Mono-Higgs searches at the HL-LHC

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Conference of Norwegian Financial Mechanism "Early Universe" project
Jun 14-15, Bergen

Inert Doublet + Pseudoscalar (IDM + PS) Model

Additional fields

SM Higgs potential : $V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4$ $+$ $\Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + i\eta_1) \end{pmatrix}$ $+$ η_2

no Yukawa

The scalar potential :

$$\begin{aligned} V =& \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 \\ &+ \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\{\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c.\} \\ &+ \frac{\mu_\eta^2}{2}\eta_2^2 + \frac{\lambda_\eta}{4}\eta_2^4 + \frac{\lambda_{1\eta}}{2}|\Phi_1|^2\eta_2^2 + \frac{\lambda_{2\eta}}{2}|\Phi_2|^2\eta_2^2 + \mu_{12\eta}\{i\Phi_1^\dagger\Phi_2\eta_2 + h.c.\}, \end{aligned}$$

$$\begin{pmatrix} A \\ a \end{pmatrix} = \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$$

Higgs bosons : h , H, $H^\pm$, A , a $(m_A > m_a)$

a ≡ Dark matter candidate

12 input parameters : $v, \quad m_h, \quad \mu_2^2, \quad m_a, \quad m_A, \quad m_H, \quad m_{H^\pm}, \quad \theta, \quad \lambda_2, \quad \lambda_\eta, \quad \lambda_{\eta 1}, \quad \lambda_{\eta 2},$

Relevant couplings fixed by the Model :

$$\begin{aligned} \lambda_{hAA} &= -\frac{c_\theta^2(m_A^2 - \mu_2^2)}{v} - \frac{1}{2}vs_\theta^2\lambda_{1\eta}\,, \\ \lambda_{haa} &= -\frac{s_\theta^2(m_a^2 - \mu_2^2)}{v} - \frac{1}{2}vc_\theta^2\lambda_{1\eta}\,, \\ \lambda_{hAa} &= -\frac{s_\theta c_\theta}{v}(-2\mu_2^2 + m_a^2 + m_A^2 - v^2\lambda_{1\eta}) \end{aligned}$$

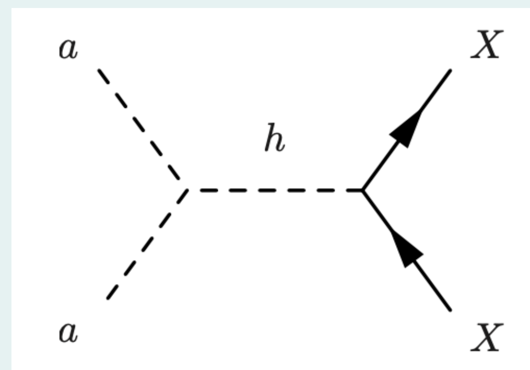
$$\begin{aligned} g_{AHZ} &= -\frac{g_Z}{2}c_\theta\,, \quad g_{aHZ} = -\frac{g_Z}{2}s_\theta, \\ g_{AH^\pm W^\mp} &= \mp i\frac{g}{2}c_\theta\,, \quad g_{aH^\pm W^\mp} = \mp i\frac{g_Z}{2}s_\theta, \\ g_{HH^\pm W^\mp} &= \mp i\frac{g}{2}\,. \end{aligned}$$

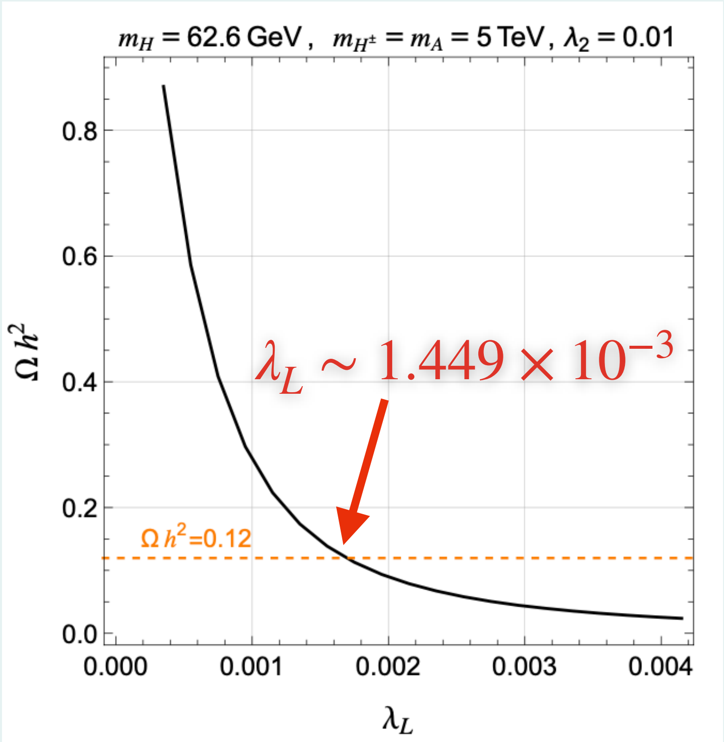
IDM + PS Model : Constraints

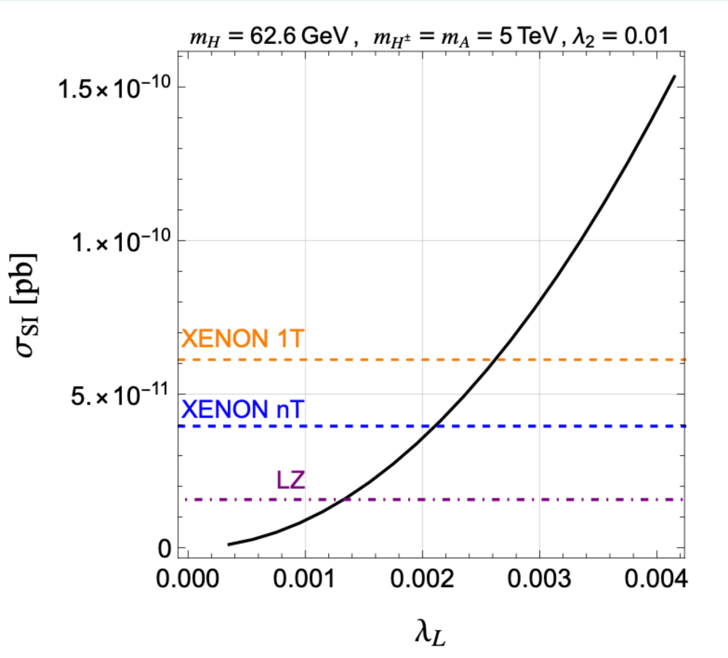
From electroweak oblique parameter constraints : $m_H = m_{H^\pm}$

Controls the DM annihilation rate → $$\lambda_{haa} = -\frac{s_\theta^2(m_a^2 - \mu_2^2)}{v} - \frac{1}{2} v c_\theta^2 \lambda_{1\eta}$$

DM annihilation process in the region $m_a \sim m_h/2$ →







We choose the following benchmark point :

$$m_a = 62.6 \text{ GeV}, \lambda_{1\eta} = 0.1, \theta = \frac{\pi}{4}, \mu_2 = 84.38 \text{ GeV}.$$

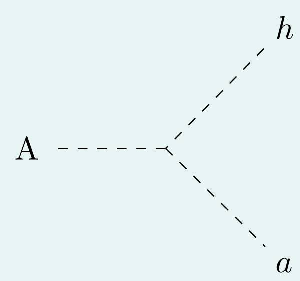
satisfies dark matter relic density and direct detection bound.

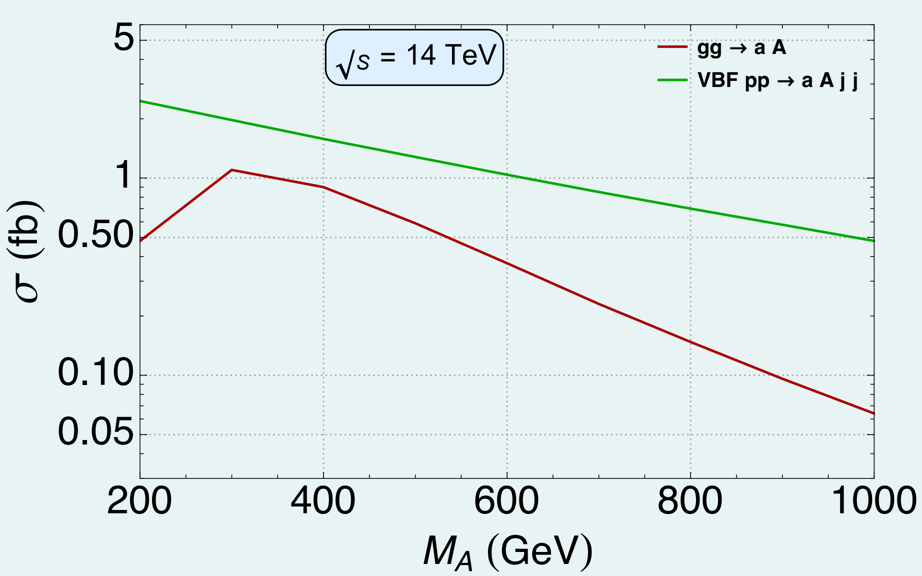
… Calculated by Kodai

IDM + PS Model : Signal and parameter values

Mono-h signal in IDM+PS model

$$\lambda_{hAa} = -\frac{s_\theta c_\theta}{v}(-2\mu_2^2 + m_a^2 + m_A^2 - v^2\lambda_{1\eta})$$

