SHERPA
EVENT GENERATOR FOR THE LHC

Stefan Höche[1]
Institute for Particle Physics and Phenomenology
Durham University

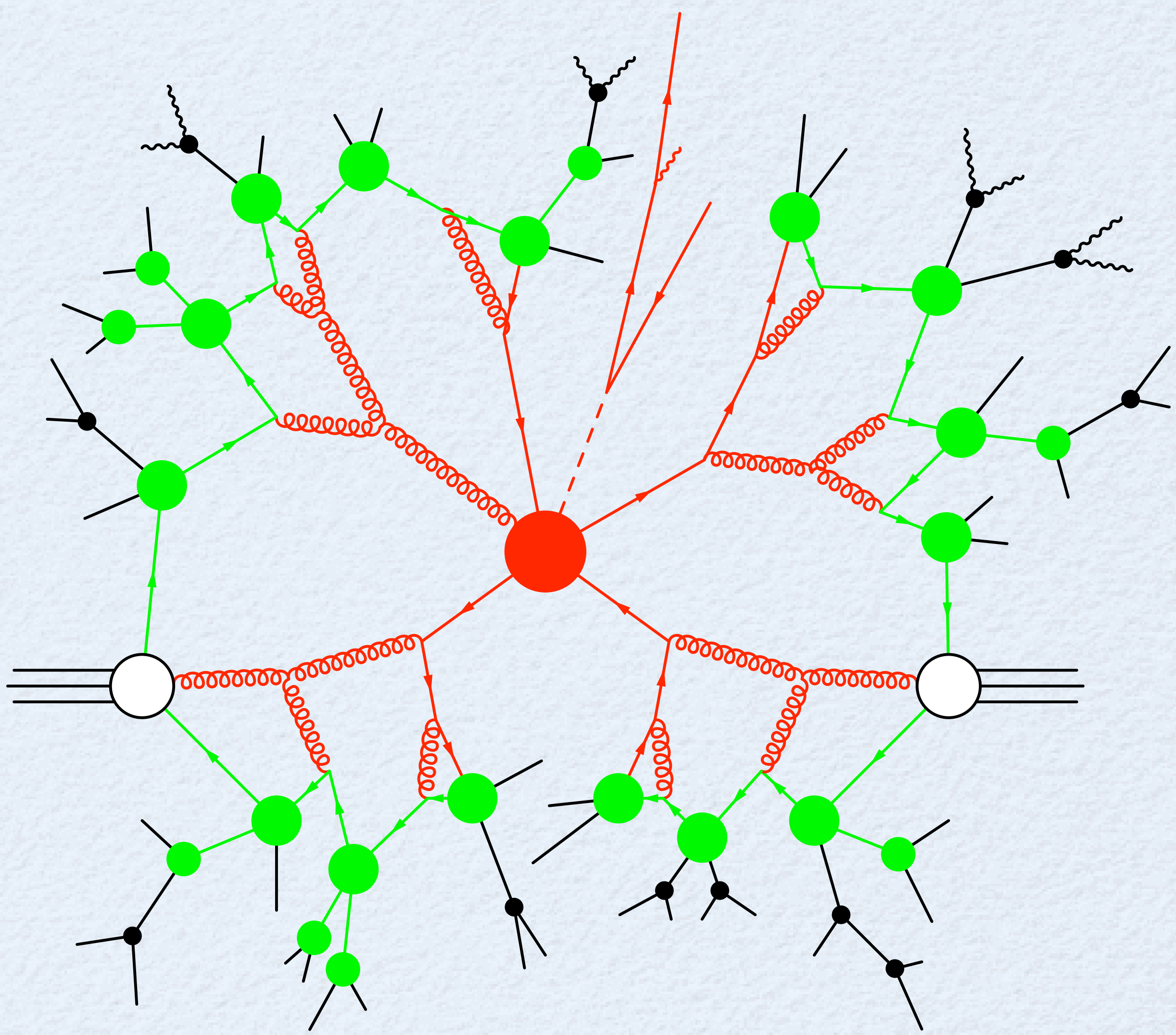
[1] for Sherpa: Tanju Gleisberg, SH, Frank Krauss, Steffen Schumann, Marek Schönherr, Frank Siegert & Jan Winter

The Sherpa Framework

This talk is not exhaustive ... but focused on recent developments

But what's in the box in general ?

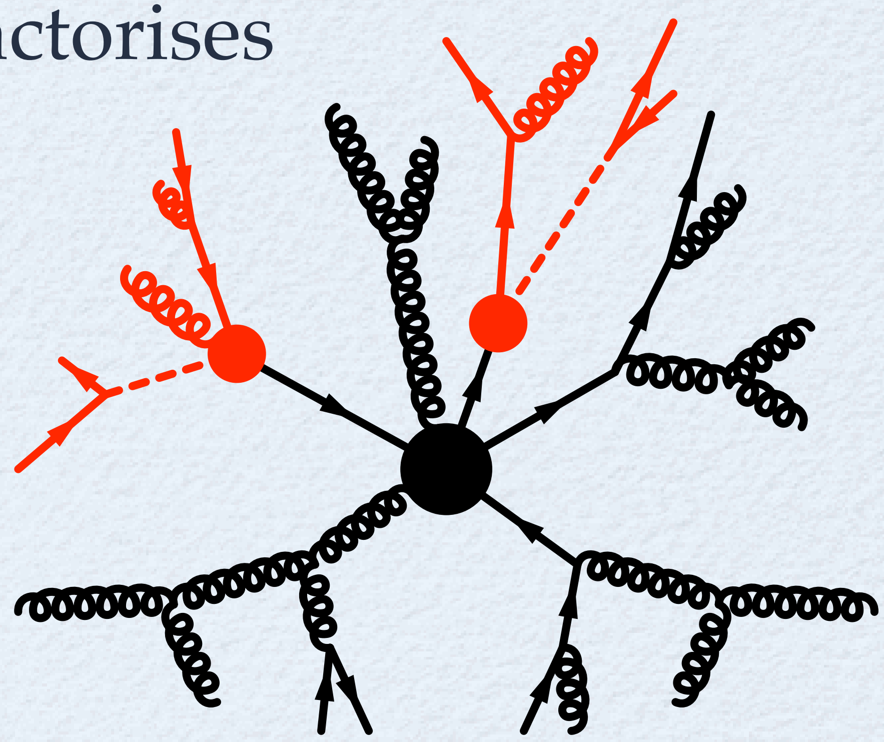
- Matrix element (ME) generators
  - AMEGIC++
  - NEW COMIX (~version 1.2)
- Shower generators
  - Parton shower (PS)
  - NEW CS-subtraction based shower
- Merging of ME & PS (CKKW)
  - Standard CKKW
  - NEW CKKW for heavy flavours
- Cluster fragmentation
- Hadron decay module
- Multiple parton interaction generator



ME-PS merging & heavy flavours

Consider top pair production at the LHC

- Narrow width approximation ➡ full ME factorises into **production** and **decay** parts



Schematically: $\mathcal{A}^{(\mathbf{n})} = \mathcal{A}_{\text{prod}}^{(\mathbf{n}_{\text{prod}})} \otimes \prod_{\mathbf{i}\in\text{decays}} \mathcal{A}_{\text{dec},\mathbf{i}}^{(\mathbf{n}_\mathbf{i})}$

How is it simulated in Sherpa ?

