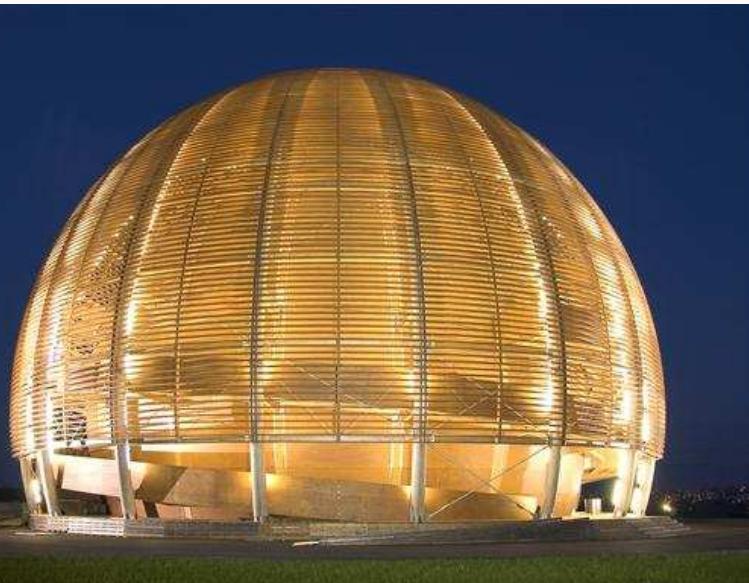


Top quark AFB in shower Monte Carlos

[Mini-workshop – Tools for precision and discovery physics with top quarks]

Peter Skands, Bryan Webber, Jan Winter

– CERN –



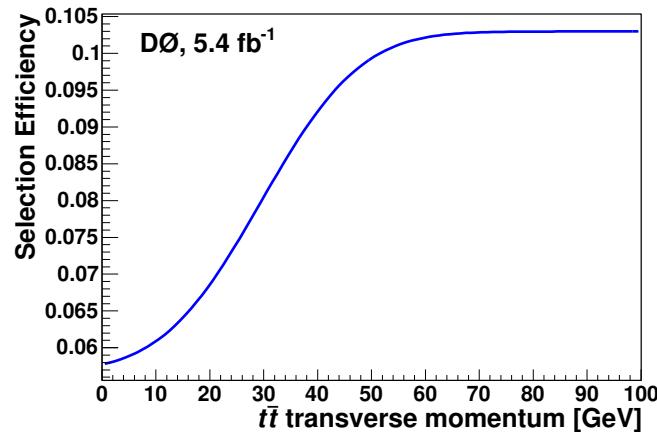
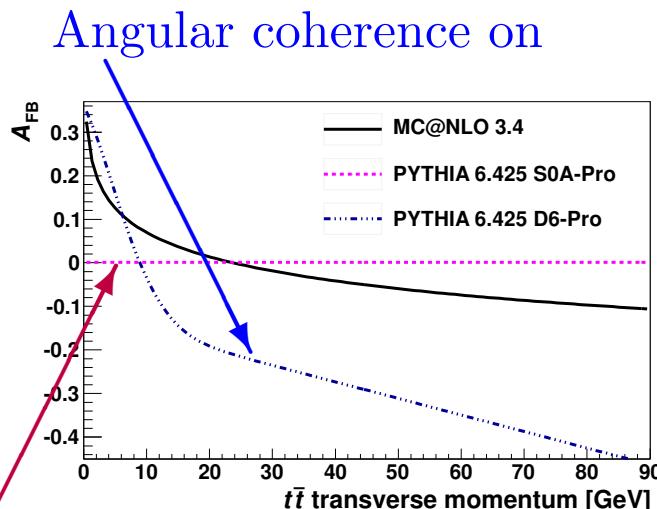
- *Colour coherence leads to asymmetric radiation.*
- *Physics implemented in LO shower generators.*
- *Inclusive asymmetry.*
- *Comparison between shower models.*

Story began with a plot made by DØ

[SLIDE FROM DOUG ORBAKER'S TALK @ TOP AFB & BOOSTED REGIME CERN WS IN MAY]

A_{FB} and top pair p_T

- Is amount of gluon radiation the same for forward and backward events?



Angular coherence off

- If correlation exists, backward events selected more often than forward events
- Effect on measurement is included in systematics: -1.6%

CDF results for asymmetry versus pair pT

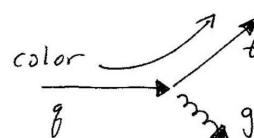
[SLIDES FROM DAN AMIDEI'S TALK @ TOP AFB & BOOSTED REGIME CERN WS IN MAY]

rapidity difference: $\Delta y = y_t - y_{\bar{t}}$

$$A_{FB}(O) = \frac{\frac{d\sigma}{dO} \Big|_{\Delta y > 0} - \frac{d\sigma}{dO} \Big|_{\Delta y < 0}}{\frac{d\sigma}{dO} \Big|_{\Delta y > 0} + \frac{d\sigma}{dO} \Big|_{\Delta y < 0}}.$$

p_t (ttbar) dependence of the asymmetry

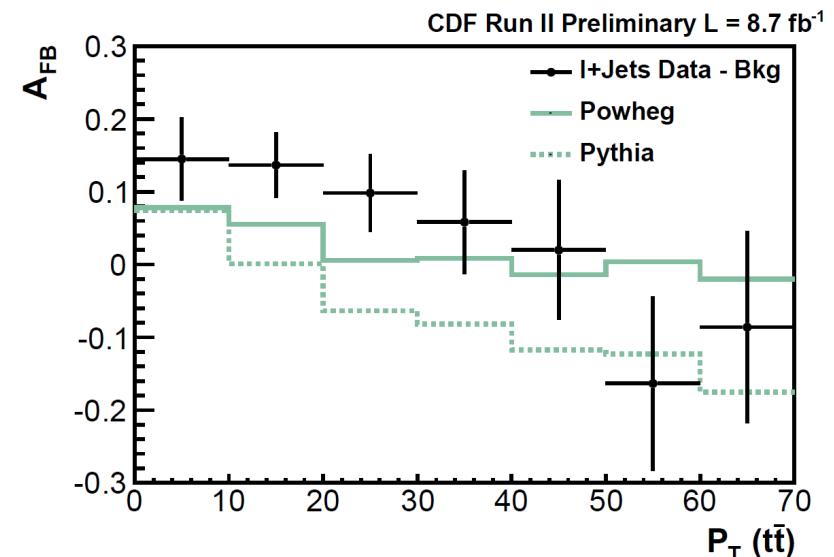
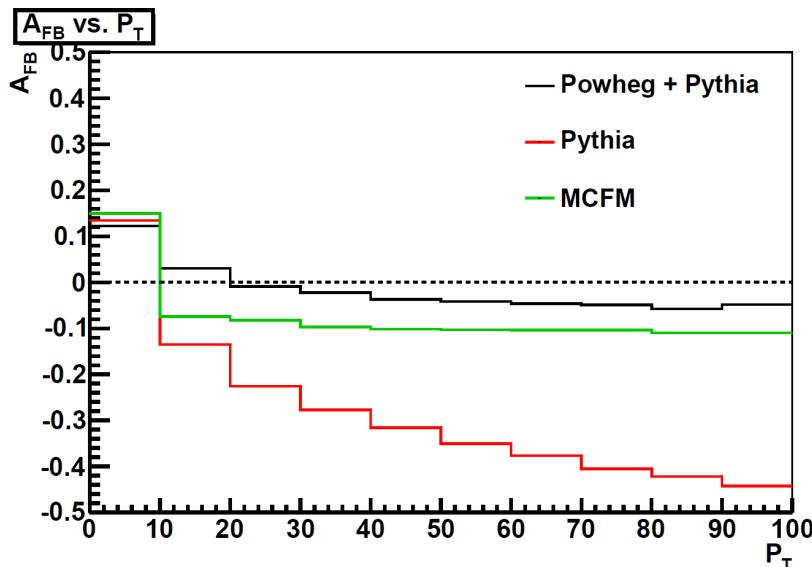
- 1) color coherence \rightarrow backwards top correlated w/ $p_t \neq 0$
- 2) NLO tt+j has negative A_{fb}



p_t (ttbar) dependence of the asymmetry

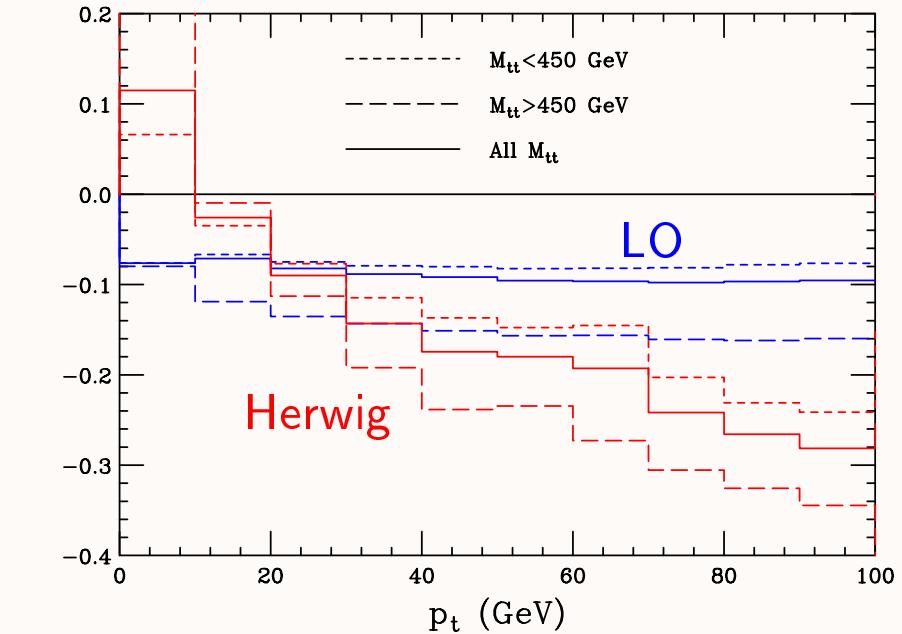
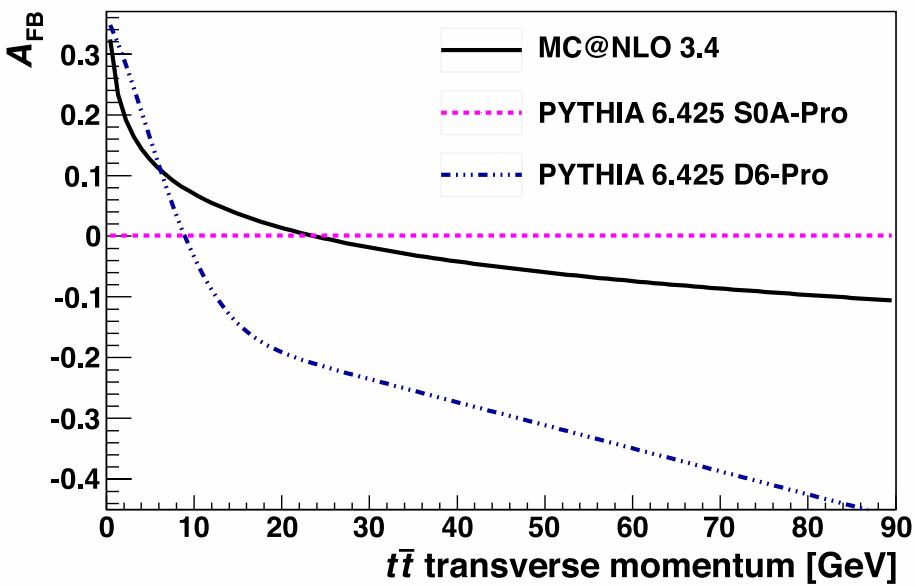
- examine at background subtracted level
- data vs powheg/pythia shower vs pythia neat

expectation @ MC truth:

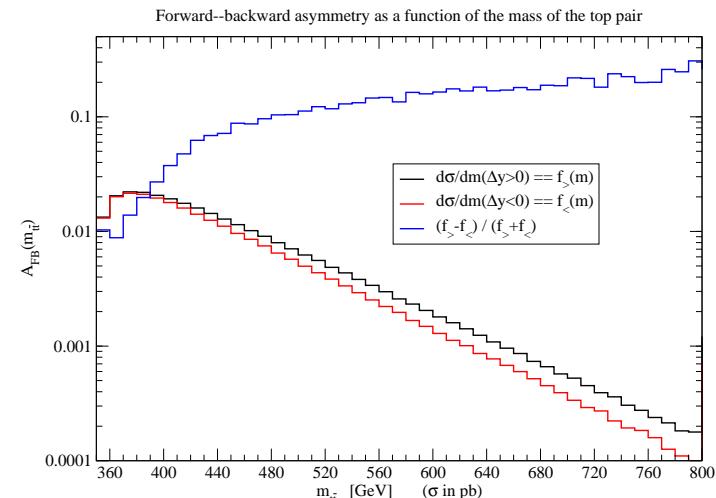
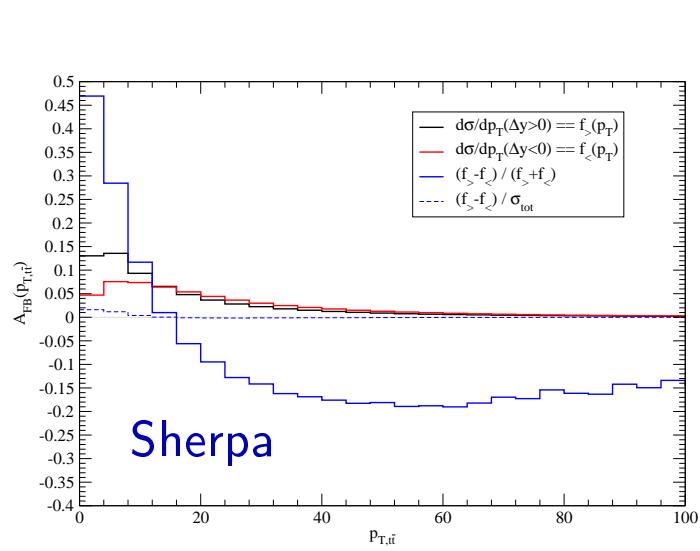


First cross-checks

[PLOT UPPER LEFT FROM DØ – ARXIV:1107.4995]



- coherent shower Monte Carlos (MCs) contain/enhance asymmetry



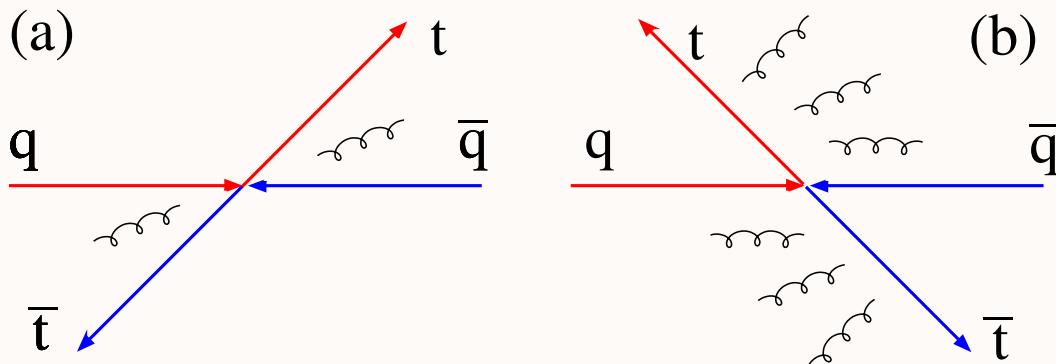
Colour coherence

In $q\bar{q} \rightarrow t\bar{t}$, there are (IF) colour flows from incoming quark to top quark and vice versa.

“Forward” dipoles – less space space for emission, less likely to radiate.

