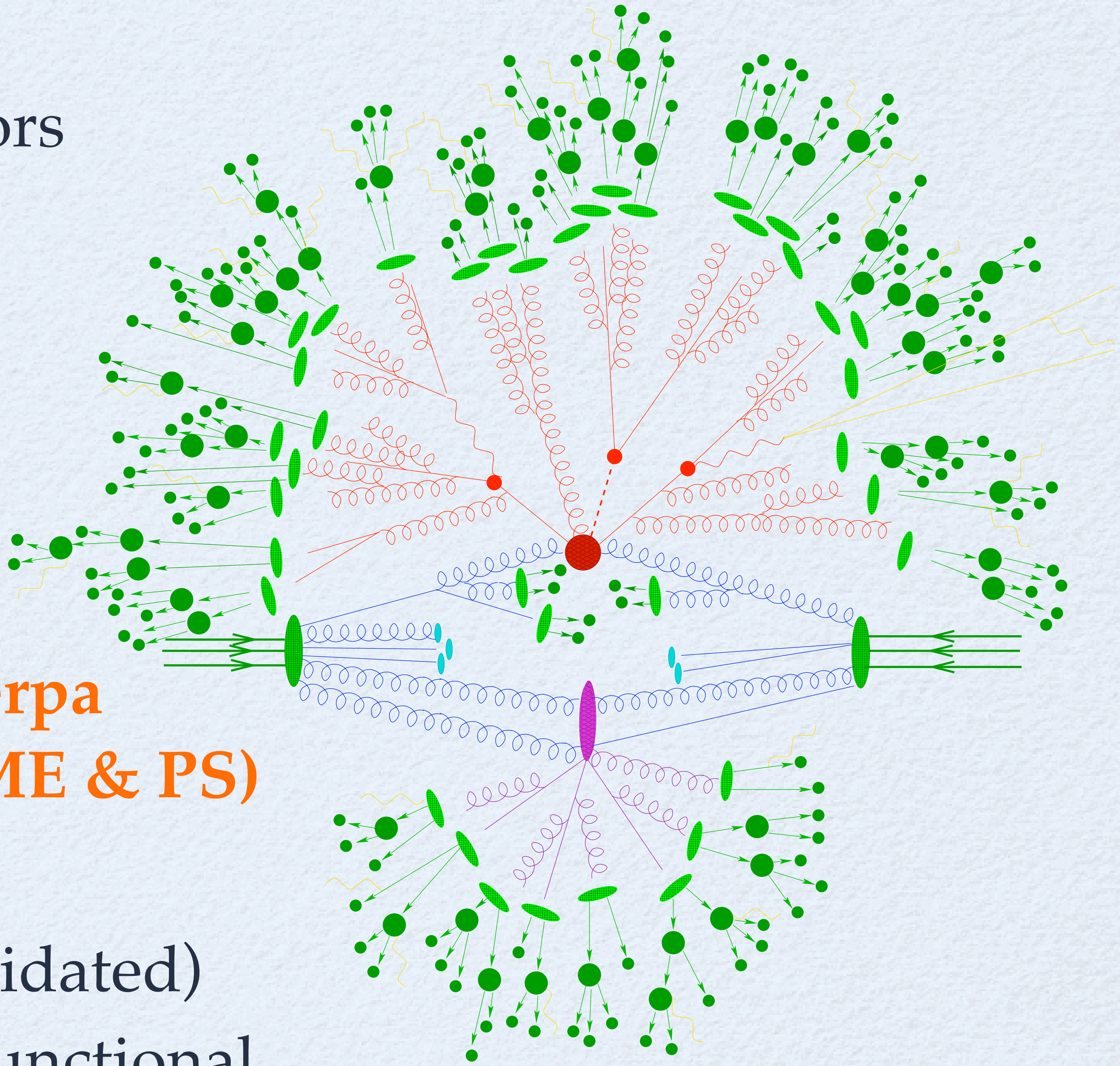
SHERPA - IN BRIEF

Stefan Höche[1]
Institute for theoretical Physics
University of Zurich

[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
- Multiple Parton Interactions
- Cluster fragmentation
- Hadron decays

The traditional strength of Sherpa is the hard perturbative part (ME & PS)

Current release series 1.1.x

- New fragmentation (to be validated)
- Hadron decay module fully functional
- New module for soft photon radiation (YFS approach)

ME'S IN SHERPA - AMEGIC++

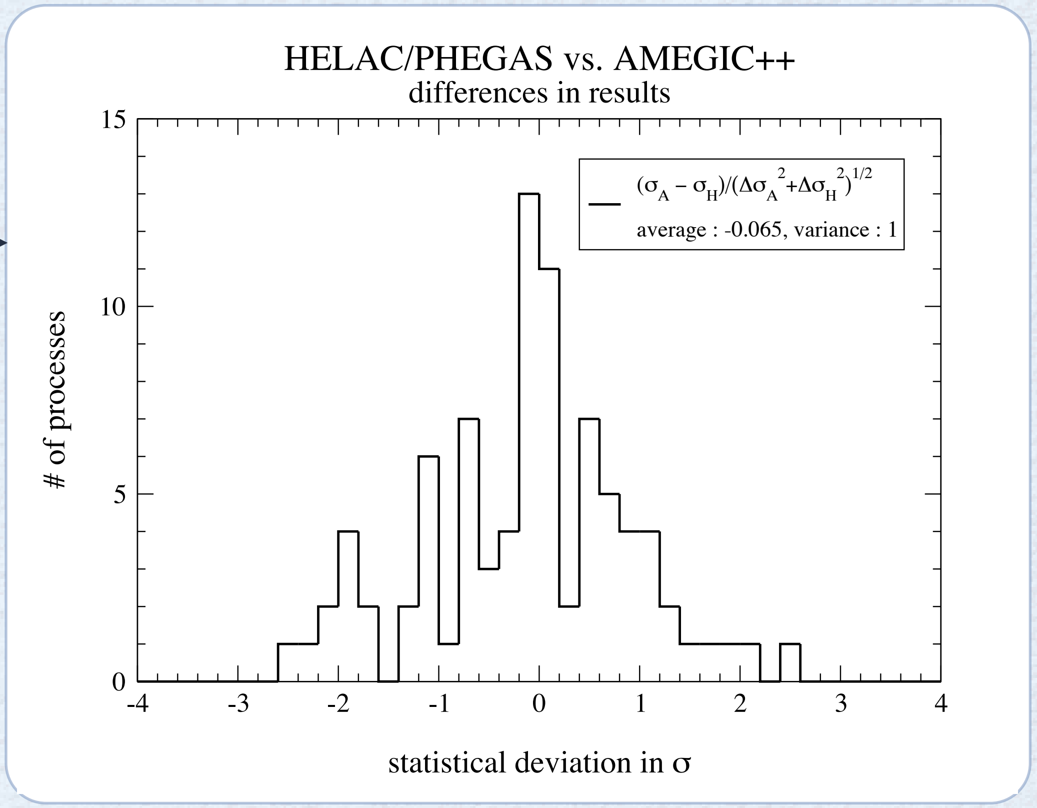
F. Krauss, R.Kuhn, G. Soff; JHEP 02 (2002) 044

Sherpas built-in standard ME generator AMEGIC++:

- Fully automated calculation of (polarized) cross sections in the SM(+AGC), MSSM and ADD model
- Expandable, easy implementation of new models
  FeynRules reader currently being validated

Extensively tested:

- $e^+e^- \rightarrow 6f$ comparison vs. HELAC/PHEGAS
  deviations in 86 processes EPJC 34(2004)173 →
- Comparison of 2→2 MSSM processes vs. WHIZARD/O'Mega & SMadGraph
  PRD 73 (2006) 055005
  http://www.sherpa-mc.de/susy_comparison
- Comparison during MC4LHC Workshop
  http://mlm.home.cern.ch/mlm/mcwshop03/mcwshop.html

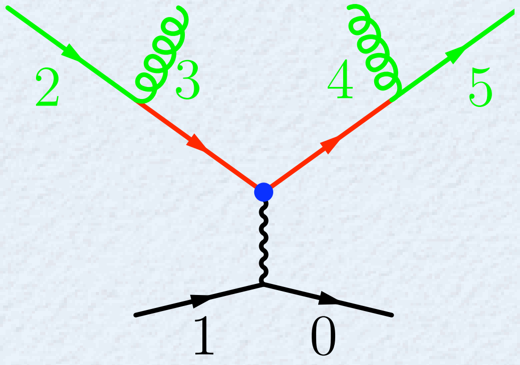


AMEGIC++ - WORKFLOW

F. Krauss, R.Kuhn, G. Soff; JHEP 02 (2002) 044

AMEGIC++ is an ME-generator-generator:

- Given initial and final state, AMEGIC++ constructs all diagrams
- Diagrams are translated into C++ code employing the helicity formalism NPB 262 (1985) 235, PLB 350 (1995) 225
- Corresponding phase space mappings are generated



↔

$$\mathbf{D}_{\mathrm{iso}}(\mathbf{23},\mathbf{45}) \otimes \mathbf{P}_0(\mathbf{23}) \otimes \mathbf{P}_0(\mathbf{45}) \otimes \mathbf{D}_{\mathrm{iso}}(\mathbf{2},\mathbf{3}) \otimes \mathbf{D}_{\mathrm{iso}}(\mathbf{4},\mathbf{5})$$

(allows efficient mapping of potentially complicated peak structure in subsequent PS integration, see later)

- C++ code, representing all the above is stored to disk, must be compiled, is then linked dynamically and used to compute cross sections and generate events

AMEGIC++ - PERFORMANCE

- Example: ME-Generator comparison in context of MC4LHC
(http://indico.cern.ch/categoryDisplay.py?categId=152)

X-sects (pb)	$e^-\bar{\nu}_e + n$ QCD jets					
Number of jets	0	1	2	3	4	5	6
`ALPGEN`	3904(6)	1013(2)	364(2)	136(1)	53.6(6)	21.6(2)	8.7(1)
`AMEGIC++`	3908(3)	1011(2)	362.3(9)	137.5(5)	54(1)		
`CompHEP`	3947.4(3)	1022.4(5)	364.4(4)				
`GR@PPA`	3905(5)	1013(1)	361.0(7)	133.8(3)	53.8(1)		
`JetI`	3786(81)	1021(8)	361(4)	157(1)	46(1)		
`MadEvent`	3902(5)	1012(2)	361(1)	135.5(3)	53.6(2)		

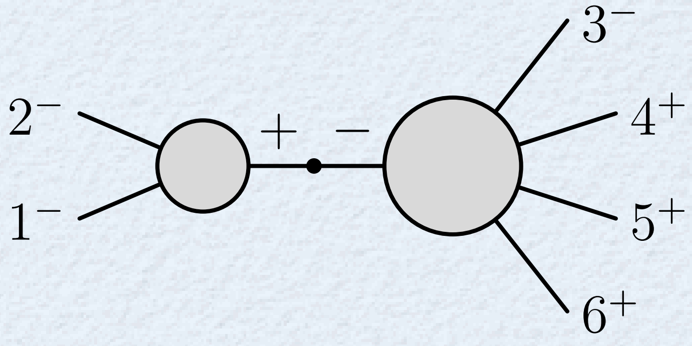
Fill these !

