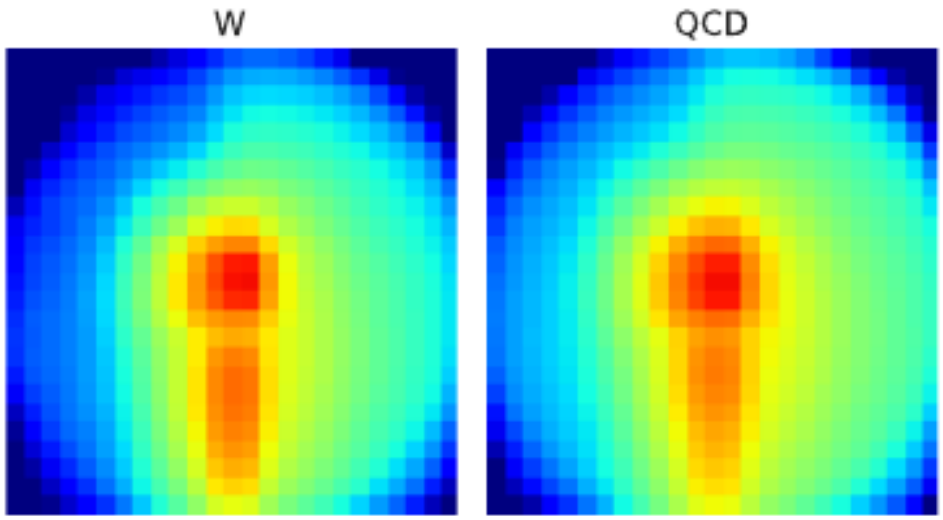
Top, Higgs and Electroweak Theory



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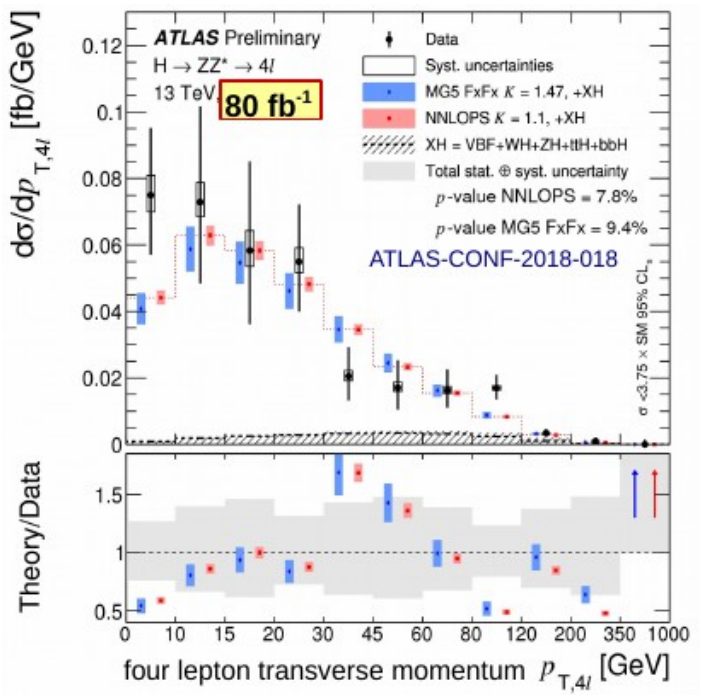
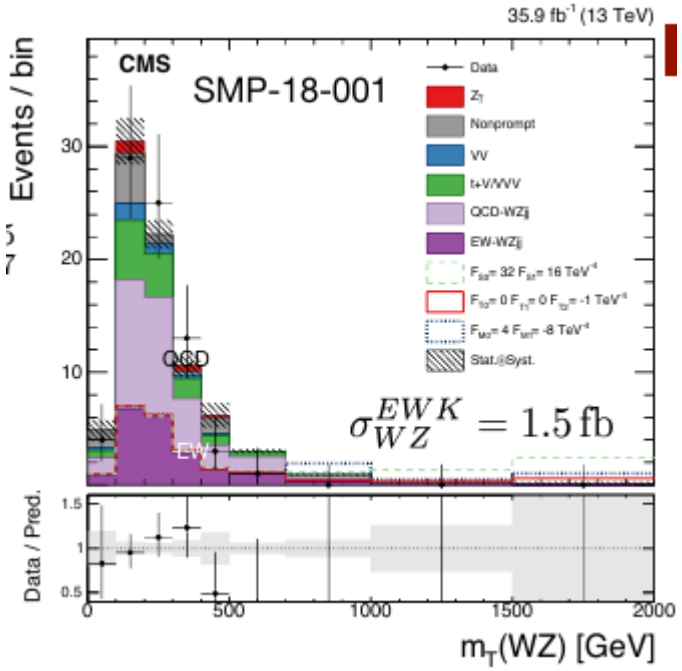
Outline

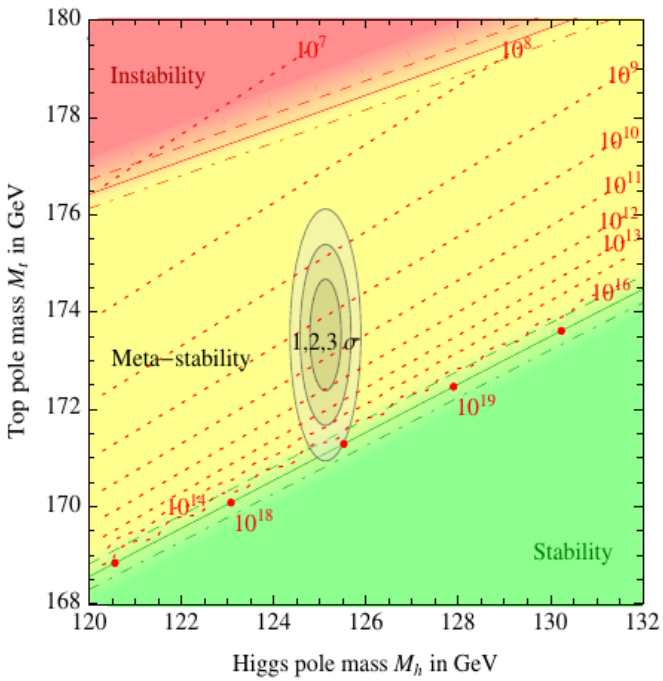
- Fantastic ICHEP for top, Higgs and electroweak physics.
  - Theory working hard to match experimental precision.
    - Feeds back into new theory constraints.
- Orthogonal development: resonance tagging with machine learning.

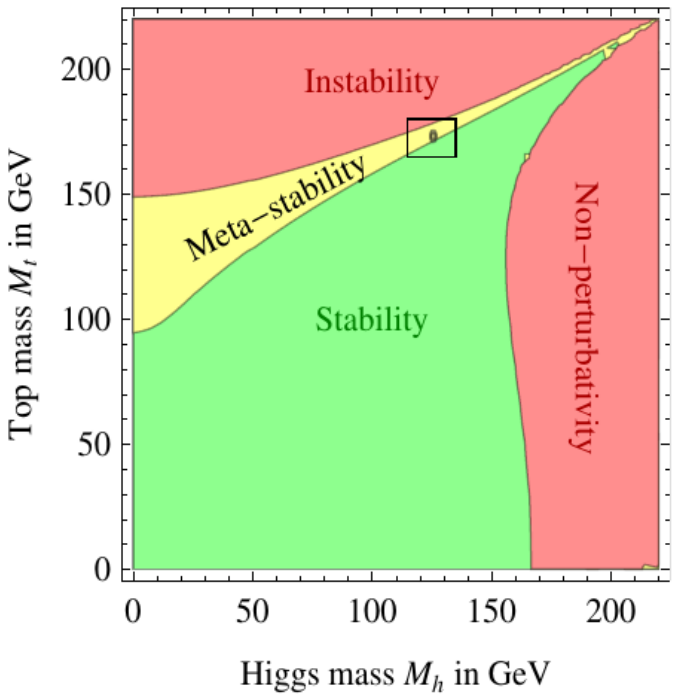




Top Physics

- Top quark is pivotal to understanding BSM and EWSB
- Largest coupling with the SM Higgs: hierarchy problem.
  - Top mass: Meta-stability of the SM vacuum.

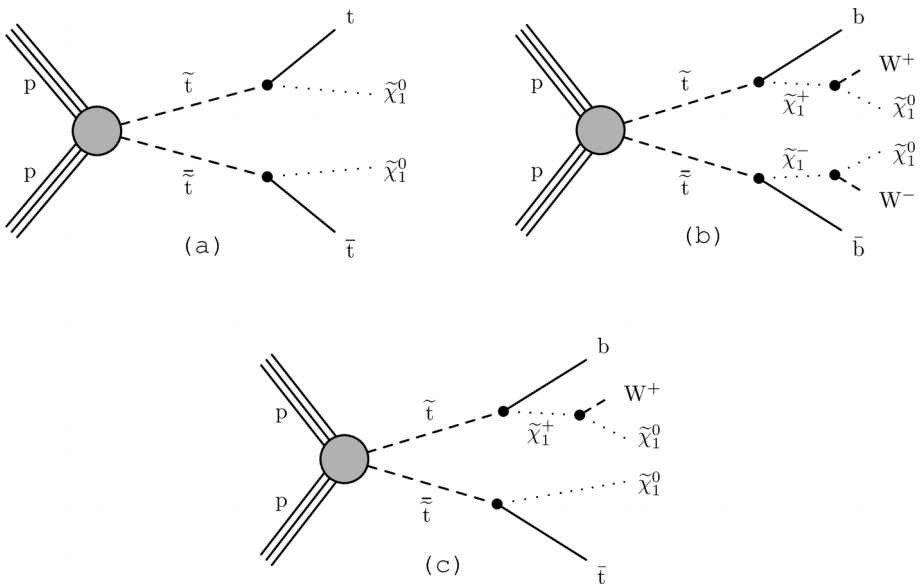


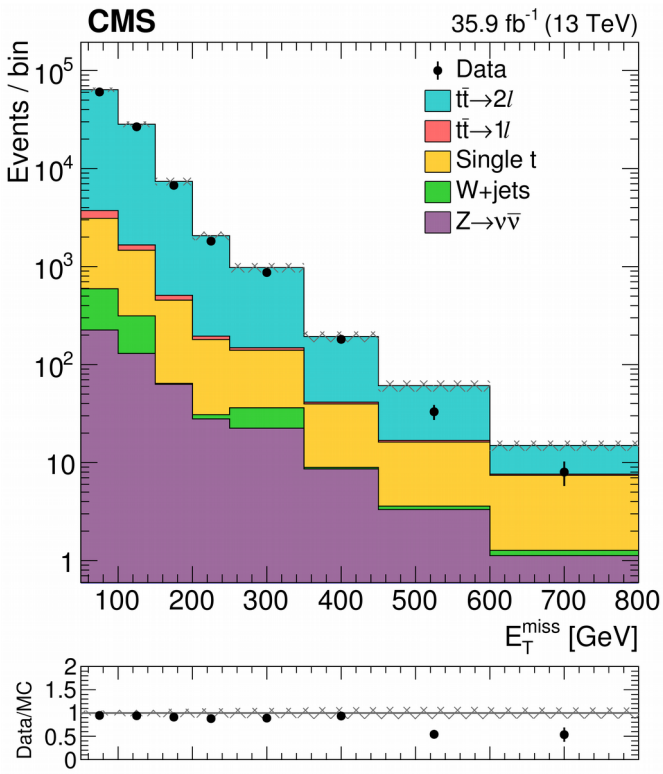


Degrassi et al, 2012; Buttazzo et al, 2013

Top Physics

- Top is pivotal to understanding BSM and EWSB
- Strongest interacting particle with the SM Higgs: hierarchy problem.
- Missing energy from top decays key backgrounds for many BSM searches.





CMS-SUS-16-051 (single-lepton stops)

Top Physics

- Top physics is high precision physics.
  - $\sigma_{t\bar{t}}$ (pb):

13 TeV				
Top Mass (GeV)	**Central value**	**Scale uncert.**	**PDF+alphaS uncert.**	**Mass uncert.**
172.5	831.76	+19.77 -29.20	+35.06 -35.06	+23.18 -22.45
173.2	815.96	+19.37 -28.61	+34.38 -34.38	+22.67 -21.95
14 TeV				
Top Mass (GeV)	**Central value**	**Scale uncert.**	**PDF+alphaS uncert.**	**Mass uncert.**
172.5	984.50	+23.21 -34.69	+41.31 -41.31	+27.14 -26.29
173.2	966.01	+22.68 -33.89	+40.52 -40.52	+26.54 -25.71

LHCTopWG

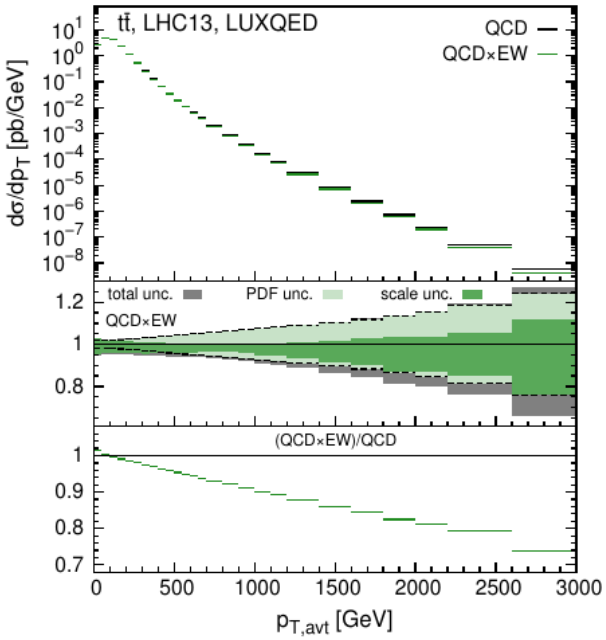
- Tops are everywhere at LHC (inc. LHCb and p-Pb!)
  - In Run 2 so far ~ 180 million $t\bar{t}$ pairs
- In Run 3, the LHC will become (nearly) GigaTop: need theory precision to match!

