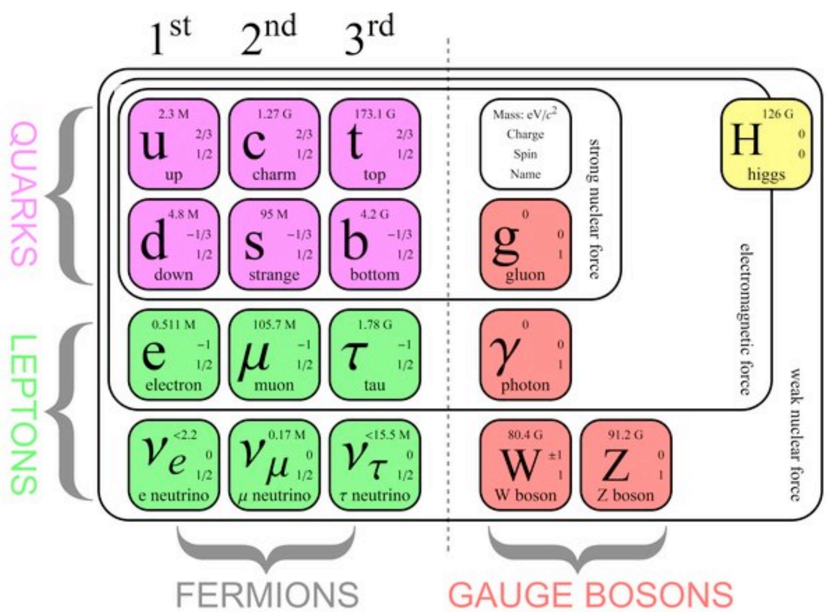
Research Opportunities at LIP's Phenomenology Group

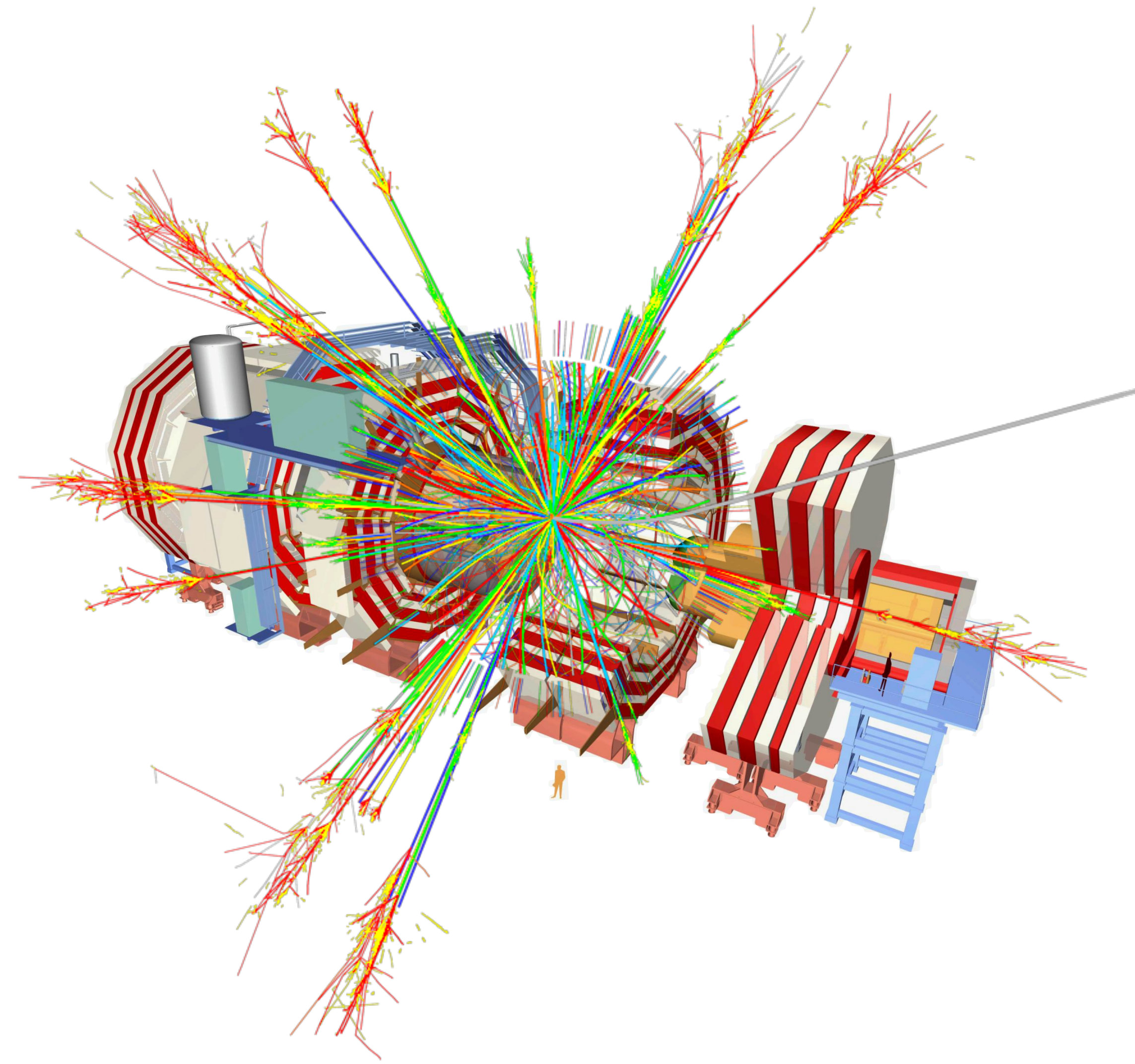
9th mini-school on Particle and Astroparticle Physics, Oeiras 5-6 February, 2024

Pablo Guerrero Rodríguez (on behalf of the LIP Pheno Group)

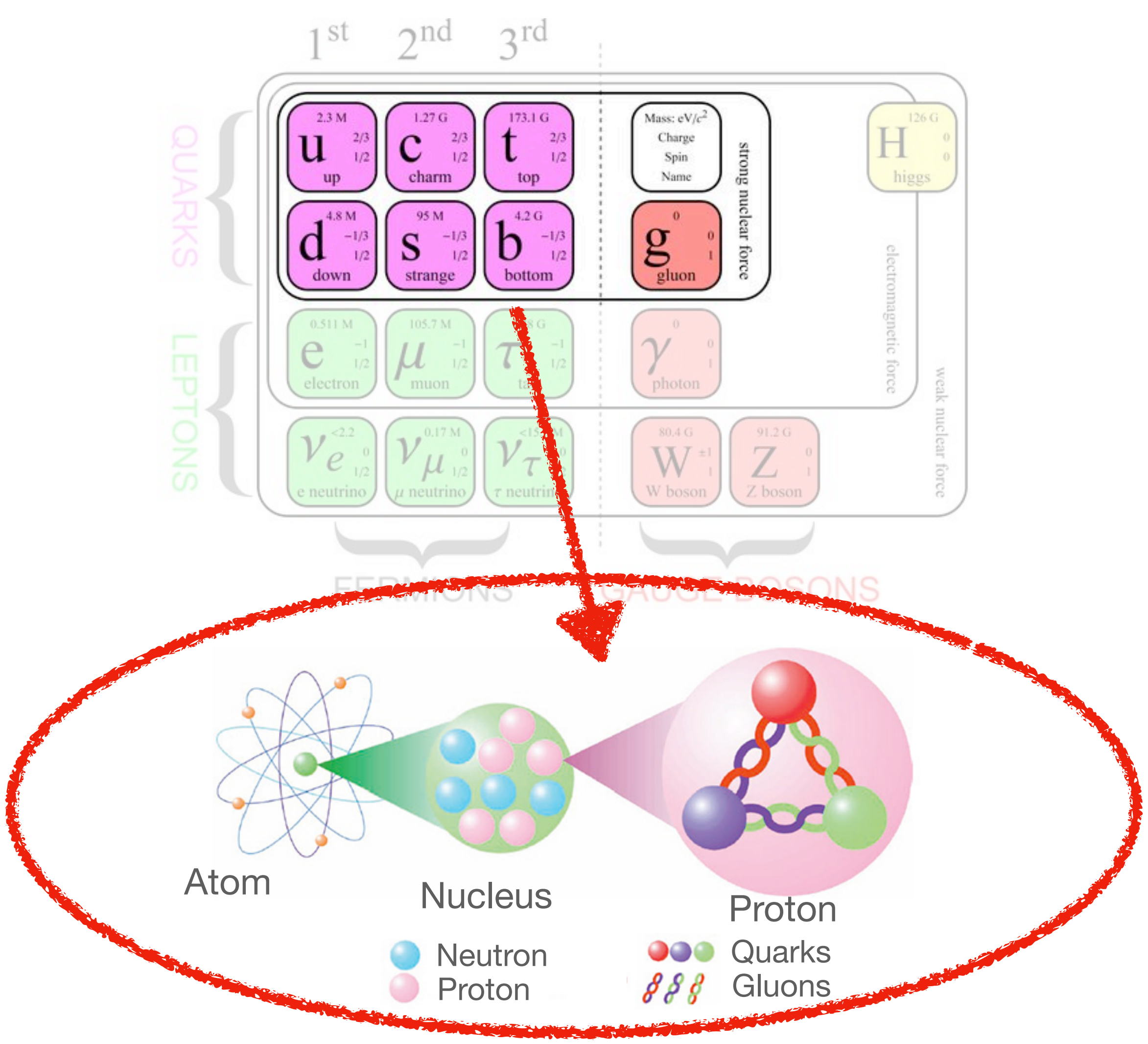
Phenomenology in a nutshell:



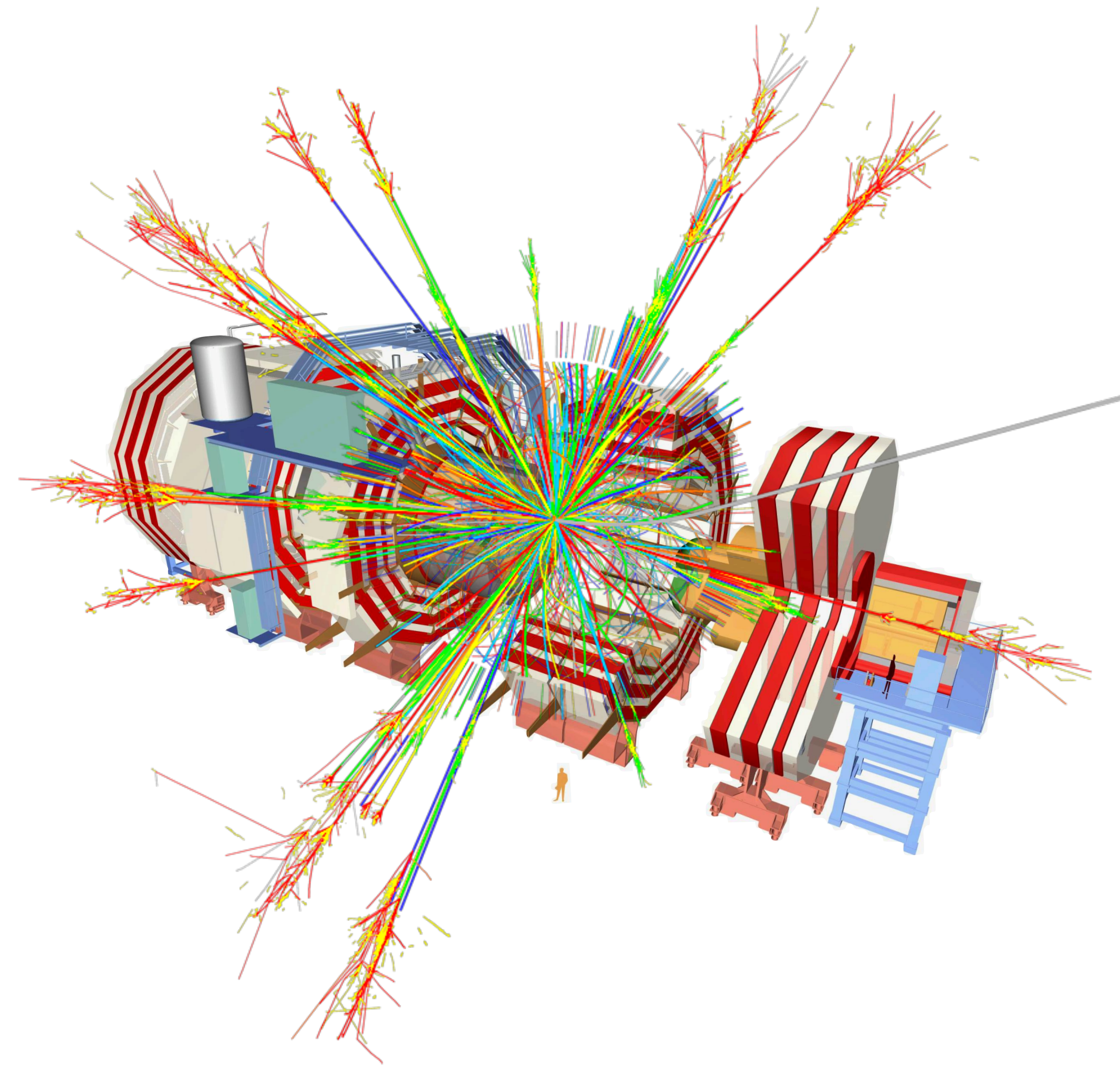
vs.