X-sects (pb)	$e^+\nu_e + n$ QCD jets						
Number of jets	0	1	2	3	4	5	6
`ALPGEN`	5423(9)	1291(13)	465(2)	182.8(8)	75.7(8)	32.5(2)	13.9(2)
`AMEGIC++`	5432(5)	1277(2)	466(2)	184(1)	77.3(4)		
`CompHEP`	5485.8(6)	1287.5(7)	467.3(8)				
`GR@PPA`	5434(7)	1273 (2)	467.7(9)	181.8(5)	76.6(3)		
`JetI`	5349(143)	1275(12)	487(3)	212(2)			
`MadEvent`	5433(8)	1277(2)	464(1)	182(1)	75.9(3)		

HIGH-MULTI QCD ME'S WITHCSW

T. Gleisberg, SH, F. Krauss, R. Matyskiewicz; arXiv:0808.3672 [hep-ph]

- Twistor-inspired techniques (CSW rules) help speeding up calculation of pure QCD & QCD associated ME's for high multiplicities
- Big advantage: Up to $\mathbf{N_{out} = 7}$ only up to 3 MHV-amplitudes must be sewed together
- **So how far can we go with it ?**

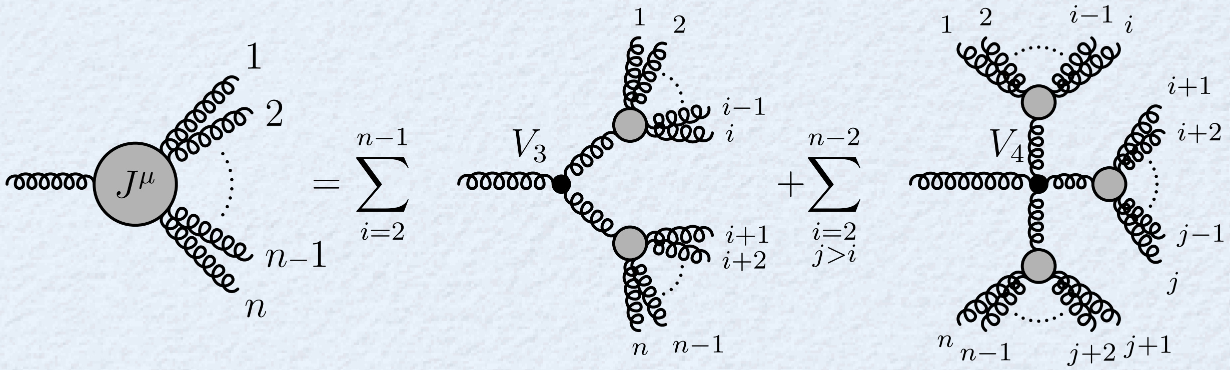


$pp \to n$ jets gluons only	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$
MC cross section [pb]	$8.915 \cdot 10^7$	$5.454 \cdot 10^6$	$1.150 \cdot 10^6$	$2.757 \cdot 10^5$	$7.95 \cdot 10^4$
stat. error	0.1%	0.1%	0.2%	0.5%	1%
	integration time for given stat. error [s]				
CSW (HAAG)	4	165	1681	12800	$2 \cdot 10^6$
CSW (CSI)	-	480	6500	11900	197000
AMEGIC (HAAG)	6	492	41400	-	-
COMIX (RPG)	159	5050	33000	38000	74000
COMIX (CSI)	-	780	6930	6800	12400

VERY HIGH-MULTI ME'S - COMIX

T. Gleisberg, SH; arXiv:0808.3674 [hep-ph]

- Colour dressed Berends-Giele recursion currently seems best for very large multis JHEP 08 (2006) 062
  - ➜ New ME generator **COMIX**



- Fully general SM implementation
- Key point: Vertex decomposition of all four-particle vertices (Growth in computational cost determined by # of legs at vertices)
- Example: performance in QCD benchmark (2➜n gluon)

World record ;-)

gg → ng	Cross section [pb]				
n	8	9	10	11	12
$\sqrt{s}$ [GeV]	1500	2000	2500	3500	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)				

- So the ME is ticked off, but how about the phasespace ?

COMIX - PHASESPACE RECURSION

T. Gleisberg, SH; arXiv:0808.3674 [hep-ph]

State-of-the art in phasespace generation: factorise PS using

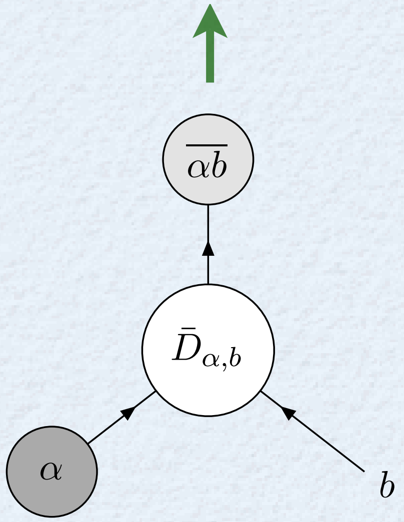
$$\mathrm{d}\mathbf{\Phi_n}\left(\mathbf{a},\mathbf{b};\mathbf{1},\ldots,\mathbf{n}\right)=\mathrm{d}\mathbf{\Phi_{n-m+1}}\left(\mathbf{a},\mathbf{b};\pi,\mathbf{m}+\mathbf{1},\ldots,\mathbf{n}\right)\,\frac{\mathrm{d}\mathbf{s}_\pi}{\mathbf{2}\pi}\,\mathrm{d}\mathbf{\Phi_m}\left(\pi;\mathbf{1},\ldots,\mathbf{m}\right)$$

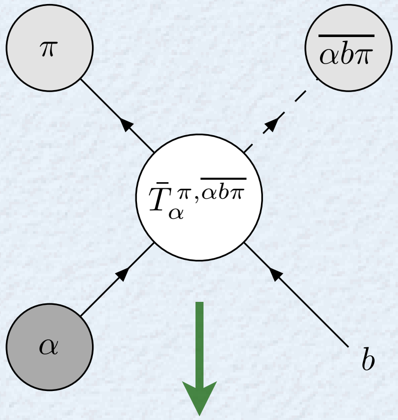
Remaining basic building blocks of the phasespace:

- “Propagators“ $\mathbf{P}_{\boldsymbol{\pi}}=\begin{cases}\mathbf{1} & \text{if } \boldsymbol{\pi} \text{ external}\\ \dfrac{\mathbf{d}\boldsymbol{s_\pi}}{\mathbf{2}\boldsymbol{\pi}} & \text{else}\end{cases}$

- “Vertices”

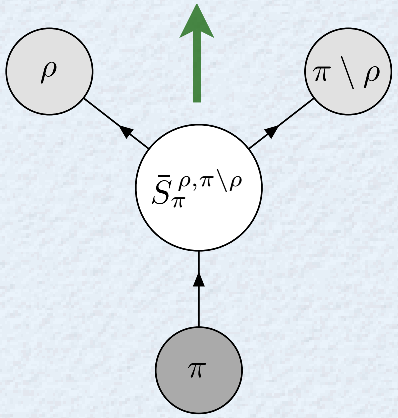
$$(\mathbf{2}\pi)^{\mathbf{4}}\,\mathrm{d}^{\mathbf{4}}\mathbf{p}_{\alpha\mathbf{b}}\,\delta^{(\mathbf{4})}(\mathbf{p}_\alpha+\mathbf{p_b}-\mathbf{p}_{\alpha\mathbf{b}})$$





$$\mathbf{T}_\alpha^{\pi,\overline{\alpha\mathbf{b}\pi}}=\frac{\lambda(\mathbf{s}_{\alpha\mathbf{b}},\mathbf{s}_\pi,\mathbf{s}_{\overline{\alpha\mathbf{b}\pi}})}{\mathbf{16}\pi^{\mathbf{2}}\,\mathbf{2}\,\mathbf{s}_{\alpha\mathbf{b}}}\;\mathrm{d}\cos\theta_\pi\,\mathrm{d}\phi_\pi$$

$$\mathbf{S}_\pi^{\pi,\pi\setminus\rho}=\frac{\lambda(\mathbf{s}_\pi,\mathbf{s}_\rho,\mathbf{s}_{\pi\setminus\rho})}{\mathbf{16}\pi^{\mathbf{2}}\,\mathbf{2}\,\mathbf{s}_\pi}\;\mathrm{d}\cos\theta_\rho\,\mathrm{d}\phi_\rho$$



same function but different sampling

Arrows → Momentum flow

COMIX - PHASESPACE RECURSION

T. Gleisberg, SH; arXiv:0808.3674 [hep-ph]

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

  Example: s-channel phasespace recursion

$$\mathbf{d\Phi_S}\left(\pi\right) = \mathbf{F}^{-1}\left[\sum \alpha\left(\mathbf{S}_{\pi}^{\rho,\pi\setminus\rho}\right)\right]^{-1}$$

Weights for adaptive multichanneling

$$\times\,\mathbf{F}\left[\sum \alpha\left(\mathbf{S}_{\pi}^{\rho,\pi\setminus\rho}\right)\mathbf{S}_{\pi}^{\rho,\pi\setminus\rho}\,\mathbf{P}_{\rho}\,\mathbf{d\Phi_S}\left(\rho\right)\,\mathbf{P}_{\pi\setminus\rho}\,\mathbf{d\Phi_S}\left(\pi\setminus\rho\right)\right]$$

- Example process:

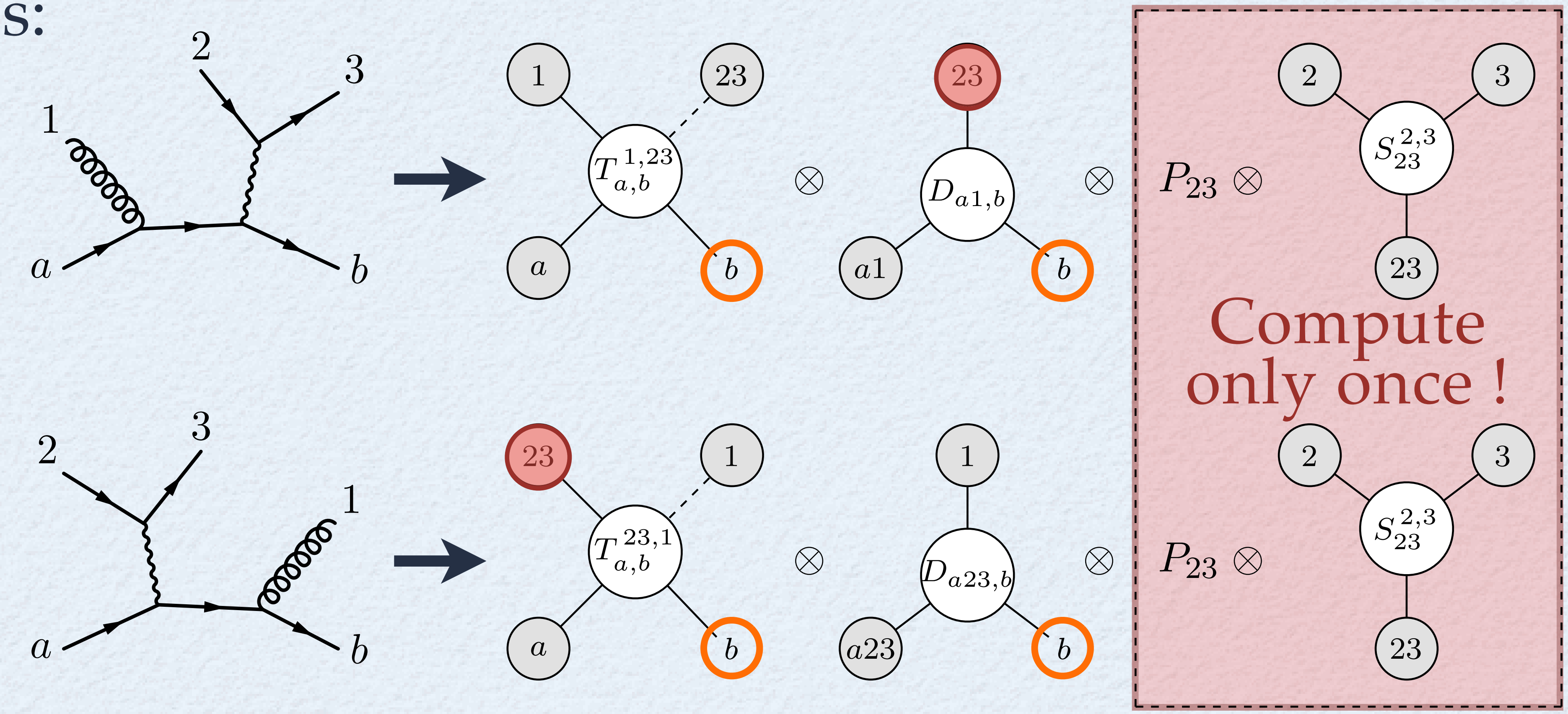
  $\mathbf{pp \rightarrow e^+e^-g}$

“b” is fixed

↓

Every weight is unique !

