Recent Developments in Sherpa

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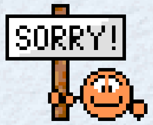
OUTLINE

This talk is not exhaustive ...

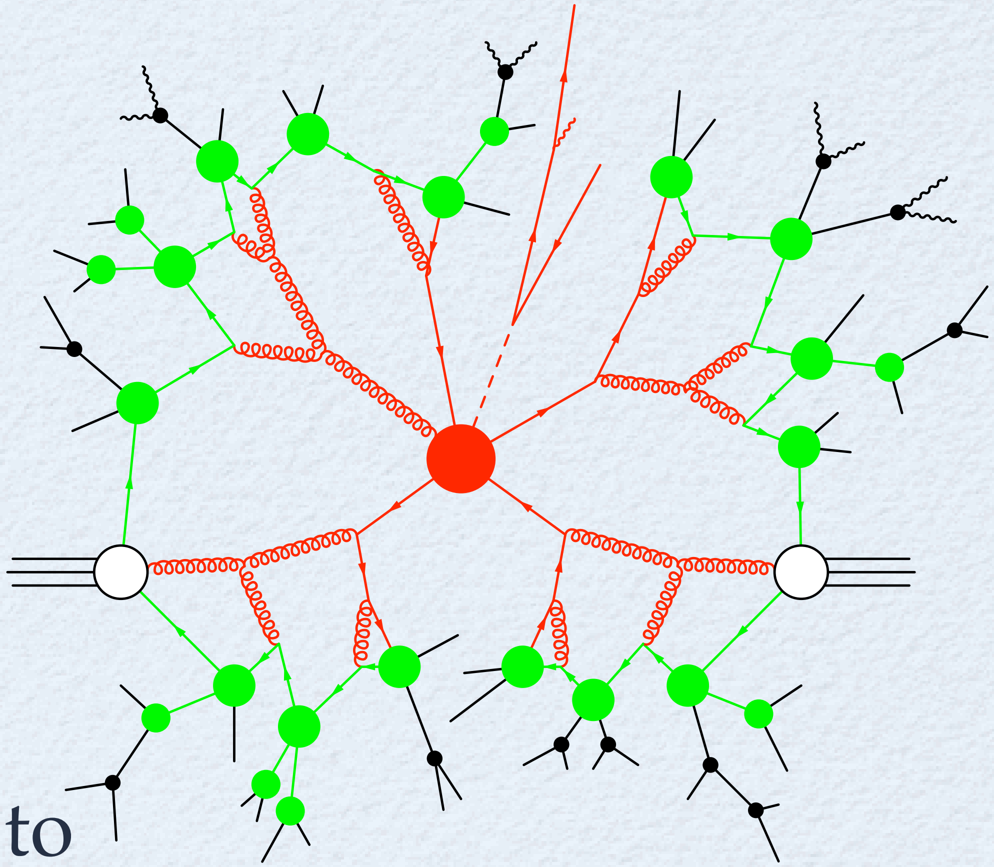
... but covers some new aspects of the generator only 

- The Sherpa framework
- Matrix Elements
  - AMEGIC++
  - NEW COMIX
- CKKW
  - Standard CKKW
  - NEW CKKW in heavy flavour production and decay
- Hadron decays
  - The HADRONS package
  - NEW B-Mixing

The Sherpa Framework

Key features:

- Automatic ME generation
  via AMEGIC++ (tree level)
- Generation of QCD/QED radiation
  via APACIC++ (PYTHIA-like PS)
- Merging of ME and PS according to
  CKKW JHEP 11 (2001) 063, JHEP 08 (2002) 015
- Simulation of multiple interactions acc. to
  Phys. Rev. D36 (1987) (own model in preparation)
- Cluster fragmentation in preparation
  (currently string fragmentation via PYTHIA)
- Own hadron decay framework including a τ decay library



Sherpa is the framework, responsible for steering the generator

Hard ME's in Monte Carlos

- General task: generate events (unweighted or weighted) according to the differential cross section

$$\mathbf{d}\sigma = \frac{\mathbf{1}}{\mathbf{F}}\mathbf{d\Phi}|\mathcal{M}|^{\mathbf{2}}$$

➡ Two steps:
- calculate the hard matrix element $|\mathcal{M}|^{\mathbf{2}}$
- sample the phase space $\mathbf{\Phi}$

- Problems:
  - calculation of hard ME rather complex for large number of final state particles, even at tree level (factorial growth of diagrams)
    Example: W+5 jets: about 7000 diagrams
  - high-dimensional phase space (3N-4) with probably sharply peaked integrand (e.g. QCD multi-parton matrix elements) and cuts on kinematic variables

ME's in Sherpa: AMEGIC++

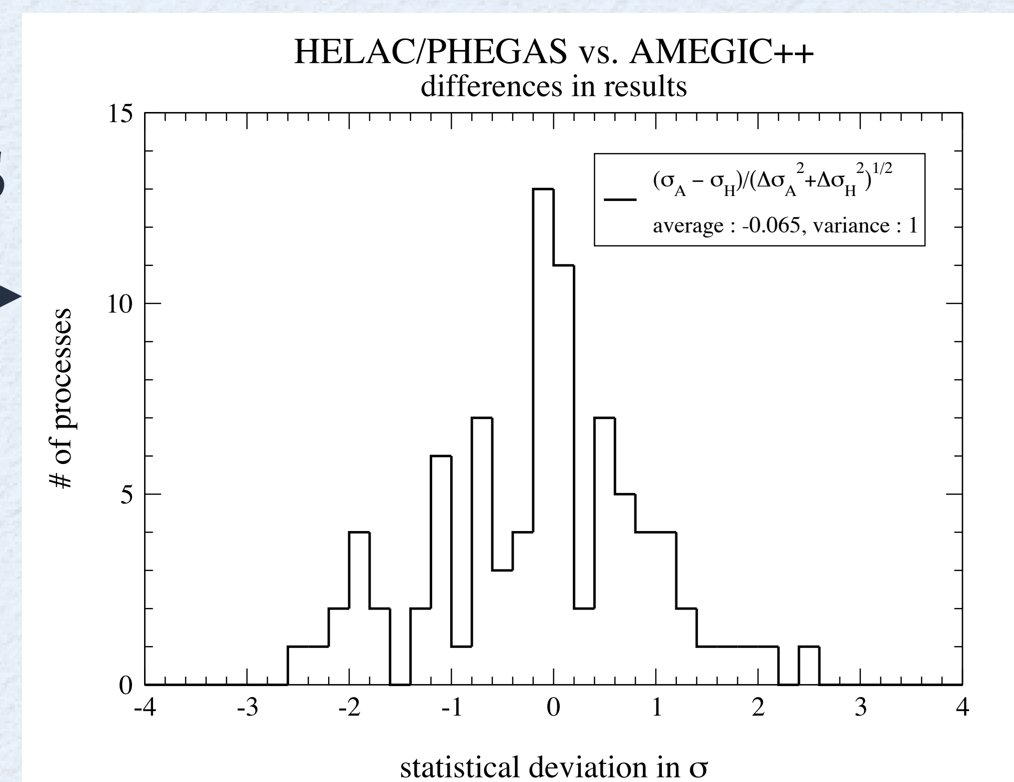
JHEP 02 (2002) 044

Sherpas built-in ME generator AMEGIC++ provides

- 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 implement new models)

Extensively tested, e.g.

- $e^+e^- \rightarrow 6f$ comparison vs. HELAC/PHEGAS deviations in 86 processes EPJC 34(2004)173 →
- Comparison of arbitrary $2 \rightarrow 2$ MSSM processes vs. WHIZARD/O'Mega & SMadGraph Hagiwara, Kilian, Krauss, Ohl, Plehn, Rainwater, Reuter, Schumann Phys.Rev.D73(2006)055005



Stefan Höche, RAL, 10.9.2007

COMIX: ME's via recursion

JHEP 08 (2006) 062

- QCD: Comparison with other approaches shows superiority of CDBG/Dyson-Schwinger-based methods **for numerics**

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

CO → colour ordered

CD → colour dressed

Final State	BG CO	BG CD	BCF CO	BCF CD	CSW CO	CSW 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 (~3^n)

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

COMIX: ME's via Recursion

- Take approach serious and extend to full SM
  - ➡ New ME generator **COMIX**
- Promising results for all processes attempted so far, i.e.
  - pp → W+N jets where N up to 5
  - pp → Z+N jets where N up to 5
  - 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: performance

- Some recent results ...
  - QED benchmark processes: ME performance w/o colours

Process	# Graphs	#Currents / # Vertices	Time [s / 10^4 pts] AMEGIC++	Time [s / 10^4 pts] COMIX
$\tau\tau \to \mathbf{2}\gamma$	2	7 / 4	0.4	0.5
$\tau\tau \to \mathbf{3}\gamma$	6	12 / 12	1.8	1.3
$\tau\tau \to \mathbf{4}\gamma$	24	21 / 32	33	4.1
$\tau\tau \to \mathbf{5}\gamma$	120	38 / 80	297	15
$\tau\tau \to \mathbf{6}\gamma$	720	71 / 192	-	61
$\tau\tau \to \mathbf{2}\tau$	2	7 / 4	0.2	0.5
$\tau\tau \to \mathbf{4}\tau$	36	25 / 45	7.2	5.1
$\tau\tau \to \mathbf{6}\tau$	1728	91 / 400	875	101
$\tau\tau \to \mathbf{8}\tau$	158400	336 / 3325	-	2841

COMIX: PERFORMANCE

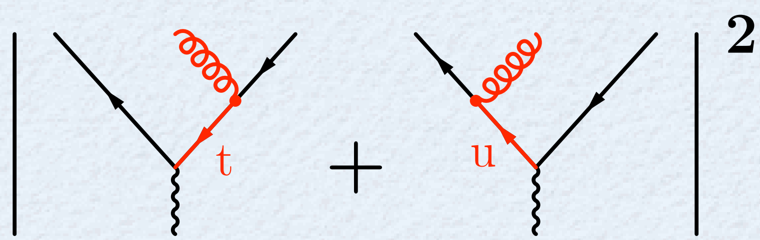
- Some very recent results ...
  - Recursive phasespace performance in W/Z+jets @ LHC

    Cuts: $66\,\mathbf{GeV} \leq \mathbf{m}_{l\bar{l}} \leq 116\,\mathbf{GeV}$, 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%
Z+4 jets	running ...	W+4 jets	running ...
Z+5 jets	running ...	W+5 jets	running ...

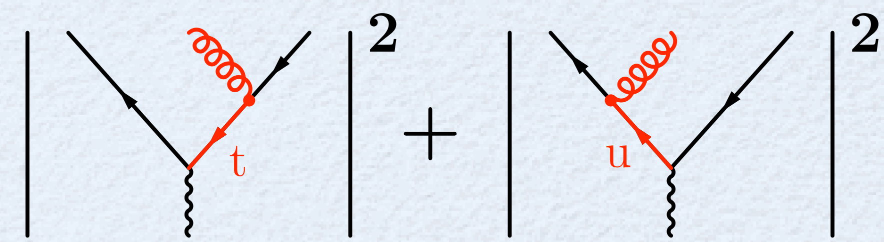
WHY CKKW ?

