NLL-accurate PanScales showers for hadron collisions

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Ringberg Castle, Germany
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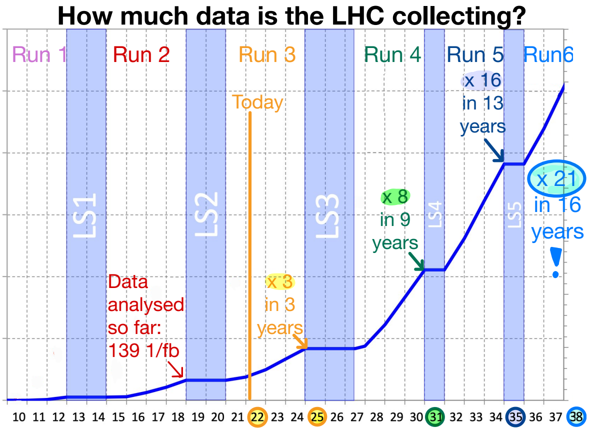
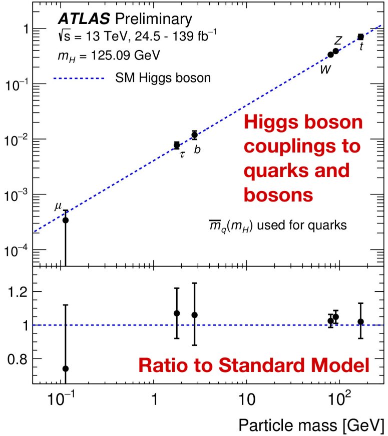
Based on:
"**PanScales showers for hadron collisions: a fixed-order study**" [arXiv:2205.02237],
"**PanScales showers for hadron collisions: all-orders validation**" [arXiv:2207.09467],
M. van Beekveld, S.F.R., K. Hamilton, G. Salam, A. Soto Ontoso, G. Soyez, R. Verheyen

- The LHC aims at $\times 20$ its current statistics
- More precise measurements *e.g.* in the **Higgs** sector: success of the **Standard Model** or hints of **new physics**

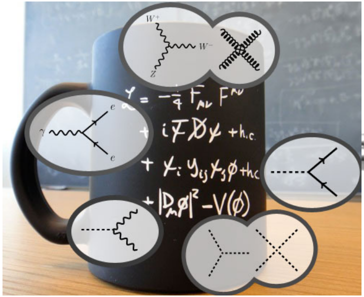


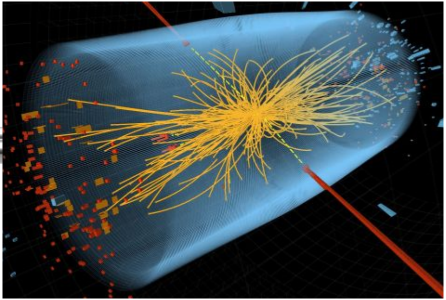


LHC: future prospects

- The LHC aims at $\boxed{\times 20}$ its current statistics
- More precise measurements *e.g.* in the **Higgs** sector: success of the **Standard Model** or hints of **new physics**
- This also requires **accurate theoretical predictions** ...

and a **connection** between **theory** & **experiment**!

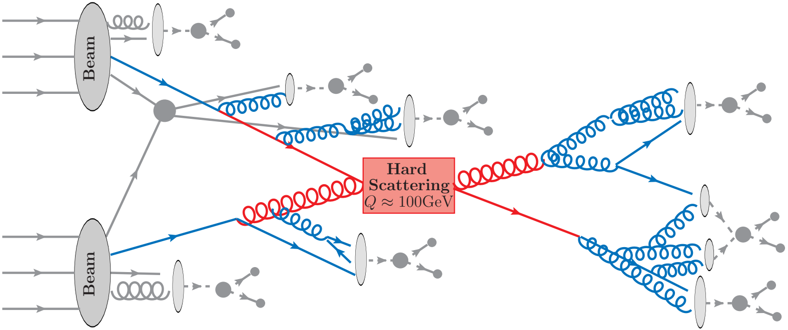




Ideal world **Reality**

Shower Monte Carlo Generators and Parton Showers

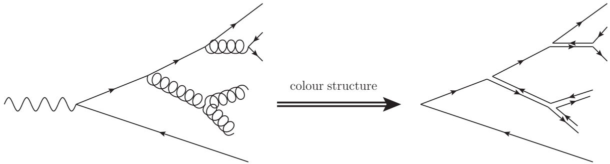
Shower Monte Carlo generators describe complex collider events, which are characterized by a **large number of particles**. **Parton Showers** (PS) are the core of SMC. They evolve the **hard system** from a hard scale $\mathbf{Q} \sim \mathbf{100} - \mathbf{1000}$ **GeV** to hadronic scales $\mathbf{\Lambda} \sim \mathbf{1}$ **GeV**, adding softer and softer partons (**quarks** and **gluons**), which are later-on converted into **hadrons**.



This evolution generates large **logarithms** of the scale ratios which are resummed by the PS.