QCD Phenomenology in a nutshell:

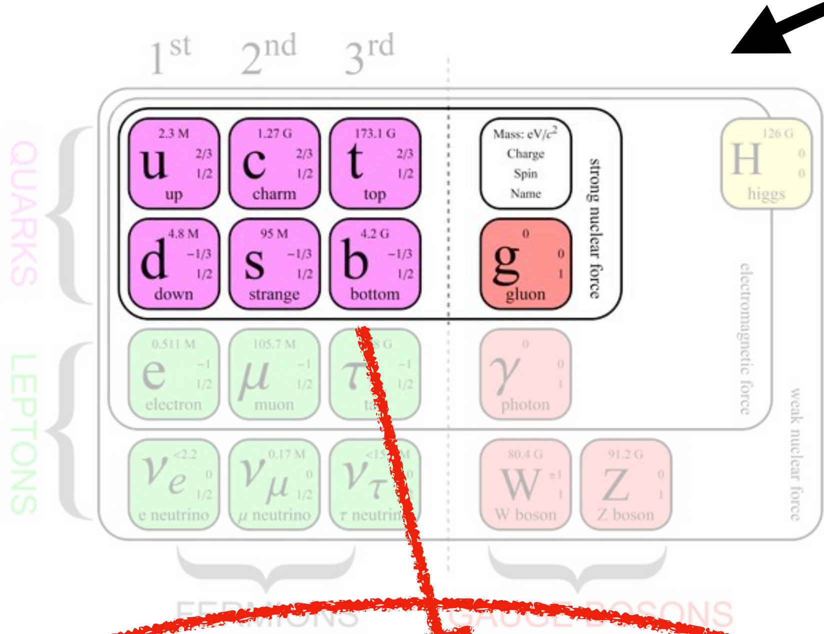


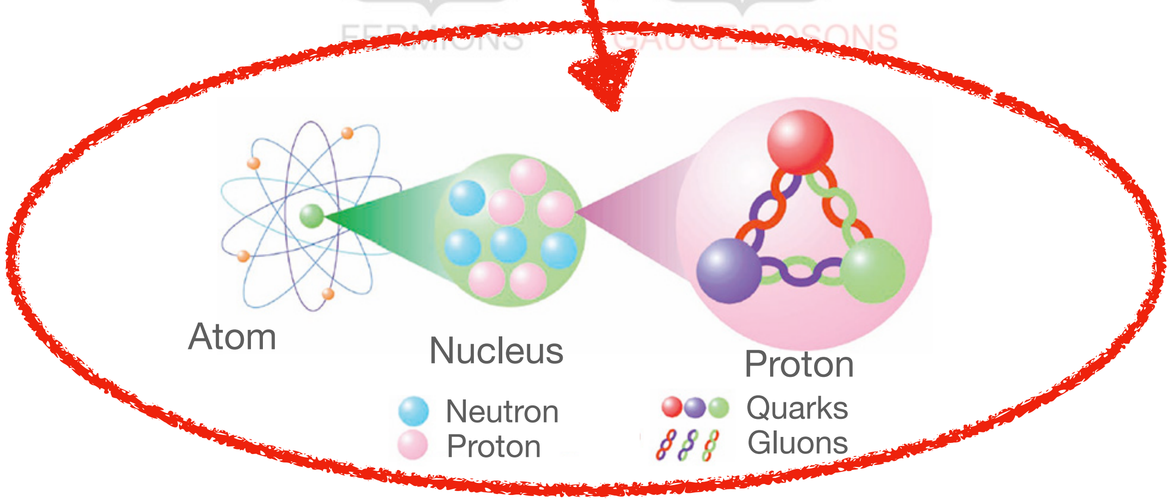
vs.



QCD Phenomenology in a nutshell:

The experiment motivates the theory





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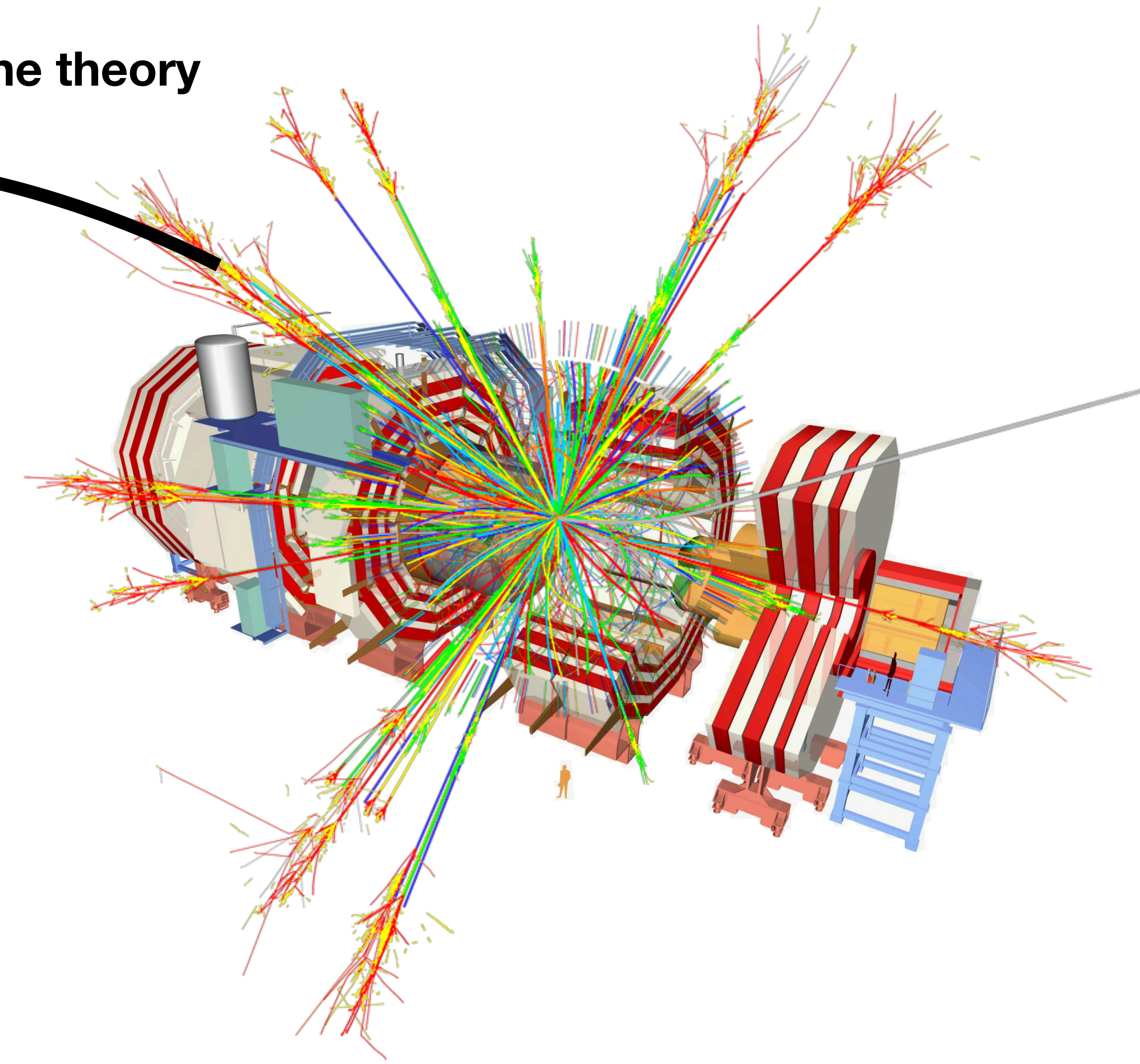

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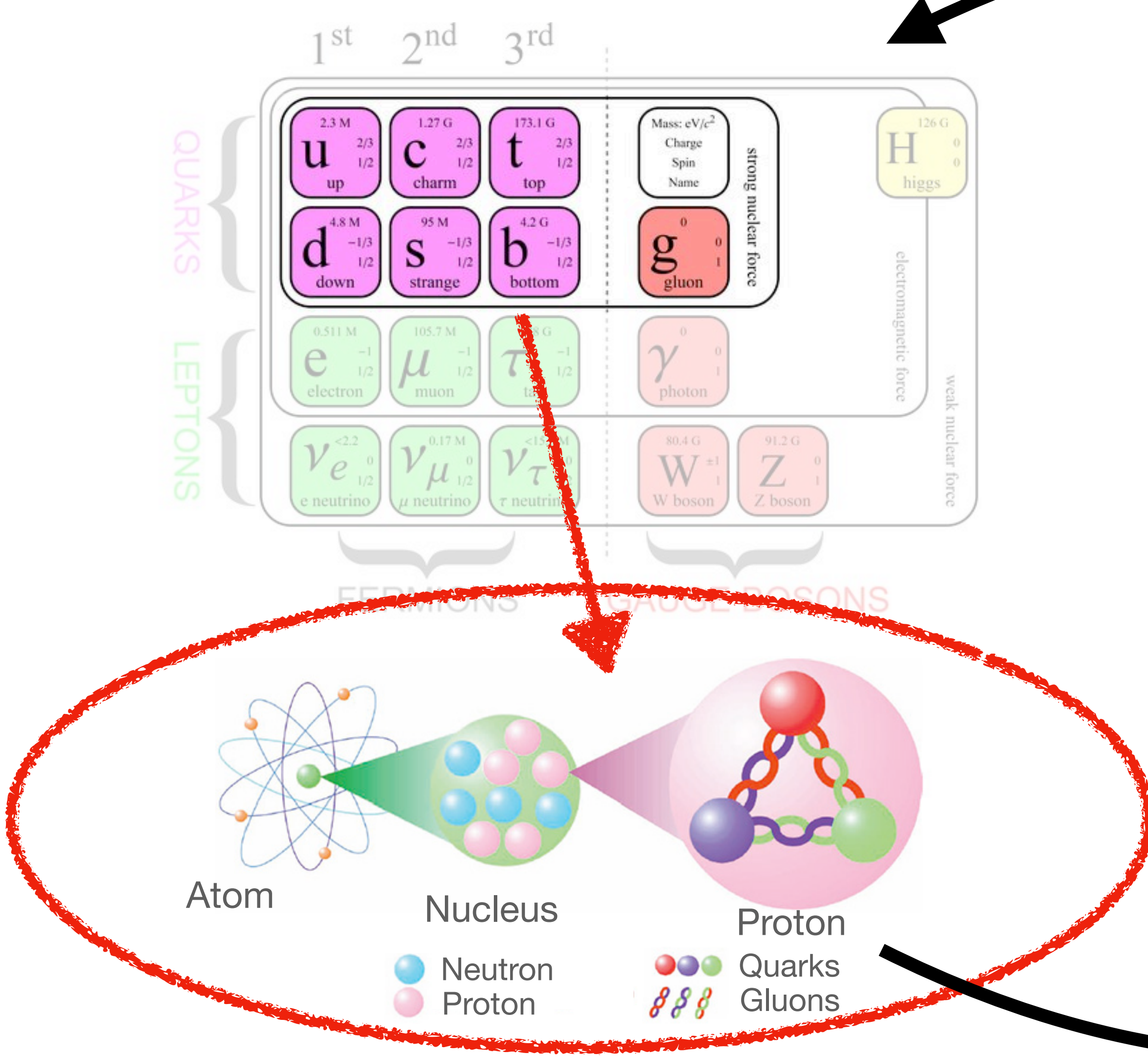

