Jet Mass Spectrum for Groomed and Ungroomed Top Jets

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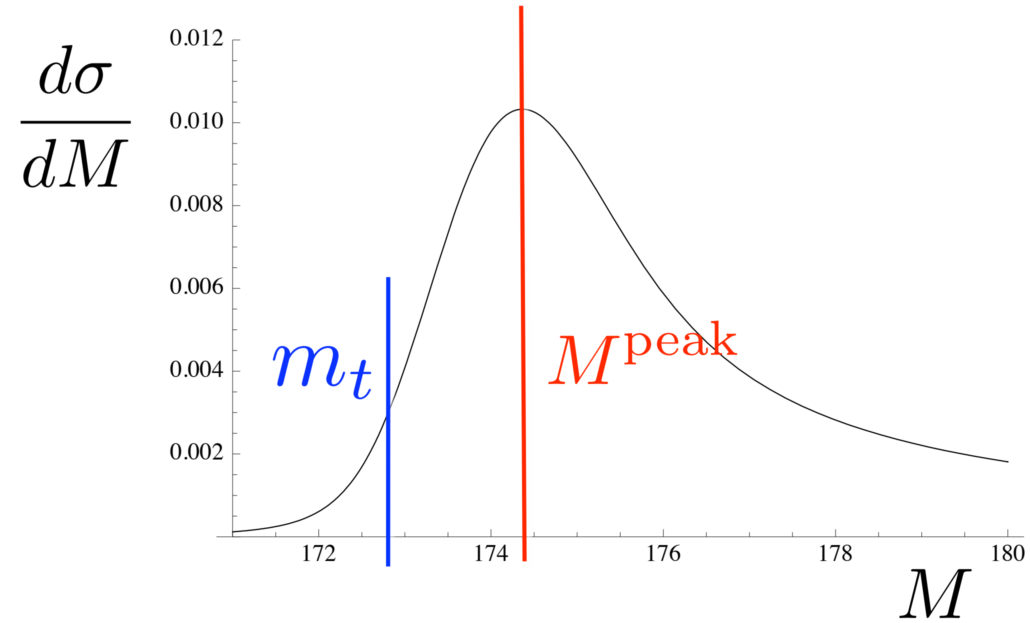
based on: Hoang, Mantry, Pathak, IS (1708.02586 + ongoing work)

Sante Fe Jets and Heavy Flavor Workshop
January 2018

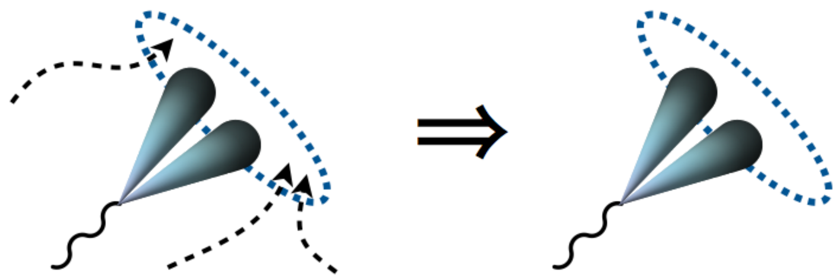
Outline

- Motivation for Studying Top Jets:
  Top Mass from Jet Mass measurement
  Quantify Soft Effects

$$M^2 = \Big(\sum_{i\in J} p_i^\mu\Big)^2$$



- Factorization Theorems: Ungroomed and Groomed



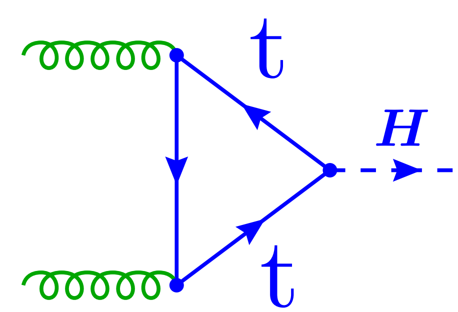
- Calibration of Monte Carlo and Comparisons

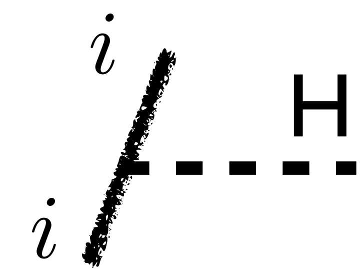
- Conclusion

The Top Quark is Special

- Largest Mass $m_t = 173\,\mathrm{GeV}$ → Largest Higgs Coupling

Dominates Higgs Production



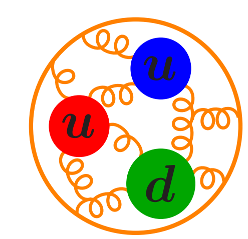


$\propto m_i$

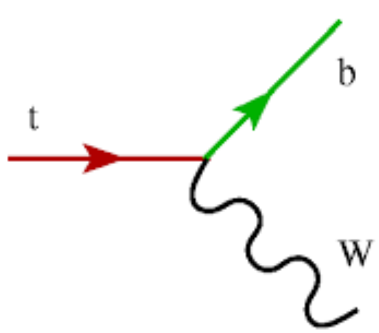
- The only quark that decays before it binds into a hadron

Top width $\Gamma_t = 1.4\,\mathrm{GeV} \quad > \quad \Lambda_{\mathrm{QCD}} \simeq 0.3\,\mathrm{GeV}$

confinement scale



$t \to bW$



The Top Quark is Special

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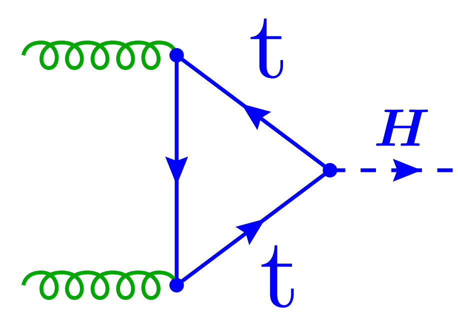

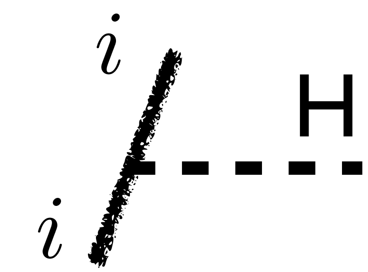

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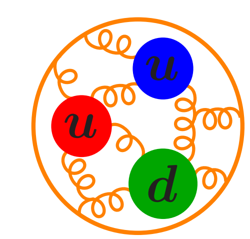

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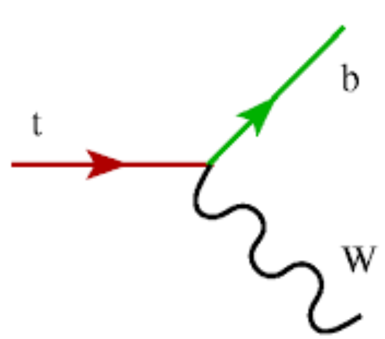
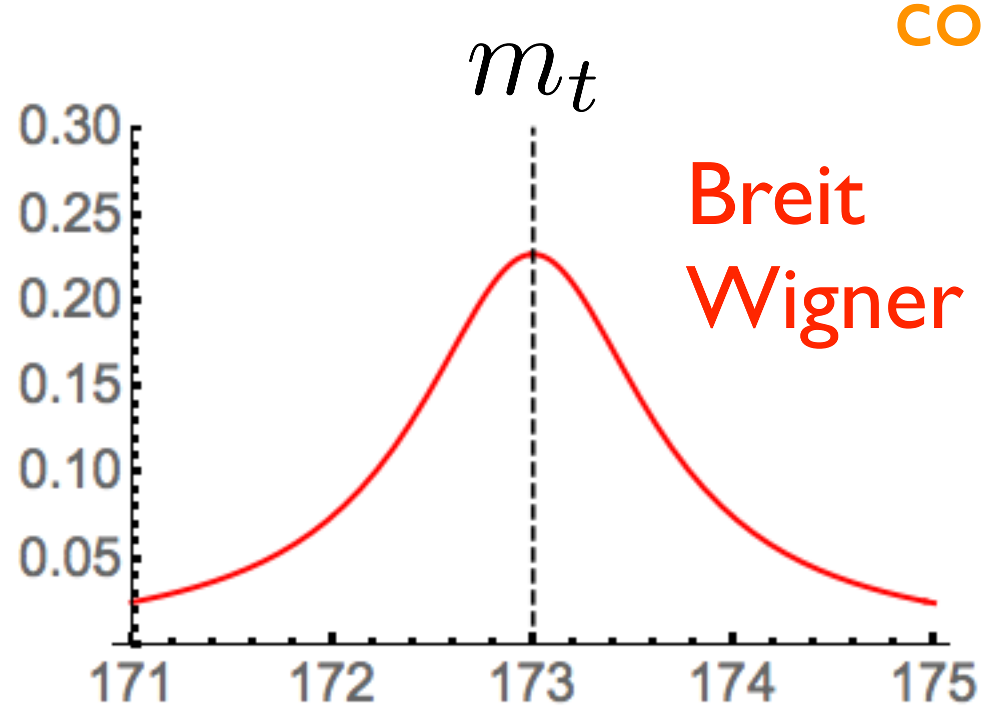


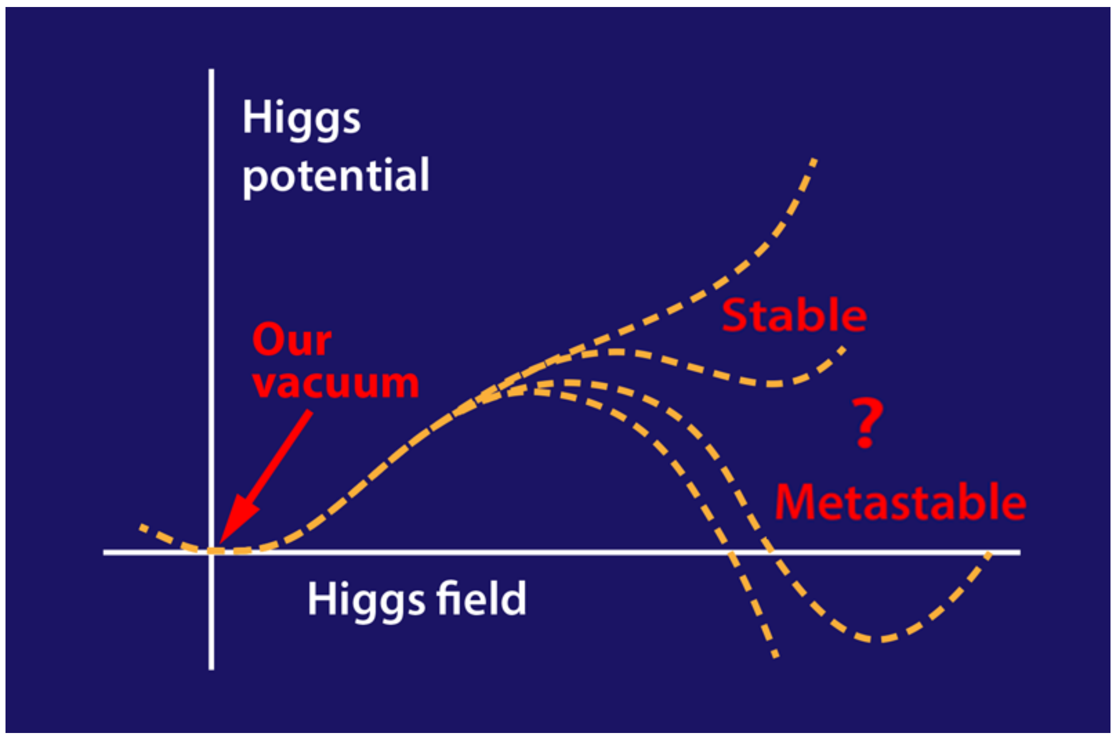


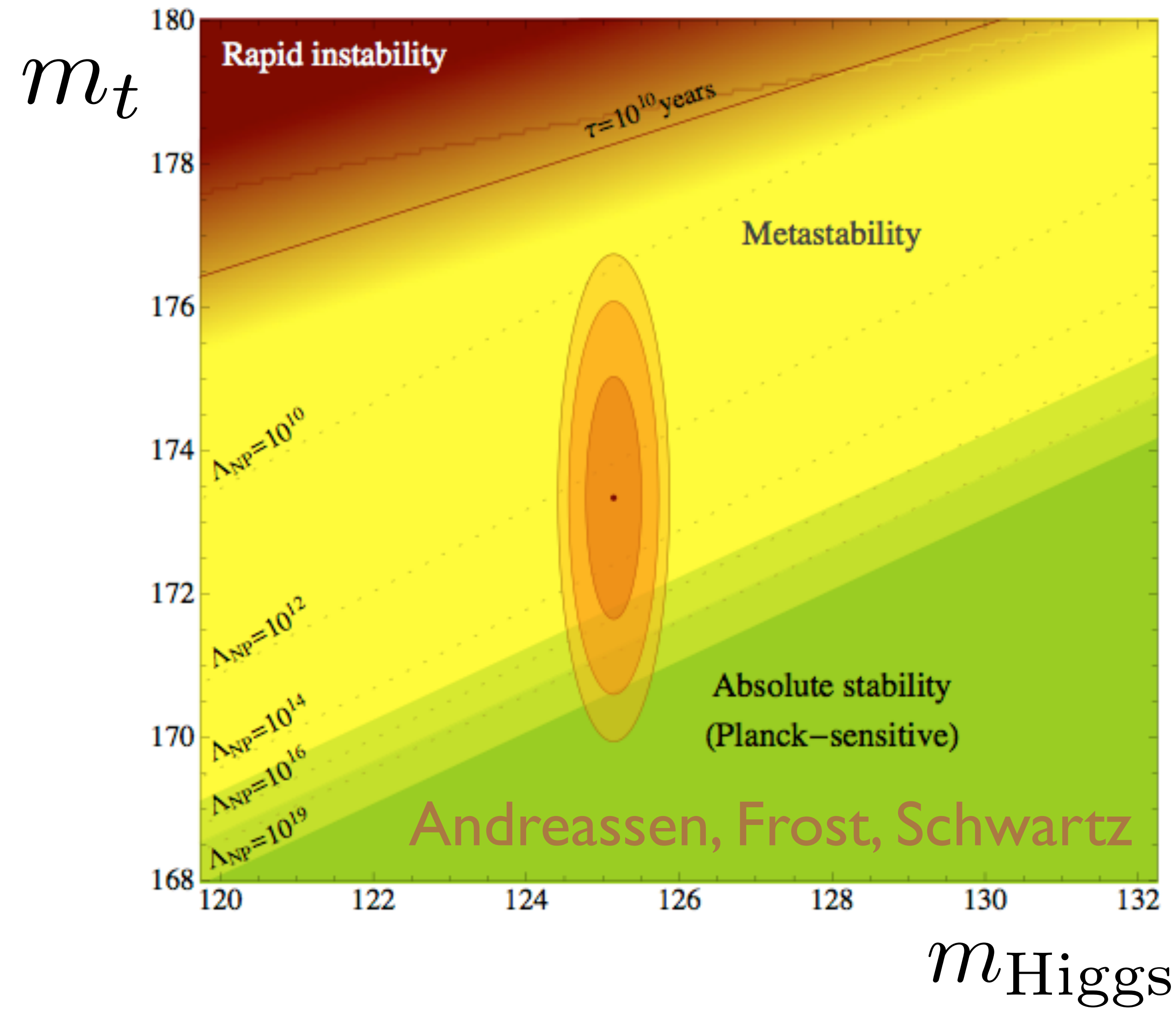
Breit Wigner

$$\frac{1}{\left(\frac{q^2 - m_t^2}{m_t}\right)^2 + \Gamma_t^2}$$

Why should I care about a precision m_t ?

- Stability of the Standard Model vacuum!





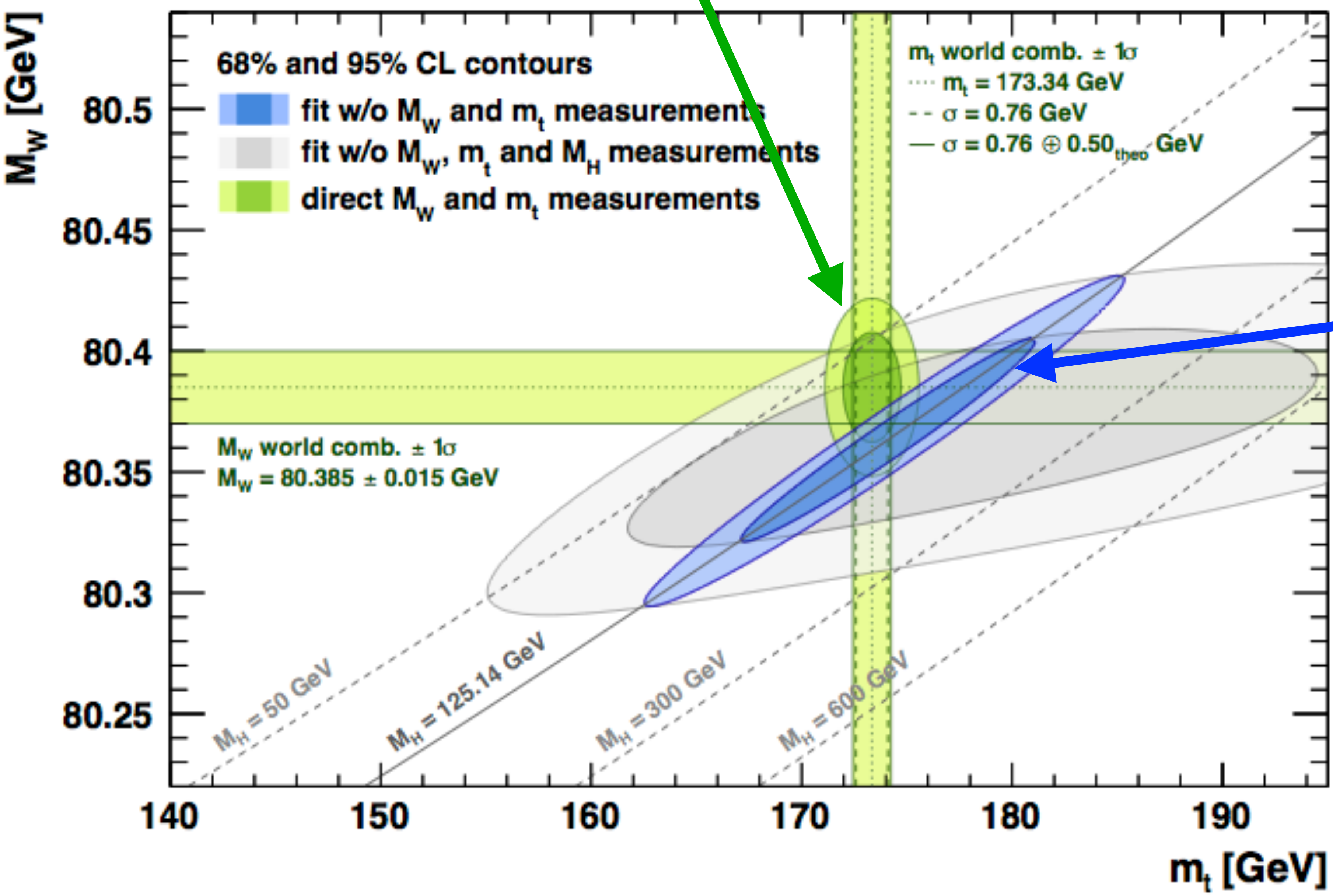
uncertainty dominated by m_t

Butazzo, Degrassi, Giardino, Giudice, Sala

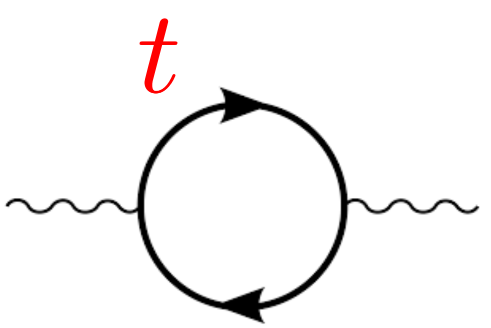
- Precision Electro-weak Measurements

Direct Measurements

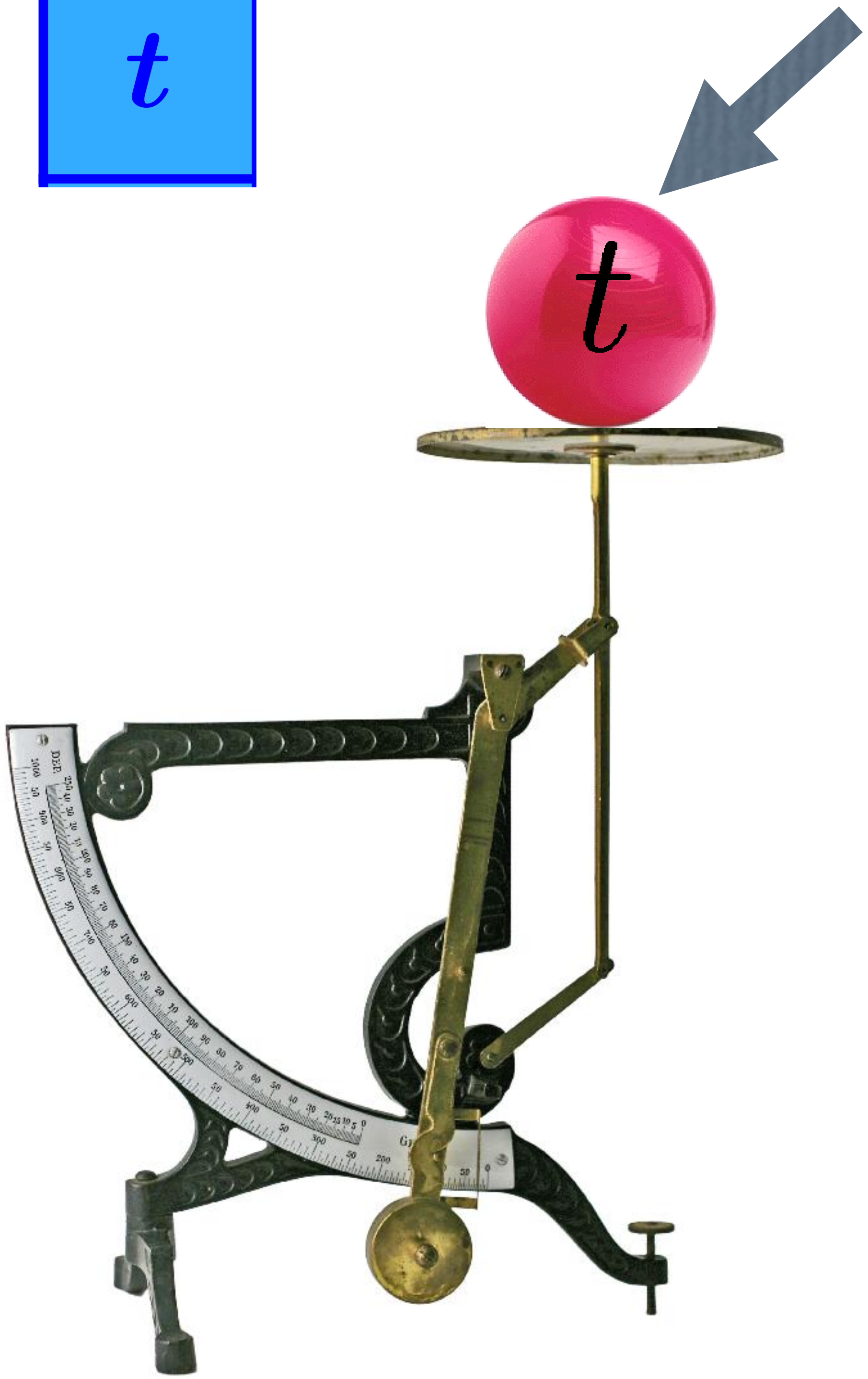
Gfitter group, 2014



Indirect Global Fit



t

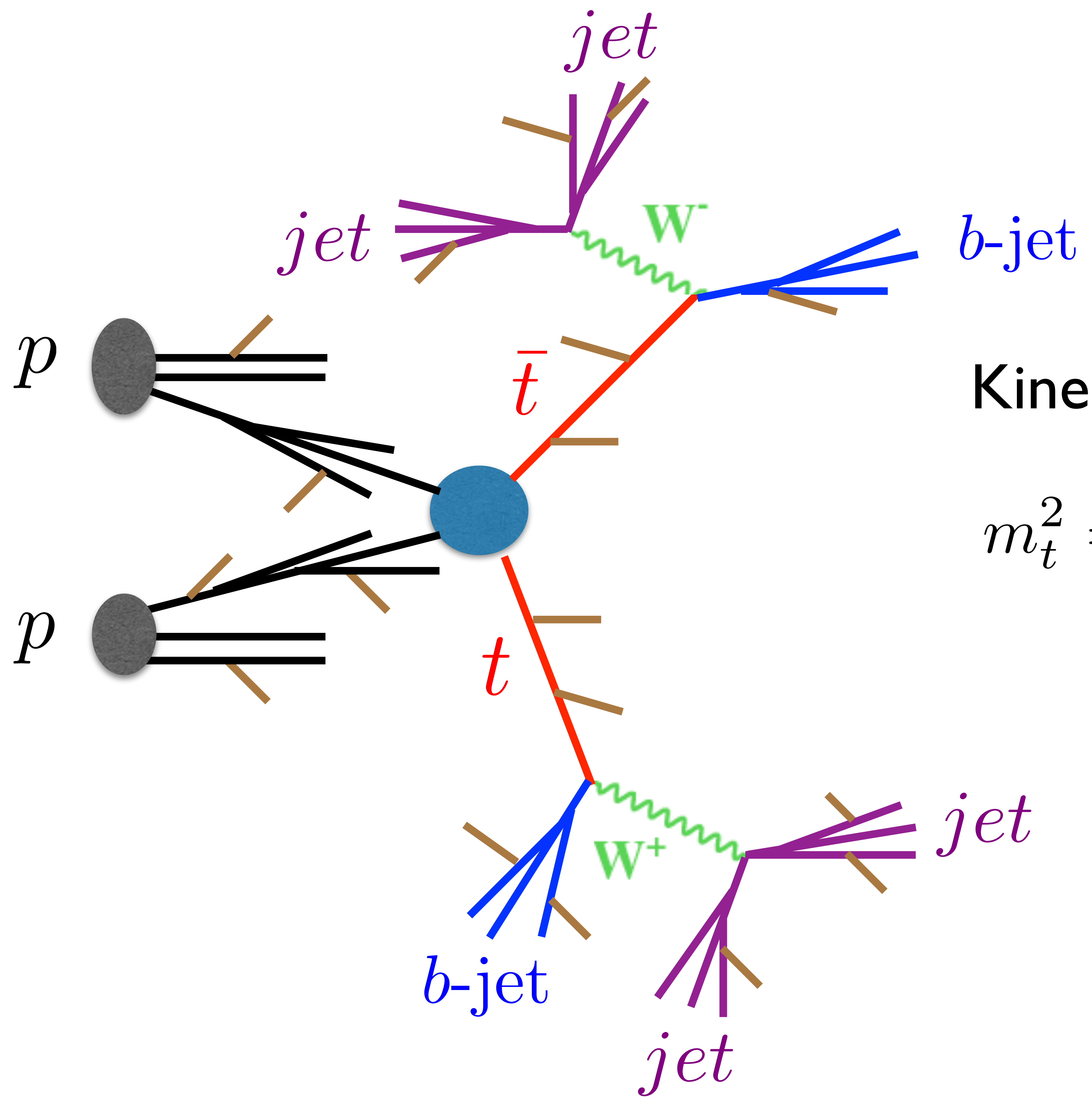


Heaviest known elementary particle.
As heavy as 180 protons!

