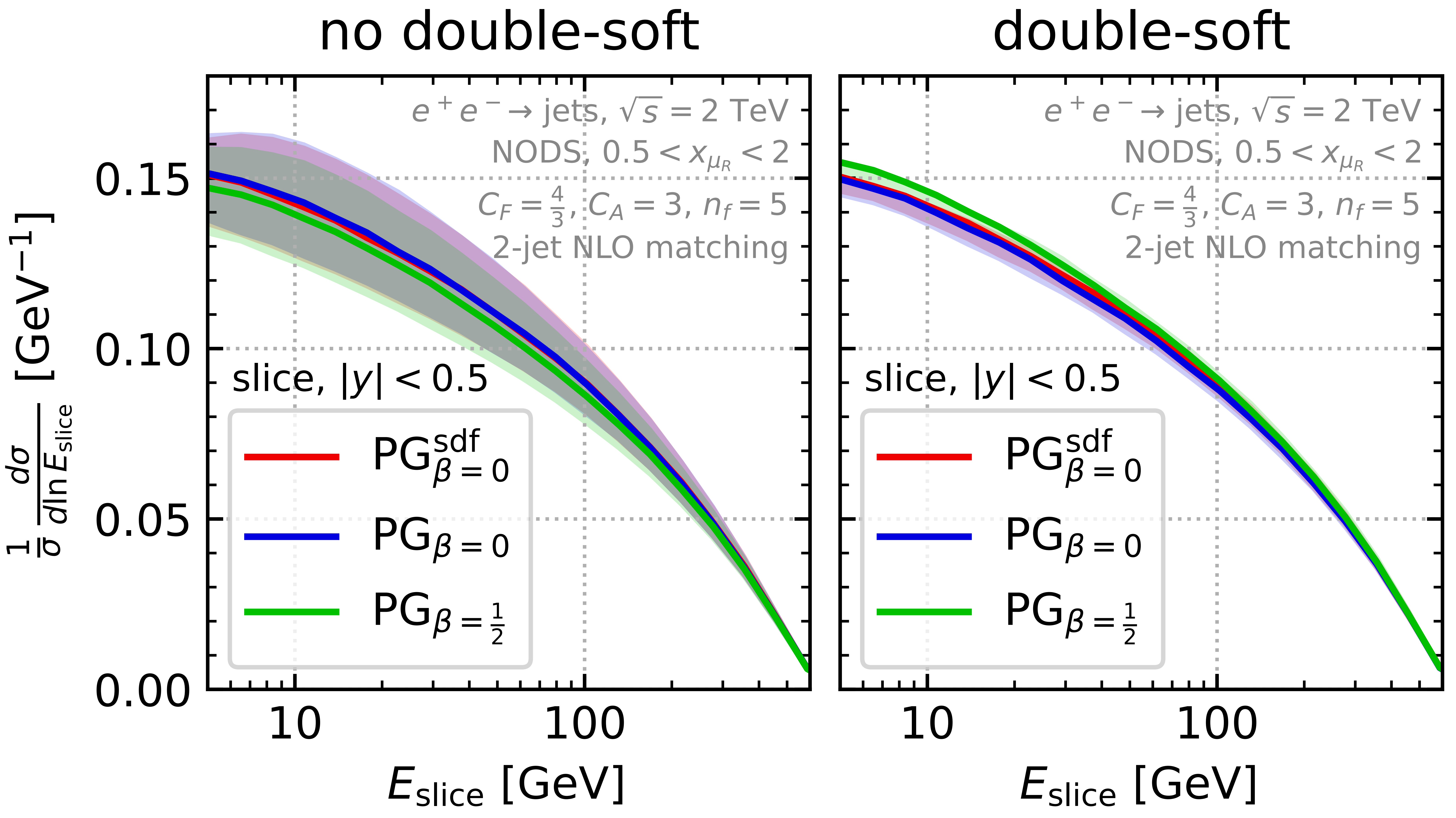


ΔK vanishes for large rapidities since virtual corrections to soft-collinear emissions are OK for NLL showers

Non-global observables at “NNLL”

S.F.R., Hamilton, Karlberg, Salam, Scyboz, Soyez
2307.11142

- Energy flow in slice between two 1 TeV jets
- First time non-global obs is known at **Next-to-Single Logs** (at leading N_c) including the **full n_f dependence**
- **Double-soft reduces uncertainty band**



Uncertainty here is estimated varying the renormalisation scale

$$\alpha_s^{\mathrm{CMW}}(k_t; x_R) = \alpha_s(x_R k_t)\left(1 + \frac{\alpha_s(x_R k_t)}{2\pi}(K_{\mathrm{CMW}} + \Delta K(\Phi)) + 2\alpha_s(x_R k_t) b_0 (1-z) \ln x_R\right)$$

