UNIVERSITY OF SUSSEX

MARIE CURIE ACTIONS

UK Research and Innovation

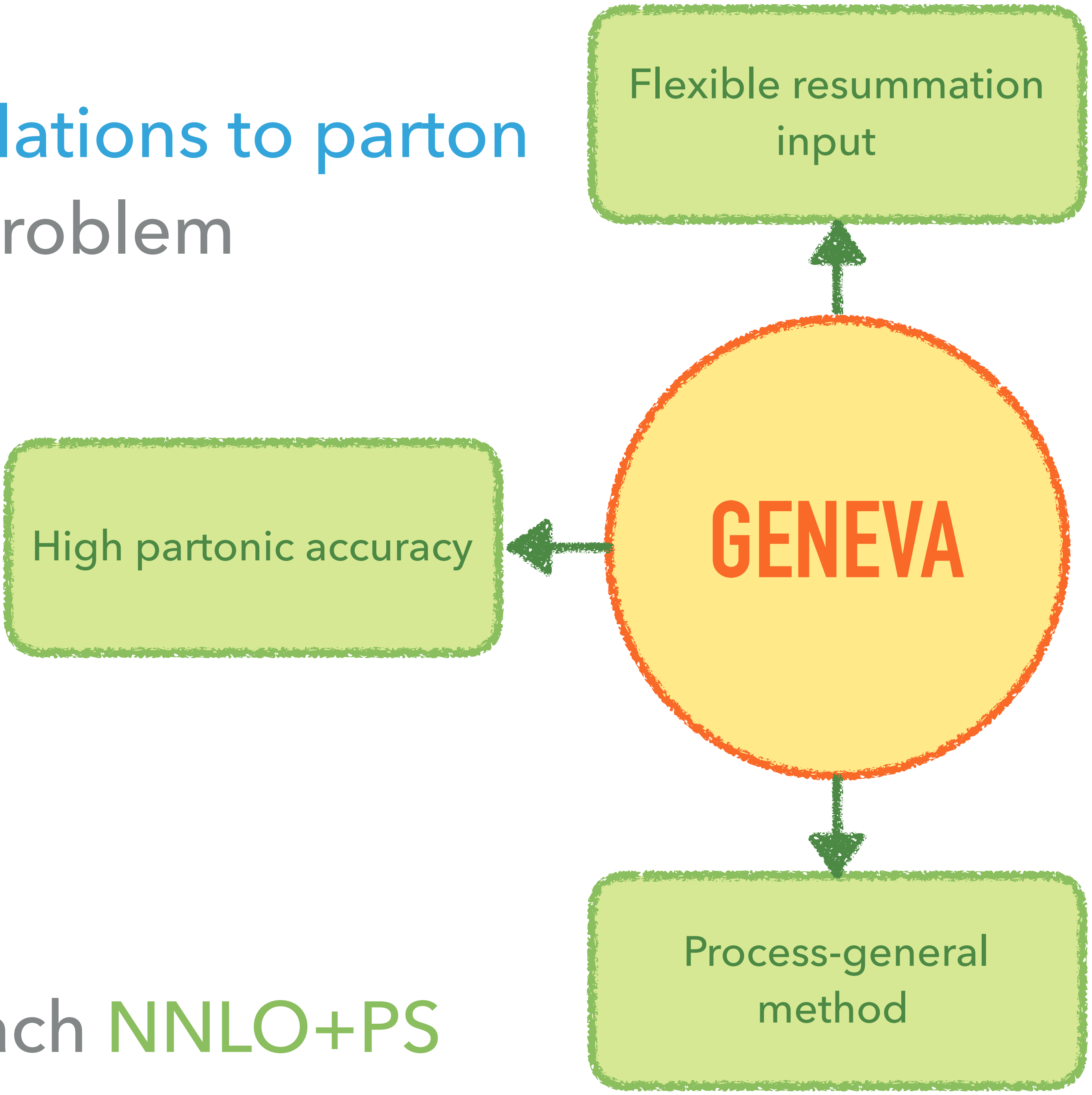
NNLO+PS IN GENEVA: RECENT DEVELOPMENTS

MATTHEW A. LIM

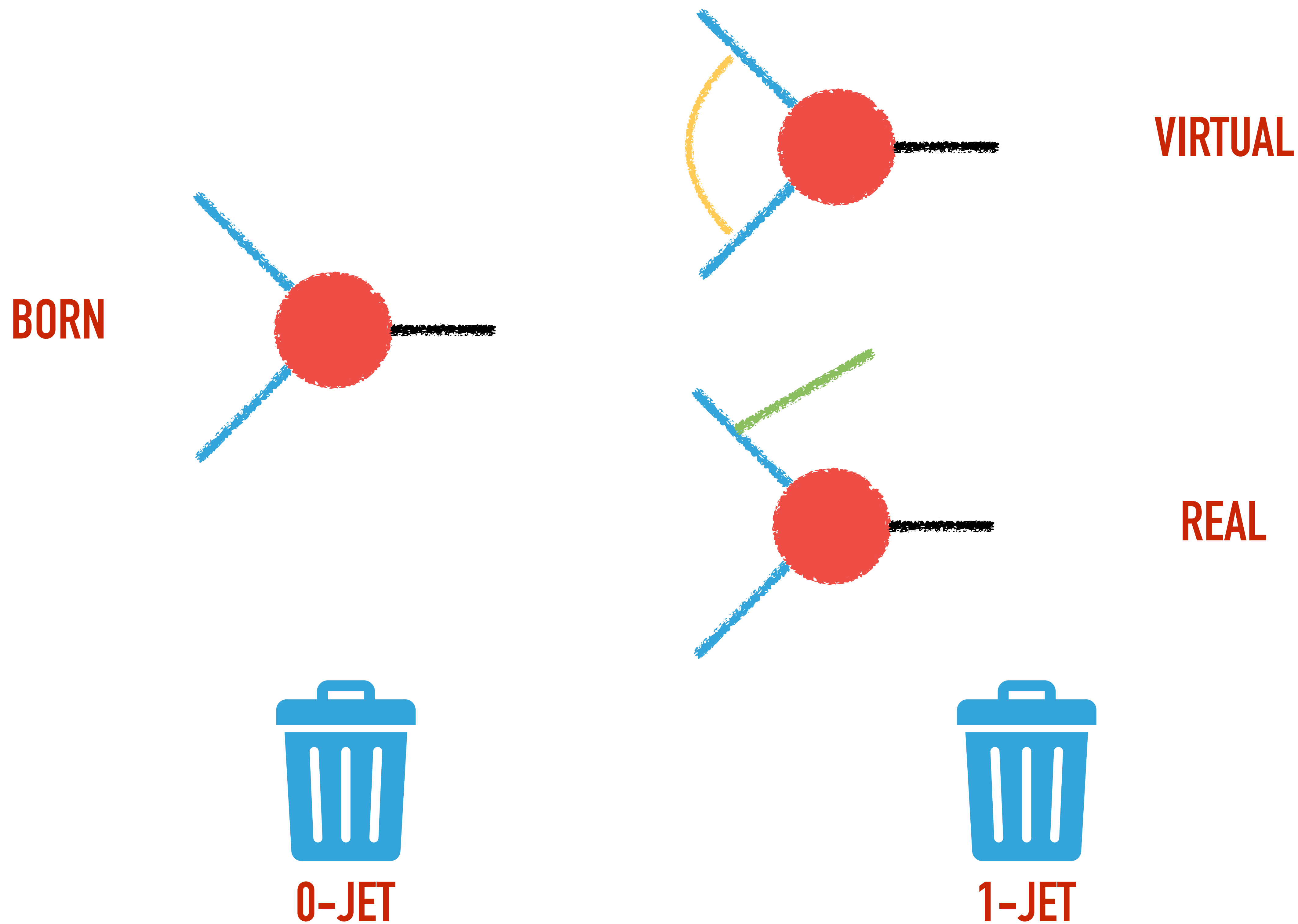
LOOPFEST XXII, SOUTHERN METHODIST UNIVERSITY, DALLAS

HIGHER ORDER MONTE CARLO EVENT GENERATORS

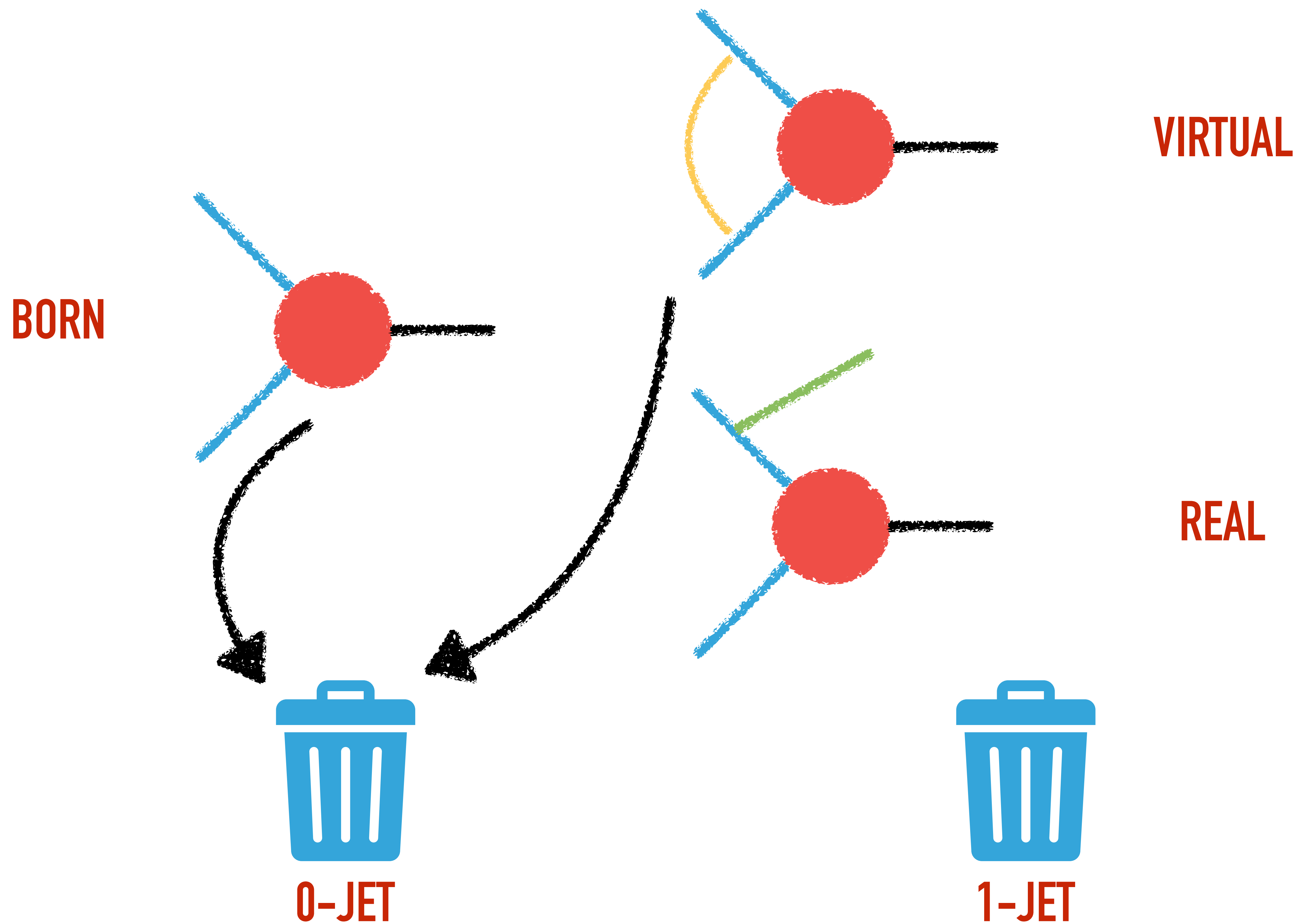
- Matching fixed order calculations to parton showers is a well-studied problem
- At NLO, several successful methods available - POWHEG, MC@NLO, KrkNLO, multiplicative-accumulative…
- GENEVA is a method to reach NNLO+PS accuracy