Tevatron	$m_t^{\mathrm{MC}} = 174.34 \pm 0.64 \quad \mathrm{GeV}$
CMS	$m_t^{\mathrm{MC}} = 172.44 \pm 0.49 \quad \mathrm{GeV}$
ATLAS	$m_t^{\mathrm{MC}} = 172.84 \pm 0.70 \quad \mathrm{GeV}$

measured from jets with help of Monte Carlo simulations

Direct Reconstruction Methods (Tevatron & LHC)



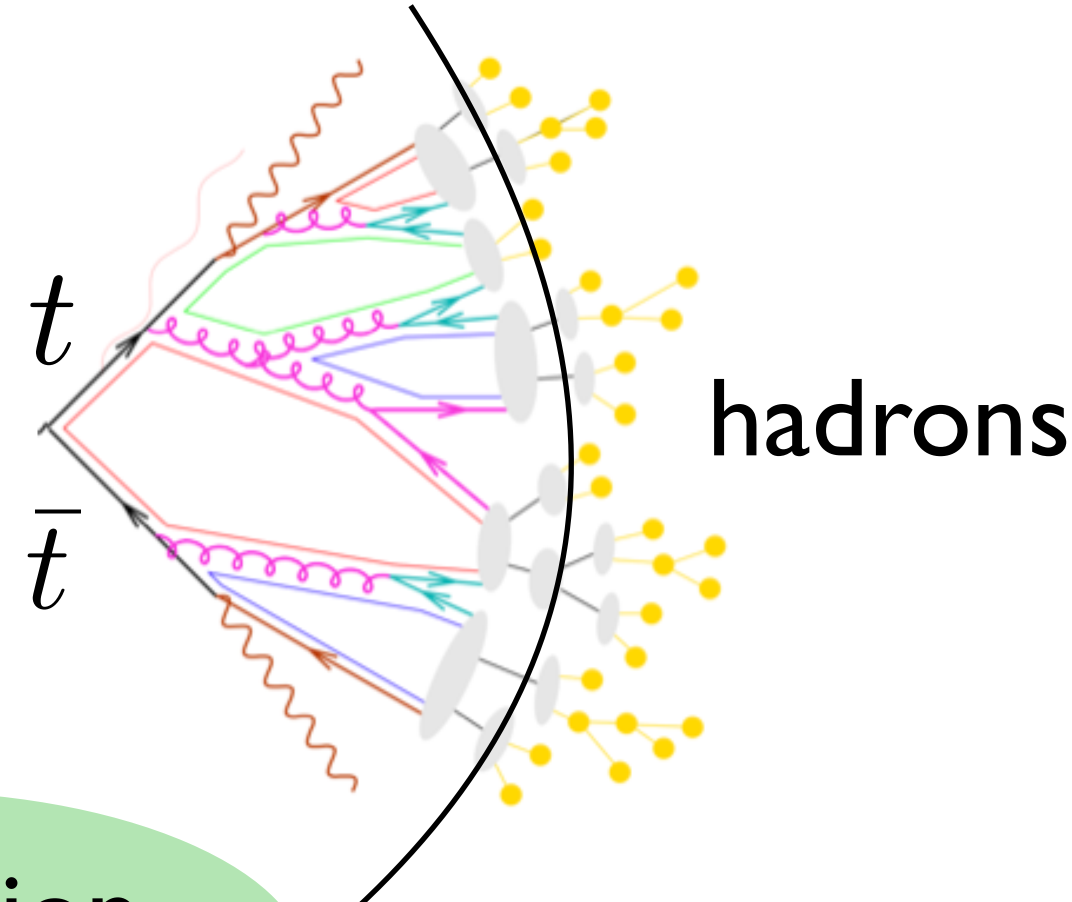
Kinematic Fit:

$$m_t^2 = p_t^2 = (p_{Jb} + p_{J1} + p_{J2})^2$$

$\mathcal{L}:$

$m_t^{\rm pole}, \overline{m}_t, m_t^{\rm MSR}, \ldots$

Theory (QFT)



$\Lambda^{\rm shower} = 1\,{\rm GeV}$

Simulation
(Monte Carlo)

$m_t^{\rm MC}$

Experiment

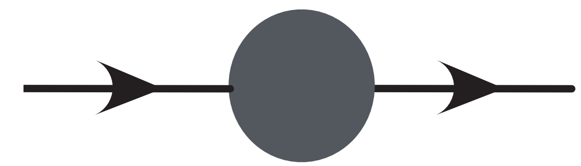
Definition ?

$m_t = m_t^{\rm MC} + \,?$

an additional uncertainty $\sim 1\,{\rm GeV}$

Mass Definitions:

- **Pole Mass**



$$\propto \frac{1}{\not{p} - m_t^{\rm pole}}$$

Mass that naturally appears in Breit Wigner.

Has a (renormalon) ambiguity $\Delta m_t^{\rm pole} \sim \Lambda_{\rm QCD}$

- $\overline{\rm MS}$ **Mass** $\overline{m}_t$

No Ambiguity. ✓ Not compatible with Breit Wigner. X

$$m_t^{\rm pole} = \overline{m}_t + \underbrace{0.4\,\alpha_s \overline{m}_t}_{7\,{\rm GeV}} + \ldots \qquad 7\,{\rm GeV} \gg \Gamma_t = 1.4\,{\rm GeV}$$

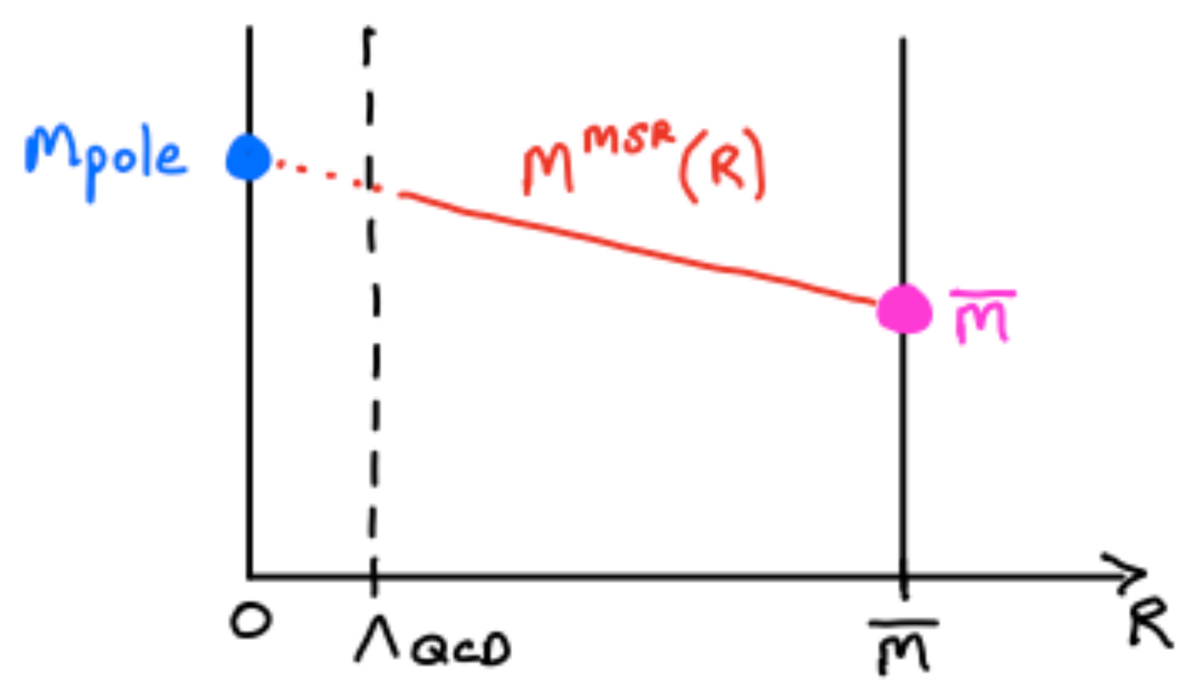
- **MSR Mass** $m^{\rm MSR}(R)$ (Hoang, Jain, Scimemi, IS, 2008)

a mass which nicely interpolates

take $R = 1\,{\rm GeV}$

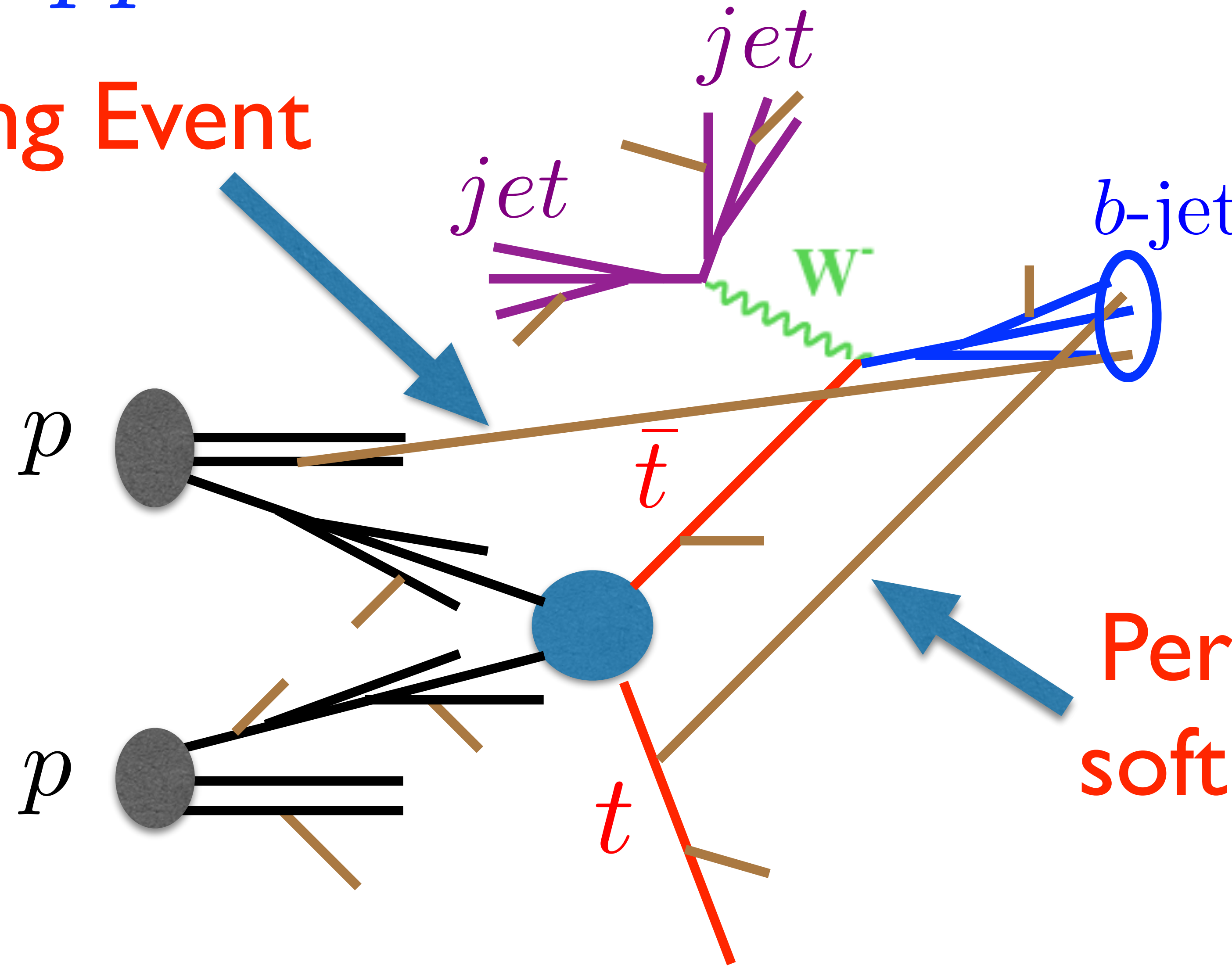
No Ambiguity $R > \Lambda_{\rm QCD}$ ✓

Breit Wigner $R \sim \Gamma_t$ ✓



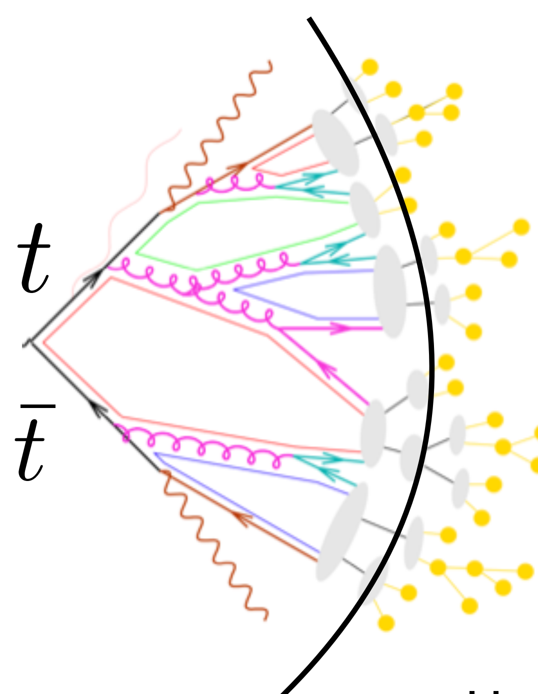
Soft Effects in $pp \to t\bar{t}X$

MPI / Underlying Event



Perturbative soft radiation

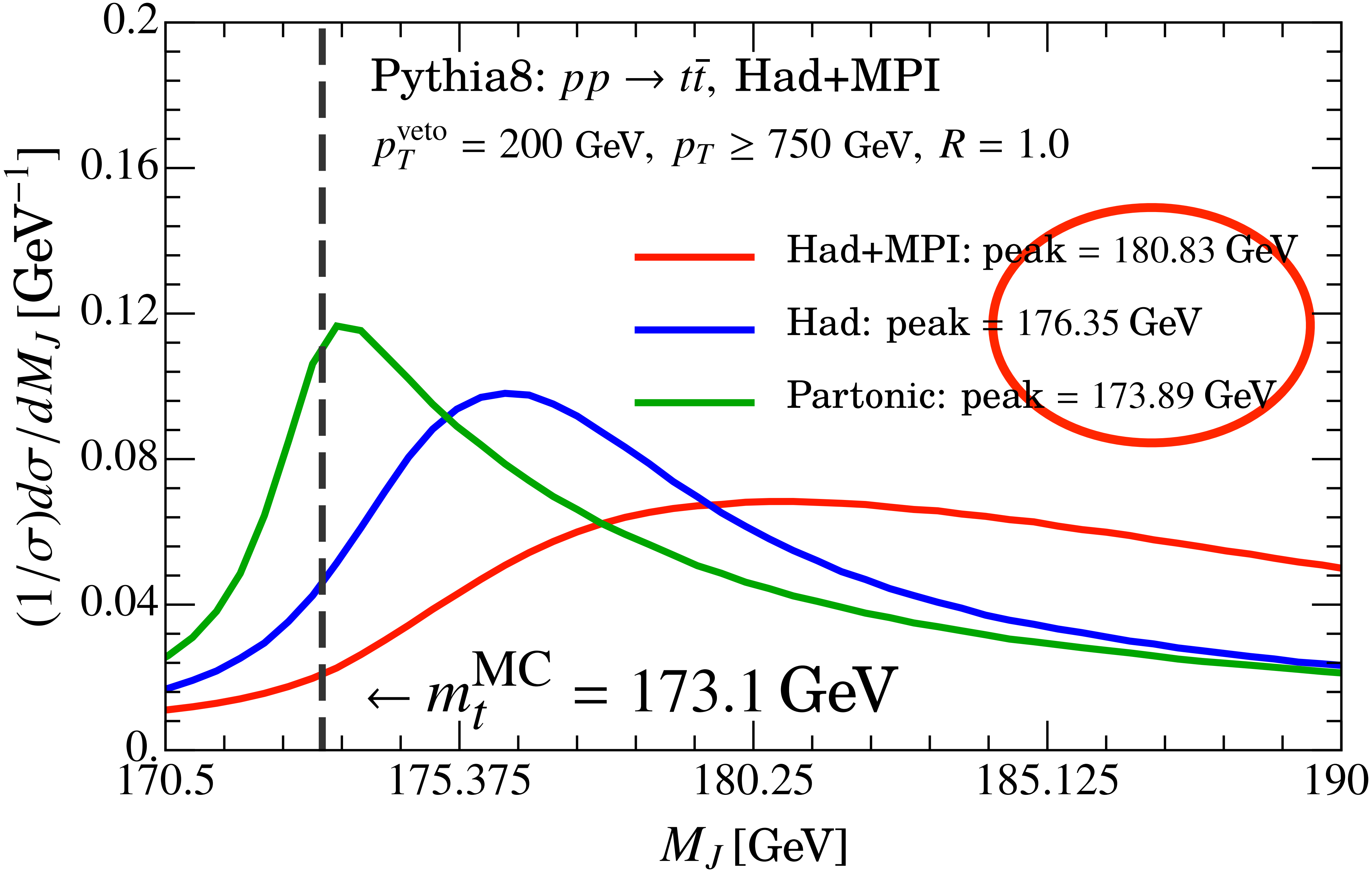
Hadronization



hadrons

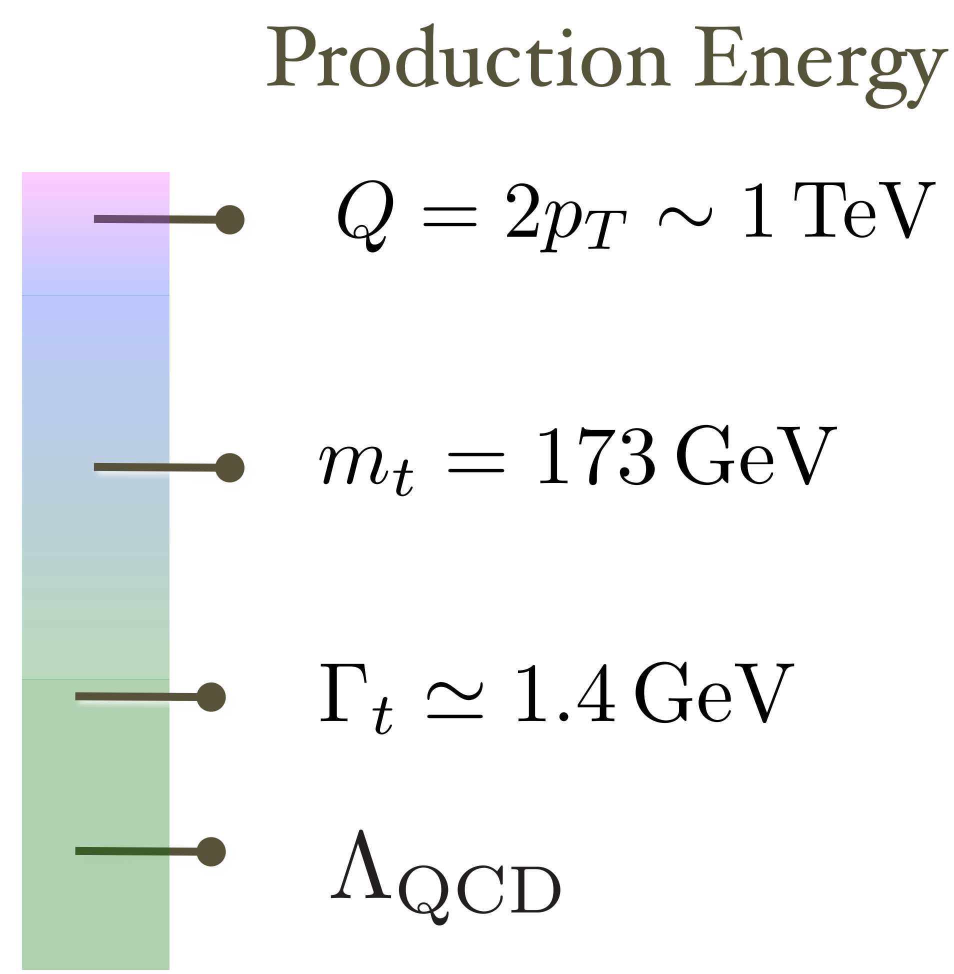
$pp \to t\bar{t}$

Soft Effects can be significant. eg. Jet Mass in Pythia



Theory Issues for $pp \to t\bar{t}X$

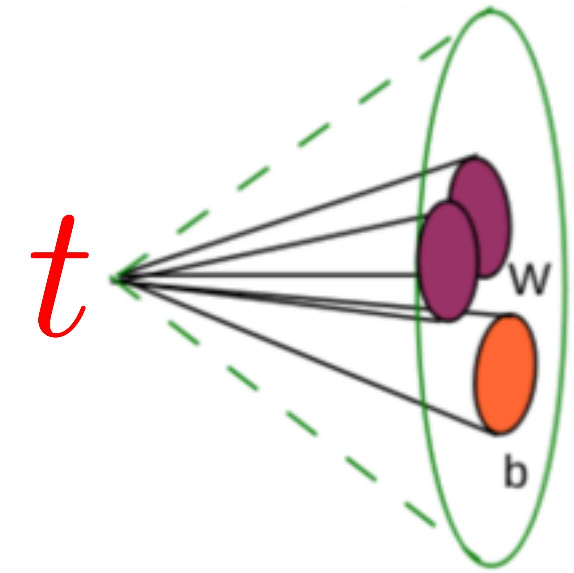
- jet observable
- suitable top mass scheme for jets
- initial state radiation
- final state radiation
- underlying event/MPI
- color reconnection
- parton distributions
- sum large logs $Q \gg m_t \gg \Gamma_t$
- hadronization



First simplification:

- boosted top quarks, $Q = 2p_T \gg m_t$

  enables us to be inclusive over decay products



Use EFT tools:

Soft-Collinear EFT (SCET)

Heavy Quark EFT (HQET)

factorization, logs,
non-perturbative effects

$Q = 2p_T \sim 1\,\text{TeV}$

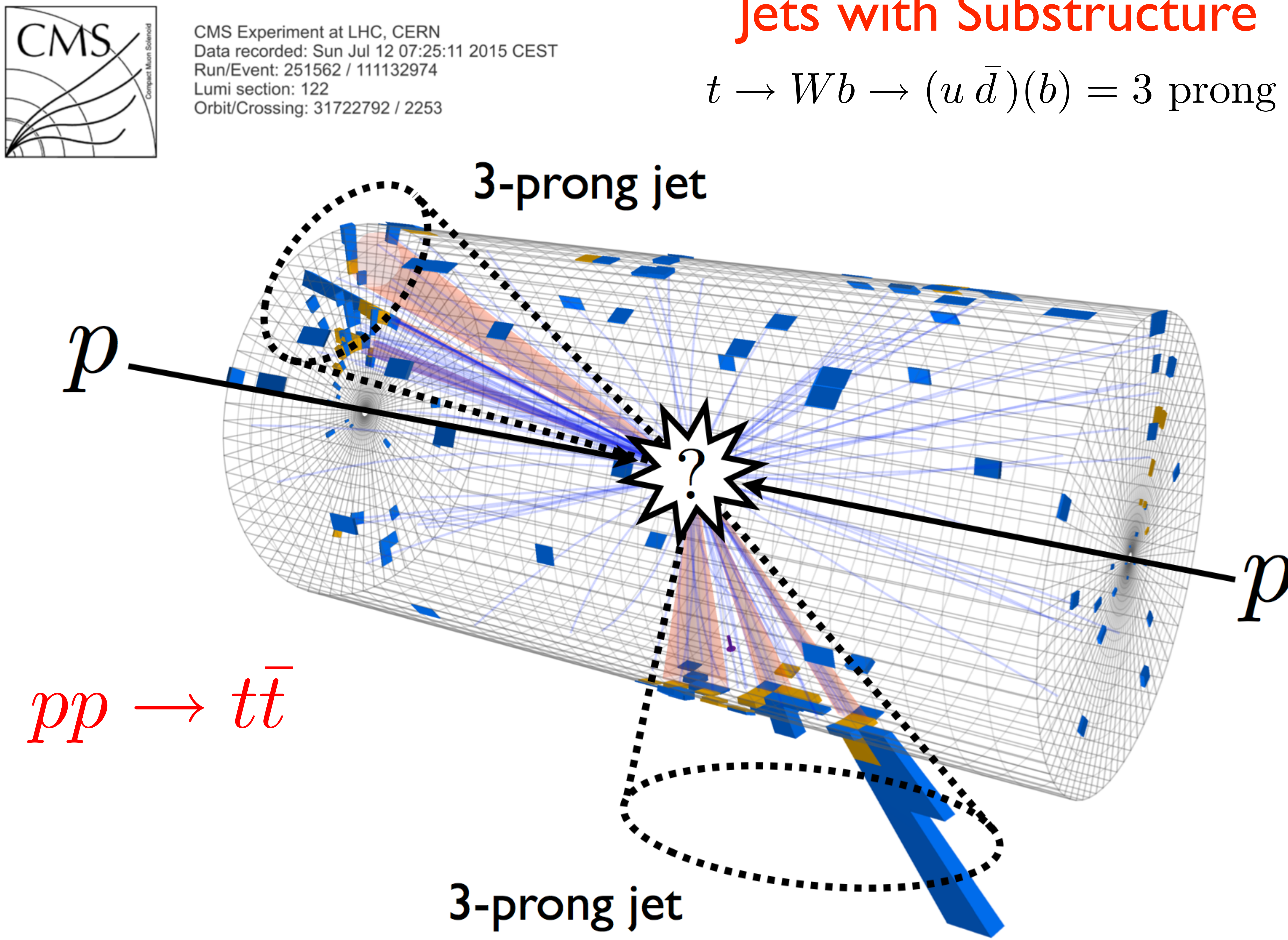
$m_t = 173\,\text{GeV}$

$\Gamma_t \simeq 1.4\,\text{GeV}$

Λ_{QCD}

Jets with Substructure

$$t \to Wb \to (u\,\bar{d})(b) = 3 \text{ prong jet}$$



$$pp \to t\bar{t}$$

Theory Issues for $pp \to t\bar{t}X$

- jet observable ★
- suitable top mass for jets ★
- initial state radiation
- final state radiation ★
- underlying event/MPI
- color reconnection ★
- parton distributions
- sum large logs $Q \gg m_t \gg \Gamma_t$ ★
- hadronization ★

First

$e^+e^- \to t\bar{t}X$

and the issues ★

Factorization for double jet-mass:

Fleming, Hoang, Mantry, IS (2007)

Hard Functions

control over mass scheme

$$\left(\frac{d^2\sigma}{dM_t^2\, dM_{\bar t}^2}\right)_{\rm hemi} = \sigma_0 H_Q(Q,\mu_m) H_m\Big(m,\frac{Q}{m},\mu_m,\mu\Big)$$
$$\times J_B\Big(\hat s_t - \frac{Q\ell}{m},\Gamma,\delta m,\mu\Big) J_B\Big(\hat s_{\bar t} - \frac{Q\ell'}{m},\Gamma,\delta m,\mu\Big) S_{\rm hemi}(\ell-k,\ell'-k',\mu) F(k,k')$$

Answer

QCD

SCET

HQET

(boosted HQET)
Jet Functions

Evolution and decay of top quark close to mass shell

$$\hat s_t \equiv \frac{M_t^2 - m^2}{m} \sim \Gamma \ll m$$

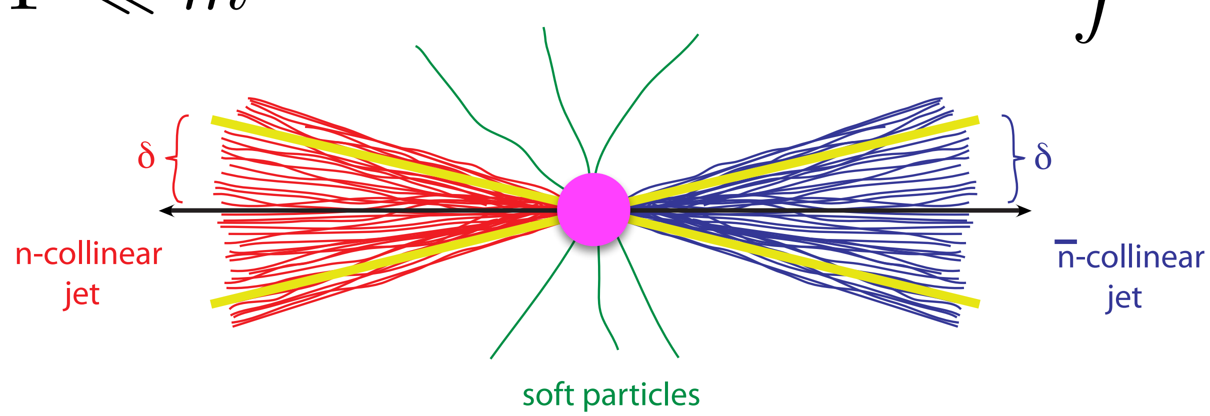
Soft Function

Perturbative Cross talk

Hadronization

dominant effect is from first moment

$$\Omega_1 = \int dk'\, dk\, k\, F(k,k')$$



Factorization for double jet-mass:

