a place of mind

THE UNIVERSITY OF BRITISH COLUMBIA

PHYSICS ASTRONOMY

# ttH Signal Modelling and Systematics on ATLAS

Canadian Association of Physicists Congress 2014 - Sudbury, ON/Canada

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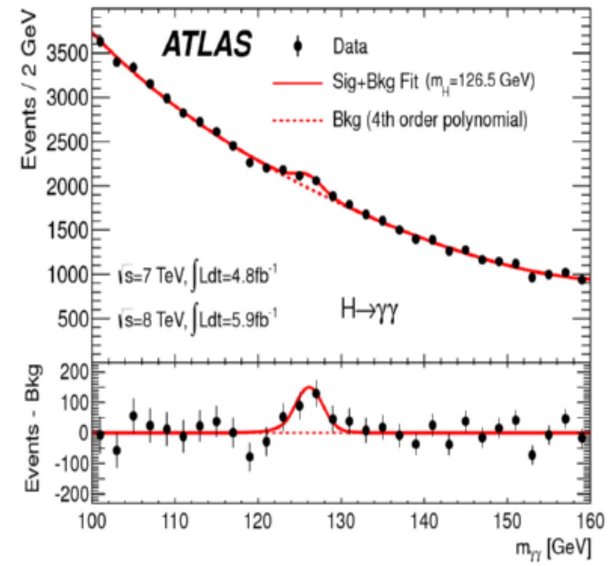
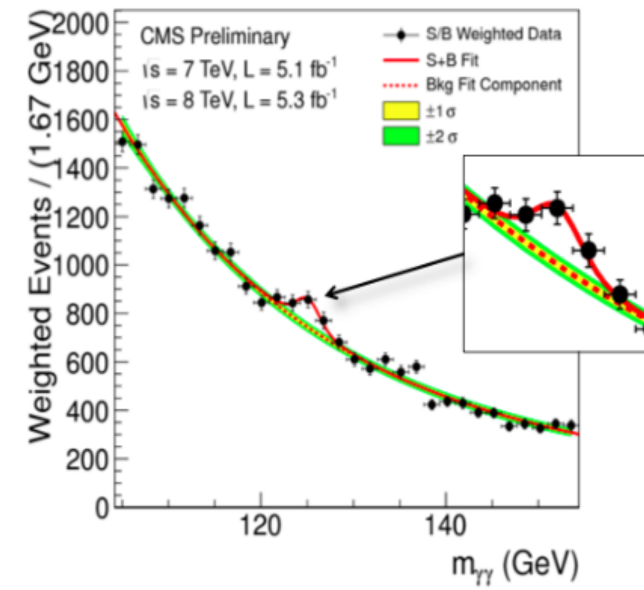
ATLAS EXPERIMENT

# Introduction

- Higgs boson discovered in bosonic decay modes
  - ATLAS: 126.0 ± 0.4 (stat.) ± 0.4 (syst.) GeV
  - CMS: 125.3 ± 0.4 (stat.) ± 0.5 (syst.) GeV




Phys. Lett. B716 (2012) 1-29 and 30-61

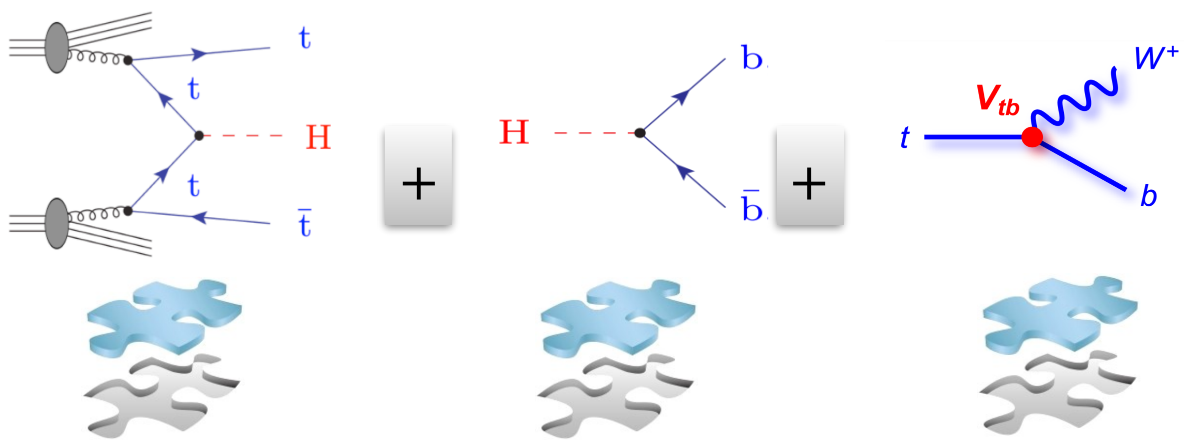
- Evidence for fermonic decay modes
  - **ATLAS**: H → ττ (4.1 σ)
  - **CMS**: combination of H → ττ and H → bb (4.0 σ)

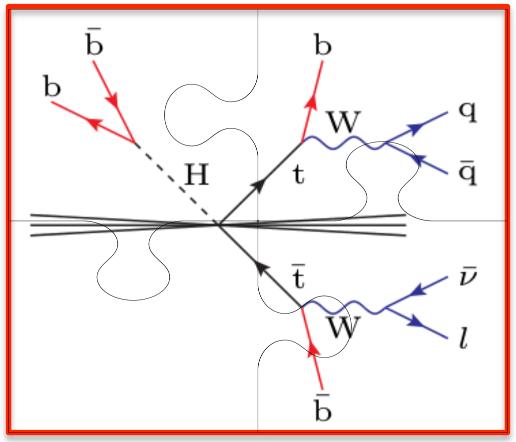
- ggH production and H →γγ decays yield **indirect** evidence for **top-Higgs Yukawa** coupling
  - Might depend on new physics distributions

- ttH production provides **direct** probe of top-Higgs Yukawa coupling → $\sigma_{\mathrm{t\bar{t}H}} \sim g^2_{\mathrm{t\bar{t}H}}$
  - Allows the probe of new physics in ggH, Hγγ, HγZ

# Motivation

**ttH (H → bb):**




- Represents search of a very **small signal** on top of a **not so well known background**
  - Usage of MVA techniques
    - ttH analysis relies on robust signal and background models

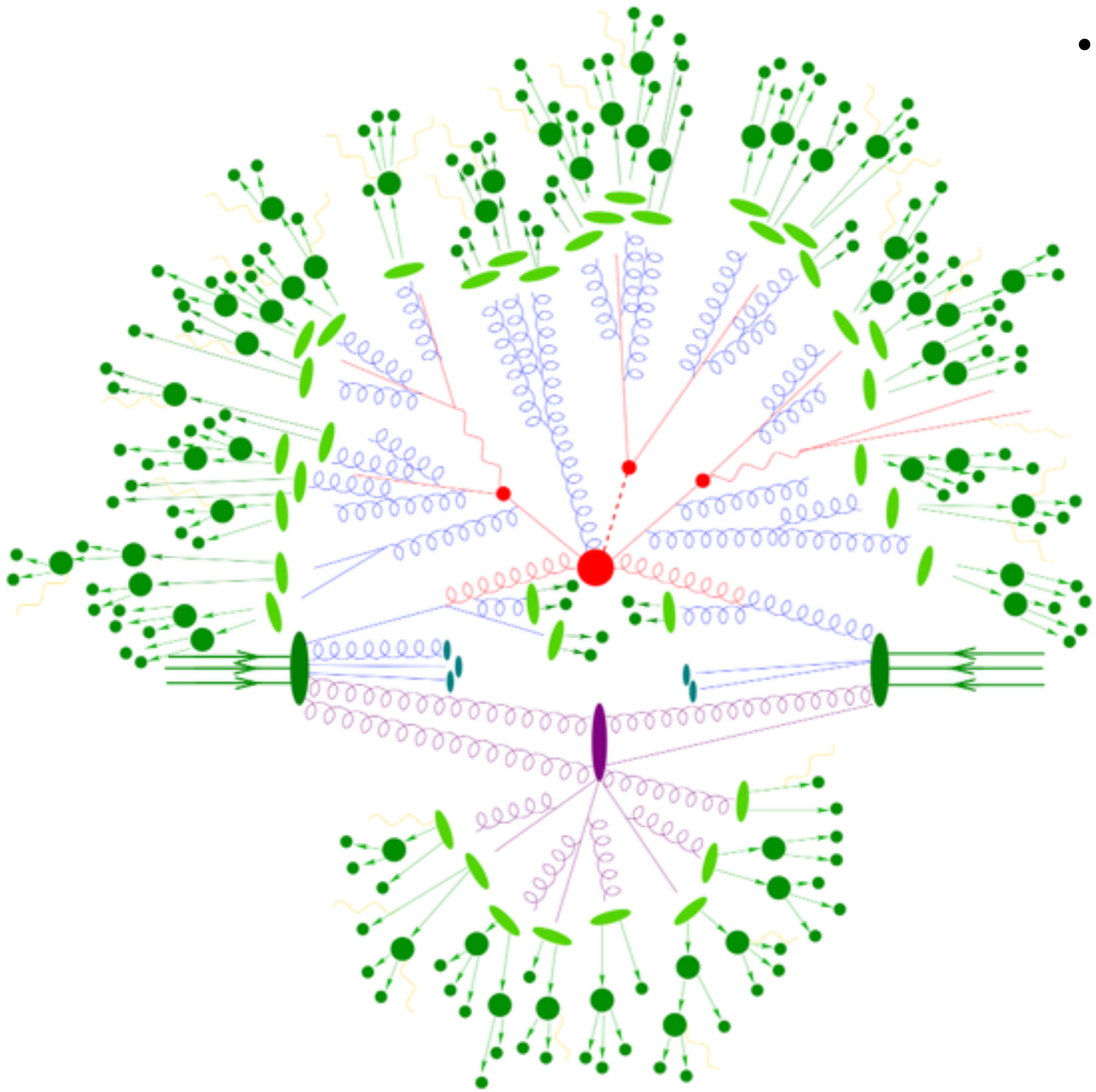
**Signal modelling**

- Analyze variety of MC generators on the market (state-of-the-art picture)
- Studies performed on truth level (parton&particle level)

**Systematic modelling uncertainties**

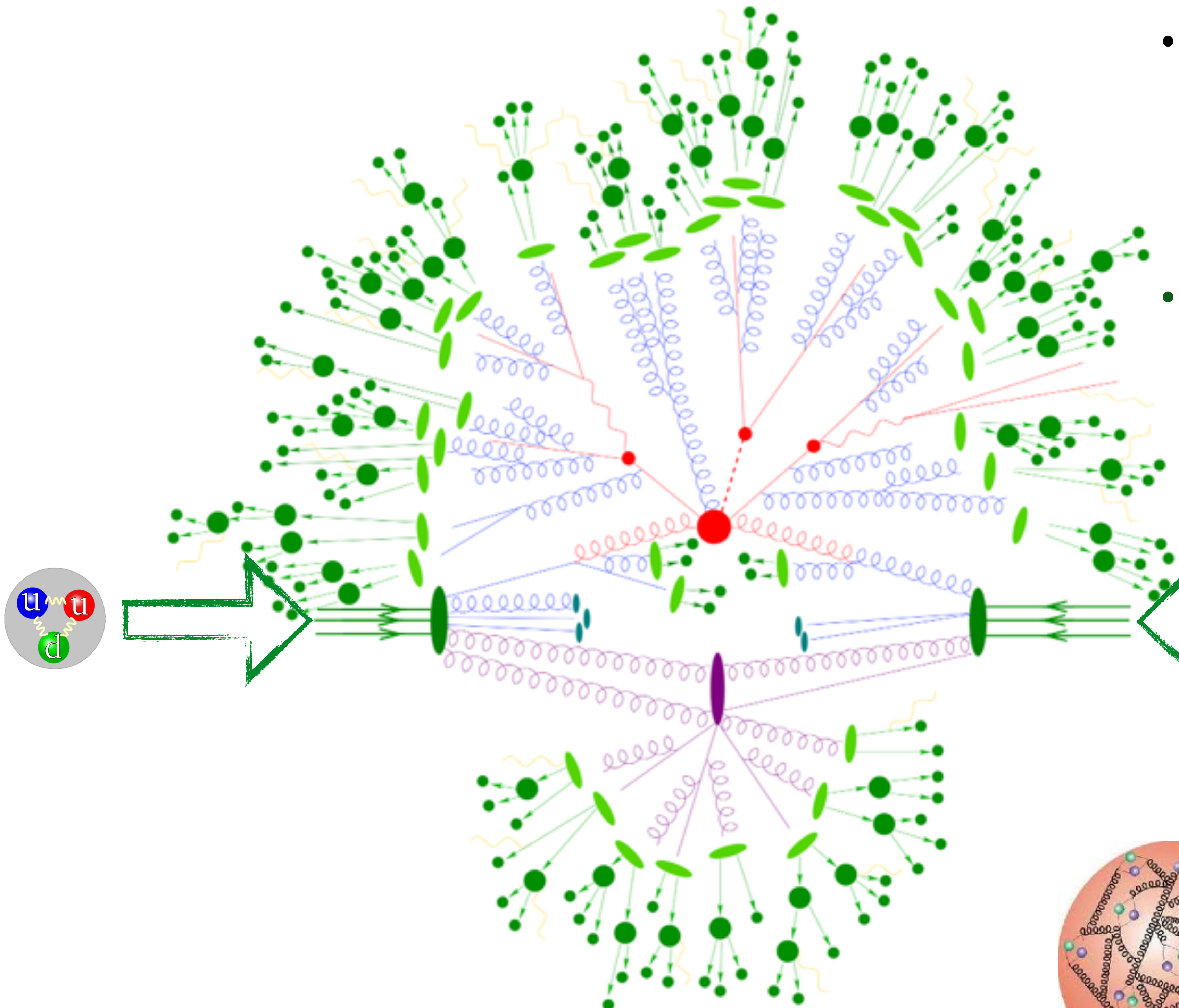
- Assess modelling uncertainties to the signal model
- Renormalisation/factorisation scale choice, PDF uncertainty, <u>Parton Shower uncertainty</u>, …

# Modern MC generators

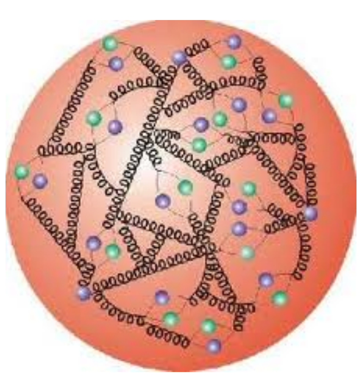


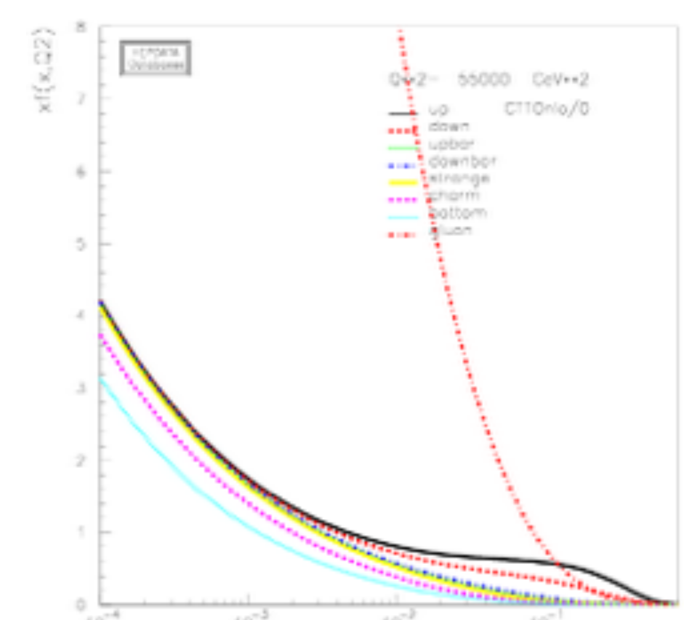
- Full MC event representation
  - ttH event

# Modern MC generators



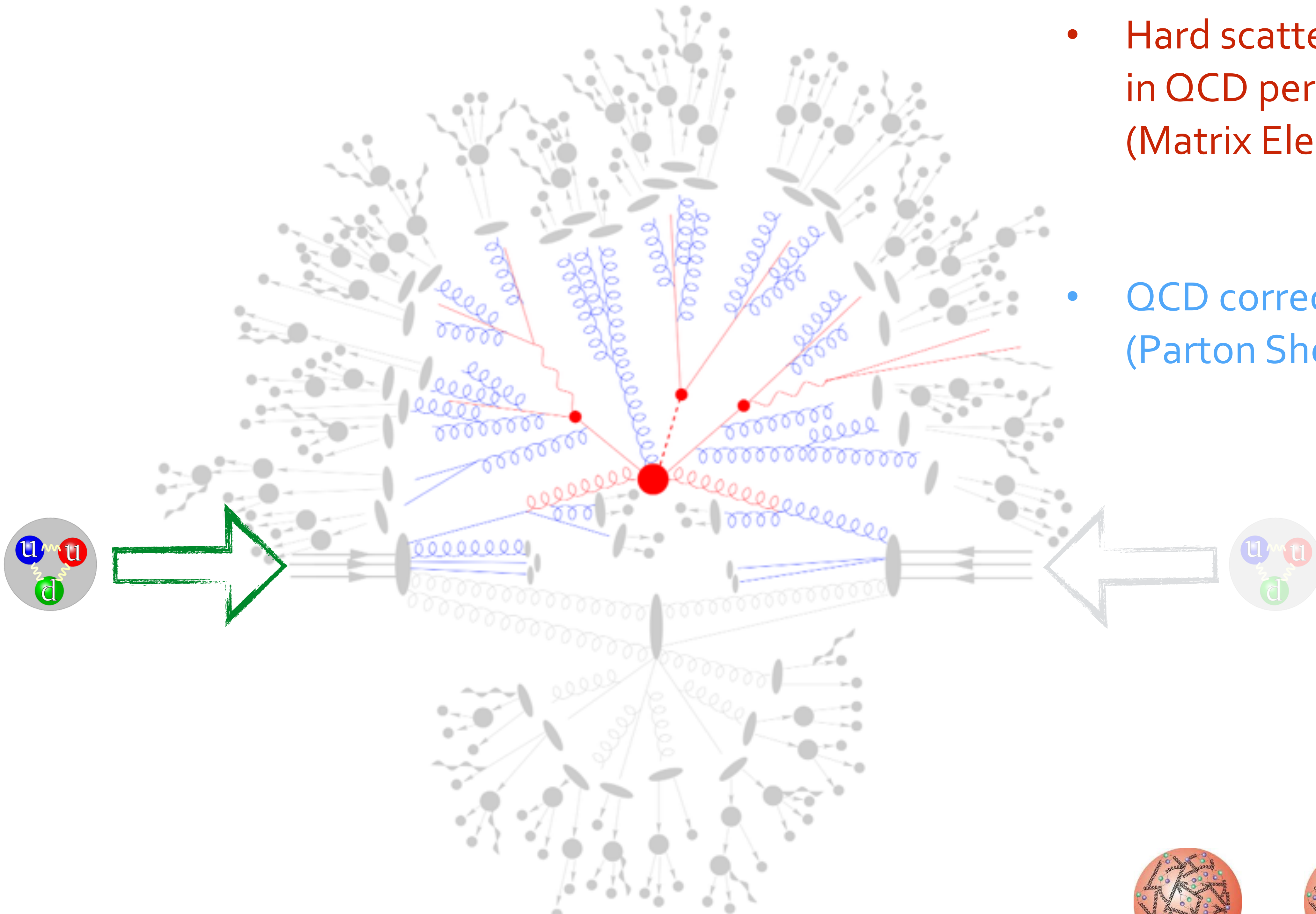

- Full MC event representation
  - ttH event
- Parton Density Function's (PDFs)



