7th Lisbon mini-school on Particle and Astroparticle Physics – 9th -14th May 2022

Phenomenology@LIP

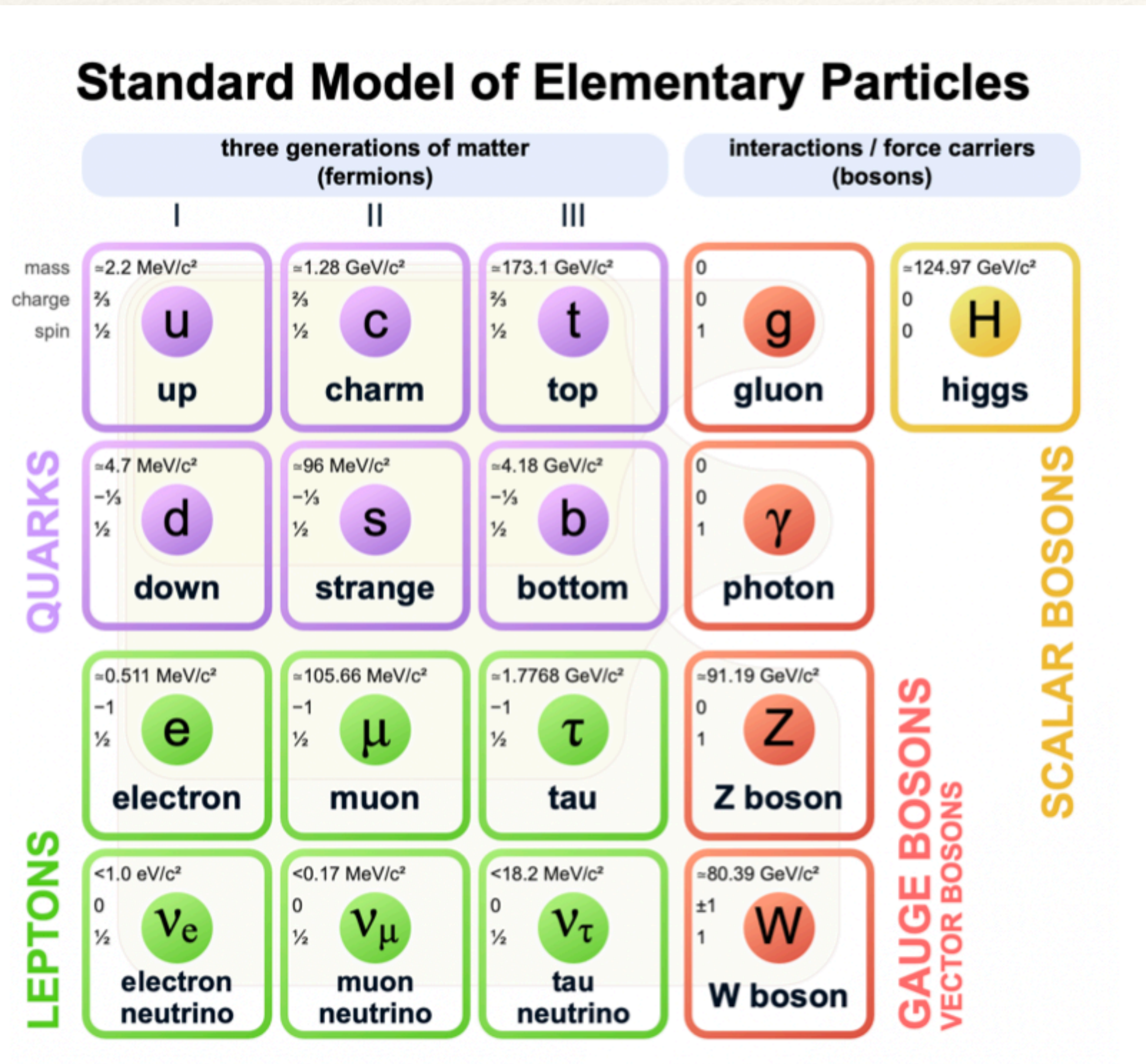
João Pires, LIP
[on behalf of the group]

What is particle physics phenomenology?

- *What are the fundamental constituents which comprise the Universe?*
- *How do they interact?*
- *What holds them together?*

The Standard Model of Particle Physics

- *Our current best answer to these questions lies in the Standard Model of Particle Physics*



- *The building blocks of matter: **6 quarks** and **6 leptons** (fermions - spin 1/2) organized in three families*
- *The mediators of the fundamental electromangetic, weak and strong interactions (bosons - spin 1)*
- *Local gauge invariance symmetry of the fundamental interactions dictates how the matter particles interact with each other via gauge bosons exchange*

- *The Higgs mechanism completes the Standard Model: predicts the masses for the electroweak gauge bosons and the existence of an elementary spin 0 scalar particle the Higgs Boson*

Particle Physics Phenomenology

- *Similarly to classical Mechanics, the Standard Model of Particle Physics has a Lagrangian formulation*

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\Psi} \not{D} \psi \\
& + D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi) \\
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Describes the kinematics of the gauge bosons

Describes **quarks** *and* **leptons** *as well as their interactions*

Describes the Higgs particle

Makes **quarks** *and* **leptons** *massive*

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Extracting theory predictions from $\mathcal{L}$ requires all aspects of modern physics

- *Special relativity*
- *Relativistic Quantum Mechanics*
- *Quantum Field Theory*

Particle Physics Phenomenology

- *Phenomenology research sits at the interface between theoretical particle physics and experiments with particle colliders*
- *A practical example: The Standard Model Higgs at the LHC*

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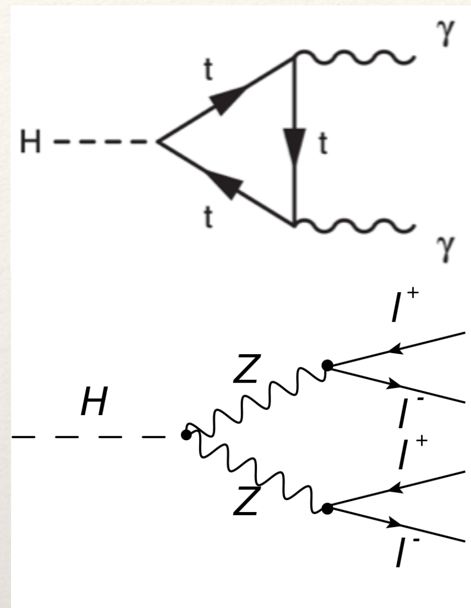

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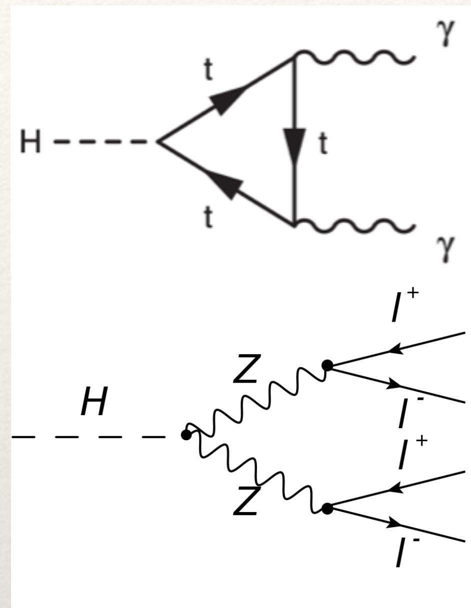

$$\Gamma(h^0 \to \gamma\gamma) = \frac{\alpha_{em}^3 m_h^3}{144\pi^2 m_W^2 \sin^2\theta_w}\Big|\sum_f Q_f^2 N_c(f) I_f(\tau_f) - I_W(\tau_W)\Big|^2$$

$$\Gamma(H \to ZZ) = \frac{1}{8\pi}\frac{M_Z^4}{M_H v^2}\left(1 - \frac{4M_Z^2}{M_H^2}\right)^{1/2}\left(3 + \frac{1}{4}\frac{M_H^4}{M_Z^4} - \frac{M_H^2}{M_Z^2}\right)$$

