Recent Developments in Sherpa

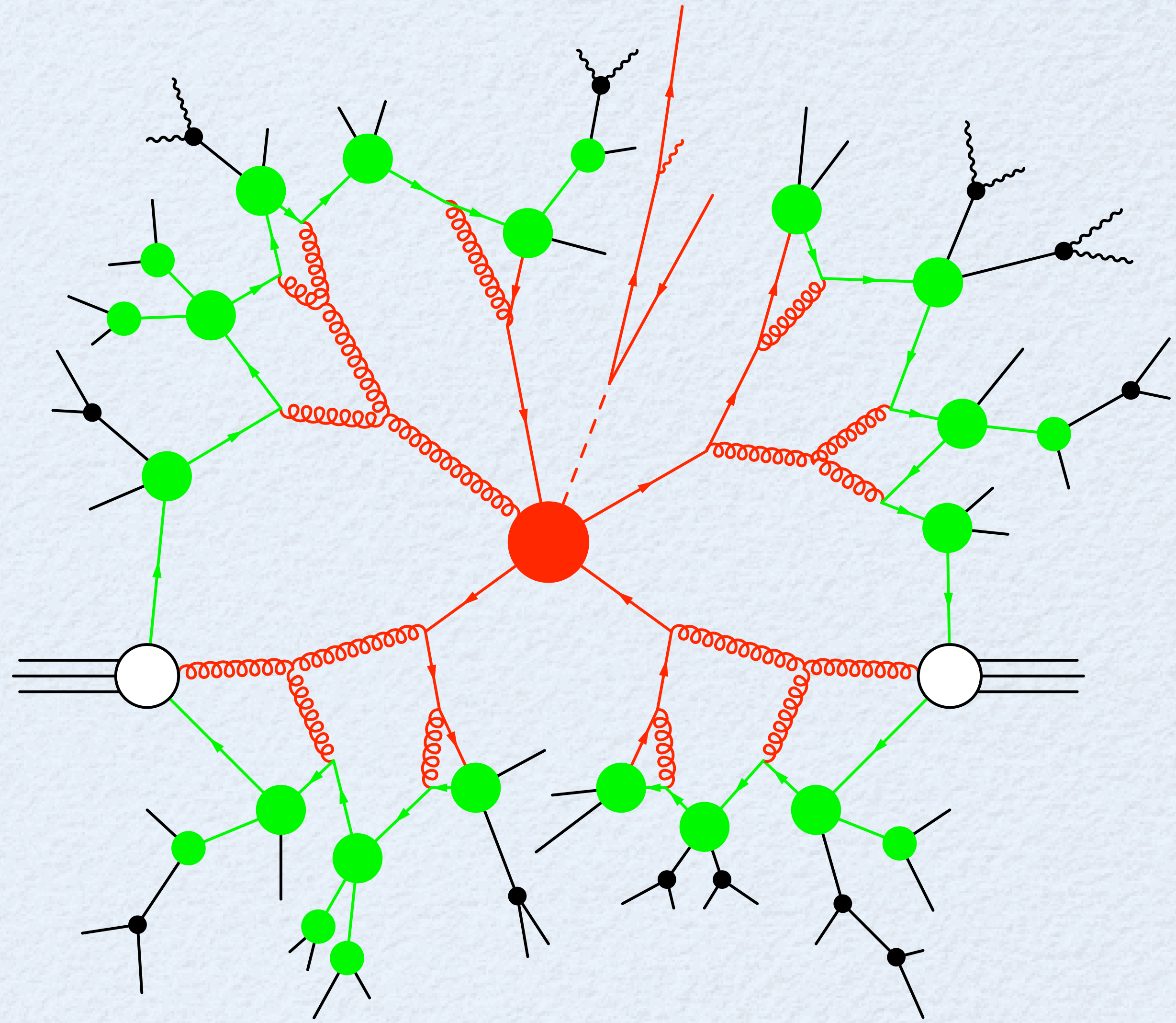
Stefan Höche[1]
Institute for Particle Physics Phenomenology
Durham University

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

The Sherpa Framework

What is in the box ?

- Matrix element (ME) generators
- Shower (PS) generators
- Merging of ME & PS (CKKW)
- Cluster fragmentation
- Hadron decays
- Multiple parton interactions



Sherpa itself is the framework
that combines all the above

Latest version: Release 1.1.0 / 1.1.1

- Cluster fragmentation completed (remains to be tuned)
- Hadron decay module fully functional
- New module for soft photon radiation (YFS approach)

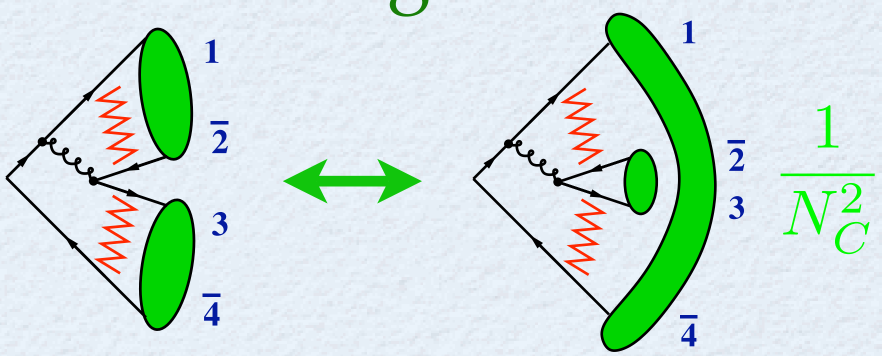
Cluster Fragmentation

Eur. Phys. J. C36 (2004) 381

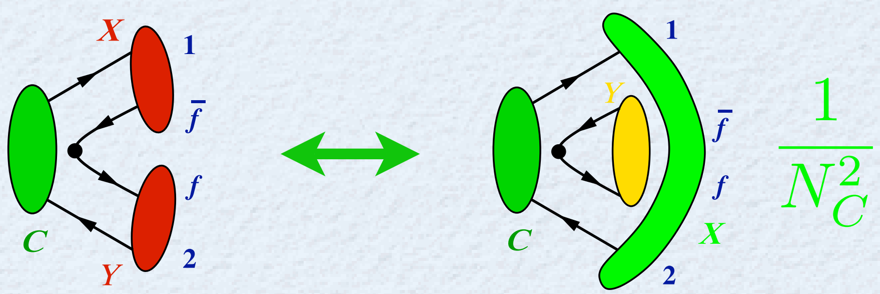
Sherpas previous cluster fragmentation model:

- Colour ordered partons transformed into primary clusters according to combination of
  - kinematical weight
  - colour weight

$$\mathbf{W_{ij,\,kl}} = \frac{\mathbf{t_0}}{\mathbf{t_0 + 4(w_{ij} + w_{kl})^2}}$$



- Clusters decayed according to overlap between cluster and hadron mass spectrum
  - cluster mass in hadron regime → transition to hadron
  - else → 2-body decay
    C→HH, C→CH or C→CC
    combined weight applied again[1]

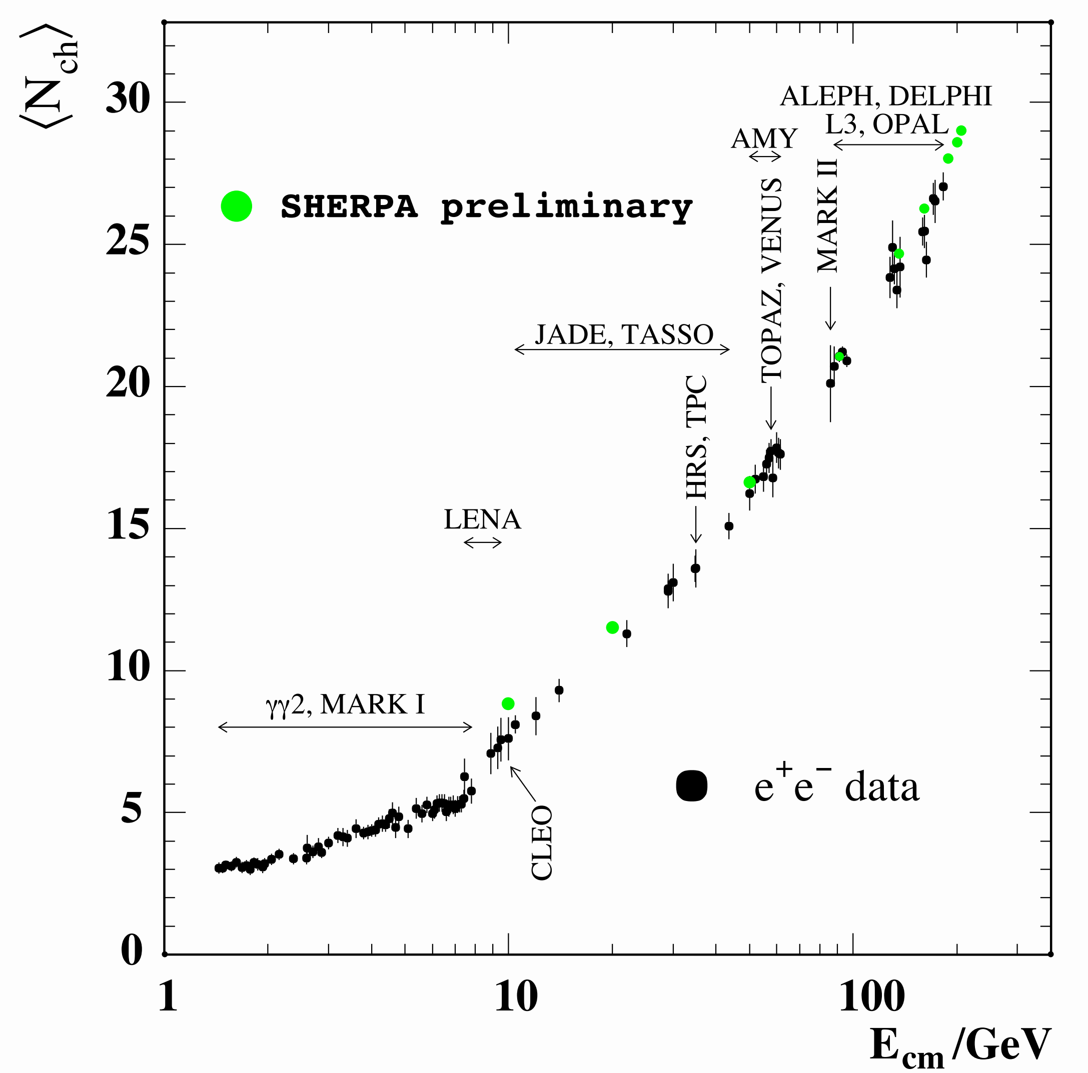


[1] with t_0 replaced by Q_0 (hadronic scale)

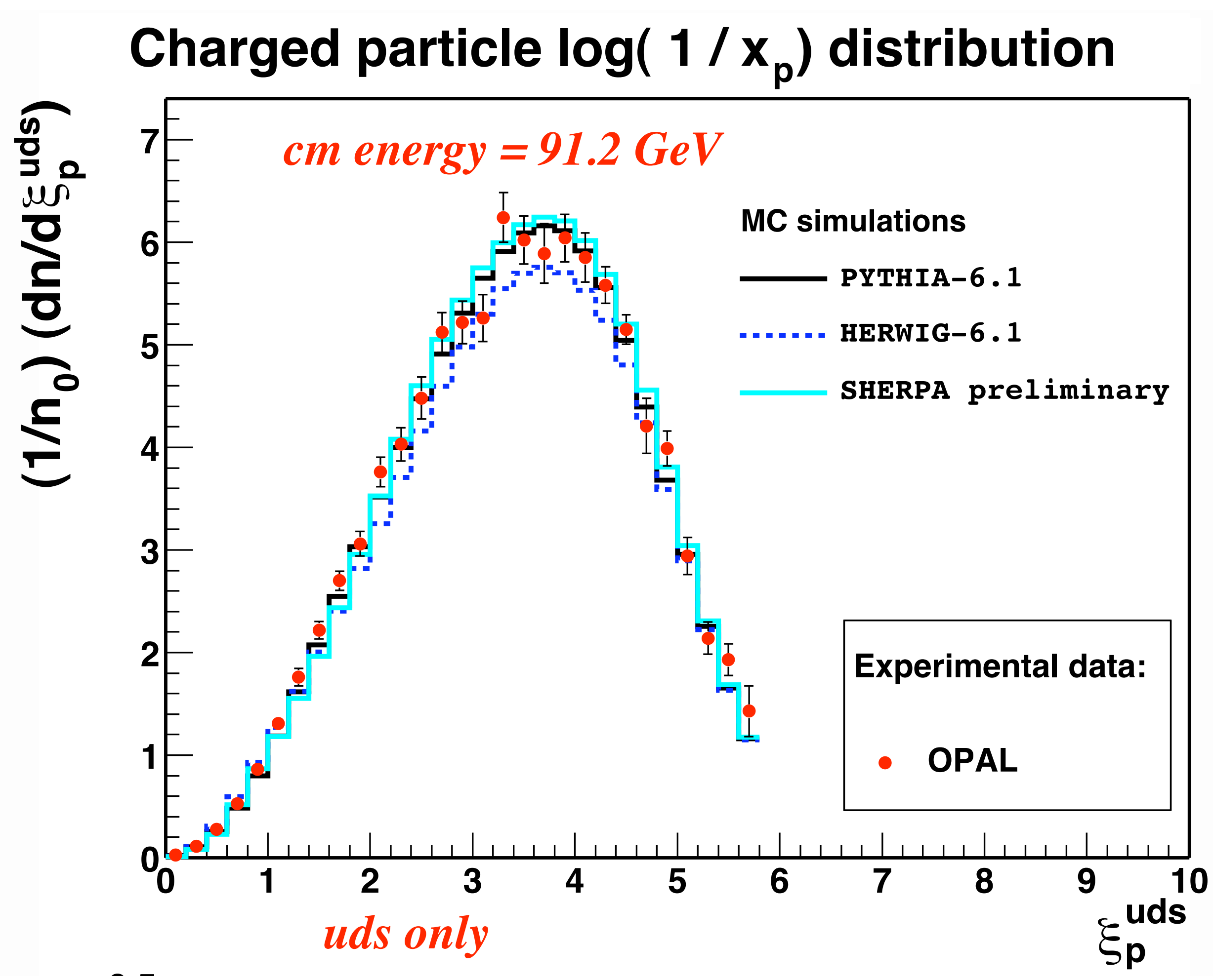
Cluster Fragmentation

Eur. Phys. J. C36 (2004) 381

- $N_{charged}$ vs. E_{cms}



- charged scaled momentum



Cluster Fragmentation

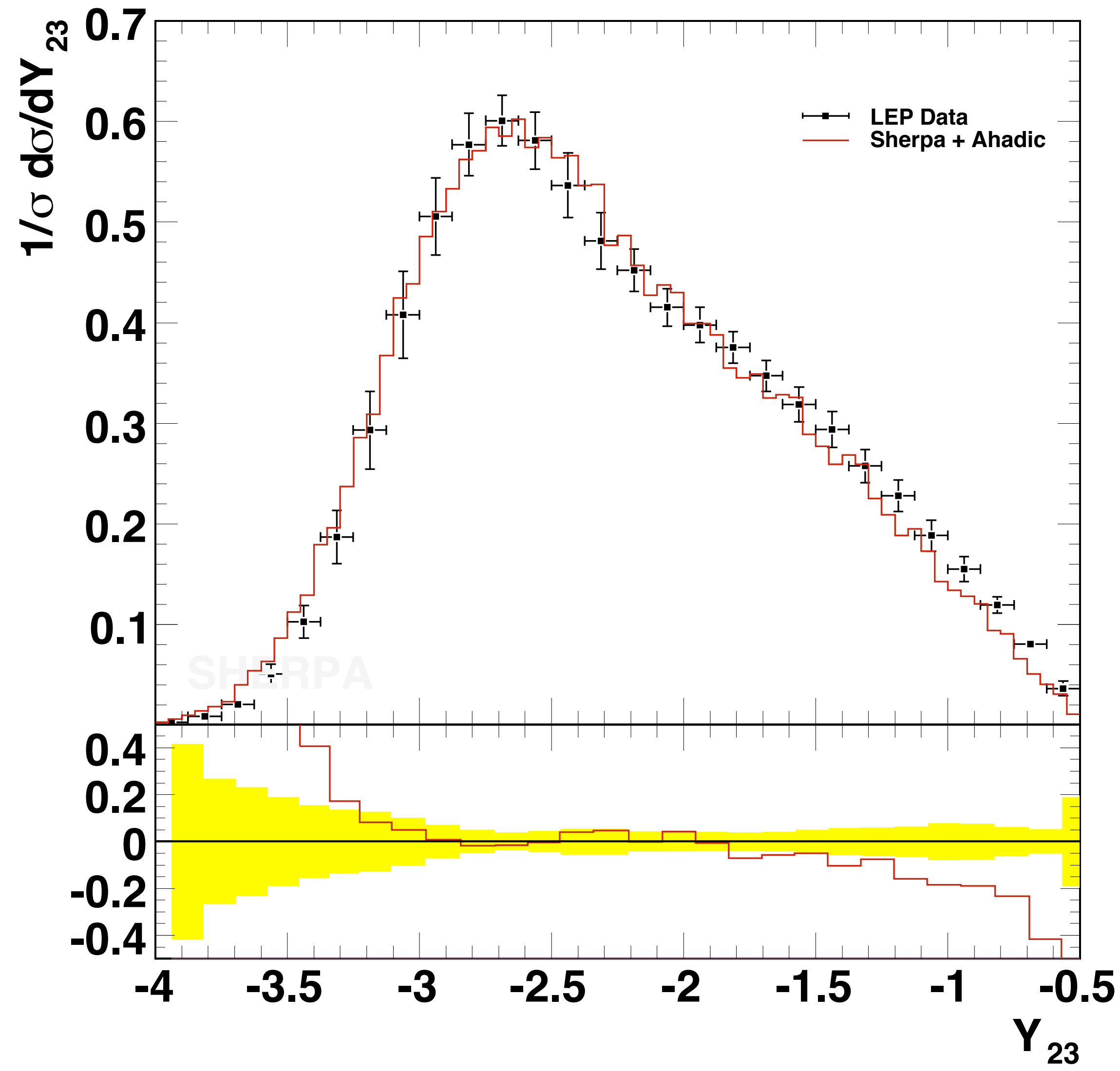
F. Krauss, J.Winter; in preparation

Improvements over old model:

