Top quark mass (parameter) from an LHC shape analysis

"Mtop determination using the Mlb method".

Jan Winter

jwinter@mpp.mpg.de

Max Planck Institute for Physics

Munich

Top quark mass (parameter) from an LHC shape analysis

[Workshop on Top physics at the LC – LPNHE Paris]

Jan Winter

– MPP Munich, Germany –

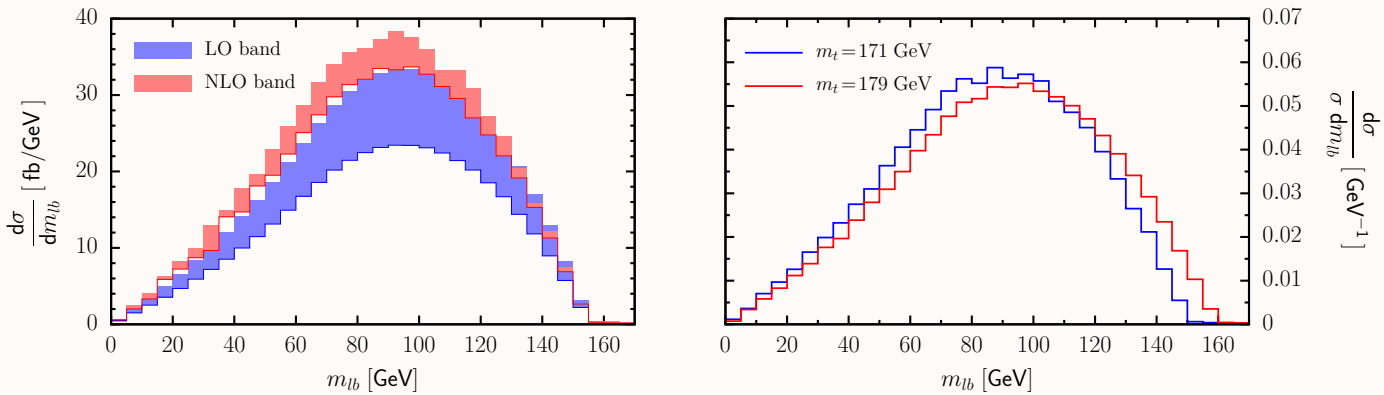
➡ ***Will briefly discuss:***

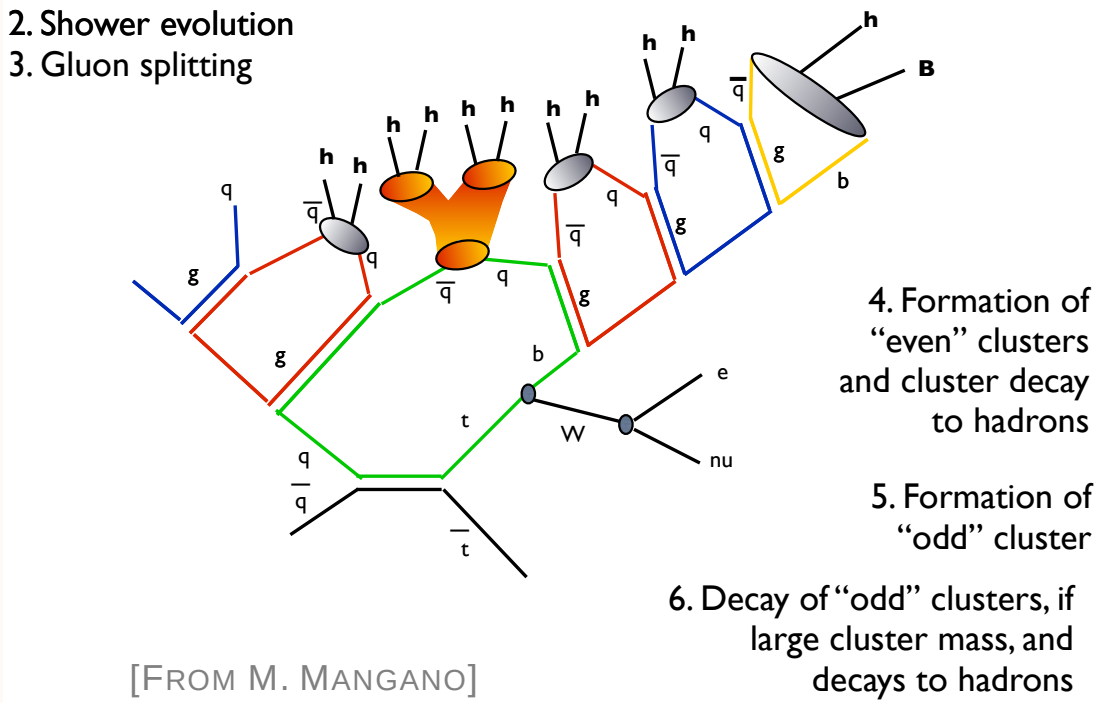
- ***Top quark mass determination and scale uncertainties.***
- ***Top quark asymmetries and higher orders.***
- ***Summary & Outlook.***

Intro note: top quark mass determination

[From Biswas, Melnikov, Schulze, arXiv:1006.0910]

- accurate and reliable measurement of top quark mass is important
- precisely measured in experiments but we have trouble to relate this mass parameter to a top quark mass we can control
- several proposals to extract it from kinematic distributions describable with pQCD (renormalization schemes can be switched)
- this still requires object identification, i.e. non-perturbative corrections have to be estimated
- preliminary studies by M. Mangano indeed point to $\mathcal{O}(1)$ GeV effects (there is also an earlier study by P. Skands and D. Wicke)



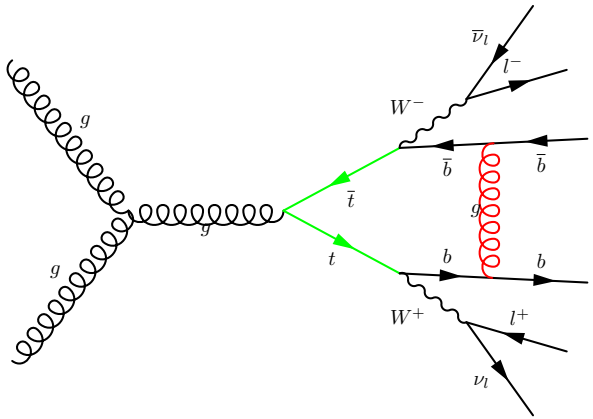


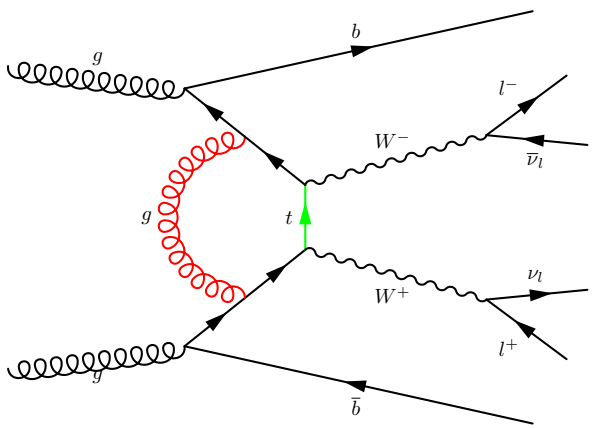
[From M. Mangano]

$WWb\bar{b}$ production at NLO

➡ ***Parton-level calculation done using GoSam+Sherpa NLO framework.***

[From J. Schlenk]





- Top quark pair production and decay including nonresonant contributions
- Both W bosons decay into leptons
- The approximation $m_b = 0$ is made
- First calculated at NLO by Denner, Dittmaier, Kallweit, Pozzorini (2011) and Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek (2011)
- Previous top quark calculations were done under the assumption that production and decay factorise (neglects contributions suppressed by powers of $\frac{\Gamma_t}{m_t} \sim 0.02$) Biswas, Melnikov, Schulze (2010)
- NNLO corrections to production of stable top quarks were calculated recently Czakon, Fiedler, Mitov (2013)

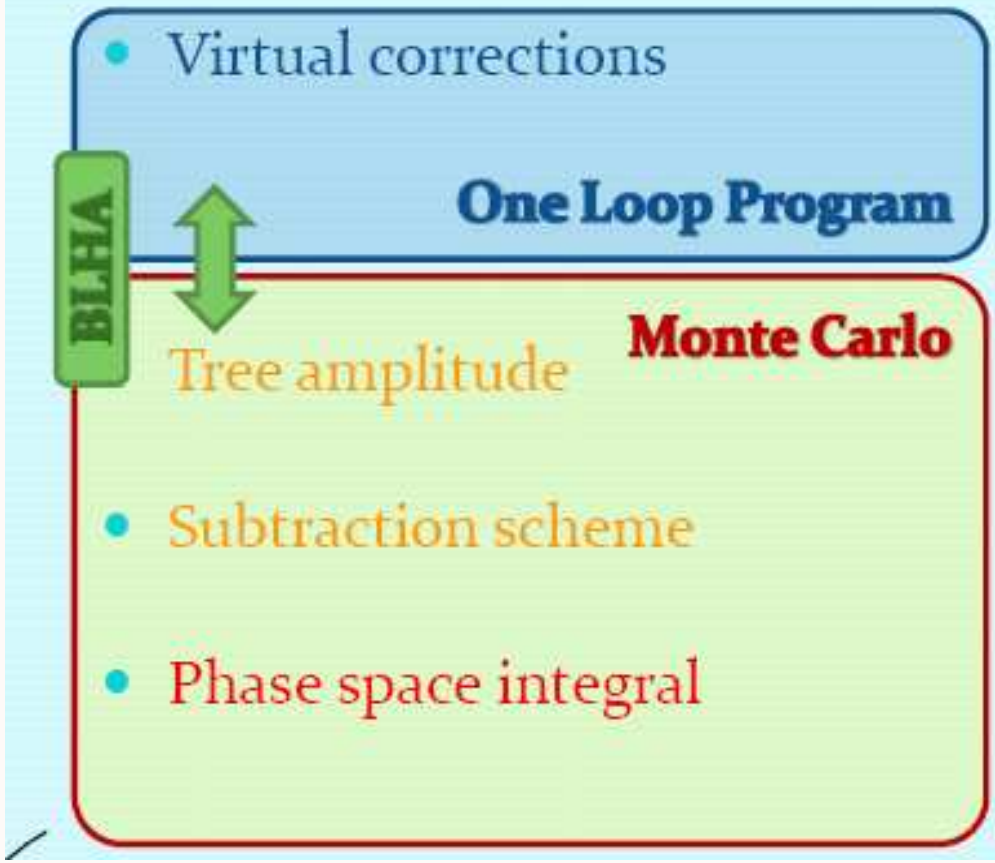
[New work including bottom quark mass, Frederix (2013), Pozzorini et al. (2013)]

