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HL-LHC SM $HH \to b\bar{b}\tau^+\tau^-$ prospects in the ATLAS Experiment

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Outline

- Introduction
- List of questions from Luca:
  - Signal efficiency
  - Background yields, split by processes considered
  - Background yields at a certain signal yield (to restrict to the most sensitive BDT/NN regions and have an idea of the S/B there)
  - Tau fake rates assumed in the analysis
  - Tau efficiency assumed in the analysis
  - Contribution to the sensitivity split by the decay channels ($\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$, $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$)
- Adding:
  - Binning criteria
  - Information about BDT

Using new cross-section:
$\sigma_{HH}^{ggF}(14 \text{ TeV}) = 36.69$ fb

$HH \to b\bar{b}\tau^+\tau^-$ HL-LHC prospects

extrapolation of the Run-2 result: $\int Ldt = 36.1 \to \int Ldt = 3000$ fb^{-1}

Signal and background distributions scaled by $f = \int Ldt|_{\text{target}} / \int Ldt|_{\text{current}}$

Signal and background distributions scaled to 14 TeV cross-sections

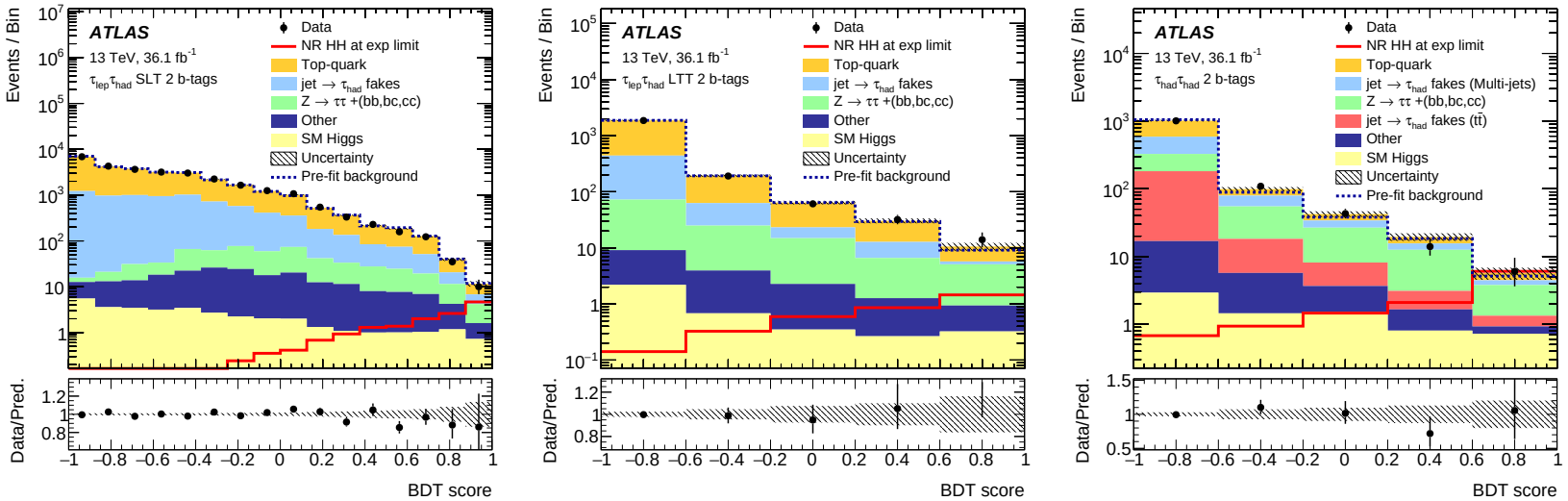
Normalizations fixed to the best Run-2 fit values

Pixel TDR detector layout $\to$ improved b-tagging performance (8% per b-jet)

Run-2 analysis strategy

$\tau_{\text{lep}}\tau_{\text{had}}$		$\tau_{\text{had}}\tau_{\text{had}}$	
Single lepton trigger	Lepton tau trigger	Single tau trigger	Di-tau trigger
SLT	LTT	STT	DTT

