"Ugly Ducklings-Turned-Swans" in the Top Quark Sector

Doojin Kim

UF UNIVERSITY of FLORIDA

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With Kaustubh Agashe, Roberto Franceschini, Sungwoo Hong, Kyoungchul Kong, Myeonghun Park, Markus Schulze, and Kyle Wardlow: 1209.0772; 1212.5230; 1309.4776; 1503.03836; 1503.03872 and Works in progress

1. Introduction

- **Ugly duckling = Swan**

Before

1. Introduction

- **Ugly duckling = Swan**

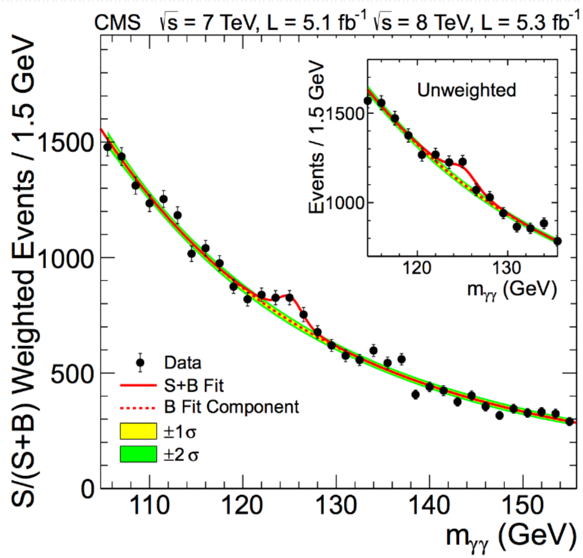
Before

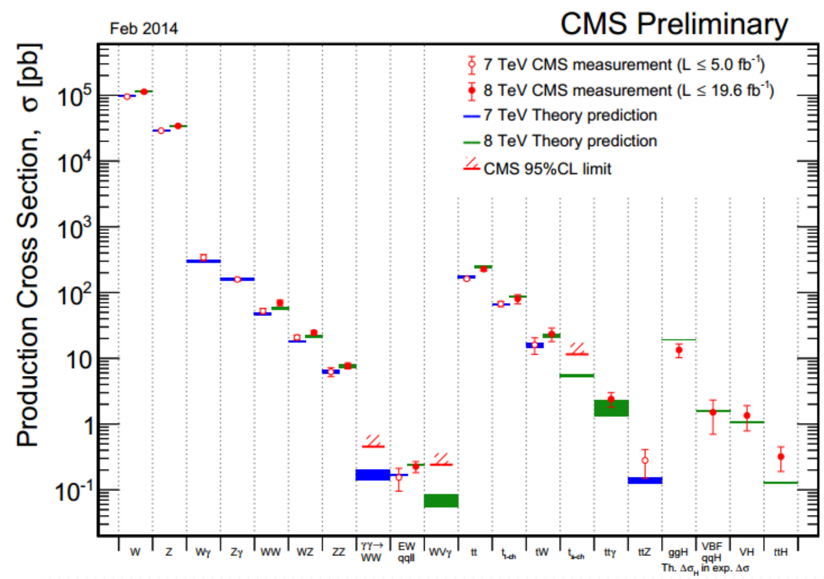
After

1. Introduction

LHC Run I

- ❑ Higgs discovery, SM precision measurement





- ❑ SM having unexplained issues (e.g., neutrino mass, dark matter, gauge hierarchy puzzle etc)
- ❑ Many new physics models: theory-motivated and phenomenology-motivated
- ❑ No hint of new physics signature

1. Introduction

LHC Run II

- LHC Run II will be marked by **precision studies** and searches for **small signals**

- Precision measurement by different approaches/methods
- New physics searches: searching for buried "Arkenstone" out of a tons of "treasure"

- New ideas/approaches
  - ✓ Providing different systematics
  - ✓ Facilitating discovery of new particles

1. Introduction

Ugly ducklings in physics

- "Ugly ducklings" in physics?
  - ✓ Some variables/approaches/techniques could be considered **as problematic /not useful/not well under control** (depending on the questions/channels at hand)
  - ✓ Likely to be avoided/disregarded/used with prescriptions to remove problematic issues in relevant analyses

1. Introduction

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With different points of view for them, such "Ugly Ducklings" in physics can be reborn as "Beautiful Swans" especially in the LHC era

Contents

2. "Ugly Ducklings" in Top Sector

Why top sector?

- LHC as a top quark factory: top pairs: 950,000 fb x 300/fb = **285 M** at 14 TeV (NNLO+NNLL, M. Cacciari. Czakon, M. Mangano, A. Mitov and P. Nason (2012), P. Brnreuther, M. Czakon and A. Mitov (2012), M. Czakon and A. Mitov (2012, 2013), M. Czakon, P. Fiedler and A. Mitov (2013))

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- ❑ Top properties well measured/studied since its discovery at TeVatron, e.g., LHC combined eμ, σ_{tt} = **240.6±1.4(stat.)±5.7(syst.)±6.2(lumn.) pb**, CMS-PAS TOP-14-016, ATLAS-CONF-2014-054, m_t = **173.34±1.4(stat.)±5.7(syst.)**, World combination March 2014 (ATLAS, CDF, CMS, D0)

2. "Ugly Ducklings" in Top Sector

Why top sector? (continued)

- Still rooms for NP to hide, e.g., $\Gamma_t = 2.0 \pm 0.5$ **GeV**, Particle Data Group (2012)

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- ❑ Largest quantum correction to higgs mass
  - ✓ Highly promising sector/window to new physics

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- ❑ New physics in the production level (faking tt signature)
  - ✓ Better constrained/ruled out in the relevant parameter space of the new physics models (e.g. Czakon, Mitov, Papucci, Ruderman and Weiler ’14)
- ❑ New physics in the decay level (via rare decays of top)
  - ✓ Better chance to have new physics signals

2. “Ugly Ducklings” in Top Sector

“Ugly ducklings” in the top sector

- ❑ Three ugly duckling siblings
- ❑ Energy distribution
  - ✓ NOT Lorentz invariant vs. longitudinal boost-invariant transverse quantities at hadron colliders

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  - ✓ NOT fully understood vs. tree-level process (cf. DM search)

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  - ✓ NOT Lorentz invariant vs. longitudinal boost-invariant transverse quantities at hadron colliders
- ❑ Extra radiation (mostly via QCD)
  - ✓ NOT fully understood vs. tree-level process (cf. DM search)
- ❑ Mis-bottom-tagging (mostly charm)
  - ✓ NOT easy to distinguish from bottom-initiated jets

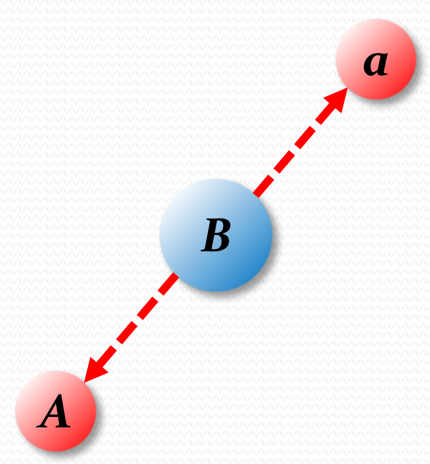
Energy distribution

3. Energy Distribution

Motivation

- A simple 2-body decay of a heavy resonance B into A and ***massless*** visible a

Rest frame of particle *B*



- Energy of visible particle a is **mono-chromatic** and **simple** function of masses in the rest frame of particle B

$$E^* = \frac{m_A^2 - m_B^2}{2m_A}$$

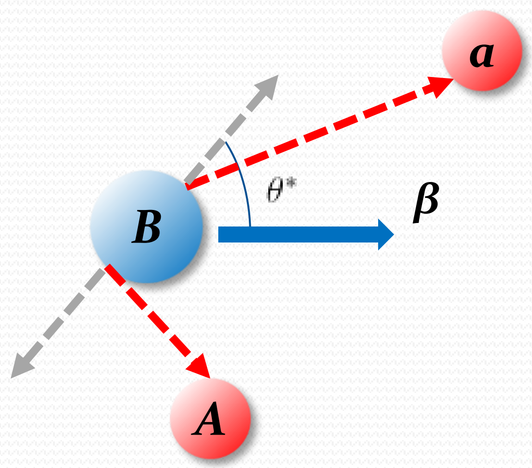
  - ✓ E^* : energy of visible particle measured in the rest frame of particle B
- E^* is measured, mass of A is known → **mass of *B* can be measured!** and vice versa
- Great to be on this special frame!

3. Energy Distribution

2-body decay kinematics in the lab frame

- Energy (not a Lorentz-invariant) of particle a should be Lorentz-transformed

Laboratory frame



- Depending on m_A and m_B *plus* ***unknown*** **boost factor** $\gamma = 1/\sqrt{1-\beta^2}$ and **emission angle** of particle a from the axis of $\vec{\beta}$

$$E = E^{*}\gamma(1 + \beta\cos\theta^{*})$$

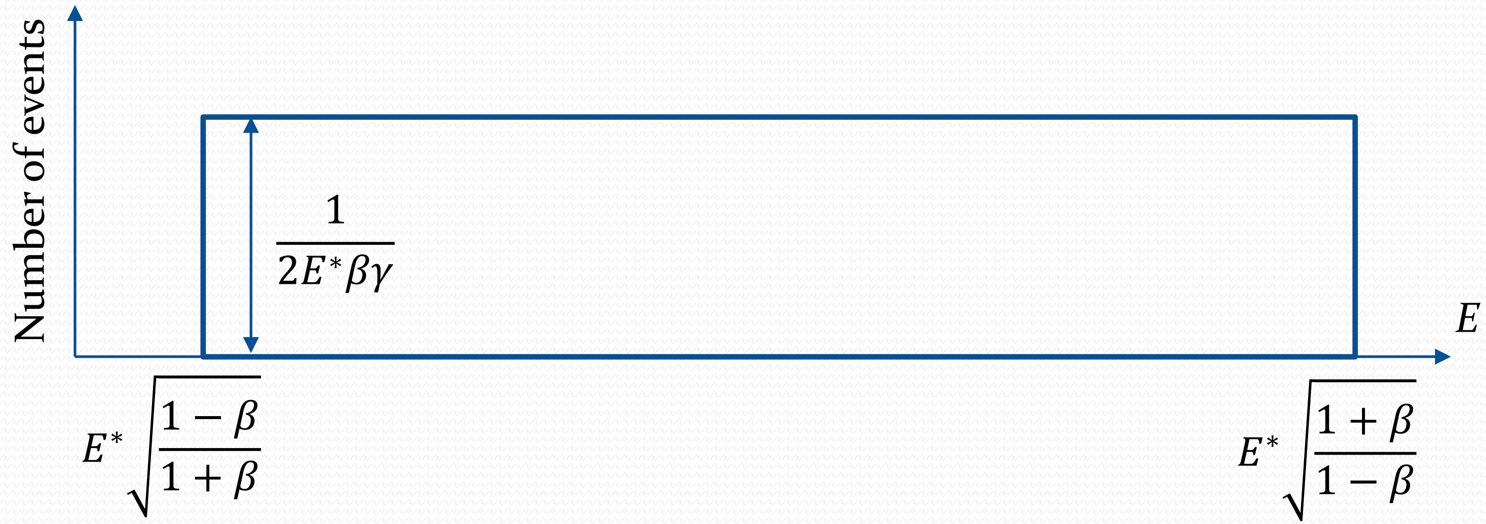
- No longer fixed energy of particle a in the lab frame, but a function of $\gamma, \theta^{*} \rightarrow$ becoming a distribution due to variation in them $\rightarrow$ information **loss**?!

