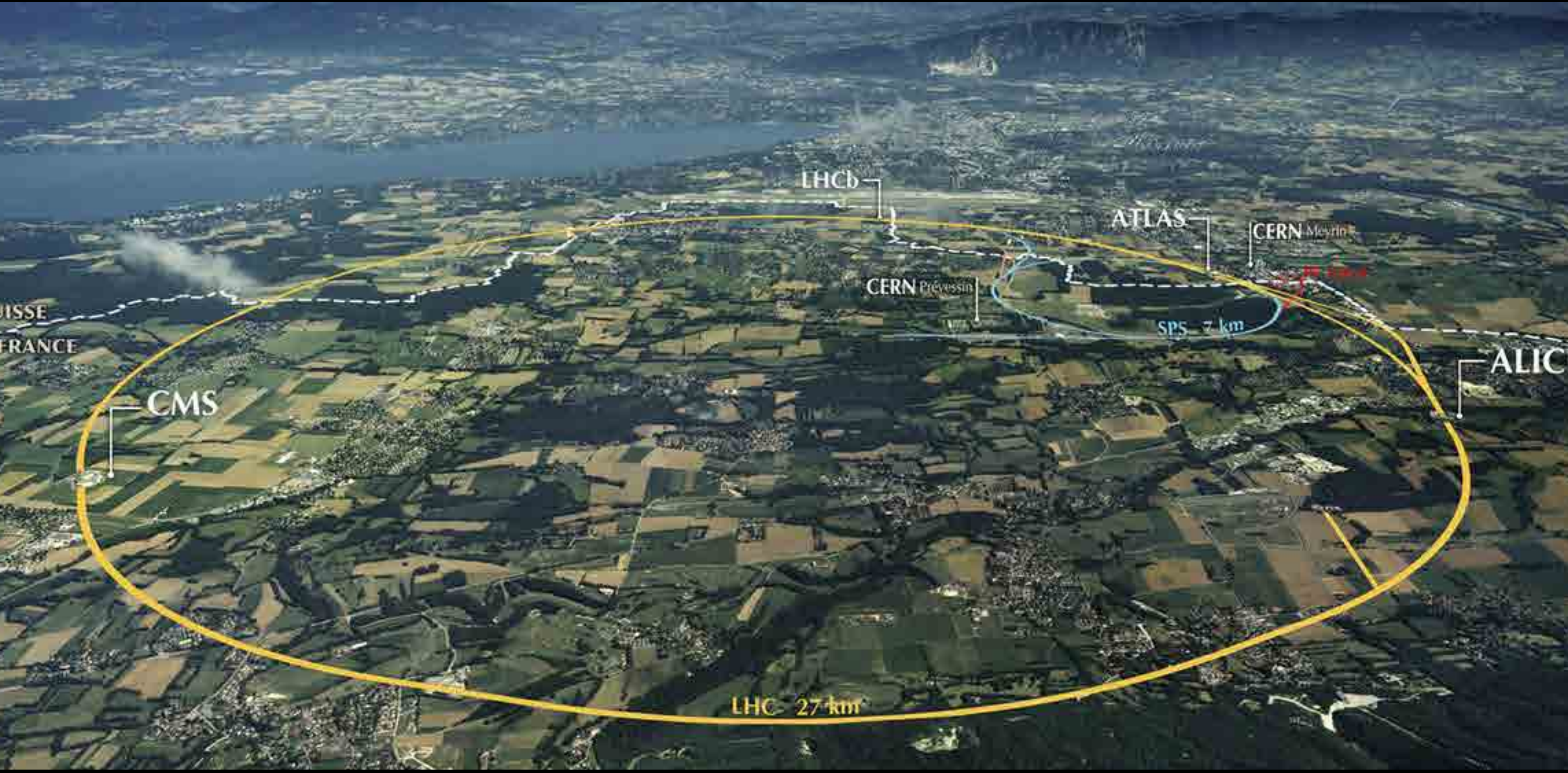
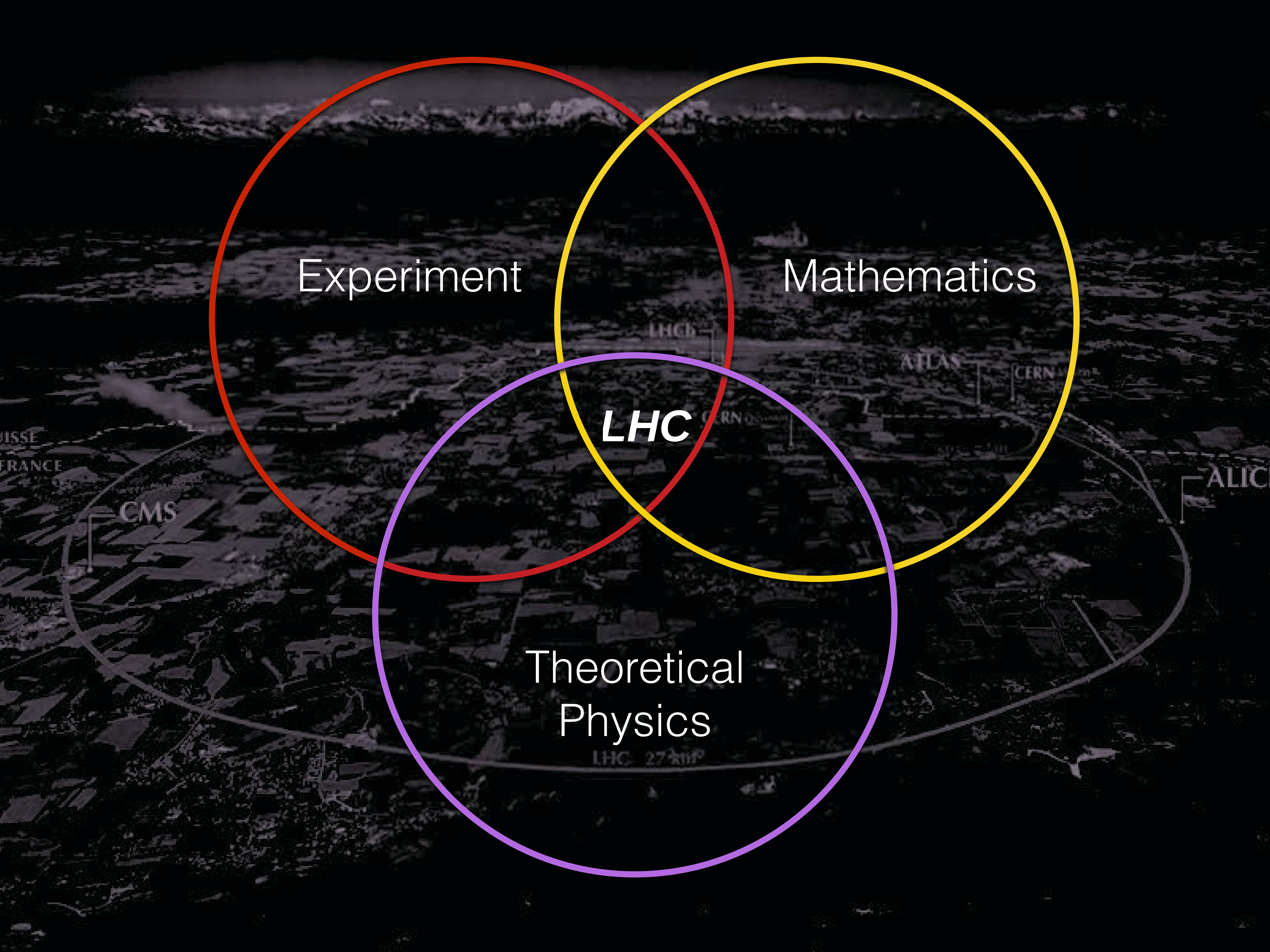
Colliding frontiers: the search for new physics at the LHC

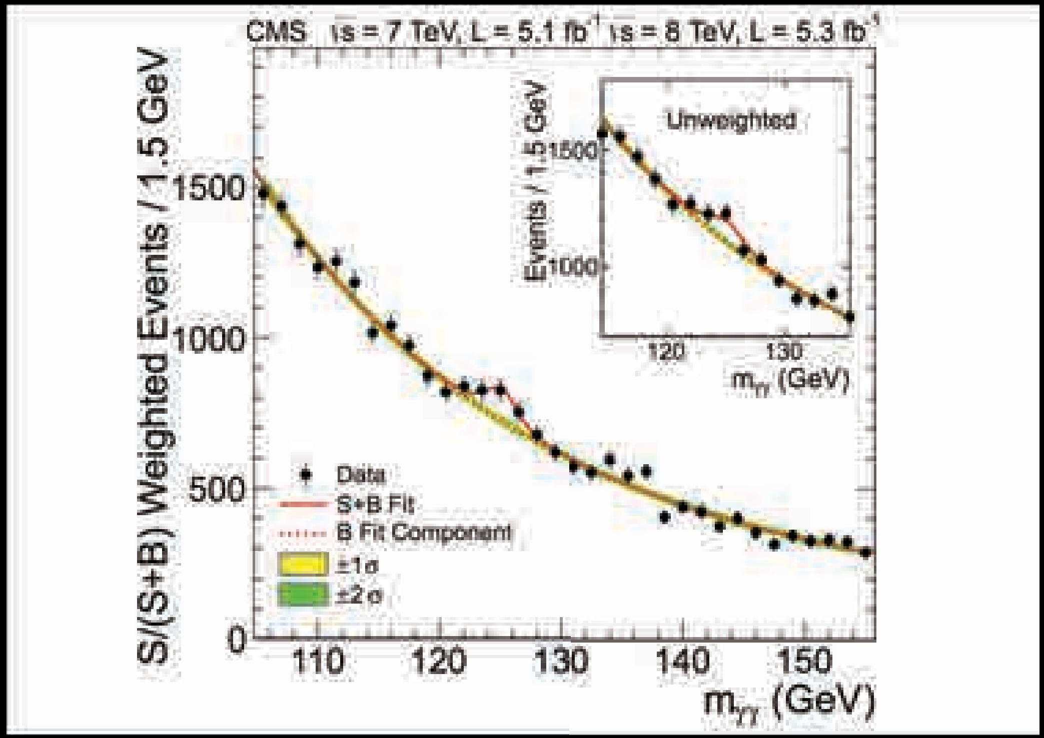


Tom Melia
Berkeley Theoretical Physics


Experiment
Mathematics
LHC
Theoretical
Physics
LHCb
ATLAS
CERN
CMS

The Large Hadron Collider

Run 1 discovered the Higgs boson and completed the standard model



But there remain unresolved puzzles in our understanding

The origin of the electroweak scale

Three generations

Fermion masses

Gauge groups and charges

QCD theta angle

…

The Large Hadron Collider

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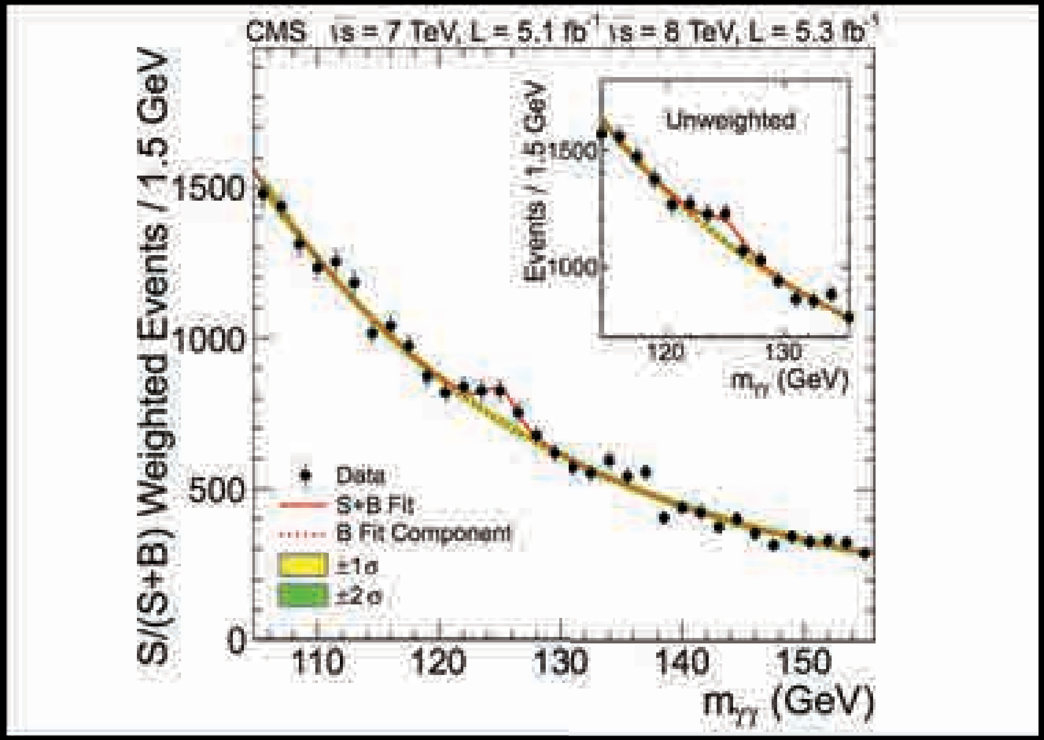
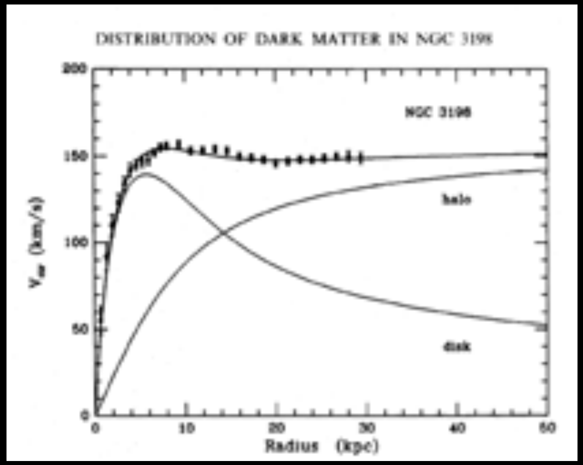
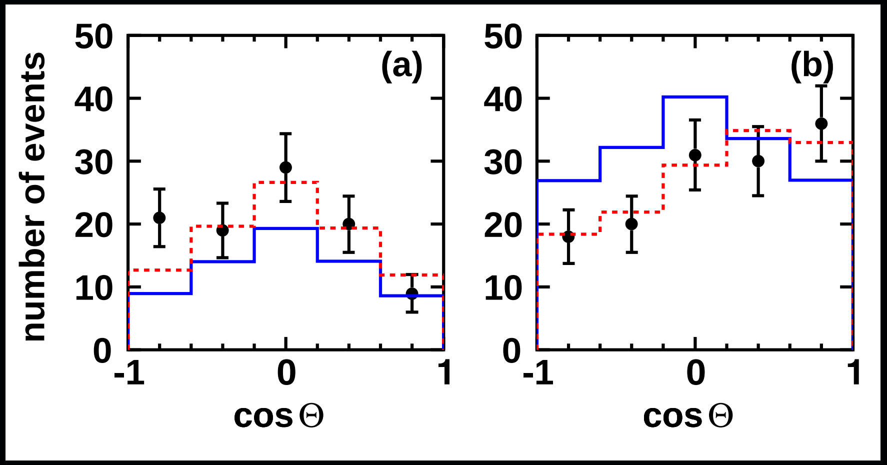


But there remain unresolved puzzles in our understanding

Dark matter



Neutrino masses



Gravity

…

The Large Hadron Collider

Run 2 and beyond at the LHC will be a driving force in the search for new physics

What we discover will shape our ideas about nature and the future of our field

An LHC path to new physics

New particle produced
at the LHC?

yes

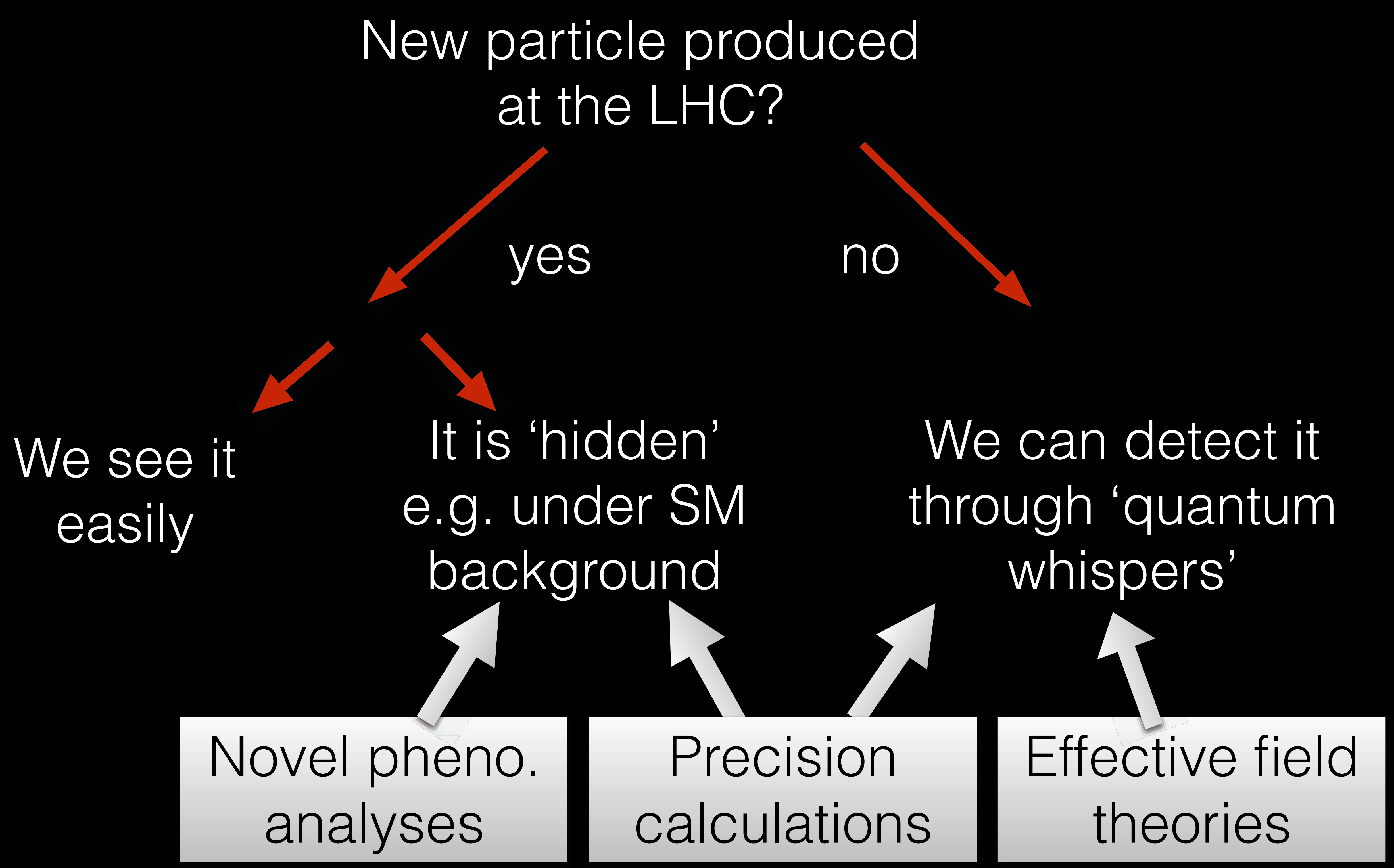
no

We see it
easily

It is ‘hidden’
e.g. under SM
background

We can detect it
through ‘quantum
whispers’

An LHC path to new physics



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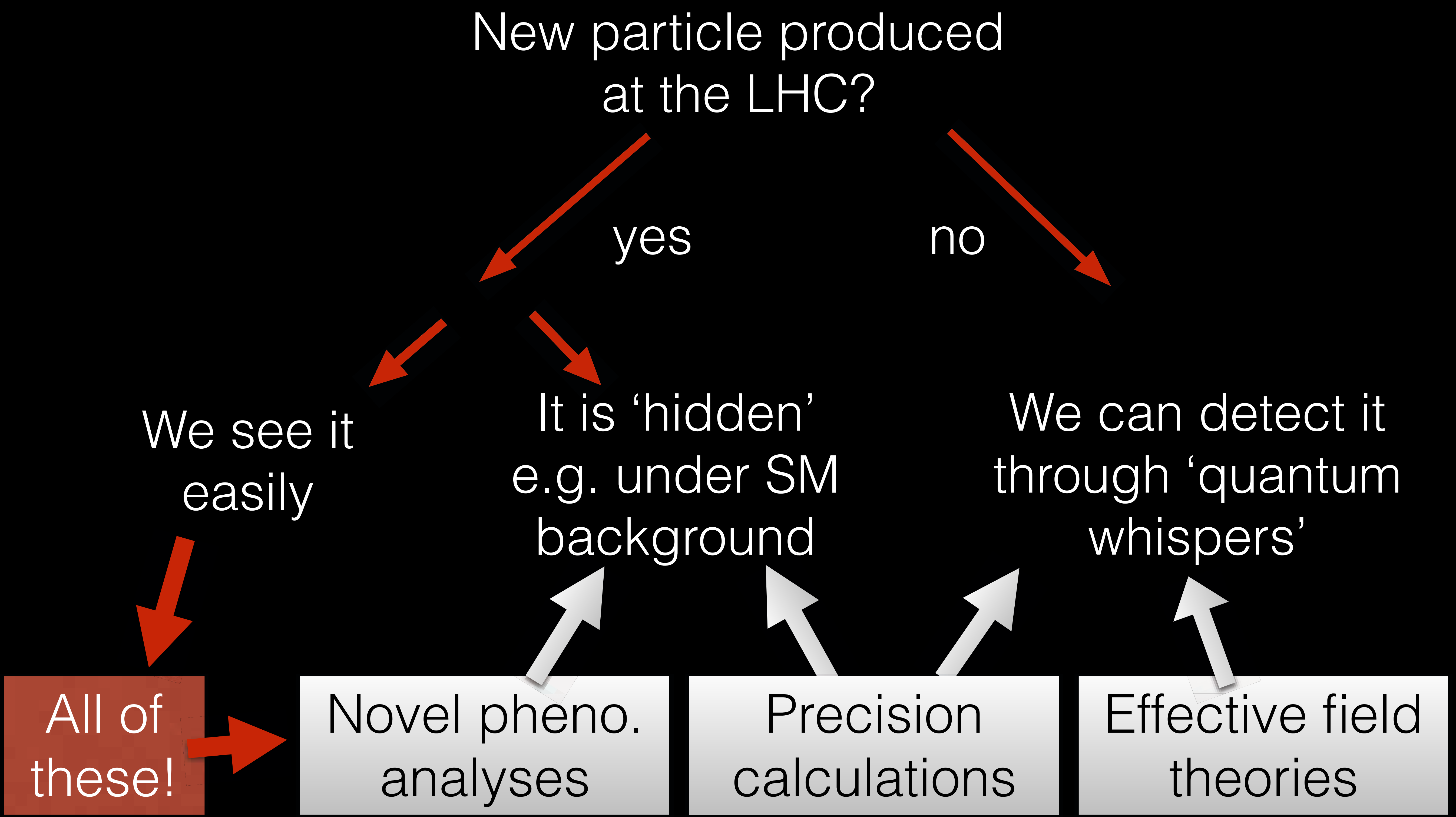
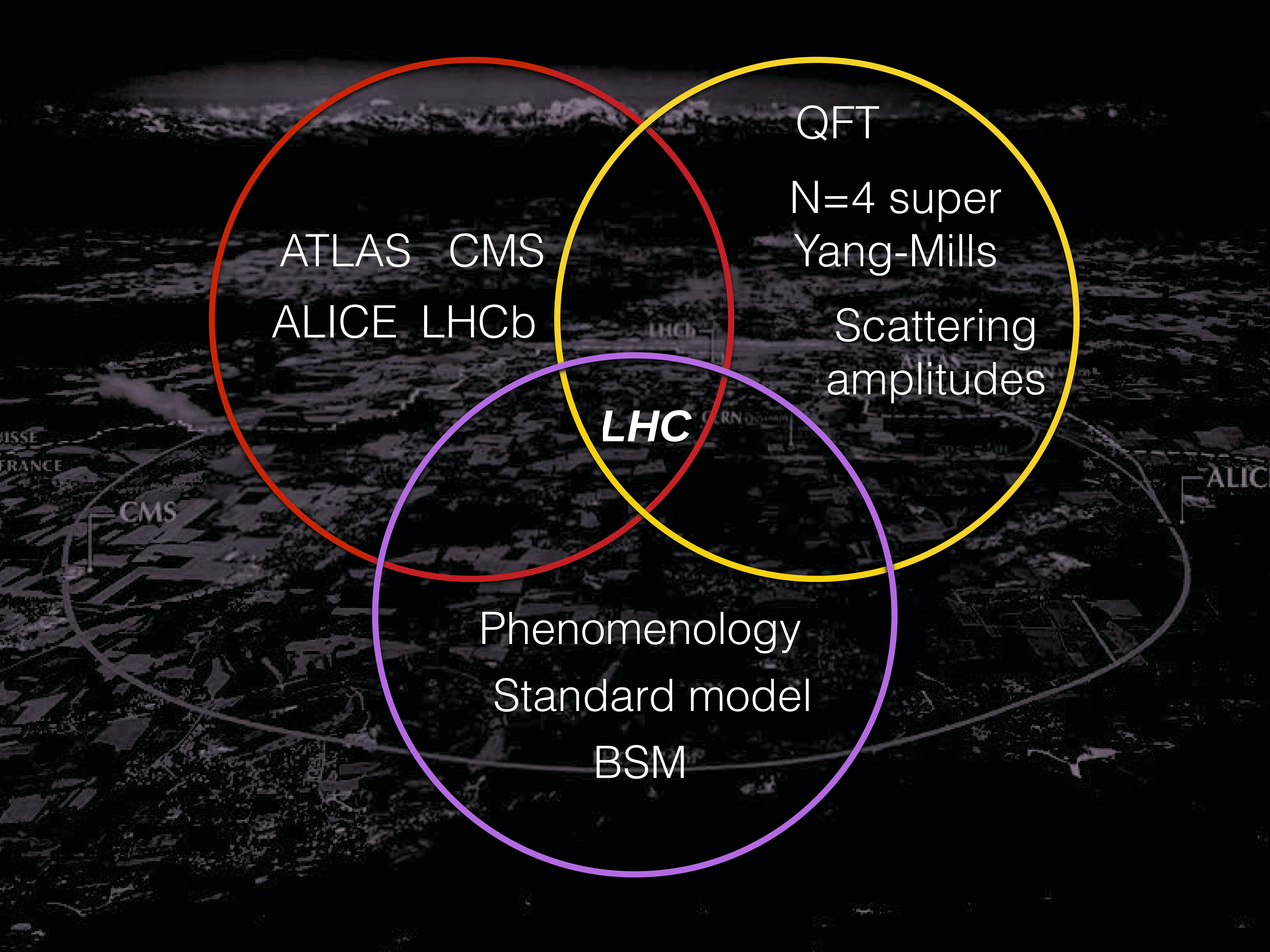
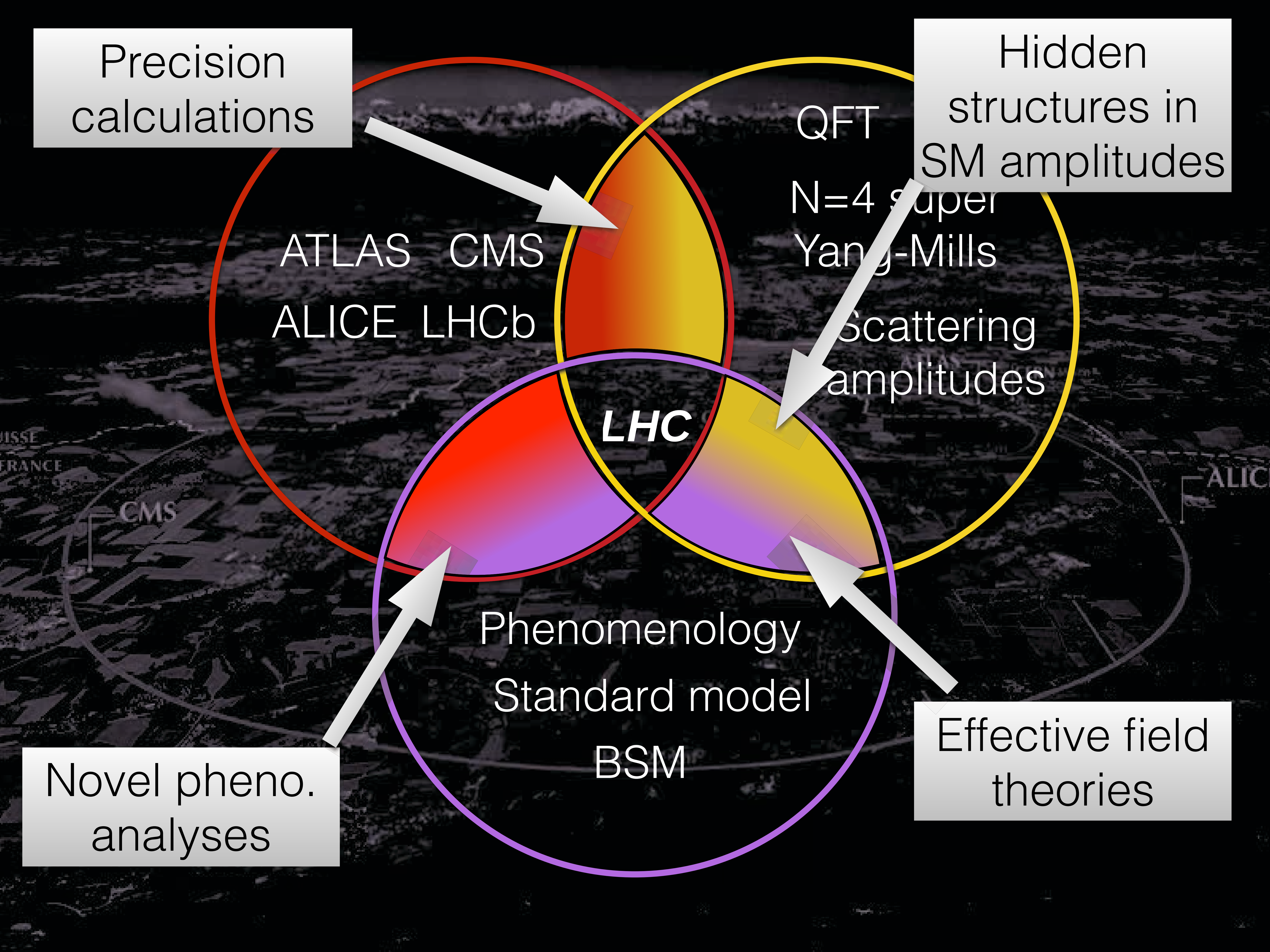



