Photon Interactions in Sherpa

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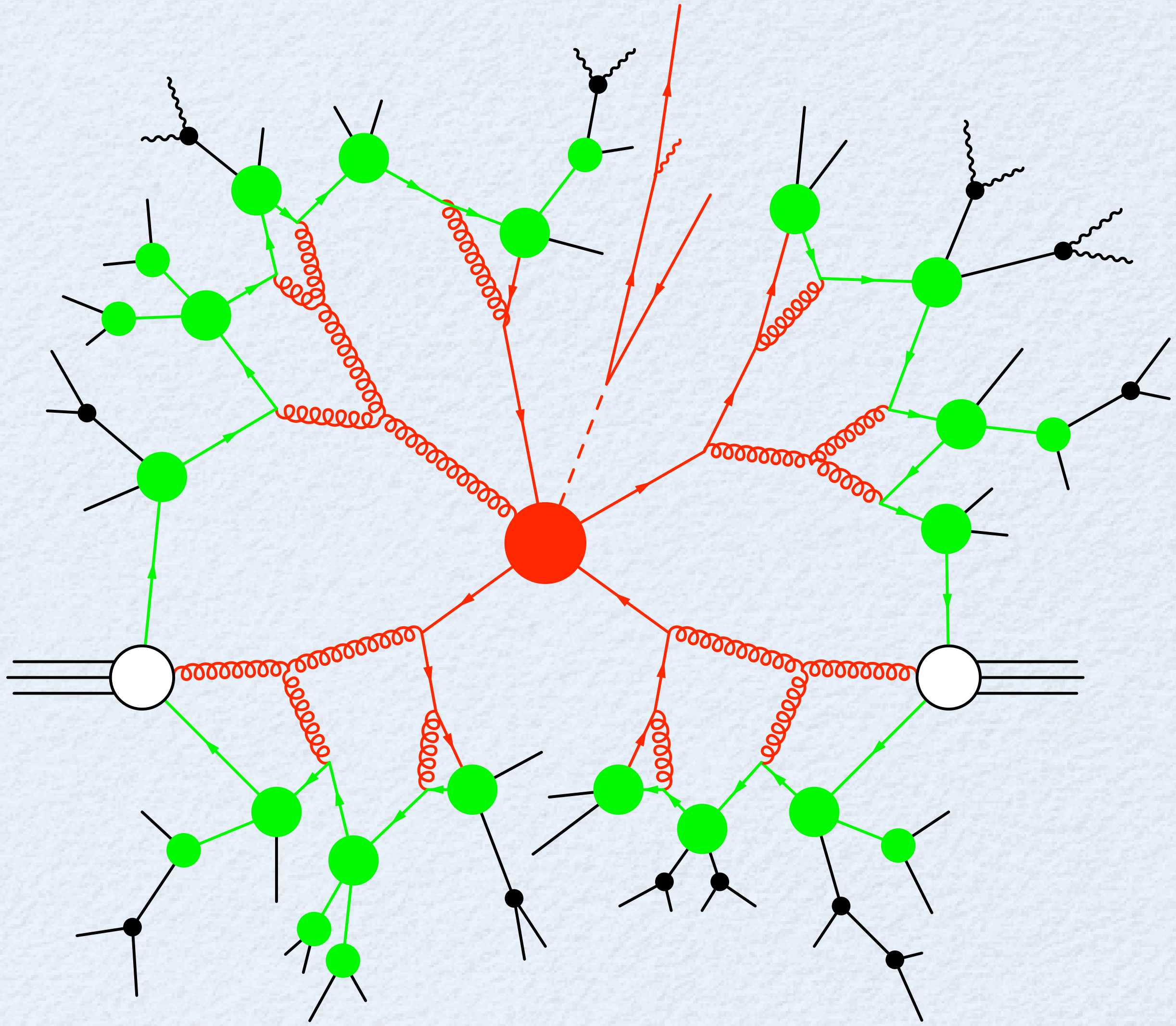
[1] for Sherpa: Tanju Gleisberg, SH, Frank Krauss, Steffen Schumann, Marek Schönherr, Frank Siegert & Jan Winter

OUTLINE

This talk does not contain much about photons ...

So what is it about ?

- 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

How do photons fit in ?

- Sherpa provides γ beamspectrum (p→pγ by T. Pierzchala) & PDF
- all the rest is "standard", so let's talk about the rest first ...

What is CKKW and why ?

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

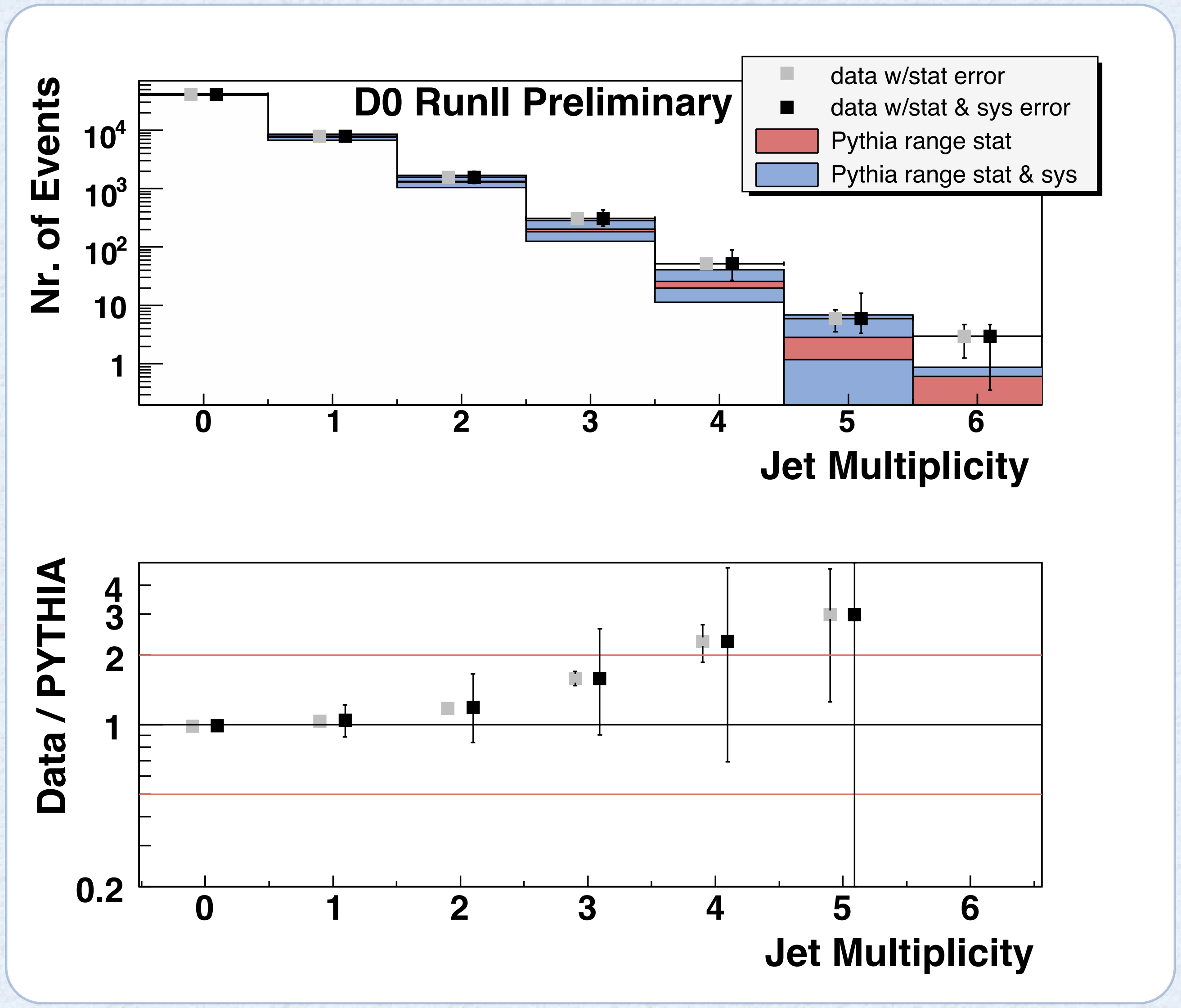
- Good description of hard radiation (ME)
- Correct intrajet evolution (PS)

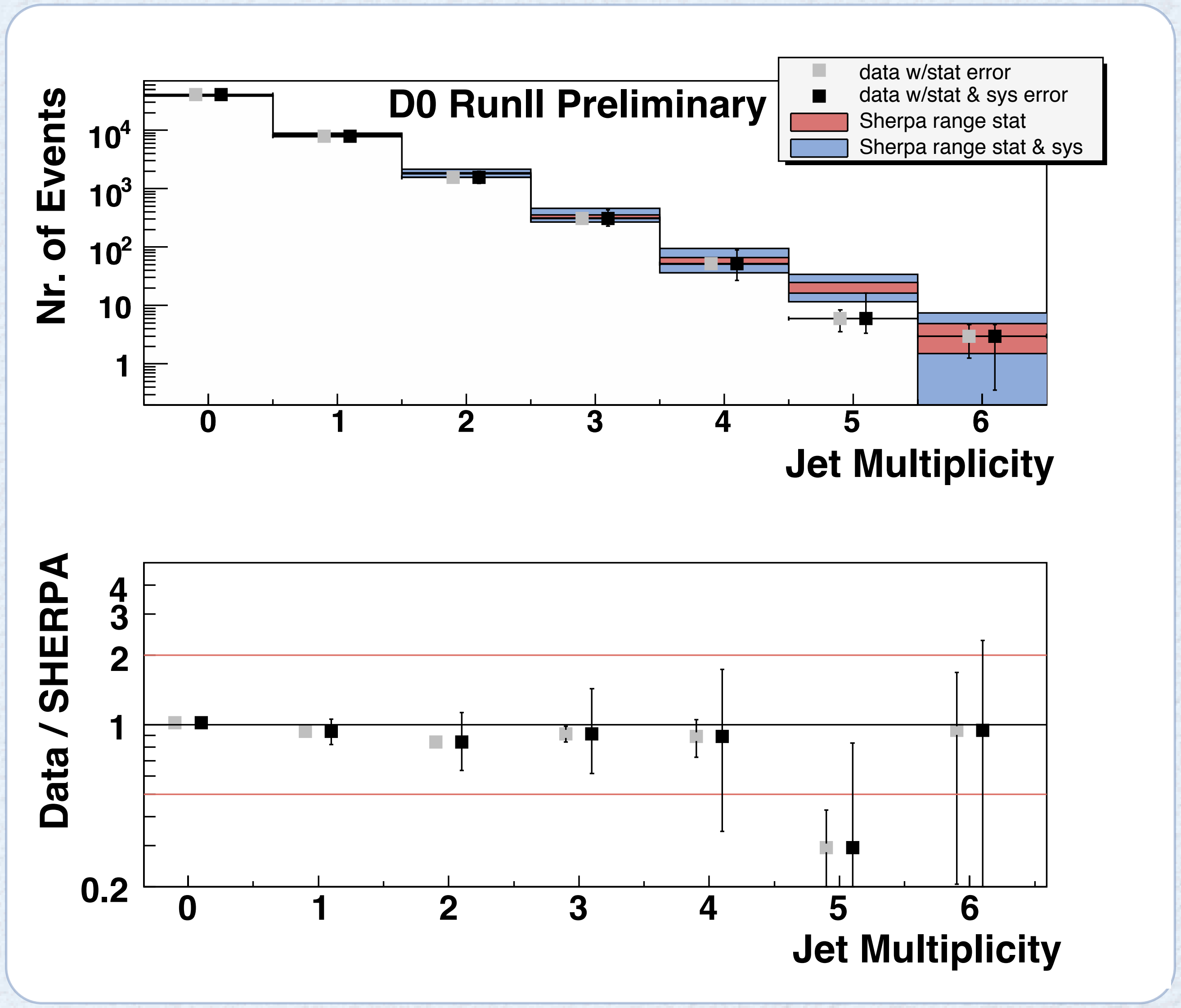
- Strategy: Separate phase space
  - Jet production region → ME
  - Intrajet evolution region → PS
- **Free parameter: Separation cut Q_{cut}** (K_T-type jet measure)

