

Theoretical Introduction: Mass

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What is Mass all about?



What are we measuring?

Moving towards physical final states

The top quark is not stable

- ▶ due to its large width, Γ_t , top quark decays before hadronizing ...
- ▶ top quarks not directly measured – presence always inferred through their decay products: **leptons, (b)jets, missing energy**
- ▶ To compare to stable top predictions, experiments have to
 - ▶ extrapolate their measurements from fiducial to inclusive
 - ▶ extrapolate/model from particle-level to top-quark partons
- ▶ this back-modelling depends on Monte Carlo
 - ▶ these steps currently use MCs that **treat top decay at LO**
 - ⇒ no reliable estimate of uncertainty on shape & normalization due to higher order corrections to decay
 - ▶ each MC generator has a different shower
 - ⇒ is the top ‘parton’ one arrives at is a **MC-dependent** object?

Is the top “parton” one arrives at is a MC-dependent object?

Yes. Seems unavoidable (at hadron colliders):

Parton vs. Particle.

Something different about shower/decay/hadronization of a top quark that cannot be 100% extractable from non-top events.

Even leptonic observables have implicit MC-dependence (how much?).

$m_{in} \neq m_{out}$: calibration/offset.

We expect different generators to converge on the same result *eventually*.

Tuned to same data, but different PS logarithms and NP models, which extrapolate differently.

What is the meaning of what we are measuring?

Thornier question: defer to Andreas K talk (later)

30s overview: Relate:

$$m_\Theta : 6 \simeq m_P = m_{\mathcal{L}} + N \int_0^{m_{\mathcal{L}}} dl \alpha_s(l),$$

What happens for $l < \Lambda_{\text{QCD}}$?

Take PV, but contour above and below pole lead to a different answer:

Renormalon Ambiguity

AK: 100 MeV or so.

Response to: We are doing it all wrong.

Borrowing from P. Nason (hep-ph/1712.02796)

Perturbative argument: MCs are only LO.

Non-perturbative argument I: jets have non-perturbative corrections, avoid them.

Non-perturbative argument II: non-perturbative models in MCs are ad-hoc, do better.

MCs are only LO

House Built of Straw

LO ME: no way to meaningfully relate to $m_{\mathcal{L}}$

Marquard: 2015qpa:

$$m_p = m + \underbrace{7.557}_{\text{NLO}} + \underbrace{1.617}_{\text{NNLO}} + \underbrace{0.501}_{\text{N}^3\text{LO}} + \underbrace{0.195 \pm 0.005}_{\text{N}^4\text{LO}} \text{ GeV.}$$

for $m = 163.643 \text{ GeV}$ and $\alpha_s^{(6)}(m) = 0.1088$.

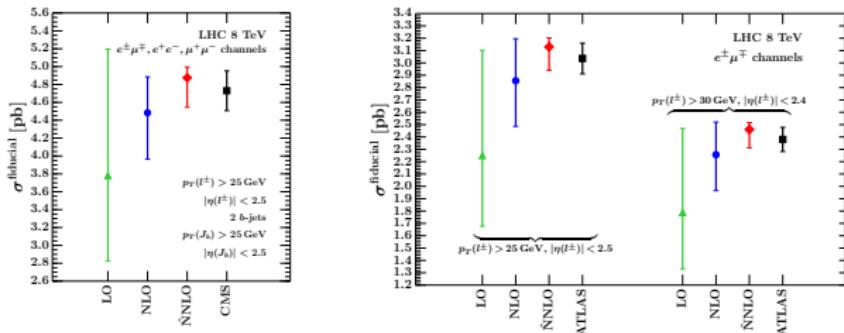
Predictions for physical final states

Fiducial cross sections: di-lepton channel

Gao, AP '17

Two different fiducial volumes investigated:

- ▶ CMS (8 TeV): require 2 b jets, $p_T(J_b) > 25$ GeV, $|\eta(J_b)| < 2.5$,
 $p_T(l^\pm) > 25$ GeV, $|\eta(l^\pm)| < 2.5$
- ▶ ATLAS (8 TeV): $p_T(l^\pm) > 25(30)$ GeV, $|\eta(l^\pm)| < 2.5(2.4)$

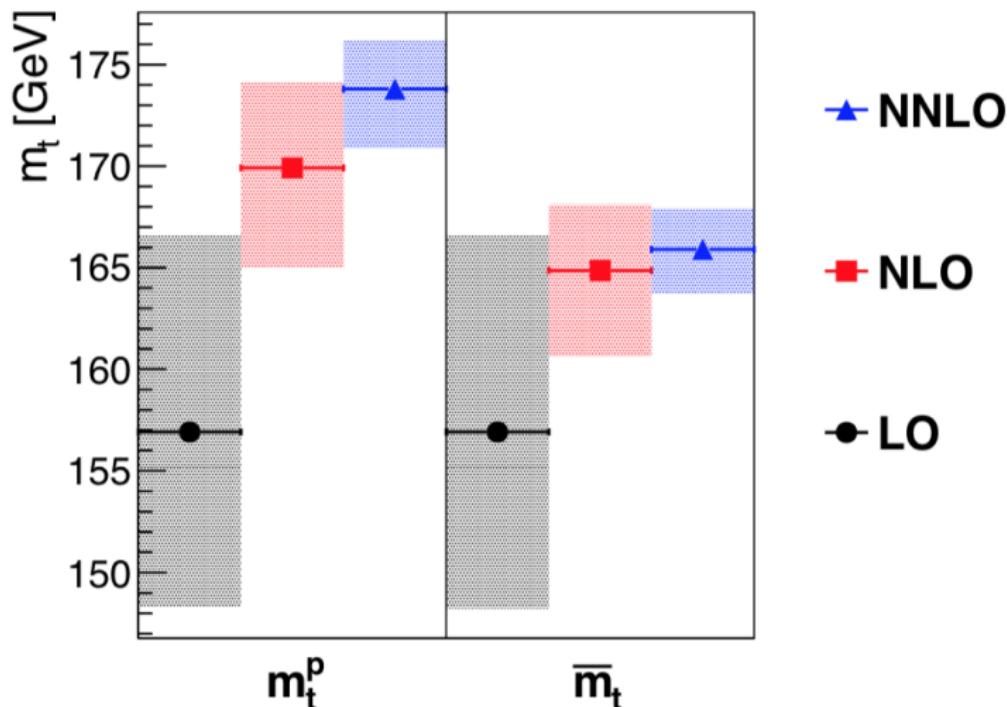


- ▶ corrections beyond NLO important
- ✓ improvement in agreement between theory and measurements

(continued)

arXiv:1511.00841v2

Inclusive $t\bar{t}$ production cross section extraction:



Problems with the argument

First, predictions at NLO ME + PS now.

