Quantum tests at LHC

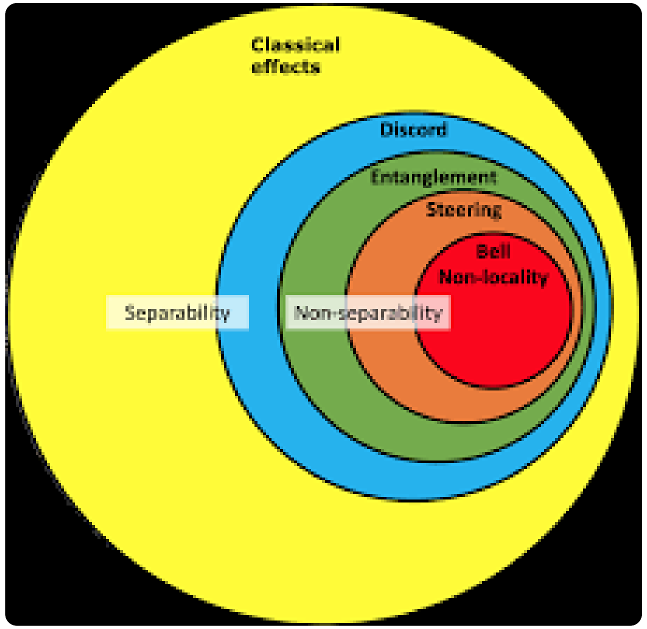
FEDERICA FABBRI

*BASED ON [EUR. PHYS. J. C **84**, 20 (2024)] F. FABBRI, J. HOWARTH, T. MAURIN*

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

QUANTUM INFORMATION PRINCIPLES AT COLLIDERS



- In the last few years > 100 papers on the possibility to apply quantum information principles at colliders
- Consider the spin of a particle as the representation of a qu***d***it
- Use fundamental properties of a quantum state, generally used in QIT and QC, to study the particles created at colliders
  - **Entanglement**
  - **Violation of Bell's inequality**
  - Discord
  - Steering
  - Magic

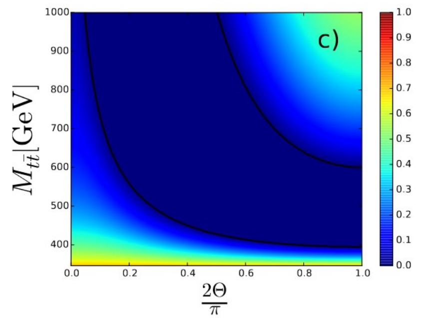
NICE…BUT HOW?

- Multipurpose detectors as ATLAS and CMS were not designed to this purpose
  - We can not measure the spins of the particles created at colliders per event.
- We can exploit the chiral nature of the weak interaction:
  - Relates the direction of the decay products to the spin of the parent particle
  - The spin analysing power quantifies this relation
    - Vary with the decay product
- By measuring some angular distribution of the decay products we can extract some information of the parent particle spin
  - We need to average on multiple similar state
  - Integrate on distributions of the normalised differential cross section as a function of some angle
  - **Quantum tomography**
    - $p(l^{\pm}{}_{\hat{n}};\rho) = \frac{3}{4\pi} tr\left(\rho \Pi_{\pm;\hat{n}}\right)$, Π projection operators

WHICH ANGLE?

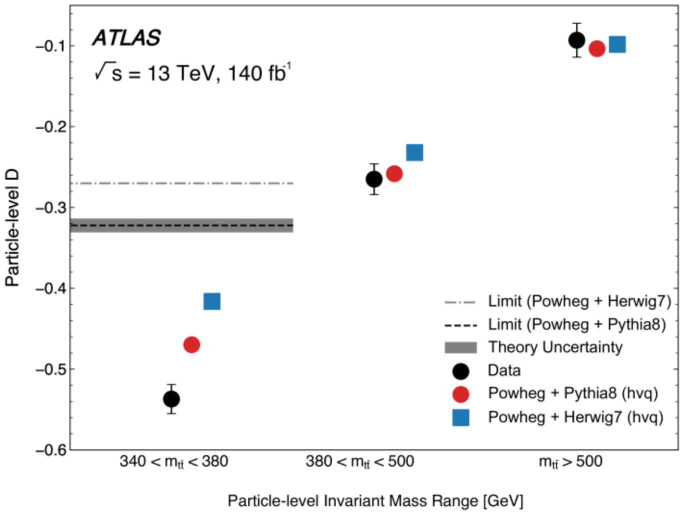
- The entire information of a quantum state is encapsulated in the spin density matrix
  - The angles are the ones between the target particle decay products and the reference frame
  - The best frame is the one maximising the "spin correlations", in many cases this is the "helicity" frame
    - Defined in the rest frame of the interesting particle
- Starting from the spin density matrix several information on the state can be extracted: e.g. entanglement
- Measure the full spin density matrix, depending on the process, can be a very or just complicated
  - It is easier to have some "entanglement witness"

JR Munoz de Nova, Y. Afik
[Eur.Phys.J.Plus 136 (2021) 9, 907]

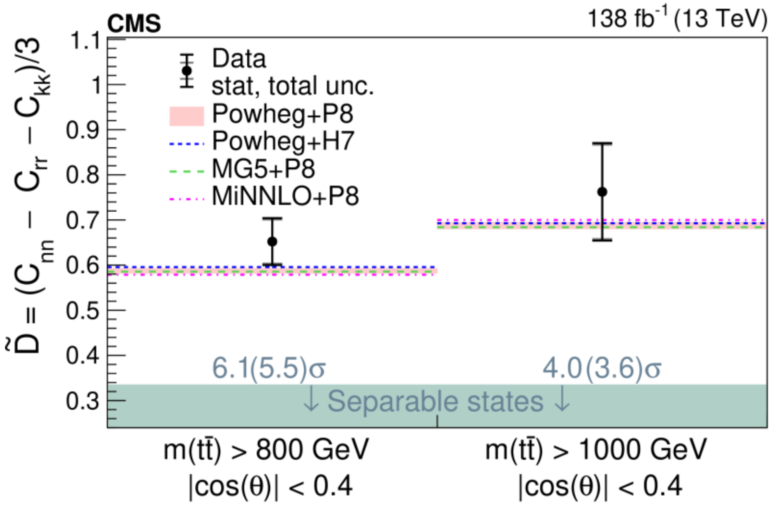


CURRENT STATUS

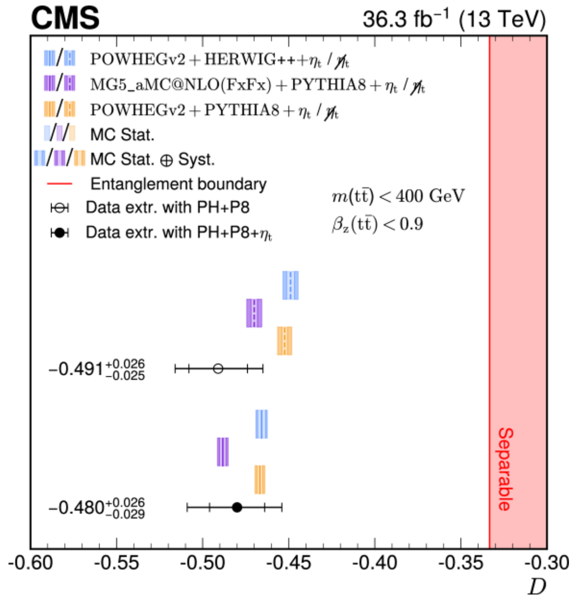
- Both ATLAS and CMS observed entanglement in top-quark pair production
  - Both at threshold then in the high p_T region



[Nature 633 (2024) 542]

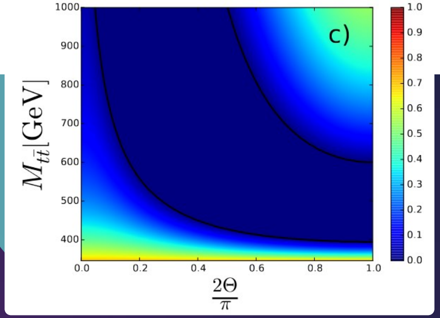


[PRD 110 (2024) 112016]



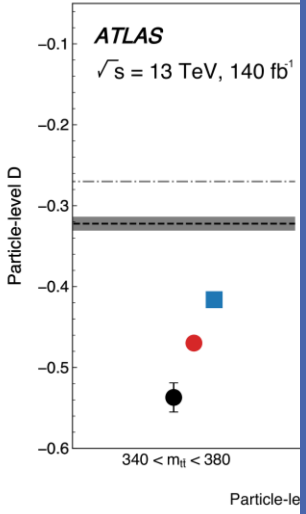
[ROPP 87 (2024) 117801]

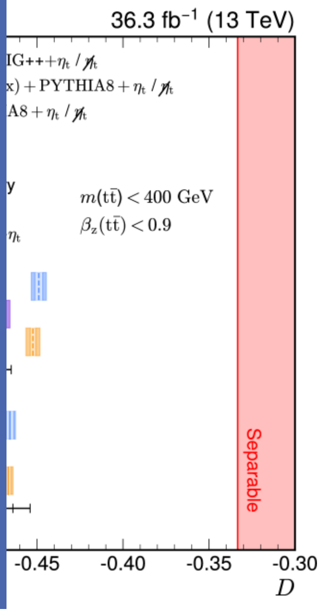
JR Munoz de Nova, Y. Afik
Eur.Phys.J.Plus 136 (2021) 9, 907



