The “lumergy” dilemma

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ROBERTO FRANCESCHINI (ROMA 3 UNIVERSITY)

ROMA TRE UNIVERSITÀ DEGLI STUDI

INFN Roma3

Colliders are for …

HIGH ENOUGH?

In particle physics colliders are generally used:

- study known particles and interactions (study of electrons and positron in QED)
- search new particles/establish new interactions (discovery of the Higgs boson, 2012)

Activity based on two main pillars:

- high-energy
- high-intensity

When is it high enough?

When is it high-enough?

HIGH ENERGY

Energy:

- look at LHC results
- look at the LHC results with a specific question in mind(!)

Luminosity:

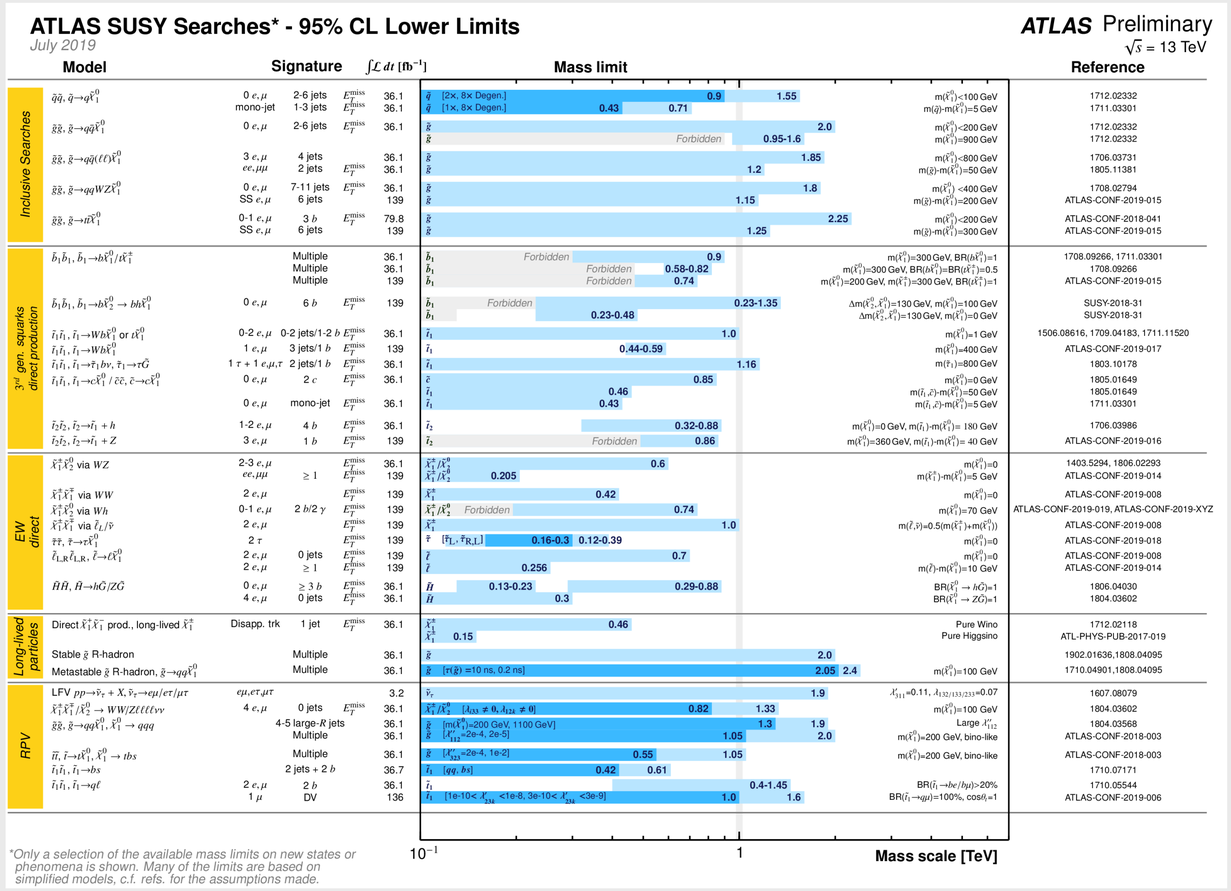
- a longer discussion

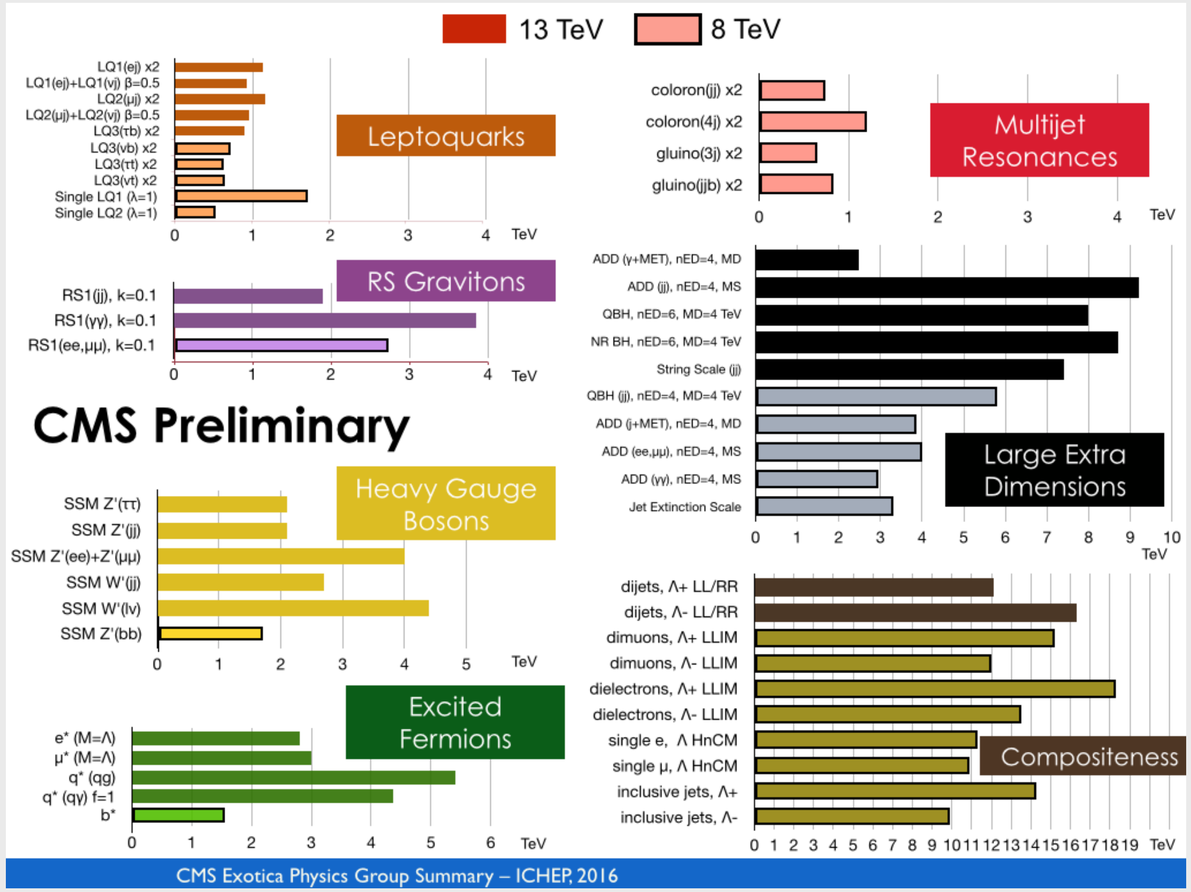
LHC ruled out new physics at N TeV…

LHC ruled out new physics at the TeV …

SUMMARY

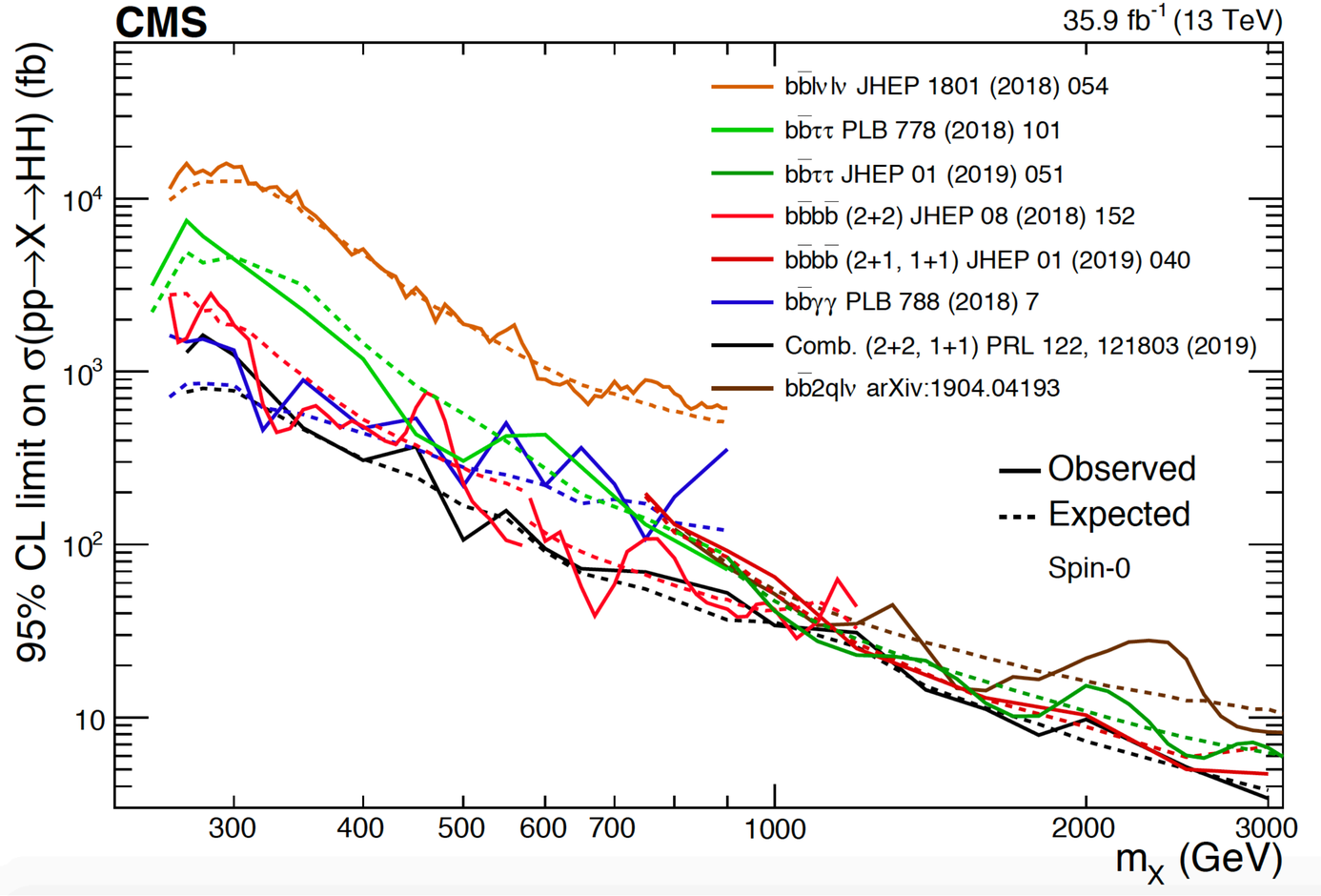
OF THE SUMMARIES





What about electroweak scalars?

