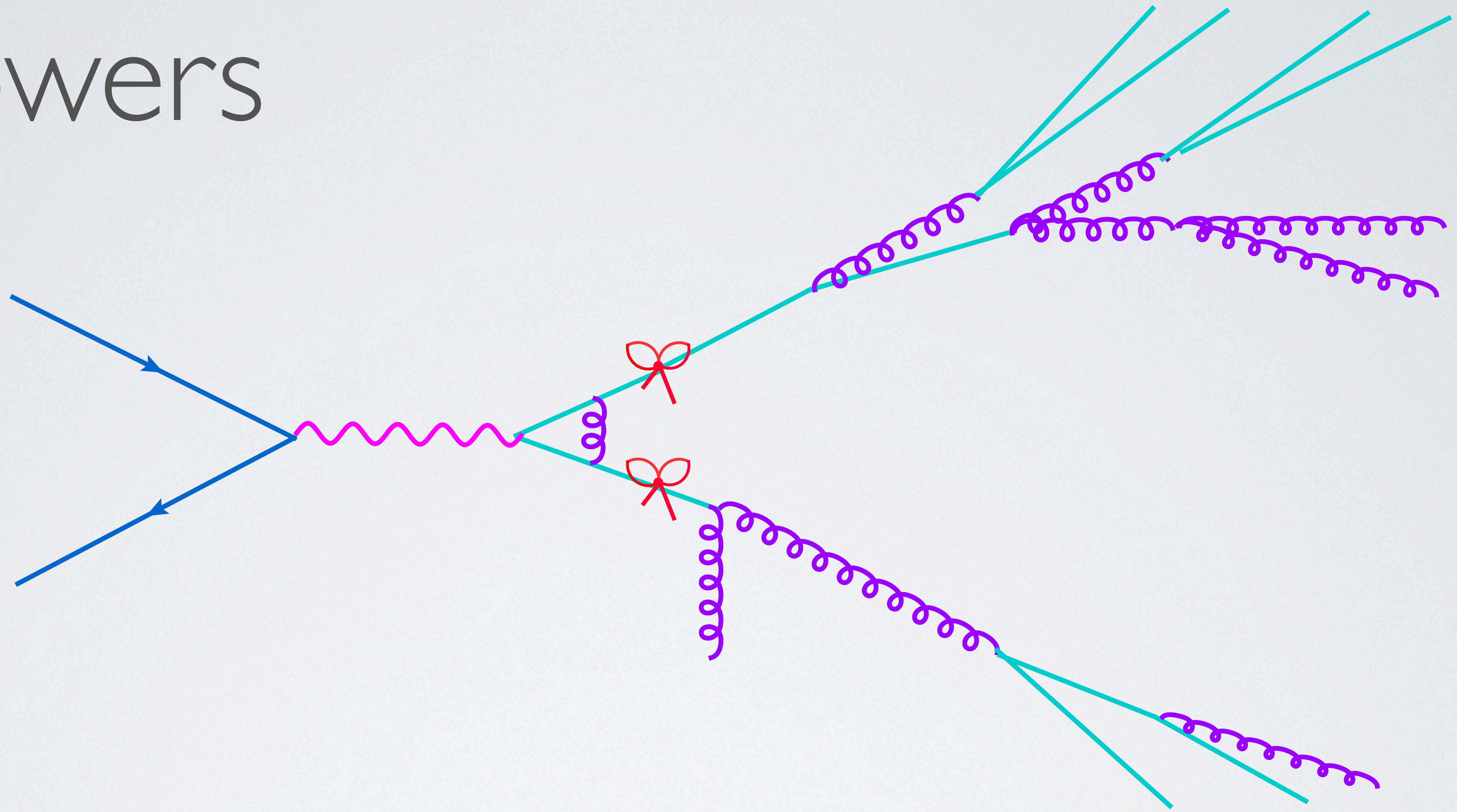
NLO matching for Antenna Showers



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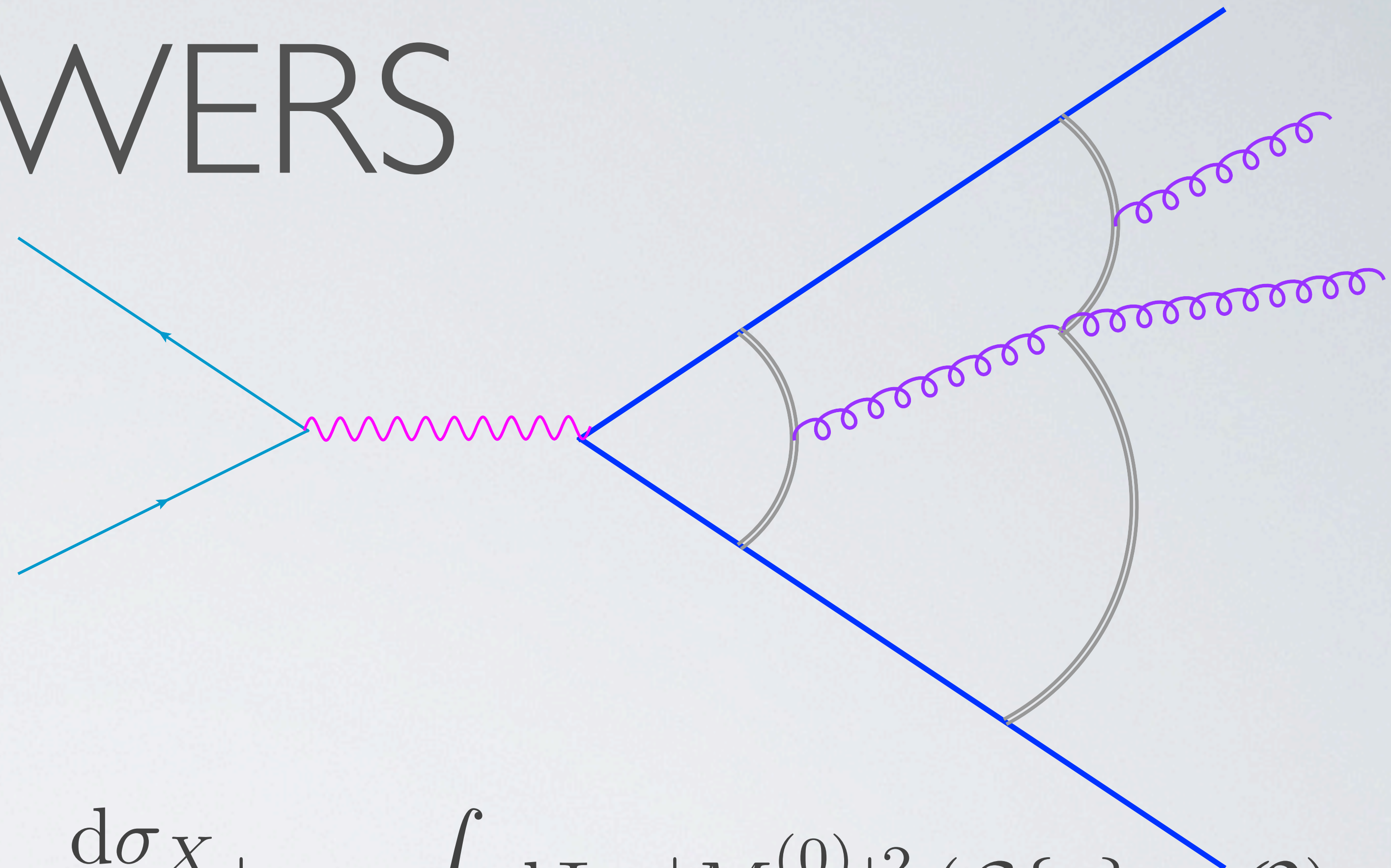
NIKHEF

DIPOLE SHOWERS



- Markov chain
- Insert evolution operator $$\frac{d\sigma_X}{d\mathcal{O}}|_{\mathcal{S}} = \int d\Phi_X |M_X^{(0)}|^2 \left(\mathcal{S}\{p\}_X, \mathcal{O}\right)$$

