Precision Top Mass Determination at the LHC with Jet Grooming

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In Collaboration with
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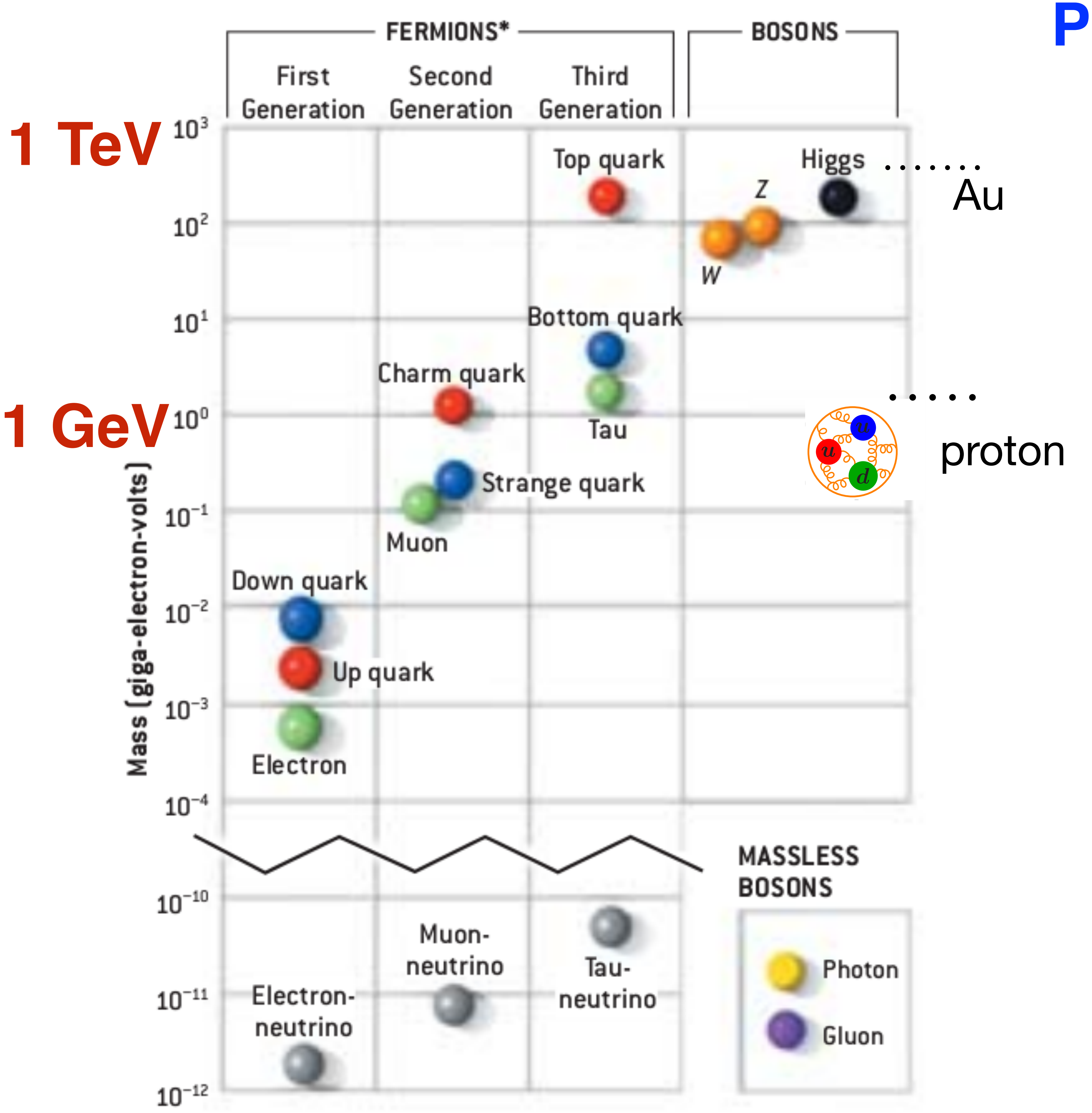
January 2017
ICTS-TIFR, Bangalore

Particle Masses



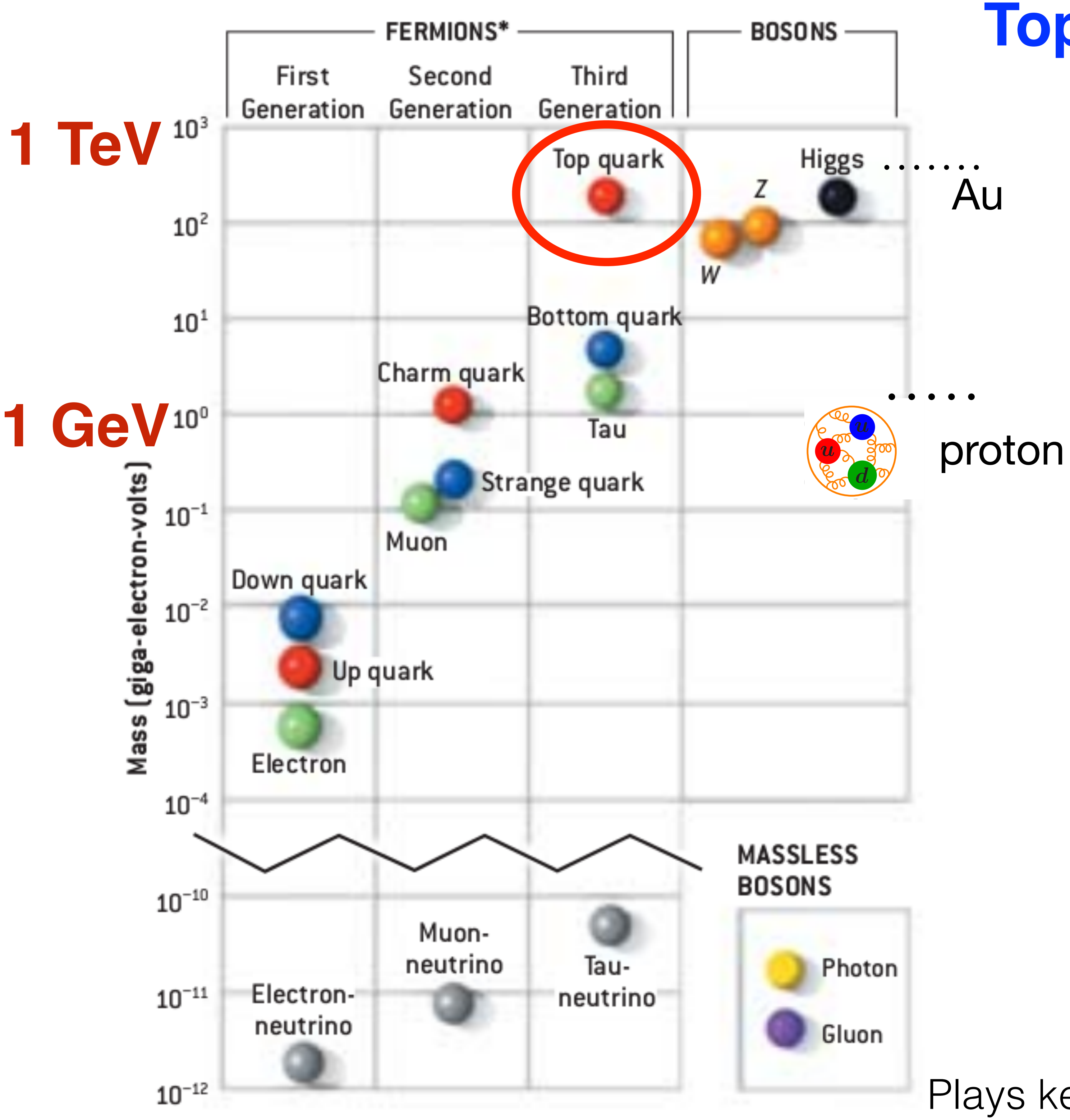
1 TeV

1 GeV

Au

proton

Top Quark is special



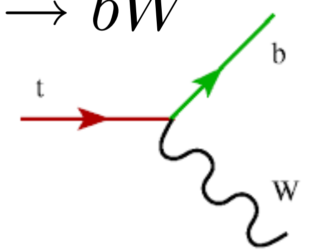
Heaviest known elementary particle is the **top quark**

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

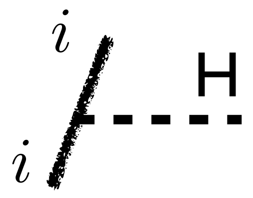
$$> m_H = 125\,\mathrm{GeV}$$

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

$$t \to bW$$



Largest Mass ->
Largest coupling to Higgs



$\propto m_i$

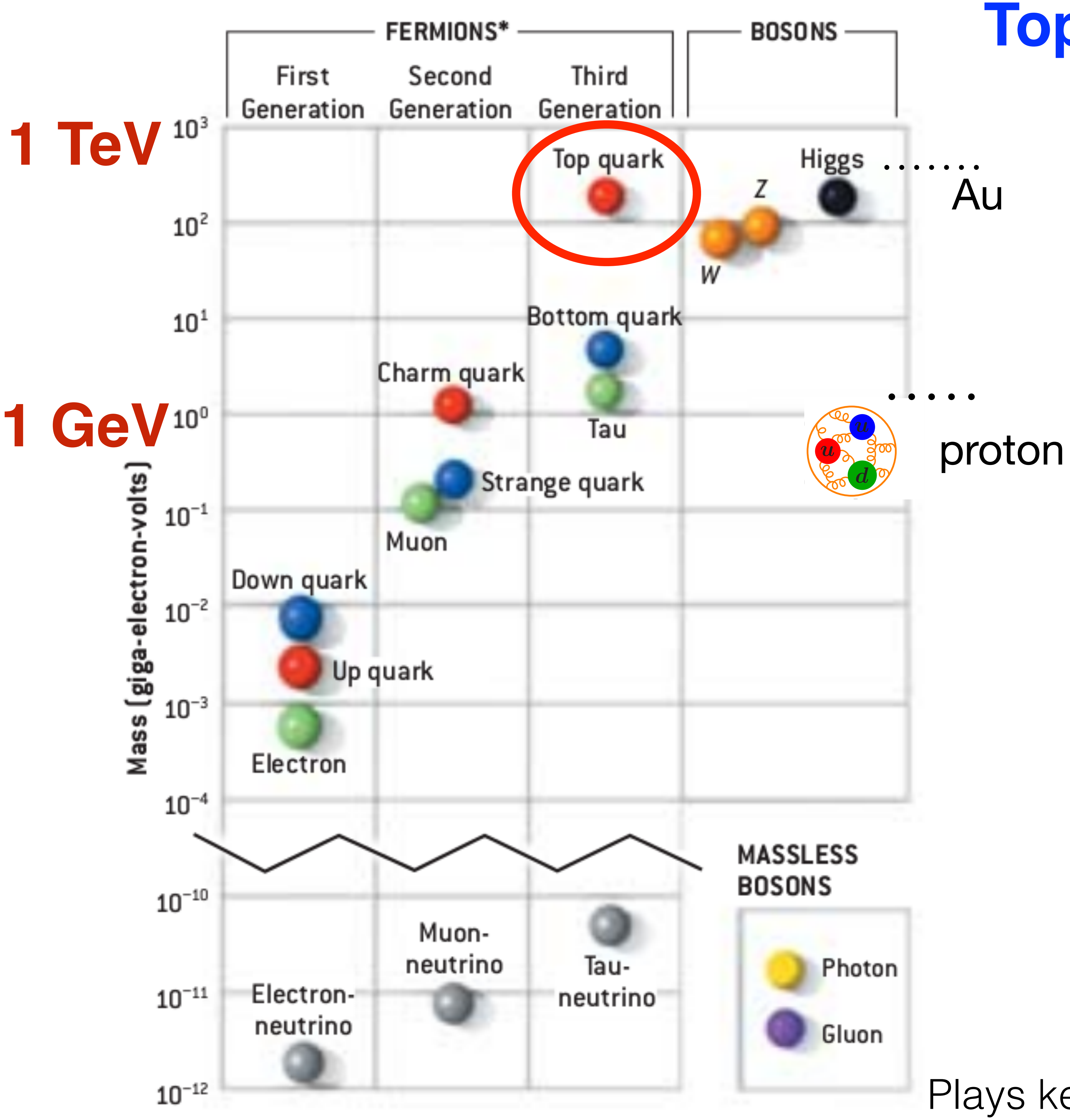
Dominant higgs production

Plays key role in BSM searches $Z' \to t\bar{t}$

Great exercise in jet tagging

$$t\bar{t} \to H,\ H \to b\bar{b}$$

Top Quark is special



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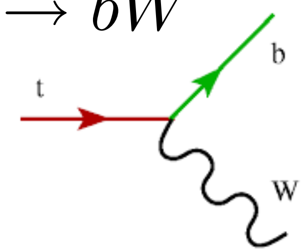

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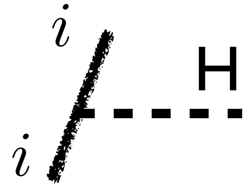

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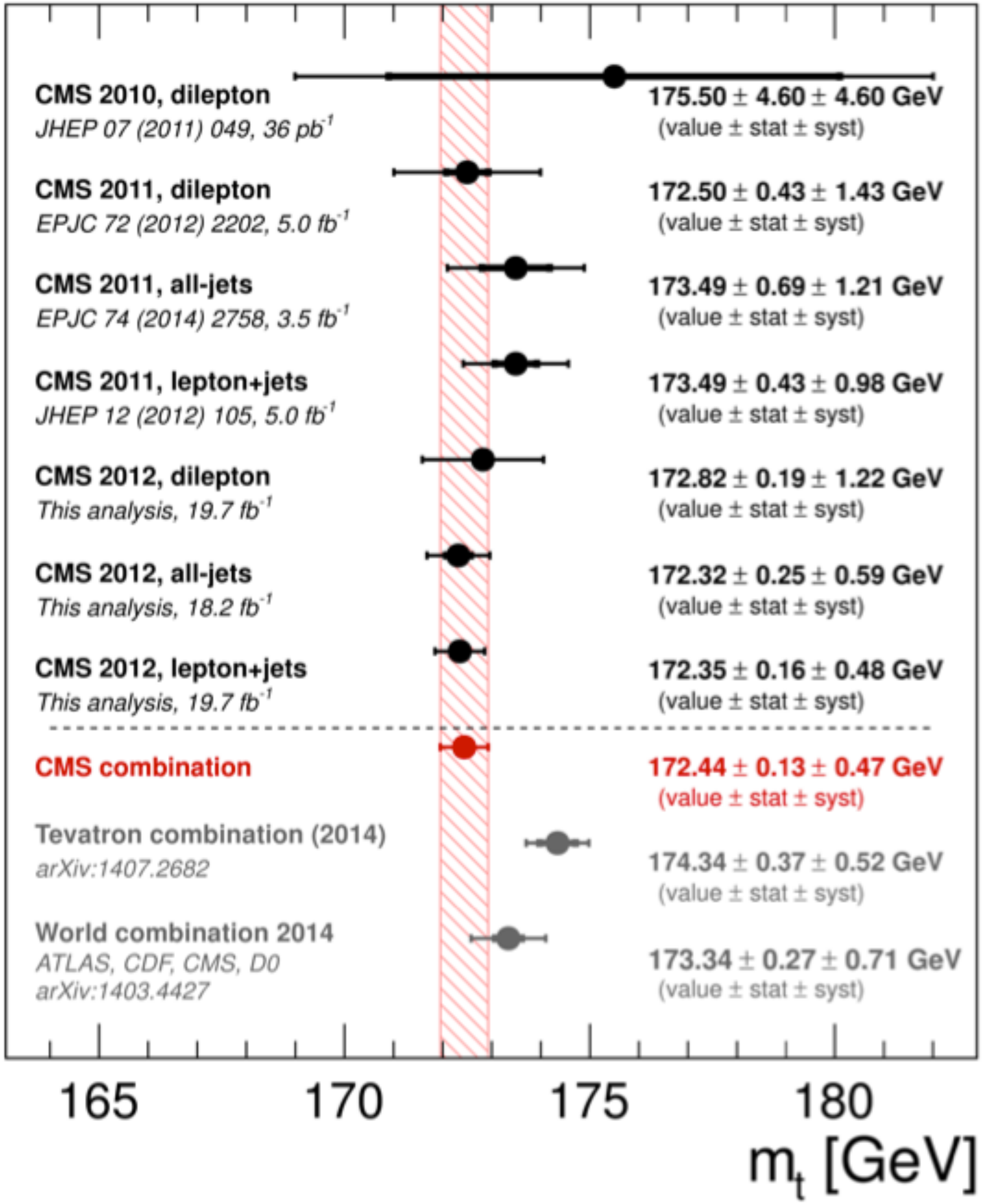
This talk: exploiting jet grooming for precision top quark physics.

Precision Measurements



Tevatron (2014): $m_t = 174.34 \pm 0.64$ GeV

CMS Run 1 (2015): $m_t = 172.44 \pm 0.49$ GeV

ATLAS Run 1 (2016): $m_t = 172.84 \pm 0.70$ GeV

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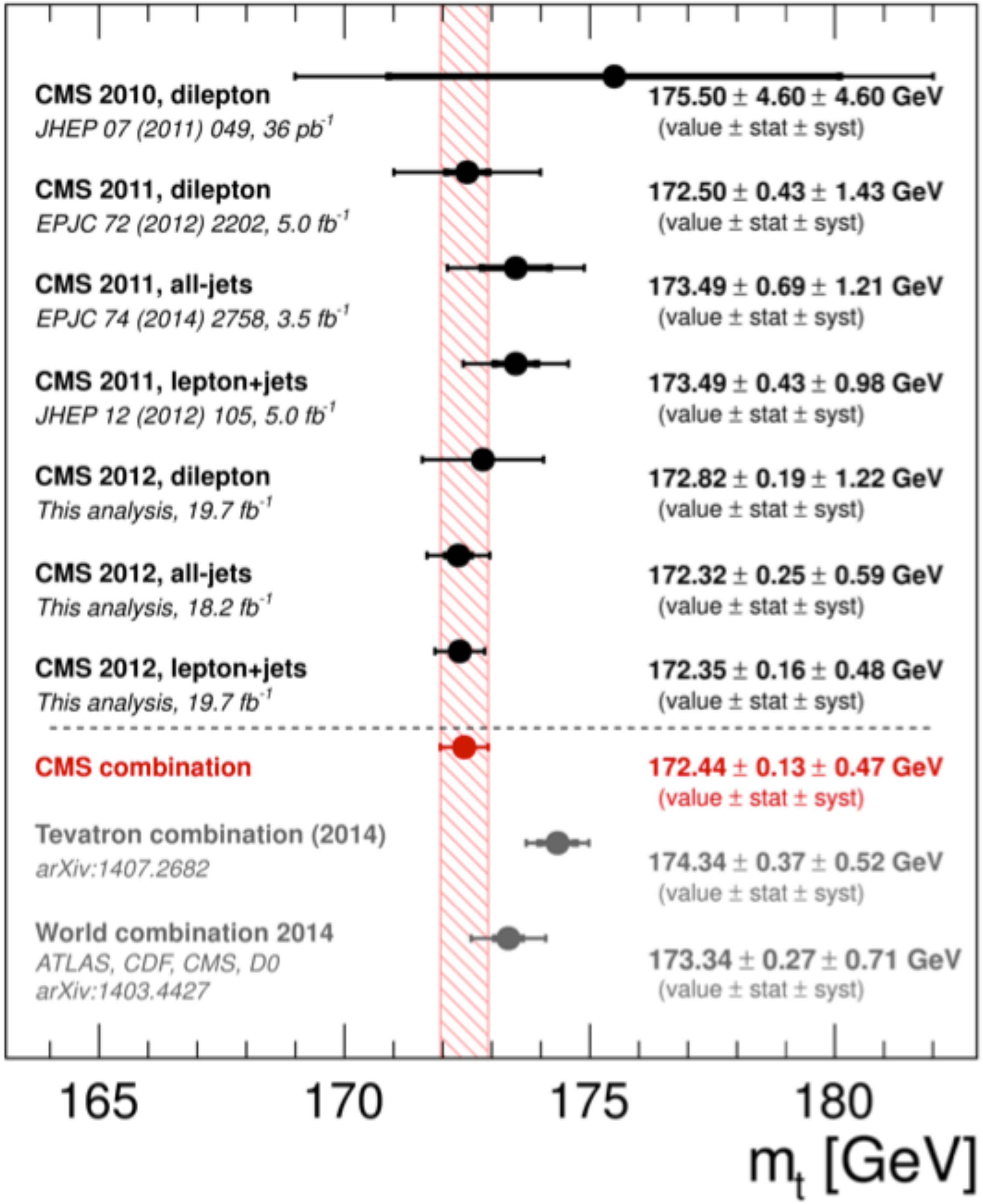

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0.3% sys + 0.07% stat!

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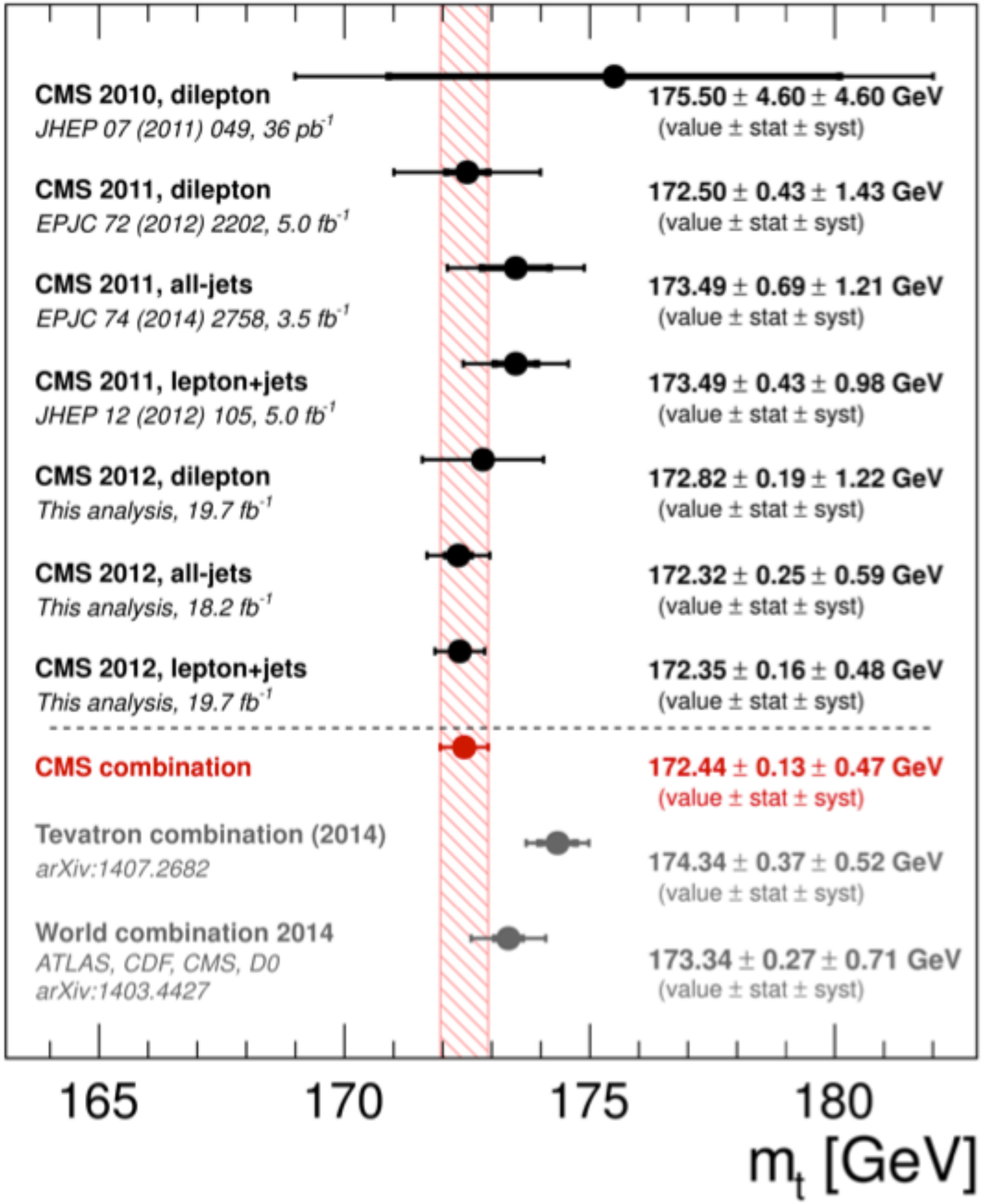

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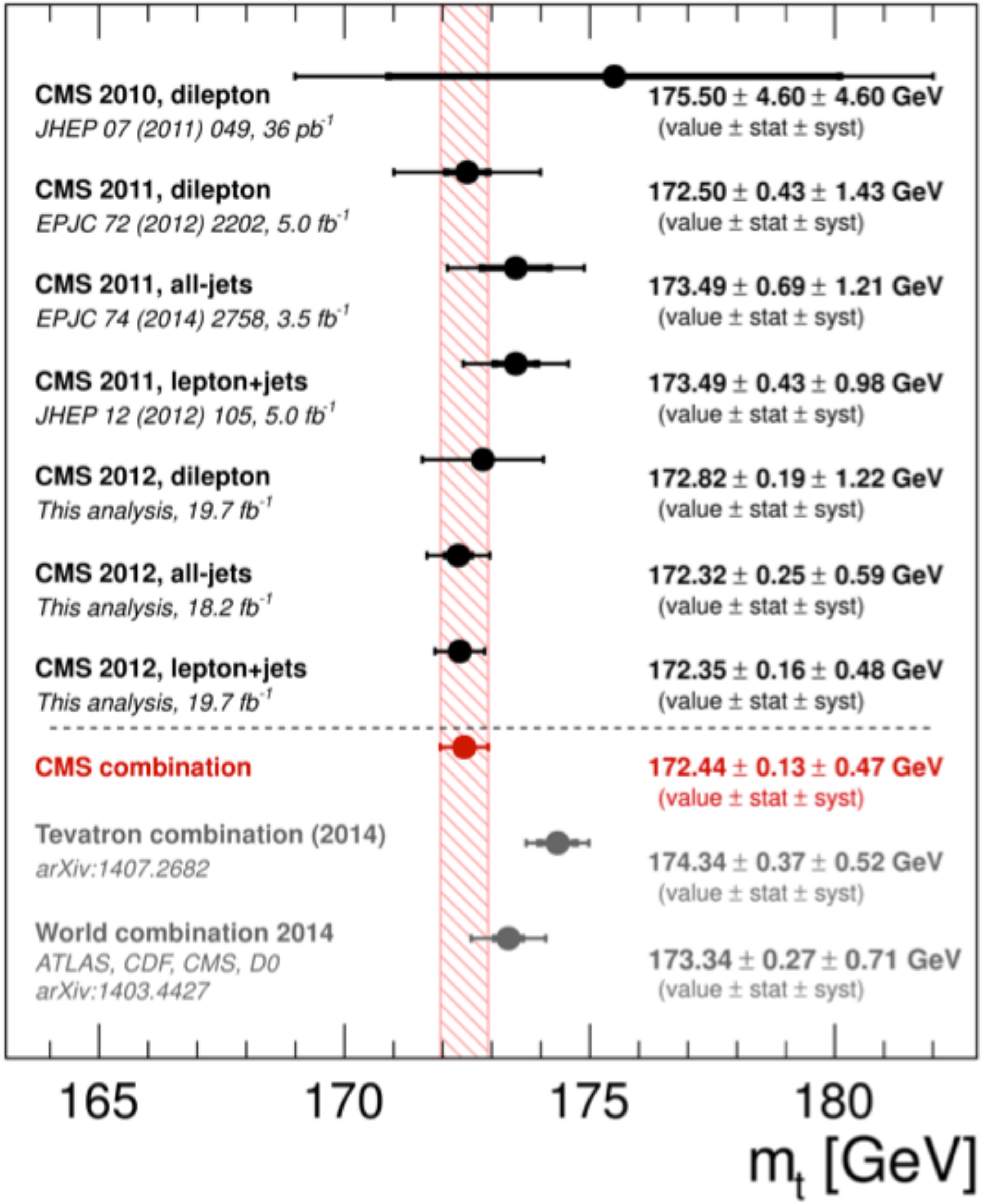
In this talk we discuss another source of uncertainty

Precision Measurements



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In this talk we discuss
another source of uncertainty

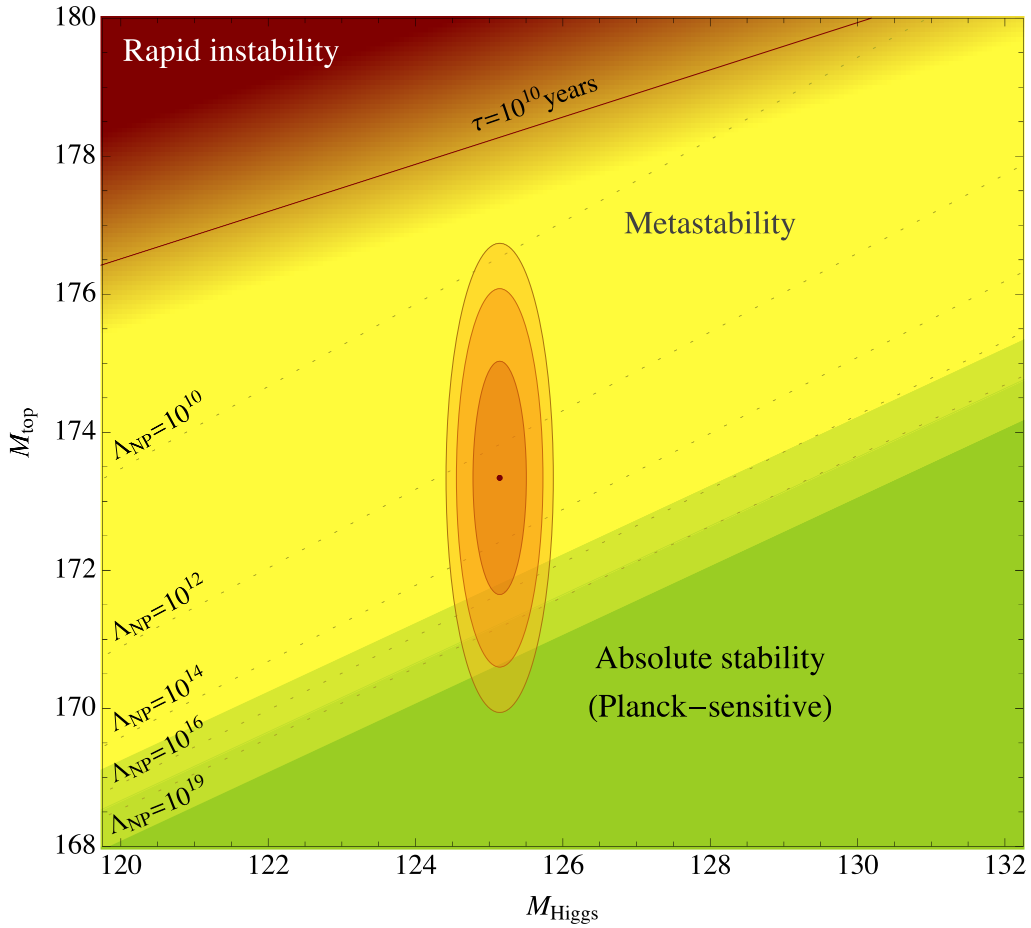
What mass is it?