QFT
N=4 super
Yang-Mills
Scattering
amplitudes
ATLAS CMS
ALICE LHCb
LHC
Phenomenology
Standard model
BSM



Precision calculations
Hidden structures in SM amplitudes
QFT
N=4 super Yang-Mills
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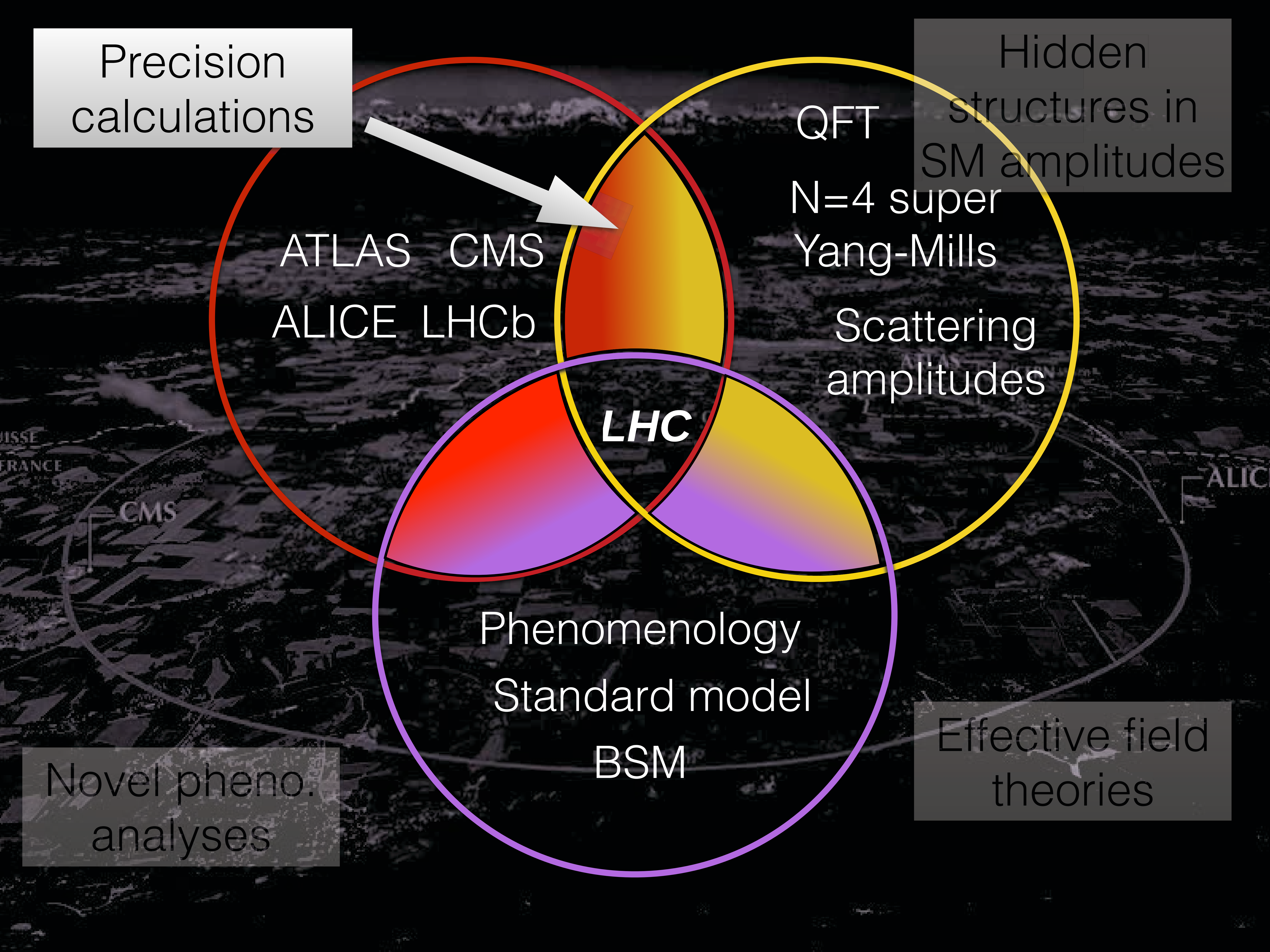
BSM
Novel pheno. analyses
Effective field theories



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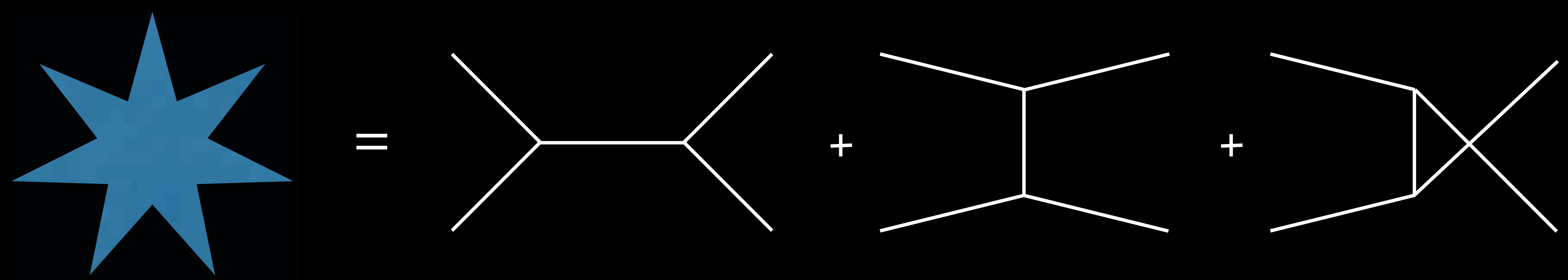
The connection between theory and experiment

Scattering amplitudes

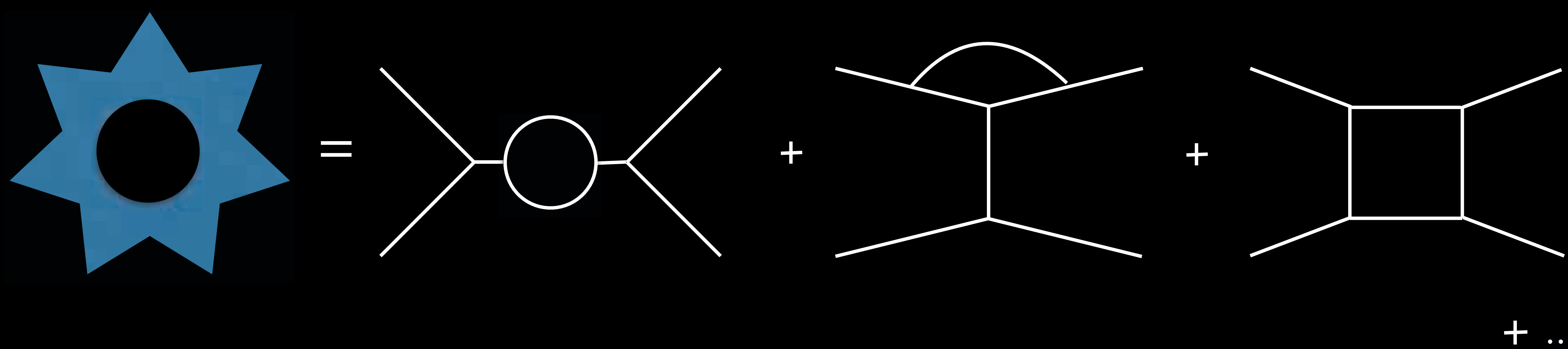


Feynman rules evaluate to give function of momenta of the particles

Tree amplitude is a rational function of Lorentz invariants $p_1 \cdot p_2\,,\ \ p_1 \cdot p_3\,,\ p_1 \cdot p_4.$

The connection between theory and experiment

Scattering amplitudes

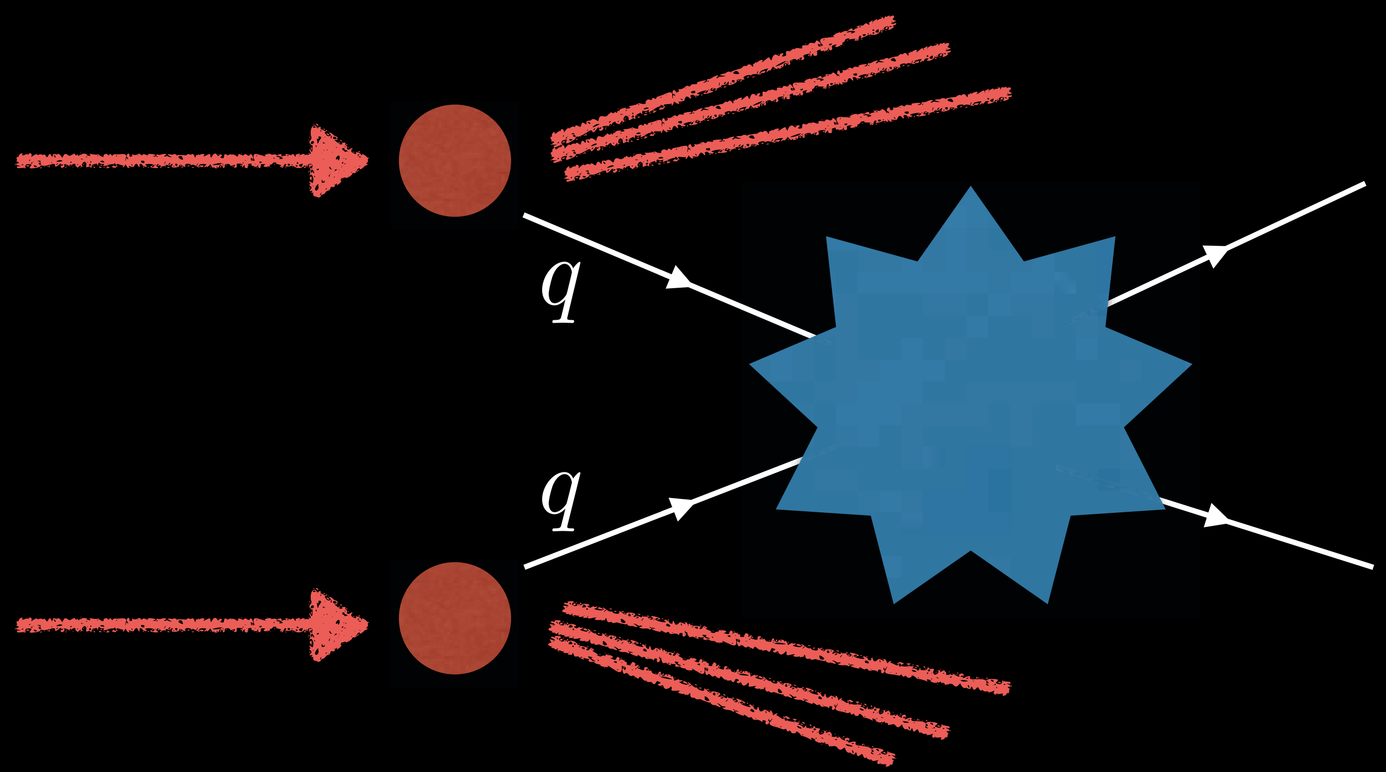


Quantum corrections ordered in perturbative expansion

Precision calculations

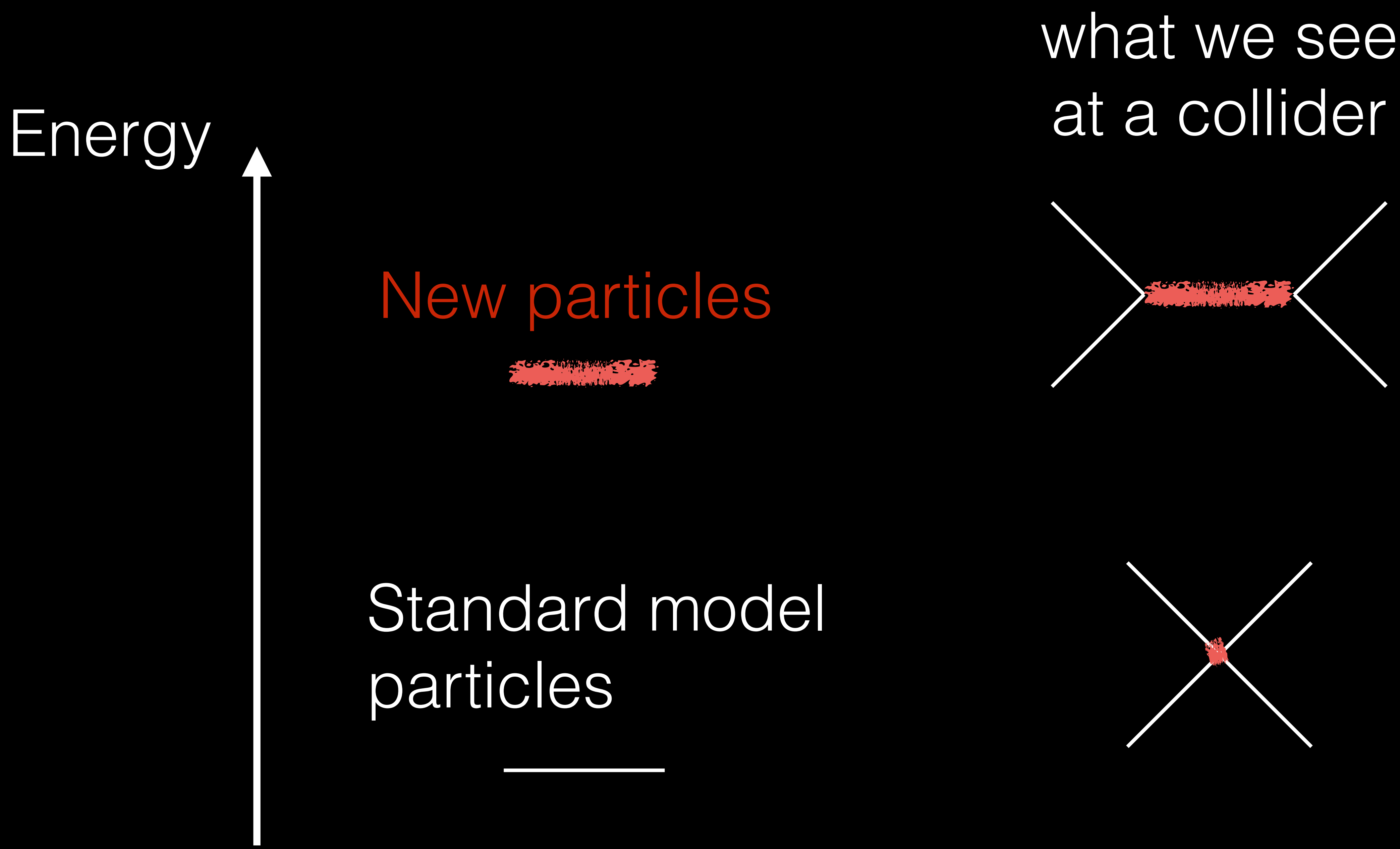
Why precision?

LHC processes necessarily involve quarks and gluons



Strong coupling ~0.1 (vs ~1/137 for electroweak processes) means higher perturbative orders more important

‘Quantum whispers’ — indirect hints of new physics



‘Quantum whispers’ — indirect hints of new physics

Quantum effects are detectable…

…and they tend to be democratic (if they aren’t, some high energy symmetry is at play)

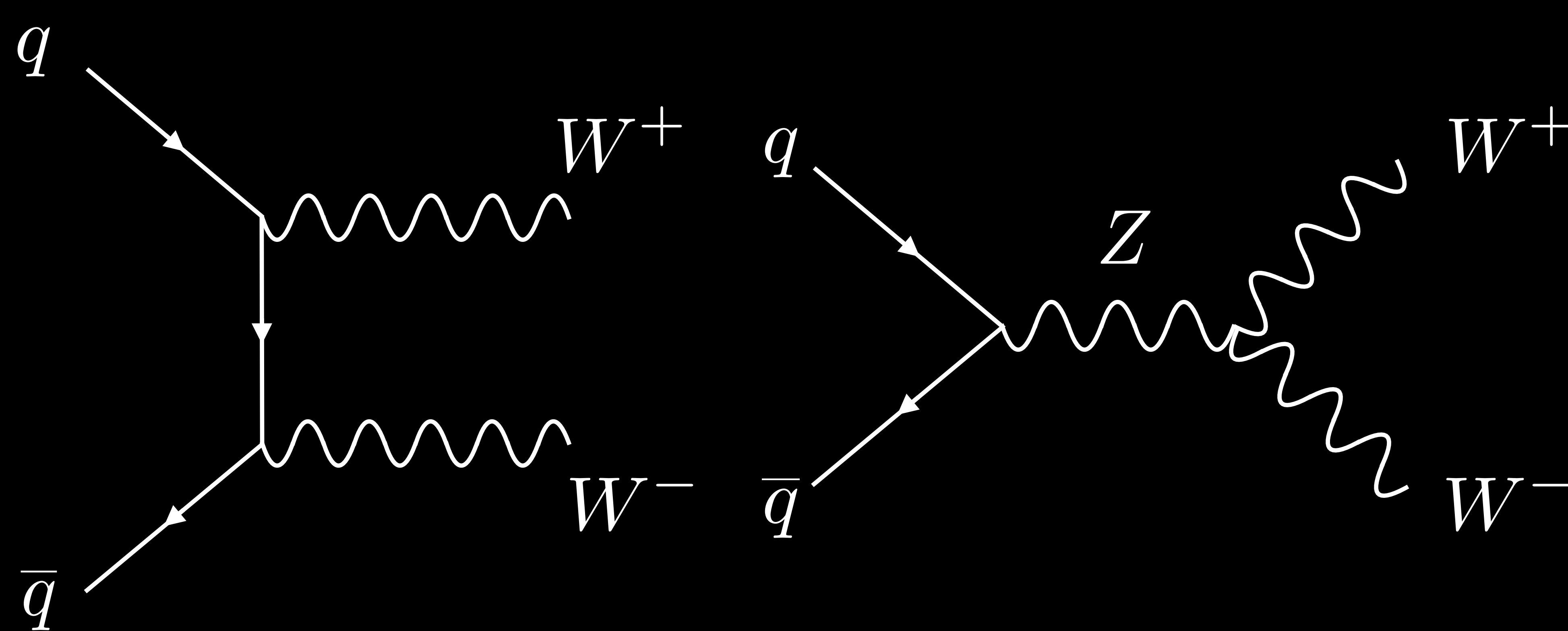
$$\mathcal{L} = \sum_i c_i \mathcal{O}_i$$

so write down everything allowed by the low energy symmetries

Effective field theories

EW boson pair production

Production of WW, WZ, ZZ



EW boson pair production

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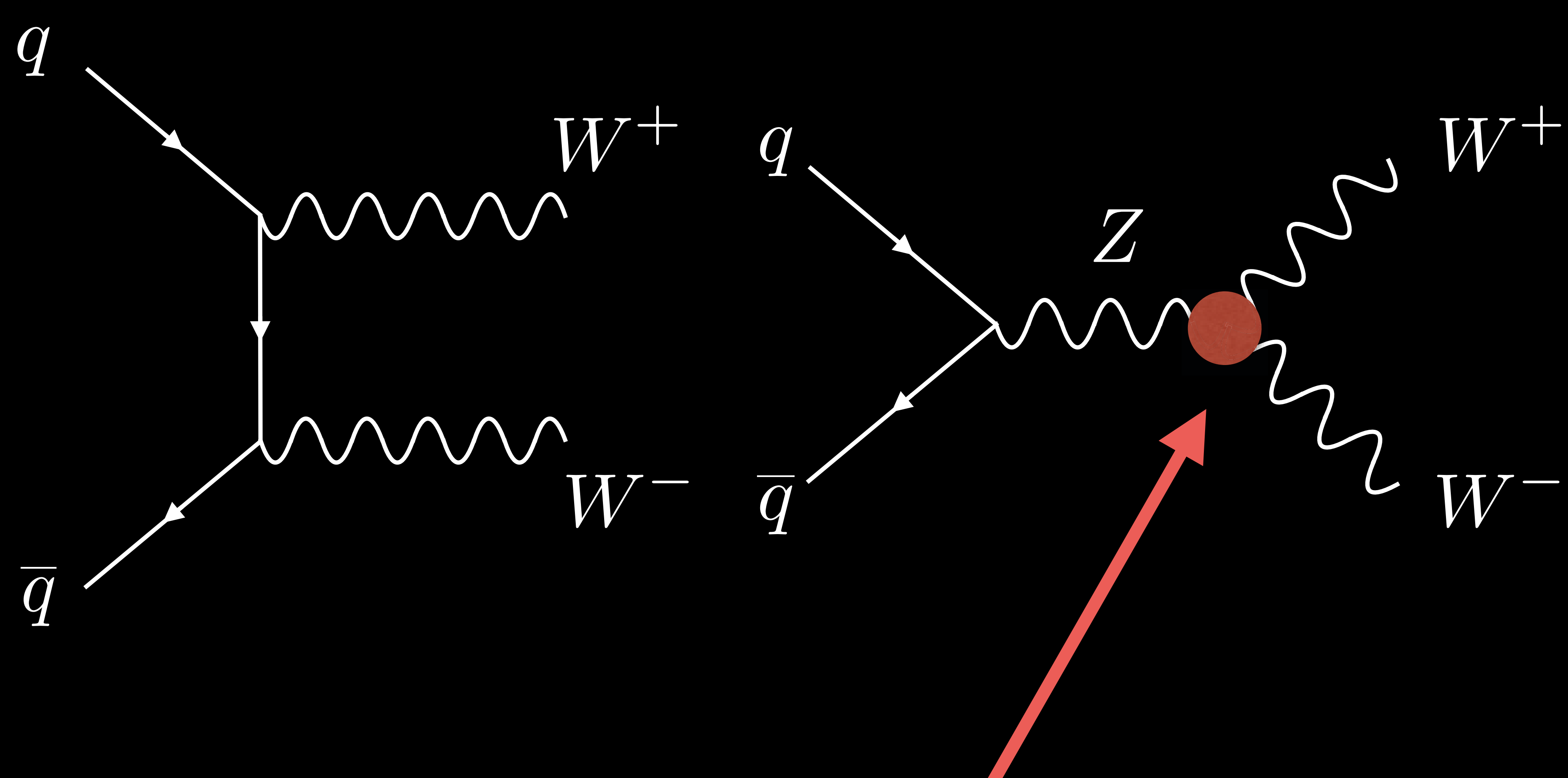
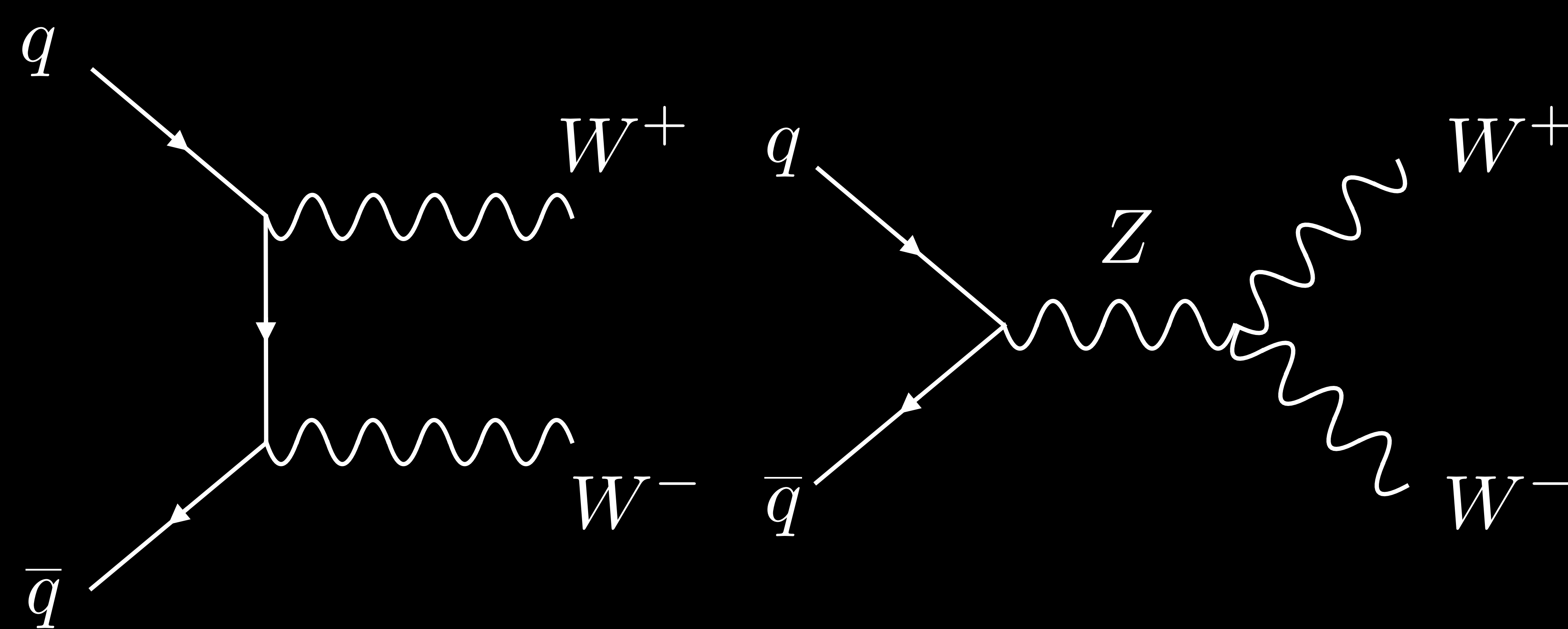


Probe 'quantum whispers' = 'anomalous tri-linear couplings'