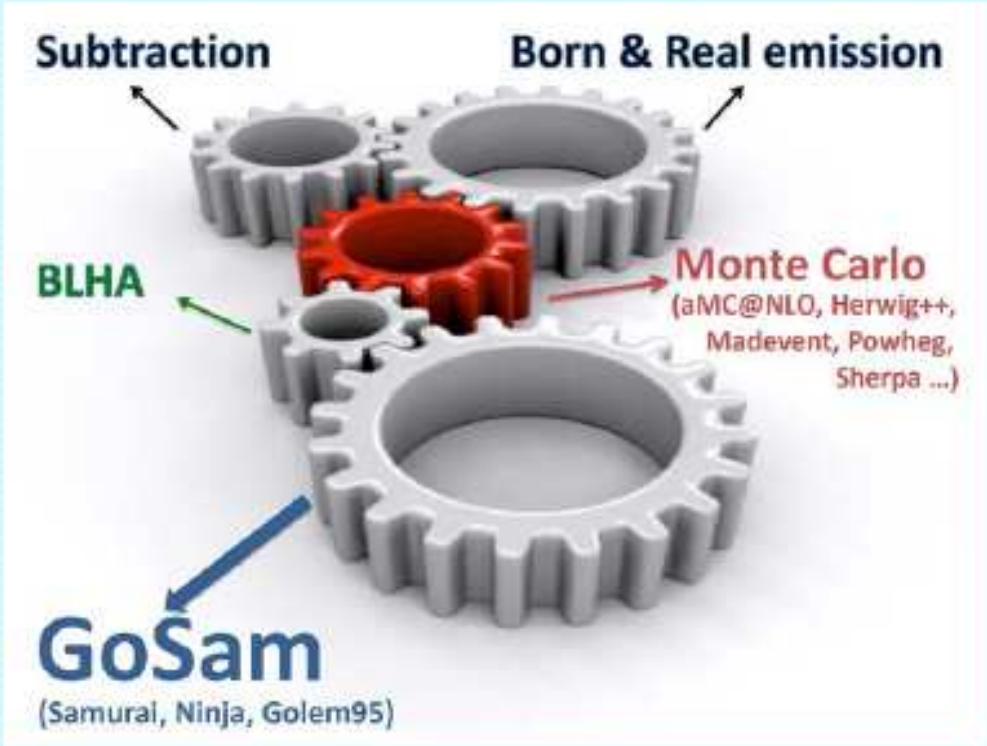
GoSam+Sherpa combined MC package

[From G. Luisoni]

➡ ***Ingredients for the NLO calculation.***

$$\sigma_{\mathrm{NLO}} = \int_{\mathrm{d}\Phi_m} \mathrm{d}\sigma_{\mathrm{Born}} + \int_{\mathrm{d}\Phi_{m+1}} \left(\mathrm{d}\sigma^{\mathrm{R}}_{\mathrm{NLO}} - \mathrm{d}\sigma^{\mathrm{S}}_{\mathrm{NLO}}\right) + \int_{\mathrm{d}\Phi_m} \left[\int_{\mathrm{d}\Phi_1} \mathrm{d}\sigma^{\mathrm{S}}_{\mathrm{NLO}} + \mathrm{d}\sigma^{V}_{\mathrm{NLO}}\right]$$





Quick note on the inclusive cross section

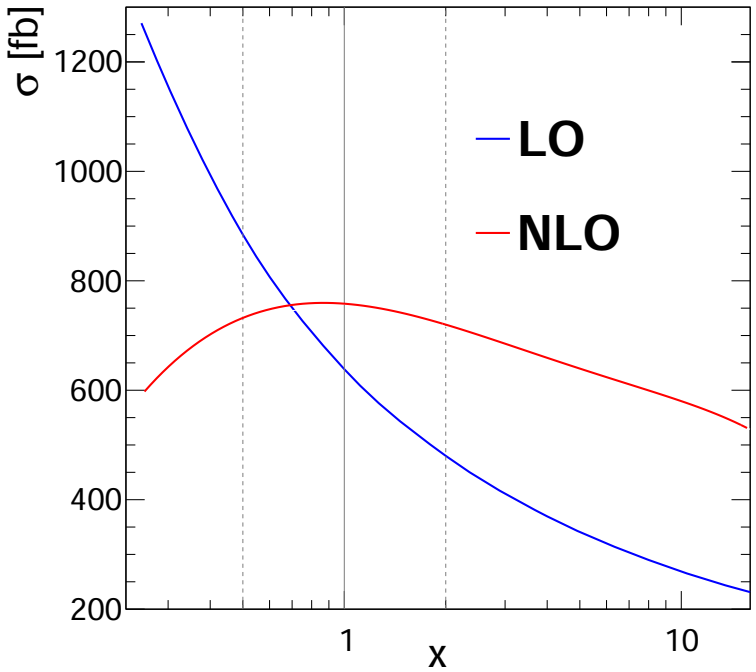
➡ ***Parton-level NLO calculation based on GoSam+Sherpa framework.***

[From J. Schlenk]

Renormalization scale:

$$\mu = \frac{\hat{H}_T}{2} = \frac{1}{2}\sum_i p_{T,i}$$

Scalar sum over transverse momenta of all final state particles

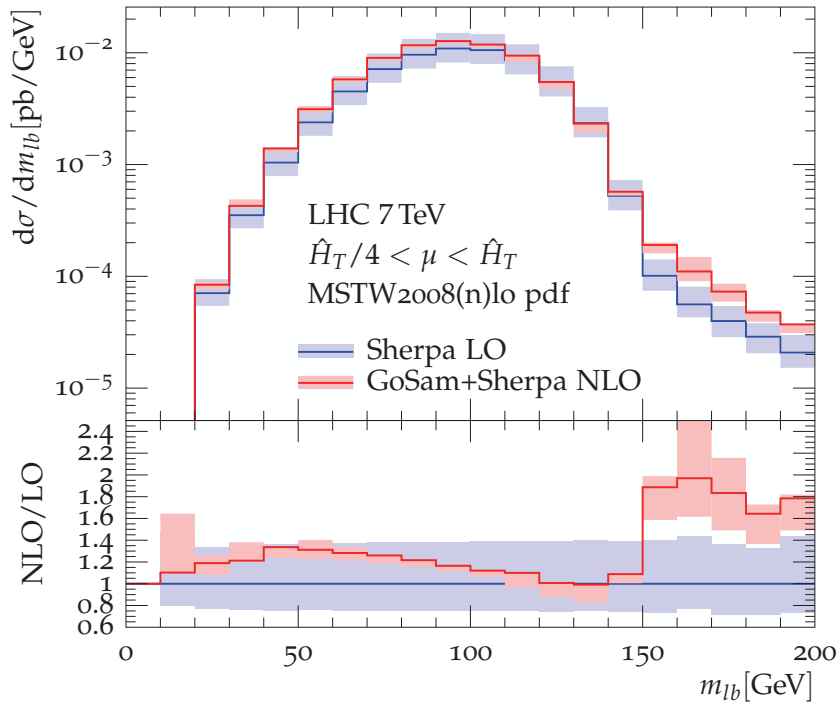


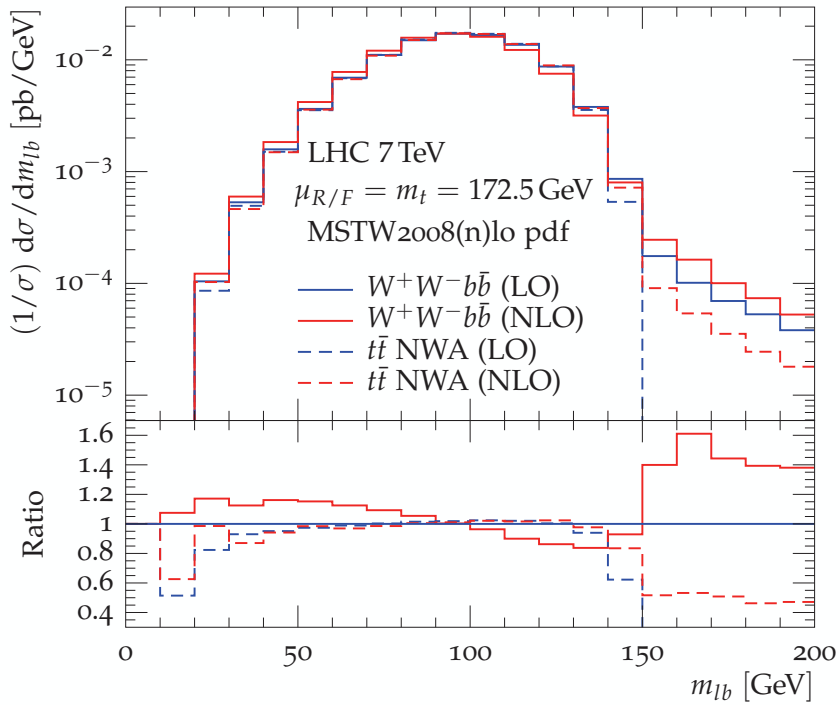
$$x = \frac{\mu}{\hat{H}_T/2}$$

The mlb distribution at NLO

➡ ***Parton-level NLO calculation based on GoSam+Sherpa framework.***

[FROM J. SCHLENK]





- Important NLO corrections to the shape of m_{lb}
- Values of m_{lb} larger than $\sqrt{m_t^2 - m_W^2}$ are kinematically forbidden in narrow width approximation at LO

• follow ATLAS strategy: use charged-lepton b-jet pairing minimizing sum of both m_{lb} and average.