Sudakov form factor: no emission probability

$$\begin{aligned}\mathcal{S}(\{p\}, Q_{start}, Q_{stop}) &= \Delta(\{p\}, Q_{start}, Q_{stop}) \\ &+ \Sigma_{IK\to ijk} \int_{Q_{stop}}^{Q_{begin}} \frac{d\Phi_3^{ijk}}{d\Phi_2^{IK}} a_{j/IK} \Delta(\{p\}, Q_{start}, Q^{ijk}) \mathcal{S}(\{p\}_{n+1}^{IK\to ijk}, Q_{restart}^{ijk}, Q_{stop})\end{aligned}$$

antenna, branching probability

We will consider FSR in Z decay to obtain a final state shower

MATCHING LO

- start with trial emission $\longrightarrow$ veto for right distribution

- apply multiplicative accept probability

Madgraph

$$P^{\mathrm{ME}}_{X+1} = \frac{|M_{X+1}(\{p\}_{X+1})|^2}{\sum_k a_k^{\mathrm{PS}}(\{\hat{p}\}_n^{[k]} \leftarrow \{p\}_{n+1})|M_X(\{\hat{p}\}_X^{[k]})|^2}$$

antenna

- Probability in Sudakov form factor (non emission probability) is adapted

VINCIA

- Developed by Giele, Kosower & Skands (hep-ph/0707.3652)
- Based on Dipole-Antennae

▶Z decay LO matched to 6 jets

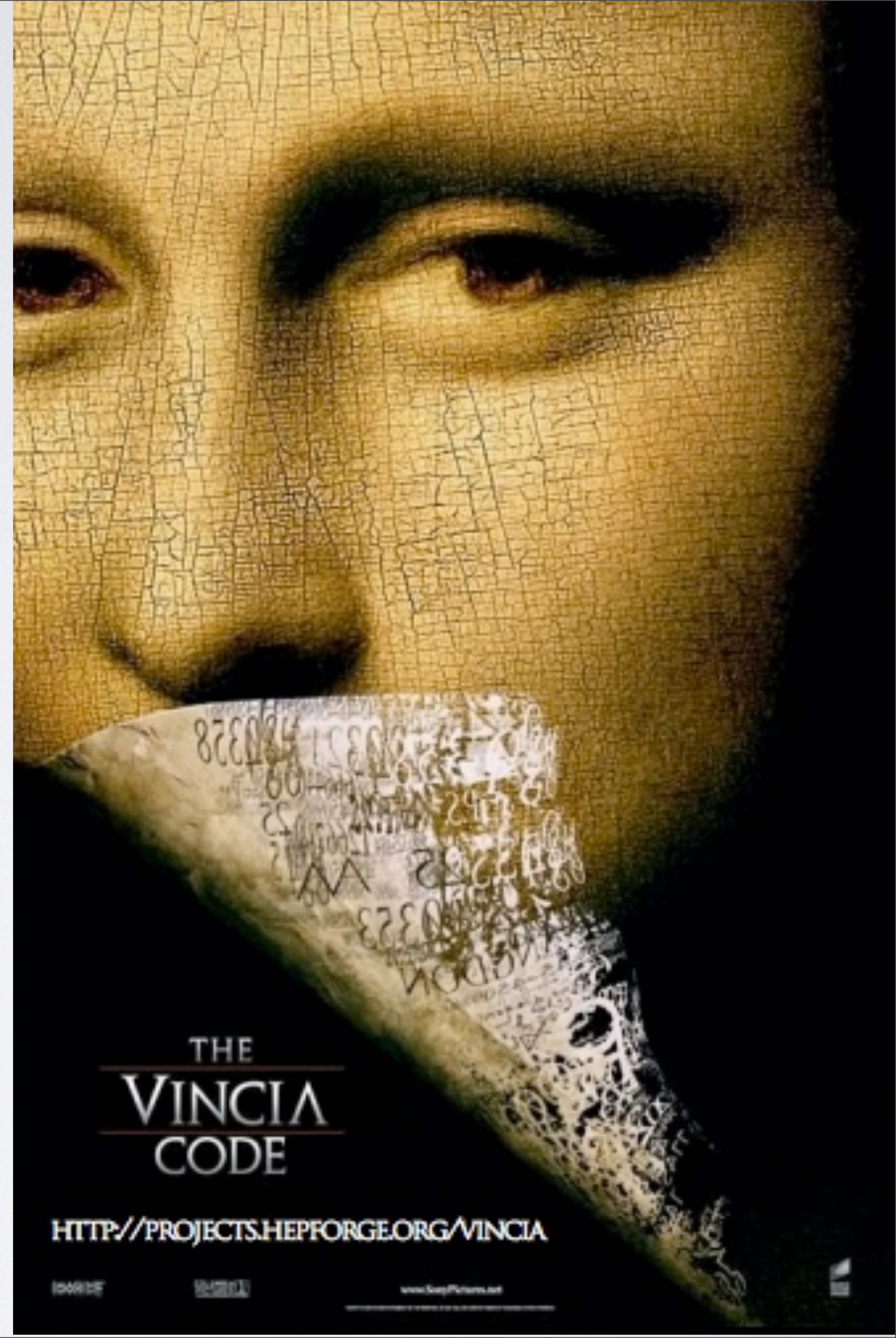
▶Sector Antennae (Skands, Villerjo-Lopez)

▶Massive Antennae (Skands, Gehrmann-de-Ridder, Ritzmann)

▶Helicity dependent Antennae (in progress: Larkoski, Villerejo-Lopez, Skands)

▶ISR (in progress: Giele, Kosower, Ritzmann)

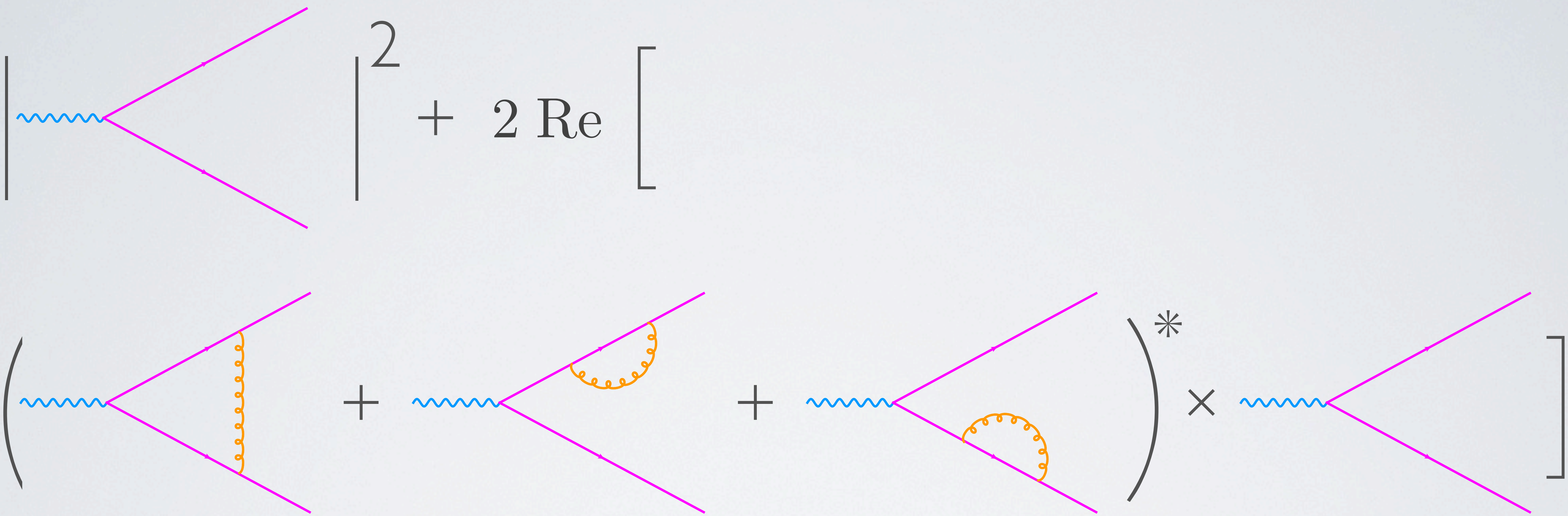
▶NLO matching (in progress: Hartgring, Laenen, Skands