- Cluster splittings motivated by perturbative QCD
  - Massive dipole splitting kinematics with limited $\mathbf{p}_\perp$
  - Splitting weight
    $$w \propto \frac{\alpha_s(\mathbf{p}_\perp^2)}{\mathbf{p}_\perp^2}$$
    with non-perturbative tunable strong coupling

→ No dependence on unphysical constituent mass of the gluon !

- Durham jet rate at LEP I



Hadron Decays

F. Krauss, T. Laubrich, F. Siegert: in preparation

Main features of Sherpas decay package

- Decay kinematics according to ME's with form factors
- Treatment of neutral meson mixing and related CP violation
- Partonic decays for incomplete decay tables
- Spin correlation algorithm with full spin information from AMEGIC++ matrix element

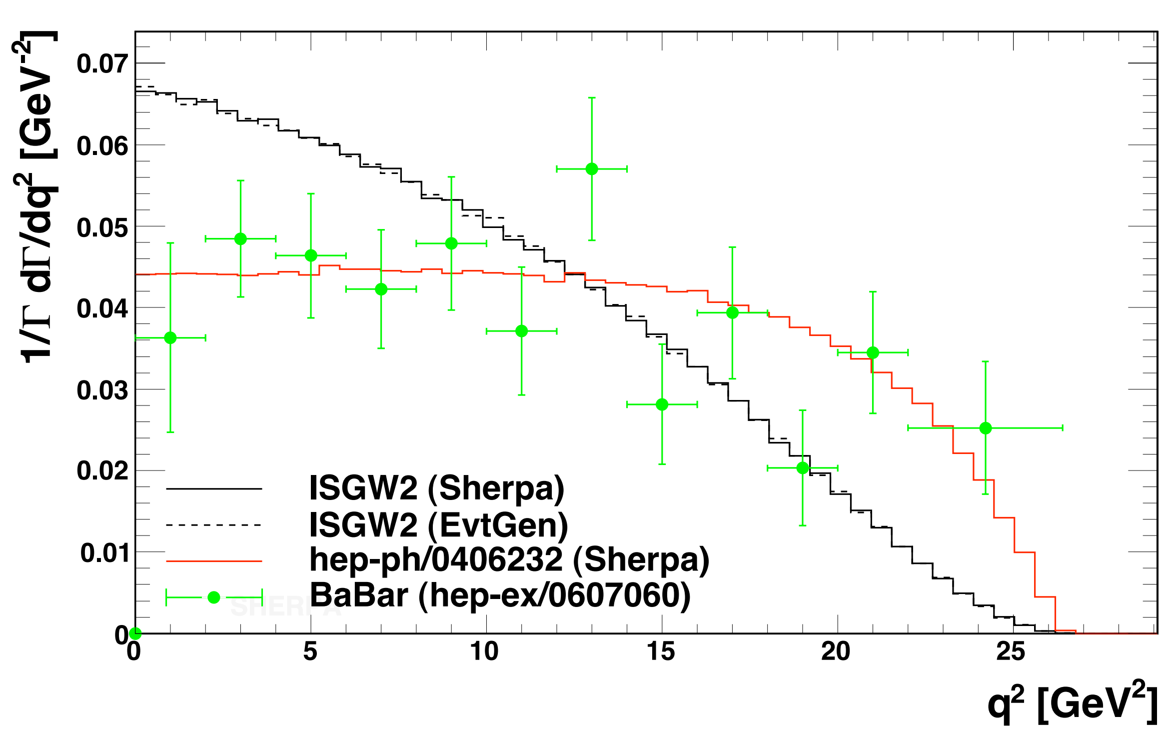
Current status

- Decay tables for ~ 400 particles
- ~ 2500 decay channels
- ~ 400 decay channels with form factors

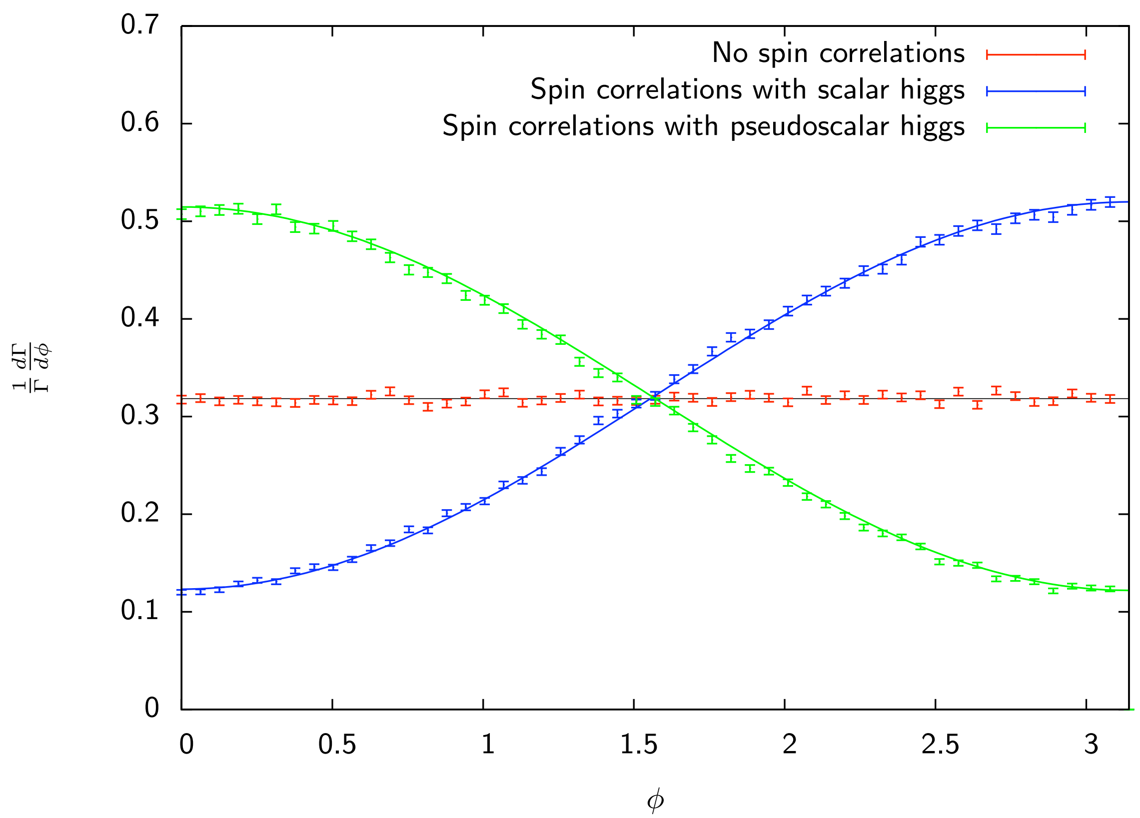
Hadron Decays

F. Krauss, T. Laubrich, F. Siegert: in preparation
SC analytical: Acta Phys.Polon.B34(2003)4549

- **Matrix Elements and form factors**: e.g. in $\mathbf{B} \to \pi \nu_\mathbf{l} \bar{\mathbf{l}}$

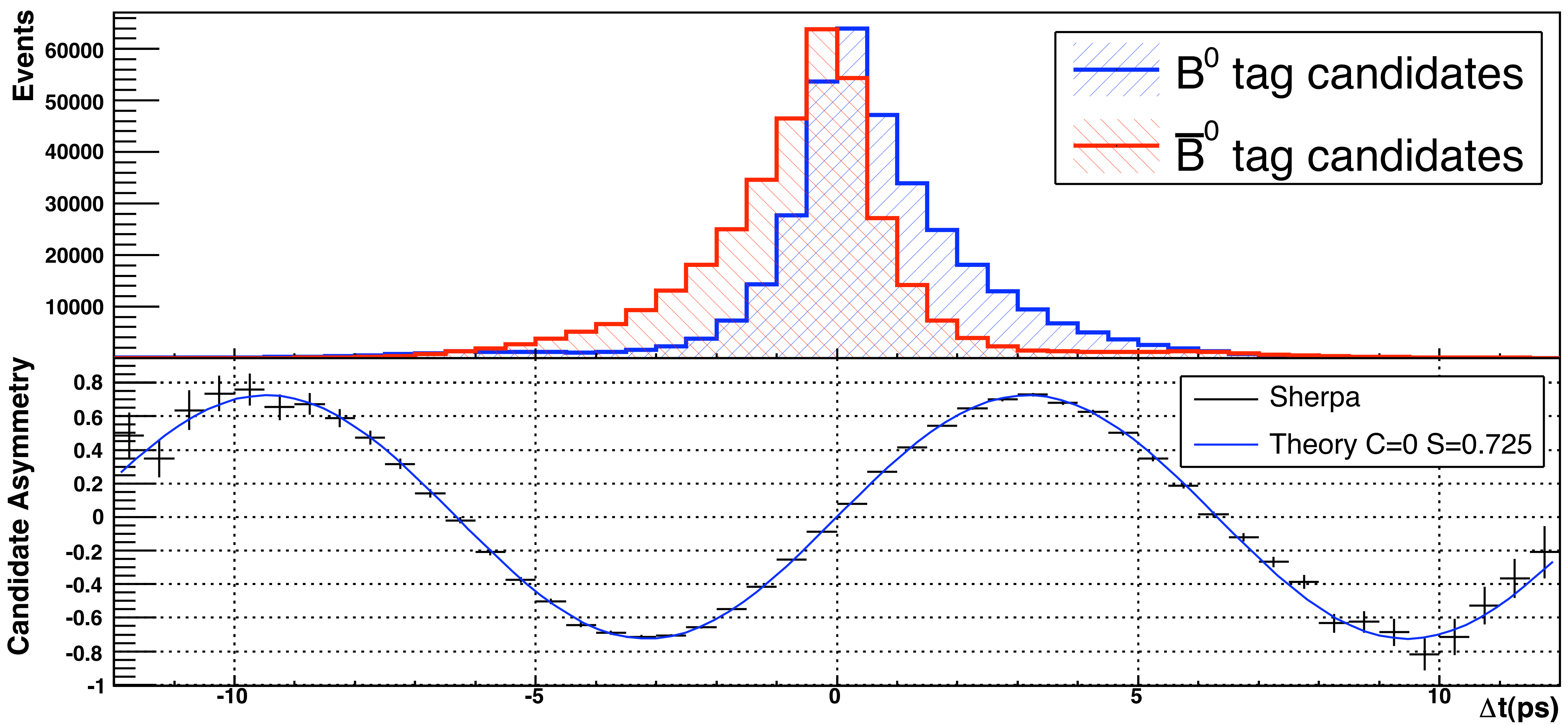


- **Spin correlations**: e.g. in $\mathbf{h} \to \tau^+\tau^- \to \pi^-\nu_\tau\pi^+\bar{\nu}_\tau$



F. Krauss, T. Laubrich, F. Siegert: in preparation

- **B-mixing**: e.g.
  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



Soft Photon Radiation

F. Krauss, M. Schönherr: in preparation

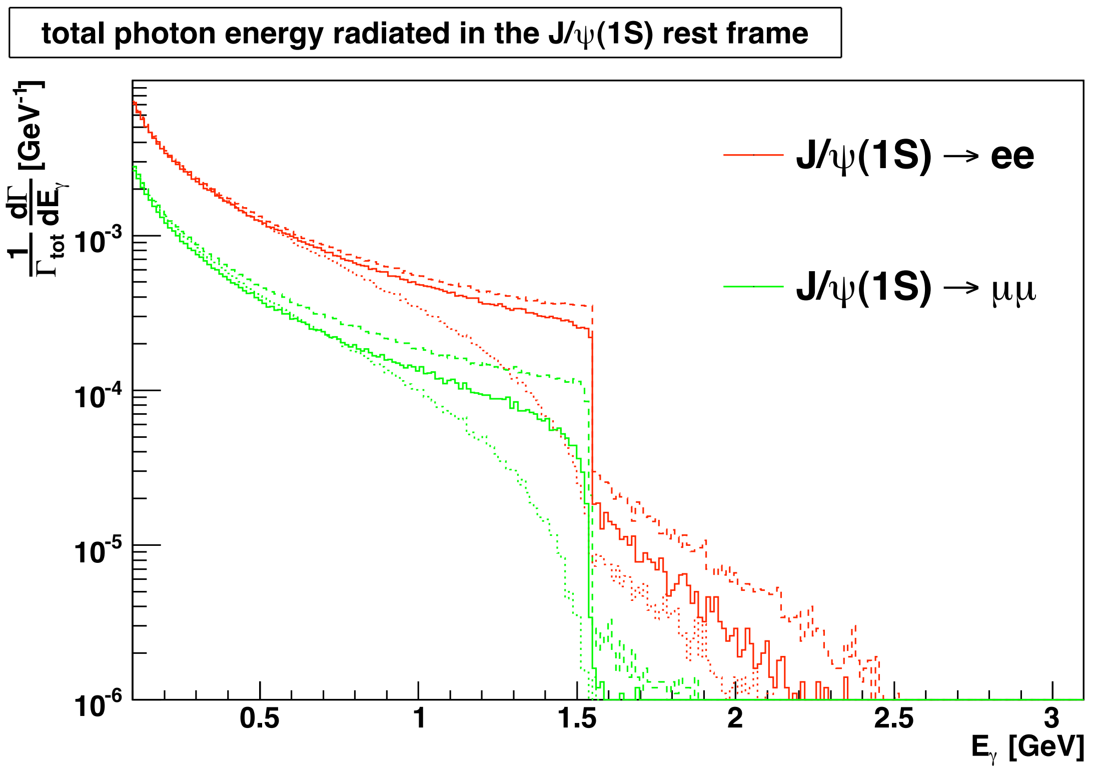
YFS simulation with the PHOTONS++ module