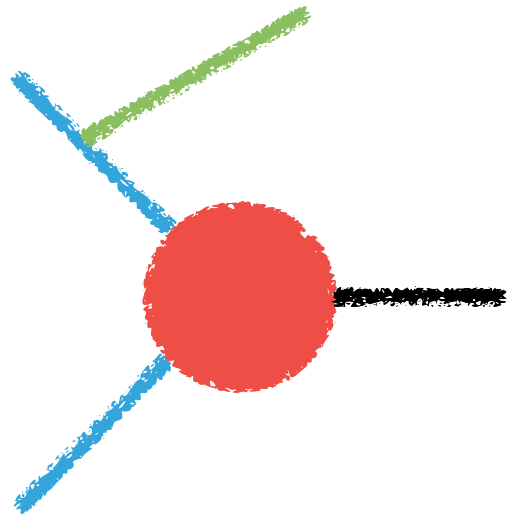
DEFINING IR-FINITE EVENTS



DEFINING IR-FINITE EVENTS



DEFINING IR-FINITE EVENTS



REAL

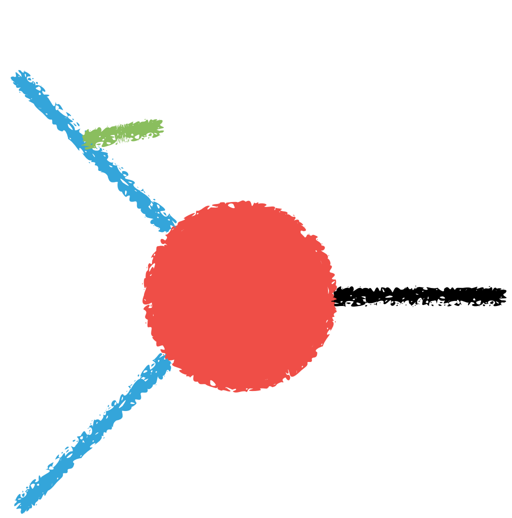
0-JET

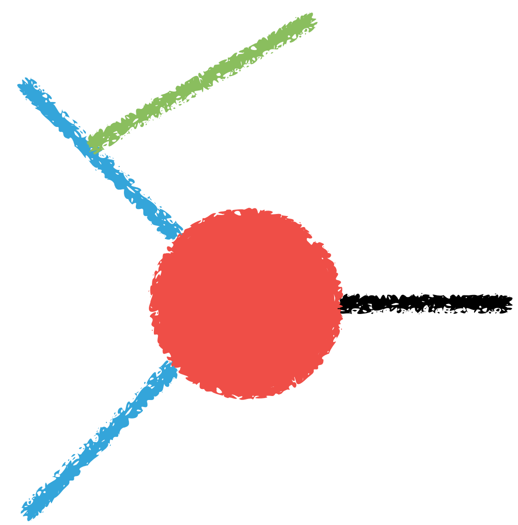
1-JET

DEFINING IR-FINITE EVENTS

SOFT/COLL. REAL

$$r_0 < r_0^{\mathrm{cut}}$$





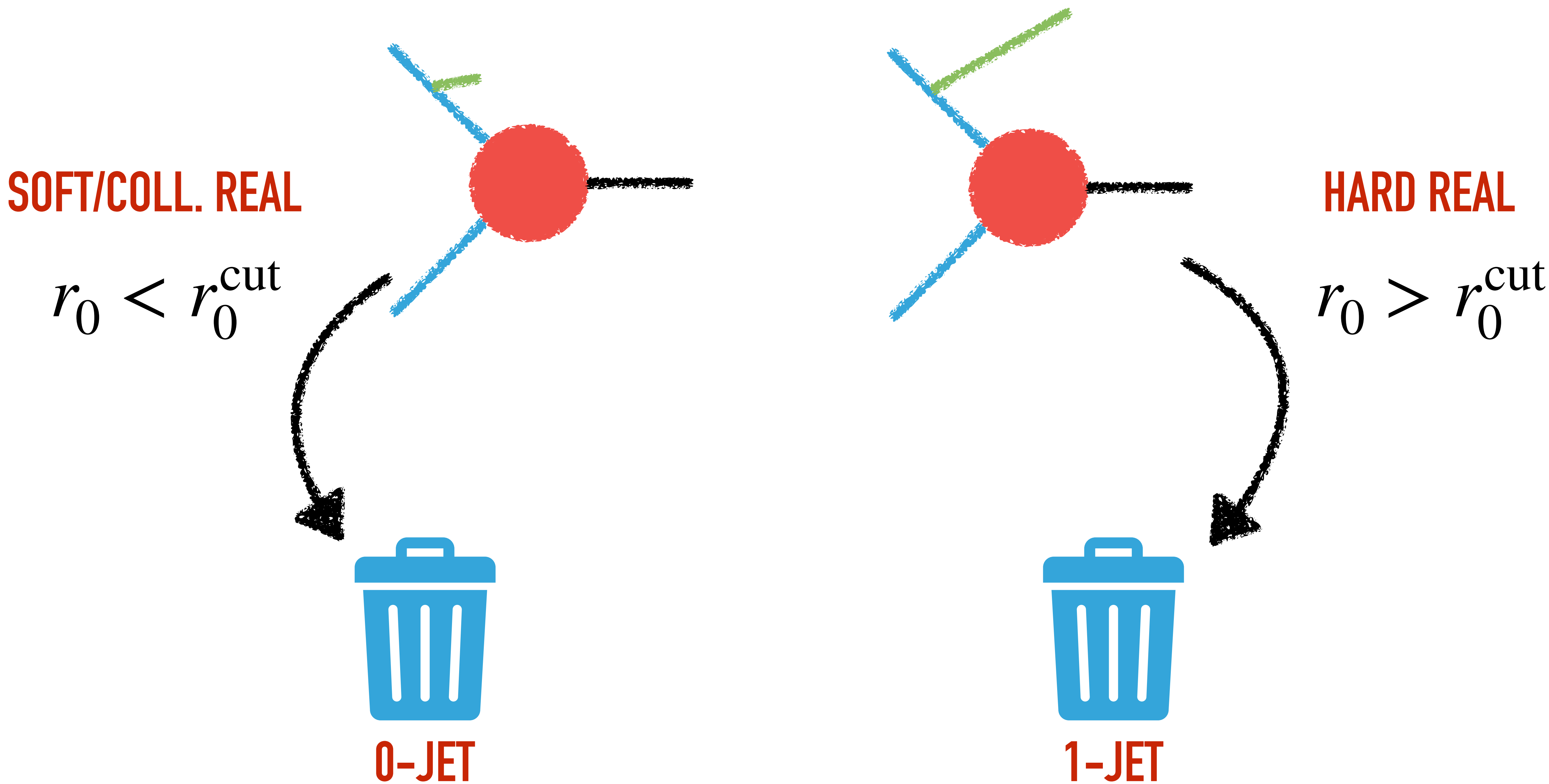
HARD REAL

$$r_0 > r_0^{\mathrm{cut}}$$

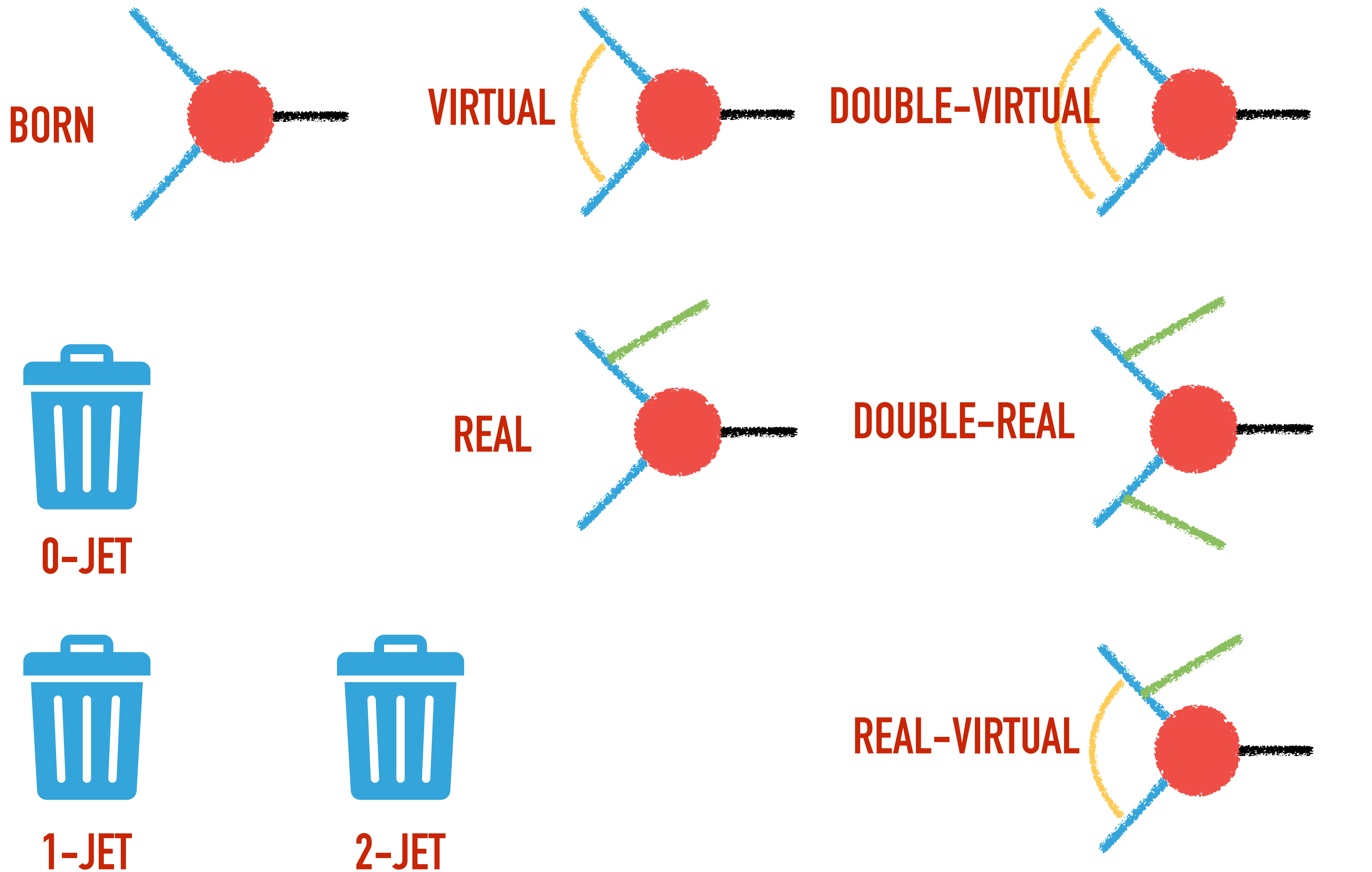
0-JET

1-JET

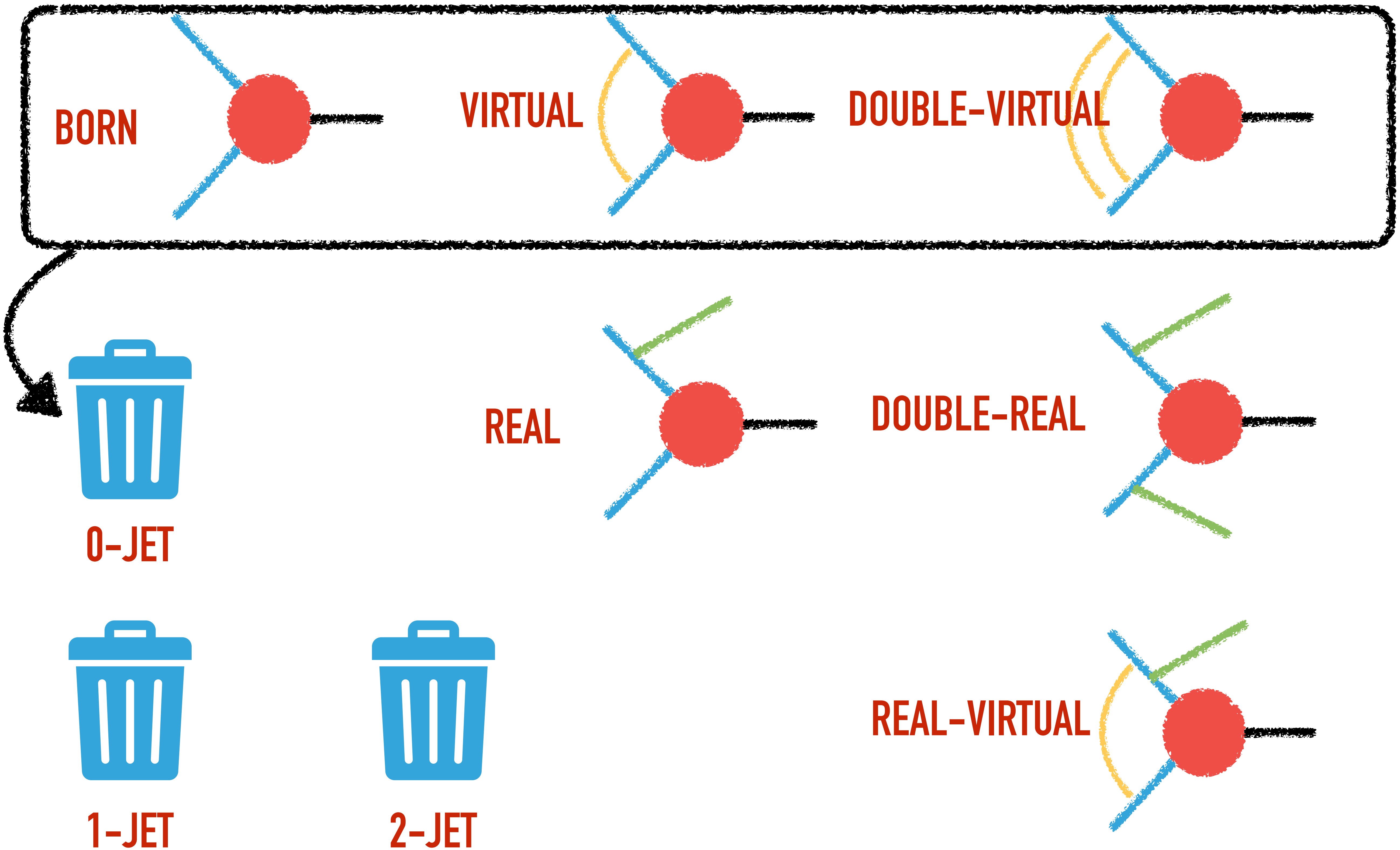
DEFINING IR-FINITE EVENTS



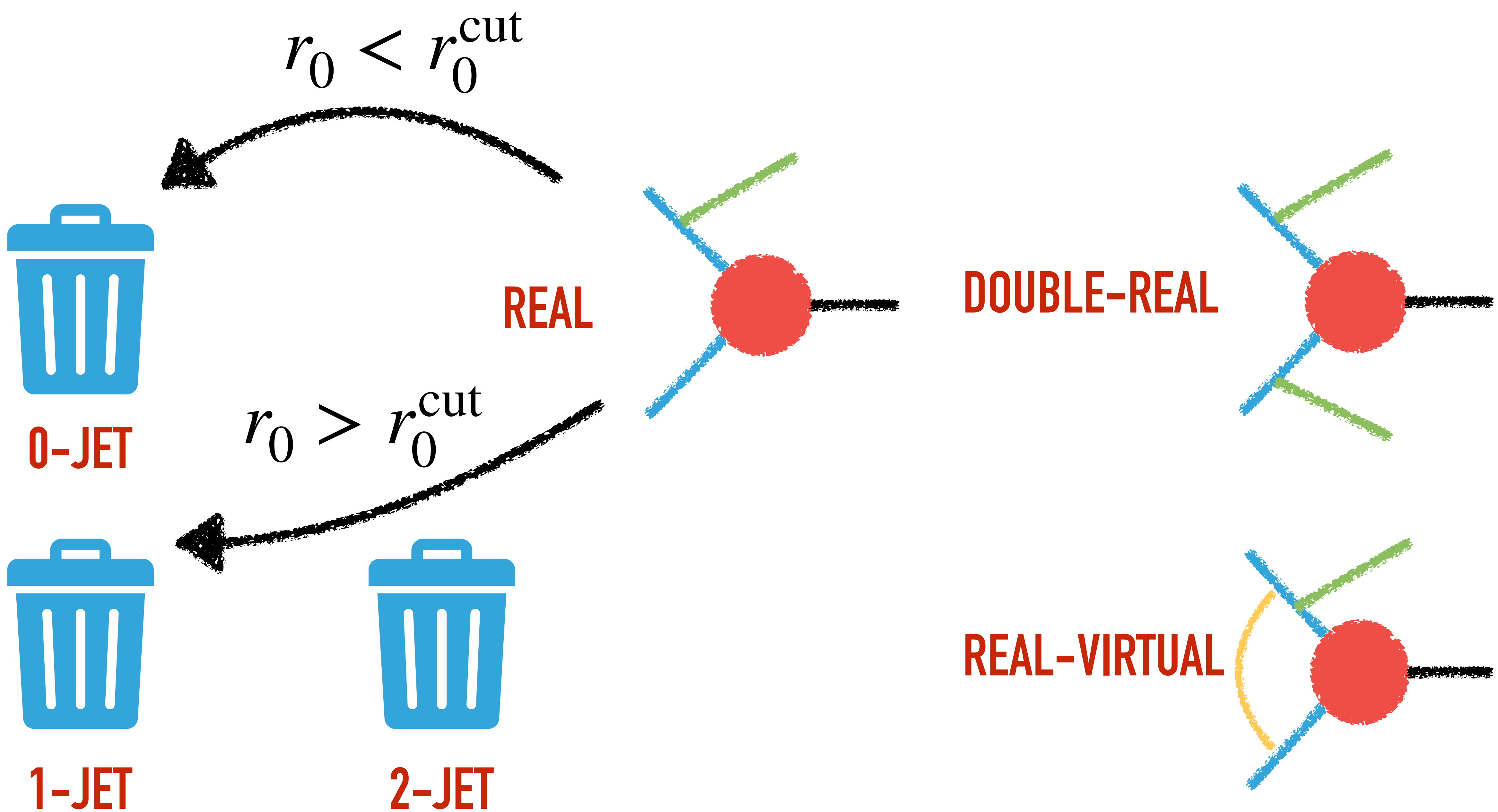
DEFINING IR-FINITE EVENTS



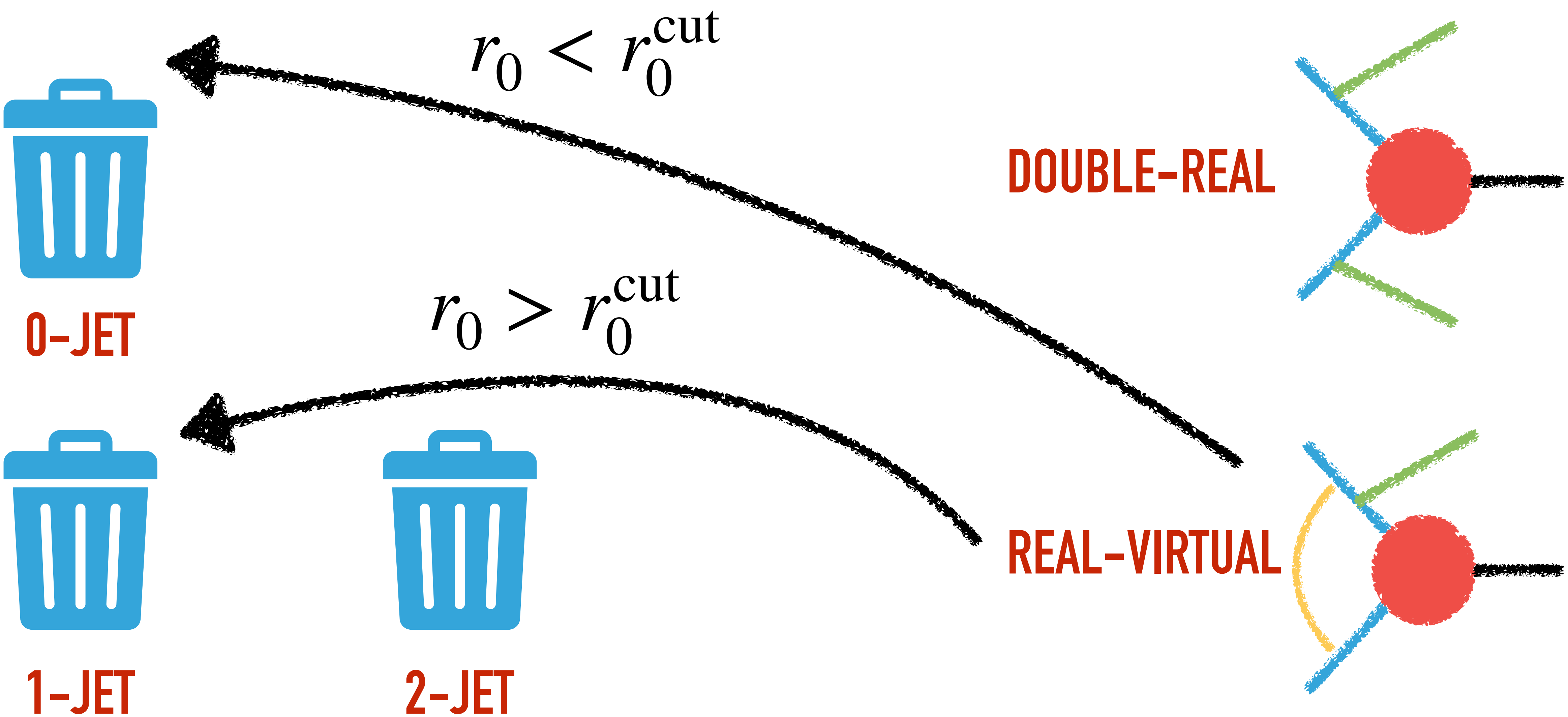
DEFINING IR-FINITE EVENTS



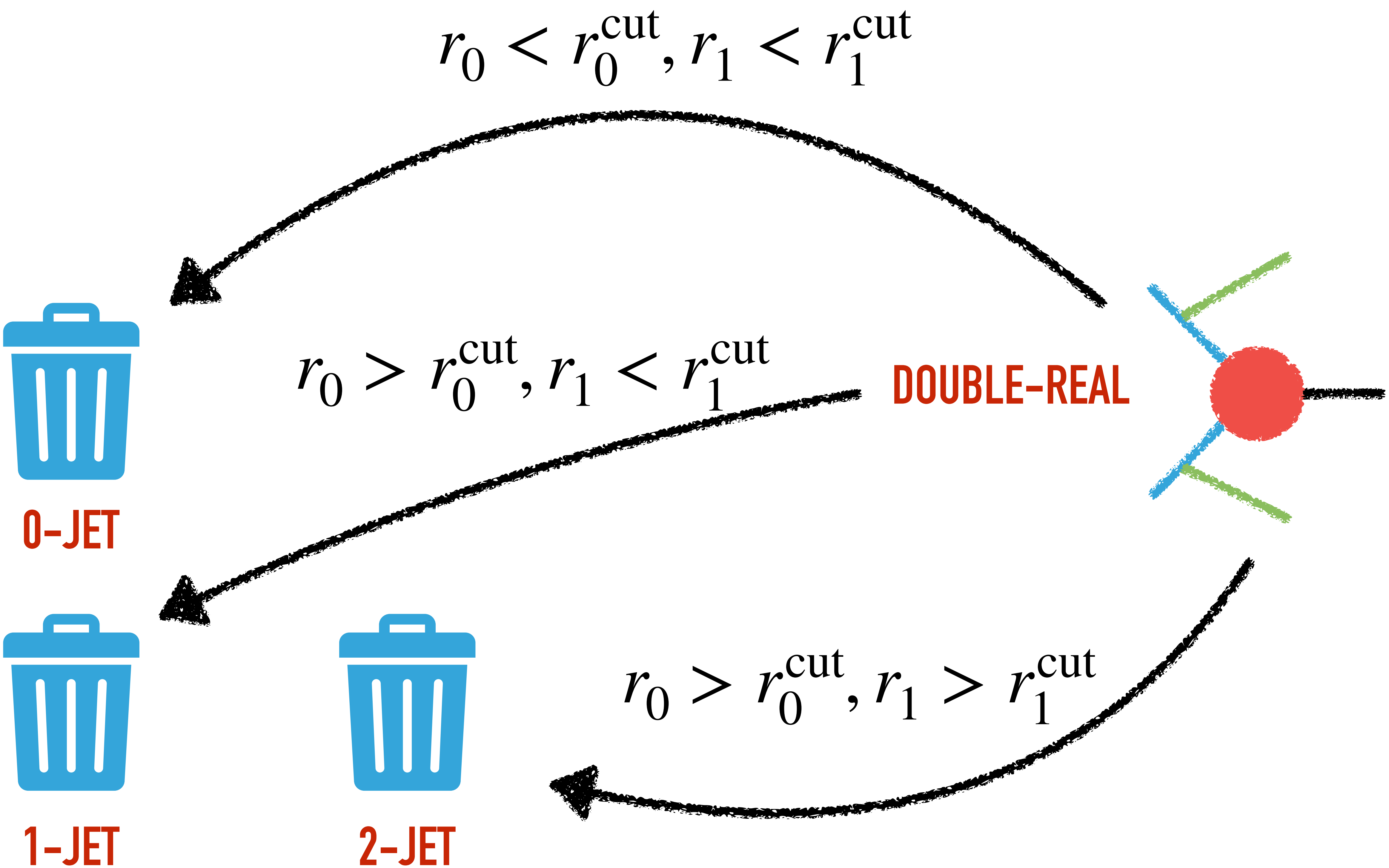
DEFINING IR-FINITE EVENTS



DEFINING IR-FINITE EVENTS



DEFINING IR-FINITE EVENTS



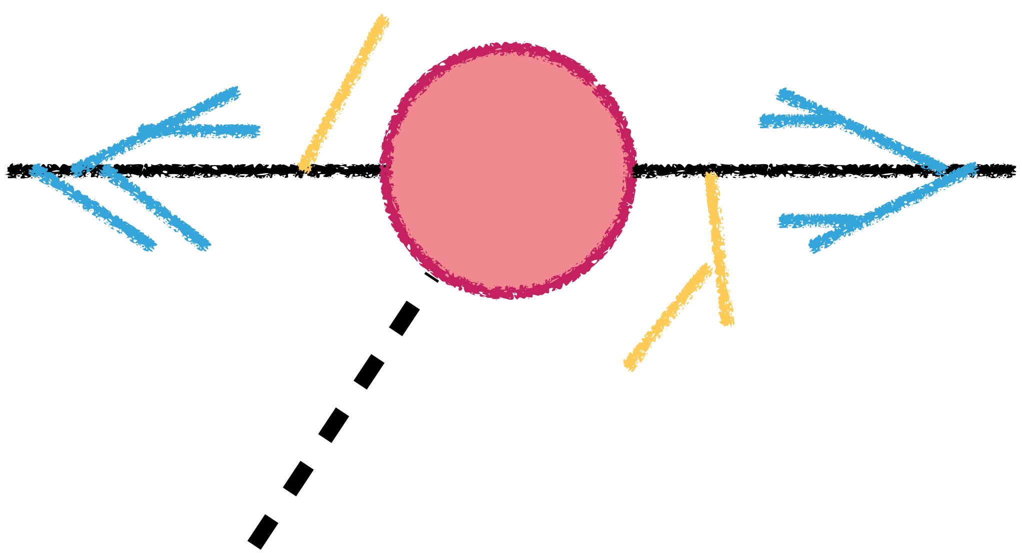
DEFINING IR-FINITE EVENTS

- Defining events this way introduced a projection from a higher multiplicity to a lower multiplicity phase space
- Results are only (N)NLO accurate up to power corrections in r_0^{cut} - as $r_0^{\text{cut}} \to 0$, exact fixed order result is recovered
- Causes large logarithms to appear which spoil perturbative convergence!

$$L = \log(Q/r_0^{\text{cut}})$$ becomes large…

RESUMMATION FROM EFFECTIVE FIELD THEORIES

- Soft-Collinear effective theory formalism - an EFT with QCD as its UV limit



- QCD Lagrangian split into low-energy modes

- For $r_0 \ll Q$, the partonic cross section typically factorises:

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}r_0} \approx H(Q,\mu_H)\, B_i(r_0,\mu_B) \otimes B_j(r_0,\mu_B) \otimes S(r_0,\mu_S)$$

SOFT-COLLINEAR EFFECTIVE THEORY

- Beam and soft functions correspond to matrix elements of collinear/soft SCET modes, hard function gives matching onto full QCD (Wilson coefficient)