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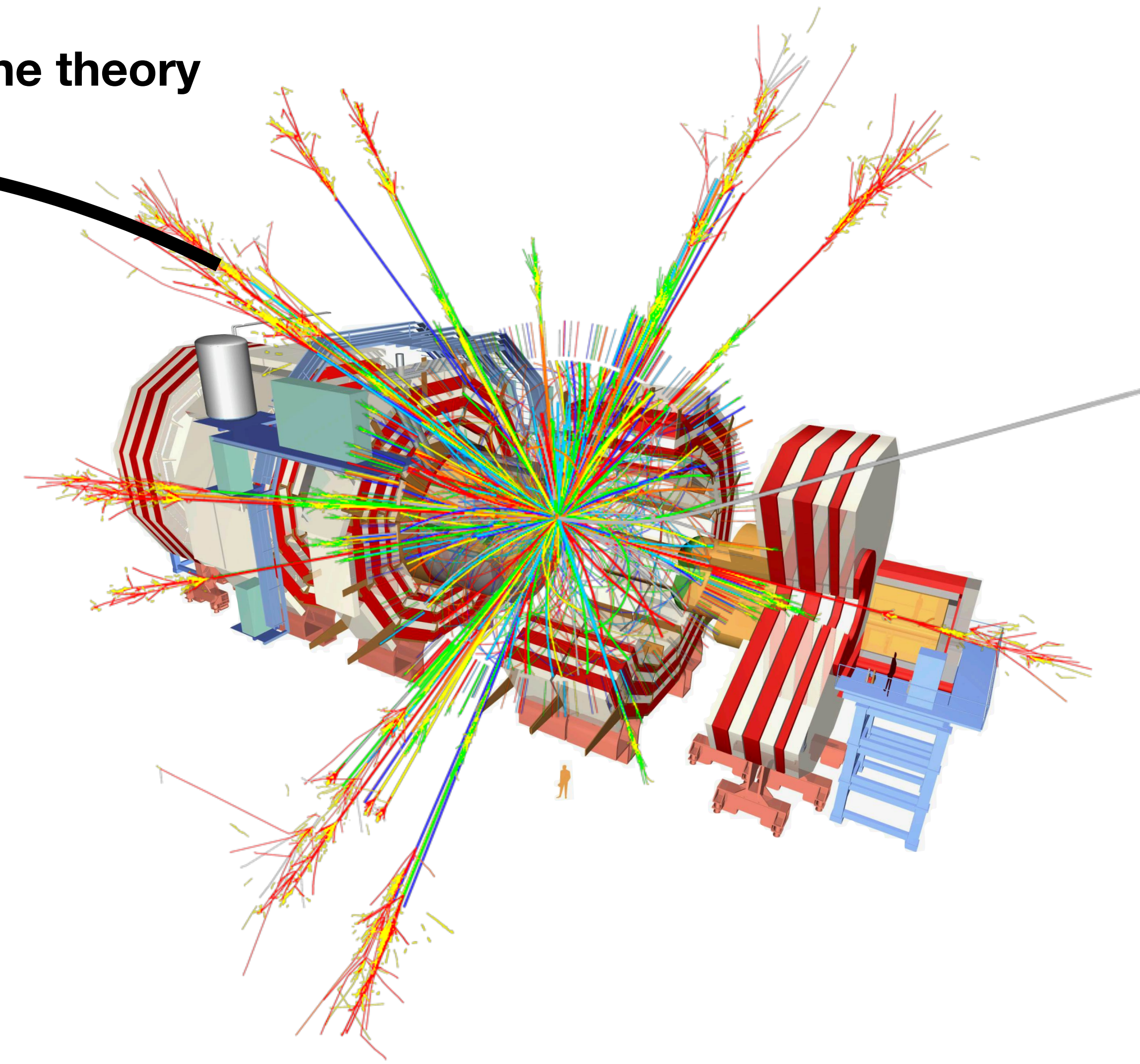
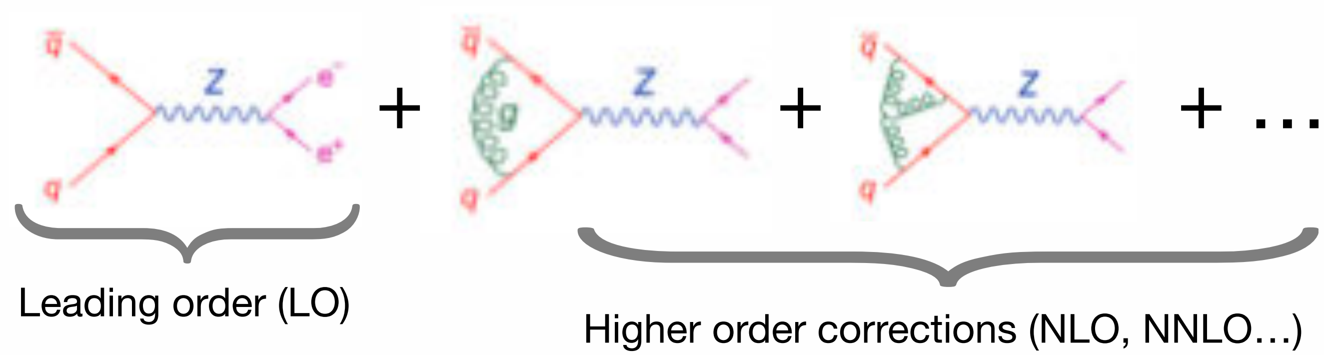


The theory proposes an experiment

Research activity at Pheno@LIP

- Precision QCD

$$\hat{\sigma} = \sigma_{LO} \left(1 + \frac{\alpha_s}{2\pi} \sigma_1 + \left(\frac{\alpha_s}{2\pi} \right)^2 \sigma_2 + \left(\frac{\alpha_s}{2\pi} \right)^3 \sigma_3 + \ldots \right)$$



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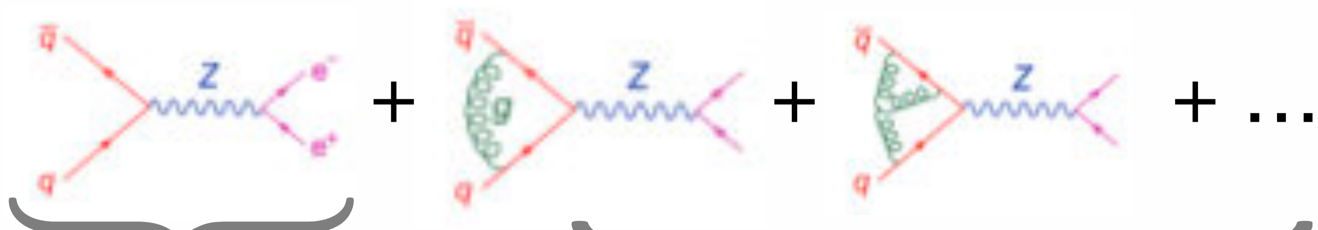
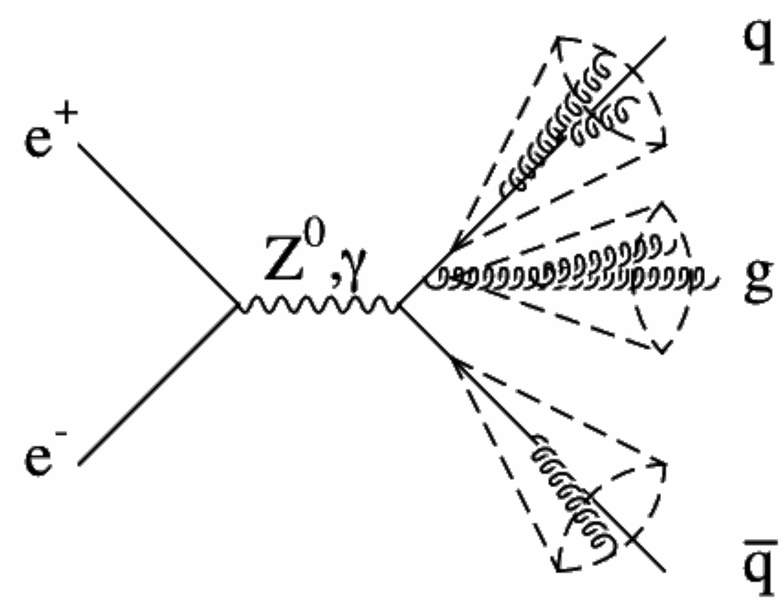


Leading order (LO)

Higher order corrections (NLO, NNLO…)

2022 - Joana Reis: "Implementation of quark mass effects in QCD three-jet production observables produced by hadronic decays of the Z-boson at FCC-ee collider"



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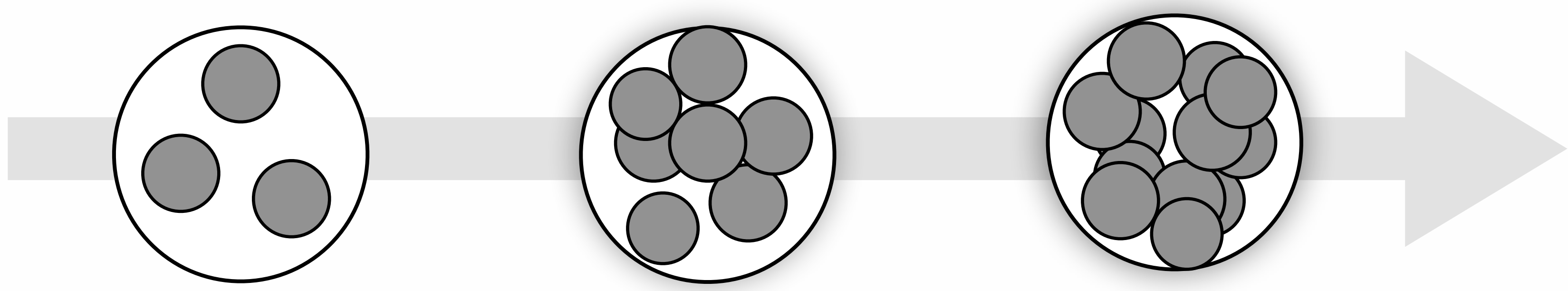
- High energy limit of QCD resummation



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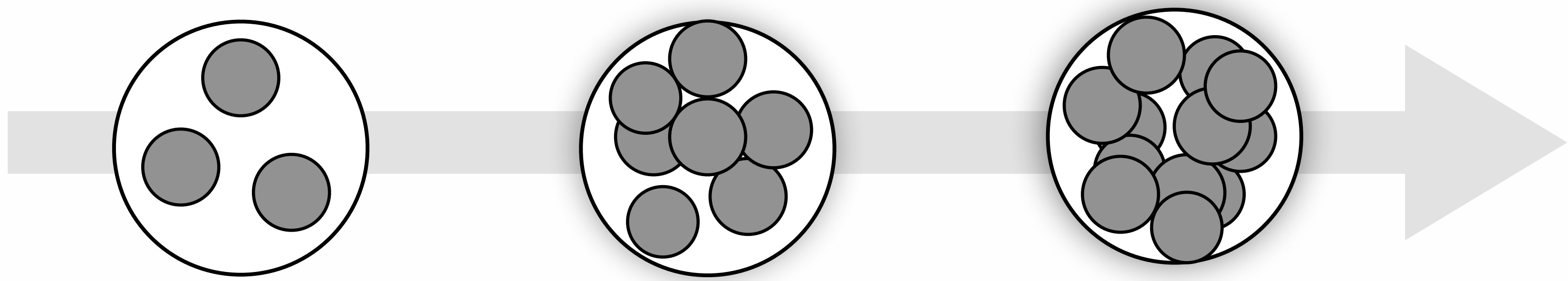
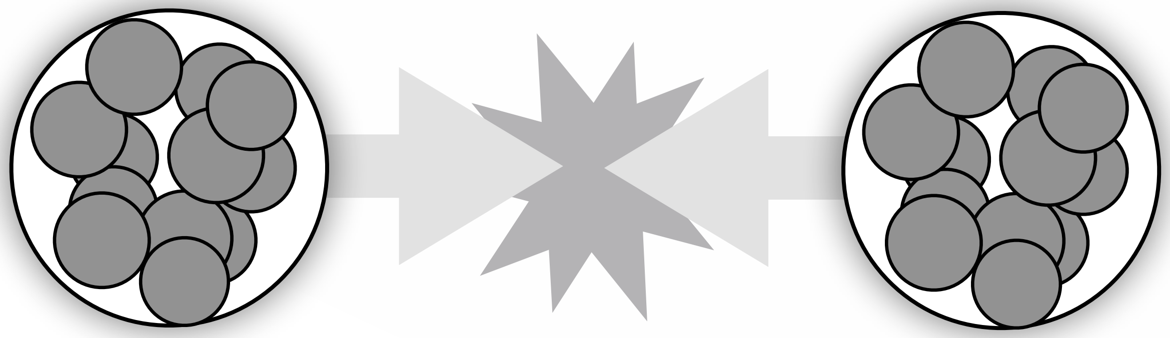
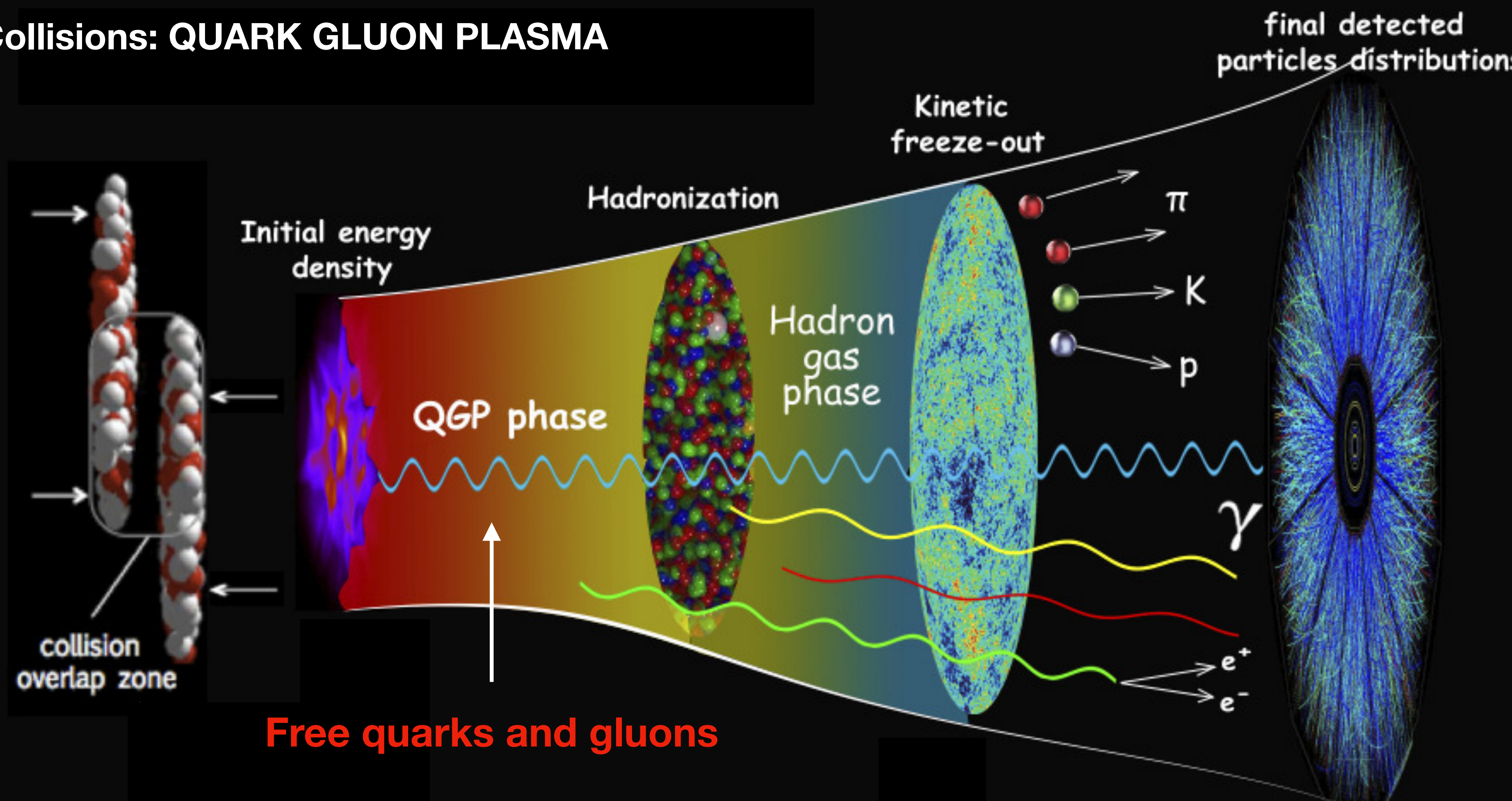


