

Multi-Boson Production and the Muon Yukawa Coupling

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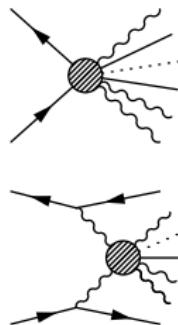
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Multi-Boson Physics

New phenomenology at a **multi-TeV** lepton collider:

1. Multi-boson production (**annihilation**)
2. ... and **vector-boson fusion** to multiple bosons

leading to multi-fermion final states with resonance structure.



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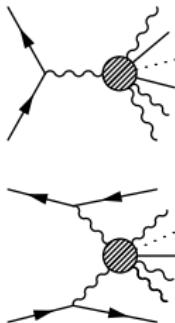
(Also: rich (multi-)top, and all light/jet physics)

Task

Measure **all** interactions of multiple SM particles **exclusively** and with **precision**, from threshold to up to 2 orders of magnitude above EW scale

⇒ talks by WULZER, MALTONI, XIE, ...

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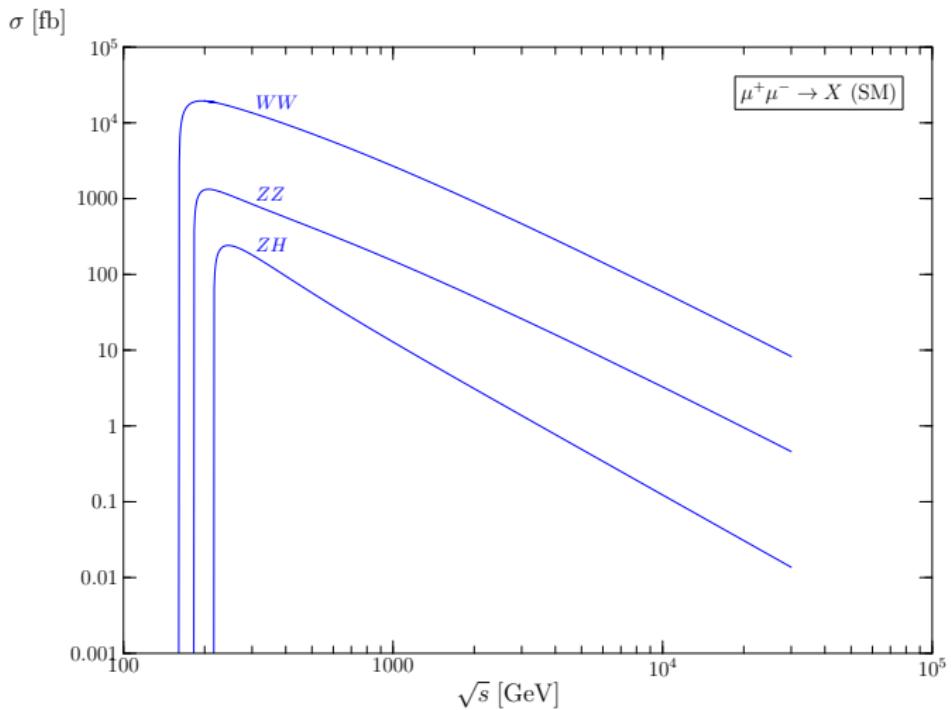
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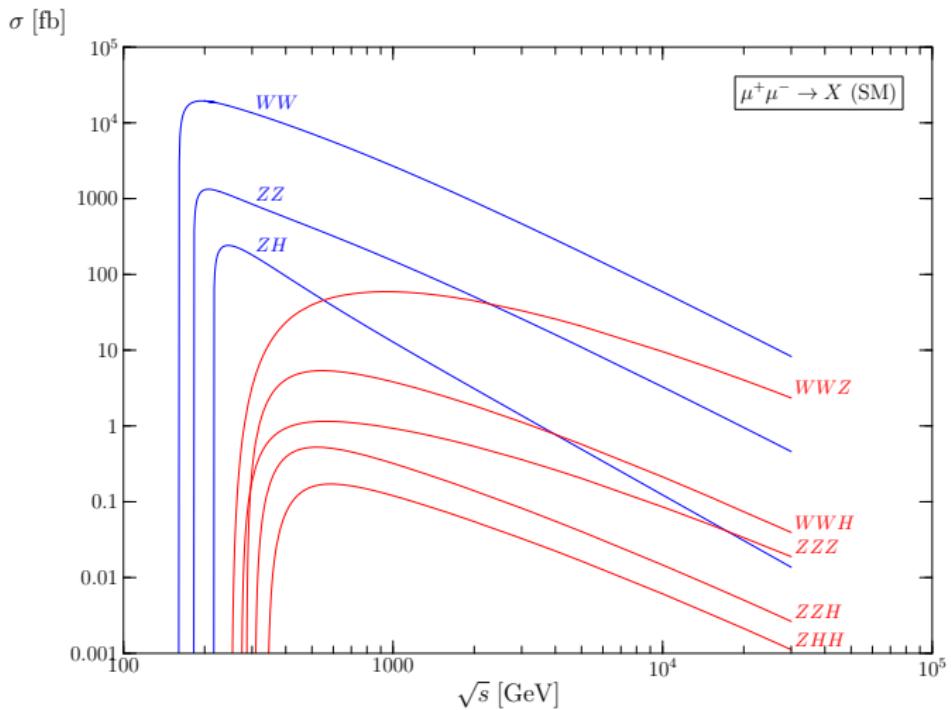
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Annihilation to Multi-Boson: Cross Sections