Peak of such an energy distribution
= rest-frame energy

3. Energy Distribution

Existence of energy peak – primer

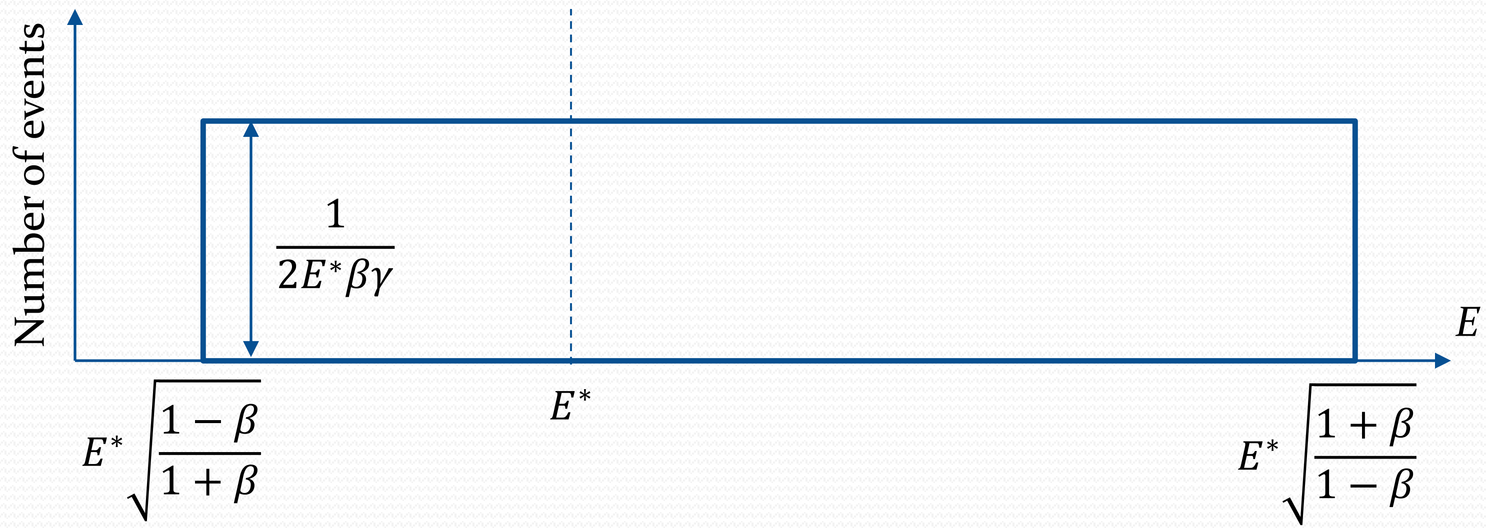
- Lorentz transformation: $E = E^*\gamma(1 + \beta\cos\theta^*)$
- Unpolarized/scalar mother particles
  - ✓ $\cos\theta^*$ becomes flat $\rightarrow E$ is also flat (simple chain rule)



3. Energy Distribution

Existence of energy peak – primer (continued)

- Lower bound (upper bound) smaller (bigger) than E^* (for **any** boost)
  - ✓ **No other** E gets **larger** contribution from a given boost than does $E = E^*$
  - ✓ **No other** E is contained in **every** rectangle
- **Asymmetric** on linear E (symmetric on logarithmic E)

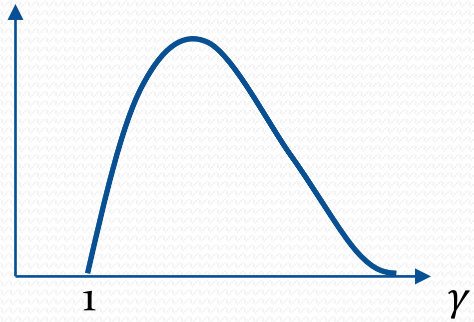


3. Energy Distribution

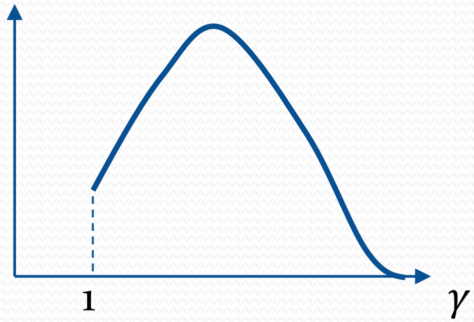
Existence of energy peak – primer (continued)

- Distribution in E: summing up the contributions from all relevant boost factors
  - ✓ **"Stacking up" rectangles** weighted by boost distribution (Lebesque-type integral)
  - ✓ Energy distribution has a unique **peak** at $E = E^*$ (**Agashe, Franceschini, and DK '12,** also Stecker '71)
- Details of the boost distribution (depending on production mechanism, PDFs, mother masses…) **NOT** matters

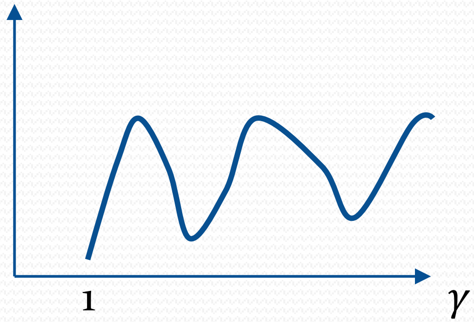
1) rise-and-fall



2) rise-and-fall with non-zero at $\gamma = 1$



3) more crazy (?)



3. Energy Distribution

"Stacking up" rectangles

- ❑ E^* must be the **location of the peak**!

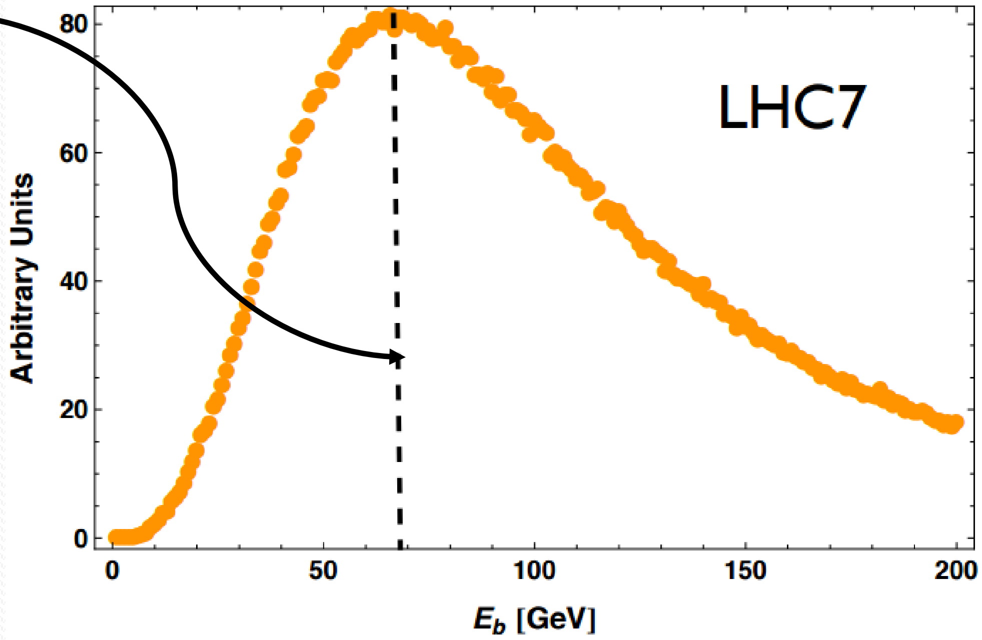
3. Energy Distribution

Bottom energy from top decay

- Bottom mass negligible: peak is expected **not** to shift

from $E_b^* = \frac{m_t^2 - m_W^2 + m_b^2}{2m_t} = 68$ GeV

modified



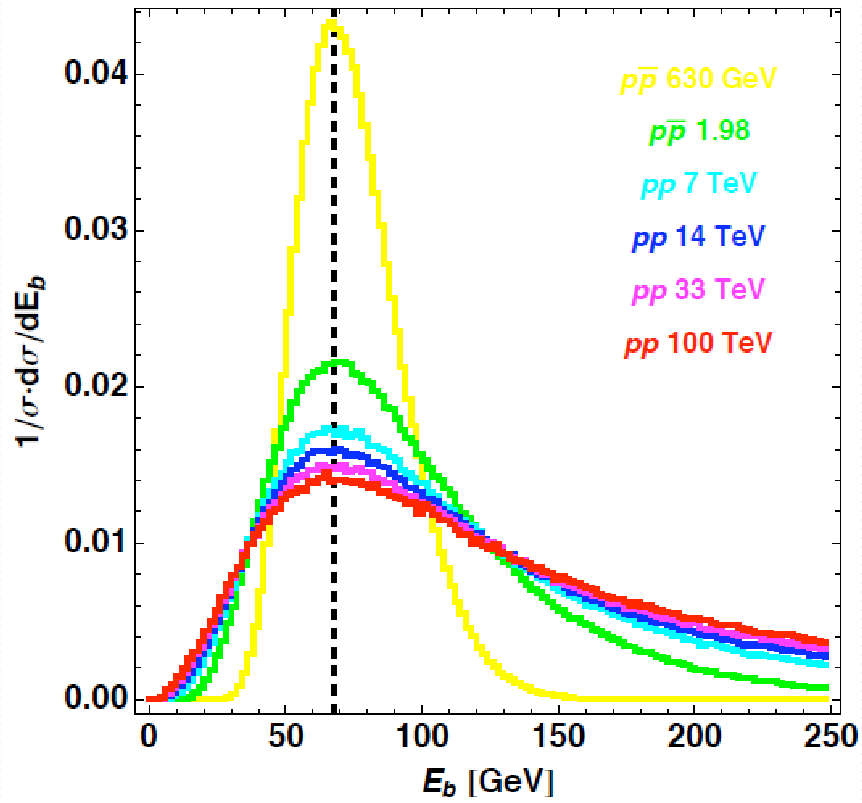
- … maybe an "accident"?!

3. Energy Distribution

Different CM energy colliders

- "**Invariant**" (under boost distributions) feature in non-invariant energy distribution holds even with colliders of different center-of-mass energies and types

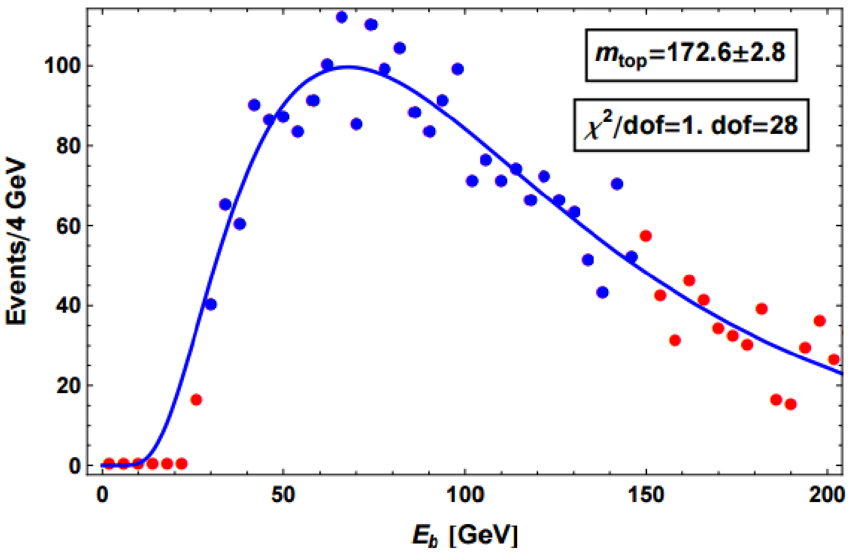
- Shape can change, while peak does **NOT** change



3. Energy Distribution

Example pseudo-experiment at detector level

- ❑ Proof of the concept using 100 pseudo experiments from MadGraph5+Pythia+Delphes (ATLAS-2012-097)
- ❑ Fit with blue dots
- ❑ consistent with the input value
- ❑ Fit **NOT** spoiled by cuts or detector effects!!