(can be labeled by shaded blobs)



Compute only once !

COMIX - PERFORMANCE

T. Gleisberg, SH; arXiv:0808.3674 [hep-ph]

- Example: Drell-Yan+b-pair+jets
  comparison with ALPGEN & AMEGIC++

σ [pb]	Number of jets					
$e^-e^+ + b\bar{b}$ + QCD jets	0	1	2	3	4	5
Comix	18.90(3)	6.81(2)	3.07(3)	1.536(9)	0.763(6)	0.37(1)
ALPGEN	18.95(8)	6.80(3)	2.97(2)	1.501(9)	0.78(1)	
AMEGIC++	18.90(2)	6.82(2)	3.06(4)			

All partons !

- Example: b-pair + jets
  comparison with ALPGEN & AMEGIC++

σ [μb]	Number of jets						
$b\bar{b}$ + QCD jets	0	1	2	3	4	5	6
Comix	471.2(5)	8.83(2)	1.813(8)	0.459(2)	0.150(1)	0.0531(5)	0.0205(4)
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 - HELPFUL TECHNICALITIES

T. Gleisberg, SH; arXiv:0808.3674 [hep-ph]

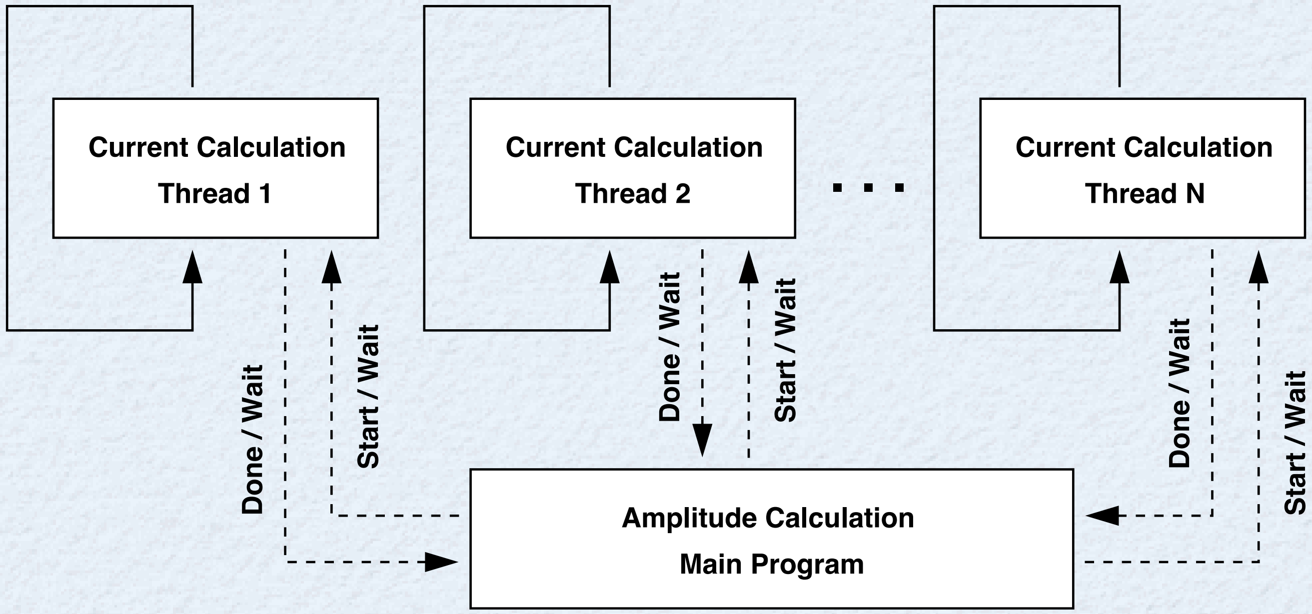
- General structure of recursion (ME and phasespace):

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

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

➡ Straightforward multithreading algorithm

Use as many processors/cores as you like !



Current Calculation Thread 1

Current Calculation Thread 2

. . .

Current Calculation Thread N

Done / Wait

Start / Wait

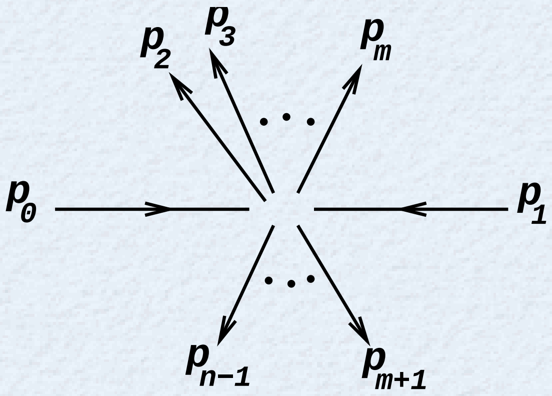
Amplitude Calculation Main Program

Identical procedure for ME and phasespace due to same recursion

COLOUR & PHASE SPACE SAMPLING

T. Gleisberg, SH; arXiv:0808.3674 [hep-ph]

- QCD processes have typical antenna structure with numerous terms

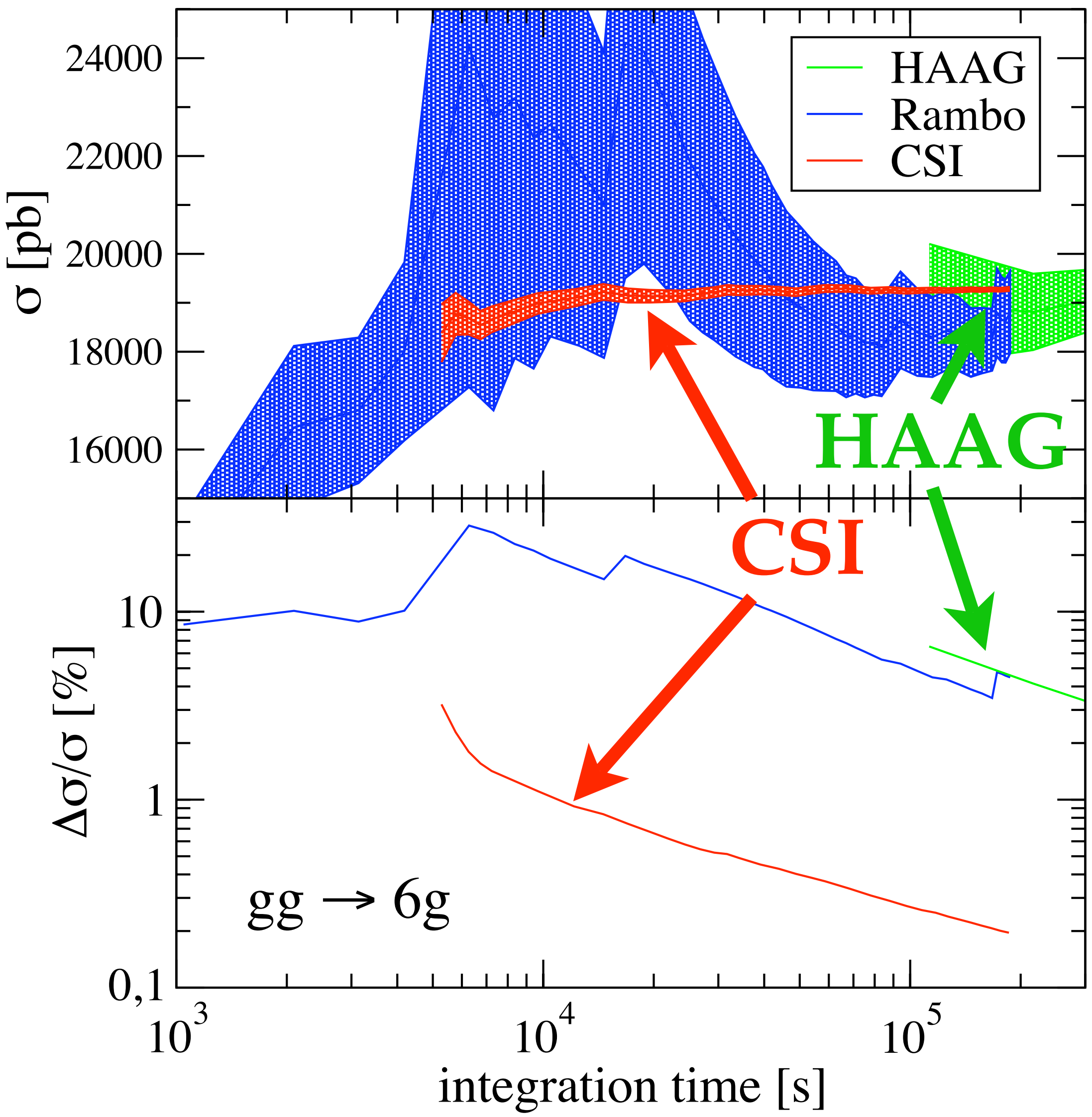


$$\propto \frac{1}{(p_0p_1)(p_1p_2)\dots(p_{n-2}p_{n-1})(p_{n-1}p_0)}$$

- HAAG can generate momenta according to specific antenna
- Sample colours → configuration defines which antennae occur

→ For every colour space point a multichannel of HAAGs can be constructed on the flight → CSI

CSI - Colour Sampling Integrator

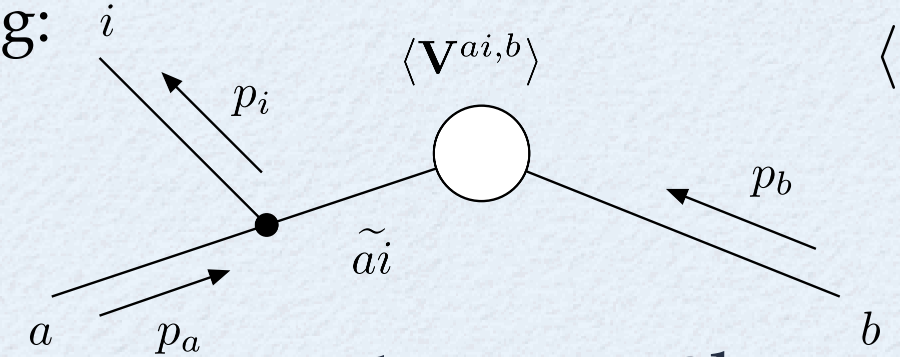


CS-Subtraction based Shower

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

- Catani-Seymour subtraction terms
  - ➜ General framework for QCD NLO calculations
    (here projected onto large N_C limit)
- Splitting of parton $\widetilde{\mathbf{ij}}$ into partons i and j, spectator k
  - ➜ Momentum reshuffled locally, spectator enters splitting function !

e.g. initial-initial splitting:



$$\langle \mathbf{V}^{\mathbf{ai},\mathbf{b}}(\mathbf{x}_{\mathbf{i},\mathbf{ab}}) \rangle = \mathbf{P}_{\mathbf{a}\to\widetilde{\mathbf{ai}}\,\mathbf{i}}(\mathbf{x}_{\mathbf{i},\mathbf{ab}})$$

