Observation of the excess of top-antitop events near the threshold at LHC.
Is it toponium?

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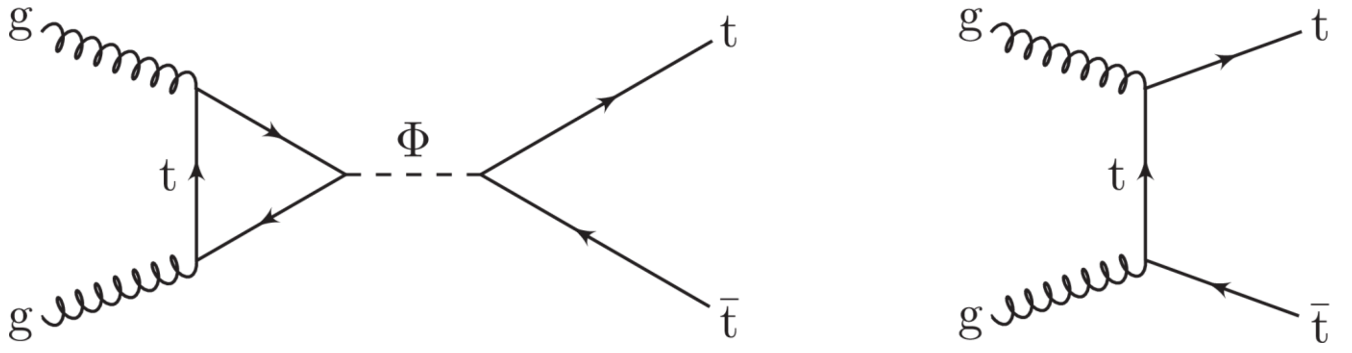

Born

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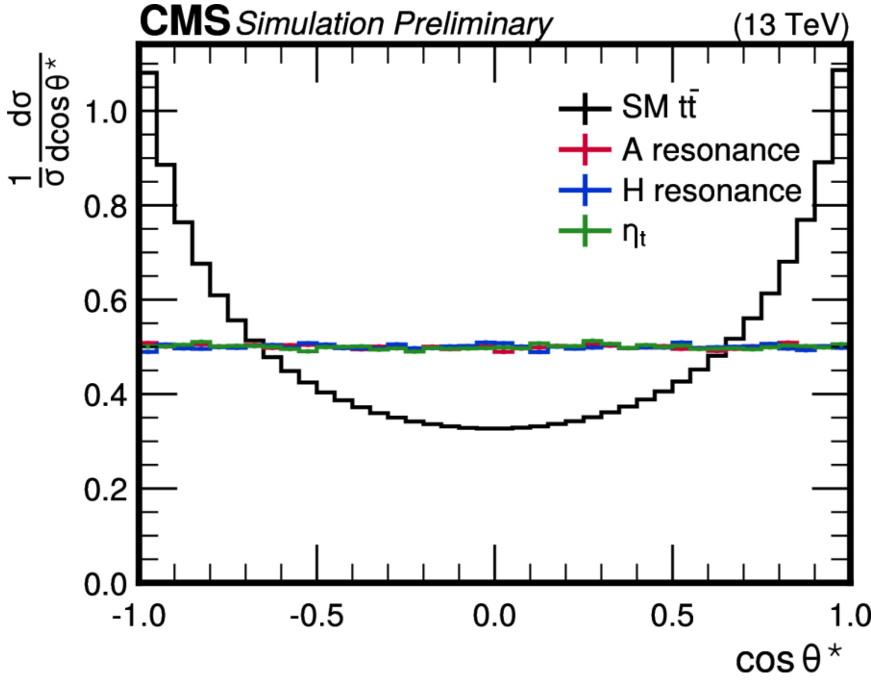
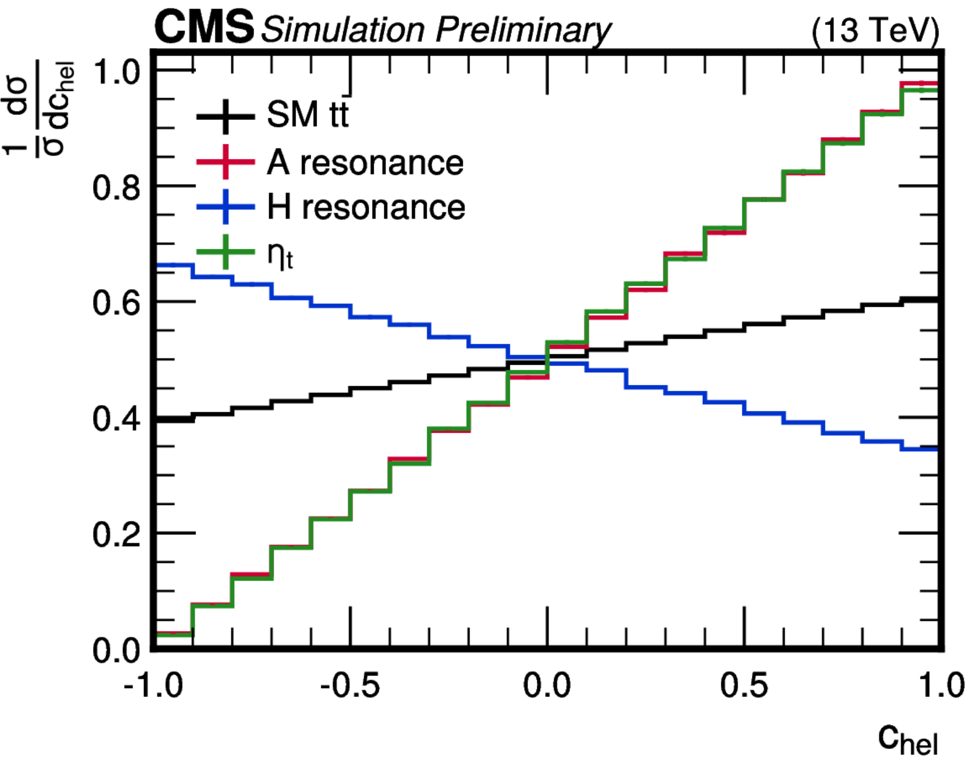
- ATLAS-25 – ATLAS-CONF-2025-008, TOPQ-2025-11, to be submitted to Rep. Prog. Phys.

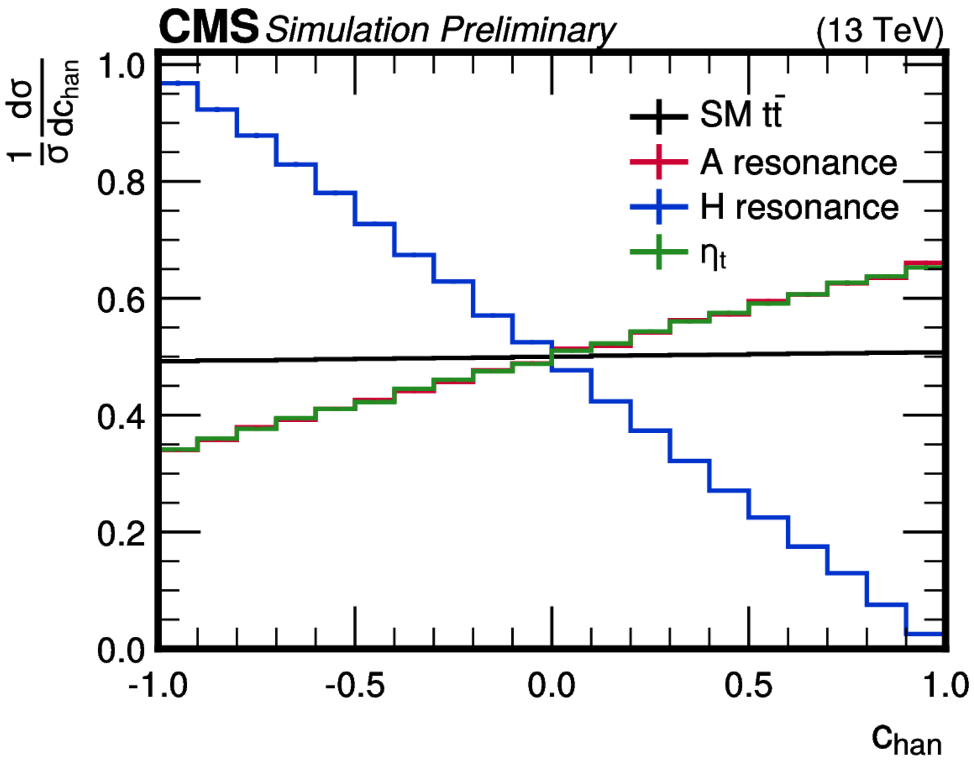
First observation by CMS

- 28.09.2024 CMS PAS HIG-22-013
- Strong motivation to search for pseudo-scalar Higgs $A \to t\bar{t}$
- $\sqrt{s} = 13$ TeV   L=138 fb^{-1} in Run-2 (2016-2018)
- pp→ $t\bar{t}\,X$ dominated by $gg \to t\bar{t}$
- One lepton channel $t\bar{t} \to$ bW + bW $\to$ b lν + b jj
- Two leptons channel $t\bar{t} \to$ bW + bW $\to$ b lν + b lν
- >=3(2)jets with p_T> 30 GeV and η<2.4, >=2(1) jet b-tagged
- isolated muons and electron with p_T> 20 GeV and η<2.4
- neutrino momentum p^{ν} reconstructed by kinematics using p_T^{miss} and constrains from top and W masses
- $m_{t\bar{t}}$ reconstructed with typical resolution of 23% (~80 GeV)
- $\theta^*_{t_l}$ - angle between leptonic top in zero momentum frame (ZMF) and the direction of $t\bar{t}$ in laboratory frame used for single lepton channel
- $cos\theta^*_{t_l}$ distribution is flat for spin-0 signals
- In fixed order (FO) pQCD $|cos\theta^*_{t_l}|$ peaks towards high value due to other spin states