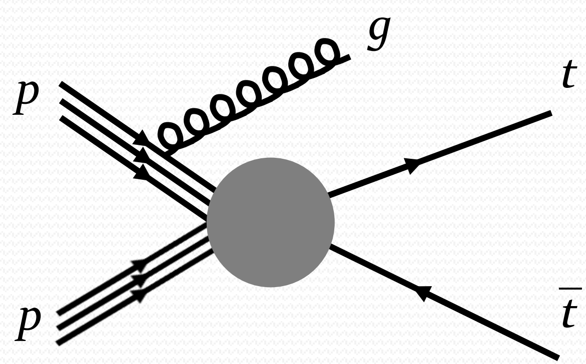
$$m_{top} = 173.1 \pm 2.5 \text{ GeV (stat.) with 5/fb LHC7}$$

- ❑ LO effects are well under control → **CMS at work!!!**

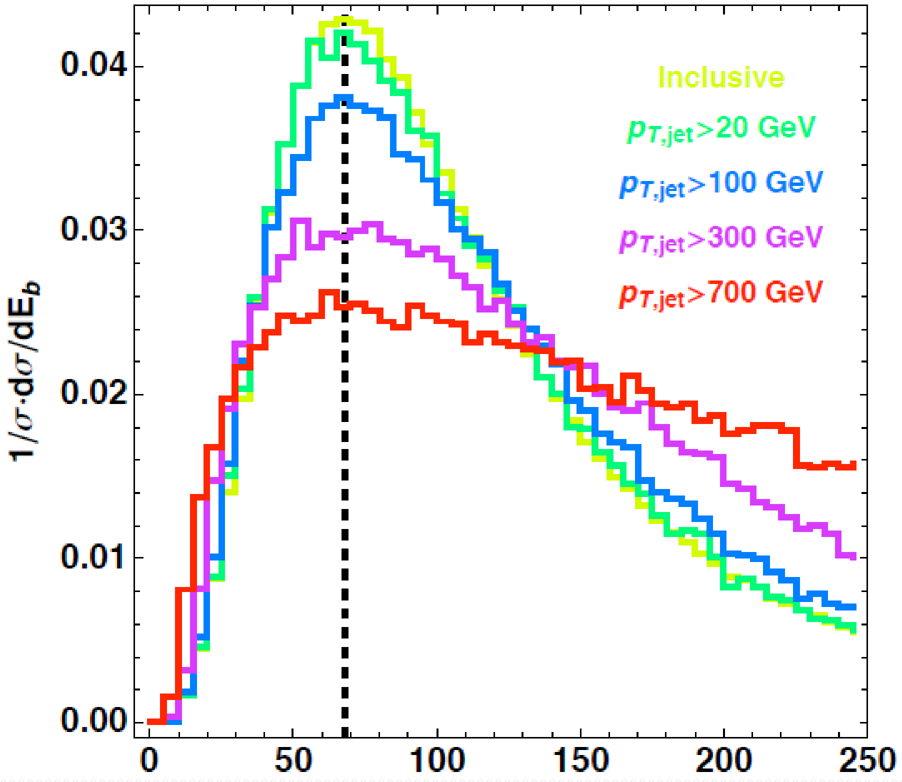
3. Energy Distribution

Energy peak at production NLO

- Recoil of the $t\bar{t}$ system by ISR



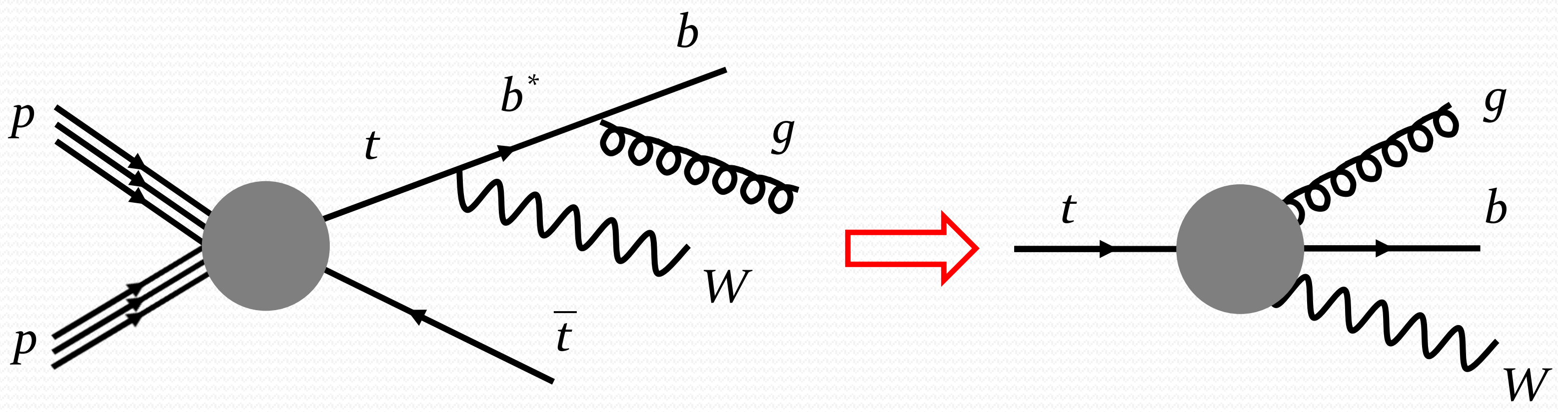
- Top quark getting more boost → different boost distribution → change in width of distribution, but **NO** shift in the energy-peak!!



3. Energy Distribution

Energy peak at decay NLO

- 3-body decay of top quark at decay NLO

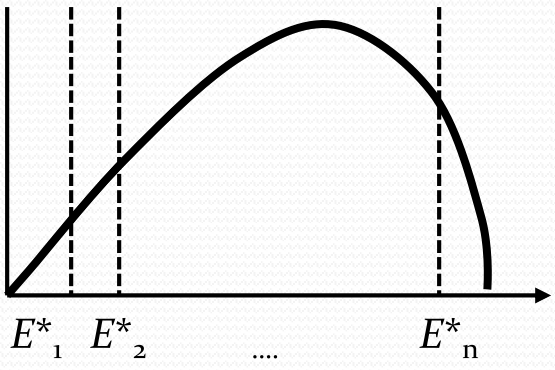


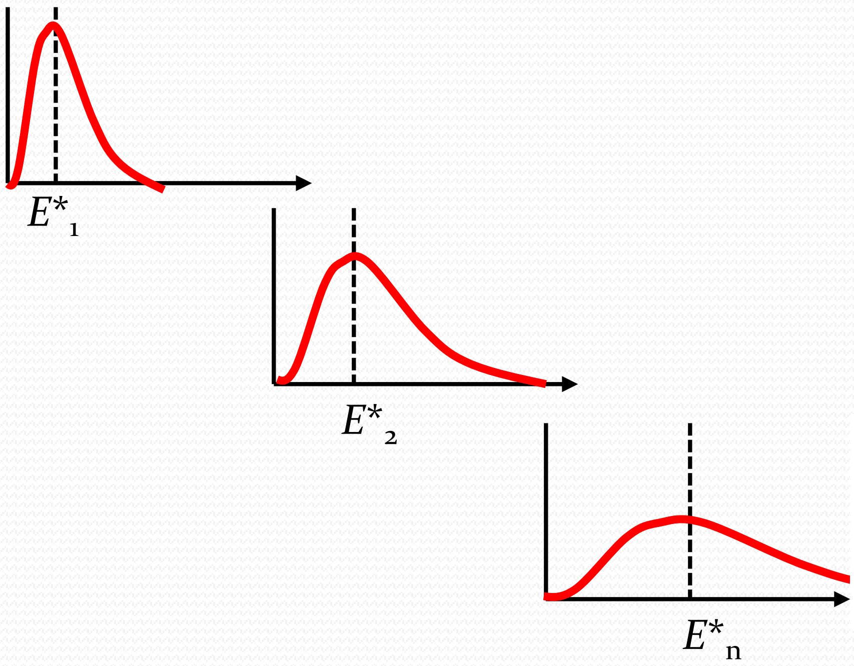
- Fraction of bottom energy carried away by final state radiation jet
  - ✓ Peak **shifts** to the lower energy regime!

3. Energy Distribution

Energy peak in three-body decay

- Energy of visible particle given by a distribution, **NOT** fixed unlike 2-body decay!
- Each value of the rest-frame energy goes through similar argument in 2-body kinematics

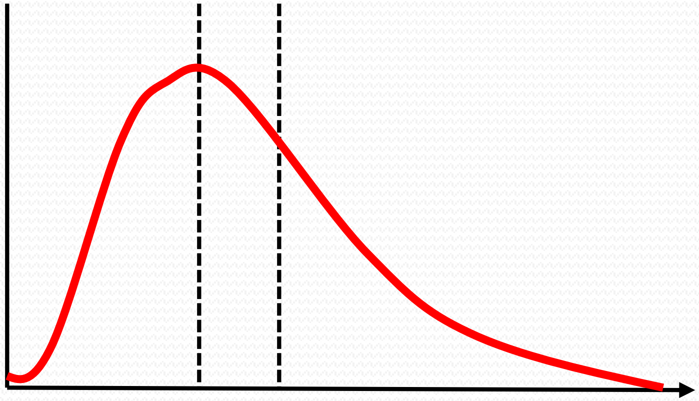




3. Energy Distribution

2 body vs. 3 body

- Peak position **smaller than** the maximum rest-frame energy (**Agashe, Franceschini, DK, and Wardlow '12**)



- E_{peak} : model-dependent
- Neglecting hard emission from a bottom quark, i.e., jet-veto
- Safe from soft radiation off bottom (according to the detector-level simulation study)
- (Typically) suppressed by $\frac{\alpha_s}{\pi}$, i.e., small perturbation in the LO phenomenon

3. Energy Distribution

Motivation to top mass measurement

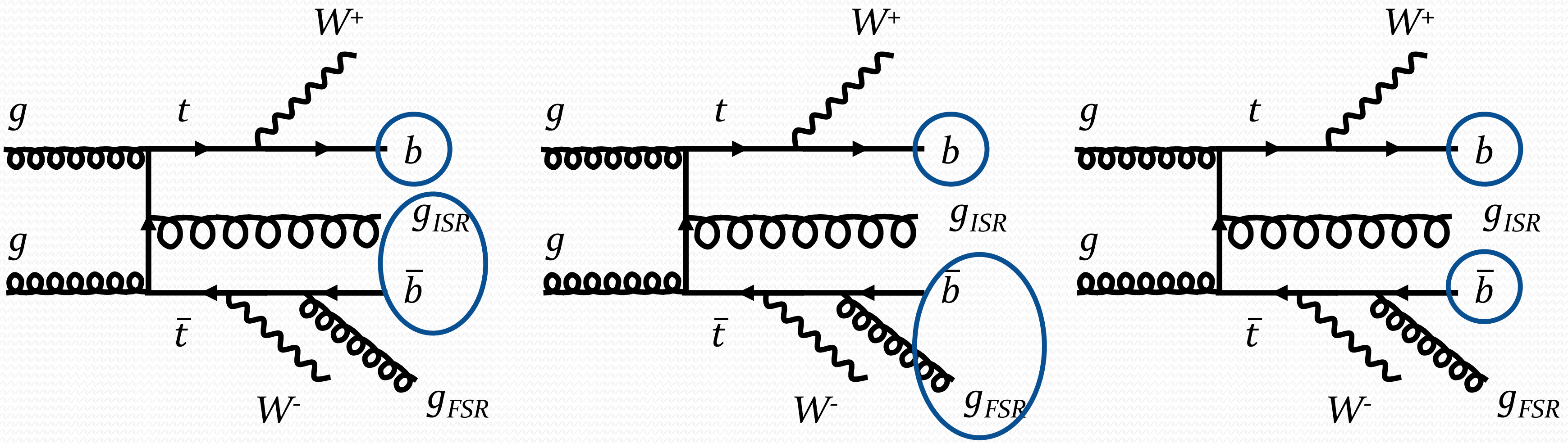
- Beginning with an "example/test" to prove the principle
- Evolved into a "serious" measurement of top mass
- Why another method?!
  - ✓ (Theoretically) physical mass (like top mass measurement using the endpoints of kinematic variables) vs. Monte Carlo mass (like template method) etc.
  - ✓ (Experimentally) different systematics, independent measurement etc.

