

Status of the Alaric Parton Shower

QCD@LHC 2026

[JHEP 12 (2024) 156]

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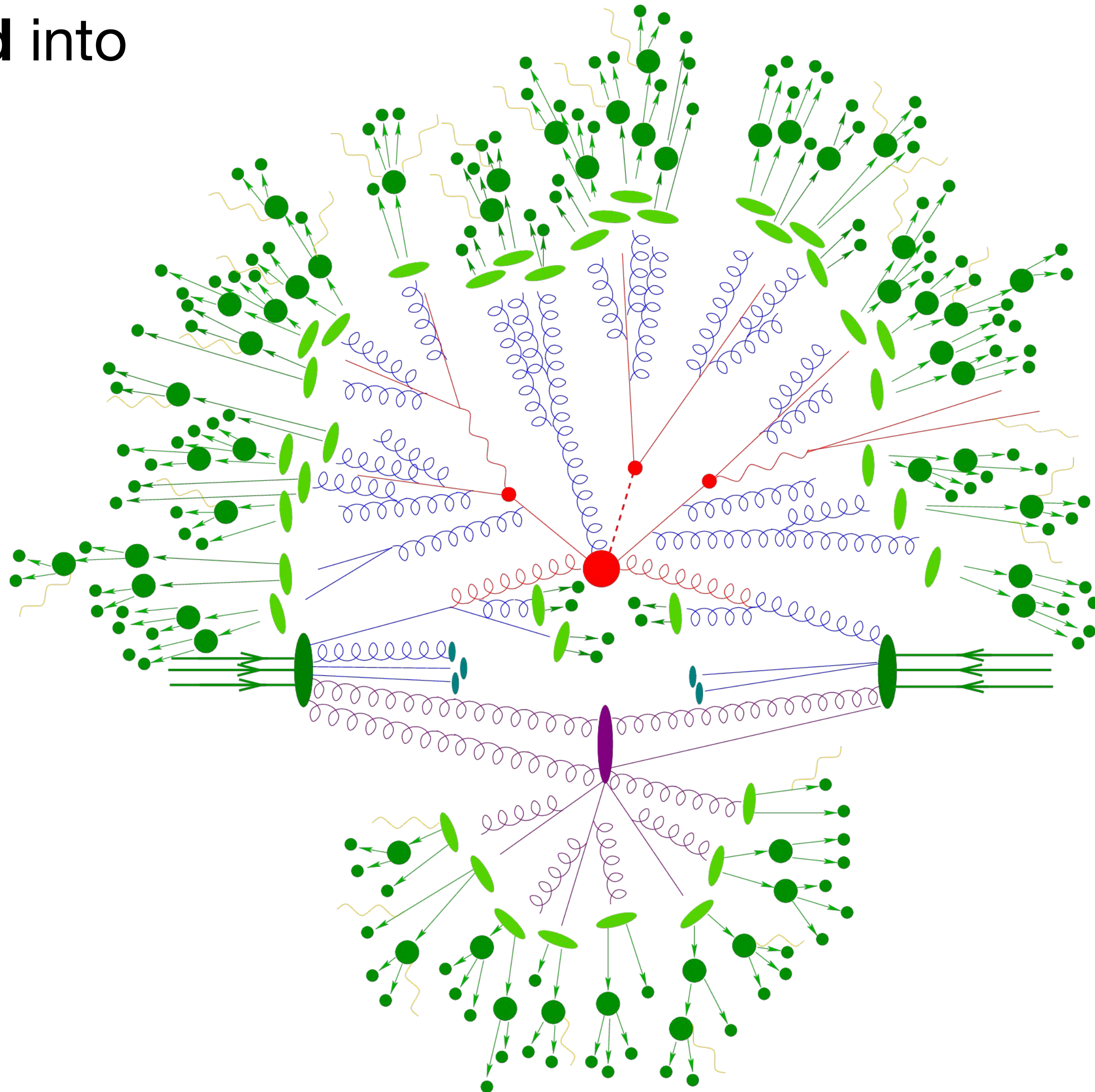
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Event Generators and Parton Showers

- Event simulation **factorised** into

- **Hard Process**
- **Parton Shower**
- **PDF/Underlying event**
- **Hadronisation**
- **QED radiation**
- **Hadron Decays**

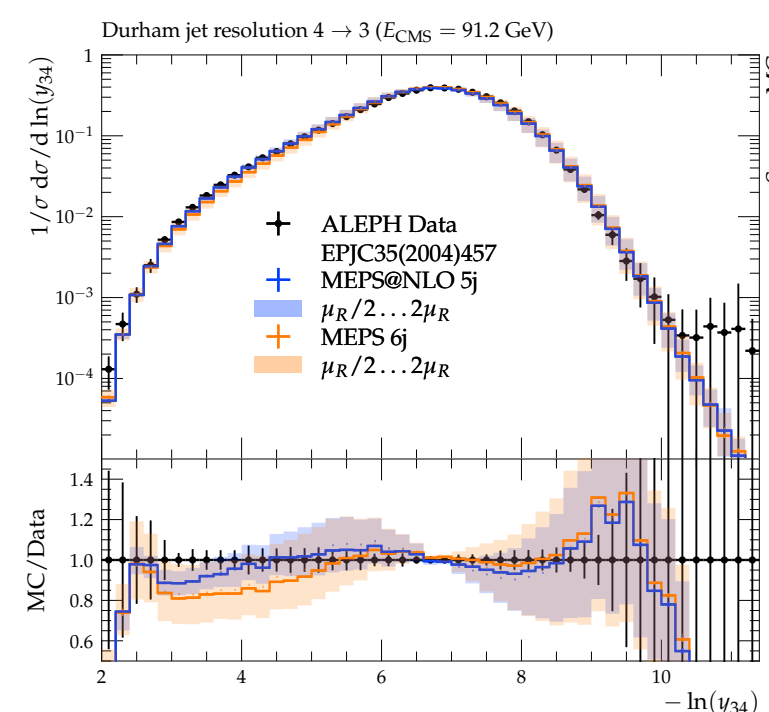
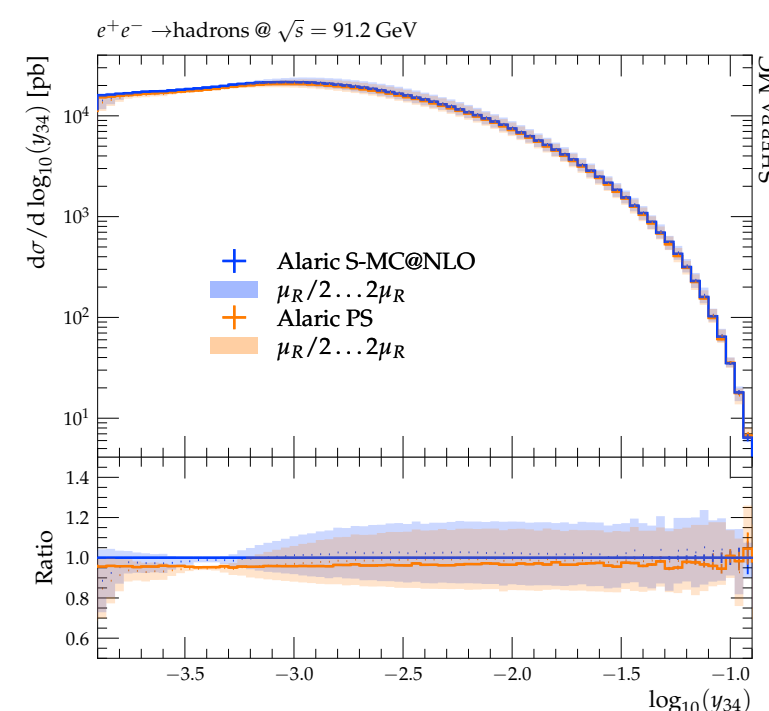


Update Baseline

- Alaric introduced in [Herren et al. '22]
 - Coherence** through multiplicative matching between soft eikonal and collinear splitting functions
 - Global recoil** scheme takes into account PanScales insights on **recoil safety** requirements at NLL
 - Massive** kinematics



