# The World Machine LHC: Jets, Higgs, and Beyond

*(or: "a strong machine for weak interactions")*

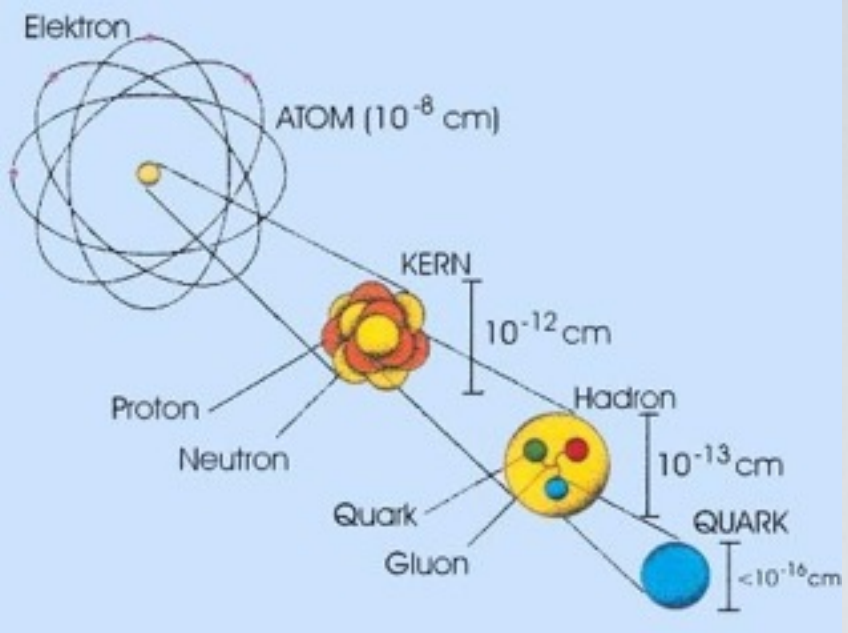
Jürgen R. Reuter, DESY

# Why colliders?

Resolving power: $\Delta x \sim \Delta E^{-1}$ $\Rightarrow$

High energy accelerators

| System | Size | Energy |
|---|---|---|
| Molecules | $10^{-8}$ m | ~ meV |
| Atoms | $10^{-10}$ m | ~ eV … keV |
| Nuclei | $10^{-14}$ m | ~ MeV … 10 MeV |
| Nucleons | $10^{-15}$ m | ~ 1 GeV |
| Quarks, Leptons, Higgs | $10^{-18}$ m | ~ 1 TeV |



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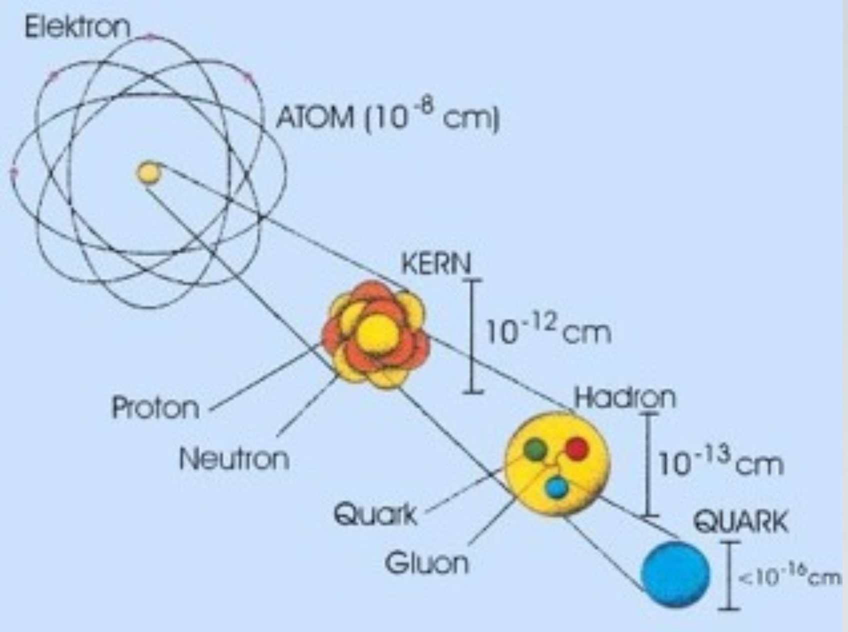

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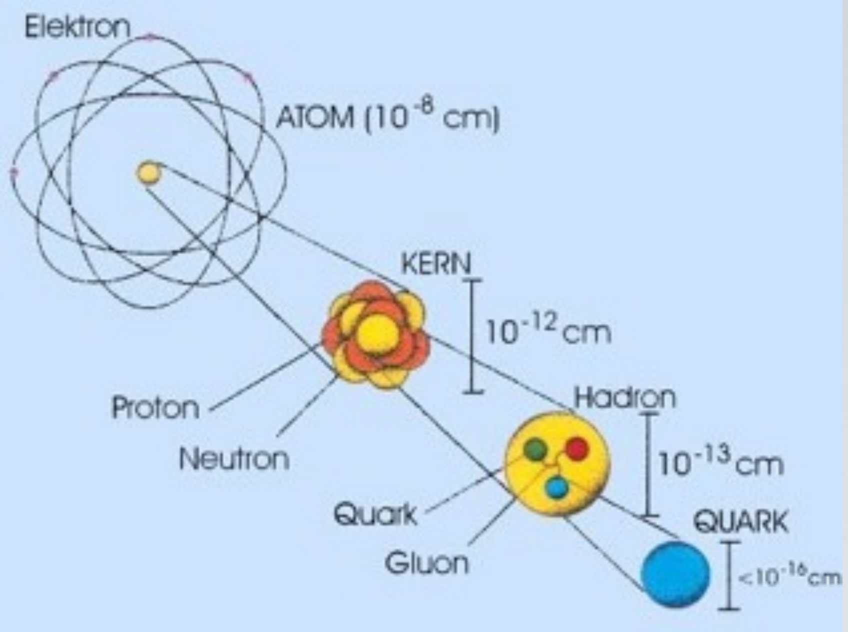
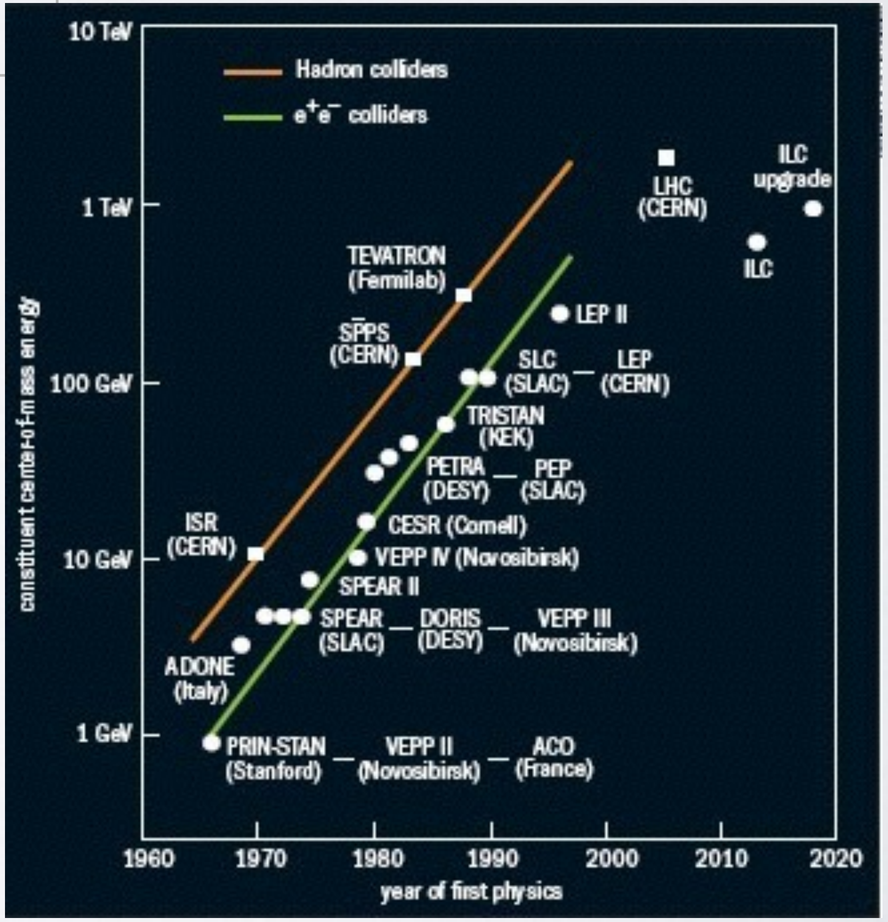
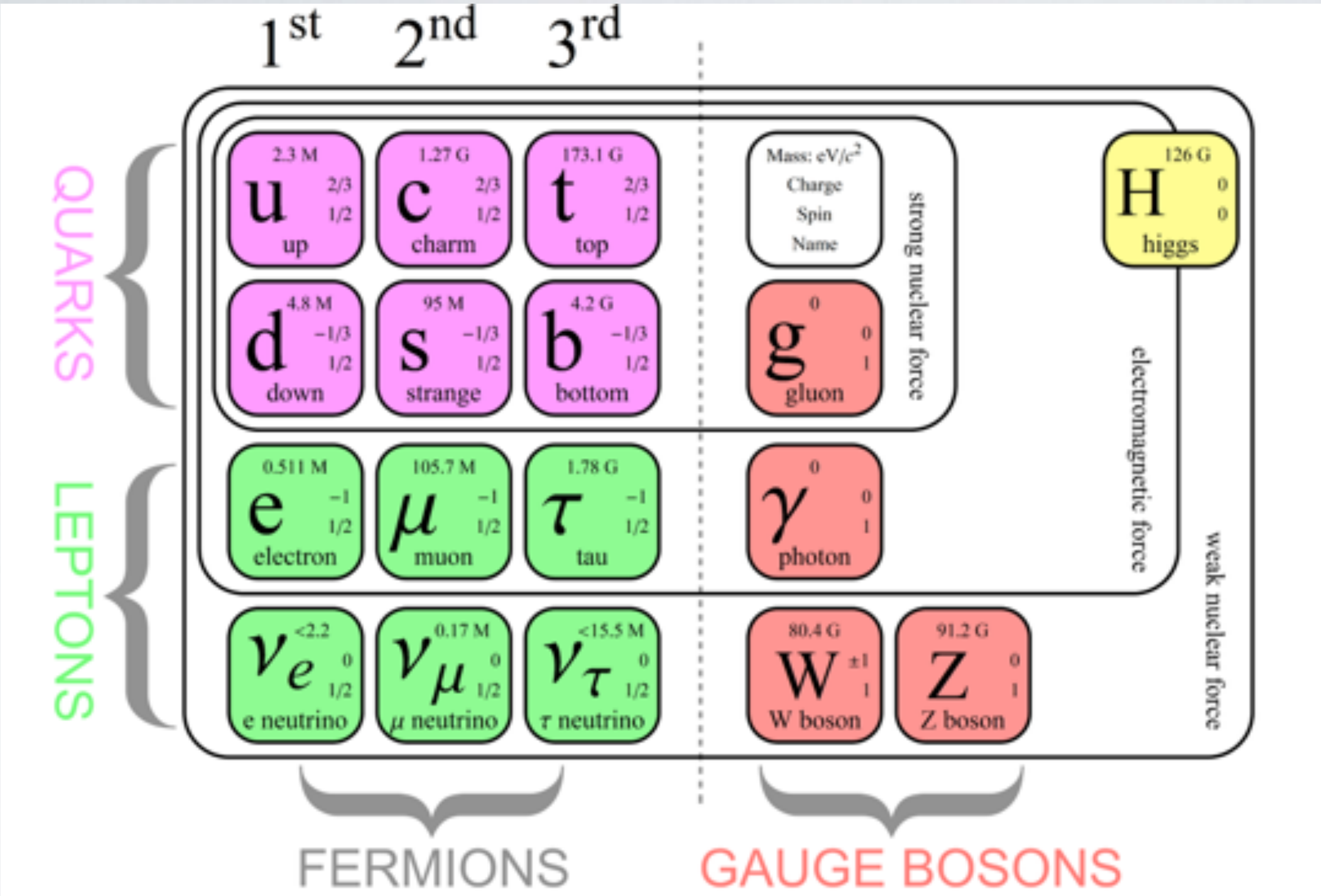




# Again, why? The 'Standard Model' in a Nutshell



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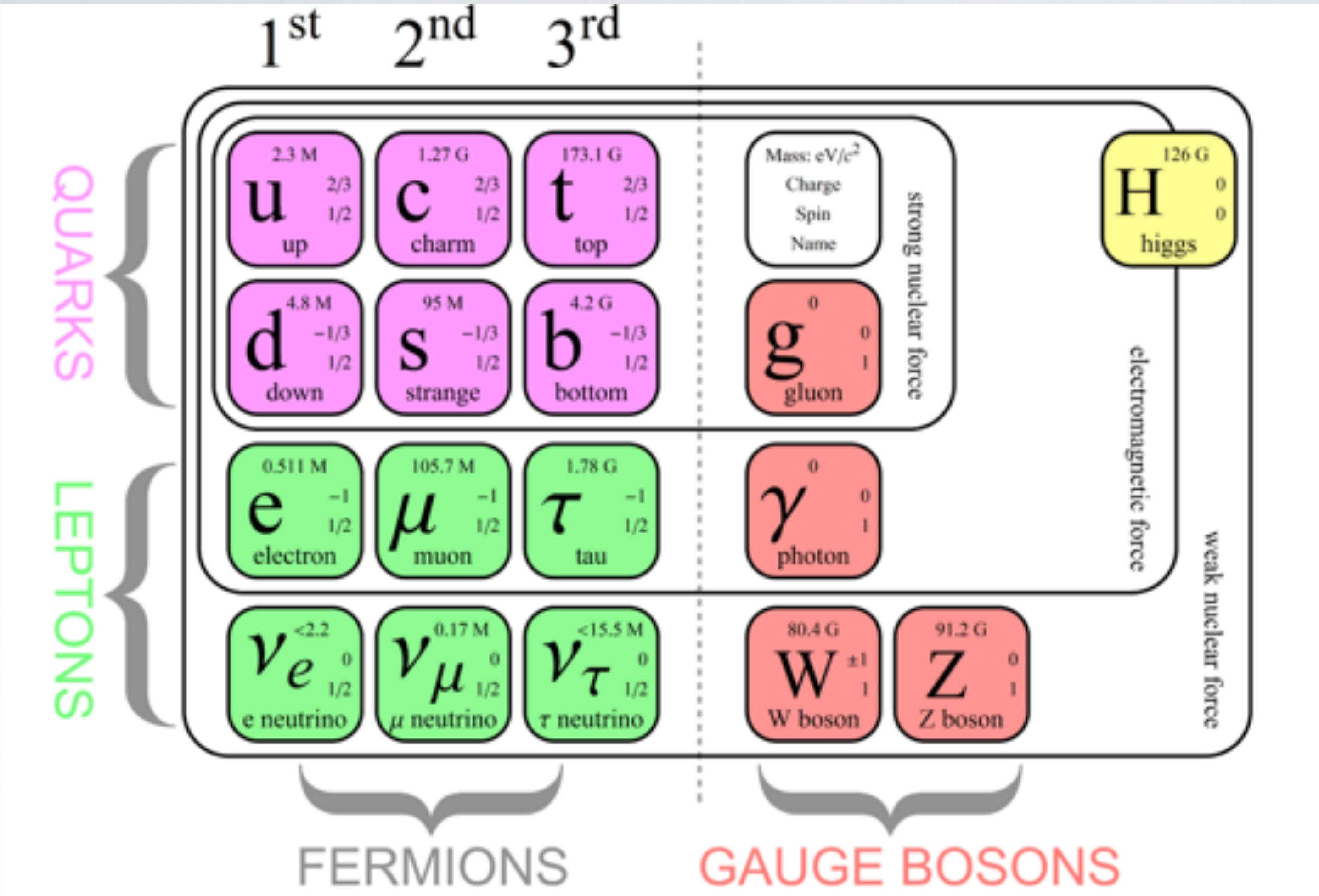

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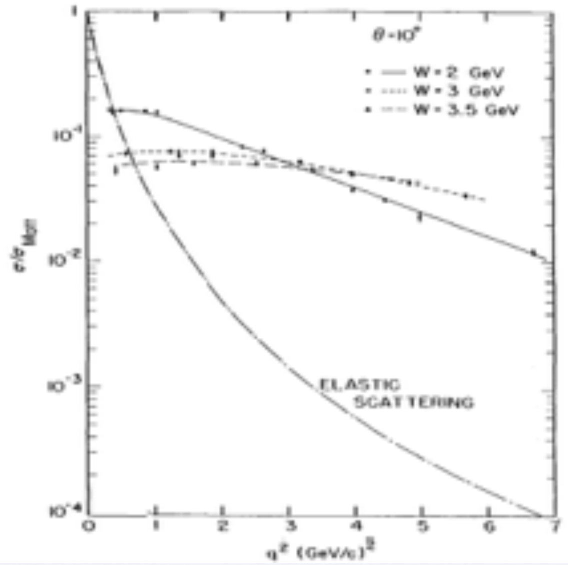

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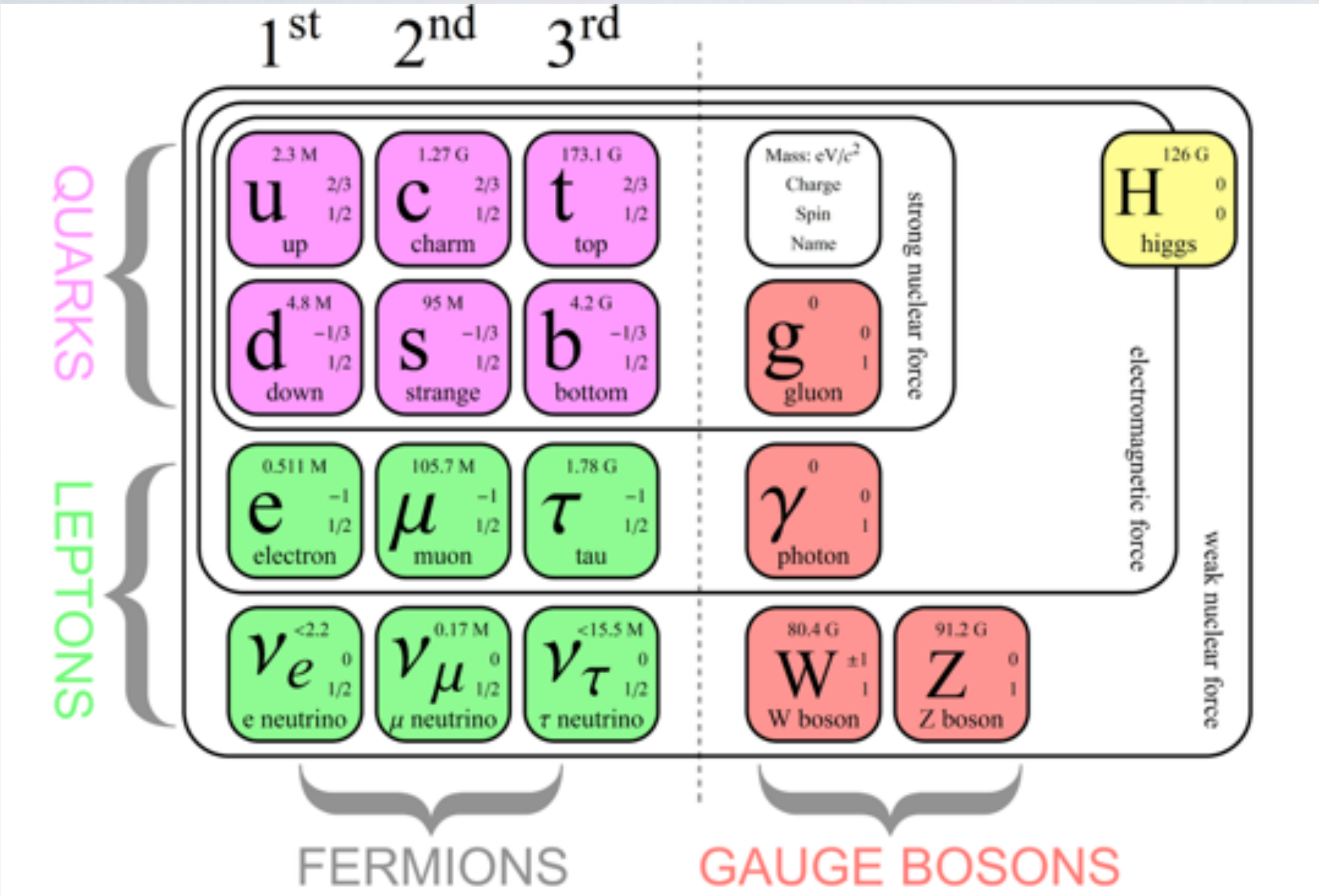

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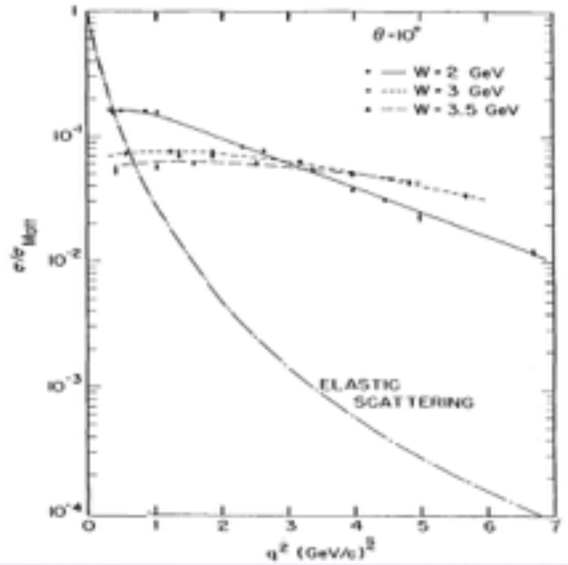

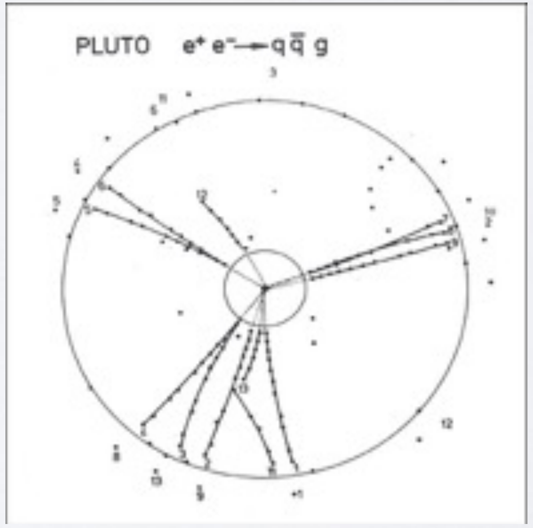

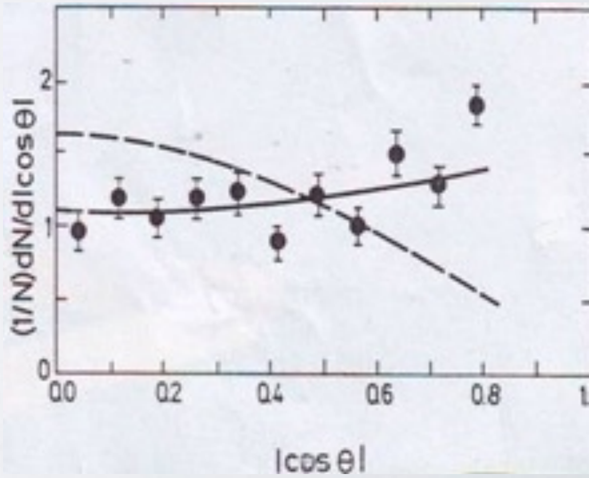

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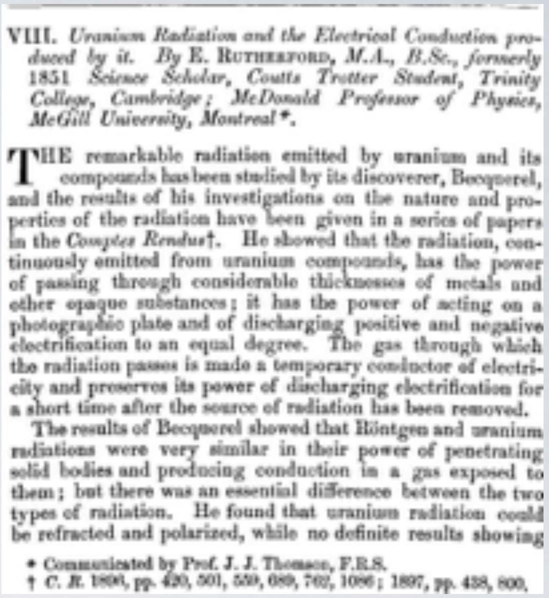
$$\mathcal{L}_{eff.} = \frac{c_F}{v^2} \cdot \overline{\Psi}_d \gamma^\mu (1-\gamma^5) \Psi_u \times \overline{\Psi}_u \gamma_\mu (1-\gamma^5) \Psi_d$$



VIII. *Uranium Radiation and the Electrical Conduction produced by it.* By E. Rutherford, *M.A., B.Sc., formerly 1851 Science Scholar, Coutts Trotter Student, Trinity College, Cambridge; McDonald Professor of Physics, McGill University, Montreal**.

THE remarkable radiation emitted by uranium and its compounds has been studied by its discoverer, Becquerel, and the results of his investigations on the nature and properties of the radiation have been given in a series of papers in the *Comptes Rendus*†. He showed that the radiation, continuously emitted from uranium compounds, has the power of passing through considerable thicknesses of metals and other opaque substances; it has the power of acting on a photographic plate and of discharging positive and negative electrification to an equal degree. The gas through which the radiation passes is made a temporary conductor of electricity and preserves its power of discharging electrification for a short time after the source of radiation has been removed.

The results of Becquerel showed that Röntgen and uranium radiations were very similar in their power of penetrating solid bodies and producing conduction in a gas exposed to them; but there was an essential difference between the two types of radiation. He found that uranium radiation could be refracted and polarized, while no definite results showing

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* Communicated by Prof. J. J. Thomson, F.R.S.

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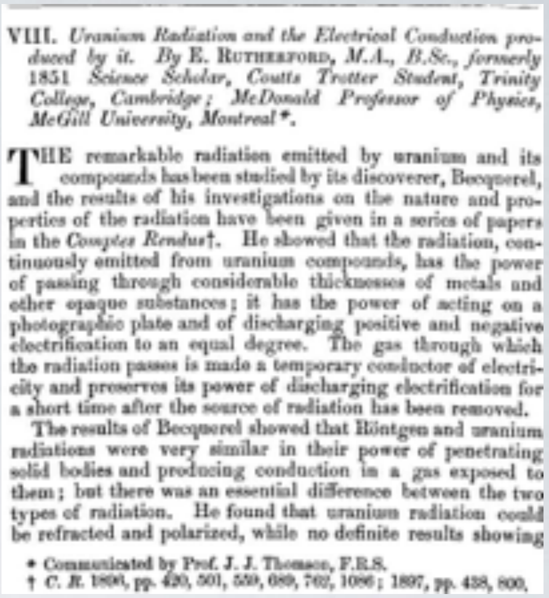

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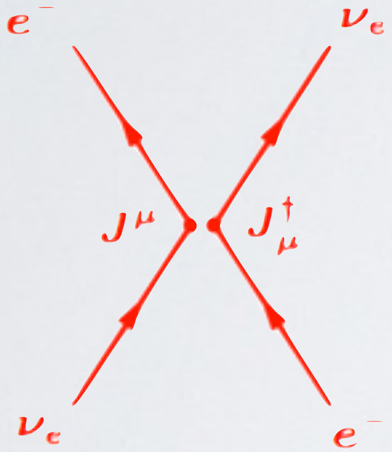
Effective theory leads to invalidity / unitarity violation at higher energies



$$\sigma(e^-\nu_e \to e^-\nu_e) \longrightarrow \sim \frac{s}{\pi v^2}$$

S-wave unitarity demands: $\sqrt{s} \lesssim 500\,\mathrm{GeV}$

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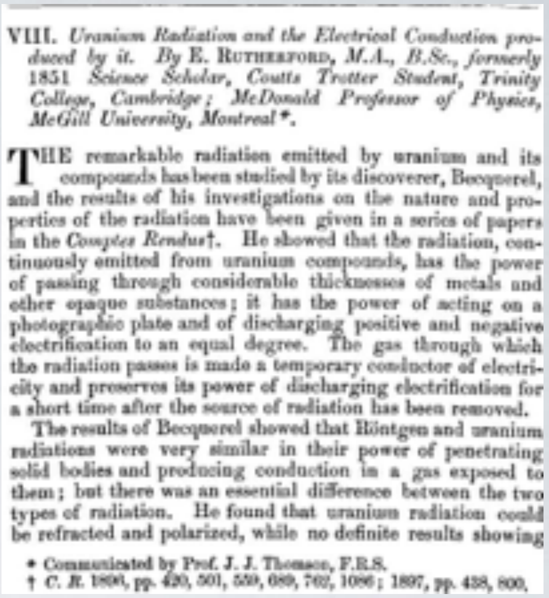

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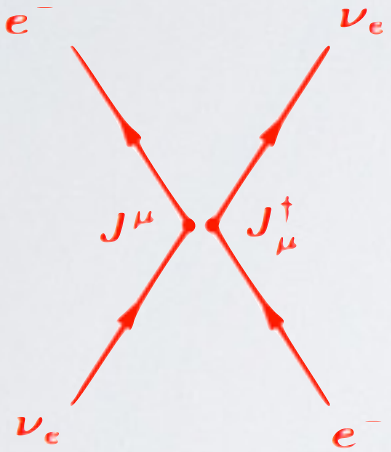

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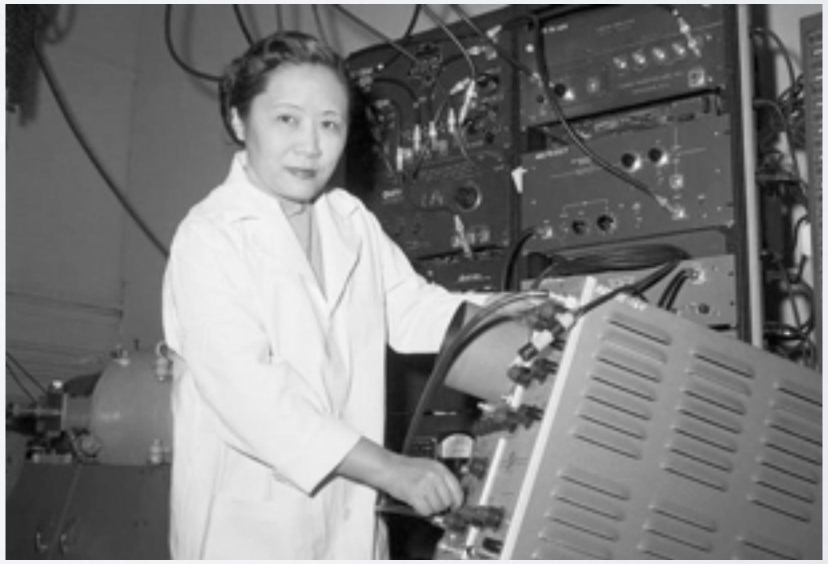
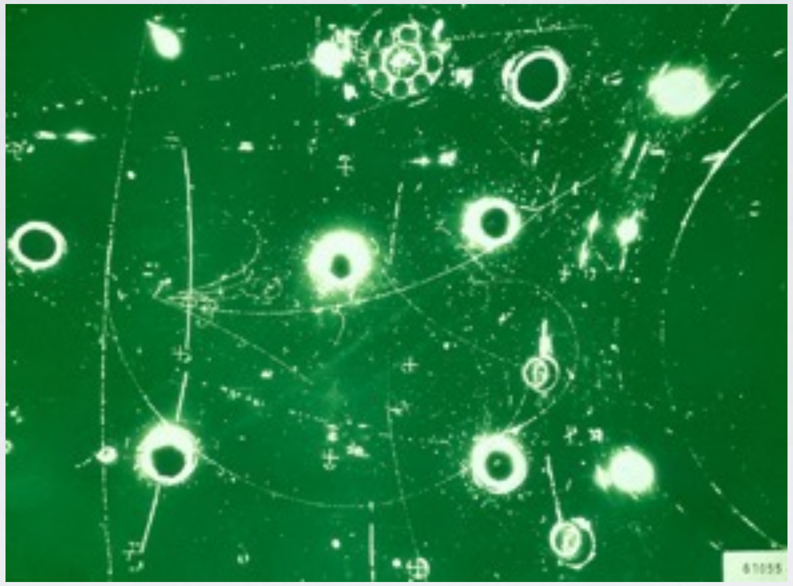
- *P* violation, 1955
- Neutrino is left-handed, 1956
- *CP* violation, 1964
- Brout-Englert-Higgs mechanism, 1960/61/64



# The mystery of Electroweak Symmetry Breaking



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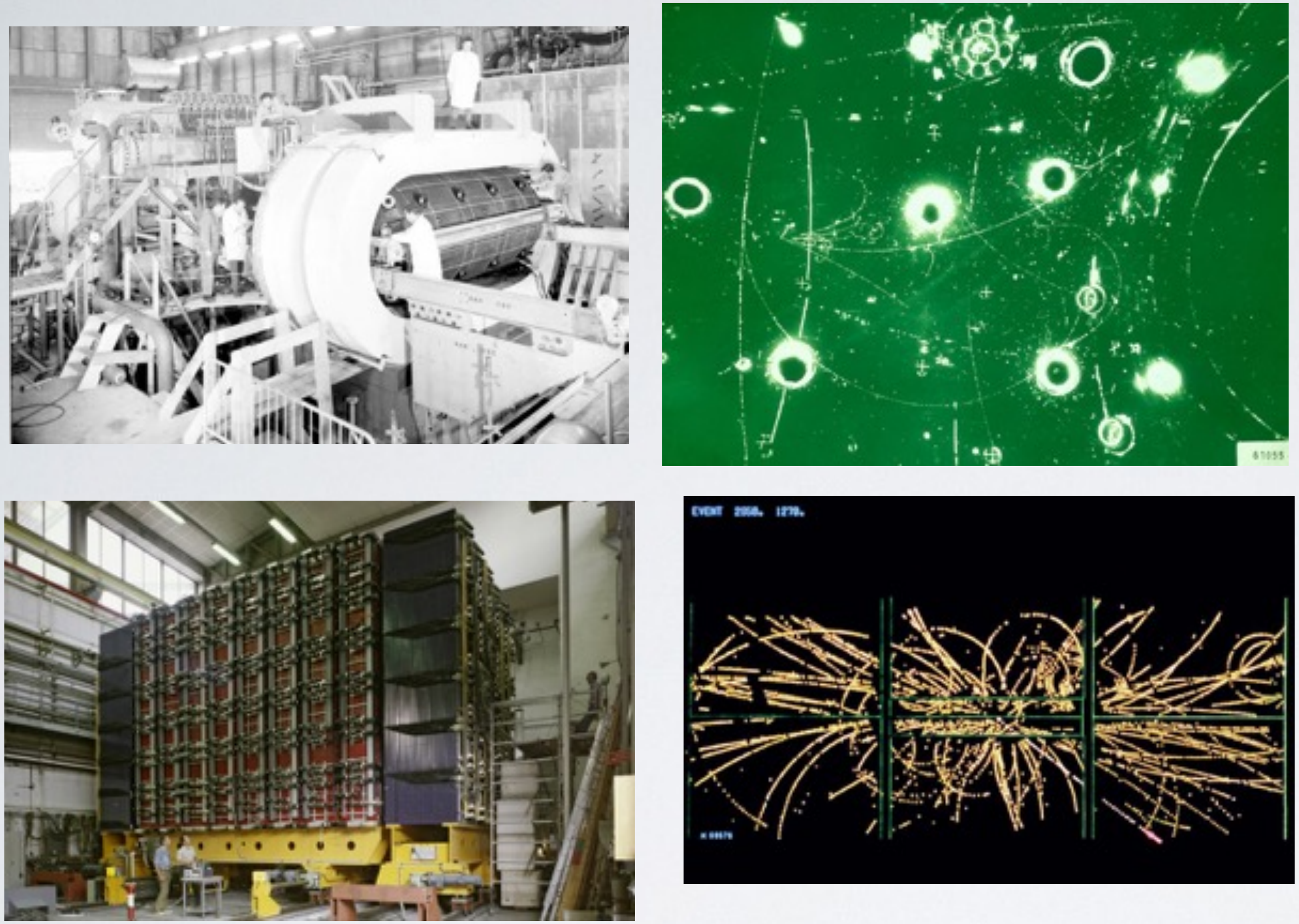

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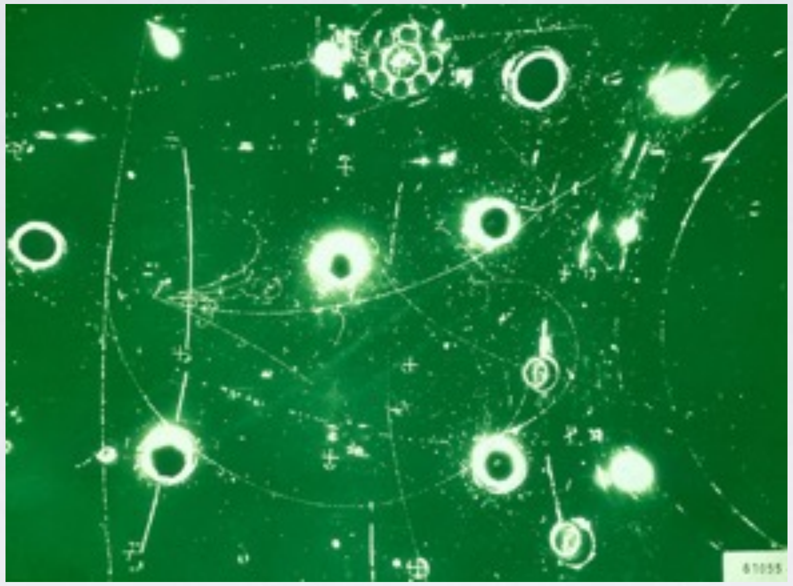

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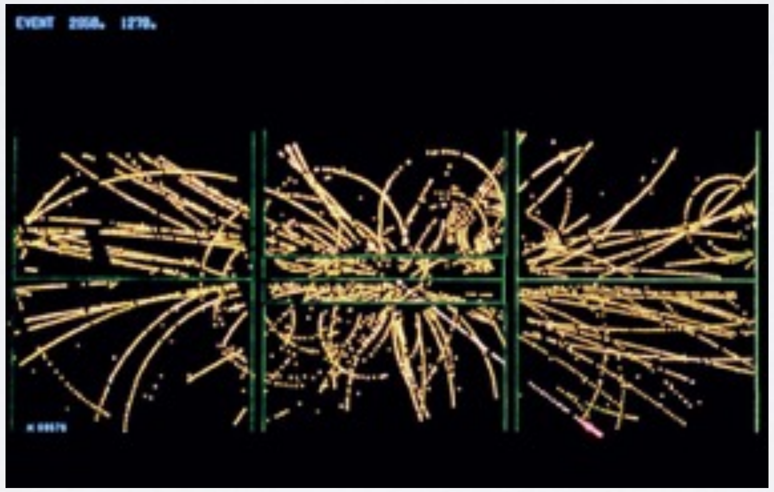

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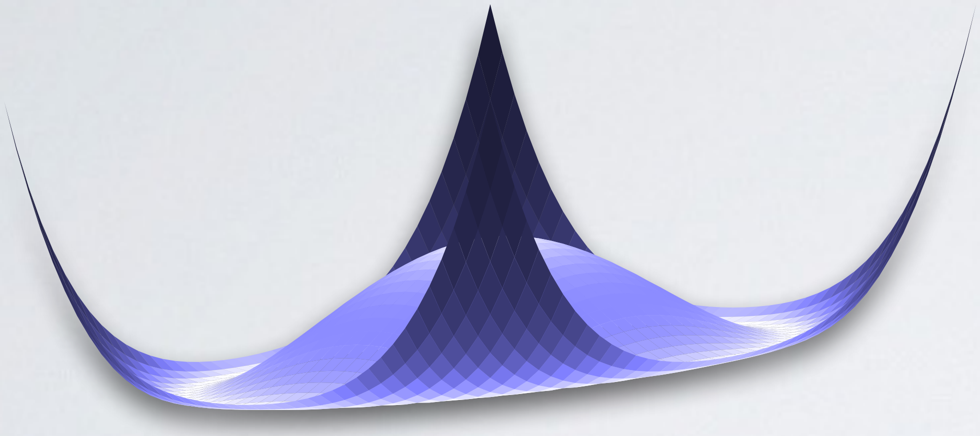
- All mass terms are forbidden by symmetry (except for the Higgs)

| $Q_L$ | $u_R$ | $d_R$ | $L_L$ | $e_R$ | $H$ | $\nu_R$ |
|---|---|---|---|---|---|---|
| $(\mathbf{2},\mathbf{3})_{\frac{1}{3}}$ | $(\mathbf{1},\mathbf{3})_{\frac{4}{3}}$ | $(\mathbf{1},\mathbf{3})_{-\frac{2}{3}}$ | $(\mathbf{2},\mathbf{1})_1$ | $(\mathbf{1},\mathbf{1})_{-2}$ | $(\mathbf{2},\mathbf{1})_1$ | $(\mathbf{1},\mathbf{1})_0$ |

# The Higgs breaking parameterization

$$V(\phi) = -\mu^2 |\phi|^2 + \frac{\lambda}{2} (|\phi|^2)^2$$



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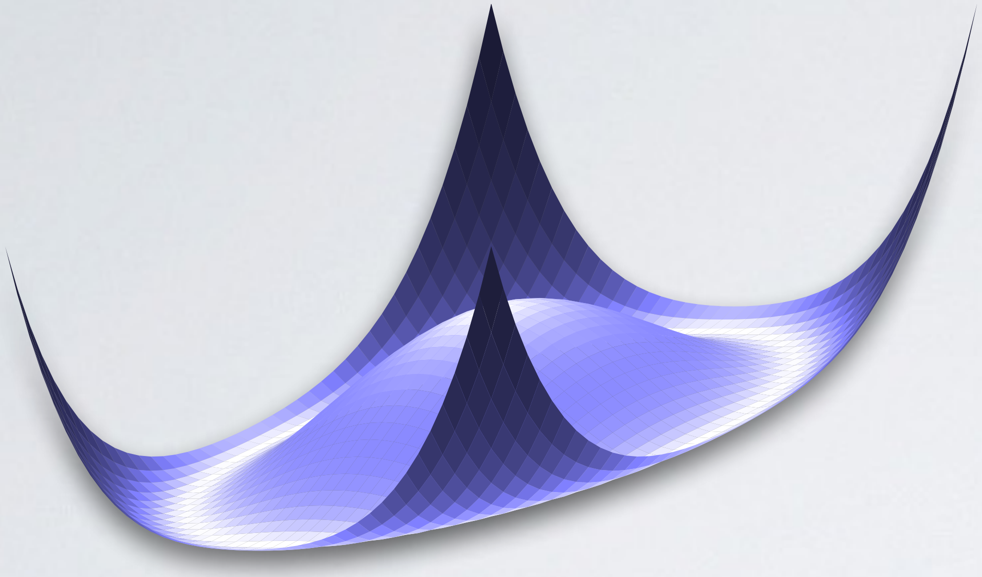

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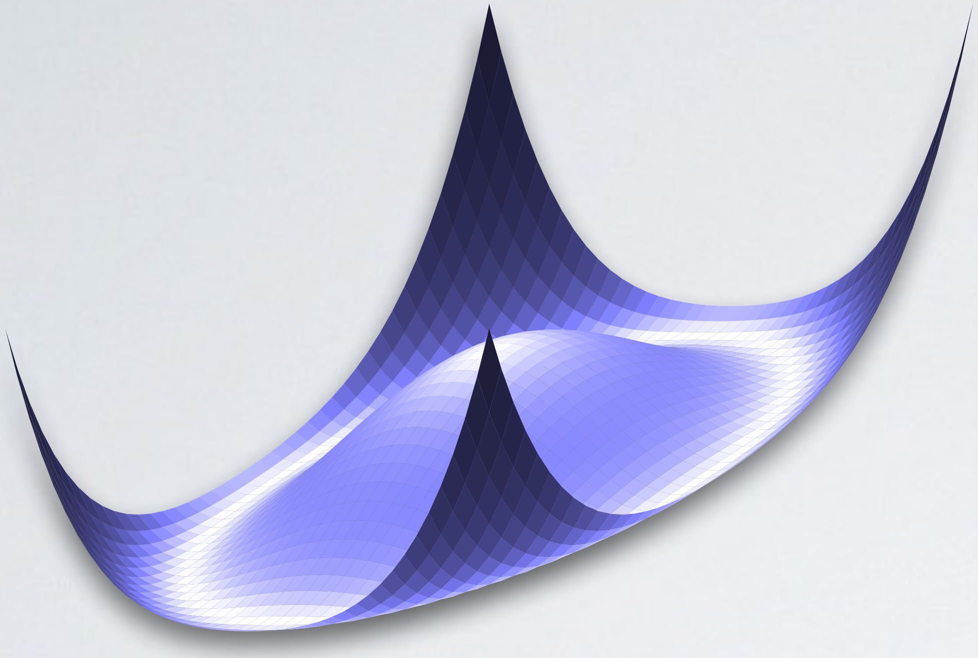

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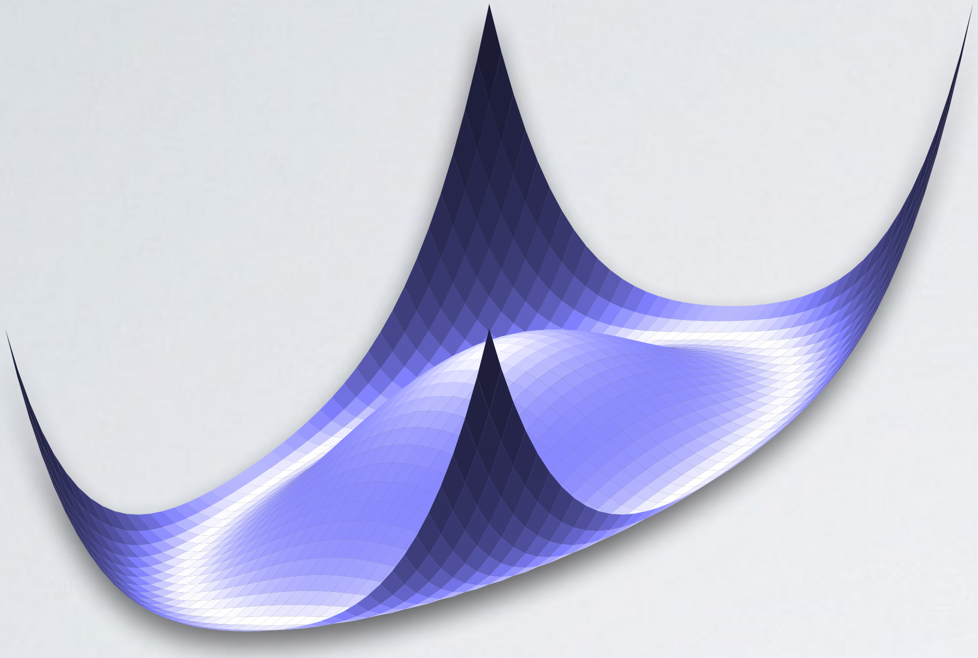

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- Radial excitation (massive): Higgs field
- Phase: Goldstone boson

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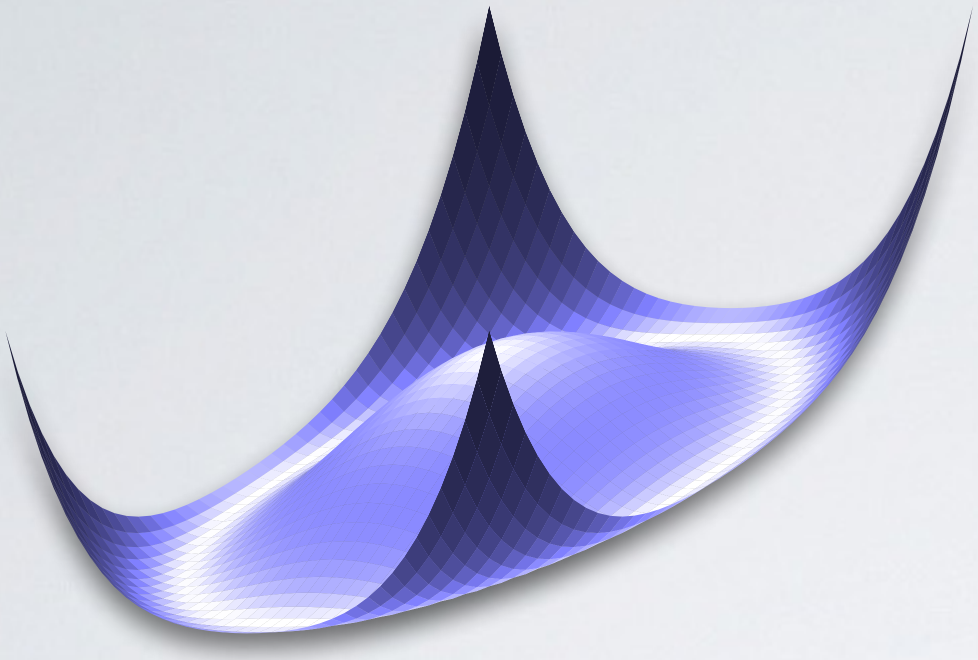

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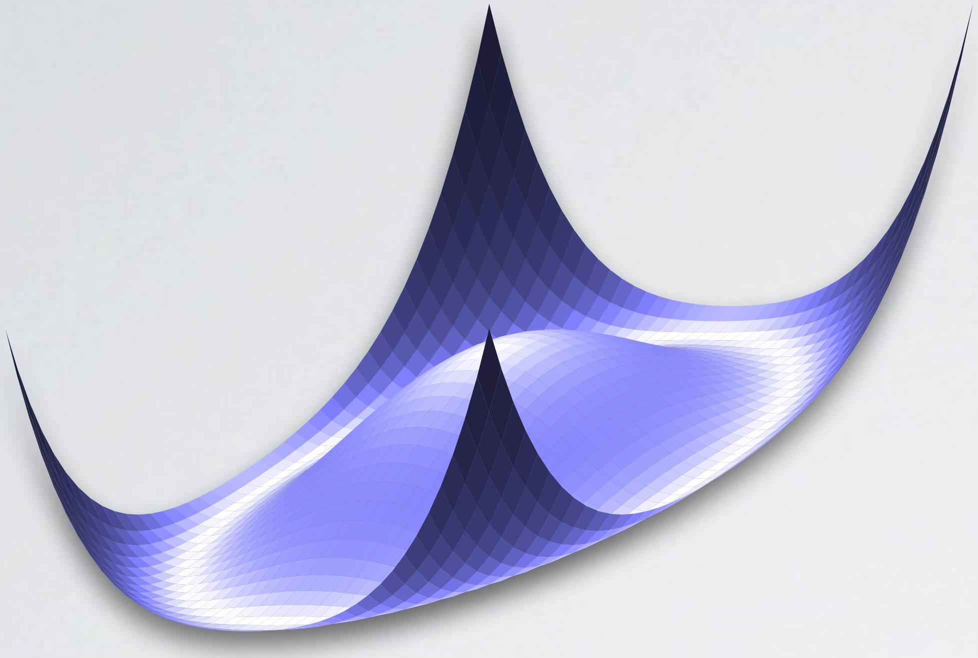

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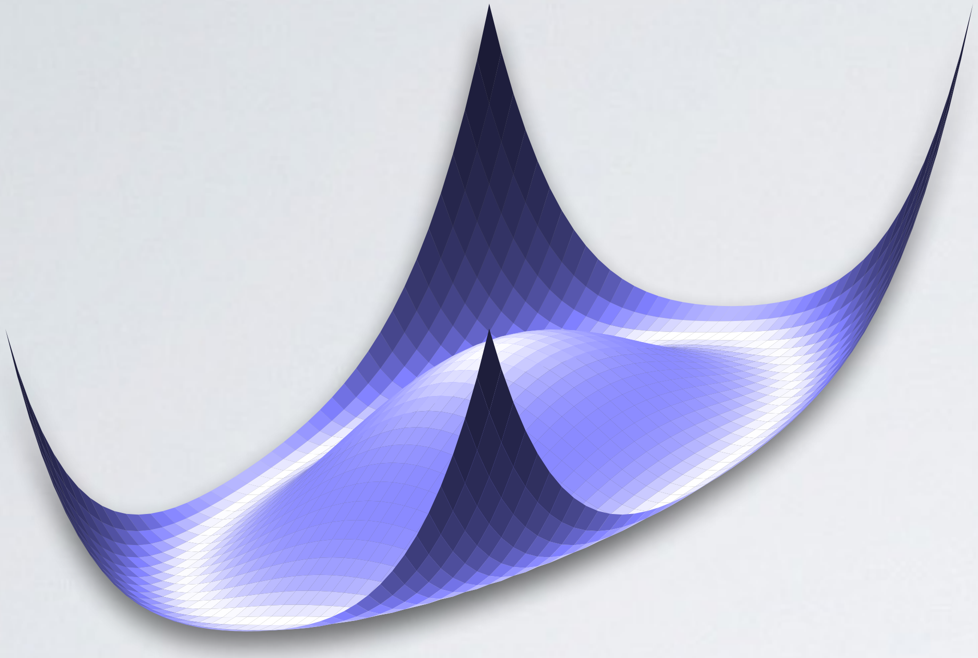

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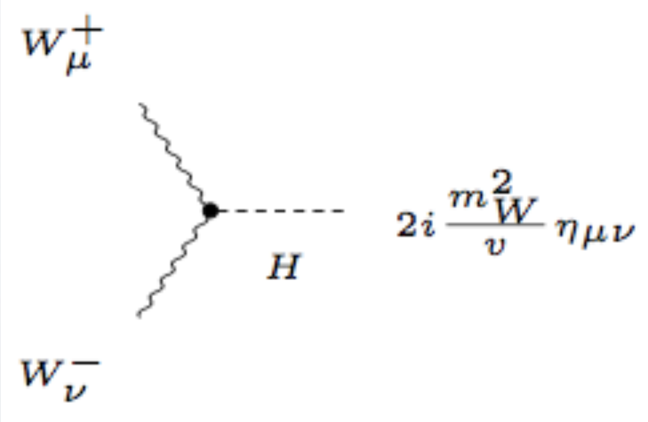
Particle masses ∝ Higgs coupling strength ⟺ Higgs couples ∝ particle masses

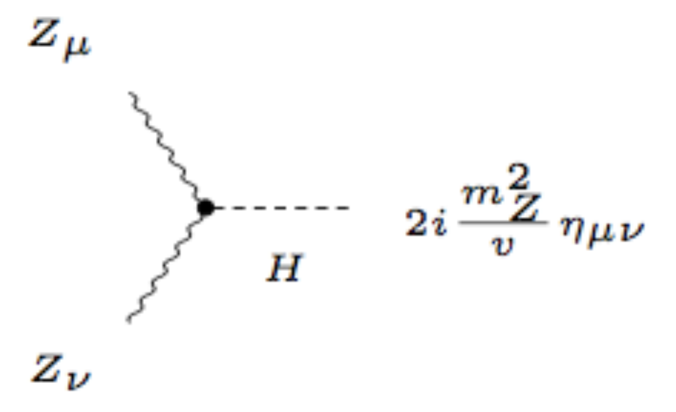
$$\boxed{m_W = gv/2}$$

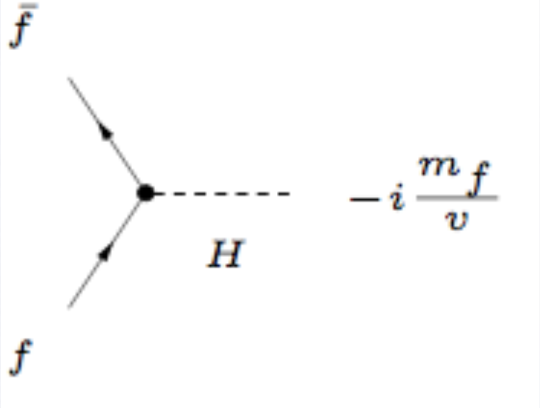
$$\boxed{m_Z = gv/(2\cos\theta_W)}$$

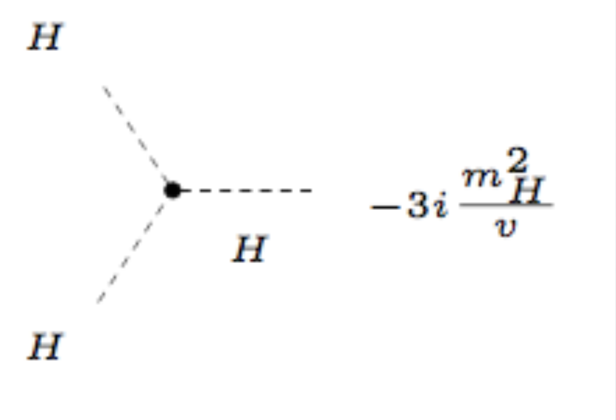
$$\boxed{m_f = vY_f/\sqrt{2}}$$

$$\boxed{m_H = v\sqrt{\lambda}}$$









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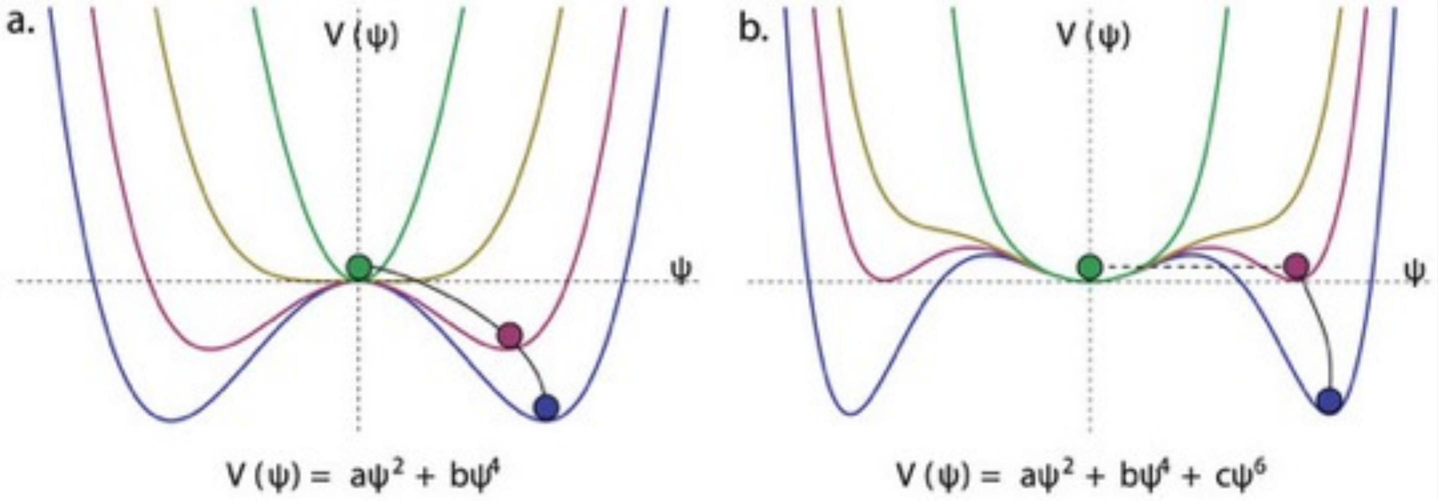

Effective potential could be more complicated [?]