Even LO generators have:

$$f(\hat{s}) \frac{1}{(\hat{s} - m^2)^2 + \hat{s}\Gamma^2(\sqrt{\hat{s}})}.$$

Soft radiation $\sim \Gamma_t$ affects this, but how much?

Must depend on the observable.

Plus, there is a tradeoff between theory and experimental error in the selection of fiducial volume (extrapolation) for total σ

jets have non-perturbative corrections, avoid them

House Built of Wood

arXiv:1407.2763

Label	Observable
1	$p_T(\ell^+)$
2	$p_T(\ell^+\ell^-)$
3	$M(\ell^+\ell^-)$
4	$E(\ell^+) + E(\ell^-)$
5	$p_T(\ell^+) + p_T(\ell^-)$

Label	Extended name	Accuracy	Parton shower	Spin correlations
1	NLO+PS+MS	NLO	Yes	Yes
2	LO+PS+MS	LO	Yes	Yes
3	NLO+PS	NLO	Yes	No
4	LO+PS	LO	Yes	No
5	fNLO	NLO	No	No
6	fLO	LO	No	No

Table 2: Calculational scenarios considered in this paper. The rightmost column reports the inclusion of *production* spin correlations; decay spin correlations are included in all cases.

(continued)

obs.	$m_t^{(3)} - m_t^{(5)}$	$m_t^{(3)} - m_t^{\text{pd}}$	$m_t^{(4)} - m_t^{(6)}$	$m_t^{(4)} - m_t^{\text{pd}}$
1	$-0.35^{+1.14}_{-1.16}$	+0.12	$-2.17^{+1.50}_{-1.80}$	-0.67
2	$-4.74^{+1.98}_{-3.10}$	+11.14	$-9.09^{+0.76}_{-0.71}$	+14.19
3	$+1.52^{+2.03}_{-1.80}$	-8.61	$+3.79^{+3.30}_{-4.02}$	-6.43
4	$+0.15^{+2.81}_{-2.91}$	-0.23	$-1.79^{+3.08}_{-3.75}$	-1.47
5	$-0.30^{+1.09}_{-1.21}$	+0.03	$-2.13^{+1.51}_{-1.81}$	-0.67

Table 4: Impact of parton showers on mass extractions. See the text for details.

Not the final result: only meant to demonstrate that there still are significant corrections/uncertainties for some “clean” observables.

Problems with this argument

They still observe residual EG dependence.

Light jets – even b-jets – well studied. Need to understand the difference from having an intermediary top – not the full magnitude.

If dogmatic, forced to throw away data (remember the M_W extraction from LEP?)

Question: how well can NP effects be tamed.

Can some top data be sacrificed to reduce top specific effects?

(Like PDFs, not known a priori, but evolution is)

non-perturbative models in MCs are ad-hoc, do better

House Built of Brick

Agreed. Come up with something better!

Use data to kill current models!

CR model (exchange of low-momentum gluons with color)

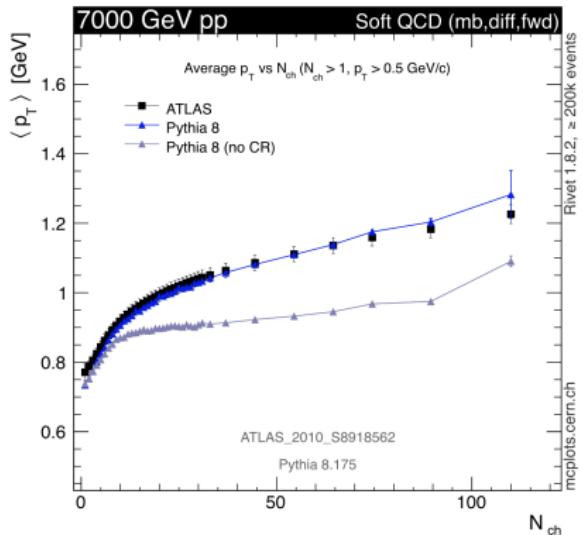
changes length of strings (multiplicity $\sim \ln \sqrt{s}$)

changes direction of momentum flow (gluon is a kink on string)