- ME generator AMEGIC++ provides decay chains (projection onto relevant diagrams)
- PS generator APACIC++ provides production & decay shower off heavy partons (+ standard showering)
- **CKKW ME-PS merging is applied separately and independent within production and each decay**

... what does that mean ?

Merging of ME & PS: CKKW

Matrix Elements

Advantage

- Exact to fixed order
- Include all interferences

Drawback

- Calculable only for low FS multiplicity ($n \leq 6$-8)

Parton Showers

Advantage

- Resum all (next-to) leading logarithms to all orders

Drawback

- Interference effects only through angular ordering

Combine both approaches: CKKW

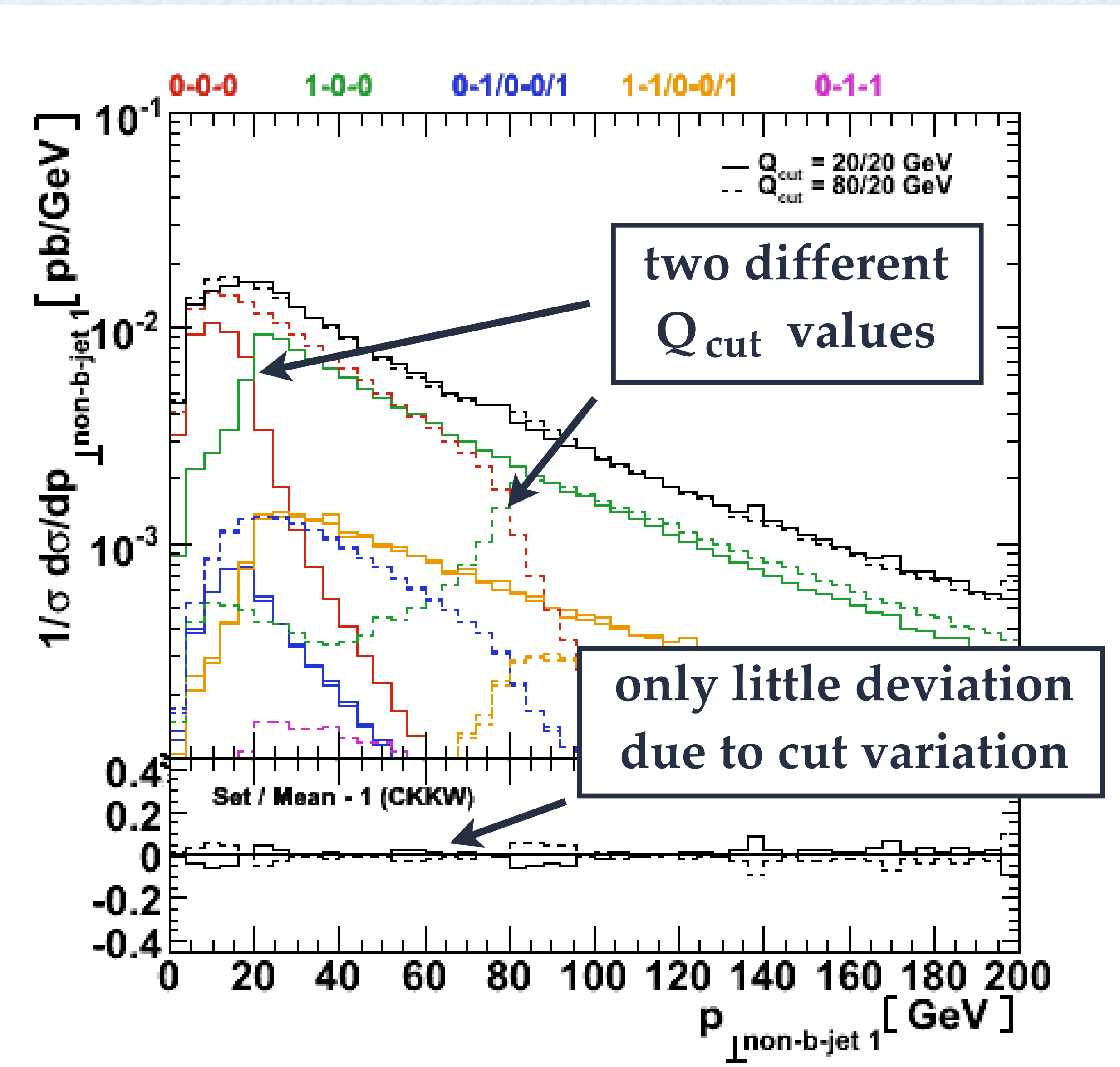
- Good description of hard radiation (ME)
- Correct intrajet evolution (PS)

- Strategy: Separate phase space
  - Jet production region → ME
  - Intrajet evolution region → PS
- **Free parameter: Separation cut Q_{cut}** (K_T-type jet measure)

