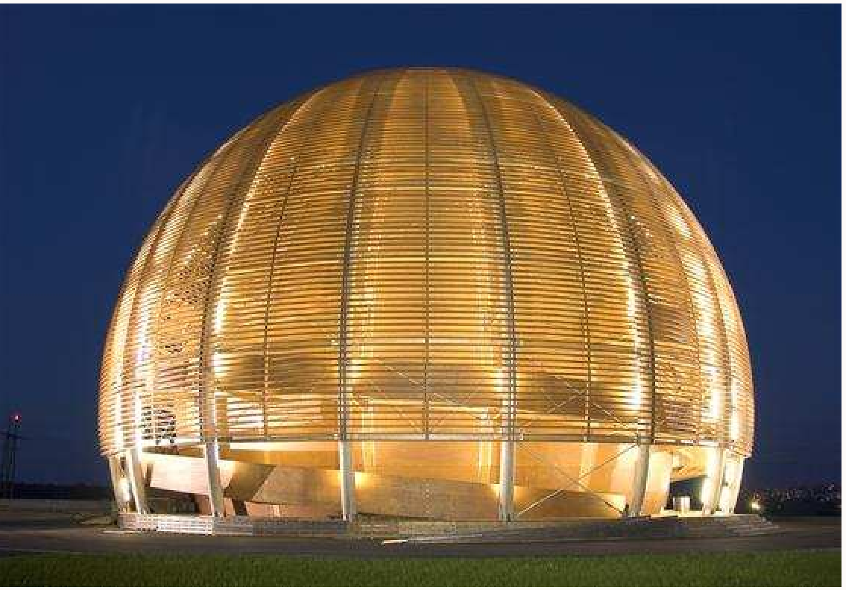
Top quark FB asymmetry in shower Monte Carlos

[Fermilab Theory Seminar – One West]

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.*

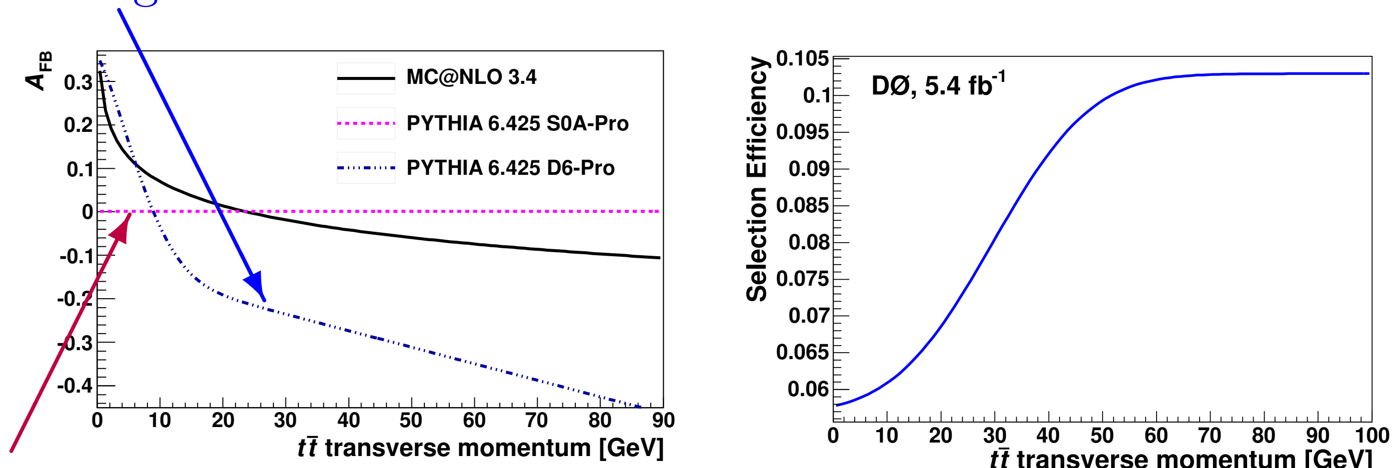
Story began with a plot made by DØ

[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 on



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

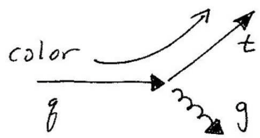
[SLIDES FROM DAN AMIDEI'S TALK @ TOP AFB & BOOSTED REGIME CERN WS IN MAY]

rapidity difference: $\Delta y = y_t - y_t$

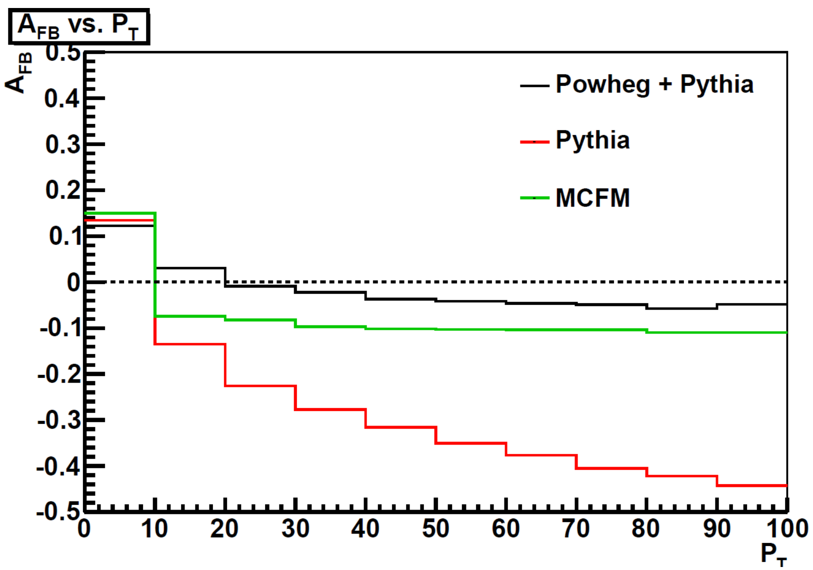
$$A_{\mathrm{FB}}(O) = \frac{\left.\frac{d\sigma}{dO}\right|_{\Delta y>0} - \left.\frac{d\sigma}{dO}\right|_{\Delta y<0}}{\left.\frac{d\sigma}{dO}\right|_{\Delta y>0} + \left.\frac{d\sigma}{dO}\right|_{\Delta y<0}}$$

p_t (ttbar) dependence of the asymmetry

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

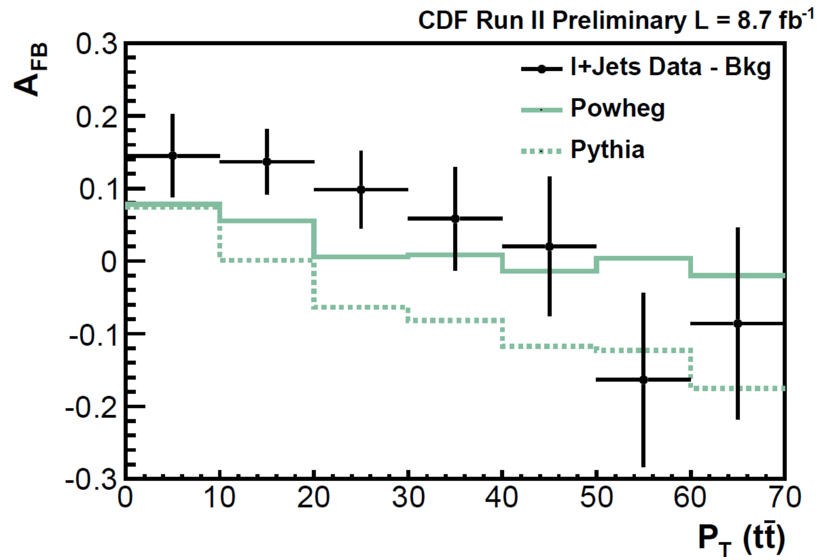


expectation @ MC truth:



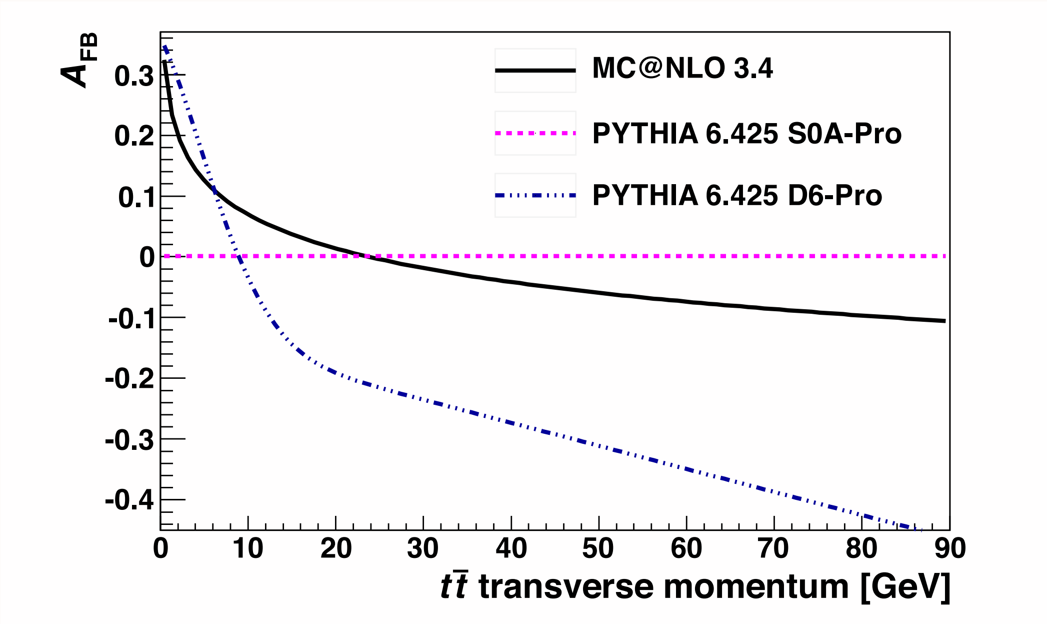
p_t (ttbar) dependence of the asymmetry

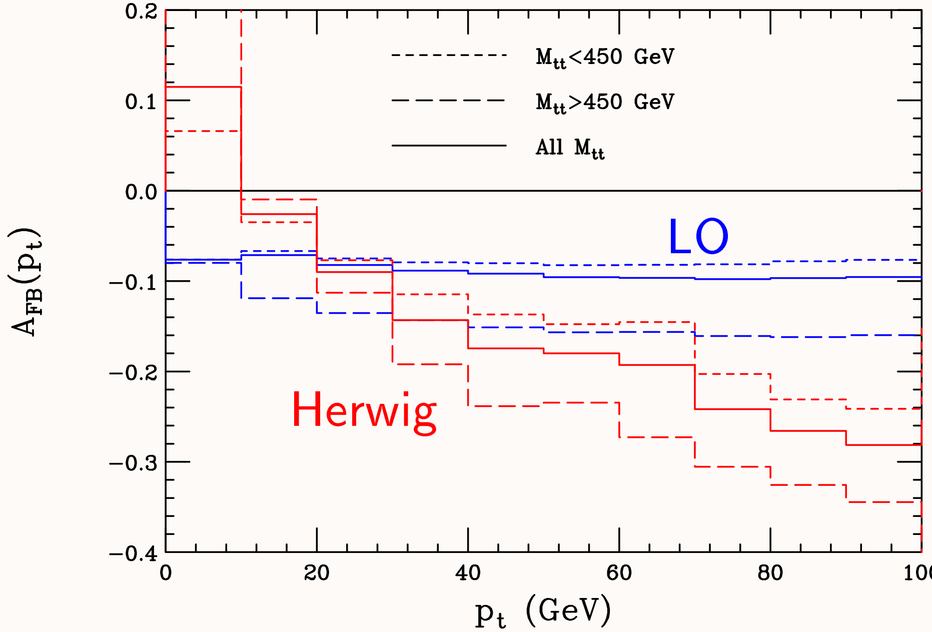
- examine at background subtracted level
- data vs powheg/pythia shower vs pythia neat



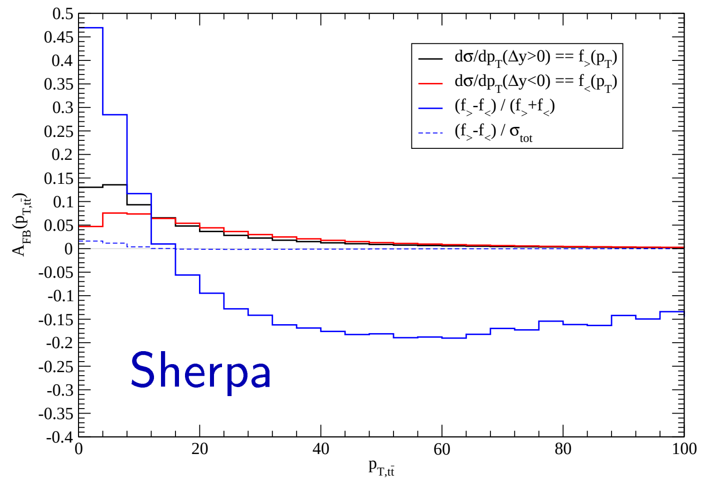
First cross-checks

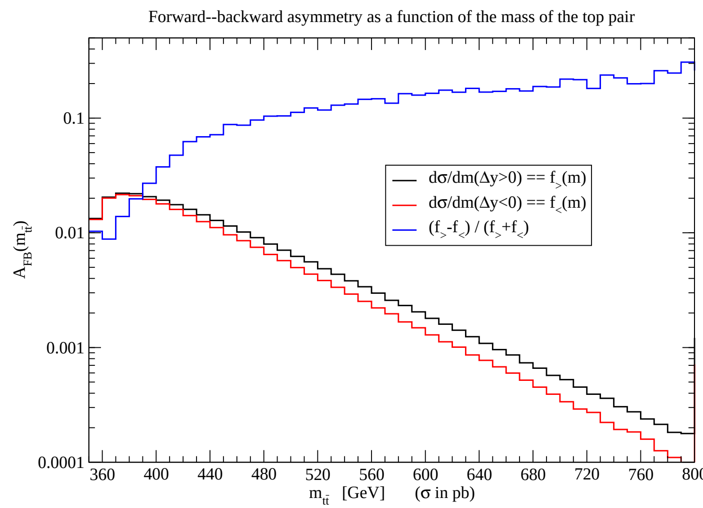
[PLOT UPPER LEFT FROM DØ – ARXIV:1107.4995]





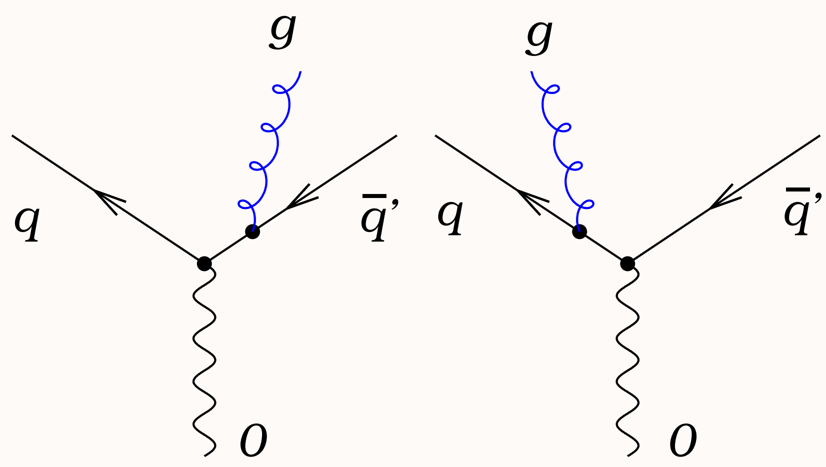
- coherent shower Monte Carlos (MCs) contain/enhance asymmetry





Angular ordering

➡ ***Soft gluon emission off external QCD lines is enhanced and shows coherence pattern.***