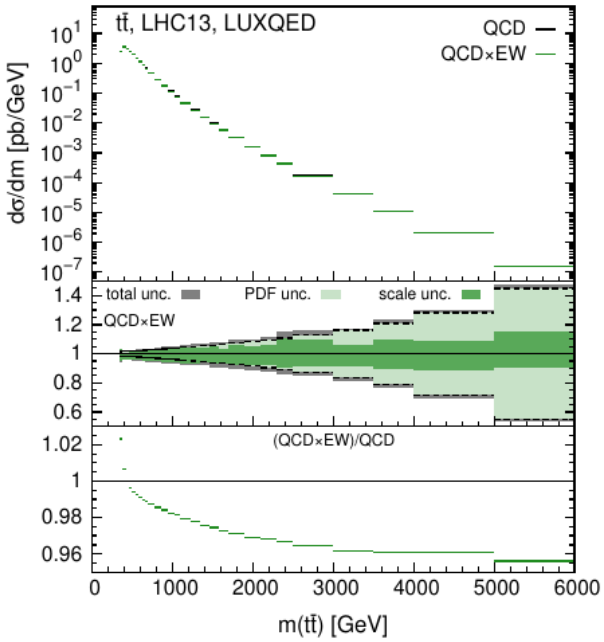
Parallels: Burns (p-Pb),Sierra (LHCb)

$$\alpha_s^2 \sim \alpha$$
$$NNLO \rightarrow NLO_{EW}$$

Top Physics

- Current state-of-the-art: NNLO + NLO_{EW} — Czakon et al, 1705.04105
- NLO_{EW} effects impact tails.
- Boosted tops → scale hierarchies → resummation
- Currently: NNLO + NNLL': — Czakon et al, 1803.07623
- Working towards NNNLL: — Wang et al, 1804.05218
- Moving beyond NWA: NLO + NLO_{EW} off-shell — Heinrich et al, 1709.08615; Denner et al, 1607.05571



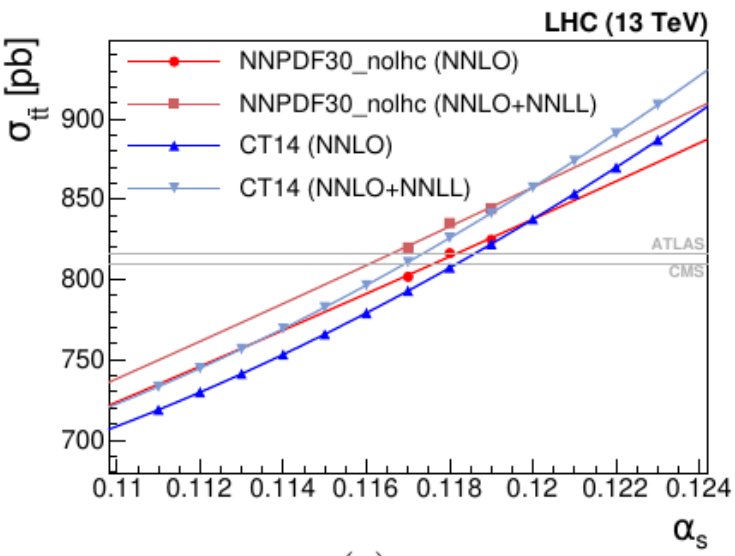


Also: matching with parton showers...

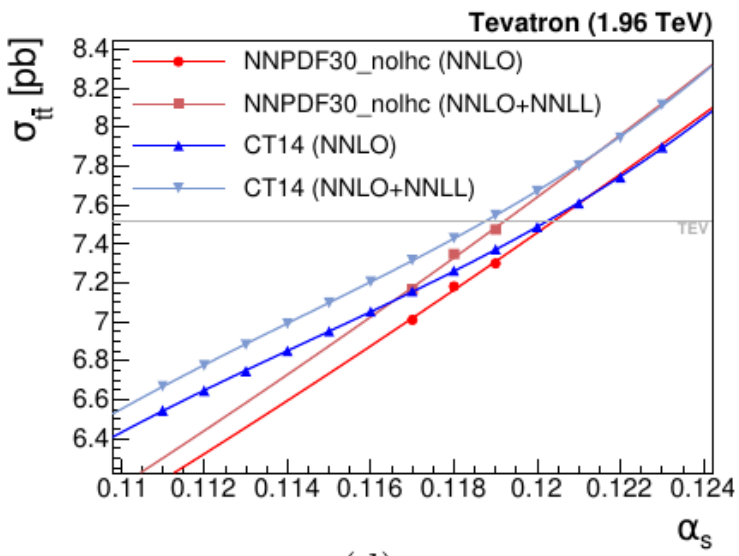
Example: α_S from $\sigma_{t\bar{t}}$

- Use NNLO (+NNLL) cross-sections at different energies to extract value of strong coupling.
- Current world average: $\alpha_s(M_Z^2) = 0.1181 \pm 0.0011$

	$\sigma_{t\bar{t}}$ [pb]	Statistical unc. [%]	Systematic unc. [%]	Luminosity unc. [%]	E_{beam} unc. [%]	Exp. m_t unc. [%]
ATLAS (7 TeV) [16]	182.5	1.7%	2.3%	2.0%	0.3%	$^{-0.2\%}_{+0.2\%}$
ATLAS (8 TeV) [16]	242.4	0.7%	2.3%	2.1%	0.3%	$^{-0.2\%}_{+0.2\%}$
ATLAS (13 TeV) [17]	816.3	1.0%	3.3%	2.3%	0.2%	$^{-0.3\%}_{+0.3\%}$
CMS (7 TeV) [13]	173.4	1.2%	2.5%	2.2%	0.3%	$^{-0.2\%}_{+0.2\%}$
CMS (8 TeV) [13]	244.1	0.6%	2.4%	2.6%	0.3%	$^{-0.4\%}_{+0.4\%}$
CMS (13 TeV) [14]	809.8	1.1%	4.7%	2.3%	0.2%	$^{-0.8\%}_{+0.8\%}$
TEV (1.96 TeV) [18]	7.52	2.7%	3.9%	2.8%	0.0%	$^{-1.1\%}_{+1.4\%}$



(c)



(d)

Also: high precision $\sin\theta_W$ in DY from ATLAS (Vincter).

Klijnsma, Bethke, Dissertori, Salam, 1708.07495

CMS, 1307.1907

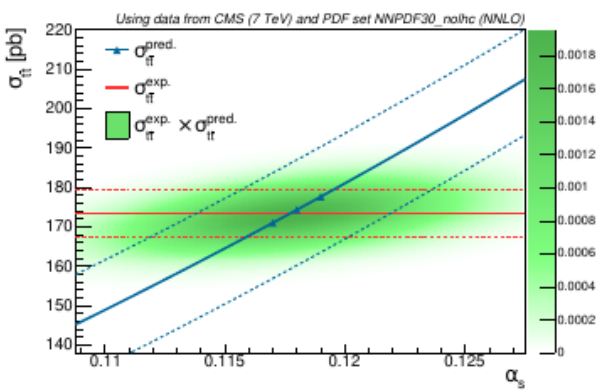
Example: α_S from $\sigma_{t\bar{t}}$

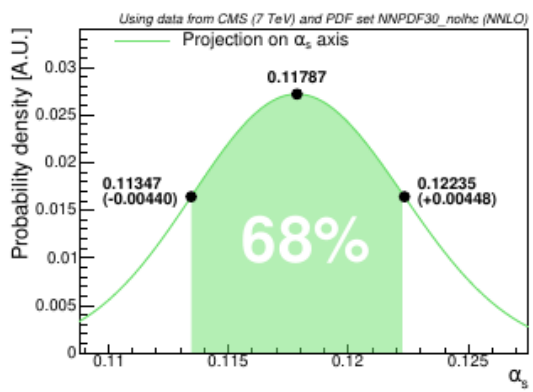
- Top quark pole mass $m_t = 173.2 \pm 0.87\,\mathrm{GeV}$
- Bayesian stats: Theory prediction=prior, experimental result=likelihood function.
- Marginalise posterior to get pdf for strong coupling constant.

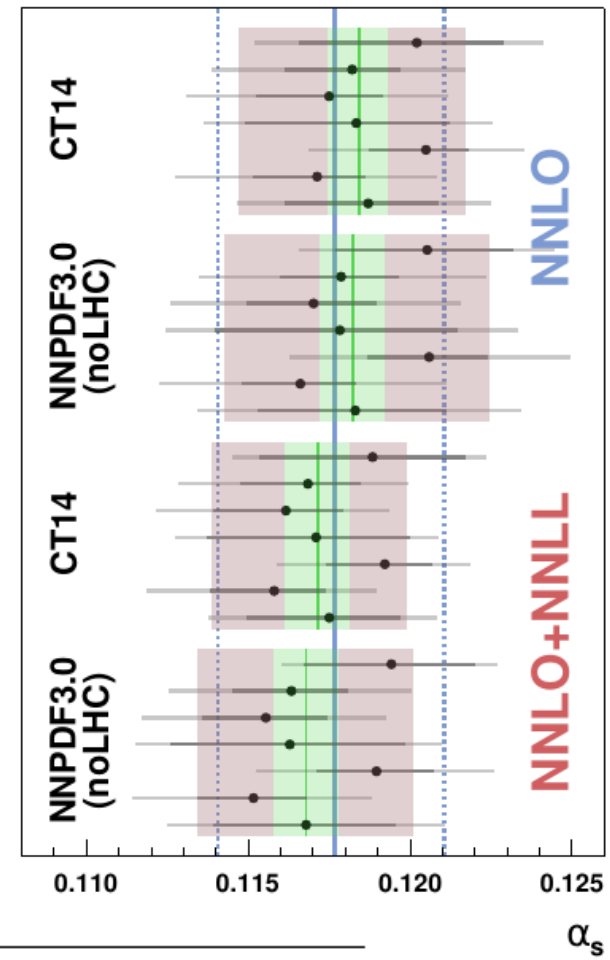
$$\alpha_s(M_Z^2) = 0.1177^{+0.0034}_{-0.0036}$$

$$f^{\mathrm{pred}}(\sigma_{t\bar{t}}\,|\,\alpha_s) = f^{\mathrm{PDF}}(\sigma_{t\bar{t}}\,|\,\alpha_s) \otimes f^{m_t}(\sigma_{t\bar{t}}\,|\,\alpha_s) \otimes f^{\mathrm{Scale}}(\sigma_{t\bar{t}}\,|\,\alpha_s)\,,$$

$$L(\alpha_s) = \int f^{\mathrm{pred}}(\sigma_{t\bar{t}}\,|\,\alpha_s) \cdot f^{\mathrm{exp}}(\sigma_{t\bar{t}}\,|\,\alpha_s)\,\mathrm{d}\sigma_{t\bar{t}}\,.$$







	Center	Stat.	Syst.	E_{beam}	Lumi.	m_t	PDF	Scale	Total
Average	0.1177	$^{+0.0003}_{+0.0003}$	$^{+0.0007}_{+0.0007}$	$^{+0.0001}_{+0.0001}$	$^{+0.0006}_{+0.0007}$	$^{+0.0012}_{+0.0013}$	$^{+0.0020}_{+0.0024}$	$^{+0.0022}_{+0.0021}$	$^{+0.0034}_{-0.0036}$

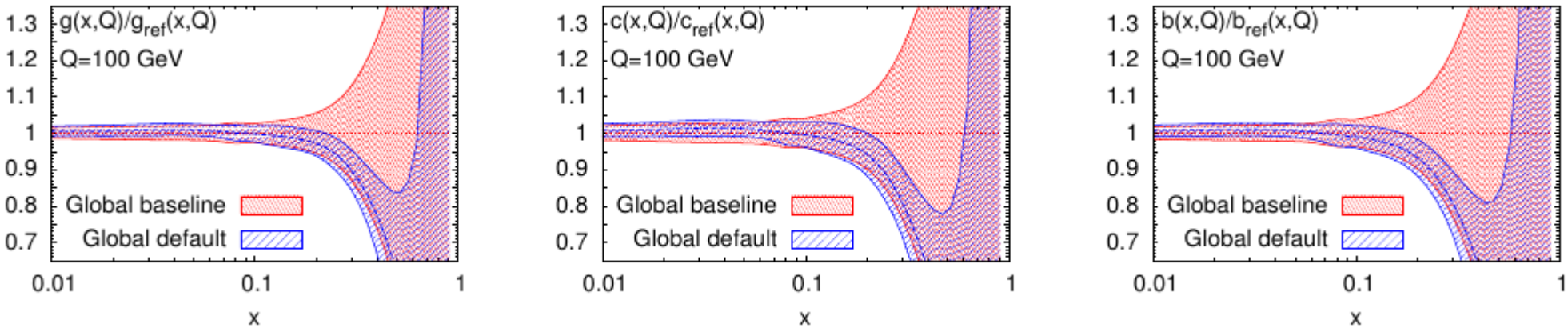
Klijnsma, Bethke, Dissertori, Salam, 1708.07495

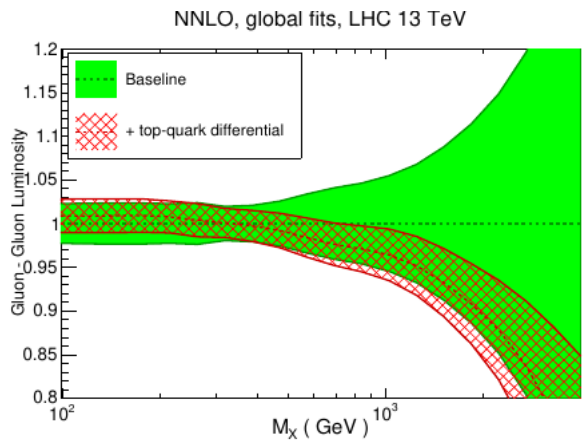
CMS, 1307.1907

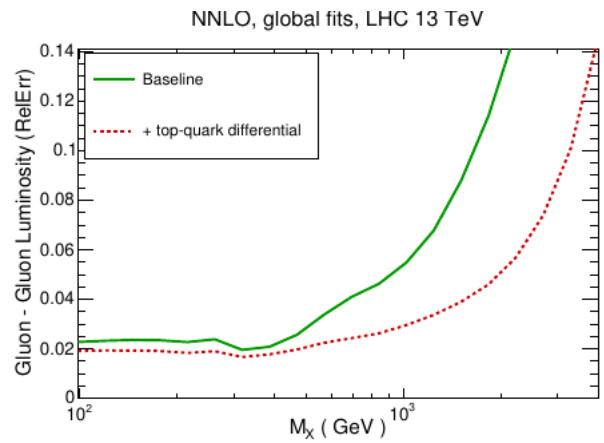
Example: Large-x gluon PDF from differential $\sigma_{t\bar{t}}$

- NNLO fully differential distributions (stable tops)
- Enables NNLO PDF fits with top-quark pair distributions.
- Decreases uncertainty in PDFs at large-x.

