Top-Physics with Sherpa
CKKW & Heavy Flavours

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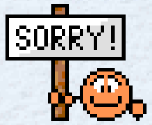
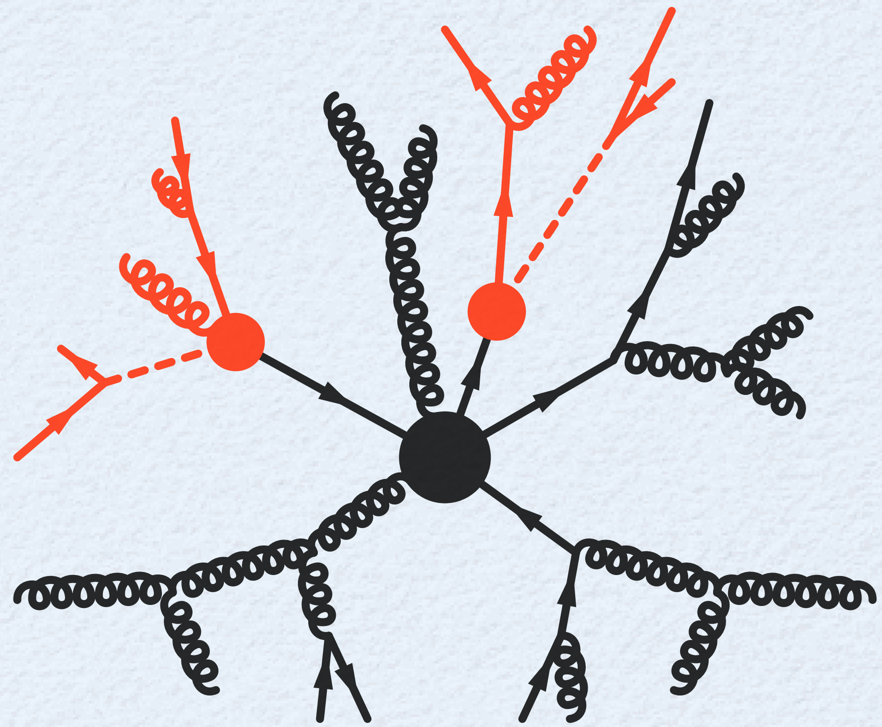
OUTLINE

This talk is not exhaustive ... 

... but focused on the perturbative part of $t\bar{t}$ production

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

Schematically:



- In the context of Monte Carlo event generation we need
  - Matrix Elements (ME) for production & decay
  - Parton Showers (PS) for production & decay
  - A merging prescription for ME & PS

ME's in Sherpa: AMEGIC++

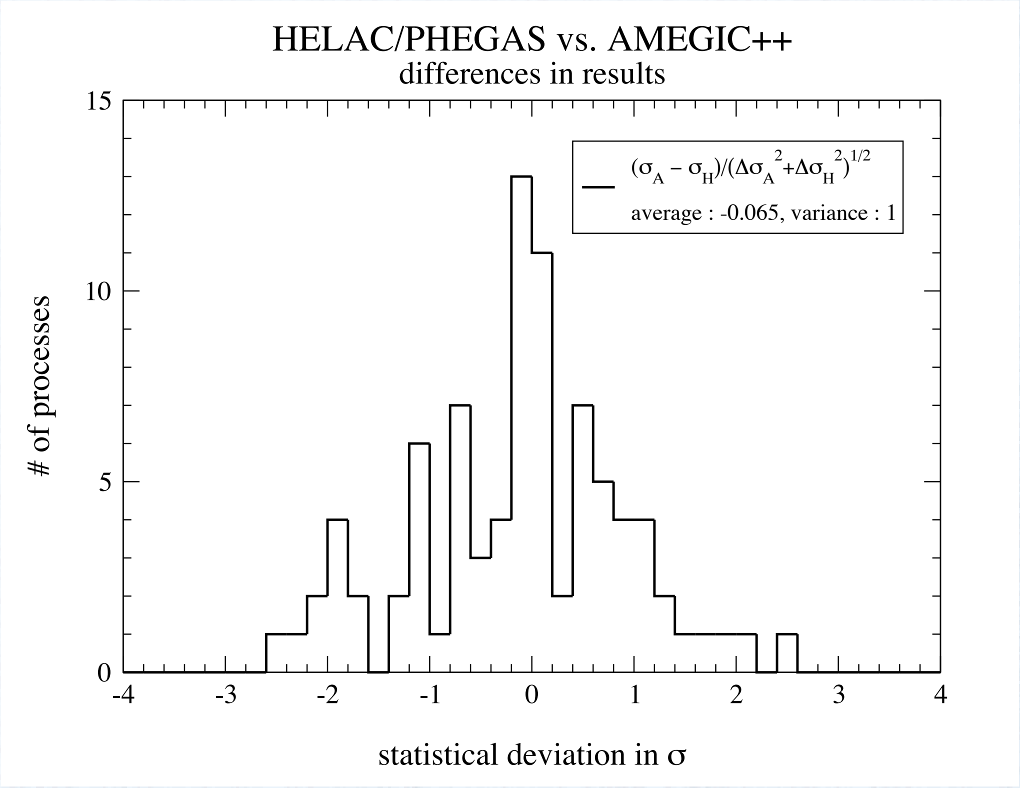
JHEP 02 (2002) 044

Sherpas built-in standard ME generator is AMEGIC++:

- Fully automated calculation of (polarized) cross sections in the SM(+AGC), MSSM and ADD model
- Performance comparable to that of dedicated codes
- Expandability (users can easily implement new models)

Extensively tested:

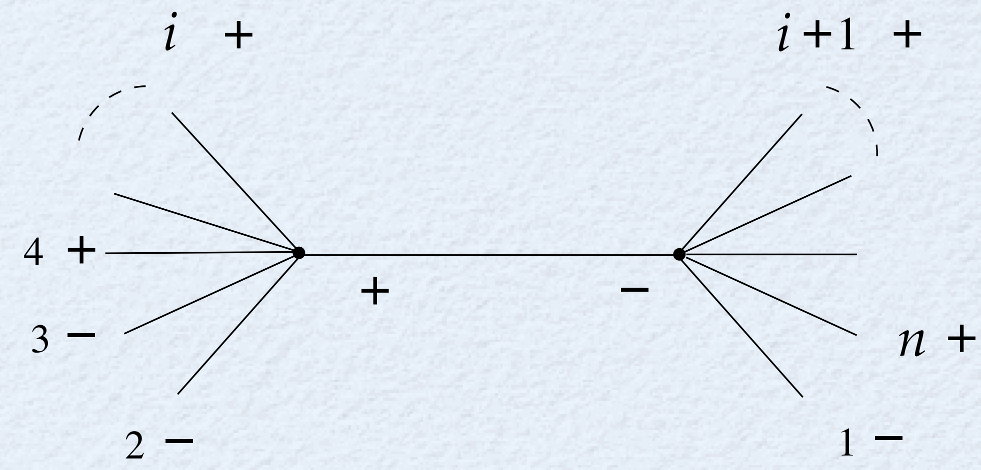
- $e^+e^- \rightarrow 6f$ comparison vs. HELAC/PHEGAS deviations in 86 processes EPJC 34(2004)173 →
- Comparison of arbitrary 2→2 MSSM processes vs. WHIZARD/O'Mega & SMadGraph Phys.Rev.D73(2006)055005 http://www.sherpa-mc.de/susy_comparison



ME's in SHERPA: AMEGIC++

based on hep-th/0403047

- New twistor-inspired techniques (CSW vertex rules) help speeding up calculation of massless pure QCD ME's
- Advantage: Up to $\mathbf{N_{out} = 7}$ only up to 3 MHV-amplitudes must be sewed together



Process	Time [s] for 10^5 points Conventional	Time [s] for 10^5 points CSW rules	Conventional / CSW-rules
2g $\rightarrow$ 4g	1977	19	104.1
2g $\rightarrow$ 5g	n/a	429	n/a
2q $\rightarrow$ 4g	124	14	8.9
2q $\rightarrow$ 5g	43636	290	148.4
2q $\rightarrow$ 2q'+2g	8	6	1.33
2q $\rightarrow$ 2q'+3g	810	74	10.8
2q $\rightarrow$ 2q+2g	24	10	2.4
2q $\rightarrow$ 2q+3g	3923	118	33
2j $\rightarrow$ 4j	4082	202	20.2
2j $\rightarrow$ 5j	n/a	12103	n/a