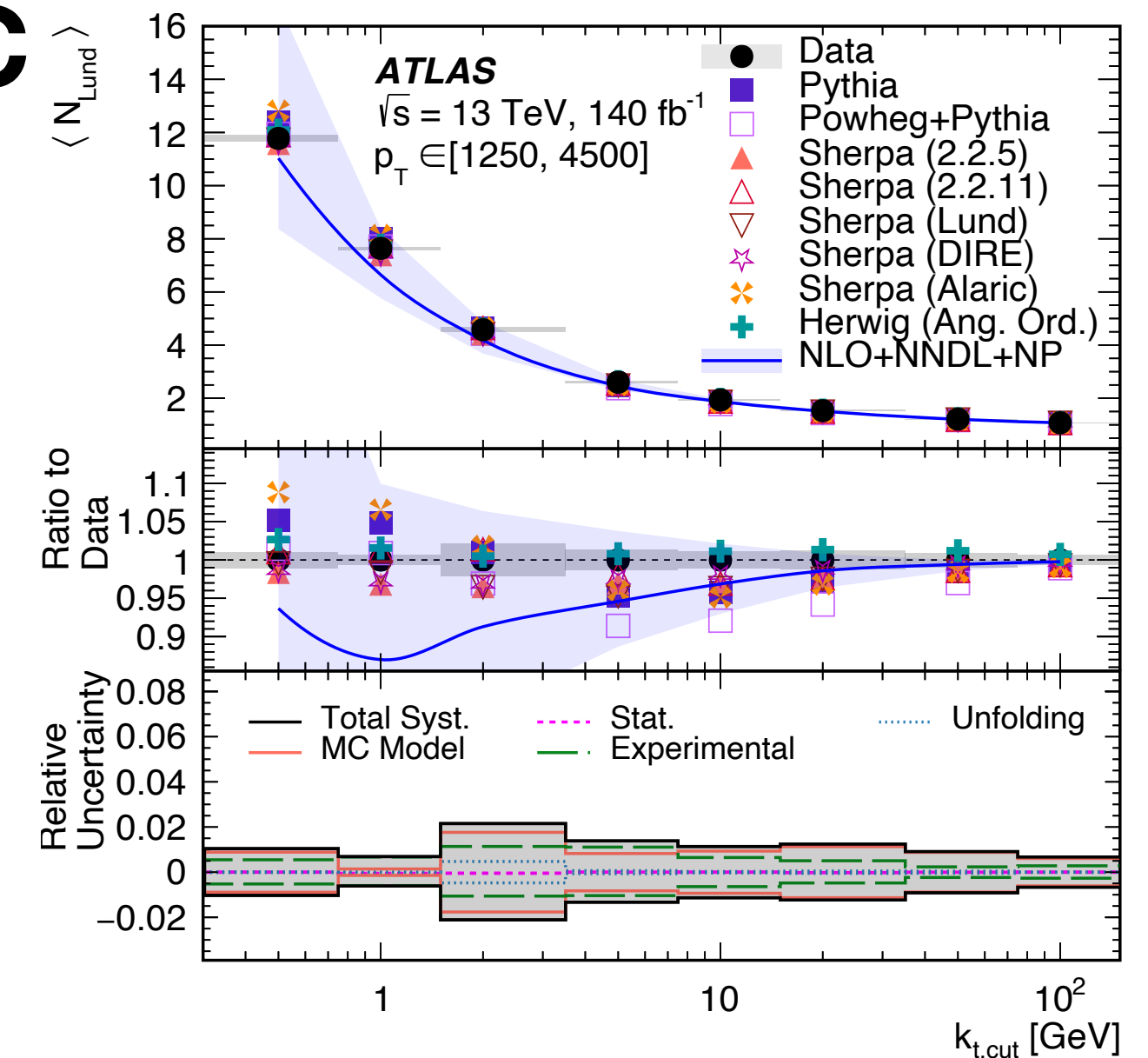
[Dasgupta et al. '20]
[vanBeekveld et al. '22]



- Extension to **hadron colliders** + LO merging [Höche, Krauss, DR '24]

- First **LHC pheno**

[ATLAS '24]

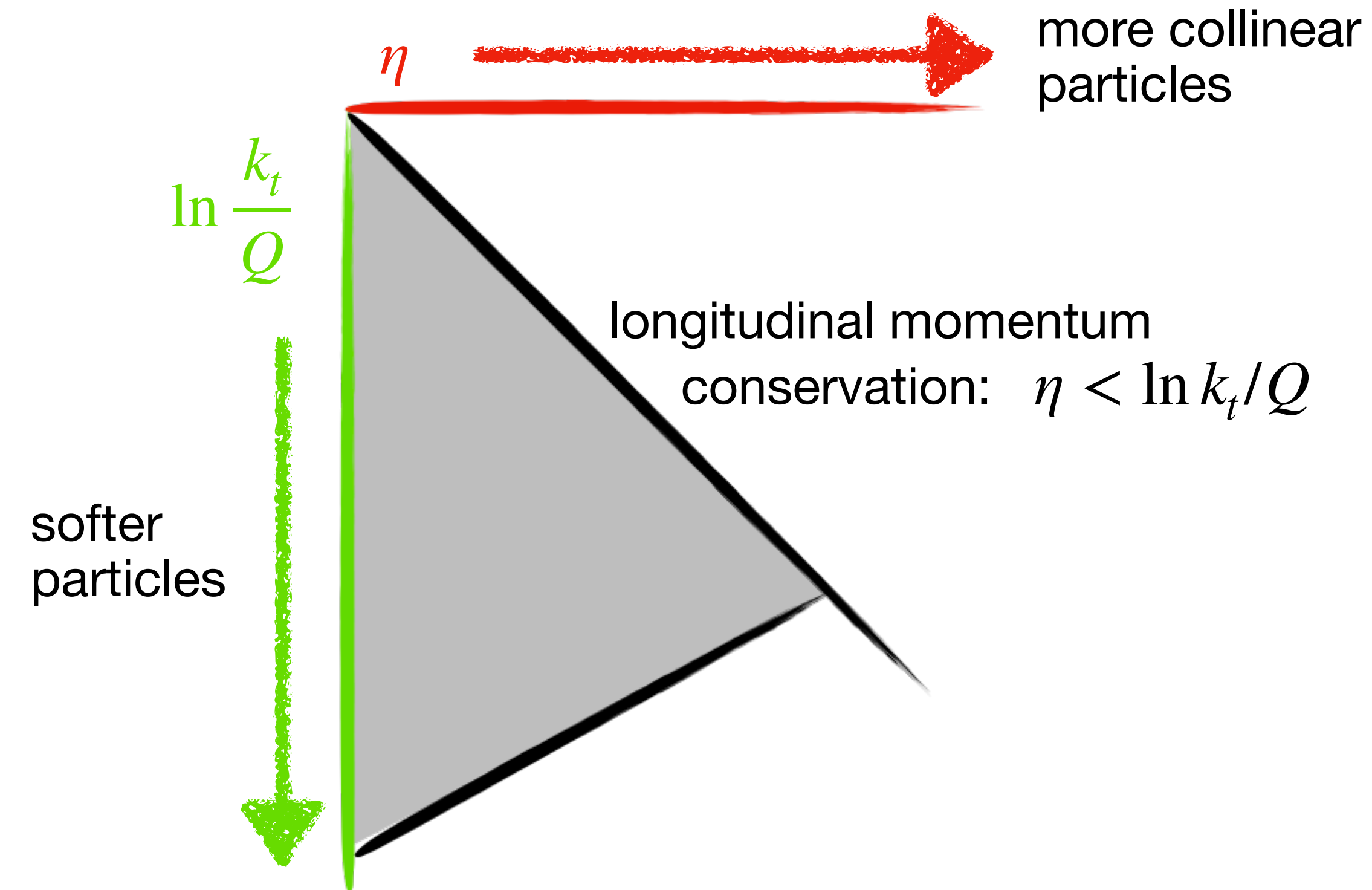


- NLO matching and MEPS@NLO** merging for colour singlet decay [Höche, Krauss, Meizinger, DR '25]

Parton showers - Cliff notes version

- Evolution governed by no-emission probability (Sudakov factor)
- Main ingredients to a shower:
 1. splitting kernels $P(z)$ captures soft and collinear limits of matrix elements
 2. fill phase space ordered in evolution variable $(k_t, \theta, q^2, \dots) \Rightarrow$ here k_t ordered shower
 3. generate new final state after emission according to recoil scheme

$$\sim \exp \left[- \int_{t_0}^{t_1} \frac{dk_t}{k_t} dz \frac{\alpha_s}{2\pi} P(z) \right]$$



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Plan for this talk:

1. Splitting kernels and Spin correlations
2. Matching Resonance Aware Kinematics
3. Width Aware Shower Kernels

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Spin correlations

- Traditional approach:
 - Spin-density matrices traced through parton shower history
 - Efficient algorithm by Collins, Knowles [Collins '88], [Knowles '88,'90]
 - Part of Herwig for long time, also for dipole shower [Richardson, Webster '18]
 - Extended to soft region [Karlberg, Salam, Scyboz, Verheyen '21]
[Hamilton, Karlberg, Salam, Scyboz, Verheyen '21]
- Here instead, re-consider splitting functions, Gordon decomposition