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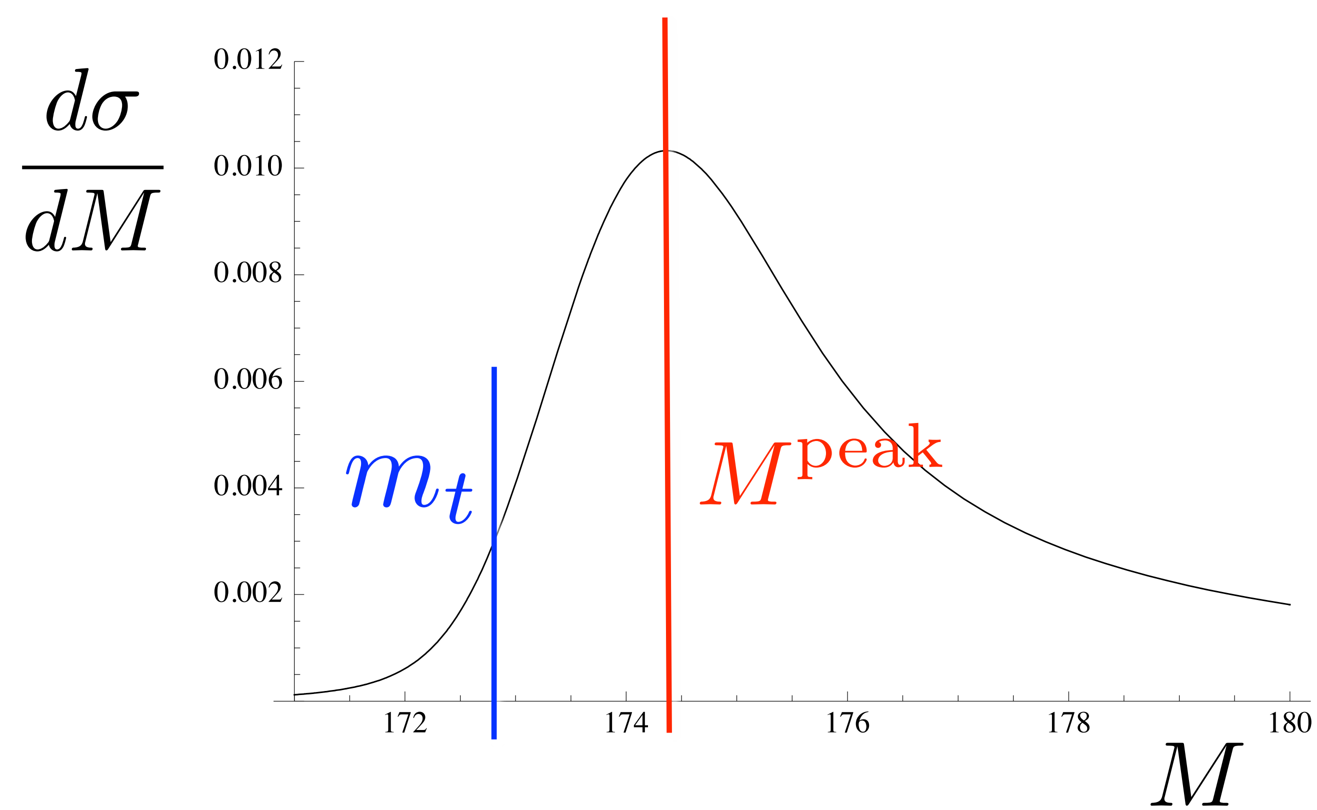
Answer

$$\left(\frac{d^2\sigma}{dM_t^2\,dM_{\bar t}^2}\right)_{\text{hemi}} = \sigma_0 H_Q(Q,\mu_m) H_m\Big(m,\frac{Q}{m},\mu_m,\mu\Big)$$
$$\times J_B\Big(\hat s_t - \frac{Q\ell}{m},\Gamma,\delta m,\mu\Big) J_B\Big(\hat s_{\bar t} - \frac{Q\ell'}{m},\Gamma,\delta m,\mu\Big) S_{\text{hemi}}(\ell-k,\ell'-k',\mu) F(k,k')$$

$$M^{\text{peak}} \simeq m_t + \Gamma_t(\alpha_s + \alpha_s^2 + \ldots) + \frac{Q\Omega_1}{m_t}$$

measure this

extract this



One application: Top Mass Calibration

Butenschoen, Dehnadi, Hoang, Mateu, Preisser, IS
PRL 2016

$$m_t = m_t^{\mathrm{MC}} + \underbrace{\ldots}$$

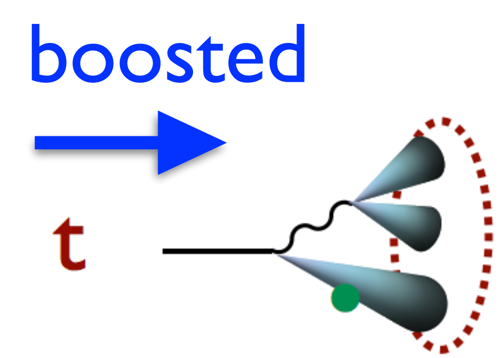
determined by fit to common observable

$$\frac{d\sigma}{d\tau_2} = f(m_t^{\mathrm{MSR}}, \alpha_s(m_Z), \Omega_1, \Omega_2, \ldots, \mu_H, \mu_J, \mu_S, \mu_M, R, \Gamma_t)$$

$$\tau_2 \sim M_t^2 + M_{\bar{t}}^2$$

any scheme — non-perturbative — renorm. scales — finite lifetime

$$m_t^{\mathrm{pole}}, \overline{m}_t, m_t^{\mathrm{MSR}}, \ldots$$



Theory (QFT)

$e^+e^- \to t\bar{t}$
calibration

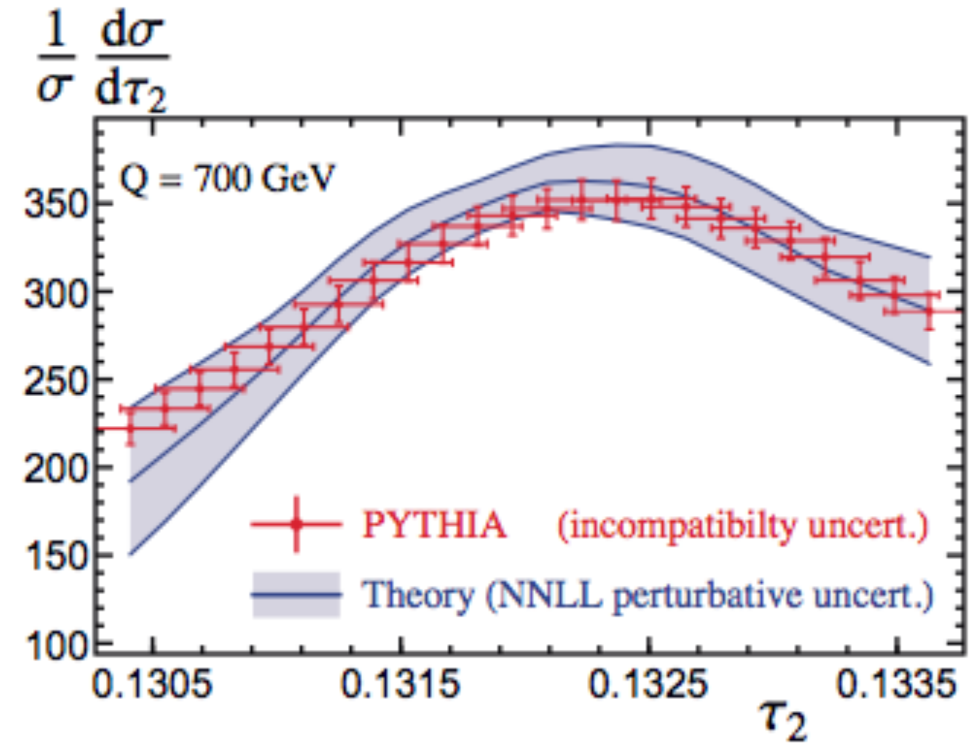
Simulation
(Monte Carlo)

$e^+e^- \Longrightarrow pp$

Experiment

m_t^{MC}

Example from Fit to Pythia8 Simulation:



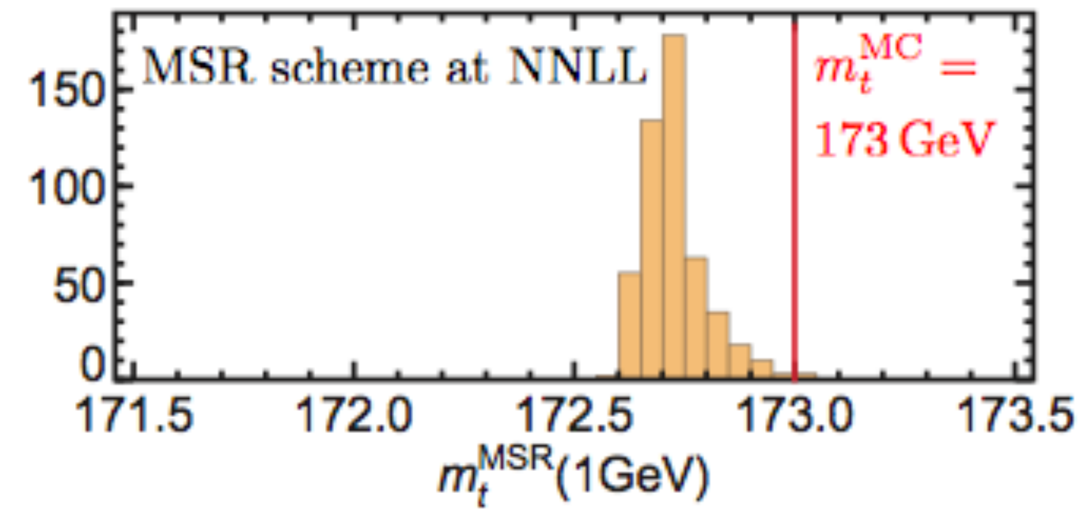
Results:

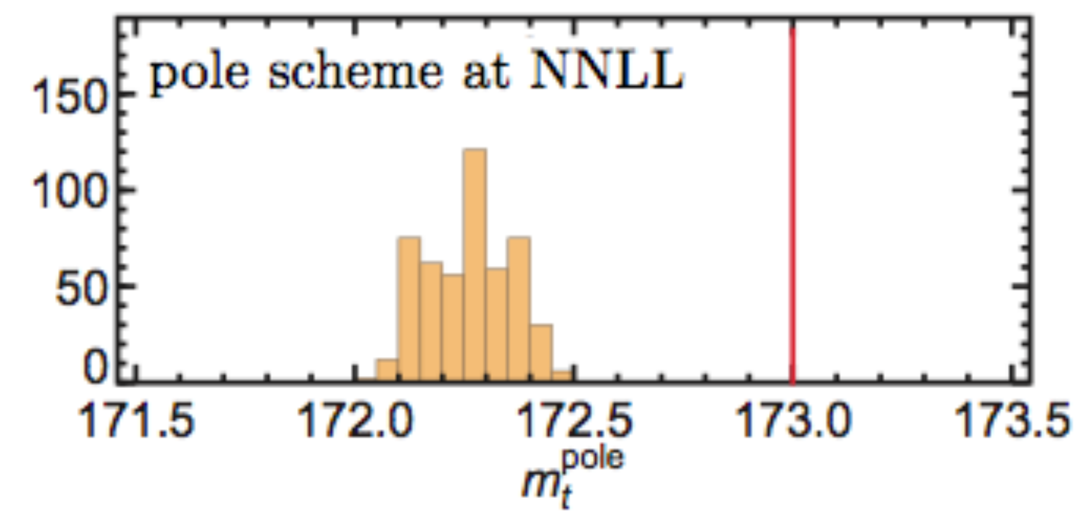
- Depend on which QFT based theory mass is used for fit.
- Provides uncertainties:

$$\text{input: } m_t^{\text{MC}} = 173\,\text{GeV}$$

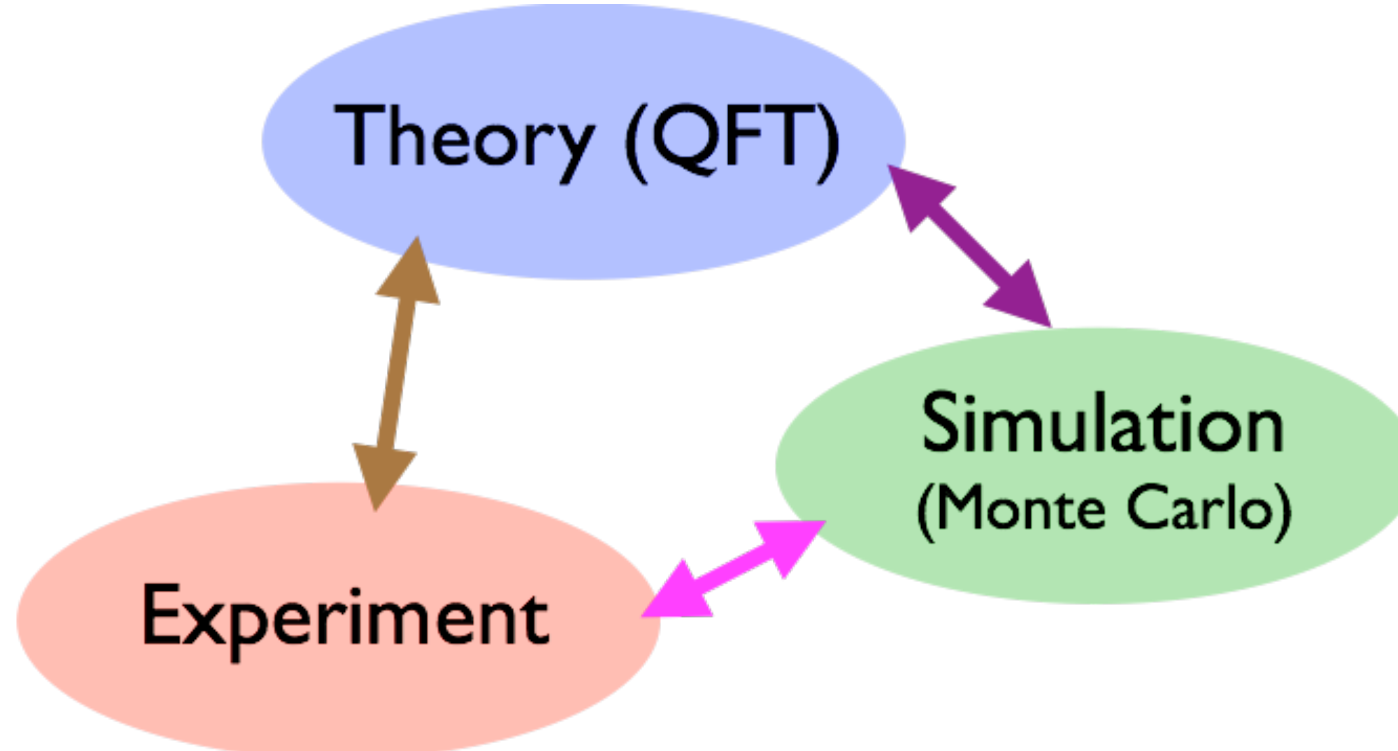
$$m_t^{\text{pole}} = 172.43 \pm 0.28\,\text{GeV}$$

$$m_t^{\text{MSR}} = 172.82 \pm 0.22\,\text{GeV}$$



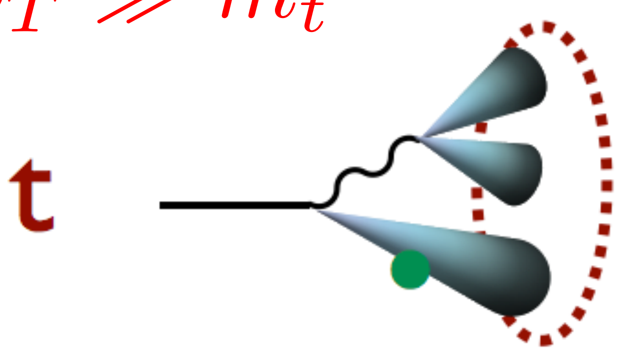


Calculate $pp \to t\bar{t}$



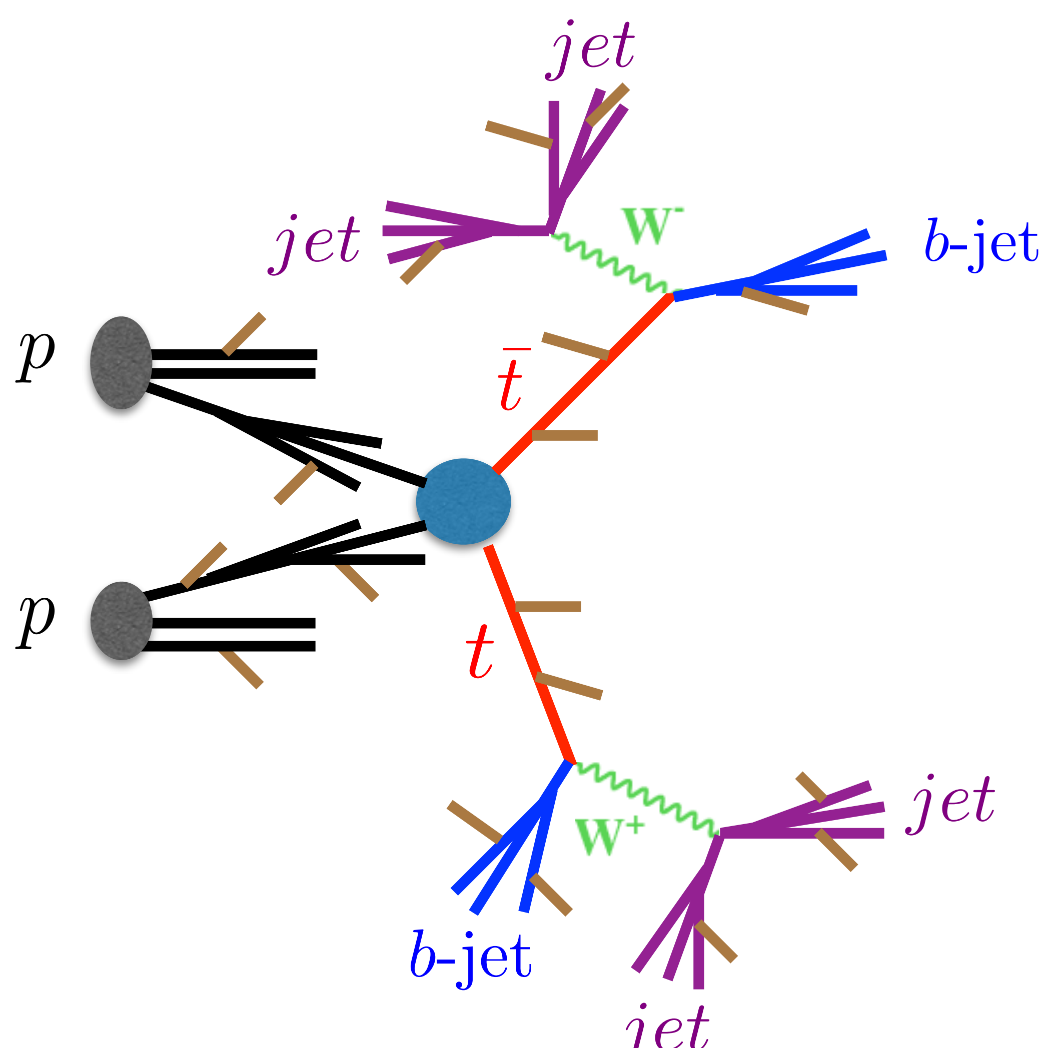
boosted top:

$p_T \gg m_t$



jet mass

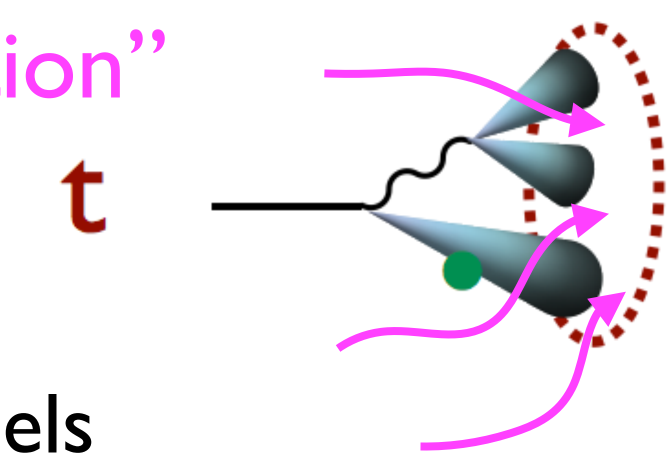
M_J



Theory Issues for $pp \to t\bar{t}X$

- jet observable $\star$ Jet Mass in Jet of radius R
- suitable top mass for jets $\star$
- initial state radiation $\star$ Jet veto
- final state radiation $\star$
- underlying event/MPI ← "contamination"
- color reconnection $\star$
- parton distributions $\star$ multiple channels
- sum large logs $Q \gg m_t \gg \Gamma_t$ $\star$
- hadronization $\star$

$\star$ can handle with SCET/HQET

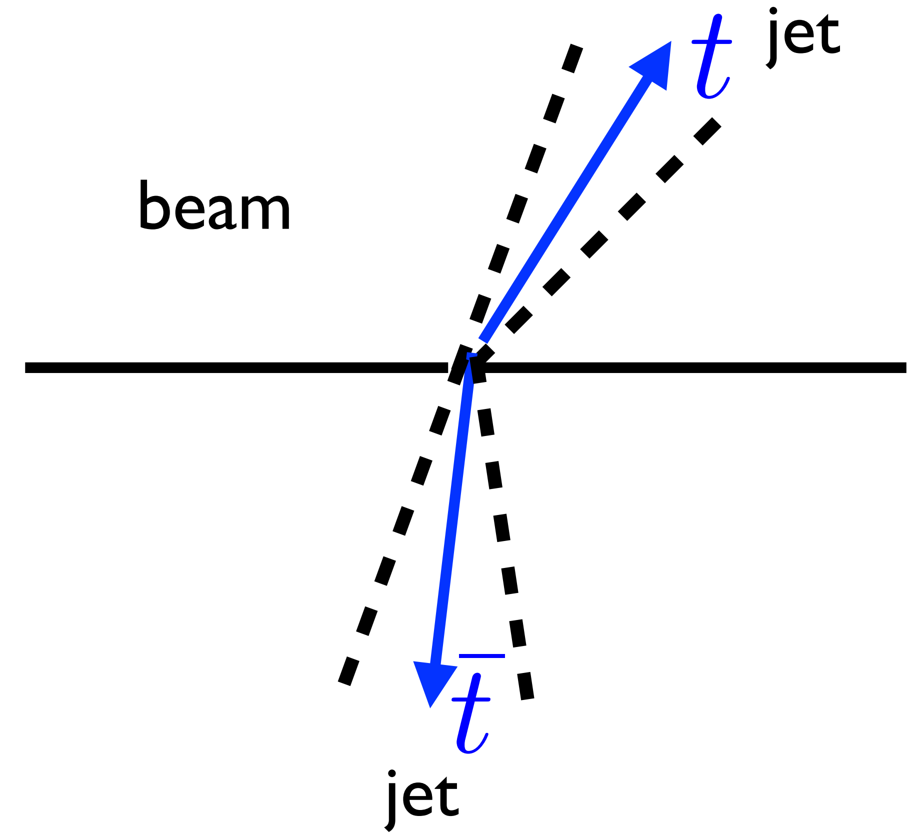


N-jettiness event shapes for hadron colliders

IS, Tackmann, Waalewijn (2010)

$$\mathcal{T}_2 = \min_{n_t, n_{\bar{t}}} \sum_i \min\{\rho_{\rm jet}(p_i, n_t), \rho_{\rm jet}(p_i, n_{\bar{t}}), \rho_{\rm beam}(p_i)\}$$

$$= \mathcal{T}_2^{t} + \mathcal{T}_2^{\bar{t}} + \mathcal{T}_2^{\rm beam}$$



$\mathcal{T}_2^{t} = \dfrac{M_{J1}^2}{Q_t}$ gives jet-mass

$\mathcal{T}_2^{\rm beam}$ gives jet-veto

Ungroomed Factorization Formula:

Hoang, Mantry, Pathak, IS (to appear soon)

$$\frac{d^2\sigma}{dM_{J1}^2 \, dM_{J2}^2 \, d\mathcal{T}_2^{\rm beam}} = {\rm tr}\Big[\hat{H}_{Qm} \hat{S}(\mathcal{T}_2^{\rm beam}, R, \ldots) \otimes F\Big] \otimes J_B \otimes J_B \otimes \mathcal{I}\mathcal{I} \otimes f\, f$$