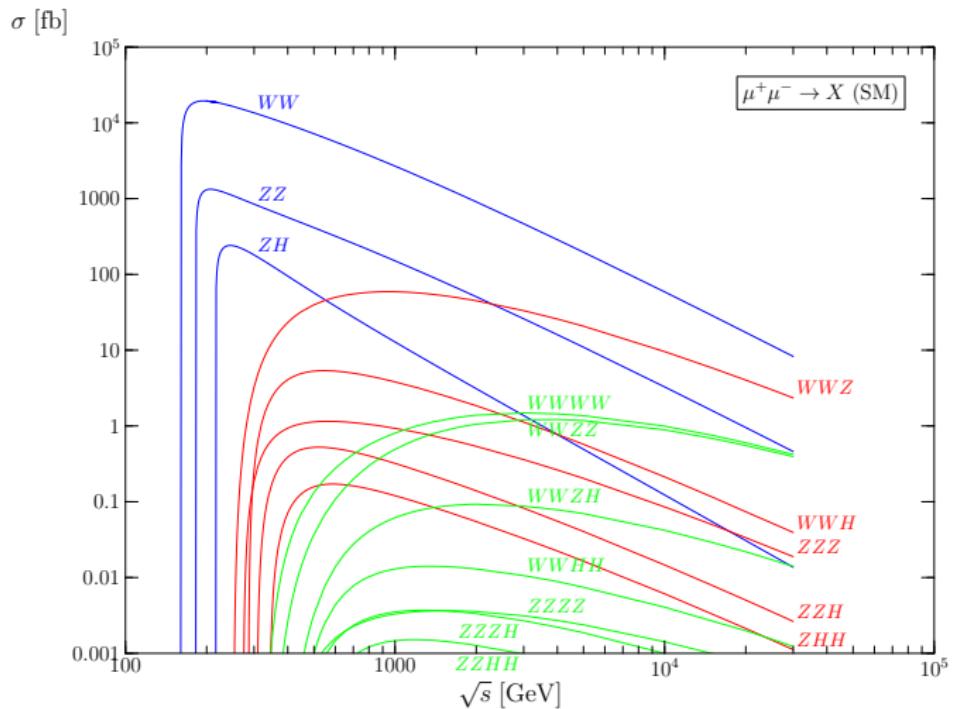
Calculation: WHIZARD (\Rightarrow from CLICdp studies, cf. CERN YR / arXiv:1812.02093.)
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