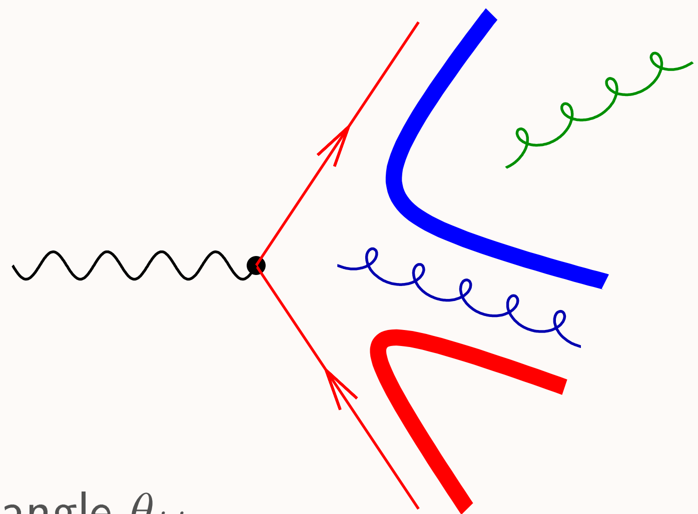
- soft enhancement corresponds to colour factor $\times$ universal, spin-independent term (eikonal factor)

$$d\sigma_{n+1} \;=\; d\sigma_n \,\frac{d\omega}{\omega}\frac{d\Omega}{2\,\pi}\frac{\alpha_s}{2\,\pi}\sum\nolimits_{i,j} C_{ij} W_{ij}$$

(gluon energy ω and solid angle Ω, $C_{ij} = -\boldsymbol{Q}_i \cdot \boldsymbol{Q}_j$)

- radiation function defines antenna pattern of process

$$W_{ij} \;=\; \frac{\omega^2\, p_i \cdot p_j}{p_i \cdot p_g \; p_j \cdot p_g} \;\equiv\; W_{ij}^{[i]} + W_{ij}^{[j]} \qquad \text{(massless emitters)}$$



- take $d\Omega = d\cos\theta_{ig} d\phi_{ig}$ plus azimuthal averaging

$$\int_0^{2\pi} \frac{d\phi_{ig}}{2\,\pi} \;=\; \frac{1}{1-\cos\theta_{ig}} \;\text{ if } \theta_{ig} < \theta_{ij}\,, \qquad =\; 0 \text{ otherwise}$$

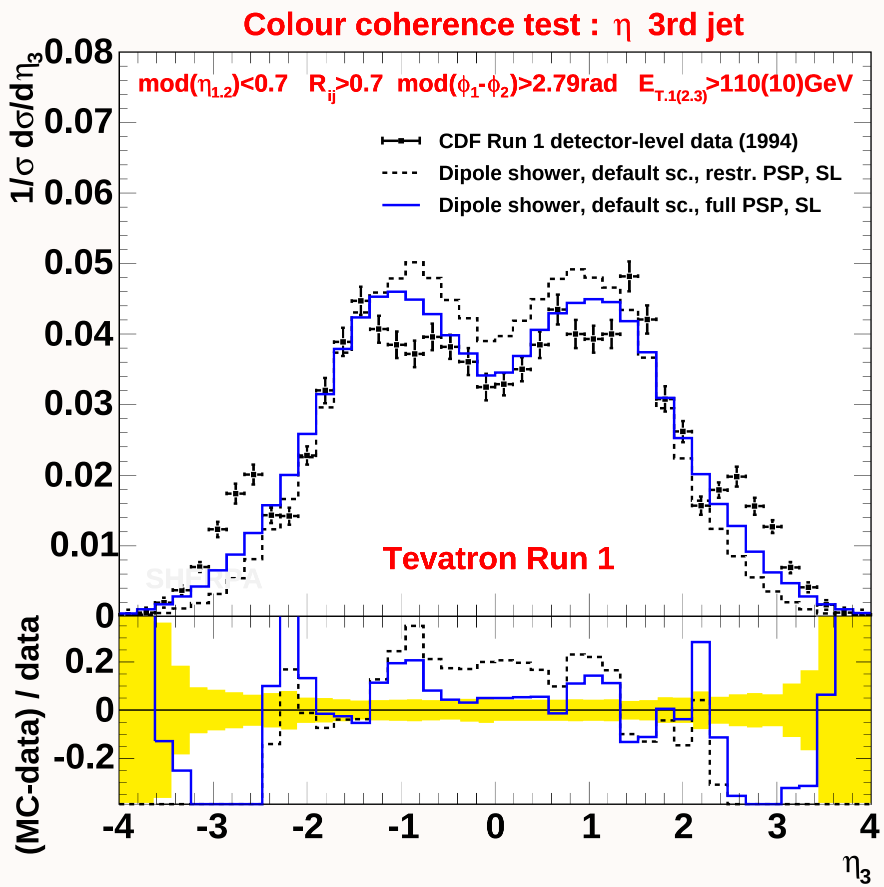
- Contributions are confined to cone around i (j) of opening angle θ_{ij}.
- Gluons at large angle cannot resolve individual colour charges, only net charge of system.

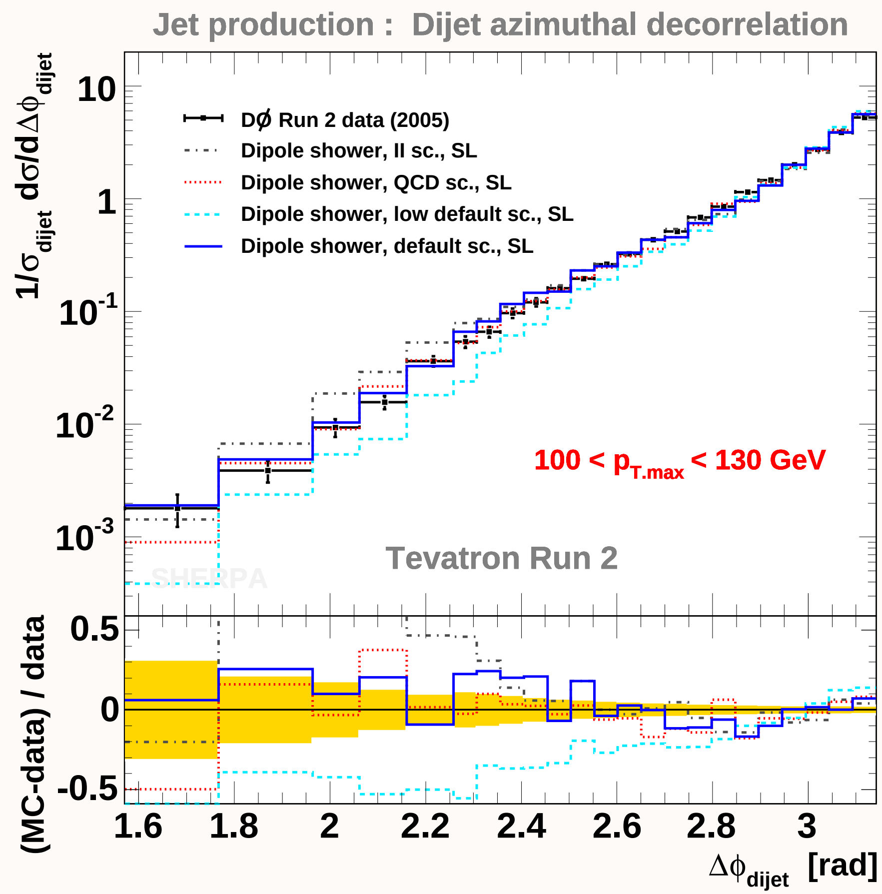
[Chudakov effect in QED]

Colour-dipole shower for hadronic collisions

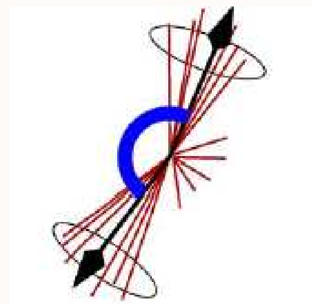
[Winter, Krauss, JHEP 07 (2008) 040]

➡ *Testbed: inclusive jet production @ Tevatron Run I & II*





- qualitative test for the inclusion of colour coherence – uncorrected data
  CDF [Abe et al., Phys. Rev. **D50** (1994) 5562]
- stringent test of QCD radiation pattern – dijet azimuthal decorrelation
  DØ [Abazov et al., PRL **94** (2005) 221801]



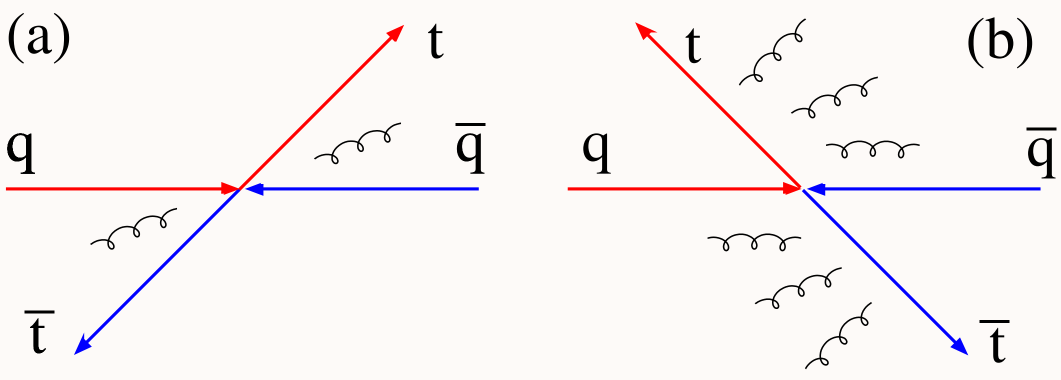
Colour coherence

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

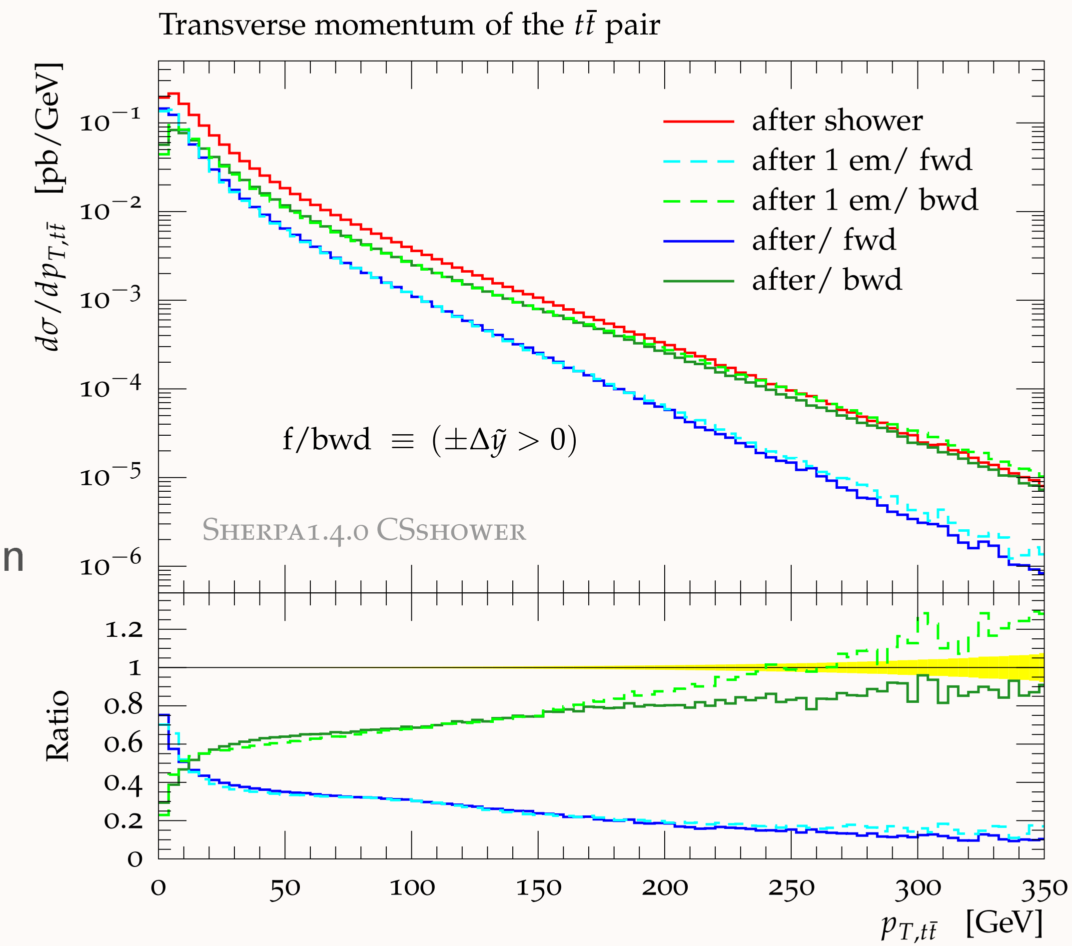
"Forward" dipoles – less space space for emission, less likely to radiate.

"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

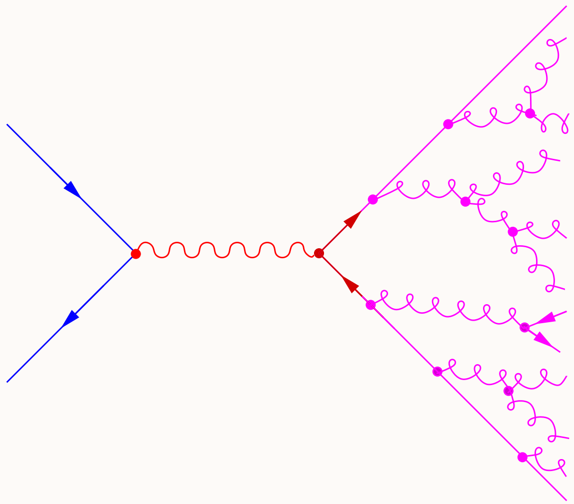
- shower Monte Carlos versus fixed order
- generation of an inclusive asymmetry by LO shower Monte Carlos
- comparison between different parton shower models
- time permitting, discussion of additional plots

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]*

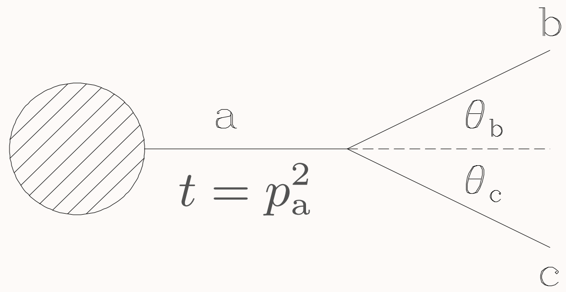


- QCD amplitudes factorize in the coll/soft limit.