CURRENT STATUS

- Both ATLAS and CMS observed entanglement in top-quark pair production
  - This is the only experimental results directly targeting quantum observables:
    - There are re-interpretation of LHCb measurements to extract the Bell's inequality violation in mesons.
  - ATLAS and CMS are currently working to extend these concepts to other final states
    - There is already a large foundation of phenomenology work
  - Belle2 is currently studying decoherence among flavour entangled mesons





Nature 633 (2024) 542

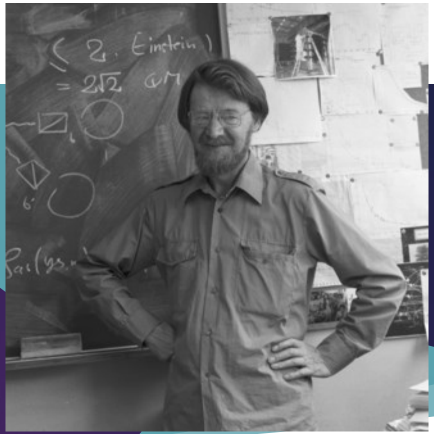
PRD 110 (2024) 112016

ROPP 87 (2024) 117801

QUANTUM INFORMATION IN HIGGS FINAL STATE

- The second channel that was looked at for these kind of measurement is the Higgs final state, decaying to vector bosons
  - The vector boson decay imprint on the decay product direction the information of the parent particle spin
    - Mitigated in the ZZ channel
- More complicated than the top-pair case:
  - The bosons must be interpreted as qutrit
  - For a generic bipartite mixed qutrit system it is not possible to calculate the concurrence, there are other quantities, e.g. a lower bound
- The bosons originate from a scalar decay
  - Greatly simplifies the spin density matrix
  - They are entangled across the whole phase space
    - The entanglement depend from the difference between the Higgs mass and the boson masses.
- Oppositely to the top-pair production this is a rare process, so statistics is an issue

BELL'S INEQUALITY



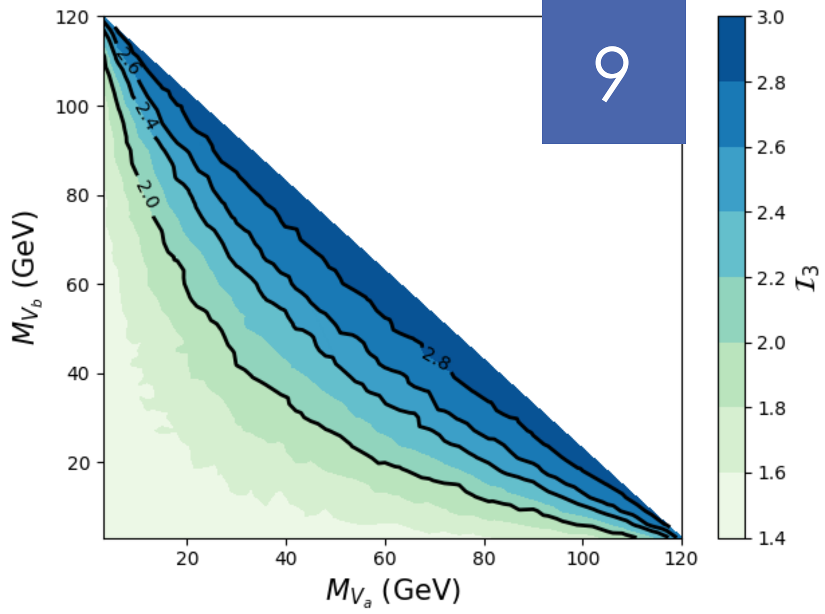
- As a reply to a criticism from Einstein, Podolsky and Rosen about quantum mechanics being an un-complete theory (1935) (EPR paradox)
  - Reality must follow a theory that respects locality and realism, but there are hidden variables that we can not measure
- Jhon Bell proposed a measurable test to verify the nature of reality, Bell's inequality (1964)

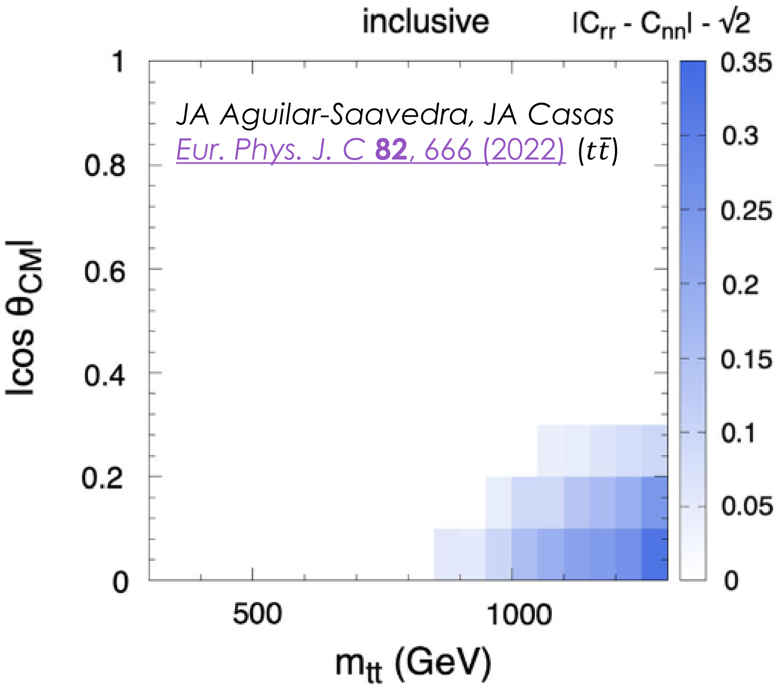
$$B = \langle QS \rangle + \langle RS \rangle + \langle RT \rangle - \langle QT \rangle$$

- Where Q,R and S,T are results of 4 "experiments", the first operated by A and the others by operator B that can only give -1 or 1 as outcome.
  - For example, the polarization of two particles on 4 different axes
  - There is no way that this equation goes beyond 2 if locality and realism are respected
  - If the axes are chosen well and the two particles are entangled, then according to quantum mechanics this inequality can reach 2√2
- Nobel prize in 2022 on a "loophole" free Bell experiment with photons

BELL'S INQUALITY VIOLATION

- The original reason why this final state is so appealing is the possibility to measure Bell's inequality violation
  - The Bell's inequality can be represented using an operator that acts on the spin density matrix ($Tr[\rho O_{Bell}]$)
  - The prospect for observing a violation of the classical limit is very different in H→VV* and top-pair production





H→VV* SPIN DENSITY MATRIX

The whole spin density matrix for a system of 2 qutrits can be represented in this form (using the Gell-mann basis):

$$\rho = \frac{1}{9} I_3 \otimes I_3 + \sum_{i=1}^{8} f_i \lambda_i \otimes I_3 + \sum_{j=i}^{8} g_j I_3 \otimes \lambda_j + \sum_{j=i}^{8} h_{ij} \lambda_i \otimes \lambda_j$$

The spin density matrix is defined by 80 parameters, each can be reconstructed/measured using a quantum tomography approach.

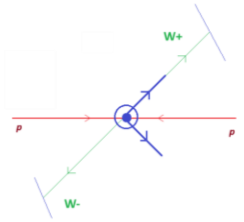
The violation of the Bell's inequality in this final state requires the measurement of a limited number of coefficients, not the calculation of the full matrix.

CHOICE OF THE FINAL STATE

- One of the two bosons is always off-shell
  - The boson can still be interpreted as a qutrit, if it decays to massless particles
- The final state should be completely reconstructed to build the V boson rest frame
  - $H \to \ell\nu\ell\nu$ is under constrained
- Different particles have different spin analysing power
  - We need to identify the flavour of the final state
  - Charged leptons are ideal candidates
- The cross section for $H \to ZZ^*$ is lower and the direction of the decay products is less related to the parent particle spin.