Czakon, Heymes, Mitov, 1511.00549







Czakon et al, 1611.08609

CMS, 1711.03143

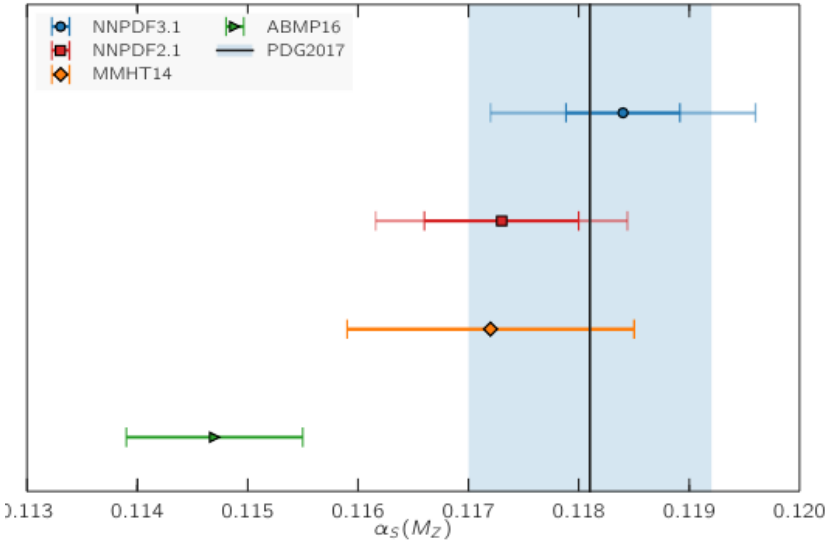
NNPDF Collaboration, 1706.00428

NNPDF with NNLO distributions

- Include NNLO differential top pairs, NNLO Z transverse momentum, NNLO inclusive jet production.
- Allows extraction of strong coupling constant
- Current world average: $\alpha_s(M_Z) = 0.1181 \pm 0.0011$
- Result from NNPDF: $\alpha_s^{\rm NNLO}(m_Z) = 0.1185 \pm 0.0005^{\rm exp} \pm 0.0001^{\rm meth} \pm 0.0011^{\rm th} = 0.1185 \pm 0.0012\ (1\%)\,,$

Future possible improvements from:

- Use of boosted tops: (NLO EW, resummation)
- Particle-level distributions: towards NNLO with decays.

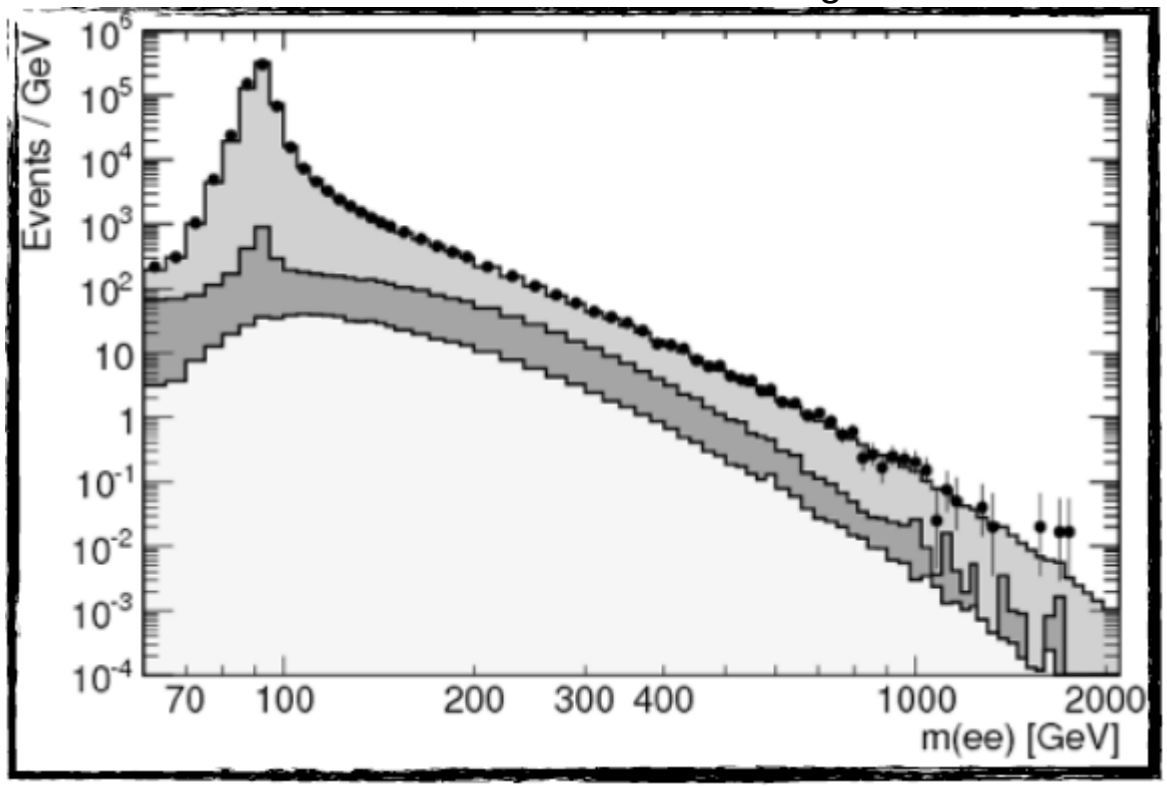


Ball et al (NNPDF), 1802.03398

EFT for BSM

- Precision measurements and calculations applicable to BSM interpretations too.
  - Particularly true for differential information!

Image Credit: F Riva



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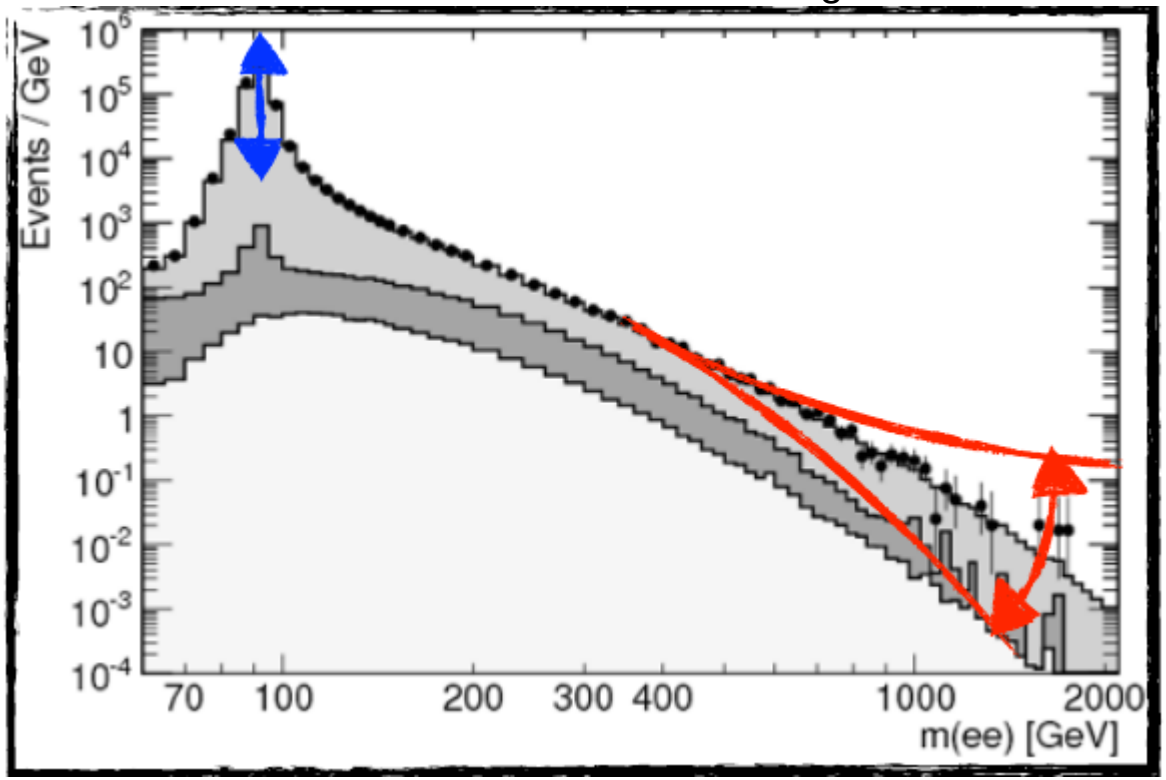

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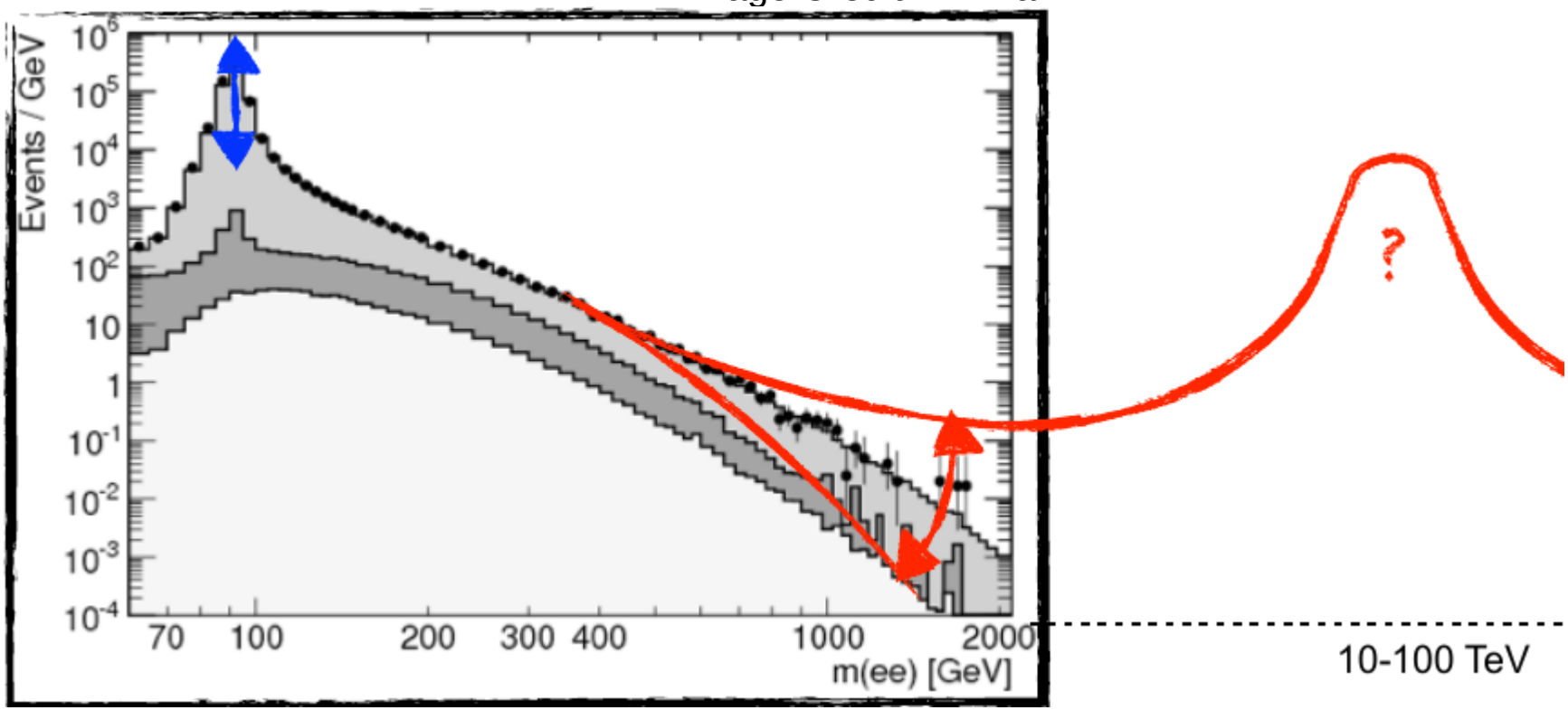


EFT for BSM

$$\mathcal{L}^{eff} = \mathcal{L}^{SM} + \sum_i c_i^{(6)} \frac{\mathcal{O}_i^{(6)}}{\Lambda^2} + \sum_i c_i^{(8)} \frac{\mathcal{O}_i^{(8)}}{\Lambda^4} + \cdots$$