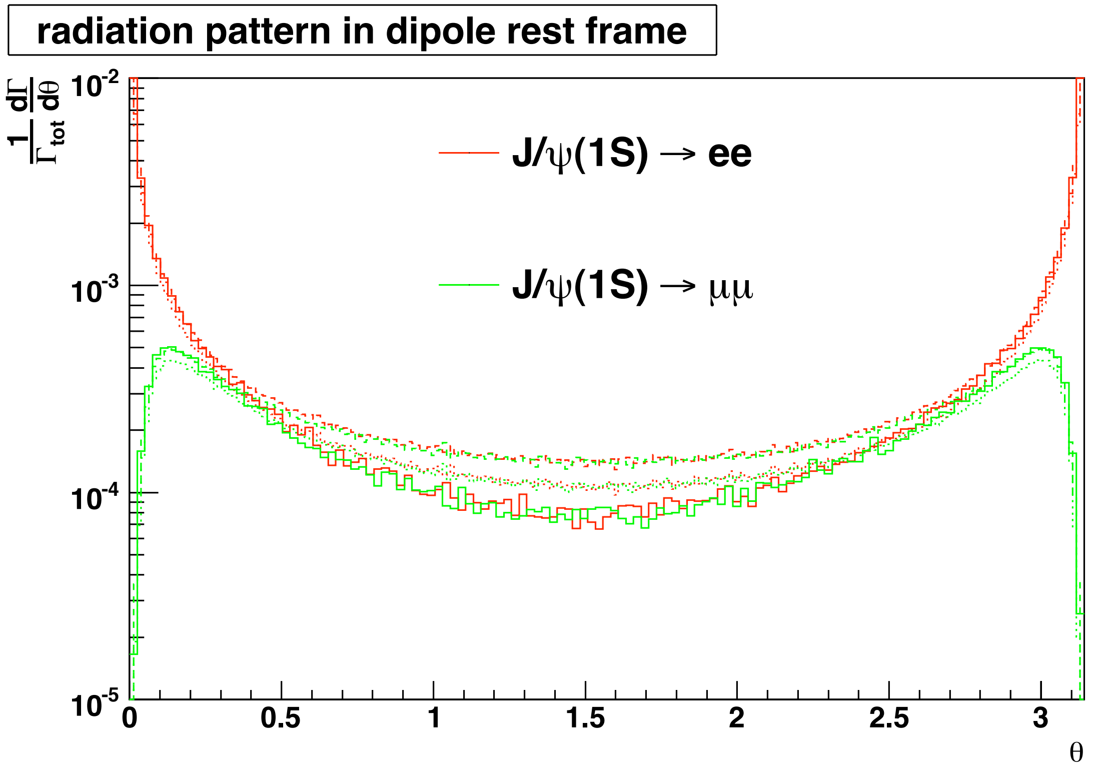
- Sums all contributions of soft photon radiation
  exact in soft limit, perturbative series for hard emissions
- Hard emission effects up to $\mathcal{O}(\alpha)$ incorporated
  generally via approximated ME in quasi-collinear limit
- Important cases with $\mathcal{O}(\alpha)$ real and/or virtual exact ME's
  $\mathbf{V} \to \mathbf{FF},\ \mathbf{V} \to \mathbf{SS},\ \mathbf{S} \to \mathbf{FF},\ \mathbf{S} \to \mathbf{SS},\ \tau \to \mathbf{l}\nu_\mathbf{l}\nu_\tau$
- ME corrections for radiative semi-leptonic meson decays
  (form factor model) under way
- Implemented for hadron and τ decays, but
  no limitation on final state and/or its complexity

Soft Photon Radiation

F. Krauss, M. Schönherr: in preparation

- **Example: Decay $J/\psi \to l\bar{l}$**
  - soft radiation only (dotted)
  - collinear approximated ME (dashed)
  - exact ME (solid)



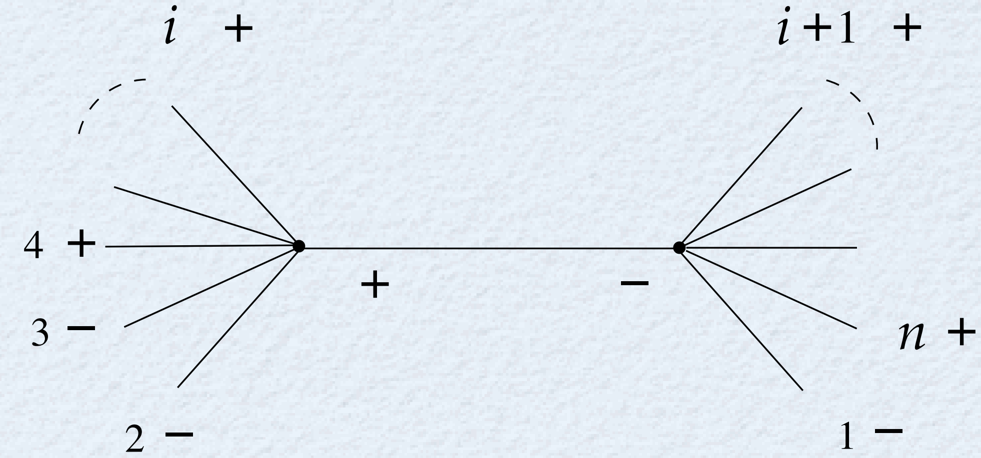


The Immediate Future

High-Multi ME's with CSW

T. Gleisberg, SH, F. Krauss, R. Matyskiewicz; in preparation

- Twistor-inspired techniques (CSW rules) speed up calculation of pure QCD ME's for medium multiplicites
- 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 → 4g	1977	19	104.1
2g → 5g	n/a	429	n/a
2q → 4g	124	14	8.9
2q → 5g	43636	290	148.4
2q → 2q'+2g	8	6	1.33
2q → 2q'+3g	810	74	10.8
2q → 2q+2g	24	10	2.4
2q → 2q+3g	3923	118	33
2j → 4j	4082	202	20.2
2j → 5j	n/a	12103	n/a

Newly accessible processes

Significant speedup

Very High-Multi ME's: COMIX

T. Gleisberg, SH: in preparation

- Revisited "old-fashioned" Berends-Giele recursion JHEP 08(2006)062
  - ➡ New ME generator **COMIX**
- Fully general implementation of SM interactions
- Key point: Vertex decomposition of all four-particle vertices
  (Growth in computational complexity at tree-level
  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
    Gives reasonable performance (e.g. MC4LHC setup[1])

efficiency	Number of jets					
$e^+\nu_e$ + QCD jets	0	1	2	3	4	5
$\varepsilon = 10^{-3}$	$1.5{\cdot}10^{-1}$	$2.4{\cdot}10^{-2}$	$9.1{\cdot}10^{-3}$	$2.0{\cdot}10^{-3}$	$6.7{\cdot}10^{-4}$	$1.0{\cdot}10^{-4}$
$\varepsilon = 10^{-6}$	$1.6{\cdot}10^{-2}$	$4.5{\cdot}10^{-3}$	$3.3{\cdot}10^{-3}$	$1.2{\cdot}10^{-3}$	$4.3{\cdot}10^{-4}$	$7.5{\cdot}10^{-5}$

$$\mathbf{eff}. = \langle \mathbf{w} \rangle / \mathbf{w}^{\varepsilon}_{\max} \quad \text{where} \quad \mathbf{1} - \langle \min(\mathbf{w}, \mathbf{w}^{\varepsilon}_{\max}) \rangle / \langle \mathbf{w} \rangle = \varepsilon \ll \mathbf{1}$$

[1] http://mlm.home.cern.ch/mlm/mcwshop03/mcwshop.html

COMIX: Phasespace recursion

Basics: Nucl. Phys. B9 (1969) 568

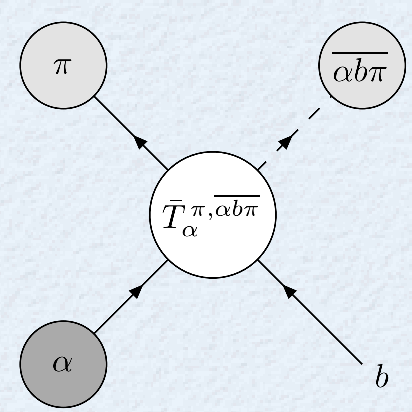
- State-of-the art approach for general phasespace generation:

  Factorise PS using

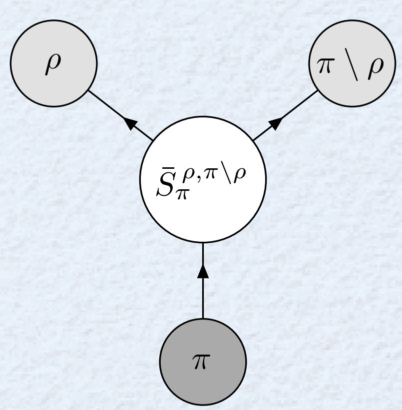
$$\mathrm{d}\mathbf{\Phi_n}\left(\mathbf{a},\mathbf{b};\mathbf{1},\ldots,\mathbf{n}\right)=\mathrm{d}\mathbf{\Phi_m}\left(\mathbf{a},\mathbf{b};\mathbf{1},\ldots,\mathbf{m},\bar{\pi}\right)\,\mathrm{d}s_\pi\,\mathrm{d}\mathbf{\Phi_{n-m}}\left(\pi;\mathbf{m}+\mathbf{1},\ldots,\mathbf{n}\right)$$

  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

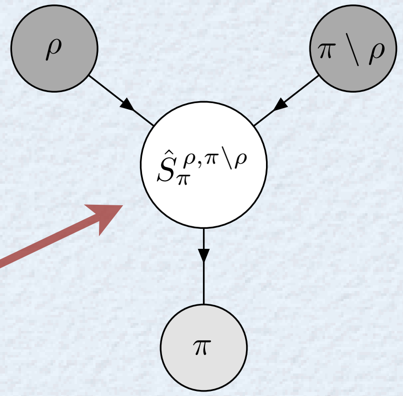
COMIX: Phasespace recursion

T. Gleisberg, SH: in preparation

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

S-channel phasespace (schematically)

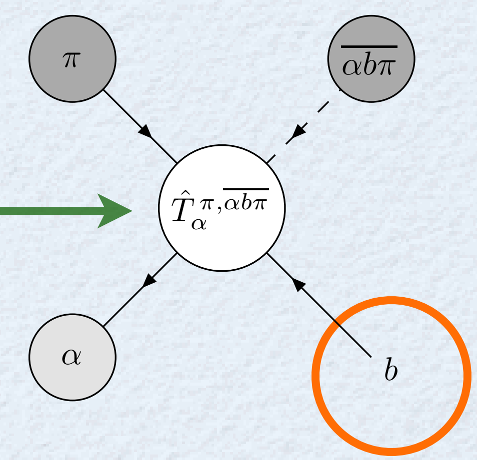
$$\mathrm{d}\Phi_S(\pi) = \Big[\sum \alpha\big(S_\pi^{\rho,\pi\setminus\rho}\big)\Big]^{-1}$$
$$\times\Big[\sum \alpha\big(S_\pi^{\rho,\pi\setminus\rho}\big)\, S_\pi^{\rho,\pi\setminus\rho}\, P_\rho\, \mathrm{d}\Phi_S(\rho)\; P_{\pi\setminus\rho}\, \mathrm{d}\Phi_S(\pi\setminus\rho)\Big]$$



Weights for adaptive multichanneling

T-channel phasespace (schematically)

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



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

Arrows ➡ Weight flow !

➡ Factorial growth of PS-channels tamed

COMIX: TECHNICALITIES

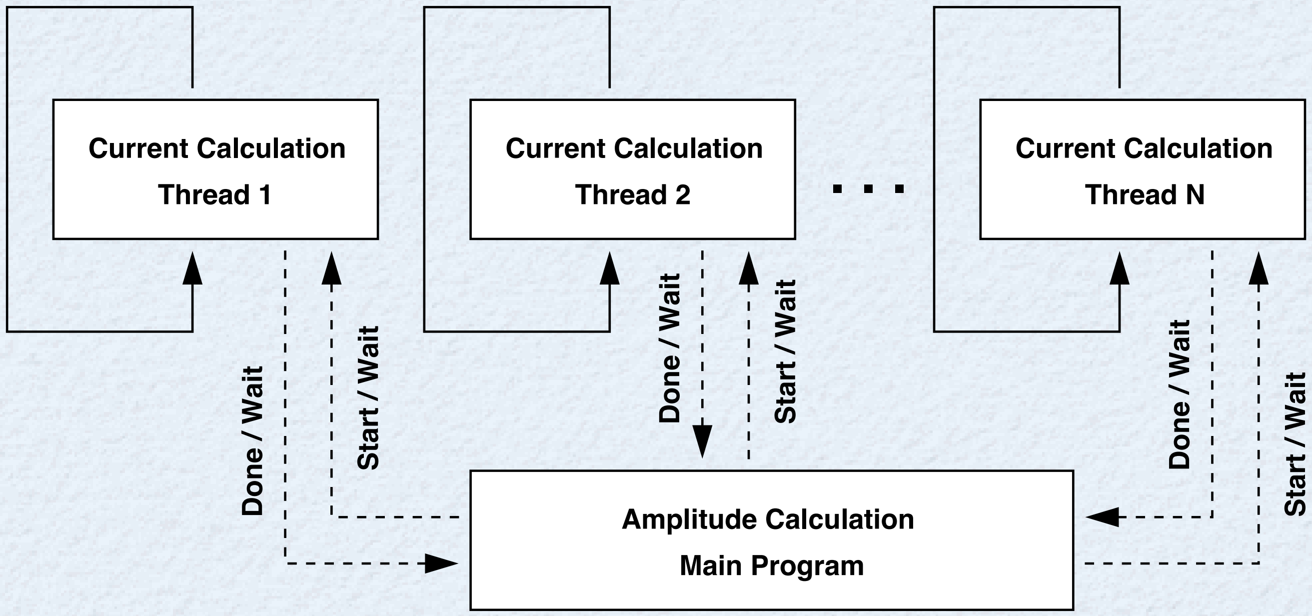
T. Gleisberg, SH: in preparation

- General structure of recursion (ME and phasespace):

$$\mathcal{J}_\alpha\,(\pi) = P_\alpha\,(\pi) \sum_{\mathcal{V}_\alpha^{\alpha_1,\,\alpha_2}} \sum_{\mathcal{P}_2(\pi)} \mathcal{S}\,(\pi_1,\pi_2)\;\mathcal{V}_\alpha^{\alpha_1,\,\alpha_2}\,(\pi_1,\pi_2)\;\mathcal{J}_{\alpha_1}\,(\pi_1)\,\mathcal{J}_{\alpha_2}\,(\pi_2)$$

n-particle currents only depend on m<n-particle currents

➡ Straightforward multithreading algorithm
(use as many processors / cores as you like)



Identical procedure for ME and phasespace due to same recursion !

Comix: Performance

T. Gleisberg, SH: in preparation

- Performance in QCD benchmarks

World record !

gg → ng	Cross section [pb]				
n $\sqrt{s}$ [GeV]	8 1500	9 2000	10 2500	11 3500	12 5000
Comix	0.755(3)	0.305(2)	0.101(7)	0.057(5)	0.026(1)
Phys. Rev. D67(2003)014026	0.70(4)	0.30(2)	0.097(6)		
Nucl. Phys. B539(1999)215	0.719(19)				

- "Real life" example: Drell-Yan pair + jets
  comparison with other ME generators

All partons !