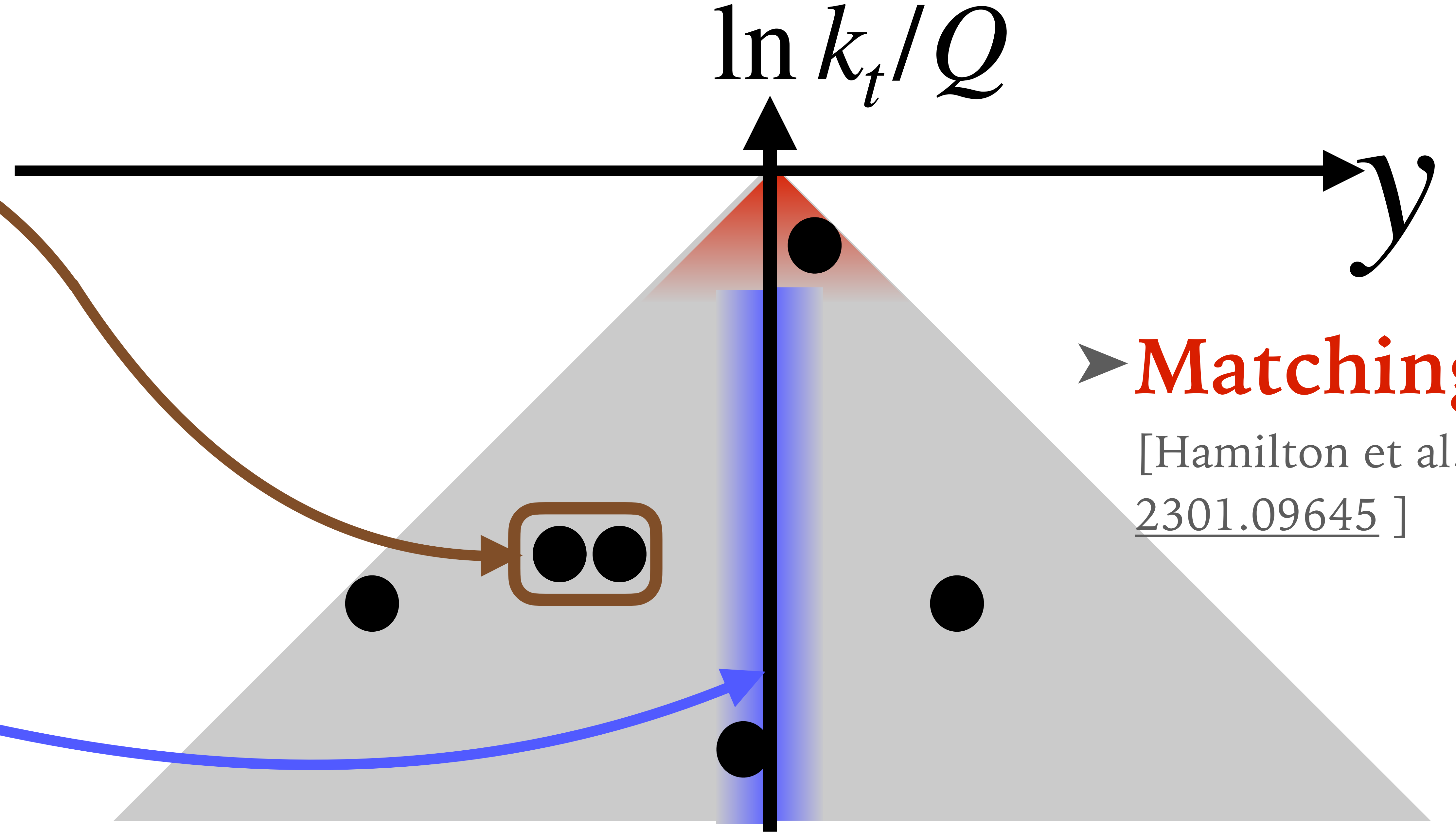
Building a **NNLL** shower

SFR et al, 2307.11142

- **Double-soft "reweighting"** for neighbouring soft-collinear emsns
- NLO corrections for soft, large-angle emissons

$$\alpha_s^{\text{eff}}(k_t) = \alpha_s(k_t)\left(1 + \frac{\alpha_s(k_t)}{2\pi}(K_1 + \Delta K_1)\right)$$

Catani, Marchesini, Webber, '91



- **Matching**

[Hamilton et al. 2301.09645]