- A BDT classification applied in the SR, BDT score used as a final discriminant.
- 3 signal regions: $\tau_{\text{lep}}\tau_{\text{had}}$ SLT, $\tau_{\text{lep}}\tau_{\text{had}}$ LTT, $\tau_{\text{had}}\tau_{\text{had}}$



- Varied λ_{HHH}: LTT category not included, BDT trained on $\kappa_\lambda = 20$ signal used
- Freely floating normalizations: $t\bar{t}$ constrained from the low $\tau_{\text{lep}}\tau_{\text{had}}$ BDT region and Z+heavy flavor from the $Z(\rightarrow \mu\mu) + b\bar{b}$ CR

Extrapolation strategy

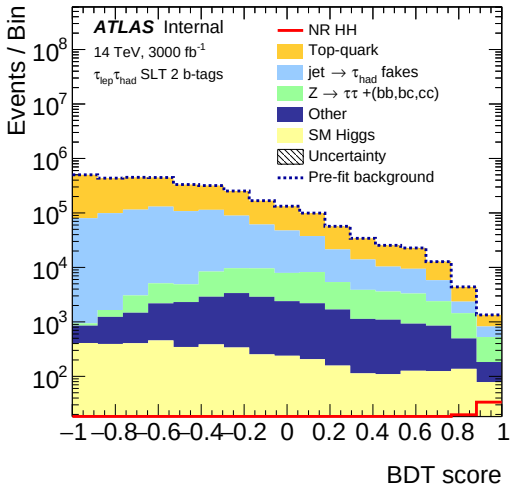
- Normalizations fixed to best Run 2 fit values:
  1. $Z(\rightarrow \tau\tau) + b\bar{b}$ scaled up by 1.34, uncertainty 12%
     - Acceptance based extrapolation uncertainties: 35% for $\tau_{\text{had}}\tau_{\text{had}}$, 29% for $\tau_{\text{lep}}\tau_{\text{had}}$
  2. $t\bar{t}$ normalization unchanged, uncertainty 12%
     - Acceptance based extrapolation to $\tau_{\text{had}}\tau_{\text{had}}$: 32% up, 30 % down
- Signal and backgrounds scaled to 14 TeV cross-sections (1.18 for data-driven)
- Assuming the same performance, analysis, triggers and +8% in b-tag efficiency

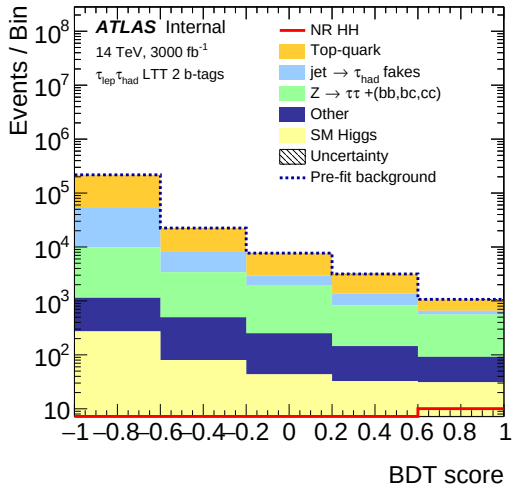
Considering 4 different scenarios:

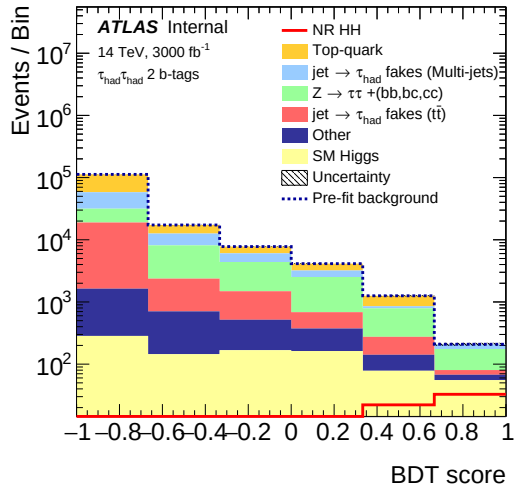
1. Current systematic uncertainties
2. Current systematic uncertainties, MC stat. unc. neglected :
   Fractional impact on $\Delta\mu$ goes from 18% (Run-2) to 84% (HL-LHC)
3. Baseline :
   12% unc on $t\bar{t}$ and $Z + b\bar{b}$ scaled down with lumi, acceptance extrapolation unc halved, VH scaled to 5%, $t\bar{t}H$ to 10%, all cross-section uncertainties halved, MC statistical uncertainty neglected, stat unc for data-driven bgds scaled to follow Poisson distribution
4. No systematic uncertainties

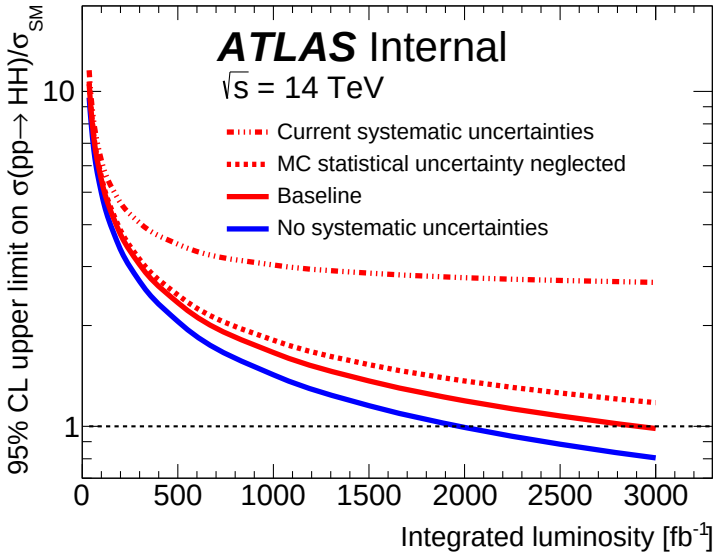
Results of the extrapolation

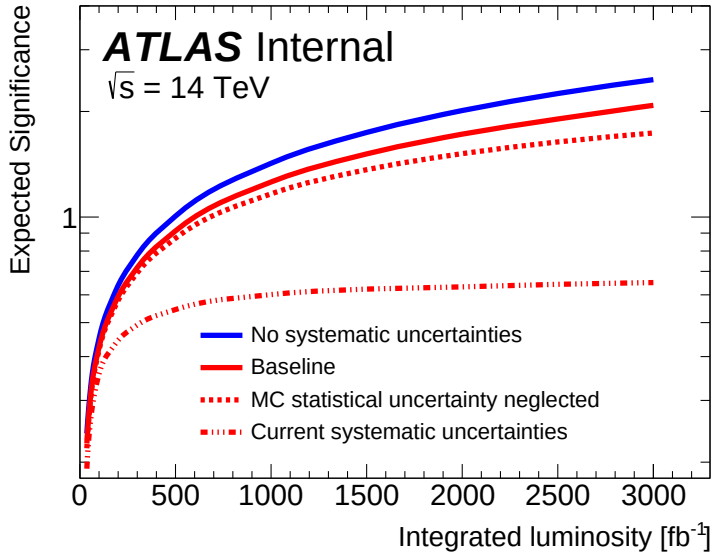
- 3 signal regions: $\tau_{\text{lep}}\tau_{\text{had}}$ SLT, $\tau_{\text{lep}}\tau_{\text{had}}$ LTT, $\tau_{\text{had}}\tau_{\text{had}}$











Results of the extrapolation

Contribution to the sensitivity split by the decay channels:

Scenario	limits			significance		
	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	comb.	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	comb.
No systematic unc.	0.89	1.97	0.80	2.25	1.00	2.46
Baseline	1.09	3.18	0.99	1.92	0.62	2.08
MC stat. unc. neg.	1.27	3.39	1.18	1.63	0.60	1.74
Current systematics	2.82	10.88	2.69	0.63	0.17	0.65

- The $\tau_{\text{had}}\tau_{\text{had}}$ channel performs significantly better than $\tau_{\text{lep}}\tau_{\text{had}}$
- $\tau_{\text{lep}}\tau_{\text{had}}$: BDT trained against $t\bar{t}$ background
  (can be improved by including Z+jets and single H backgrounds)
- $\tau_{\text{had}}\tau_{\text{had}}$: BDT trained against the sum of all backgrounds

Signal acceptance $\times$ efficiency: Same as in the Run 2 analysis
($\tau_{\text{had}}\tau_{\text{had}}$: 2.9 %, $\tau_{\text{lep}}\tau_{\text{had}}$ combined: 4.2 %, $\tau_{\text{lep}}\tau_{\text{had}}$ SLT: 3.5 %)

Results of the extrapolation

Background yields at a certain signal yield
(to restrict to the most sensitive BDT/NN regions and have an idea of the S/B there)

Full SR	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (SLT)	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (LTT)	$\tau_{\text{had}}\tau_{\text{had}}$ channel
$t\bar{t}$ fake-τ_{had}	-	-	20400 ± 2200
$t\bar{t}$	2218000 ± 13000	176000 ± 2300	57600 ± 2000
Single top	129200 ± 2800	8240 ± 230	4490 ± 150
Multi-jet fake-τ_{had}	-	-	33500 ± 2100
Fake-τ_{had}	867000 ± 13000	51100 ± 2300	-
$Z \rightarrow \tau\tau + (cc, bc, bb)$	51800 ± 2100	14550 ± 580	23800 ± 1100
Other	24300 ± 1000	1710 ± 160	2550 ± 350
SM Higgs	4280 ± 360	459 ± 36	892 ± 62
Total background	3295300 ± 1800	252050 ± 500	143240 ± 380
SM HH	106.8 ± 6	23.9 ± 1.3	80.6 ± 7.7

Signal Region (Baseline, post-fit)

Results of the extrapolation

Background yields at a certain signal yield
(to restrict to the most sensitive BDT/NN regions and have an idea of the S/B there)

Last 2 bins	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (SLT)	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (LTT)	$\tau_{\text{had}}\tau_{\text{had}}$ channel
$t\bar{t}$ fake-τ_{had}	-	-	146 ± 19
$t\bar{t}$	1833 ± 42	1783 ± 28	371 ± 30
Single top	718 ± 22	416 ± 36	32.3 ± 2.8
Multi-jet fake-τ_{had}	-	-	97 ± 17
Fake-τ_{had}	639 ± 35	-	1210 ± 34
$Z \rightarrow \tau\tau + (cc, bc, bb)$	1291 ± 68	1151 ± 74	610 ± 61
Other	464 ± 24	177 ± 18	75 ± 10
SM Higgs	216 ± 11	63.6 ± 3.3	133.5 ± 8.1
Total background	5732 ± 91	4228 ± 89	1465 ± 88
SM HH	52.1 ± 2.6	16.17 ± 0.82	53.5 ± 5

Last 2 bins of the BDT distribution (Baseline, post-fit)

Results of the extrapolation

Background yields at a certain signal yield
(to restrict to the most sensitive BDT/NN regions and have an idea of the S/B there)