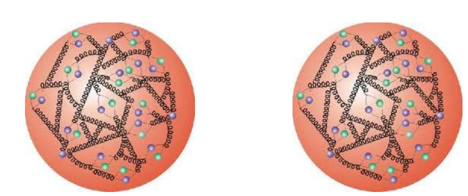


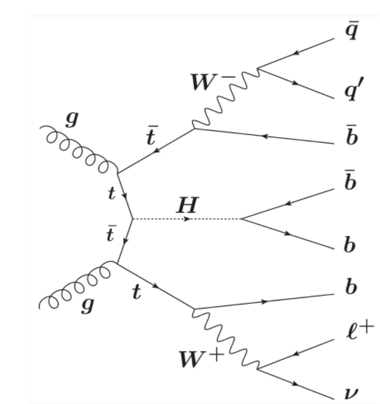
Phys. Rev. **D82** (2010) 074024

# Modern MC generators



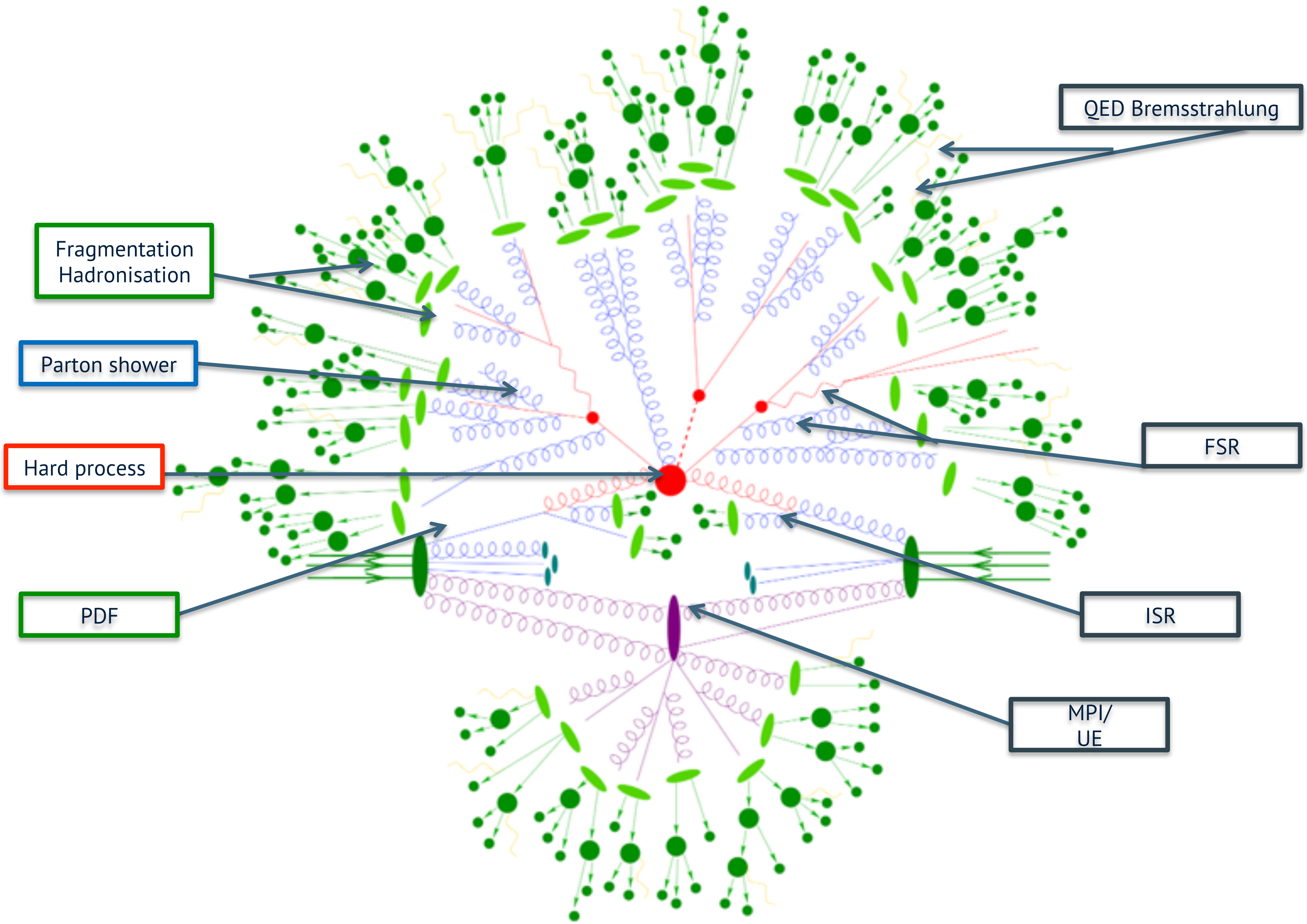

- Hard scattering at fixed order in QCD perturbation theory (Matrix Element)
- QCD corrections to all orders (Parton Shower)



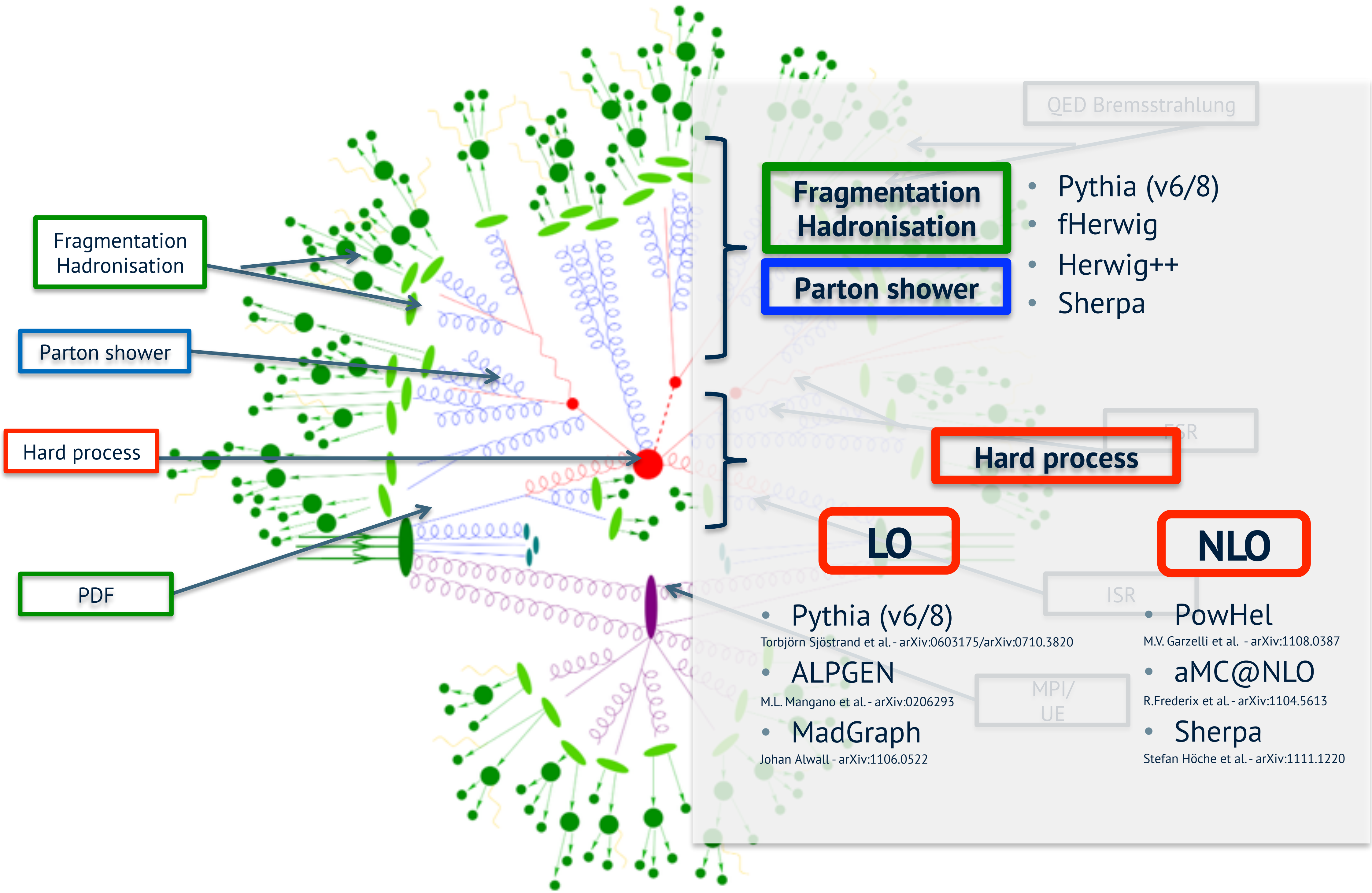



$$\sigma_{\mathrm{h_1h_2}} = \sum_{\mathrm{i,j}} \int\int dx_1 dx_2 f_{i/h_1}(x_1, \mu_F^2) f_{j/h_2}(x_2, \mu_F^2) \hat{\sigma}(x_i, x_j, \mu_R^2)$$

# MC model systematics

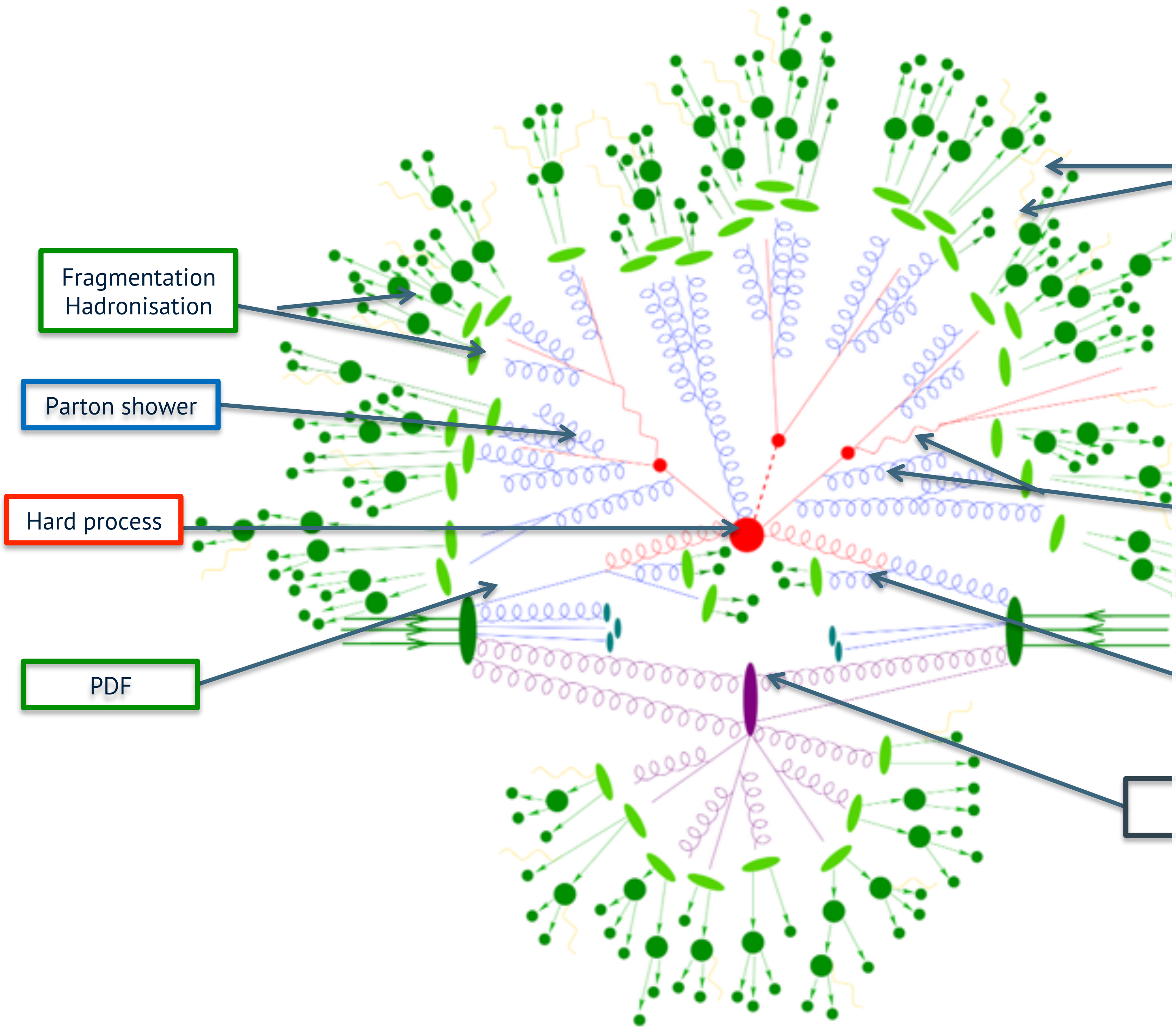


# MC model



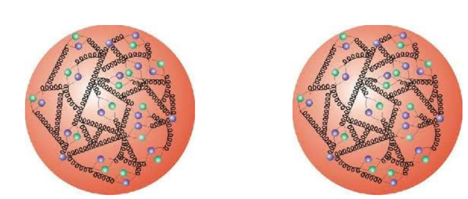

- Current ttH (H→bb) signal baseline is **PowHel+Pythia** & PDF: CT10nlo

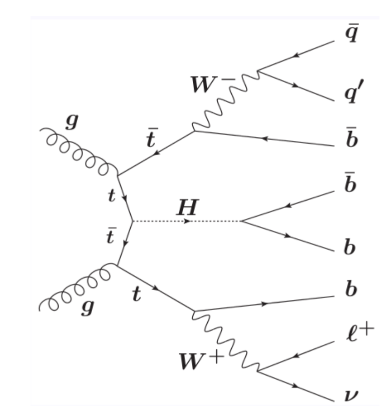
# MC model systematics




Assessed model systematics

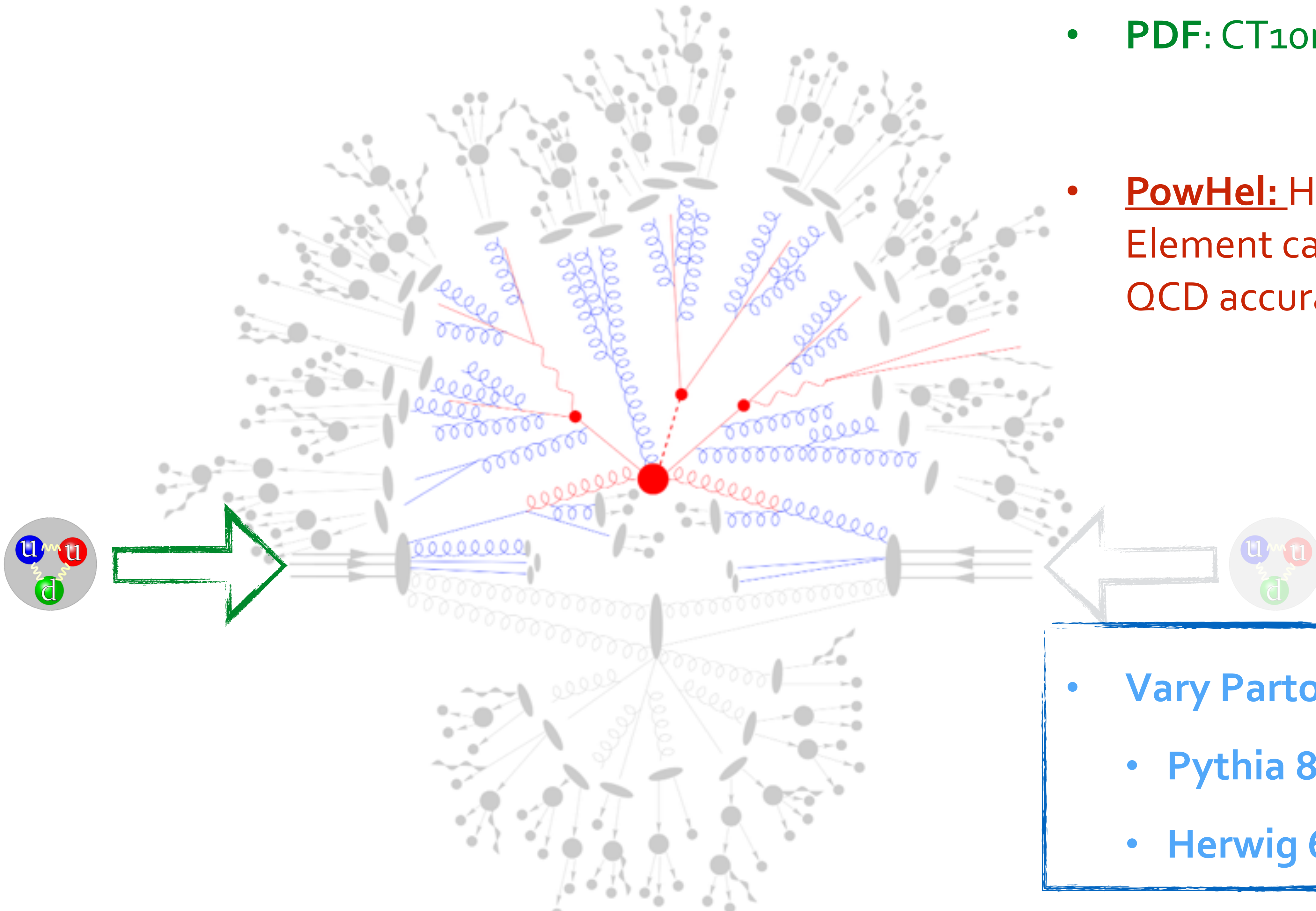
- ✓ PDF uncertainty
- ✓ Renormalisation/factorisation scale (variation)
- ✓ Scale choice
  - static/dynamic
- ✓ **Parton Shower uncertainty**






$$\sigma_{h_1 h_2} = \sum_{i,j} \int \int dx_1 dx_2 f_{i/h_1}(x_1, \mu_F^2) f_{j/h_2}(x_2, \mu_F^2) \hat{\sigma}(x_i, x_j, \mu_R^2)$$

# Parton shower systematic




- **PDF**: CT10nlo
- **PowHel:** Hard Matrix Element calculation at NLO QCD accuracy