Newly accessible processes

HIGH-MULTIPLICITY ME'S: COMIX

JHEP 08 (2006) 062

- QCD: Comparison with on-shell methods shows superiority of CDBG/Dyson-Schwinger algorithms **for numerics**

Computation time $2 \to n$ gluon ME for 10^4 phase space points, sampled in helicity and colour

CO → colour ordered

CD → colour dressed

Final State	BG		BCF		CSW	
	CO	CD	CO	CD	CO	CD
$2g$	0.24	0.28	0.28	0.33	0.31	0.26
$3g$	0.45	0.48	0.42	0.51	0.57	0.55
$4g$	1.20	1.04	0.84	1.32	1.63	1.75
$5g$	3.78	2.69	2.59	7.26	5.95	5.96
$6g$	14.2	7.19	11.9	59.1	27.8	30.6
$7g$	58.5	23.7	73.6	646	146	195
$8g$	276	82.1	597	8690	919	1890
$9g$	1450	270	5900	127000	6310	29700
$10g$	7960	864	64000	-	48900	-

Factorial growth tamed !
Now exponential ($\sim 3^n$)

Other methods much slower due to unsuitable natural color basis and/or large number of vertices

HIGH-MULTIPLICITY ME'S: COMIX

- Take approach serious and extend to full SM
  - ➔ New ME generator **COMIX**
- Promising results for all processes attempted e.g.
  - pp ➔ 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 10 (QCD benchmark process)
  - other EW / QCD ...
- Key point: Vertex decomposition of all four-particle vertices
  (Growth in computational complexity for CDBG
  determined solely by number of external legs at vertices)
- So the ME is ticked off, but how about the phasespace ?
  - ➔ Employ recursive methods analogous to ME calculation
    Basic Idea: Nucl. Phys. B9 (1969) 568

COMIX: Phasespace recursion

Nucl. Phys. B9 (1969) 568

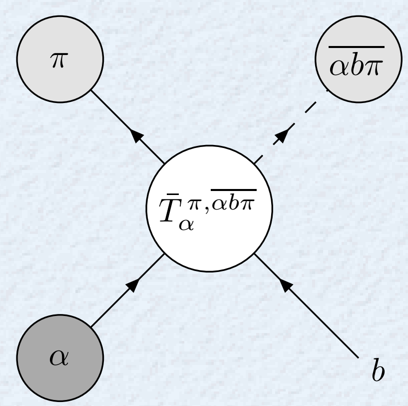
- State-of-the art approach for general phasespace generation:

  Factorise PS using

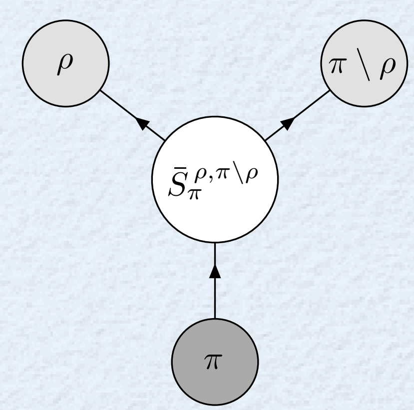
$$\mathrm{d}\boldsymbol{\Phi}_{\mathbf{n}}\,(\mathbf{a},\mathbf{b};\mathbf{1},\ldots,\mathbf{n}) = \mathrm{d}\boldsymbol{\Phi}_{\mathbf{m}}\,(\mathbf{a},\mathbf{b};\mathbf{1},\ldots,\mathbf{m},\bar{\pi})\;\mathrm{d}s_{\pi}\,\mathrm{d}\boldsymbol{\Phi}_{\mathbf{n-m}}\,(\pi;\mathbf{m}+\mathbf{1},\ldots,\mathbf{n})$$

  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"



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



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

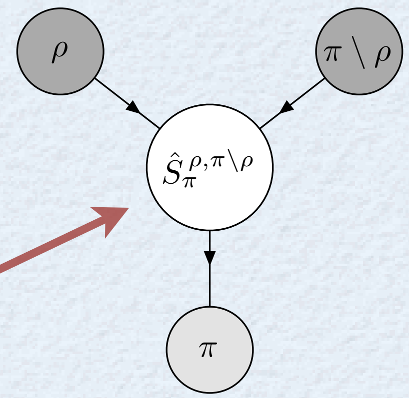
Arrows → Momentum flow

Comix: Phasespace recursion

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

S-channel phasespace (schematically)

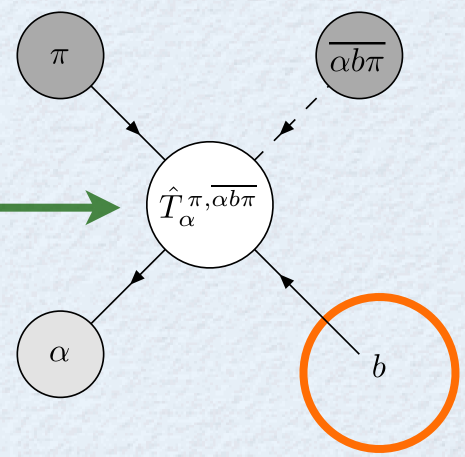
$$
\mathrm{d}\Phi_S\left(\pi\right) = \Big[\sum \alpha\left(S_\pi^{\rho,\pi\setminus\rho}\right)\Big]^{-1}
\times \Big[\sum \alpha\left(S_\pi^{\rho,\pi\setminus\rho}\right) S_\pi^{\rho,\pi\setminus\rho}\, P_\rho\, \mathrm{d}\Phi_S\left(\rho\right)\, P_{\pi\setminus\rho}\, \mathrm{d}\Phi_S\left(\pi\setminus\rho\right)\Big]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



Weights for adaptive multichanneling

T-channel phasespace (schematically)

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



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

Arrows ➡ Weight flow !

➡ Factorial growth of PS-channels tamed

COMIX: PERFORMANCE

- QED benchmark processes: ME performance w/o colours

Process	# Graphs	#Currents / # Vertices	Time [s / 10^4 pts] AMEGIC++	Time [s / 10^4 pts] COMIX
$\tau\tau \to 4\tau$	36	25 / 45	7.2	5.1
$\tau\tau \to 8\tau$	158400	336 / 3325	-	2841

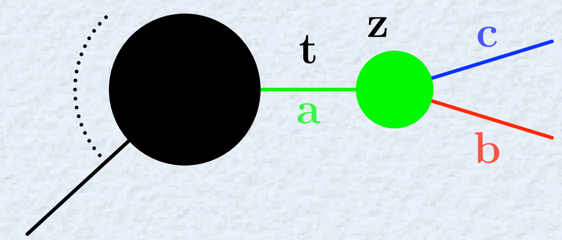
- Phasespace performance in W/Z+jets @ LHC
  Cuts: $\mathbf{66\,GeV \leq m_{l\bar{l}} \leq 116\,GeV}$, CDF Run II K_T-algo @ 20GeV

Process	Efficiency	Process	Efficiency
Z+0 jet	8.50%	W+0 jet	19.13%
Z+1 jet	1.05%	W+1 jet	1.50%
Z+2 jets	0.60%	W+2 jets	0.48%
Z+3 jets	0.15%	W+3 jets	0.16%