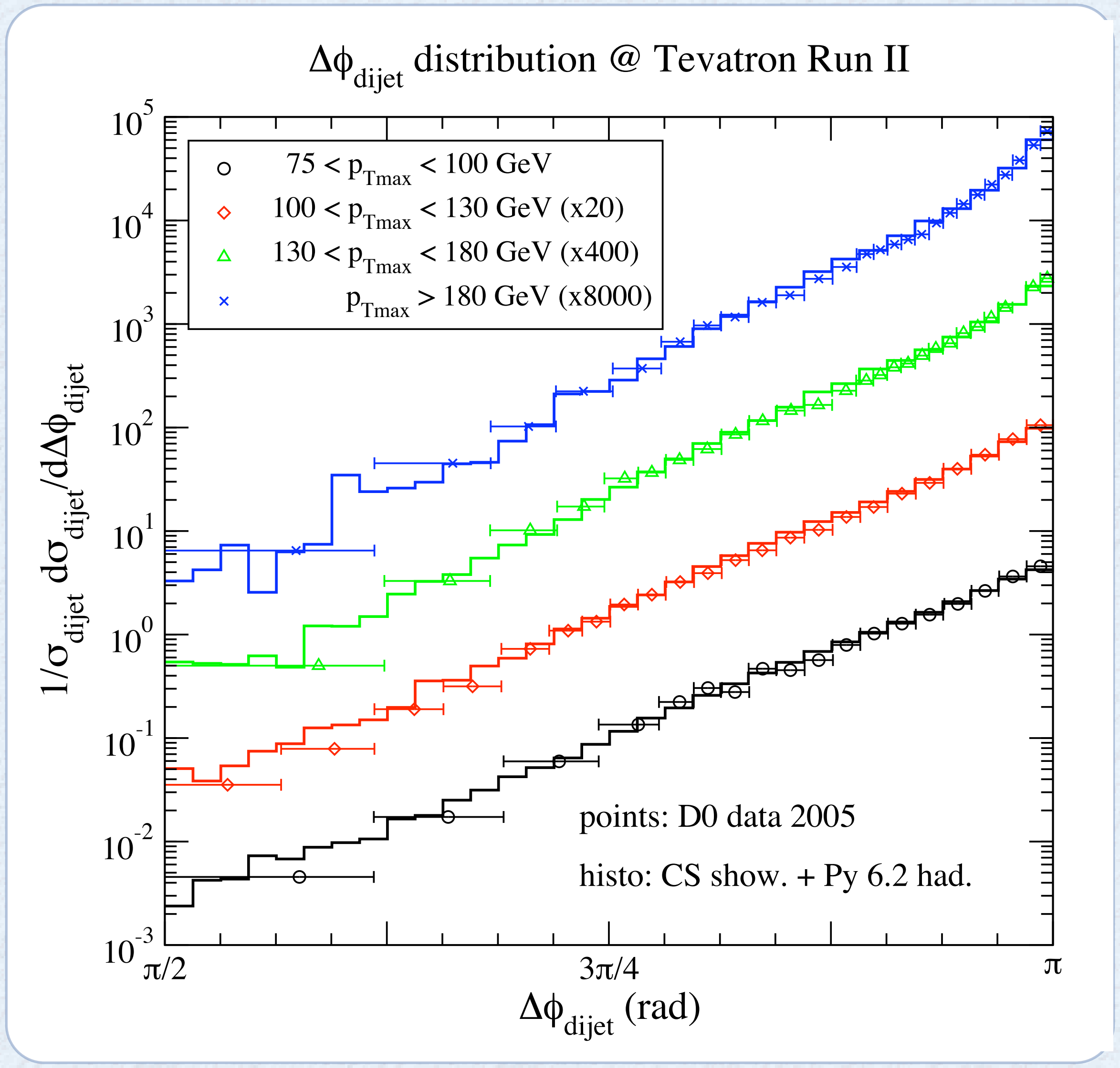
$$\mathbf{x}_{\mathbf{i},\mathbf{ab}} = \frac{\mathbf{p}_\mathbf{a}\mathbf{p}_\mathbf{b} - \mathbf{p}_\mathbf{i}\mathbf{p}_\mathbf{a} - \mathbf{p}_\mathbf{i}\mathbf{p}_\mathbf{b}}{\mathbf{p}_\mathbf{a}\mathbf{p}_\mathbf{b}}$$

- Advantages over conventional Parton Shower
  - ➜ Excellent approximation of ME
  - ➜ Much better analytic control
- Implemented into Sherpa for the general case
  (final-final, initial-final and initial-initial dipoles)

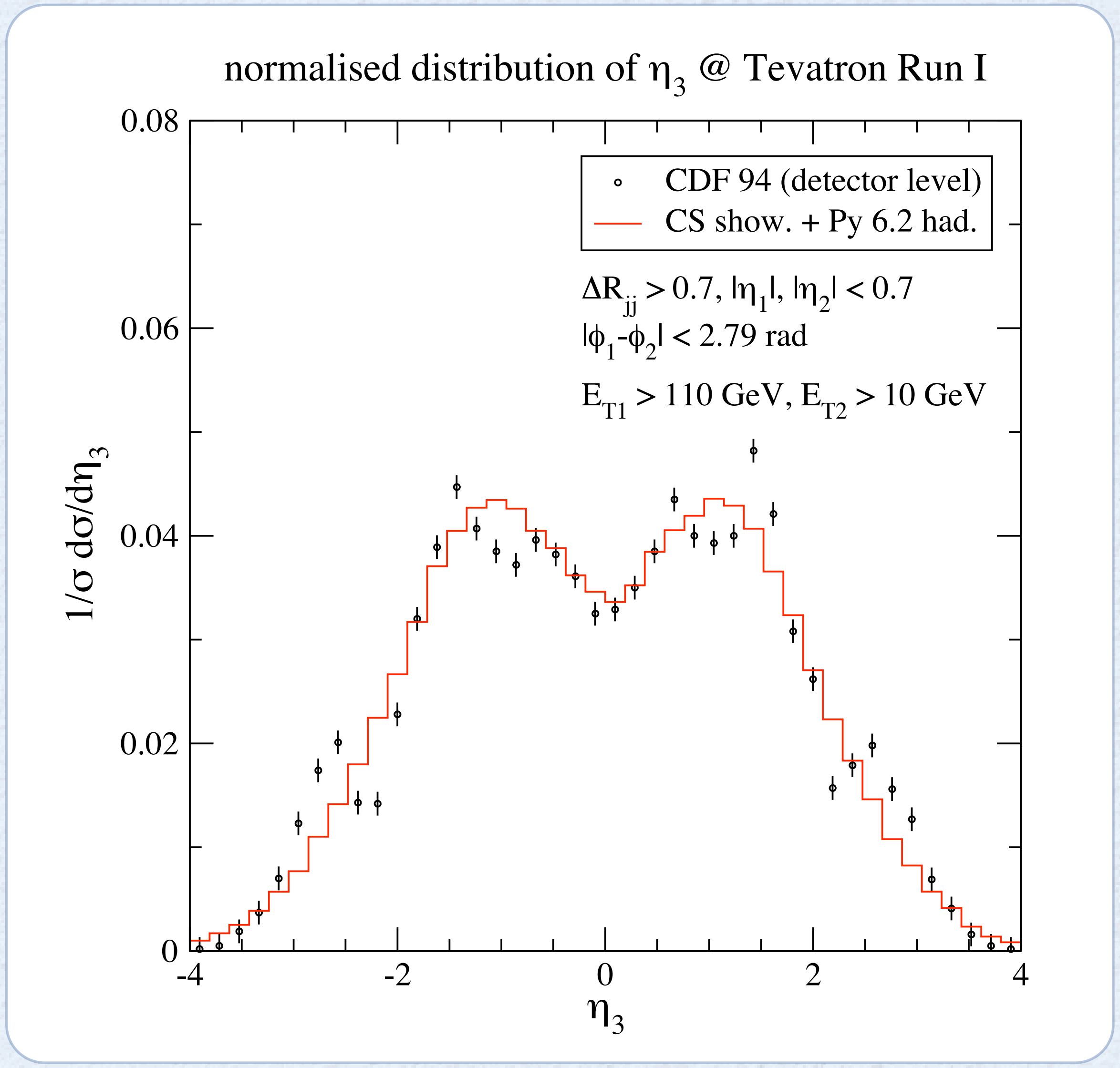
CS-SUBTRACTION BASED SHOWER

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

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



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



ME+PS - WHY SHOULD WE DO IT ?

Matrix Elements

Advantage

- Exact to fixed order
- Include all interferences

Drawback

- Calculable only for low FS multiplicity (n≤8-10)

Parton Showers

Advantage

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

Drawback

- Interference effects only through angular ordering

Combine both approaches: CKKW

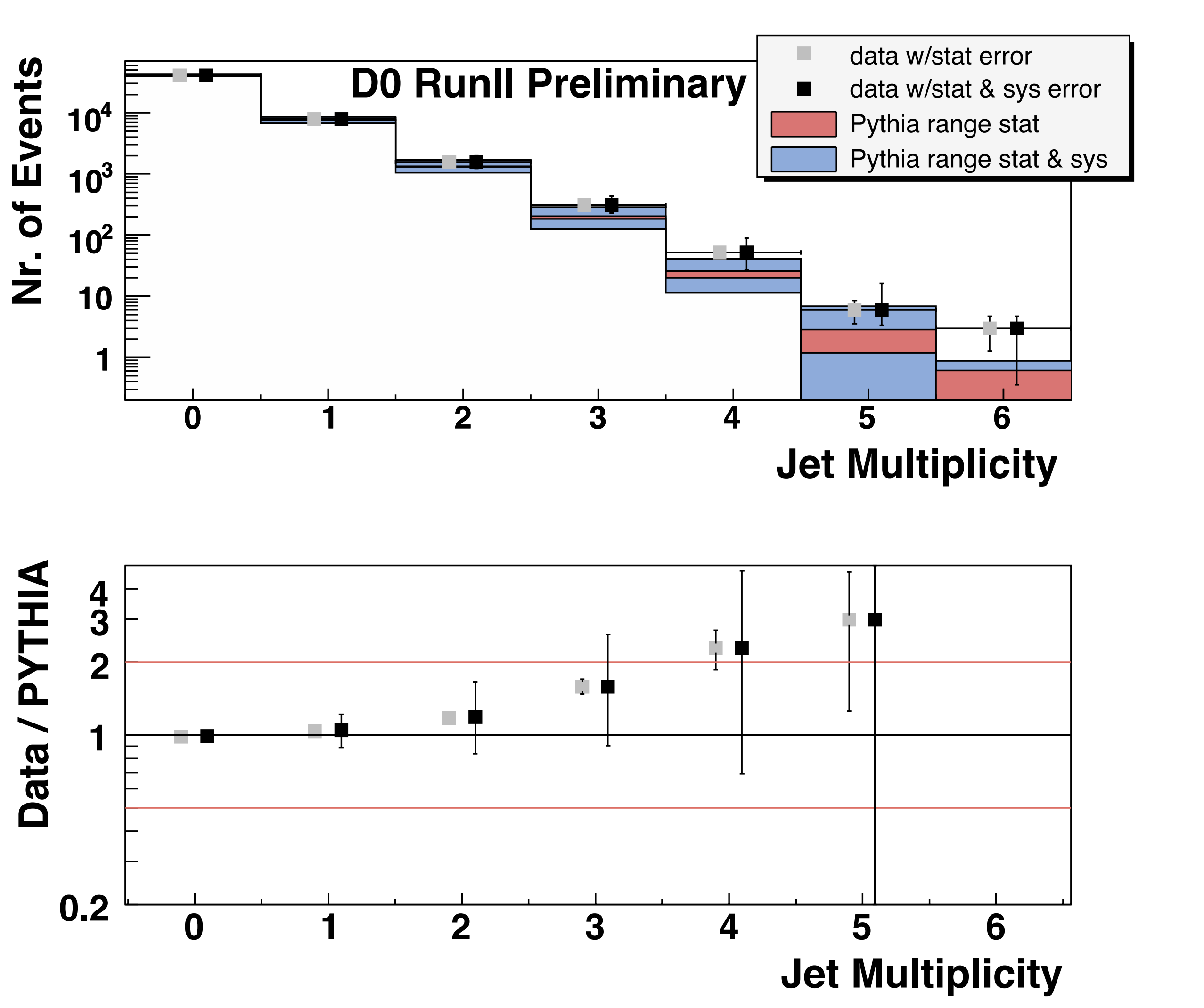
- Good description of hard radiation (ME)
- Correct intrajet evolution (PS)