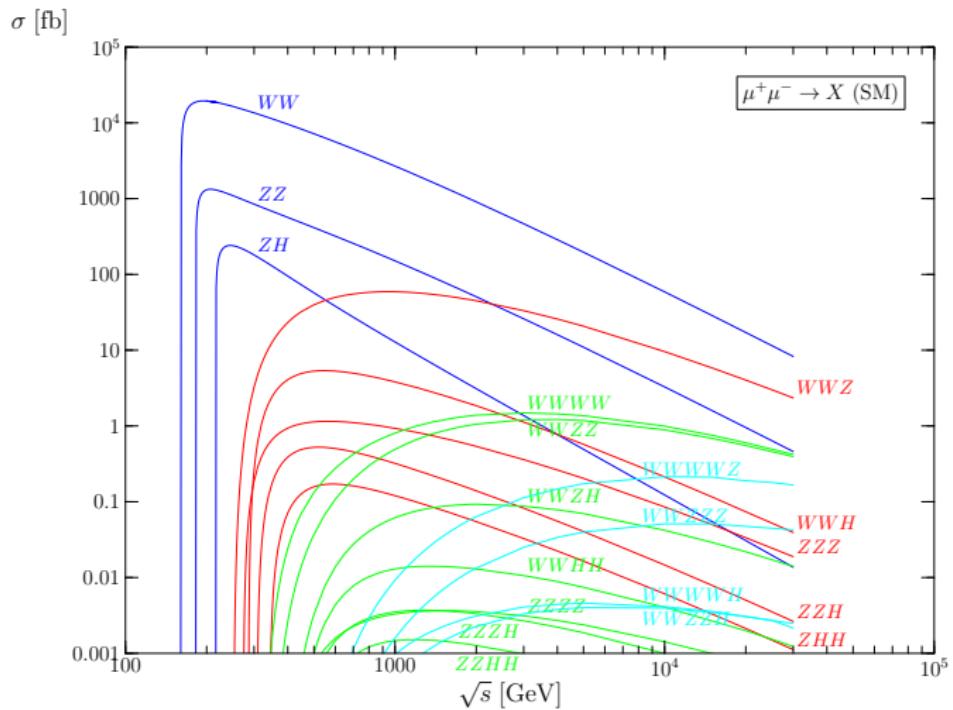
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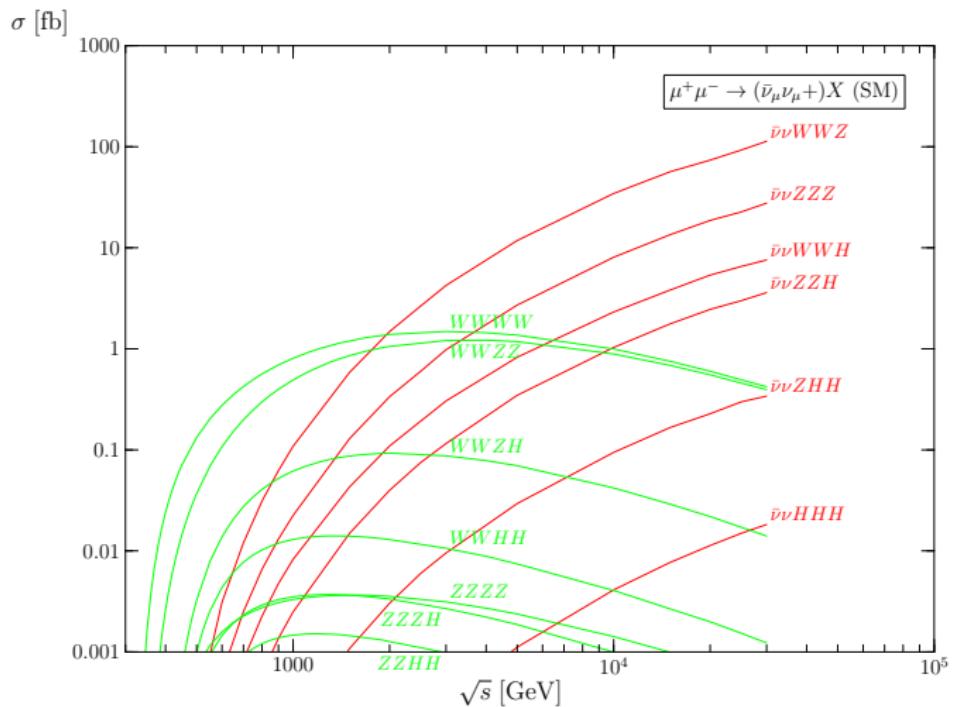