Results $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$

- The original proposal for the Bell inequality measurement in $H \rightarrow WW^*$
  - Dilepton final state
- This relation leads to the following Bell Inequality operator
  - $I_3^{xy} = \frac{8}{\sqrt{3}}\langle \xi_x^+ \xi_x^- + \xi_y^+ \xi_y^- \rangle + 25 \left\langle \left((\xi_x^+)^2 - \left(\xi_y^+\right)^2 \right) \left(\left(\xi_y^-\right)^2 - (\xi_x^-)^2 \right) \right\rangle + 100 \langle \xi_x^+ \xi_y^+ \xi_x^- \xi_y^- \rangle$
- ξ are the cosine between the lepton direction and the helicity basis
  - The Bell's inequality violation depend on the choice of the frame, $I_3^{xyz} = \max(\langle I_3^{xy} \rangle, \langle I_3^{yz} \rangle, \langle I_3^{zx} \rangle)$



Expt. Assumptions	Truth	'A'	'B'	'C'
Min $p_T(\ell)$ [GeV]	0	5	20	20
Max $\|\eta(\ell)\|$	–	2.5	2.5	2.5
σ_{smear} [GeV]	0	5	5	10
Number of events	34.3k	19.7k	6.5k	5.4k
Fraction of events	0.48	0.27	0.090	0.075
$\mathcal{I}_3^{xyz}$	2.62	2.40	2.75	2.16
Signif. $(\mathcal{I}_3^{xyz} - 2)$	11.7σ	5.2σ	5.3σ	1.0σ

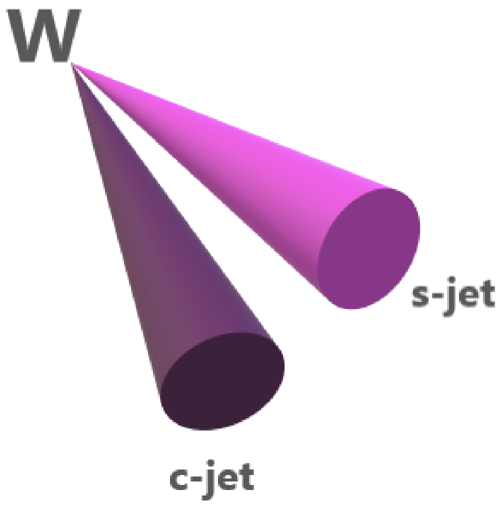
- Assumptions on the ability to resolve the whole final state
- The worst scenario included a 10 GeV resolution on the reconstructed W 4-momentum

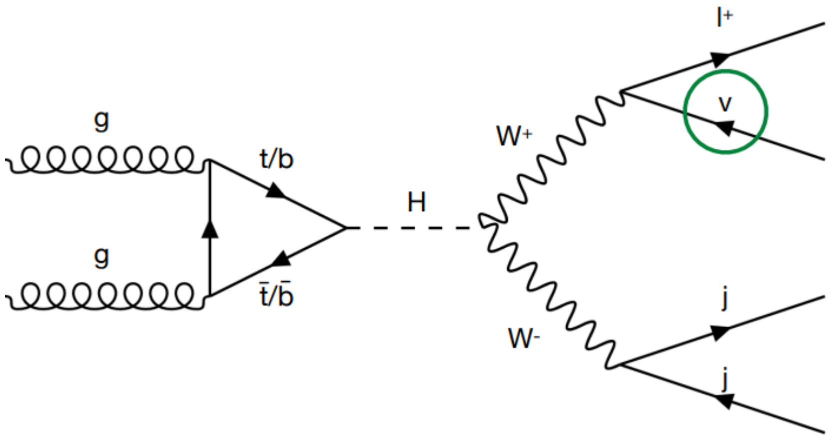
Phys.Lett.B 825 (2022)

Eur. Phys. J. C 84, 20 (2024)

SEMI-LEPTONIC FINAL STATE

- The main limitation to precision of the dilepton channel is the presence of two neutrinos.
- The semi-leptonic final state solves this problem but with 2 limitations:
  - Overwhelming background
  - Identify a spin analyzer on the hadronic side
- The spin analyser is 1 or -1 for each particle
  - A quark can be used as analyser, but we must identify the flavour





NUMERICAL SIMULATION SETUP

- MC simulation of the main processes of interest: $H(ggH \to WW^*), t\bar{t}, W(\to \ell\nu) + jets, WW$.
  - All processes simulated beyond LO and including PS effects.
- No detector simulation but analysis on “particle level” objects:
  - Dressed leptons
  - Jets reconstructed with “stable” final state particles
    - Test including smearing performed
  - Missing Energy on the transverse plane
- Various inefficiencies simulated:
  - Realistic cuts on central (eta < 2.5) Jets (25 GeV) and leptons (20 GeV)
  - Efficiencies and inefficiencies on b-tagging and c-tagging
    - Effects of mis-reconstruction fully included in the result
- Unfolding to parton level to retrieve the result
  - Estimate of the inflation of the statistical uncertainties

SELECTION

- pre-selection:
  - Exactly 1 lepton with $p_T > 20$ GeV
  - Exactly 0 b-tagged jets
- c-tagging selection:
  - 2 or more jets, exactly one of which must be c-tagged.
  - At least 1 (c-jet,l-jet) pair with $|m_{cl} - 80.6| < 10$ GeV
- Maximum 2 light jets.
- Invariant mass of the lepton and the c-tagged jet $m(\ell c) <$ 80 GeV.

Rejects background including top-quarks

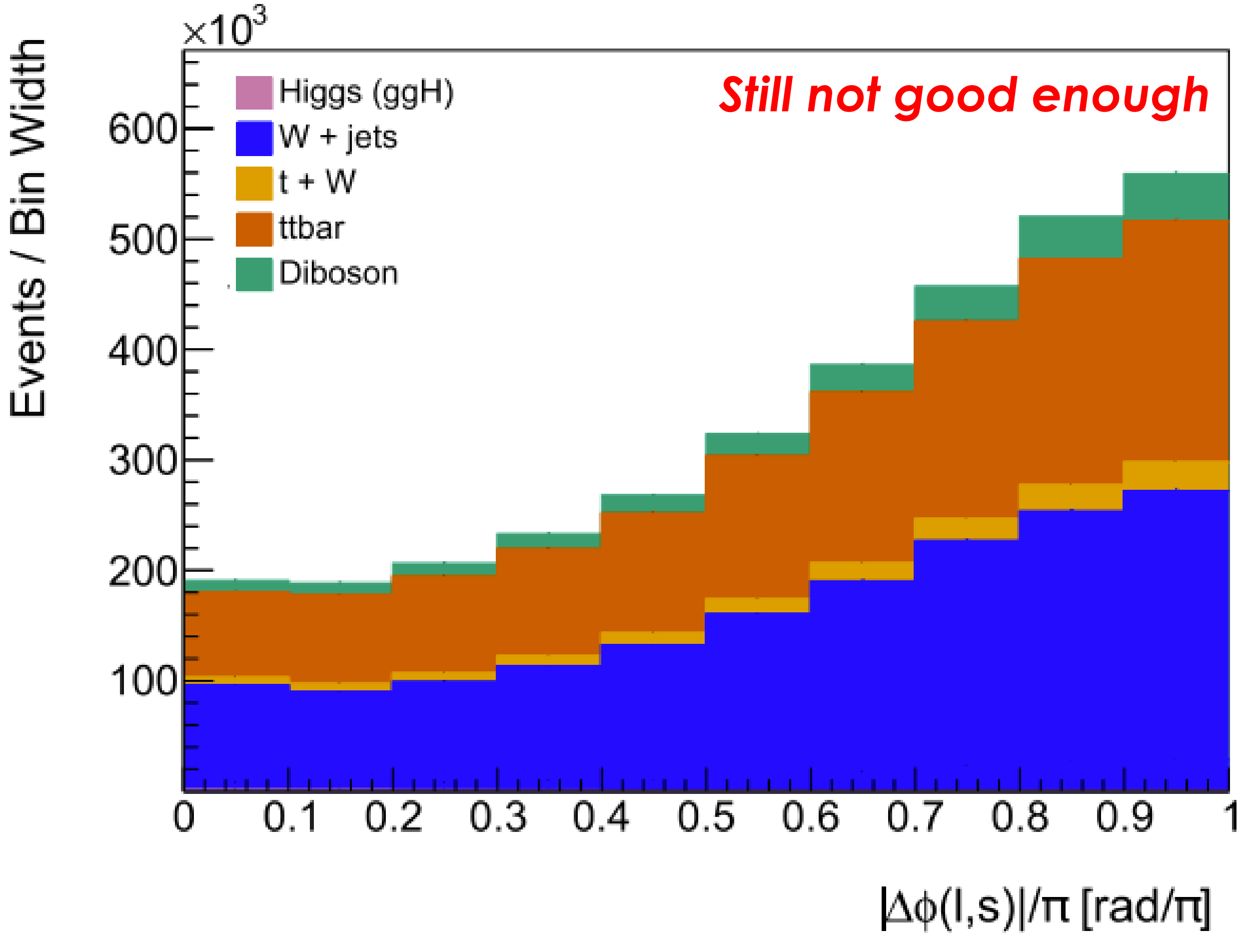
Rejects all SM bkg that tend to have 0 or 2 c-jets in the final state

Allows to identify the s-jet
Rejects final state without an on-shell W in the final state

Rejects tt events with a mis-reconstructed b-jets as c-jet or light jet

SELECTION

- pre-selection:
  - Exactly 1 lepton with
  - Exactly 0 b-tagged jet
- c-tagging selection:
  - 2 or more jets, exactly
  - At least 1 (c-jet,l-jet) p
- Maximum 2 light jets.
- Invariant mass of the lepton
  80 GeV.