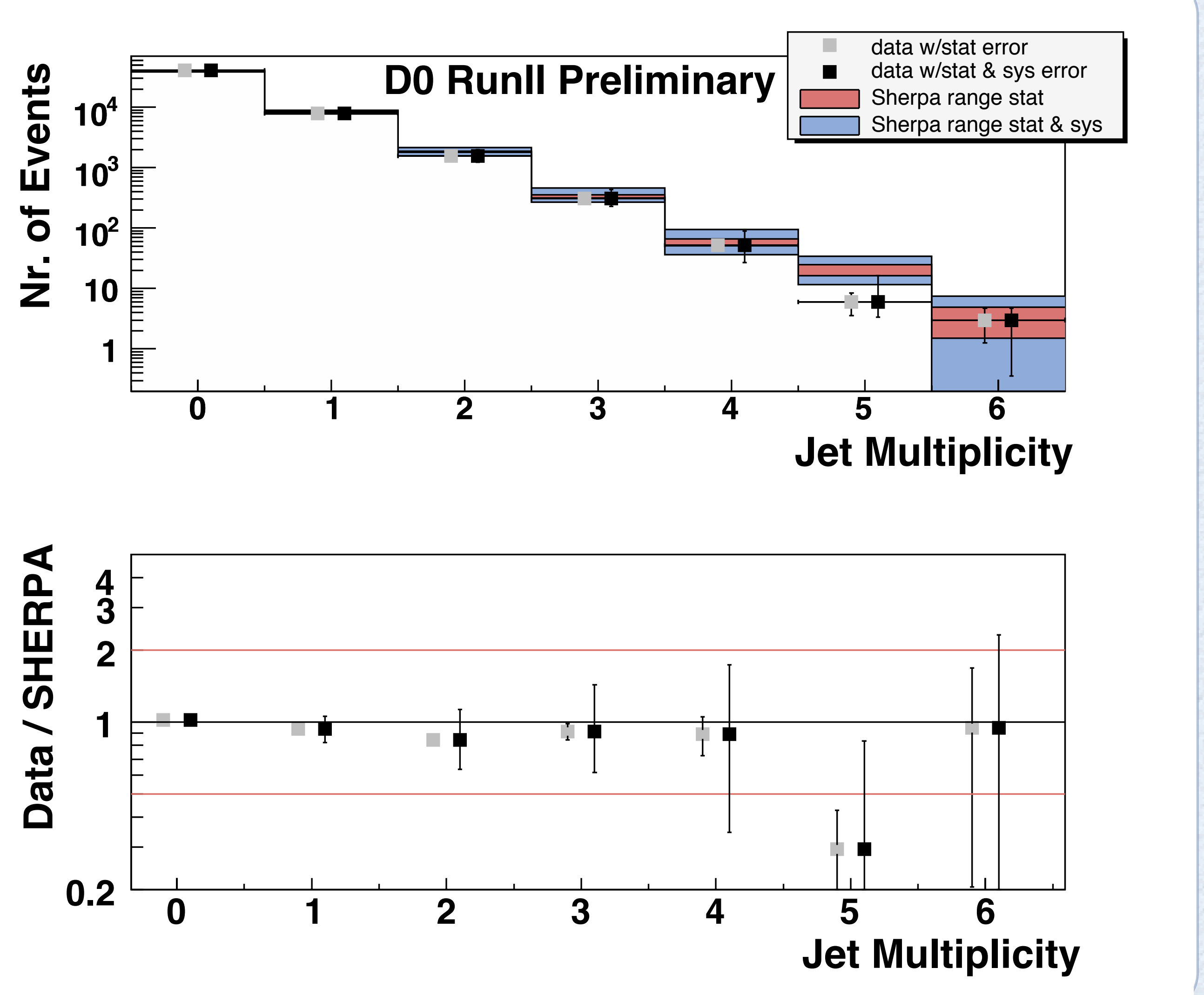
- Strategy: Separate phase space
  - Jet production region → ME
  - Intrajet evolution region → PS
- **Free parameter: Separation cut Q_{cut}** (K_T-type jet measure)

CKKW - Z+JETS @ TEVATRON

The DØ collaboration, DØ note 5066-CONF

- Jet multiplicity





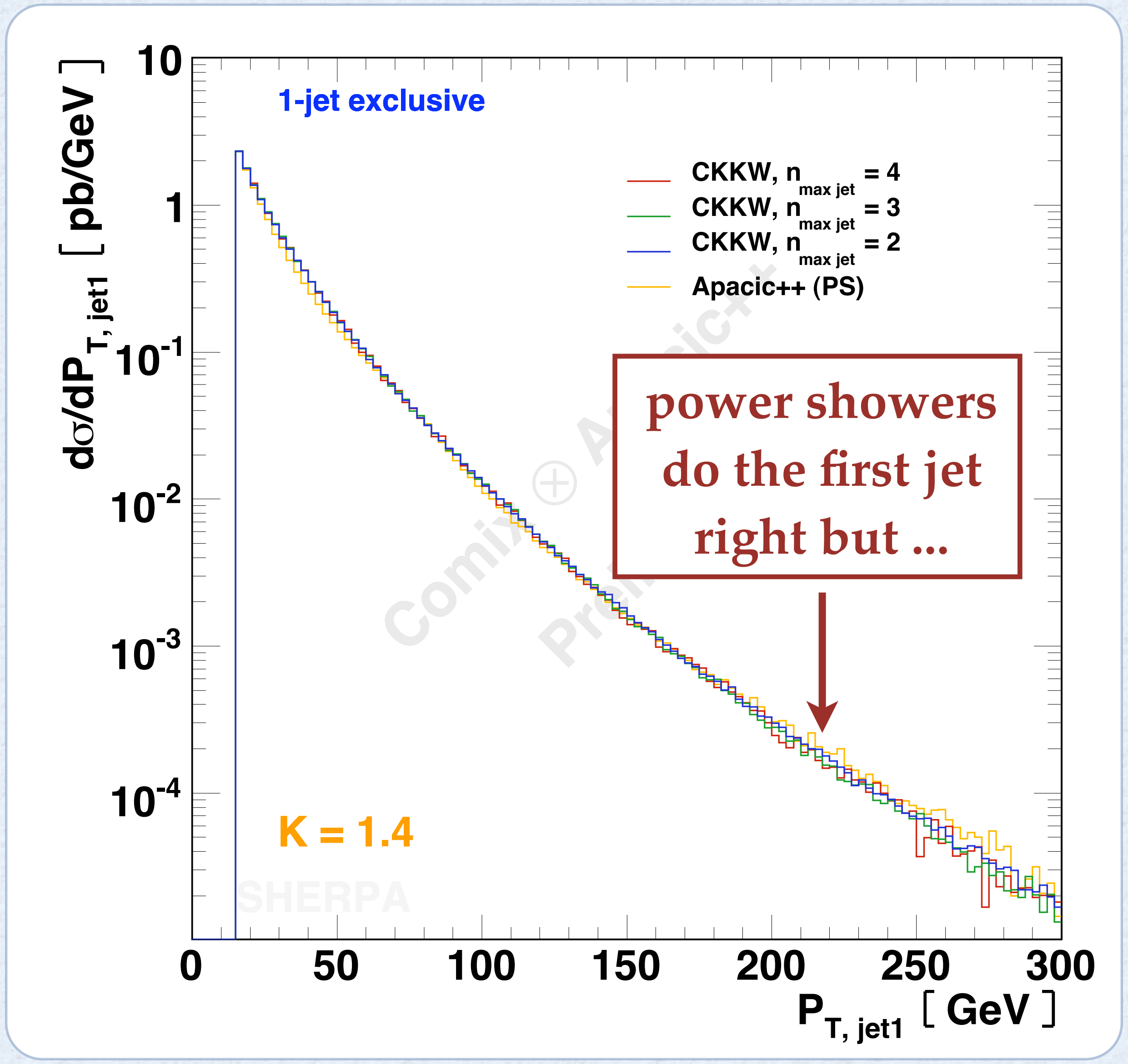
- Pythia 6.2
  normalized to data

- Sherpa 1.0
  normalized to data

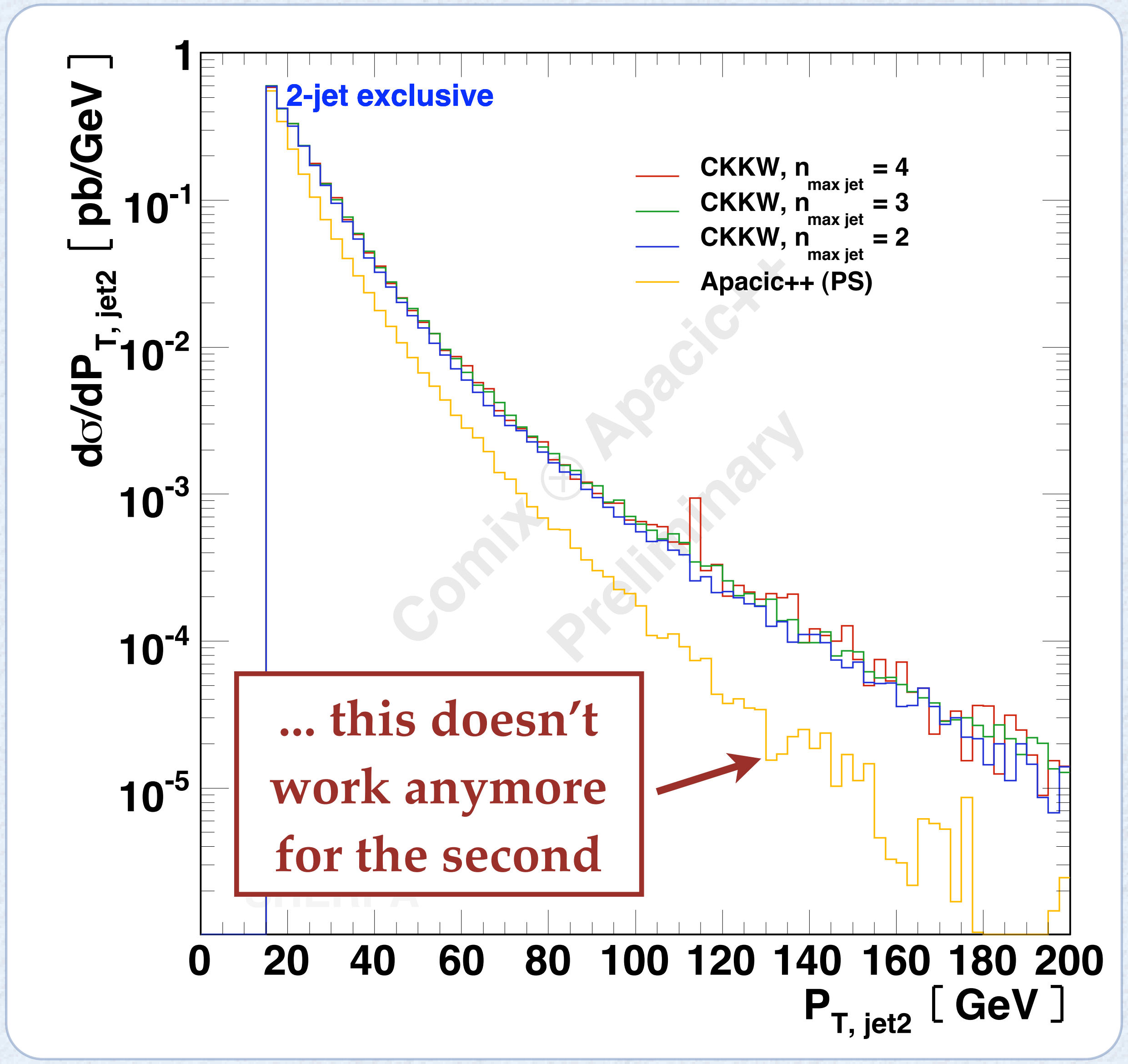
CKKW WITH COMIX

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

- pp➔ll+jets at the Tevatron
  exclusive jet-p_T , comparison vs. PS



power showers do the first jet right but ...