MATCHING NLO

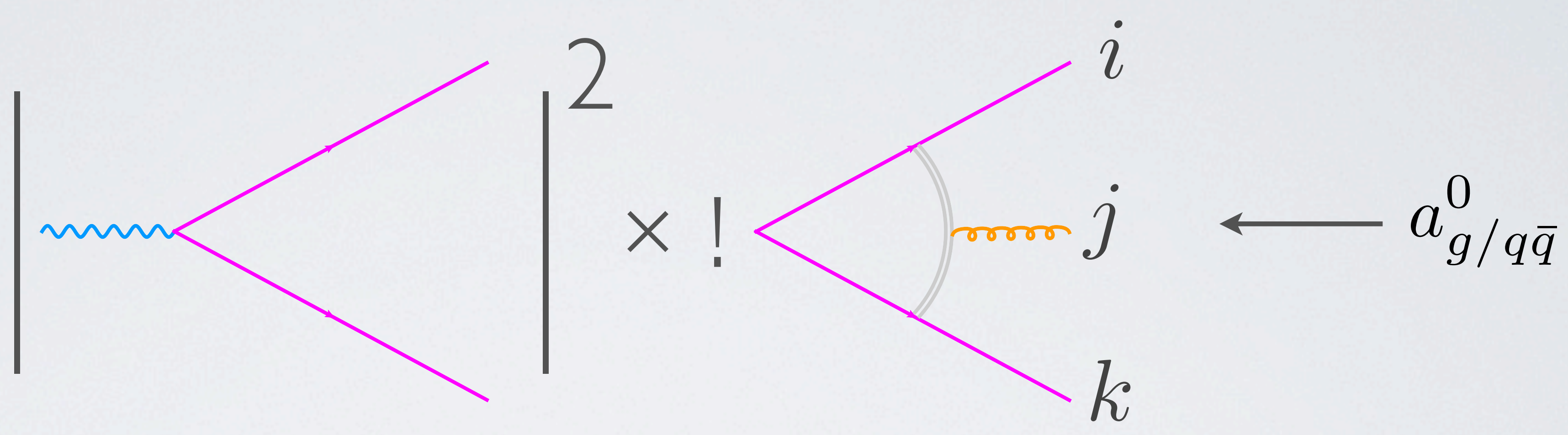
- First demonstrate for $Z \longrightarrow 2$ jets at NLO
- NLO is more challenging than LO due to infinities of loop calculation

MATCHING NLO



$$\left|M_2^{(0)}(\Phi_2)\right|^2 + 2\,\mathrm{Re}\left[M_2^{(1)}(\Phi_2)M_2^{(0)*}(\Phi_2)\right]$$

MATCHING NLO



No emission probability

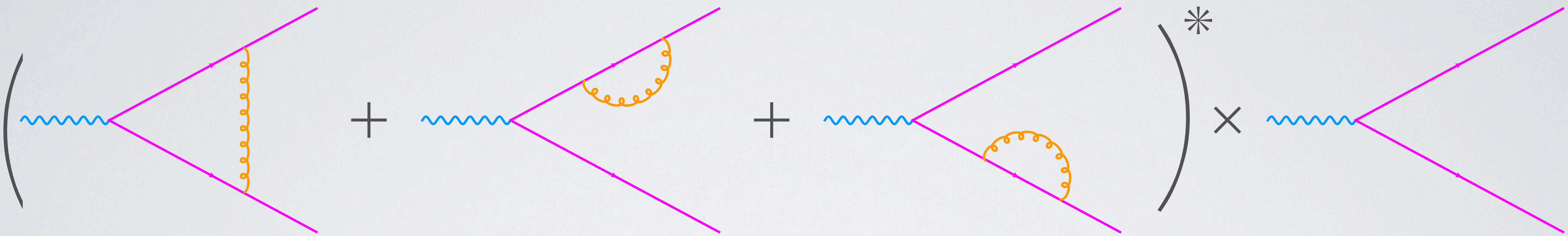
$$\left|M_2^0\left(\Phi_2\right)\right|^2 \Delta_2\left(\hat{s},0\right)$$

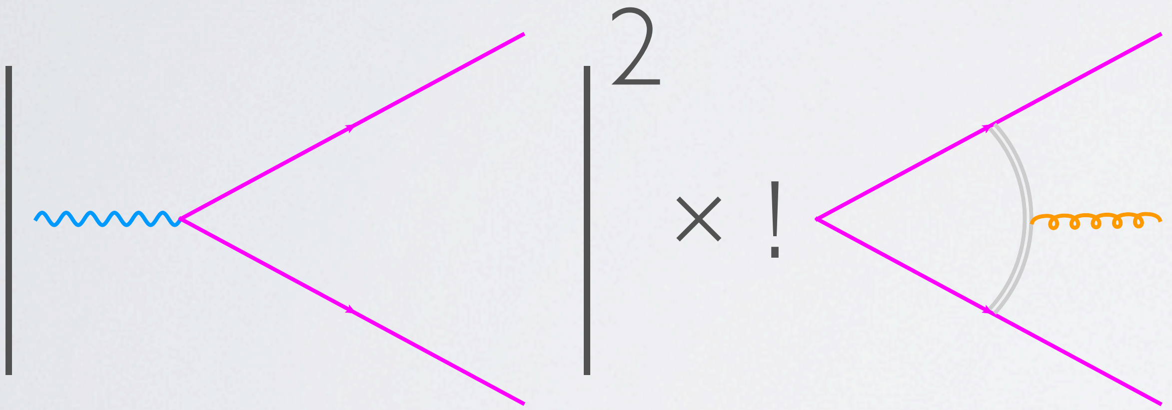
$$\Delta_2(\hat{s},0) = 1 - \int_0^{\hat{s}} \mathrm{d}\Phi_{3/2} a^0_{g/q\bar{q}}\left(\Phi_{3/2}\right) + \mathcal{O}\left(\alpha_s^2\right)$$

$$\downarrow$$

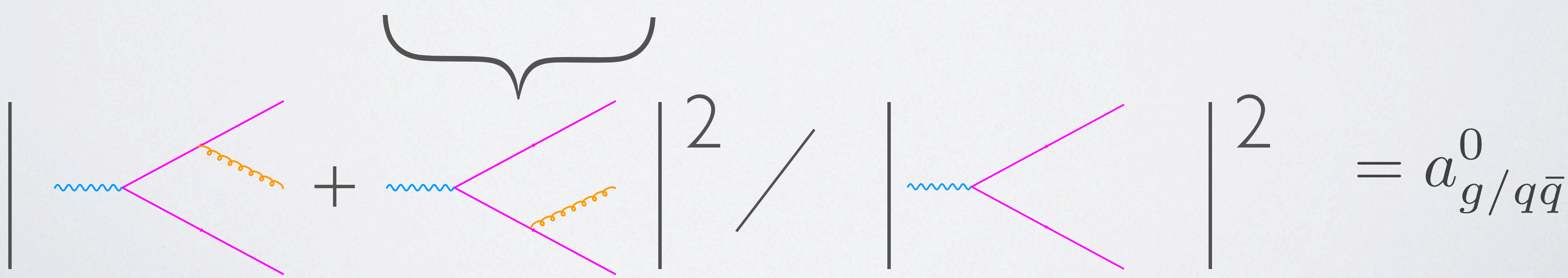
$$\propto \mathrm{d}s_{ij}\mathrm{d}s_{jk}$$