CKKW: Z+Jets @ Tevatron

The DØ collaboration, DØ note 5066-CONF

- Jet multiplicity





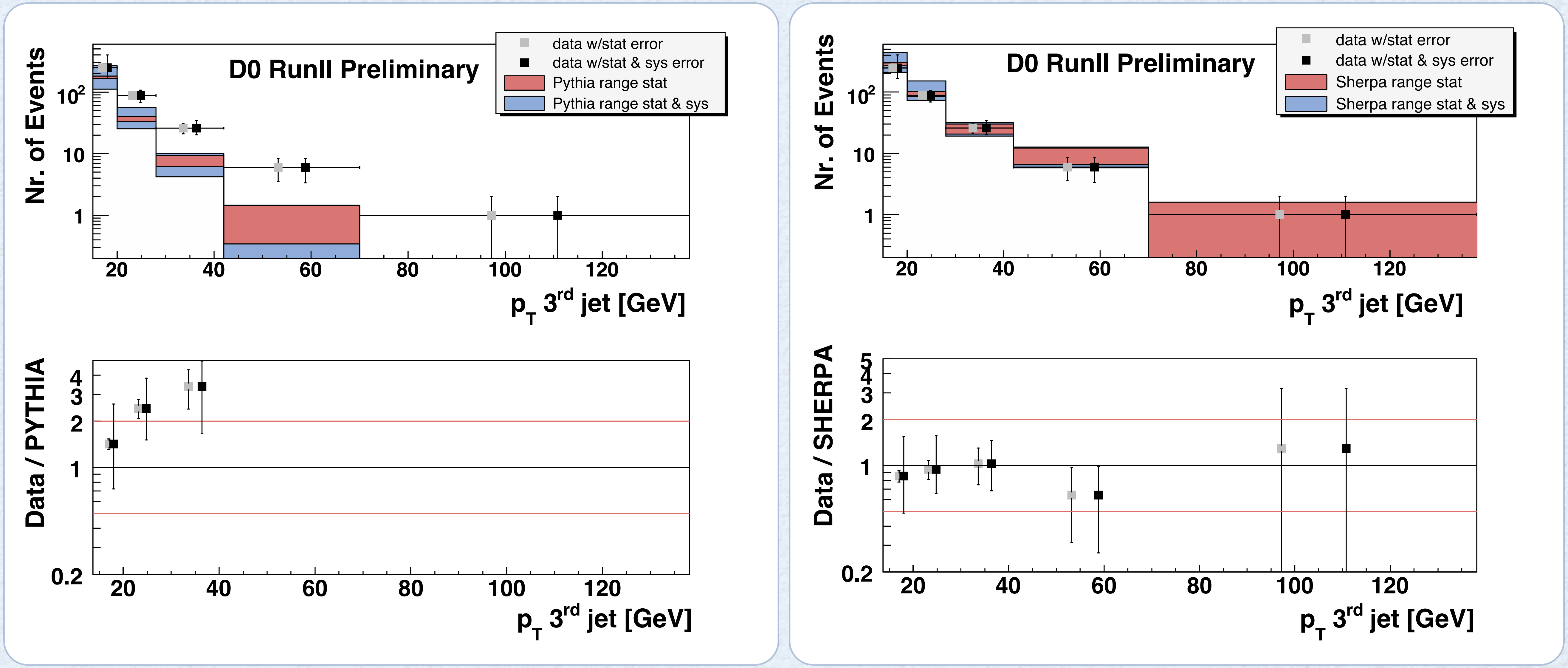
- Pythia 6.2
  normalized to data

- 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
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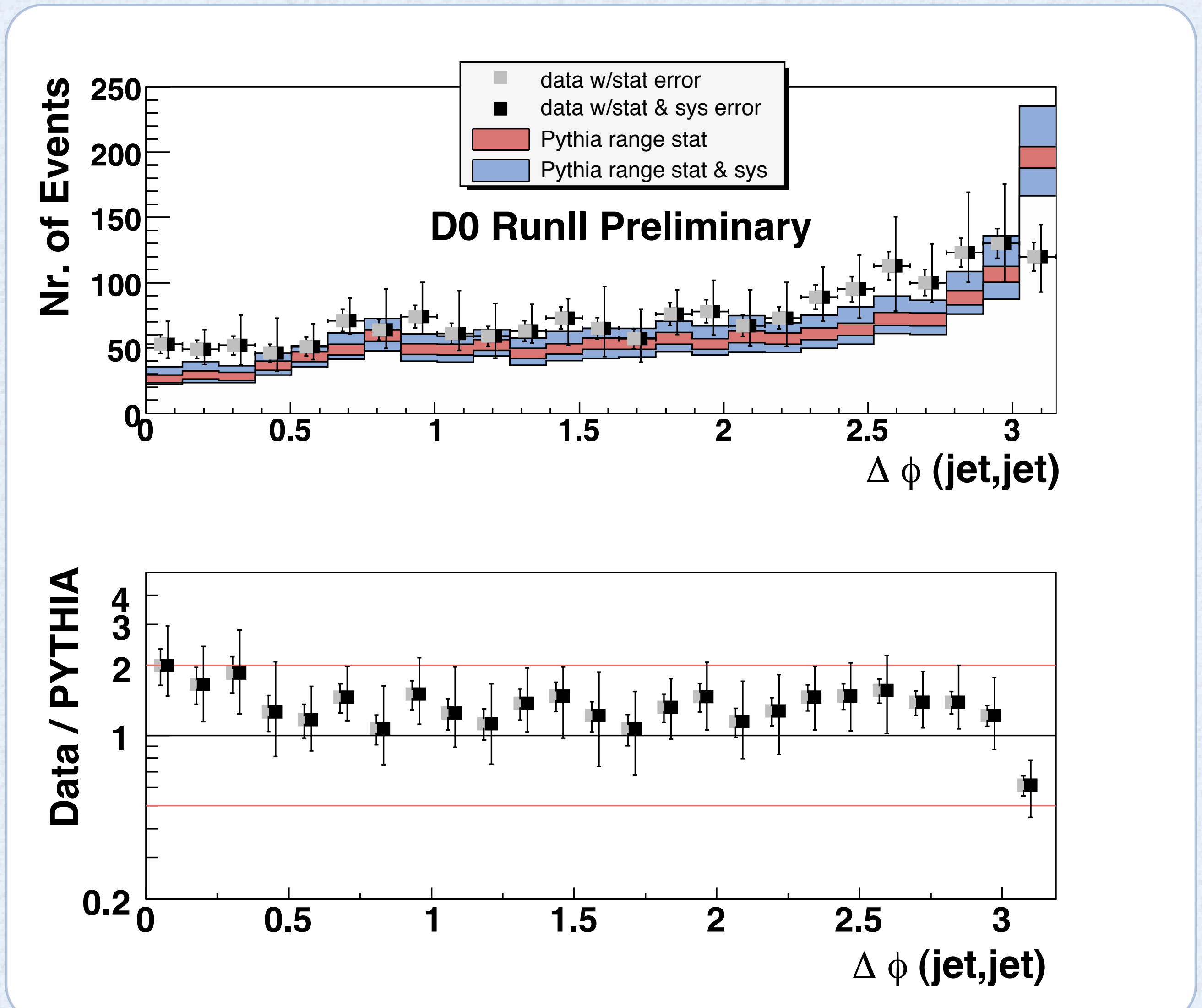
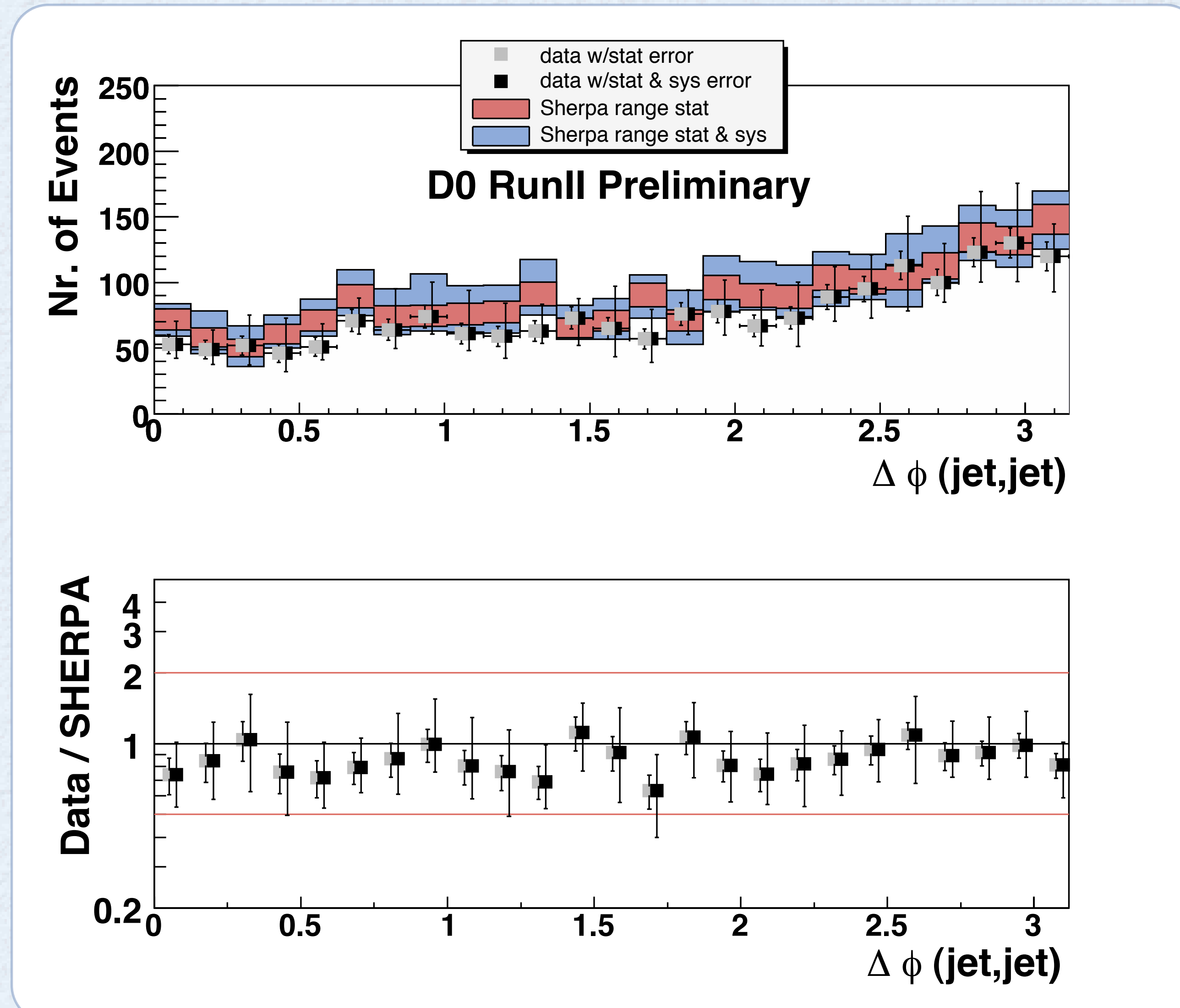
CKKW: Z+jets @ Tevatron

The DØ collaboration, DØ note 5066-CONF

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





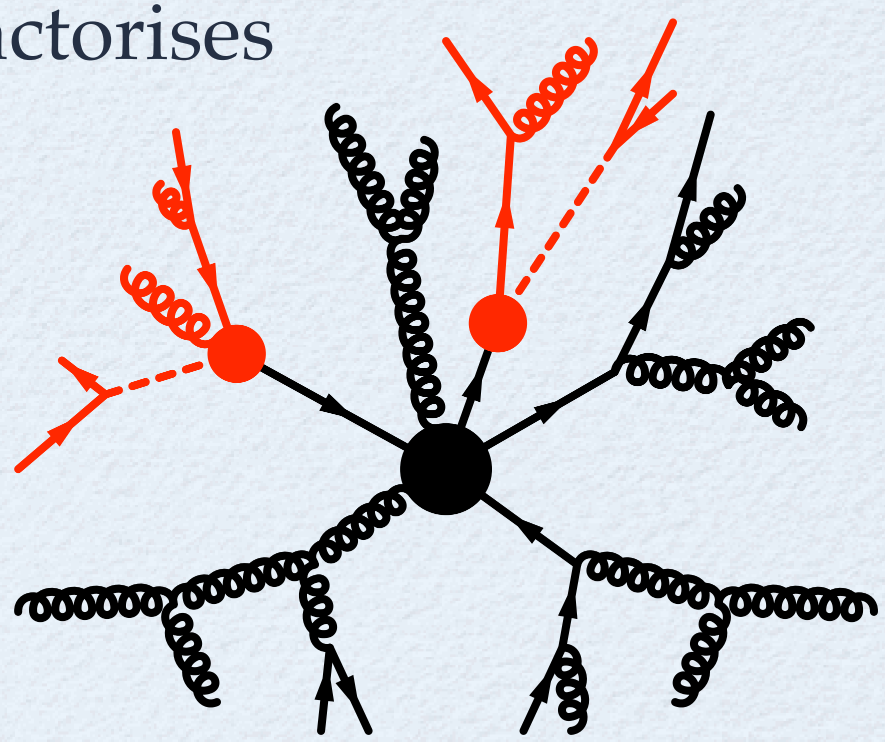
- Pythia 6.2
  normalized to data

- Sherpa 1.0
  normalized to data

CKKW extensions

Consider heavy flavour production

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



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

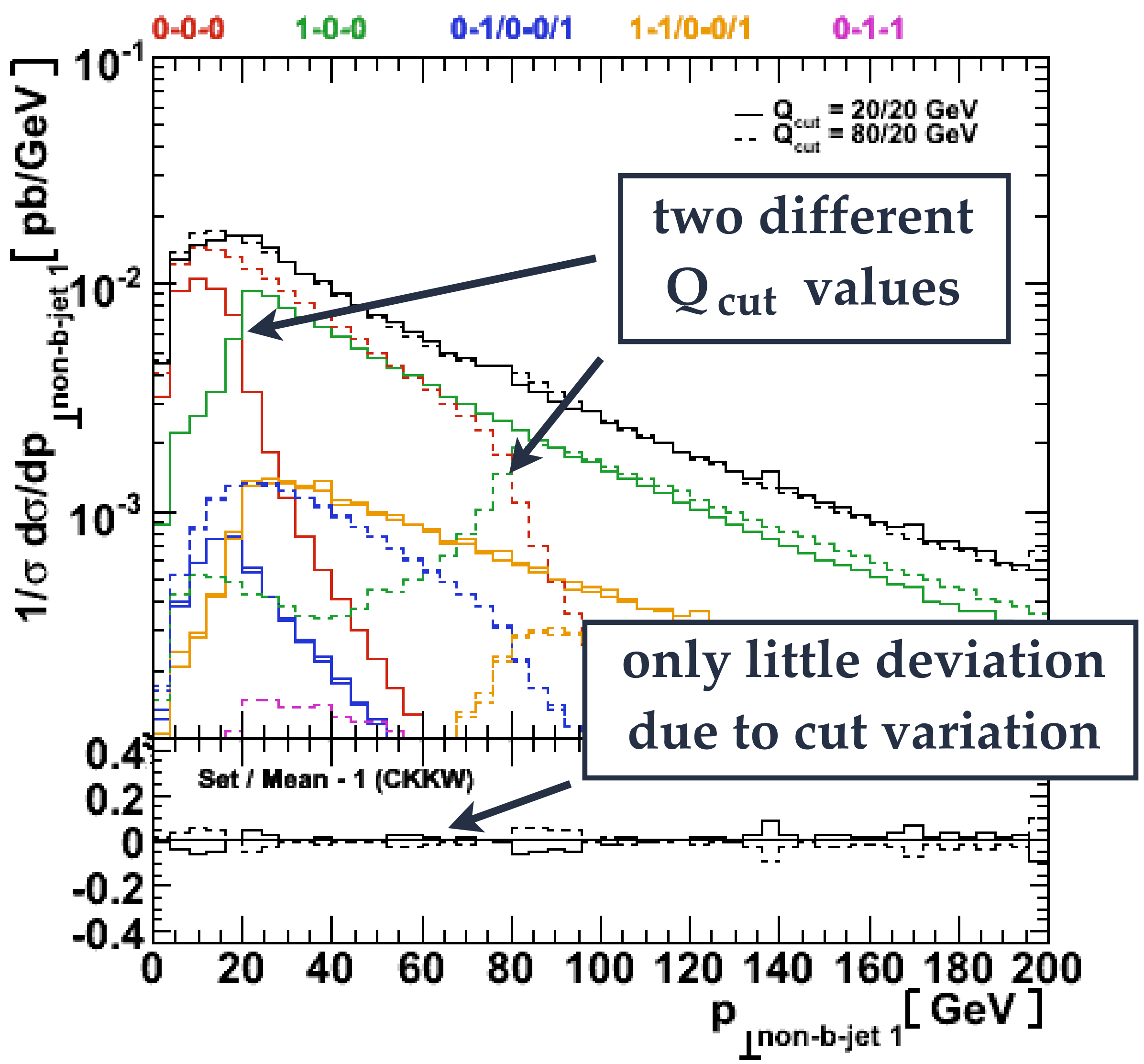
How is it simulated in Sherpa ?

- 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**

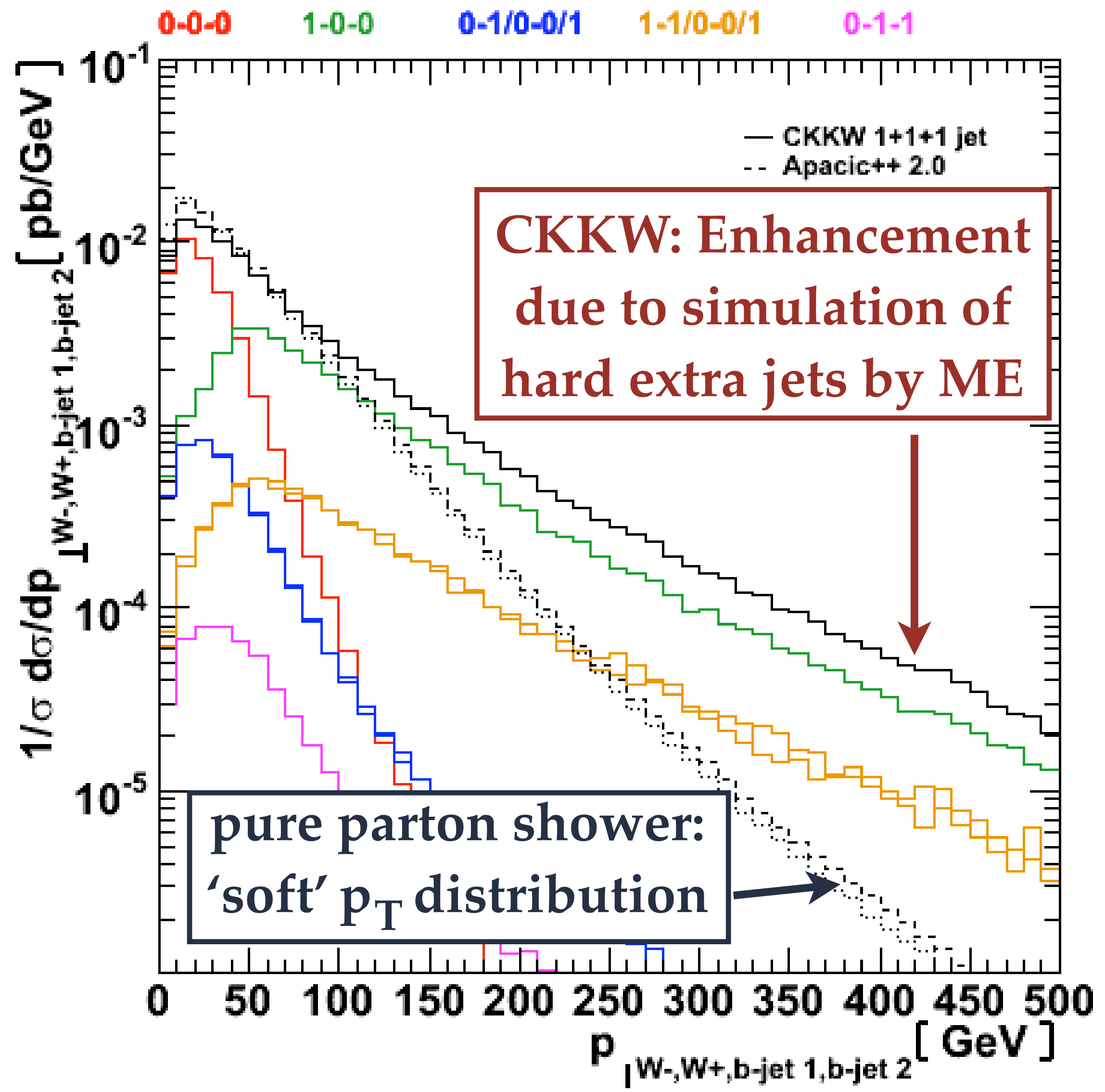
Method is fully general and applicable e.g. in SUSY production