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Annihilation Processes: Properties

- ▶ Beyond 1 TeV: 4- and 5-Boson production (and more)
- ▶ Naive hierarchy breaks down beyond 10 TeV: EW splitting
[...; HAN, MA, XIE 2020]
- ▶ Log-enhancement / Sudakov suppression
 $\Rightarrow WW \sim WWZ / ZH \sim WWH / \dots$
- ▶ Neutral final states suppressed by $\sim 1/100$ w.r.t. charged states
(less if separation cuts applied)

Annihilation vs VBS: Cross Sections



Annihilation vs VBS: Properties (SM)

Total cross sections: VBS takes over at 2 TeV.

VBS:

- ▶ Increases rapidly
- ▶ Most of cross section at threshold
- ▶ Highly boosted final state (**forward/backward**)

Annihilation:

- ▶ Decreases slowly
- ▶ Most of cross section at highest energy
- ▶ One Boson highly off-shell
- ▶ Final state in rest frame (**central**)

⇒ Annihilation processes important for analysis at all energies.

The Muon Mass (and Yukawa)

- ▶ Physics: We don't know whether the SM mass-generation mechanism applies just to the heavy particles, or also to the 1./2. generation.
- ▶ Logical possibility: Muon mass not (only) generated by SM Higgs
⇒ consider arbitrary Yukawa coupling.
- ▶ Extreme scenario (for illustration): $\lambda_{H\mu\mu} = 0$

The Muon Yukawa: experiment

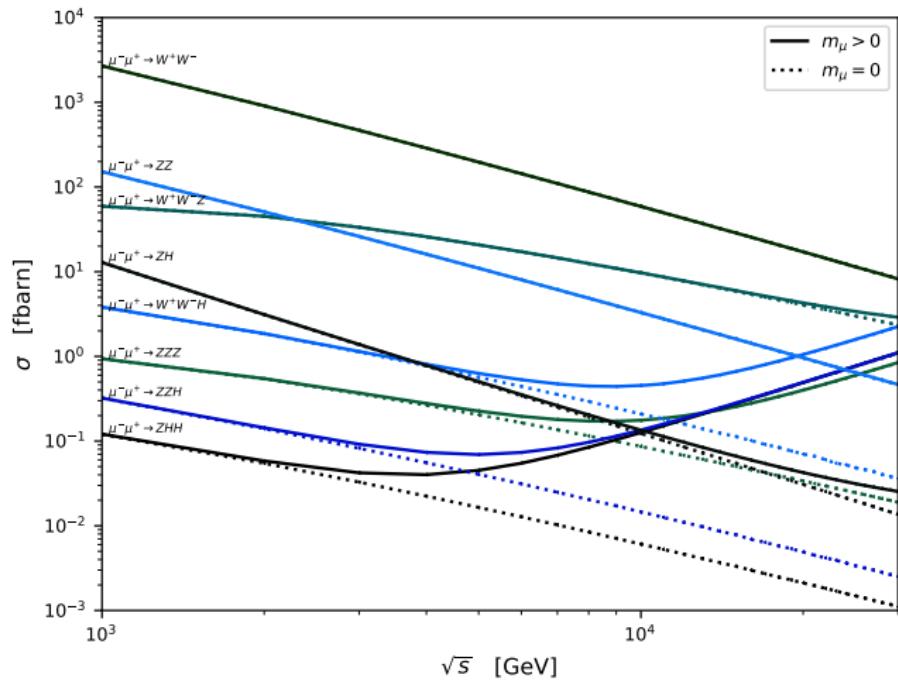
1. LHC: $H \rightarrow \mu\mu$ ($\sim 20\%$)
2. Low-E Muon Collider: $\mu^+\mu^- \rightarrow H$ precisely (on resonance)
3. High-E Muon Collider: Multi-boson production.

The absence of the muon Yukawa coupling spoils delicate gauge cancellations in multi-boson processes.



If $\lambda_{H\mu\mu} = 0$, various multi-boson processes become enhanced at multi-TeV.