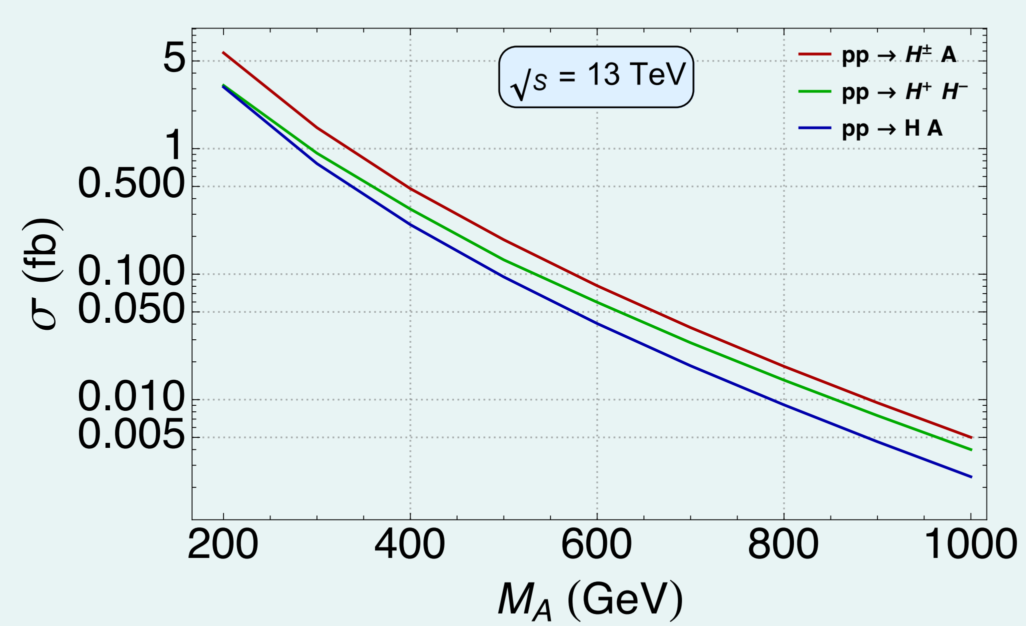




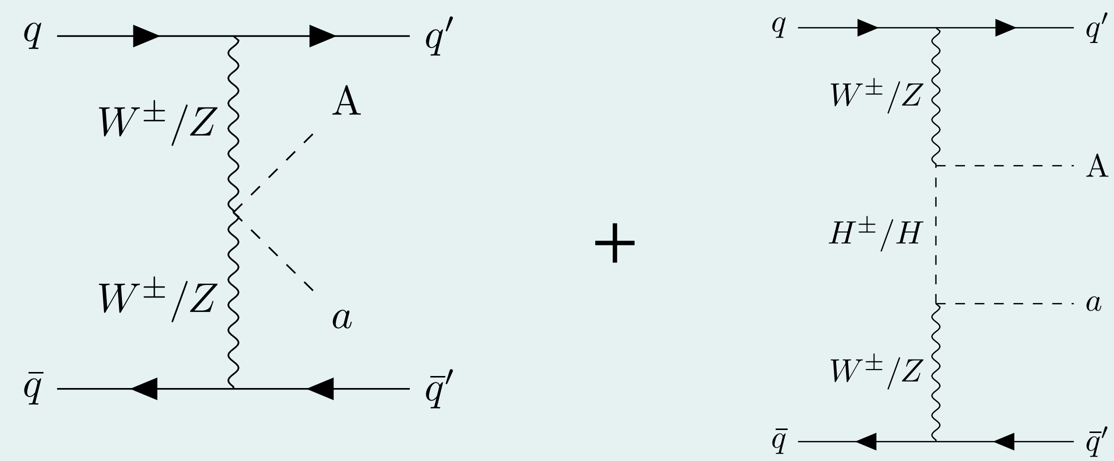
No current search for mono-Higgs in VBF channel.
Appreciable production rate for VBF production.
Advantage of having VBF topology for reducing backgrounds.

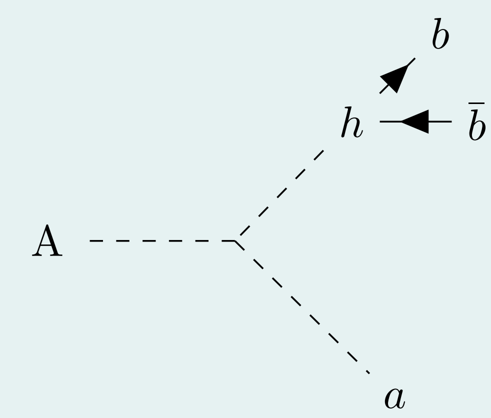
Initial values :

$$v = 246 \text{ GeV}$$
$$m_h = 125 \text{ GeV}$$
$$m_A = [200 : 1000] \text{ GeV}$$
$$m_H = m_{H^\pm} = m_A + 100 \text{ GeV}$$
$$m_a = 62.6 \text{ GeV}$$
$$\theta = \frac{\pi}{4}$$
$$\lambda_\eta = \lambda_{1\eta} = \lambda_{2\eta} = \lambda_2 = 0.1$$
$$\mu_2 = 100.727 \text{ GeV}$$
$$\Gamma(h) = 4 \text{ MeV}$$
$$\Gamma(a) = 0$$
$$Br(A \to ha) = 100\,\%$$
$$Br(H^\pm \to W^\pm A) + Br(H^\pm \to W^\pm a) = 100\,\%$$
$$Br(H \to ZA) + Br(H \to Za) = 100\,\%$$



Mono-Higgs Signal and Backgrounds





Feynman diagrams for the **signal** process : $pp \to aAjj,\ A \to ah,\ h \to b\bar{b}$

VBF topology, Final state : **2 b-jets + 2 forward light-jets +** $\not{E}_T$

Backgrounds : $t\bar{t}$, QCD 2b 2j 2ν, Vh + jets, VV + jets, $t\bar{t}$X +jets, single t

$(V = W/Z)$ $(X = h/W/Z)$

ggF $h \to b\bar{b} + \not{E}_T$ analysis : ATLAS-CONF-2021-006

VBF $h \to b\bar{b}$ analysis : 2011.08280

Collider Analysis : Event selection

Signal process is generated with IDM + pseudoscalar Model.

Madgraph (parton level process) → Pythia (showering) → Delphes (detector analysis)

b-tag efficiency : 77%
c mistag : 20.4%
light jet mistag : 0.9%

1907.05120

HL-LHC detector card

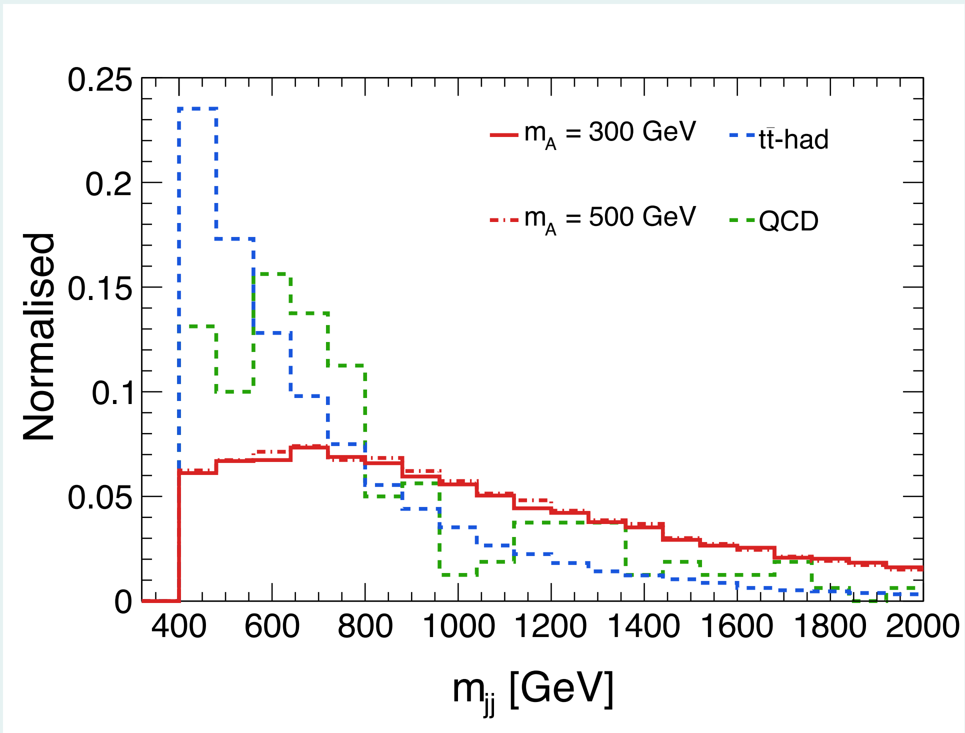
CERN Yellow Report
https://e-publishing.cern.ch/index.php/CYRM/article/view/952