EW boson pair production

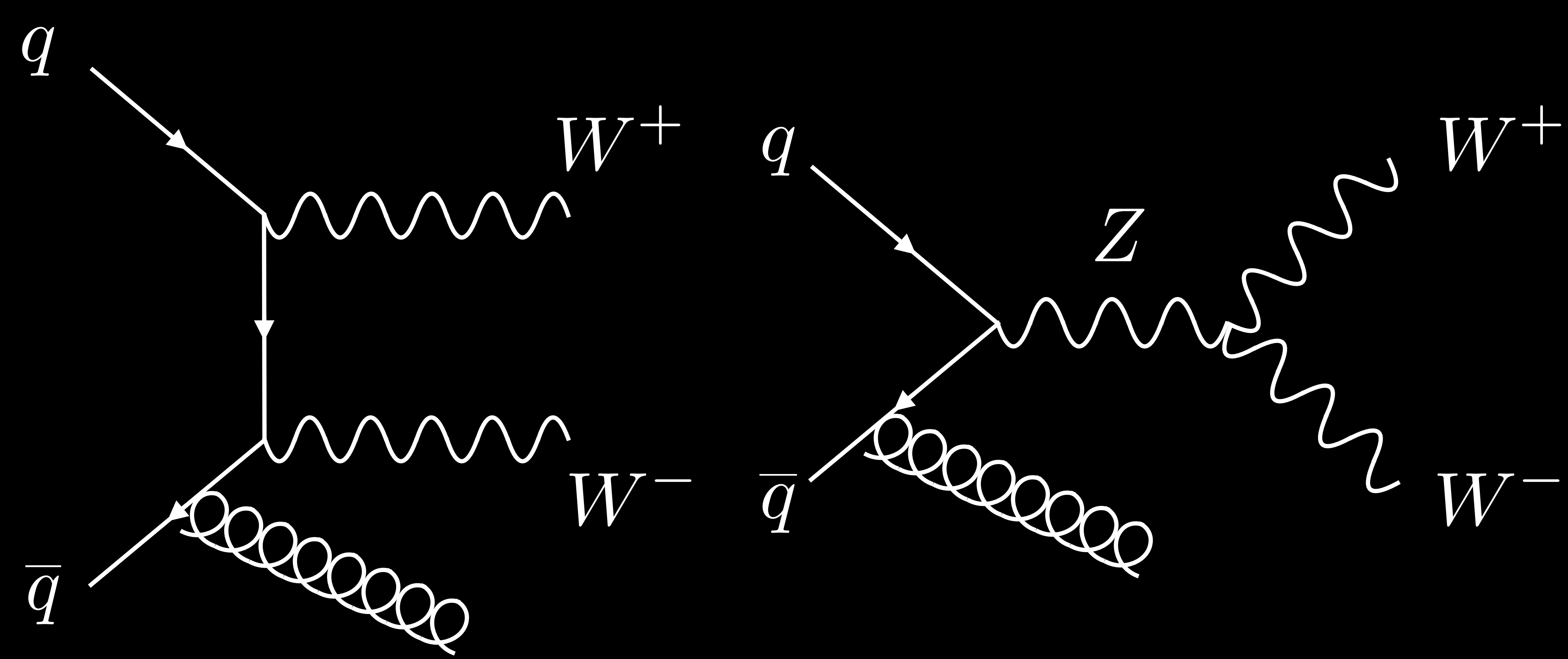
Production of WW, WZ, ZZ



Background to Higgs, new particle production

EW boson pair production

Production of WW, WZ, ZZ



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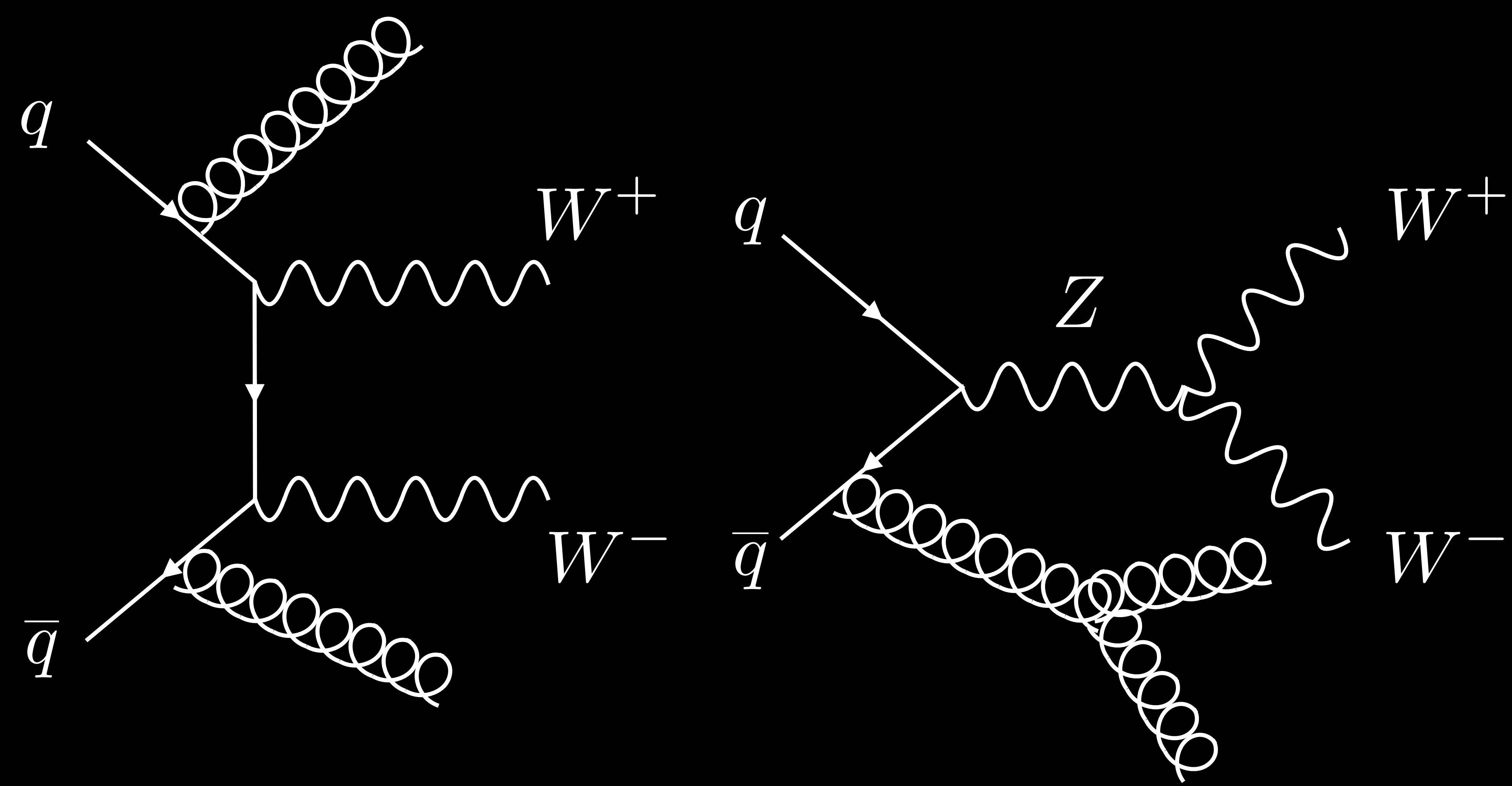

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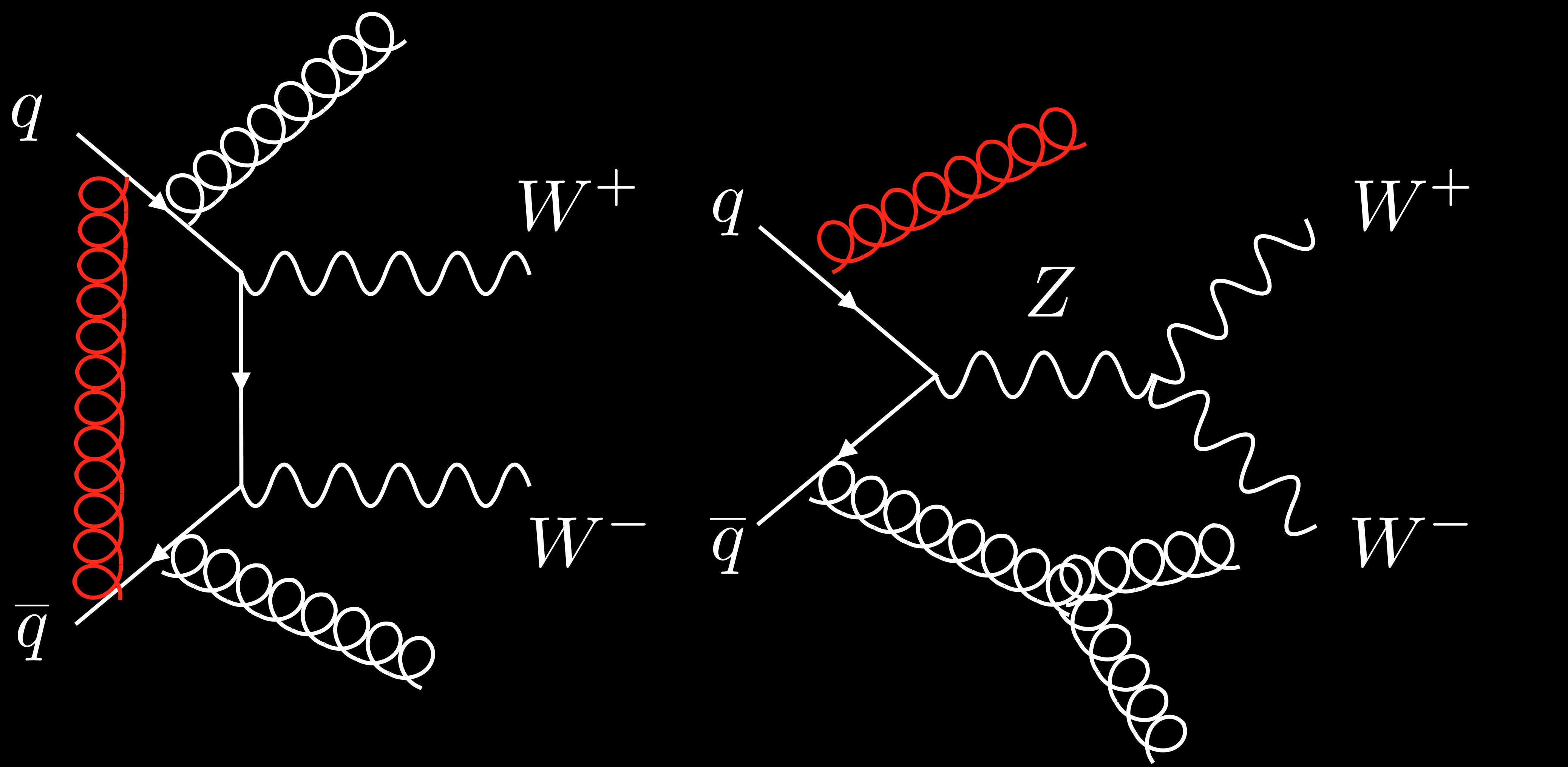
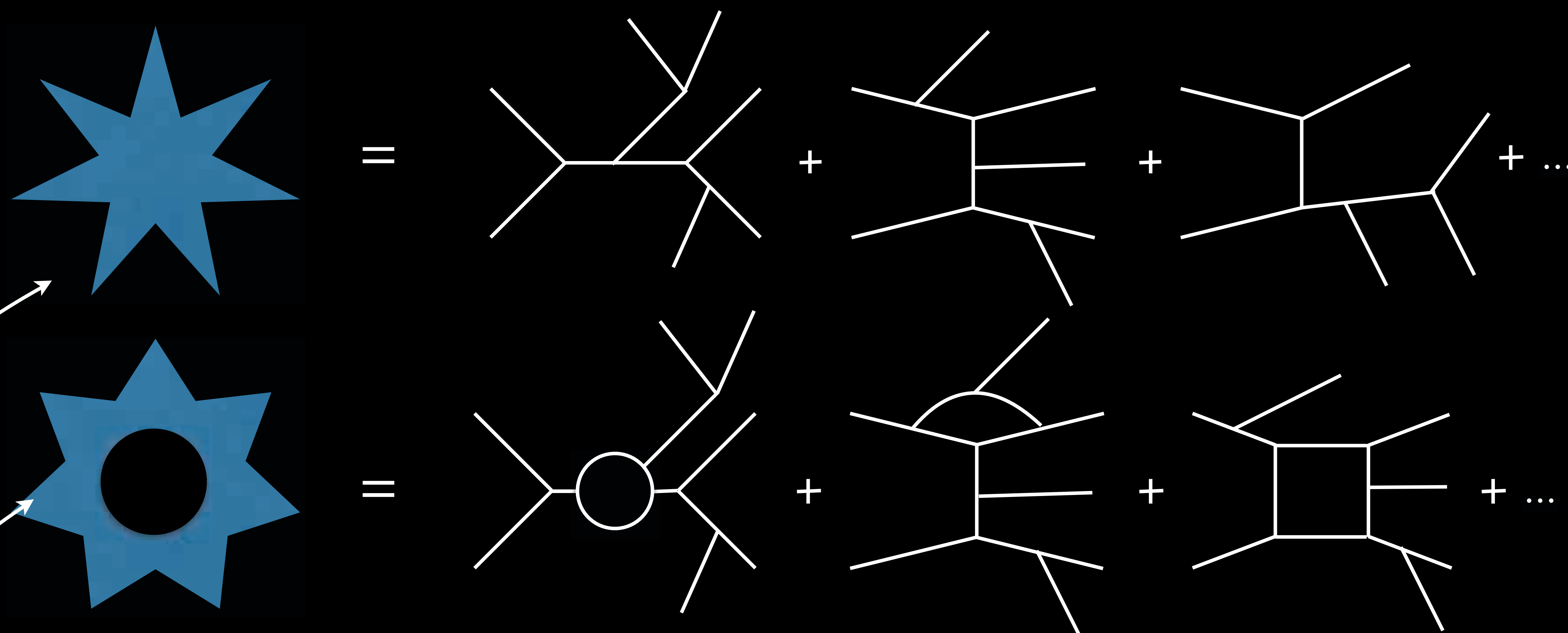


Next-to-leading order (NLO) in QCD coupling

Where does N=4 SYM come in?



7 gluons = ~2500 diagrams

even worse for one-loop amplitude…

Where does N=4 SYM come in?

Two crucial ideas imported from N=4 SYM

Recursion — work directly with the amplitudes

Britto, Cachazo, Feng 2005

Britto, Cachazo, Feng, Witten 2005

(Berends, Giele 1988)

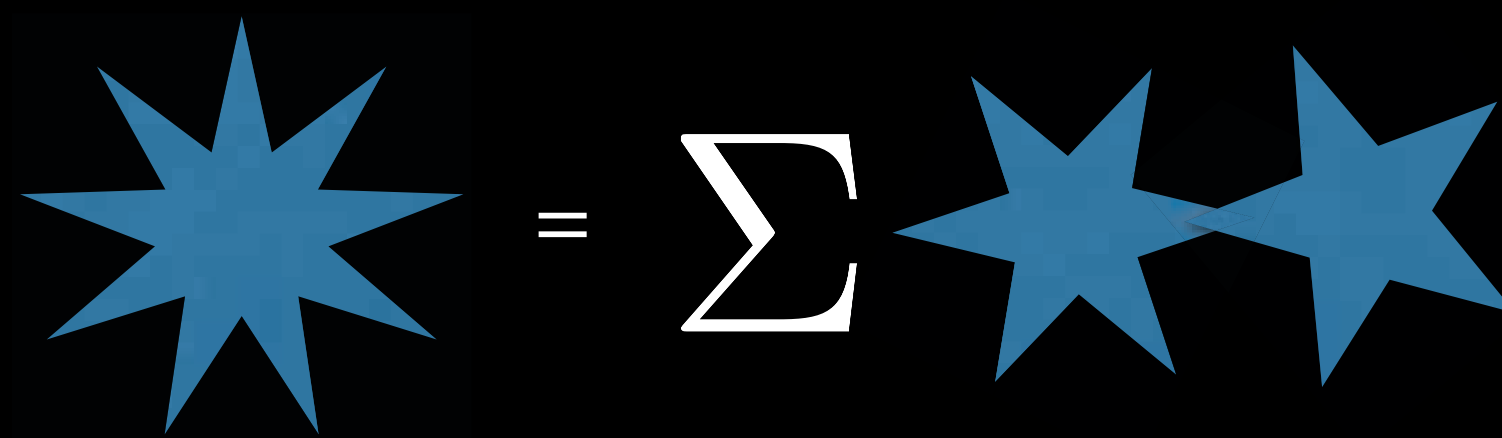
Unitarity — glue tree *amplitudes* to form loop *amplitudes*

Britto, Cachazo, Feng 2005

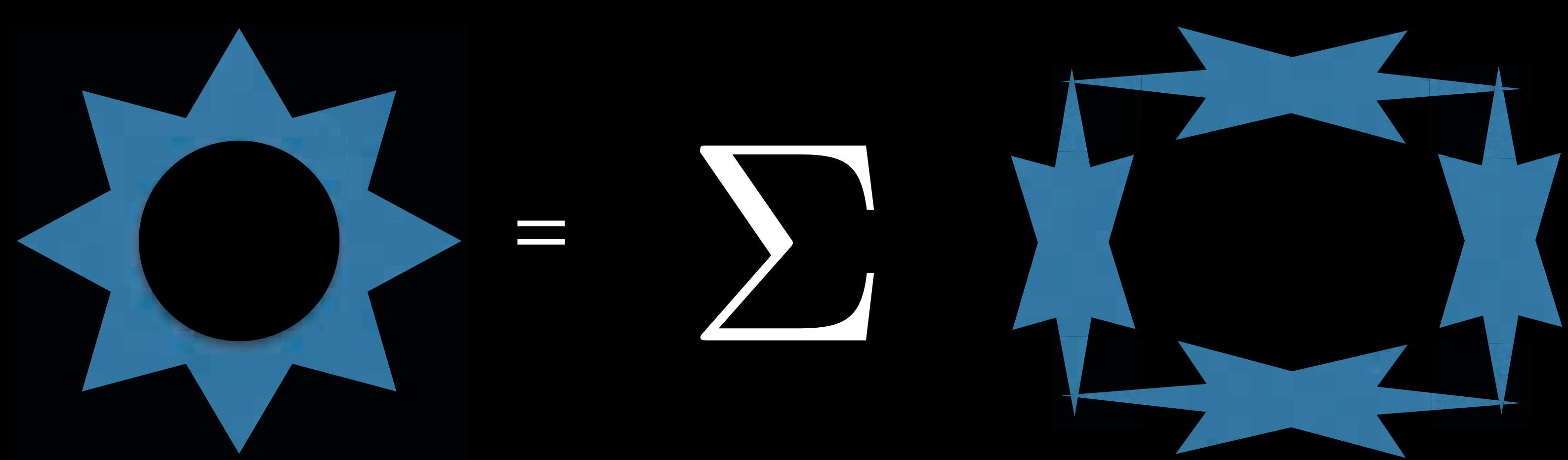
Where does N=4 SYM come in?

Two crucial ideas imported from N=4 SYM

Recursion



Unitarity



Where does N=4 SYM come in?

These techniques apply to colour-ordered amplitudes…

Mangano, Parke, Xu 1986

…an idea borrowed from string theory

$$\underset{\text{n gluons}}{\mathcal{A}} = \sum_{\mathcal{P}(2,..,n)} \mathrm{Tr}(T^{a_1}, T^{a_2}, \ldots, T^{a_n})\; A(1, 2, \ldots, n)$$

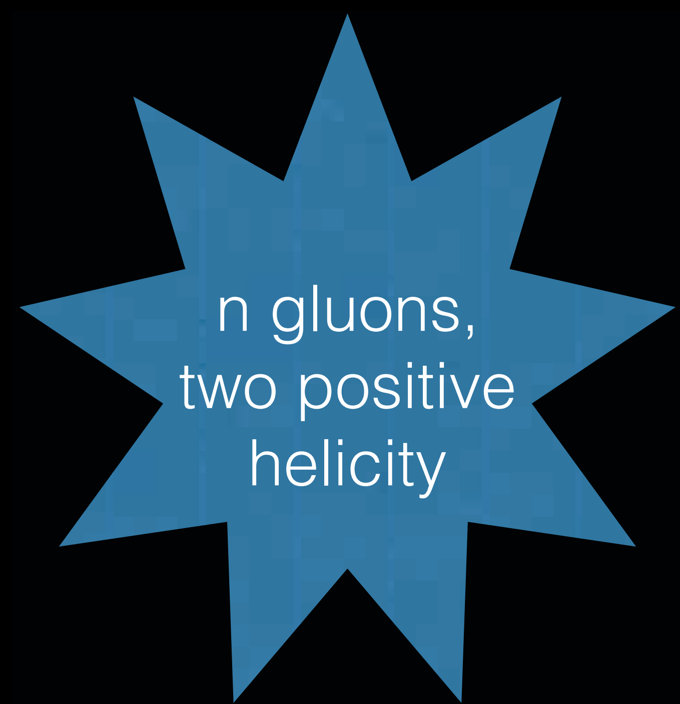
‘Chan-Paton’ factors

n gluons

Where does N=4 SYM come in?

Dramatic example: the Parke-Taylor formula

Parke, Taylor 1986

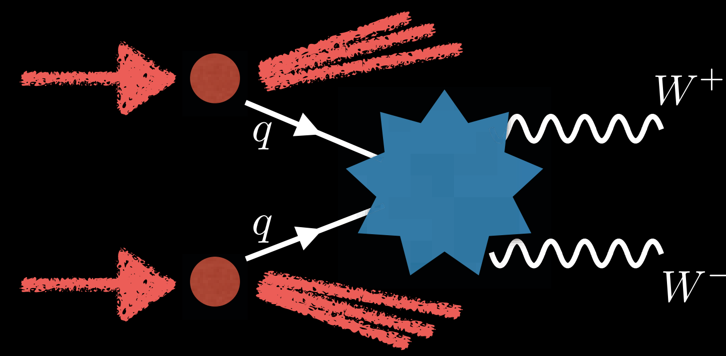


$$= i g^{n-2} \frac{\langle 12 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \ldots \langle n1 \rangle}$$

$$\langle ij \rangle = \sqrt{2 p_i \cdot p_j} e^{i\phi}$$

this shift in philosophy has had a large impact on LHC precision

‘N=4 feedback’



$pp \to W^+W^+jj$ NLO POWHEG

TM, Melnikov, Rontsch, Zanderighi 10

TM, Nason, Rontsch, Zanderighi 11

$pp \to W^+W^-jj$ NLO

TM, Melnikov, Rontsch, Zanderighi 11

$pp \to W^+W^-j$ NLO

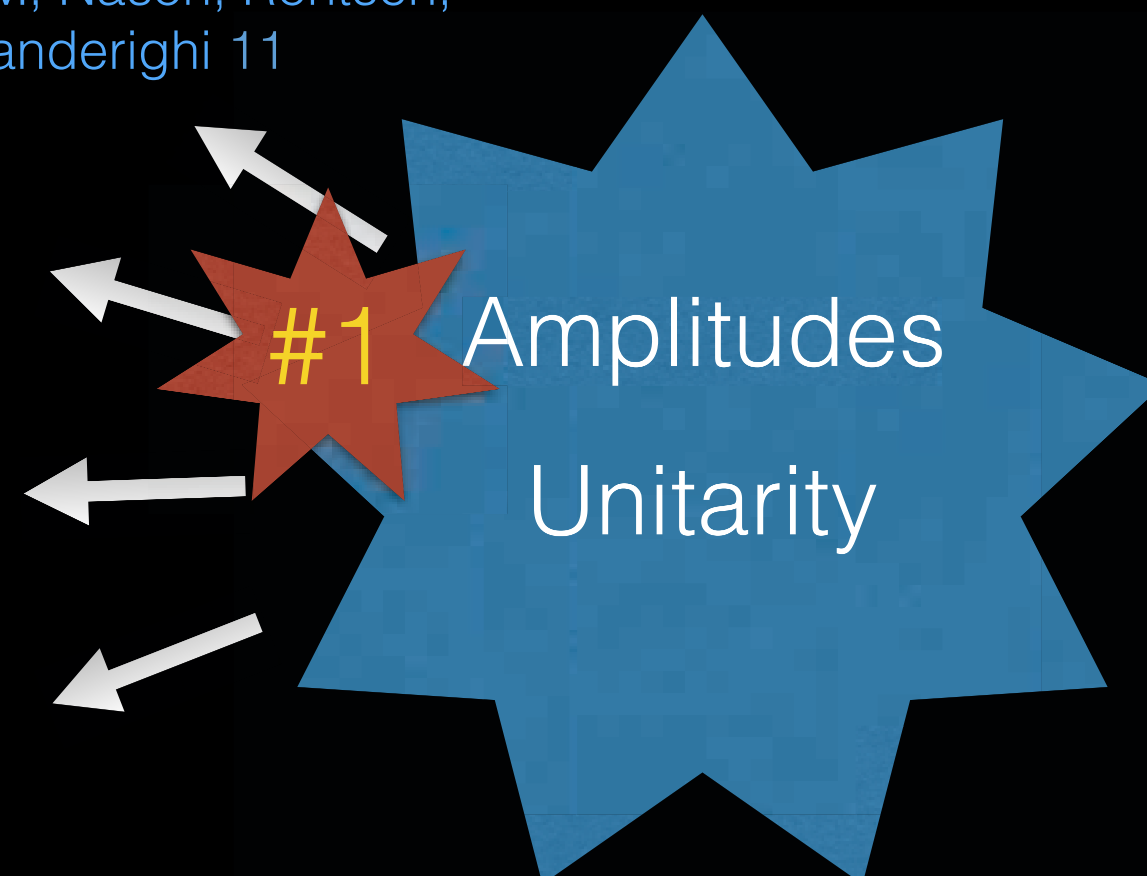
TM, Melnikov, Rontsch, Zanderighi 12

$gg \to W^+W^-g$ (N)NLO

TM, Melnikov, Rontsch, Zanderighi 12

$pp \to WW,\ WZ,\ ZZ$ POWHEG

TM, Nason, Rontsch, Zanderighi 11
Hamilton, TM, Monni, Re, Zanderighi 16



Experimental analyses

>70 published ATLAS and CMS papers

POWHEG Codes
TM, Nason, Rontsch, Zanderighi

Fiducial cross sections and anomalous couplings

Measurements of $W^{\pm}Z$ production cross sections in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector and limits on anomalous gauge boson self-couplings

Measurement of the ZZ Production Cross Section in pp Collisions at $\sqrt{s}$ = 13 TeV with the ATLAS Detector

Measurement of ZZ production in pp collisions at $\sqrt{s} = 7$ TeV and limits on anomalous ZZZ and $ZZ\gamma$ couplings with the ATLAS detector

Measurement of the W^+W^- cross section in pp collisions at $\sqrt{s}$ = 8 TeV and limits on anomalous gauge couplings

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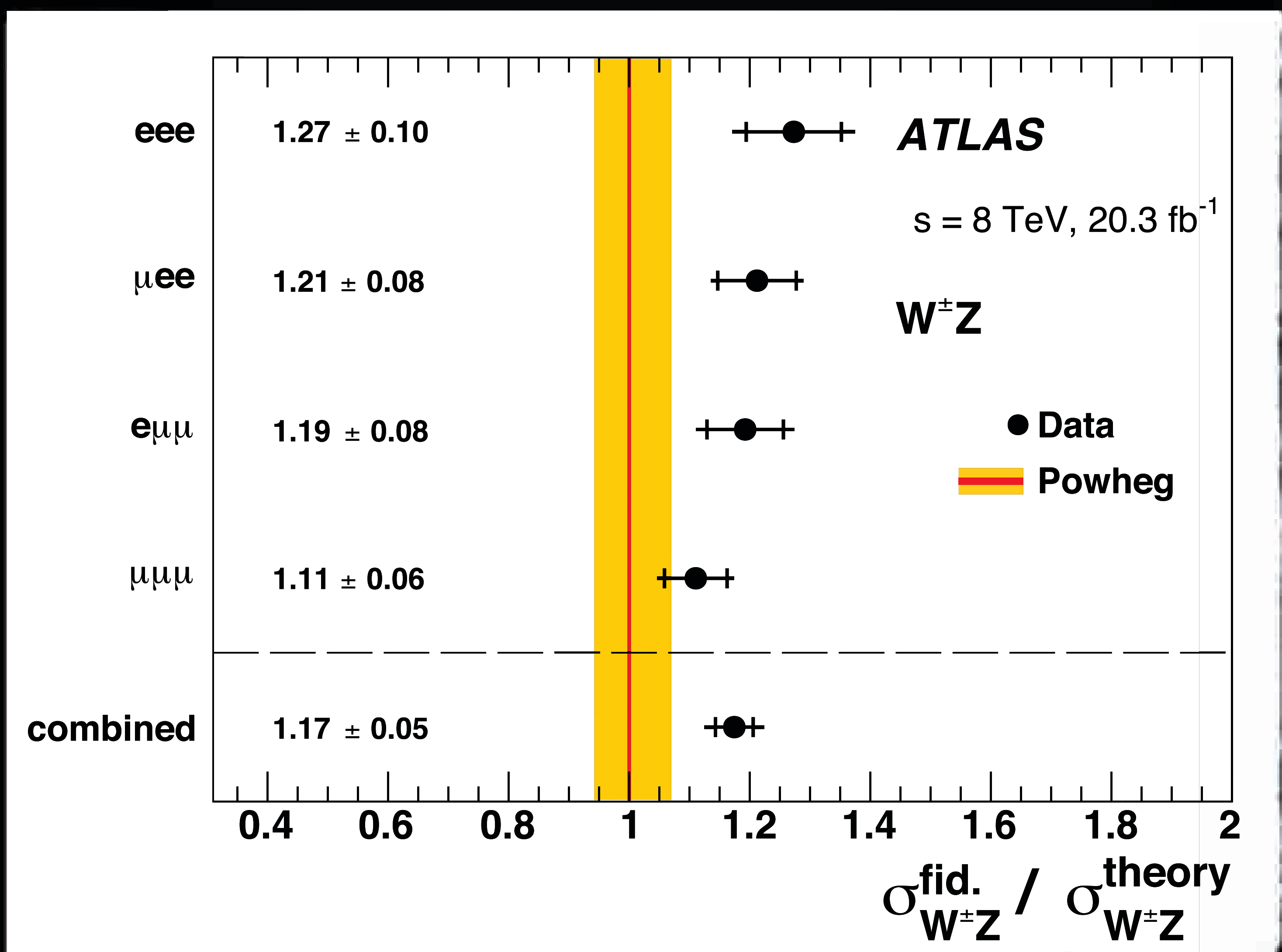