SINGLETS ARE ELUSIVE



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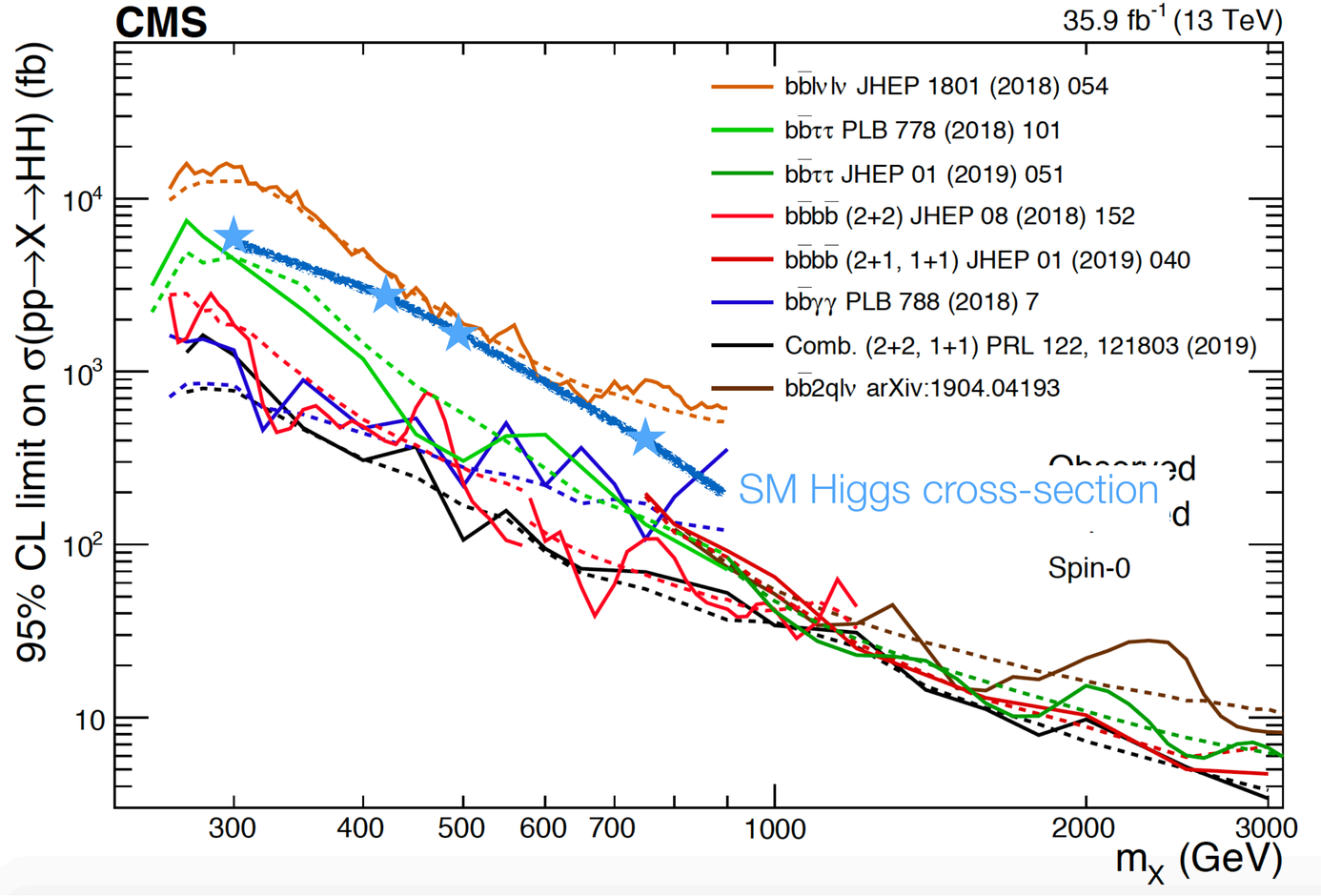

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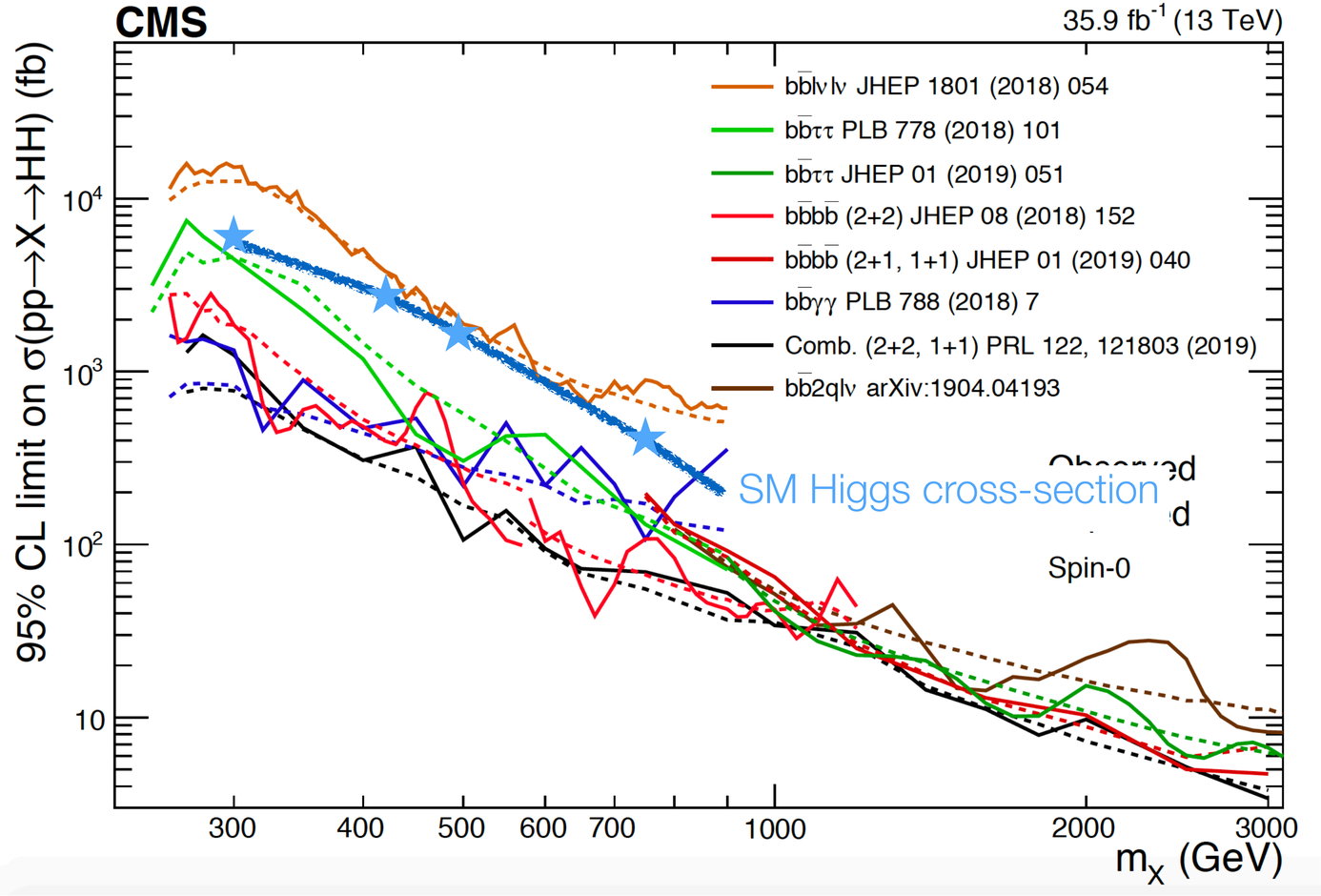
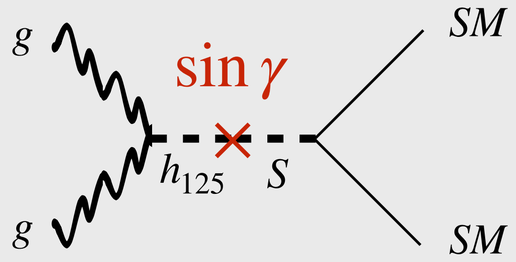


$$\sigma(\phi) \sim \sin^2\theta_{h\phi} \cdot \sigma(h_{SM} \text{ with } m_\phi)$$

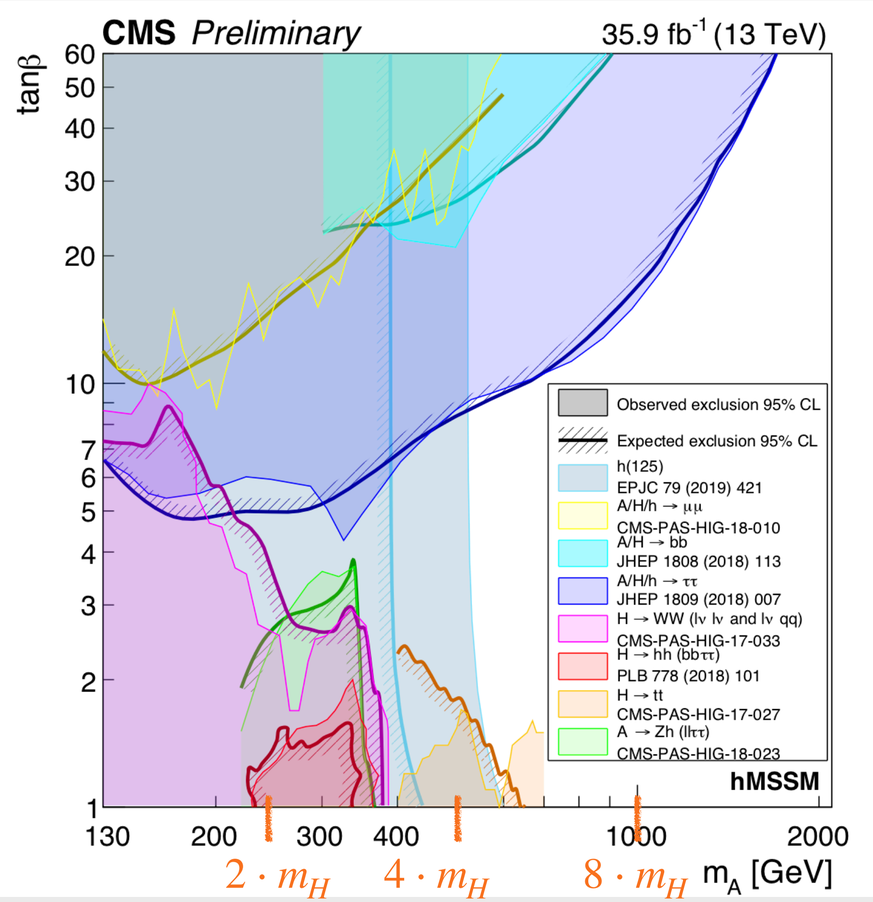


$$\Rightarrow \sin\theta \lesssim 0.3$$

$$\sin\theta \simeq \left(\frac{m_h}{m_H}\right)^{\alpha} \Rightarrow m_H \simeq 2 \div 3 \cdot m_h$$

What about electroweak scalars?

DOUBLETS ARE ABOUT AS TOUGH TO CATCH



There is in general a weak sensitivity to new scalars, because of:

- **“small” cross-sections**
- **large backgrounds**

it is hard to explore the scalar sector and the only big discovery of the LHC may be left unmatched … even if light scalars may exist.

lots of space for

Interesting New Physics sub-TeV

how much lumi?

Few “clear” luminosity targets

DISCOVERY OF NEW PHYSICS

- a “handful” of new physics events for a spectacular signature (e.g. $W^{\pm} \to \ell^{\pm}\nu$)
- hundreds of events (somewhat clear signature, but needs background rejection)
- 10^N events for a signature buried in background (e.g. $h \to b\bar{b}$ at hadron colliders)

Few "clear" luminosity targets

MEASUREMENT OF KNOWN PHYSICS

- W, Z bosons known at 10^{-3} level (LEP&SLC)
- h boson known at $10^{-1} \rightarrow 10^{-2}$ by the end of HL-LHC
- t quark known at $10^{-2} \rightarrow 10^{-3}$ by the end of HL-LHC*

Few "clear" luminosity targets

MEASUREMENT OF KNOWN PHYSICS

$$\frac{\delta O}{O} \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{\sigma \cdot \mathscr{L}}}$$

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- t quark known at $10^{-2} \rightarrow 10^{-3}$ by the end of HL-LHC*

