Perturbative Inputs to Event Generators

SM@LHC conference, 7 May 2024

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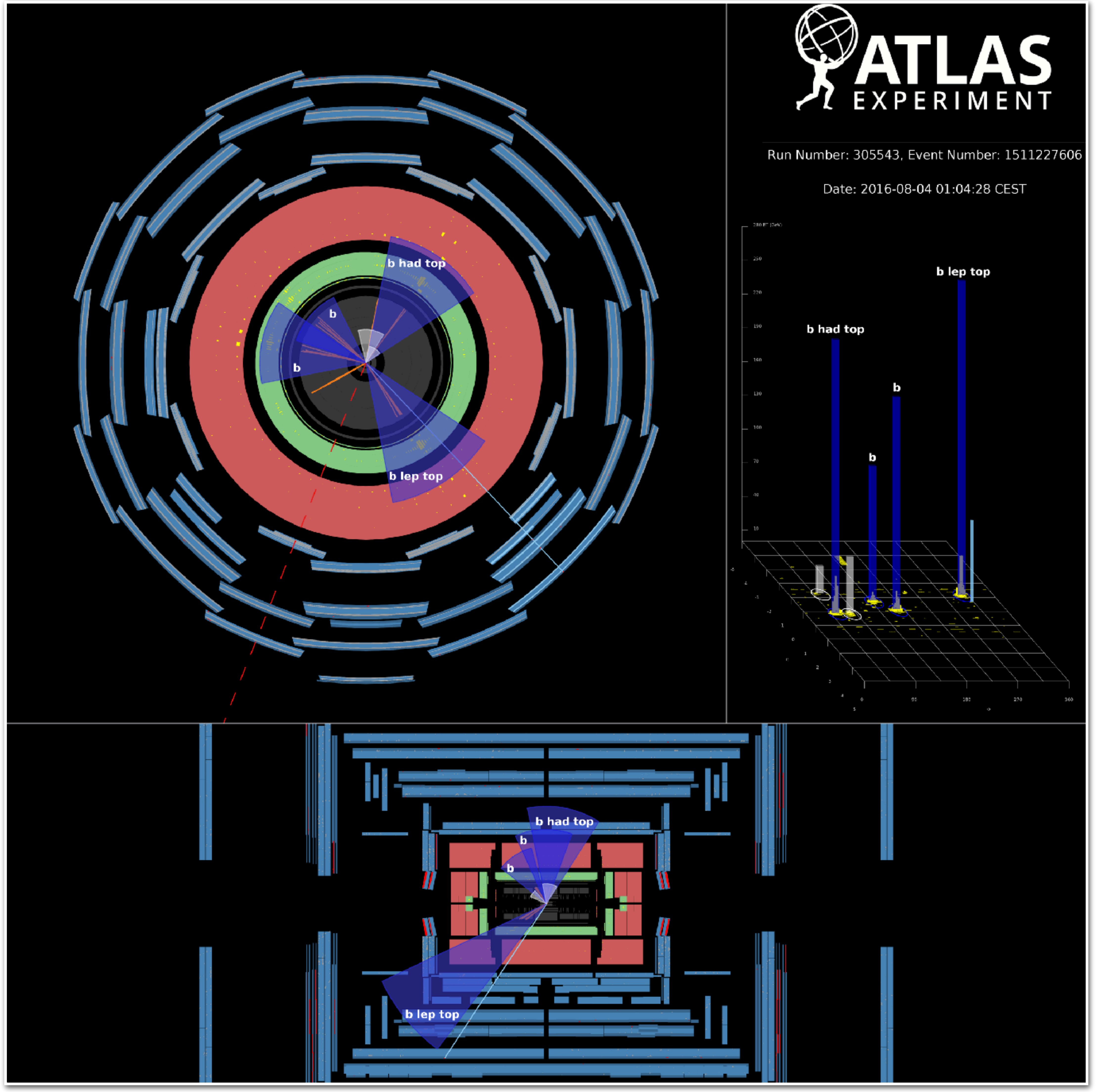
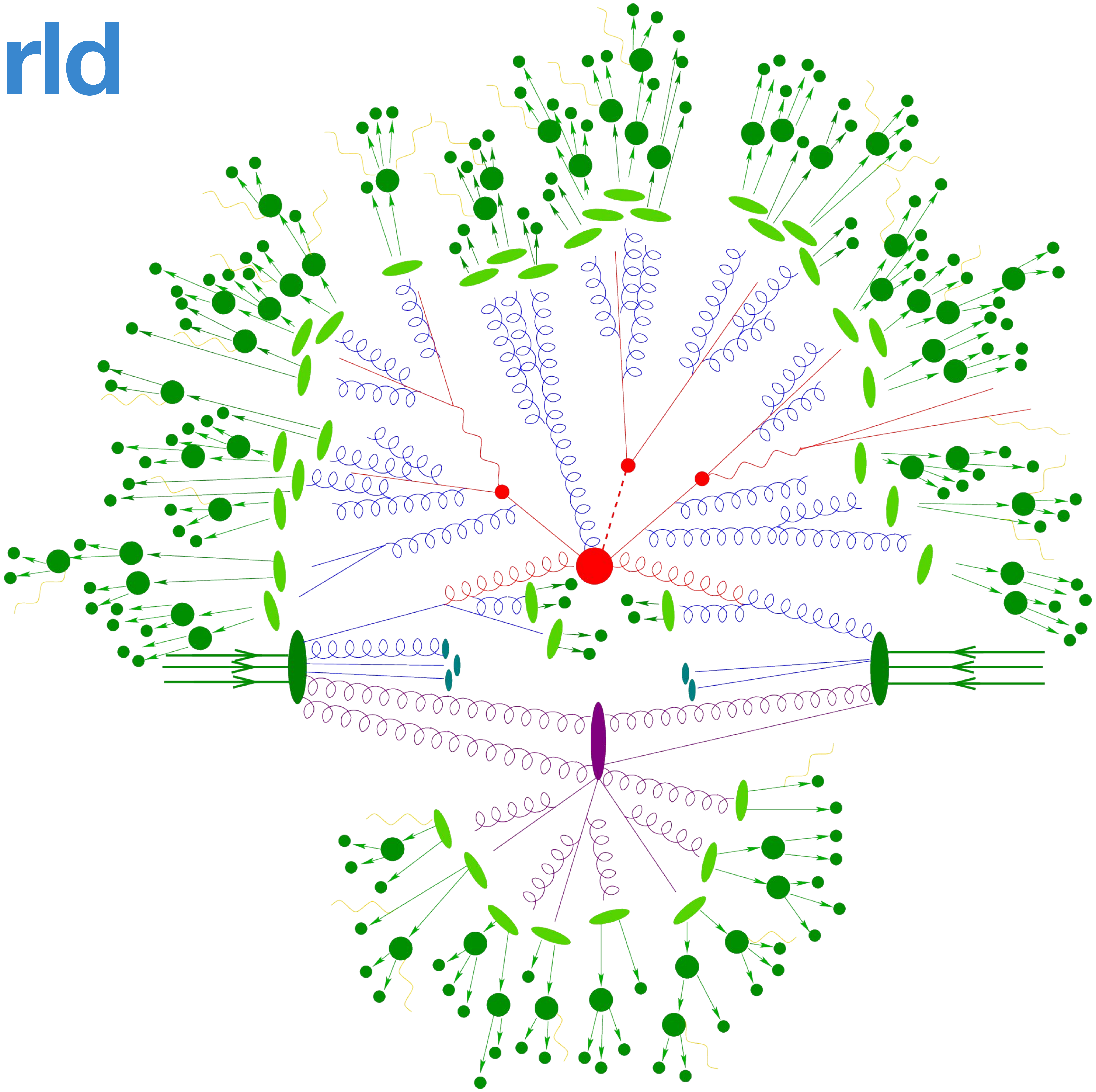
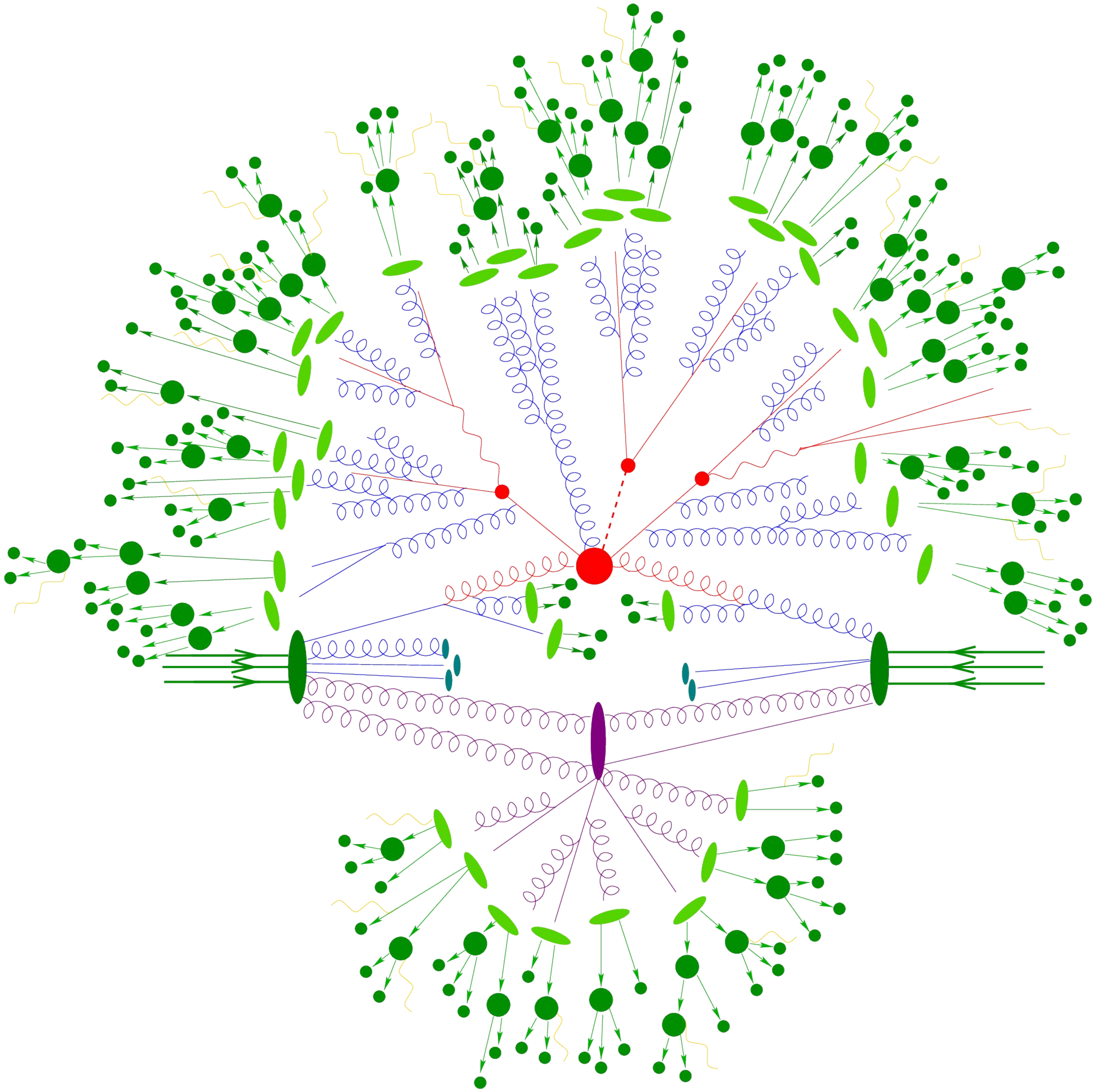
Colliders in the real world