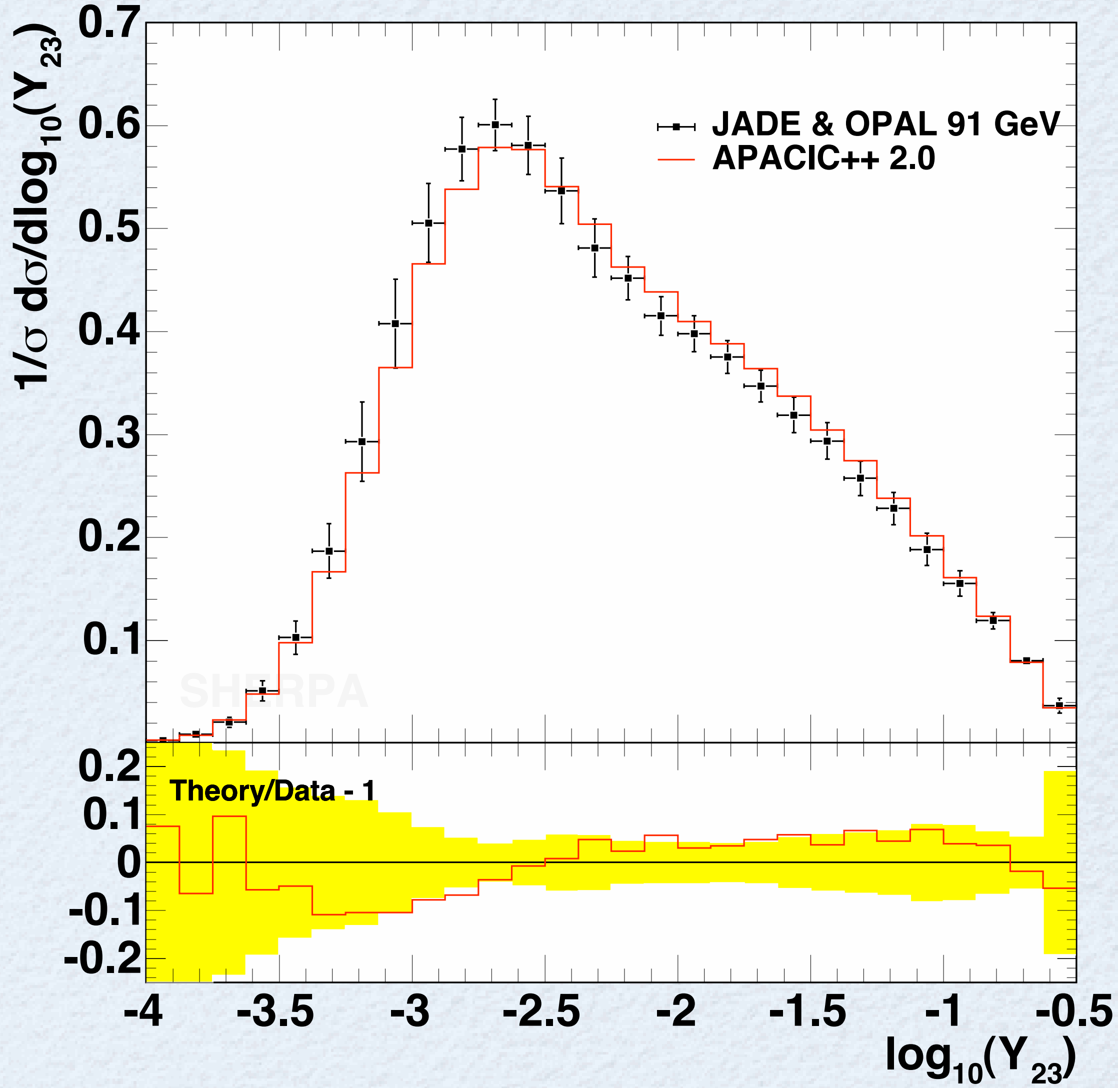
PS's in SHERPA: APACIC++

R. Kuhn, F. Krauss, G. Ivanyi, G. Soff CPC 134 (2001) 223
F. Krauss, A. Schälicke, G. Soff, hep-ph/0503087

Basic features of APACIC++ :

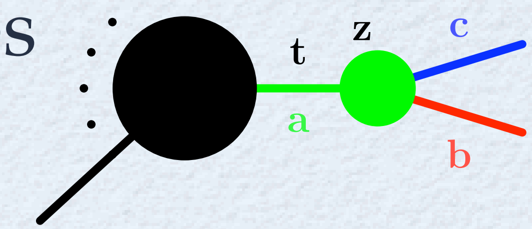


- Virtuality ordered parton cascade, colour coherence imposed by angular veto
- Final & initial state showering in e^+e^- & hadron collisions (no DIS-like situations)
- Algorithm similar to virtuality ordered PYTHIA parton shower
- Extensively tested, e.g. vs. LEP data (hadronisation: PYTHIA)



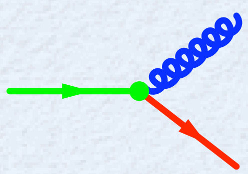
APACIC++: Heavy Quark Production

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

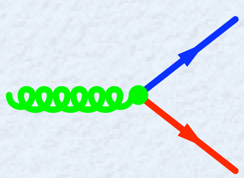


$$|\mathbf{M}(\mathbf{b},\mathbf{c},\ldots,\mathbf{n})|^2 \;\to\; |\mathbf{M}(\mathbf{a},\ldots,\mathbf{n})|^2\,\frac{8\pi\alpha_s}{\mathbf{t}-\mathbf{m_a^2}}\,\mathbf{P_{a\to bc}(z)}$$

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

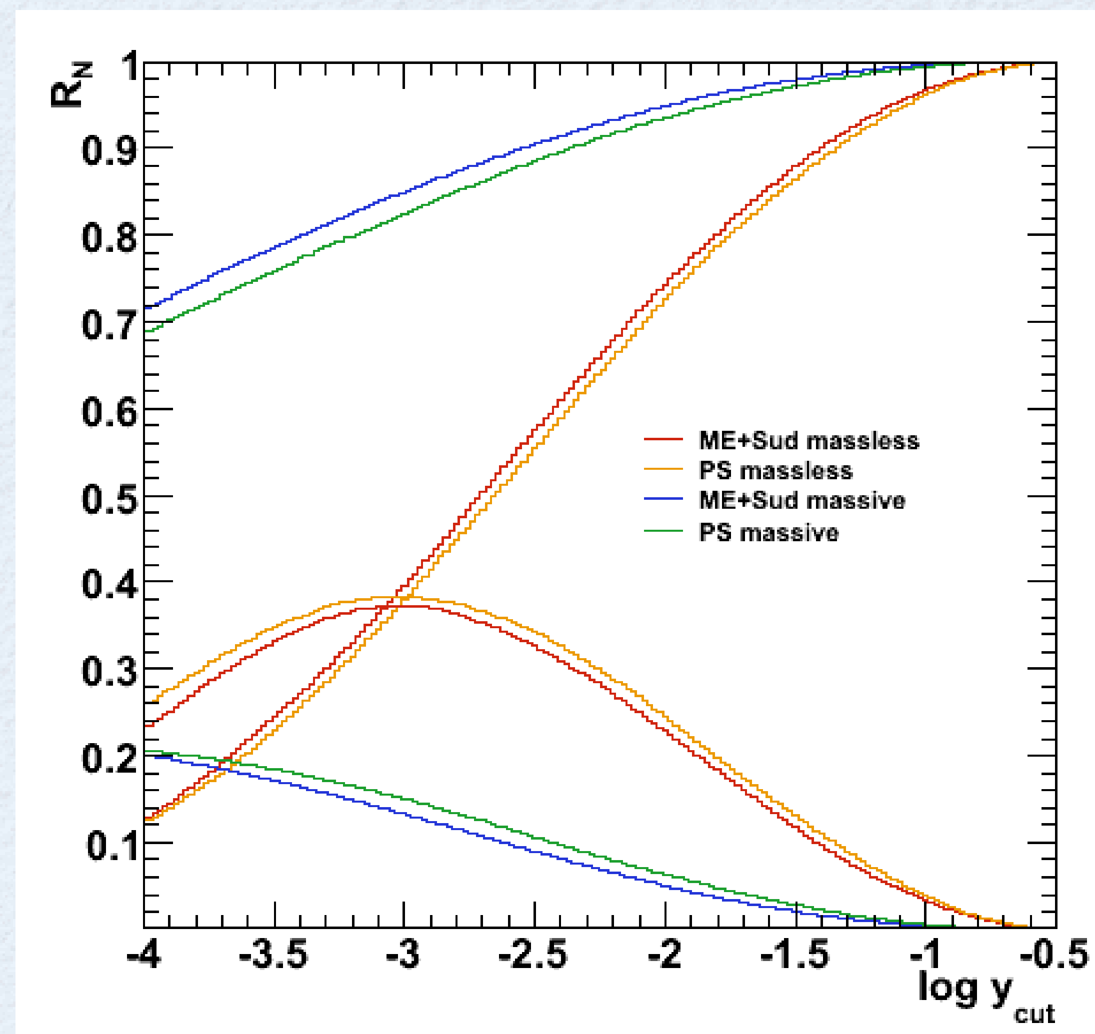


$$\Rightarrow\; \mathbf{C_F}\left(\frac{\mathbf{1}+\mathbf{z^2}}{\mathbf{1}-\mathbf{z}}-\frac{\mathbf{2z(1-z)m^2}}{\mathbf{q^2}+\mathbf{(1-z)^2m^2}}\right)$$