Matrix Elements



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

Parton Showers



$$d\sigma_{n+1} = d\sigma_n \otimes \sum_{a\in q,g} \frac{dt}{t} dz \frac{\alpha_s(t,z)}{2\pi} P_{a\to bc}(z)$$

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

➡ Basic idea of CKKW: Combine both approaches to have

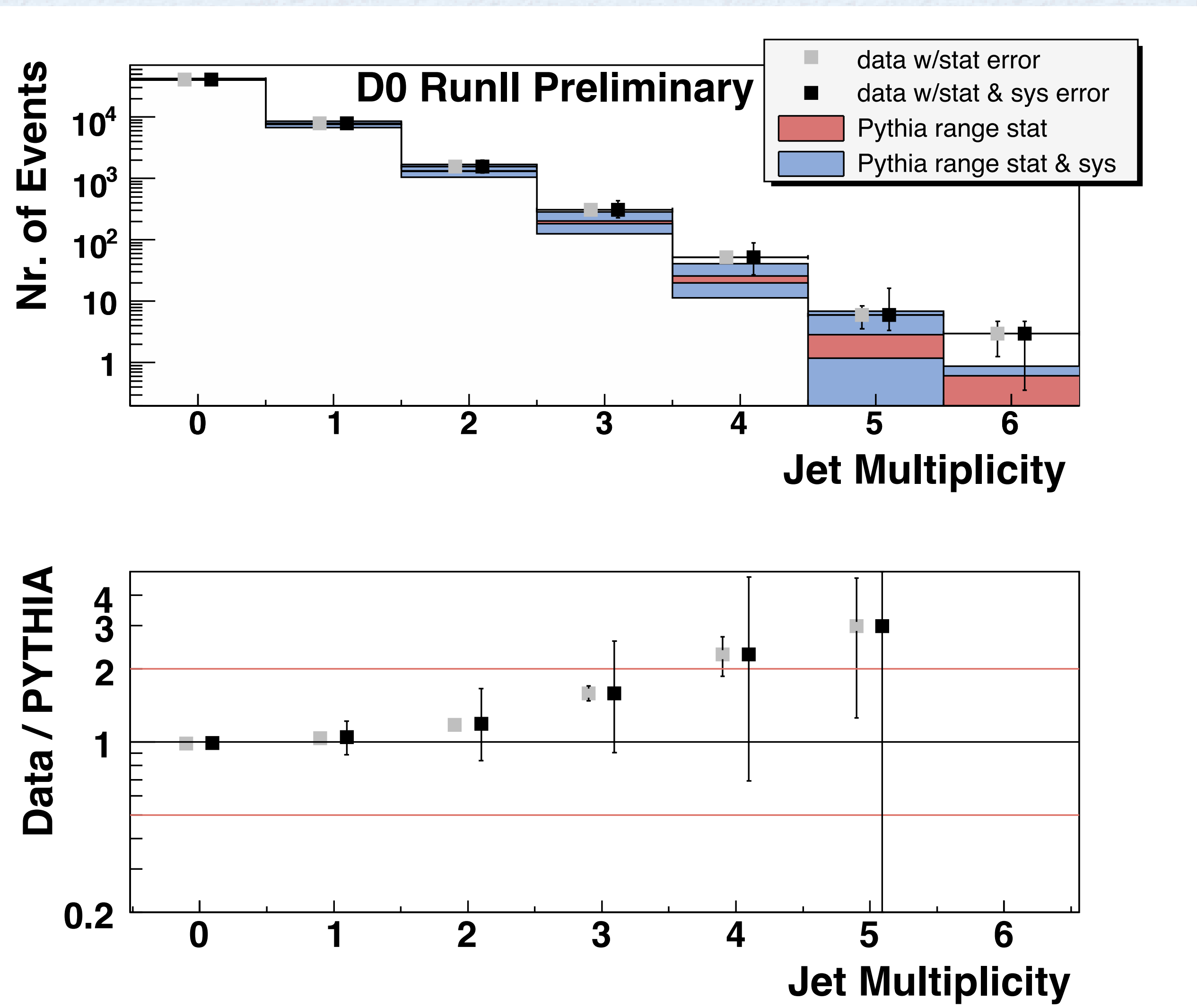
- Good description of hard/wide angle radiation (ME)
- Correct intrajet evolution (PS)

