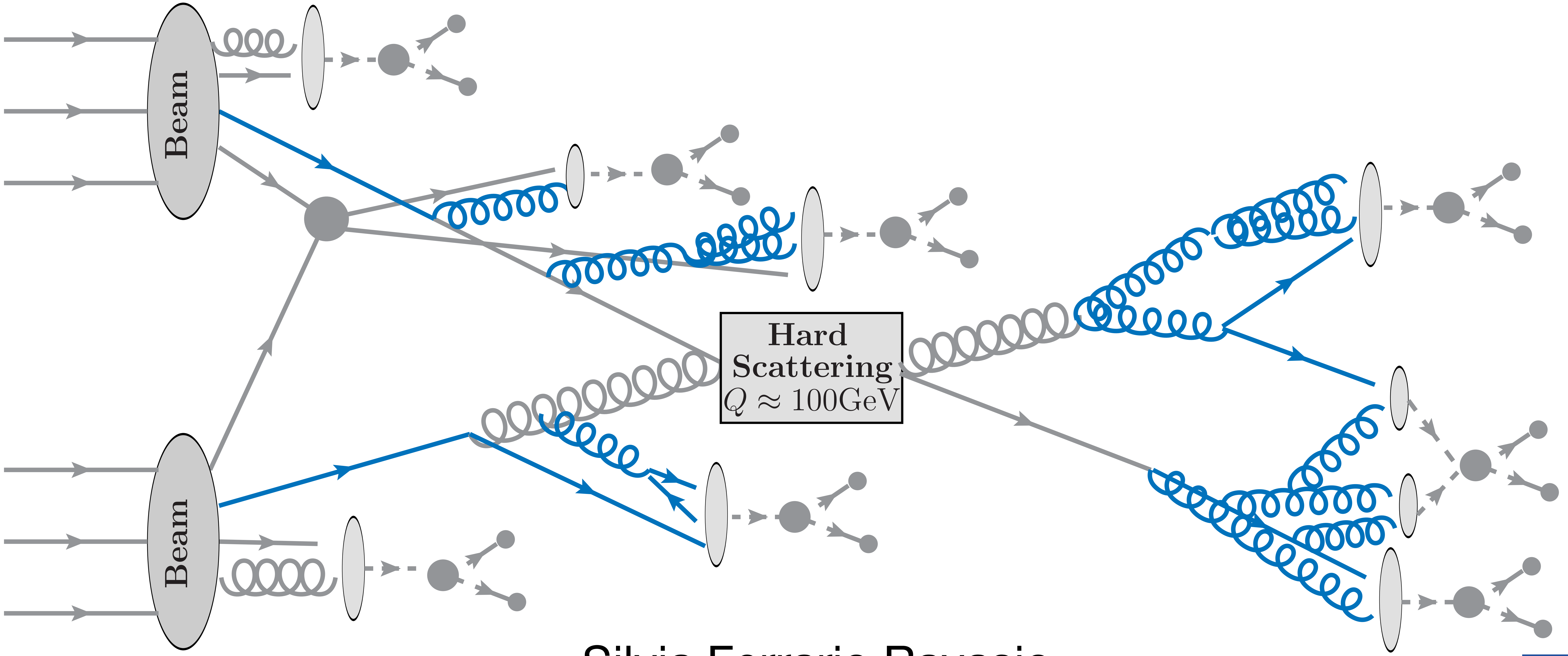
Recent Progresses in Parton Showers with higher logarithmic accuracy



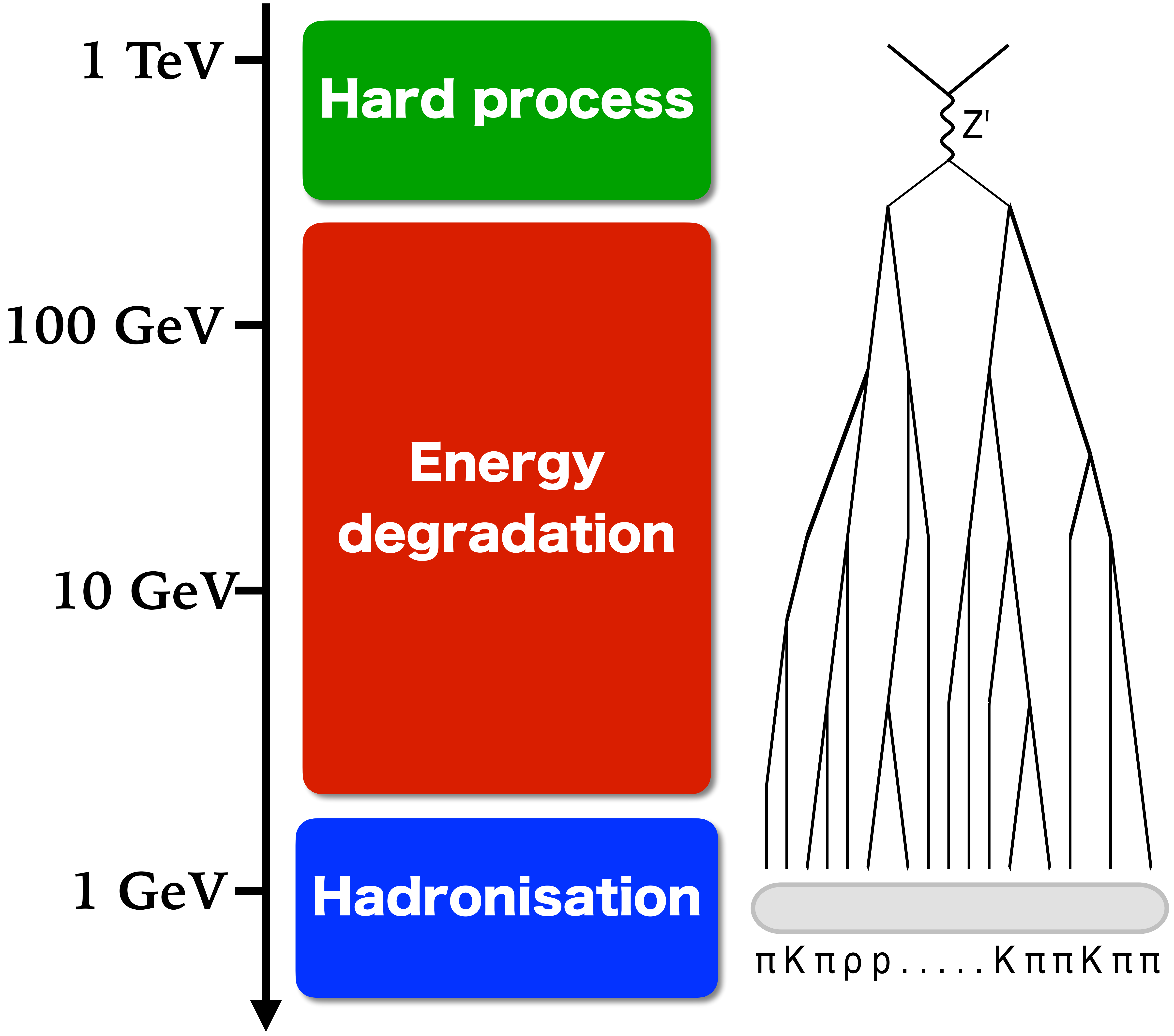
Silvia Ferrario Ravasio

7th FCC Physics Workshop

31st January 2024, Laboratoire d'Annecy de physique des particules

Shower Monte Carlo event generators

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



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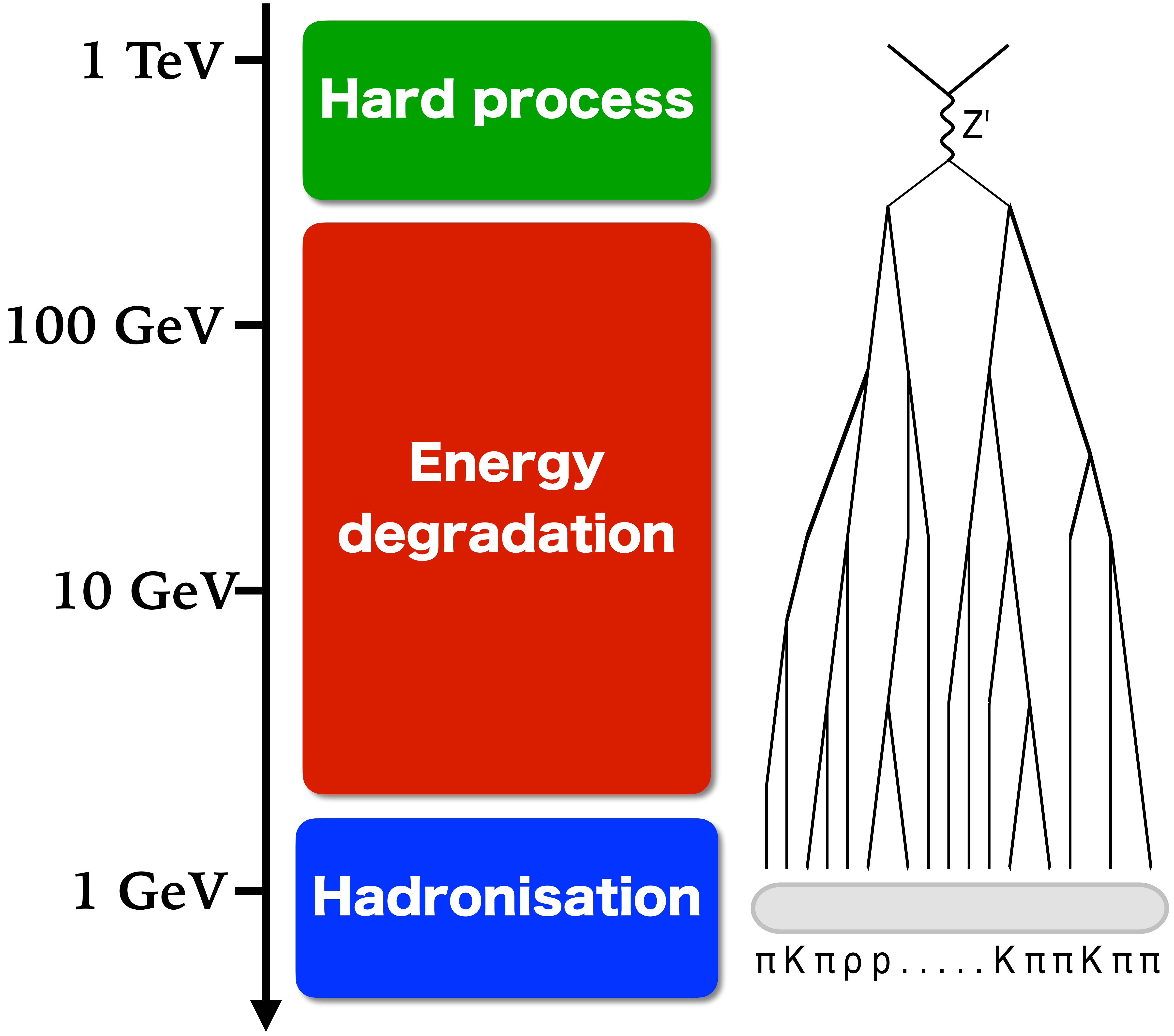

Parton Showers

- Energy degradation of hard particles produced during the collision
- Recent and future developments to reach percent level precision

Shower Monte Carlo event generators

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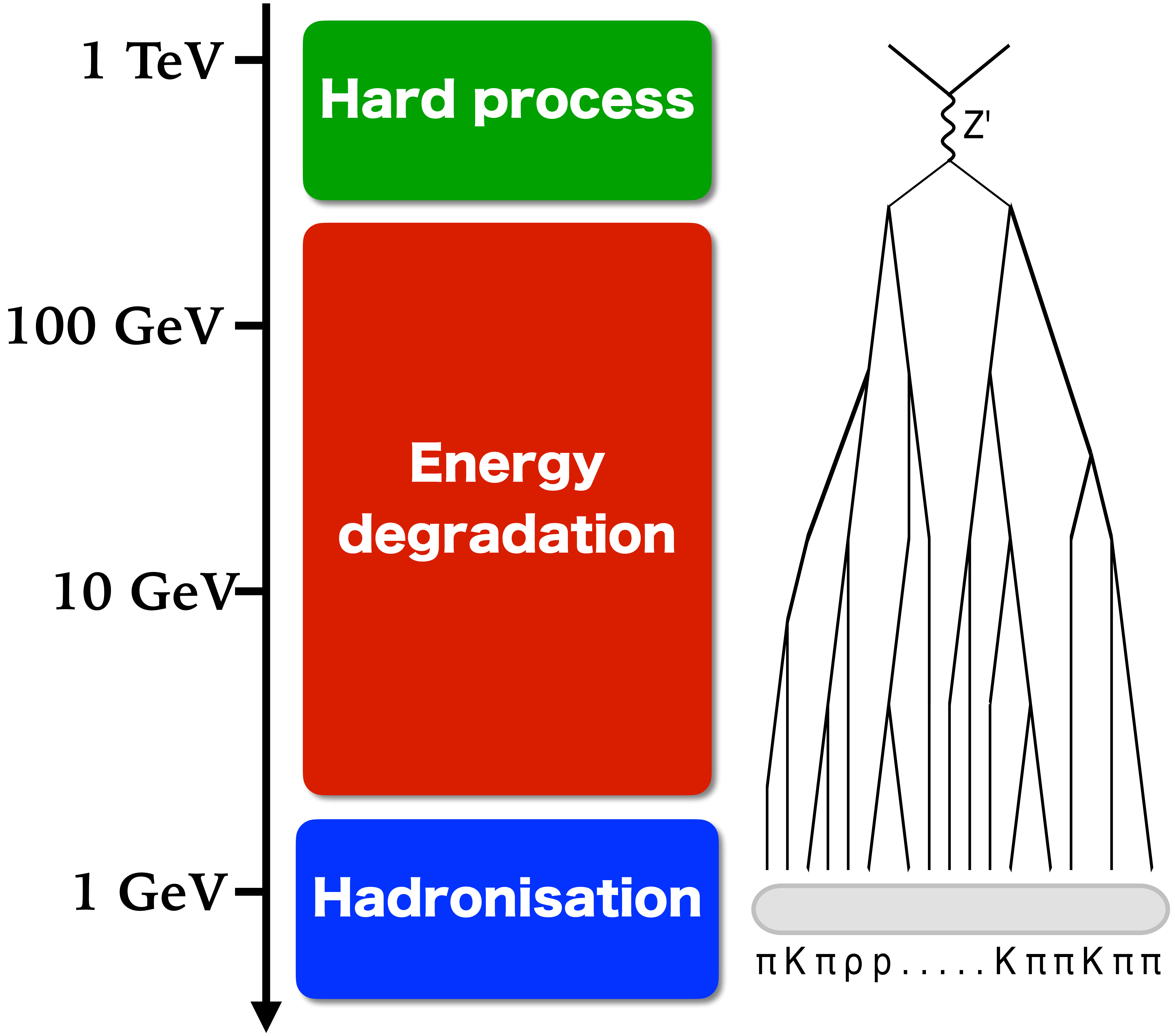