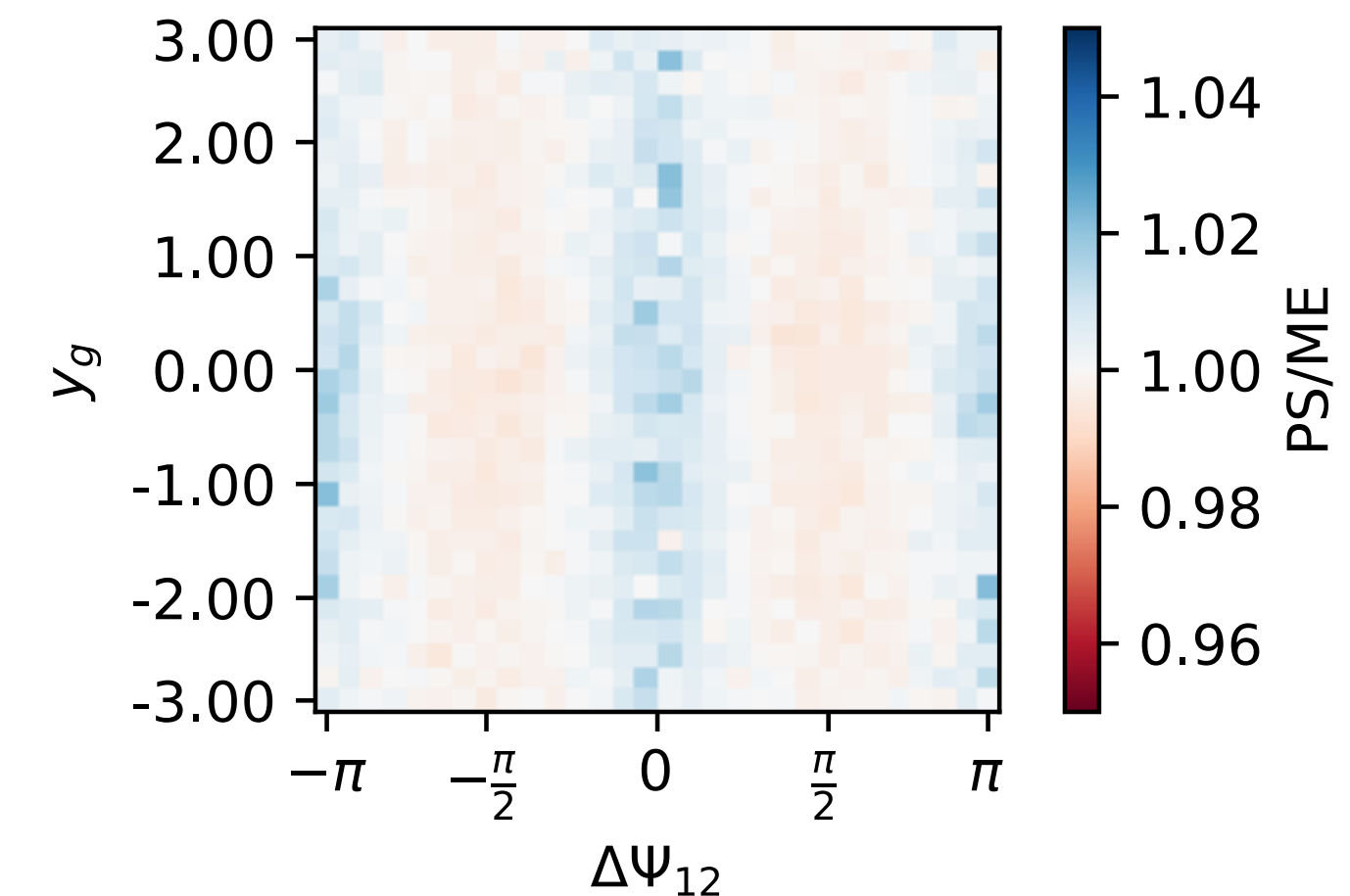
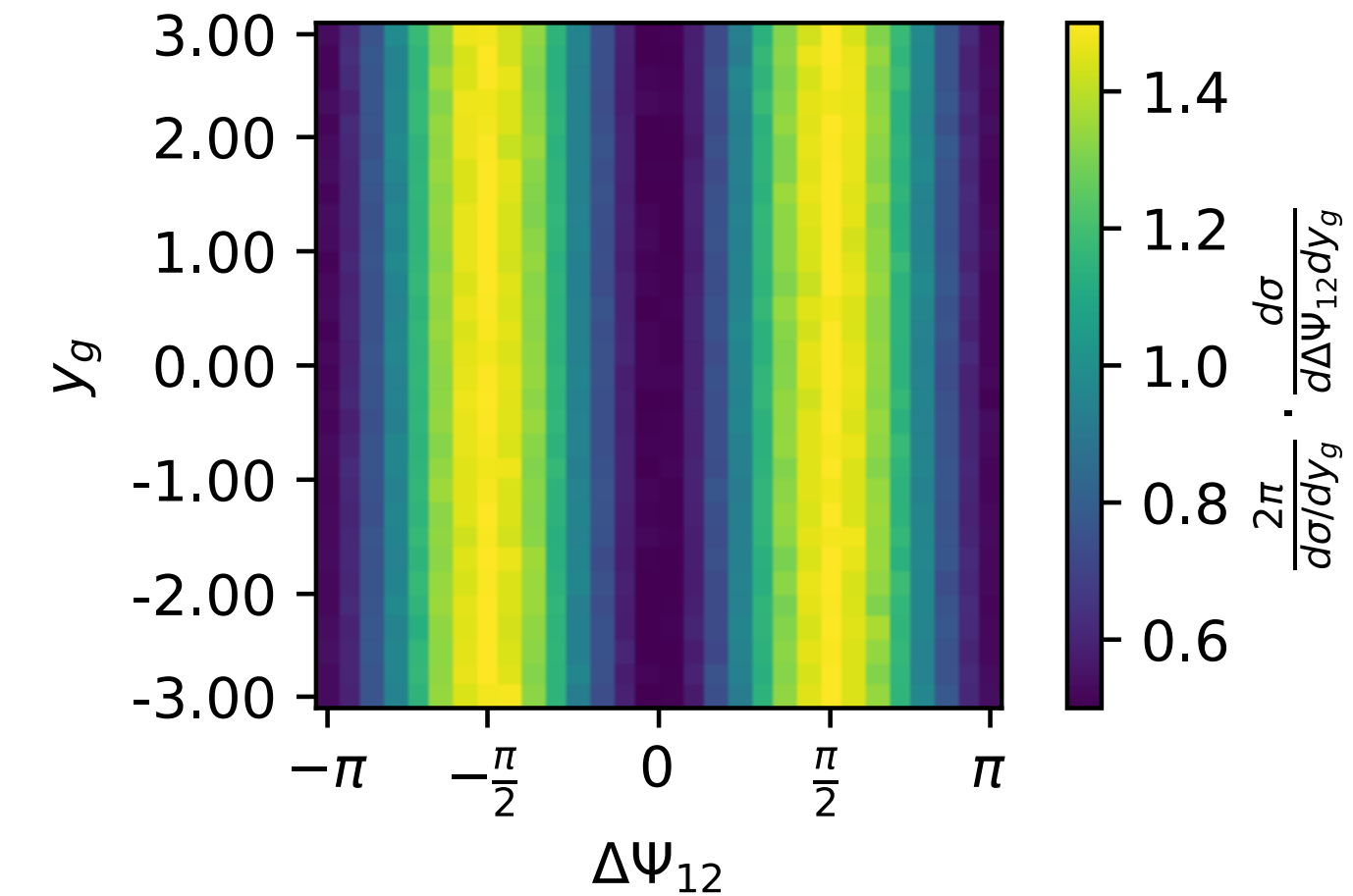
$$\frac{\not{p} + \not{q}}{(p + q)^2} T_{ij}^a \gamma^\mu = T_{ij}^a \left[S^\mu(p, q) + \frac{i\sigma^{\nu\mu} q_\nu}{(p + q)^2} - \frac{\gamma^\mu \not{p}}{(p + q)^2} \right] \quad [\text{Campbell, Höche, Knobbe, Preuss, DR '25}]$$

$$S^\mu(p, q) = \frac{(2p + q)^\mu}{(p + q)^2}$$

Leading term is scalar Interaction!

Spin correlations in Alaric

- **Scalar** part of the theory:
 - **doesn't know about spin**, just emission of vector bosons with production current J^μ given by scalar QCD
- **Remainder “decays”** of gluons into gluon or quark pairs
 - **spin dependent** contribution
$$\propto J^\mu \langle \mu | V | \nu \rangle J^\nu$$
 - contraction can be calculated once in **decay!**



[Hoppe, Höche, Siebert, DR '25]

[Campbell, Höche, Knobbe, Preuss, DR '25]

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Kinematics and Resonance Awareness

- Assume we have identified subset of momenta $(\tilde{p}_W, \tilde{p}_b)$ to come from resonance:

- Dominant diagrams will contain **propagator**

$$\left[\left((\tilde{p}_W + \tilde{p}_b)^2 - m_t^2 \right) + m_t^2 \Gamma_t^2 \right]^{-1}$$