Maximum Likelihood (ML) technique

[From A.A. Maier]

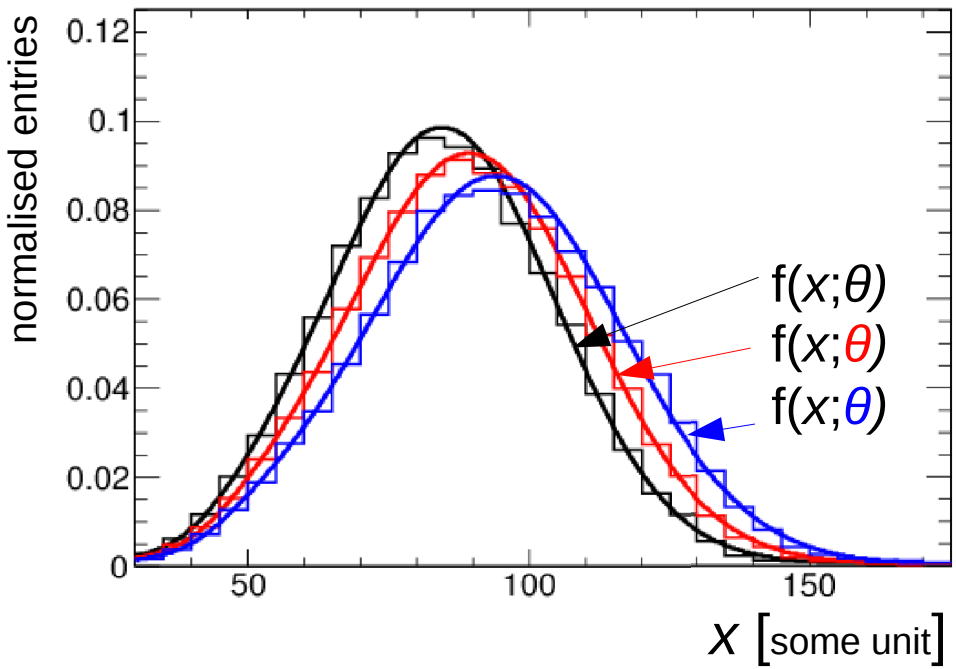
- Consider a random variable *x*, called estimator, following some sufficiently known pdf f(*x*;*θ*) with one parameter *θ*, that is to be determined.

- The ML method finds that parameter by maximising the following function for all *n* data values:

$$L(\theta) = \prod_{i=1}^{n} f(x_i;\theta)$$

- Here are some example fits of the pdf (solid lines) to three MC distributions (histograms) for different parameters *θ*

- Works also for parameter vectors $\vec{\theta}$ in multiple dimensions



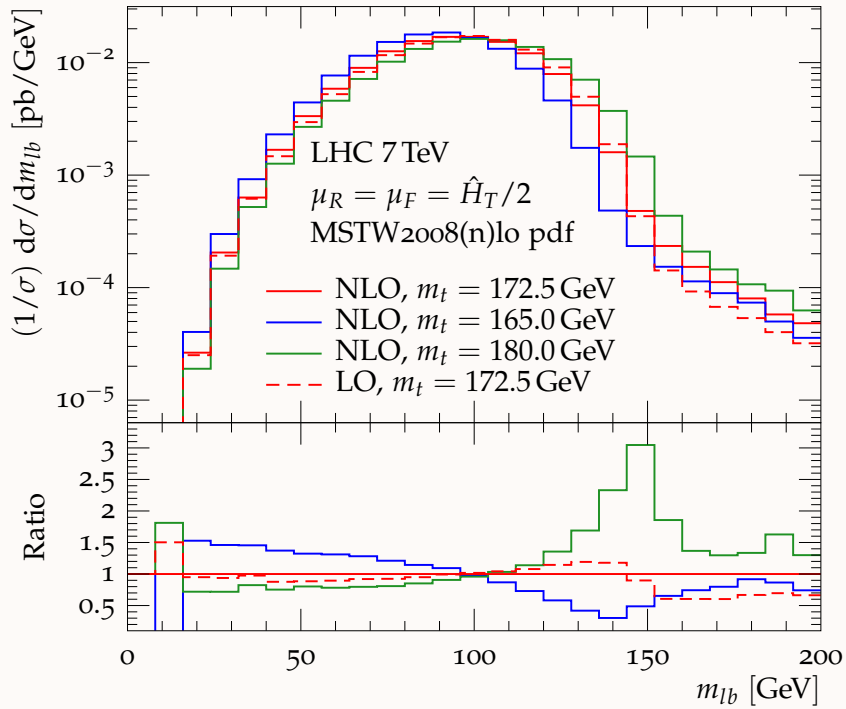
- for the dilepton channel, use one-dimensional template method, with $\theta \rightarrow m_t$ and x fit params to m_{lb}.

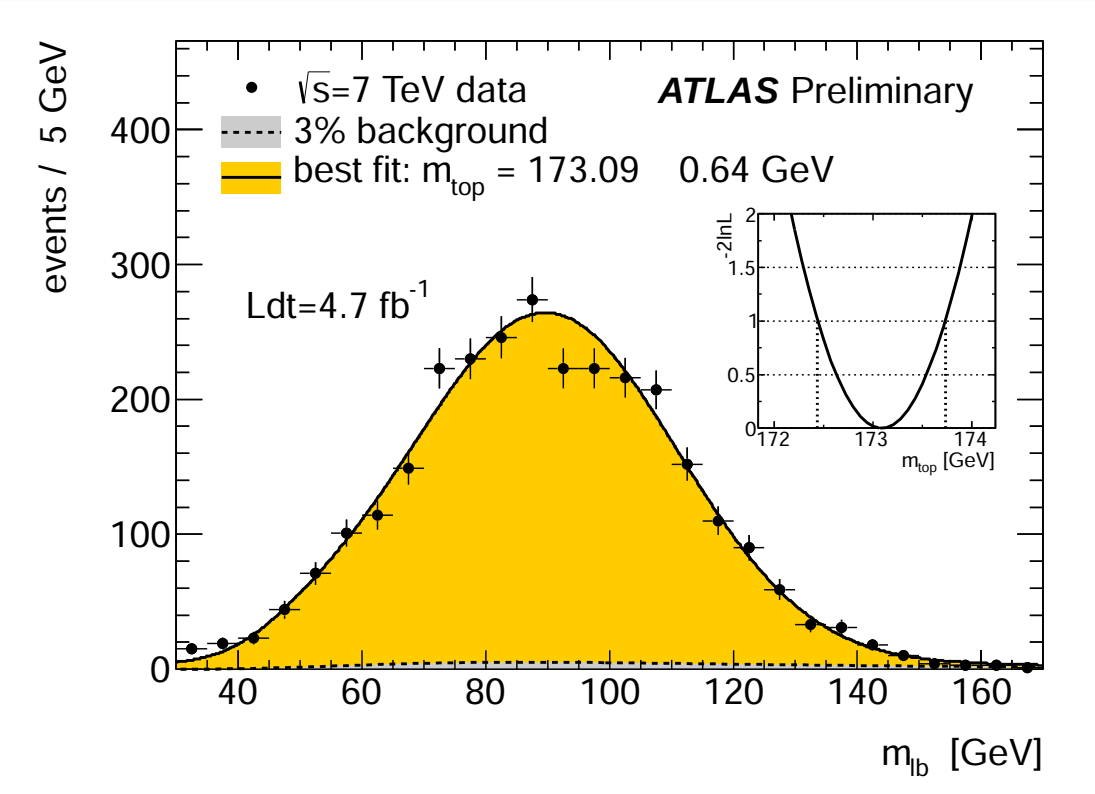
Top quark mass determination using the mlb method

Parametrize "your" theory (mlb predictions).

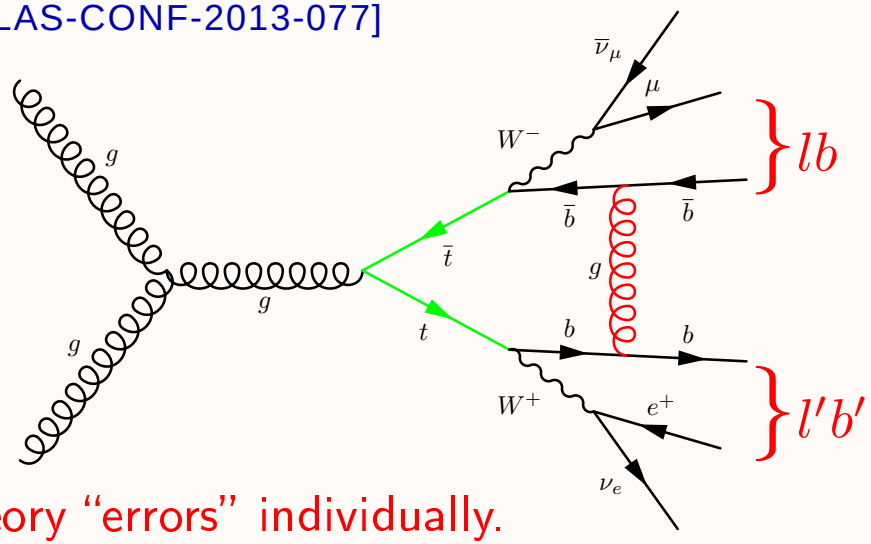
- Full QCD NLO prediction for $W^+W^-b\bar{b}$ in dilepton channel: m_{lb} distribution is sensitive to top quark mass.
- ATLAS uses one-dim. template method to determine m_t. Theory uncertainty has been estimated to 0.8 GeV.