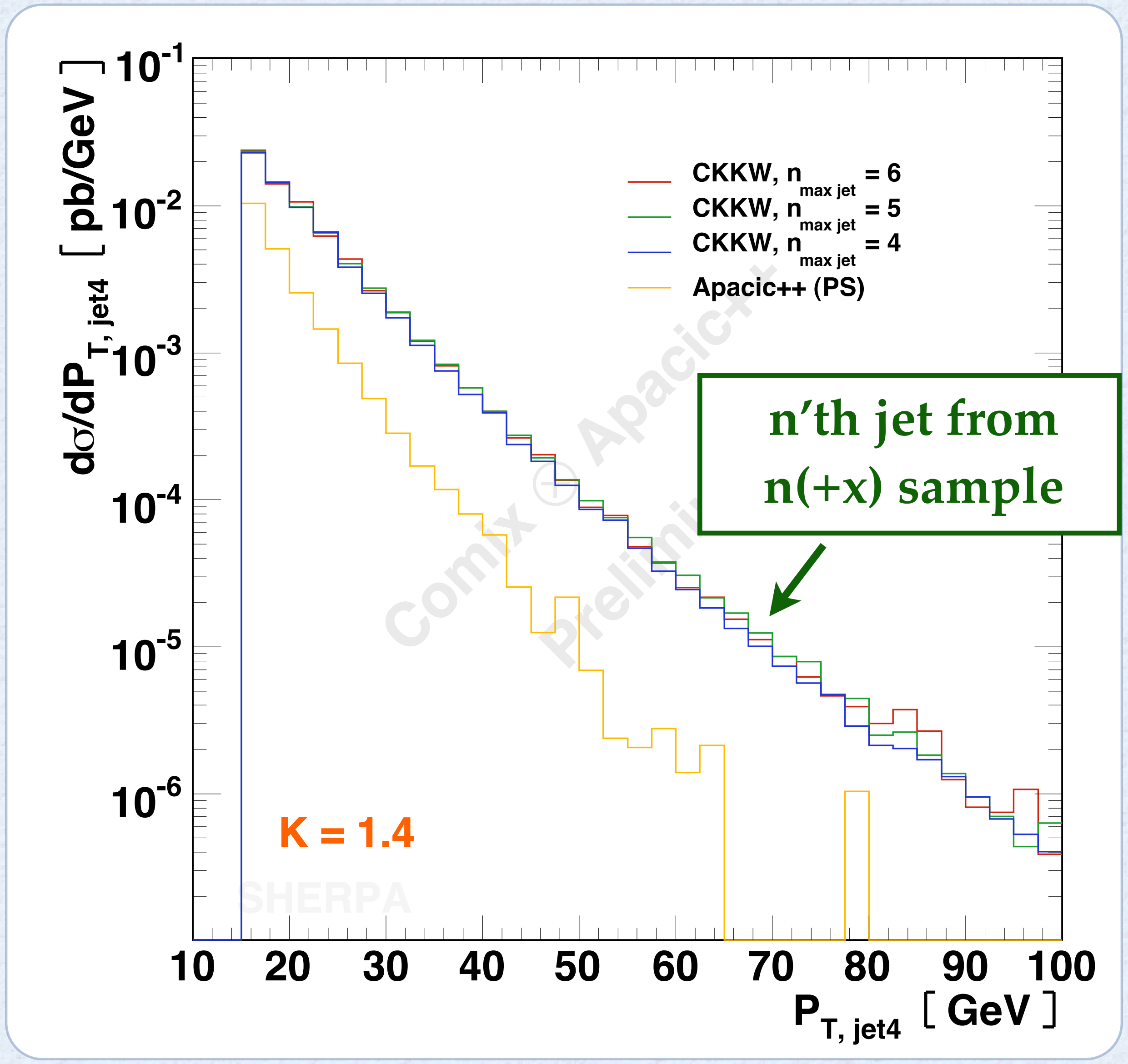


... this doesn't work anymore for the second

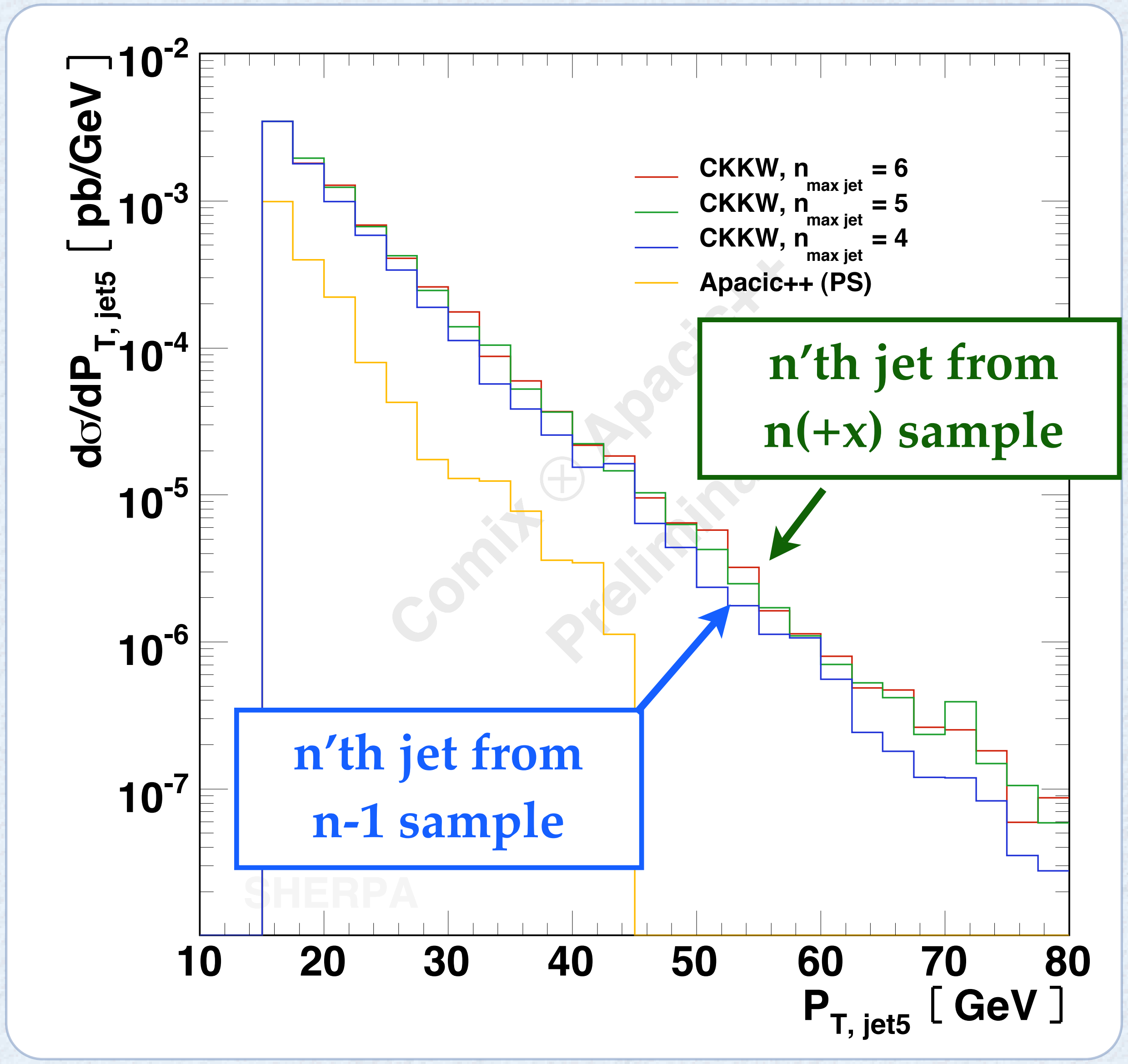
CKKW WITH COMIX

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

- pp ➔ ll+jets at the Tevatron
  inclusive jet-p_T , effect of N_{max} variation



n’th jet from
n(+x) sample



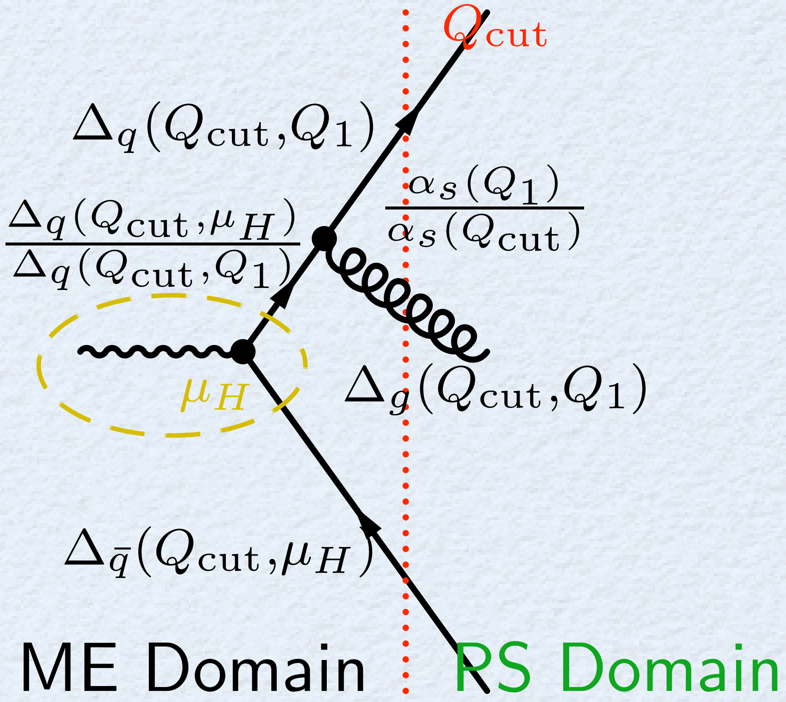
n’th jet from
n(+x) sample

n’th jet from
n-1 sample

CKKW - Cooking Recipe

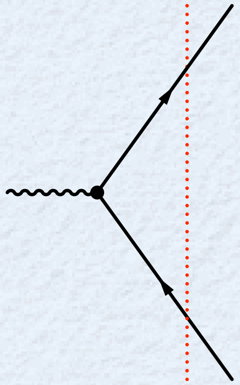
JHEP 0111 (2001) 063, JHEP 0208 (2002) 015

- Select final state multiplicity and kinematics according to σ ‘above’ $Q_{\rm cut}$ (NLO real emission in ME cut from below)
- K_T-cluster backwards to define PS history and starting conditions (find core process)
- **Reweight ME** using NLL Sudakov factors to obtain exclusive samples at $Q_{\rm cut}$
- Start the parton shower at the hard scale **Veto all PS emissions harder than $Q_{\rm cut}$** (NLO real emission in PS cut from above)



➡ This yields the correct jet rates at NLL
Generic example: 2-jet rate in ee→qq

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



CAN WE IMPROVE CKKW ?