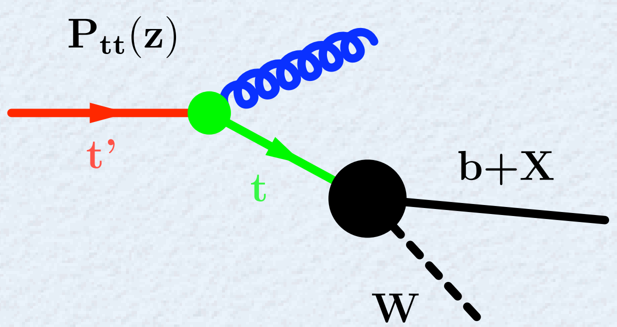
$$\Rightarrow\; \mathbf{T_R}\left(\mathbf{1}-\mathbf{2z(1-z)}+\frac{\mathbf{2z(1-z)m^2}}{\mathbf{q^2}+\mathbf{m^2}}\right)$$

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



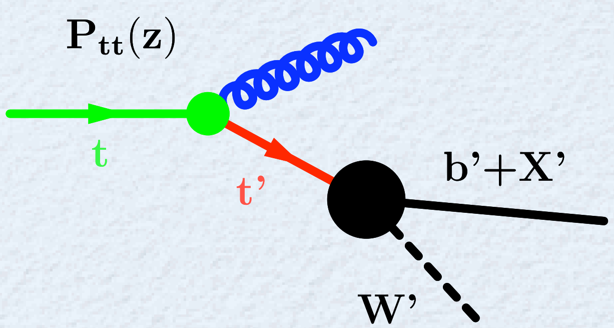
APACIC++: Heavy Quark Production

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

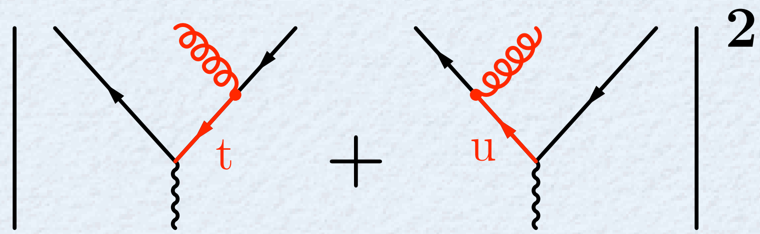
PS in decay



- 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

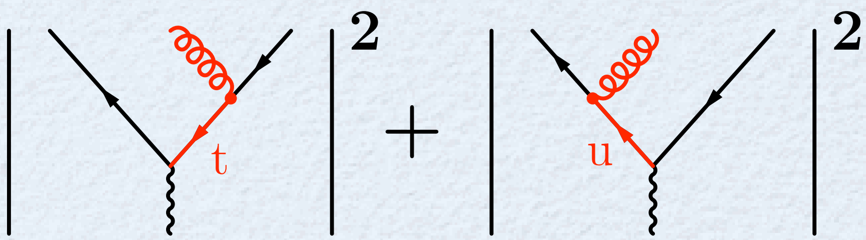
Merging of ME & PS: CKKW

Matrix Elements



- Exact to fixed order in running coupling
- Include all quantum interferences
- Calculable only for low FS multiplicity (n≤6-8)

Parton Showers



$$\mathrm{d}\sigma_{\mathbf{n+1}} = \mathrm{d}\sigma_{\mathbf{n}} \otimes \sum_{\mathbf{a}\in\mathbf{q},\mathbf{g}} \frac{\mathrm{d}\mathbf{t}}{\mathbf{t}}\mathrm{d}\mathbf{z}\frac{\alpha_{\mathbf{s}}(\mathbf{t},\mathbf{z})}{\mathbf{2}\pi}\mathbf{P}_{\mathbf{a}\to\mathbf{bc}}(\mathbf{z})$$

- Resum all (next-to) leading logarithms to all orders
- Interference effects only through angular ordering

➡ Basic idea of CKKW: Combine both approaches to have

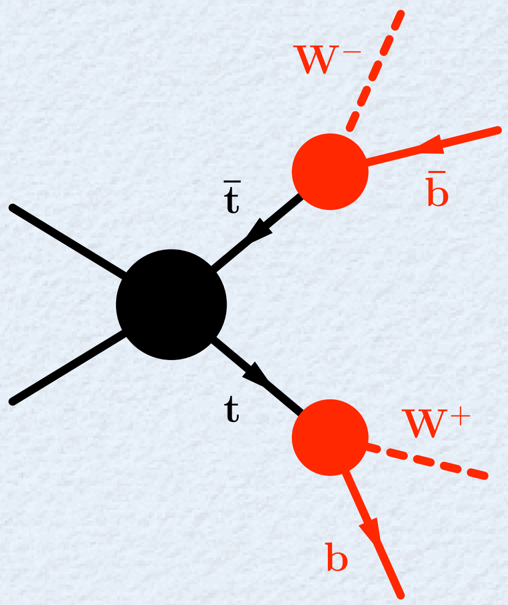
- Good description of hard / wide angle radiation (ME)
- Correct intrajet evolution (PS)

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

CKKW & Heavy Flavours

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

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



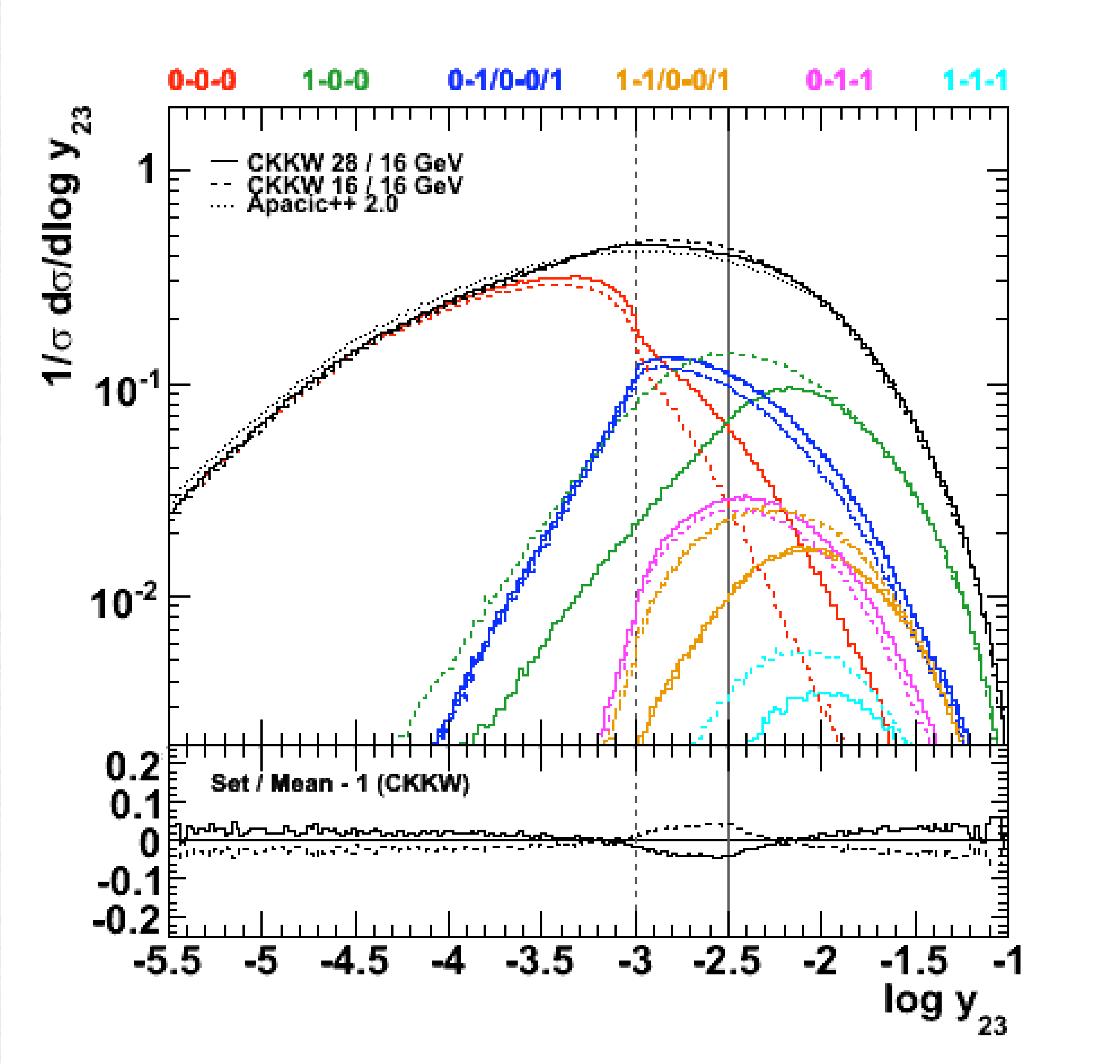
Generator setup:

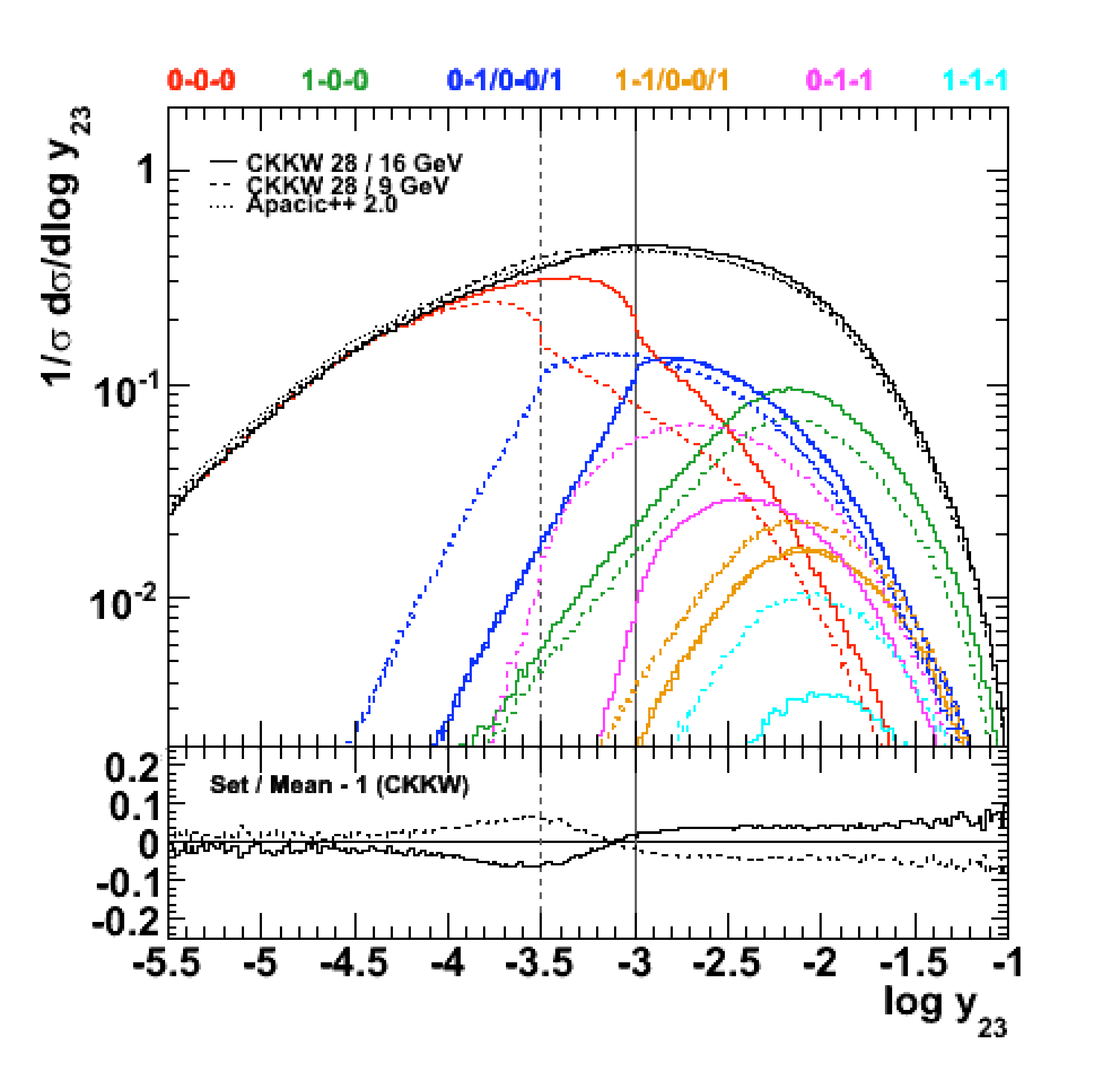
- AMEGIC++ provides decay chain treatment to project onto relevant Feynman diagrams
  Intermediate particle masses distributed according to Breit-Wigner
- APACIC++ provides production & decay shower off heavy partons
- **CKKW is applied separately and completely independent within production and each decay**

➡ Yields all combinations of parton multiplicities in ME up to $\mathbf{N}_{\mathbf{max,prod}} \otimes \prod_{\mathbf{i}\in\mathbf{decays}} \mathbf{N}_{\mathbf{max,dec\ i}}$, i.e. 1-0-0, 0-1-0, ... in $\mathbf{e^+e^-} \to \mathbf{t\bar{t}}$

Top pair production in e^+e^-

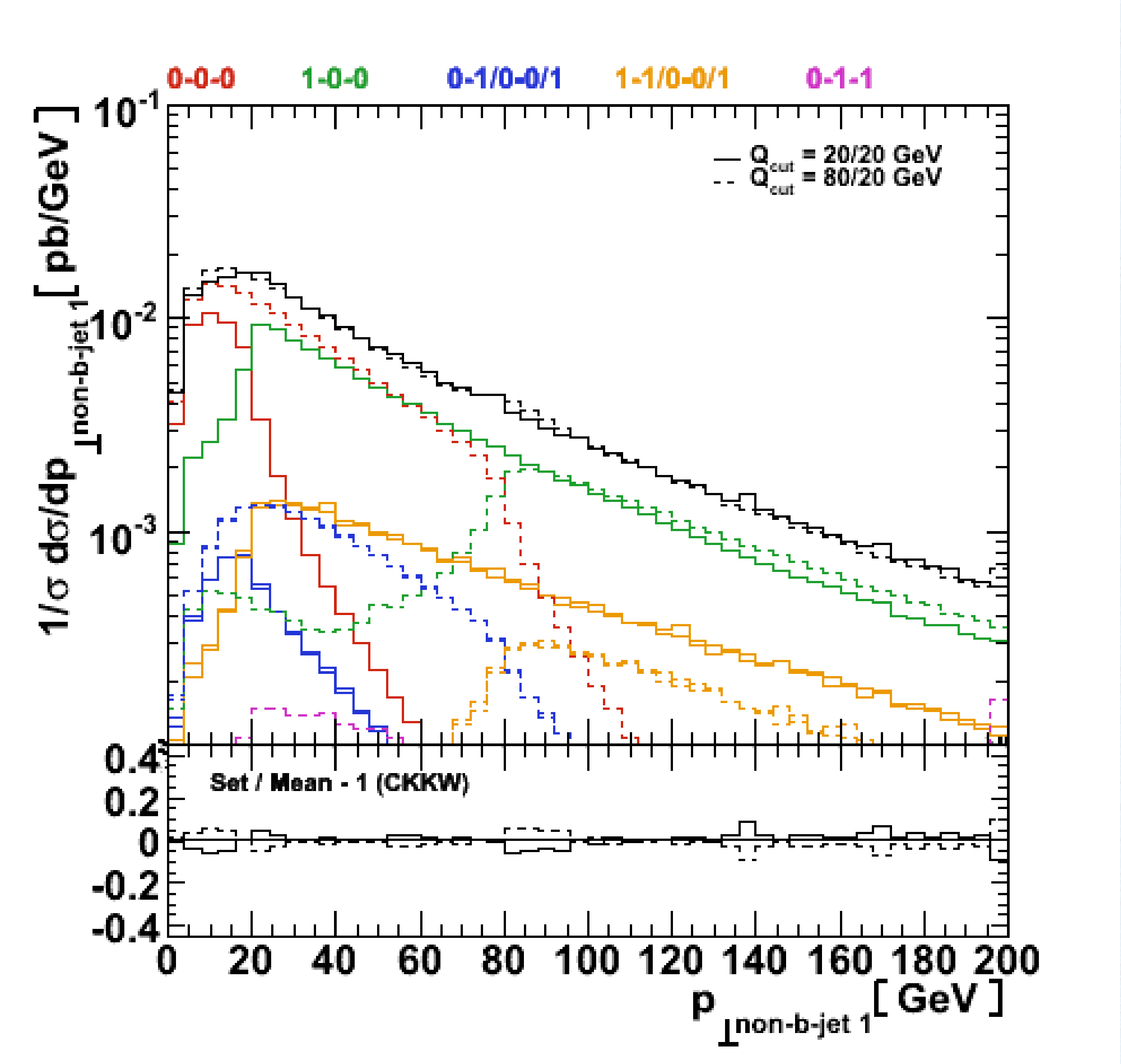
- Sanity check of procedure: Jet differential rates in e^+e^-
  - Q_{cut} - variation in production
  - Q_{cut} - variation in decays