Matching

- See A. Karlberg

Parton Showers

- Energy degradation of hard particles produced during the collision
- Recent and future developments to reach percent level precision

Hadronisation

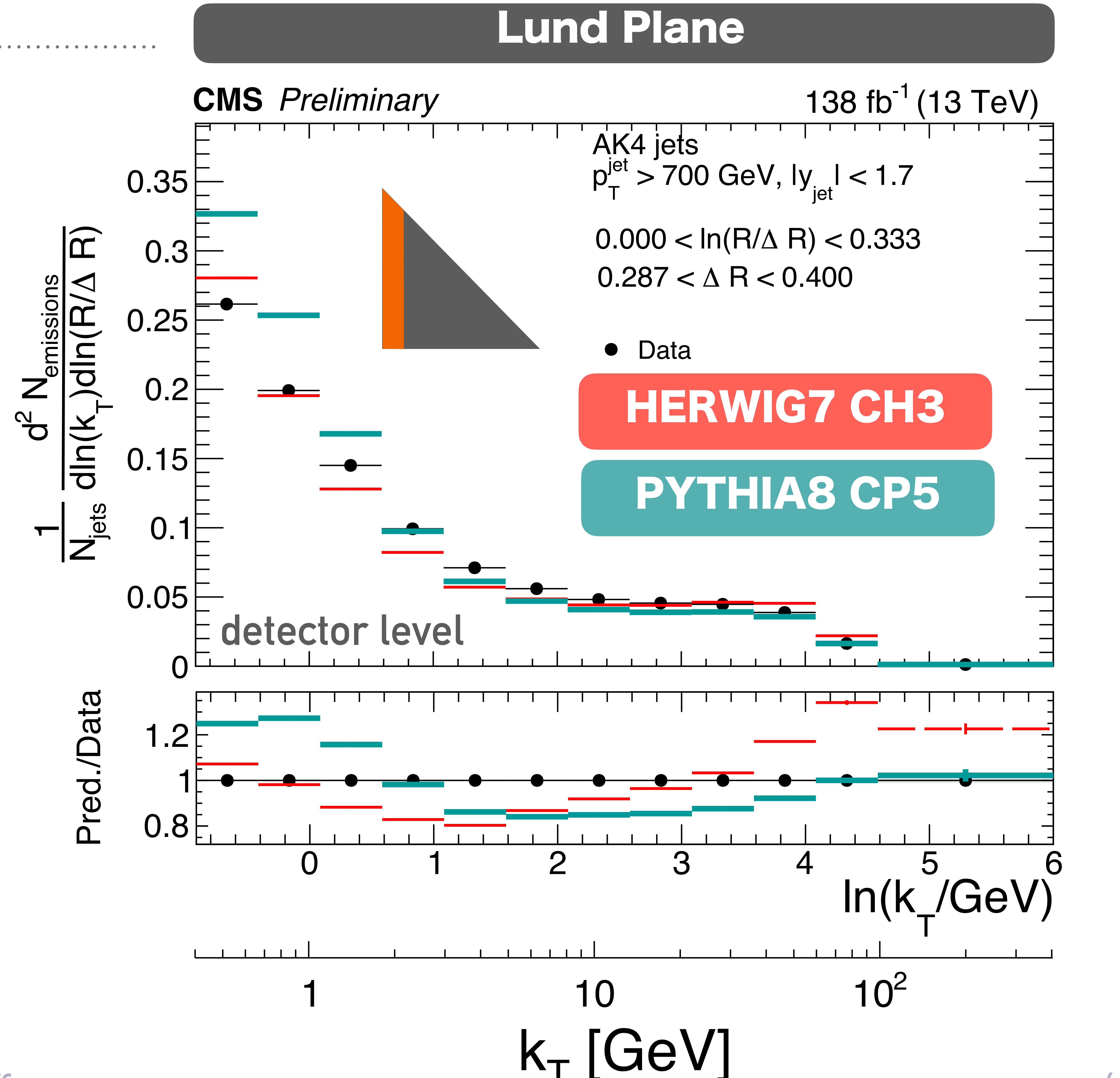
- Tuned to parton showers

QED

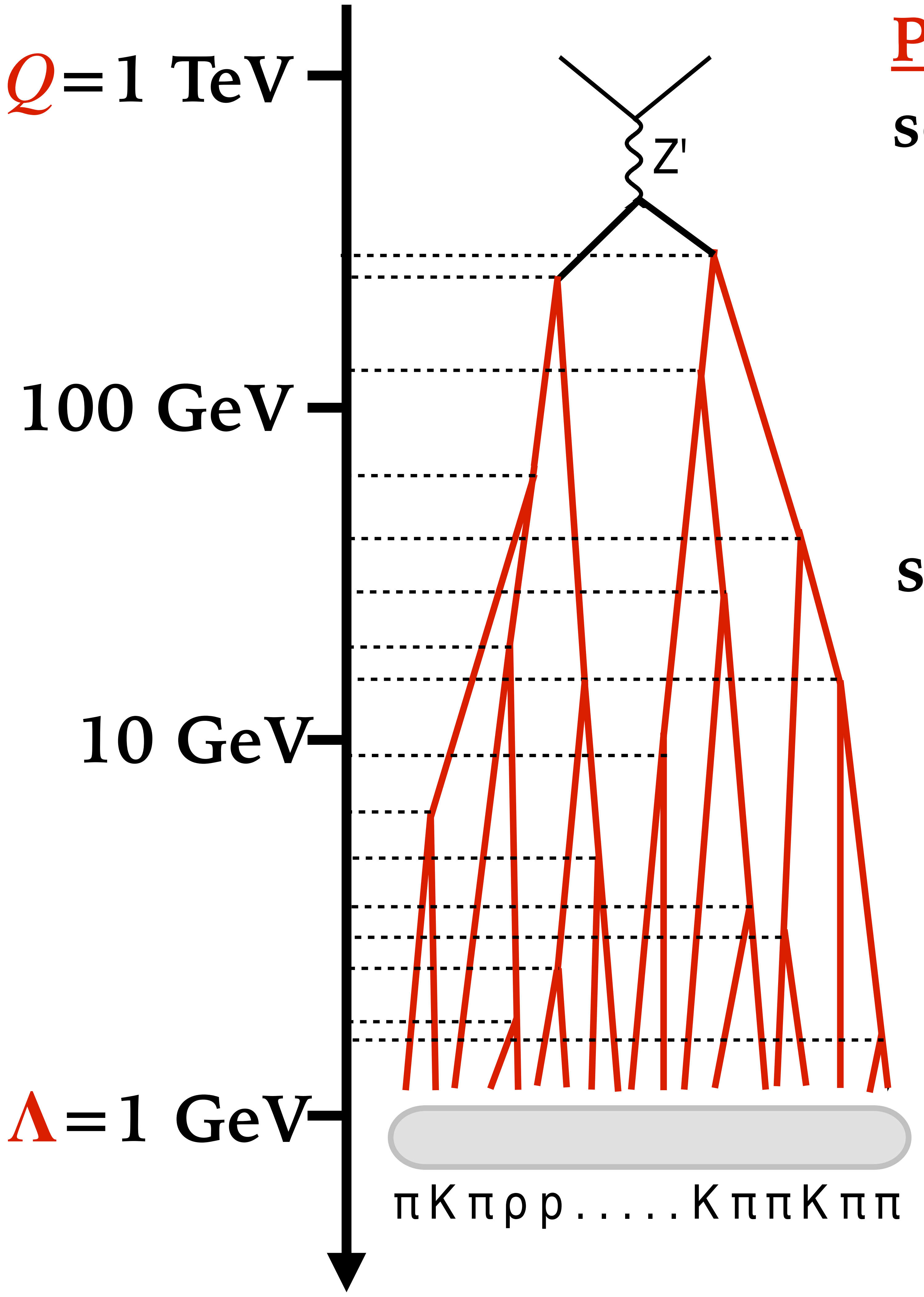
- A lot of work to be done! (See e.g. Reutgens, Frixione, Stagnitto)

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 meet the precision target of the **FCC**!



Logarithmically-accurate Parton Showers



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

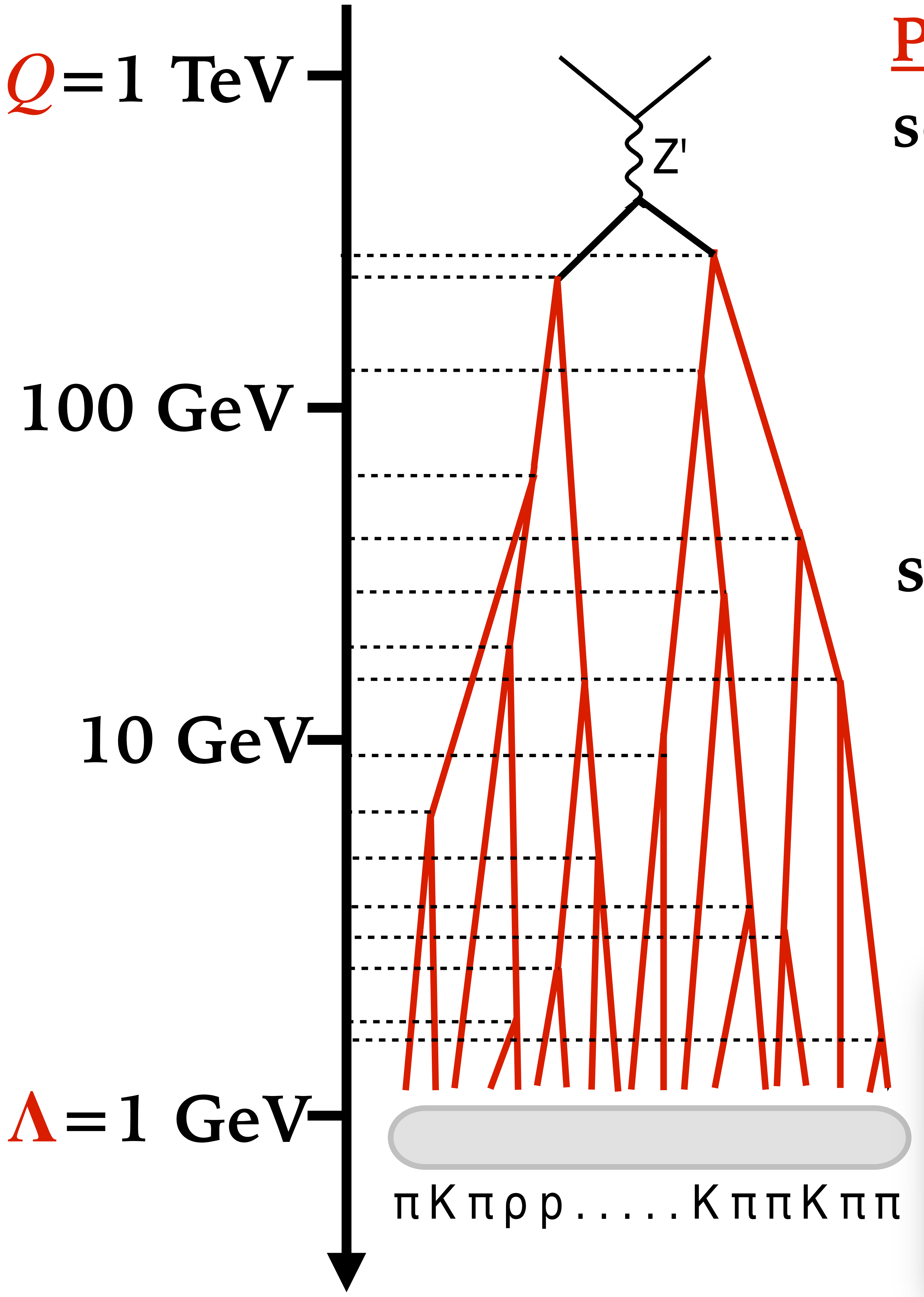
$$L = \ln \frac{Q}{\Lambda} \gg 1$$

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

Logarithmically-accurate Parton Showers



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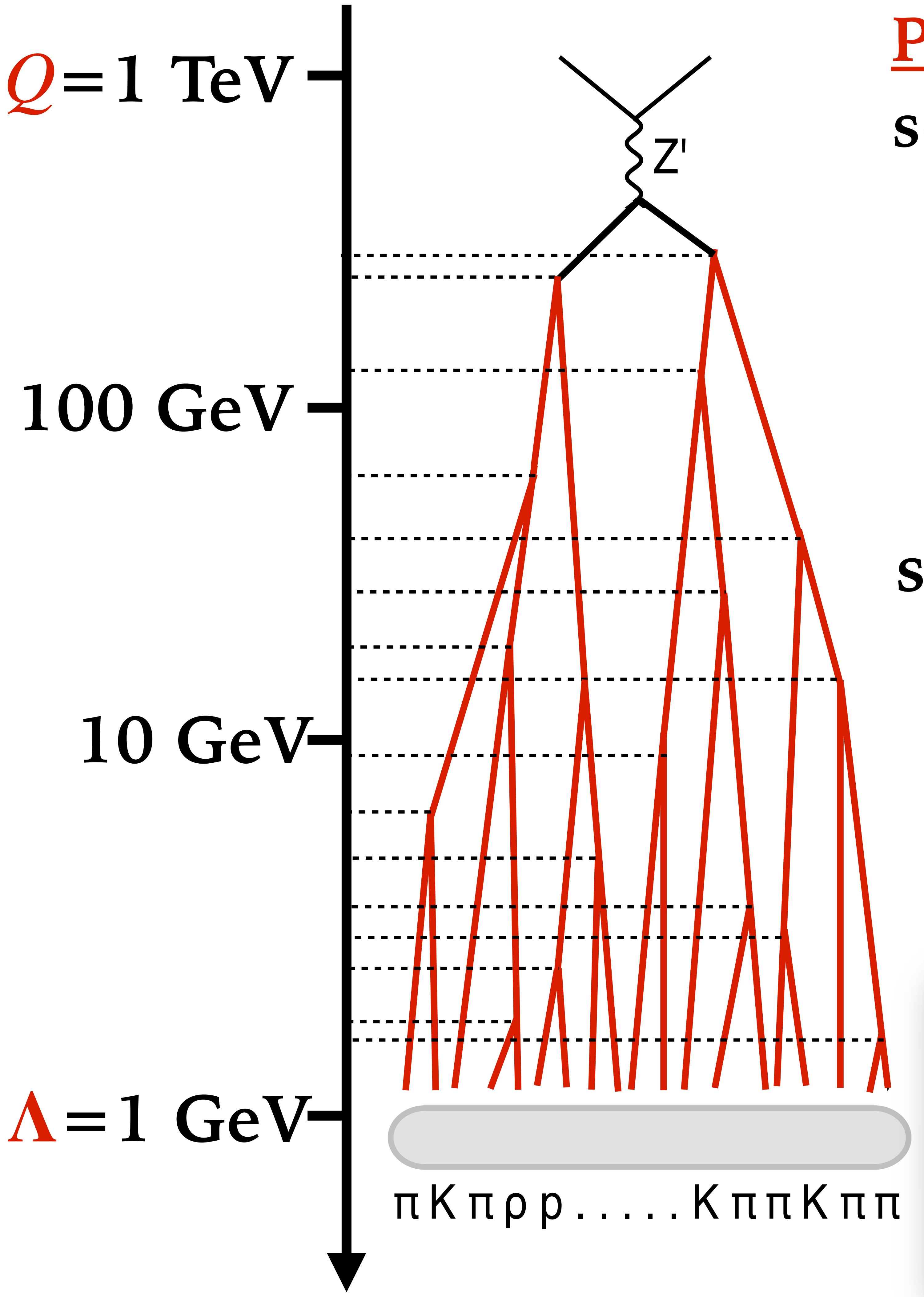
??