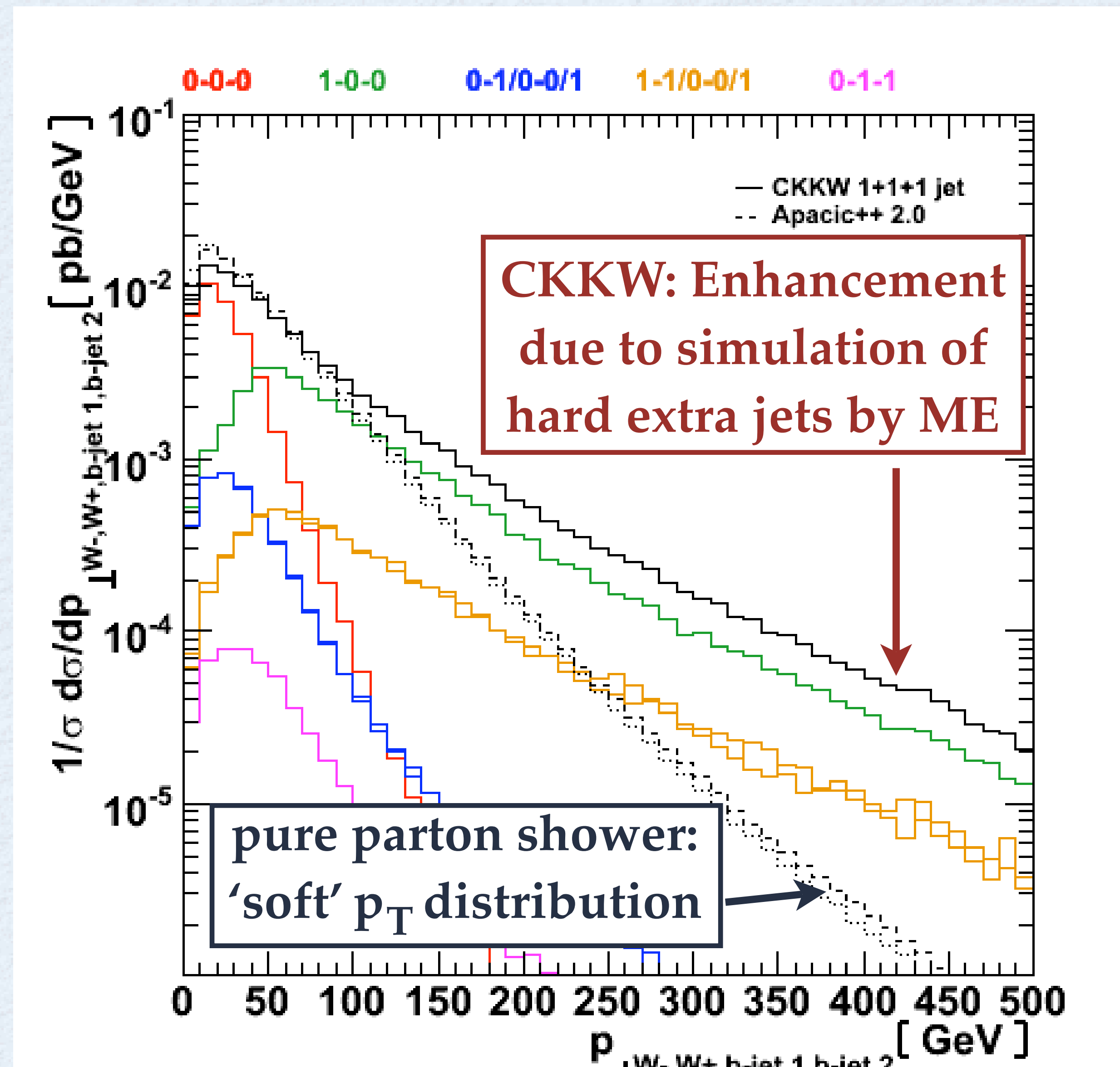
JHEP 08(2002)015; JHEP 11(2001)063

TOP PAIR PRODUCTION @ LHC

- Sanity check of the procedure
  - Q_{cut} - variation in production



- Why it is necessary ...
  - $p_\perp$ of $t\bar{t}$ pair



High-Multiplicity ME's: COMIX

- Revisited "old-fashioned" Berends-Giele recursion JHEP 08(2006)062
  - ➜ New ME generator **COMIX**
- **Fully general implementation of SM interactions**
  What you could do, for example:
  - pp ➜ W/Z+N jets where so far N up to 6 (all partons !)
  - pp ➜ $\mathbf{N\ jets + t\left[W^{+}b + M\ jets\right]\bar{t}\left[W^{-}\bar{b} + M\ jets\right]}$
    where so far {N,M} up to {2,1}
  - pp ➜ N gluons where N up to 12 (QCD benchmark)
  - pp ➜ N jets where N up to 8 (all partons !)
- Key point: Vertex decomposition of all four-particle vertices
  (Growth in computational complexity for CDBG
  determined solely by number of external legs at vertices)
- The ME is ticked off, but how about the phasespace ?
  - ➜ Recursive method analogous to ME calculation
    Basic Idea: Nucl. Phys. B9 (1969) 568

Comix: Performance

Setup: http://mlm.home.cern.ch/mlm/mcwshop03/mcwshop.html

- Performance in QCD processes (error in brackets)

σ [μb]	Number of jets						
jets	2	3	4	5	6	7	8
Comix	331.2(4)	22.78(6)	4.95(3)	1.234(4)	0.355(2)	0.099(4)	0.047(1)
ALPGEN	331.7(3)	22.49(7)	4.81(1)	1.176(9)	0.330(1)		
AMEGIC++	331.0(4)	22.78(6)	4.95(2)				

σ [μb]	Number of jets						
$b\bar{b}$ + QCD jets	0	1	2	3	4	5	6
Comix	470.8(5)	8.83(2)	1.826(8)	0.459(2)	0.151(2)	0.0544(6)	0.023(2)
ALPGEN	470.6(6)	8.83(1)	1.822(9)	0.459(2)	0.150(2)	0.053(1)	0.0215(8)
AMEGIC++	470.3(4)	8.84(2)	1.817(6)				

σ [pb]	Number of jets						
$t\bar{t}$ + QCD jets	0	1	2	3	4	5	6
Comix	755.0(8)	749(1)	523(1)	311.7(8)	171.5(6)	90.6(5)	50(1)
ALPGEN	755.4(8)	748(2)	518(2)	310.9(8)	170.9(5)	87.6(3)	45.1(8)
AMEGIC++	754.4(3)	747(1)	520(1)				