σ [pb]	Number of jets						
e^-e^+ + QCD jets	0	1	2	3	4	5	6
Comix	723.5(4)	187.9(3)	69.7(2)	27.14(7)	11.09(4)	4.68(2)	2.02(2)
ALPGEN	723.4(9)	188.3(3)	69.9(3)	27.2(1)	10.95(5)	4.6(1)	1.85(1)
AMEGIC++	723.0(8)	188.2(3)	69.6(2)	27.21(6)	11.1(1)		

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

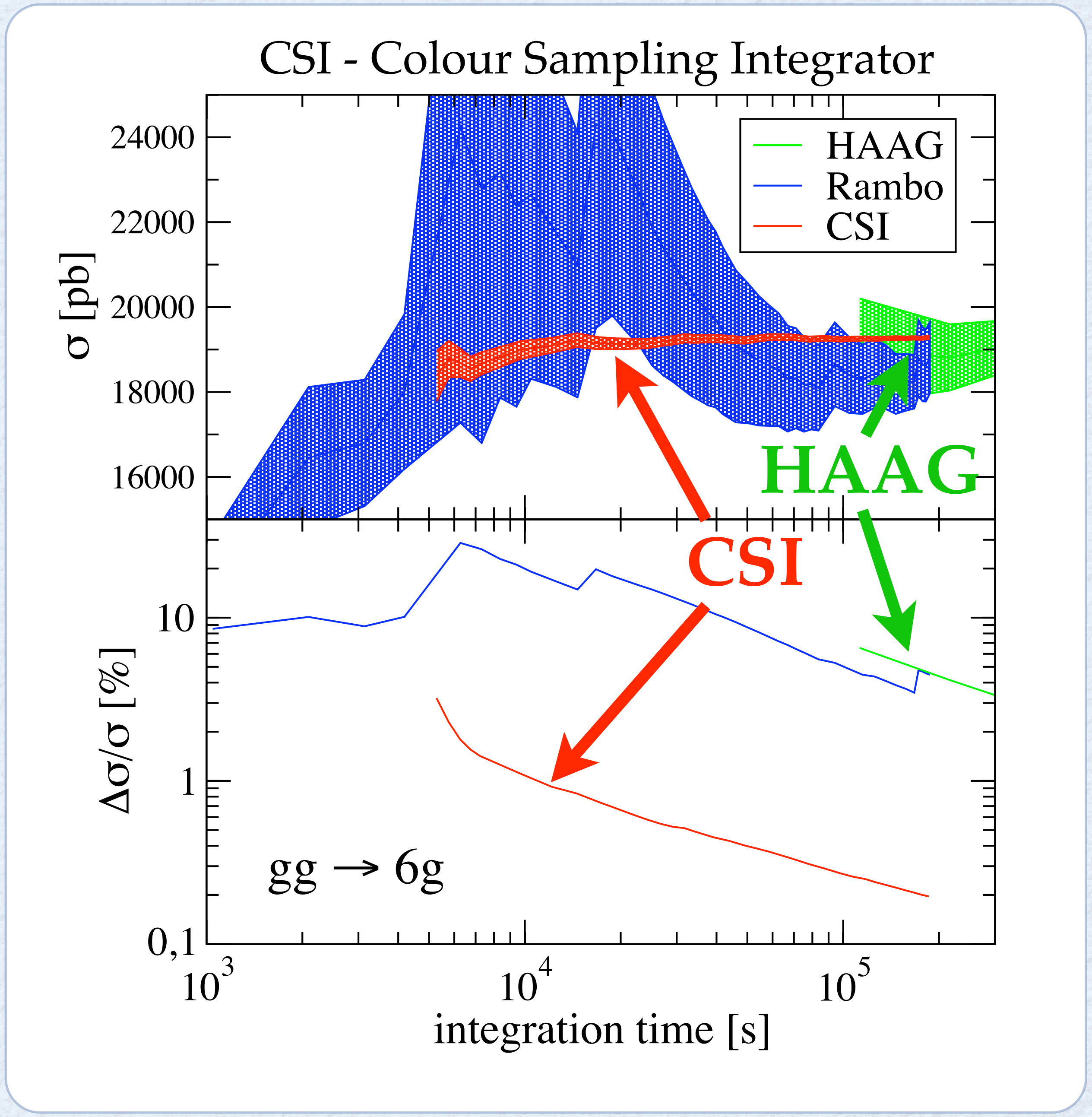
COMIX: PERFORMANCE

T. Gleisberg, SH: in preparation

- Subprocess cross sections for 7- and 8-jet production in MC4LHC comparison setup

σ [nb]	Number of jets n	
QCD jets	7	8
$gg \to ng$	48.9(6)	14.8(3)
$gg \to (n-2)g\,2q$	17.0(1)	5.9(1)
$gg \to (n-4)g\,4q$	1.69(2)	0.72(1)
$gg \to (n-6)g\,6q$	0.0404(3)	0.0290(4)
$gg \to 8q$	-	0.000169(3)
$gq \to (n-1)g\,1q$	30.4(2)	9.9(2)
$gq \to (n-3)g\,3q$	8.5(1)	3.33(8)
$gq \to (n-5)g\,5q$	0.569(5)	0.300(6)
$gq \to (n-7)g\,7q$	0.00483(5)	0.0068(2)
$qq \to ng$	0.0209(2)	0.0068(1)
$qq \to (n-2)g\,2q$	5.06(5)	1.76(3)
$qq \to (n-4)g\,4q$	1.01(1)	0.47(1)
$qq \to (n-6)g\,6q$	0.0372(5)	0.029(1)
$qq \to 8q$	-	0.00017(2)

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



Brief Review: Why 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

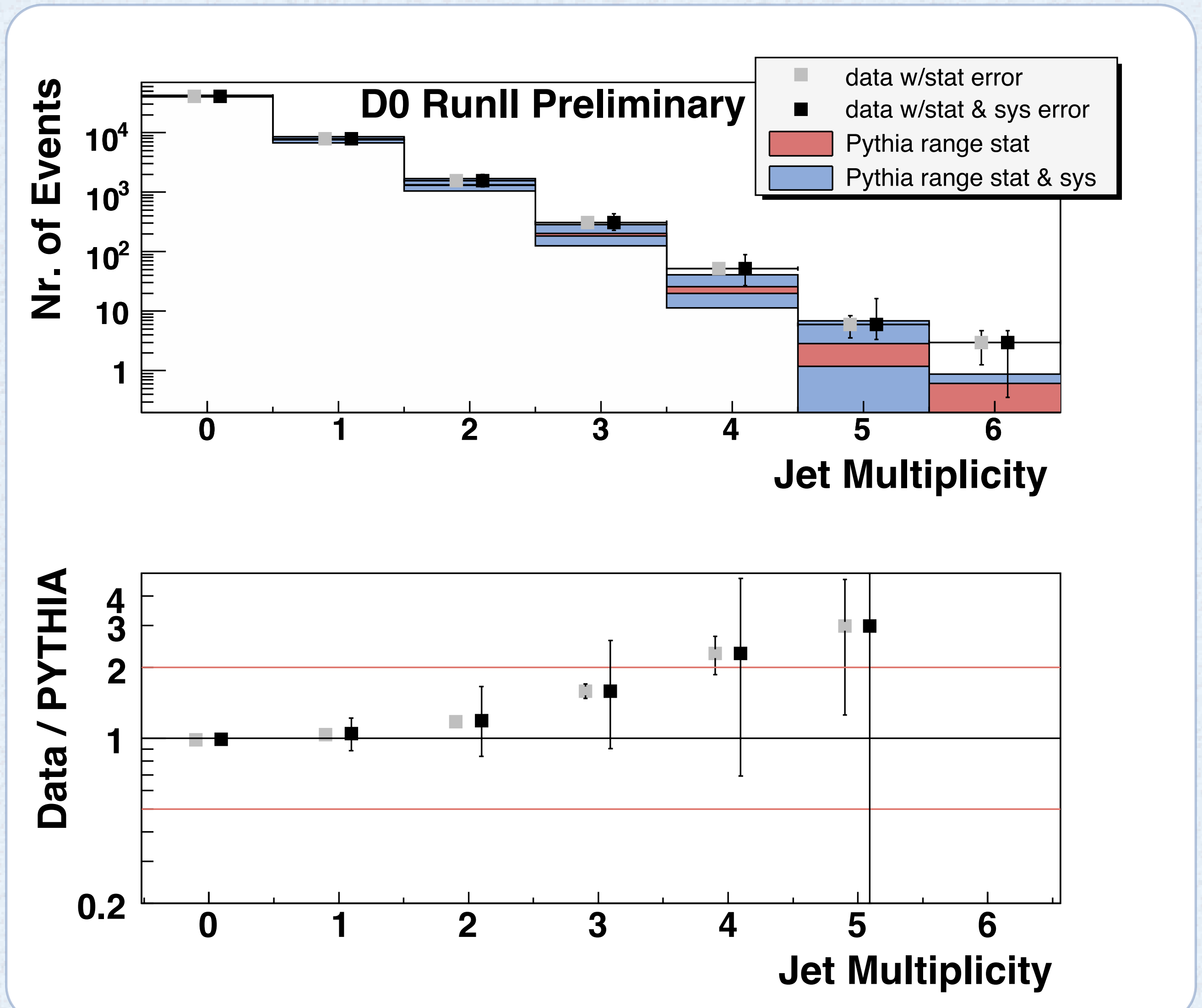
- Good description of hard radiation (ME)
- Correct intrajet evolution (PS)

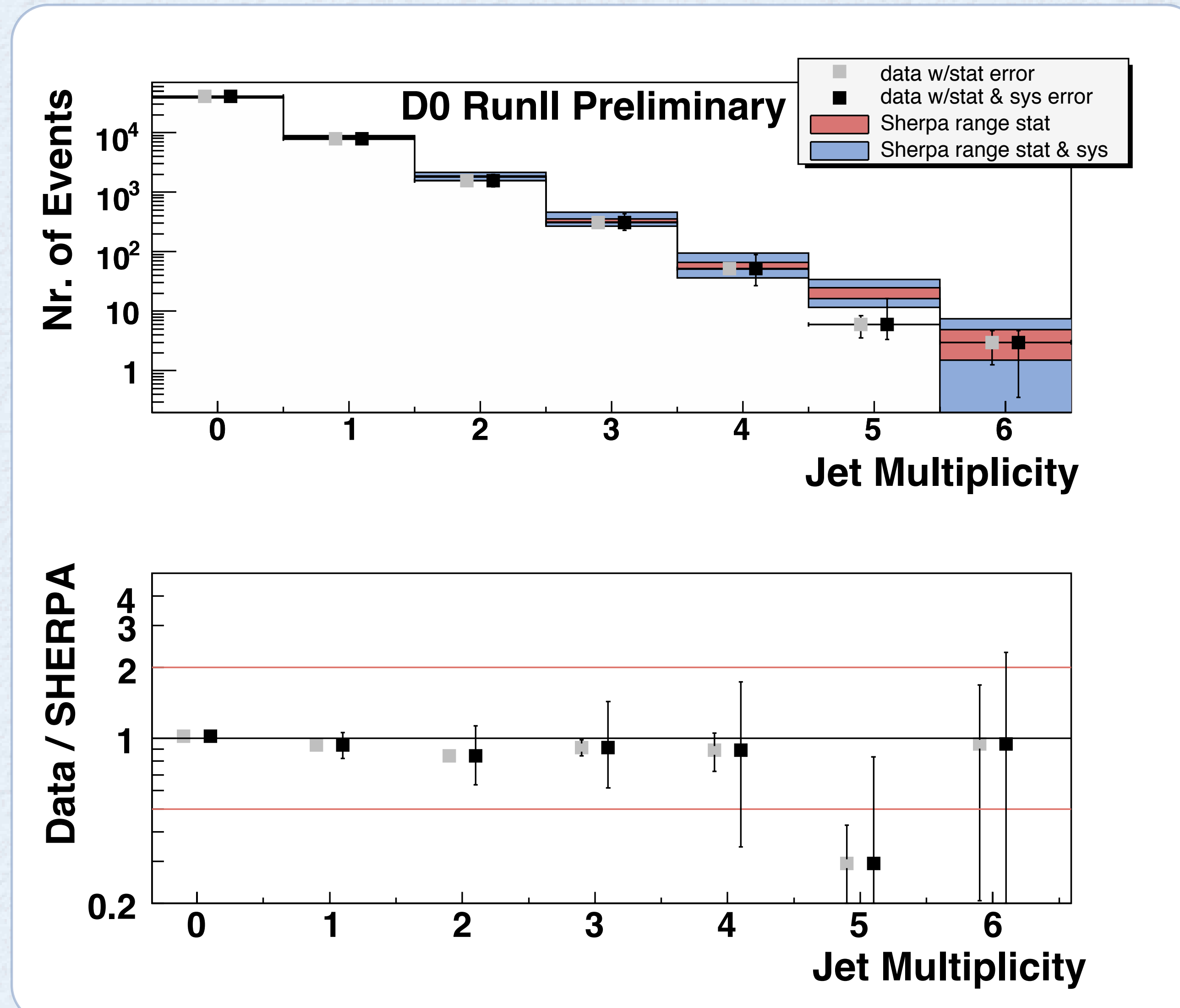
- Strategy: Separate phase space
  - Jet production region → ME
  - Intrajet evolution region → PS
- **Free parameter: Separation cut Q_{cut}** (K_T-type jet measure)