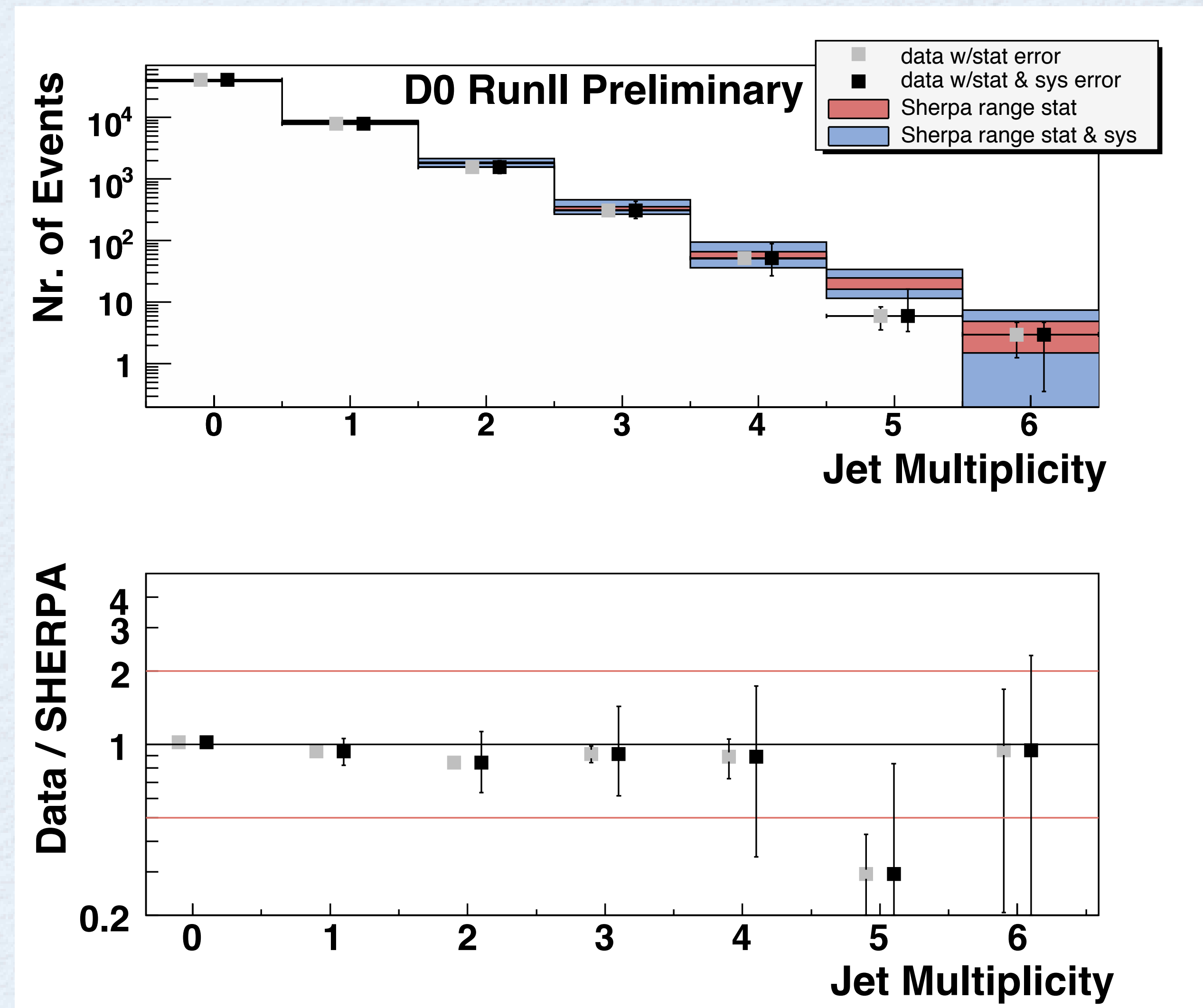
JHEP 08(2002)015; JHEP 11(2001)063

CKKW: Z+Jets @ Tevatron

The DØ collaboration, DØ note 5066-CONF

- Jet multiplicity





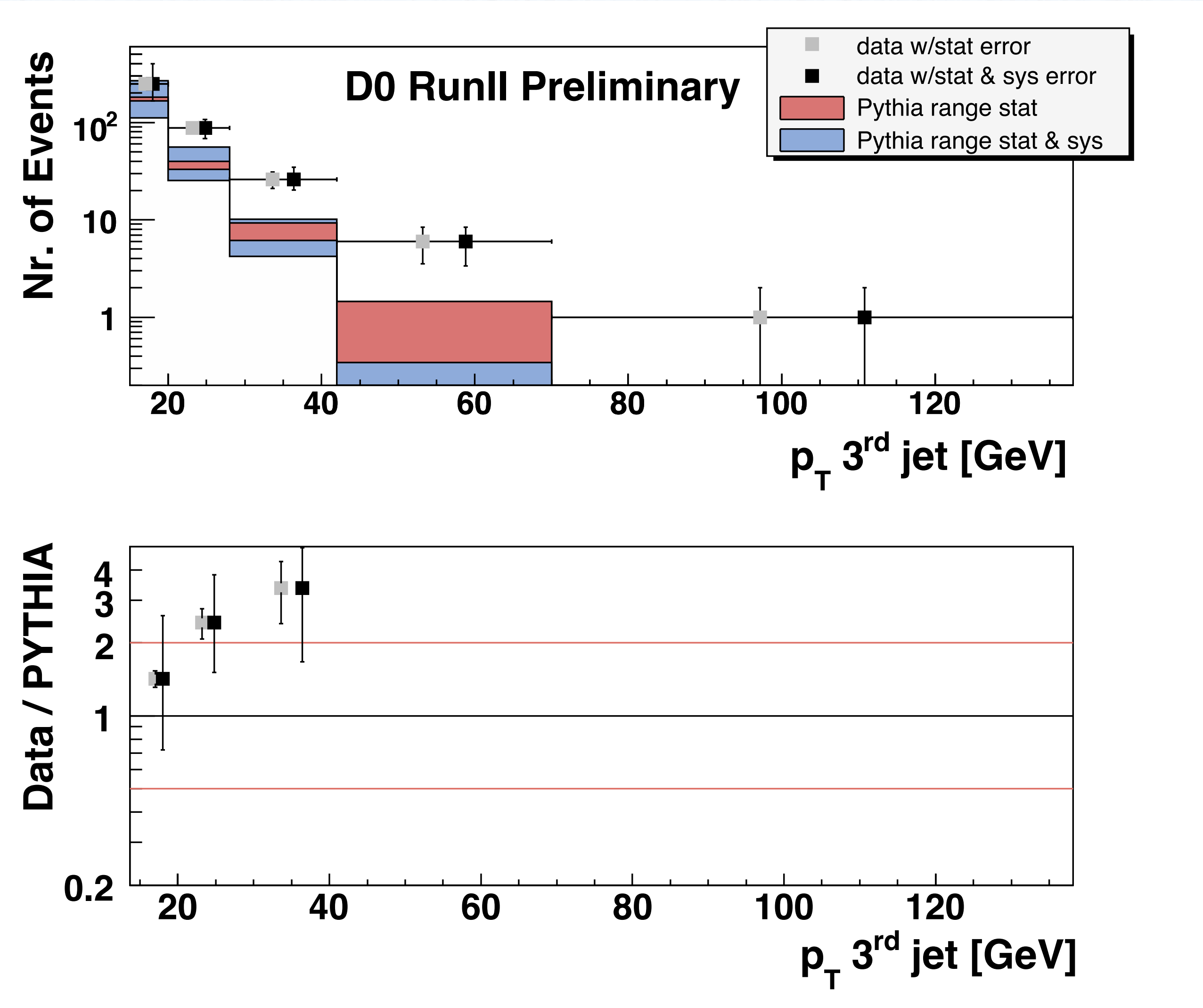
- Pythia 6.2
  normalized to data

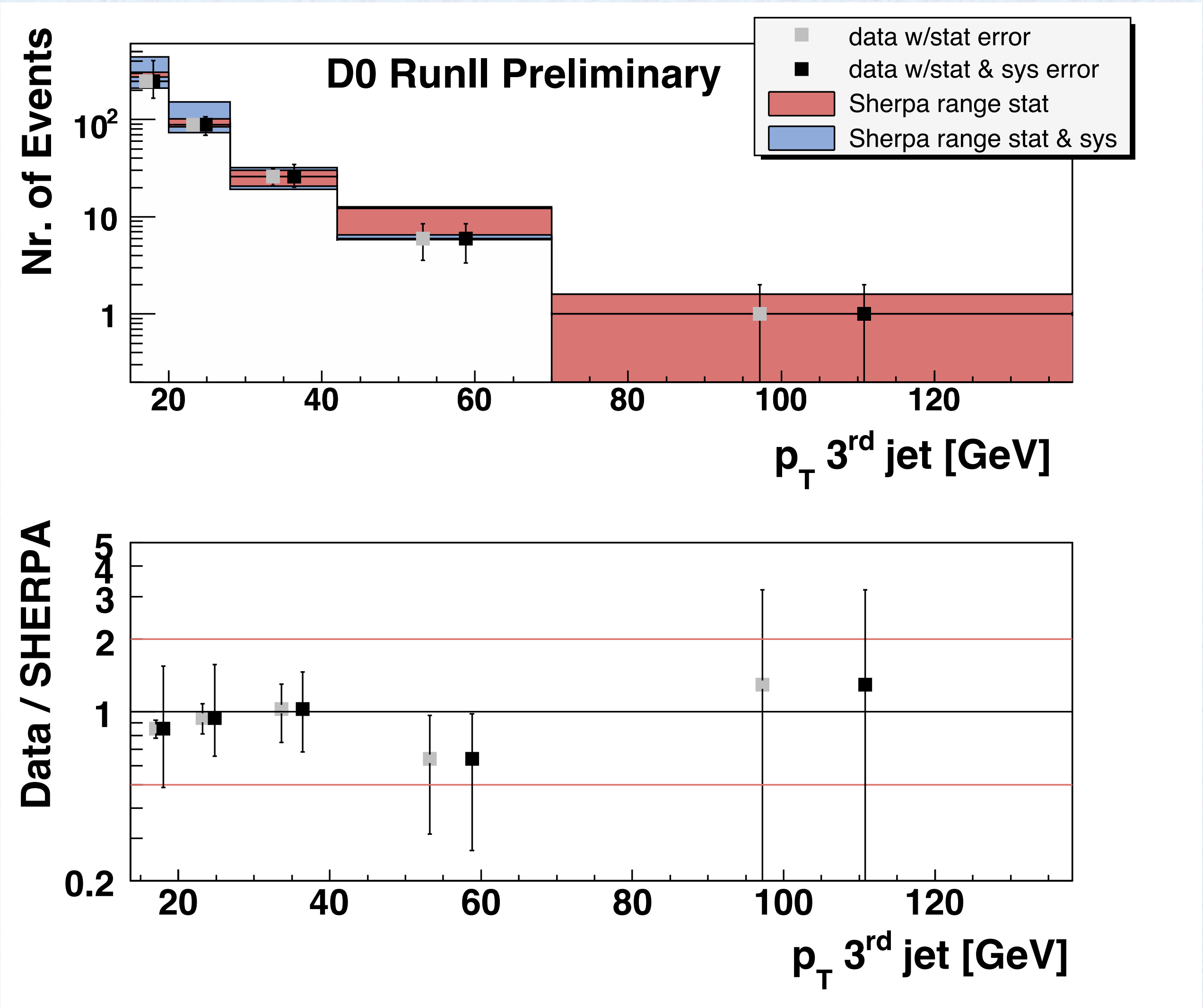
- Sherpa 1.0
  normalized to data

CKKW: Z+JETS @ TEVATRON

The DØ collaboration, DØ note 5066-CONF

- Jet-p_T, jet 3





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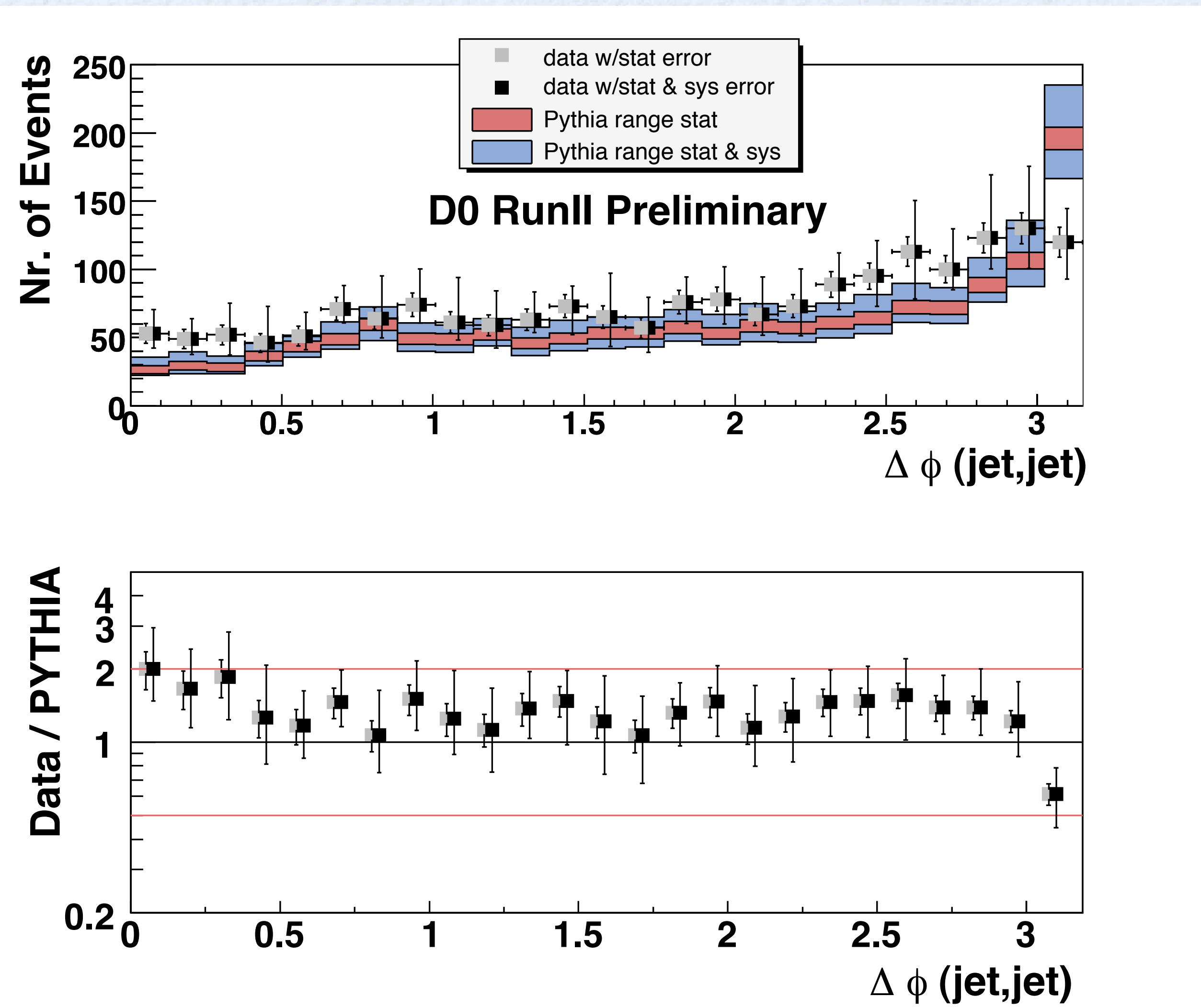
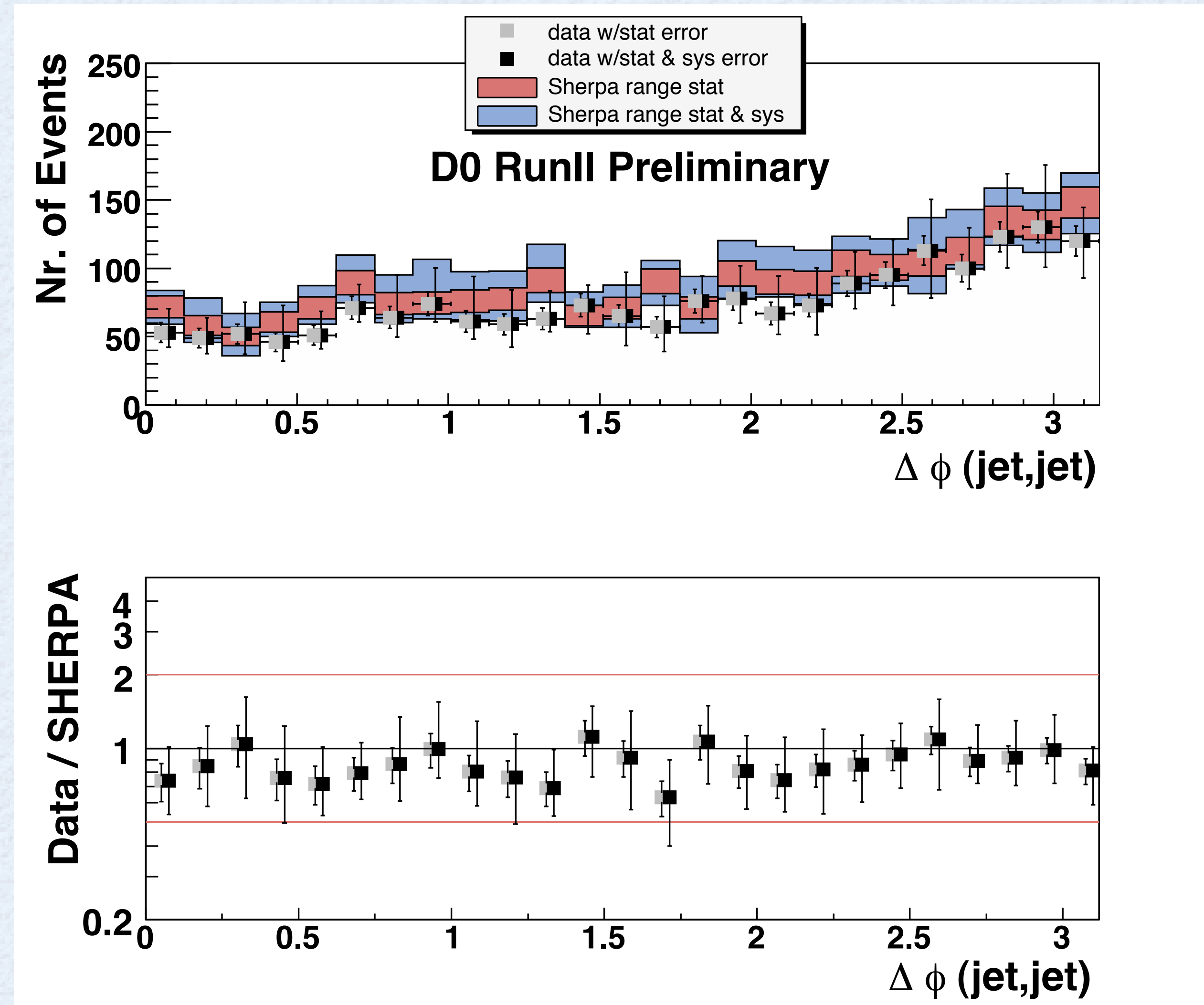
CKKW: Z+jets @ Tevatron