➡ Recursive definition of multiple emissions:

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

(e.g. coll limit)



(Altarelli–Parisi splitting functions)

- 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 $\mu_0 = \mathcal{O}(1\,\mathrm{GeV})$]*

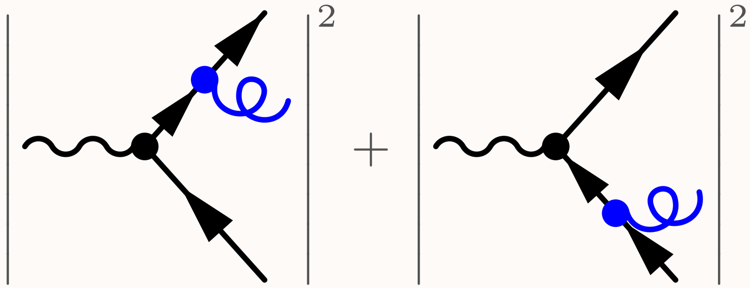
Parton showers (PSs)

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

- propagator factor for $q \longrightarrow qg$ 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

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

- probability for no resolvable emission off quark line between t and t_0:
  Sudakov form factor $\quad (P_{q\to qg}(z) = C_F \frac{1+z^2}{1-z}$ ... spin averaged AP kernel)

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

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

Shower predictions = LO+LL predictions

Examples for shower Monte Carlos

- Pythia – virtuality ordering, $1 \to 2$ (old) and p_T ordering, $2 \to 3$ [Sjöstrand, Skands, Mrenna]
- Herwig(++) – angular ordering, $1 \to 2$ [Webber, Marchesini, Seymour, Richardson]
- Ariadne – Lund colour dipole model, p_T ordering, full $2 \to 3$ [Lönnblad, Gustafson, Andersson]
- Vincia – antenna shower, p_T & other orderings, full $2 \to 3$ [Giele, Kosower, Skands]
- Sherpa's CSshower – based on CS subtraction terms, p_T ordering, $2 \to 3$ [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-branching showers work well in soft limit.***

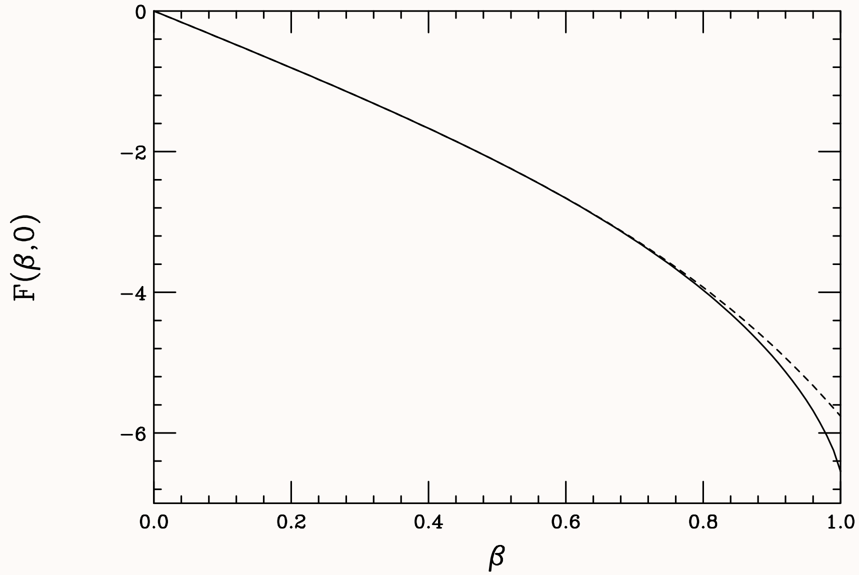
- One gluon emission process

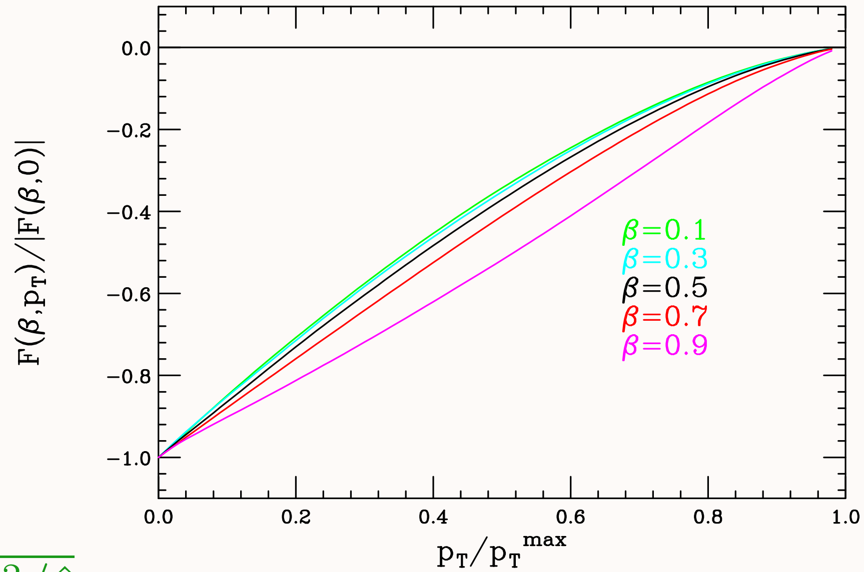
$$q(p_1) + \bar{q}(p_2) \to Q(p_3) + \bar{Q}(p_4) + g(k)$$

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

- Approximations used:
- MCs do "Born $\times$ W_{ij}'s $\times$ $2\,C_F$" 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: $F(\beta, 0) = -4\,\beta - \beta^3 - \ldots$

$$\frac{p_T}{\hat{\sigma}_B}\frac{d\hat{\sigma}_A}{dp_T} = \frac{\alpha_S}{\pi}\frac{(N^2-4)}{N}F(\beta, p_T) \qquad \beta = \sqrt{1 - 4\,m^2/\hat{s}}$$





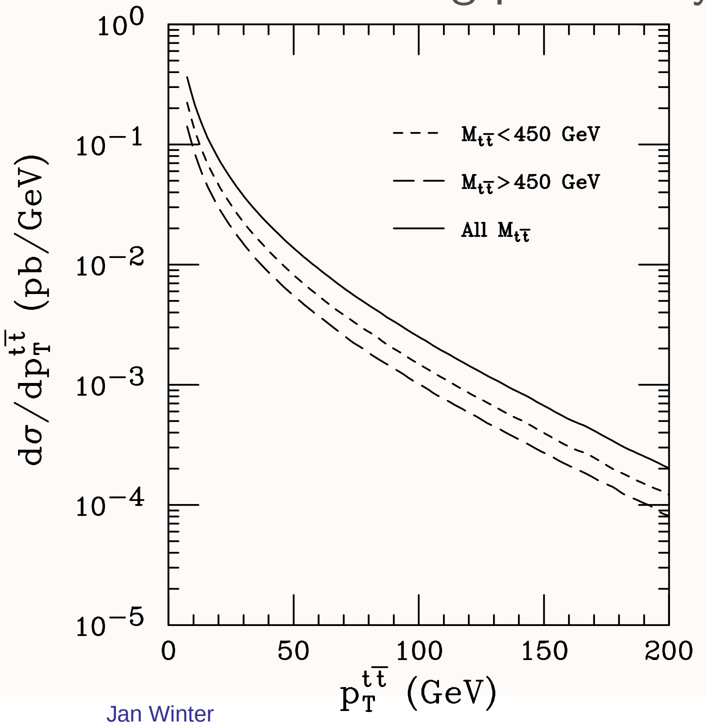
Fixed order versus Sudakov suppression

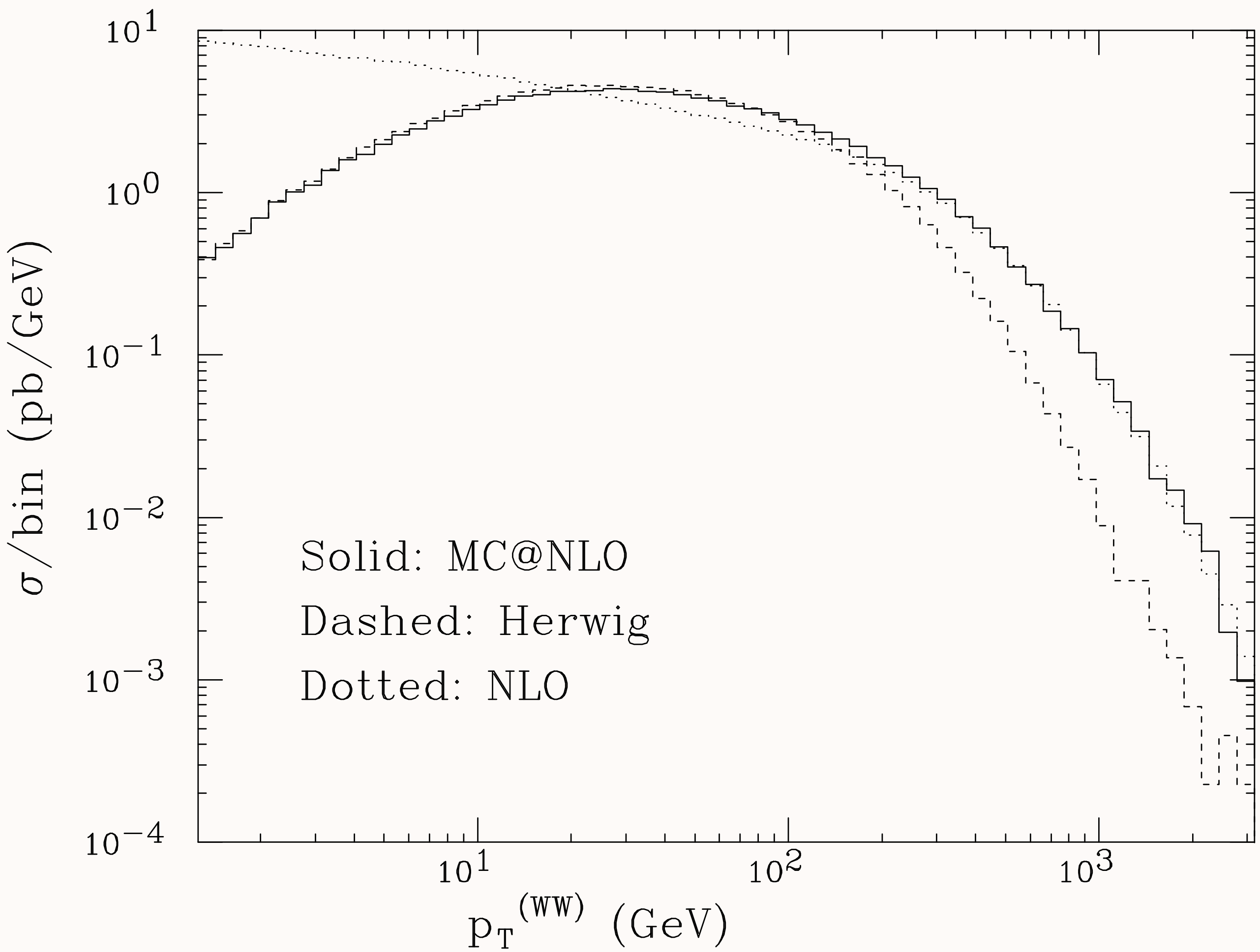
for example MC@NLO: S. Frixione and B.R. Webber, JHEP ***06*** (2002) 029

➡ $pp \to W^+W^- + X$ @ 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

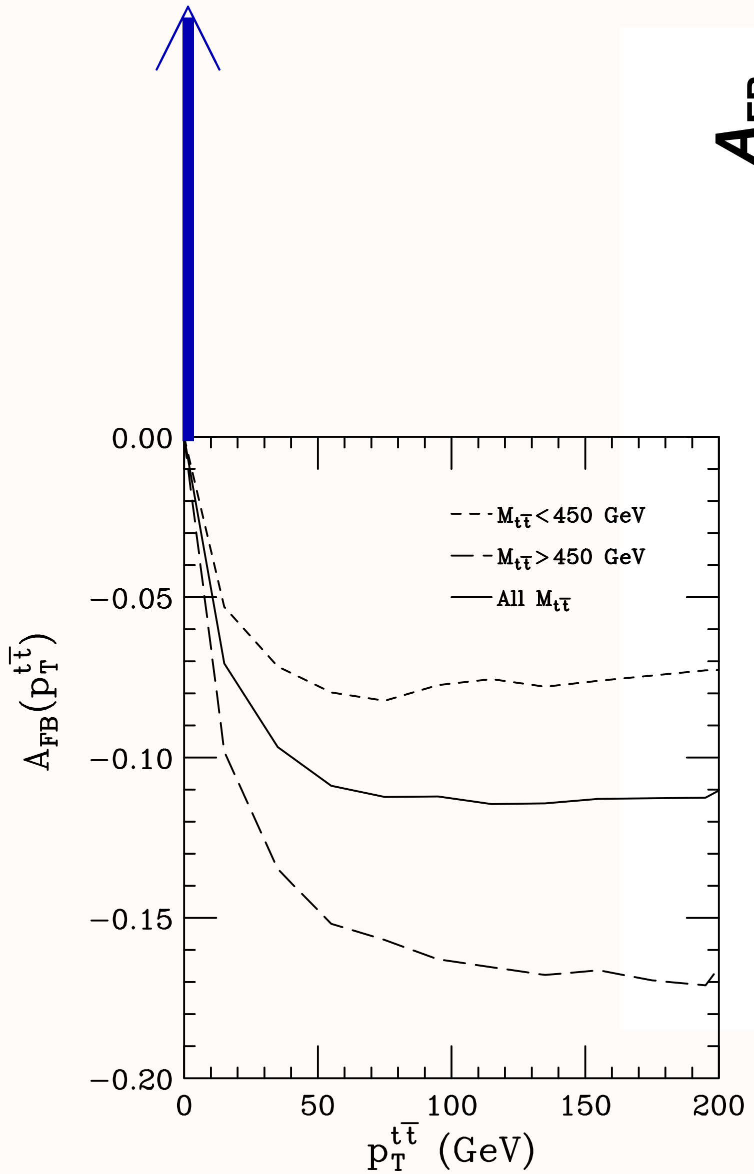


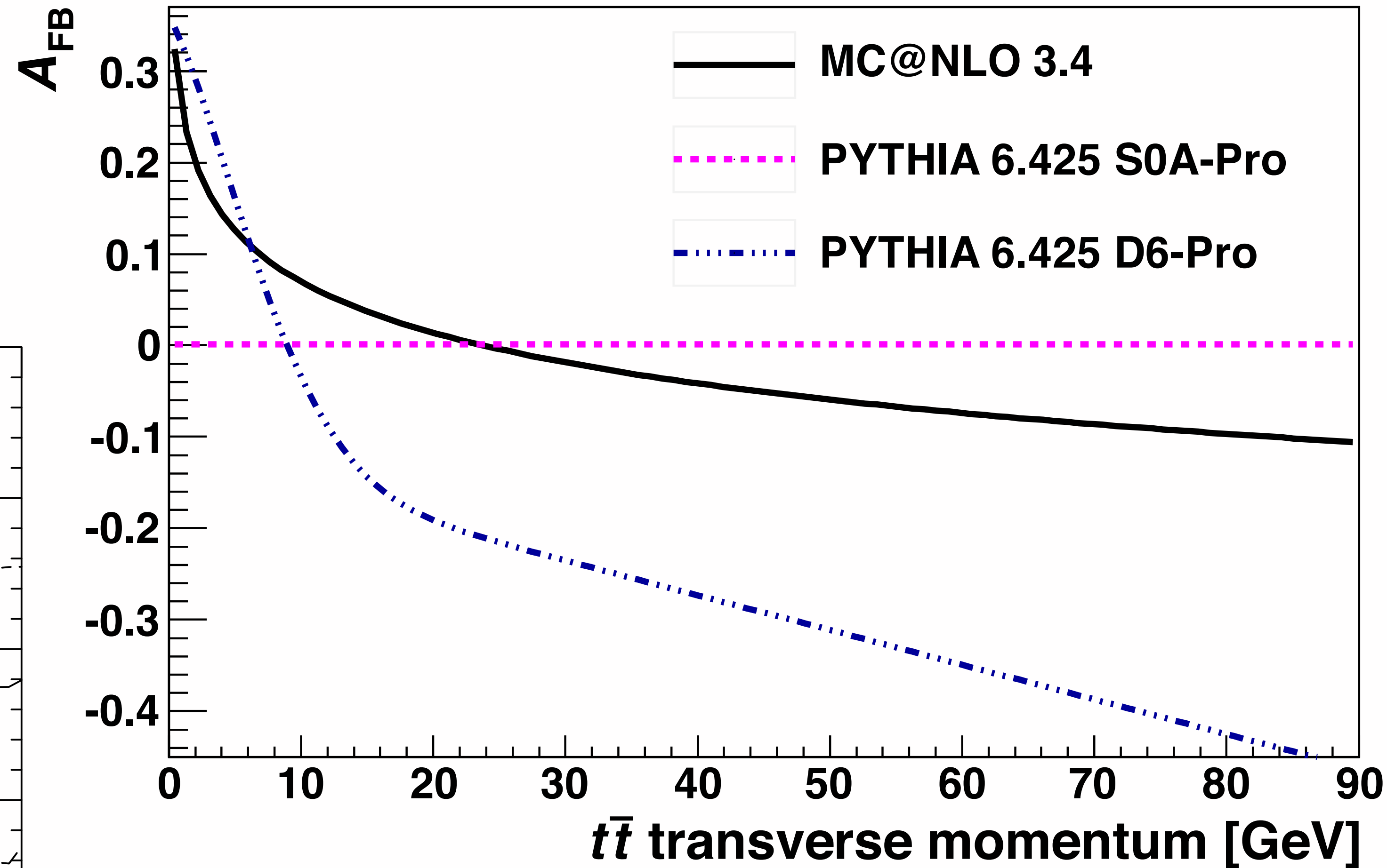


⇐ corresponding fixed-order $p_T^{t\bar{t}}$ plot (using MCFM)