- **Vary Parton Shower model**
  - **Pythia 8**
  - **Herwig 6**

# Parton shower systematic

**Reweighting procedure at truth level**

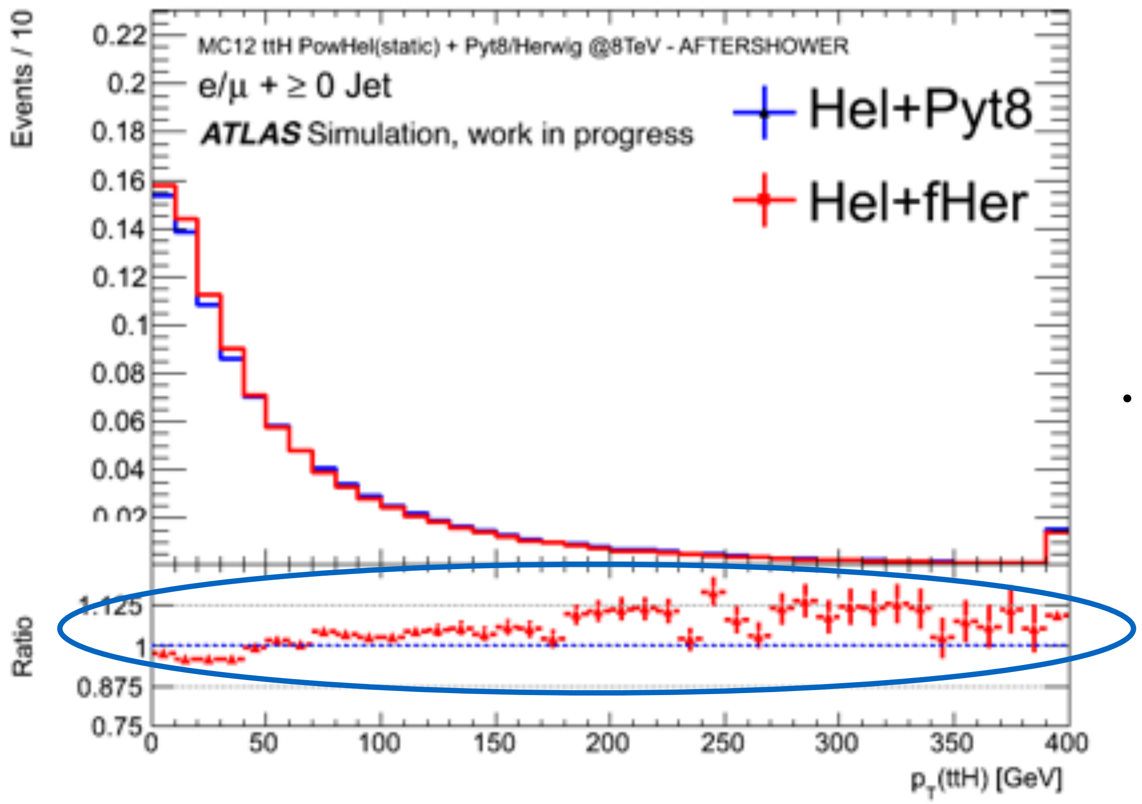
Understand and reproduce the MC generator specific event record

1. Investigate kinematic distributions
2. If appreciable differences are observed
3. Reweight
   - take bin-by-bin ratio or functional form
4. Investigate impact on other kinematic distributions
5. Iterate 1-4 if necessary

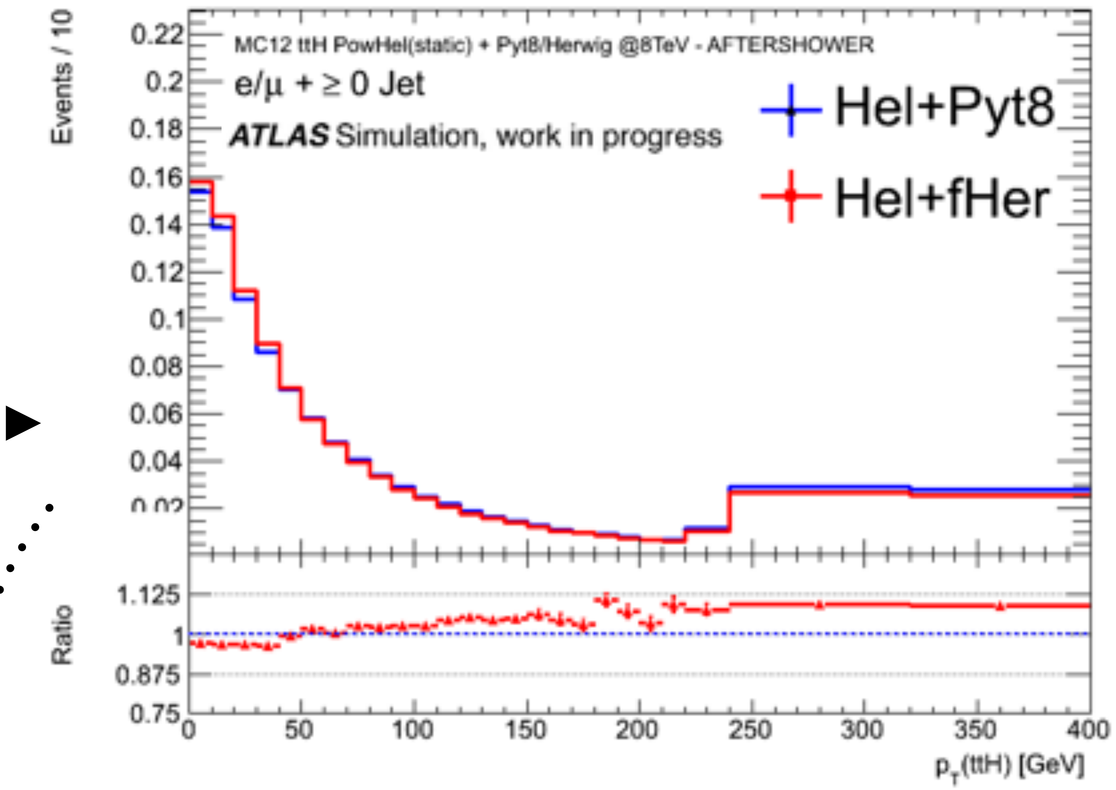
- Minimize kinematic differences
- Apply reweighting functions as event-weight → systematic

# Reweighting procedure

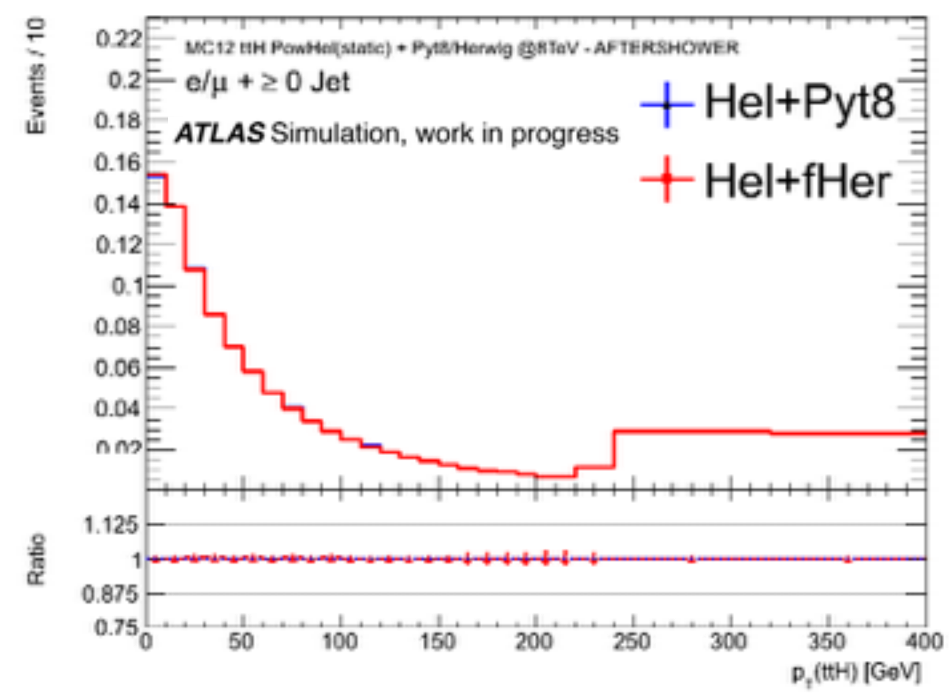
- Investigate variety of kinematic distributions on truth level
- ttH-pT distribution showed most significant differences (good start)




Rebinned



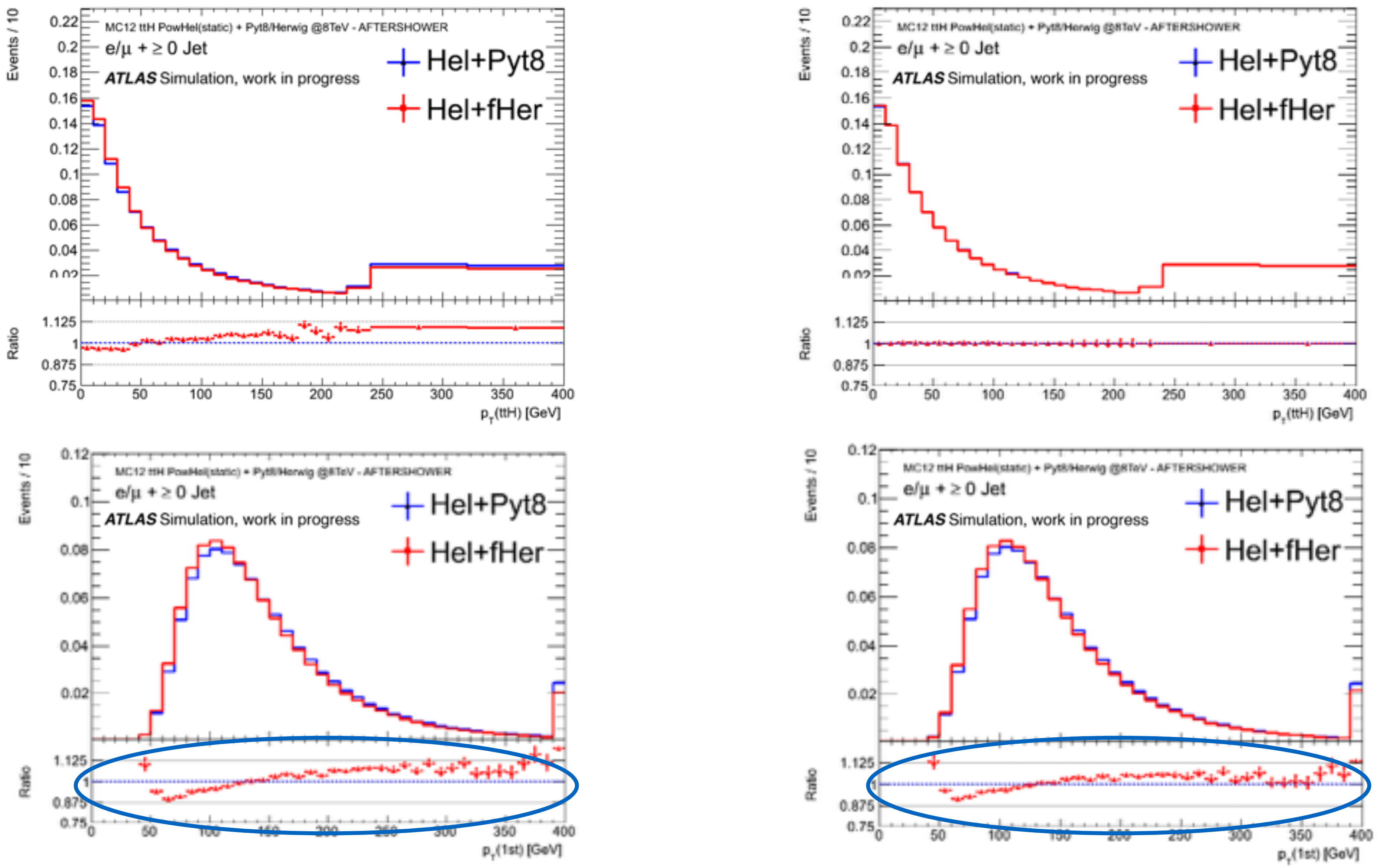

ev. weight




- Take ratio of two contributions
- Apply different numbers as event weight
  - Closure

# Reweighting procedure

- Before and after ttH-pT reweighting
  - Small impact on other kinematic distributions




ttH pT

leading particle jet pT

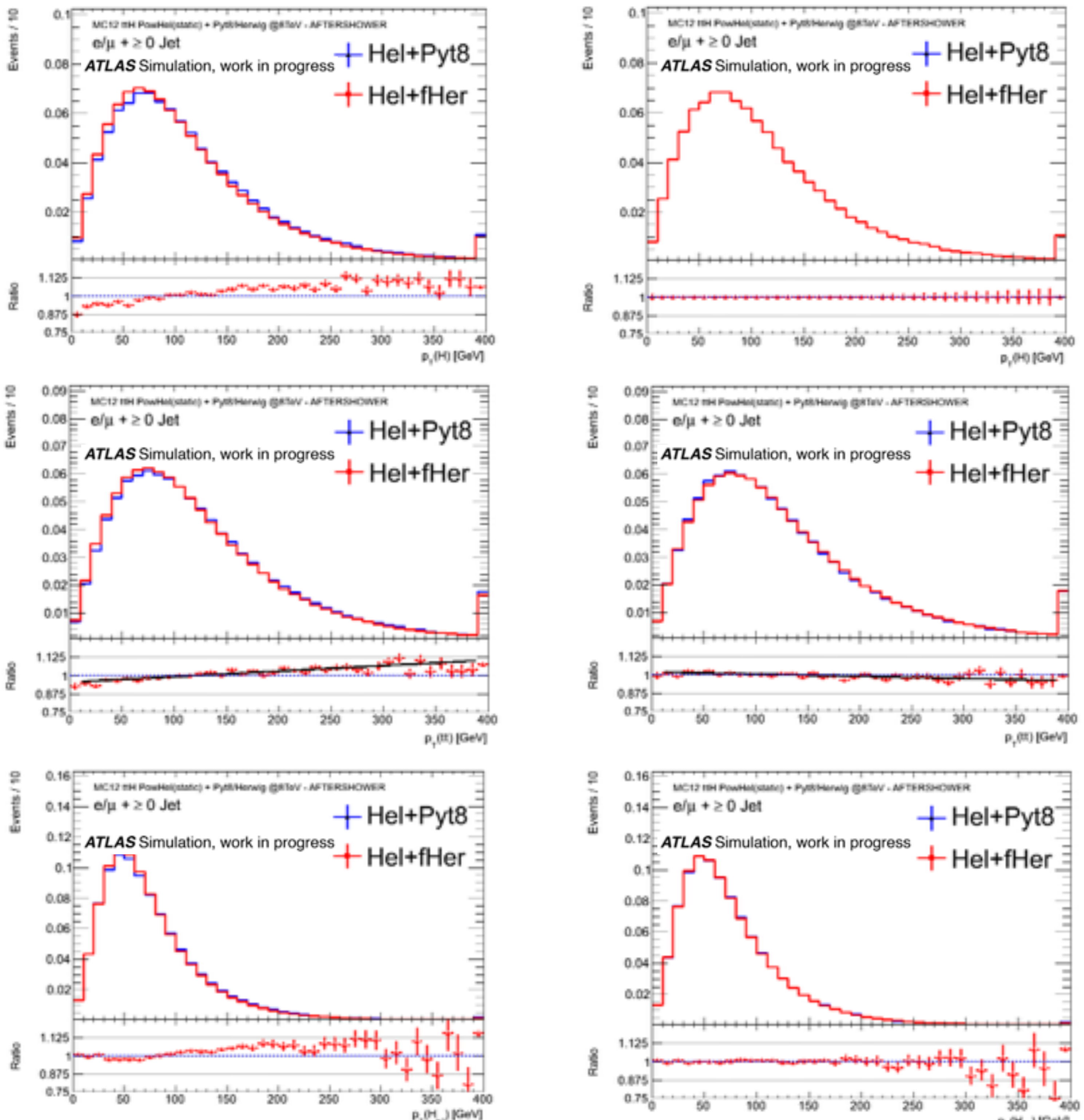
- Second reweighting → Higgs pT

# Reweighting procedure

- "sequential" reweighting of Higgs pT (**after ttH-pT rew.**)

before

after




Higgs pT

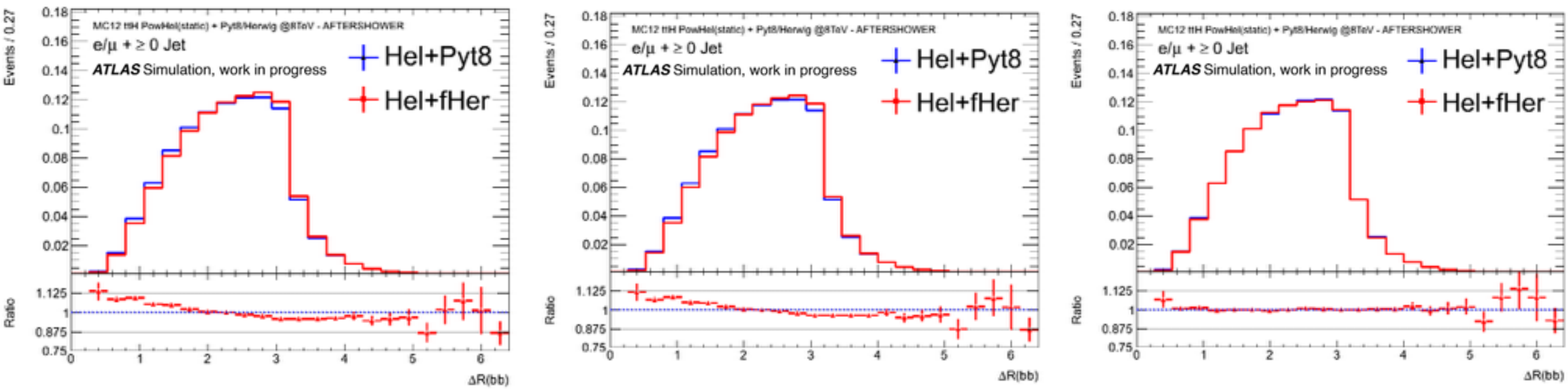
ttbar pT

2nd b from Higgs pT

# Reweighting procedure

- Reweighting impact
  - → minimize differences in variety of kinematic distributions

**ΔR(b,b)**




1st rew.

1st &2nd rew.