ding top-

nd to
nal state

an on-

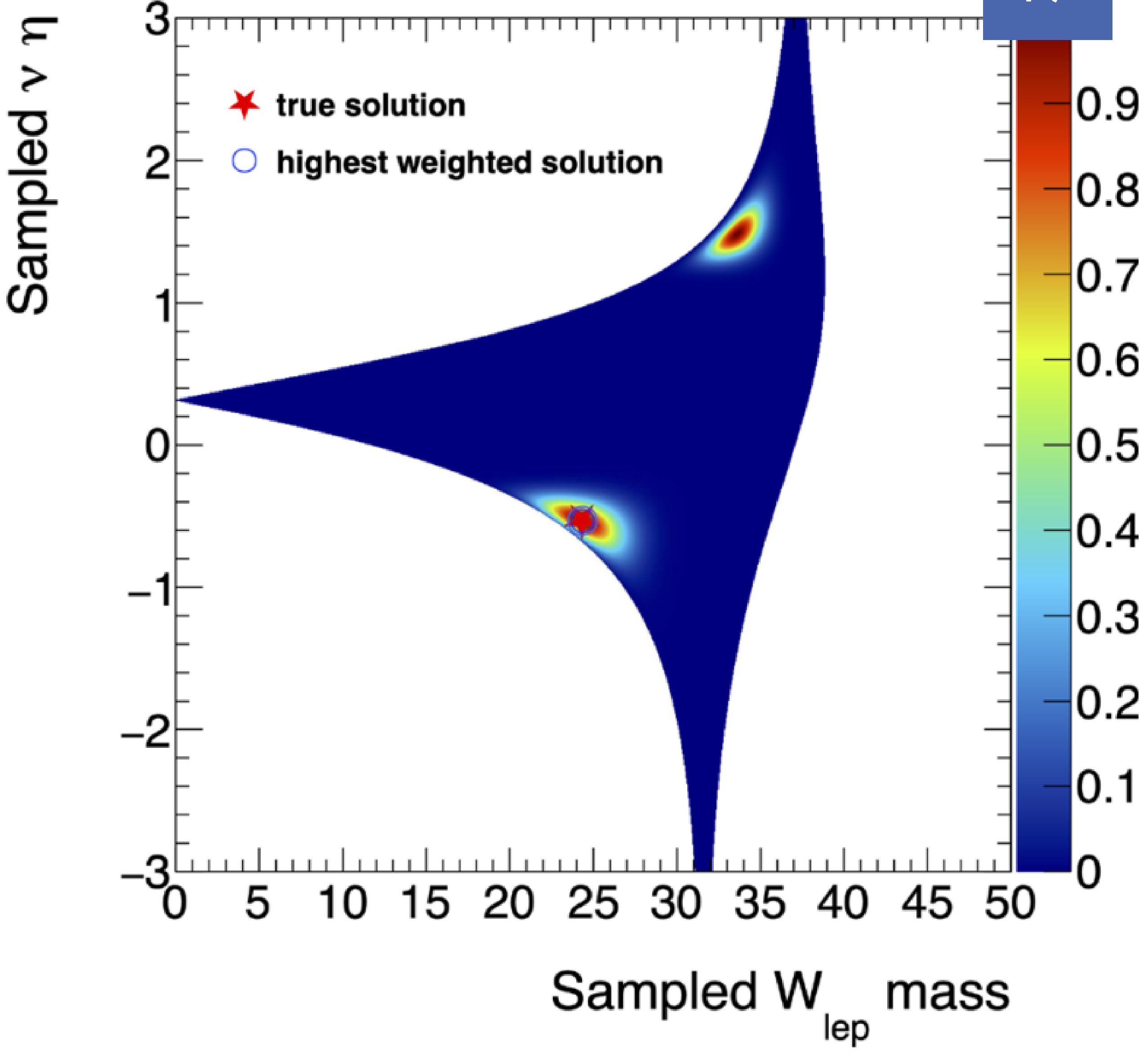
is-
jet or light

NW-RECONSTRUCTION

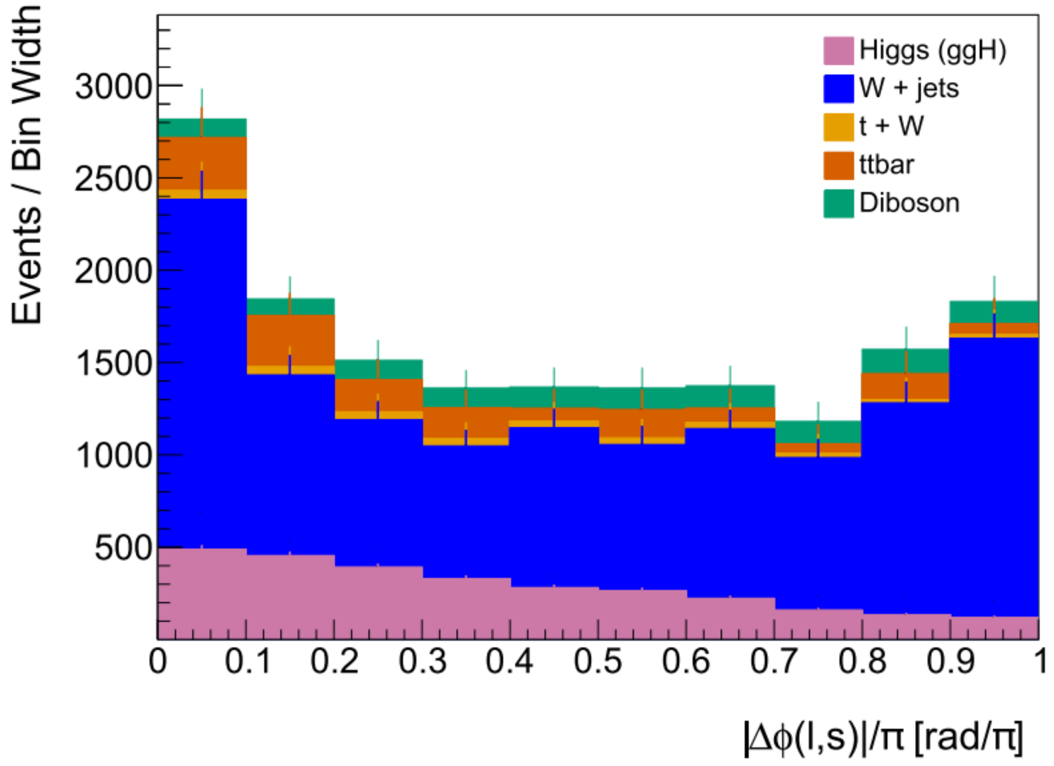
- Sample the phase space of Wlep mass and Pz of the neutrino
- For each point evaluate a weight as:

$$w = \exp\left(\frac{(\nu_x - P_x^{miss})^2}{\sigma_x^2}\right) \cdot \exp\left(\frac{(\nu_y - P_y^{miss})^2}{\sigma_y^2}\right)$$

- The solution with the highest weight is the preferred solution



SELECTED EVENTS



Process	Idealised	$\epsilon_c = 40\%$
W + jets	13131 ± 785	10444 ± 664
WW	2298 ± 31	1137 ± 22
$t\bar{t}$	601 ± 76	1453 ± 119
tW	217 ± 8	350 ± 11
Higgs	5967 ± 76	2843 ± 56
S/(S+B)	0.27	0.18

- This number drops to 13% if considering also jet smearing that simulate the detector effects.
- In a real analysis the simulation can be highly improved considering sophisticated ML techniques

MEASURING BELL'S INEQUALITY VIOLATION

- For every event we defined 3 observables:

$$\mathcal{O}'^{1}_{xy} = \frac{8}{\sqrt{3}}\langle O^{1}_{xy}\rangle$$

$$O^{1}_{xy} = \xi^{+}_{x}\xi^{-}_{x} + \xi^{+}_{y}\xi^{-}_{y}$$

$$\mathcal{O}'^{2}_{xy} = 25\langle O^{2}_{xy}\rangle$$

$$O^{2}_{xy} = ((\xi^{+}_{x})^{2} - (\xi^{+}_{y})^{2})((\xi^{-}_{x})^{2} - (\xi^{-}_{y})^{2})$$

$$\mathcal{O}'^{3}_{xy} = 100\langle O^{3}_{xy}\rangle,$$

$$O^{3}_{xy} = \xi^{+}_{x}\xi^{+}_{y}\xi^{-}_{x}\xi^{-}_{y},$$

- Once the final state is fully reconstructed, we can go to the Higgs rest frame and then the 2 W rest frames.
- Measure the angles between the s-jet/lepton and the reference frames
- Obtain a distribution collecting all events and unfold it to parton level
  - Calculated using directly the quarks and leptons from the MC simulation
  - No cuts applied

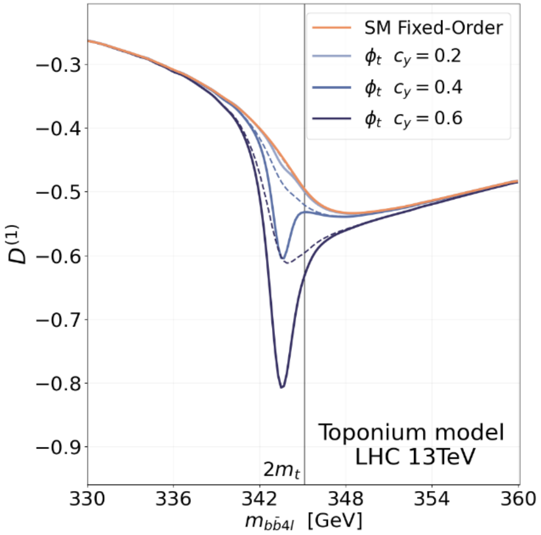
Results

- Hard to do with the Run2 and Run3 (2016-2018) luminosity collected by LHC
  - It is also interesting to just measure the Higgs in this channel
  - Possibility to have a full reconstruction of the final state
- Good perspective for HL-LHC
- There are several “improvement” possible in a real analysis:
  - Charm tagging optimization
  - Improvement of the NW
  - Inclusion of ML
- There are also aspects that needs to be investigated in more details
  - Systematic uncertainties