Spin correlation observables in two leptons channel

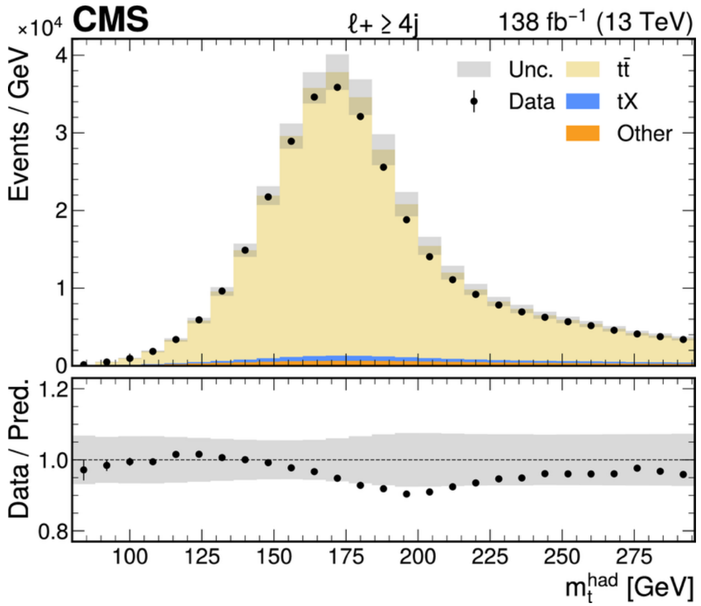




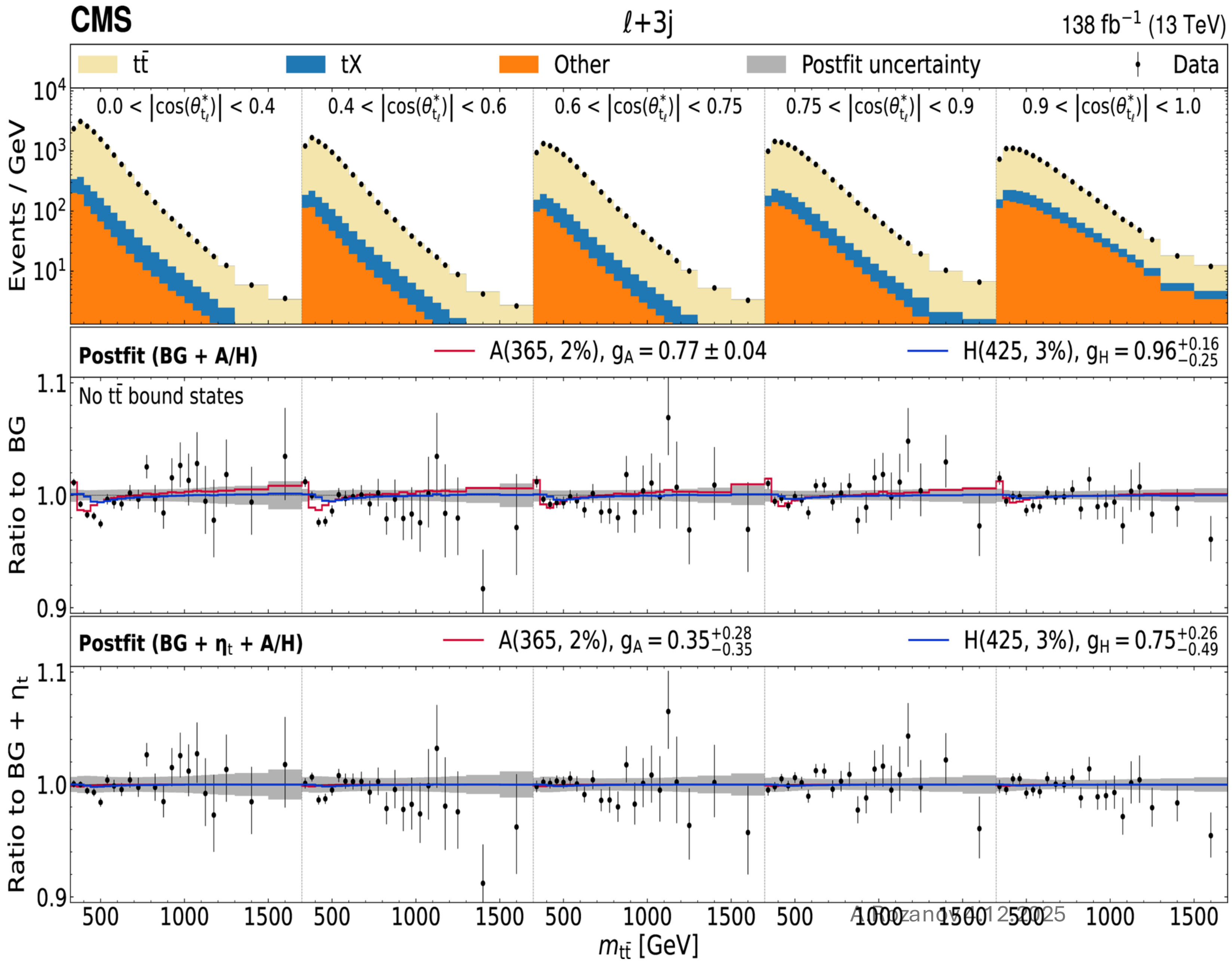
- For two leptons channel observable $c_{hel} = \widehat{l_t^+} \cdot \widehat{l_{\bar{t}}^-}$ is scalar product of two leptons unit vectors in the rest frames of t and t̄ respectively
- c_{han} - similar scalar product, but flipping the sign of the component parallel to the top quark direction
- Spin correlation observable rather flat for SM top production, but steep and opposite for pseudoscalar A or scalar H production

Background estimation and signal simulation

- pQCD $t\bar{t}$ Production at NLO accuracy using POWHEG v2 generator
- normalized with TOP++ 2.0 program at NNLO and including soft-gluon re-summation at NNLL order
- reweighted for NNLO pQCD and NLO EW corrections using MATRIX and HATHOR 2.1 programs
- Predicted cross-section 833.9 pb
- Single top are generated at NLO using POWHEG v2(t-channel), POWHEG(s-channel) and MadGraph5_aMC@NLO(tW-channel)
- A/H production by LO in MADGRAPH5_aMC@NLO 2.65 generator
- η_t production in LO in MADGRAPH5_aMC@NLO 2.65 generator with mass of 343 GeV and width of 7 GeV.