Colliders for theorists

- Event simulation factorised into
  - Hard Process
  - Parton Shower
  - PDF/Underlying event
  - Hadronisation
  - QED radiation
  - Hadron Decays



Colliders for theorists

- Event simulation factorised into
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  - Hadronisation

- Event simulation factorised into
  - perturbative QCD / SM
  - resummation based on pQCD
  - connection to factorisation [see talk by T. Cridge]
  - NP modelling [see talk by S.Gieseke]

Colliders for theorists

- Event simulation factorised into
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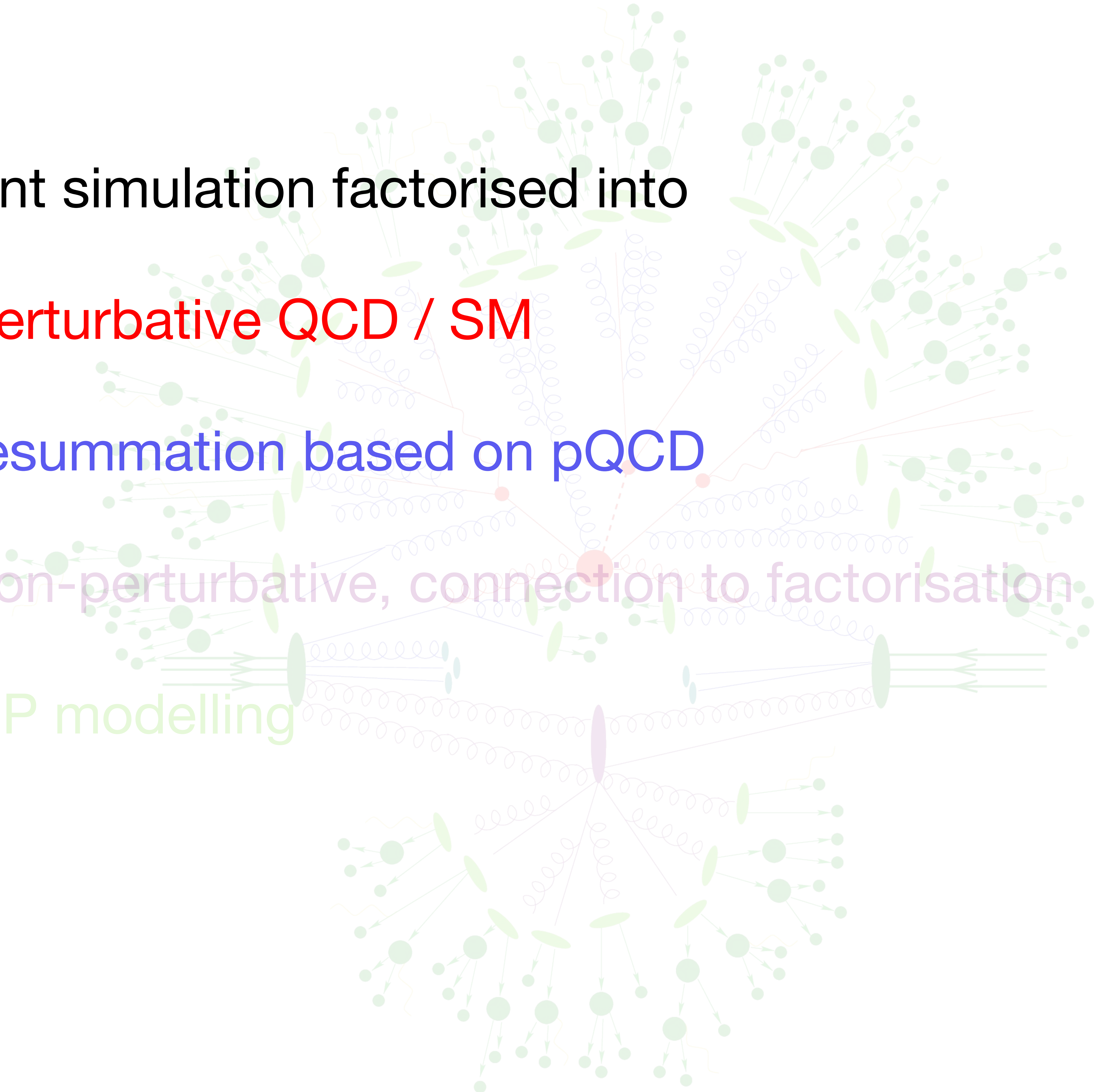
- Event simulation factorised into
  - perturbative QCD / SM
  - resummation based on pQCD
  - non-perturbative, connection to factorisation
  - NP modelling

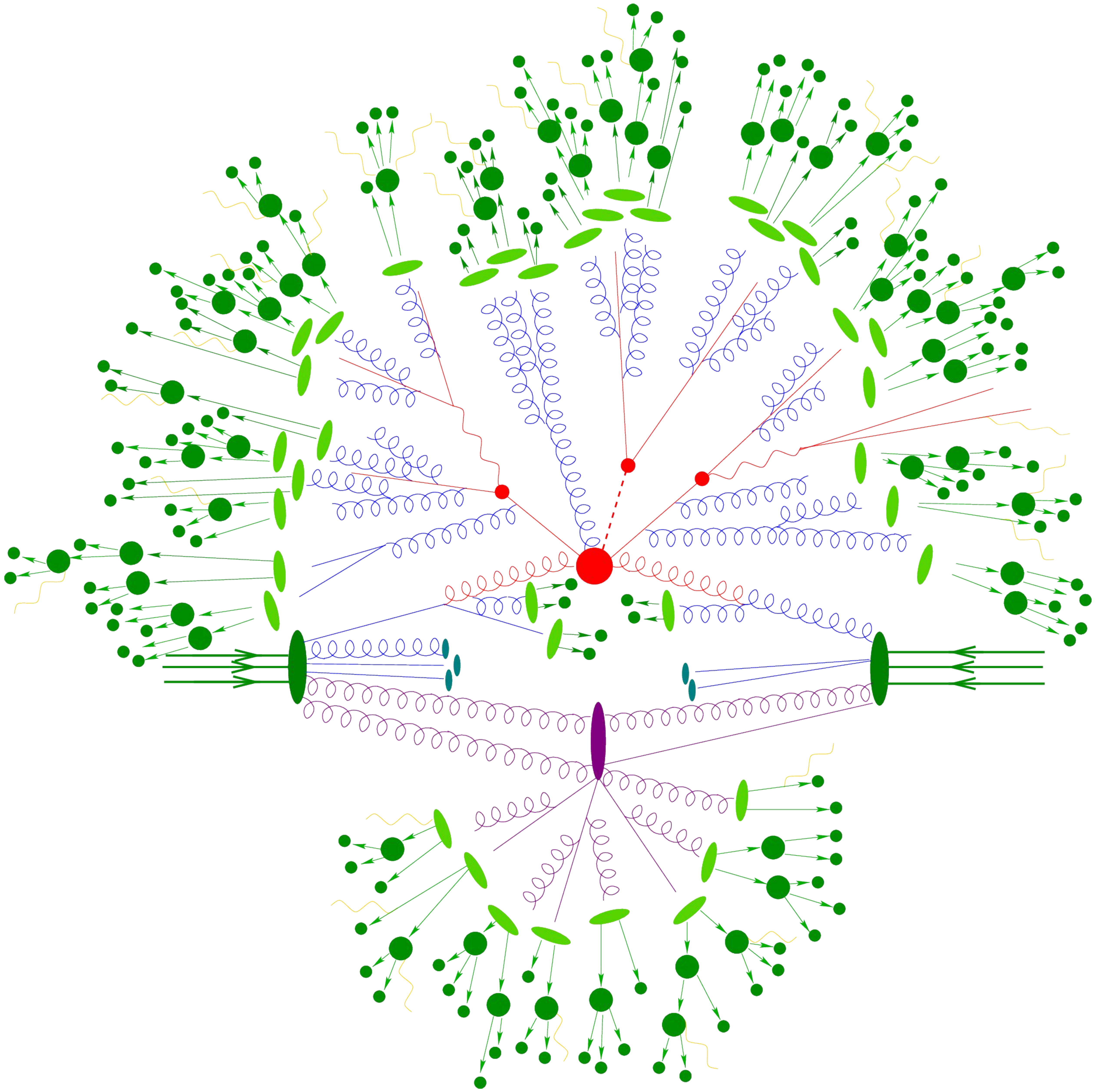


Matching

- Event simulation factorised into
  - Hard Process
  - Parton Shower
  - Underlying event
  - Hadronisation
  - Hadron Decays