- D5: Weinberg operator
- D6: 59 operators.
- Study effects of these, or a subset
- E.g. those which affect the top physics: 16 operators

$$O_{qq}^{(1)} = (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q) \qquad O_{uW} = (\bar{q}\sigma^{\mu\nu}\tau^I u)\tilde{\varphi} W_{\mu\nu}^I \qquad O_{\varphi q}^{(3)} = i(\varphi^\dagger \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}\gamma^\mu \tau^I q)$$

$$O_{qq}^{(3)} = (\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q) \qquad O_{uG} = (\bar{q}\sigma^{\mu\nu} T^A u)\tilde{\varphi} G_{\mu\nu}^A \qquad O_{\varphi q}^{(1)} = i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}\gamma^\mu q)$$

$$O_{uu} = (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u) \qquad O_G = f_{ABC} G_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu} \qquad O_{uB} = (\bar{q}\sigma^{\mu\nu} u)\tilde{\varphi} B_{\mu\nu}$$

$$O_{qu}^{(8)} = (\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u) \qquad O_{\tilde{G}} = f_{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu} \qquad O_{\varphi u} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}\gamma^\mu u)$$

$$O_{qd}^{(8)} = (\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d) \qquad O_{\varphi G} = (\varphi^\dagger \varphi) G_{\mu\nu}^A G^{A\mu\nu} \qquad O_{\varphi \tilde{G}} = (\varphi^\dagger \varphi) \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$$

$$O_{ud}^{(8)} = (\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)\,.$$

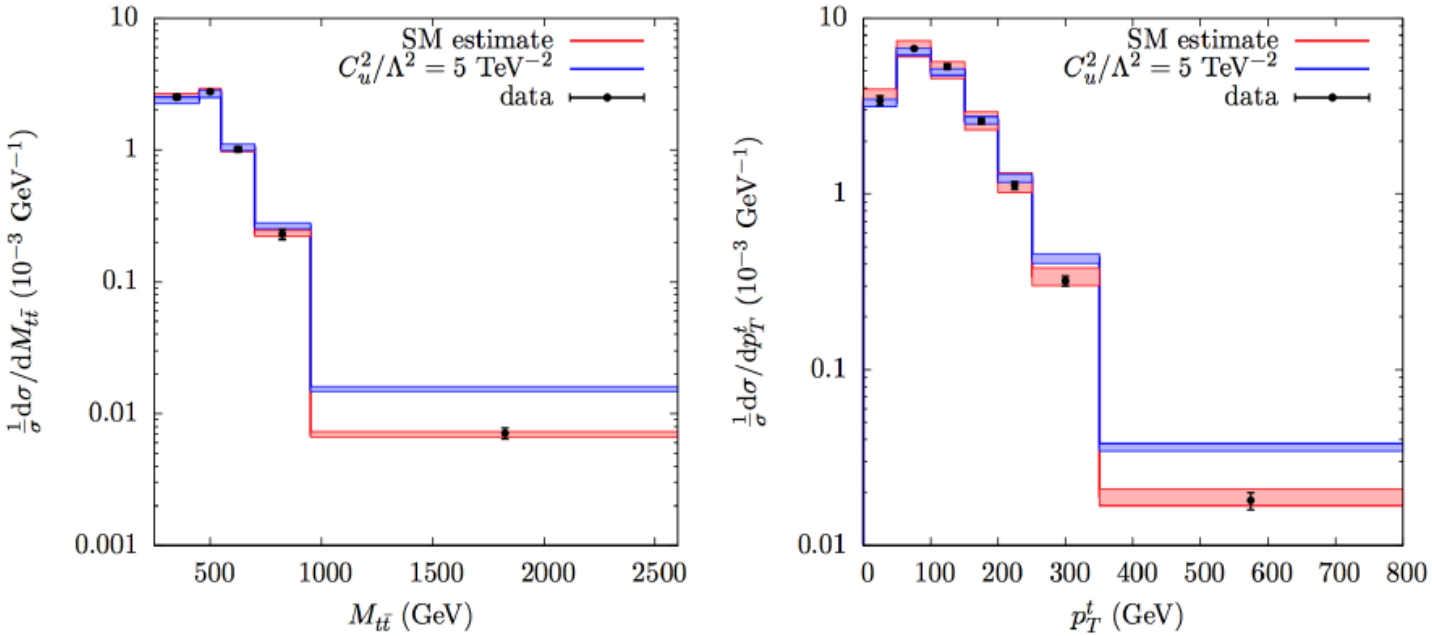
EFT for BSM

$$\mathcal{L}^{eff} = \mathcal{L}^{SM} + \sum_i c_i^{(6)} \frac{\mathcal{O}_i^{(6)}}{\Lambda^2} + \sum_i c_i^{(8)} \frac{\mathcal{O}_i^{(8)}}{\Lambda^4} + \cdots$$

Hot off the press: Top-EFT at ILC/CLIC. Improve HL-LHC constraints by $\mathcal{O}(10^2)$

Durieux et al, 1807.02121

Sensitivity in top-pair production distributions.
Moving from parton → particle level distributions



Buckley et al, 1512.03360
Miller Parallel

EFT for BSM

- Neutral Diboson Processes: pp → ZZ, WW
  - Probe anomalous triple gauge couplings
- NNLO differential for all relevant final states, off-shell

Grazzini et al, 1507.02565

Kallweit, Wiesemann, 1806.05941

- Only enter at dimension at 8 in the effective Lagrangian
  - 4 of these operators, 3 which violate CP.

Degrande, 1308.6323

$$\mathcal{O}_{WW} = iH^\dagger W_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H\,,$$
$$\mathcal{O}_{BW} = iH^\dagger B_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H\,,$$
$$\mathcal{O}_{BB} = iH^\dagger B_{\mu\nu} B^{\mu\rho} \{D_\rho, D^\nu\} H\,.$$

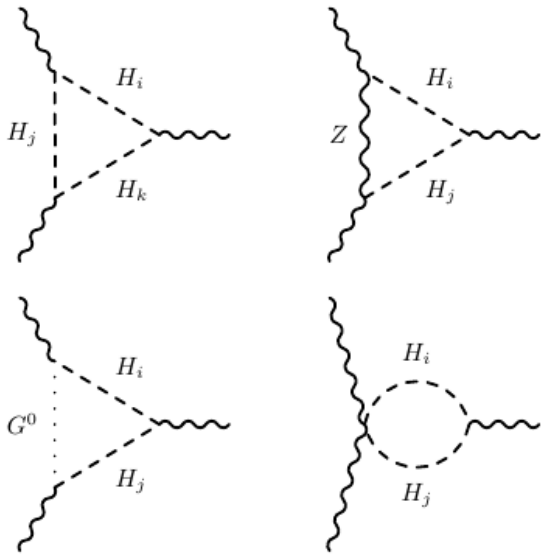
$$\Gamma^{\alpha\beta\mu}(q_1, q_2, P) = \frac{i(P^2 - m_Z^2)}{m_Z^2} \left[f_4^Z (P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) - f_5^Z \epsilon^{\mu\alpha\beta\rho} (q_1 - q_2)_\rho \right] . \quad (1)$$

$$\longleftrightarrow \quad f_4^Z = \frac{M_Z^2 v^2}{2 c_W s_W} \frac{(c_W^2 c_{WW} + 2 c_W s_W c_{BW} + 4 s_W^2 c_{BB})}{\Lambda^4}\,,$$

Corbett, MJD, Englert, Nordstrom, 1710.07530

Belusca-Maito et al, 1710.05563

EFT for BSM



- What models are we probing?
- Spin-0: Complex 2HDM
- Cross-sections are $\mathcal{O}(10^{-3})\,\mathrm{fb}$

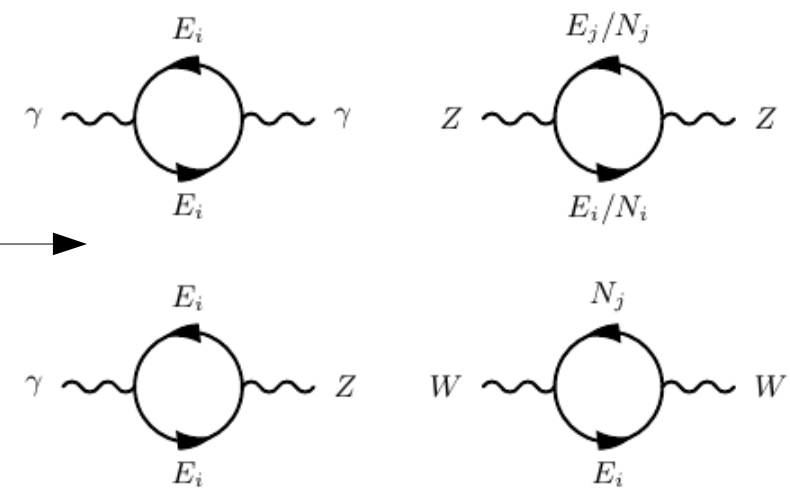
Spin 0

Matching shows C2HDM operators are dimension 12!

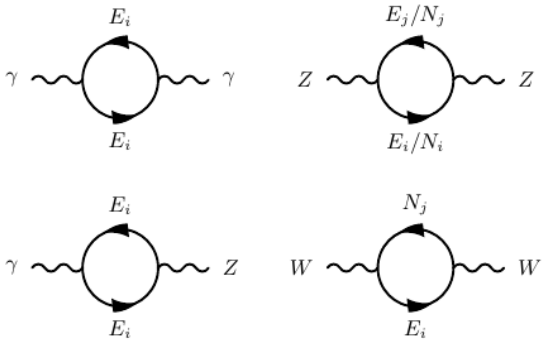
- Spin ½: Vectorlike fermions
- Small cross-sections at LHC.
- Need to take STU constraints into account

Spin ½

$$
\begin{aligned}
-\mathcal{L}_{\text{mass}} \supset\; & m_l \bar{l}'_L l''_R + m_e \bar{e}''_L e'_R + m_\nu \bar{\nu}''_L \nu'_R + \text{h.c.} \\
& + Y'_c (\bar{l}'_L H) e'_R + Y''_c (\bar{l}''_R H) e''_L + \text{h.c.} \\
& + Y'_\nu (\bar{l}'_L \widetilde{H}) \nu'_R + Y''_\nu (\bar{l}''_R \widetilde{H}) \nu''_L + \text{h.c.}\,.
\end{aligned}
$$



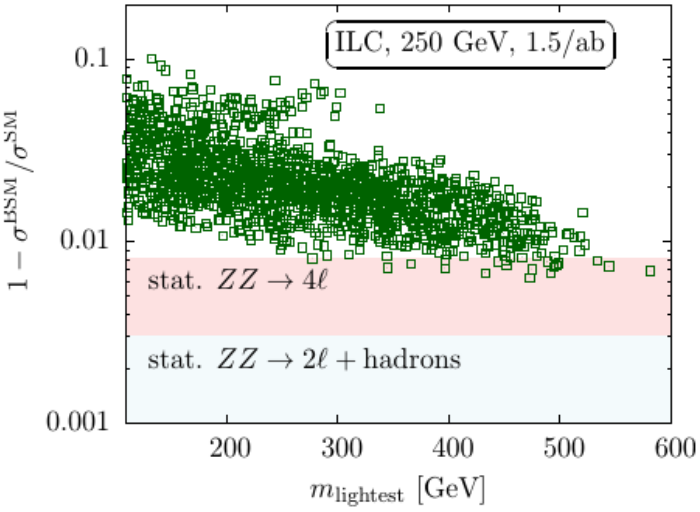
Corbett, MJD, Englert, Nordstrom, 1710.07530 Gounaris et al, 9910395 Belusca-Maito et al, 1710.05563

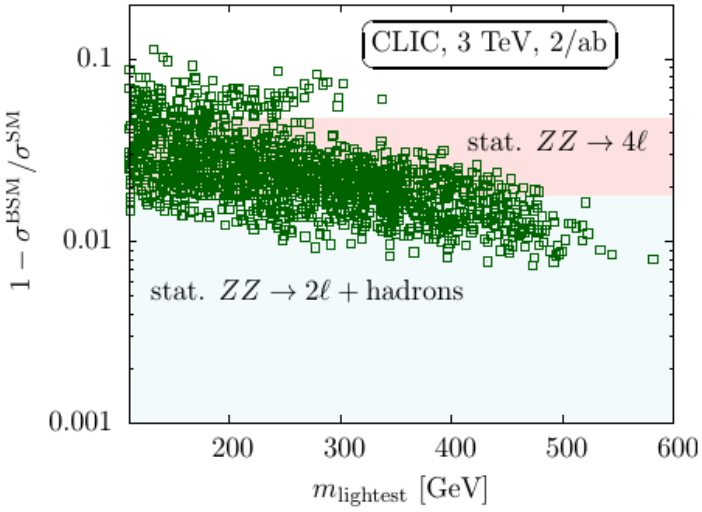


EFT for BSM

- Spin ½: Vectorlike fermions
- Small cross-sections again at LHC.

