EW Radiation Challenges and Opportunities

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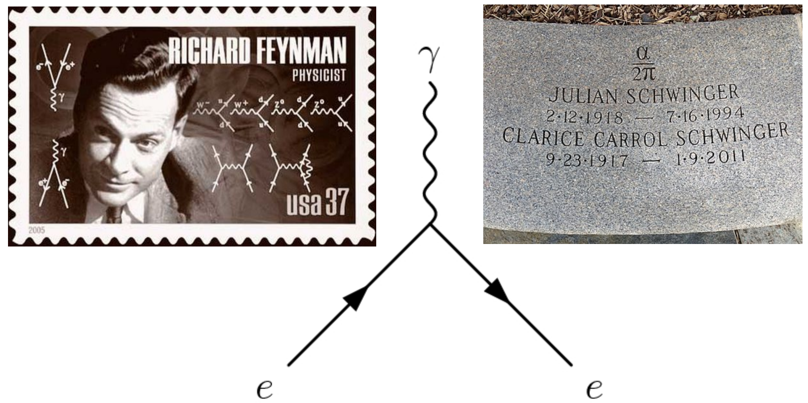
For references, and much more, see here

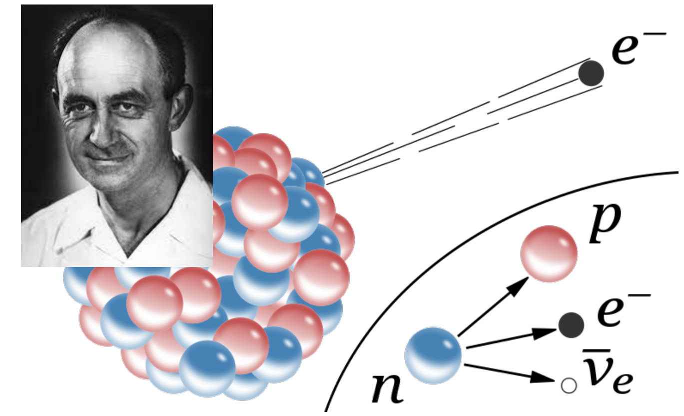
Towards a Muon Collider

Review submitted to EPJC

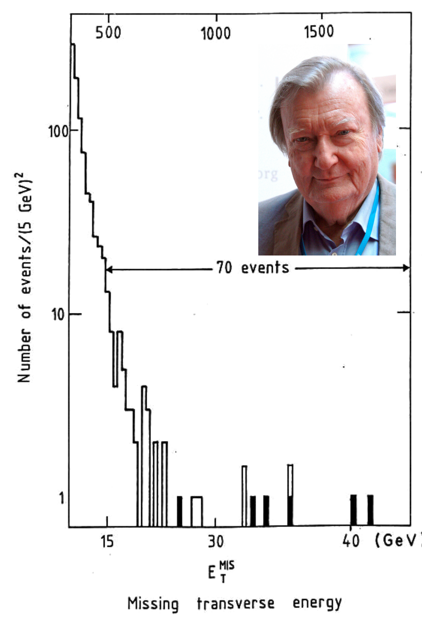
Multifaceted ElectroWeak Interactions

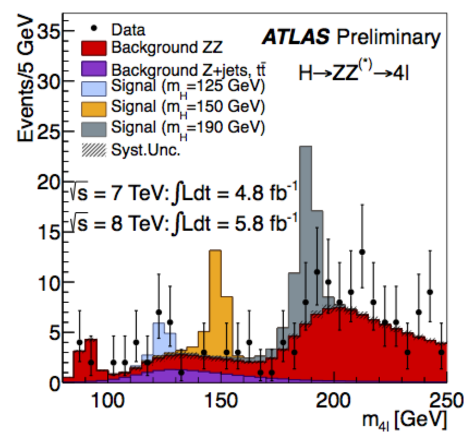
$E \ll m_W$

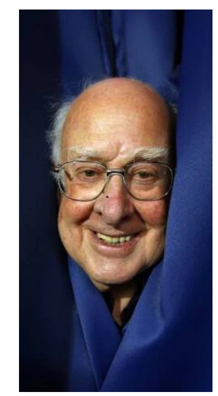


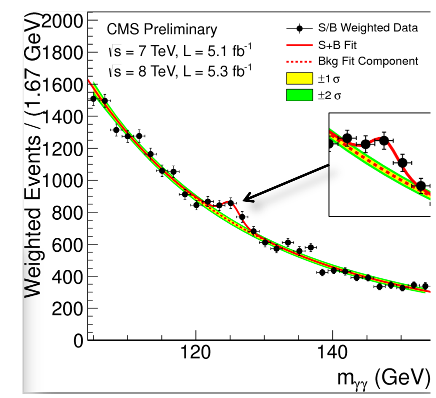


$E \gtrsim m_W$









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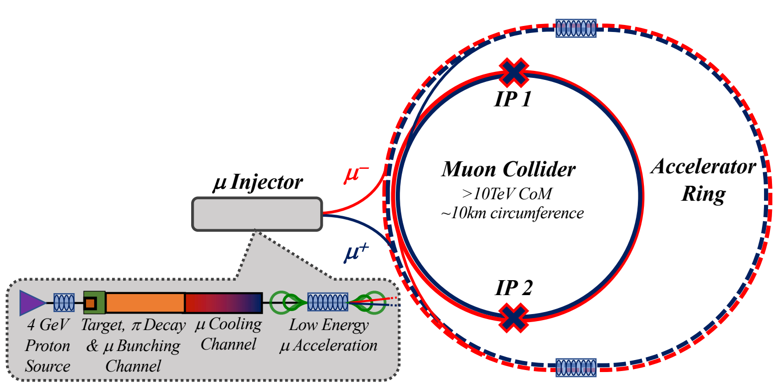

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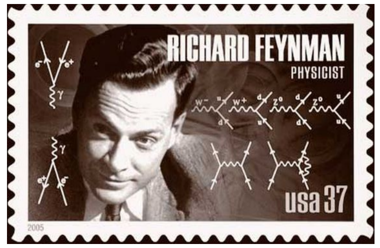

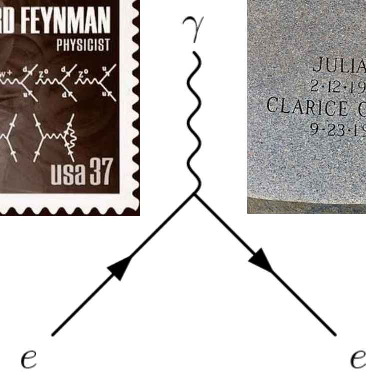

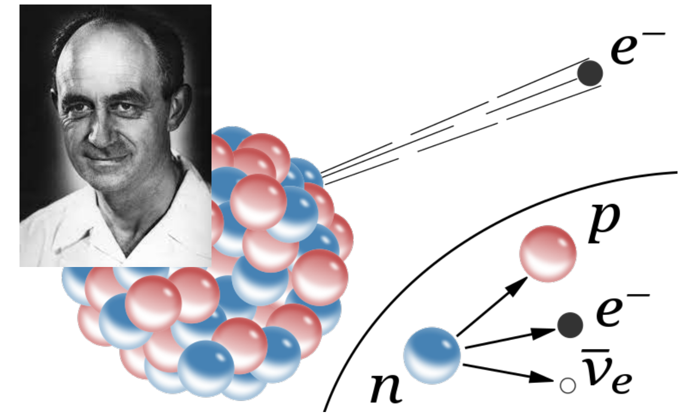

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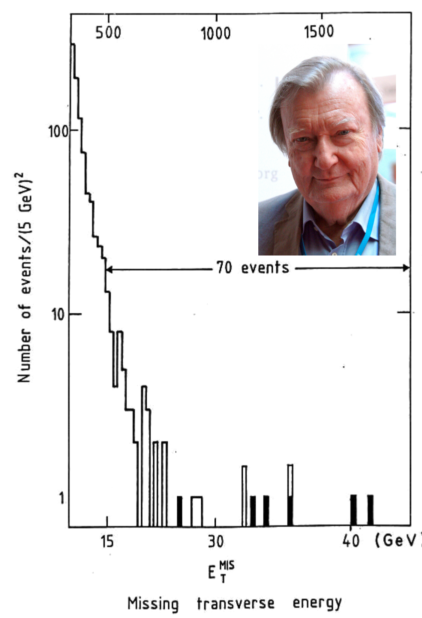
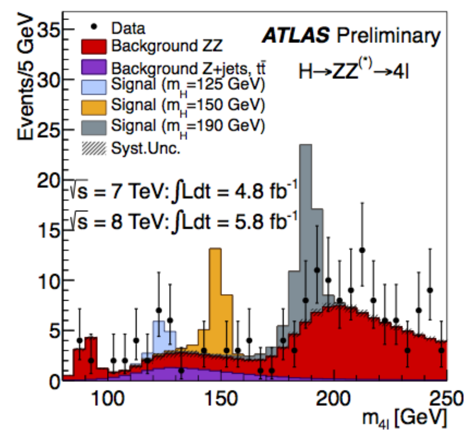
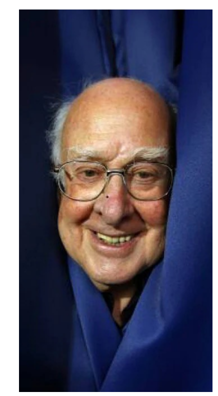
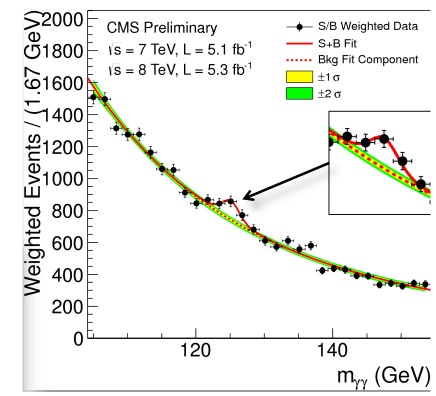


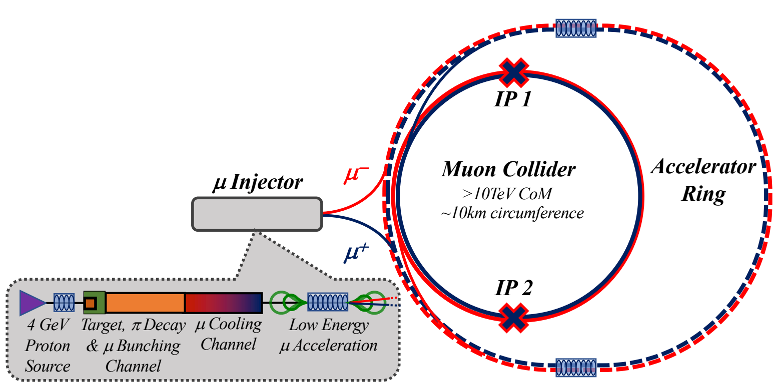






$E \gg m_W$

Maybe, we will see new interactions



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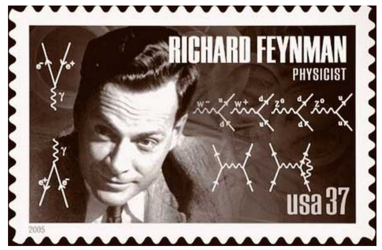

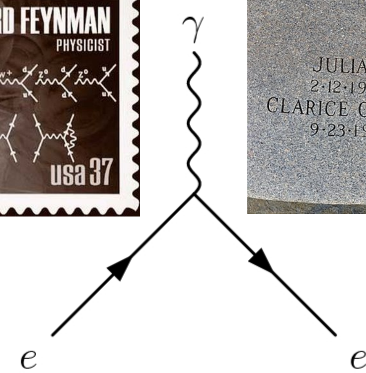

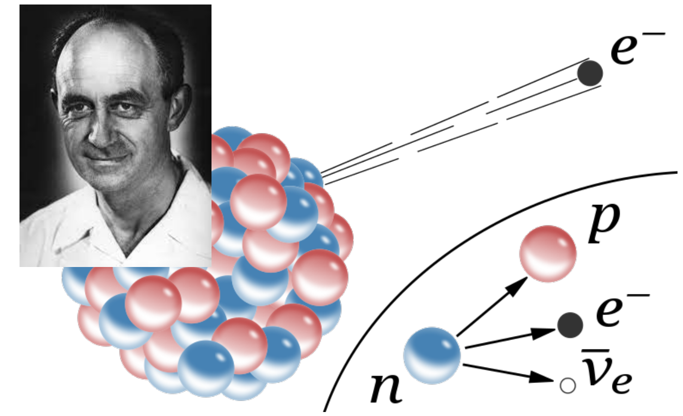

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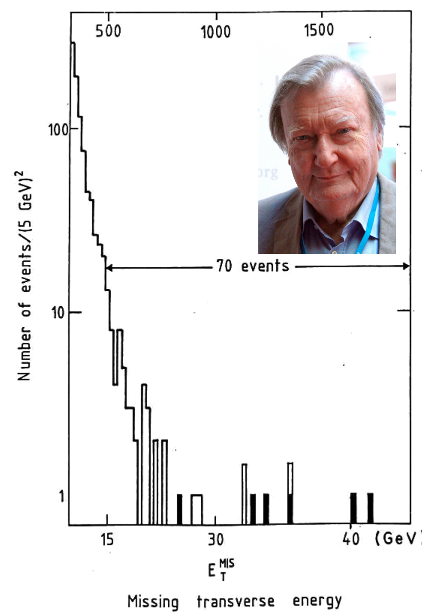
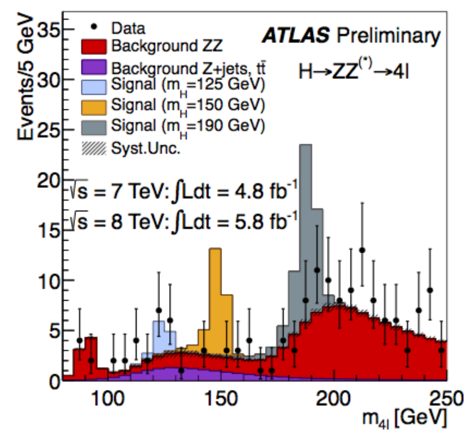
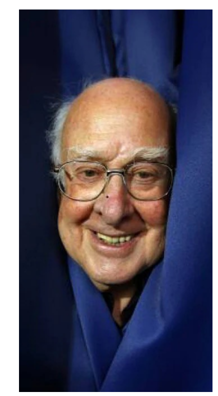
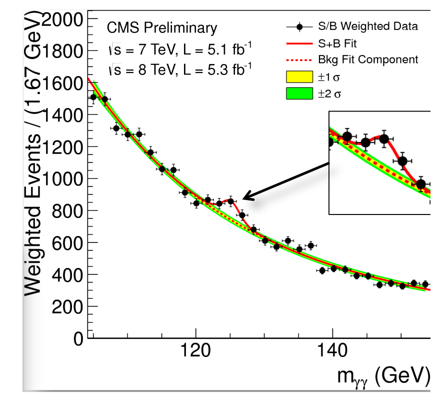