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

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!

Logarithmically-accurate Parton Showers



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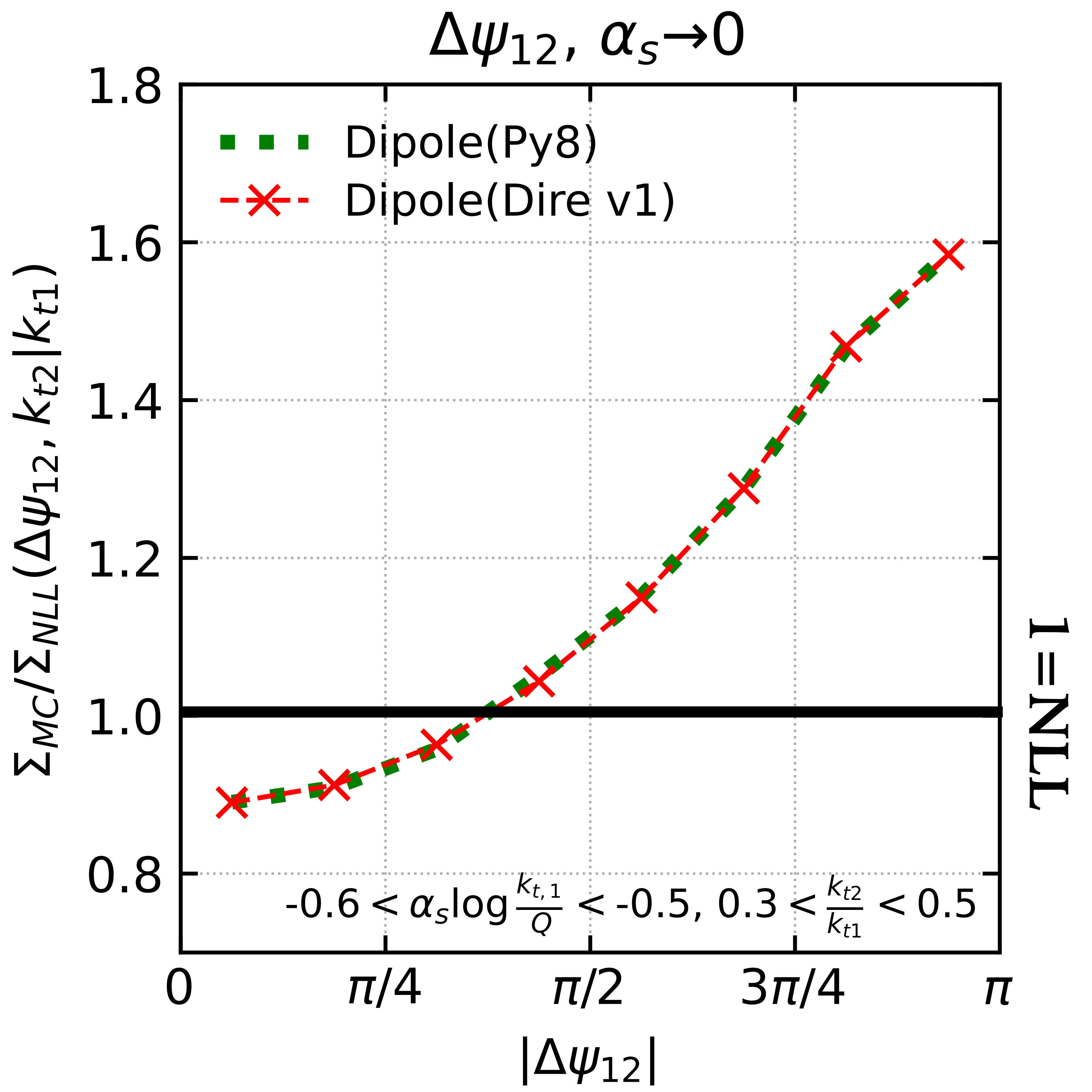
For $Q \sim 50 - 10000$ GeV, $\beta_0 \alpha_s L \sim 0.3 - 0.5$:
Next-to-Leading Logarithms needed for **%-level** precision!

What is available in Shower Monte Carlo generators?

➤ Showers routinely used to interpret LHC (and LEP) data are **not NLL**!

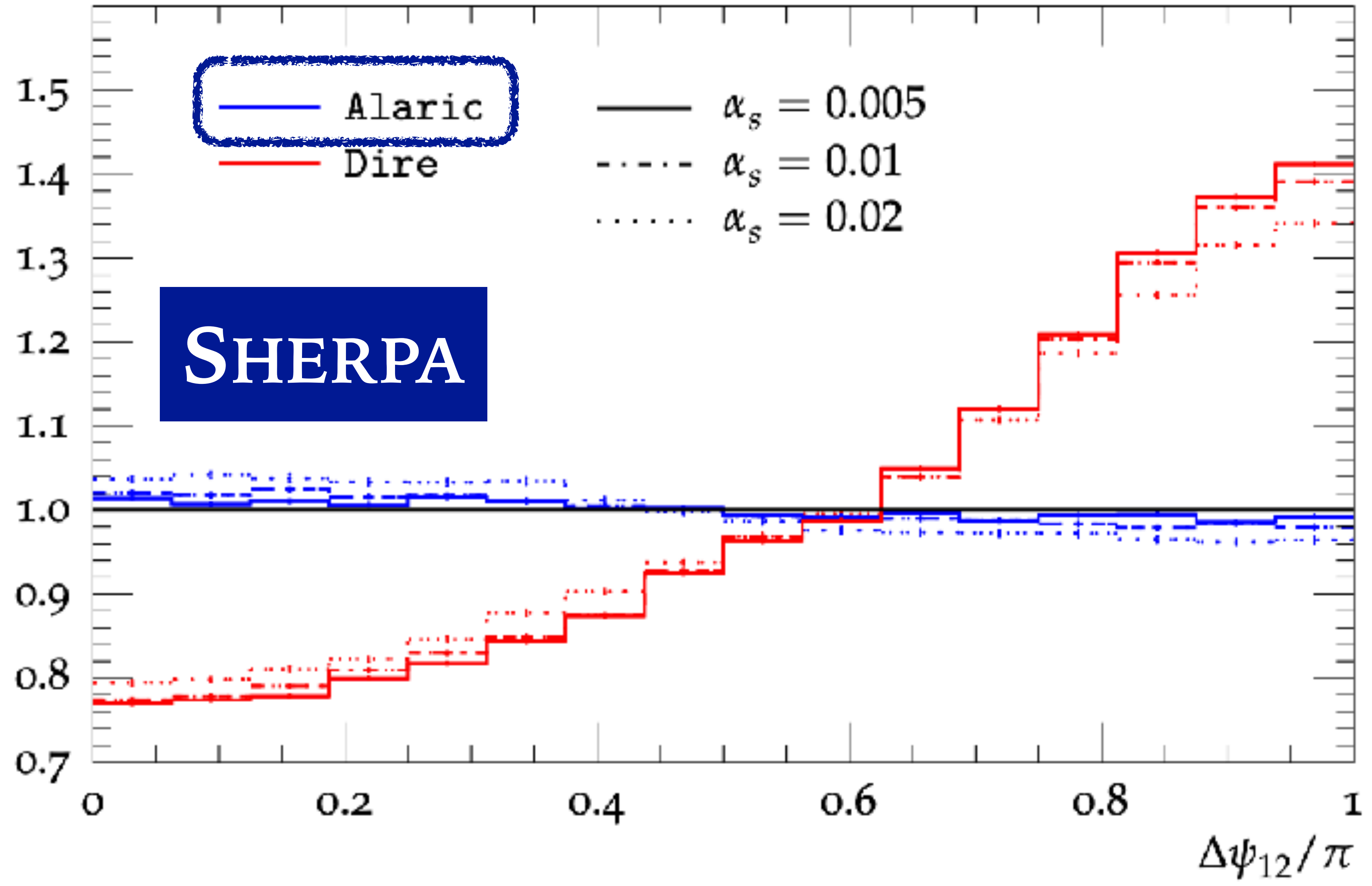
Dasgupta et al. 2002.11114



What can be available in Shower Monte Carlo generators?

- ➤ Showers routinely used to interpret LHC (and LEP) data are **not NLL**!
- ➤ **Many groups** are independently formulating new showers with **NLL accuracy for e^+e^-**

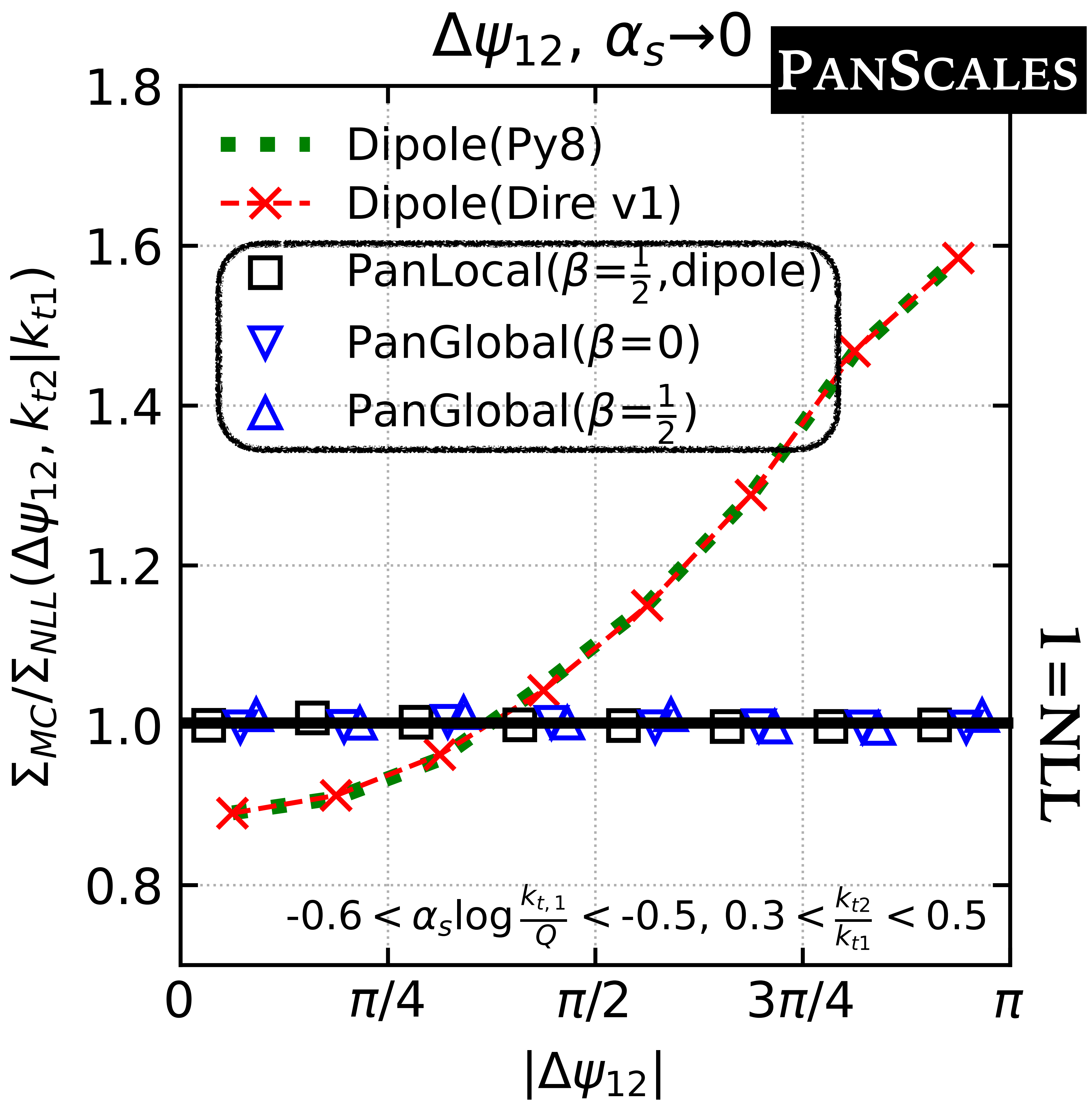
Herren et al. 2208.06057



DEDUCTOR
Nagy&Soper, 2011.04777

CVOLVER
Forshaw et. al, 2003.06400

Dasgupta et al. 2002.11114



From LL to NLL: what's new?