Need to take STU constraints into account





Similar ideas for Higgs:

Craig et al, 1305.5251

Englert, McCullough 1330.1526

D8 operators can be generated by

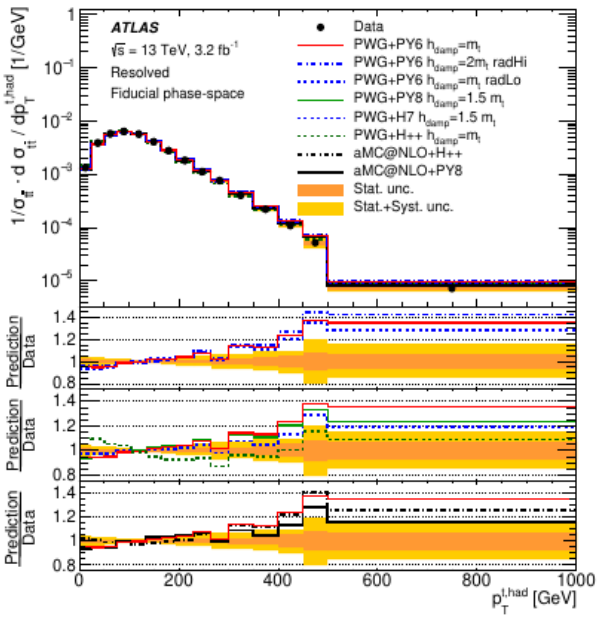
Bellazzini, Riva, 1806.09640

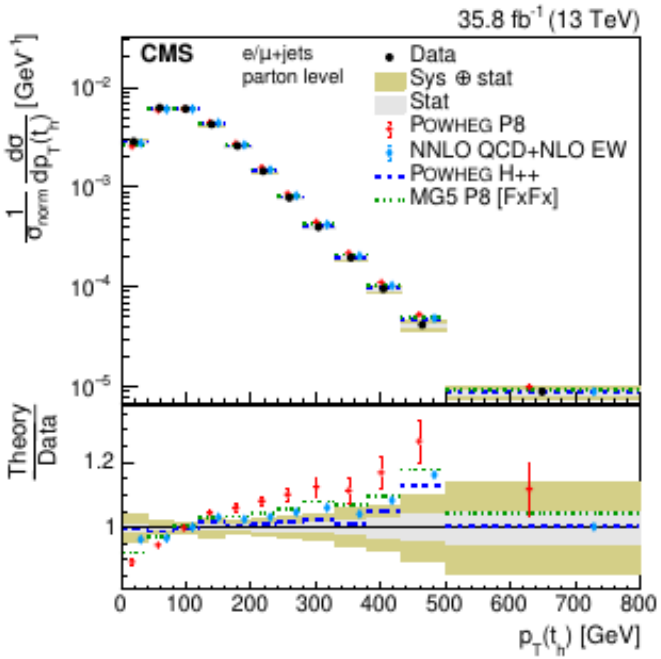
→ Spin 2 resonances (e.g. KK gravitons)

→ Pseudo-Goldstini (non-linearly realised supersymmetry)

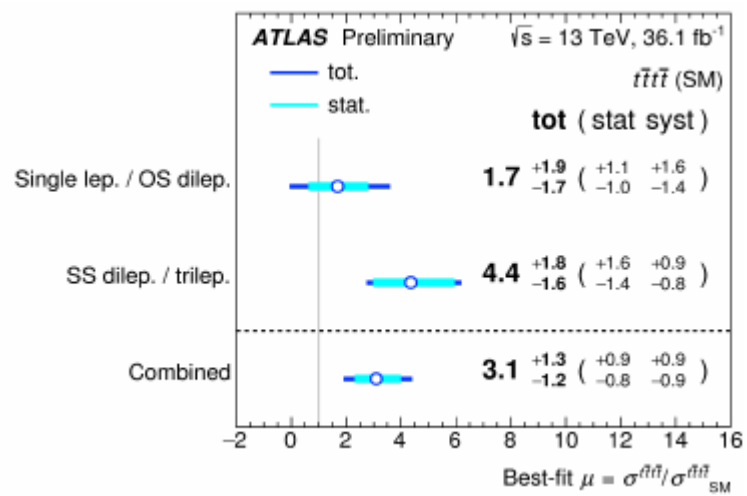
Corbett, MJD, Englert, Nordstrom, 1710.07530 Gounaris et al, 9910395 Belusca-Maito et al, 1710.05563

To be resolved

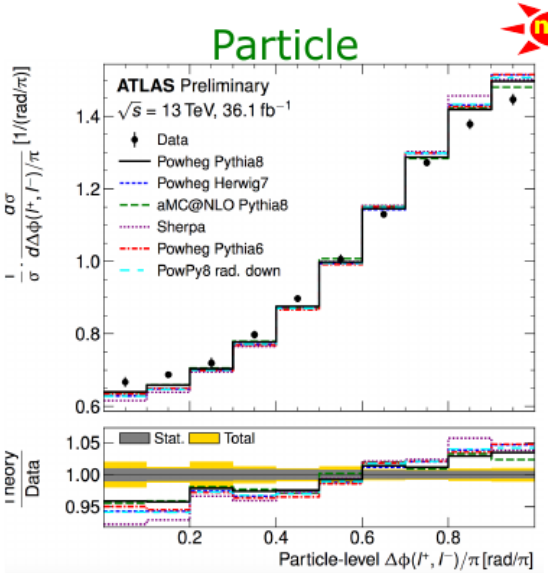




lepton+jets

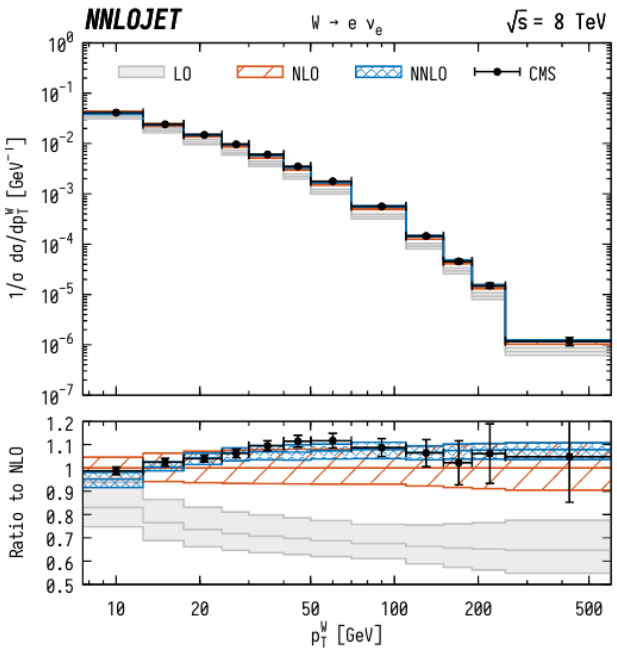


Particle

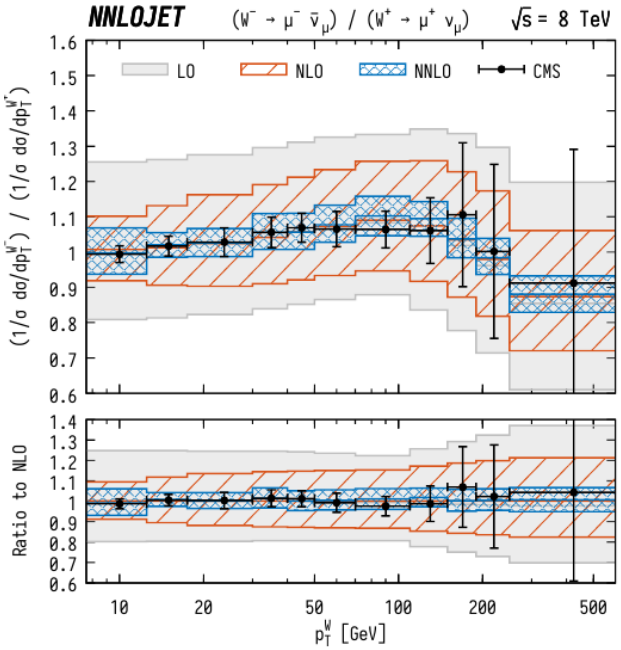


Parallels: Burns, Berta, Peters, Zenaiev

Theory frontier continues to move

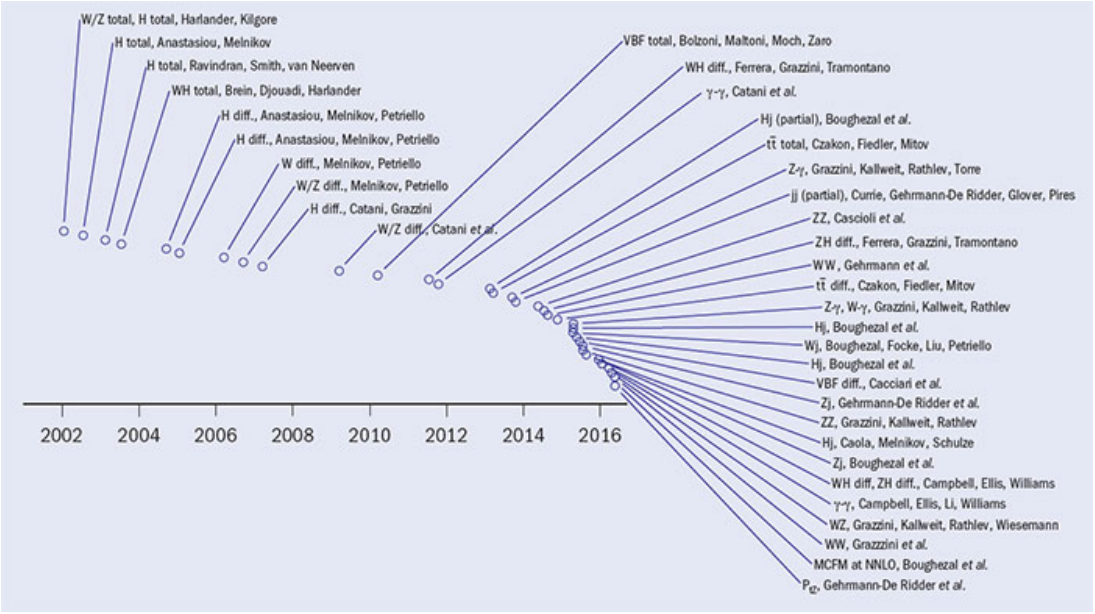


NNLO pt distributions in vector boson production



Gehrmann-de Ridder et al, 1712.07543

- Differential distributions
- Finite-mass effects in diboson production
  - NNLO QCD + NLO EW
  - Decays and matching to showers



2017 LH Proceedings, 1803.07977

Image credit: Salam

Les Houches Top Quark Wishlist

process	known	desired
$pp \to t\bar{t}$	$\mathrm{N^2LO_{QCD}}$+$\mathrm{NLO_{EW}}$ $\mathrm{NLO_{QCD}}$ (w/ decays, off-shell effects) $\mathrm{NLO_{EW}}$ (w/ decays, off-shell effects)	$\mathrm{N^2LO_{QCD}}$ (w/ decays)
$pp \to t\bar{t} + j$	$\mathrm{NLO_{QCD}}$ (w/ decays) $\mathrm{NLO_{EW}}$	$\mathrm{N^2LO_{QCD}}$+$\mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t} + 2j$	$\mathrm{NLO_{QCD}}$ (w/ decays)	$\mathrm{NLO_{QCD}}$+$\mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t} + Z$	$\mathrm{NLO_{QCD}}$+$\mathrm{NLO_{EW}}$ (w/ decays)	
$pp \to t\bar{t} + W$	$\mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$	$\mathrm{NLO_{QCD}}$+$\mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t/\bar{t}$	$\mathrm{N^2LO_{QCD}}$*(w/ decays)	$\mathrm{N^2LO_{QCD}}$+$\mathrm{NLO_{EW}}$ (w/ decays)

Table I.4: Precision wish list: top quark final states. $\mathrm{N^2LO_{QCD}}^*$ means a calculation using the structure function approximation.

2017 LH Proceedings, 1803.07977

Les Houches Vector Bosons Wishlist (partial)

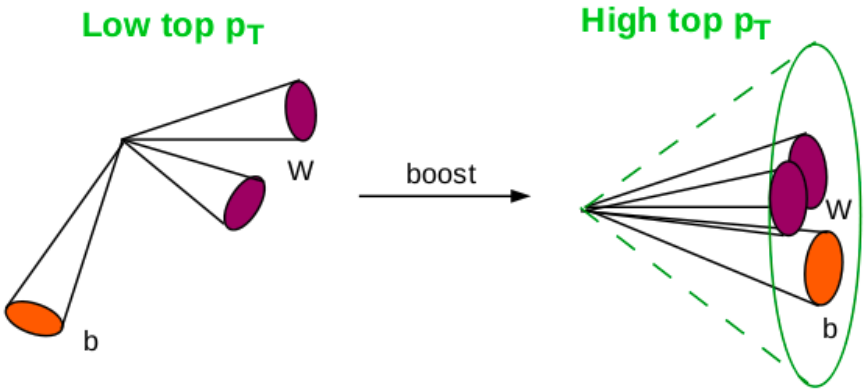
process	known	desired
$pp \to V$	$\mathrm{N^3LO}_{\mathrm{QCD}}^{(z\to 0)}$ (incl.) $\mathrm{N^2LO}_{\mathrm{QCD}}$ $\mathrm{NLO}_{\mathrm{EW}}$	$\mathrm{N^3LO}_{\mathrm{QCD}}+\mathrm{N^2LO}_{\mathrm{EW}}+\mathrm{N}^{(1,1)}\mathrm{LO}_{\mathrm{QCD}\otimes\mathrm{EW}}$
$pp \to VV'$	$\mathrm{N^2LO}_{\mathrm{QCD}}$ $\mathrm{NLO}_{\mathrm{EW}}$ $\mathrm{NLO}_{\mathrm{QCD}}$ (gg channel)	$\mathrm{N^2LO}_{\mathrm{QCD}}+\mathrm{NLO}_{\mathrm{EW}}$ $\mathrm{NLO}_{\mathrm{QCD}}$ (gg channel, w/ massive loops)
$pp \to V + j$	$\mathrm{N^2LO}_{\mathrm{QCD}}+\mathrm{NLO}_{\mathrm{EW}}$	hadronic decays
$pp \to V + 2j$	$\mathrm{NLO}_{\mathrm{QCD}}+\mathrm{NLO}_{\mathrm{EW}}$ $\mathrm{NLO}_{\mathrm{EW}}$	$\mathrm{N^2LO}_{\mathrm{QCD}}$
$pp \to V + b\bar{b}$	$\mathrm{NLO}_{\mathrm{QCD}}$	$\mathrm{N^2LO}_{\mathrm{QCD}}$ $+\mathrm{NLO}_{\mathrm{EW}}$
$pp \to VV' + 1j$	$\mathrm{NLO}_{\mathrm{QCD}}$ $\mathrm{NLO}_{\mathrm{EW}}$ (w/o decays)	$\mathrm{NLO}_{\mathrm{QCD}}+\mathrm{NLO}_{\mathrm{EW}}$
$pp \to VV' + 2j$	$\mathrm{NLO}_{\mathrm{QCD}}$	$\mathrm{NLO}_{\mathrm{QCD}}+\mathrm{NLO}_{\mathrm{EW}}$

+jets, Higgs (not shown)...