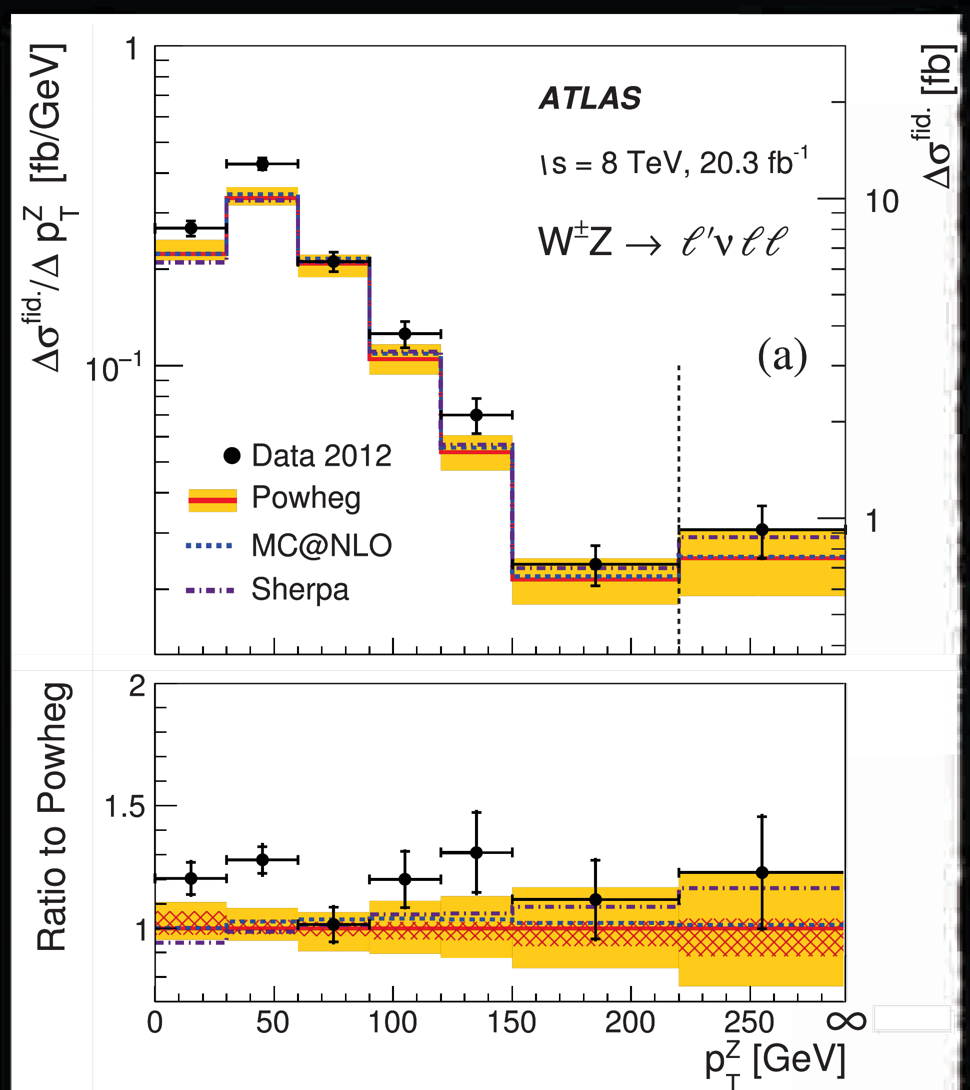

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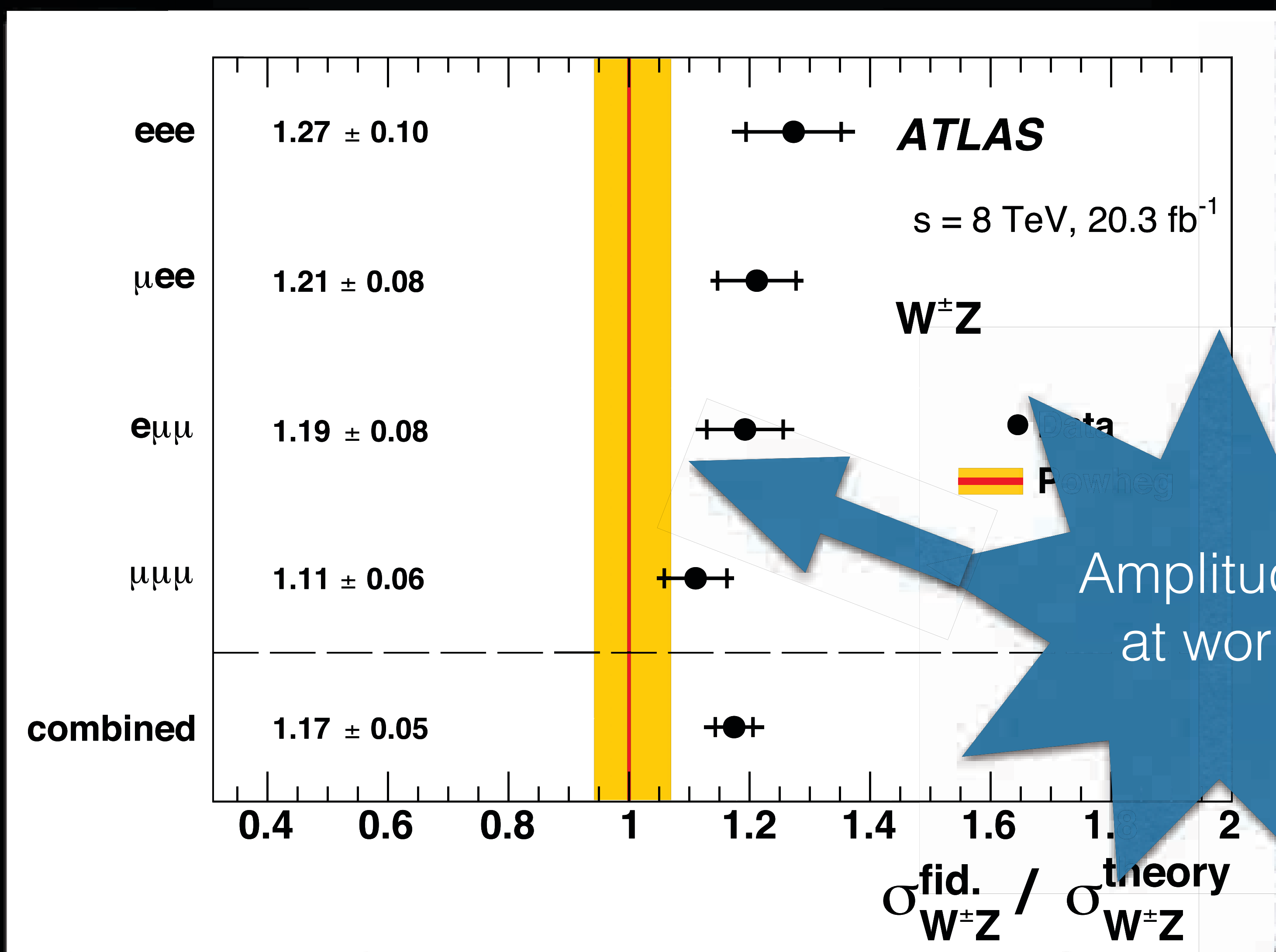
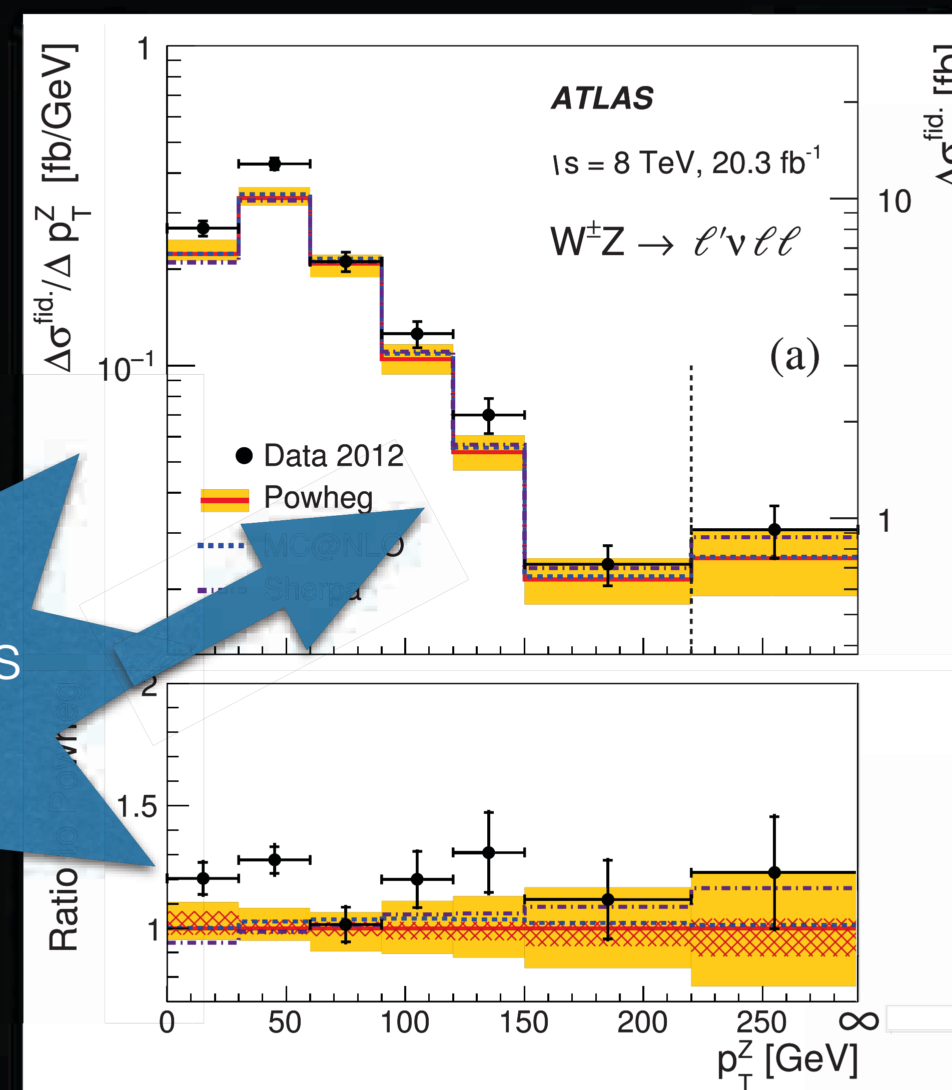
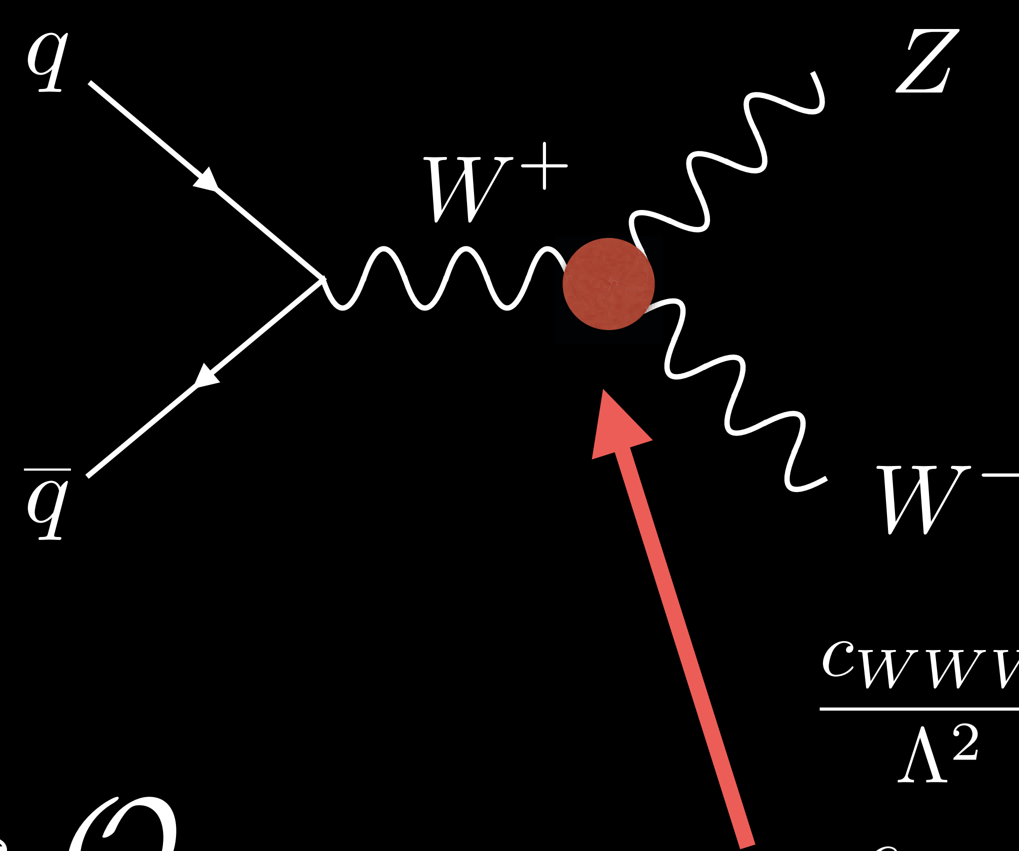




Amplitudes at work!

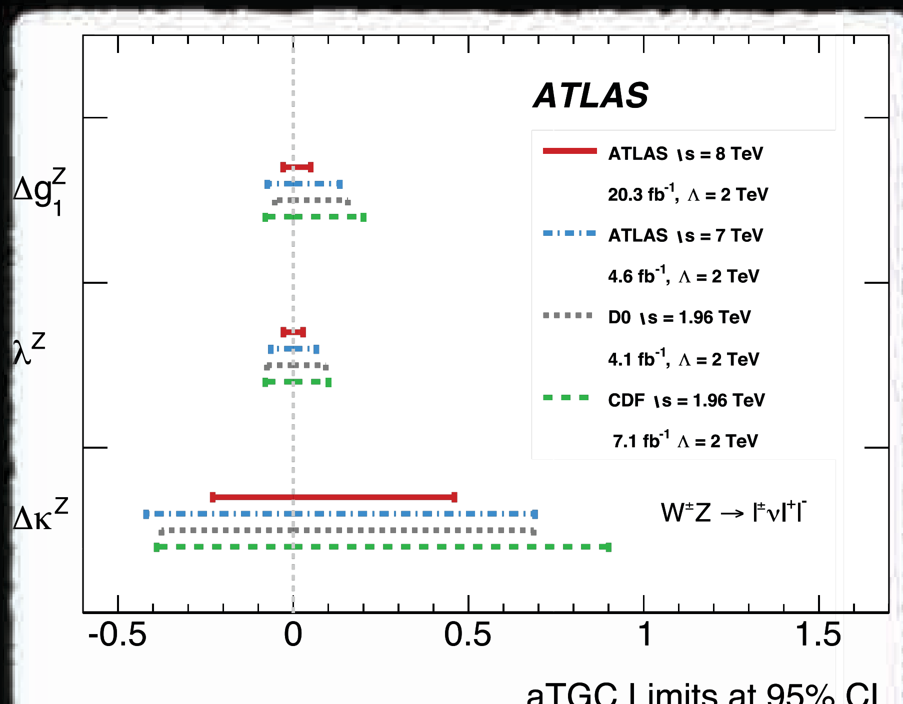


$$\frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}(W_{\mu\nu}W_{\nu\rho}W_{\rho\mu})$$

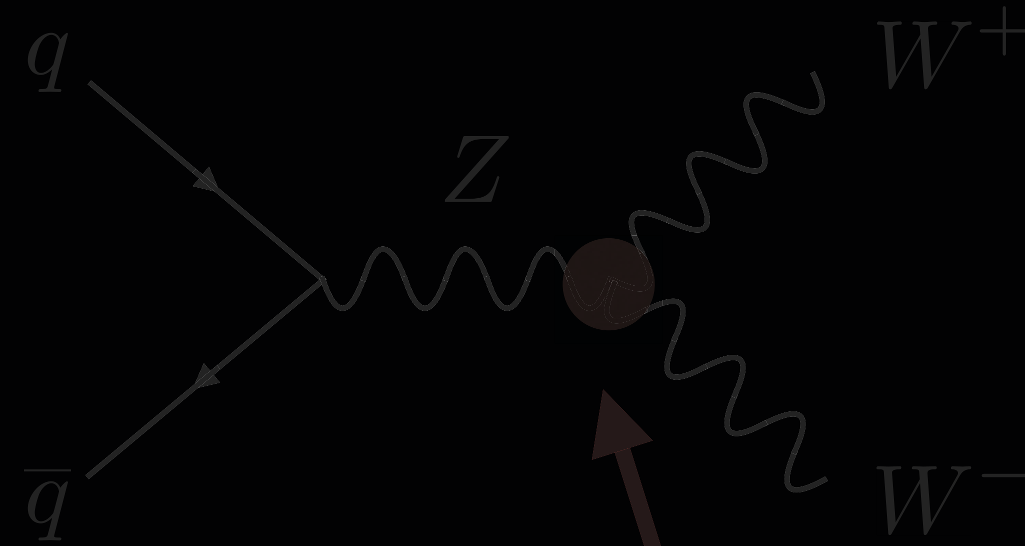
$$\mathcal{L} = \sum_i c_i \mathcal{O}_i$$

$$\frac{c_W}{\Lambda^2}(D_\mu H)^\dagger W_{\mu\nu} D_\nu H$$

$$\frac{c_B}{\Lambda^2}(D_\mu H)^\dagger B_{\mu\nu} D_\nu H$$



EFT coupling	Expected [TeV^{-2}]	Observed [TeV^{-2}]
c_W/Λ^2	[−3.7 ; 7.6]	[−4.3 ; 6.8]
c_B/Λ^2	[−270 ; 180]	[−320 ; 210]
c_{WWW}/Λ^2	[−3.9 ; 3.8]	[−3.9 ; 4.0]



$$\mathcal{L} = \sum_i c_i O_i$$

Setting strongest limits on new physics…

$$\frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}(W_{\mu\nu}W_{\nu\rho}W_{\rho\mu})$$

$$\frac{c_W}{\Lambda^2}(D_\mu H)^\dagger W_{\mu\nu} D_\nu H$$

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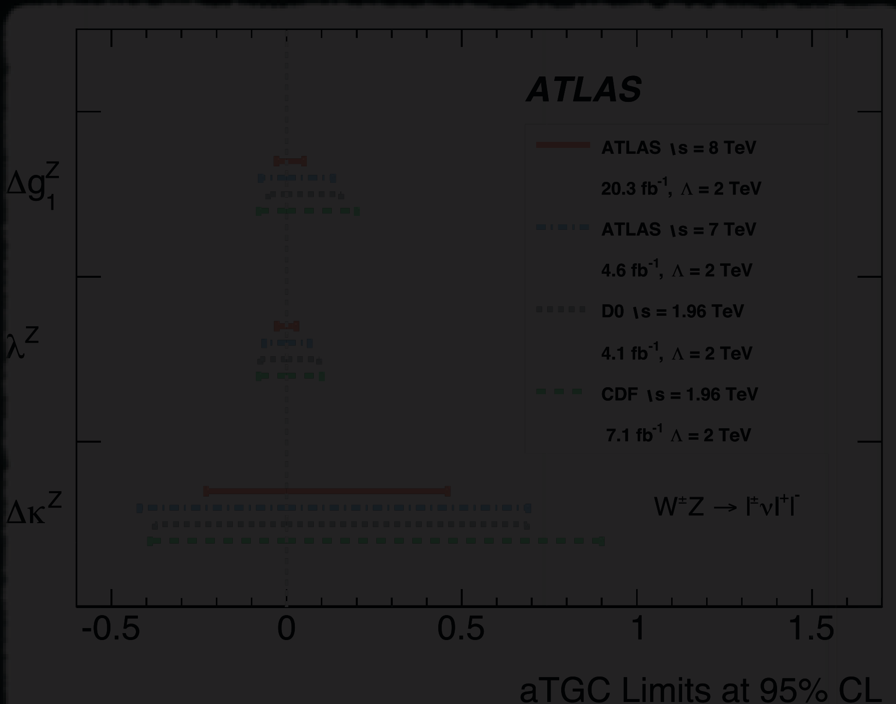

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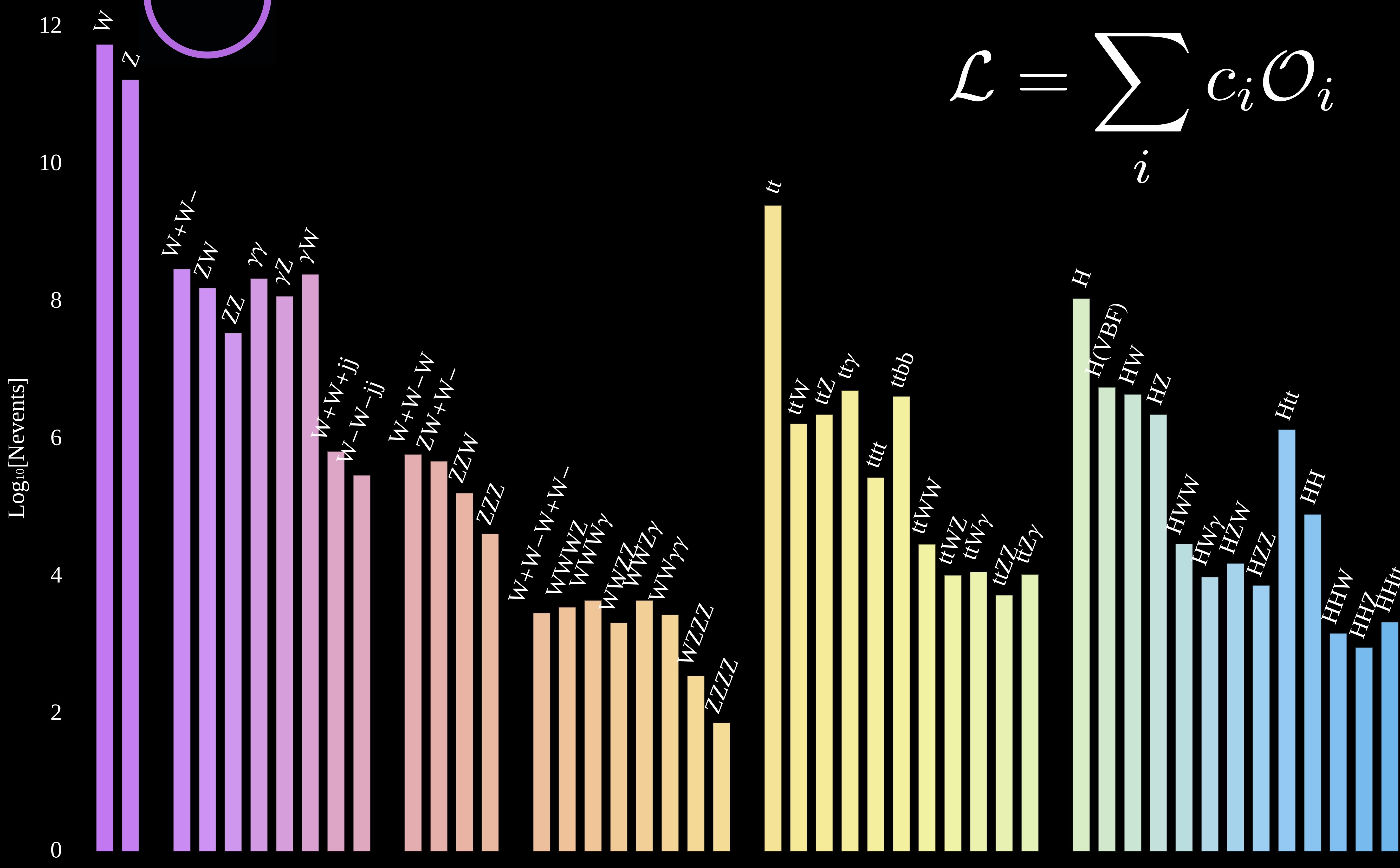
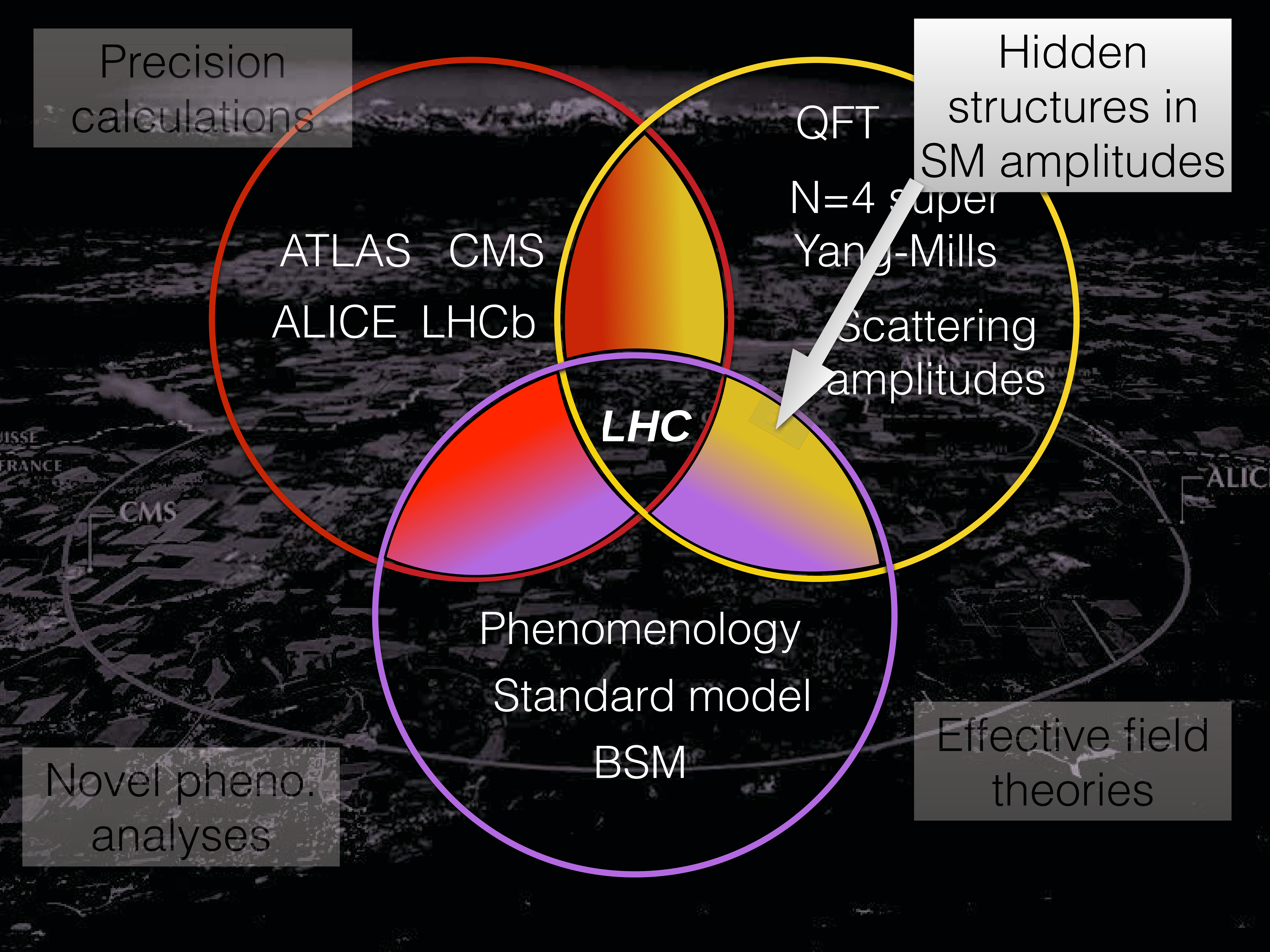
Zoo of opportunities…

$$\mathcal{L} = \sum_i c_i \mathcal{O}_i$$





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Searching for secrets in the standard model

Searching for secrets in the standard model

Amplitudes at play!