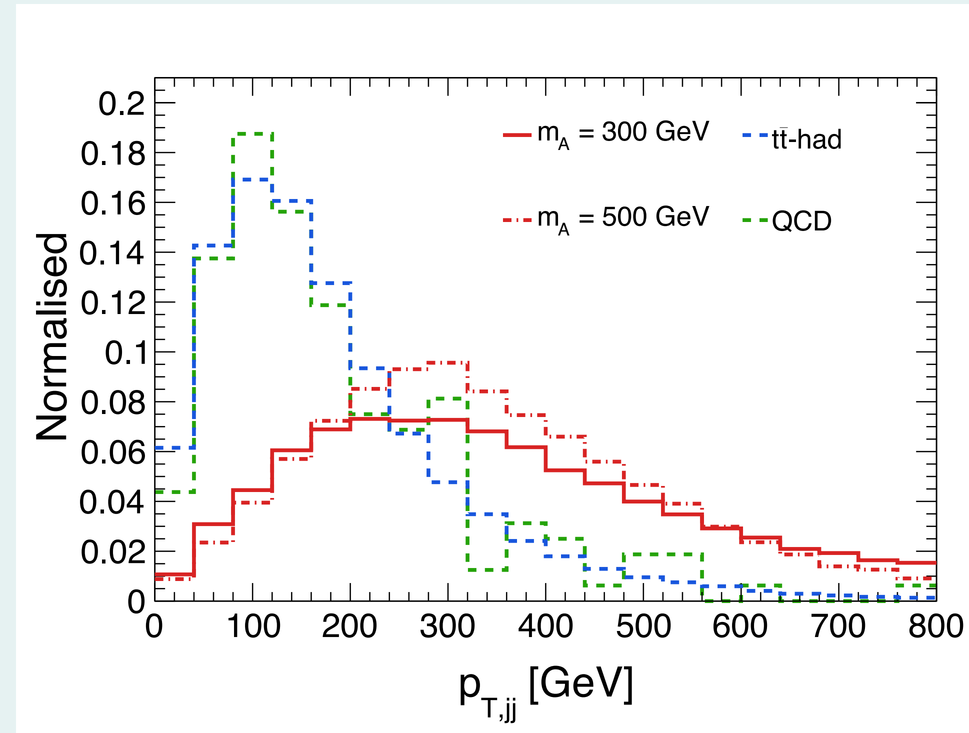
A. 2 b-jets ($N_b = 2$) with $p_T > 30$ GeV and $|\eta| < 4.0$.
B. 0 leptons ($N_\ell = 2$) with $p_T > 20$ GeV and $|\eta| < 4.0$.
C. At least 2 light-jets ($N_j \geq 2$) with $p_T > 30$ GeV and $|\eta| < 4.0$.
D. with/without : Two forward light jets : $\eta_{j1} * \eta_{j2} < 0$, jets are p_T ordered.
E. Generation level cuts : $\not{E}_T \geq 50$ GeV and $m_{jj} > 400$ GeV.

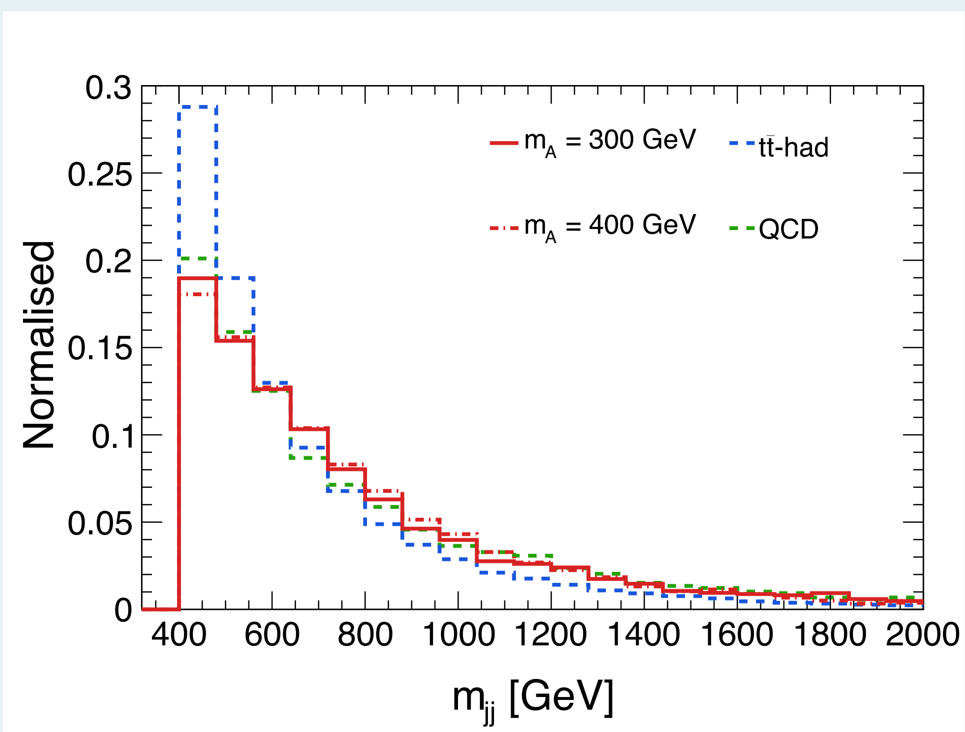
Signal process for $m_A = 300,\ 400/500$ GeV.
Backgrounds: QCD 2b 2j 2ν and $t\bar{t}$ - hadronic (different tag-efficiencies)