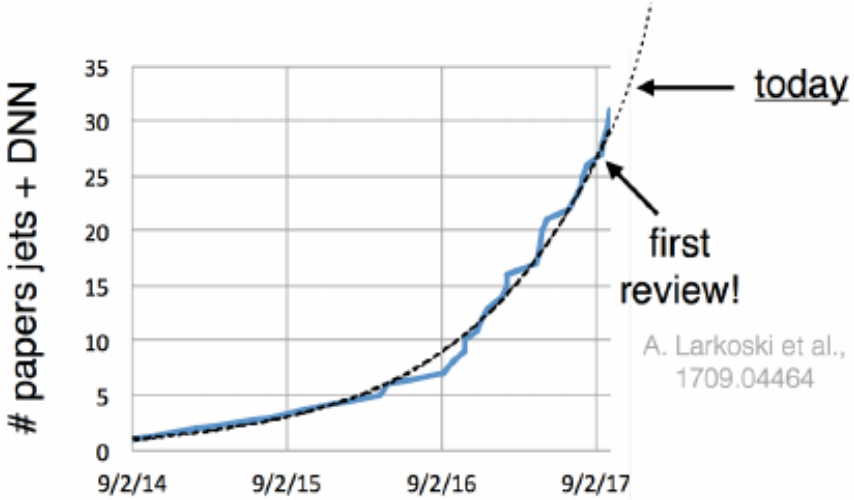
2017 LH Proceedings, 1803.07977

Machine learning for phenomenology

- Many problems in collider phenomenology are now being attacked with machine learning (ML) methods.
- In particular: deep learning.



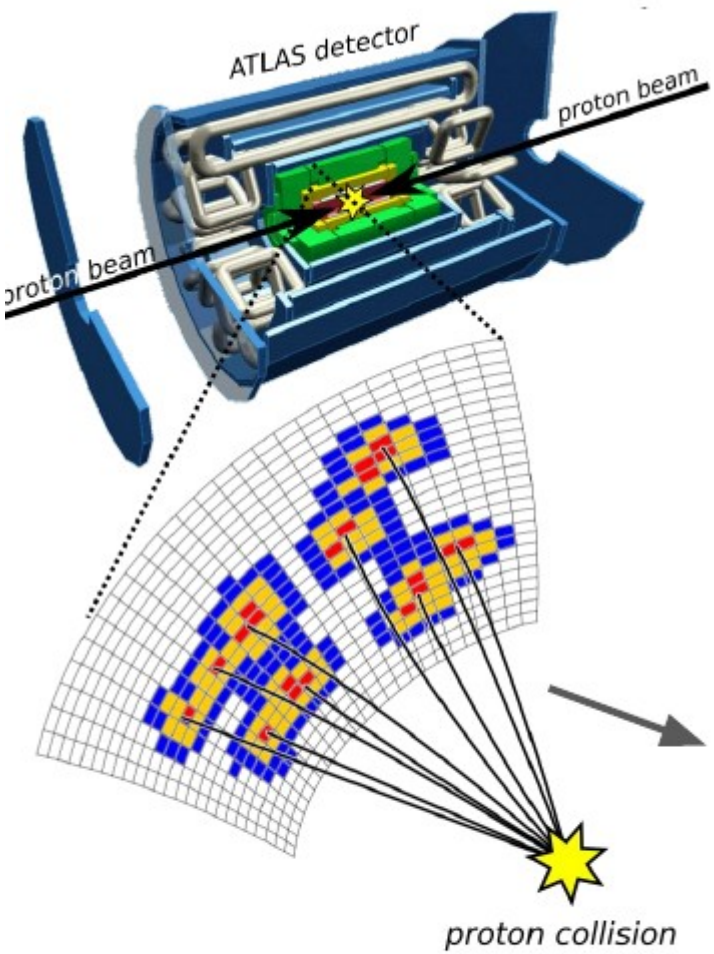
- (Boosted) Jet/Resonance Tagging
- Fast detector simulations (showers in calorimeters, etc)
- Pileup mitigation
- Jet clustering
- Bump-hunting
- More...



Larkoski et al, 1709.04464
Guest et al, 1806.11484

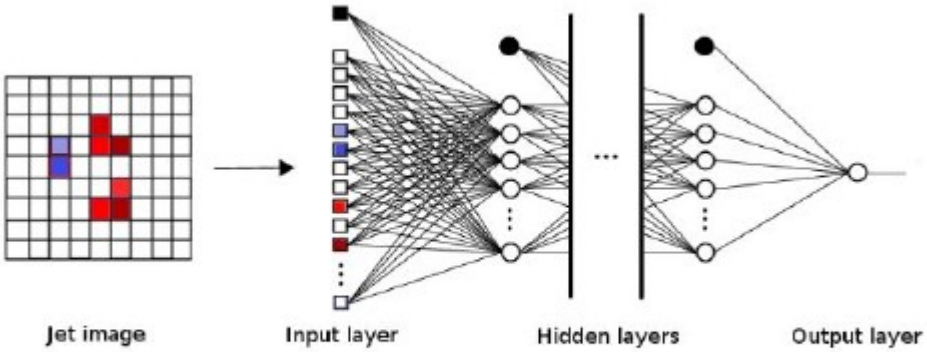
Plenary: Yokohama, Sexton-Kennedy
Parallel Sessions: Stoye, Schramm

Machine Learning Jet Substructure



Flattening the calorimeter into a 2D image...

"Jet Images": Use deep neural networks used in computer vision to discriminate between jets.

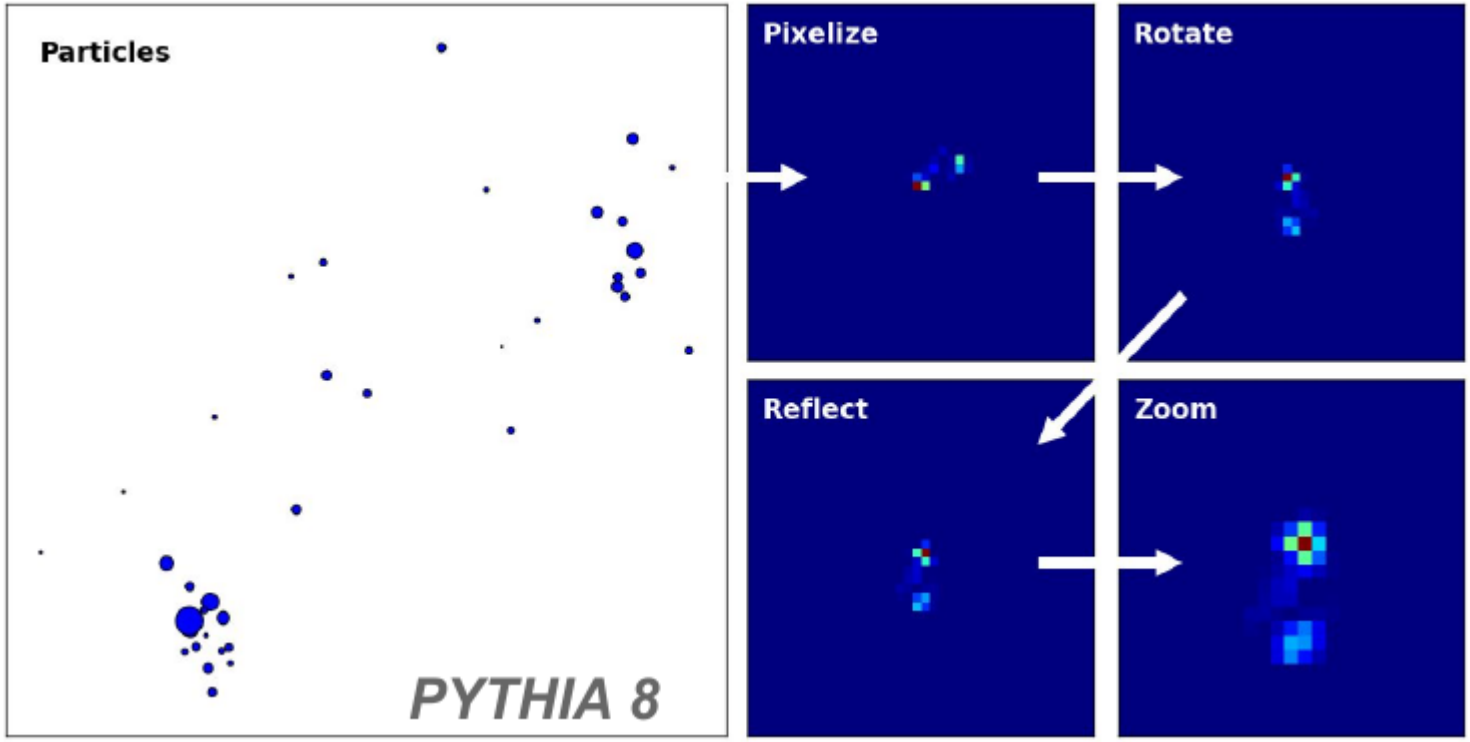


de Oliveira et al, 2015

Image: N. Dawe

Machine Learning Jet Substructure

- Sum transverse energy in calo tower in 0.1x0.1 grid in eta-phi space.
  - Perform translations, rotations, reflections in eta-phi space
    - (Zoom to minimise pt dependence)
      - Crop and normalise

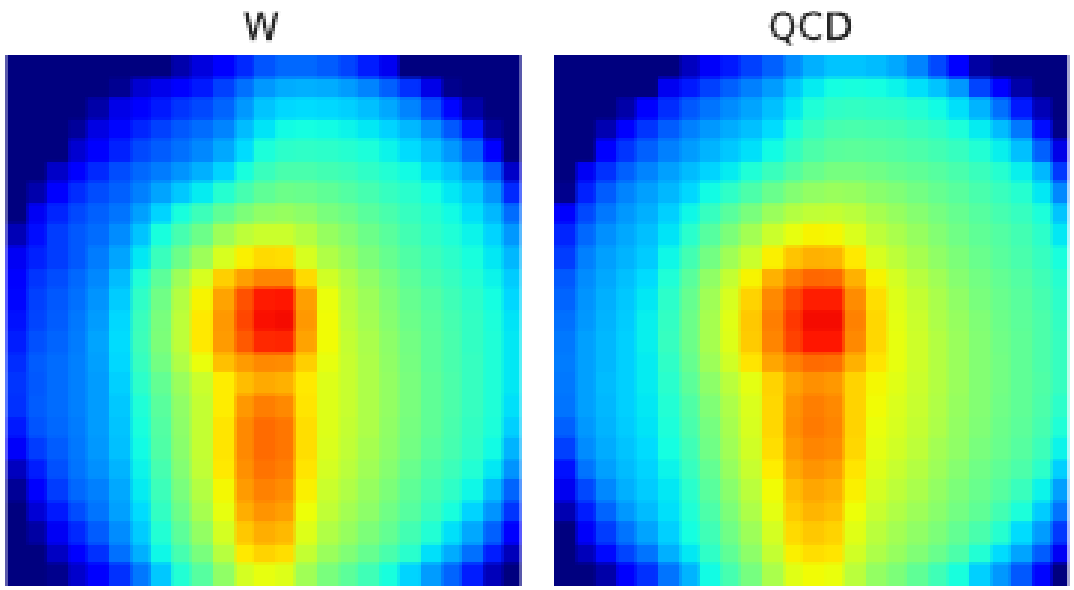


Barnard, Dawe, MJD, Rajcic, 1609.00607

de Oliveira et al, 2015

Machine Learning Jet Substructure

- Sum transverse energy in calo tower in 0.1x0.1 grid in eta-phi space.
  - Perform translations, rotations, reflections in eta-phi space
    - (Zoom to minimise pt dependence)
      - Crop and normalise
  - Average Jet-Images for W jets and QCD jets