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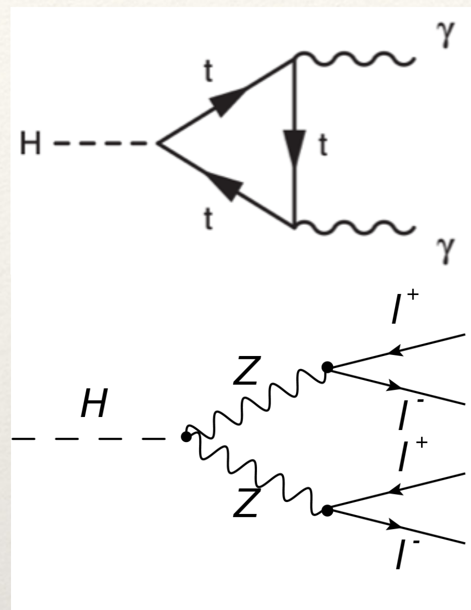

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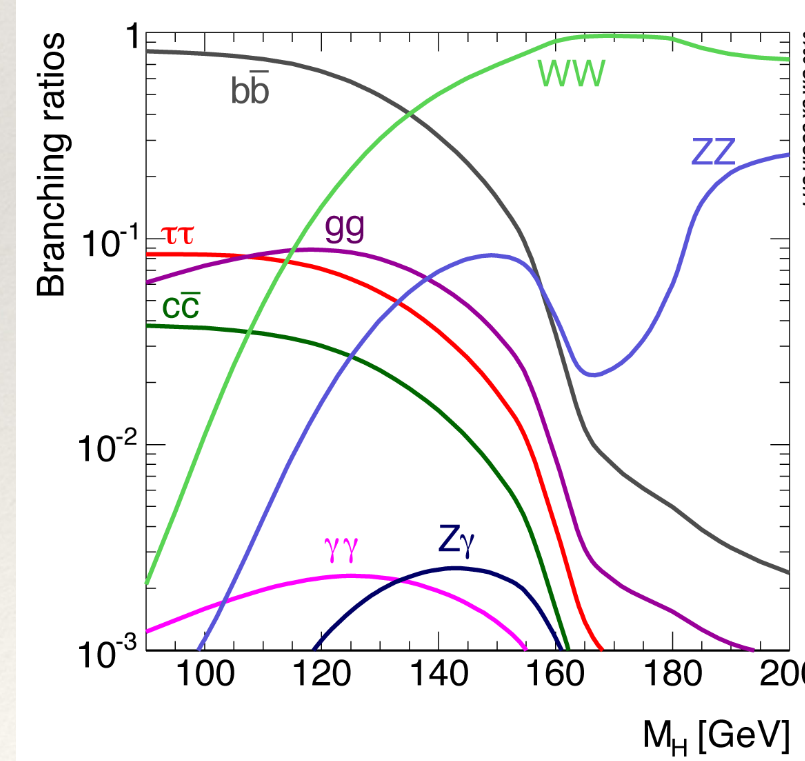

Higgs decay modes as function of M_H (Standard Model theory)

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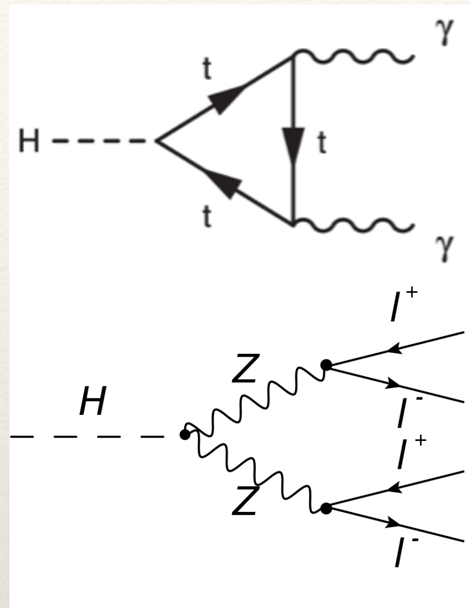

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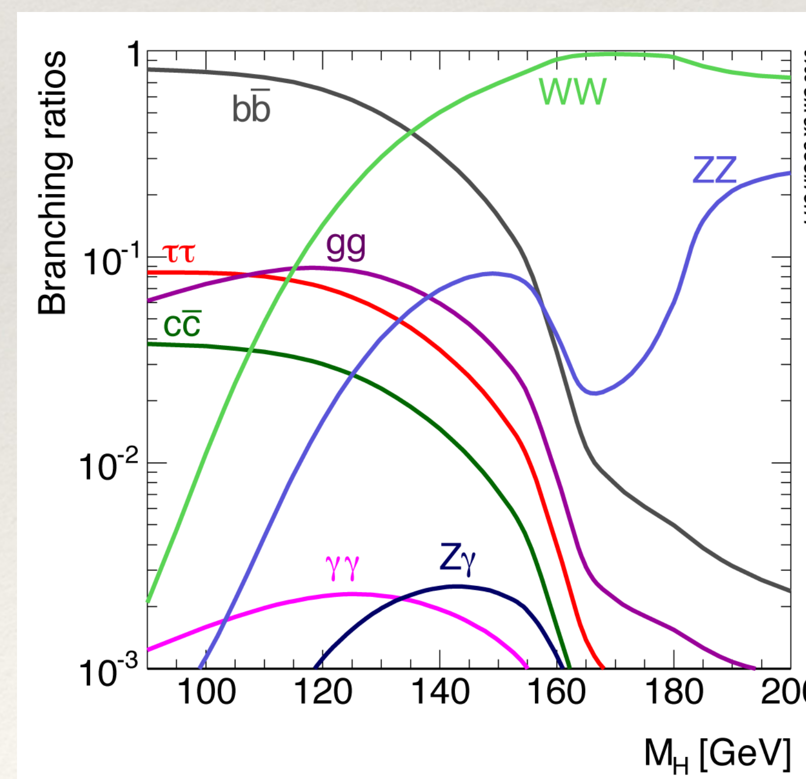

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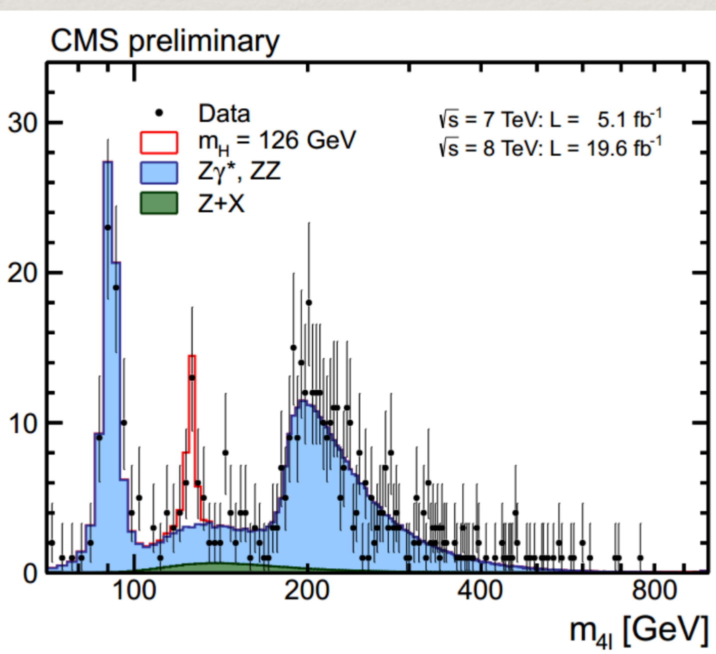
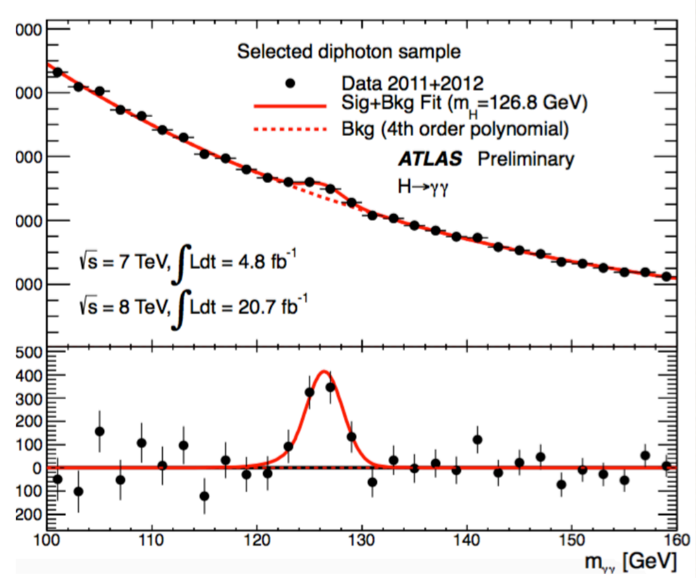