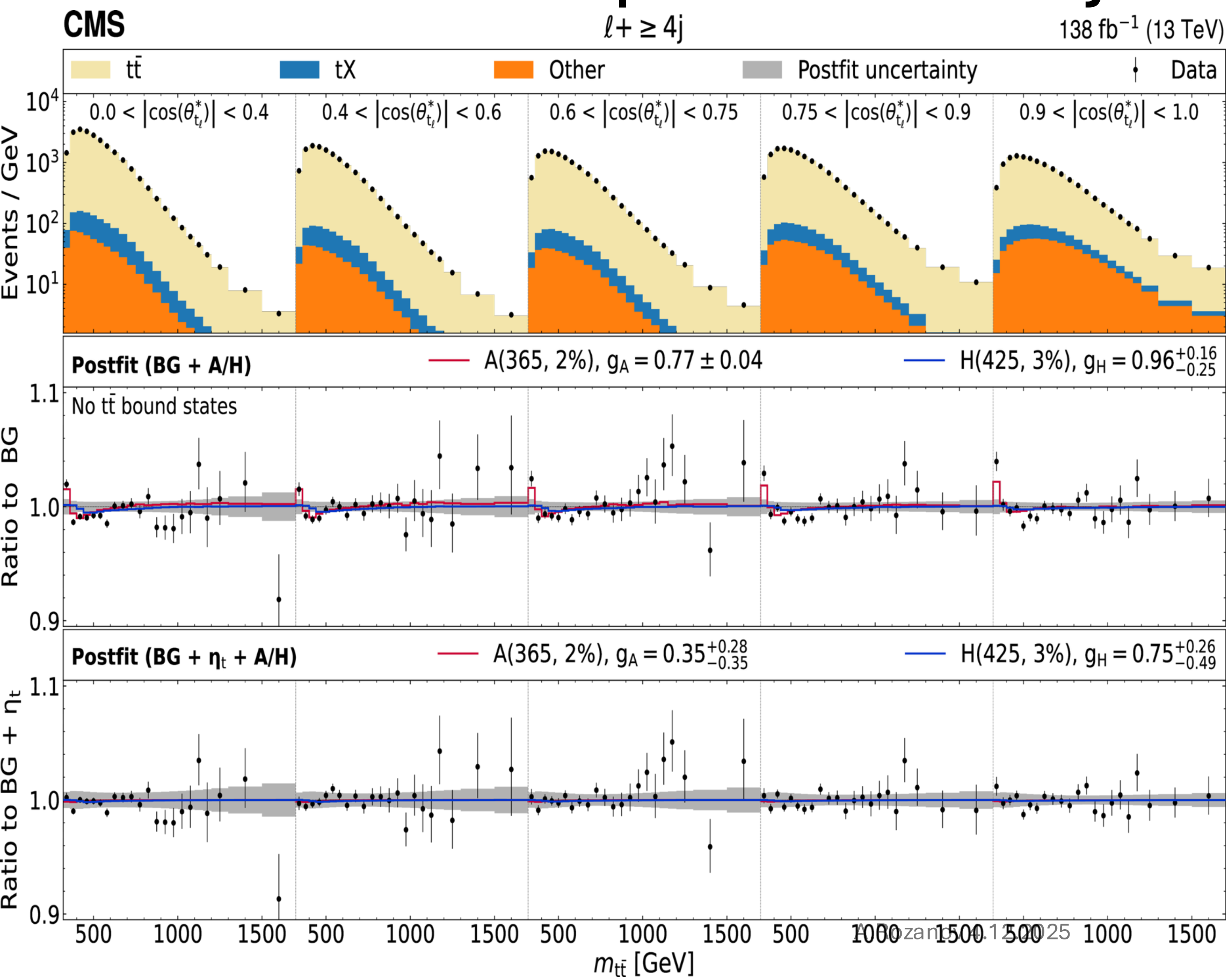


Observation in lepton and 3 jets sample



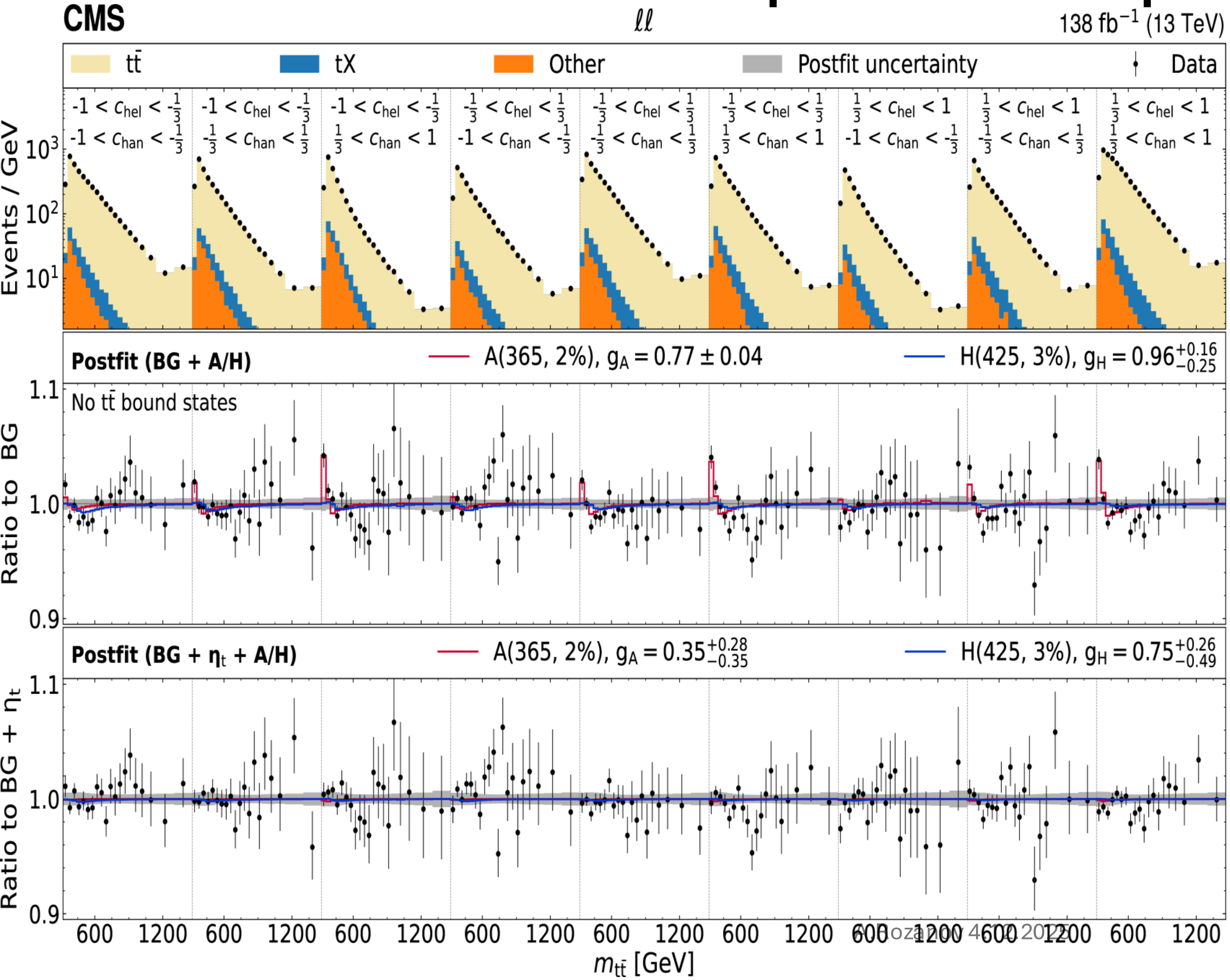
- Low $m_{t\bar{t}}$ signal observed in all $cos\theta^*_{t_l}$ bins
- Assuming only pQCD background there are some hints of A(365) signal
- Assuming the mixture of pQCD and toponium η_t there is no hints for A(365) signal

Observation in lepton and ≥4 jets sample



- Low $m_{t\bar{t}}$ signal observed in all $cos\theta^*_{t_l}$ bins
- Assuming only pQCD background there are some hints of A(365) signal
- Assuming the mixture of pQCD and toponium η_t there is no hints for A(365) signal

Observation in two leptons sample



- Low $m_{t\bar{t}}$ signal observed mostly in big c_{hel} and big c_{han} bins, as expected for pseudoscalar particle
- Assuming only pQCD background there are some hints of A(365) signal
- Big interest from theory community, as multi-Higgs models are popular
- Assuming the mixture of pQCD and toponium η_t background there is no hints for A(365) signal

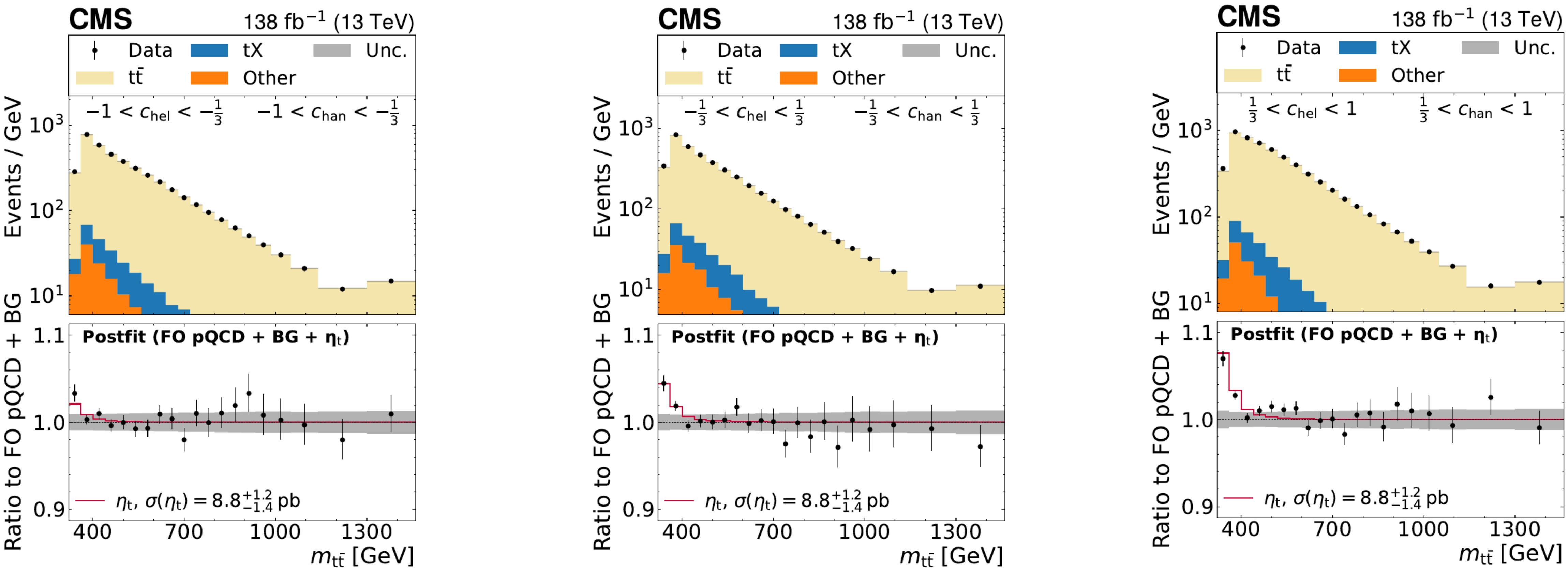
First CMS results

- An excess of the data above pQCD background prediction is observed near the kinematical $t\bar{t}$ production threshold
- With pure pQCD background assumption A(365) interpretation is discussed
- Excess is consistent with the simplified model of toponium η_t m=343 GeV and Γ = 7 GeV with 7.1 pb cross-section
- In case of addition of η_t to pQCD background, no need for A(365) contribution
- Discussion that the origin of η_t is quasi-bound state from NR QCD

Second observation by CMS

- 31.03.2025 CMS-TOP-24-007
- Same data sample $\sqrt{s} = 13$ TeV L=138 fb^{-1} in Run-2 (2016-2018)
- Only two leptons channel $t\bar{t} \rightarrow bW + bW \rightarrow b\,l\nu + b\,l\nu$
- >=2 jets with with p_T> 30 GeV and $\boldsymbol{\eta}$<2.4, >=1 jet b-tagged with p_T> 20 GeV
- isolated muons and electron with p_T> 20(30) GeV and $\boldsymbol{\eta}$<2.4
- neutrino momentum p^{ν} reconstructed by kinematic fit using p_{T}^{miss} and constrains from top and W masses
- $m_{t\bar{t}}$ reconstructed with typical resolution of 15-25%
- $c_{hel} = \widehat{l_t^+} \cdot \widehat{l_{\bar{t}}^-}$ and c_{han} spin correlation variables
- Backgrounds as in the first analysis
- Pseudoscalar η_t production in LO in MADGRAPH5_aMC@NLO 2.65 generator with mass of 343 GeV and width of 2.8 GeV.