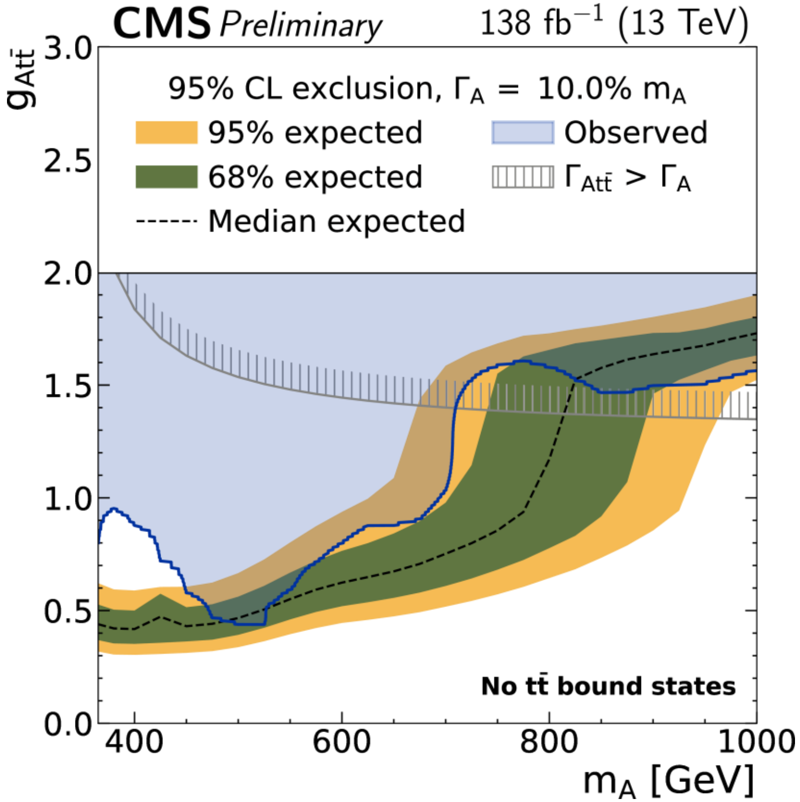
Luminosity [fb^{-1}]	$\langle \mathcal{B}^{zx}_{\mathrm{CGLMP}} \rangle$ (idealised)	Significance (idealised)
139	2.45 ± 0.25 (0.18)	1.8 (2.5)
300	2.45 ± 0.17 (0.12)	2.65 (3.75)
3000	2.45 ± 0.05 (0.04)	9.0 (11.25)

WHY MIX QI PRINCIPLE AND HEP?

- Direct search of new physics at collider:
  - Provide an orthogonal information compared to bump hunting
    - In the top quark case already allowed to (maybe) find a new particle (bound state expected from the SM)



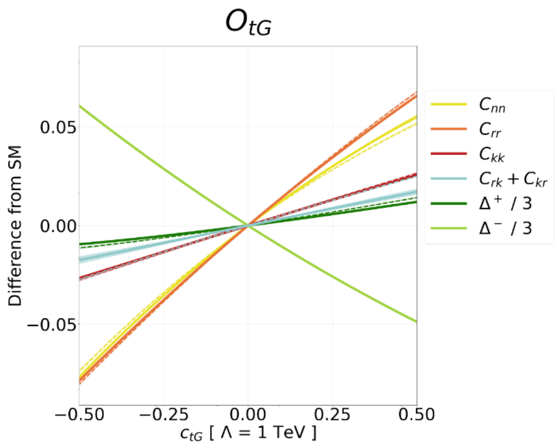
JHEP03(2024)099

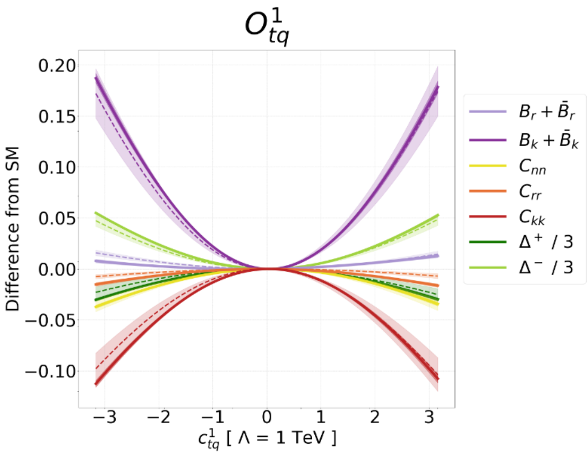


CMS-PAS-HIG-22-013

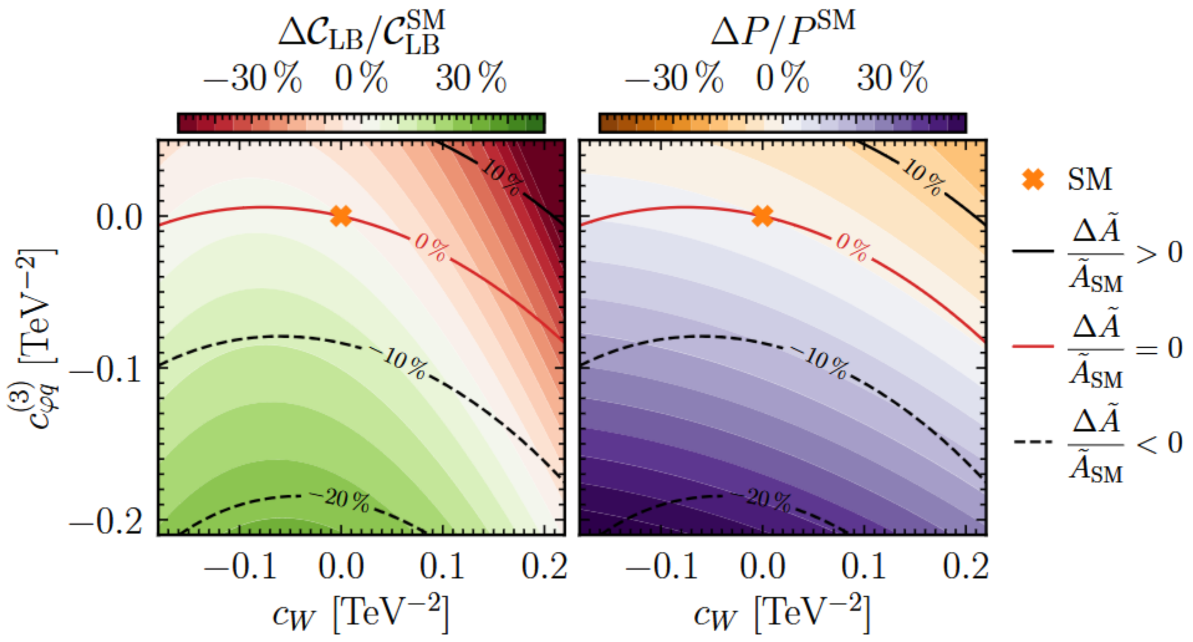
WHY MIX QI PRINCIPLE AND HEP?

- Direct search of new physics at collider
- In-direct search of new physics
  - Anomalous coupling
  - EFT





Severi, Vryonidou JHEP01(2023)148



Aoude, Madge, Maltoni, Matani
JHEP12(2023)017

WHY MIX QI PRINCIPLE AND HEP?

- Direct search of new physics at collider
- In-direct search of new physics
- Fundamental test of the SM.
  - Highest energy test of entanglement
  - The QM also proposes a limit for Bell’s inequality
    - The highest possible energy scale is a good region where to test this

WHY MIX QI PRINCIPLE AND HEP?