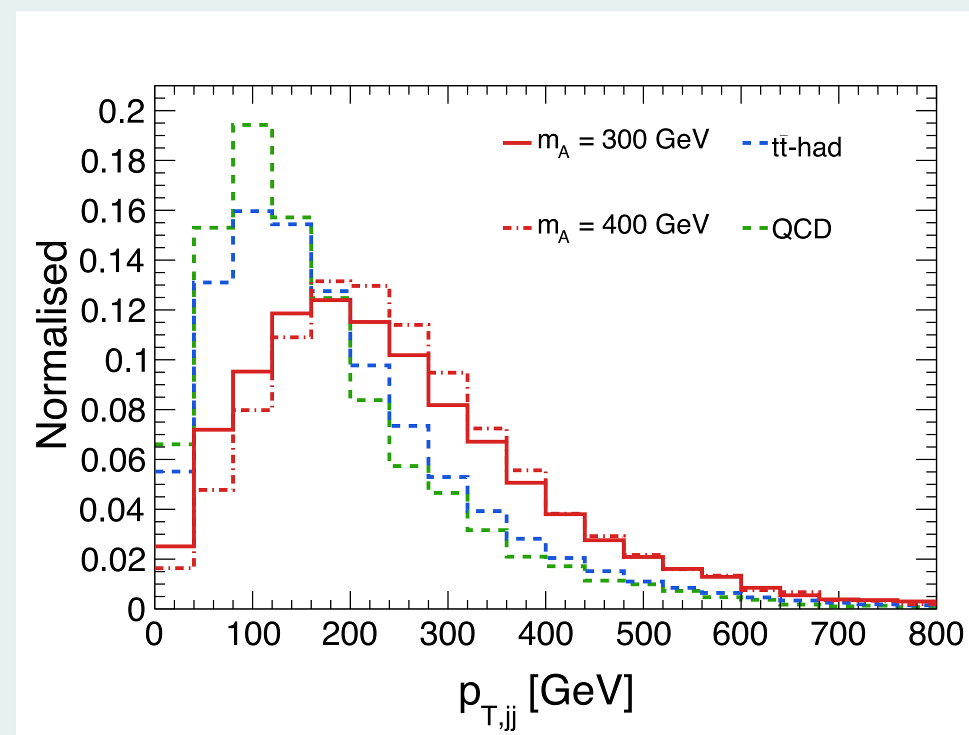
Collider Analysis : Kinematic variables

$\eta_{j1} * \eta_{j2} < 0$







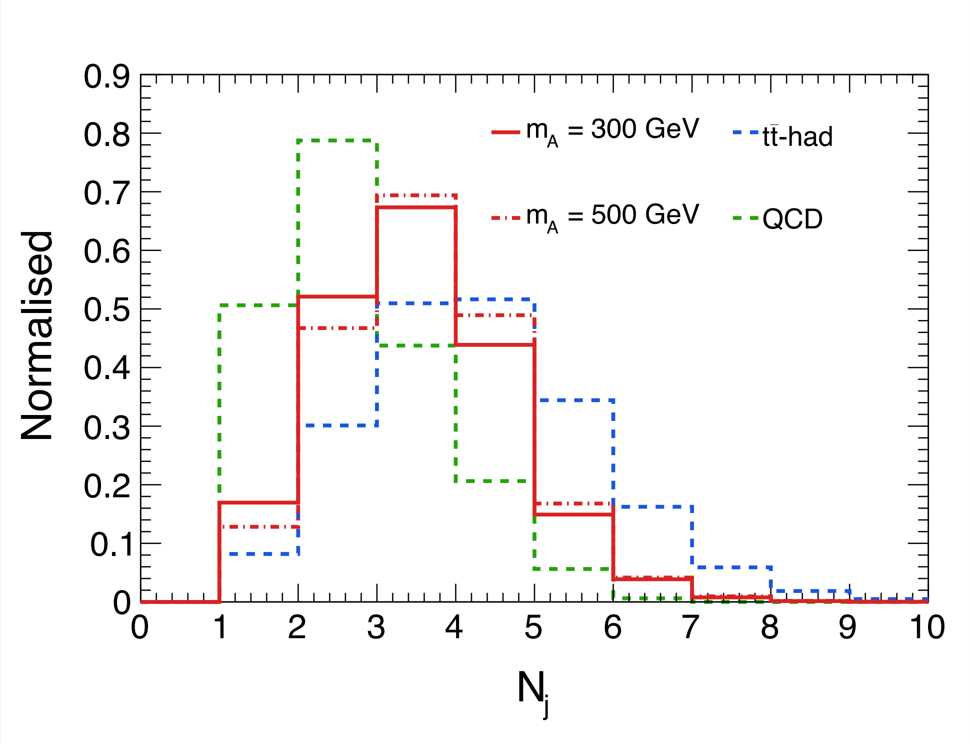


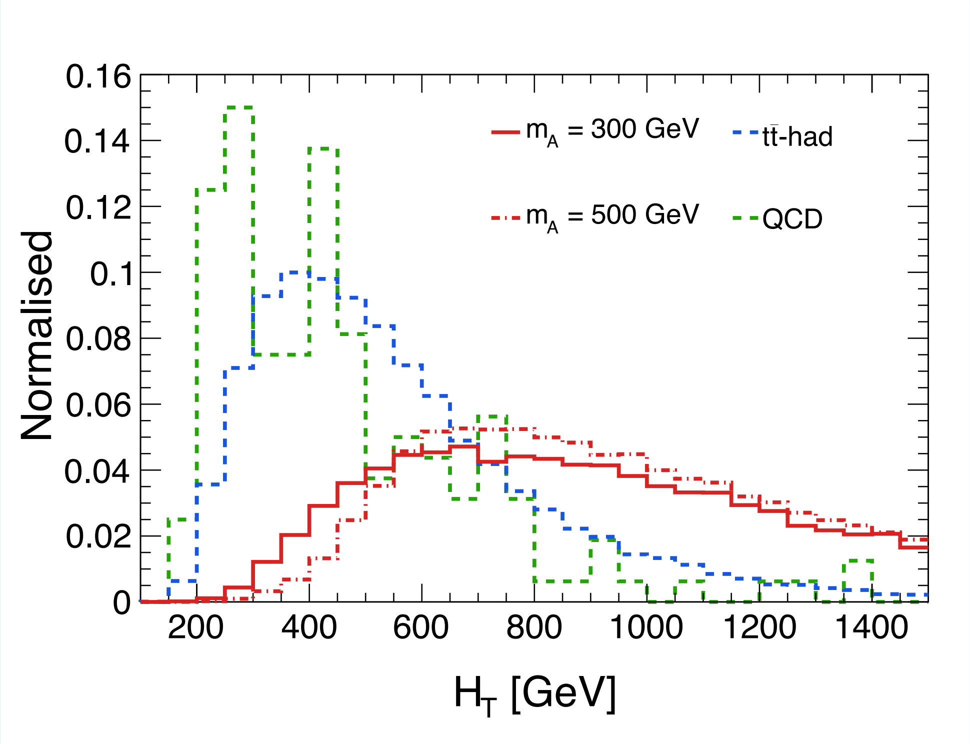
Invariant mass of di-jet pair

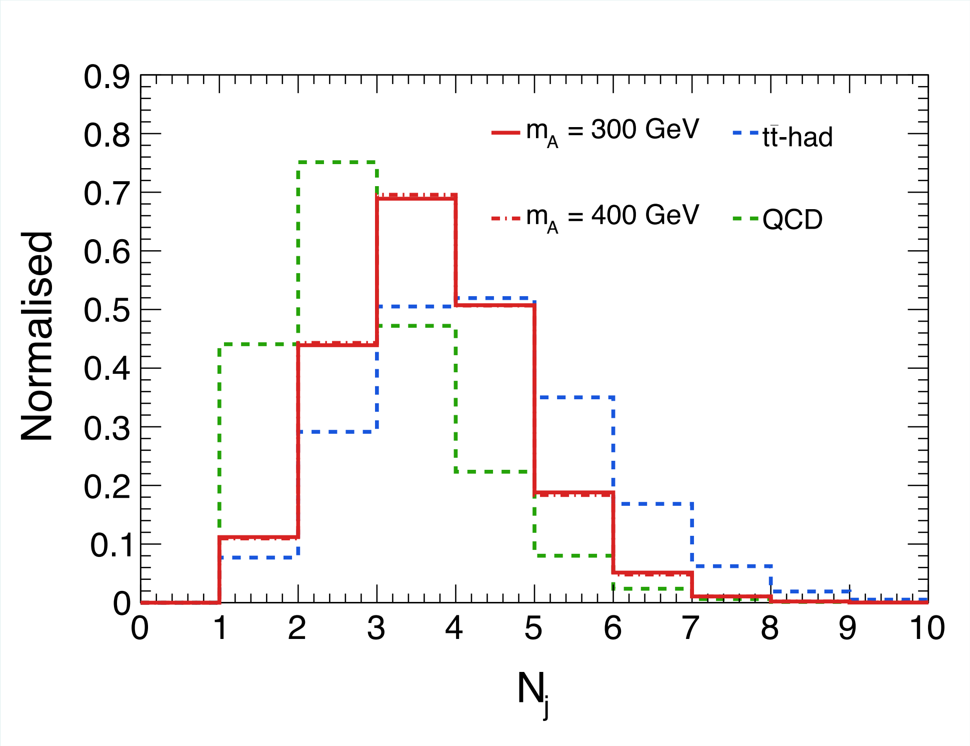
Transverse momentum of di-jet pair

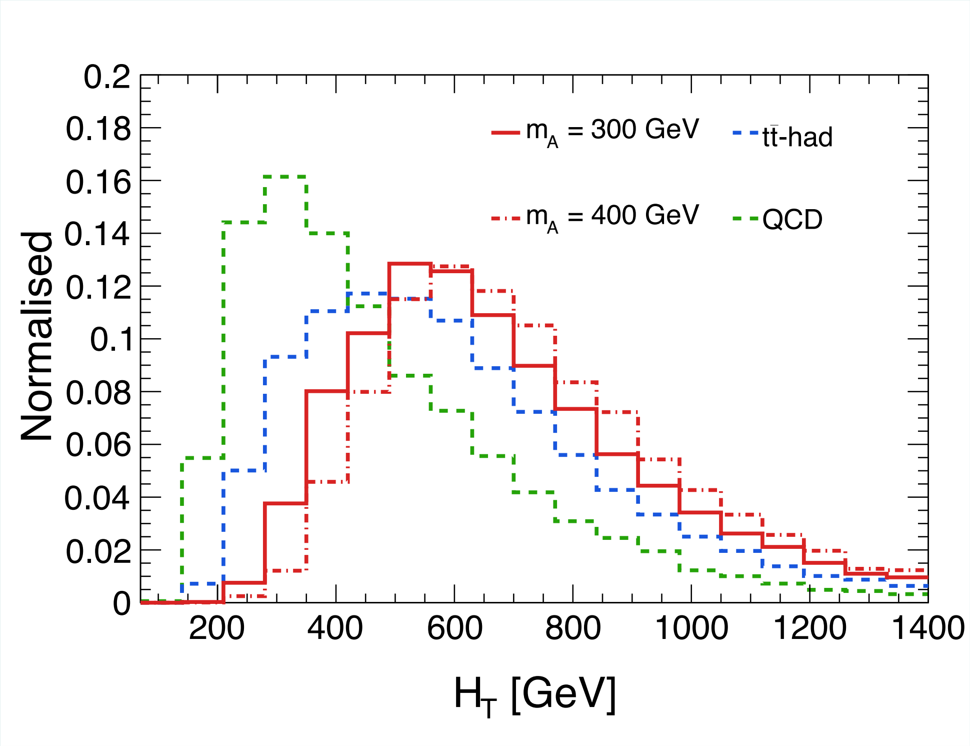
Collider Analysis : Kinematic variables

$\eta_{j1} * \eta_{j2} < 0$







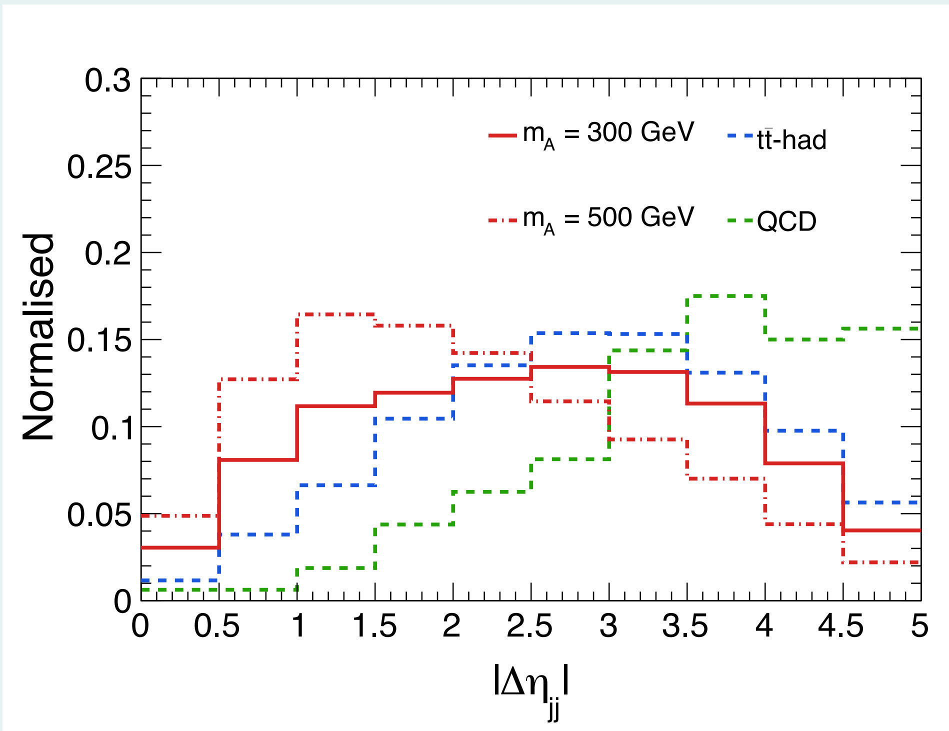


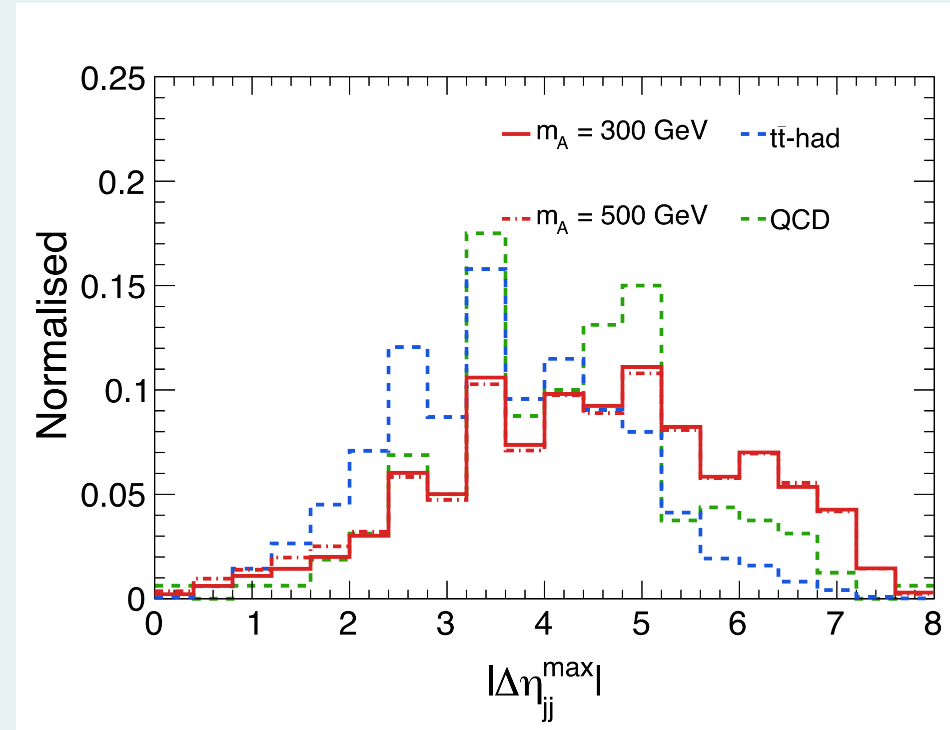