- Heavy ion collisions



Heavy Ion Collisions: QUARK GLUON PLASMA



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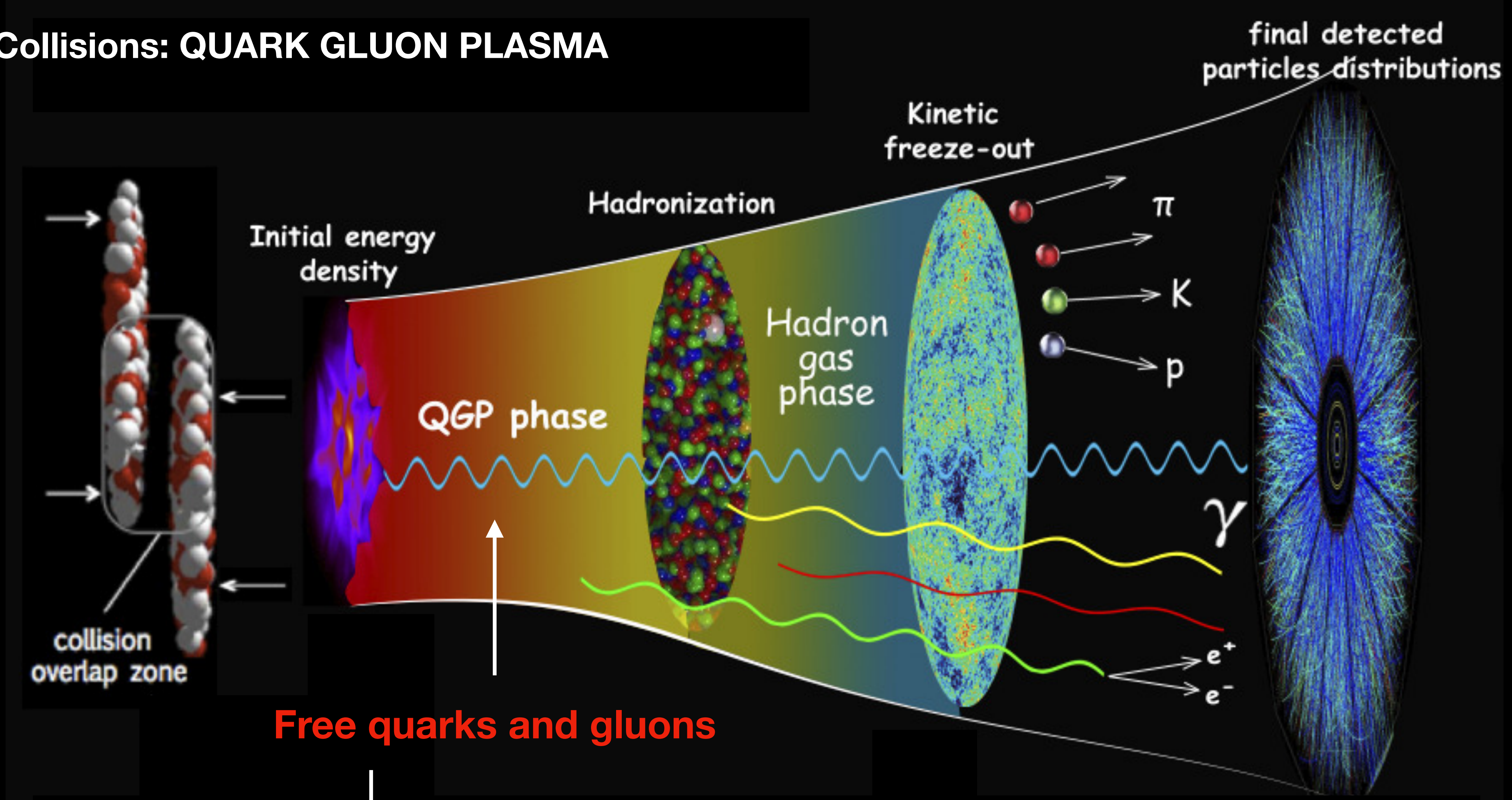
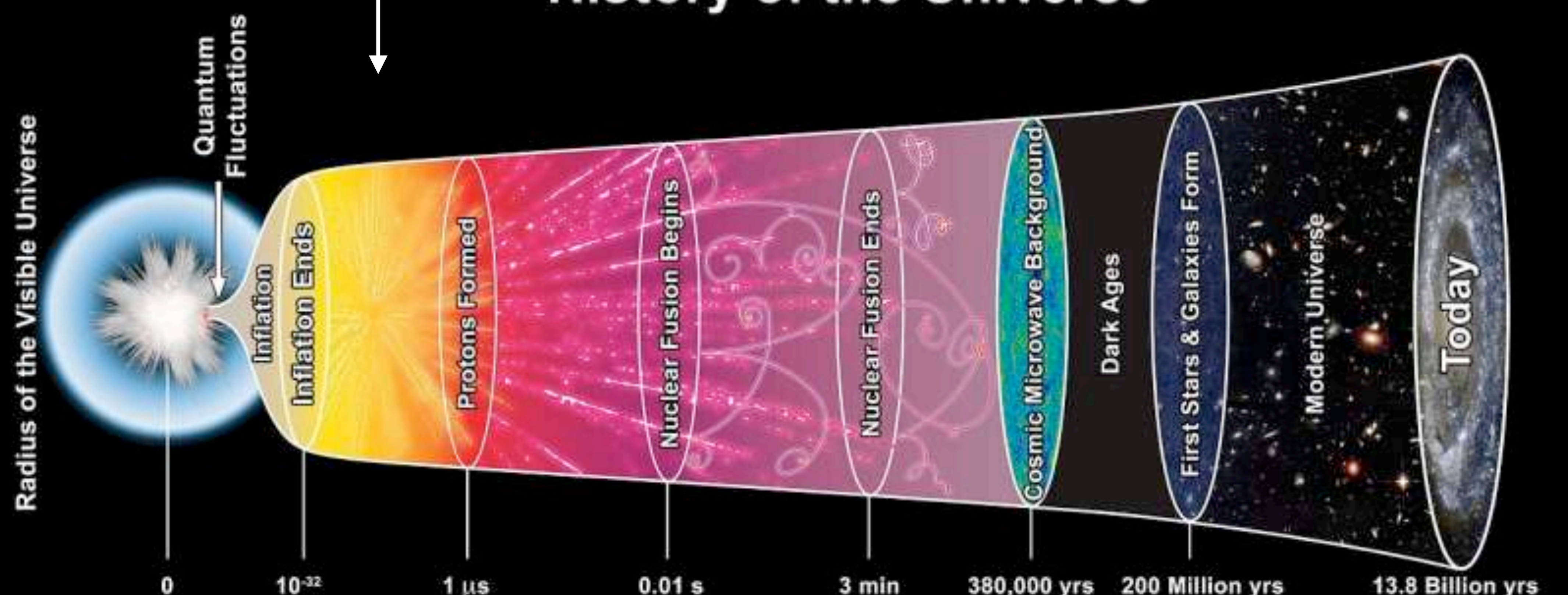
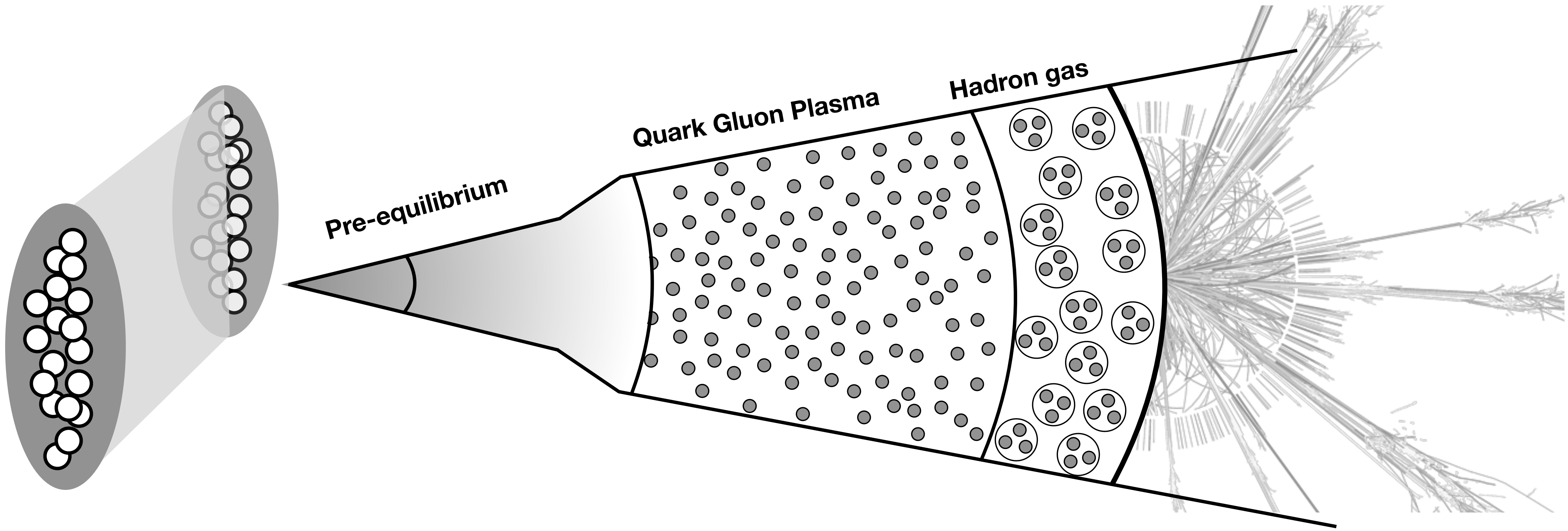


History of the Universe

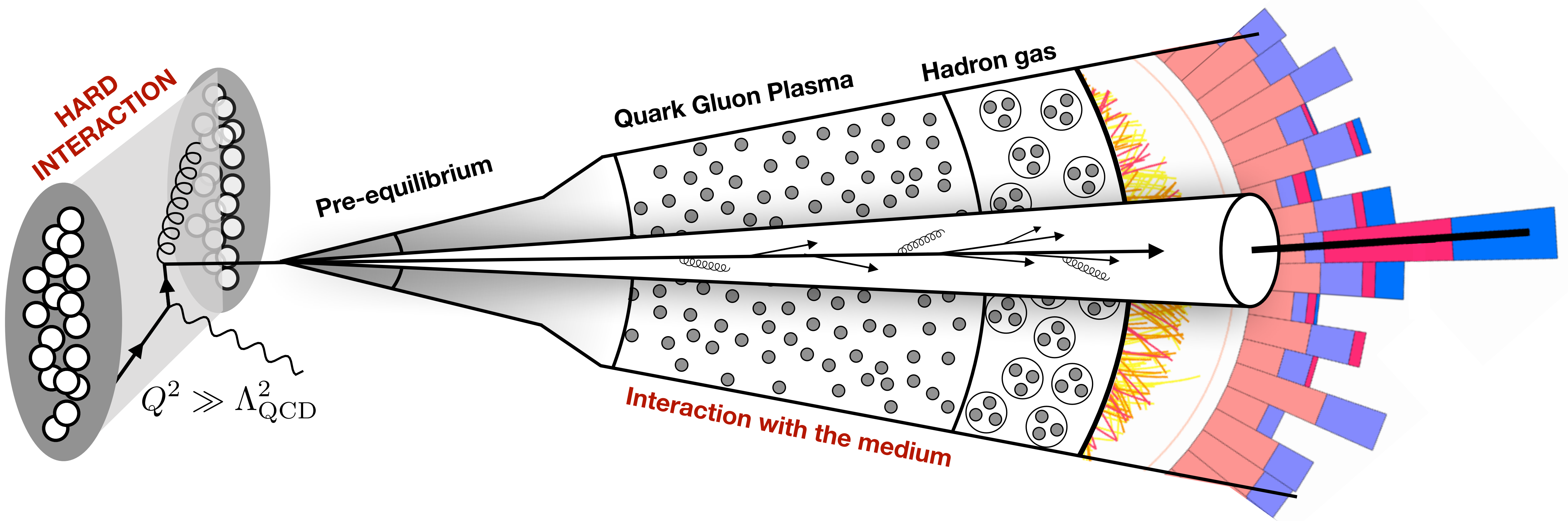


How do we study the QGP?