Hidden structure in SM amplitudes

Long understood that SM tree amplitudes with gluons and one flavour of quark are 'effectively supersymmetric'

Parke, Taylor 1985 Kunszt 1986

(g^a, λ^a) N=1 super-multiplet

Apart from the colour (adjoint gluino) these have identical interactions as a massless quark with a gluon

Hidden structure in SM amplitudes

Long understood that SM tree amplitudes with gluons and one flavour of quark are 'effectively supersymmetric'

Parke, Taylor 1985 Kunszt 1986

$$(g^a, \lambda^a)$$ N=1 super-multiplet

$$\mathcal{A} = \sum_{\mathcal{P}(2,..,n)} \mathrm{Tr}(T^{a_1}, T^{a_2}, \ldots, T^{a_n})\ A(1, 2, \ldots, n)$$

goes beyond just
using the techniques…

Hidden structure in SM amplitudes

All N=4 super Yang-Mills tree amplitudes are known in closed (and concise) form

Drummond, Henn 2009

$(g^+, \lambda_A, \phi_{AB}, \overline{\lambda}_A, g^-)$ N=4 super-multiplet

$$A = 1, 2, 3, 4$$

Hidden structure in SM amplitudes

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gluons and four flavours of massless ‘quarks’

Hidden structure in SM amplitudes

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Drummond, Henn 2009

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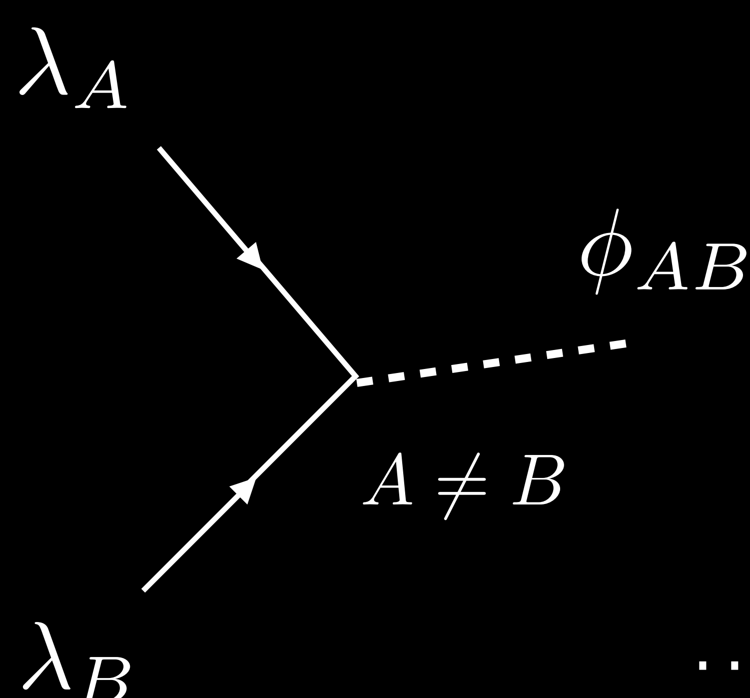


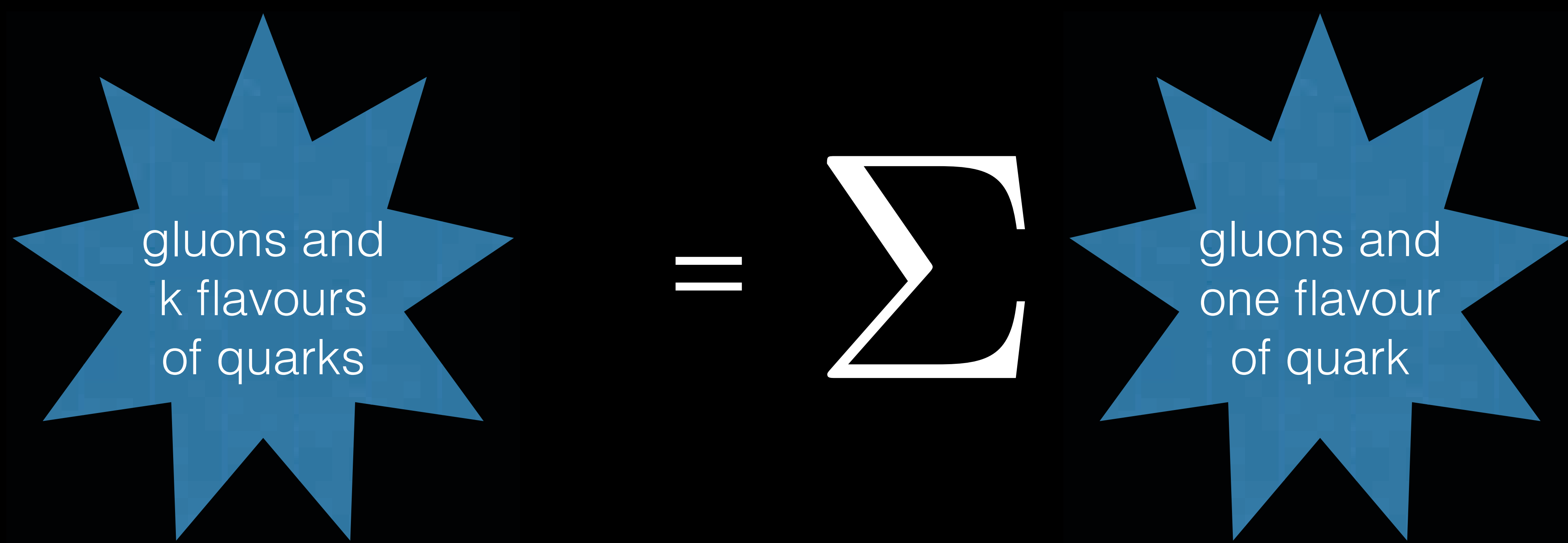
…scalars contaminate the amplitudes

Dixon, Henn, Plefka, Schuster 2011

‘Emergent flavour’

It turns out that it is possible to express any k-flavour QCD tree amplitude in terms of one-flavour amplitudes

TM 2014



All massless QCD from N=4 SYM

Dyck word structure

Understanding a basis for these amplitudes is crucial for this

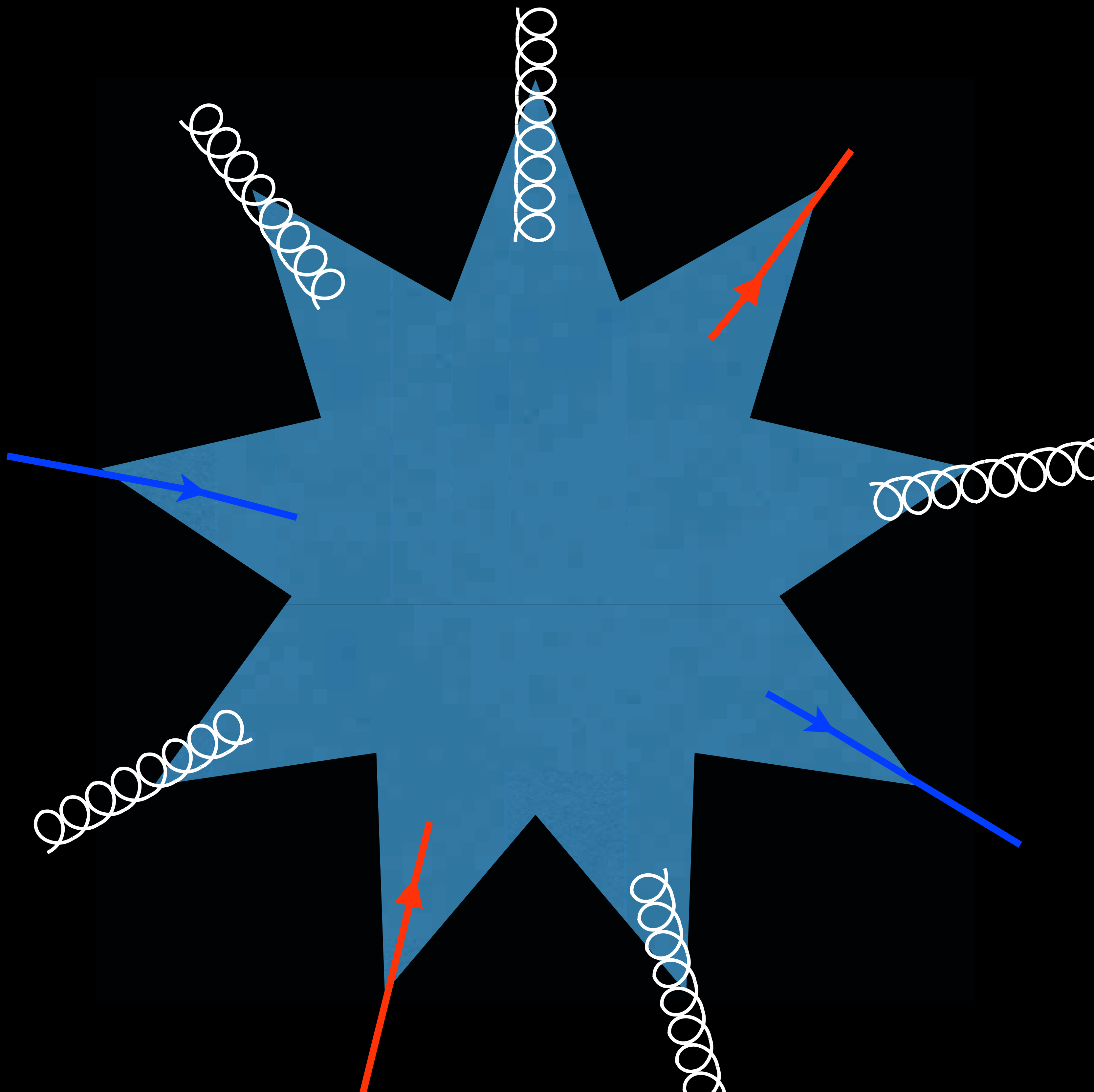
Structure based around ‘Dyck words’
TM 2013

Dyck word structure

String of r Xs and r Ys such that the number of Xs is always greater than or equal to the number of Ys in any initial segment of the string.

r=1	XY				
r=2	XXYY	XYXY			
r=3	XXXYYY	XXYXYY	XXYYXY	XYXXYY	XYXYXY

Planarity



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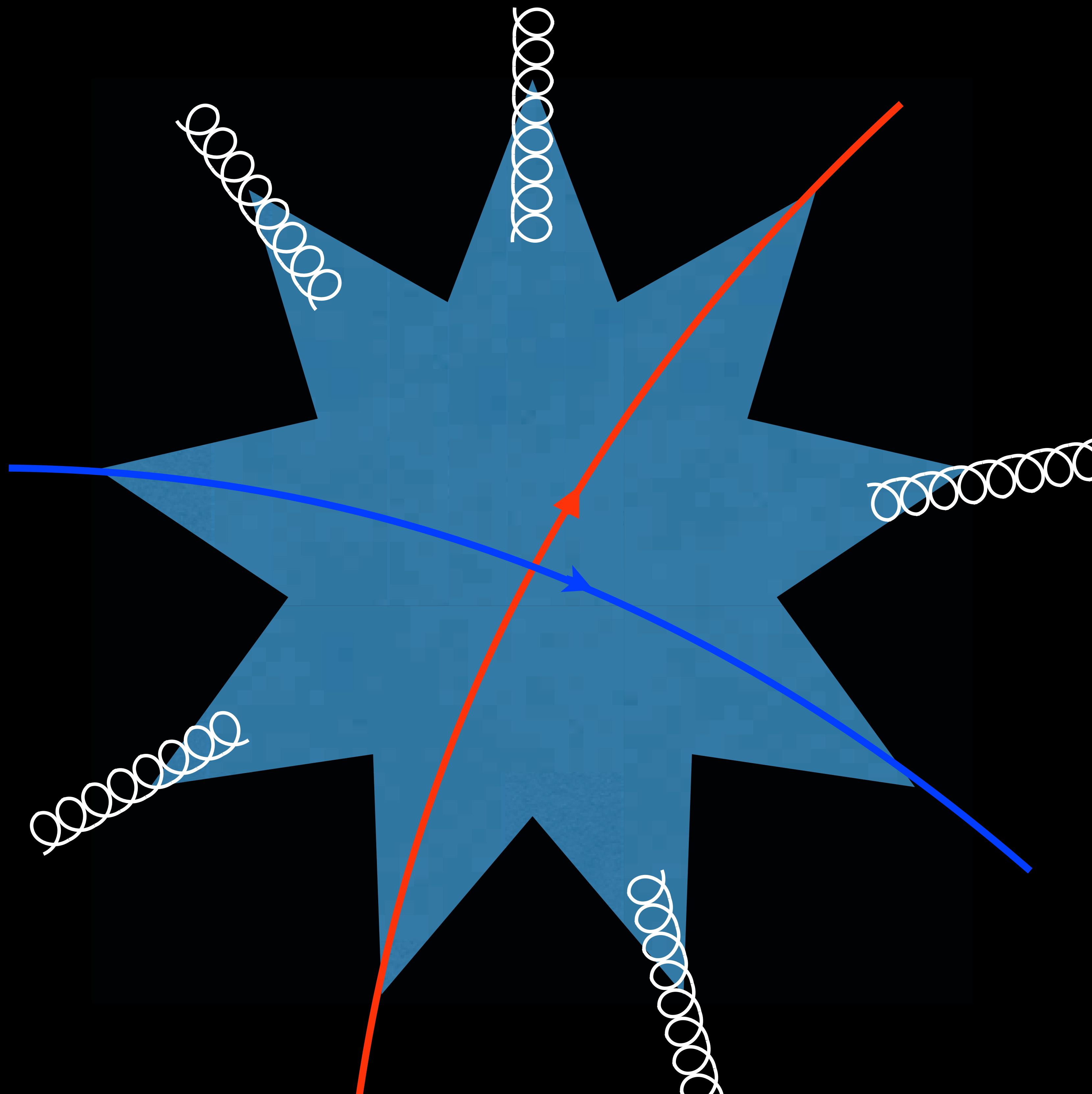
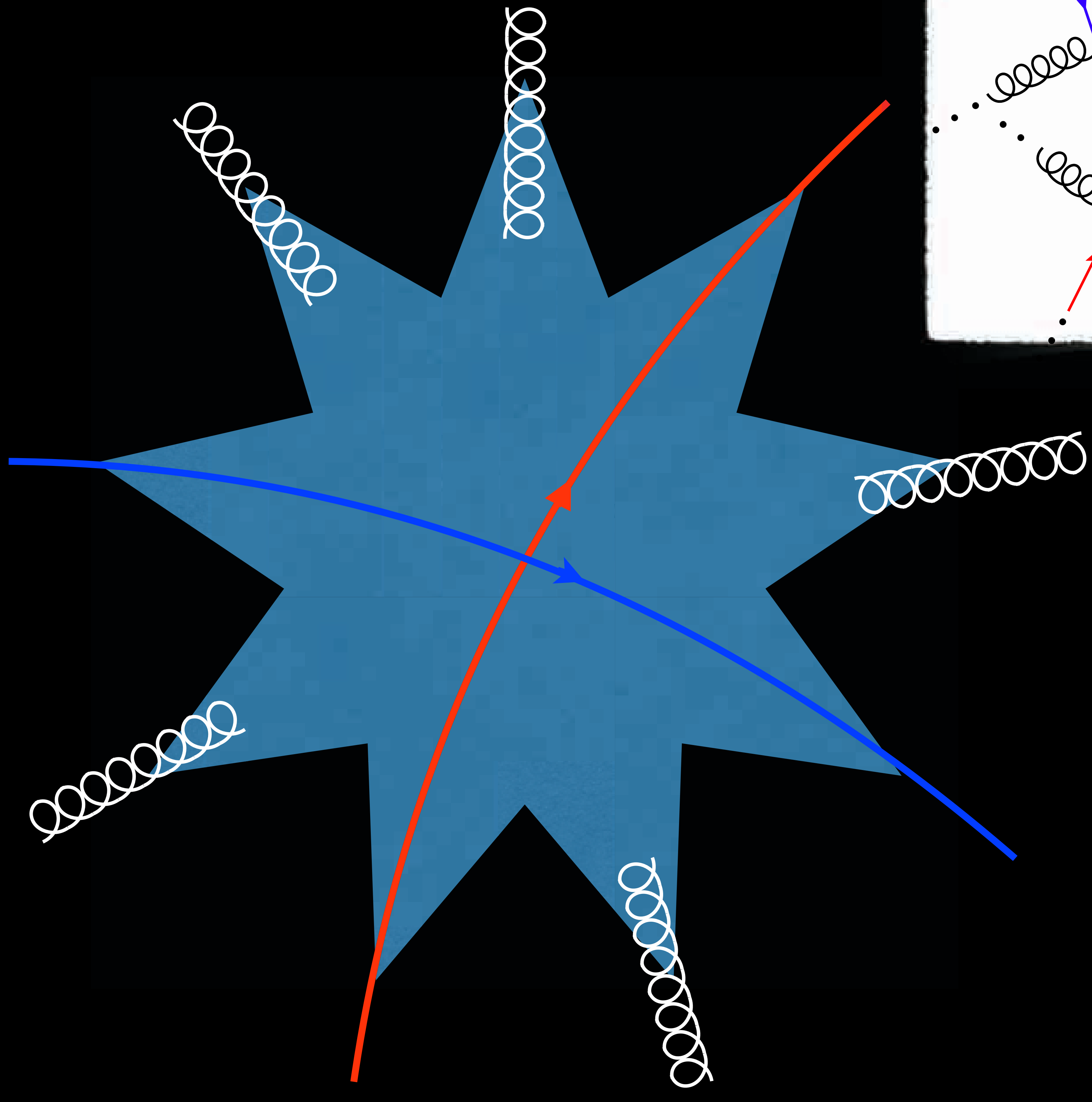
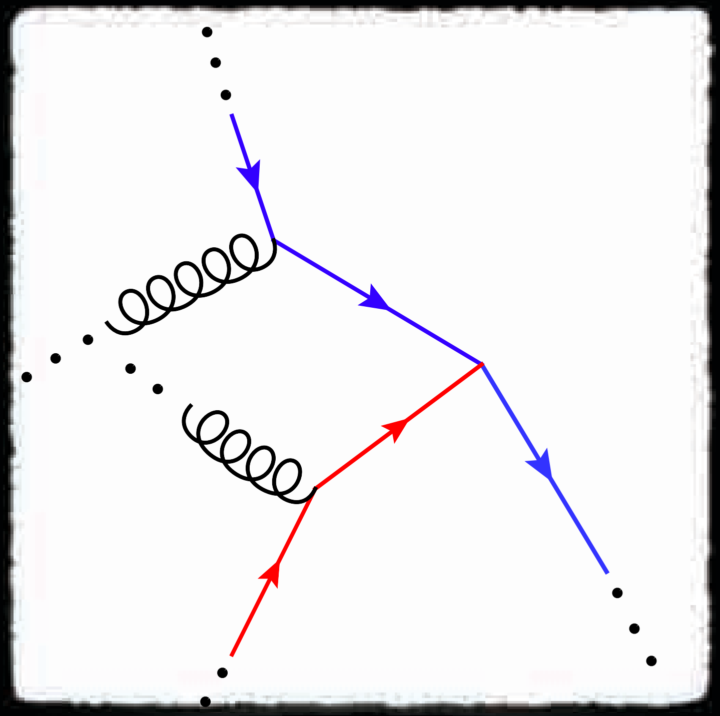