Building a **NNLL** shower

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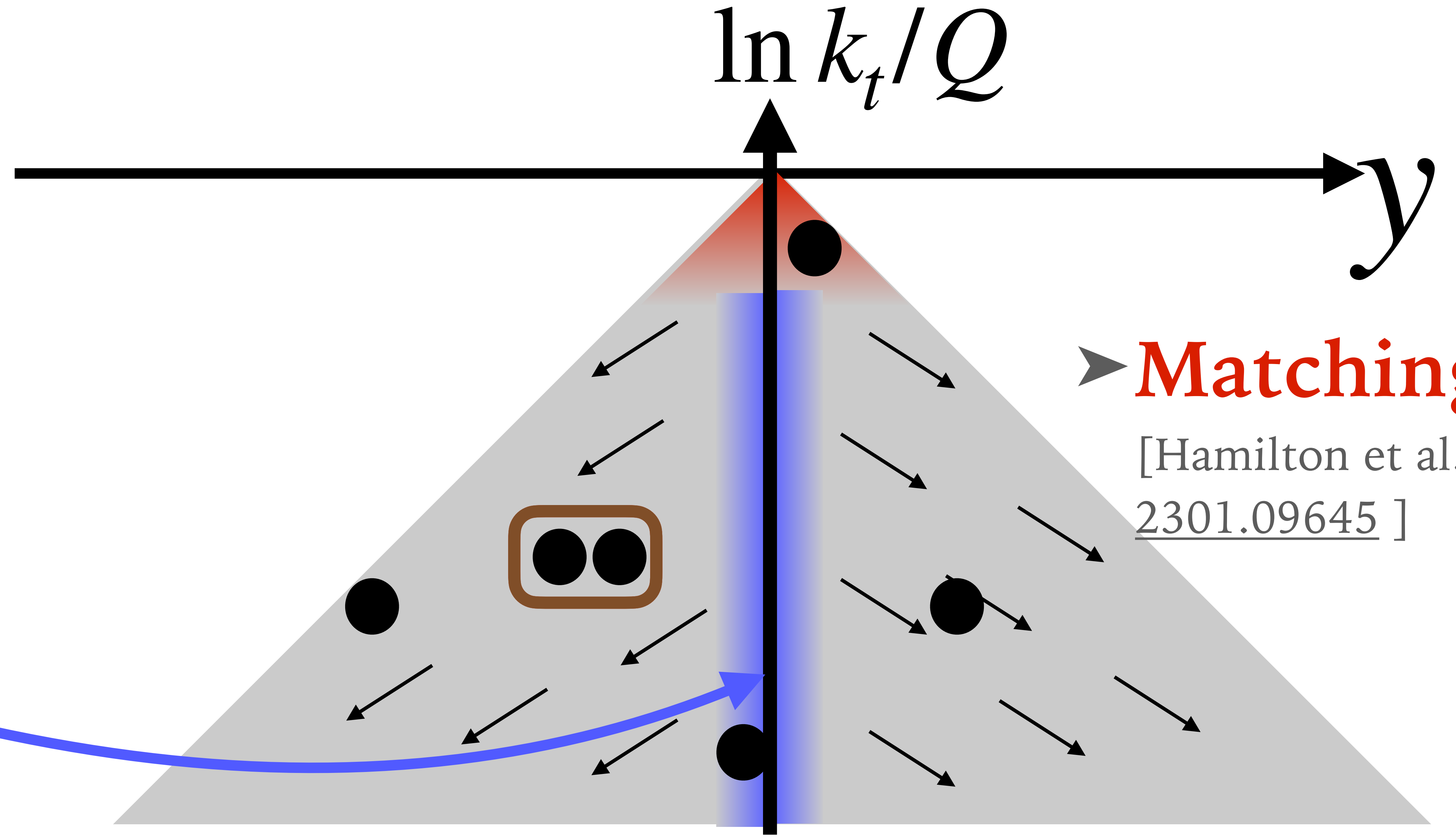

- **Matching** [Hamilton et al. 2301.09645]