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

- Select atics accord (NLO w)
- K_T-clu ry and st ss)
- **Re**weight ME using NLL Sudakov factors to c
- Sta
  Vet
  (NLO real emission in PS cut from above)

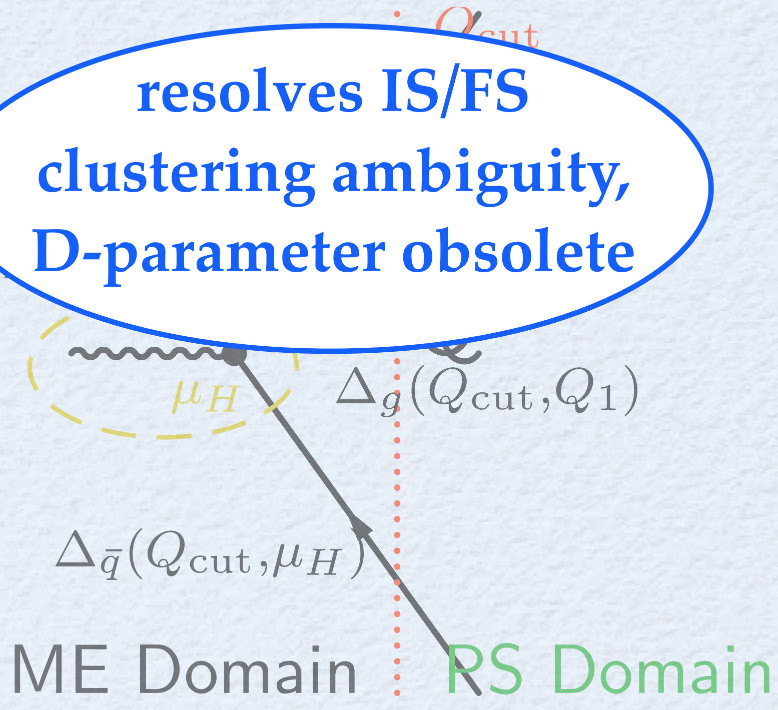
Usual K_T-type measure does not take beam assignment into account (possible solution in NPB 406 (1993) 187)

pQCD is crossing invariant and so the measure must be

resolves IS/FS clustering ambiguity, D-parameter obsolete

Clustering does not necessarily reconstruct sensible history according to NLL formalism

NLL resummation is not the end of the story ordering must be guided by shower evolution



decouples phase space separation and shower history construction

This yields th rates at NLL
Generi ee→qq

R$_2$ $\Big)\dfrac{\boldsymbol{\Delta}(\mathbf{q},\mu_{\rm hard})}{\boldsymbol{\Delta}(\mathbf{Q}_{\rm cut},\mu_{\rm hard})}\Big)$

CS-based shower allows better control over jet veto

Stefan Höche, MPI Workshop Perugia, 30.10.2008

“CKKW 2.0” Sneak Preview

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

- Solution to the phasespace separation problem, CS - inspired

  → Identify two-particle poles of real NLO ME through

masses included

$$Q^2_{ij} = 2\,p_i p_j \,\min\left\{\frac{1}{C_{i,j}}, \frac{1}{C_{j,i}}\right\} \qquad C_{i,j} = \max_{k} \begin{cases} \dfrac{p_i p_k}{(p_i + p_k) p_j} - \dfrac{m_i^2}{2\,p_i p_j} & \text{if } j = g \\ 1 & \text{else} \end{cases}$$

max over colour partners

New separation criterion has good theoretical behaviour

- Soft limit (j → gluon)

$$\frac{1}{Q^2_{ij}} \rightarrow \frac{1}{\lambda^2}\,\frac{1}{2\,p_i\,q}\left[\frac{p_i p_k}{(p_i + p_k)\,q} - \frac{m_i^2}{2\,p_i q}\right] \leftarrow$$

correct part of eikonal

- (Quasi-)Collinear limit

$$\frac{1}{Q^2_{ij}} \rightarrow \frac{1}{2\,\lambda^2}\,\frac{1}{p^2_{ij} - m_i^2 - m_j^2}\,\max\left\{\tilde{C}_{i,j}\,,\,\tilde{C}_{j,i}\right\}$$

$$\tilde{C}_{i,j} \rightarrow \begin{cases} \dfrac{2\,z}{1 - z} - \dfrac{m_i^2}{p_i p_j} & \text{if j=g} \leftarrow \\ 2 & \text{else} \end{cases}$$

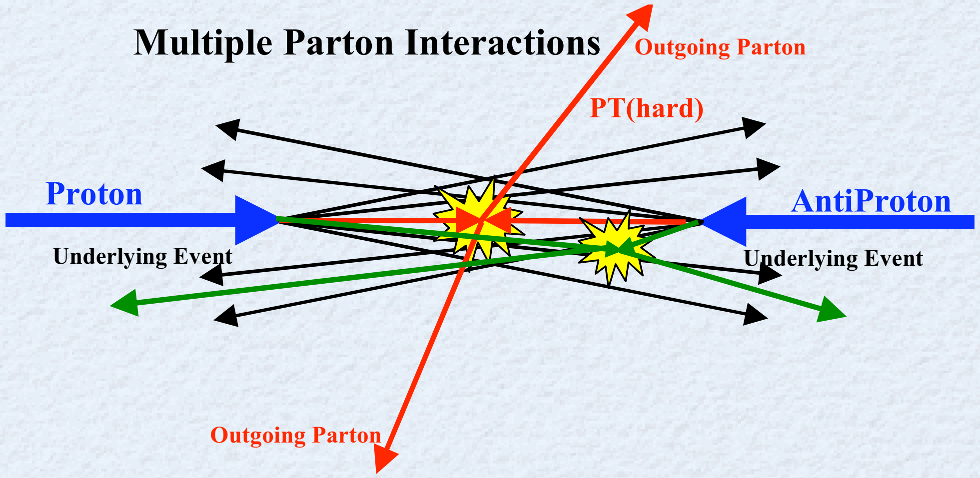
leading term of DGLAP kernel

MPI SIMULATION AND CKKW

in hep-ph/0601012

Sherpas current multiple parton interaction (MPI) module

- Based on the PYTHIA model
  T. Sjöstrand & M. van Zijl, PRD 36 (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, $\mu_{\rm MI}$
- Current Sherpa algorithm (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

in hep-ph/0601012

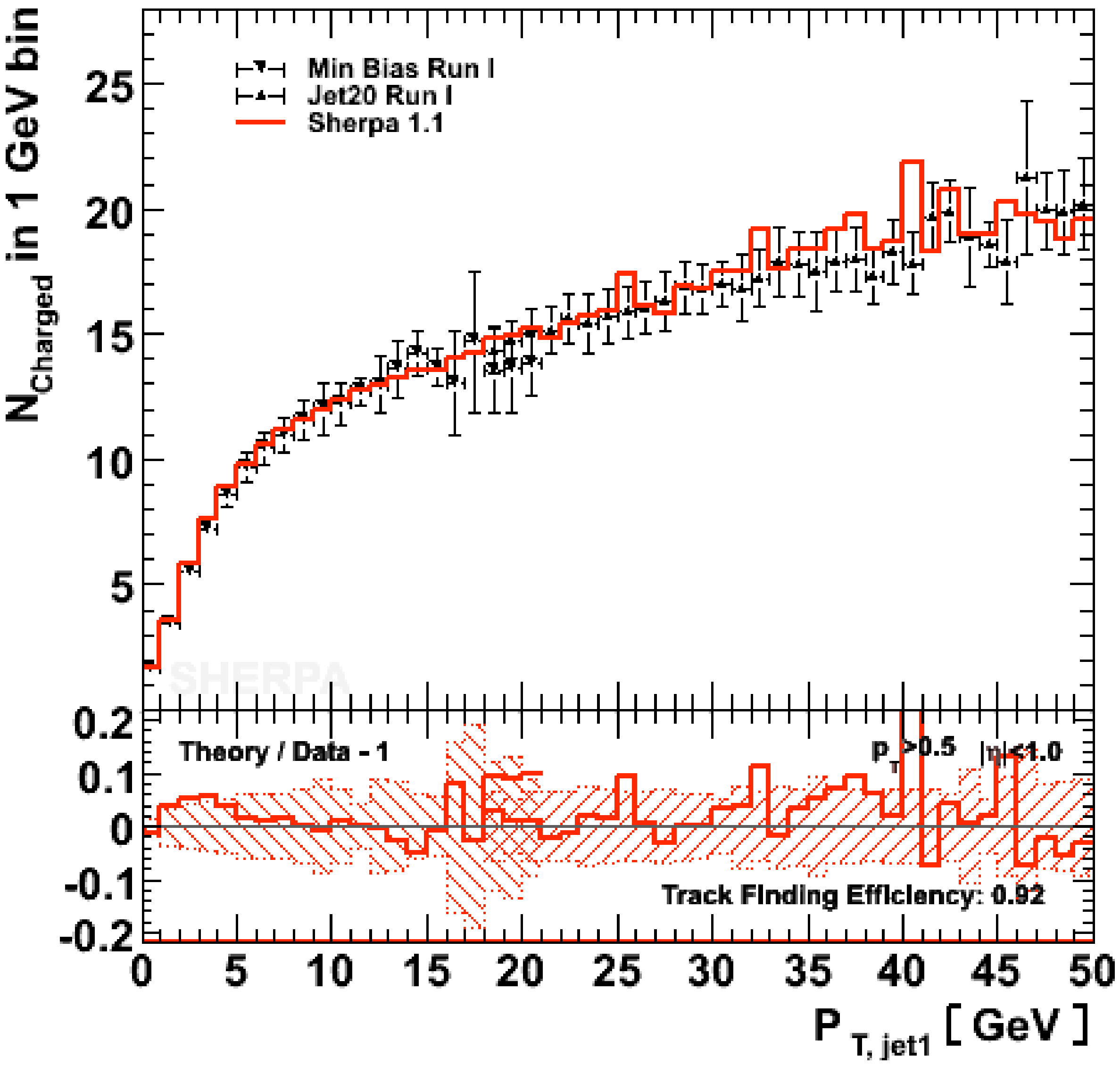
Our current "best fit" for CDF

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

To take home ...

- Highly dependent on $p_{T,\min}$ and PDF
- Does not give a prediction for LHC energies

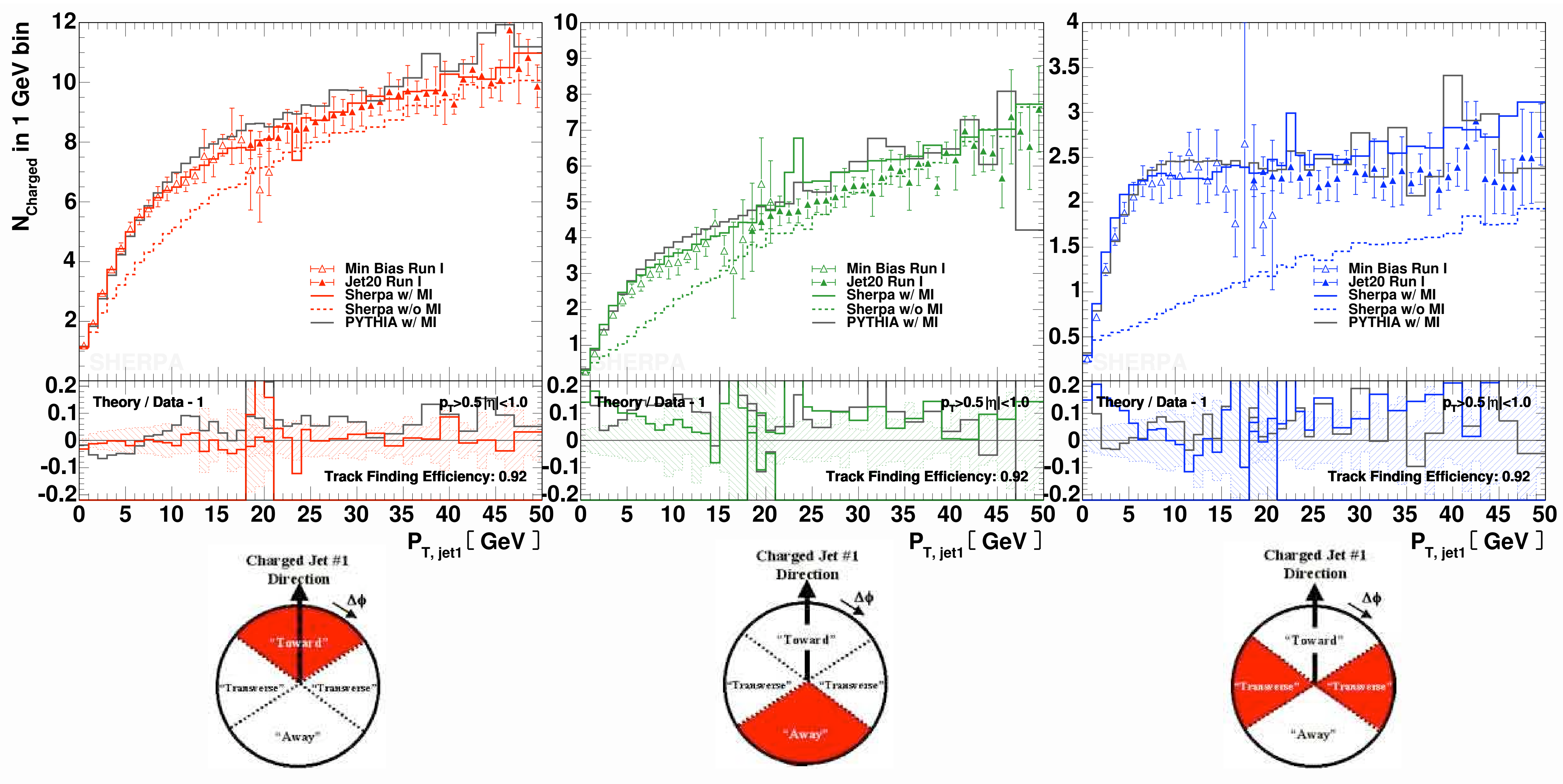
- N_{Charged} vs. $p_{T,\text{jet1}}$ in CTC, Run I