Dipole Showers in a nutshell

- **Parton showers** describe the **energy degradation** of fast-moving partons via **softer and softer emissions**



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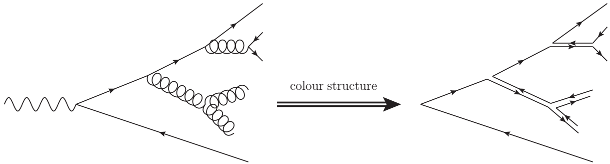

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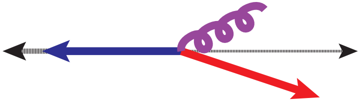

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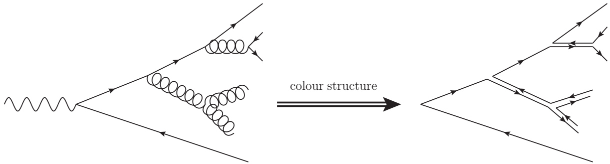

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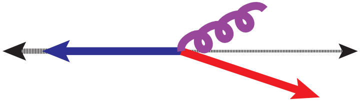
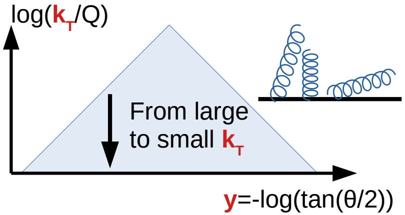
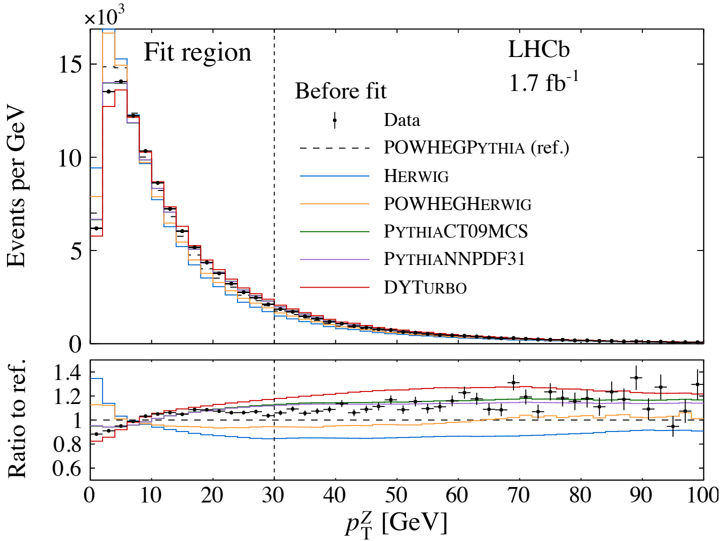




- emissions are ordered in **transverse momentum** k_t (*except Deductor, which is "virtuality" ordered*)
- "easy" to **match/merge** with F.O. calculations because one needs to correct only the first emissions

W-boson mass measurements [LHCb, 2109.01113]



$p_{T,Z}$, which is measured very precisely, is used to calibrate $p_{T,W}$ in W boson mass extractions.

$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm \mathbf{17}_{\textbf{theory}} \pm 9_{\text{PDF}} \text{ MeV}$$

The envelope in the different PS predictions causes the **dominant theory uncertainty (11 MeV)** in m_W

How to assess the accuracy

- **Tame the PS accuracy** to exploit the potential of colliders!
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Logarithmic counting to define the accuracy!

- From **analytic resummation**

$$\Sigma(\underbrace{V}_{\text{obs}} < Q\, e^{\underbrace{-\mathbf{L}}_{\text{large log}}}) = \exp(\underbrace{\mathbf{L} g_{\text{LL}}(\alpha_s \mathbf{L})}_{\text{leading log}} + \underbrace{g_{\text{NLL}}(\alpha_s \mathbf{L})}_{\text{next-to-leading log}} + \dots)$$

$\alpha_s L \sim 0.55$ if $Q = 100$ and $v = 1$ GeV: **NLL** are $\mathcal{O}(1)$!

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PanScales criteria for assessing NLL

1. Behaviour of the exact **amplitudes** in singular limits [Dasgupta et al., JHEP **09** (2018), 033]
2. Logarithmic **resummation** results [Dasgupta et al., Phys. Rev. Lett. **125** (2020) no.5, 052002]

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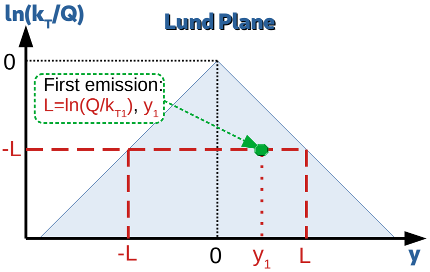
Also the **CVolver** (Platzer, Foreshaw, Holguin et al.), **Deductor** (Nagy & Soper) and **Alaric** (S. Hoche et al.) collaborations addressed this topic, but here I focus on **PanScales**

- Case of study: emission of two soft gluons, well separated in **rapidity** are **independent**

$$e^+e^- \to q\bar{q}: \quad \boxed{dP_2 = \frac{C_F^2}{2!}\prod_{i=1}^{2}\frac{2\alpha_s(k_{T,i})}{\pi}\frac{dk_{T,i}}{k_{T,i}}dy_i} \quad y_i = -\log\left(\tan\left(\frac{\theta}{2}\right)\right) \text{ and } k_{T,i} = \text{transverse mom}$$

- **Lund plane**= phase space available to an emission in terms of $\log Q/k_T = L$ and y



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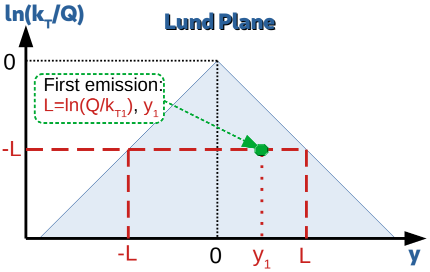