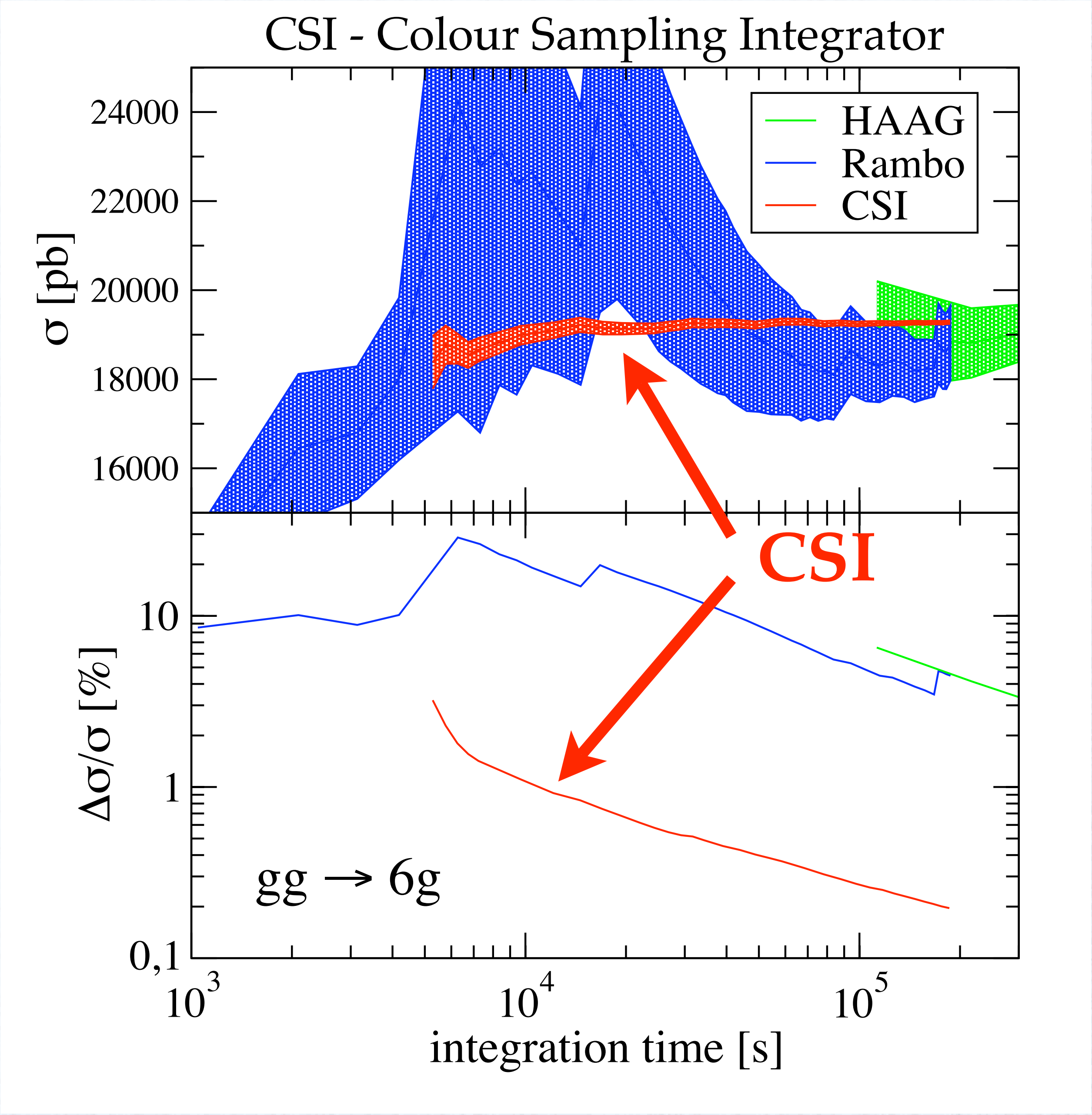
COMIX: PERFORMANCE

- Efficiencies: LHC setup
  Cuts: $66\,\mathrm{GeV} \le m_{l\bar{l}} \le 116\,\mathrm{GeV}$,
  CDF Run II K_T-algo @ 20GeV

Process	Efficiency
Z+0 jet	8.50%
Z+1 jet	1.05%
Z+2 jets	0.60%
Z+3 jets	0.15%

Process	Efficiency
W+0 jet	19.13%
W+1 jet	1.50%
W+2 jets	0.48%
W+3 jets	0.16%

- **Also new:** HAAG-based QCD integrator for colour sampling



Summary and Outlook

Sherpa is much more than what I talked about ...

Sherpas and collaborators currently work on:

- Hadron decays including B-Mixing (version 1.1)
- Preparing the two new showers for ME-Shower merging
  ➡ systematics studies with different shower prescriptions
- BSM beyond the MSSM:
  Little Higgs, MWTC ➡ J. Ferland (ATLAS, Montreal), ...
- Interfaces to Athena ➡ J. Ferland (ATLAS, Montreal)
  and CMS software ➡ M. Merschmeyer (CMS, Aachen)
- Grid support: At the IPPP, we run Sherpa on the Grid !
  Multithreading: Speed up the calculation with more CPU's !

Next release: Version 1.1, ~April 2008

Updates on Sherpa can be found on

www.sherpa-mc.de

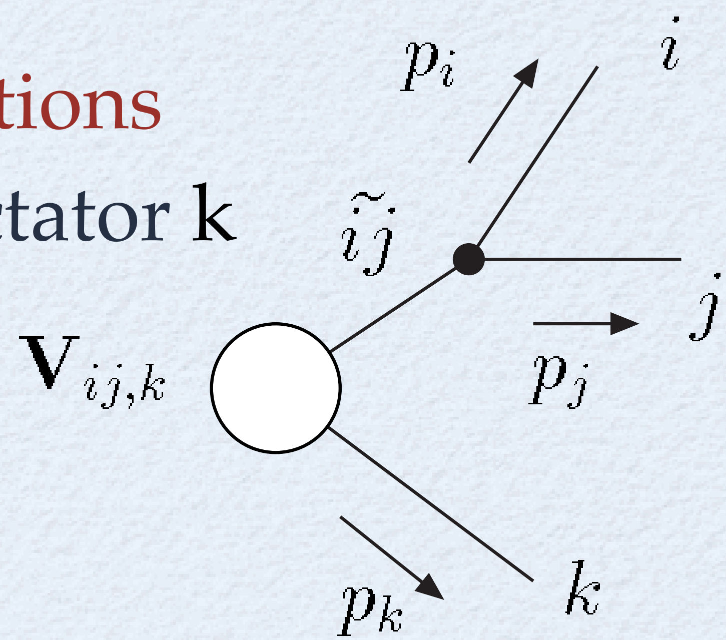
E-mail us at

info@sherpa-mc.de

CS-subtraction based Shower

F.Krauss, S.Schumann, JHEP03(2008)038

- Catani-Seymour subtraction terms
  → General framework for QCD NLO calculations
- Splitting of parton $\tilde{ij}$ into partons i and j, spectator k
- Advantages over Parton Shower
  → Full phasespace coverage
  → Good approximation of ME
  → Better analytic control
- Implementation into Sherpa
  for the general case, i.e. final-final
  initial-final and initial-initial dipoles



e.g. final-final splitting:

$$\langle \mathbf{V}_{q_i,g_j,k} \rangle (\tilde{z}_i, y_{ij}, k) =$$

$$C_F \left(\frac{2}{1-\tilde{z}_i+\tilde{z}_i y_{ij,k}} - (1+\tilde{z}_i) \right)$$