Mass distributions in 3 out of 9 bins

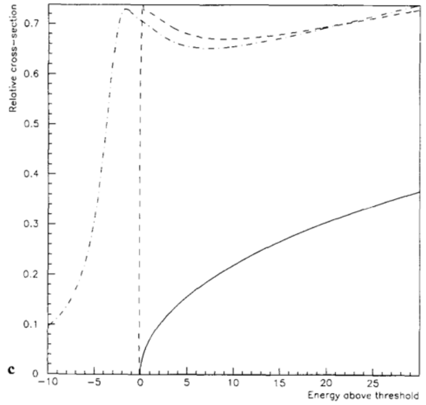


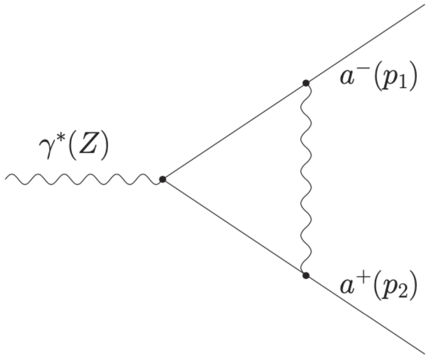
- First and last bins include underflow and overflow
- Signal increase at high value of c_{hel} and c_{han} as expected for pseudoscalar
- Statistical significance exceed 5 sigma
- Fitted cross-section $\sigma(\eta_t) = 8.8 \pm 0.5(\text{stat})\, ^{+1.1}_{-1.3}(\text{syst})\ \text{pb} = 8.8^{+1.2}_{-1.4}\ \text{pb}$

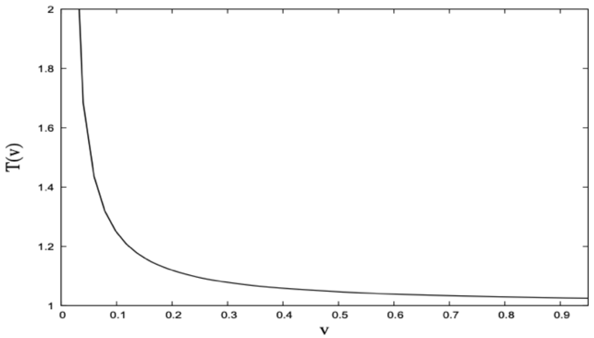
Discussion of CMS results

- High quality experimental work to observe very small excess of ~1% total $t\bar{t}$ cross-section
- We can not agree with A(365) interpretation, as pQCD background is not the full SM background
- We do not agree with toponium interpretation
- Pseudoscalar η_t production model is artificial ad-hoc addition, not natural SM part
- Our arguments are on the following slides…

History

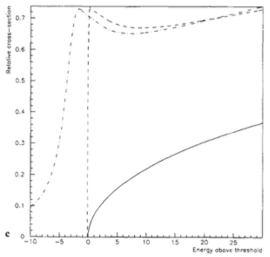






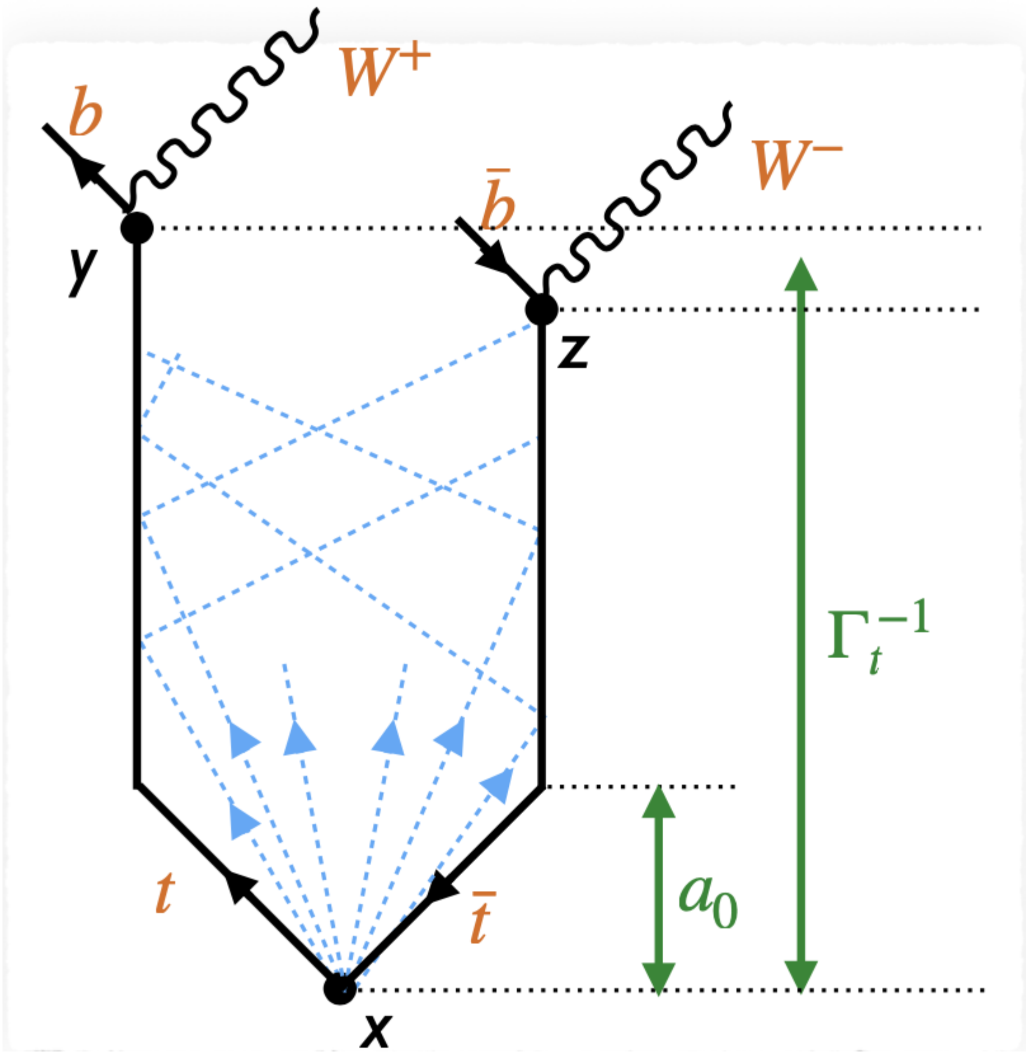
- At threshold energy Born cross-section of pair production of stable particles is exactly zero
- Sommerfeld-31 demonstrated that the correction due to re-scattering of charged particles (QED) in the final state is proportional to wave function at the origin $|\Psi(0)|^2$
- Gamow-28 has shown that the same factor is relevant for the description of Coulomb barrier (QED) in nuclear interactions.
- Sakharov-48 derived using non-relativistic Schrodinger equation this factor for charged pair (QED) production.
- Dramatic increase of the cross-section near threshold, usually called Sommerfeld-Gamow-Sakharov (SGS) factor. It is non-relativistic quantum mechanics effect calculated to all orders in α.
- Same effect of increase of cross-section in oppositely charged particles annihilation or fusion reactions (quantum tunnelling)
- Electromagnetic SGS factor T= η /(1-exp(- η)) where η=2 π α / v, v- relative velocity of the pair of particles v=2 β or better v=2 β /(1+β^2) (relativistic case by Arbuzov-12)
- Strong SGS factor T= η /(1-exp(- η)) in $t\bar{t}$ production where η=(8/3) π α_s / v (approximation of stable top) (at e^+e^- by Bigi-86 ,Fadin-87, at LHC by Bigi-86, Fadin-90)
- Fadin-Khoze-Sjostrand predicted that top pairs are produced on gluon fusion near threshold in pseudoscalar state (Fadin-90)
- Toponium (like charmonium, bottomonium etc) is the resonance part of SGS effect, which may be important or not depending on the quark lifetime, but SGS effect is always present

Application to $t\bar{t}$ production at LHC



- Fadin-Khoze-Sjostrand calculated T-factor for $t\bar{t}$ production with short living top Γ_t (Fadin-90)
- $T = (4\pi / m_t^2 \beta)\ Im(G(0,0))$, where $G(x,y)$ is the Green function of $t\bar{t}$ system
- In Fadin-90 analytical formulas of $Im(G(0,0))$ with terms like $1/(E^2+\Gamma_t^2)$ are given
- Both color singlet state (dominant and positive near threshold) and color octet state (positive below threshold, but negative above threshold) are calculated
- In case of low mass top and small Γ_t bound states (toponium) appears in G(x,y). Should we expect toponium with actual m_t=173 GeV and Γ_t =1.49 GeV ? See next slides ...
- Running $\alpha_s = (12\pi) / (23 \ln(m_t \sqrt{(E^2+\Gamma_t^2)}/\Lambda^2))$, Λ=200 MeV . Any modern update of this running α_s ?
- T factor in Fadin-90 is given to respect to Born approximation. What if NLO or NNLO are available? Double counting? See next slides...
- Similar calculations are done later in Sumino-10 and Fuks-24 with higher orders FO pQCD