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.

$$\Delta\sigma_{+-} = \int d\sigma^{\rm LO}\big|_{\Delta y>0} \left[\Delta_+ + (1-\Delta_+)(P_{++} - P_{+-})\right] \quad \Rightarrow \Delta y > 0 \text{ evts @ ME level, before shower}$$

$$- \int d\sigma^{\rm LO}\big|_{\Delta y<0} \underbrace{\left[\Delta_- + (1-\Delta_-)(P_{--} - P_{-+})\right]}_{\text{action of shower: no branching + branching(s)}} \quad \Rightarrow \Delta y < 0 \text{ evts @ ME level, before shower}$$

- 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

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

- 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

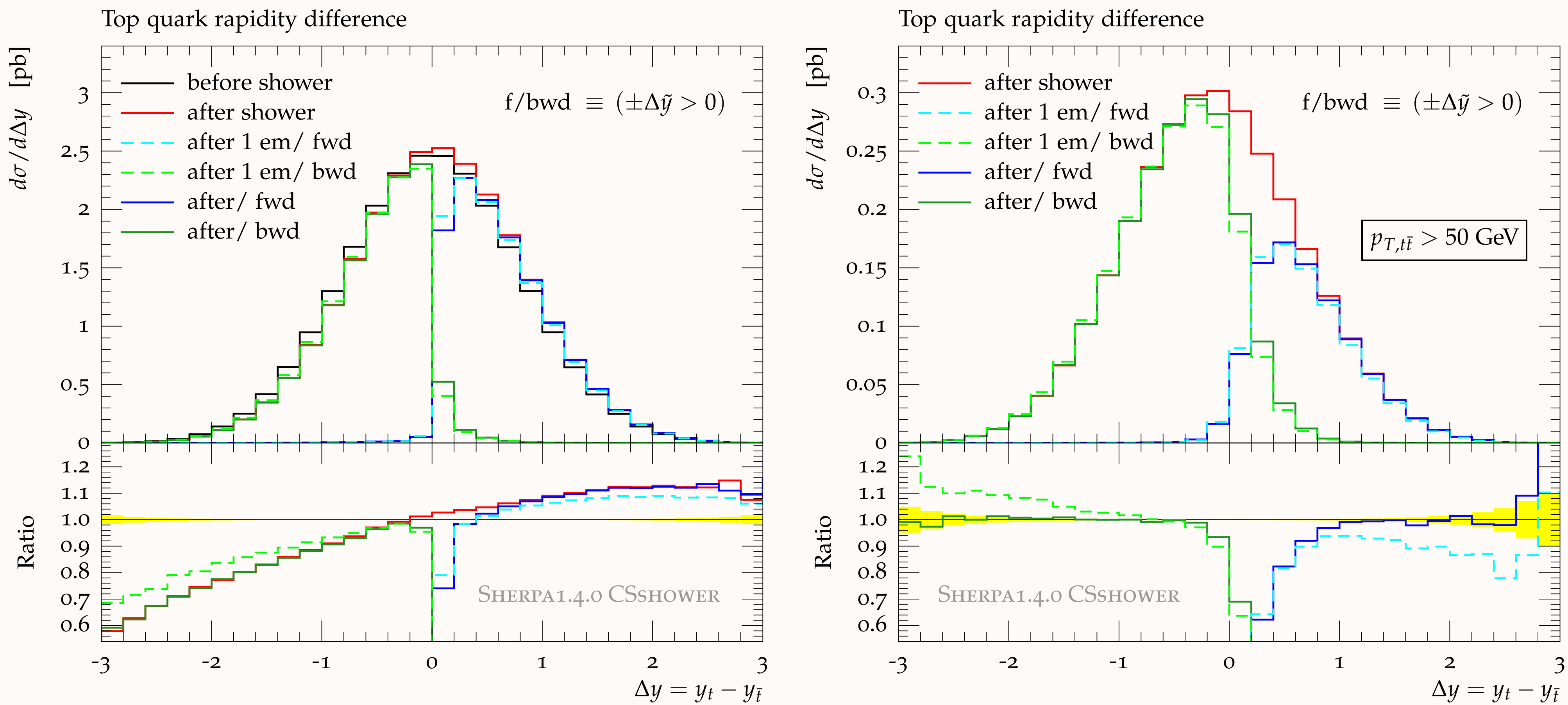
Longitudinal recoil effects – migration

[Skands, Webber, Winter, arXiv:1205.1466]

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

➡ migration is small, local, favouring $- \to +$ 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]*

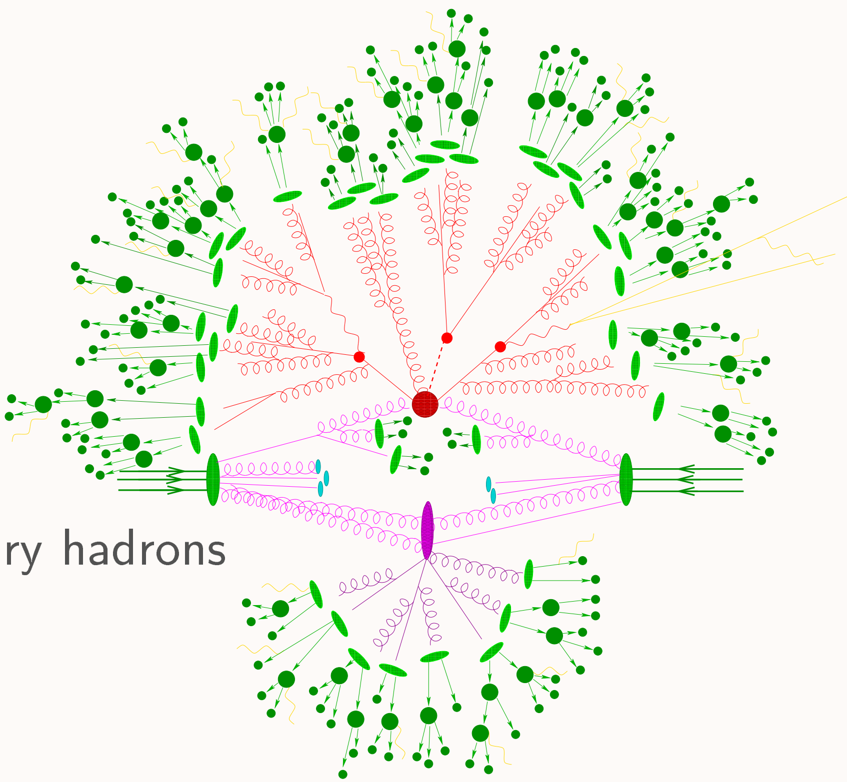
- ***Hard process/interaction (hard jet production)***
  exact matrix elements $|\mathcal{M}|^2$
- ***QCD bremsstrahlung (soft/coll multiple emissions)***
  initial- and final-state parton showering

⇐ only parts used in our analysis

- ***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



Inclusive asymmetry produced by LO generators

Model	Version [tune]	Inclusive	$m_{t\bar{t}}$/GeV < 450	$m_{t\bar{t}}$/GeV > 450	$p_{T,t\bar{t}}$/GeV < 50	$p_{T,t\bar{t}}$/GeV > 50
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

- different recoil strategies implemented in the different models
- recoil effects are $\sim$ leading wrt. LO asymmetry (eval. by MCFM)

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

$$A_{\rm FB}^{\rm (cut)} = \frac{\sigma^{\rm (cut)}\big\rfloor_{\Delta y>0} - \sigma^{\rm (cut)}\big\rfloor_{\Delta y<0}}{\sigma^{\rm (cut)}}$$

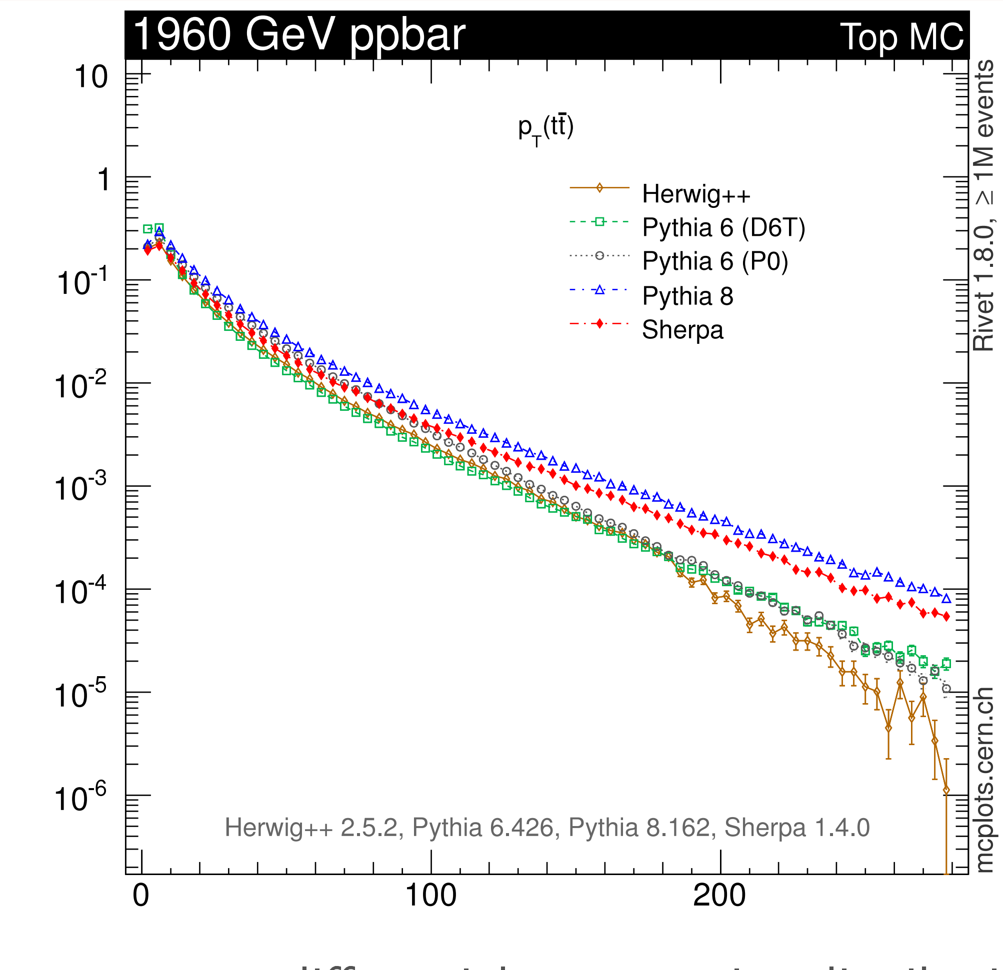
Differential asymmetry produced by LO generators

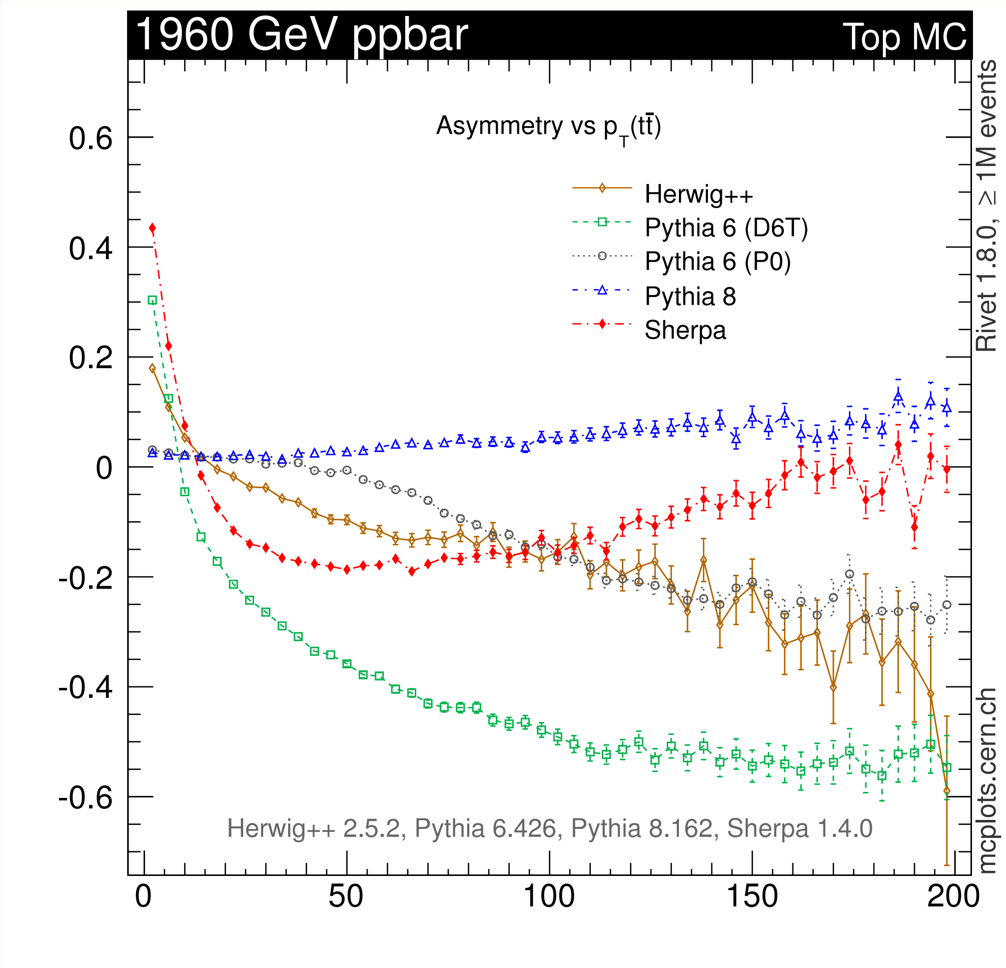
[Skands, Webber, Winter, arXiv:1205.1466]

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





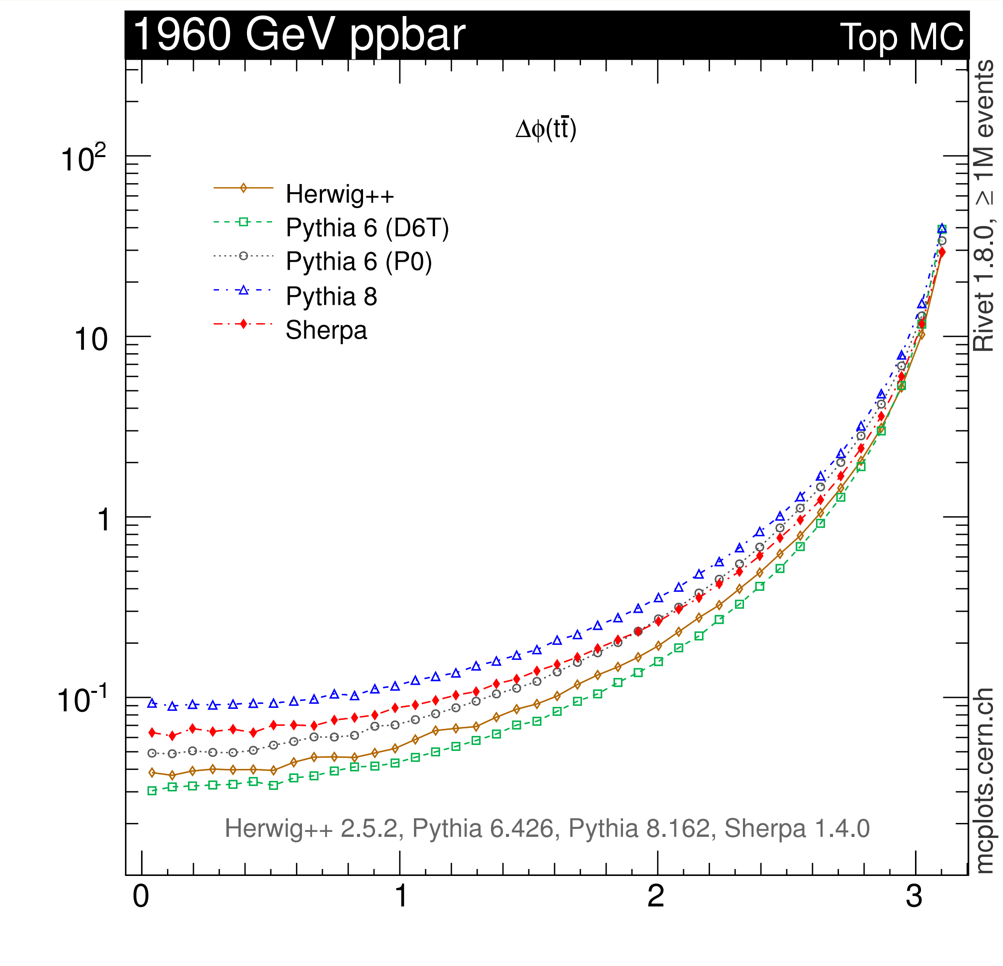
- $p_{T,t\bar{t}}$ differential cross section distribution