CKKW: Top pairs @ LHC

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



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



ME's in SHERPA: AMEGIC++

R. Kuhn, F. Krauss, G. Soff JHEP 0202:044, 2002

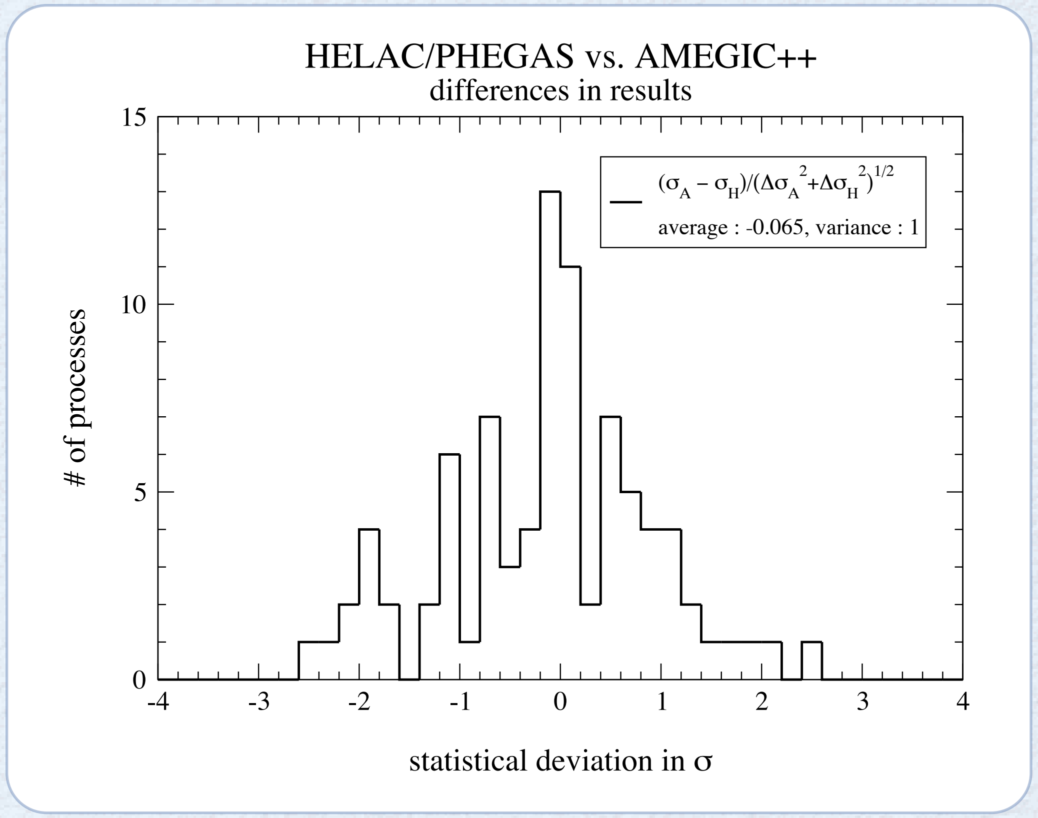
What does AMEGIC++ provide ?

Flexibility

- **Fully automated** calculation of (polarized) cross sections in the SM, MSSM and ADD model
- Expandability: **FeynRules reader, dynamic add-on model libs**
- Performance well comparable to that of dedicated codes

Reliability

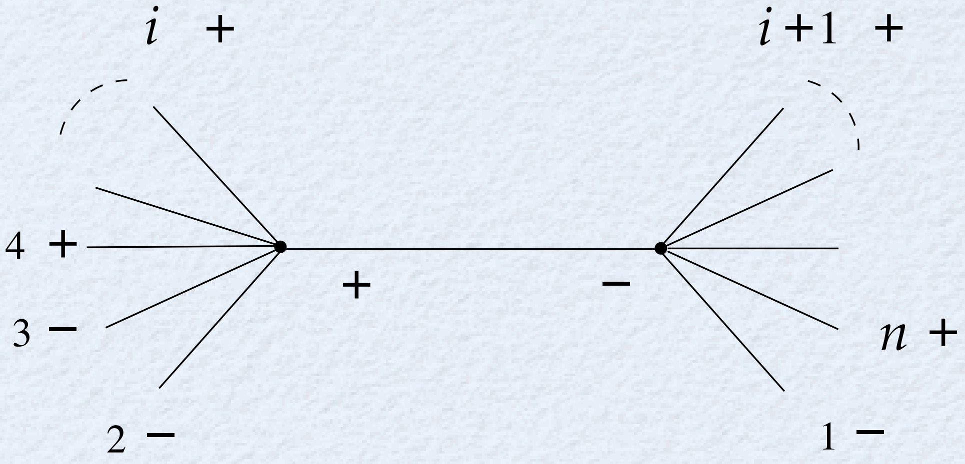
- $e^+e^- \rightarrow 6f$ comparison vs. HELAC/PHEGAS EPJ C34 (2004) 173 →
- Comparison of arbitrary 2→2 MSSM processes vs. WHIZARD/O'Mega & SMadGraph Phys. Rev. D73(2006) 055005
- MC4LHC ME generator comparison http://mlm.home.cern.ch/mlm/mcwshop03/mcwshop.html



CSW Recursion in AMEGIC++

based on hep-th/0403047

- New twistor-inspired techniques (CSW vertex rules) help speeding up calculation of pure QCD ME's for higher multiplicites
- Advantage: Up to $\mathbf{N_{out}} = \mathbf{7}$ 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**
  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 (see backup)

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)	0.019(2)
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: b-pair + jets
  comparison with other ME generators

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)				

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

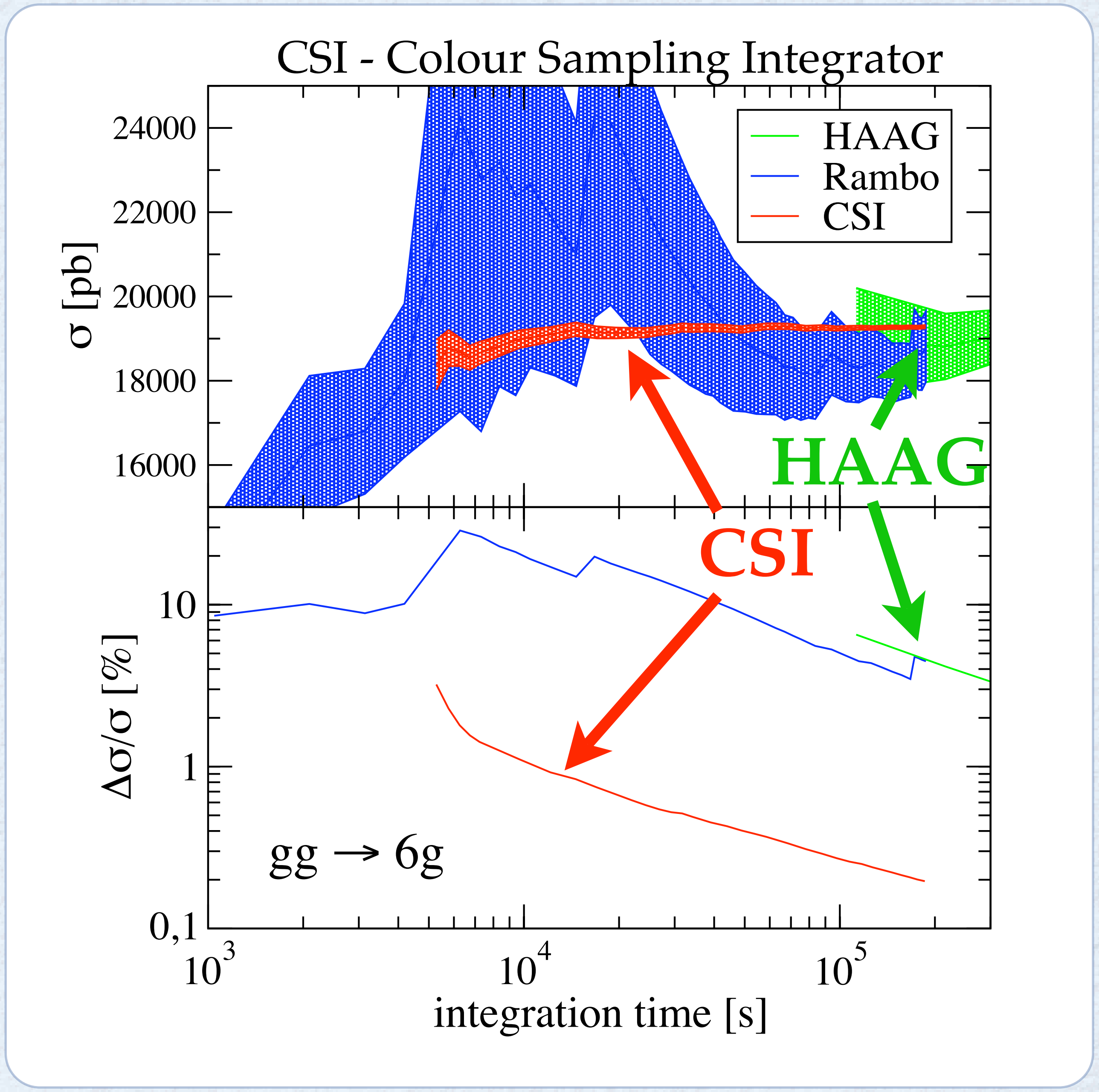
COMIX: PERFORMANCE

T. Gleisberg, SH: in preparation

- Efficiencies: LHC @ 14 TeV
  Cuts: $66\,\mathrm{GeV} \leq m_{l\bar{l}} \leq 116\,\mathrm{GeV}$,
  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%

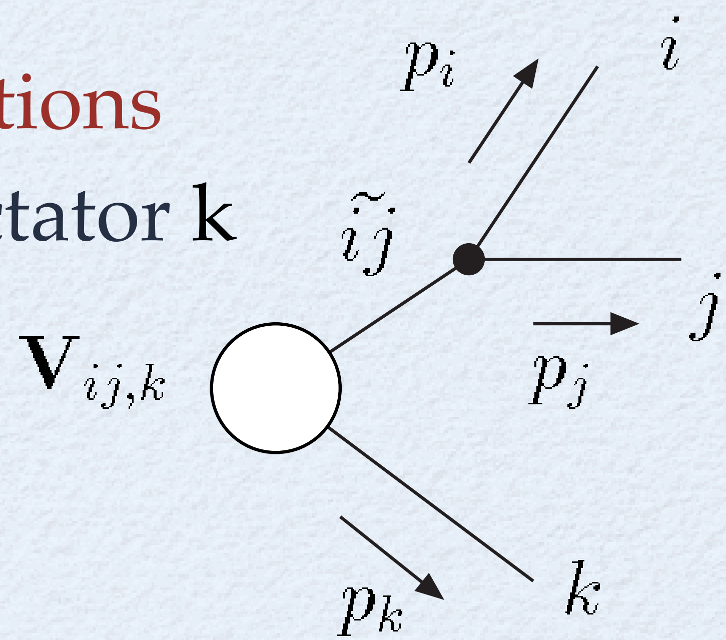
- **Also new:** HAAG-based QCD integrator for colour sampling



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:

$$\langle \mathbf{V}_{q_i,g_j,k} \rangle (\tilde{z}_i, y_{ij}, k) = C_F \left(\frac{2}{1-\tilde{z}_i+\tilde{z}_i y_{ij,k}} - (1+\tilde{z}_i) \right)$$

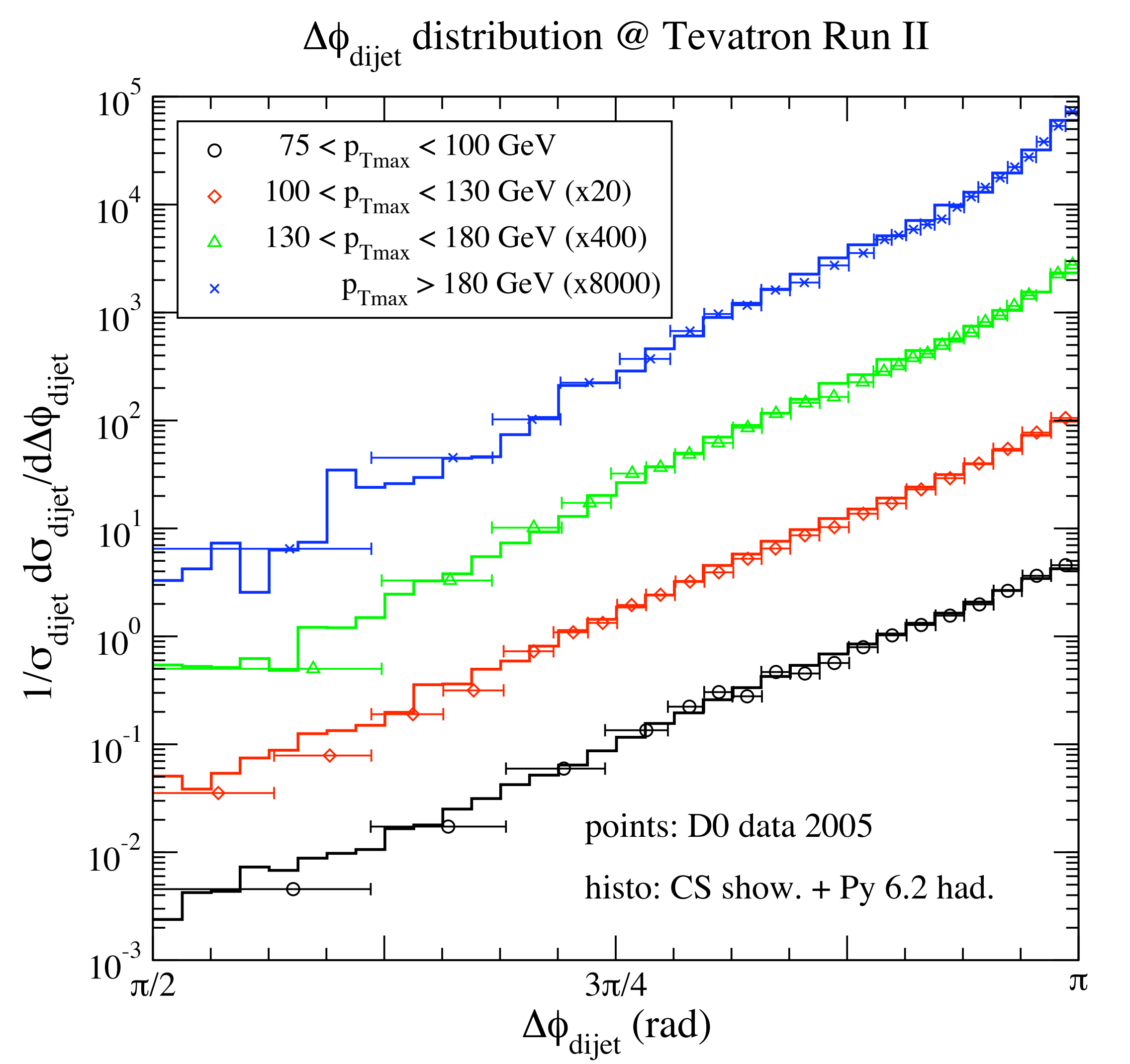
$$y_{ij,k} = \frac{p_i p_j}{p_i p_k + p_j p_k + p_i p_j}$$