- Some doable challenges (**Agashe, Franceschini, DK and Schulze, in progress**)
  - ✓ 3-body decay due to FSR
  - ✓ Renormalization/factorization scale choice
  - ✓ Jet energy resolution/jet formation

3. Energy Distribution

Production & decay NLO

- ❑ In real situation, jet definition is important; even ISR could affect the energy

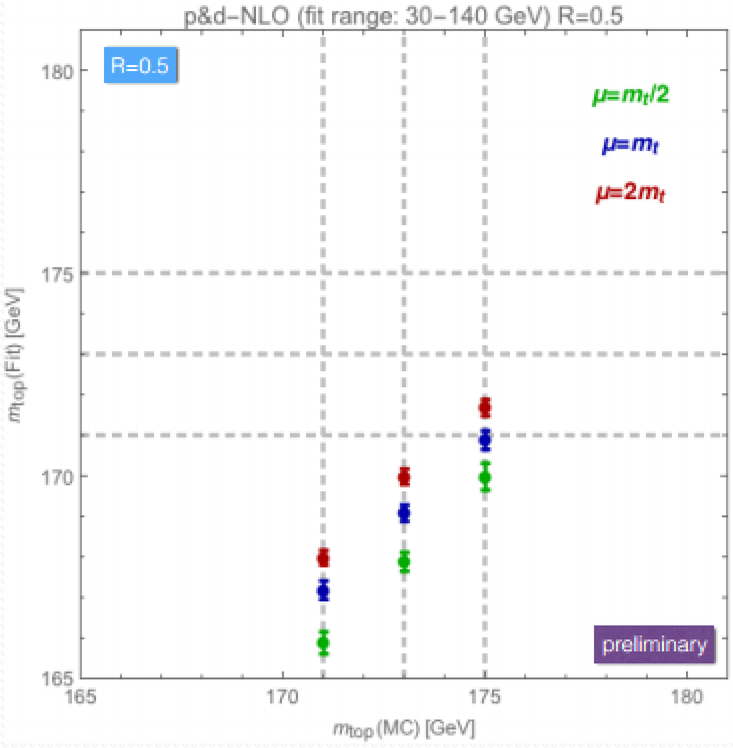


- ❑ Large jet radius capturing more FSR jets, but more contaminated by ISR jets
- ❑ Small jet radius losing more FSR jets, but less contaminated by ISR jets

3. Energy Distribution

Production & decay NLO: small R

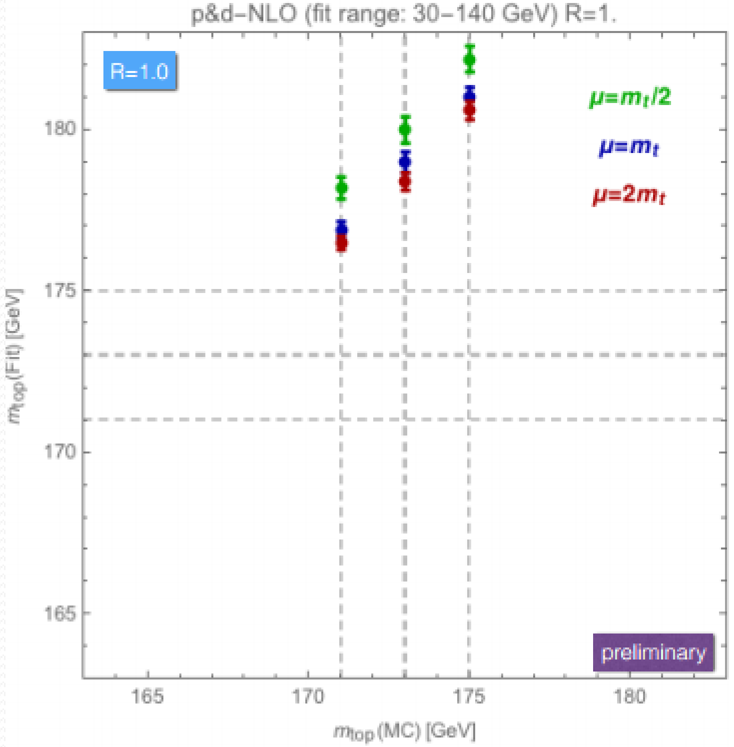
- Small R: R=0.5 (anti-kt, MCFM)
- Less contamination by ISR jets, but losing more FSR jets
  - ✓ Energy peak shifts to the lower energy regime
- Decay NLO sensitivity to the scale choice: ± 1 GeV on the top mass



3. Energy Distribution

Production & decay NLO: large R

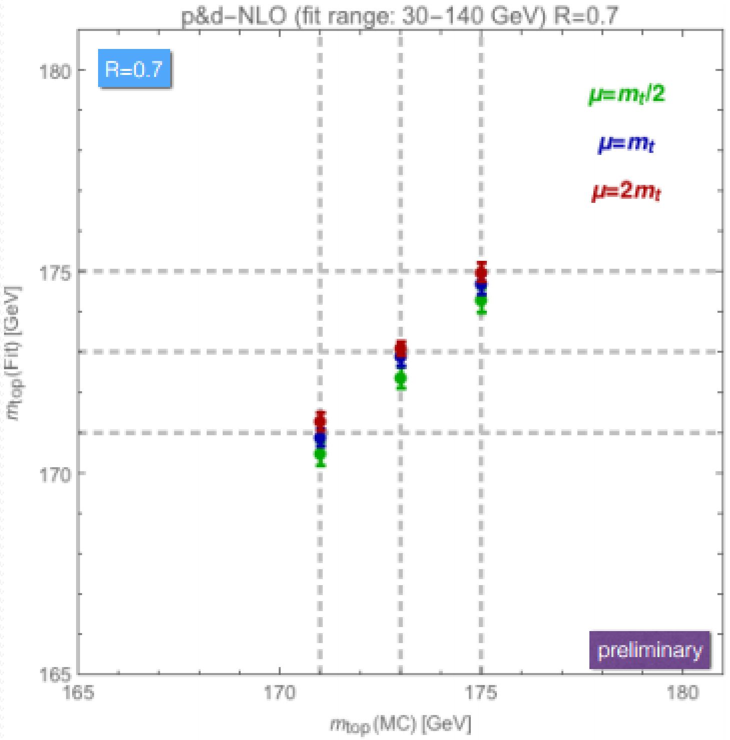
- ❑ Large R: R=1.0 (anti-kt, MCFM)
- ❑ More contamination by ISR jets, but capturing more FSR jets
  - ✓ Energy peak shifts to the higher energy regime
- ❑ Decay NLO sensitivity to the scale choice: ± 1 GeV on the top mass



3. Energy Distribution

Production & decay NLO: "decent" R

- "Decent" R: R=0.7 (anti-kt, MCFM)
- Decent contamination by ISR jets, and capturing decent number of FSR jets
  - ✓ Cancellation between the two effects?
  - ✓ **NO** shift in the energy peak
- Decay NLO sensitivity to the scale choice: $\pm$ 0.5 GeV on the top mass



3. Energy Distribution

Mild corrections from NLO

- Top decay still as in SM
- Theoretical systematics based on (**small**) parameters
  - ✓ δ_{prod}: PDF uncertainty, new physics in the production level (still unpolarized top)
  - ✓ f_{pol}: new physics contribution with polarized top
  - ✓ ϵ_{FSR}: NLO effect, jet-veto
- Bottom jet energy peak correction

$$\delta E_b^*/E_b^* = f_{pol} + \epsilon_{FSR} \times \delta_{prod}$$

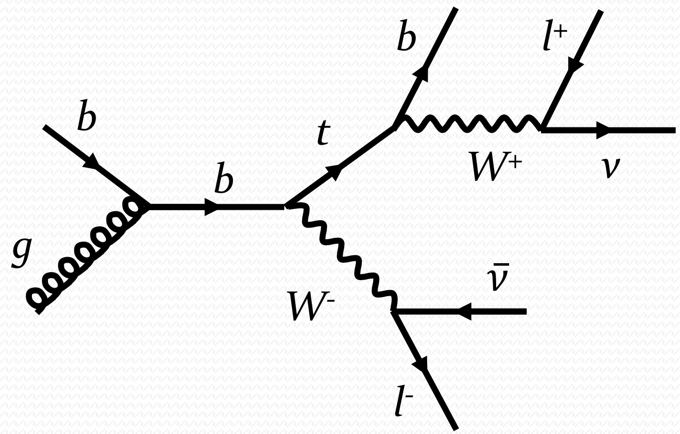
- ϵ_{FSR} for QCD/SM production is **calculable** and has been being studied (**Agashe, Franceschini, DK and Schulze, in progress**)
  - ✓ Conventional methods ~δ_{prod} vs. energy-peak ~$\epsilon_{FSR} \times \delta_{prod}$

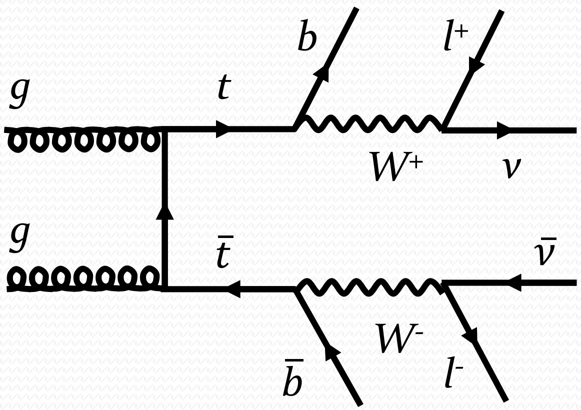
Extra Radiation

4. Extra Radiation

Motivation

- ❑ (For example,) separating tW from dominant $t\bar{t}$ background





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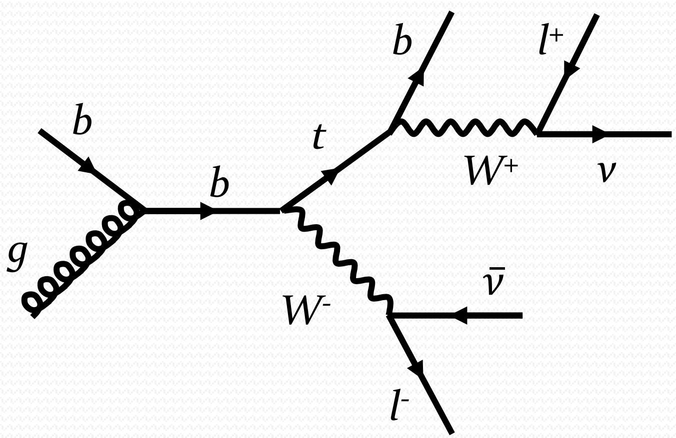
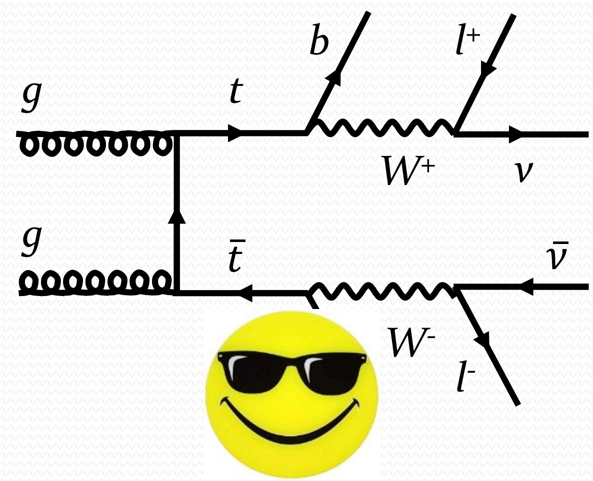




- ❑ Once a bottom is missed, they are
  - ✓ the same in the final state
  - ✓ kinematically very similar to each other
- ❑ Any "**killer**" kinematic variables to distinguish them from each other?

4. Extra Radiation

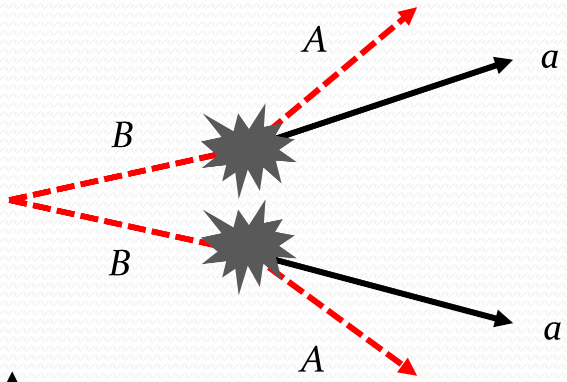
Quick review on M_{T2}

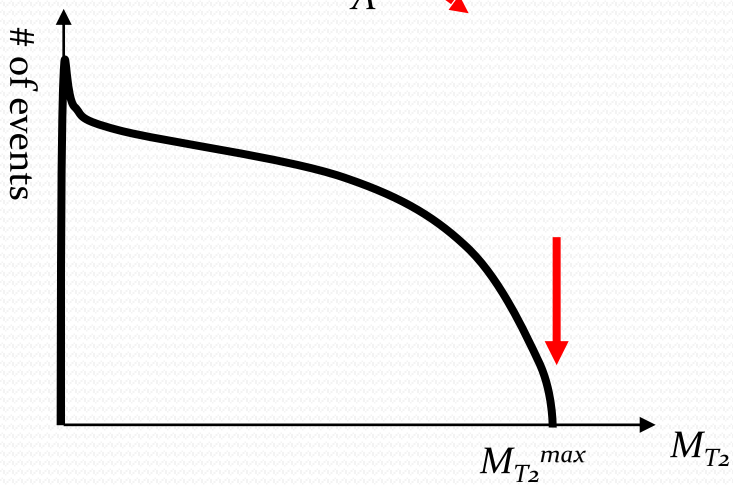
- Stransverse mass (M_{T_2}): a generalization of M_T