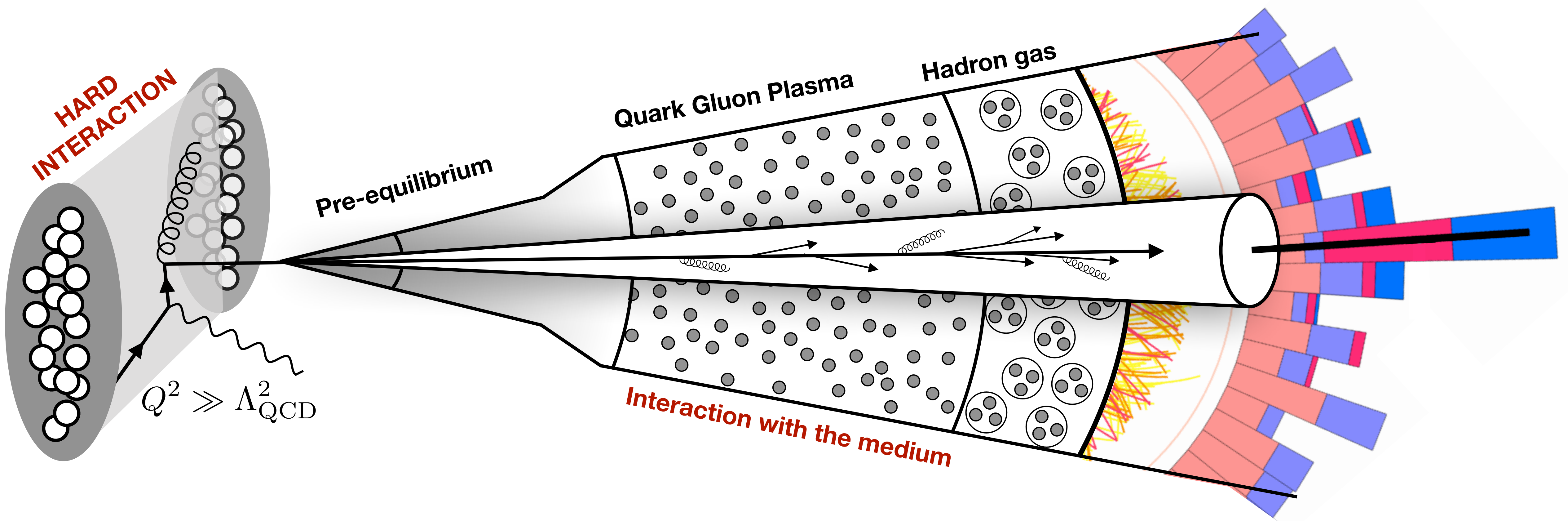
How do we study the QGP?

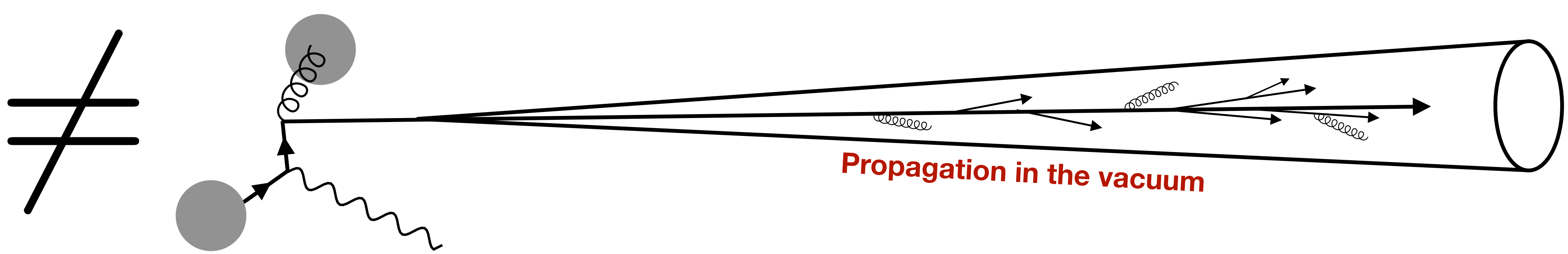
- **Jets** are produced very early in the collision, interacting with the QGP **during its entire lifetime**



How do we study the QGP?

- **Jets** are produced very early in the collision, interacting with the QGP **during its entire lifetime**
- Jets in HICs are modified with respect to the pp reference (**Jet Quenching**)





- **These modifications allow us to learn about the QGP**

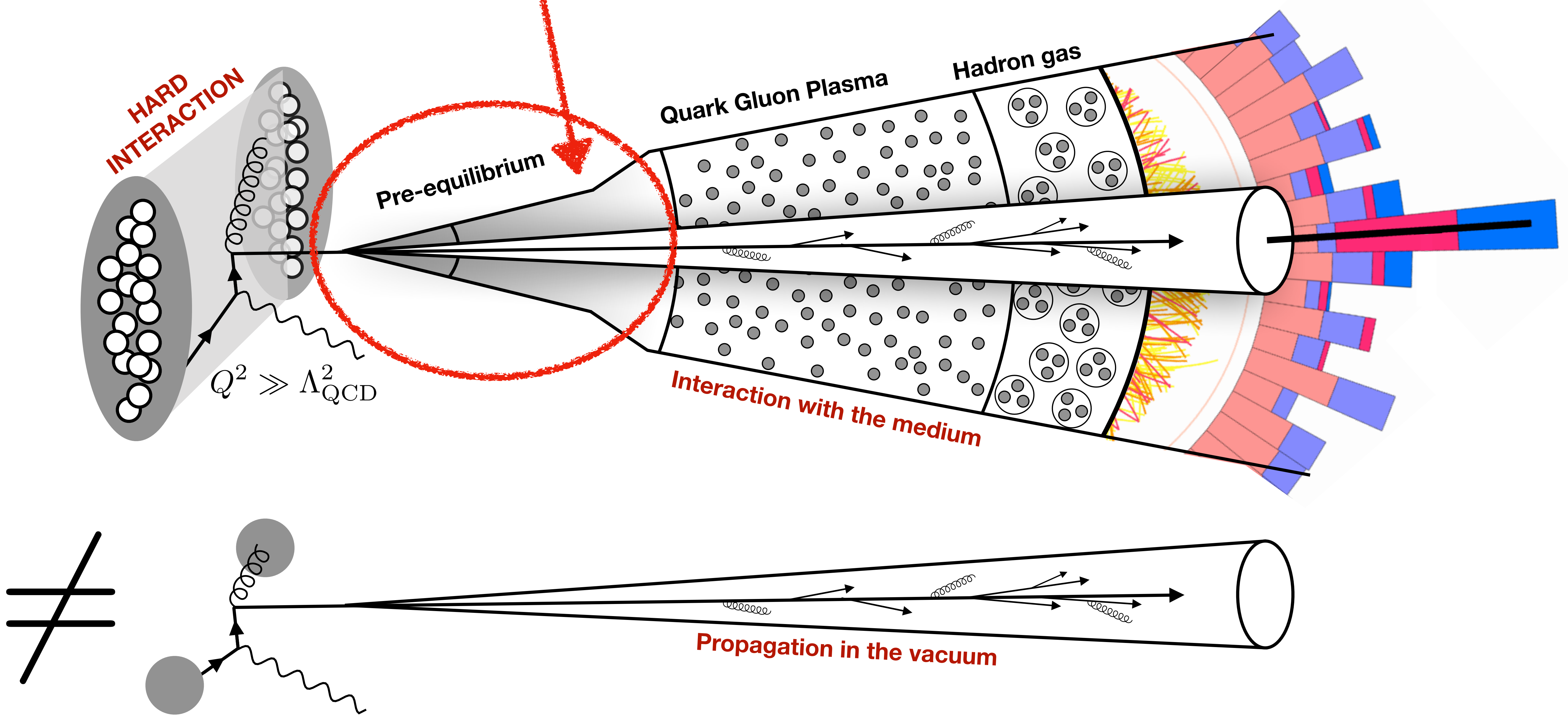
...the QGP?

2023 - José Soares Santos: "Glasma Role in Jet Quenching Effects”

2022 - Guilherme Crispim: "Pre-equilibrium of the Quark-Gluon Plasma"

...acting with the QGP **during its entire**

...eference (**Jet Quenching**)



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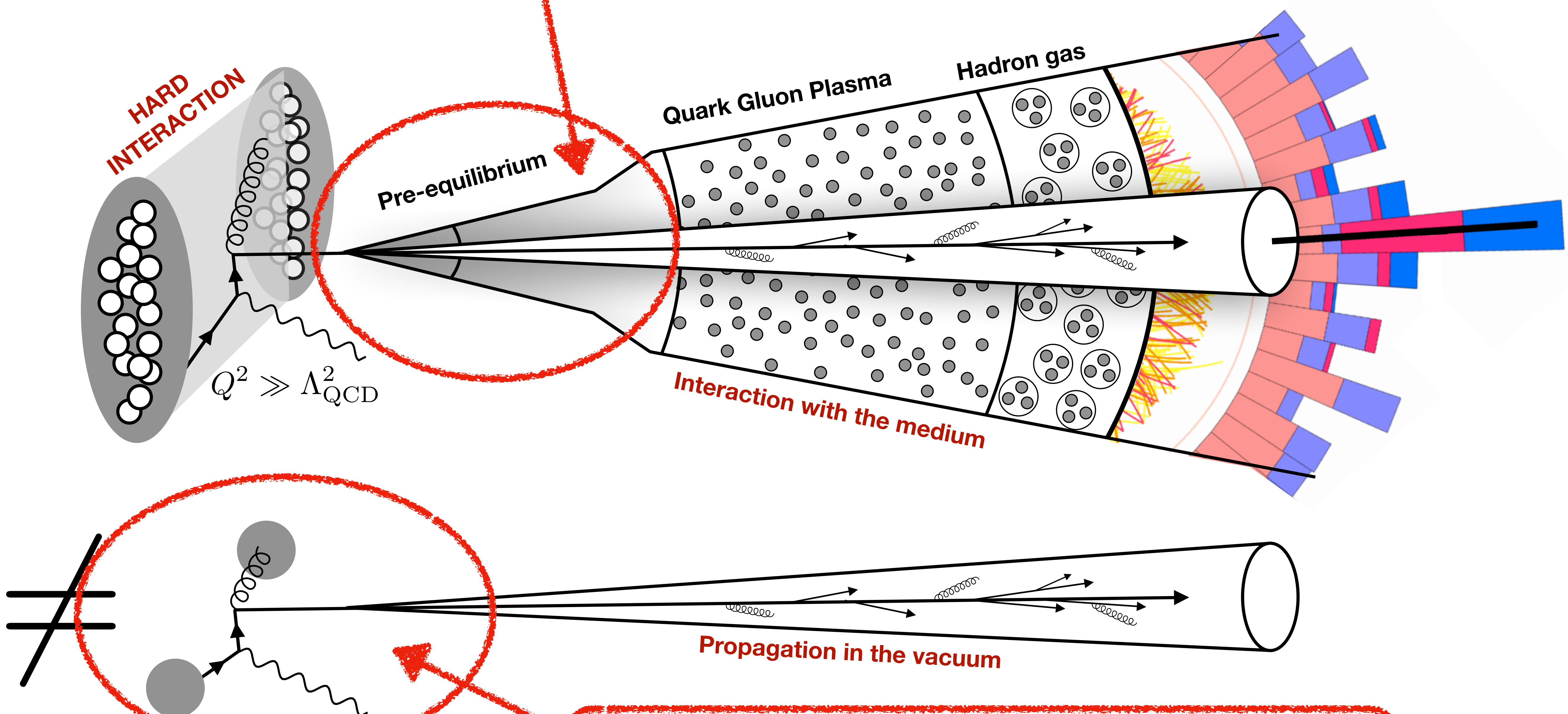

2023 - Diogo Costa: "Improving the vacuum baseline for in-medium jet physics studies”