Planarity

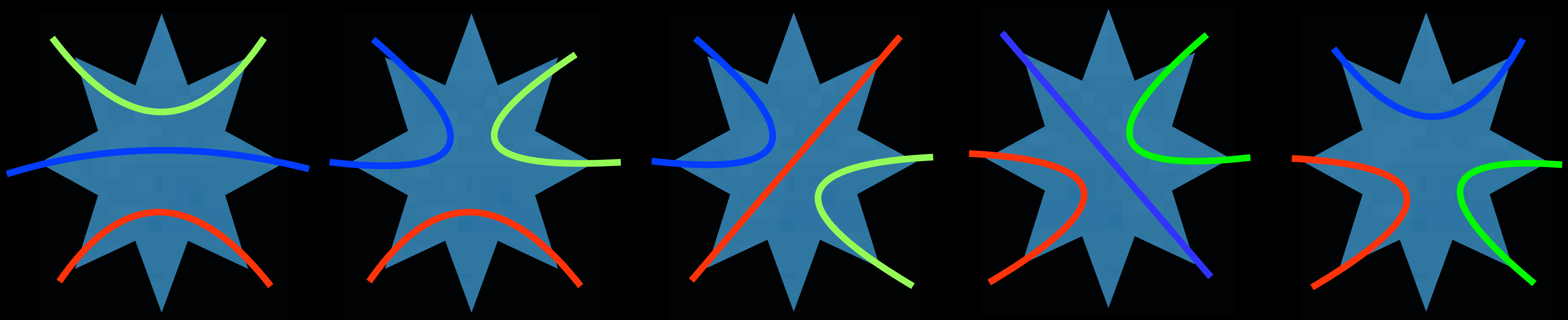




Dyck word structure

r=3

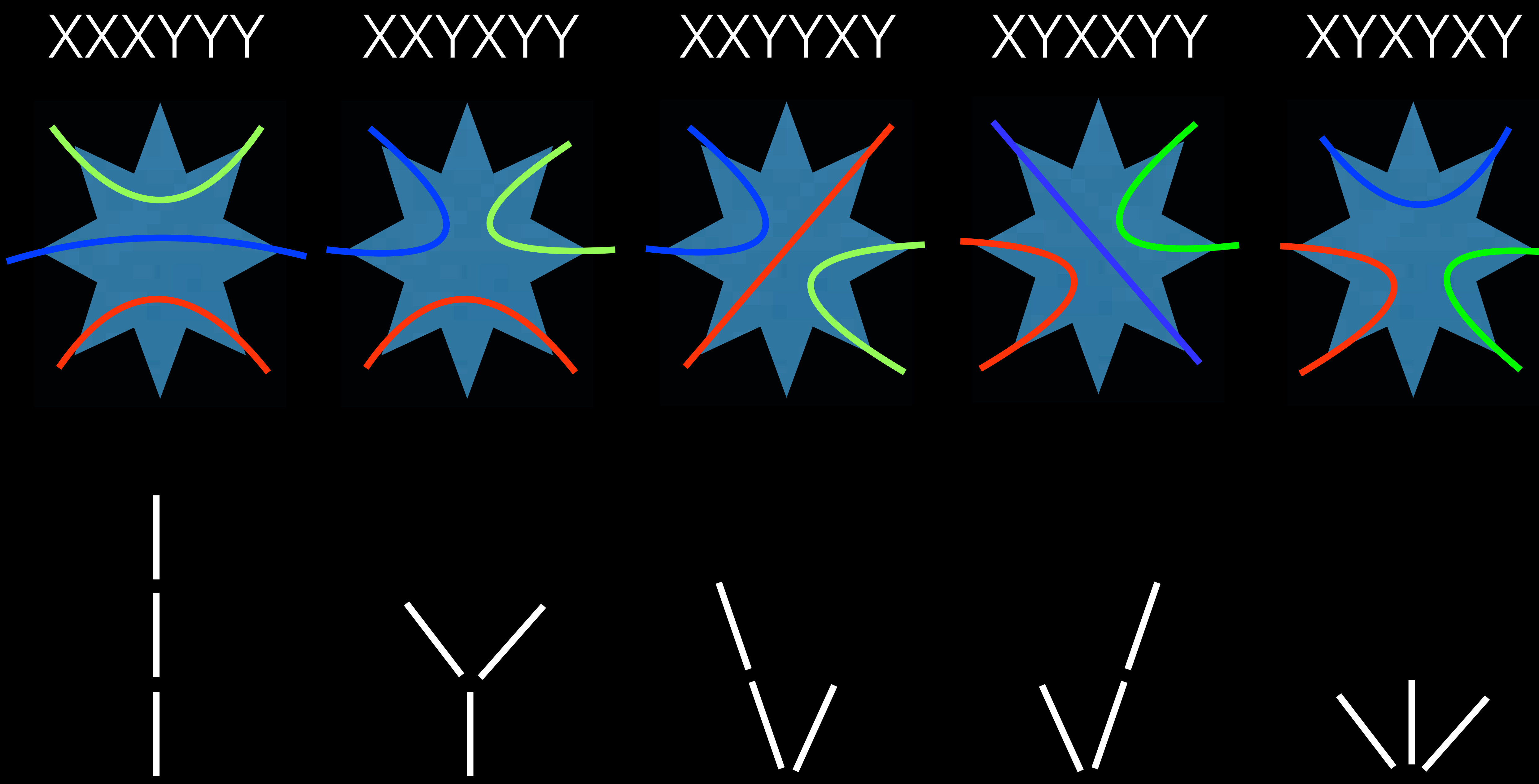
XXXYYY XXYXYY XXYYXY XYXXYY XYXYXY



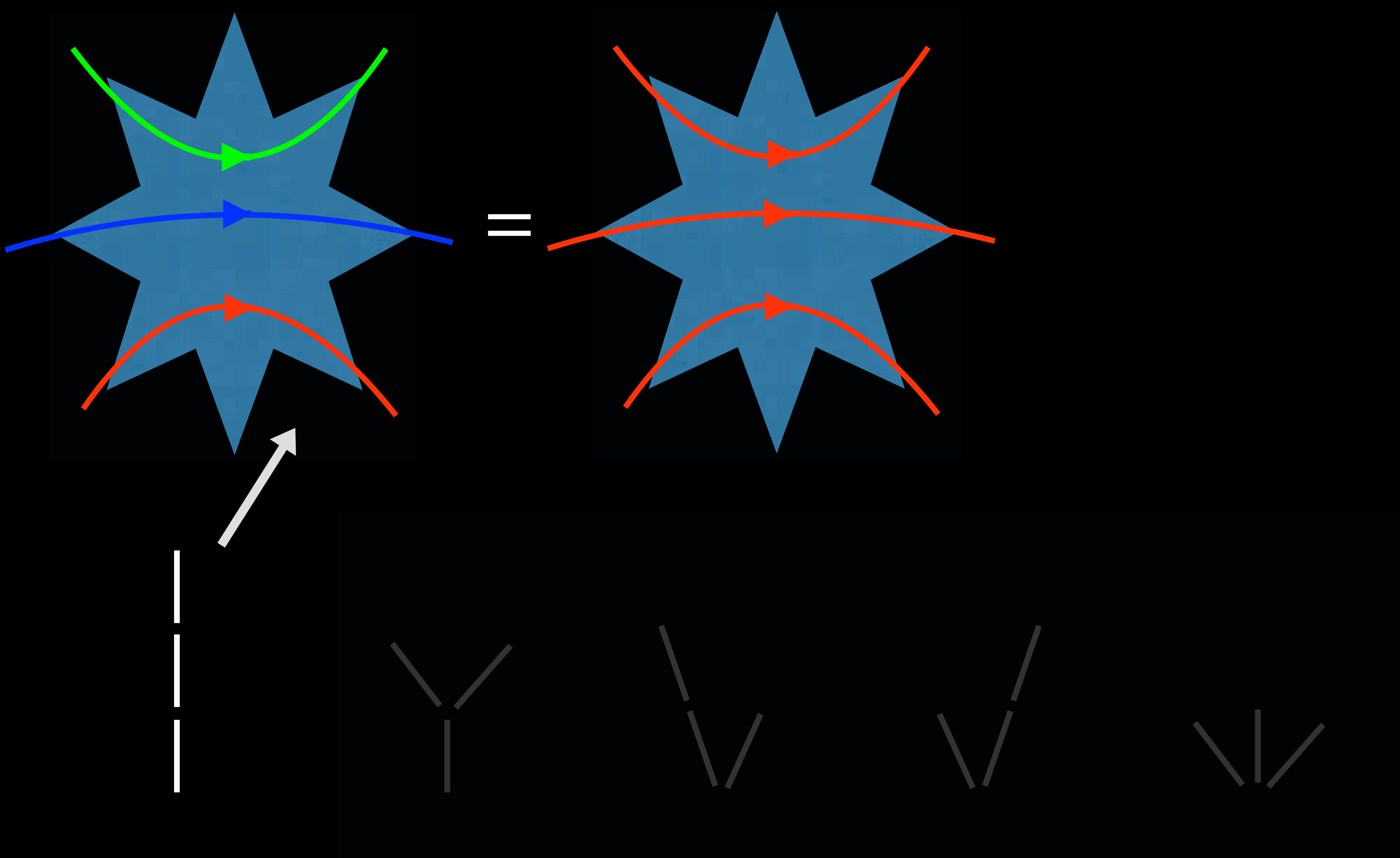
determines # independent amplitudes

One flavour recursion

r=3



One flavour recursion



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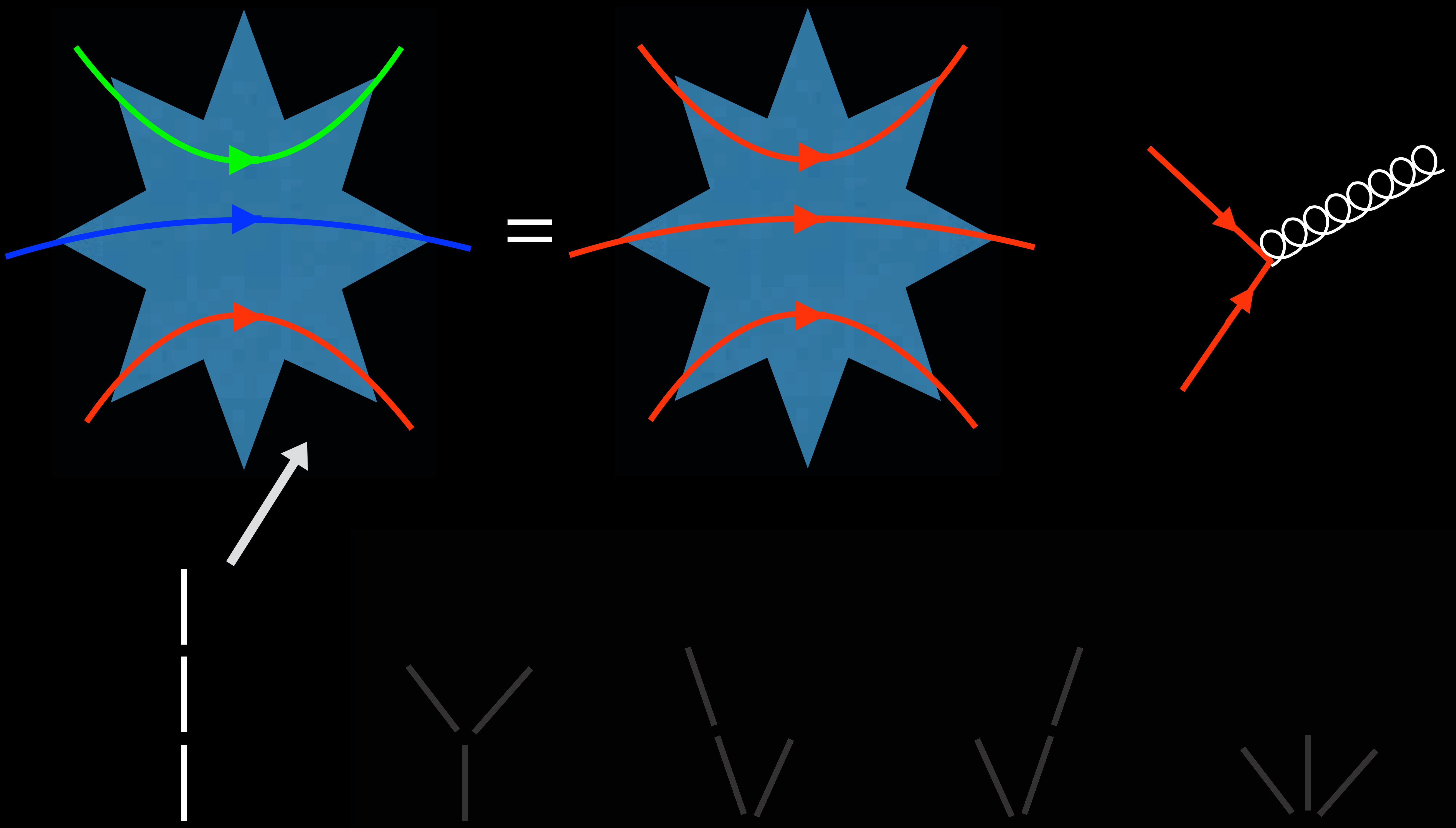
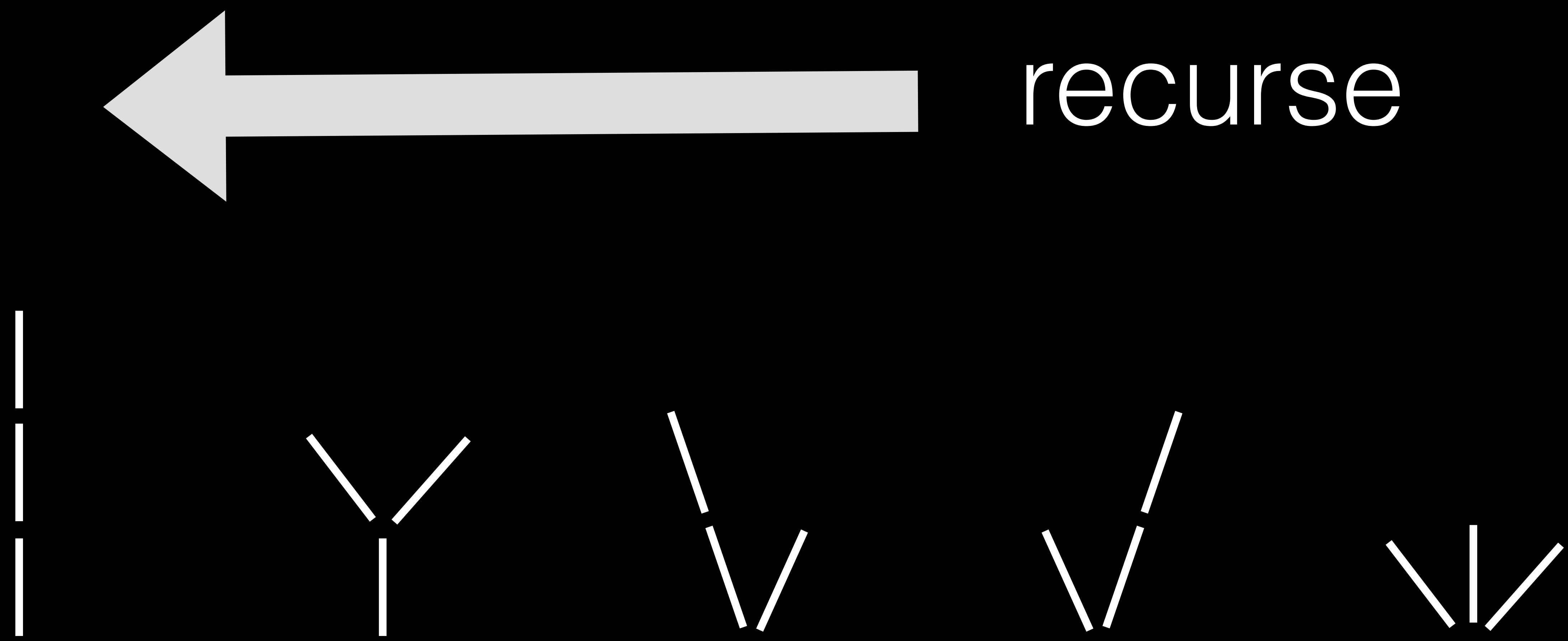


One flavour recursion



More feedback into QCD

This basis has provided a bridge for some of the most recent developments in the amplitudes field to be imported into QCD…

More feedback into QCD

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BCJ relations $\longrightarrow$ QCD trees

Bern, Carrasco, Johansson 2008

Johansson, Ochirov 2015
de la Cruz, Kniss, Weinzierl 2015

CHY representation $\longrightarrow$ QCD trees

Cachazo, He, Yuan 2014,15

de la Cruz, Kniss, Weinzierl 2015

More feedback into QCD

JO conjecture on simple way
to put colour back correctly…

$$\mathcal{A}^{\text{tree}}_{n,k} = \sum_{\sigma \in \text{Melia basis}}^{\varkappa(n,k)} C(\underline{1}, \overline{2}, \sigma)\, A(\underline{1}, \overline{2}, \sigma)\,,$$

Johansson, Ochirov 2015

c.f.

$$\mathcal{A} = \sum_{\mathcal{P}(2,..,n)} \text{Tr}(T^{a_1}, T^{a_2}, \ldots, T^{a_n})\; A(1, 2, \ldots, n)$$

More feedback into QCD

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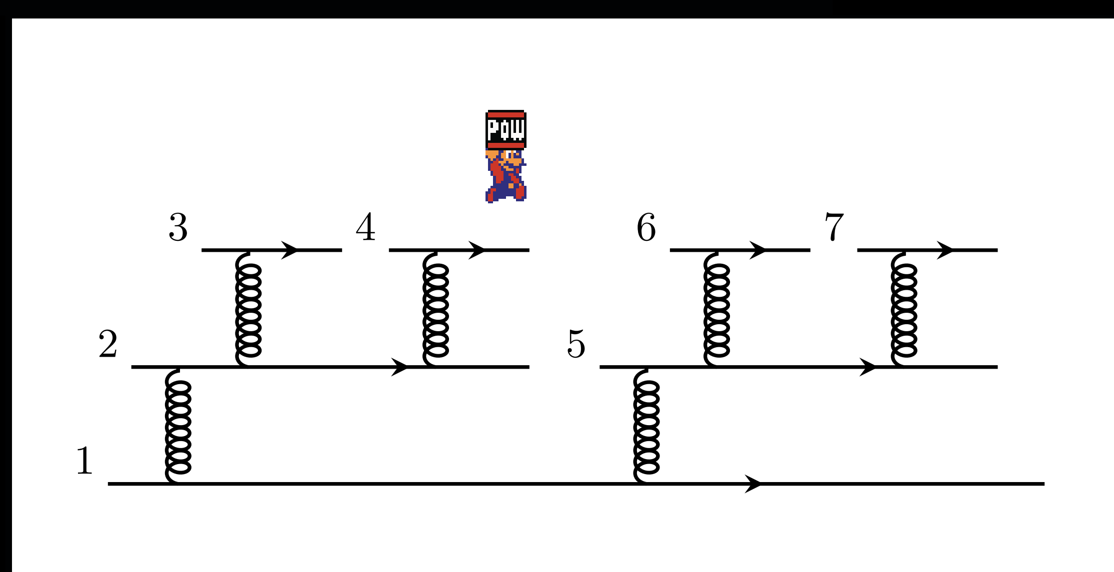
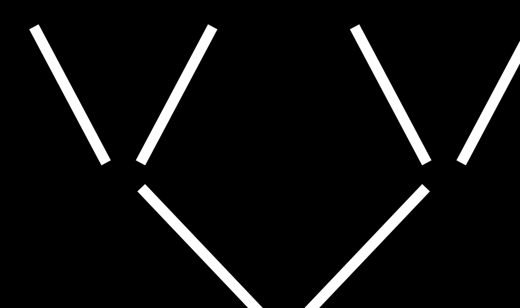
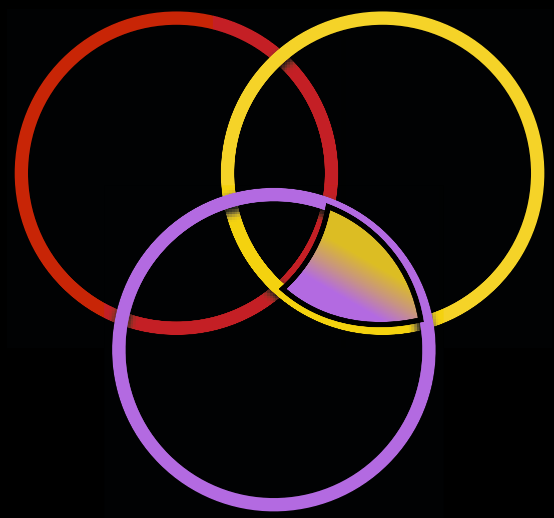
Proof using ‘Mario World’ Feynman diagrams

TM 2015



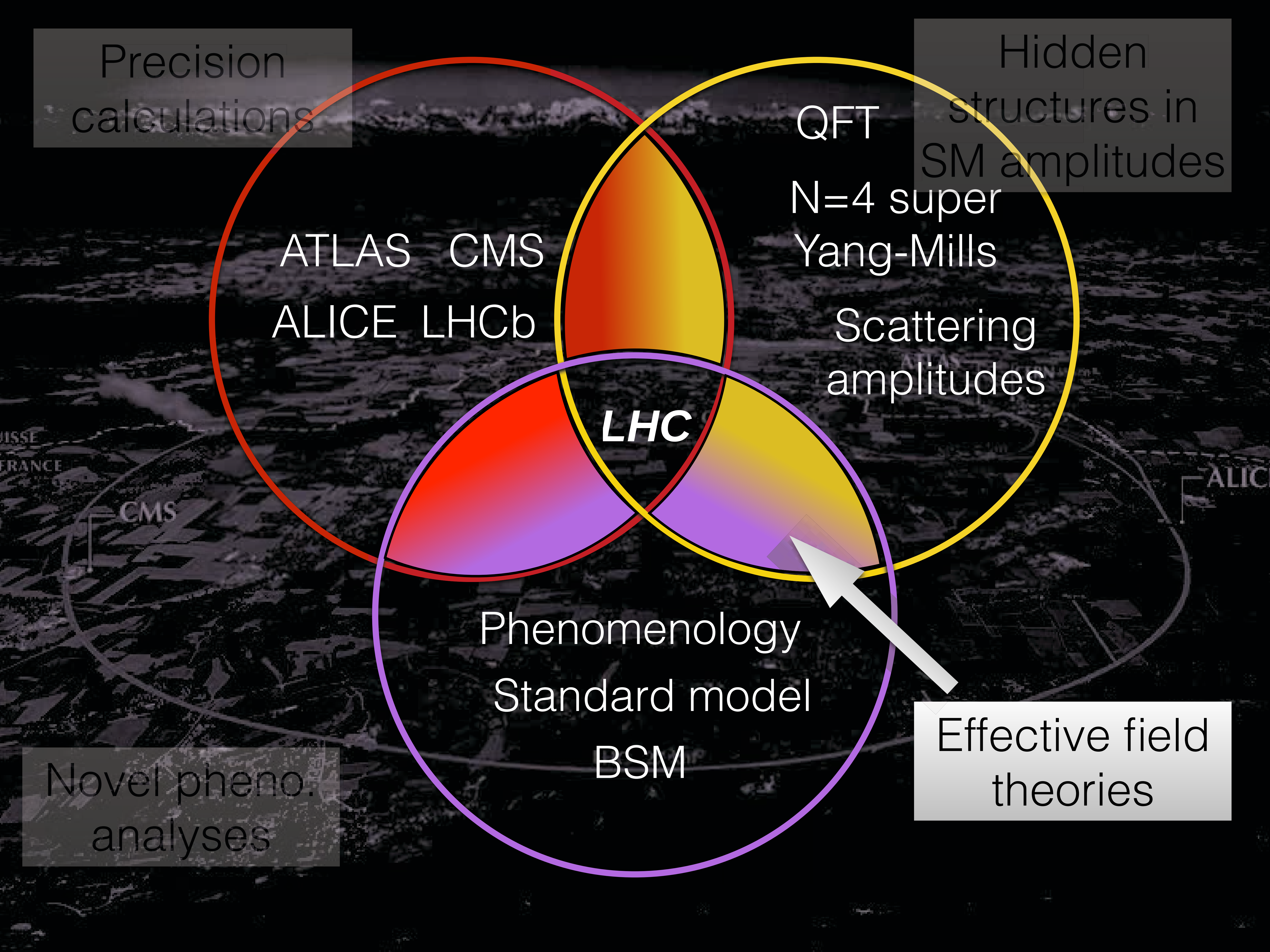




There are secrets in the standard model…

‘One flavour’ was pretty well hidden

What does it mean?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SUISSE
FRANCE
CMS
ALICE
ATLAS

Surprises in the structure of EFT

Ongoing work to understand mathematical structure of EFTs on general grounds

Henning, Lu, TM, Murayama 2015,16…

The importance and ubiquity of EFTs has been understood for decades — remarkable that very basic questions about their structure are (were) unknown

Lightening review…

$$\mathcal{L} = \sum_i c_i \mathcal{O}_i$$

It turns out the structure of an operator basis is controlled by the conformal algebra

Organize into irreps. of the conformal group — the basis is spanned by primary operators

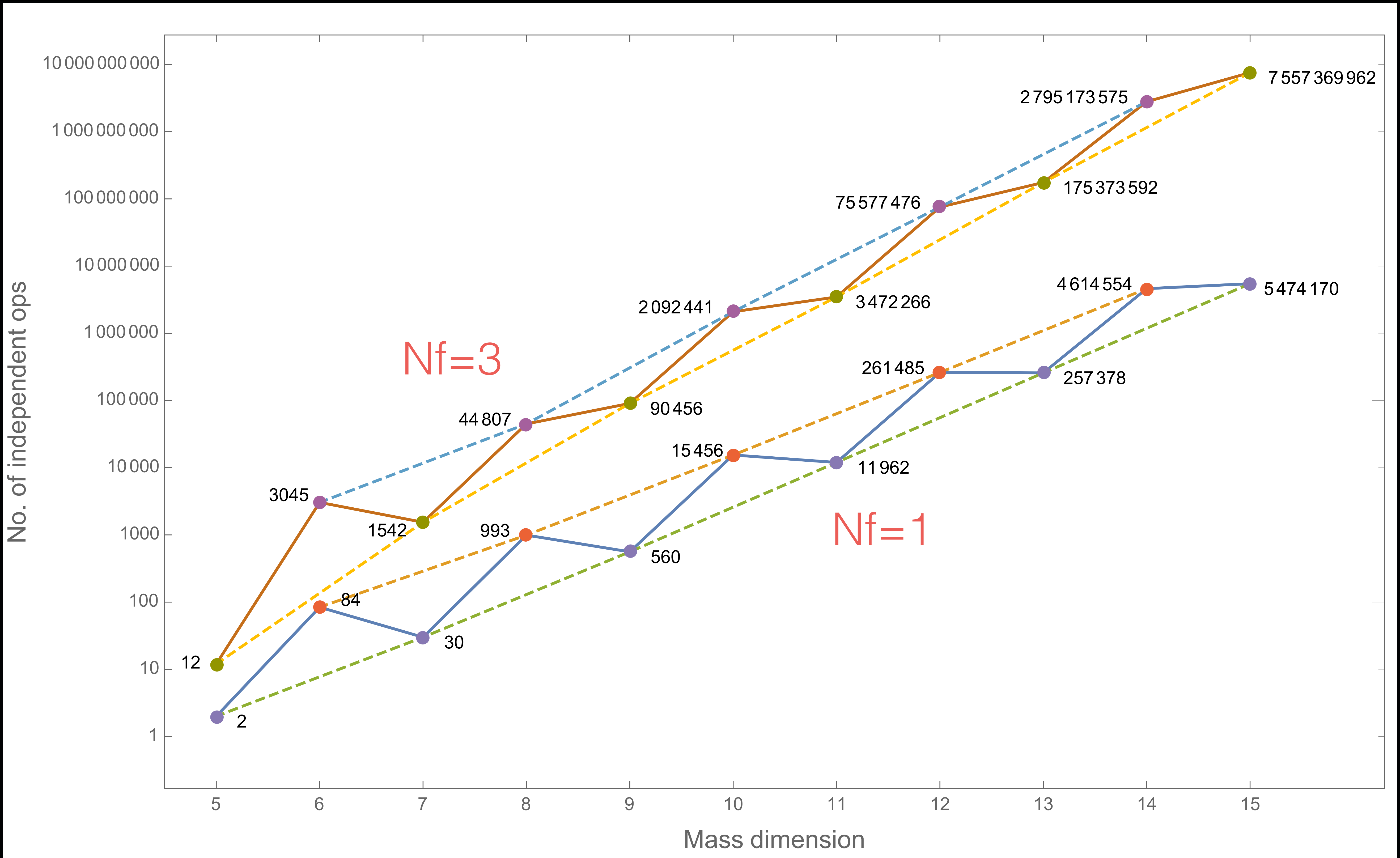
Application to the SM

On this operator basis we defined a generating function — Hilbert series

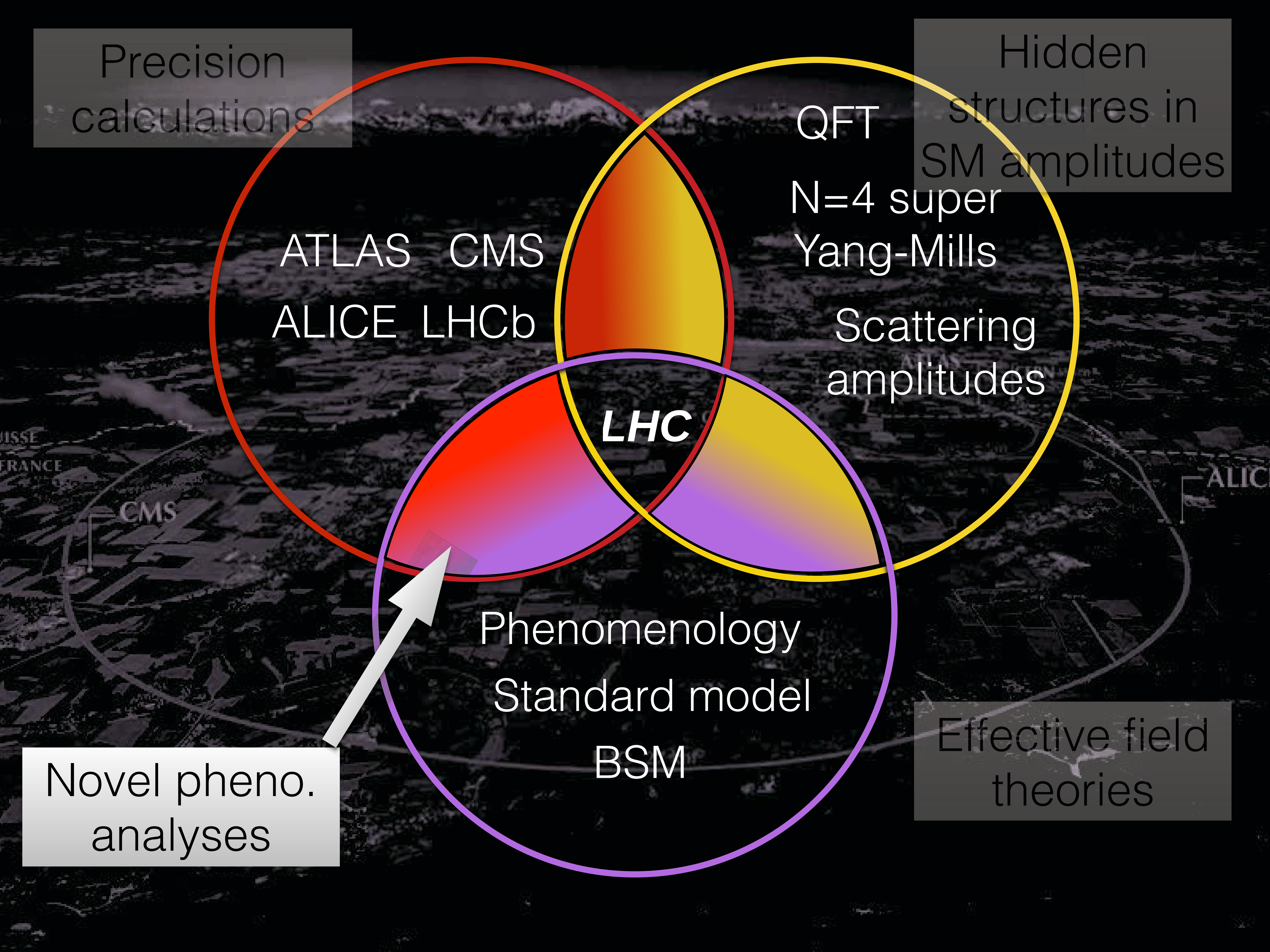
Evaluate to count the number of independent operators at a given mass dimension in the SM

Buchmuller, Wyler 1986 ←	dim 6, 1 gen.
Grzadkowski et. al. 2010 ←	dim 6, 1 gen, corrected
Manohar et. al. 2013 ←	dim 6, Nf gen.
Lehman, Martin 2014 ←	dim 7, Nf gen.
	dim 8, 1 gen.

Counting in the SM EFT



Henning, Lu, TM, Murayama 2015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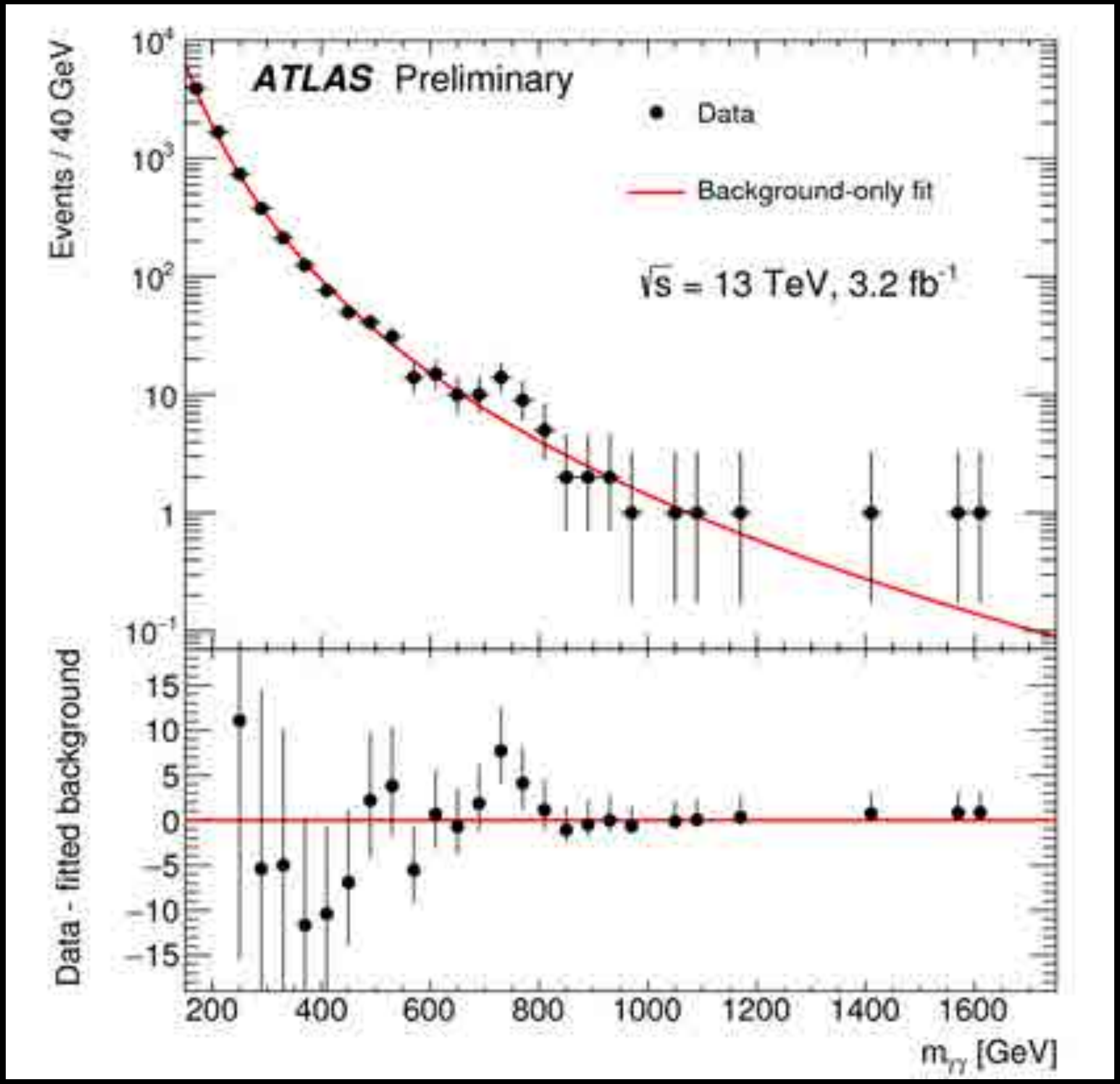
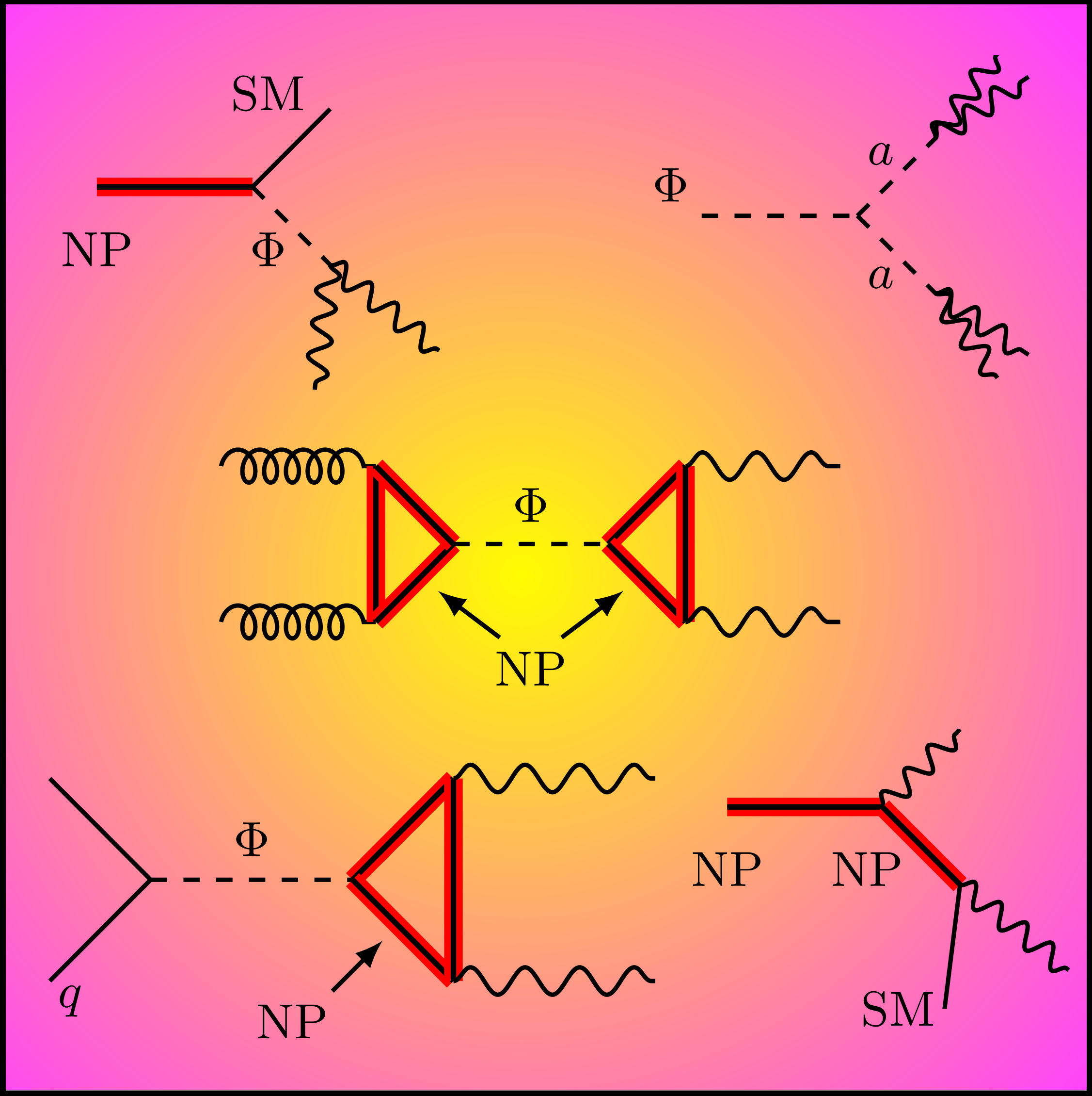
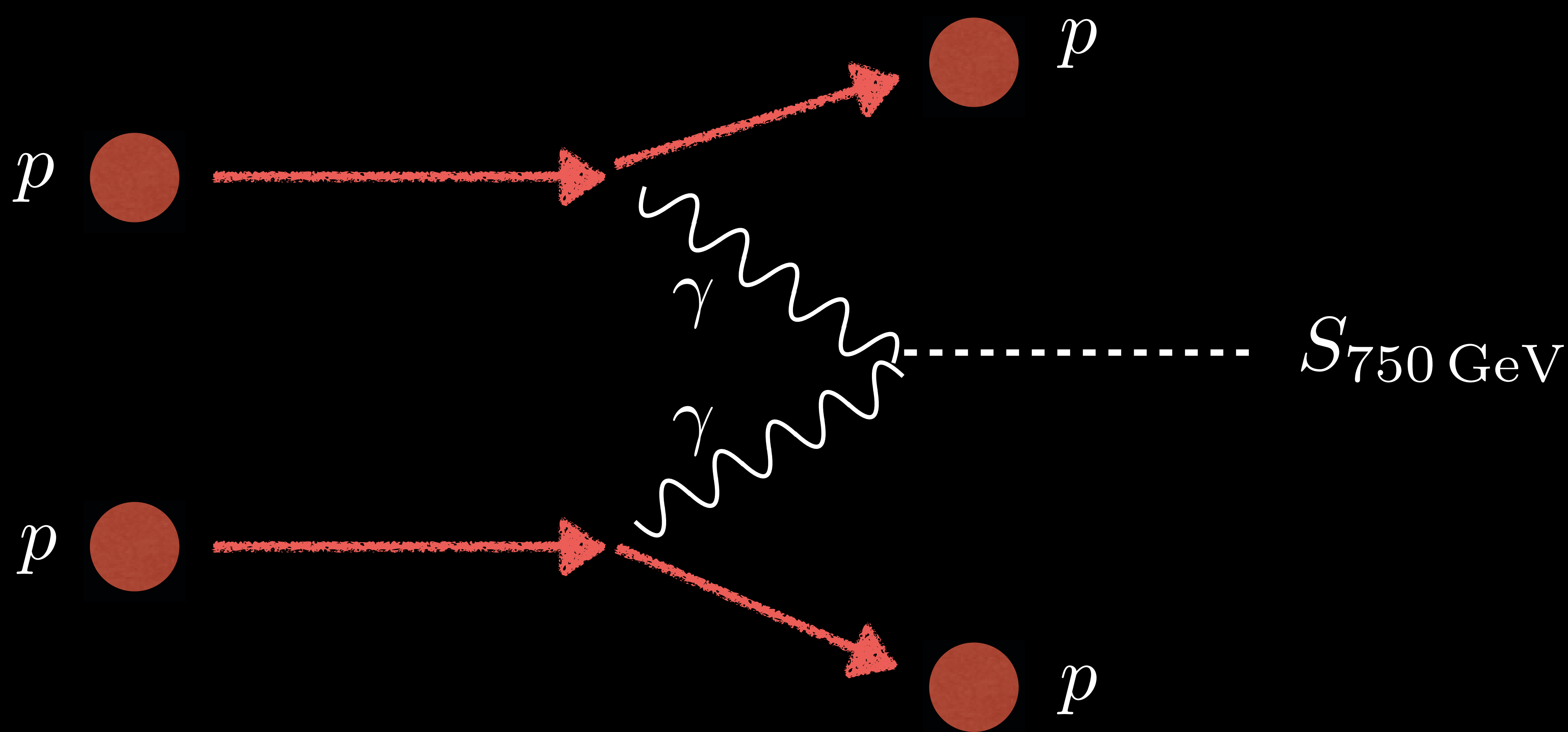
We have entered a new energy regime — anything might happen!