How precisely do we know the mass definition?

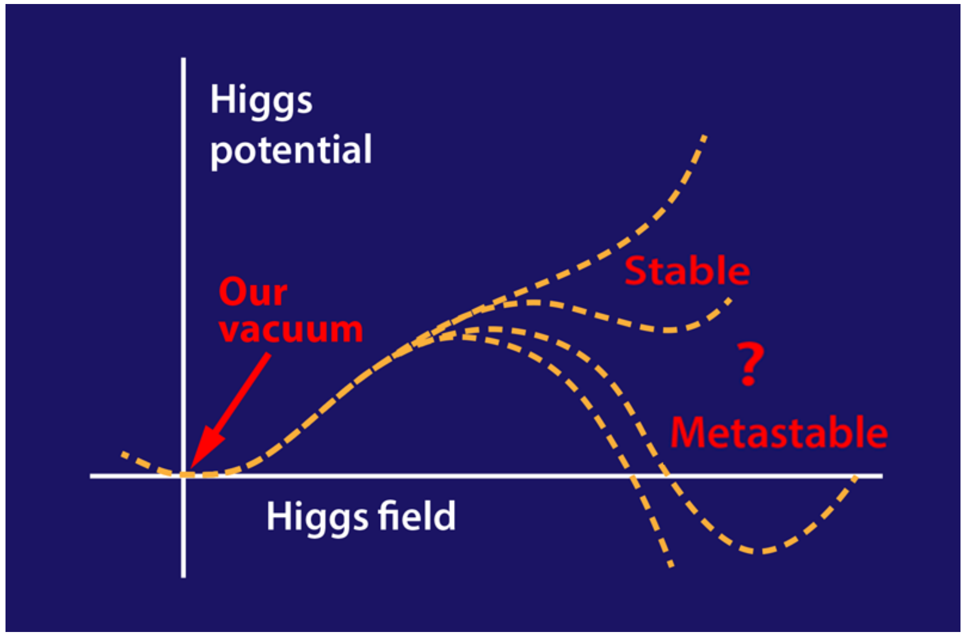
$$\delta m_t \sim 1\,\mathrm{GeV}$$

Why should we care about a precision m_t?

- Stability of SM vacuum
- Precision electroweak measurements
- LHC searches



Andreassen, Frost, Schwartz



Butazzo, Degrassi, Giardino, Giudice, Sala

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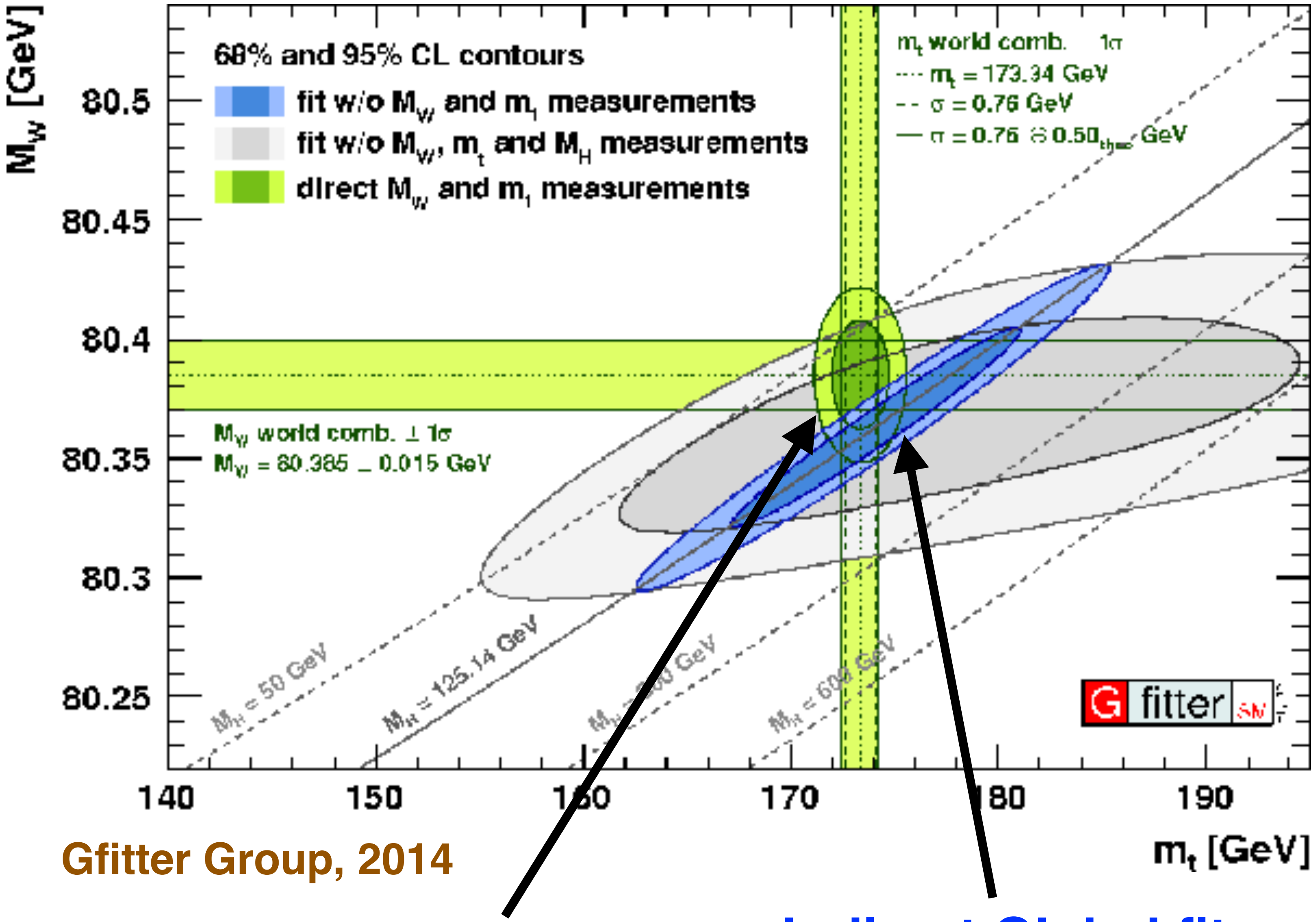
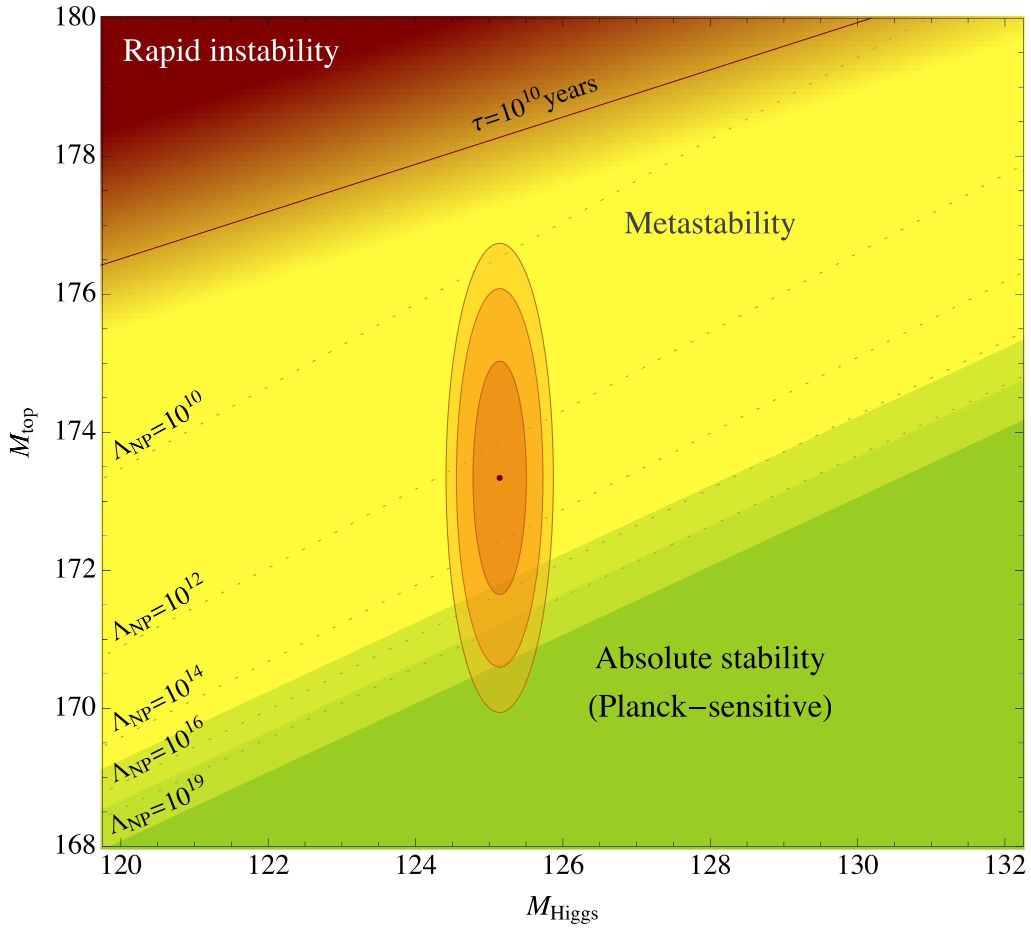


Gfitter Group, 2014

Direct measurements

Indirect Global fit



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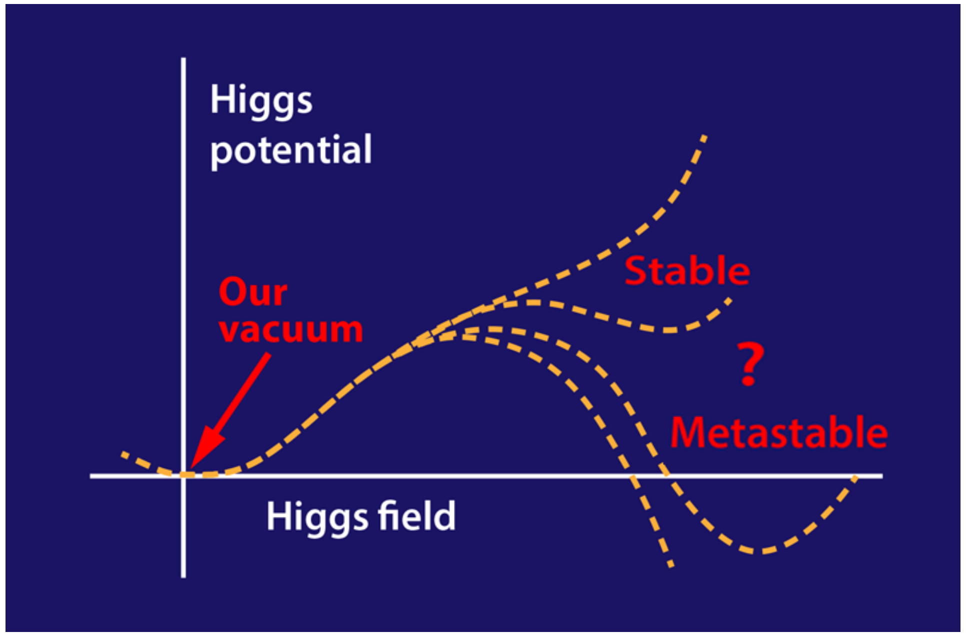


Significant contribution to uncertainty due to m_t

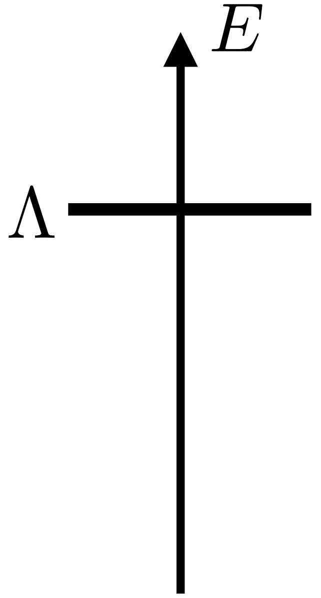
Butazzo, Degrassi, Giardino, Giudice, Sala

Outline

- **Overview**
  - Mass renormalization schemes, Monte Carlo mass
  - Theory issues for top jets at the LHC
  - Effective field theories for top jets

- **Top mass determination at the LHC**
  - Soft Drop Grooming on top jets
  - Pythia Studies
  - Pythia and Theory Comparison

Mass in Quantum Field Theory



Mass in quantum field theory gets renormalized and absorbs high energy divergences

$$\mathcal{L}^{\mathrm{SM}}(m_t, \alpha_s, \ldots, \Lambda)$$

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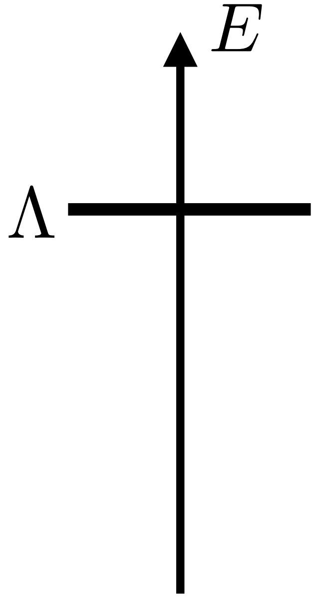
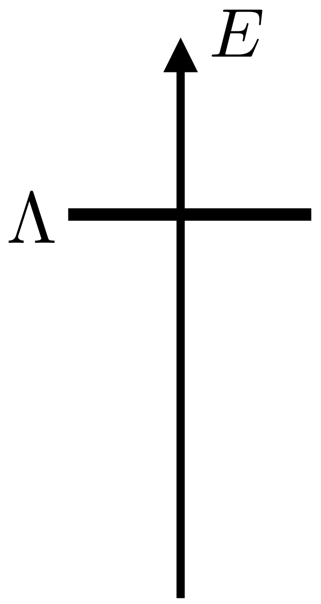


To be able to do more than one calculation and know we are talking about the same parameter requires **giving them a precise definition (eg. “top mass scheme”).**

Mass in Quantum Field Theory



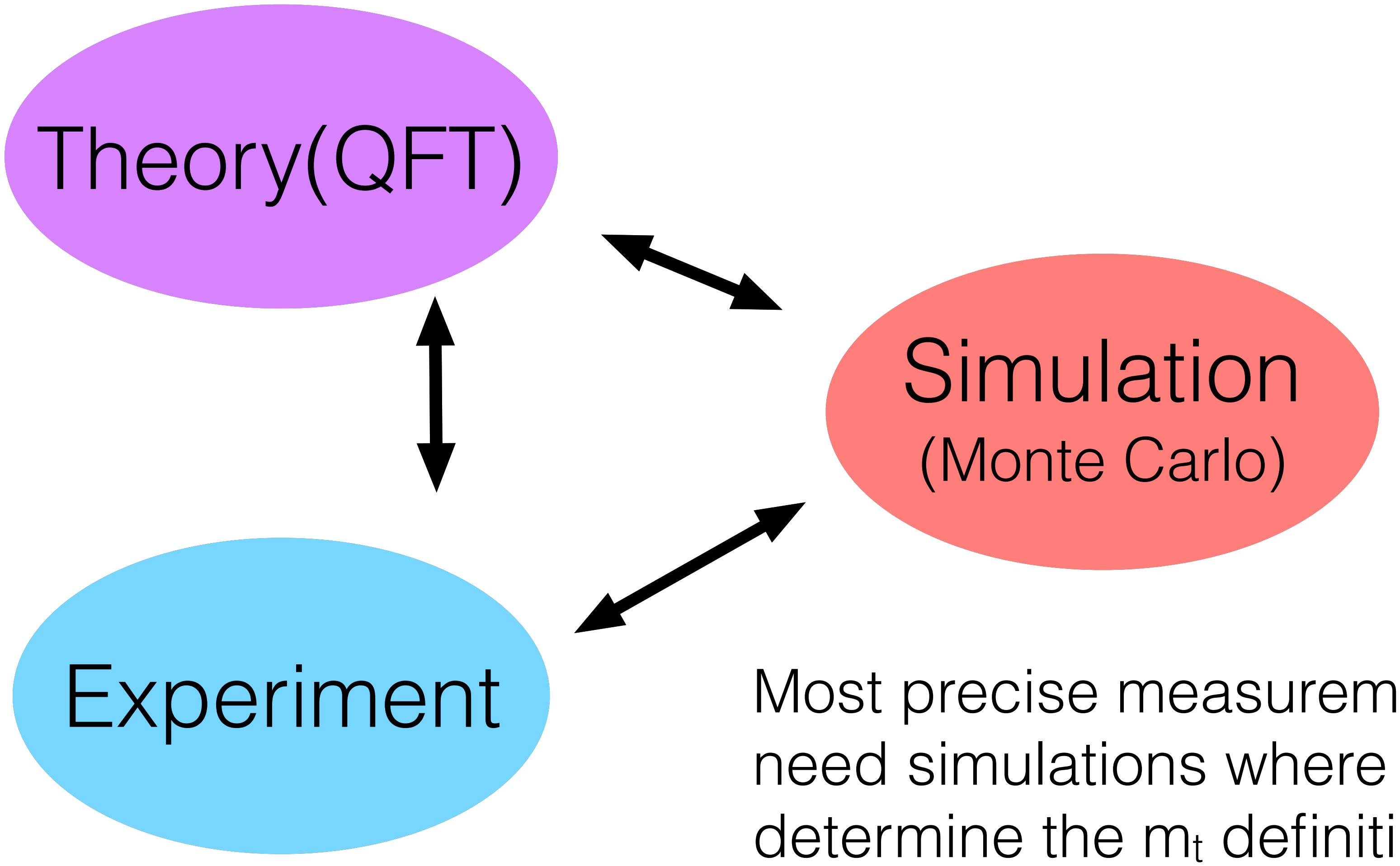
Mass in quantum field theory gets renormalized and absorbs high energy divergences.

$$\mathcal{L}^{\mathrm{SM}}(m_t, \alpha_s, \ldots, \Lambda)$$

To be able to do more than one calculation and know we are talking about the same parameter requires **giving them a precise definition (eg. “top mass scheme”).**

$\mathcal{L}:$

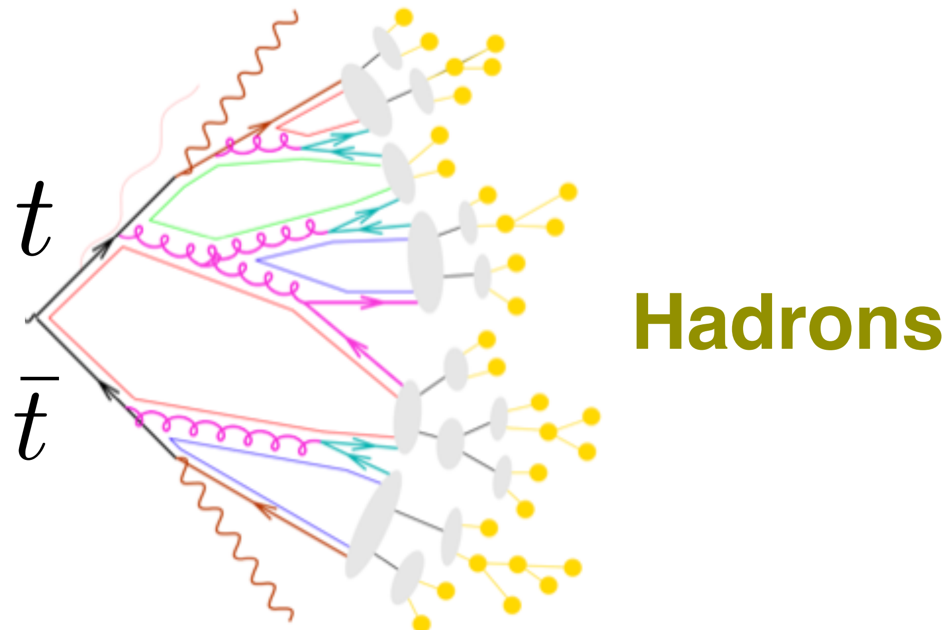
$$m_t^{\mathrm{pole}}, \overline{m}_t, m_t^{\mathrm{MSR}}, \ldots$$



Theory(QFT)

Simulation
(Monte Carlo)

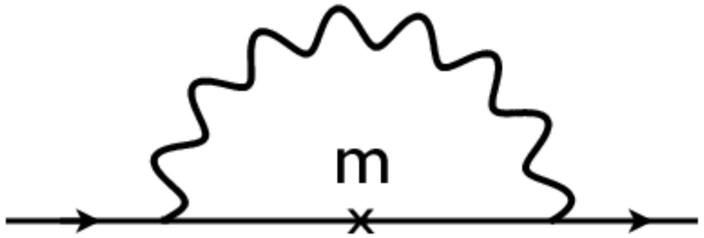
Experiment



Most precise measurements need simulations where it’s hard to determine the m_t definition.

Mass in Quantum Field Theory

$$m^{\rm bare} \to m^{\rm bare} + \Sigma(m^{\rm bare})$$



$$\Sigma(m) = \tfrac{3}{4} C_F \tfrac{\alpha_s}{\pi} m \left(\tfrac{1}{\epsilon} + \text{finite} \right) + \mathcal{O}(\alpha_s^2)$$

Pick a renormalization scheme $m^{\rm bare} = m^{\rm ren} + \delta_m$

Mass in Quantum Field Theory

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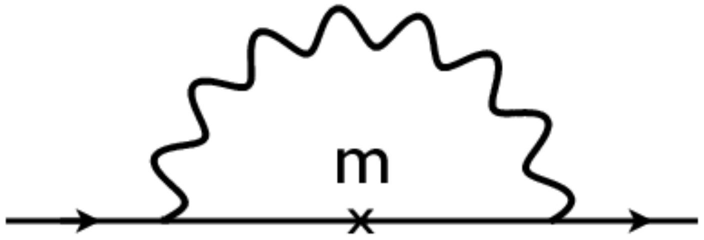

Pick a renormalization scheme $m^{\text{bare}} = m^{\text{ren}} + \delta_m$

- Pole Mass - Remove the full one loop correction Σ
- $\overline{\text{MS}}$ mass - Remove the $1/\epsilon$ term from Σ

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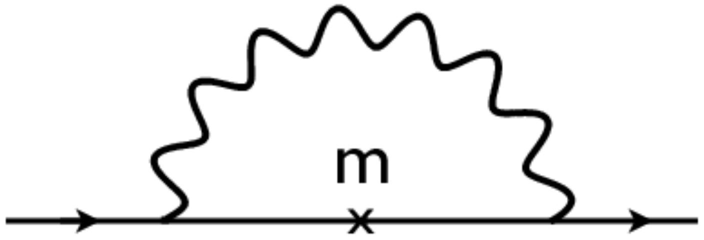

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Choice of scheme can affect accuracy: b decay width example

$$\Gamma(b \to u e \bar{\nu}) = \frac{G_F^2 |V_{ub}|^2}{192\pi^3} {m_b}^5 \left[1 + \kappa_1 \frac{\alpha_s(m_b)}{\pi} \epsilon + \kappa_2 \frac{\alpha_s^2(m_b)}{\pi^2} \epsilon^2 + \dots\right]$$

$$\Gamma(b \to u e \bar{\nu}) = \frac{G_F^2 |V_{ub}|^2}{192\pi^3} (m_b^{pole})^5 \left[1 - 0.17\epsilon - 0.13\epsilon^2 + \dots\right]$$

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Hoang, Ligeti, Manohar 1998

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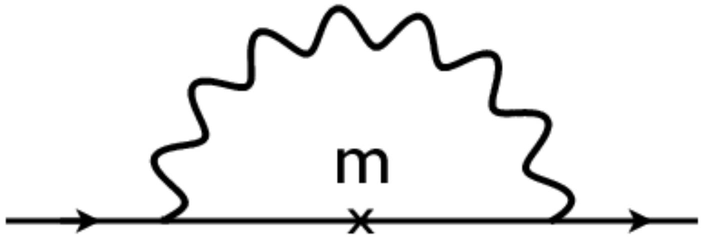

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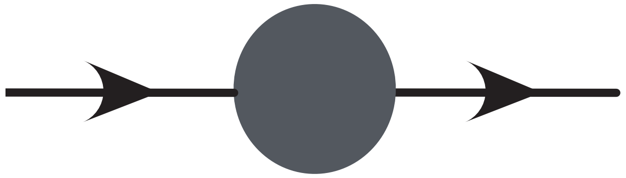
Significant improvement from using 1S scheme for m_b
defined using binding potential of bottomonium.

Hoang, Ligeti, Manohar 1998

What makes certain schemes better (worse) than others?

- Pole Mass

Full propagator:



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

pole at m_t

Like a free particle

Compatible with Breit Wigner

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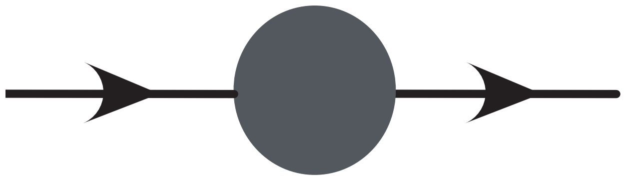


$$\propto \frac{1}{\not{p} - m_t^{\text{pole}}}$$

pole at m_t

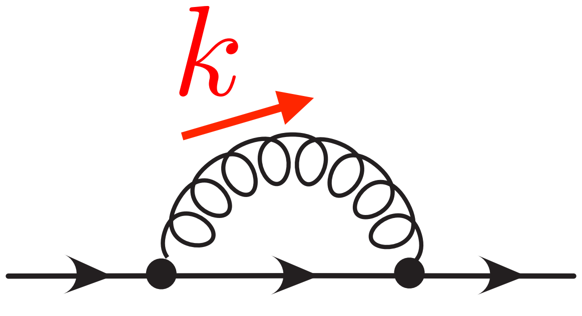
Like a free particle

Compatible with Breit Wigner

Good for electron in QED, but not for quarks.

Factorially diverging series (eg. bubble graphs) leads to an intrinsic uncertainty in the definition of pole mass.

$$\int_0 dk$$



$$n!\,\alpha_s^{n+1}$$

$$\Delta m_t^{\text{pole}} \sim \Lambda_{\text{QCD}}$$

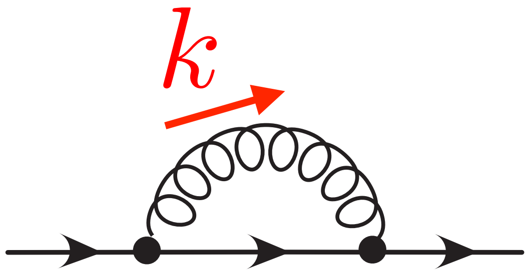
Beneke 1998

What makes certain schemes better (worse) than others?

- $\overline{\mathrm{MS}}$ Mass $\overline{m}_t$

No ambiguity ✓

$$\int_{\mu=\overline{m}_t} dk$$

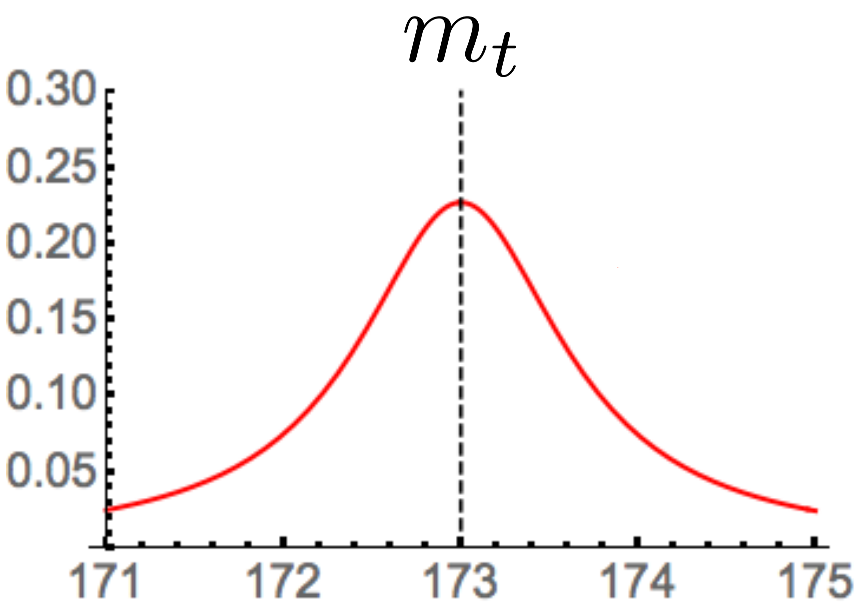


NOT compatible with Breit Wigner X

$$\frac{\Gamma_t}{[M^2 - m_t[\alpha_s]^2]^2 + \Gamma_t^2\, m_t[\alpha_s]^2}$$

$$\sigma^{\rm th}(m_t, \{Q\}) \to \int d\hat{s}_t\, \sigma^{\rm th}(\hat{s}_t, \{Q\}) \times \frac{\Gamma_t}{[\hat{s}_t^2 - m_t^2]^2 + \Gamma_t^2\, m_t^2}$$

$$\sigma^{\rm LO} \to \sigma^{\rm NLO}, \qquad \overline{m_t} \to \overline{m_t} + \delta\overline{m_t}$$



Need to expand BW in δm/m

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

Swamps the Breit Wigner

Fleming, Hoang, Mantry, Stewart 1998

What makes certain schemes better (worse) than others?