low momentum \sim shower cutoff $\sim \frac{1}{2}$ GeV

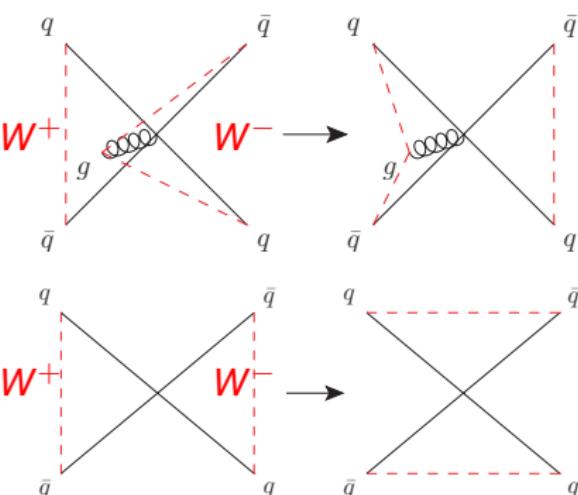
Phenomenology of Color Reconnections

Needed to explain hadronic activity



Most sensitive distribution to tune

Only extreme CRs ruled out at LEP



Limited M_W extraction to $\ell\nu jj$

The top mass uncertainty from CR

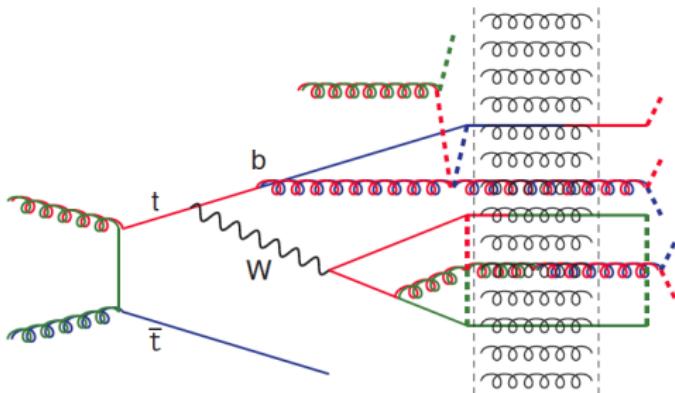
$$\Gamma_t \approx 1.5 \text{ GeV}$$

$$\Gamma_W \approx 2 \text{ GeV}$$

$$\Gamma_Z \approx 2.5 \text{ GeV}$$

\Rightarrow

$$c\tau \approx 0.1 \text{ fm}$$



Decays occur when p “pancakes” have passed, after MPI/ISR/FSR with $p_T \geq 2 \text{ GeV}$, but inside hadronization colour fields.

Experimentalists achieve impressive m_t precision,

e.g. CMS $m_t = 172.35 \pm 0.16 \pm 0.48 \text{ GeV}$ (PRD93 (2016) 072004),
whereof $\text{CR} \pm 0.10 \text{ GeV}$

from PYTHIA 6.4 Perugia 2011 $|\text{CR} - \text{noCR}|$

Is this realistic?

Comments

Argument for need is weak, driven by the model.

On the other hand, universality cannot be ruled out.

Updated effect on m_t (SA/TS): 500 MeV

PS/JC new model: substantially less, but also trouble describing UE in general.

Important (and hard) to retune to do these studies.

Moving Forward

Now you know something (I hope more) about the theory issues concerning the top mass (at hadron colliders)

What to do?

Access what ME+PS is doing and is it correct?

Develop a system for including/testing better/different calculations.

Assess dependence on NP parameters and correlations

Access what ME+PS is doing and is it correct?

arXiv:1801.04826

	PS only		full	
	No smearing	smearing	No smearing	smearing
$b\bar{b}4\ell$	172.522 GeV	171.403 GeV	172.793 GeV	172.717 GeV
$t\bar{t}dec - b\bar{b}4\ell$	-18 ± 2 MeV	$+191 \pm 2$ MeV	$+21 \pm 6$ MeV	$+140 \pm 2$ MeV
$hvq - b\bar{b}4\ell$	-24 ± 2 MeV	-89 ± 2 MeV	$+10 \pm 6$ MeV	-147 ± 2 MeV

Table 1: Differences in the $m_{Wb_j}^{\max}$ for $m_t=172.5$ GeV for $t\bar{t}dec$ and hvq with respect to $b\bar{b}4\ell$, showered with **Pythia8.2**, at the NLO+PS level and at the full hadron level. Results obtained after smearing the m_{Wb_j} distribution with a Gaussian function with a 15 GeV width are also shown in order to mimic effects due to experimental uncertainties.

	No smearing		15 GeV smearing	
	He7.1	Py8.2 – He7.1	He7.1	Py8.2 – He7.1
$b\bar{b}4\ell$	172.727 GeV	$+66 \pm 7$ MeV	171.626 GeV	$+1091 \pm 2$ MeV
$t\bar{t}dec$	172.775 GeV	$+39 \pm 5$ MeV	171.678 GeV	$+1179 \pm 2$ MeV
hvq	173.038 GeV	-235 ± 5 MeV	172.319 GeV	$+251 \pm 2$ MeV

Table 2: m_{Wb_j} peak position for $m_t=172.5$ GeV obtained with the three different generators, showered with **Herwig7.1** (He7.1). The differences with **Pythia8.2** (Py8.2) are also shown.

Develop a system for including/testing better/different calculations

In Situ Shower Parameter Variation

- ▶ Includes renormalisation-scale and non-singular term variations
- ▶ Output = vector of alternative weights for each event
- ▶ quick estimate of uncertainties without needing separate runs
- ▶ a single sample to run through detector simulation etc.
- ▶ (hadronisation etc also only has to be carried out once).
- ▶ choose which variations you want, how large, correlated/uncorrelated

Shower is iterative selection of branchings:

$$\mathcal{R}_t \in [0, 1] = \Delta(t_0, t) = \exp \left(- \int_t^{t_0} dt_1 \int dz_1 P(t_1, z_1) \right)$$

$P(t, z) = \frac{\alpha_s(t)}{2\pi} \frac{P(z)}{t}$ is complicated :: use veto algorithm

Understanding the veto algorithm

$$\mathcal{P}_0(t) = \exp \left\{ - \int_t^{\bar{t}} g(t') dt' \right\} g(t) \underbrace{\frac{f(t)}{g(t)}}_{p_{\text{acc}}} = f(t) e^{- \int_t^{\bar{t}} g dt'}$$

$$\mathcal{P}_1(t) = \int_t^{\bar{t}} dt_1 e^{- \int_{t_1}^{\bar{t}} g dt'} g(t_1) \underbrace{\left[1 - \frac{f(t_1)}{g(t_1)} \right]}_{p_{\text{rej}}} e^{- \int_t^{t_1} g dt'} g(t) \underbrace{\frac{f(t)}{g(t)}}_{p_{\text{acc}}}$$

$$\mathcal{P}_1(t) = \mathcal{P}_0(t) \int_t^{\bar{t}} dt_1 [g(t_1) - f(t_1)]$$

$$\sum_i \mathcal{P}_i(t) = \mathcal{P}_0(t) \exp \left\{ \int_t^{\bar{t}} [g(t_1) - f(t_1)] dt_1 \right\} = f(t) e^{- \int_t^{\bar{t}} f dt'}$$