The DØ collaboration, DØ note 5066-CONF

- $\Delta\phi_{\mathbf{jet1},\,\mathbf{jet2}}$





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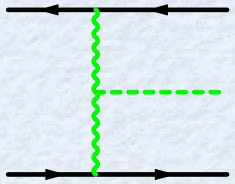
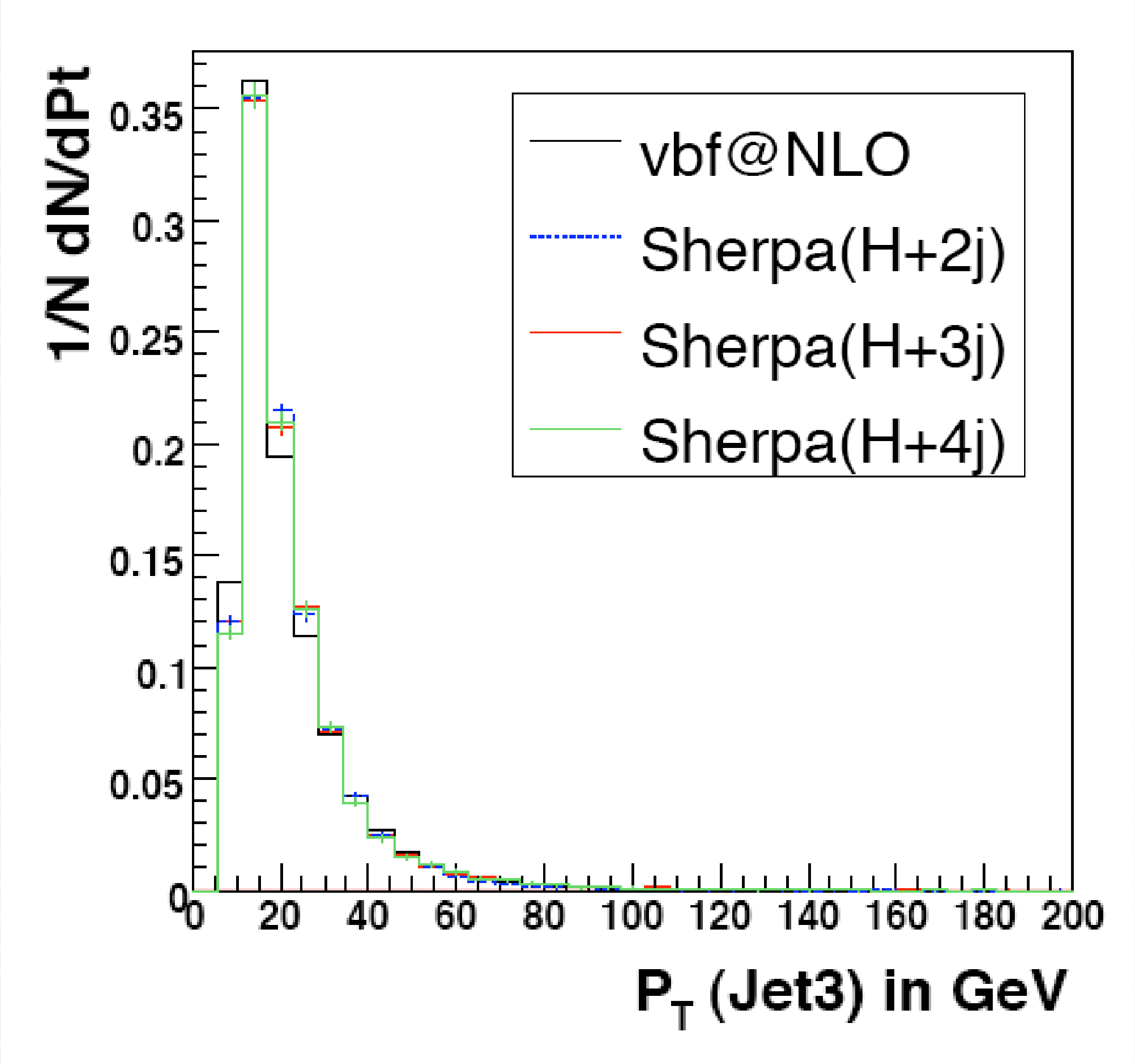
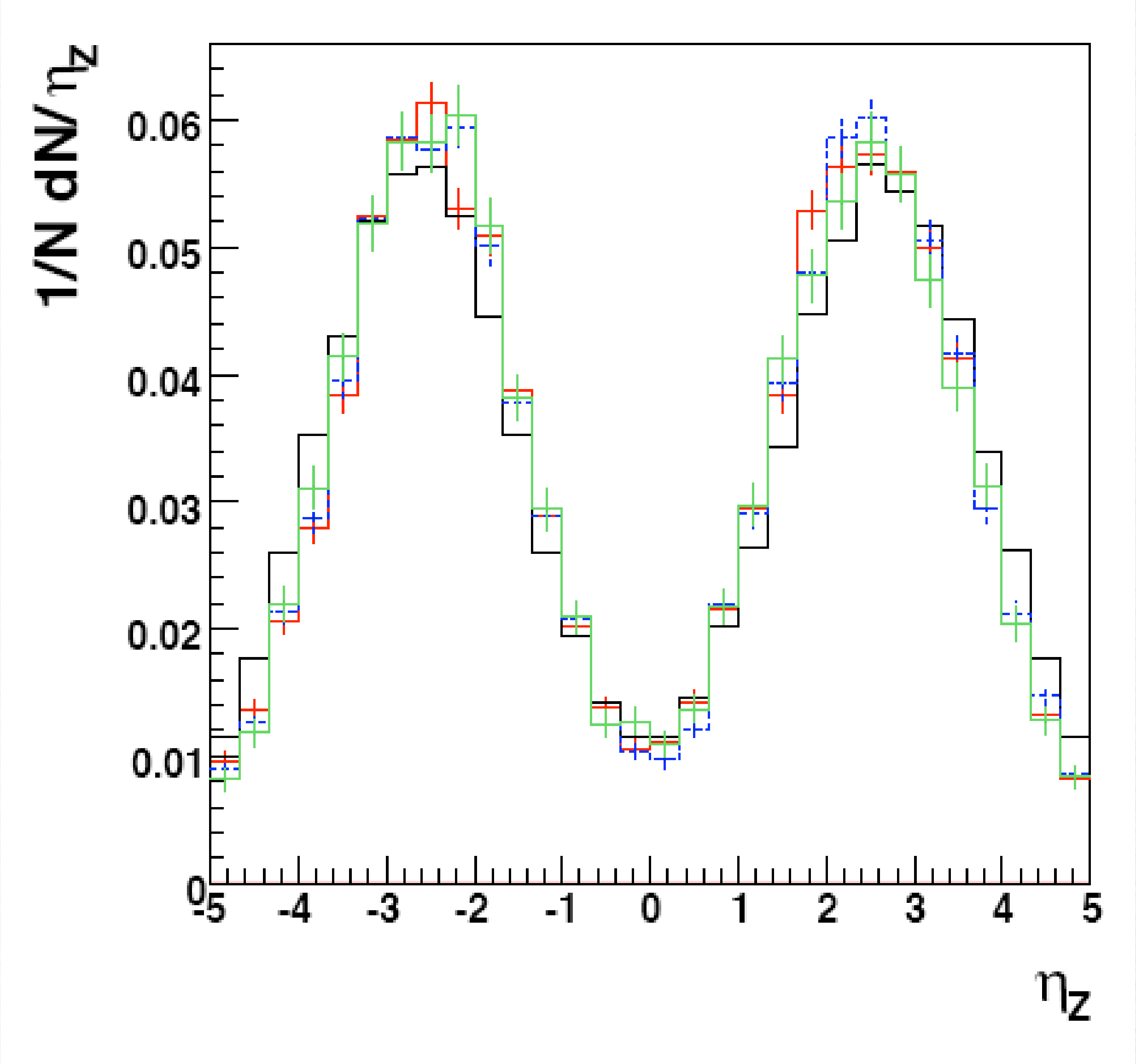
CKKW: Higgs in WBF @ LHC



thesis by T. Köchling (U Bonn)
supervisor M. Schumacher

- Predictions for WBF
  - $p_{T,jet3}$
  - The Zeppenfeld plot





CKKW: Higgs in WBF @ LHC

- Predictions for WBF

thesis by T. Köchling (U Bonn)
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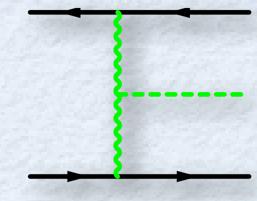
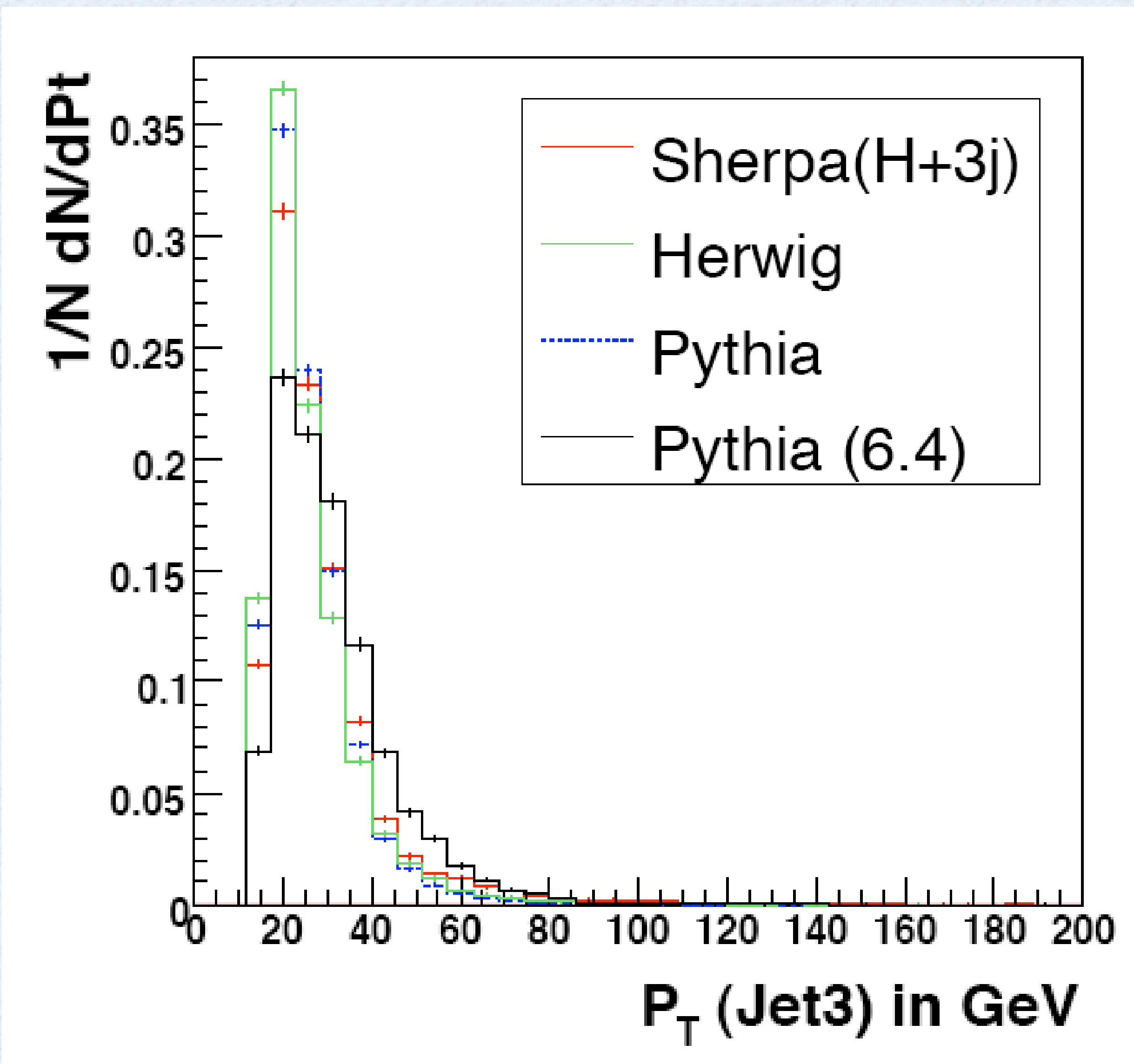
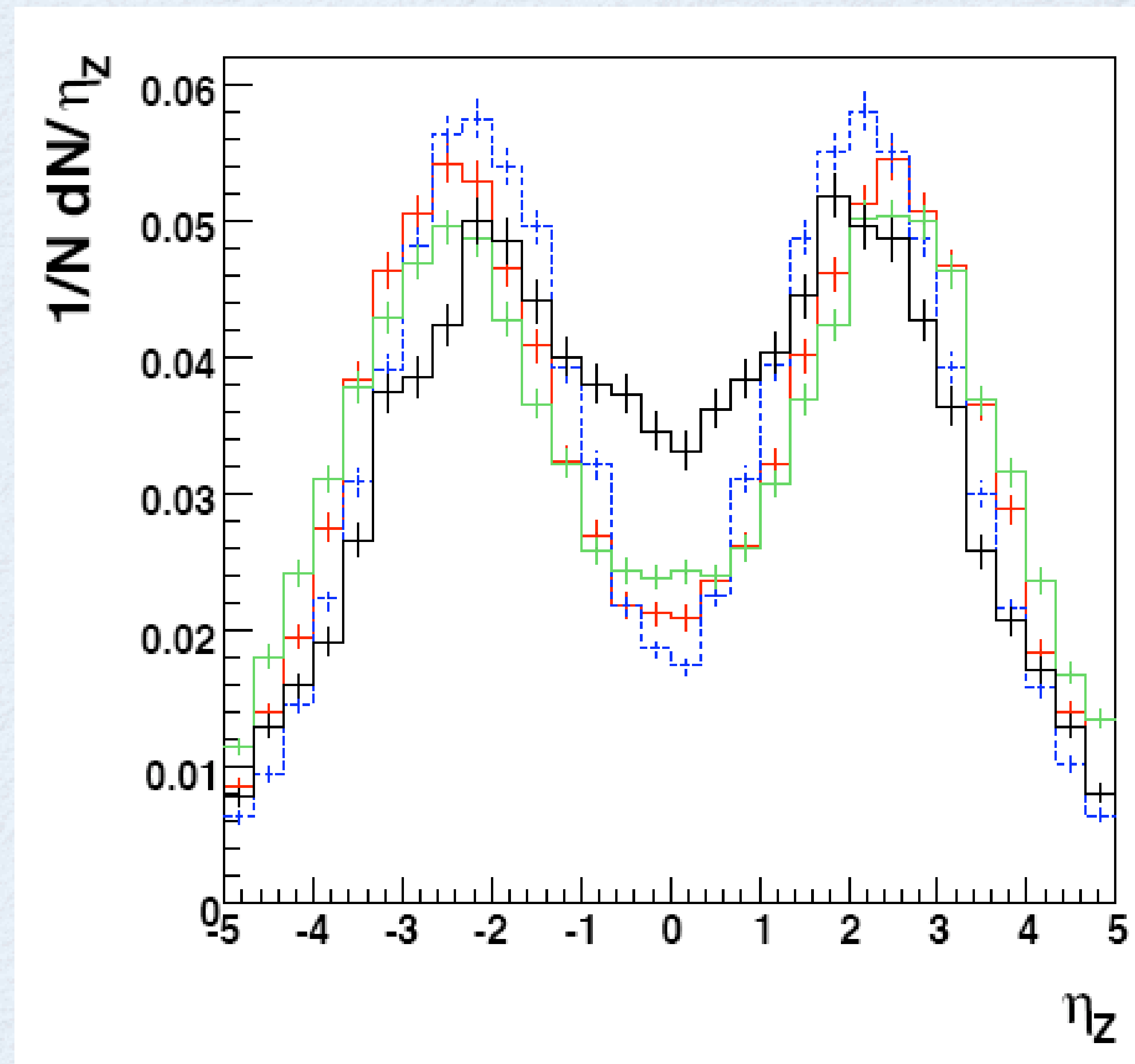