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

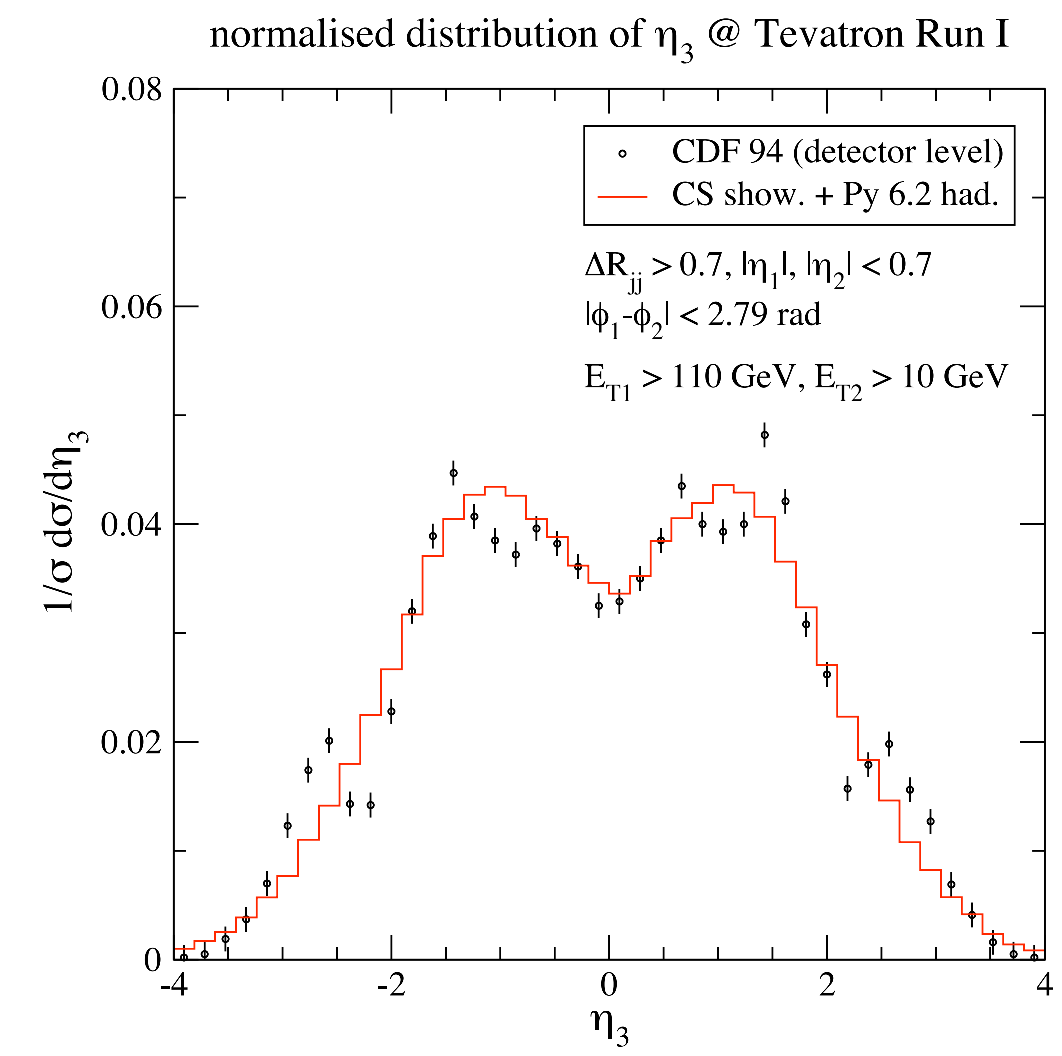
CS-subtraction based shower

JHEP03(2008)038

- pp → jets
  Phys. Rev. Lett. 94 (2005) 221801



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

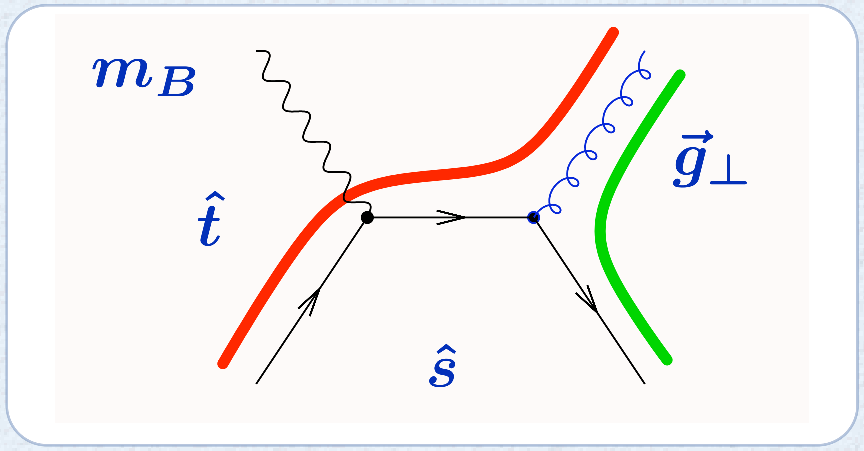


Dipole shower for hadron collisions

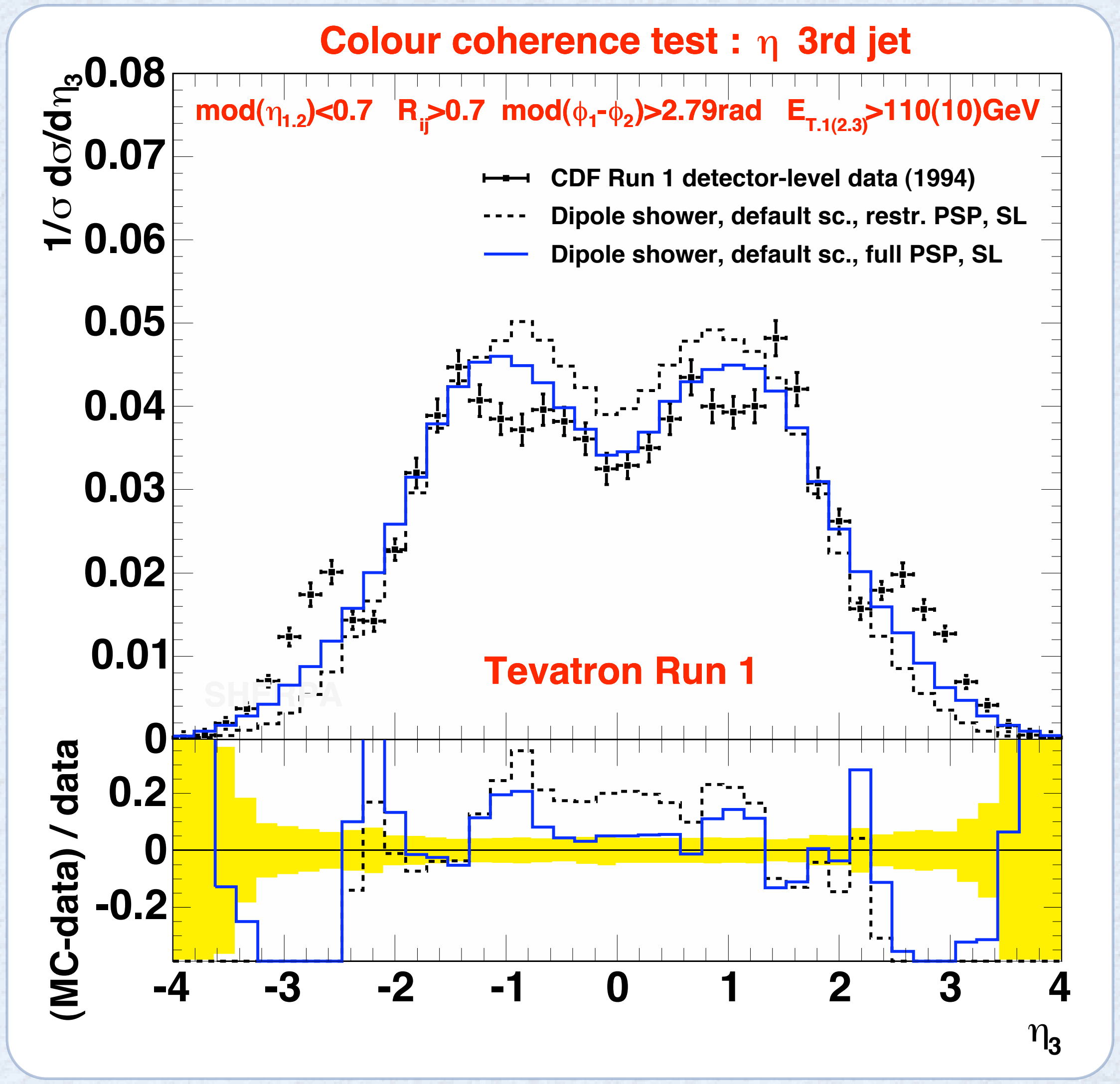
arXiv: 0712.3913 [hep-ph]

- 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:

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



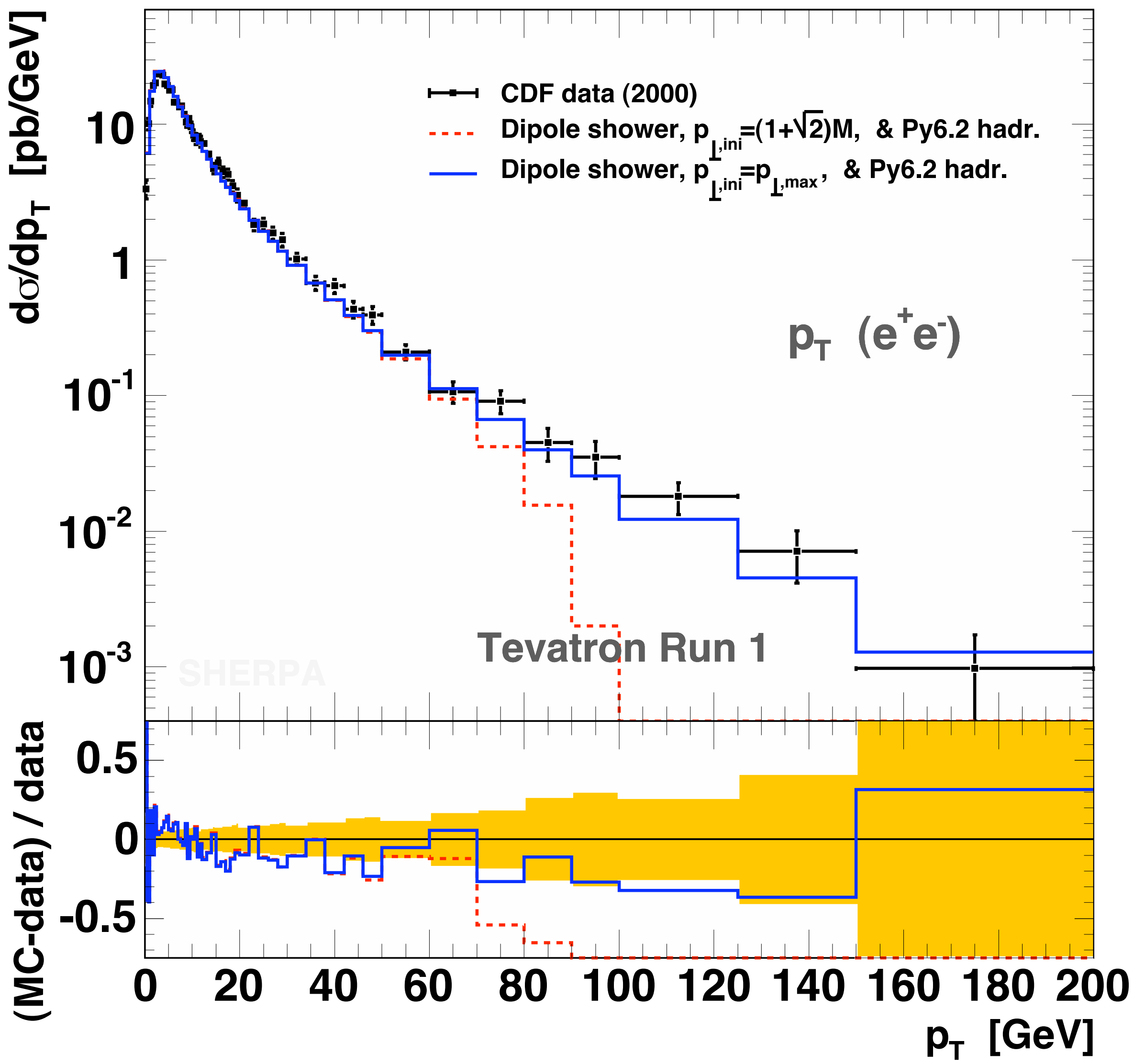
- pp → jets Phys. Rev. D50 (1994) 5562

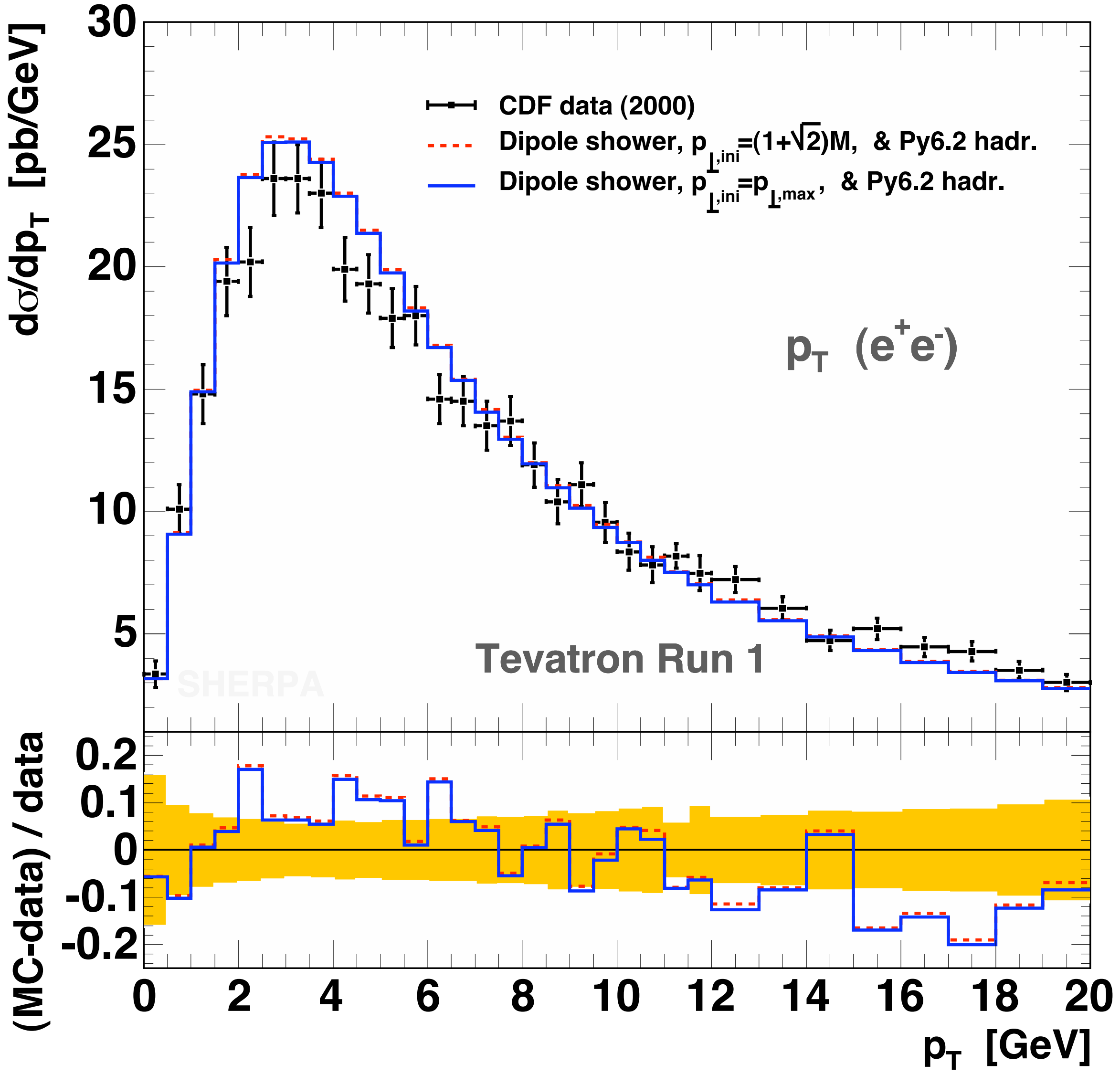


Dipole shower for hadron collisions

arXiv: 0712.3913 [hep-ph]

- First emission by construction ME-corrected



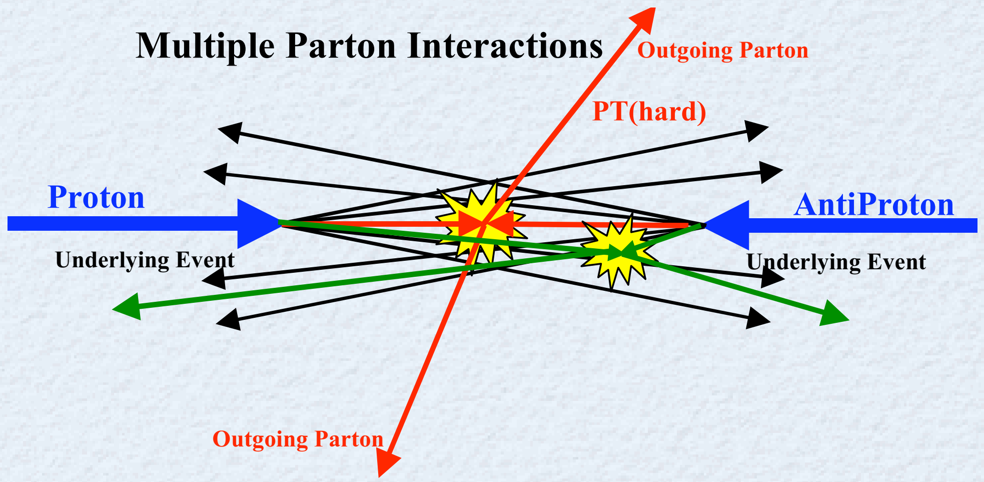


MPI Simulation in Sherpa

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, $\mu_{\rm MI}$
- Sherpa algorithm (works for arbitrary n-jet ME):
  - Employ K_T-algorithm to define 2→2 core process
  - Set starting scale $\mu_{\rm MI}$ to p_T of final state QCD parton(s) from this process and veto partons harder than $\mu_{\rm MI}$ (from PS) in secondary interactions