- MSR Mass

Define using $\overline{\text{MS}}$ coefficients a_{nk}

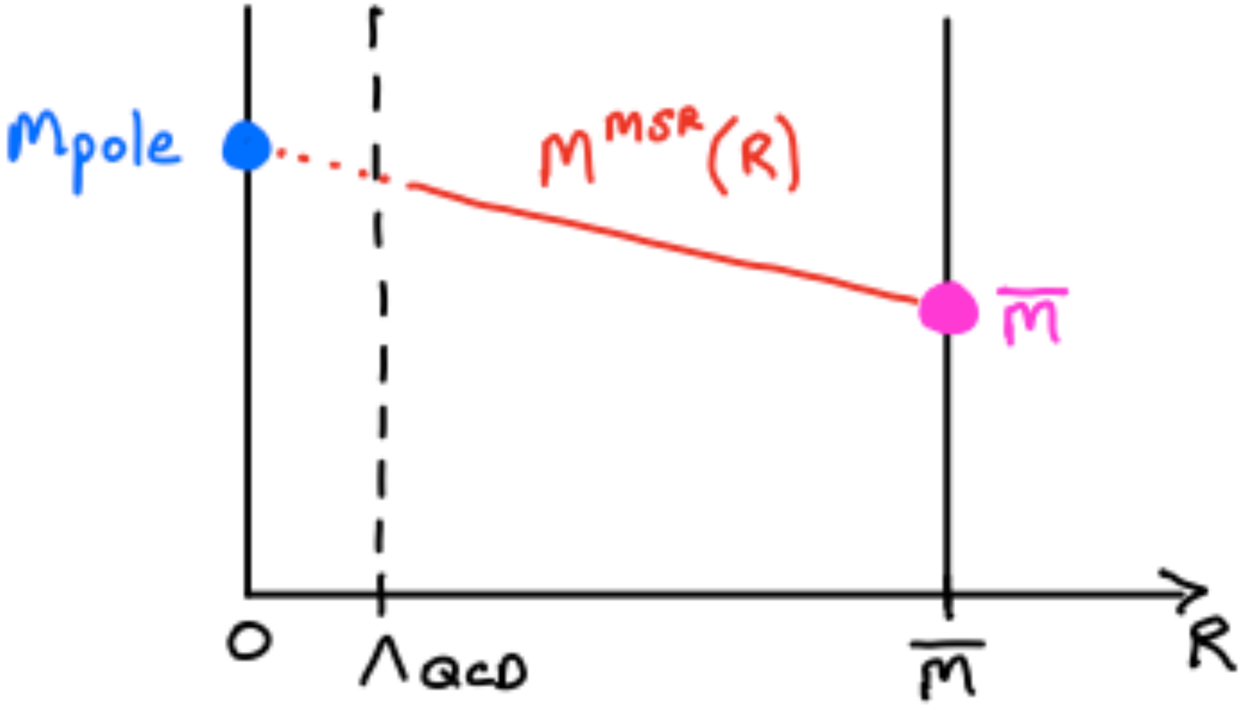
$$m_t^{pole} = m_t(R,\mu) + \delta m_t(R,\mu)$$

$$\delta m_t(R,\mu) = R \sum_{n=1}^{\infty} \sum_{k=0}^{n} a_{nk} \left[\frac{\alpha_s(\mu)}{4\pi}\right] \ln^k\left(\frac{\mu}{R}\right)$$

No ambiguity, R > Λ_{QCD} ✓

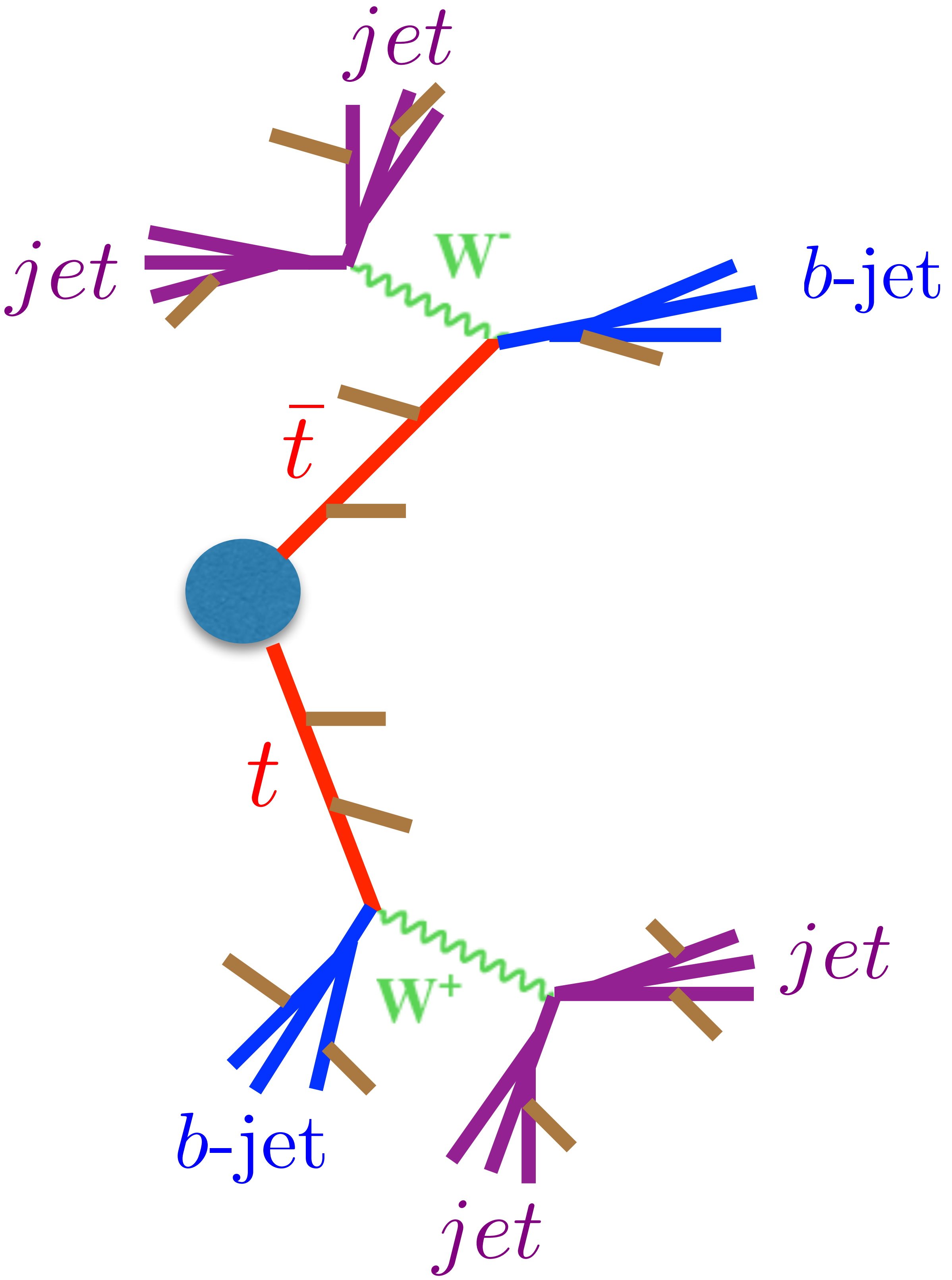
Compatible with Breit Wigner, R ~ Γ_t ✓

Nicely interpolates



Hoang, Jain, Scimemi, Stewart 2008

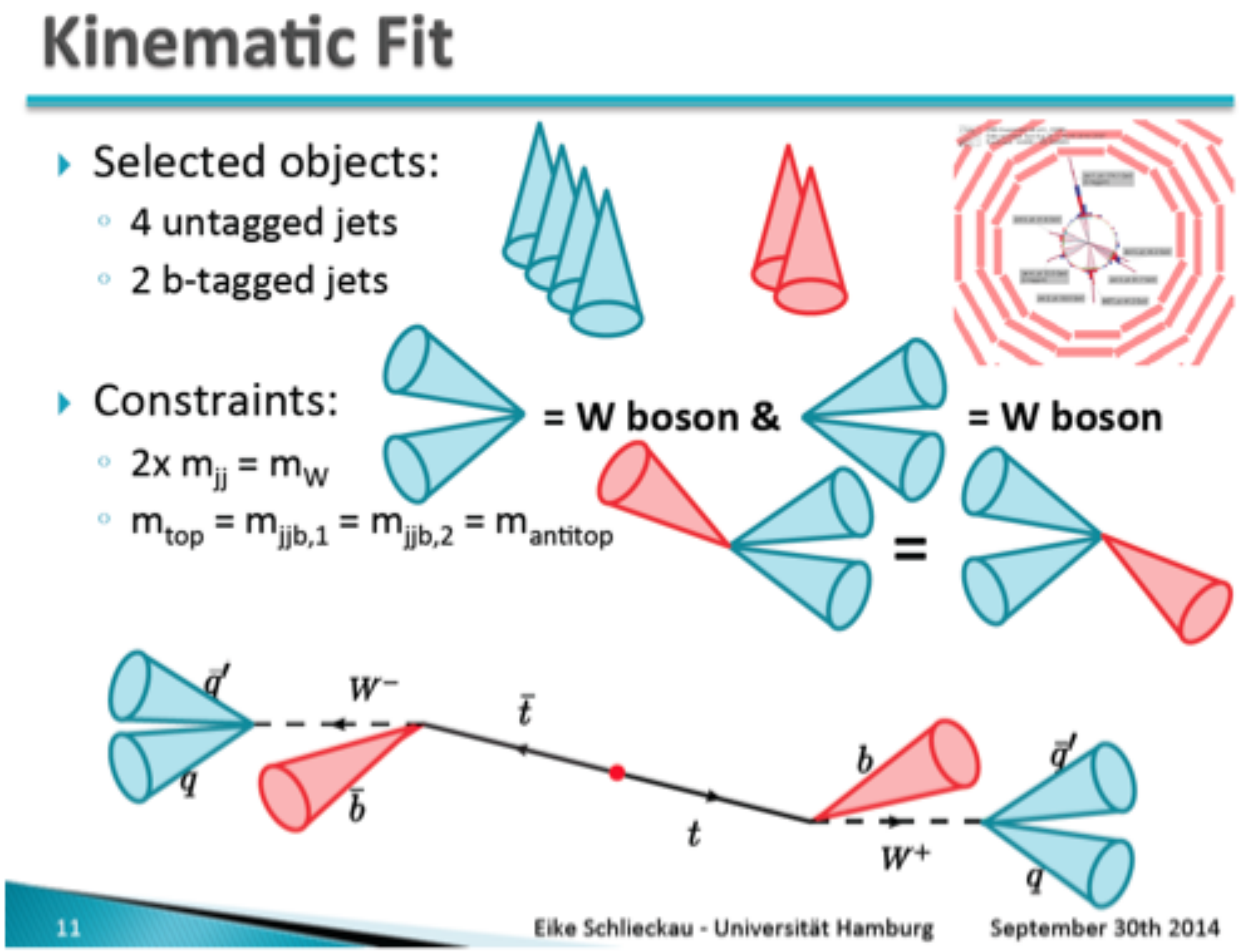
Direct Reconstruction Methods (Tevatron and LHC)



Kinematic Fit:

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

Direct Reconstruction Methods (Tevatron and LHC)

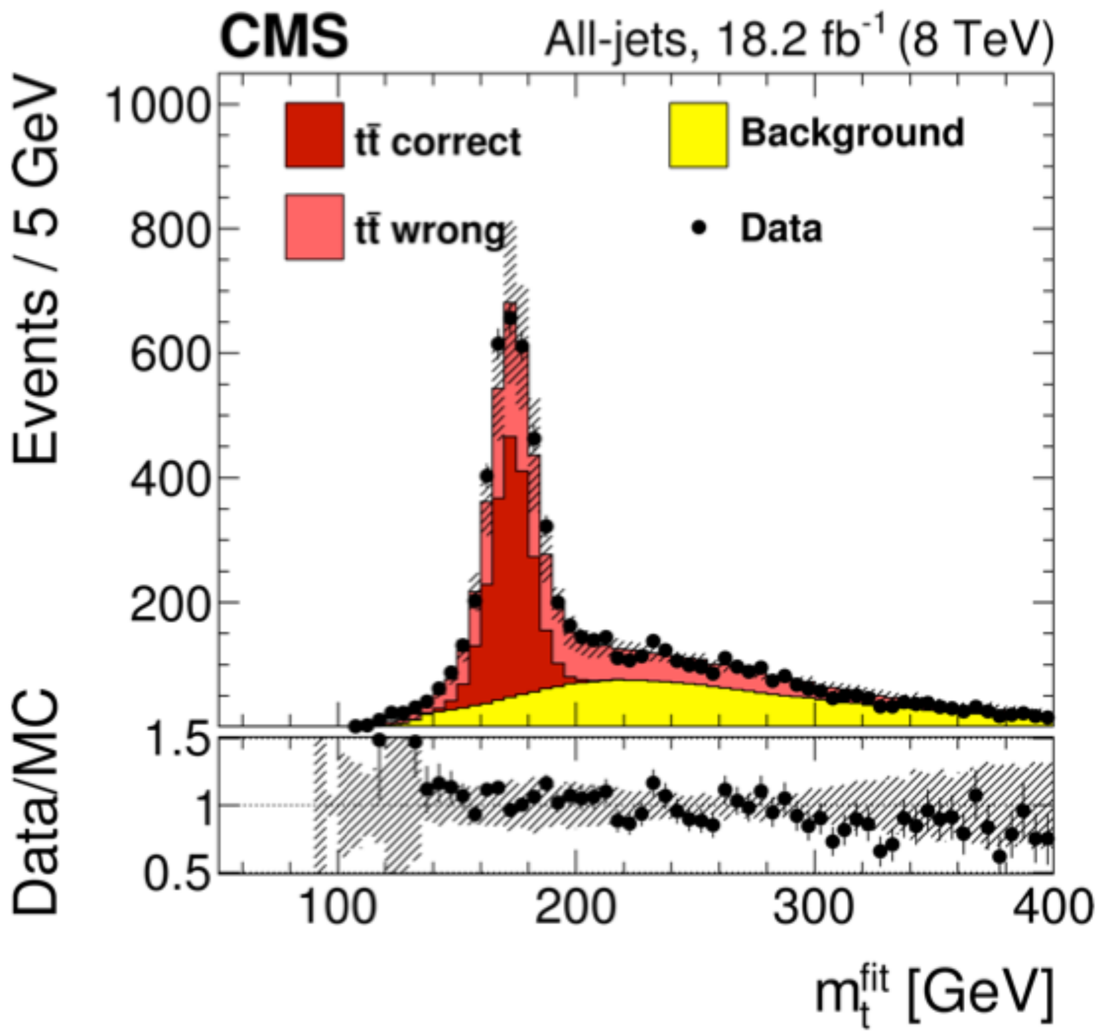


Kinematic Fit

- Selected objects:
  - 4 untagged jets
  - 2 b-tagged jets
- Constraints:
  - 2x $m_{jj} = m_W$
  - $m_{top} = m_{jjb,1} = m_{jjb,2} = m_{antitop}$

= W boson & = W boson

=



all-jets channel at 8 TeV

Use Monte Carlo simulations for templates.

Determine the best fit value of MC top mass parameter:

CMS Run 1 (2015): $m_t = 172.44 \pm 0.49$ GeV

Direct Reconstruction Methods (Tevatron and LHC)

CMS Run 1 (2015): $m_t = 172.44 \pm 0.49$ GeV

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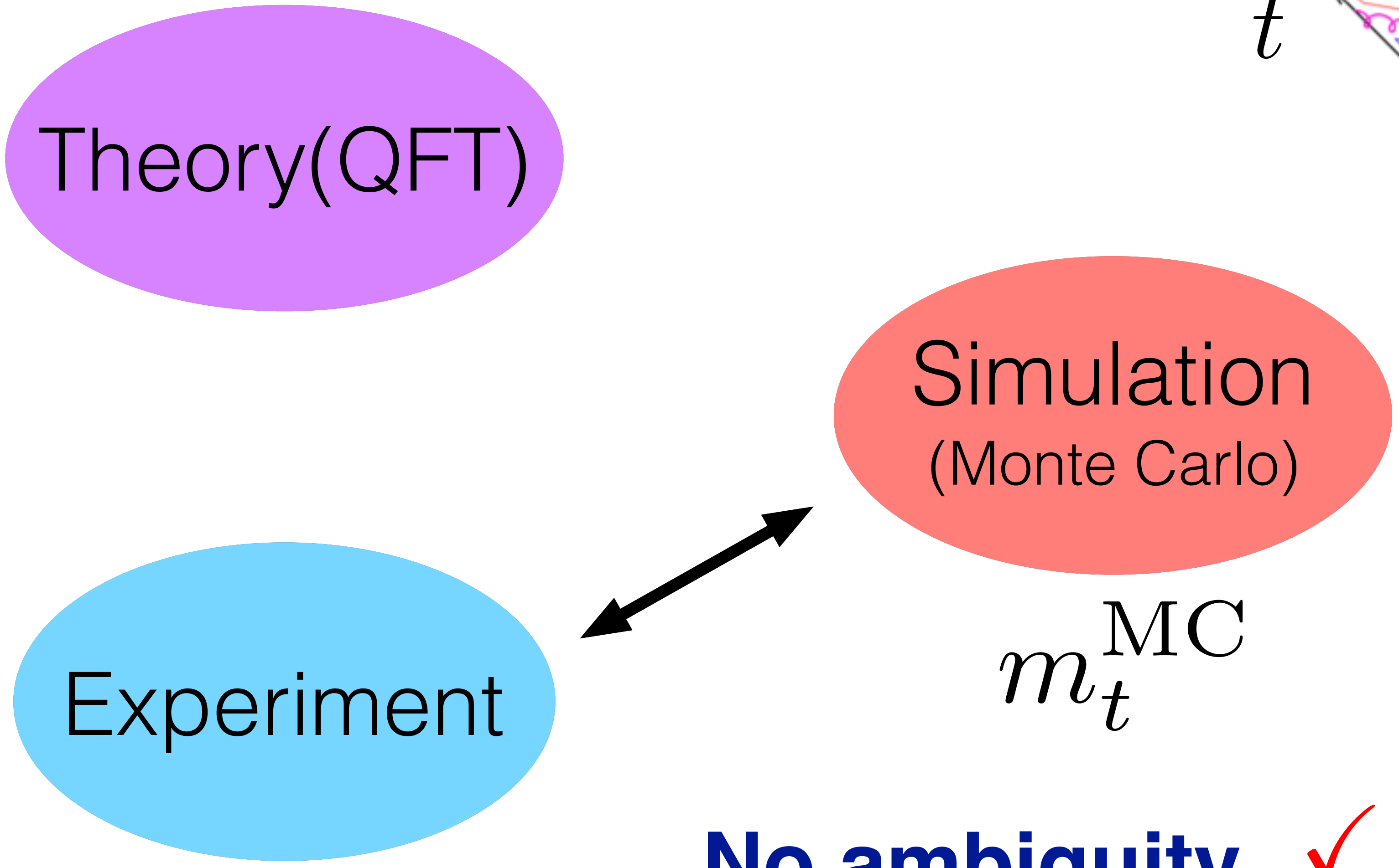


$$\Lambda^{\rm shower} = 1\,{\rm GeV}$$

$$m_t^{\rm MC}$$

No ambiguity ✓

Compatible with Breit Wigner ✓

Definition?

Direct comparison of theory and experiment

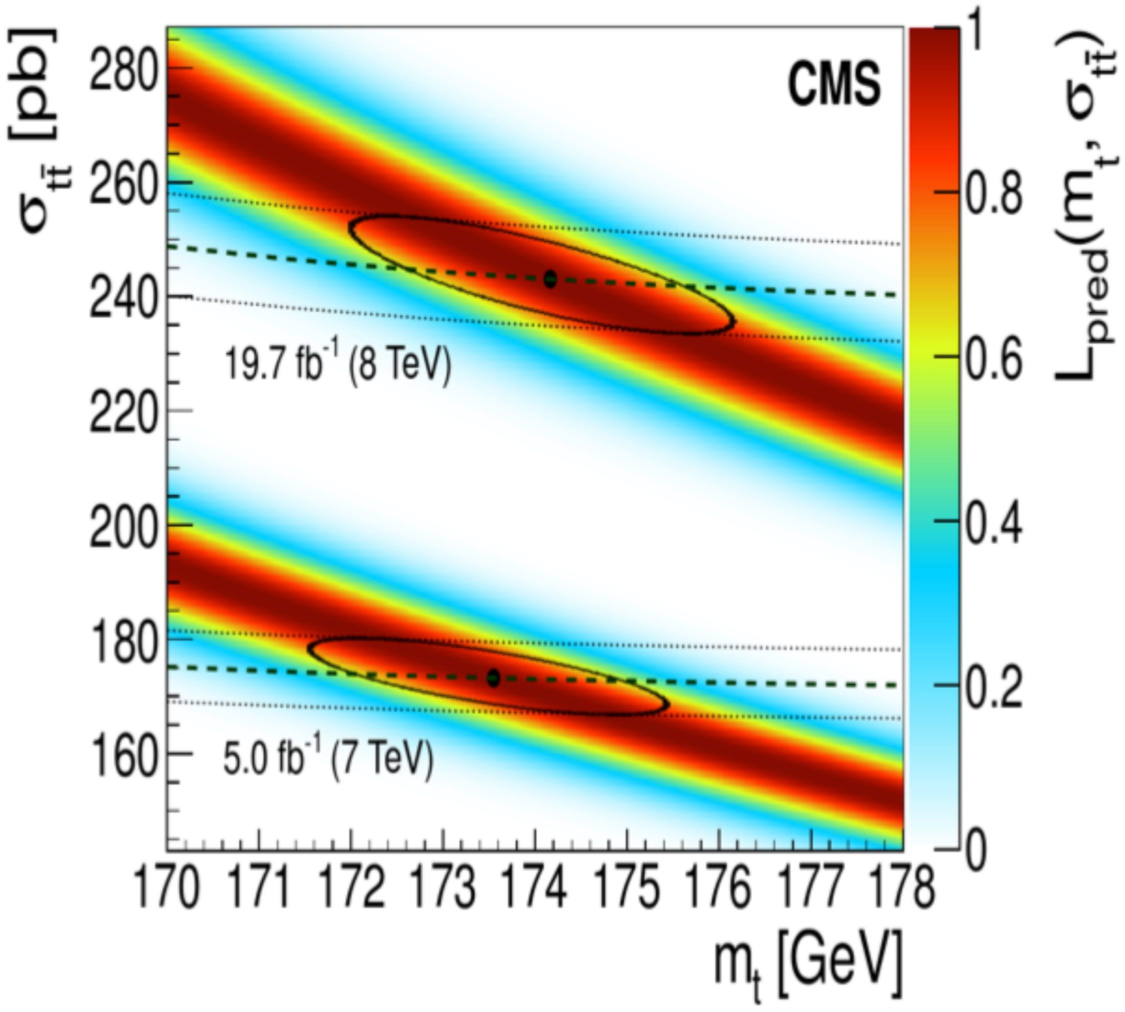
eg. Pole mass from Total Cross Section

$$\sigma^{\mathrm{exp}}(pp \to t\bar{t}) = \sigma^{\mathrm{th}}_{t\bar{t}}(m_t)$$

	m_t [GeV]
NNPDF3.0	$173.8^{+1.7}_{-1.8}$
MMHT2014	$174.1^{+1.8}_{-2.0}$
CT14	$174.3^{+2.1}_{-2.2}$

Czakon, Fielder, Mitov (13)

CMS arXiv:1603.02303



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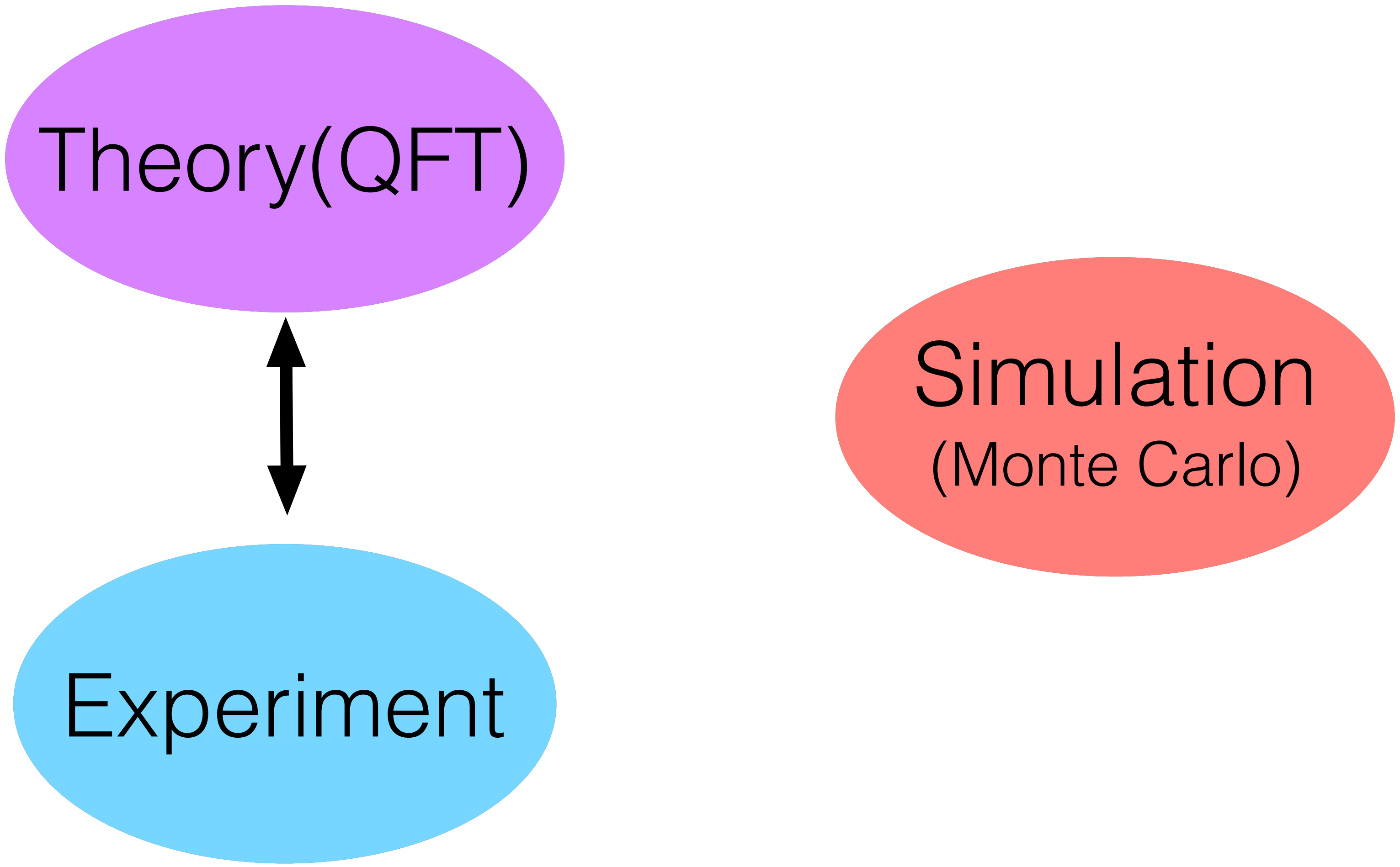
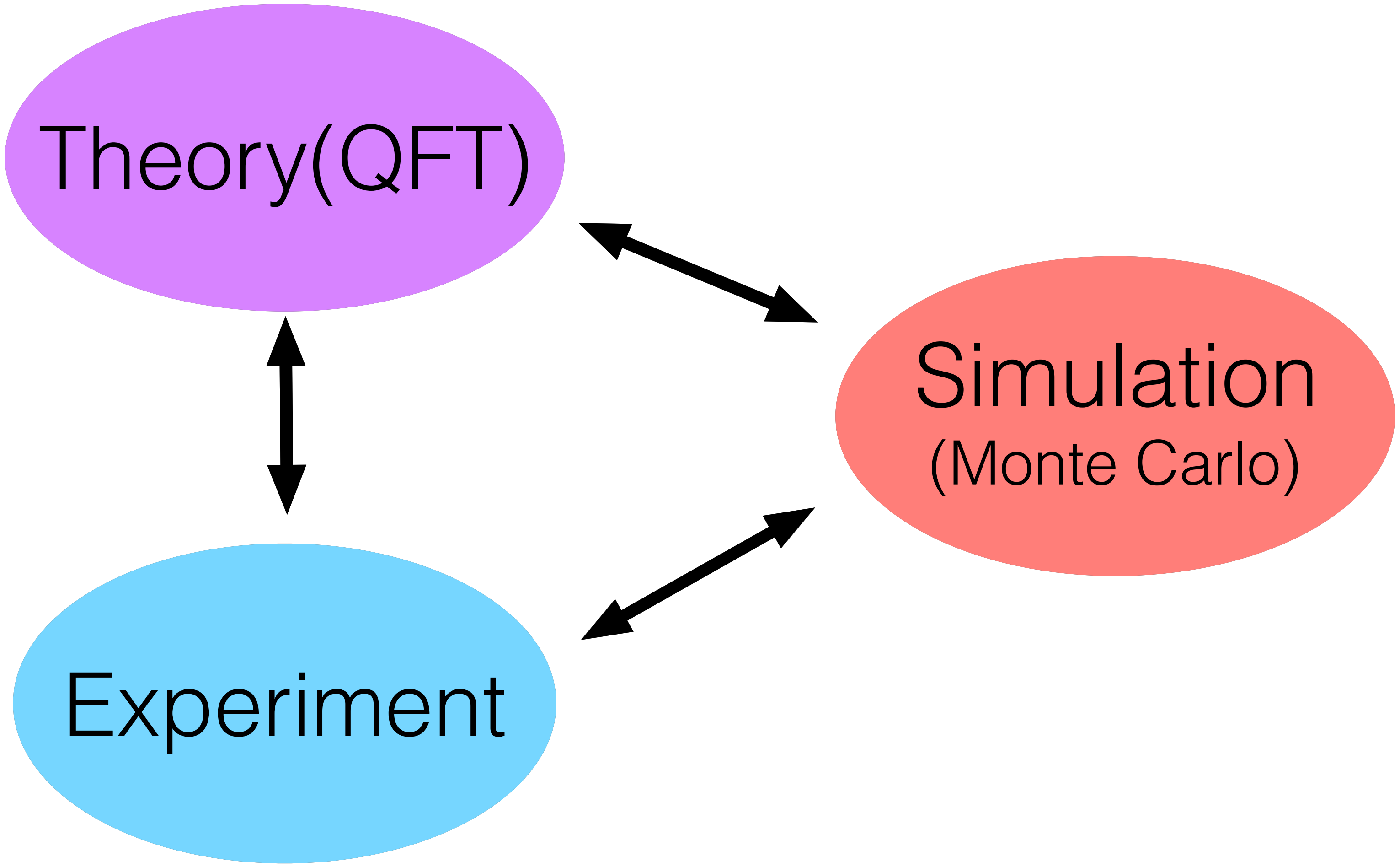


Improving Top Mass Measurement at the LHC

- Use kinematically sensitive LHC observable
- Theoretically tractable in QFT
- Control Contamination

$$M_t^{\text{peak}} = m_t \; + \text{(nonperturbative effects)} + \text{(perturbative effects)}$$



Theory(QFT)