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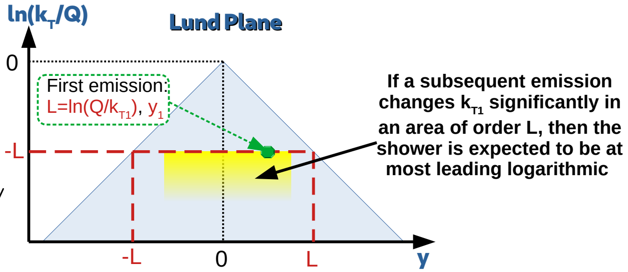
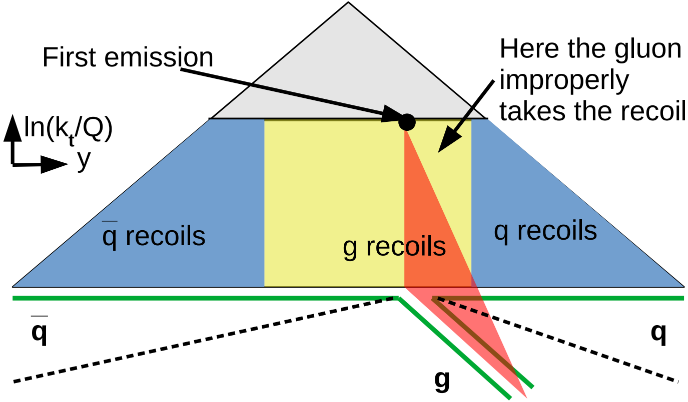
- **Lund plane**= phase space available to an emission in terms of $\log Q/k_T = L$ and y
- If a second emission disturbs a first one in an area $\mathcal{O}(L^2)$, it is not **LL**!
- If the rapidity range in which a subsequent emission affects the first one grows linearly with $L = -\log(k_{T,1}/Q)$, then the shower cannot be **NLL**!

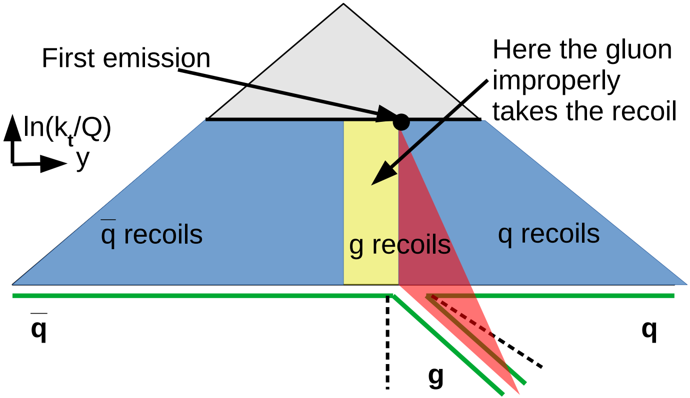


- State-of-the art dipole showers, which are LL, are ordered in **transverse momentum** $v = \kappa_t$;
- Momentum conservation is fully local, the parton closer in angle to k **in the dipole frame** takes the **transverse momentum recoil**



- Issues due to how $k_\perp$ is redistributed can be seen already from the second emission (from $e^+e^- \to q\bar{q}$)

- Defining y in the **event-frame** partially improves but does not solve the issue



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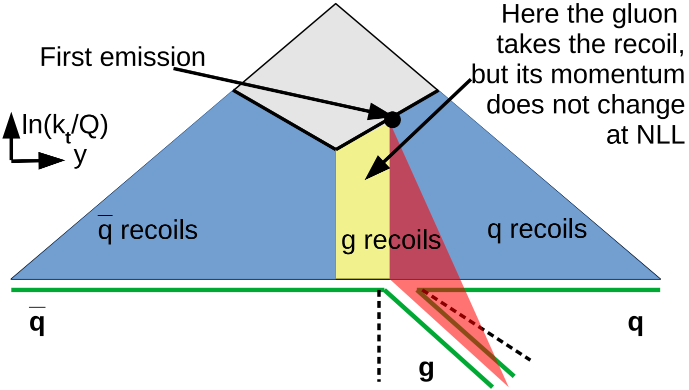
- But we can choose the **ordering variable** such than when the gluon improperly recoils, $\vec{k}_{T,1} \gg \vec{k}_{T,2}$, so $\vec{k}_{T,1} \to \vec{k}_{T,1} - \vec{k}_{T,2} \approx \vec{k}_{T,1}$

$$\mathbf{v^2} \sim (\mathbf{k_t^2})^{1-\beta} \underbrace{(q^2)^\beta}_{\text{virtuality}} \quad \mathbf{0} < \beta < \mathbf{1}$$

- We call this shower **PanLocal**



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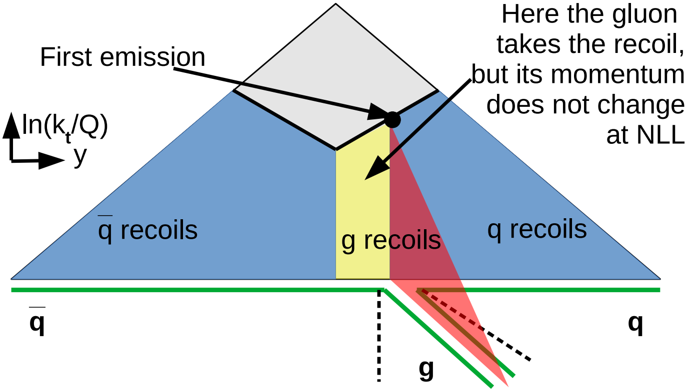
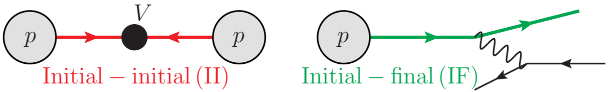


- To implement **transverse-momentum ordered** showers then one needs to redistribute the transverse momentum recoil globally → **PanGlobal**.
  All the particles are boosted to ensure full-momentum conservation. The boost mainly affects hard particles, leaving **soft** ones **unchanged**.