  (Lester and Summers '99; Barr, Lester, and Stephens '03; Cho, Choi, Kim and Park '07)

  - ✓ full usage of both decay sides
  - ✓ MET relating both decay sides
  - ✓ **bounded above**
  - ✓ M_{T2}^{max} as a **simple** function of mass parameters

$$M_{T2}^{\max} = \frac{m_B^2 - m_A^2}{m_B}$$

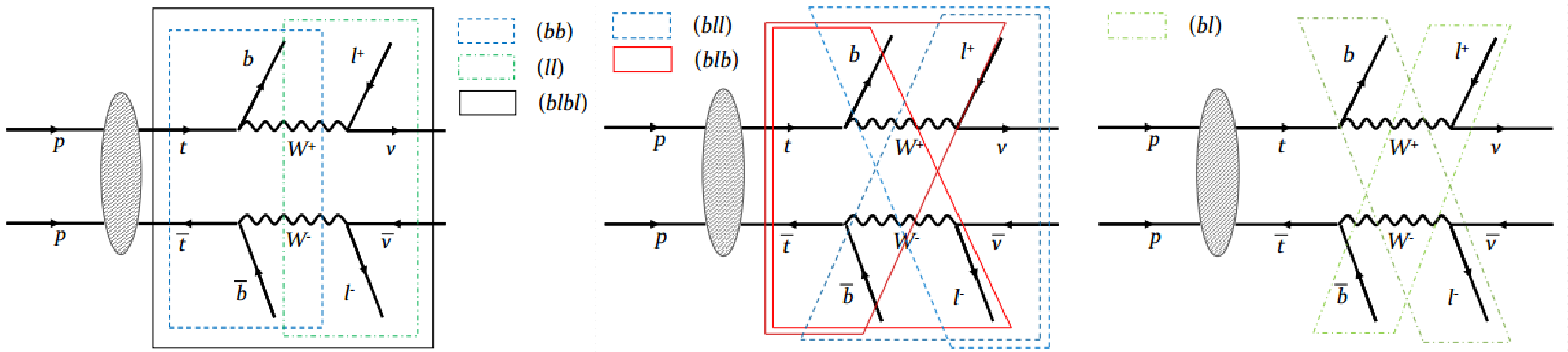




4. Extra Radiation

Subsystem M_{T2}

- More than one visible particle per decay side → richer structure/more M_{T2} variables
- Various subsystems depending on particles whose mass is minimized and particles which are considered invisible (Burns, Kong, Matchev and Park '08)
- 3 symmetric subsystems and 3 asymmetric subsystems for $t\bar{t}$



4. Extra Radiation

tW vs. $t\bar{t}$ at LO

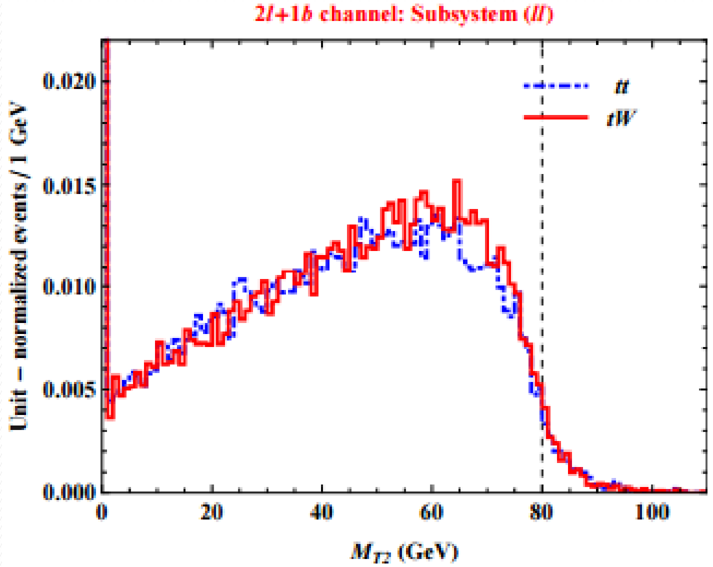
- Requiring 1 bottom-tagged jet + 2 opposite signed leptons
- Observed bottoms and leptons coming from the decay of the same particles in both tW and $t\bar{t}$
  - ✓ Their typical momentum scale is similar
  - ✓ Any kinematic variables processed with visible 4 momenta are likely to develop similar distributions
- Impact of missing bottom jet
  - ✓ reshuffling of the distribution of overall initial state radiation

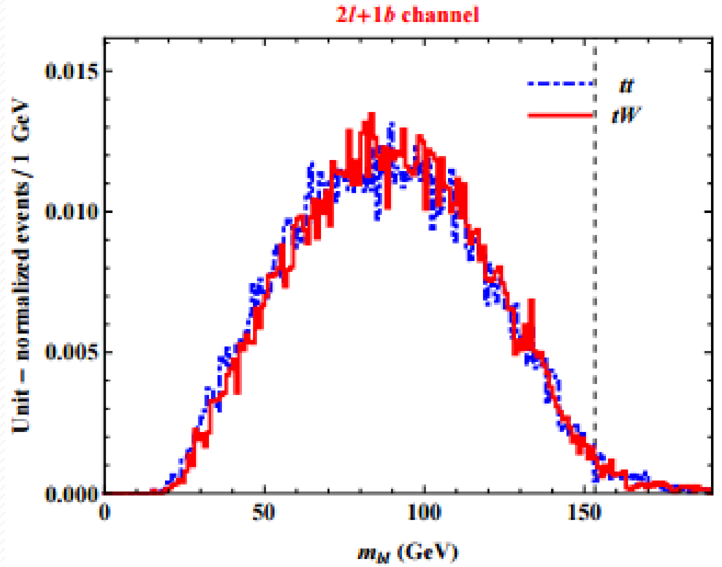
- No "killer" kinematic variables motivating machine learning procedure such as MVA or BDT

4. Extra Radiation

Results at LO

- ❑ Detector level simulation together with event selections of CMS collaboration
- ❑ Any kinematic variables seeming hopeless as expected

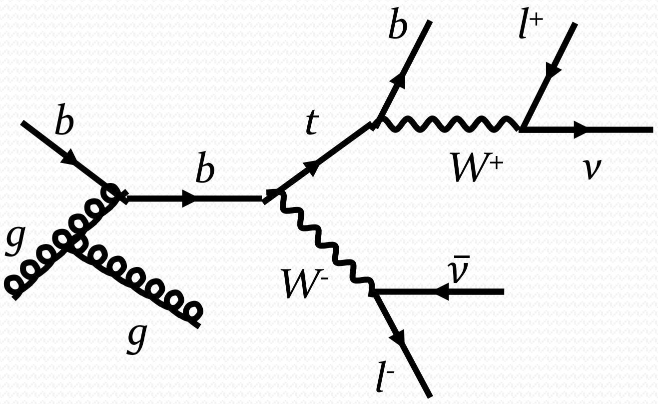




4. Extra Radiation

tW vs. $t\bar{t}$ at "NLO"

- ❑ Attaching an extra jet into the leading order diagram of tW process
  - ✓ Requiring 2 bottom-tagged jets + 2 opposite signed leptons or 1 bottom-tagged jet + 1 regular jet + 2 opposite signed leptons

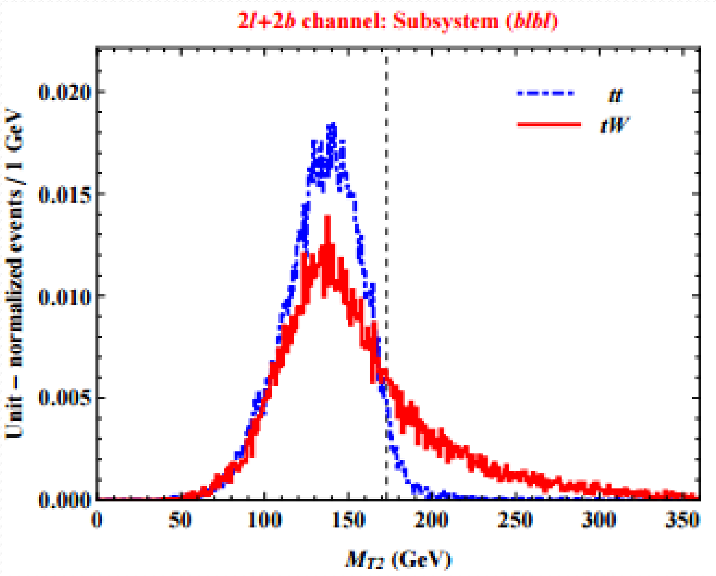


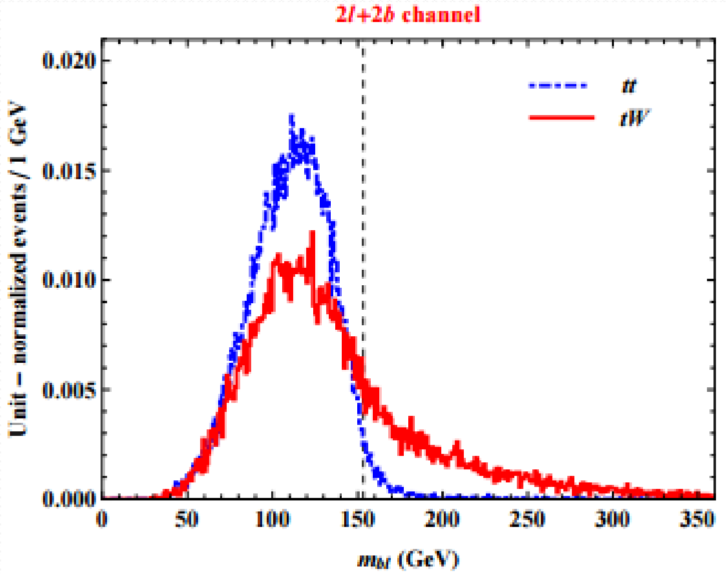
- ❑ Additional jet requirement retrieving the leading order diagram of $t\bar{t}$
  - ✓ Relevant event topology well-defined → distributions in kinematic variables **upper-bounded**
- ❑ Event topology for tW process ill-defined → distributions can be stretched **far beyond** the $t\bar{t}$ endpoints; tW endpoints dictated by hardness of ISR jets (**DK and Kong `15**)

4. Extra Radiation

Results at "NLO"

- ❑ Detector level simulation together with event selections of CMS collaboration
- ❑ 2 bottom-tagged jets + 2 opposite signed leptons



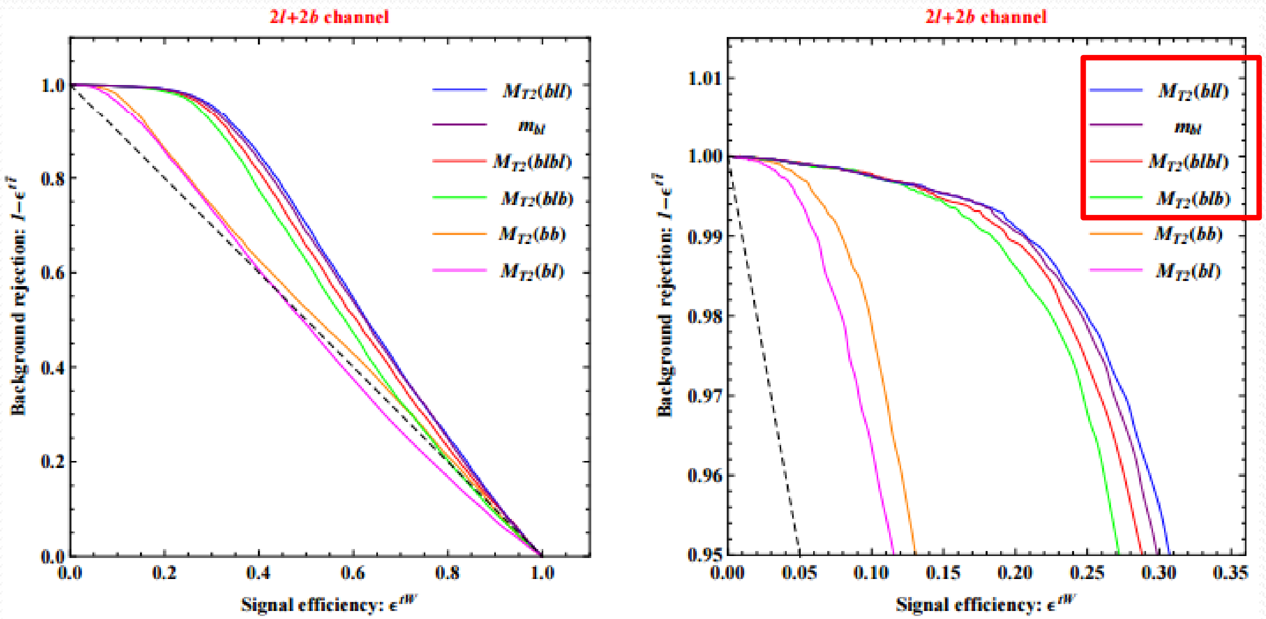


- ❑ Large fraction of tW events found beyond the kinematic endpoints for $t\bar{t}$ (dashed lines)