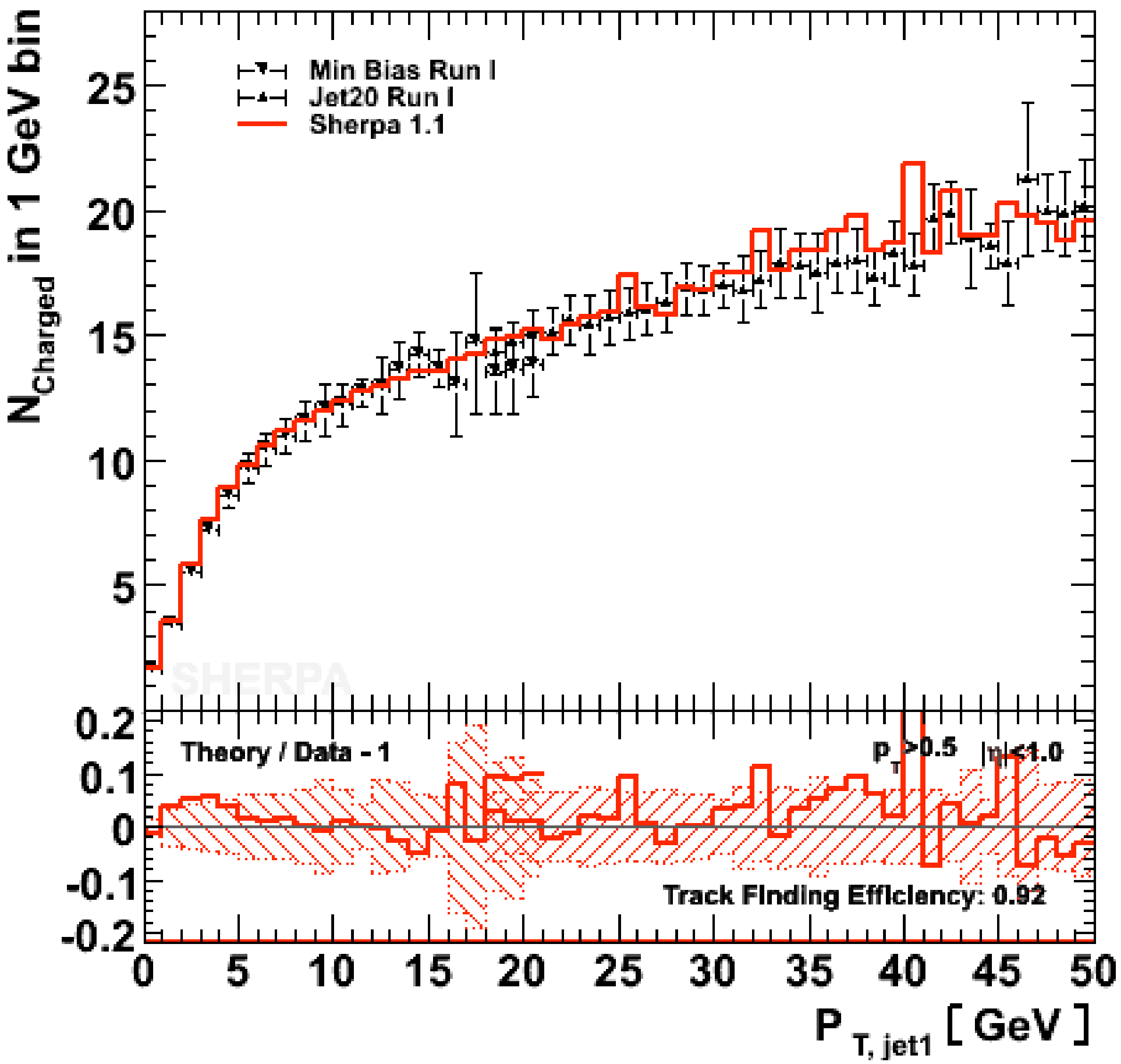
MPI results from Sherpa

hep-ph/0601012

Our current "best fit" for CDF

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

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



To take home ...

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

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

$$\sigma = \frac{\pi^2}{2S} \sum_{a^{(1)}} \int \mathrm{d}y_1 \int \mathrm{d}k_{1\perp}^2 \int \mathrm{d}\phi_1 \int \mathrm{d}y_n$$
$$\times\; f^{(1)}(x^{(1)}, z^{(1)}, k_{1\perp}^2, \bar{k}_{2\perp}^{(1)2})\, f^{(2)}(x^{(2)}, z^{(2)}, k_{n\perp}^2, \bar{k}_{n-1\perp}^{(2)2})\, \frac{1}{2\xi^{(1)\,2}\xi^{(2)\,2}S}\, \frac{1}{\Delta_{a_1}(y_1, y_2)}$$
$$\times \left[\prod_{i=2}^{n} \int \frac{\mathrm{d}\phi_i}{2\pi} \int \mathrm{d}y_i \int \frac{\mathrm{d}k_{i\perp}^2}{k_{i\perp}^2} \frac{\alpha_s(k_{i\perp}^2)}{\pi} \sum_{a_i} C_{a_{i-1}a_i}(q_{i-1}, k_i)\, \Delta_{a_i}(y_i, y_{i-1}) \right]$$

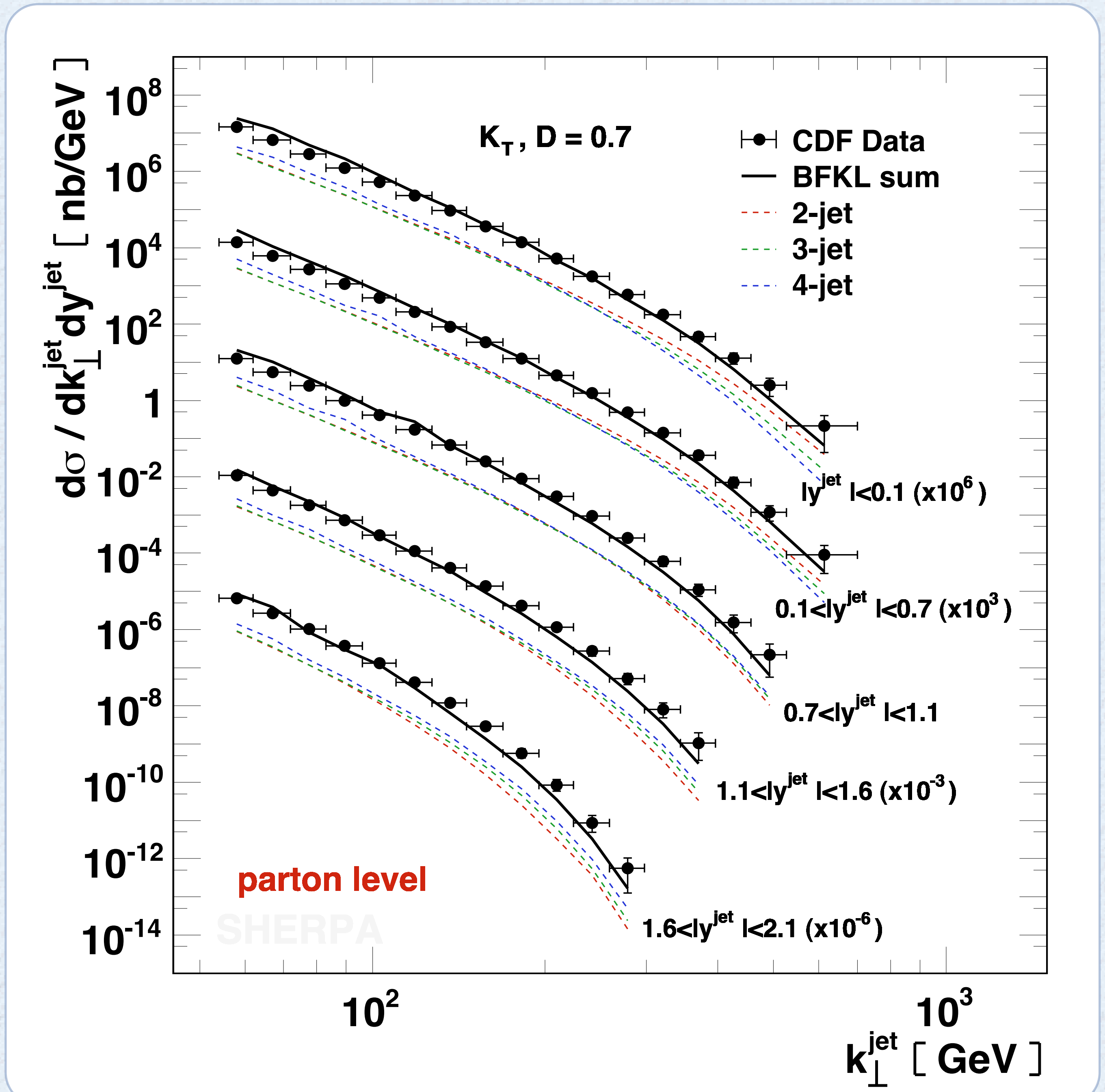
Markovian algorithm to generate splittings from $\Delta_{a_i}(y_i, y_{i-1})$ in the spirit of a parton shower

➡ number of emissions determined on the flight

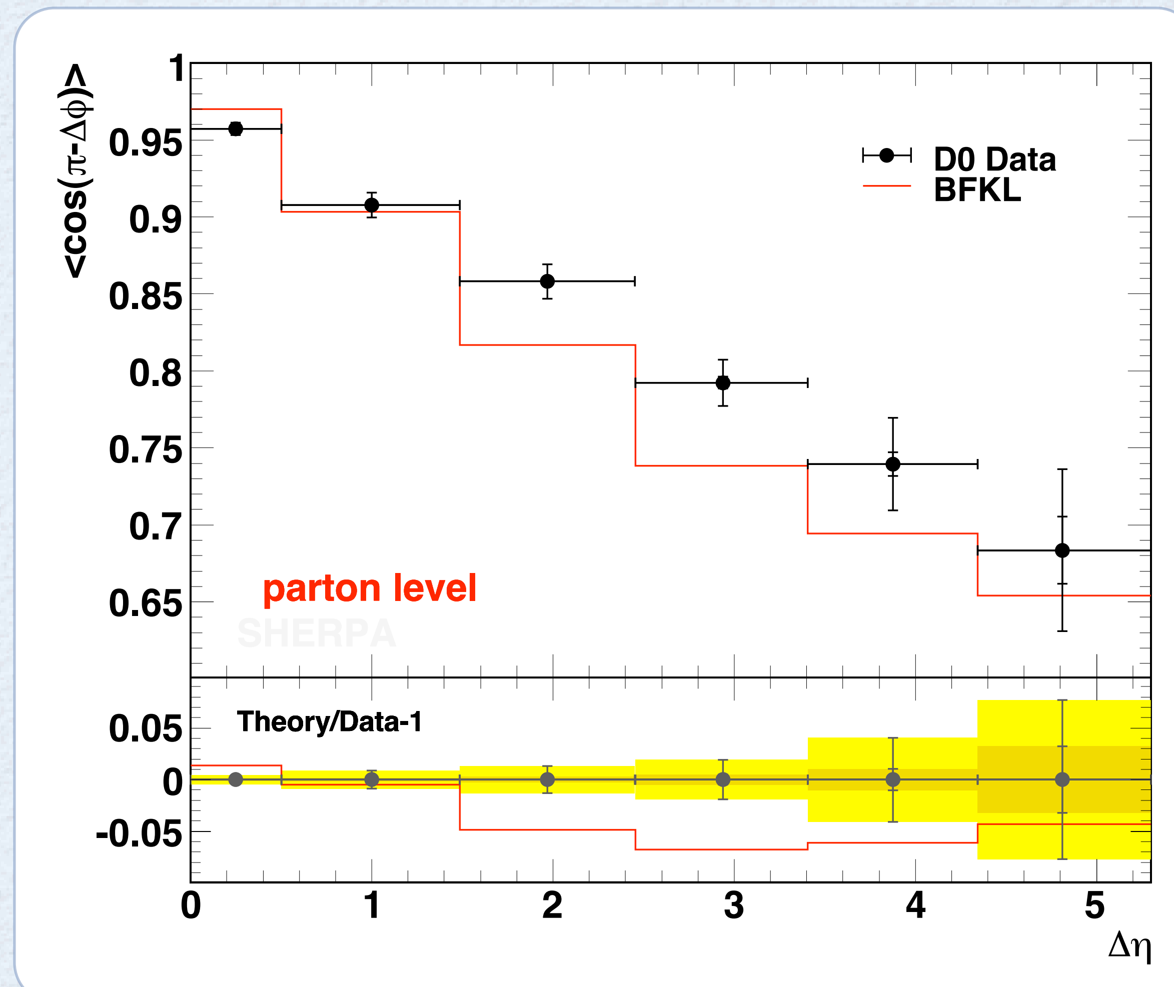
Towards a new MPI model

arXiv: 0705.4577 [hep-ph]

- Jet - p_T spectra PRD75(2007)092006



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



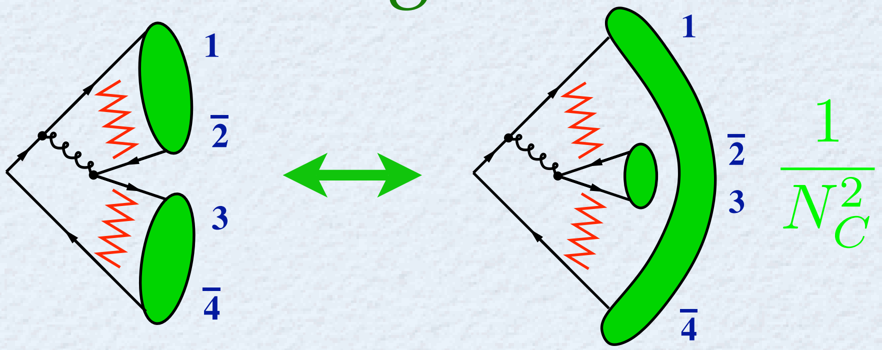
Cluster Fragmentation

Eur. Phys. J. C36 (2004) 381

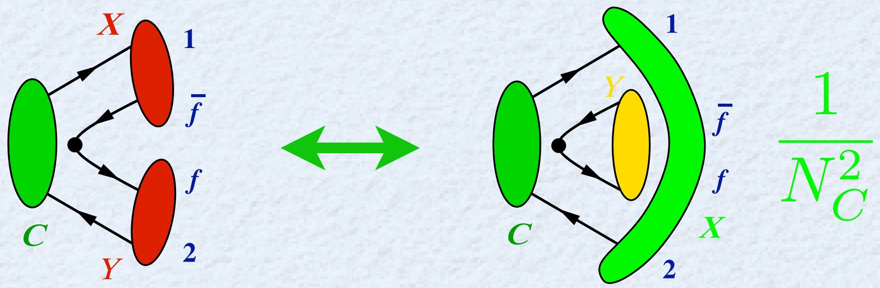
Sherpas cluster fragementation model:

- 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 mass 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]