PDFs

hard

pert. soft

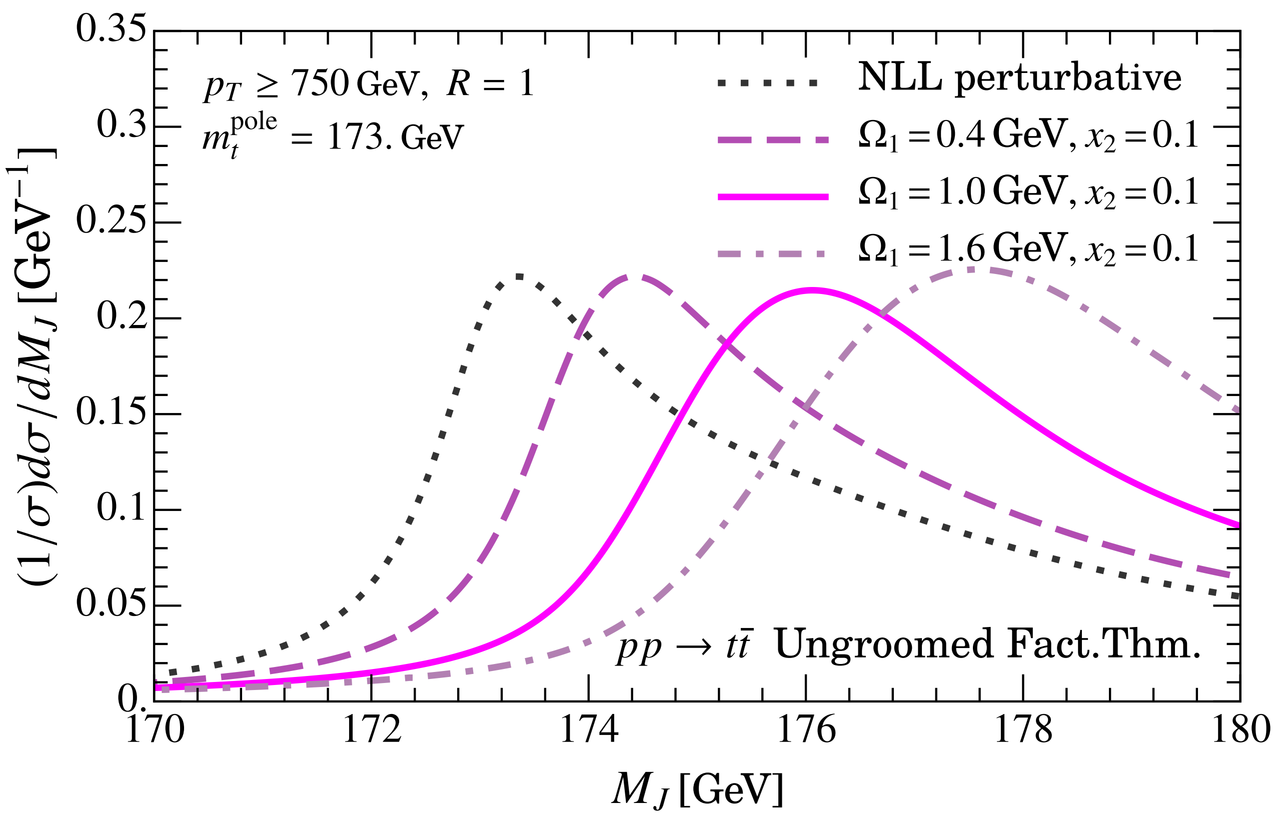
hadronization

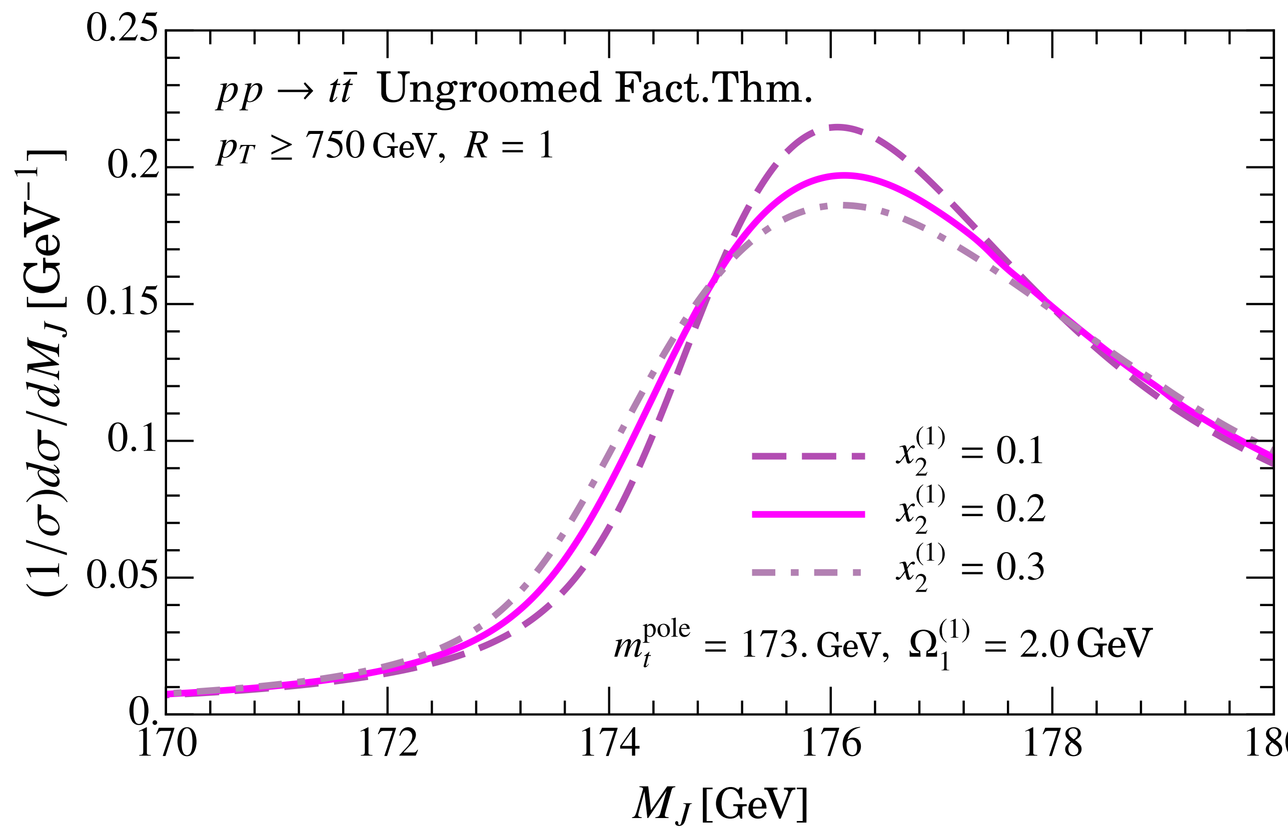
initial state radiation

same Jet functions!

generalizes ee result to LHC

Hadronization effects





first moment Ω_1 dominates

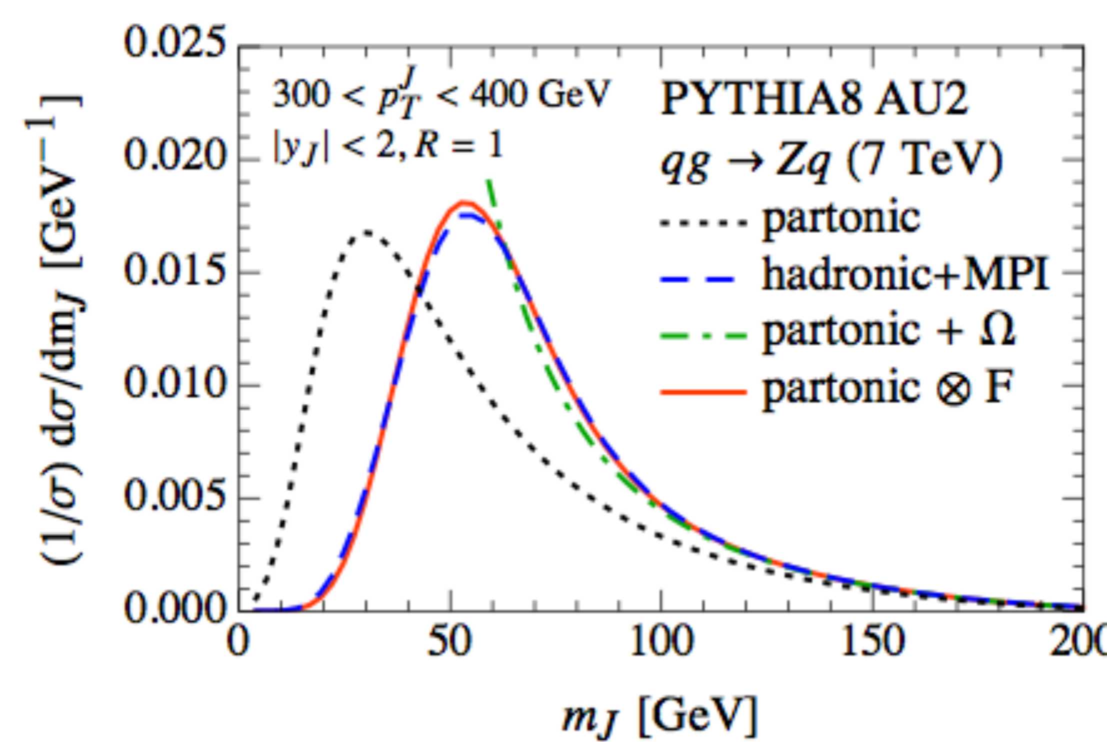
$$x_2 = \frac{\Omega_2 - \Omega_1^2}{\Omega_1^2}$$

higher moments Ω_2 , ... give smaller effects

MPI / UE effects: $\Omega_1^{\rm MPI}$

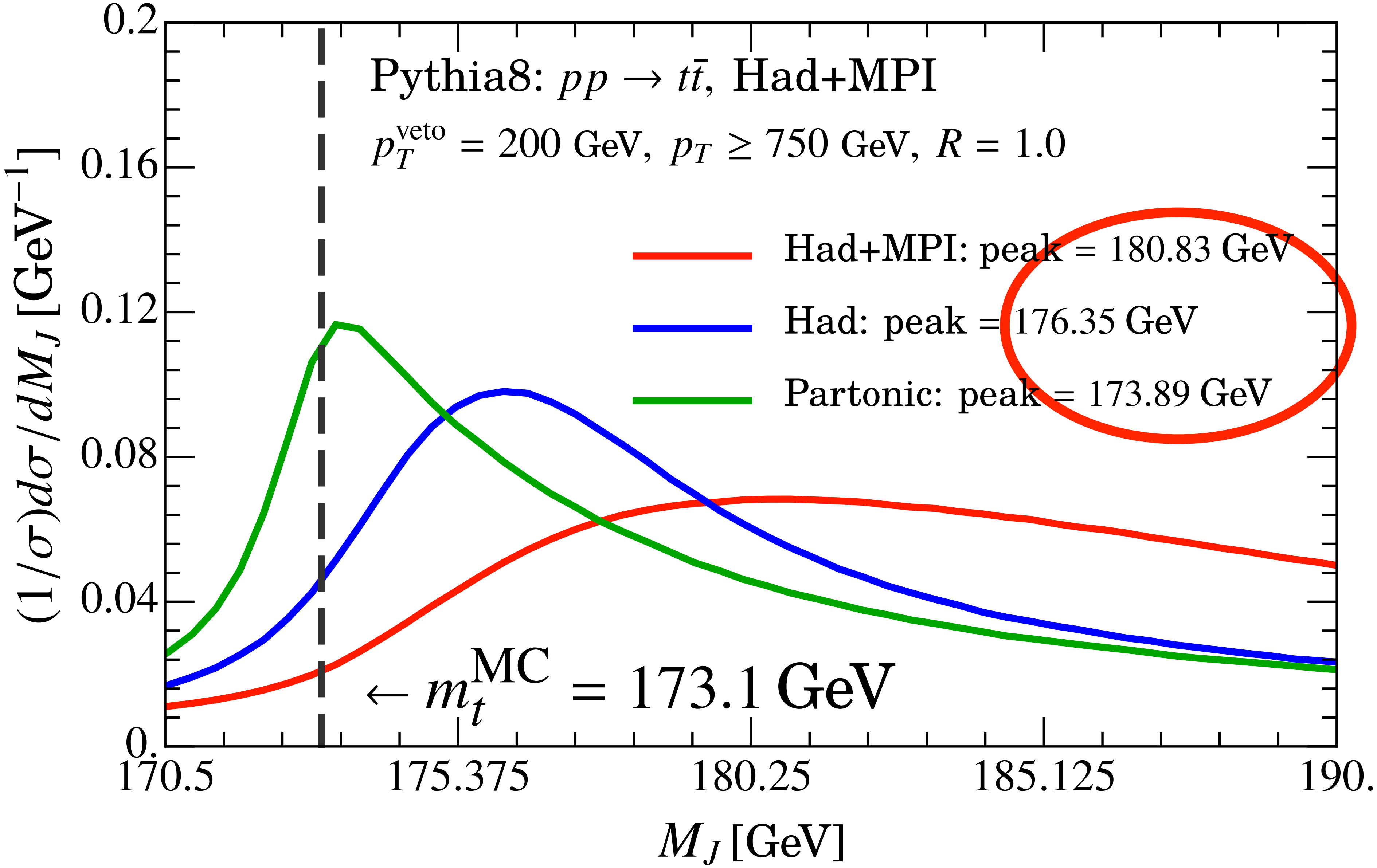
jet mass from massless quarks & gluons, known that using a larger $\Omega_1^{\rm MPI} > \Omega_1$ accurately captures MPI effects

(IS, Tackmann, Waalewijn 2015)



$pp \to t\bar{t}$

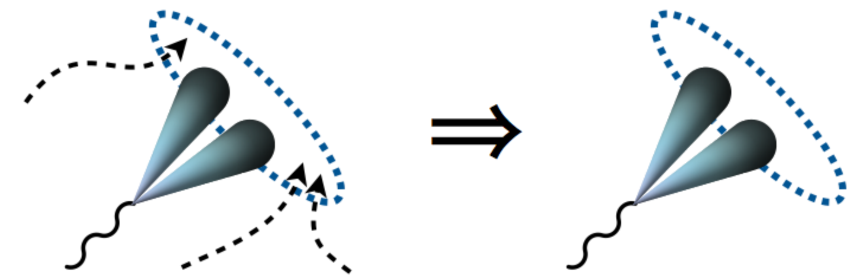
Issue is that MPI contamination is significant (Pythia), so uncertainty from this modeling may be too large for a precision measurement.



Soft Drop

Larkoski, Marzani, Soyez, Thaler 2014

Grooms soft radiation from the jet



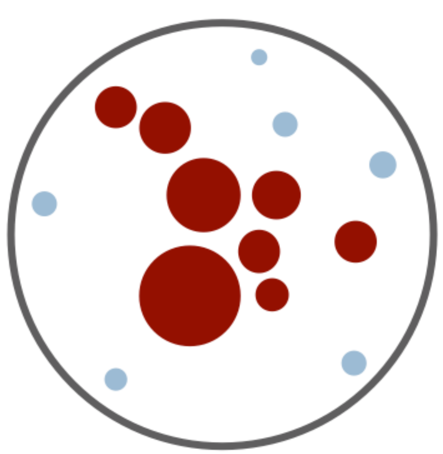
$$\frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}} > z_{\text{cut}} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}$$

ie.

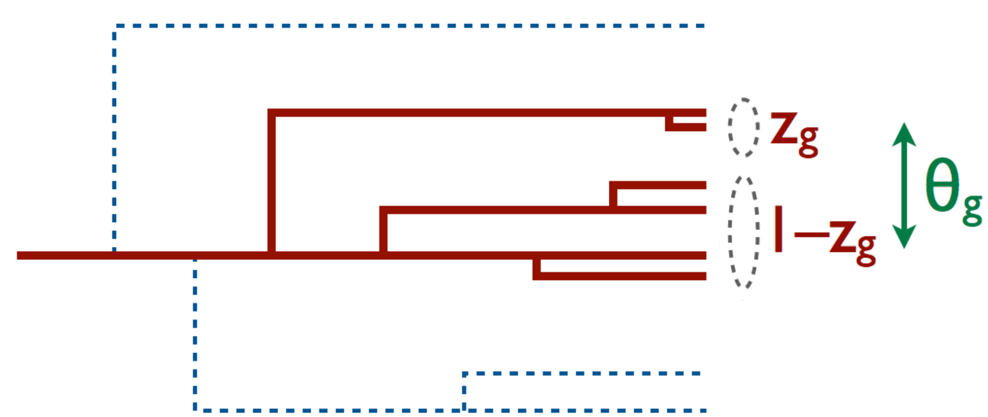
$$z > z_{\text{cut}}\ \theta^{\beta}$$

two grooming parameters

Groomed Jet



Groomed Clustering Tree



Can still carry out calculations: Larkoski, Marzani, Soyez, Thaler 2014

Fri, Larkoski, Schwartz, Yan 2016

Light Soft Drop for tops

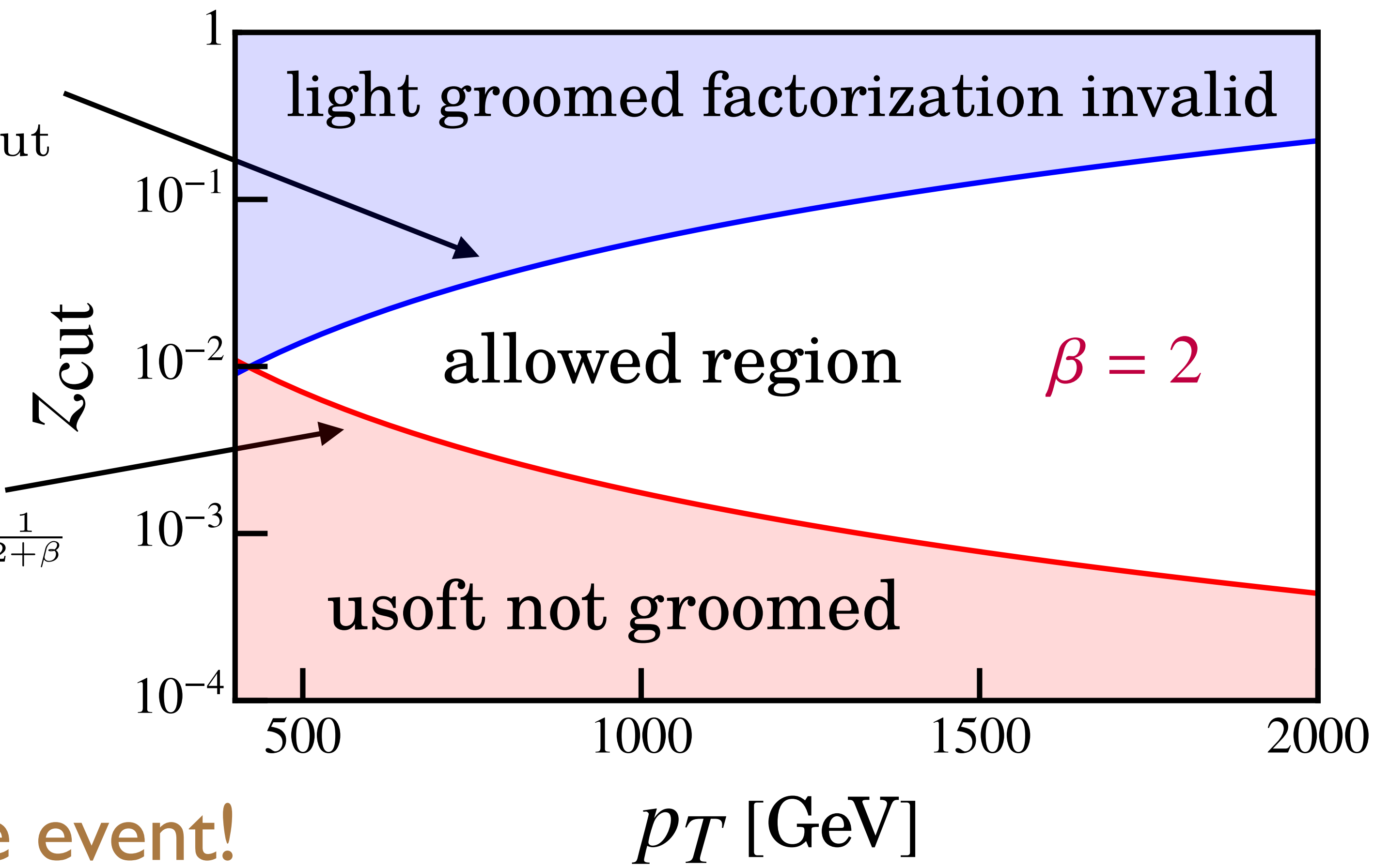
Hoang, Mantry, Pathak, IS (2017)

$$z_{\rm cut} \sim 0.01$$

$$Q = 2\,p_T \cosh(\eta_J)$$

To derive fact. theorem:

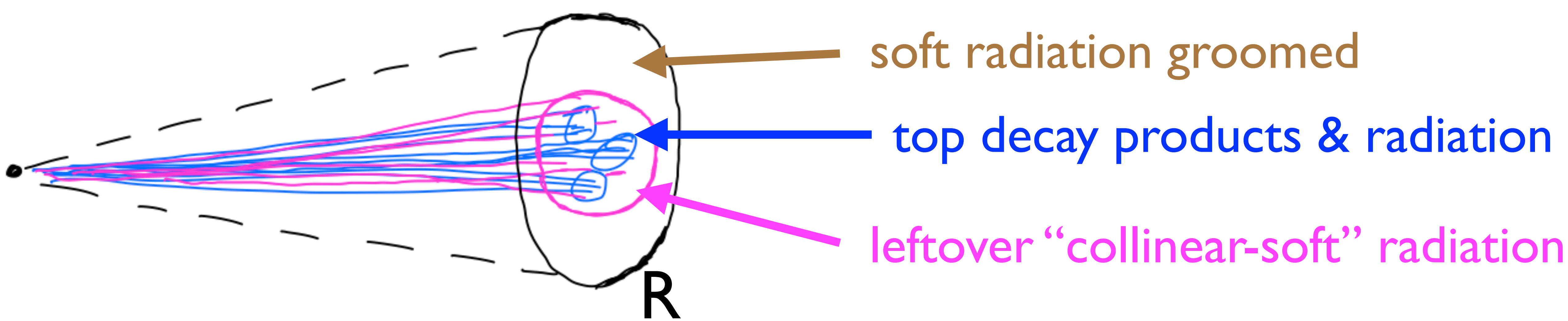
$$\frac{\Gamma_t}{4m_t}\left(\frac{Q}{4m_t}\right)^{\beta} \gtrsim z_{\rm cut}$$



Remove soft contamination.

$$z_{\rm cut}^{\frac{1}{2+\beta}} \gg \frac{1}{2}\left(\frac{\Gamma_t}{m_t}\frac{4m_t^2}{Q^2}\right)^{\frac{1}{2+\beta}}$$

Decouples top-jet from rest of the event!



Light Soft Drop for tops $z_{\rm cut} \sim 0.01$

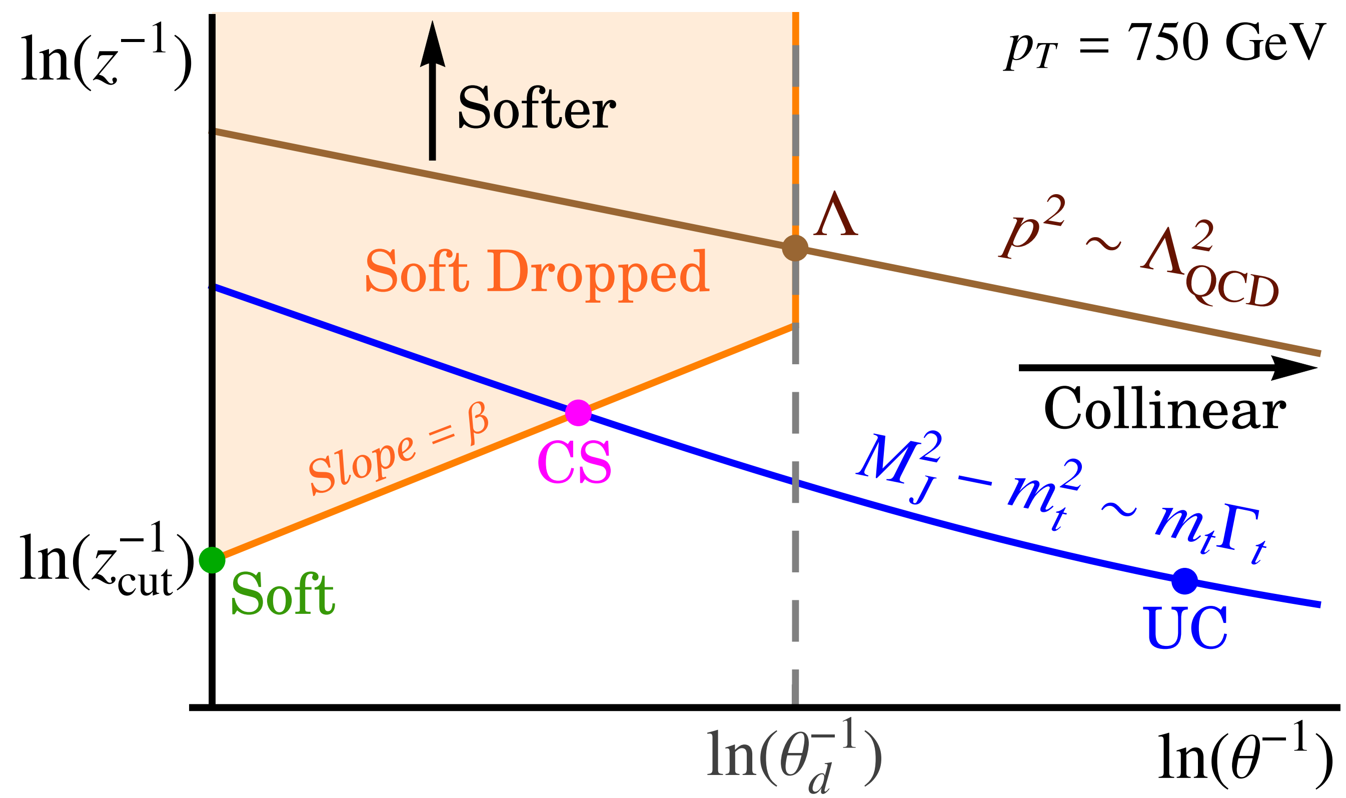
$$Q = 2\,p_T \cosh(\eta_J)$$

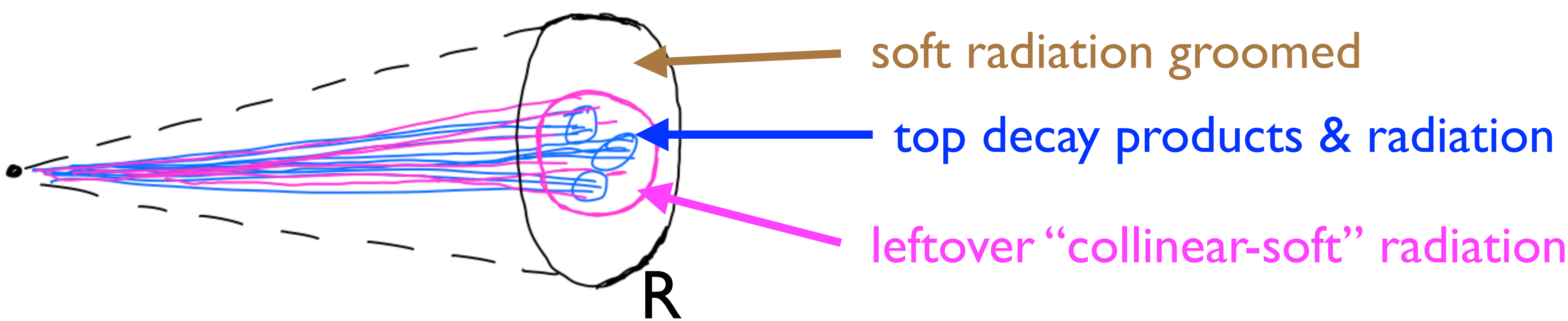
To derive fact. theorem: $\frac{\Gamma_t}{4m_t}\left(\frac{Q}{4m_t}\right)^{\beta} \gtrsim z_{\rm cut}$

Remove soft contamination. $z_{\rm cut}^{\frac{1}{2+\beta}} \gg \frac{1}{2}\left(\frac{\Gamma_t}{m_t}\frac{4m_t^2}{Q^2}\right)^{\frac{1}{2+\beta}}$

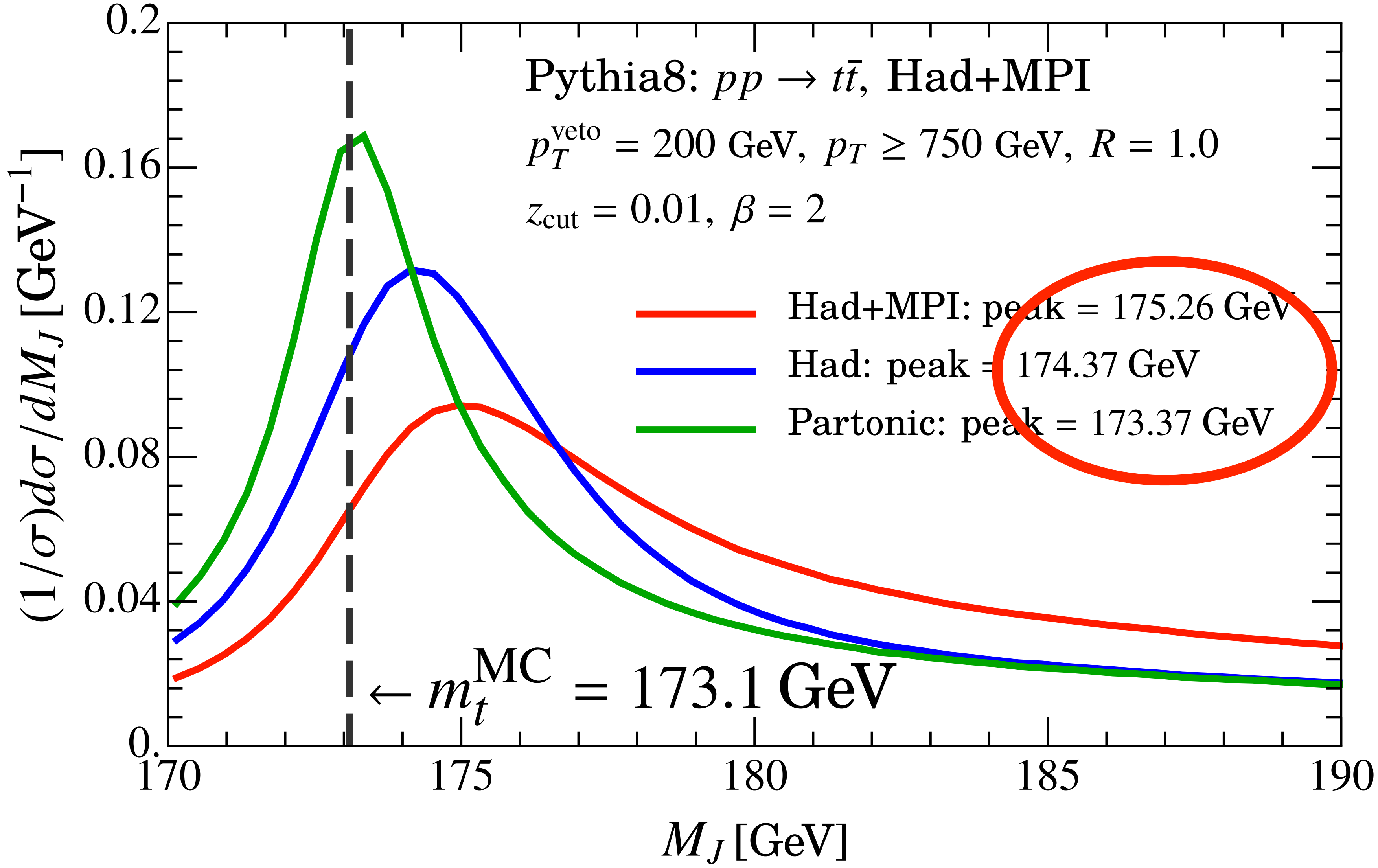
Decouples top-jet from rest of the event!