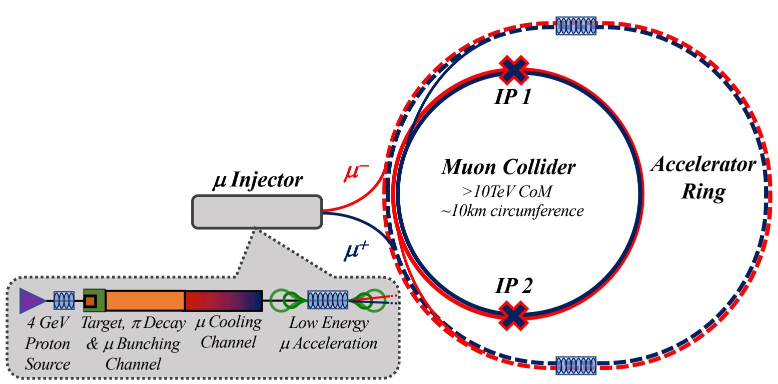


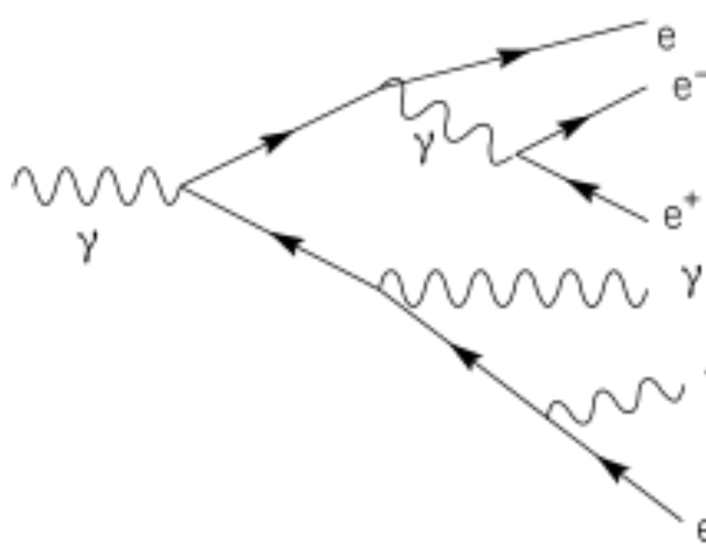


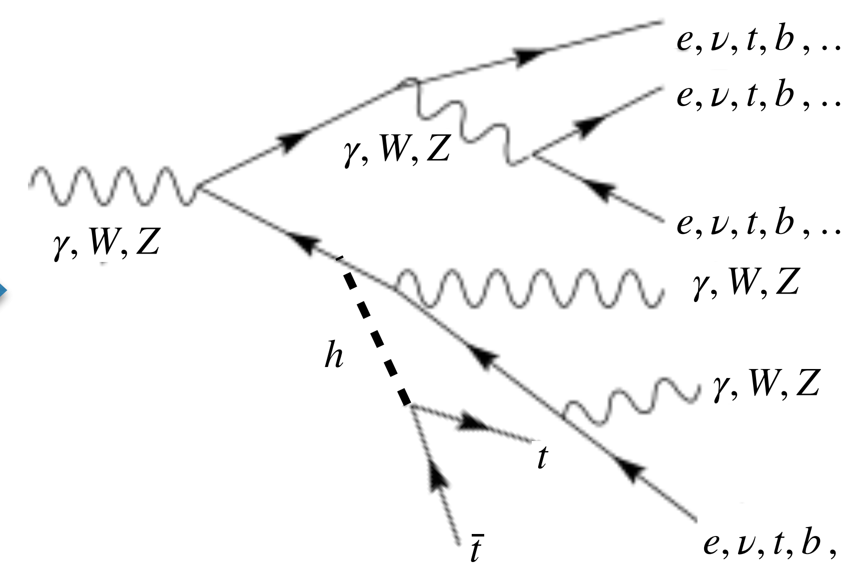


$E \gg m_W$

For sure, we will see this:







EW Radiation

We will observe the nearly-massless EW gauge theory

$$E \gg m_W$$

Large muon collider energy (E)

Small IR cutoff scale (m_W)

Scale separation entails enhancement of Radiation effect.

Like QCD ($E \gg \Lambda_{\mathrm{QCD}}$) and QED ($E \gg m_\gamma = 0$), **but:**

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EW symmetry is broken:

- EW color is observable ($W \neq Z$).
- KLN Theorem non-applicable.
- (inclusive observables not safe)

$\Rightarrow$

Practical need of computing EW Radiation effects

- Enhanced by $\log^{(2)} E^2/m_{\mathrm{EW}}^2$

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→ **Practical need** of computing EW Radiation effects
Enhanced by $\log^{(2)} E^2/m_{\rm EW}^2$

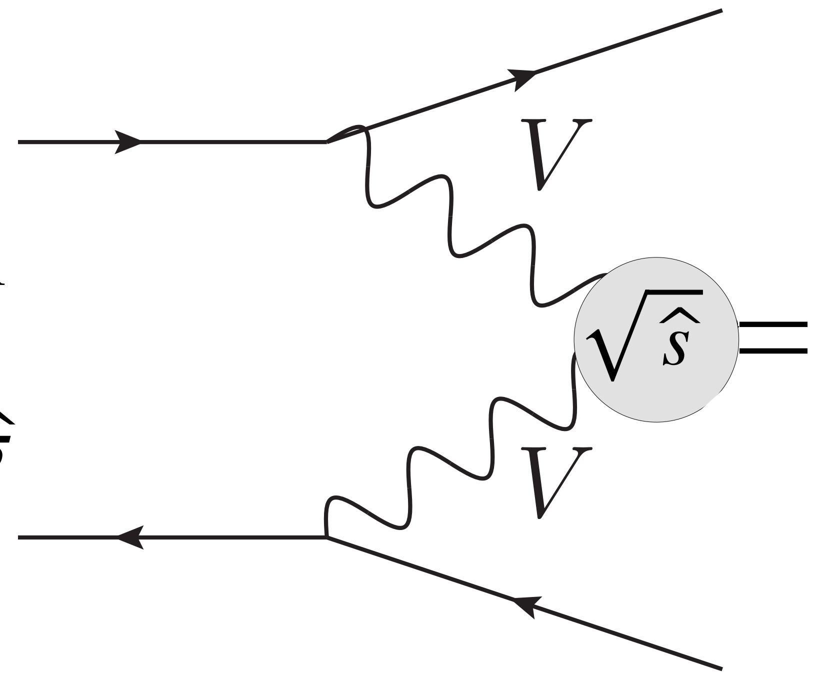
EW theory is Weakly-Coupled
The IR cutoff is physical

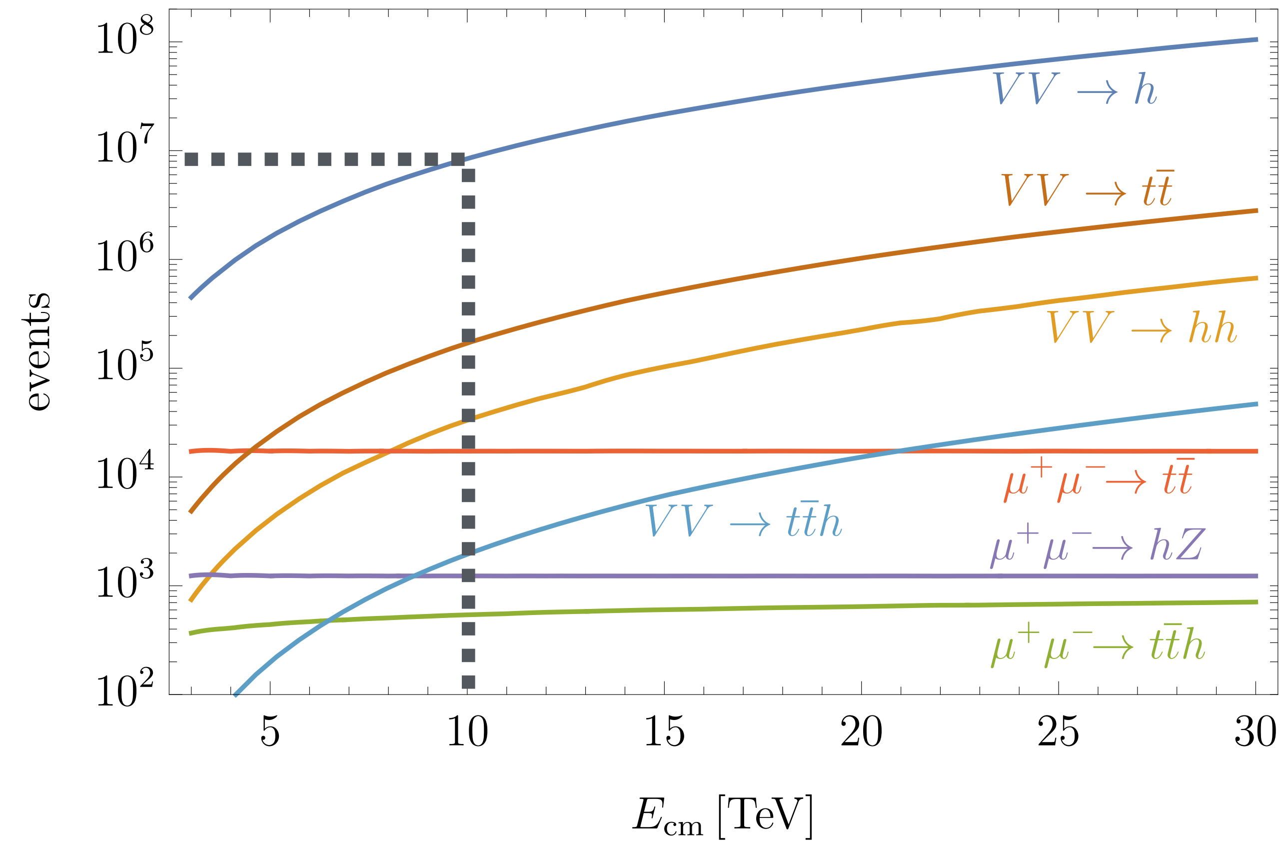
→ **First-Principle** predictions **must** be possible
For arbitrary multiplicity final state

Opportunities I: low/medium energy

Almost on-shell
V-bosons in muon

$$\sigma = \int d\tau \frac{d\mathscr{L}}{d\tau} \hat{\sigma}$$





Enhancement of **low-energy** V-B Scattering: $\hat{\sigma} \approx \frac{1}{\hat{s}} \gg \frac{1}{E^2}$

Splitting suppression from weak coupling compensated by
$\log E^2/m_{\rm EW}^2$

VBF yield growth with $E_{\rm cm}$ due to collider luminosity growth:
$L \propto E^2$