- $O(10^6)$ Z bosons
- $O(10^3)$ "usable" h bosons
- $O(10^6)$ usable t quarks

High-lumi vs. High-energy

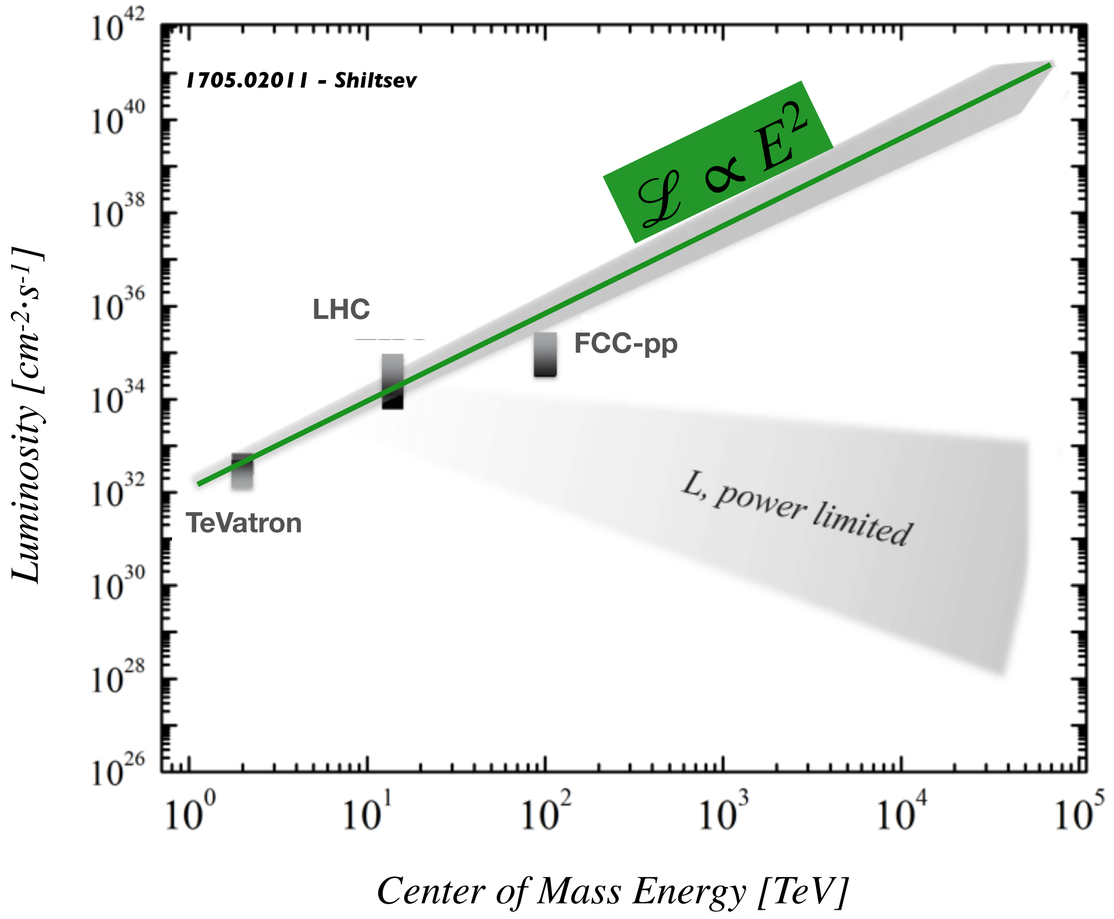
LUMI-ENERGY | TENSION

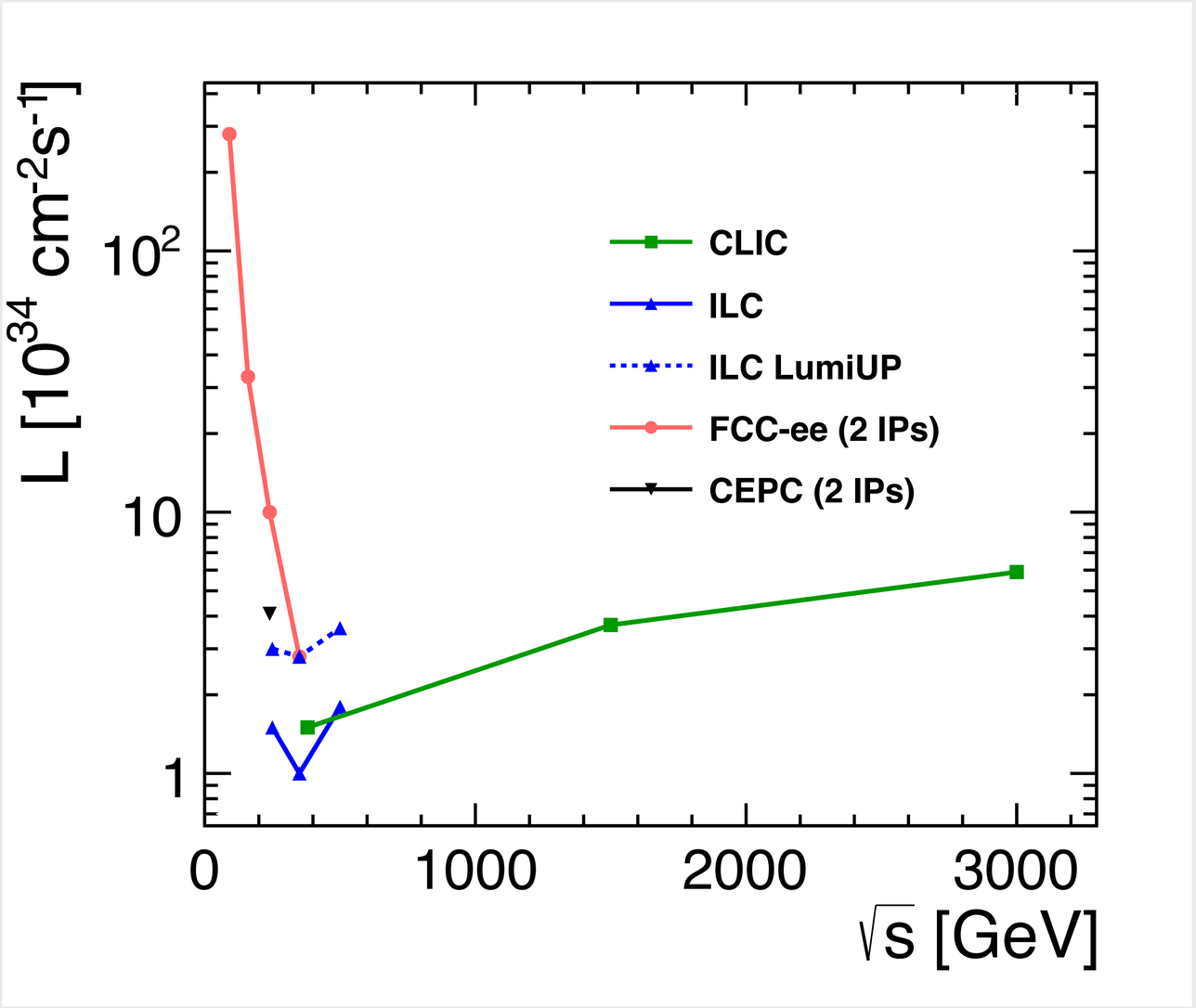
$$\sigma(ab \to cd) \propto \underbrace{\frac{1}{\Phi_{ab}}}_{\text{flux}} \cdot \overbrace{P_{ab\to cd}}^{\text{probability}} \quad \Rightarrow \quad \sigma(ab \to cd) \propto \frac{1}{E_a E_b} \cdot \#$$

Careful balance between Energy and Lumi

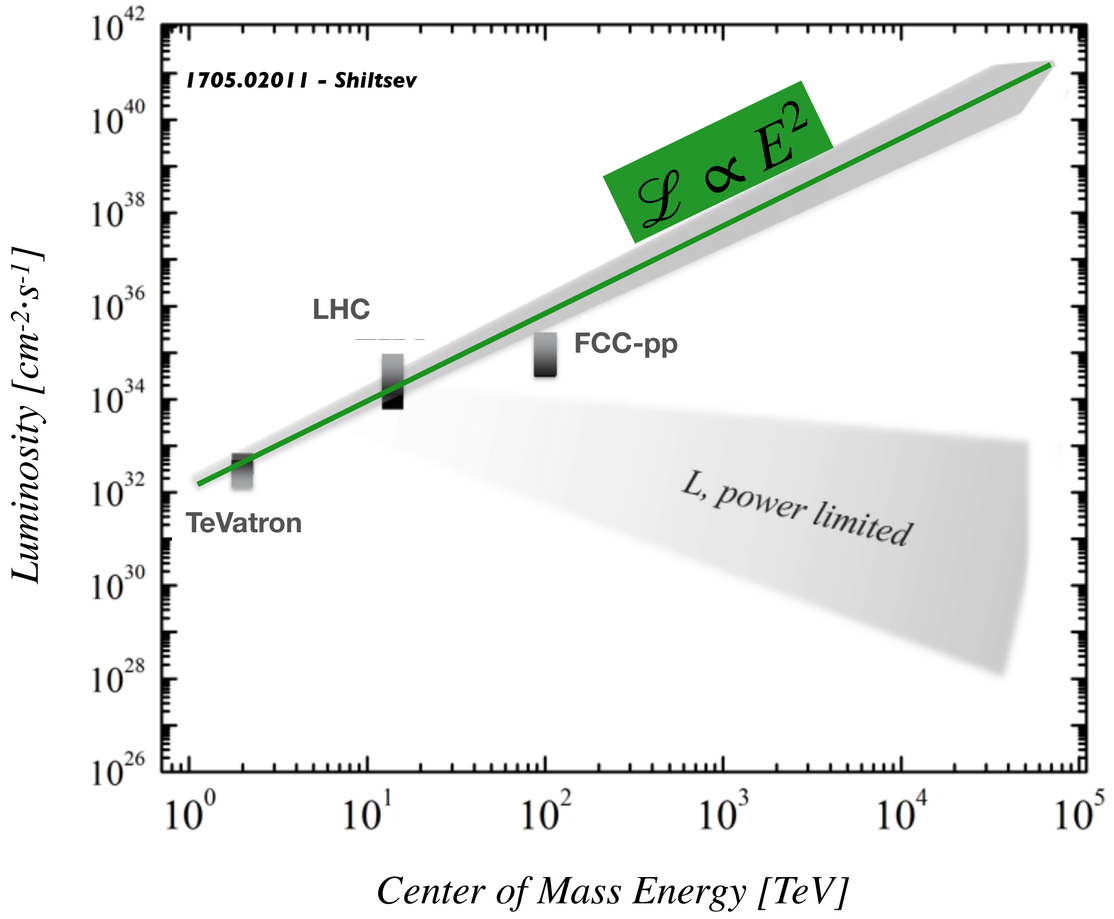
Some

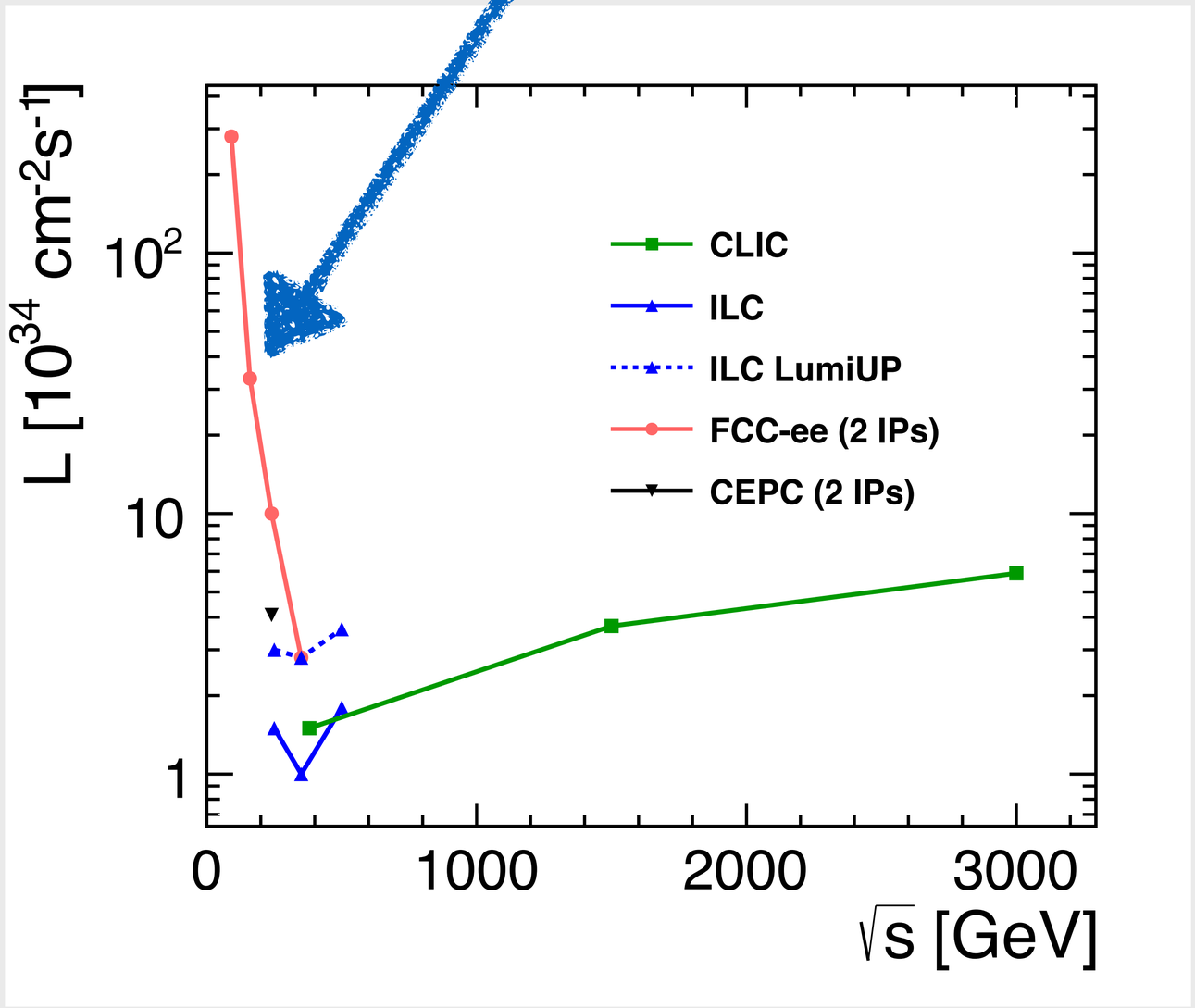
Concrete Examples


1705.02011 - Shiltsev
$\mathcal{L} \propto E^2$
LHC
FCC-pp
TeVatron
L, power limited
Luminosity [cm-2·s-1]
Center of Mass Energy [TeV]