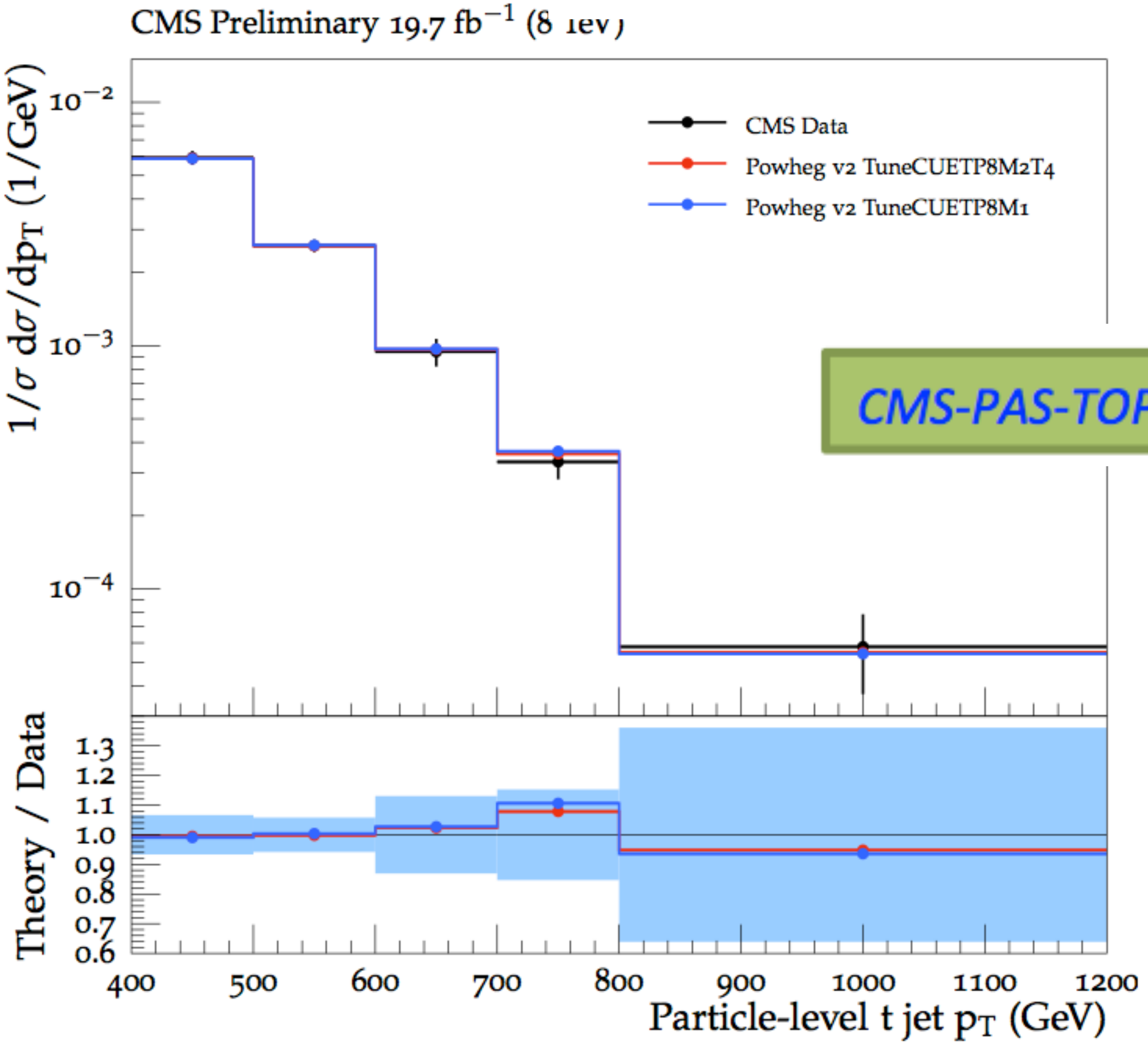
Simulation
(Monte Carlo)

Experiment

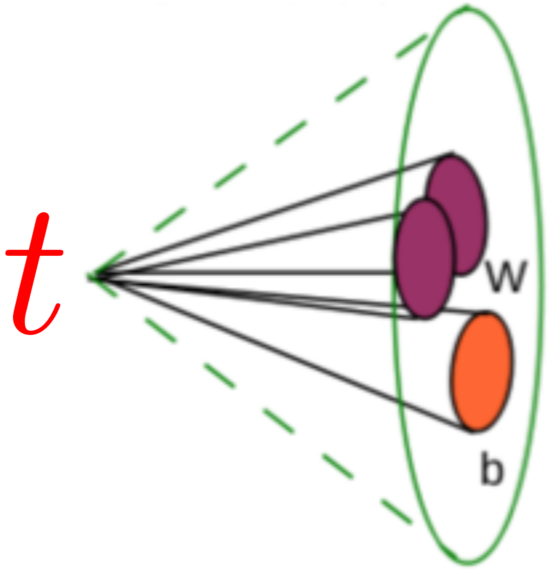
First Simplification: Boosted Top Quarks

Enables us to be inclusive over decay products.

$$Q = 2p_T \gg m_t$$



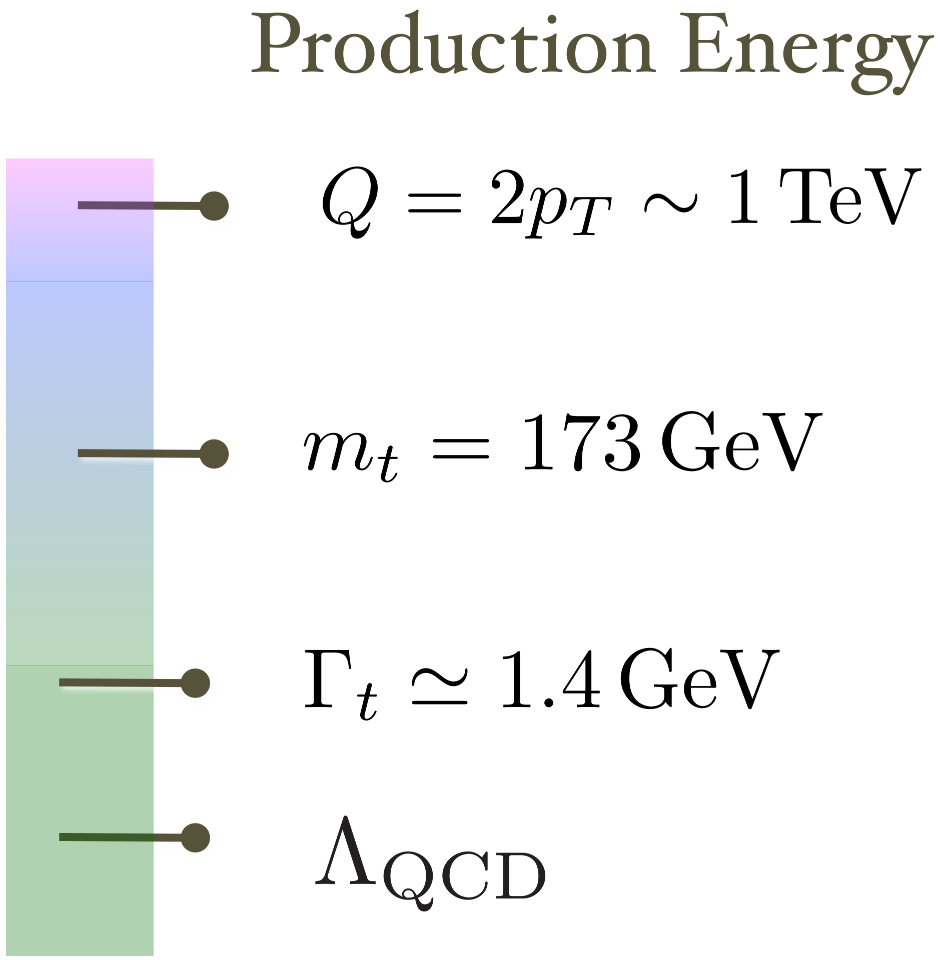
CMS-PAS-TOP-16-021



Theory issues for $pp \to t\bar{t}$

- jet observable
- suitable top mass for jets
- initial state radiation
- final state radiation
- underlying event/ MPI
- color reconnection
- beam remnant
- parton distributions
- sum large logs

$$Q \gg m_t \gg \Gamma_t \gg \Lambda_{\mathrm{QCD}}$$



Production Energy

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

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

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

Λ_{QCD}

Issues relevant for lepton colliders

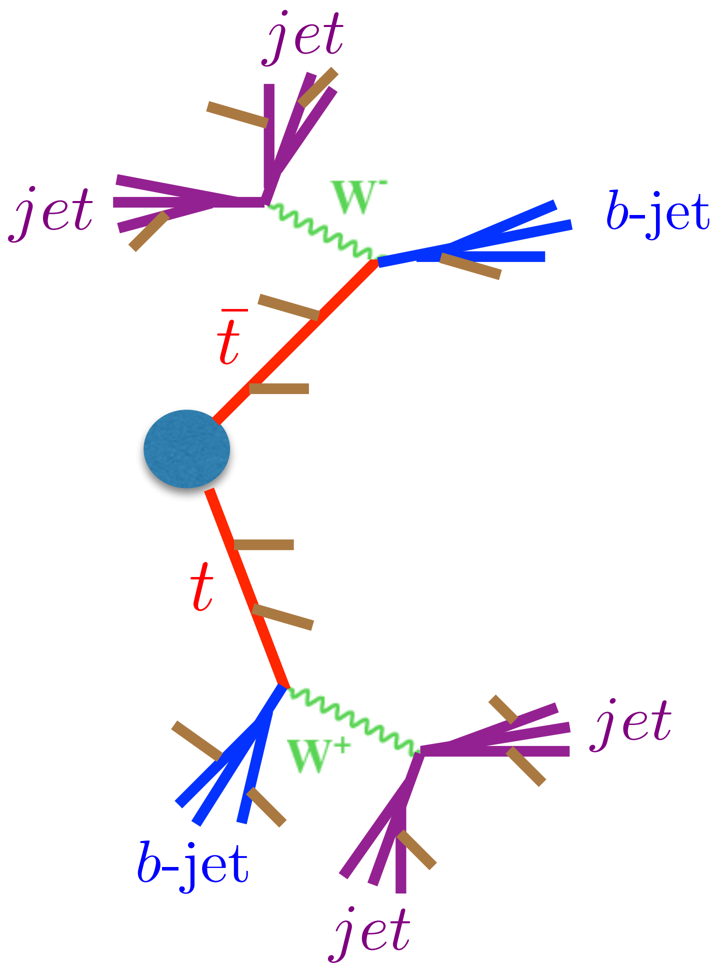
- jet observable ★ ★
- suitable top mass for jets ★
- initial state radiation
- final state radiation ★
- underlying event/ MPI
- color reconnection
- beam remnant
- parton distributions
- sum large logs ★

$$Q \gg m_t \gg \Gamma_t \gg \Lambda_{\rm QCD}$$

First

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

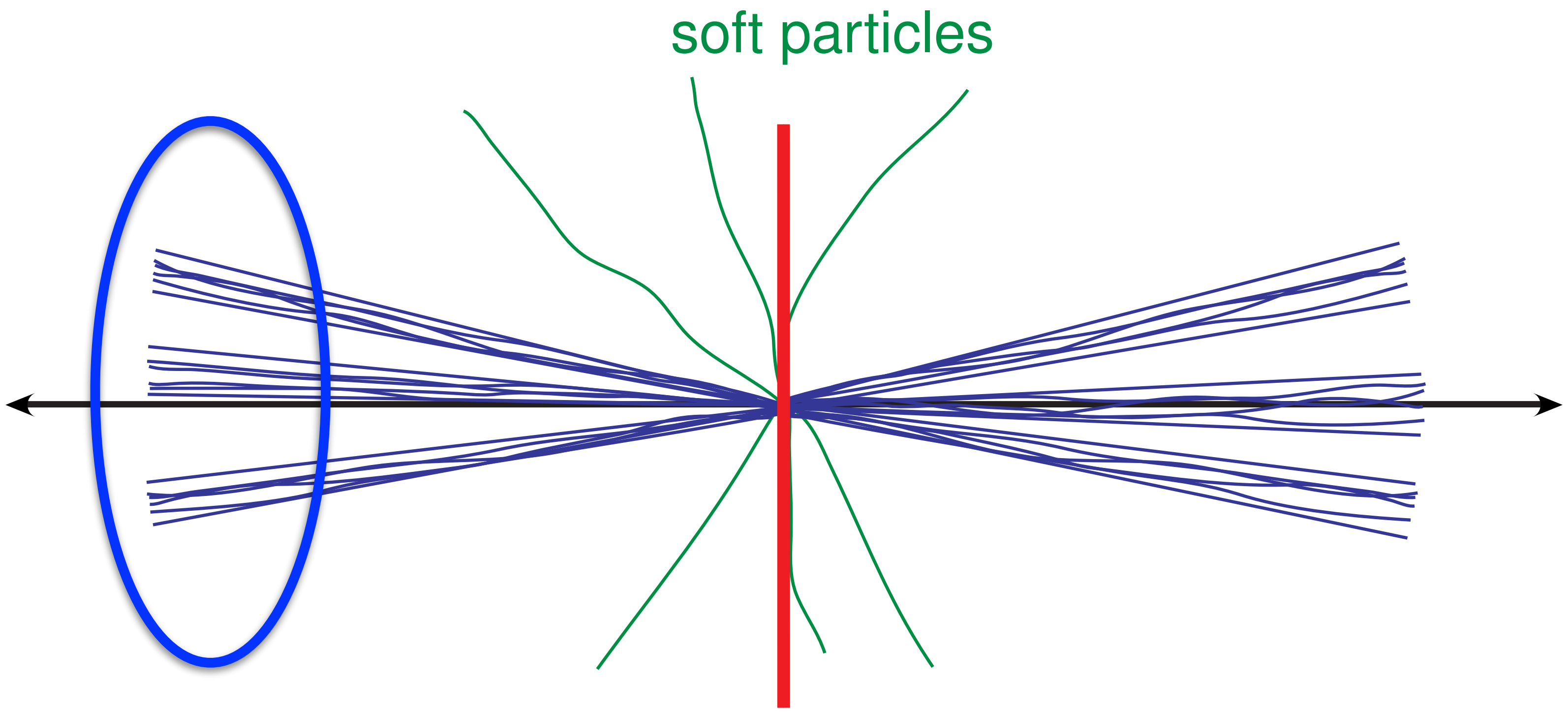
and the issues ★



Measure what observable?

Jet Invariant Mass

$$M_t^2 = \Big(\sum_{i\in a} p_i^\mu\Big)^2$$



Jet of Radius R

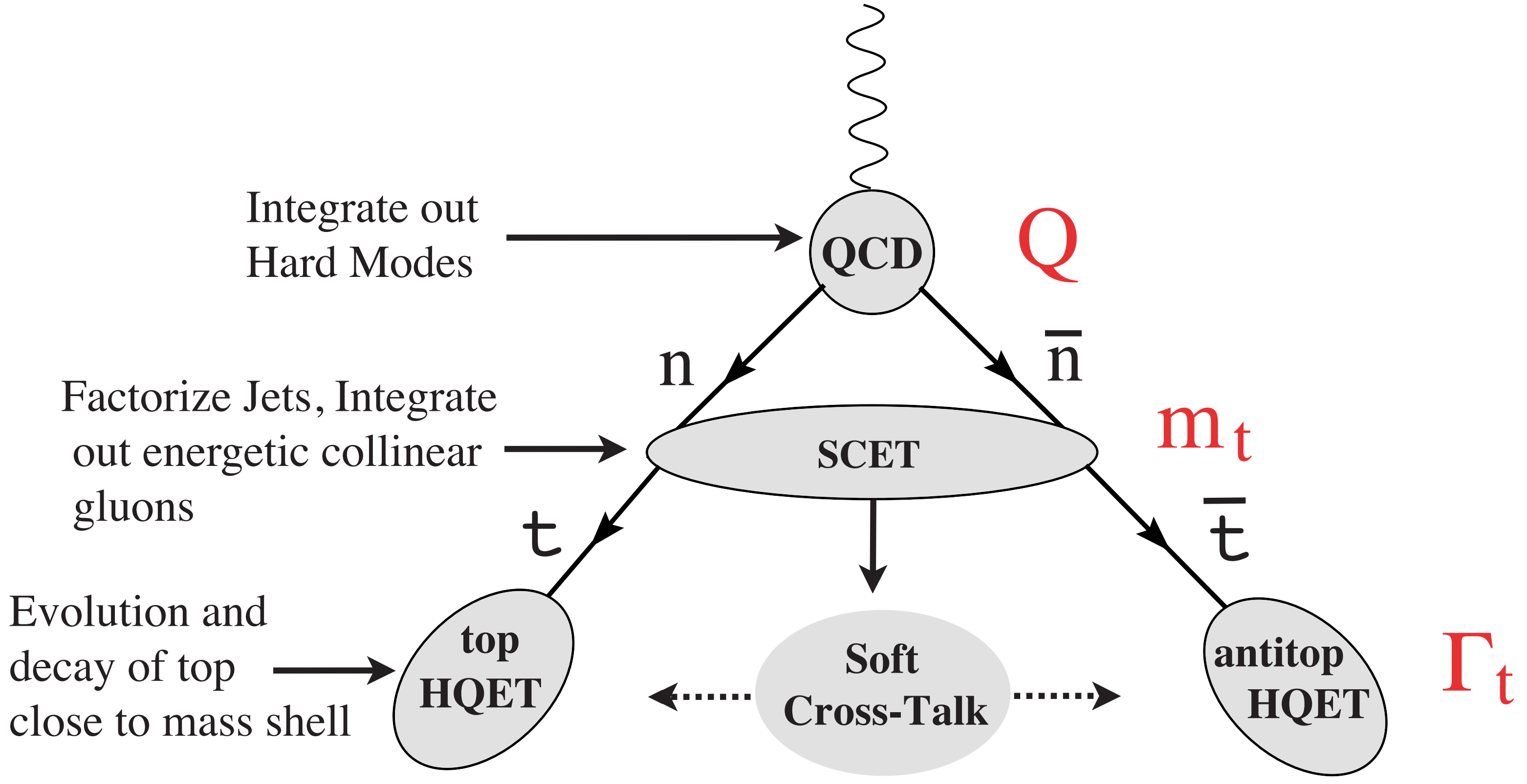
EFTs for Boosted Tops in the Peak Region

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

$$\frac{d^2\sigma}{dM_t^2\, dM_{\bar{t}}^2}$$

Peak Region:

$$M_{t,\bar{t}}^2 - m^2 \sim m\Gamma \ll m^2$$



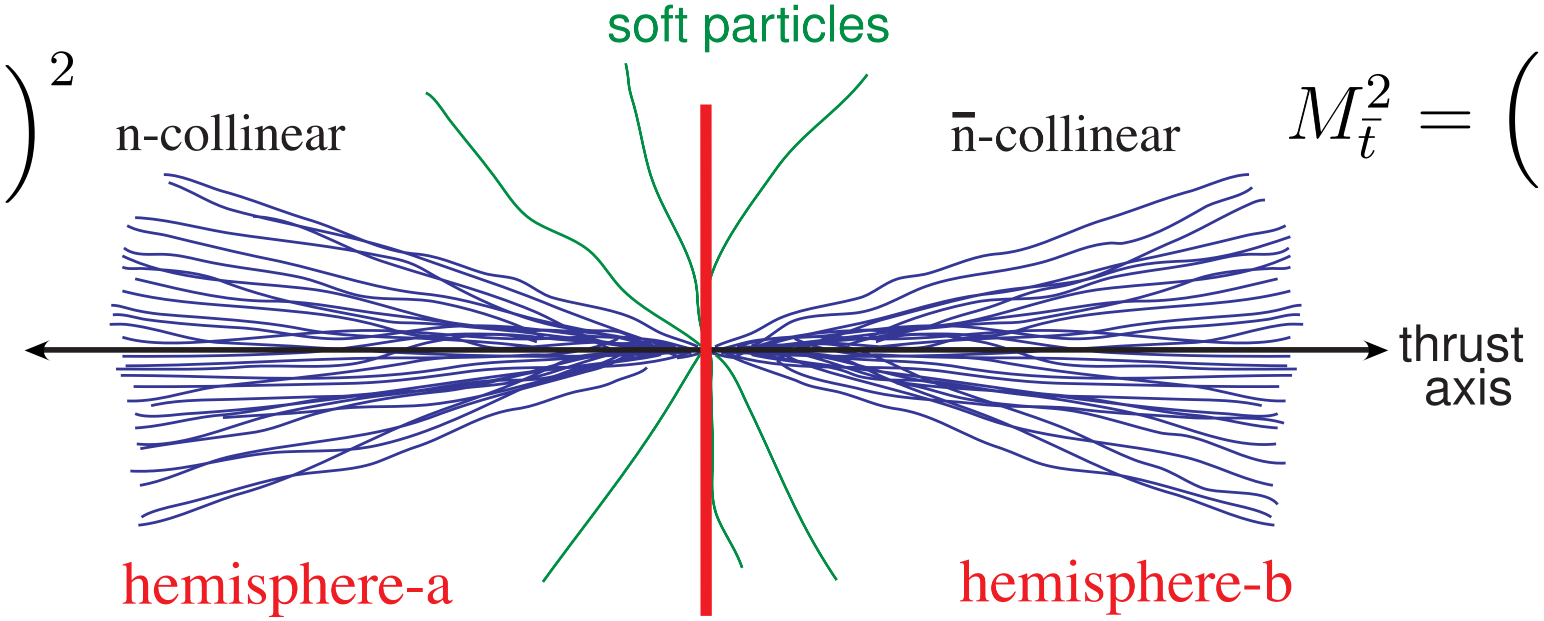
Integrate out Hard Modes

Factorize Jets, Integrate out energetic collinear gluons

Evolution and decay of top close to mass shell

Fleming, Hoang, Mantry, Stewart 2007

$$M_t^2 = \Big(\sum_{i\in a} p_i^\mu\Big)^2$$



$$M_{\bar{t}}^2 = \Big(\sum_{i\in b} p_i^\mu\Big)^2$$

Factorized Cross Section

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}M_t^2\mathrm{d}M_{\bar{t}}^2}\right)_{\text{hemi}} = \sigma_0\, H_Q(Q,\mu_m)\, H_m\!\left(m_J, \frac{Q}{m_J}, \mu_m, \mu\right)$$
$$\times \int \mathrm{d}l^+\mathrm{d}l^-\, J_B\!\left(\hat{s}_t - \frac{Ql^+}{m_J}, \Gamma_t, \delta m\; \mu\right) J_B\!\left(\hat{s}_{\bar{t}} - \frac{Ql^-}{m_J}, \Gamma_t, \delta m, \mu\right)$$
$$\times\, S_{\text{hemi}}(l^+ - k, l^- - k', \mu)\, F(k,k')$$

Soft Function

Perturbative Cross talk

Hadronization

(boosted HQET)
Jet Functions

Evolution and decay of top quark close to mass shell

Control Over Mass Scheme

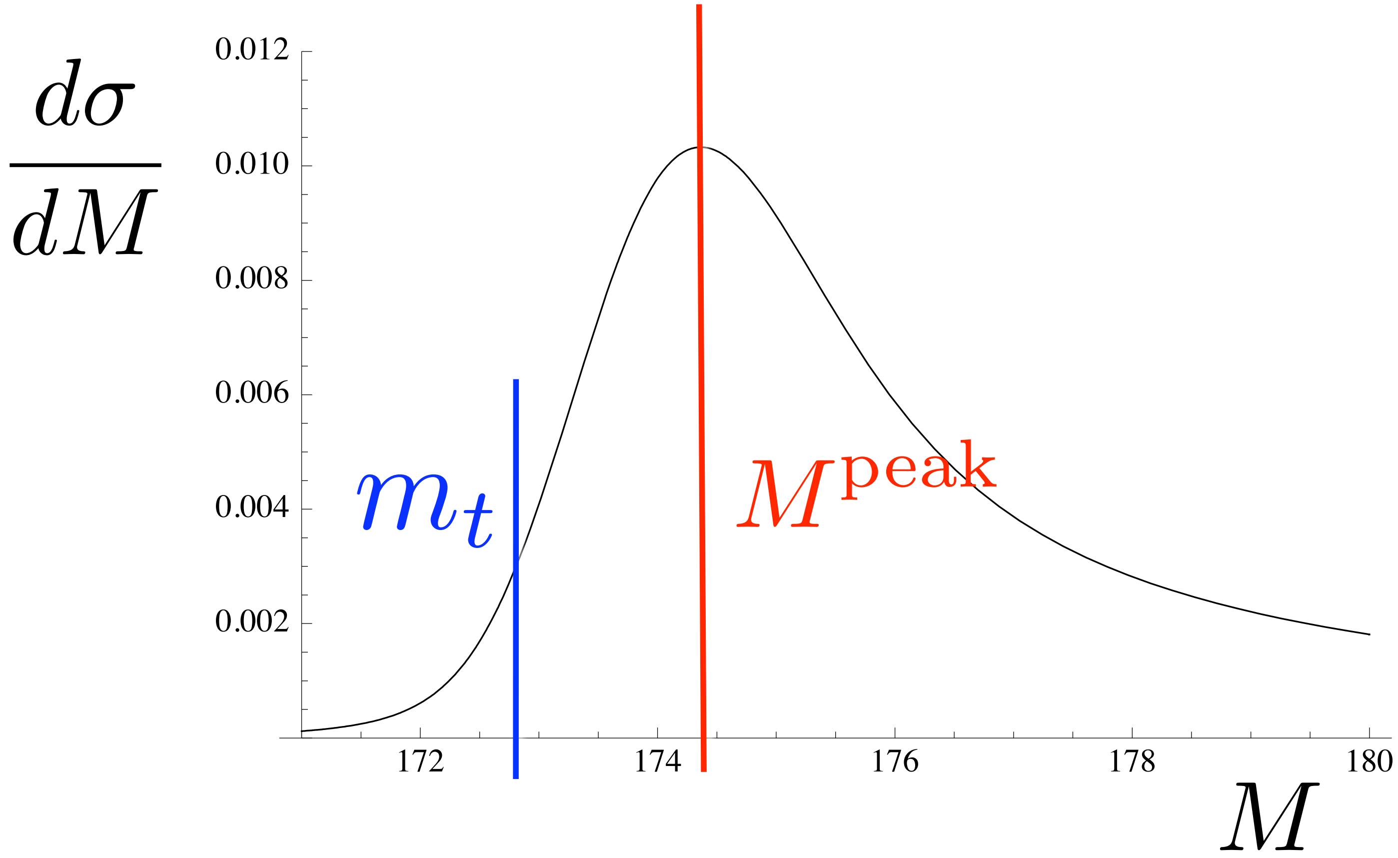
Factorized Cross Section

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}M_t^2\mathrm{d}M_{\bar t}^2}\right)_{\text{hemi}} = \sigma_0\, H_Q(Q,\mu_m)\, H_m\!\left(m_J, \frac{Q}{m_J}, \mu_m, \mu\right)$$
$$\times \int \mathrm{d}l^+\mathrm{d}l^- J_B\!\left(\hat s_t - \frac{Ql^+}{m_J}, \Gamma_t, \delta m, \mu\right) J_B\!\left(\hat s_{\bar t} - \frac{Ql^-}{m_J}, \Gamma_t, \delta m, \mu\right)$$
$$\times\, S_{\text{hemi}}(l^+ - k, l^- - k', \mu)\; F(k,k')$$

$$M^{\text{peak}} = m_t + \Gamma_t(\alpha_s + \alpha_s^2 + \ldots) + \frac{Q\Lambda_{\text{QCD}}}{m_t}$$

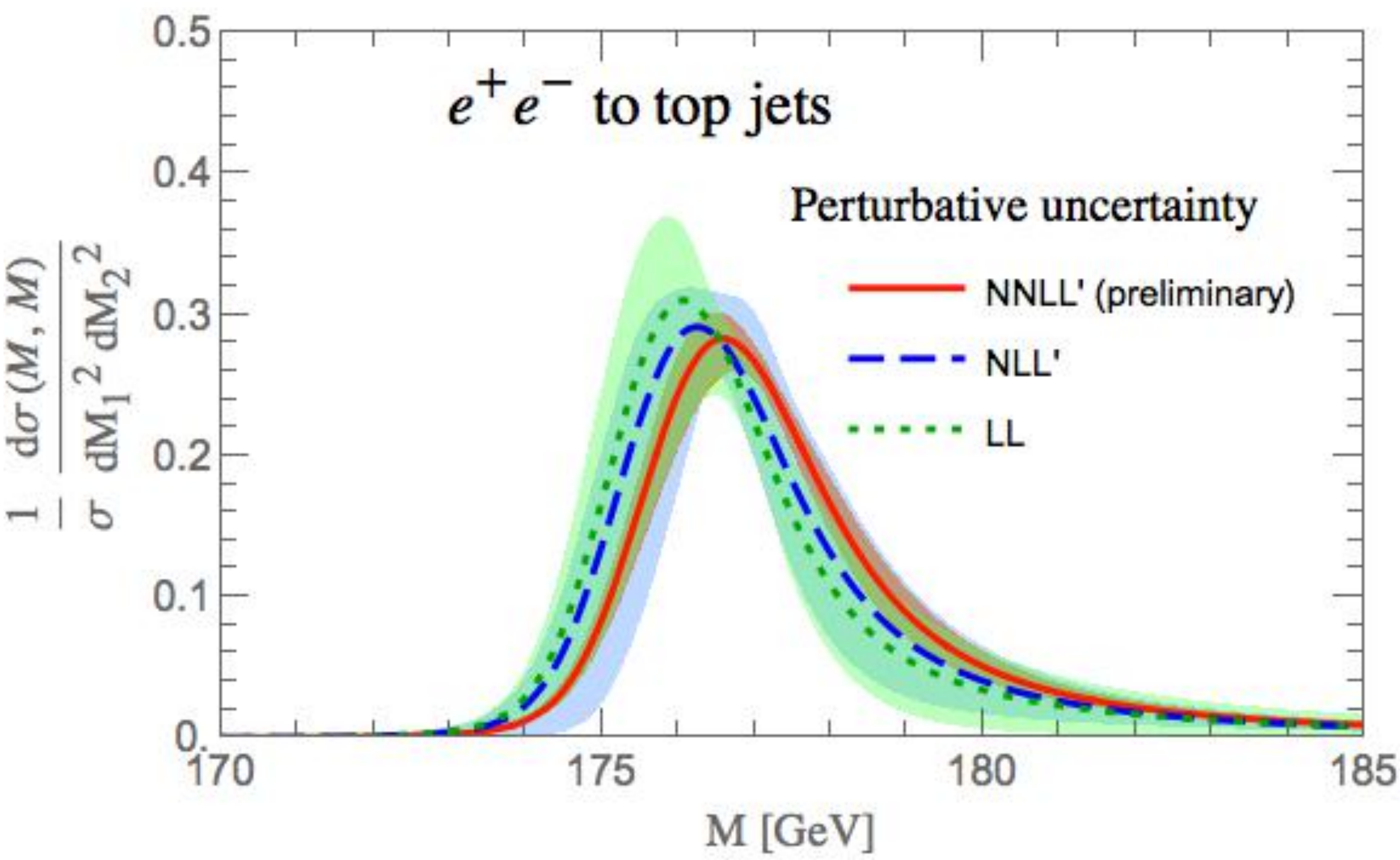
measure this

extract this

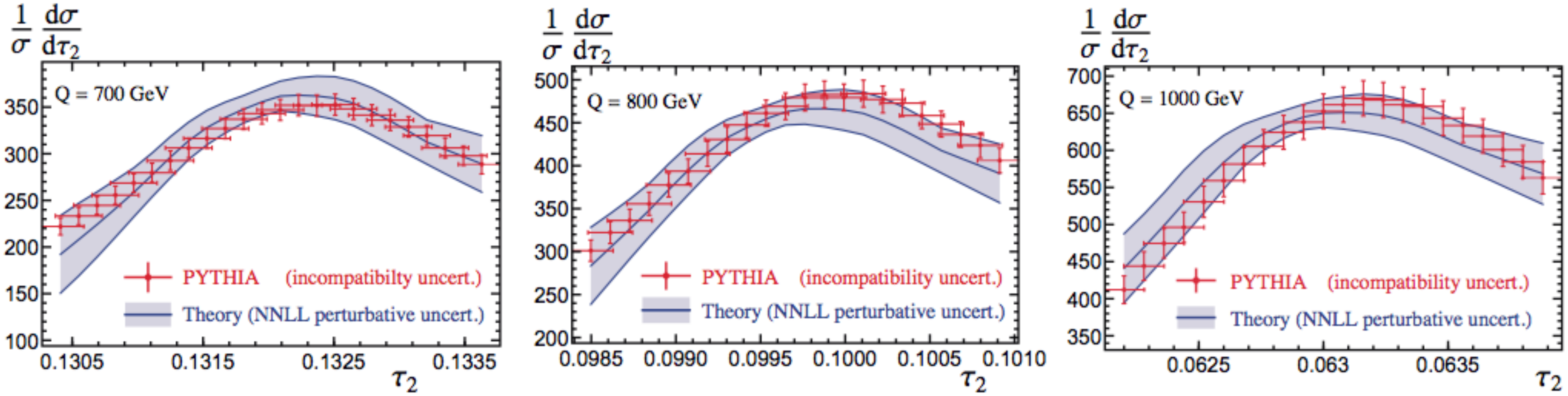


$$\hat s_t \equiv \frac{M_t^2 - m^2}{m} \sim \Gamma \ll m$$

Factorized Cross Section at NNLL+O(α_s^2)