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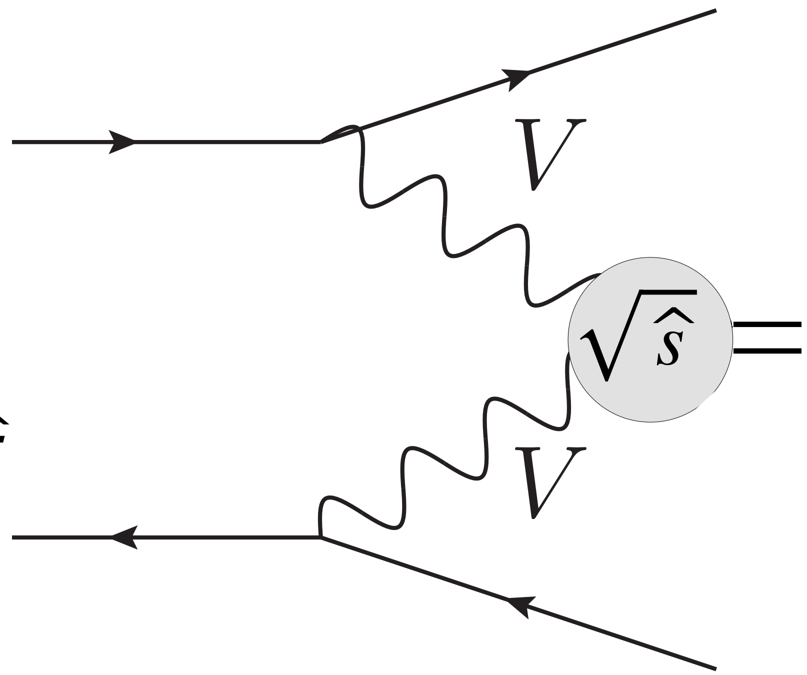
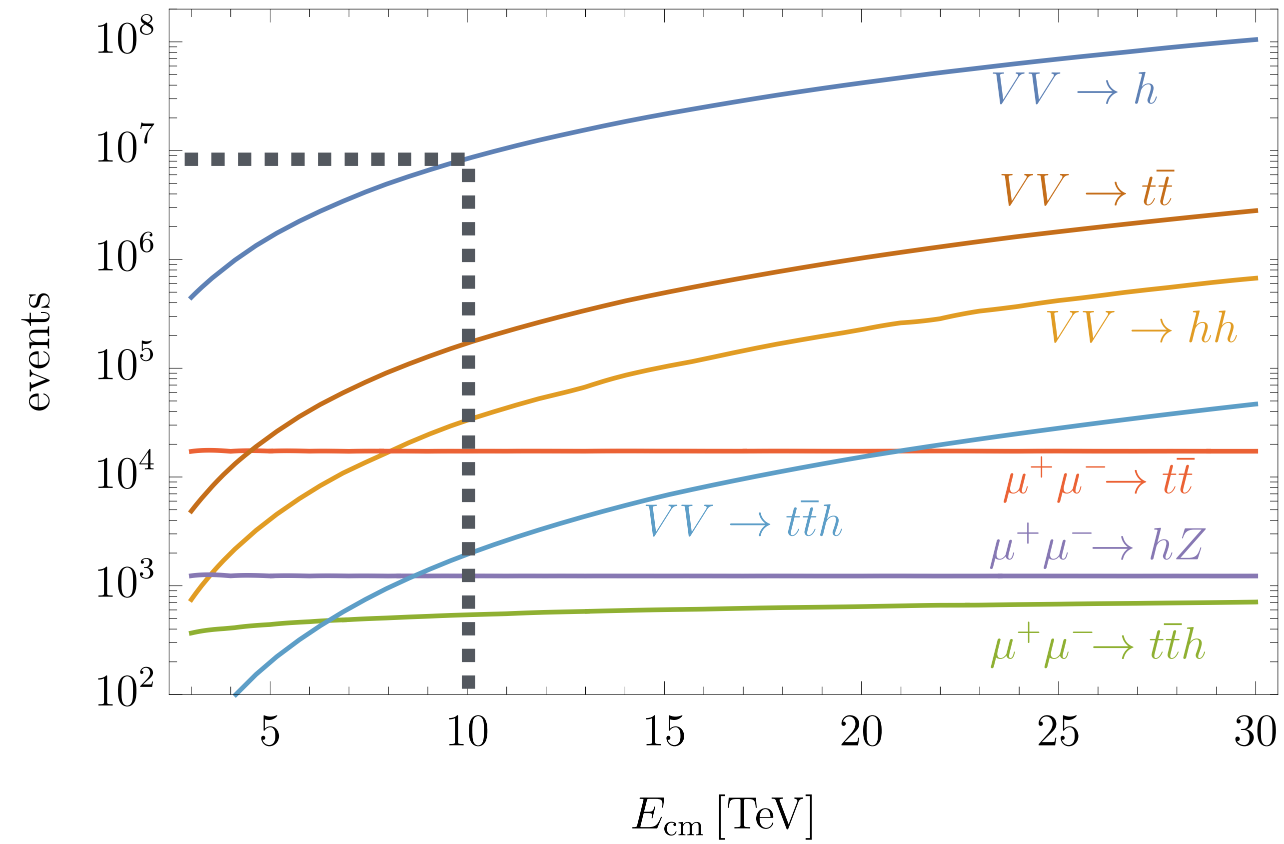


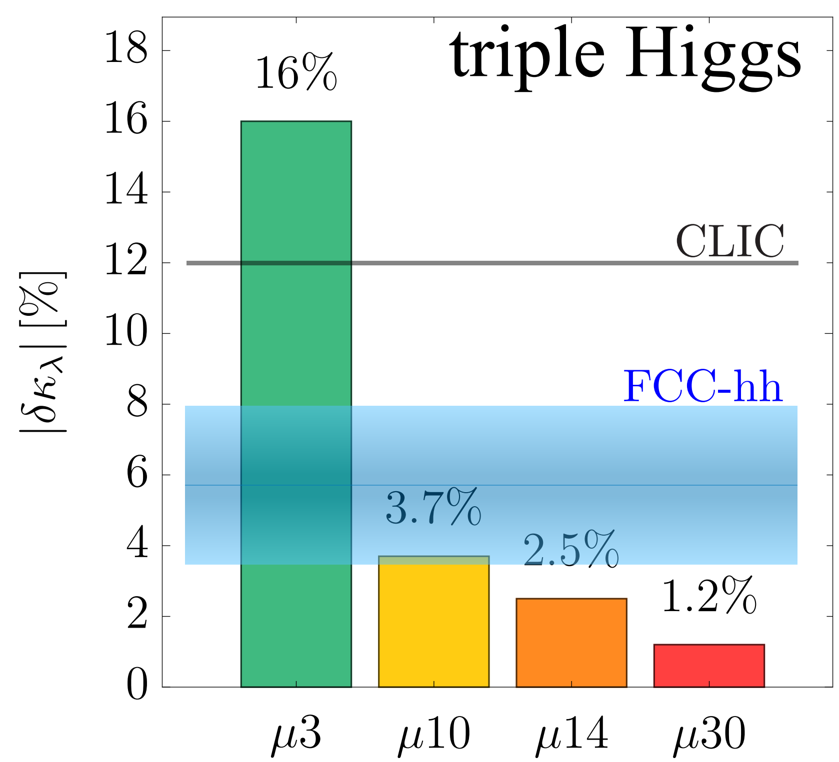


Opportunity for high-precision (high-statistics) measurement of, e.g., H couplings

single Higgs

	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
$\kappa_{Z\gamma}$	10	7.2	7.1
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
κ_t^*	3.3	3.1	3.1

* No input used for the MuC



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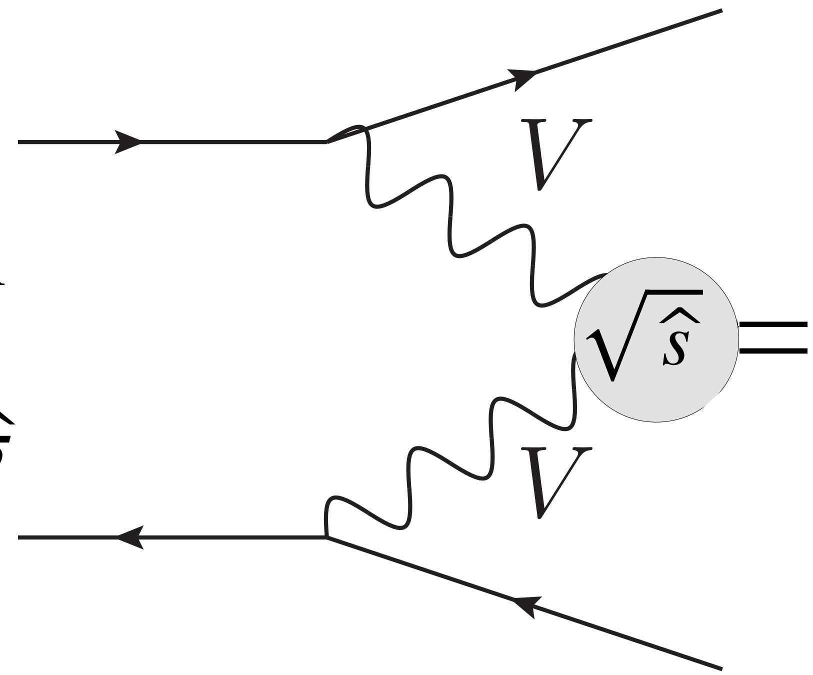