Initial-state radiation in state-of-the-art Dipole showers



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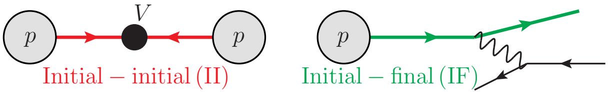

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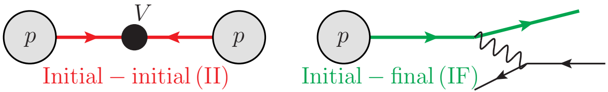

- In IF dipoles the final-state leg recoils also for ISR. In DY, the Z boson recoils only after the first emission! But resummation tell us low-k_T region is dominated by emissions with opposite $\vec{k}_\perp$ which cancels in the sum!

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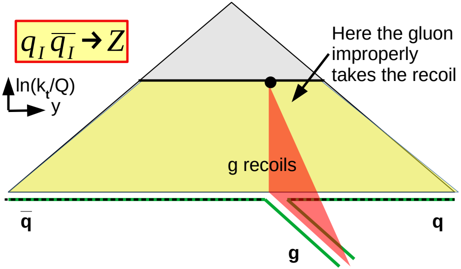
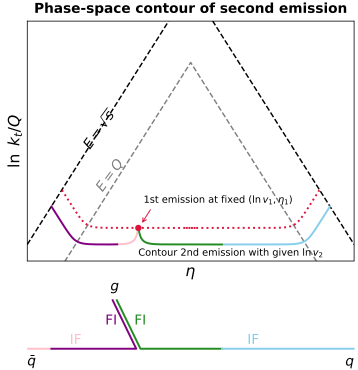


- To remedy this Platzer and Gieseke ('09) proposed to give the $p_\perp$ recoil to the incoming partons and then boost to realign it with the beams (option available in Dire, Höche, Prestel '15): this renders DY "not worse" than the case with partons only in the final state (left plot)

What happens to the **first gluon** and to the Z **boson** transverse momentum after a **second emission** is added for state-of-the-art dipole showers?



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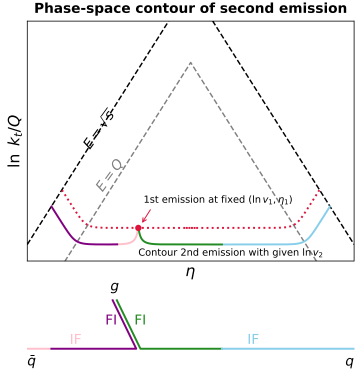

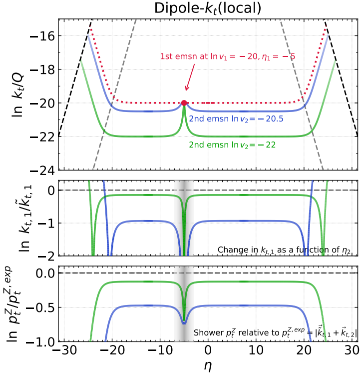

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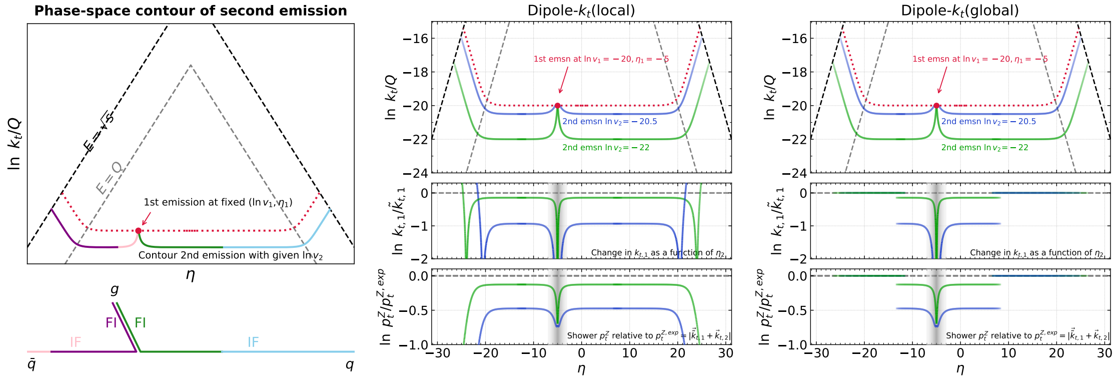