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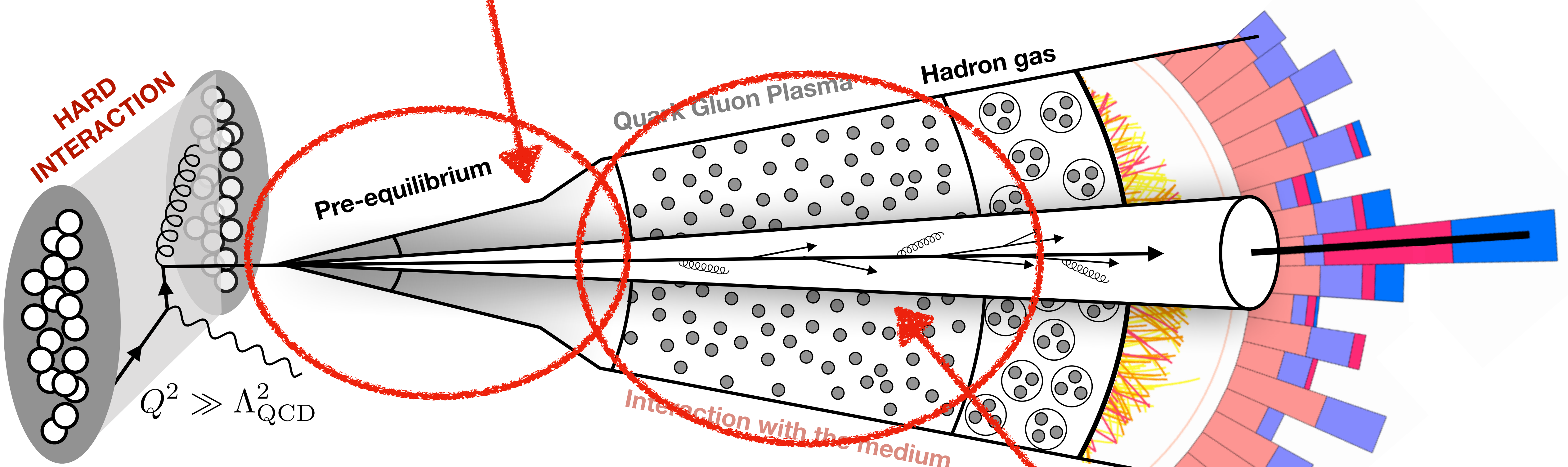

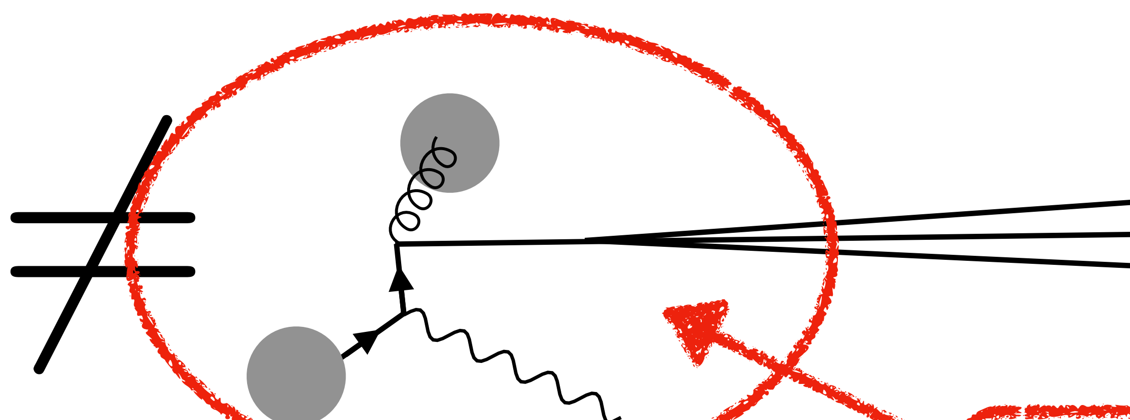

2022 - Lénea Luís: “Deciphering jet quenching effects through a quantile ratio”

2020 - Tomás Cabrito: "The soft-hard antenna spectrum in presence of a QGP”

(...)

- **These modifications allow us** ...

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On-going MsC theses at Pheno@LIP

- 2023 - Diogo Costa: “Improving the vacuum baseline for in-medium jet physics studies”
- 2023 - Inês Alexandre Serra: “Heavy Quarks Formation time”
- 2023 - José Santos: “Glasma role in jet quenching effects”
- 2022 - Guilherme Crispim: “Pre-equilibrium of the Quark-Gluon Plasma”
- 2020 - Guilherme Calé: “Jet-jet correlations in QCD”
- 2020 - Tomás Cabrito: “The soft-hard antenna spectrum in presence of a QGP”

Recently finished MsC theses

- 2023 - Pedro Chaves: “Probing Dark Matter with Higgs Bosons and Top Quarks”
- 2022 - Lénea Luís: “Deciphering jet quenching effects through a quantile ratio”
- 2022 - Marco Leitão: “QGP effects on Energy Correlators inside jets”
- 2021 - João Humberto Gomes: “Deep Learning in QCD Jets”
- 2019 - Bruno Miguel Tavares Lopes da Silva: “Jet Quenching in Small Systems”

On-going PhD theses at Pheno@LIP

- 2023 - Nuno Olavo: “Charting QCD jet evolution in extreme conditions”
- 2022 - Dario Vaccaro: “Formal and phenomenological studies in the high energy limit of QCD”
- 2021 - André Cordeiro: “Jetography in Heavy Ion Collisions”
- 2021 - João Arruda Gonçalves: “Disentangling and Quantifying Jet-Quenching With Generative Deep Learning”
- 2021 - João Martins da Silva: “The substructure of in-medium jets”
- 2018 - Mariana Araújo: “Quarkonium production studies at LHC energies: towards the understanding of bound-state formation by the strong force”

Last year’s summer internships

- Jay Nesbitt: “Deciphering Jet Quenching Effects with Novel Analysis Tools”
- Hugo Amaral: “Obtaining high-precision predictions for jet production at the LHC in perturbative QCD”
- André Alves: “Obtaining high-precision predictions for top-pair production at the LHC in perturbative QCD”
- Sebastião Fonseca: “Studying Higgs production at the LHC and at future colliders”

Join us!

- Check our group's website:

https://pages.lip.pt/pheno/

- Found something interesting? Got any questions? Contact us:

phenomenology@lip.pt

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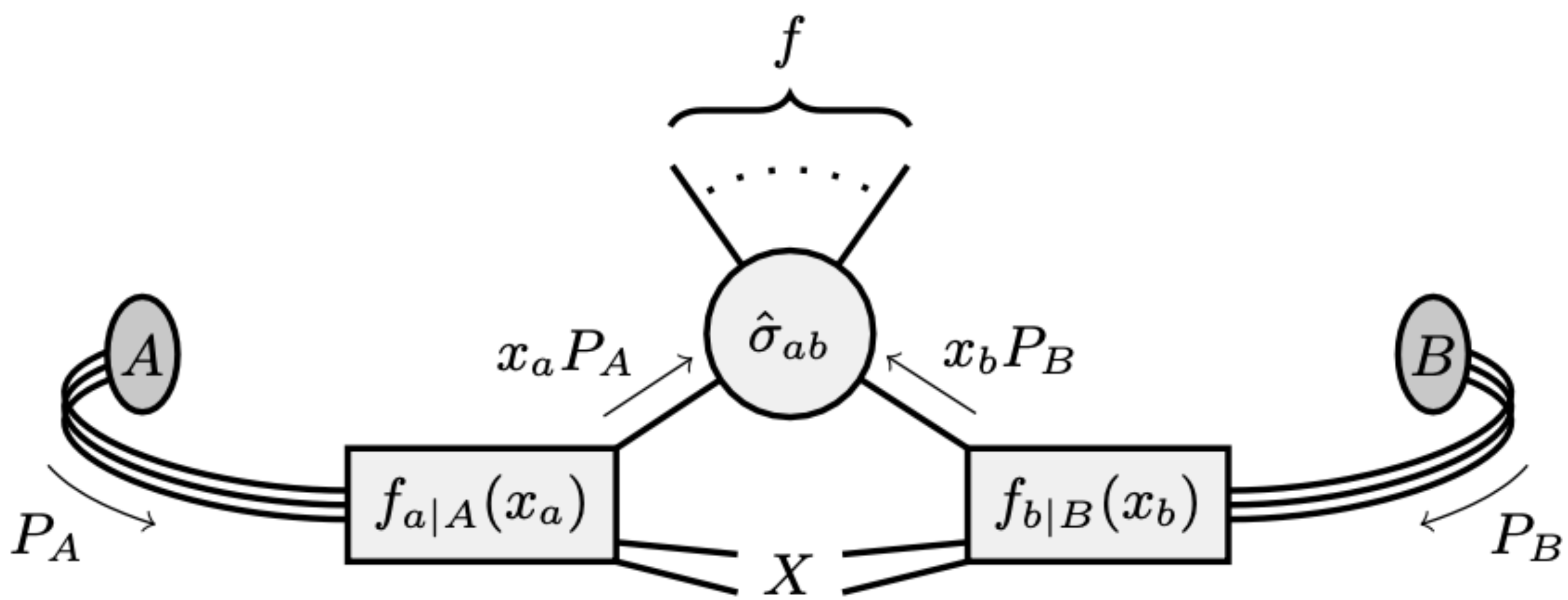
Thank you

BACK-UP

QCD precision

Inclusive cross section formula for a hard scattering process producing a final-state f initiated by proton-proton collisions at the LHC



$$\sigma(P_A, P_B) = \sum_{ab} \int \mathrm{d}x_1 \mathrm{d}x_2 \, f_{a|A}(x_a, \mu_F^2) f_{b|B}(x_b, \mu_F^2) \hat{\sigma}_{ab}(p_a, p_b, \alpha_s(\mu_R^2), s/\mu_R^2, s/\mu_F^2)$$

parton distribution functions
(non-perturbative, universal)

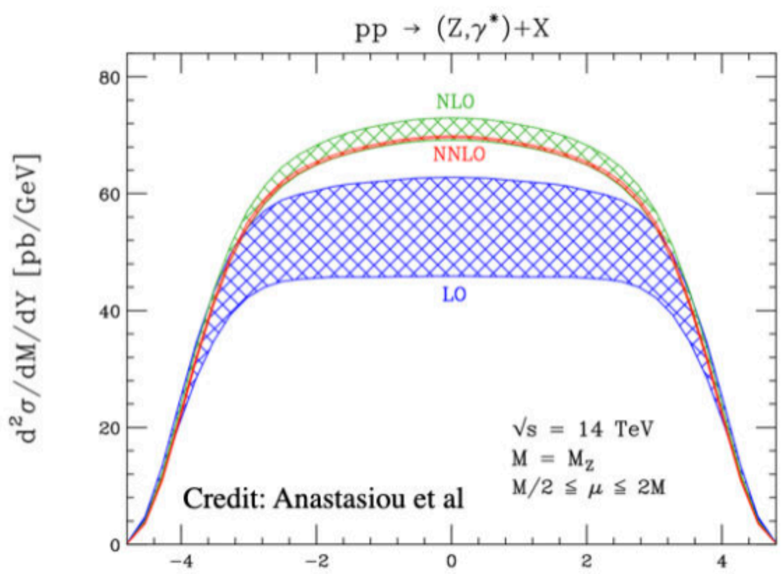
hard scattering
(perturbation theory)

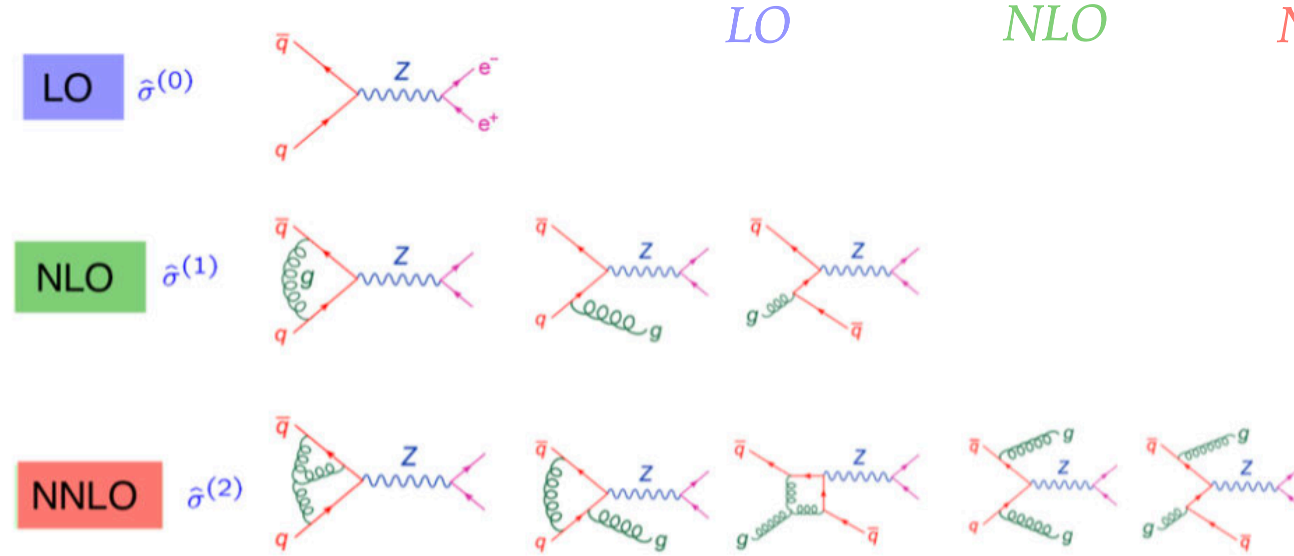
Slide courtesy of João Ramalho Pires

$$\sigma(P_A, P_B) = \sum_{ab} \int \mathrm{d}x_1 \mathrm{d}x_2 \boxed{f_{a|A}(x_a, \mu_F^2) f_{b|B}(x_b, \mu_F^2)} \boxed{\hat{\sigma}_{ab}(p_a, p_b, \alpha_s(\mu_R^2), s/\mu_R^2, s/\mu_F^2)}$$