Modes:





MPI contamination reduced by factor of 5 with Light Soft Drop (eg. 4.5 GeV to 0.9 GeV):



Factorization with Soft Drop on one jet:

Hoang, Mantry, Pathak, IS (2017)

$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu) \int d\hat{s}'\, d\Phi_d\, D_t(\hat{s}', \Phi_d,\, m/Q) \int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\Big)$$
$$\times \int dk\, S_C\Big[\Big(\ell - \frac{mk}{Q} h\big(\Phi_d, \frac{m}{Q}\big)\Big)(2^\beta Q z_{\rm cut})^{\frac{1}{1+\beta}}, \beta, \mu\Big]\, F_C(k, 1)$$

Factorization with Soft Drop on one jet:

Hoang, Mantry, Pathak, IS (2017)

$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu) \int d\hat{s}'\, d\Phi_d\, D_t(\hat{s}', \Phi_d, m/Q) \int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\Big)$$
$$\times \int dk\, S_C\Big[\Big(\ell - \frac{mk}{Q} h\Big(\Phi_d, \frac{m}{Q}\Big)\Big)(2^\beta Q z_{\rm cut})^{\frac{1}{1+\beta}}, \beta, \mu\Big]\, F_C(k, 1)$$

Norm
(rest of the event)

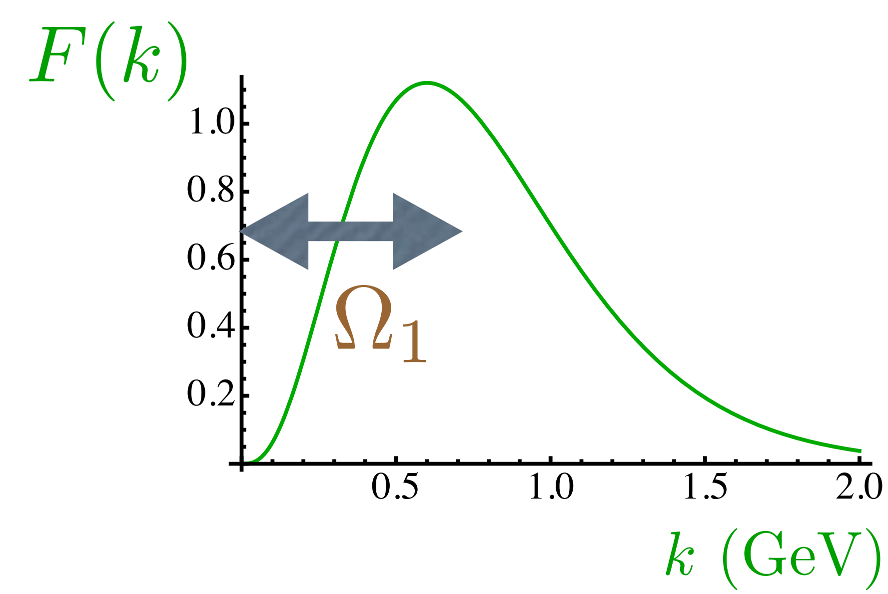
left over perturbative
collinear-soft radiation

dynamics of top
& its decay products

control of
mass scheme

non-perturbative
soft radiation

$\Omega_1,\ x_2$



Factorization with Soft Drop on one jet:

Hoang, Mantry, Pathak, IS (2017)

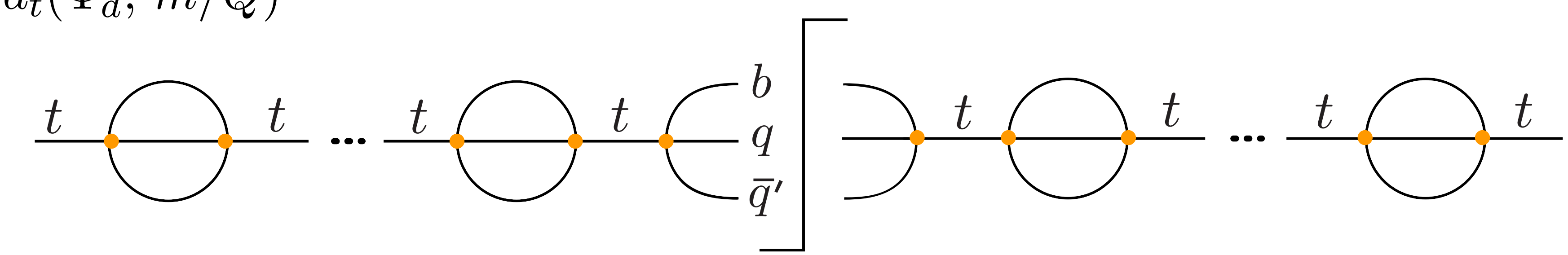
$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu) \int d\hat{s}'\, d\Phi_d\, D_t(\hat{s}', \Phi_d, m/Q) \int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\Big)$$
$$\times \int dk\, S_C\Big[\Big(\ell - \frac{mk}{Q} h\Big(\Phi_d, \frac{m}{Q}\Big)\Big)(2^\beta Q z_{\rm cut})^{\frac{1}{1+\beta}}, \beta, \mu\Big]\, F_C(k, 1)$$

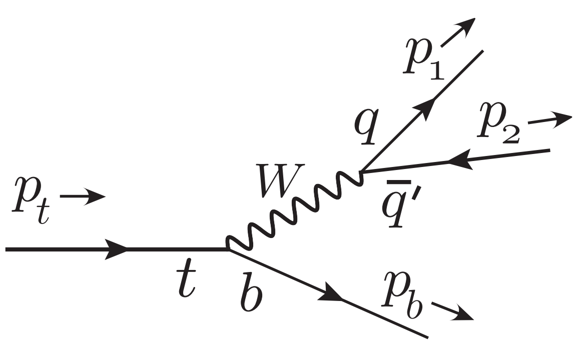
"decay" fact. thm.

$$Q \lesssim 4 m_t \left(2 m_t z_{\rm cut}/\Lambda_{\rm QCD}\right)^{1/\beta}$$

Soft drop stops when comparing energetic top decay products

$$D_t(\hat{s}', \Phi_d, m/Q) = \frac{\Gamma_t}{\pi(\hat{s}'^2 + \Gamma_t^2)}\, d_t(\Phi_d, m/Q)$$





$\Phi_d = 5$ phase space variables for decay

Factorization with Soft Drop on one jet:

Hoang, Mantry, Pathak, IS (2017)

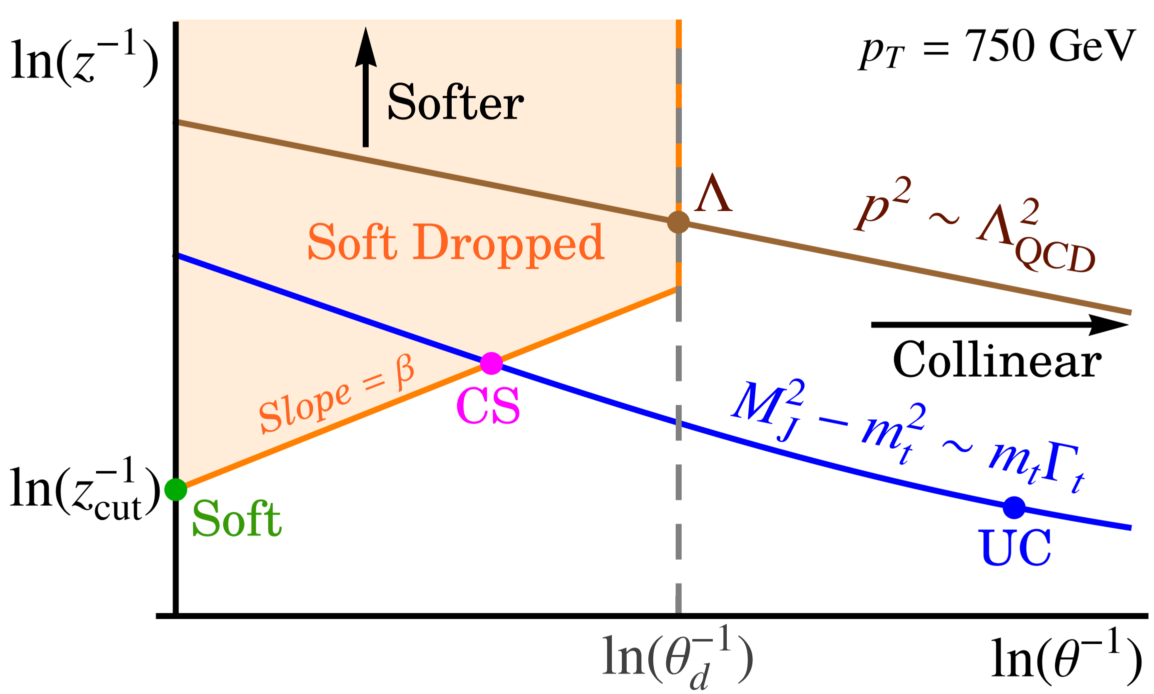
$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu) \int d\hat{s}'\, d\Phi_d\, D_t(\hat{s}', \Phi_d, m/Q) \int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t} - \hat{s}', \delta m, \mu\Big)$$
$$\times \int dk\, S_C\Big[\Big(\ell - \frac{mk}{Q} h\big(\Phi_d, \frac{m}{Q}\big)\Big)\big(2^\beta Q z_{\rm cut}\big)^{\frac{1}{1+\beta}}, \beta, \mu\Big]\, F_C(k, 1)$$

"decay" fact. thm.

$$Q \lesssim 4 m_t \left(2 m_t z_{\rm cut}/\Lambda_{\rm QCD}\right)^{1/\beta}$$

$$\tan(\theta_d/2) = \frac{m}{Q} h\big(\Phi_d, \frac{m}{Q}\big)$$

Soft drop stops when comparing energetic top decay products



θ_d is angle to jet-axis of last decay product reclustered by soft-drop

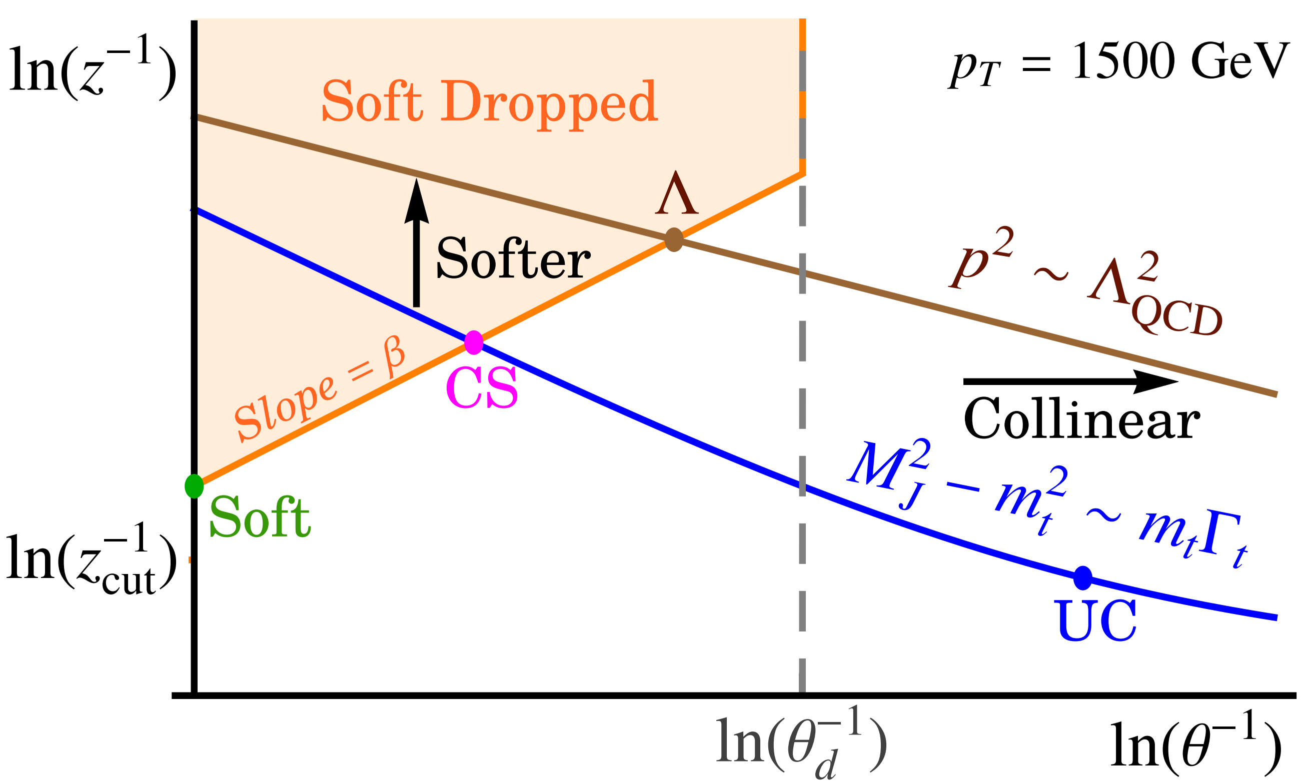
Factorization with Soft Drop on one jet:

Hoang, Mantry, Pathak, IS (2017)

"high-pT" $Q \gtrsim 4m_t(2m_t z_{\rm cut}/\Lambda_{\rm QCD})^{1/\beta}$

decay products well inside groomed jet

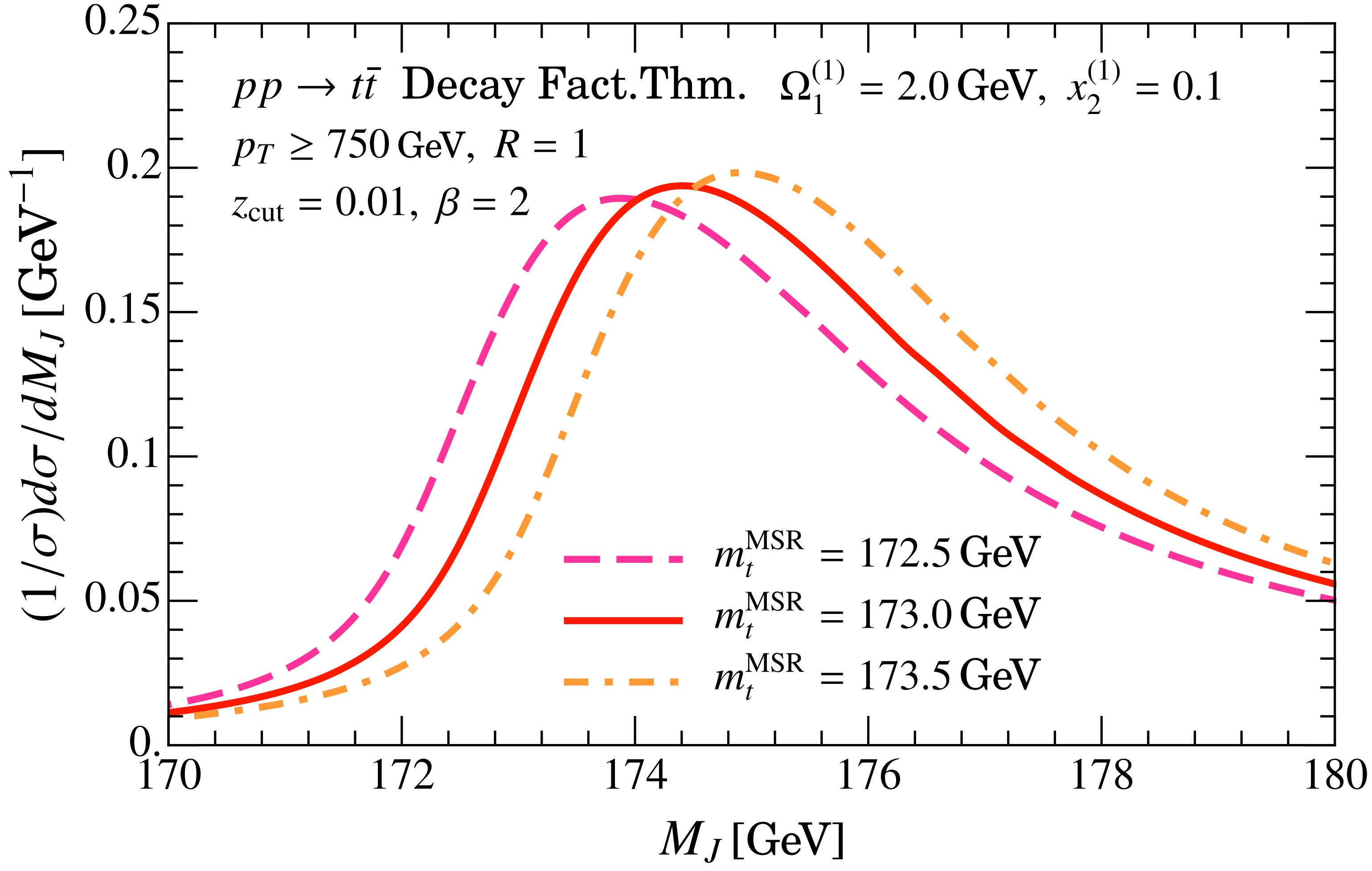
$$\frac{d\sigma(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu) \int d\ell\, J_B\Big(\frac{M_J^2 - m_t^2 - Q\ell}{m_t}, \Gamma_t, \delta m, \mu\Big)$$
$$\times \int dk\, S_C\Big[\Big(\ell - k\Big(\frac{k}{2^\beta Q z_{\rm cut}}\Big)^{\frac{1}{1+\beta}}\Big)(2^\beta Q z_{\rm cut})^{\frac{1}{1+\beta}}, \beta, \mu\Big]\, F_C(k,\beta)$$



Groomed Factorization Results (NLL + Hadronization)

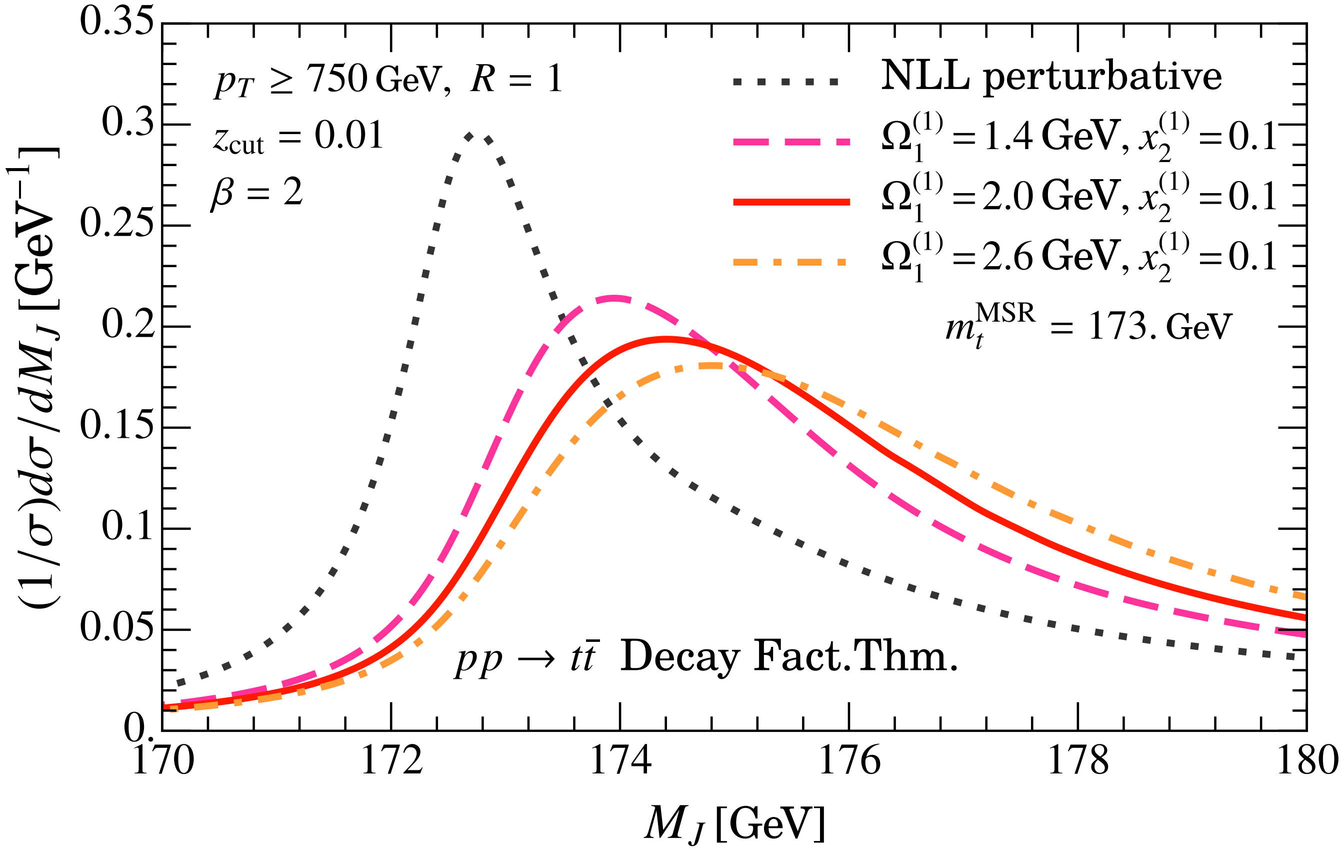
Groomed Factorization Results

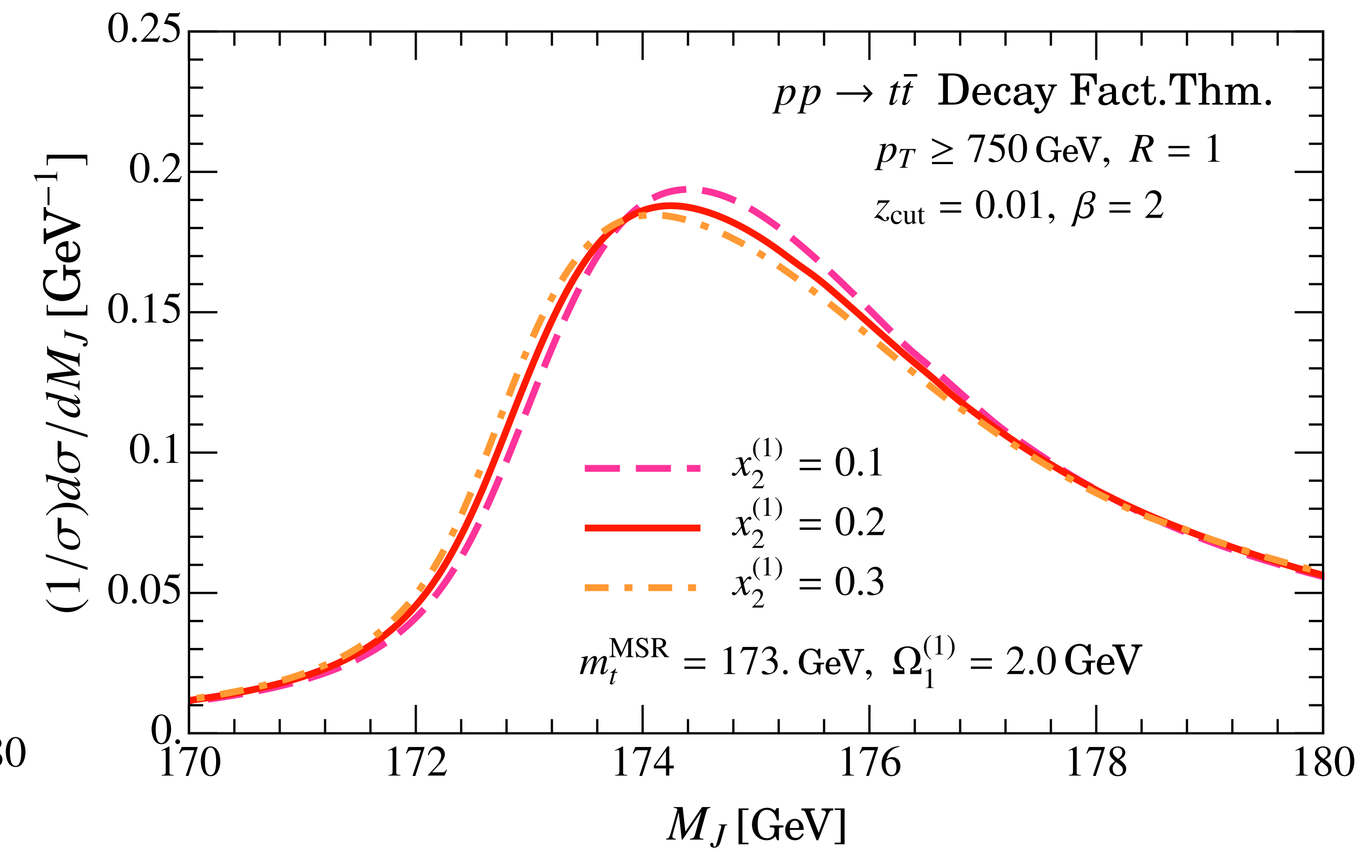
sensitive to top mass:



Groomed Factorization Results

Hadronization effects (smaller than ungroomed):