Total number of light jets

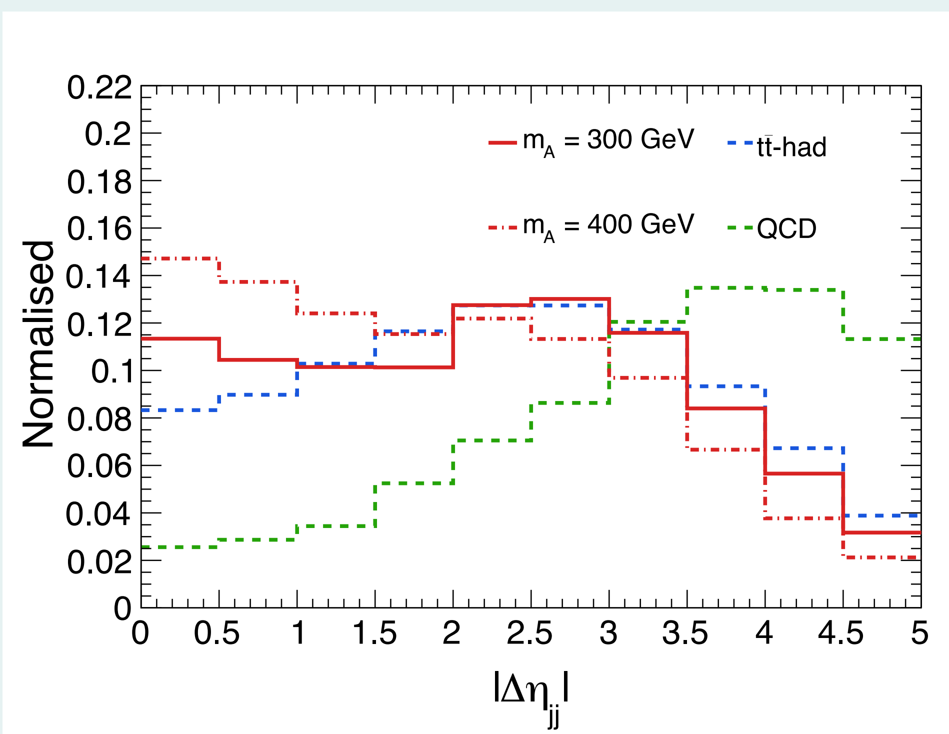
Scalar p_T sum of visible objects

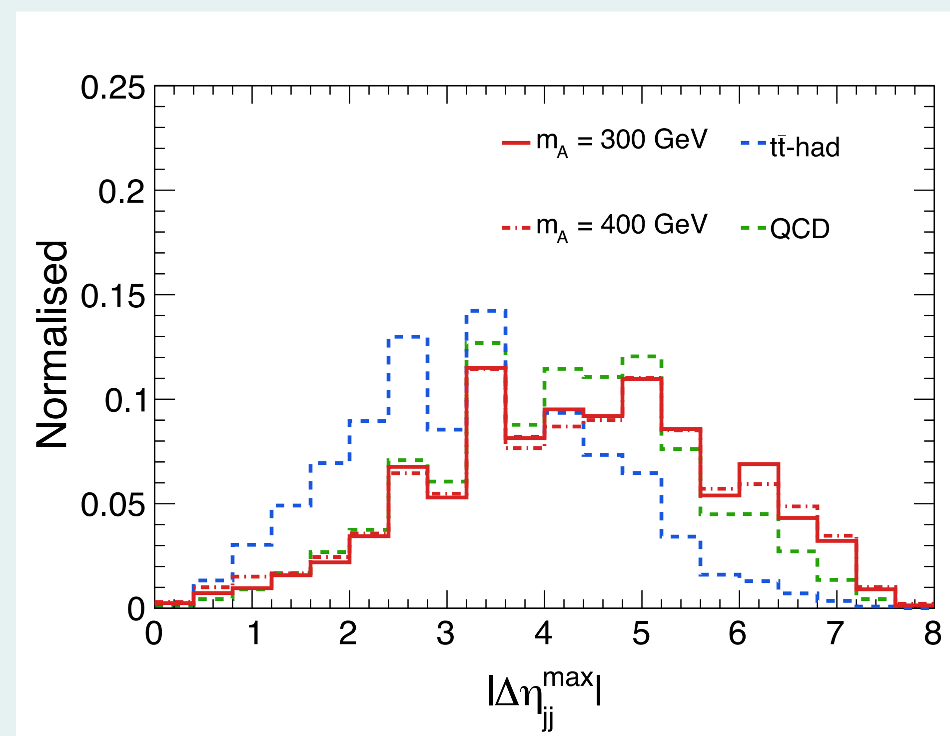
Collider Analysis : Kinematic variables

$\eta_{j1} * \eta_{j2} < 0$







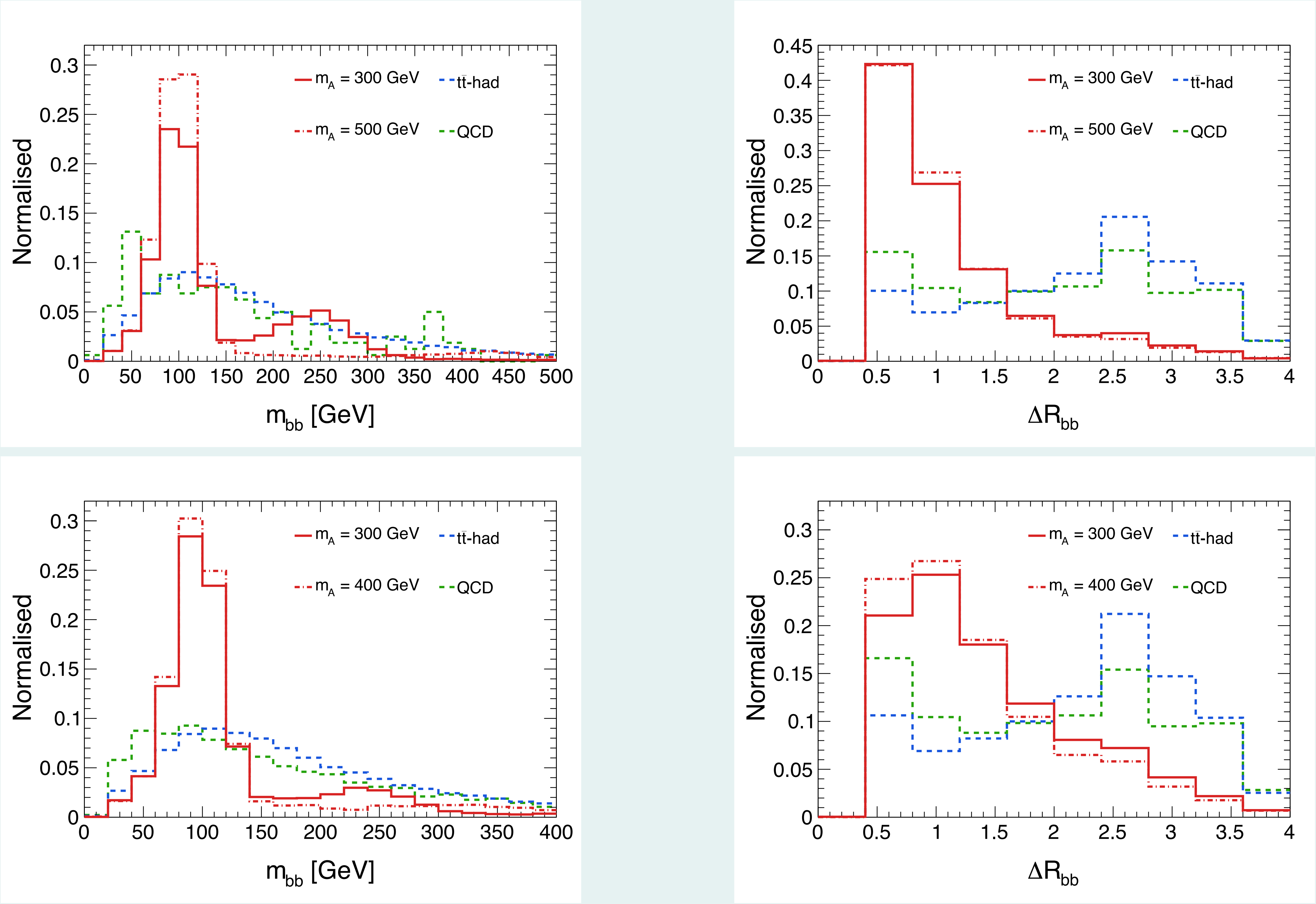


$\Delta\eta$ separation between hardest jets

Maximum $\Delta\eta$ separation between jets

Collider Analysis : Kinematic variables

$\eta_{j1} * \eta_{j2} < 0$

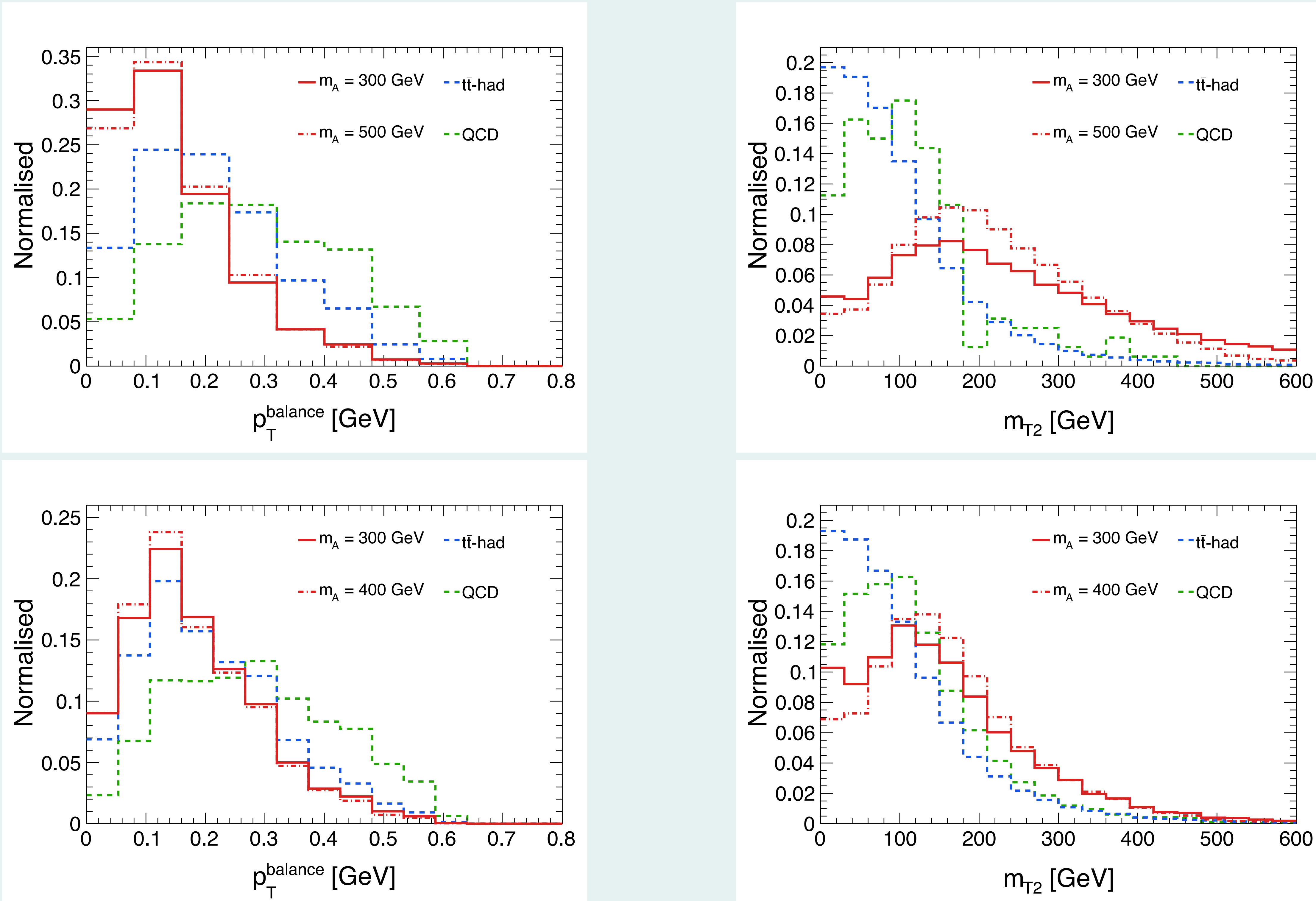


Invariant mass of $b\bar{b}$ pair