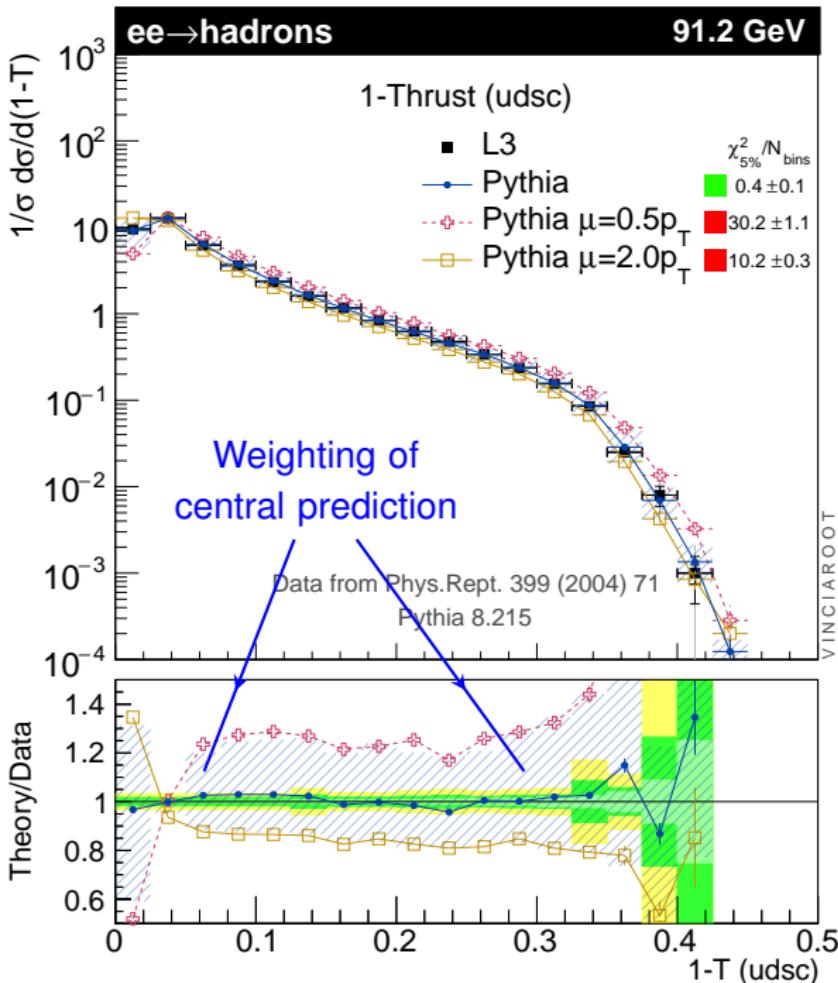
Variations on a theme

$$\underbrace{f \rightarrow f'}_{\alpha_s(\mu_R) \rightarrow \alpha_s(c\mu_R)} \Rightarrow p_{\text{acc}}, p_{\text{rej}} \rightarrow p'_{\text{acc}}, p'_{\text{rej}}$$

Careful account of weights (ratios of probabilities) allows for uncertainty estimates

Similar methodology can be used to bias (say rare) emissions

Even negative weights can be handled (expected at NLL)



Assess dependence on NP parameters and correlations

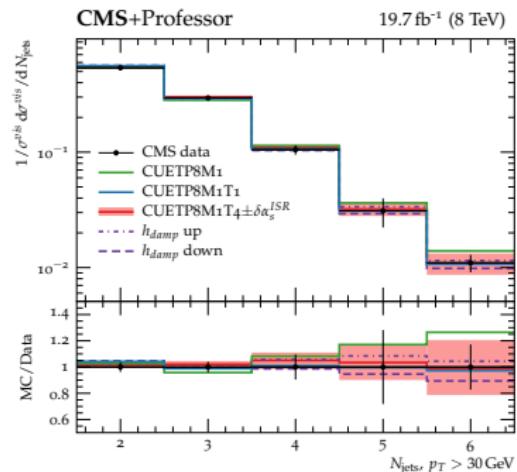
Evolution of Pythia8 Tune in CMS Run2

- ▶ So far have used Tune CUETP8M1 for most samples
(arXiv:1512.00815)
 - ▶ Re-tuning of UE parameters on top of Monash, α_S and other shower parameters left untouched
 - ▶ In particular this means $\alpha_S=0.1365$ used for both ISR and FSR in the shower, despite using 0.118 in the ME for NLO samples and 0.130 for LO samples
- ▶ Tuning of shower parameters in particular revisited

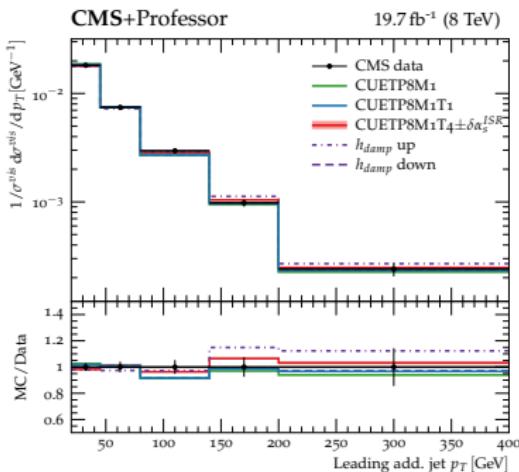
Pythia8 Shower Tuning with $t\bar{t}$ (CMS-PAS-TOP-16-021)

- ▶ Differences observed between generators, and sensitivity to shower α_s in $t\bar{t}$ production in kinematics/multiplicity of additional jets
- ▶ Retune PS ISR α_s and POWHEG hdamp using POWHEG+Pythia $t\bar{t}$ vs dilepton+jets data, yields (much) lower value of $\alpha_s^{ISR} = 0.1108$

Njets ($p_T > 30$ GeV)



Lead jet p_T



What I want (we need)

TUNES that are:

DATA DRIVEN (go back to LEP where possible)

FAMILIES (not just best fit, but a number of good fits akin to PDFs)

TARGETED (specific to the relevant kinematics and acceptance)

Machinery, expertise exist. Just need the will.