4. Extra Radiation

Results at "NLO"

- ROC curves: background rejection vs. signal acceptance

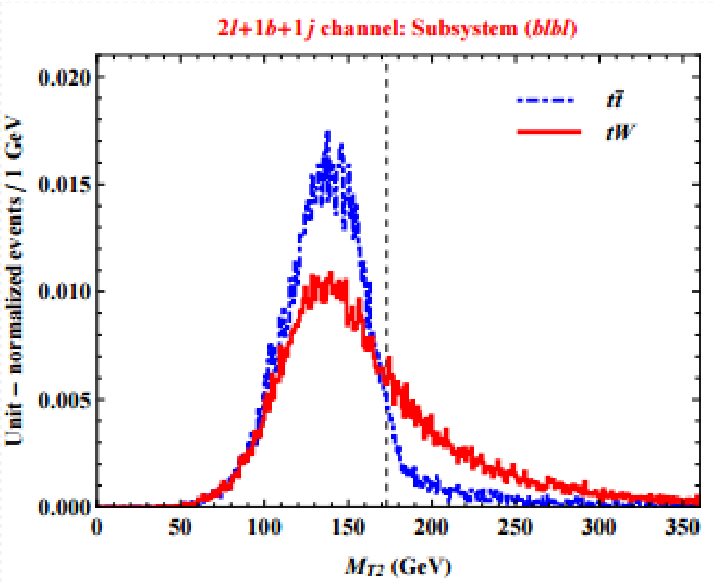


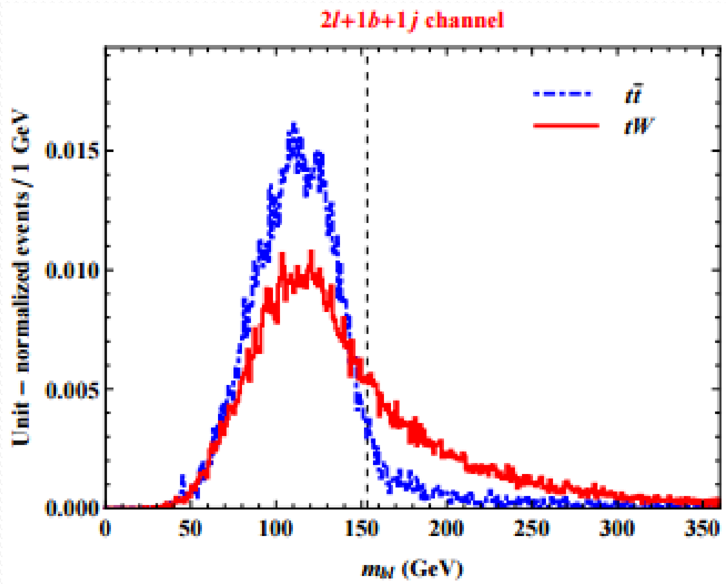
- First four variables show good performance, while the other two show decent performance
- 99.5% (99%) background rejection vs. 5% (20%) signal acceptance

4. Extra Radiation

Results at "NLO"

- ❑ Detector level simulation together with event selections of CMS collaboration
- ❑ 1 bottom-tagged jet + 1 regular jet + 2 opposite signed leptons



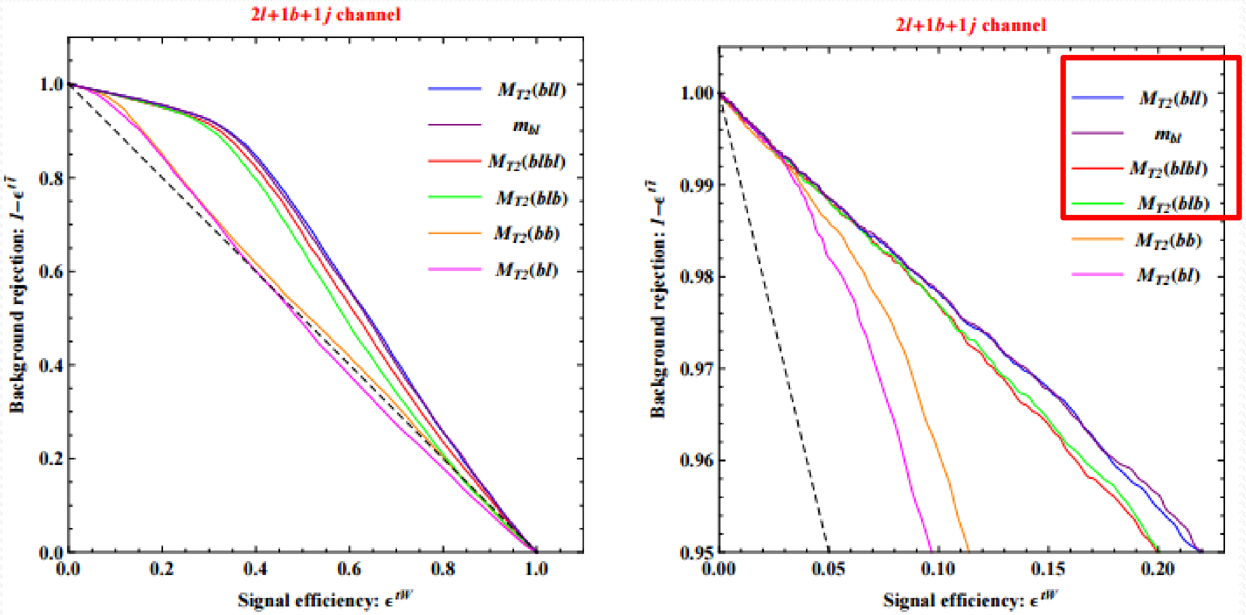


- ❑ Again large fraction of tW events found beyond the kinematic endpoints for $t\bar{t}$

4. Extra Radiation

Results at "NLO"

- ROC curves: background rejection vs. signal acceptance



- First four variables show good performance, while the other two show decent performance
- More chance of accepting ISR jets in $t\bar{t}$: slightly worse performance than previous channel

4. Extra Radiation

Application to new physics

- Generically applicable to topology distinction between

$$A\bar{A} \to (Bb)(\bar{B}\bar{b}) \to (Ccb)(\bar{C}\bar{c}\bar{b}) \text{ vs. } A\bar{B} \to (Bb)(\bar{B}) \to (Ccb)(\bar{C}\bar{c})$$

- New physics examples

  1) $\tilde{t}\bar{\tilde{t}}$ vs. $\tilde{t}\tilde{\chi}_1^-$ (or $\bar{\tilde{t}}\tilde{\chi}_1^+$) where $\tilde{t} \to \tilde{\chi}_1^+ b \to b\ell^+\tilde{\nu}$ and similarly, $\bar{\tilde{t}} \to \tilde{\chi}_1^- \bar{b} \to \bar{b}\ell^-\tilde{\nu}$

  2) $\tilde{g}\tilde{g}$ vs. $\tilde{g}\tilde{q}$ (or $\tilde{g}\bar{\tilde{q}}$) where $\tilde{g} \to q\tilde{q} \to q\bar{q}\tilde{\chi}_1^0$

Mis-Bottom-Tagging

5. Mis-Bottom-Tagging

Motivation

- Given a signal process involving charm quark-induced jets in the final state, e.g., a rare decay process of top quark,

$$pp \to t\bar{t} \to (bH^+)(\bar{b}W^-) \to (b\bar{b}c)(\bar{b}\ell^-\bar{\nu})$$

- its dominant background, i.e., semi-leptonic $t\bar{t}$

$$pp \to t\bar{t} \to (bW^+)(\bar{b}W^-) \to (b\bar{s}c)(\bar{b}\ell^-\bar{\nu})$$

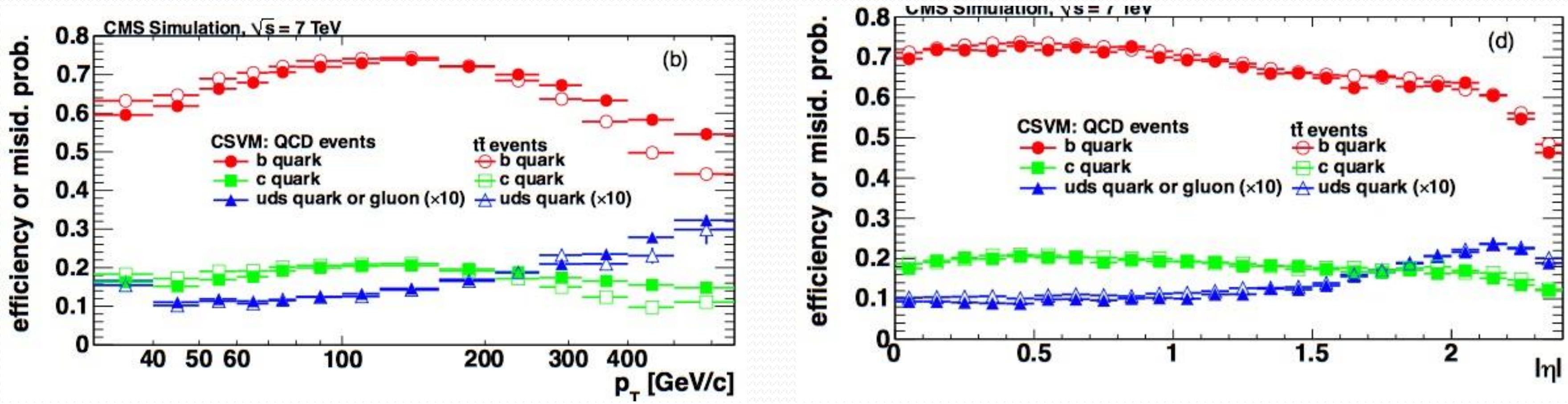
- typical event selection would be 3 bottom-tagged jets + 1 regular jet + 1 lepton + MET

- To increase the signal-over-background, 1 more bottom-tagged jet could be required based on the observation that (**DK and Park, in progress**)

mis-tagging rate for charm quark > mis-tagging rate for light quarks

5. Mis-Bottom-Tagging

Bottom-tagging efficiency



- Bottom-tagging efficiency (ϵ_b): ~70%, mis-tagging efficiency for charm quark (ϵ_c): ~20%, mis-tagging efficiency for light quarks (ϵ_s): ~1%
- (Very rough and optimistic) estimation: $\bar{b}c$ (signal) vs. $\bar{s}c$ (background)
  - ✓ $\frac{S}{B} \sim \frac{\epsilon_b(1-\epsilon_c)}{(1-\epsilon_s)\epsilon_c}$ (3 b-jets) $\rightarrow \frac{S}{B} \sim \frac{\epsilon_b\,\epsilon_c}{\epsilon_s\,\epsilon_c}$ (4 b-jets): increased by a factor of ~25

5. Mis-Bottom-Tagging

Issues

- Combinatorics, p_T and η dependence of tagging efficiency

- Charm-quark tagging? … mis-c-tagging rate for bottom quark, simultaneous requirement of bottom and charm quark taggings, etc… In general, analysis would be quite involved

- Small mass gap between top and charged Higgs: too soft a bottom jet to be detected