CKKW: Z+JETS @ TEVATRON

The DØ collaboration, DØ note 5066-CONF

- Jet multiplicity





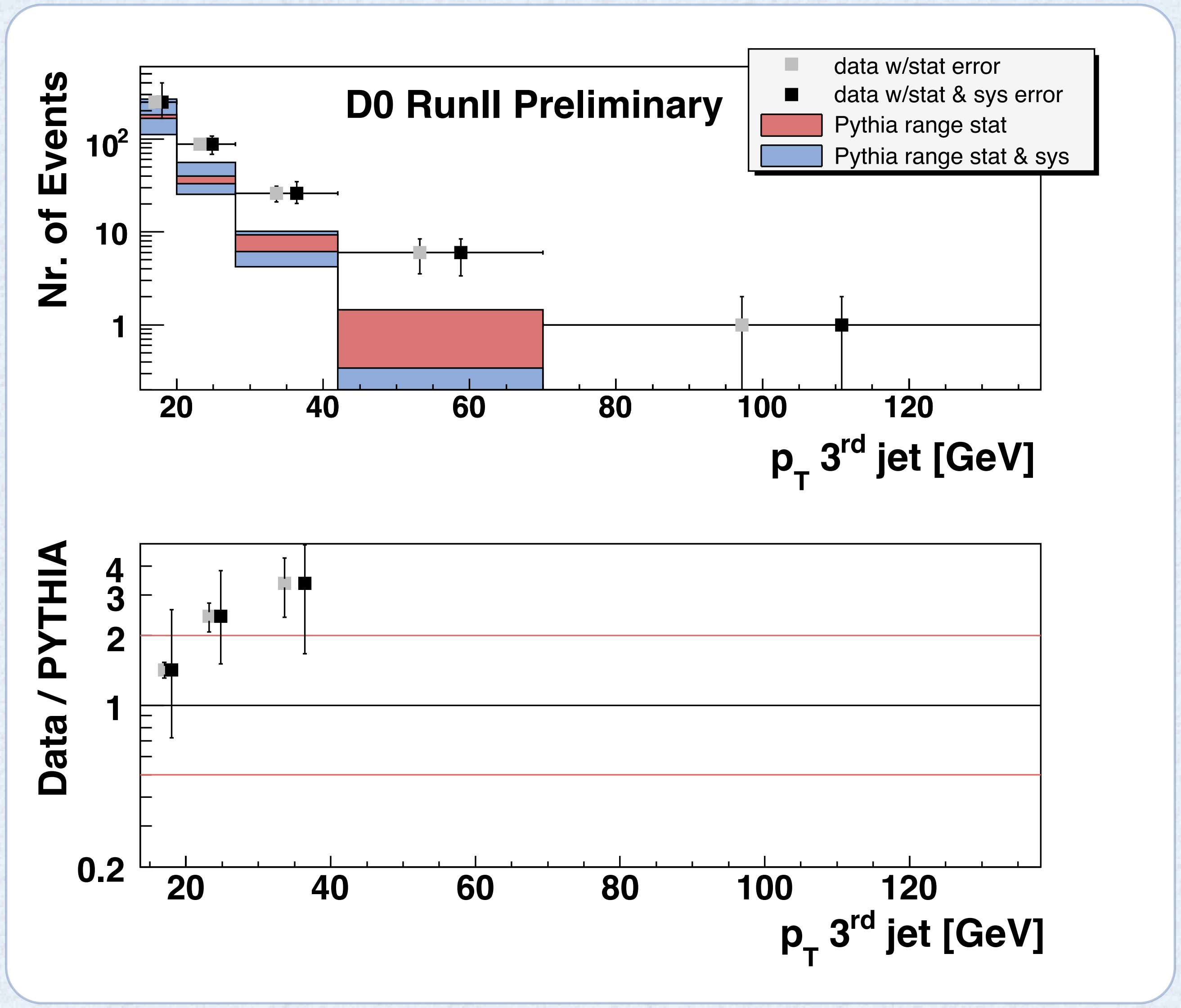
- Pythia 6.2
  normalized to data

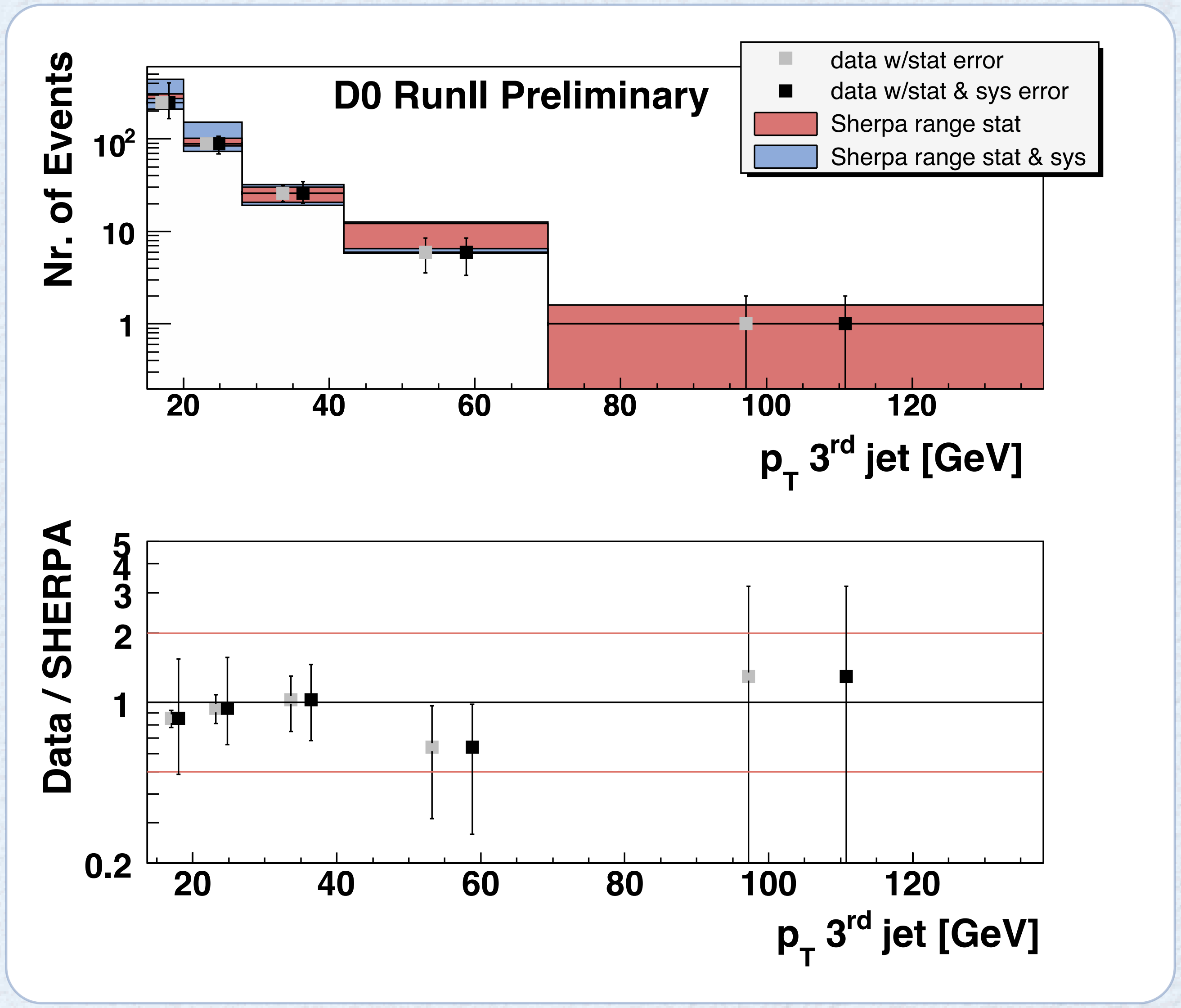
- Sherpa 1.0
  normalized to data

CKKW: Z+Jets @ Tevatron

The DØ collaboration, DØ note 5066-CONF

- Jet-p_T, jet 3





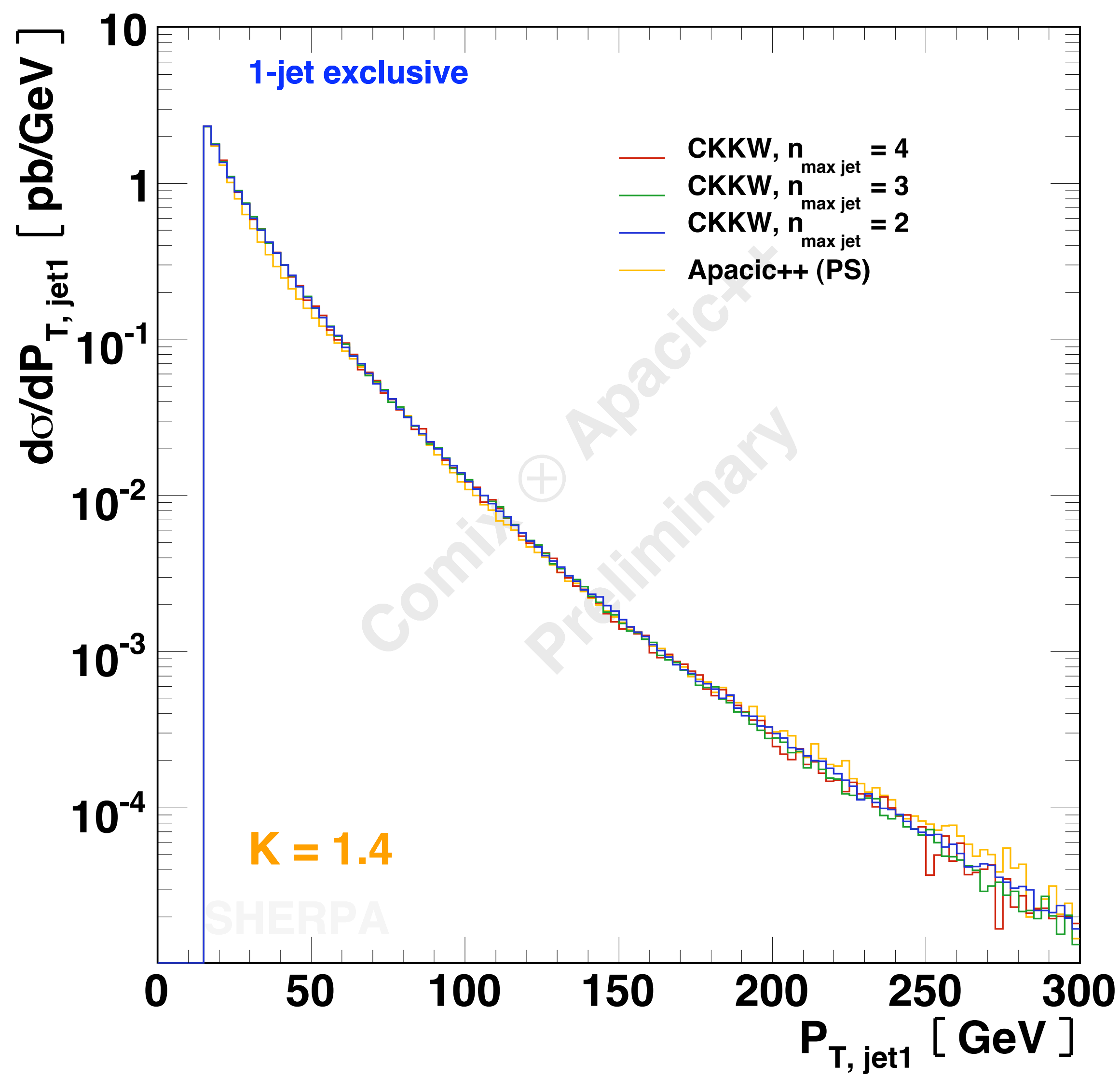
- Pythia 6.2
  normalized to data

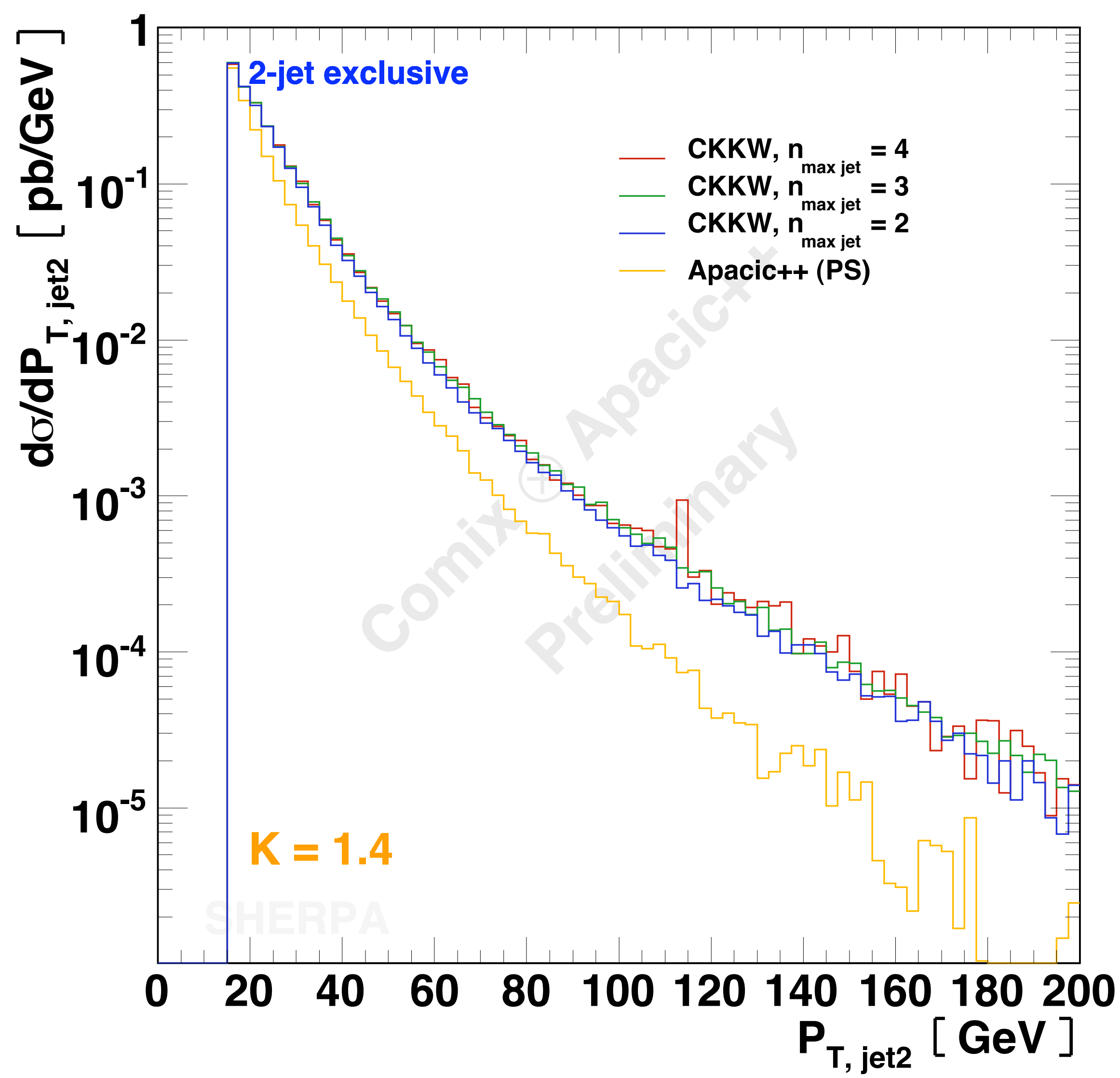
- Sherpa 1.0
  normalized to data

CKKW WITH COMIX

F. Krauss, SH, S.Schumann, F. Siegert: in preparation

- pp→ll+jets at the Tevatron
  exclusive jet-p_T

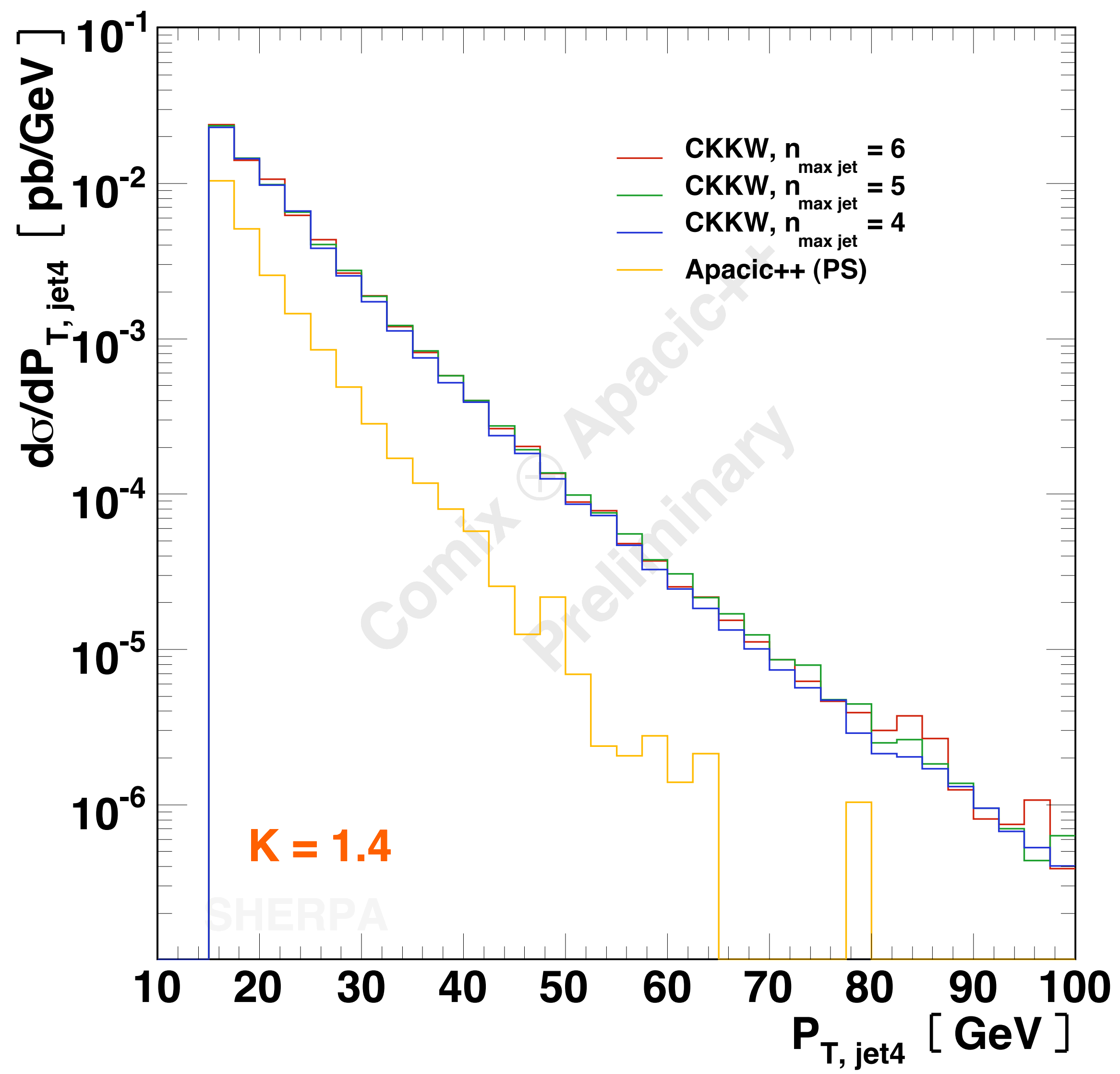


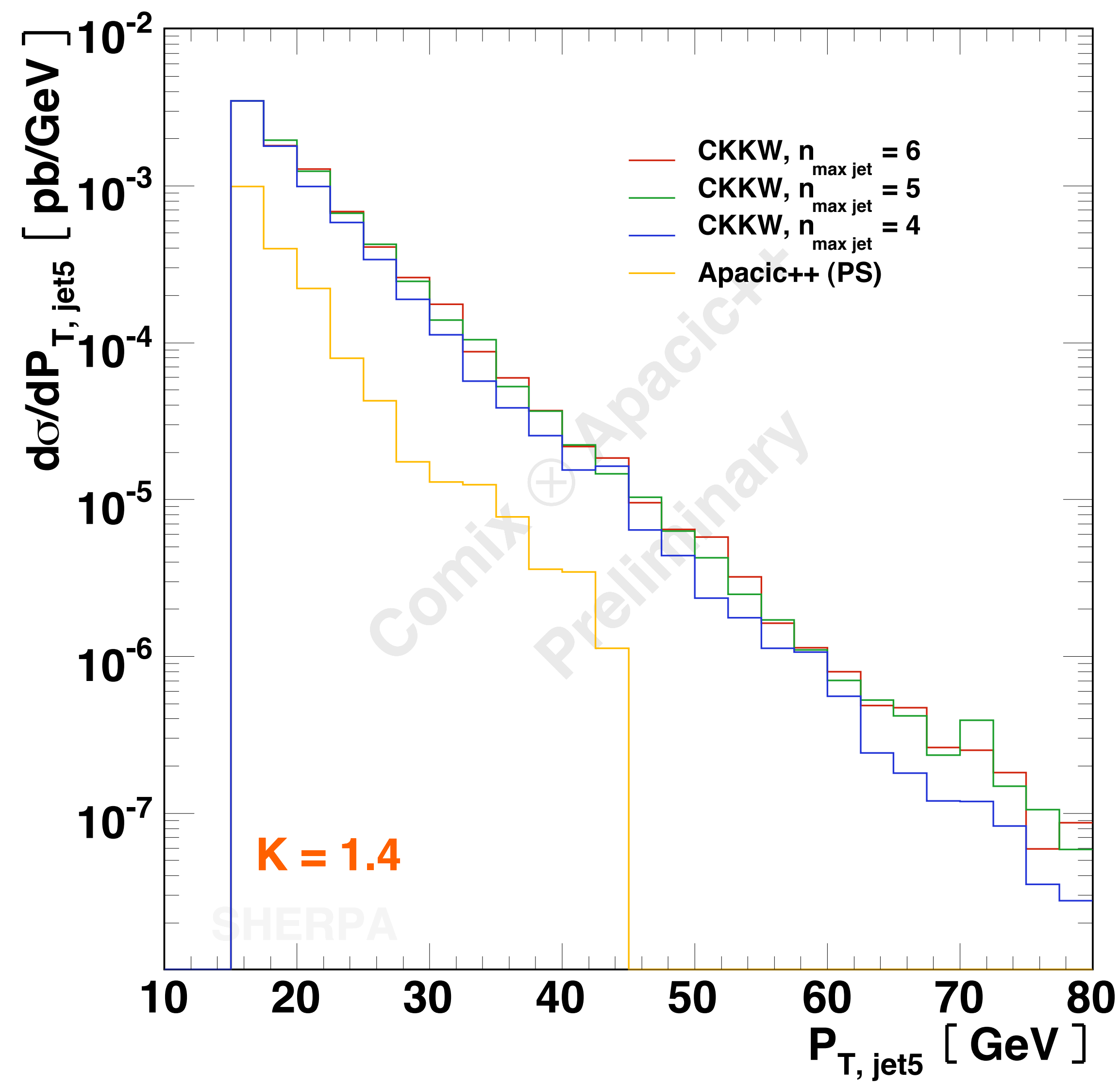


CKKW WITH COMIX

F. Krauss, SH, S.Schumann, F. Siegert: in preparation

- pp→ll+jets at the Tevatron
  inclusive jet-p_T

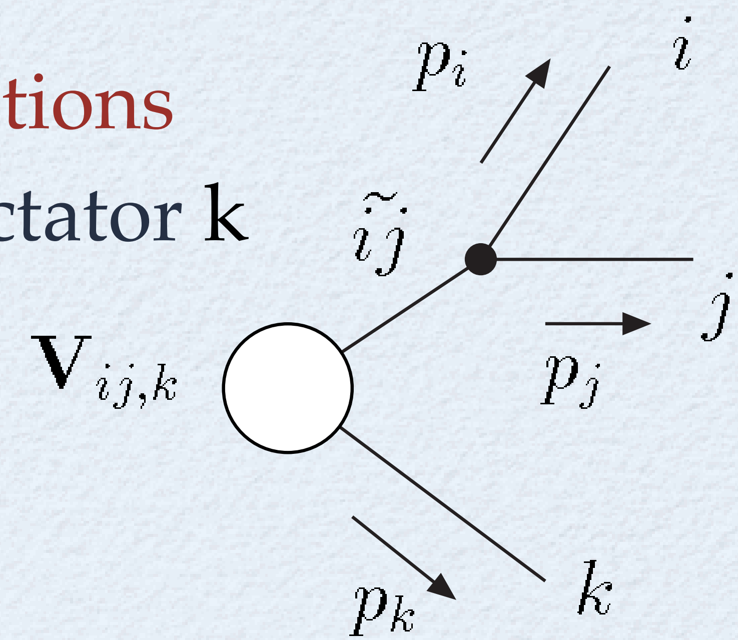