- Each component of factorisation theorem is evaluated at its own scale $\Longrightarrow$ no large logs! Evolution to common scale via double-log RGE resums large log terms.

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}\ln H(\Phi_0,\mu) = \Gamma_{\mathrm{cusp}}\ln\frac{\mu_H^2}{\mu^2} + \gamma_H$$

- Accuracy improvable by going to higher loop orders

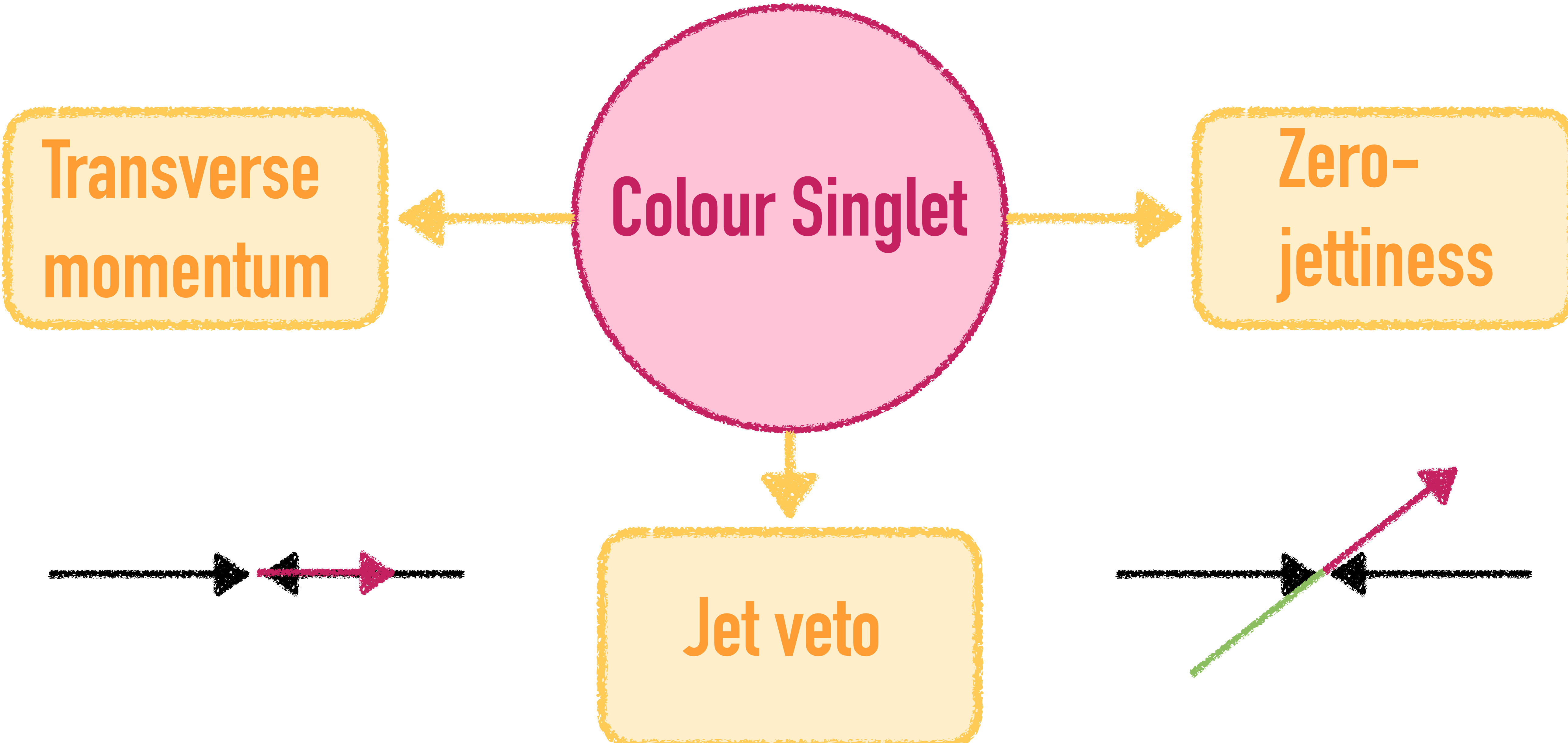
COMBINING RESUMMED AND FIXED ORDER CALCULATIONS IN GENEVA

- Additive matching procedure to combine resummed and FO calculations, which are then passed to shower

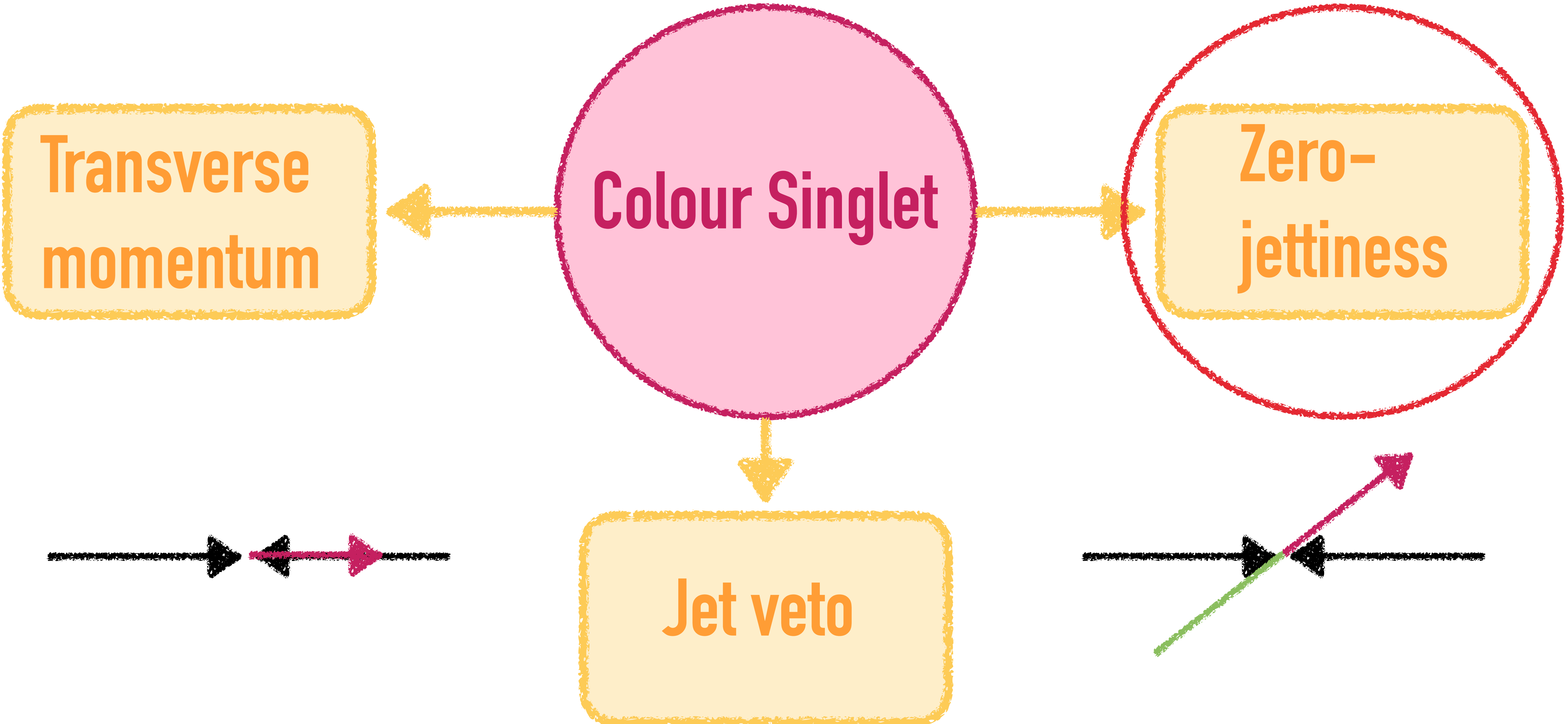
$$\frac{\mathrm{d}\sigma^{\mathrm{MC}}}{\mathrm{d}\Phi_1} = \frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0 \mathrm{d}r_0}\mathscr{P}(z,\phi) + \frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\Phi_1} - \left[\frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0 \mathrm{d}r_0}\mathscr{P}(z,\phi)\right]_{\alpha_s^2}$$

- Splitting function $\mathscr{P}$ makes resummation fully differential in higher multiplicity phase space
- Cancellations between FO and res. exp. are made local in r_0 by using an appropriate mapping for the FO

RESOLUTION VARIABLES



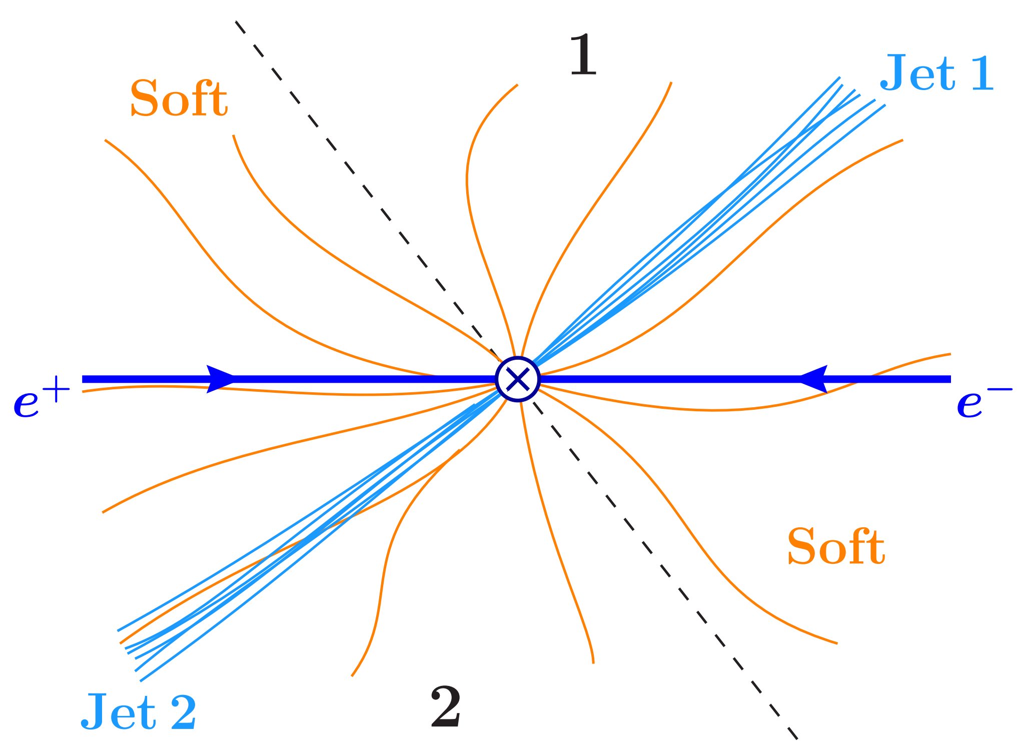
RESOLUTION VARIABLES

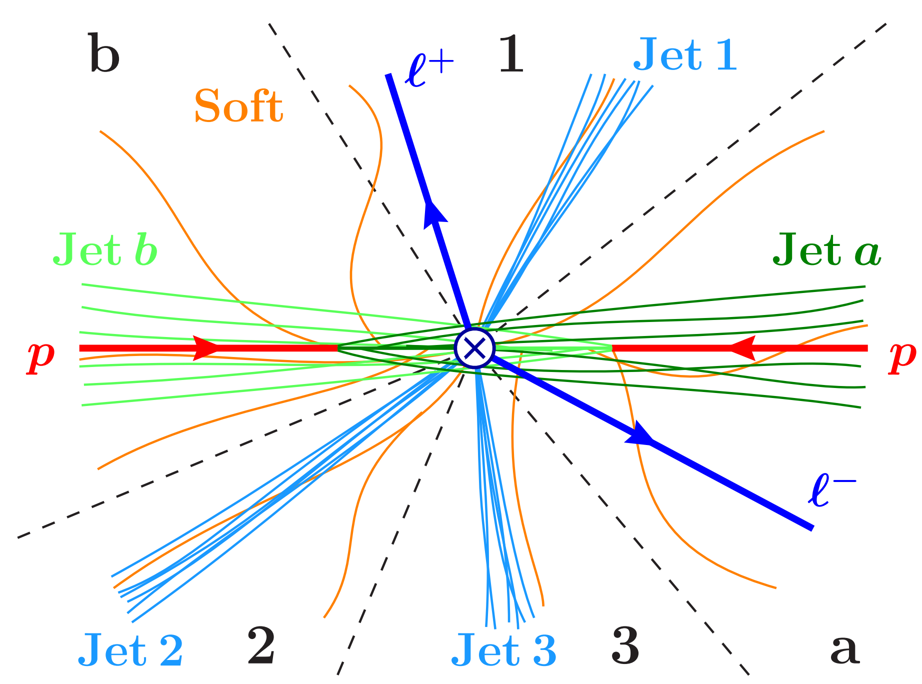


THE N-JETTINESS OBSERVABLE

- $\mathcal{T}_N = 0$ implies there are exactly N pencil-like jets
- Large $\mathcal{T}_N$ implies a spherical distribution of radiation

$$\mathcal{T}_N = \frac{2}{Q} \sum_k \min\{q_a \cdot p_k, q_b \cdot p_k, q_1 \cdot p_k, \ \ldots, q_N \cdot p_k\}$$





ZERO-JETTINESS RESUMMATION FOR COLOUR SINGLET

SCET allows us to write a factorisation formula as

$$\frac{d\sigma^{\text{resum}}}{d\Phi_0 d\mathcal{T}_0} = \sum_{ij} \int dt_a dt_b \, B_i(t_a, x_a, \mu_B) \, B_j(t_b, x_b, \mu_B) \, H_{ij}(\Phi_0, \mu_H) \, S\left(\mathcal{T}_0 - \frac{t_a + t_b}{Q}, \mu_S\right)$$

Beams

Hard

Soft

All single-scale objects!