→ Verify size of th. uncertainties using more advanced calc's!





[ATLAS-CONF-2013-077]



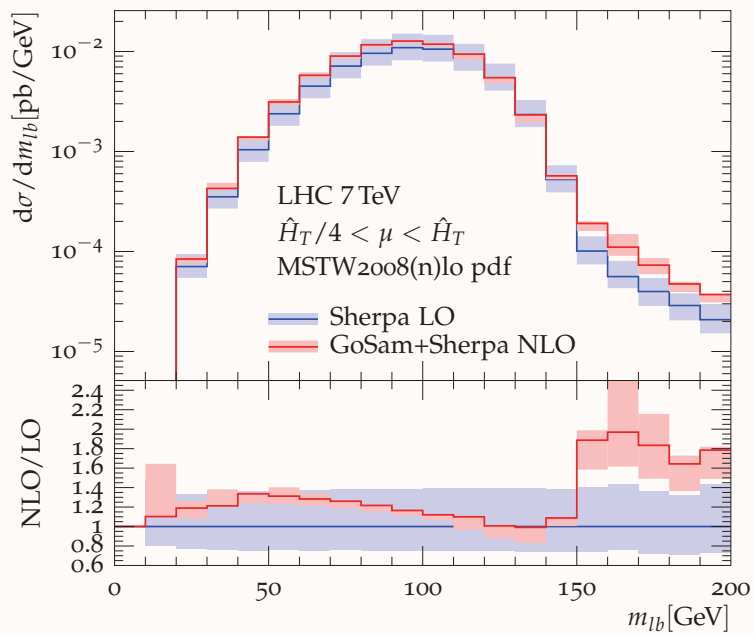
➡ Use pseudo-data to study different types of theory "errors" individually.

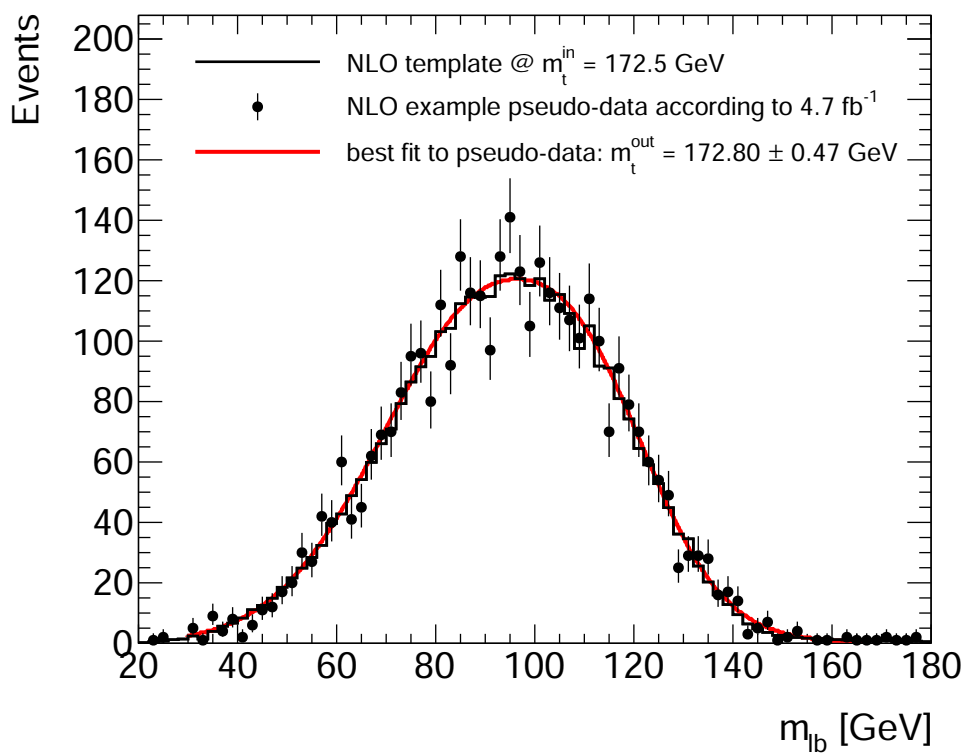
Scale uncertainties and the mlb method

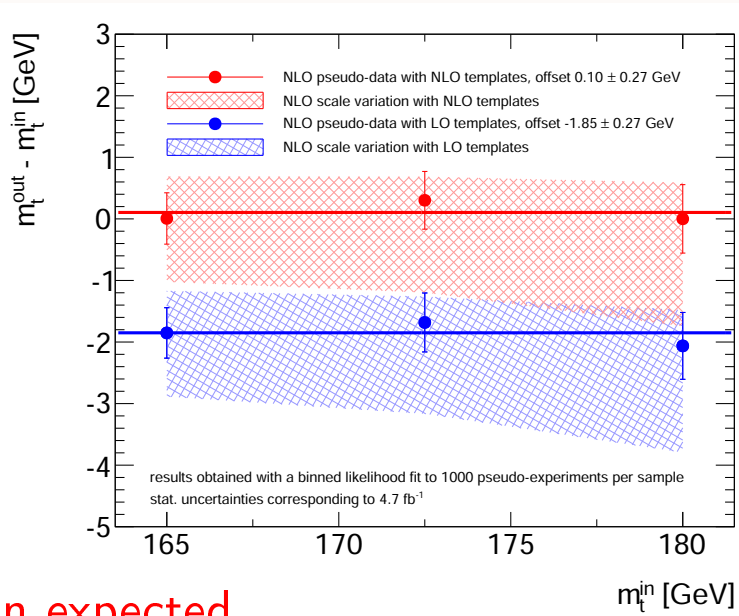
[Heinrich, Maier, Nisius, Schlenk, Winter, arXiv:1312.6659]

Single out effect of NLO scale uncertainties on top mass.

- Use mlb method in a parton-level analysis where we assume that data follows full QCD NLO prediction for dileptonic $W^+W^-b\bar{b}$ [pseudo-data].
- Apply/test against the theories given by default scale choice NLO and LO predictions (templates) [hypotheses].



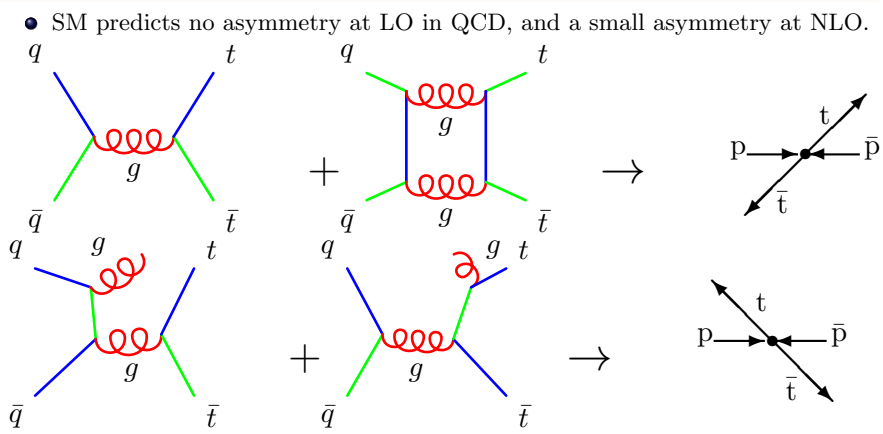




➡ Impacts top quark mass determination more than expected.

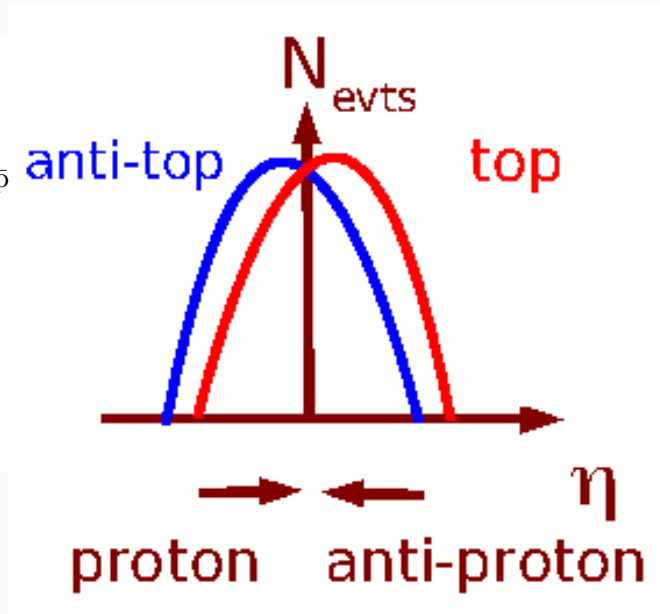
Few notes on top quark forward–backward asymmetry.