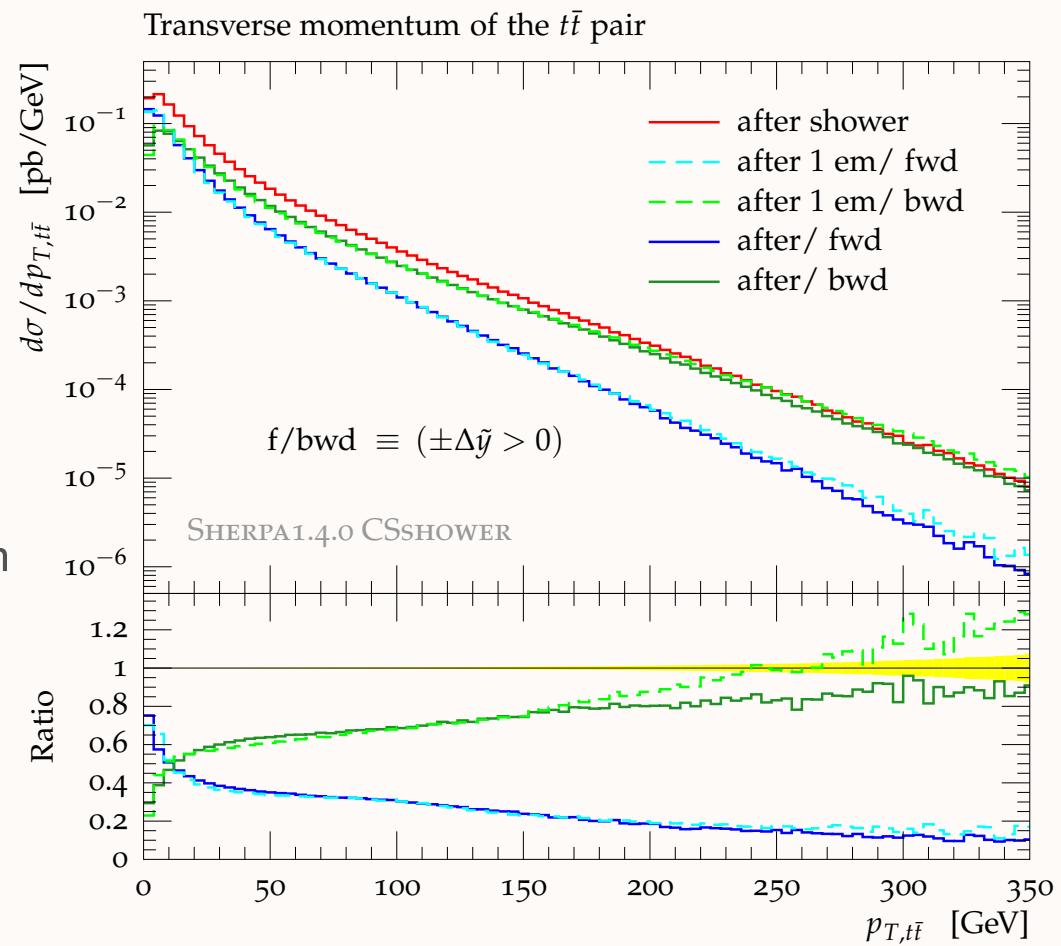
“Backward” dipoles – more violent acceleration of colour, hence more QCD radiation.

- (a) Forward configuration



- (b) Backward configuration

- Colour coherence
 - asymmetric real emission
- Extra emission
 - more recoil for backward top pairs



QCD Coherence and the Top Quark Asymmetry

- in collaboration with Peter Skands and Bryan Webber
- shower Monte Carlos versus fixed order
- generation of an inclusive asymmetry by LO shower Monte Carlos
- comparison between different parton shower models
- time permitting, discussion of additional plots

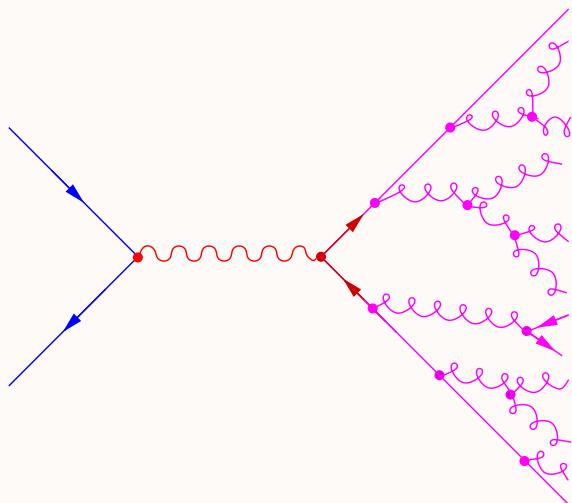
Jet production from parton showers – basics

Inclusive multi-“jet” predictions traditionally described by parton showers. (formally LO+LL accuracy)

→ QCD emissions preferably populate collinear and soft phase-space regions.

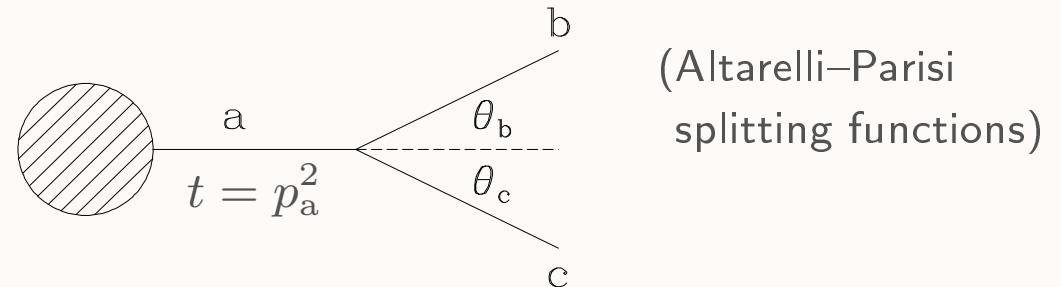
[Pythia, Herwig, Ariadne, CSshower, Vincia]

[large kinematic logs of (μ^2/t) at all orders]



- QCD amplitudes factorize in the coll/soft limit.
- Recursive definition of multiple emissions:

$$d\sigma_{n+1} = d\sigma_n \frac{\alpha_s(t)}{2\pi} \frac{dt}{t} dz P_{a \rightarrow bc}(z) \quad (\text{e.g. coll limit})$$



- coll/soft parton emissions iteratively added to the initial/final states [LL resummation]
- good description of bulk of radiation and particle multiplicity growth
- partonic ensemble evolved down to hadronization scale [ordering variable Q, ϑ, p_T]
- provides suitable input for universal hadronization models [@ scale $\mu_0 = \mathcal{O}(1 \text{ GeV})$]

Parton showers (PSs)

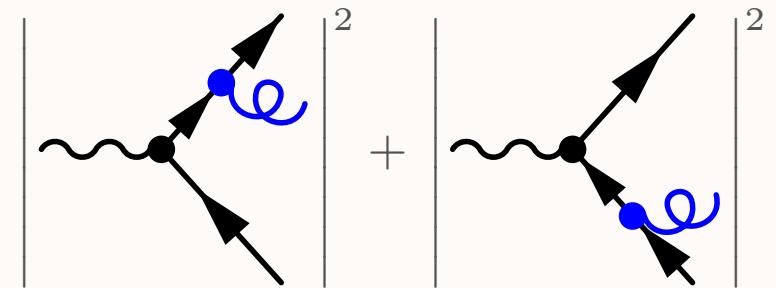
→ ***QCD emissions preferably populate collinear and soft phase-space regions***

- propagator factor for $q \rightarrow qg$ splitting

$$[p_q + p_g]^{-2} \approx [2E_q E_g (1 - \cos \theta_{qg})]^{-2}$$

soft and collinear singularities

- cross section factorizes in the collinear limit



$$|\mathcal{M}_{q\bar{q}g}|^2 d\Phi_{q\bar{q}g} \approx |\mathcal{M}_{q\bar{q}}|^2 d\Phi_{q\bar{q}} \frac{\alpha_s}{2\pi} \left(\frac{dt_{qg}}{t_{qg}} P_{q \rightarrow qg}(z_q) + \frac{dt_{\bar{q}g}}{t_{\bar{q}g}} P_{\bar{q} \rightarrow \bar{q}g}(z_{\bar{q}}) \right)$$

- probability for **no resolvable emission** off quark line between t and t_0 :

Sudakov form factor ($P_{q \rightarrow qg}(z) = C_F \frac{1+z^2}{1-z}$... spin averaged AP kernel)

$$\Delta_q(t_0, t) = \exp \left\{ - \int_{t_0}^t \frac{dt'}{t'} \int_{z_-}^{z_+} dz \frac{\alpha_s}{2\pi} P_{q \rightarrow qg}(z) \right\}, \quad z_+ = 1 - z_-, \quad z_- = \sqrt{t_0/t'}$$

- probability for splitting at $t_1 < t \Rightarrow dP = \Delta_q(t_1, t) \frac{\alpha_s}{2\pi} \frac{1}{t_1} P_{q \rightarrow qg}(z) dt_1 dz$

Shower predictions = LO+LL predictions

Examples for shower Monte Carlos

- Pythia – virtuality ordering, $1 \rightarrow 2$ (old) and p_T ordering, $2 \rightarrow 3$ [SJÖSTRAND, SKANDS, MRENNA]
- Herwig(++) – angular ordering, $1 \rightarrow 2$ [WEBBER, MARCHESINI, SEYMOUR, RICHARDSON]
- Ariadne – Lund colour dipole model, p_T ordering, full $2 \rightarrow 3$ [LÖNNBLAD, GUSTAFSON, ANDERSSON]
- Vincia – antenna shower, p_T & other orderings, full $2 \rightarrow 3$ [GIELE, KOSOWER, SKANDS]
- Sherpa's CSshower – based on CS subtraction terms, p_T ordering, $2 \rightarrow 3$ [SCHUMANN, KRAUSS]

Limitations

- shower seeds/cores are LO (QCD) processes only
- lack of high-energetic large-angle emissions
- semi-classical picture; quantum interferences and correlations only approximate
- shower evolution proceeds in the limit of large N_C (number of colours)

Comparison with fixed order

→ ***Coherent showers work well in soft limit.***

- One gluon emission process

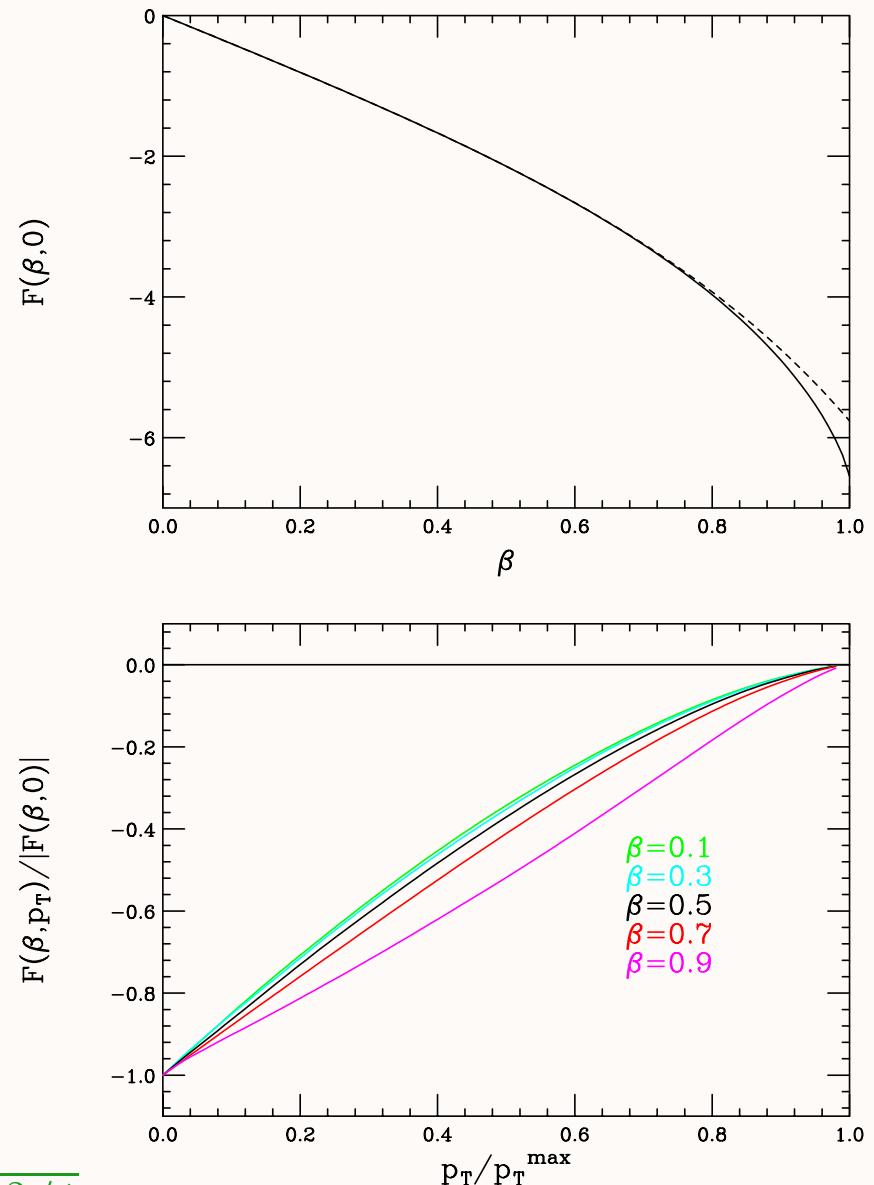
$$q(p_1) + \bar{q}(p_2) \rightarrow Q(p_3) + \bar{Q}(p_4) + g(k)$$

$$\begin{aligned} \mathcal{M}_A &\equiv \overline{\sum} |M(q\bar{q} \rightarrow Q\bar{Q}g)|^2 - \overline{\sum} |M(q\bar{q} \rightarrow \bar{Q}Qg)|^2 \\ &= g^6 \frac{C_F(N^2 - 4)}{N^2} \left[\left(\frac{t_1^2 + t_2^2 + u_1^2 + u_2^2}{s_1 s_2} + \frac{2m^2}{s_1} + \frac{2m^2}{s_2} \right) \right. \\ &\quad \left. \times (W_{13} + W_{24} - W_{14} - W_{23}) - \frac{8m^2}{s_1 s_2} \left(\frac{t_1 - u_2}{v_2} + \frac{t_2 - u_1}{v_1} \right) \right] \end{aligned}$$

- Approximations used:
- MCs do “Born $\times W_{ij}$ ’s $\times 2C_F$ ” using dipole radiation function $W_{ij} = -(p_i/p_i \cdot k - p_j/p_j \cdot k)^2$
- replace $(N^2 - 4)$ by $(N^2 - 1) \Rightarrow 60\%$ overestimate
- neglect 2nd and reduce 1st term in [...] onto Born
- In soft limit: $F(\beta, 0) = -4\beta - \beta^3 - \dots$

$$\frac{p_T}{\hat{\sigma}_B} \frac{d\hat{\sigma}_A}{dp_T} = \frac{\alpha_S}{\pi} \frac{(N^2 - 4)}{N} F(\beta, p_T)$$