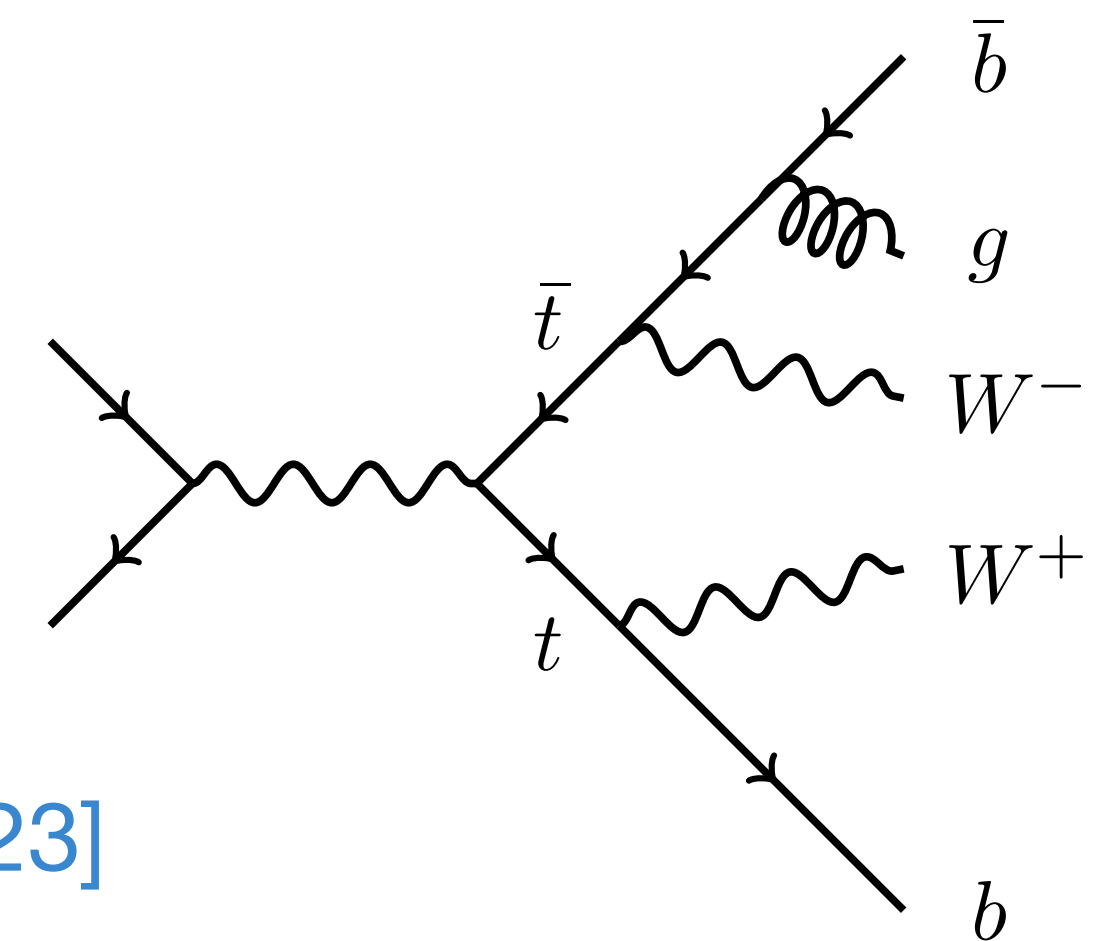
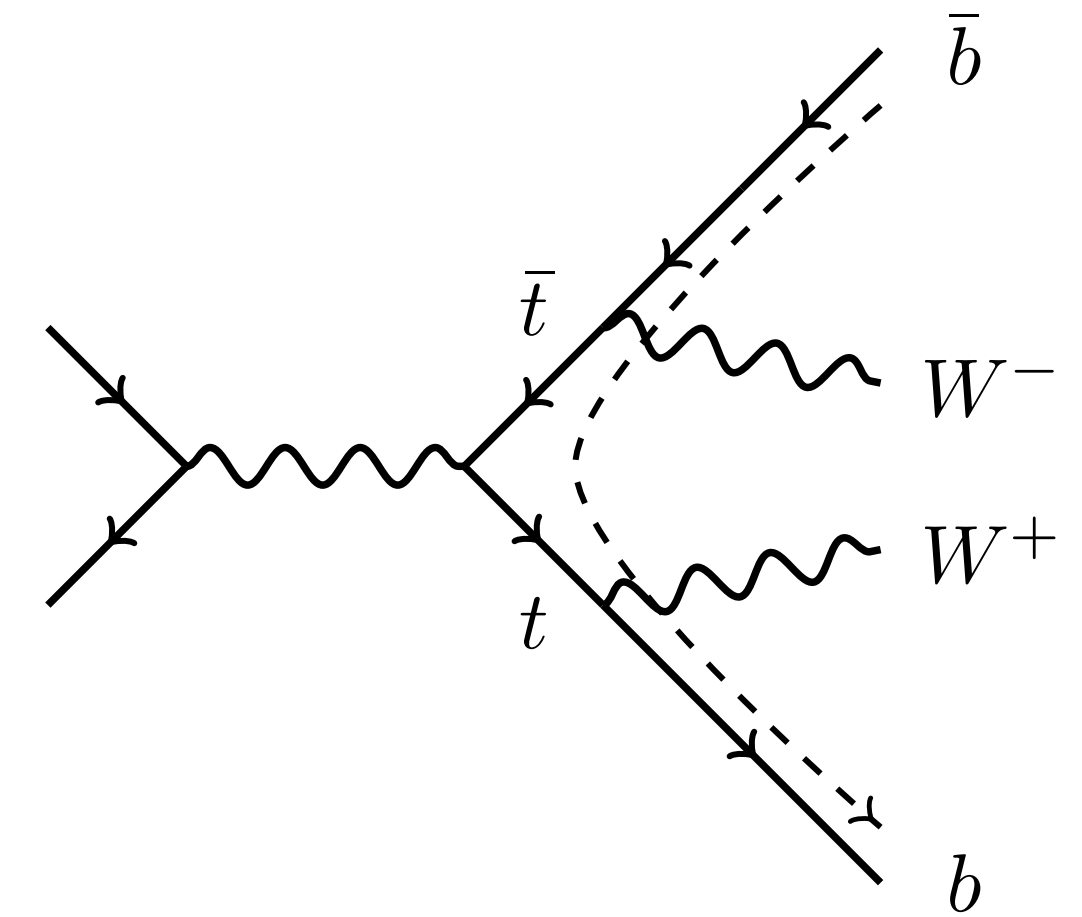
- Let b emit a gluon $\tilde{p}_W, \tilde{p}_b \rightarrow p_W, p_b, p_g$:
can **change propagator significantly**,
unless $\tilde{p}_W + \tilde{p}_b = p_W + p_b + p_g$
(**not** satisfied in standard, local dipole schemes!)
- Well recognised problem, with several solutions

[Ježo, Nason '15] [Ježo, Lindert, Nason, Oleari, Pozzorini '16]

[Ferrario Ravasio, Ježo, Nason, Oleari, '18] [Ježo, Lindert, Pozzorini '23]

[Denner, Lombardi, Pellen, Pelliccioli '26]

[Höche, Liebschner, Siegert '19]