➤ ***Hard partonic cross section*** process dependent contribution → ***computable in perturbation theory***

$$\hat{\sigma} = \underbrace{\boxed{\hat{\sigma}^{(0)}}}_{LO} + \alpha_s^1 \underbrace{\boxed{\hat{\sigma}^{(1)}}}_{NLO} + \alpha_s^2 \underbrace{\boxed{\hat{\sigma}^{(2)}}}_{NNLO} + \ldots$$





Theory challenges:

- Smaller theory uncertainties require calculations of higher order QCD effects to observables measured at the LHC
- Development of analytical and computational studies for phenomenological analysis of particle collision processes at the LHC
- Development of calculation methods in the group → antenna subtraction at NNLO
- Development of Monte Carlo parton-level event generator programs → NNLOJET

Slide courtesy of João Ramalho Pires

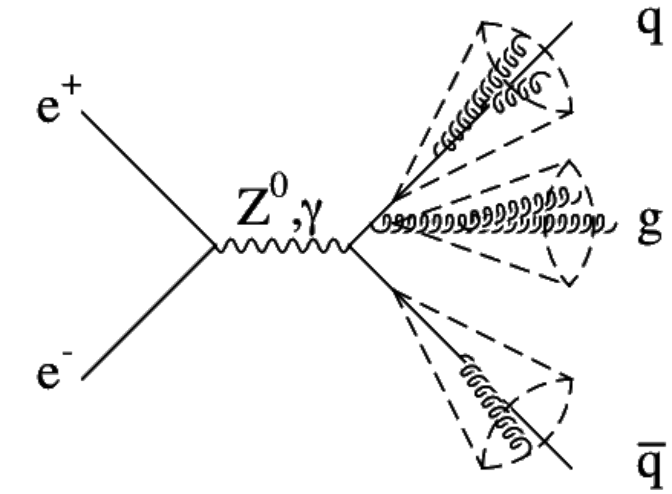
QCD precision program at FCCee

- No parton distributions functions, hadron remnant, underlying event
- Provides clean environment to study QCD dynamics

QCD programme
- Enormous statistics with $Z \to \ell\ell$, qq(g)
- Complemented by 100,000 $H \to gg$

1. $\alpha_S(m_Z)$ with per-mil accuracy
2. Quark and gluon fragmentation studies
3. Clean non-perturbative QCD studies

Aim one order of magnitude improvement in the precision of α_s with FCCee with respect to LEP



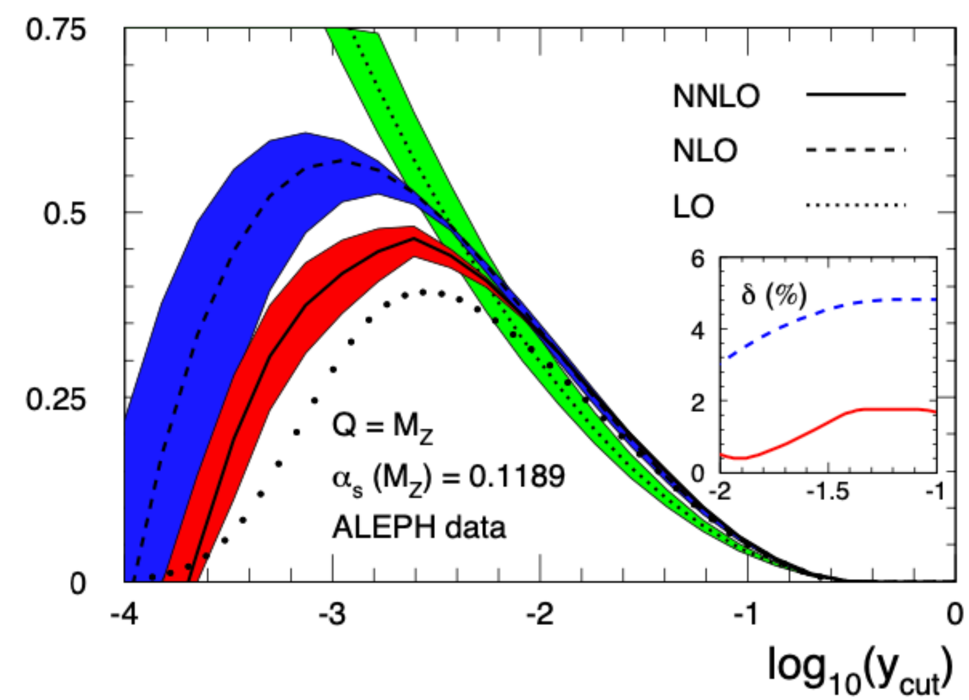
Enormous statistics with $Z \to qq(g)$

5×10^{12} $e^+e^- \to Z$ ⟶ LEP x 10^5

<u>Theory challenges:</u>

- Smaller uncertainties require the inclusion of massive *b*-quark effects (current calculations beyond NLO use massless *b-quark*)

Joana Reis MSc 23'

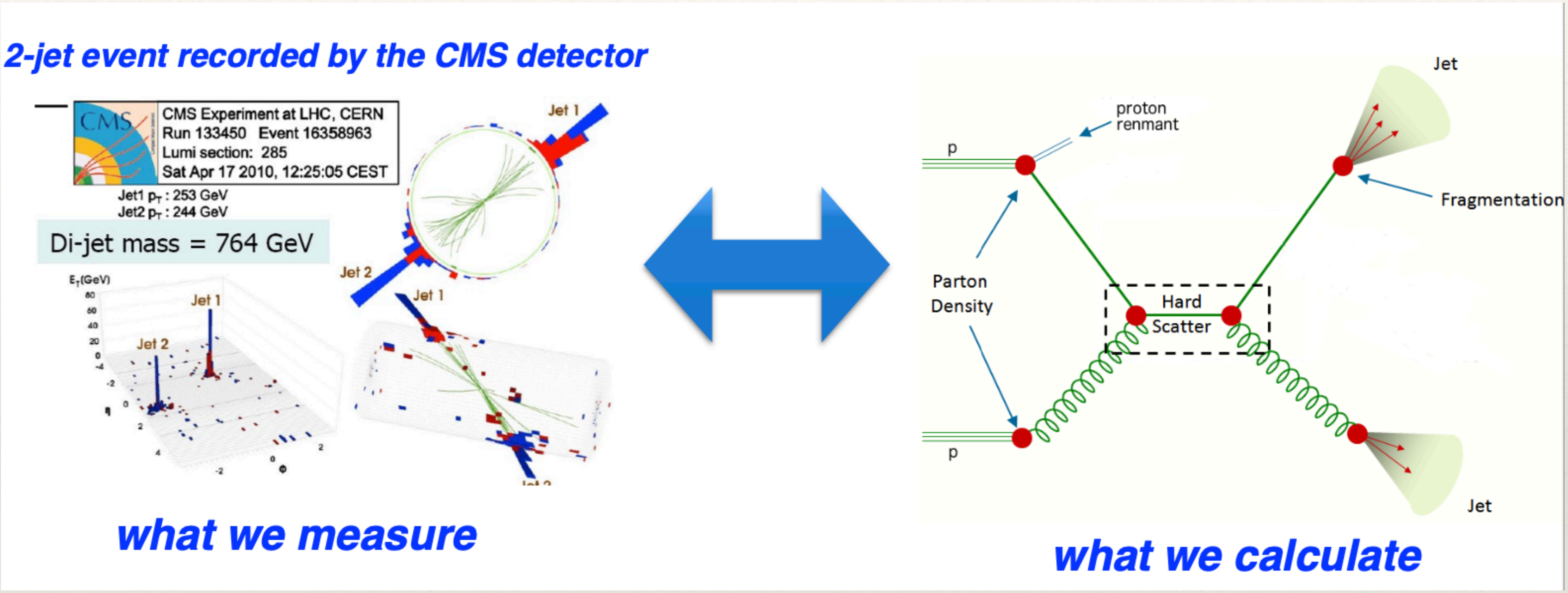


3-jet rate measurement at LEP and α_s extraction

$$\alpha_s(M_Z) = 0.1175 \pm 0.0020(exp) \pm 0.0015(th)$$

Slide courtesy of João Ramalho Pires

QCD phenomenology in pp-collisions at the LHC

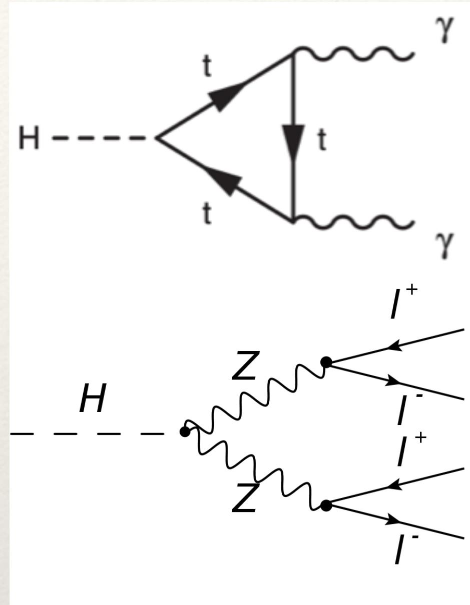


Slide courtesy of João Ramalho Pires

Particle Physics Phenomenology

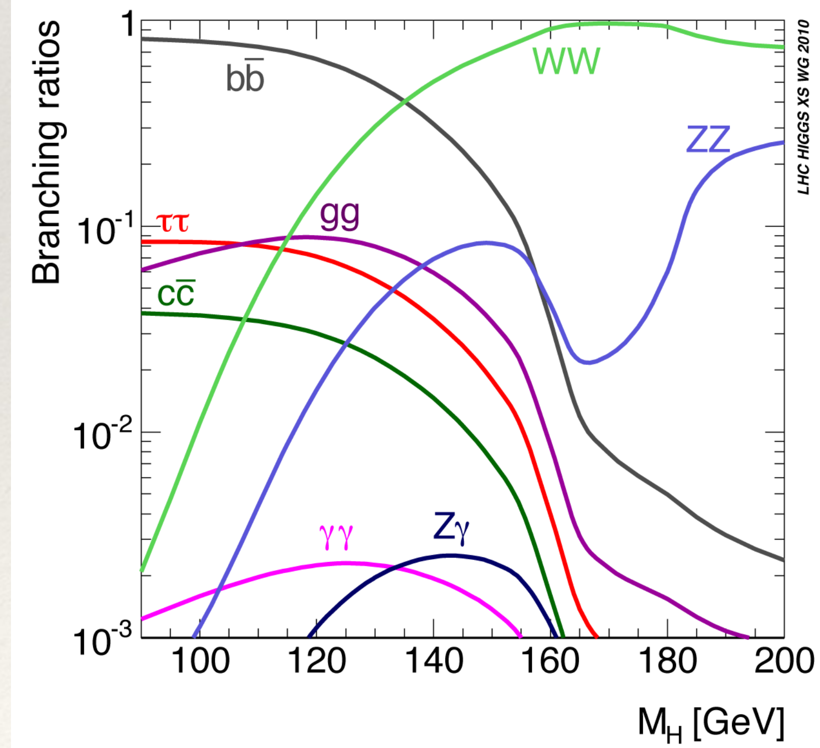
- *Phenomenology research sits at the interface between theoretical particle physics and experiments with particle colliders*
- *A practical example: The Standard Model Higgs at the LHC*

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

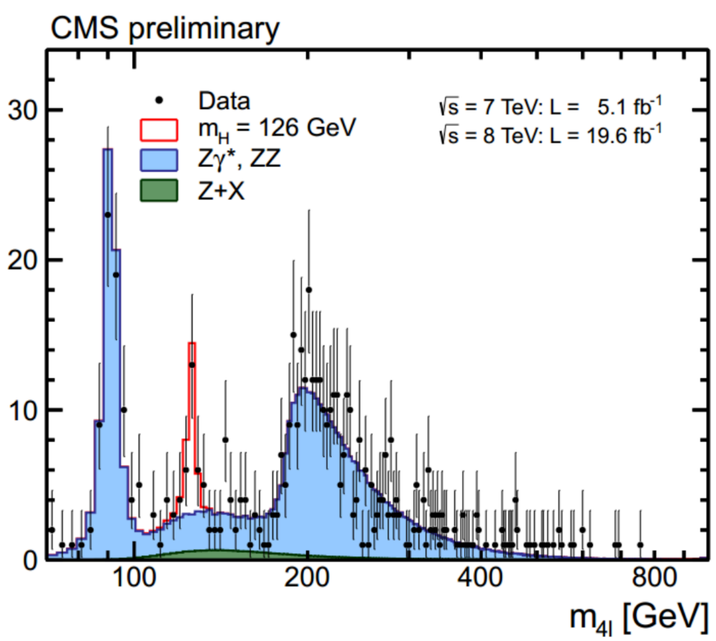


$$\Gamma(h^0 \to \gamma\gamma) = \frac{\alpha_{em}^3 m_h^3}{144\pi^2 m_W^2 \sin^2\theta_w}\Big|\sum_f Q_f^2 N_c(f) I_f(\tau_f) - I_W(\tau_W)\Big|^2$$