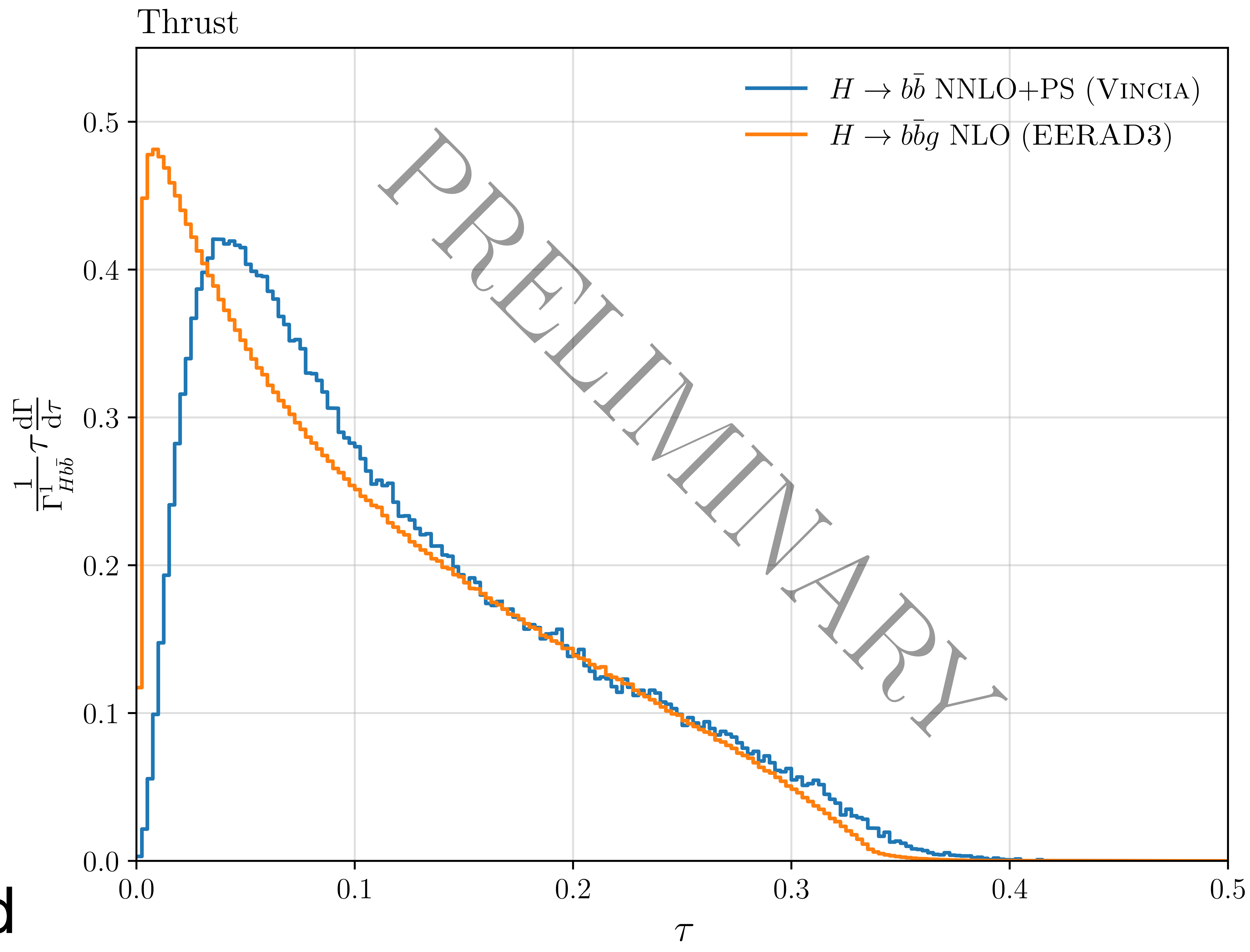
Standard for LHC SM pheno:

- matching to NLO QCD, 2 main schemes: Powheg [Nason '04] and MC@NLO [Frixione, Webber '02]



Selected developments

- matching to NNLO (inclusive for some processes) in principle available in several approaches:
  - Geneva [Alioli, Bauer, Berggen, Tackmann, Walsh, Zuberi '13] …
  - MINNLO [Monni, Nason, Re, Wiesemann, Zanderighi '19] …
  - UNLOPS [Höche, Li, Prestel '15] …
- first steps towards differential NNLO in Vincia, "Powheg-style" matching based on matrix element corrections [Skands, Preuss '23]

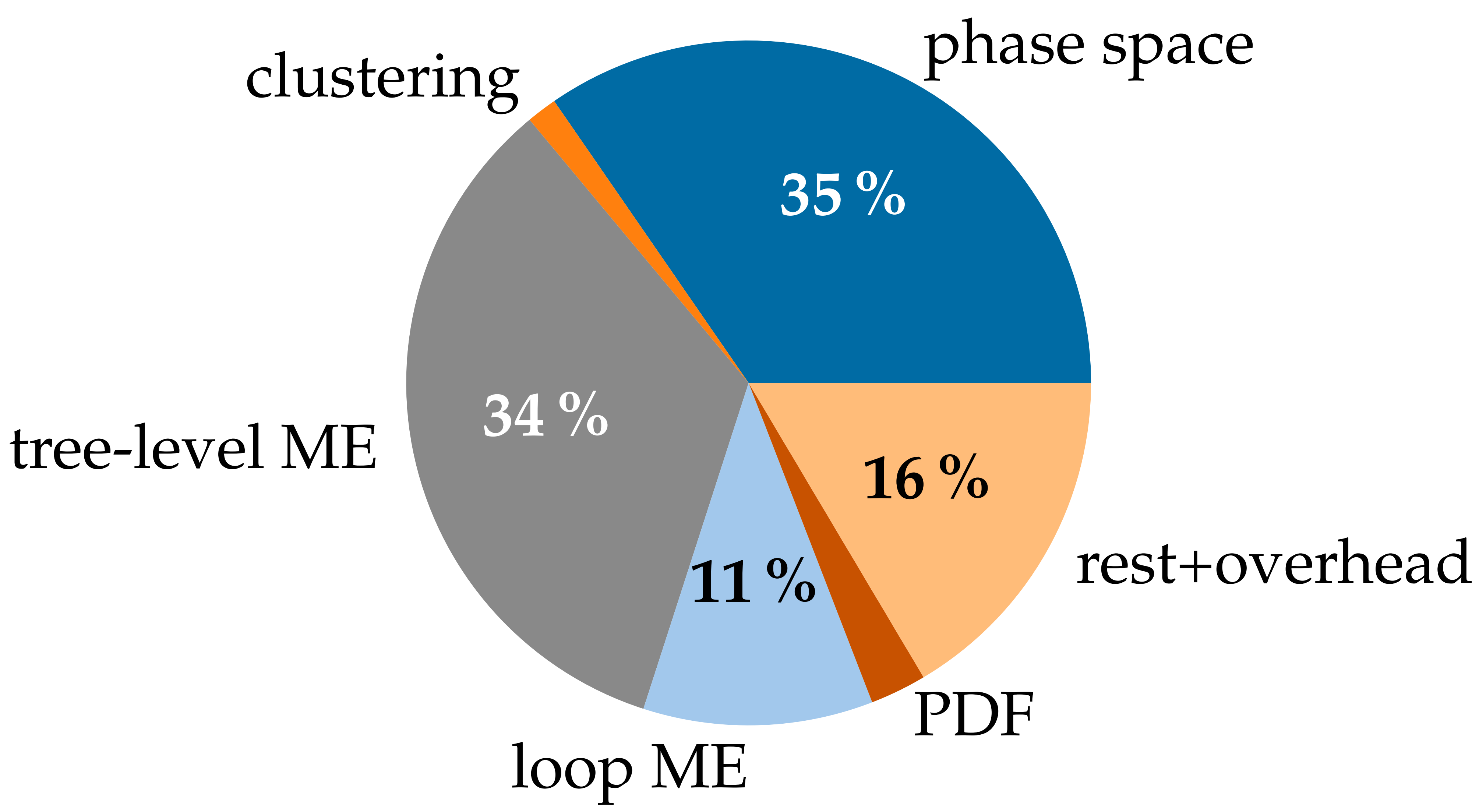


[Talk by C. Preuss HP2 '22]

Selected developments

- including electroweak corrections, in various approximations [see talk by S. Schumann]
- advancements in available fixed order calculations [see talk by M. Grazzini + specialised talks]
- efficient implementation LO/NLO calculation,
  - see e.g. [Bothmann et. al. '22]
  - improvements by $\mathcal{O}(10)$ factors in Sherpa event generation