# Conclusions

- Search for ttH (H→bb) represents search of a very small signal on top of a not so well known background
- A lot of effort and complexity in order to increase the sensitivity to the signal:
  - Multiple multivariate discriminants
    - Relies on a robust signal and background model
  - Several control regions to control the background normalization and reduce the effect of systematic uncertainties
- Investigation & dedicated comparisons of different MC predictions for ttH process
  - varying QCD accuracy and physics features
- Several systematics assessed
  - Illustrated reweighting procedure

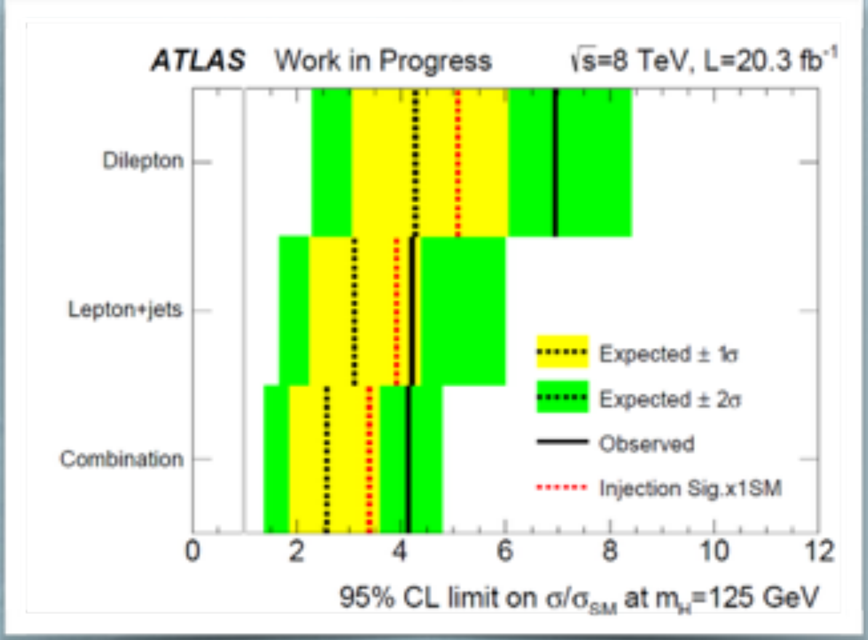
# Backup

# ANALYSIS RESULTS

# ttH analysis results

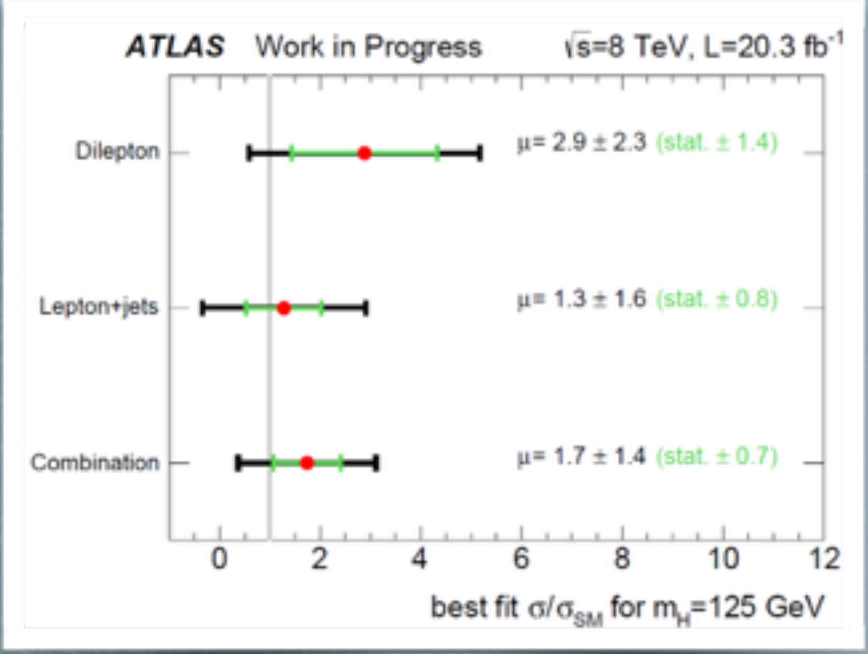
- Data corresponding to 20.3 $fb^{-1}$ @8 TeV
- **Observed and expected** (median, for the background-only hypothesis) @95% C.L. **upper limits** on ttH cross section relative to the SM prediction with $m_H$ = 125 GeV

| | Observed | Expected |
|---|---|---|
| Single lepton | 4.2 | 3.10 |
| Dilepton | 6.95 | 4.27 |
| **Combination** | **4.14** | **2.57** |




- Observed **signal strength** (@$m_H$ = 125 GeV)

| | signal strength | uncertainty |
|---|---|---|
| Single lepton | 1.28 | 1.62 |
| Dilepton | 2.88 | 2.29 |
| **Combination** | **1.74** | **1.36** |



# ttH @ATLAS and @CMS

- Most sensitive ttH (H → bb) result @LHC
  - ATLAS ttH (H → bb) @7 TeV: l+jets ($m_H$ = 125 GeV):

| ATLAS: upper limit on σ/σ (ATLAS-CONF-2012-135) | Observed | Expected |
|---|---|---|
| Combination | 13.1 | 10.5 |

  - CMS ttH (H →bb) @8 TeV: comb. of l+jets, dilepton and tau channel ($m_H$ = 125 GeV):

| CMS: upper limit on σ/ $\sigma_{SM}$ (CMS-PAS-HIG-13-019) | Observed | Expected |
|---|---|---|
| Combination | 5.2 | 4.1 |

  - ATLAS ttH (H →γγ) @8 TeV: comb. of l+jets and allhadronic ($m_H$ = 126.8 GeV):

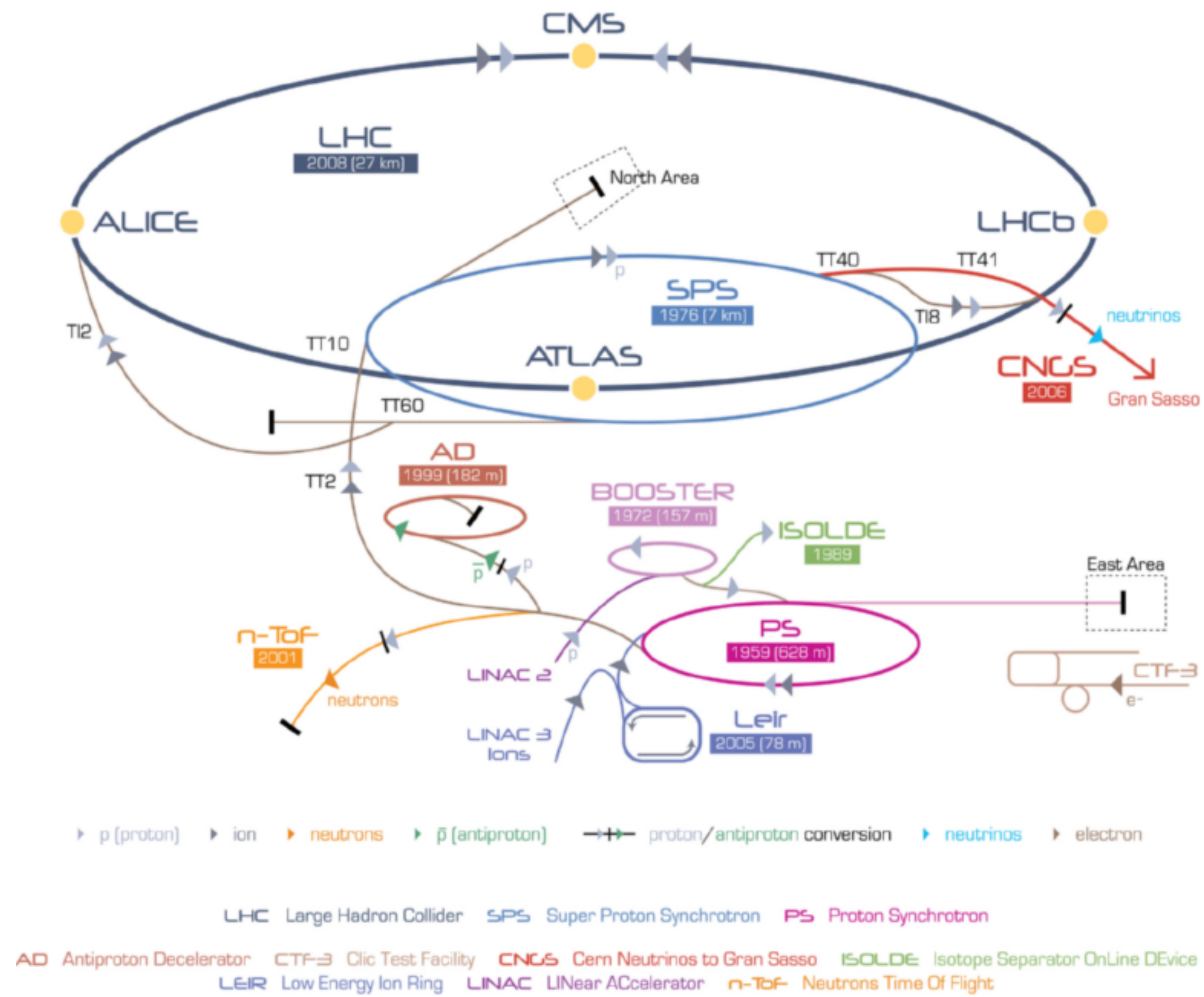
| ATLAS: upper limit on σ/σ (ATL-CONF-2013-080) | Observed | Expected |
|---|---|---|
| Combination | 4.7 | 5.4 |

# LHC & ATLAS

# LHC beam injection

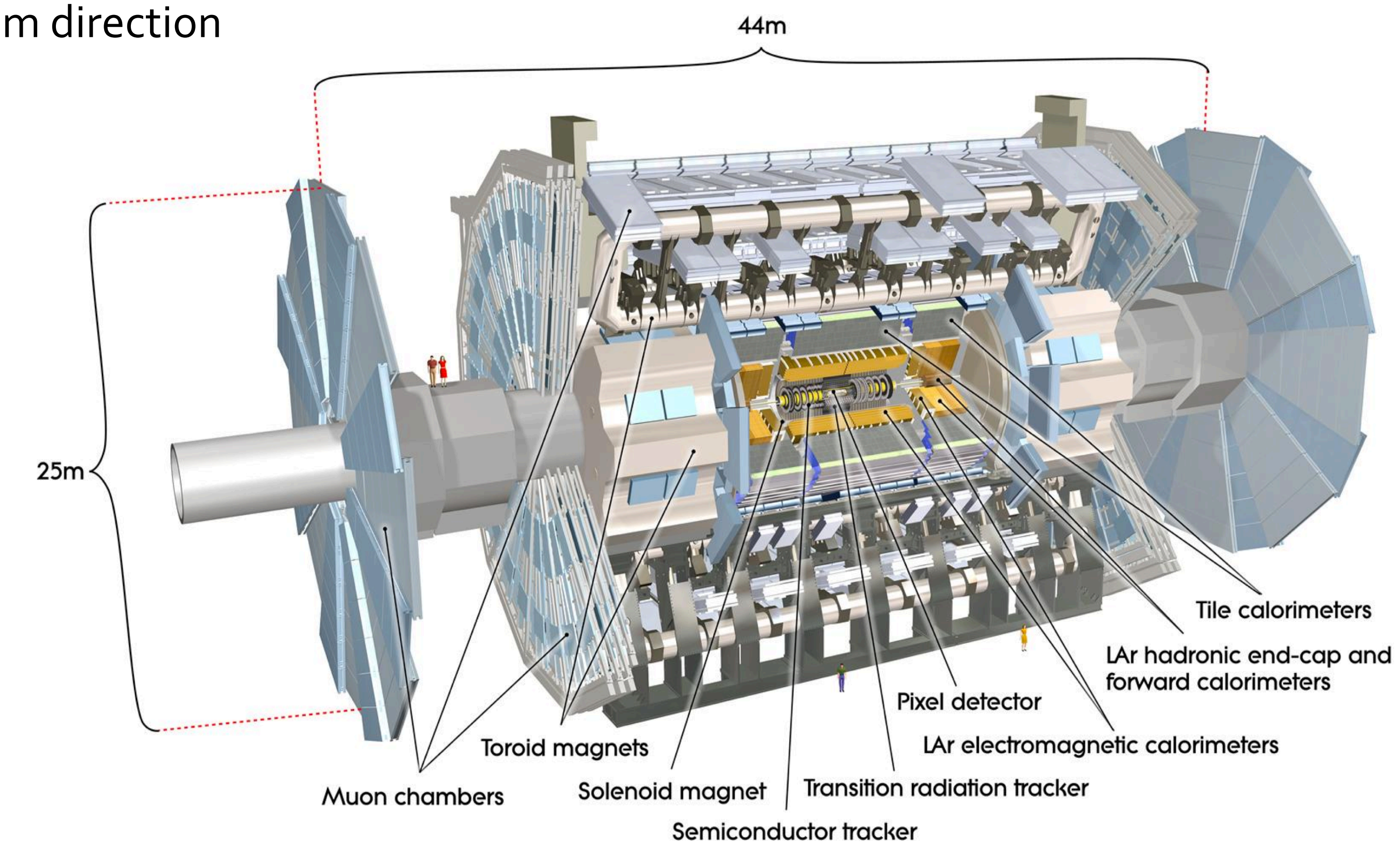
- p-p collisions
- Pre-acceleration in LINAC2 ~ 50 MeV
- BOOSTER ~1.4 GeV
- Proton Synchrotron (PS) ~ 25 GeV
- Super Proton Synchrotron ~450 GeV
- LHC:
  - → 20 minutes acceleration and beam optimization
- Design:
  - → 2808 proton bunches
  - → ~ 1.15 x 1011 protons per bunch
  - → 25 ns separation
  - → 40 mio. Collisions per second
- Four experiments:

  ATLAS, CMS, LHCb, ALICE



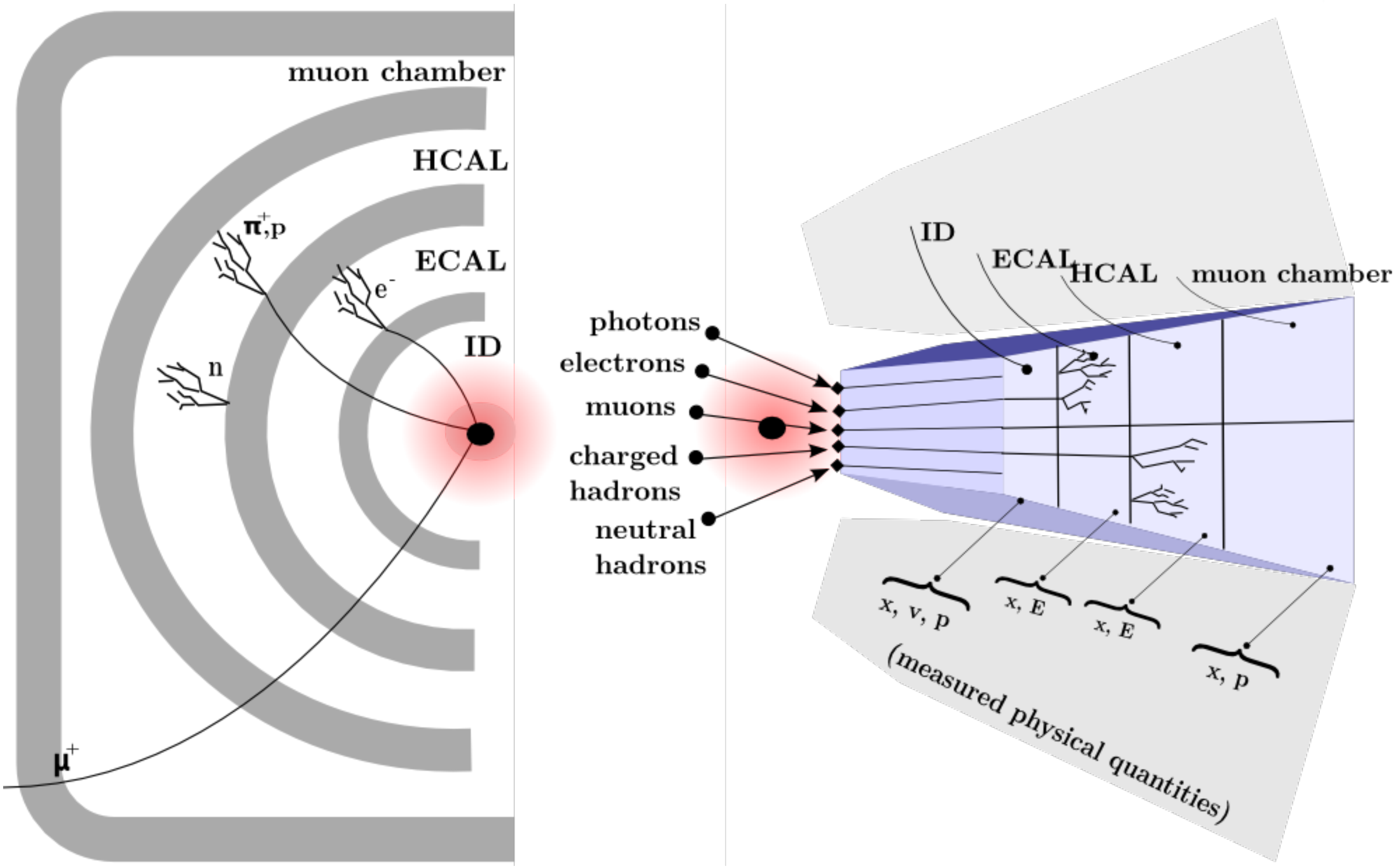
# The ATLAS detector

- Forward-backward asymmetric
- Right-handed coordinate system
  - → axis: x to LHC center, y to surface, z is beam direction
- Cylindrical coordinates $(r, \phi)$
  - → transverse plane
- pseudorapidity $\eta = -\ln(\tan\theta/2)$