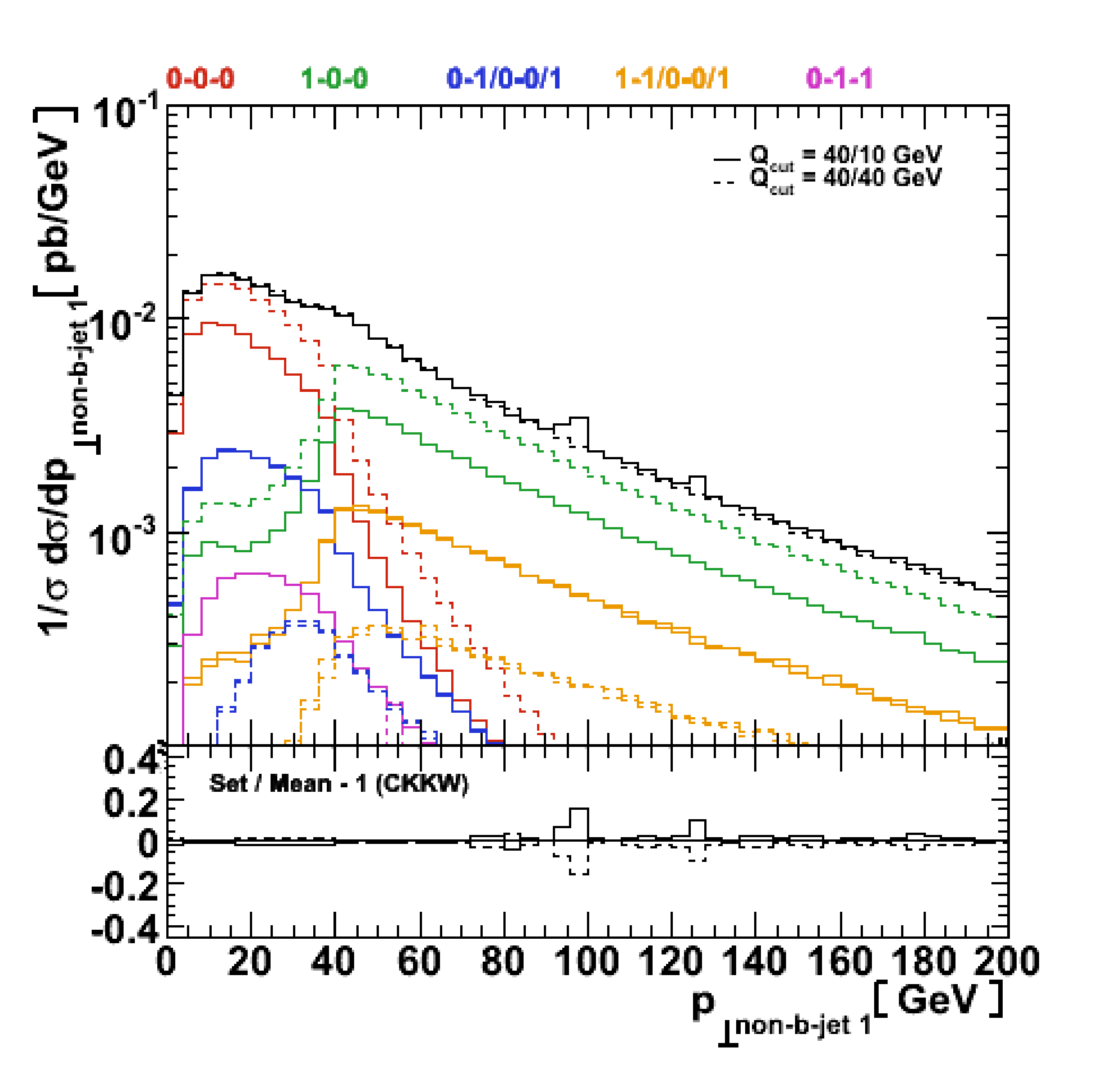




Top pair production @ LHC

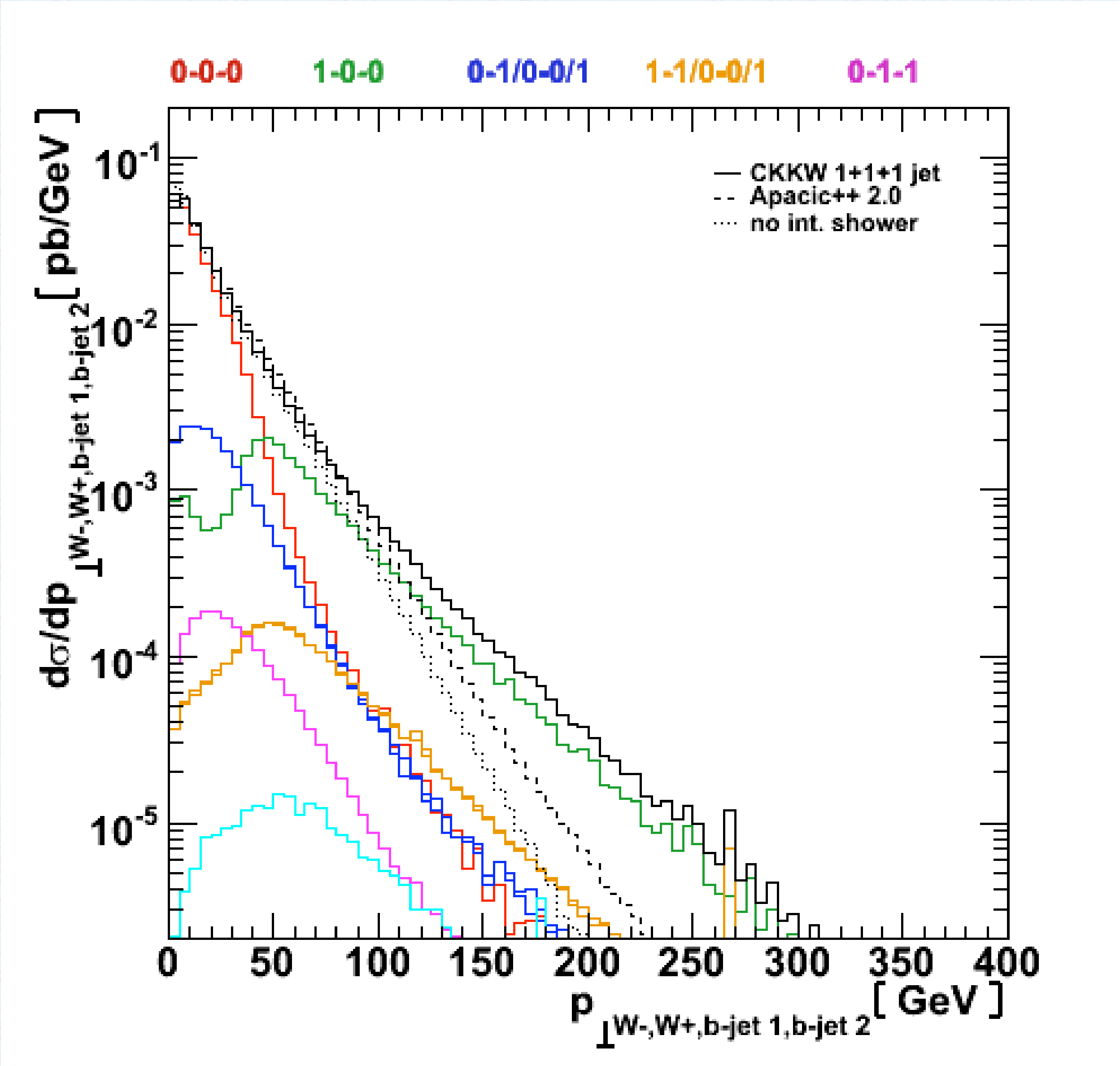
- Sanity check of procedure: Jet transverse momenta in pp
  - Q_{cut} - variation in production
  - Q_{cut} - variation in decays