- $p_{T,jet3}$

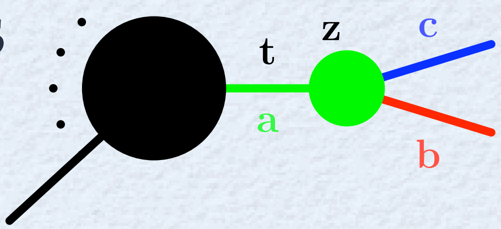


- The Zeppenfeld plot



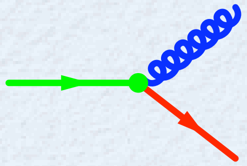
PS in Heavy Quark Production

- In quasi-collinear limit ($b \leftrightarrow$ heavy quark) ME factorises

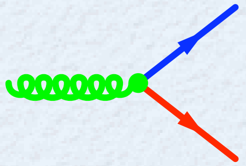


$$|\mathbf{M}(\mathbf{b}, \mathbf{c}, \ldots, \mathbf{n})|^2 \;\rightarrow\; |\mathbf{M}(\mathbf{a}, \ldots, \mathbf{n})|^2 \, \frac{8\pi\alpha_s}{\mathbf{t} - \mathbf{m_a^2}} \, \mathbf{P_{a\rightarrow bc}(z)}$$

- 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

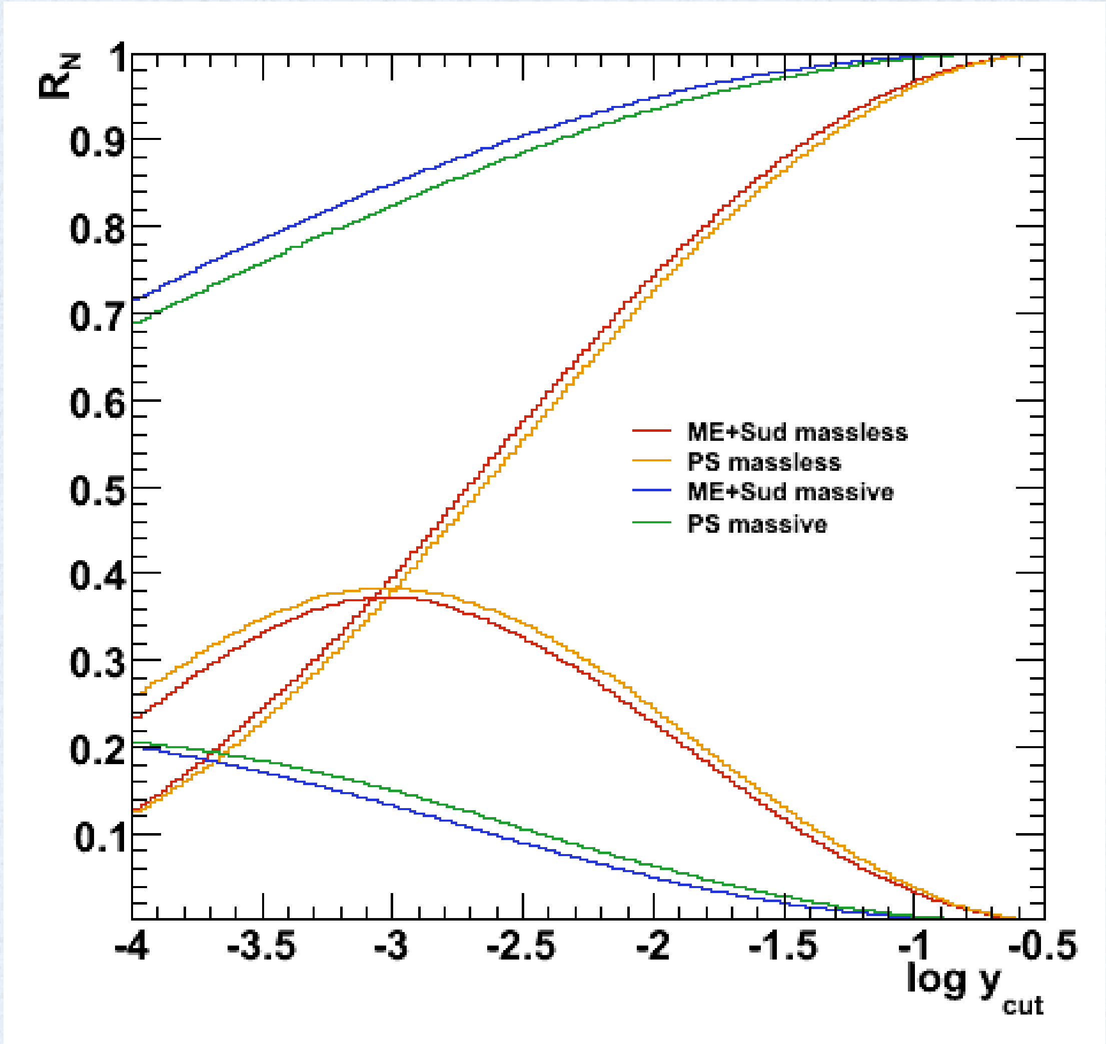


$$\rightarrow \mathbf{C_F} \left(\frac{\mathbf{1 + z^2}}{\mathbf{1 - z}} - \frac{\mathbf{2z(1-z)m^2}}{\mathbf{q^2 + (1-z)^2 m^2}} \right)$$



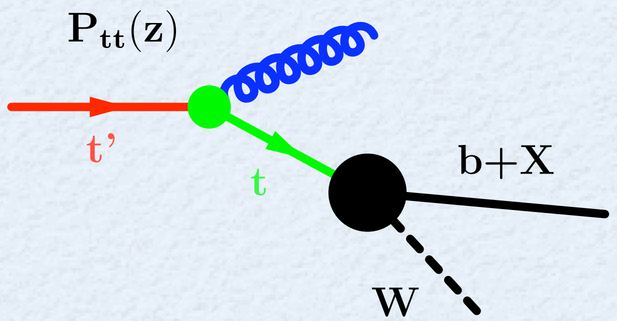
$$\rightarrow \mathbf{T_R} \left(\mathbf{1 - 2z(1-z)} + \frac{\mathbf{2z(1-z)m^2}}{\mathbf{q^2 + m^2}} \right)$$

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



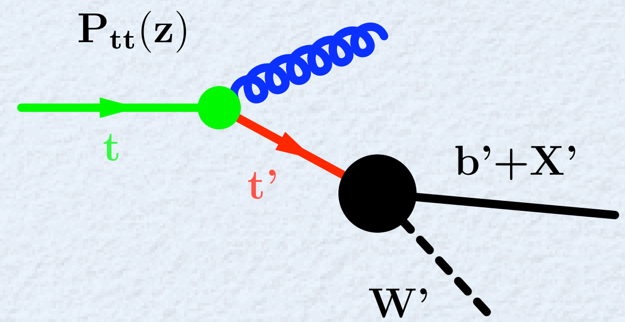
PS in heavy quark production

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

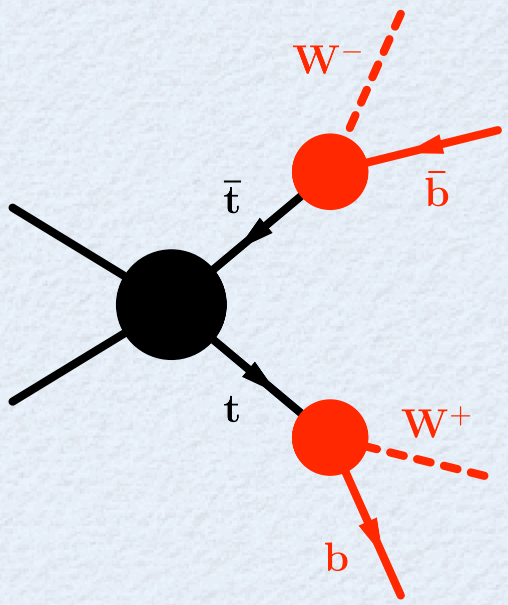


- Off-shell daughter partons
  - ! Decay kinematics need to be reconstructed
  - ➜ Choice: Reconstruct in cms of decayed quark, such that $\vec{\mathbf{p}}/|\vec{\mathbf{p}}|$ is preserved
- ISR-like situation
- Evolution stops if $\mathbf{p}_\perp$ reaches width of decaying quark

CKKW & Heavy Flavours

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

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



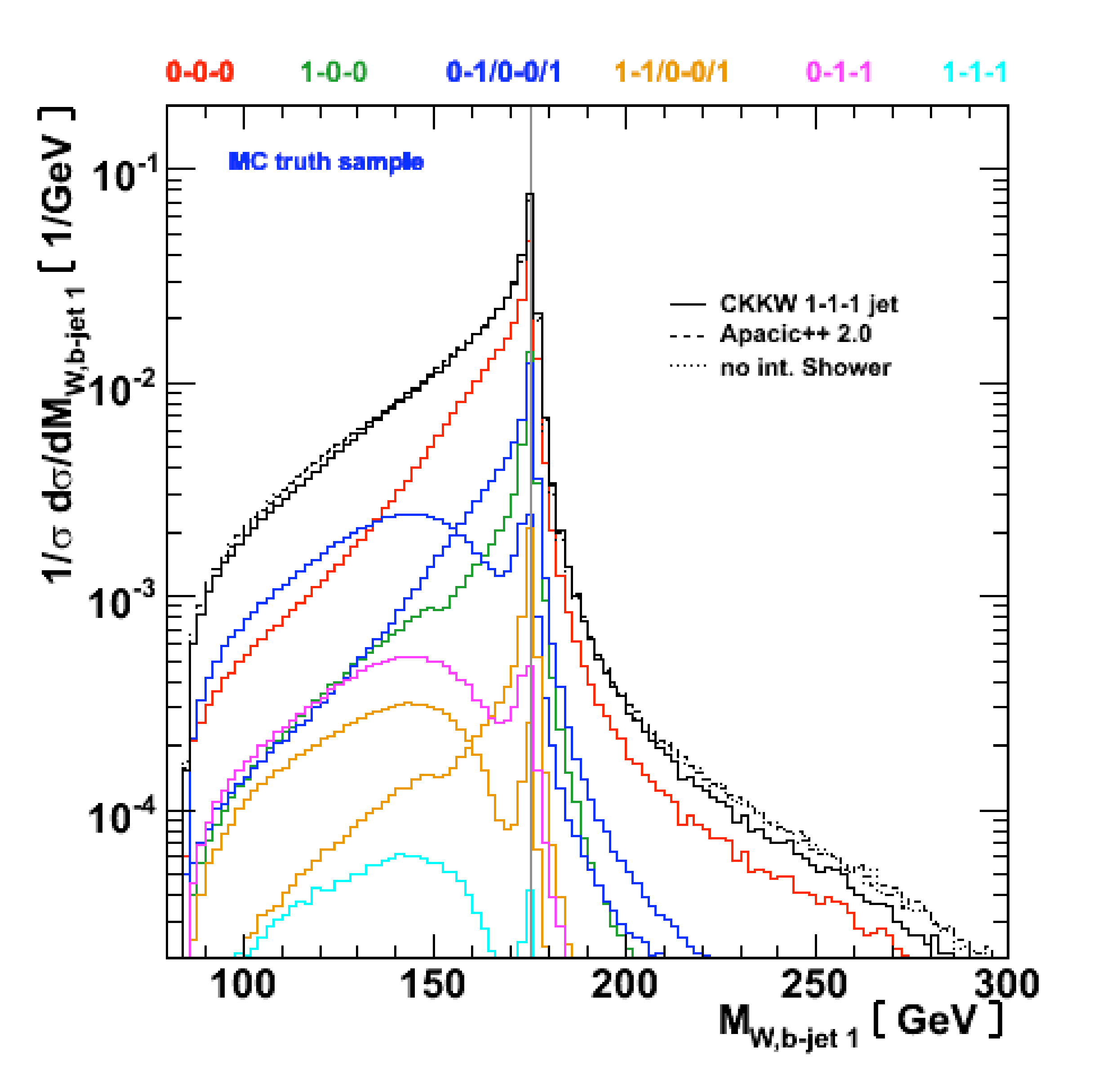
Generator setup:

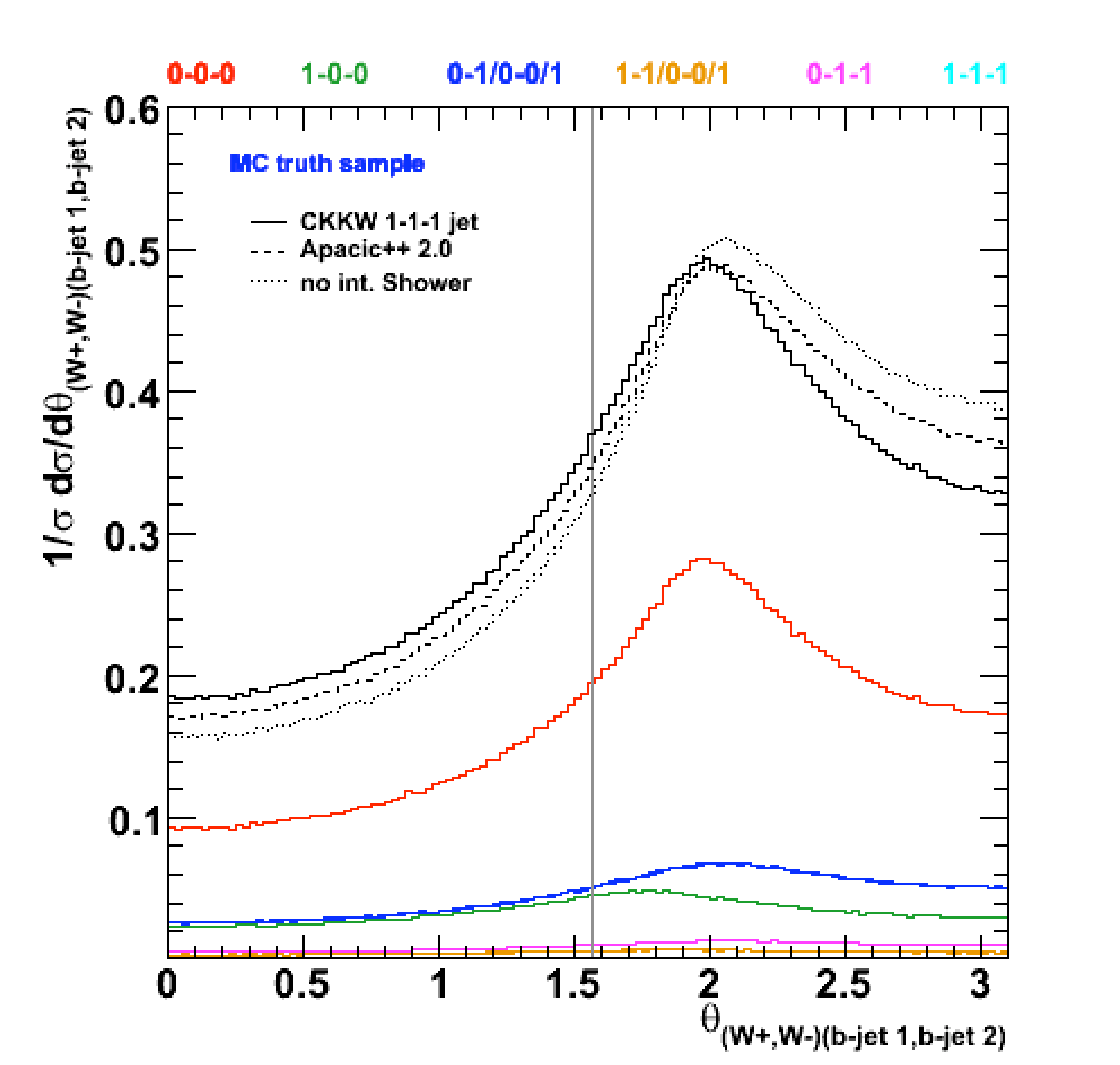
- AMEGIC++ provides decay chain treatment to project onto relevant Feynman diagrams
  Intermediate particle masses distributed according to Breit-Wigner
- APACIC++ provides production & decay shower off heavy partons
- **CKKW is applied separately and completely independent within production and each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

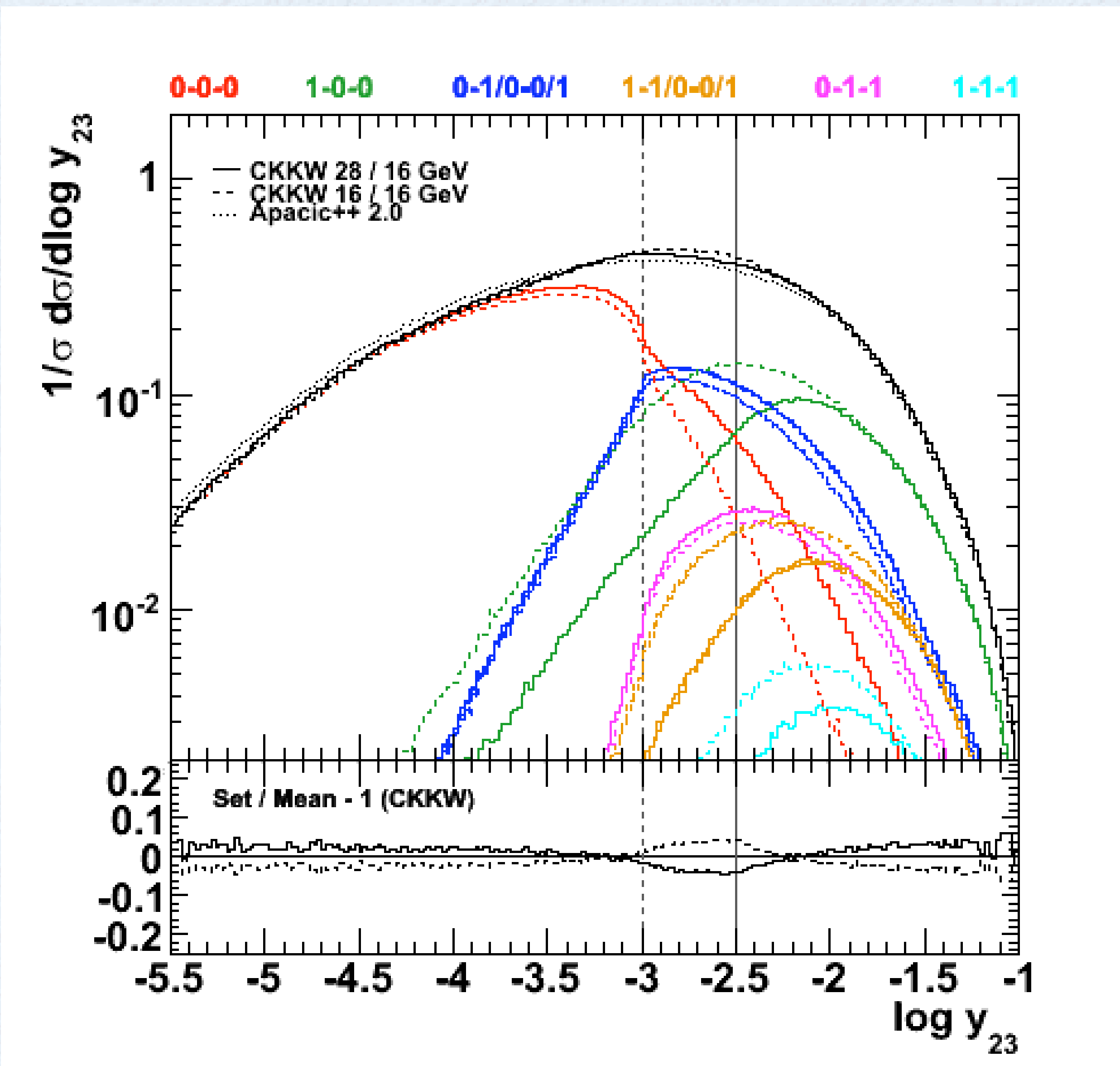
- Sanity check of procedure: Correlations in e^+e^-
  - Reconstructed top mass
  - Four particle plane angle