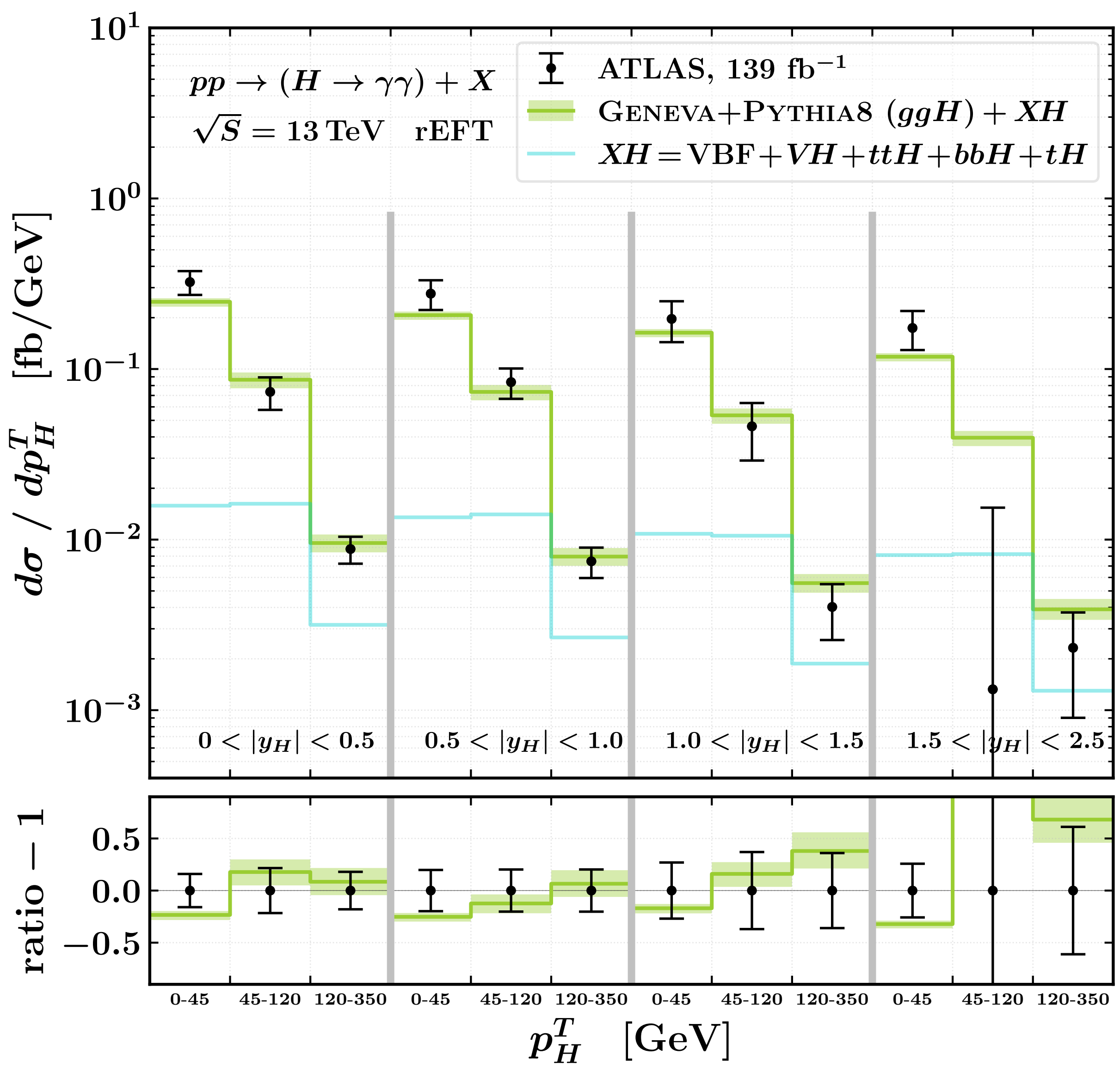
Resummation via RGE running to common scale:

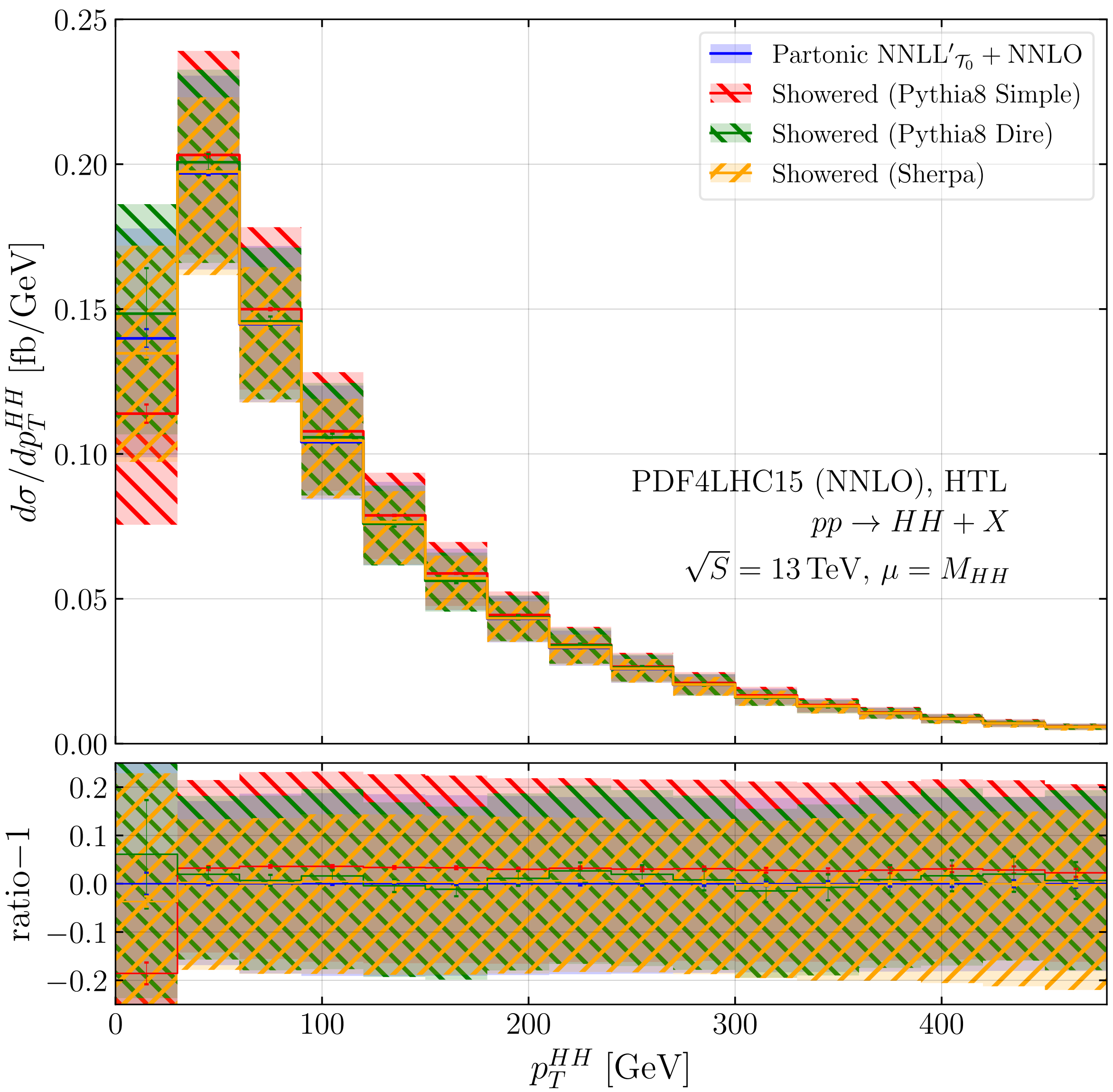
$$B_i(t_a, x_a, \mu) = B_i(t_a, x_a, \mu_B) \otimes U_B(\mu, \mu_B)$$

Resums logs of μ/μ_B

0910.0467, I. Stewart, F. Tackmann, W. Waalewijn

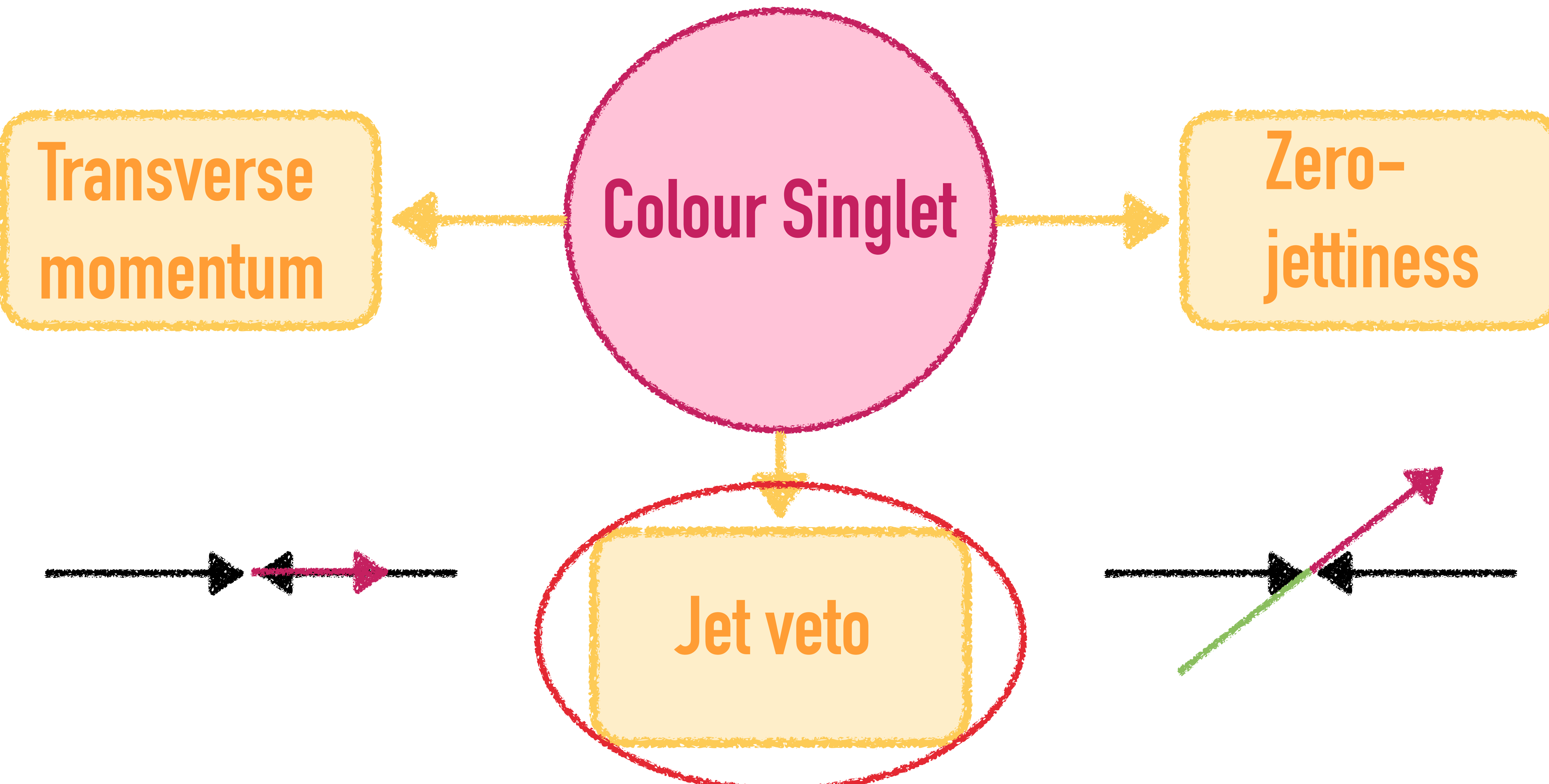
ZERO-JETTINESS RESUMMATION IN GENEVA





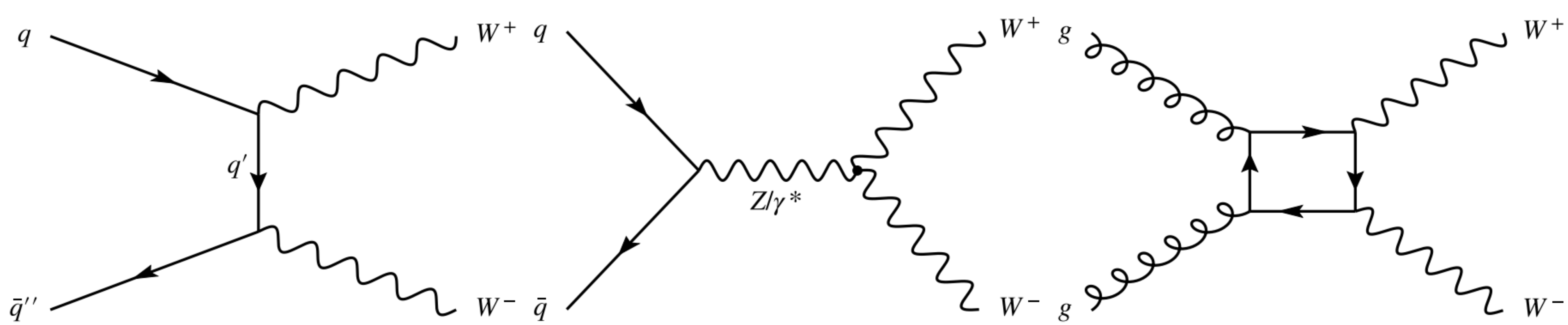
2212.10489, 2301.11875, S. Alioli, G. Billis, A. Broggio, A. Gavardi, S. Kallweit, MAL, G. Marinelli, R. Nagar, D. Napoletano

RESOLUTION VARIABLES



GENEVA USING JET VETO RESUMMATION

- W^+W^- production an interesting case study - jet vetoes used in analyses to reject $t\bar{t}$ background
- Aim to improve description of jet-vetoed cross section within an NNLO+PS event generator
- Combine NNLL′ resummation for WW + 0 jets with NLL′ resummation for WW + 1 jet to define events at NNLO



FACTORISATION WITH A JET VETO FOR COLOUR SINGLET

- Consider colour singlet production, vetoing all jets with $p_T > p_T^{\rm veto}$. Resummation has been studied in both QCD and SCET. T. Becher, M. Neubert, 1205.3806, F. Tackmann, J. Walsh, S. Zuberi, 1206.4312, A. Banfi, G. Salam, G. Zanderighi, 1203.5773, I. Stewart, F. Tackmann, J. Walsh, S. Zuberi, 1307.1808, T. Becher, M. Neubert, L. Rothen, 1307.0025
- Factorisation into hard, beam and soft functions

$$\frac{\mathrm{d}\sigma(p_T^{\rm veto})}{\mathrm{d}\Phi_0} = H(\Phi_0, \mu)\ [B_a \times B_b](p_T^{\rm veto}, R, x_a, x_b, \mu, \nu)\ S_{ab}(p_T^{\rm veto}, R, \mu, \nu)$$

  - Radius of vetoed jets R
  - Additional scale ν necessary to separate soft/collinear modes (SCET II)