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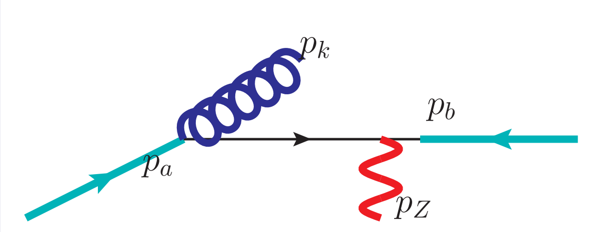
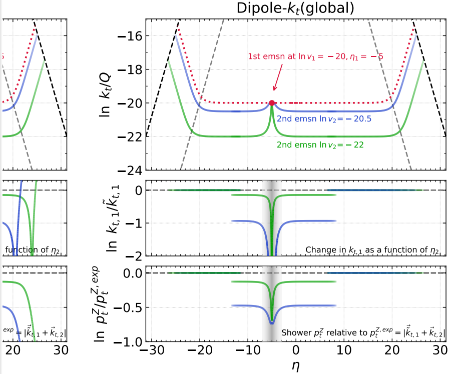
PanLocal starting point

Giving transverse momentum recoil to the incoming parton and the apply a global boost seems the less worse option...



To get PanLocal:

1. Measure the rapity in the Z boson rest frame
2. Ordering variable $v^2 = \sqrt{k_t^2 q^2}$



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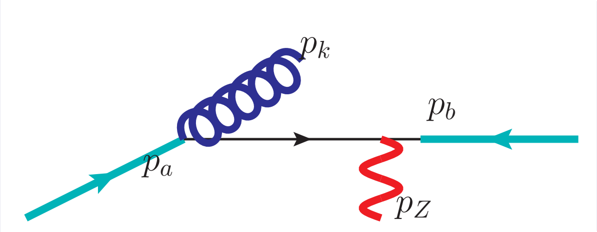

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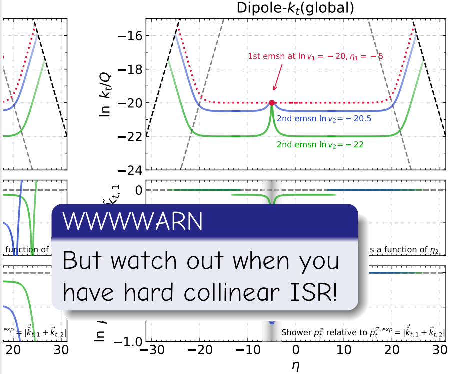


WWWWARN

But watch out when you have hard collinear ISR!

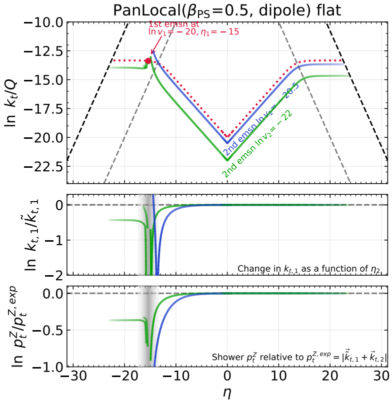
van Beekveld, SFR, Salam, Soto-Ontoso, Soyez, Verheyen, [arXiv:2205.02237]

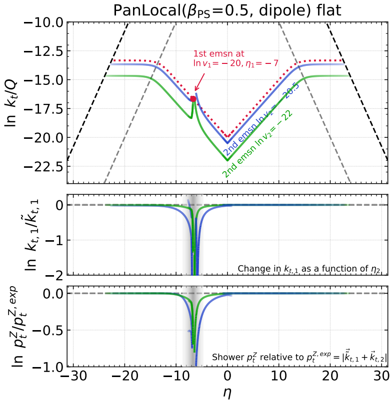
PanLocal for hadron collisions

We use $\mathbf{v} \approx k_t e^{-|\eta|/2}$ for soft-collinear emissions (like for FSR) and restore **transverse momentum** conservation for very collinear emissions.

ISR: $\kappa^2_{t,\text{shower}} = \dfrac{|k^2_\perp|}{(1+a_k)^{\frac{2}{1+\beta}}}$

FSR: $\kappa^2_{t,\text{shower}} = |k^2_\perp|$





PanGlobal for hadron collisions

- To have $\beta = 0$ (i.e. k_t-ordering) we cannot conserve the **transverse momentum** locally.
- In the $\boxed{Z \to q\bar{q}}$ variant of **PanGlobal**, the **whole final-state is boosted** to absorbe the transverse momentum of the emission, and the hardest partons (typically the original $q\bar{q}$ pair) takes the recoil;