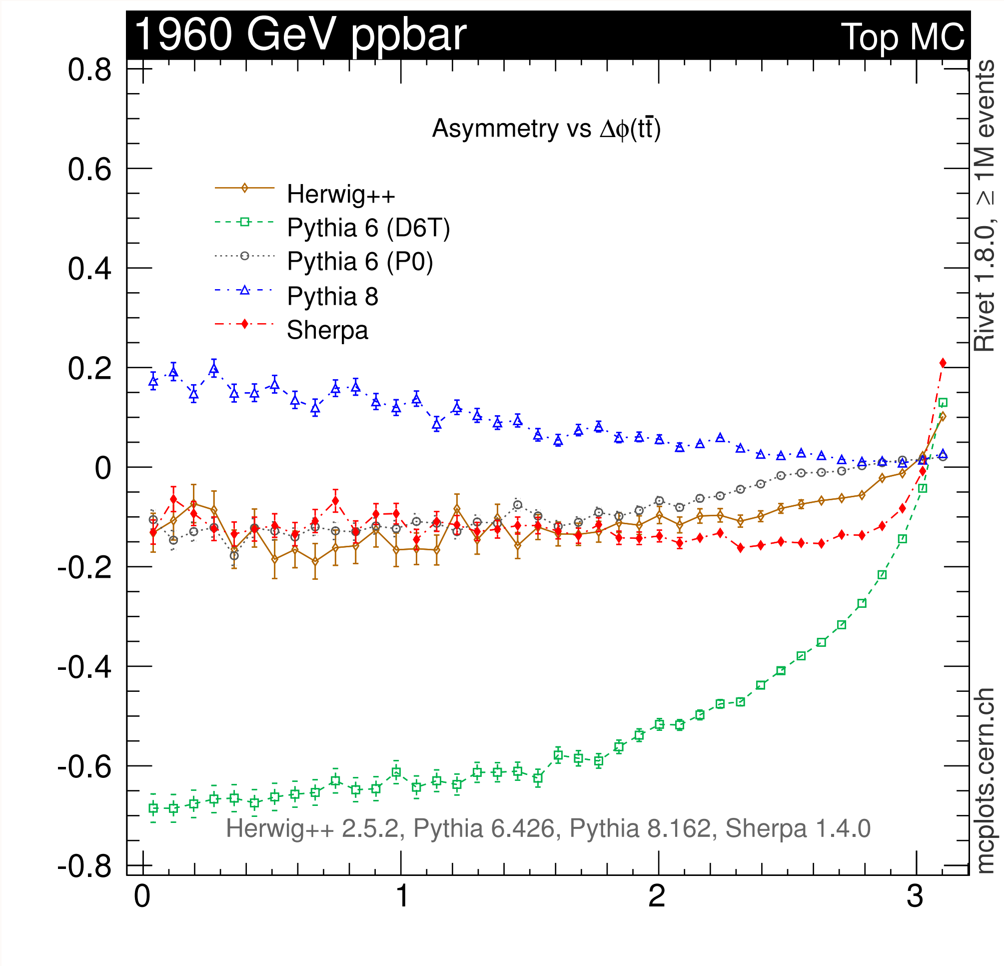
Differential asymmetry produced by LO generators

[SKANDS, WEBBER, WINTER, ARXIV:1205.1466]

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

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

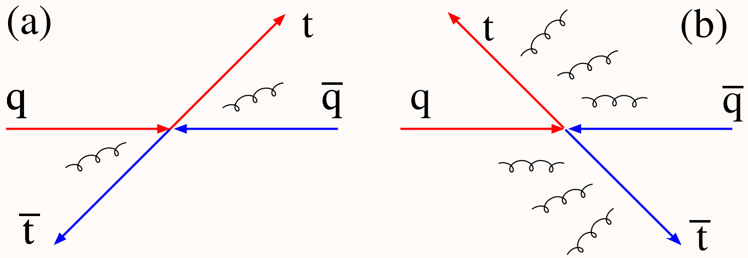




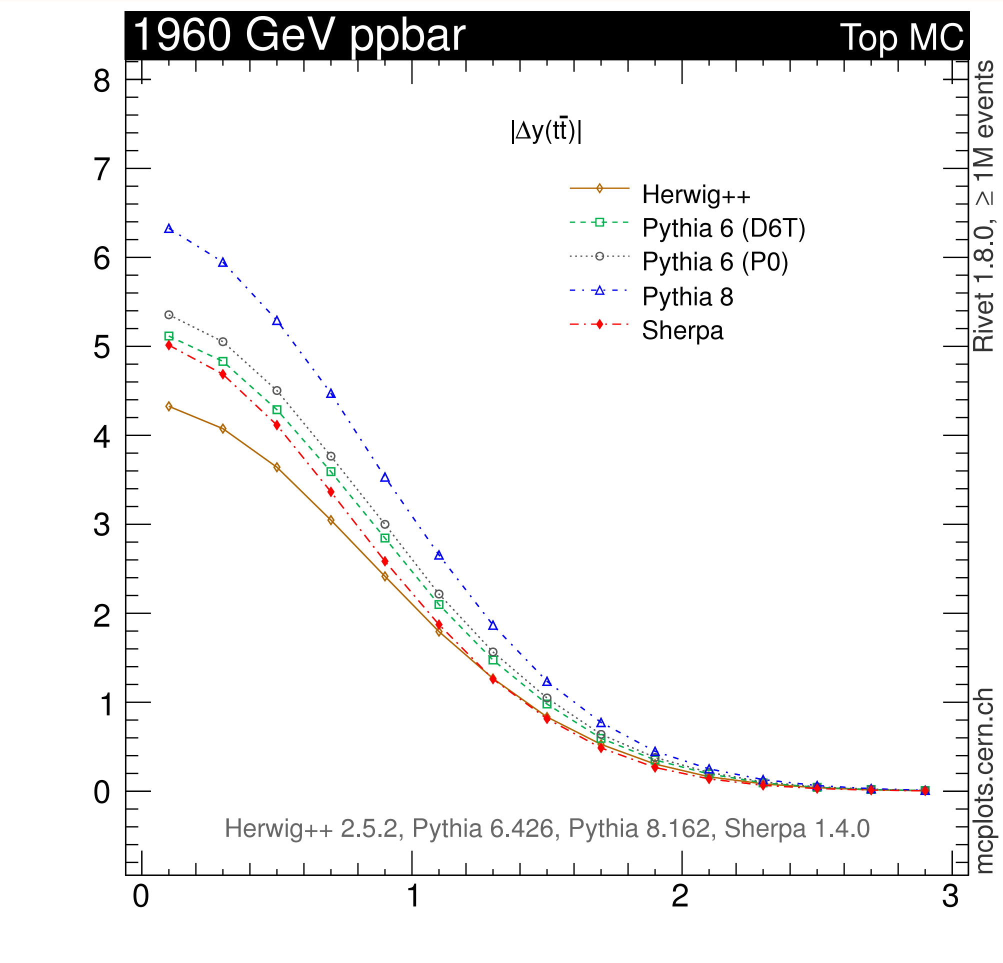
- differential cross section for $\Delta\phi$ between transverse momenta of tops

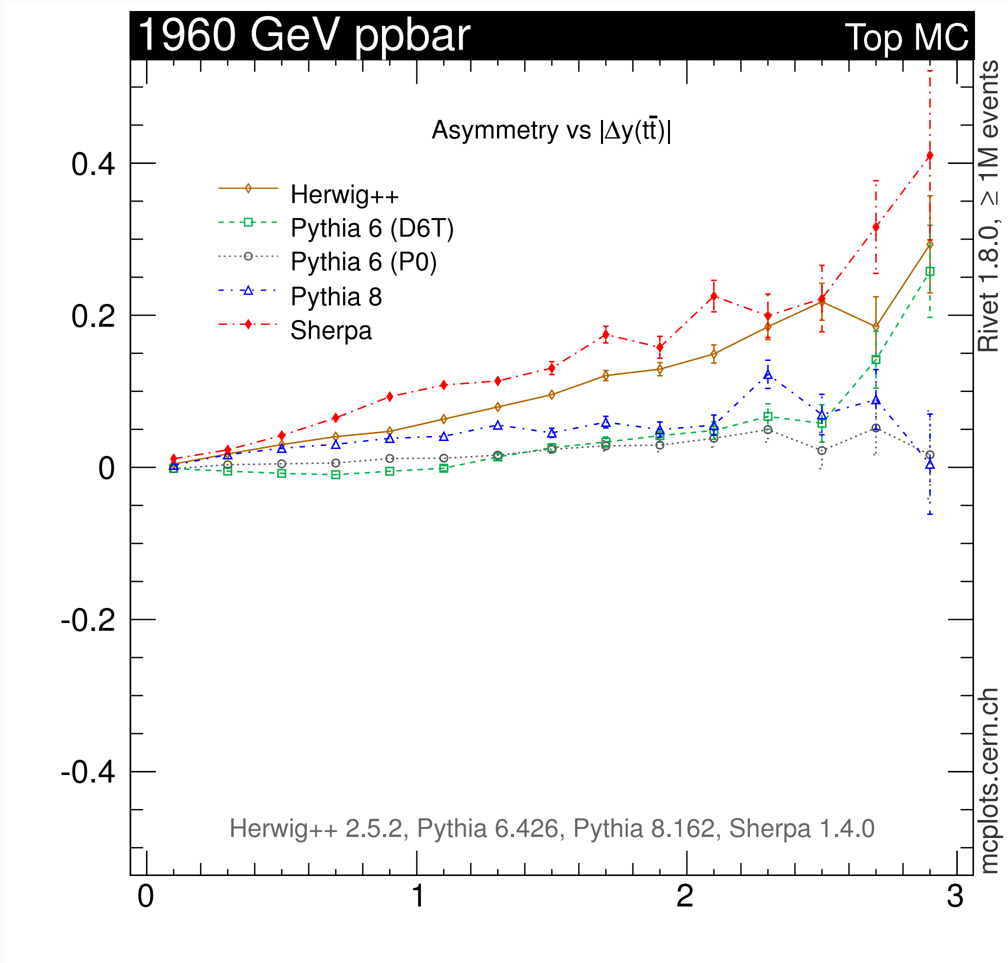
Differential asymmetry produced by LO generators

[Skands, Webber, Winter, arXiv:1205.1466]



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





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

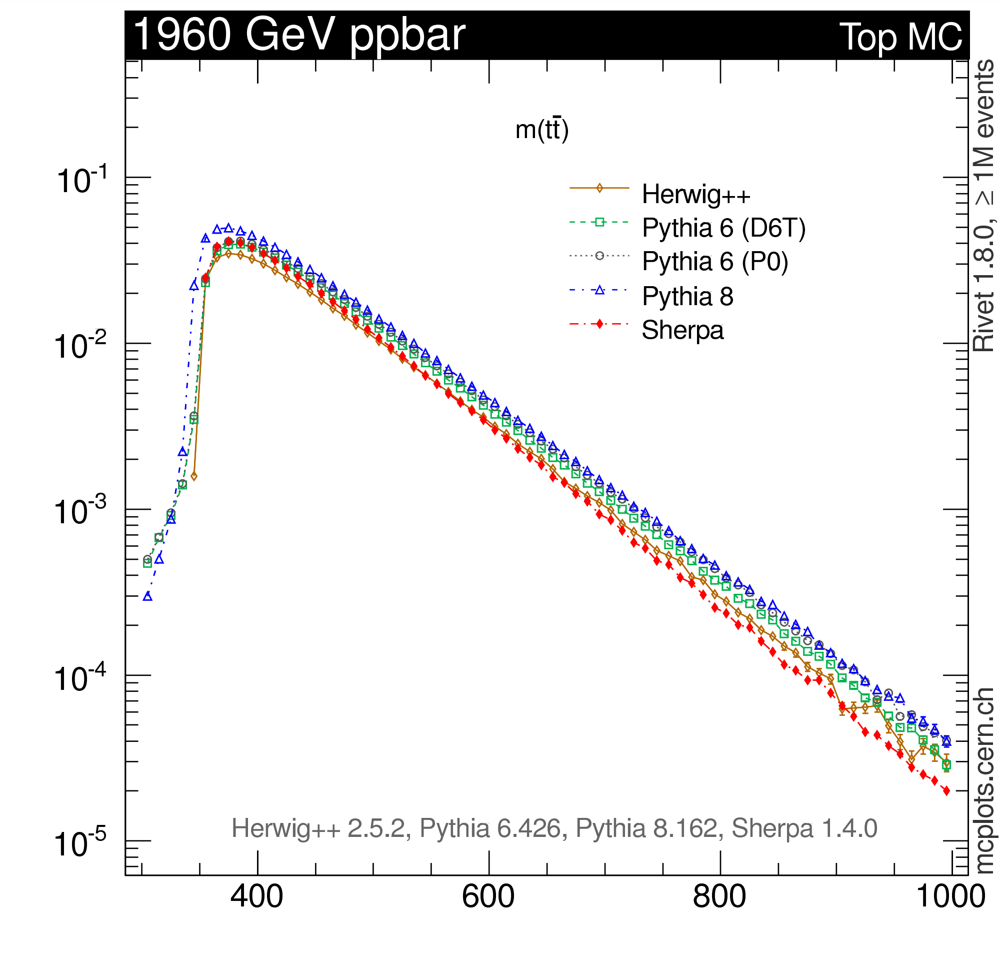
Differential asymmetry produced by LO generators