$$\beta = \sqrt{1 - 4m^2/\hat{s}}$$



Fixed order versus Sudakov suppression

for example MC@NLO: S. Frixione and B.R. Webber, JHEP **06** (2002) 029

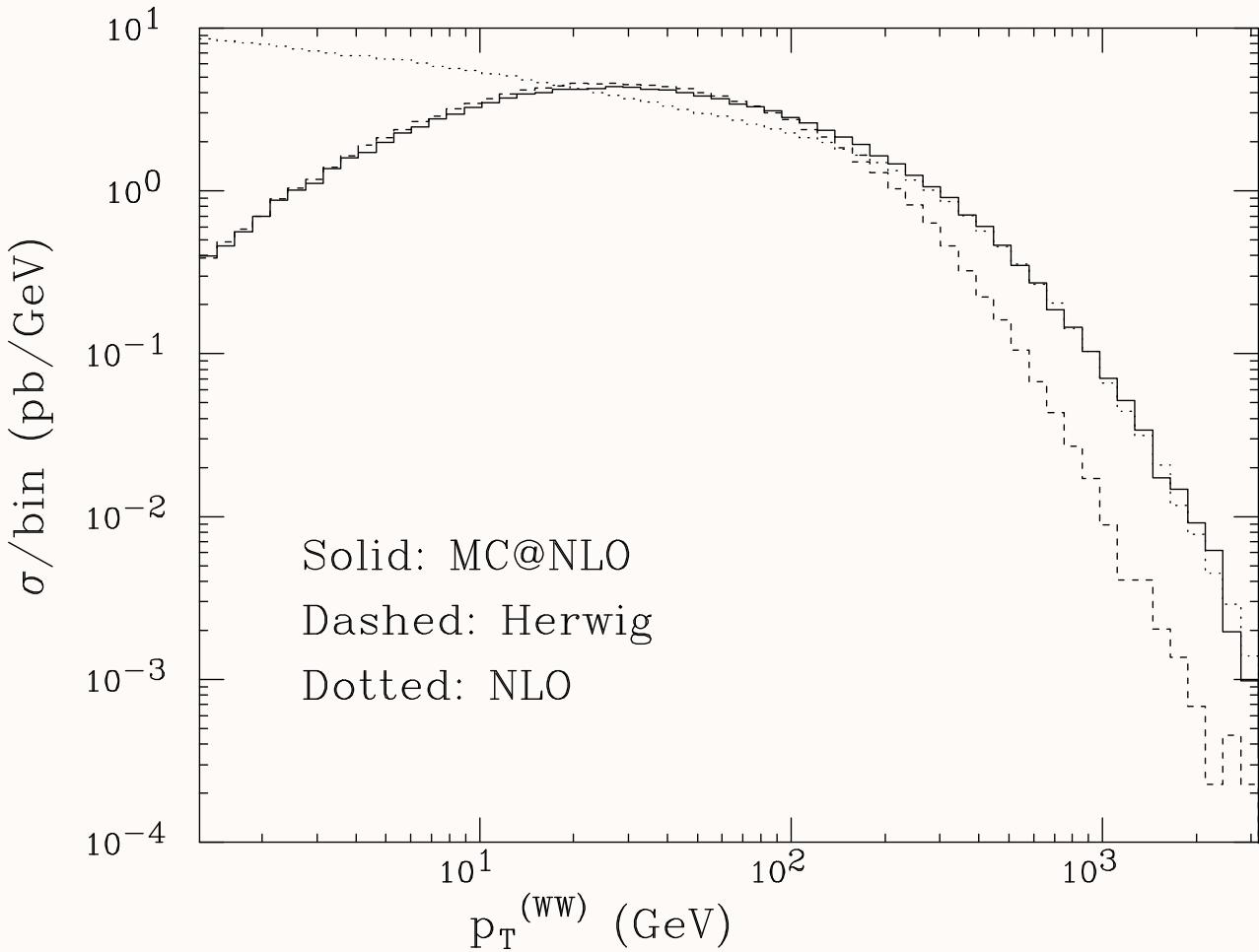
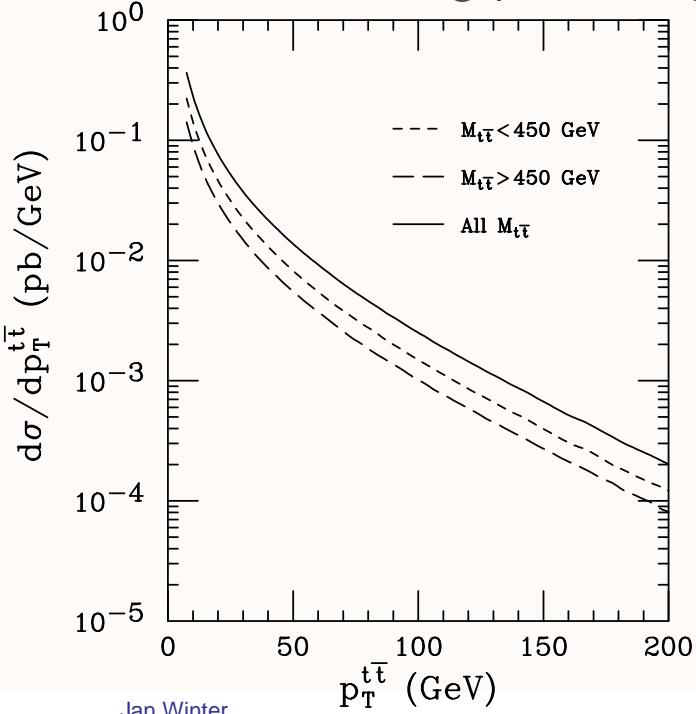
→ $pp \rightarrow W^+W^- + X$ @ 14 TeV LHC: • p_T of the WW system

→ rate & shape comparison

MC@NLO vs. Herwig PS
and NLO prediction

• PS has real-emission
contribution due to
initial/final-state branching

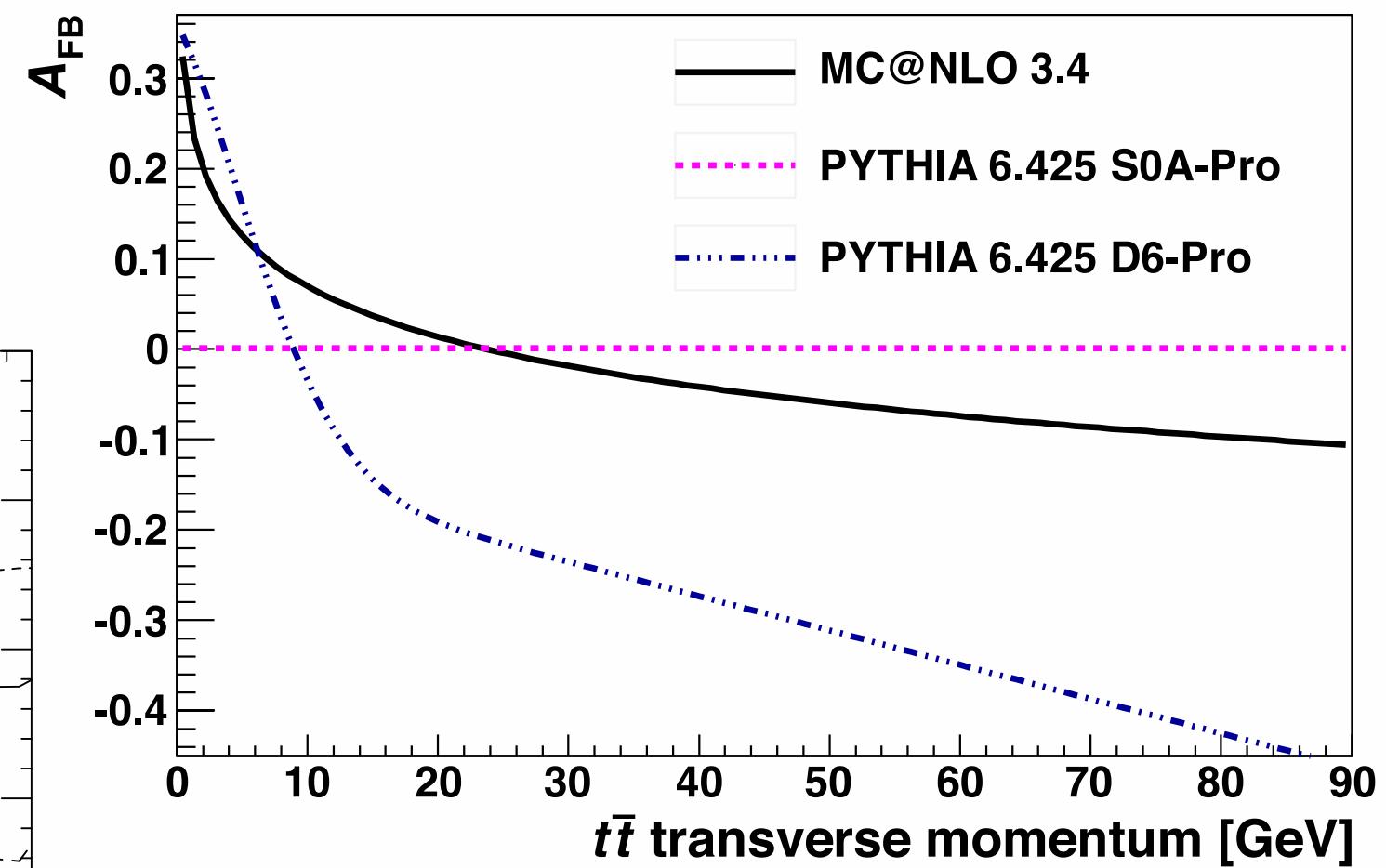
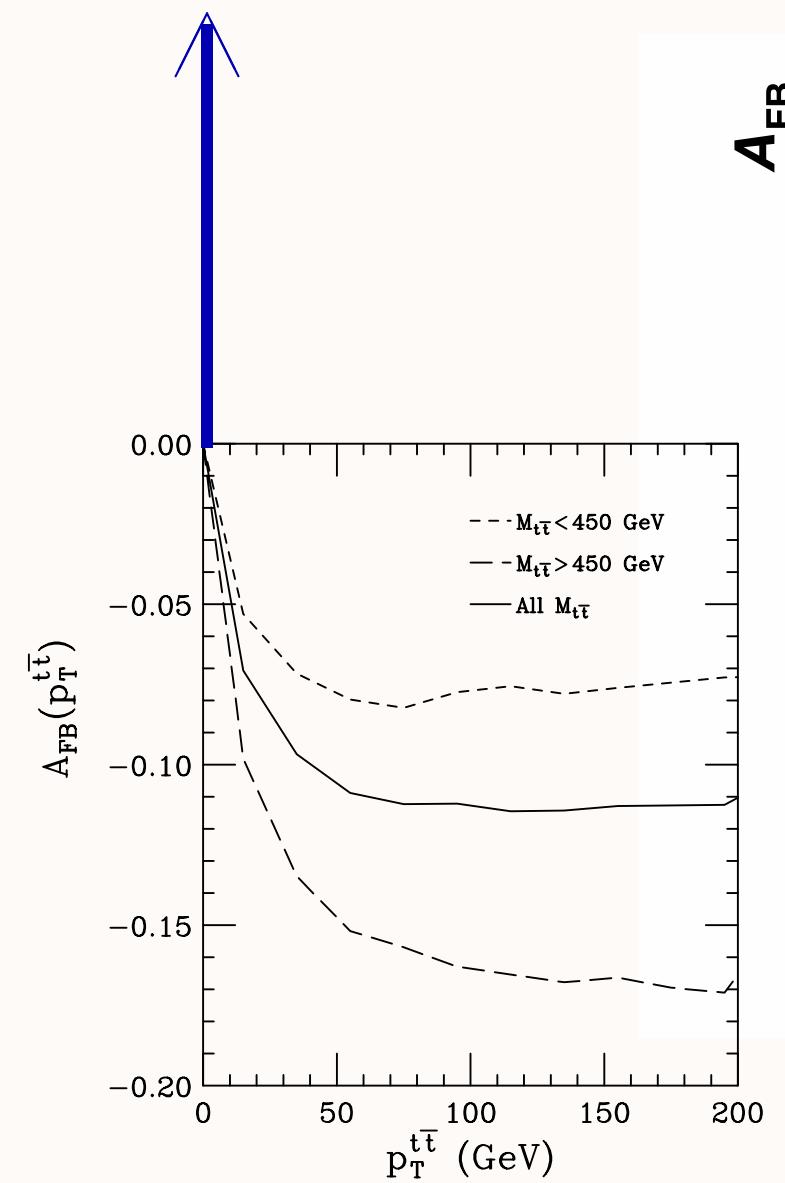
• PS has virtual contribution
due to no-branching probability



← corresponding fixed-order $p_T^{t̄t}$ plot (using MCFM)

Fixed order versus Sudakov “pT smearing”

[PLOT ON RIGHT FROM DØ – ARXIV:1107.4995]



Inclusive asymmetry in parton showers

→ If shower kinematics allow for migrations, a net inclusive asymmetry can be generated.

- showers are unitary, preserve total inclusive cross section (LO)
- BUT asymmetry is not protected by unitarity \Rightarrow migration from $\Delta y > 0$ to $\Delta y < 0$ and v.v.

$$\begin{aligned} \Delta\sigma_{+-} &= \int d\sigma^{\text{LO}} \Big|_{\Delta y > 0} [\Delta_+ + (1 - \Delta_+)(P_{++} - P_{+-})] \quad \Rightarrow \Delta y > 0 \text{ evts @ ME level, before shower} \\ &\quad - \int d\sigma^{\text{LO}} \Big|_{\Delta y < 0} [\Delta_- + (1 - \Delta_-)(P_{--} - P_{-+})] \quad \Rightarrow \Delta y < 0 \text{ evts @ ME level, before shower} \end{aligned}$$

$\underbrace{\hspace{10em}}$
action of shower: no branching + branching(s)

- unitarity links (no-)migration probabilities: $P_{++} = 1 - P_{+-}$ and $P_{--} = 1 - P_{-+}$
- Soft colour coherence: $1 > \Delta_+ > \Delta_-$ (Sudakov effect)
- rapidity ordering preserved if $P_{+-} = P_{-+} \equiv 0$ \Rightarrow no asymmetry

$$\Delta\sigma_{+-} = -2 \int d\sigma^{\text{LO}} \Big|_{\Delta y > 0} (1 - \Delta_+) P_{+-} + 2 \int d\sigma^{\text{LO}} \Big|_{\Delta y < 0} (1 - \Delta_-) P_{-+}$$

- 2nd term dominates plus recoil treatment in showers usually leads to $P_{-+} > P_{+-}$
- generates approximate positive inclusive asymmetry ... notice !, ...
- $\Delta\sigma_{+-}$ starts at $\mathcal{O}(\alpha_s)$ wrt. Born \Rightarrow effect represents approx. LO contrib. to incl. asymmetry

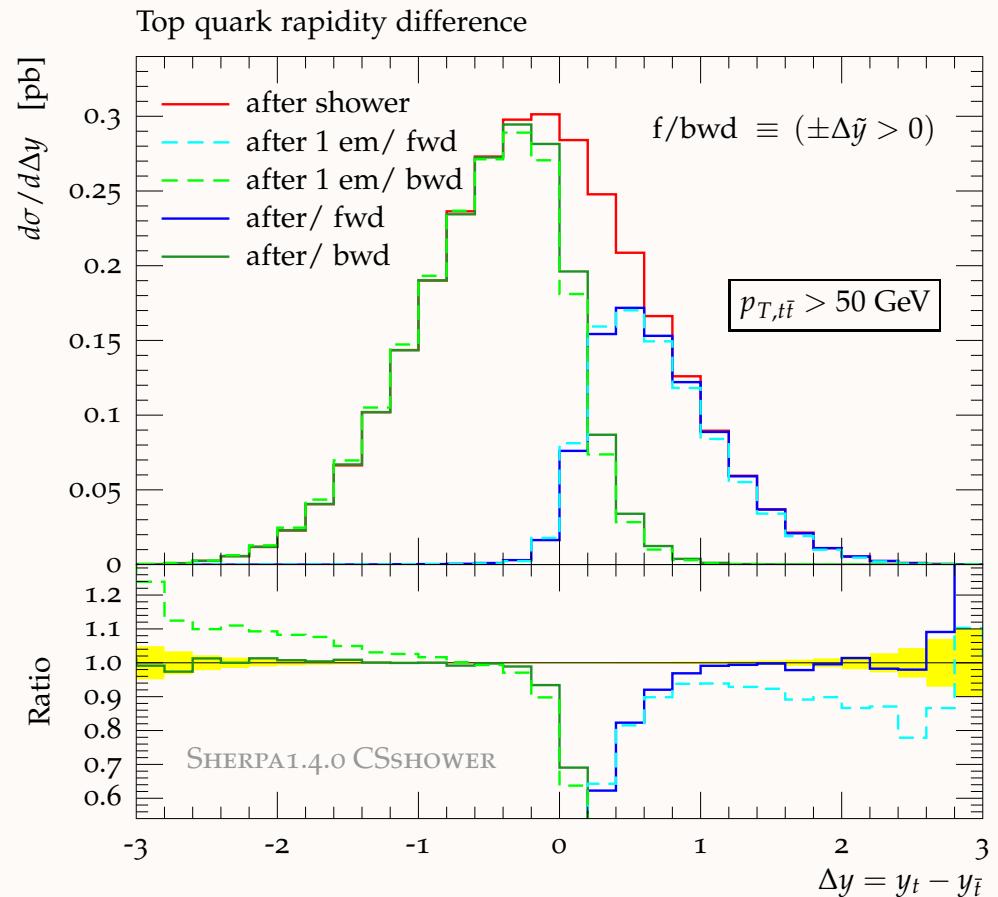
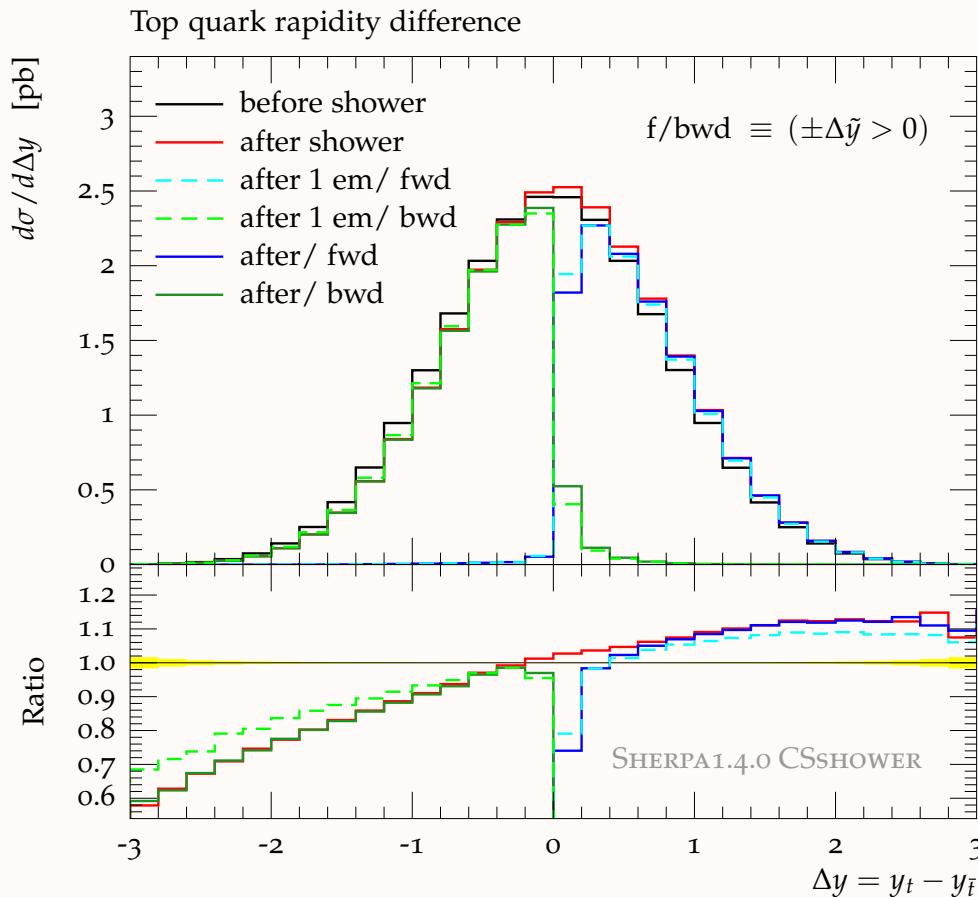
Longitudinal recoil effects – migration

[SKANDS, WEBBER, WINTER, ARXIV:1205.1466]

Simple dipole picture where gluon emission on average stretches LF dipole can give $\Delta y = \Delta \tilde{y} + \epsilon$ ($\epsilon > 0$).