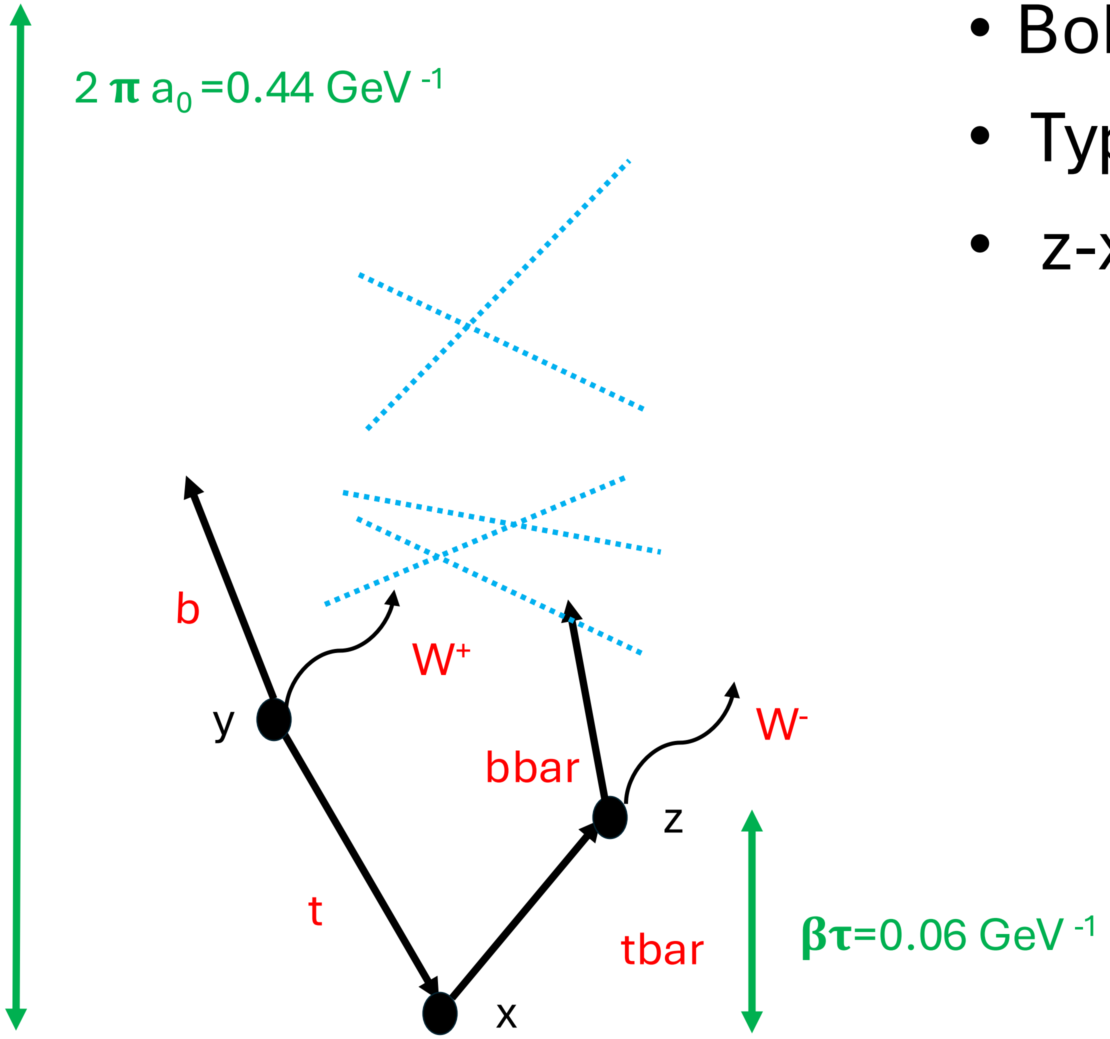
Position-space of $t\bar{t}$ by B.Fuks



- Bohr radius $a_0 = 1/(C_f\, \boldsymbol{\alpha}_s\, m_t/2) = 0.07\ \text{GeV}^{-1}$
- Top lifetime $\boldsymbol{\tau} = \boldsymbol{\Gamma}_t^{-1} = 0.6\ \text{GeV}^{-1}$
- Toponium states expected by B.Fuks as $a_0 \ll \boldsymbol{\tau}$

- But it is in the ultra-relativistic approximation $z\text{-}x = \boldsymbol{\beta}\, \boldsymbol{\tau}$, so $\boldsymbol{\beta}=1$ in this picture
- But top should rotate, so typical distance is orbit circumference $2\,\boldsymbol{\pi}\, a_0$

Position-space of $t\bar{t}$ should be



- Bohr orbit $2\,\pi\, a_0 = 2\pi/(C_f\, \alpha_s\, m_t/2) = 0.44\ \text{GeV}^{-1}$
- Typical top velocity $\beta_t = 0.1$
- $z\text{-}x = \beta\tau = \beta\Gamma_t^{-1} = 0.06\ \text{GeV}^{-1}$

- $z\text{-}x = \beta\Gamma_t^{-1} << 2\,\pi\, a_0$ so the system decays before the oscillations within potential barrier
- No toponium states expected, but final state wave function correction is important
- Absence of toponium with such top mass was noticed in many publications, for example Bigi-86 where this time-space picture was given

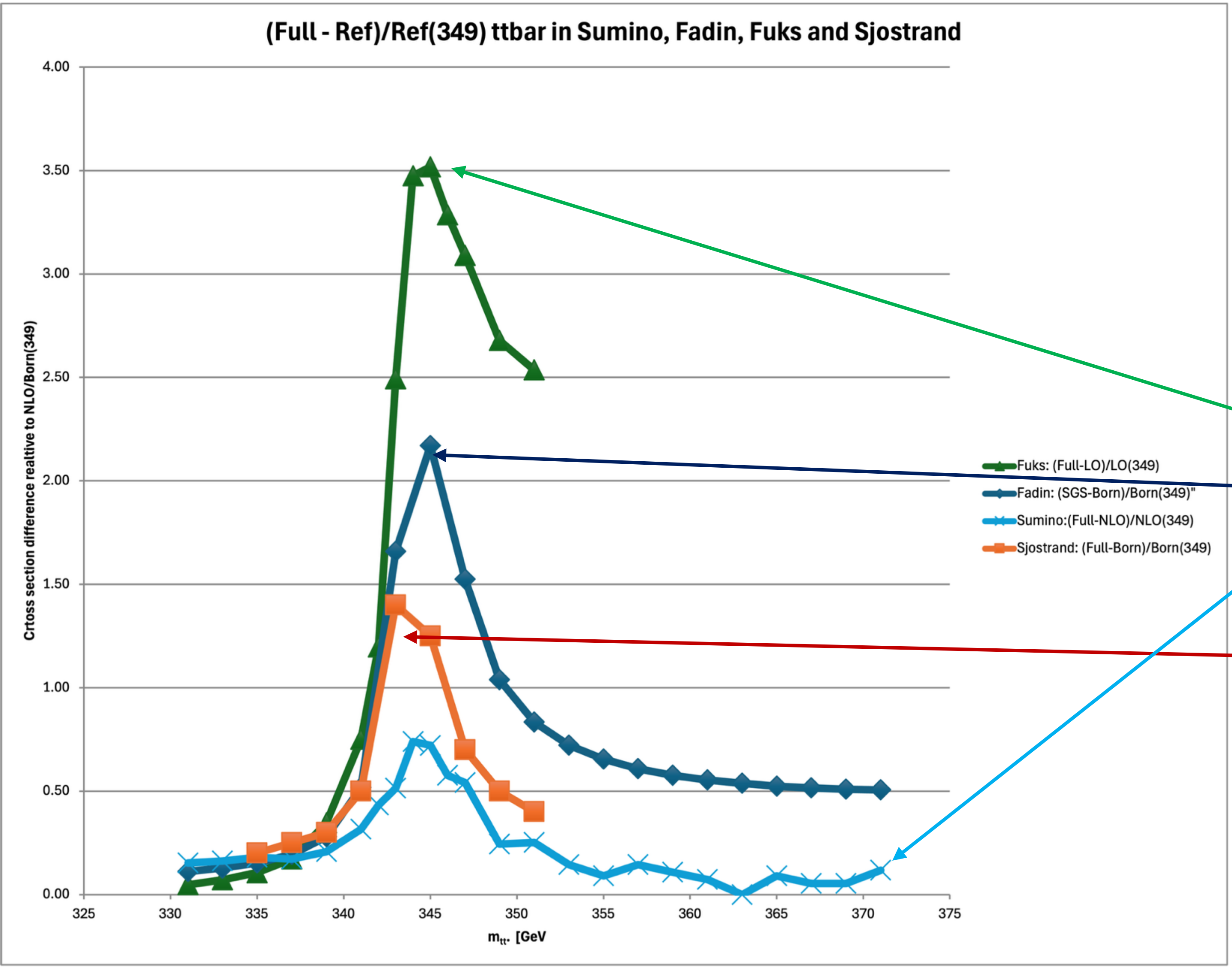
Double counting in case of NLO or NNLO ?