Last bin	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (SLT)	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (LTT)	$\tau_{\text{had}}\tau_{\text{had}}$ channel
$t\bar{t}$ fake-τ_{had}	-	-	12.9 ± 2
$t\bar{t}$	234.7 ± 5.8	360 ± 29	0
Single top	283 ± 15	53.8 ± 2.5	0
Multi-jet fake-τ_{had}	-	-	33.7 ± 7.2
Fake-τ_{had}	298 ± 11	96.6 ± 8.6	-
$Z \rightarrow \tau\tau + (cc, bc, bb)$	343 ± 19	467 ± 44	95 ± 16
Other	105 ± 5.4	61 ± 6.8	12.2 ± 2.1
SM Higgs	78.3 ± 3.7	31 ± 1.6	55.3 ± 3.4
Total background	1343 ± 25	1069 ± 55	209 ± 17
SM HH	32.8 ± 1.6	9.82 ± 0.51	31.9 ± 3

Last bin of the BDT distribution (Baseline, post-fit)

Tau efficiency and fake rate

Tau efficiency and fake rates assumed in the analysis:

- Since this is an extrapolation of the Run 2 analysis, we use the "medium" τ ID working point (60/55 % efficiency)
- Background where jets are faking hadronically decaying τs estimated in a data-driven way:
  - $\tau_{\text{lep}}\tau_{\text{had}}$: Combined Fake Factor method ($t\bar{t}$, multijet, W+jets)
  - $\tau_{\text{had}}\tau_{\text{had}}$: ABCD method (multijet) and Fake Factor method ($t\bar{t}$)
- For the extrapolation we assume the same τ ID efficiency and fake-rates
- For multijet processes we assume 18% increase in cross-section for going from 13 to 14 TeV.

Binning criteria

- Binning used for $bb\tau\tau$:

- BDT binning transformed from right based on stat error and min events
  - $\sigma_B/N_B < x\% \times N_S/N_S^{\text{tot}}$ and $N_B > y$

	x	y
lh SLT res	20	10
lh other	40	10
hadhad	50	5

- N_B - prefit number of expected background events in bin i
- N_S - prefit number of expected signal events in bin i
- σ_B/N_B - prefit relative background uncertainty in bin i
- N_S/N_S^{tot} - prefit fraction of signal events in bin i
- Binning criteria is kept the same as in Run 2, but the binning itself changes as it depends on the number of expected background events

Binning changes in hadhad

- Sensitivity driven by $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel. Initial distributions have 1000 bins and the binning is determined as explained in previous slide from right to left:
  - Run 2: bins $= \{1002,733,647,551,438,0\}$
  - 36.1 fb^{-1}: bins $= \{1002,751,666,567,467,0\}$
  - 60 fb^{-1}: bins $= \{1002,768,675,578,474,355,0\}$
  - 100 fb^{-1}: bins $= \{1002,779,685,586,487,372,0\}$ and constant after
  - Prefit relative background statistical uncertainty in the last bin around 20 %, signal fraction around 40 %
  - If we would fix the bin edges to Run 2, the stat-only limit would change from $0.8 \times \sigma_{SM}$ to $0.99 \times \sigma_{SM}$

- Binning determined using the extrapolated Run 2 statistical uncertainties:
  - No reduction of MC statistical uncertainty
  - No scaling of the statistical uncertainty of data-driven backgrounds with lumi is taken into account

Sensitivity extrapolation summary

step	Stat-only $[\sigma/\sigma_{SM}]$	note	binning
Run 2	11.02 norm to 33.41	-	
14 TeV, 36.1 fb^{-1}	9.58 norm to 36.69	higher b-tag eff	changed
14 TeV, 60 fb^{-1}	6.73 norm to 36.69	higher b-tag eff	changed
14 TeV, 3000 fb^{-1}	0.80 norm to 36.69	higher b-tag eff	changed
14 TeV, 3000 fb^{-1}	0.99 norm to 36.69	higher b-tag eff	Run 2 binning
14 TeV, 3000 fb^{-1}	0.87 norm to 36.69	same b-tag eff	changed
14 TeV, 3000 fb^{-1}	0.99 norm to 36.69	higher b-tag eff	Run 2 binning
14 TeV, 3000 fb^{-1}	1.07 norm to 36.69	same b-tag eff	Run 2 binning

backup slides