Higgs discovery plot in ZZ (CMS experiment at the LHC)



Higgs discovery plot in $\gamma\gamma$ (ATLAS experiment at the LHC)

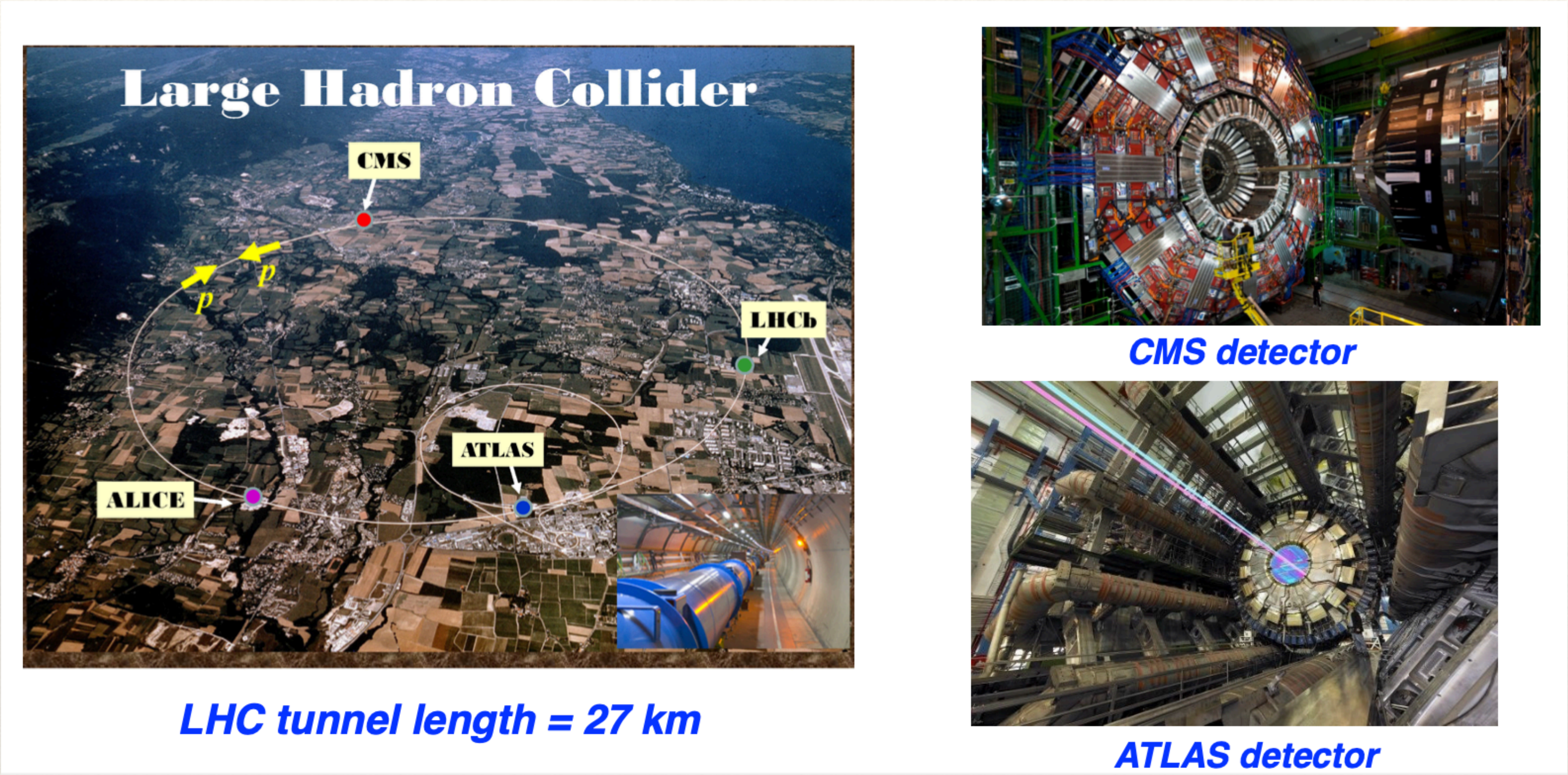
pheno@LIP :: what we do

pheno@LIP :: what we do

- SM/BSM :: observables for new Physics searches at colliders [Minho/Coimbra]
- QCD precision and automation [Lisboa]
- Quark Gluon Plasma [mostly its characterisation with jets] :: theory :: Monte Carlo simulation :: observables

- in all the above Machine Learning techniques are increasingly being used
- in all the above rely on data from the LHC particle collider and its experiments to test our results

pheno@LIP :: what we do



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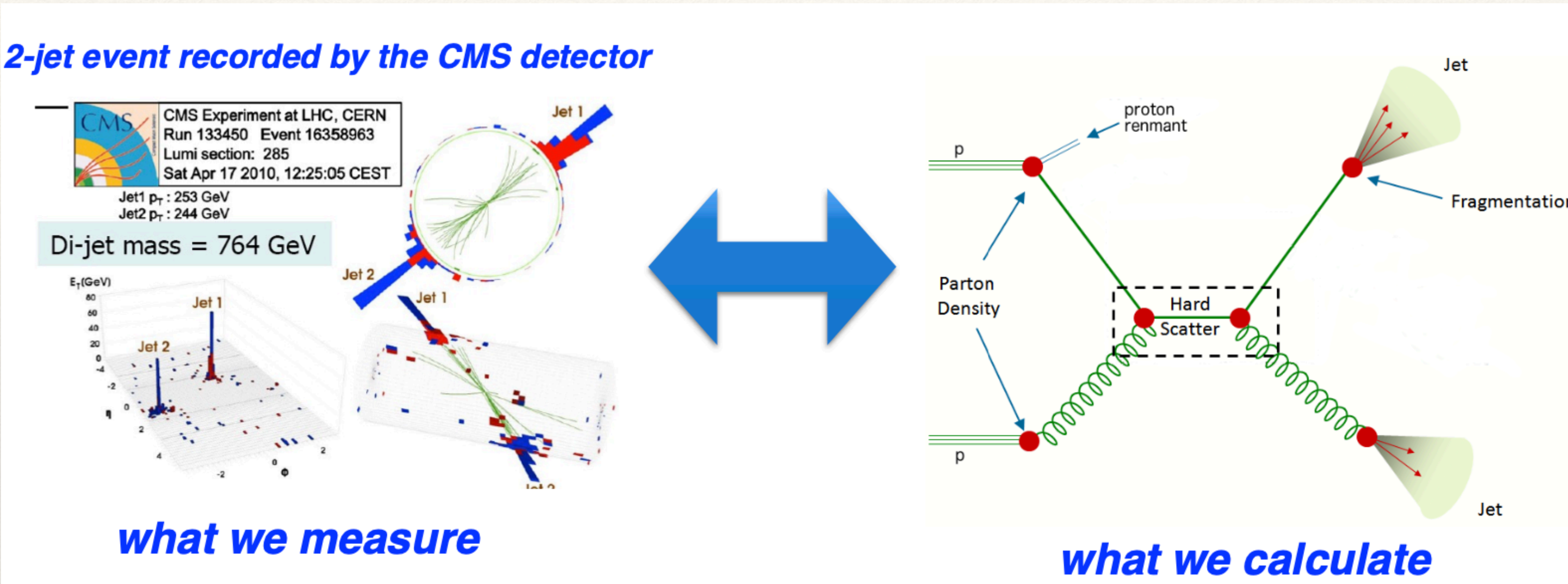
QCD phenomenology in pp-collisions at the LHC