$pp \to e^+e^-$+0,1,2j@NLO+3,4,5j@LO

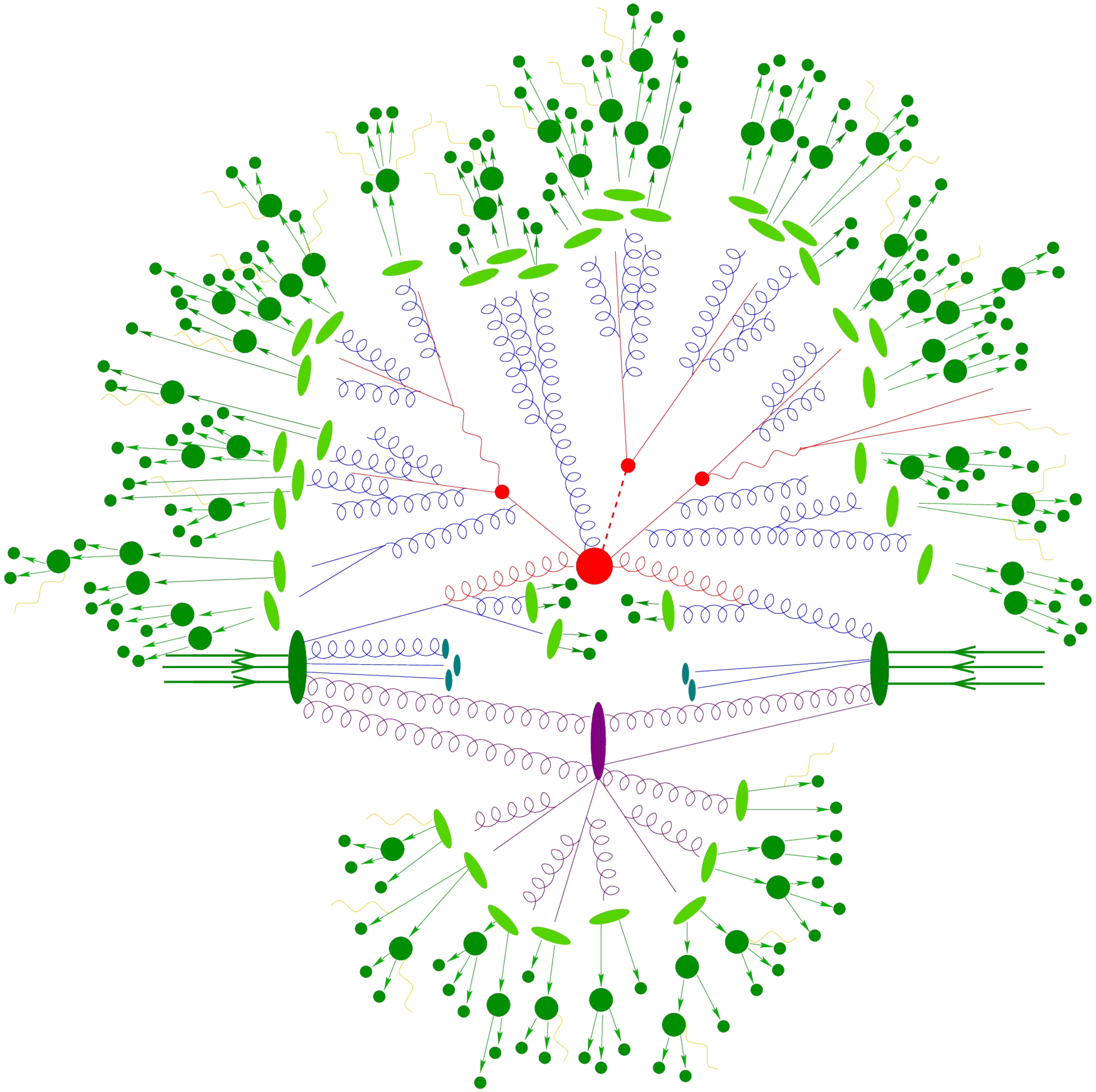


Parton Showers

- Event simulation factorised into
  - Hard Process
  - Parton Shower

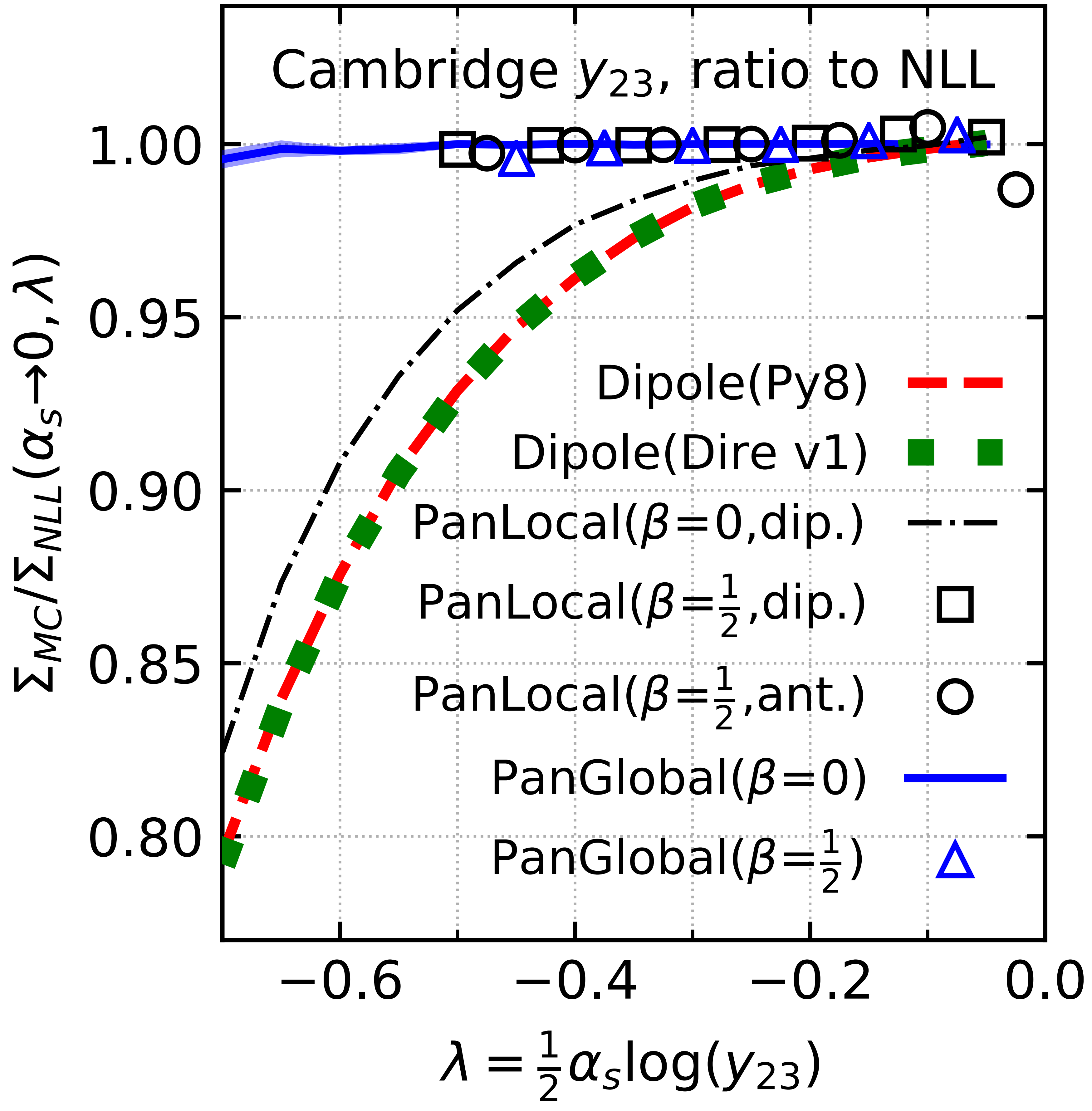
Standard for LHC SM pheno:

- angular ordered parton shower in Herwig
- dipole/antenna showers in Pythia 8 (default showers, Dire, Vincia), Herwig 7, Sherpa (default CS shower, Dire)



New Parton Showers - NLL accuracy

- typical claim based on accuracy of splitting functions etc.
  - parton showers ~ NLL accurate if CMW scheme for strong coupling is used
- observation in [Dasgupta, Dreyer, Hamilton, Monni, Salam ’18] (PanScales collaboration):
  - subtleties arise in distribution of recoil for subsequent emissions ⇒ phase space where accuracy is spoiled if soft gluon absorbs recoil
  - + in colour assignment
  - also: set of tests for shower accuracy [Dasgupta, Dreyer, Hamilton, Monni, Salam ’20]



Compare: resummation e.g. in CAESAR

- factorisation of matrix elements in soft collinear limit well known
- how to extract NLL observable independent (i.e. without additional information)?
- method from [Banfi, Salam, Zanderighi ’05]: need explicit implementation of soft-collinear limit*:

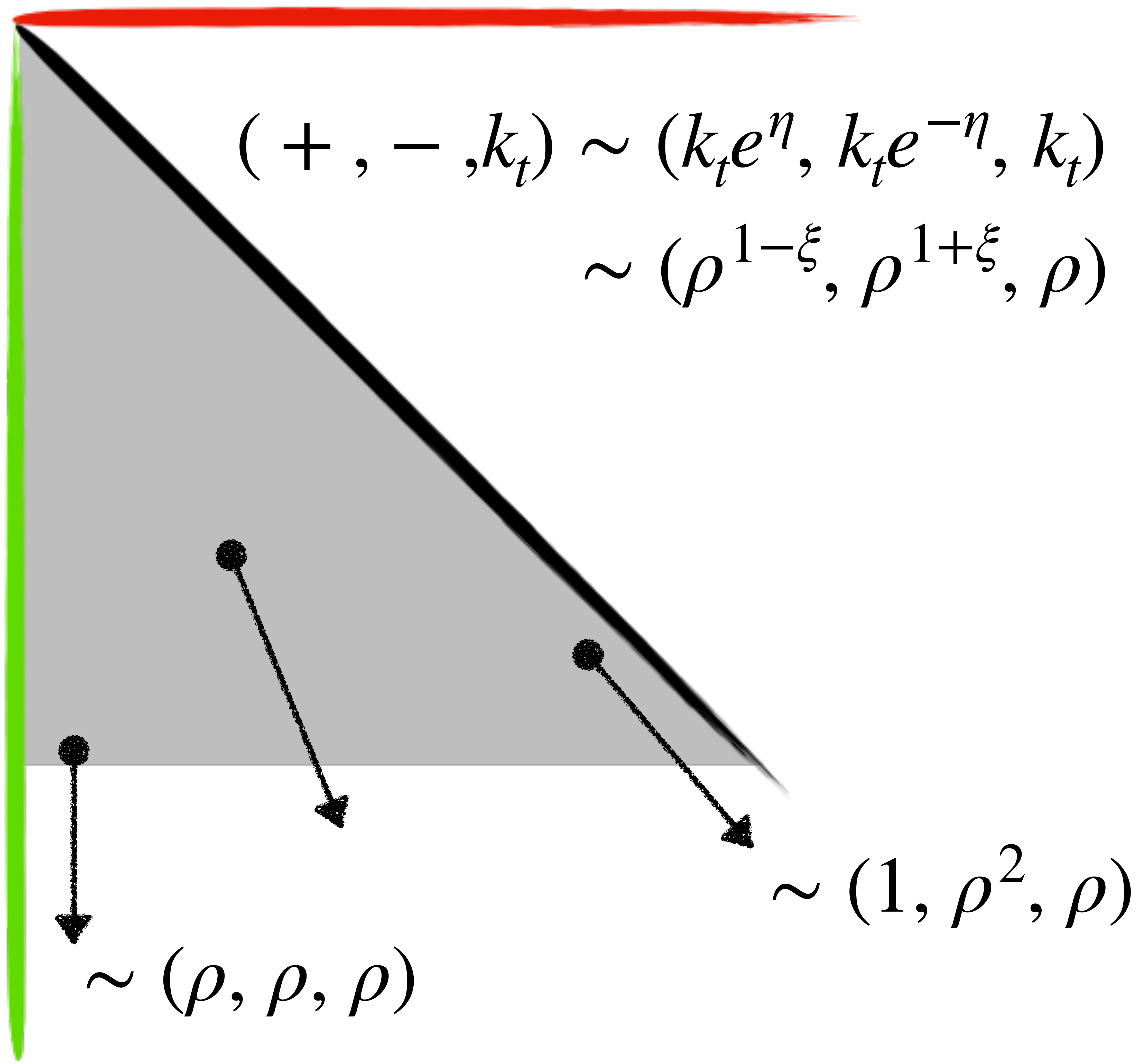
$$k_t^\rho = k_t \rho \qquad \xi = \frac{\eta}{\eta_{\max}}$$