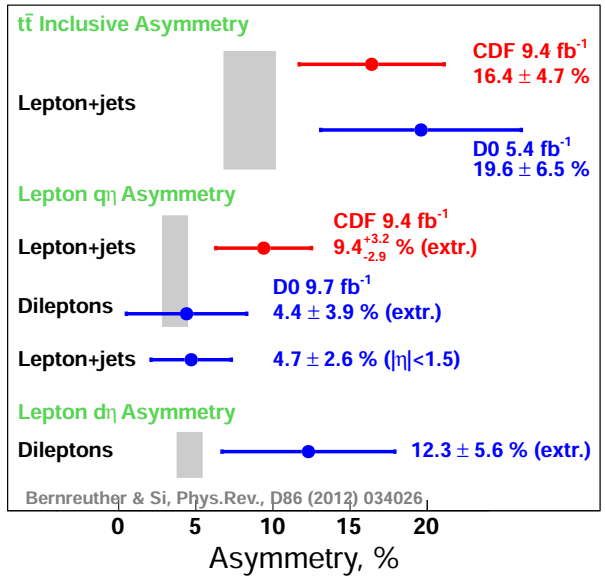
What is measured?



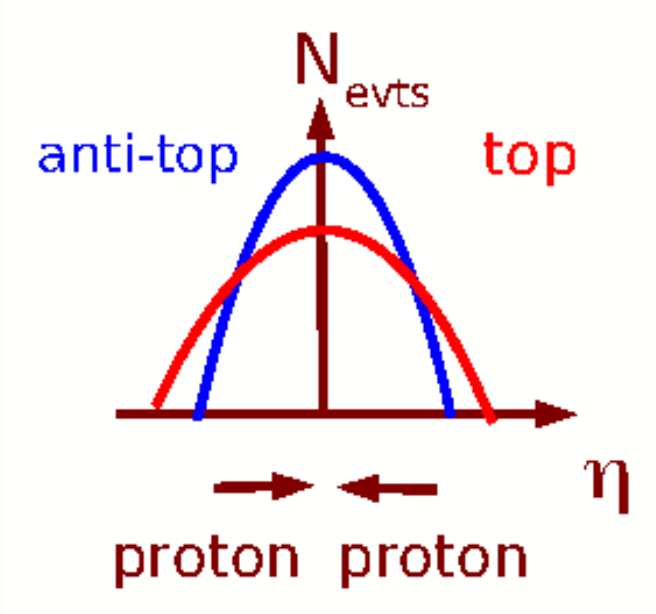
- $A_{\mathrm{FB}} = 5.0\%$ leading order prediction from NLO top pair production.
  [Kuhn, Rodrigo, PRL81(1998)]
- $A_{\mathrm{FB}} = 7.3\%$ including NNLL resummation corrections.
  [Ahrens et al. Phys.Rev. D84 (2011) 074004]
- $A_{\mathrm{FB}} \simeq 9.0\%$ including electroweak corrections.
  [Hollik, Pagani, arXiv:1107.2606]

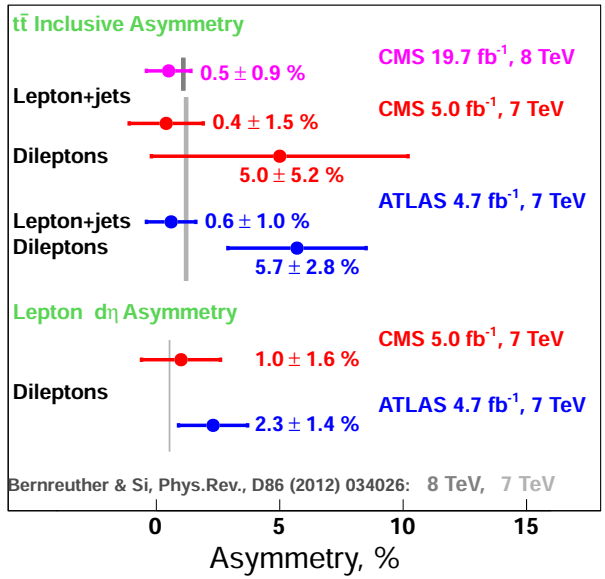
Tevatron





LHC

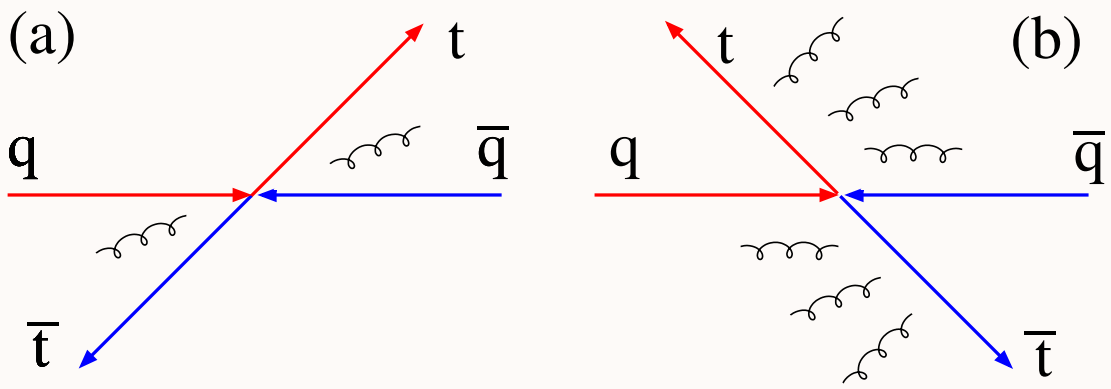




Top quark asymmetries

➡ ***Colour coherence in top quark pair production.***

(a) forward (b) backward configurations



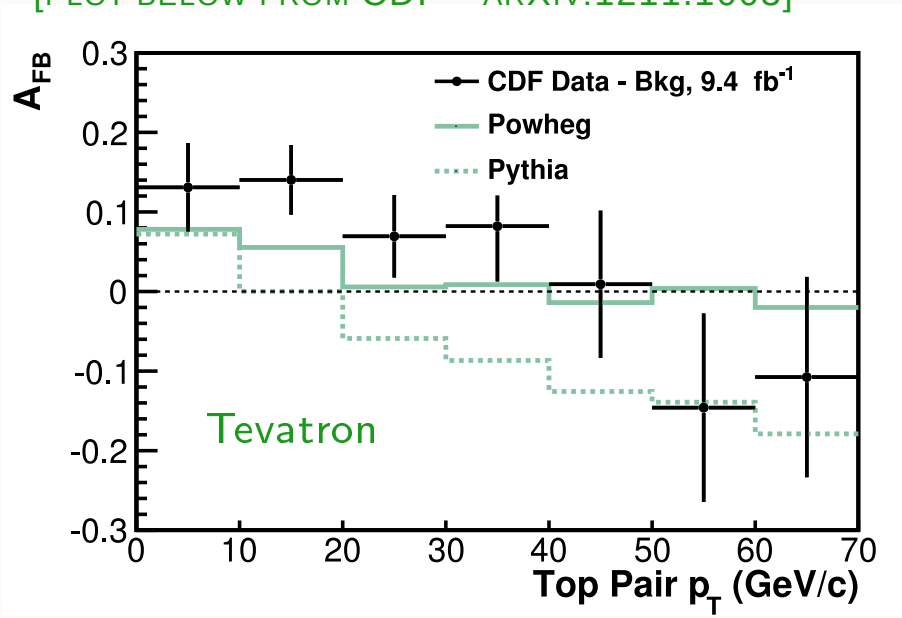
- colour charges more strongly accelerated in "backward" dipoles
- rapidity difference: $\Delta y = y_t - y_{\bar{t}}$

  where $y \equiv \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$

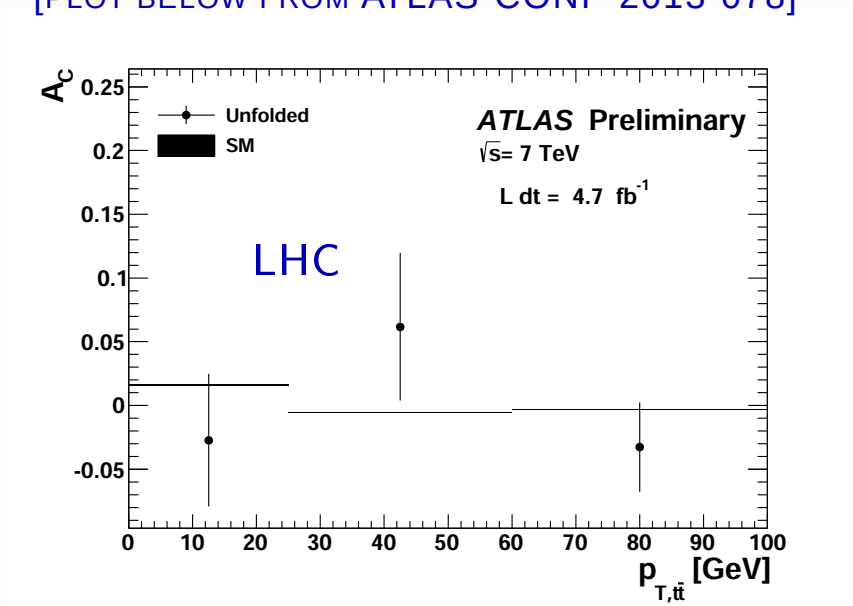
$$A_{\rm FB}(O) = \frac{\left.\frac{d\sigma}{dO}\right]_{\Delta y>0} - \left.\frac{d\sigma}{dO}\right]_{\Delta y<0}}{\left.\frac{d\sigma}{dO}\right]_{\Delta y>0} + \left.\frac{d\sigma}{dO}\right]_{\Delta y<0}}$$

- How accurate are our SM predictions?
  $\Rightarrow$ Test the new standard in Monte Carlos.