ΔR separation between b-jets

Collider Analysis : Kinematic variables

$\eta_{j1} * \eta_{j2} < 0$



Vectorial/scalar p_T sum of visible objects

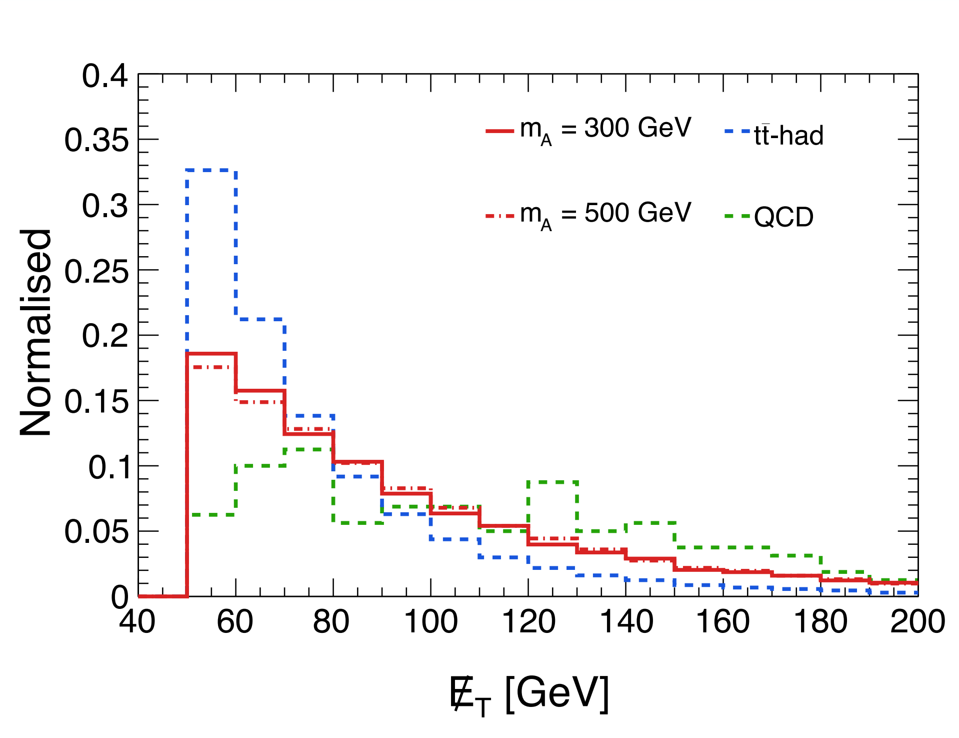
2011.08280

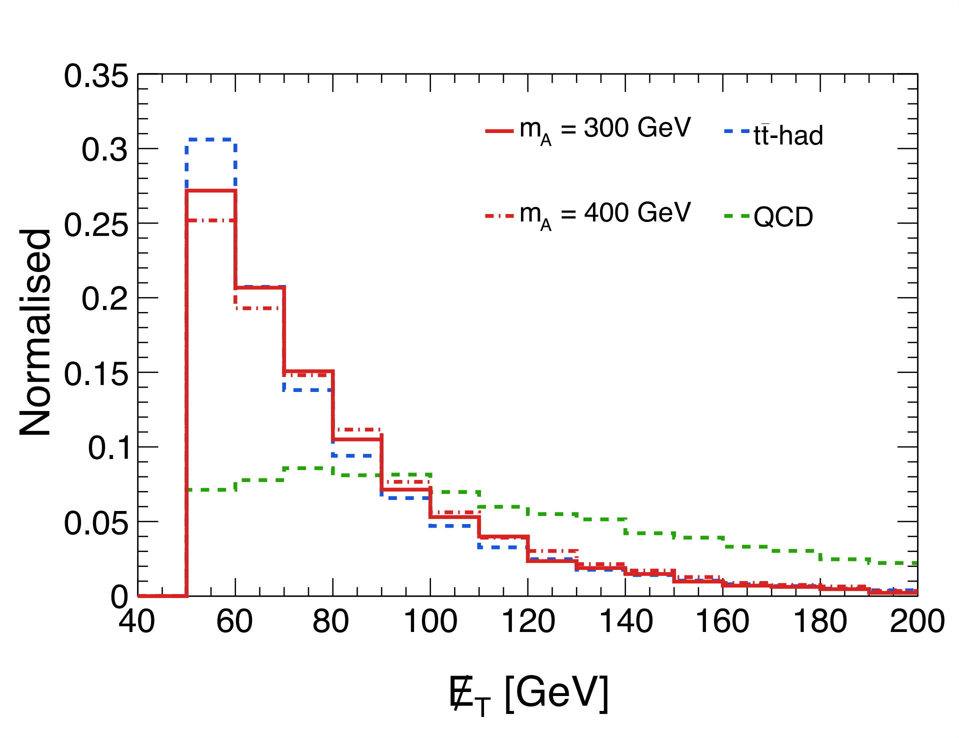
Stransverse mass

hep-ph/9906349, 1309.6318

Collider Analysis : Kinematic variables

$\eta_{j1} * \eta_{j2} < 0$

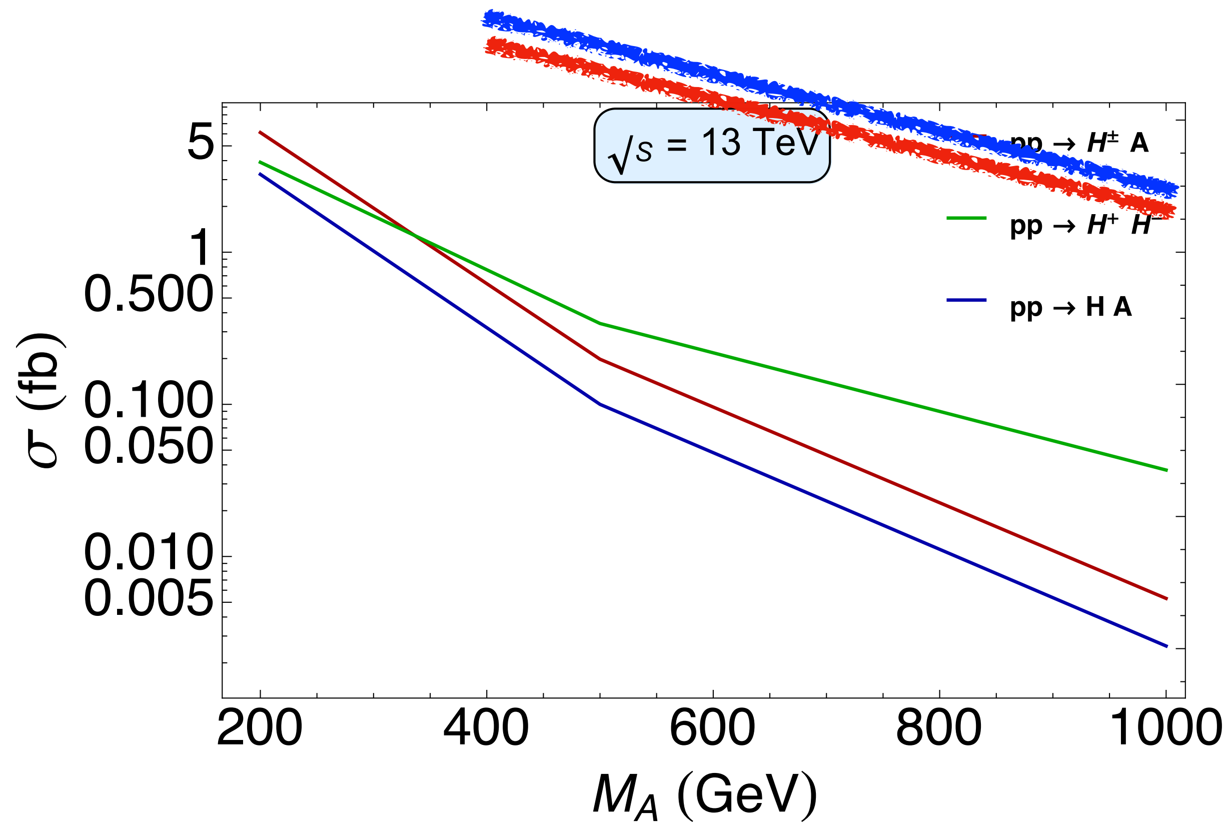


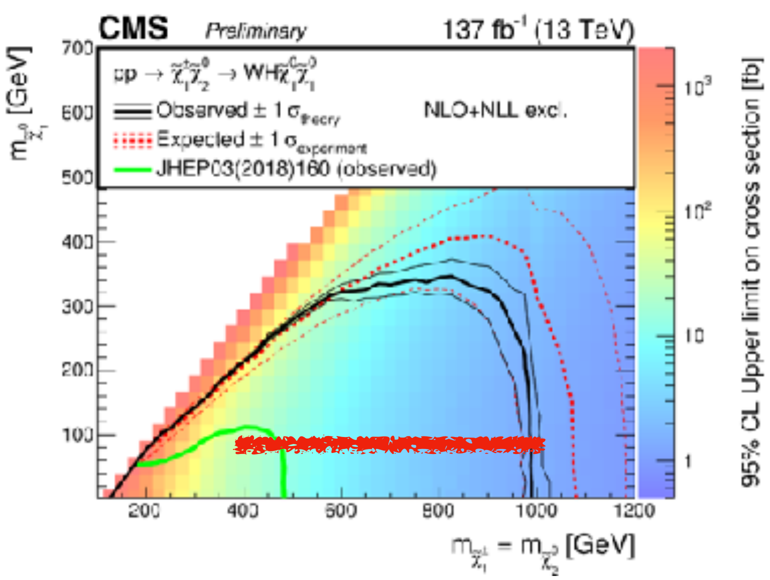


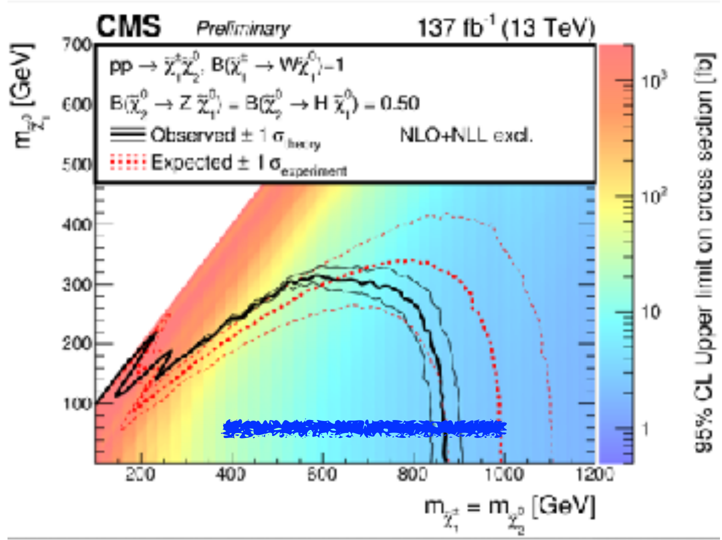
Missing energy