FACTORISATION WITH A JET VETO FOR COLOUR SINGLET+JET

$$\sigma(p_T^{\mathrm{cut}}) = H(p_T, Y, \eta_J) \times B_a(p_T^{\mathrm{cut}}, \omega_a)\, B_b(p_T^{\mathrm{cut}}, \omega_b) \times J(p_T\, R_J) \times S(p_T^{\mathrm{cut}}) \times \mathcal{S}^R(p_T^{\mathrm{cut}}\, R_J) \times \mathcal{S}^{\mathrm{NG}}(p_T^{\mathrm{cut}}/p_T)$$

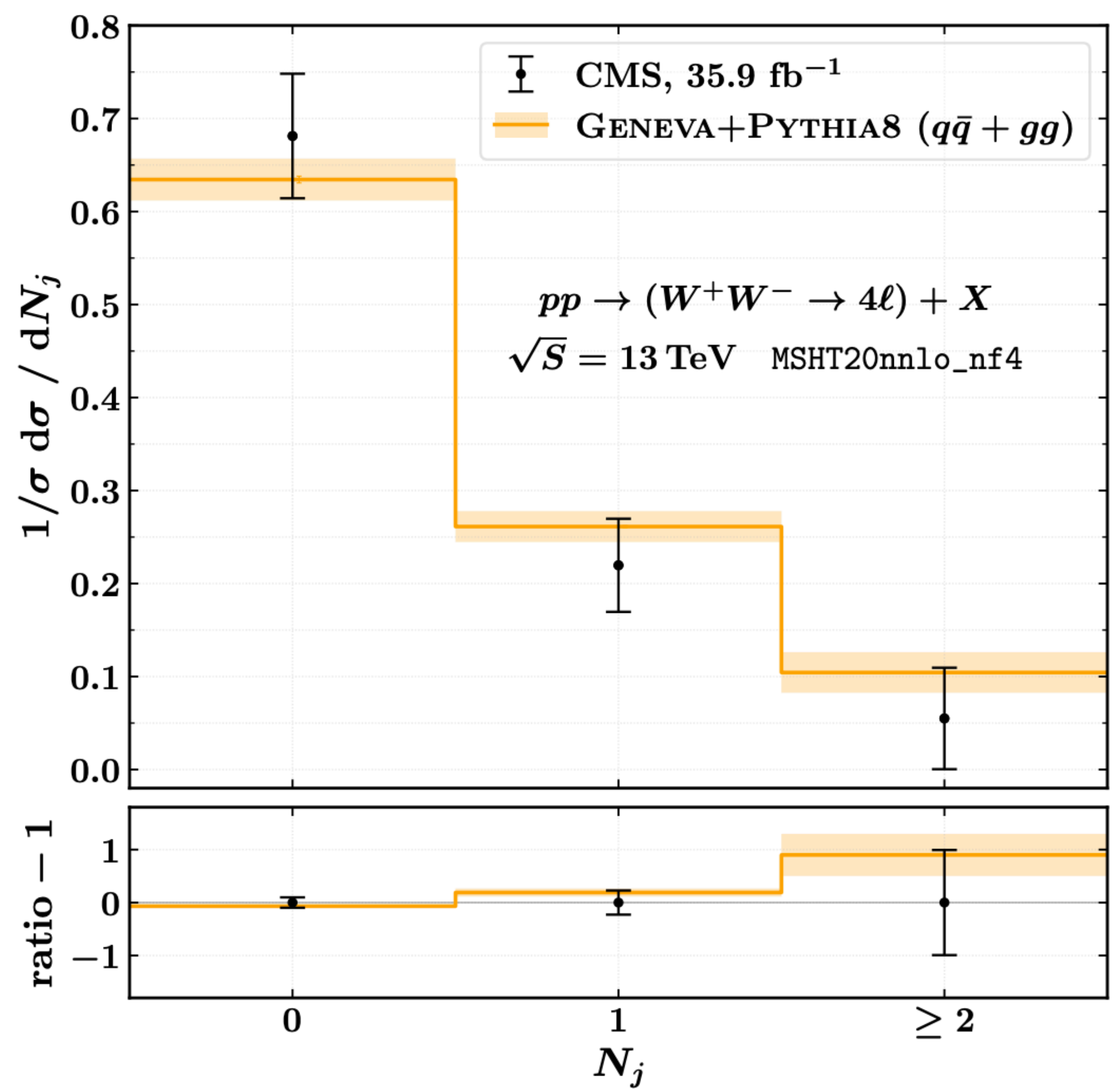
Global soft — Soft-collinear — Nonglobal soft

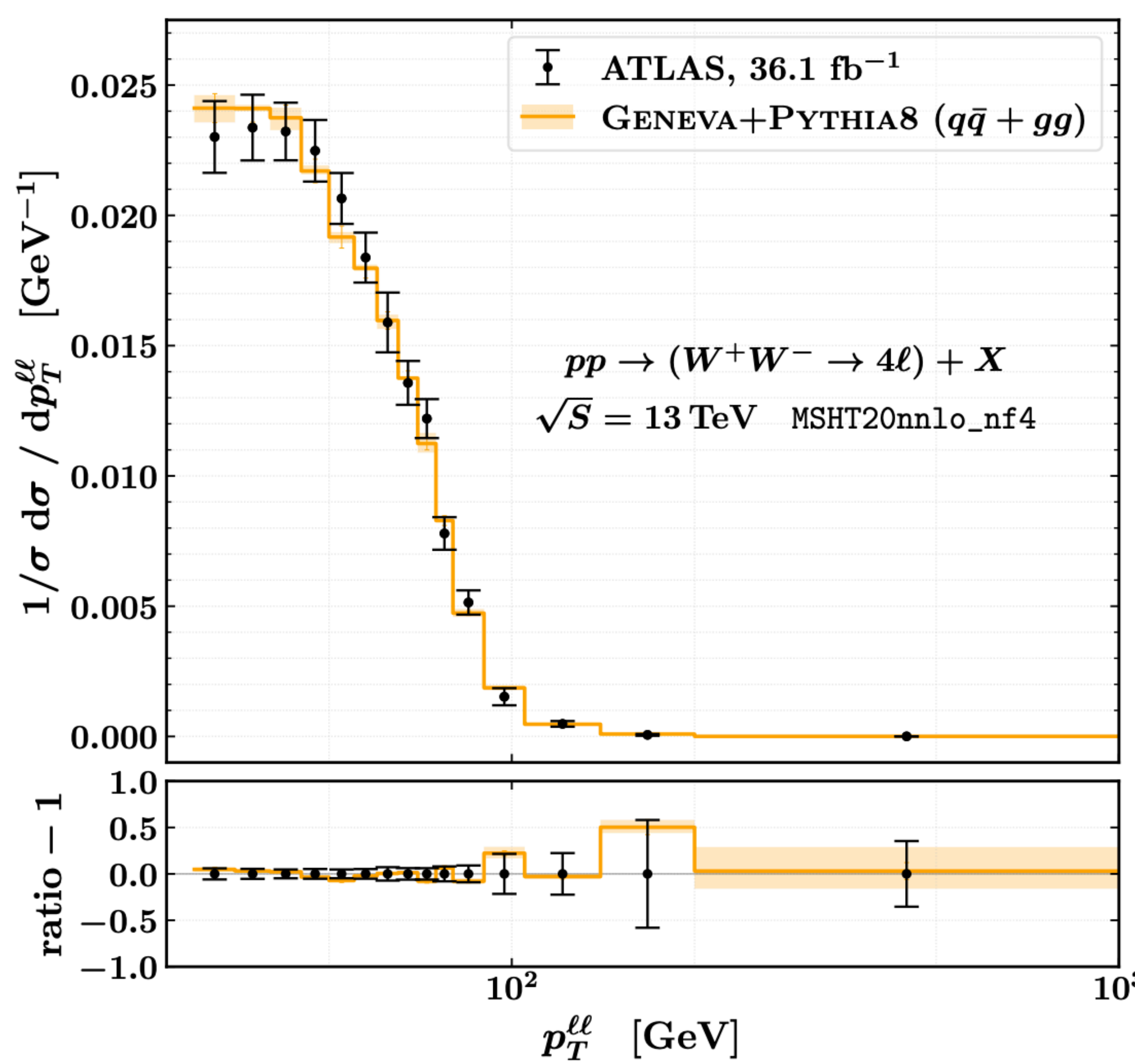
- Need also resummation in presence of additional hard jet to NLL′ in order to separate 1- and 2-jet bins
- Factorisation and resummation for this process studied over 10 years ago - recently revisited with higher accuracy and improved treatment of soft sector

Liu X., F. Petriello, 1210.1906, 1303.4405, P. Cal, MAL, D. Scott, F. Tackmann, W. Waalewijn, 24XX.YYYY

COMPARISON TO ATLAS/CMS

- Compared with ATLAS/CMS measurements

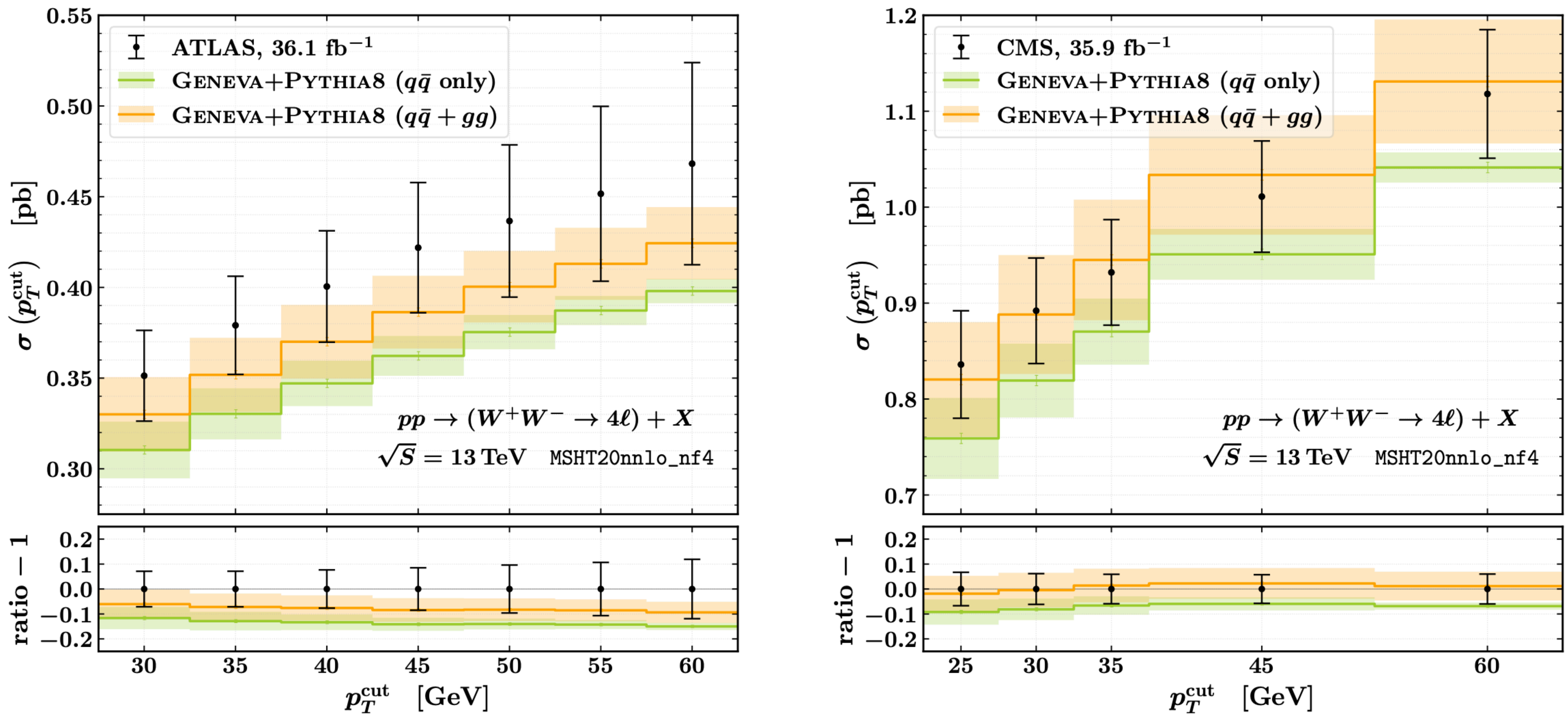




2308.11577 A. Gavardi, MAL, S. Alioli, F. Tackmann

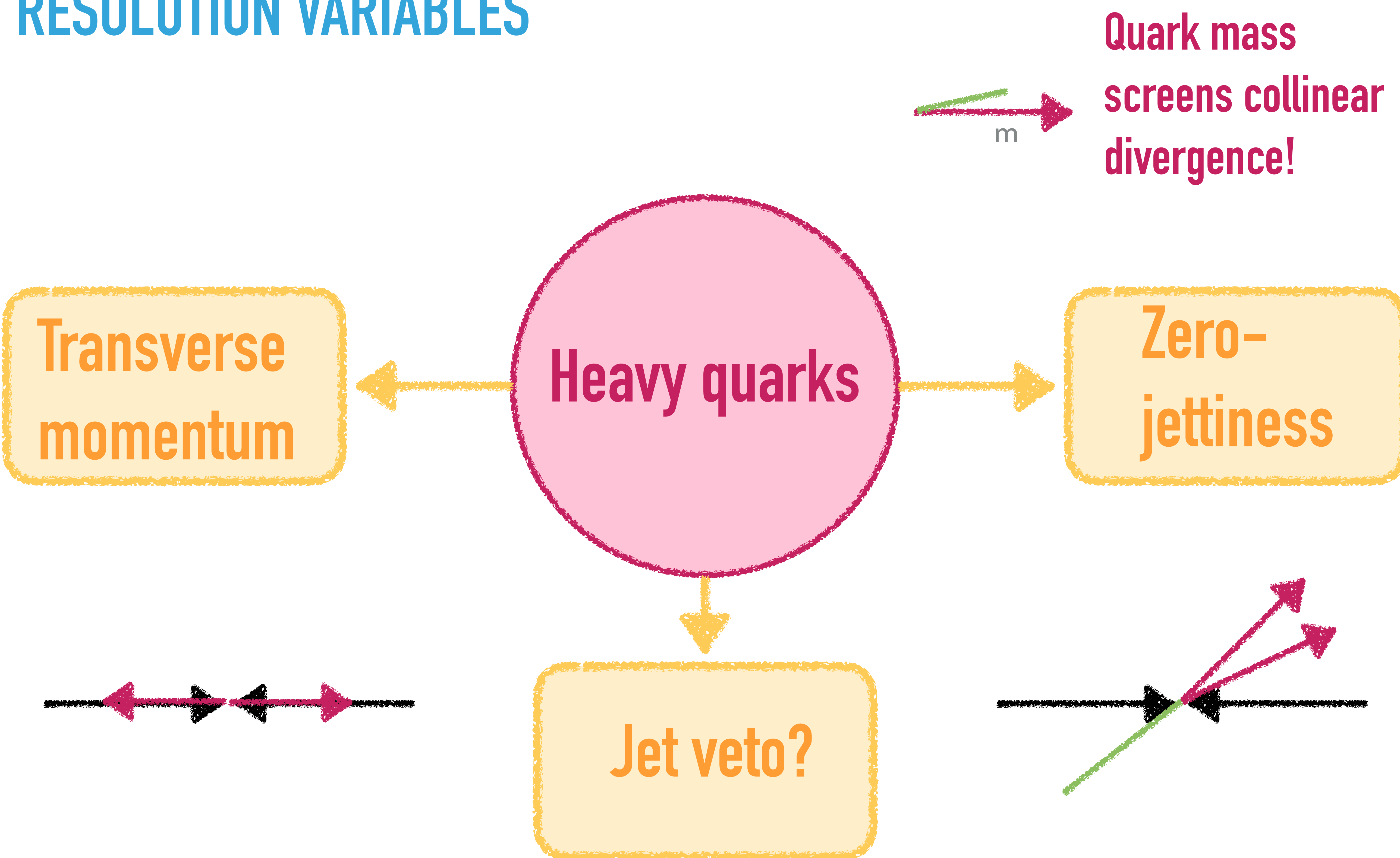
COMPARISON TO ATLAS/CMS

- Vetoed cross section measurements



2308.11577 A. Gavardi, MAL, S. Alioli, F. Tackmann

RESOLUTION VARIABLES



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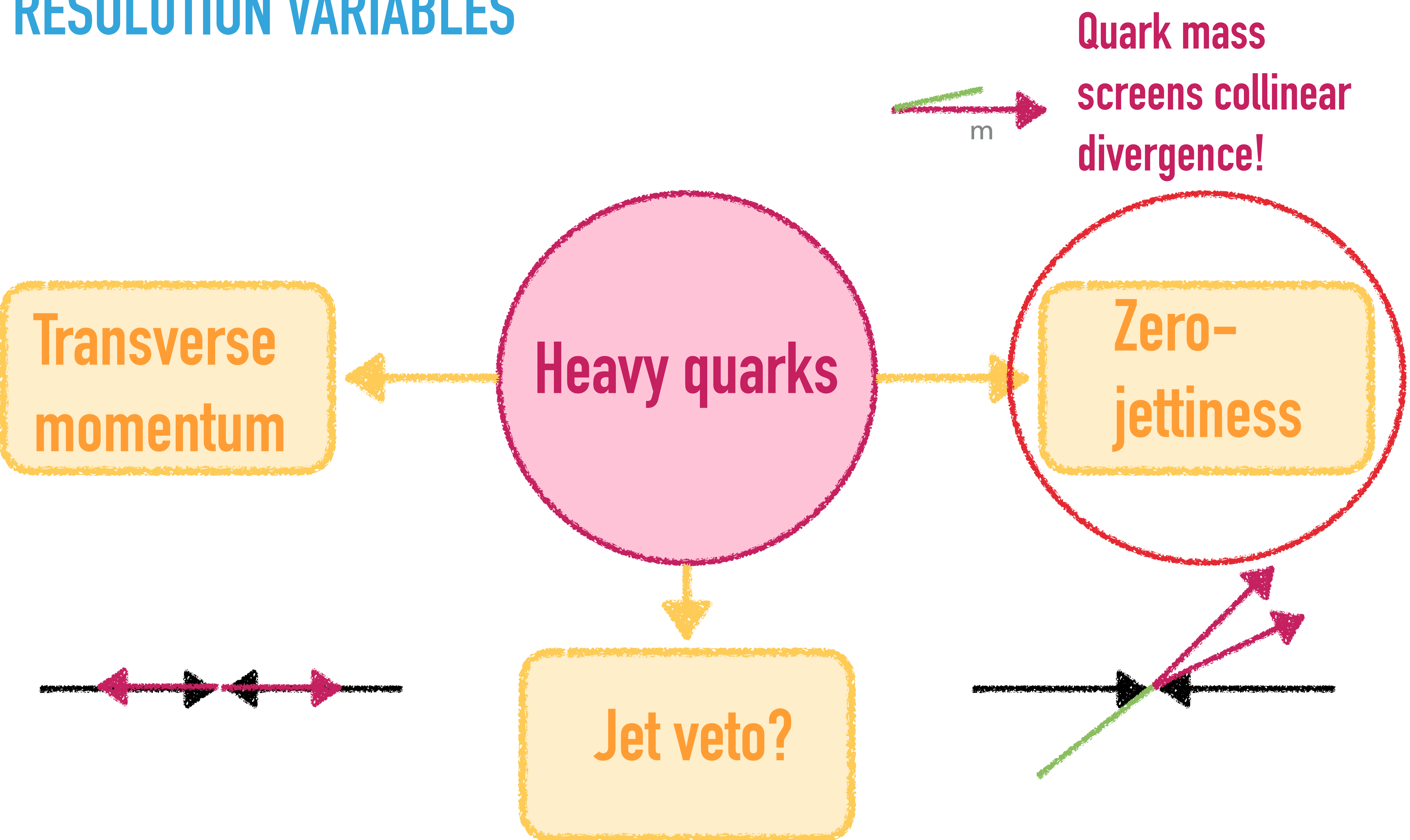