→ migration is small, local, favouring $- \rightarrow +$ direction; largest effect already after 1st emission

radiation imbalance wins over more severe migration



- Δy distribution for various LO $\Delta \tilde{y}$ generation and shower modes

Monte Carlo event generation

Event generators are used to model multi-hadron final states of high-energy particle collisions.

Factorization approach: divide jet simulation into different phases – use Monte Carlo methods.

→ Perturbative Phases: [parton jets]

- **Hard process/interaction (hard jet production)**

exact matrix elements $|\mathcal{M}|^2$

- **QCD bremsstrahlung (soft/coll multiple emissions)**

initial- and final-state parton showering

- **Multiple/Secondary interactions**

modelling the underlying event

→ Non-perturbative Phases: [jet confinement – particle jets]

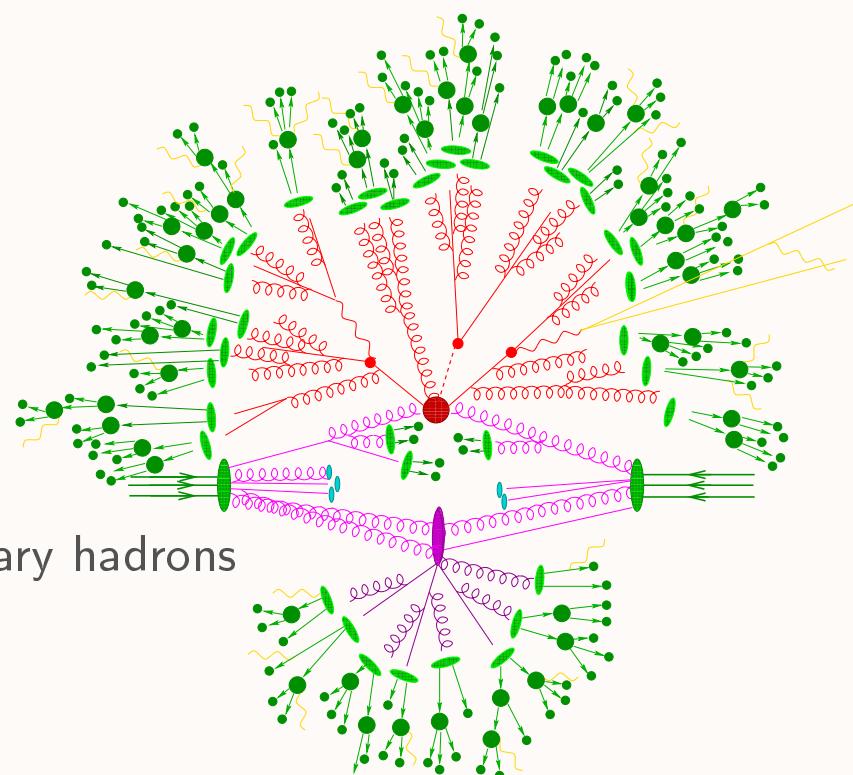
- **Hadronization**

phenomenological models to convert partons into primary hadrons

- **Hadron decays**

phase-space or effective models to decay unstable into stable hadrons as observed in detectors

⇐ only parts used in our analysis



Inclusive asymmetry produced by LO generators

Model	Version	Inclusive	$m_{t\bar{t}}/\text{GeV}$		$p_{T,t\bar{t}}/\text{GeV}$		• different recoil strategies implemented in the different models
			< 450	> 450	< 50	> 50	
	[tune]						• recoil effects are \sim leading wrt. LO asymmetry (eval. by MCFM)
HERWIG++	2.5.2 [def]	3.9	2.7	6.0	5.8	-14.3	
PYTHIA 6	6.426 [def]	-0.1	-0.8	1.2	2.5	-42.5	
PYTHIA 6	6.426 [D6T]	-0.2	-1.1	1.2	3.2	-43.4	
PYTHIA 6	6.426 [P0]	0.8	0.7	1.1	1.8	-8.6	
PYTHIA 8	8.163 [def]	2.5	2.4	2.8	2.4	4.8	
SHERPA	1.4.0 [def]	5.5	3.5	9.2	8.7	-15.4	
SHERPA	1.3.1 [def]	6.3	3.3	12.1	9.6	-15.8	
QCD	LO	6.0	4.1	9.3	7.0	-11.1	

- *This and what follows based on simple analysis*
- comparable with “production level” results
- LO $q\bar{q}, gg \rightarrow t\bar{t}$ production and showering
- custom-made Rivet analysis, used for all generators
- Thanks to Anton Karneyeu,
MCPLLOTS: <http://mcplots.cern.ch>

$$A_{\text{FB}}^{(\text{cut})} = \frac{\sigma^{(\text{cut})}|_{\Delta y > 0} - \sigma^{(\text{cut})}|_{\Delta y < 0}}{\sigma^{(\text{cut})}}$$

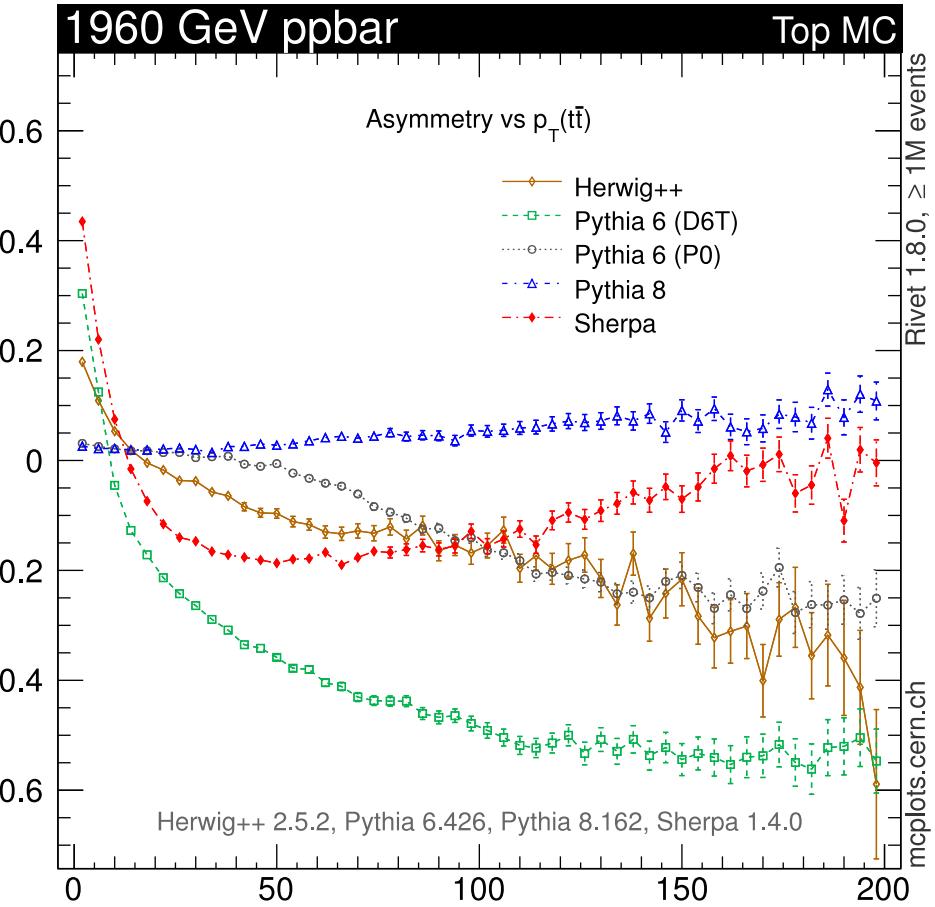
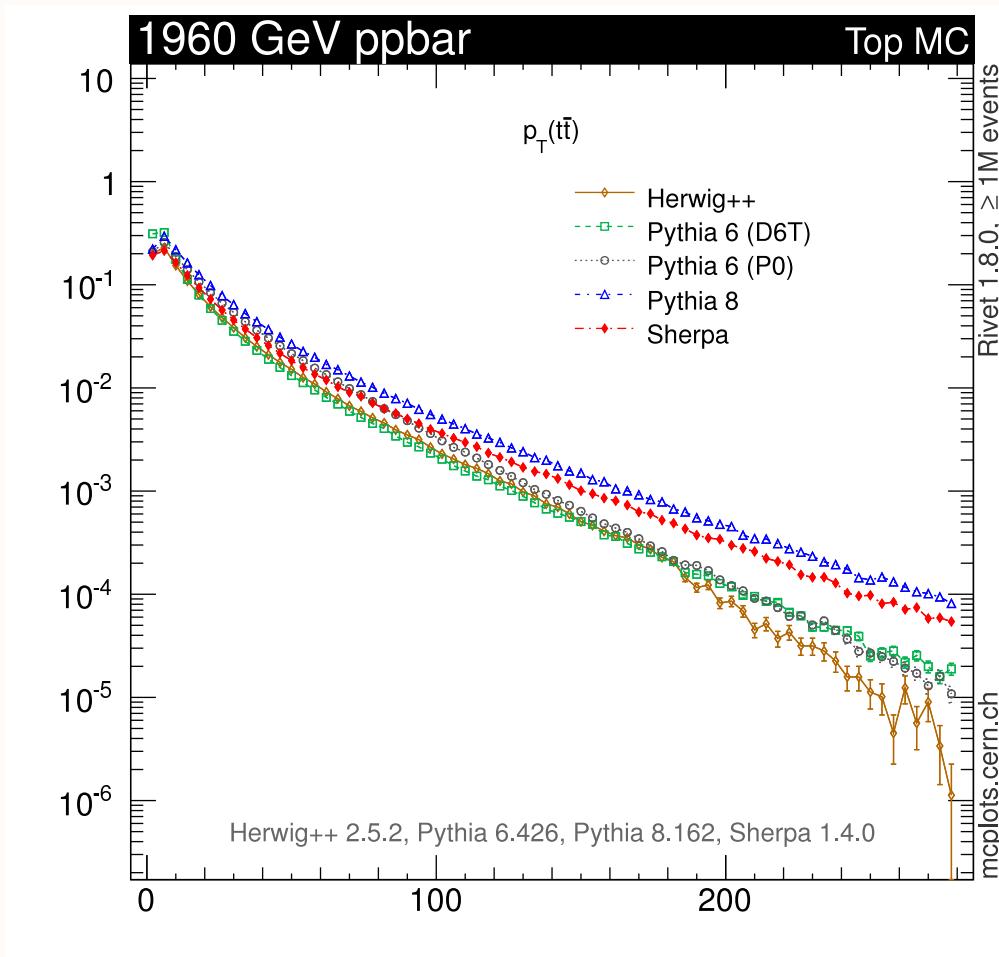
Differential asymmetry produced by LO generators

[SKANDS, WEBBER, WINTER, ARXIV:1205.1466]

QCD coherence built in for Herwig++ and Sherpa, Pythia 6 has options with varying amounts of coherence.

→ Pythia 8 version used here does not have QCD coherence implemented

Asymmetry as function of the top-pair p_T

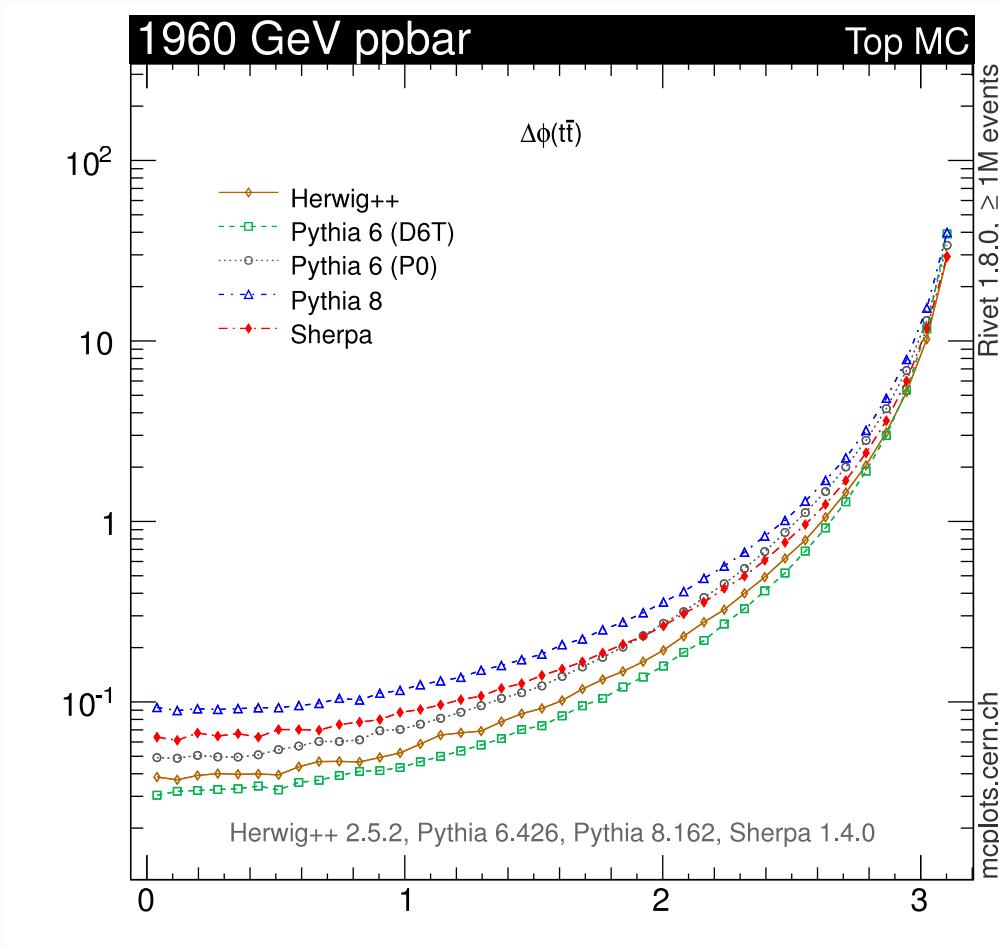


- $p_{T,t\bar{t}}$ differential cross section distribution

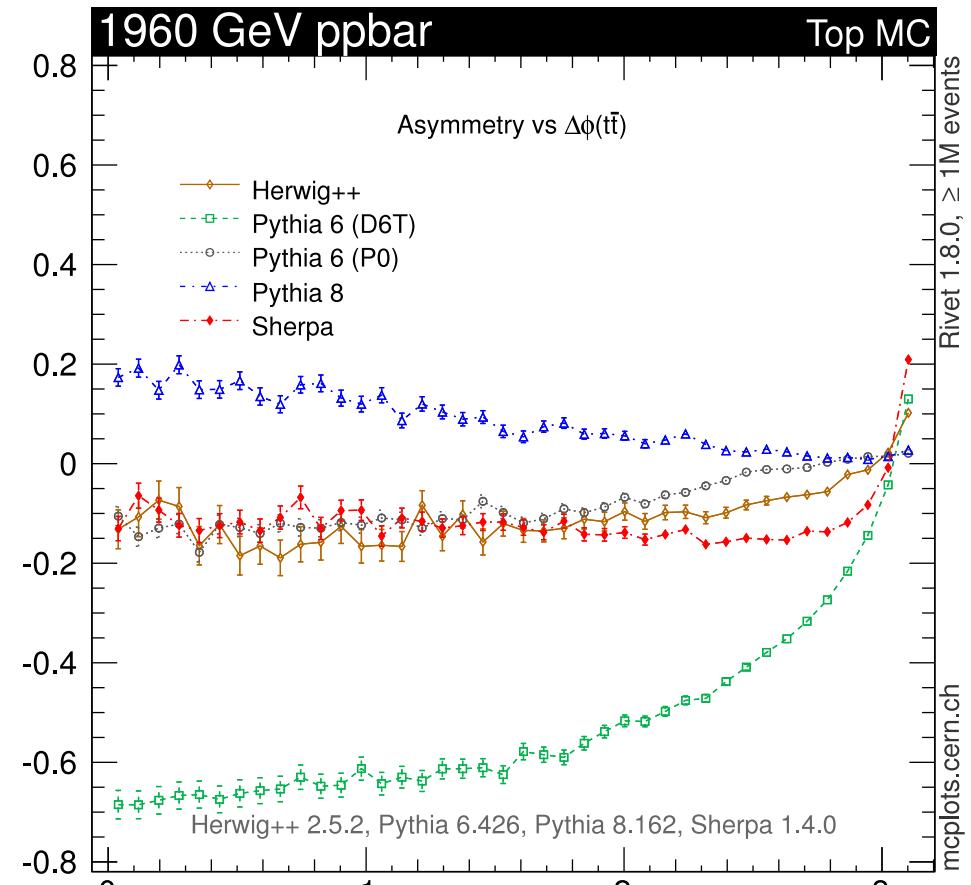
Differential asymmetry produced by LO generators