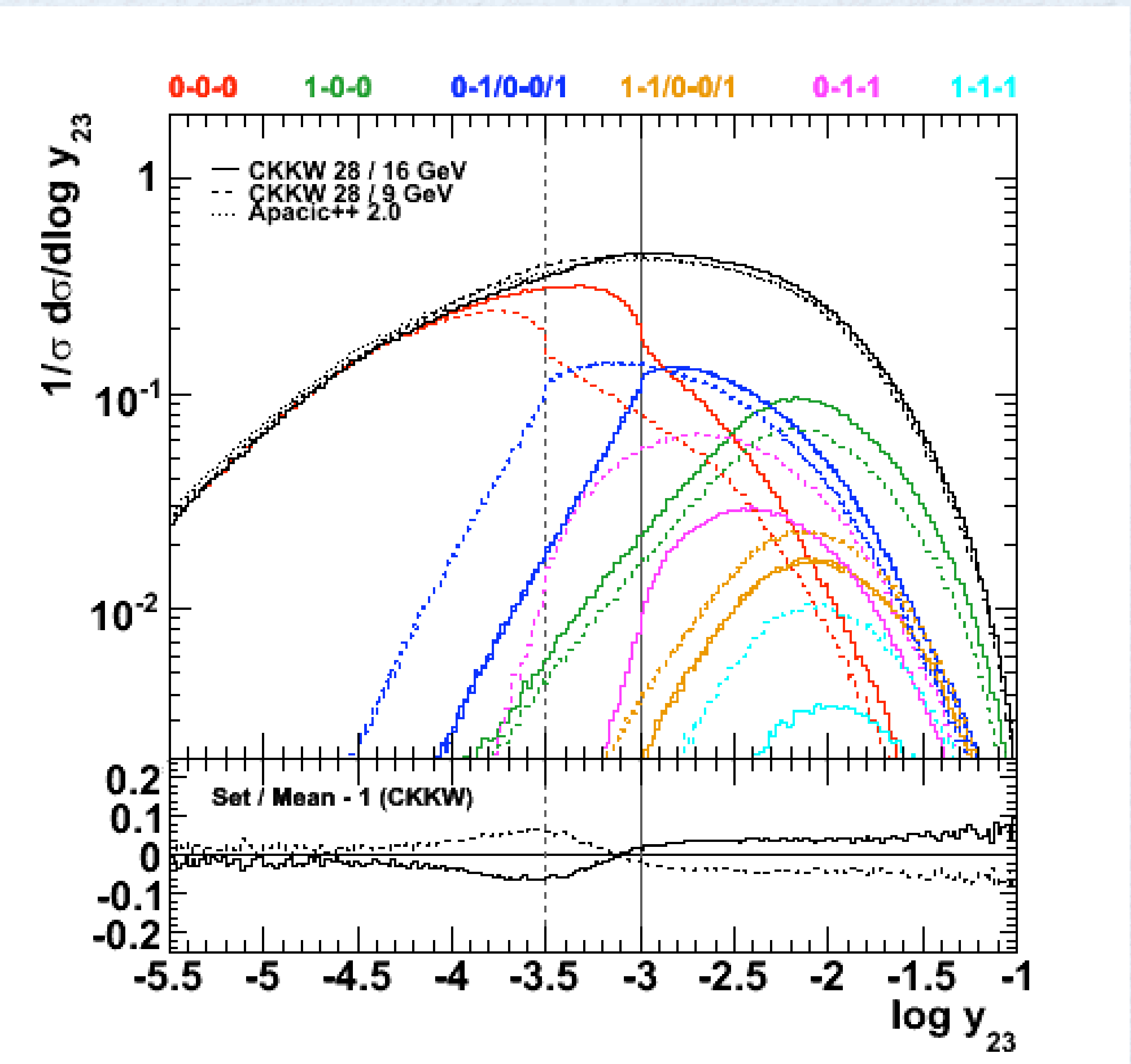


TOP PRODUCTION IN e^+e^-

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

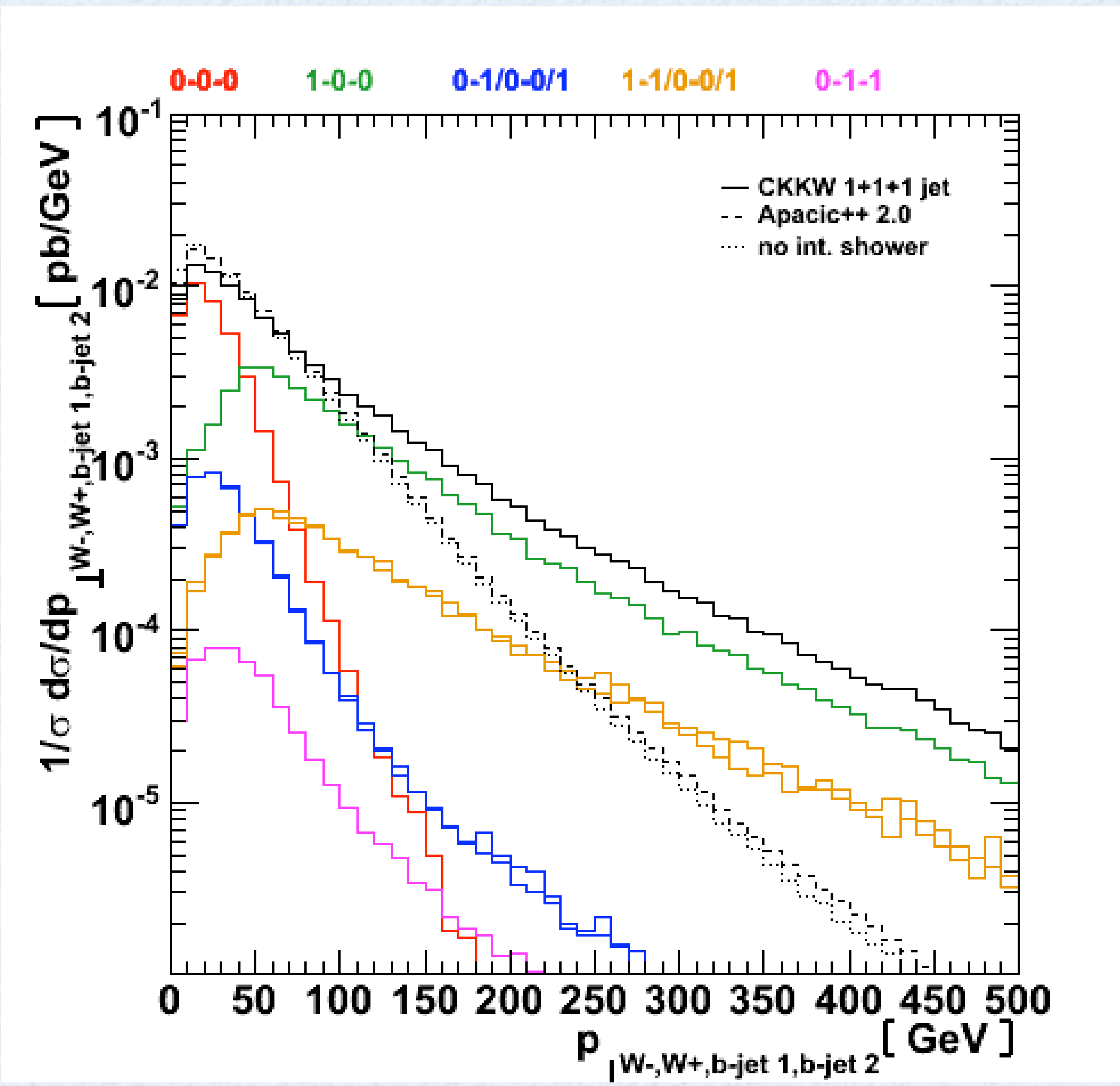


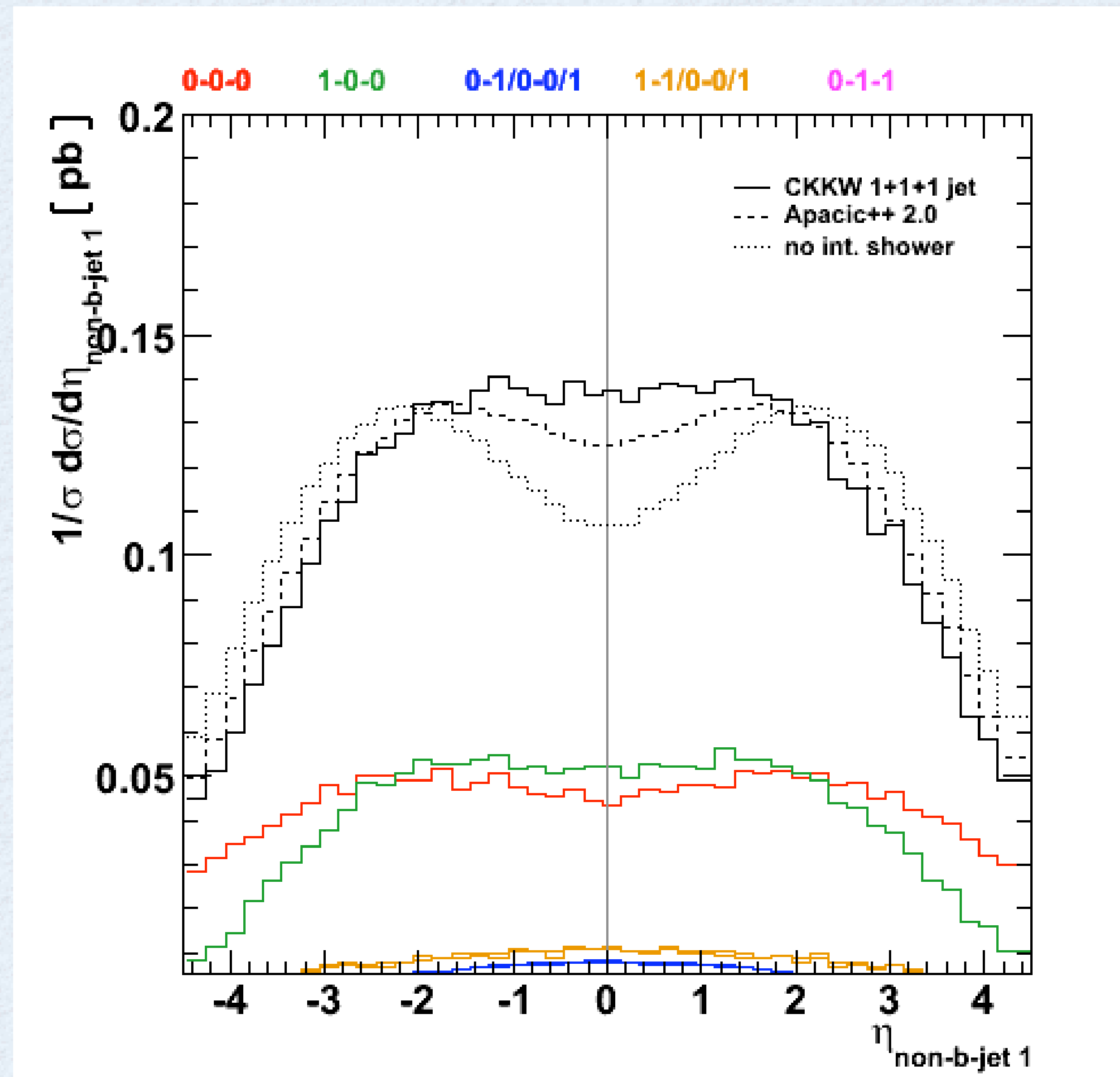
  - Q_{cut} - variation in decays



Top pair production @ LHC

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





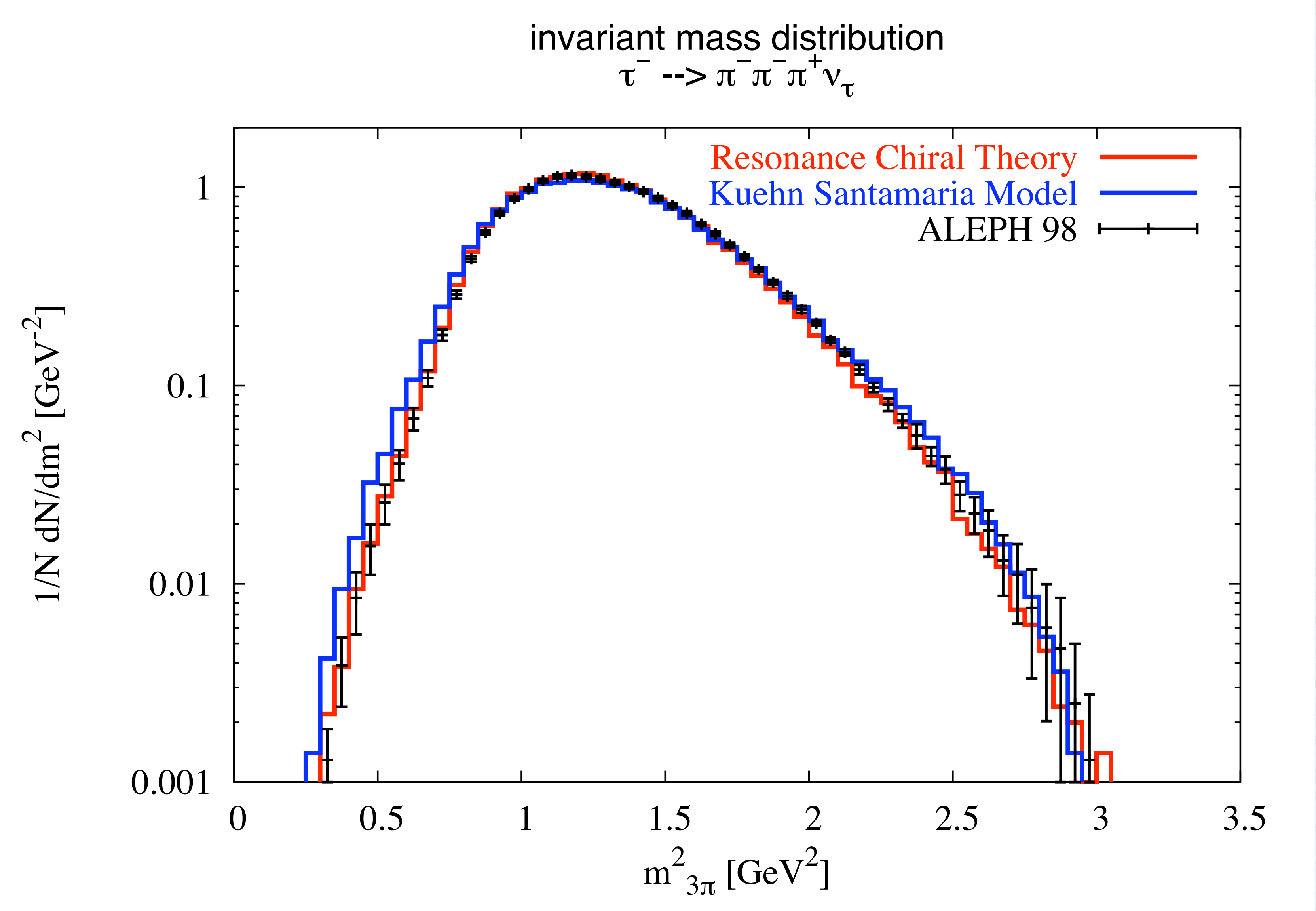
Hadron Decays

Sherpas hadron decay package HADRONS:

- Full flexibility, all information is read from parameter files
  (branching ratios, decay channels, form factors, integrators)
- Extremely easy to extend with specific decay modes / models
  (feel free to add your favourite decay ...)
- Full spin information from matrix element, if needed
- Extensively tested in τ decays
- Many hadron decays added, but not released yet
  (PYTHIA still does hadronisation and hadron decays ...)

Decays: A Variety of Models

- Invariant mass spectrum in $\tau \longrightarrow \nu_\tau \, \pi^- \pi^- \pi^+$