ZERO-JETTINESS RESUMMATION FOR HEAVY QUARK PAIRS

SCET allows us to write a factorisation formula as

$$\frac{d\sigma^{\text{resum}}}{d\Phi_0 d\mathcal{T}_0} = \sum_{ij} \int dt_a dt_b \, B_i(t_a, x_a, \mu_B) \, B_j(t_b, x_b, \mu_B) \, \mathrm{Tr}\left\{ \mathbf{H}_{ij}(\Phi_0, \mu_H) \, \mathbf{S}\left(\mathcal{T}_0 - \frac{t_a + t_b}{Q}, \Phi_0, \mu_S\right)\right\}$$

Same as before

Matrices in colour space!

Arises from exchange of soft gluons from heavy quark lines.
Evolution equations more complicated:

$$\mathbf{H}(\Phi_0, \mu) = \mathbf{U}(\Phi_0, \mu, \mu_H)\mathbf{H}(\Phi_0, \mu_H)\mathbf{U}^\dagger(\Phi_0, \mu, \mu_H)$$

2111.03632, S. Alioli, A. Broggio, MAL

ZERO-JETTINESS RESUMMATION FOR HEAVY QUARK PAIRS

Derived for the first time! Ingredients partially unknown.

$$\frac{d\sigma^{\text{resum}}}{d\Phi_0 d\mathcal{T}_0} = \sum_{ij} \int dt_a dt_b \, B_i(t_a, x_a, \mu_B)\, B_j(t_b, x_b, \mu_B) \, \mathrm{Tr}\left\{ \mathbf{H}_{ij}(\Phi_0, \mu_H) \, \mathbf{S}\left(\mathcal{T}_0 - \frac{t_a + t_b}{Q}, \Phi_0, \mu_S\right)\right\}$$

Known up to 3-loops

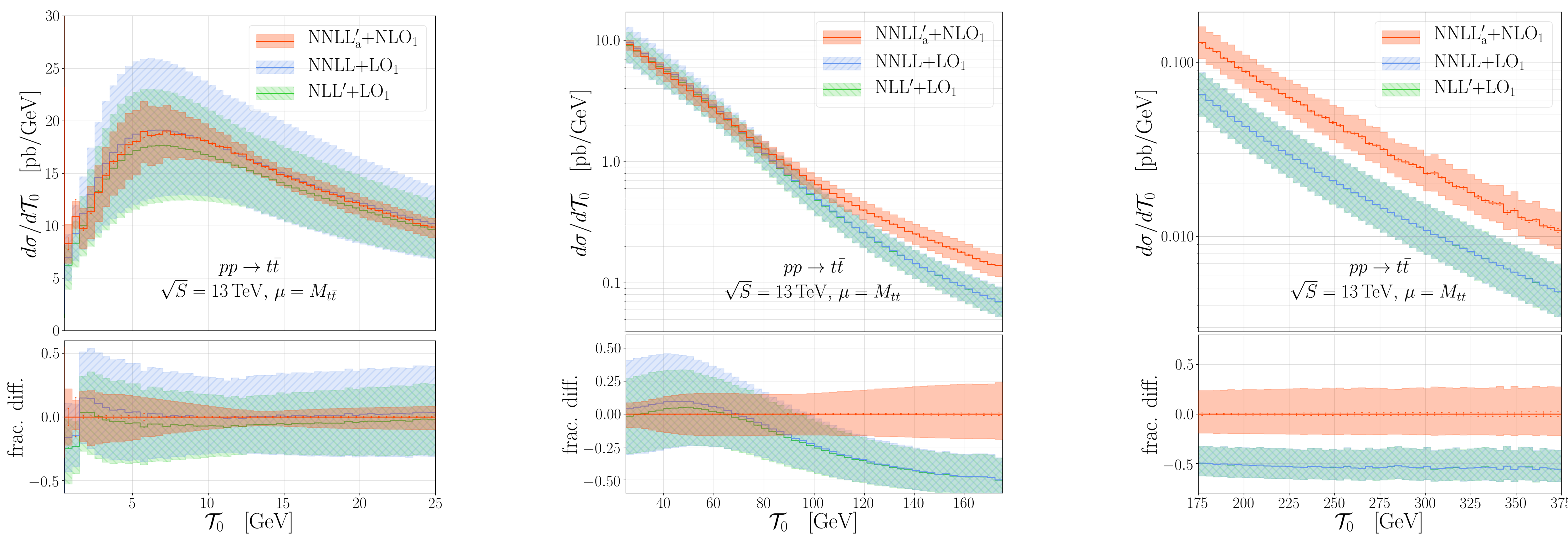
Known up to 2-loops (in principle)

Unknown!

We computed the soft function up to 1-loop. Some 2-loop terms can be obtained via RGE.

2111.03632, S. Alioli, A. Broggio, MAL

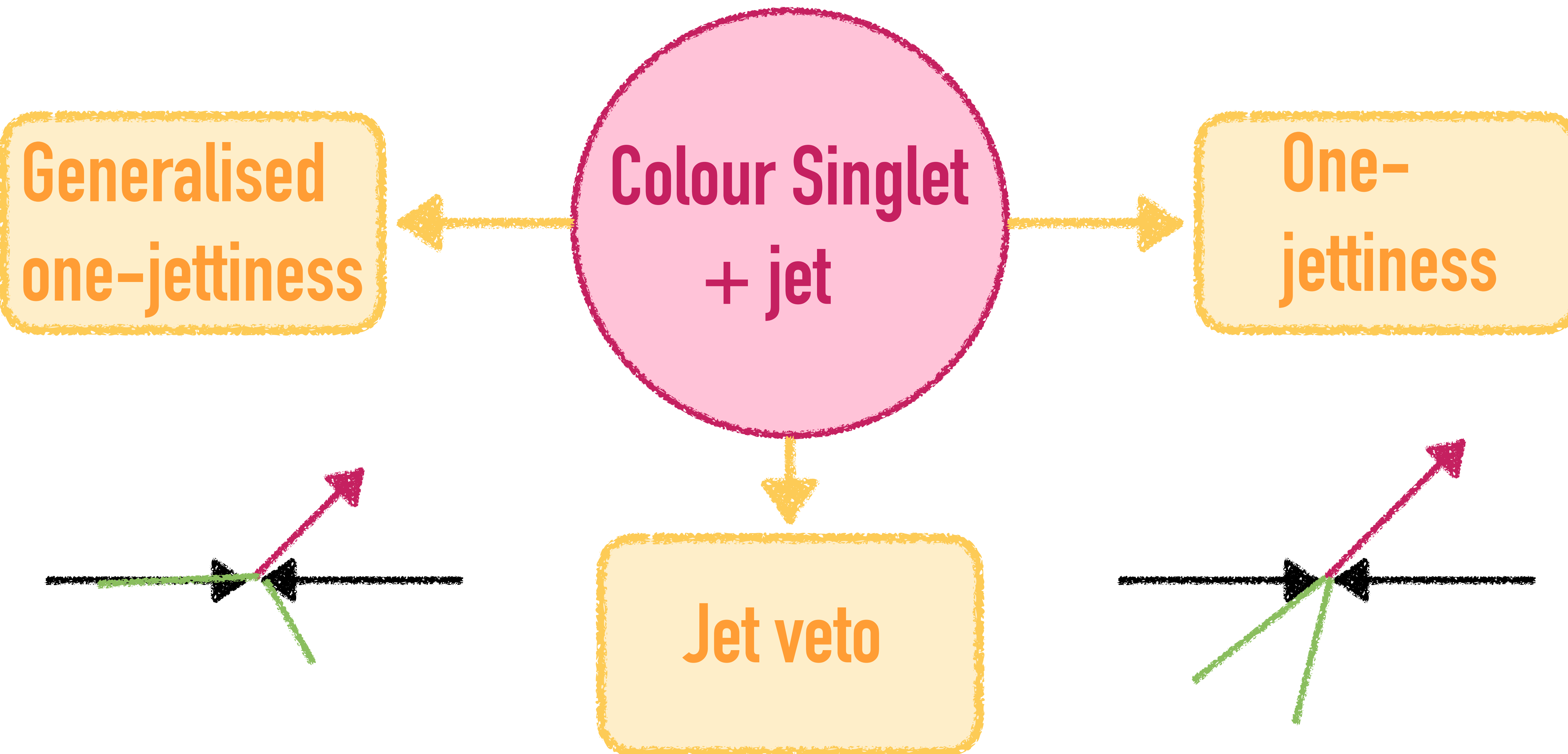
ZERO-JETTINESS RESUMMATION FOR TOP-QUARK PAIRS



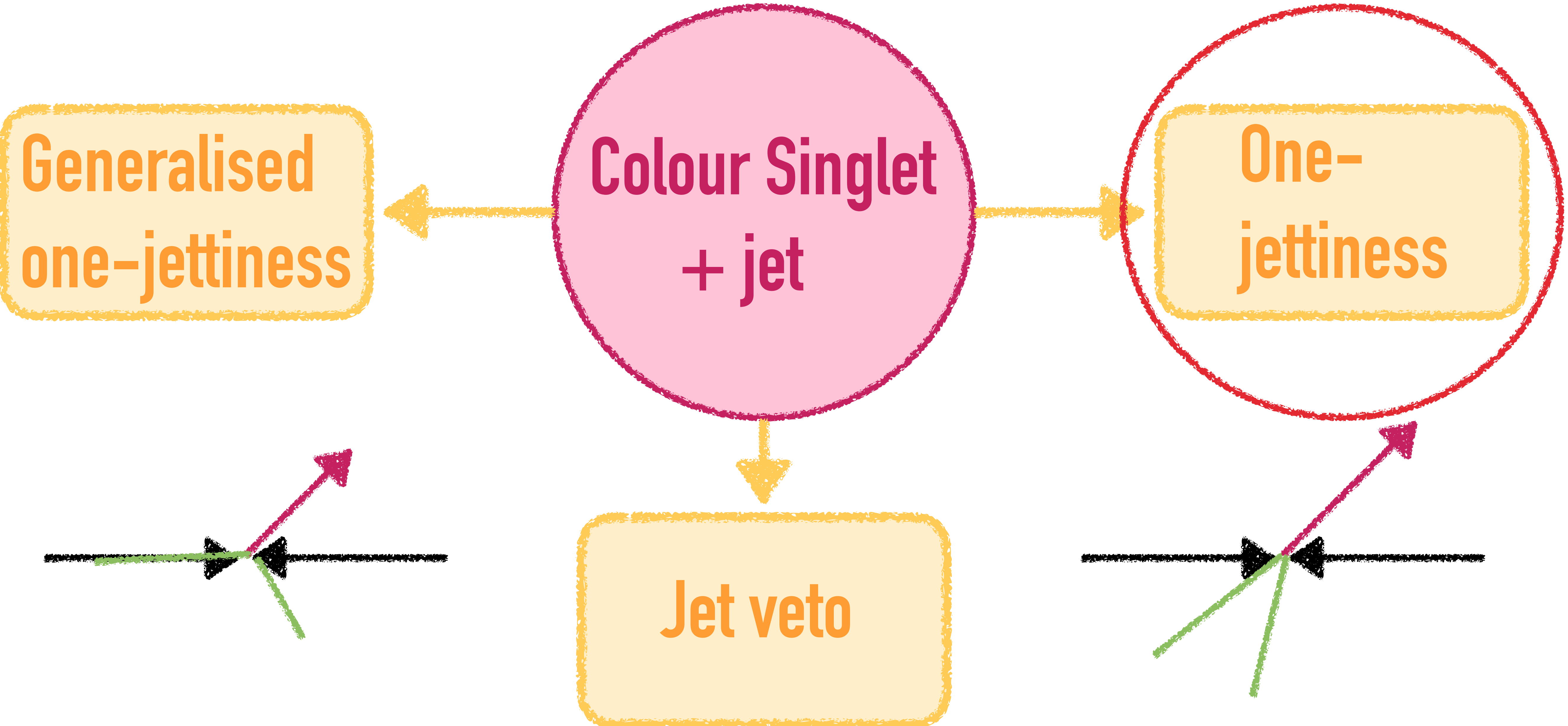
- Still missing - two-loop hard (not included here) and one piece of the two-loop soft.
- Allows approximate NNLL' accuracy.

2111.03632, S. Alioli, A. Broggio, MAL

RESOLUTION VARIABLES



RESOLUTION VARIABLES



ONE-JETTINESS RESUMMATION FOR COLOUR SINGLET + JET

Similar factorisation to zero-jet case:

$$\frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\Phi_1\mathrm{d}\mathcal{T}_1} = \sum_{ijk}\int \mathrm{d}t_a\mathrm{d}t_b\mathrm{d}s_J \;\; B_i(t_a, x_a, \mu_B)\, B_j(t_b, x_b, \mu_B)\, J_k(s_J, \mu_J)\, \mathrm{Tr}\left\{\mathbf{H}_{ij}(\Phi_1, \mu_H)\;\; \mathbf{S}\left(\mathcal{T}_1 - \frac{t_a}{Q_a} - \frac{t_b}{Q_b} - \frac{s_J}{Q_J}, \Phi_1, \mu_S\right)\right\}$$

New jet function

- Only three coloured legs - colour algebra is diagonal
- Ingredients for N^3LL all known, we use new numerical of two-loop soft function from SoftSERVE
- One-jettiness definition requires choice of frame - can evaluate energies in lab or in CS centre-of-mass

0910.0467, 1302.0846, T. Jouttenus, I. Stewart, F. Tackmann, W. Waalewijn

ONE-JETTINESS RESUMMATION FOR COLOUR SINGLET + JET

- Interesting colour structures arise in the hard anomalous dimension at N3LL

$$\boldsymbol{\Gamma}(\{\underline{s}\},\mu) = \frac{\gamma_{\text{cusp}}(\alpha_s)}{2}\left[(C_{R_3}-C_{R_1}-C_{R_2})\ln\frac{\mu^2}{(-s_{12})} + \text{cyclic permutations}\right]$$
4-loop

$$+\gamma^1(\alpha_s)+\gamma^2(\alpha_s)+\gamma^3(\alpha_s)+\frac{C_A^2}{8}f(\alpha_s)\,(C_{R_1}+C_{R_2}+C_{R_3})$$
3-loop

$$+\sum_{(i,j)}\left[-f(\alpha_s)\,\mathcal{T}_{iijj}+\sum_R g^R(\alpha_s)\,(3\mathcal{D}^R_{iijj}+4\mathcal{D}^R_{iiij})\ln\frac{\mu^2}{-s_{ij}}\right]$$

1908.11379, T. Becher, M. Neubert

$$\mathcal{D}^R_{ijkl} = d_R^{abcd}\boldsymbol{T}_i^a\boldsymbol{T}_j^b\boldsymbol{T}_k^c\boldsymbol{T}_l^d \qquad \mathcal{T}_{ijkl} = f^{ade}f^{bce}(\boldsymbol{T}_i^a\boldsymbol{T}_j^b\boldsymbol{T}_k^c\boldsymbol{T}_l^d)_+$$

$$d_R^{a_1\ldots a_n} = \text{Tr}_R(\boldsymbol{T}^{a_1}\ldots\boldsymbol{T}^{a_n})_+ \equiv \frac{1}{n!}\sum_\pi \text{Tr}(\boldsymbol{T}_R^{a_{\pi(1)}}\ldots\boldsymbol{T}_R^{a_{\pi(n)}})$$