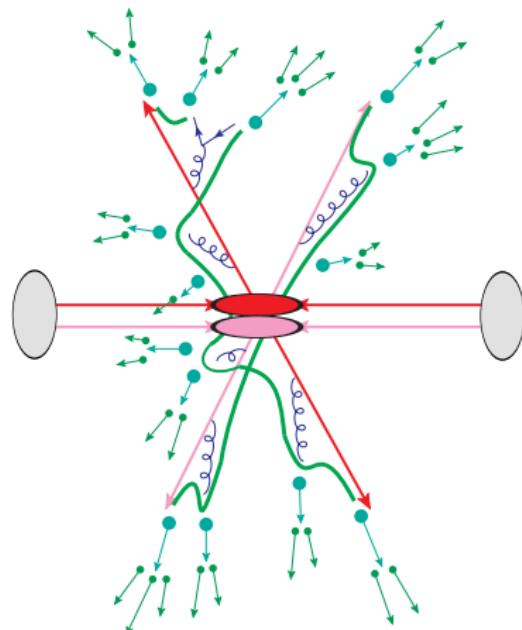
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BACK-UP

What is Pythia8?

A machine that generates realistic, high-energy particle collision event records using all the Standard Model physics we know.



Short-distance cross section:

$$\mu_r^H, \mu_f^H, \text{PDF}^H, \alpha_s^H$$

Parton shower:

$$\mu_q^{PS}, \mu_r^{PS}, \mu_f^{PS}, \mu_{cut}^{PS}, \text{PDF}^{PS}, \alpha_s^{PS}$$

Multiple interactions:

$$\mu_q^{MPI}, \text{PDF}^{MPI}, \alpha_s^{MPI} \dots$$

String fragmentation:

$$f(z), \text{string } p_T, \text{tension}$$

Beams:

Primordial k_T , remnants

Particle Decays:

BRs, MEs, BE correlations

...

Full Disclosure

A large number of parameters need to be fit (**tuned**) to data to make predictions

Anonymous reviewer:

*It is well-known in scientific computing that with enough **parameters**, all **discrepancies** between simulation and data can be **eliminated**. However if the underlying algorithms or model in the simulation are flawed, the resulting over-parameterized, data-fit code still cannot predict new results*

...

Apparent parameters < # Actual parameters

Some parameters are just necessary choices (cutoffs, PDF, etc)

Effective parameters < # Remaining parameters

Amount of information in differential data \gg # Effective parameters

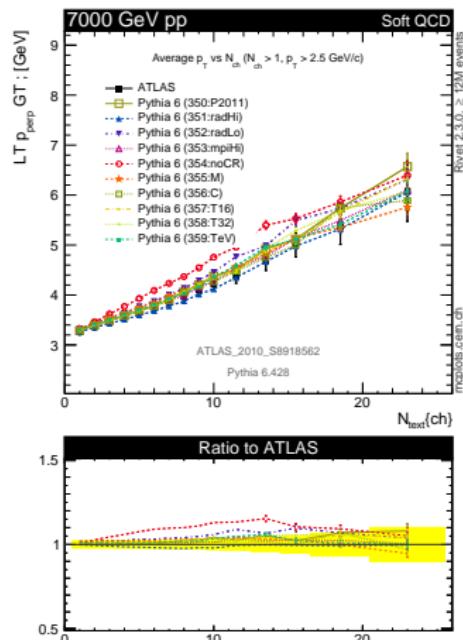
Perturbative QCD calculation also has inputs: α_s , μ_R , μ_F , PDFs and is limited in predictions

Minimal # parameters $\sim 15 - 20$

Best Tune vs Good Tunes

Results today on a **Central** or **Best** Tune

We tune to make predictions **AND** assess uncertainty



- ▶ Uncertainty \neq differences btw central tunes of different generators
- ▶ *ad hoc* envelopes of tunes for Py6, but not systematic
- ▶ Professor can automatically produce envelopes, but underutilized
- ▶ tune \leftrightarrow detector simulation
- ▶ see reweighting later

Monash 2013 Tune Parameters

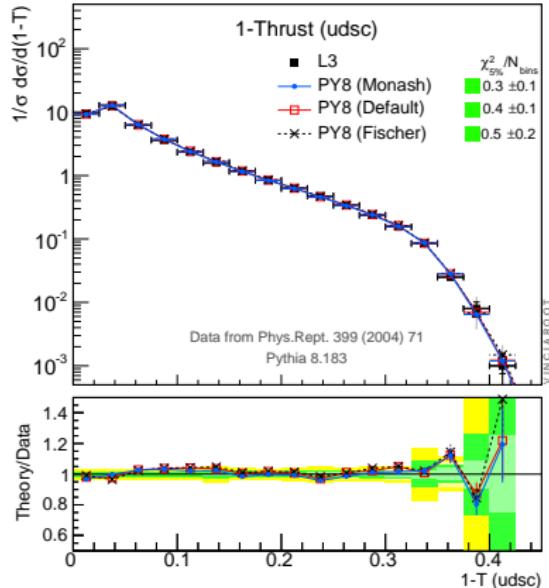
Final-state radiation (FSR) parameters.