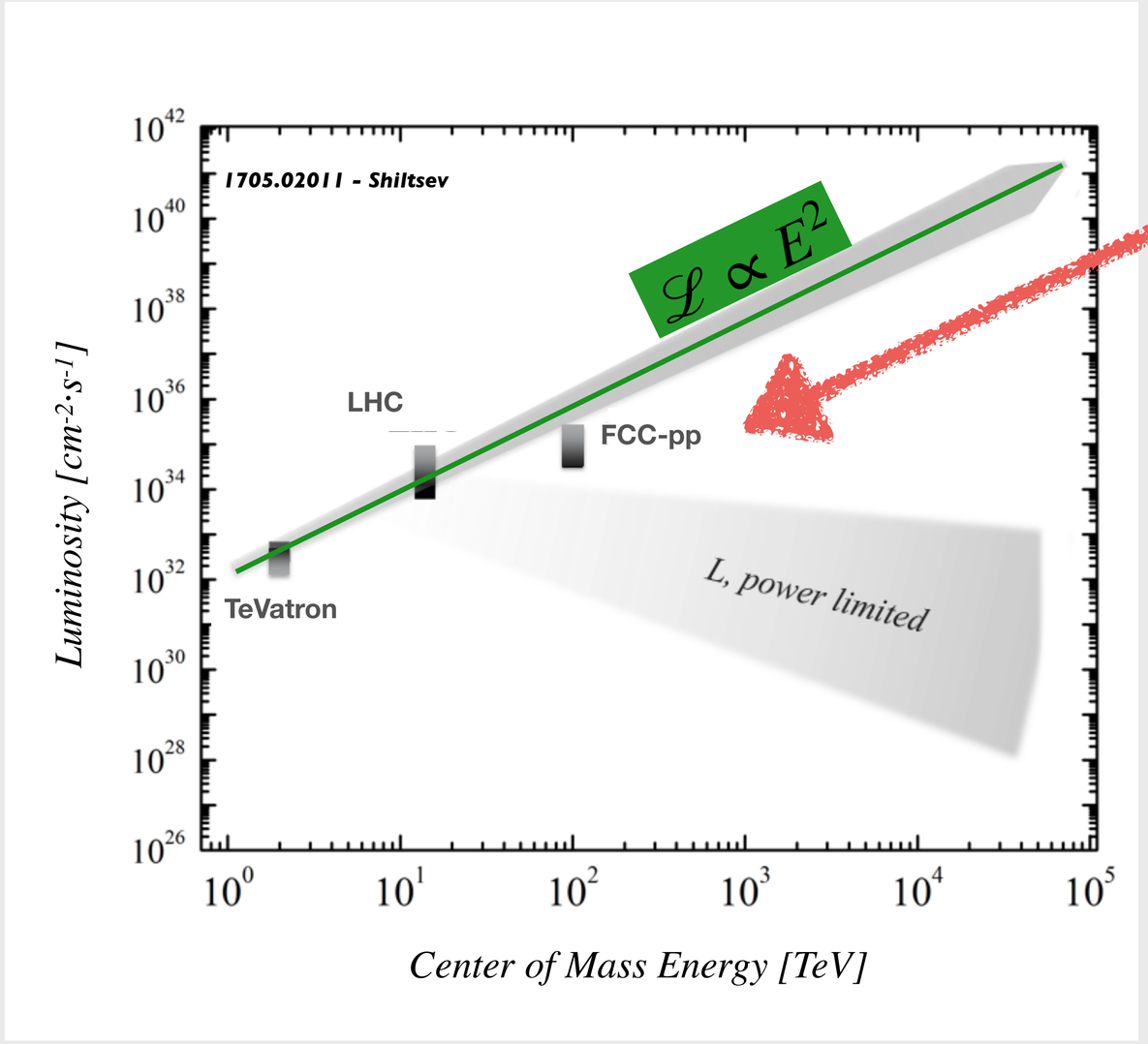

CLIC
ILC
ILC LumiUP
FCC-ee (2 IPs)
CEPC (2 IPs)
L [10^34 cm^-2 s^-1]
√s [GeV]