ONE-JETTINESS RESUMMATION FOR COLOUR SINGLET + JET

- Explicit computation reveals previously unknown relations between colour factors

$$\Gamma(\{\underline{s}\},\mu) = \frac{\gamma_{\rm cusp}(\alpha_s)}{2}\left[(C_{R_3} - C_{R_1} - C_{R_2})\ln\frac{\mu^2}{(-s_{12})} + \text{cyclic permutations}\right]$$

4-loop

$$+\gamma^1(\alpha_s) + \gamma^2(\alpha_s) + \gamma^3(\alpha_s) + \frac{C_A^2}{8} f(\alpha_s)\,(C_{R_1} + C_{R_2} + C_{R_3})$$

3-loop

$$+\sum_{(i,j)}\left[-f(\alpha_s)\,\mathcal{T}_{iijj} + \sum_R g^R(\alpha_s)\,(3\mathcal{D}^R_{iijj} + 4\mathcal{D}^R_{iiij})\ln\frac{\mu^2}{-s_{ij}}\right]$$

1908.11379, T. Becher, M. Neubert

$$3(\boldsymbol{\mathcal{D}}^R_{iijj} + \boldsymbol{\mathcal{D}}^R_{jjii}) + 4(\boldsymbol{\mathcal{D}}^R_{iiij} + \boldsymbol{\mathcal{D}}^R_{jjji}) = (D_{kR} - D_{iR} - D_{jR})\,\mathbf{1} \qquad i \neq j \neq k$$

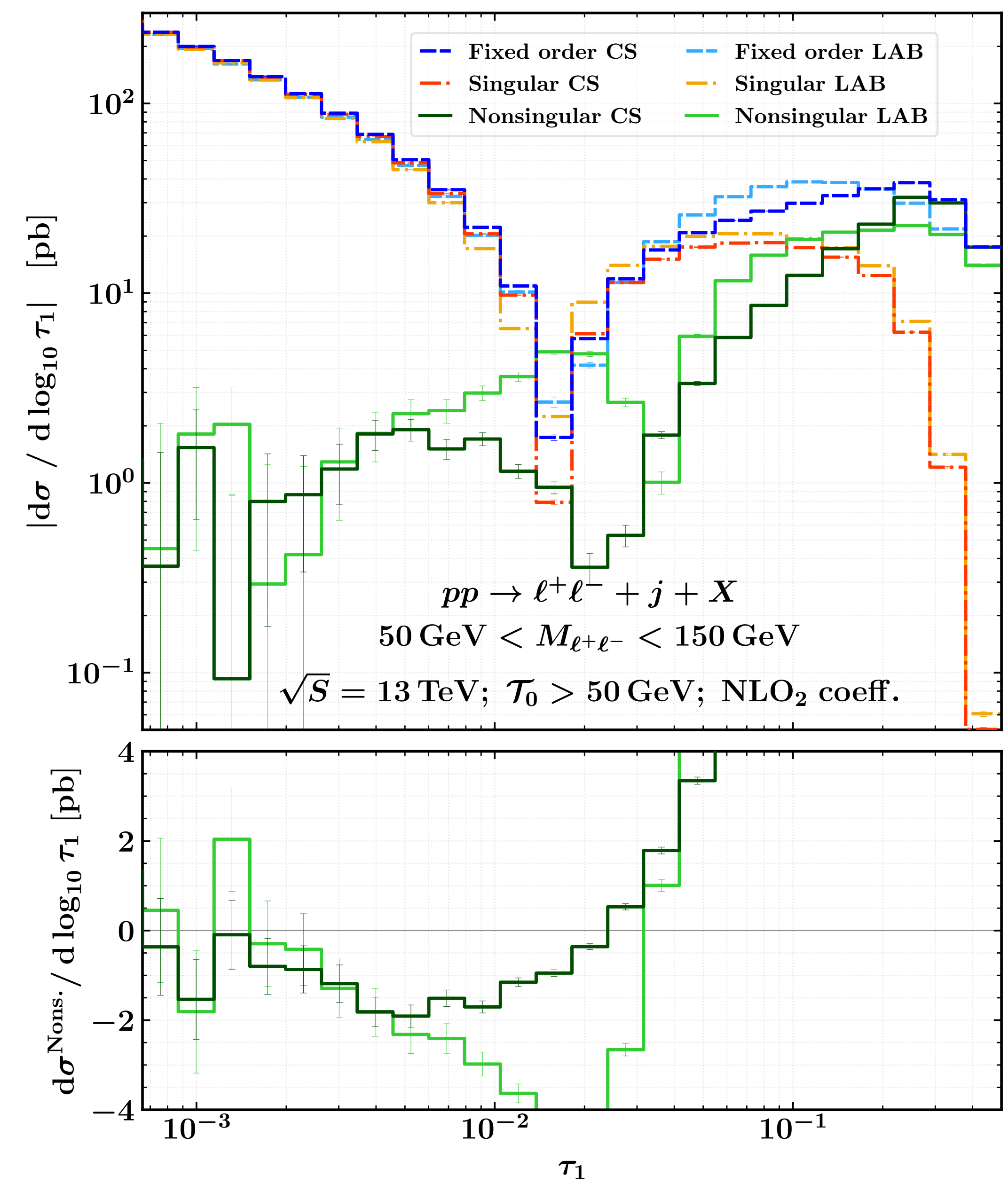
c.f. quadratic case

$$\boldsymbol{T}_a \cdot \boldsymbol{T}_b = [\boldsymbol{T}_c^2 - \boldsymbol{T}_a^2 - \boldsymbol{T}_b^2]/2$$

$$C_4(R_i, R) = \frac{d_{R_i}^{abcd} d_R^{abcd}}{N_{R_i}} \equiv D_{iR}$$

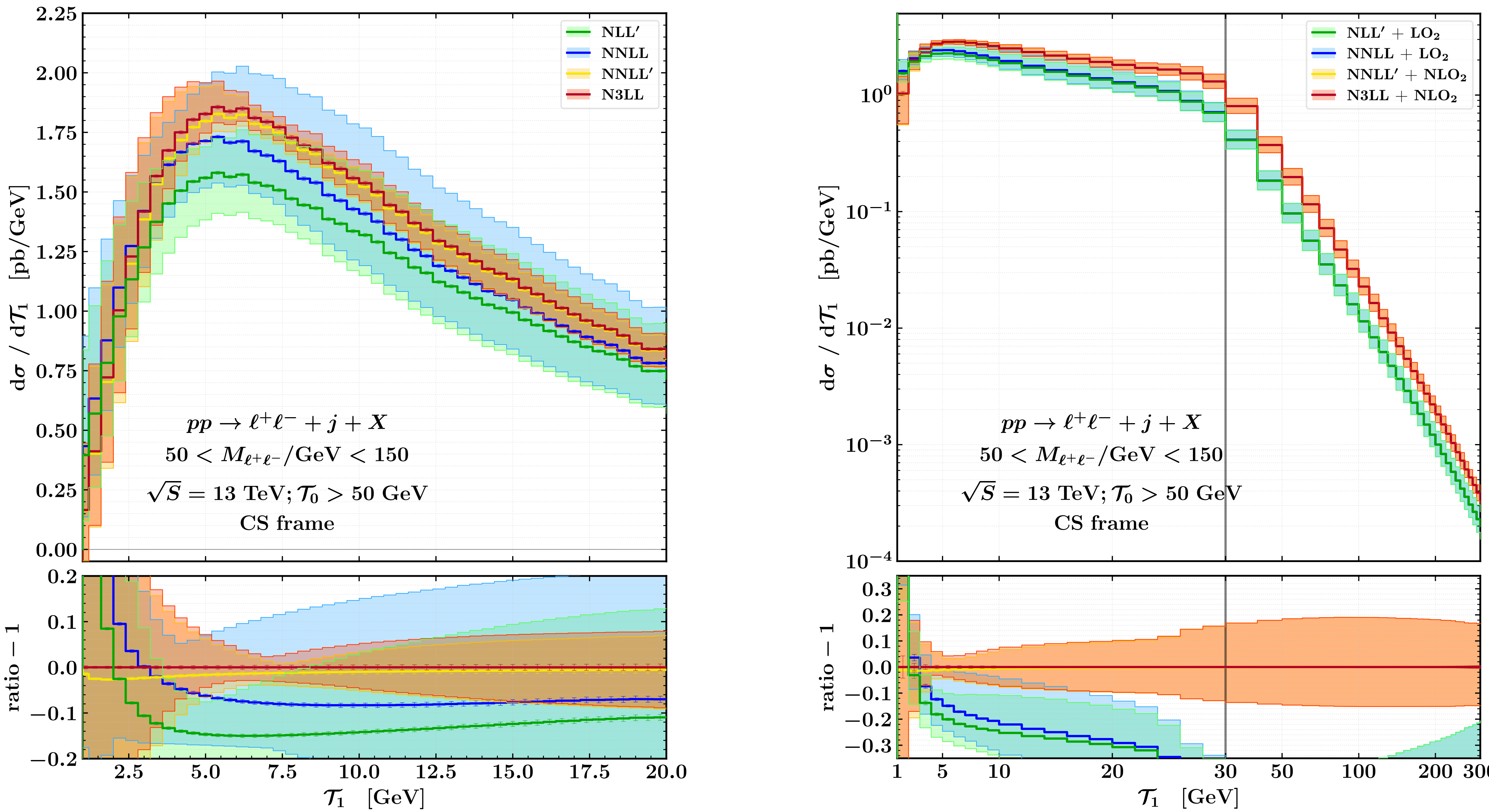
FIXED-ORDER VALIDATION OF ONE-JETTINESS FACTORISATION

- Factorisation theorem must reproduce result of fixed order in the small $\tau_1 = \mathcal{T}_1/Q$ limit
- Size of nonsingular difference has implications for numerical accuracy of slicing calculations



2312.06496, S. Alioli, G. Bell, G. Billis, A. Broggio, B. Dehnadi, MAL, G. Marinelli, R. Nagar, D. Napoletano, R. Rahn

RESUMMED AND MATCHED ONE-JETTINESS SPECTRA



2312.06496, S. Alioli, G. Bell, G. Billis, A. Broggio, B. Dehnadi, MAL, G. Marinelli, R. Nagar, D. Napoletano, R. Rahn

CONCLUSIONS

- GENEVA allows matching of NNLO calculations to parton shower algorithms for a range of colour singlet production processes
- Ongoing work aims to extend this to heavy quark production and processes with jets
- Main limitation is availability of suitable resummed calculation - SCET allows these to be obtained in a systematic way, different resolution variables to be explored

CONCLUSIONS

- Recent colour singlet results include single and double Higgs production using zero-jettiness, WW production using jet transverse momentum
- Zero-jettiness for top-quark pair production also studied
- Recent work pushes one-jettiness resummation to N^{3}LL for $Z + \text{jet}$, full NNLO+PS generator is work in progress

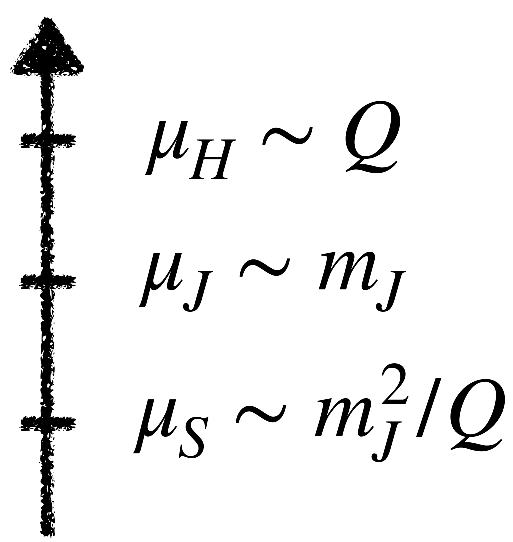
Thanks for your attention!

BACKUP SLIDES

SCET I VS SCET II

- 'Simple' SCET problems can be either two- or three-scale, depending on nature of observable

- Three-scale case: $\mu_S \ll \mu_J \ll \mu_H$, covered by SCET I



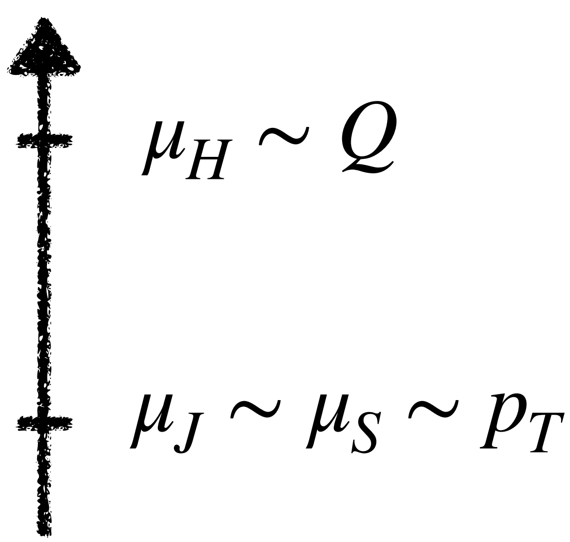
$$\mathrm{d}\hat{\sigma} \approx H(Q,\mu)\, J(m_J,\mu) \otimes S(m_J^2/Q,\mu)$$

$$\ln^2 \frac{Q^2}{m_J^2} = \frac{1}{2}\ln^2\frac{Q^2}{\mu^2} - \ln^2\frac{m_J^2}{\mu^2} + \frac{1}{2}\ln^2\frac{m_J^4}{Q^2\mu^2}$$

SCET I VS SCET II

- 'Simple' SCET problems can be either two- or three-scale, depending on nature of observable

- Two-scale case: $\mu_S \sim \mu_J \ll \mu_H$, covered by SCET II



$$\mathrm{d}\hat{\sigma} \approx H(Q,\mu)\; J(p_T,\mu) \otimes S(p_T,\mu)$$

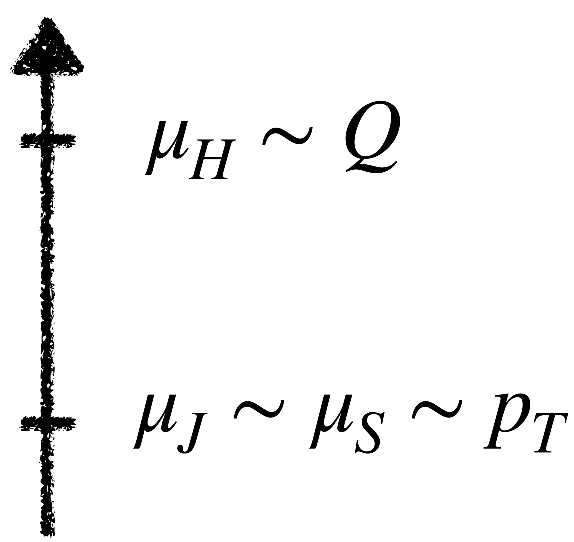
$$\ln^2 \frac{Q^2}{p_T^2} = \ln^2 \frac{Q^2}{\mu^2} - \ln^2 \frac{p_T^2}{\mu^2} + ?$$

- Jet and soft functions ill-defined in dimensional regularisation

SCET I VS SCET II

- 'Simple' SCET problems can be either two- or three-scale, depending on nature of observable

- Two-scale case: $\mu_S \sim \mu_J \ll \mu_H$, covered by SCET II



$$d\hat{\sigma} \approx H(Q,\mu)\; J(p_T,\mu,Q,\nu) \otimes S(p_T,\mu,Q,\nu)$$

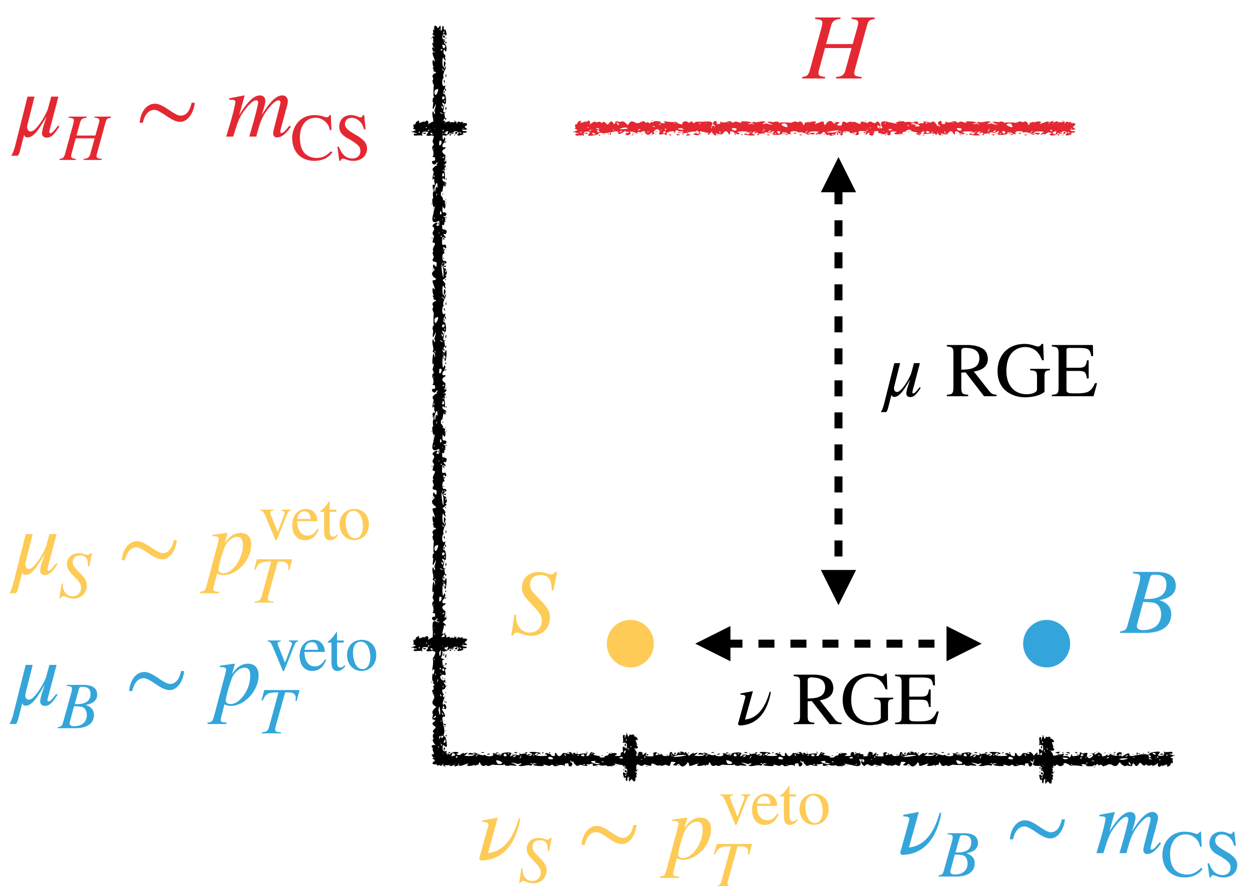
$$\ln^2 \frac{Q^2}{p_T^2} = \ln^2 \frac{Q^2}{\mu^2} - \ln^2 \frac{p_T^2}{\mu^2} - 2\ln \frac{p_T^2}{mu^2} \ln \frac{Q^2}{\nu^2} - 2\ln \frac{p_T^2}{\mu^2} \ln \frac{\nu^2}{p_T^2}$$