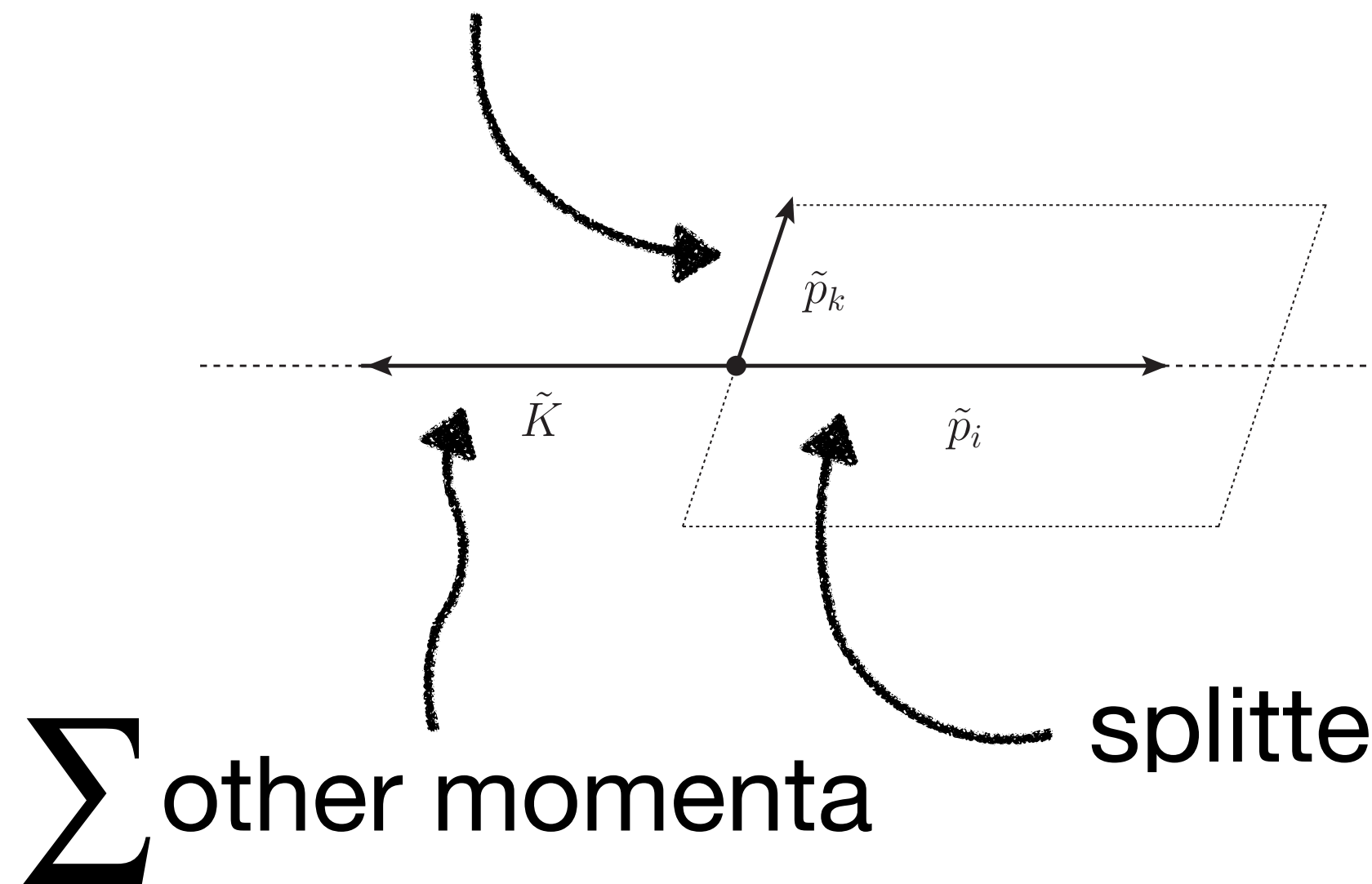


Alaric - radiation kinematics

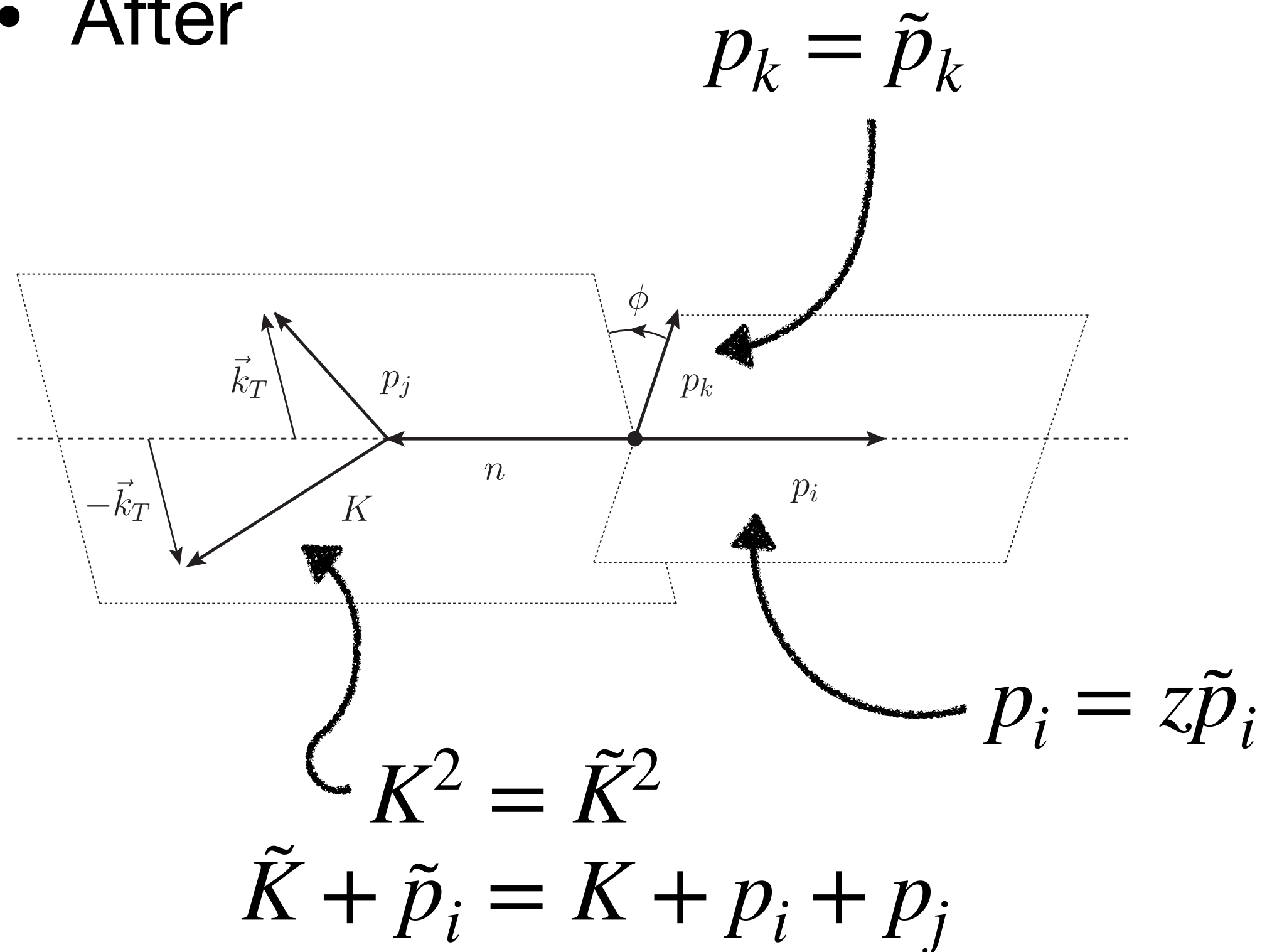
- Global kinematics — critical for **logarithmic accuracy at NLL**

- Before

colour



- After



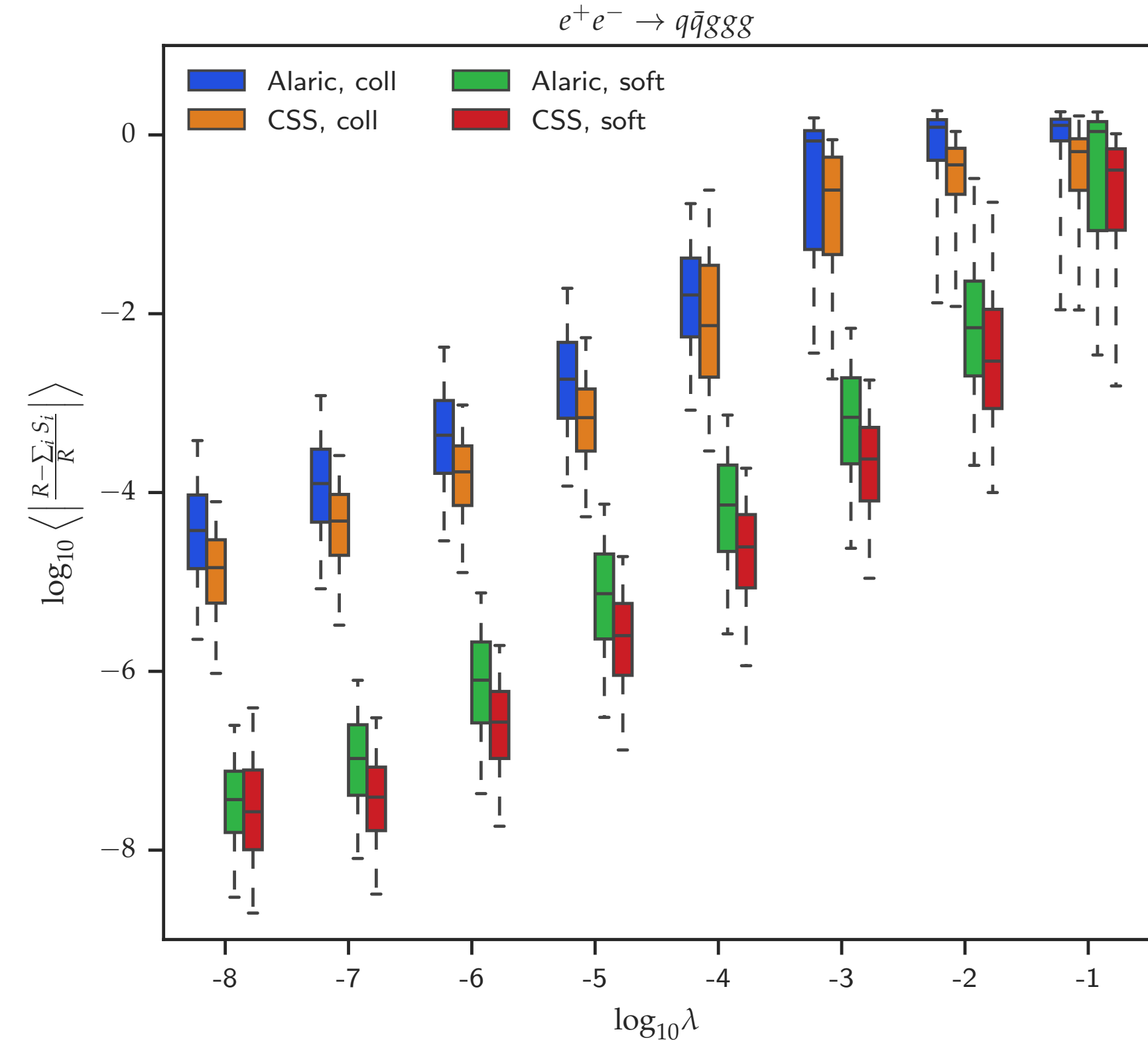
$$k_i^\mu \rightarrow \Lambda^\mu_\nu k_i^\nu$$

[Catani, Seymour

$$\Lambda^\mu_\nu = g^\mu_\nu - \frac{(K + \tilde{K})^\mu (K + \tilde{K})_\nu}{K \cdot \tilde{K} + \tilde{K}^2} + 2 \frac{K^\mu \tilde{K}_\nu}{\tilde{K}^2} \rightarrow \Lambda^\mu_\nu \tilde{K}^\nu = K^\mu$$