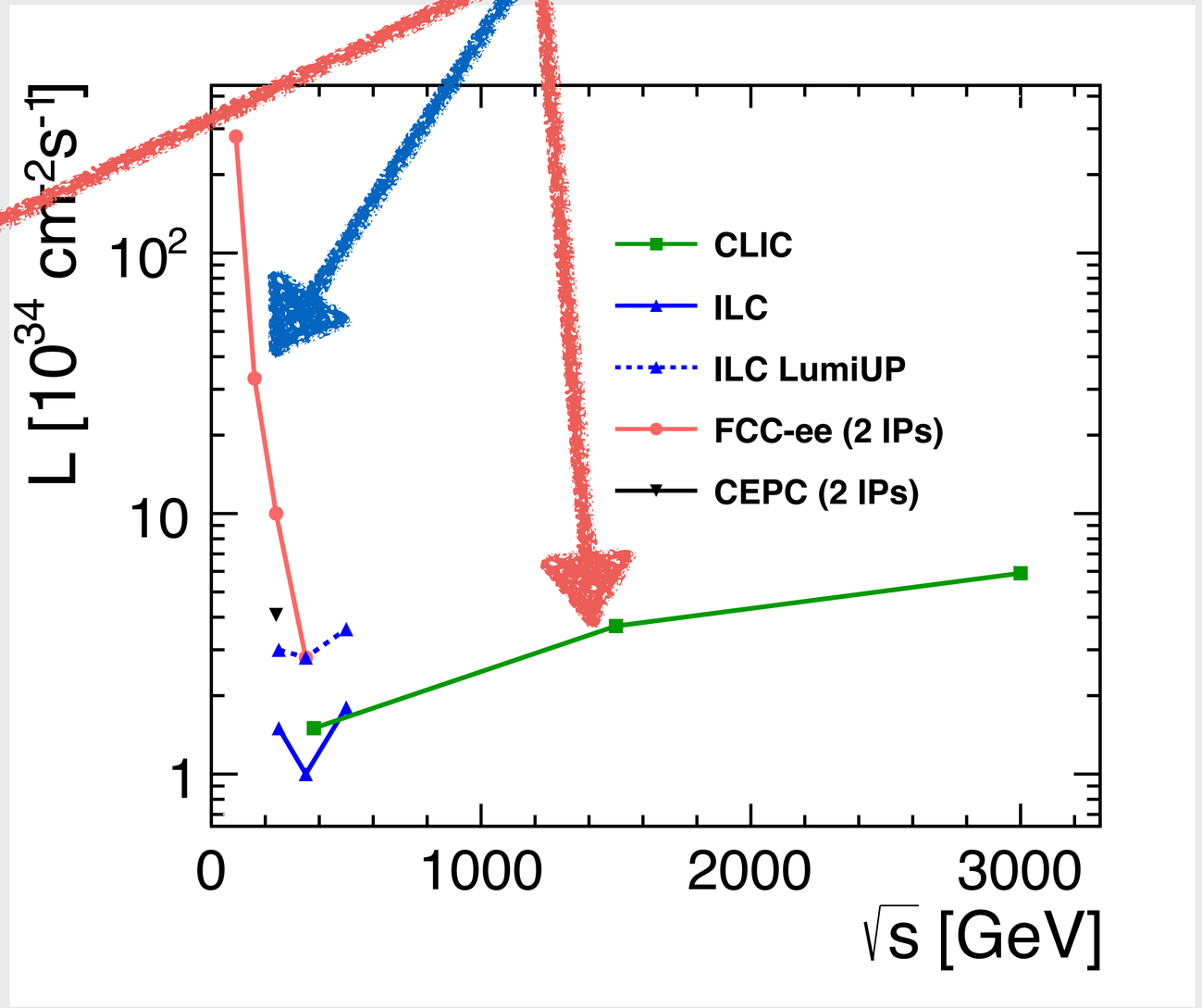
Luminosity falls too fast

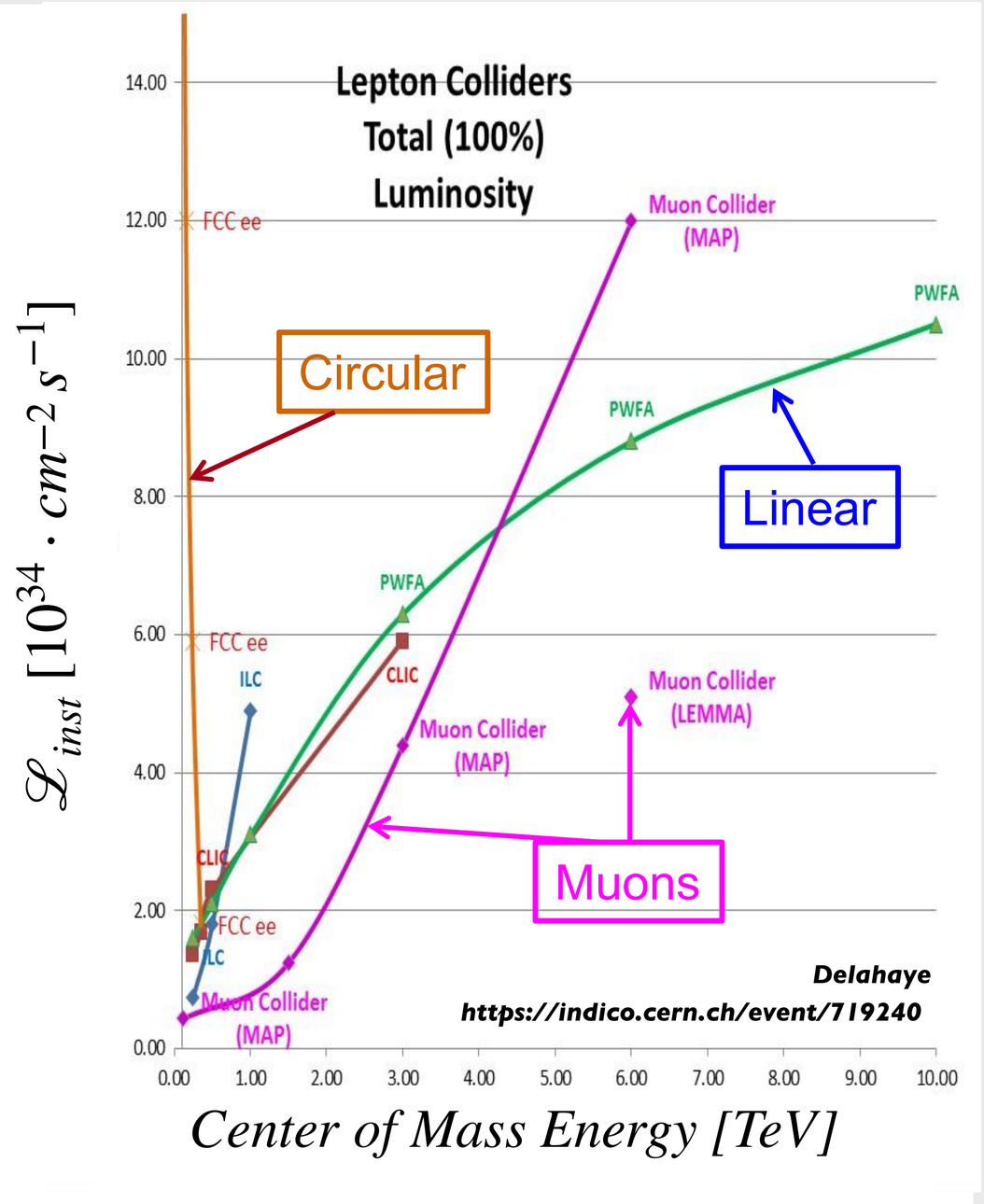




Luminosity is not growing fast enough







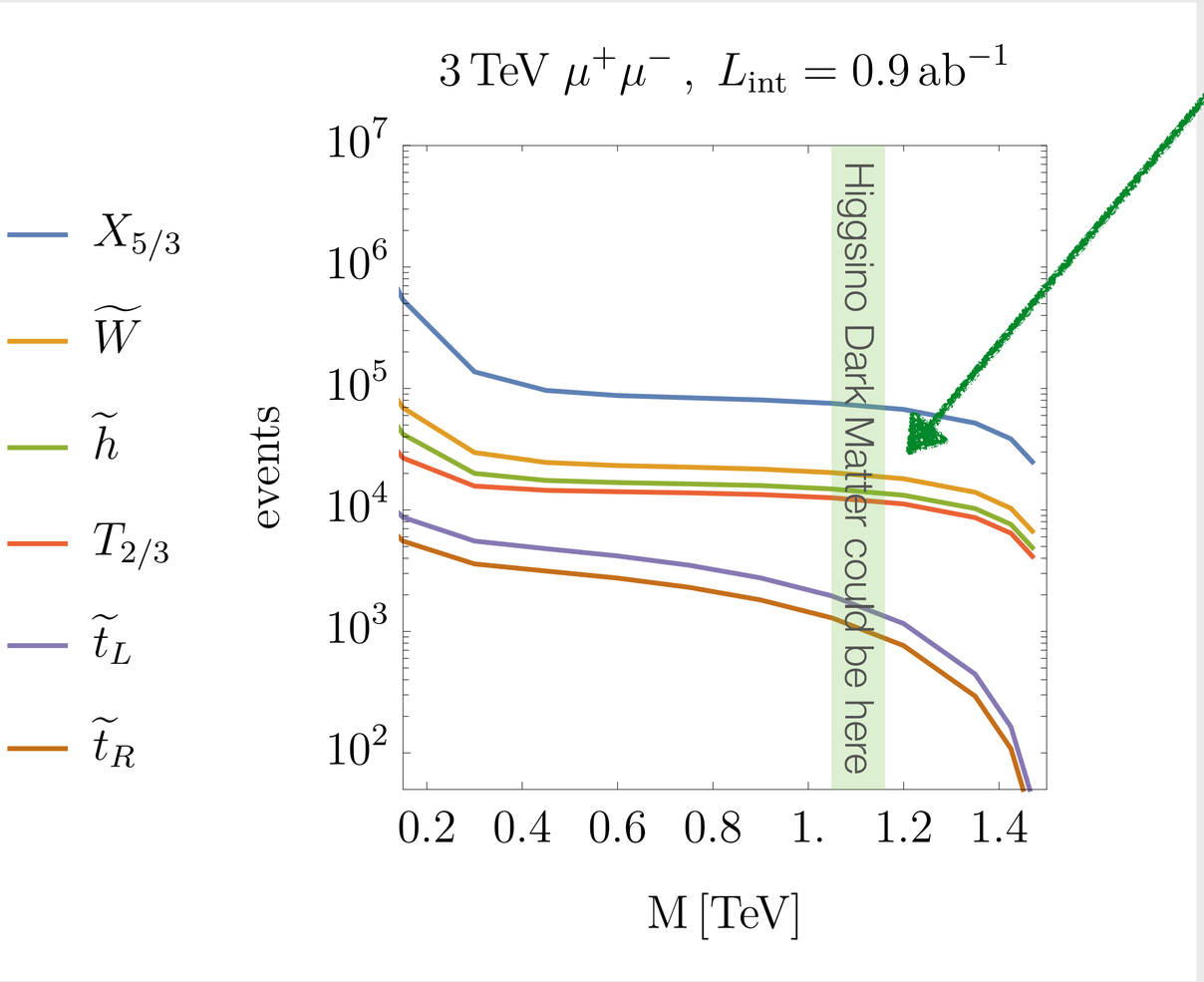
- No well-established technology in sight to reach high energy and keep large enough luminosity
- Lots of R&D on beams and accelerators is needed to enable a flourishing future for high energy physics

Some

Concrete Examples

$\ell^+\ell^- \to$ new physics

VALENCE COLLISIONS



10^4 events for $\mathscr{L} \simeq ab^{-1}$

barely sufficient for exclusion at 95% CL

BEST POSITION TO OBSERVE ANY SIGN OF ELECTROWEAK NEW PHYSICS

(e.g. in the Higgs sector, or from new strong interactions at the TeV, fermions mass and mixing generation at the TeV)

Any sign of SUSY below the TeV will be observable, no matter if the sparticles are colored or not.

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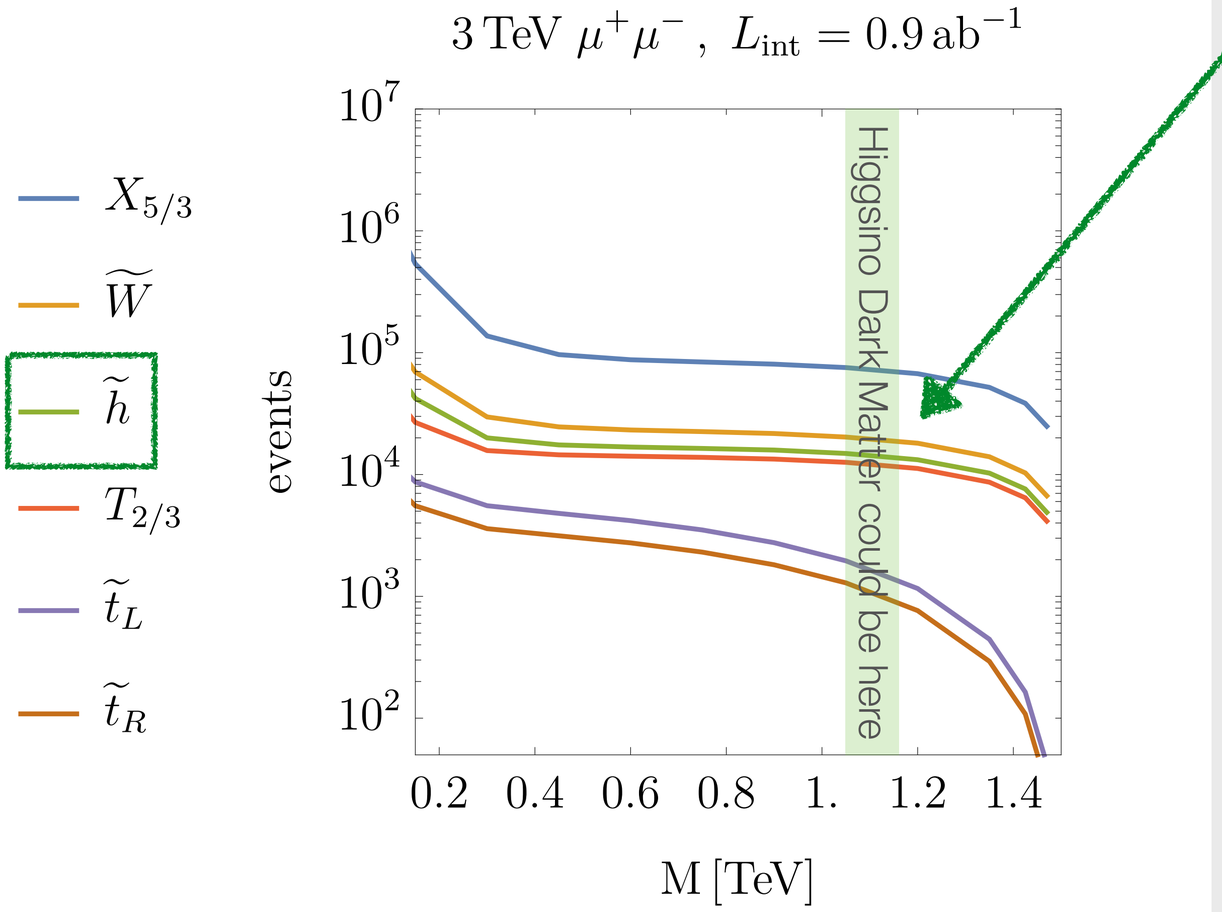

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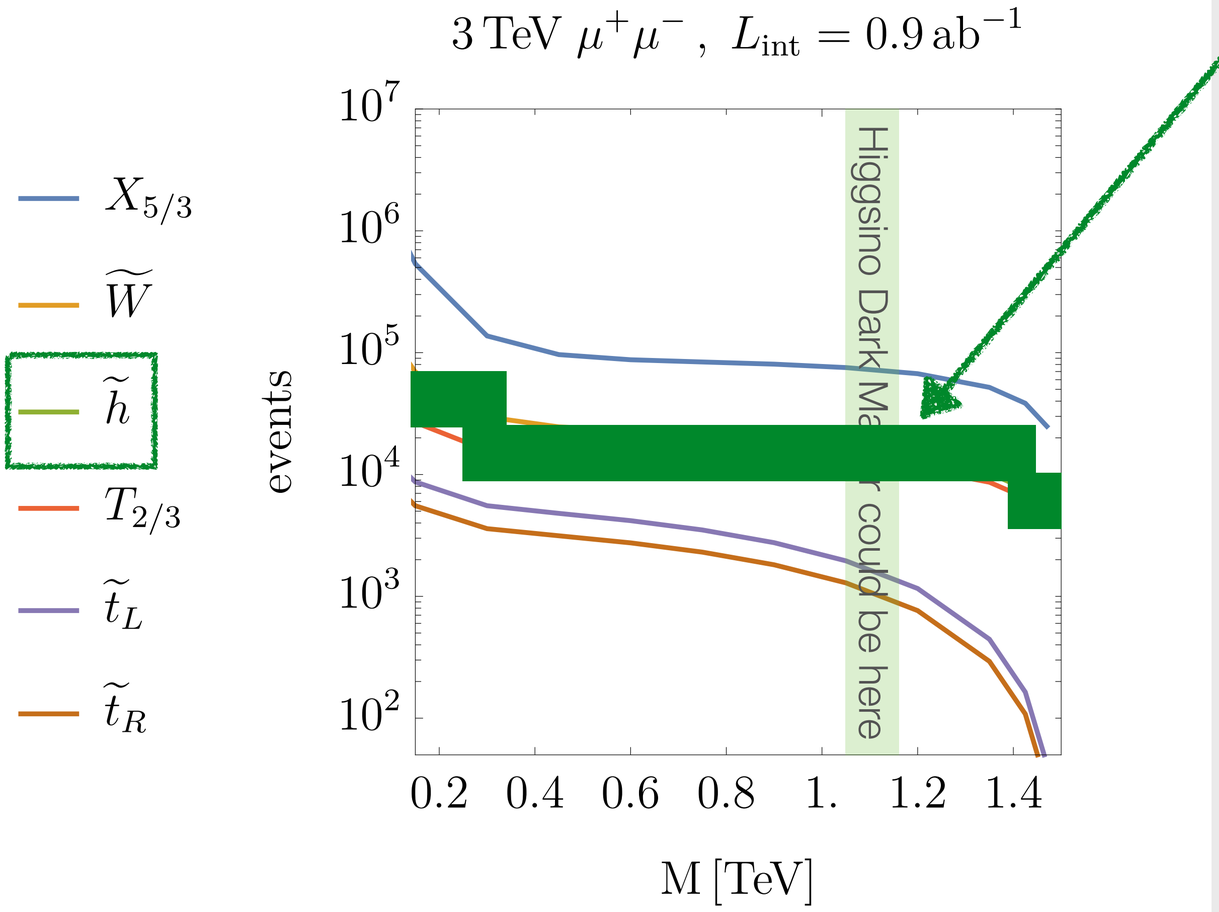

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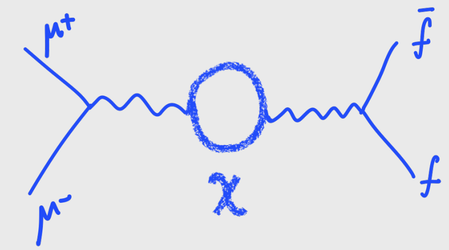
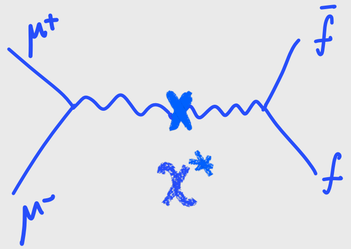
$\ell^+\ell^- \to f\bar{f}, W^+W^-, Zh$