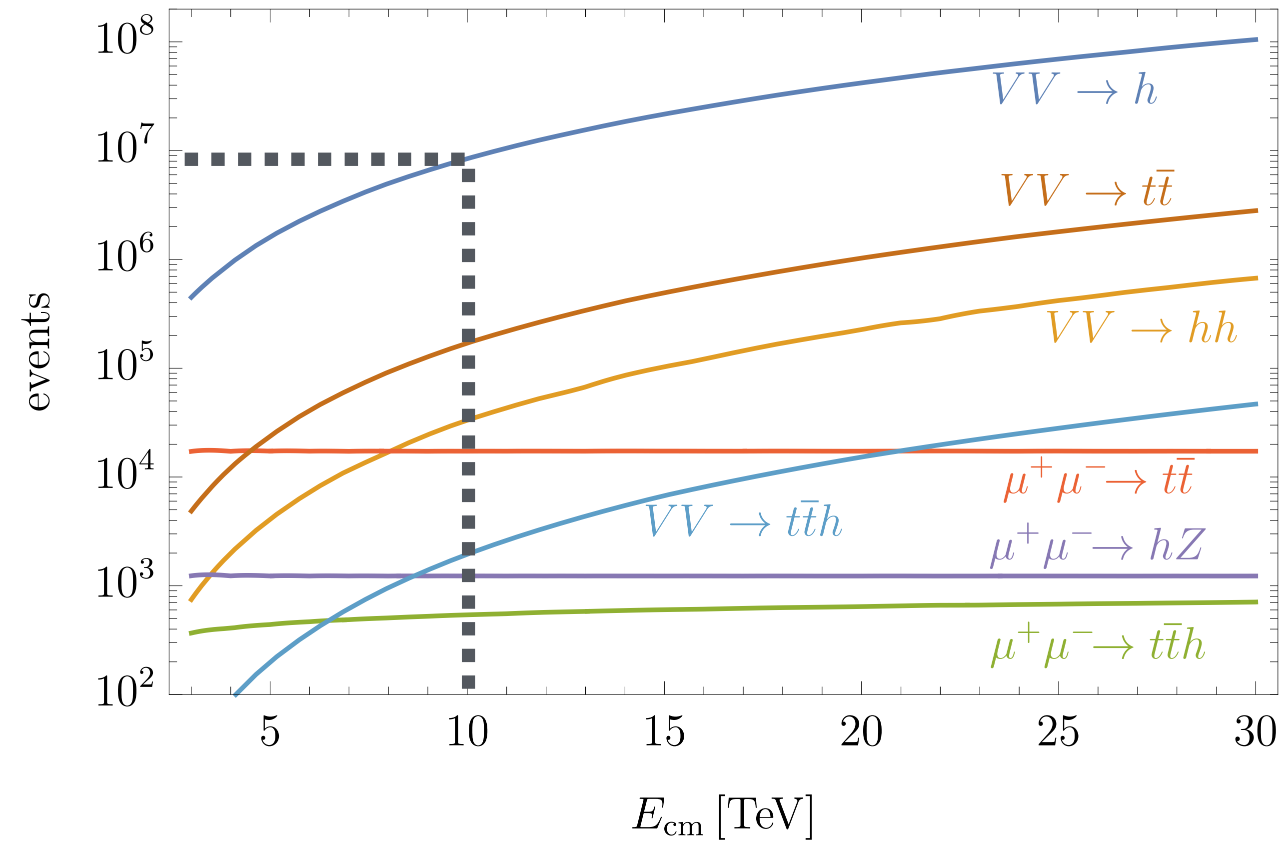

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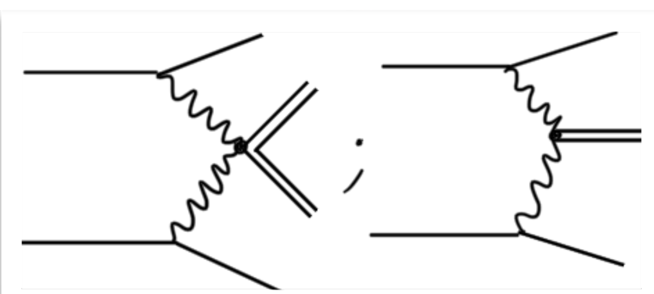
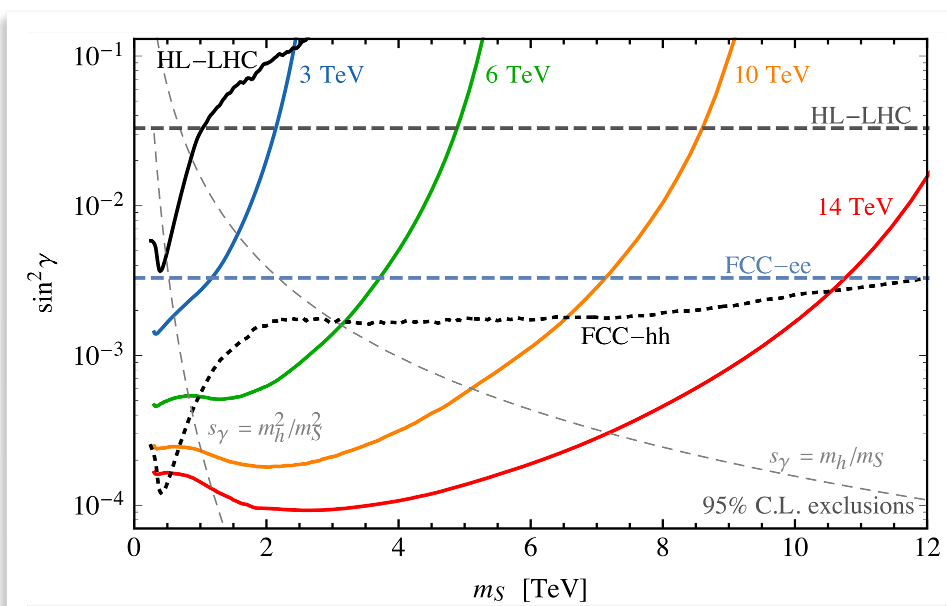
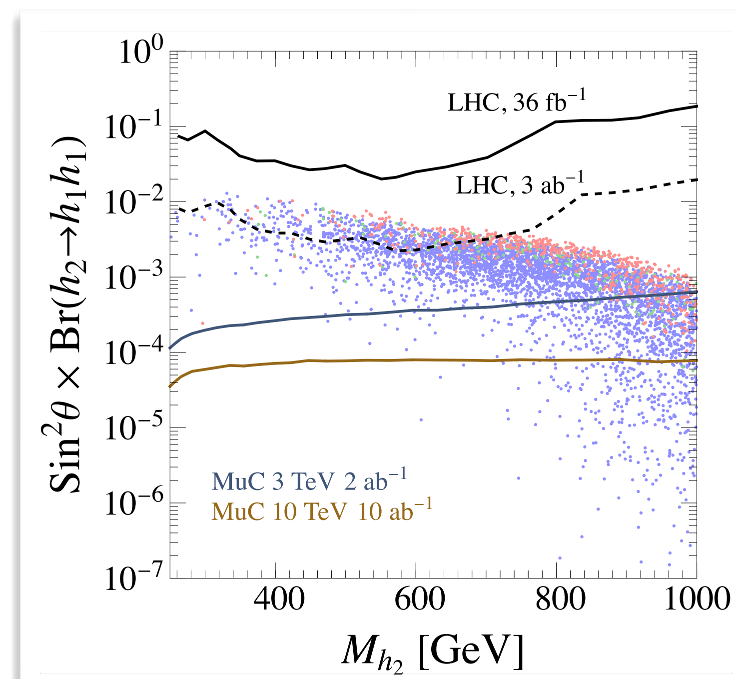
Opportunity for Higgs-coupled BSM



$|H|^2 \cdot X^2$; or $|H|^2 \cdot X$





model with 1st order EWphTr

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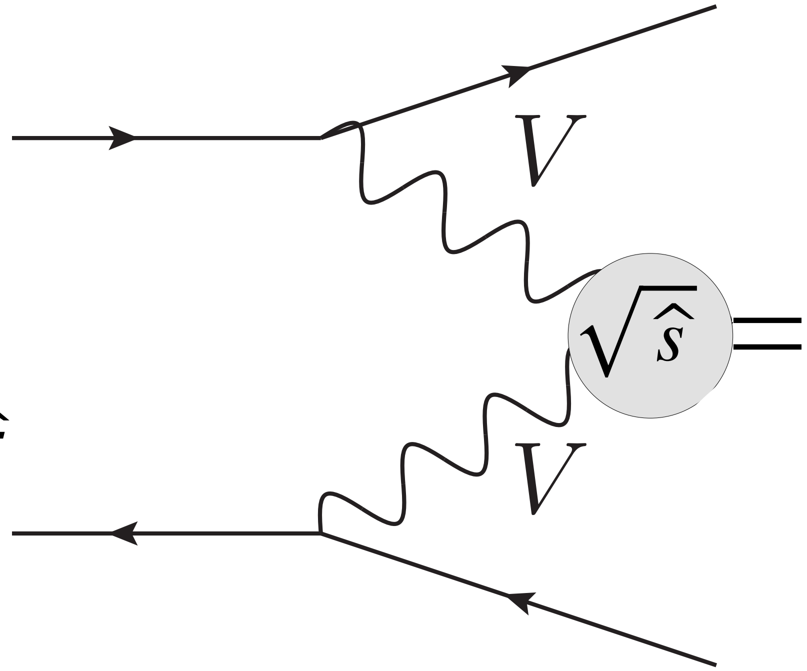
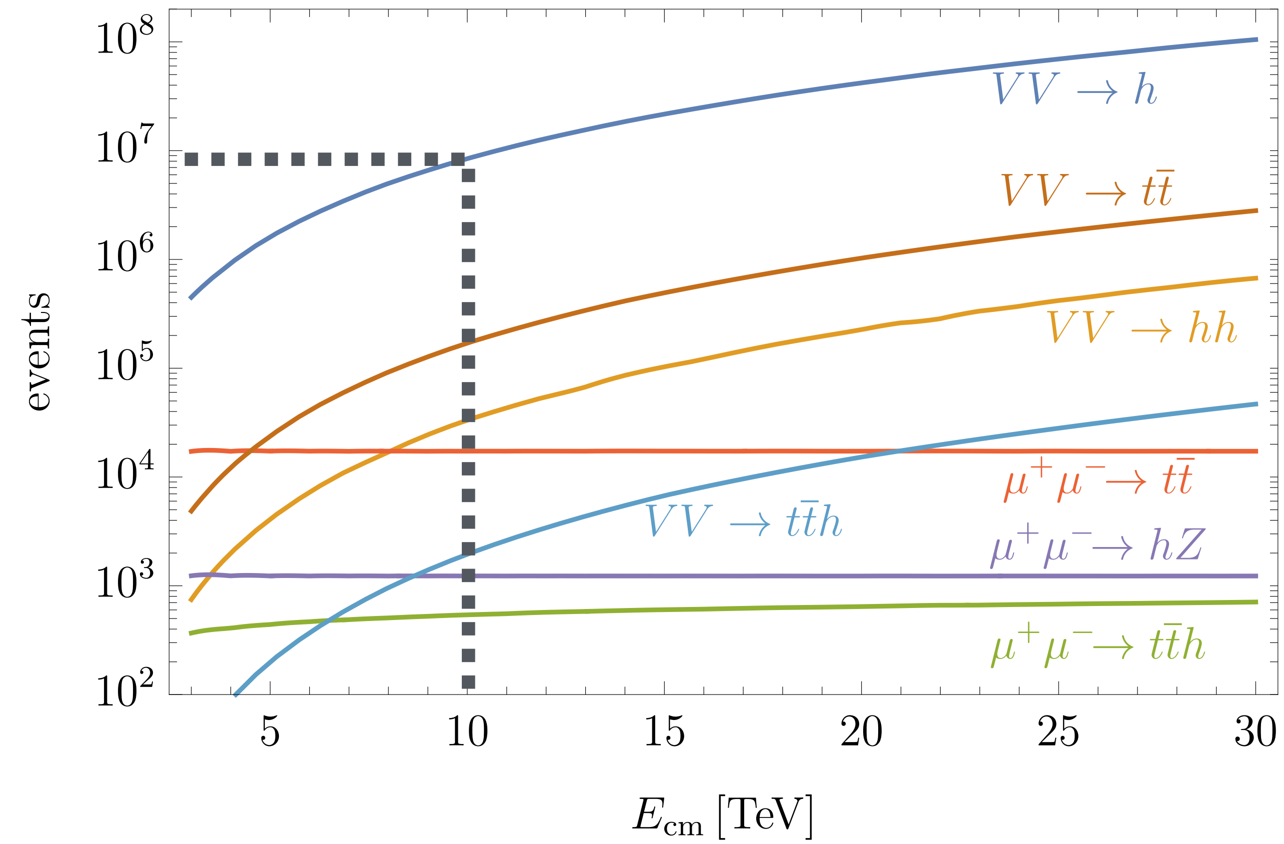
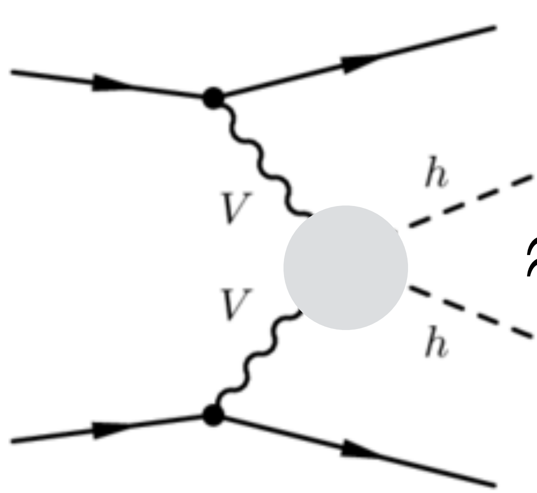




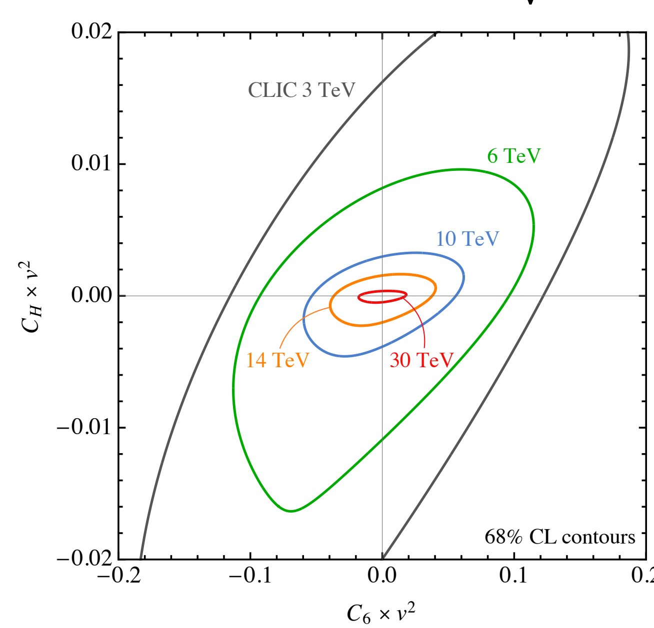
Opportunity for high-precision (high-statistics) measurement of, e.g., H couplings