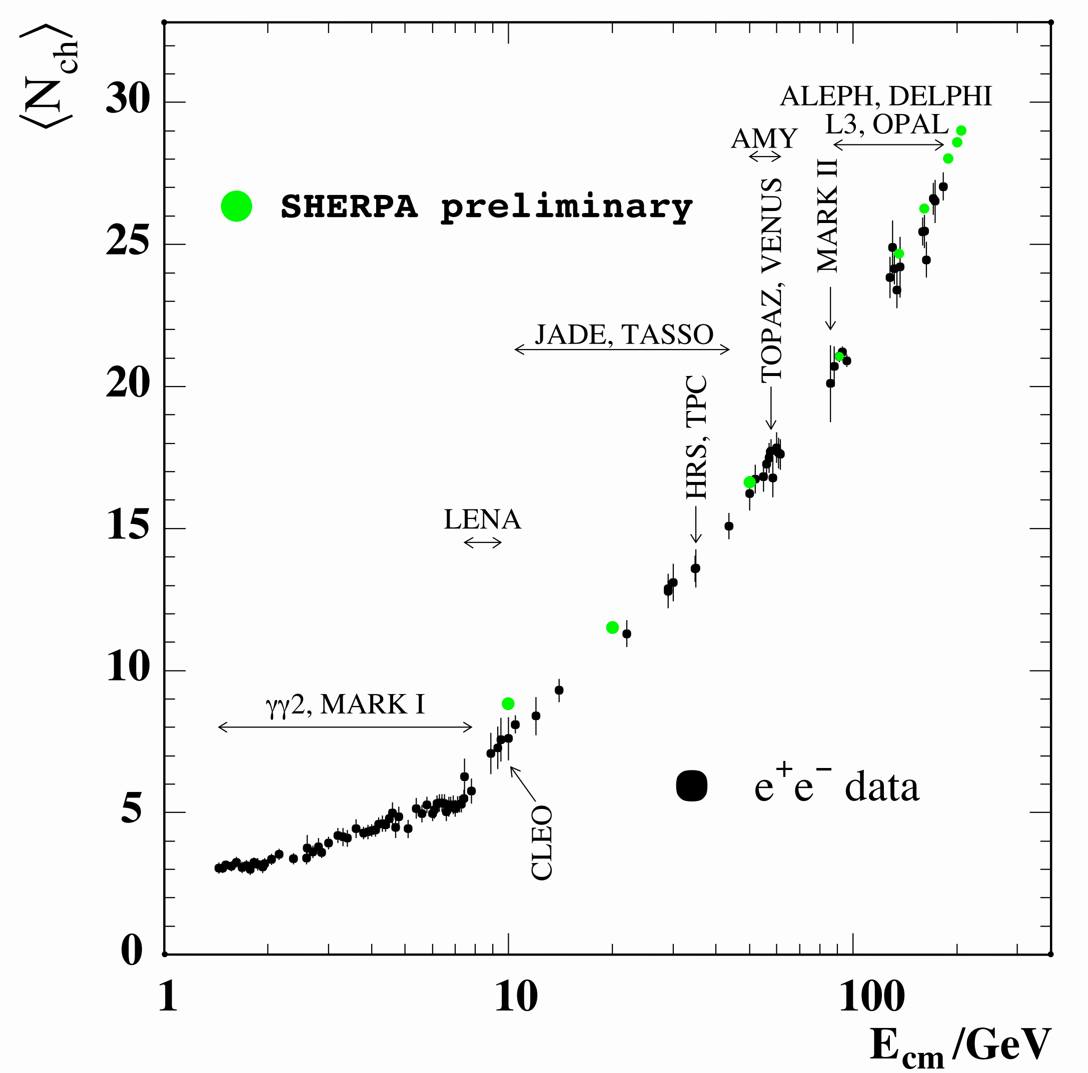


[1] with t_0 replaced by Q_0 (hadronic scale)

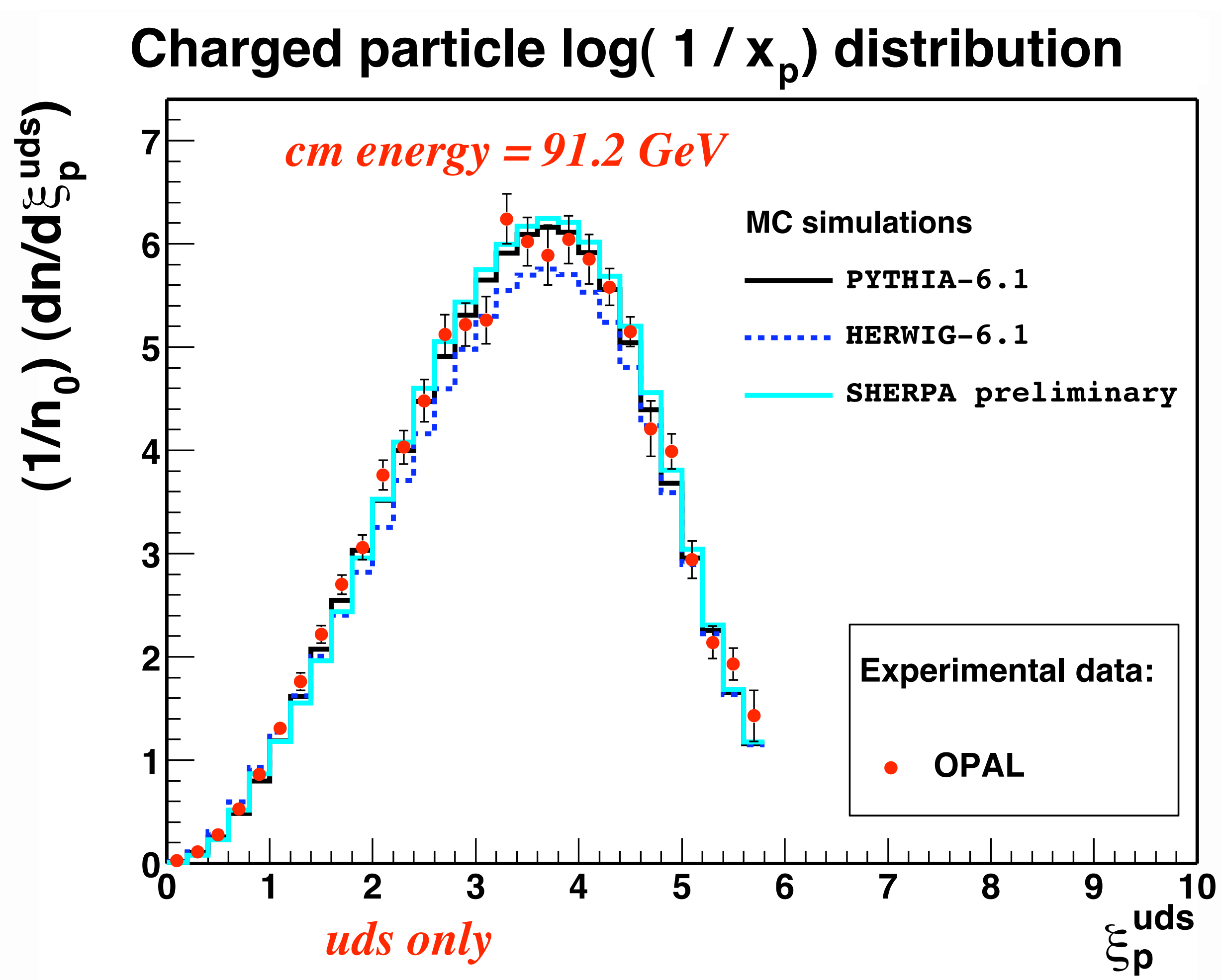
CLUSTER FRAGMENTATION

Eur. Phys. J. C36 (2004) 381

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



- charged scaled momentum



Hadron Decays

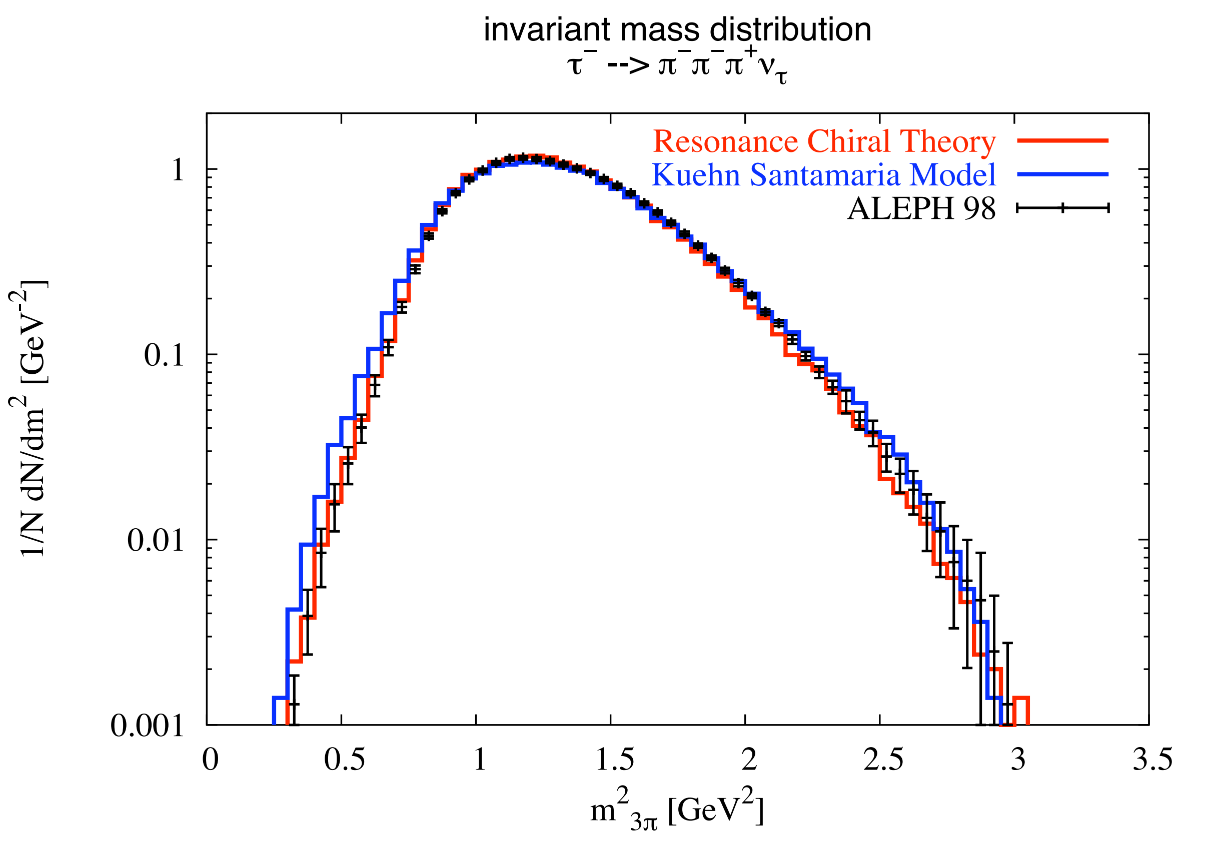
Features of Sherpas hadron decay package

- 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 ...)
- Spin correlation algorithm with full spin information from AMEGIC++ matrix element
- Extensively tested in τ - and hadron decays
- B-mixing implemented in full generality
- First fully functional release with version 1.1

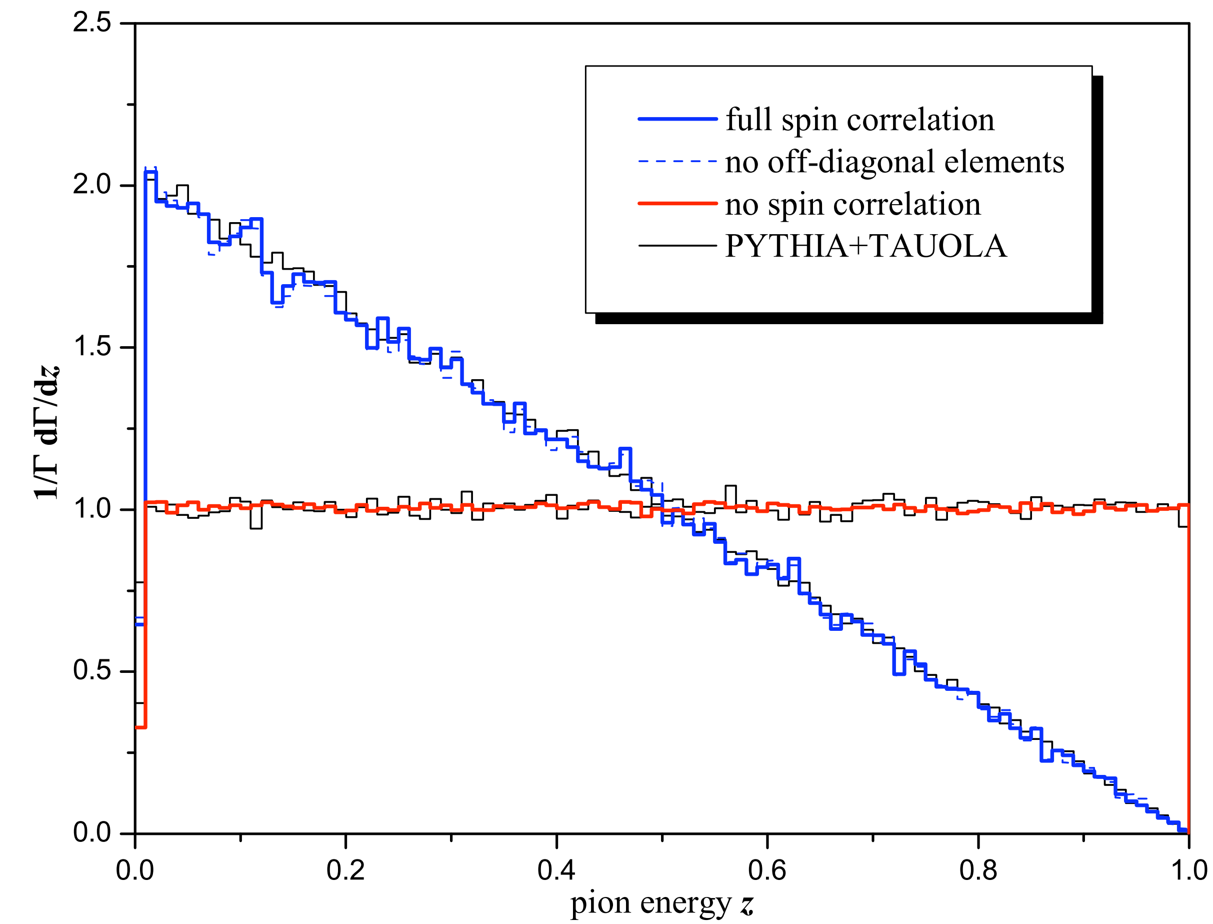
Hadron Decays: Results

F. Siegert, F. Krauss: in preparation
PYTHIA+TAUOLA: hep-ph/0101311

- **Many models**: e.g. $\tau \to \nu_\tau \pi^- \pi^- \pi^+$



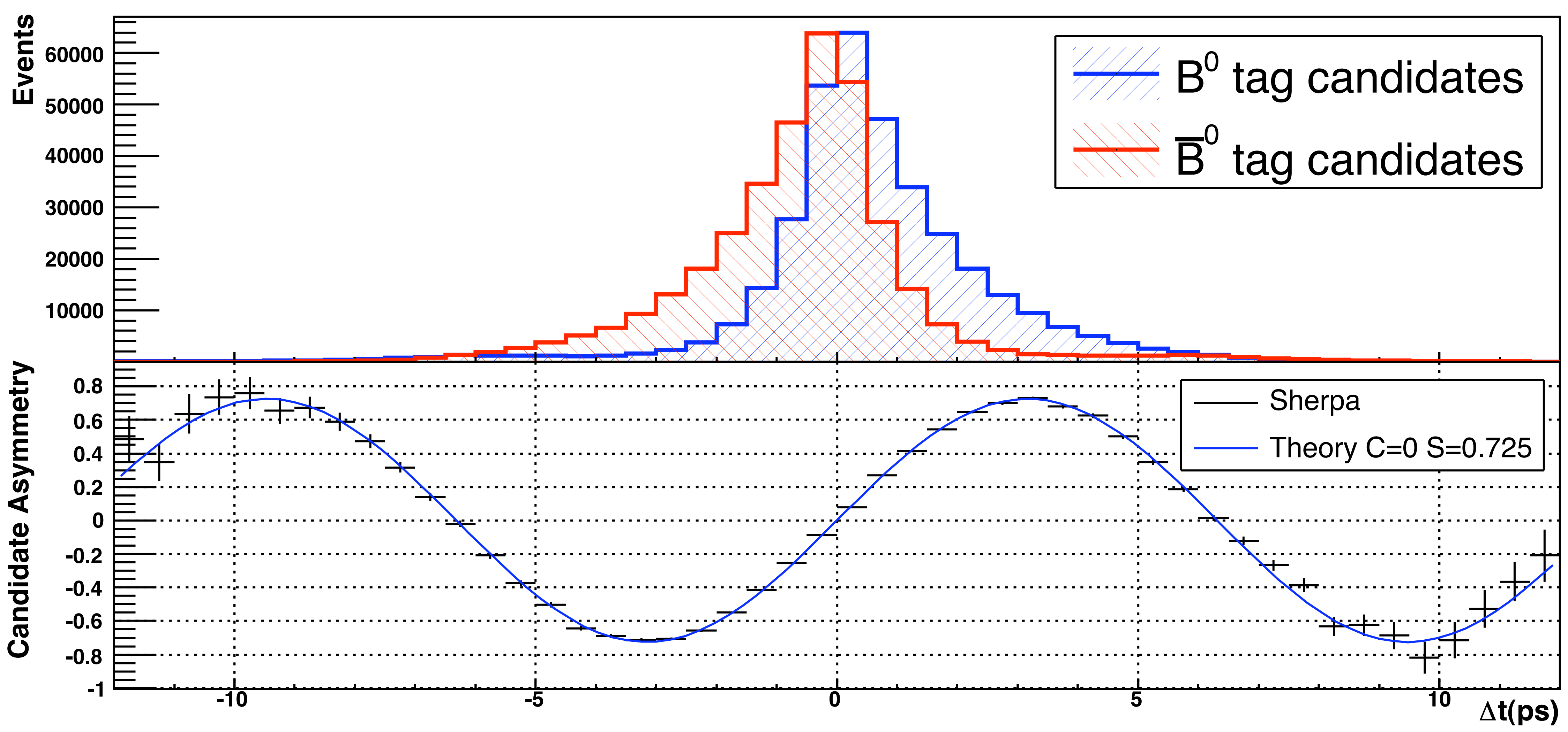
- **Spin correlations**: e.g. $\mathbf{Z} \to \mathbf{W}^+\mathbf{W}^-, \mathbf{W}^- \to \tau^- \bar{\nu}_\tau \to \nu_\tau \pi \bar{\nu}_\tau$