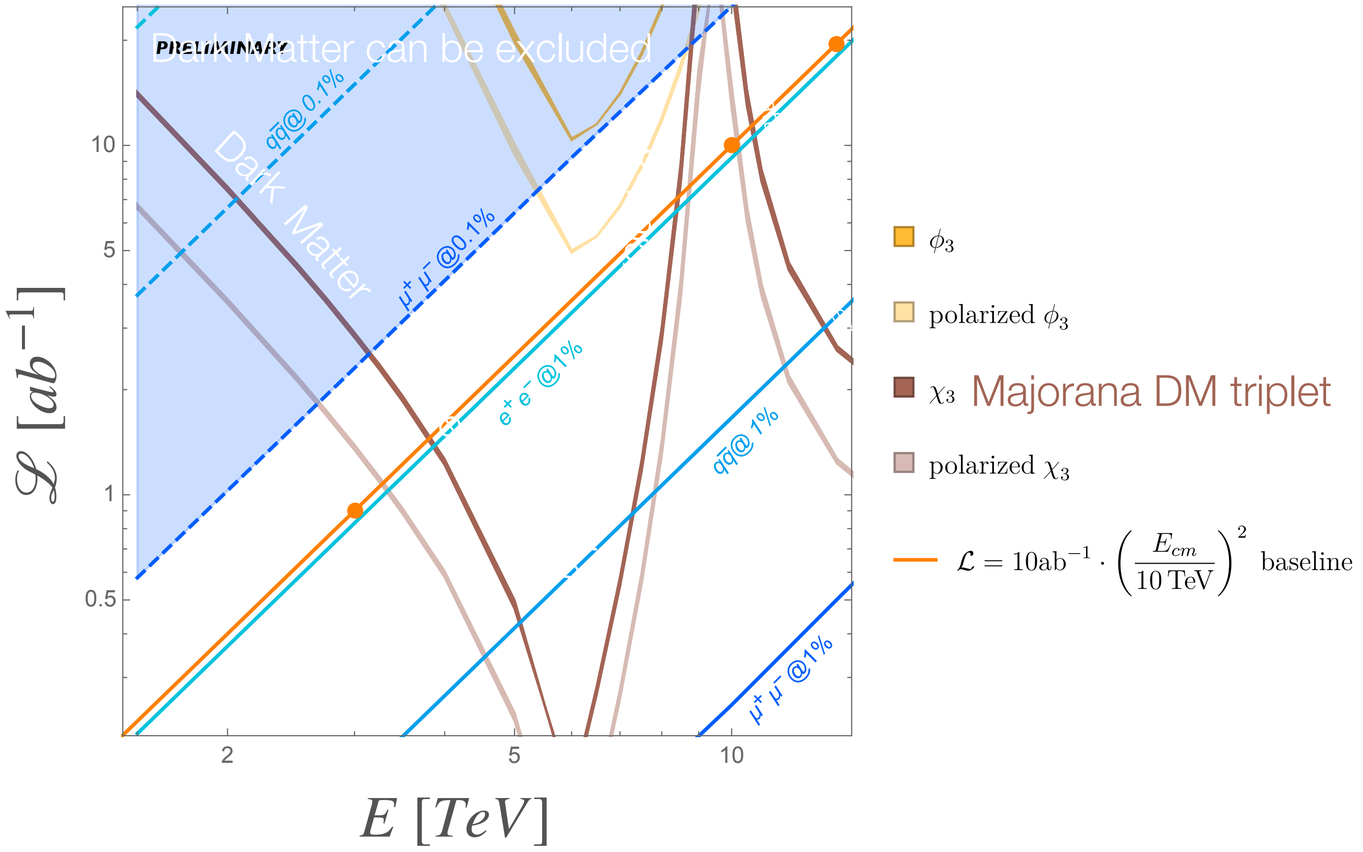
PRECISION | TOTAL CROSS-SECTION



χ is heavy/light new physics



- fiducial cross-sections are significantly affected by off-shell new physics heavier than the collider kinematic reach



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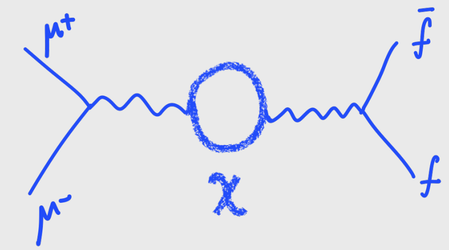

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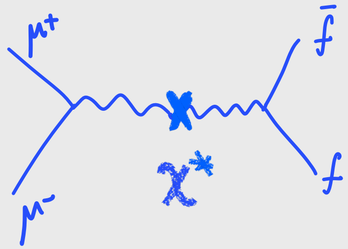

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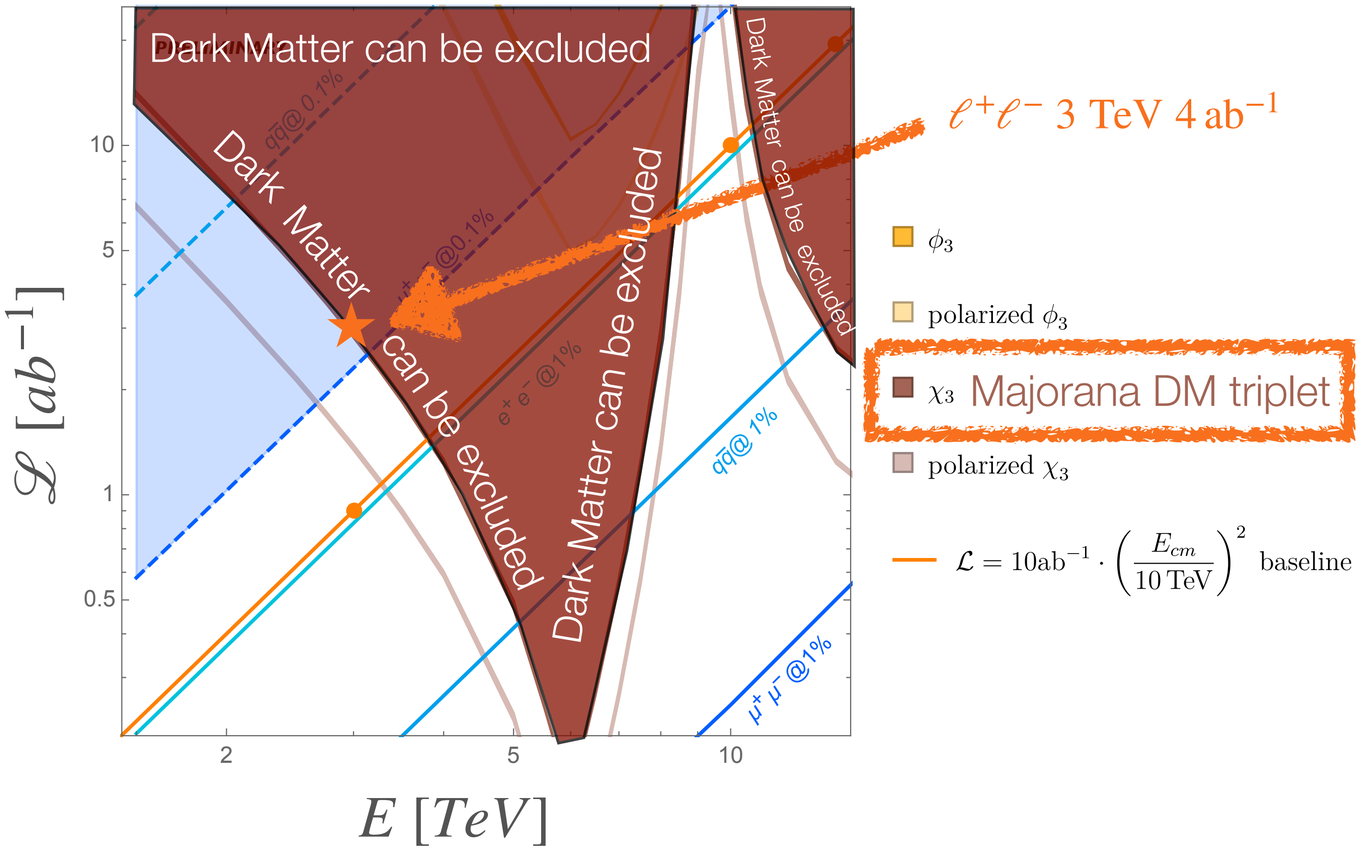
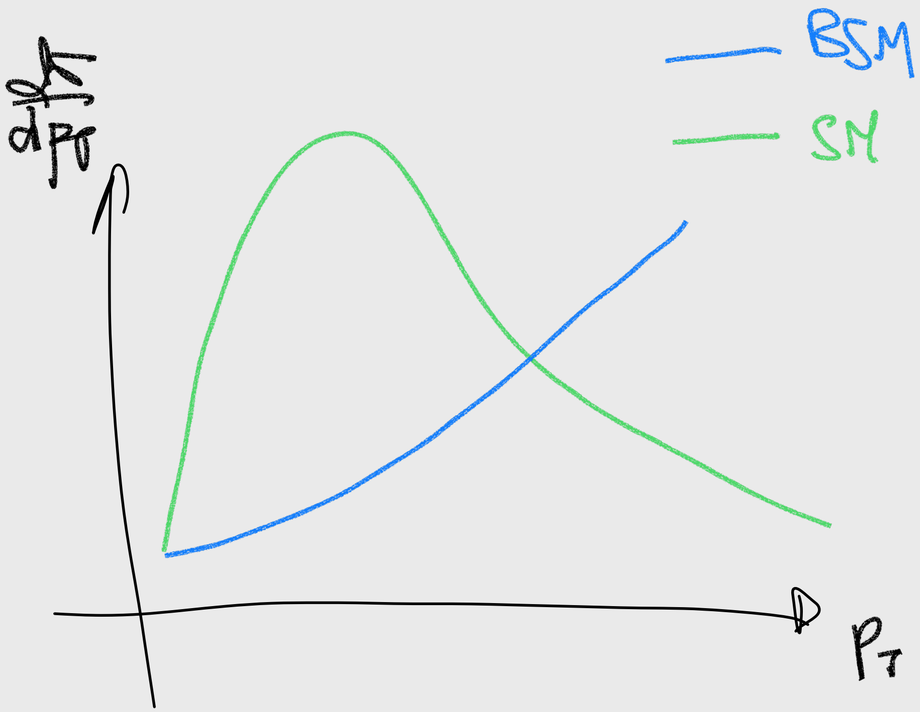


SM works wonderfully!

New Physics may fit well in a EFT (new contact interactions)

- effects grow at larger energies like $\nu e^- \to \nu e^-$ in Fermi Theory



$$\frac{d\sigma}{dp_T}$$

measurements sensitive to a range of mass scales

- sensitive to a range of energy scales
- progress is easy to measure: bounds on new Fermi constants

as NP effects may grow quadratically with energy

$$\Delta O = O_{NP} - O_{SM} \sim \left(\frac{E}{v}\right)^2$$

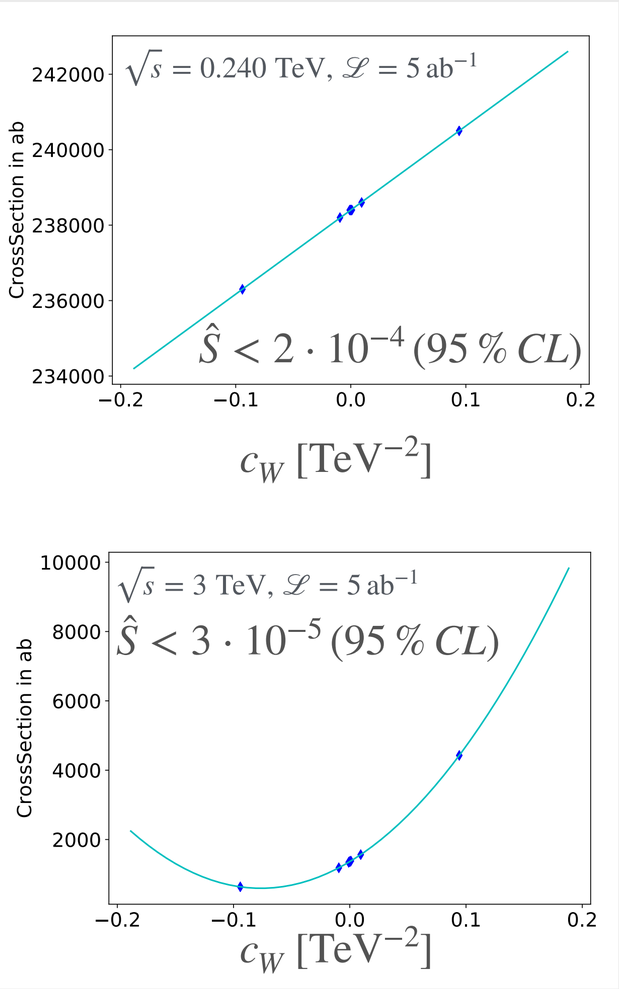
1% at m_Z is worse than 10% at 1 TeV

$\ell^+\ell^- \to Zh$

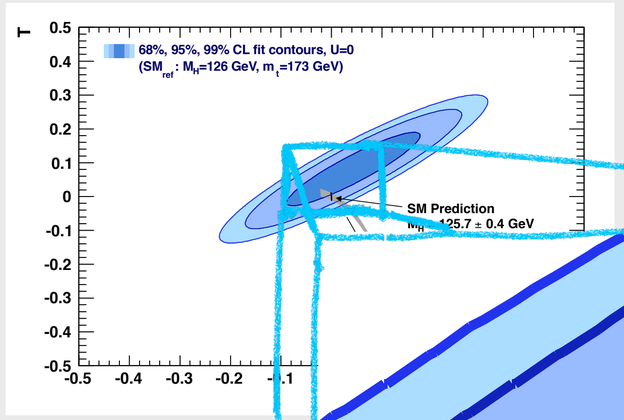
TOTAL RATE

$$\sigma_{Zh} = \left| A^{(00)}_{SM} \right|^2 + A^{00}_{SM} \cdot A^{00}_{BSM} + \dots$$