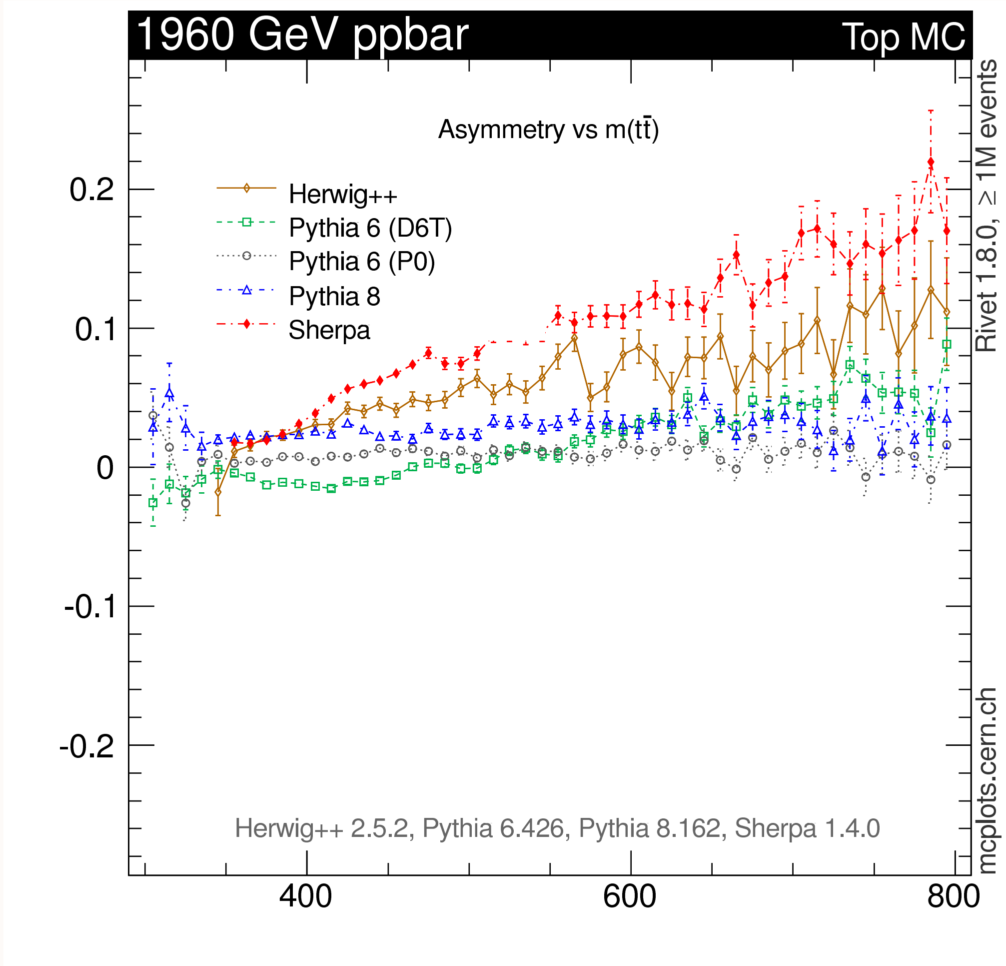
[Skands, Webber, Winter, arXiv:1205.1466]

➡ 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





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

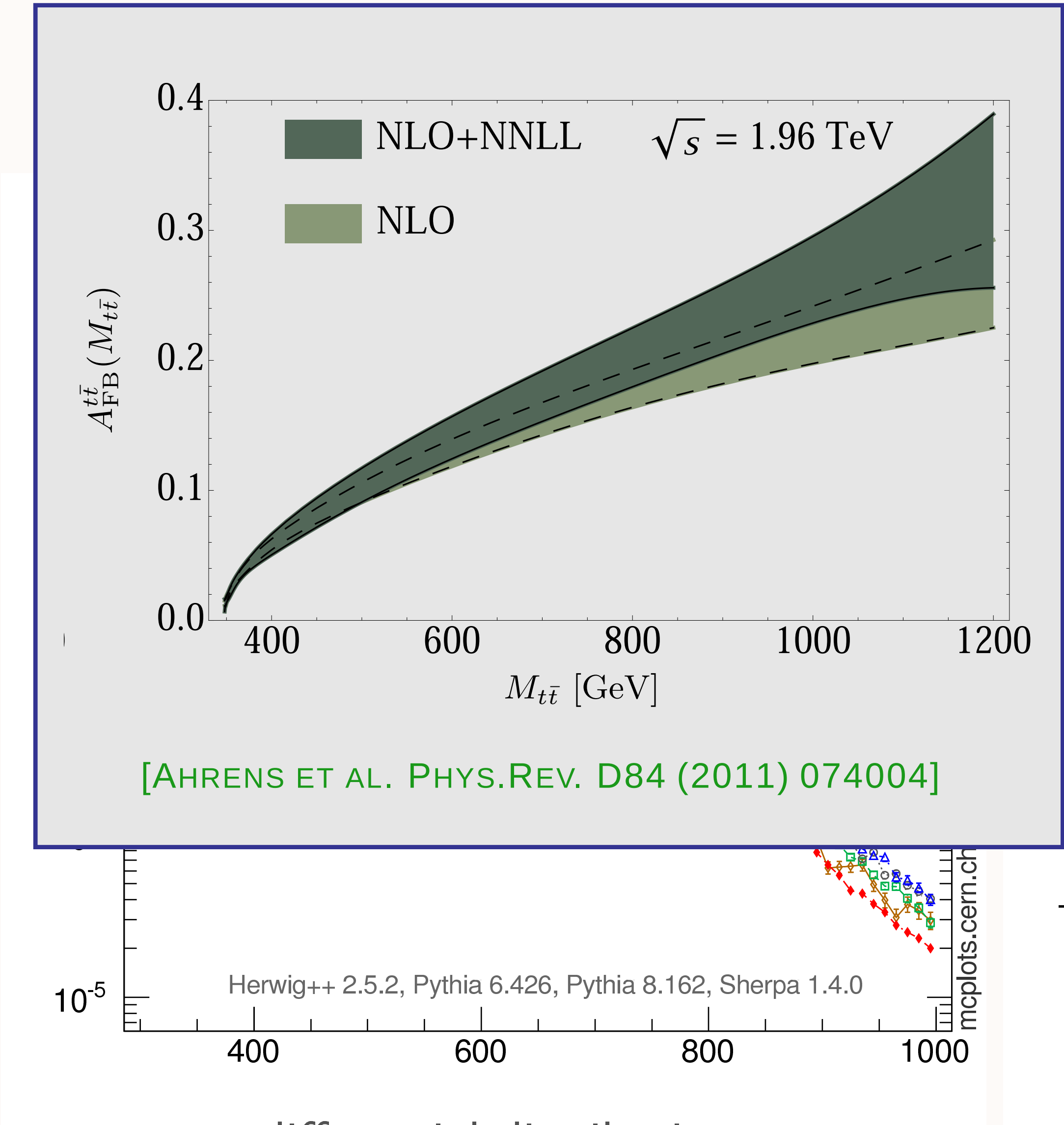
Differential asymmetry produced by LO generators

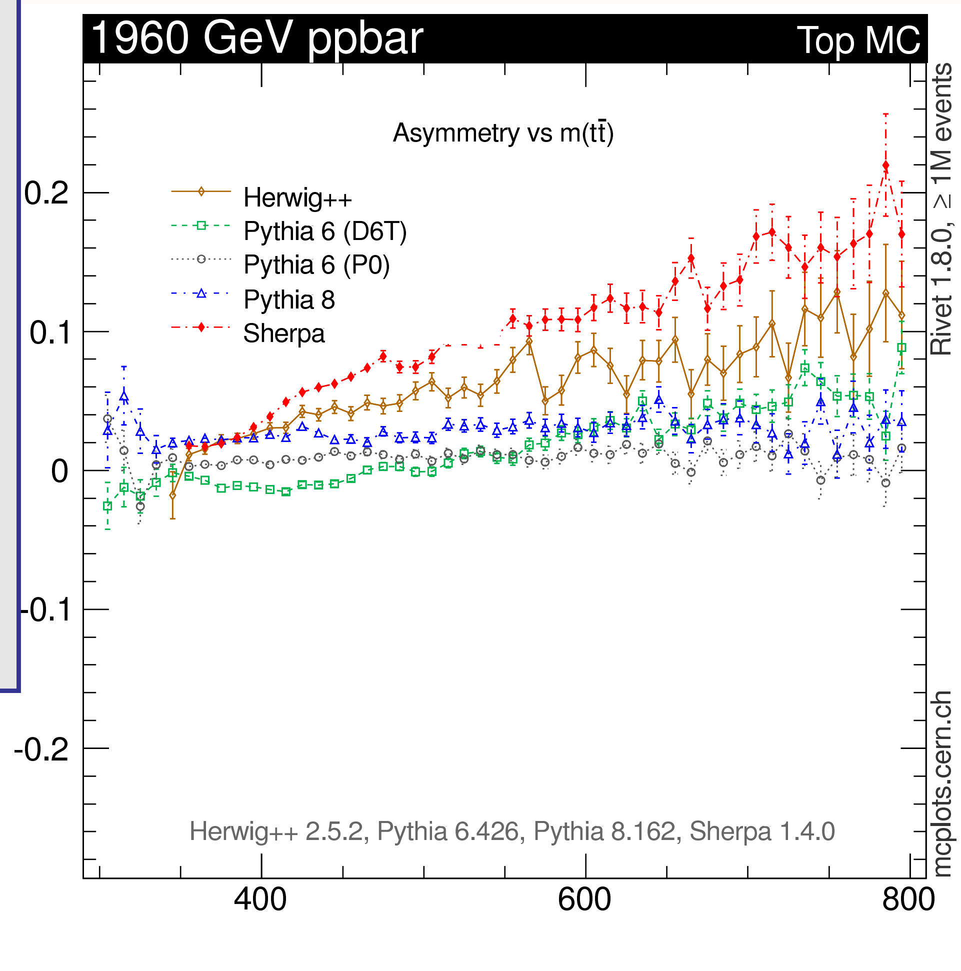
[Skands, Webber, Winter, arXiv:1205.1466]

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

$\cos\Delta\phi$

Asymmetry as a function of the pair mass





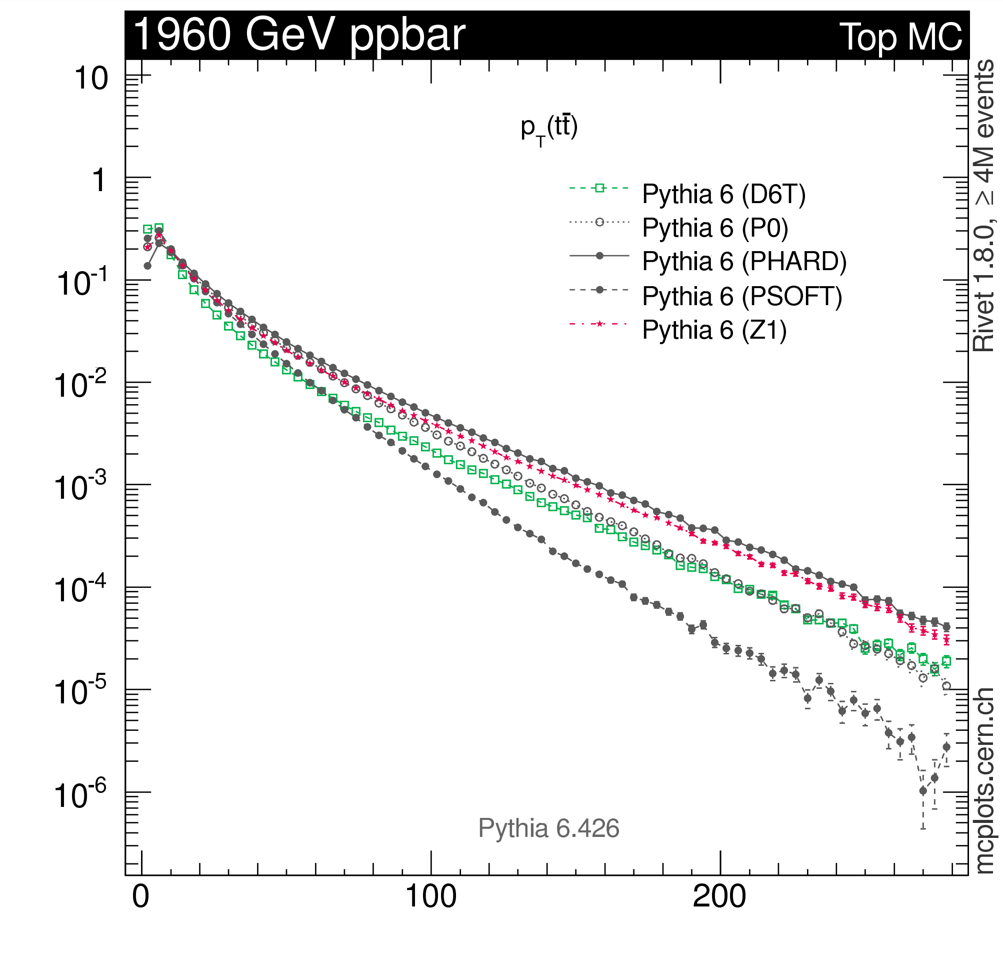
- $m_{t\bar{t}}$ differential distribution

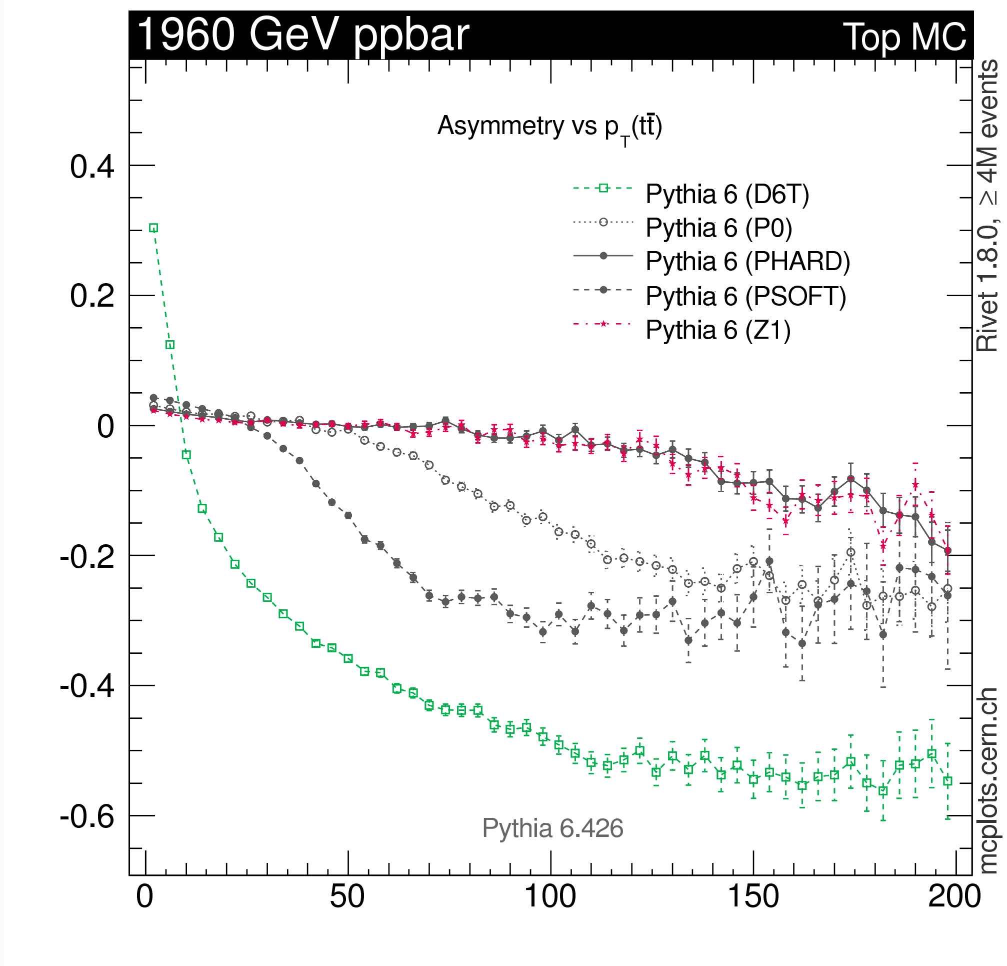
Different Pythia 6 shower models

[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

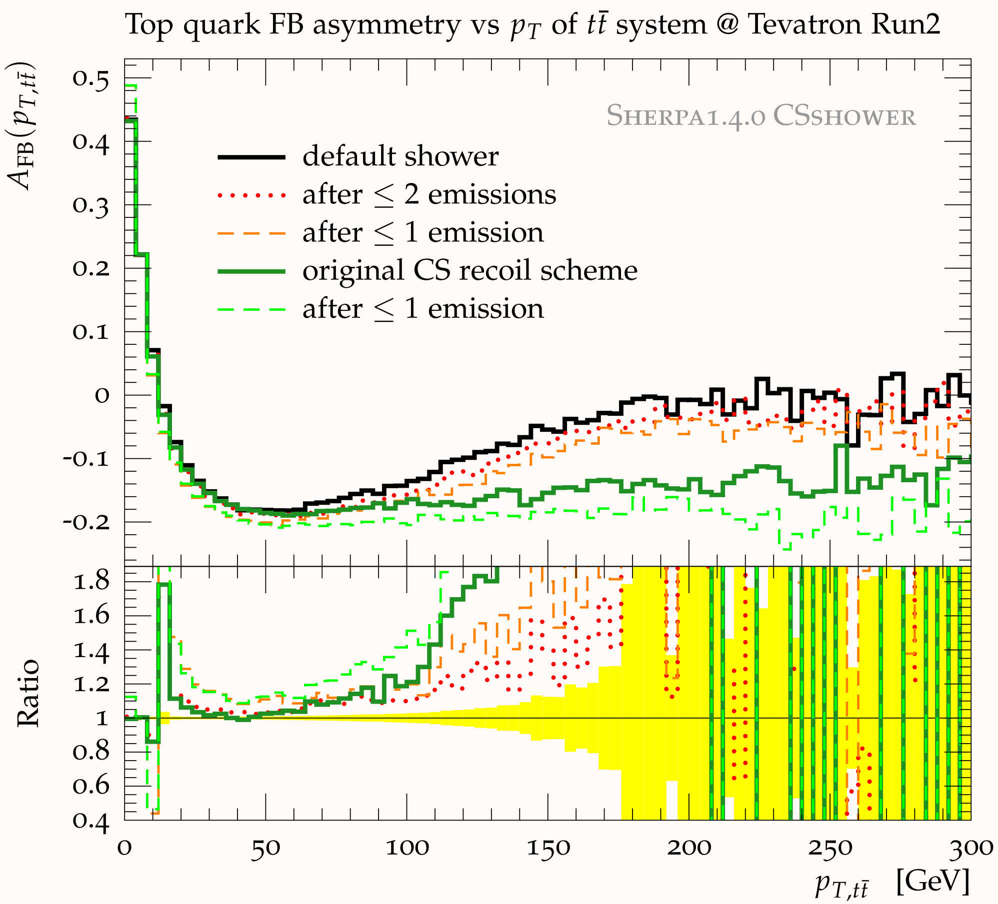
Different recoil-scheme options in Sherpa