[PLOT BELOW FROM CDF – ARXIV:1211.1003]



[PLOT BELOW FROM ATLAS-CONF-2013-078]



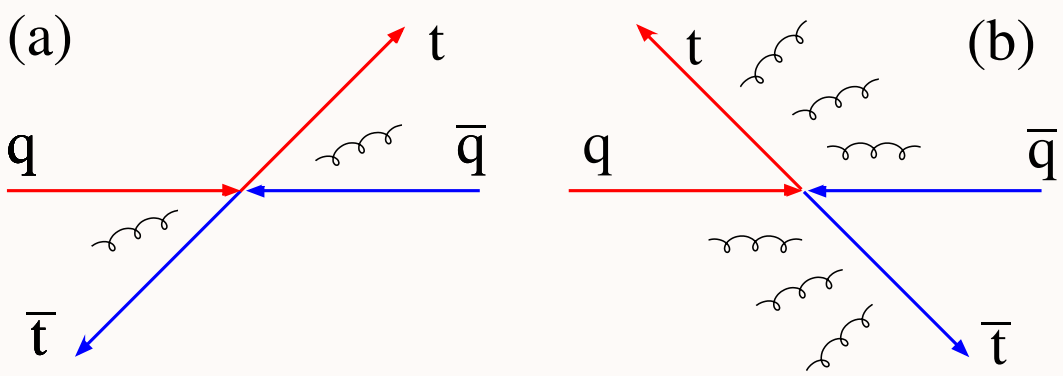
Colour coherence effect

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

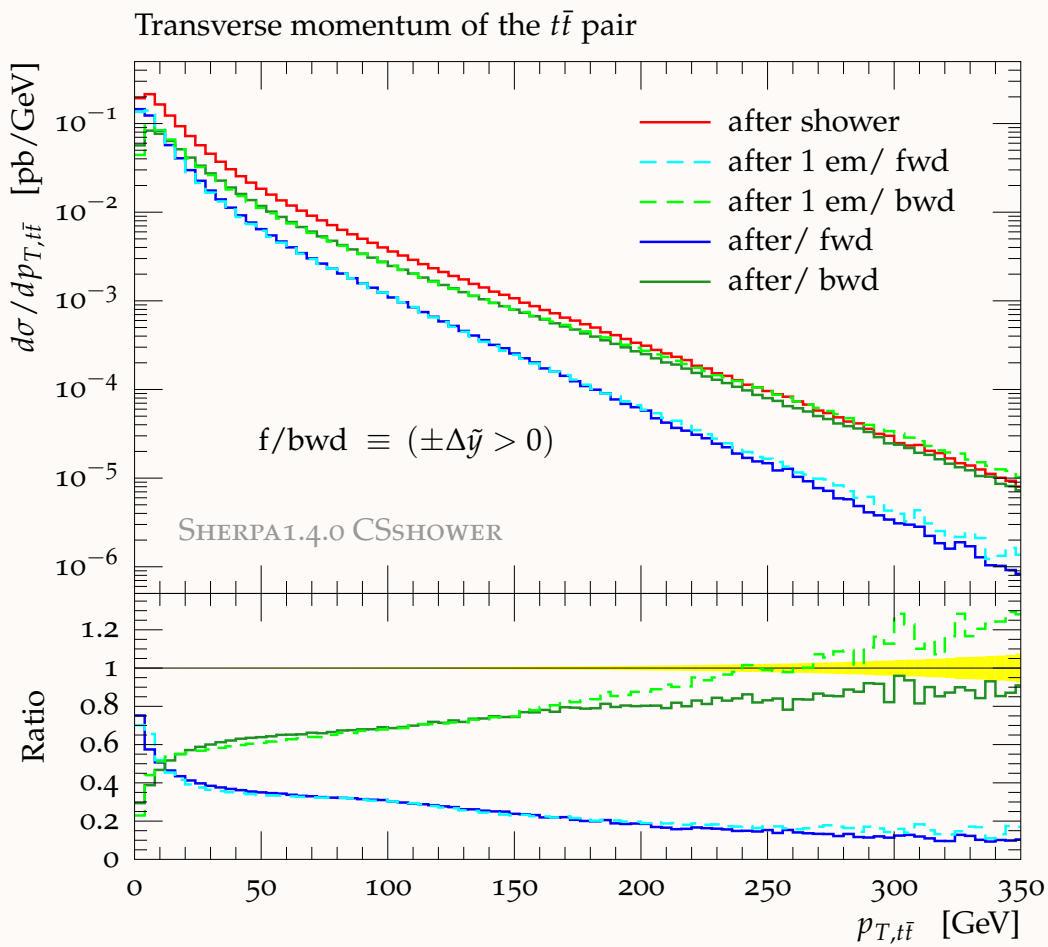
"Forward" dipoles – less space space for emission, less likely to radiate.

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

- (a) Forward configuration



- (b) Backward configuration



- Colour coherence (leads to angular ordering)
  ➡ asymmetric real emission
- Extra emission (confined to cone as large as $\theta_{\rm ini}$)
  ➡ more recoil for backward top pairs

Monte Carlo event generation

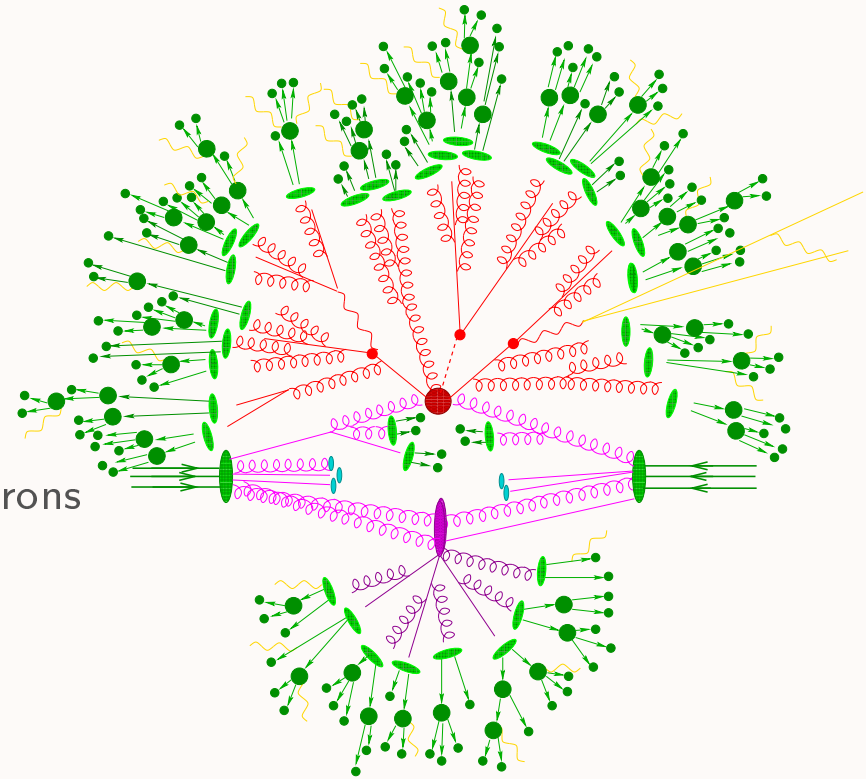
Event generators are used to model multi-hadron final states of high-energy particle collisions.

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 $|\mathcal{M}|^2$ ***[ME]***
- ***QCD bremsstrahlung (soft/coll multiple emissions)***
  initial- and final-state parton showering ***[PS]***
- ***Multiple/Secondary interactions***
  modelling the underlying event

⇐ current frontier is ME+PS matching at NLO+(∼N)LL and merging different jet bins with no double counting



➡ ***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

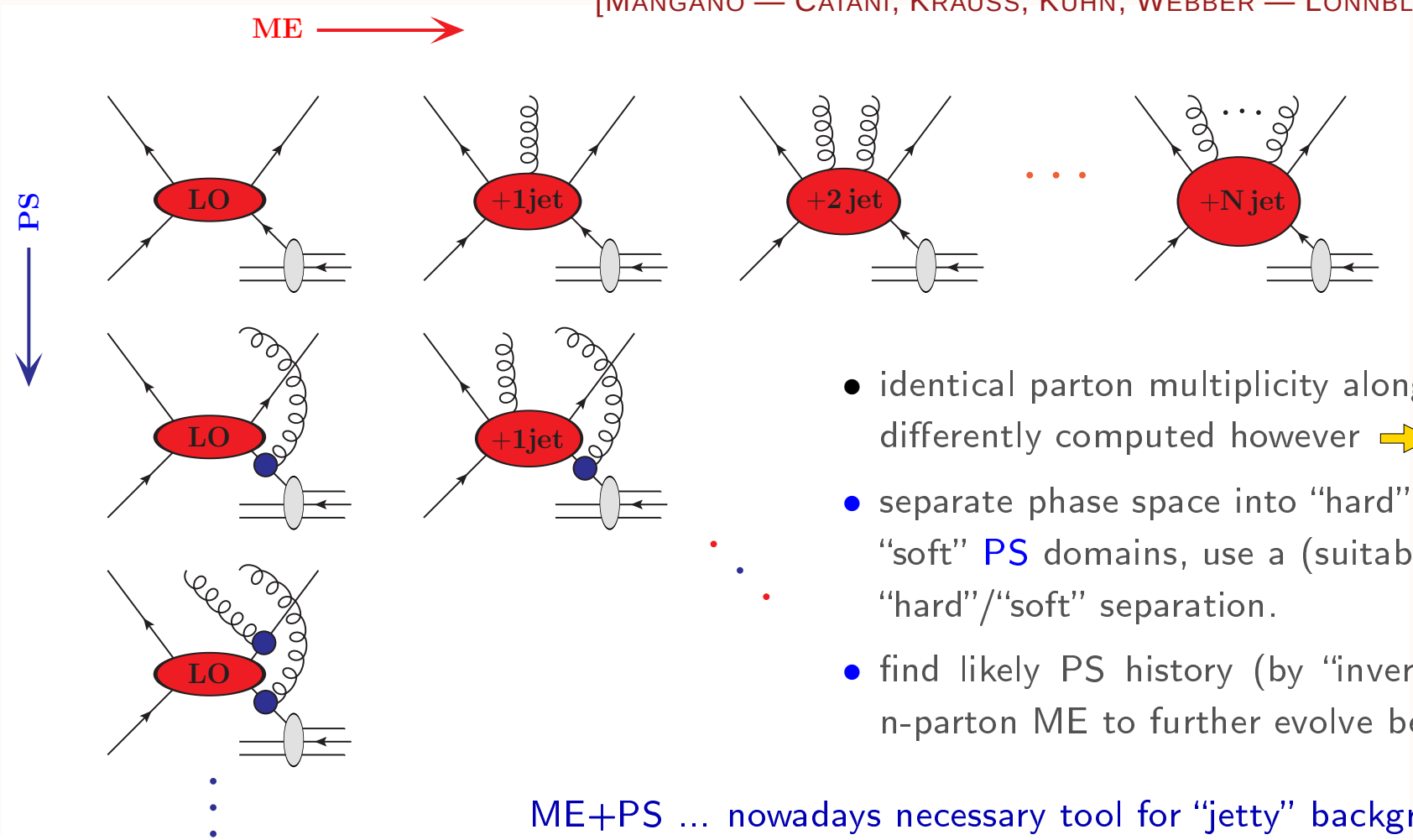
Matrix-element + parton-shower merging (ME+PS)