MPI results from Sherpa

in hep-ph/0601012

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

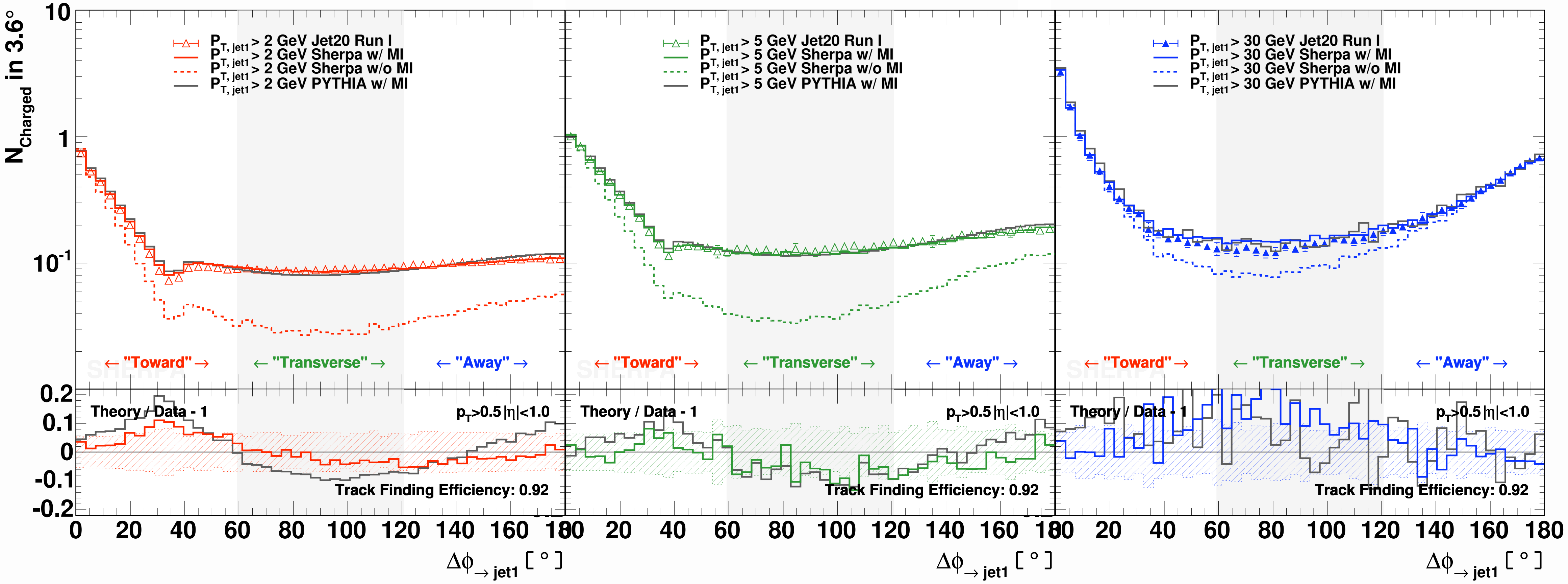


Stefan Höche, MPI Workshop Perugia, 30.10.2008

MPI RESULTS FROM SHERPA

in hep-ph/0601012

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



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

TOWARDS A NEW MPI MODEL

SH, F. Krauss, T. Teubner; 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

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

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

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

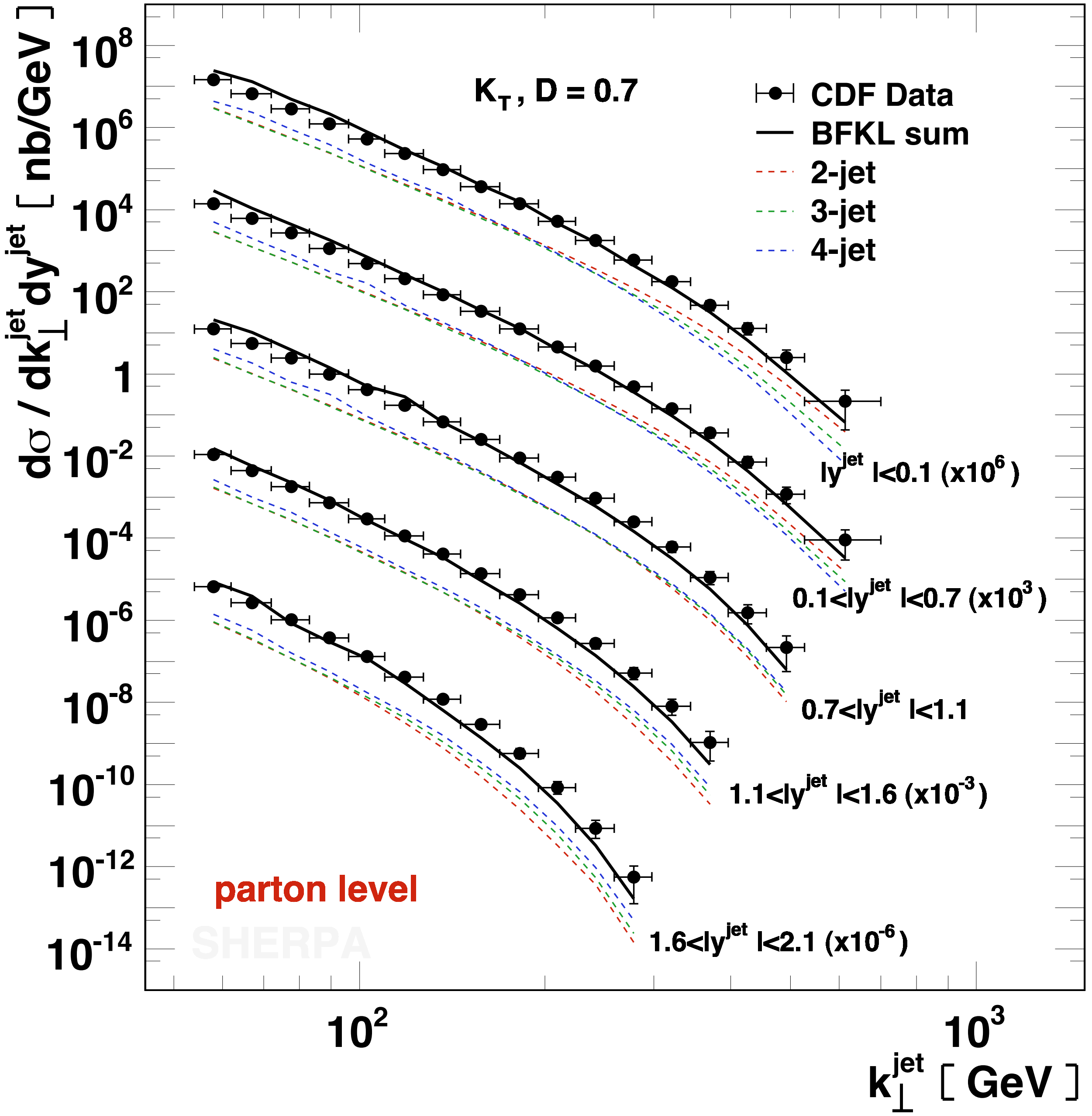
Markovian algorithm to generate splittings from $\Delta_{a_i}(y_i, y_{i-1})$ in the spirit of a parton shower

➔ number of emissions determined on the flight

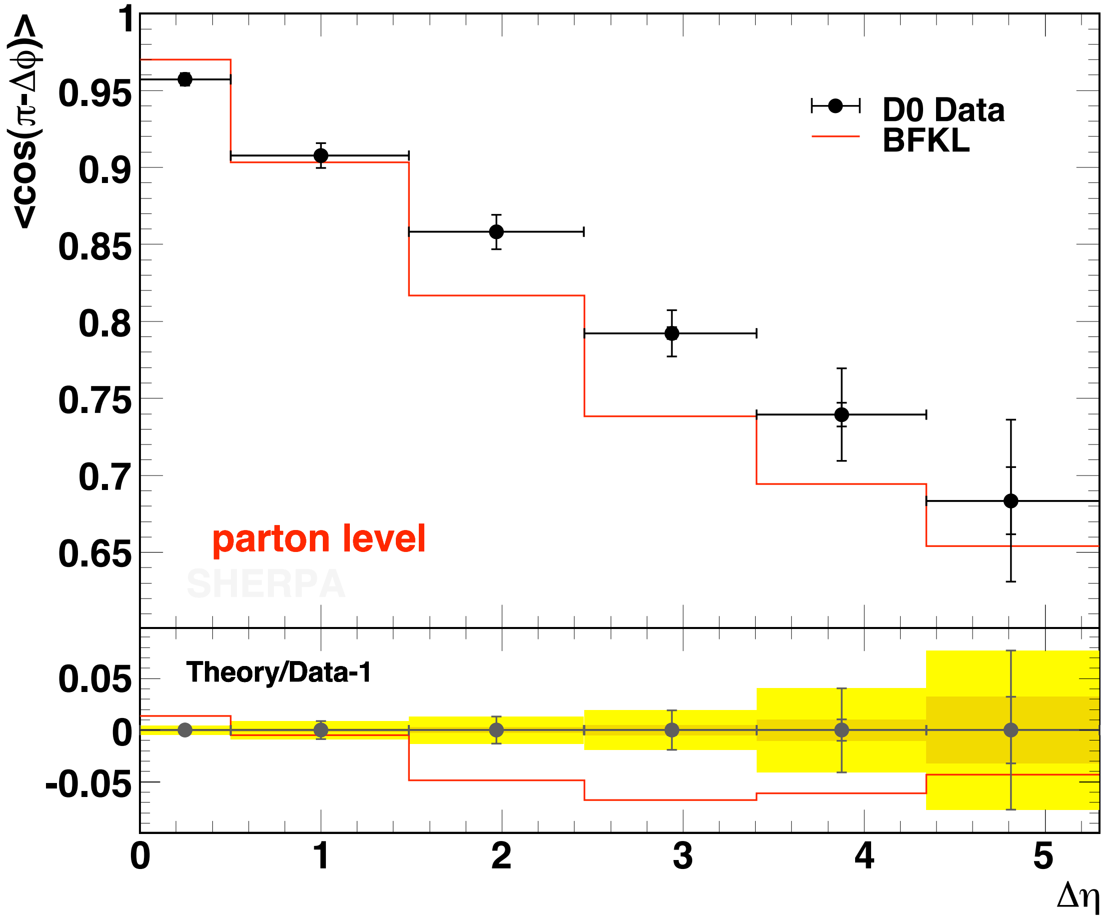
TOWARDS A NEW MPI MODEL

SH, F. Krauss, T. Teubner; arXiv: 0705.4577 [hep-ph]

- Jet - p_T spectra PRD 75 (2007) 092006



- Azimuthal decorrelation of widely separated jets PRL 77 (1996) 595



OUTLOOK

Other recent developments

- Catani-Seymour subtraction in AMEGIC++ EPJC 53 (2008) 501
- Dipole Shower JHEP 07 (2008) 040
- YFS Generator, Decay package, Fragmentation to be published

Short term goals

- Validate fragmentation
- Fully implement & validate new merging strategy
- Work on new MPI model (manpower needed)

Long term goals

- Extend ME-PS merging to NLO level

Updates on Sherpa can (mostly) be found on

WWW.SHERPA-MC.DE

E-mail us at

INFO@SHERPA-MC.DE