[SKANDS, WEBBER, WINTER, ARXIV:1205.1466]

→ high p_T and low $\Delta\phi$ are correlated



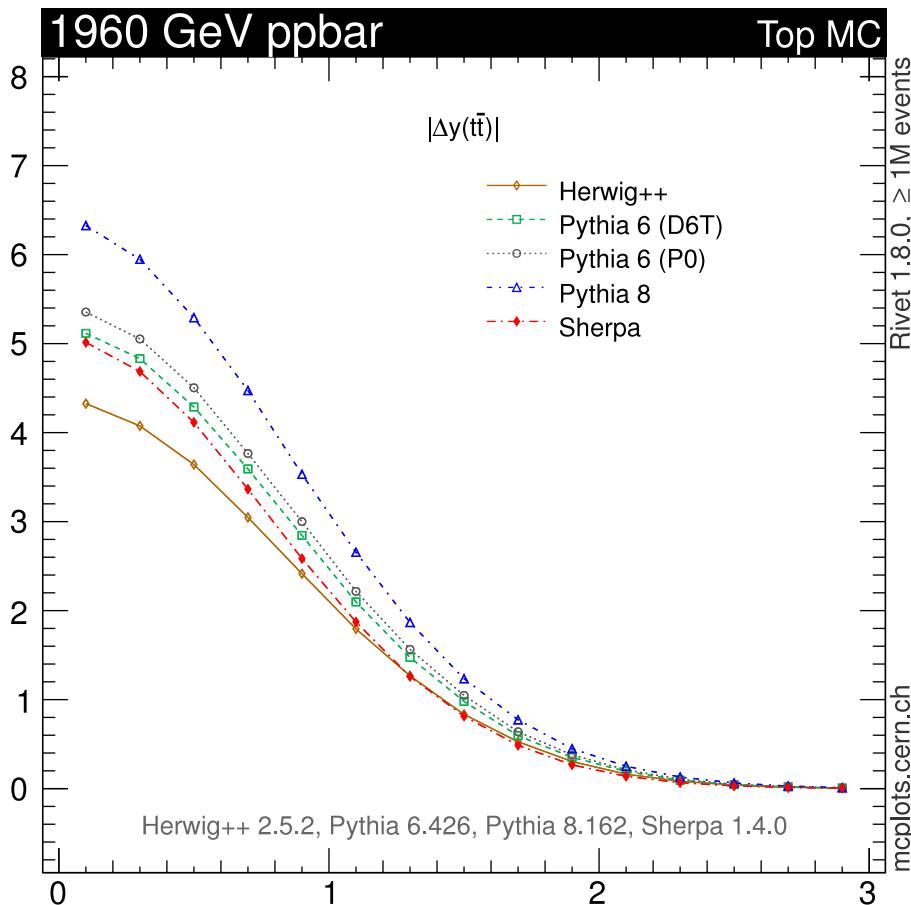
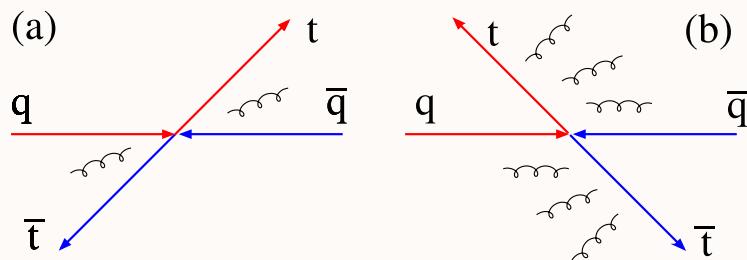
Asymmetry as function of azimuthal angle $\Delta\phi$



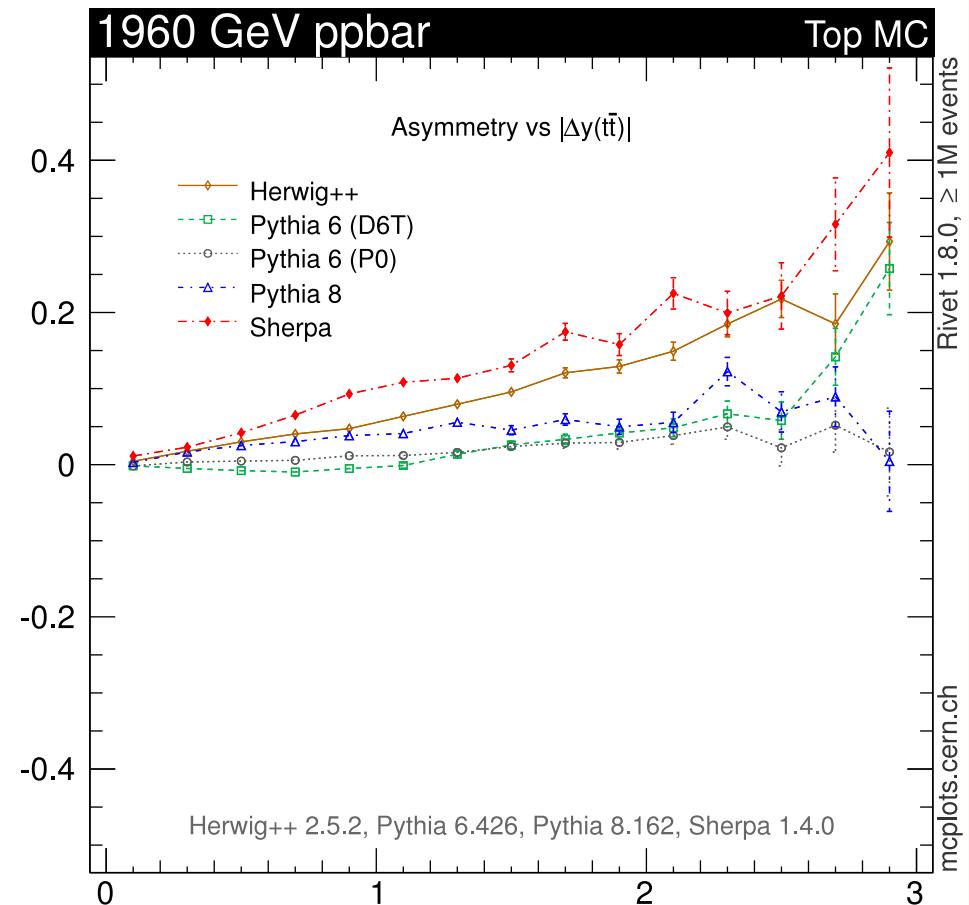
- differential cross section for $\Delta\phi$ between transverse momenta of tops

Differential asymmetry produced by LO generators

[SKANDS, WEBBER, WINTER, ARXIV:1205.1466]



Asymmetry versus absolute rapidity difference $|\Delta y|$



- differential cross section for $|\Delta y|$ observable

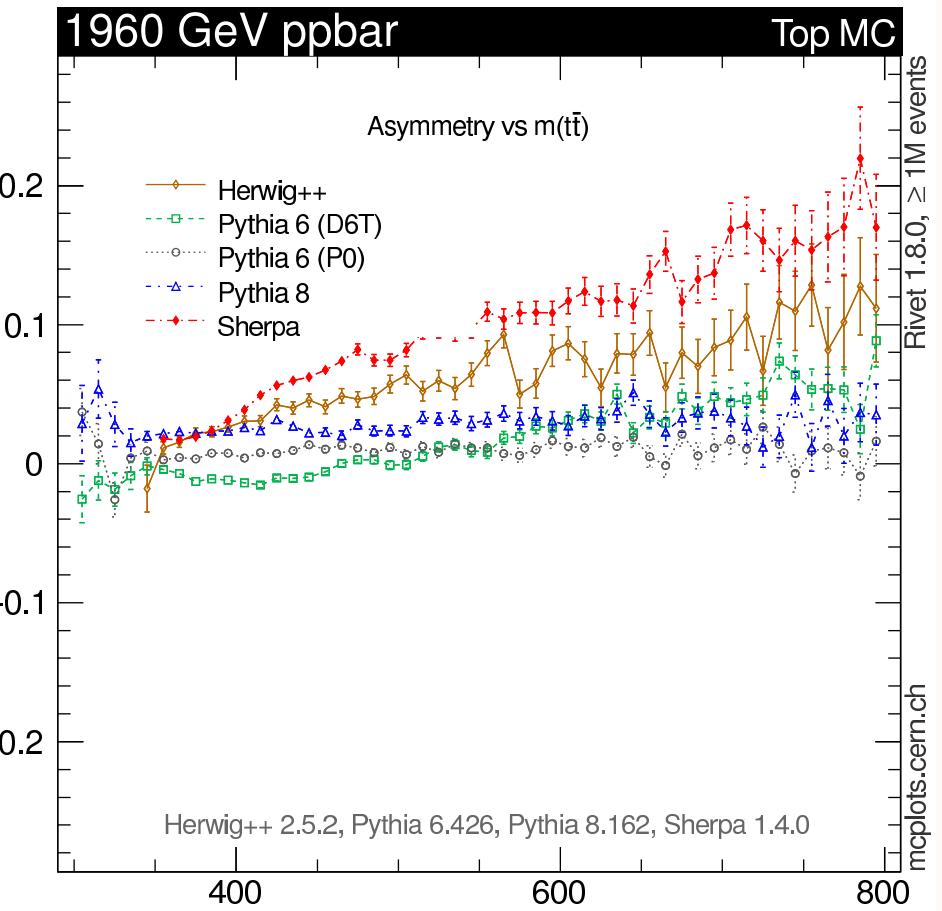
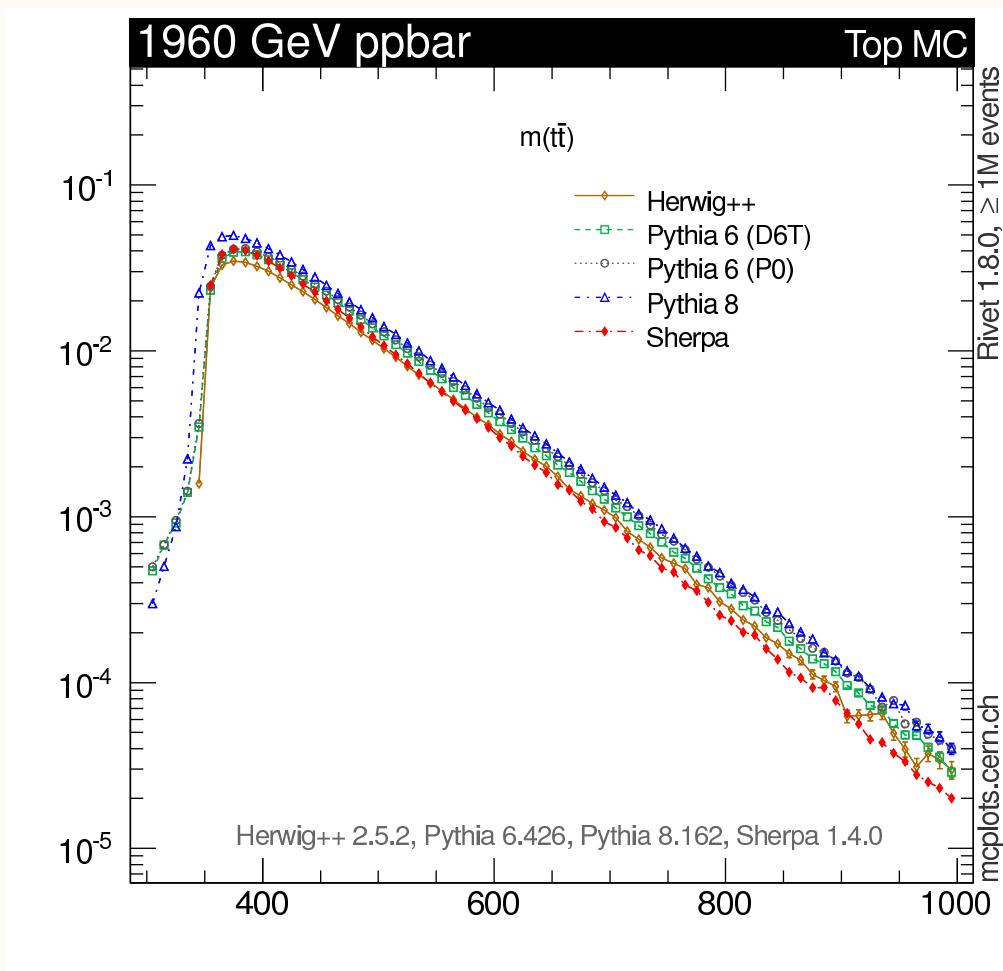
Differential asymmetry produced by LO generators

[SKANDS, WEBBER, WINTER, ARXIV:1205.1466]

→ mass dependence driven by dependence on Δy and $\Delta\phi$, Sudakov region applies over entire mass range

$$m_{t\bar{t}}^2 = m_t^2 + m_{\bar{t}}^2 + 2 E_{T,t} E_{T,\bar{t}} \cosh \Delta y - 2 p_{T,t} p_{T,\bar{t}} \cos \Delta\phi$$