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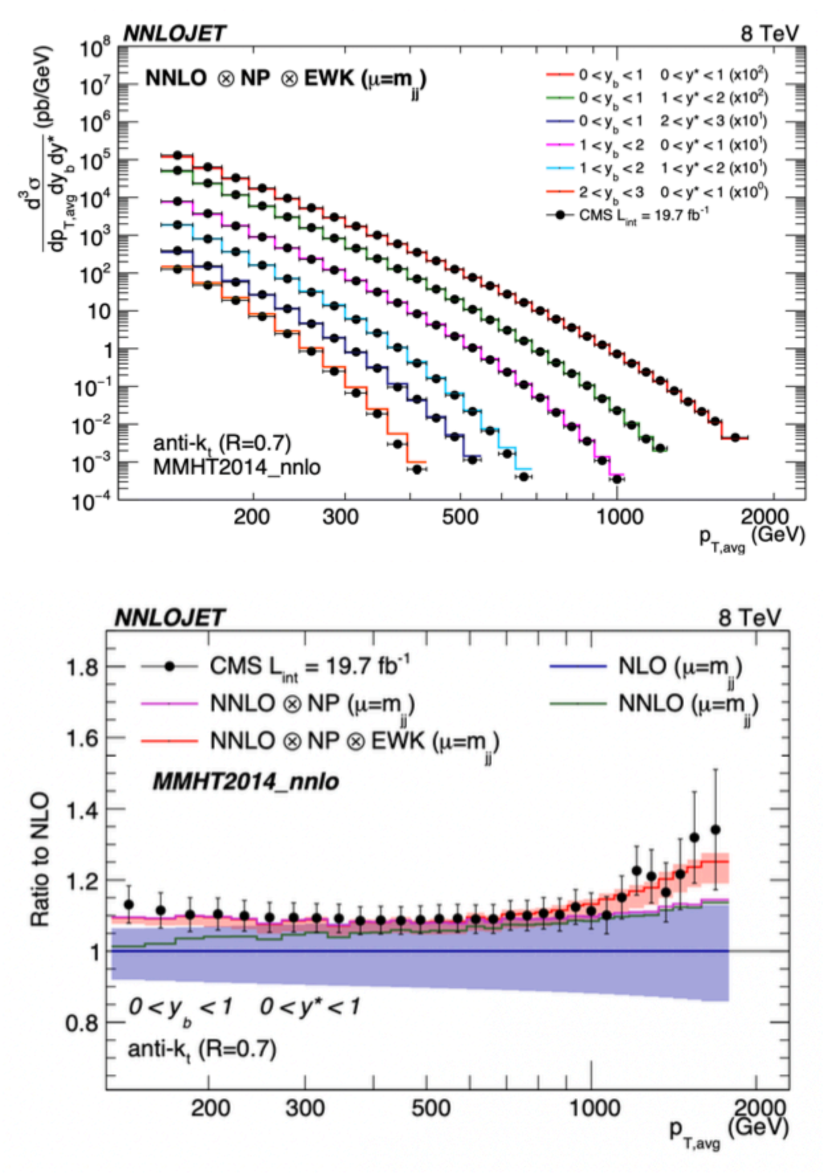

Triple differential dijet cross section at the LHC ***Phys. Rev. Lett. 123, 102001 (2019)***

- At a hadron-collider machine such as the LHC QCD radiative corrections are large and need to be computed in perturbation theory and be included in physics analysis

$$\hat{\sigma}(p_1, p_2) = \sigma_{LO}\left(1 + \frac{\alpha_s}{2\pi}\sigma_1 + \left(\frac{\alpha_s}{2\pi}\right)^2 \sigma_2 + \left(\frac{\alpha_s}{2\pi}\right)^3 \sigma_3 + \dots\right) \qquad \alpha_s(M_Z) = 0.118$$

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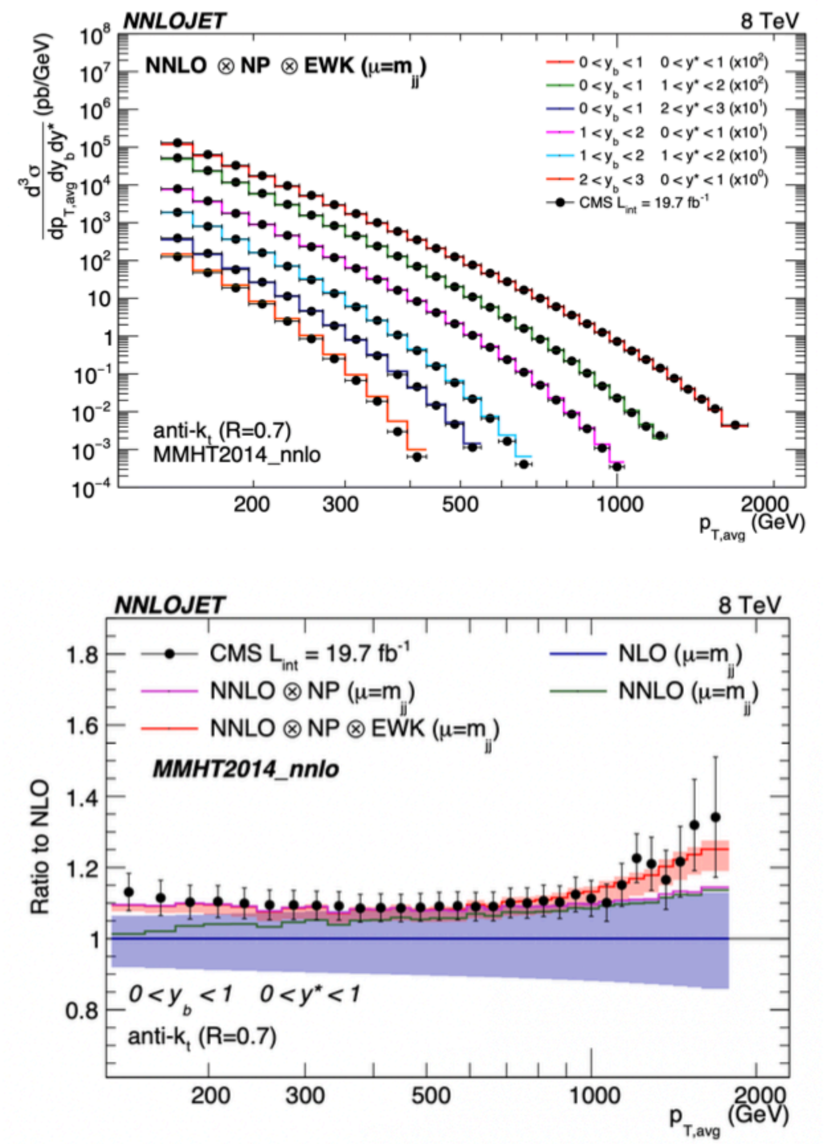

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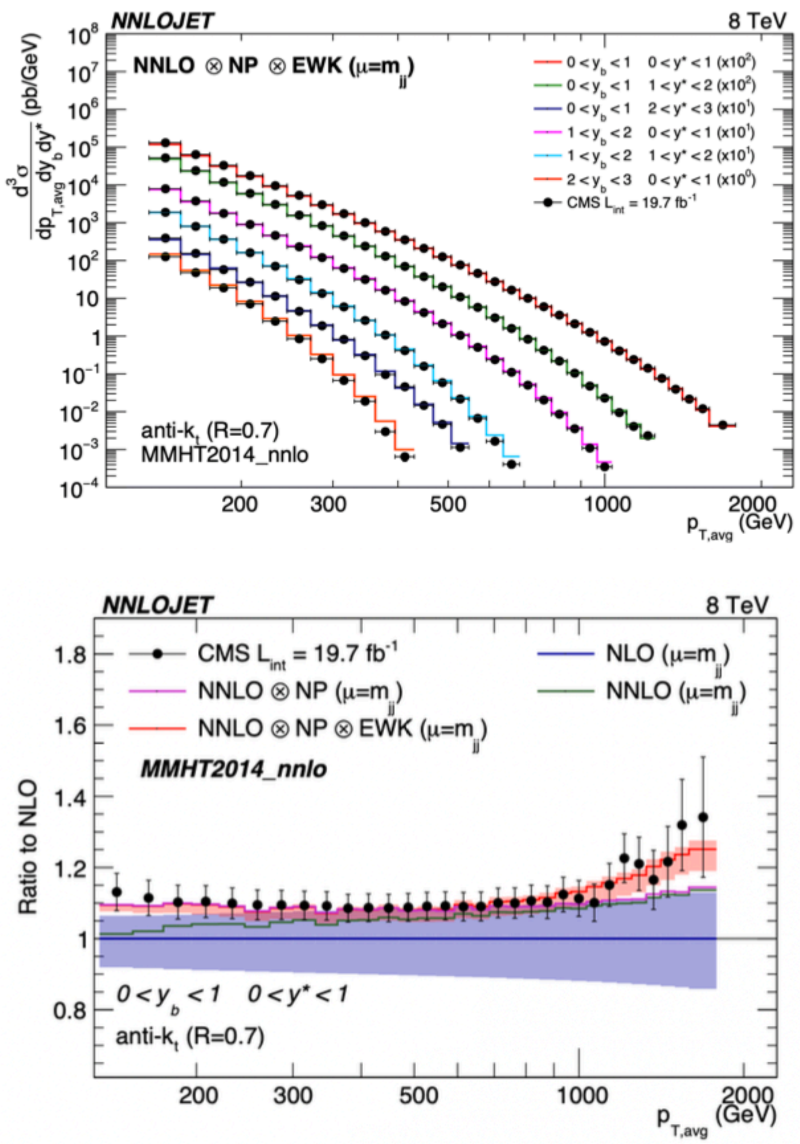
- NNLOJET: ongoing development of a Parton-level generator to compute cross sections and related observables in the Standard Model for the LHC through NNLO accuracy in the QCD perturbative expansion