Drift in rapidity *of an emission when it further branches*

$$\int 2C_F d\eta \Delta K_1(\eta) \propto \langle \Delta y \rangle$$

$\Rightarrow$ ***correct the shower mistake***

Building a **NNLL** shower

SFR et al, 2307.11142

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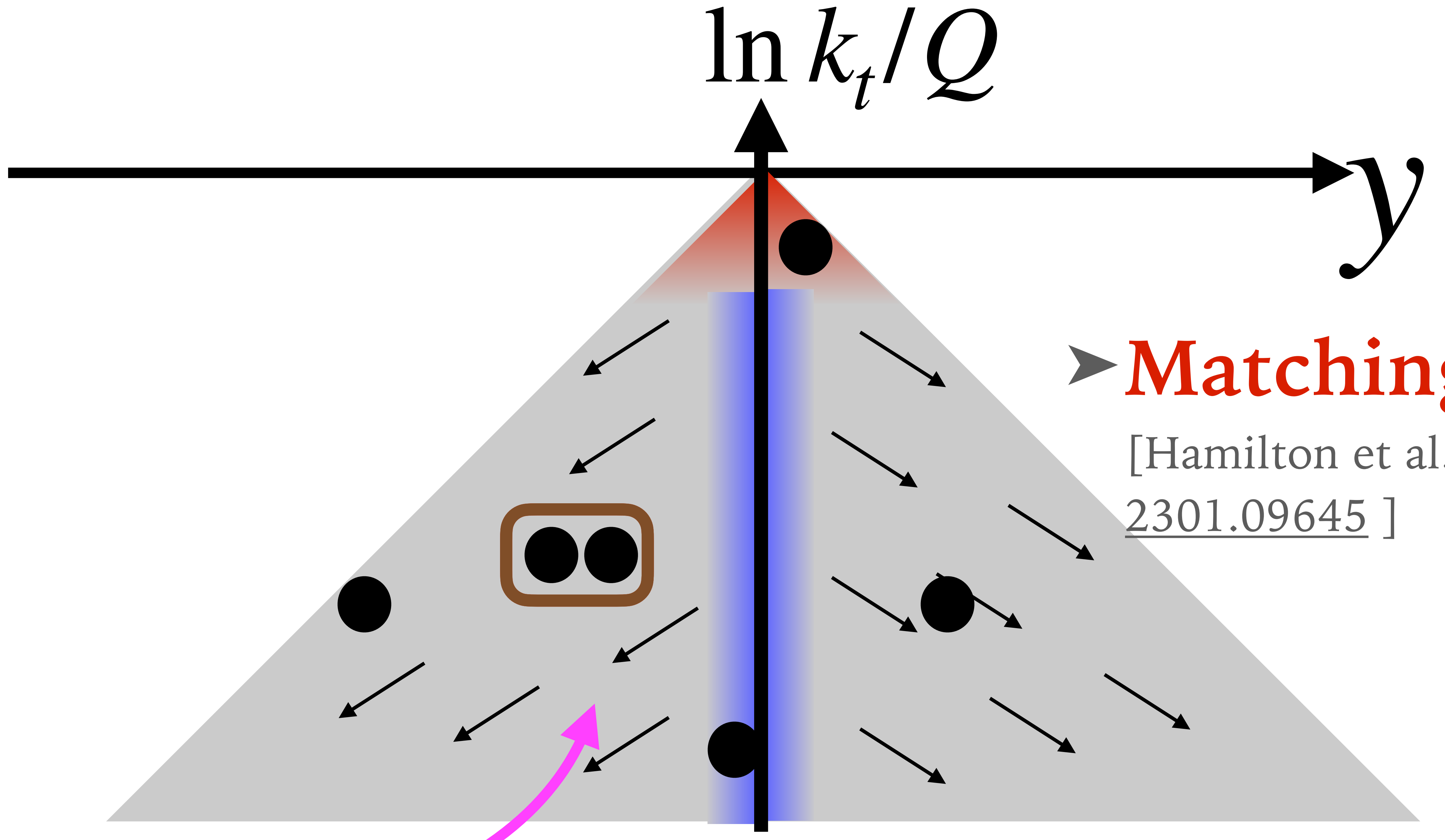
- **<u>NNLO corrections</u>** for **soft-collinear emsns**

$$\alpha_s^{\rm eff}(k_t) = \alpha_s(k_t)\left(\ldots + \frac{\alpha_s^2(k_t)}{4\pi^2}(K_2 + \Delta K_2)\right)$$

Banfi, El-Menoufi, Monni, 1807.11487



- **Matching** [Hamilton et al. 2301.09645]

<u>Drift in $\ln k_t$</u> *of an emission when it further branches*

$$\Delta K_2 \propto \beta_0 \langle \Delta \ln k_t \rangle$$

$\Rightarrow$ ***correct the shower mistake***

At this accuracy, it is sufficient to get the average

Building a **NNLL** shower

SFR et al, 2307.11142

- **Double-soft "reweighting"** for neighbouring soft-collinear emsns
- NLO corrections for soft, large-angle emissons

$$\alpha_s^{\rm eff}(k_t) = \alpha_s(k_t)\left(1 + \frac{\alpha_s(k_t)}{2\pi}(K_1 + \Delta K_1)\right)$$