- Yes, in case NLO or NNLO is used instead of Born, some double counting is present in T-factor
- In QED case Arbuzov-12 make the following procedure to avoid double counting:
- $\boldsymbol{\sigma}^{corr} = \boldsymbol{\sigma}^{Born} \; (T - \boldsymbol{\pi} \boldsymbol{\alpha} / v - \boldsymbol{\pi}^2 \boldsymbol{\alpha}^2 / 3v^2 - \ldots) + \boldsymbol{\Delta\sigma}^{1\text{-loop}} + \boldsymbol{\Delta\sigma}^{2\text{-loop}} + \ldots$
- In QCD case it is more complicated due to color effects
- In Fuks-24 the double counting is corrected by:

$\boldsymbol{\sigma}^{corr} = (\boldsymbol{\sigma}^{Born} + \boldsymbol{\Delta\sigma}^{1\text{-loop}}) \; (T-1)$, where $T=|G/G_0|^2$ G- Green function of toponium, G_0 – Green function for the free Hamiltonian

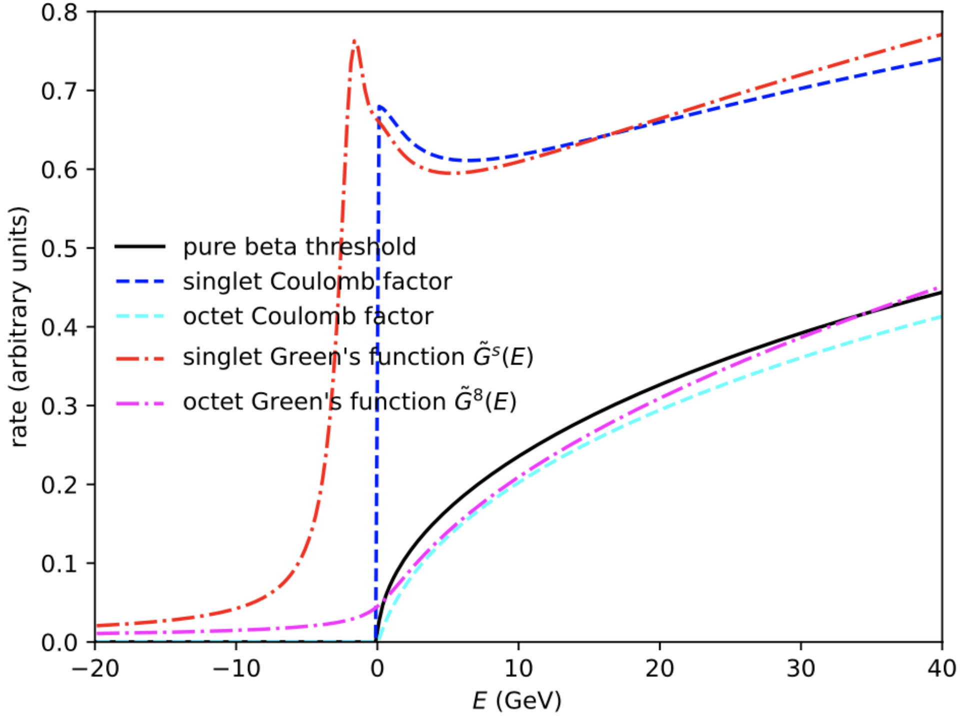
- Different procedure to avoid double counting in Sumino-10 by interpolation between threshold region and pQCD region. How precise it is?

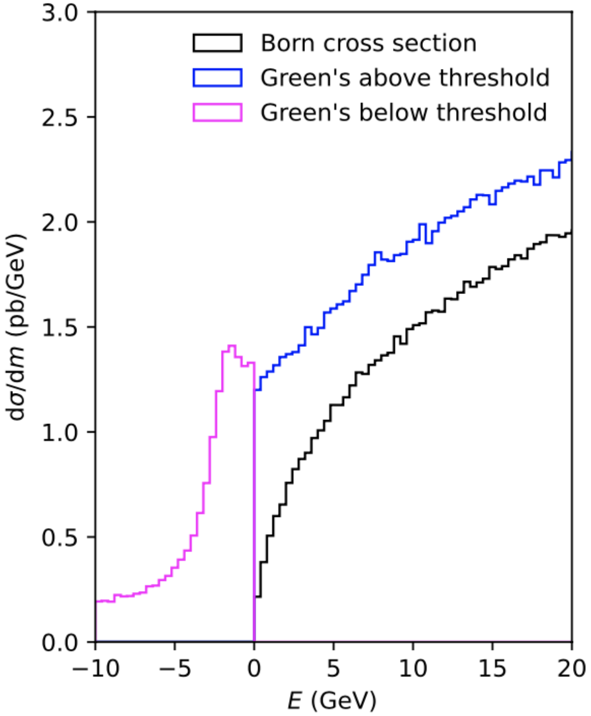
Comparison Fadin90 vs Sumino10, Fuks24, Sjostrand25

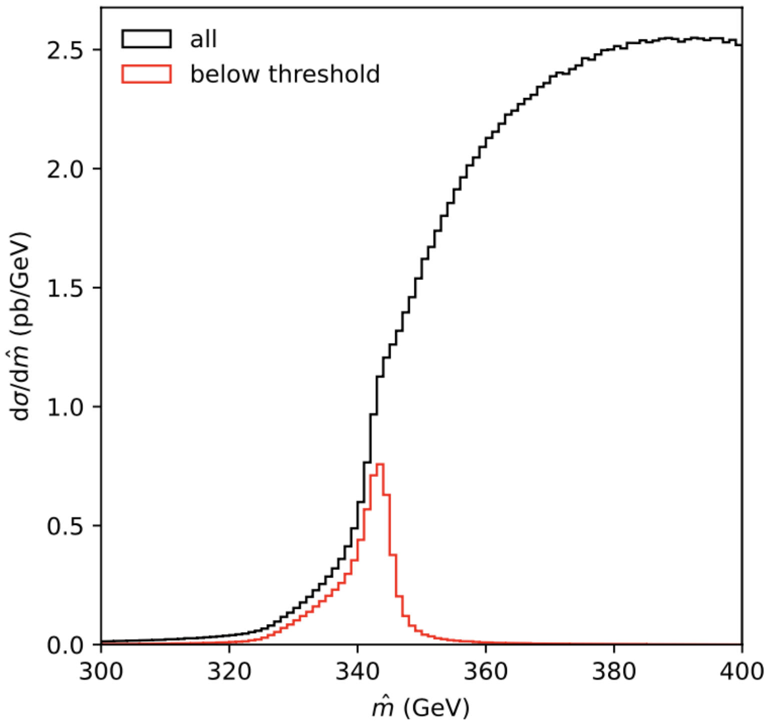


- Normalize cross-sections to reference at m_{tt}=349 GeV (Ref(349)) in order to avoid differences in gg PDFs, K-factors, branchings etc
- Plot (Full-Ref)/Ref(349)
- Where "Ref" is Born for Fadin-90 and Sjostrand-25, NLO for Sumino-10 and LO for Fuks-24
- Special calculation for Fadin-90 with m_t=173 GeV and data from figures for Sumino-10 and Fuks-24 and Sjostrand-25
- 4 shapes are similar in form
- Fuks-24 (only color singlet) is higher than Fadin-90 (2/7singlet+5/7octet)
- Sumino-10 (pQCD mix of singlet/octet) is lower than Fadin-90
- Sjostrand-25 (2/7singlet+5/7octet+qq singlet) is lower than Fadin-90
- Differences are due to different single/octet mixtures and treatment of double counting?
- α_s (m_{tt}) running in Fadin-90, others??

PYTHIA 8.316 implementation of threshold effects







- PYTHIA 8.316 implementation of SGS effect is described in Sjostrand-25
- Absolute cross section 6.76 pb for E < 0 GeV
- Private extrapolation to E<20 GeV give ~ 16 pb (to subtract double counting if compared with experimental results)

Discussions

- SGS factor is very well-known effect and should be introduced in SM background before searching for H or A decays to $t\bar{t}$. Not including it and limiting SM background to pQCD may produce false results like recent A(365) signal.
- Top decay length is much smaller than characteristic Bohr orbit ($z\text{-}x = \beta\Gamma_t^{-1} << 2\pi a_0$) so the system decays before the oscillations within potential barrier. Due to that one should call the amplification of cross section near $t\bar{t}$ threshold as "final state wave function effect" rather than "toponium".
- Is it reasonable to "search for toponium" while SGS factor quantum effect should exist in any case? Not possible to not have it.
- The formulas are given as SGS (Sommerfeld-Gamow-Sakharov) factor in the article of Fadin, Khoze and Sjostrand in 1990 starting from Born approximation. Now it is implemented in Pythia 8.316, see Sjostrand-25. Similar calculations are done by Sumino-10, Fuks-24 and Garzelli-24 starting from NLO and LO approximations. These calculations gives similar shapes of SGS factor vs $m_{tt.}$, but different size. Different color singlet/octet mixture and double counting between SGS and NLO?