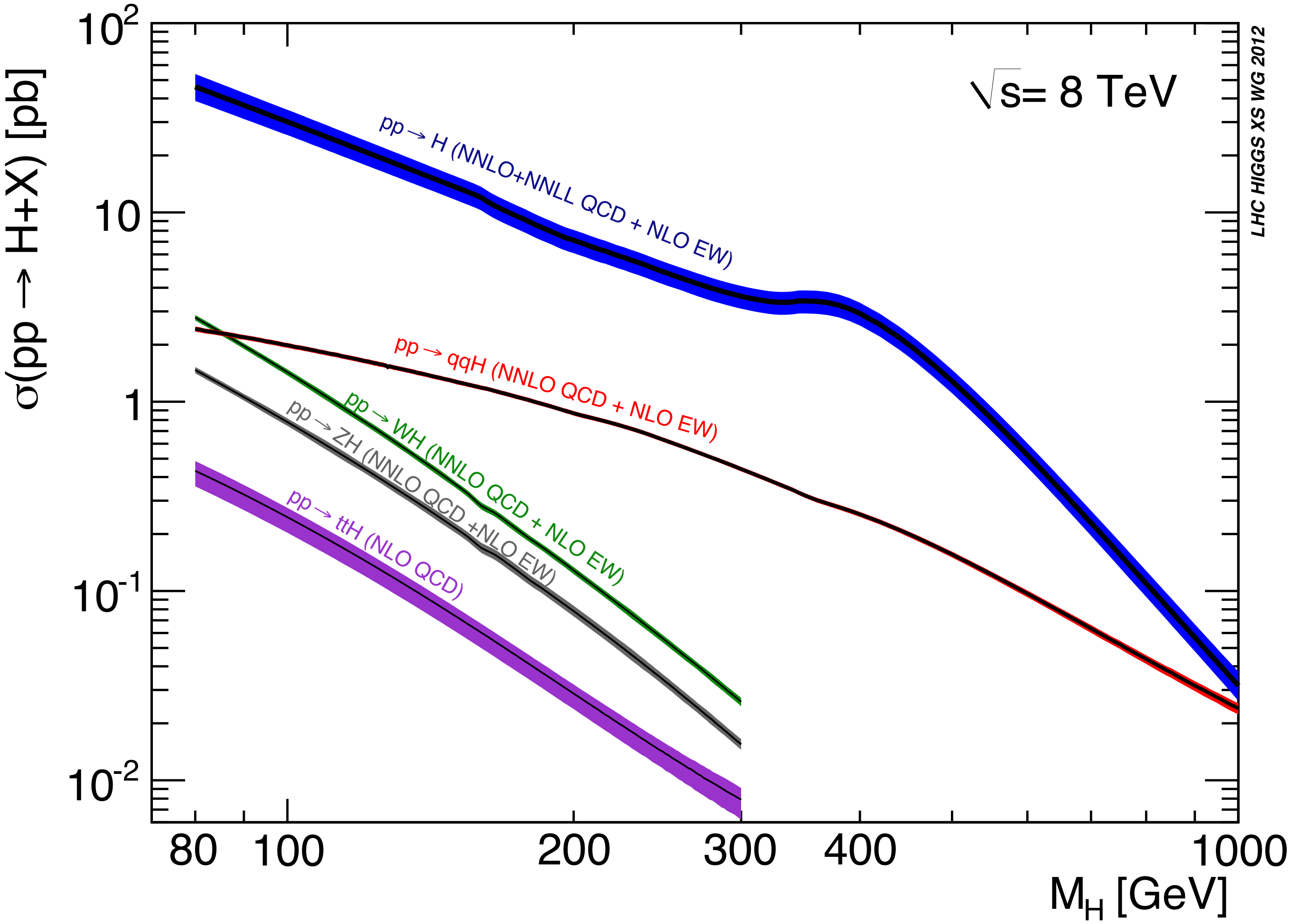

- **ID** $|\eta| < 2.5$ : → charge and momentum
- Solenoid: axial magnetic field (2 T)
- **ECAL** $|\eta| < 3.2$ : sampling (lead/argon)
  - → energy and position
- **HCAL** $|\eta| < 1.7$ : sampling (iron/scint. Tile)
  - → energy and position
- **MS** $|\eta| < 2.7$ : 3 air-core toroids with 8 coils, precision tracking chamber
  - → charge and momentum

# Particle detection

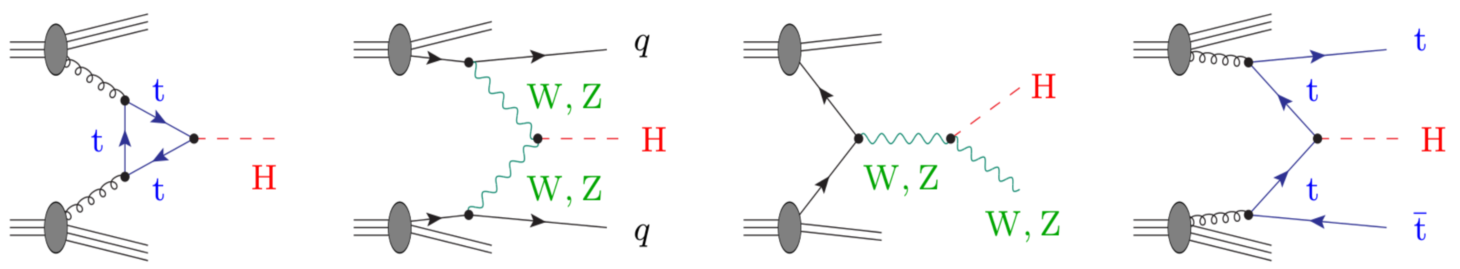


# HIGGS & TOP PHENOMENOLOGY

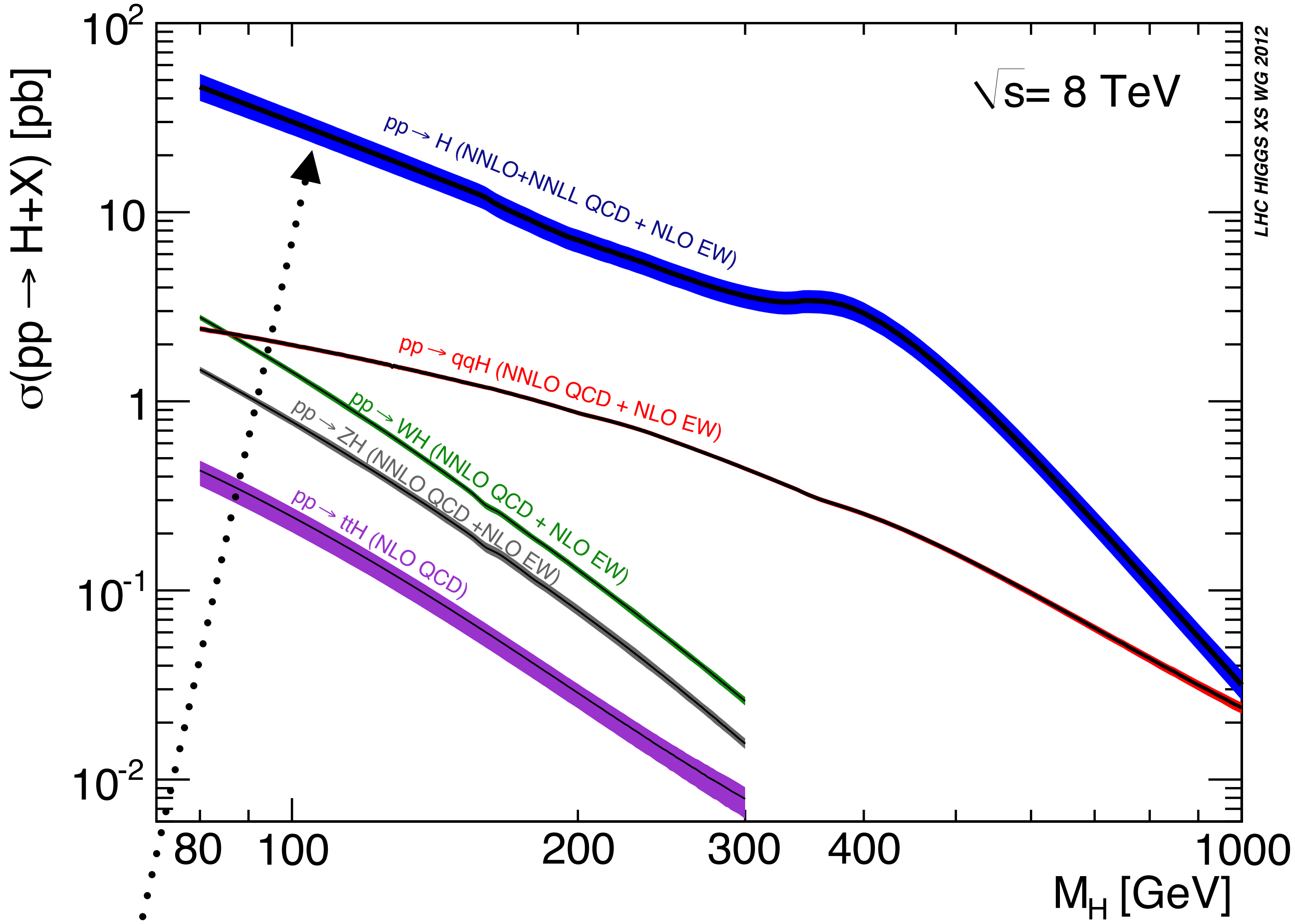
# Higgs production

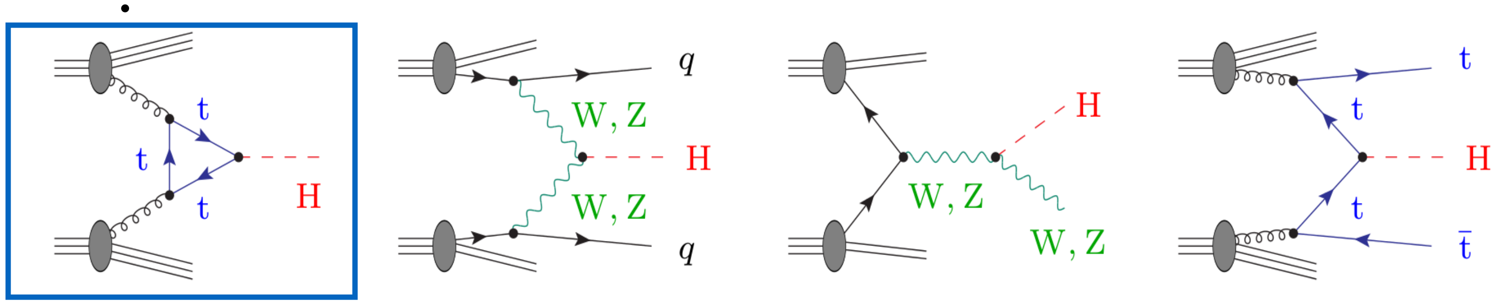



- Higgs coupling ~ particle mass
  - $g_{ffH} \sim m_f/v$
  - $g_{VVH} \sim M^2_V/v$
    - v ~ 246 GeV
  - Higgs coupling more likely to heavy particles



# Higgs production

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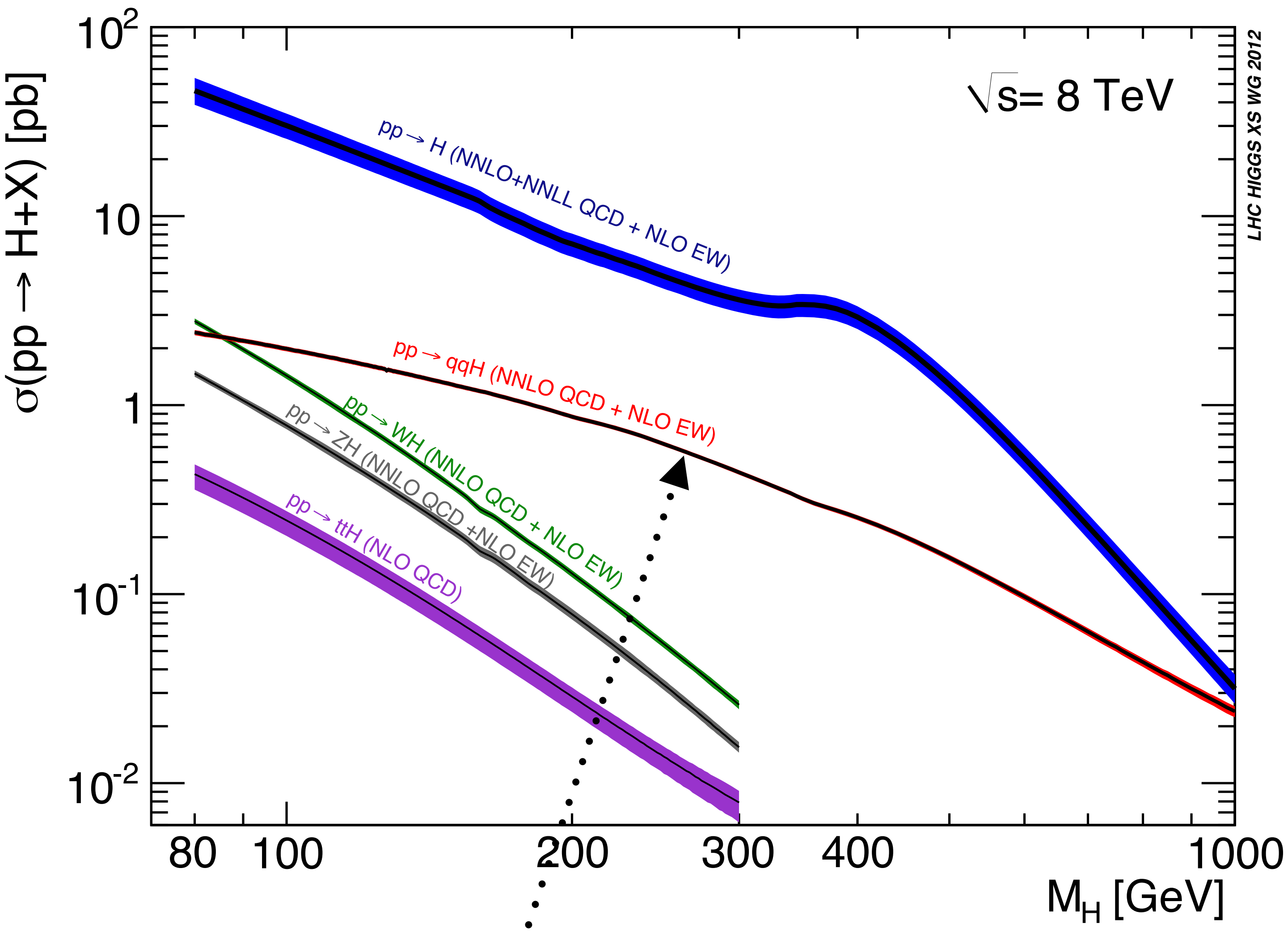
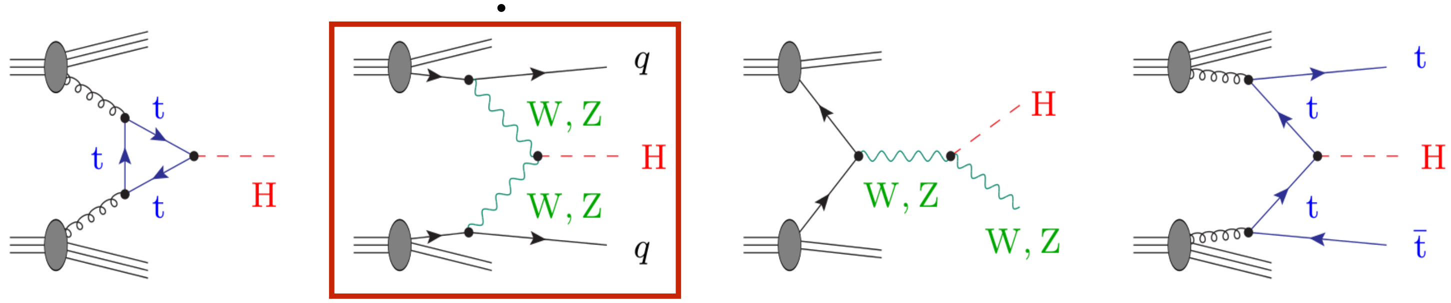
    - v ~ 246 GeV
  - Higgs coupling more likely to heavy particles

**Gluon-gluon fusion (gg):**

- dominating production process
- loop-induced pure process initiated
- by two gluons
  - → dom. contr. → top
  - → subleading contr. → bottom (<10%)
- Strong dependence on renormalization and factorisation scale
  - → higher order corrections very important
- @ mH = 125 GeV → Xsec = 19.52 pb
- known to NNLO with O(15%)

# Higgs production



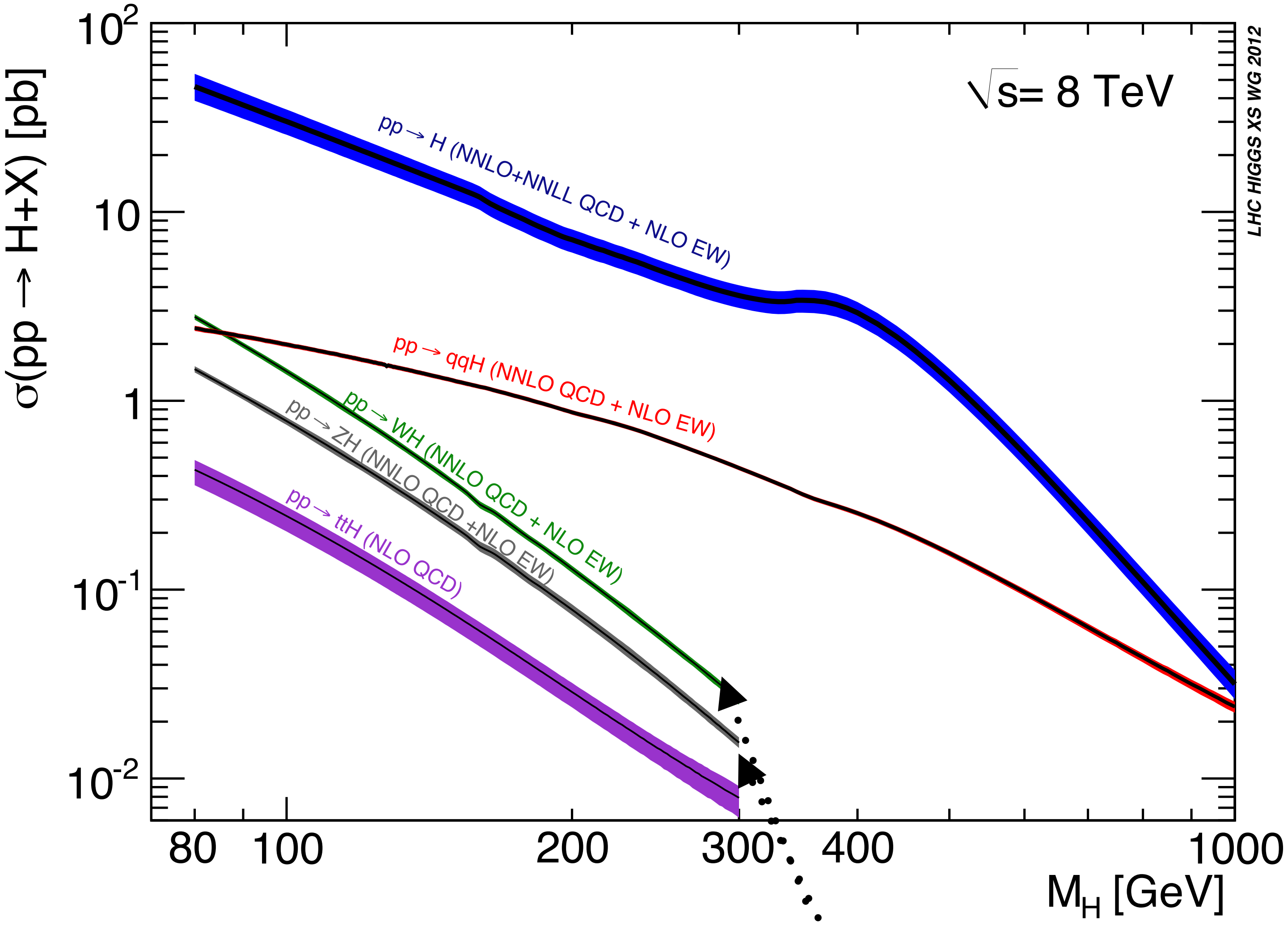



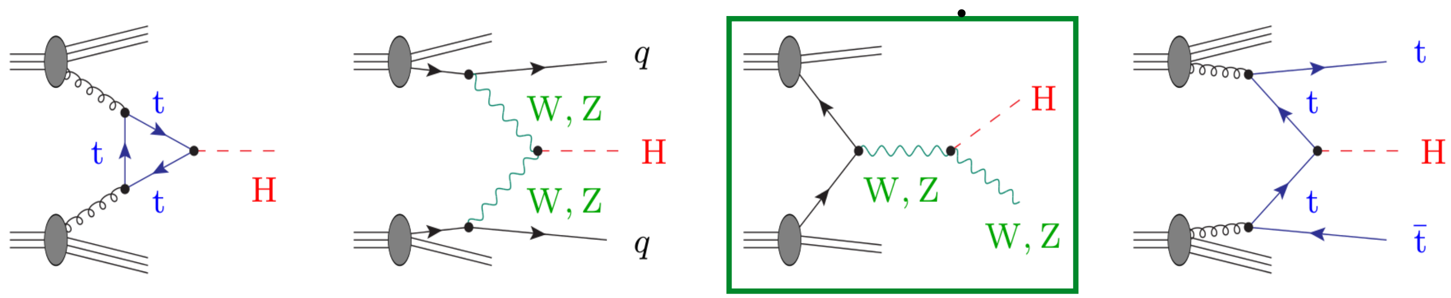

- Higgs coupling ~ particle mass
  - $g_{ffH} \sim m_f/v$
  - $g_{VVH} \sim M^2_V/v$
    - v ~ 246 GeV
  - Higgs coupling more likely to heavy particles