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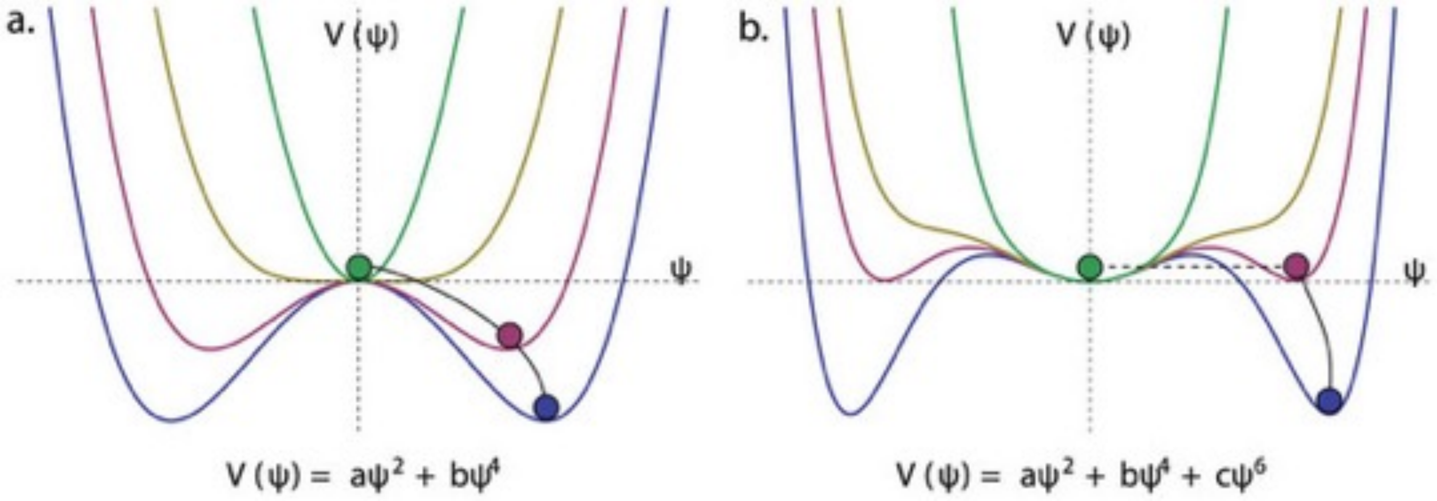

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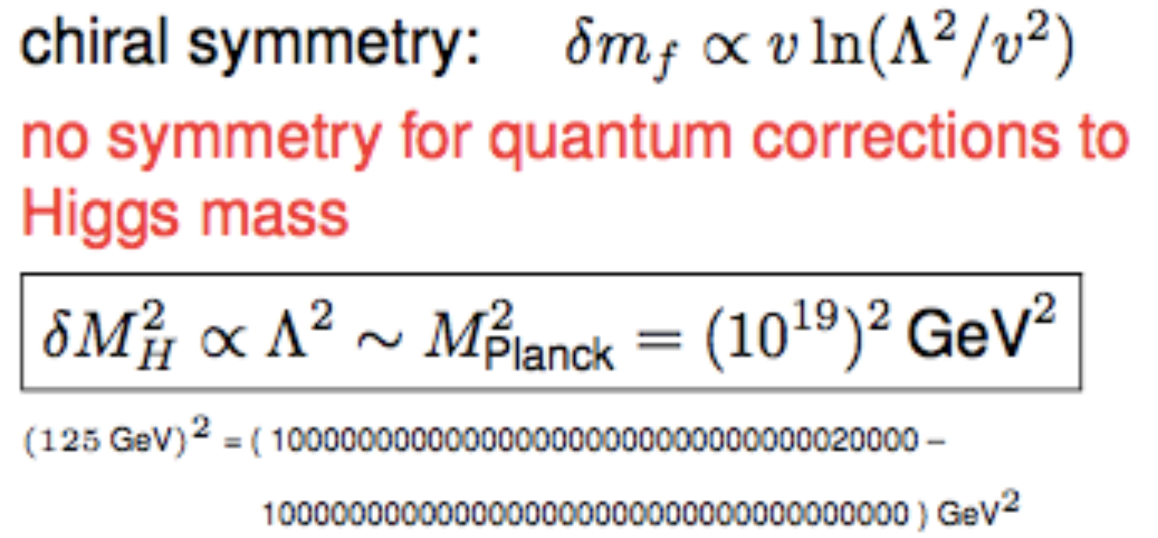

chiral symmetry: $\delta m_f \propto v \ln(\Lambda^2/v^2)$

no symmetry for quantum corrections to Higgs mass

$$\boxed{\delta M_H^2 \propto \Lambda^2 \sim M_{\text{Planck}}^2 = (10^{19})^2\,\text{GeV}^2}$$

$(125\,\text{GeV})^2 = (\,100000000000000000000000000000000020000 -$

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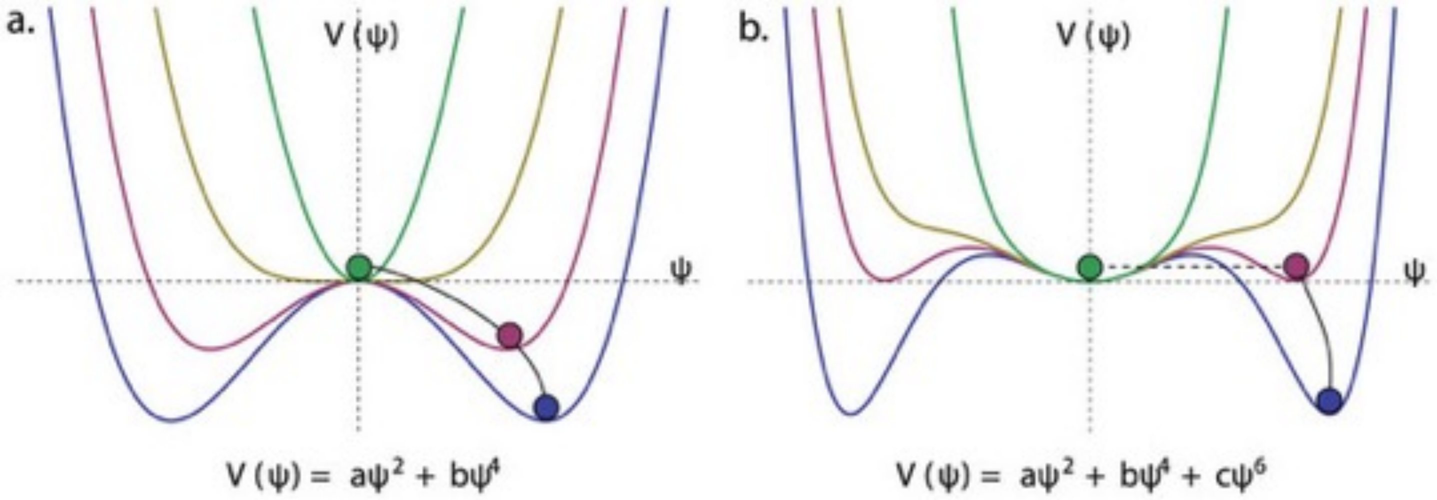

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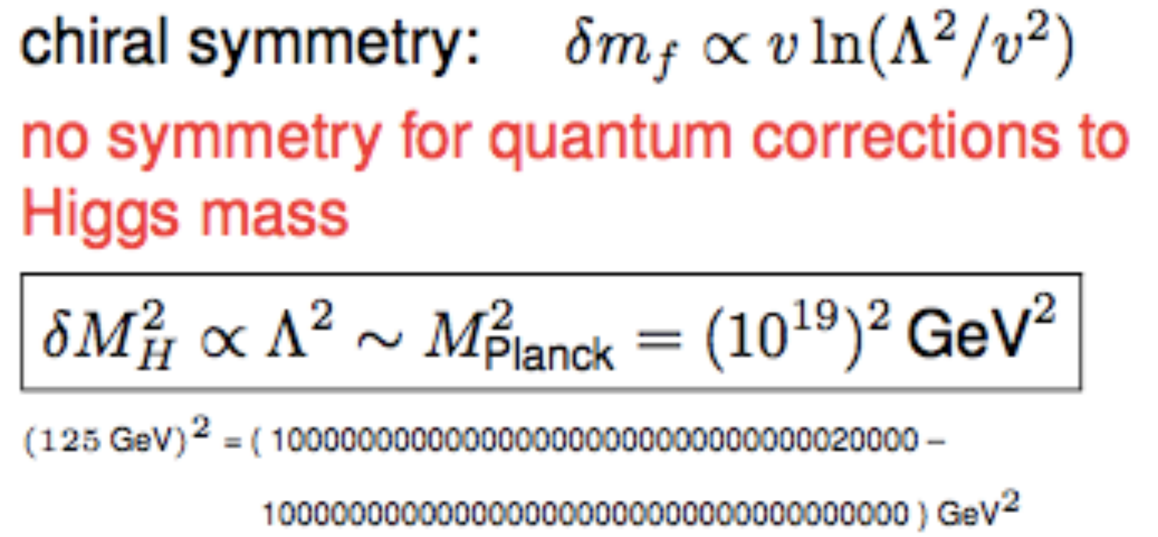

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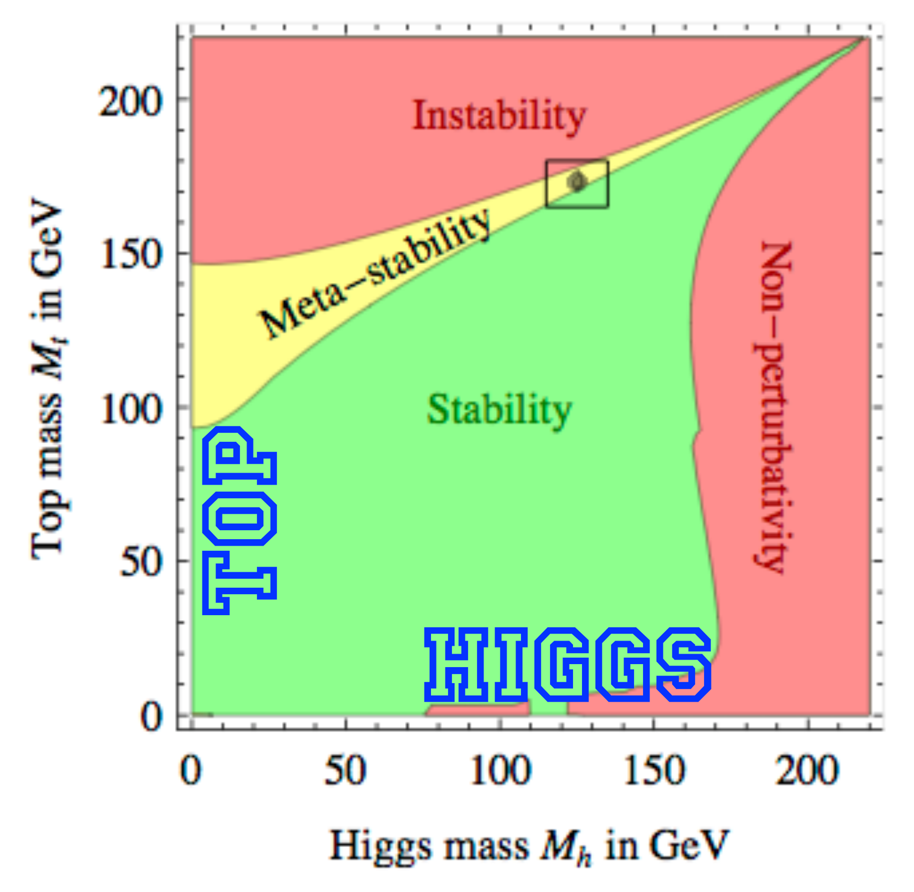
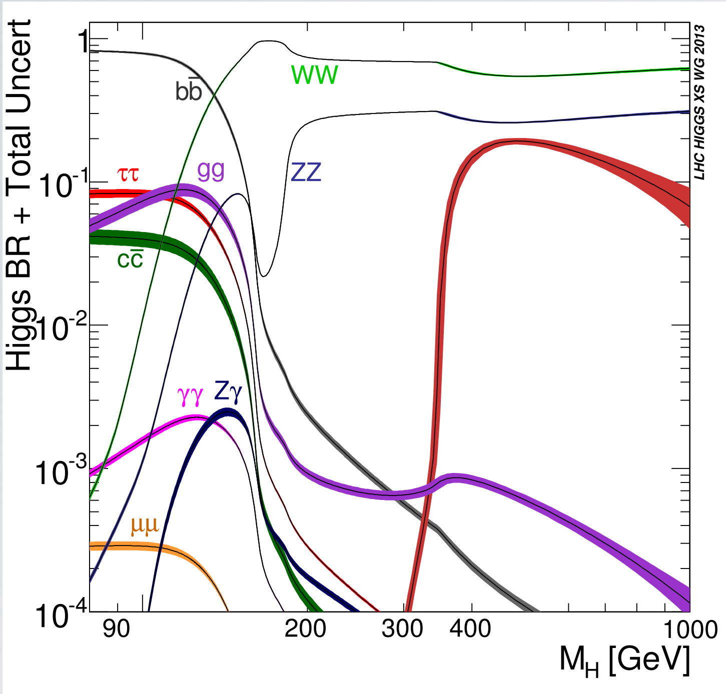
## Electroweak vacuum



(note: plot under assumptions of NO additional BSM )

# The Higgs boson at a hadron collider



- Higgs decays into heaviest particles
- becomes strongly interacting at ~ 0.5 - 1.0 TeV
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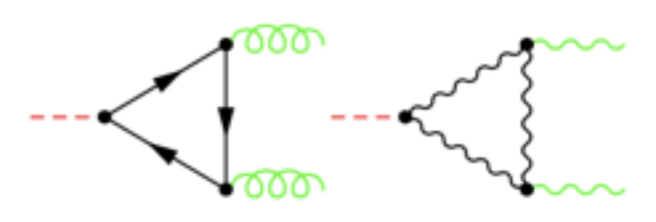
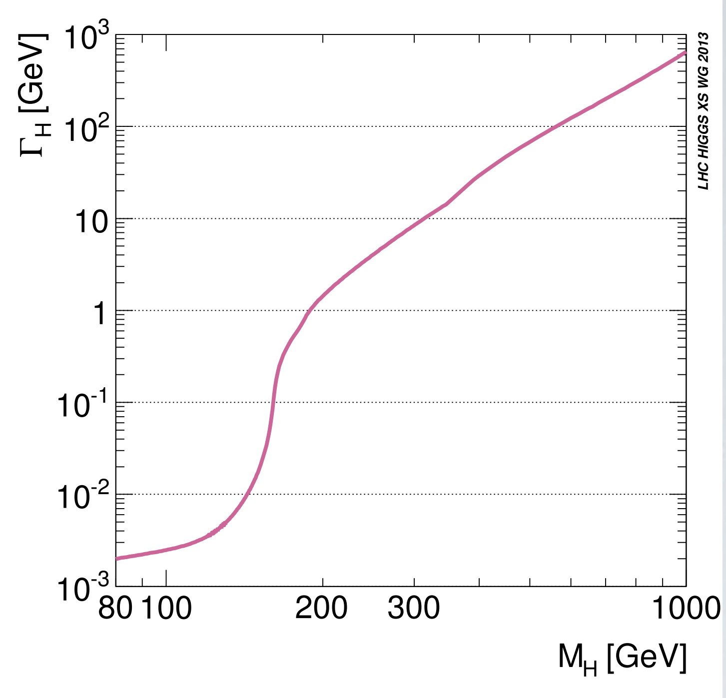
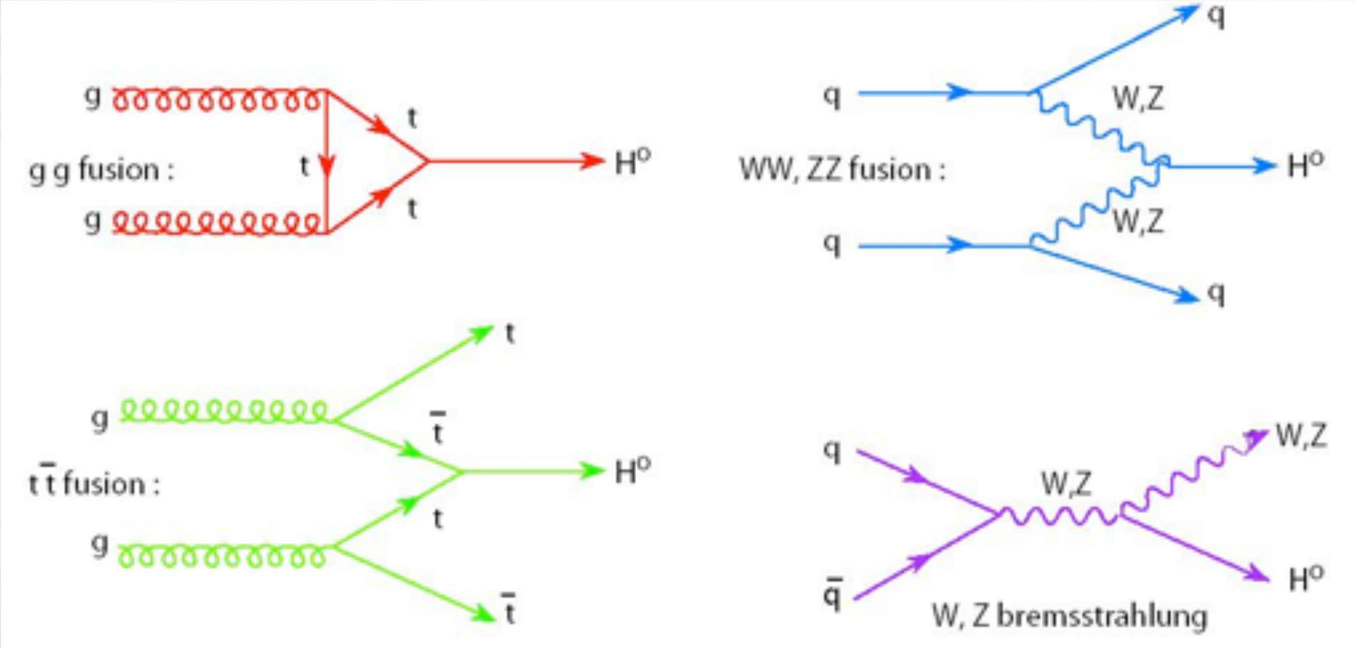
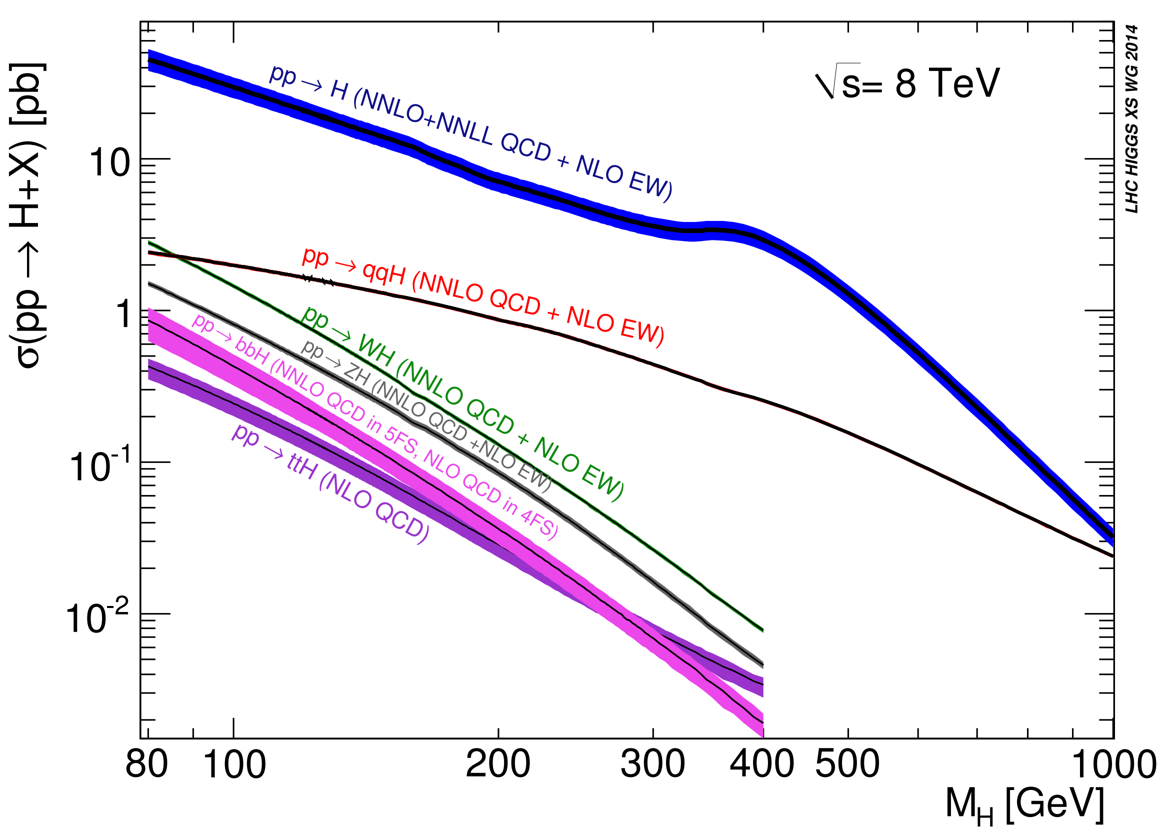
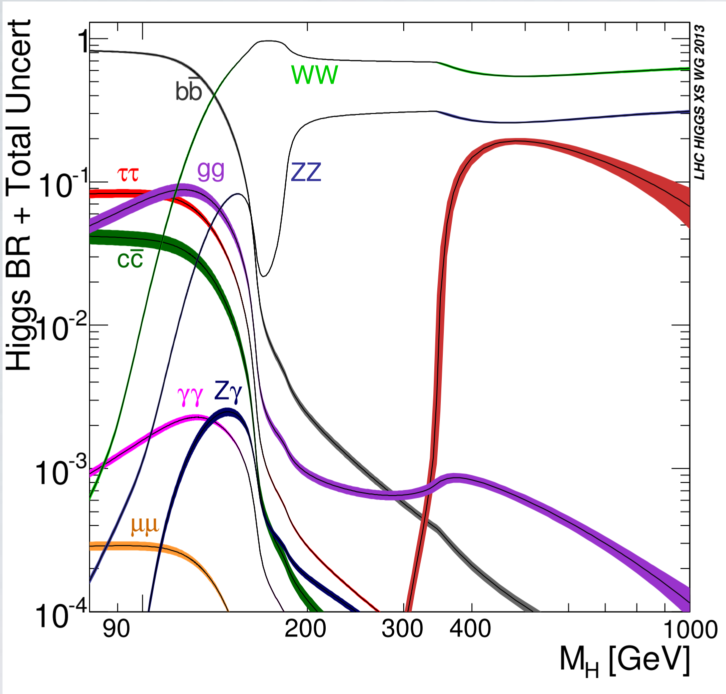








# The Higgs boson at a hadron collider



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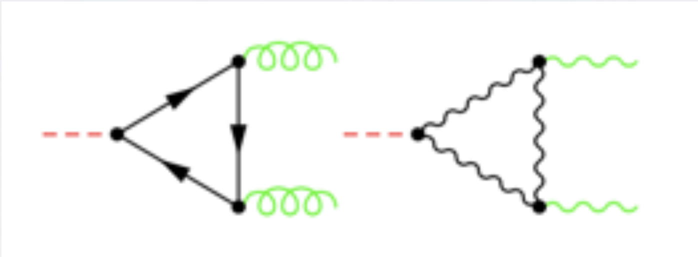

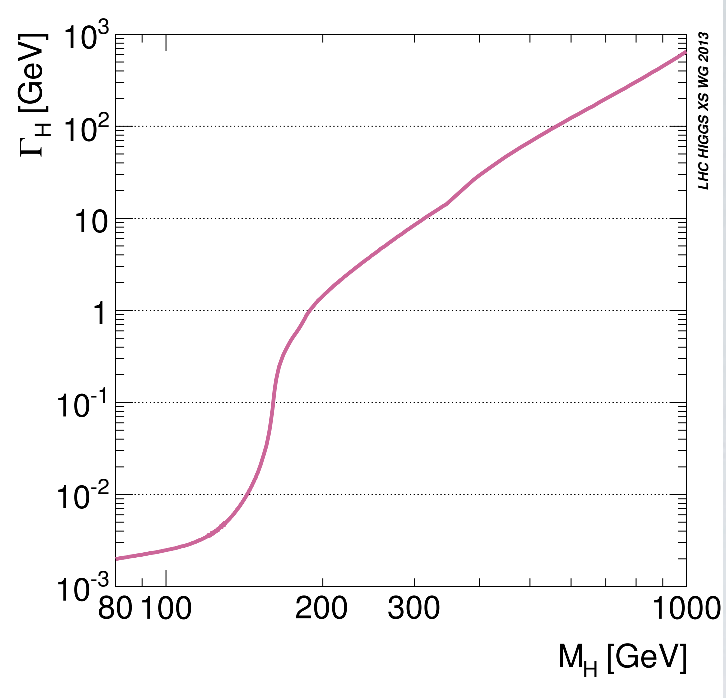

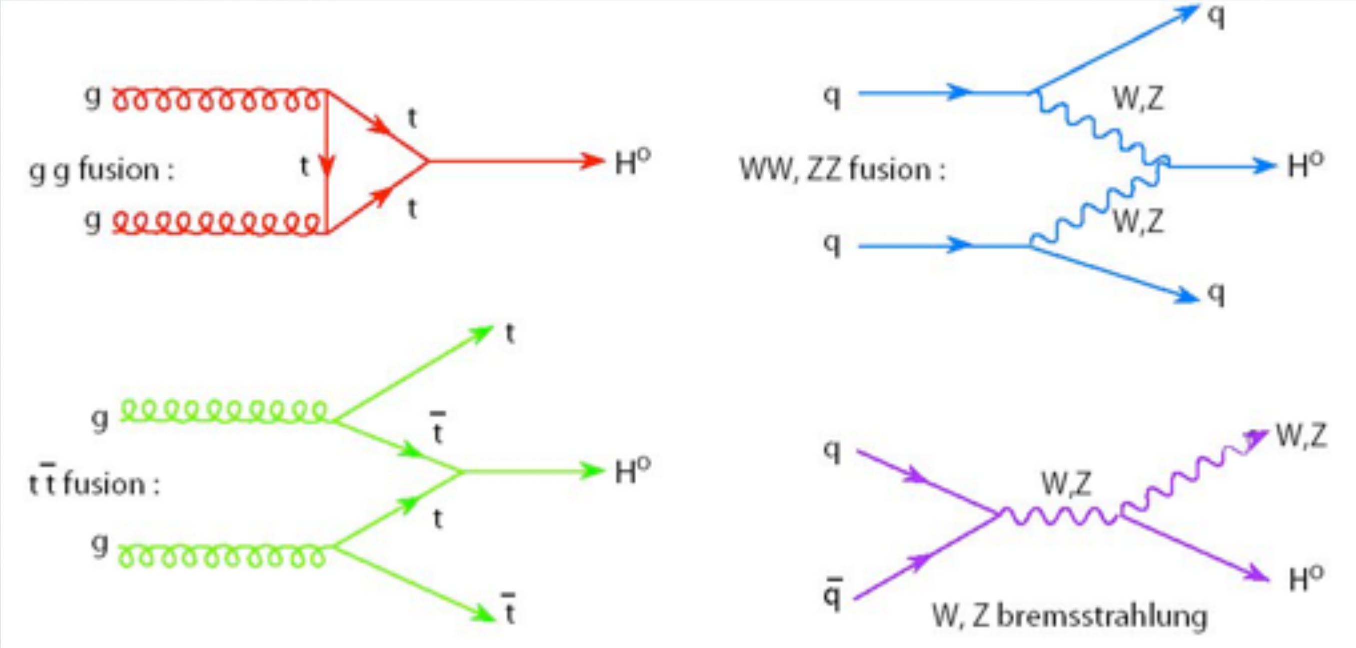

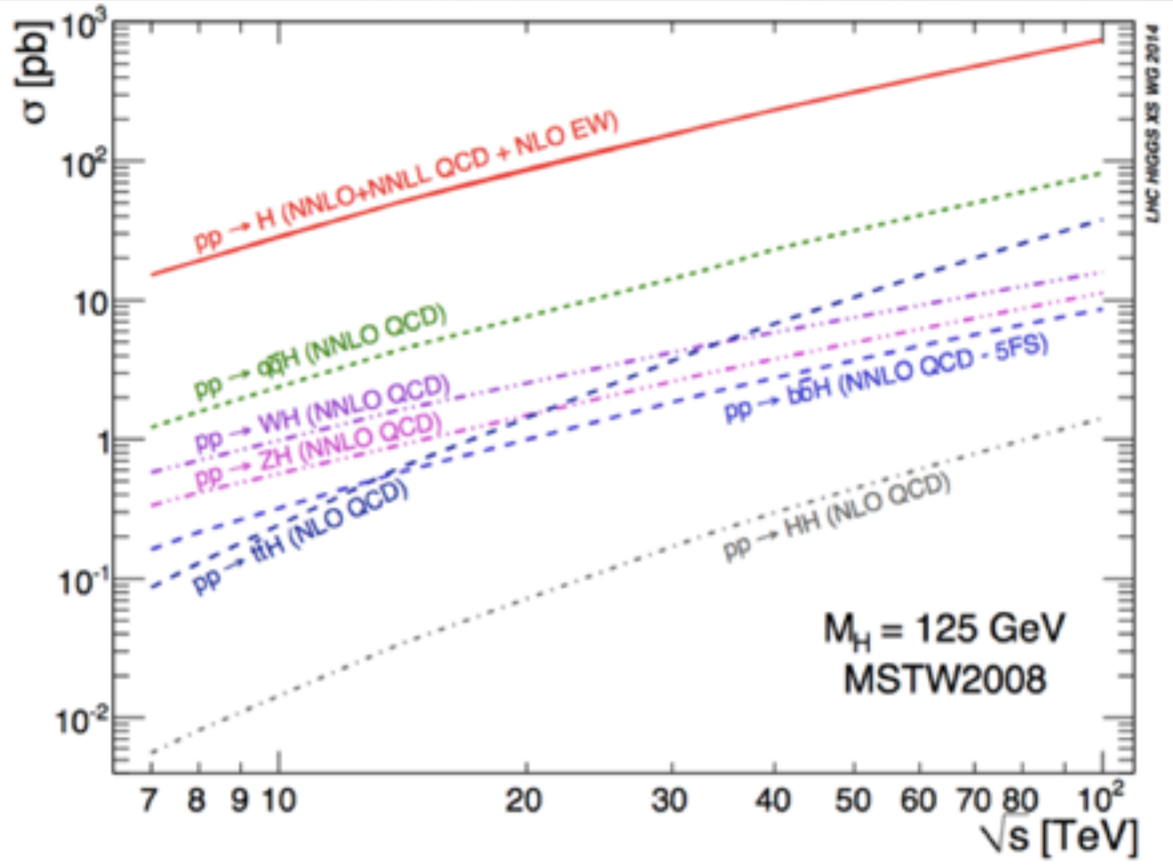

# The “guaranteed” SSC discovery

Superconducting Super Collider (SSC): 87.1 km tunnel, design: 40 TeV *pp* collisions

1999

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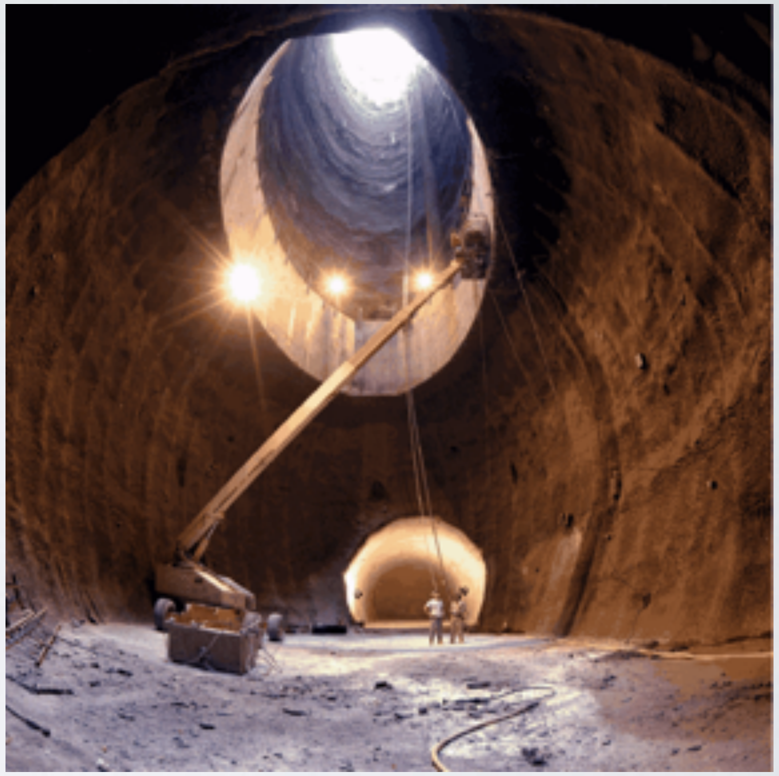

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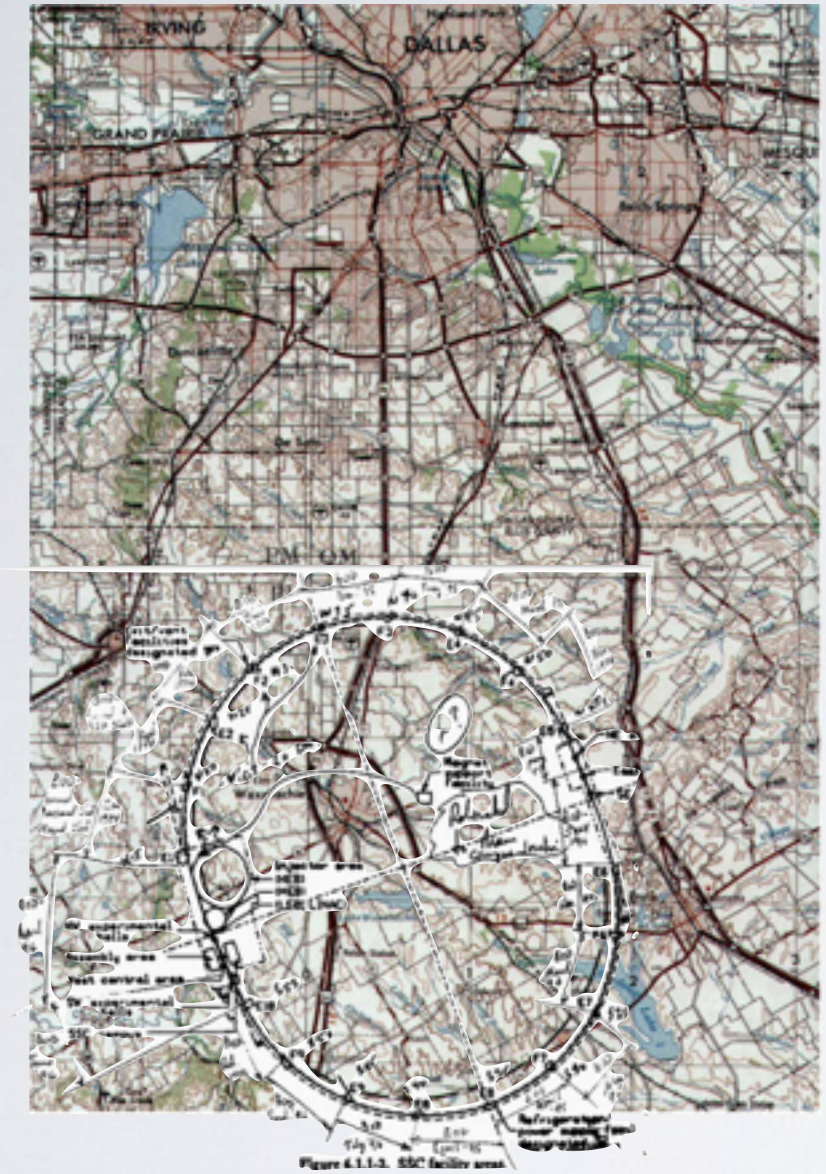

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The New York Times

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By CLIFFORD KRAUSS,
Published: June 25, 1993

An amendment to the energy and water appropriations bill that was intended to kill the program passed by a vote of 280 to 150, with 171 Democrats joining 108 Republicans and one independent in voting against the project. Sixty-five Republicans and 85 Democrats voted in favor of the supercollider. The House also voted to kill the project last year, but by a far narrower margin, 232 to 181.

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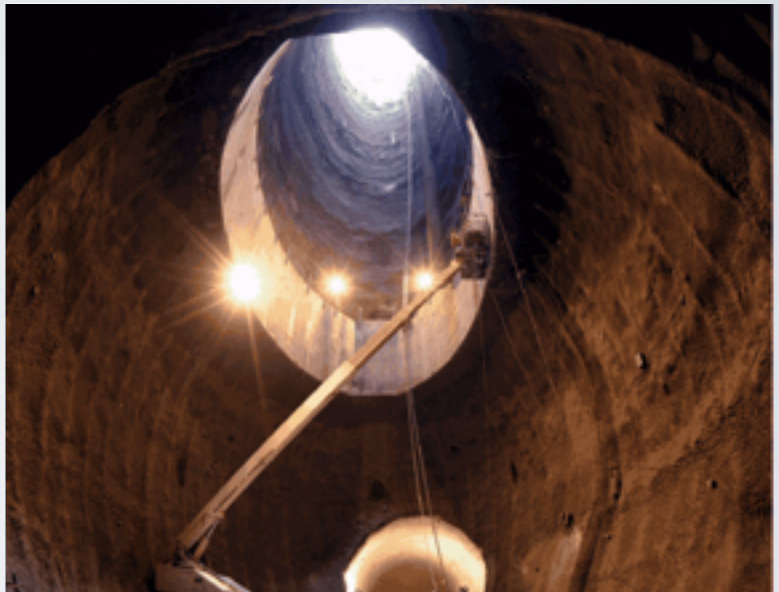

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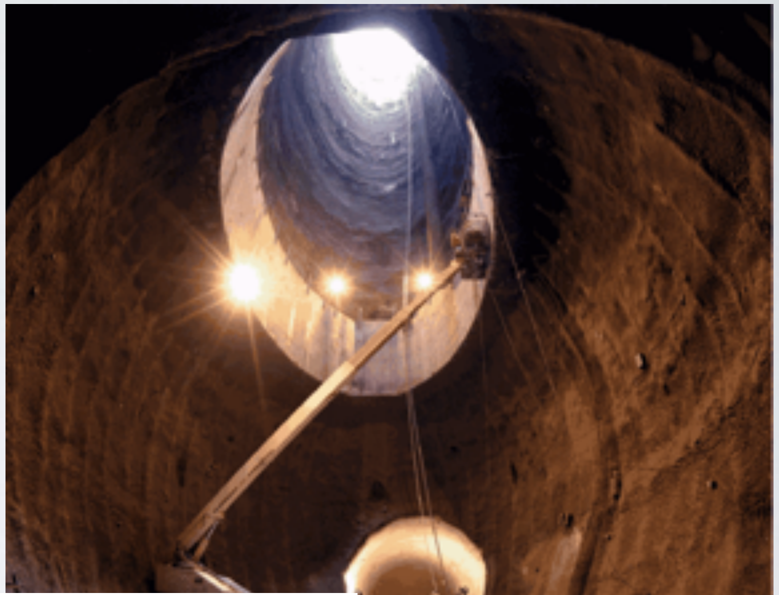

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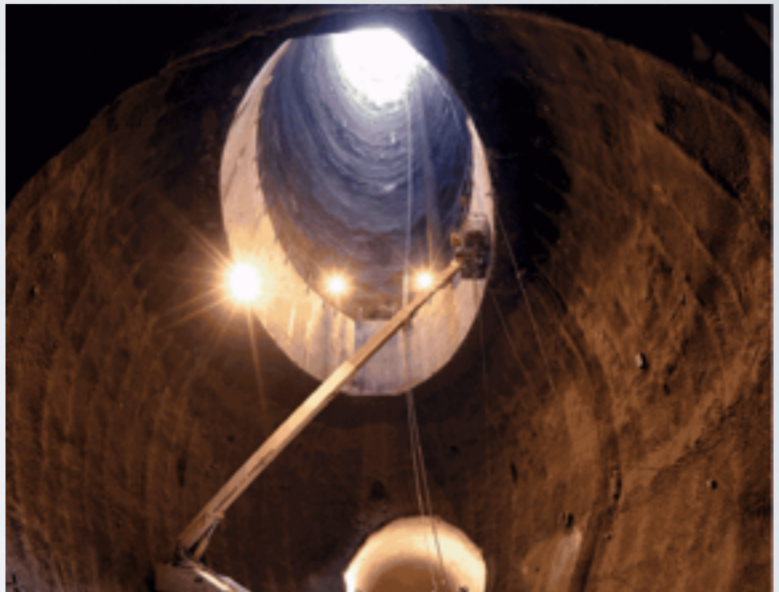

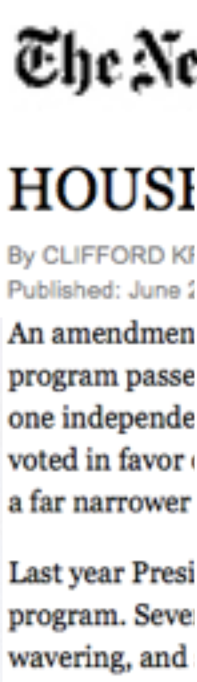

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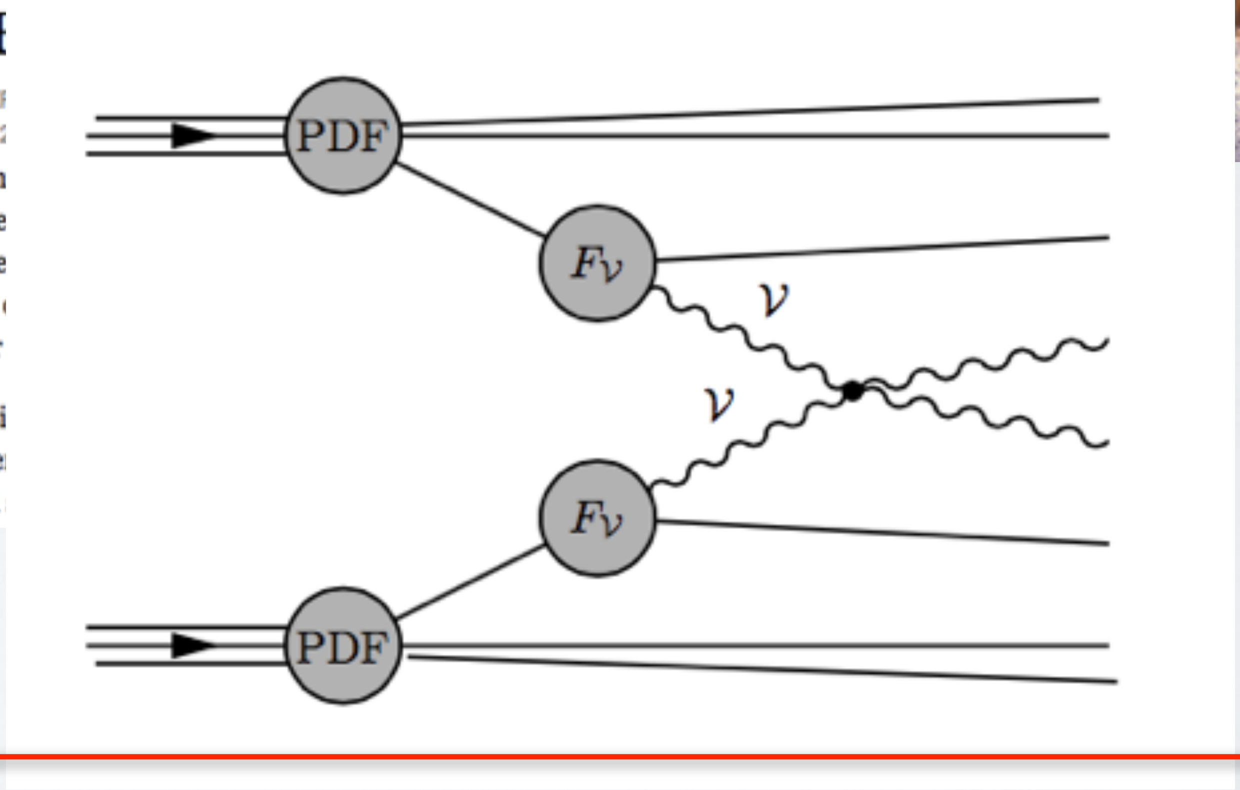

1999

Either Higgs discovery or something in *WW* scattering at 1-1.5 TeV

# The “guaranteed” LHC discovery

Optical Theorem (Unitarity of the S(cattering) Matrix):

$$\sigma_{\text{tot}} = \text{Im}\left[\mathcal{M}_{ii}(t=0)\right]/s \qquad t = -s(1-\cos\theta)/2$$

Partial wave amplitudes:

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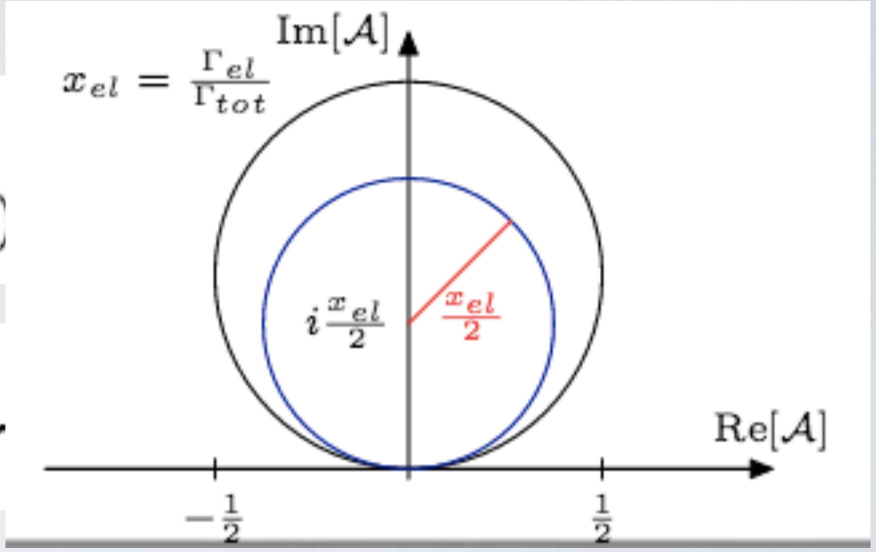

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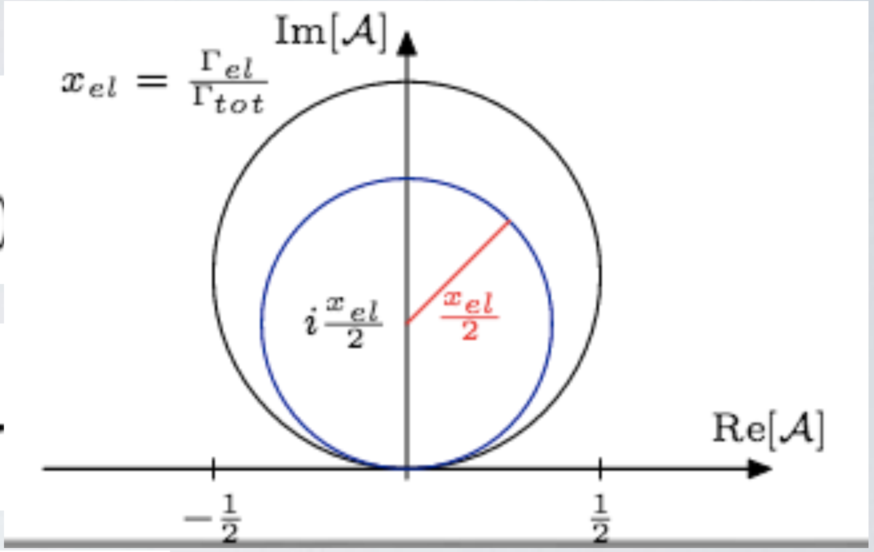

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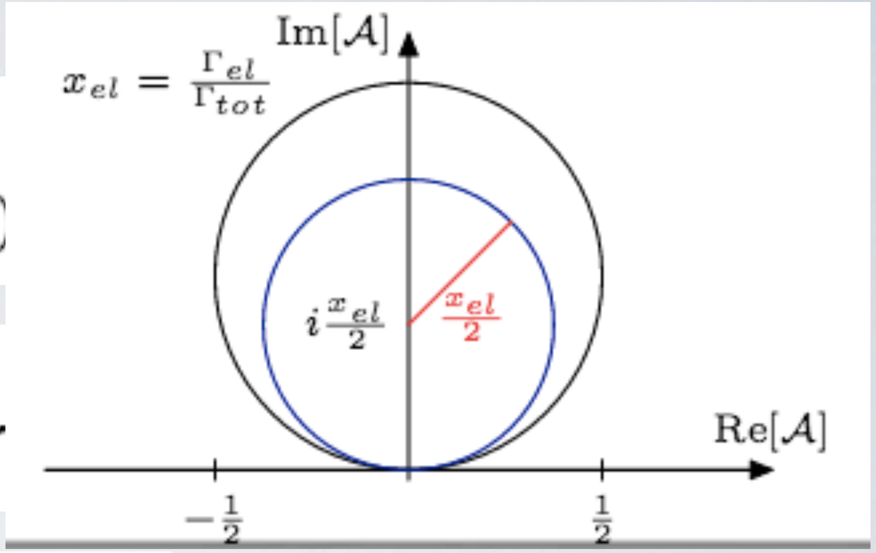

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SM longitudinal isospin eigenamplitudes ($\mathcal{A}_{I,\text{spin}=J}$):

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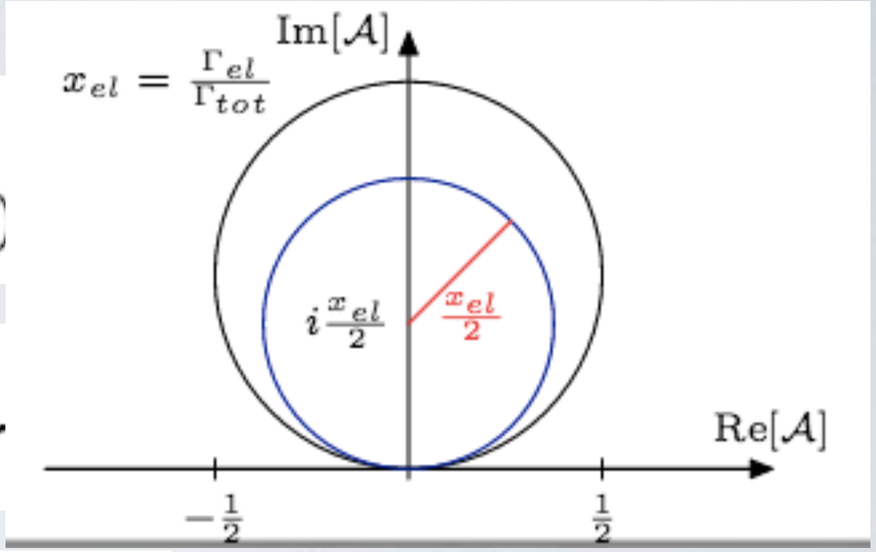

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Lee/Quigg/Thacker, 1973

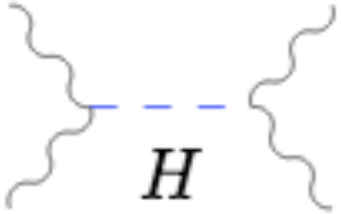
exceeds unitarity bound $|\mathcal{A}_{IJ}| \lesssim \frac{1}{2}$ at:

$$I = 0: \qquad E \sim \sqrt{8\pi}v = 1.2\,\text{TeV}$$

$$I = 1: \qquad E \sim \sqrt{48\pi}v = 3.5\,\text{TeV}$$

$$I = 2: \qquad E \sim \sqrt{16\pi}v = 1.7\,\text{TeV}$$

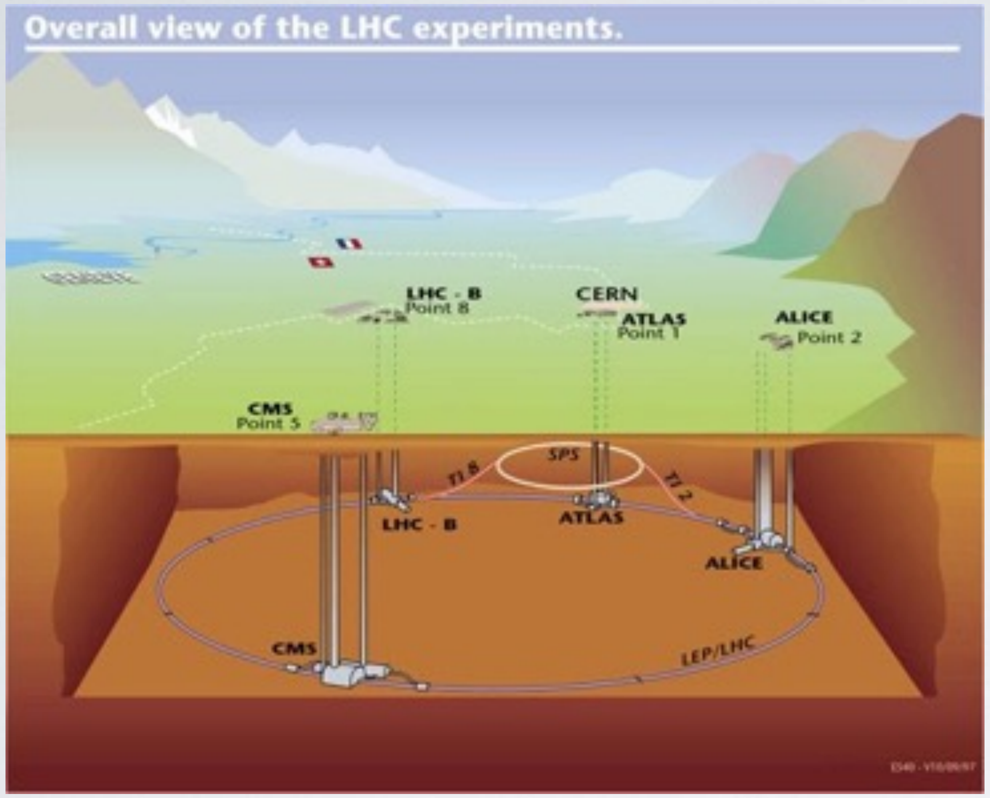
Higgs exchange:

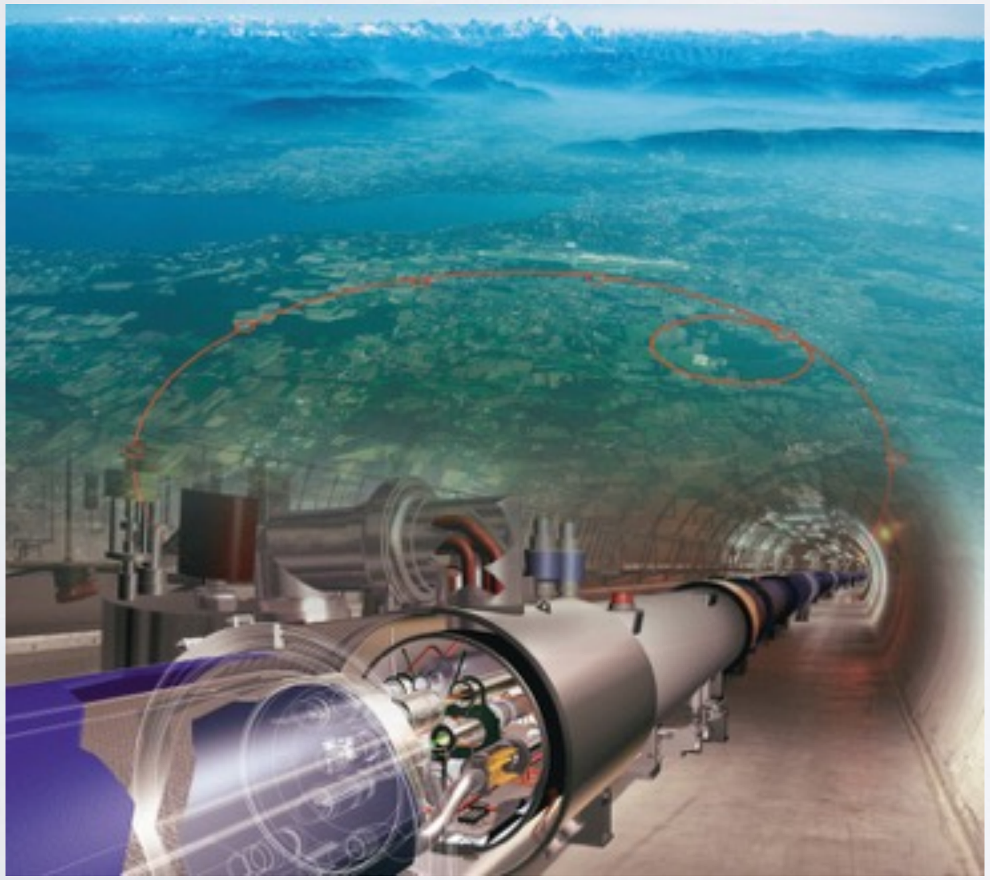


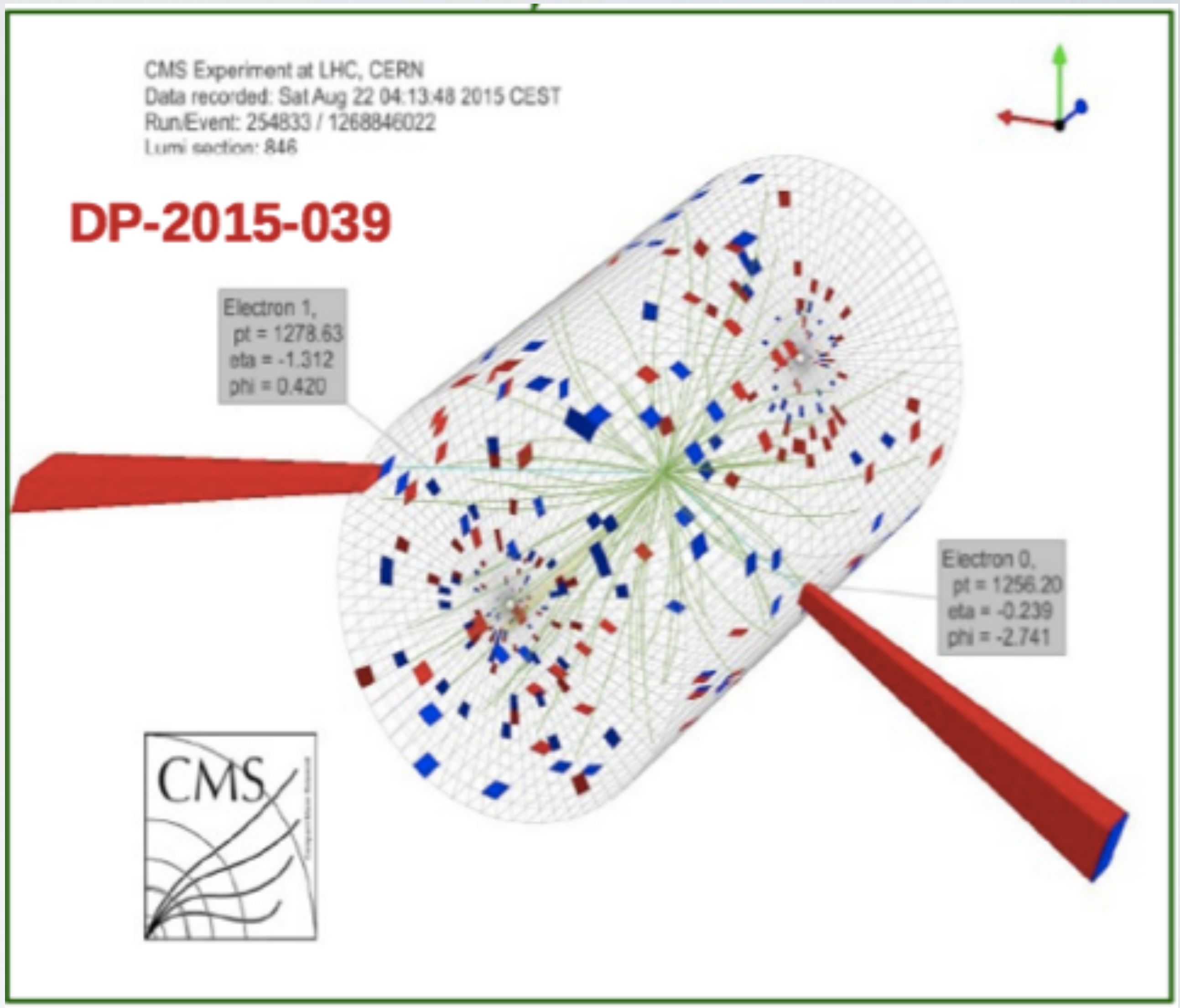
$$\mathcal{A}(s,t,u) = -\frac{M_H^2}{v^2}\frac{s}{s-M_H^2}$$

Unitarity: $M_H \lesssim \sqrt{8\pi}v \sim 1.2\,\text{TeV}$

# The Challenge of the Large Hadron Collider



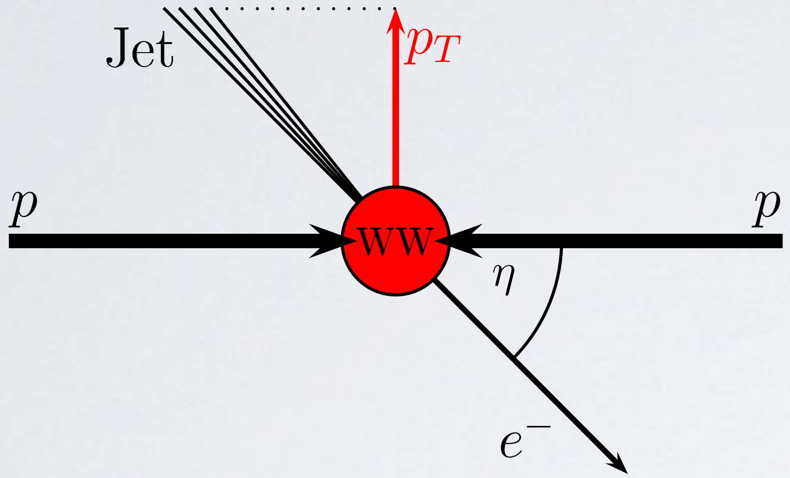


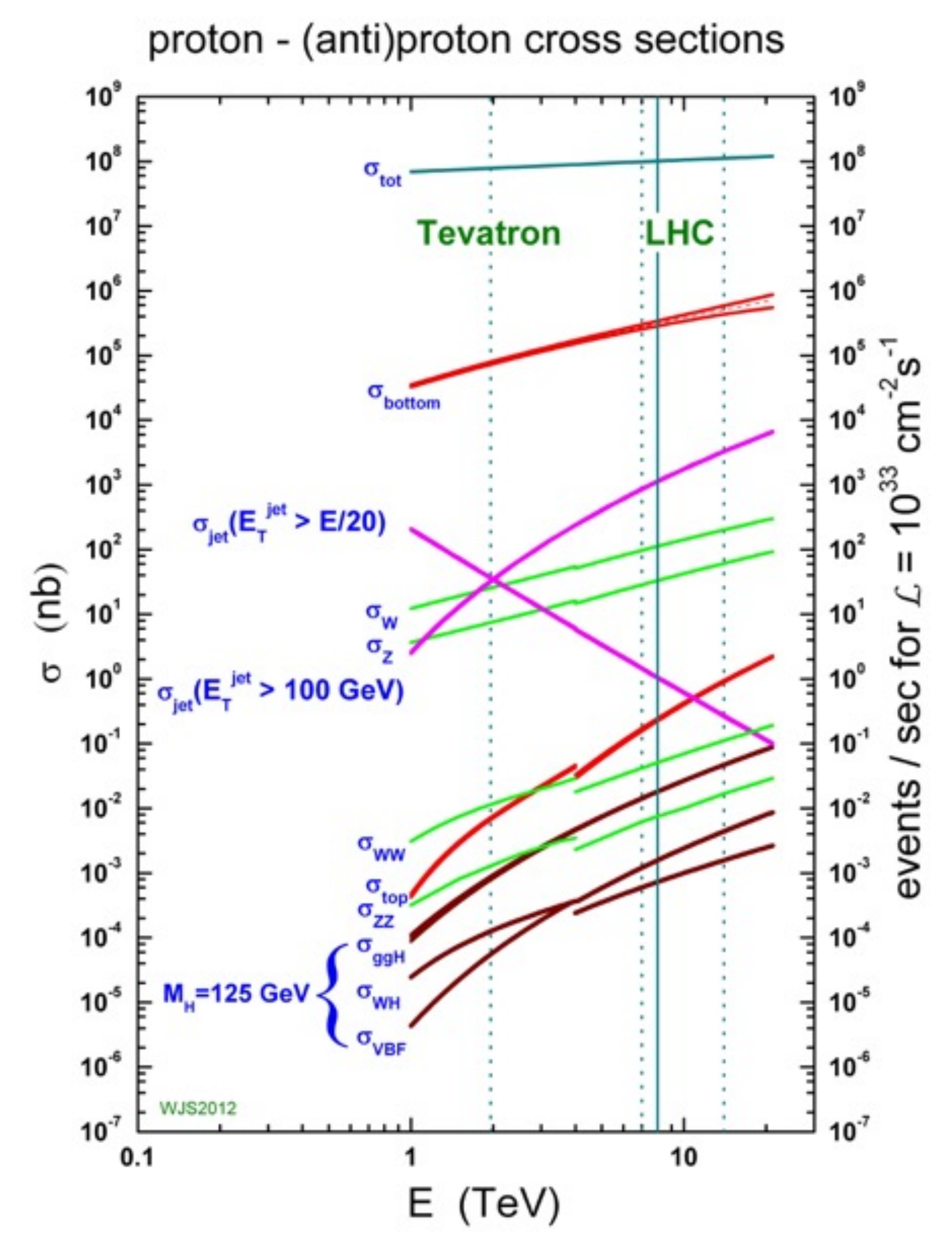


CMS Run II event: M(*ee*) = 2.9 TeV

# The Challenge of the Large Hadron Collider

- Different partonic subprocesses: *qq, qg, gg*
- No fixed partonic energy





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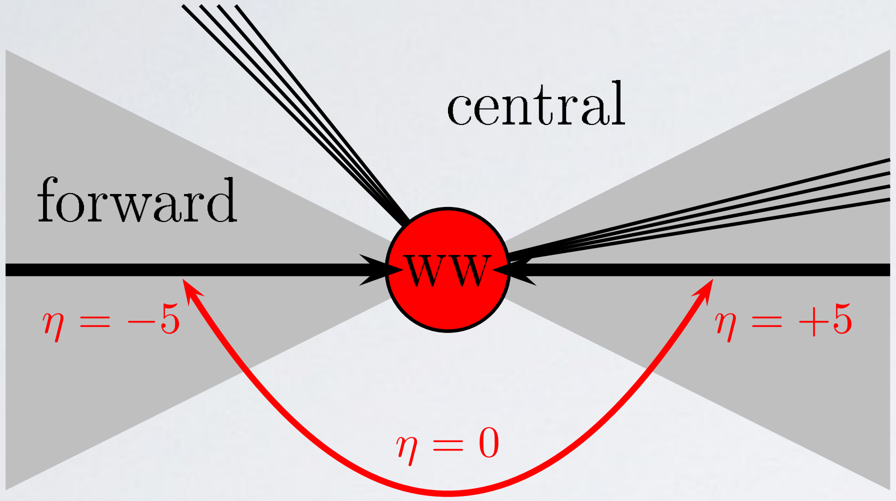
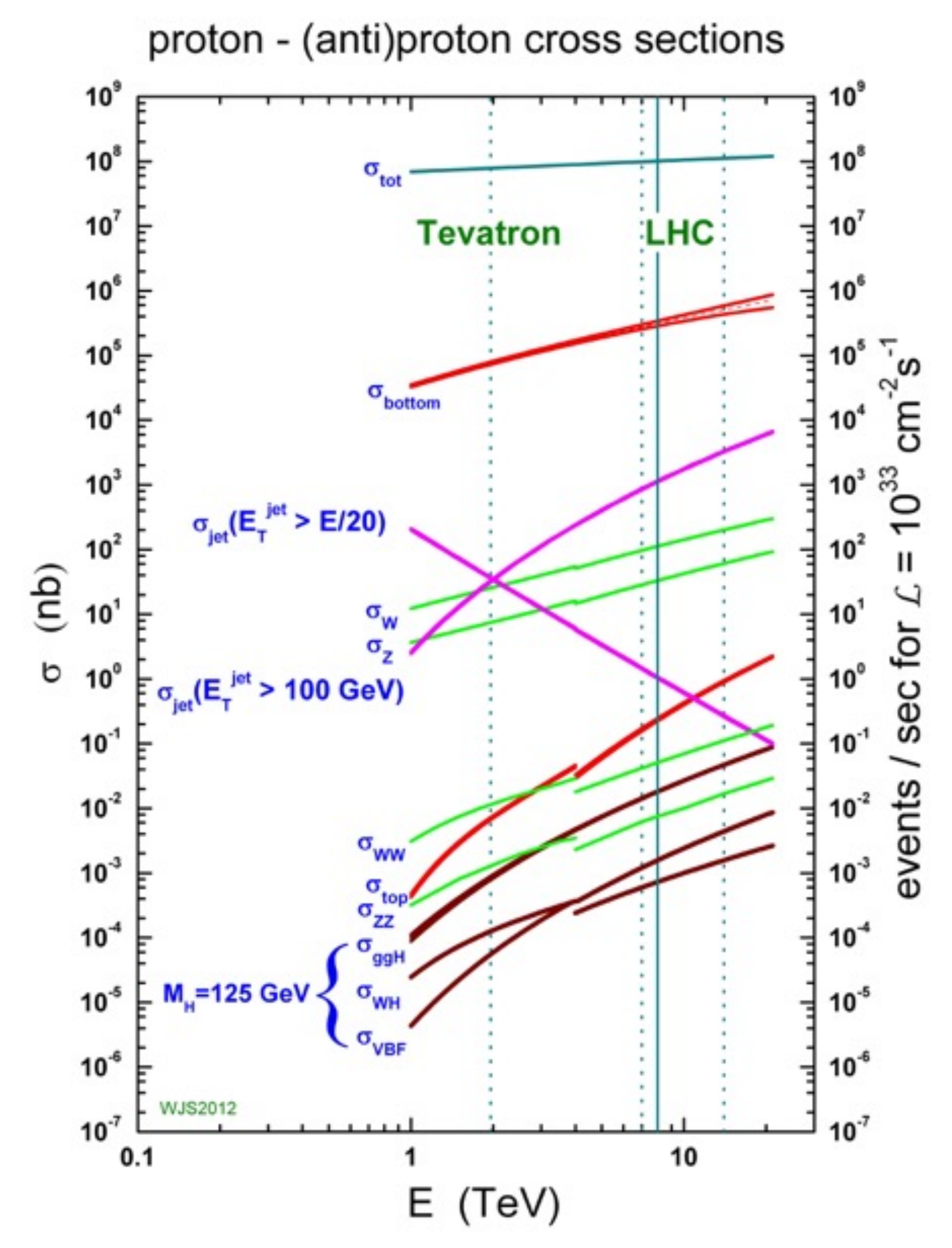


- Luminosity: $10^{34}$ cm$^{-2}$ s$^{-1}$
- Huge rates for jets, bottom, tops
- 6,000,000 bottoms / sec
- Need for hard- and software trigger



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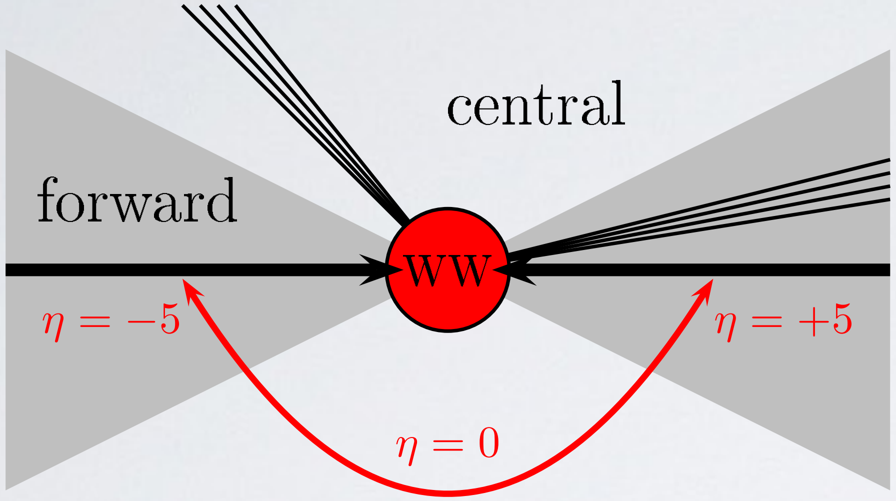

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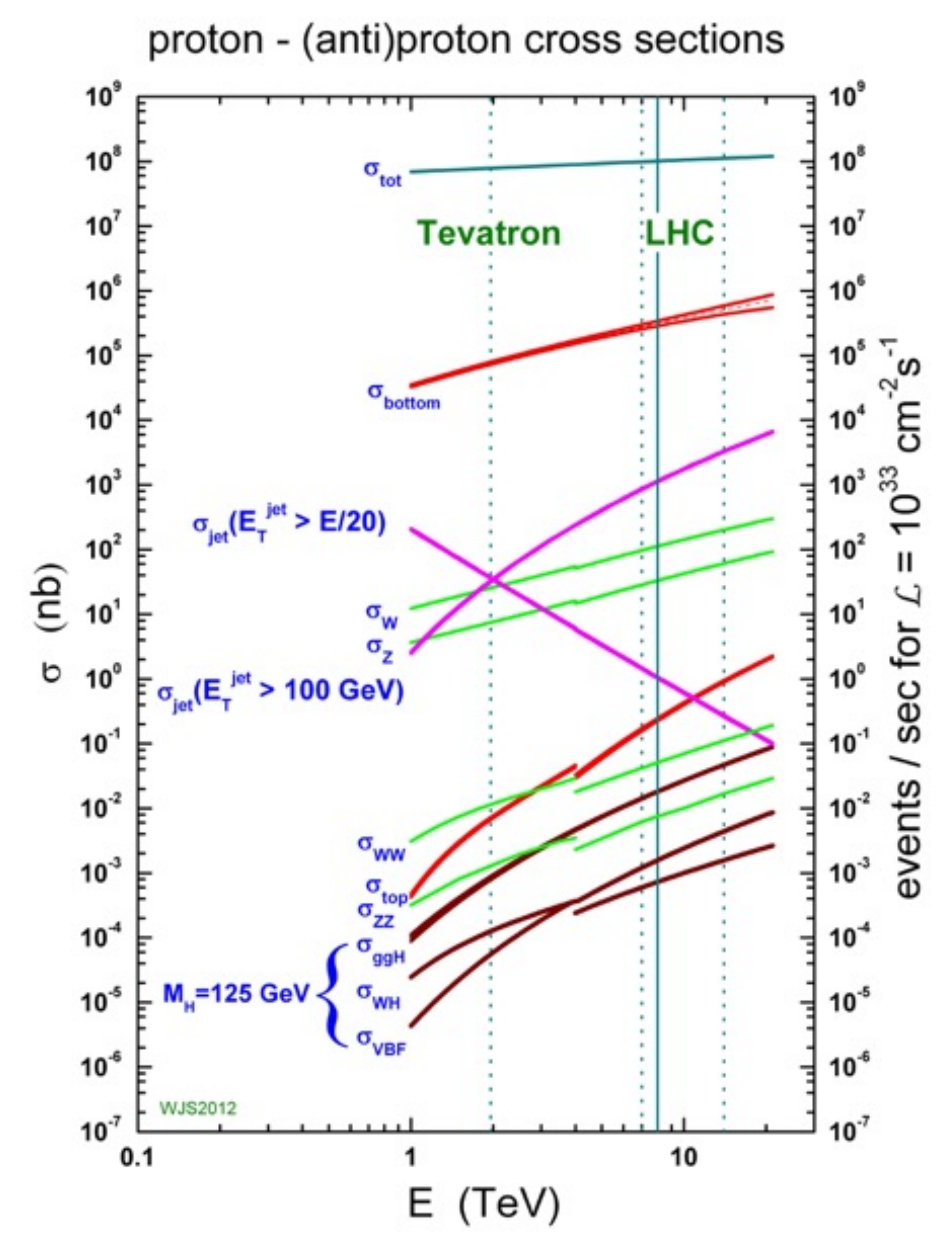
S.Weinberg:

> *"To find something interesting at the LHC is like you would like to find out for what a single dollar in the U.S. federal budget has been spent for."*



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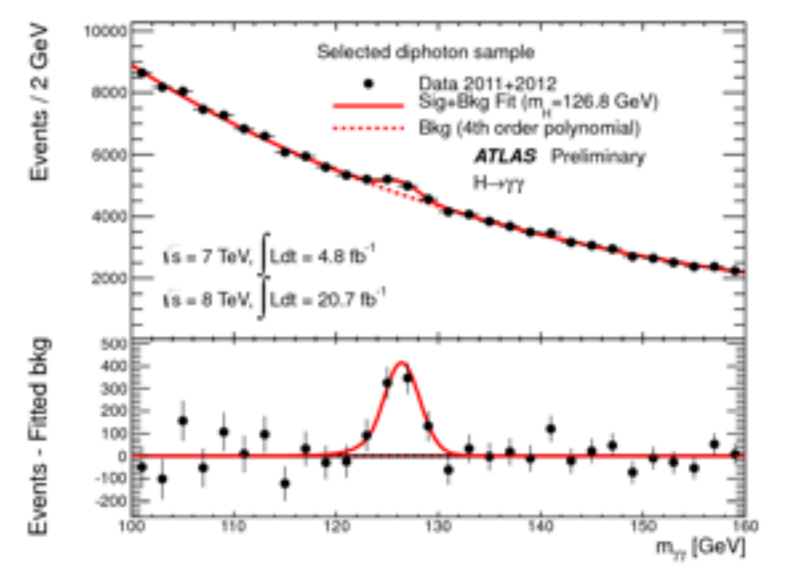

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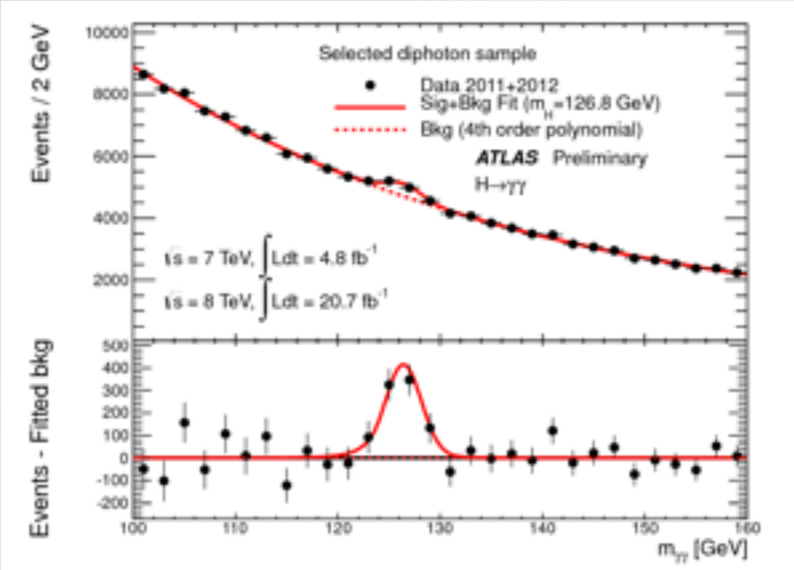

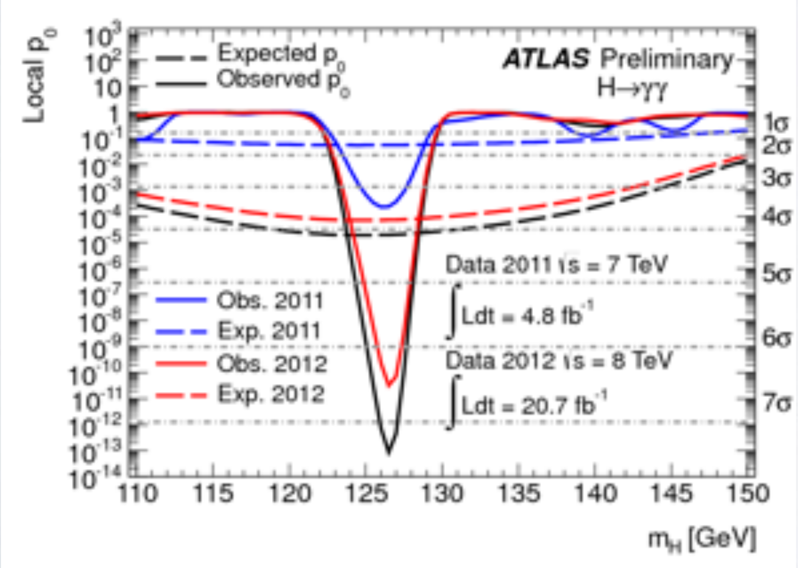

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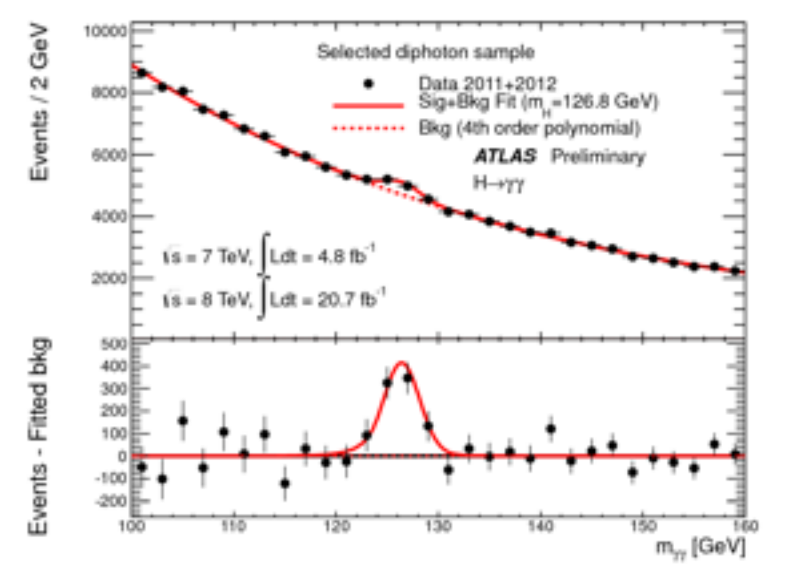

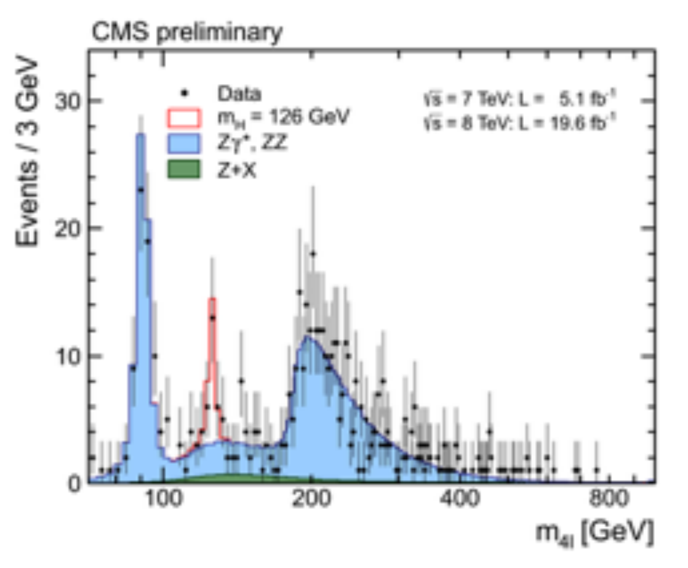

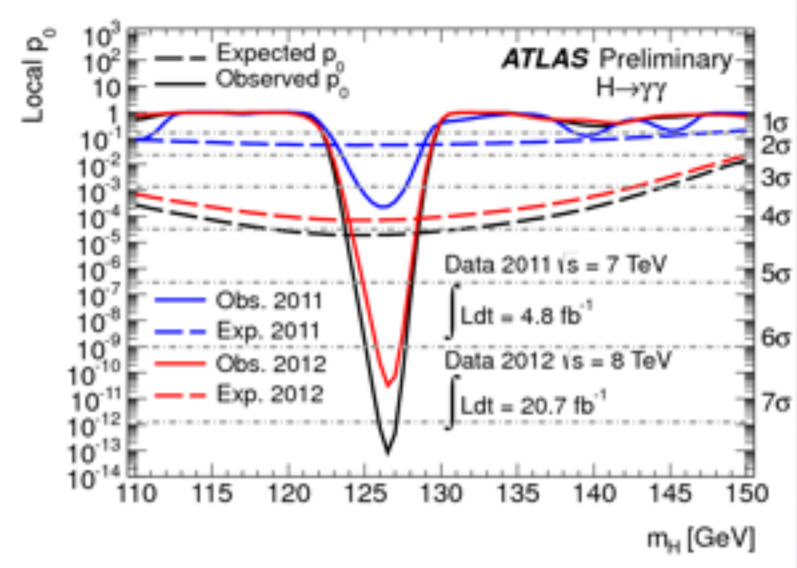

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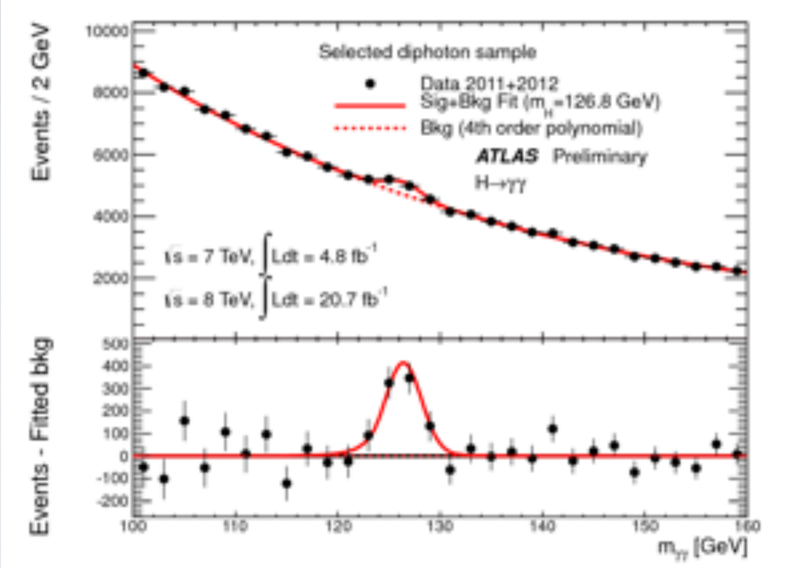

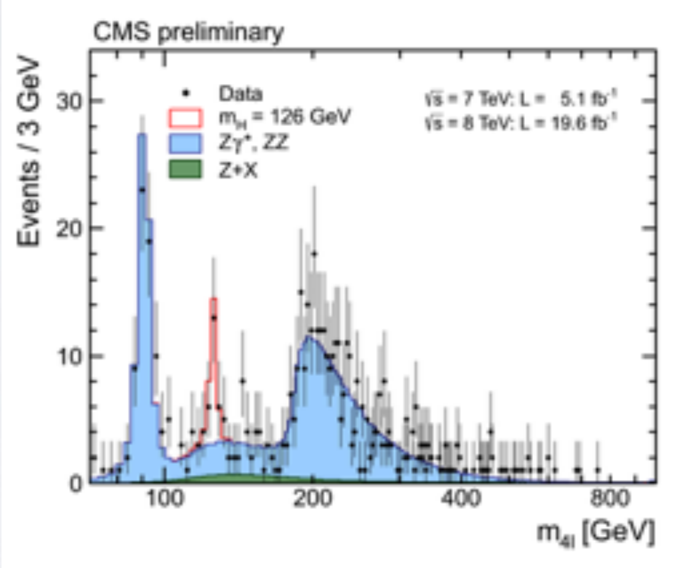

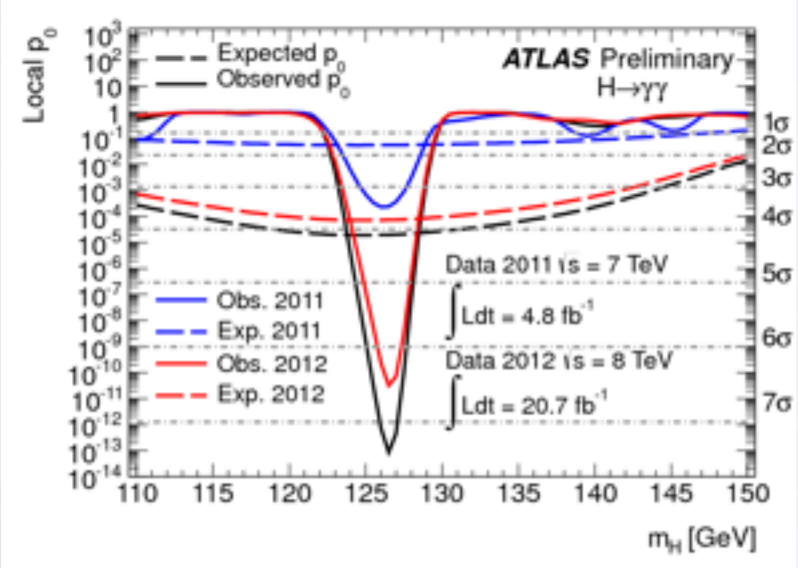

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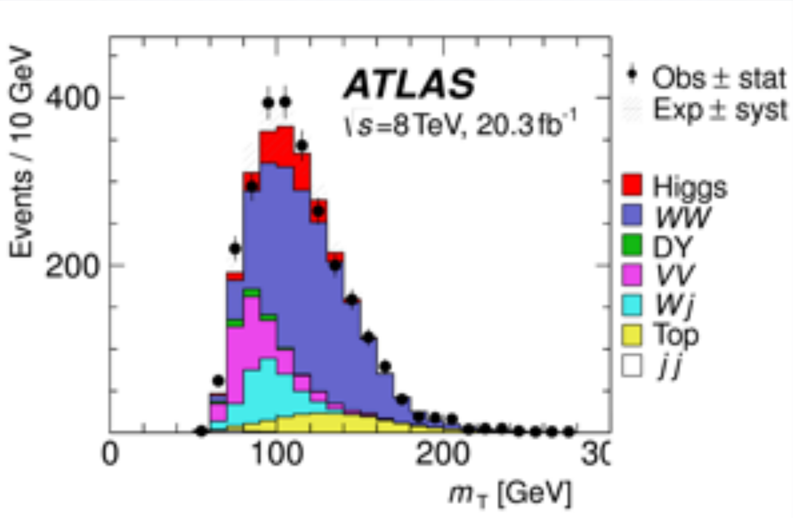

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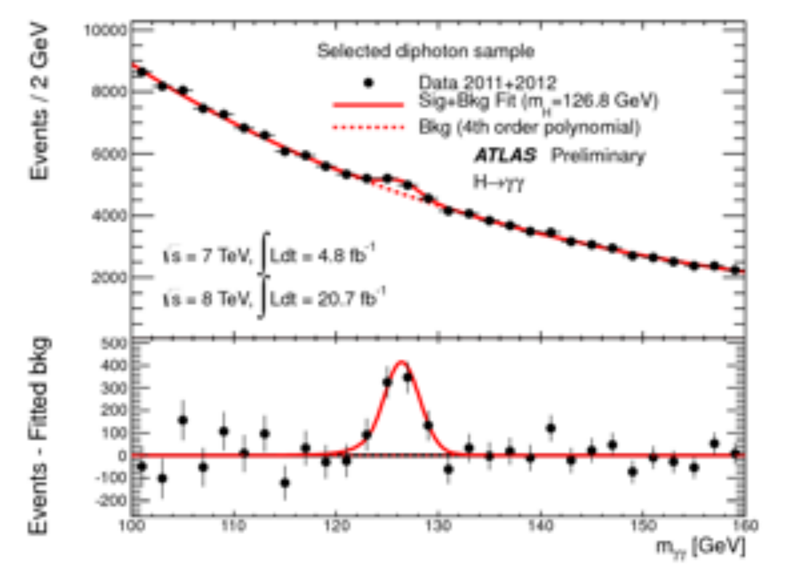

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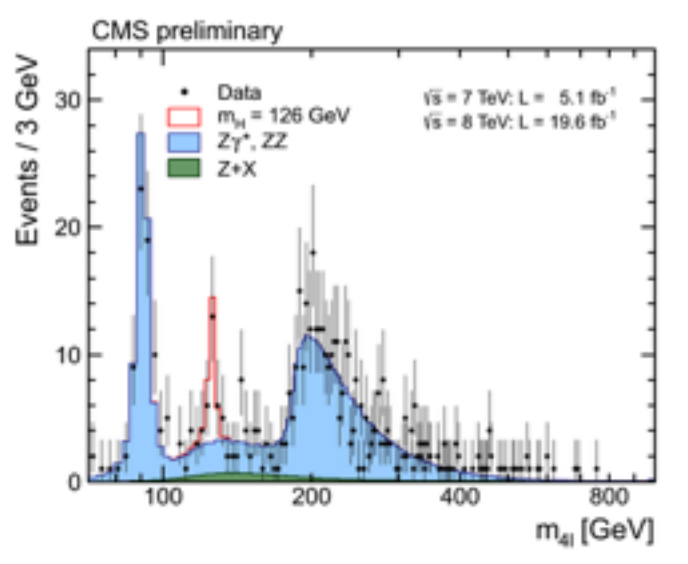
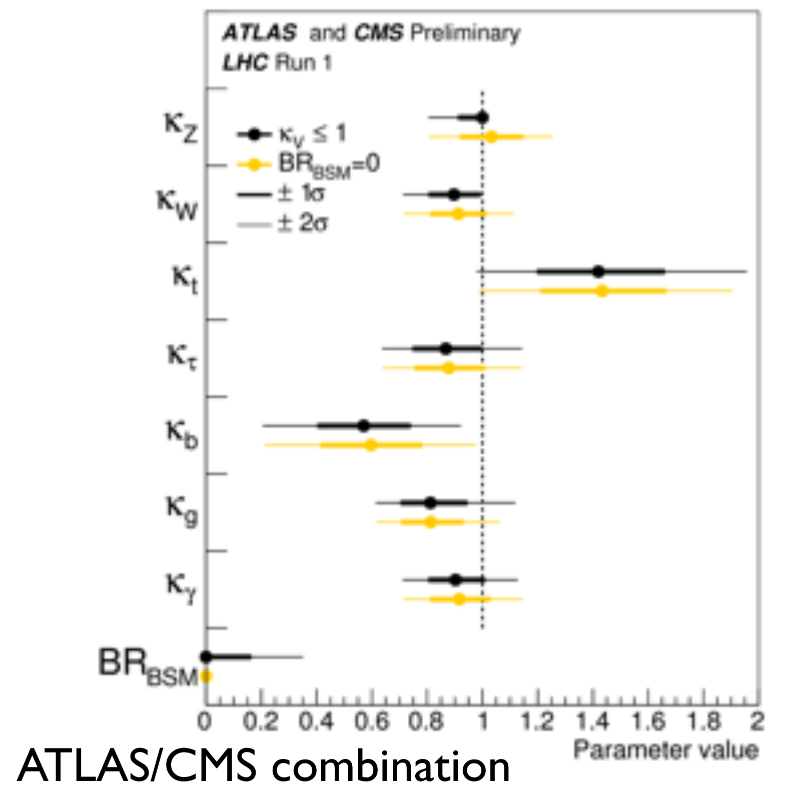
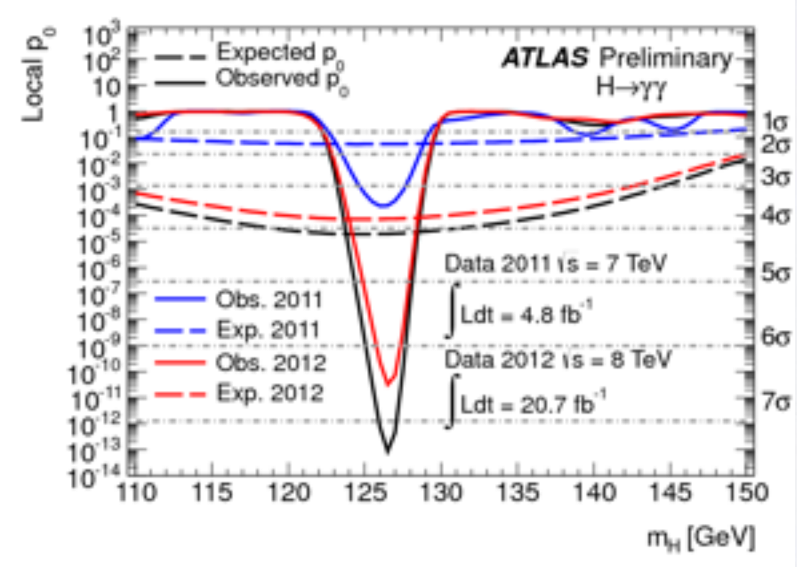




ATLAS/CMS combination



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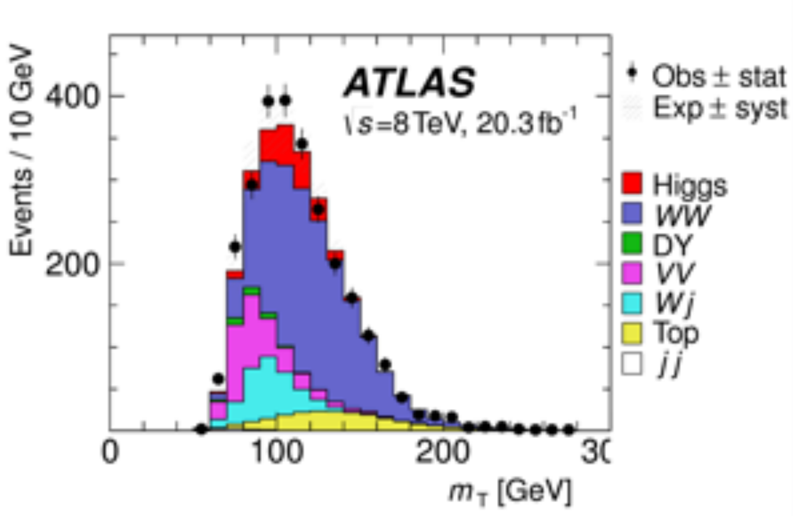