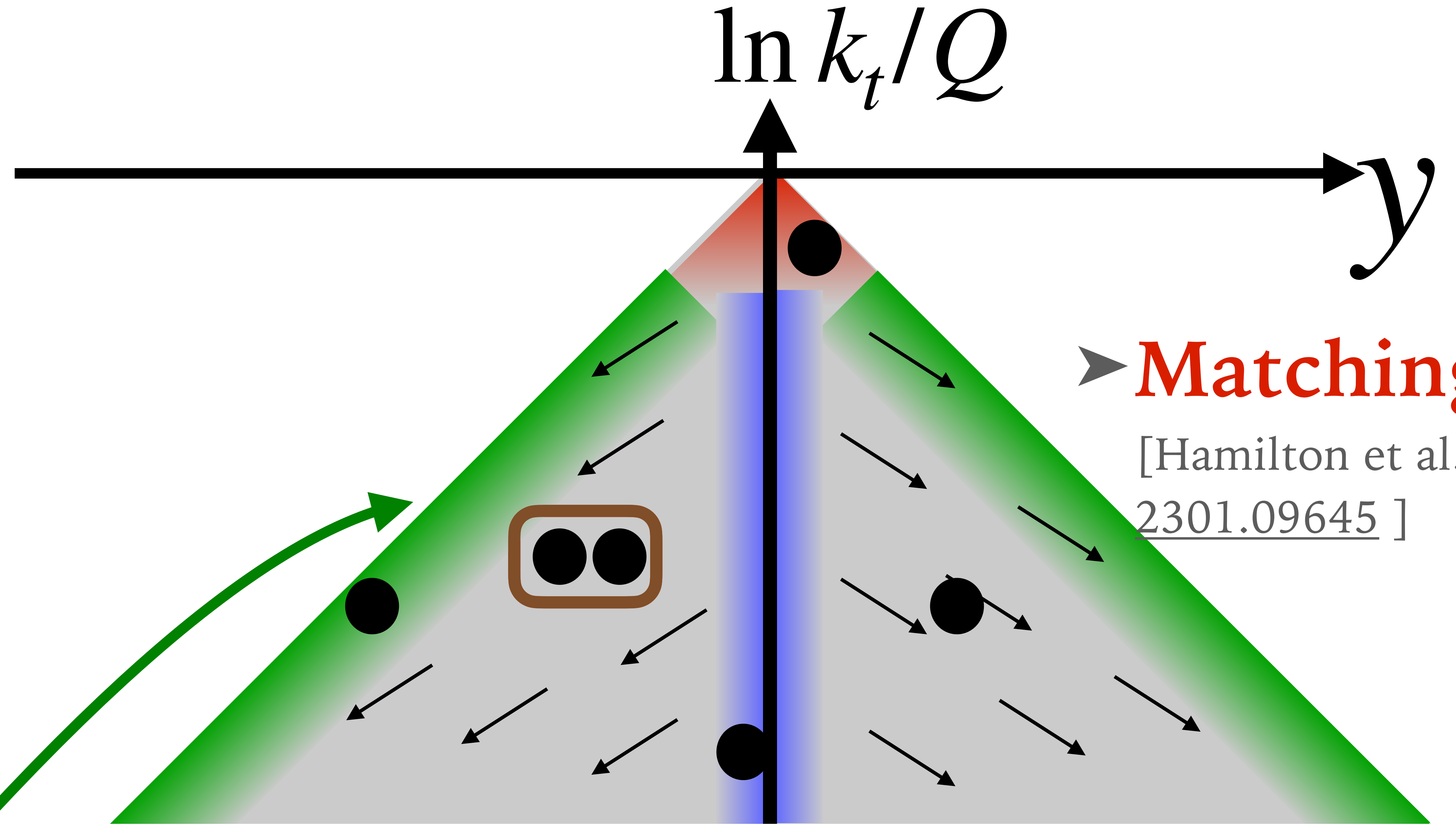
- **<u>NNLO corrections</u>** for **soft-collinear emsns**

$$\alpha_s^{\rm eff}(k_t) = \alpha_s(k_t)\left(\ldots + \frac{\alpha_s^2(k_t)}{4\pi^2}(K_2 + \Delta K_2)\right)$$

- **<u>NLO corrections</u>** for **collinear emsns**

$$d\mathscr{P}_{\rm coll} \propto P(z)\left(1 + \frac{\alpha_s}{2\pi}\left(B_2(z) + \Delta B_2(z)\right)\right)$$

Dasgupta, El-Menoufi 2109.07496,
+van Beekveld, Helliwell, Monni 2307.15734,
++Karlberg 2402.05170



- **Matching** [Hamilton et al. 2301.09645]

<u>Drift in $\ln z = \ln k_t + y$</u> *of an emission when it further branches*

$$\int P(z)dz\Delta B_2(z) \propto -\langle \Delta z \rangle$$

$\Rightarrow$ ***correct the shower mistake***

At this accuracy, it is sufficient to get the integral right, not the functional form of $\Delta B_2(z)$

Building a **NNLL** shower

A new standard for the logarithmic accuracy of parton showers

Melissa van Beekveld,[1] Mrinal Dasgupta,[2] Basem Kamal El-Menoufi,[3] Silvia Ferrario Ravasio,[4] Keith Hamilton,[5] Jack Helliwell,[6] Alexander Karlberg,[4] Pier Francesco Monni,[4] Gavin P. Salam,[6,7] Ludovic Scyboz,[3] Alba Soto-Ontoso,[4] and Gregory Soyez[8]