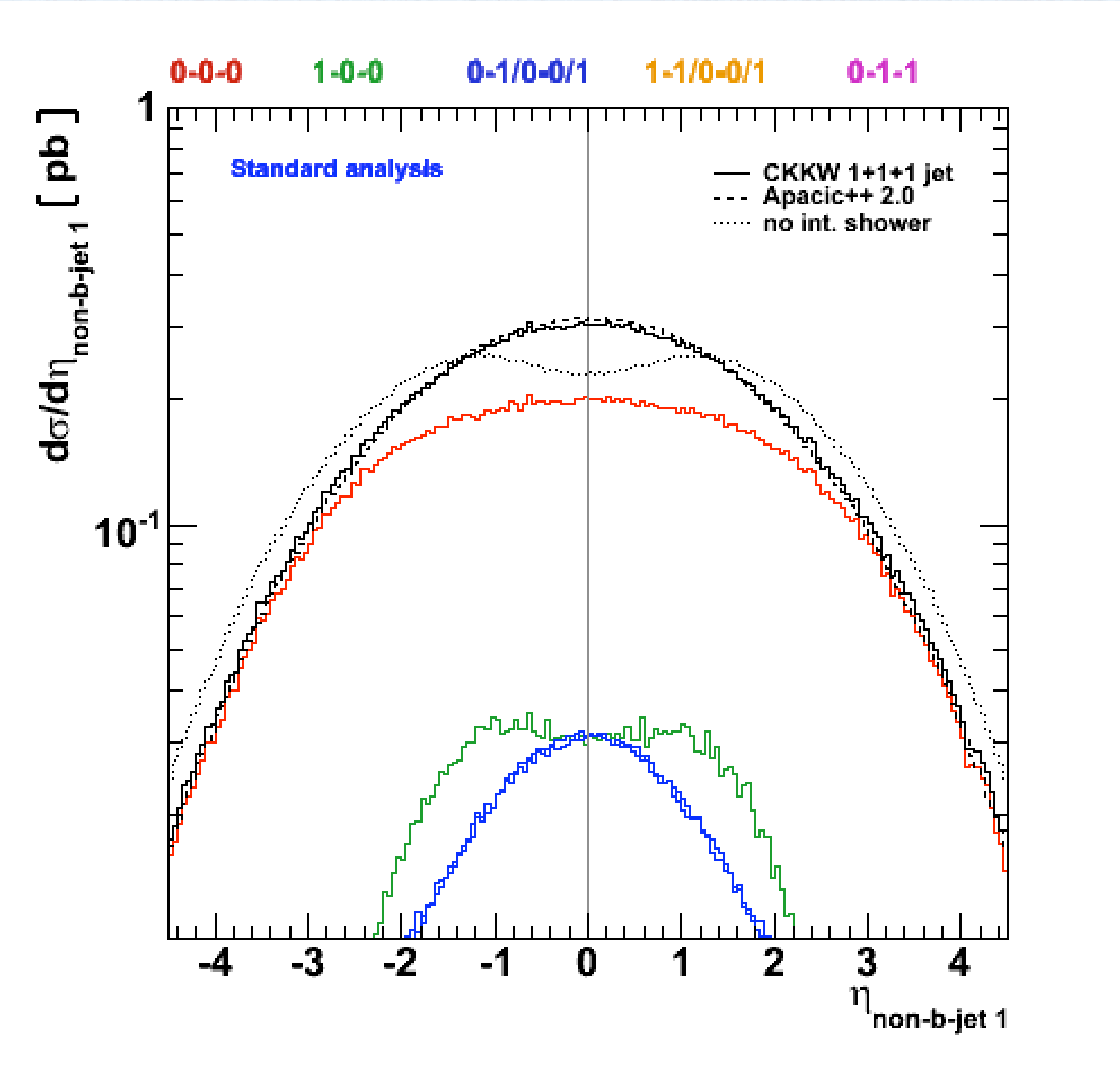




Top pair production @ Tevatron

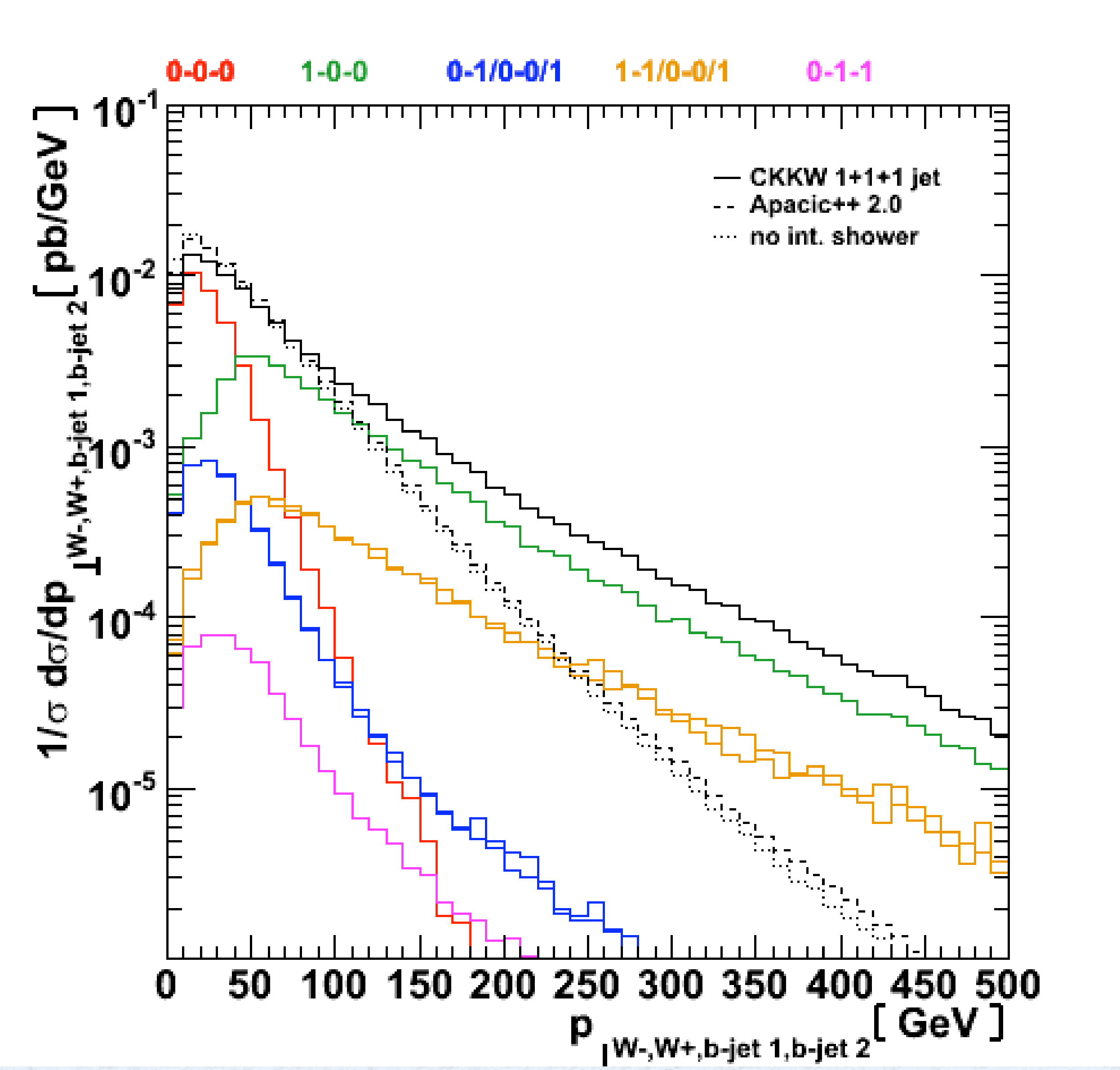
- Application: $t\bar{t}$ production at the Tevatron
  - $p_\perp$ of $t\bar{t}$ pair
  - η of first extra jet