6. Summary

Conclusions

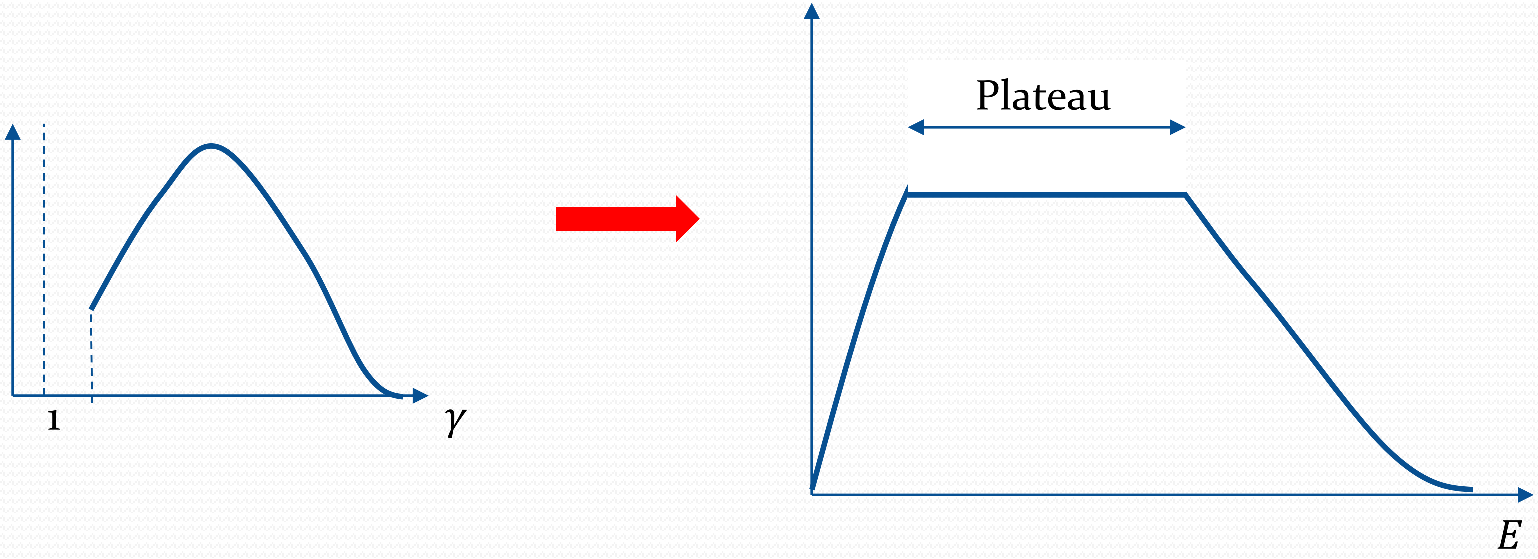
- Seemingly NOT useful variables/techniques/ approaches can be reinterpreted as useful (with careful study) in the context of precision study and discovery potential
- 3 topics were discussed with physics examples in the top sector
  - ✓ Energy distribution
  - ✓ Extra radition
  - ✓ Mis-bottom tagging
- More “ugly ducklings” can be reborn as “beautiful swans”

Thank you!

Back-up

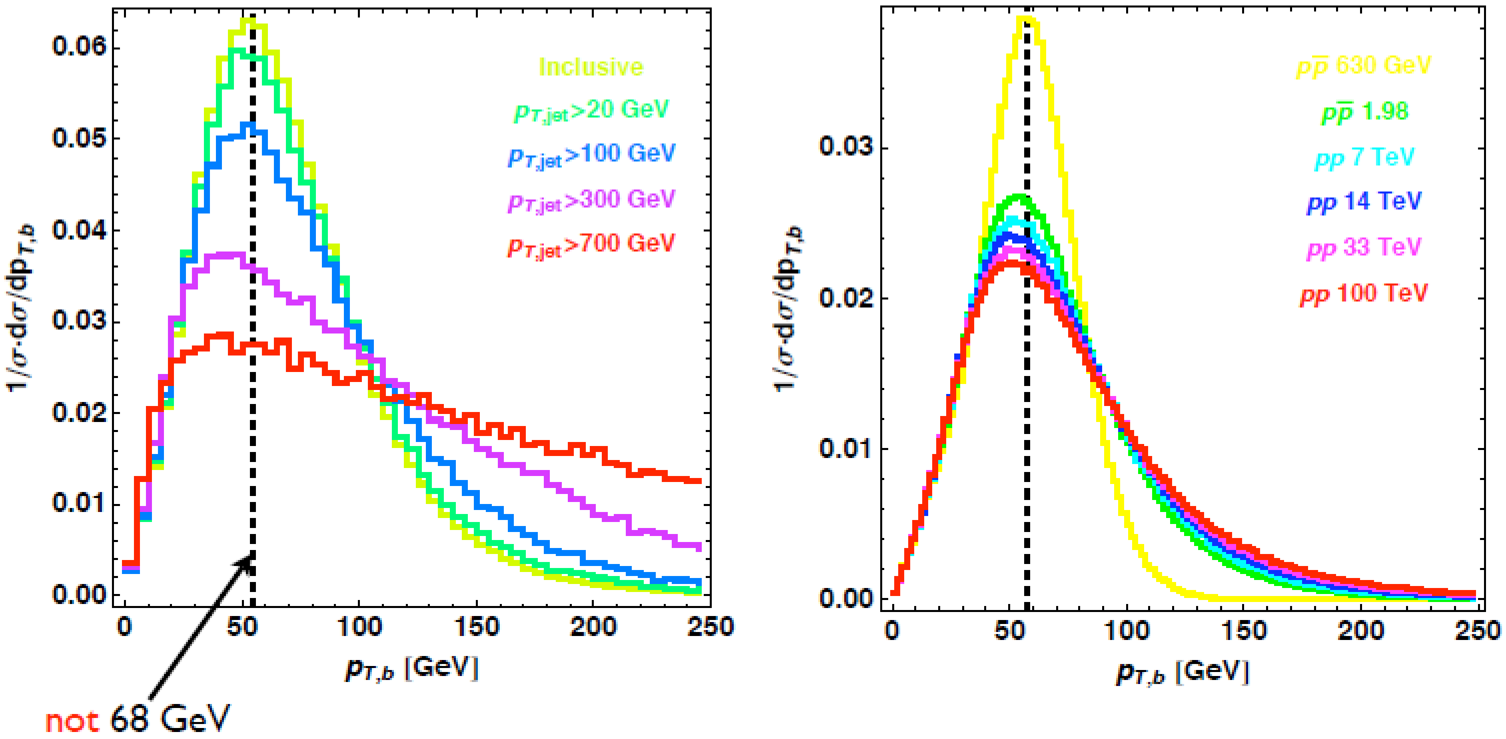
Plateau in energy distribution

- If the distribution starts from $\gamma \neq 1$, then the relevant energy distribution will develop a plateau in the middle of it.



Back-up

No "accident" in p_T



- Peak and shape change

Back-up

Formal proof

- First derivative

$$f(E) = \int_{\frac{1}{2}\left(\frac{E}{E^*}+\frac{E^*}{E}\right)}^{\infty} d\gamma \frac{g(\gamma)}{2E^*\sqrt{\gamma^2-1}} \qquad f'(E) = \frac{\mathrm{sgn}\left(\frac{E^*}{E}-\frac{E}{E^*}\right)}{2EE^*} g\left(\frac{1}{2}\left(\frac{E}{E^*}+\frac{E^*}{E}\right)\right)$$

- Vanishing derivative gives the extrema → Here this is the same as solving $g = 0$.
- Remember last assumption: $g(\gamma)\neq 0$ near $\gamma = 1$

  → This is typical for particles produced at colliders.
- Two possibilities: $g(1) = 0$ or $g(1) \neq 0$
- $g(1)=0$: $f'(E=E^*) \propto g(1)=0$ → f has a unique extremum at $E=E^*$.
- $g(1)\neq 0$: $f'(E)$ flips its sign at $E=E^*$ due to the sign function (from + to -). → the distribution has a **cusp** at $E=E^*$ which appears as a peak.

Back-up

Fitting function: functional properties of generic *f*(*E*)

- f is a function with an argument of $\frac{1}{2}\left(\frac{E}{E^*}+\frac{E^*}{E}\right)$, i.e., even under $\frac{E}{E^*} \leftrightarrow \frac{E^*}{E}$ or $E \rightarrow \frac{E^{*\,2}}{E}$.

  ← clear from the expression of *f*(*E*)

$$f(E) = \int_{\frac{1}{2}\left(\frac{E}{E^*}+\frac{E^*}{E}\right)}^{\infty} d\gamma \frac{g(\gamma)}{2E^*\sqrt{\gamma^2-1}}$$

- f is maximized at $E=E^*$.

  ← proven heuristically and formally

- f vanishes as E approaches 0 or ∞.

  ← the integral expression of *f*(*E*) becomes trivial in those limits.

- f becomes a δ-function in some limiting case.

  ← if any of mother particles are NOT boosted, i.e., the rest frame, then f should return a δ-functionlike distribution.

Back-up

Fitting function: proposal of a "simple" *ansatz*

$$f(E) = \frac{1}{K_1(p)} \exp\left[-\frac{p}{2}\left(\frac{E}{E^*} + \frac{E^*}{E}\right)\right]$$

- $K_1(p)$: modified Bessel function of the second kind of order 1
- p : fitting parameter which encodes the width of the peak
- E^* as a ***fitting parameter*** can be extracted by fitting!
- All four properties are satisfied. → for the last property, use the asymptotic behavior of $K_1(p)$

$$K_1(p) \overset{p\to\infty}{\to} \sim \frac{e^{-p}}{\sqrt{p}}\left(1 + \mathcal{O}\left(\frac{1}{p}\right)\right)$$

- Proposed ansatz does not develop a cusp so that it is more suitable for the case of $g(1)=0$, e.g., pair-production of mothers (cf. the case of $g(1)\neq 0$, single production of mothers).

Back-up

A brief look into the massive case

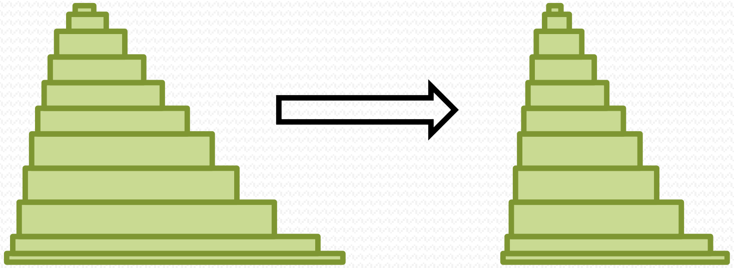
- Energy of the visible particle should be Lorentz-transformed in a modified way.

$$E = E^* \gamma + p^* \sqrt{\gamma^2 - 1} \cos\theta^*$$

- Each rectangle's coverage becomes shrunken.

$$E \in [E^*\gamma - p^*\sqrt{\gamma^2-1},\ E^*\gamma + p^*\sqrt{\gamma^2-1}]$$

$$2E^*\sqrt{\gamma^2-1} \longrightarrow 2p^*\sqrt{\gamma^2-1}$$



- One modification : the lower bound is ***NOT*** smaller than E^* for some boost factors! (while the upper bound is still greater than E^* for any boost factor)

  $\rightarrow$ Our argument is not applicable for such boost factors, and E^* cannot be the location of the peak. : $E_{peak} \geq E^*$ $\rightarrow$ The critical boost factor can be calculable.

  $\gamma_{cr} = 2\gamma^{*2} - 1$ with γ^* being the boost factor of the visible particle in the rest frame

Back-up

A brief look into the massive case

- For the top decay,

$$\gamma^* \approx 15 \quad \longrightarrow \quad \gamma_{\rm cr}^{\rm top} \approx 450$$

  → This value is not accessible given the current LHC-14TeV.

  → The peak still stays at E=E^*.

- Another modification : symmetry property w.r.t E=E^* does ***NOT*** hold!
- Such a symmetry property implies $\frac{E_{\rm lb}E_{\rm ub}}{E^{*2}} = 1$ for any γ.

  → One possible estimator for deviation : $\delta_m = \frac{E_{\rm lb}E_{\rm ub}}{E^{*2}} - 1 = \frac{m_b^2}{E^{*2}}(\gamma^2 - 1) = \frac{\gamma^2 - 1}{\gamma^{*2}}$

  → δ_m can be large for large m_b and γ.