FSR Parameters	Monash 13	(Default)	Comment
TimeShower:alphaSvalue	= 0.1365	= 0.1383	! Effective alphaS(mZ) value
TimeShower:alphaSorder	= 1	= 1	! Running order
TimeShower:alphaSuseCMW	= off	= off	! Translation from $\overline{\text{MS}}$ to CMW
TimeShower:pTmin	= 0.50	= 0.40	! Cutoff for QCD radiation
TimeShower:pTminChgQ	= 0.50	= 0.40	! Cutoff for QED radiation
TimeShower:phiPolAsym	= on	= on	! Asymmetric azimuth distributions

$$\text{FSR: } \mu_R^2 = p_{\perp \text{evol}}^2 = z(1-z)Q^2 ,$$

with $Q^2 = p^2 - m_0^2$ the offshellness of the emitting parton (with on-shell mass m_0), and z the energy fraction appearing in the DGLAP splitting kernels, $P(z)$.

pTmin :: avoid Landau pole



Hadronic Z decays at $\sqrt{s} = 91.2$ GeV. The Thrust distribution in light-flavor tagged events, compared with L3 data

$$\alpha_s(M_Z) = 0.1365 \neq 0.13$$

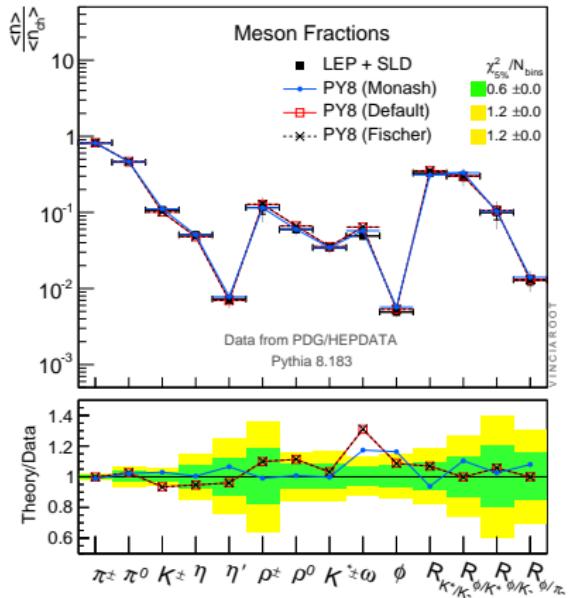
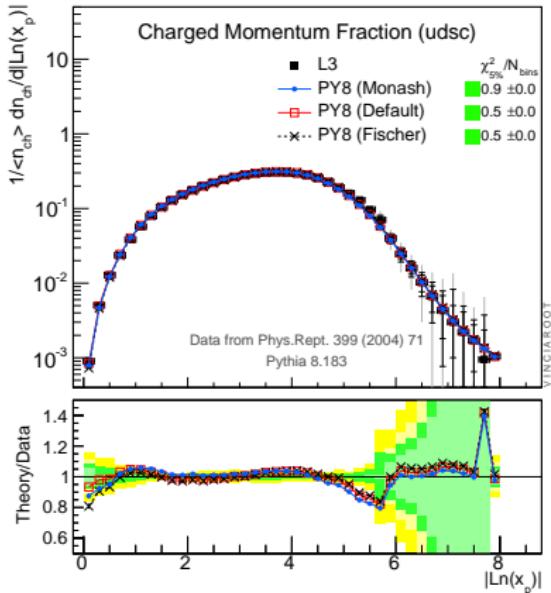
$$\text{CMW} \neq \overline{\text{MS}}$$

$$\Lambda_{\text{CMW}} = 1.6 \Lambda_{\overline{\text{MS}}}$$

Choice of cutoff, hadronization parameters also impact prediction

String-breaking parameters.

HAD Parameters	Monash 13	(Default)	Comment
# String breaks: pT and z distributions			
StringPT:sigma	= 0.335	= 0.304	! Soft pT in string breaks (in GeV)
StringPT:enhancedFraction	= 0.01	= 0.01	! Fraction of breakups with enhanced pT
StringPT:enhancedWidth	= 2.0	= 2.0	! Enhancement factor
StringZ:aLund	= 0.68	= 0.3	! Lund FF a (hard fragmentation supp)
StringZ:bLund	= 0.98	= 0.8	! Lund FF b (soft fragmentation supp)
StringZ:aExtraSquark	= 0.0	= 0.0	! Extra a when picking up an s quark
StringZ:aExtraDiquark	= 0.97	= 0.50	! Extra a when picking up a diquark
StringZ:rFactC	= 1.32	= 1.00	! Lund-Bowler c-quark parameter
StringZ:rFactB	= 0.855	= 0.67	! Lund-Bowler b-quark parameter
# Flavour composition: mesons			
StringFlav:ProbStoUD	= 0.217	= 0.19	! Strangeness-to-UD ratio
StringFlav:mesonUDvector	= 0.5	= 0.62	! Light-flavour vector suppression
StringFlav:mesonSvector	= 0.55	= 0.725	! Strange vector suppression
StringFlav:mesonCvector	= 0.88	= 1.06	! Charm vector suppression
StringFlav:mesonBvector	= 2.2	= 3.0	! Bottom vector suppression
StringFlav:etaSup	= 0.60	= 0.63	! Suppression of eta mesons
StringFlav:etaPrimeSup	= 0.12	= 0.12	! Suppression of eta' mesons
# Flavour composition: baryons			
StringFlav:probQQtoQ	= 0.081	= 0.09	! Diquark rate (for baryon production)
StringFlav:probSQtoQQ	= 0.915	= 1.000	! Strange-diquark suppression
StringFlav:probQQ1toQQ0	= 0.0275	= 0.027	! Vector diquark suppression
StringFlav:decupletSup	= 1.0	= 1.0	! Spin-3/2 baryon suppression
StringFlav:suppressLeadingB	= off	= off	! Optional leading-baryon suppression
StringFlav:popcornSpair	= 0.9	= 0.5	!
StringFlav:popcornSmeson	= 0.5	= 0.5	!