**Vector boson fusion (VBF):**

- two vector bosons mediated by quarks fuse to Higgs
- not pure: additional particles
- char. signature:
  - 2 jets in forward region
  - gap in rapidity distribution
- @ mH = 125 GeV → Xsec = 1.58 pb
- known to NLO with O(5%)

# Higgs production



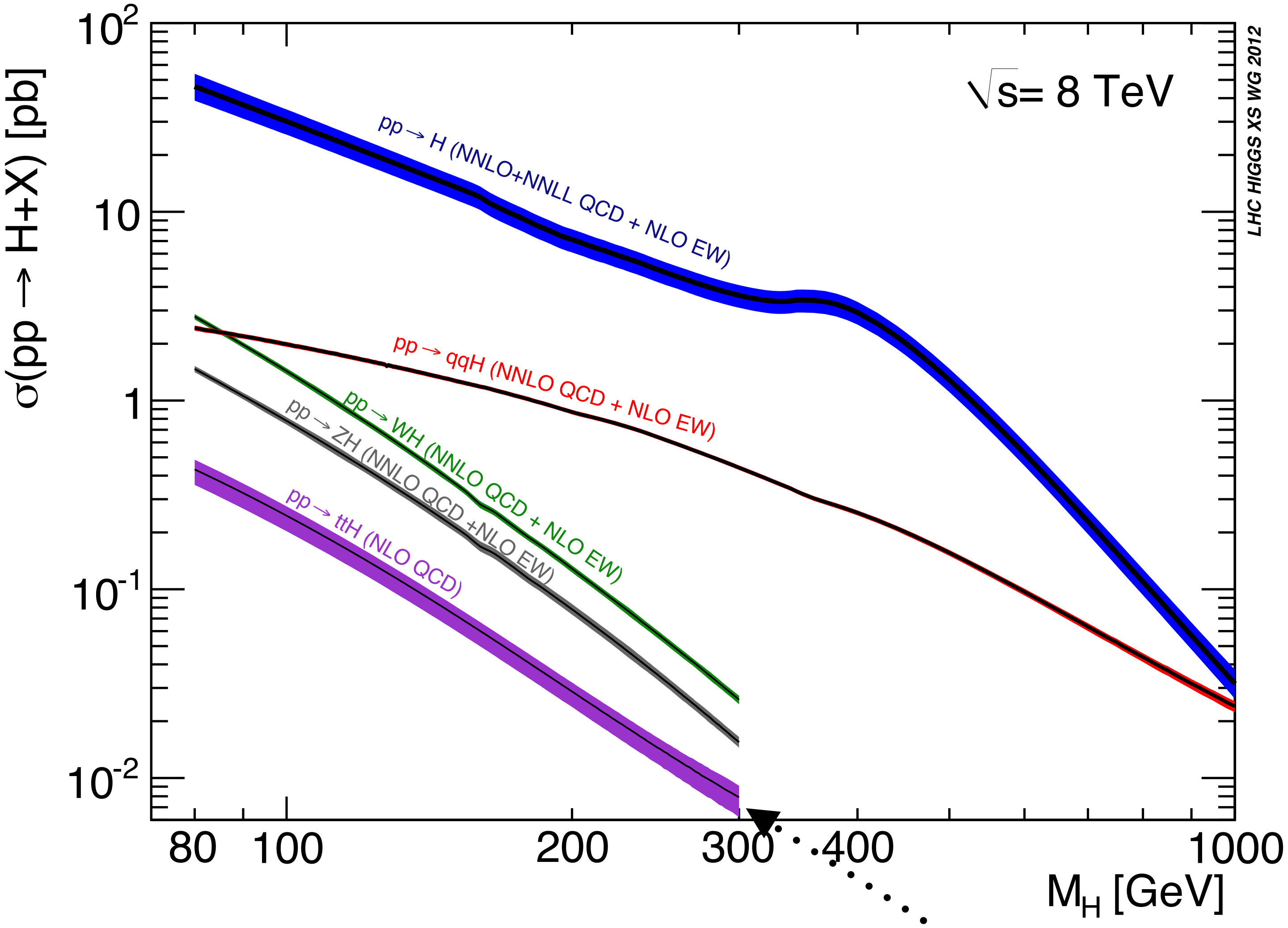




- Higgs coupling ~ particle mass
  - $g_{ffH} \sim m_f/v$
  - $g_{VVH} \sim M^2_V/v$
    - v ~ 246 GeV
  - Higgs coupling more likely to heavy particles

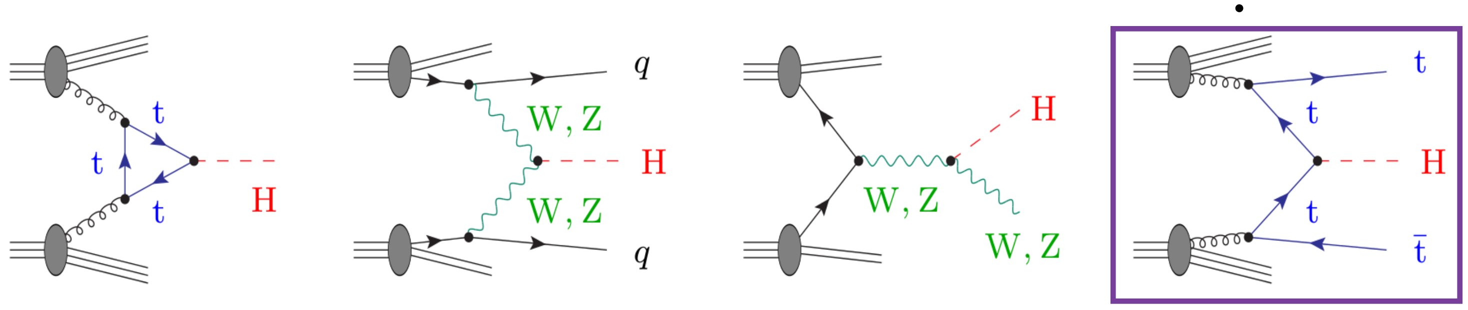
**Higgs strahlung (VH):**

- directly sensitive to gVVH
  - → associated production overcomes
- problem of large background
- @ mH = 125 GeV → Xsec = 1.09 pb

# Higgs production




- Higgs coupling ~ particle mass
  - $g_{ffH} \sim m_f/v$
  - $g_{VVH} \sim M^2_V/v$
    - v ~ 246 GeV
  - Higgs coupling more likely to heavy particles

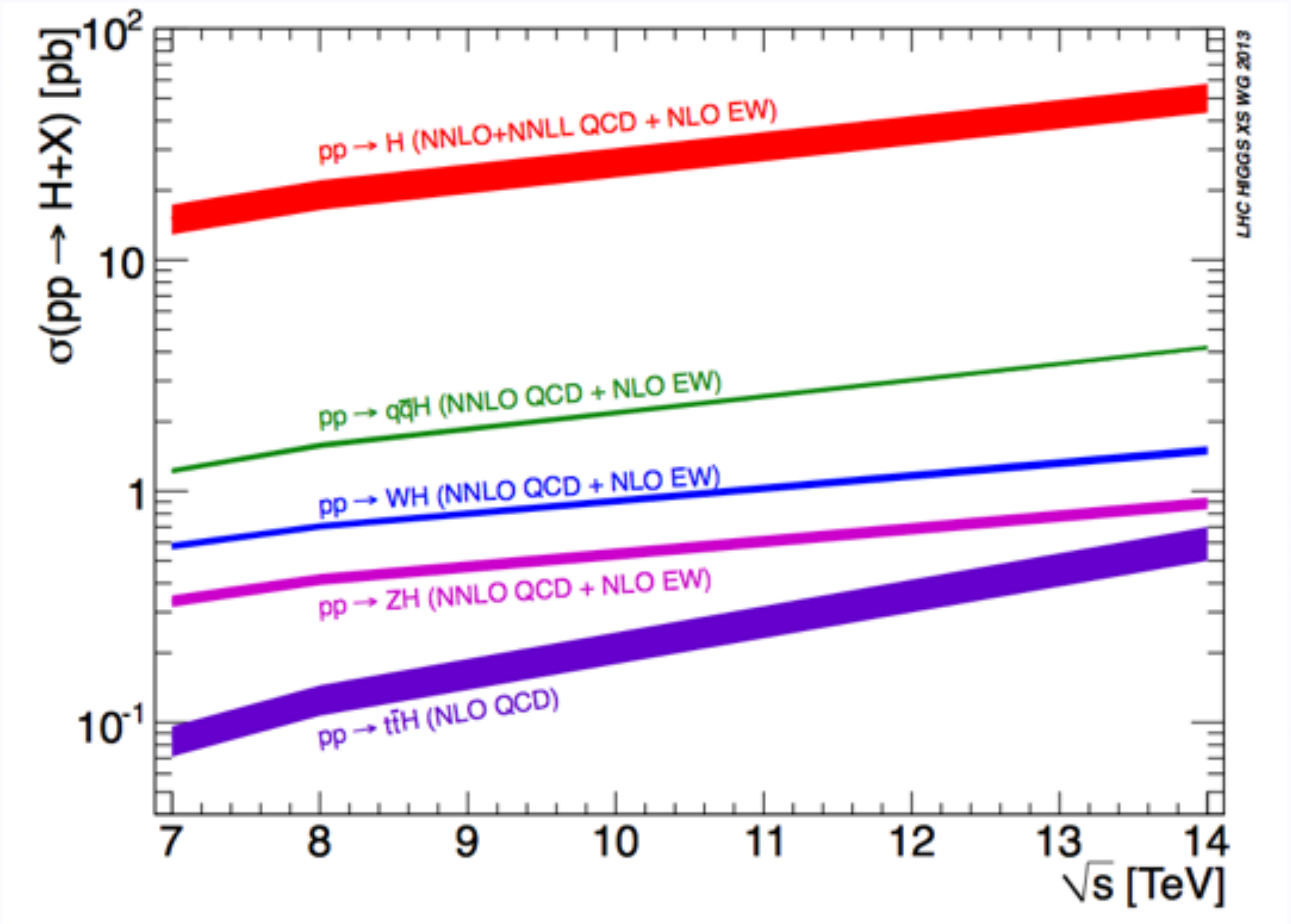



## ttH associated production:

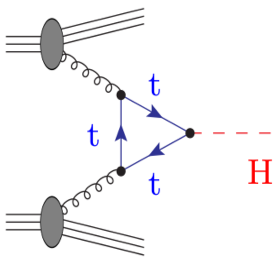
- directly sensitive to gffH
- important for small mH
- → associated production overcomes
- problem of large background
- @ mH = 125 GeV → Xsec = 0.13 pb

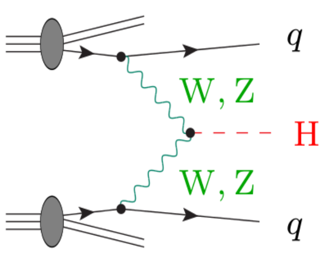
# Higgs production

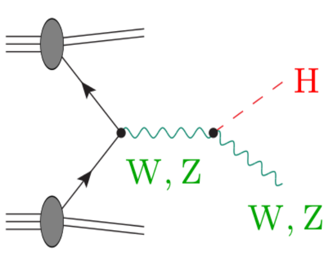
- Higgs production cross section with respect to the center-of-mass energy

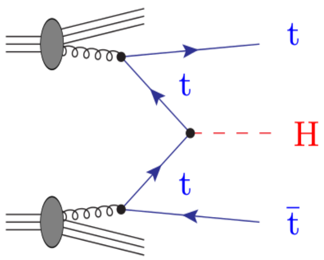



**Increasing factor from 7 to 14 TeV**



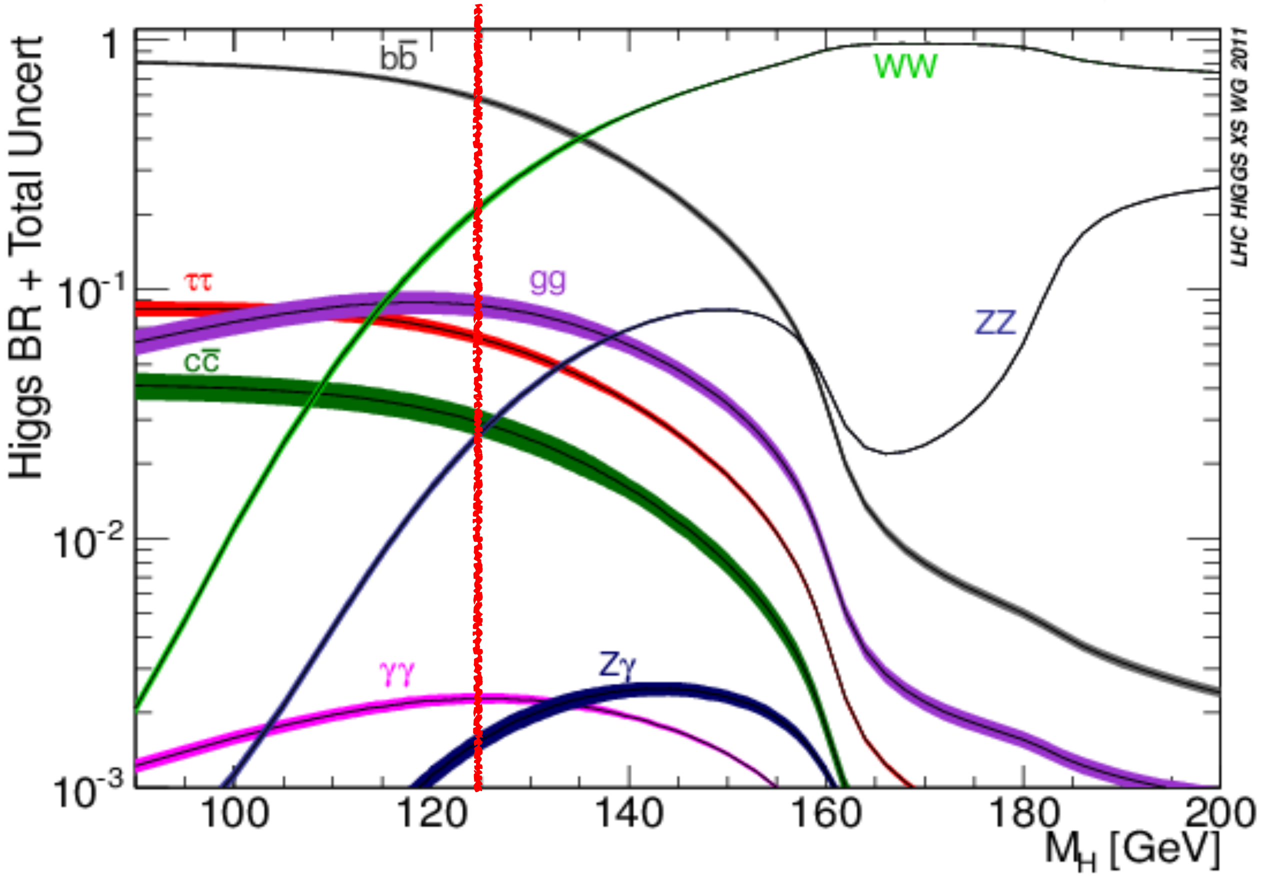



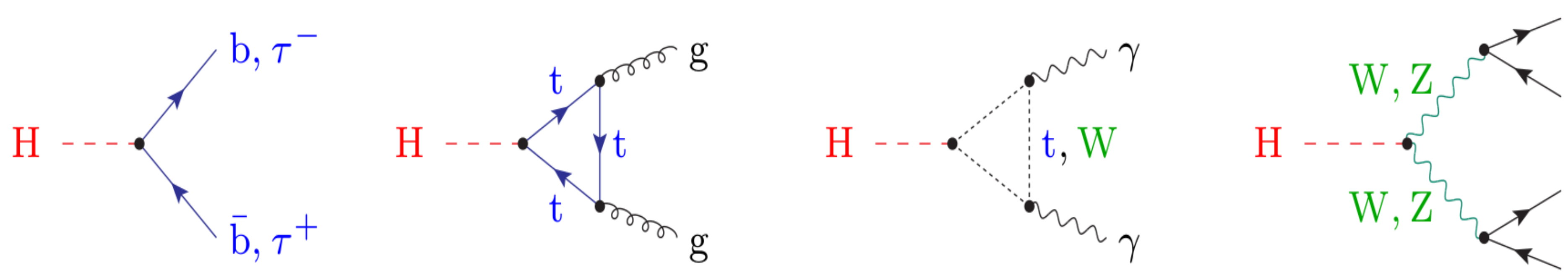

x3-4 x3-4 x2.5-3 x7-8

# Higgs decay

- @$m_H$ = 125 GeV:
  - **H → bb**
    → dominant process
    → large QCD multijet background
    → prevents Higgs search with gg and VBF production
  - **H → gg**:
    → QCD dominated background
    → high rate
  - **H → γγ**:
    → clean signature
    → small BR