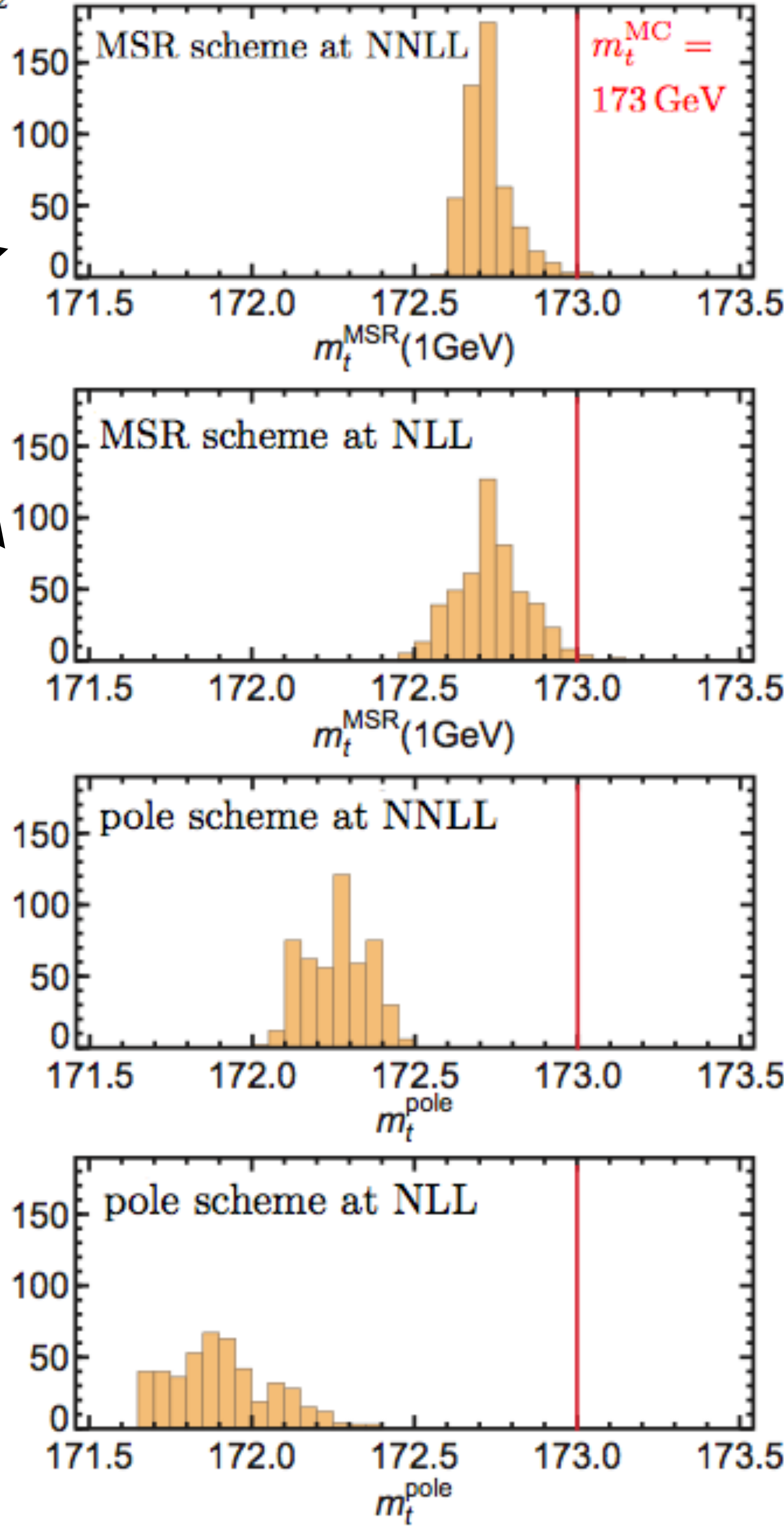
To appear soon

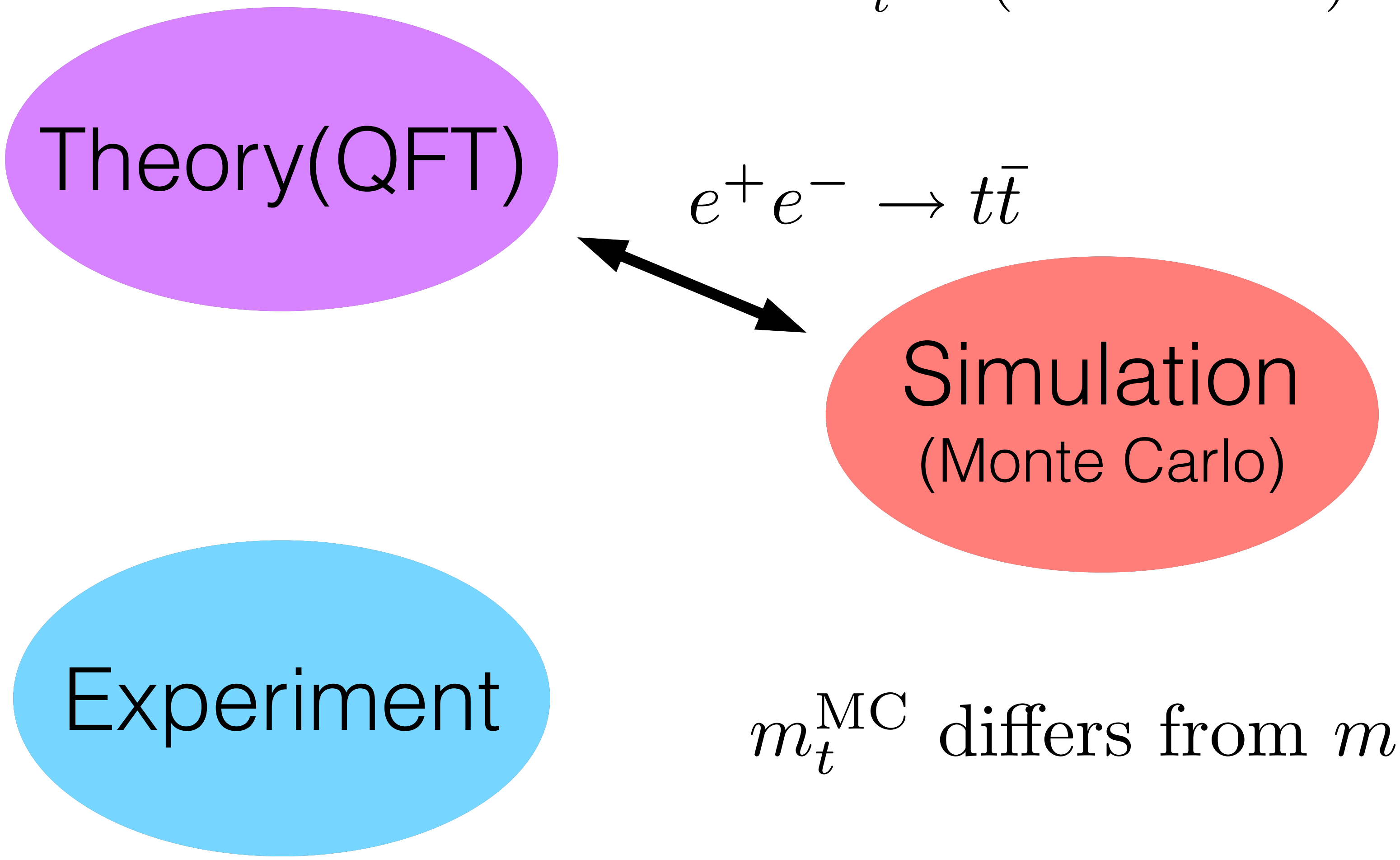


Top Mass Calibration of Monte Carlo

m_t^{MC} compatible with

$m_t^{\mathrm{MSR}}(R = 1\,\mathrm{GeV})$





Theory(QFT)

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

Simulation
(Monte Carlo)

Experiment

m_t^{MC} differs from m_t^{pole}

Butenschoen, Dehnadi, Hoang, Mateu, Priesser, Stewart 2016

Top Mass Determination at the LHC

A. Hoang, S. Mantry, AP, I. Stewart

Theory issues for $pp \to t\bar{t}$

- **jet observable** $\star\ \star$ **Jet Mass in Jet of Radius R**
- **suitable top mass for jets** $\star$
- **initial state radiation** $\star$
- **final state radiation** $\star$
- **underlying event/ MPI**
- **color reconnection** $\star$
- **beam remnant** $\star$ **Jet Veto**
- **parton distributions** $\star$ **Multiple Channels**
- **sum large logs** $Q \gg m_t \gg \Gamma_t \gg \Lambda_{\rm QCD}$ $\star$

Factorization for $e^+ e^-$ can be extended to pp to account for issues with $\star$

“Contamination”

Factorization for $pp \rightarrow t\bar{t}$

Can be extended to pp using 2-jettiness. A. Hoang, S. Mantry, AP, I. Stewart

(Stewart, Tackmann, Waalewijn)

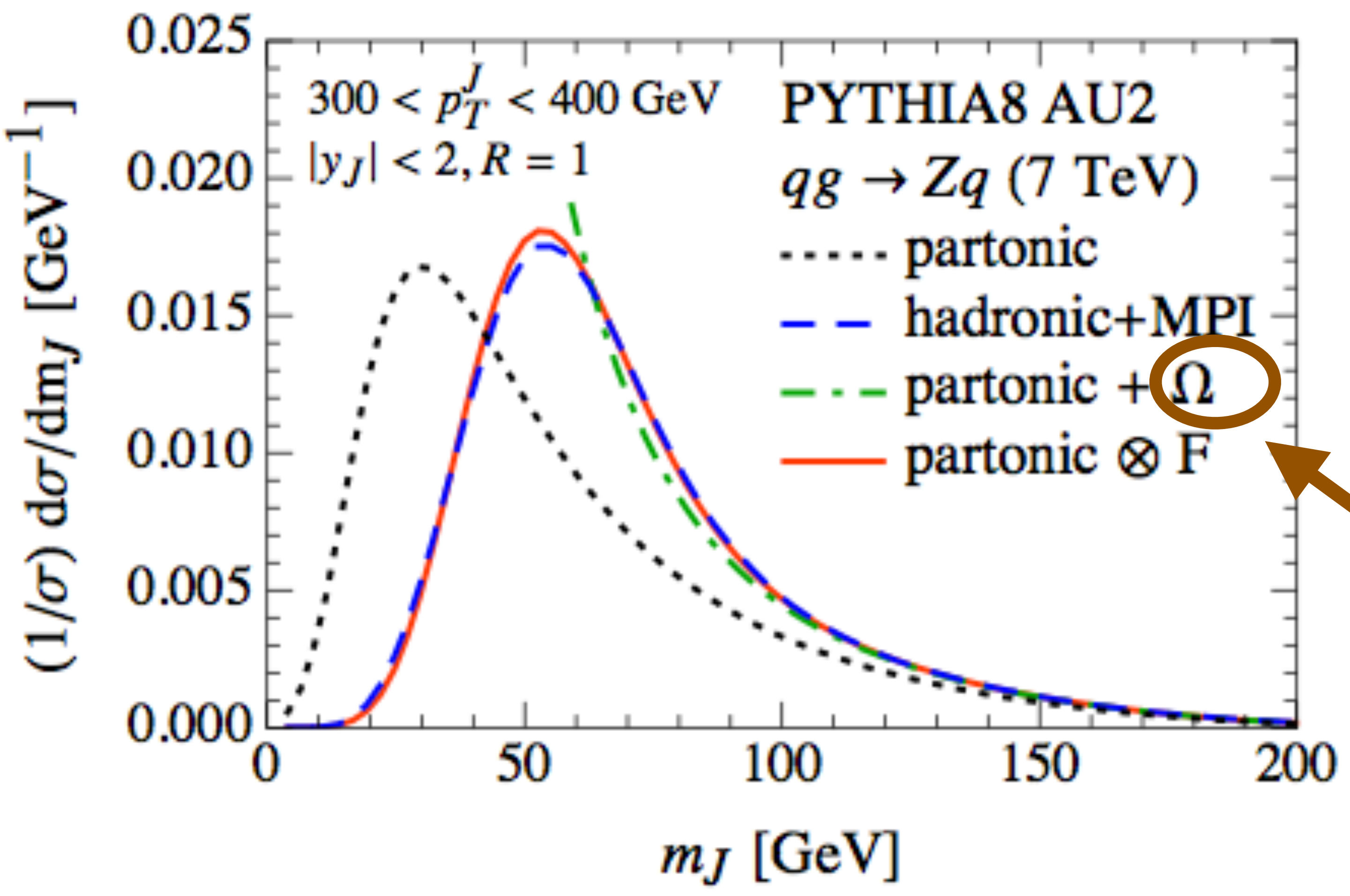
$$\frac{d^2\sigma}{dM_{J1}^2\, dM_{J2}^2\, d\mathcal{T}^{\rm cut}} = \mathrm{tr}\Big[\hat{H}_{Qm}\hat{S}(\mathcal{T}^{\rm cut}, R, \ldots)\otimes F\Big]\otimes J_B \otimes J_B \otimes \mathcal{I}\mathcal{I} \otimes f\, f$$

Jet Veto in Beam Region

Same Jet Functions!

Initial State Radiation

PDFs



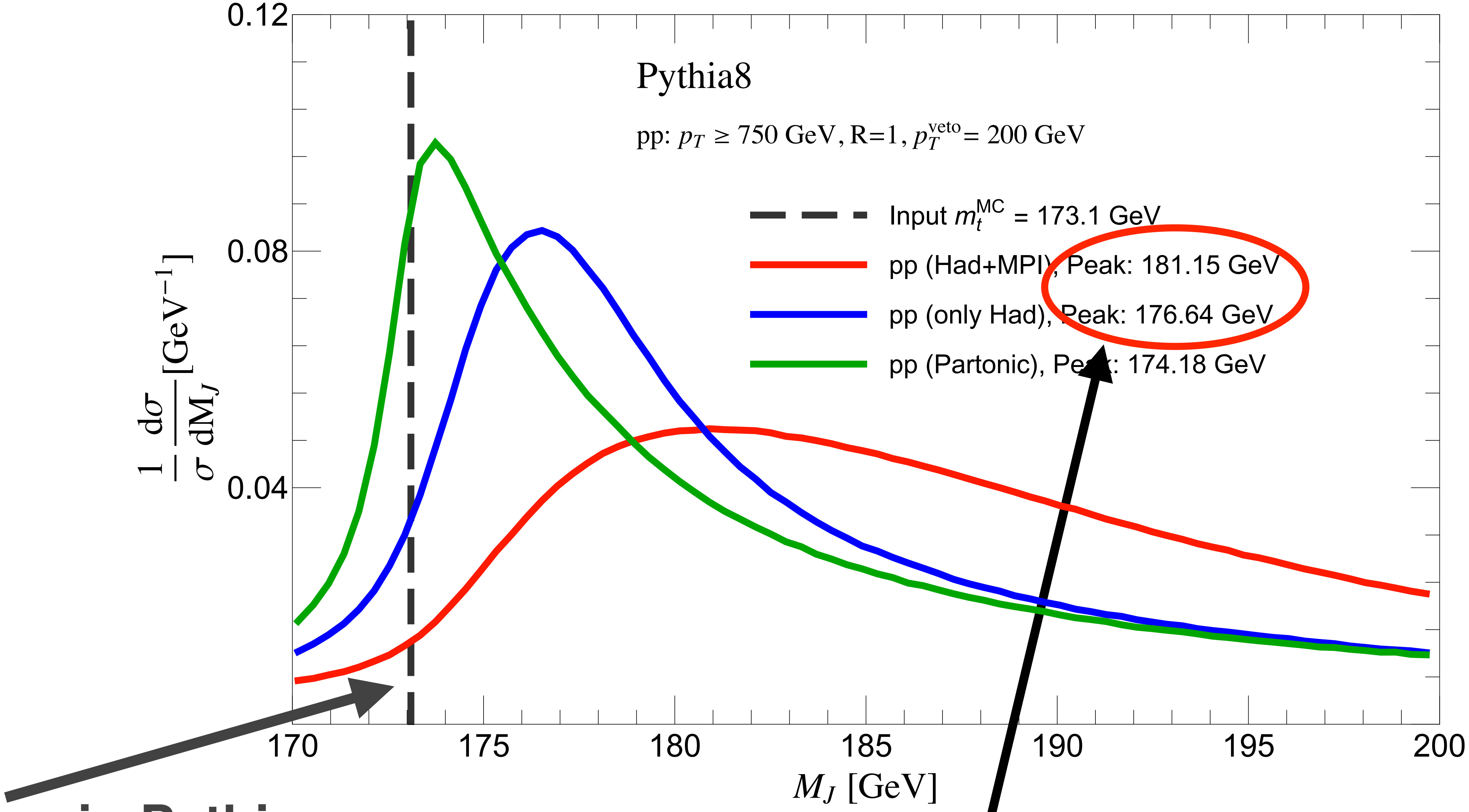
BUT control of Underlying Event is model dependent.

Same model used for Hadronization can describe UE by (primarily) tuning one parameter Ω.

$$\Omega = \int \mathrm{d}k\, k\, F(k)$$

Stewart, Tackmann, Waalewijn, 2015

Effect of UE/MPI

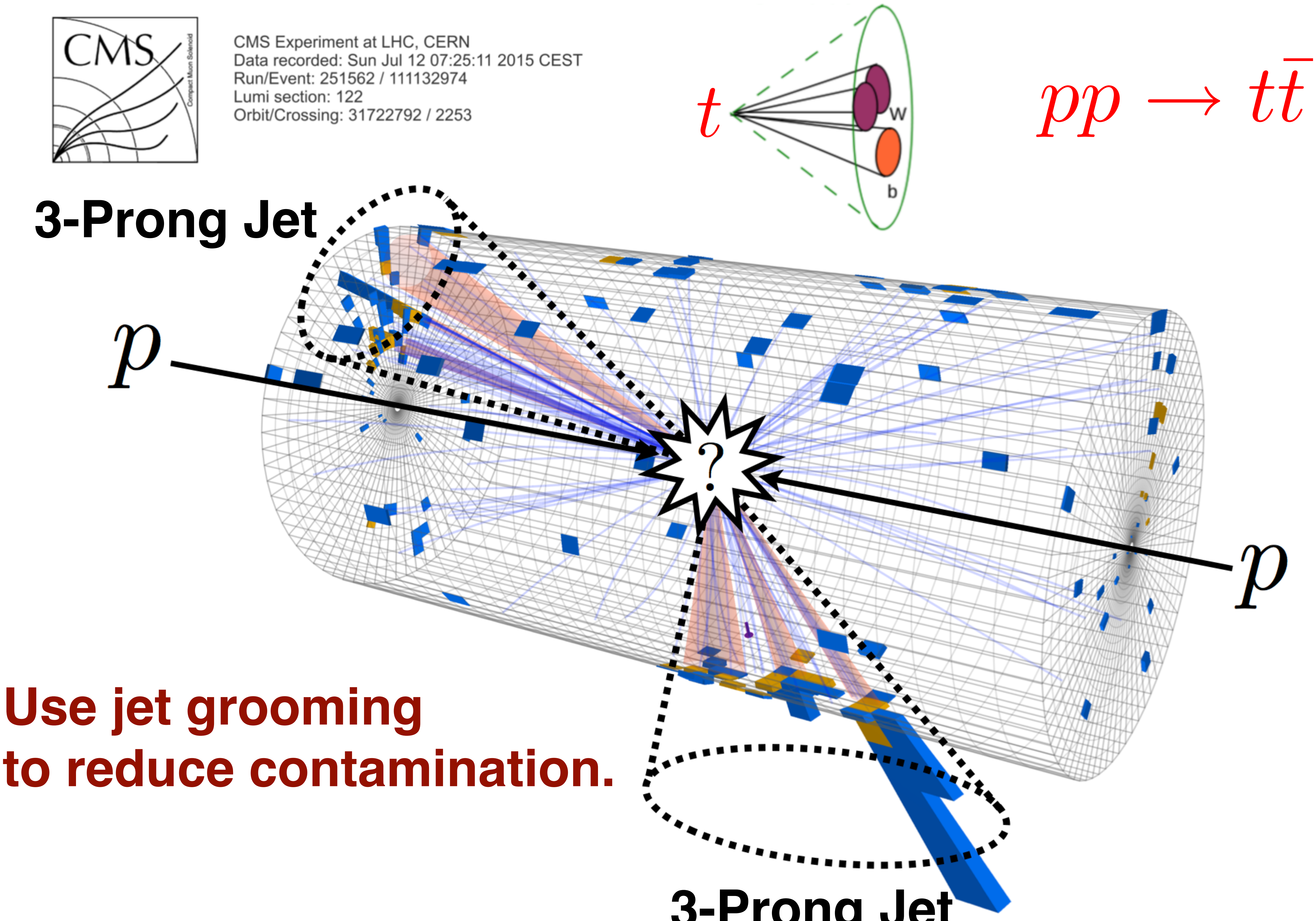


Input mass in Pythia
m_t = 173.1 GeV

Significant contamination

It is not ideal to have such a large shift from the contamination that needs to be modeled.

Second Simplification: Jet Substructure Techniques



$pp \to t\bar{t}$

Use jet grooming to reduce contamination.

Soft Drop

Larkoski, Marzani, Soyez, Thaler 2014

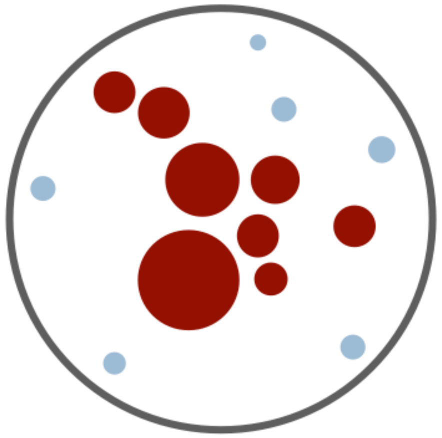
Grooms soft radiation from the jet

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

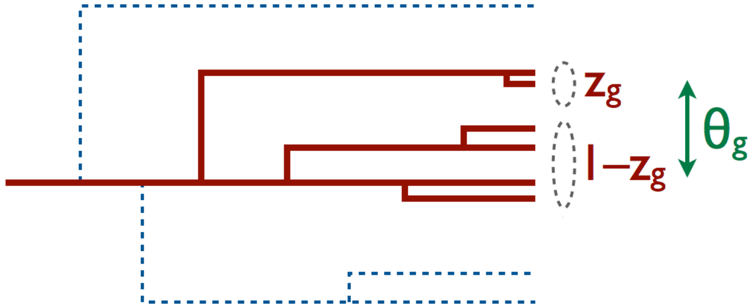
$$z > z_{\text{cut}} \; \theta^{\beta}$$

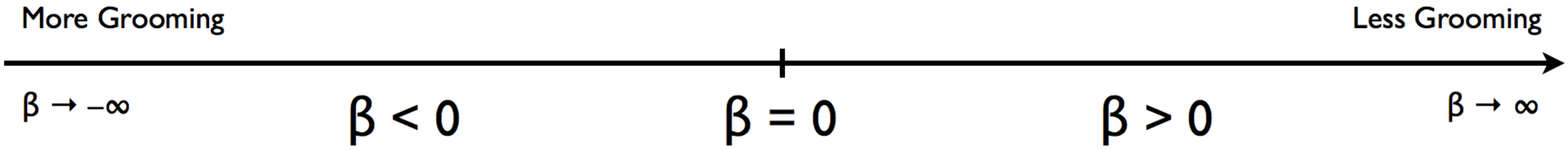
two grooming parameters

Groomed jet



Groomed Clustering tree





More Grooming

Less Grooming

$\beta \to -\infty$

$\beta < 0$

$\beta = 0$

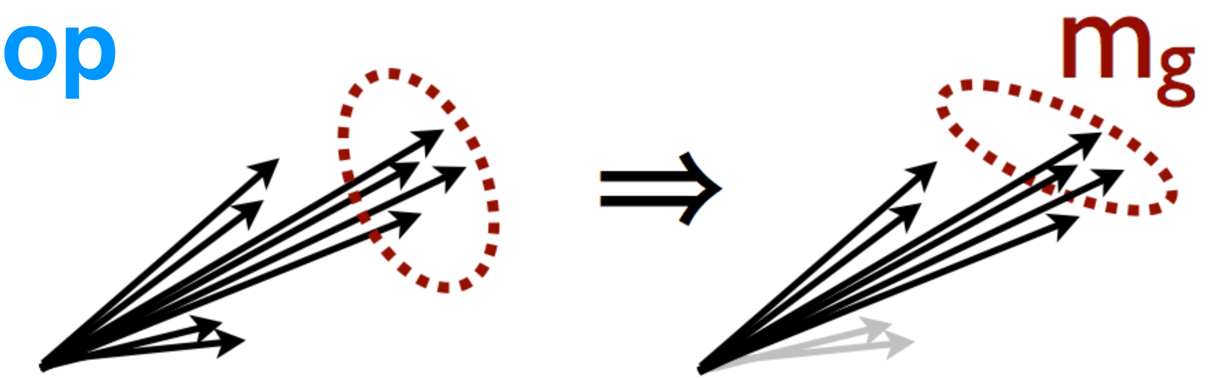
$\beta > 0$

$\beta \to \infty$

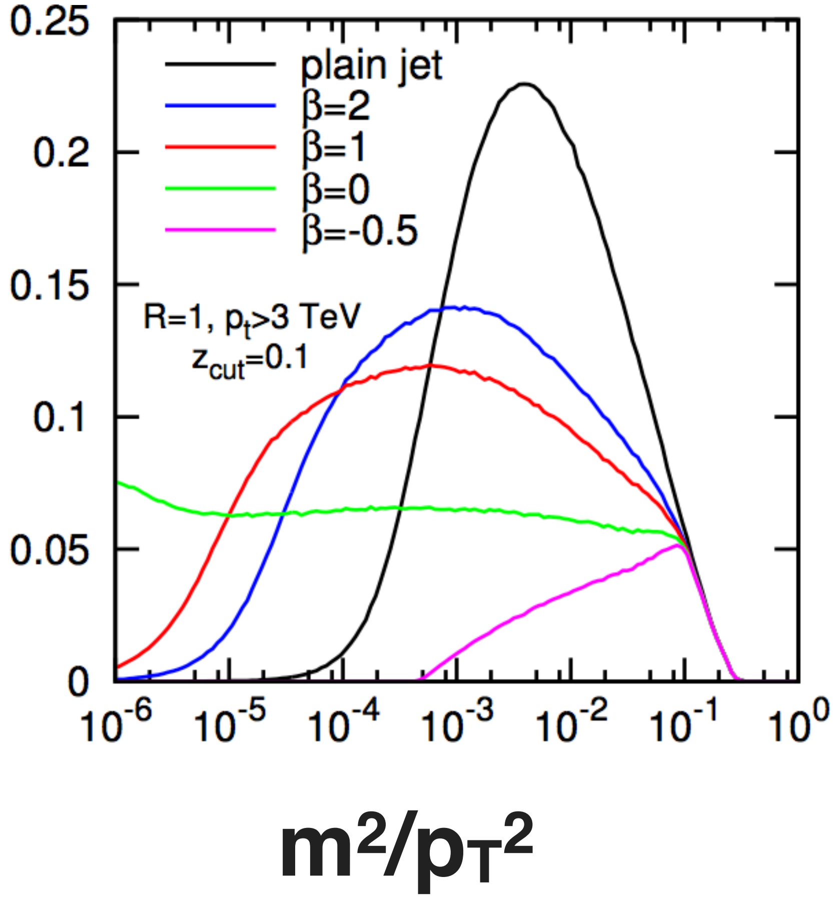
Soft Drop

Calculating Mass?