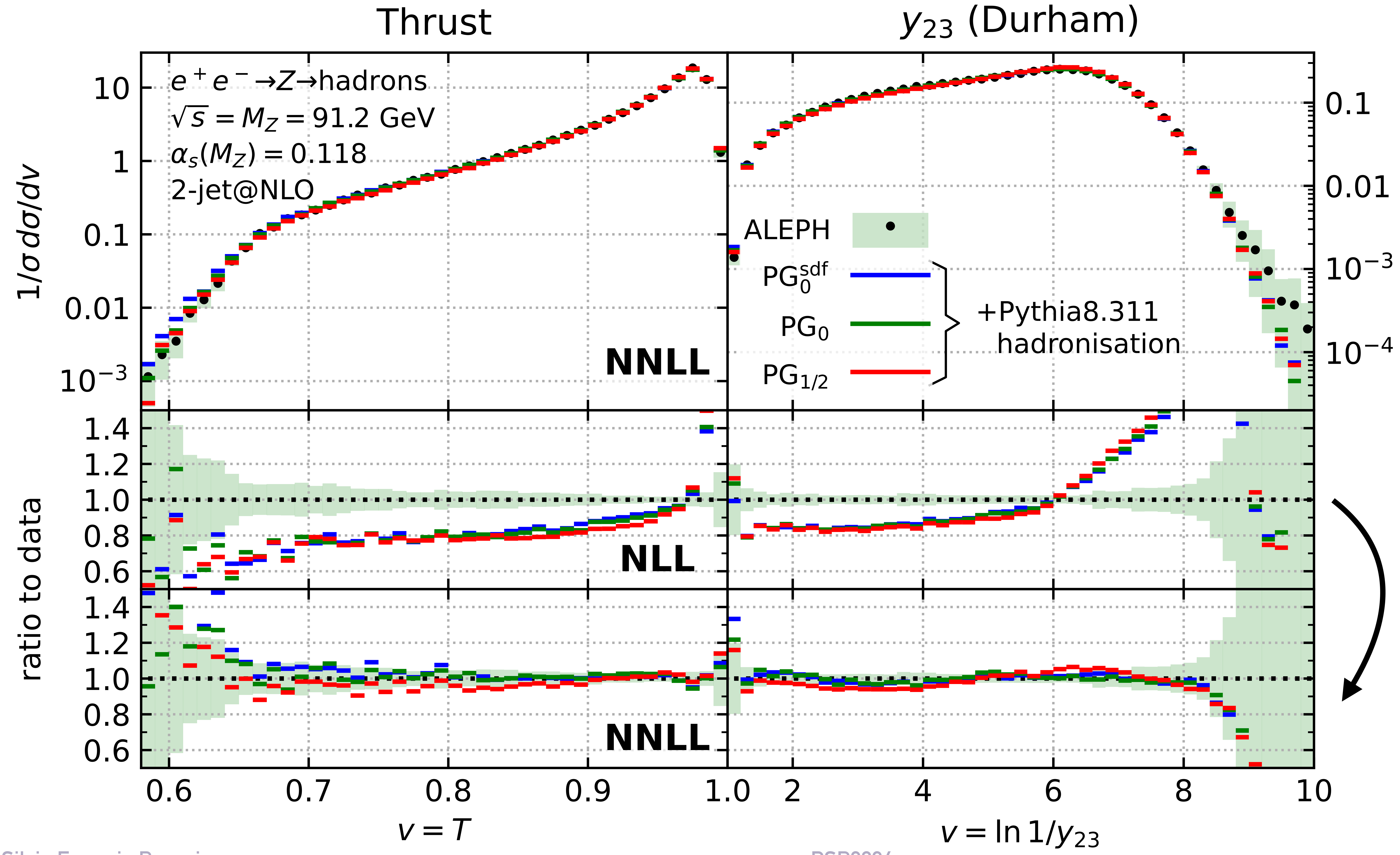
We report on a major milestone in the construction of logarithmically accurate final-state parton showers, achieving next-to-next-to-leading-logarithmic (NNLL) accuracy for the wide class of observables known as event shapes. The key to this advance lies in the identification of the relation between critical NNLL analytic resummation ingredients and their parton-shower counterparts. Our analytic discussion is supplemented with numerical tests of the logarithmic accuracy of three shower variants for more than a dozen distinct event-shape observables in two final states. The NNLL terms are phenomenologically sizeable, as illustrated in comparisons to data.

2406.02661

Dasgupta, El-Menoufi 2109.07496,
+van Beekveld, Helliwell, Monni 2307.15734,
++Karlberg 2402.05170