Hadron decays: results

F. Siegert, F. Krauss: in preparation

- **B-mixing**: e.g.
  Decay rate asymmetry $B_0 \to J/\Psi K_s \leftrightarrow \bar{B}_0 \to J/\Psi K_s$
  in $\Upsilon(4s) \to B_0\bar{B}_0$ events

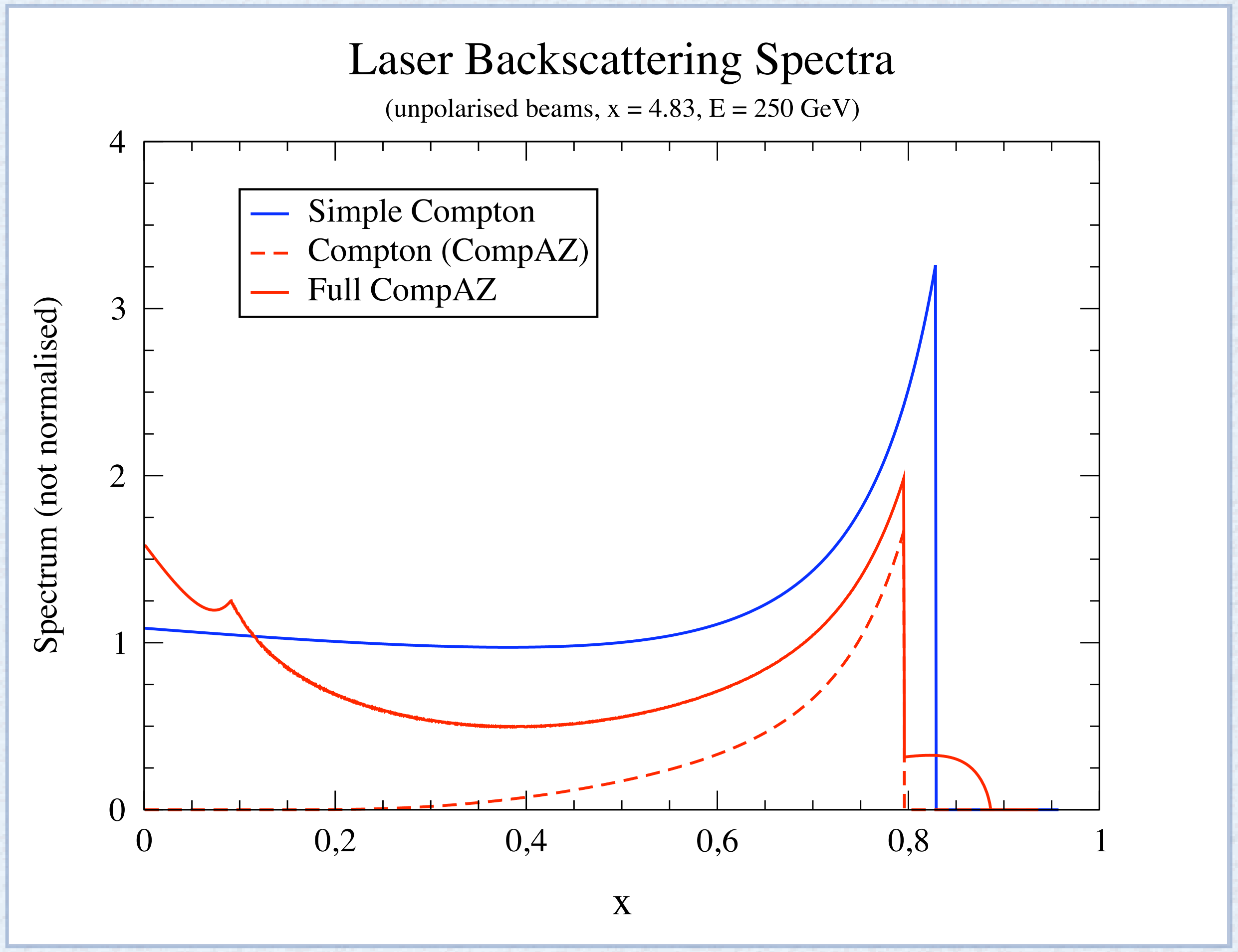


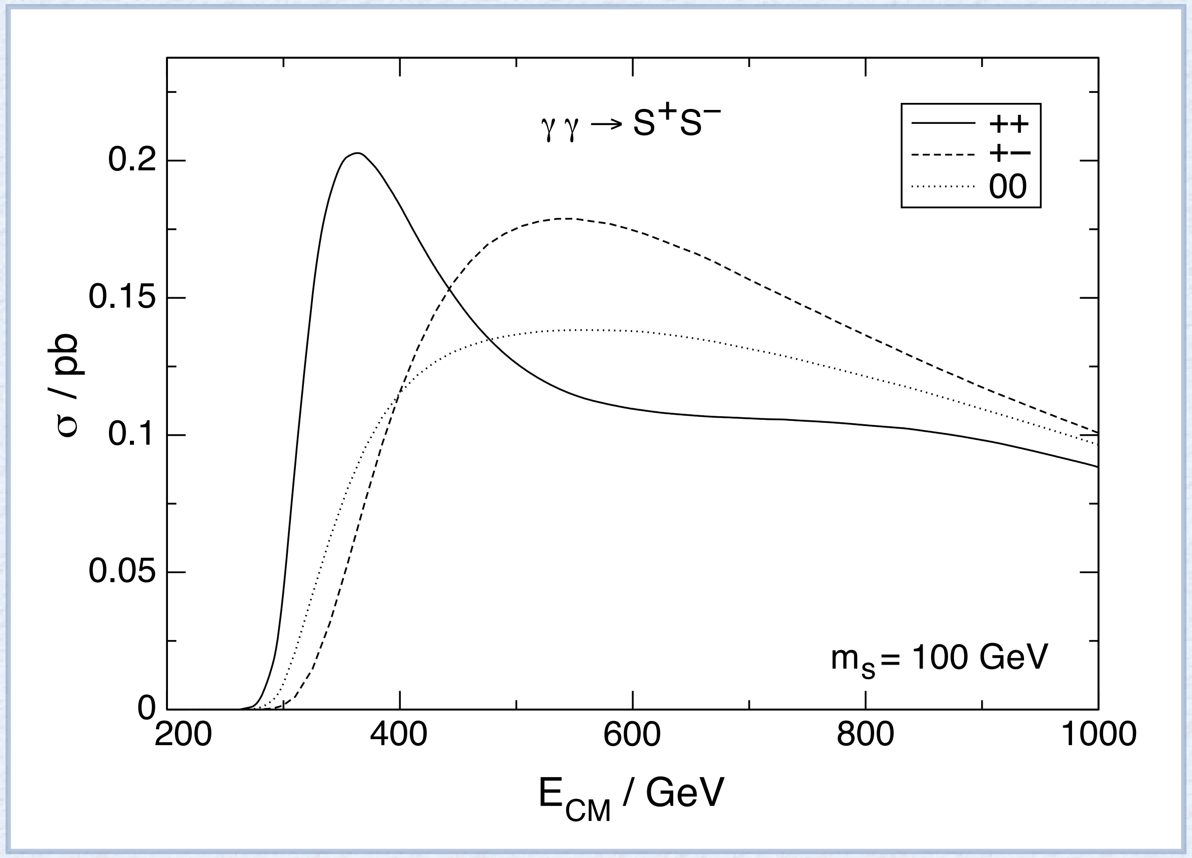
Photon Interactions

Prog. Part. Nucl. Phys. 53 (2004) 329

Now that we know the rest ...

- Sherpa provides LASER back-scattering beam spectrum acc. to Acta Phys. Polon. B34 (2003) 2741
- cross section in $\gamma\gamma \to \tilde{\mu}^+ \tilde{\mu}^-$





- Beam spectrum for p → pγ acc. to Phys. Lett. C15 (1975) 181 implemented by T. Pierzchala ported into v1.1 during this WS

Summary and Outlook

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

Sherpas and collaborators currently also work on:

- 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)
  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 1.1.0
available on Genser and HepForge

Updates on Sherpa can be found on

WWW.SHERPA-MC.DE

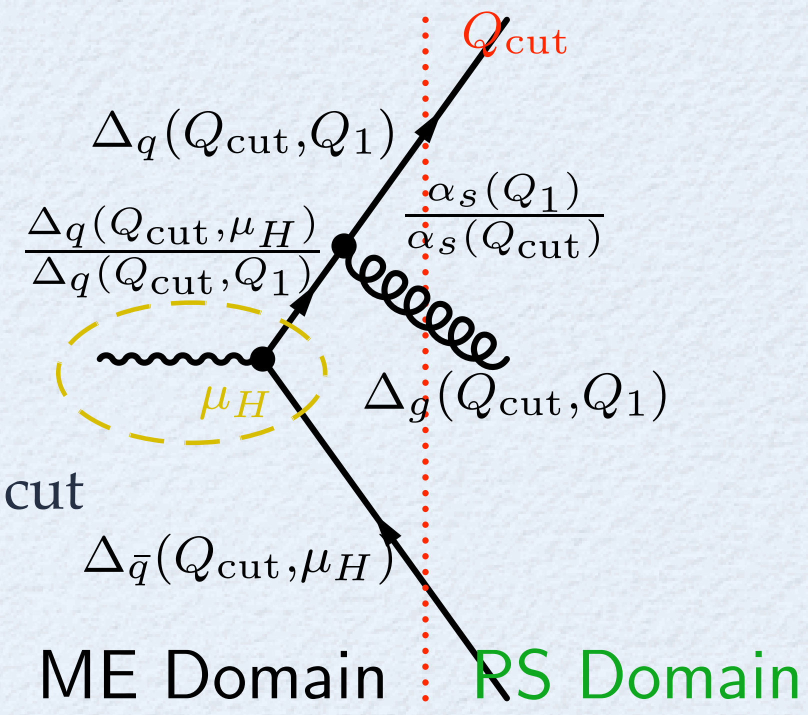
E-mail us at

INFO@SHERPA-MC.DE

CKKW in a nutshell

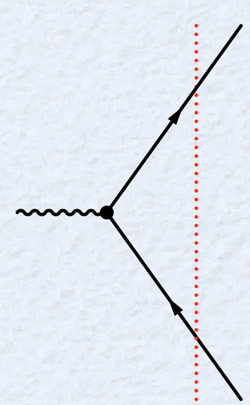
JHEP 0111 (2001) 063
JHEP 0208 (2002) 015

- 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}



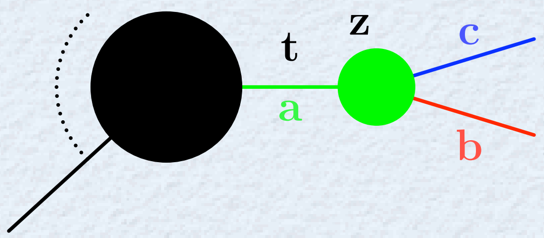
➡ This yields the correct jet observables !
Generic example: 2-jet rate in ee→qq

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



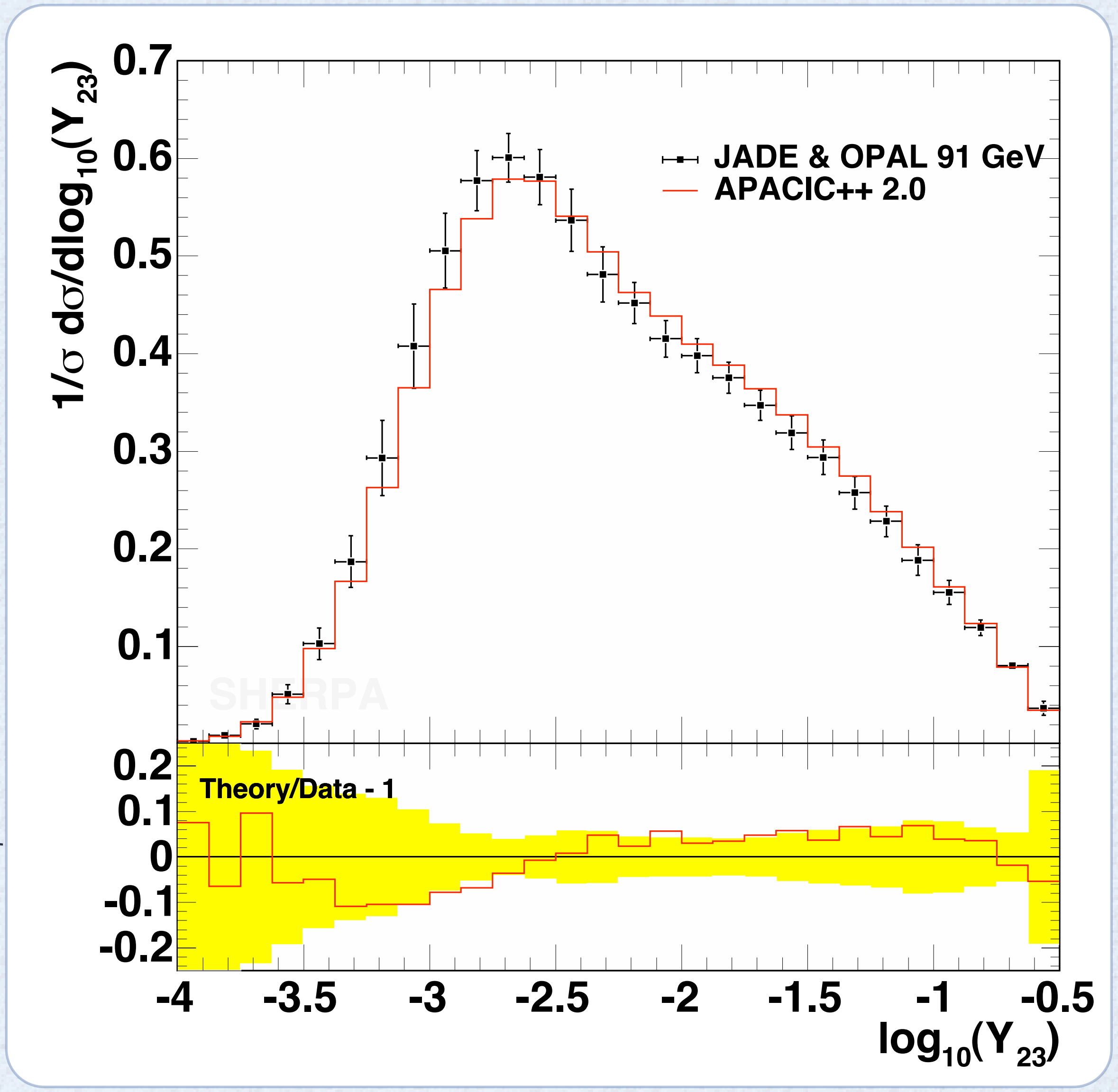
PS in SHERPA: APACIC++

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



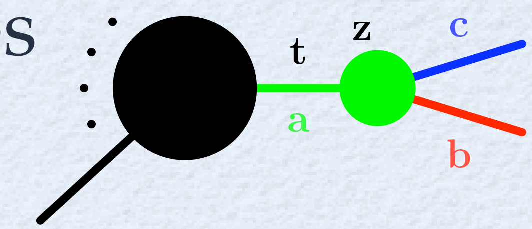
Basic features of APACIC++ :

- 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)



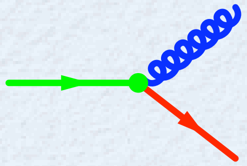
APACIC++: Heavy Quark Production

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

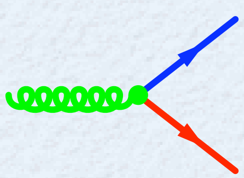


$$|\mathbf{M}(\mathbf{b},\mathbf{c},\ldots,\mathbf{n})|^2 \;\rightarrow\; |\mathbf{M}(\mathbf{a},\ldots,\mathbf{n})|^2\,\frac{8\pi\alpha_s}{\mathbf{t}-\mathbf{m_a^2}}\,\mathbf{P_{a\to bc}(z)}$$