QCD phenomenology in pp-collisions at the LHC

Phenomenological applications of jet data and QCD theory



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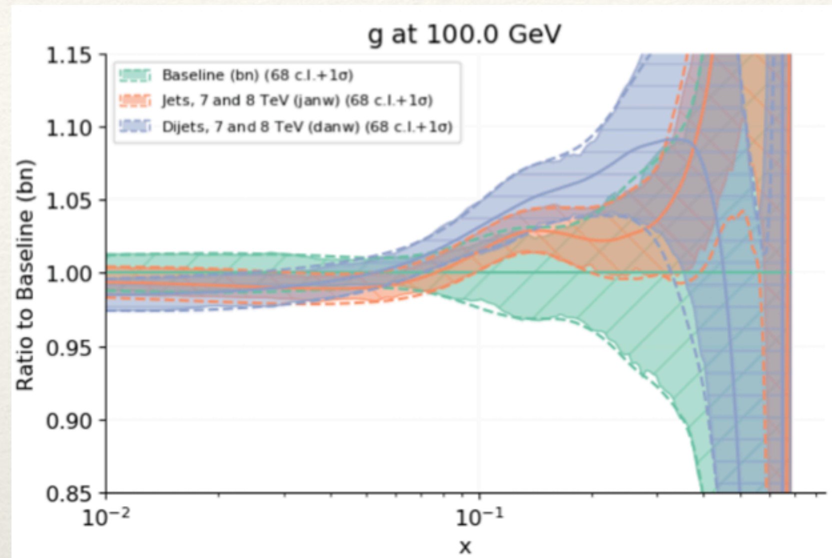
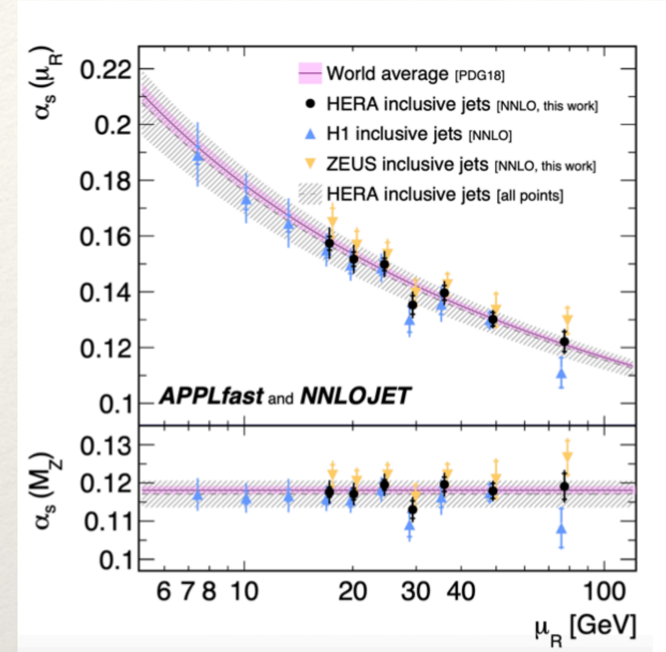


Phenomenology of NNLO jet production at the LHC and its impact on parton distributions ***Eur.Phys.J.C 80 (2020) 8, 797***

Jet data shrinks gluon-PDF uncertainties



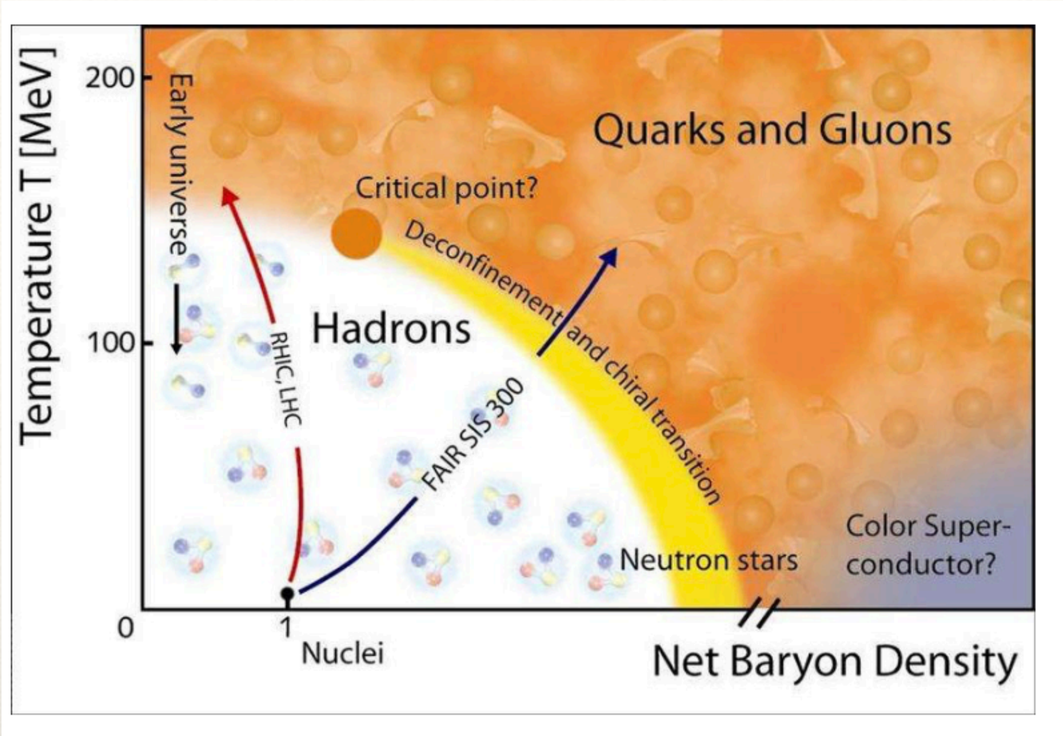
$$\alpha_s(M_Z) = 0.1178\,(15)_{\rm exp}\,(21)_{\rm th}.$$

Calculations for deep inelastic scattering using fast interpolation grid techniques at NNLO in QCD and the extraction of α_s from HERA data ***Eur.Phys.J.C 79 (2019) 10, 845***

Jet data probes the strong coupling constant behaviour at high-energies

QCD phenomenology in Heavy-ion collisions at the LHC

- Phenomenology of Heavy-Ions: why?
  - Access the high temperature and density domain of QCD: the QGP
  - In the time interval of 10^{-10}–10^{-6} s after the Big Bang, matter existed in the form of a quark–gluon plasma
  - Early conditions after the Big Bang recreated at the LHC via the collisions of an heavy-ion Pb-Pb system accelerated to $\sqrt{s}$=5.02 TeV