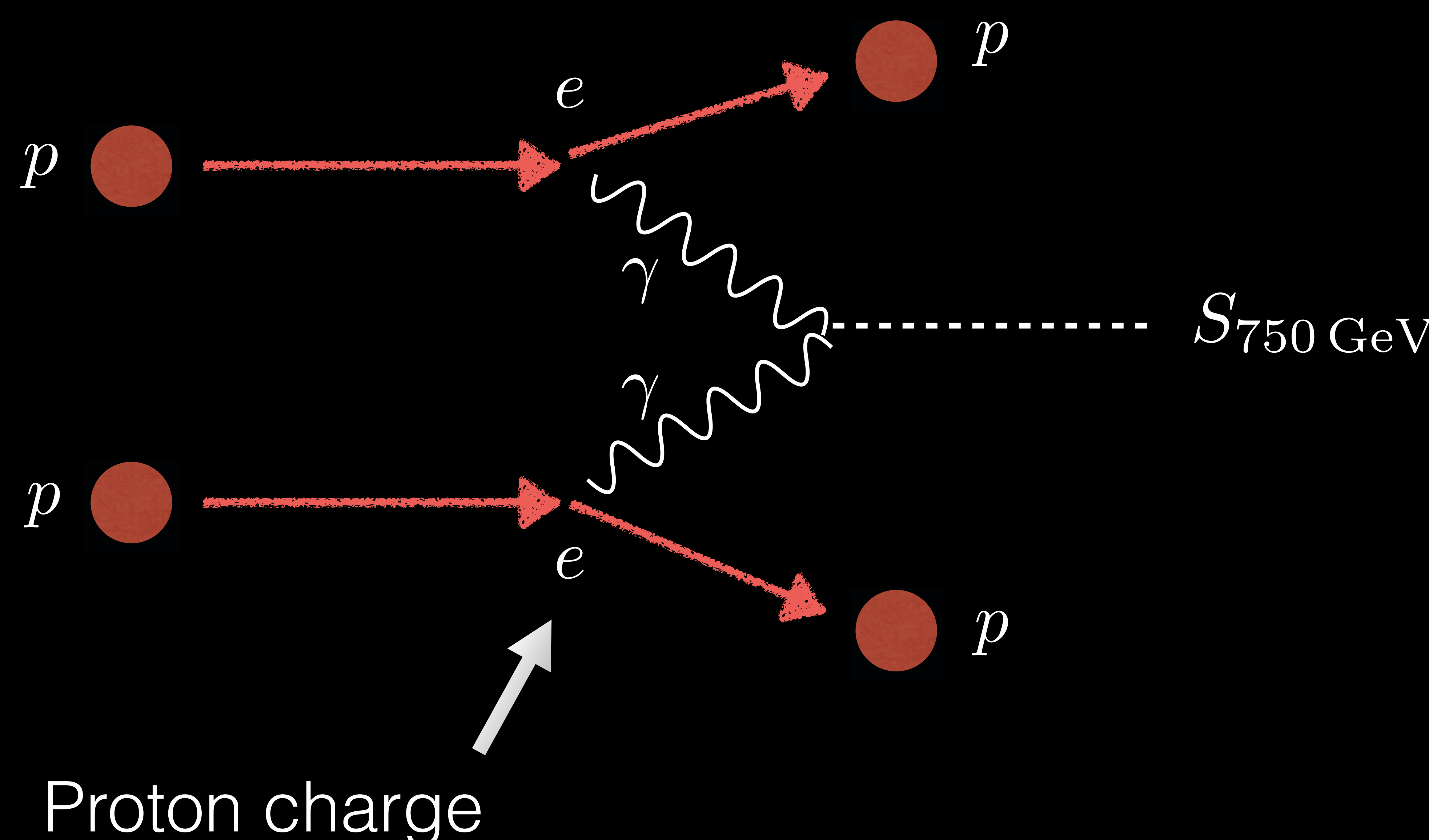
Knapen, TM, Papucci, Zurek 2015

Photon-photon fusion in elastic scattering



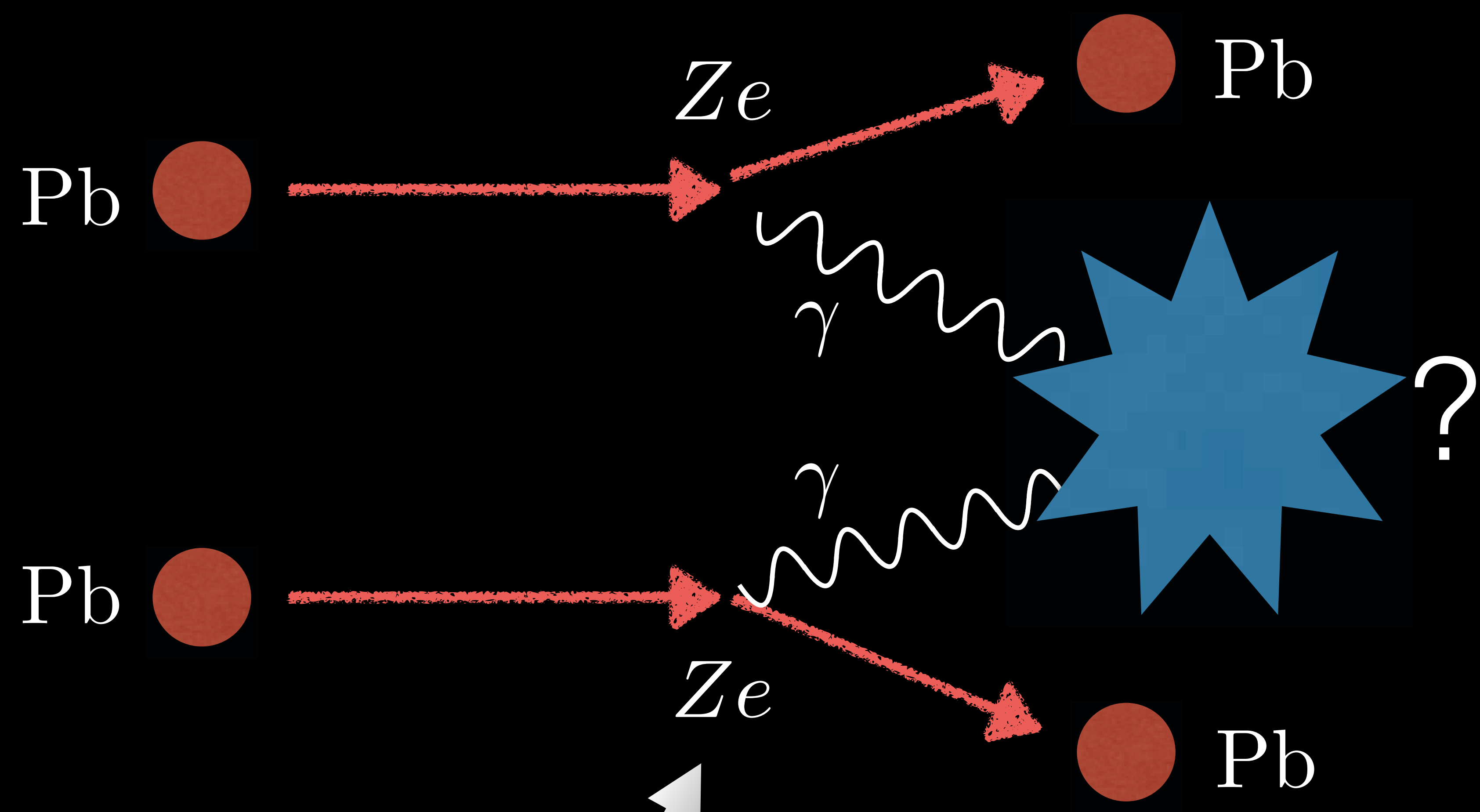
Csaki, Hubisz, Terning 15
…

Photon-photon fusion in elastic scattering



Heavy ion ‘photon collider’

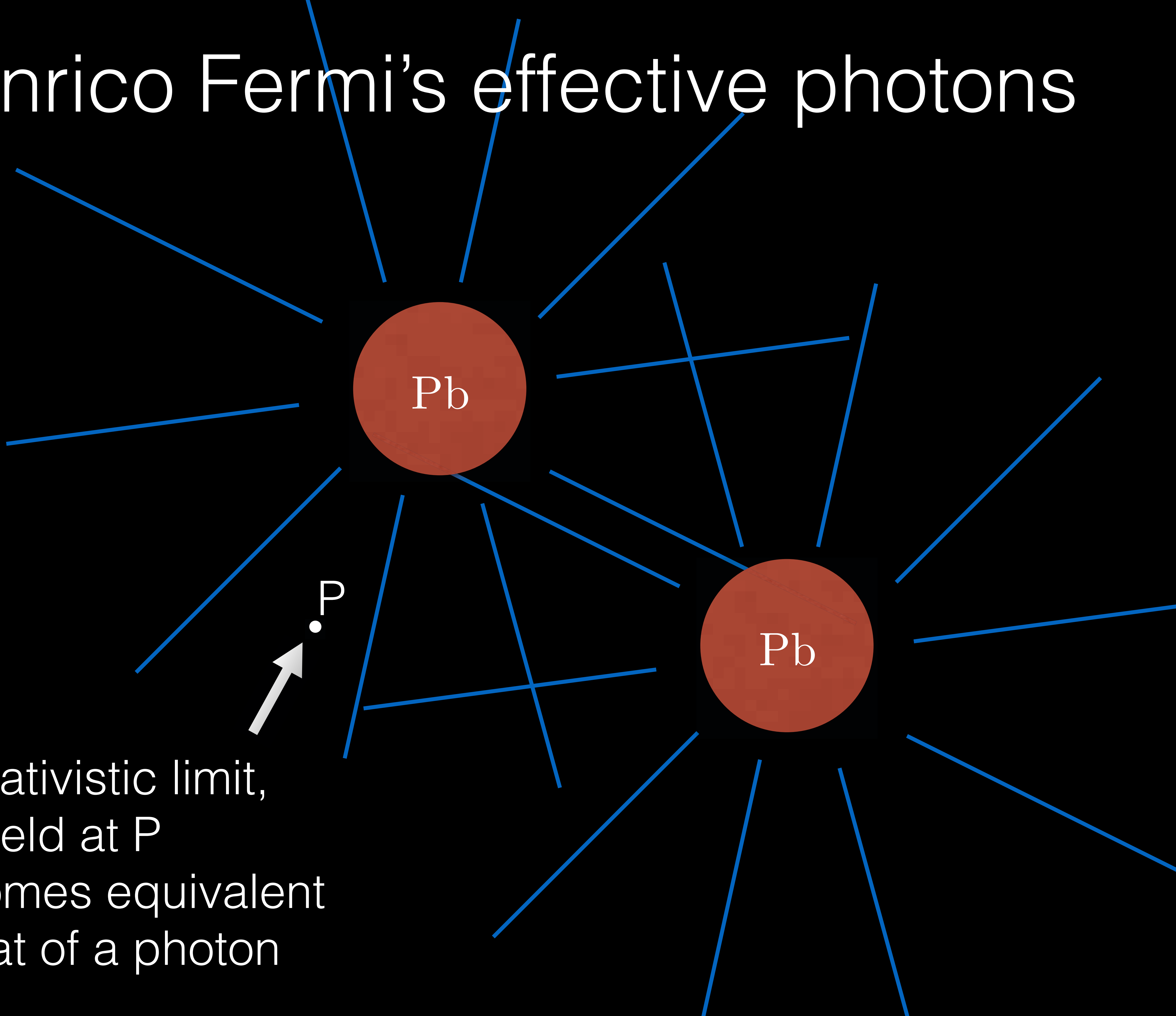
(RHICs ‘Gold Flashlight’)



Lead charge
Z=82

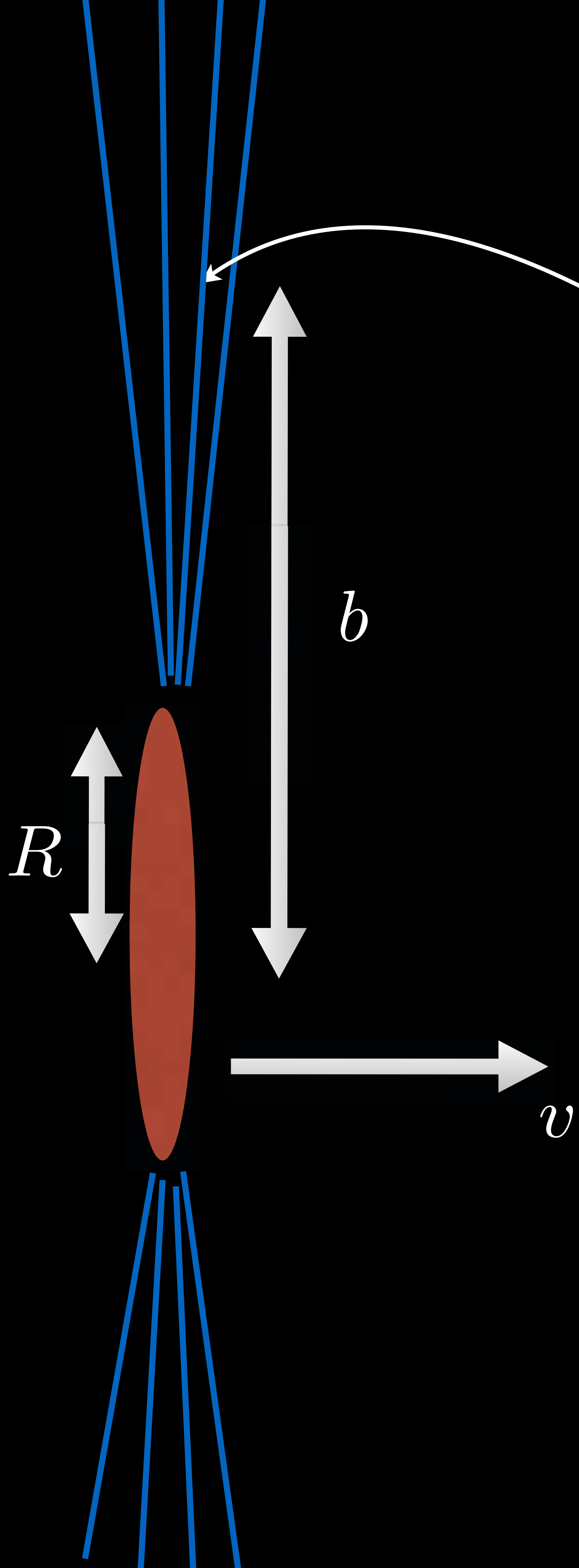
$Z^4 \sim 5x10^7$

Enrico Fermi's effective photons



In relativistic limit,
EM field at P
becomes equivalent
to that of a photon

Mass reach



$$\Delta t \sim \frac{b}{\gamma v} \implies \omega_{\max} \sim \frac{\gamma}{b}$$

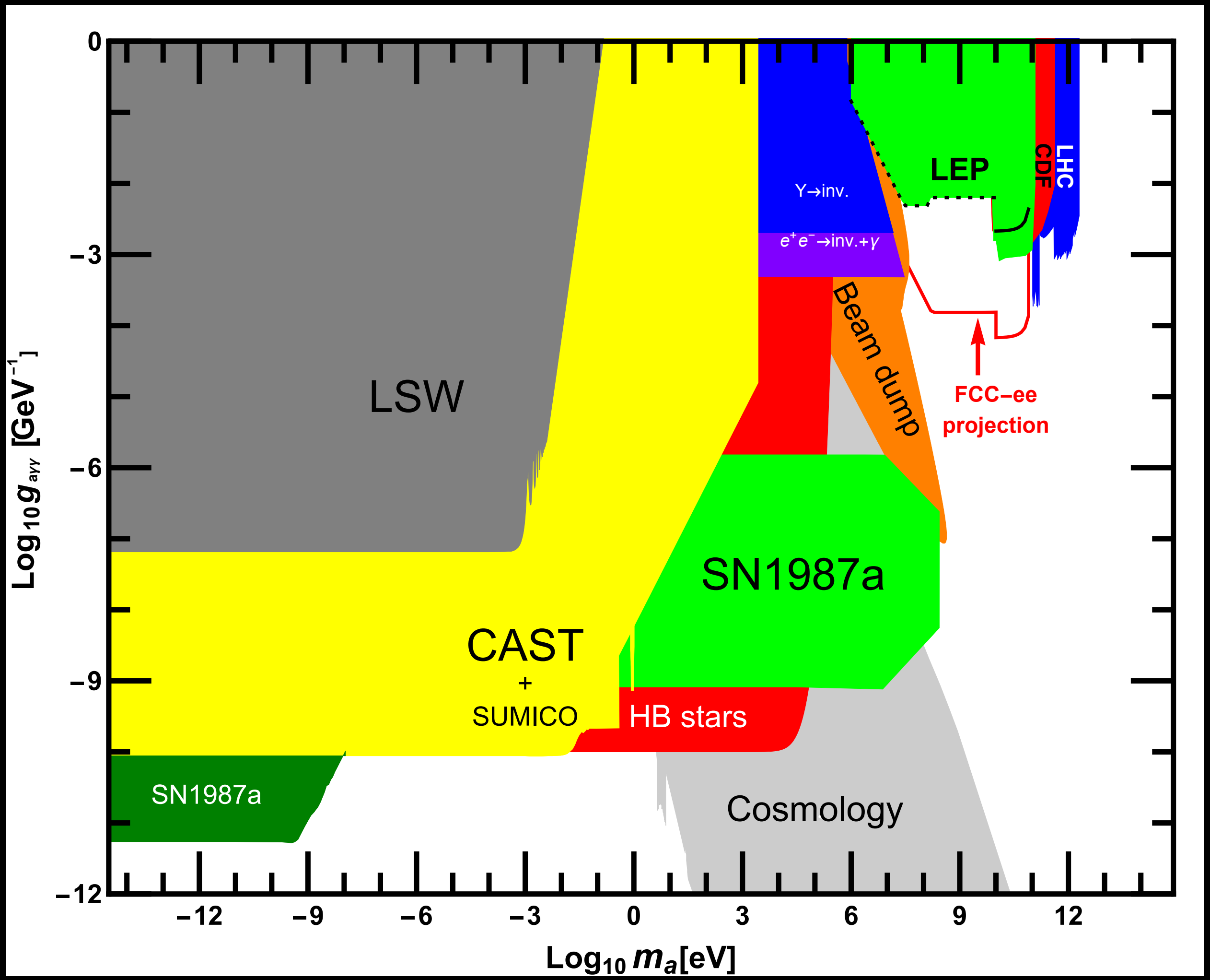
	$b_{\min} = 2R$	E_{nucleon}	$2\omega_{\max}$
p	1.6 fm	7.5 TeV	1500 GeV
Pb	14 fm	5.6 TeV	160 GeV

Search for axion like particles

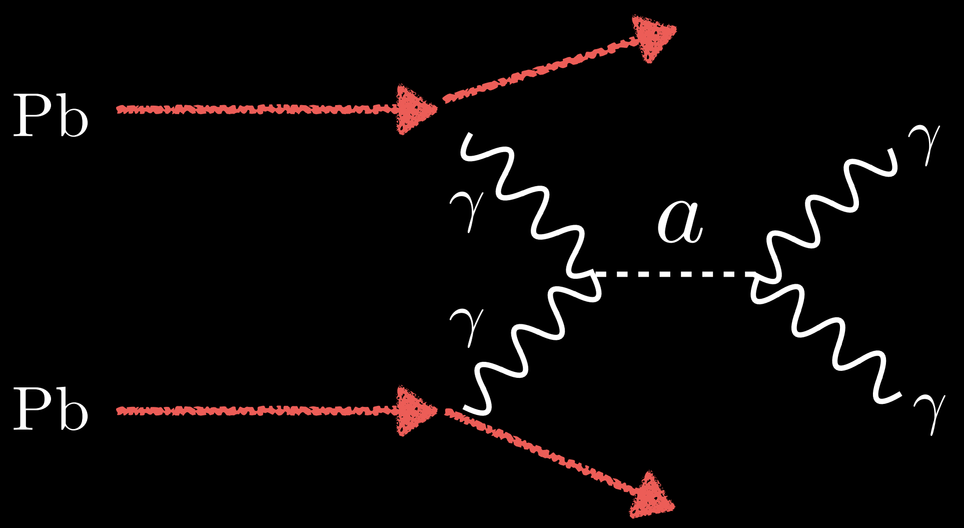
Knapen, Lin, Lou, TM 16

$$\mathcal{L} = \frac{1}{2}(\partial a)^2 - \frac{1}{2}M^2 a^2 - \frac{a}{\Lambda} F^{\mu\nu} \widetilde{F}^{\mu\nu}$$

e.g. pseudo Nambu-Goldstone boson from some spontaneously broken symmetry



Jaeckel, Spannowsky 15



Sensitive to mass range M~GeV

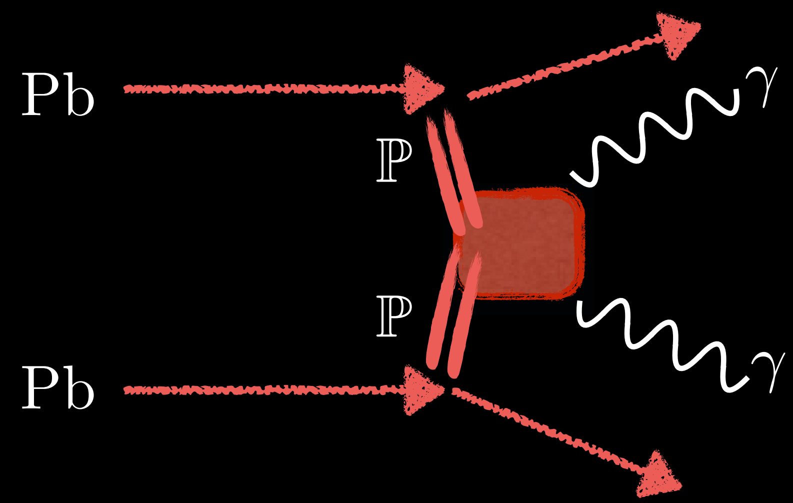
How to trigger?