$$\eta^\rho = \eta - \xi \ln \rho$$

and assume

$$V(k_i^\rho) = \rho V(k_i)$$

→ numerically evaluate phase space integrals in this limit



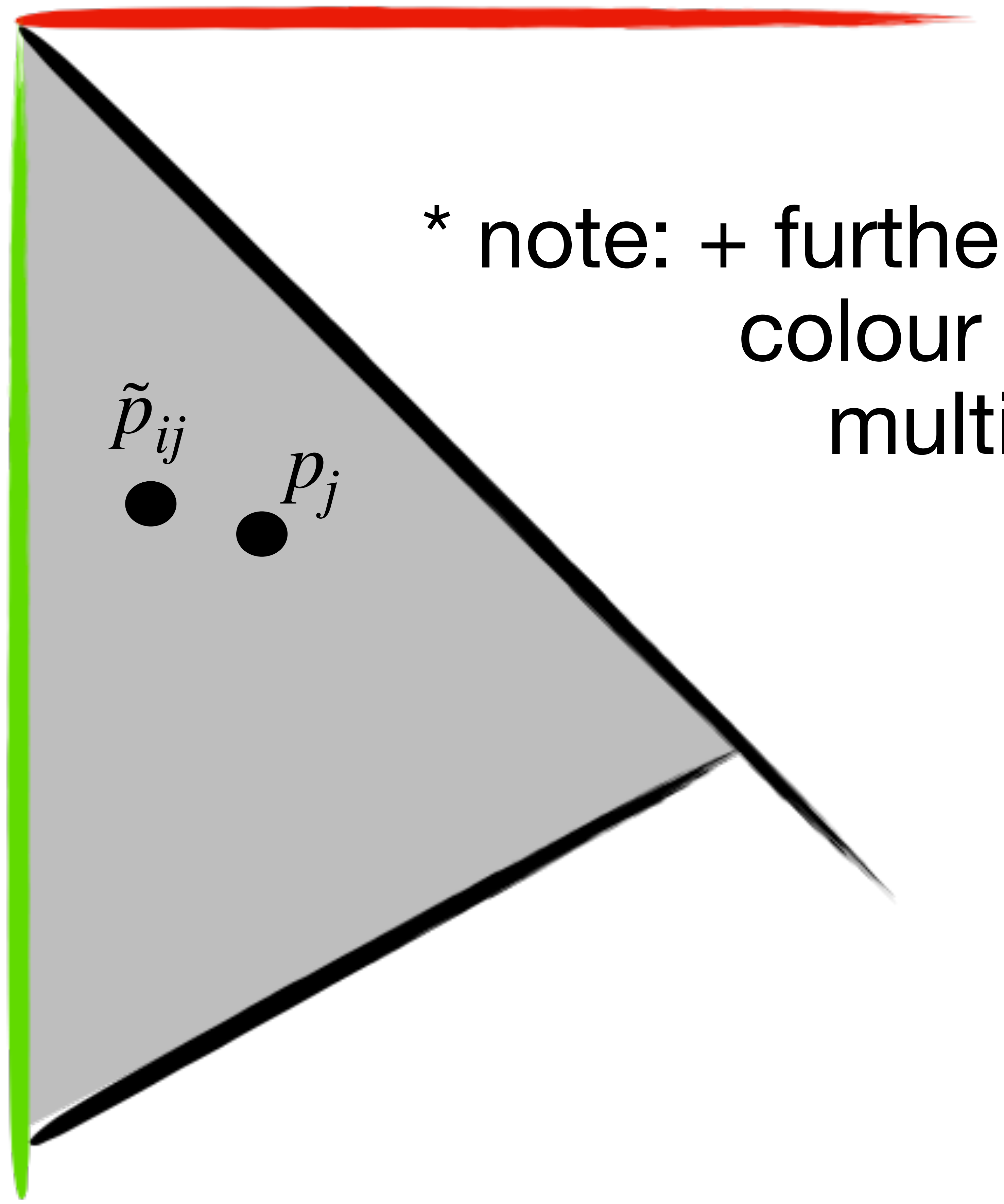
* example assuming $V(k_t, \eta) \sim k_t/Q$ for brevity

Effect of recoil on accuracy

- question: do recoil effects indeed vanish in soft limit (i.e. $\rho \to 0$)?*
  [Dasgupta,Dreyer,Hamilton,Monni,Salam '18]

$$p_i = z\tilde{p}_{ij} + (1-z)y\tilde{p}_k + k_\perp$$
$$p_j = (1-z)\tilde{p}_{ij} + zy\tilde{p}_k - k_\perp$$
$$p_k = (1-y)\tilde{p}_k\ .$$

- consider situation where we first emit $\tilde{p}_{ij}$ from p_a, p_b, then emit p_j, $\tilde{p}_{ij} \to p_i, p_j$



* note: + further problems for colour assignment in multiple emissions

- transverse momentum of p_i will be $k_t^i \sim k_t^{ij} + k_t^j \to k_t^{ij}$ as $\dfrac{k_t^j}{k_t^i} \to 0$

- but, relevant limit is $\dfrac{\Delta k_t^i}{k_t^i} \to \dfrac{\rho k_t^j}{\rho k_t^i} = \mathcal{O}(1)$

New Parton Showers - NLL accuracy

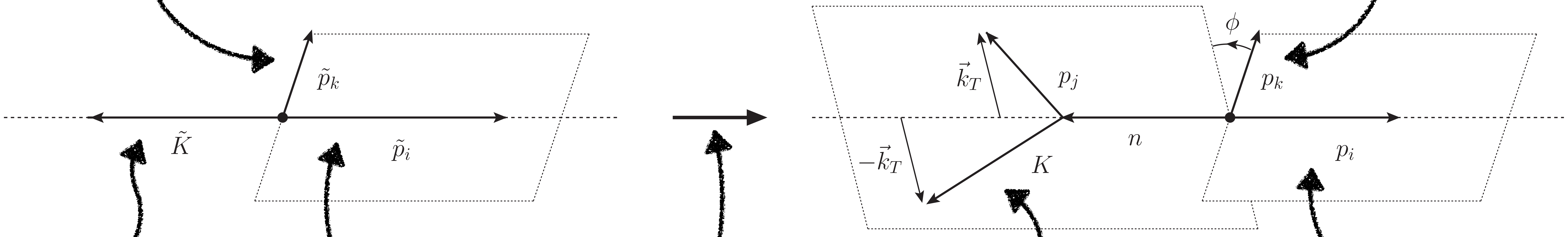
- Several solutions/re-evaluations of parton shower concepts:
- [Dasgupta, Dreyer, Hamilton,Monni, Salam, Soyez ’20], [vanBeekveld, Ferrario Ravasio, Hamilton, Salam, Soto-Ontoso,Soyez ’22]
    - partitioning of splitting functions and appropriate choice of evolution variable can lead to NLL accurate shower for local and global recoil strategies
- [Forshaw, Holguin, Plätzer ’20]
    - Connections between angular ordered and dipole showers
- [Nagy, Soper ’11]
    - local transverse, global longitudinal recoil
- [Herren, Krauss, DR, Schönherr, Höche ’22]
    - global recoil, enables analytic comparison to resummation and proof of NLL accuracy
- [Preuss ’24]
    - global recoil in antenna shower Vinca

Example Solution: Alaric

- Before splitting:
- After splitting:

colour spectator

$p_k = \tilde{p}_k$



$\sum$ other momenta k_i

splitter

$p_i = z\tilde{p}_i$

$K^2 = \tilde{K}^2$

$\tilde{K} + \tilde{p}_i = K + p_i + p_j$

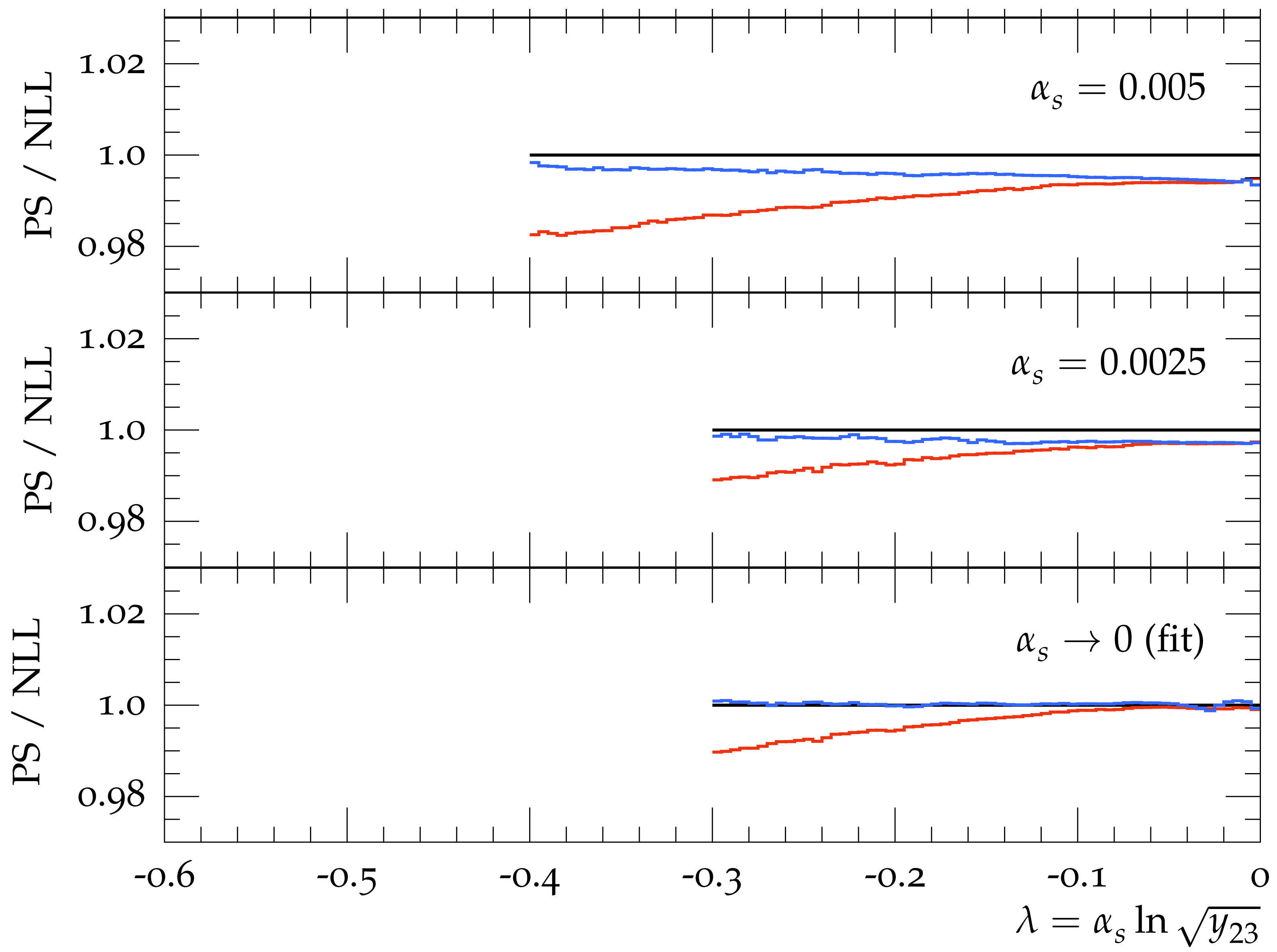
$$k_i^\mu \to \Lambda^\mu{}_\nu k_i^\nu$$

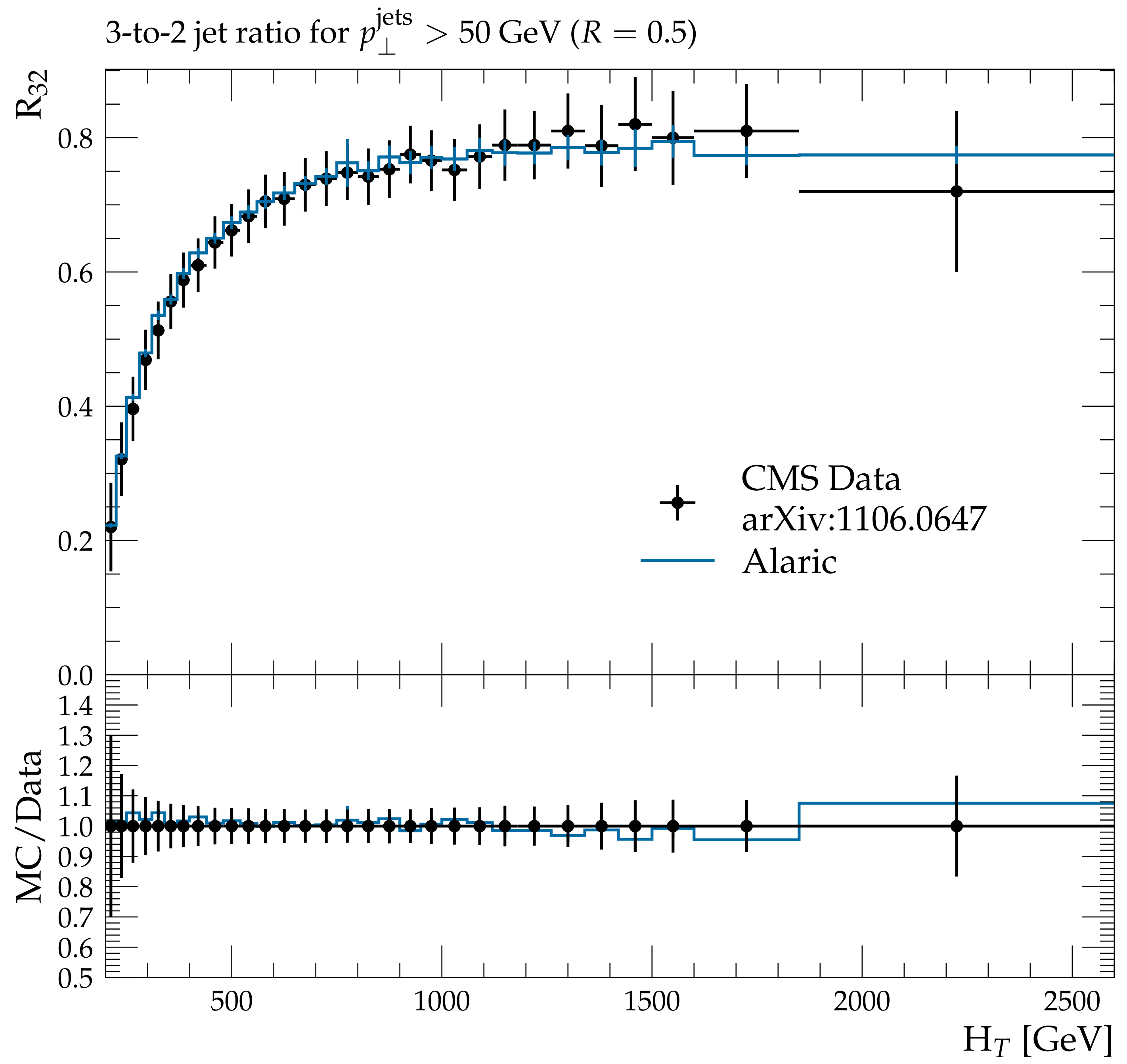
[Catani, Seymour '97]

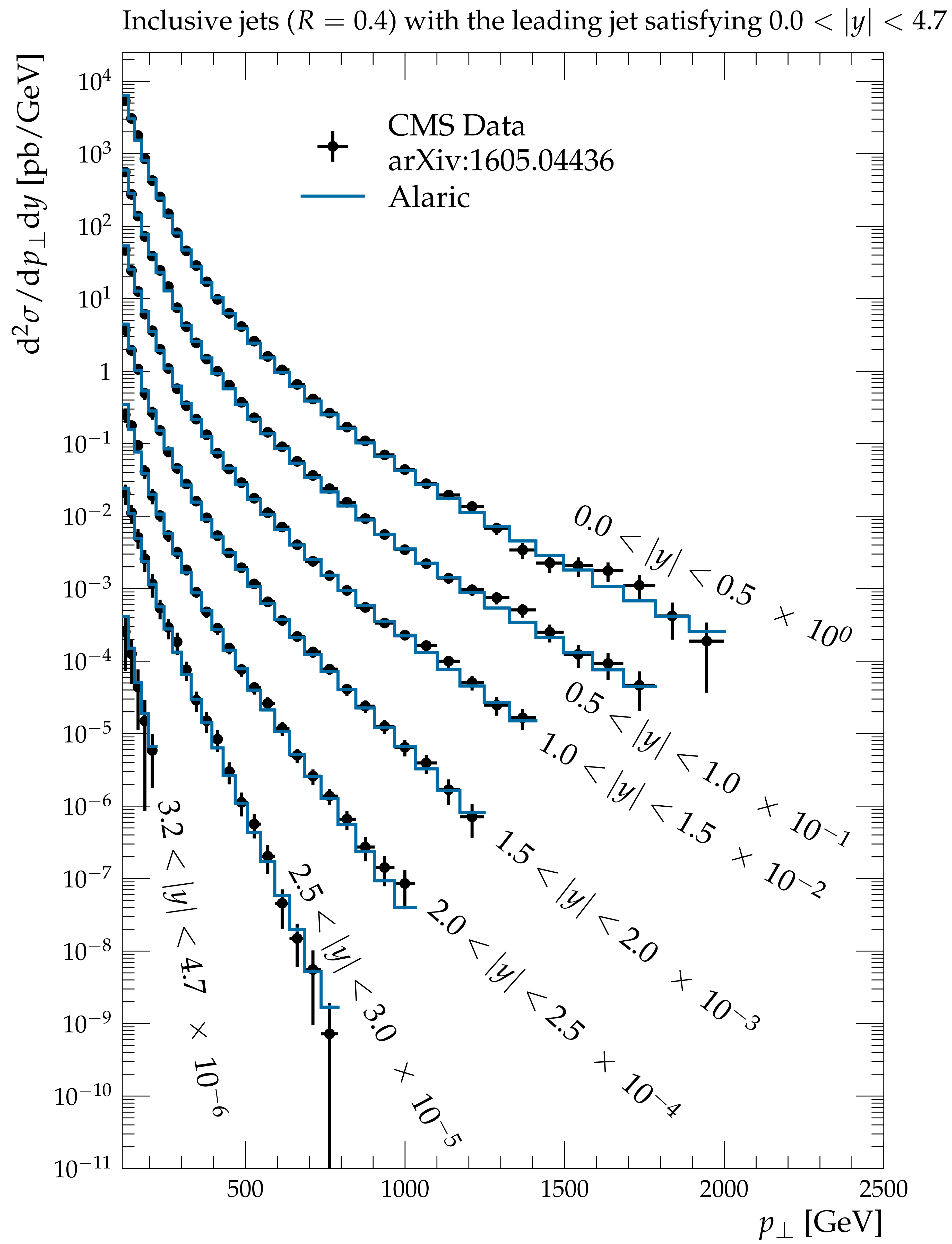
$$\Lambda^\mu{}_\nu = g^\mu{}_\nu - \frac{(K+\tilde{K})^\mu (K+\tilde{K})_\nu}{K\cdot\tilde{K} + \tilde{K}^2} + 2\frac{K^\mu \tilde{K}_\nu}{\tilde{K}^2} \quad \to \quad \Lambda^\mu{}_\nu \tilde{K}^\nu = K^\mu$$