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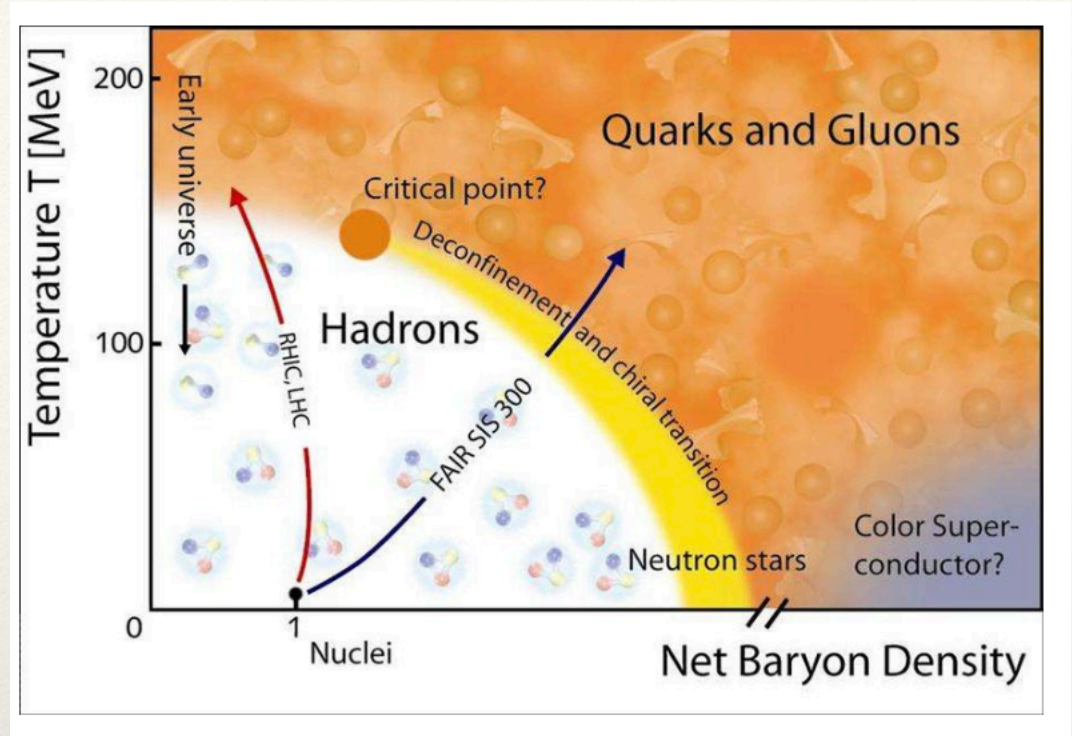

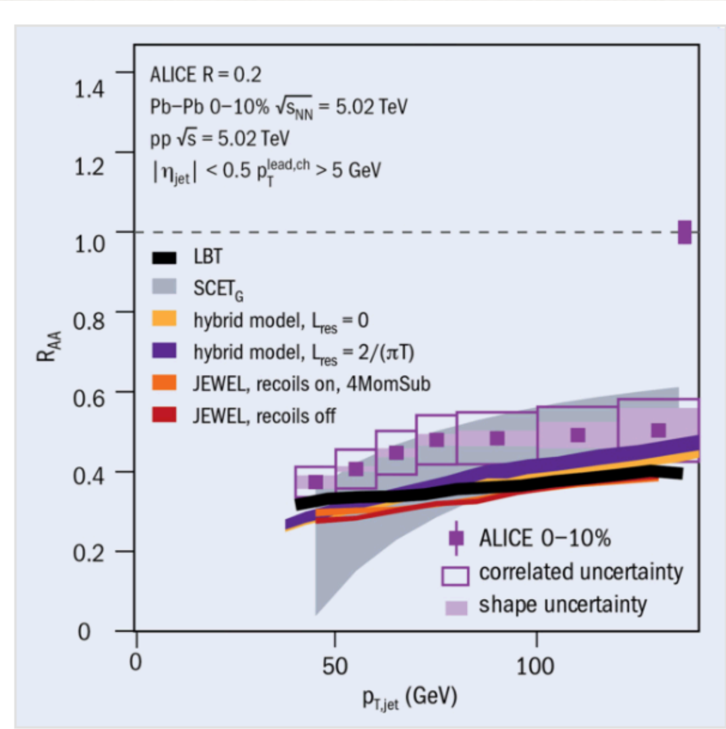

Fig. 1. The ratio of jet yields in Pb-Pb collisions relative to pp collisions (appropriately scaled) compared to four theoretical predictions. Credit: CERN

- In the presence of the quark-gluon plasma jets will loose energy as they propagate through the medium: → jet quenching
- Opportunities at the LIP phenomenology group to develop state of the art existing Monte Carlo Generators to describe the interaction of the jets with the medium and study its properties

Angular Structure of Jet Quenching Within a Hybrid Strong/Weak Coupling Model ***JHEP 03 (2017) 135***

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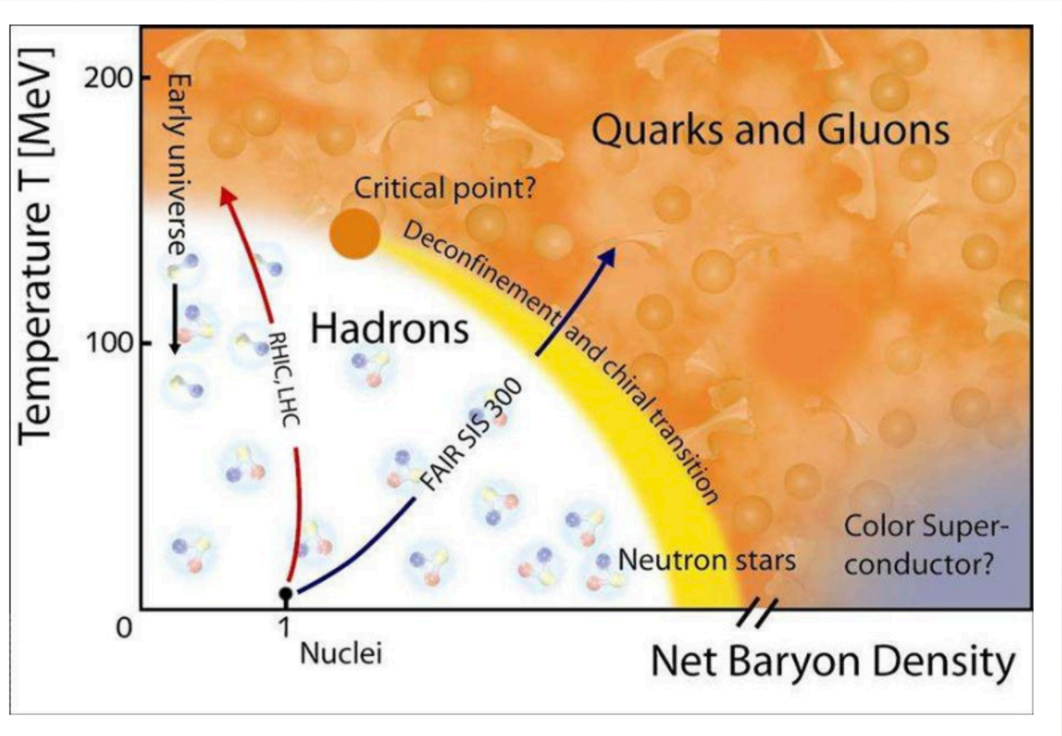