  …

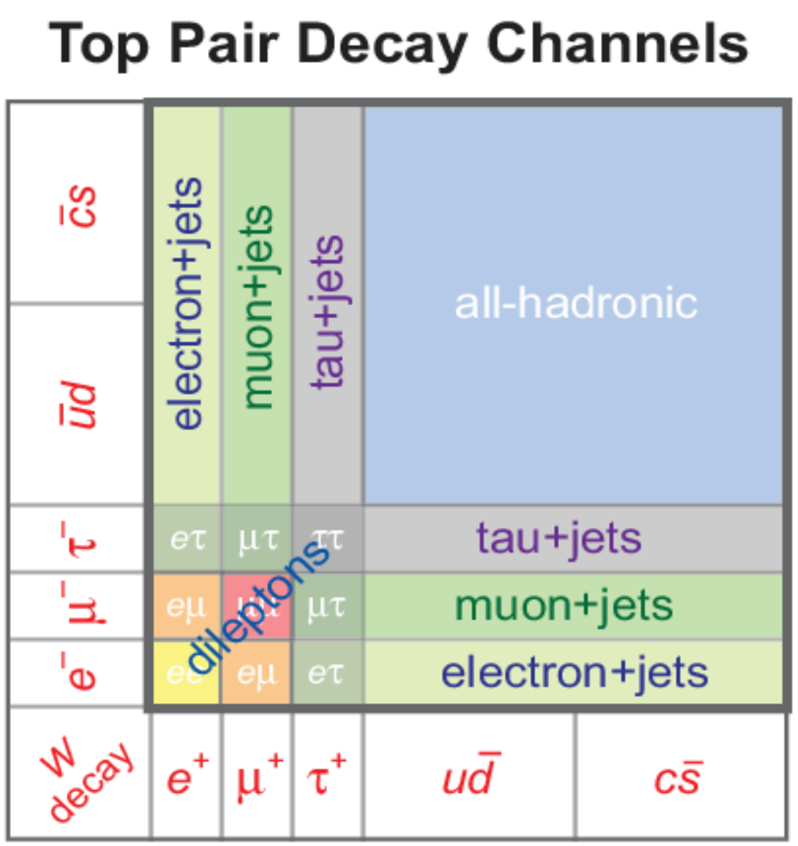


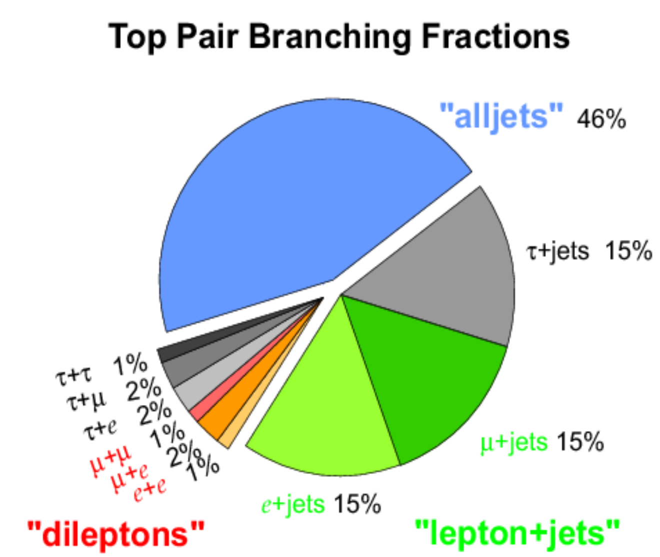



# Top decay

**tt pair decay modes (channels):**

- all-hadronic (BR=0.462):
  - Both W decay hadronically → 4 jets + 2 b-jets
  - Overwhelming QCD multijet background
- leptons plus jets (BR=0.435):
  - One W decays leptonically, one hadronically
    → 2 jets + 2 b-jets, high pT lepton + neutrino
  - Modest background contribution: mainly W + jets
- dileptonic (BR=0.103):
  - Both W decay leptonically → 2 b-jets, two leptons + neutrinos
  - Lowest background contribution: mainly Z + jets



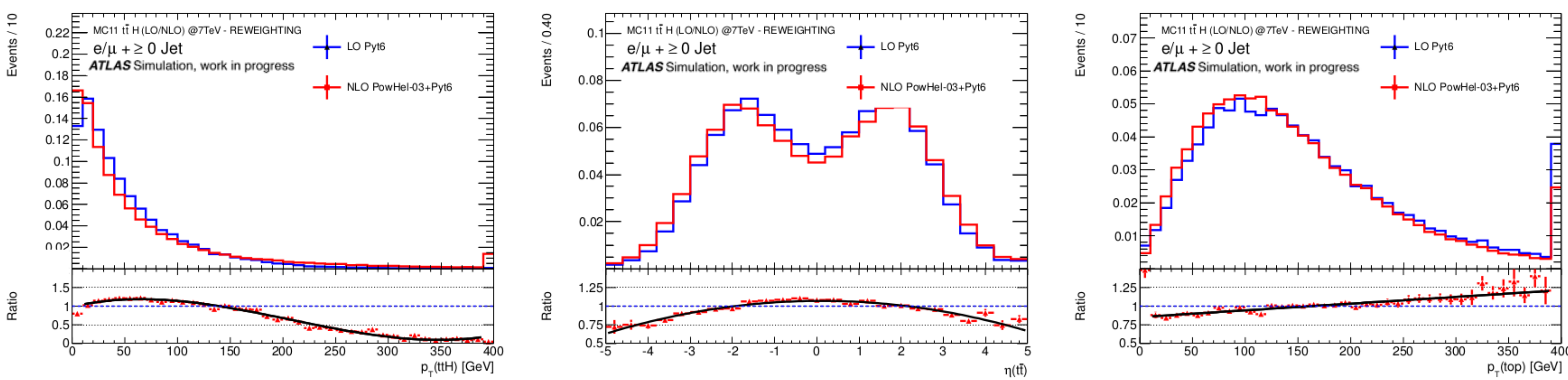



# REWEIGHTING

# LO/NLO reweighting

- Default ttH signal model was Pythia (Pythia6 @7TeV / Pythia8 @8TeV)
- Obtained NLO QCD accuracy prediction (PowHel) from theorists [Europhys.Lett. 96:11001,2011]

- Reweighted Pythia to PowHel → based on comparison of basic truth level kinematics
- PowHel with **static scale** ($m_t + m_H /2$)




- three (one) reweighting functions (fit LO/NLO ratio) @7TeV (@8TeV)

→ functions are applied as a multiplicative event-weight to the Pythia signal sample

# OTHER SIGNAL SYSTEMATICS

# Higher orders and scale variation

**Hadronic cross-section:**

$$\sigma_{h_1h_2} = \sum_{i,j} \int\int dx_1 dx_2 \underbrace{f_{i/h_1}(x_1,\mu_F^2)}_{\text{PDF}_i} \underbrace{f_{j/h_2}(x_2,\mu_F^2)}_{\text{PDF}_j} \underbrace{\hat{\sigma}(x_i,x_j,\mu_R^2)}_{\text{Xsec}_{\text{partonic}}}$$

→ Partonic Xsec depends on the *renormalization scale* $\mu_R$ (short distance) → pQCD

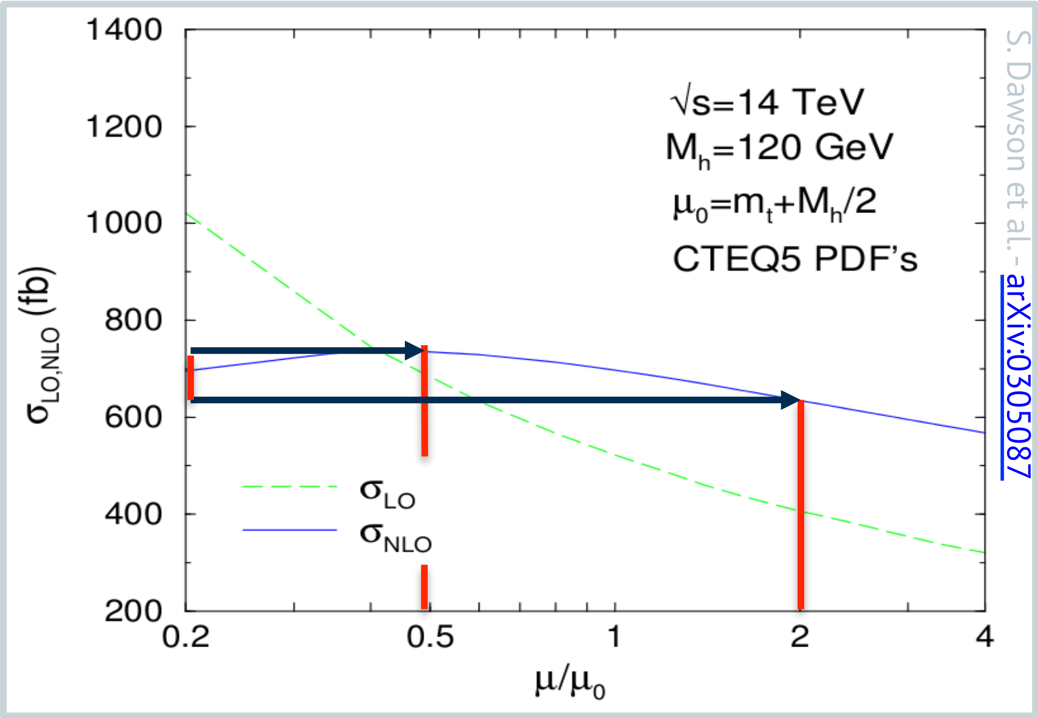
→ PDF's depend on *factorization scale* $\mu_F$ (long distance) → global fits and data

**Factorization theorem:**

- allows the separation of non-perturbative (long distance) from perturbative (high energy) dynamics in QCD in certain kinematic regimes

- Non-physical scales are introduced in order to deal with divergencies occuring in perturbation theory
  - → cancel out when all orders in the perturbative expansion were considered
  - → remain when stopping calculation at a fixed order

- Choice of scale is rather subjective
  - → Should be chosen close to the physical scale of the process
  - → Needs to be evaluated on a case-by-case basis




**Assign model systematic** by varying the scale by a factor of two

# Static scale variation

- Variation of **static scale** by a factor of two

$\mu_0 = m_t + m_H/2$ → $\sigma_{PowHel} = 104.27$ fb

$\mu = 2\mu_0$ → $\sigma_{PowHel} = 91.98$ fb

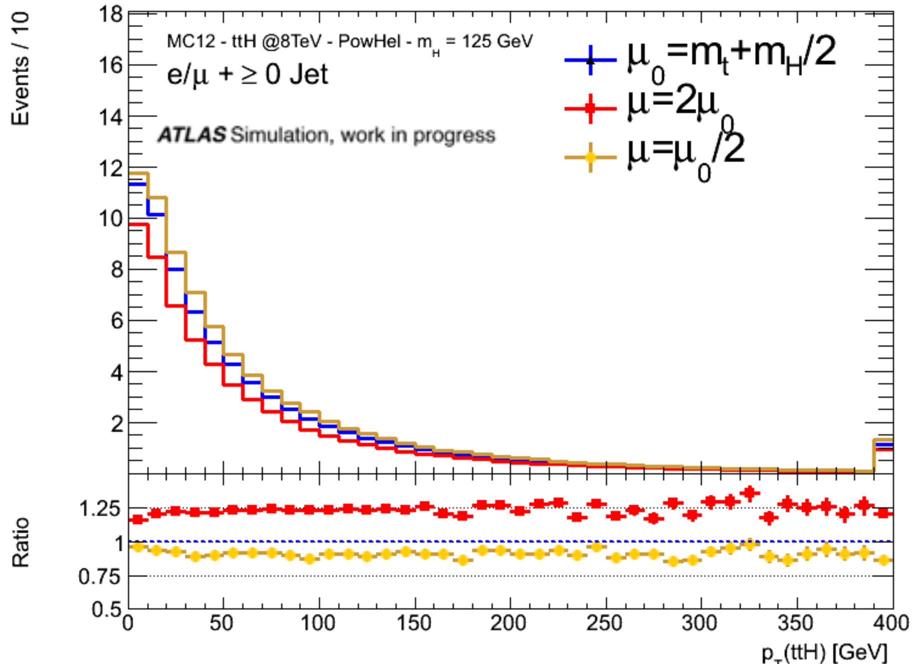
$\mu = \mu_0/2$ → $\sigma_{PowHel} = 106.9$ fb

**Static scale**

$$\mu_0 = m_t + m_H/2$$

- Normalized to **cross-section**:
  - Differences in rate for up- and down scale samples

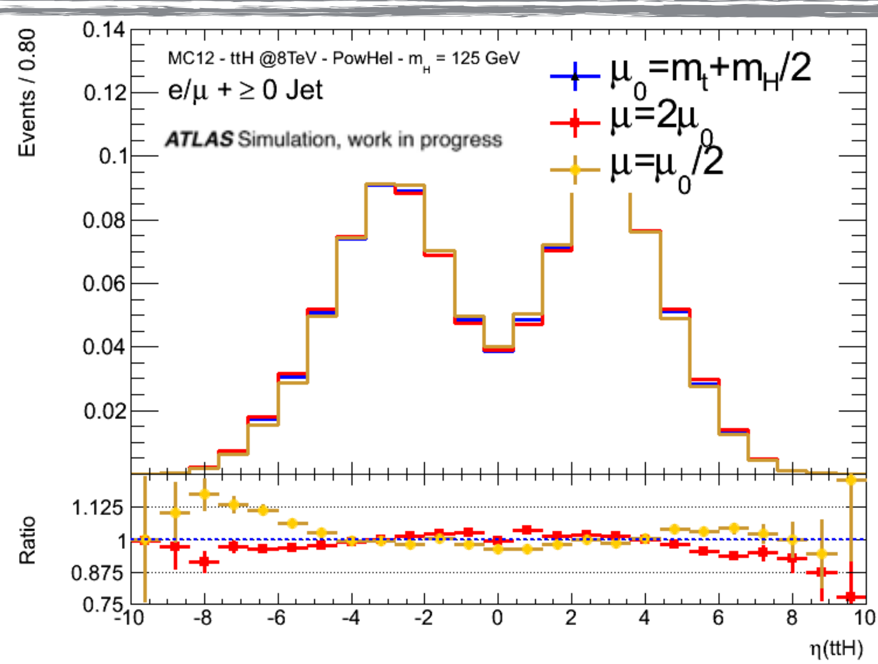
    → As expected from theory




- Normalized to **unity**:

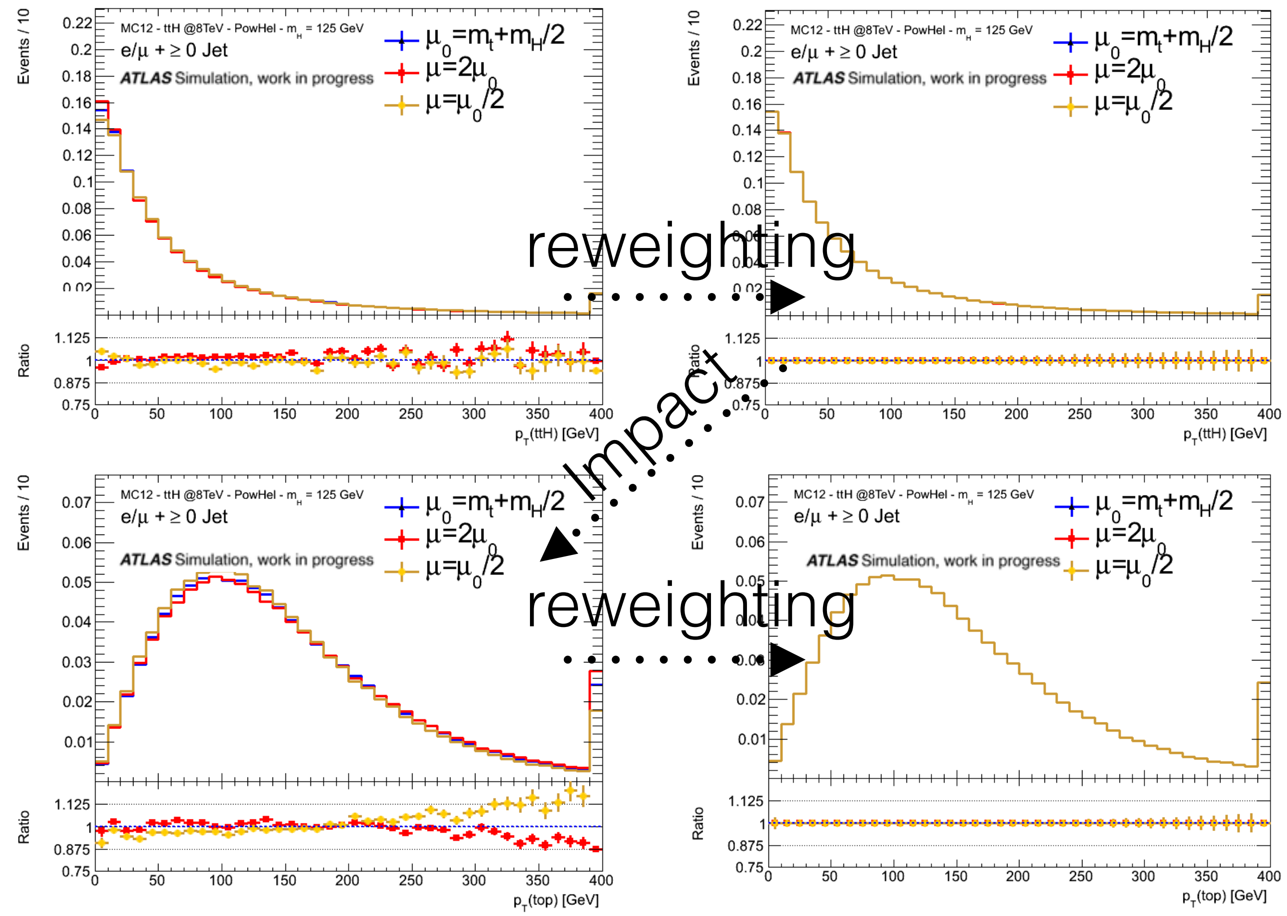
  → Investigate shape differences

  → Significant discrepancies occur in different kinematic distributions



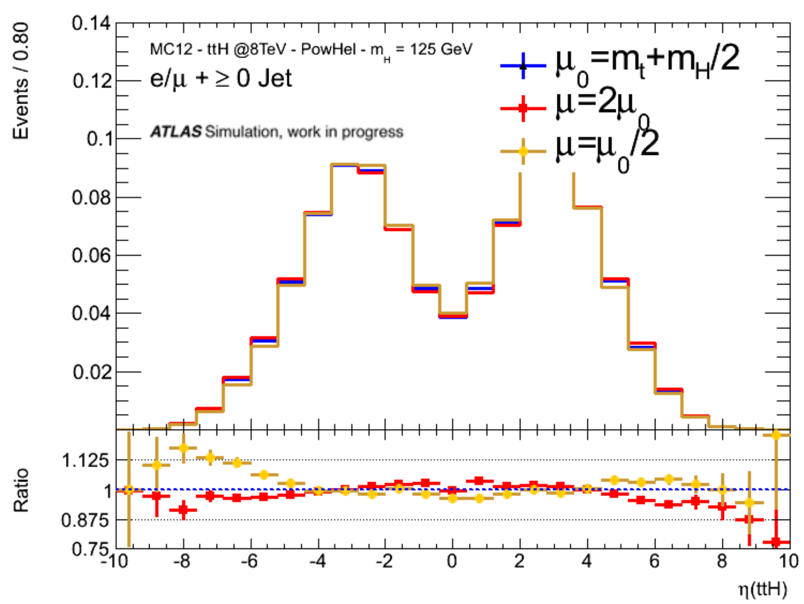
# Static scale variation - shape uncertainty