CS-Subtraction based Shower

JHEP03(2008)038

- Catani-Seymour subtraction terms
  ➜ General framework for QCD NLO calculations
- Splitting of parton $\tilde{\mathbf{ij}}$ 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:

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

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

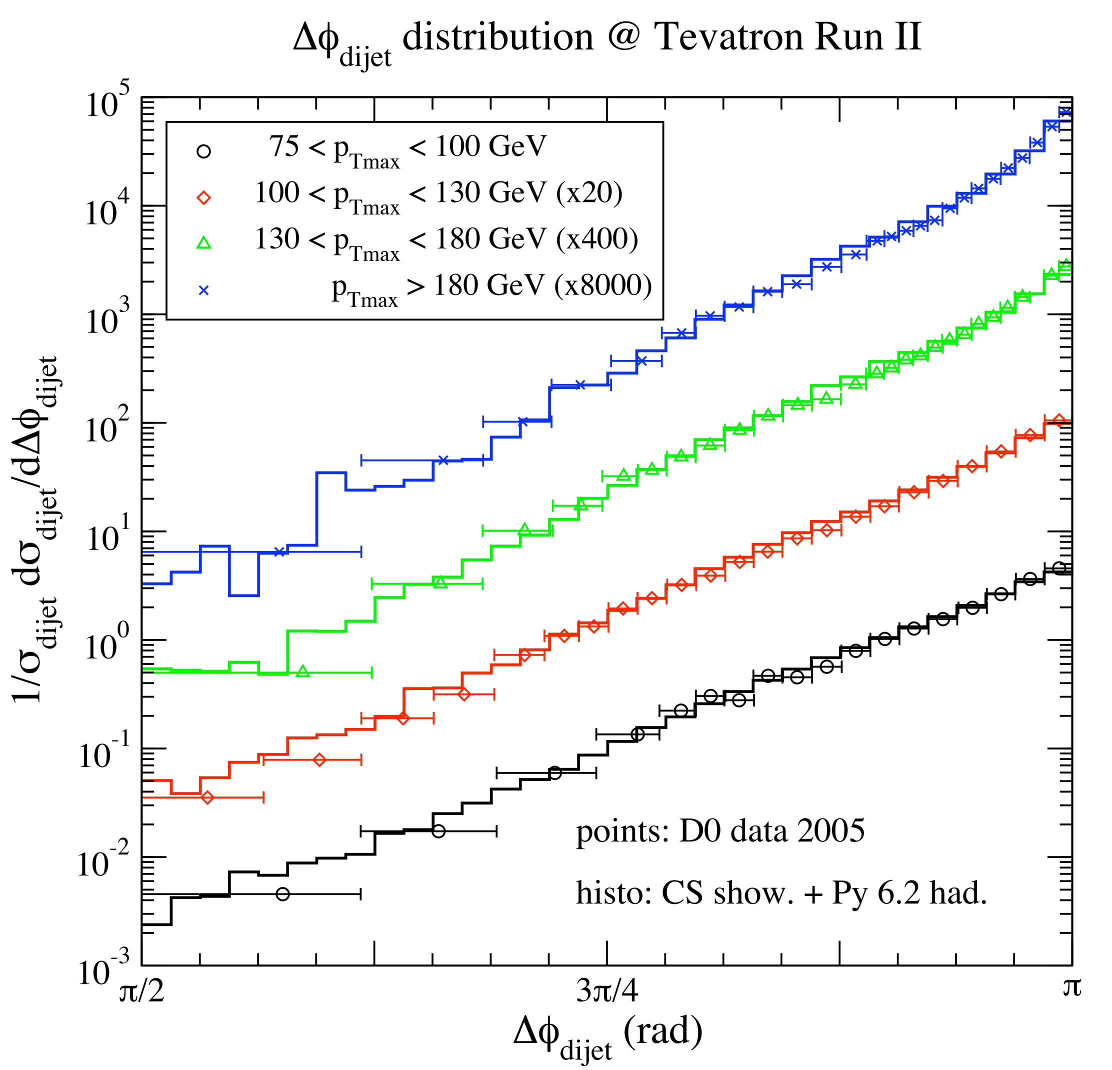
$$y_{ij,k} = \frac{p_i p_j}{p_i p_k + p_j p_k + p_i p_j}$$

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

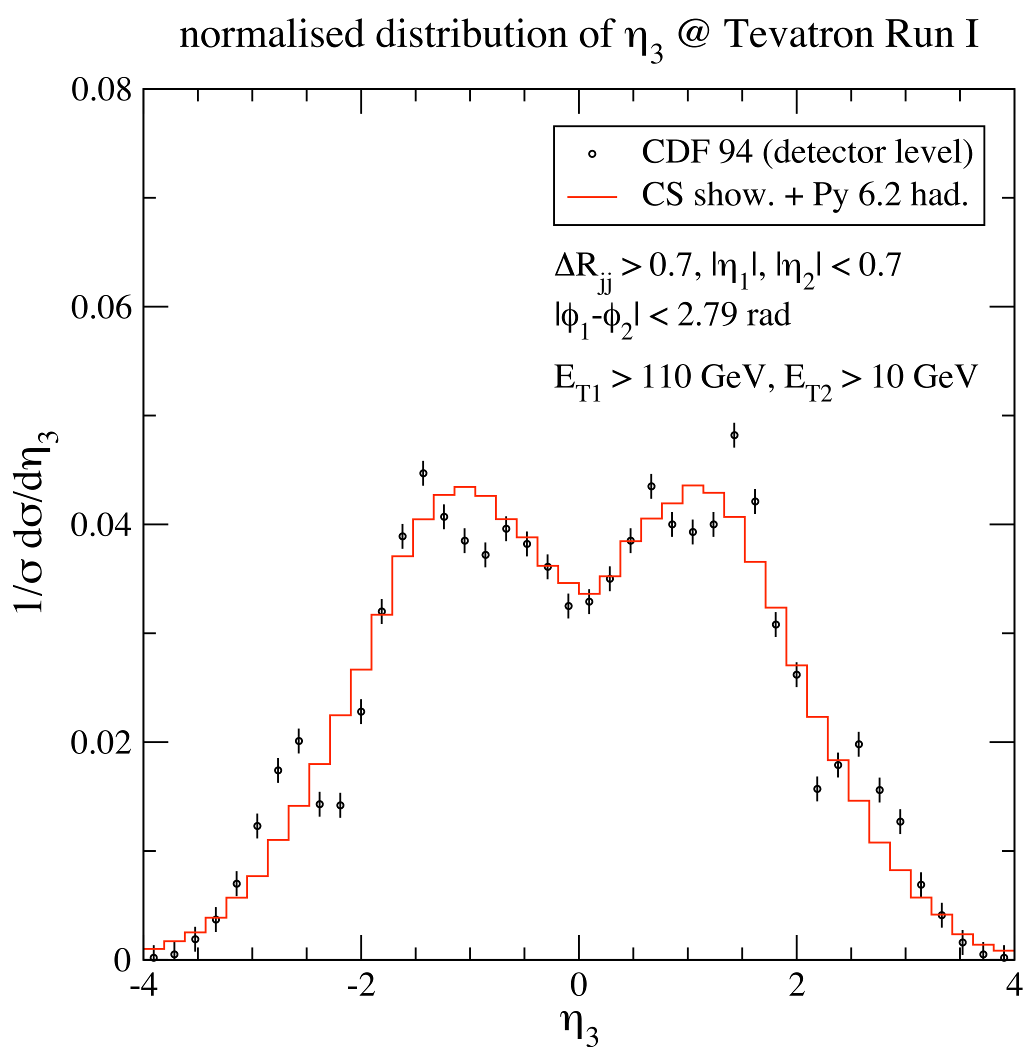
CS-subtraction based shower

JHEP03(2008)038

- $pp \to$ jets
  Phys. Rev. Lett. 94 (2005) 221801



- $pp \to$ jets
  Phys. Rev. D50 (1994) 5562

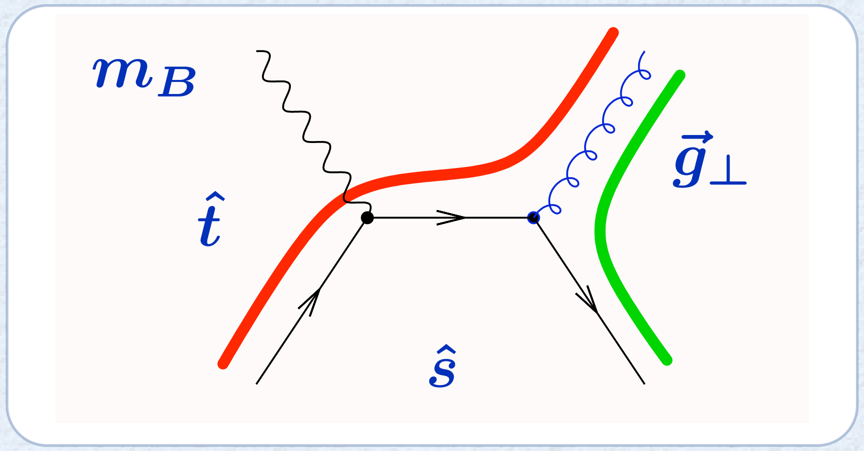


Dipole shower for hadron collisions

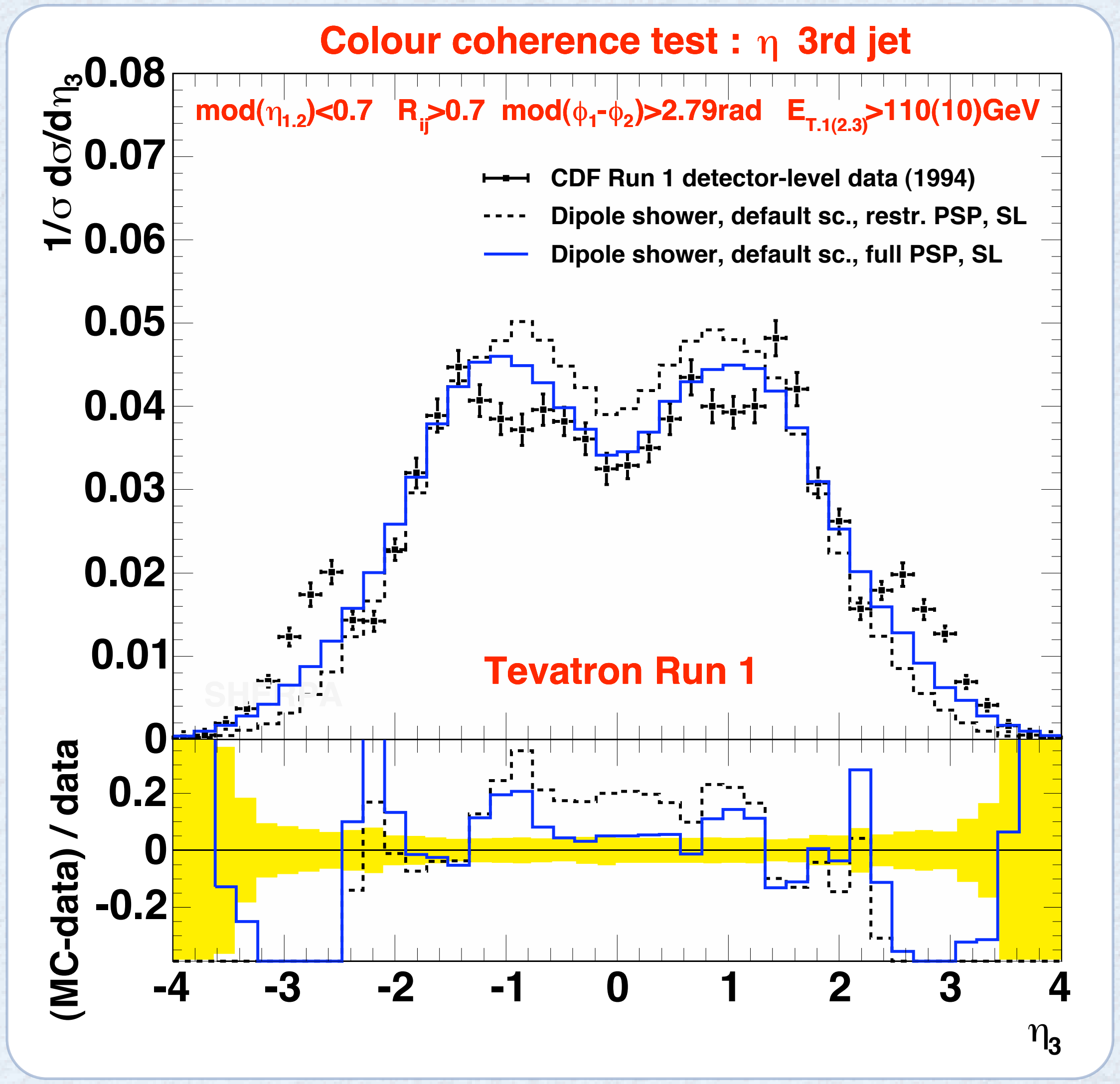
arXiv: 0712.3913 [hep-ph]