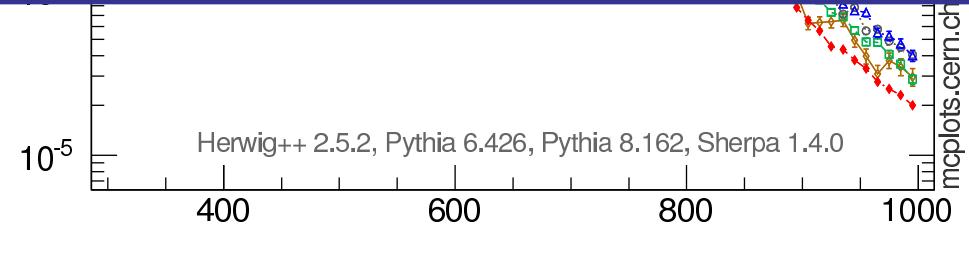
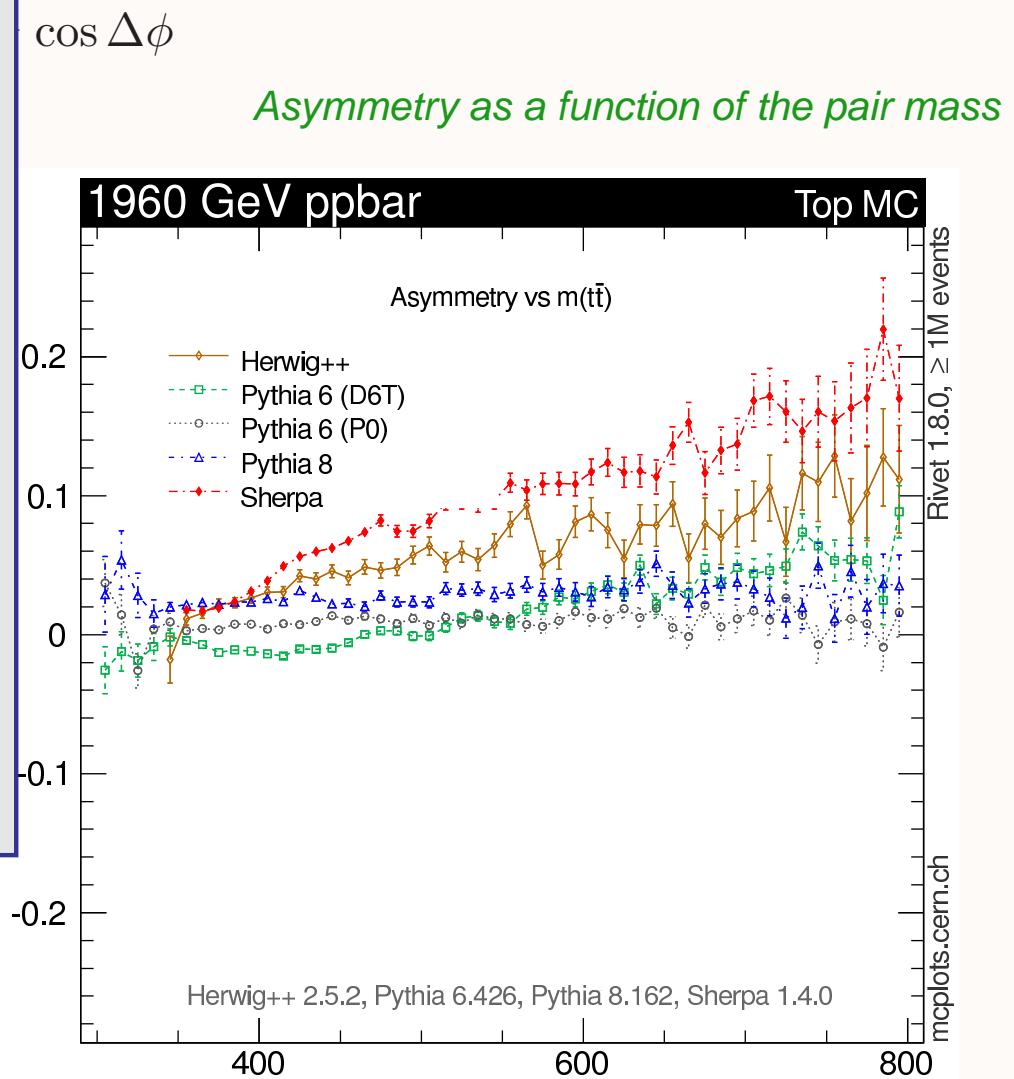
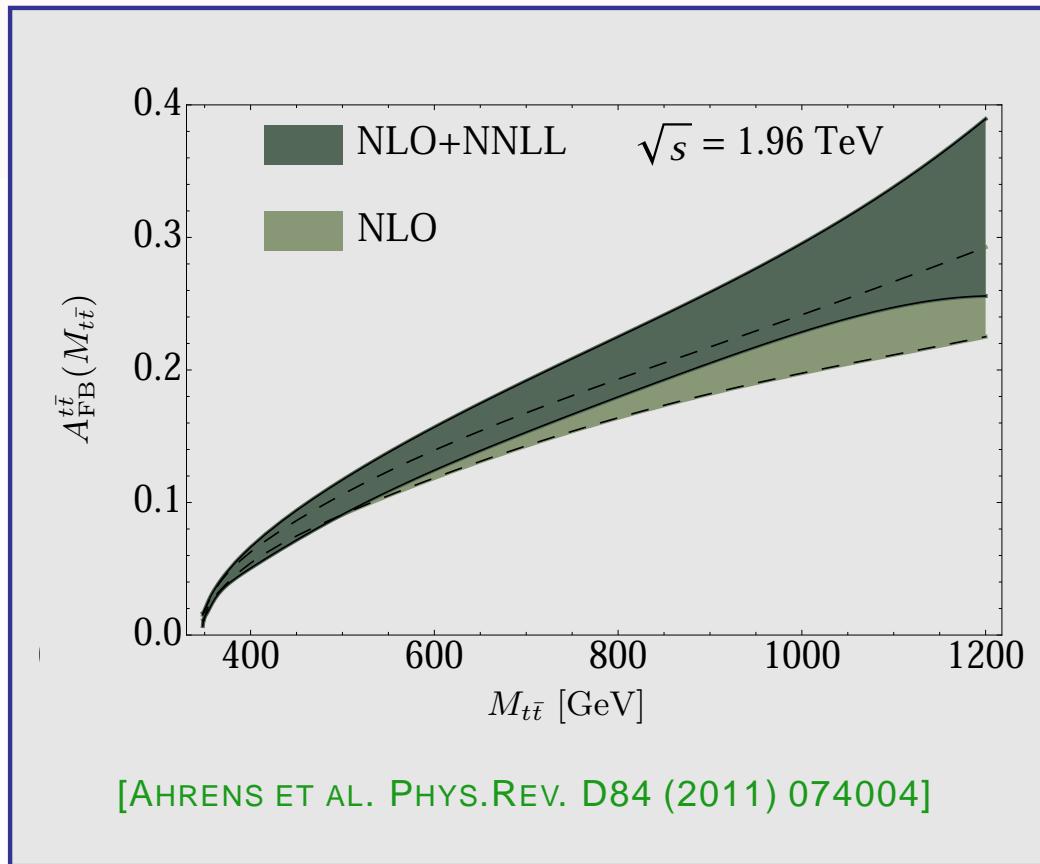
Asymmetry as a function of the pair mass



Differential asymmetry produced by LO generators

[SKANDS, WEBBER, WINTER, ARXIV:1205.1466]

→ mass dependence driven by dependence on Δy and $\Delta\phi$, Sudakov region applies over entire mass range

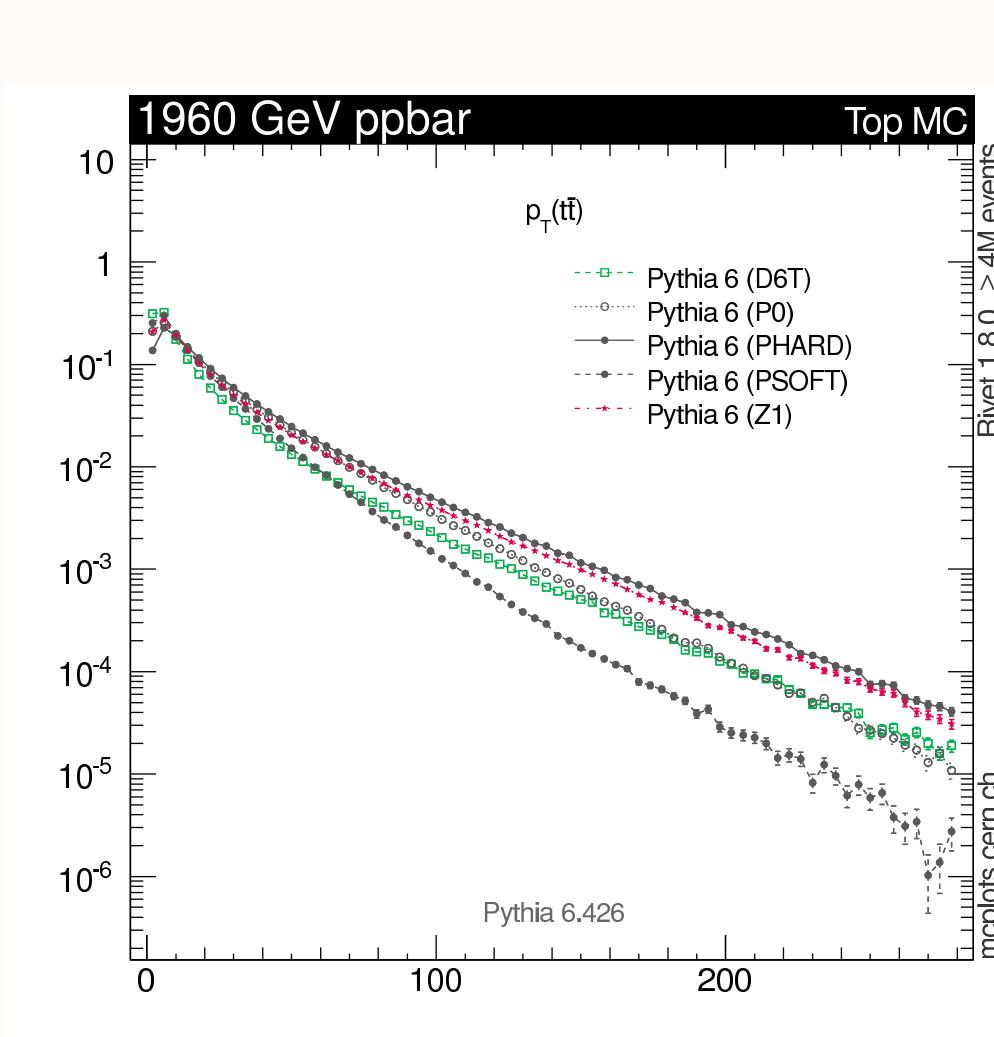


- $m_{t\bar{t}}$ differential distribution

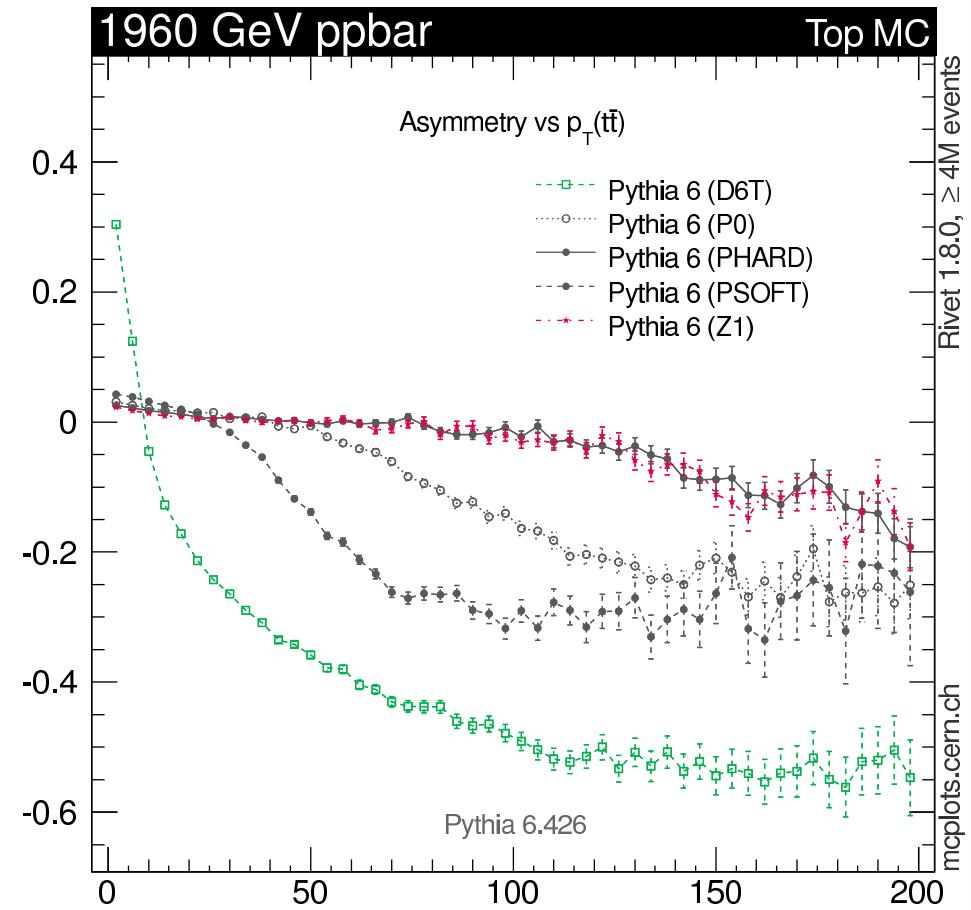
Different Pythia 6 shower models

[SKANDS, WEBBER, WINTER, ARXIV:1205.1466]

→ Pythia 6 has options with varying amounts of coherence.



Asymmetry as function of the top-pair p_T



- $p_{T,t\bar{t}}$ differential cross section distribution

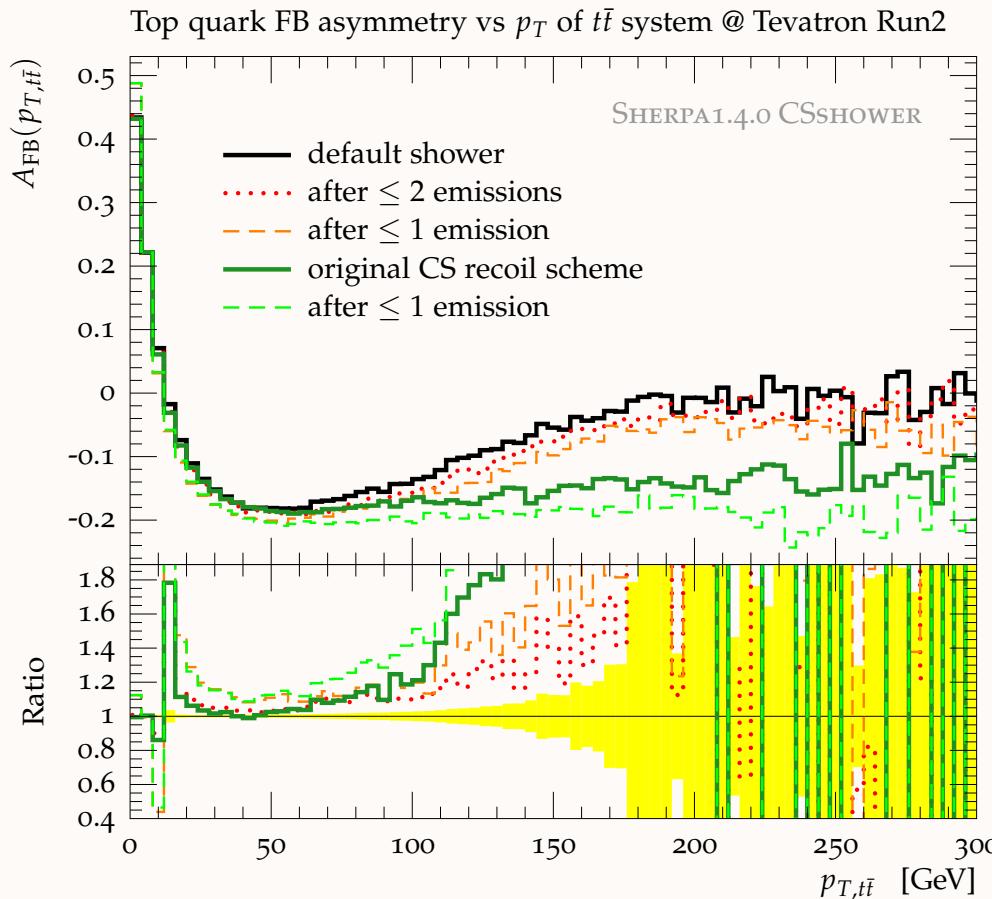
Different recoil-scheme options in Sherpa

[SKANDS, WEBBER, WINTER, ARXIV:1205.1466]

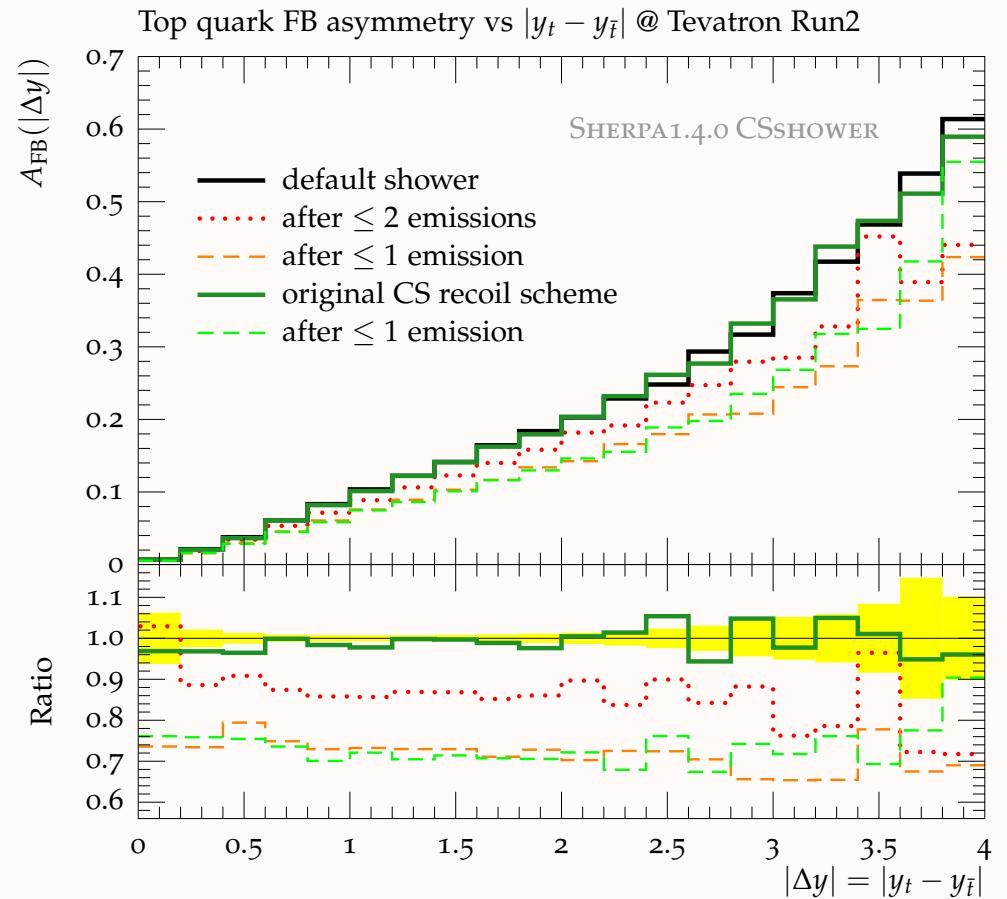
Sherpa's CSshower provides two options for treating the recoils. \Rightarrow Recoil options affect high p_T .