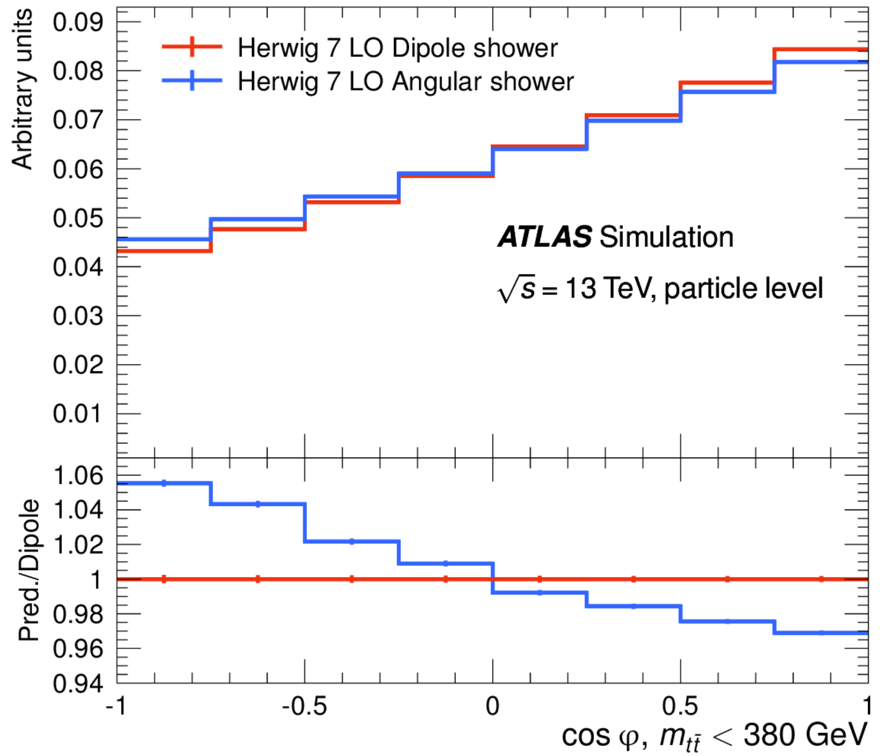
- Direct search of new physics at collider
- In-direct search of new physics
- Fundamental test of the SM.
  - Highest energy test of entanglement
  - The QM also proposes a limit for Bell's inequality
    - The highest possible energy scale is a good region where to test this
- Fundamental QIT that are more easily done at colliders:
  - Discord ellipse
  - Entanglement & Decay
  - Probing decoherence models
  - Relation between magic and entanglement?
  - Multiparticle entanglement

Thank you

BACKUP

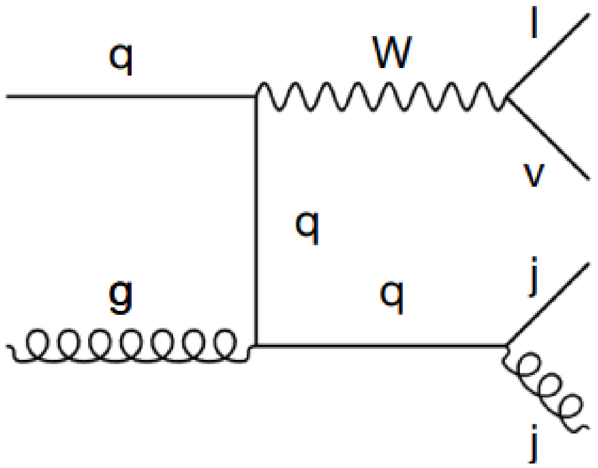
SEEMS EASY: COMPLICATIONS

- The lepton need to be boosted in the parent rest frame
  - Need to reconstruct the system, but there are 2 neutrinos
  - At least I have enough kinematic constraints
- To observe entanglement, I need to be in a very small region of the phase space
  - Poor resolution, difficulties in reconstruction
- Large sensitivity to the signal modelling