$c_W = \hat{S}/m_W^2$



LEP



current

10x

10x

$\ell^+\ell^-$ 3 TeV

$$\hat{S}_{95\%} \lesssim \frac{1.2 \cdot 10^{-4}}{E_{beam}/\text{TeV} \cdot \sqrt{\mathscr{L}/\text{ab}^{-1}}}$$

$\ell^+\ell^- \to Zh$

Ever higher energy colliders can exploit "precise" measurements at the 10% level

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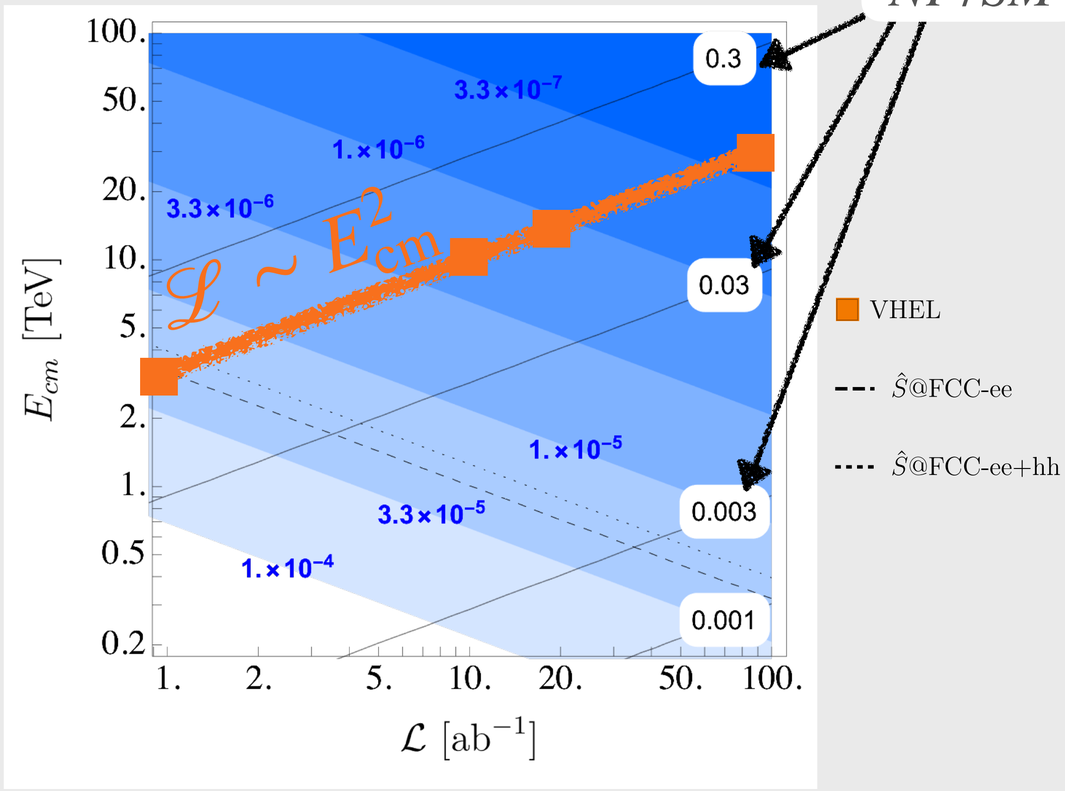

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$$c_W = \hat{S}/m_W^2$$

$$c_W \lesssim 0.02\,\text{TeV}^{-2} \frac{1}{E_{beam}/\text{TeV}} \cdot \frac{1}{\sqrt{\mathscr{L}/\text{ab}^{-1}}}$$

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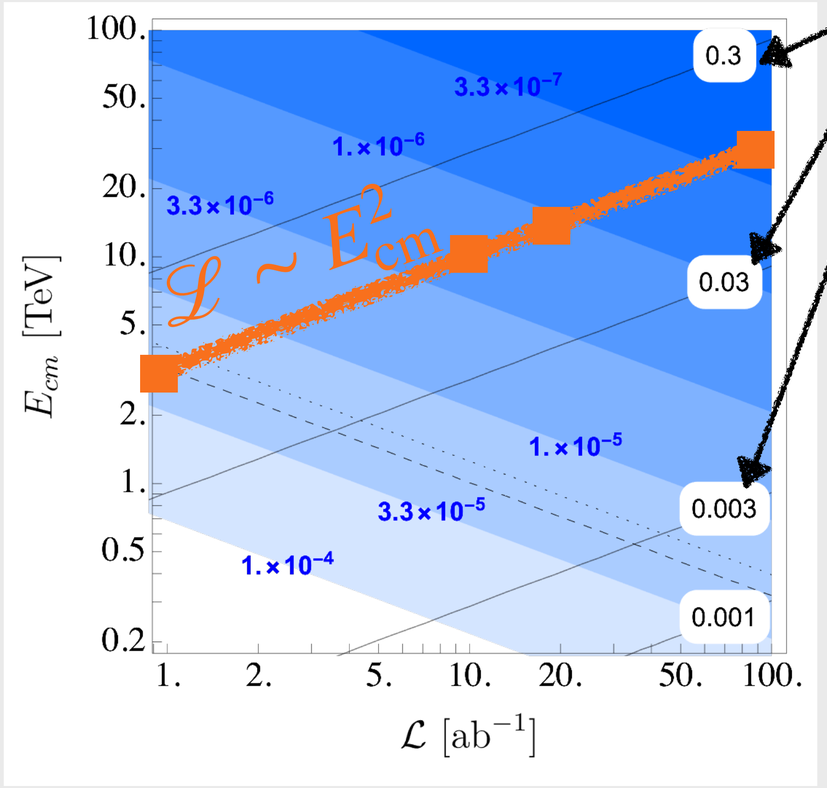

NP/SM

VHEL

$\hat{S}$@FCC-ee

$\hat{S}$@FCC-ee+hh

$\hat{S} < 3 \cdot 10^{-5}\,(95\,\%\,CL)$ ← $\mathscr{L} = 5\,\text{ab}^{-1}$

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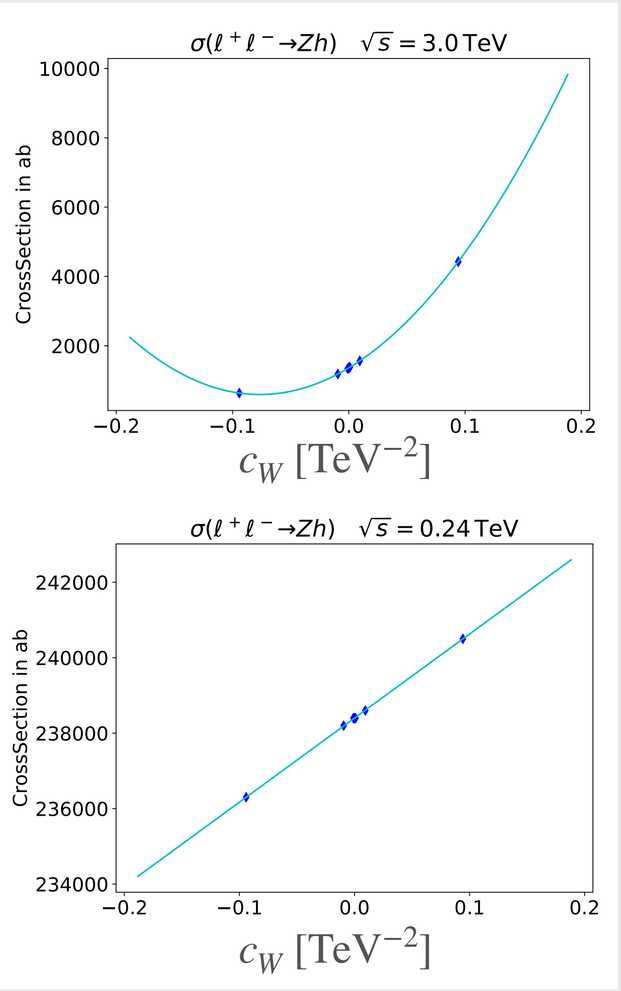

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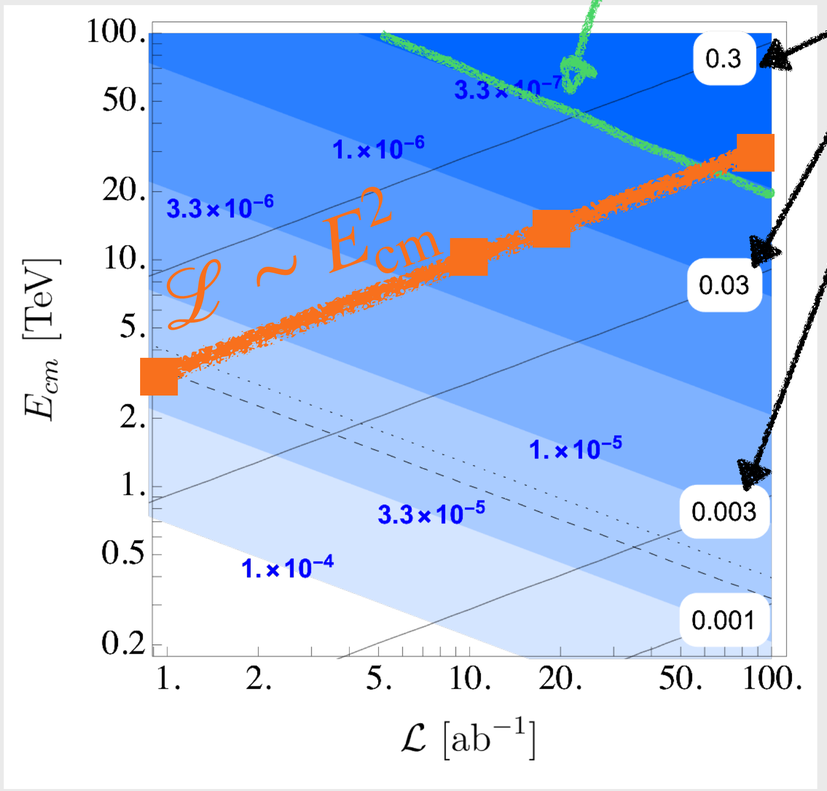
$\hat{S} \sim 10^{-7}$



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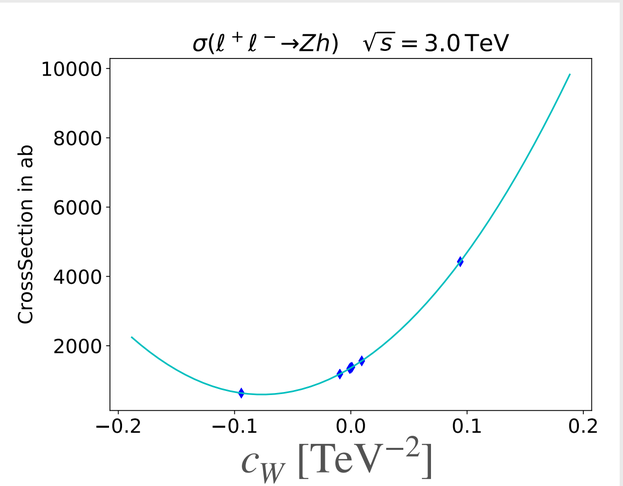