→ original CS scheme treats recoils more locally, IF dipole is decoupled from rest of event

longitudinal recoil treatment is effectively the same



- Asymmetry versus $p_T, t\bar{t}$



- Asymmetry versus $|\Delta y|$

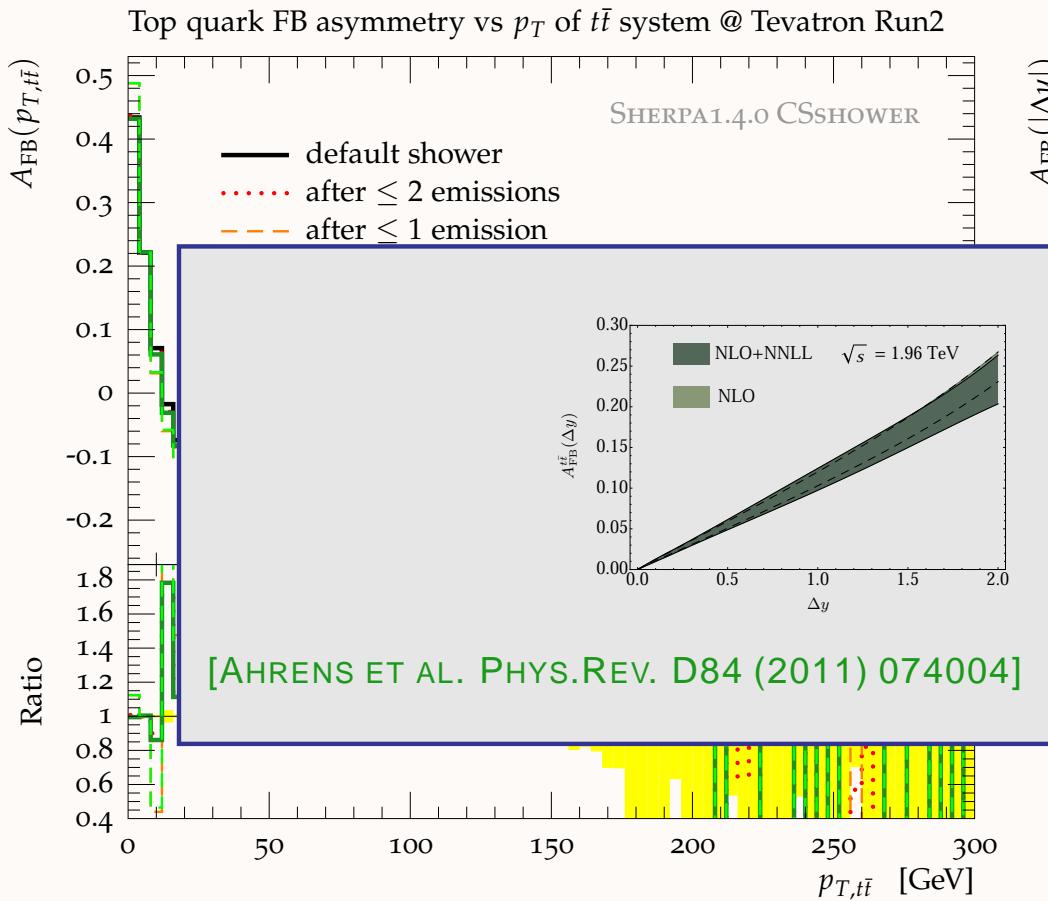
Different recoil-scheme options in Sherpa

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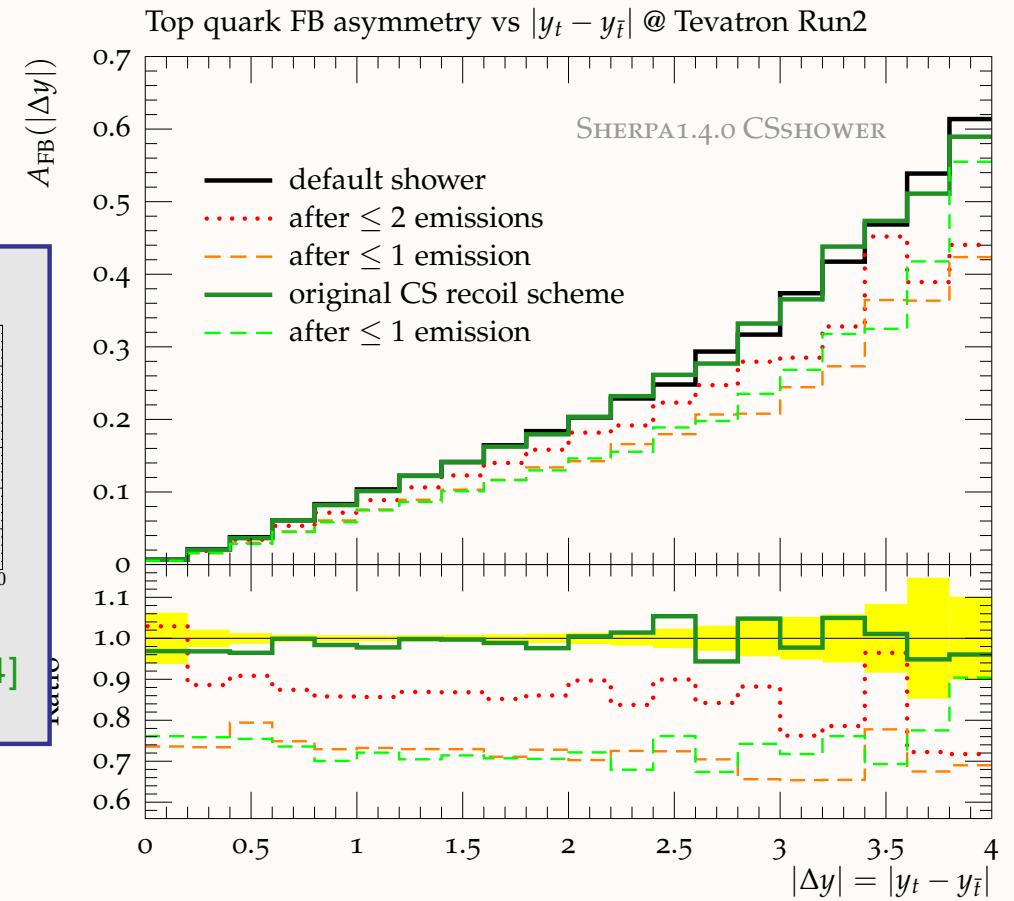
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- Asymmetry versus $p_{T,t\bar{t}}$

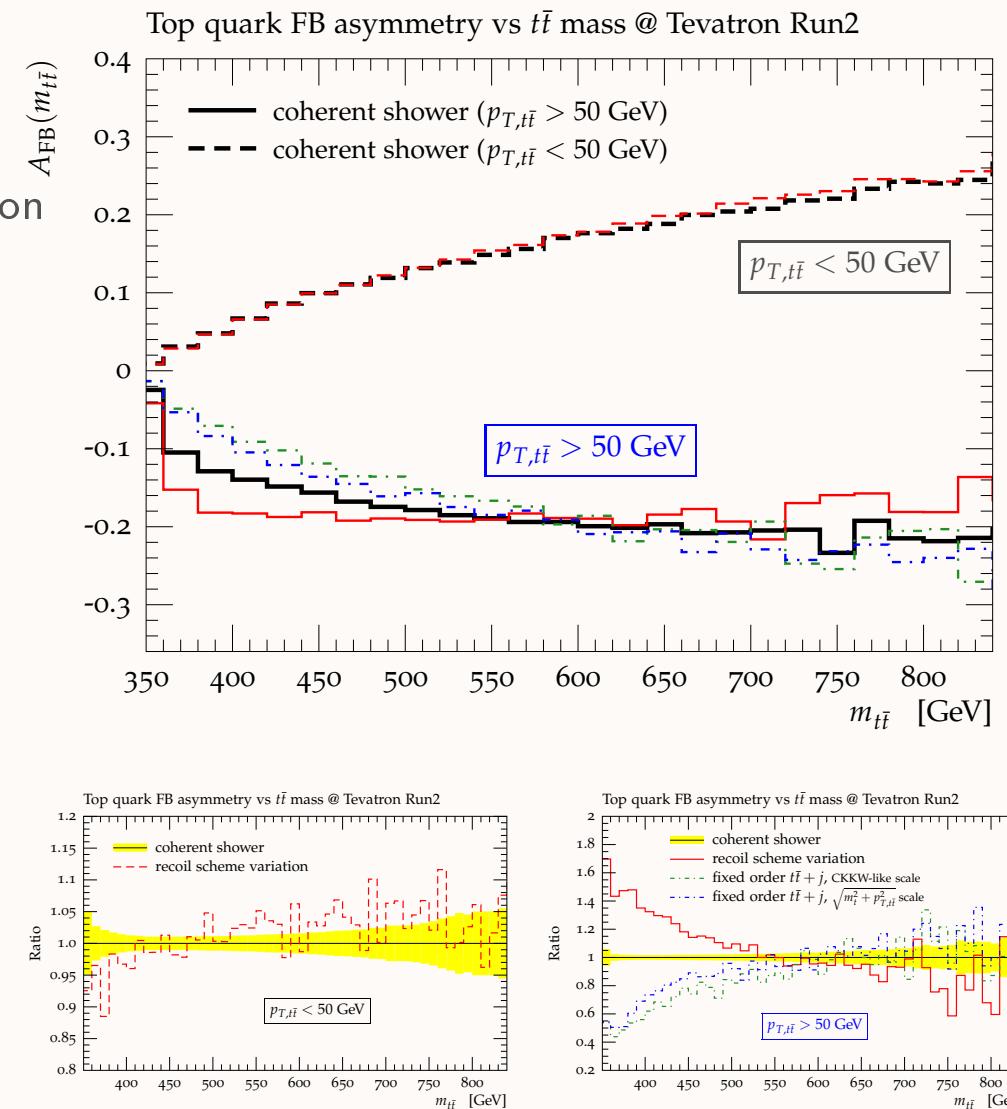
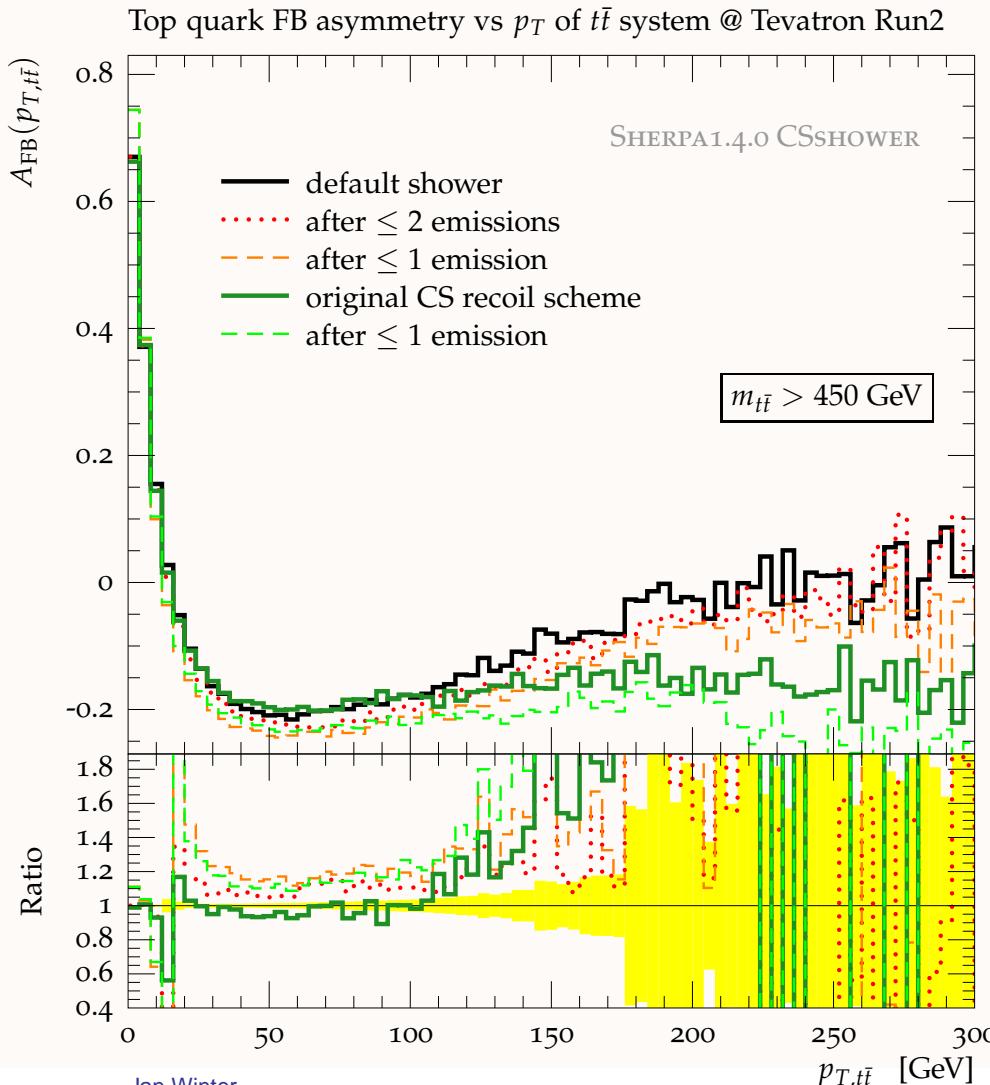


- Asymmetry versus $|\Delta y|$

Cut on top-pair mass versus cut on top-pair pT

→ ***Sign change – striking general prediction.***

- $m_{t\bar{t}}$ cut mostly affects low p_T prediction
- $p_{T,t\bar{t}}$ cut separates Sudakov(+) from hard(−) region