... to get the integral ... functional form of $\Delta B_2(z)$

NNLL showers vs NLL showers: pheno outlook



The PanScales collaboration, *2406.02661*

Agreement to **data substantially better** when using **NNLL** showers

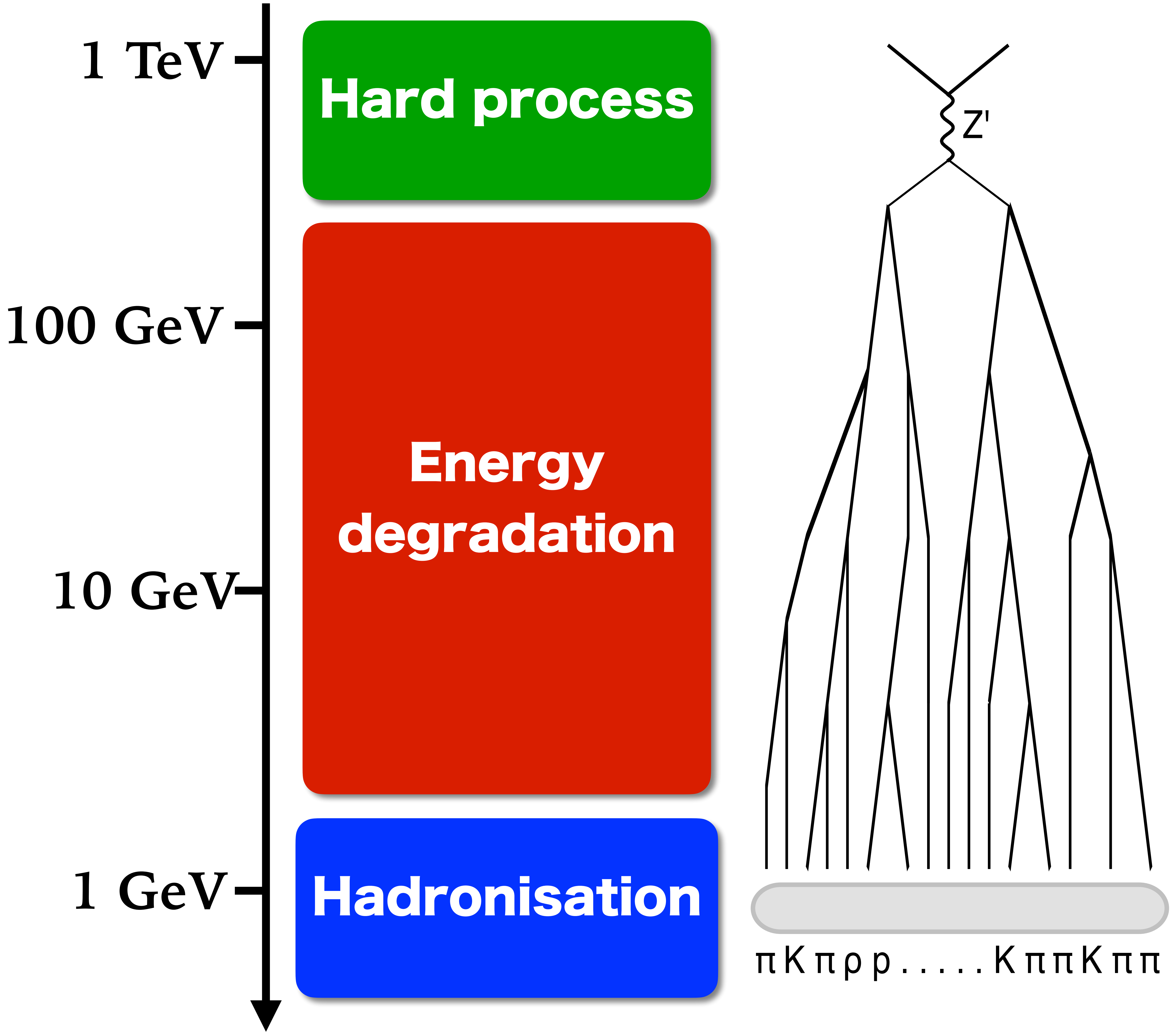
Conclusions

- Collider phenomenology critically relies on **Parton Showers**
- Parton Showers can be considered highly flexible **resummation tools**
- The logarithmic accuracy of **analytic resummations** is (almost always) ahead of the parton shower one: precious input to boost current showers
- Recent **paradigm shift** in the shower community with many **NLL showers** appearing
- Current focus: getting NLL showers ready for **phenomenology** (masses, matching, generic processes), as well as going **beyond NLL**
- Combining **fixed order and logarithmic accuracy** is still an open issue
- QCD showers the current bottleneck at the LHC, but let's not forget about **QED and EW**, relevant for precise EW measurements and the FCC
- In this talk I focused on the semi-classical approach, but **amplitude-level evolution** (CVolver [Forshaw, Plätzer, Sjödahl, Holguin + …], and Deductor [Nagy, Soper]) will certainly offer advantages in terms of colour and spin handling, so stay tuned!

Backup

Shower Monte Carlo event generators

Shower Monte Carlo Event Generators = **default tool** for interpreting collider data