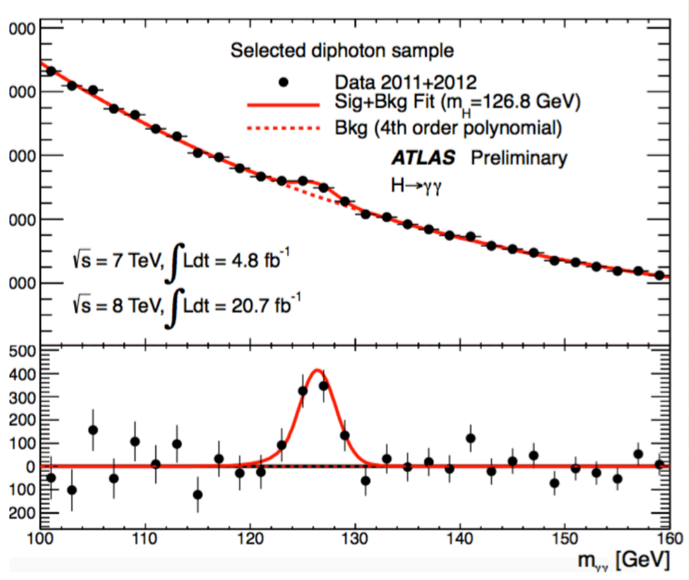
$$\Gamma(H \to ZZ) = \frac{1}{8\pi}\frac{M_Z^4}{M_H v^2}\left(1 - \frac{4M_Z^2}{M_H^2}\right)^{1/2}\left(3 + \frac{1}{4}\frac{M_H^4}{M_Z^4} - \frac{M_H^2}{M_Z^2}\right)$$



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



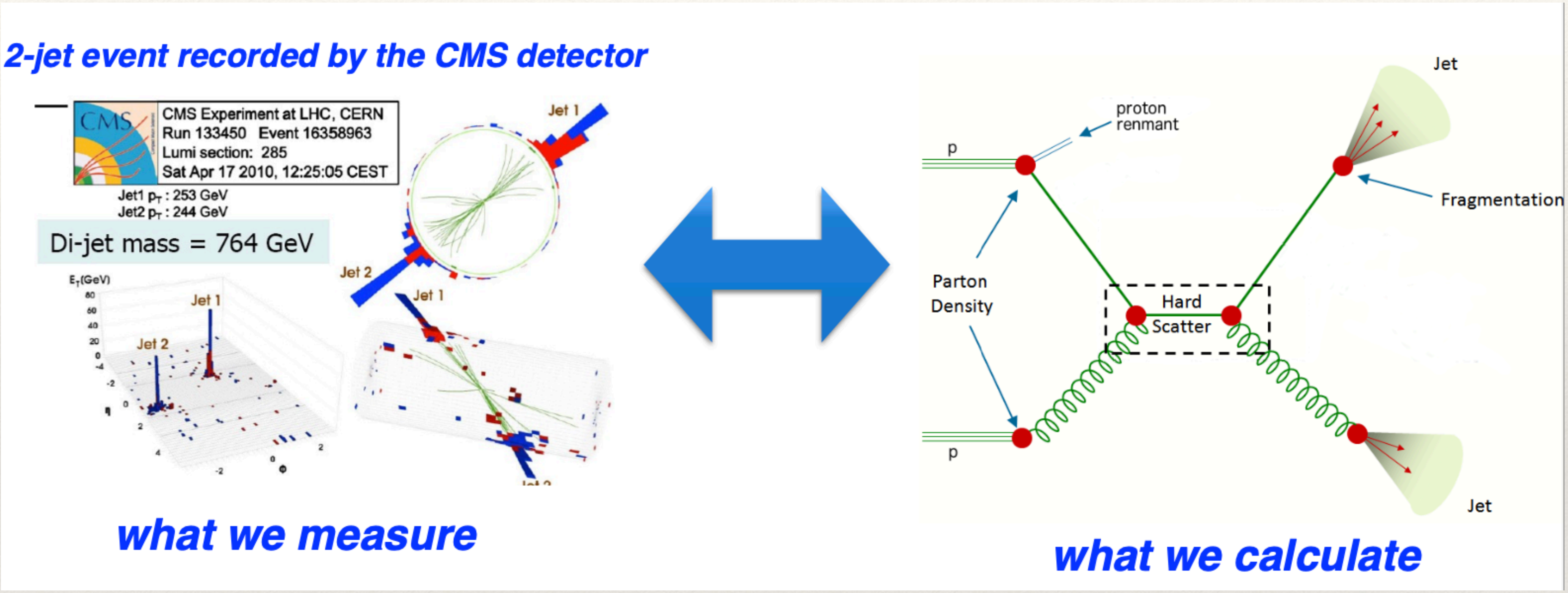
Higgs discovery plot in ZZ (CMS experiment at the LHC)



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

Slide courtesy of João Ramalho Pires

QCD phenomenology in pp-collisions at the LHC



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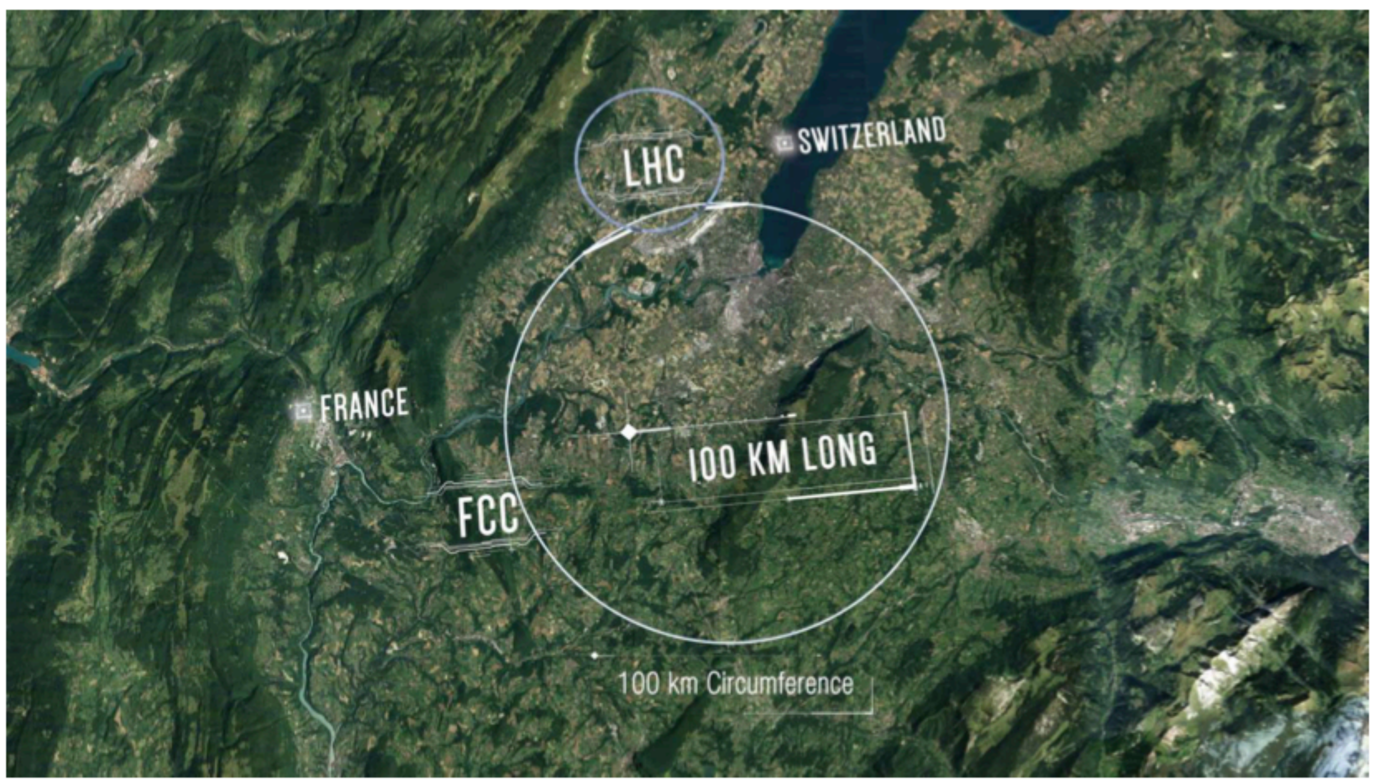
The Future Circular Collider project FCC

- 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



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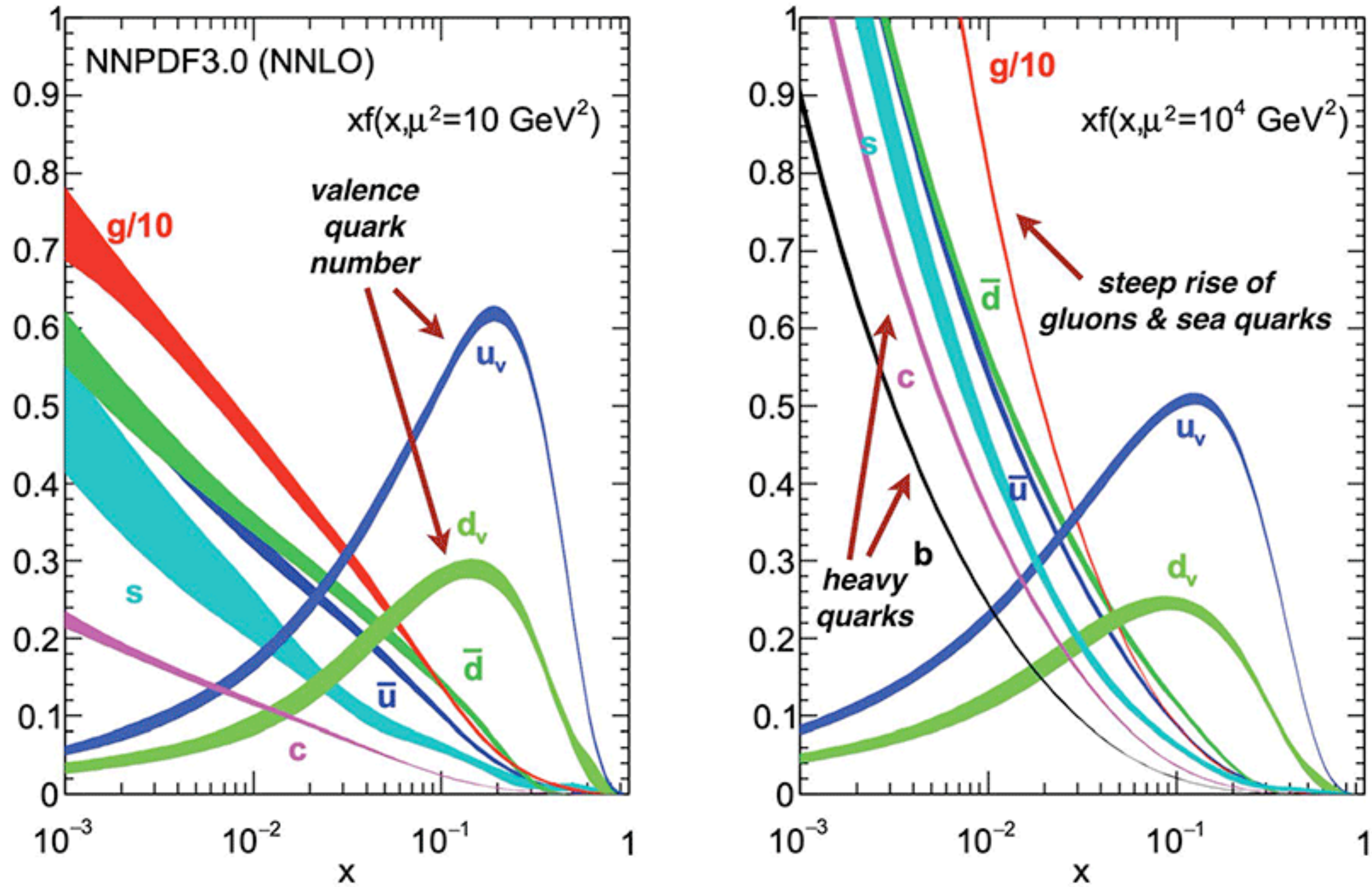
Parton distribution functions

- In these experiments, the **Parton Distribution Functions (PDFs)** are measured as a function of x and Q^2



Source: Juan Rojo 2019 (arXiv:1910.03408)

- As the resolution scales change, the observed proton substructure changes too
- At fixed Q^2 and **small-x (high energy)** the partonic content of the proton is **vastly dominated by gluons**