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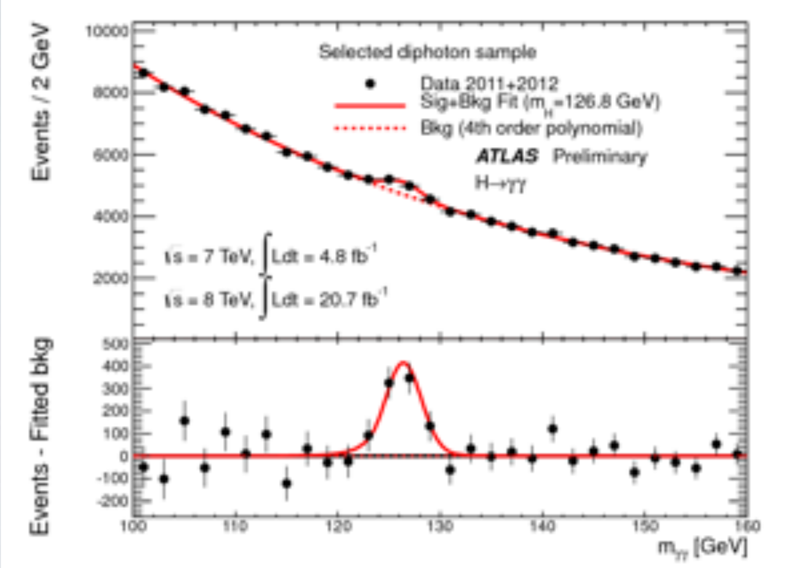
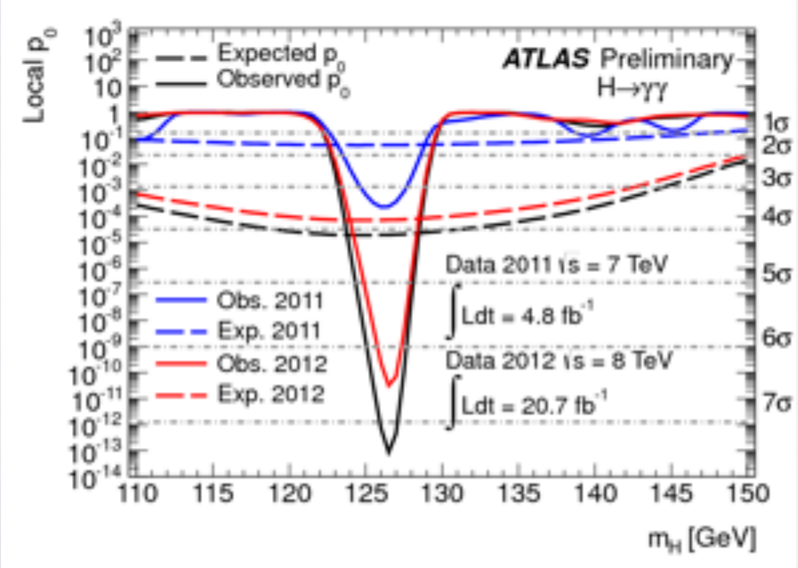
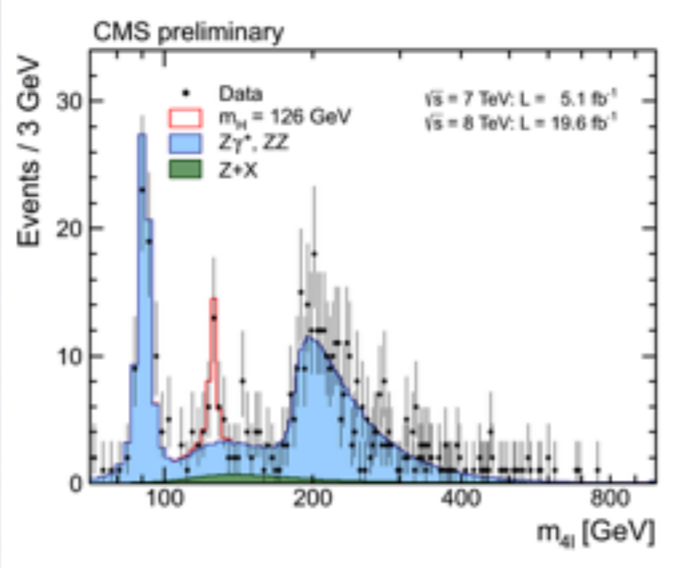
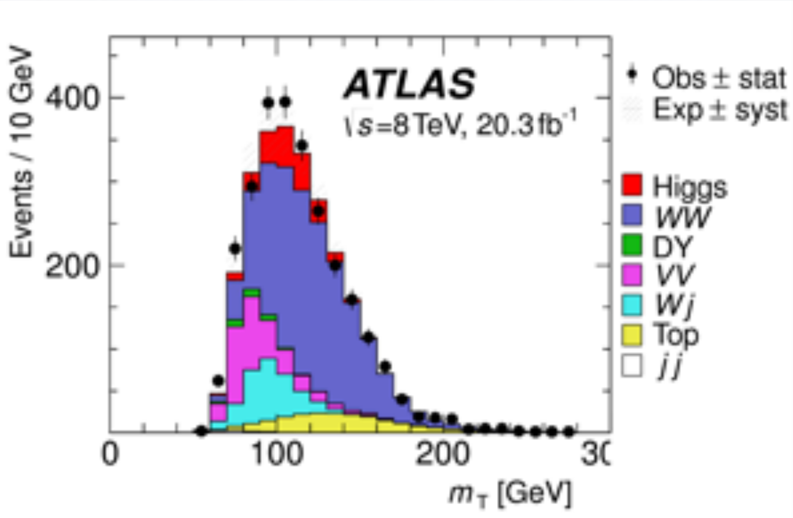


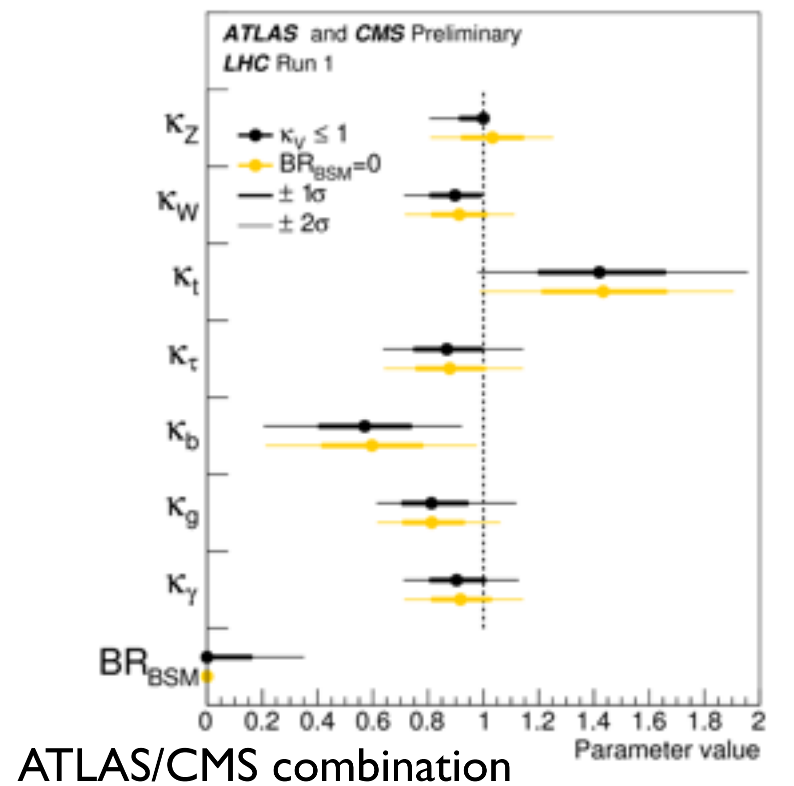


$\boxed{pp \to H \to ZZ^* \to \ell\ell\ell\ell}$



$\boxed{pp \to H \to WW^* \to \ell\nu\ell\nu}$





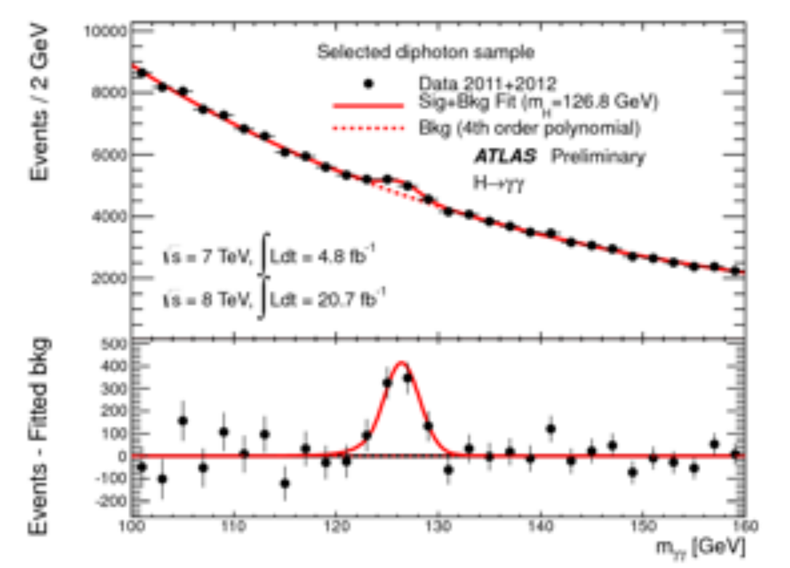
ATLAS/CMS combination

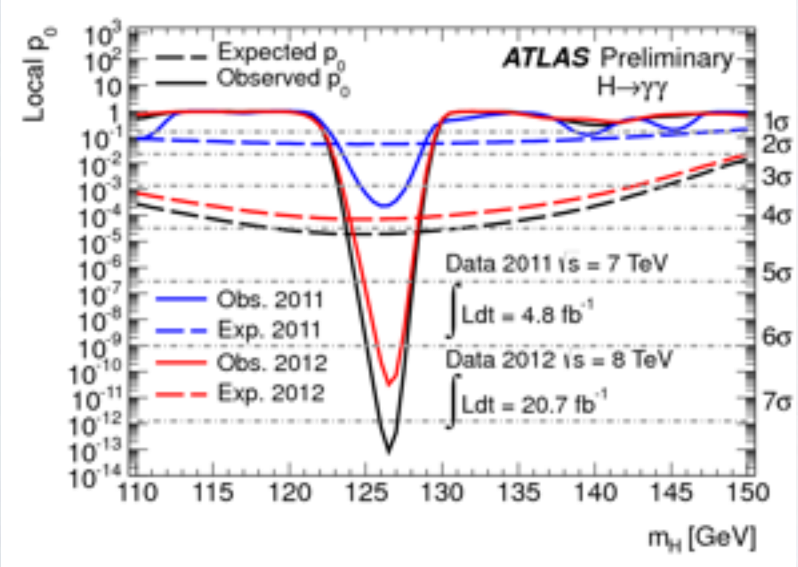
What's the most important radiative correction for LHC physics?

# The Higgs boson discovery

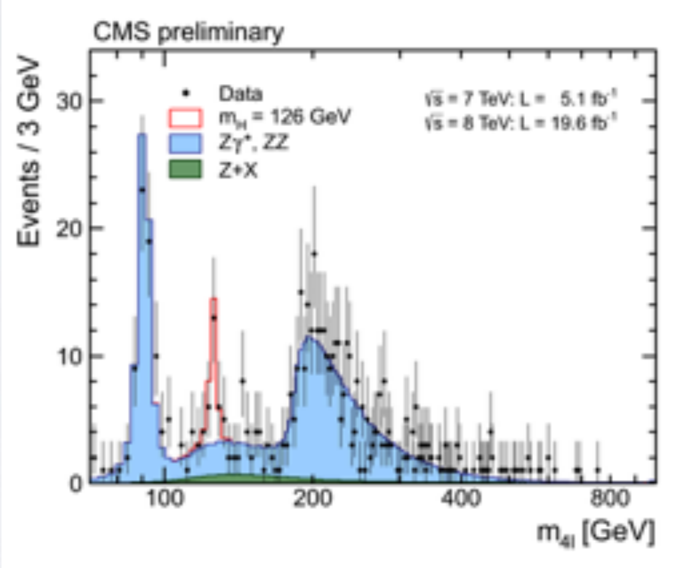
- July, 4th 2012: Discovery of a new particle, Nobel prize Dec., 10th 2013 F. Englert, P. Higgs
- A scalar boson with mass 125 GeV → a Higgs-like boson → a Higgs boson → the BEH boson

$\boxed{pp \to H \to \gamma\gamma}$





$\boxed{pp \to H \to ZZ^* \to \ell\ell\ell\ell}$



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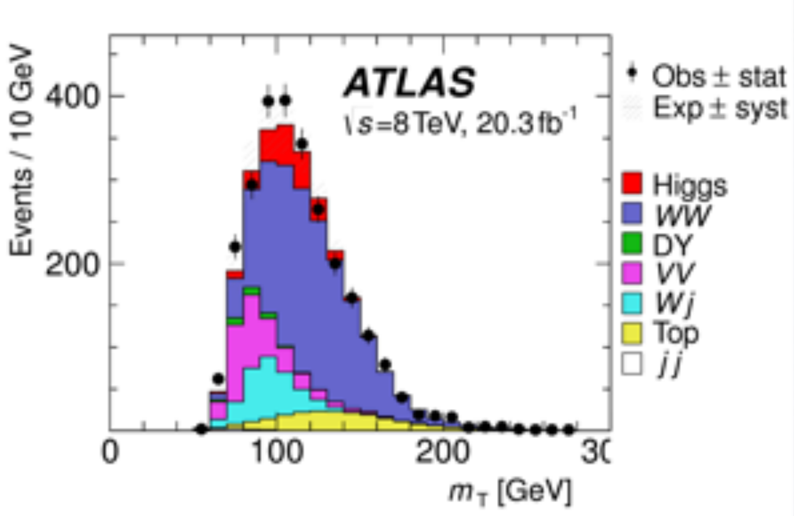
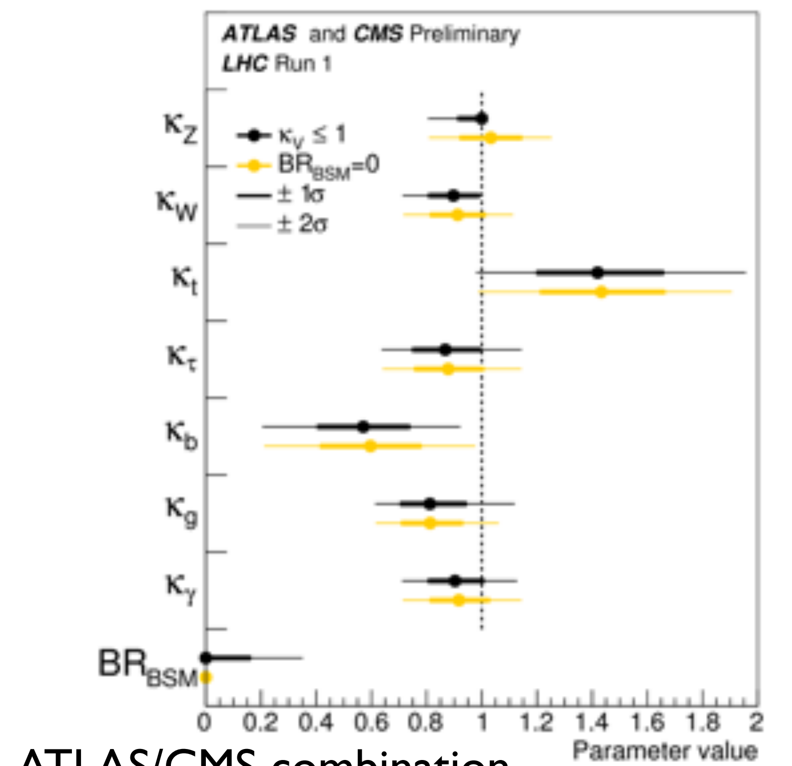


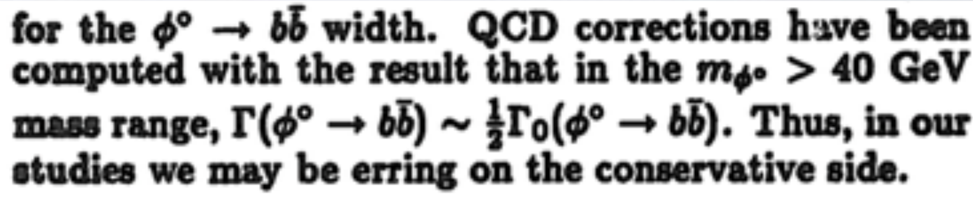


ATLAS/CMS combination

What's the most important radiative correction for LHC physics?

$$\boxed{\Gamma_{bb}} \Longrightarrow$$

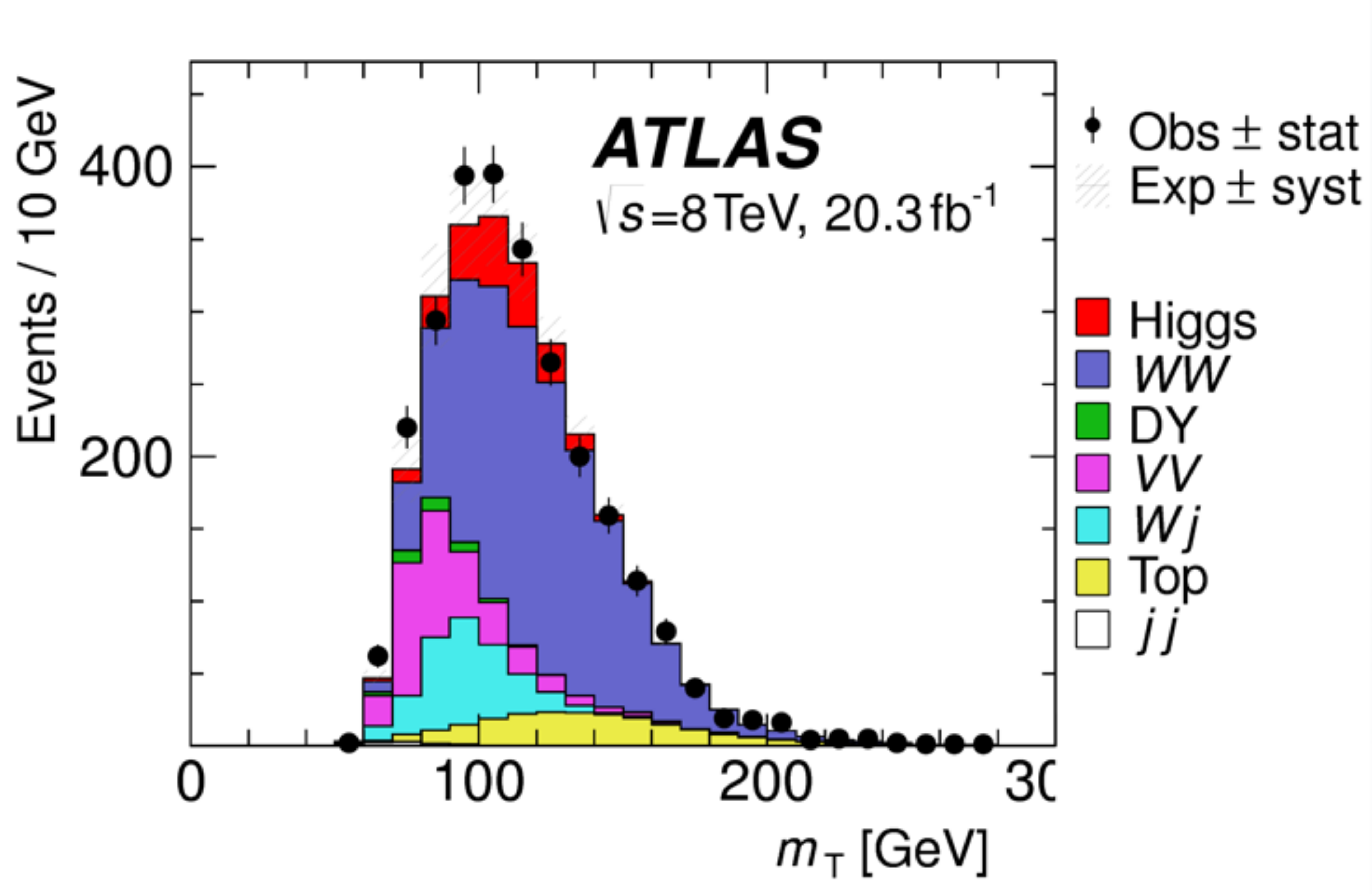
$$\mathrm{BR}(H \to bb) : 95\% \to 57\%$$



**for the $\phi^0 \to b\bar{b}$ width. QCD corrections have been computed with the result that in the $m_{\phi^0} > 40$ GeV mass range, $\Gamma(\phi^0 \to b\bar{b}) \sim \frac{1}{2}\Gamma_0(\phi^0 \to b\bar{b})$. Thus, in our studies we may be erring on the conservative side.**

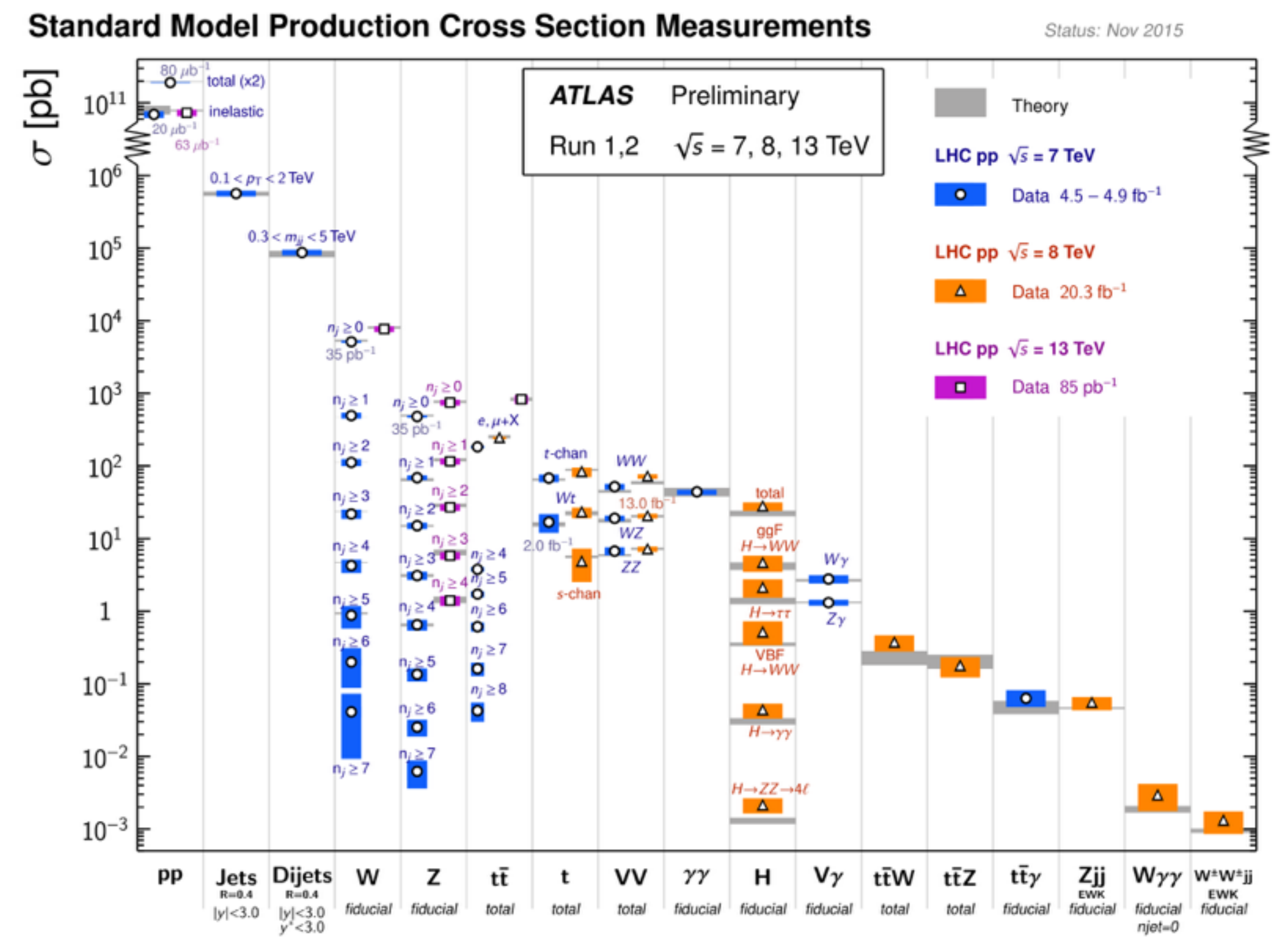
J. Gunion, SSC status, 1989

# The shiny result revisited: …



Many different channels must be known to very high precision in order to detect the signal !!!

# What goes into theory prediction?



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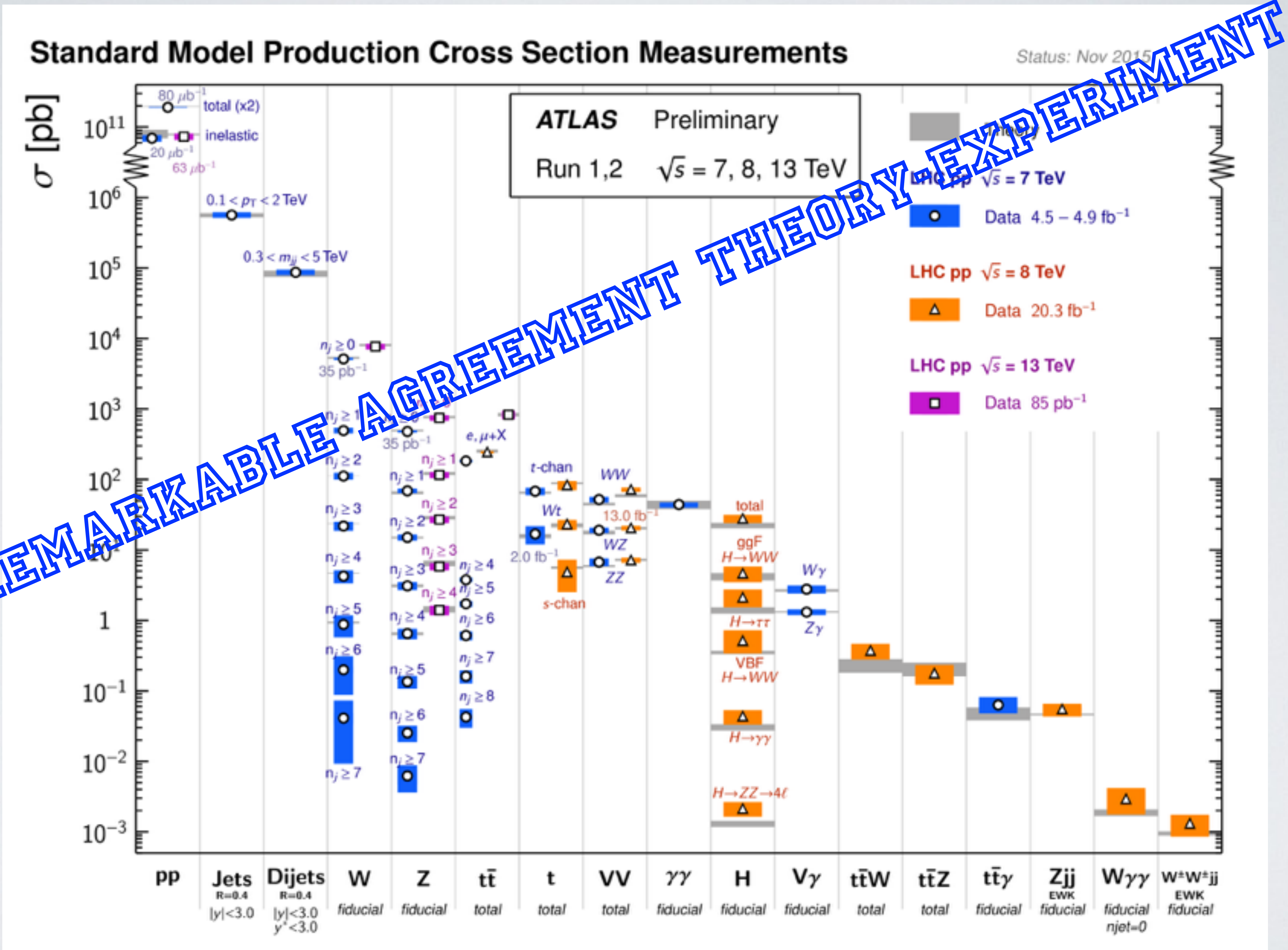

REMARKABLE AGREEMENT THEORY-EXPERIMENT

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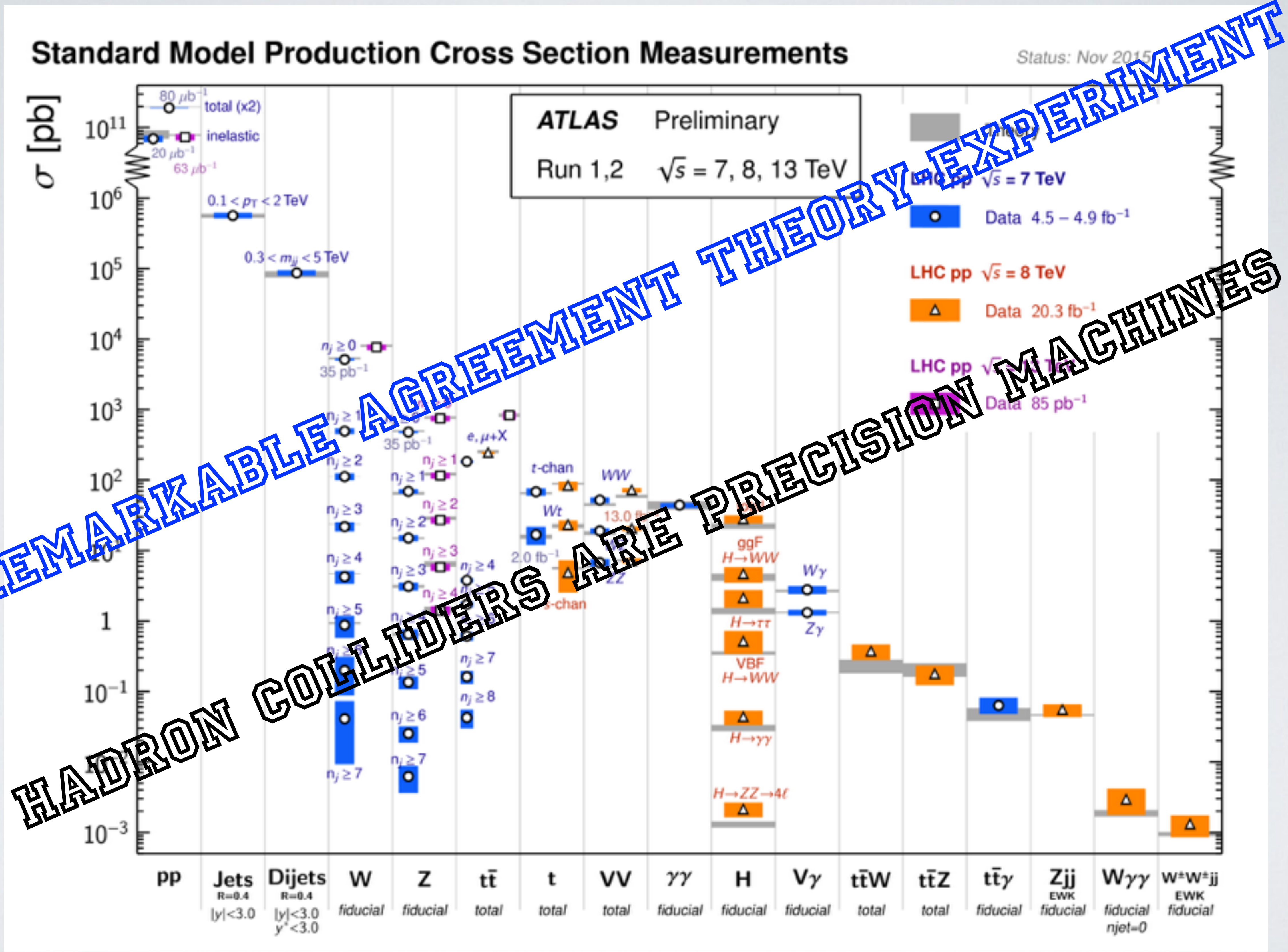
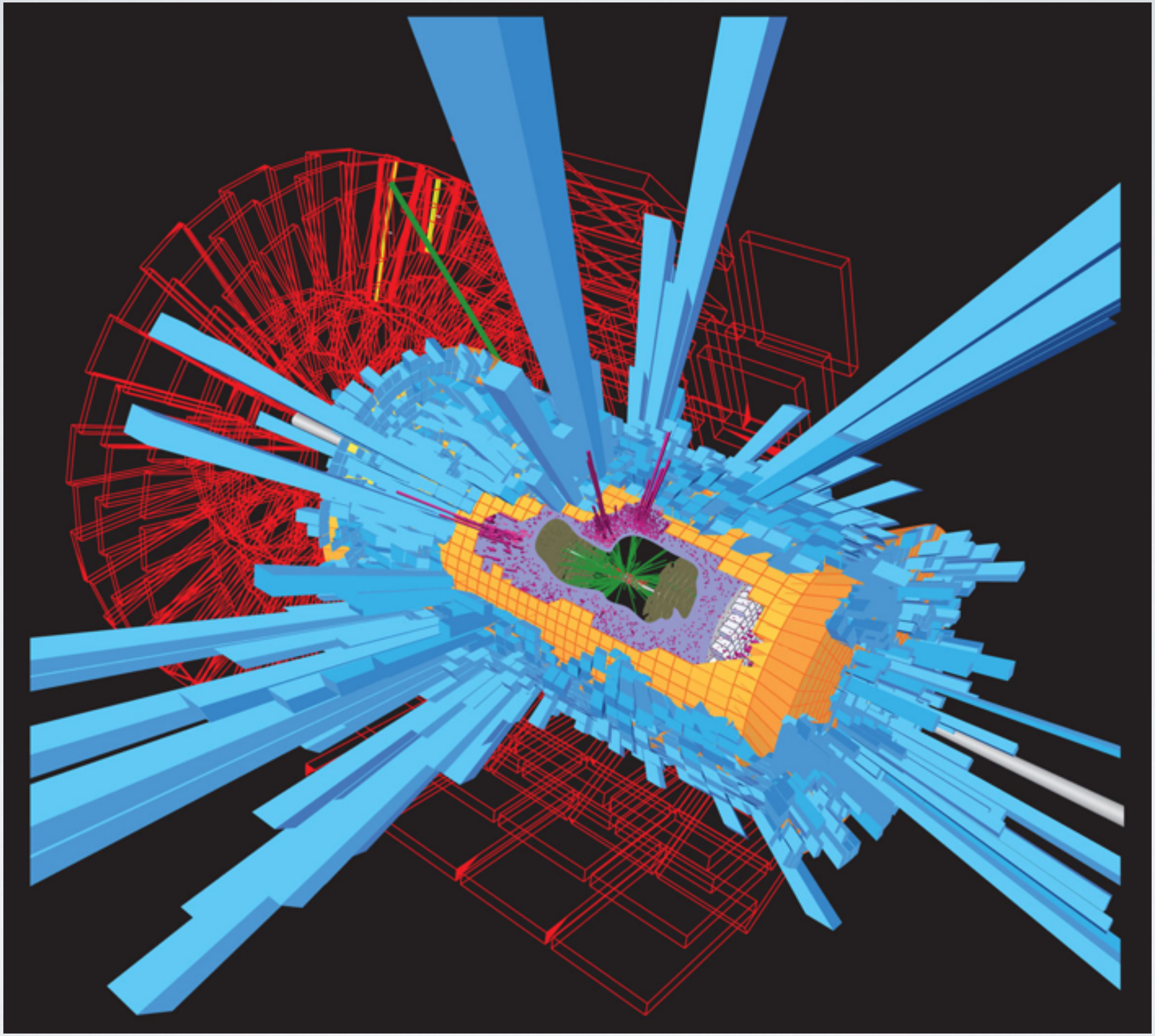


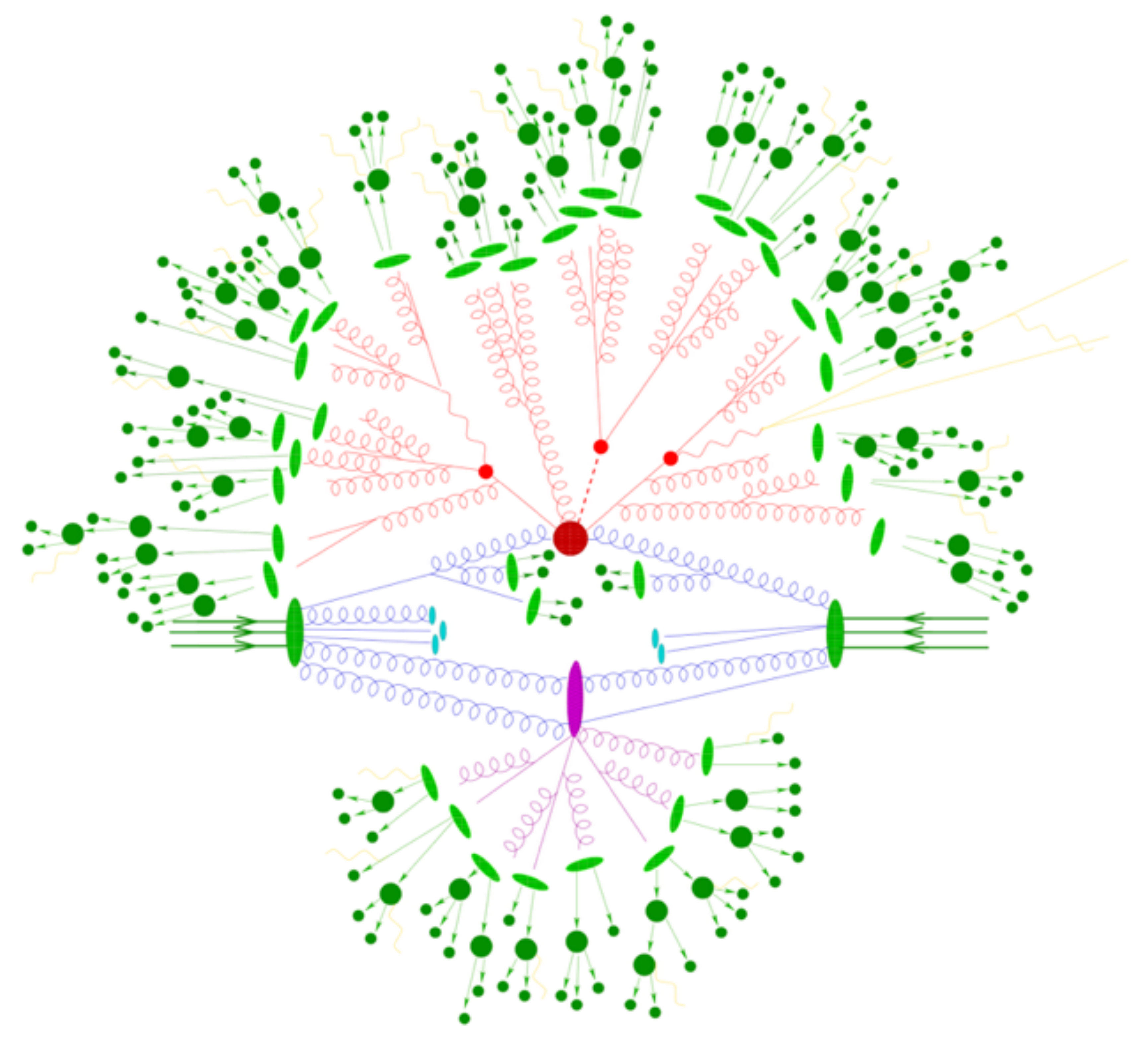
**REMARKABLE AGREEMENT THEORY-EXPERIMENT**

**HADRON COLLIDERS ARE PRECISION MACHINES**

# Events at hadron colliders … Experiment



# Events at hadron colliders … Theory



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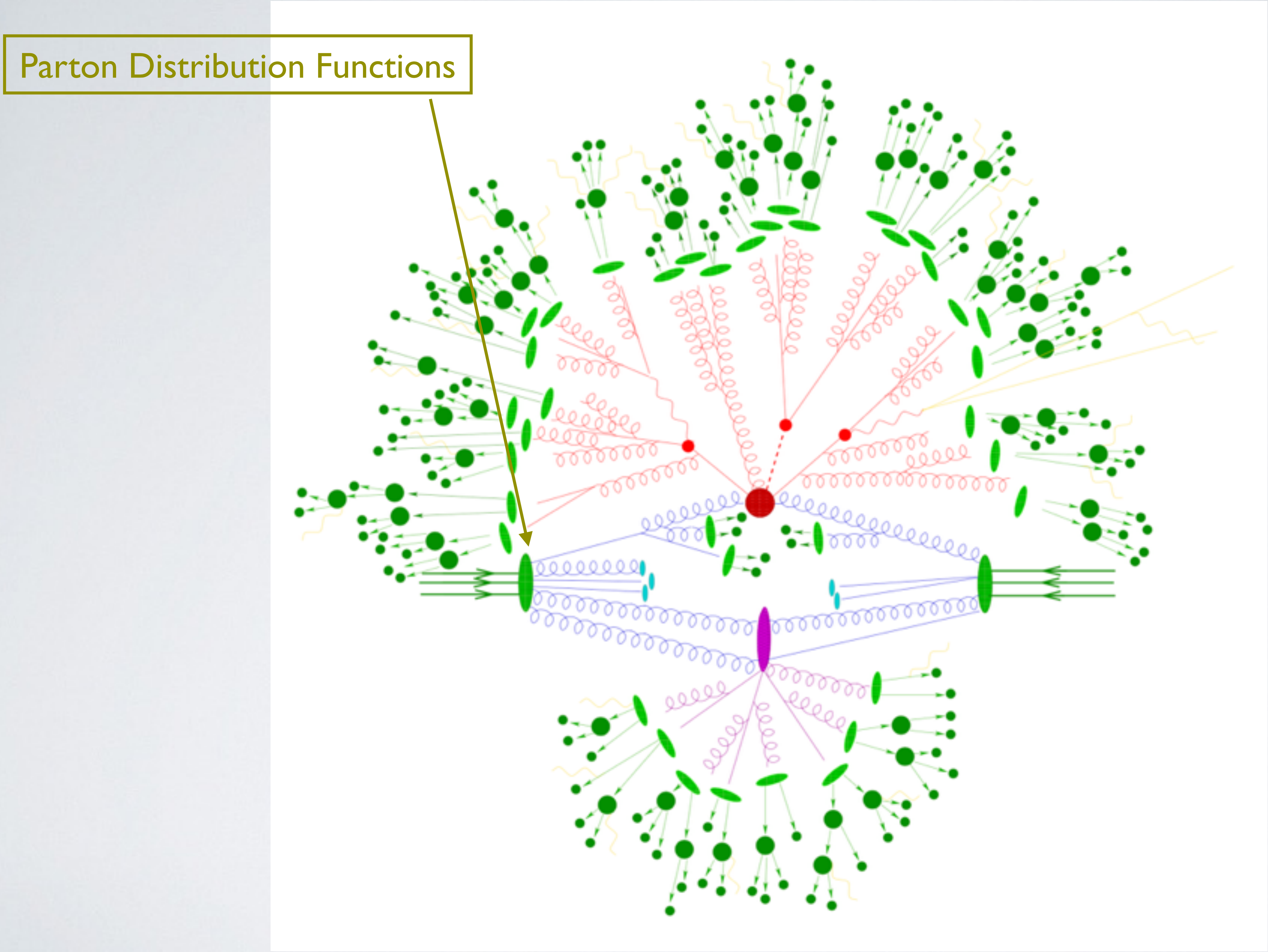
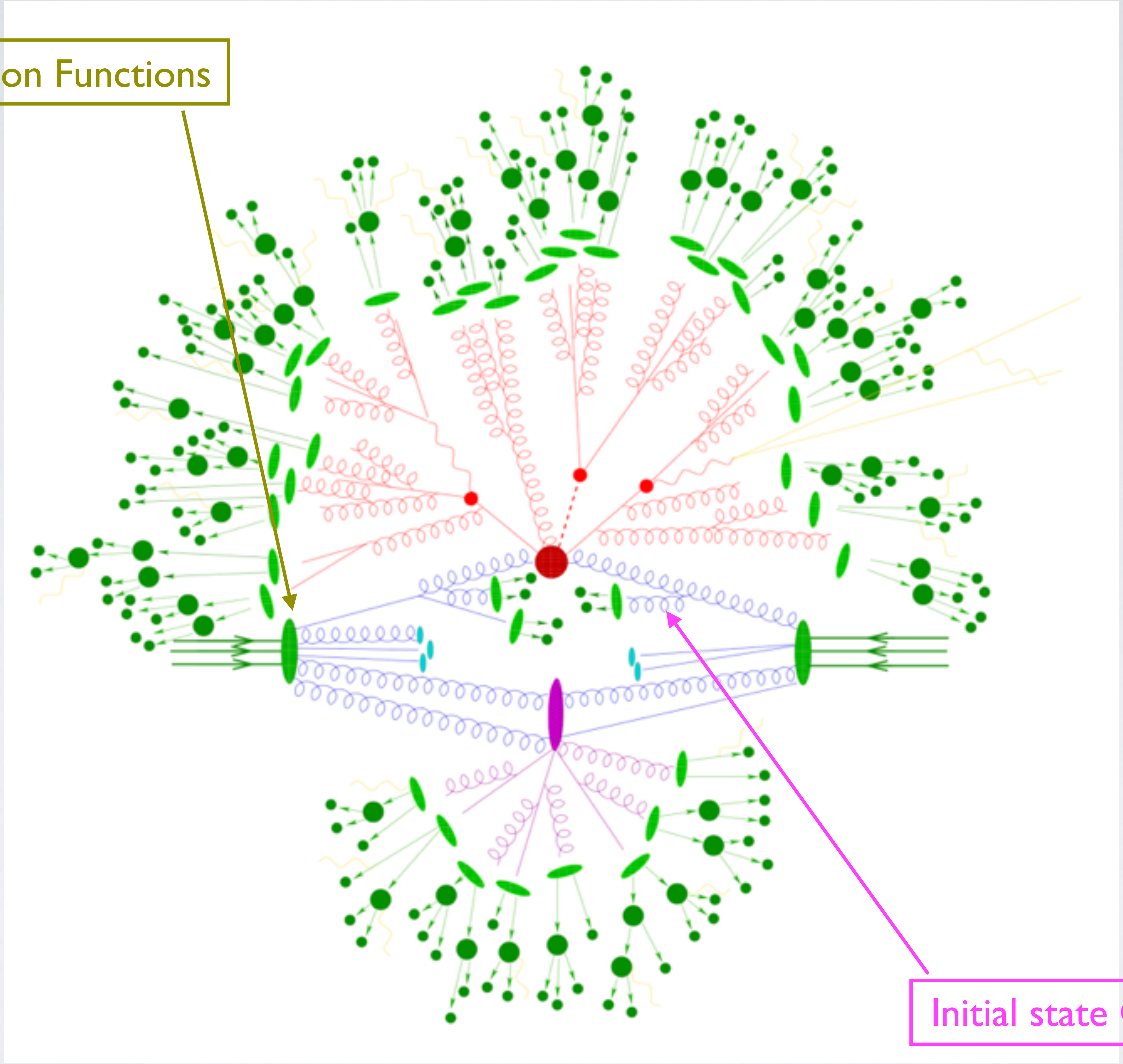


Parton Distribution Functions

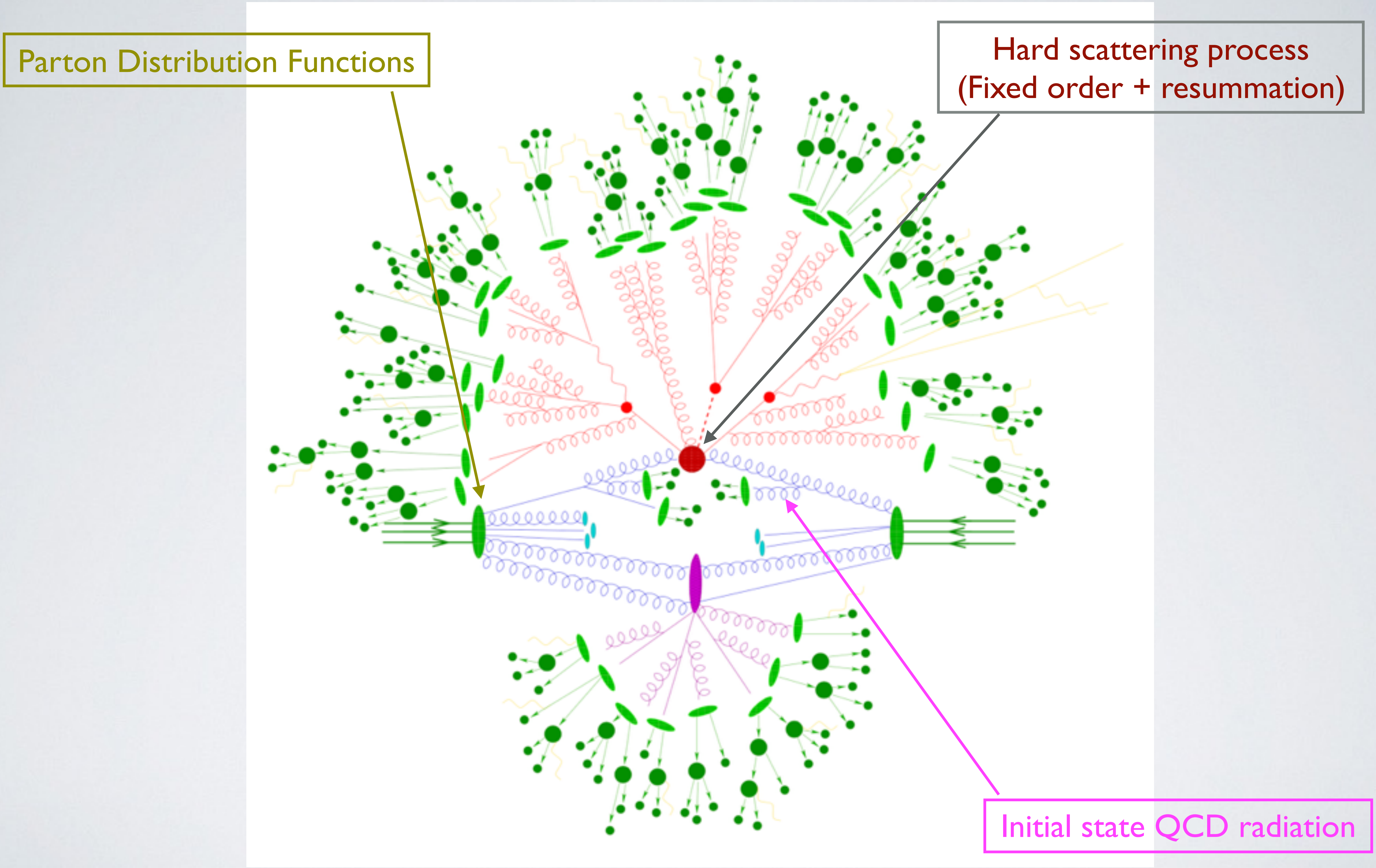
# Events at hadron colliders … Theory



Parton Distribution Functions

Initial state QCD radiation

# Events at hadron colliders … Theory

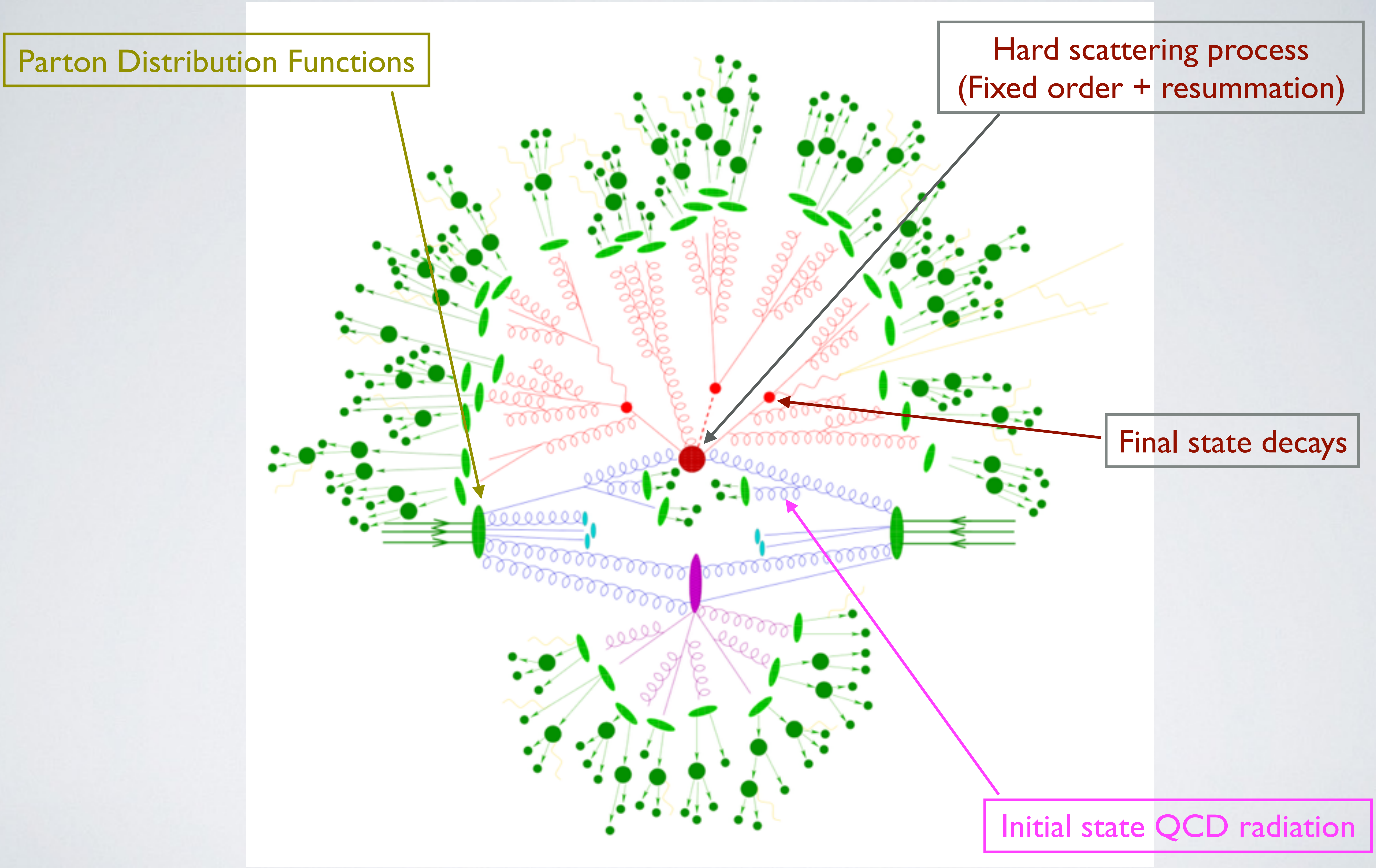


Parton Distribution Functions

Hard scattering process
(Fixed order + resummation)