Daniel Reichelt

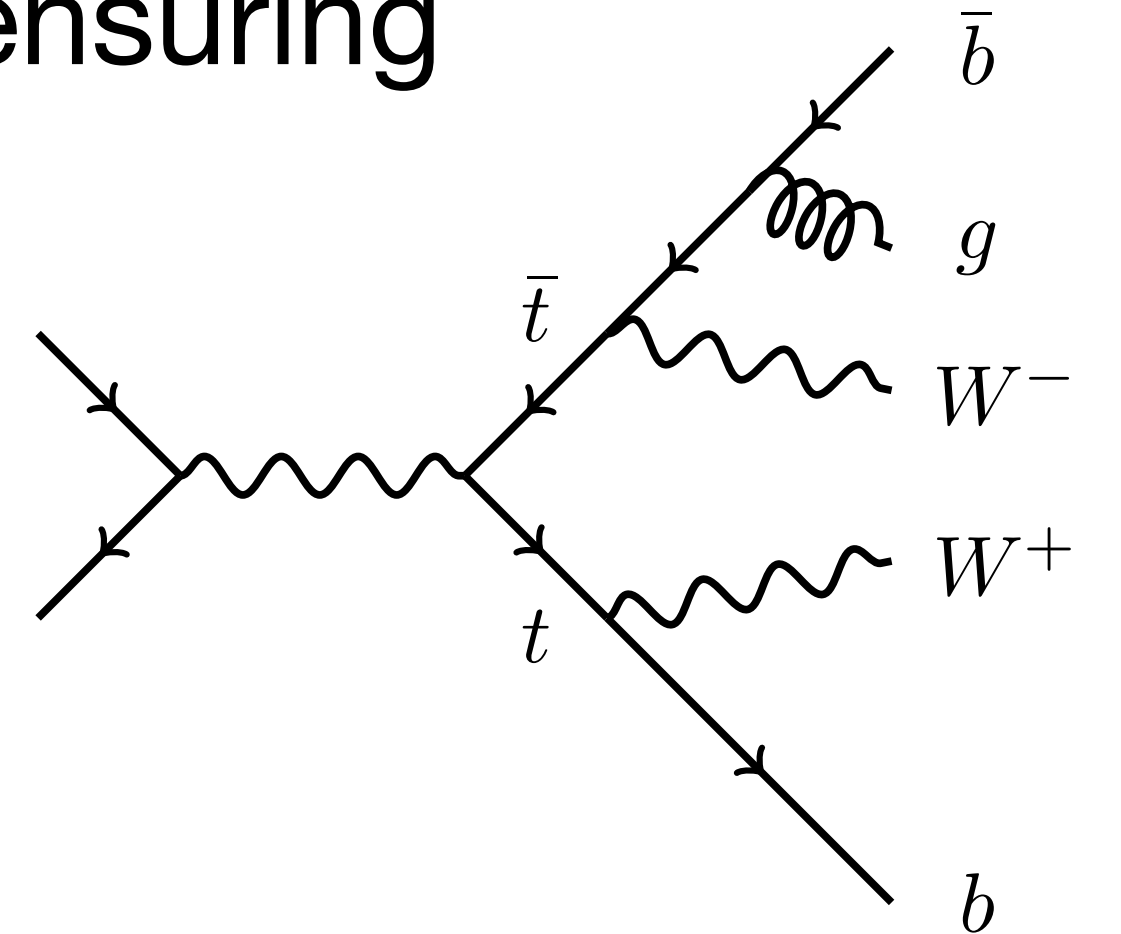
- NLO matching in Sherpa based on dedicated subtraction scheme implementation
- need to work more for the implementation (only FS so far)
- but ensure PS and subtraction are fully consistent, automated for any process once implemented
- include spin correlations in first emission (“SH-MC@NLO”)



$e^+e^- \rightarrow n \text{ jets @ } 91.2 \text{ GeV}$ $\mu_R = \sqrt{s}, y_{n,n-1} > (10 \text{ GeV})^2/s$		I [pb]	ΔI [pb]	RS [pb]	ΔRS [pb]	IRS [pb]	ΔIRS [pb]	$\Delta IRS/NLO$
$n=3$	CS	5118.85	0.37	-1034.4	1.4	4084.45	1.4	0.1‰
	ALARIC	5174.47	0.38	-1087.6	1.8	4086.84	1.8	0.1‰
	CS-ALARIC						-2.39 ± 2.32	
$n=4$	CS	938.97	0.12	-94.45	0.73	844.52	0.74	0.5‰
	ALARIC	922.36	0.12	-79.75	0.70	842.61	0.71	0.5‰
	CS-ALARIC						1.91 ± 1.03	
$n=5$	CS	46.1544	0.015	-2.341	0.058	43.813	0.060	1‰
	ALARIC	44.6125	0.014	-0.857	0.067	43.756	0.068	1‰
	CS-ALARIC						0.057 ± 0.091	

Alaric kinematics and Resonance awareness

- Similar kinematics previously explored in context of resonance aware showers
- Key observation: [Höche, DR '26] [Höche, Liebschner, Siebert '19]
- $\tilde{K}$ is **arbitrary**, momentum conservation implemented by ensuring
$$\tilde{K} + \tilde{p}_i = K + p_i + p_j$$
- Identify $\tilde{K} + \tilde{p}_i$ as resonance, i.e. $\tilde{K} = \tilde{p}_W$ for $\tilde{p}_i = \tilde{p}_b$
- **Preserving mass of resonance “for free”**
(some care needed in partial fractioning of eikonal)
- For now assume resonance identification trivial (i.e. by charges in $W^+W^-b\bar{b}$)



Parton showers - Cliff notes version

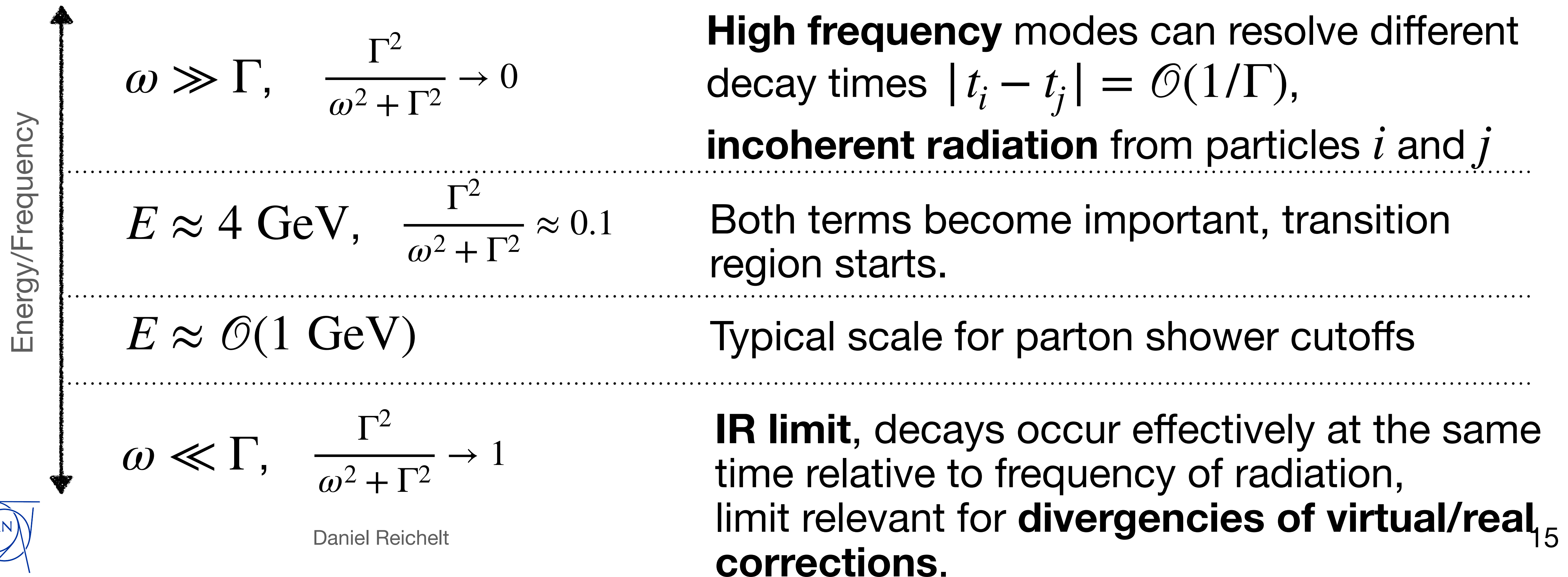
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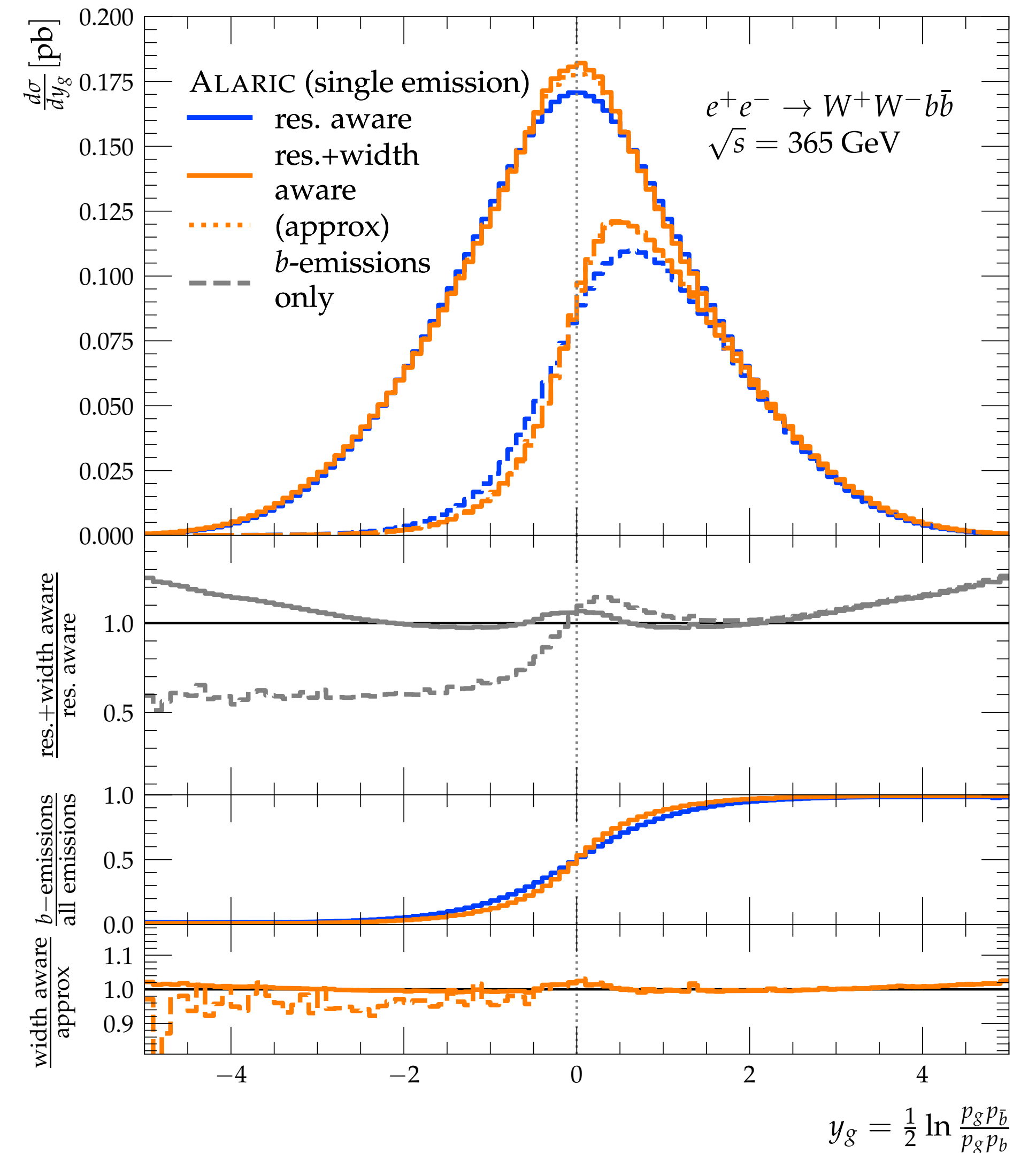
Width-Awareness - The Physics Picture