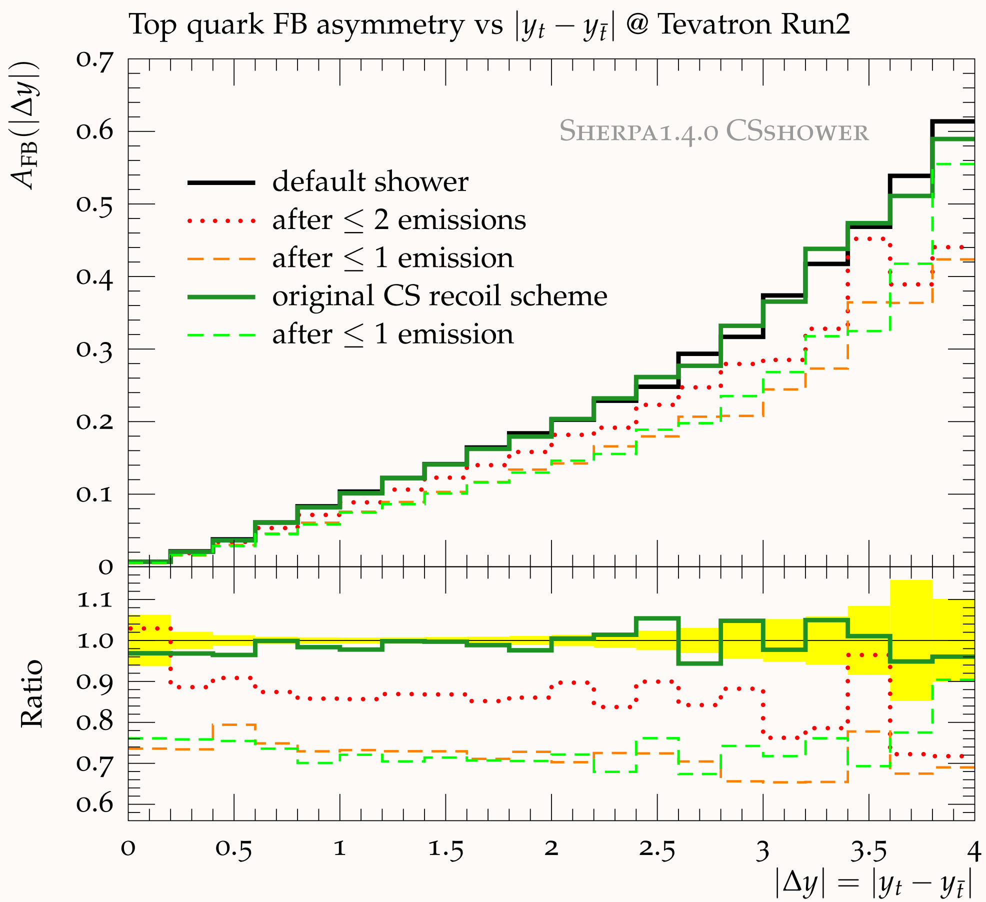
[SKANDS, WEBBER, WINTER, ARXIV:1205.1466]

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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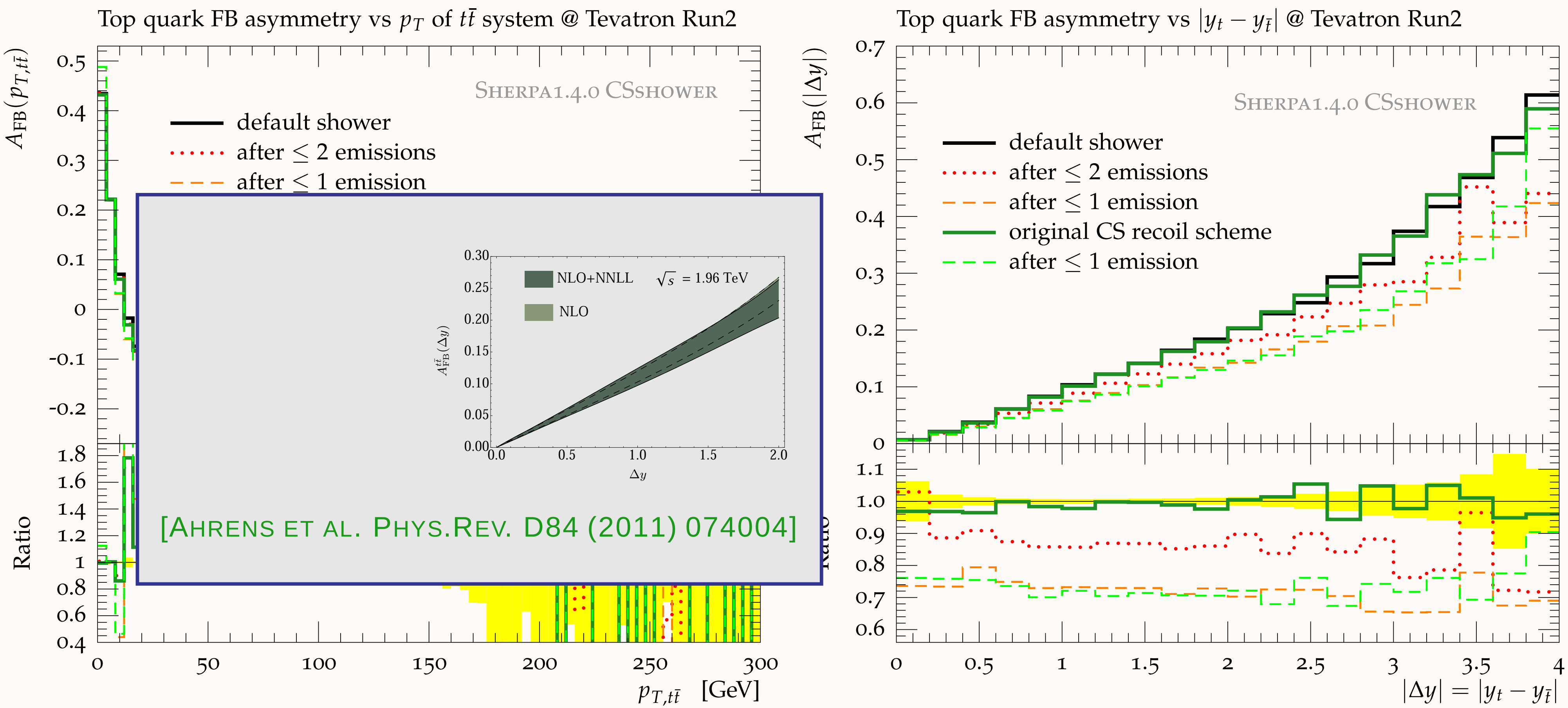
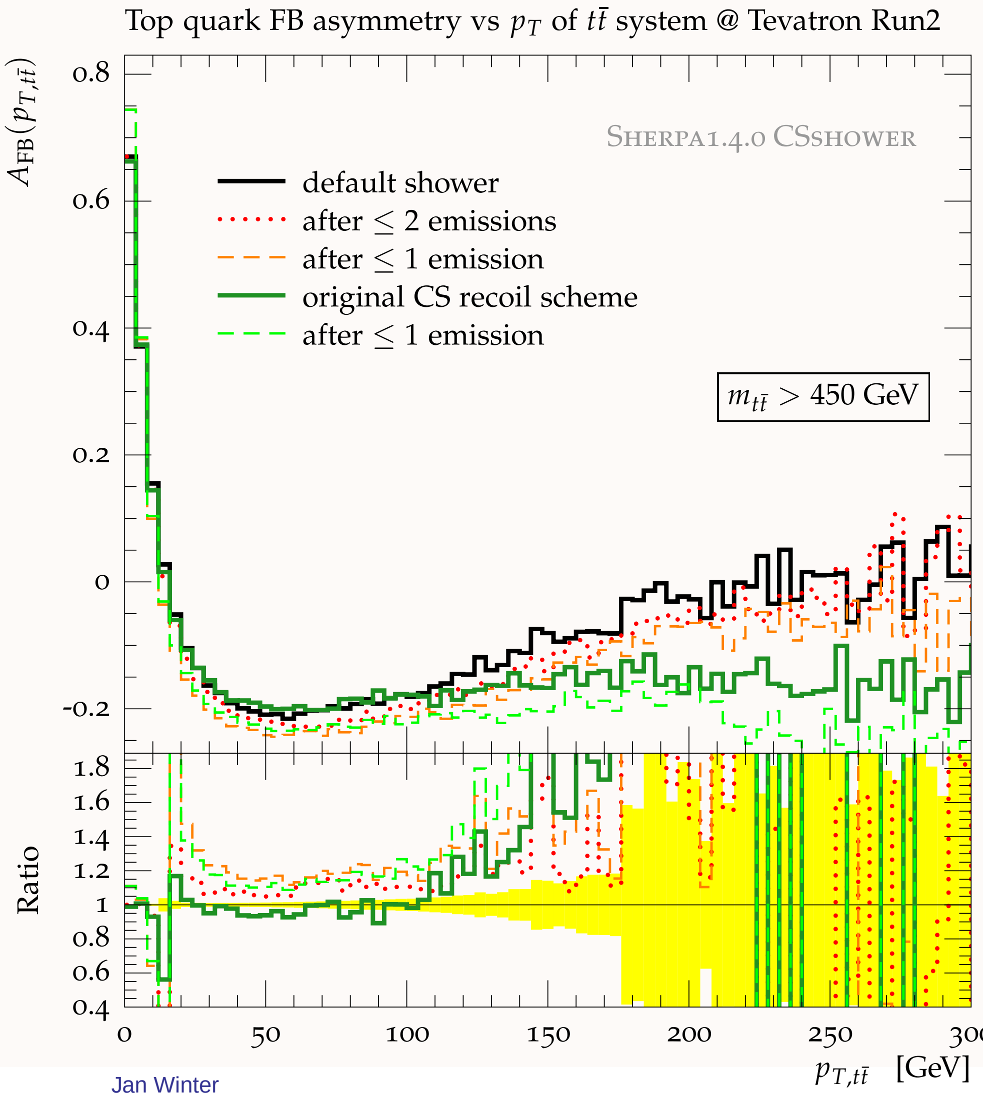


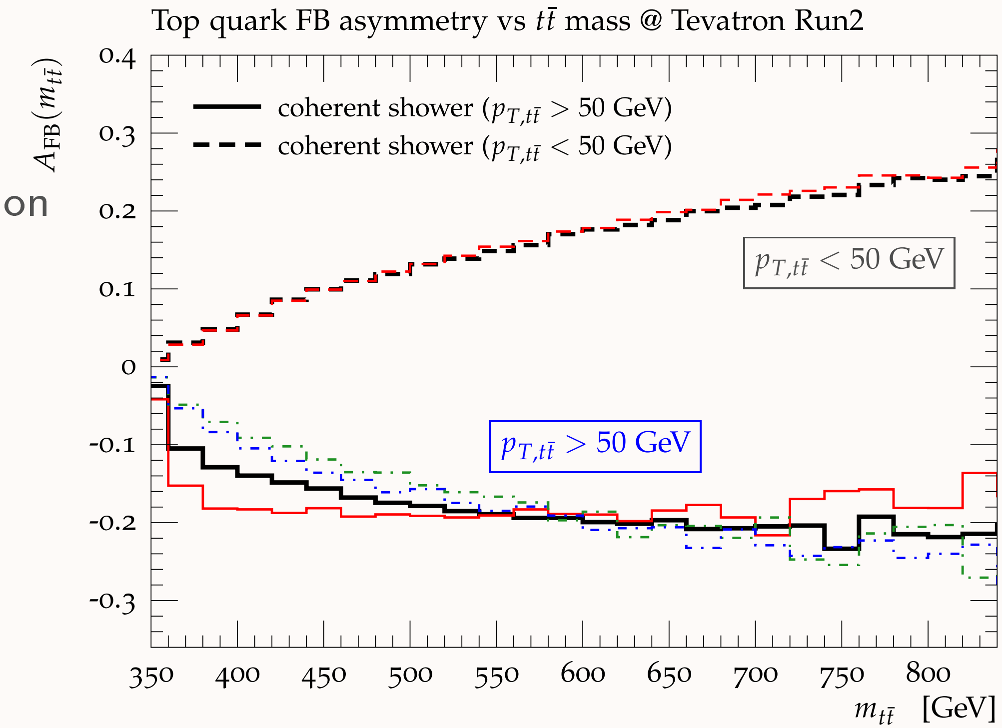
- Asymmetry versus $p_{T,t\bar{t}}$
- Asymmetry versus $|\Delta y|$

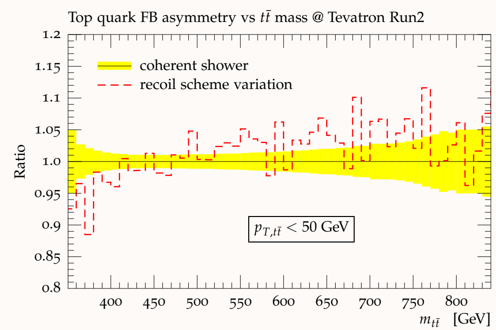
Cut on top-pair mass versus cut on top-pair pT

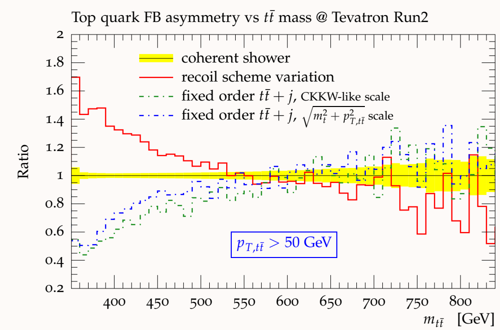
➡ ***Sign change – striking general prediction.***

- $m_{t\bar{t}}$ 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 $A_{\rm FB}$ to optimize recoils?)