Initial state QCD radiation

# Events at hadron colliders … Theory



Parton Distribution Functions

Hard scattering process
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Final state decays

Initial state QCD radiation

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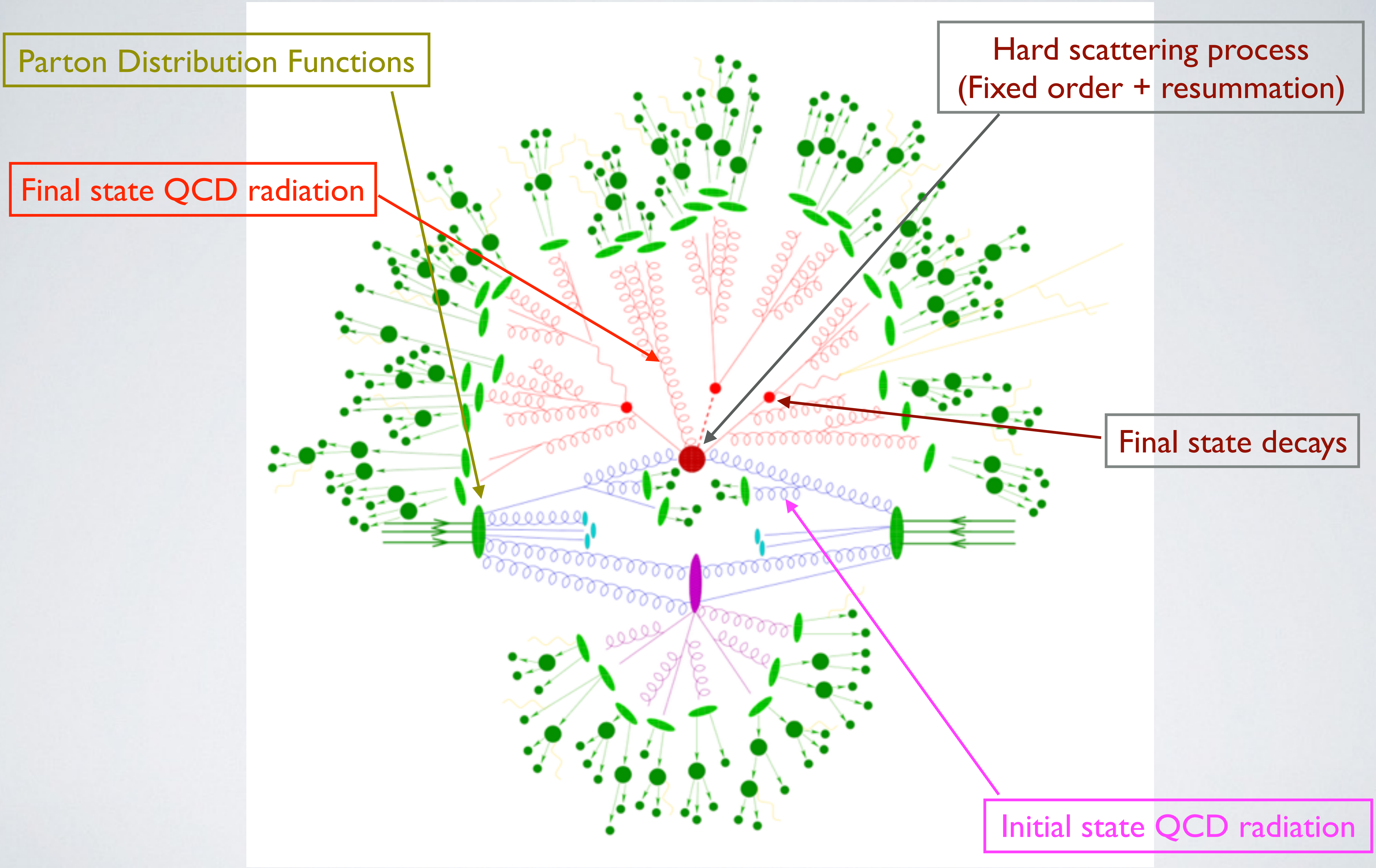

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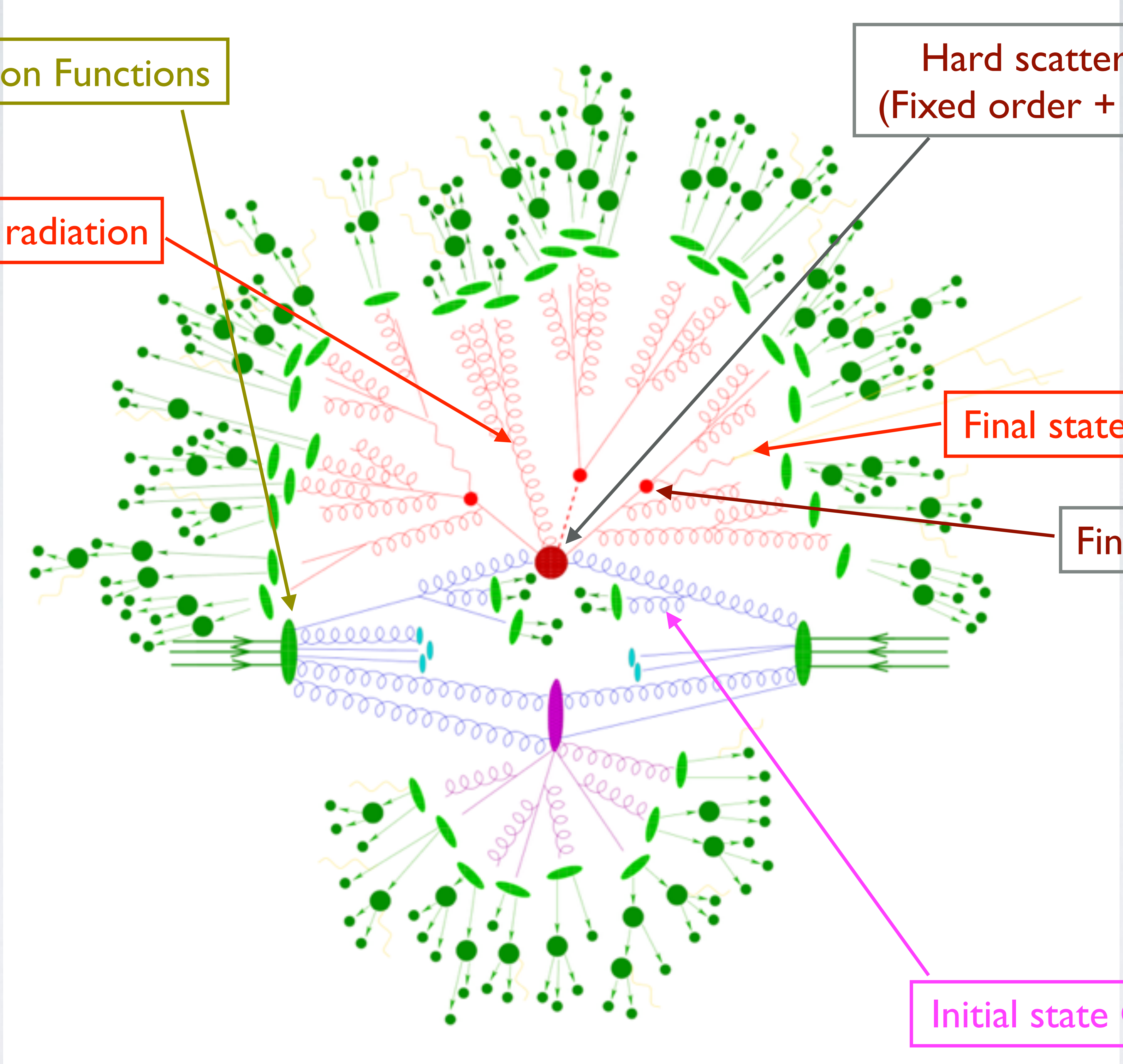

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Hard scattering process
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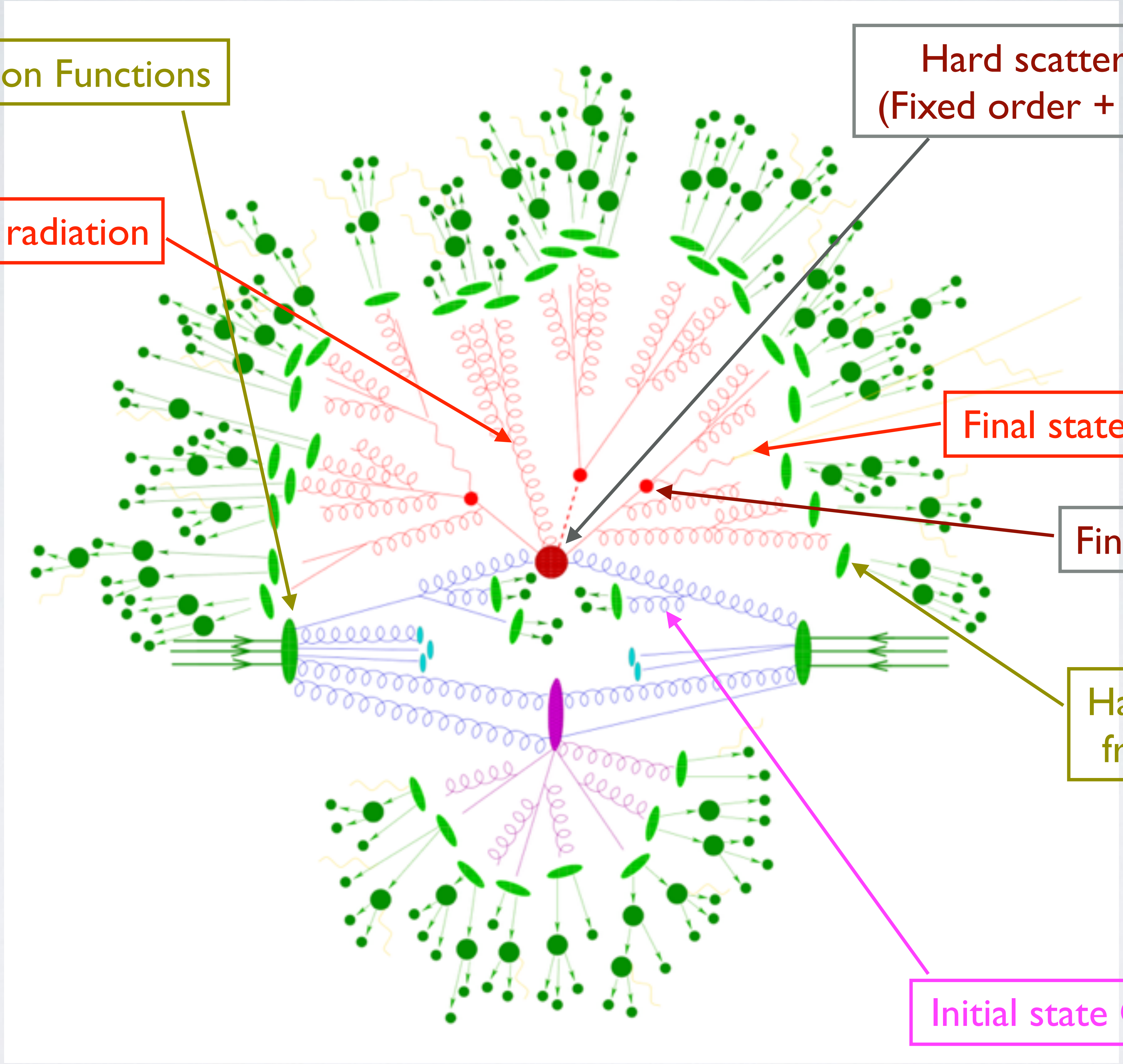
Final state QCD radiation

Final state QED radiation

Final state decays

Initial state QCD radiation

# Events at hadron colliders … Theory



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Hadronization /
fragmentation

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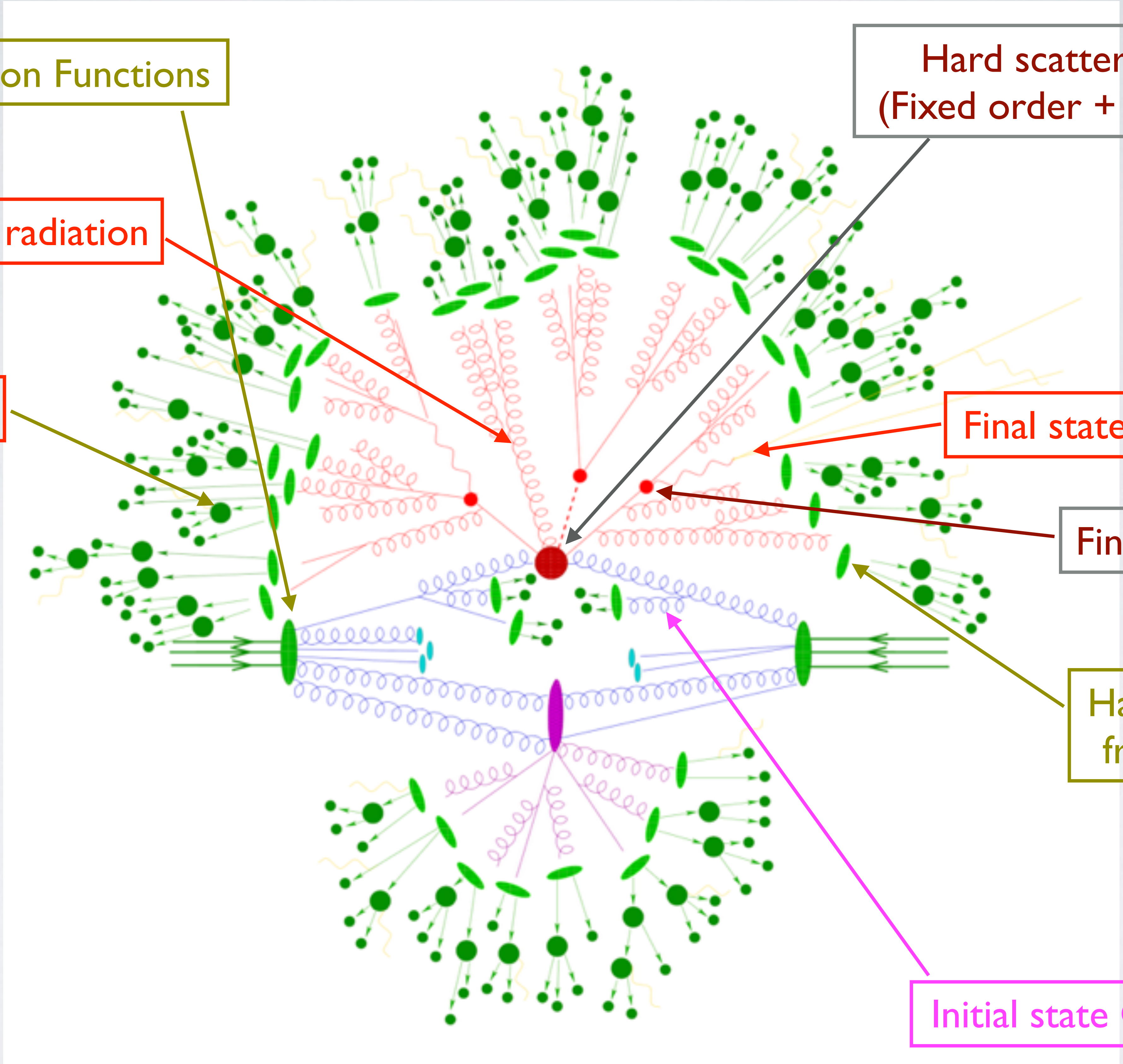
# Events at hadron colliders … Theory



Parton Distribution Functions

Final state QCD radiation

Hadronic decays

Hard scattering process
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Final state QED radiation

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Hadronization /
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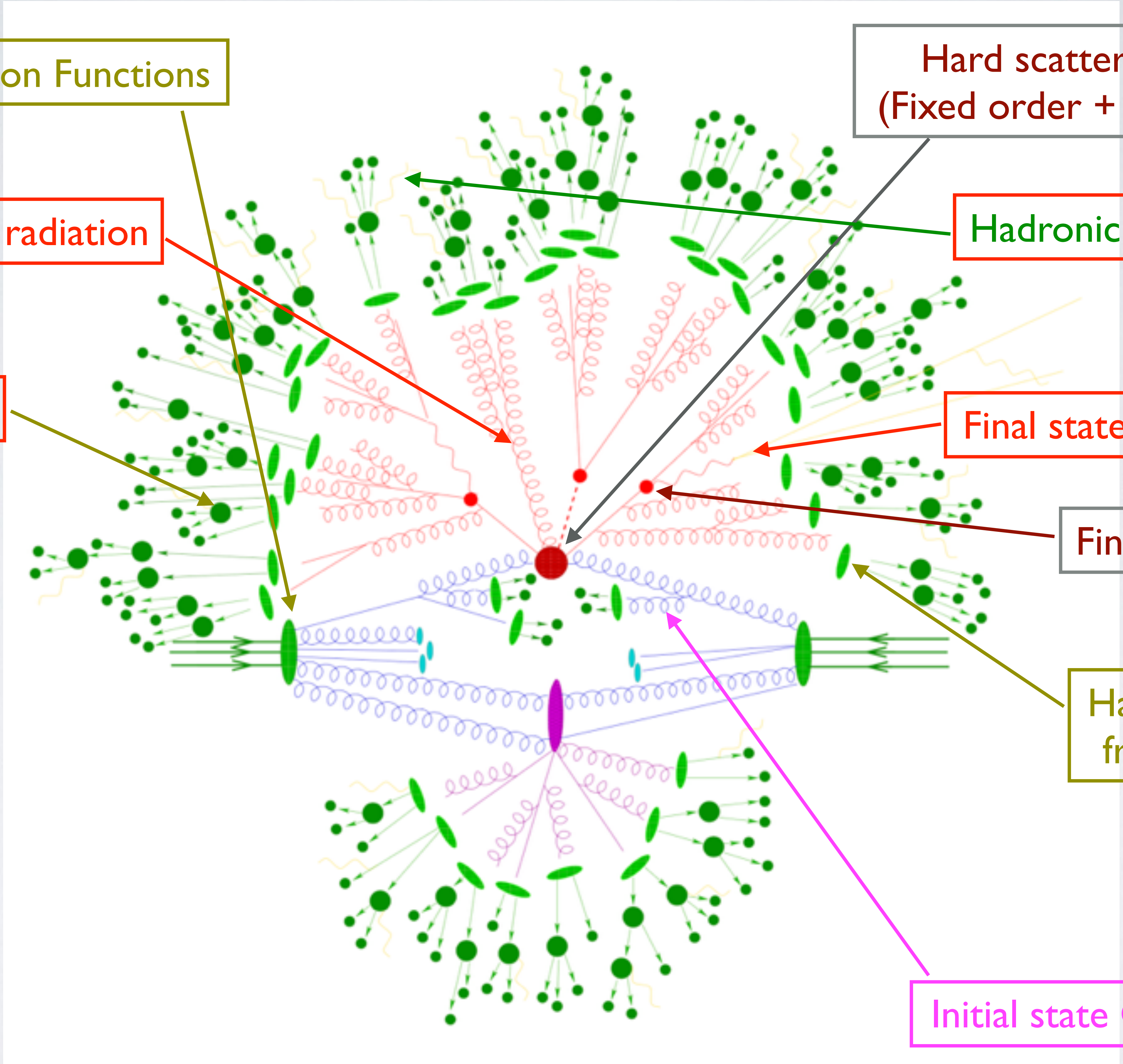
Initial state QCD radiation

# Events at hadron colliders … Theory



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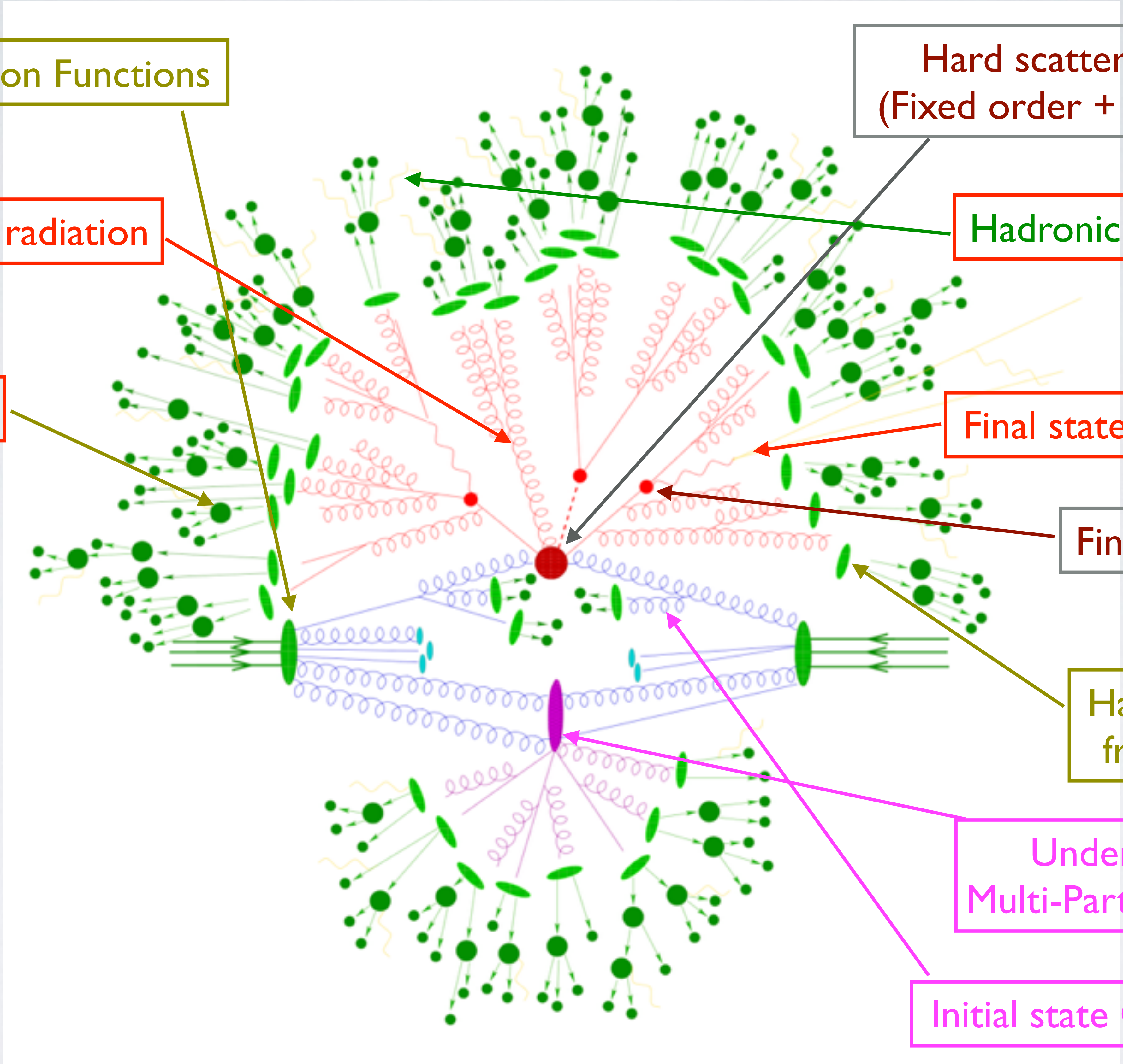

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Hadronization /
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Underlying Event:
Multi-Parton Interactions

Initial state QCD radiation

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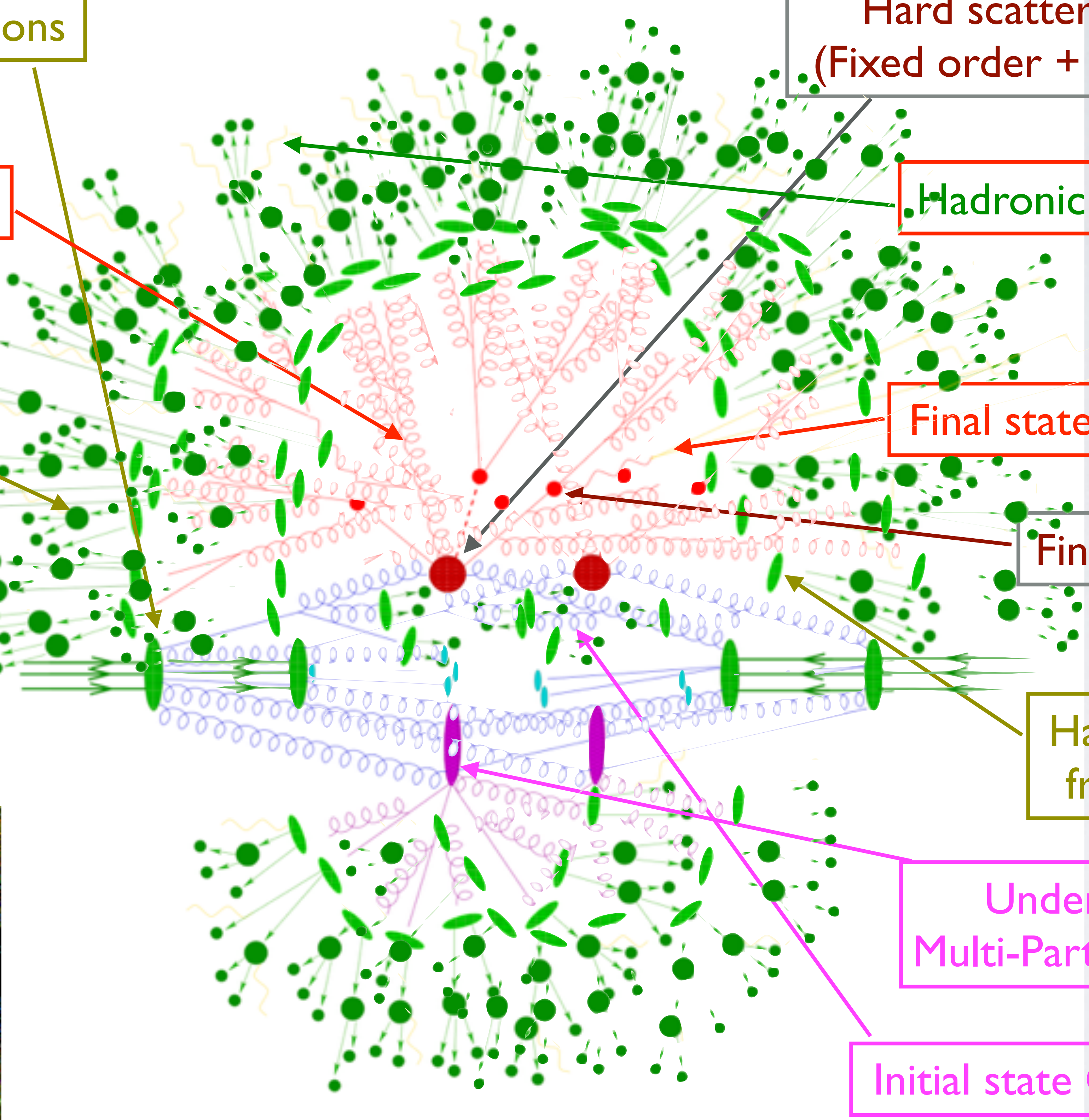

Parton Distribution Functions

Final state QCD radiation

Hadronic decays

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Hadronic QED radiation

Final state QED radiation

Final state decays

Hadronization / fragmentation

Underlying Event:
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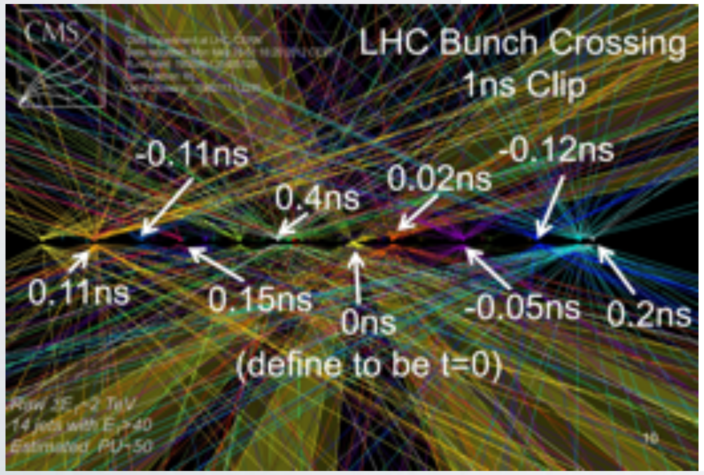
Initial state QCD radiation

Pile up



# Hard process: Fixed order perturbation theory

- Perturbative amplitudes for 2 → *n* scattering grows factorially with *n*
- Recursive algorithms [Parke/Taylor, '86; Berends/Giele, '88; Caravaglios et al., 1998; Ohl/JRR, 2000; Papadopoulos, 2001

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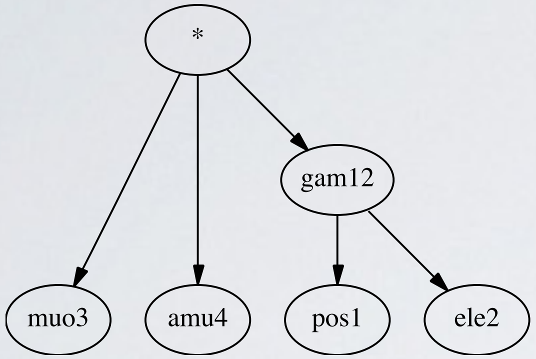

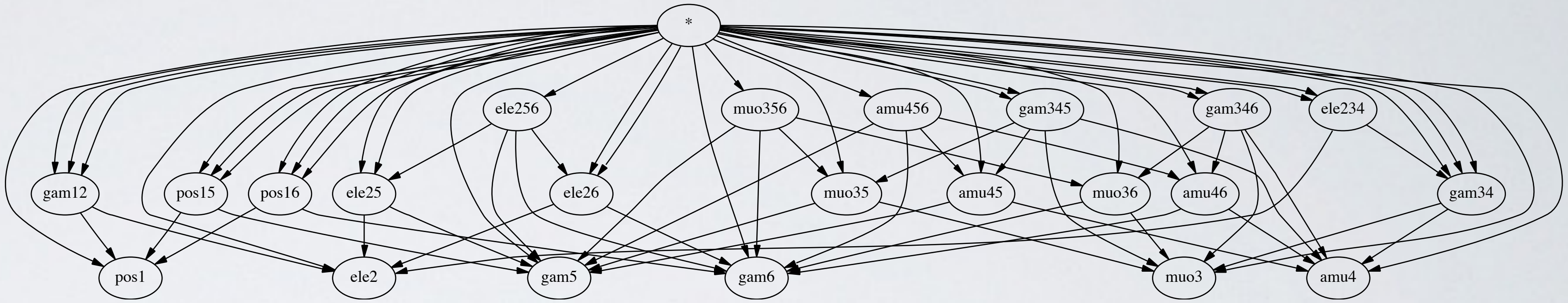

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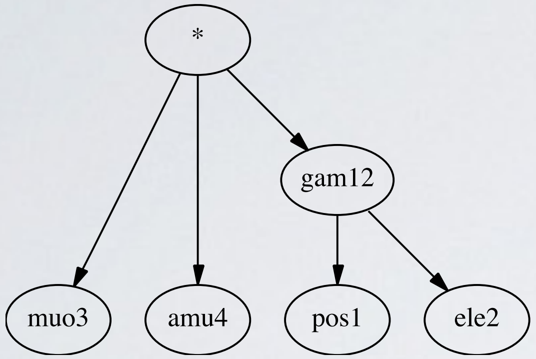
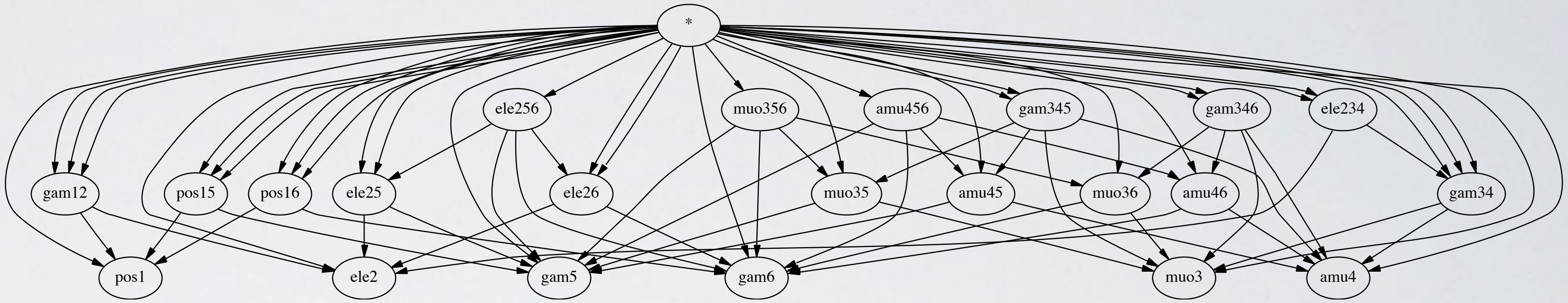
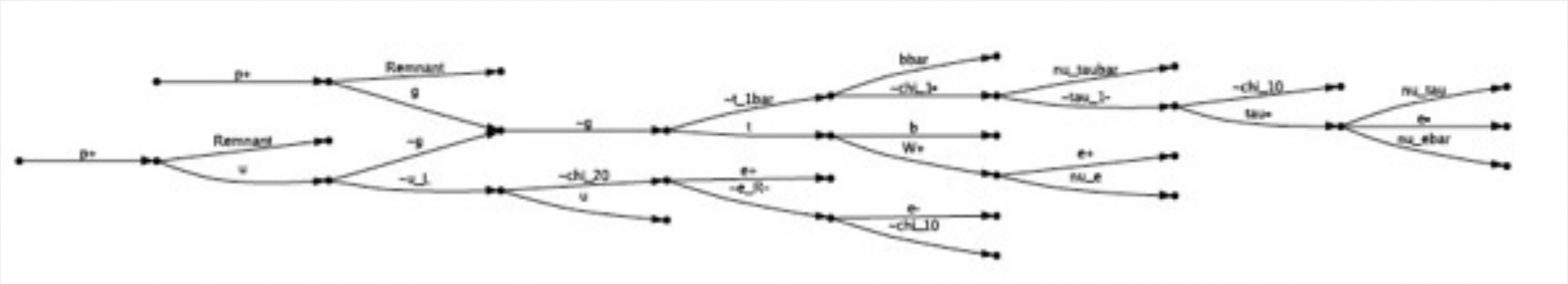




- Tree-level problem solved (for the matrix elements)
- Several smaller or bigger issues remaining:
- Large number of external legs, processes treated factorized as cascades



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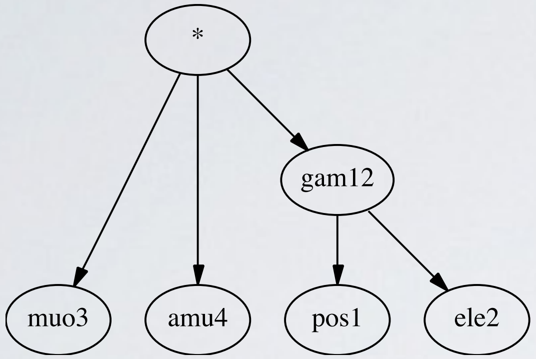

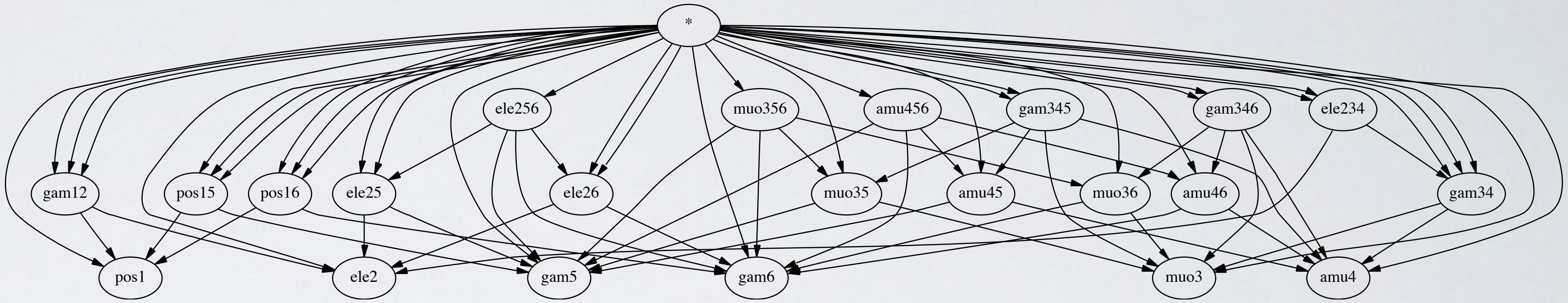

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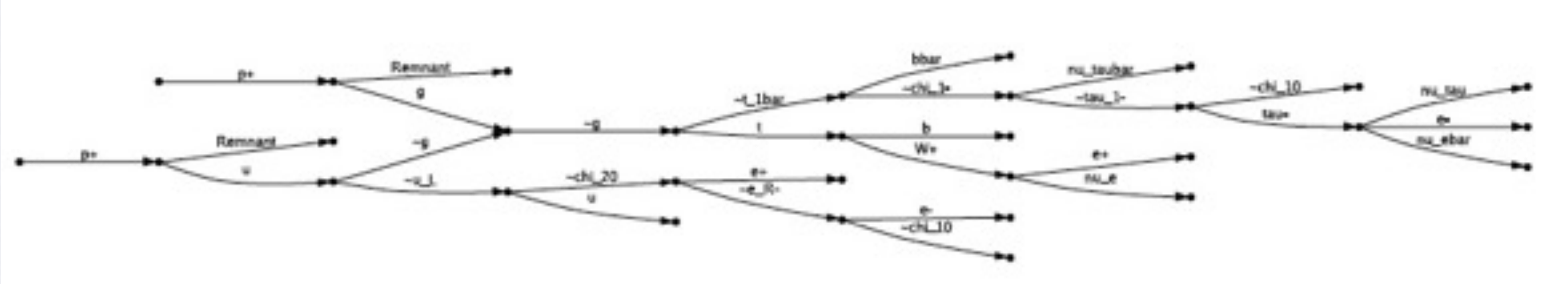


- Multi-dimensional phase-space integration
- Major bottleneck!
- Several algorithms: flat [RAMBO], simplistic heuristics [ALPGEN], diagram-based [MadEvent], [QCD-]radiation driven [SAGE], resonance/singularity importance-ordered [WHIZARD]

$$\sigma \sim \int \sum_{h_k, c_k} |\mathcal{M}(p_k, h_k, c_k)|^2 \prod_i \frac{d^3 p_i}{(2\pi)^3 2p_i^0}$$

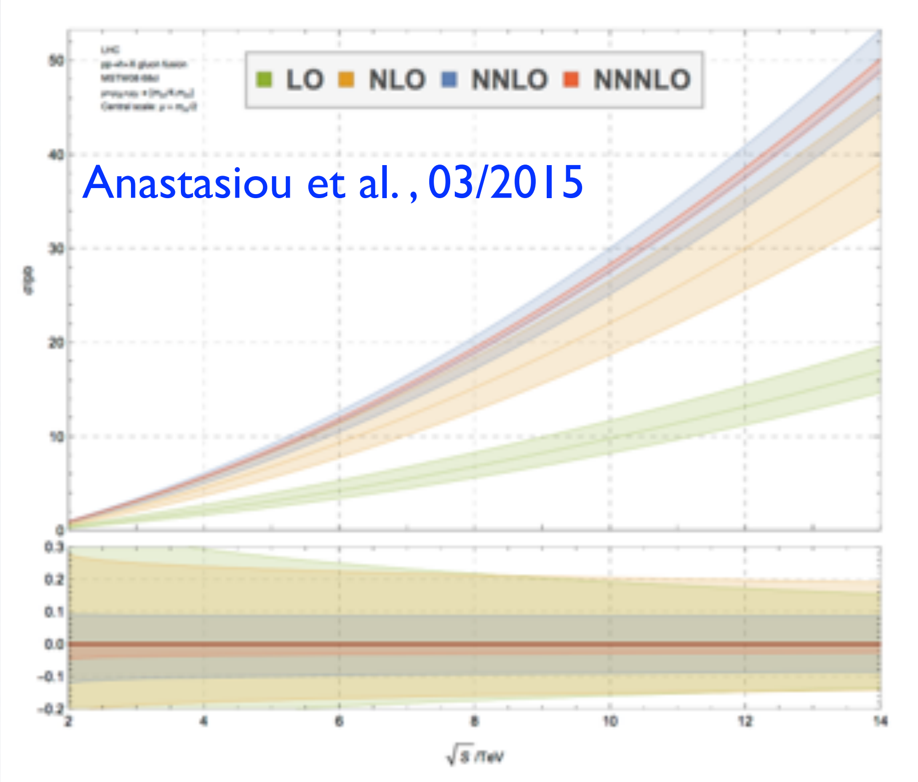
- Complicated QCD color algebra ⇔ high-dimensional color flow matrices
- Light flavor degeneracies in jets

# Higher Order Calculations

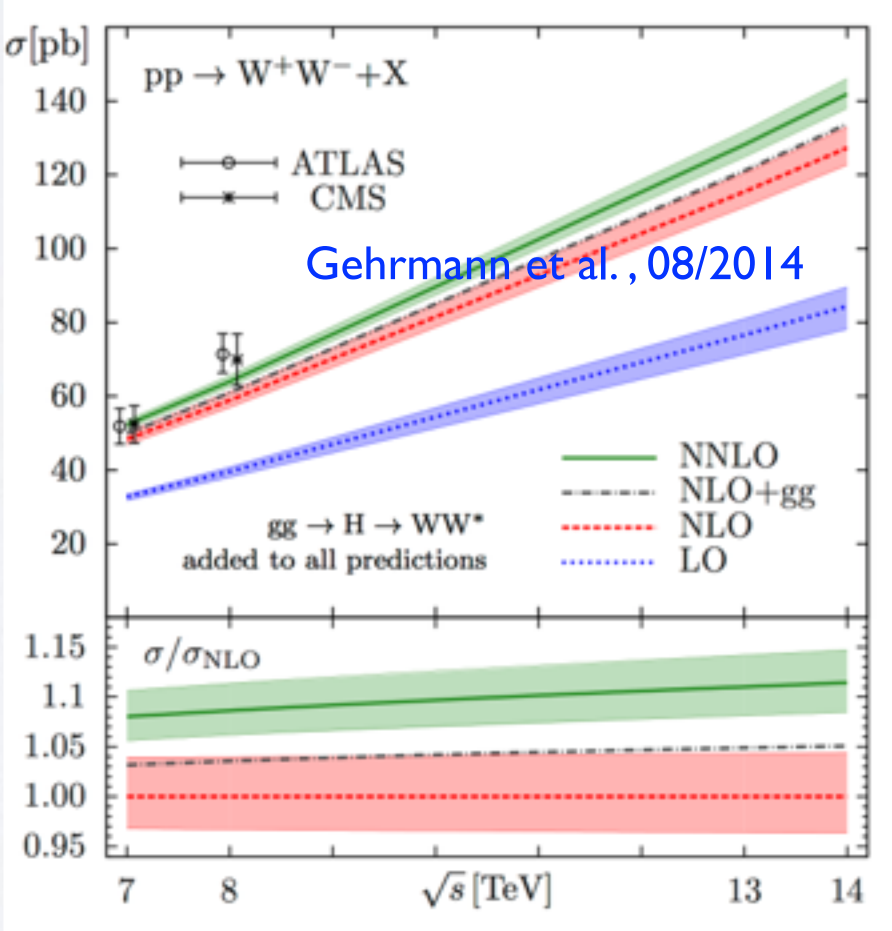
- Large (QCD) corrections at hadron colliders
- Example: Higgs production in gluon fusion

  [K factor: $\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$ or $\sigma_{\mathrm{NNLO}}/\sigma_{\mathrm{LO}}$ ]

- Virtual corrections: loop diagrams



Anastasiou et al. , 03/2015



Gehrmann et al. , 08/2014

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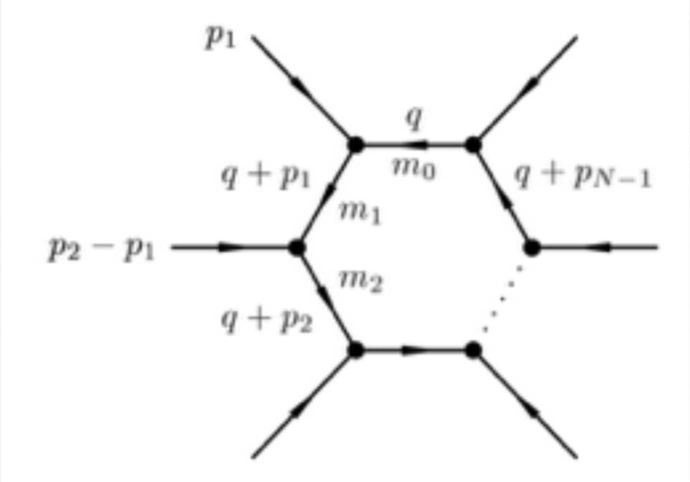

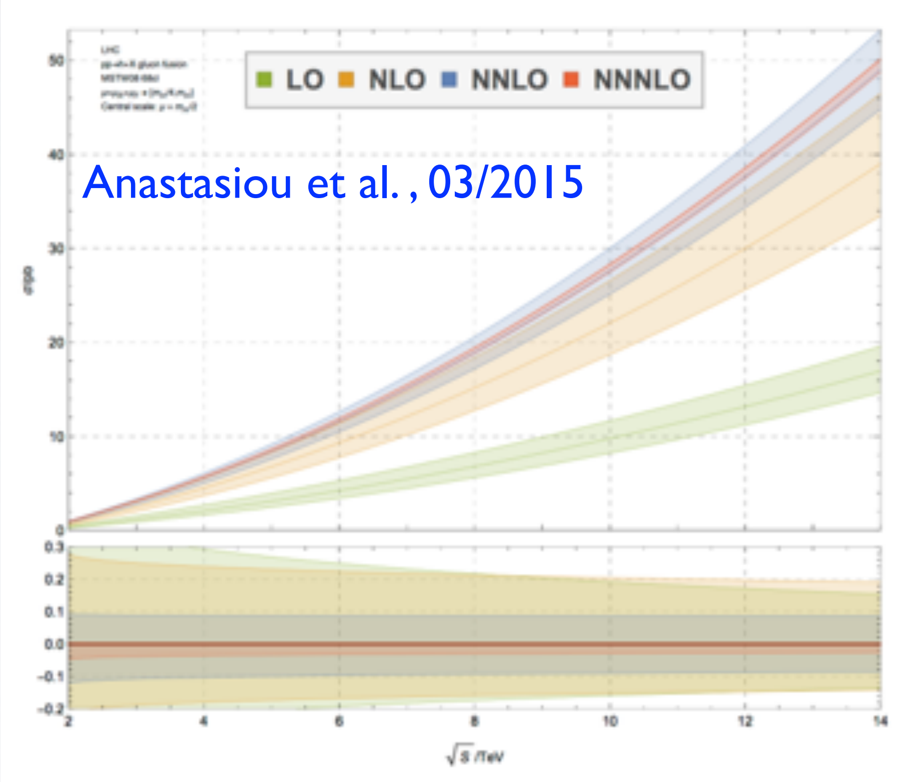
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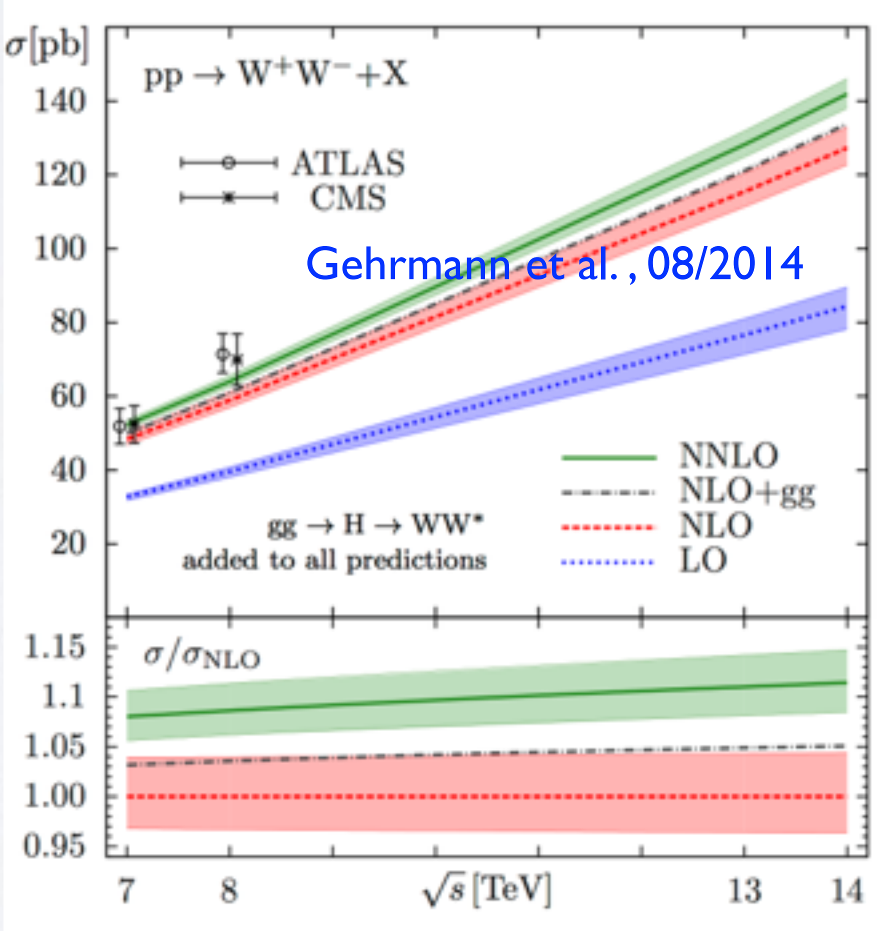
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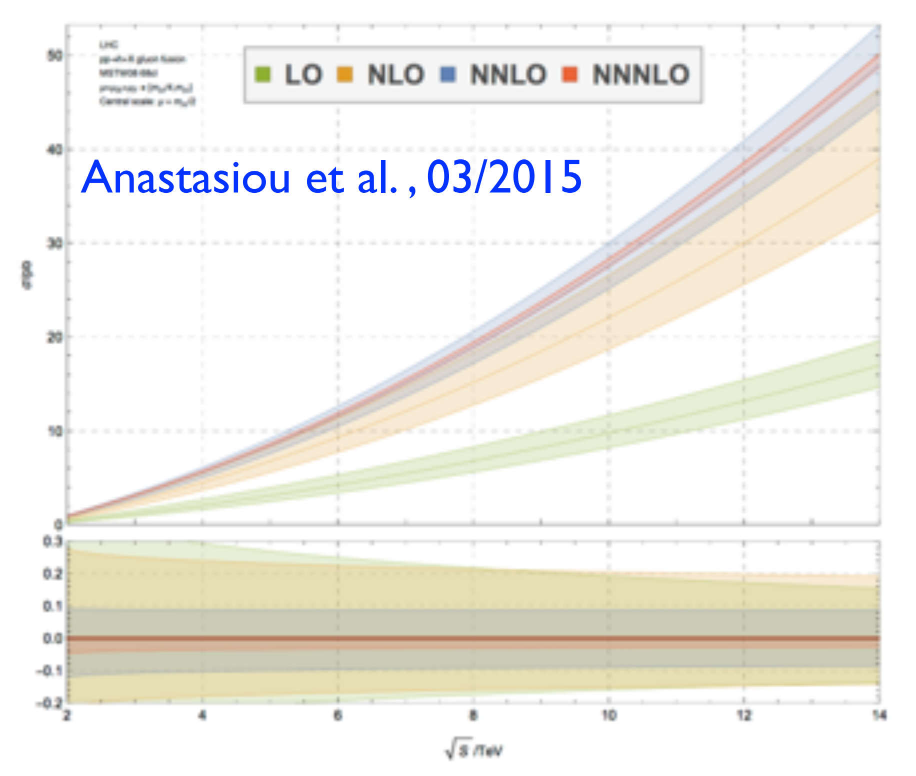
- Soft and collinear singularities given by QCD splittings:



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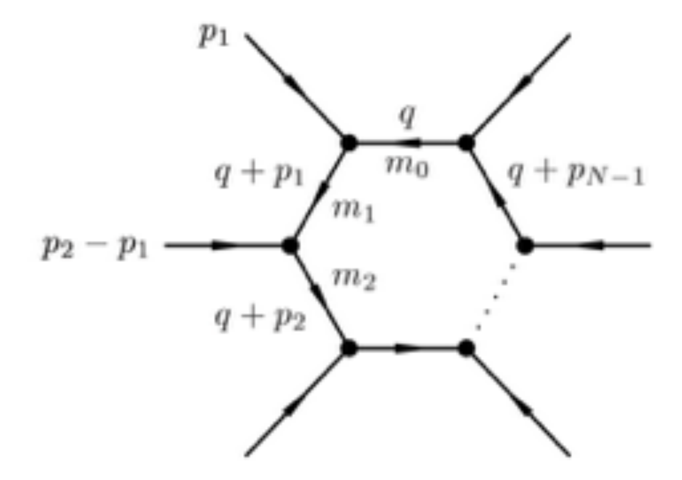
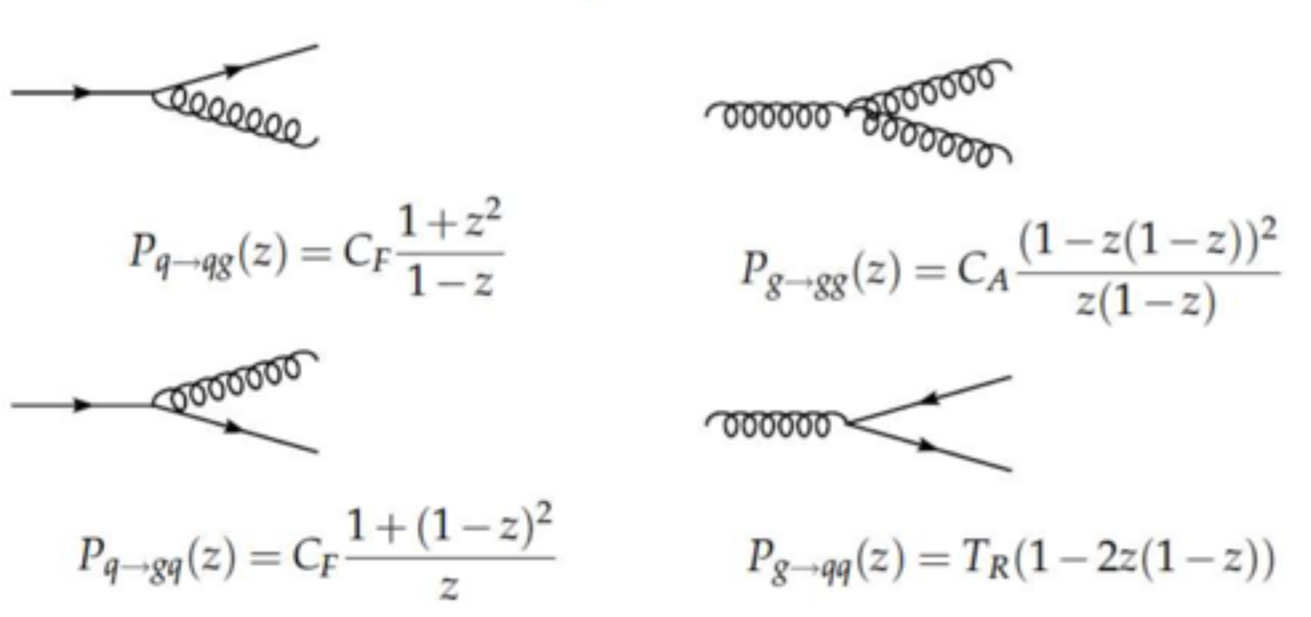


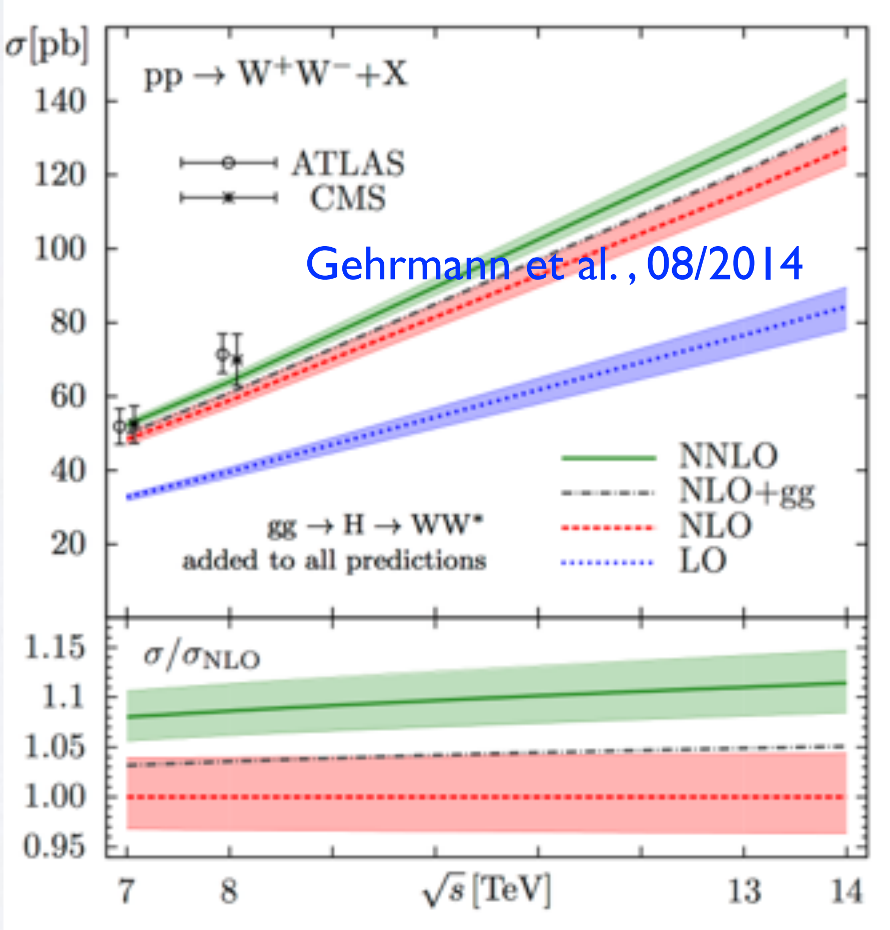


$P_{q\to qg}(z) = C_F \frac{1+z^2}{1-z}$

$P_{g\to gg}(z) = C_A \frac{(1-z(1-z))^2}{z(1-z)}$

$P_{q\to gq}(z) = C_F \frac{1+(1-z)^2}{z}$

$P_{g\to qq}(z) = T_R(1-2z(1-z))$



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# “Automation”

- General structure of NLO cross section:

$$\mathrm{d}\sigma_n^{\mathrm{NLO}} = \underbrace{\mathrm{d}\Phi_n \mathcal{B}_n}_{\text{Born approximation}} \quad + \quad \underbrace{\mathrm{d}\Phi_n \mathcal{V}_n}_{\text{renormalized virtual correction, IR-divergent}} \quad + \quad \underbrace{\mathrm{d}\Phi_{n+1} \mathcal{R}_{n+1}}_{\text{real correction, IR-divergent}}$$

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- 1990’s: “Subtraction algorithms” (process independently cancel IR-divergences exactly)

FKS [Frixione/Kunszt/Signer, ’96], CS-Dipoles [Catani/Seymour, ’98] [FKS: Kinematics vs. Dipoles/CS: shower]

$$\mathrm{d}\sigma_n^{\mathrm{NLO}} = \mathrm{d}\Phi_n \left[ \mathcal{B}_n + \mathcal{V}_n + \mathcal{B}_n \otimes S \right] + \mathrm{d}\Phi_{n+1} \left[ \mathcal{R}_{n+1} - \mathcal{B}_n \otimes \mathrm{d}S \right]$$

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Born approximation

renormalized virtual correction, IR-divergent

real correction, IR-divergent

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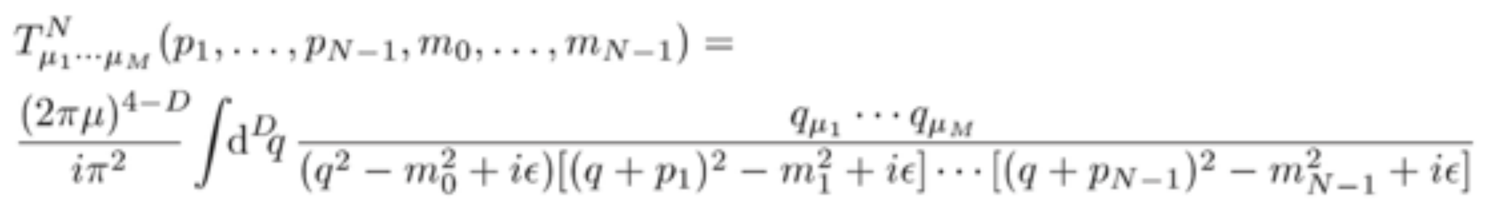
- Subtraction terms automated in Monte Carlo generators: Helac, Herwig, Madgraph, Sherpa, Whizard ….
- Difficulties not mentioned: phase space stability, bin migration, clustering, NLO cuts etc.
- 2000’s-2010’s: “Automation” of virtual amplitudes Blackhat, Gosam, MadLoop, OpenLoops, Recola ….



$$T^N_{\mu_1\cdots\mu_M}(p_1,\ldots,p_{N-1},m_0,\ldots,m_{N-1}) =$$
$$\frac{(2\pi\mu)^{4-D}}{i\pi^2}\int d^Dq \frac{q_{\mu_1}\cdots q_{\mu_M}}{(q^2-m_0^2+i\epsilon)[(q+p_1)^2-m_1^2+i\epsilon]\cdots[(q+p_{N-1})^2-m_{N-1}^2+i\epsilon]}$$

# “Automation”

- General structure of NLO cross section:

$$\mathrm{d}\sigma_n^{\mathrm{NLO}} = \underbrace{\mathrm{d}\Phi_n \mathcal{B}_n}_{\text{Born approximation}} \quad + \quad \underbrace{\mathrm{d}\Phi_n \mathcal{V}_n}_{\text{renormalized virtual correction, IR-divergent}} \quad + \quad \underbrace{\mathrm{d}\Phi_{n+1} \mathcal{R}_{n+1}}_{\text{real correction, IR-divergent}}$$

- 1990’s: “Subtraction algorithms” (process independently cancel IR-divergences exactly)
  FKS [Frixione/Kunszt/Signer, ’96], CS-Dipoles [Catani/Seymour, ’98]   [FKS: Kinematics vs. Dipoles/CS: shower]

$$\mathrm{d}\sigma_n^{\mathrm{NLO}} = \mathrm{d}\Phi_n \left[ \mathcal{B}_n + \mathcal{V}_n + \mathcal{B}_n \otimes S \right] + \mathrm{d}\Phi_{n+1} \left[ \mathcal{R}_{n+1} - \mathcal{B}_n \otimes \mathrm{d}S \right]$$

- Subtraction terms automated in Monte Carlo generators: Helac, Herwig, Madgraph, Sherpa, Whizard ….
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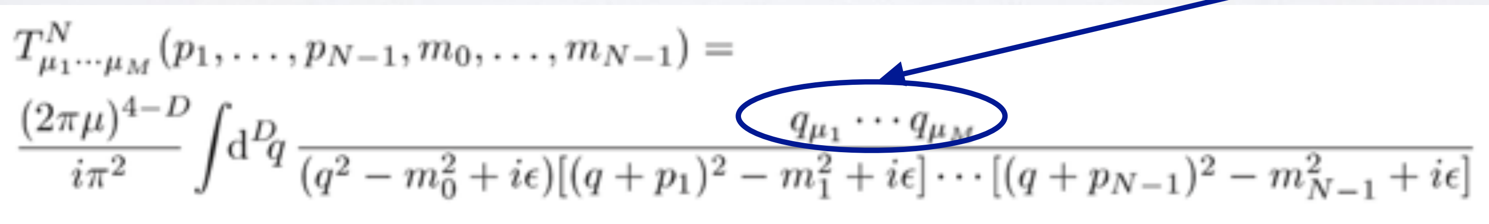
Tensor reduction (numerically stable)   [Denner/Dittmaier, 2005]



$$T^N_{\mu_1\cdots\mu_M}(p_1,\ldots,p_{N-1},m_0,\ldots,m_{N-1}) = \frac{(2\pi\mu)^{4-D}}{i\pi^2}\int \mathrm{d}^D q \, \frac{q_{\mu_1}\cdots q_{\mu_M}}{(q^2-m_0^2+i\epsilon)[(q+p_1)^2-m_1^2+i\epsilon]\cdots[(q+p_{N-1})^2-m_{N-1}^2+i\epsilon]}$$

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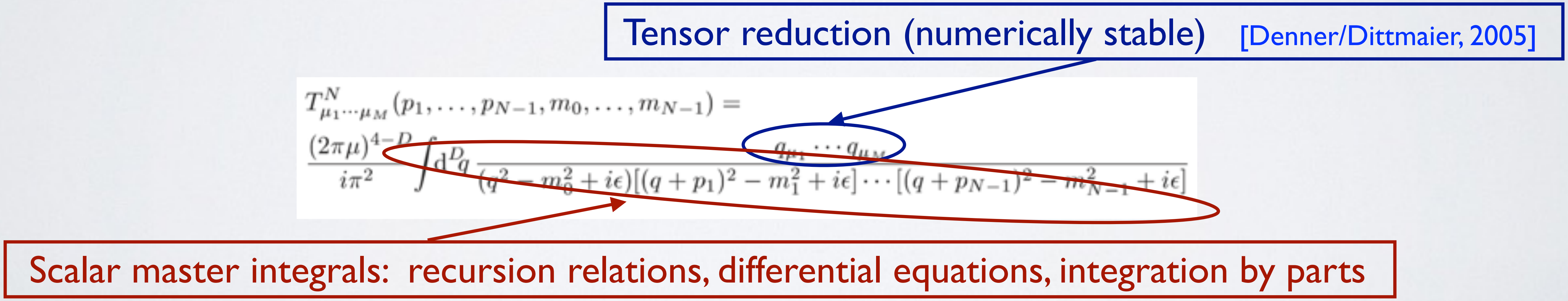

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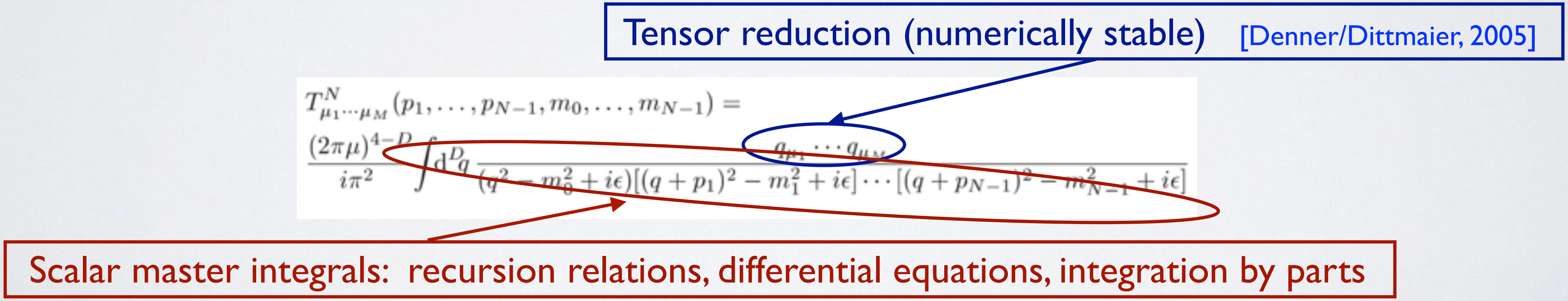

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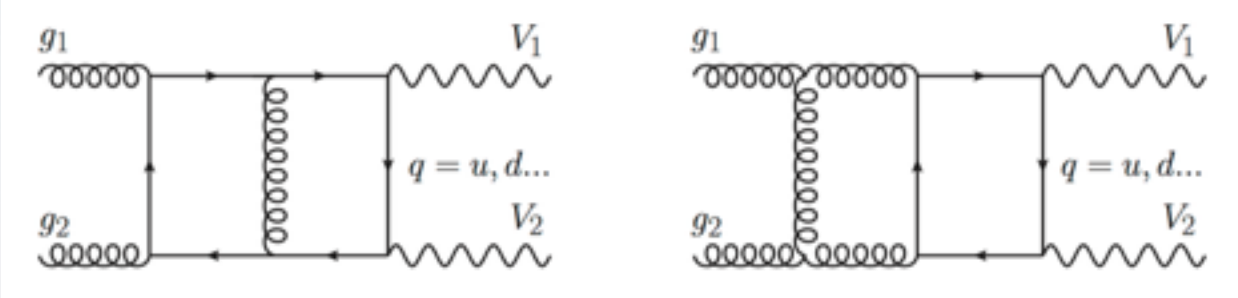
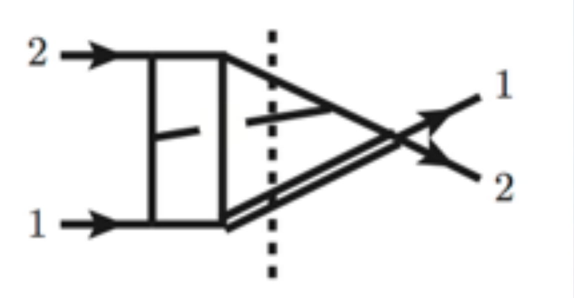
- “Automation” is rather simplification: never switch off your brain !!!

# NNLO QCD (and beyond)

- **Battlefront of precision calculations:** virtual NNLO 2 → 2, NNNLO 2 → 1





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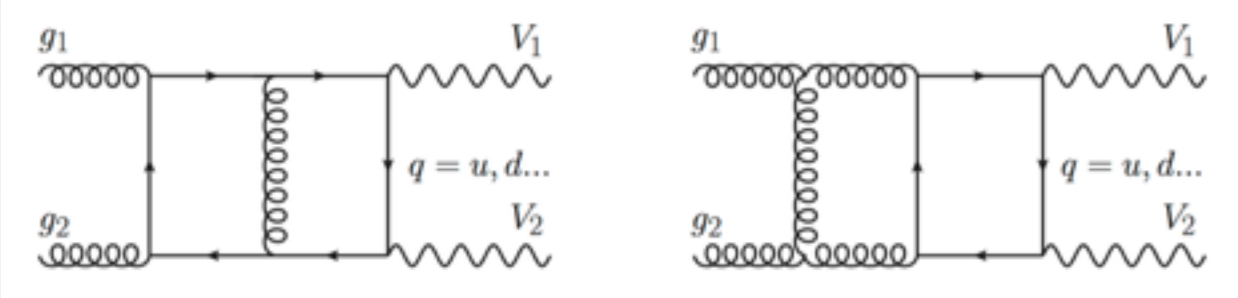

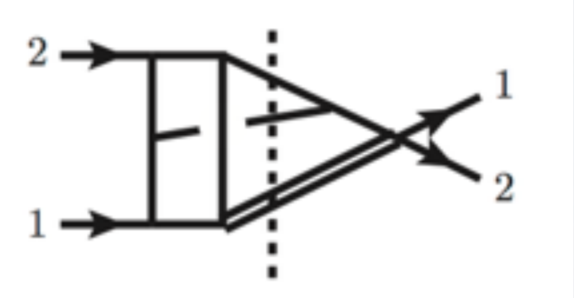

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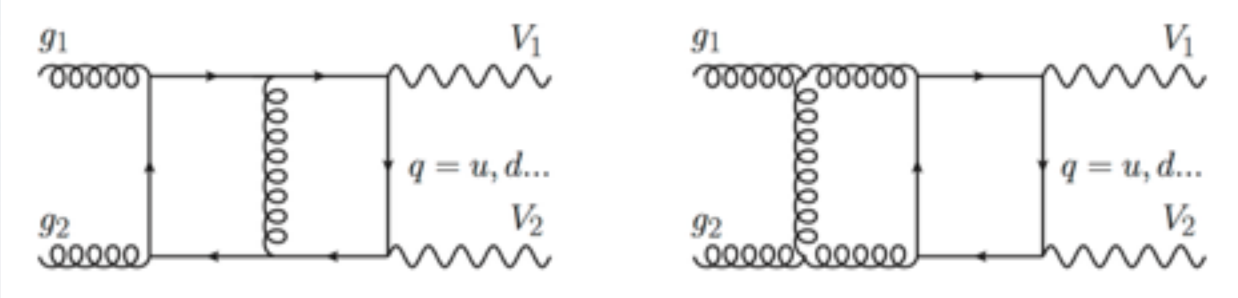

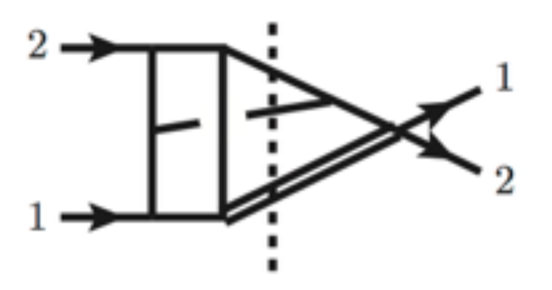

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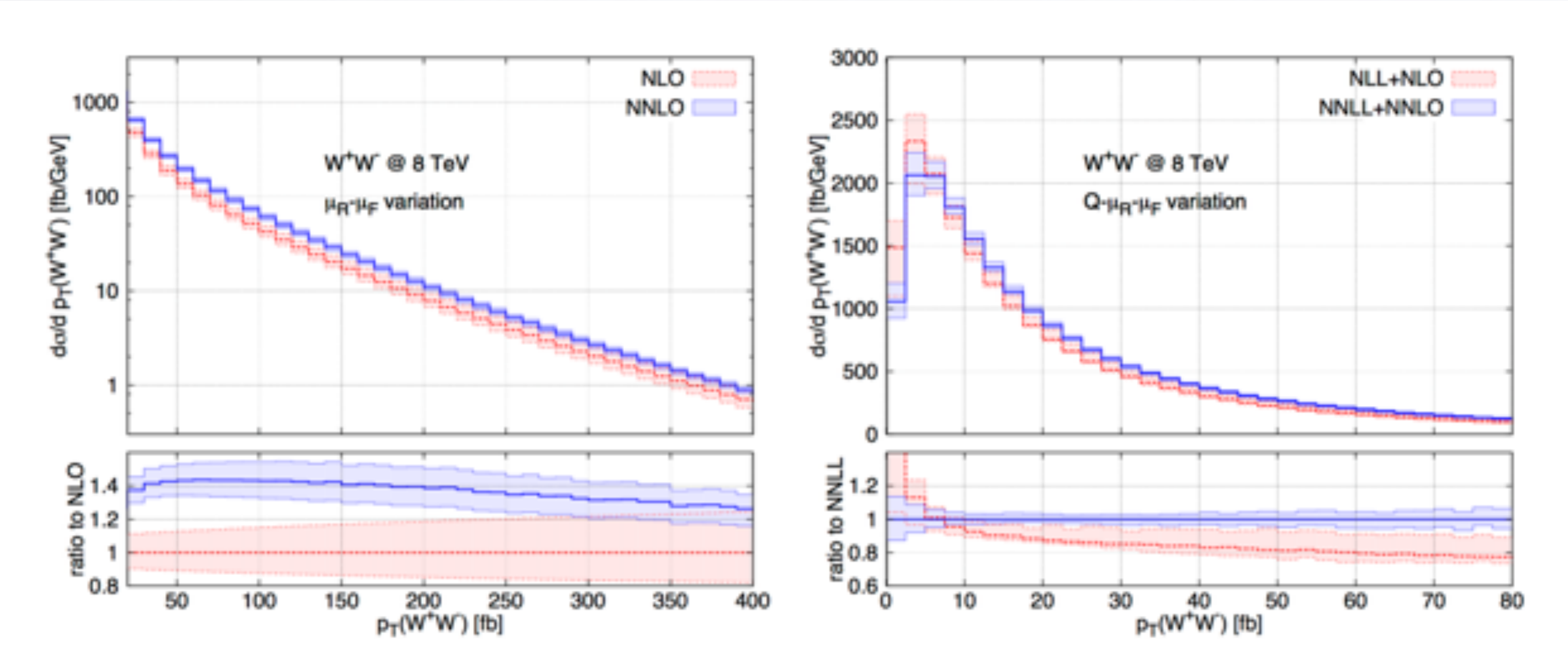

Grazzini/Kallweit/Rathlev/Wiesemann, 07/2015

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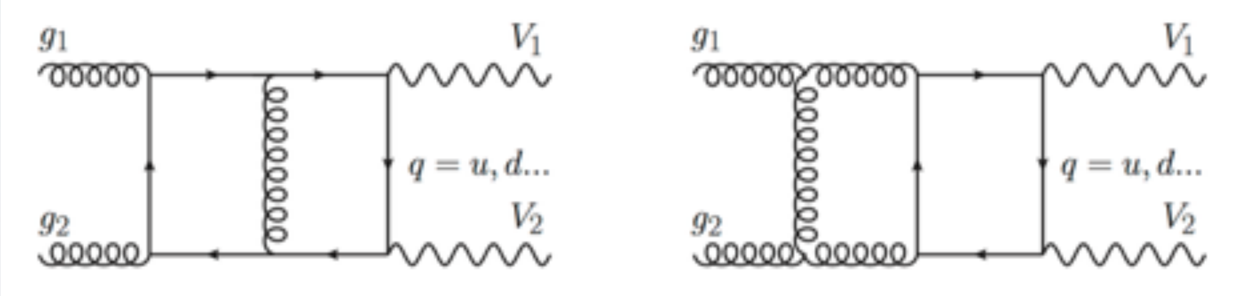

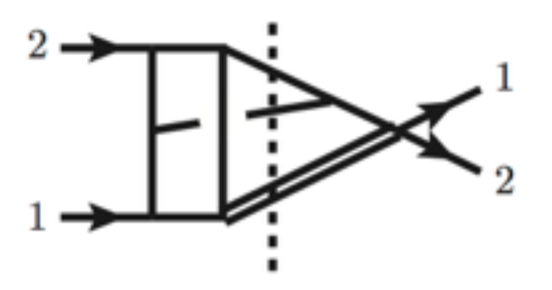

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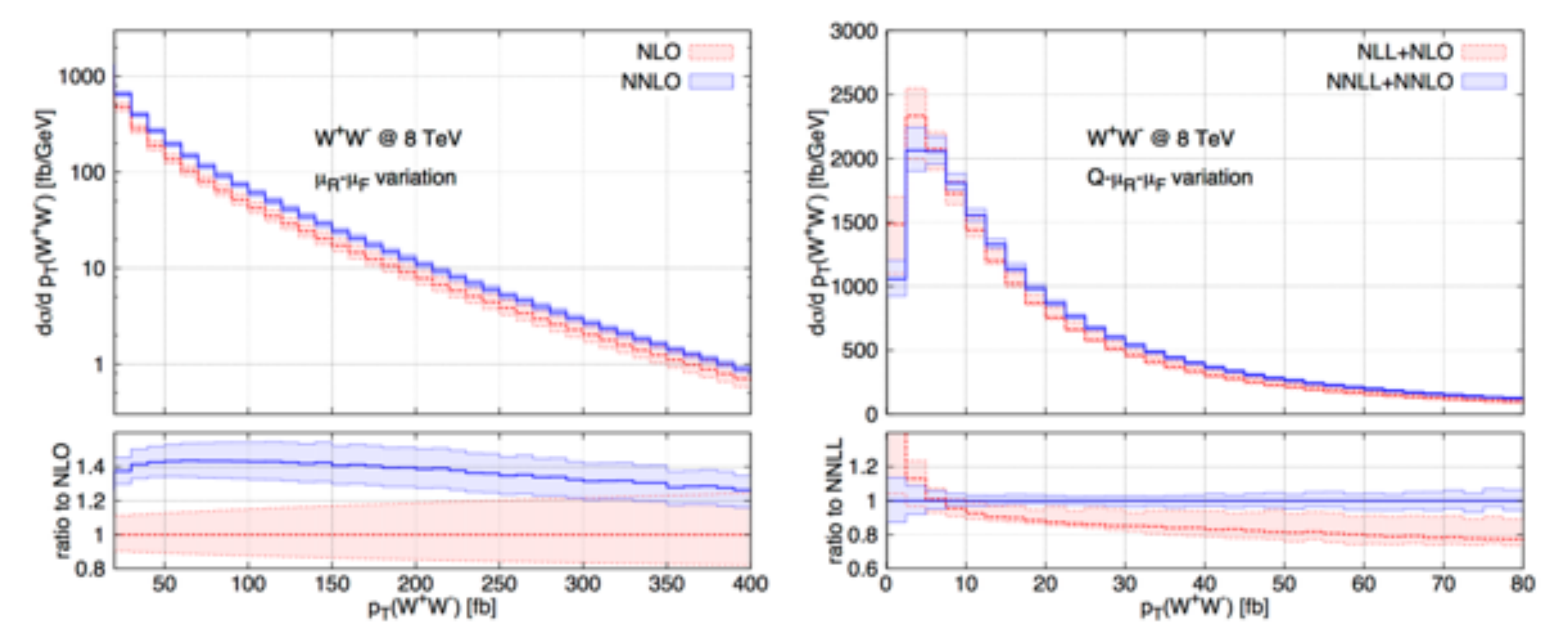

Crucial for exclusive measurements (jet vetoes)

Grazzini/Kallweit/Rathlev/Wiesemann, 07/2015

# Electroweak Corrections

- Rule of thumb: NNLO QCD ~ NLO Electroweak $\alpha_s \sim 0.1, \quad \alpha \sim 0.01$
- Several tools deliver EW NLO: [Gosam], OpenLoops, Recola [not public]
- Master integrals more complicated [several different mass scales]
- Subtraction formalism tedious [interference of different QCD and EW orders]

- Big effects at high energies:
  EW Sudakov logarithms $\boxed{-\alpha \log^2 \left[\frac{M_W^2}{\hat{s}}\right]}$
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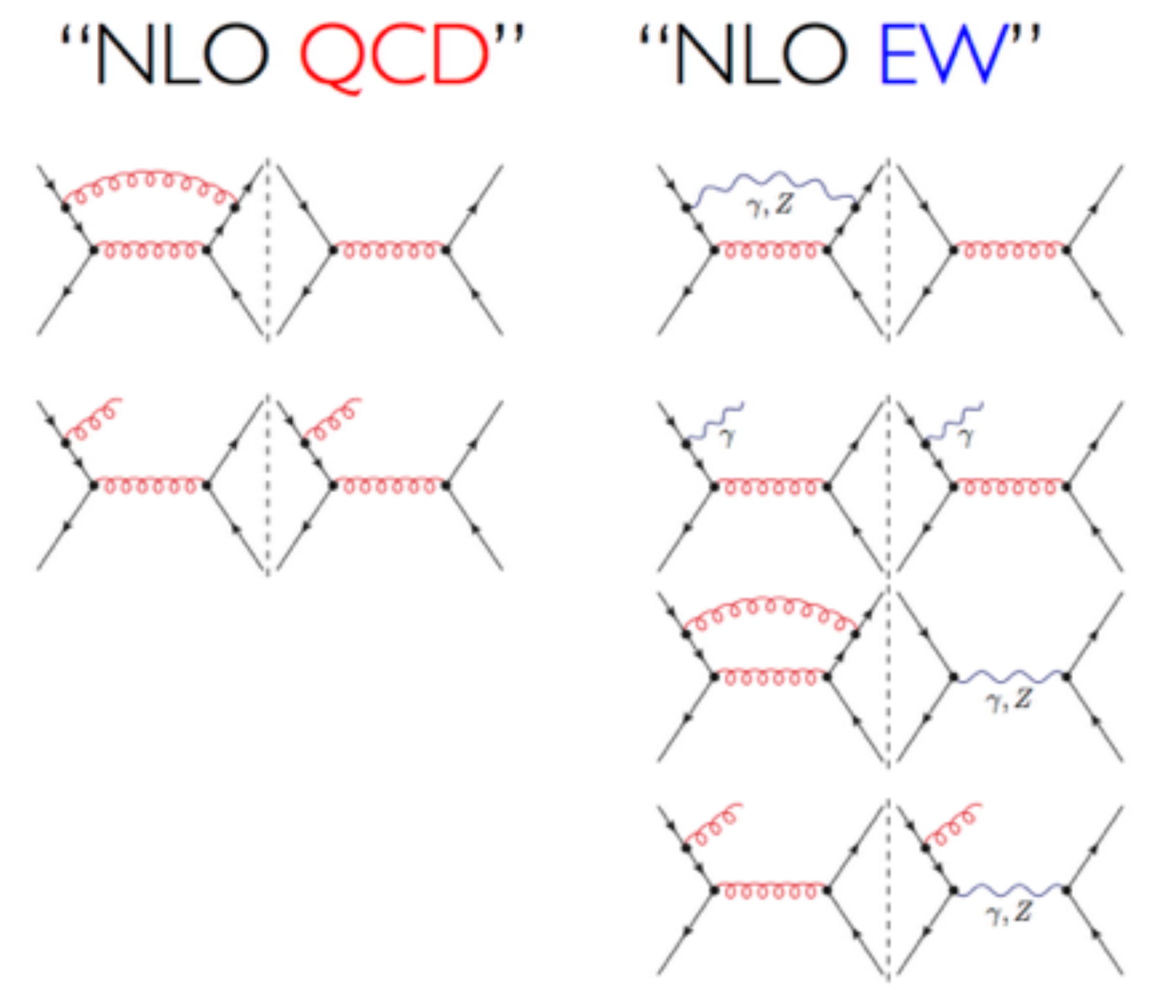

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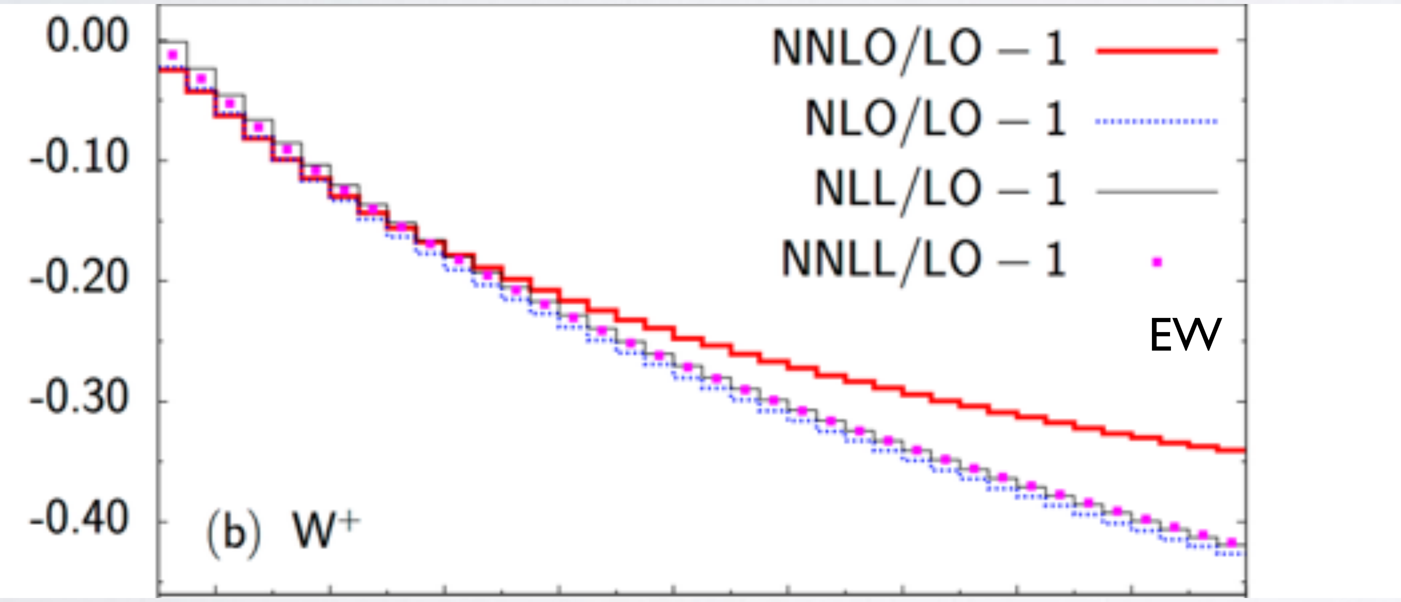

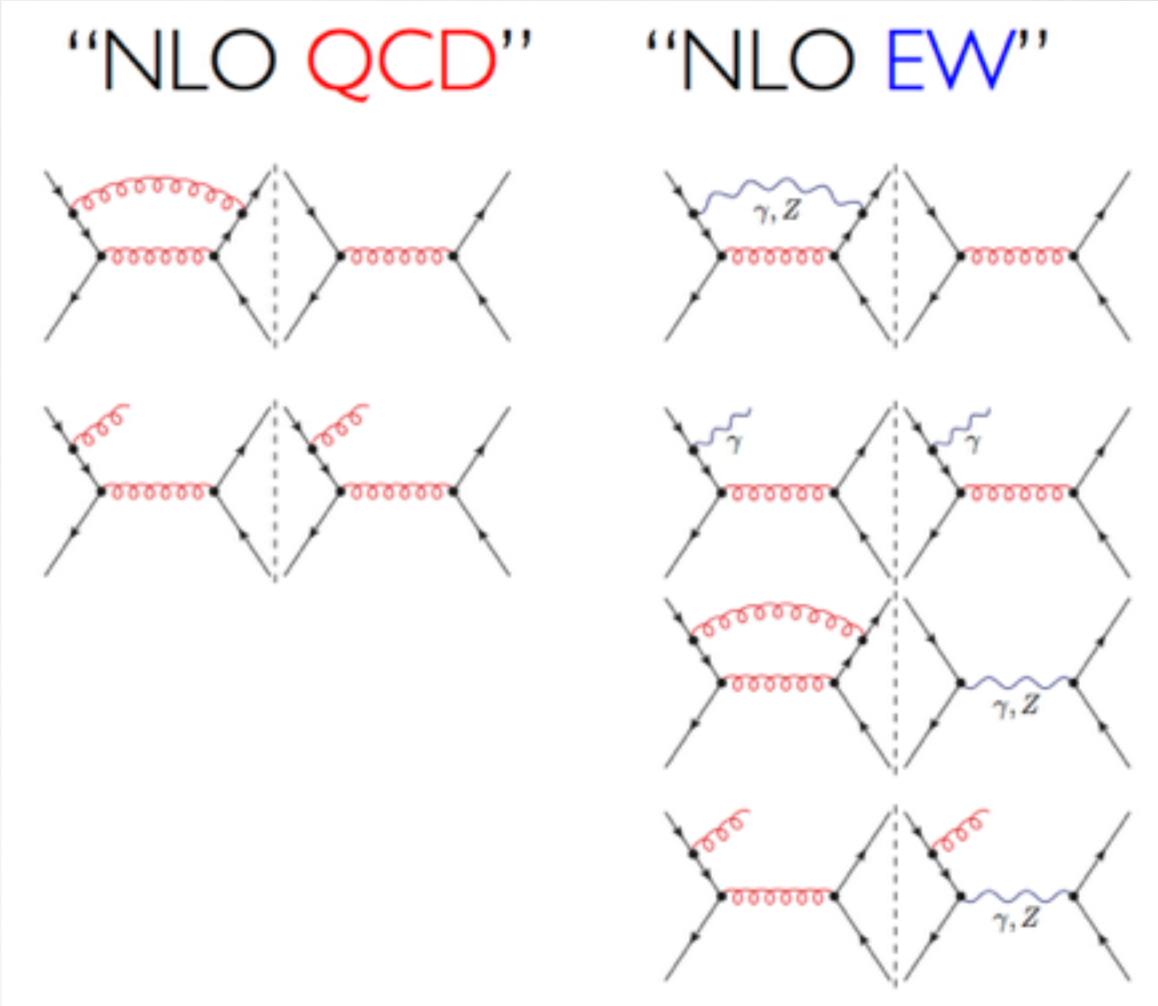

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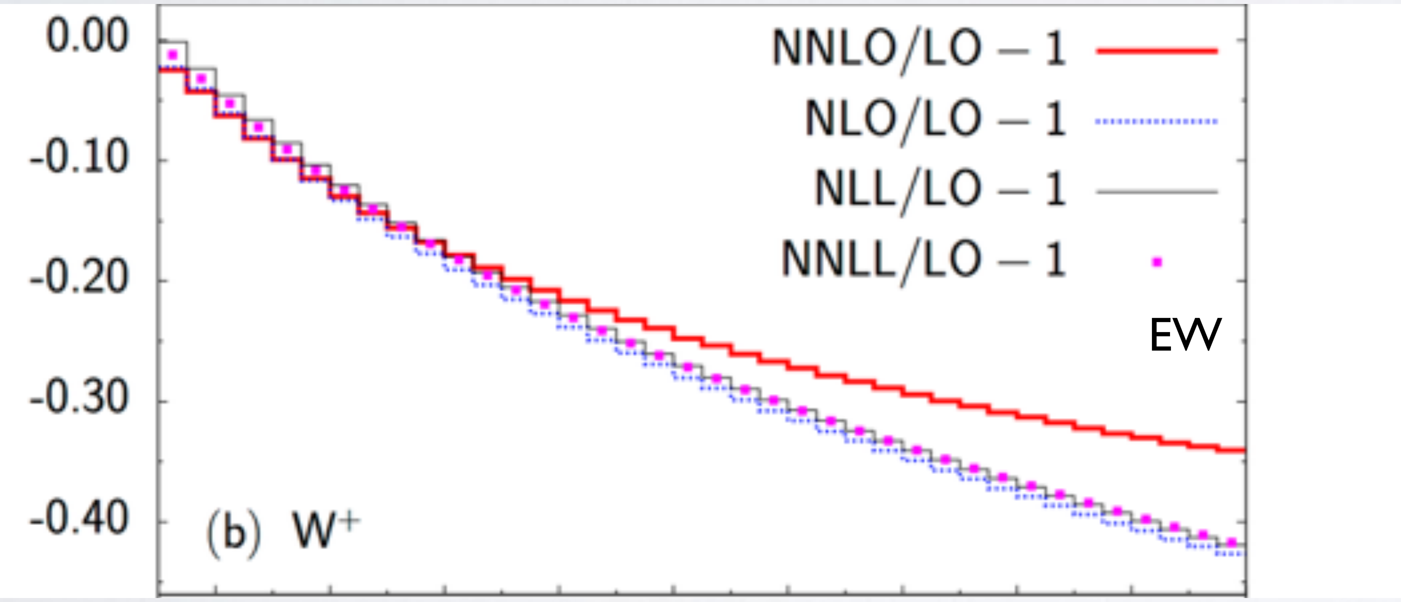
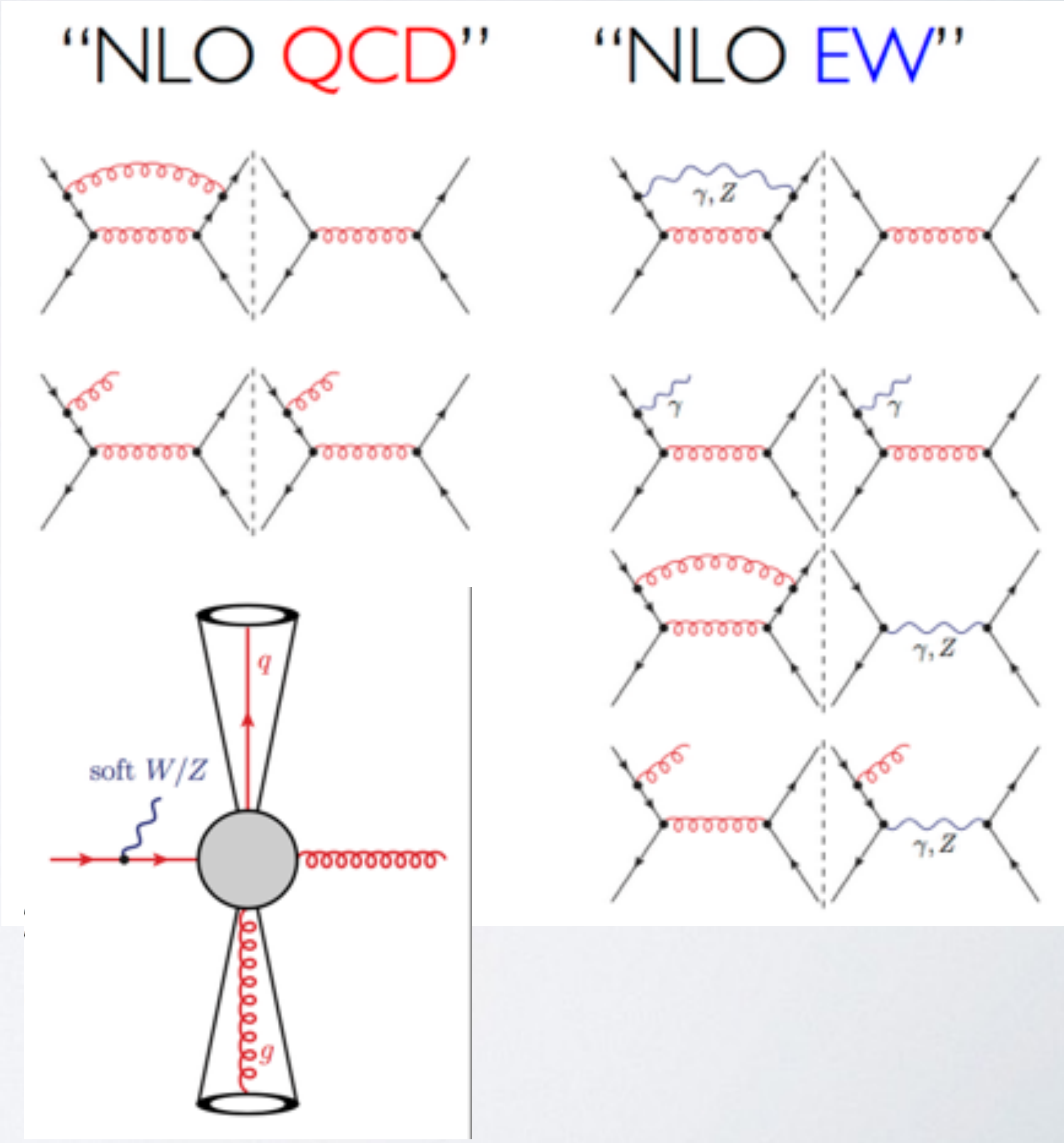




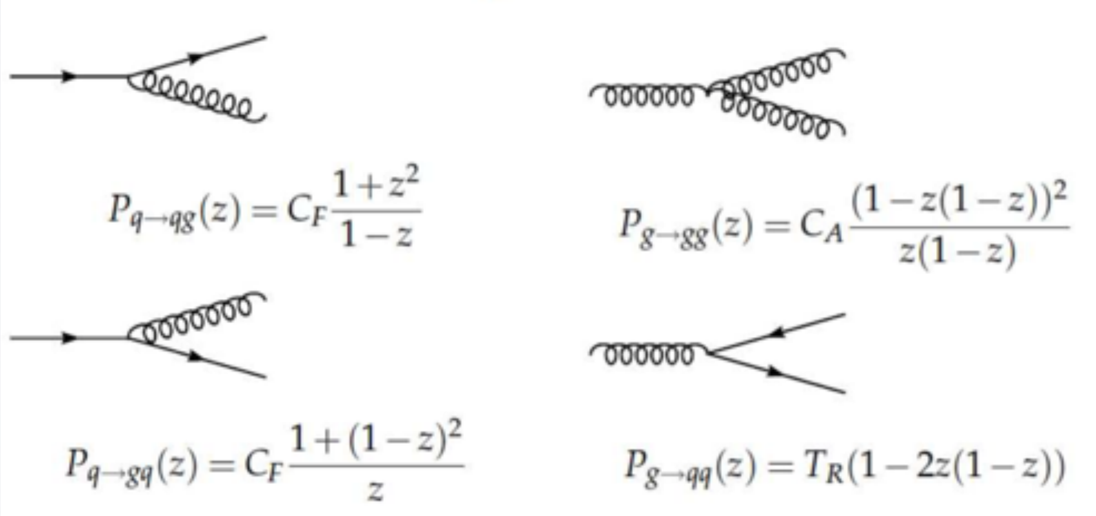
Tricky QCD/EW interplay: *Wjj* NLO vs. Dijet NLO

# Loops and legs …

# ISR & FSR: Parton Showers

- Full matrix elements for processes with up to 100 partons are not feasible
- Approximation by parton showers
- Splitting probability *i* → *jk*

$$\mathrm{d}\Gamma_{i\to jk}(t) = \frac{\mathrm{d}t}{t}\frac{\alpha_s}{2\pi}\int \mathrm{d}z\frac{\mathrm{d}\phi}{2\pi}P_{i\to jk}(t,z,\phi)$$



$$P_{q\to qg}(z) = C_F\frac{1+z^2}{1-z}$$

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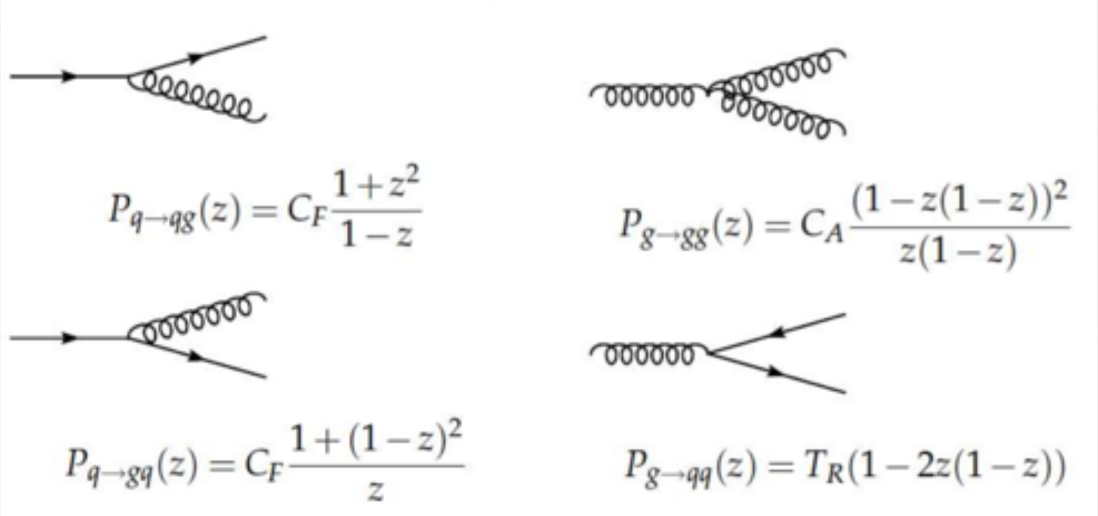