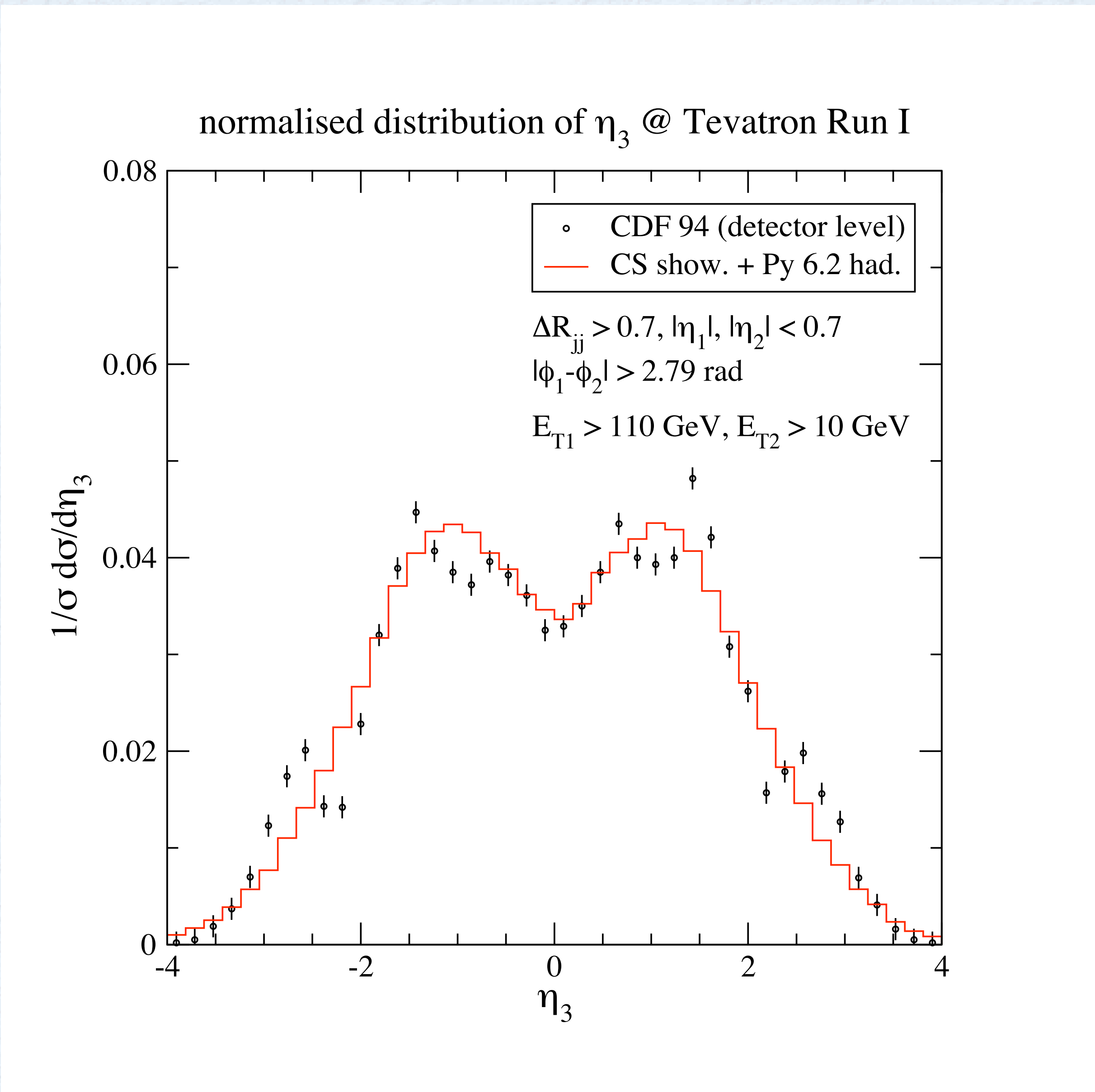
$$y_{ij,k} = \frac{p_i p_j}{p_i p_k + p_j p_k + p_i p_j}$$