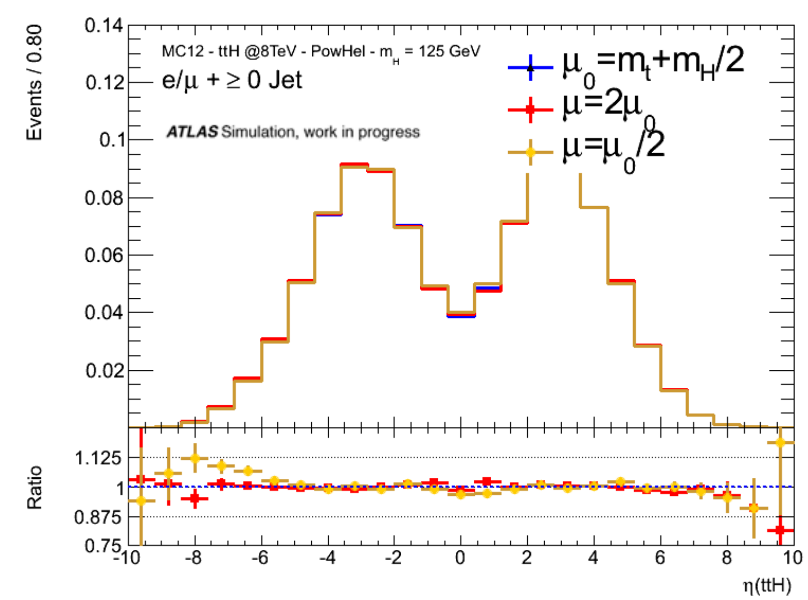
- Most significant differences occur in ttH-pT distribution
  1. Reweight ttH-pT
     - Closure in ttH-pT
     - Impact on other kinematic distributions
  2. Reweight top-pT




## Overall effect on other kinematic distributions

ttH-eta

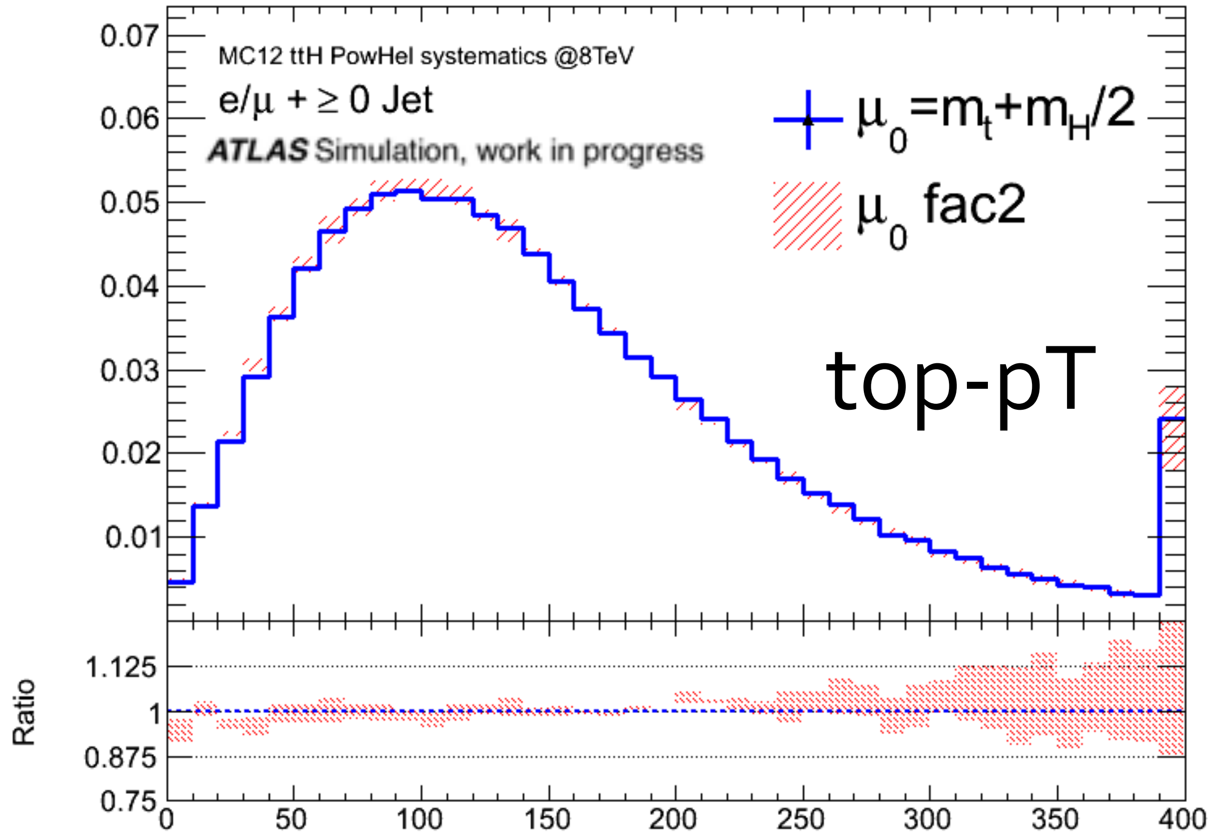


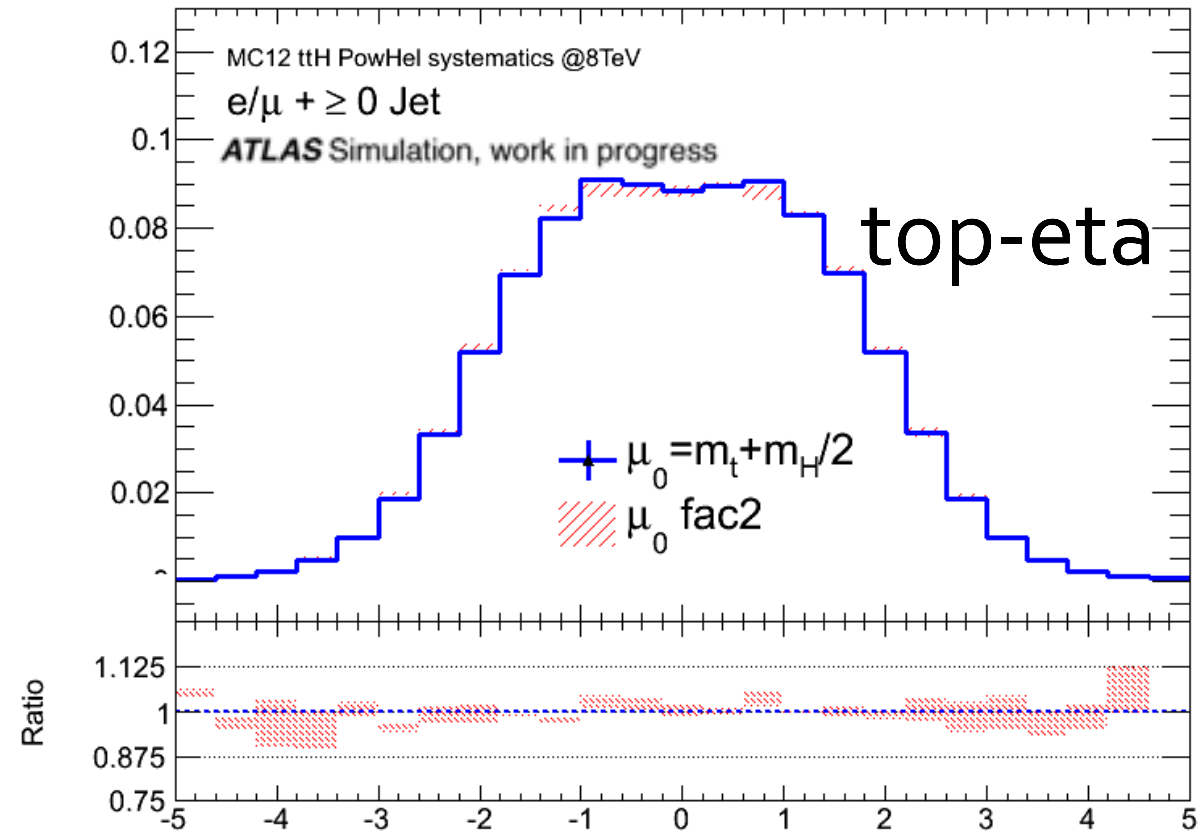



# Static scale variation – error band

- Apply inverse reweighting as multiplicative event-weight to the nominal signal sample

  → Error band $\mu_0$ fac2




- **Is it sufficient to only consider this systematic?**

# Scale choice systematic

- Does the choice of the scale shows an impact?

  - Static scale is reasonable at production threshold

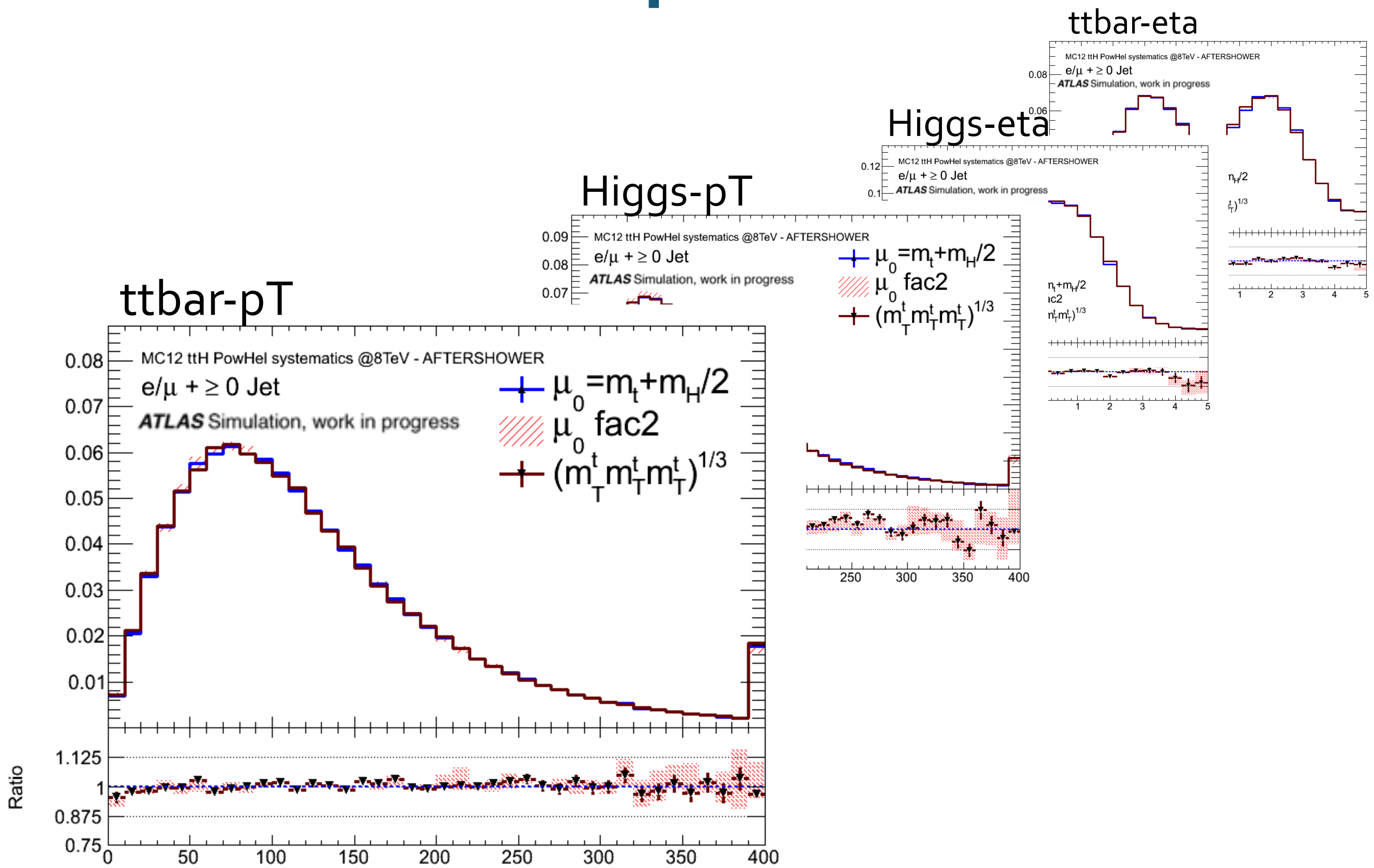
$$\mu_0 = m_{\mathrm{t}} + m_{\mathrm{H}}/2$$

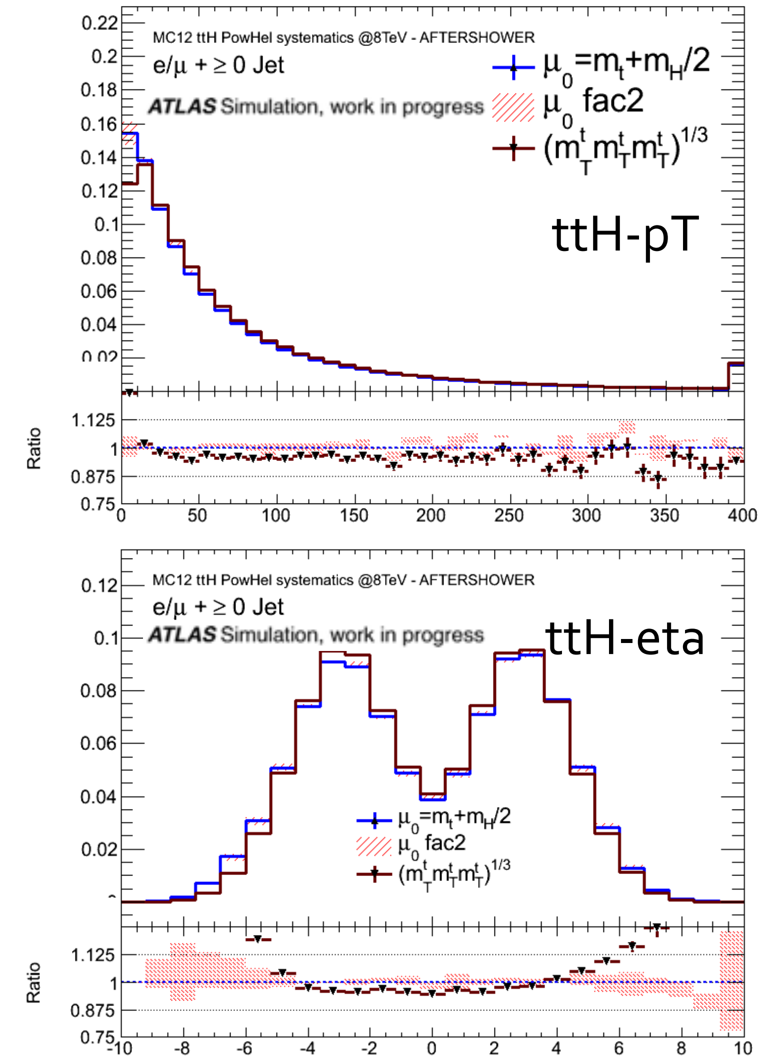
  - Dynamic scale for high $p_T$ regions

$$\mu_0 = (m_{\mathrm{T}}^{t} m_{\mathrm{T}}^{\bar{t}} m_{\mathrm{T}}^{H})^{\frac{1}{3}}$$

- Is the prediction of the dynamic scale covered by the applied systematic for the static scale?

# Scale choice impact

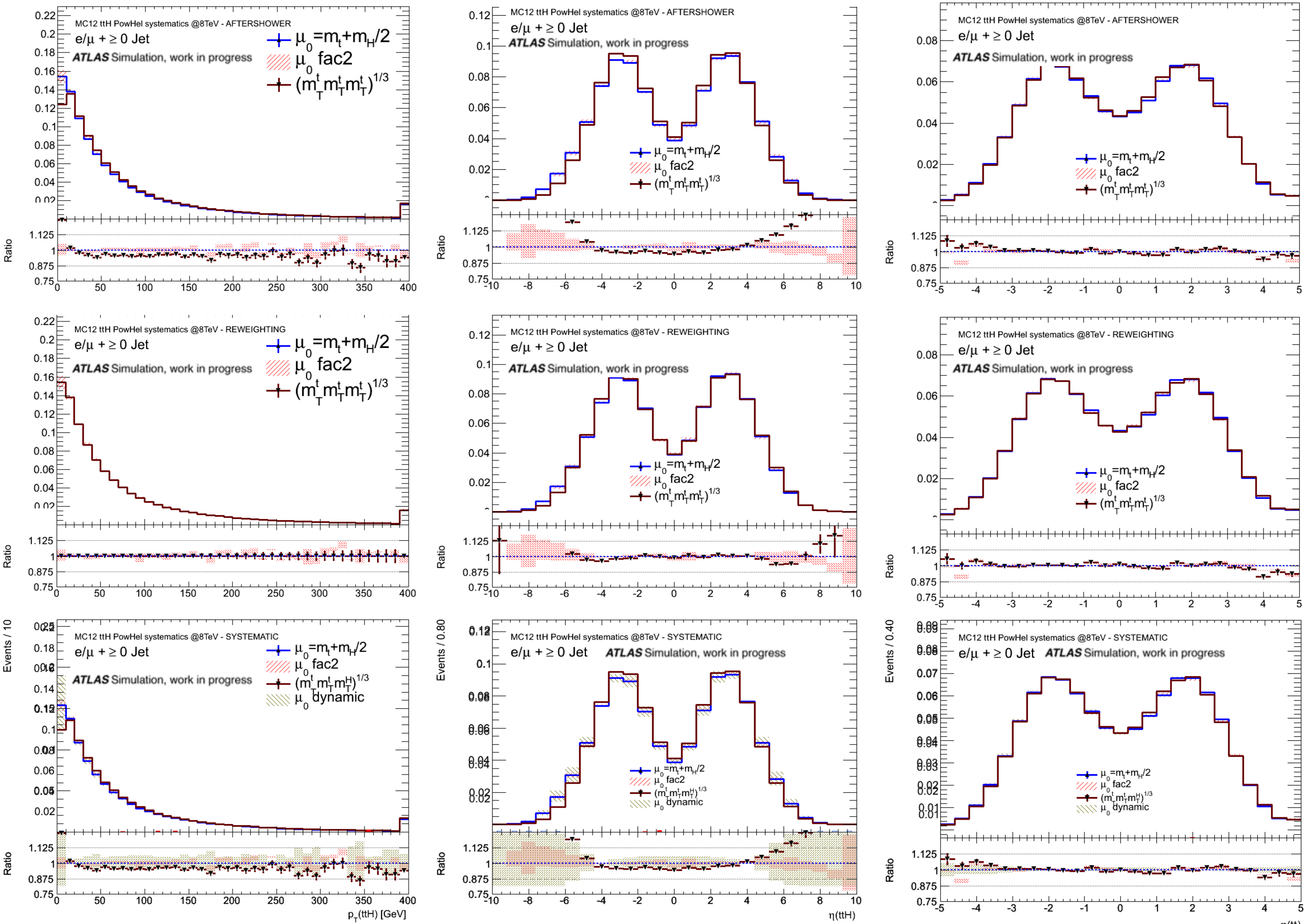



- Dynamic scale is covered by the static scale systematic
- **NOT**: ttH-pT and -eta
- Repeat reweighting in ttH-pT → apply additional systematic
  - symmetrize

# Scale choice reweighting

ttH-pT | ttH-eta | ttbar-eta




before rew

after rew

symmetrized error bands

# Signal scale systematics

- What we end up with:
  - Static scale variation systematic
  - Scale choice systematic