Fixed Order prediction at NLO





Shower prediction at NLO



MATCHING NLO

$$\left|M_2^{(0)}(\Phi_2)\right|^2 + 2\mathrm{Re}\left[M_2^{(1)}(\Phi_2)M_2^{(0)*}(\Phi_2)\right] - \left|M_2^0\left(\Phi_2\right)\right|^2\left(1 - \int_0^{\hat{s}} \mathrm{d}\Phi_{3/2}a^0_{g/q\bar{q}}\left(\Phi_{3/2}\right)\right)$$

$$= \left|M_2^{(0)}(\Phi_2)\right|^2\left(2I_{qq}^{(1)}(\epsilon,s) - 4\right)$$

$$= \left|M_2^{(0)}(\Phi_2)\right|^2\left(-2I_{qq}^{(1)}(\epsilon,s) + \frac{19}{4}\right)$$

$$\text{Fixed Order} - \text{Shower} = C_F\frac{\alpha_s}{\pi}\left(-4 + \frac{19}{4}\right)\left|M_2^{(0)}(\Phi_2)\right|^2 = \frac{\alpha_s}{\pi}\left|M_2^{(0)}(\Phi_2)\right|^2$$

MATCHING NLO

- reinstalling hadronization scale yields same result

fixed order

$$\left|M_2^{(0)}(\Phi_2)\right|^2 \left(1 + \frac{2\mathrm{Re}\left[M_2^{(1)}(\Phi_2) M_2^{(0)*}(\Phi_2)\right]}{\left|M_2^{(0)}(\Phi_2)\right|^2} + \int_0^{Q^2_{\mathrm{had}}} \mathrm{d}\Phi_{3/2}\, a^0_{g/q\bar{q}}(\Phi_{3/2})\right)$$

$$\downarrow$$

$$\int_0^{Q^2_{\mathrm{had}}} = \int_0^{\hat{s}} - \int_{Q^2_{\mathrm{had}}}^{\hat{s}}$$

shower

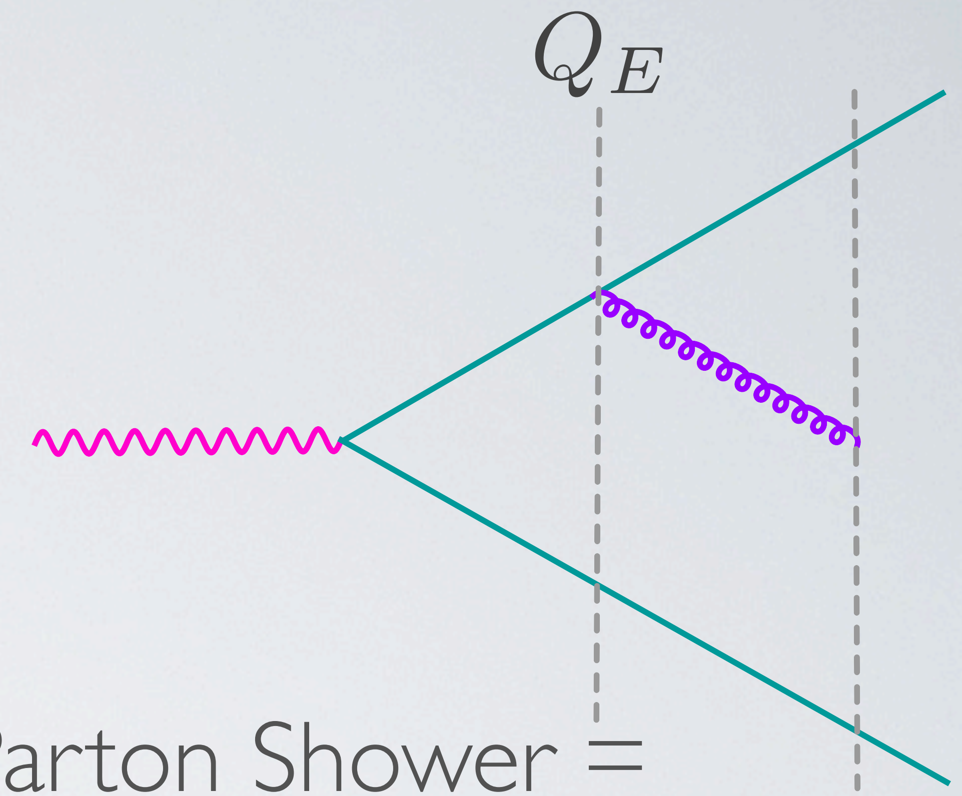
$$\left|M_2^0\right|^2 \left(1 - \int_{Q^2_{\mathrm{had}}}^{\hat{s}} \mathrm{d}\Phi_{3/2}\, a^0_{g/q\bar{q}}\left(\Phi_{3/2}\right) + \mathcal{O}\left(\alpha_s^2\right)\right)$$

MATCHING NLO

- 2 jet case is different since there's no probability emission to adapt
- matching is implemented by changing the weight, so

$$\left|M_2^0\left(\Phi_2\right)\right| \to \left(1 + \frac{\alpha_s}{\pi}\right)\left|M_2^0\left(\Phi_2\right)\right|$$

MATCHING NLO



- Ready for 3 jet case: Fixed Order - Parton Shower =

$$\left|M_3^{(0)}(\Phi_3)\right|^2 + 2\mathrm{Re}\left[M_3^{(1)}(\Phi_3)M_3^{(0)*}(\Phi_3)\right]$$
$$- \quad \left(1+\frac{\alpha_s}{\pi}\right)\left|M_2^0\left(\Phi_2\right)\right|^2 \Delta_2\left(\hat{s}, Q_E^2\right) a_3^0\left(\Phi_{3/2}\right) \Delta_3\left(Q_R^2, 0\right)$$

same integral as 2 jet case
but now only down till finite scale

poles now arising due to the
requirement of no 3→4 branching

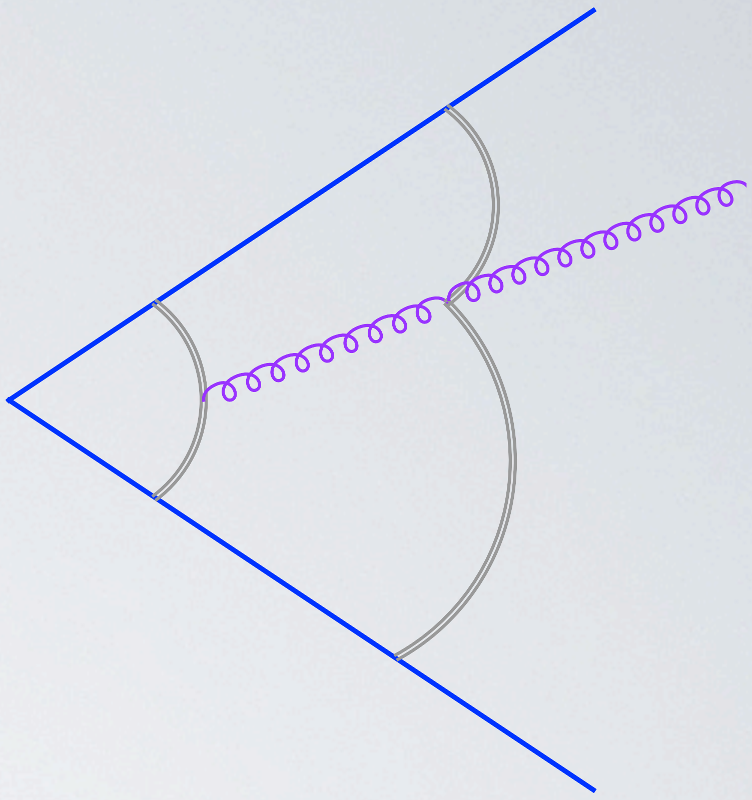
MATCHING NLO

$$\frac{2\,\mathrm{Re}\left(M_3^{(1)} M_3^{(0)*}\right)}{|M_3^{(0)}|^2} = \frac{\alpha_s}{2\pi}\,(\mathrm{LC}+\mathrm{QC})$$