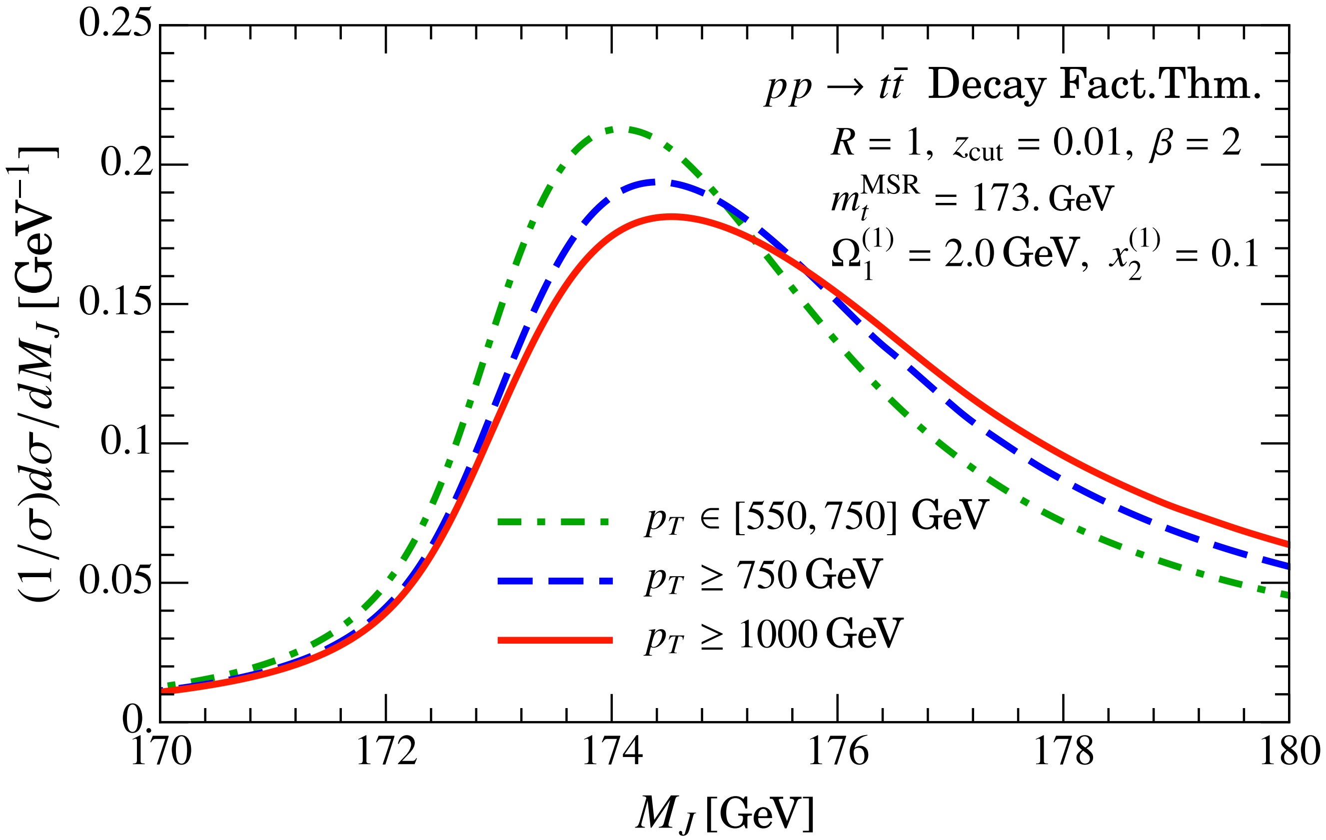


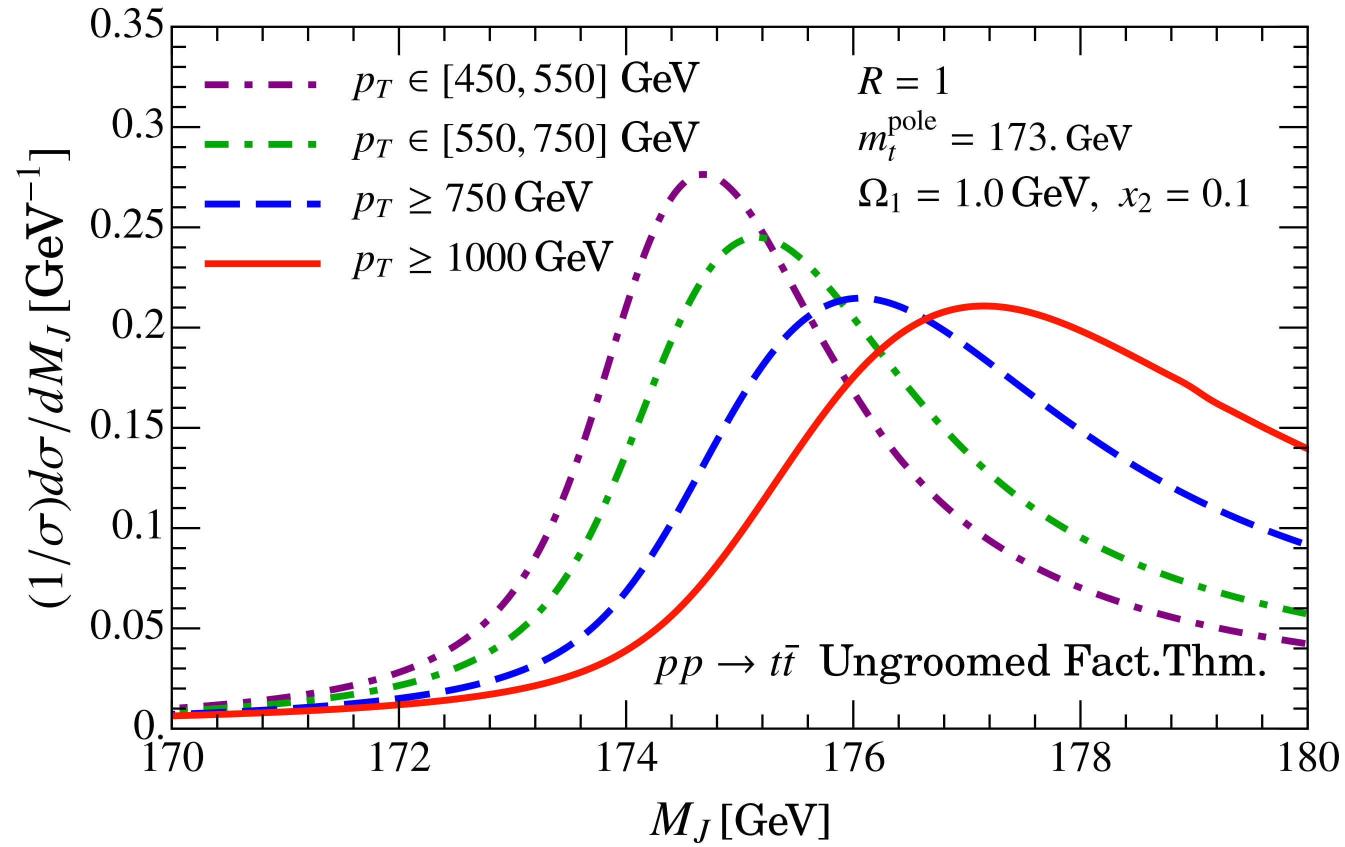
Ω_1 dominates

$x_2 = \dfrac{\Omega_2 - \Omega_1^2}{\Omega_1^2}$ smaller

Groomed Factorization Results

pT dependence (smaller than ungroomed):





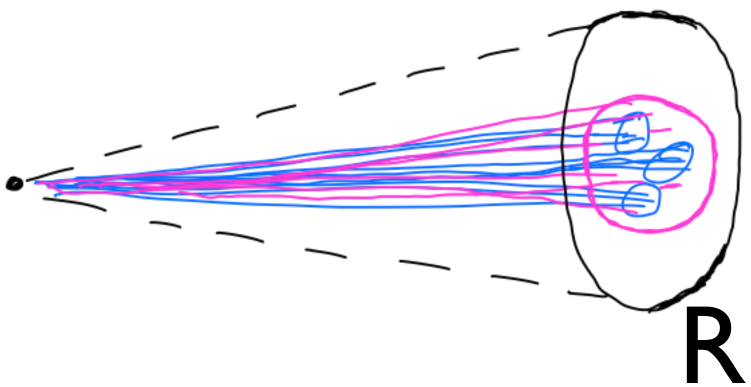
Soft Drop groomed

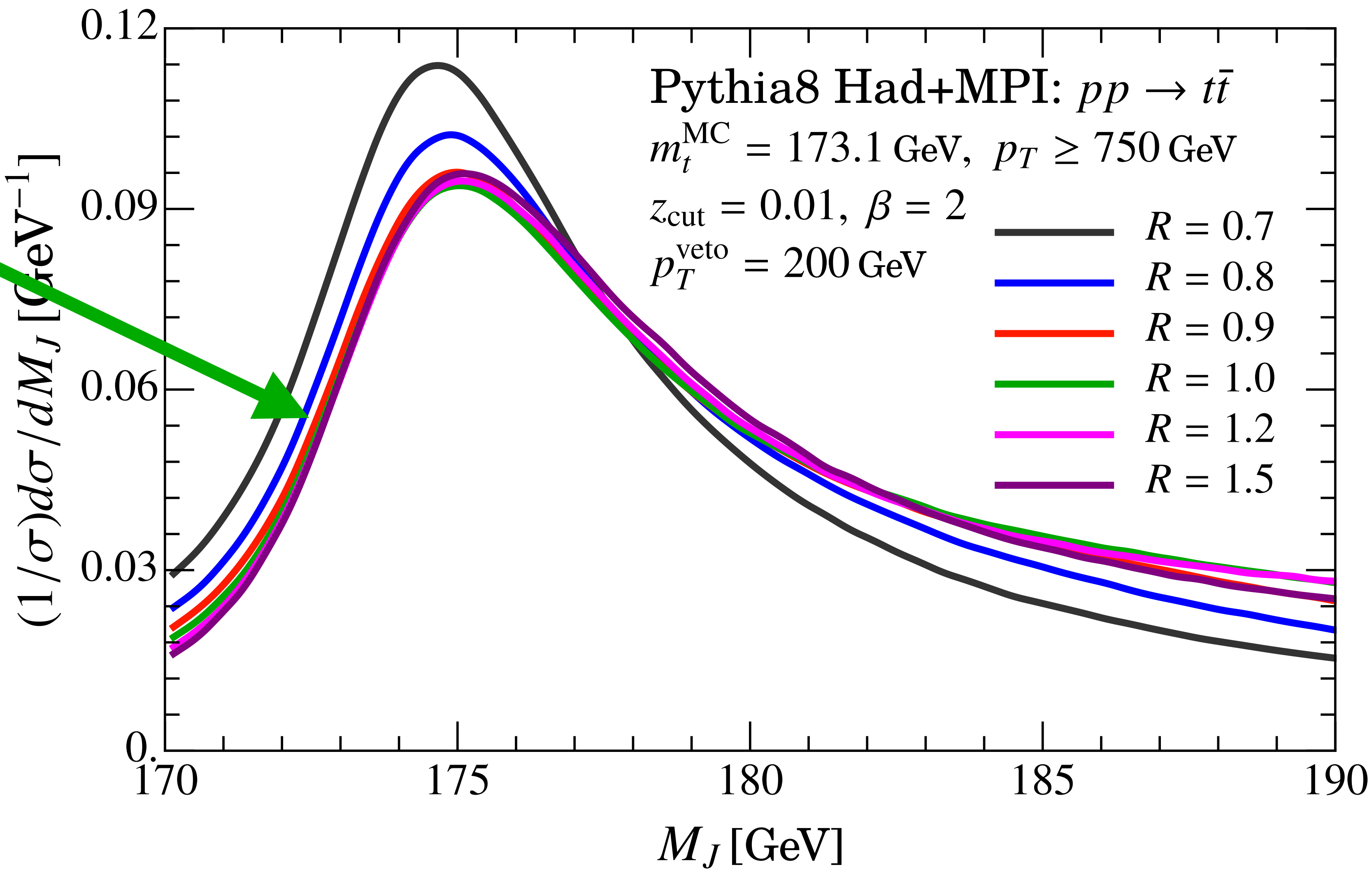
Ungroomed

Test Theory Predictions with Simulations

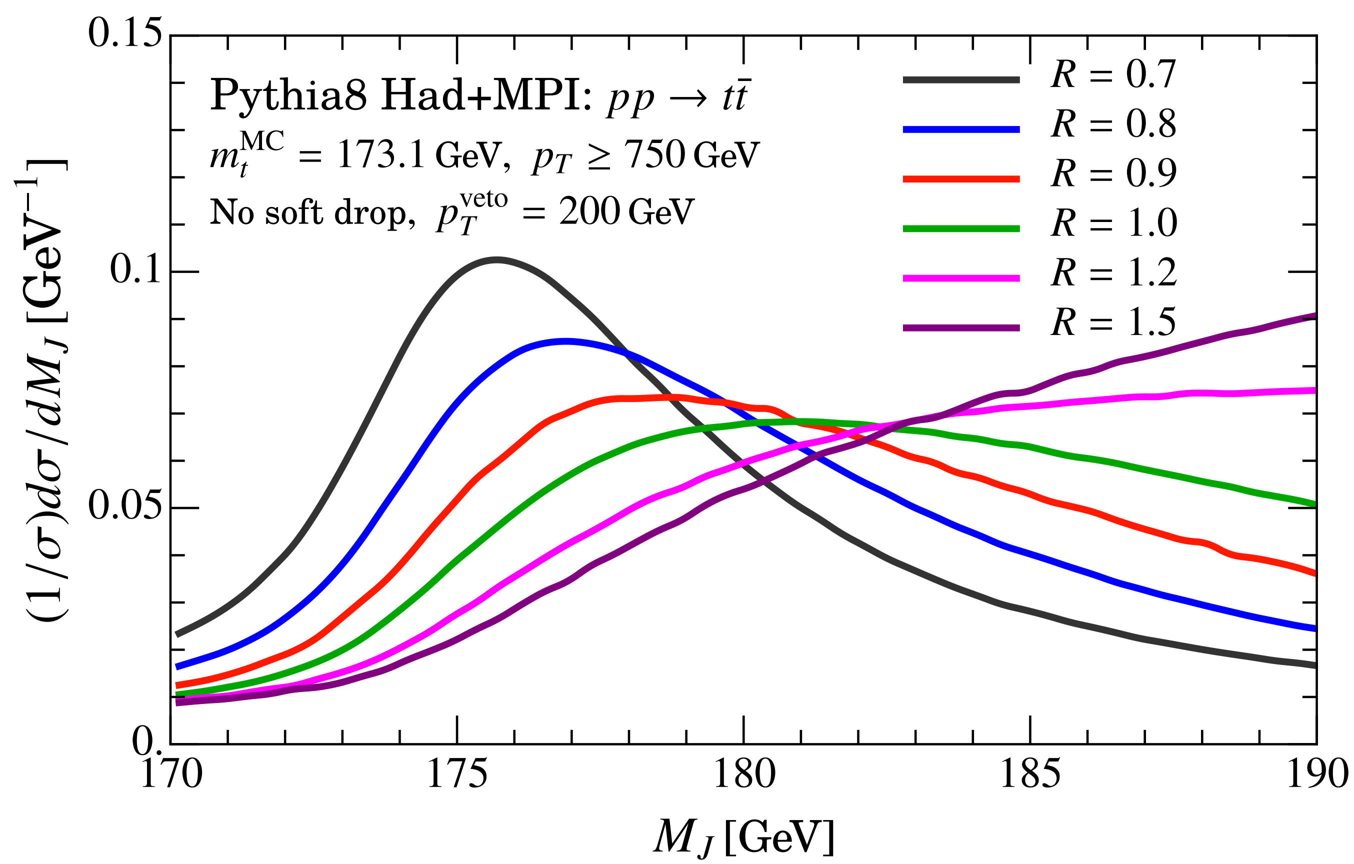
Predict:
independent of
Jet Radius

✓





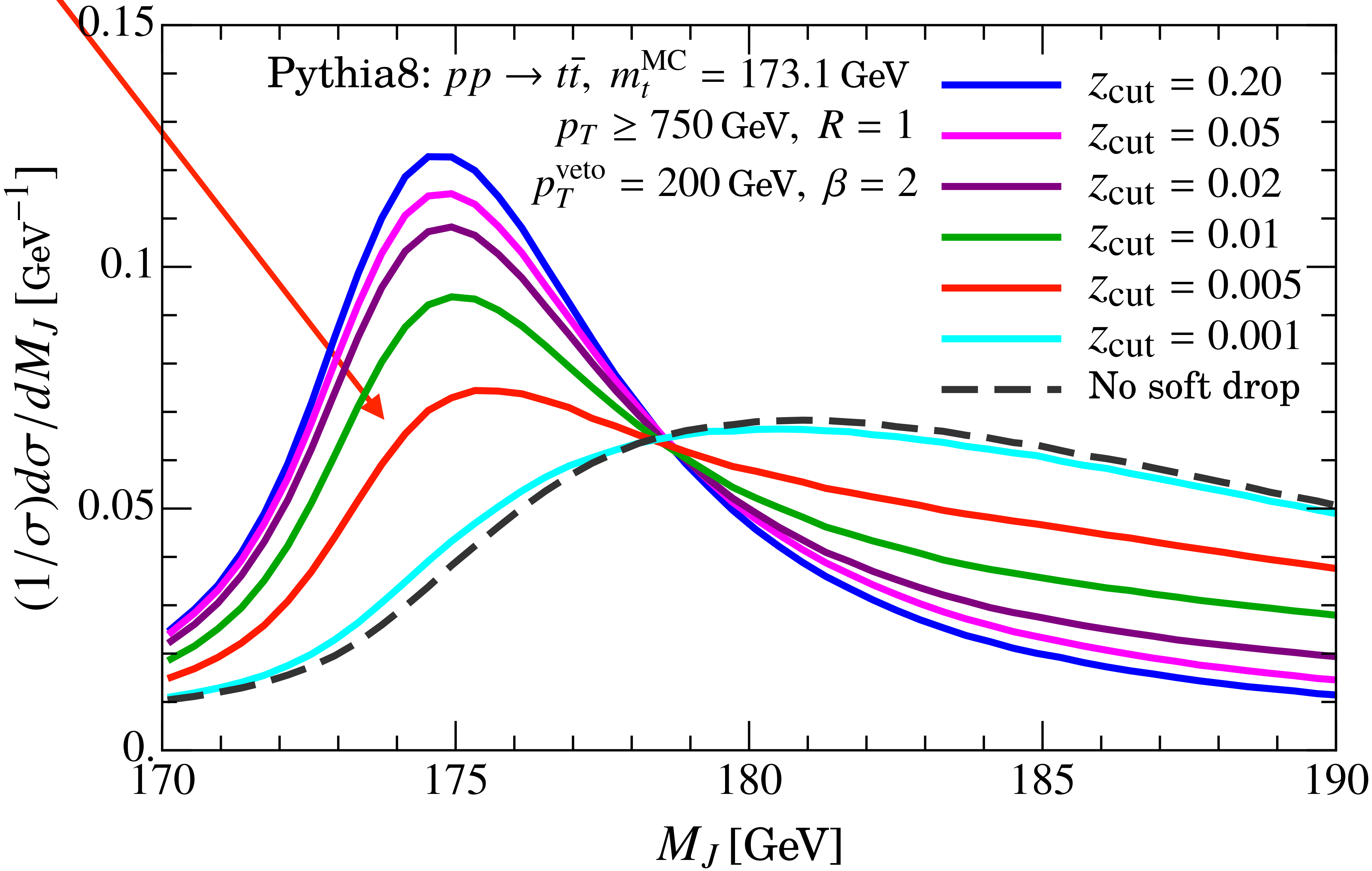
Without
Soft Drop
(huge):



z_{cut} dependence (simulation)

Predict transition for "light Soft Drop" ✓

most contamination
is removed



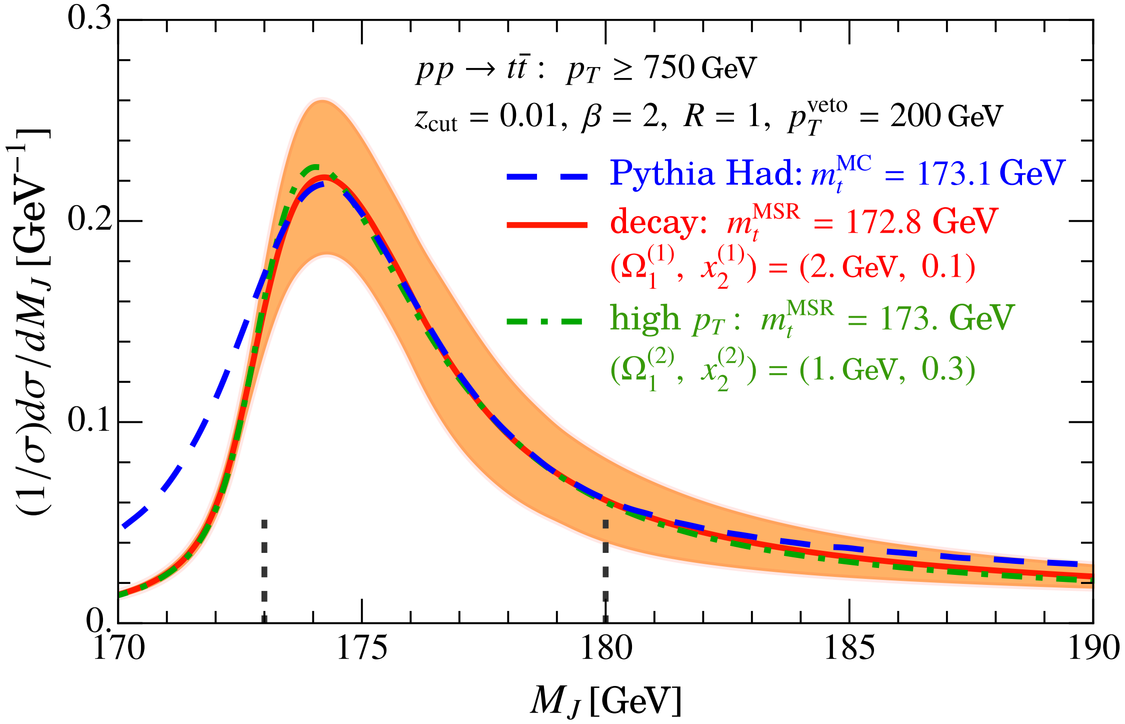
Fit Factorization to Simulations (Calibration)