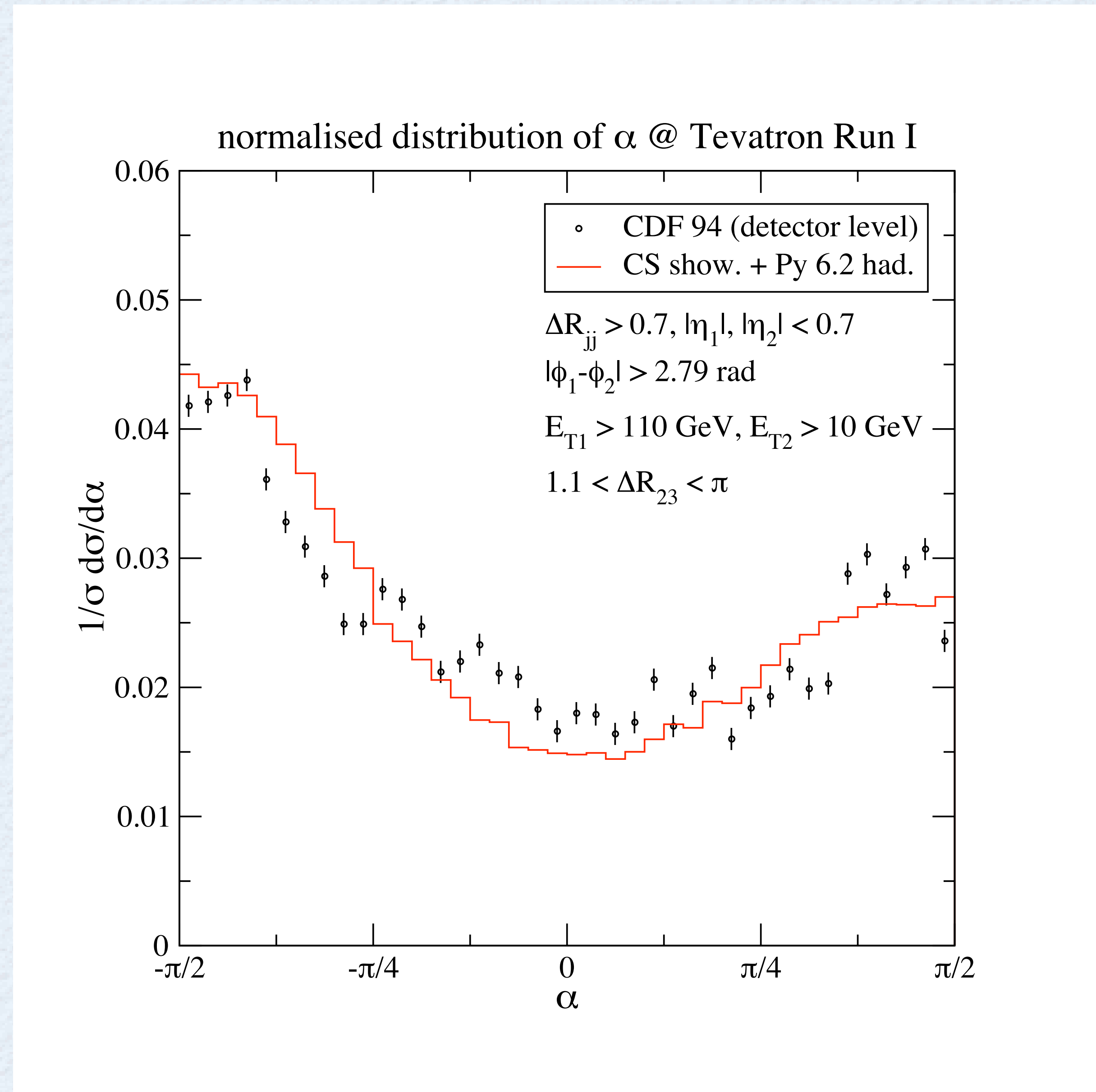
$$z_i = \frac{p_i p_k}{p_i p_k + p_j p_k}$$

CS-Subtraction based shower

F.Krauss, S.Schumann, JHEP03(2008)038

- Results for pp→jets Phys. Rev. D50 (1994) 5562





COMIX: Phasespace recursion

Nucl. Phys. B9 (1969) 568

- State-of-the art approach for general phasespace generation:

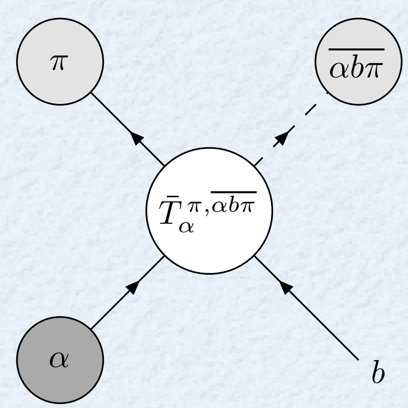
  Factorise PS using

$$\mathrm{d}\mathbf{\Phi_n}\left(\mathbf{a},\mathbf{b};\mathbf{1},\ldots,\mathbf{n}\right) = \mathrm{d}\mathbf{\Phi_m}\left(\mathbf{a},\mathbf{b};\mathbf{1},\ldots,\mathbf{m},\bar\pi\right)\,\mathrm{d}s_\pi\,\mathrm{d}\mathbf{\Phi_{n-m}}\left(\pi;\mathbf{m}+\mathbf{1},\ldots,\mathbf{n}\right)$$

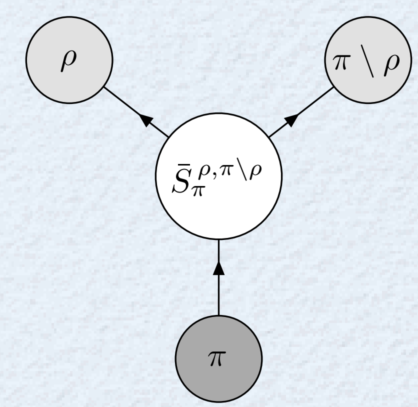
  Remaining basic building blocks of the phasespace:

  - "Propagators" $\mathbf{P}_{\boldsymbol{\pi}} = \begin{cases} \mathbf{1} & \text{if } \boldsymbol{\pi} \text{ or } \overline{\boldsymbol{\pi}} \text{ external} \\ \mathbf{d}\boldsymbol{s}_{\boldsymbol{\pi}} & \text{else} \end{cases}$

  - Decay "vertices"



$$\mathbf{S}_\pi^{\pi,\pi\setminus\rho} = \frac{\lambda(\mathbf{s}_\pi,\mathbf{s}_\rho,\mathbf{s}_{\pi\setminus\rho})}{\mathbf{8}\,\mathbf{s}_\pi}\,\mathrm{d}\cos\theta_\rho\,\mathrm{d}\phi_\rho$$



$$\mathbf{T}_\alpha^{\pi,\overline{\alpha\mathbf{b}\pi}} = \frac{\lambda(\mathbf{s}_{\alpha\mathbf{b}},\mathbf{s}_\pi,\mathbf{s}_{\overline{\alpha\mathbf{b}\pi}})}{\mathbf{8}\,\mathbf{s}_{\alpha\mathbf{b}}}\,\mathrm{d}\cos\theta_\pi\,\mathrm{d}\phi_\pi$$

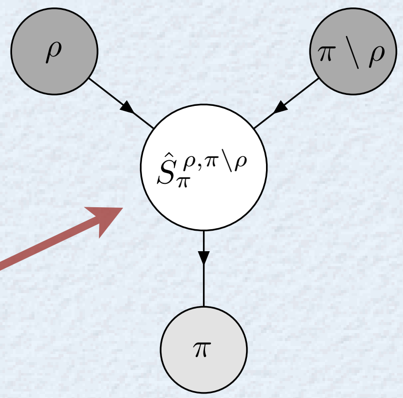
Arrows → Momentum flow

COMIX: Phasespace Recursion

- Basic idea: Take above recursion literally and "turn it around"

S-channel phasespace (schematically)