- NLL accuracy achieved for **<u>lepton collider</u>** processes ensuring parton showers reproduce the QCD matrix element in the presence of **soft gluons separated in angle**

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- **Lepton - hadron** colliders (and **VBF**): **PanScales**, van Beekveld, SFR 2305.08645
- **Hadron - hadron colliders:**
  colour-singlet in **PanScales** (van Beekveld, SFR et al., 2205.02237 + 2207.09467), and **Deductor** (Nagy&Soper, 0912.4534)
  generic processes: ongoing efforts in **Alaric** and **PanScales**

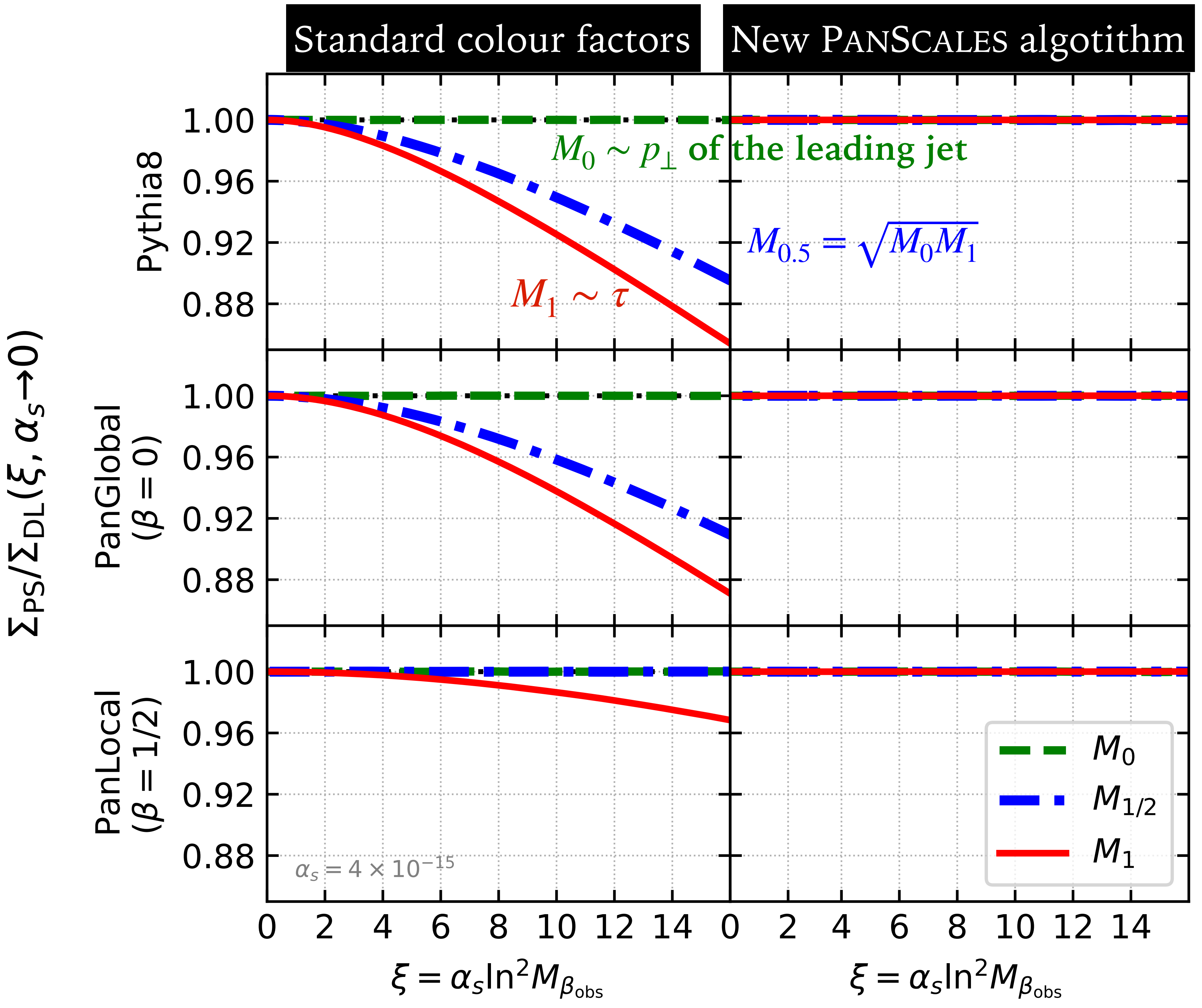
From LL to NLL: what's new?

- NLL accuracy achieved for **generic collider** processes ensuring parton showers reproduce the QCD matrix element in the presence of **soft gluons separated in angle**

- **Subleading-colour corrections** in **PanScales**, as parton showers are derived in the large number of colour limit

$$C_F = \frac{C_A}{2} - \frac{1}{2N_c}$$

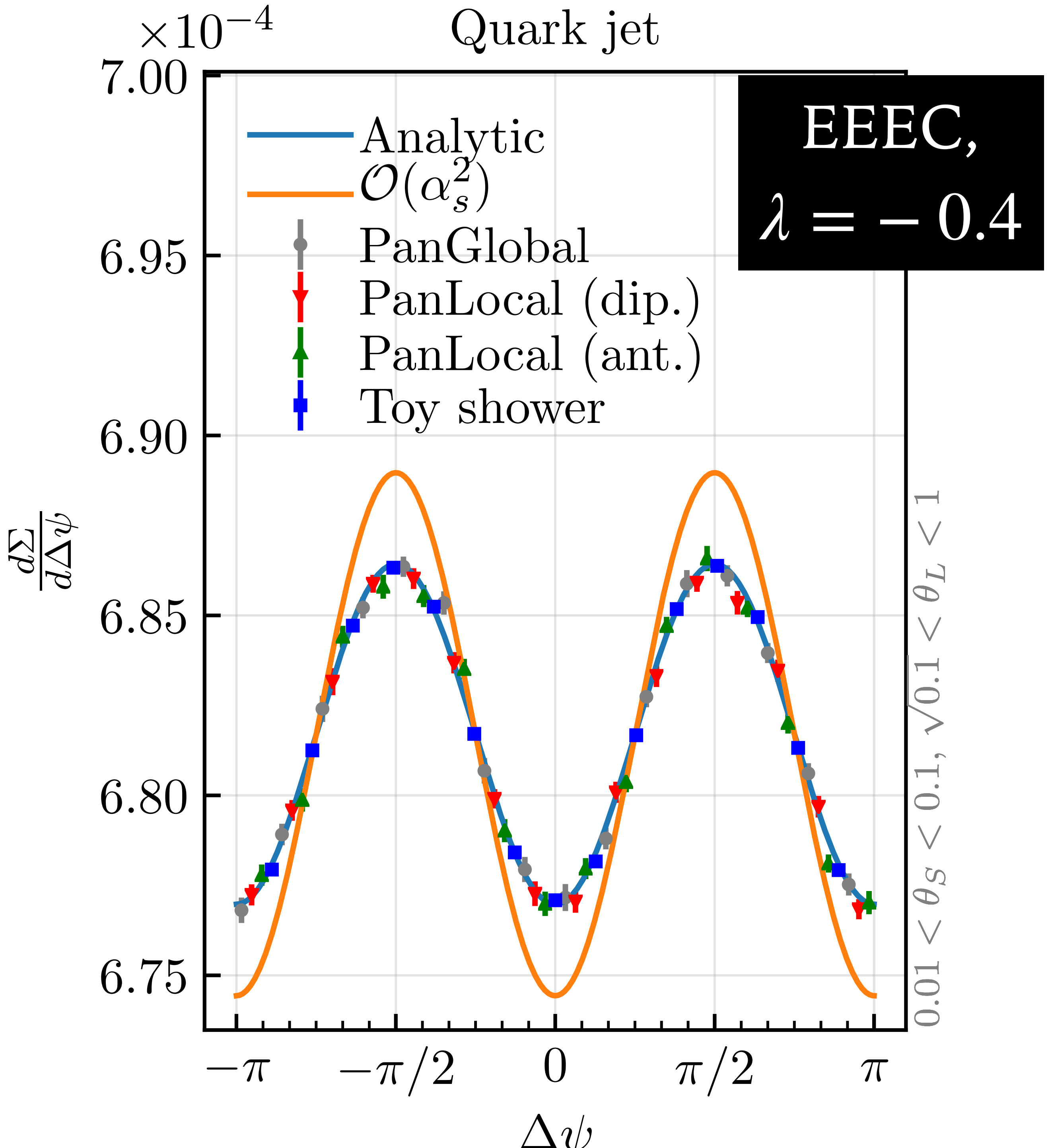
[K. Hamilton et al., 2011.10054]



From LL to NLL: what's new?

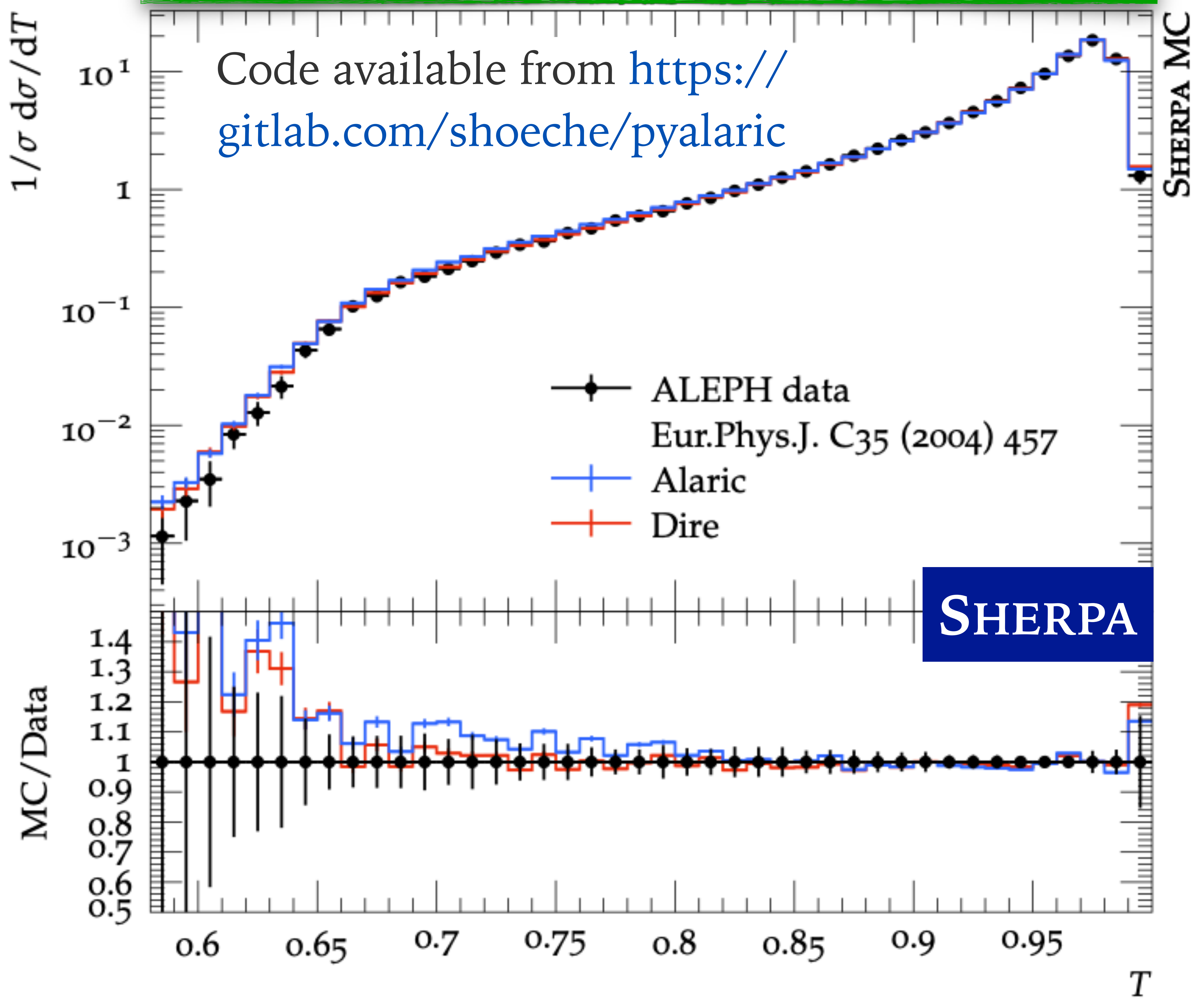
- NLL accuracy achieved for **generic collider** processes ensuring parton showers reproduce the QCD matrix element in the presence of **soft gluons separated in angle**

- Subleading-colour corrections in **PanScales**, [K. Hamilton et al., 2011.10054]
- Spin correlations in **PanScales**, [A. Karlberg et al., 2103.16526 + 2111.01161], based on the **Collin-Knowles** ('88) algorithm (also available in **Herwig7**, Richardson &Webster 1807.01955)