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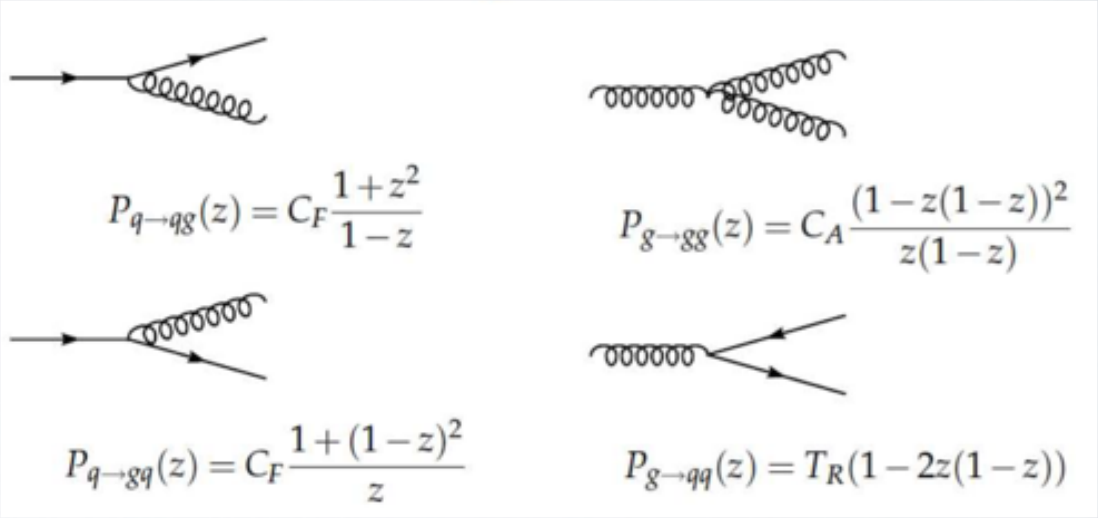

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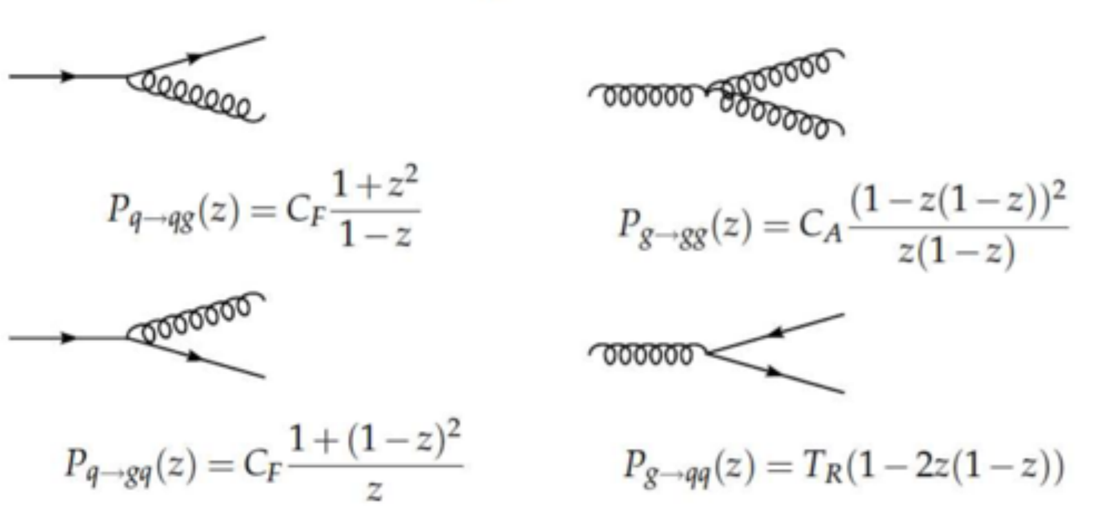

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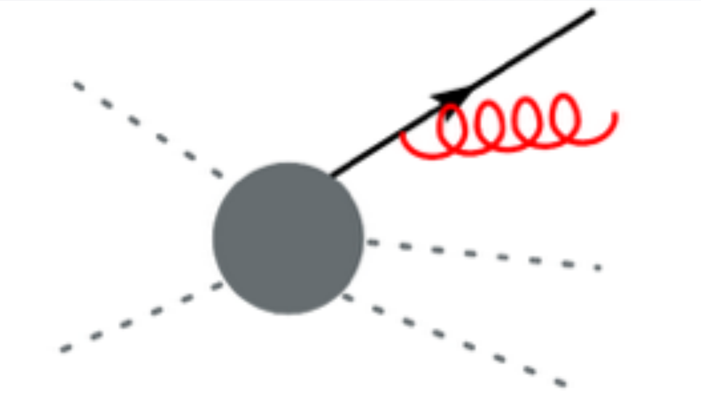
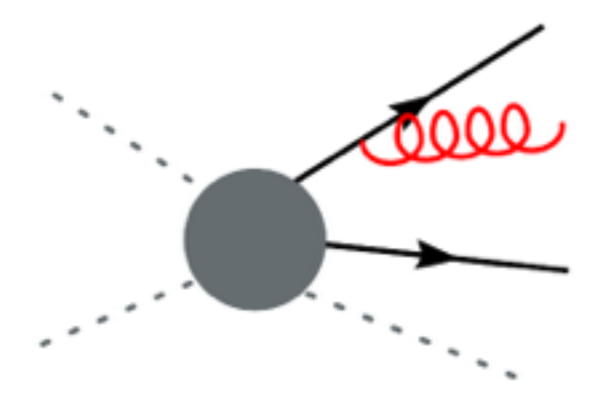
- Final state radiation (FSR): time-like showers
- Initial state radiation (ISR): space-like showers (PDF reweighting, makes time-like shower again)
- 1 → 2 vs. 2 → 3 splitting (Dipoles, antennae)





# Matching and Merging

- **Jet production:** matrix elements (ME) exact at fixed order, good description of hard/large-angle emissions
- **Jet evolution:** parton shower (PS) resum logarithms, good description of soft/collinear emissions
- **Matching @ LO/NLO:** [MLM, Powheg, CKKW, GKS]
  - Cross section at LO/NLO accuracy
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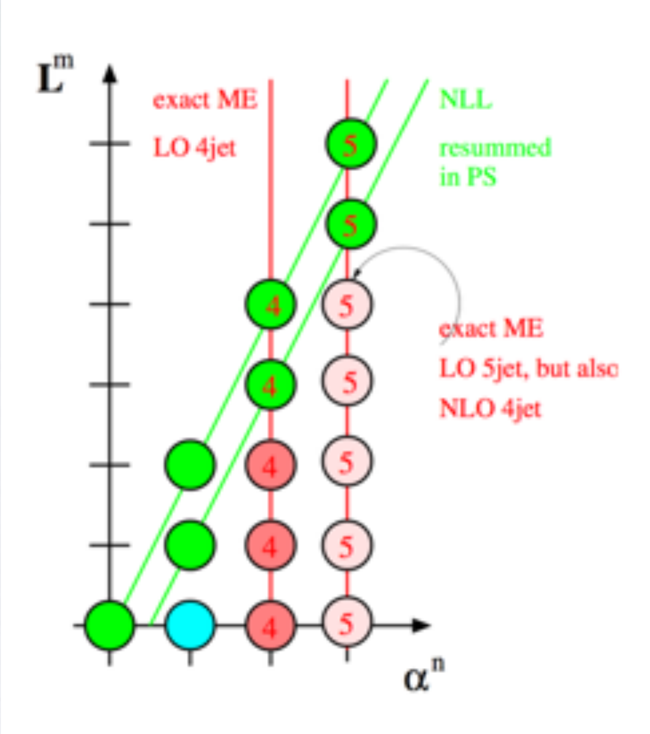

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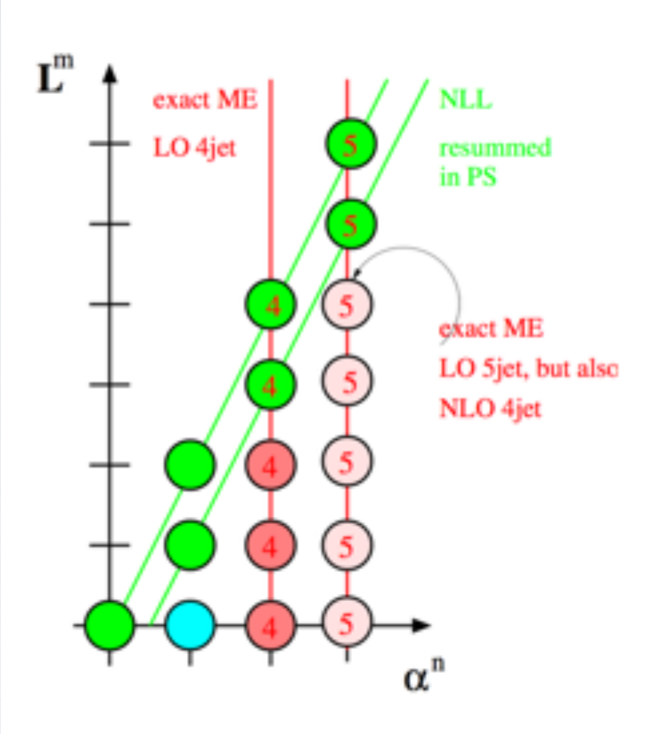

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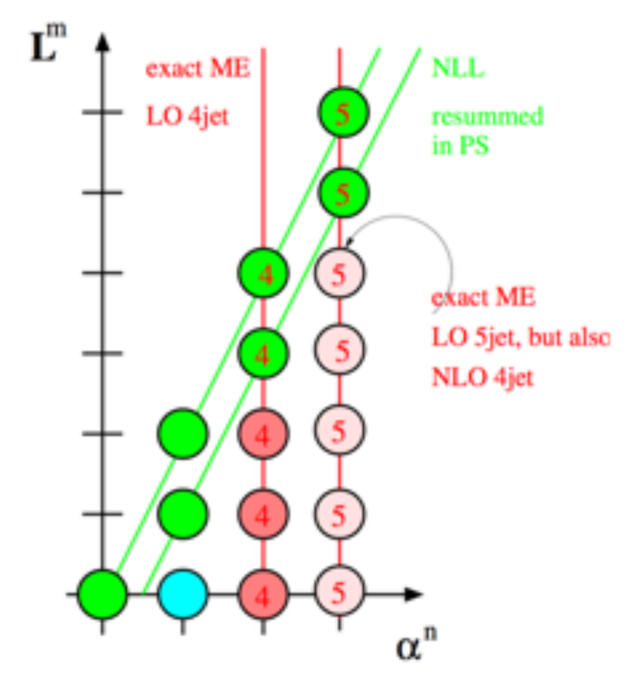
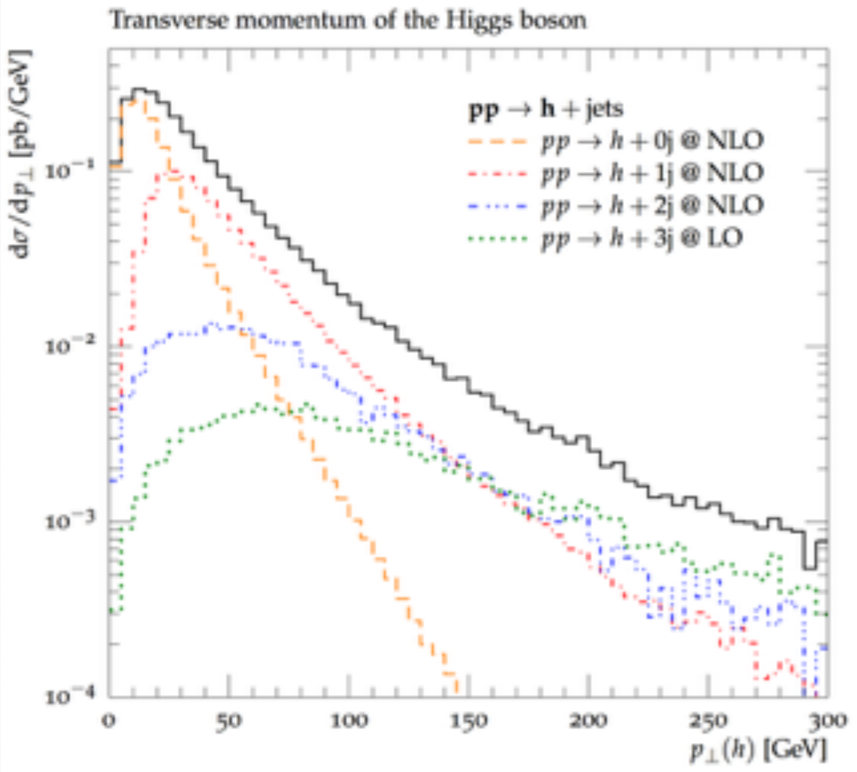


**Inclusive jet samples: avoid double-counting**

- Matrix elements populate hard regime
- Parton showers populate soft region
- Separate regions by jet measure $Q_j$



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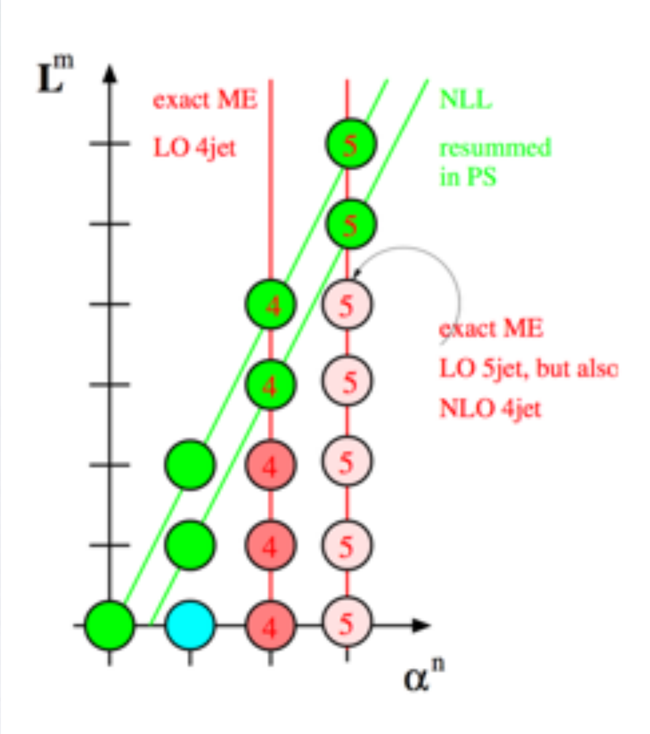

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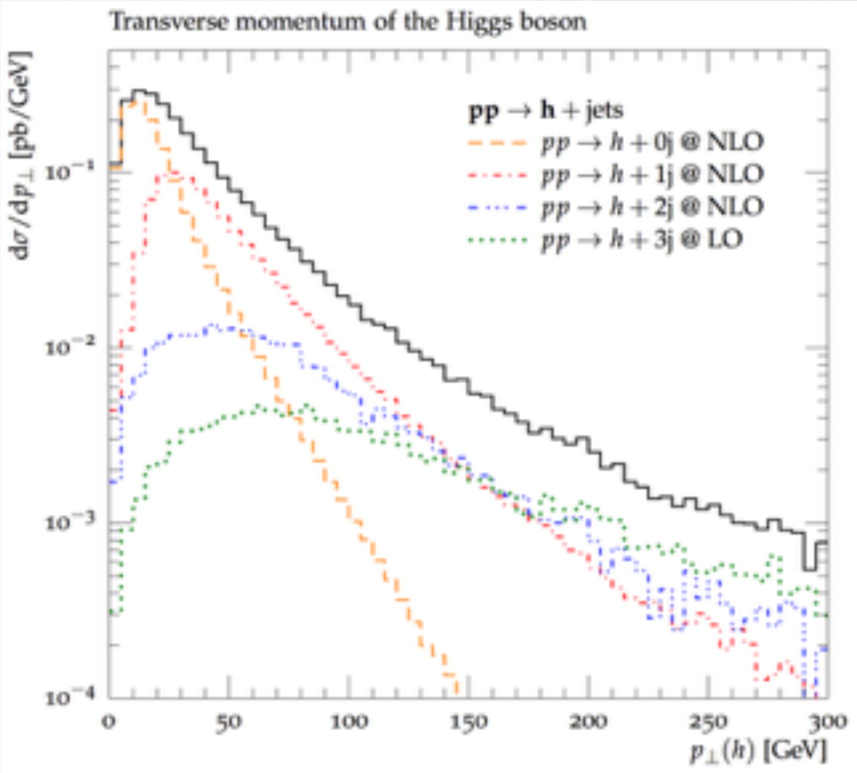

WIP: non-leading color, EW showers, access higher logs, spin

# Hadronization / Fragmentation

- Quark and gluon jets hadronize at low energy scales (fragmentation)
- Non-perturbative physics: has to be extracted from experiment [mainly $e^+e^- \to$ hadrons, DIS ]
- Old models [1970s]: flux tubes, independent fragmentation [Feynman/Field, 1970; Isajet]
- Independent fragmentation dresses bare quarks: "last quark", Lorentz invariance, infrared safety

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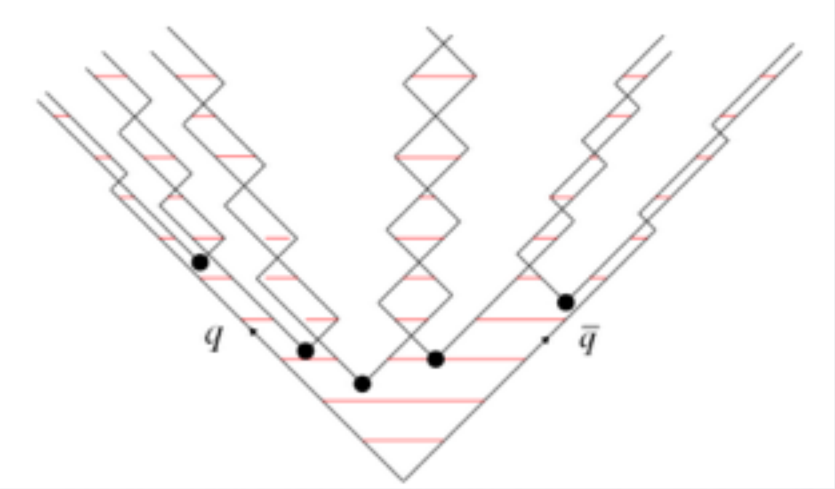
- Non-perturbative physics: has to be extracted from experiment [mainly $e^+e^- \rightarrow$ hadrons, DIS ]
- Old models [1970s]: flux tubes, independent fragmentation [Feynman/Field, 1970; Isajet]
- Independent fragmentation dresses bare quarks: "last quark", Lorentz invariance, infrared safety

**Lund string fragmentation model** [Pythia]

- based on old string model of strong interactions
- Strong physical motivation, but: invented without PS in mind
- Universal description of data (ee fit → hadrons)
- Plethora of parameters: $\sim O(1)$ per hadron
- Baryon production difficult [string junctions, popcorn]



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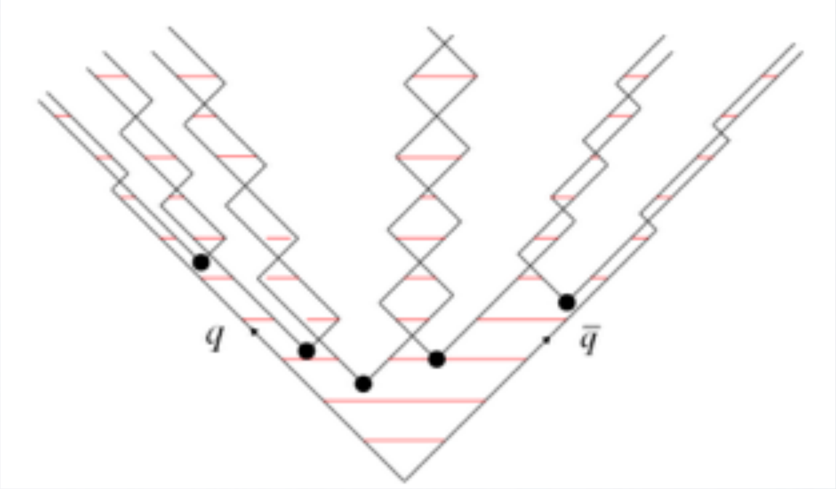

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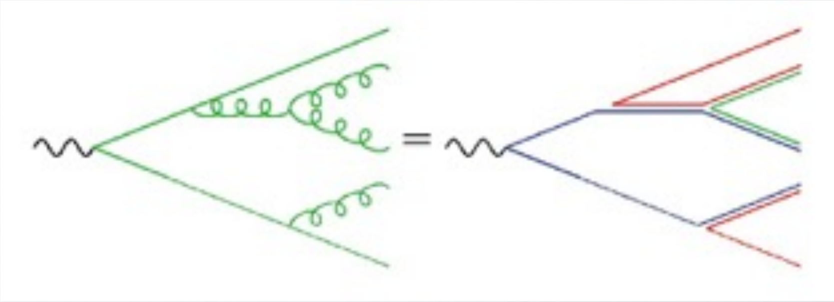

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- Large $N_C$ limit: planar graphs dominate
- Cluster: continuum of high-mass resonances, decay to hadrons
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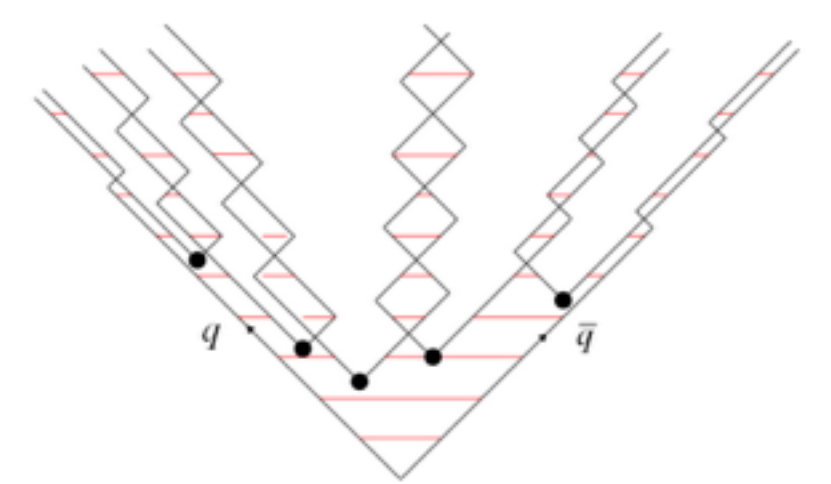

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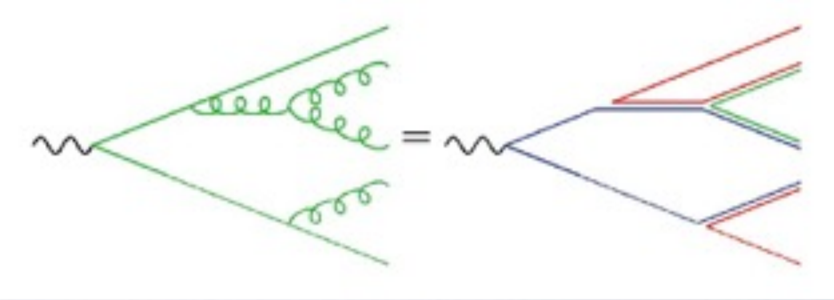

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All programs use either Lund or Cluster or a Hybrid version of both!

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Final-state hadronic QED radiation for shower shapes and correct distributions

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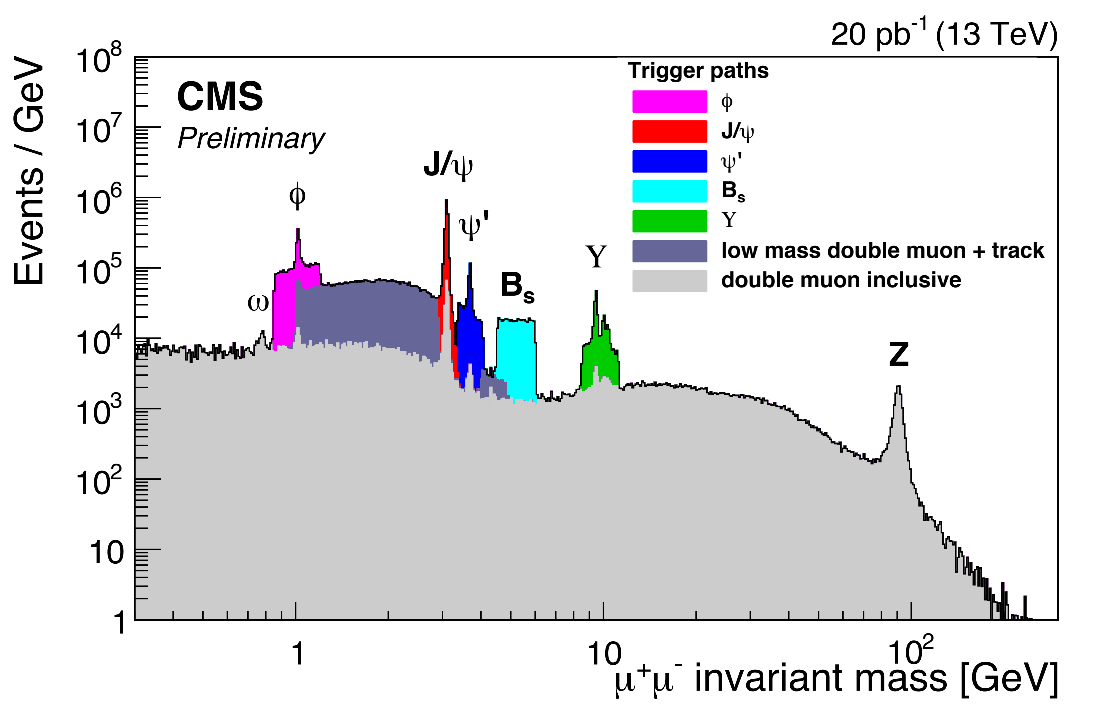
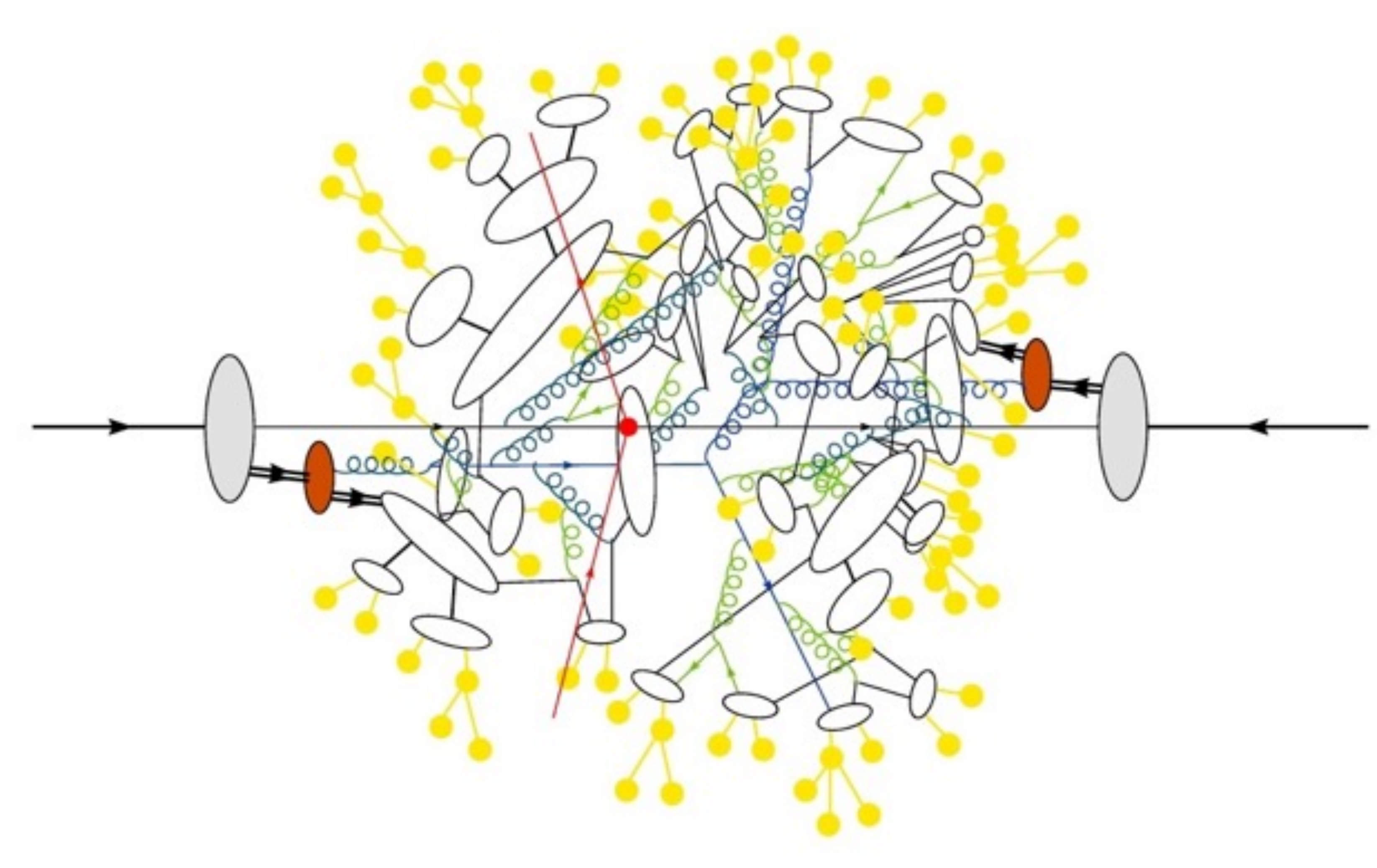


# Underlying Event

Many different definitions and names: UE, Multi-Parton interactions (MI, MPI), Minimum Bias

- "everything that is not of interest"
- multiple parton interaction from same hadron
- Beam remnants: soft interactions with interleaved ISR

- Phenomenological models
- e.g. eikeonal approximation to optical theorem
- Lots of dirty details



Best reference:
Pythia manual [Sjöstrand et al.]

# General Searches for New Physics

*“If I’d only knew* ***which*** *haystack.....”*

# Status in 2015, incl. 13 TeV data

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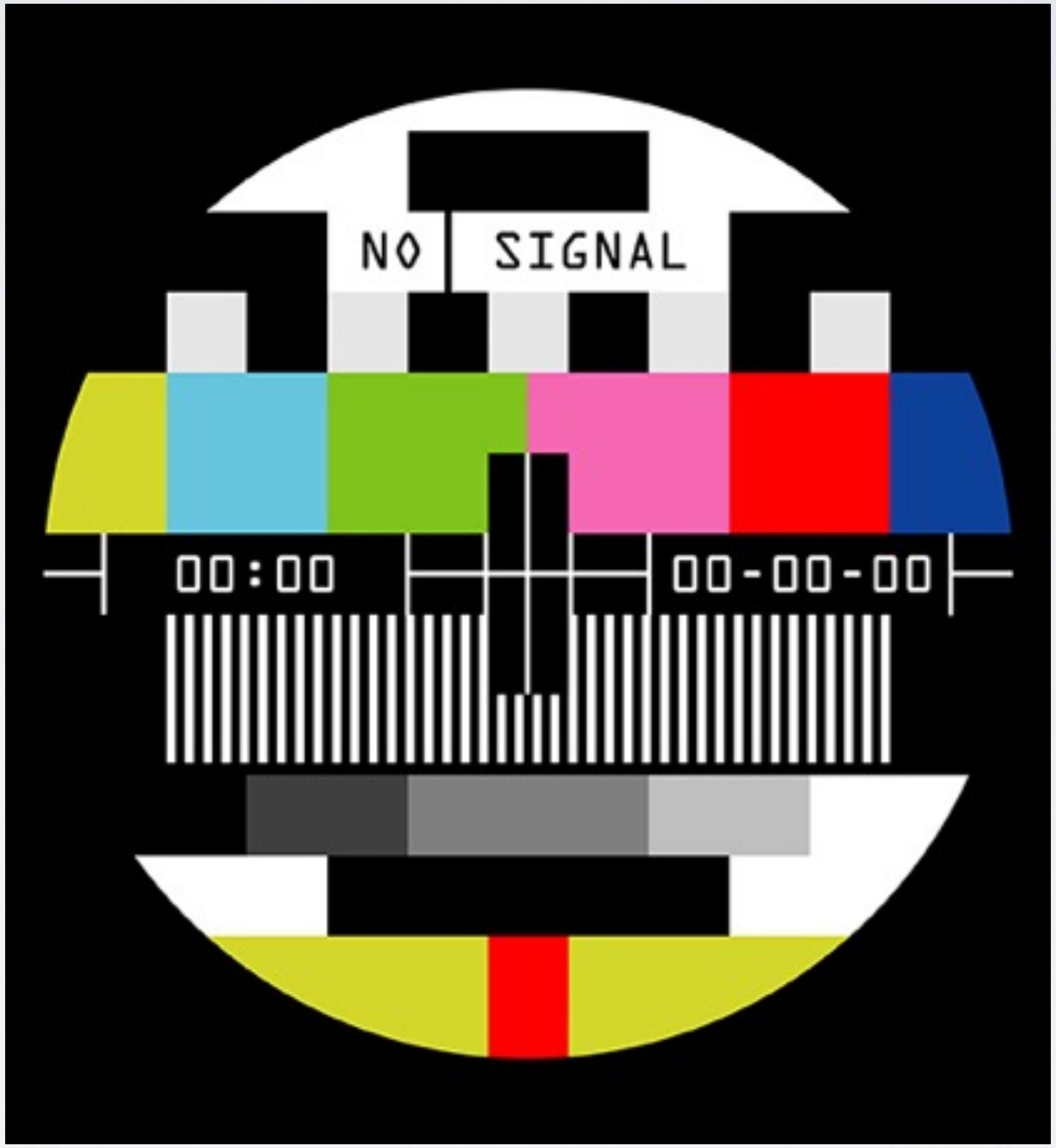

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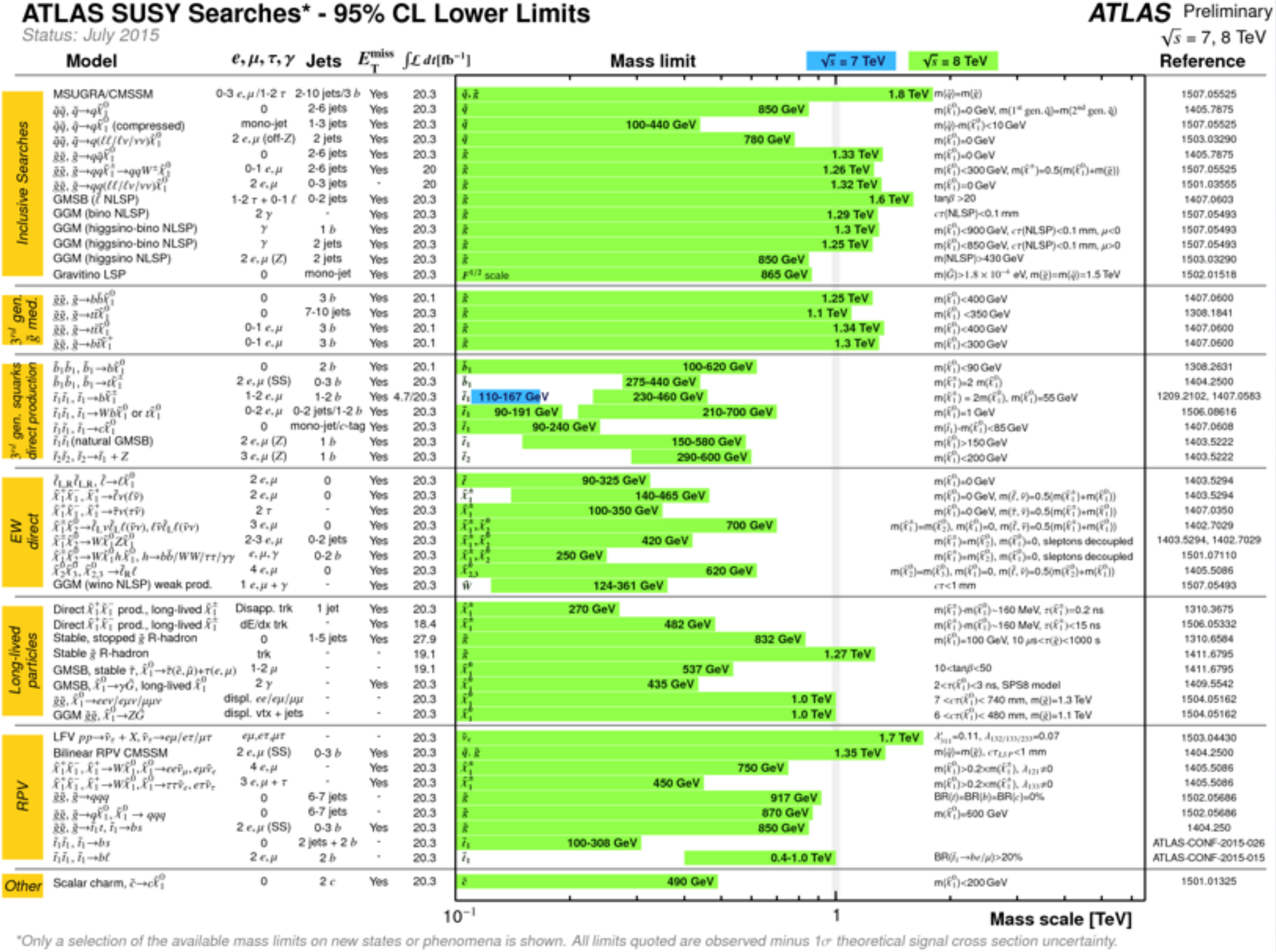


**ATLAS SUSY Searches* - 95% CL Lower Limits**

Status: July 2015

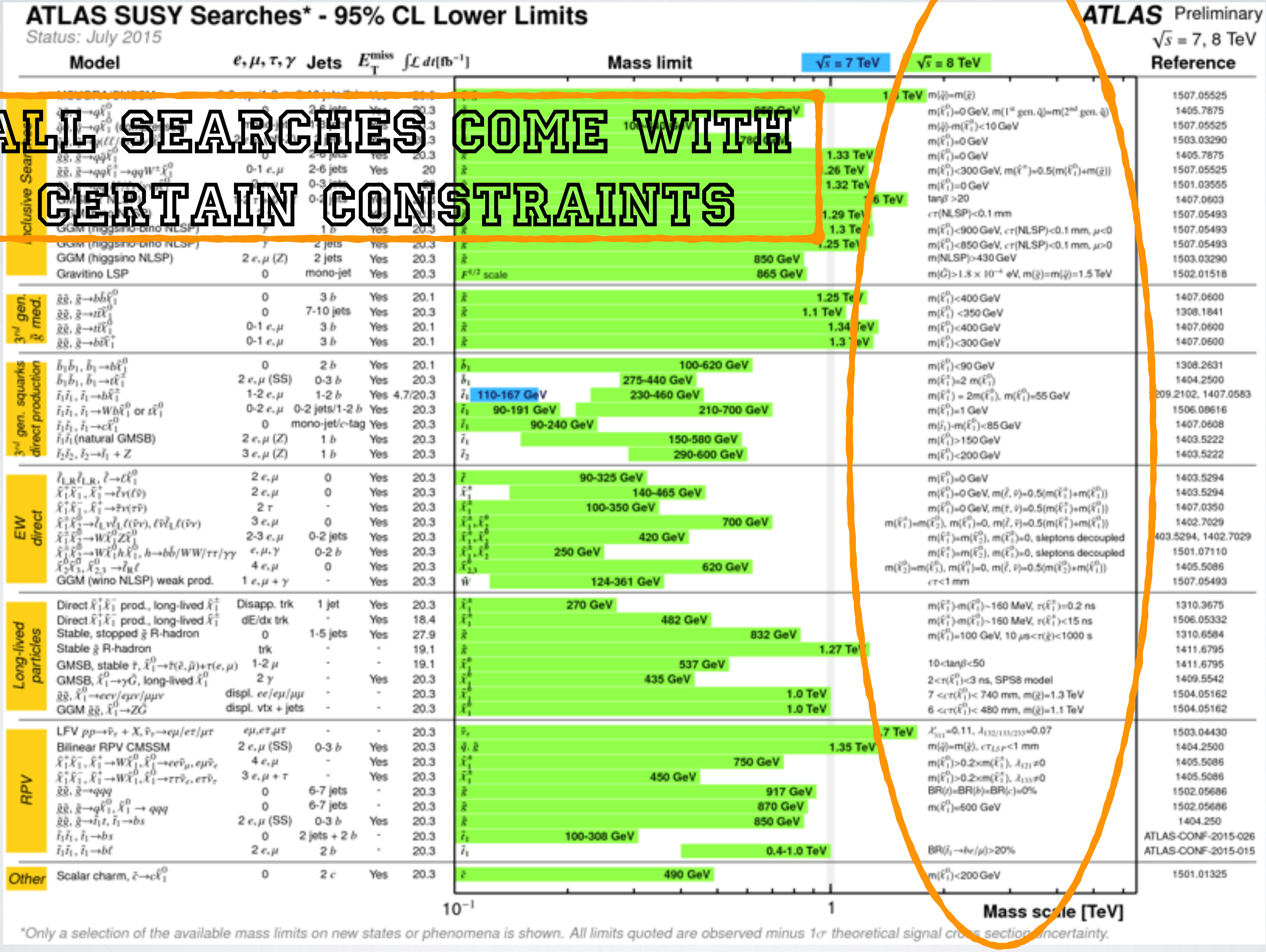
**ATLAS** Preliminary

$\sqrt{s} = 7, 8$ TeV

| | Model | $e, \mu, \tau, \gamma$ | Jets | $E_T^{miss}$ | $\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$ | Mass limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Inclusive Searches | MSUGRA/CMSSM | 0-3 $e,\mu$/1-2 $\tau$ | 2-10 jets/3 $b$ | Yes | 20.3 | $\tilde{q},\tilde{g}$ 1.8 TeV | $m(\tilde{q})=m(\tilde{g})$ | 1507.05525 |
| | $\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | $\tilde{q}$ 850 GeV | $m(\tilde{\chi}_1^0)$=0 GeV, $m(1^{st}$ gen. $\tilde{q})=m(2^{nd}$ gen. $\tilde{q})$ | 1405.7875 |
| | $\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed) | mono-jet | 1-3 jets | Yes | 20.3 | $\tilde{q}$ 100-440 GeV | $m(\tilde{q})-m(\tilde{\chi}_1^0)$<10 GeV | 1507.05525 |
| | $\tilde{q}\tilde{q}$, $\tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$ | 2 $e,\mu$ (off-$Z$) | 2 jets | Yes | 20.3 | $\tilde{q}$ 780 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | 1503.03290 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | $\tilde{g}$ 1.33 TeV | $m(\tilde{\chi}_1^0)$=0 GeV | 1405.7875 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$ | 0-1 $e,\mu$ | 2-6 jets | Yes | 20 | $\tilde{g}$ 1.26 TeV | $m(\tilde{\chi}_1^0)$<300 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$ | 1507.05525 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$ | 2 $e,\mu$ | 0-3 jets | - | 20 | $\tilde{g}$ 1.32 TeV | $m(\tilde{\chi}_1^0)$=0 GeV | 1501.03555 |
| | GMSB ($\tilde{\ell}$ NLSP) | 1-2 $\tau$ + 0-1 $\ell$ | 0-2 jets | Yes | 20.3 | $\tilde{g}$ 1.6 TeV | $\tan\beta$ >20 | 1407.0603 |
| | GGM (bino NLSP) | 2 $\gamma$ | - | Yes | 20.3 | $\tilde{g}$ 1.29 TeV | $c\tau$(NLSP)<0.1 mm | 1507.05493 |
| | GGM (higgsino-bino NLSP) | $\gamma$ | 1 $b$ | Yes | 20.3 | $\tilde{g}$ 1.3 TeV | $m(\tilde{\chi}_1^0)$<900 GeV, $c\tau$(NLSP)<0.1 mm, $\mu$<0 | 1507.05493 |
| | GGM (higgsino-bino NLSP) | $\gamma$ | 2 jets | Yes | 20.3 | $\tilde{g}$ 1.25 TeV | $m(\tilde{\chi}_1^0)$<850 GeV, $c\tau$(NLSP)<0.1 mm, $\mu$>0 | 1507.05493 |
| | GGM (higgsino NLSP) | 2 $e,\mu$ ($Z$) | 2 jets | Yes | 20.3 | $\tilde{g}$ 850 GeV | m(NLSP)>430 GeV | 1503.03290 |
| | Gravitino LSP | 0 | mono-jet | Yes | 20.3 | $F^{1/2}$ scale 865 GeV | $m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV | 1502.01518 |
| $3^{rd}$ gen. $\tilde{g}$ med. | $\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$ | 0 | 3 $b$ | Yes | 20.1 | $\tilde{g}$ 1.25 TeV | $m(\tilde{\chi}_1^0)$<400 GeV | 1407.0600 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0 | 7-10 jets | Yes | 20.3 | $\tilde{g}$ 1.1 TeV | $m(\tilde{\chi}_1^0)$ <350 GeV | 1308.1841 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 $e,\mu$ | 3 $b$ | Yes | 20.1 | $\tilde{g}$ 1.34 TeV | $m(\tilde{\chi}_1^0)$<400 GeV | 1407.0600 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$ | 0-1 $e,\mu$ | 3 $b$ | Yes | 20.1 | $\tilde{g}$ 1.3 TeV | $m(\tilde{\chi}_1^0)$<300 GeV | 1407.0600 |
| $3^{rd}$ gen. squarks direct production | $\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$ | 0 | 2 $b$ | Yes | 20.1 | $\tilde{b}_1$ 100-620 GeV | $m(\tilde{\chi}_1^0)$<90 GeV | 1308.2631 |
| | $\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$ | 2 $e,\mu$ (SS) | 0-3 $b$ | Yes | 20.3 | $\tilde{b}_1$ 275-440 GeV | $m(\tilde{\chi}_1^{\pm})$=2 $m(\tilde{\chi}_1^0)$ | 1404.2500 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$ | 1-2 $e,\mu$ | 1-2 $b$ | Yes | 4.7/20.3 | $\tilde{t}_1$ 110-167 GeV<br>230-460 GeV | $m(\tilde{\chi}_1^{\pm}) = 2m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV | 1209.2102, 1407.0583 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$ | 0-2 $e,\mu$ | 0-2 jets/1-2 $b$ | Yes | 20.3 | $\tilde{t}_1$ 90-191 GeV<br>210-700 GeV | $m(\tilde{\chi}_1^0)$=1 GeV | 1506.08616 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ | 0 | mono-jet/$c$-tag | Yes | 20.3 | $\tilde{t}_1$ 90-240 GeV | $m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV | 1407.0608 |
| | $\tilde{t}_1\tilde{t}_1$(natural GMSB) | 2 $e,\mu$ ($Z$) | 1 $b$ | Yes | 20.3 | $\tilde{t}_1$ 150-580 GeV | $m(\tilde{\chi}_1^0)$>150 GeV | 1403.5222 |
| | $\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$ | 3 $e,\mu$ ($Z$) | 1 $b$ | Yes | 20.3 | $\tilde{t}_2$ 290-600 GeV | $m(\tilde{\chi}_1^0)$<200 GeV | 1403.5222 |
| EW direct | $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 $e,\mu$ | 0 | Yes | 20.3 | $\tilde{\ell}$ 90-325 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | 1403.5294 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$ | 2 $e,\mu$ | 0 | Yes | 20.3 | $\tilde{\chi}_1^{\pm}$ 140-465 GeV | $m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ | 1403.5294 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$ | 2 $\tau$ | - | Yes | 20.3 | $\tilde{\chi}_1^{\pm}$ 100-350 GeV | $m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ | 1407.0350 |
| | $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$ | 3 $e,\mu$ | 0 | Yes | 20.3 | $\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 700 GeV | $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ | 1402.7029 |
| | $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$ | 2-3 $e,\mu$ | 0-2 jets | Yes | 20.3 | $\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 420 GeV | $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled | 1403.5294, 1402.7029 |
| | $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$ | $e,\mu,\gamma$ | 0-2 $b$ | Yes | 20.3 | $\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 250 GeV | $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled | 1501.07110 |
| | $\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$ | 4 $e,\mu$ | 0 | Yes | 20.3 | $\tilde{\chi}_{2,3}^0$ 620 GeV | $m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$ | 1405.5086 |
| | GGM (wino NLSP) weak prod. | 1 $e,\mu+\gamma$ | - | Yes | 20.3 | $\tilde{W}$ 124-361 GeV | $c\tau$<1 mm | 1507.05493 |
| Long-lived particles | Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$ | Disapp. trk | 1 jet | Yes | 20.3 | $\tilde{\chi}_1^{\pm}$ 270 GeV | $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns | 1310.3675 |
| | Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$ | dE/dx trk | - | Yes | 18.4 | $\tilde{\chi}_1^{\pm}$ 482 GeV | $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$<15 ns | 1506.05332 |
| | Stable, stopped $\tilde{g}$ R-hadron | 0 | 1-5 jets | Yes | 27.9 | $\tilde{g}$ 832 GeV | $m(\tilde{\chi}_1^0)$=100 GeV, 10 $\mu$s<$\tau(\tilde{g})$<1000 s | 1310.6584 |
| | Stable $\tilde{g}$ R-hadron | trk | - | - | 19.1 | $\tilde{g}$ 1.27 TeV | | 1411.6795 |
| | GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$ | 1-2 $\mu$ | - | - | 19.1 | $\tilde{\chi}_1^0$ 537 GeV | 10<$\tan\beta$<50 | 1411.6795 |
| | GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | 2 $\gamma$ | - | Yes | 20.3 | $\tilde{\chi}_1^0$ 435 GeV | 2<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model | 1409.5542 |
| | $\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$ | displ. $ee/e\mu/\mu\mu$ | - | - | 20.3 | $\tilde{\chi}_1^0$ 1.0 TeV | 7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV | 1504.05162 |
| | GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$ | displ. vtx + jets | - | - | 20.3 | $\tilde{\chi}_1^0$ 1.0 TeV | 6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV | 1504.05162 |
| RPV | LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$ | $e\mu,e\tau,\mu\tau$ | - | - | 20.3 | $\tilde{\nu}_\tau$ 1.7 TeV | $\lambda'_{311}$=0.11, $\lambda_{132/133/233}$=0.07 | 1503.04430 |
| | Bilinear RPV CMSSM | 2 $e,\mu$ (SS) | 0-3 $b$ | Yes | 20.3 | $\tilde{q},\tilde{g}$ 1.35 TeV | $m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm | 1404.2500 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$ | 4 $e,\mu$ | - | Yes | 20.3 | $\tilde{\chi}_1^{\pm}$ 750 GeV | $m(\tilde{\chi}_1^0)>0.2\times m(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq0$ | 1405.5086 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$ | 3 $e,\mu+\tau$ | - | Yes | 20.3 | $\tilde{\chi}_1^{\pm}$ 450 GeV | $m(\tilde{\chi}_1^0)>0.2\times m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$ | 1405.5086 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$ | 0 | 6-7 jets | - | 20.3 | $\tilde{g}$ 917 GeV | BR($t$)=BR($b$)=BR($c$)=0% | 1502.05686 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to q\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$ | 0 | 6-7 jets | - | 20.3 | $\tilde{g}$ 870 GeV | $m(\tilde{\chi}_1^0)$=600 GeV | 1502.05686 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$ | 2 $e,\mu$ (SS) | 0-3 $b$ | Yes | 20.3 | $\tilde{g}$ 850 GeV | | 1404.250 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$ | 0 | 2 jets + 2 $b$ | - | 20.3 | $\tilde{t}_1$ 100-308 GeV | | ATLAS-CONF-2015-026 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$ | 2 $e,\mu$ | 2 $b$ | - | 20.3 | $\tilde{t}_1$ 0.4-1.0 TeV | BR($\tilde{t}_1\to be/\mu$)>20% | ATLAS-CONF-2015-015 |
| Other | Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$ | 0 | 2 $c$ | Yes | 20.3 | $\tilde{c}$ 490 GeV | $m(\tilde{\chi}_1^0)$<200 GeV | 1501.01325 |

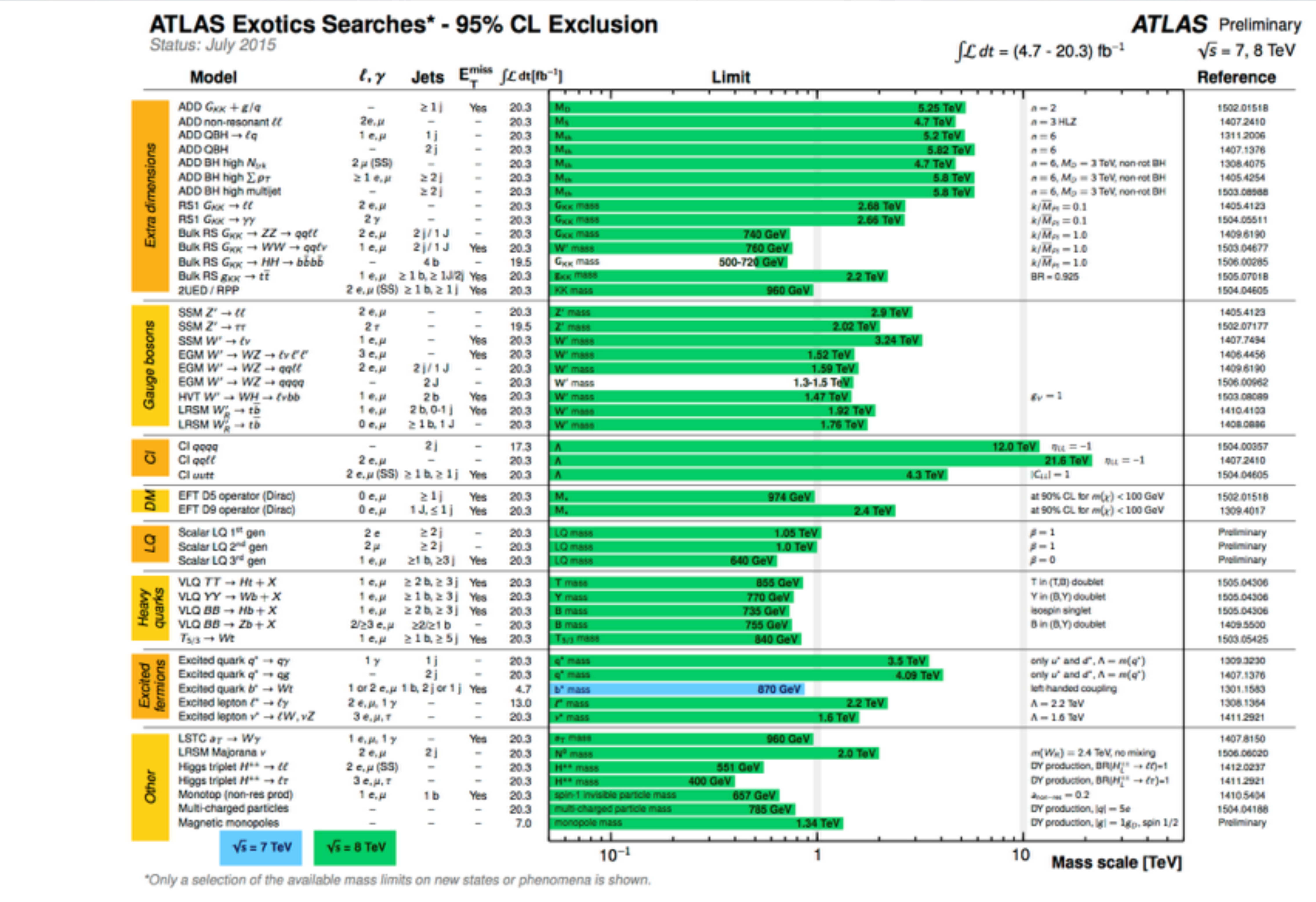
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1$\sigma$ theoretical signal cross section uncertainty.