StringZ:aLund = 0.68

StringZ:bLund = 0.98

StringZ:aExtraDiquark = 0.97

StringZ:aExtraSquark = 0.00

StringFlav:ProbStoUD = 0.217

StringFlav:mesonUDvector = 0.5

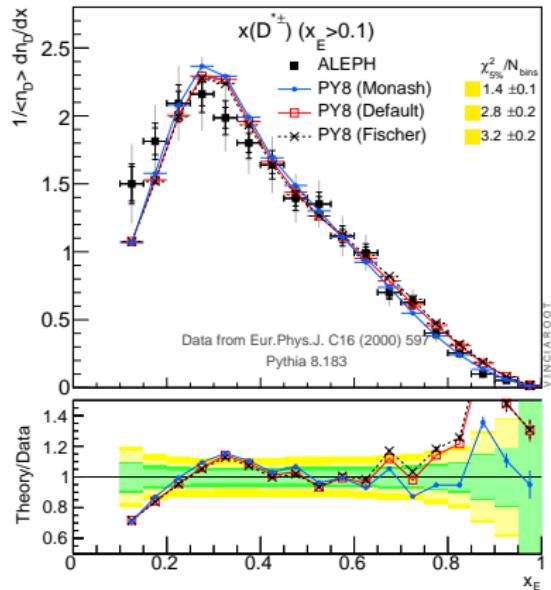
StringFlav:mesonSvector = 0.55

StringFlav:etaSup = 0.60

StringFlav:etaPrimeSup = 0.12

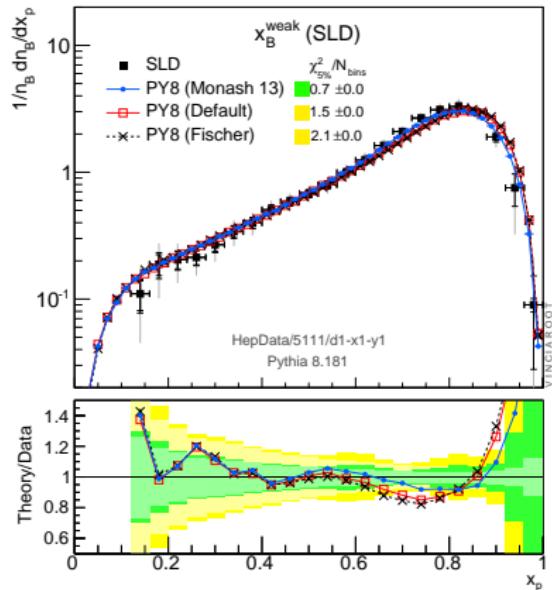
Heavy Flavor Tuning

$$f_{\text{massive}}(z, m_Q) \propto \frac{f(z)}{z^{br_Q m_Q^2}} \quad g \rightarrow c\bar{c}, b\bar{b}$$



StringZ:rFactC = 1.32

StringZ:rFactB = 0.855



Universality Assumption

Final state effects (FSR, hadronization) are tuned in the relatively clean $e^+ e^-$ environment

- ▶ Somewhat problematic, because kinematics is limited, e.g. not much $g \rightarrow Q\bar{Q}$ splitting

Any differences in hadron collisions come from environment

- ▶ Color flow from initial to final state
- ▶ High density of colored partons

Must/should test this!

Initial-state radiation (ISR) and primordial- k_T parameters.

ISR Parameters	Monash 13	(Default)	Comment
SpaceShower:alphaSvalue	= 0.1365	= 0.137	! Effective alphaS(mZ) value
SpaceShower:alphaSorder	= 1	= 1	! Running order
SpaceShower:alphaSuseCMW	= off	= off	! Translation from $\overline{\text{MS}}$ to CMW
SpaceShower:samePTasMPI	= off	= off	! ISR cutoff type
SpaceShower:pT0Ref	= 2.0	= 2.0	! ISR pT0 cutoff
SpaceShower:ecmRef	= 7000.0	= 1800.0	! ISR pT0 reference ECM scale
SpaceShower:ecmPow	= 0.0	= 0.0	! ISR pT0 scaling power
SpaceShower:rapidityOrder	= on	= on	! Approx coherence via y-ordering
SpaceShower:phiPolAsym	= on	= on	! Azimuth asymmetries from gluon pol
SpaceShower:philntAsym	= on	= on	! Azimuth asymmetries from interference
TimeShower:dampenBeamRecoil	= on	= on	! Recoil dampening in final-initial dipoles
BeamRemnants:primordialKTsoft	= 0.9	= 0.5	! Primordial kT for soft procs
BeamRemnants:primordialKTHard	= 1.8	= 2.0	! Primordial kT for hard procs
BeamRemnants:halfScaleForKT	= 1.5	= 1.0	! Primordial kT soft/hard boundary
BeamRemnants:halfMassForKT	= 1.0	= 1.0	! Primordial kT soft/hard mass boundary

Parton Distribution Functions

Parton-distribution (PDF) and Matrix-Element (ME) parameters.

PDF and ME Parameters	Monash 13	(Default)	Comment
PDF:pSet	= 13	= 8	! PDF set for the proton
SigmaProcess:alphaSvalue	= 0.130	0.135	! alphaS(MZ) for matrix elements
MultiPartonInteractions:alphaSvalue	= 0.130	0.135	! alphaS(MZ) for MPI

Need to choose one:

- ▶ several independent groups/methodologies

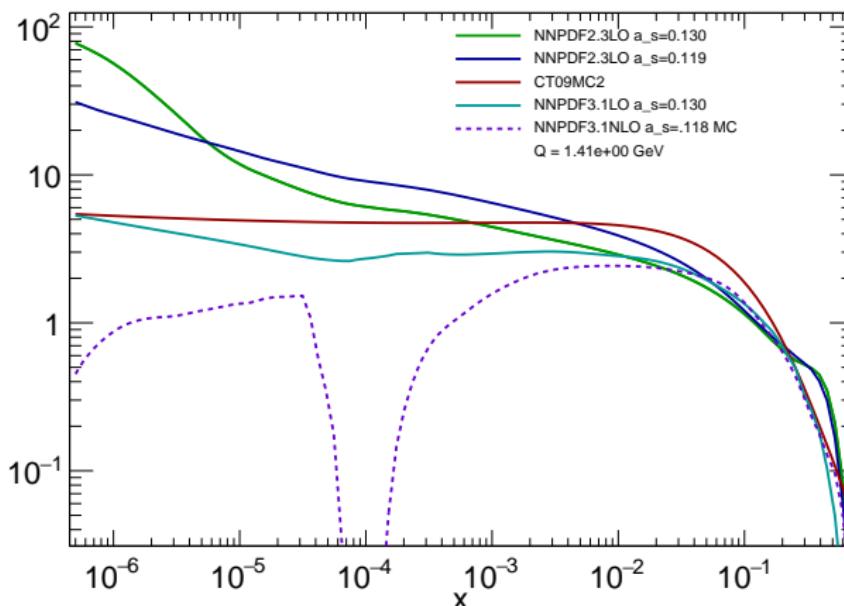
Impacts physics in several places:

- ▶ parton shower
- ▶ multi-parton interactions
- ▶ kinematics of hard process
- ▶ used at high AND low Q^2

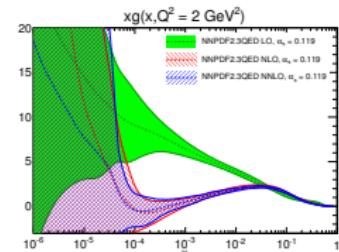
Behavior of different PDFs

Different approaches, assumptions

$xg(x, Q)$, comparison



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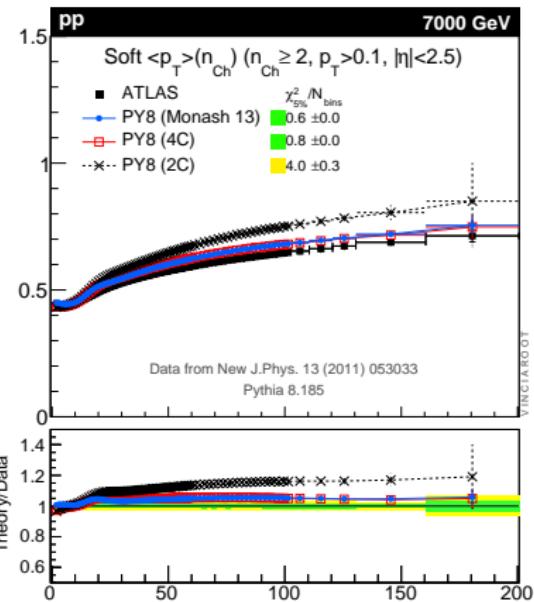
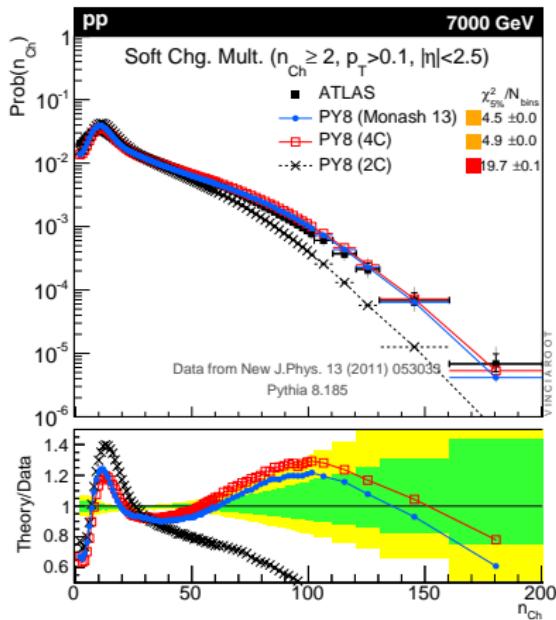
Eigenvalues or
replicas of equivalent
PDFs

Only central values shown

$x g(x, Q^2) < 0$ sensible, but algorithms must know about it.

Multi-Parton-Interaction (MPI), Color-Reconnection (CR), and Diffractive parameters.

MPI Parameters	Monash 13	(Default)	Comment
MultipartonInteractions:pT0Ref	= 2.28	= 2.085	! MPI pT0 IR regularization scale
MultipartonInteractions:ecmRef	= 7000.0	= 1800.0	! MPI pT0 reference ECM scale
MultipartonInteractions:ecmPow	= 0.215	= 0.19	! MPI pT0 scaling power
MultipartonInteractions:bProfile	= 3	= 3	! Transverse matter overlap profile
MultipartonInteractions:expPow	= 1.85	= 2.0	! Shape parameter
BeamRemnants:reconnectRange	= 1.8	= 1.5	! Color Reconnections
SigmaTotal:zeroAXB	= on	= on	! Carried over from 4C
SigmaDiffractive:dampen	= on	= on	! Carried over from 4C
SigmaDiffractive:maxXB	= 65.0	= 65.0	! Carried over from 4C
SigmaDiffractive:maxAX	= 65.0	= 65.0	! Carried over from 4C
SigmaDiffractive:maxXX	= 65.0	= 65.0	! Carried over from 4C
Diffraction:largeMassSuppress	= 4.0	= 2.0	! High-mass diffraction suppression power



pT0Ref :: number of interactions,
naive number of strings

range :: color reconnections that alter string lengths, p_T of hadrons

The Eternal Struggle

Started out with intent to use simple principles.

Spent rest of life making increasingly complex models/codes.

You spend 10% of the effort and code to get to 90% of the physics, and then the going gets tough.

Particle physics is more complex than we would wish, but simpler than it could have been.

Why stick with event generators?

Our objective is to understand physics, not to write code.

But often code offers a unique way to gain insight.