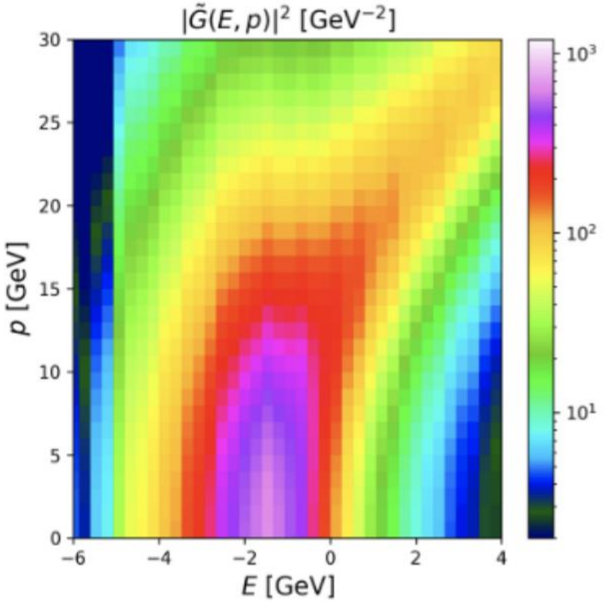
Observation by ATLAS

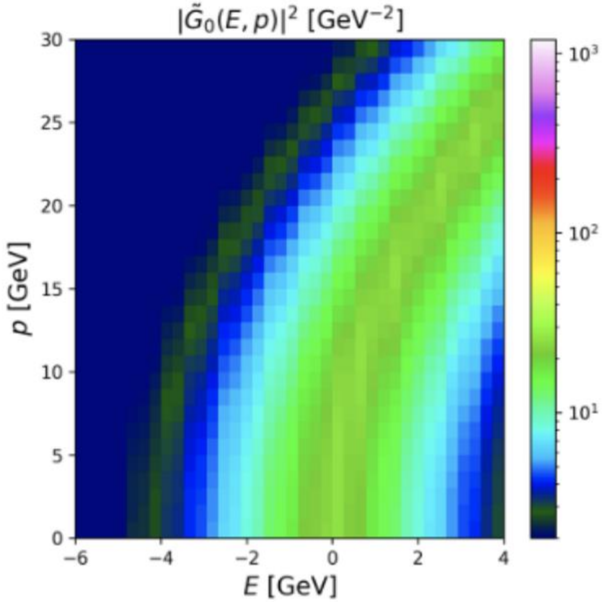
- 06.07.2025 ATLAS-CONF-2025-008
- Data sample $\sqrt{s} = 13$ TeV L=140 fb^{-1} in Run-2 (2015-2018)
- Only two leptons channel $t\bar{t} \to bW + bW \to b\, l\nu + b\, l\nu$
- >=2 jets with p_T> 25 GeV and η<2.5, >=1 b-tagged
- trigger lepton with p_T> 24/27/28 GeV
- isolated muons with p_T> 10 GeV and η<2.5
- isolated electron with p_T> 10 GeV and η<2.47
- E_T^{miss} > 60 GeV
- neutrino momentum p^{ν} reconstructed by Elipse Method using p_T^{miss} and constrains from top and W masses
- $m_{t\bar{t}}$ reconstructed with typical resolution of 22-18%
- $c_{hel} = \widehat{l_t^+} \cdot \widehat{l_{\bar{t}}^-}$ and c_{han} spin correlation variables
- $t\bar{t}$ background at NLO accuracy using POWHEG Box v2 hvq generator with PYTHIA 8 showering, normalized with TOP++ 2.0 program at NNLO and including soft-gluon re-summation at NNLL order, reweighted for NNLO pQCD and NLO EW corrections using MATRIX and HATHOR 2.1 programs. Predicted cross-section 833.9 pb.

Model of quasi-bound-state effects in ATLAS

$$|\mathcal{M}|^2 \quad \rightarrow \quad |\mathcal{M}|^2 \left| \frac{\widetilde{G}(E; p^*)}{\widetilde{G}_0(E; p^*)} \right|^2$$

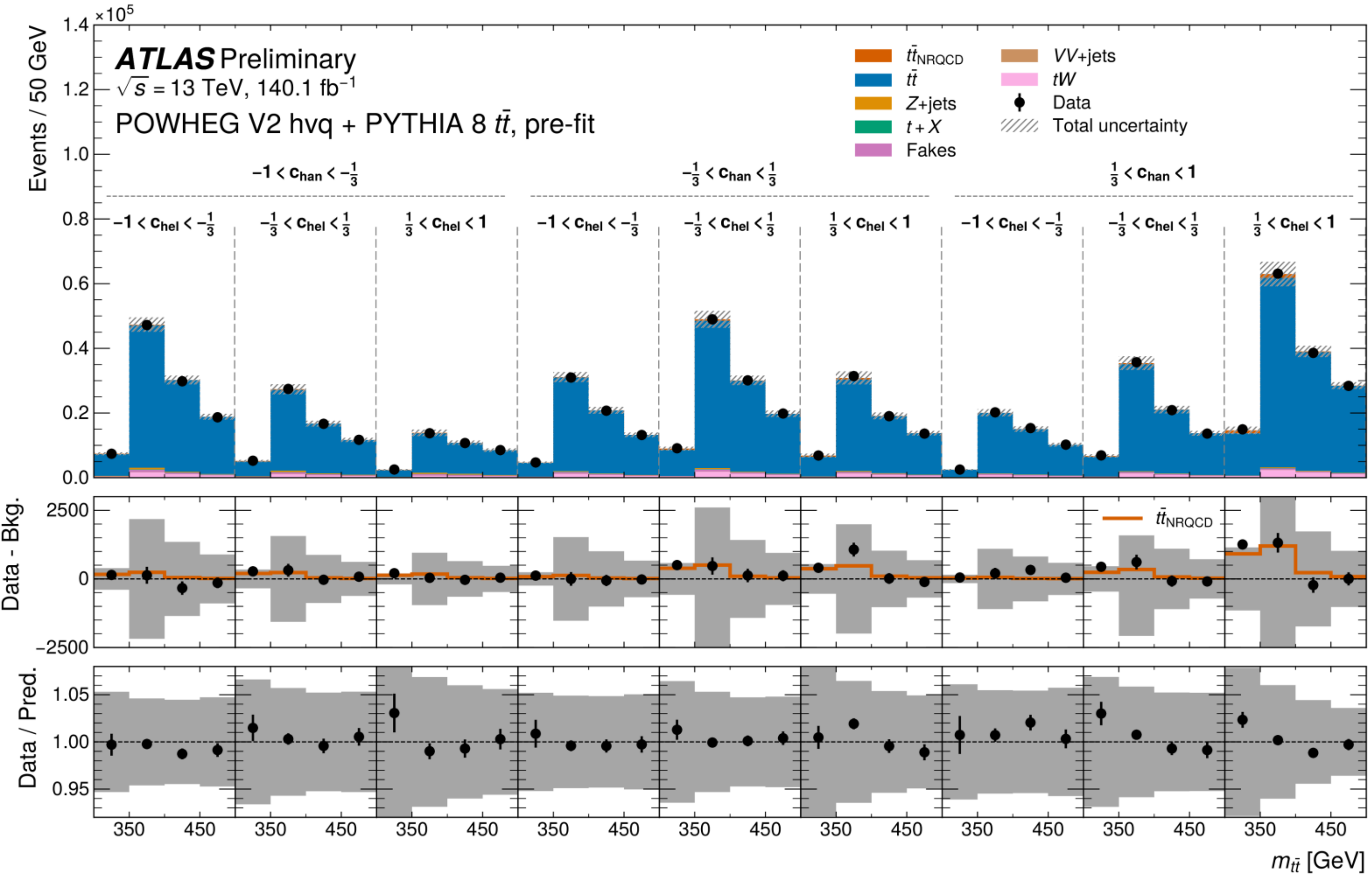
$\tilde{G}$: Green's function considering QCD potential
$\tilde{G}_0$: Free Green's function





- Formation of color singlet states is described in Fuks-24 using Green's functions of NR QCD following Fadin-90
- But Green's function in Fuks-24 is computed numerically by solving Lippmann-Schwinger equation with input from the Fourier transform of the QCD potential
- Result is used to reweight Matrix Element from LO accuracy pQCD of color singlet $t\bar{t}$ pairs in an S-wave near threshold
- Reweight only for events with $m_{t\bar{t}}$ < 350 GeV
- Double counting is assumed to be negligible
- Normalized to analytical calculation 6.43 pb (from Fuks-21)