➡ combine PS pros (resumming soft emissions) + ME pros (hard emissions, quantum interferences, correlations)

⇒ Fully populate emission's phase space with either ME or PS – avoid dead regions.

⇒ ME and PS describe the same final state – remove double counting.

[Mangano — Catani, Krauss, Kuhn, Webber — Lönnblad — Richardson]



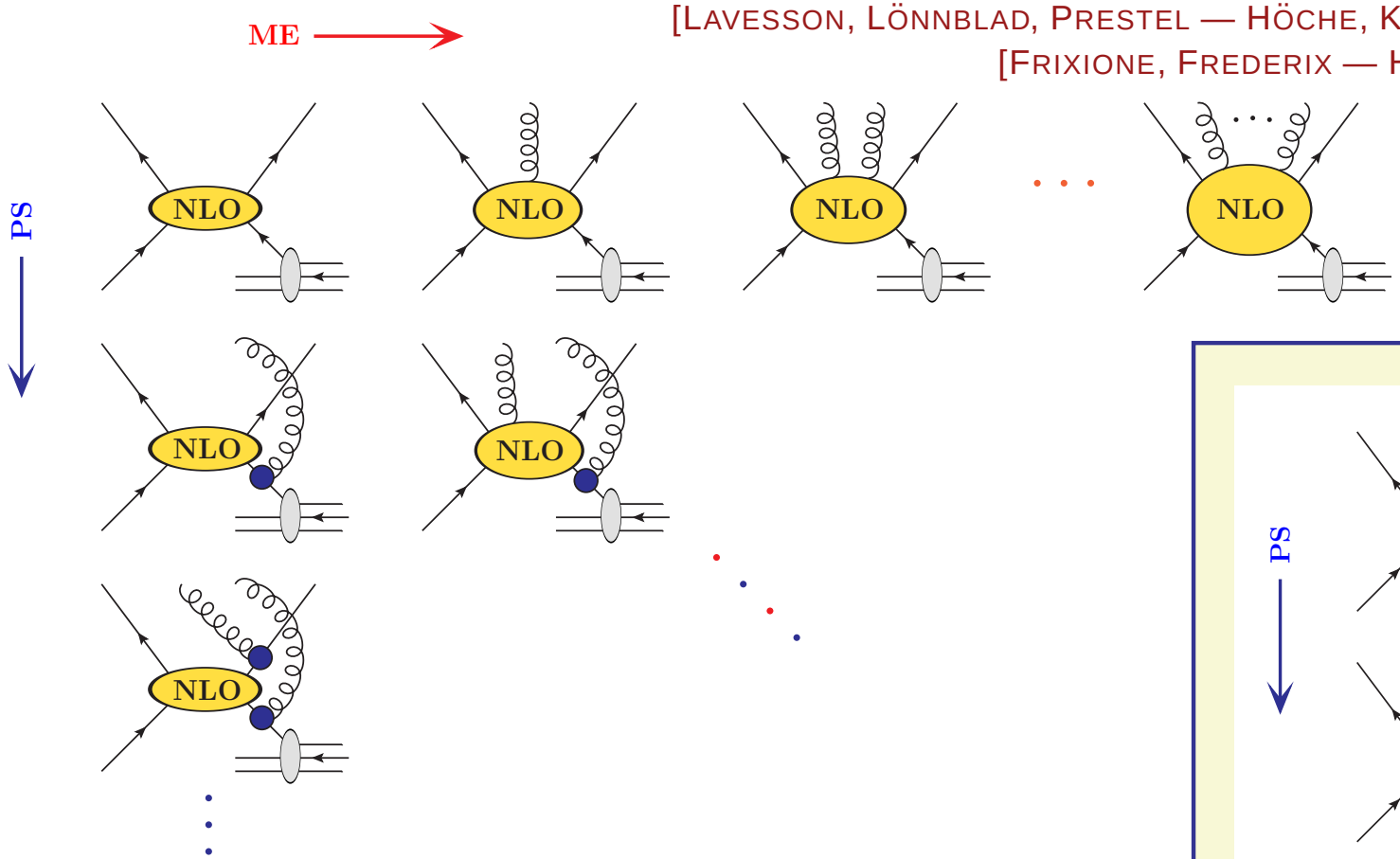
- identical parton multiplicity along diagonal, differently computed however ➡
- separate phase space into "hard" ME and "soft" PS domains, use a (suitable) jet criterion for "hard"/"soft" separation.
- find likely PS history (by "inverted" showering) for n-parton ME to further evolve beyond n partons.

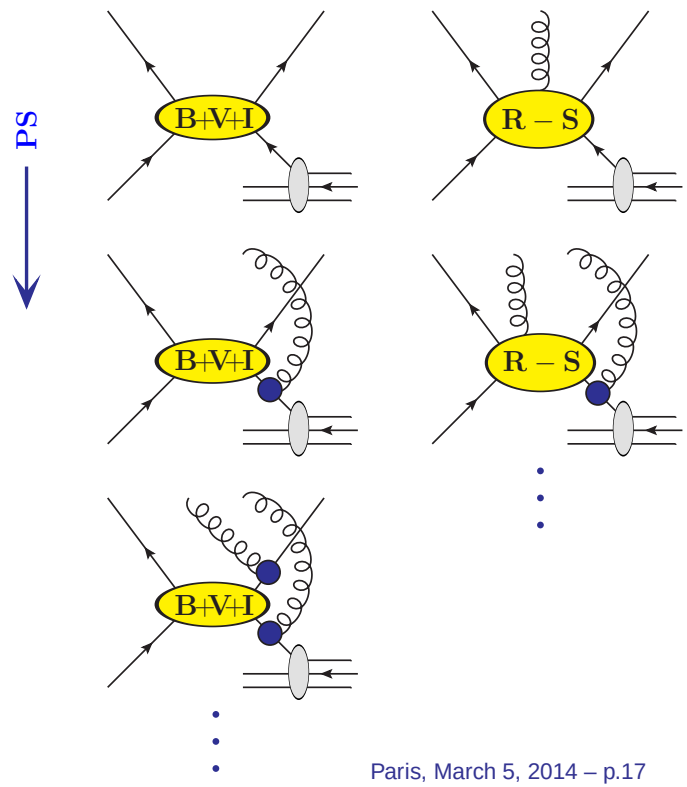
ME+PS ... nowadays necessary tool for "jetty" background simulations.

Towards a new standard

ME+PS merging with multiple NLO processes

[Lavesson, Lönnblad, Prestel — Höche, Krauss, Schönherr, Siegert]
[Frixione, Frederix — Hamilton, Nason — Plätzer]