infrared singularity operator

$$\begin{aligned}
\mathrm{LC} = \quad & N_C \Bigg[\left(2I_{qg}^{(1)}(\epsilon, \mu^2/s_{13}) + 2I_{qg}^{(1)}(\epsilon, \mu^2/s_{23}) \right) \\
& + \left(-R(y_{13}, y_{23}) + \frac{3}{2}\ln\left(\frac{Q^2}{\mu_R^2}\right) + \frac{5}{3}\ln\left(\frac{\mu_R^2}{s_{23}}\right) + \frac{5}{3}\ln\left(\frac{\mu_R^2}{s_{13}}\right) - 4 \right) \\
& + \frac{1}{a_{g/q\bar{q}}}\frac{1}{s_{123}}\Bigg[2\ln(y_{13}) \left(1 + \frac{s_{13}}{s_{12}+s_{23}} - \frac{s_{23}}{s_{12}+s_{23}} - \frac{4s_{23}s_{13}}{(s_{12}+s_{23})^2} \right) \\
& + 2\ln(y_{23}) \left(1 - \frac{s_{13}}{s_{12}+s_{13}} + \frac{s_{23}}{s_{12}+s_{13}} - \frac{4s_{23}s_{13}}{(s_{12}+s_{13})^2} \right) \\
& + \frac{1}{2}\left(\frac{s_{13}}{s_{23}} - \frac{s_{13}}{s_{12}+s_{13}} + \frac{s_{23}}{s_{13}} - \frac{s_{23}}{s_{12}+s_{23}} + \frac{s_{12}}{s_{23}} + \frac{s_{12}}{s_{13}} + 1 \right) \Bigg] \Bigg] \\
\mathrm{QL} = \quad & n_f \Bigg[\left(2I_{qg,F}^{(1)}(\epsilon, \mu^2/s_{13}) + 2I_{qg,F}^{(1)}(\epsilon, \mu^2/s_{23}) \right) \\
& + \frac{1}{6}\left(\ln\left(\frac{s_{23}}{\mu_R^2}\right) + \ln\left(\frac{s_{13}}{\mu_R^2}\right) \right) \Bigg]
\end{aligned}$$

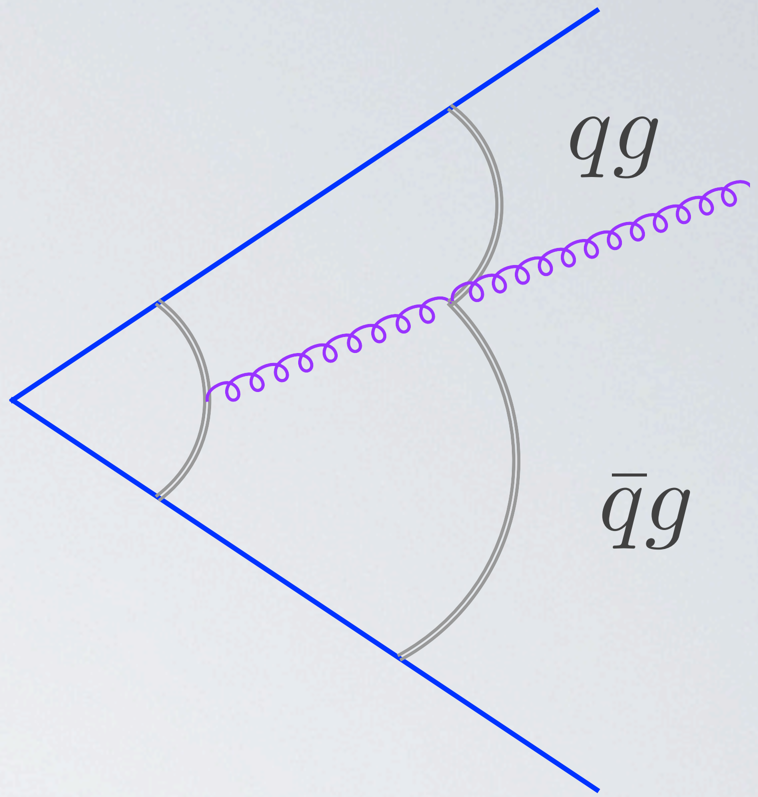
MATCHING NLO



- Need to work out Sudakov Form Factor to find the poles

$$\Delta_3(Q_R^2, 0) = 1 - \int_0^{Q_R^2} \mathrm{d}\Phi_{3/2} d^0_{g/qg}(\Phi_{3/2}) - \int_0^{Q_R^2} \mathrm{d}\Phi_{3/2}\; e^0_{q\bar{q}/qg}(\Phi_{3/2})$$
$$- \int_0^{Q_R^2} \mathrm{d}\Phi_{3/2} d^0_{g/\bar{q}g}(\Phi_{3/2}) - \int_0^{Q_R^2} \mathrm{d}\Phi_{3/2}\; e^0_{\bar{q}q/\bar{q}g}(\Phi_{3/2})$$

MATCHING NLO



- Need to work out Sudakov Form Factor to find the poles

$$\Delta_3(Q_R^2, 0) = 1 - \int_0^{Q_R^2} \mathrm{d}\Phi_{3/2} d^0_{g/qg}(\Phi_{3/2}) - \int_0^{Q_R^2} \mathrm{d}\Phi_{3/2}\ e^0_{q\bar{q}/qg}(\Phi_{3/2})$$

$$- \int_0^{Q_R^2} \mathrm{d}\Phi_{3/2} d^0_{g/\bar{q}g}(\Phi_{3/2}) - \int_0^{Q_R^2} \mathrm{d}\Phi_{3/2}\ e^0_{\bar{q}q/\bar{q}g}(\Phi_{3/2})$$

$$- \int_0^{Q_R^2} \mathrm{d}\Phi^{qg}_{3/2} d^0_{g/qg}(\Phi_{3/2}) = \int_{Q_R^2}^{s_{qg}} \mathrm{d}\Phi^{qg}_{3/2} d^0_{g/qg}(\Phi_{3/2}) - \int_0^{s_{qg}} \mathrm{d}\Phi^{qg}_{3/2} d^0_{g/qg}(\Phi_{3/2})$$

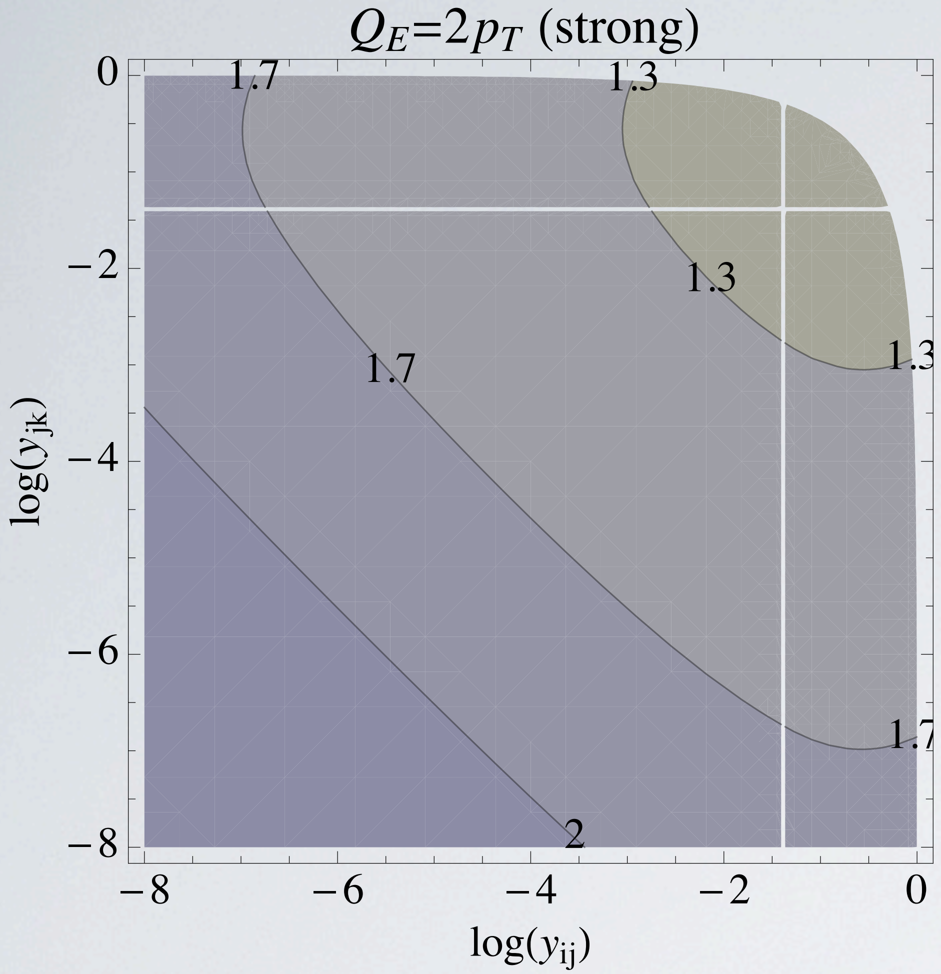
$$\int_0^{s_{qg}} \mathrm{d}\Phi^{qg}_{3/2} d^0_{g/qg}(\Phi_{3/2}) = 2I^{(1)}_{qg}(\epsilon, s_{13}) - \frac{17}{3}$$