- Top width introduces additional perturbative scale. [Dokshitzer, Khoze, Orr, Stirling '92]
- Radiation kernel dependent on Γ : $P(z) = P_{IR}(z) + (1 - \zeta(z m_t))P_{fin}(z)$ [Orr, Stirling '95]
- Interpolation between regimes by $\zeta(\omega) = \Gamma^2/(\omega^2 + \Gamma^2)$ [Khoze, Sjöstrand '94]



Width-aware parton shower radiation

- Implement **width-aware soft kernel** in Alaric. [Höche, DR '26]
- Stop shower after a single emission (theory exercise to understand effects on gluon emission pattern).
- Single out emissions from b quark (not $\bar{b}$):
 - Strong **suppression** in the **anti-collinear** hemisphere.
- Technically, further approximation is related to the frame where energy is evaluated.



- **Soft radiation pattern** should look like this.

$$V_{ij,k}^{(s,w)}(p_i, p_j, p_k, q_i) = 8\pi\mu^{2\varepsilon}\alpha_s C_i \left[\frac{2(p_i p_k)}{(p_i p_j) + (p_k p_j)} + \chi(z) \left(\frac{2(p_i q_i)}{(p_i p_j) + (q_i p_j)} - \frac{2(p_i p_k)}{(p_i p_j) + (p_k p_j)} \right) \right]$$

- **Additional contribution** to integrated soft kernel

$$\begin{aligned} I_{ik}^{(s,w)} &= \int_0^1 dz \frac{z^{1-\varepsilon}}{(1-z)^{1+2\varepsilon}} \frac{2}{\pi} \left(\frac{np_k}{np_i} \frac{l_{ik}^2}{4} \right)^\varepsilon \frac{\Gamma^2(1-\varepsilon)}{\Gamma(1-2\varepsilon)} \frac{(1-z)^2}{(1-z)^2 + \gamma^2} \\ &\quad \times \left[l_i l_{i+q_i} I_{1,1}^{(1)}(l_i l_{i+q_i}, l_{i+q_i}^2) - l_i l_{i+k} I_{1,1}^{(1)}(l_i l_{i+k}, l_{i+k}^2) \right] \\ &= \int_0^1 dz \frac{2z}{1-z} \frac{(1-z)^2}{(1-z)^2 + \gamma^2} \left[\ln \frac{p_i p_k}{p_i q_i} + \ln \left(\frac{q_i^2}{z 2 p_i q_i} + 1 \right) \right] + \mathcal{O}(\varepsilon) \end{aligned}$$

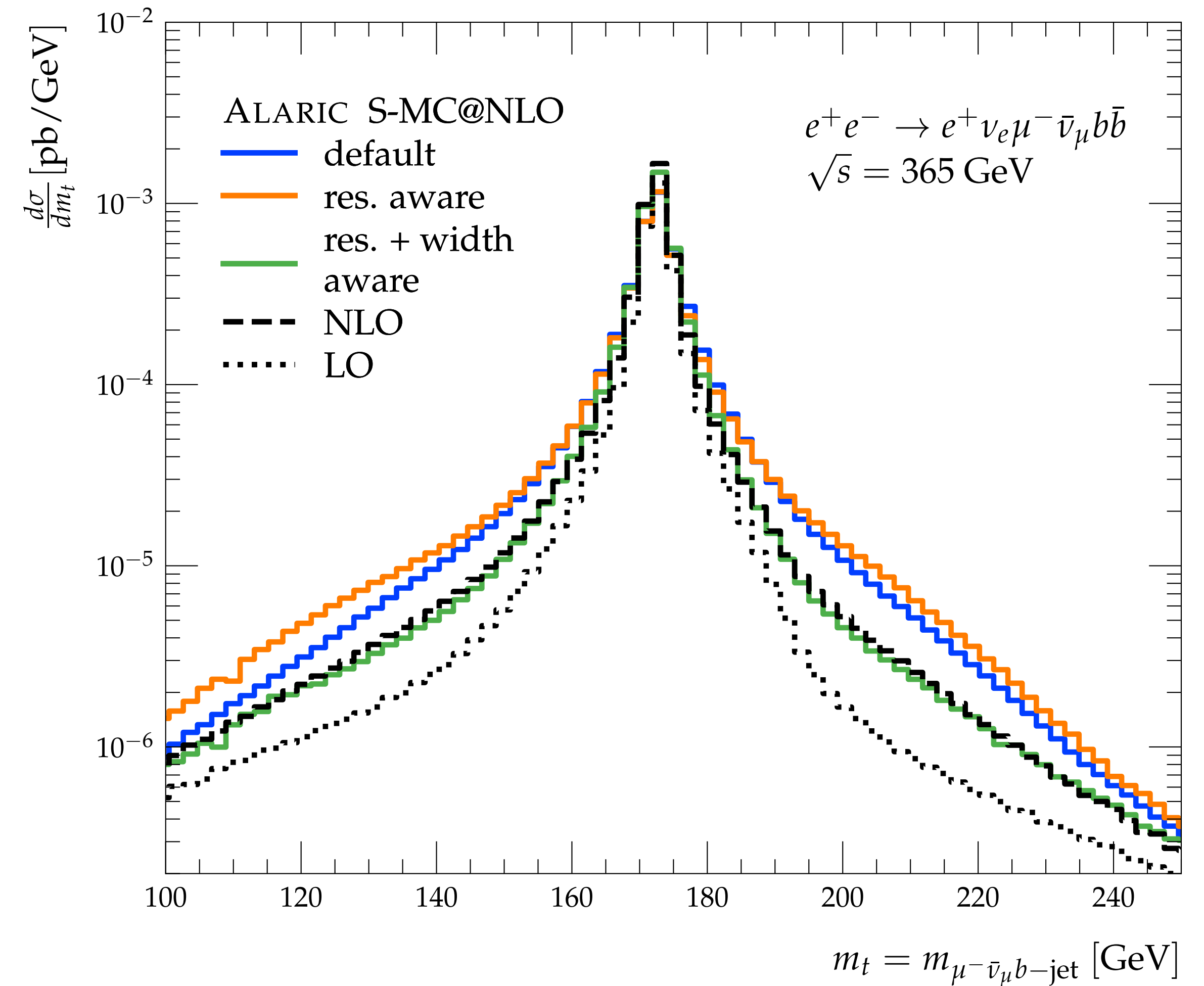
- Approx. related to frame where gluon energy is calculated.

$$\begin{aligned} p_j q_i &= (1-z) \tilde{p}_i \tilde{K} + p_i p_j \sim (1-z) \tilde{p}_i \tilde{K} \\ \frac{E_j^2}{E_j^2 + \Gamma_t^2} &= \frac{(q_i p_j)^2}{(q_i p_j)^2 + q_i^2 \Gamma_t^2} \sim \frac{(1-z)^2}{(1-z)^2 + \gamma^2} =: \chi(z), \\ \gamma &= \sqrt{q_i^2} \frac{\Gamma_t}{\tilde{p}_i \tilde{K}} \end{aligned}$$

$e^+e^- \rightarrow W^+W^-b\bar{b},$ $\sqrt{s} = 365 \text{ GeV}, \mu_R = m_t$	I [pb]	ΔI [pb]	RS [pb]	ΔRS [pb]	IRS [pb]	ΔIRS [pb]	$\Delta IRS/NLC$
CS	0.08453	0.00004	-0.02185	0.00037	0.06268	0.00038	0.5‰
ALARIC default	0.07293	0.00002	-0.00997	0.00029	0.06296	0.00029	0.4‰
ALARIC res. aware	0.13134	0.00003	-0.06908	0.00048	0.06226	0.00048	0.6‰
ALARIC res. + width aware	0.13472	0.00005	-0.07248	0.00037	0.06224	0.00037	0.5‰
CS-ALARIC default					-0.00029 ± 0.00048		
CS-ALARIC res. aware					0.00042 ± 0.00061		
CS-ALARIC res. + width aware					0.00044 ± 0.00053		