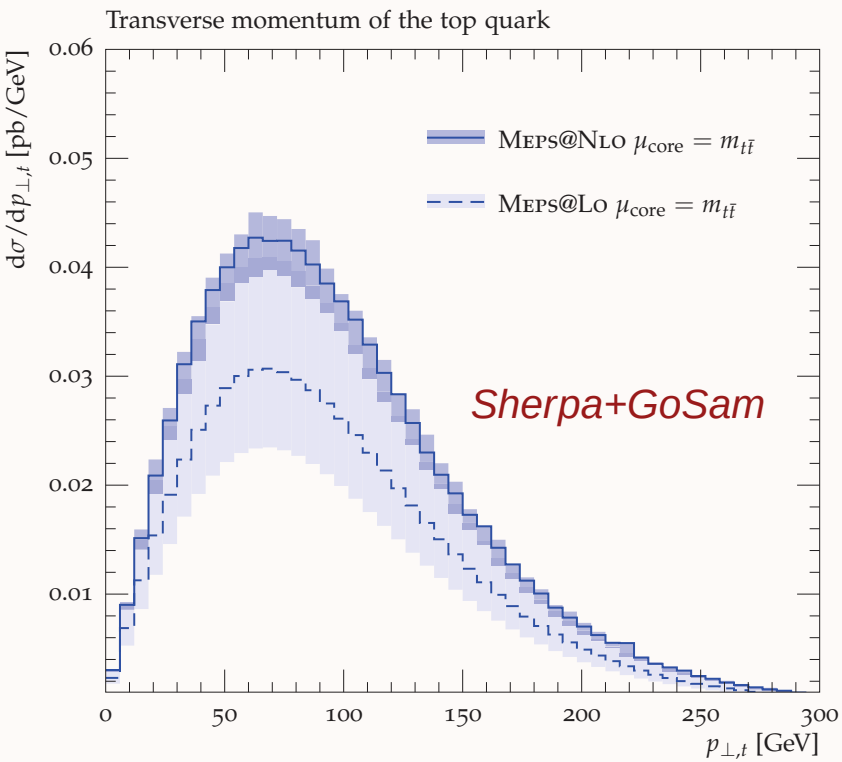


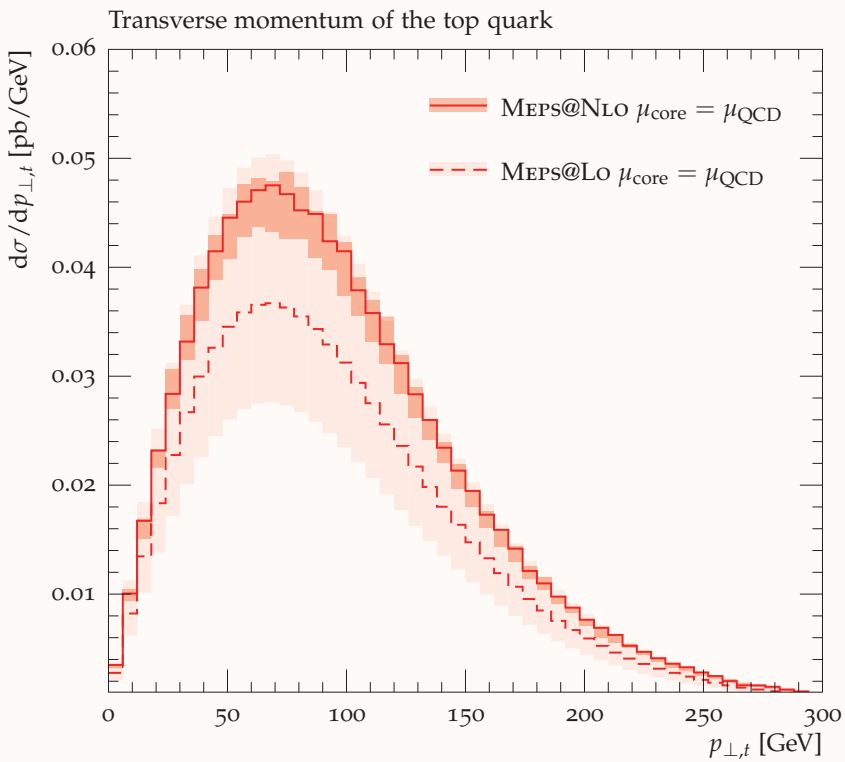
- Per jet bin, NLO+PS matching with extra jet veto.
- Make NLO contributions finite: B+V+I and R-S integrals.
- V from one-loop generators → GoSam, NJet, OpenLoops, etc
  B, R, S, I from → Sherpa;

FB differential asymmetry with ME+PS@NLO

[Höche, Huang, Luisoni, Schönherr, Winter, arXiv:1306.2703]

- Scale uncertainties provide us with an estimate of the size of missing higher-order contributions.
- Differential cross sections are more sensitive to conventional scale variations (by factors of 2) than ratios of them, such as A_{FB}. $\Rightarrow$ Different functional forms of the scale definition are needed for a more realistic estimate of the uncertainty.
- We use a scale based on the leading colour flow and compare it to the plain top quark pair mass.





$p\bar{p} \to t\bar{t}$+jets (0,1 @ NLO & virtual MEs from GoSam)

red: $\mu_{\mathrm{core}} = 2|p_i p_j|$

blue: $\mu_{\mathrm{core}} = m_{t\bar{t}}$

perturbative scale (factor) variations &

variation of merging parameter $Q_{\mathrm{cut}} \in \{5, 7, 10\}$ GeV

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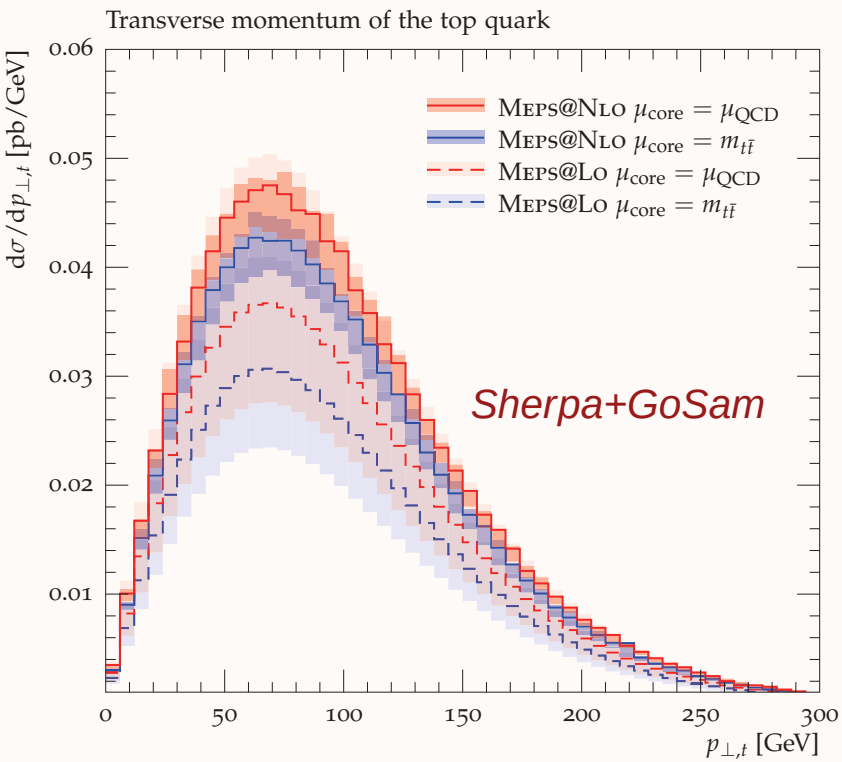

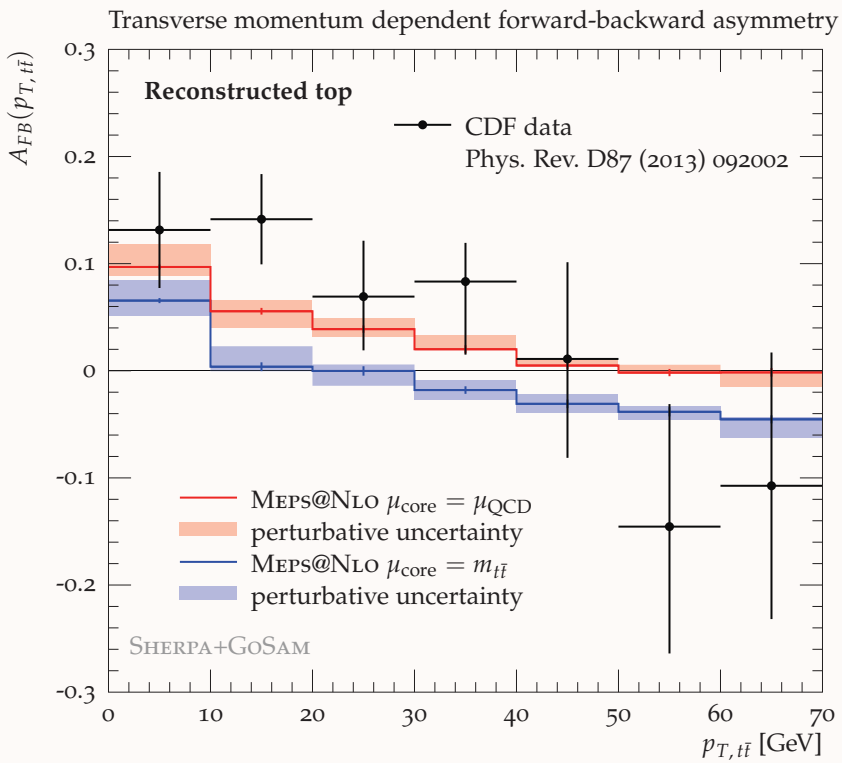

$p\bar{p} \to t\bar{t}$+jets (0,1 @ NLO & virtual MEs from GoSam)

red: $\mu_{\mathrm{core}} = 2|p_i p_j|$

blue: $\mu_{\mathrm{core}} = m_{t\bar{t}}$

perturbative scale (factor) variations &

variation of merging parameter $Q_{\mathrm{cut}} \in \{5, 7, 10\}$ GeV

➡ $A_{\mathrm{FB}}(p_{T,t\bar{t}})$ is QCD NLO accurate in all but the first bin (no EW corrections included).

Summary & Outlook.

Shape uncertainties from scale variations of the full NLO QCD corrections to $WWb\bar{b}$ production result in larger theory errors on the top quark mass determination than expected.

Validation ongoing (NLO in "decay" seems crucial). Parton showering and hadronization effects? Hadron-level predictions wanted.

Higher order QCD corrections help narrow the gap between AFB Tevatron measurements and predictions but do not resolve discrepancies completely.

Continuation of pheno studies necessary, in particular for top quark asymmetries at the LHC. Reconstruction and unfolding effects fully understood? Complete NLO predictions for AFB? LC studies?

The end.