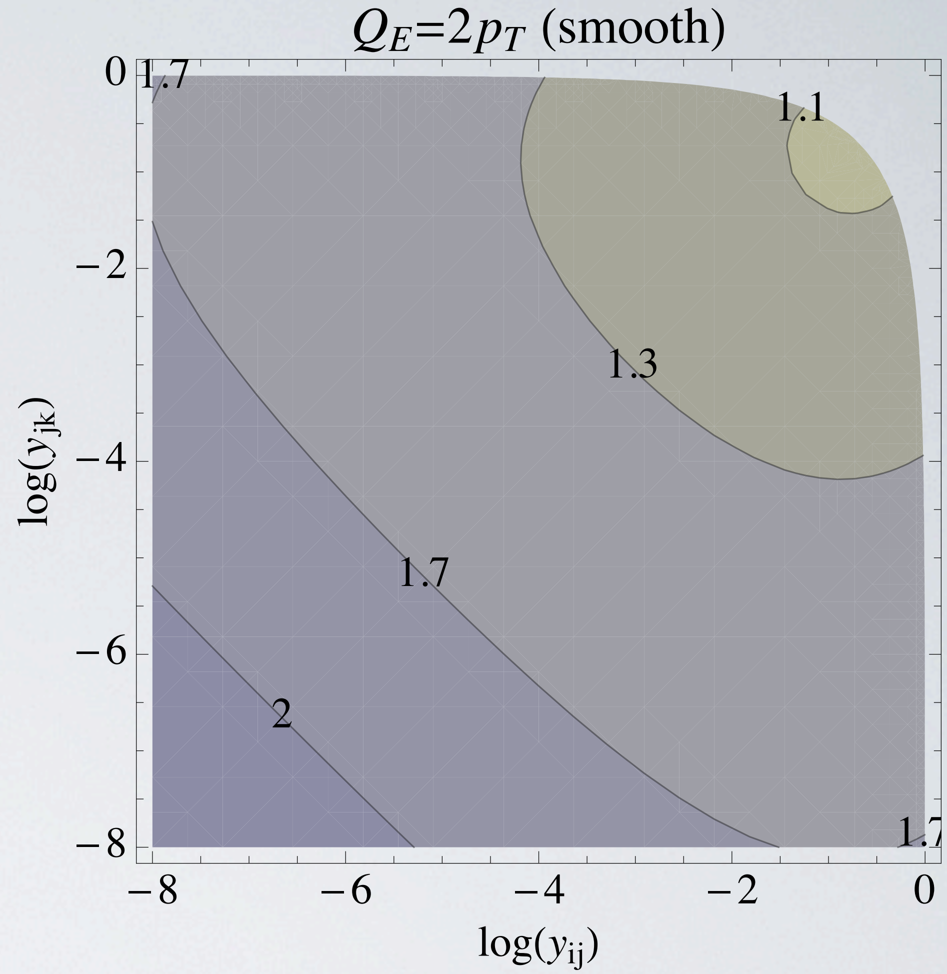
MATCHING

$$\frac{\text{Fixed Order}}{\text{Shower}} = 1 + \frac{\text{Fixed Order} - \text{Shower}}{\text{Shower}}$$