Resonance- and Width aware parton shower

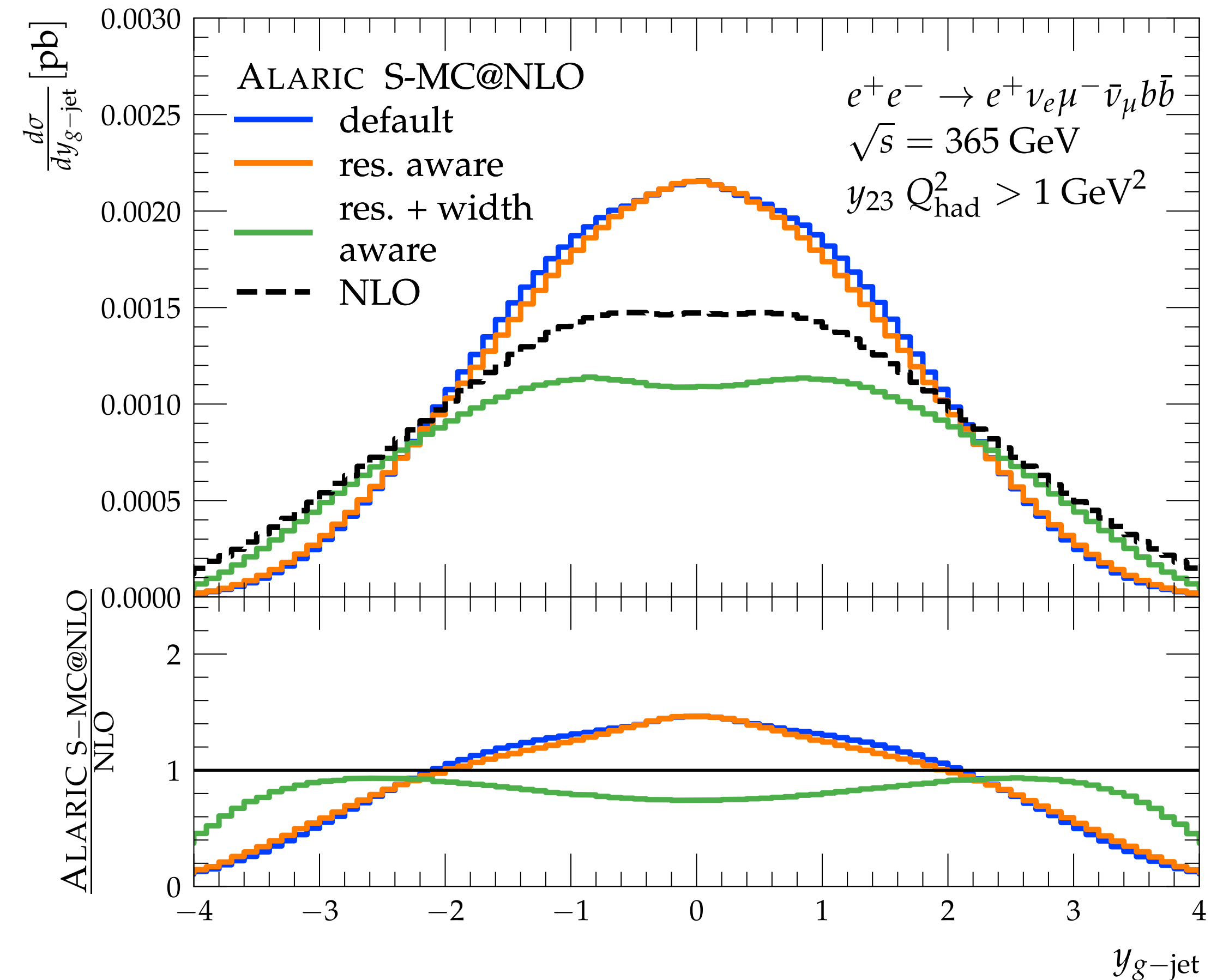
- Consider $W^+W^-b\bar{b}$ production with fully leptonic decays
- **“true” measured top mass:**
 - Including full neutrino information, b jet reconstructed with Durham algorithm
- Large effects on top of NLO in tails, both in default and resonant aware matched showers
- Only **width-aware matching** close to NLO distribution



[Höche, DR '26]

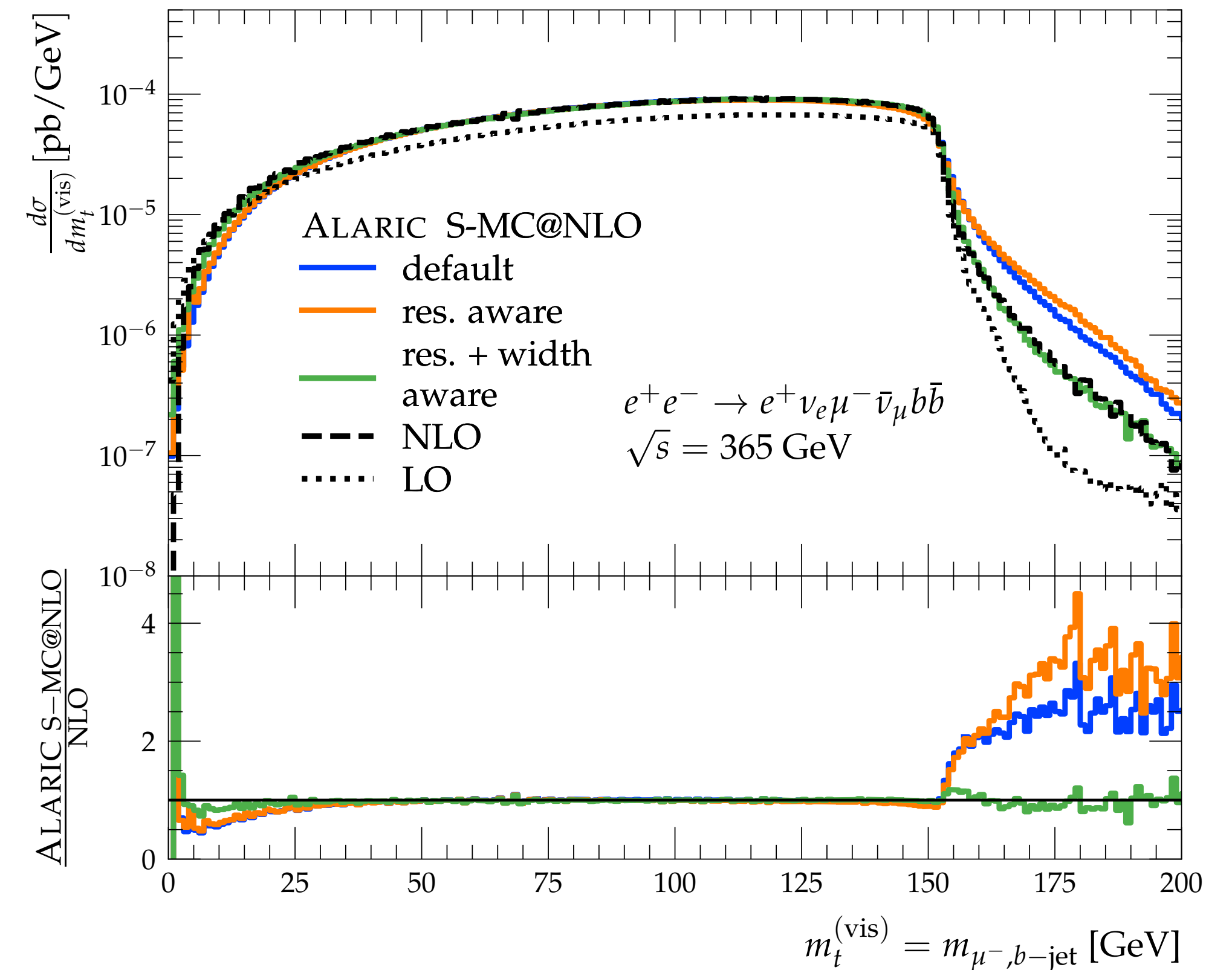
Resonance- and Width aware parton shower

- Consider $W^+W^-b\bar{b}$ production with fully leptonic decays.
- **Rapidity distribution** of additional gluon jet.
- **NLO** and **width-aware matching** show **suppression in the central region** (independent emission from separate b s).
- Other showers produce coherent radiation from $b\bar{b}$ at all energies, leading to strong enhancement.



Resonance- and Width aware parton shower

- Consider $W^+W^-b\bar{b}$ production with fully leptonic decays.
- **Visible reconstructed top mass:** mass of lepton from W decay and reconstructed b -jet
- Same large **enhancements** as before, now **concentrated in high visible mass tail.**
- Non-width-aware showers would predict significant distortion of shoulder relative to NLO expectation.



Summary

- Update on status of Alaric parton shower, after
 - Initial development as Sherpa shower with recoil-safe kinematics
 - First LHC Phenomenology and LO merging
 - First NLO matching
- New:
 - Spin correlations from semi-classical currents
 - Resonance-aware kinematics and recoil scheme
 - Width-aware evolution and matching