3-Boson Production and the Muon Yukawa



EFT: Removing the Muon Yukawa

Gauge-invariant formulation without Muon-Yukawa term: GBET

1. All orders: **Nonlinear HEFT**. Higgs can be radiated from Gauge/Goldstone but not from muon.

$$\mathcal{L}_{H\mu\mu} = -m_\mu \bar{\mu}_L \mu_R \quad \Rightarrow - m_\mu (\bar{\nu}_L, \bar{\mu}_L) \exp\left(\frac{i}{v} w \cdot \tau\right) \begin{pmatrix} 0 \\ \mu_R \end{pmatrix}$$

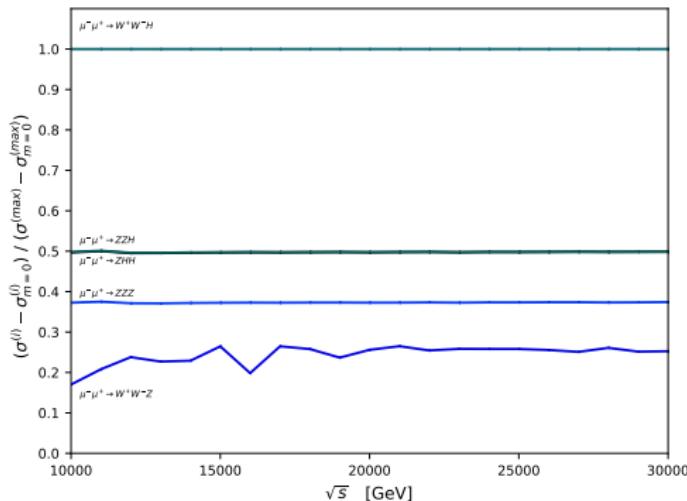
2. More conventional: **Linear SMEFT**. Higgs-muon coupling removed order by order.

$$\Delta \mathcal{L}_{H\mu\mu} = \sum_{n=0}^{\infty} c_{H\mu\mu}^{(n)} (H^\dagger H)^n (\bar{\nu}_L, \bar{\mu}_L) H \mu_R, \quad H = \begin{pmatrix} i\sqrt{2}w^+ \\ v + h + iz \end{pmatrix}$$

⇒ multiple L-bosons and Higgses but no enhancement in pure-Higgs final states (HHH)

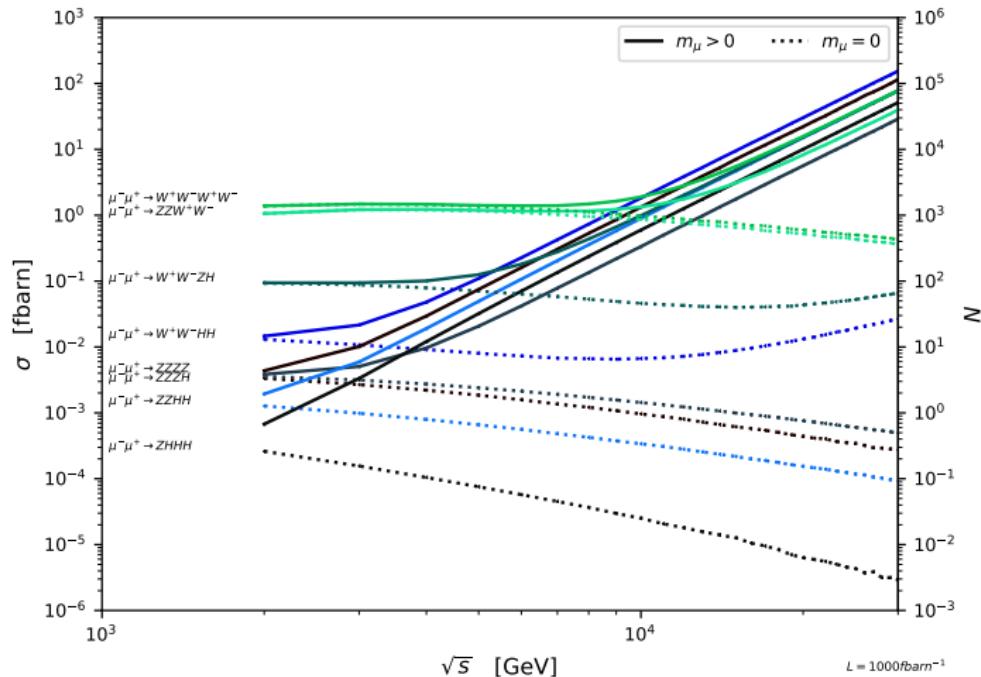
Prediction: Characteristic Pattern of Deviations