Backup Slides

Collider limit on IDM + PS model







http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS-21-008/index.html

… From Kazuki

Summary of ATLAS-CONF-2021-006

2HDM+pseudoscalar Model:

Signal : $gg \to h(\to bb) \ + \ a(\to \chi\chi) \ [b\bar{b} + \not{E}_T]$

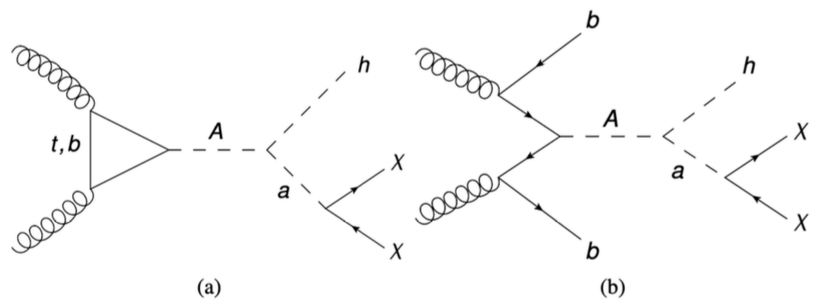


Figure 2: Feynman diagrams for the main production mechanisms of the mono-Higgs signature in the 2HDM+a scenario: gluon-gluon fusion (a) and b-associated production (b).