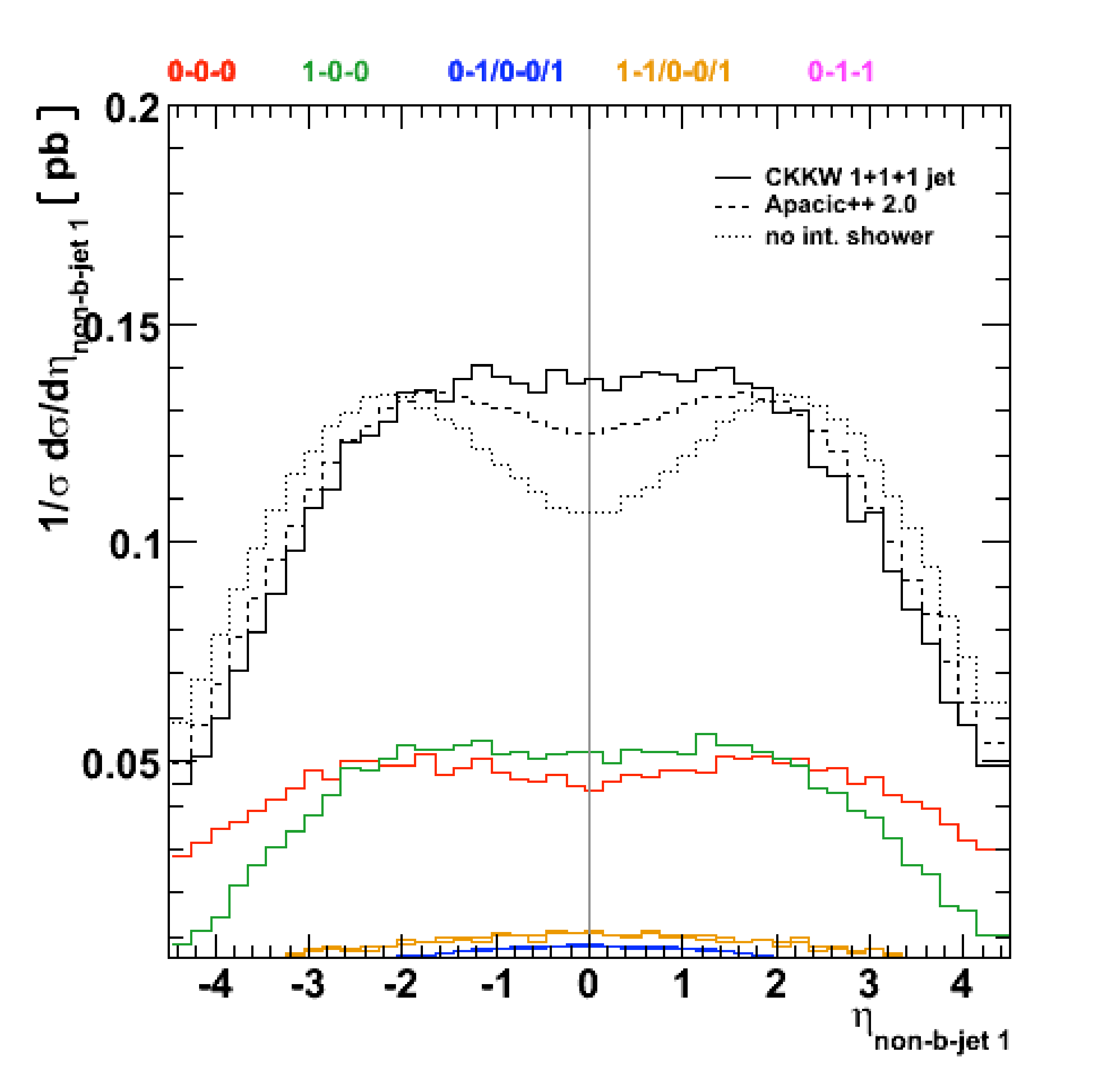




Top pair production @ LHC

- Application: $t\bar{t}$ production at the LHC
  - $p_\perp$ of $t\bar{t}$ pair
  - η of first extra jet





Summary

- The CKKW-implementation in Sherpa has been extened for decay chains, enabling e.g. more elaborate $t\bar{t}$ simulations
- A new ME-generator is well under way, pushing limits in high-multiplicity tree-level ME-calculations

We currently also work on

- New dipole shower approaches → improved ME-PS merging
- BSM physics (new models in AMEGIC++)
- QED radiation generator (YFS-based)
- Hadron decays (B-mixing done !)
- ...

Updates on Sherpa can be found on

WWW.SHERPA-MC.DE

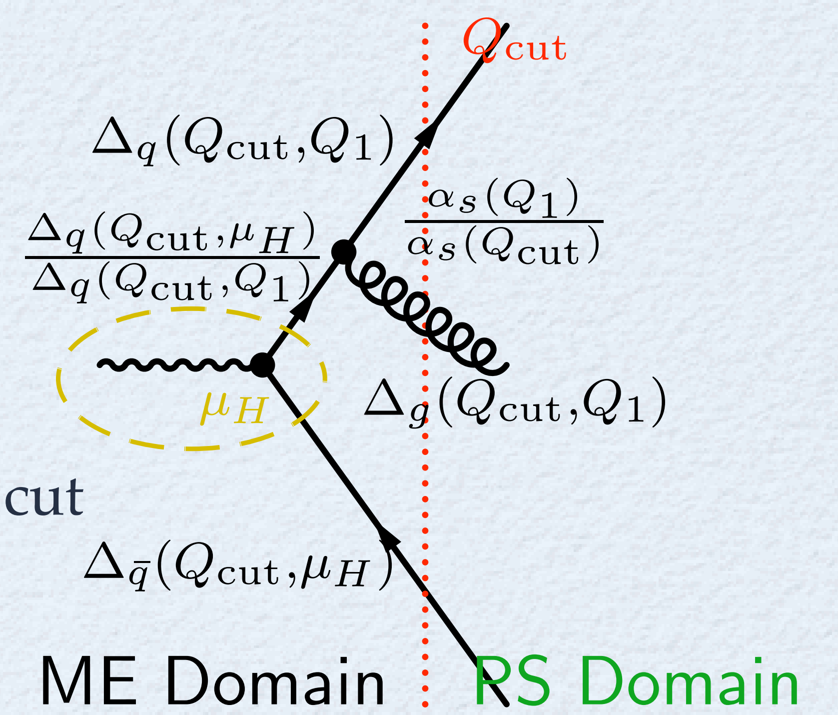
E-mail us at

INFO@SHERPA-MC.DE

CKKW in a Nutshell

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

- 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}



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

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