# Status in 2015, incl. 13 TeV data



ALL SEARCHES COME WITH CERTAIN CONSTRAINTS

# Status in 2015, incl. 13 TeV data



**ATLAS Exotics Searches* - 95% CL Exclusion**

Status: July 2015

**ATLAS** Preliminary

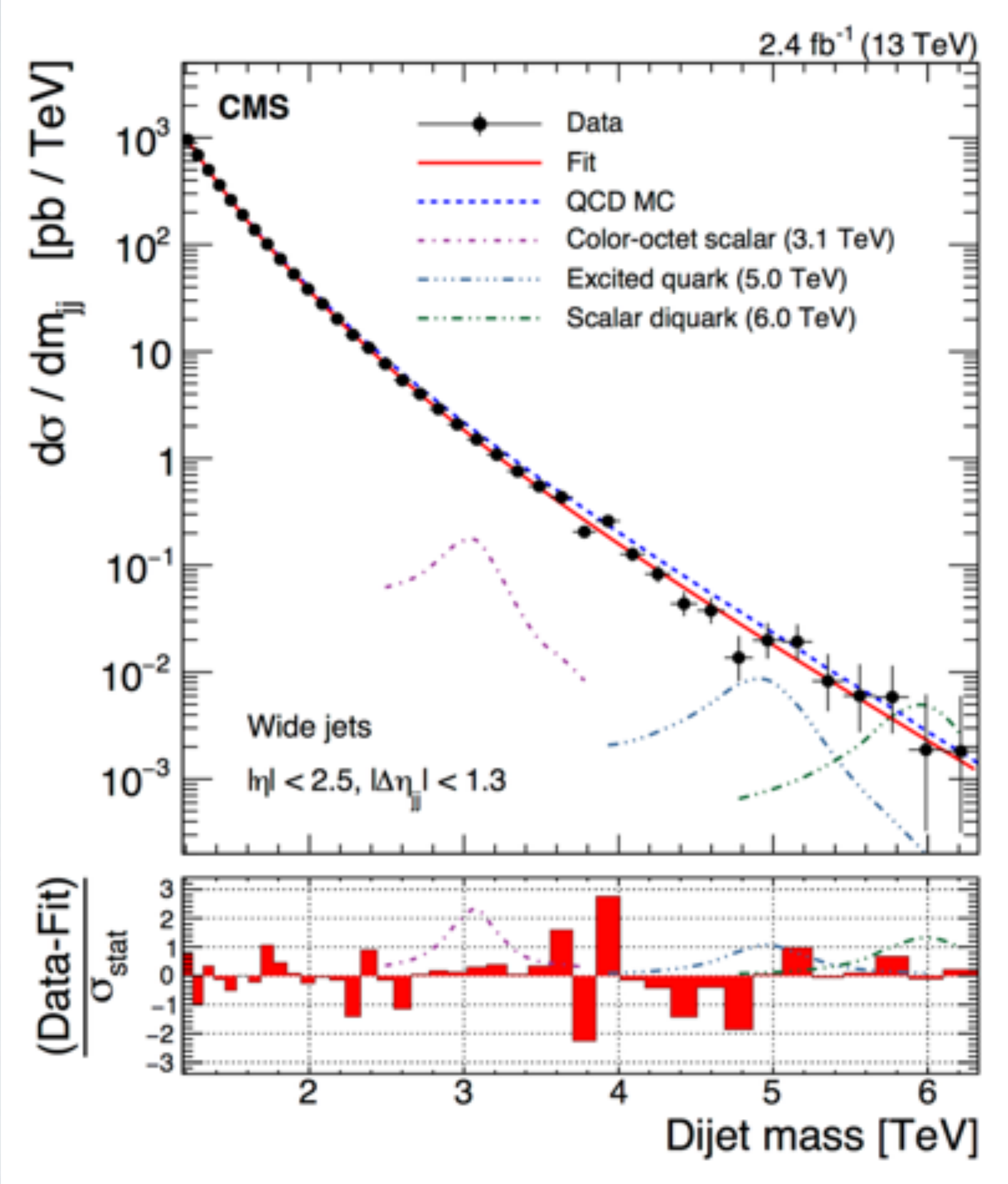
$\int\mathcal{L}\,dt = (4.7 - 20.3)\ \mathrm{fb}^{-1}$

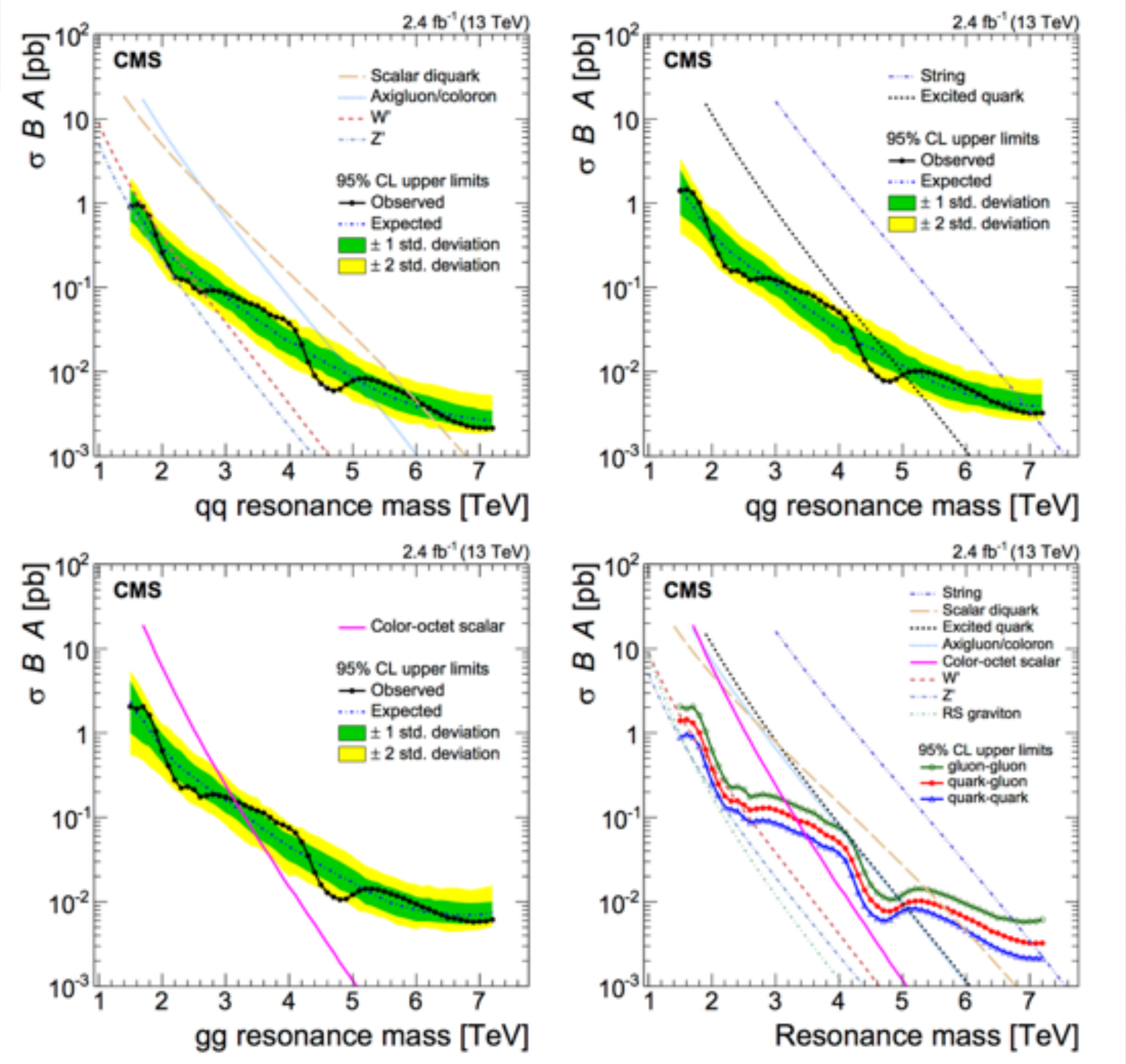
$\sqrt{s} = 7, 8$ TeV

| | Model | $\ell, \gamma$ | Jets | $E_T^{miss}$ | $\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$ | Limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Extra dimensions | ADD $G_{KK} + g/q$ | – | $\geq 1$ j | Yes | 20.3 | $M_D$ 5.25 TeV | $n = 2$ | 1502.01518 |
| | ADD non-resonant $\ell\ell$ | 2e, $\mu$ | – | – | 20.3 | $M_S$ 4.7 TeV | $n = 3$ HLZ | 1407.2410 |
| | ADD QBH $\to \ell q$ | 1 $e,\mu$ | 1 j | – | 20.3 | $M_{th}$ 5.2 TeV | $n = 6$ | 1311.2006 |
| | ADD QBH | – | 2 j | – | 20.3 | $M_{th}$ 5.82 TeV | $n = 6$ | 1407.1376 |
| | ADD BH high $N_{trk}$ | 2 $\mu$ (SS) | – | – | 20.3 | $M_{th}$ 4.7 TeV | $n = 6$, $M_D = 3$ TeV, non-rot BH | 1308.4075 |
| | ADD BH high $\sum p_T$ | $\geq 1$ $e,\mu$ | $\geq 2$ j | – | 20.3 | $M_{th}$ 5.8 TeV | $n = 6$, $M_D = 3$ TeV, non-rot BH | 1405.4254 |
| | ADD BH high multijet | – | $\geq 2$ j | – | 20.3 | $M_{th}$ 5.8 TeV | $n = 6$, $M_D = 3$ TeV, non-rot BH | 1503.08988 |
| | RS1 $G_{KK} \to \ell\ell$ | 2 $e,\mu$ | – | – | 20.3 | $G_{KK}$ mass 2.68 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1405.4123 |
| | RS1 $G_{KK} \to \gamma\gamma$ | 2 $\gamma$ | – | – | 20.3 | $G_{KK}$ mass 2.66 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1504.05511 |
| | Bulk RS $G_{KK} \to ZZ \to qq\ell\ell$ | 2 $e,\mu$ | 2 j / 1 J | – | 20.3 | $G_{KK}$ mass 740 GeV | $k/\overline{M}_{Pl} = 1.0$ | 1409.6190 |
| | Bulk RS $G_{KK} \to WW \to qq\ell\nu$ | 1 $e,\mu$ | 2 j / 1 J | Yes | 20.3 | W' mass 760 GeV | $k/\overline{M}_{Pl} = 1.0$ | 1503.04677 |
| | Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$ | – | 4 b | – | 19.5 | $G_{KK}$ mass 500-720 GeV | $k/\overline{M}_{Pl} = 1.0$ | 1506.00285 |
| | Bulk RS $g_{KK} \to t\bar{t}$ | 1 $e,\mu$ | $\geq 1$ b, $\geq 1$J/2j | Yes | 20.3 | $g_{KK}$ mass 2.2 TeV | BR = 0.925 | 1505.07018 |
| | 2UED / RPP | 2 $e,\mu$ (SS) | $\geq 1$ b, $\geq 1$ j | Yes | 20.3 | KK mass 960 GeV | | 1504.04605 |
| Gauge bosons | SSM $Z' \to \ell\ell$ | 2 $e,\mu$ | – | – | 20.3 | Z' mass 2.9 TeV | | 1405.4123 |
| | SSM $Z' \to \tau\tau$ | 2 $\tau$ | – | – | 19.5 | Z' mass 2.02 TeV | | 1502.07177 |
| | SSM $W' \to \ell\nu$ | 1 $e,\mu$ | – | Yes | 20.3 | W' mass 3.24 TeV | | 1407.7494 |
| | EGM $W' \to WZ \to \ell\nu\,\ell'\ell'$ | 3 $e,\mu$ | – | Yes | 20.3 | W' mass 1.52 TeV | | 1406.4456 |
| | EGM $W' \to WZ \to qq\ell\ell$ | 2 $e,\mu$ | 2 j / 1 J | – | 20.3 | W' mass 1.59 TeV | | 1409.6190 |
| | EGM $W' \to WZ \to qqqq$ | – | 2 J | – | 20.3 | W' mass 1.3-1.5 TeV | | 1506.00962 |
| | HVT $W' \to WH \to \ell\nu bb$ | 1 $e,\mu$ | 2 b | Yes | 20.3 | W' mass 1.47 TeV | $g_V = 1$ | 1503.08089 |
| | LRSM $W'_R \to t\bar{b}$ | 1 $e,\mu$ | 2 b, 0-1 j | Yes | 20.3 | W' mass 1.92 TeV | | 1410.4103 |
| | LRSM $W'_R \to t\bar{b}$ | 0 $e,\mu$ | $\geq 1$ b, 1 J | – | 20.3 | W' mass 1.76 TeV | | 1408.0886 |
| CI | CI $qqqq$ | – | 2 j | – | 17.3 | $\Lambda$ 12.0 TeV | $\eta_{LL} = -1$ | 1504.00357 |
| | CI $qq\ell\ell$ | 2 $e,\mu$ | – | – | 20.3 | $\Lambda$ 21.6 TeV | $\eta_{LL} = -1$ | 1407.2410 |
| | CI $uutt$ | 2 $e,\mu$ (SS) | $\geq 1$ b, $\geq 1$ j | Yes | 20.3 | $\Lambda$ 4.3 TeV | $\lvert C_{LL}\rvert = 1$ | 1504.04605 |
| DM | EFT D5 operator (Dirac) | 0 $e,\mu$ | $\geq 1$ j | Yes | 20.3 | $M_*$ 974 GeV | at 90% CL for $m(\chi) < 100$ GeV | 1502.01518 |
| | EFT D9 operator (Dirac) | 0 $e,\mu$ | 1 J, $\leq 1$ j | Yes | 20.3 | $M_*$ 2.4 TeV | at 90% CL for $m(\chi) < 100$ GeV | 1309.4017 |
| LQ | Scalar LQ 1st gen | 2 $e$ | $\geq 2$ j | – | 20.3 | LQ mass 1.05 TeV | $\beta = 1$ | Preliminary |
| | Scalar LQ 2nd gen | 2 $\mu$ | $\geq 2$ j | – | 20.3 | LQ mass 1.0 TeV | $\beta = 1$ | Preliminary |
| | Scalar LQ 3rd gen | 1 $e,\mu$ | $\geq$1 b, $\geq$3 j | Yes | 20.3 | LQ mass 640 GeV | $\beta = 0$ | Preliminary |
| Heavy quarks | VLQ $TT \to Ht + X$ | 1 $e,\mu$ | $\geq 2$ b, $\geq 3$ j | Yes | 20.3 | T mass 855 GeV | T in (T,B) doublet | 1505.04306 |
| | VLQ $YY \to Wb + X$ | 1 $e,\mu$ | $\geq 1$ b, $\geq 3$ j | Yes | 20.3 | Y mass 770 GeV | Y in (B,Y) doublet | 1505.04306 |
| | VLQ $BB \to Hb + X$ | 1 $e,\mu$ | $\geq 2$ b, $\geq 3$ j | Yes | 20.3 | B mass 735 GeV | isospin singlet | 1505.04306 |
| | VLQ $BB \to Zb + X$ | 2/$\geq$3 $e,\mu$ | $\geq$2/$\geq$1 b | – | 20.3 | B mass 755 GeV | B in (B,Y) doublet | 1409.5500 |
| | $T_{5/3} \to Wt$ | 1 $e,\mu$ | $\geq 1$ b, $\geq 5$ j | Yes | 20.3 | $T_{5/3}$ mass 840 GeV | | 1503.05425 |
| Excited fermions | Excited quark $q^* \to q\gamma$ | 1 $\gamma$ | 1 j | – | 20.3 | q* mass 3.5 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1309.3230 |
| | Excited quark $q^* \to qg$ | – | 2 j | – | 20.3 | q* mass 4.09 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1407.1376 |
| | Excited quark $b^* \to Wt$ | 1 or 2 $e,\mu$ | 1 b, 2 j or 1 j | Yes | 4.7 | b* mass 870 GeV | left-handed coupling | 1301.1583 |
| | Excited lepton $\ell^* \to \ell\gamma$ | 2 $e,\mu$, 1 $\gamma$ | – | – | 13.0 | $\ell^*$ mass 2.2 TeV | $\Lambda = 2.2$ TeV | 1308.1364 |
| | Excited lepton $\nu^* \to \ell W, \nu Z$ | 3 $e,\mu,\tau$ | – | – | 20.3 | $\nu^*$ mass 1.6 TeV | $\Lambda = 1.6$ TeV | 1411.2921 |
| Other | LSTC $a_T \to W\gamma$ | 1 $e,\mu$, 1 $\gamma$ | – | Yes | 20.3 | $a_T$ mass 960 GeV | | 1407.8150 |
| | LRSM Majorana $\nu$ | 2 $e,\mu$ | 2 j | – | 20.3 | $N^0$ mass 2.0 TeV | $m(W_R) = 2.4$ TeV, no mixing | 1506.06020 |
| | Higgs triplet $H^{\pm\pm} \to \ell\ell$ | 2 $e,\mu$ (SS) | – | – | 20.3 | $H^{\pm\pm}$ mass 551 GeV | DY production, BR($H_L^{\pm\pm} \to \ell\ell$)=1 | 1412.0237 |
| | Higgs triplet $H^{\pm\pm} \to \ell\tau$ | 3 $e,\mu,\tau$ | – | – | 20.3 | $H^{\pm\pm}$ mass 400 GeV | DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1 | 1411.2921 |
| | Monotop (non-res prod) | 1 $e,\mu$ | 1 b | Yes | 20.3 | spin-1 invisible particle mass 657 GeV | $a_{non-res} = 0.2$ | 1410.5404 |
| | Multi-charged particles | – | – | – | 20.3 | multi-charged particle mass 785 GeV | DY production, $\lvert q\rvert = 5e$ | 1504.04188 |
| | Magnetic monopoles | – | – | – | 7.0 | monopole mass 1.34 TeV | DY production, $\lvert g\rvert = 1g_D$, spin 1/2 | Preliminary |

*Only a selection of the available mass limits on new states or phenomena is shown.

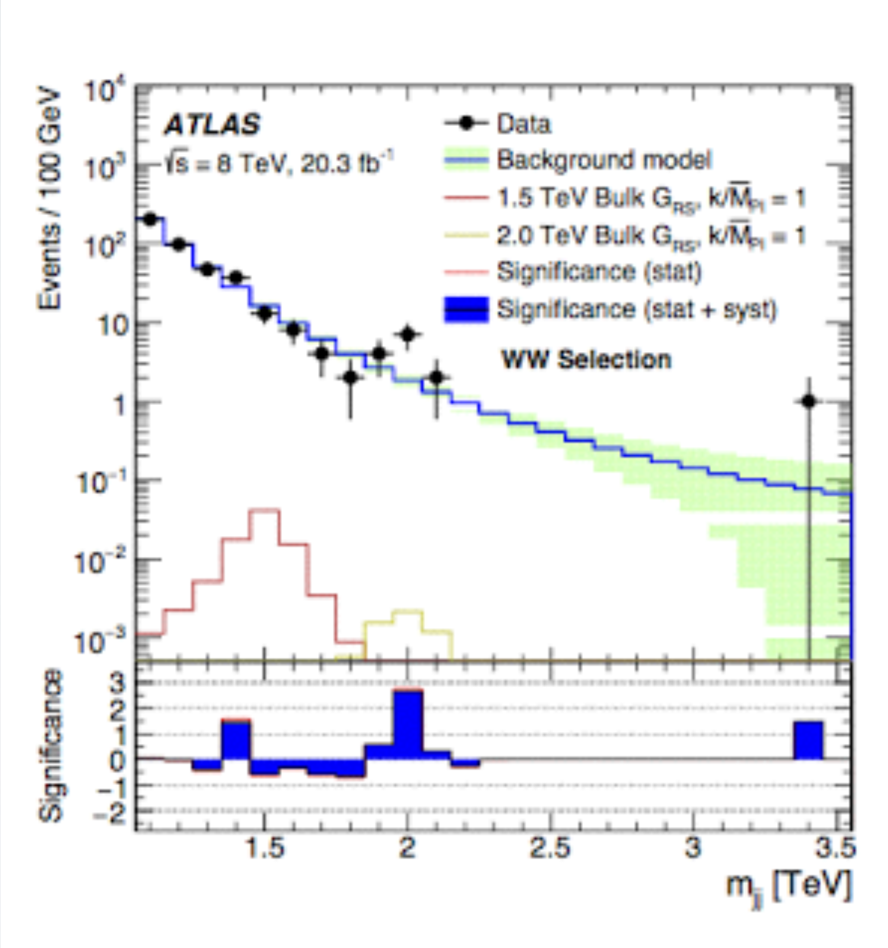
# Status in 2015, incl. 13 TeV data

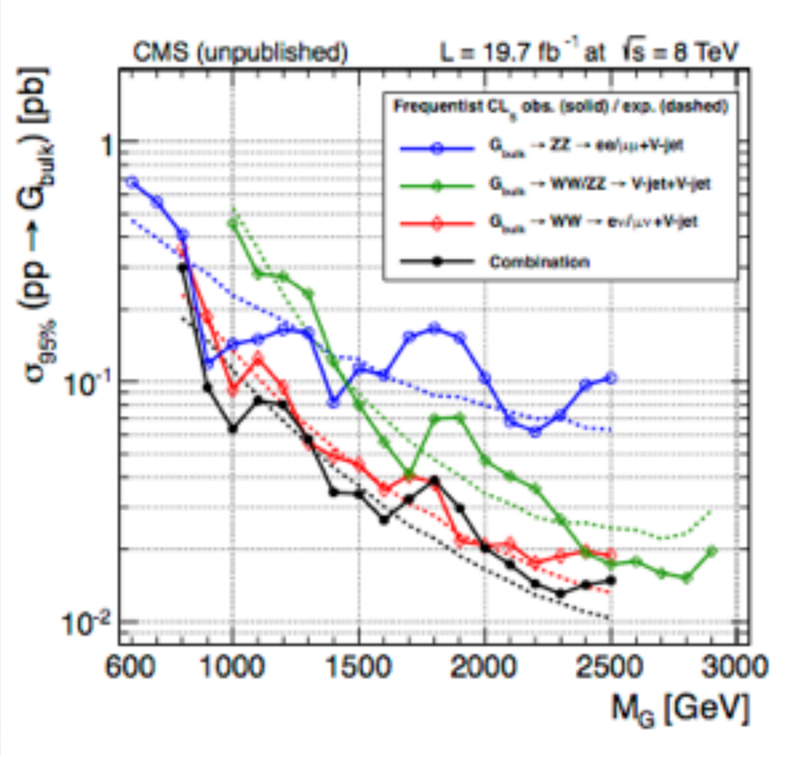




CMS, 12/2015

# A new hope …. or the SM strikes back?





ATLAS diboson "bump"; CMS upward fluctuation [gone for the moment @ 13 TeV]

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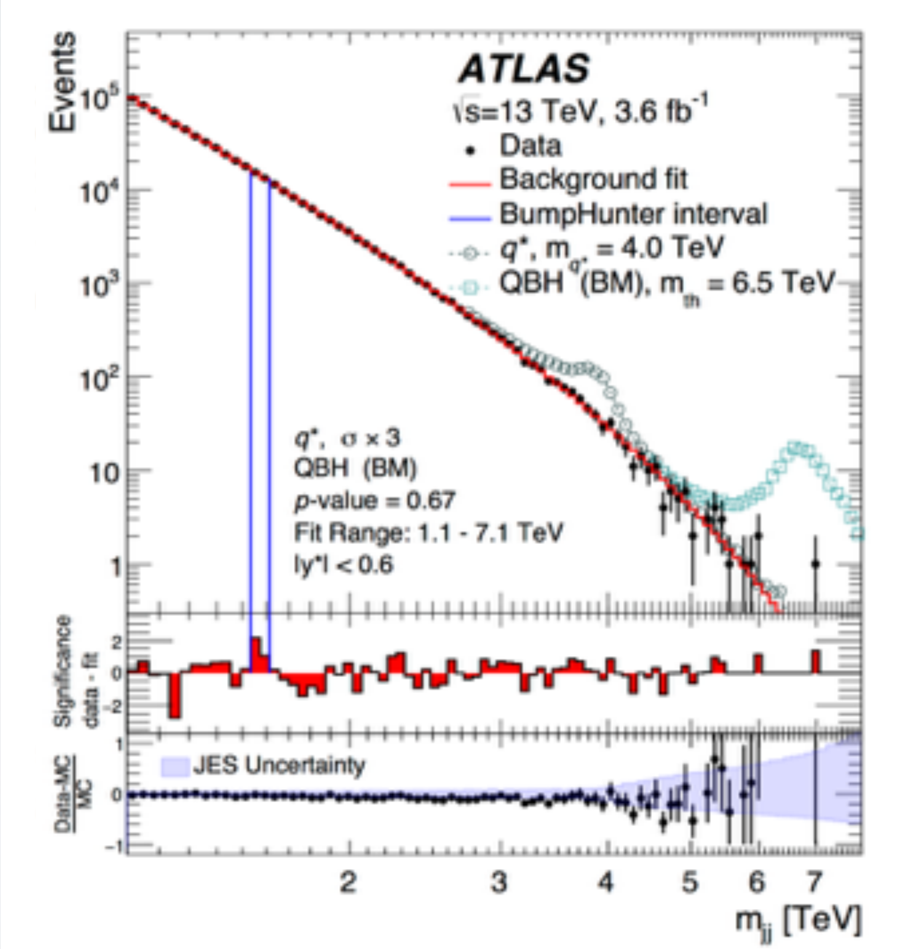

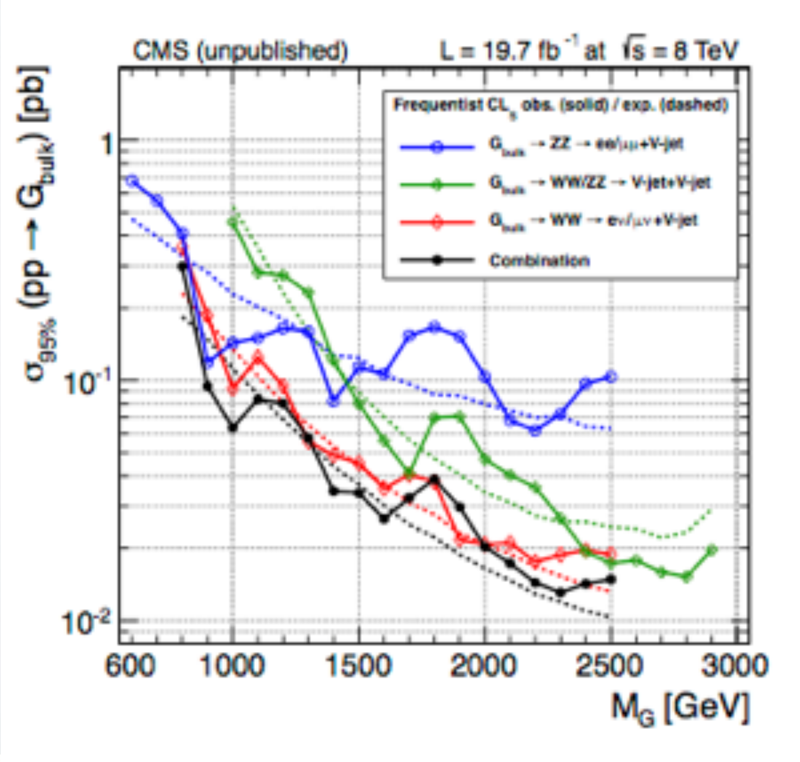

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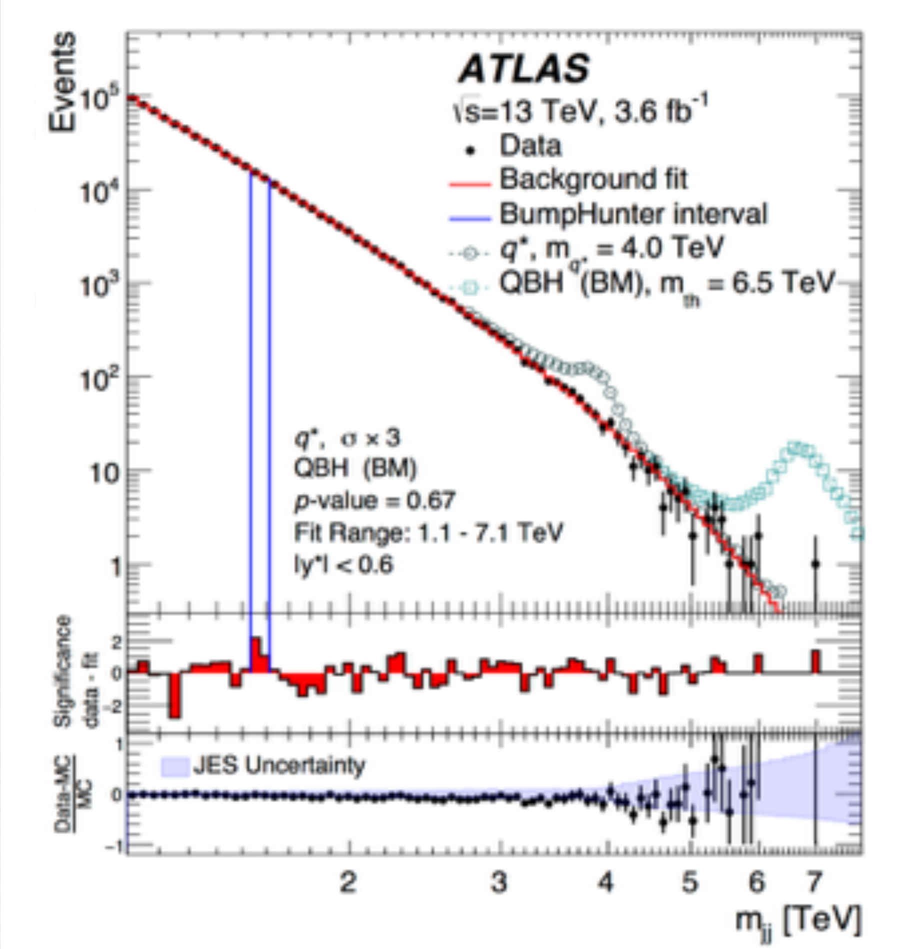

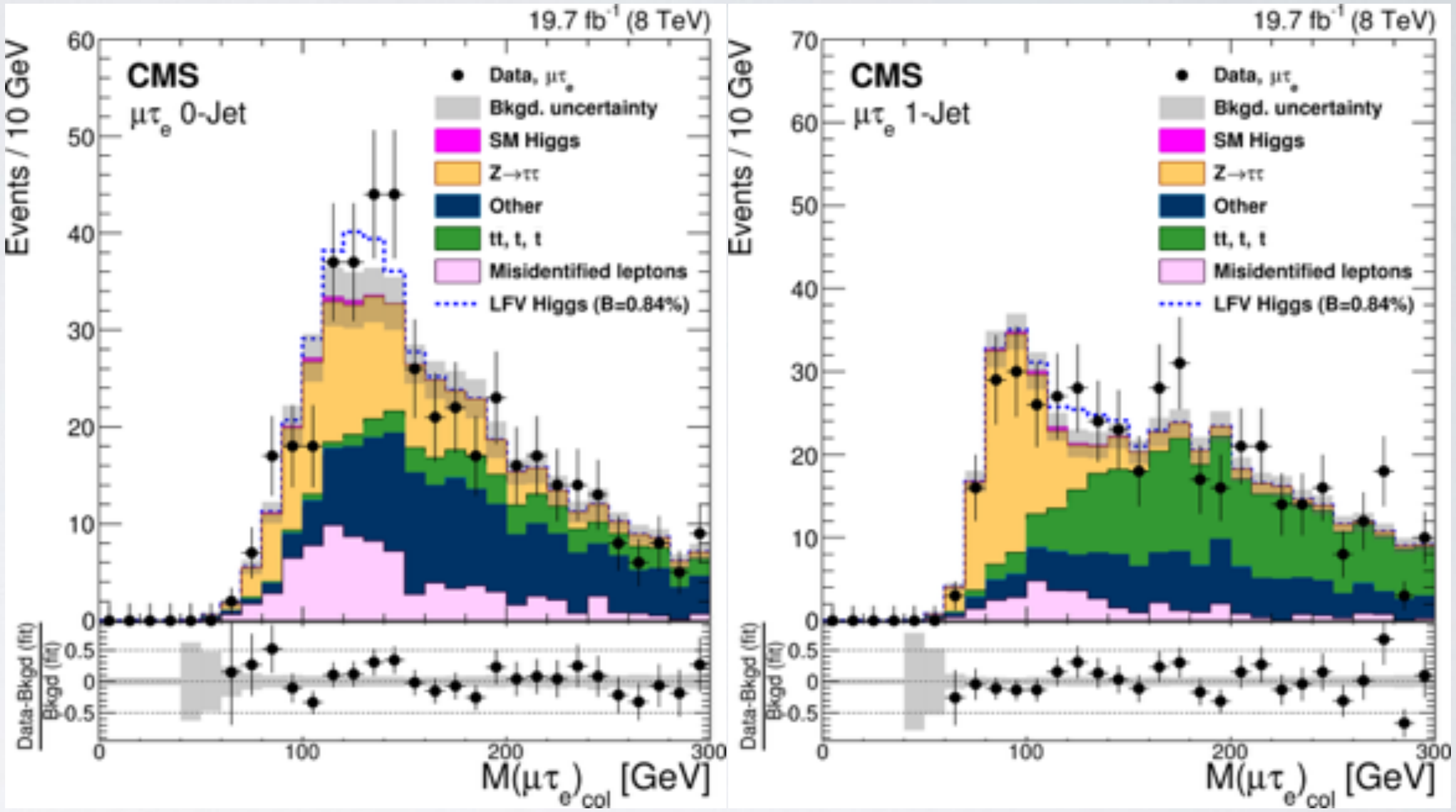

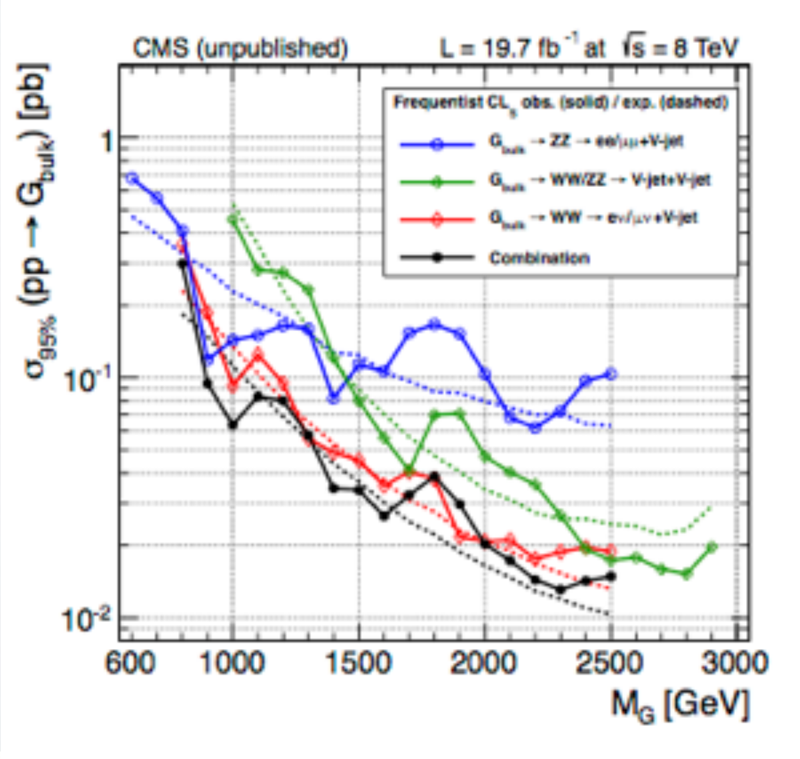

Flavour-Violating Higgs decay h(125) → μτ in ATLAS/CMS

ATLAS diboson "bump"; CMS upward fluctuation [gone for the moment @ 13 TeV]

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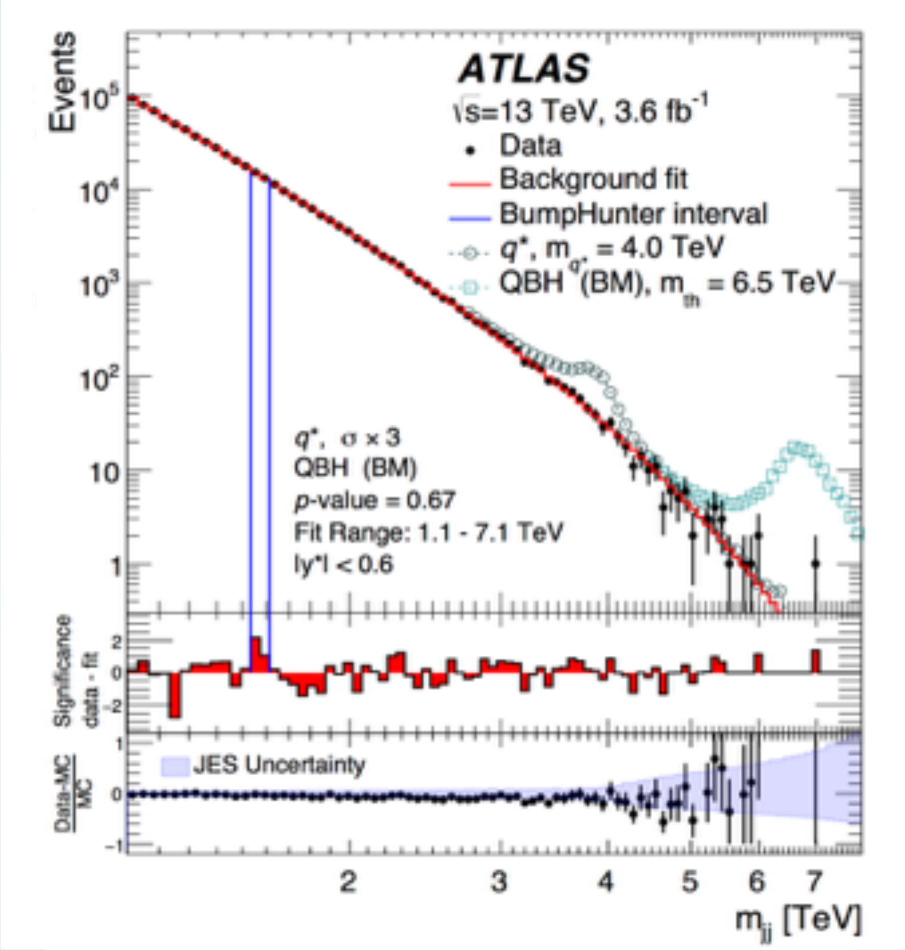
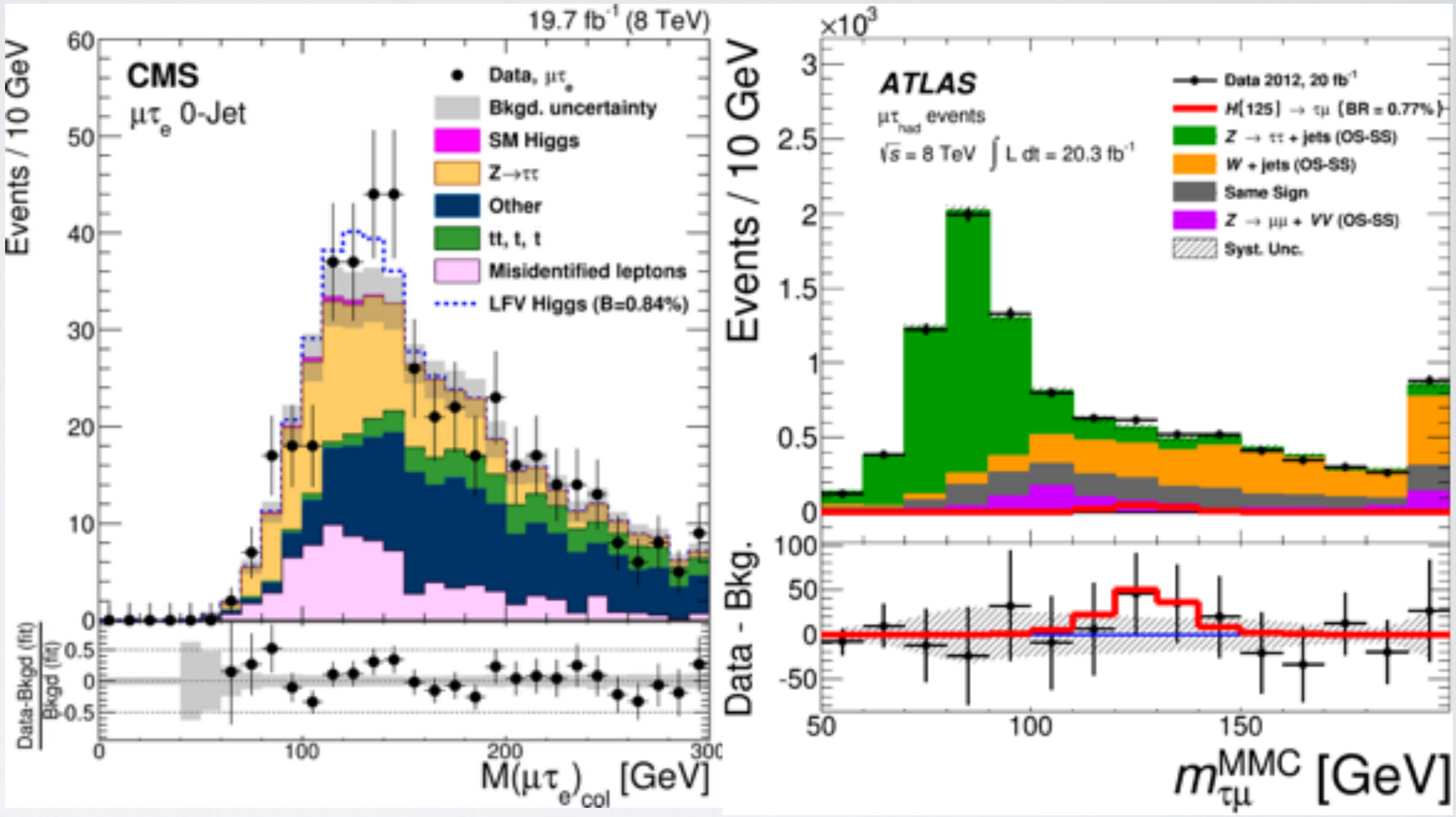
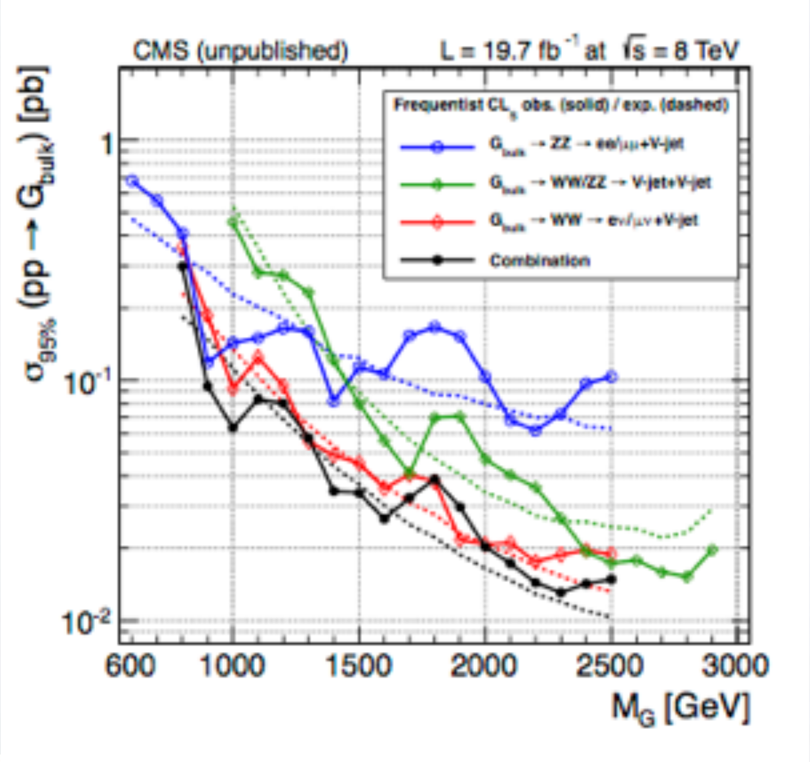




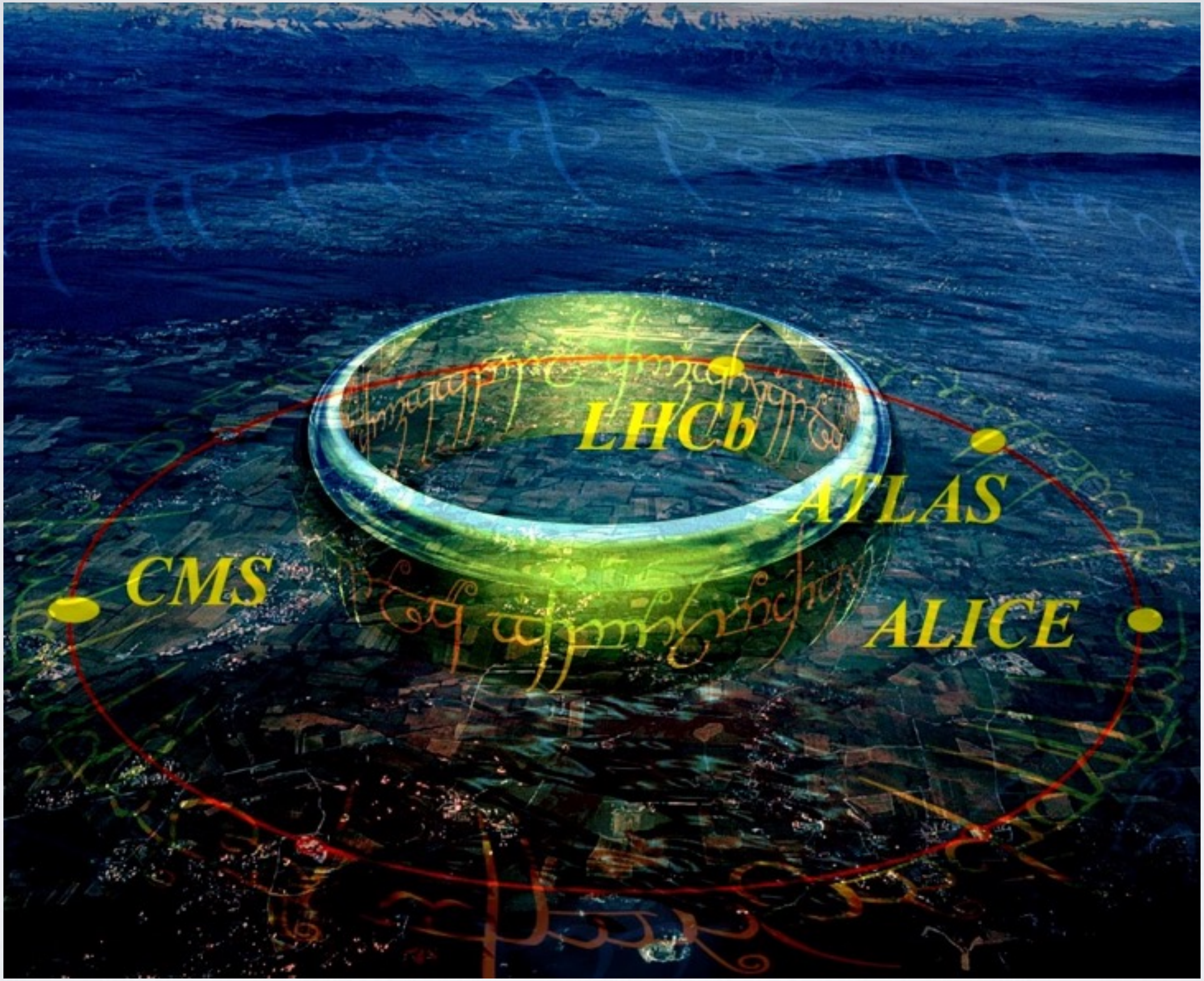
Flavour-Violating Higgs decay h(125) → μτ in ATLAS/CMS



ATLAS diboson “bump”; CMS upward fluctuation [gone for the moment @ 13 TeV]

# Conclusions and Outlook

# One Ring to Find Them … One Ring to Rule Them Out?



# … and the future comes …