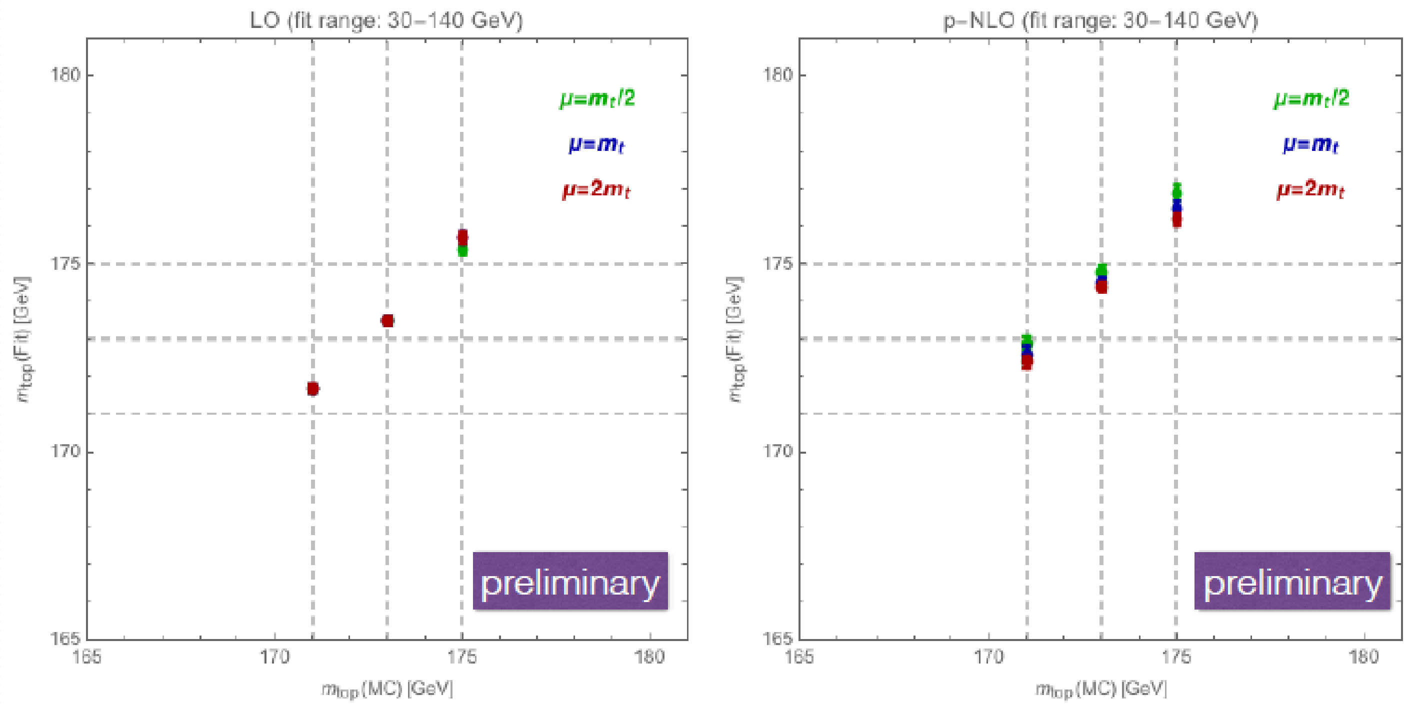
- For the top decay,

  $\gamma^* \approx 15$ and typical γ of top quarks is roughly 1.2-1.4

  → Violation of the symmetry property is negligible.

Back-up

Production NLO: scale choice (preliminary)

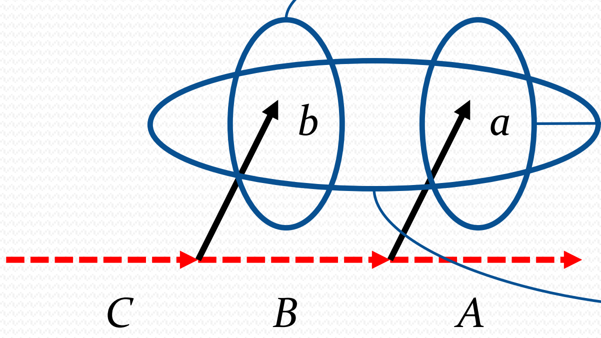


- Very little sensitivity to the scale choice (less than 0.4 GeV on the top mass)

Back-up

Mass measurement: general strategy

- Three unknowns : m_A, m_B, and m_C $\rightarrow$ three equations are needed.



$$E_b^{\text{peak}} = \frac{m_C^2 - m_B^2}{2m_C} \qquad E_a^{\text{peak}} = \frac{m_B^2 - m_A^2}{2m_B}$$

$$m_{ab}^{\max} = \frac{\sqrt{(m_C^2 - m_B^2)(m_B^2 - m_A^2)}}{m_B}$$

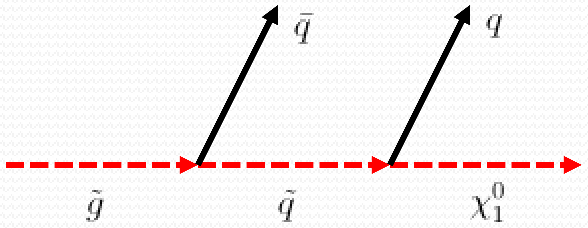
Inversion formula

$$m_C = \frac{2\, m_{ab}^{\max\,4}\, E_b^{\text{peak}}}{m_{ab}^{\max\,4} - 16\, E_b^{\text{peak}\,2}\, E_a^{\text{peak}\,2}} \qquad m_B = \frac{8\, m_{ab}^{\max\,2}\, E_b^{\text{peak}\,2}\, E_a^{\text{peak}}}{m_{ab}^{\max\,4} - 16\, E_b^{\text{peak}\,2}\, E_a^{\text{peak}\,2}}$$

$$m_A = \frac{4 m_{ab}^{\max}\, E_b^{\text{peak}}\, E_a^{\text{peak}}}{m_{ab}^{\max\,4} - 16\, E_b^{\text{peak}\,2}\, E_a^{\text{peak}\,2}} \sqrt{4\, m_{ab}^{\max\,2}\, E_b^{\text{peak}\,2} + 16\, E_b^{\text{peak}\,2}\, E_a^{\text{peak}\,2} - m_{ab}^{\max\,4}}$$

Back-up

New physics application: gluino decay



- Supersymmetry model
- Neutralino is our lightest stable particle (LSP) → *R*-parity conserving model.
- For the channel with the 1st and 2nd generation, the current bound on the gluino mass is too restricted (~ 1.5 TeV).

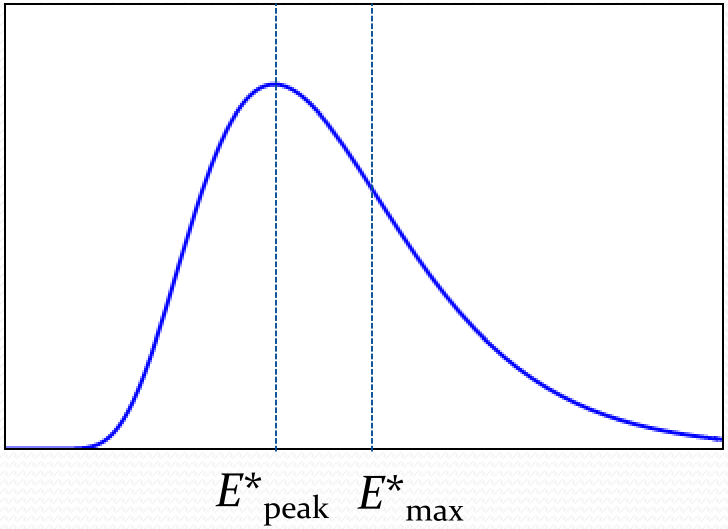
  → Production cross section of gluino might not be enough for mass measurement.
- 3rd generation is more motivated by naturalness.

  → The current bound is ~ 1 TeV (assuming 1st and 2nd generations are heavier than gluino).

Back-up

Energy distribution in the lab frame

- Each value of the rest-frame energy goes through similar argument in 2-body kinematics.

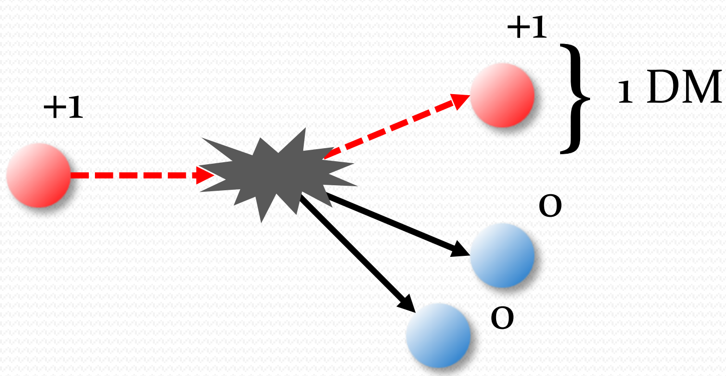


- The peak value is lower than the maximum rest-frame energy. (cf. the peak value is the same as the fixed rest-frame energy in 2-body kinematics)
- Reference values (E^*_{max} for 3-body vs. E^*_{fixed} for 2-body) can be measured by other observables such as M_{T2}.
- **Peak = Reference value → 2-body decay → Z_2**
  Peak < Reference value → 3-body decay → Z_3

Back-up

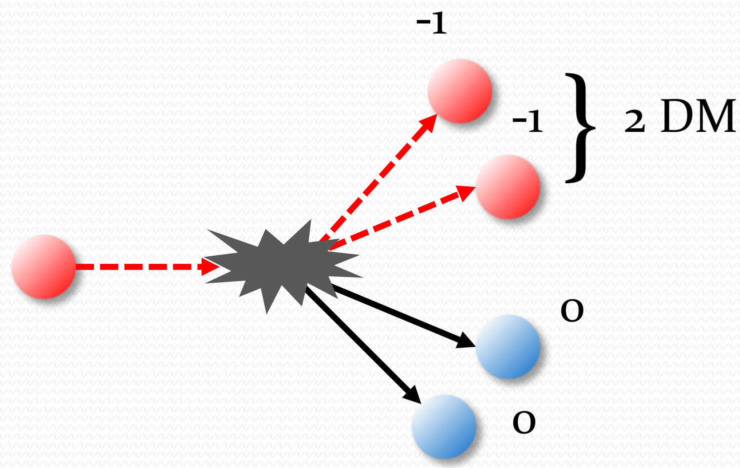
Difference in Z_2 and Z_3

- Two Z_2 charges: 0 or +1(≡-1) vs. Three Z_3 charges: 0, +1 or +2(≡-1)
- Under Z_3, a DM partner/mother can decay into 1DM or 2DM by Z_3 charge conservation.



$+1=+1+0+0+\ldots$

Present in **both** Z_2 and Z_3



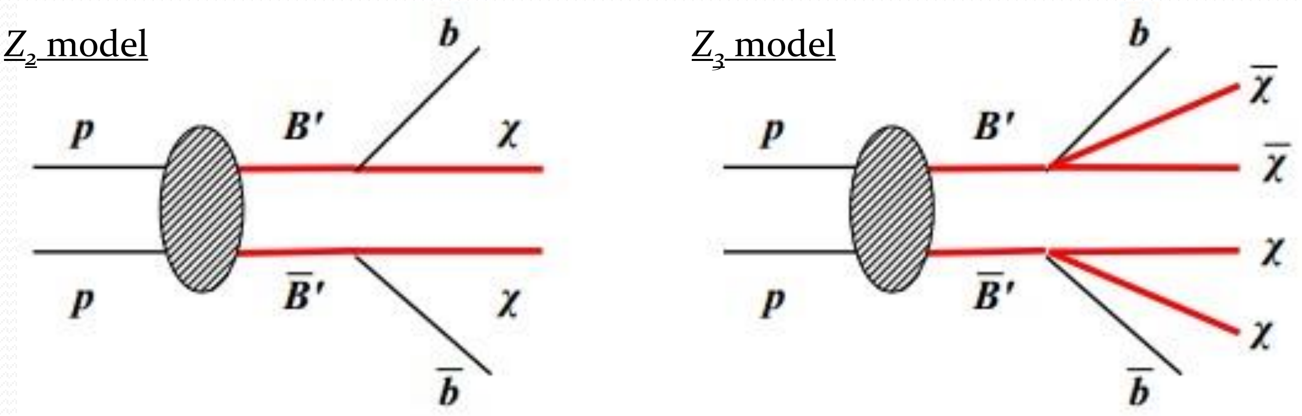
$+1=(-1)+(-1)+0+0+\ldots=-2 \equiv +1$

Present **only** in Z_3

Back-up

Model consideration

- ❑ Decay of bottom partner into 1DM/2DM + bottom



- ❑ Major background: $Z(\rightarrow 2\nu)$+2b
- ❑ Realistic cuts imposed

Back-up

- **Sample result**