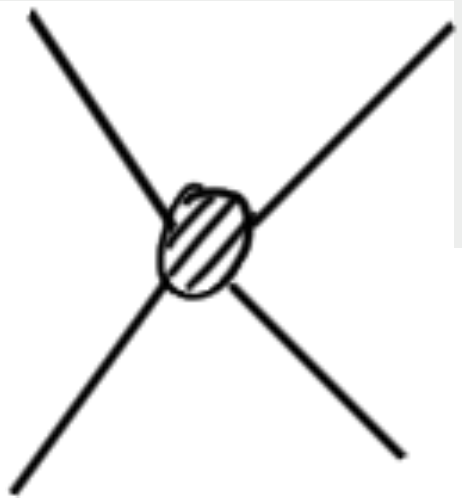
Opportunity for Higgs-coupled BSM

Opportunity (almost unexplored) for BSM VV→SMSM, at $\sqrt{\hat{s}} > 1$ TeV



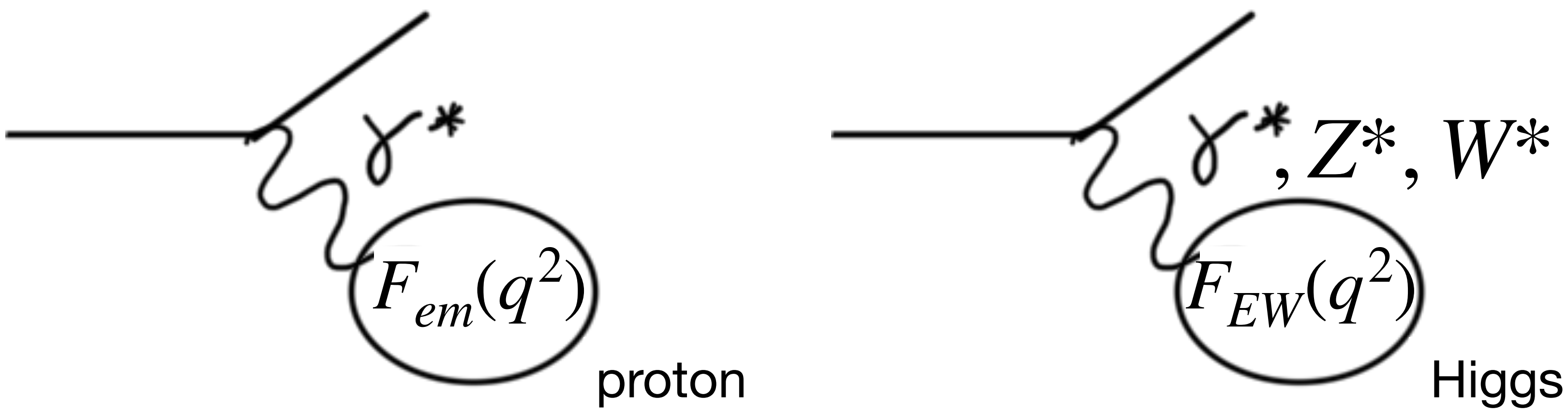
$\approx C_H \hat{s}$

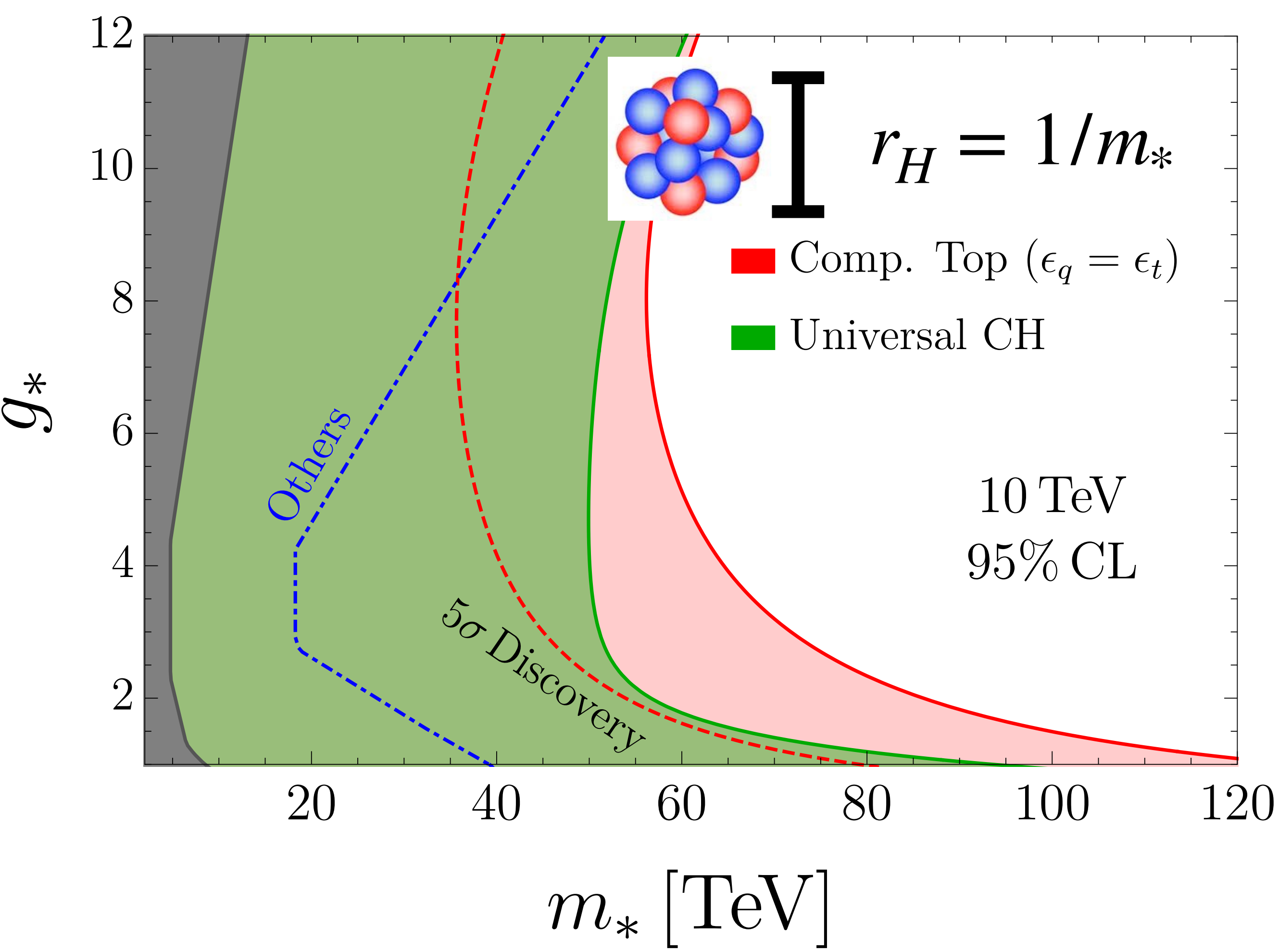


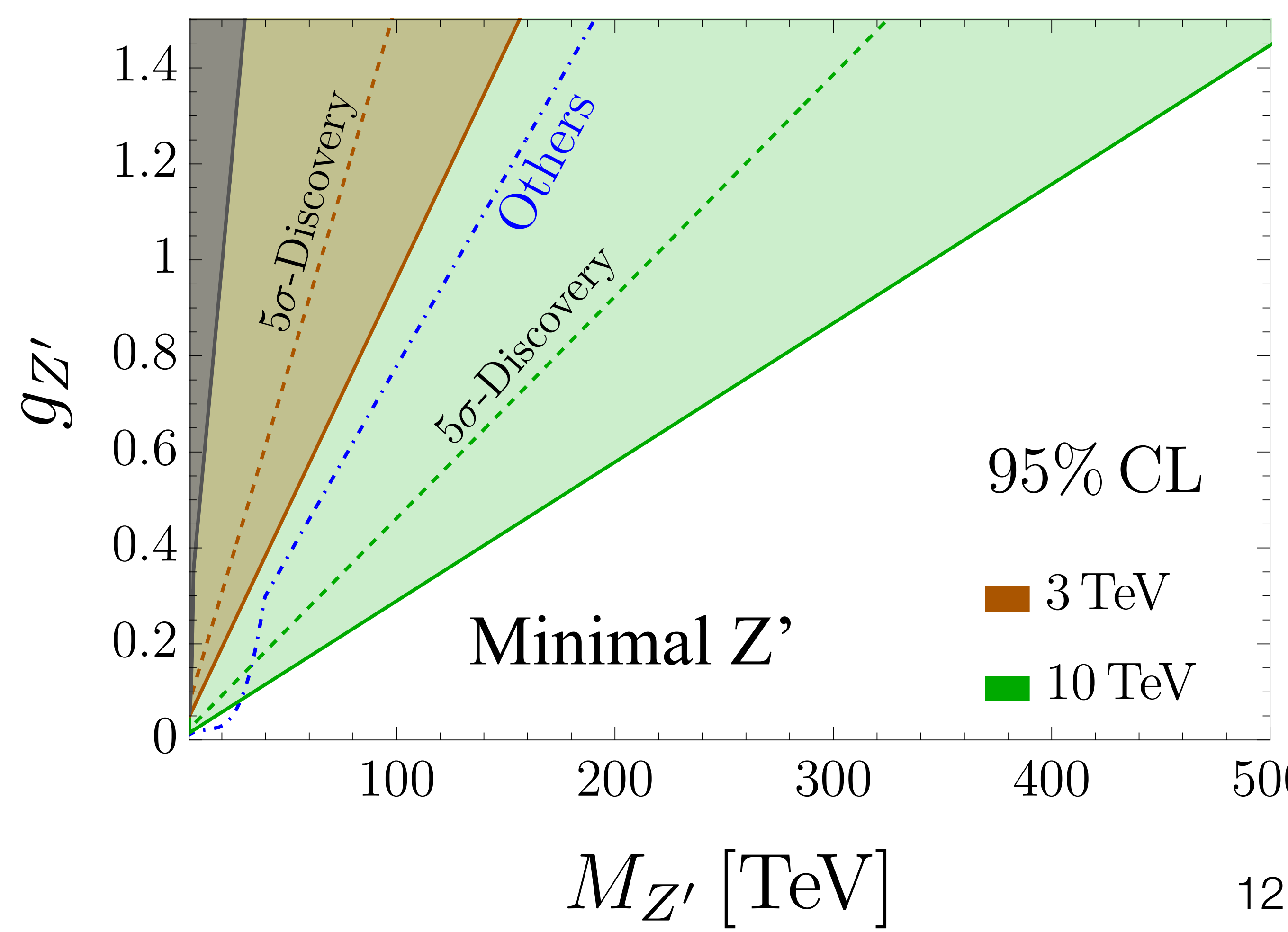


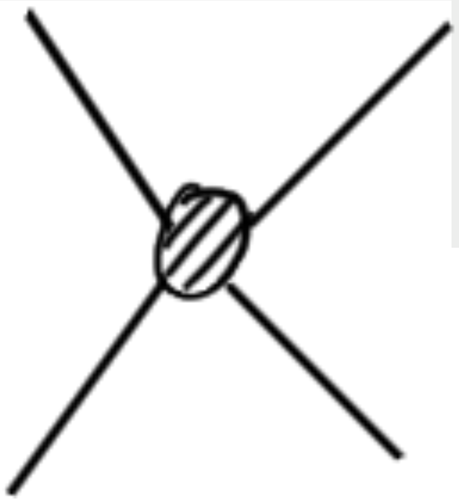
Opportunities II: high energy

Most simple 2 → 2 XS probe **directly** the 10 TeV scale
They probe **indirectly** 100 TeV if measured at %









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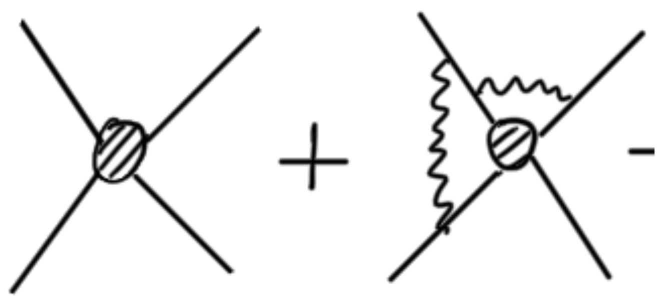
  Extremes are “Exclusive” or “Semi-Inclusive”

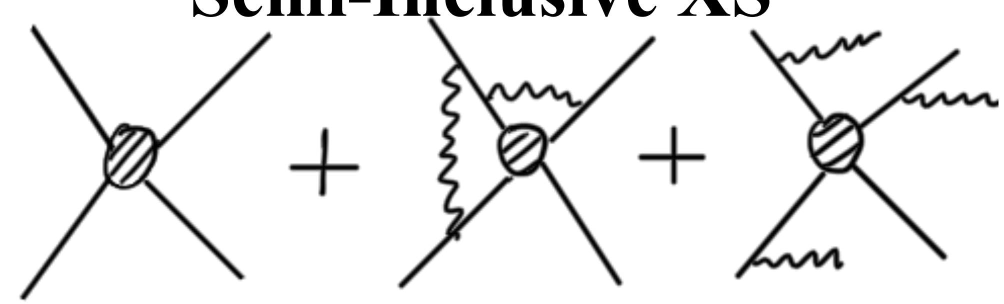
Exclusive cross-sections



Two hard bodies with **definite EW color**.
Veto on EW bosons.
Soft photons and gluons incl. of course

Unexplored options in between

Semi-Inclusive XS



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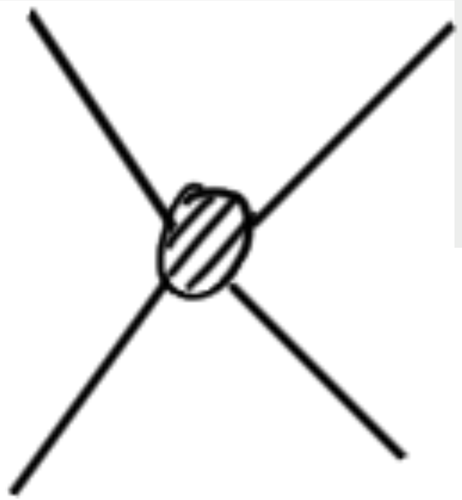

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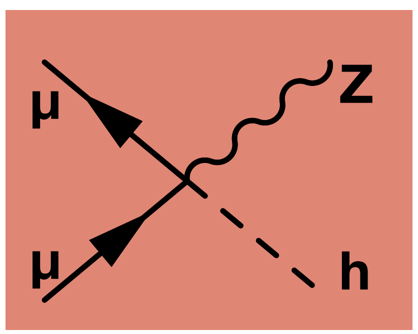

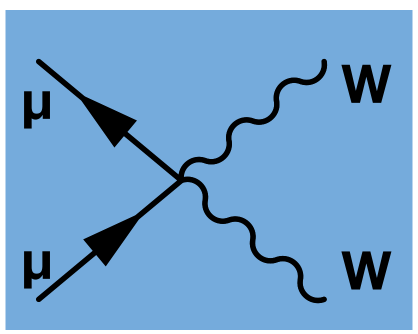

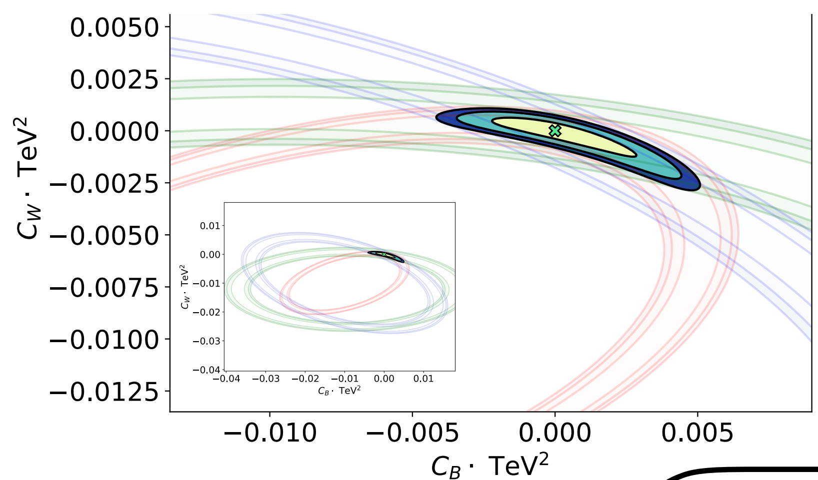

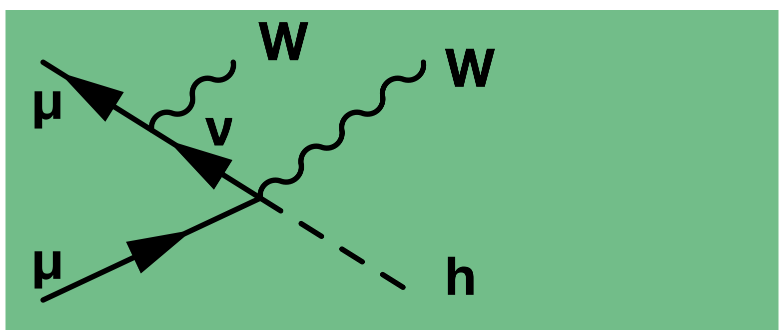

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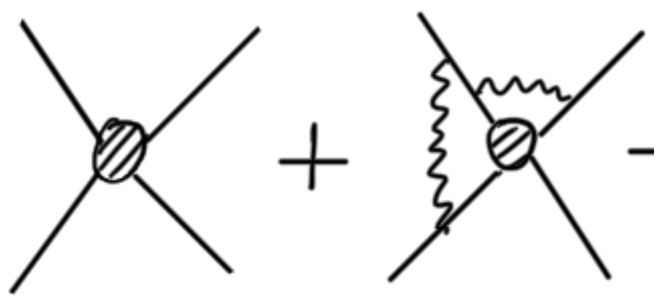