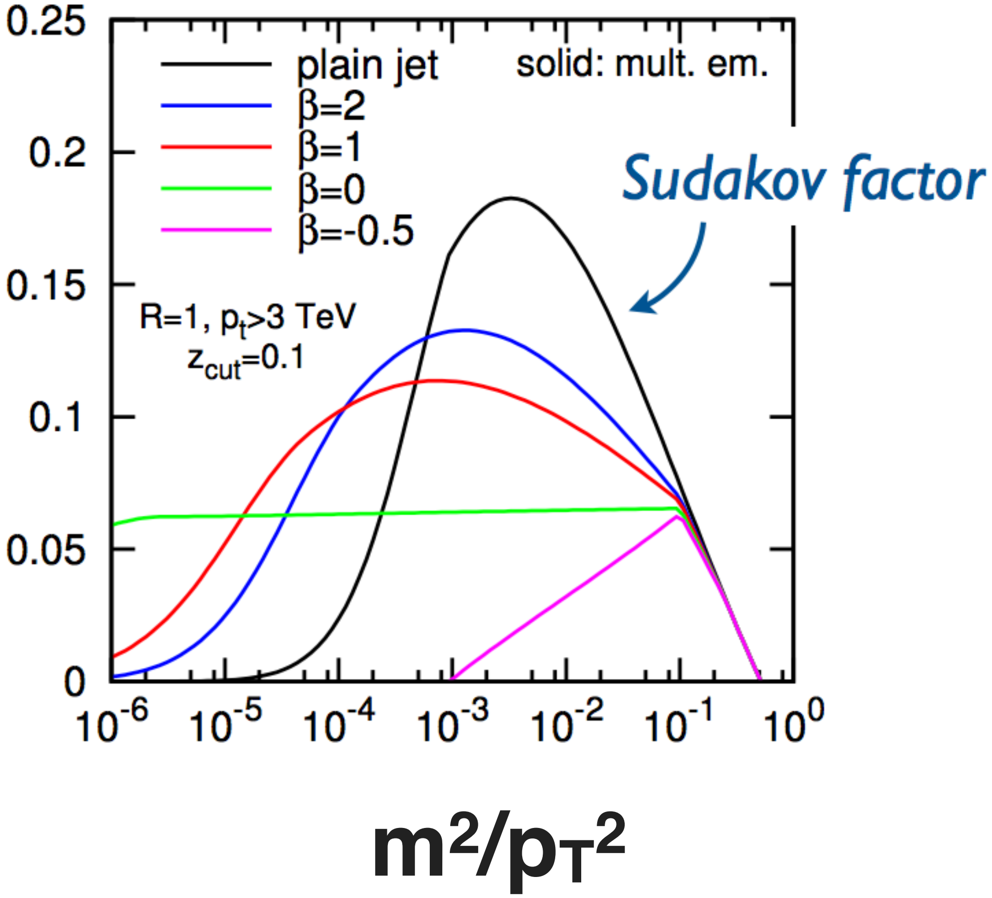
Larkoski, Marzani, Soyez, Thaler 2014

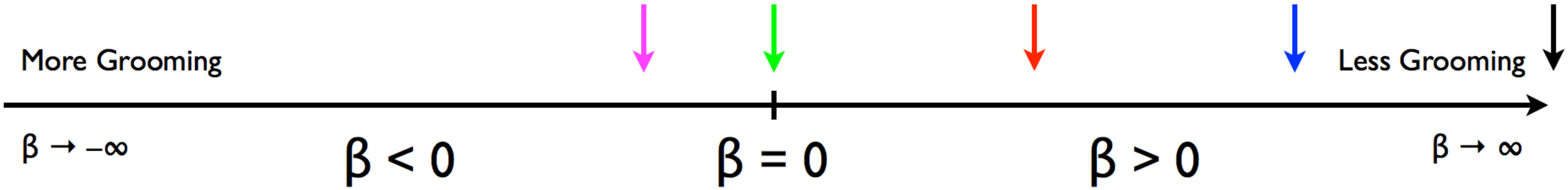


Pythia8, partonic



Pert QCD at ~ NLL





More Grooming

Less Grooming

β → −∞

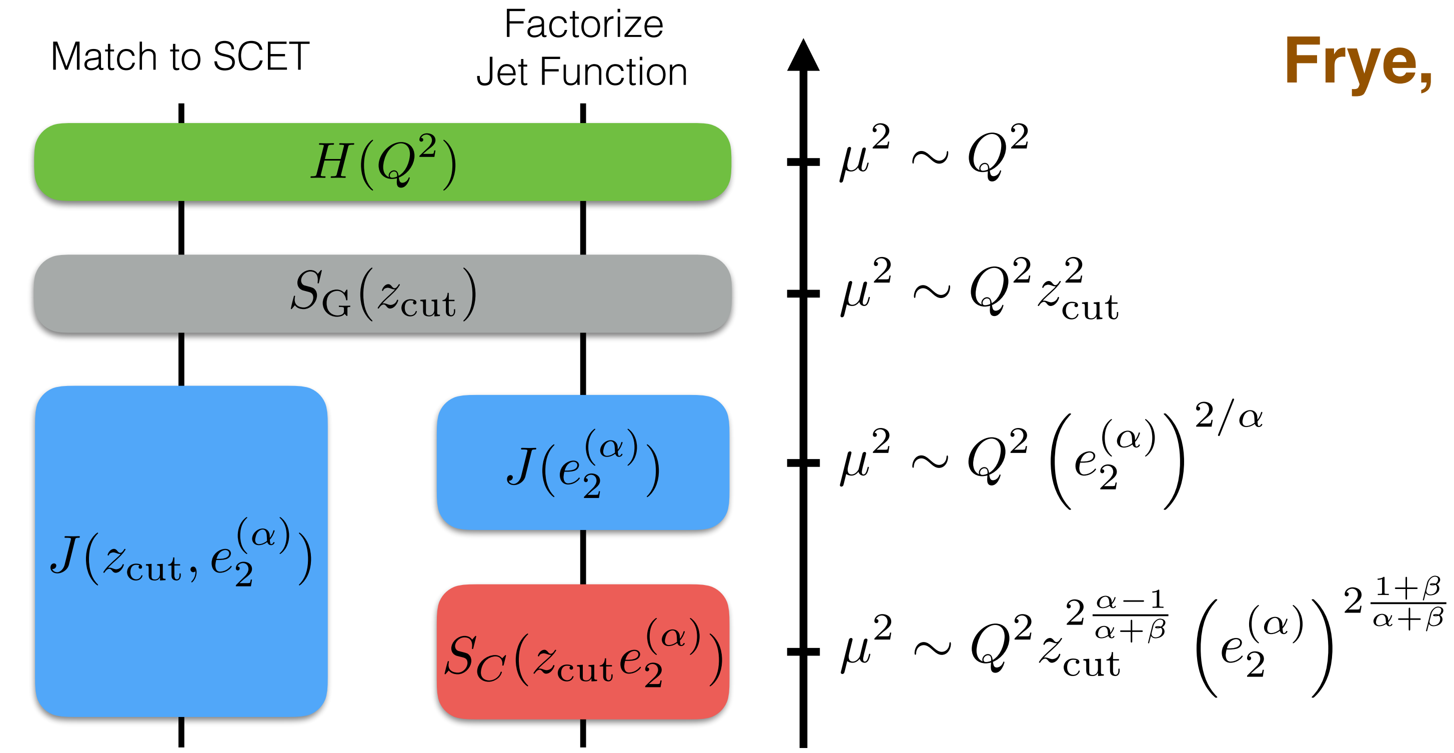
β < 0

β = 0

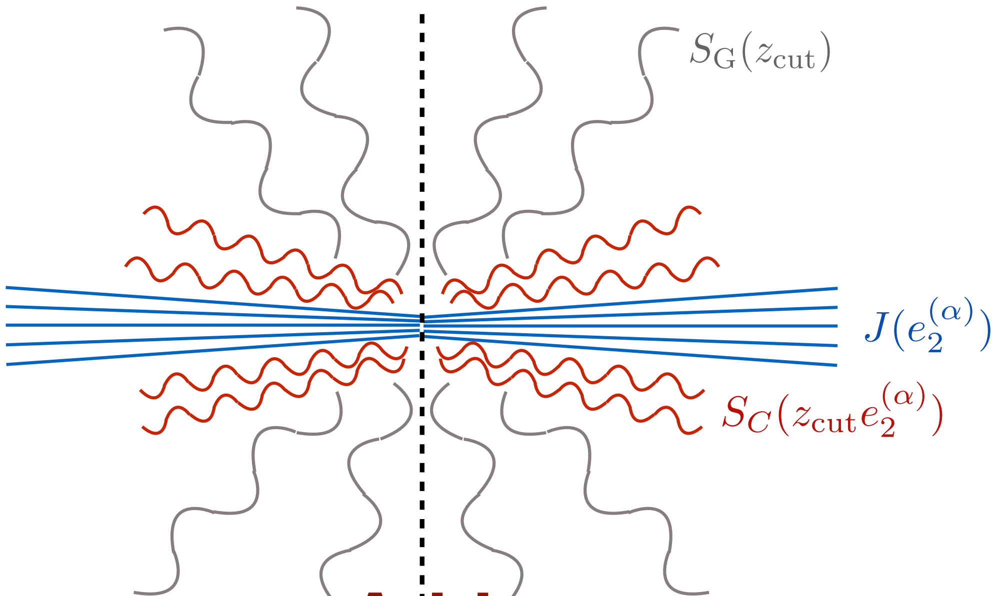
β > 0

β → ∞

Soft Drop Factorization

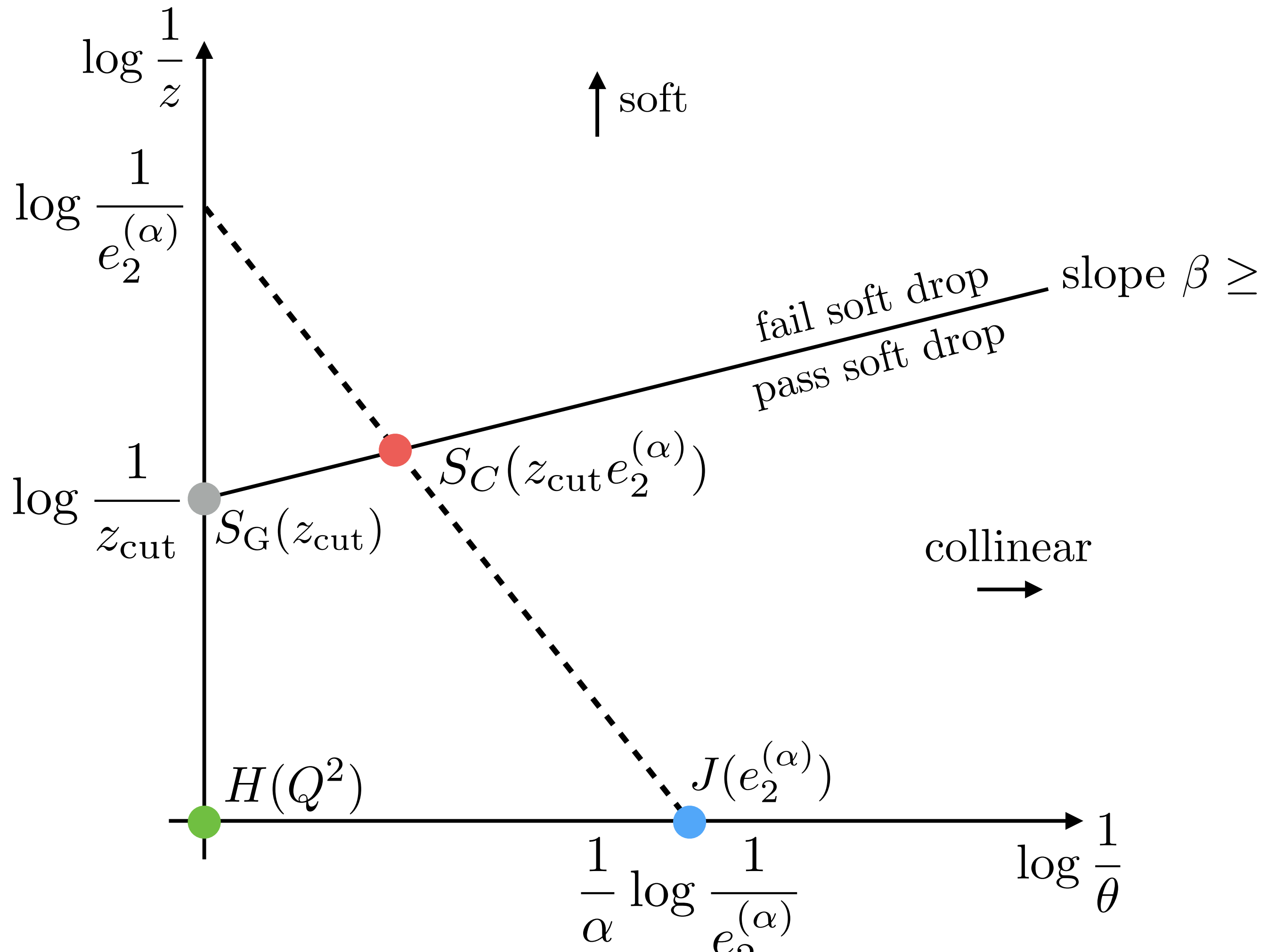


Frye, Larkoski, Marzani, Schwartz, Yan 2016



Adds Soft-Collinear Function

S_C



$$\frac{d\sigma}{de_2 \ldots} = H(Q^2) S_G(z_{\rm cut}, \beta) \times \left[S_C(e_2, z_{\rm cut}, \beta) \otimes J(e_2) \right]$$

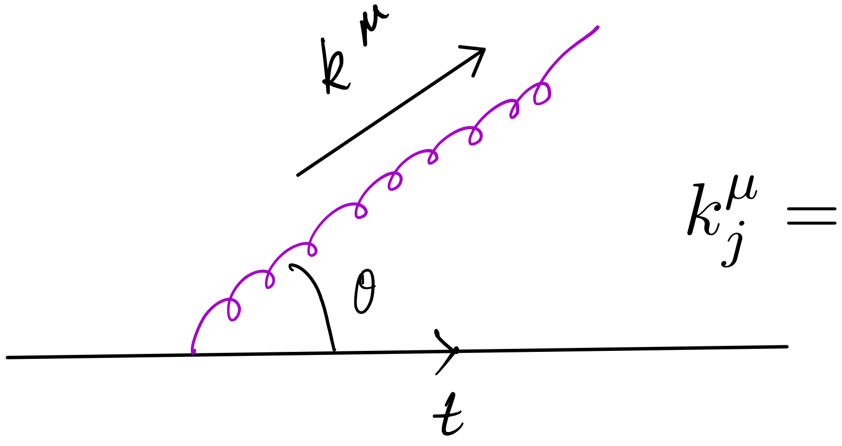
isolates measurement

achieve NNLL precision

Top Jet Mass with Soft Drop

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

Top Jet Mass with Soft Drop



A. Hoang, S. Mantry, AP, I. Stewart

$$k_j^\mu = \left(k^+, k^-, k_\perp\right) = \left(E(1-\cos\theta), E(1+\cos\theta), k_\perp\right)$$

a) Peak Region Constraint:

$$z\left[(1-\cos\theta) + \frac{m^2}{Q^2}(1+\cos\theta)\right] \sim \frac{2m\Gamma_t}{Q^2}$$

b) Soft Drop Constraint:

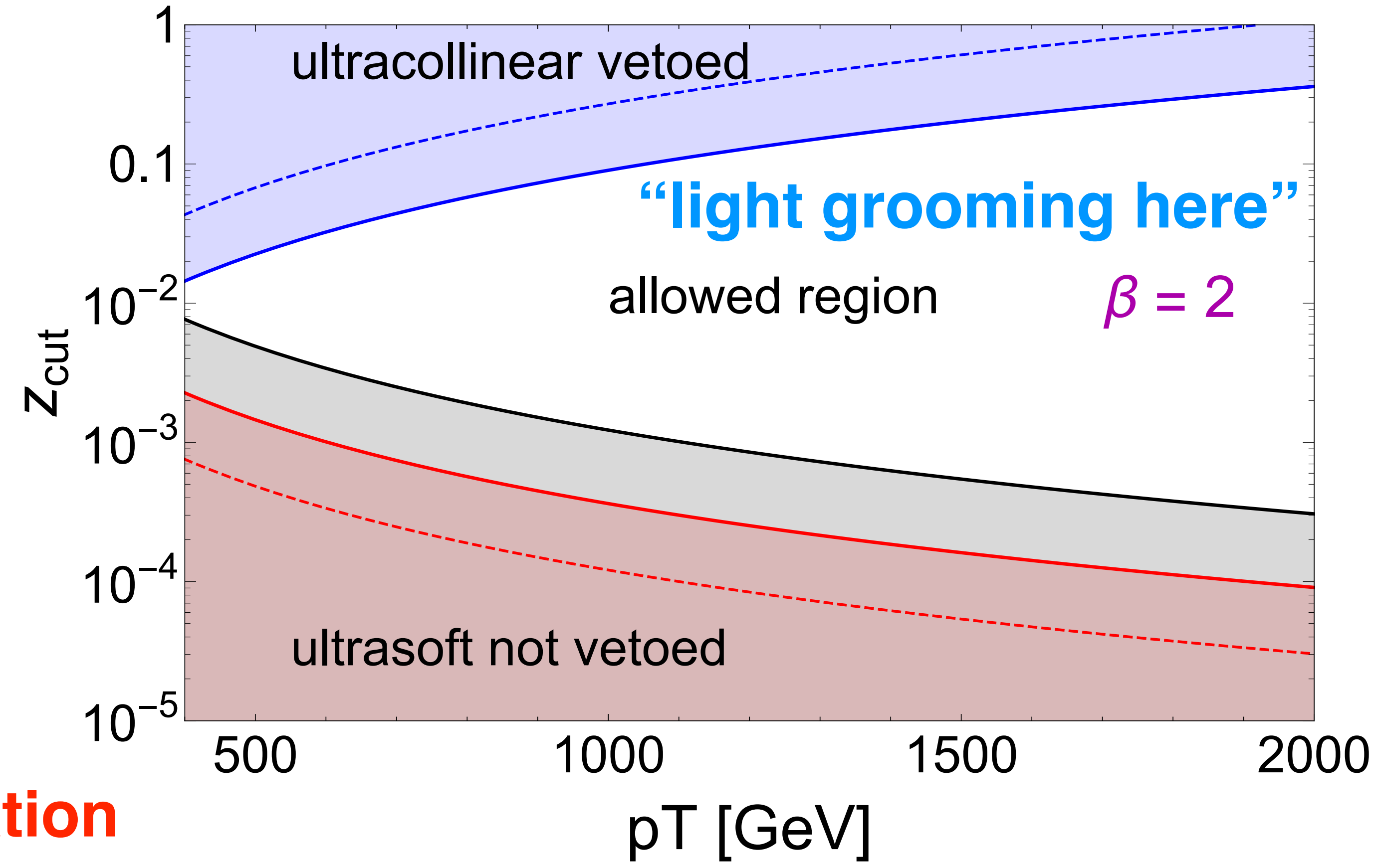
$$z > z_{\mathrm{cut}}\,\theta^\beta$$

Constraints on Soft Drop parameters:

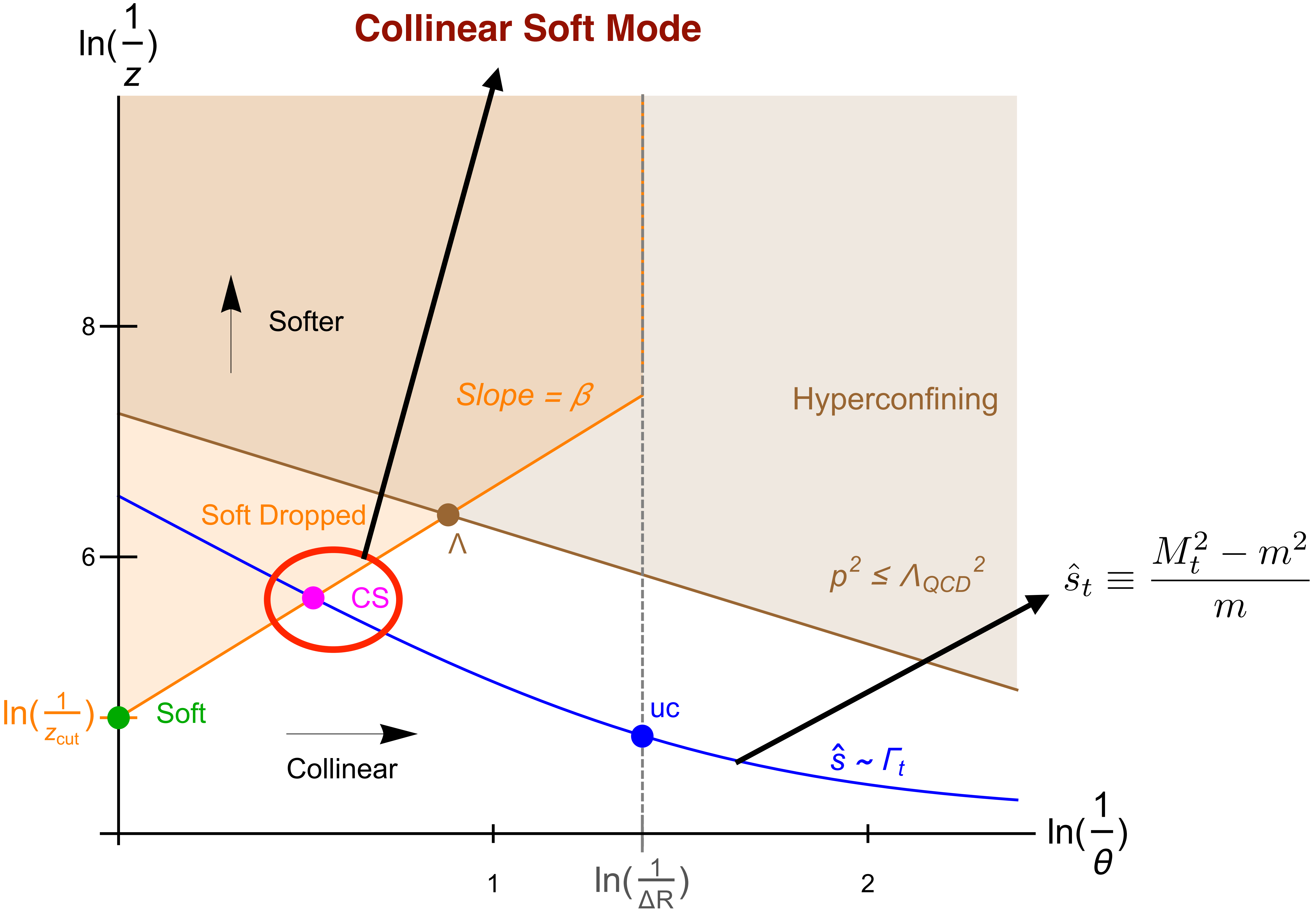
$$\frac{\Gamma_t}{m}\left(\frac{Q}{2m}\right)^\beta \gg z_{\mathrm{cut}} \gg \frac{2m\Gamma_t}{Q^2}$$

Ensure soft drop does not touch mass

Ensure soft drop removes most contamination



Top Jet Mass with Soft Drop



Collinear Soft Mode

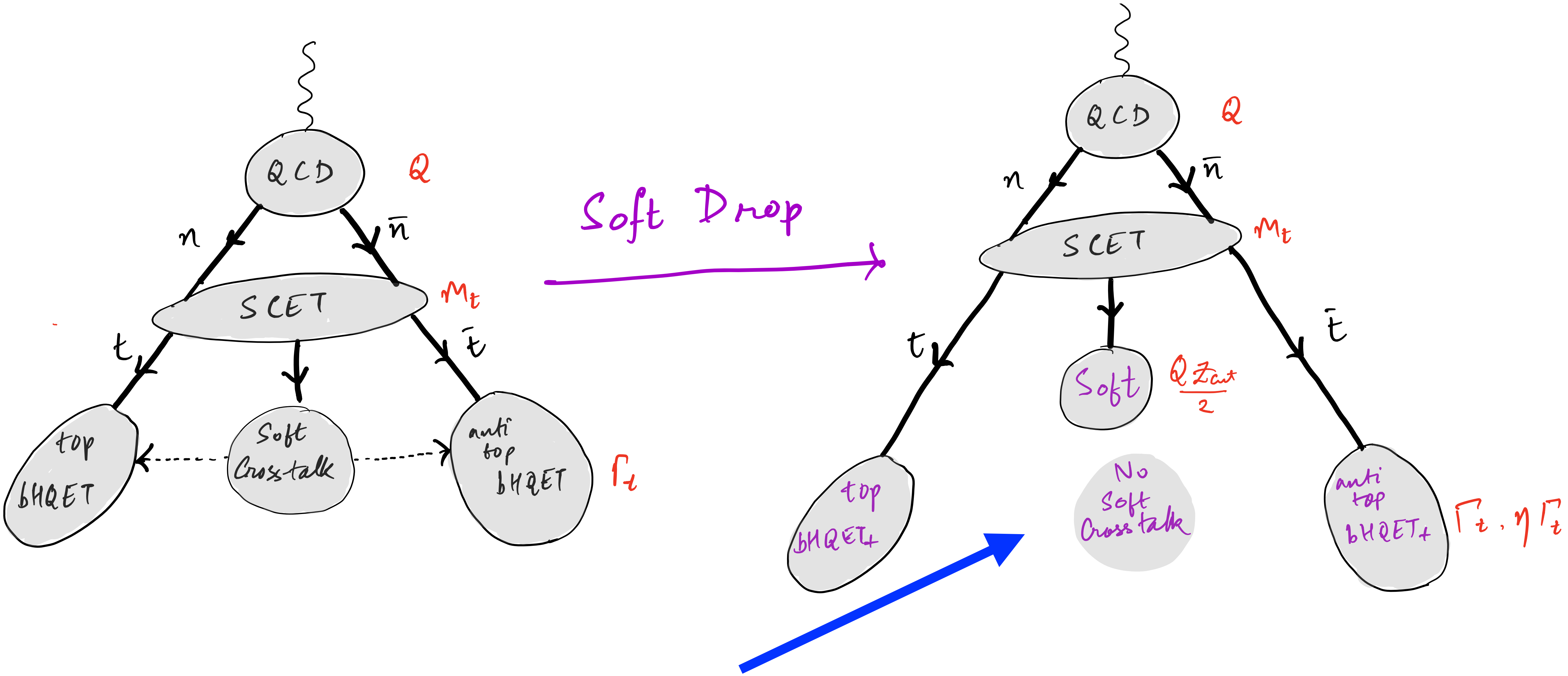
$$\hat{s}_t \equiv \frac{M_t^2 - m^2}{m}$$

Effective Theory for Groomed top jets

A. Hoang, S. Mantry, AP, I. Stewart

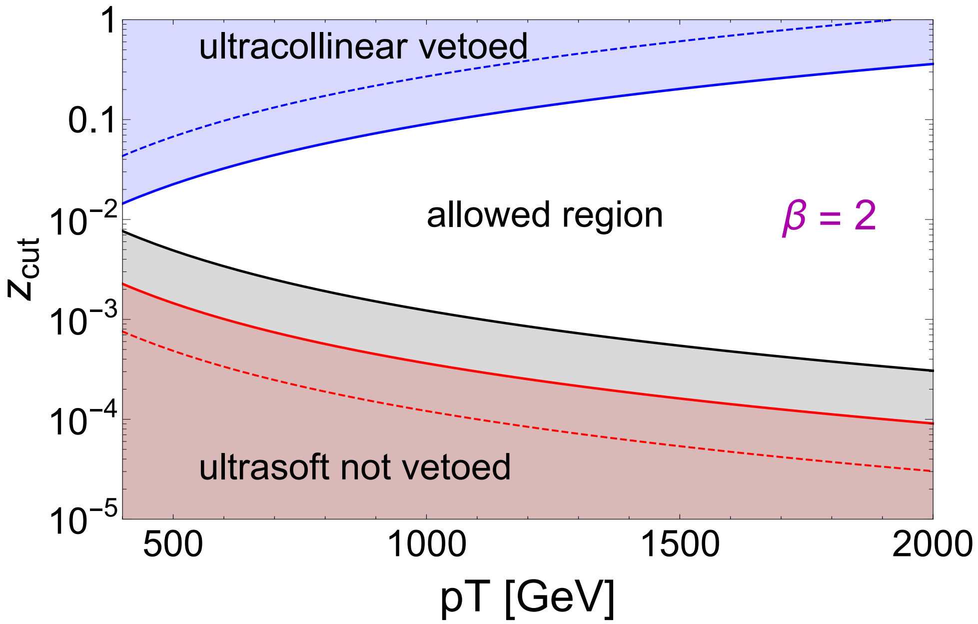
Factorization Theorem for Soft Dropped Top Jets:

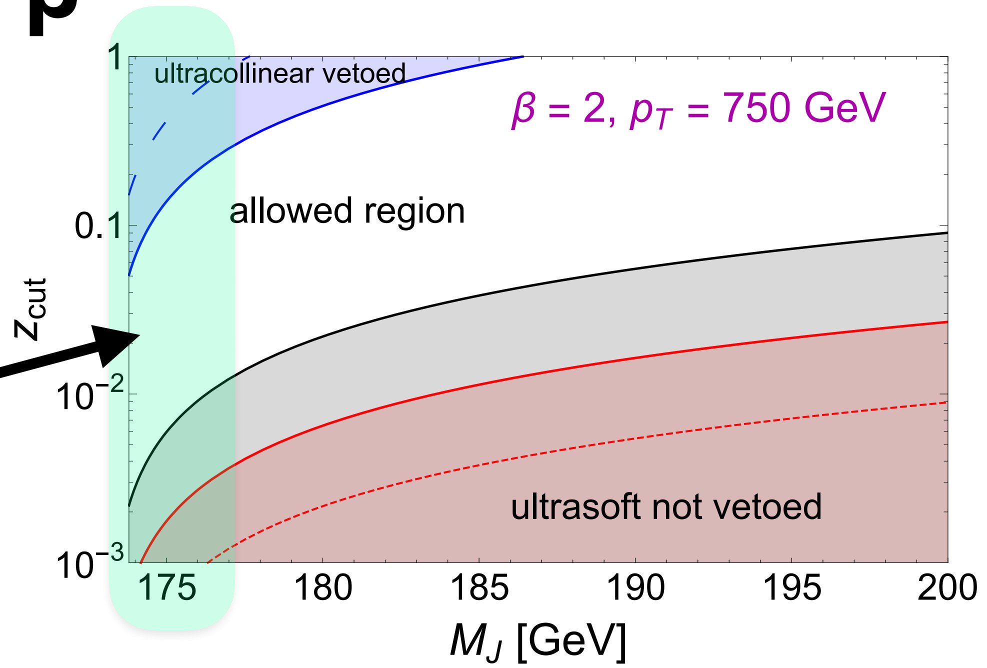
$$\frac{d\sigma}{dM_J} = N\int d\ell dk\, J_B\Big(\hat{s}_t - \frac{Q\ell}{m},\Gamma_t,\delta m\Big)\, S_C\Big[\Big(\ell - \frac{m}{Q}k\Big)^{\frac{1+\beta}{2+\beta}}\big(2^\beta Q z_{\rm cut}\big)^{\frac{1}{1+\beta}},\beta\Big]\, F_C(k)$$



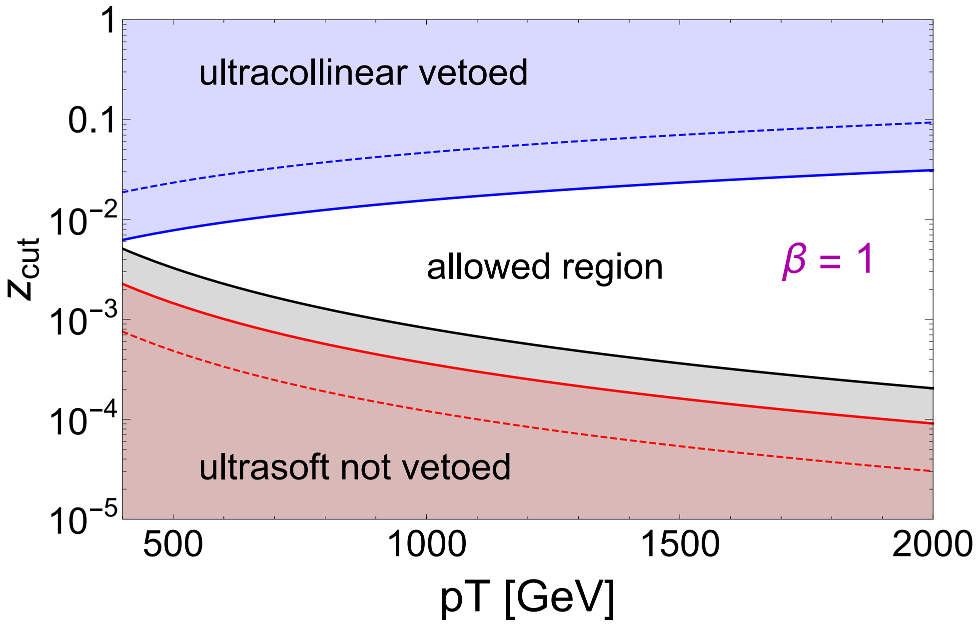
Now includes semi leptonic decays!