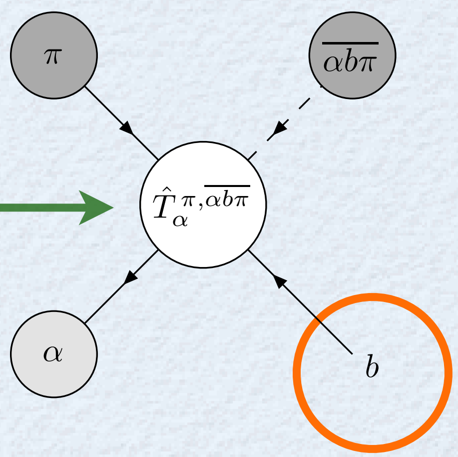
$$\mathrm{d}\Phi_S\left(\pi\right) = \left[\sum \alpha\left(S_\pi^{\rho,\pi\setminus\rho}\right)\right]^{-1} \times \left[\sum \alpha\left(S_\pi^{\rho,\pi\setminus\rho}\right)\, S_\pi^{\rho,\pi\setminus\rho}\, P_\rho\, \mathrm{d}\Phi_S\left(\rho\right)\, P_{\pi\setminus\rho}\, \mathrm{d}\Phi_S\left(\pi\setminus\rho\right)\right]$$



Weights for adaptive multichanneling

T-channel phasespace (schematically)

$$\mathrm{d}\Phi_T^{(b)}\left(\alpha\right) = \left[\sum \alpha\left(T_\alpha^{\pi,\overline{\alpha b\pi}}\right)\right]^{-1} \times \left[\sum \alpha\left(T_\alpha^{\pi,\overline{\alpha b\pi}}\right)\, T_\alpha^{\pi,\overline{\alpha b\pi}}\, P_\pi\, \mathrm{d}\Phi_S\left(\pi\right)\, P_{\overline{\alpha b\pi}}\, \mathrm{d}\Phi_T^{(b)}\left(\alpha\pi\right)\right]$$



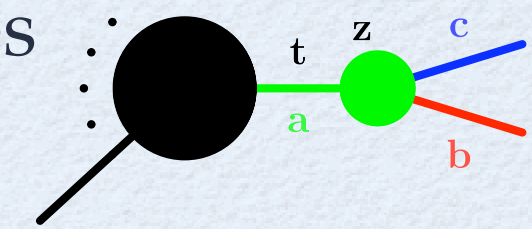
"b" is fixed ➡ Every PS-weight is unique !

Arrows ➡ Weight flow !

➡ Factorial growth of PS-channels tamed

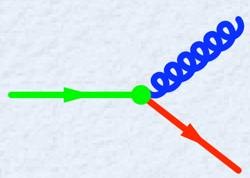
APACIC++: Heavy Quark Production

- In quasi-collinear limit (b↔heavy quark) ME factorises

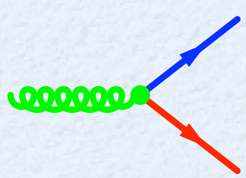


$$|\mathbf{M}(\mathbf{b},\mathbf{c},\ldots,\mathbf{n})|^2 \;\rightarrow\; |\mathbf{M}(\mathbf{a},\ldots,\mathbf{n})|^2\,\frac{8\pi\alpha_s}{\mathbf{t}-\mathbf{m}_\mathbf{a}^2}\,\mathbf{P}_{\mathbf{a}\rightarrow\mathbf{bc}}(\mathbf{z})$$

- Virtuality ordered PS ➡ evolution variable $\mathbf{t}$ changes to $\mathbf{t}-\mathbf{m}_\mathbf{a}^2$
- Splitting functions $\mathbf{P}_{\mathbf{ab}}(\mathbf{z})$ become those for massive quarks
  Nucl. Phys. B627(2002)189