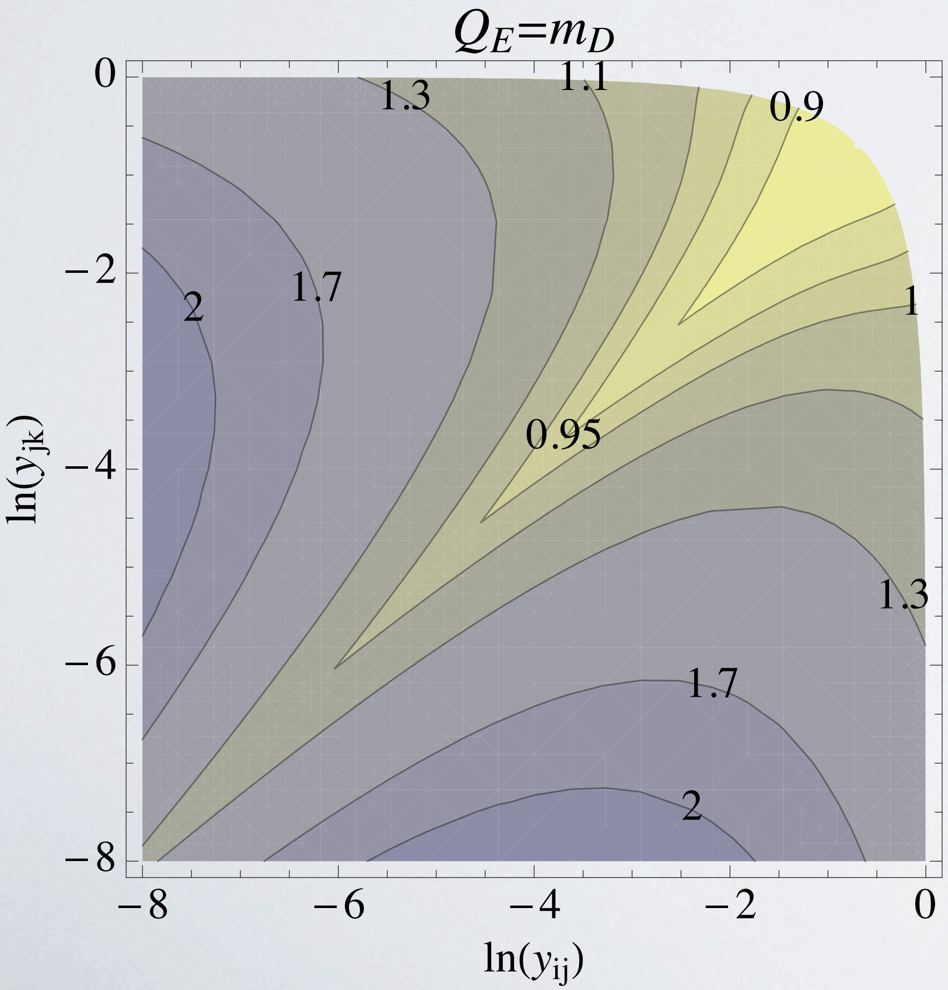
$$\downarrow$$

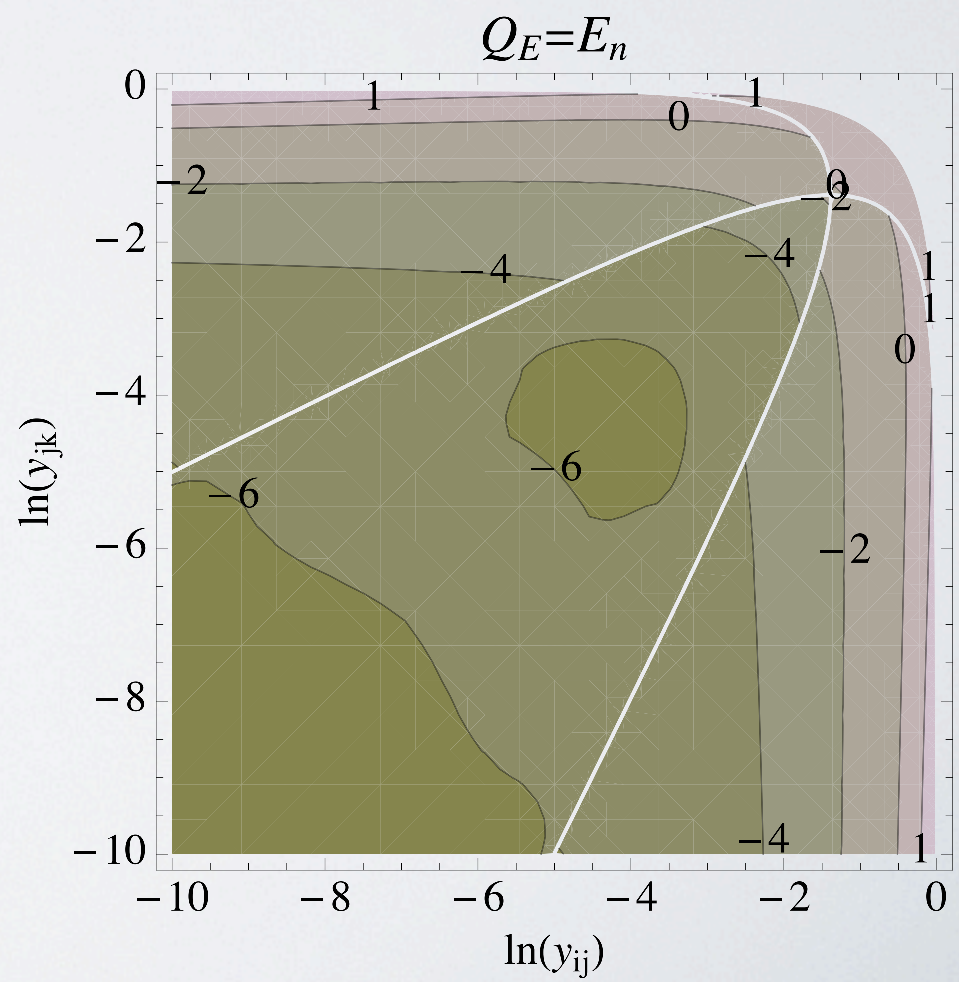
- Ready to derive Matching Factor: 1 + (Fixed Order - Shower)
- Fixed Order renormalization scale μ_R chosen equal to s
- Shower scale translated to Fixed Order scale

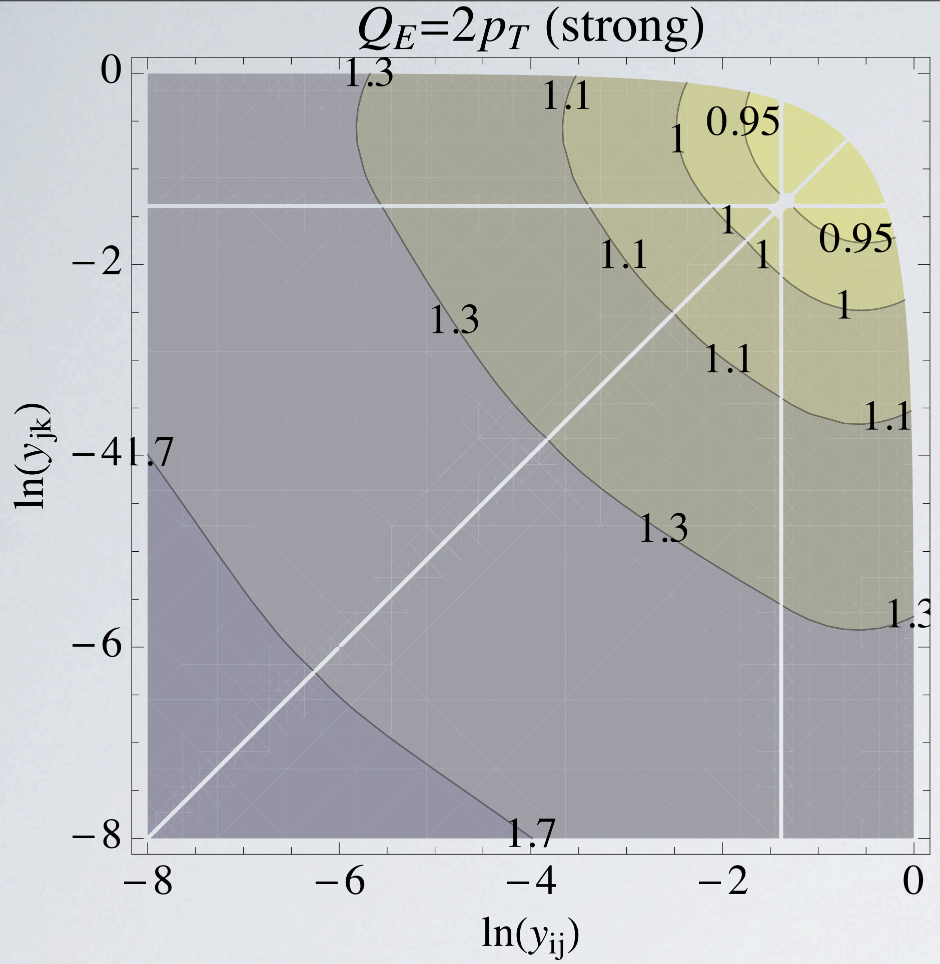

Q_E=2p_T (strong)
log(y_{jk})
log(y_{ij})

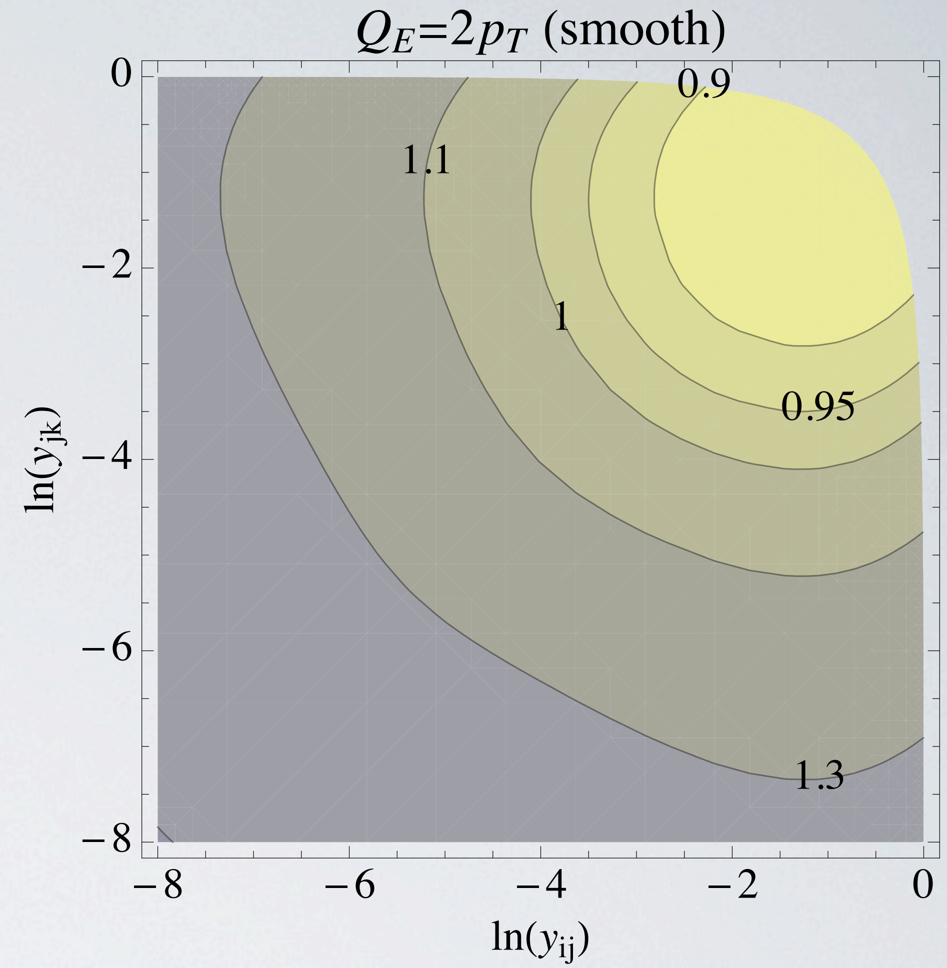

Q_E=2p_T (smooth)
log(y_{jk})
log(y_{ij})