- IS emission formulated completely perturbative
- Radiation associated to inital-inital, initial-final and final-final colour lines (dipoles)
- Beam remnants kept outside
- Transverse momentum and rapidity defined through invariants, e.g. Drell-Yan:

$$\mathbf{p}_\perp^2 = \frac{\hat{\mathbf{u}}\hat{\mathbf{t}}}{\mathbf{m}_\mathbf{B}^2} \qquad \mathbf{y} = \frac{1}{2}\ln\frac{\hat{\mathbf{u}}}{\hat{\mathbf{t}}}$$

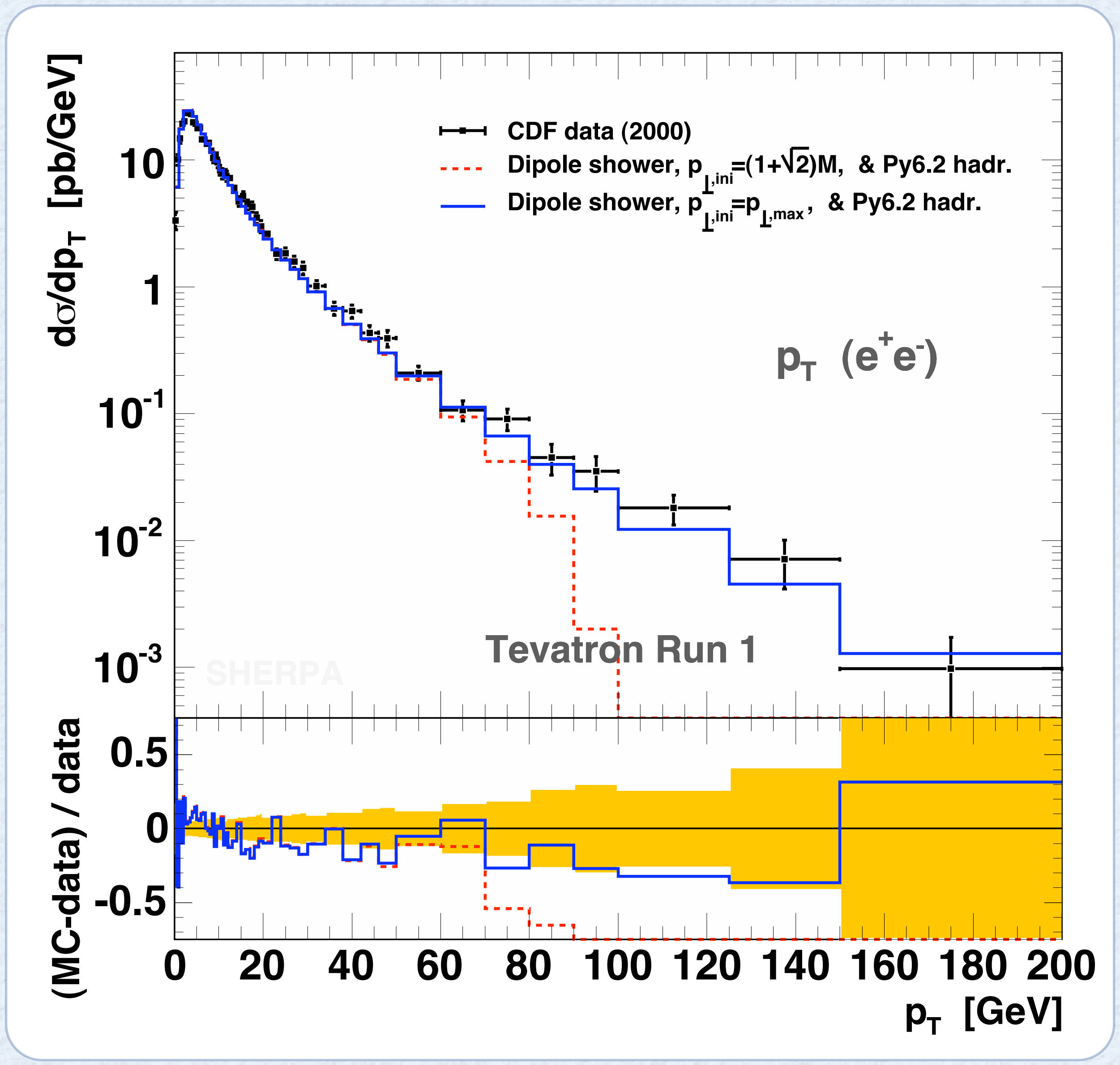


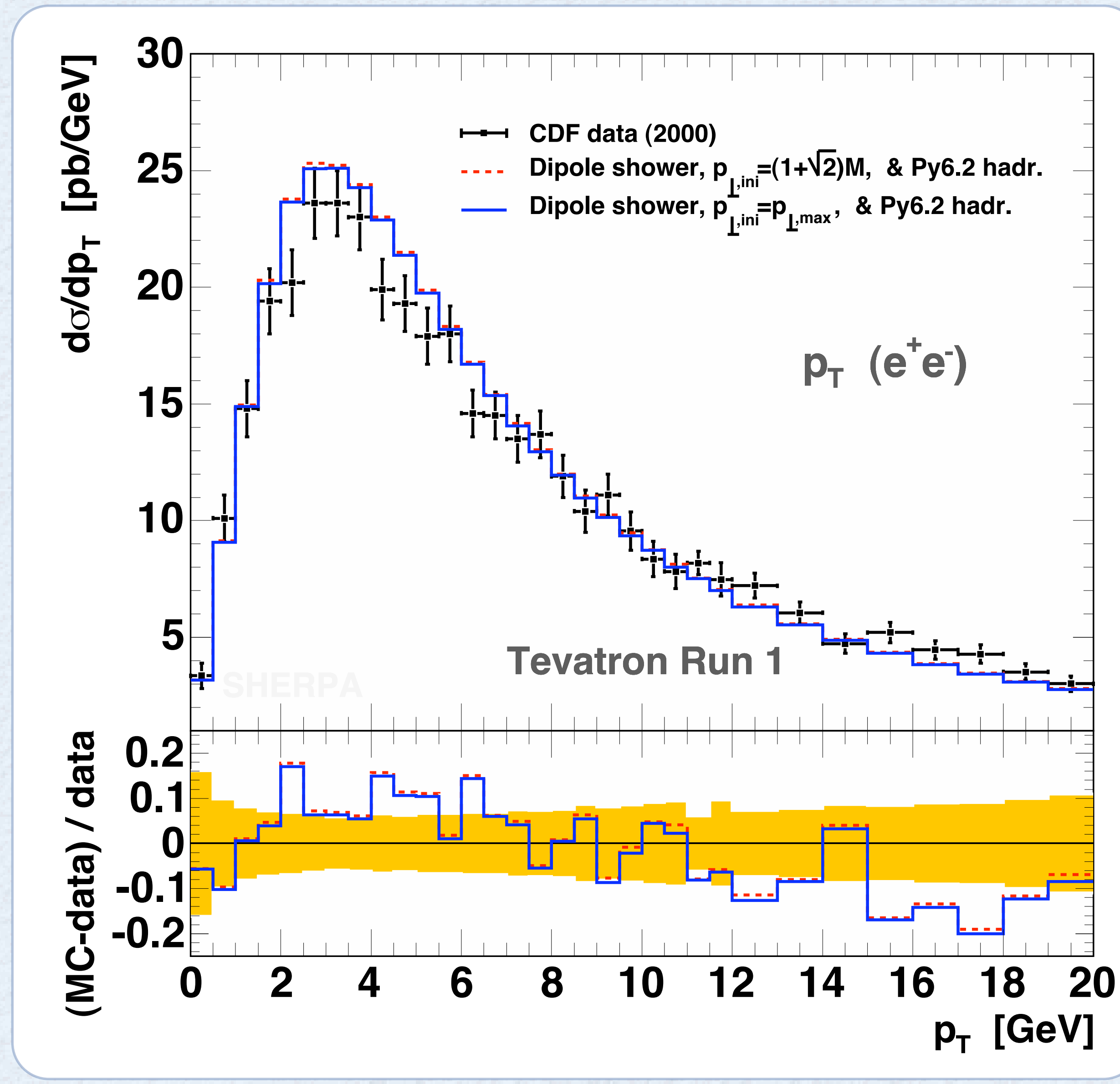
- pp→jets Phys. Rev. D50 (1994) 5562



arXiv: 0712.3913 [hep-ph]

- First emission by construction ME-corrected



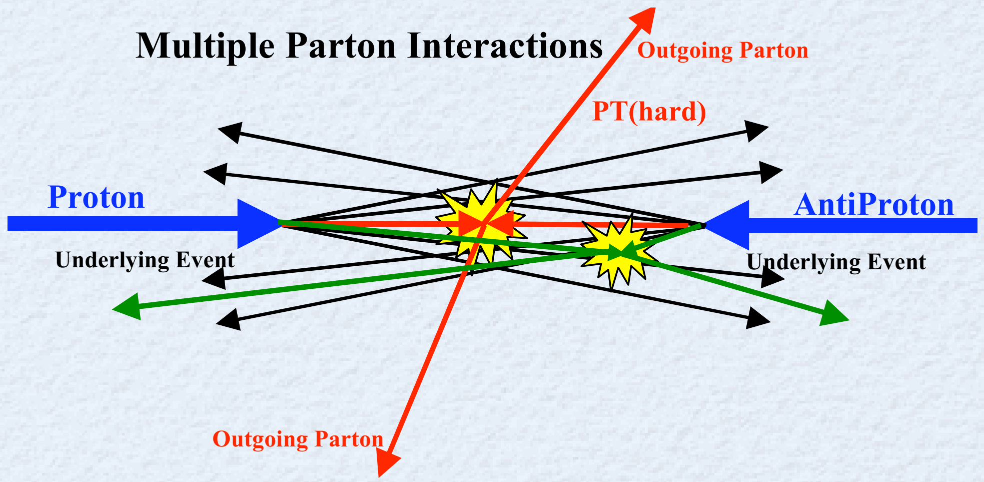


MPI simulation in Sherpa

hep-ph/0601012

Sherpas current multiple parton interaction (MPI) module

- Based on the PYTHIA model
  T. Sjöstrand & M. van Zijl, PRD36(1987)2019
- Parton showers (PS) attached to secondary interactions



Combination of MPI's with hard processes and CKKW matching

- Hard processes with final state multiplicity different from two require unique definition of starting scale for MI evolution, μ_{MI}
- Sherpa algorithm (works for arbitrary n-jet ME):
  - Employ K_T-algorithm to define 2→2 core process
  - Set starting scale μ_{MI} to p_T of final state QCD parton(s) from this process and veto partons harder than μ_{MI} (from PS) in secondary interactions

MPI results from SHERPA

hep-ph/0601012

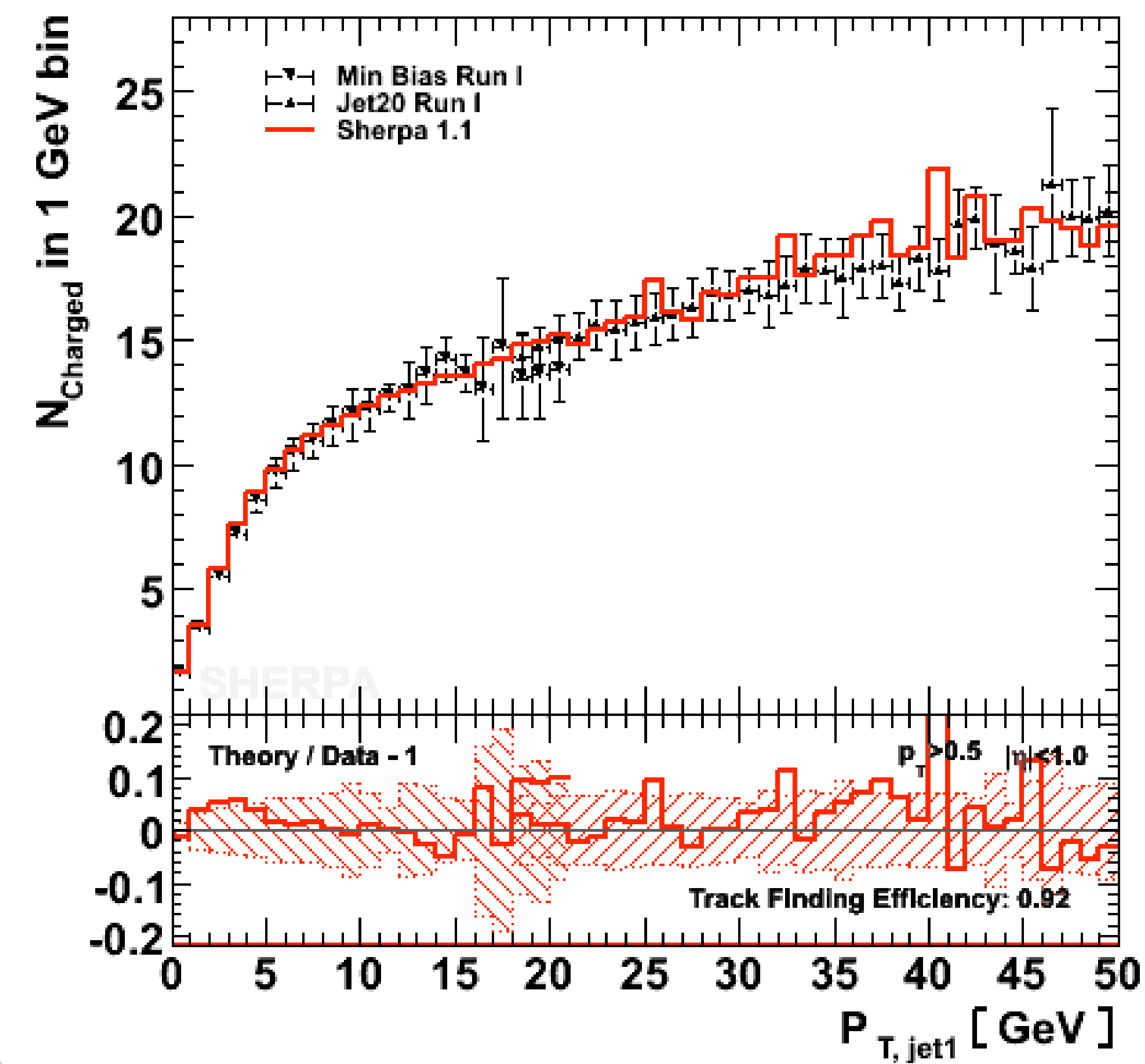
Our current "best fit" for CDF

- Lower p_T - cutoff
  - ➜ $\mathbf{p}_{\mathrm{T,min}} \approx \mathbf{2.4}$ GeV
- Moderate interaction number due to additional multiplicity from PS
  - ➜ $< \mathbf{N}^{\mathbf{2\to2}}_{\mathrm{hard}} > \approx \mathbf{2.08}$

To take home ...

- Highly dependent on $p_{T,min}$ and PDF
- Does not give any prediction for the LHC (naive scaling)

- $N_{Charged}$ vs. $p_{T,jet1}$ in CTC



Towards a new MPI model

arXiv: 0705.4577 [hep-ph]

Shortcomings of the current MPI model

- Lower p_T - cutoff defines total cross section
- Energy extrapolation depends on tuning parameter

We try to solve part of this by ...