Two new triggers prepared (CMS Ultra-Peripheral Collisions working group analysis released soon)

Two photons with E > 2 GeV and no hadronic activity in one of the forward calorimeters

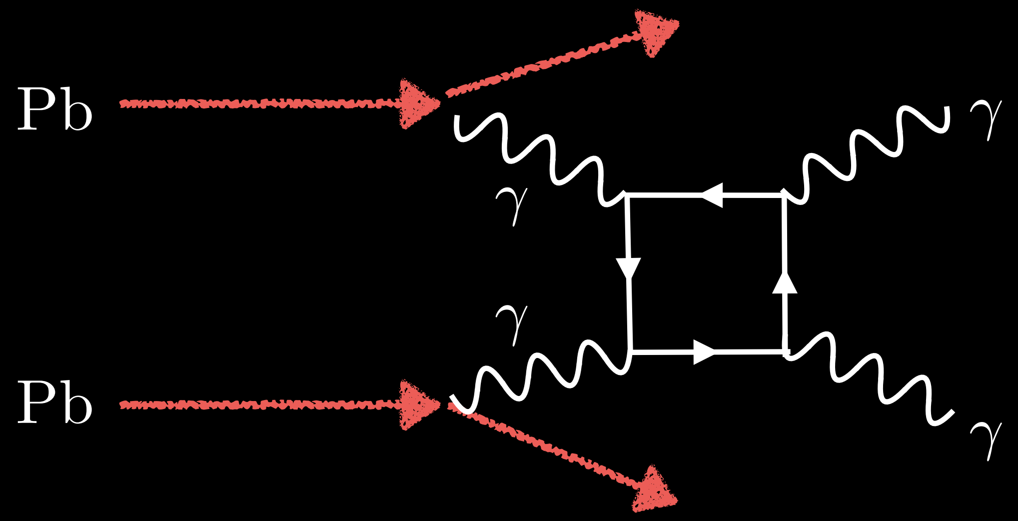
One photon E > 5 GeV and no hadronic activity in one of the forward calorimeters

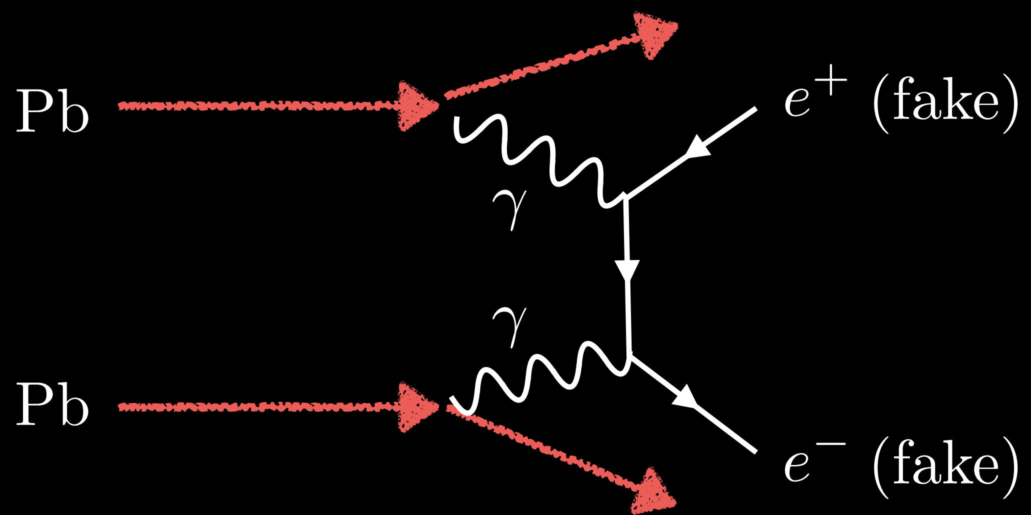
Backgrounds



CEP (Central exclusive production)

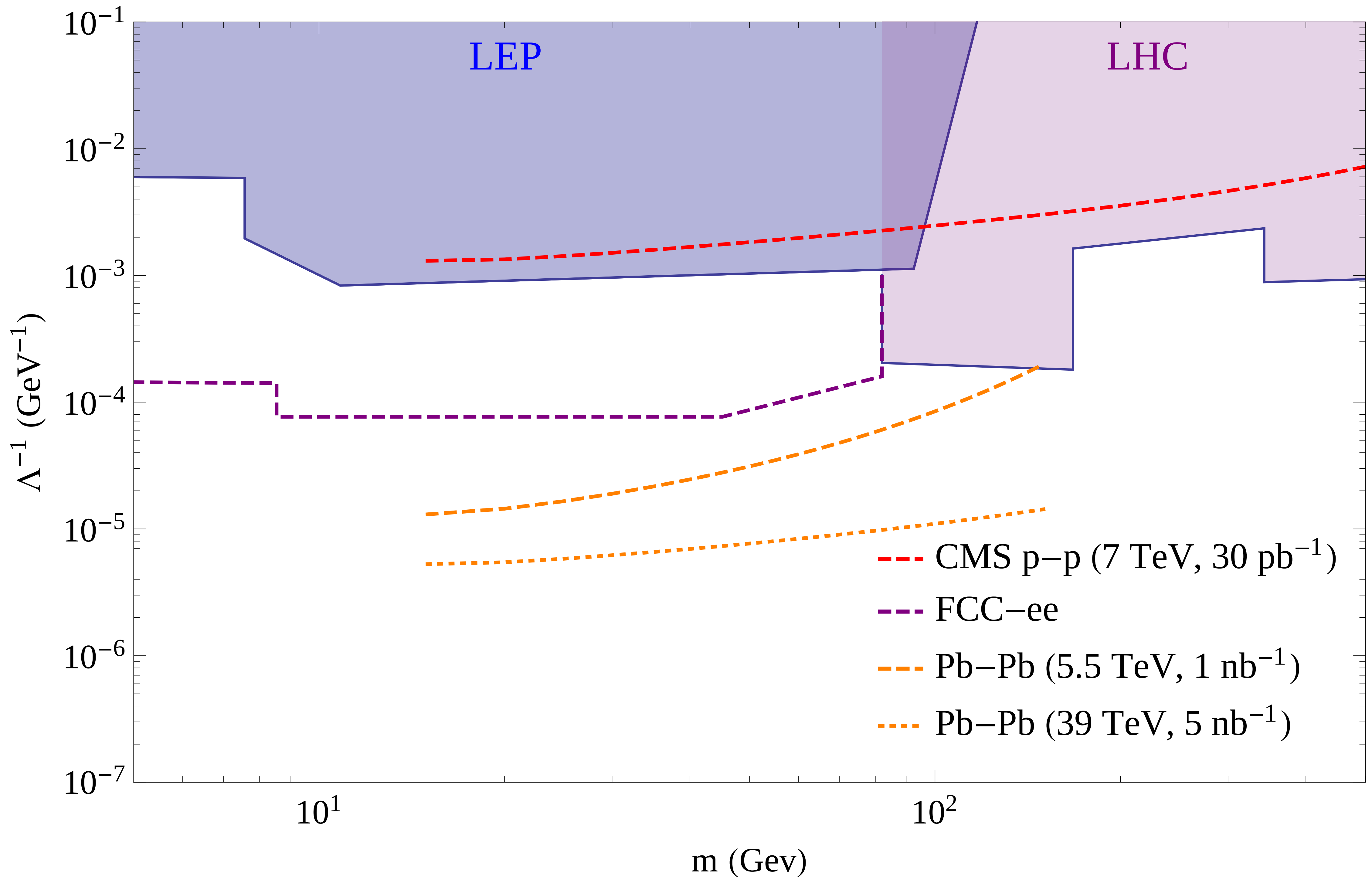
LBL (Light by light)





Fakes

(Preliminary) limits…



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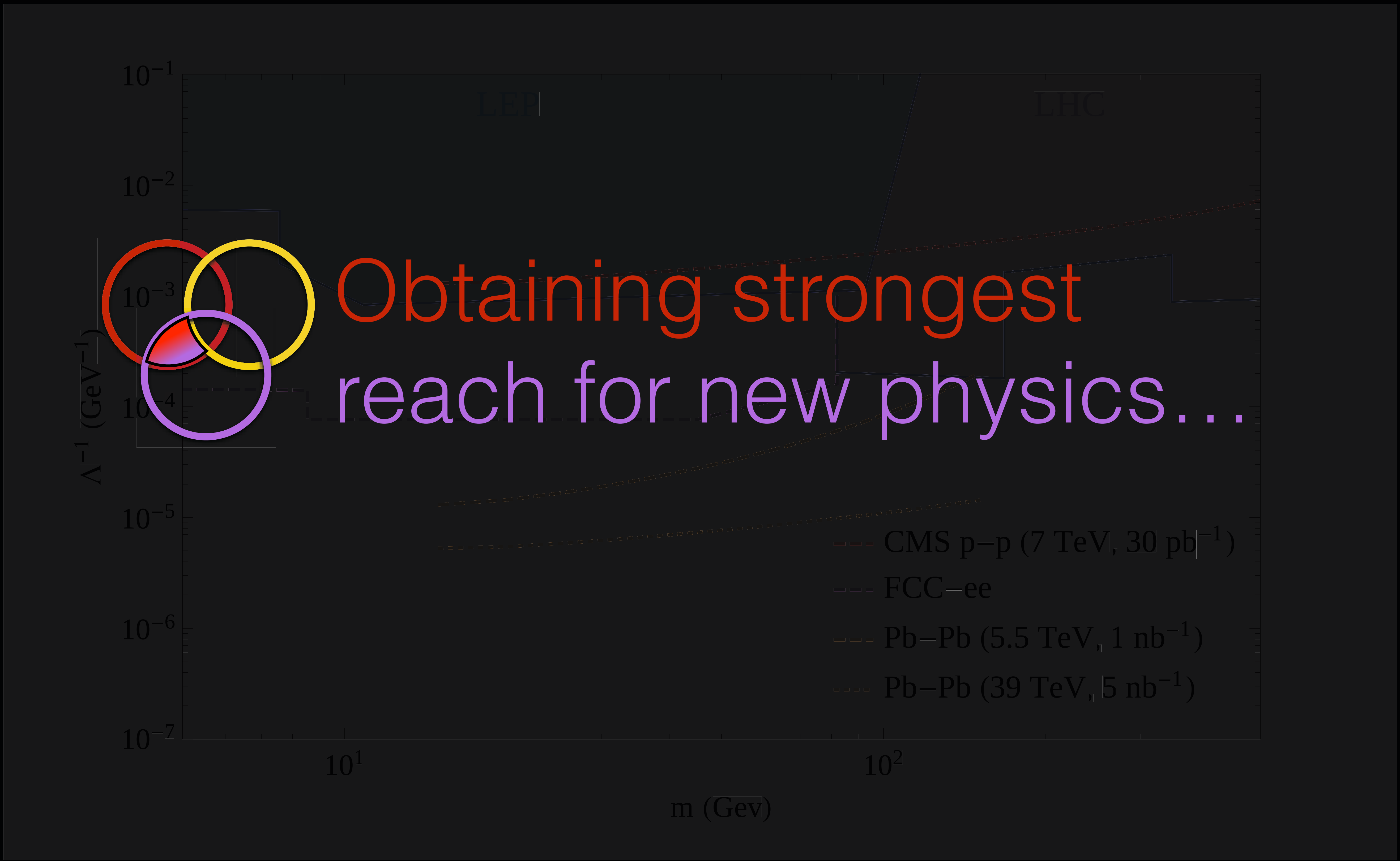
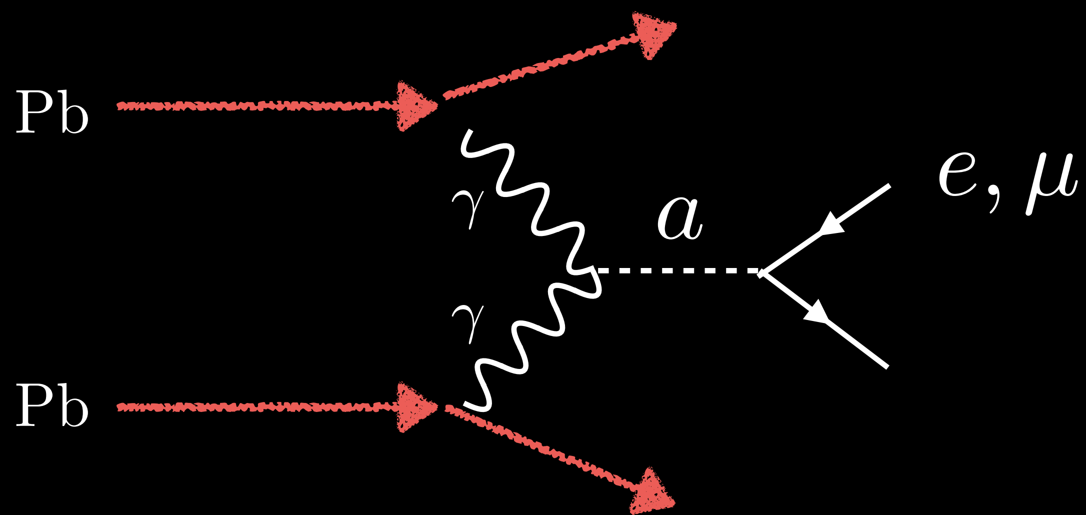


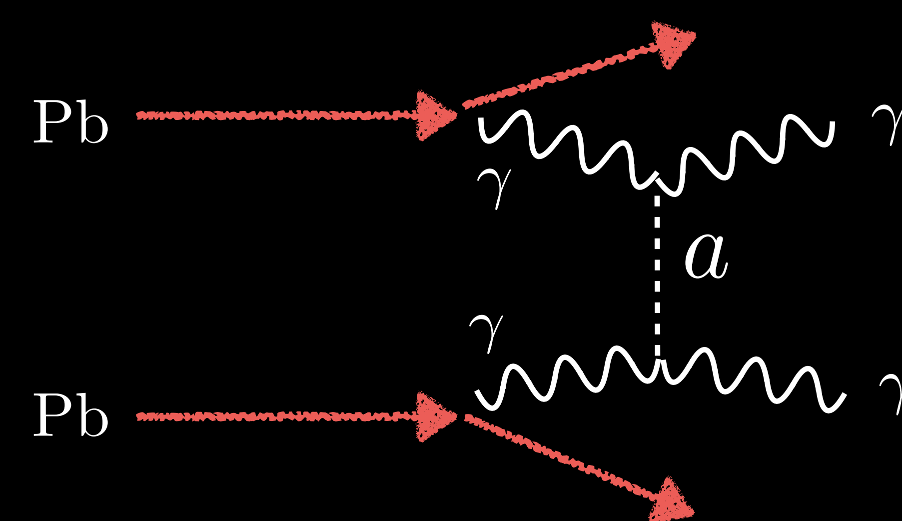
Obtaining strongest

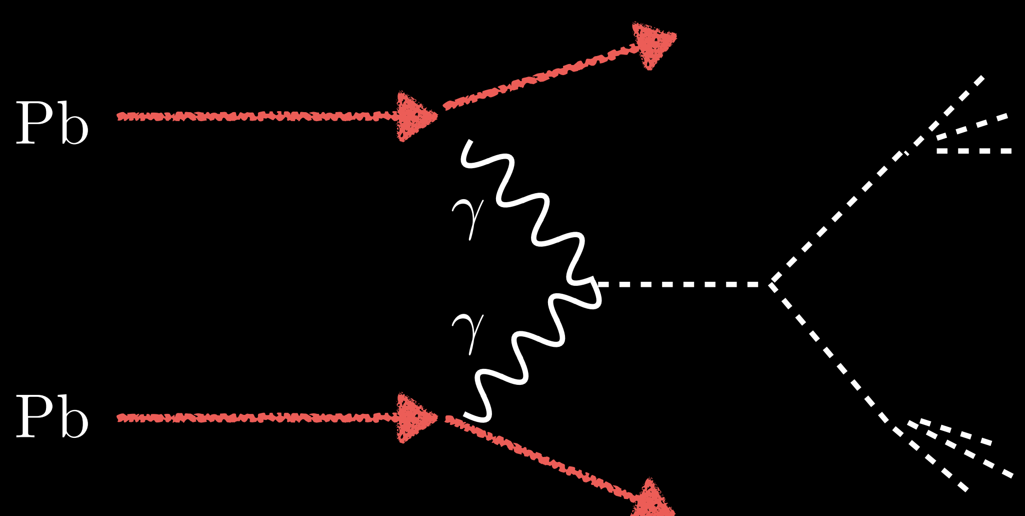
reach for new physics…

Gamma-gamma gateway…

What else can you do with the worlds highest energy ‘Lead flashlight’?

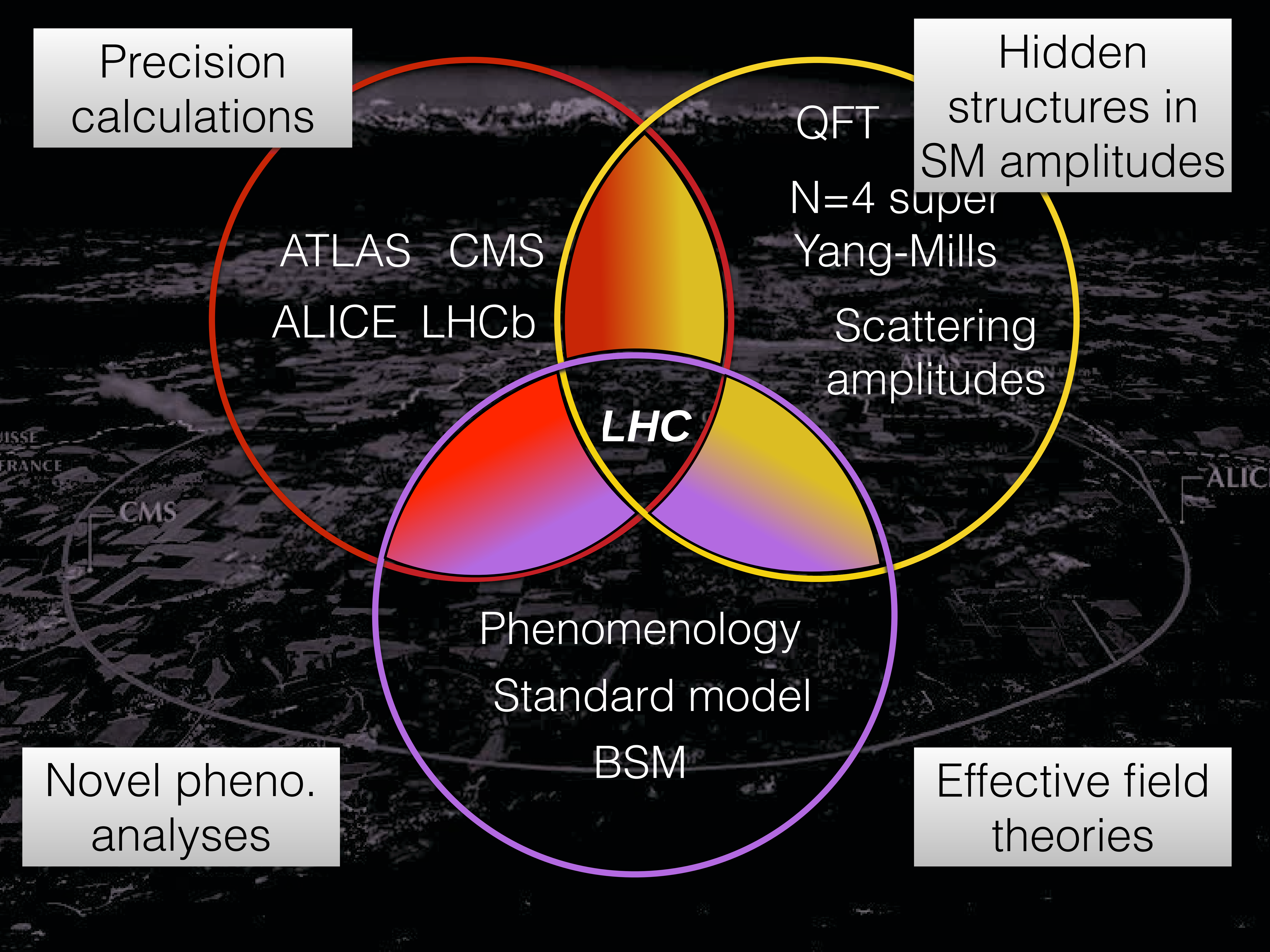






hidden valley

potential to exploit exquisite ALICE and LHCb tracking?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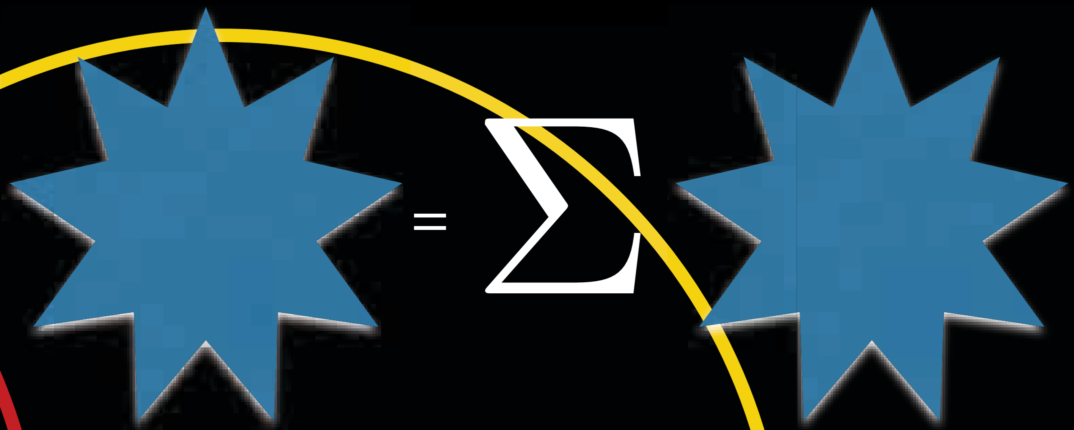
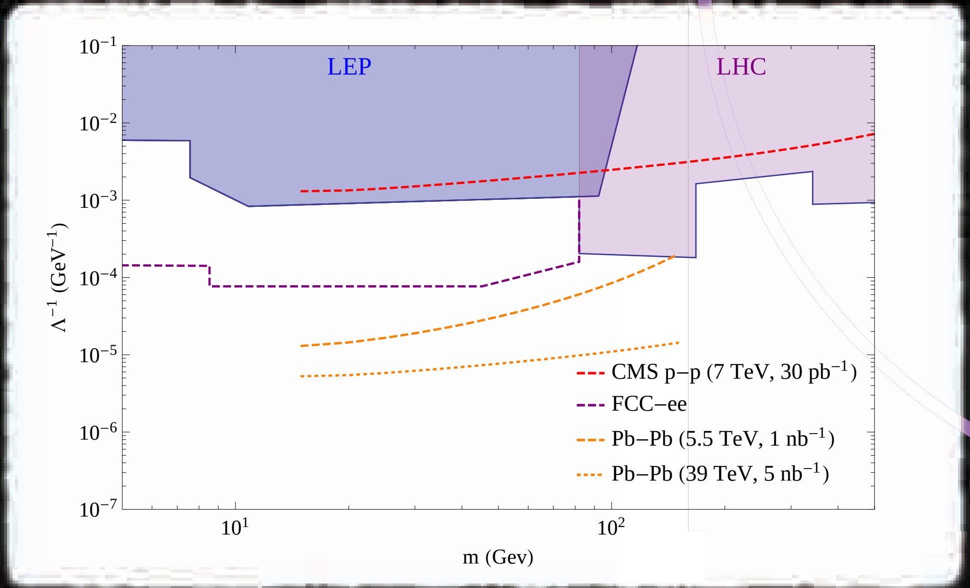
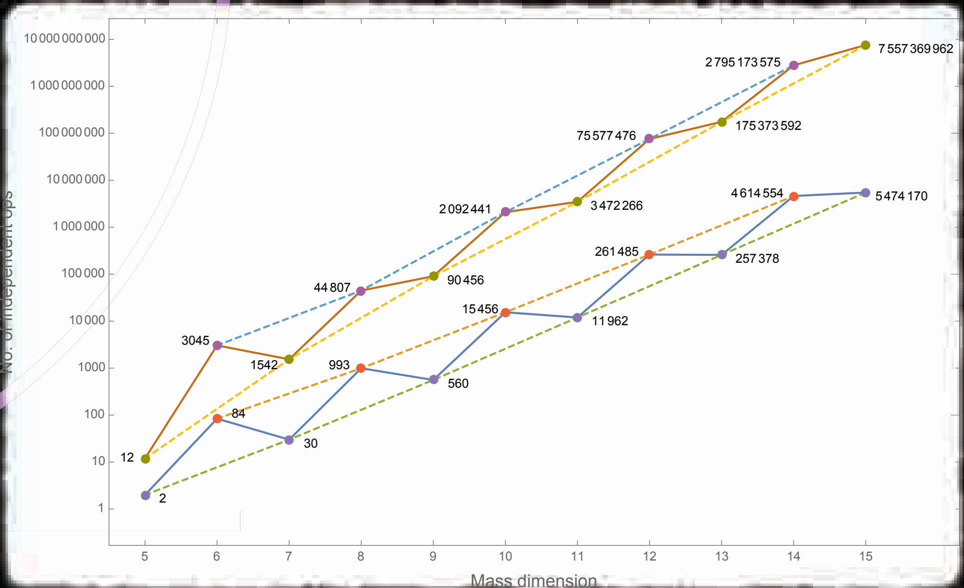
EFT coupling	Expected [TeV^{-2}]	Observed [TeV^{-2}]
c_W/Λ^2	[−3.7 ; 7.6]	[−4.3 ; 6.8]
c_B/Λ^2	[−270 ; 180]	[−320 ; 210]
c_{WWW}/Λ^2	[−3.9 ; 3.8]	[−3.9 ; 4.0]



The discovery potential of colliding frontiers…





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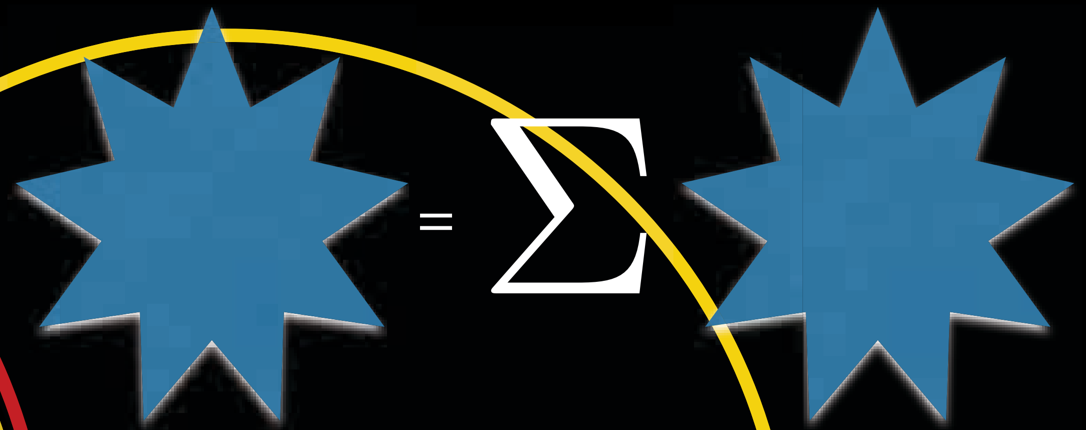
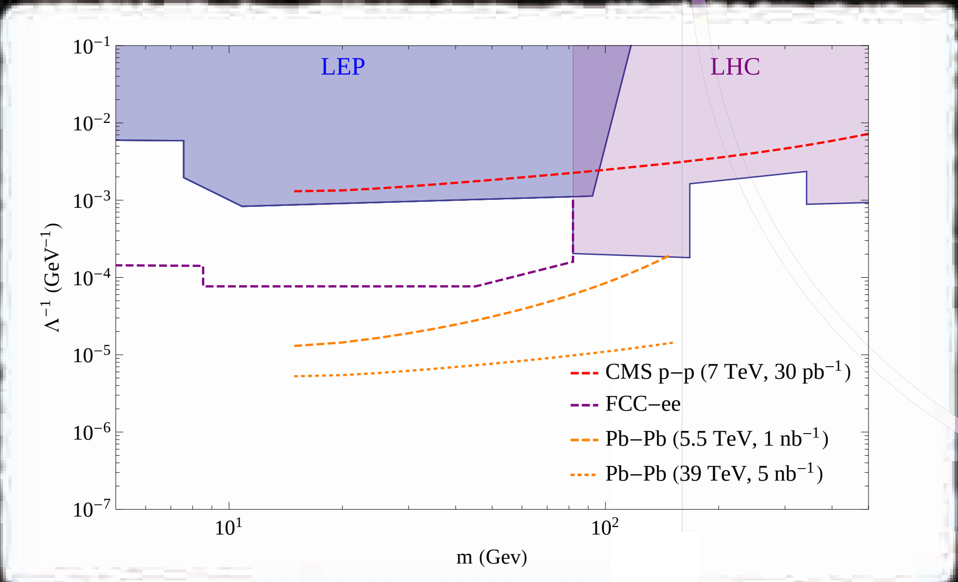
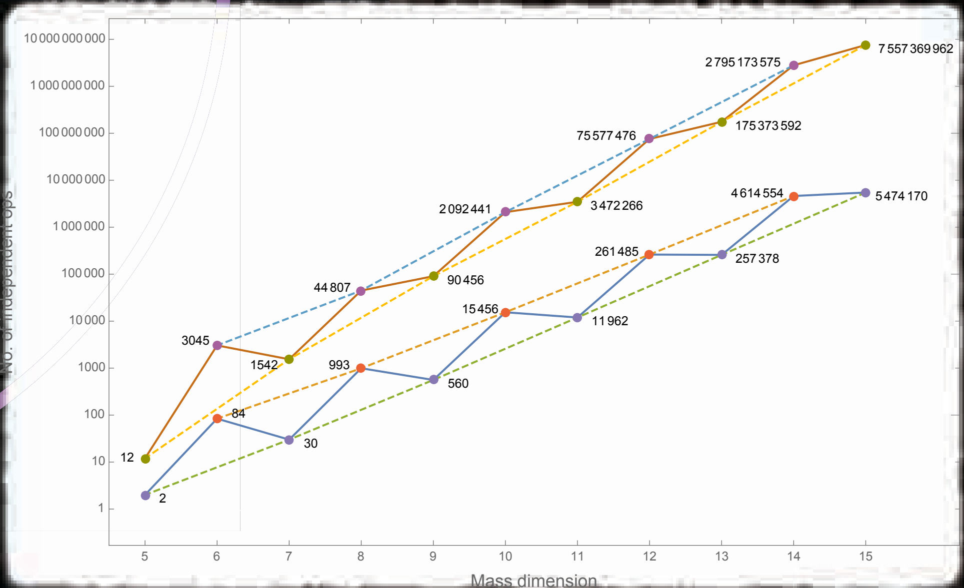


LHC has run-time outlined -2035…

…more colliders on the way





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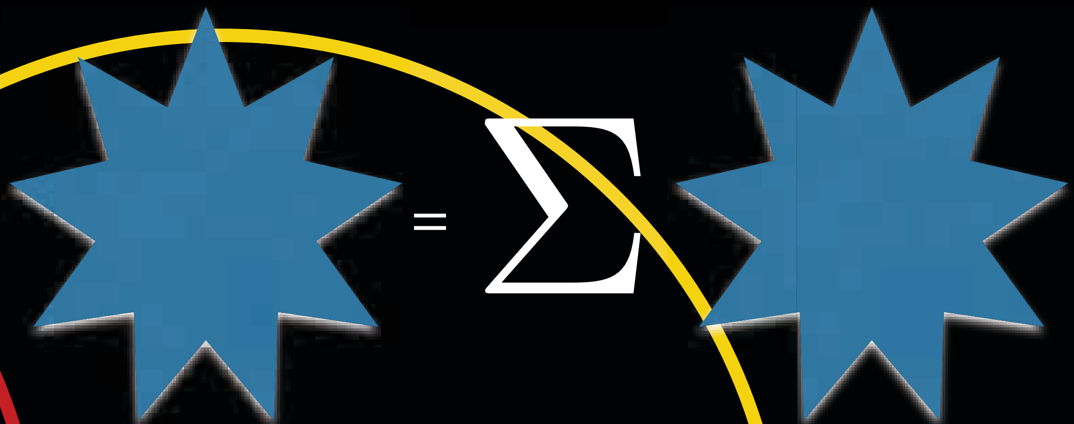

…colliding frontiers are an exciting place to be!