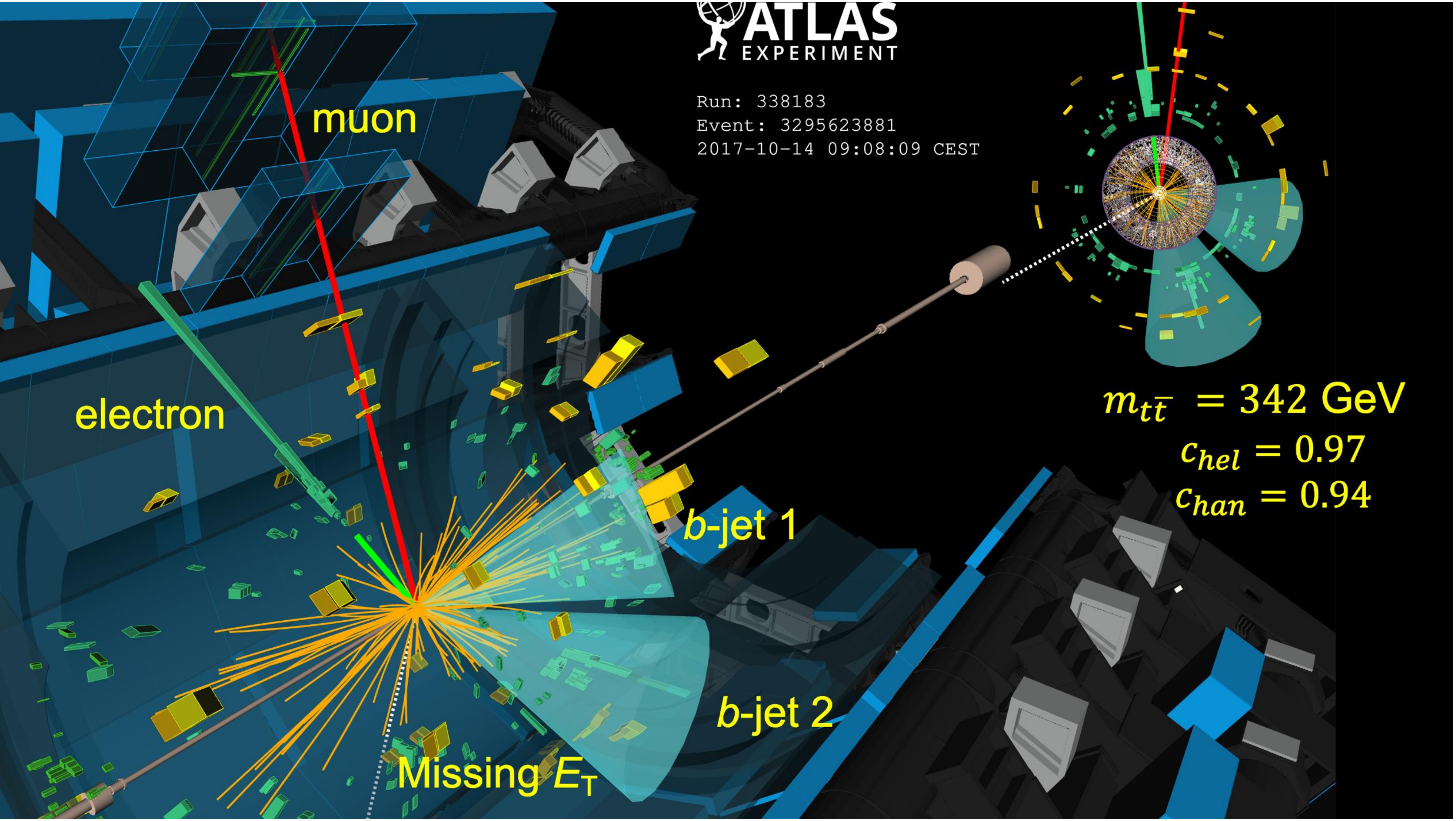
ATLAS



- Signal increase at high value of c_{hel} and c_{han} as expected for pseudoscalar state
- Statistical significance 7.7 sigma

- $\sigma\,(tt_{NRQCD}) = 9.0 \pm 1.2(\mathrm{stat}) \pm 0.6(\mathrm{syst})\ \mathrm{pb} = 9.0 \pm 1.3\mathrm{pb}$
- Predicted value is 6.4 pb, so experiment is (40±20)% larger than theory

One tt event in ATLAS



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Summary of LHC observations and theory predictions

	Cross-section	significance	Interpretation and Comments
CMS-24	7.1 pb	> 5 sigma	η_t or A(365) or mixture
CMS-25	$8.8^{+1.2}_{-1.4}$ pb	> 5 sigma	η_t simplified model and origin quasi-bound $t\bar{t}$ state
ATLAS-25	9.0 ± 1.3 pb	7.7 sigma	Color singlet S-wave pseudoscalar quasi-bound $t\bar{t}$ states
Theory: Fuks-21	6.43 pb	-	-8<E<4 GeV, from interpolation from Sumino-10, $\sqrt{s}$ =14 TeV
Theory: Sjostrand-25	6.76 pb	-	Only E<0, Born
Theory: Sjostrand-25	9.1 pb	-	Private: -8<E<4 GeV, Born
Theory: Sjostrand-25	<16 pb	-	Private: -10<E<20 GeV, Born, double counting correction to be applied
Theory: Sumino-10	9.6 pb	-	Private: -15<E<17 GeV, LO + NLO pQCD

- Signal seen as the enhancement of $t\bar{t}$ production near the threshold over FO pQCD

Quasi-bound-state formation near $t\bar{t}$ threshold ?

- The excess of events near $t\bar{t}$ threshold is explained by the term "quasi-bound-state formation near $t\bar{t}$ threshold".
- This is much better than the term "toponium", but this term has some limited validity.
- It is true that in the kinematical region E<0 ($E=m_{tt}-m_{top1}-m_{top2}$) the increase of the $t\bar{t}$ cross-section near threshold due to the final state interactions (or in other words final state wave function of $t\bar{t}$ system) is dominated by infinite sum of quasi-bound-states contributions. However in the region E>0 there is also strong increase of $t\bar{t}$ cross-section near threshold without any quasi-bound-states. Certainly part of this increase at E>0 is double counted with FO pQCD NLO corrections, but FO pQCD NLO corrections can not account for the full effect of the increase of $t\bar{t}$ cross-section near the threshold at E>0 for the following two reasons:
- a) Final state interaction NR QCD calculations are valid up to all orders, while pQCD NLO are valid only to fixed order.
- b) Fixed order (FO) NLO pQCD calculations assume validity of perturbation theory, but in the kinematical region close to the threshold the terms proportional to alpha_s/v (v is relative velocity of top-antitop) are not anymore small and the perturbative calculations are not anymore reliable.
- So the better term would be "final state NR QCD interactions" (in QED case called Sommerfeld-Gamow-Sakharov effect) or "final state $t\bar{t}$ wave function".

To do list for theoretical description of SGS effect

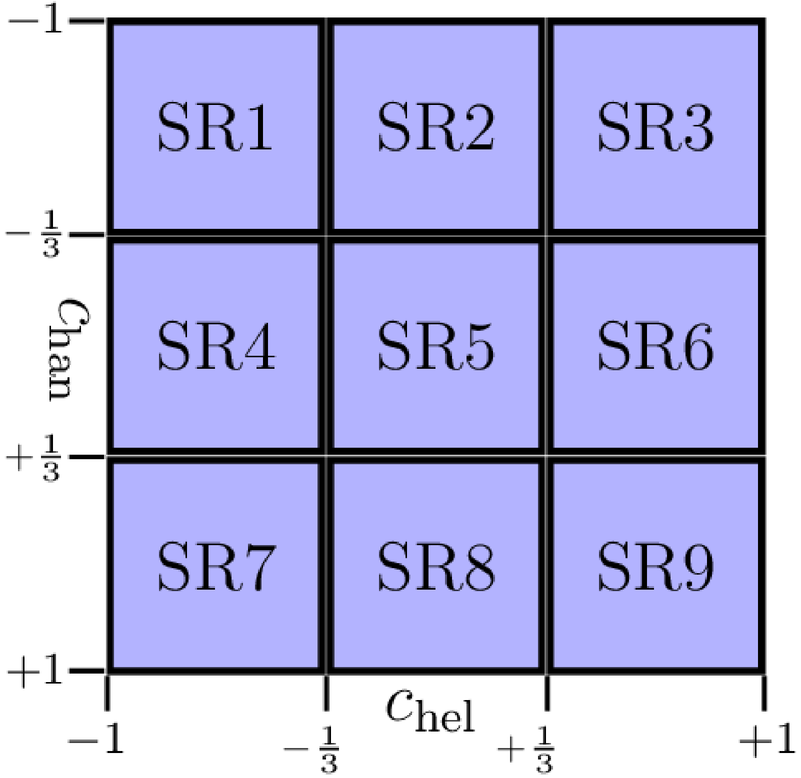
- Base approach is clear, but the devil is in many details:
- Analytical versus numerical Green functions?
- Correct color singlet versus octet composition using pQCD predictions
- Evaluate with good accuracy double counting between high FO pQCD calculations and SGS NR QCD effect
- Correct phase space factor calculations in Breit-Wigner top masses generation and SGS effect
- Is it correct to factorize top production, SGS effect and top decays?
- To check that correct relativistic formulas for relative tops velocity like Arbuzov's are used
- Introduce natural scientific smooth transition from SGS NR QCD region to relativistic FO pQCD region instead of rough-cut E<5 GeV
- Interface with real generators (Powheg, Pythia8 etc)
- Correct running of α_s near threshold
- etc etc etc

Conclusions

- Excellent experimental work of CMS and ATLAS to observe very small effect of the enhancement of the $t\bar{t}$ production near threshold. Only 1% of the total cross-section!
- Combination of ATLAS and CMS for Run2+Run3 can give already increase of statistics by a factor of 7 (already recorded). HL LHC can give another factor 5-10 in 2041.
- SGS factor is very well-known effect and should be introduced in SM background before searching for A decays, BSM η_t or other new particles. It is not true that observation of top “quasi-bound states” at LHC was unexpected.
- Top decay length is much smaller than characteristic Bohr orbit (z-x = $\boldsymbol{\beta\Gamma}_t^{-1} << 2\,\boldsymbol{\pi}\, a_0$) so tops decays before the oscillations within potential barrier. So SM “toponium” should not exist.
- Precise measurements and precise theoretical modeling of the final state $t\bar{t}$ wave function (“quasi-bound states”, NR QCD) near threshold is important for further study of new phenomena like top quarks quantum entanglement etc.

Spare

9 signal regions in c_{hel} versus c_{han} plane



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