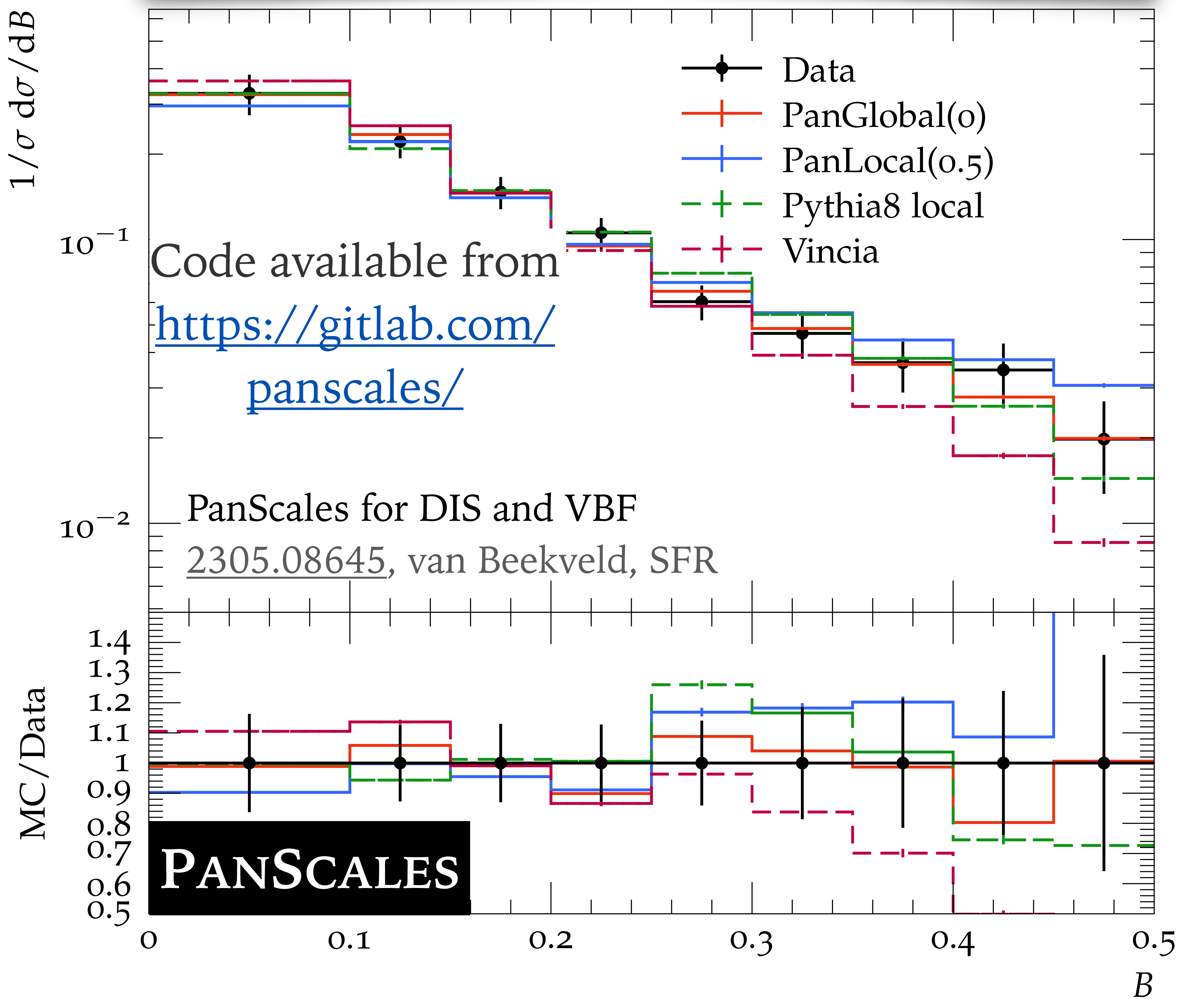


Comparison with current data

e^+e^- thrust at $\sqrt{s}$=91 GeV

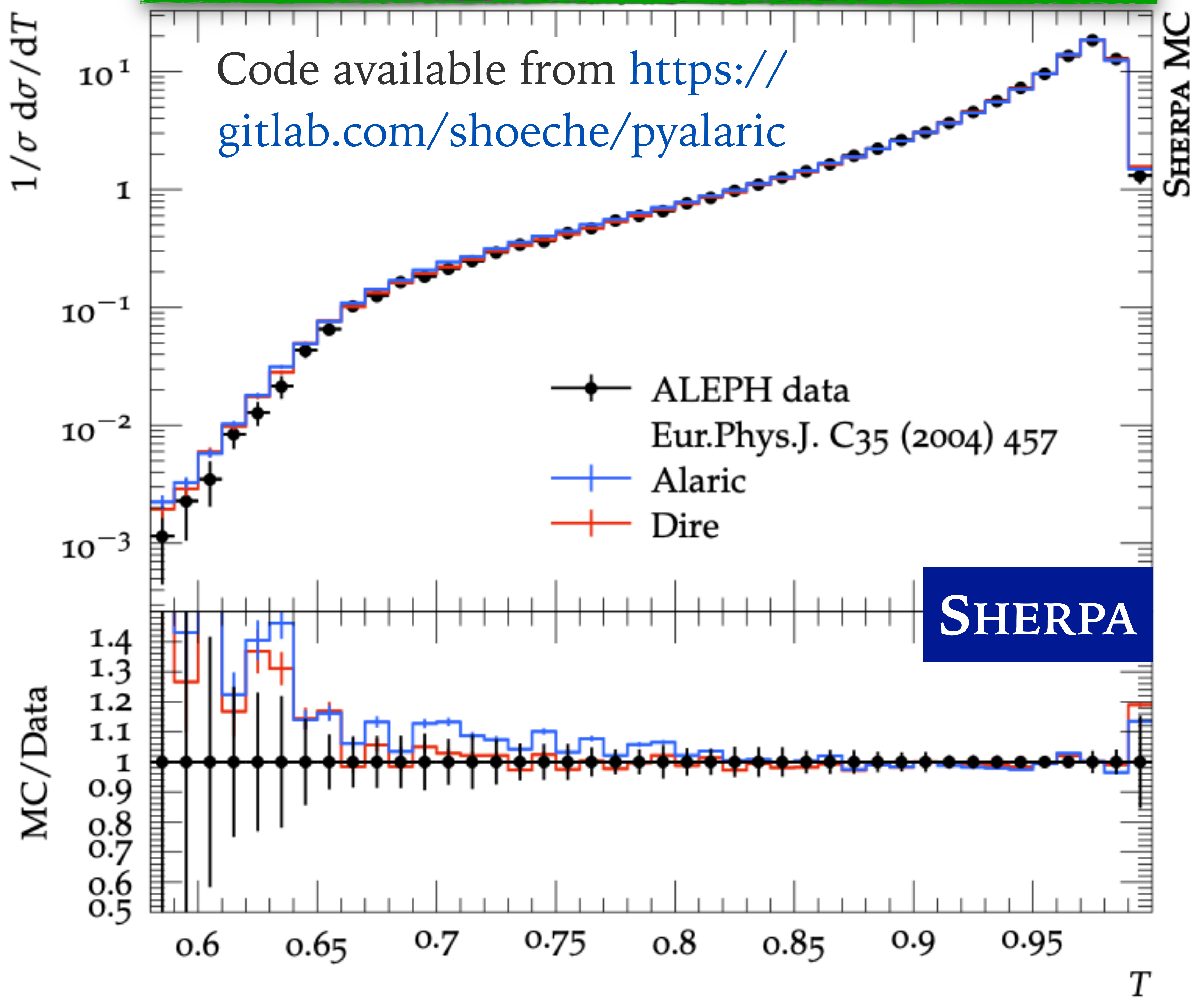


DIS broadeing at Q=58 GeV

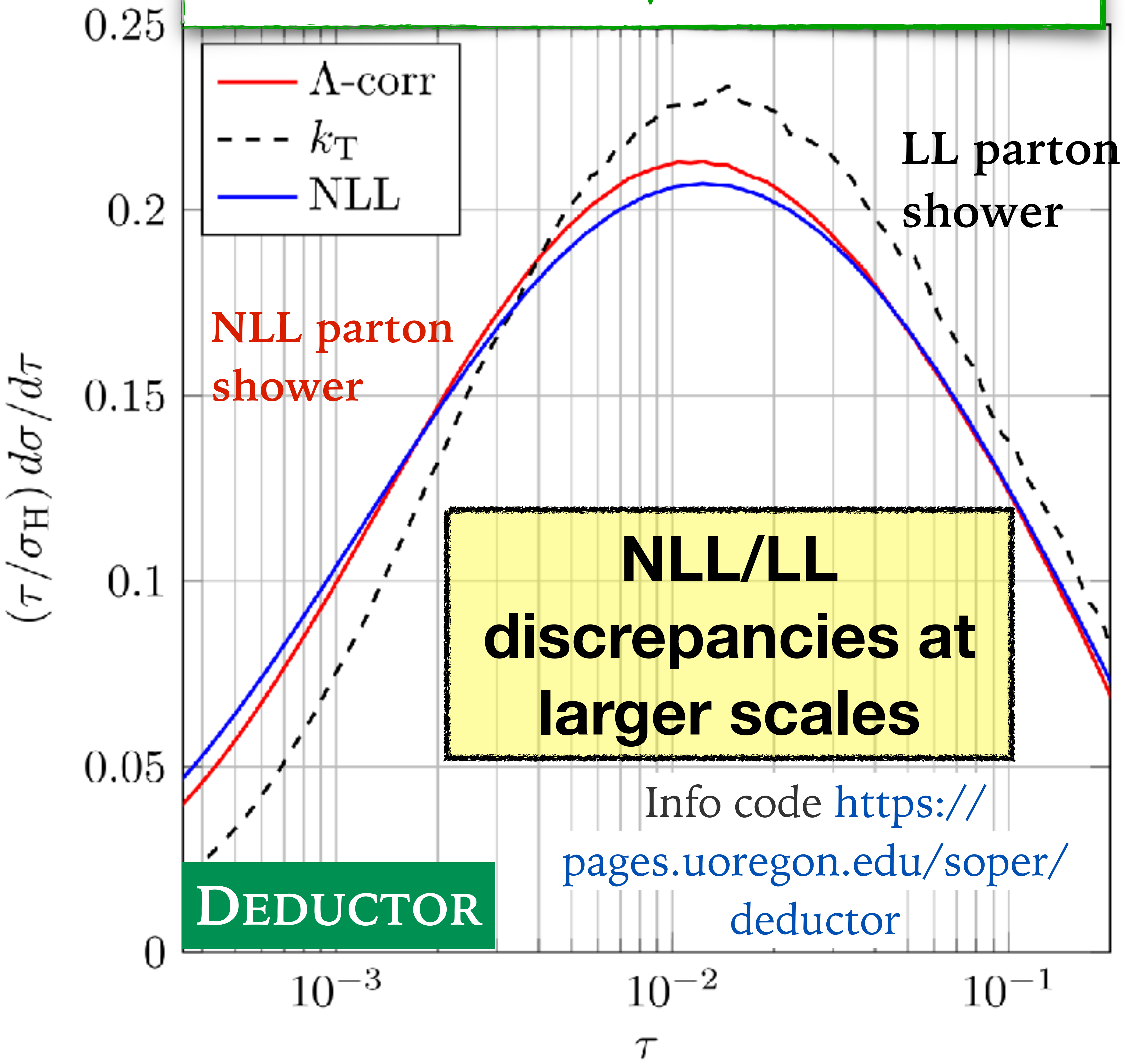


A closer look to the thrust in e^+e^- collisions

e^+e^- thrust at $\sqrt{s}$=91 GeV

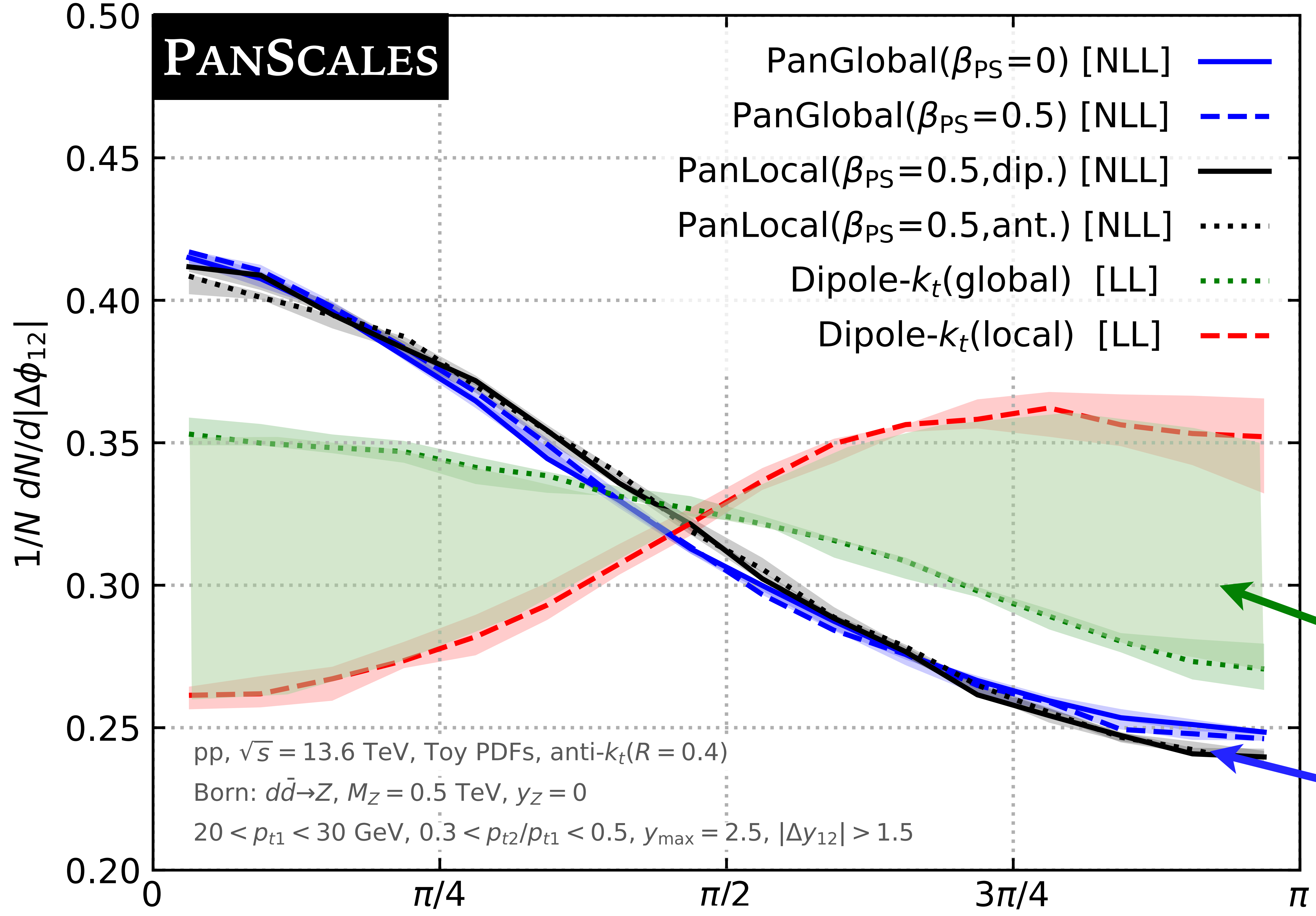


e^+e^- thrust at $\sqrt{s}$=10 TeV

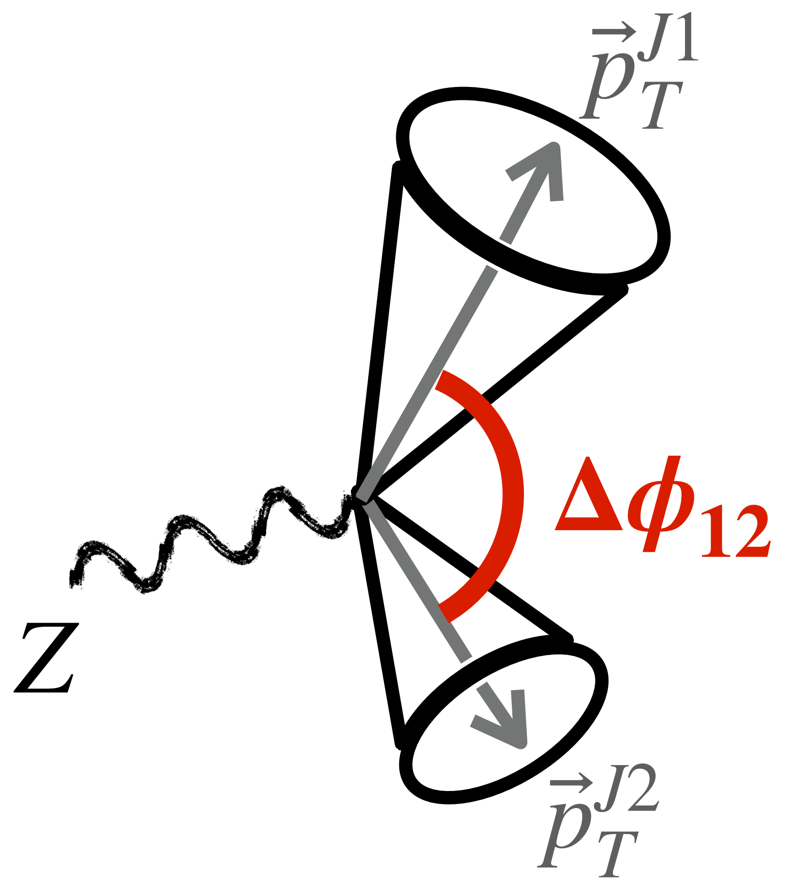


$m_{\ell\ell} = 500\,\mathrm{GeV}$

Azimuthal angle between leading jets (DY)



$\Delta\phi_{12}$



PanScales for $pp \to$ colour singlet: 2207.09467, van Beekveld, SFR, Hamilton, Salam Soto Ontoso, Soyez, Verheyen:

NLL/LL discrepancies at larger scales

LL showers

NLL showers

Towards NNLL accuracy

SFR, Hamilton, Karlberg, Salam, Scyboz, Soyez, 2307.11142

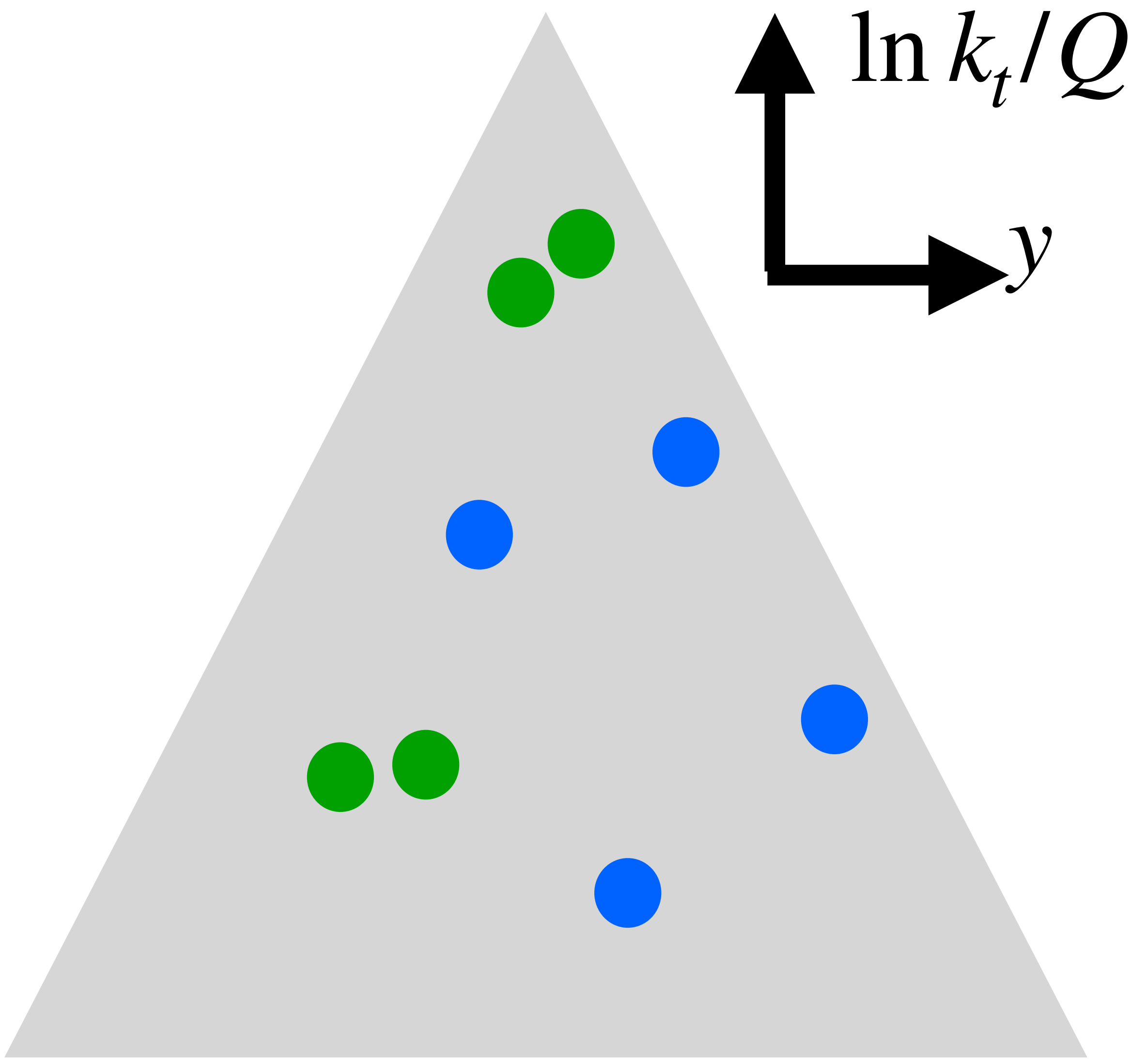
NNLL precision must be reached for percent-level precison!

SFR, Hamilton, Karlberg, Salam, Scyboz, Soyez, 2307.11142

NNLL precision must be reached for percent-level precison!

Soft emission — inclusion of real + virtual corrections

- any pair of soft emissions with commensurate energy and angles should be produced with the correct [double-soft] matrix element
- probability for any single soft emission should be NLO accurate
- NB: Vincia and Sherpa groups have also explored inclusion of the double-soft current; part of novelty here is doing so to get the log-accuracy benefit.



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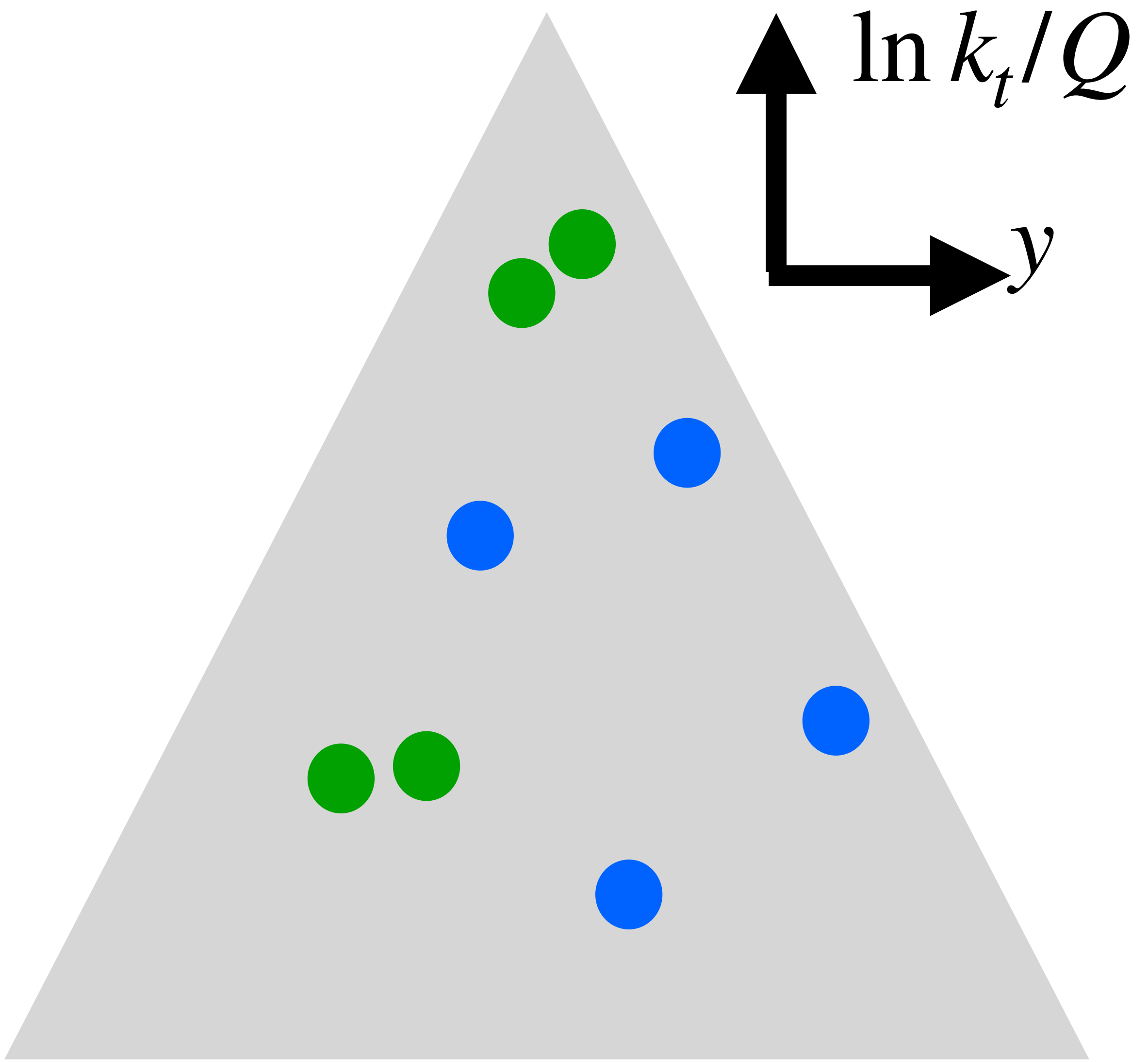


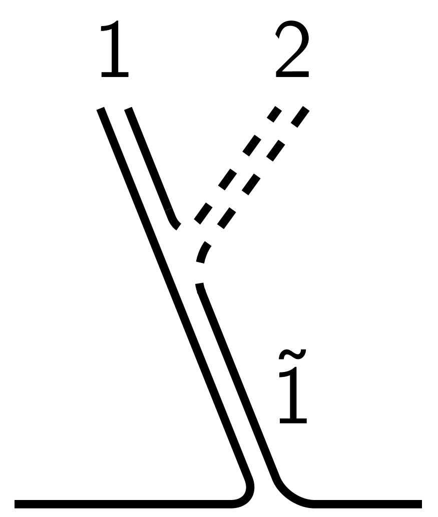
This (+NLO matching, see Karlberg's talk) **should maintain NLL accuracy and further achieve**

- **NNDL accuracy** for [subjet] multiplicities, i.e. terms $\alpha_s^n L^{2n}$, $\alpha_s^n L^{2n-1}$, $\boldsymbol{\alpha_s^n L^{2n-2}}$
- **Next-to-Single-Log (NSL) accuracy** for non-global logarithms, e.g. energy in a slice, all terms $\alpha_s^n L^n$ and $\boldsymbol{\alpha_s^n L^{n-1}}$ (at leading-N_c)

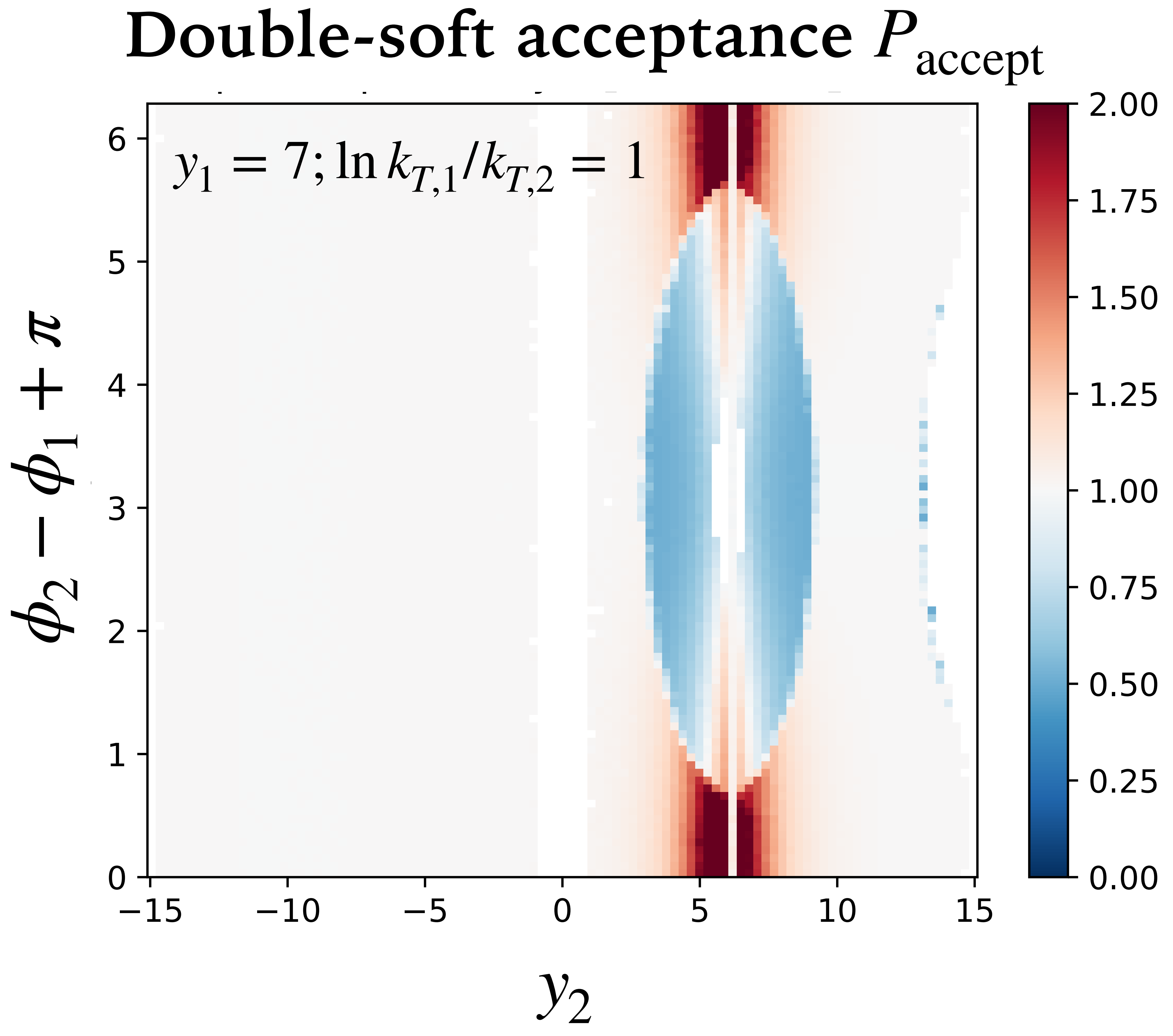
NB: done using PanGlobal, so far just in $e^+e^- \to q\bar{q}$

1. Real corrections: pair of soft emissions

SFR, Hamilton, Karlberg, Salam, Scyboz, Soyez, 2307.11142



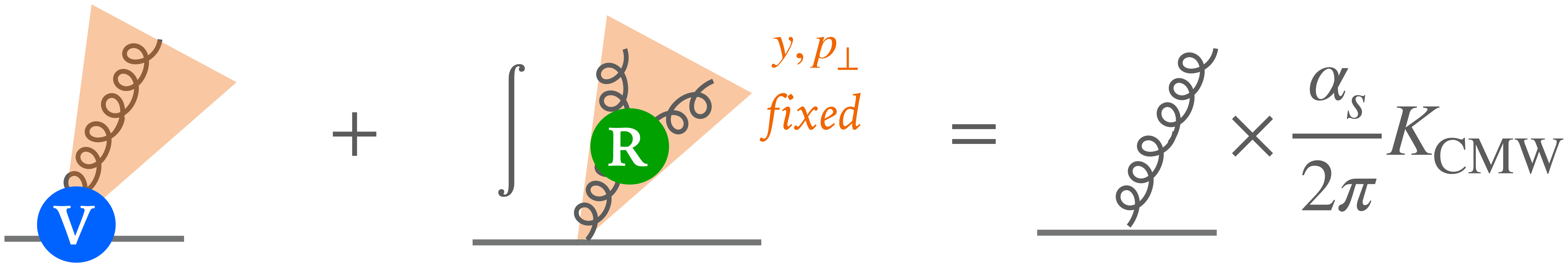
- a given two-emission configuration can come from several shower histories
- **accept a given emission with exact double-soft $M^{(\mathrm{DS})}_{\mathrm{exact}}$ divided by shower's effective double-soft matrix element** summed over the histories h that could have produced that configuration