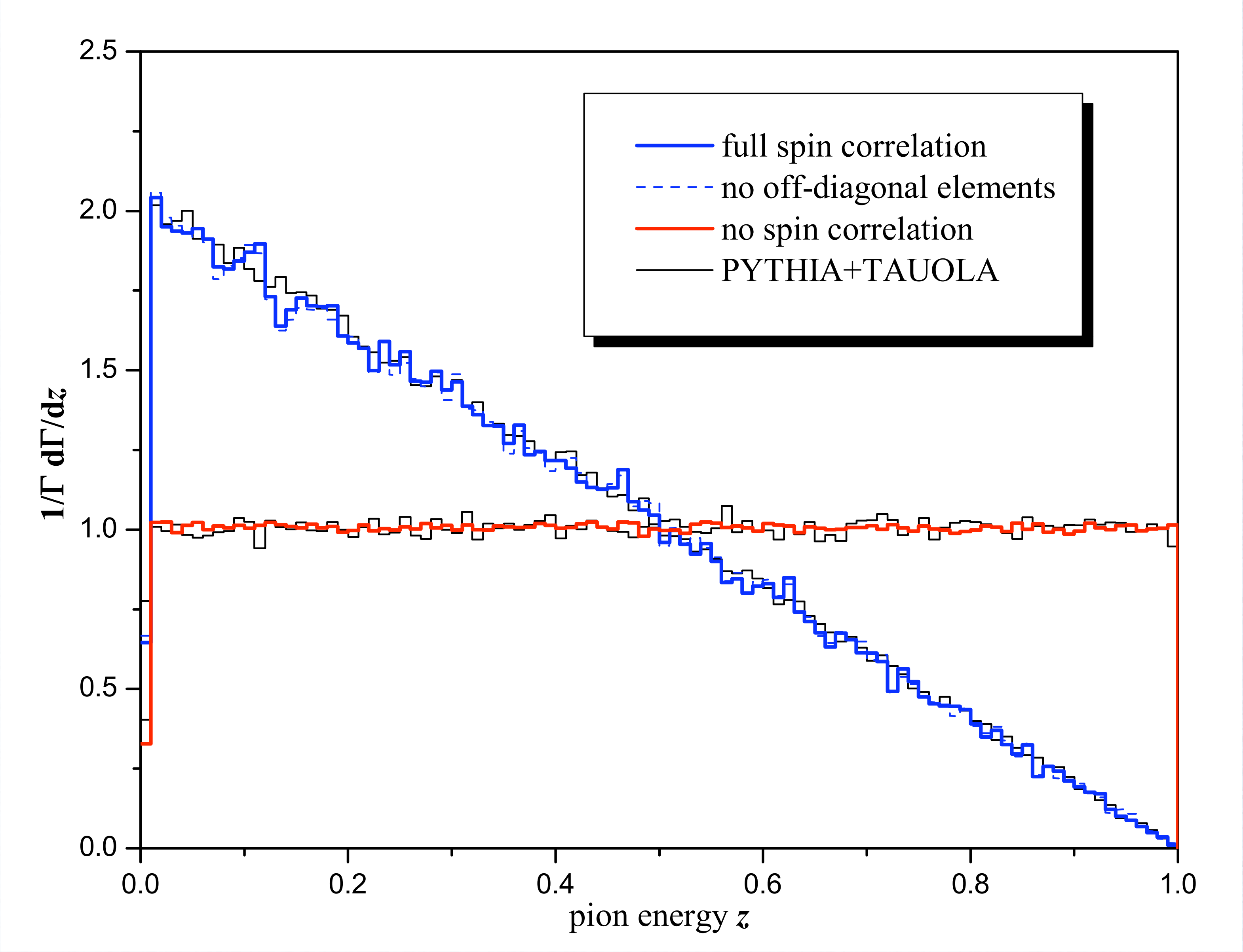


Decays: Spin correlations

PYTHIA+TAUOLA: hep-ph/0101311

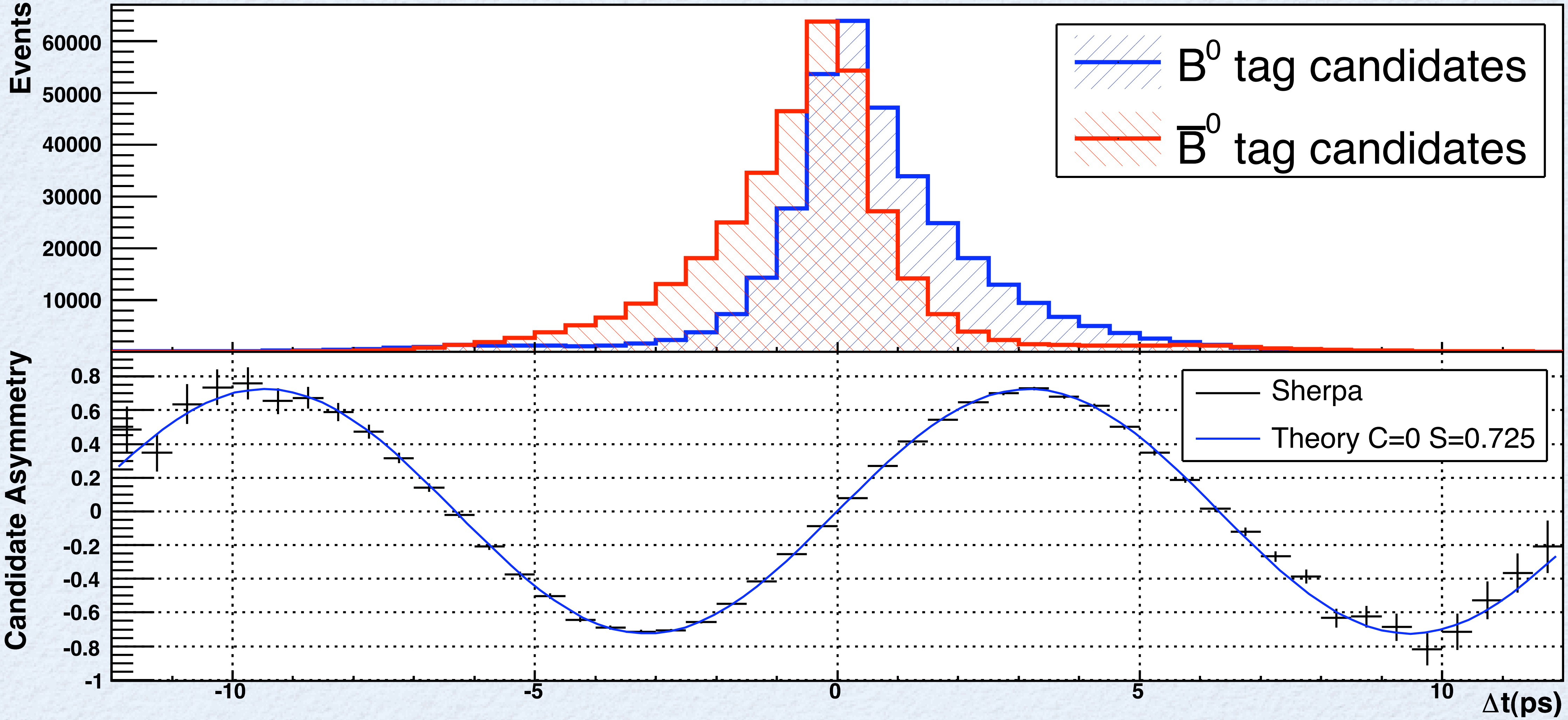
- π-energy distribution in $\mathbf{Z} \rightarrow \mathbf{W}^+\mathbf{W}^-$

  $\mathbf{W}^- \longrightarrow \tau^-\bar{\nu}_\tau \longrightarrow \nu_\tau\pi\bar{\nu}_\tau$



Decays: B-Mixing

- Decay rate asymmetry $\mathbf{B_0 \to J/\Psi K_s \leftrightarrow \bar{B}_0 \to J/\Psi K_s}$ in $\mathbf{\Upsilon(4s) \to B_0\bar{B}_0}$ events



SUMMARY

- Sherpa has proven to be a powerful tool to describe LEP and Tevatron data
- LHC predictions are in excellent agreement with other codes (e.g. hep-ph/0602031)

We currently also work on

- New dipole shower approaches ➞ improved ME-PS merging
- New multiple parton interaction model based on K_T factorisation
- QED radiation generator (YFS-based)
- ...

Updates on Sherpa can be found on

WWW.SHERPA-MC.DE

E-mail us on

INFO@SHERPA-MC.DE

COMIX: Phasespace recursion

Nucl. Phys. B9 (1969) 568

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

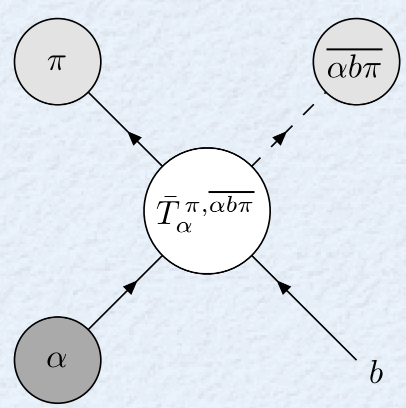
  Factorise PS using

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

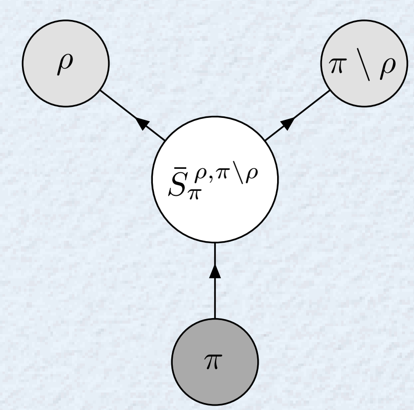
  Basic building blocks of the phasespace:

  - “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”



$$\mathbf{S}_\pi^{\pi,\pi\setminus\rho}=\frac{\lambda(\mathbf{s}_\pi,\mathbf{s}_\rho,\mathbf{s}_{\pi\setminus\rho})}{(\mathbf{2}\pi)^{\mathbf{6}}\,\mathbf{8}\,\mathbf{s}_\pi}\,\mathrm{d}\cos\theta_\rho\,\mathrm{d}\phi_\rho$$



$$\mathbf{T}_\alpha^{\pi,\overline{\alpha\mathbf{b}\pi}}=\frac{\lambda(\mathbf{s}_{\alpha\mathbf{b}},\mathbf{s}_\pi,\mathbf{s}_{\overline{\alpha\mathbf{b}\pi}})}{(\mathbf{2}\pi)^{\mathbf{6}}\,\mathbf{8}\,\mathbf{s}_{\alpha\mathbf{b}}}\,\mathrm{d}\cos\theta_\pi\,\mathrm{d}\phi_\pi$$

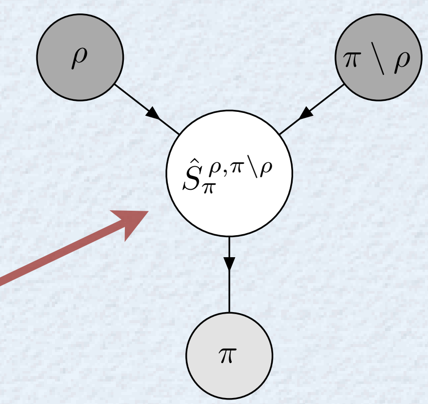
Arrows → Momentum flow

COMIX: Phasespace recursion

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

S-channel phasespace (schematically)

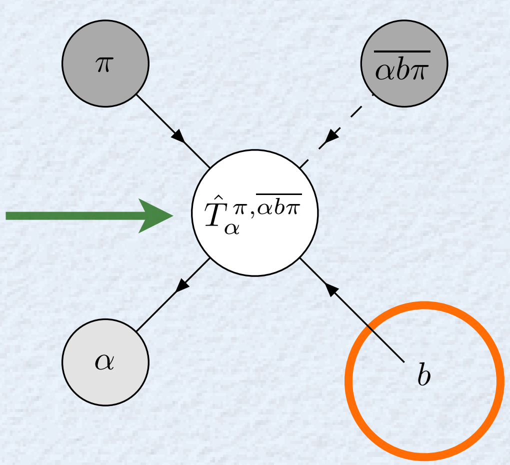
$$\mathrm{d}\Phi_S(\pi) = P_\pi \left[\sum \alpha\left(S_\pi^{\rho,\pi\setminus\rho}\right) \right]^{-1} \times \left[\sum \alpha\left(S_\pi^{\rho,\pi\setminus\rho}\right) S_\pi^{\rho,\pi\setminus\rho}\, \mathrm{d}\Phi_S(\rho)\, \mathrm{d}\Phi_S(\pi\setminus\rho) \right]$$



Weights for adaptive multichanneling

T-channel phasespace (schematically)

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



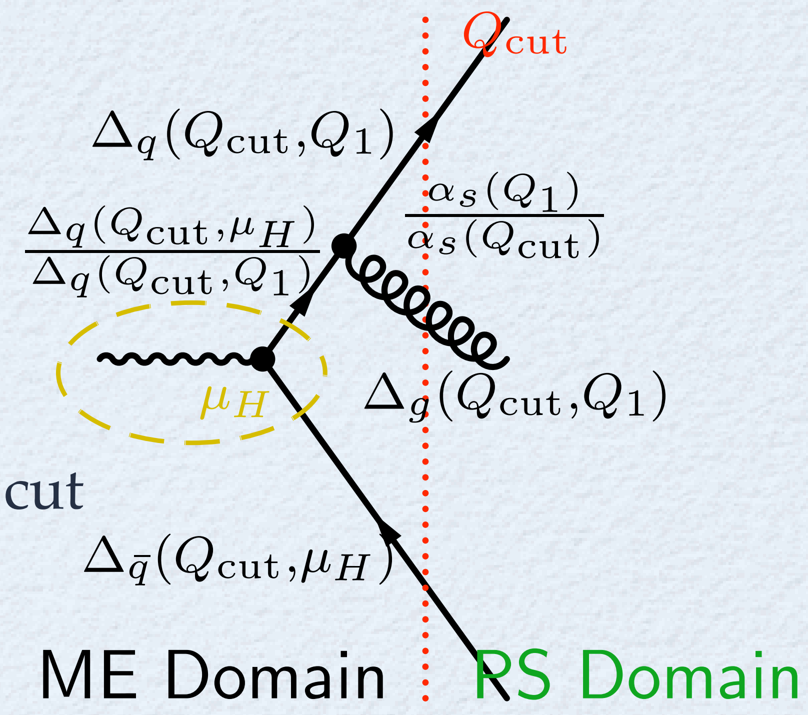
"b" is fixed ➡ Every PS-weight is unique !

Arrows ➡ Weight flow !

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

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