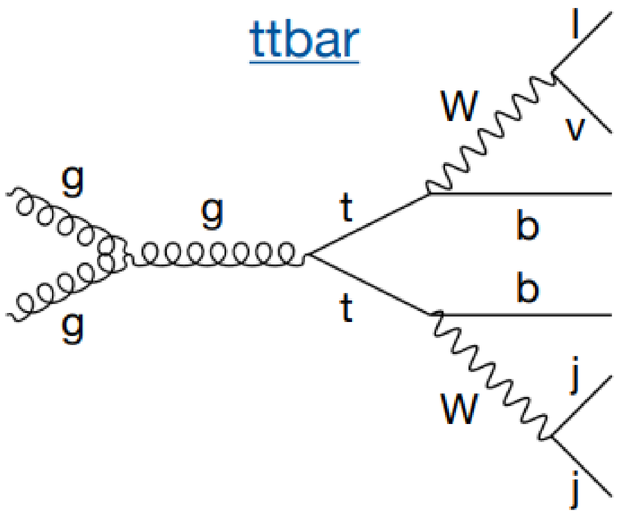


BACKGROUND

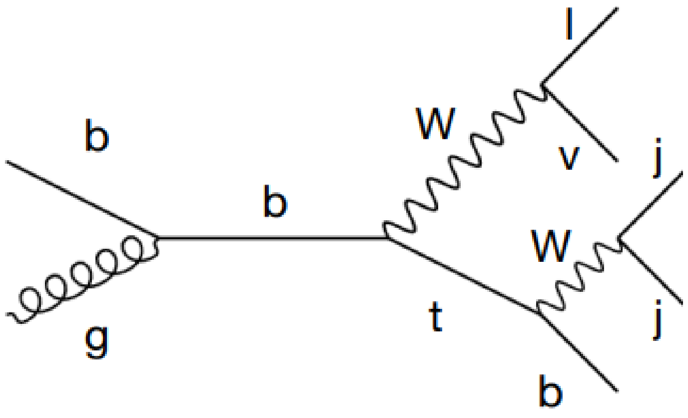
W + jets



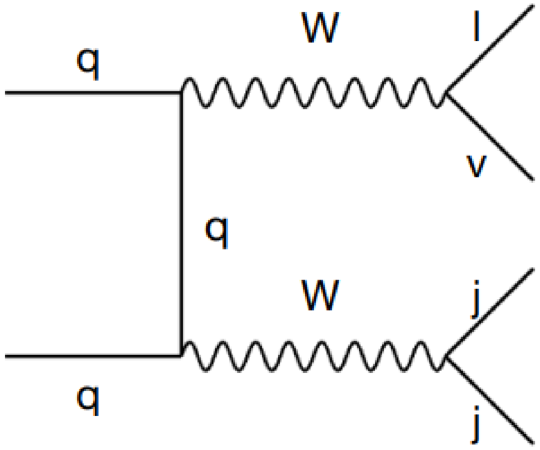
ttbar



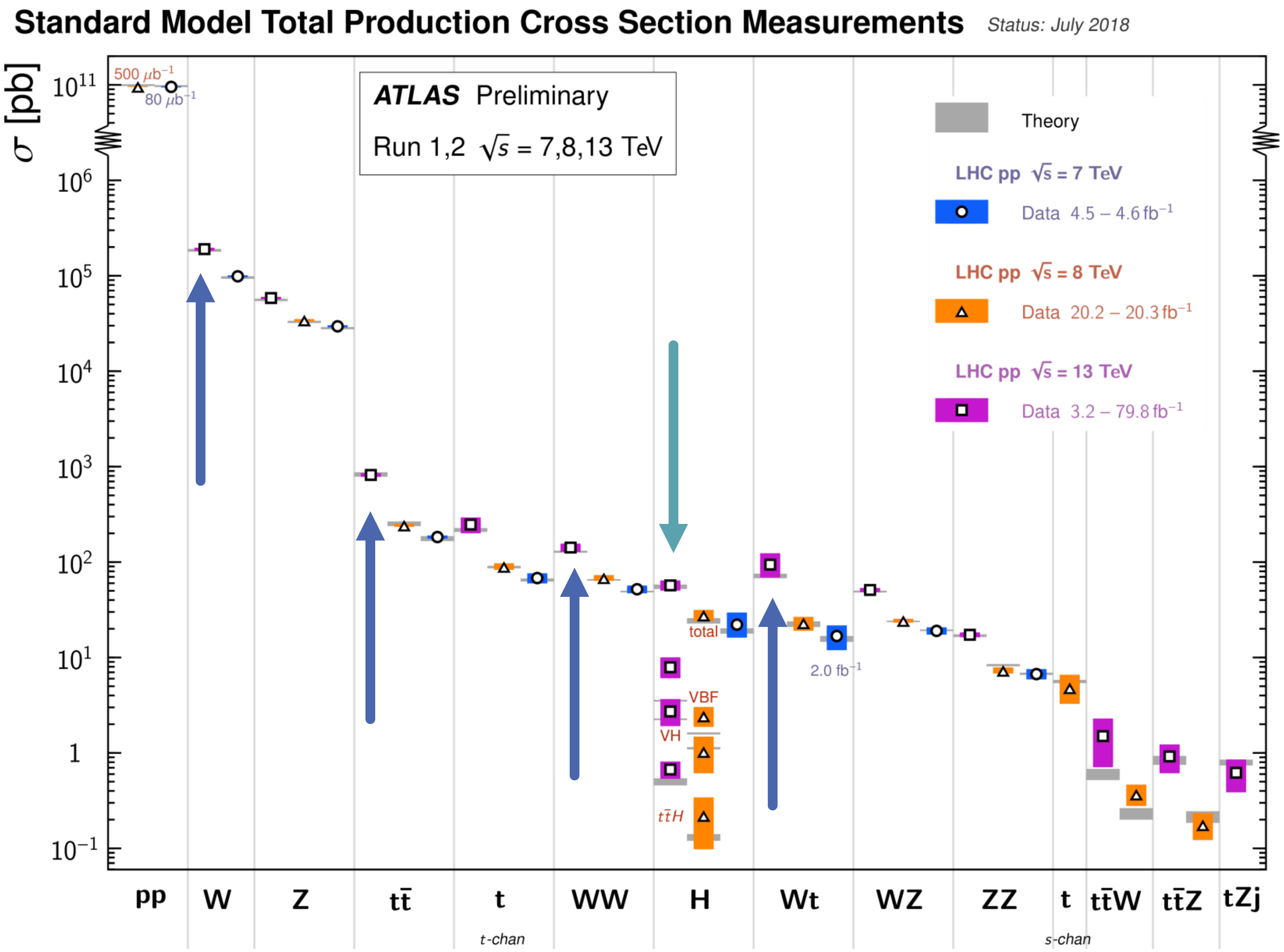
t+W



WW



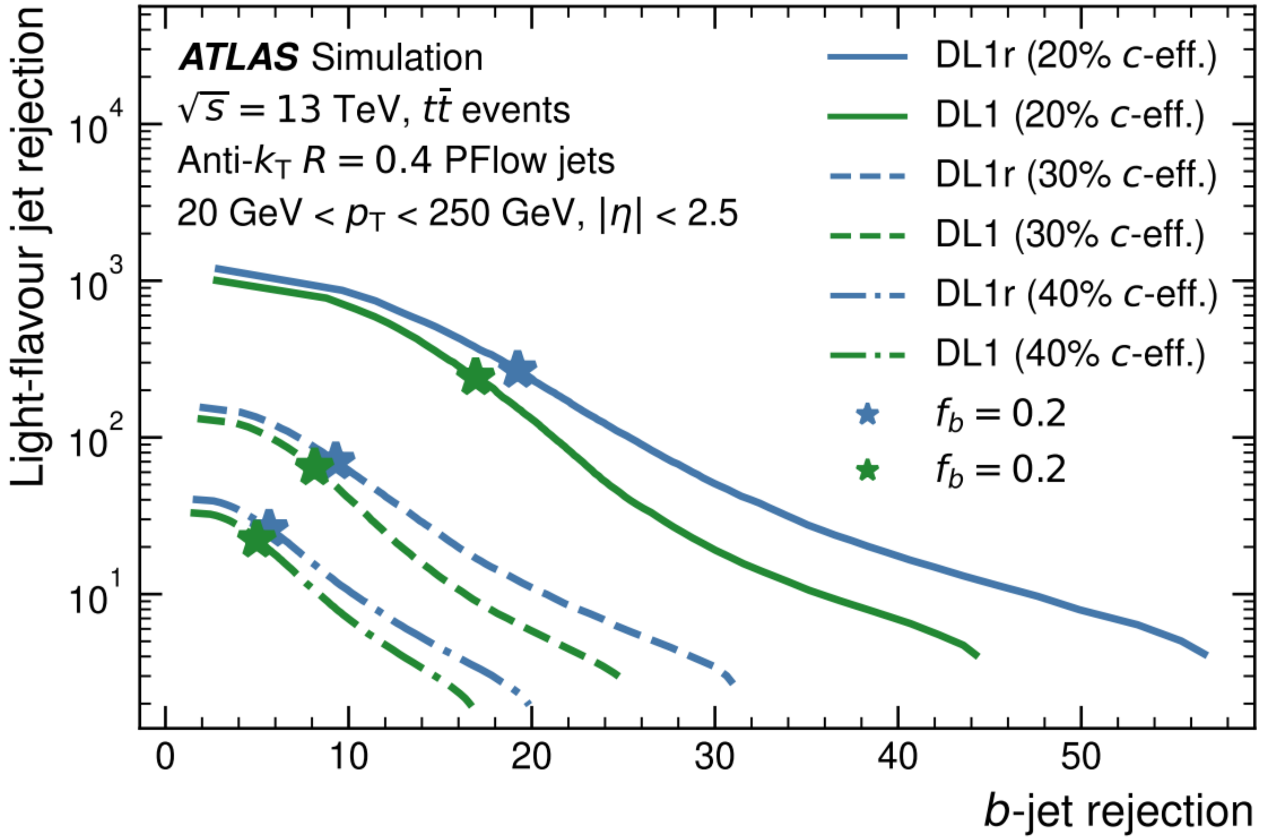
BACKGROUND



Standard Model Total Production Cross Section Measurements
Status: July 2018
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.6 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 79.8 fb⁻¹
σ [pb]
500 μb⁻¹
80 μb⁻¹
total
VBF
VH
tt̄H
2.0 fb⁻¹
pp
W
Z
tt̄
t
t-chan
WW
H
Wt
WZ
ZZ
t
s-chan
tt̄W
tt̄Z
tZj

Eur. Phys. J. C 83, 681 (2023)

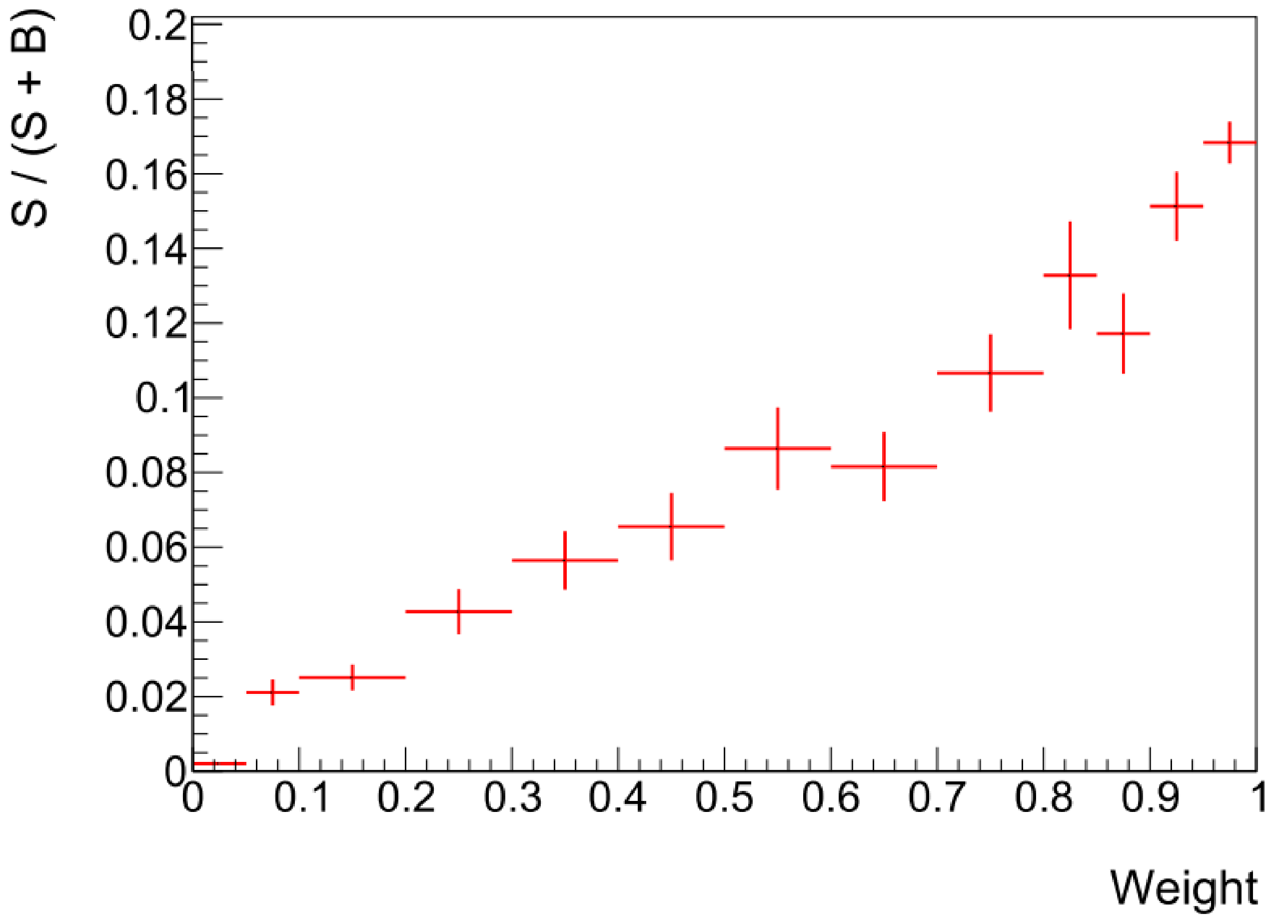
CHARM TAGGING



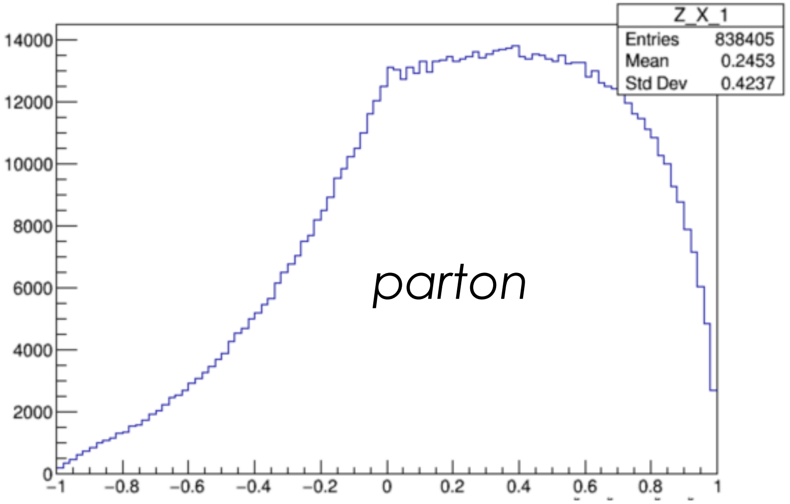
true flavour	c-tagging efficiency	b-tagging efficiency
b-jet	0.14	0.77
c-jet	0.4	0.2
l-jet	0.016	0.008