$$\mu_R = s$$

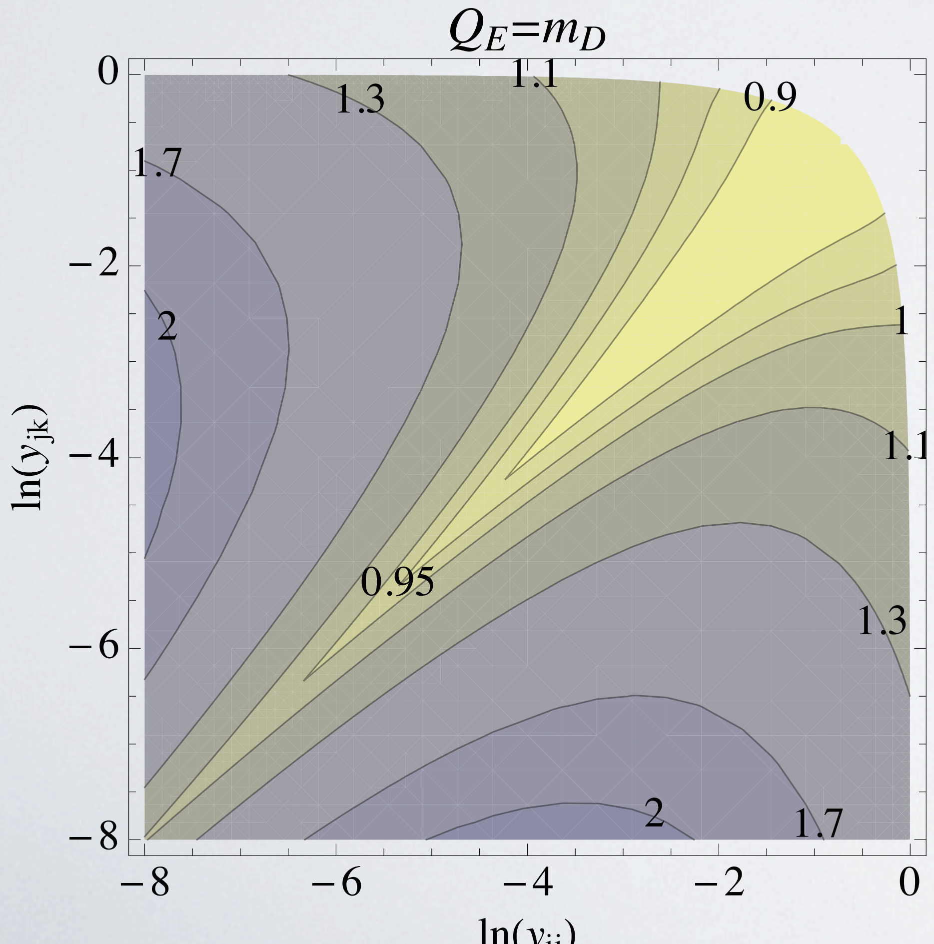

Q_E=m_D
ln(y_{jk})
ln(y_{ij})

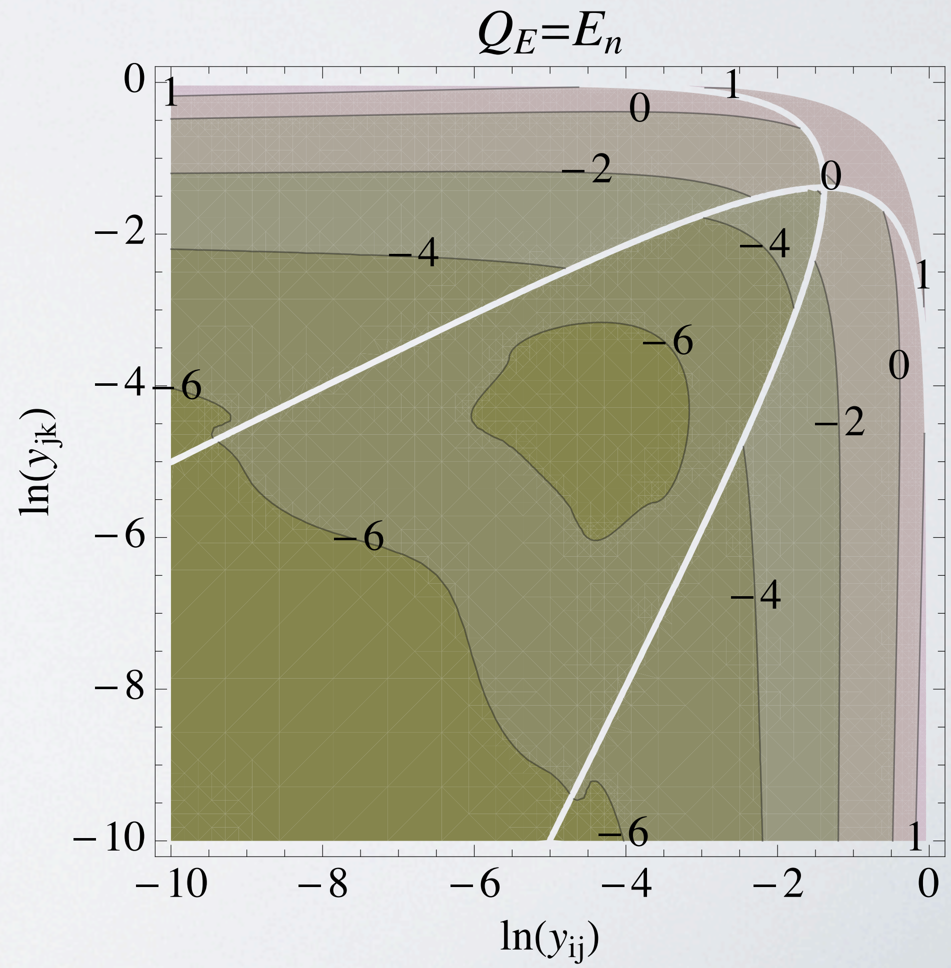

Q_E=E_n
ln(y_{jk})
ln(y_{ij})


Q_E=2p_T (strong)
ln(y_{jk})
ln(y_{ij})
1.3
1.1
1
0.95
1.7


Q_E=2p_T (smooth)
ln(y_{jk})
ln(y_{ij})
0.9
1.1
1
0.95
1.3

$$\mu_R = p_T$$


Q_E=m_D
ln(y_{jk})
ln(y_{ij})
1.3
1.1
0.9
1.7
2
1
0.95


Q_E=E_n
ln(y_{jk})
ln(y_{ij})
1
0
−1
−2
−4
−6

OUTLOOK

- Implement in the Vincia code and compare to LEP data
- Generalize for arbitrary "subtraction" scheme for one-loop calculation
- Do this for every branching in the shower…. (order α_s^2 correct shower)