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

Virtual corrections in parton showers

- For a soft emission



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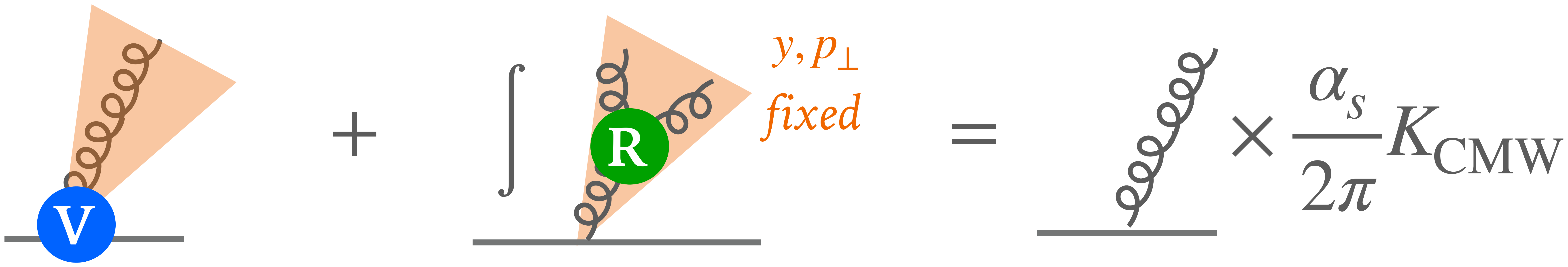

- Catani, Marchesini and Webber defined the "CMW" scheme for the coupling in the shower [*Nucl.Phys.B* 349 (1991) 635-654]

$$\alpha_s^{\text{CMW}} = \alpha_s \left(1 + \frac{\alpha_s}{2\pi} K_{\text{CMW}} \right)$$

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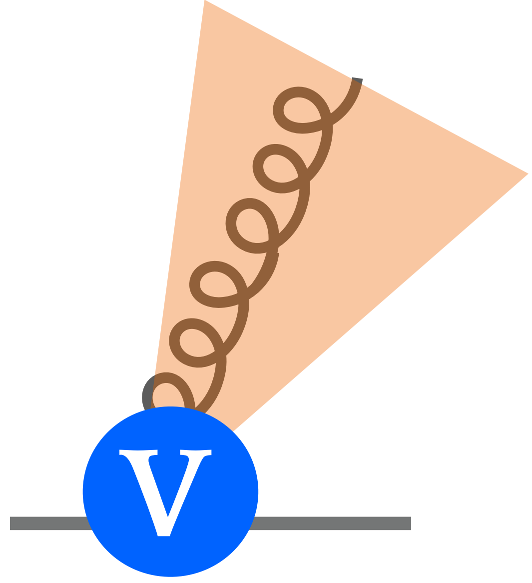
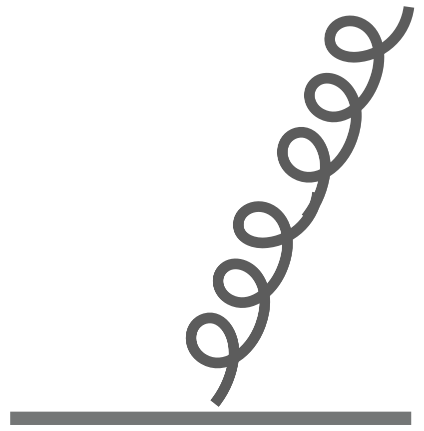


$+ \int$

$=$



$\times \frac{\alpha_s}{2\pi} K_{\mathrm{CMW}}$

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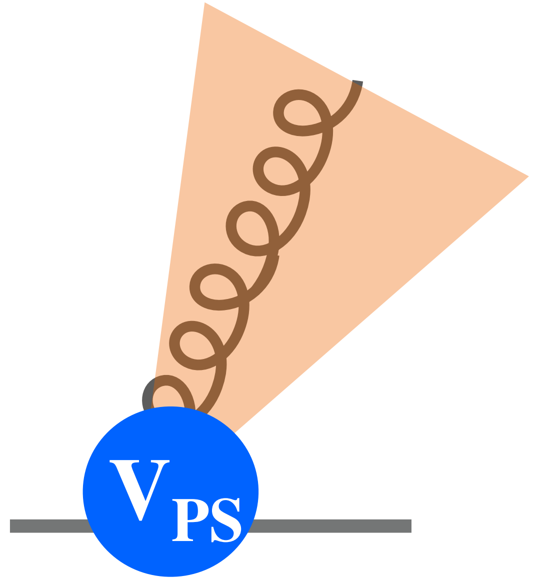
$$\alpha_s^{\mathrm{CMW}} = \alpha_s \left(1 + \frac{\alpha_s}{2\pi} K_{\mathrm{CMW}} \right)$$

At fixed "shower variables", but the rapidity and $p_\perp$ of the jet can vary



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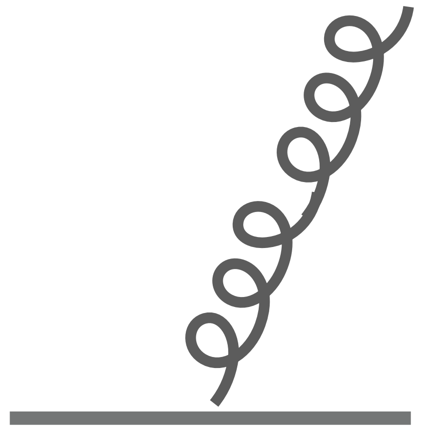
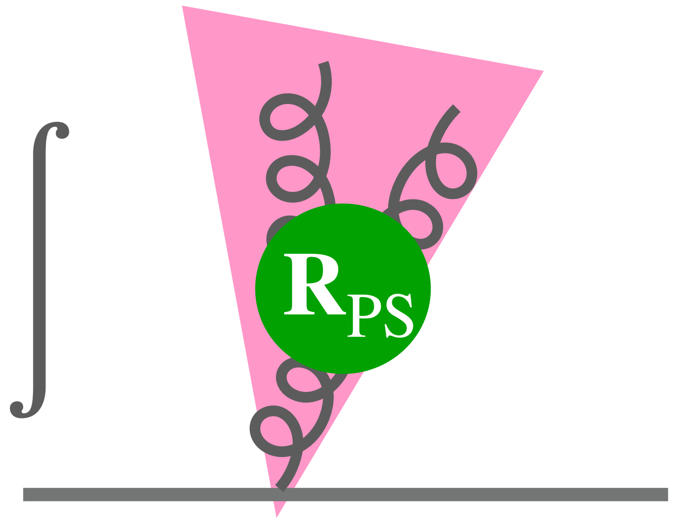


$\times \frac{\alpha_s}{2\pi} K_{\mathrm{CMW}} - \int$



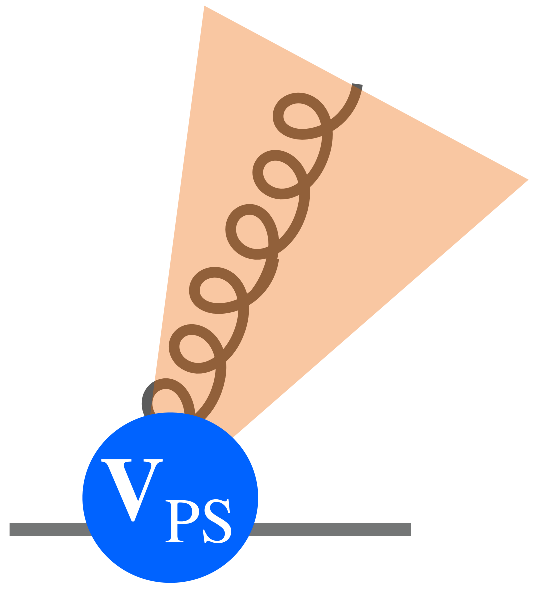
This ensures

$$\mathbf{V}_{\mathbf{PS}} + \int \mathbf{R}_{\mathbf{PS}} = \frac{\alpha_s}{2\pi} K_{\mathrm{CMW}}$$

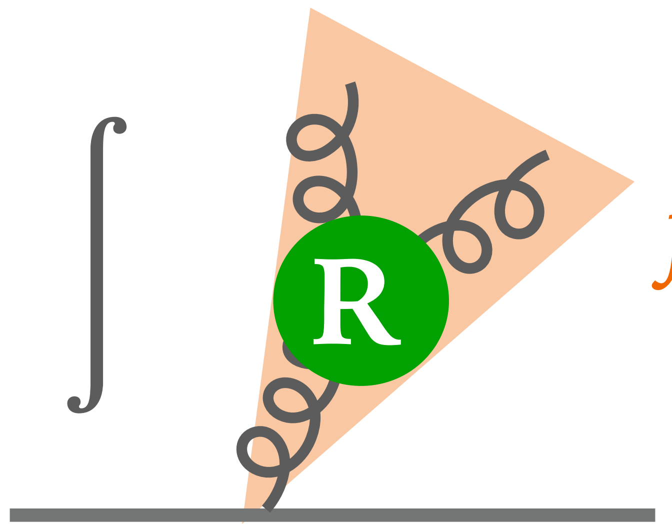
"on average"

2. Improving virtual corrections for soft emissions

With our double soft acceptance we have $\mathbf{R}_{\mathbf{PS}} = \mathbf{R}$.
To ensure



$$= \frac{\alpha_s}{2\pi} K_{\mathrm{CMW}} - \int$$

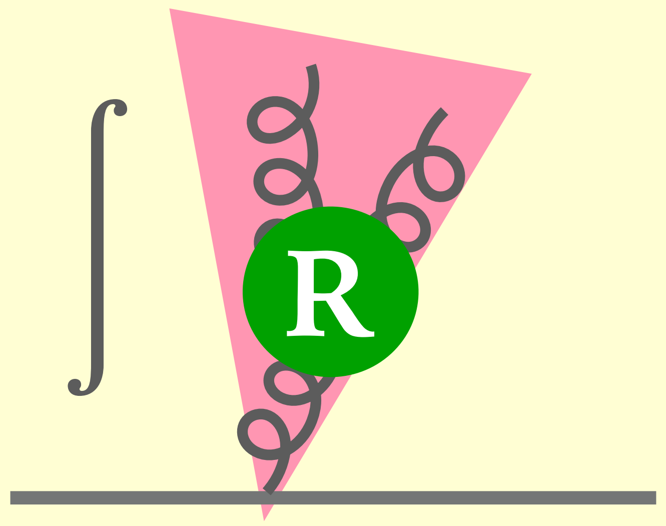


We modify the CMW scheme

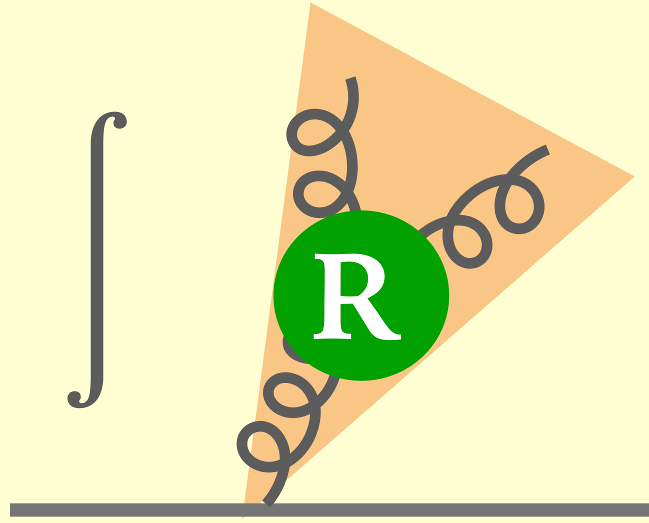
$$K_{\mathrm{CMW}} \rightarrow K_{\mathrm{CMW}} + \Delta K(\Phi^{(1)}_{\mathrm{PS}})$$

fixed "shower variables"

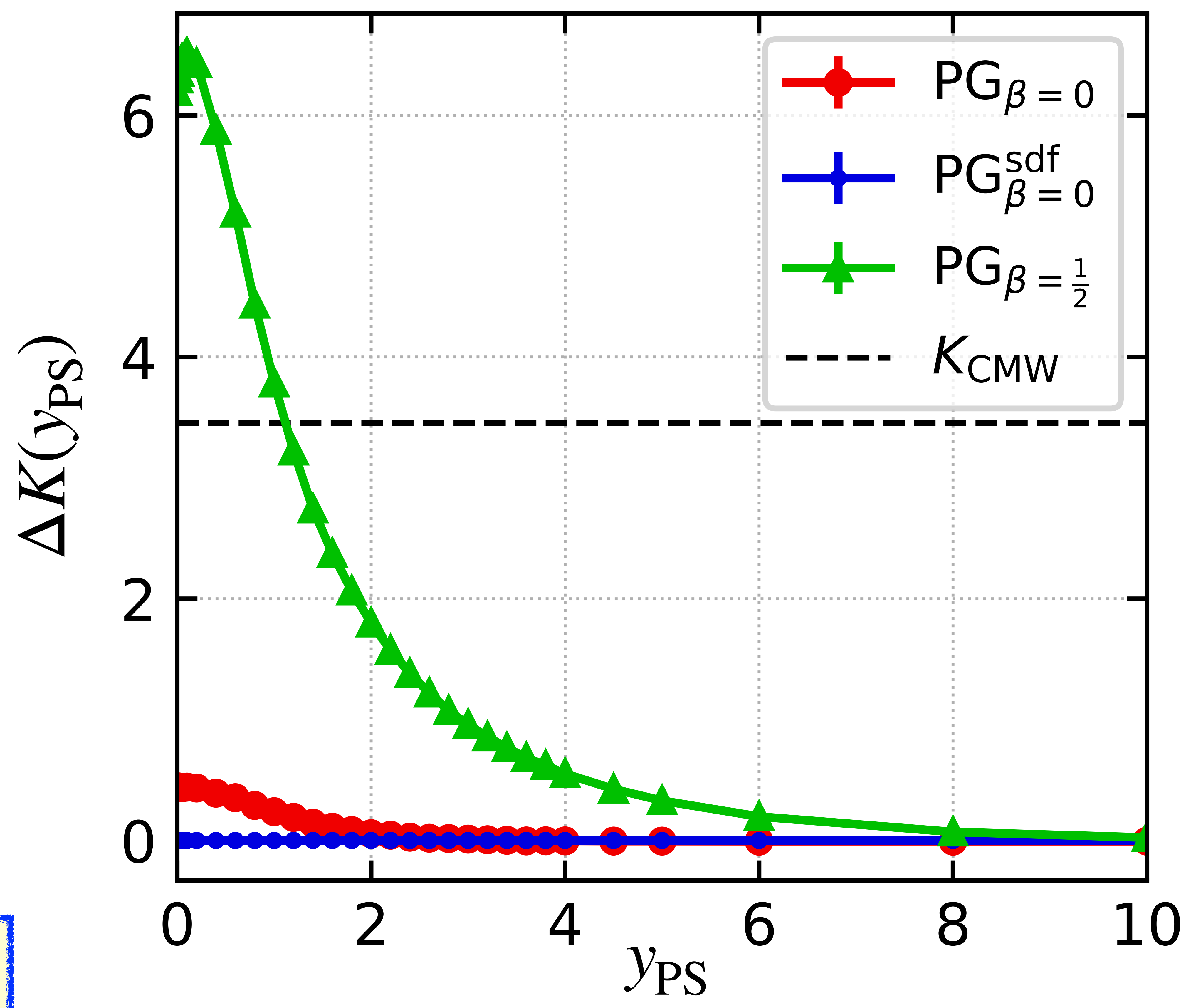
$$\frac{\alpha_s}{2\pi} \Delta K(\Phi^{(1)}_{\mathrm{PS}}) = \int$$