- Introduction of new rapidity scale ν separates soft and collinear modes

RESUMMATION OF JET VETO LOGS FOR COLOUR SINGLET

- Rapidity scale ν requires two-dimensional evolution

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}\ln S(p_T^{\mathrm{cut}}, R, \mu, \nu) = 4\Gamma_{\mathrm{cusp}}\ln\frac{\mu}{\nu} + \gamma_S \qquad \frac{\mathrm{d}}{\mathrm{d}\ln\nu}\ln S(p_T^{\mathrm{cut}}, R, \mu, \nu) = \gamma_\nu$$



GENERALISED N-JETTINESS

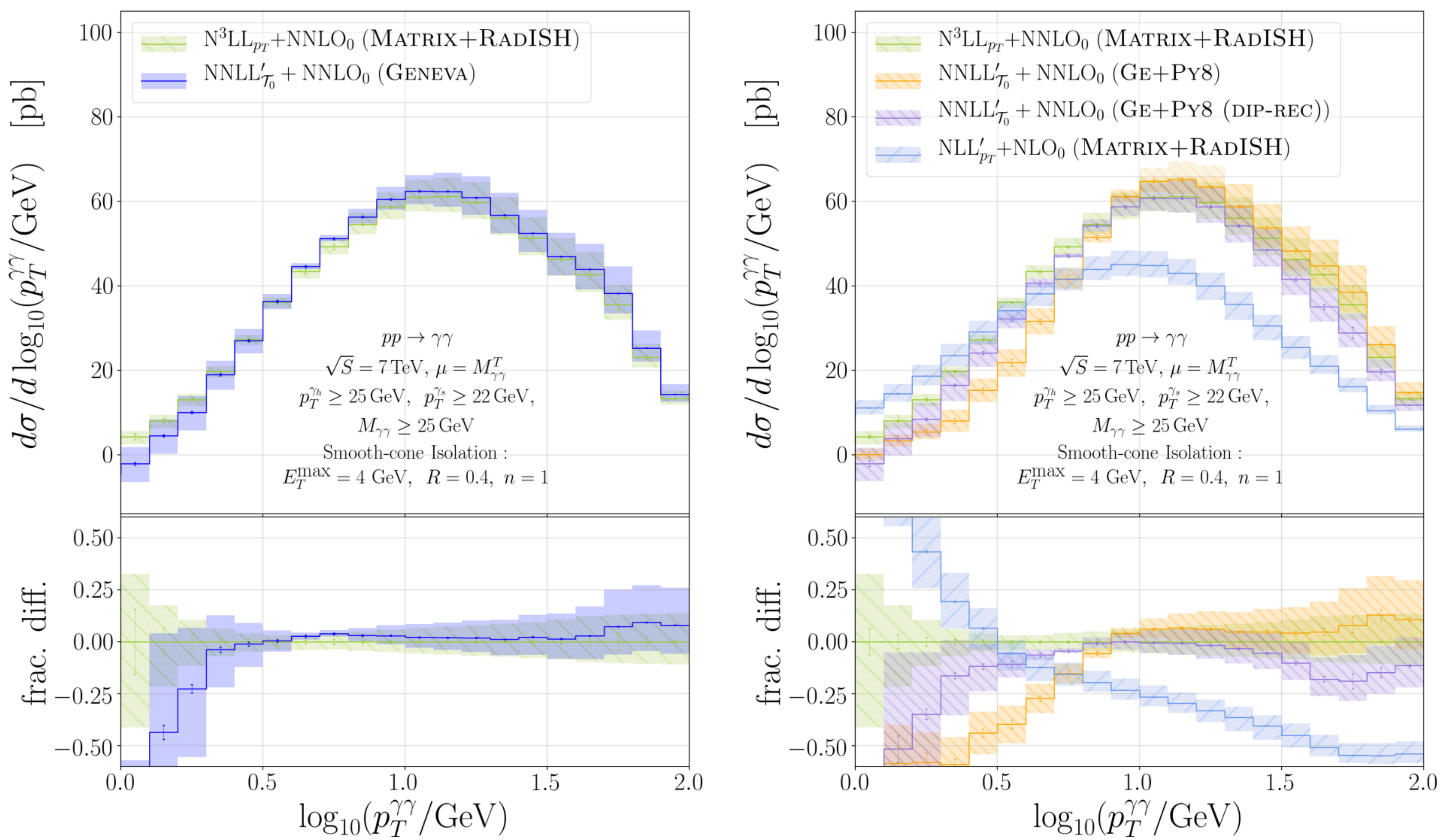
- The $\mathcal{T}_N$ metric need not measure just the invariant mass
- In jet/beam region m, define

$$\mathcal{T}^{(m)} = \sum_{i \in m} f_m(\eta_i, \phi_i) p_{Ti}$$

- Generic form of $\mathcal{T}_N$ can be invariant mass-like or transverse momentum-like (latter used in jet substructure)
- Requires different resummation (SCET-I vs SCET-II)

SHOWERED RESULTS

- Numerically examine effect of shower on accuracy



2010.10498, S. Alioli, A. Broggio, A. Gavardi, S. Kallweit, MAL, R. Nagar, D. Napoletano, L. Rottoli

SHOWERED RESULTS

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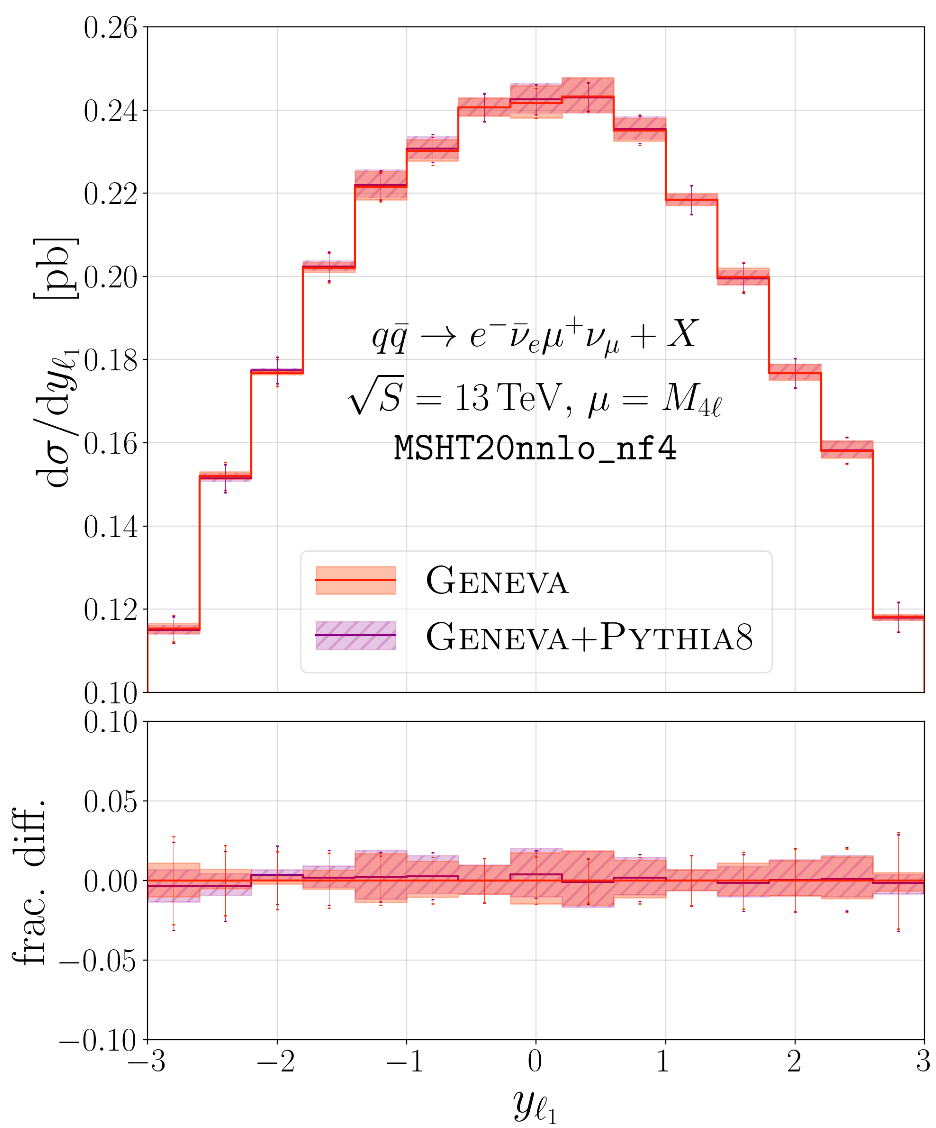

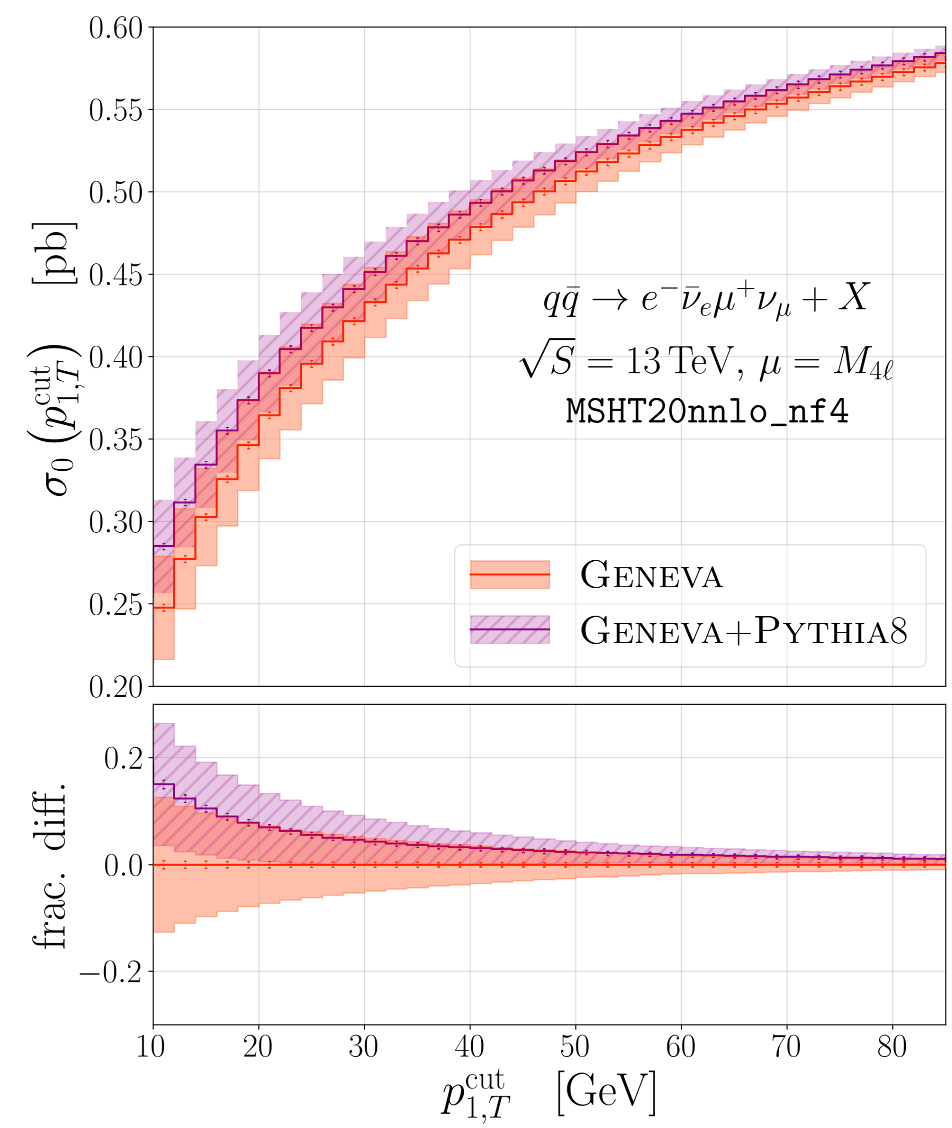

2308.11577 A. Gavardi, MAL, S. Alioli, F. Tackmann

SHOWERED RESULTS

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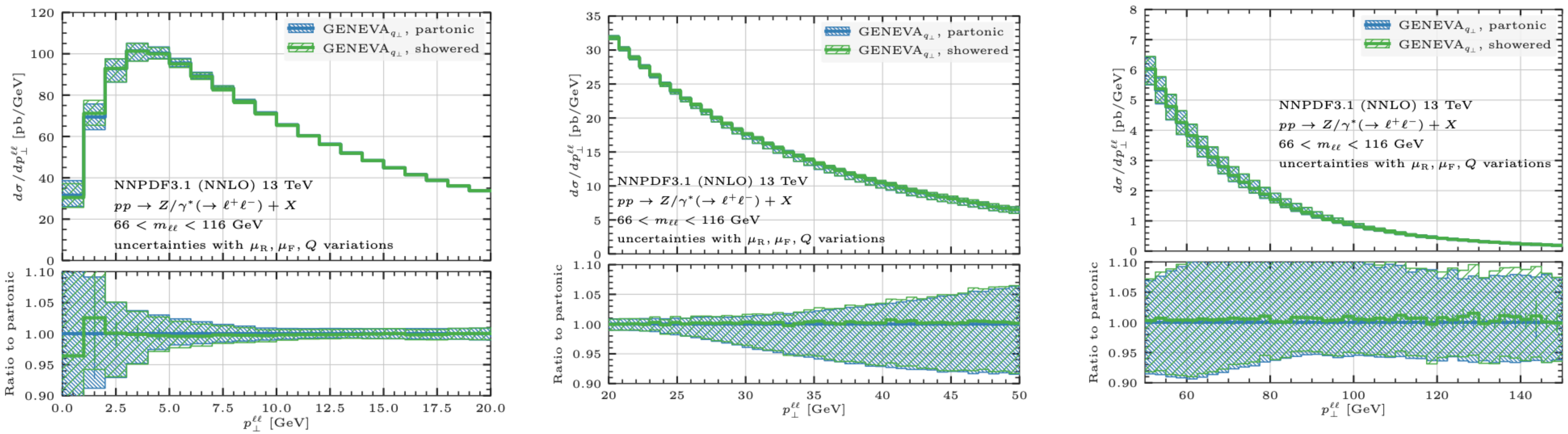

2102.08390, S. Alioli, C. Bauer, A. Broggio, A. Gavardi, S. Kallweit, MAL, R. Nagar, D. Napoletano, L. Rottoli

POWER CORRECTIONS IN JET VETO MATCHING FOR WW

$\sigma^{\text{NNLO}}_{q\bar{q}\to W^+W^-}$ [fb]	MATRIX	$p^{\text{cut}}_{1,T} = 1$ GeV	$p^{\text{cut}}_{1,T} = 5$ GeV	$p^{\text{cut}}_{1,T} = 10$ GeV
$\mu = M_{4\ell}$	1328.0	1327.9 ± 5.8	1326.1 ± 3.2	1330.4 ± 2.4
$\mu = M_{4\ell}/2$	1343.1	1344.0 ± 9.7	1346.9 ± 7.0	1346.4 ± 5.1
$\mu = 2M_{4\ell}$	1315.8	1317.1 ± 6.8	1319.5 ± 4.8	1318.1 ± 3.5

Table 1. Comparison of the GENEVA and MATRIX results for the $q\bar{q} \to W^+W^-$ inclusive cross section. Results for different values of $p^{\text{cut}}_{1,T}$ are shown; we have set $n_f = 4$ and used the `NNPDF31_nnlo_as_0118_nf_4` PDF set [73].