- 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

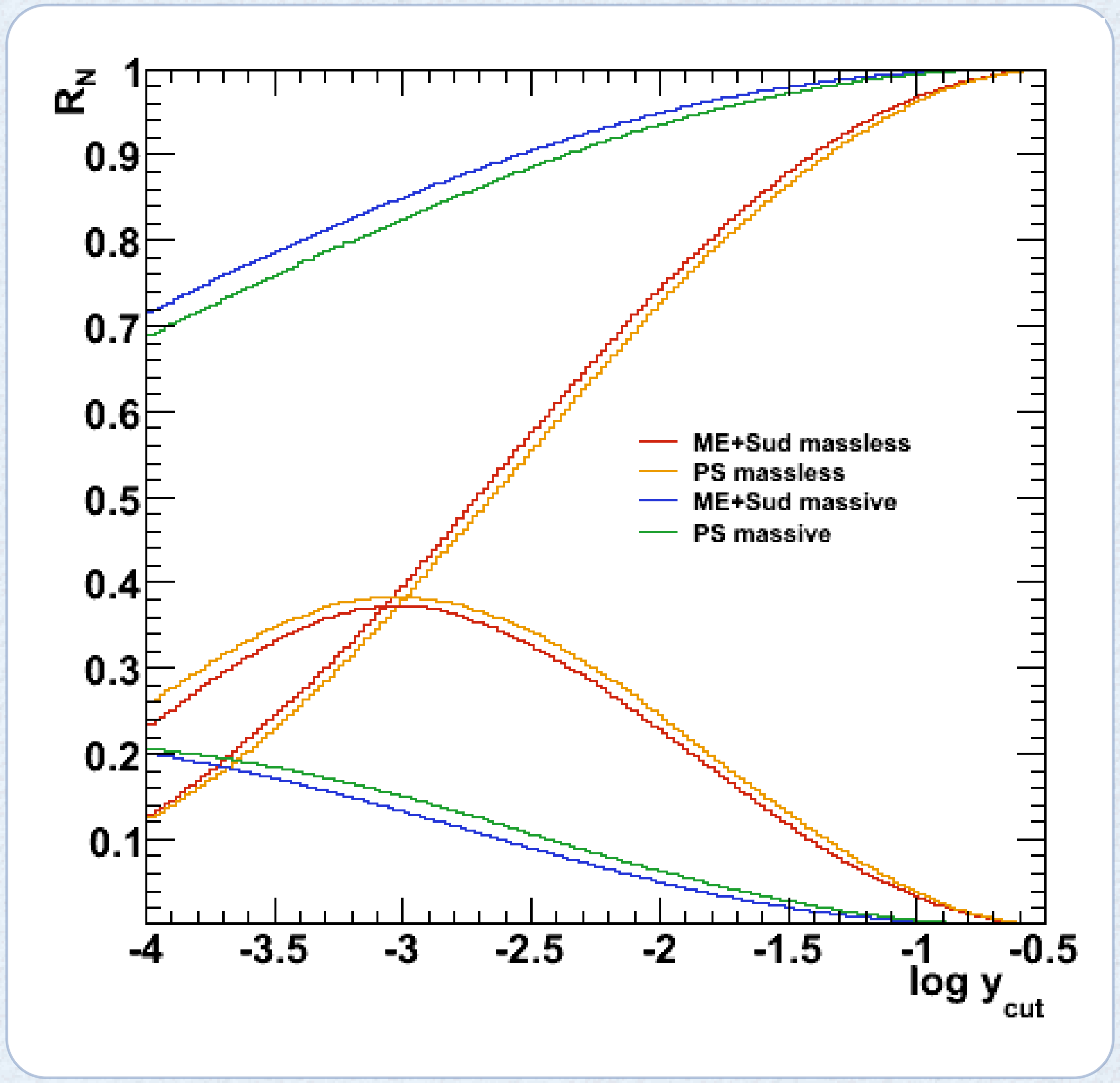


$$\Rightarrow\; \mathbf{C_F}\left(\frac{\mathbf{1}+\mathbf{z^2}}{\mathbf{1}-\mathbf{z}}-\frac{\mathbf{2z(1-z)m^2}}{\mathbf{q^2}+(\mathbf{1}-\mathbf{z})^2\mathbf{m^2}}\right)$$



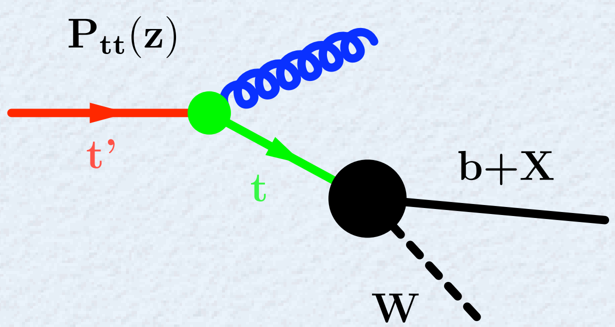
$$\Rightarrow\; \mathbf{T_R}\left(\mathbf{1}-\mathbf{2z(1-z)}+\frac{\mathbf{2z(1-z)m^2}}{\mathbf{q^2}+\mathbf{m^2}}\right)$$

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



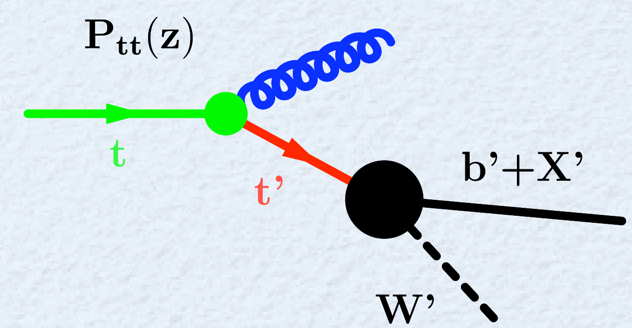
APACIC++: Heavy Quark Production

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 $\vec{p}/|\vec{p}|$ is preserved
- ISR-like situation
- Evolution stops if $p_\perp$ reaches width of decaying quark

COMIX: Phasespace recursion

Nucl. Phys. B9 (1969) 568

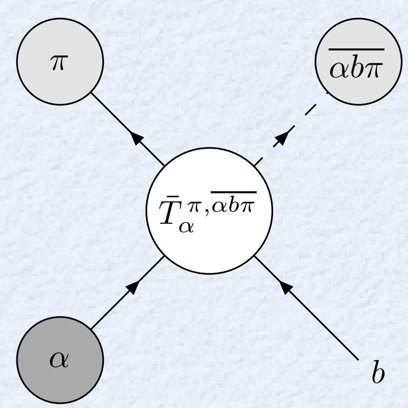
- State-of-the art approach for general phasespace generation:

  Factorise PS using

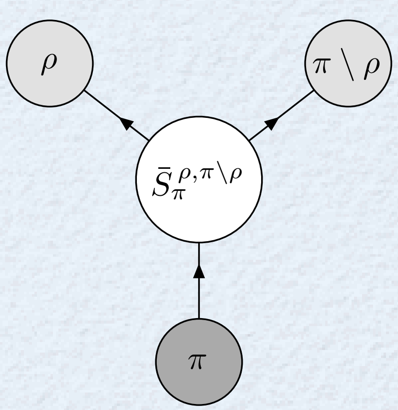
$$\mathrm{d}\mathbf{\Phi_n}\left(\mathbf{a},\mathbf{b};\mathbf{1},\ldots,\mathbf{n}\right)=\mathrm{d}\mathbf{\Phi_m}\left(\mathbf{a},\mathbf{b};\mathbf{1},\ldots,\mathbf{m},\bar{\pi}\right)\,\mathrm{d}s_\pi\,\mathrm{d}\mathbf{\Phi_{n-m}}\left(\pi;\mathbf{m}+\mathbf{1},\ldots,\mathbf{n}\right)$$

  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"



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



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

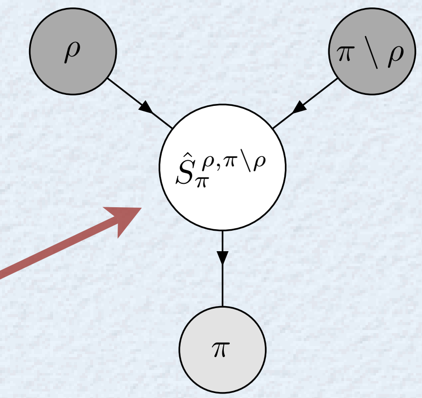
Arrows → Momentum flow

COMIX: Phasespace recursion

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

S-channel phasespace (schematically)

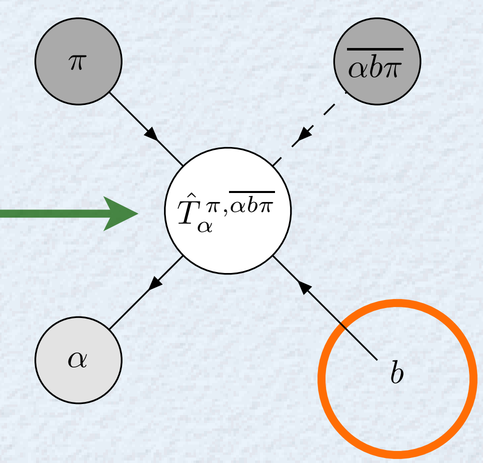
$$\mathrm{d}\Phi_S\left(\pi\right) = \left[\, \sum \alpha\left(S_\pi^{\rho,\pi\setminus\rho}\right) \right]^{-1} \times \left[\, \sum \alpha\left(S_\pi^{\rho,\pi\setminus\rho}\right)\, S_\pi^{\rho,\pi\setminus\rho}\, P_\rho\, \mathrm{d}\Phi_S\left(\rho\right)\, P_{\pi\setminus\rho}\, \mathrm{d}\Phi_S\left(\pi\setminus\rho\right)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



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 !

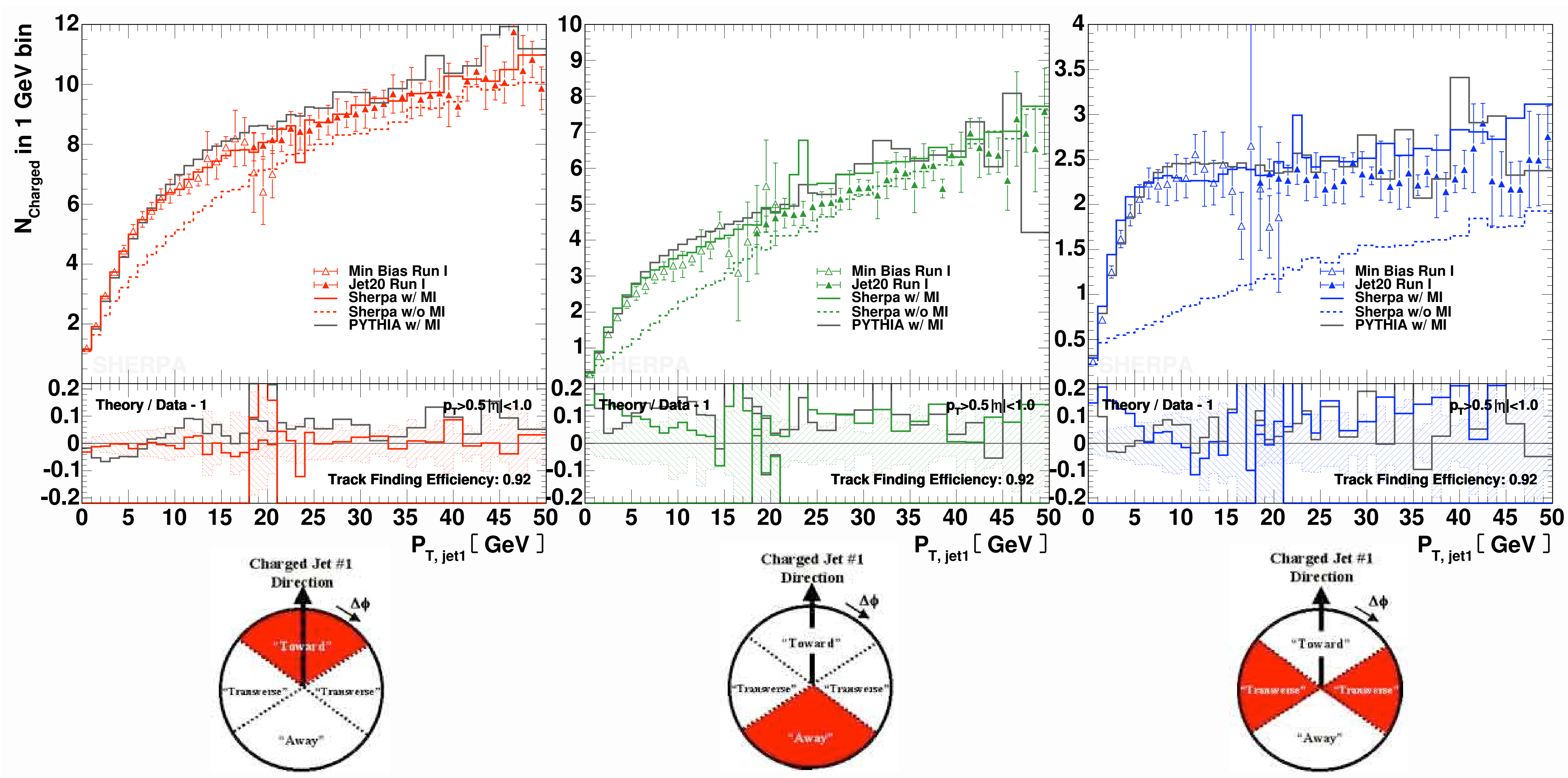
Arrows ➡ Weight flow !

➡ Factorial growth of PS-channels tamed

MPI results from Sherpa

hep-ph/0601012

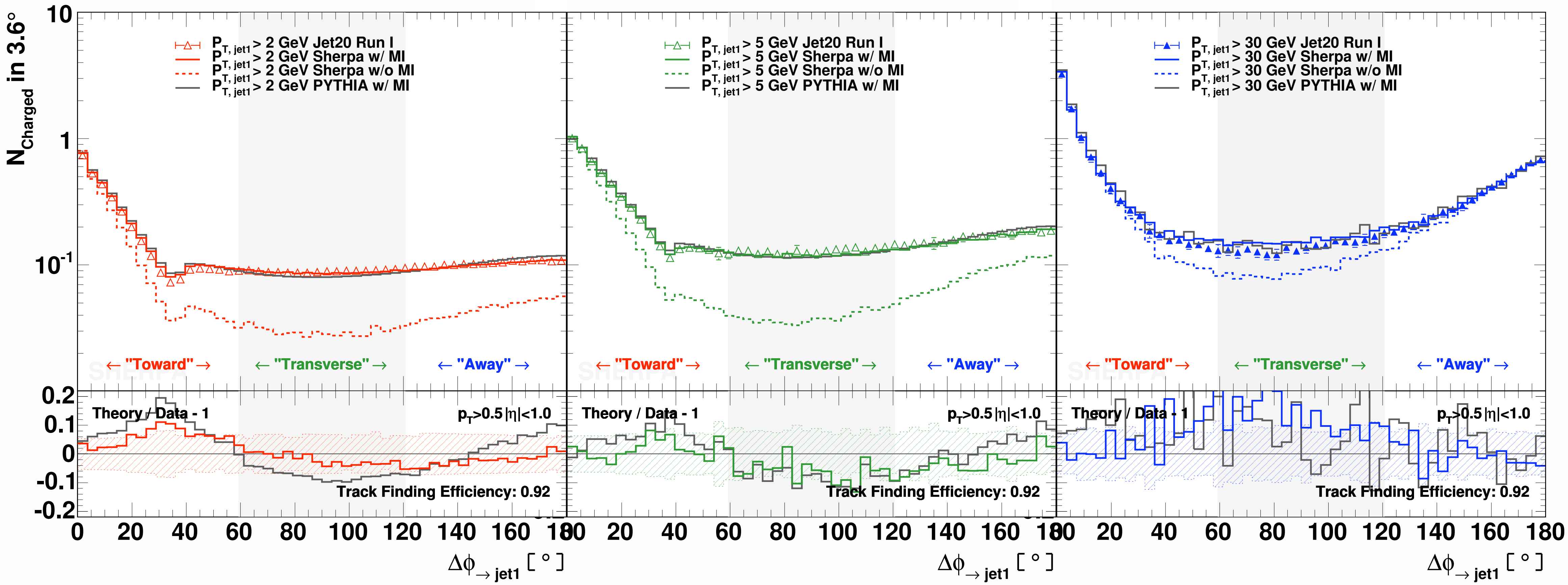
- $N_{Charged}$ vs. $p_{T,jet1}$ in CTC
  in different regions w.r.t. leading charged particle jet



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



$p_{T,\text{jet1}} > 2\text{GeV}$ $p_{T,\text{jet1}} > 5\text{GeV}$ $p_{T,\text{jet1}} > 30\text{GeV}$