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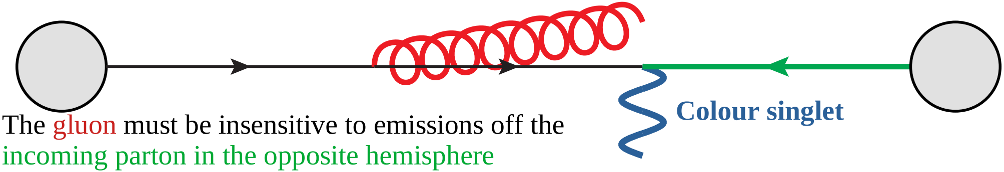
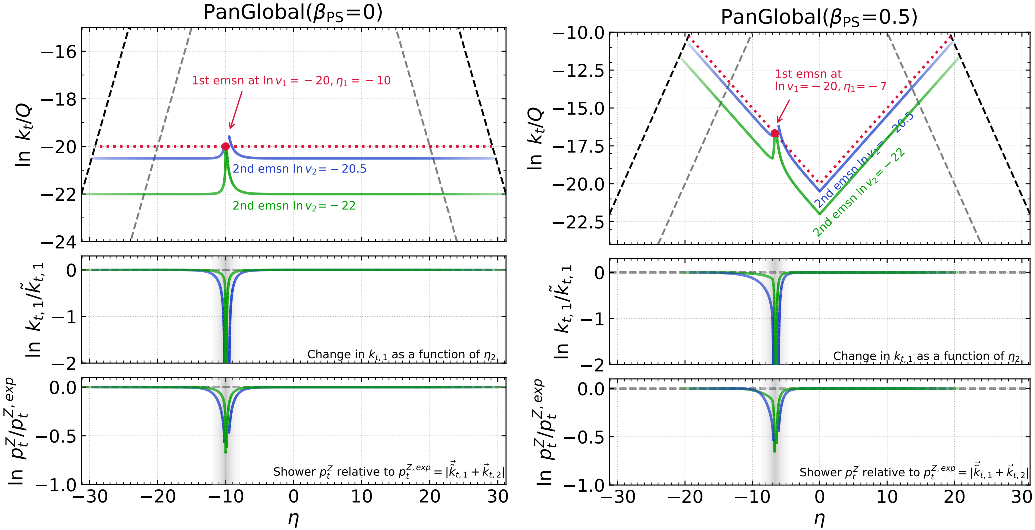
- For $\boxed{q\bar{q} \to Z}$, boosting the whole final-state is dangerous, because we can have very energetic partons produced from the backward evolution of the incoming partons that should not be affected by emissions well-separated in rapidity (interesting solution by Nagy, Soper '09, that however works only for $\beta > 0$)



- We boost only the Z **boson** to absorb the recoil (and rescale the beams to ensure momentum conservation)

Two-emission contours for PanGlobal

With this map, we can build an NLL shower ordered with several ordering scales



All-order tests: general strategy

- We want to compare against the analytic NLL result

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

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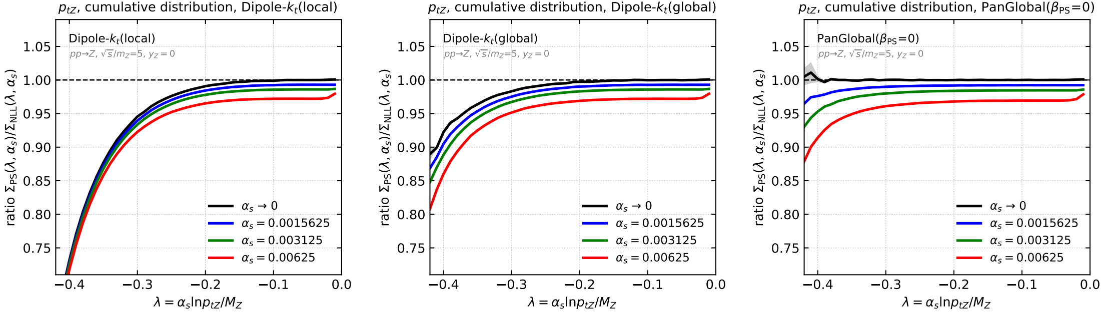
- We want to compare against the analytic NLL result

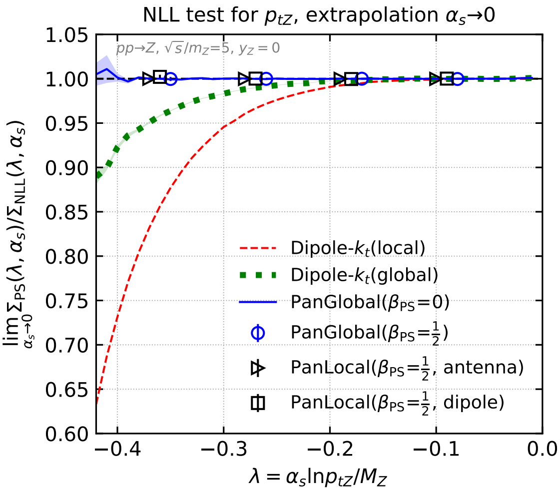
$$\Sigma(O < e^L) = \exp\left(L g_{\text{LL}}(\alpha_s L) + g_{\text{NLL}}(\alpha_s L) + \alpha_s g_{\text{NNLL}}(\alpha_s L) + \ldots\right)$$

- We want to be sure higher order corrections do not pollute our comparison: we need to extract $\Sigma_{\text{PS}}/\Sigma_{\text{analytic}}$ for $\alpha_s \to 0$ at fixed value of $\lambda = \alpha_s L$

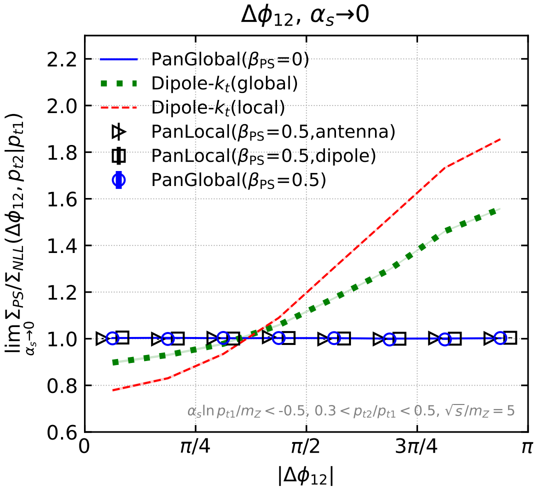


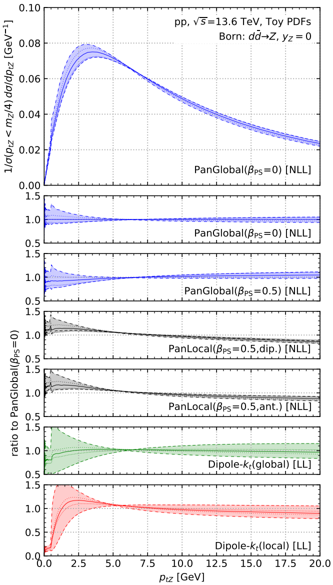
van Beekveld, SFR, Hamilton, Salam, Soto-Ontoso, Soyez, Verheyen, [arXiv:2207.09467]