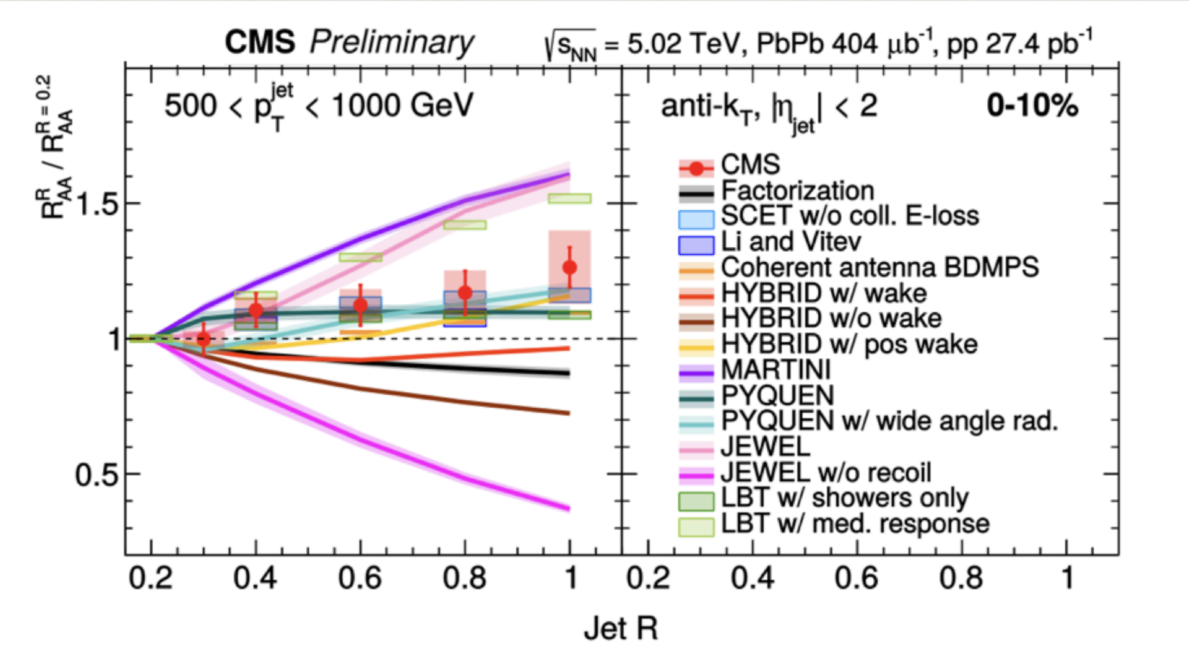

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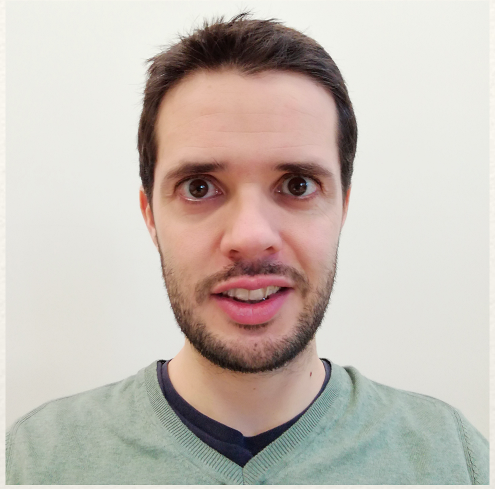
pheno@LIP :: a few of us

Guilherme Milhano [LIP-Lisboa]
Jet Physics, QGP

Liliana Apolinário [LIP-Lisboa]
Jet Physics, QGP

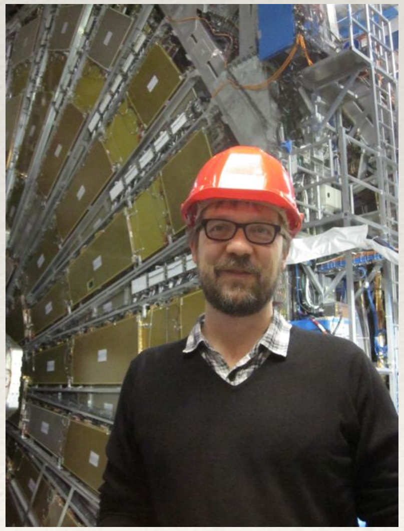


João Pires [LIP-Lisboa]
QCD precision

Grigorios Chachamis [LIP-Lisboa]
QCD precision

Nuno Castro [LIP-Minho]
SM/BSM [also ATLAS]

Miguel Romão [LIP-Minho/Lisboa]
Machine Learning, SM/BSM



Ricardo Gonçalo [LIP-Coimbra/Lisboa]
SM/BSM [also ATLAS]

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António Onofre [LIP-Minho]
SM/BSM [also ATLAS]

Ruben Conceição [LIP-Lisboa]
QGP, Cosmic Rays

Pietro Faccioli [LIP-Lisboa]
QCD quarkonium production

Pablo Rodriguez [LIP-Lisboa]
Jet Physics, QGP

pheno@LIP :: on-going PhD thesis

- 2018 - Mariana Araujo: "Quarkonium production studies at LHC energies: towards the understanding of bound-state formation by the strong force"
- 2021 - André Cordeiro: "Jetography in heavy ion collisions"
- 2021 - João Gonçalves: "Disentangling and Quantifying Jet-Quenching With Generative Deep Learning"
- 2021 - João Silva: "Towards a Yoctosecond imaging tool of the quark gluon plasma"
- 2018 - Guilherme Guedes: "Collider and astrophysical constraints to little Higgs models"

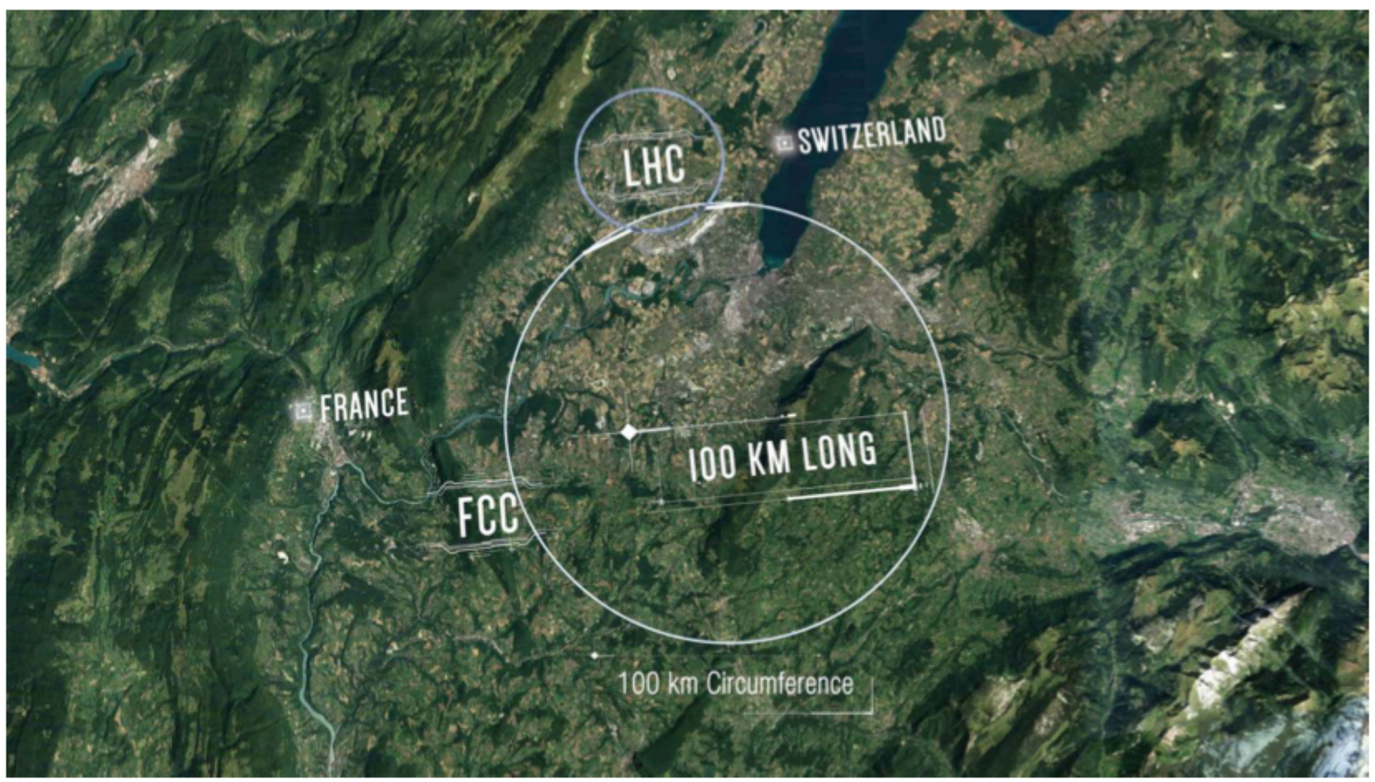
pheno@LIP :: on-going MsC thesis

- <u>2021 - João Lopes:</u> "Looking for (de)coherence effects in the Quark-Gluon Plasma"
- <u>2021 - Nuno Madureira:</u> "Jet substructure tools to identify hadronization timescales"
- <u>2021 - João Humberto Gomes:</u> "Deep Learning in QCD Jets"
- <u>2021 - Francisco Barreiro:</u> "Geometrical aspects of Jet Quenching in small systems"
- <u>2021 - Tomás Cabrito:</u> "The soft-hard antenna spectrum in presence of a QGP"
- <u>2022 - Lénea Luís:</u> "Deciphering Jet Quenching effects through a Quantile Ratio"
- <u>2021 - Manuel Mariano:</u> "Sensitivity of jet substructure observables to jet quenching in collisions of light nuclei"