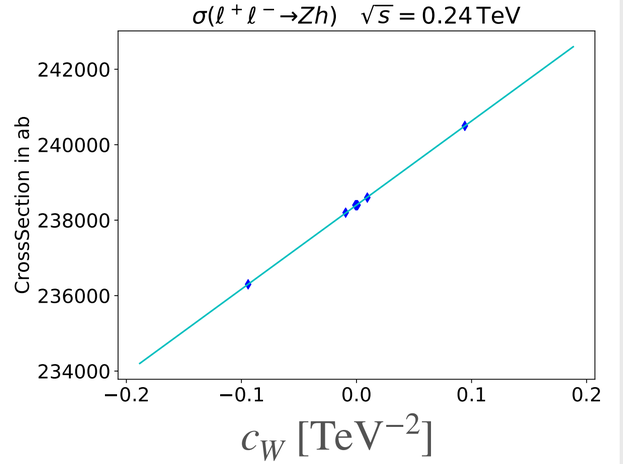

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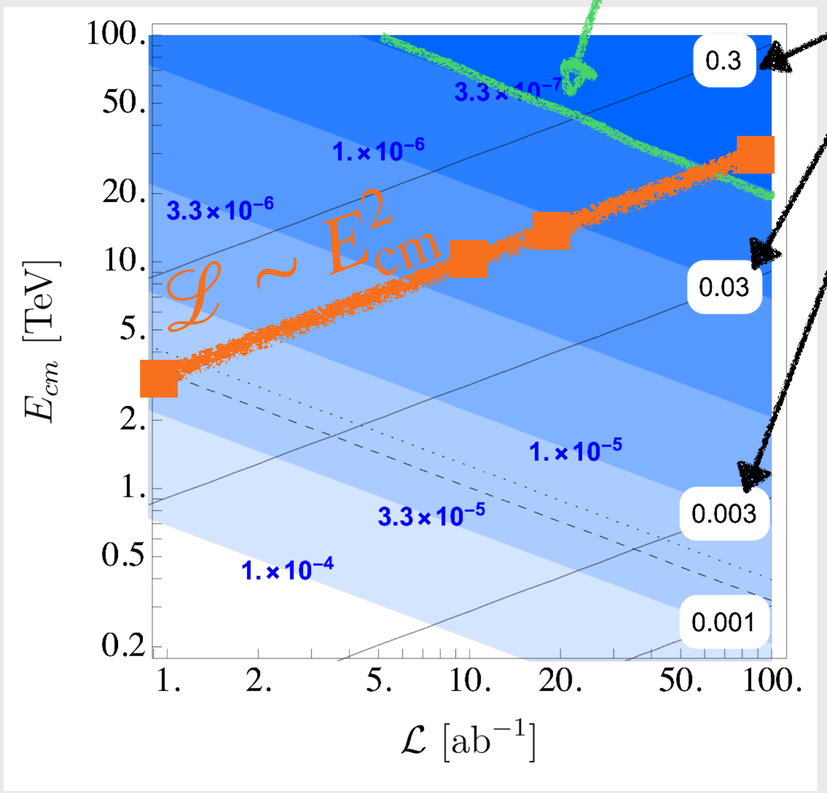
minus 7

$$\hat{S}_{95\%} \lesssim 1.2 \cdot 10^{-4} \frac{1}{E_{beam}/\text{TeV}} \cdot \frac{\hat{S} \sim 10^{-7}}{\sqrt{\mathscr{L}/\text{ab}^{-1}}}$$

NP/SM



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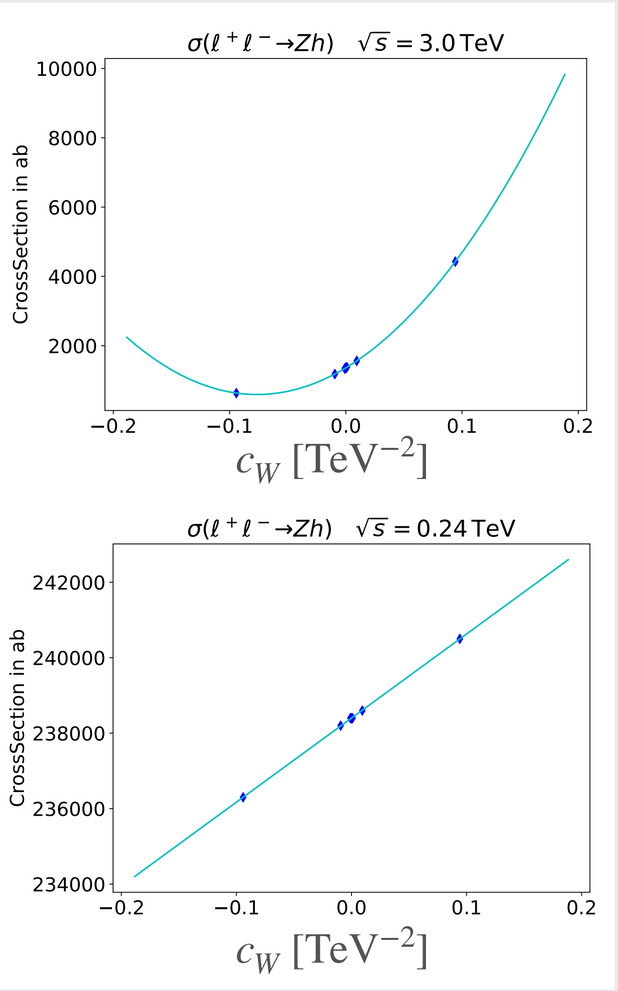

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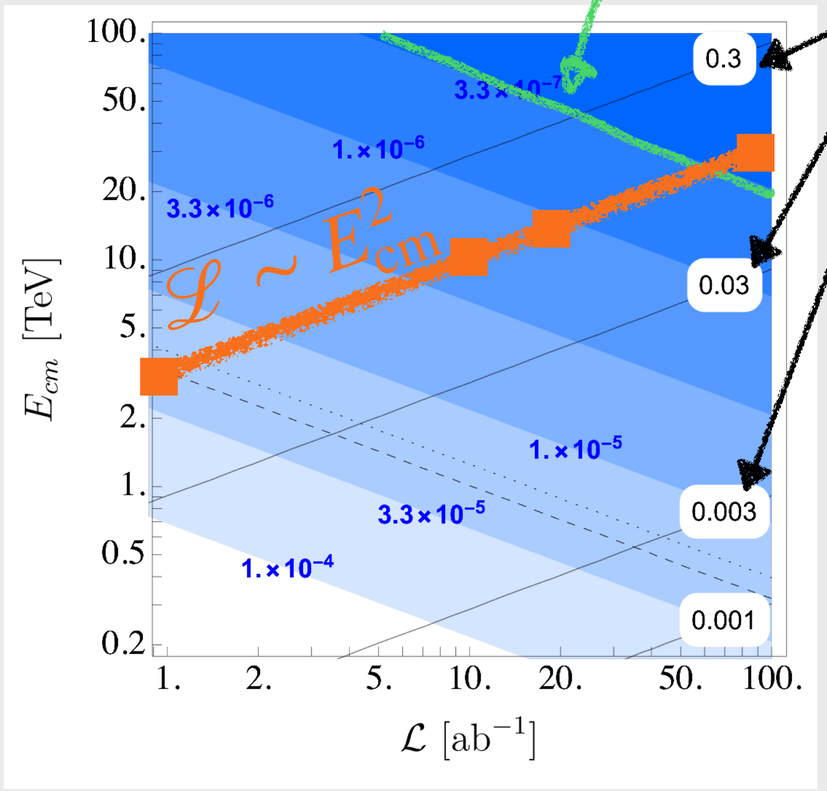
$\hat{S} \sim 10^{-7}$ minus 7



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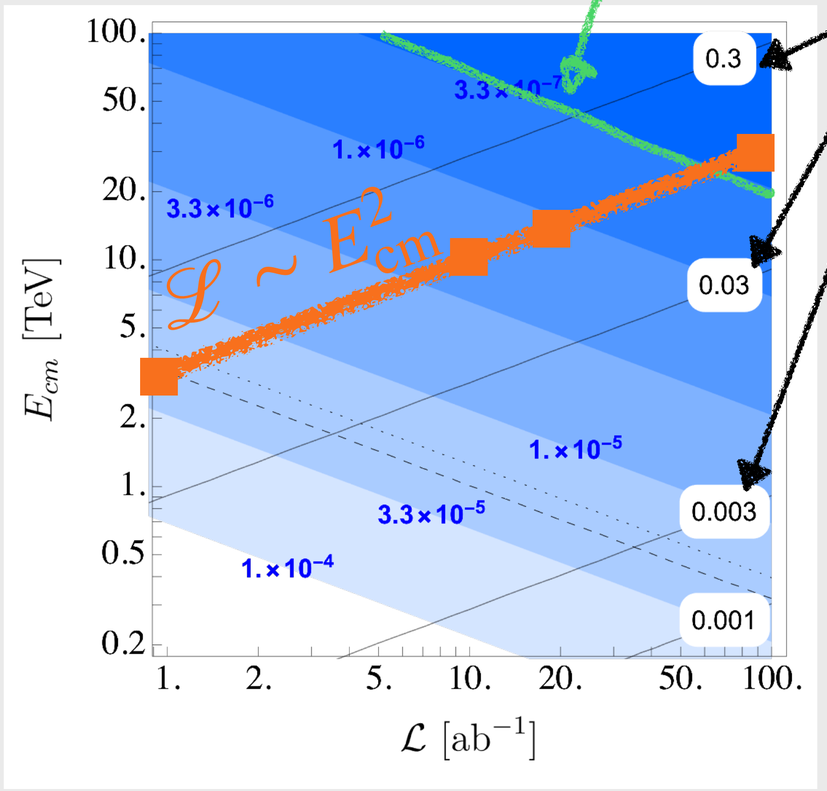

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GOING TO HIGHER ENERGY WE CAN EXPLOIT "PRECISE" MEASUREMENTS AT THE 10% LEVEL, AVOIDING THE BOTTLENECK OF SYSTEMATIC UNCERTAINTIES

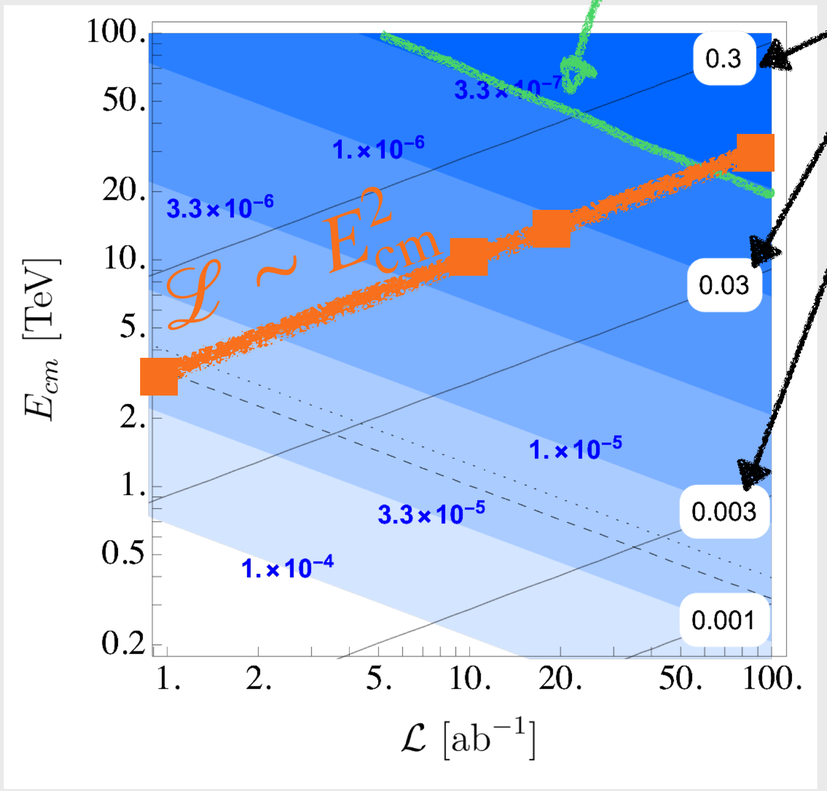
$\ell^+\ell^- \to Zh$

Ever higher energy colliders can exploit "precise" measurements at the 10% level

TOTAL RATE $\left|A^{(00)}_{SM}\right|^2 + A^{00}_{SM} \cdot A^{00}_{BSM} + \dots$

$$\hat{S}_{95\%} \lesssim 1.2 \cdot 10^{-4} \frac{1}{E_{beam}/\text{TeV}} \cdot \frac{1}{\sqrt{\mathscr{L}/\text{ab}^{-1}}}$$

$\hat{S} \sim 10^{-7}$ minus 7



NP/SM

$$\hat{S} \equiv c_W/m_W^2 \simeq \frac{\delta O}{O} \text{ at Z pole}$$

GOING TO HIGHER ENERGY WE CAN EXPLOIT "PRECISE" MEASUREMENTS AT THE 10% LEVEL, AVOIDING THE BOTTLENECK OF SYSTEMATIC UNCERTAINTIES

LUMINOSITY MUST SCALE WITH E^2

Conclusions

- Lots of targets for SM studies and New Physics searches are sub-TeV (high-energy, yes, but not out of reach!)
- The higher the energy, the more the achievable luminosity will matter!
- Lots of R&D on beams and accelerators is needed to enable a flourishing future for high energy physics
- Time from here to next update of European Strategy for Particle Physics is crucial to set the future path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Thank you!