DM candidate: $m_\chi = 10$ GeV, $y_{a\chi\chi} = 1$. This m_χ ensures Br$(a \to \chi\chi)$ is significant for all m_a. $Sin\theta = 0.35$, $m_h = 125$ GeV, $m_A = m_H = m_{H^\pm} = [250 : 2000]$ GeV, $m_a = [100 : 600]$ GeV.

Backgrounds:

Dominant: **V+jets**, $t\bar{t}$.

Sub-dominant: VV+jets, single-t, $t\bar{t}h$, Vh, $t\bar{t}V$ (V=W/Z).

—Considering the resolved category, where the b-jets are well separated, the main cuts are:

1. $\not{E}_T > 150$ GeV
2. leptons are vetoed.
3. $\Delta\phi(j_{1/2/3}, \not{E}_T) > 20°$.
4. $\not{E}_T < 500$ GeV.
5. At least two b-tagged jets.
6. $p_{T,h} > 100$ (300) GeV if $\not{E}_T < 350$ (> 350) GeV.
7. $m_T > 170/200$ GeV.
8. $50 < m_h < 280$ GeV (I dont understand this though).

Resolved	Merged
Primary E_T^{miss} trigger	
Data quality selections	
$E_T^{miss} > 150$ GeV	
Lepton veto & extended τ-lepton veto	
$\Delta\phi(\text{jet}_{1,2,3}, E_T^{miss}) > 20°$	
$E_T^{miss} < 500$ GeV	$E_T^{miss} > 500$ GeV
At least 2 small-R jets	At least 1 large-R jet
At least 2 b-tagged small-R jets	At least 2 b-tagged associated variable-R track jets
$p_{Th} > 100$ GeV if $E_T^{miss} < 350$ GeV $p_{Th} > 300$ GeV if $E_T^{miss} > 350$ GeV	—
$m_T^{b,\min} > 170$ GeV	—
$m_T^{b,\max} > 200$ GeV	—
$\mathcal{S} > 12$	—
$N_{\text{small-}R\text{ jets}} \leq 4$ if 2 b-tag $N_{\text{small-}R\text{ jets}} \leq 5$ if ≥ 3 b-tag	—
$50\,\text{GeV} < m_h < 280\,\text{GeV}$	$50\,\text{GeV} < m_h < 270\,\text{GeV}$

Table 1: Summary of selections used to define the signal regions used in the analysis. The kinematic variables are defined in the text.

Signal : $pp \to aAjj, \ A \to ha, \ h \to b\bar{b}$ [Final state : 2 b-jets + 2 forward light-jets + $\not{E}_T$]

$m_A = 400$ GeV, $\sigma = 1.7$ fb		
$p_{T,j/b/\tau_h} > 30$ GeV, $p_{T,\ell} > 20$ GeV, $\eta_{j/b/\tau_h/\ell} < 4.0$, $\ell = e/\mu$		
Cuts applied	Signal Efficiency	Yield at 3 ab^{-1}
$N_b = 2, \ N_\ell = 0$	.328	1673
$N_j \geq 2$	.323	1647
150 GeV $< \not{E}_T <$ 500 GeV	.0204	104
$p_{T,h} > 100$ (> 300) GeV if $\not{E}_T < 350$ (> 350) GeV	.019	97
$m_T^{b,min} > 170$ GeV and $m_T^{b,max} > 200$ GeV	.003	15
$S = \frac{\not{E}_T}{\sqrt{HT}} > 12$	.000013	0.066
$\Delta\phi(j/b, \not{p}_T) > 20°$	.00001	0.051

No events survive

Table 1: *The signal efficiency and yield at HL-LHC after the cuts.*

Taggging efficiencies from CERN-EP-2019-132, 1907.05120

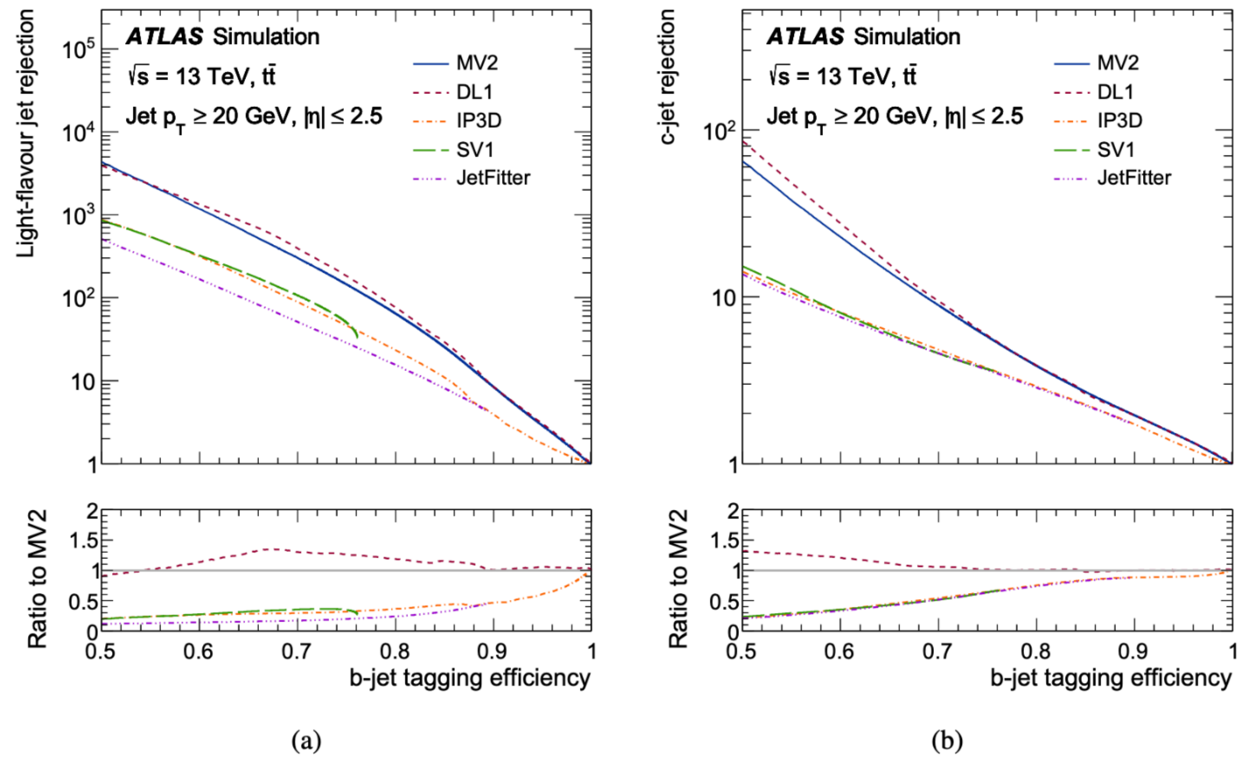


Figure 2: The (a) light-flavour jet and (b) c-jet rejections versus the b-jet tagging efficiency for the IP3D, SV1, JetFitter, MV2 and DL1 b-tagging algorithms evaluated on the baseline $t\bar{t}$ events.

Table 4: Selection and c-jet, τ-jet and light-flavour jet rejections corresponding to the different b-jet tagging efficiency single-cut operating points for the MV2 and the DL1 b-tagging algorithms, evaluated on the baseline $t\bar{t}$ events.

ϵ_b	MV2				DL1			
	Selection	Rejection			Selection	Rejection		
		c-jet	τ-jet	Light-flavour jet		c-jet	τ-jet	Light-flavour jet
60%	> 0.94	23	140	1200	> 2.74	27	220	1300
70%	> 0.83	8.9	36	300	> 2.02	9.4	43	390
77%	> 0.64	4.9	15	110	> 1.45	4.9	14	130
85%	> 0.11	2.7	6.1	25	> 0.46	2.6	3.9	29

MV2: b-tag=77%, c-mistag=1/4.9 = 20.4%, j-mistag=1/110 = 0.9%