Constraints: Vary β

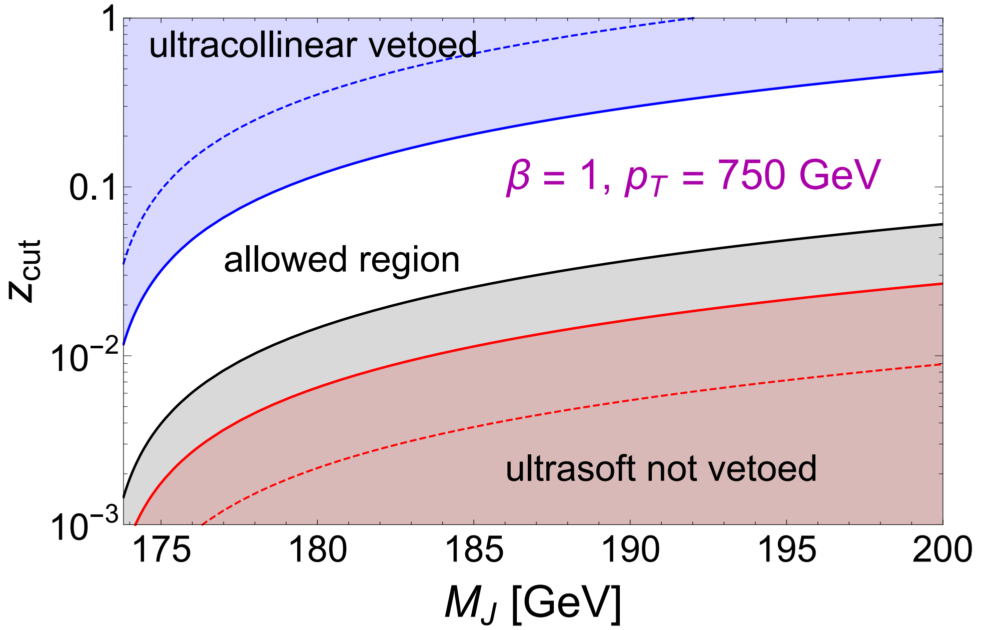


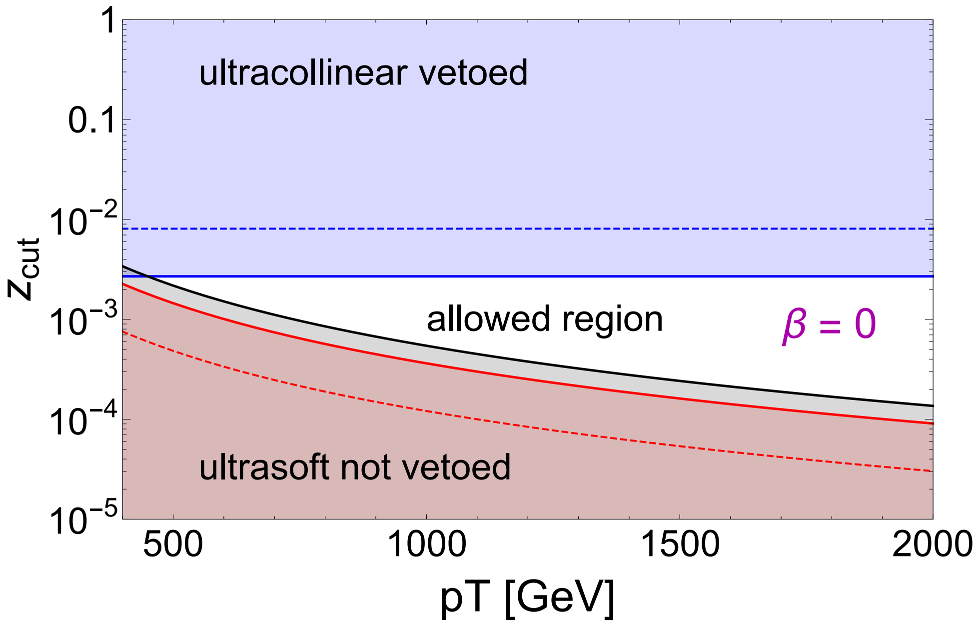


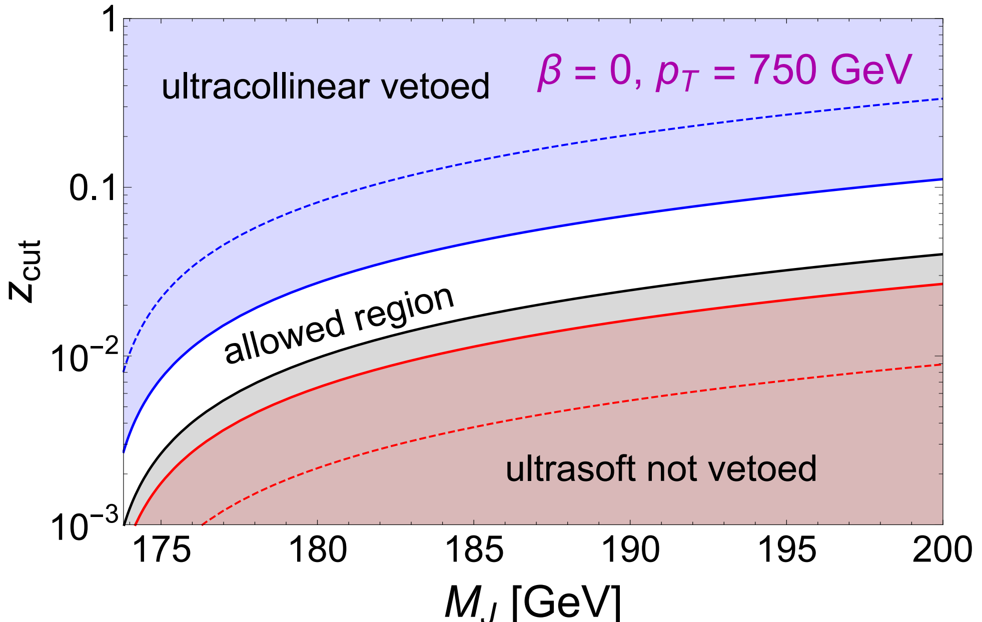
Peak Region



More grooming

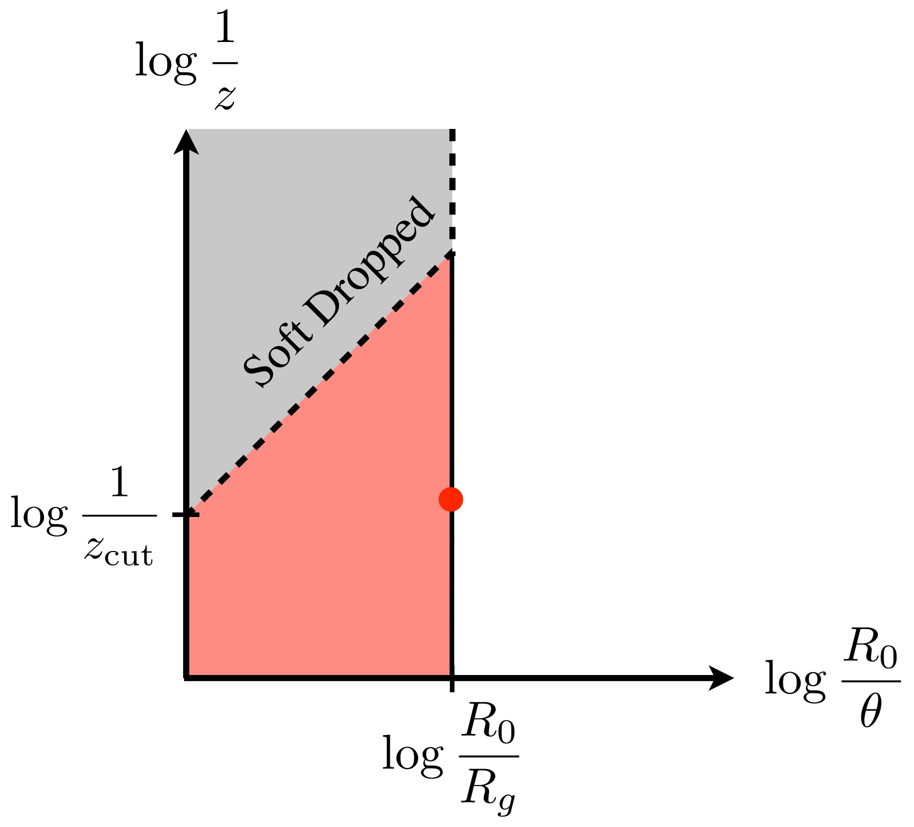




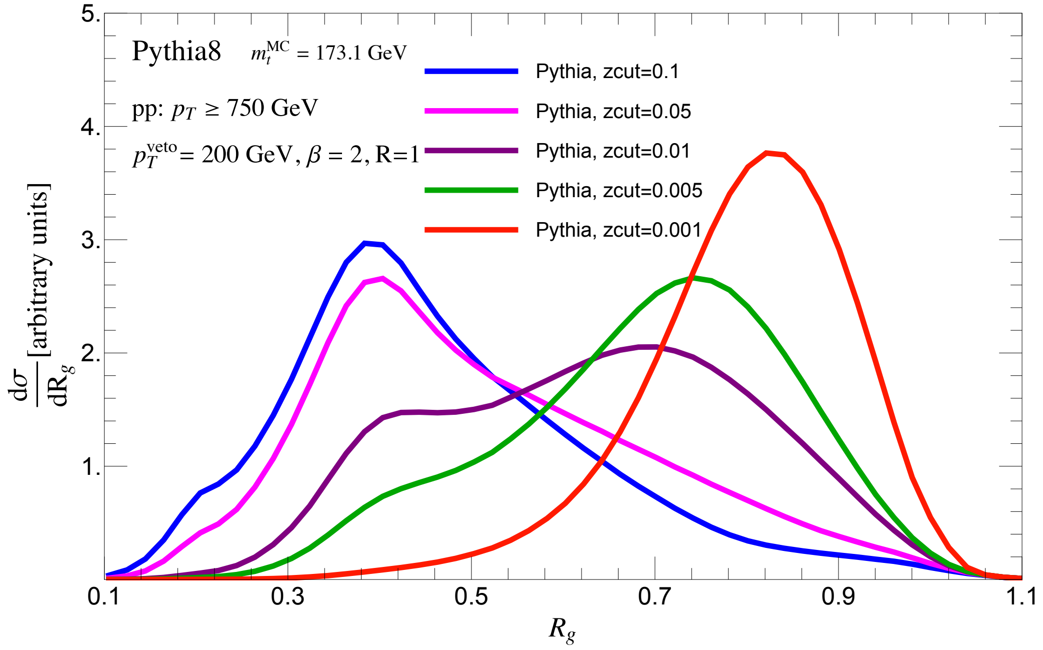


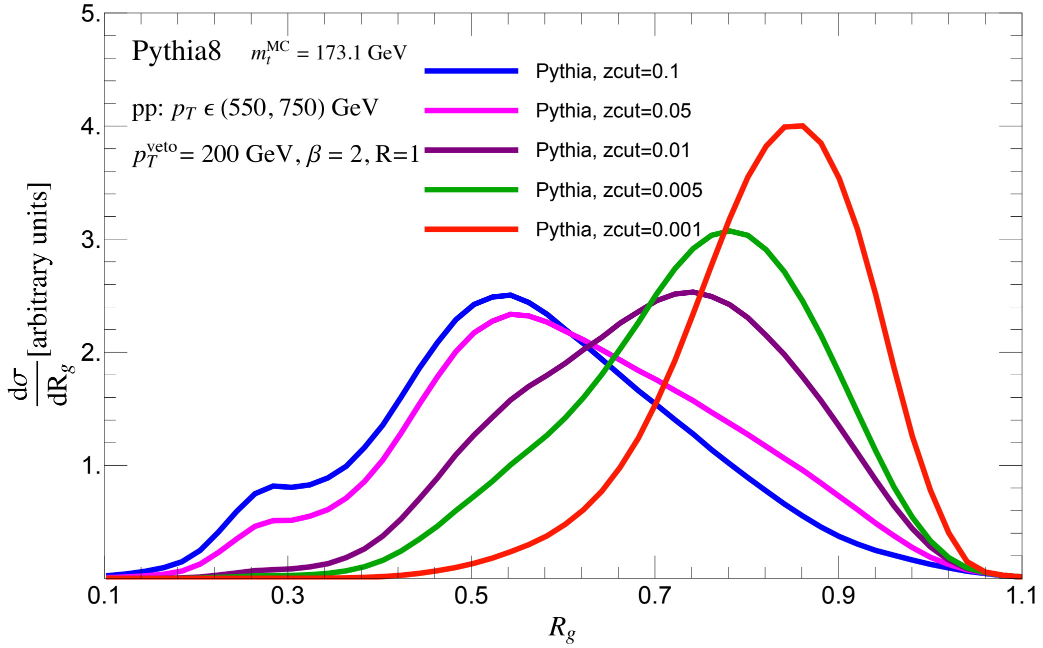
Groomed Jet Radius: R_g

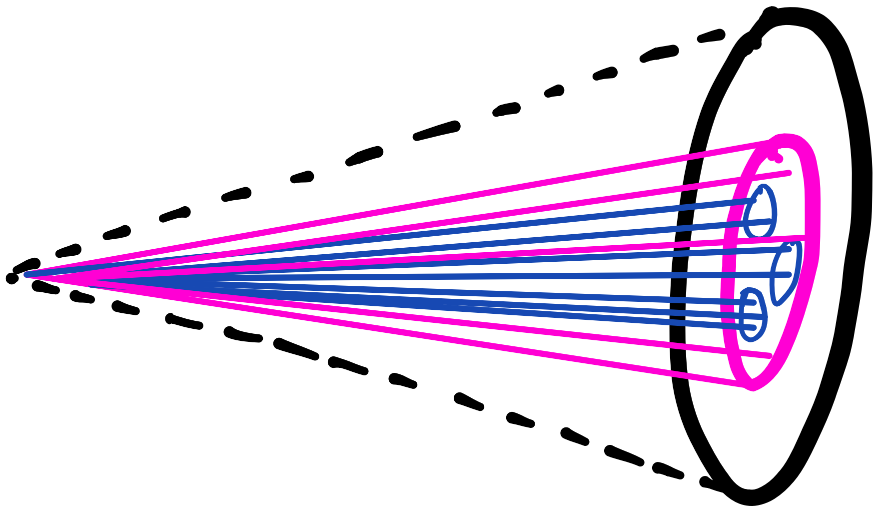
Larkoski, Marzani, Soyez, Thaler 2014

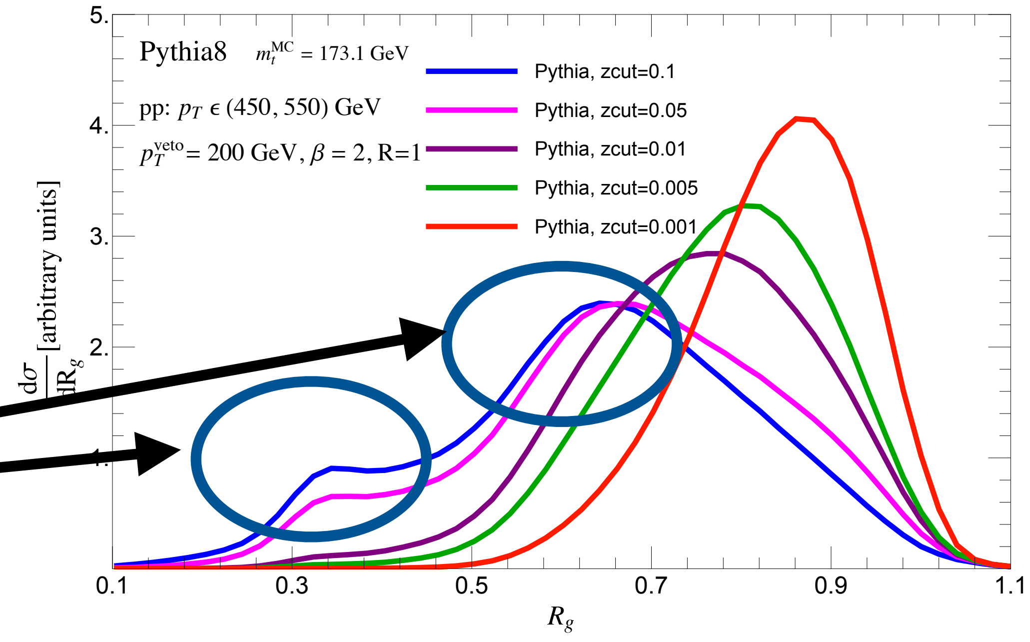


Lower p_T









from decay products

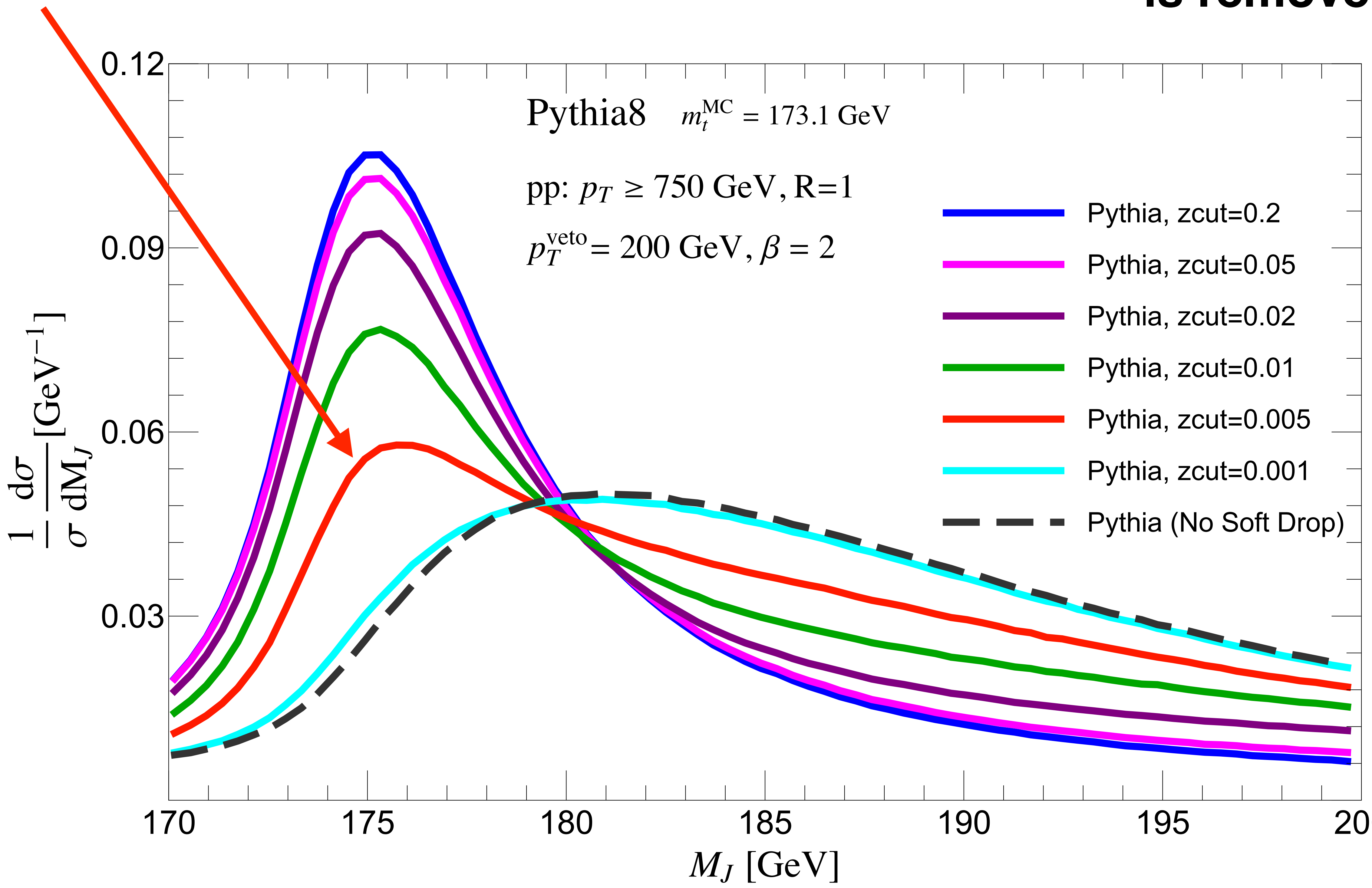
Pythia Studies

Test Theory Predictions with Simulations

z_{cut} dependence

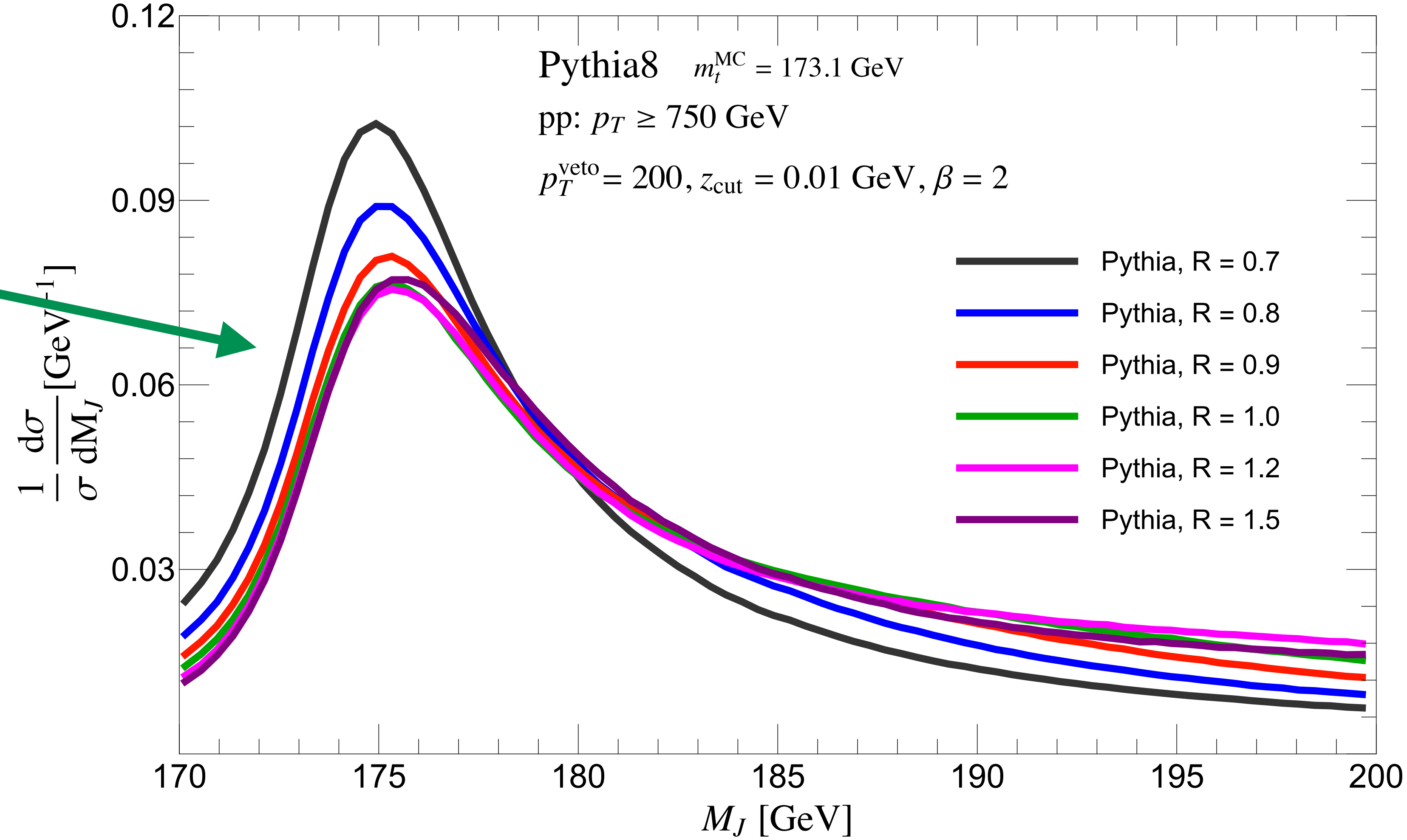
predict transition for “light Soft Drop” ✓

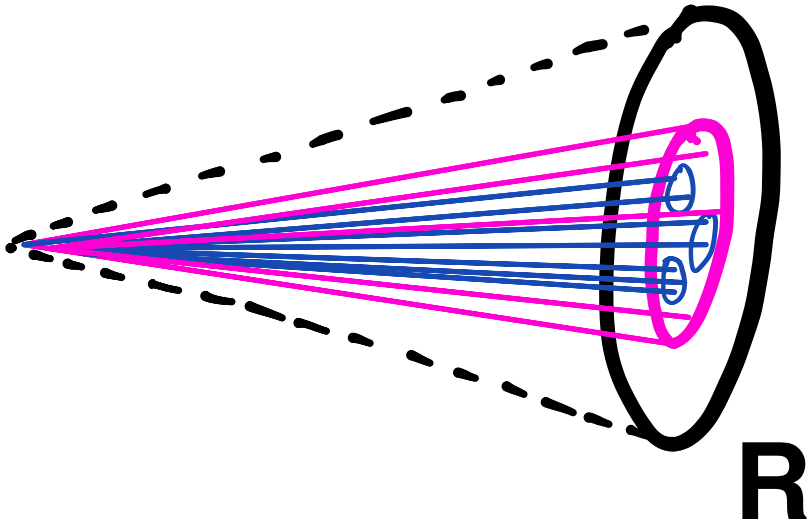
most contamination is removed



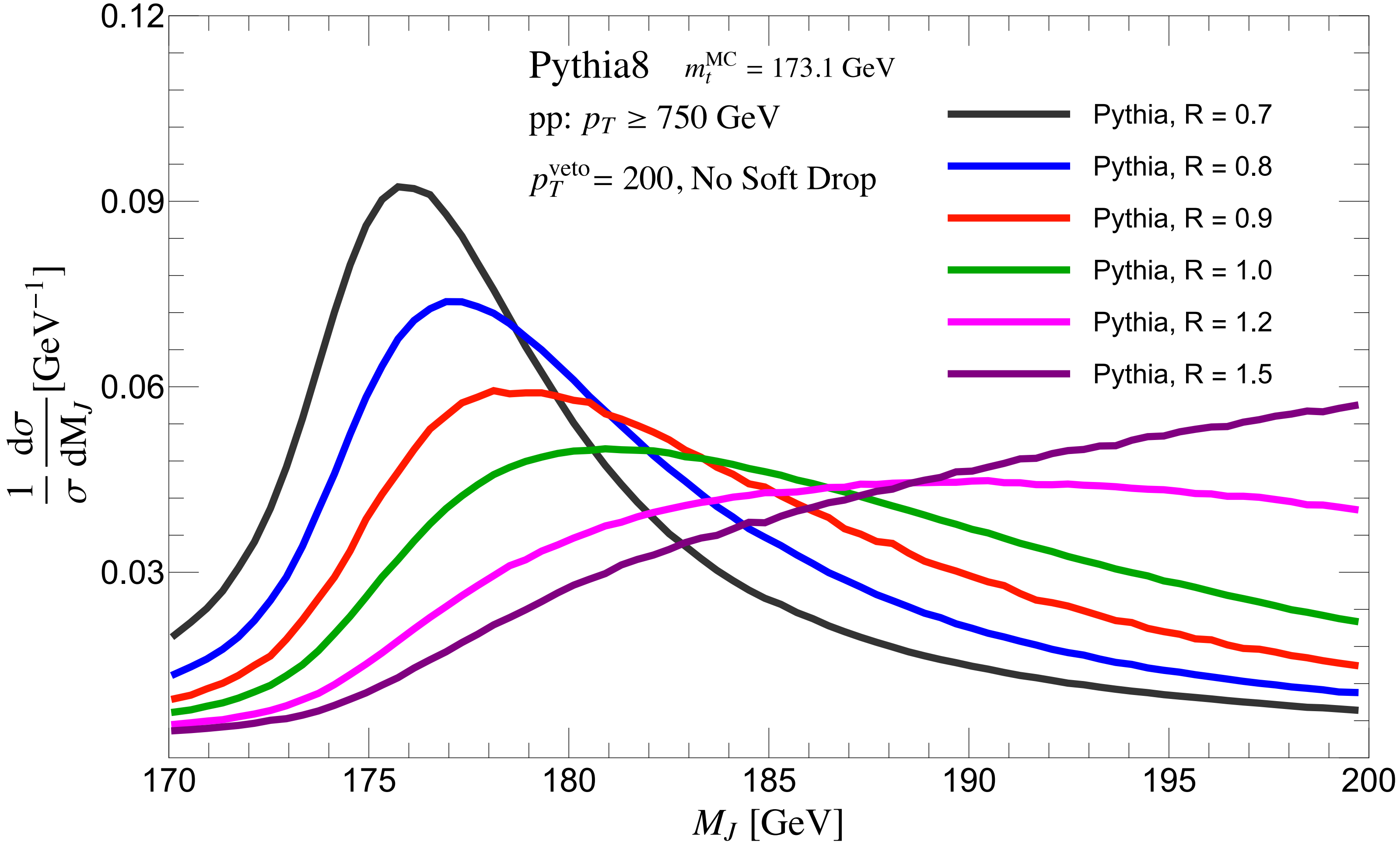
predict: independent of Jet Radius

✓



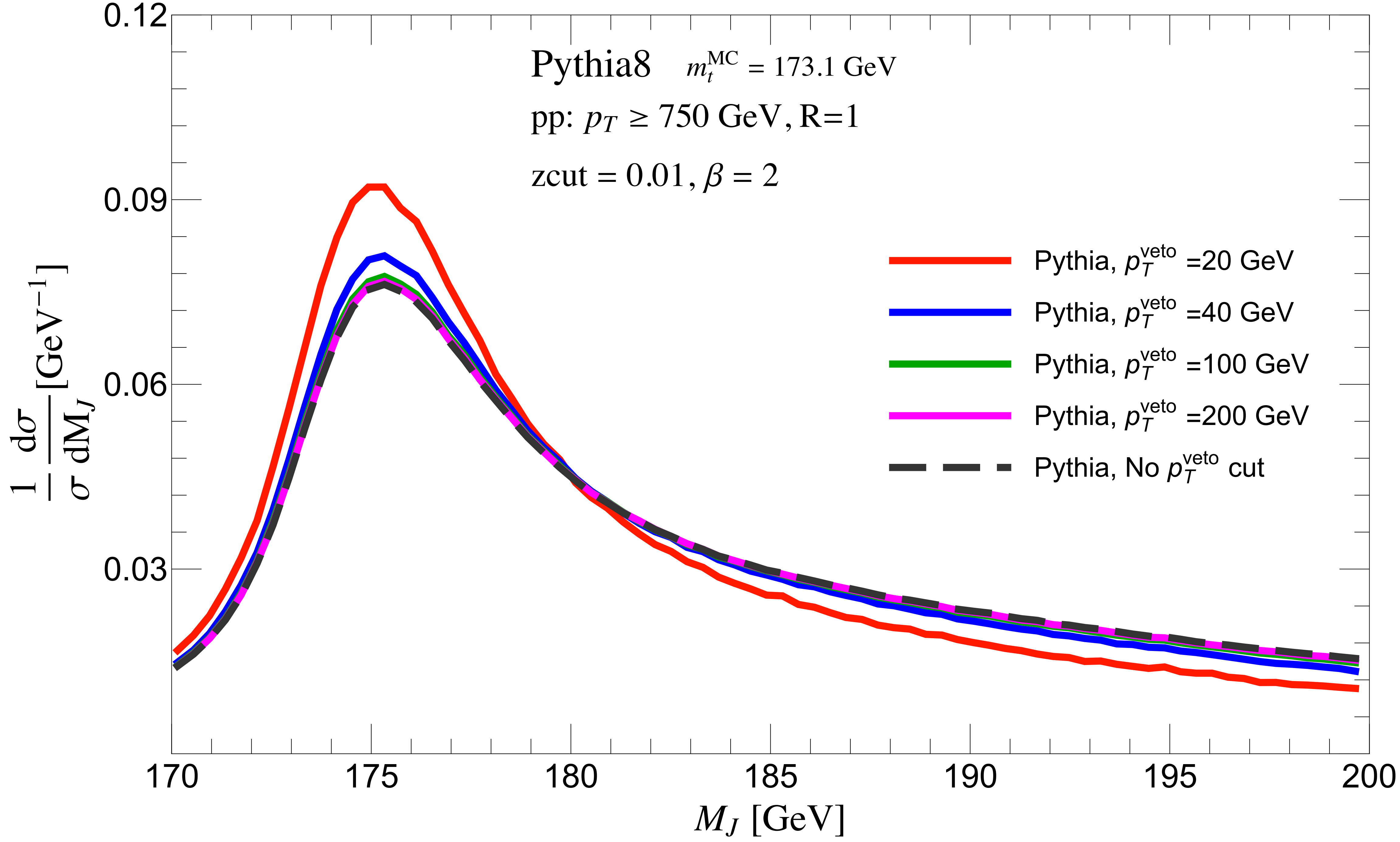


Without Soft Drop (huge):