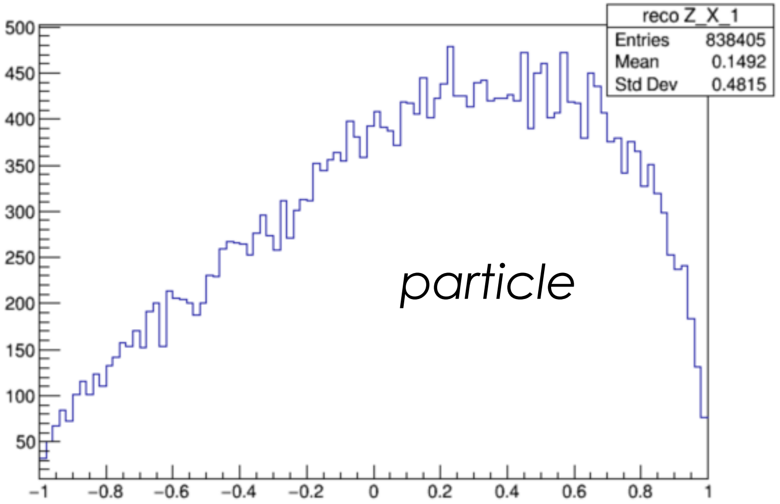
NW-SELECTION

- This also gives a tool to reject the background
  - The background do not have an Higgs boson
  - Cut on a minimal weight.
- A cut at 0.7 has a 45% efficiency on the signal and a 0.005 on the background



UNFOLDING - I





There is a significant difference between particle and parton level caused by several factors:

- Presence of selection
- Wrong solution in the NW
- Wrong combinations of jets to reconstruct the hadronic W
- Mis-identification of light jets as c-tagging

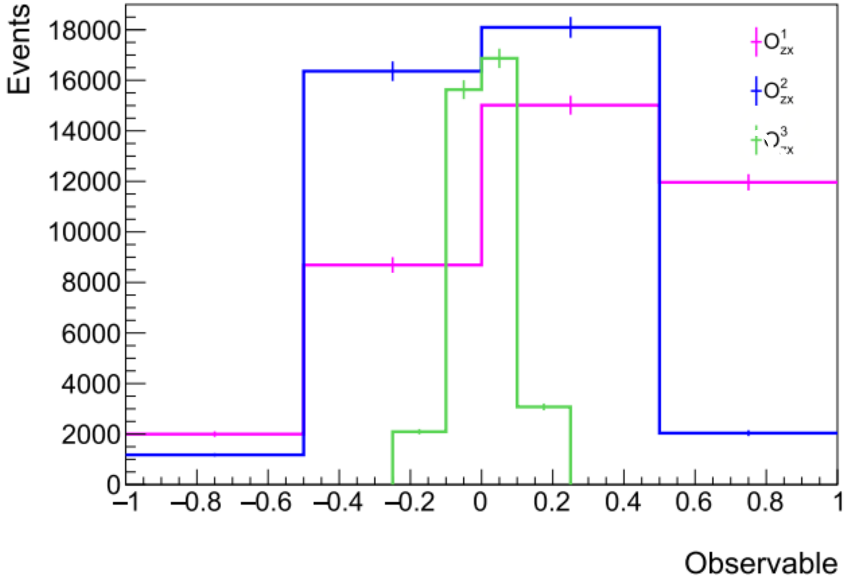
UNFOLDING - II

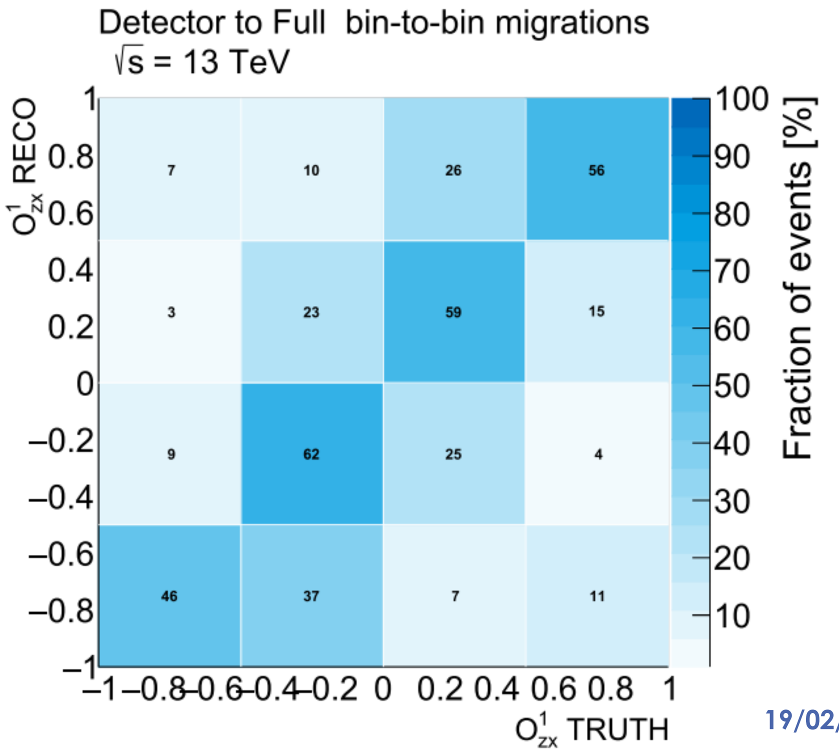
- Simple IBU unfolding applied:

$$O^{j}_{parton} = \frac{1}{eff_j} \sum_i M^{-1}_{ij}\ acc^{i}\ (O^{i}_{particle})$$

- Binning defined to have ~60% of the events on the diagonal
- The averages are defined on the

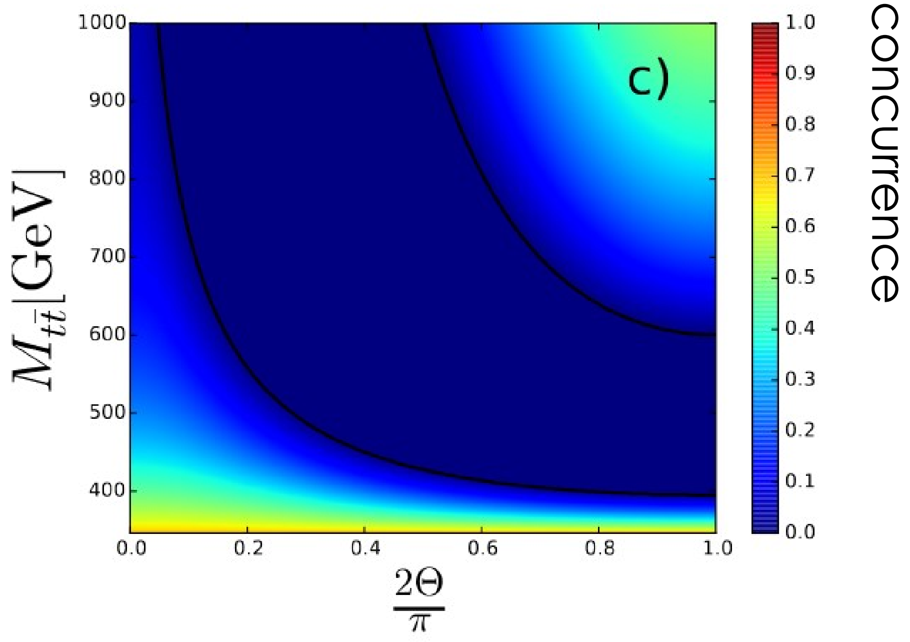
$$\mathcal{I}_3^{xyz} = \max(\langle \mathcal{B}^{xy}_{\mathrm{CGLMP}} \rangle, \langle \mathcal{B}^{yz}_{\mathrm{CGLMP}} \rangle, \langle \mathcal{B}^{zx}_{\mathrm{CGLMP}} \rangle)$$





TOP QUARK PAIRS

- The first proposal for entanglement measurement was in top-quark pairs
  - Top quark has a very short life-time and decays before the spins decorrelate
  - The top quarks is the representation of a qubit
  - We can define the spin density matrix for a pair of qubit
    - Depends on two parameters: $m(\bar{t}t)$ and $\cos(\theta)$
    - We can identify the region of the phase space where the top quark is expected to be entangled
- The entanglement is just in a tiny region of the phase space



JR Munoz de Nova, Y. Afik
Eur.Phys.J.Plus 136 (2021) 9, 907

MEASURE ENTANGLEMENT

- In the top quark case it is possible to define a very simple entanglement witness
  - Defined starting from the angles between the two charged leptons in the top quark pair decay, in the parent top-rest frame
- If D < -1/3 == Concurrance >1
  - Sufficient condition for entanglement

$$D = -3 < \cos(\varphi) >$$