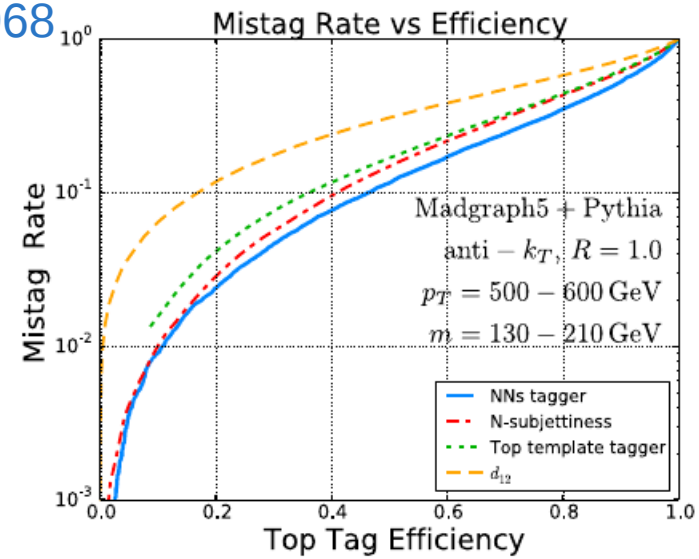
Barnard, Dawe, MJD, Rajcic, 1609.00607

de Oliveira et al, 2015

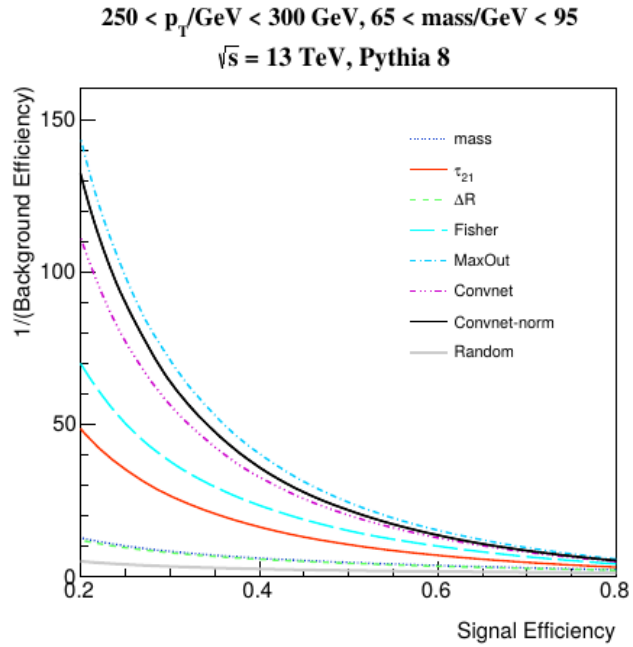
Taggers for Everything: MC

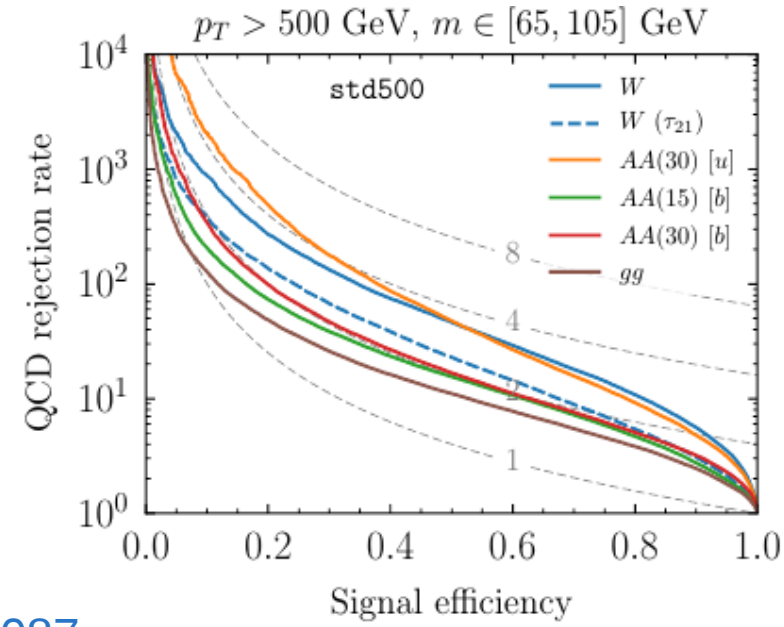
- Quark vs gluon, W/Z, Higgs, top, anti-QCD and BSM...

1501.05968

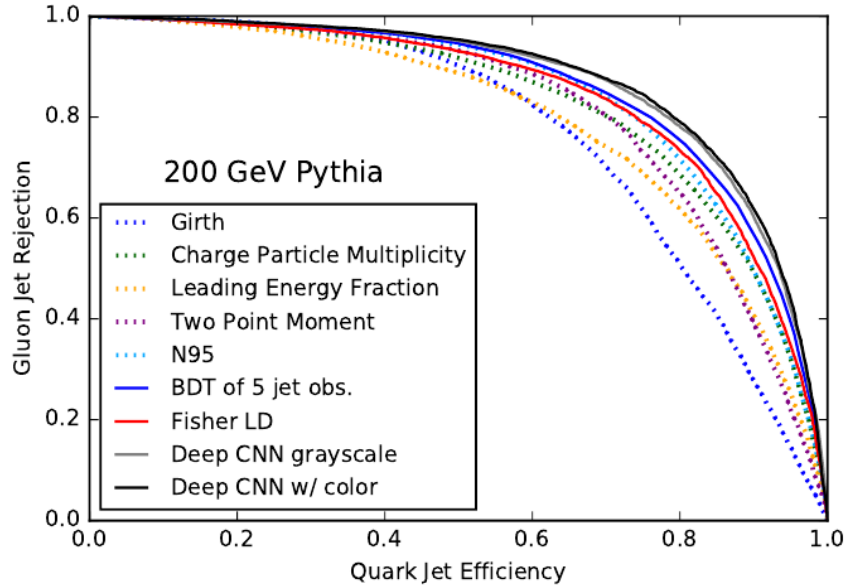


1511.05190





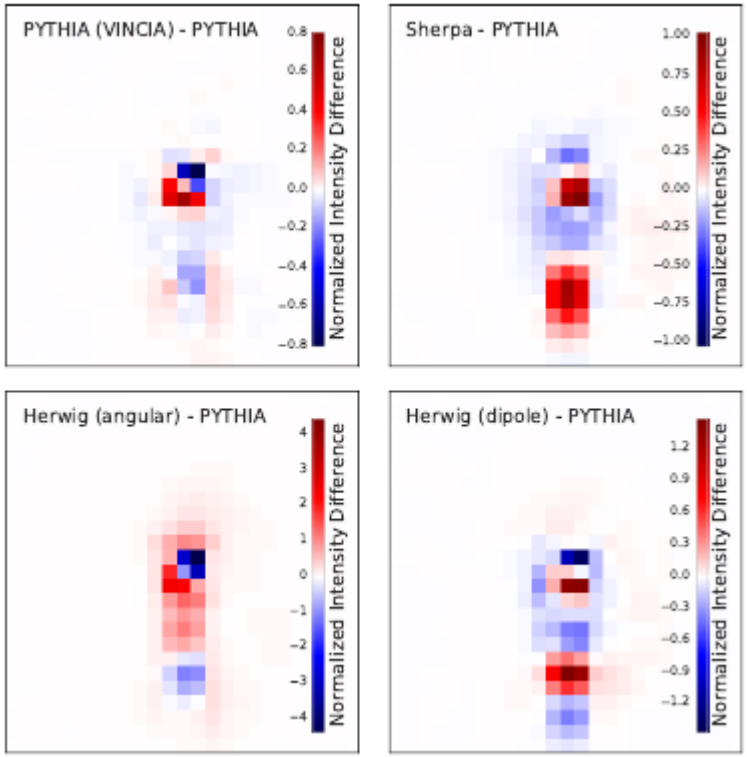
1612.01551



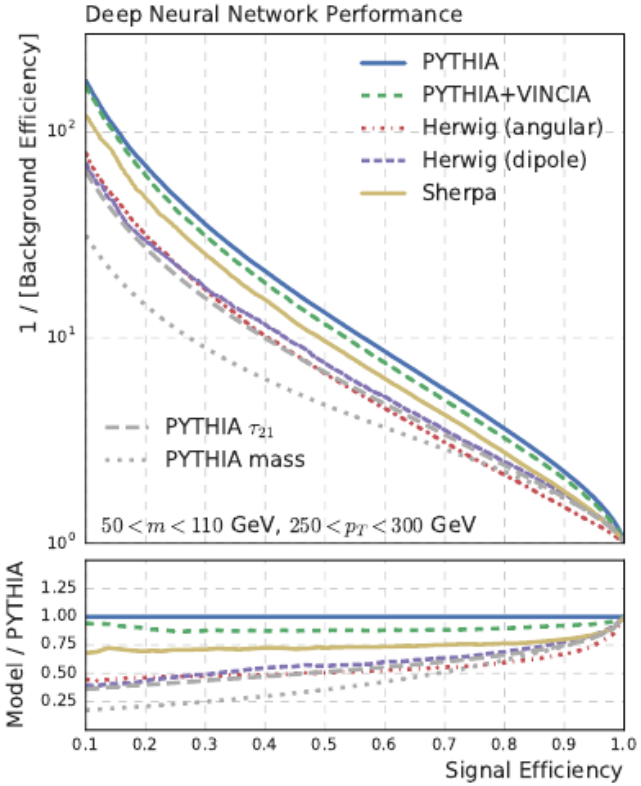
1709.01087

Machine Learning Jet Substructure

- Supervised learning: need a known training sample



Sensitive to differences between parton showers

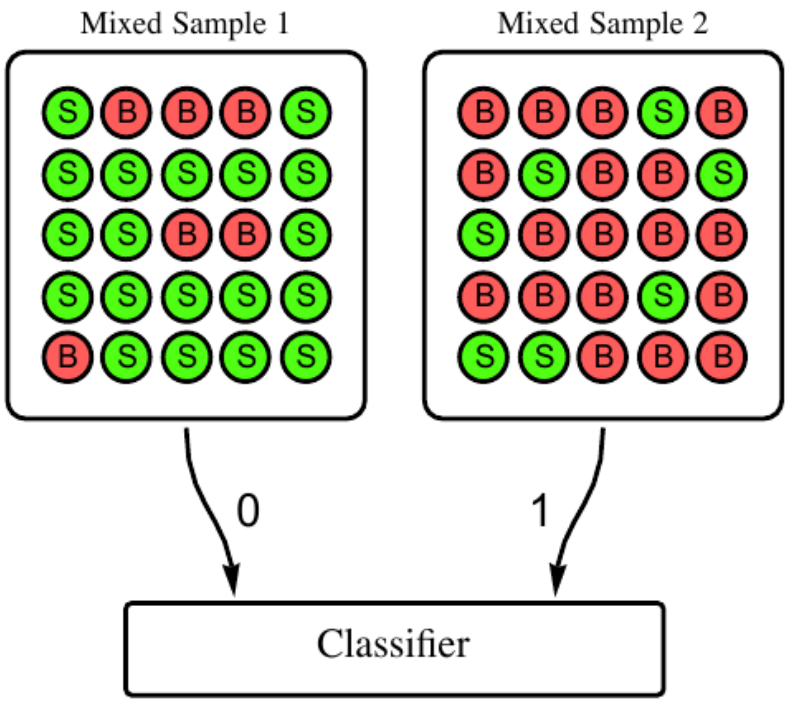


Train on data from regions of high signal purity?
e.g. semileptonic top.

Barnard, Dawe, MJD, Rajcic, 1609.00607

Machine Learning Jet Substructure

- Classifcation without Labels (CWoLa): train on mixtures of classes (QCD jets, W jets)
  - Two samples of events M1 and M2, with different proportions of signal and background.
    - Train a supervised neural network to discriminate between M1 and M2.



Dery et al 1702.00414

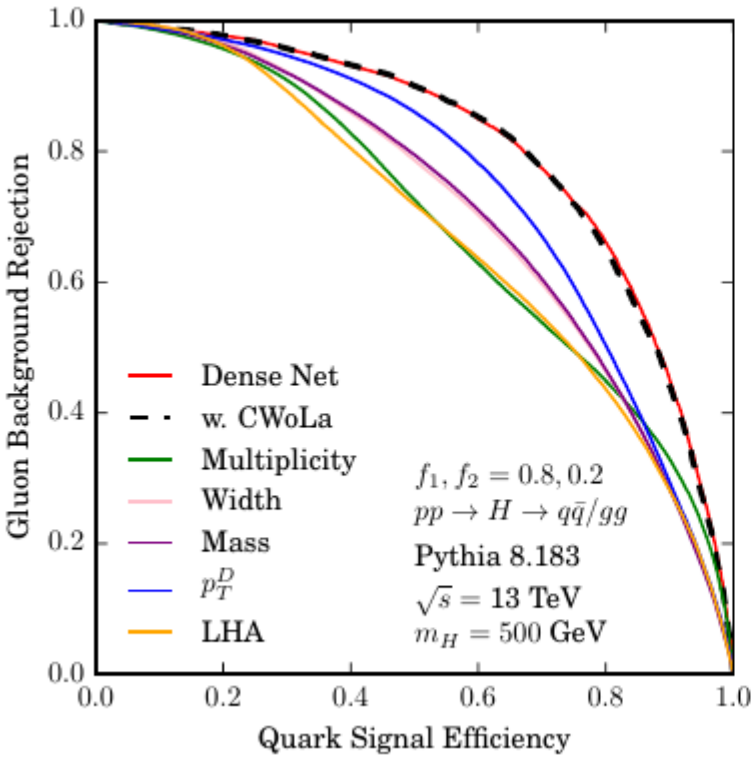
Metodiev et al, 1708.02949

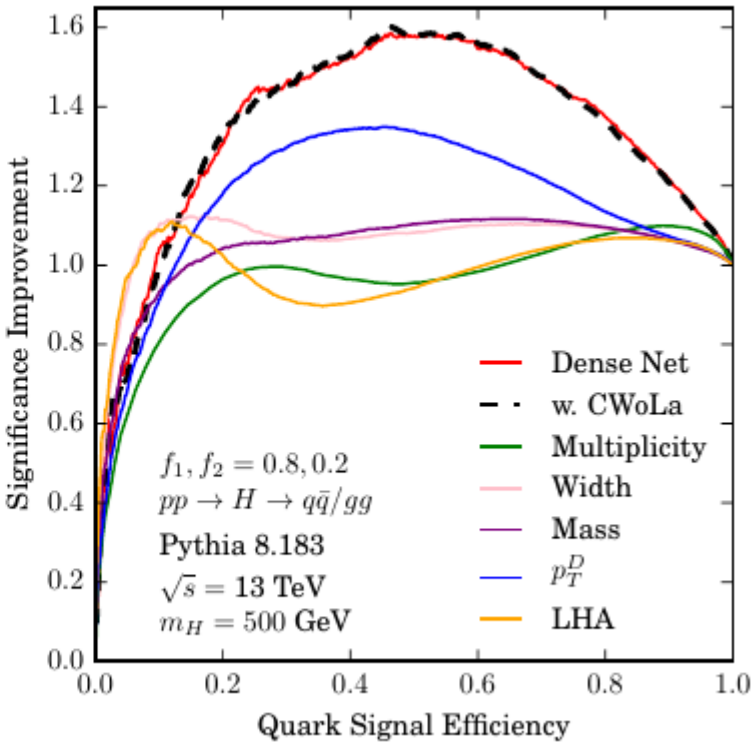
Cohen et al, 1706.09451

Komiske et al, 1801.10158

Machine Learning Jet Substructure

- This results in an optimal classifier for distinguishing S and B!
- To convert M1-M2 classifer to S-B classifier need benchmark point.
- Usually just depends on hard-scattering, not parton shower etc.