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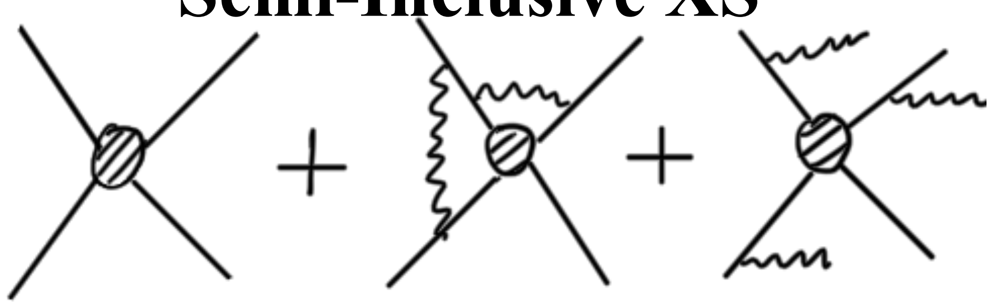

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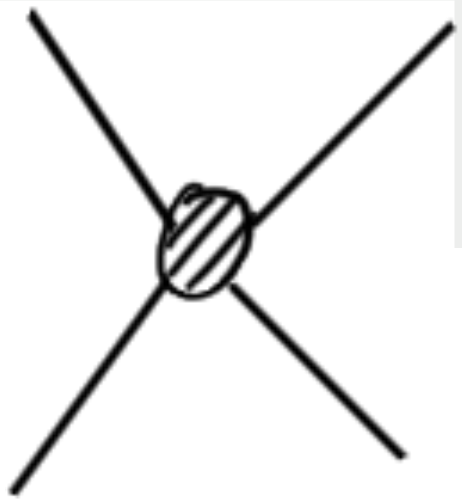

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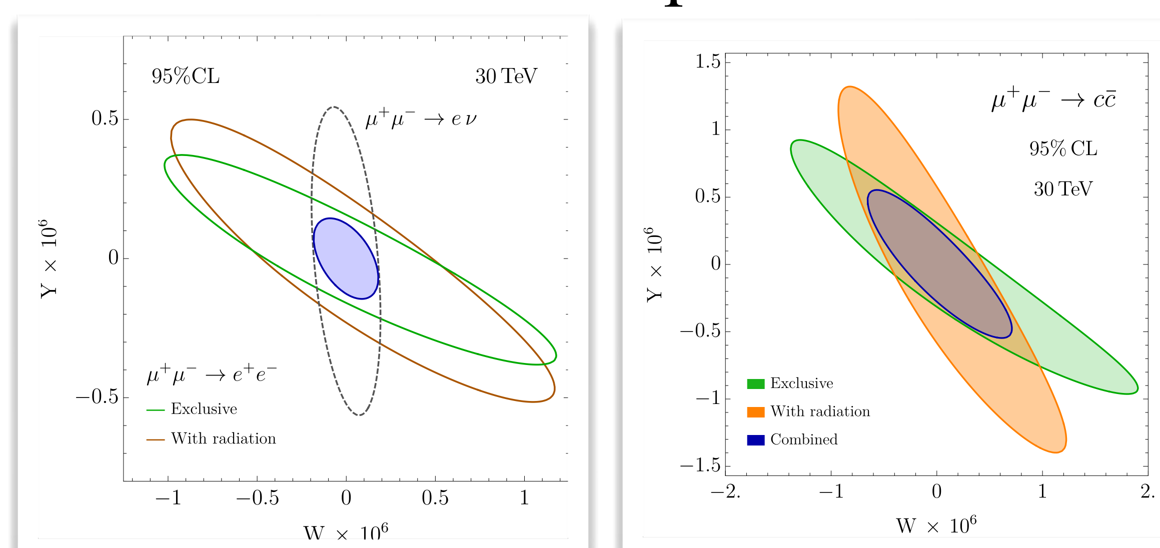

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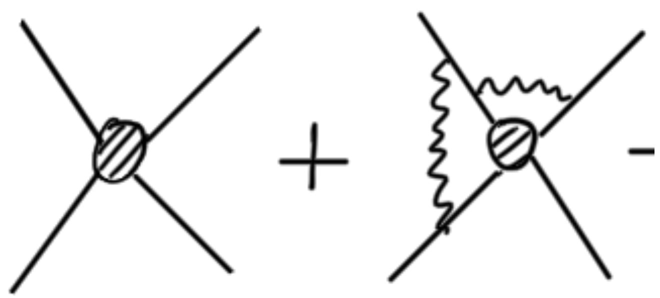

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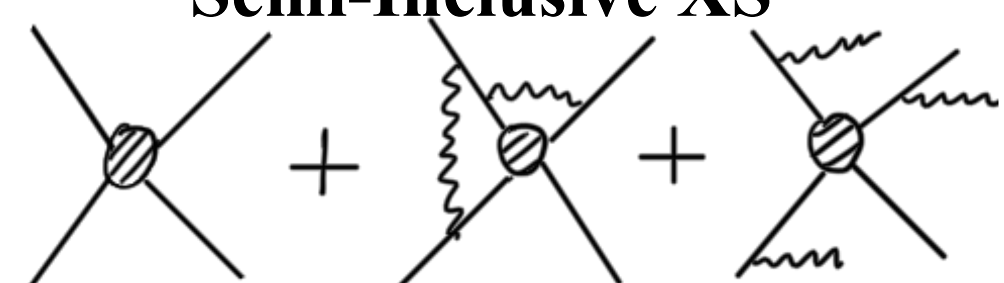

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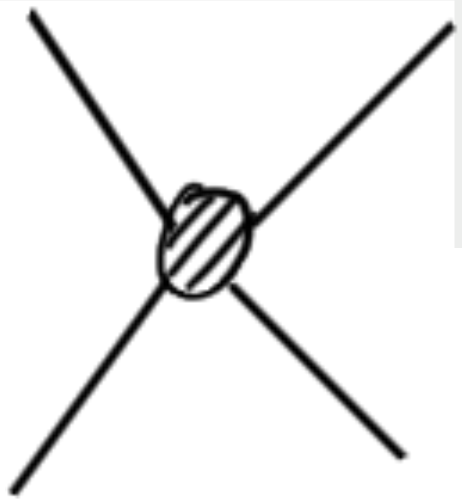

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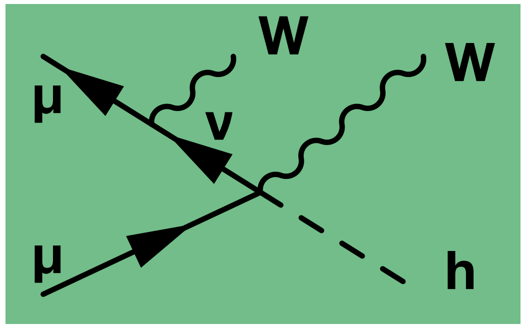
- Interesting corollaries:
  - ➡ Charged current ~ as large as neutral. Useful for BSM resonance as well
  - ➡ BSM and SM physics cannot just stay on their own!

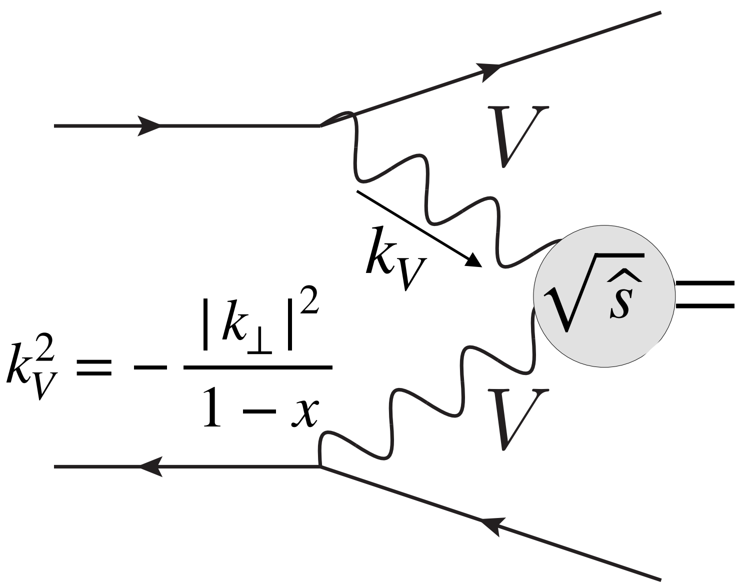


Process	N (Ex)	N (S-I)
e^+e^-	6794	9088
$e\nu_e$	—	2305
$\mu^+\mu^-$	206402	254388
$\mu\nu_\mu$	—	93010
$\tau^+\tau^-$	6794	9088
$\tau\nu_\tau$	—	2305
jj (Nt)	19205	25725
jj (Ch)	—	5653
$c\bar{c}$	9656	12775
cj	—	5653

$b\bar{b}$	4573	6273
$t\bar{t}$	9771	11891
bt	—	5713
Z_0h	680	858
$W_0^+W_0^-$	1200	1456
$W_T^+W_T^-$	2775	5027
$W^\pm h$	—	506
$W_0^\pm Z_0$	—	399
$W_T^\pm Z_T$	—	2345

Challenges I: the accuracy of EVA

Effective Vector (or, W) Approximation is EW PDF at tree-level



Validity requires nearly on-shell V in hard process:

$$m_V^2 - k_V^2 \ll \hat{s}$$

No way can work if, e.g., $\sqrt{\hat{s}} = m_H = 125\ \mathrm{GeV}$

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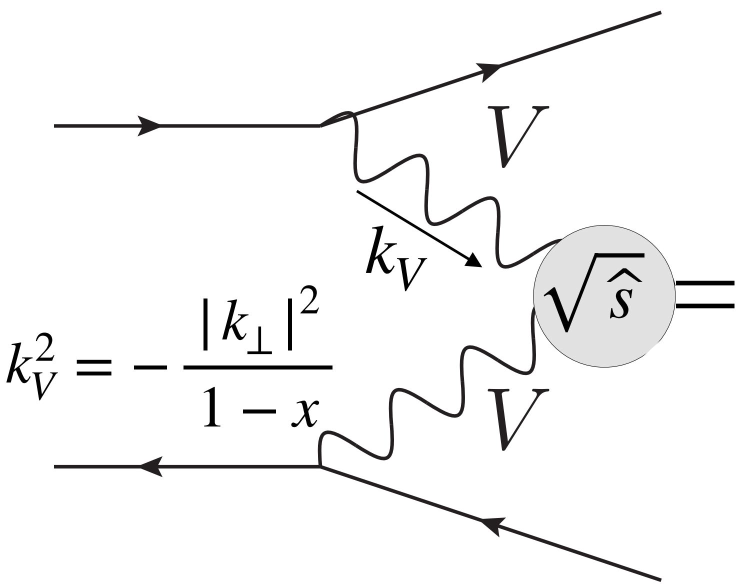