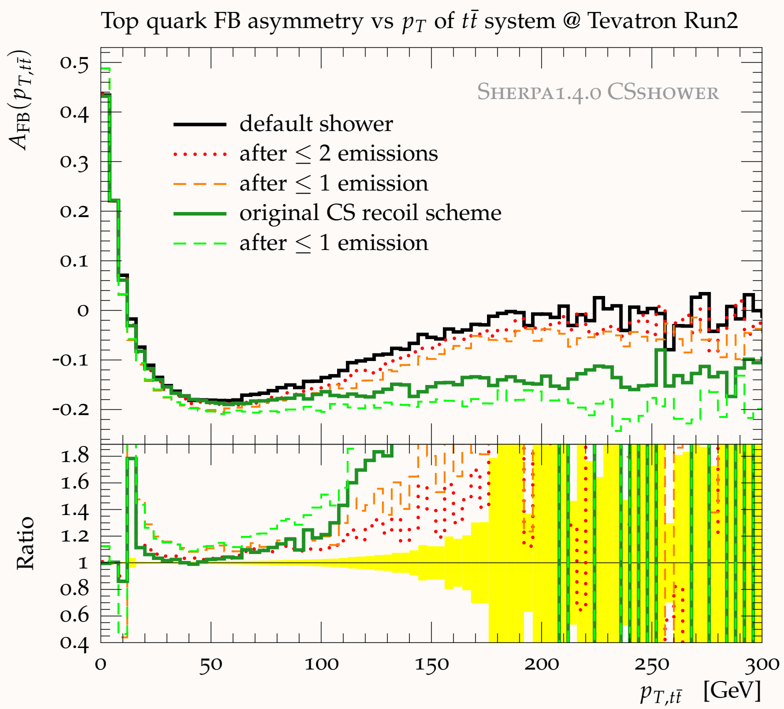
- Many directions are open for further studies.
    - effects in $t\bar{t}$ charge asymmetry @ LHC
    - assessment of NLO+PS tools wrt. asymmetry producing/enhancing shower effects
    - similarly for multi-parton ME+PS
    - comparison with higher-order parton-level calculations (production and decay)

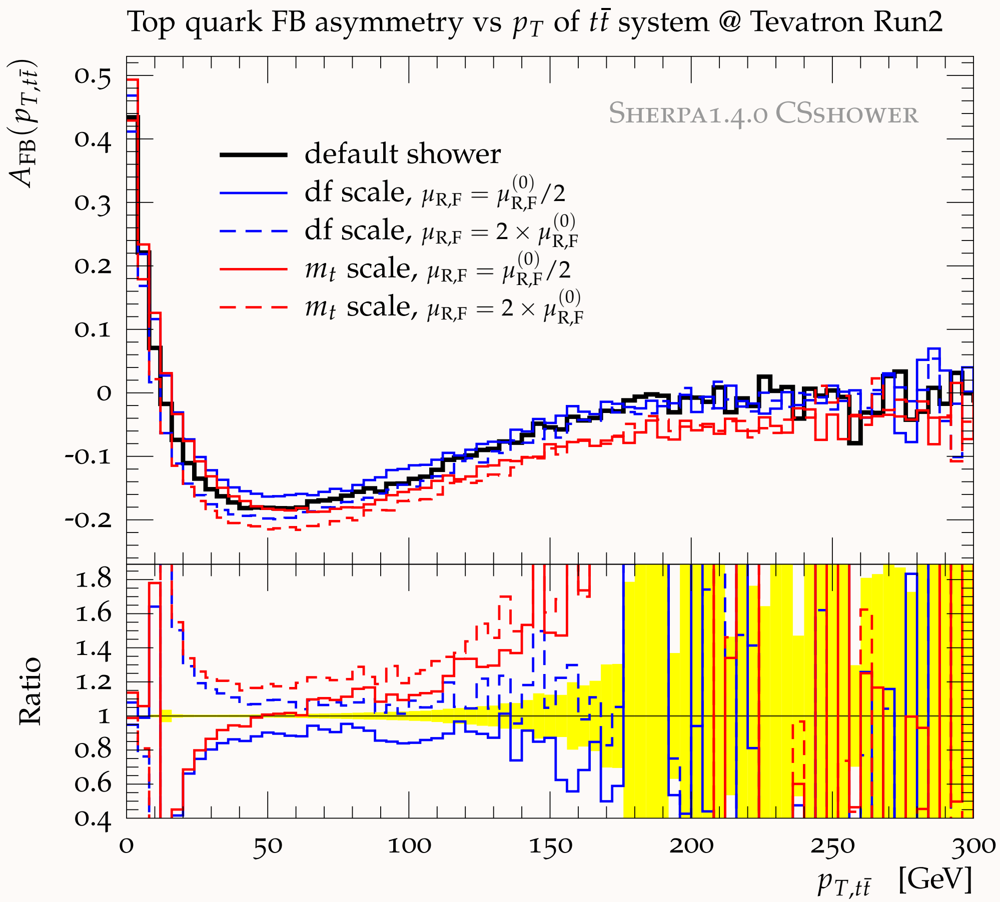
Additional material

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

Scale variations

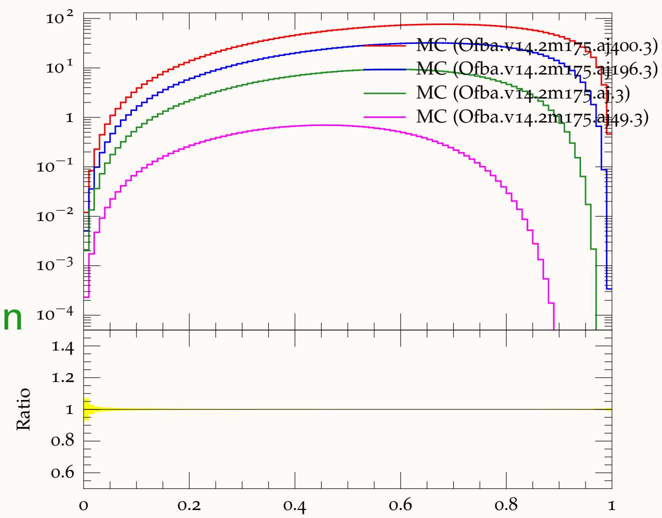
- $A_{\rm FB}(p_{T,t\bar{t}})$ – scale variation effects smaller than recoil effects
- possible x-test? $A_{\rm FB} = f(\alpha_s)$ with various but constant $\alpha_s \Rightarrow \mathcal{O}(\alpha_s)$ of recoil effects from fit

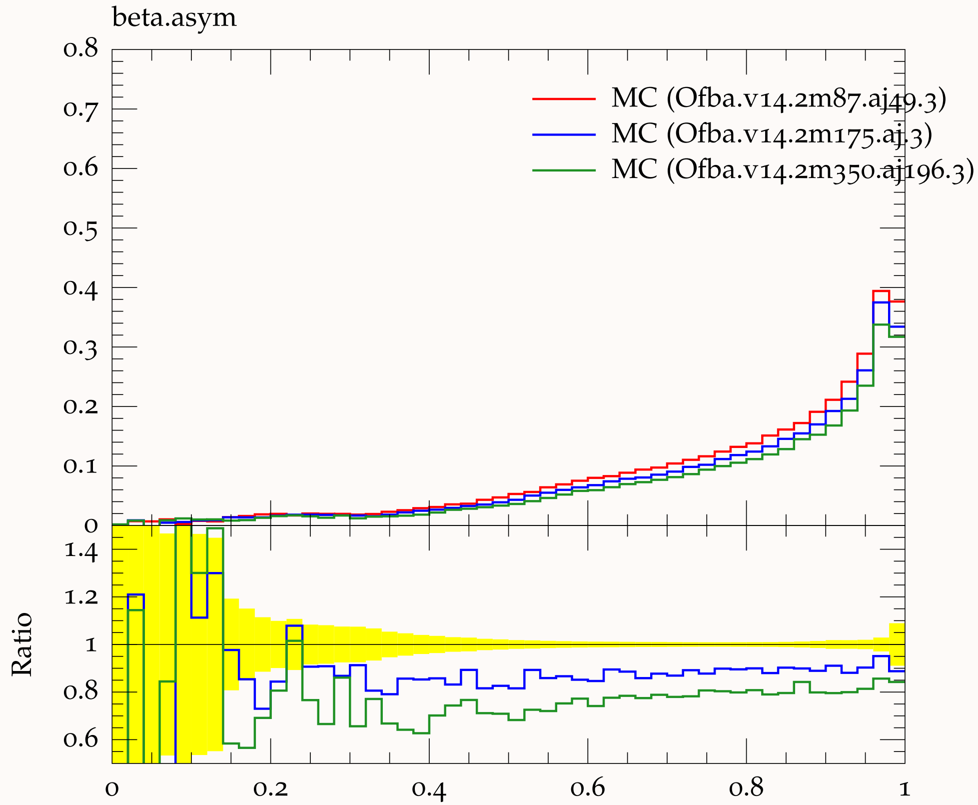


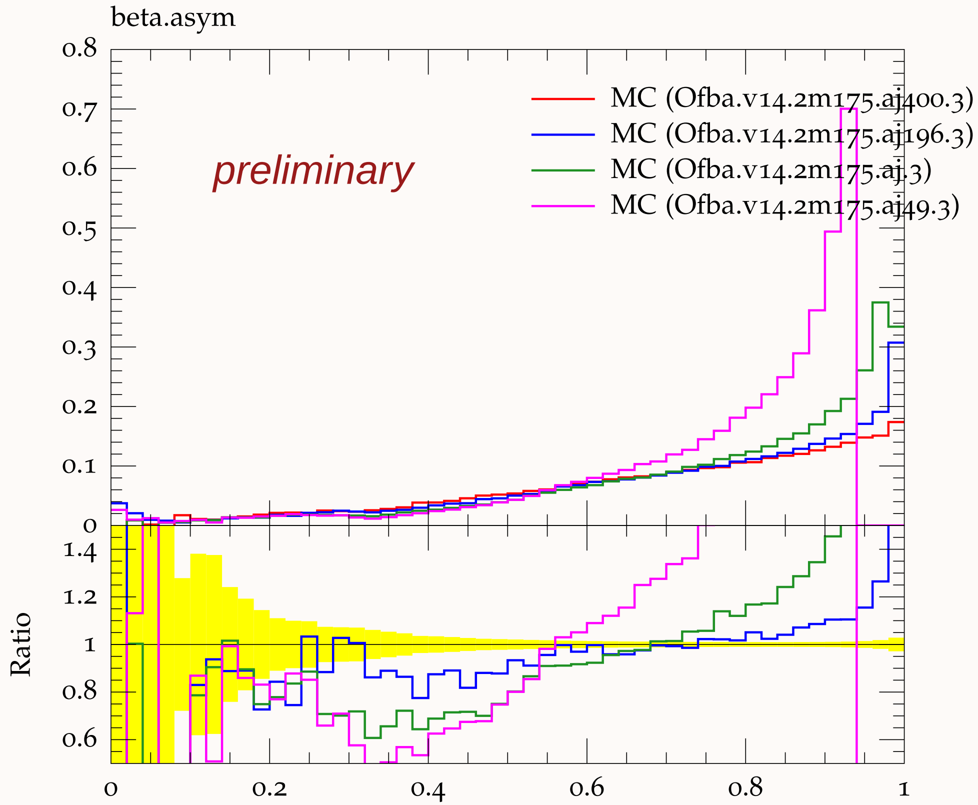


AFB vs. beta (I)

- $A_{\rm FB}(\beta)$ – only $q\bar{q} \to t\bar{t}$ @ $P\bar{P}$ machines – $\hat{s}$ from momentum sum of all FS partons (note Tevatron $\to$ 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

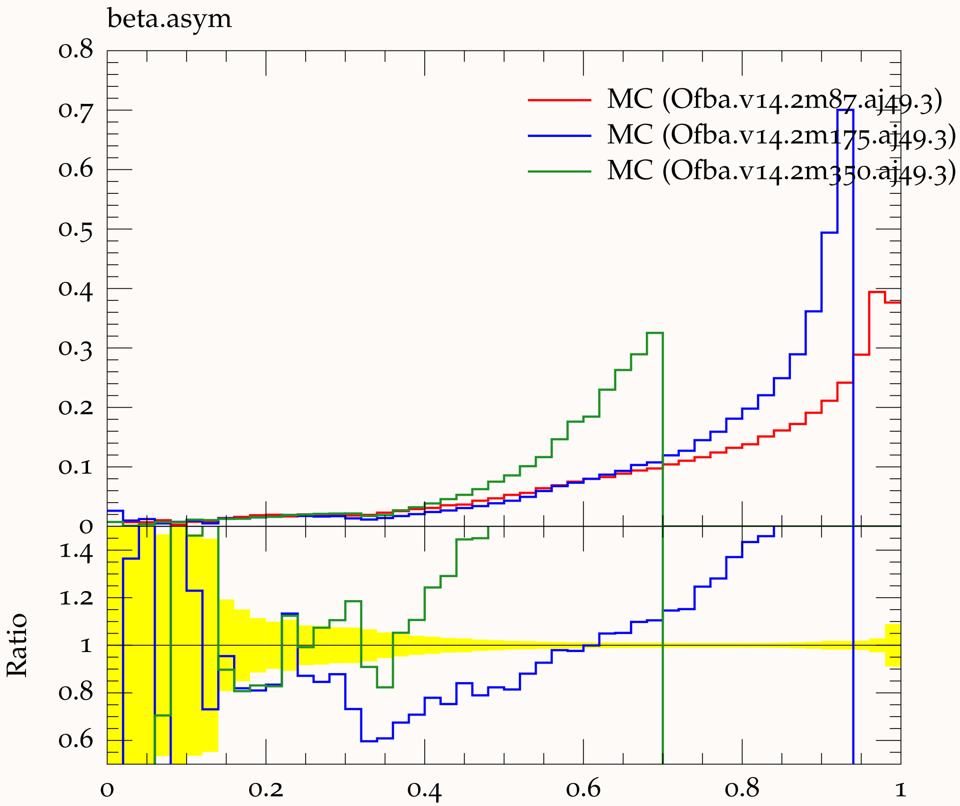


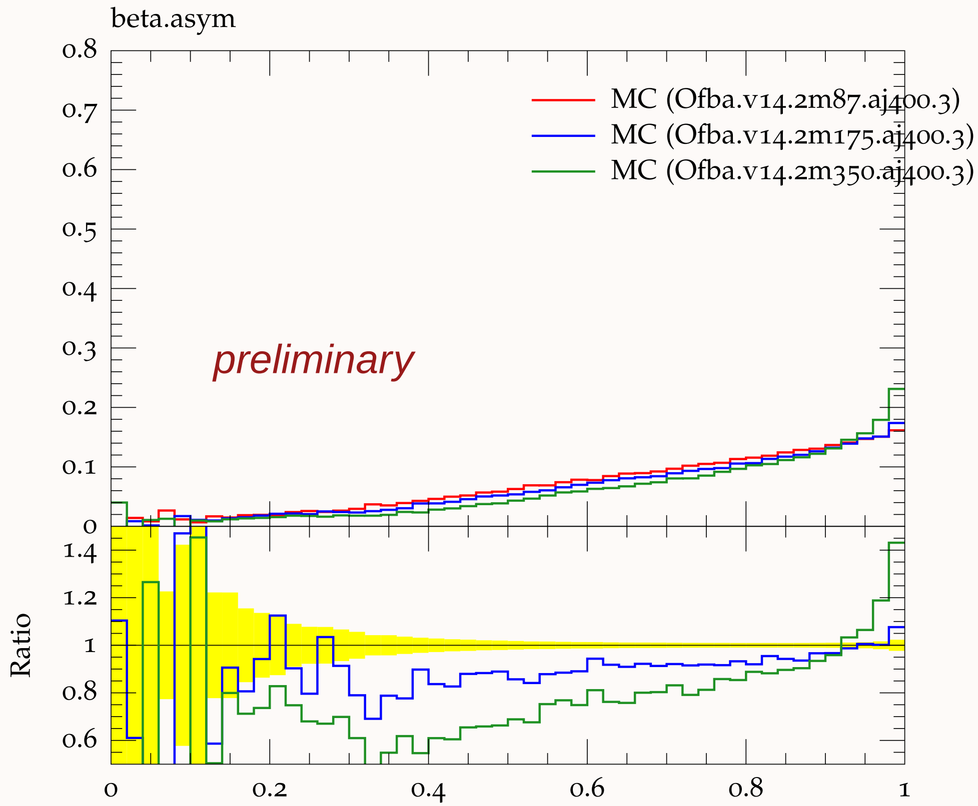




AFB vs. beta (II)

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





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