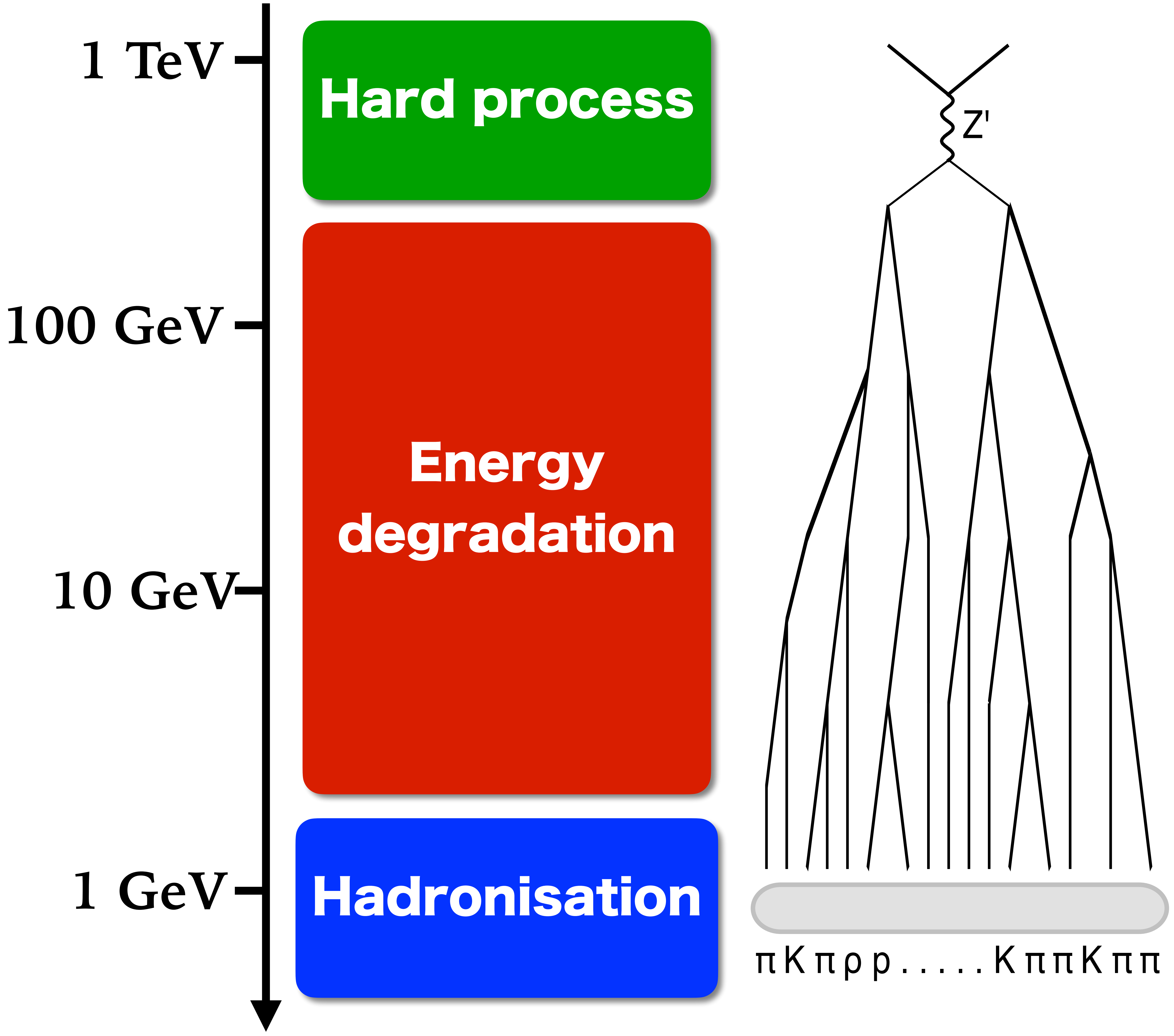


Parton Showers

- Energy degradation of hard particles produced during the collision

Shower Monte Carlo event generators

SHOWER MONTE CARLO EVENT GENERATORS = **<u>default tool</u>** for interpreting collider data



Matching

- Matching with logarithmically accurate parton showers

Parton Showers

- Energy degradation of hard particles produced during the collision

Hadronisation

- Friday's satellite meeting

Logarithmic accuracy beyond QCD

- The **angular-ordering of QCD emissions** ensures that also the **soft** limit is correct, and hence NLL accuracy is achieved
- For QED and EW, the parton branching formalism ensures **only collinear** (and soft-collinear) logs are resummed: only **LL accuracy** is expected
  - **QCD**: $\alpha_s \sim 0.1, \qquad \alpha_s L = \mathcal{O}(1) \qquad \Sigma = \exp(L g_{\mathrm{LL}}(\alpha_s L) + g_{\mathrm{NLL}}(\alpha_s L) + \ldots)$
  - **QED**: $\alpha_{em} \sim 0.01, \quad \alpha_{\mathrm{em}} L^2 = \mathcal{O}(1) \quad \Sigma = f_{\mathrm{DL}}(\alpha_{\mathrm{em}} L^2) + \boxed{\sqrt{\alpha_{\mathrm{em}}} f_{\mathrm{NDL}}(\alpha_{\mathrm{em}} L^2)} + \ldots \quad (\mathrm{DL} = \text{double logs})$

Only colliner ones are included, not soft ones: few % mistake for processes without QCD; necessary (but not sufficient) e.g. for the FCC-ee

Log Accuracy of the Angular-Orderd parton shower

- **Angular-ordering** = algorithmic implementation of the QCD **coherent branching formalism**, used for **NLL** calcultions for **global observables** (event shapes, many kinematic distributions e.g. $p_{\perp,Z}$) [Marchesini, Webber ’88; Gieseke, Stephens, Webber hep-ph/0310083]

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  - **QED**: $\alpha_{em} \sim 0.01, \quad \alpha_{\mathrm{em}} L^2 = \mathcal{O}(1) \quad \Sigma = f_{\mathrm{DL}}(\alpha_{\mathrm{em}} L^2) + \sqrt{\alpha_{\mathrm{em}}} f_{\mathrm{NDL}}(\alpha_{\mathrm{em}} L^2) + \ldots$ (DL = double logs)

QED and EW logs in other SMC tools

- SHERPA: soft QED logs implemented with the **YFS formalism** [Krauss, Price, Schönherr, 2203.10948]; one-loop virtual **EW Sudakov Logs** [Bothmann, Napoletano 2006.14635]
- PHOTOS: [Barberio, Was '94] default tool used in experiments, based on YFS, runned after the SMC simulation for QED FSR off leptons