Helicity mismatch: SM and NP sum up *incoherently*
⇒ Plot only deviation from SM, normalized by WWH

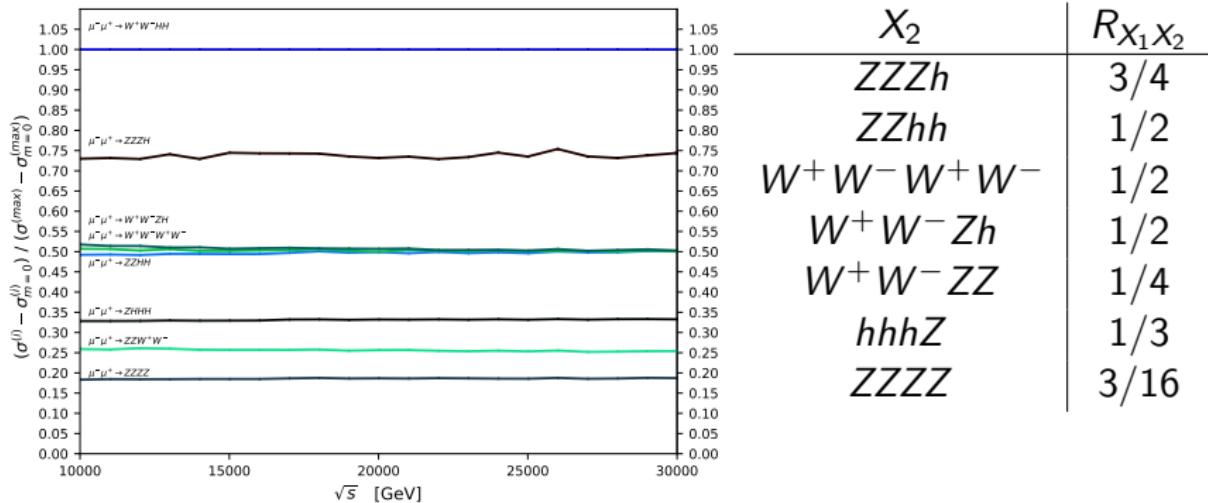


X_2	$R_{X_1 X_2}$
Zhh	$1/2$
hZZ	$1/2$
ZZZ	$3/8$
W^+W^-Z	$1/4$

Four-boson final states: even more sensitivity



Four-boson final states: Deviations



More Detailed Study

The muon Yukawa coupling probably exists, or $H \rightarrow \mu\mu$ would be absent.

Impact of an independent determination?

1. The $H \rightarrow \mu\mu$ decay and $\mu\mu \rightarrow H$ measure the absolute value of the coupling $g_{H\mu\mu}$.

The minimum rate occurs for $g_{H\mu\mu} = 0$.

2. The multi-boson production cross sections are sensitive to the absolute value of the deviation $\delta g = g_{H\mu\mu} - \frac{m_\mu}{v}$.

The minimum rate occurs for $\delta g_{H\mu\mu} = 0$.

OR: low-E muon collider: mismatch in $g_{H\mu\mu}$

⇒ guaranteed discovery at high-E muon collider

Summary

- ▶ Multi-boson production at a multi-TeV muon collider accounts for a rich phenomenology: frequent *resonant* 8, 10, ... jet events
⇒ Complete, detailed account of electroweak interactions
- ▶ Parton-shower picture for rough estimates. Quantitative results need fixed-order calculation with precise understanding of matching/mixing/mass effects and higher EW orders
- ▶ Tiny effects such as traces of family-dependent mass generation become accessible and can be studied in all exclusive channels
- ▶ Annihilation may dominate sensitivity over VBS
- ▶ Full coverage requires thorough understanding of detector geometry, combinatorics and (boson) particle ID