Z bososon p_T



$\Delta\Phi_{1,2}$ between the two leading (C/A, $R=1$) jets





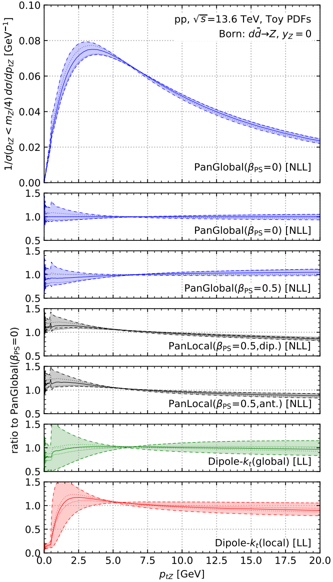
- We vary by a factor 2 the scale used to evaluate the PDF's

$$\mu_F = x_F \mu_F^{\text{central}}, \qquad x_F = 1/2, 1, 2$$

- We vary by a factor 2 the scale used to evaluate α_s, adding a compensation factor for soft emissions in NLL showers

$$\mu_R = x_R \mu_R^{\text{central}}, \quad x_R = 1/2, 1, 2 \quad \alpha_s(\mu_R)\left(1 + \frac{K}{2\pi}\alpha_s(\mu_R) + \underbrace{2(1-\xi)b_0\alpha_s(\mu_R)\log x_R}_{\text{In the soft limit evaluated at } k_t}\right)$$

(Similar to Mrenna, Skands [1605.08352])



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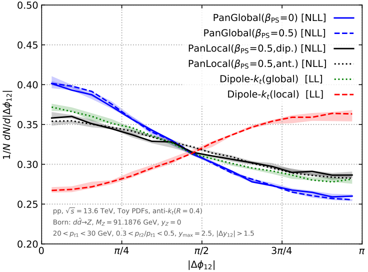
(Similar to Mrenna, Skands [1605.08352])

- Scale variations do not capture the differences among the NLL showers: open question on realistic estimate of **shower uncertainties**
- Except in the very small p_T regions, LL and NLL showers yield similar results (with the NLL ones having much smaller scale uncertainty) $\rightarrow$ **Does NLL matter?**

Exploratory pheno with $\Delta\Phi_{12}$

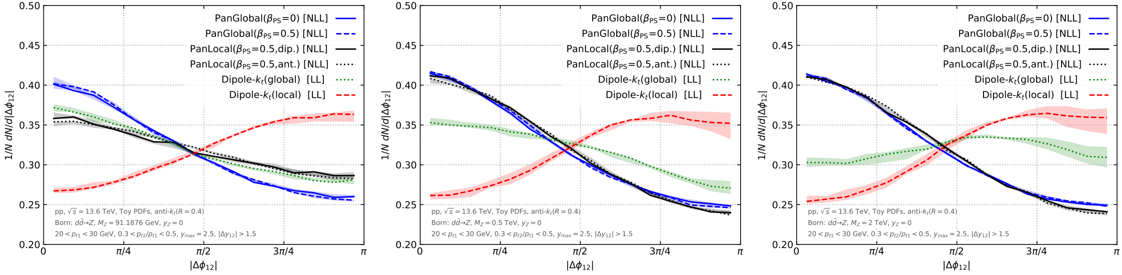
Azimuthal correlations between the two leadind (C/A, $R = 1$) jets, requiring $p_{T,1} \sim 25$ GeV, $p_{T,2} \sim 10$ GeV, $\Delta y > 1.5$ for Drell-Yan, with $y_Z = 0$ and $m_Z/\text{GeV} = $ **91**



- For **onshell Z production**, the "best" LL shower is undistinguishible from the NLL, and scale variations are much smaller than recoil scheme variations within NLL showers. Can we tune to get the correct picture at the Z pole?

Exploratory pheno with $\Delta\Phi_{12}$

Azimuthal correlations between the two leadind (C/A, $R = 1$) jets, requiring $p_{T,1} \sim 25$ GeV, $p_{T,2} \sim 10$ GeV, $\Delta y > 1.5$ for Drell-Yan, with $y_Z = 0$ and m_Z/GeV $=$ **91**, **500, 2000**