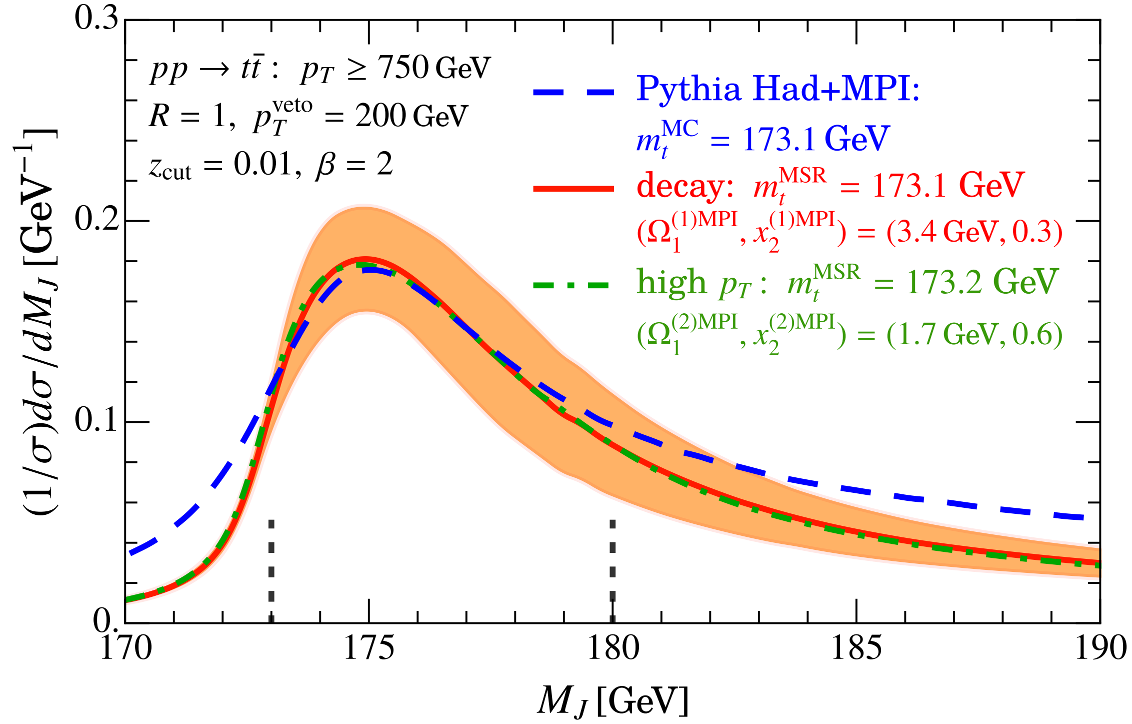
Simultaneous fit to different pTs

no MPI

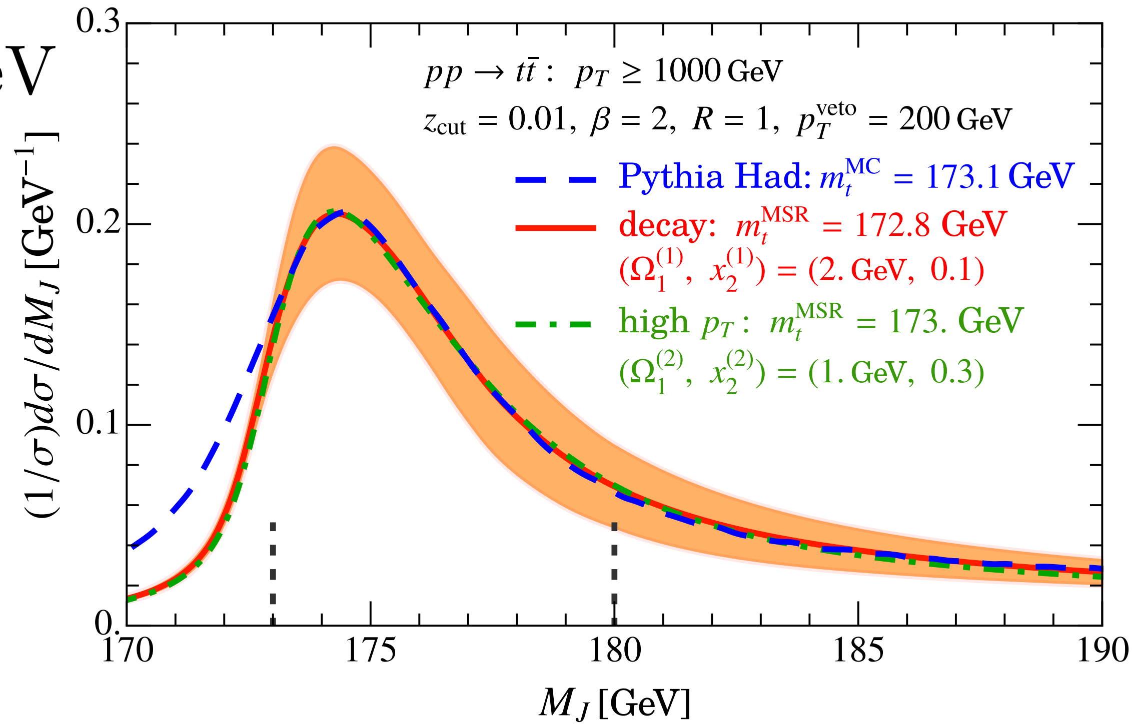
with MPI

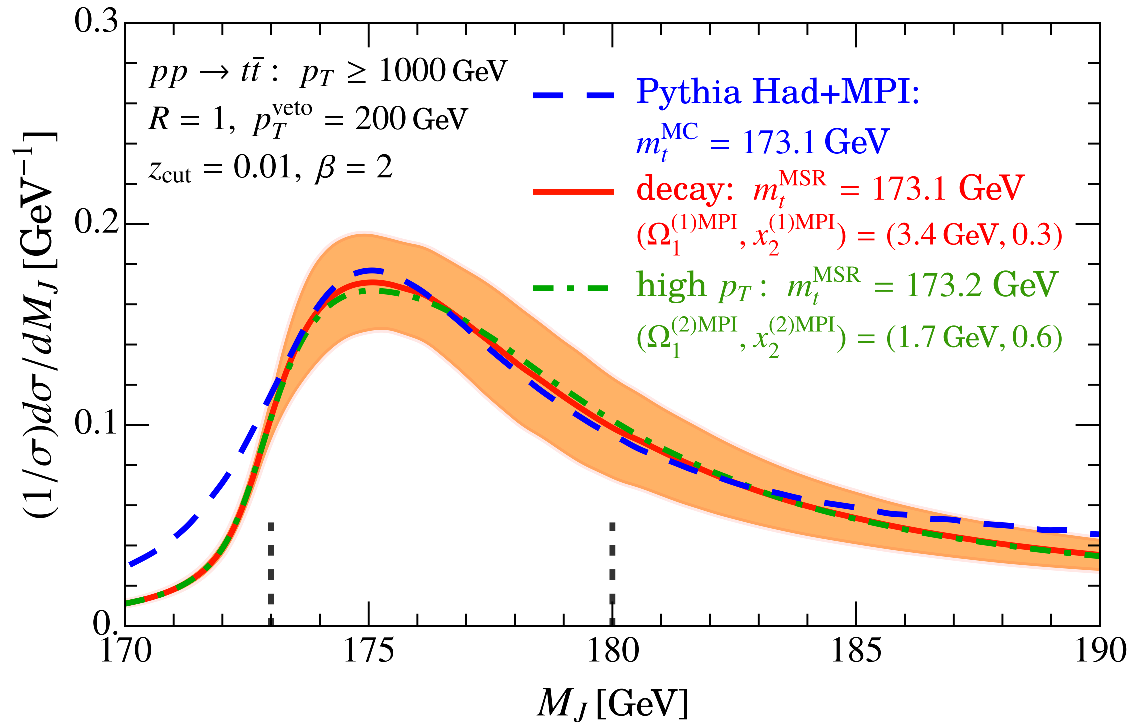
$p_T \geq 750\,\mathrm{GeV}$





$p_T \geq 1000\,\mathrm{GeV}$

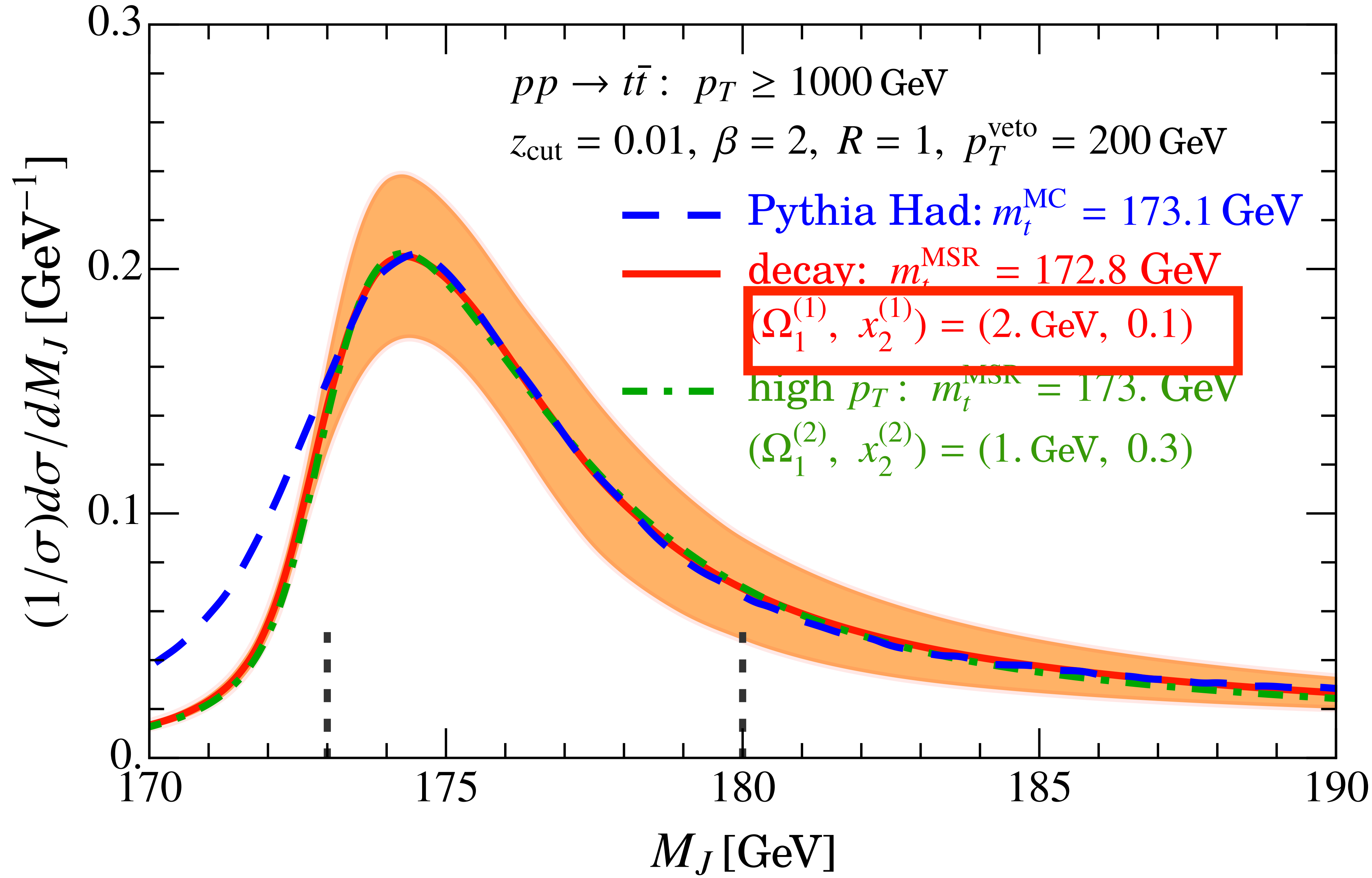




Pythia Simulation vs. Factorization (with SoftDrop)

without Contamination:

$$m_t^{\mathrm{MSR}} = 172.8\,\mathrm{GeV}$$
$$m_t^{\mathrm{MC}} = 173.1\,\mathrm{GeV}$$

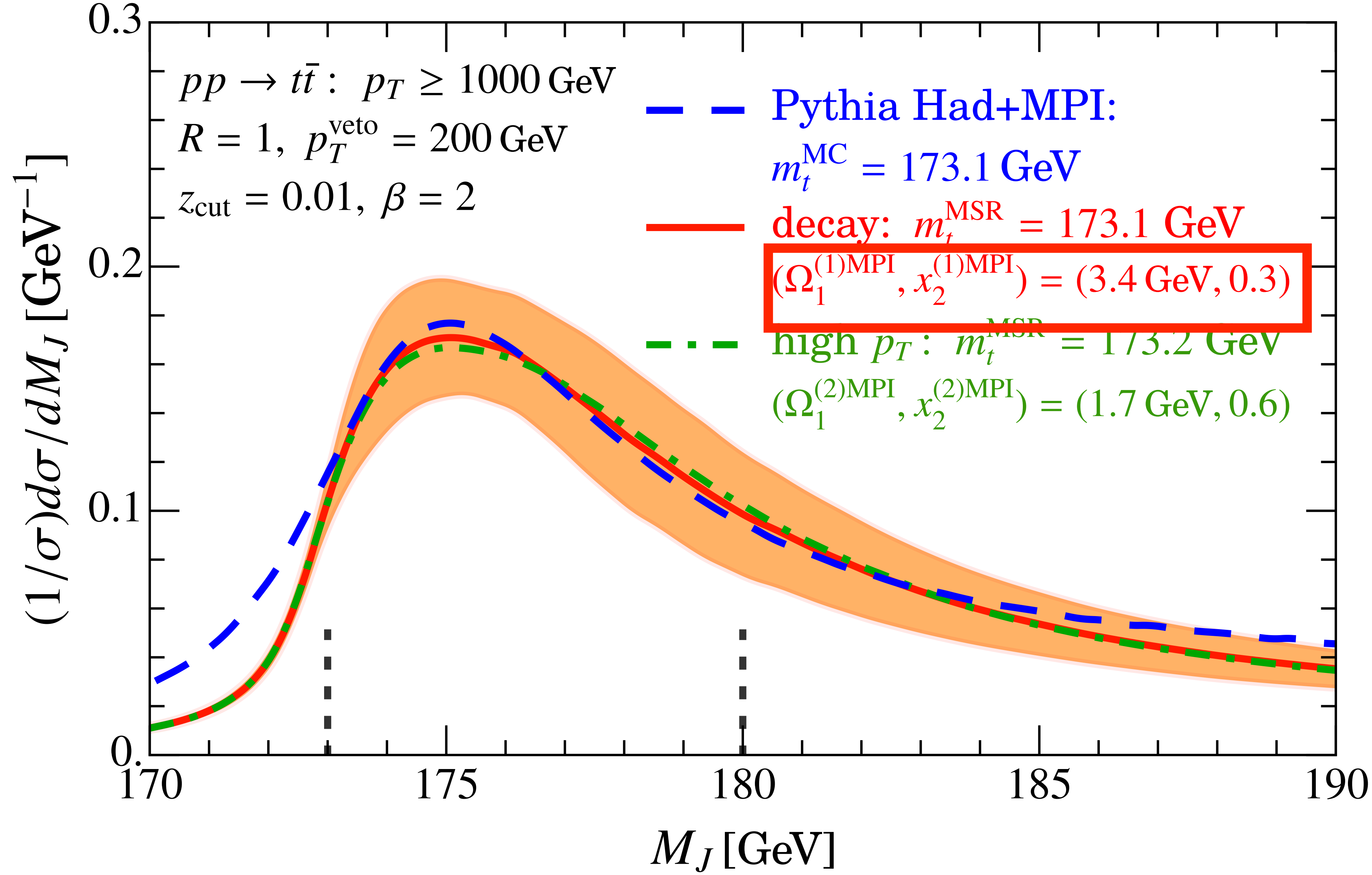


Pythia Simulation vs. Factorization (with SoftDrop)

with Contamination:

$$m_t^{\mathrm{MSR}} = 173.1\,\mathrm{GeV}$$ $\simeq$ unchanged!

$$m_t^{\mathrm{MC}} = 173.1\,\mathrm{GeV}$$



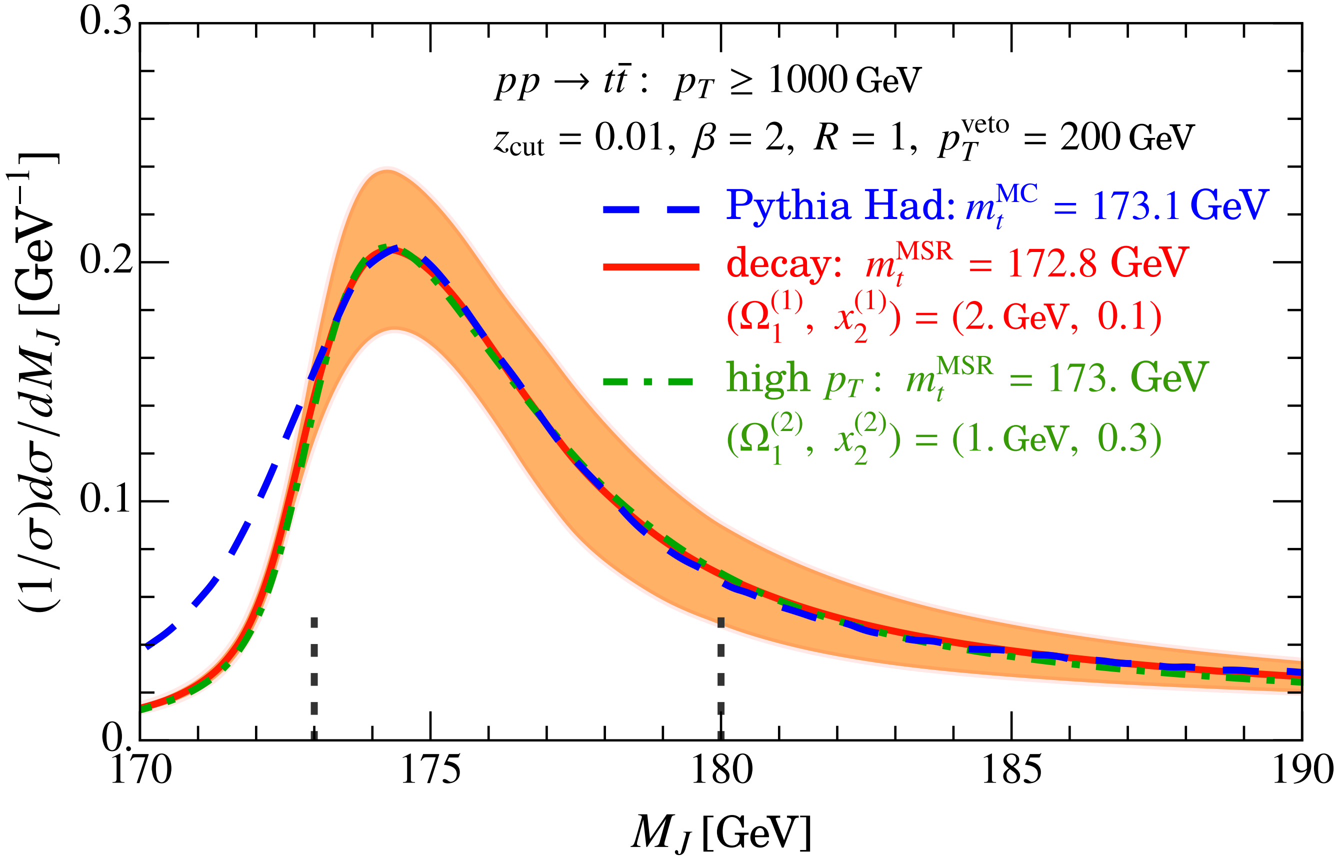
dominant change is as expected: Ω_1

MSR Mass versus Pole Mass

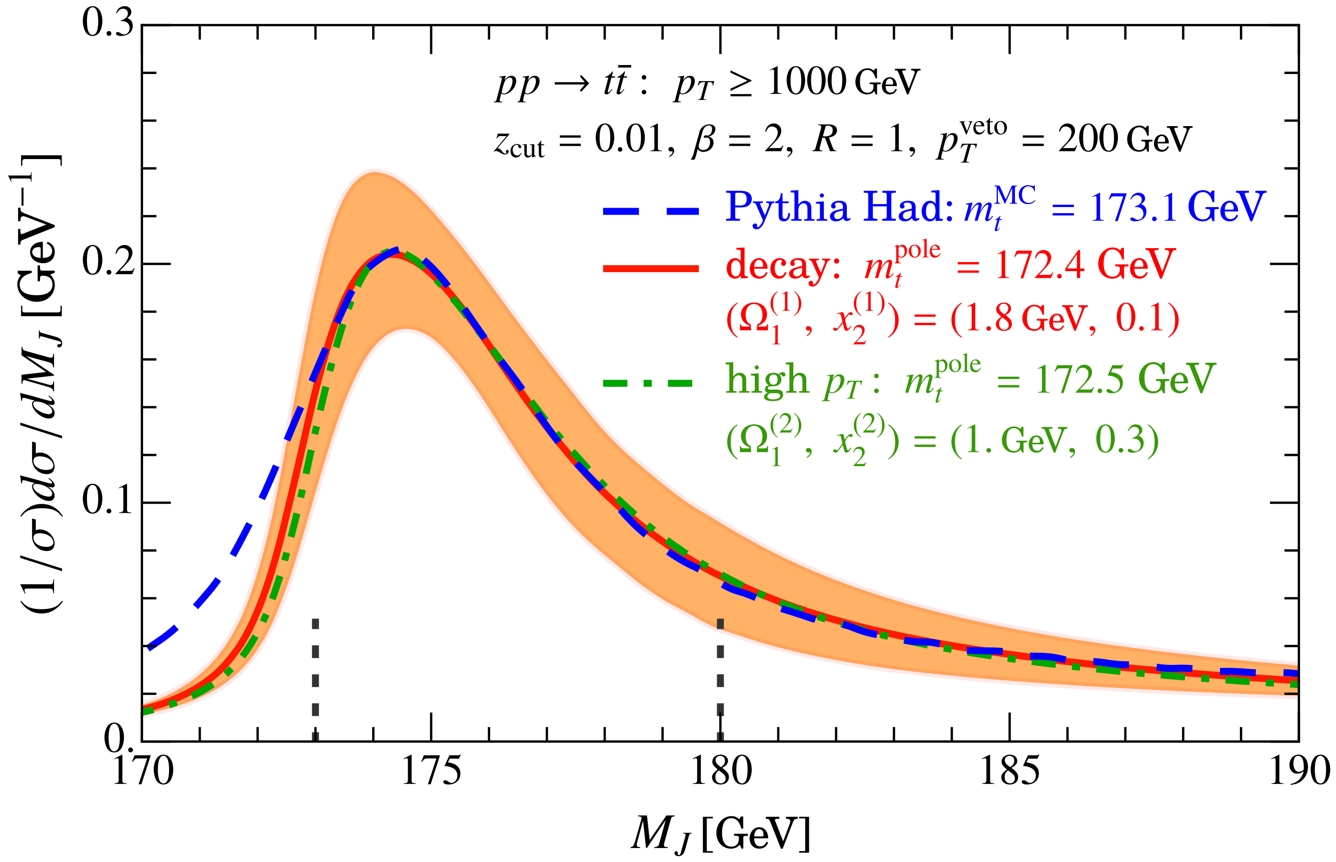
equally good fit (an order dependent shift)

pole mass comes out smaller, just like e^+e^-

MSR

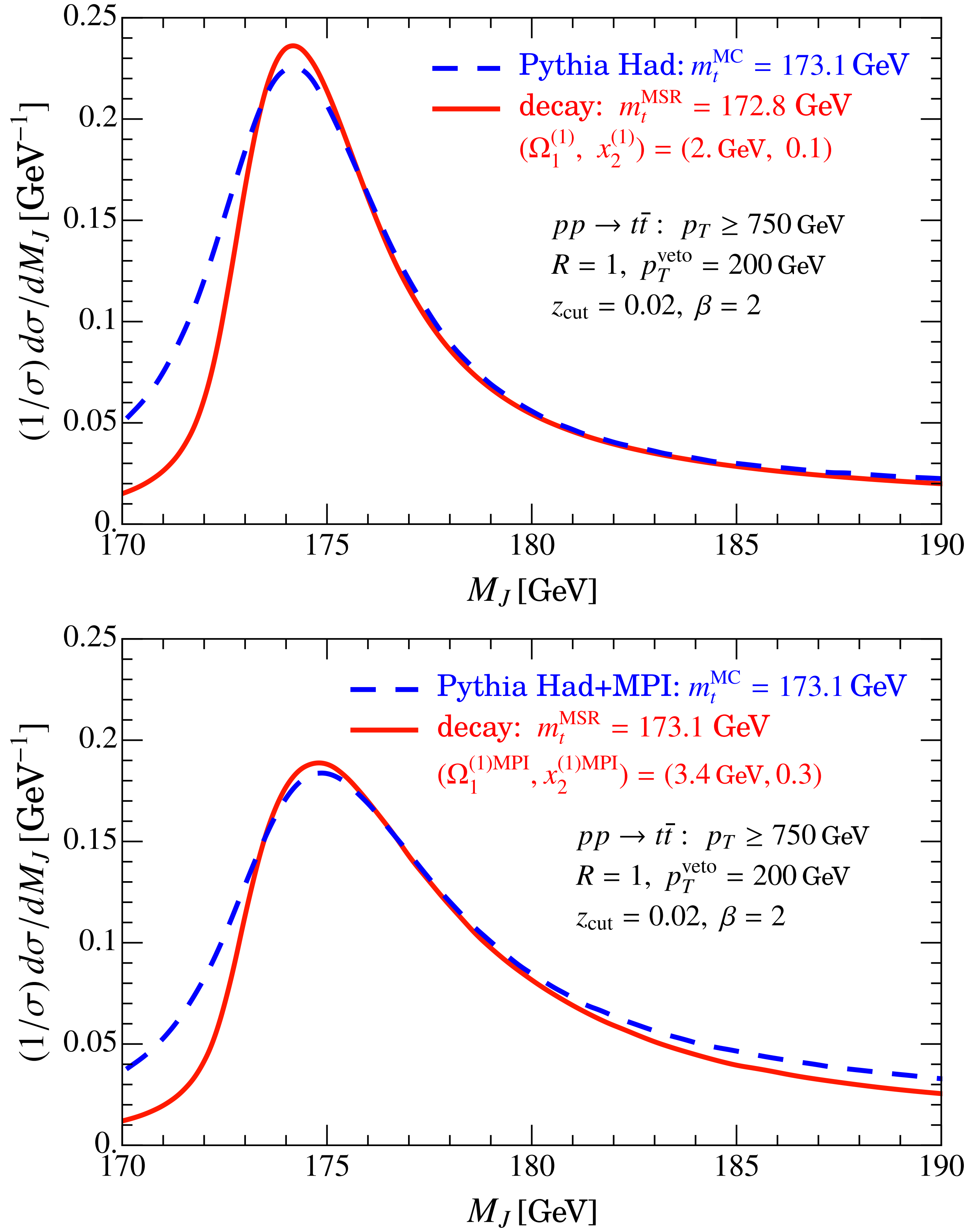


pole



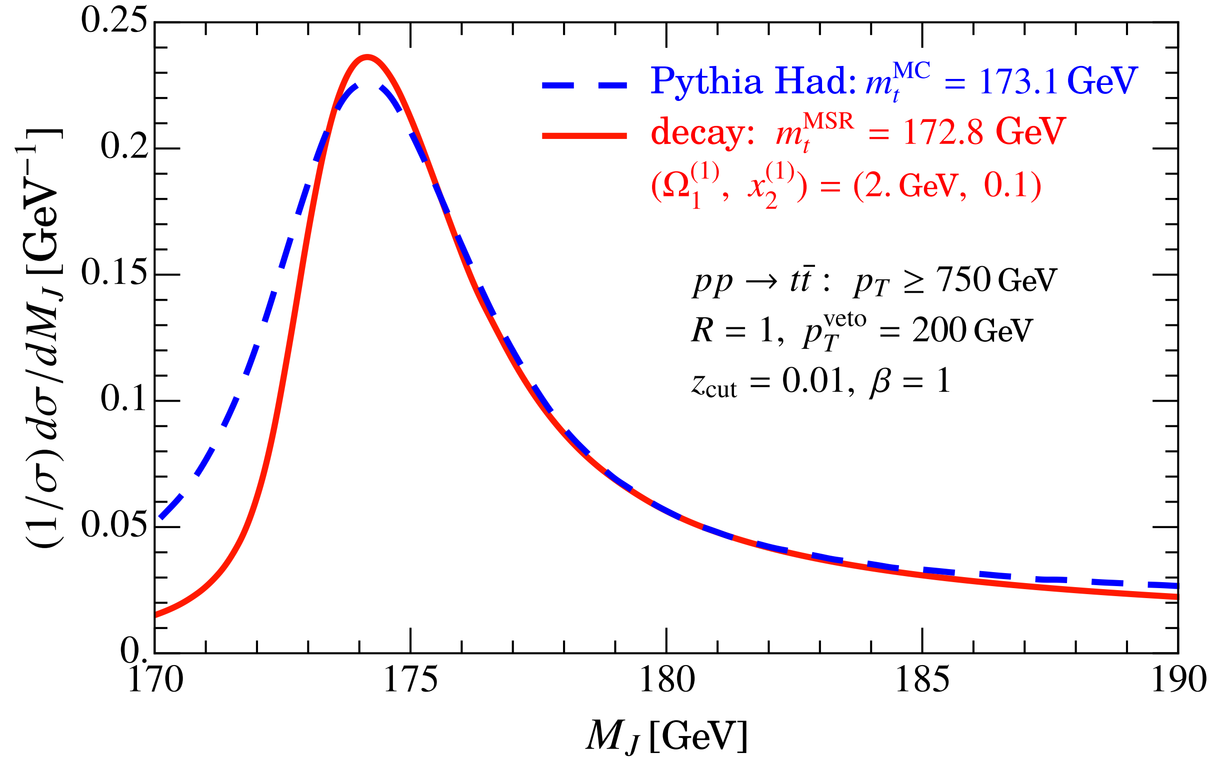
Retain agreement when we vary other knobs:

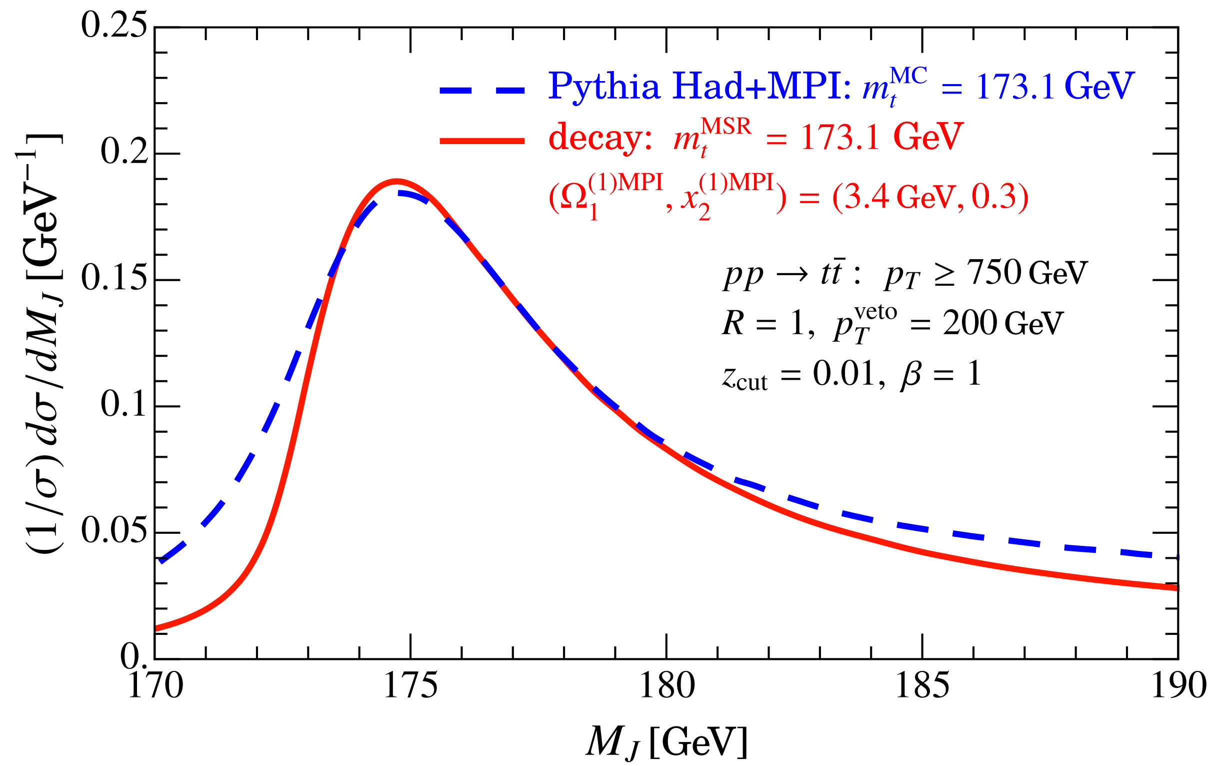
$$z_{\mathrm{cut}} = 0.02$$



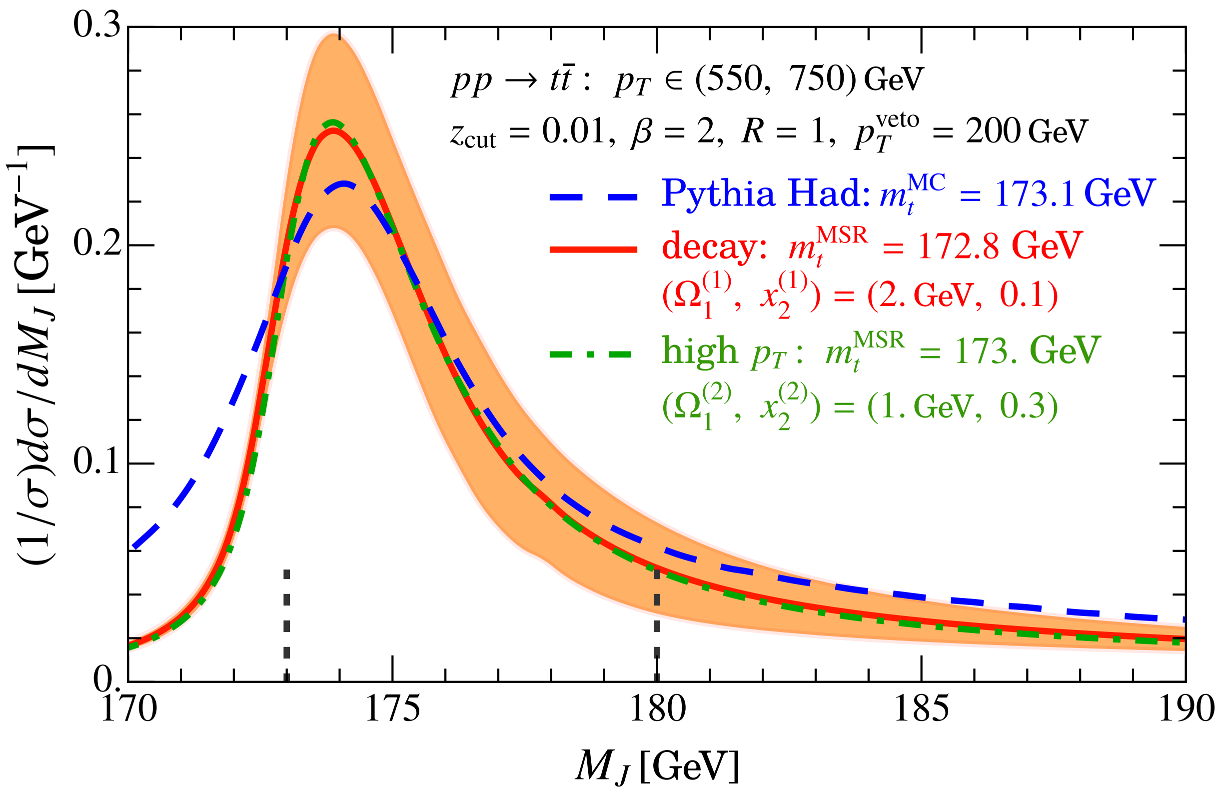
Retain agreement when we vary other knobs:

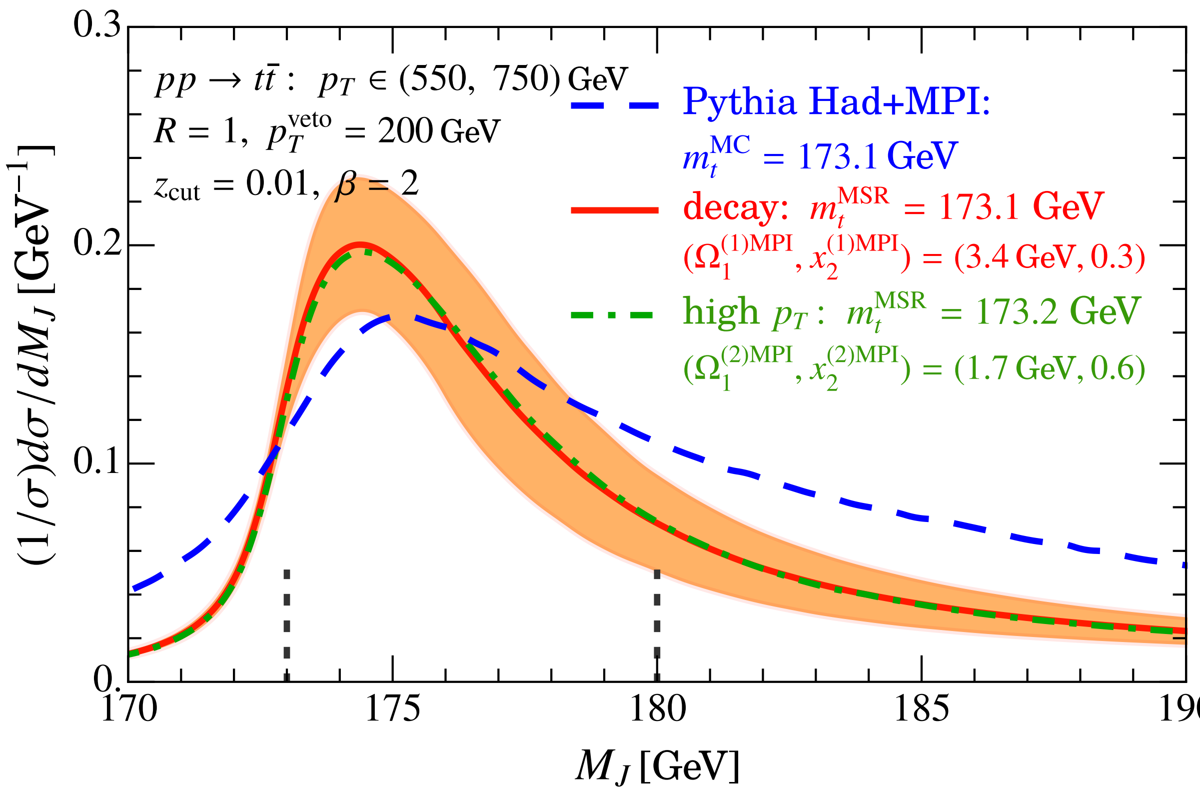
$$\beta = 1$$



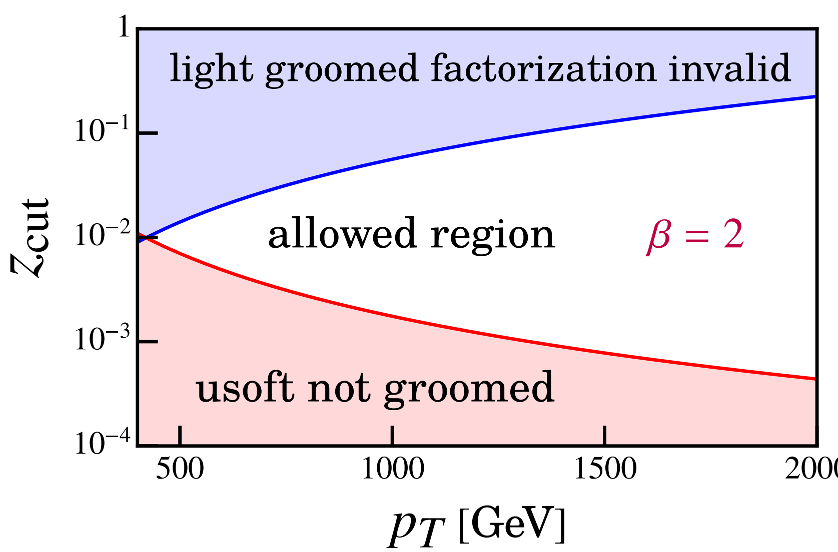


But smaller pT fails for Soft Drop:

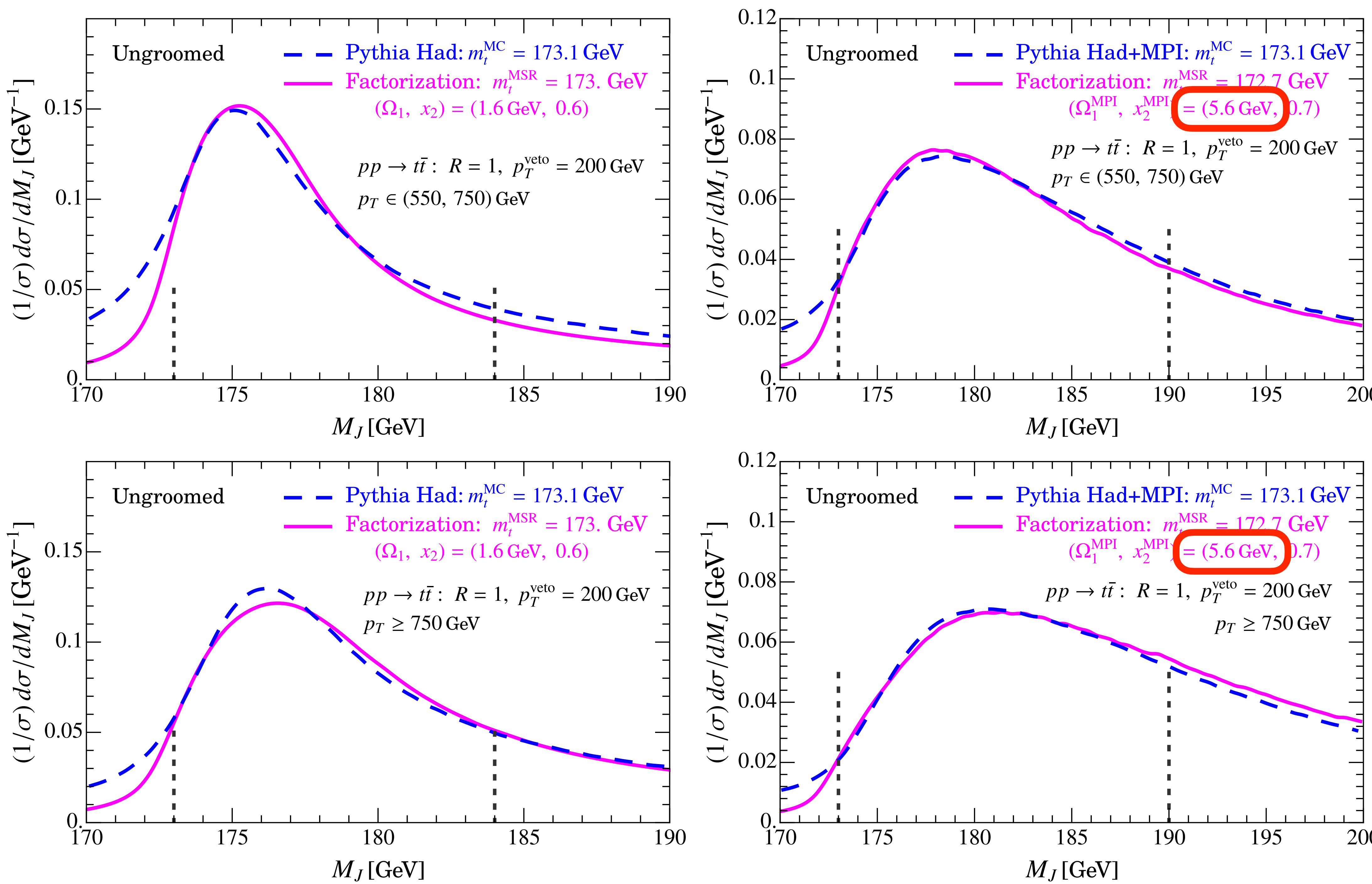




not unexpected since in pinch of validity region

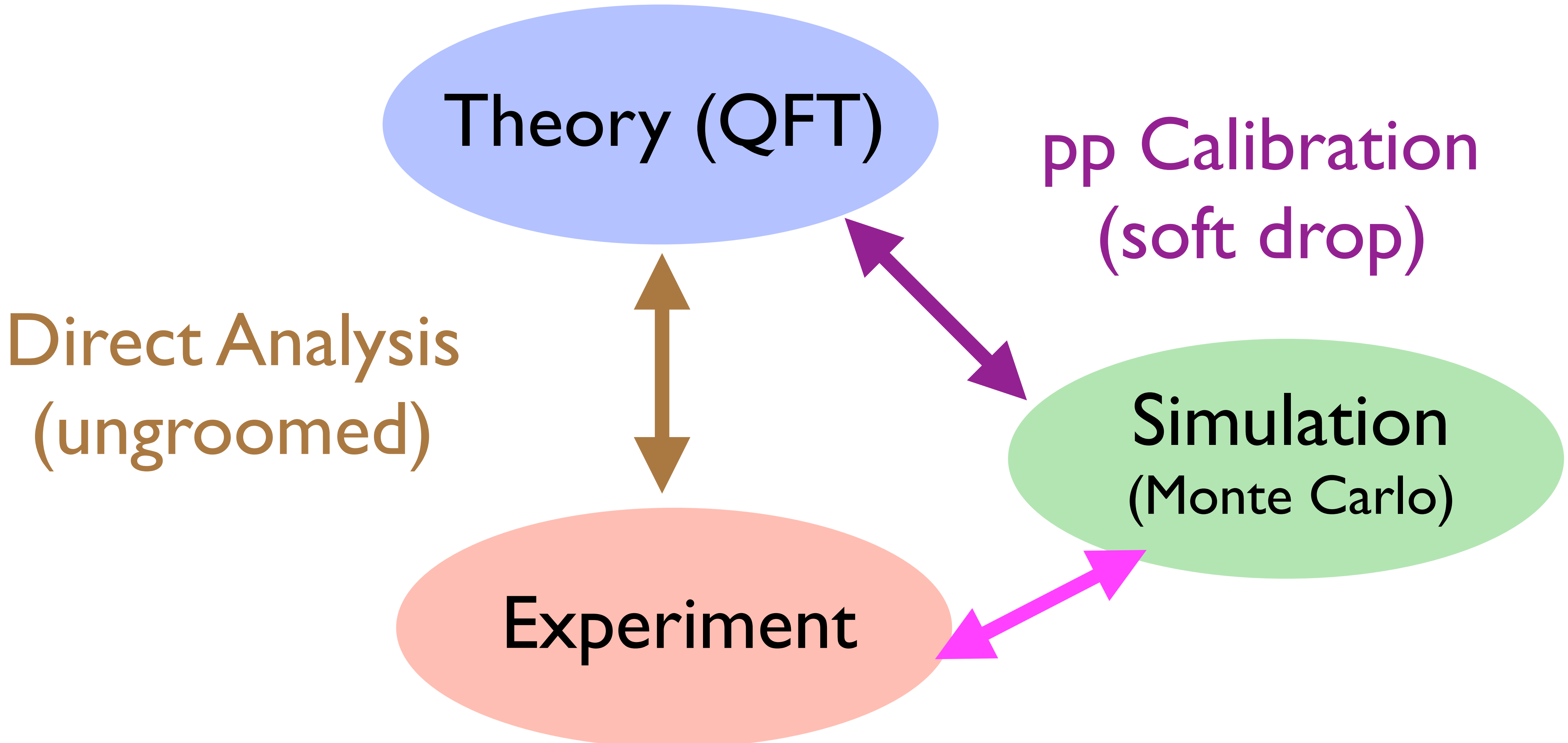


Could still use ungroomed factorization for smaller pT



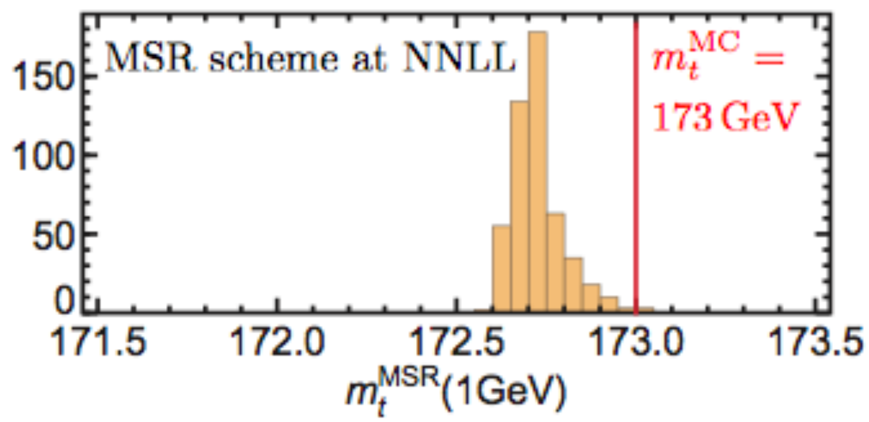
Fit works, gives a larger $\Omega_1^{\rm MPI}$ as expected

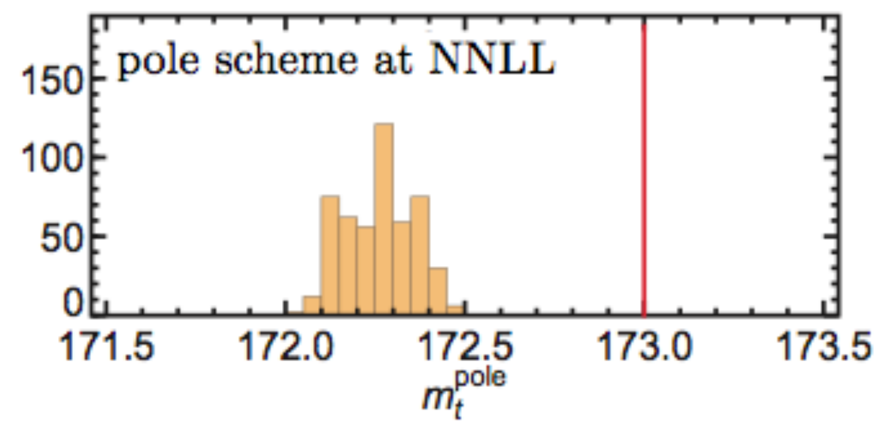
Promising new techniques to answer “what mass is it?”



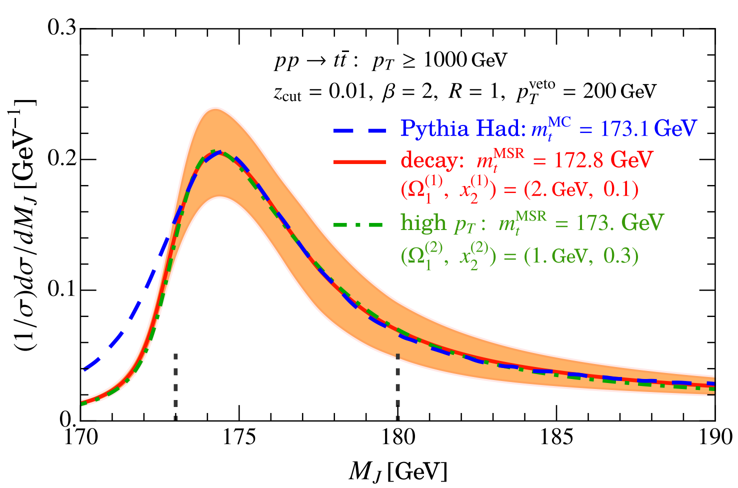
Summary

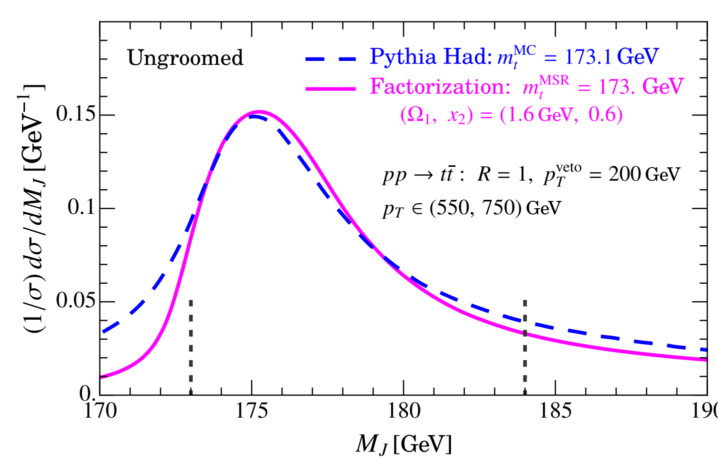
- A dominant uncertainty in the top mass is "what mass is it?"
- Answers from connecting theory (QFT) to Monte Carlo or Data
- Can Calibrate MC to determine relation: $m_t^{\mathrm{MC}} = m_t + \ldots$



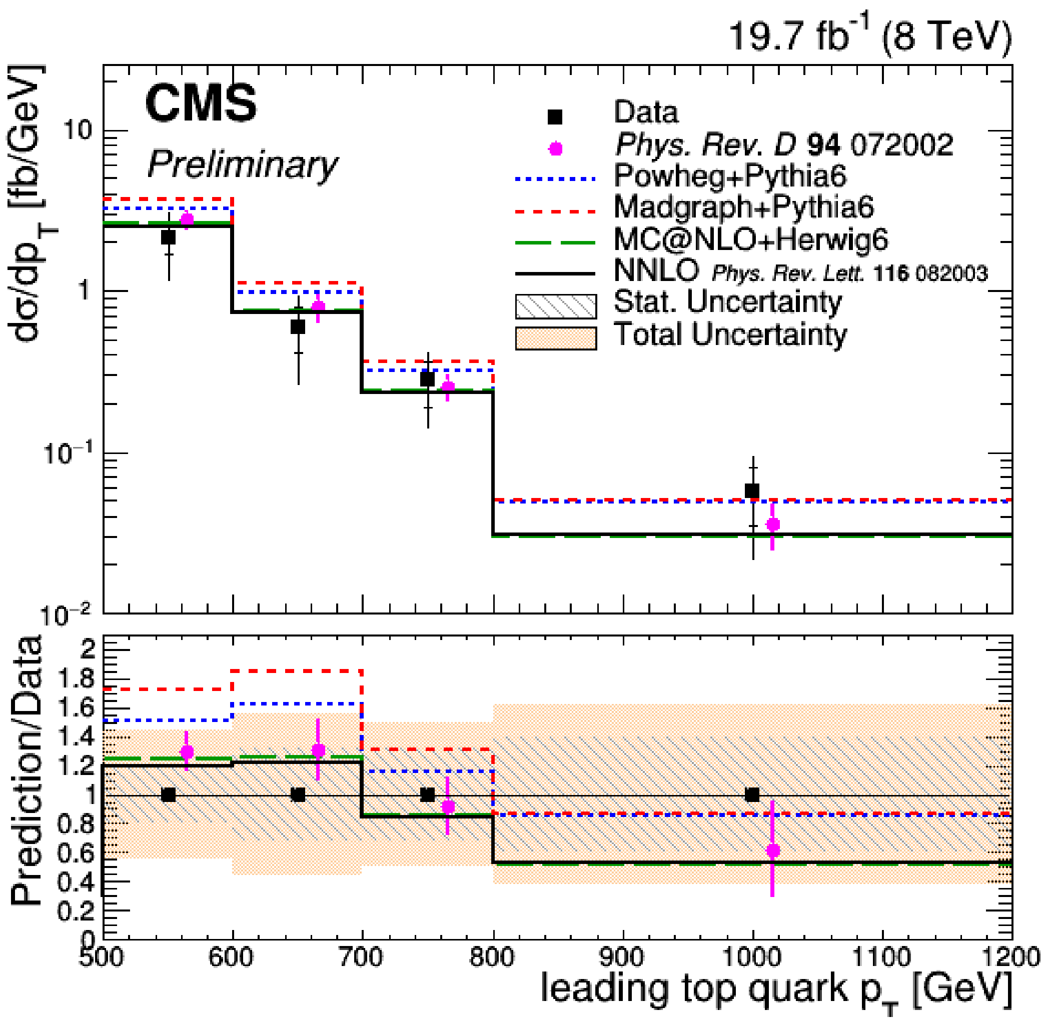


- Discussed a promising new method for Top Jet Mass predictions in pp with/without a light Soft Drop

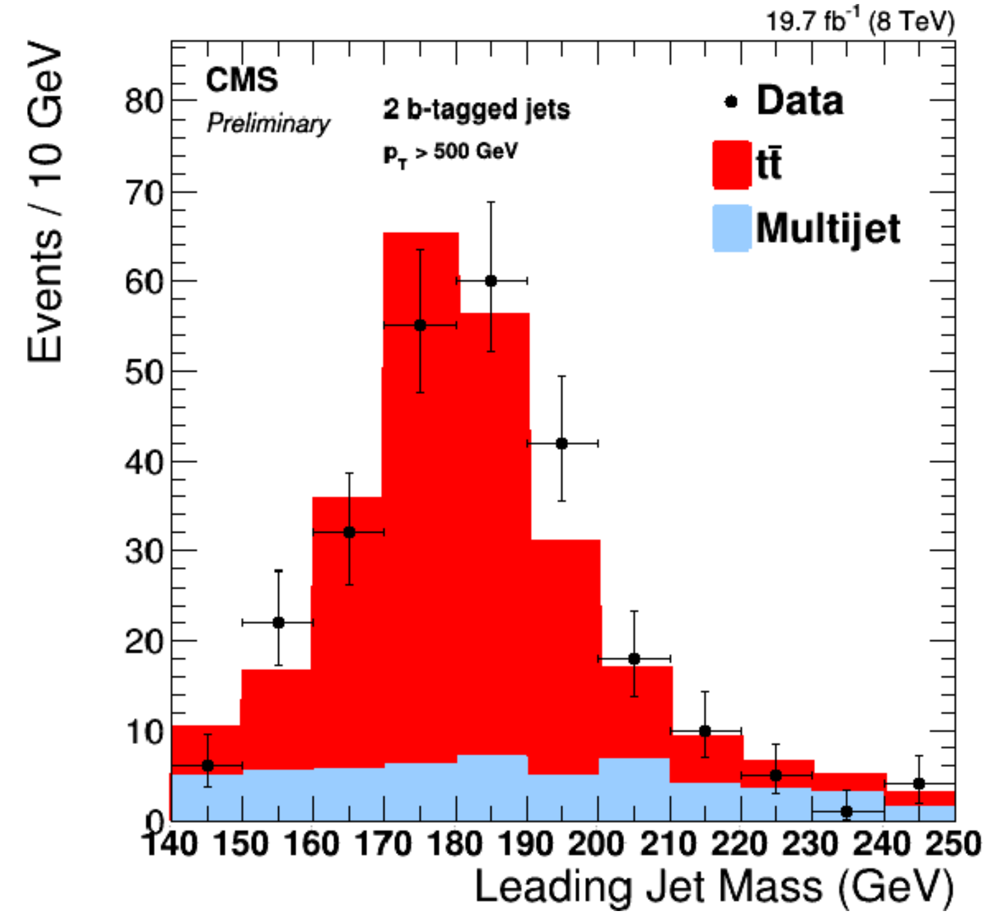




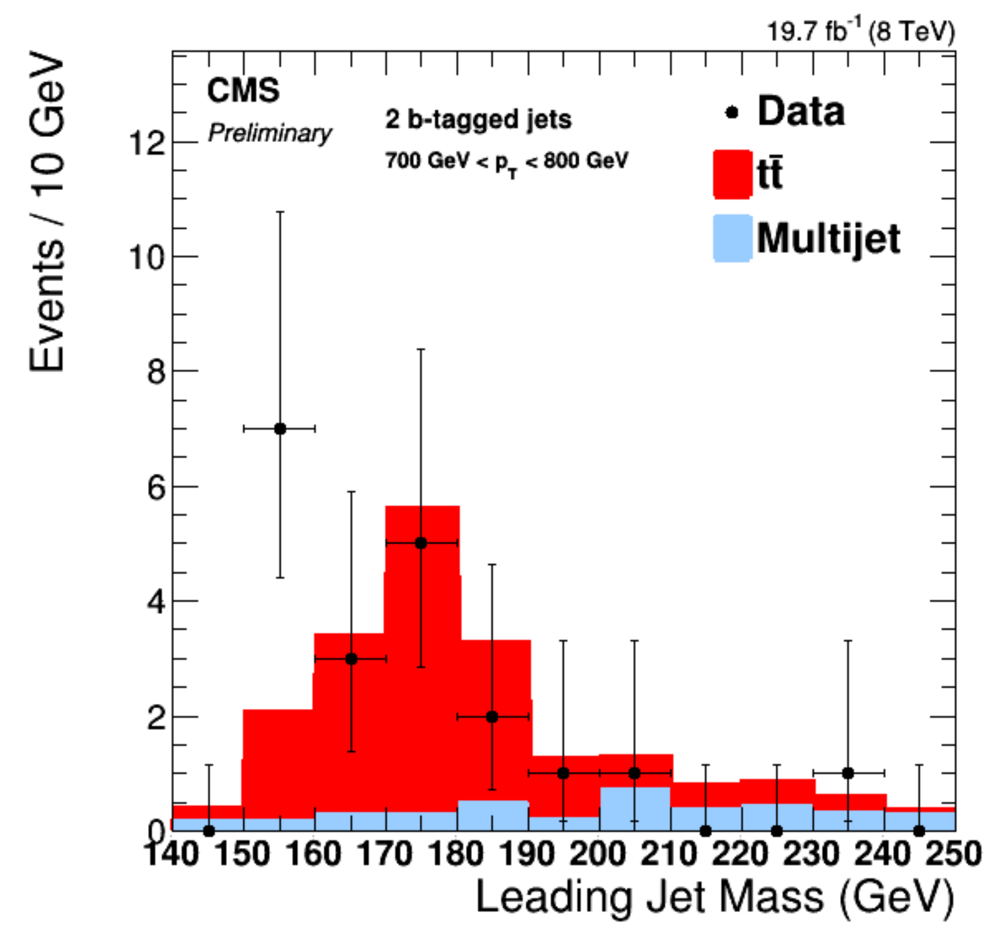
The End



19.7 fb-1 (8 TeV)
CMS
Preliminary
Data
Phys. Rev. D 94 072002
Powheg+Pythia6
Madgraph+Pythia6
MC@NLO+Herwig6
NNLO Phys. Rev. Lett. 116 082003
Stat. Uncertainty
Total Uncertainty
dσ/dp_T [fb/GeV]
Prediction/Data
leading top quark p_T [GeV]



19.7 fb-1 (8 TeV)
CMS
Preliminary
2 b-tagged jets
p_T > 500 GeV
Data
tt̄
Multijet
Events / 10 GeV
Leading Jet Mass (GeV)



19.7 fb-1 (8 TeV)
CMS
Preliminary
2 b-tagged jets
700 GeV < p_T < 800 GeV
Data
tt̄
Multijet
Events / 10 GeV
Leading Jet Mass (GeV)