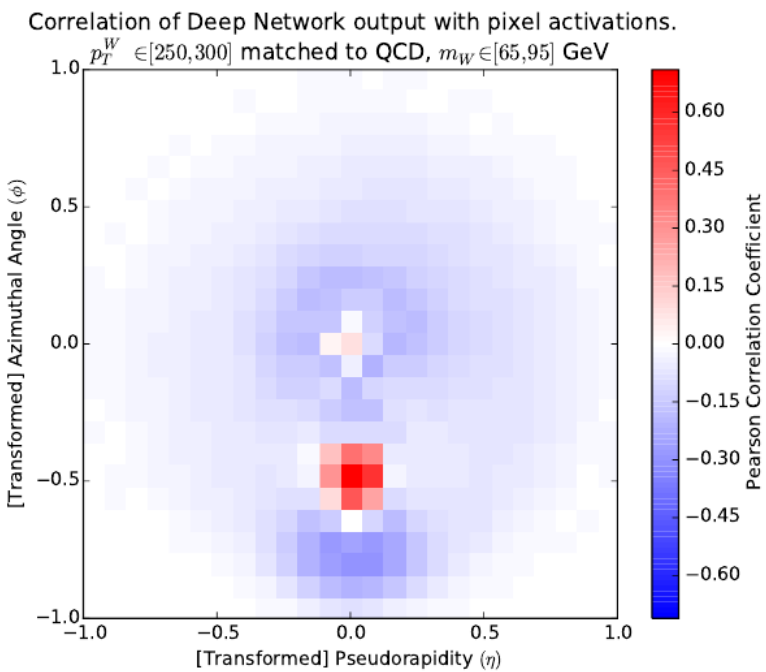


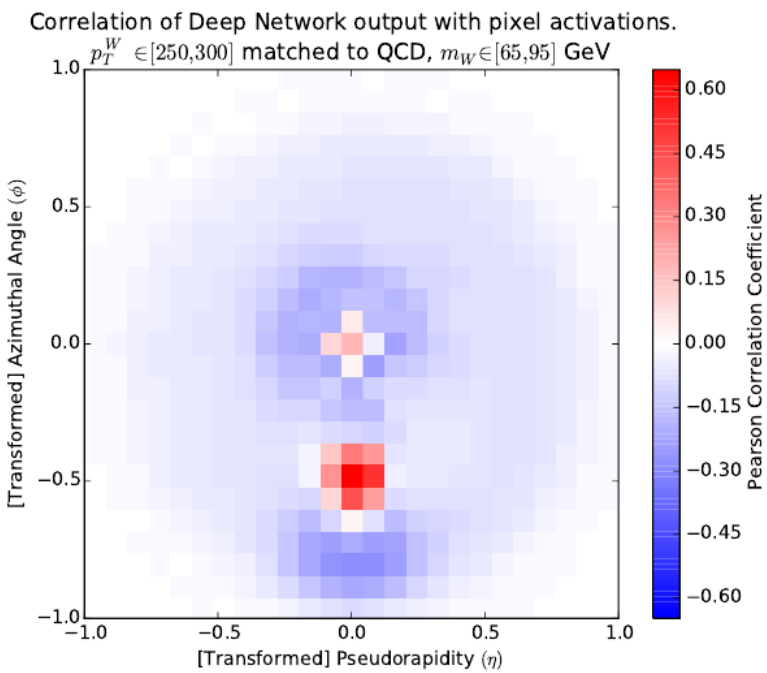


Metodiev et al, 1708.02949

What is the machine learning?

- Concern: these are fancy black boxes.
- "The more you know, the less black the boxes will be" (Ben Nachman)
  - Pixel-by-pixel convolution of DNN output with pixel-intensity
  - Subleading subjet location strongly correlated with DNN output
- Improvements over tagging variables from exploiting colour-flow and radiation patterns



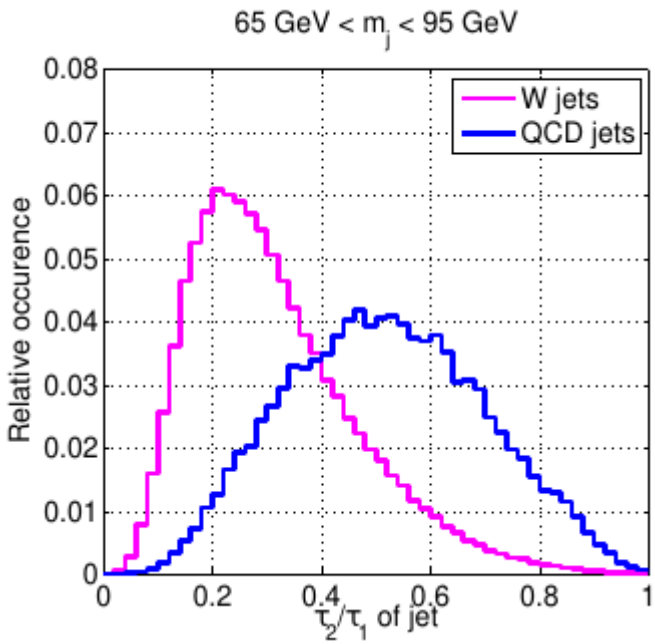


1511.05190

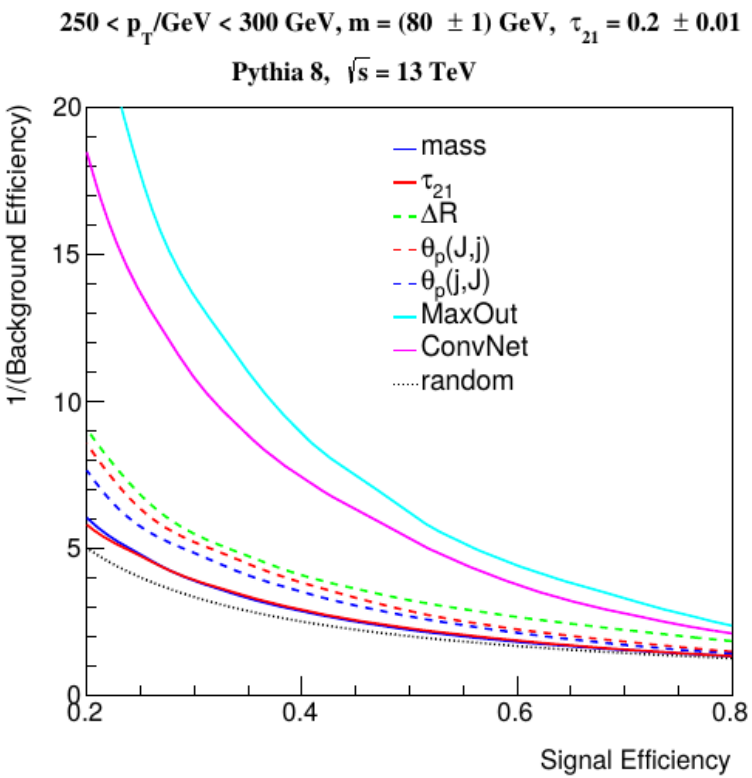
What is the machine learning?

- Are these methods accessing information outside the jet mass?
  - Or subjet location (as in n-subjettiness)?

Train in a restricted phase-space: $80 < m_J < 81\,\mathrm{GeV}$, $0.19 < \tau_{21} < 0.21$



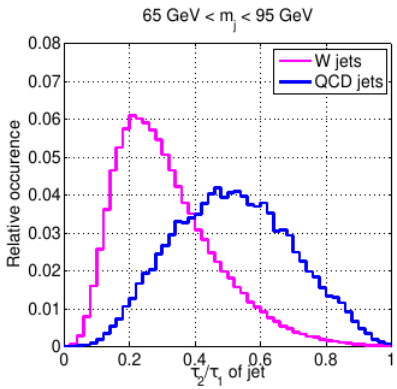
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\left\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\right\}.$$



Thaler, van Tilburg, 1011.2268

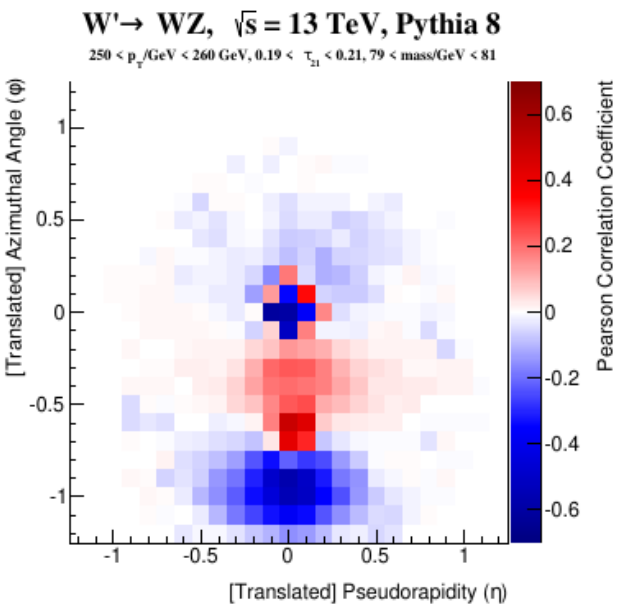
1511.05190

What is the machine learning?

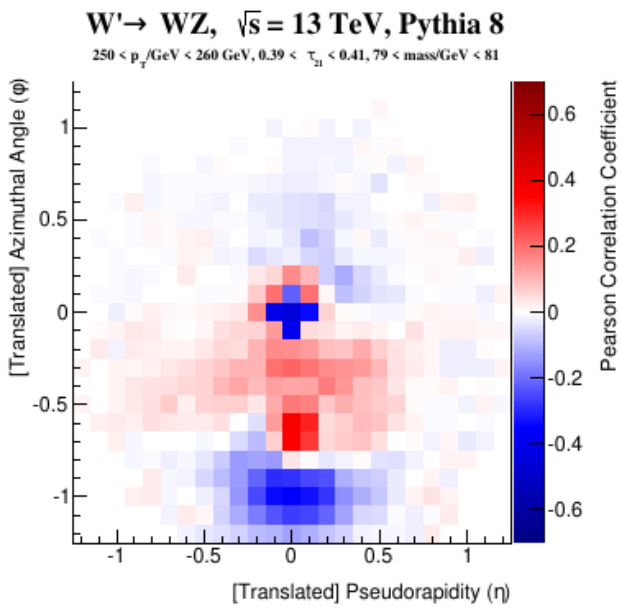


- Correlation coefficients in restricted phase space.
  - Exploiting information in radiation patterns
    - W-jets: more radiation between subjets
    - QCD-jets: radiation more widely spread

More W-like

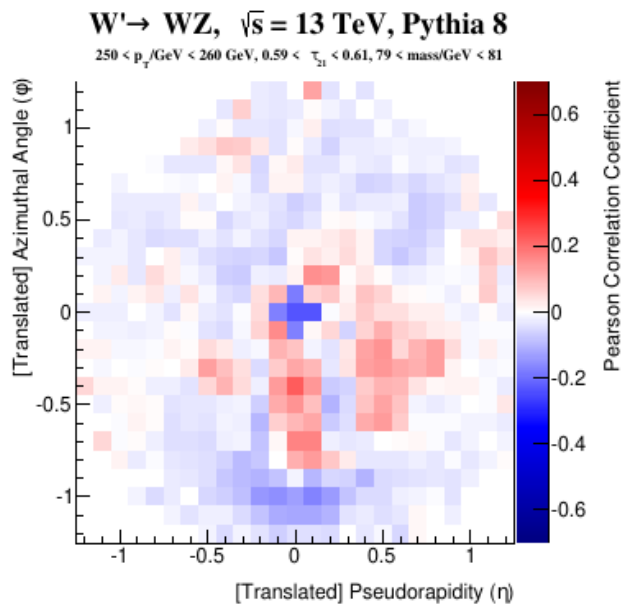


$0.19 < \tau_{21} < 0.21$



$0.39 < \tau_{21} < 0.41$

More QCD-like



$0.59 < \tau_{21} < 0.61$

1511.05190

Chang et al, 1709.10106

What is the machine learning?

- How does this feed back into theory?

Datta, Larkoski, 1704.08249 Datta, Larkoski, 1710.01305	Construct basis of functions for probing phase space with products of n-subjettiness observables based on ML considerations.
Louppe et al, 1702.00748	Four-momenta as words, clustering history as sentences
Henrion et al	Re-imagining jet clustering: jets as graphs vs jets as trees. Learn clustering metric directly from data!

Outlook

- All I want for Christmas is a chargino.
- And an extensive precision measurements program.

- Precision hadron collider physics for Top/Higgs/EW
- Requires precision predictions
- Fundamental measurements of Standard Model parameters
- Searches for New Physics
- The Age of the Differential Distribution!