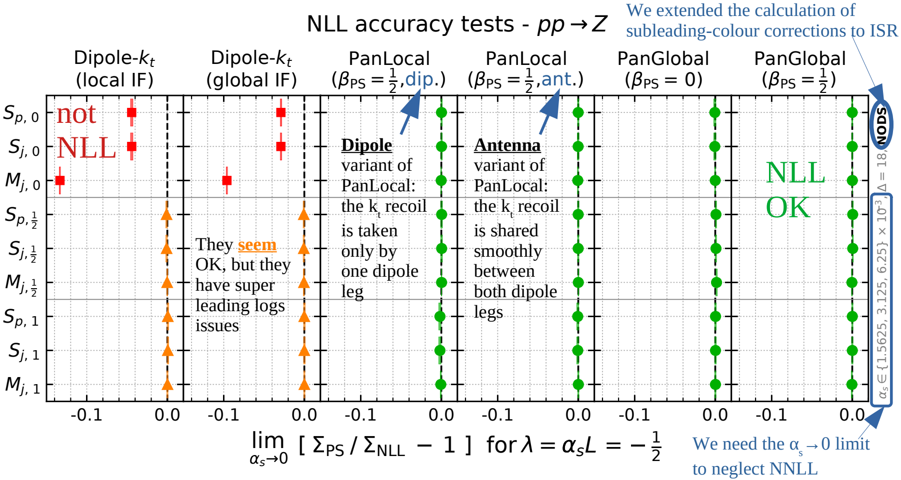
- For **onshell Z production**, the "best" LL shower is undistinguishible from the NLL, and scale variations are much smaller than recoil scheme variations within NLL showers. Can we tune to get the correct picture at the Z pole?
- For **very large mass $M_z \geq 500$ GeV**, the LL showers lead to clear distorsions wrt the NLL ones, scale variations are smaller but of the same order of magnitude of NLL shower differences: Tuning will not help if you want to be predictive across several $\sqrt{s}$, you need NLL!

Conclusions and Outlook

- **Parton Showers** are employed in almost every analysis from the LHC experimential collaborations: indispensable for **collider phenomenology**!
- The **accuracy** of Parton Showers is very **rough** compared to state-of-the-art analytic calculations, which in turn however have limited applicability (only few observables, joint resummation very difficult, analytic hadronization models not so advanced . . .)
- We can learn from analytic resummation how to build a **next-to-leading-logarithmic** shower!
- Several NLL showers for all the most relevant LHC processes are around the corner, in particular PanScales is working hard towards having a **public code** usable for phenomenology at the LHC (ongoing work on matching, masses, processes with generic jets and more).
- Long-standing issue: **shower uncertainties**. Having several and not just 1 NLL shower will help.

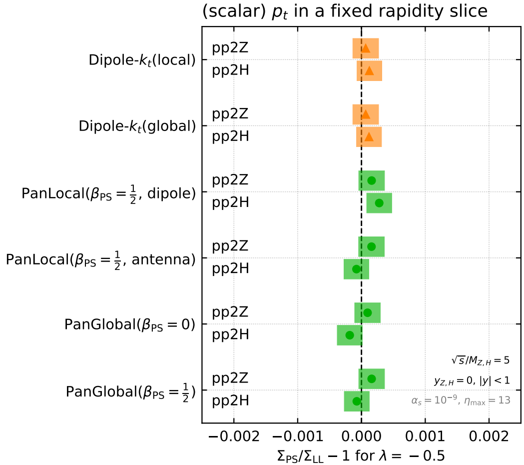
BACKUP

All-order tests: global event shapes



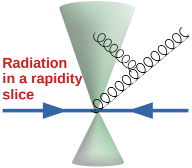
$$M_{j,\beta} = \max_{j \in \text{jets}} \left(|p_{\perp,j}| e^{-\beta|\eta_j|}\right), \quad S_{j,\beta} = \sum_{j \in \text{jets}} |p_{\perp,j}| e^{-\beta|\eta_j|}, \quad S_{p,\beta} = \sum_{p \in \text{partons}} |p_{\perp,p}| e^{-\beta|\eta_p|}$$

All-order tests: non-global observables



- **Non-global QCD observables** are characterised by a sensitivity to the full angular distribution of soft radiation emitted coherently in hard scattering processes.
- **Dipole showers** can also describe non-global oservables, such as $S_{p,0}$ (=scalar sum of $\vec{p}_\perp$) for emissions in a rapidity slice

$$\Sigma(S_{p,0} < e^L; |y| < y_{\text{cut}}) = \exp\left(g_{\text{LL}}(\alpha_s L) + \alpha_s g_{\text{NLL}}(\alpha_s L) + \ldots\right)$$



$$\log(\Sigma) = Lg_{\text{LL}}(\alpha_s L) + g_{\text{NLL}}(\alpha_s L) + \alpha_s g_{\text{NNLL}}(\alpha_s L) + \ldots = \sum_{i=1}^{\infty} (\alpha_s L)^i \left[c_{i,\text{LL}} L + c_{i,\text{NLL}} + c_{i,\text{NNLL}} L^{-1} + \ldots\right]$$

If we ignore the running of α_s, $b_0 = 0 \to g_{\text{LL}} = 0$, so at order α_s^n there cannot be more than n powers of L. If we find terms $\alpha_s^n L^m$ with $m \geq n+1$ (or $n+2$ if we include the running) those are **superleading logarithms**, which should not present (here is $e^+e^- \to q\bar{q}$ at leading colour)

$$\lim_{L\to\infty} \frac{[\log(\Sigma_{\text{PS}}) - \log(\Sigma_{\text{NLL}})]_{\alpha_s^n}}{L^n} = \begin{cases} 0 & \text{the shower is NLL} \\ \text{const} & \text{the shower is not NLL} \\ cL^i \quad \text{with } i \geq 1 & \text{there are superleading logs} \end{cases}$$