Summary & Implications

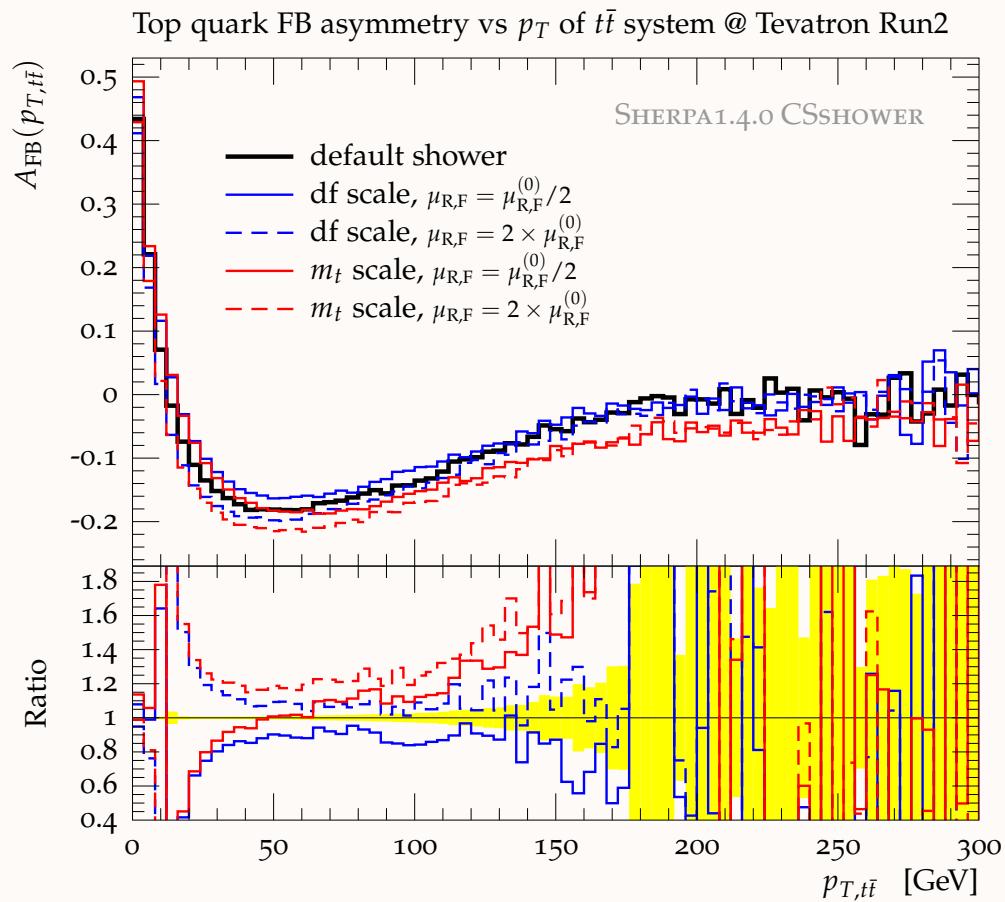
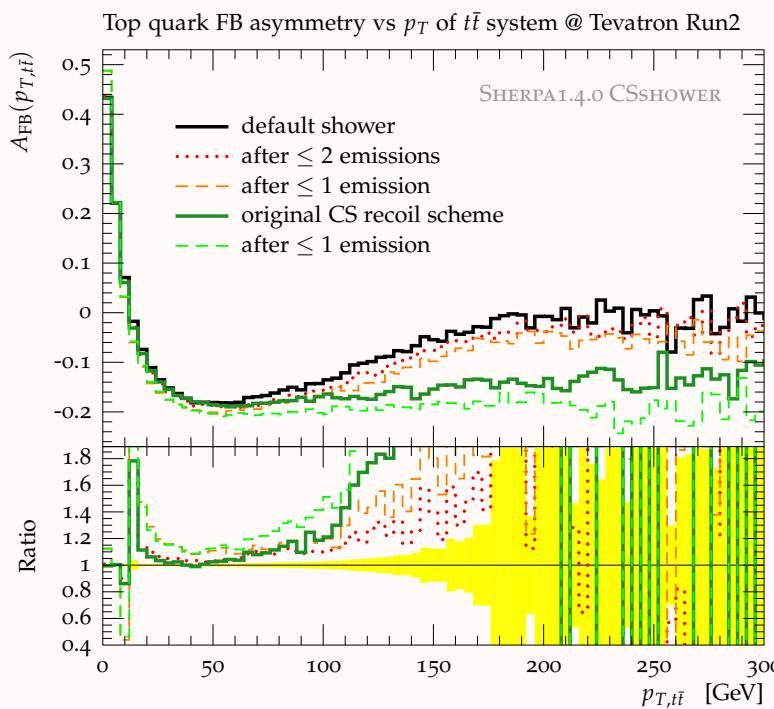
- Monte Carlo LO event generators can produce significant (differential and inclusive) asymmetries where none were previously expected.
 - One needs to be aware of that for the interpretation of experimental data.
 - Monte Carlo estimates of corrections to asymmetries could be affected by this.
- Model-dependent corrections!?
- Asymmetries in Monte Carlos arise from valid physics built into generators with coherent parton or dipole showering.
- While not quantitatively correct in every detail, important features are captured by coherent showering approximation.
 - unequal Sudakov factors for forward and backward top production
 - migration of recoiling tops between hemispheres (Use (N)LO for A_{FB} to optimize recoils?)
- Many directions are open for further studies.
 - effects in $t\bar{t}$ charge asymmetry @ LHC
 - assessment of NLO+PS tools wrt. asymmetry producing/enhancing shower effects
 - similarly for multi-parton ME+PS
 - comparison with higher-order parton-level calculations (production and decay)

Additional material

- Scale variations.
- A_{FB} as a function of $\beta = \sqrt{1 - 4 m^2/\hat{s}}$. (Preliminary.)

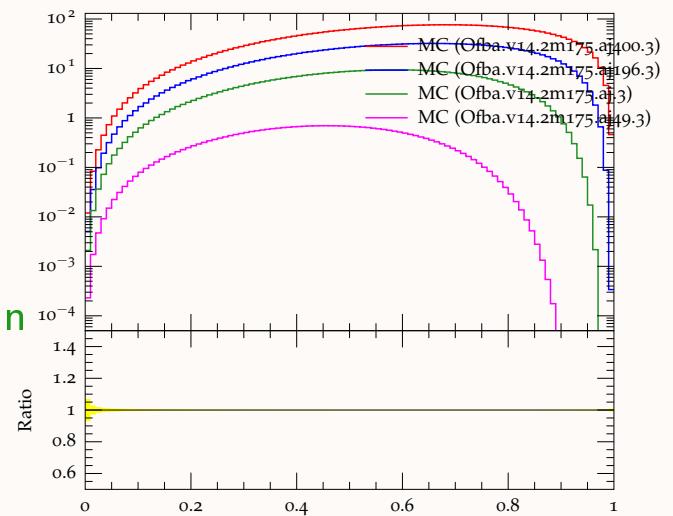
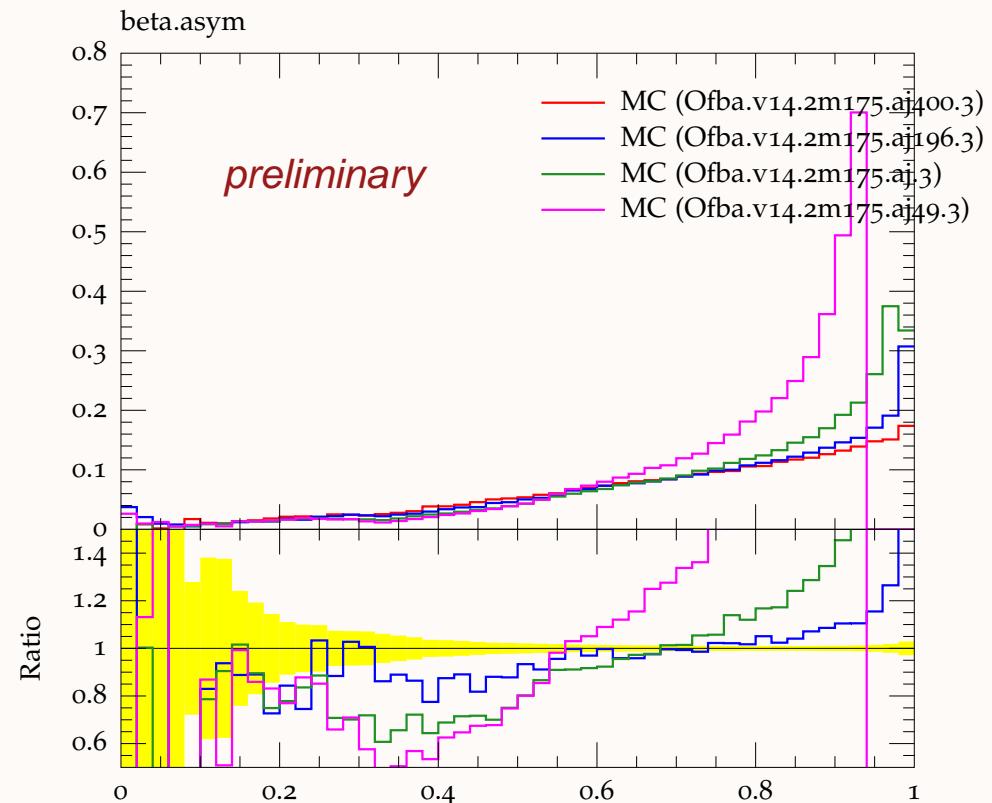
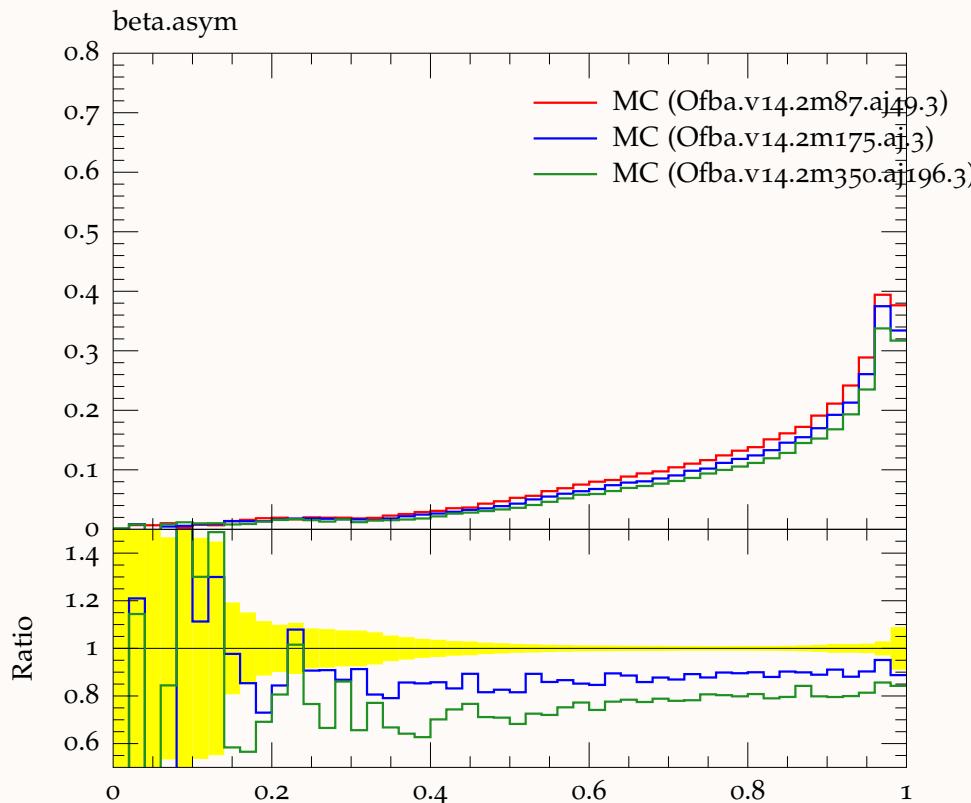
Scale variations

- $A_{\text{FB}}(p_{T,t\bar{t}})$ – scale variation effects smaller than recoil effects
- possible x-test? $A_{\text{FB}} = f(\alpha_s)$ with various but constant $\alpha_s \Rightarrow \mathcal{O}(\alpha_s)$ of recoil effects from fit



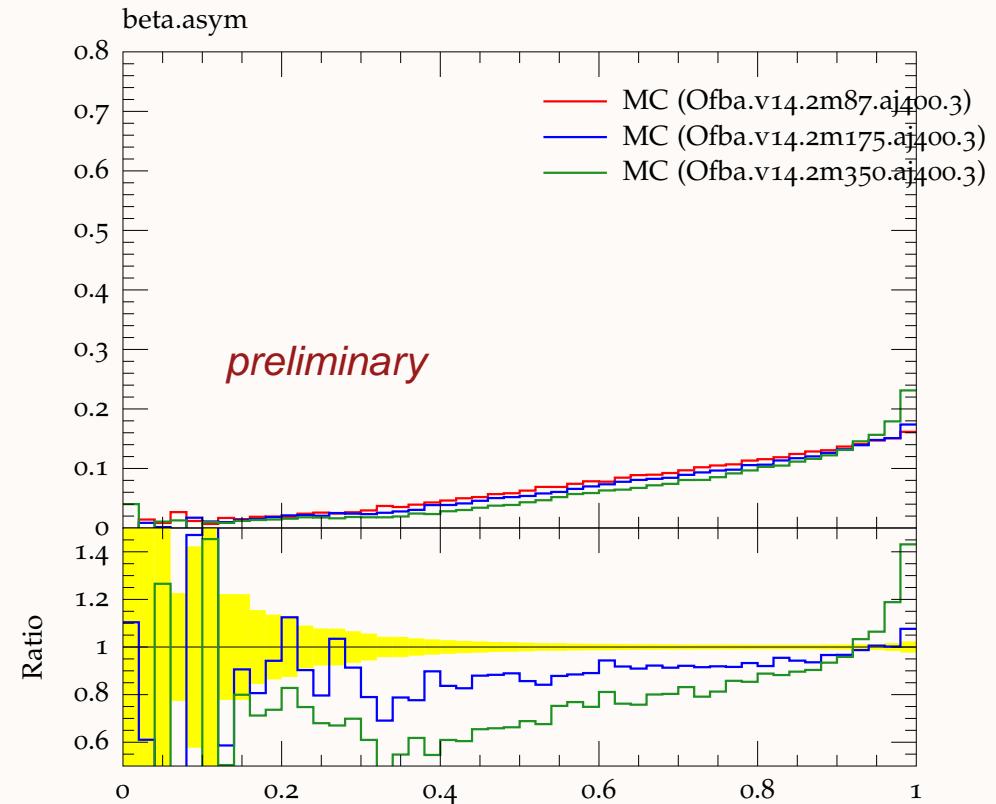
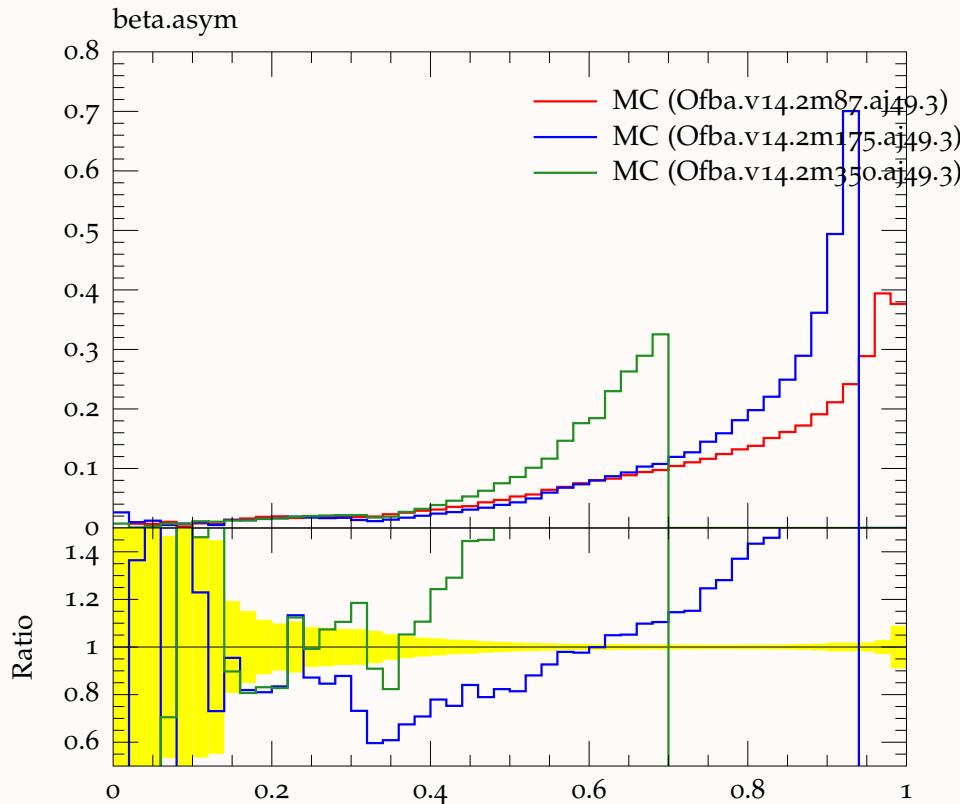
AFB vs. beta (I)

- $A_{FB}(\beta)$ – only $q\bar{q} \rightarrow t\bar{t}$ @ $P\bar{P}$ machines – \hat{s} from momentum sum of all FS partons (note Tevatron \rightarrow T'tron)
- (left) $m = m_t/2$ @ T'tron/2, $m = m_t$ @ T'tron, $m = 2m_t$ @ 2 T'tron
- (right) $m = m_t$, @ 8 TeV, @ 2 T'tron, @ T'tron, @ T'tron/2
(top) the respective β diff. distributions



AFB vs. beta (II)

- (left) $A_{\text{FB}}(\beta)$ @ 1/2 Tevatron, $m = m_t/2$, $m = m_t$, $m = 2m_t$
- (right) $A_{\text{FB}}(\beta)$ @ 8 TeV $P\bar{P}$ machine, $m = m_t/2$, $m = m_t$, $m = 2m_t$



- To avoid reconstruction/production-level discussion, measure $A_{\text{lep}}(M_{T,\text{tot}})$ instead of $A_{\text{FB}}(m_{t\bar{t}})$?