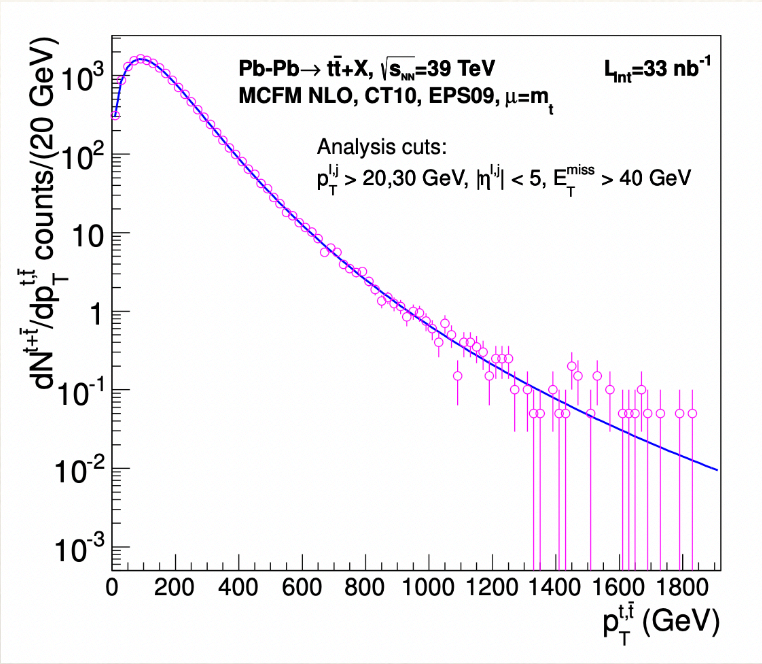
BACKUP Slides

The Future Circular Collider project FCC

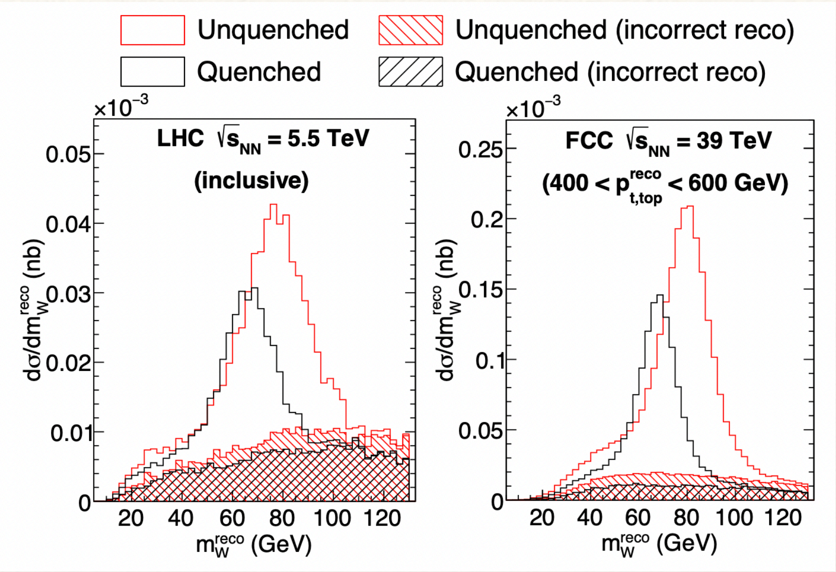
- Proposal by CERN for a future collider after the LHC
- A 100km long circumference ring to accelerate particles to higher energies than ever achieved before

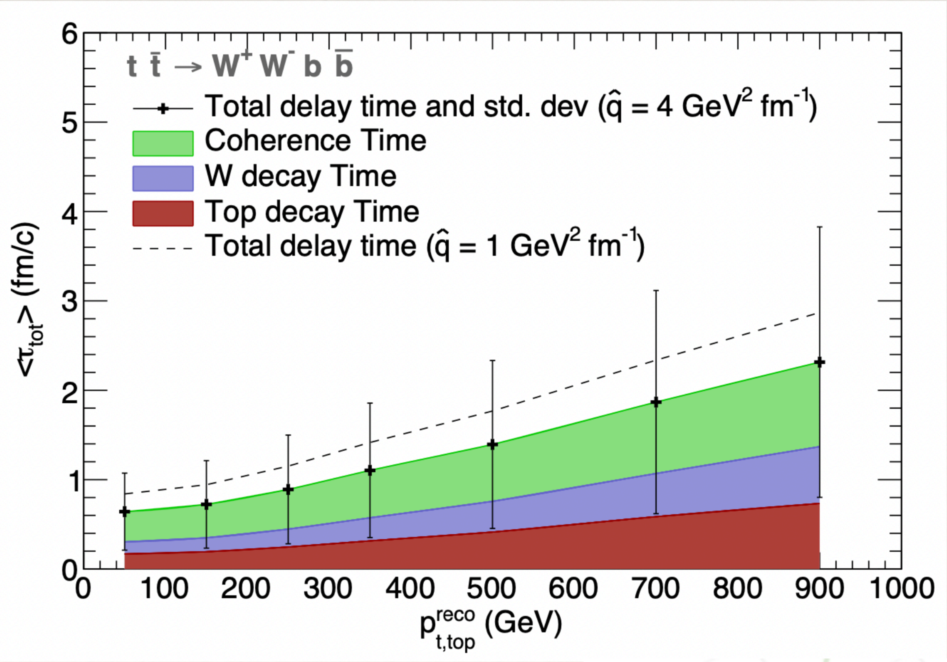


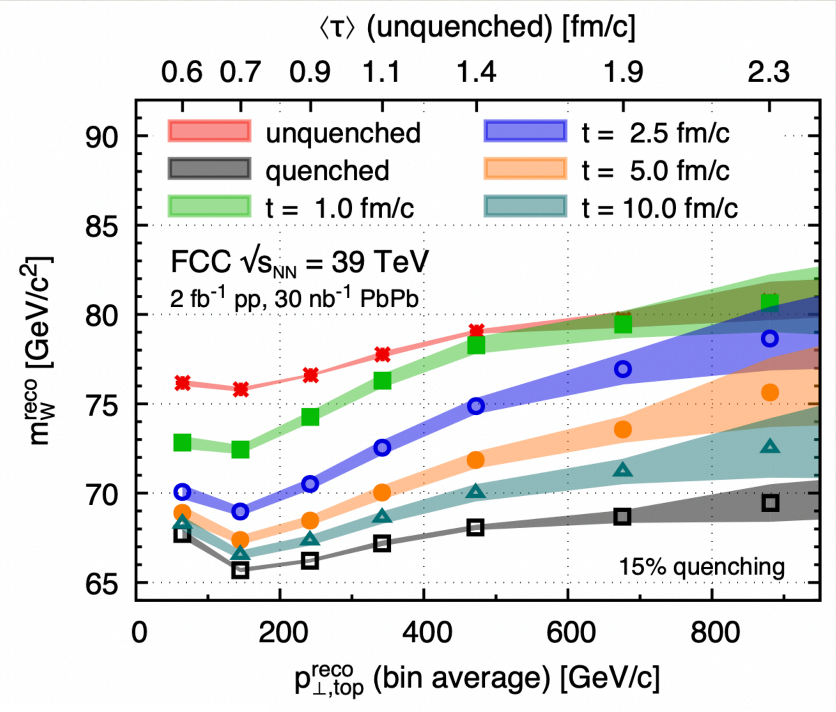
Physics of the quark-gluon plasma at the Future Circular Collider



- Large rate for top quark-pair production at the FCC
- $p_{t,top}$ proxy for total delay time for hadronic W decay products start interacting with the medium
- Reconstructed M_W distribution sensitive to quenching effects
- Boosted top quarks give access to the time profile evolution of the quak-gluon plasma







Probing the time structure of the quark-gluon plasma with top quarks

Liliana Apolinário,[1,2] José Guilherme Milhano,[1,2,3] Gavin P. Salam,[3,*] and Carlos A. Salgado[4]