$$- \int$$

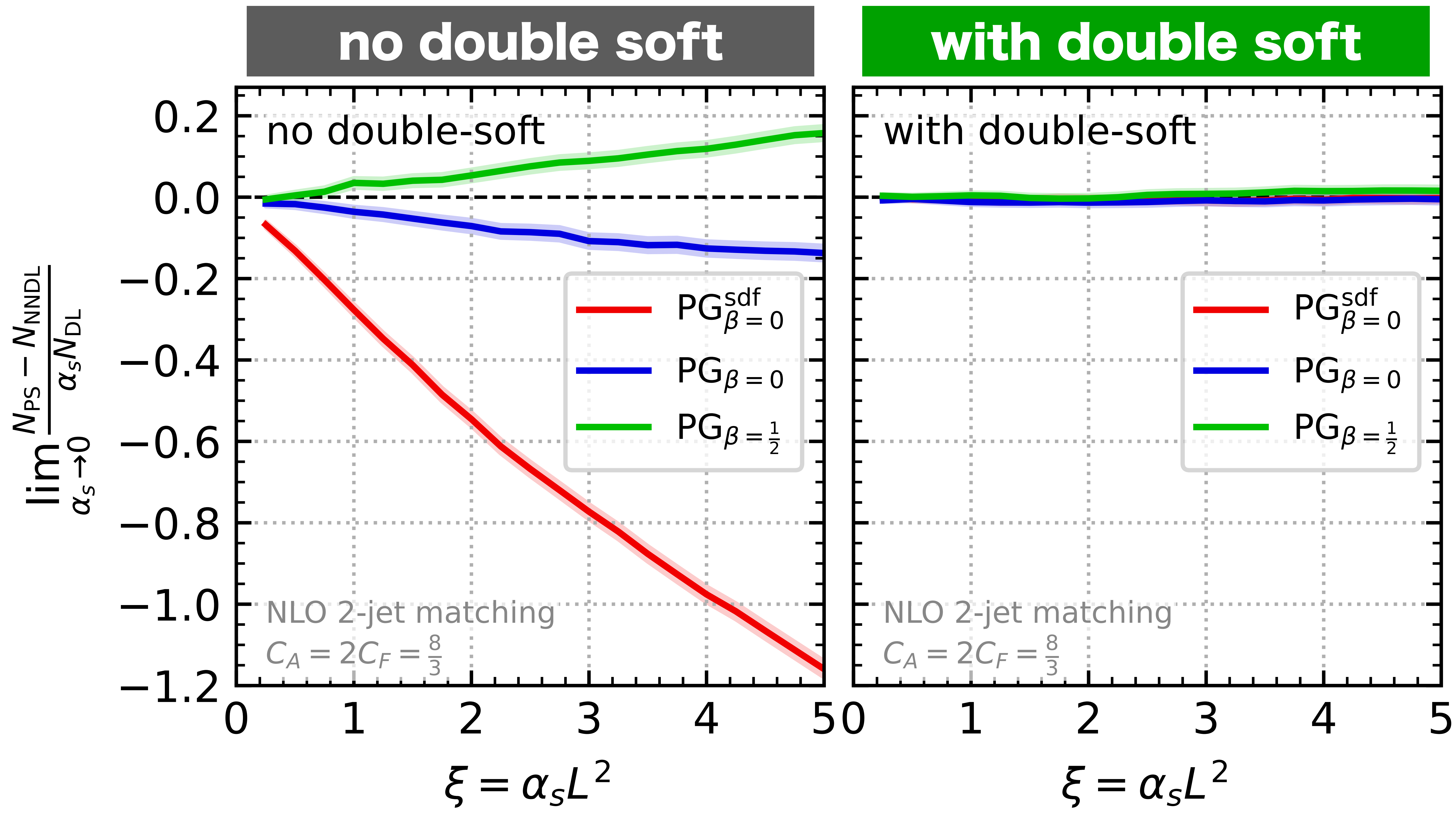


example ΔK correction



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

NNDL subjet multiplicity

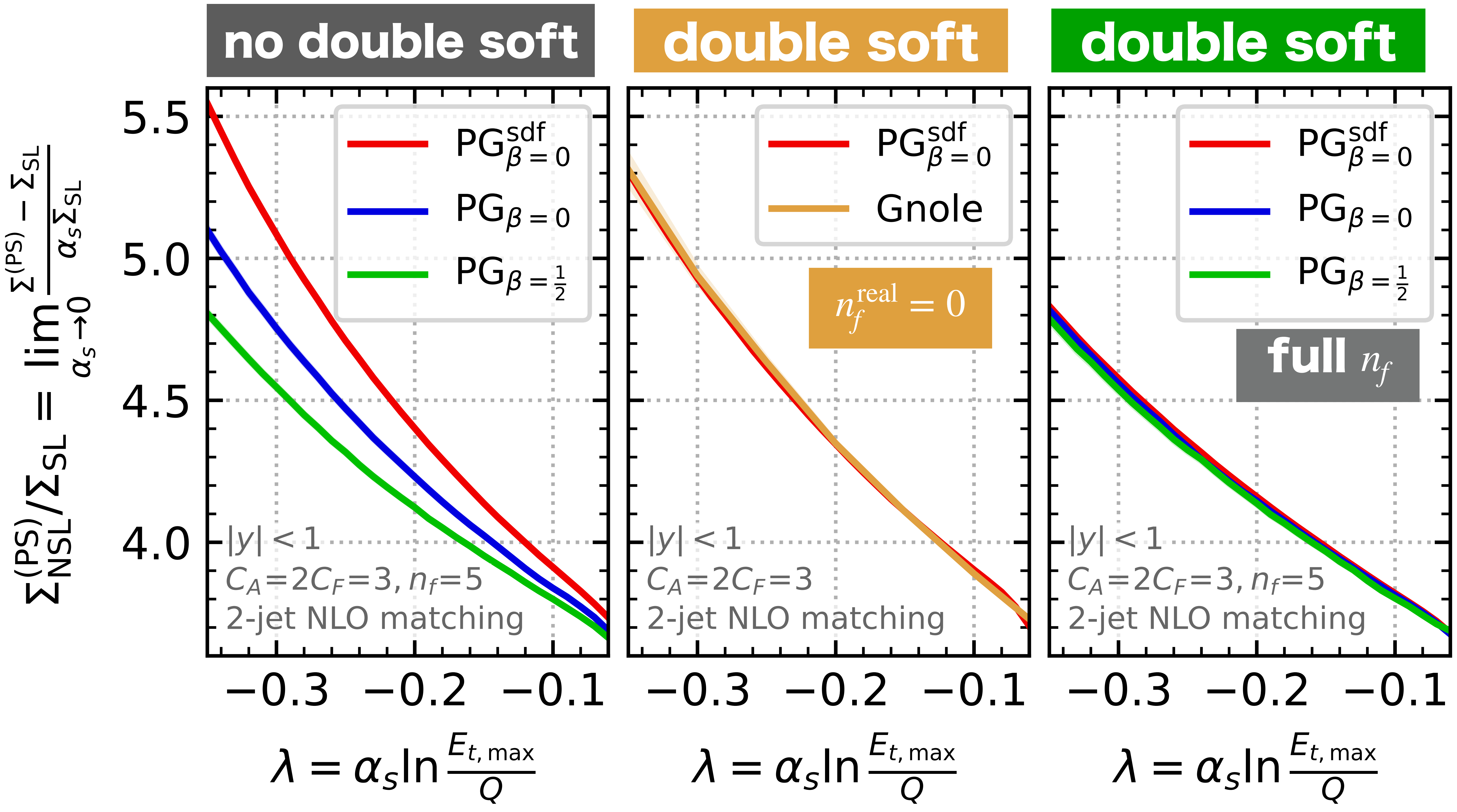


$$\lim_{\alpha_s \to 0} \frac{N_{\rm PS} - N_{\rm NNDL}}{\alpha_s N_{\rm DL}}\Bigg|_{\text{fixed } \alpha_s L^2}$$

- **NNDL ($\alpha_s^n L^{2n-2}$)** analytic resummation = Medves, Soto Ontoso, Soyez, 2205.02861
- $\alpha_s \to 0$ limit to isolate NNDL terms.
- **Double soft necessary for NNDL agreement**

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

NSL for the energy flow in a rapidity slice



$$\Sigma^{(PS)}_{NSL} = \lim_{\alpha_s \to 0} \frac{\Sigma^{(PS)} - \Sigma_{SL}}{\alpha_s}\Bigg|_{\text{fixed } \alpha_s L}, \qquad L \equiv \ln \frac{E_{t,max}}{Q}$$

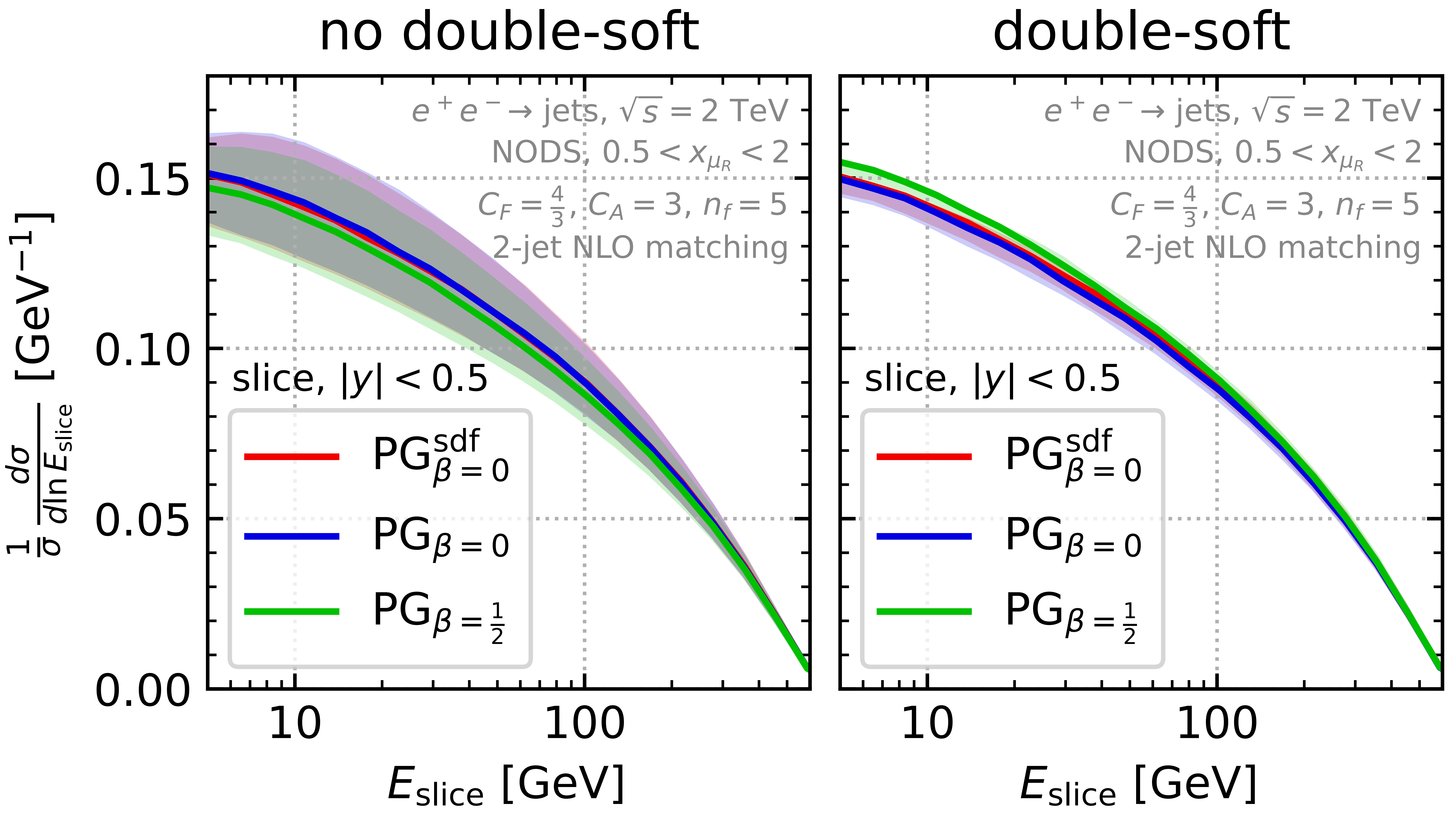
- **NSL ($\alpha_s^n L^{n-1}$)** = Banfi, Dreyer, Monni, 2104.06416, 2111.02413 **("Gnole")** [NB: see also Becher, Schalch, Xu, 2307.02283]
- **NSL agreement with Gnole for $n_f^{real} = 0$**
- First large-N_c **full-n_f** results for NSL non-global logs

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

NSL phenomenology outlook

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

- Energy flow in slice between two 1 TeV jets
- **Double-soft reduces uncertainty band**



Uncertainty here is estimated varying the renormalisation scale

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

Summary and Conclusions

- **NLL shower about to become the new standard, but not enough for the FCC!**
  - benefits of LL → NLL include reduced uncertainties (**reliable estimate uncertainties**)
  - for realistic applications we also need **massive quarks** (Deductor and Alaric already include them), at least NLO matching, and **tuning**
- **Higher log accuracy is one of the next frontiers**
  - double-soft (+ virtual) corrections: NNDL multiplicity and NSL non-global logarithms
- **Percent precision also requires these aspects not addressed here**
  - NLO and NNLO Matching
  - QED shower
  - Leading power corrections (e.g. in PDF's, Frixione&Webber 2309.15587)