Alaric at the LHC — jets

- [Höche, Krauss, DR ’24] extend Alaric method to IS evolution
- satisfactory description of inclusive and dijet events
- transverse momentum spectrum of leading jet and ratio 3-to-2 jet rate
- NLL accuracy shown numerically for FS, in addition to analytic proof

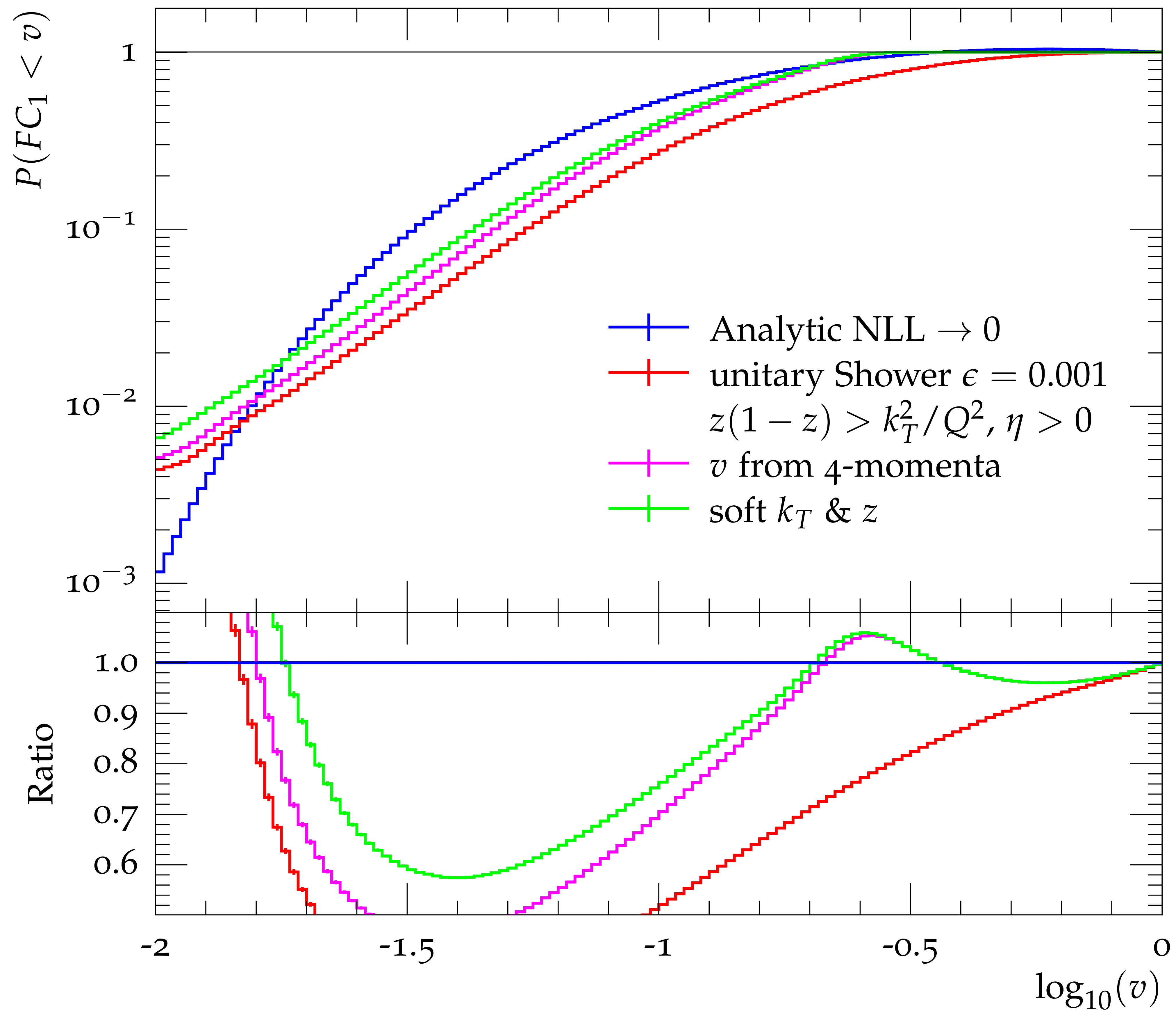






Beyond logarithmic accuracy

- Observations
  - LL and NLL accurate showers can be very similar (e.g. failing of NLL accuracy numerically undetectable for Dire in prominent observables like Thrust)
  - NLL accurate showers can differ significantly from NLL result away from strict limit
  - $\Rightarrow$ subleading effect play a significant role in phenomenological successful parton showers, more systematic understanding desirable, see also [Höche, Siegert, DR '17]



Alaric beyond NLL - subleading effects

assume Sudakov decompose like

$$p_i^\mu = z_i \hat{p}_{ij}^\mu + \frac{-k_t^2}{z_i\, 2p_{ij}\bar{n}}\, \bar{n}^\mu + k_t^\mu \ ,$$

$$p_j^\mu = z_j \hat{p}_{ij}^\mu + \frac{-k_t^2}{z_j\, 2p_{ij}\bar{n}}\, \bar{n}^\mu - k_t^\mu$$

derivation of splitting functions leads to:

$$P^{(\mathrm{F})}_{qq\,\|}(p_i, p_j, \bar{n}) = C_F\, (1-\varepsilon)(1-z_i)$$

$$P^{(\mathrm{F})}_{gg\,\|}(p_i, p_j, \bar{n}) = 2C_A\, z_i z_j \ ,$$

$$P^{(\mathrm{F})}_{gq\,\|}(p_i, p_j, \bar{n}) = T_R \left[\, 1 - \frac{2\, z_i z_j}{1-\varepsilon} \,\right] .$$

actual shower kinematics:

$$p_i = z\,\tilde{p}_i \ ,$$

$$p_j = (1-z)\,\tilde{p}_i + v\big(\tilde{K} - (1-z+2\kappa)\,\tilde{p}_i\big) - k_\perp \ ,$$

$$K = \tilde{K} - v\big(\tilde{K} - (1-z+2\kappa)\,\tilde{p}_i\big) + k_\perp \ ,$$

$$p_i = \frac{z}{1-v(1-z+\kappa)}\,\hat{p}_{ij} + \frac{z}{1-v(1-z+\kappa)}\,k_\perp + \mathcal{O}\left(\frac{k_\perp^2}{2\tilde{p}_i\tilde{K}}\right) ,$$

$$p_j = \frac{(1-z)(1-v)-v\kappa}{1-v(1-z+\kappa)}\,\hat{p}_{ij} - \frac{z}{1-v(1-z+\kappa)}\,k_\perp + \mathcal{O}\left(\frac{k_\perp^2}{2\tilde{p}_i\tilde{K}}\right)$$

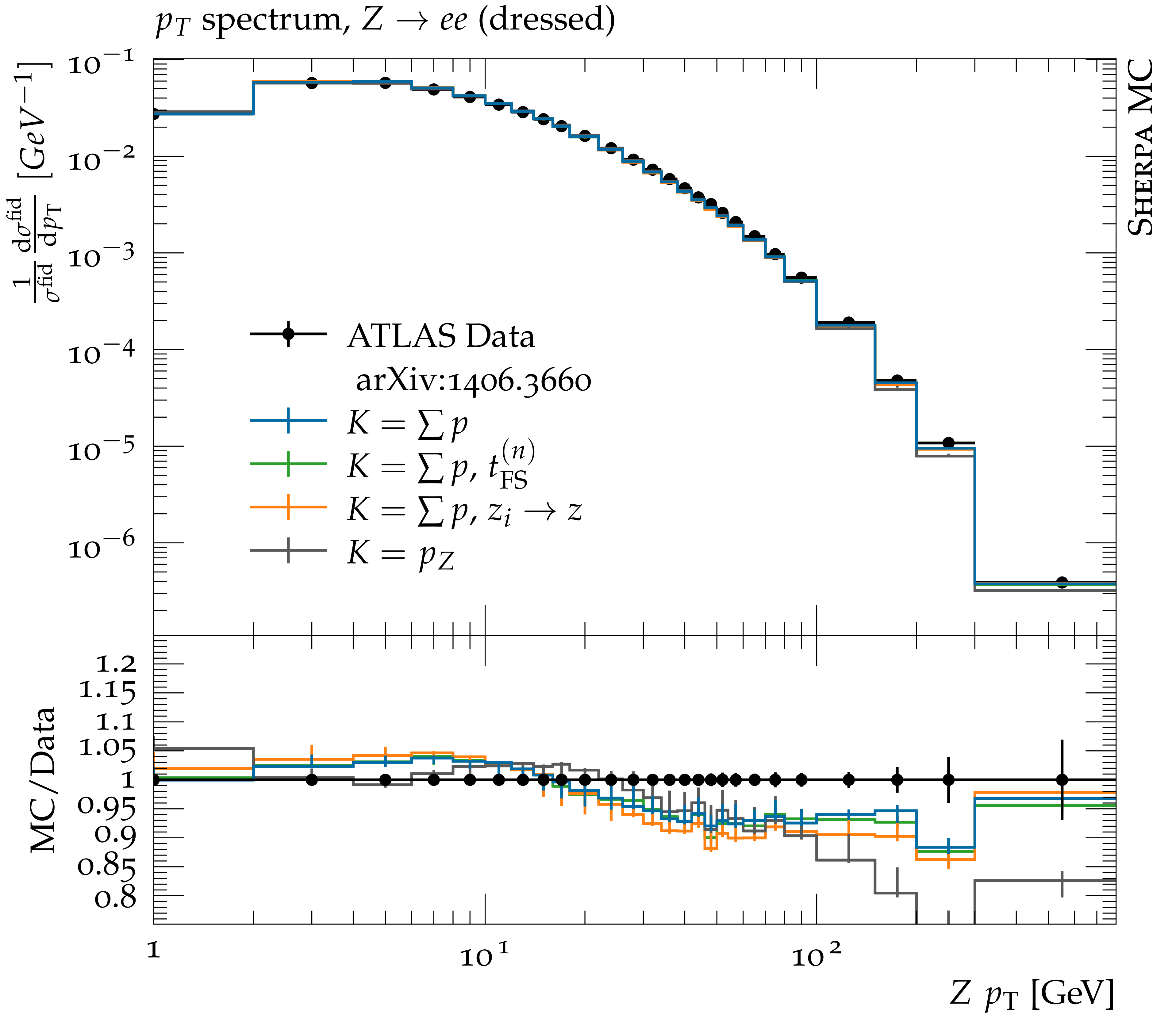
ultimately, "proper" splitting variables:

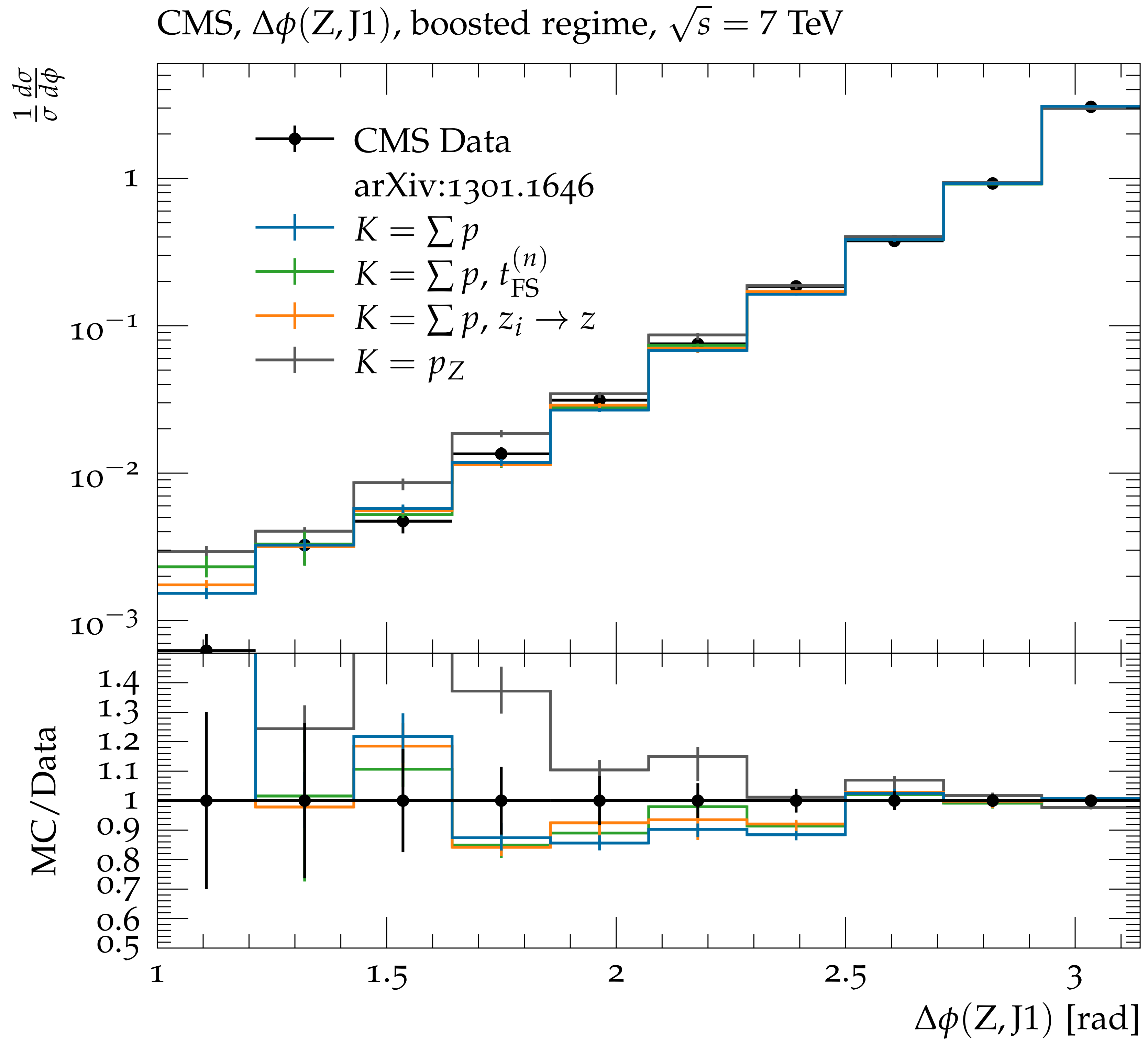
$$z_i = \frac{z}{1-v(1-z+\kappa)} \ ,$$

$$z_j = 1 - \frac{z}{1-v(1-z+\kappa)}$$

Alaric — subleading effects in Z+jets

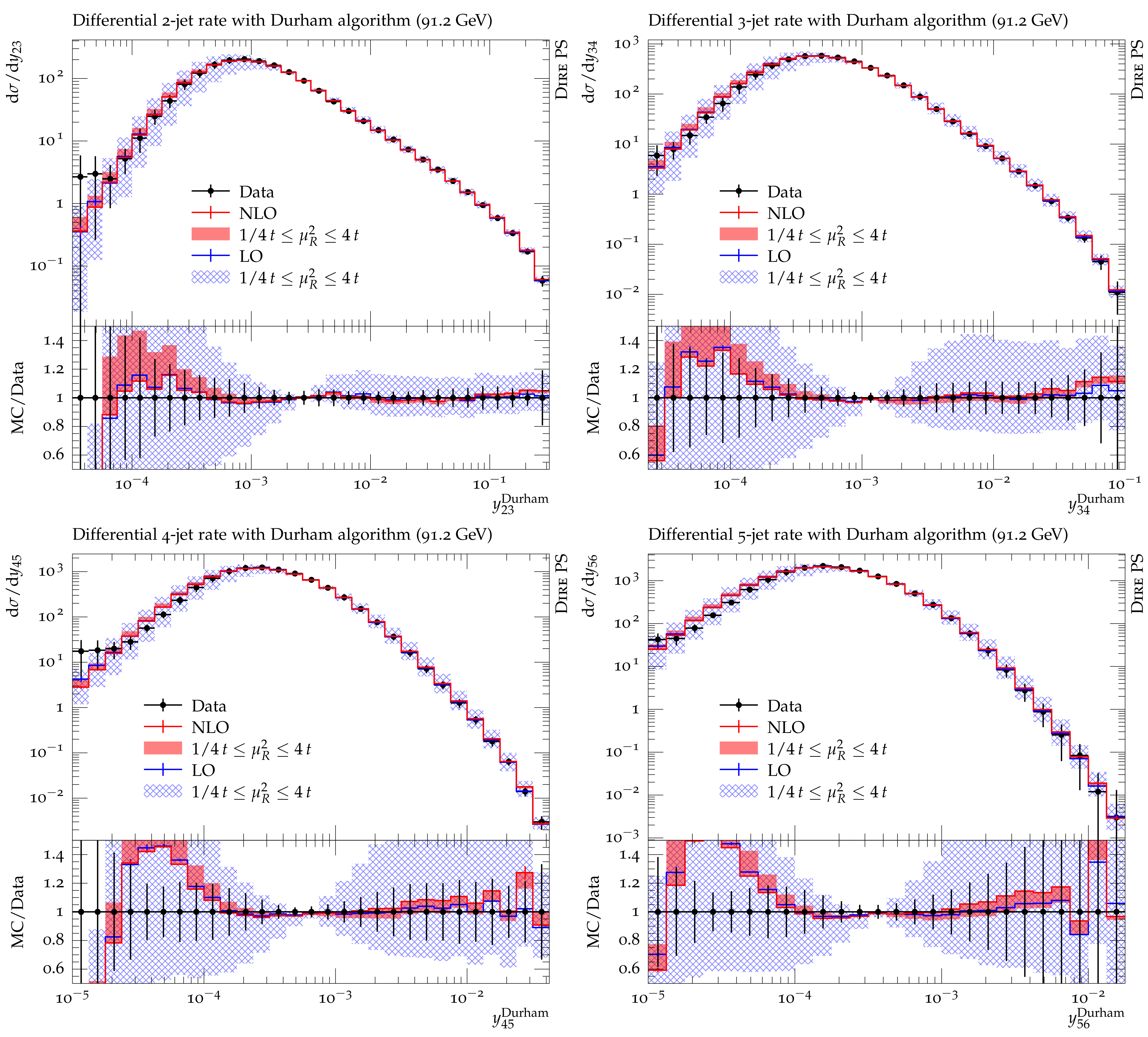
- effects/choices beyond NLL accuracy:
  - choice of evolution variable (up to factors of $z \sim 1$)
  - identify PS parameter z with z_i, z_j
  - choice of recoil momentum K (NLL accuracy needs "hard" K)





Towards NNLL - Shower Evolution at NLO

- NLO splitting kernels implemented in a parton shower [Höche, Prestel ‘17], [Dulat, Höche, Prestel ‘18]
- not in a NLL safe framework, but conceptual problems are largely solved
- more recent work on the precise relation to NNLL resummation and in other showers [Dasgupta, El-Menoufi ‘21] [Braun-White, Glover, Preuss ’23] [Ferraro Ravasio, Hamilton, Karlberg, Salam, Skybox ‘23], [van Beekveld, Dasgupta, El-Menoufi, Helliwell, Monni ’23] …



[Höche, Krauss, Prestel ’17]

Summary & other topics

- perturbative inputs to event generation, focus on parton showers and their log accuracy
- many additional topics not discussed:
    - improvements to color evolution
    - accurate matching already at NLO to achieve NLL' accuracy
    - QED precision physics / photon resummation
    - massive Quark effects
    - …