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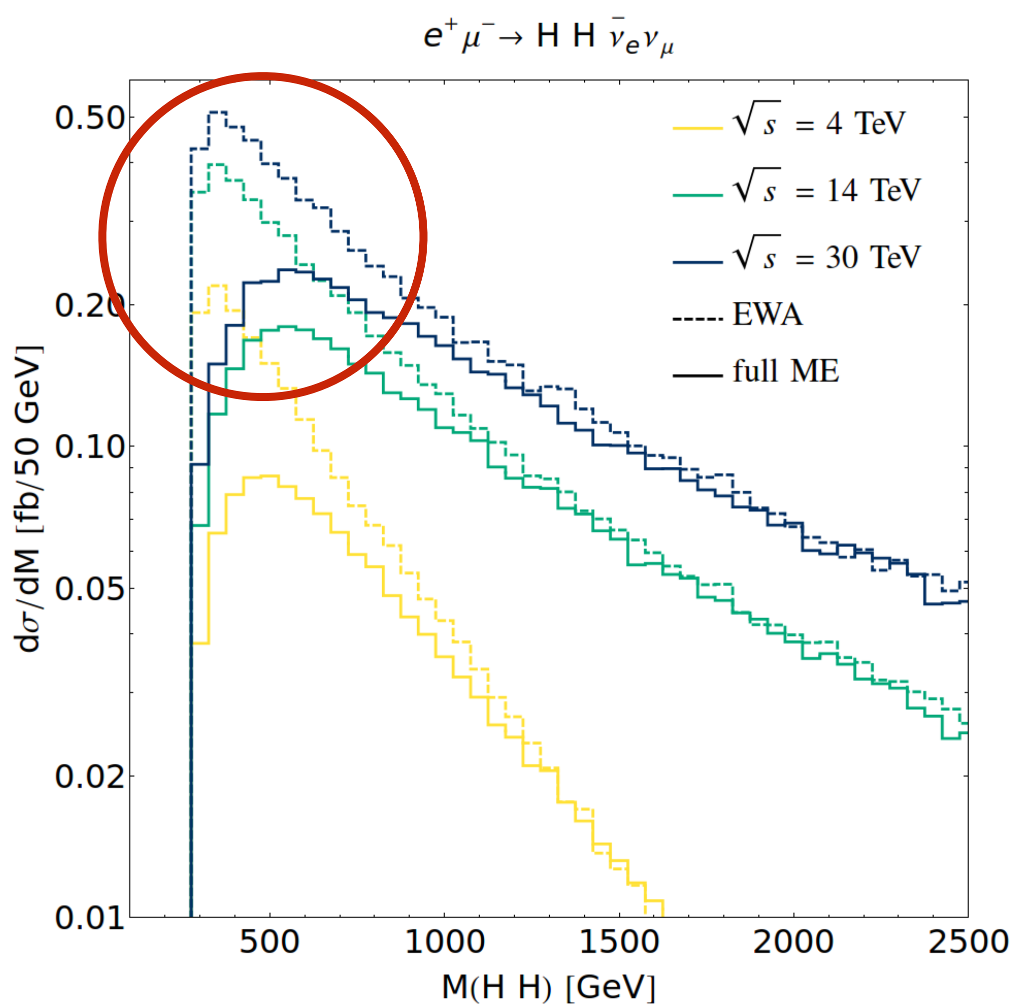
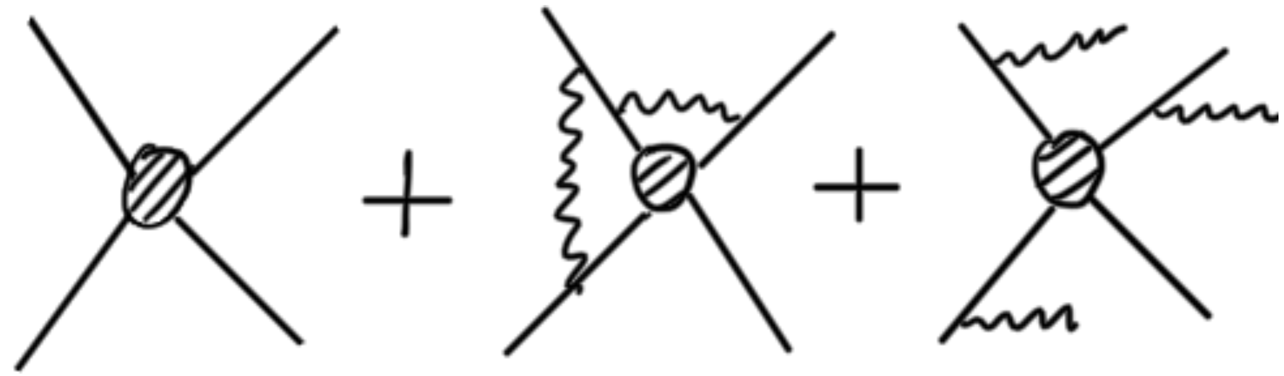
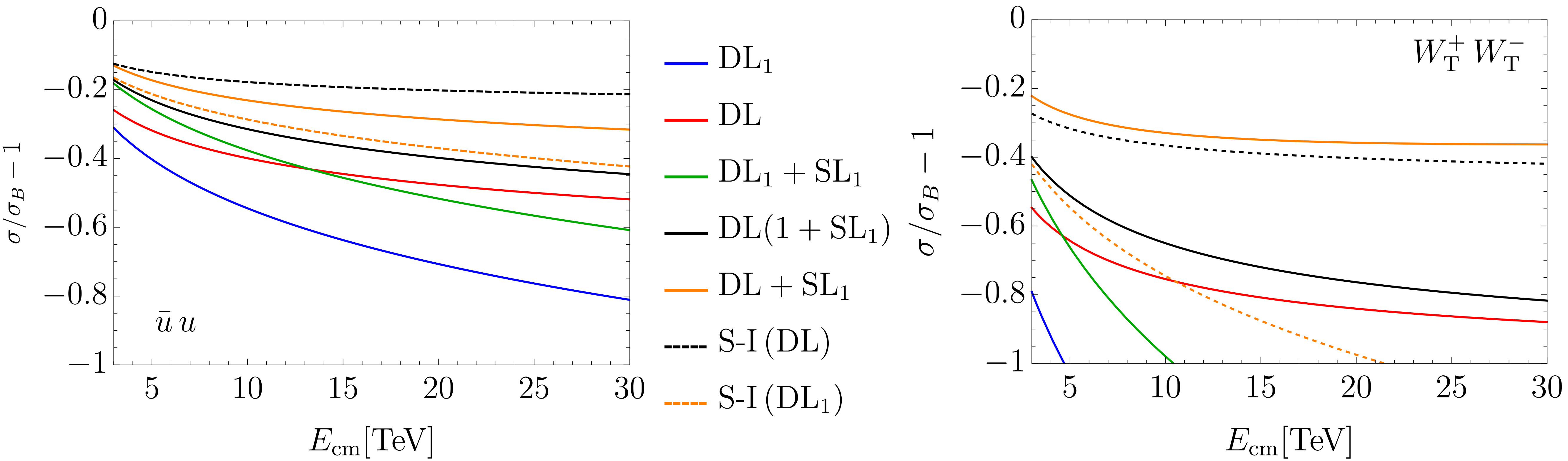


Is this an obstruction to employ PDF (and Altarelli-Parisi resummation) in Higgs production?

Need some type of matching with full ME at fixed order?

Challenges II: systematic accurate resummation

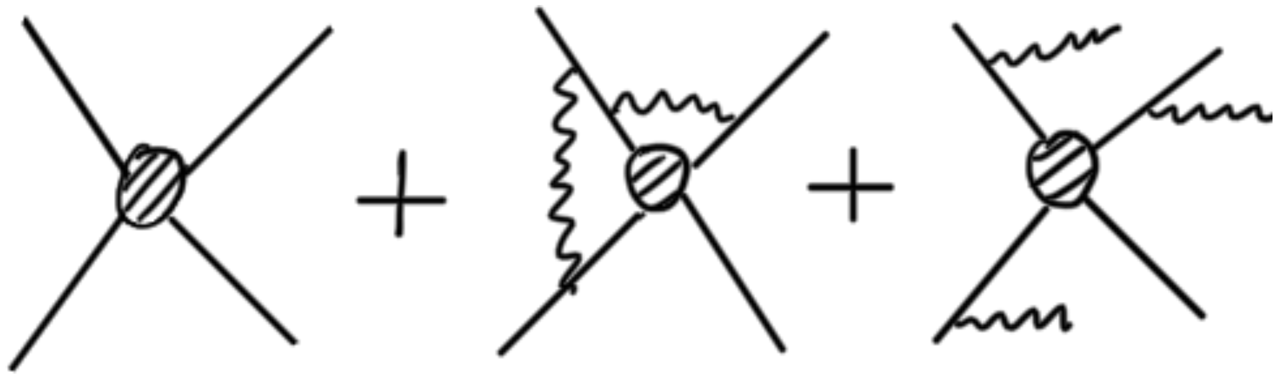




One-loop double logs range from **large** to **huge**

- Estimate: $g^2/16\pi^2 \log^2(E^2_{\rm cm}/m^2_{\rm w}) \times$ Casimir
- **Resummation** of **DL** needed
- **Precise resummation** needed: goal is %-level meas./predictions
- Single-logs resummation might be needed as well

Challenges II: systematic accurate resummation



Resummation Strategies:

- **Asymptotic Dynamics:**
  - ➡ Fully inclusive, at double log
- **Infrared Evolution Equation:**
  - ➡ Exclusive and semi-inclusive (new), at double log
- **Soft-Collinear Effective Theory:**
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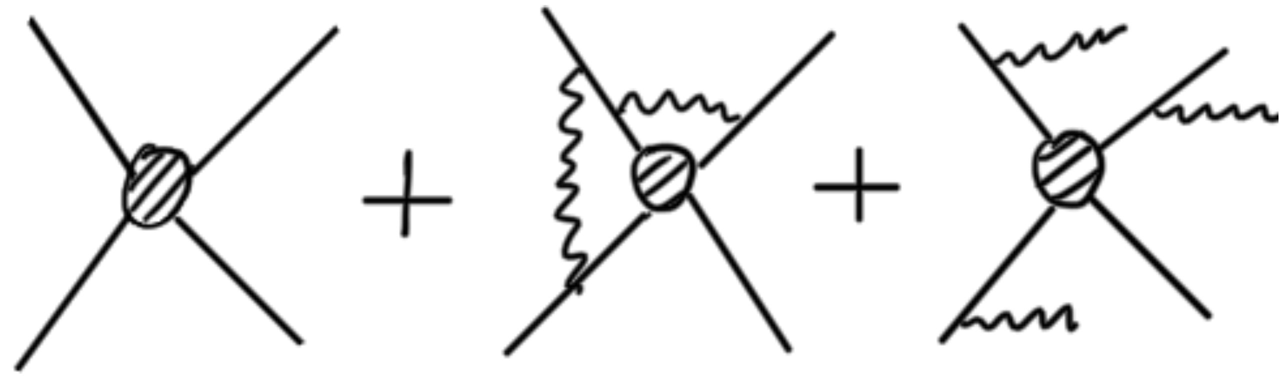

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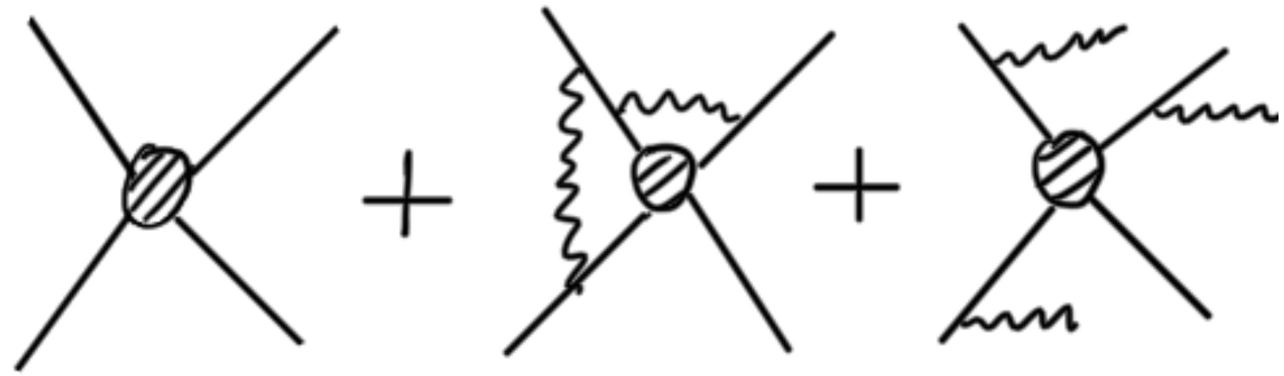

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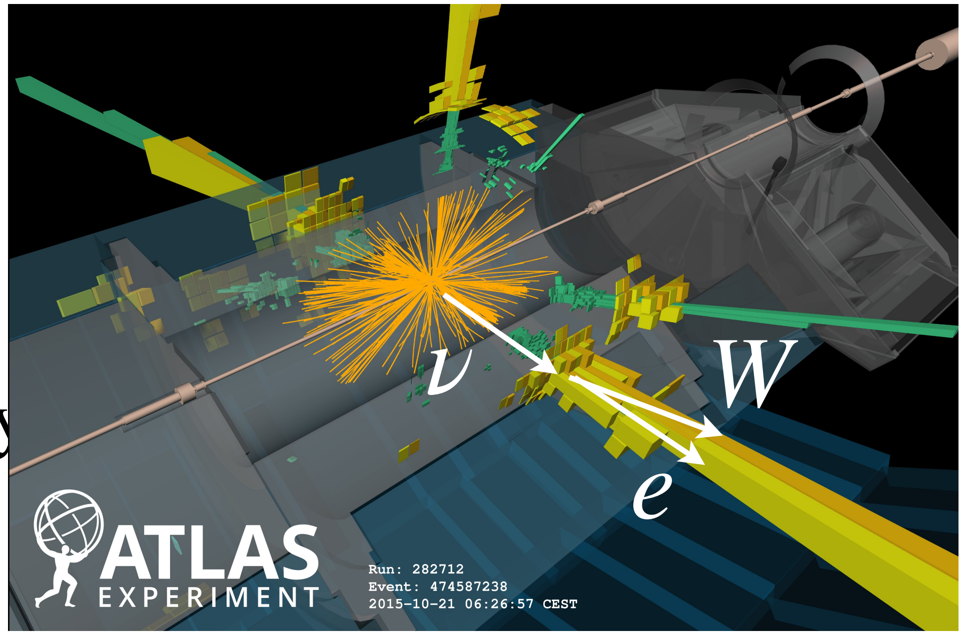