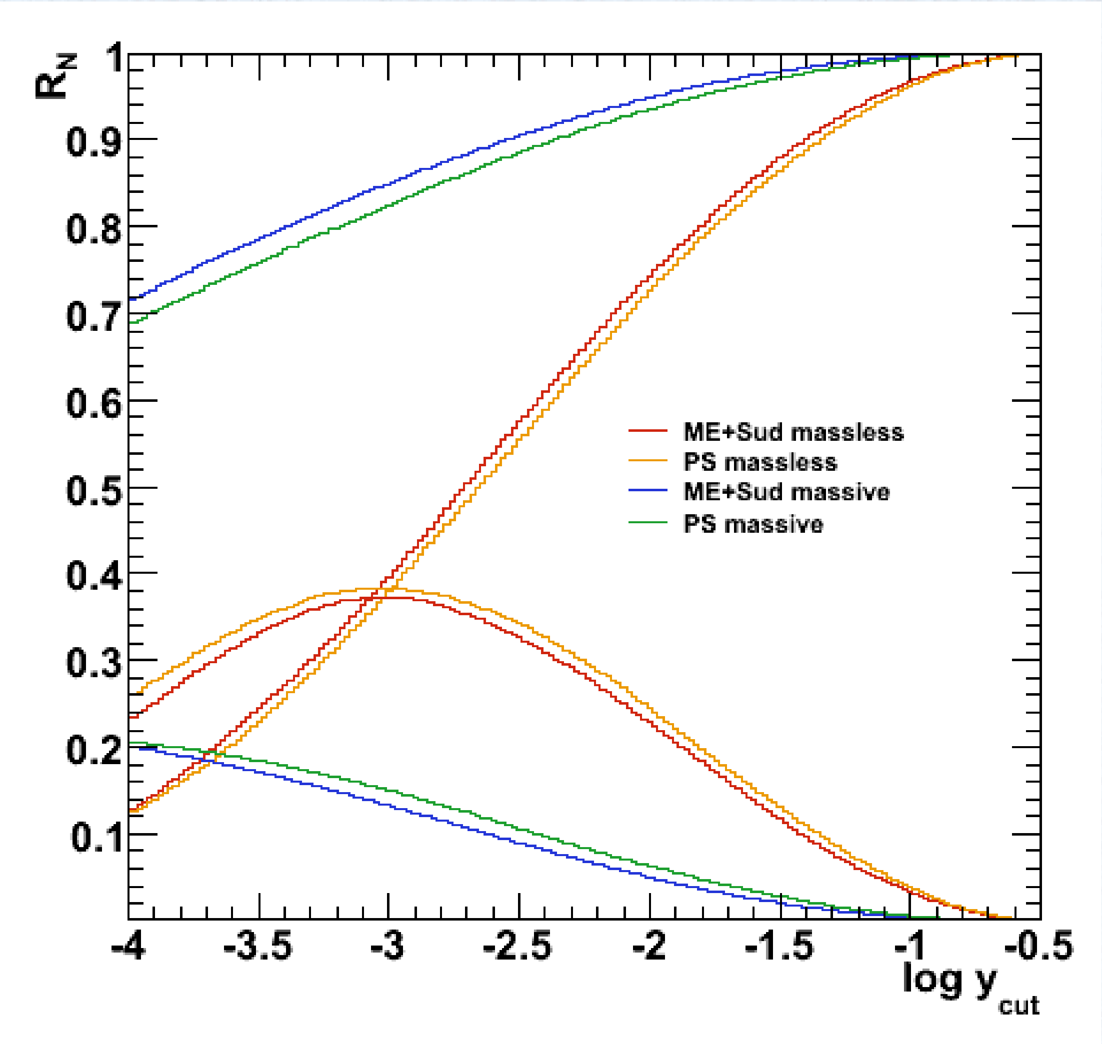


$$\rightarrow\; \mathbf{C_F}\left(\frac{\mathbf{1}+\mathbf{z}^2}{\mathbf{1}-\mathbf{z}}-\frac{\mathbf{2z}(\mathbf{1}-\mathbf{z})\mathbf{m}^2}{\mathbf{q}^2+(\mathbf{1}-\mathbf{z})^2\mathbf{m}^2}\right)$$



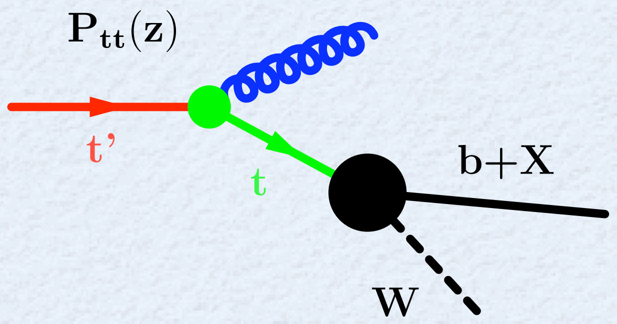
$$\rightarrow\; \mathbf{T_R}\left(\mathbf{1}-\mathbf{2z}(\mathbf{1}-\mathbf{z})+\frac{\mathbf{2z}(\mathbf{1}-\mathbf{z})\mathbf{m}^2}{\mathbf{q}^2+\mathbf{m}^2}\right)$$

- Cross-check: 2- and 3-jet fraction in $\mathbf{e}^+\mathbf{e}^- \rightarrow \mathbf{t}\bar{\mathbf{t}}$, PS vs. ME, weighted with NLL Sudakov form factors ➡
  Phys. Lett. B576(2003)135



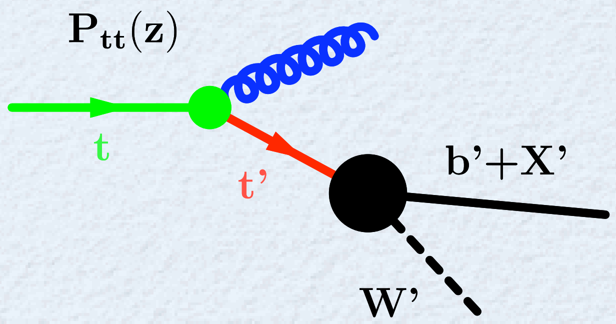
APACIC++: Heavy Quark Production

PS in production



- On-shell daughter partons
  - ➜ New decay kinematics via Lorentz transformation
    Choice: Boost into new (daughter) cms
- FSR-like situation
- Evolution stops once diced virtuality reaches on-shell mass of heavy quark

PS in decay

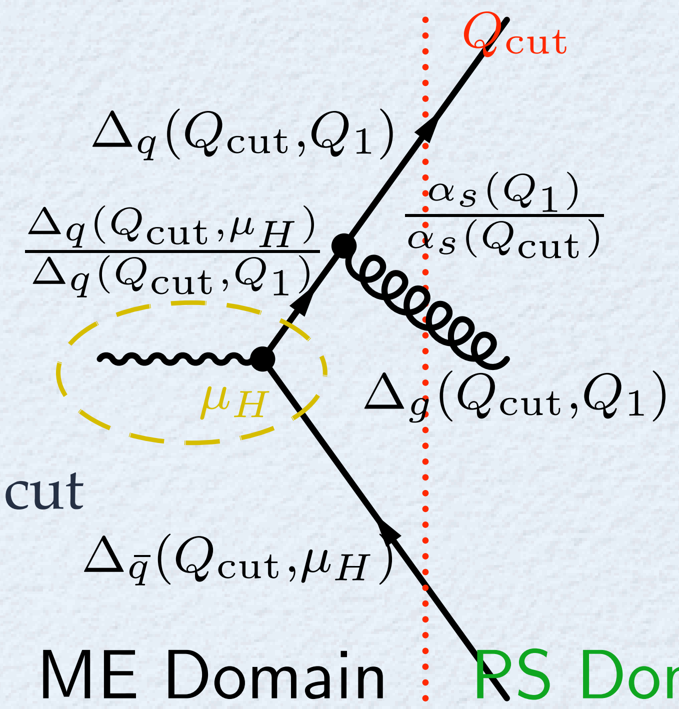


- Off-shell daughter partons
  - ⚠ Decay kinematics need to be reconstructed
  - ➜ Choice: Reconstruct in cms of decayed quark, such that $\vec{\mathbf{p}}/|\vec{\mathbf{p}}|$ is preserved
- ISR-like situation
- Evolution stops if $\mathbf{p}_\perp$ reaches width of decaying quark

CKKW in a nutshell

- Define jet resolution parameter Q_{cut} (Q-jet measure)
  ➜ divide phase space into regions of jet production (ME) and jet evolution (PS)
- Select final state multiplicity and kinematics according to σ 'above' Q_{cut}
- KT-cluster backwards (construct PS-tree) and identify core process
- **Reweight ME** to obtain exclusive samples at Q_{cut}
- Start the parton shower at the hard scale
  Veto all PS emissions harder than Q_{cut}

JHEP 0111 (2001) 063
JHEP 0208 (2002) 015



➜ This yields the correct jet rates !
Simple example: 2-jet rate in ee→qq

$$R_2(q) = \left(\Delta(Q_{\rm cut}, \mu_{\rm hard}) \frac{\Delta(q, \mu_{\rm hard})}{\Delta(Q_{\rm cut}, \mu_{\rm hard})} \right)^2$$