- Definiton of hard cross section through BFKL kernel convoluted with DUPDF's ➜ can be extended into diffractive region

$$\sigma = \frac{\pi^2}{2S}\sum_{a^{(1)}}\int \mathrm{d}y_1 \int \mathrm{d}k_{1\perp}^2 \int \mathrm{d}\phi_1 \int \mathrm{d}y_n$$

$$\times\; f^{(1)}(x^{(1)}, z^{(1)}, k_{1\perp}^2, \bar{k}_{2\perp}^{(1)2})\, f^{(2)}(x^{(2)}, z^{(2)}, k_{n\perp}^2, \bar{k}_{n-1\perp}^{(2)2})\,\frac{1}{2\xi^{(1)\,2}\xi^{(2)\,2}S}\,\frac{1}{\Delta_{a_1}(y_1, y_2)}$$

$$\times \left[\prod_{i=2}^{n}\int\frac{\mathrm{d}\phi_i}{2\pi}\int \mathrm{d}y_i \int \frac{\mathrm{d}k_{i\perp}^2}{k_{i\perp}^2}\,\frac{\alpha_s(k_{i\perp}^2)}{\pi}\sum_{a_i} C_{a_{i-1}a_i}(q_{i-1}, k_i)\,\Delta_{a_i}(y_i, y_{i-1})\right]$$

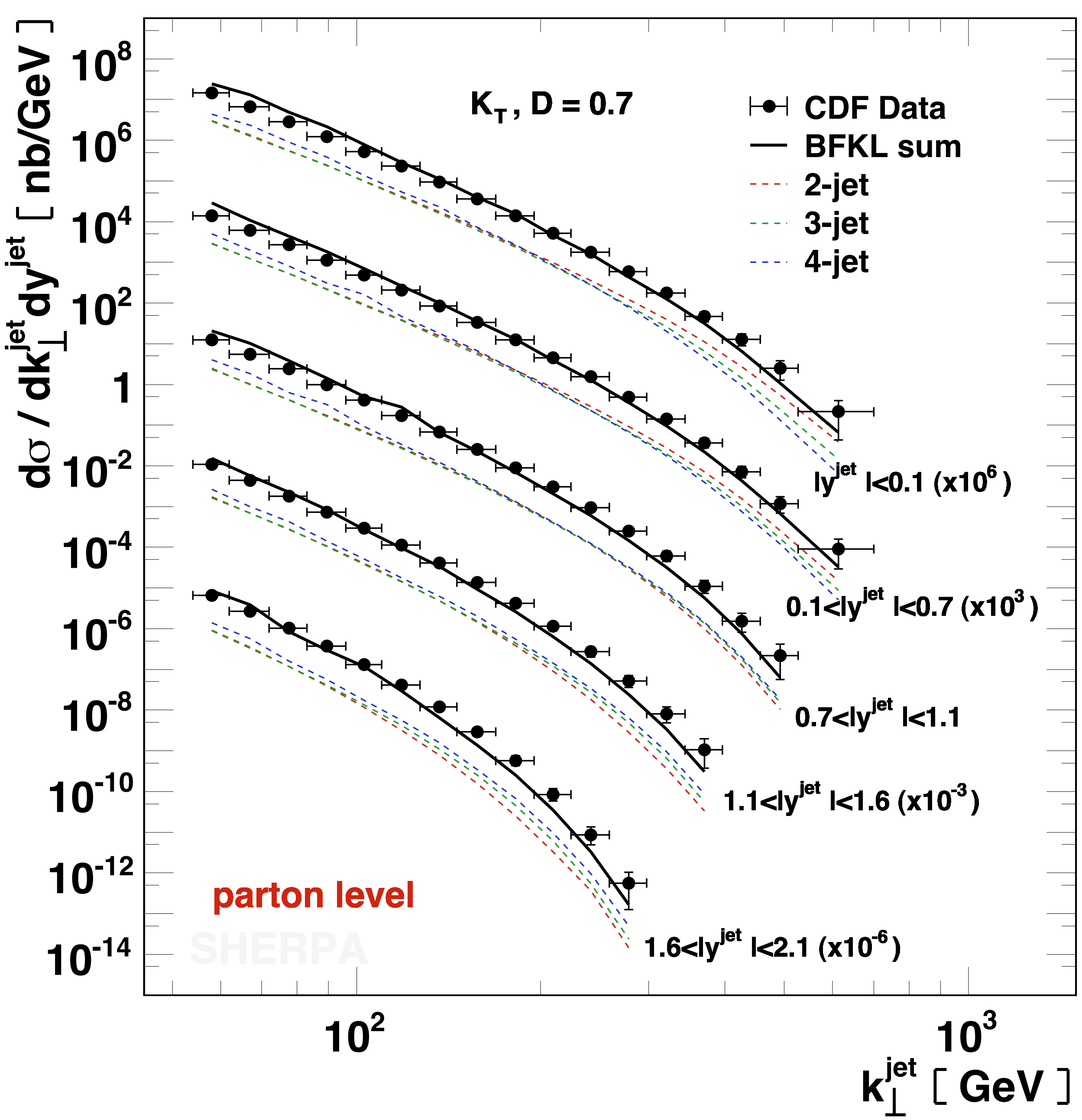
Markovian algorithm to generate splittings from $\Delta_{a_i}(y_i, y_{i-1})$ in the spirit of a parton shower

➜ number of emissions determined on the flight

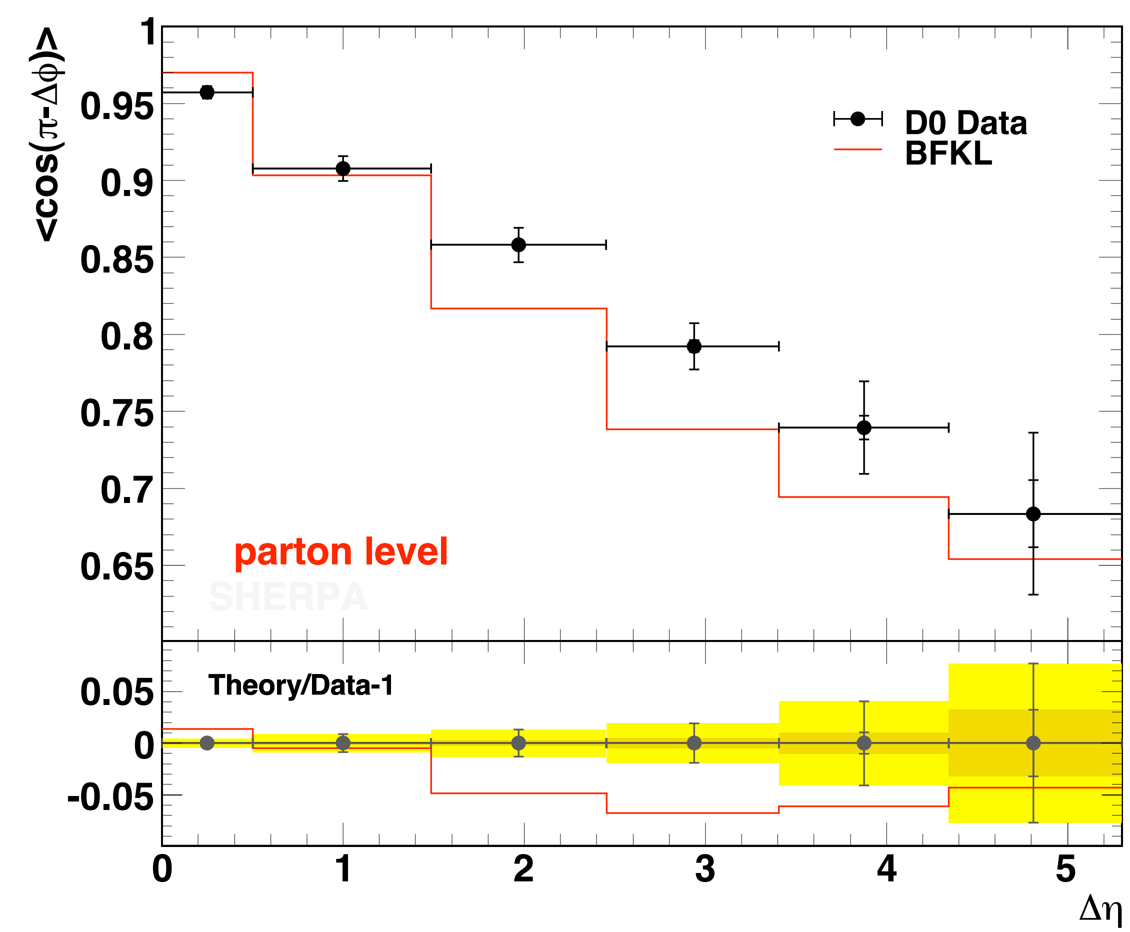
Towards a new MPI model

arXiv: 0705.4577 [hep-ph]

- Jet - p_T spectra PRD75(2007)092006



- Azimuthal decorrelation of widely separated jets PRL77(1996)595



Summary and Outlook

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

Sherpas and collaborators currently also work on:

- 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)
  and LHCb software → SH, F. Siegert, J. Stieglitz (Durham/Dortmund)
- **Grid support**: At the IPPP, we run **Sherpa on the Grid !**
  Multithreading: Speed up your computation with more CPU's !

Latest release: Version 1.1.1
available on Genser and HepForge

Updates on Sherpa can be found on

www.sherpa-mc.de

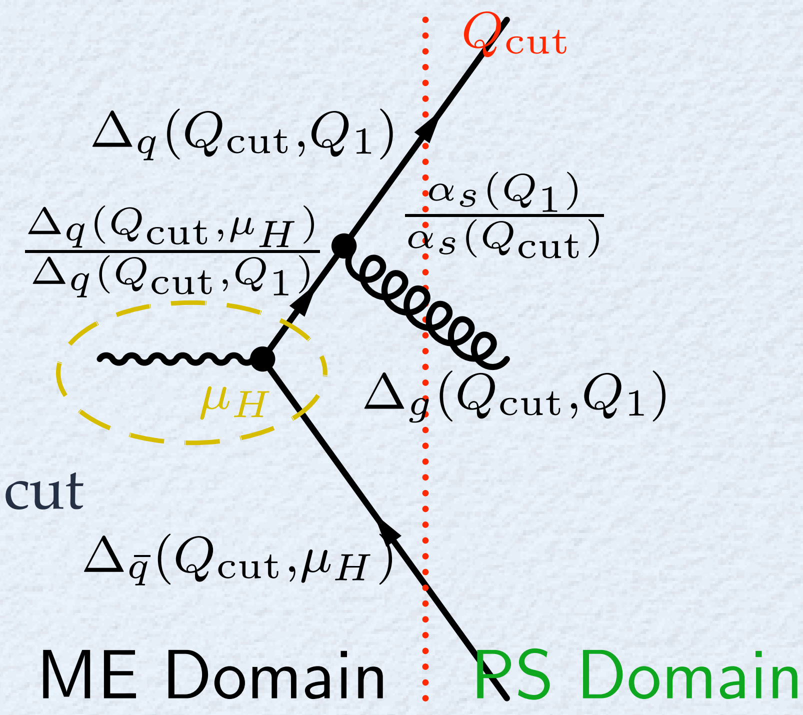
E-mail us at

info@sherpa-mc.de

CKKW in a nutshell

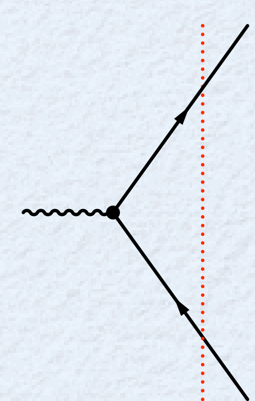
JHEP 0111 (2001) 063
JHEP 0208 (2002) 015

- 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}
- K_T -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 observables !
Generic example: 2-jet rate in ee→qq

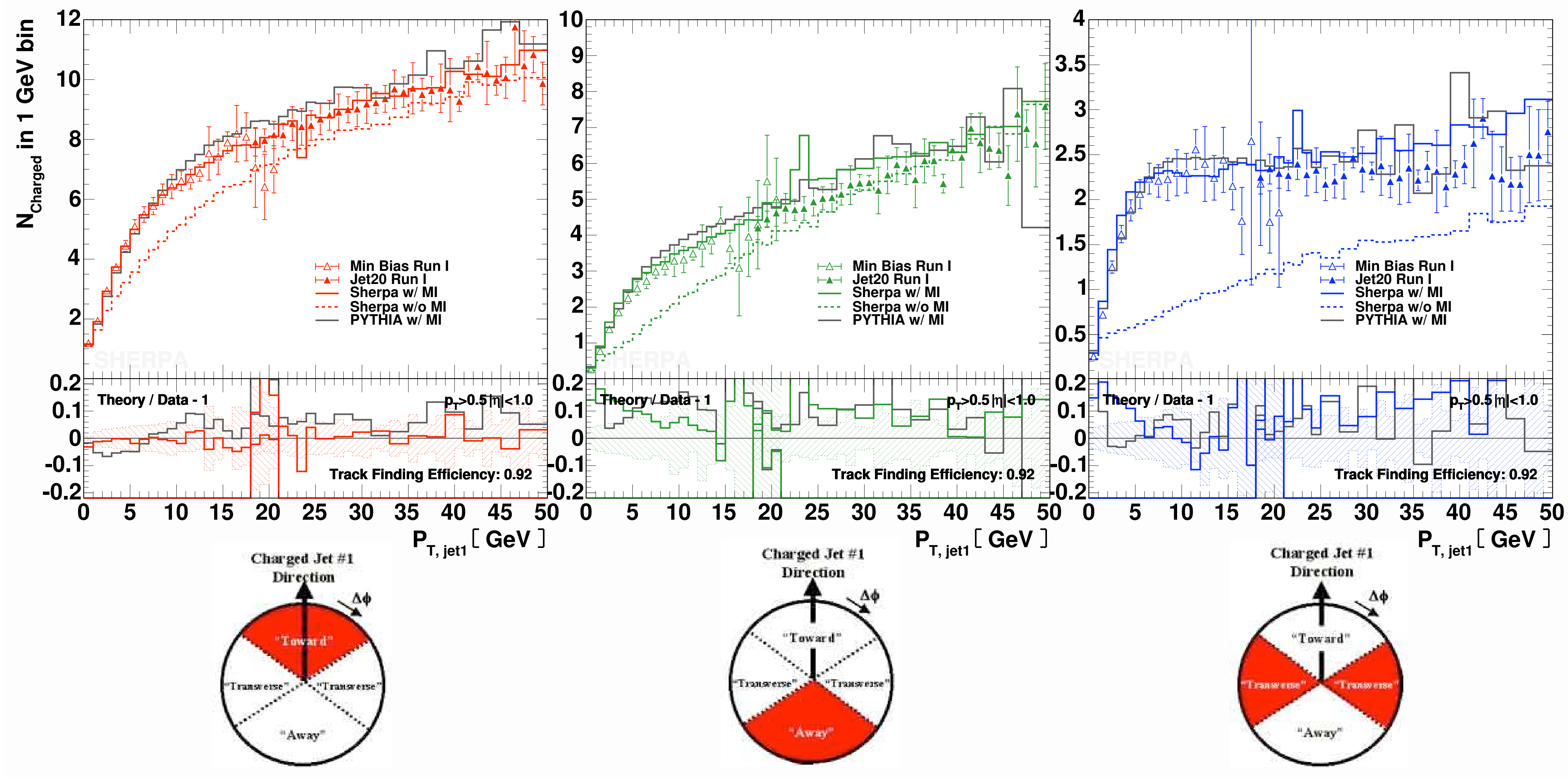
$$\mathbf{R_2(q)} = \left(\mathbf{\Delta(Q_{cut},\mu_{hard})} \frac{\mathbf{\Delta(q,\mu_{hard})}}{\mathbf{\Delta(Q_{cut},\mu_{hard})}} \right)^{\mathbf{2}}$$



MPI results from SHERPA

hep-ph/0601012

- $N_{Charged}$ vs. $p_{T,jet1}$ in CTC
  in different regions w.r.t. leading charged particle jet



MPI results from SHERPA

hep-ph/0601012

- N_{Charged} vs. $\Delta\varphi_{\text{jet1}}$ in CTC for different p_T of leading charged particle jet