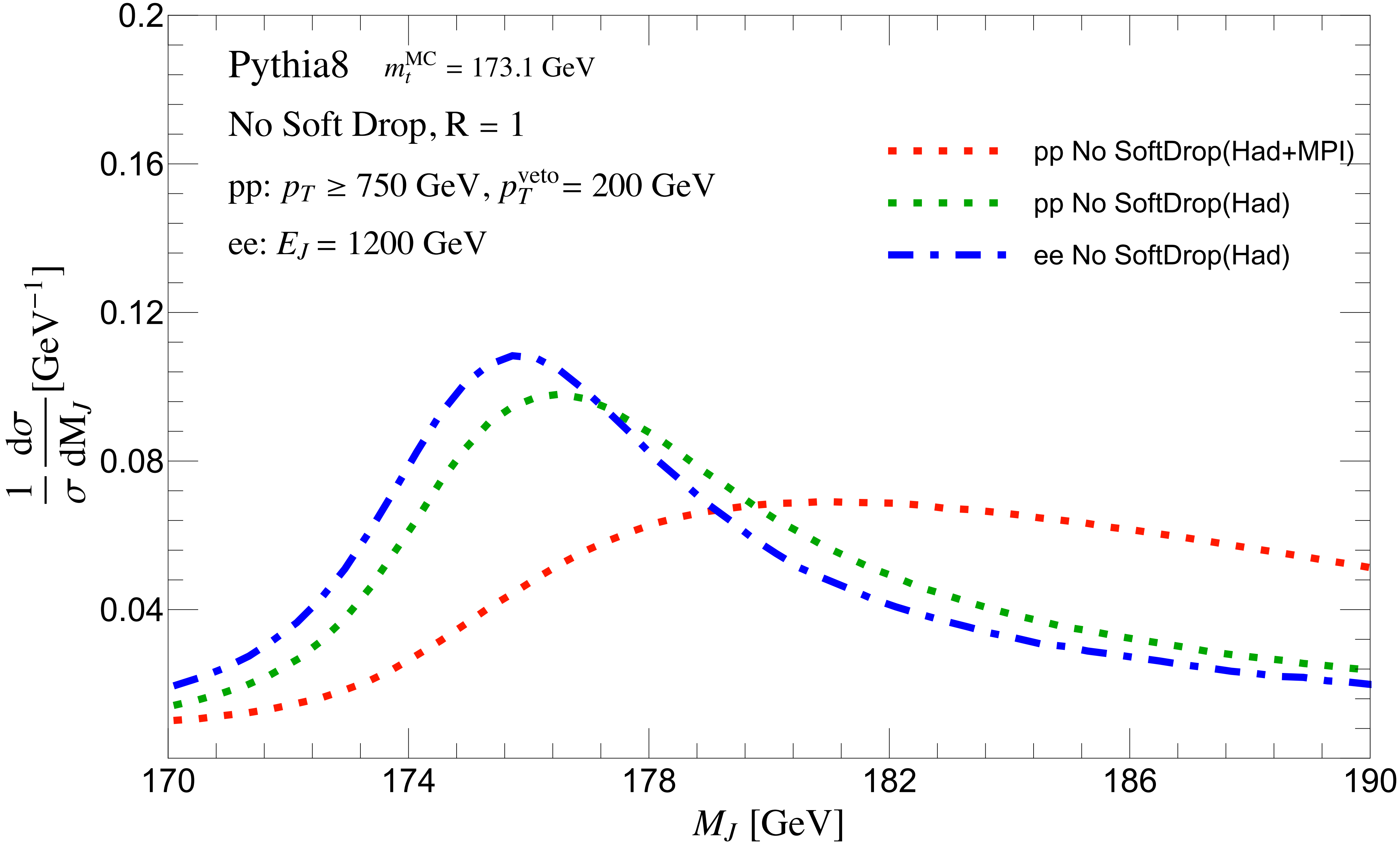
Predict independent of cutoff on radiation outside the jet (“jet veto”):

✓



Soft Drop prediction: Same Result for e^+e^- and pp collisions

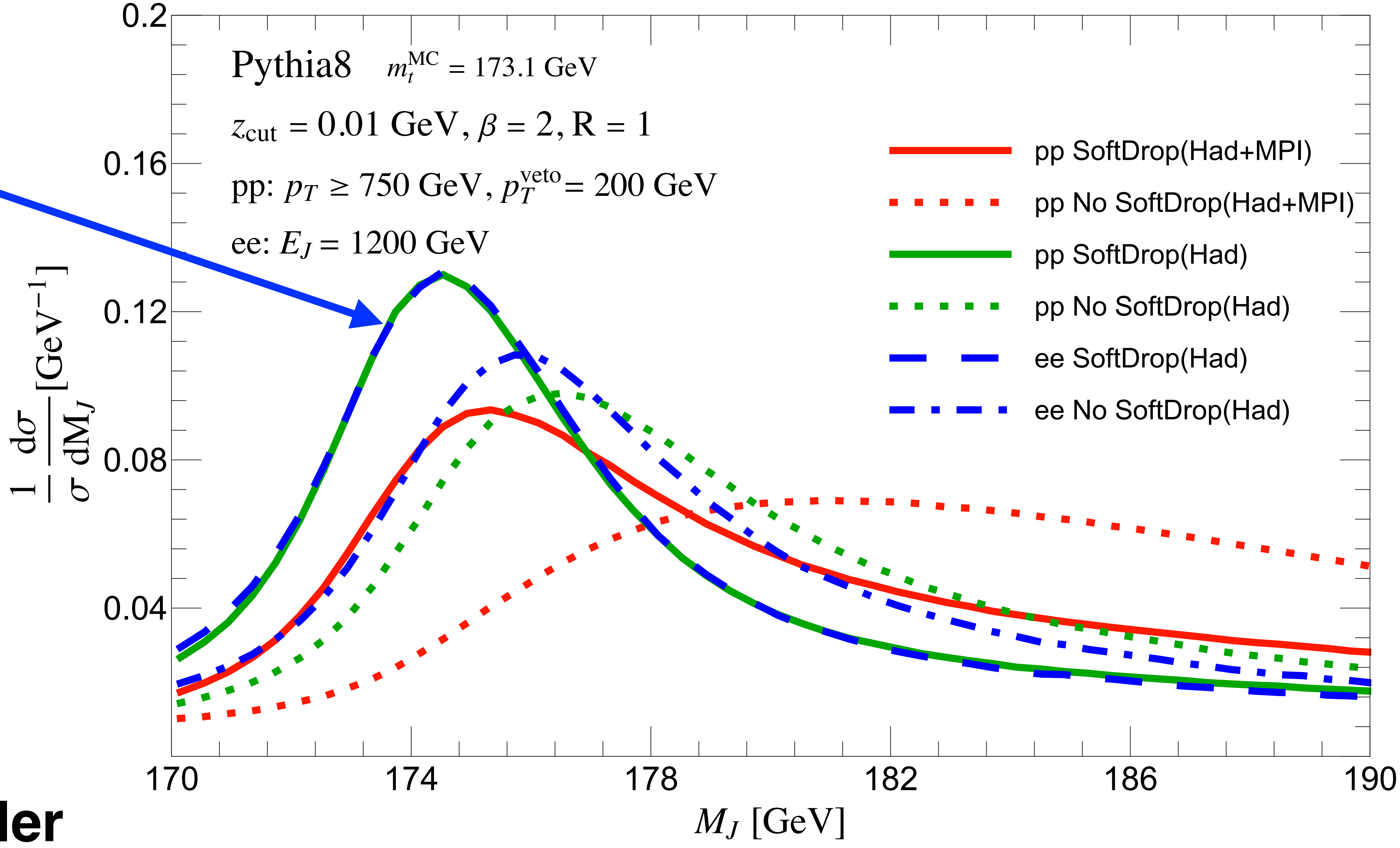
Without Soft Drop (differ):



Soft Drop prediction: Same Result for e^+e^- and pp collisions

With Soft Drop:

Great!



much smaller contamination

Compare Simulations to Our Theory

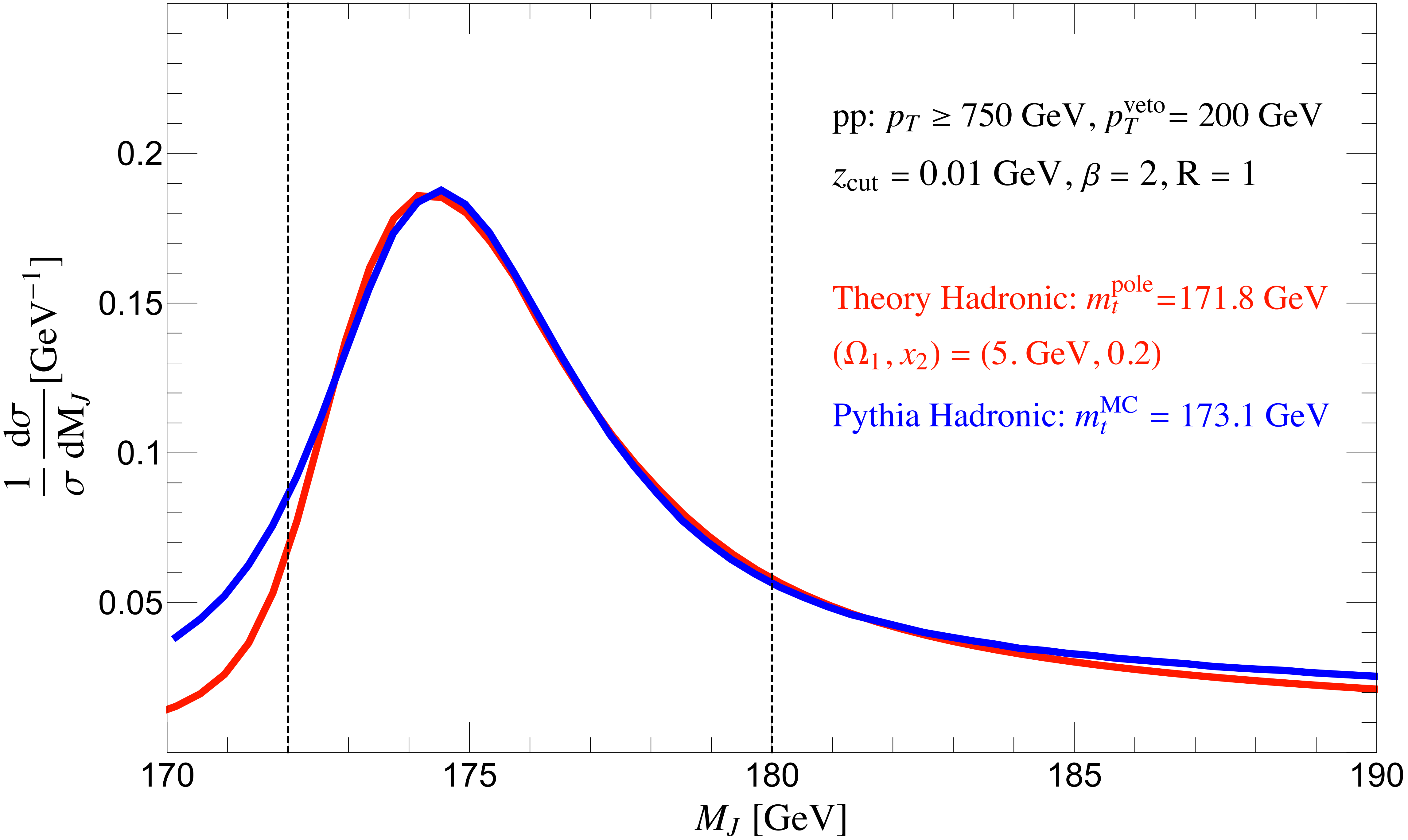
(preliminary)

Pythia Simulation vs. Theory (with Soft Drop)

without contamination:

$m_t^{\rm pole} = 171.8\ {\rm GeV}$

$m_t^{\rm MC} = 173.1\ {\rm GeV}$



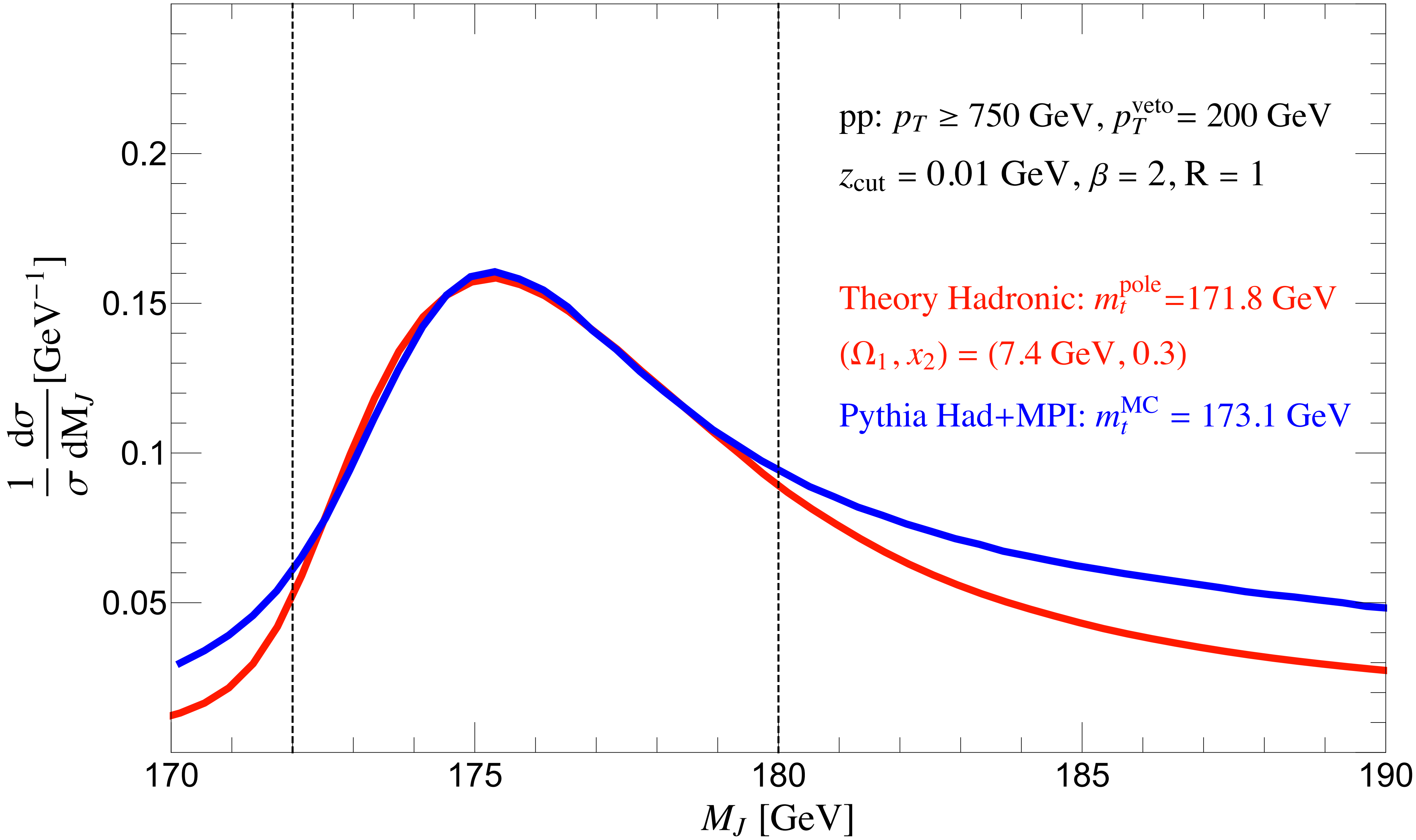
Pythia Simulation vs. Theory (with Soft Drop)

with contamination:

$$m_t^{\text{pole}} = 171.8\ \text{GeV}$$

$$m_t^{\text{MC}} = 173.1\ \text{GeV}$$

Same!

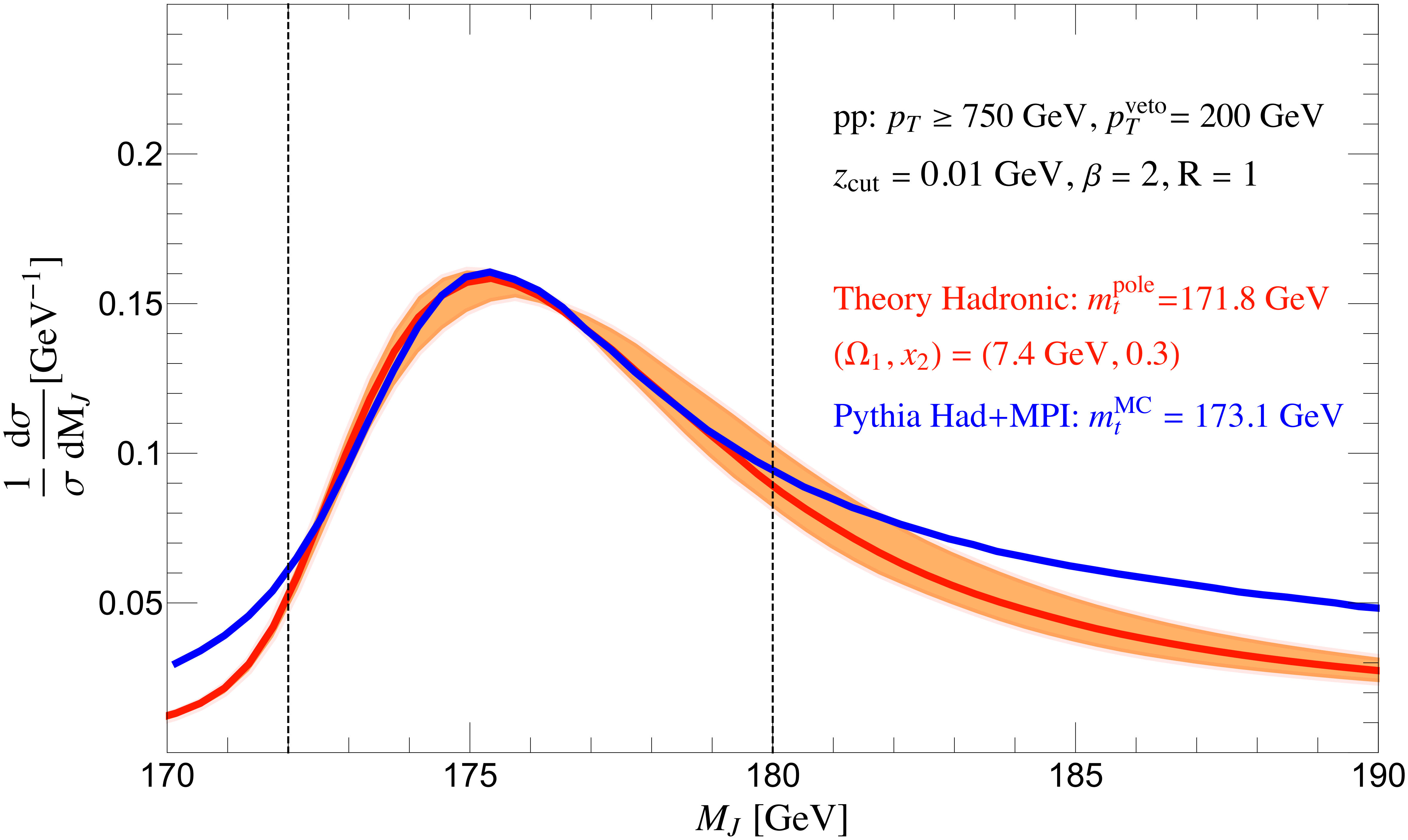


Dominant change is expected: Ω_1 (hadronization)

Pythia Simulation vs. Theory (with Soft Drop)

Add uncertainties from scale variation:

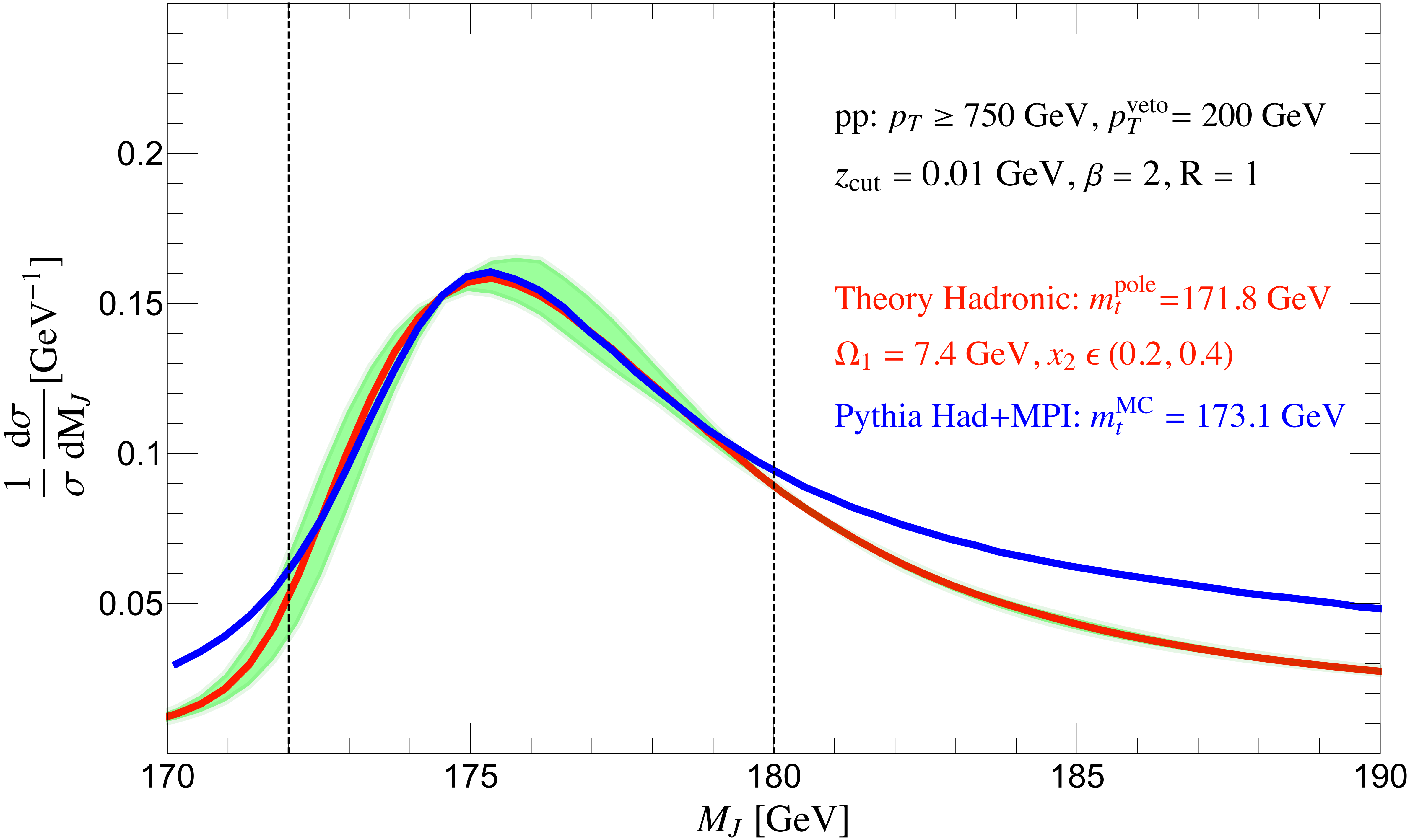
Translation of theory uncertainties to the fit parameters is in progress.



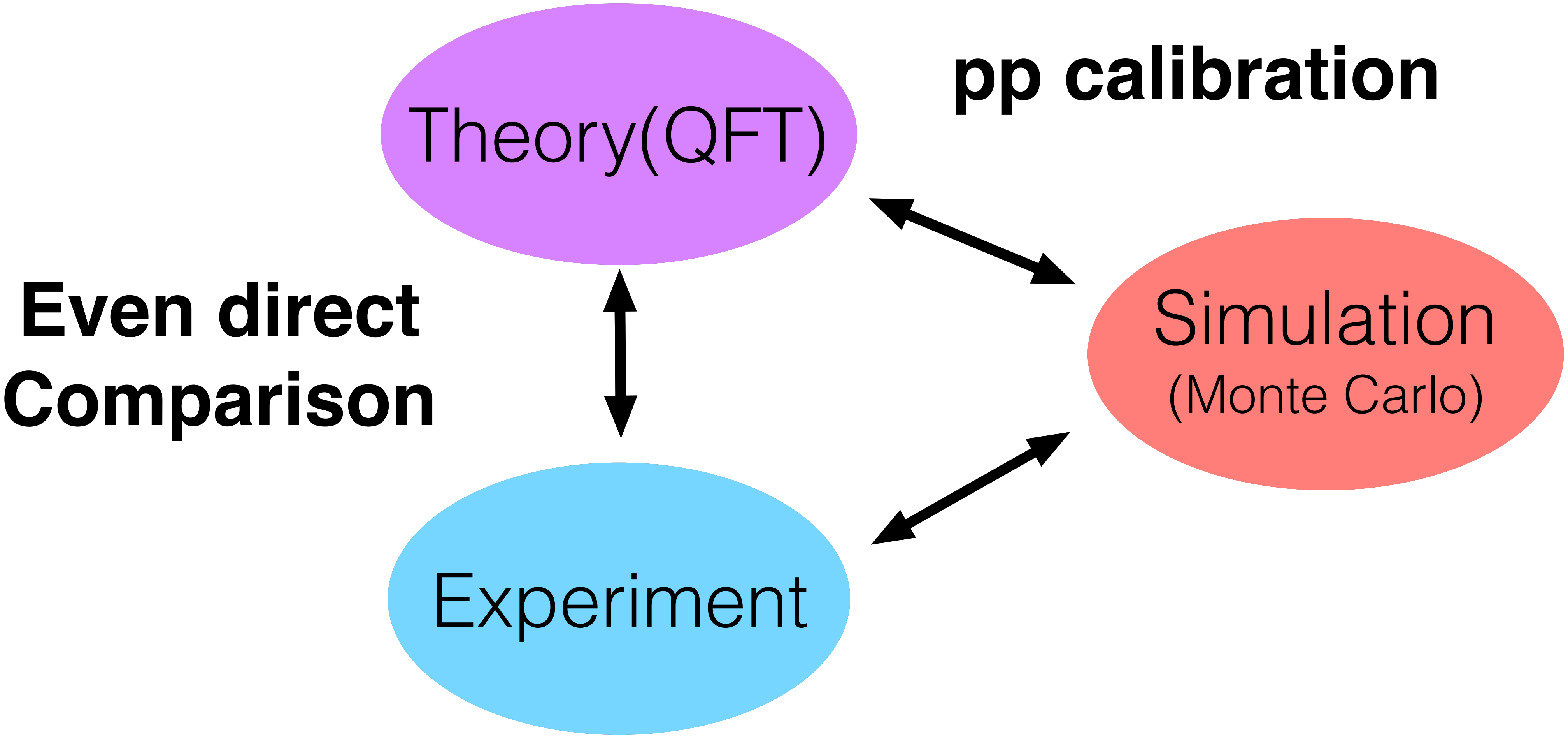
Pythia Simulation vs. Theory (with Soft Drop)

Testing sensitivity to higher moments:

$$\Omega_1 = \int \mathrm{d}k\, k\, F^{\mathrm{model}}(k) \qquad x_n = \frac{\Omega_n^c}{(\Omega_1)^n}$$



Looks very promising:



pp calibration

Theory(QFT)

Even direct Comparison

Simulation
(Monte Carlo)

Experiment

Summary

- Probing the question: “What mass are we measuring?”

- Answers from connecting theory (QFT) to Simulations or Data.

- A promising new method to measure Top Quark Mass exploiting a light Soft Drop