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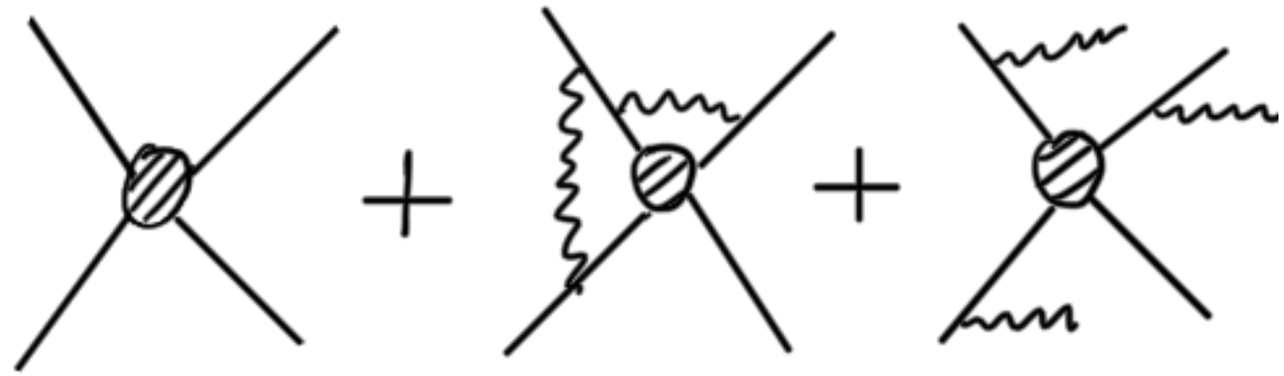

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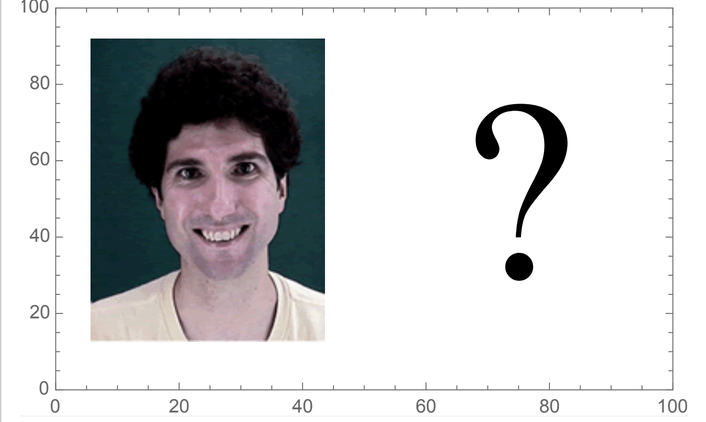
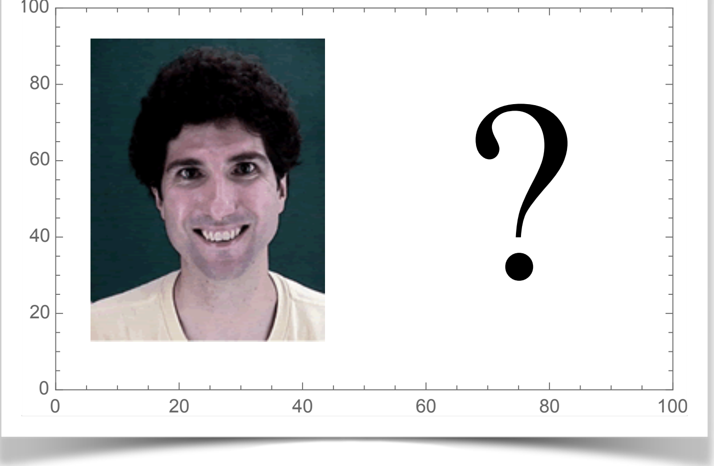
Showering:

- Surely needed by experimentalists …
  and by everybody else, to understand things like **EW jets** (e.g., ν-jet)
- Could it just replace resummation?
- Do current approaches contains (dominant) double log? How?
- See next talk



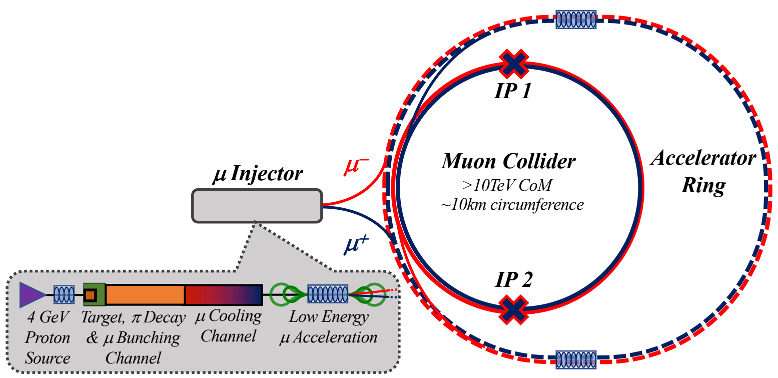
Challenges III: Markus' plot

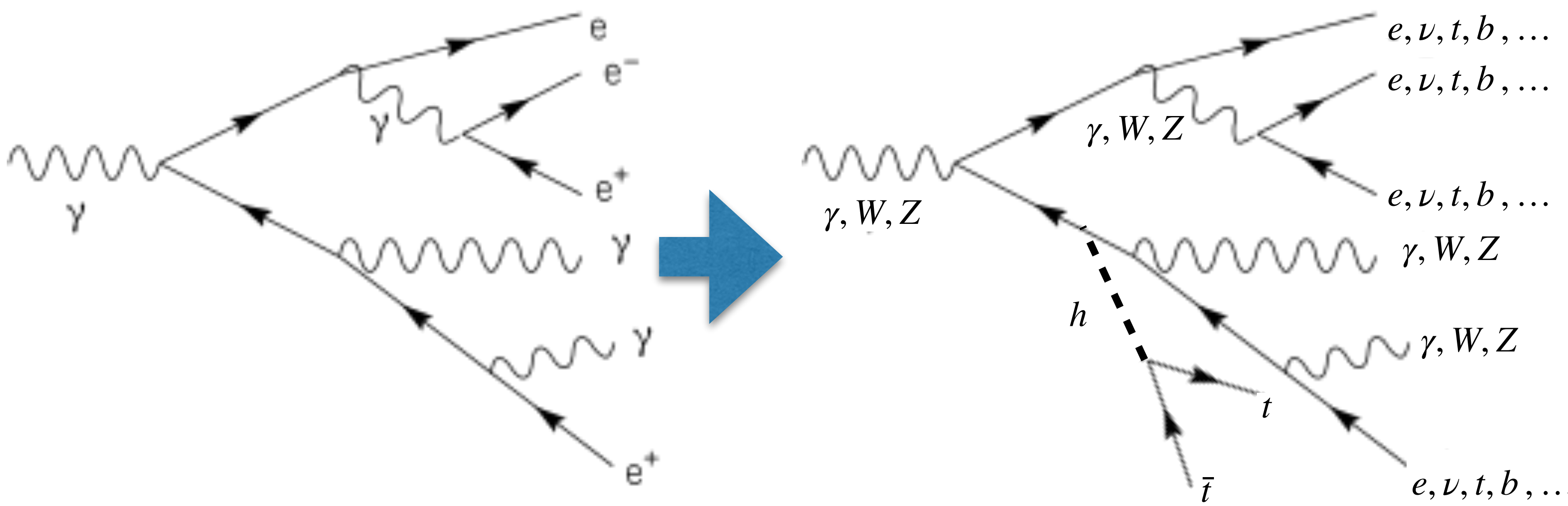


Challenges III: Markus' plot

$E \gg m_W$

For sure, we will see this:





EW Restoration?

- We can definitely observe and illustrate consequences of linearly-realised EW group. Corrections will be tiny power-like: $m_W/E \sim 10^{-2}$.
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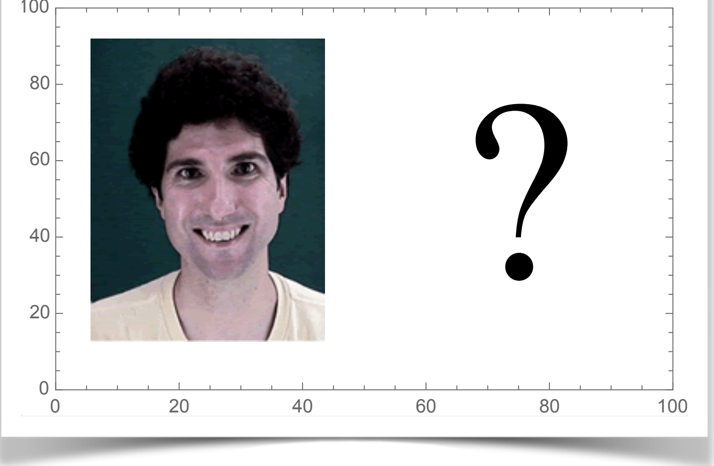

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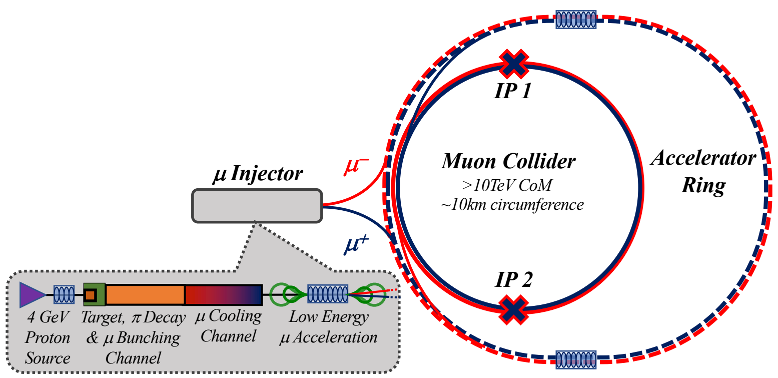

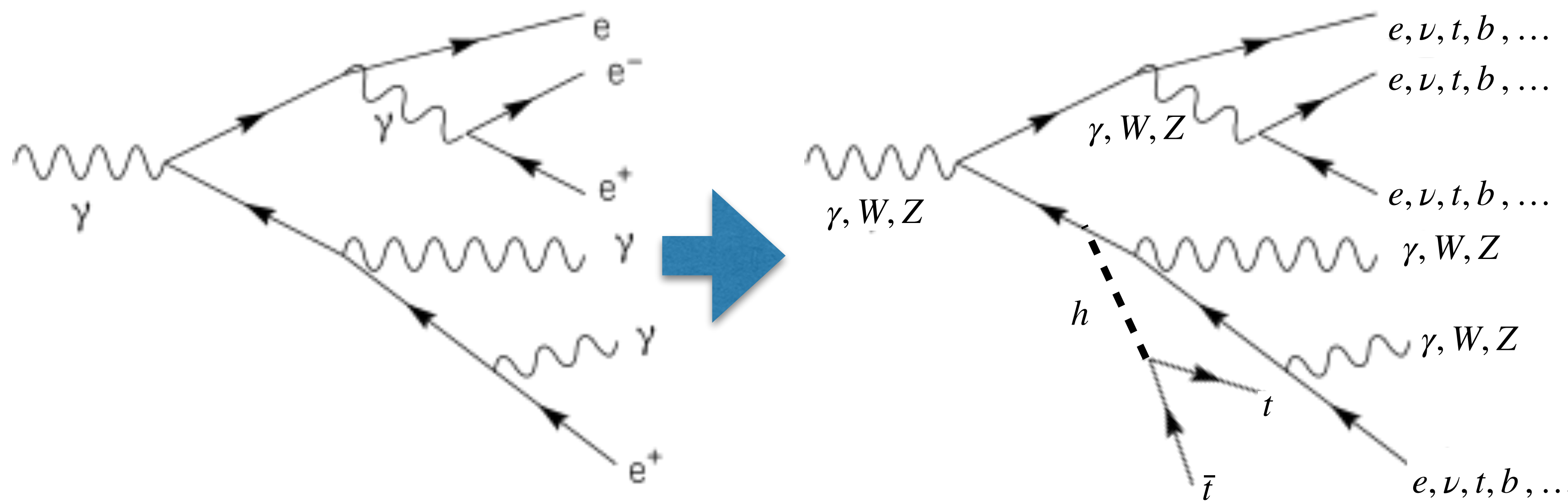

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EW Radiation

- Just count as much real radiation emitted? Check that $\nu\mu$ almost as large as $\mu\mu$?
- Sudakov is:

$$\exp\left[-g^2/16\pi^2 \log^2(E_{\rm cm}^2/m_{\rm w}^2)\times \text{Casimir}\right] \approx \exp[-1]$$

The 10 TeV MuC is right at the threshold for radiation being order one.

Conclusions

EW radiation challenges are in fact additional opportunities

- New theoretical understanding of QFT questions too long set aside
  - ➡ In fully calculable context with physical mass gap
  - ➡ Questions ultimately related with nature and "composition" of particles
- New **phenomena** provide guaranteed outcome
  - ➡ BSM-only narrative has always been partial and inadequate
  - ➡ Today, is proven **inadequate** as well
- Connects MuC with "calculation" community
  - ➡ EW radiation is "our QCD"
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Thank You !