*MadGraph School 2018 Hefei*

# FeynRules/MadGraph School on Collider Phenomenology 2018

**University of Science and Technology of China**

Hefei, Anhui, China, 19-23, November, 2018

## Scientific Programme:

Collider Phenomenology
Parton Shower and Matching/Merging
Precision Physics at the LHC: QCD Corrections
Precision Physics at the LHC: EW Corrections
Jets and Boosted Objects
Physics and Simulations at e+e- Colliders

Searching for a New World
Precision BSM at the LHC
Effective Field Theory at LHC
Effective Field Theory at e+e- Colliders
Searching for the Invisible
Dark Matter: Physics and Simulations

Simulation of New Physics Models (FeynRules)
Overview on MG5_aMC@NLO
Fast and Public Detector Simulation (Delphes)
Analyses and Reinterpretation (MadAnalysis5)
Tutorials: From the Lagrangian to the Events

## Lecturers:

Fabio Maltoni
Peter Skands
Valentin Hirschi
Davide Pagani
Michele Selvaggi
Shao-Feng Ge

Lian-Tao Wang
Hua-Sheng Shao
Eleni Vryonidou
Gauthier Durieux
Ken Mimasu
Jan Heisig

Benjamin Fuks
Olivier Mattelaer
Matteo Cacciari
Eric Conte
Kentarou Mawatari

## Local Organizing Committee:

Haipeng An (THU), Qing-Hong Cao (PKU), Shao-Long Chen (CCNU), Xin Chen (THU), Tai-Fu Feng (HBU), Jun Gao (STJU), Liang Han (USTC), Qiang Li (PKU), Yi Liao (NKU), Xiaohui Liu (BNU), Zuowei Liu (NJU), Wen-Gan Ma (USTC), Haiping Peng (USTC), Manqi Ruan (IHEP), Jing Shu (ITP), Zong-Guo Si (SDU), Jian-Xiong Wang (IHEP), Kai Wang (ZJU), Qi-Shu Yan (UCAS), Haijun Yang (STJU), Cen Zhang (IHEP), Hao Zhang (IHEP), Ren-You Zhang (USTC).

## International Advisory Committee:

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### For more information:

Web site: https://indico.ihep.ac.cn/event/7822/registration/
e-mail: Xiaozhou Li (USTC): lixiaozhou@ustc.edu.cn
Cen Zhang (IHEP): cenzhang@ihep.ac.cn
Deadline for application: 15，September，2018

中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

# The Surviver in the QGP Fireball

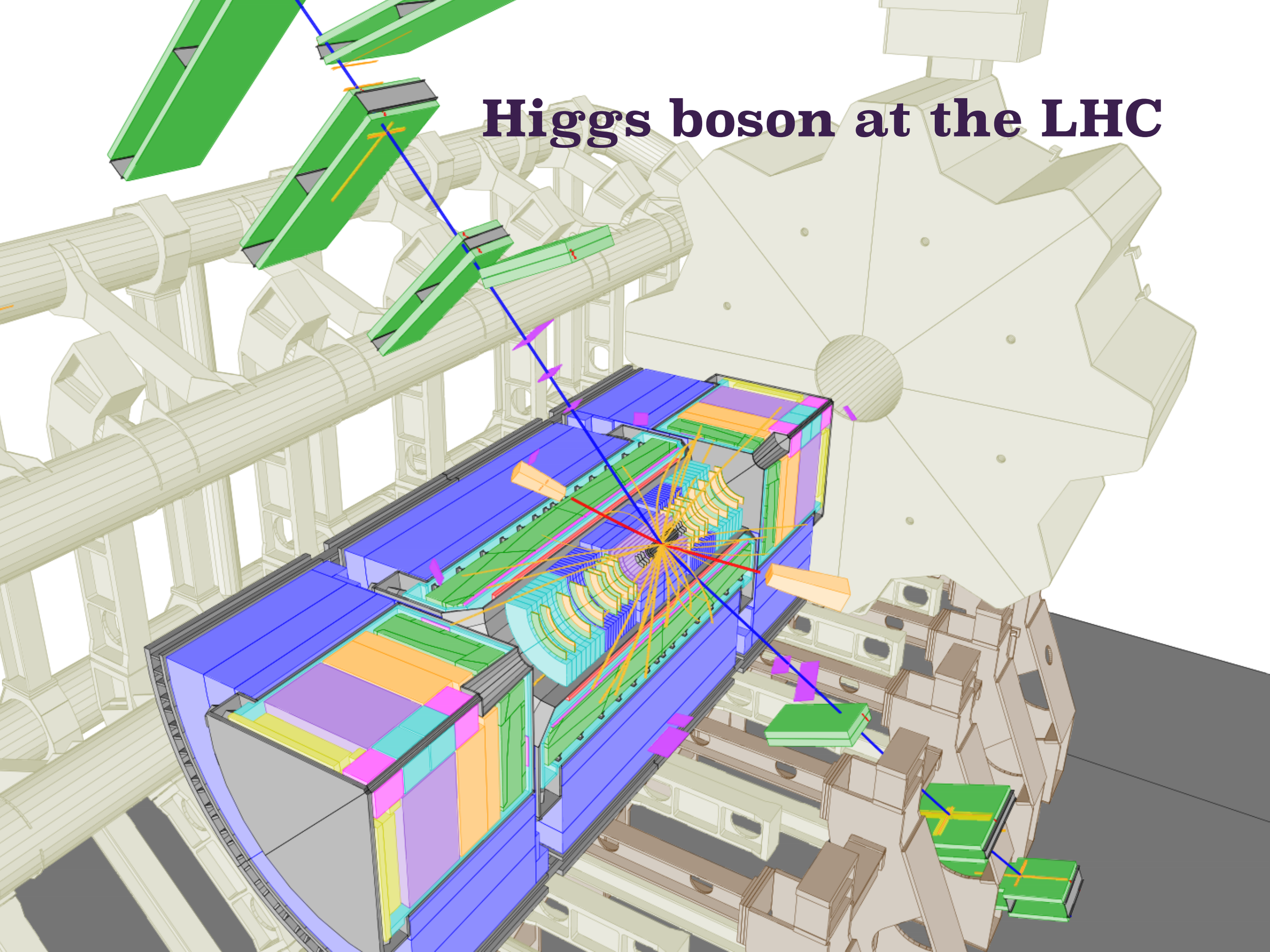
**Hao Zhang**

*Theoretical Physics Division, Institute of High Energy Physics, Chinese Academy of Sciences*

**For “第十三届TeV物理工作组学术研讨会”, Aug 20th 2018**

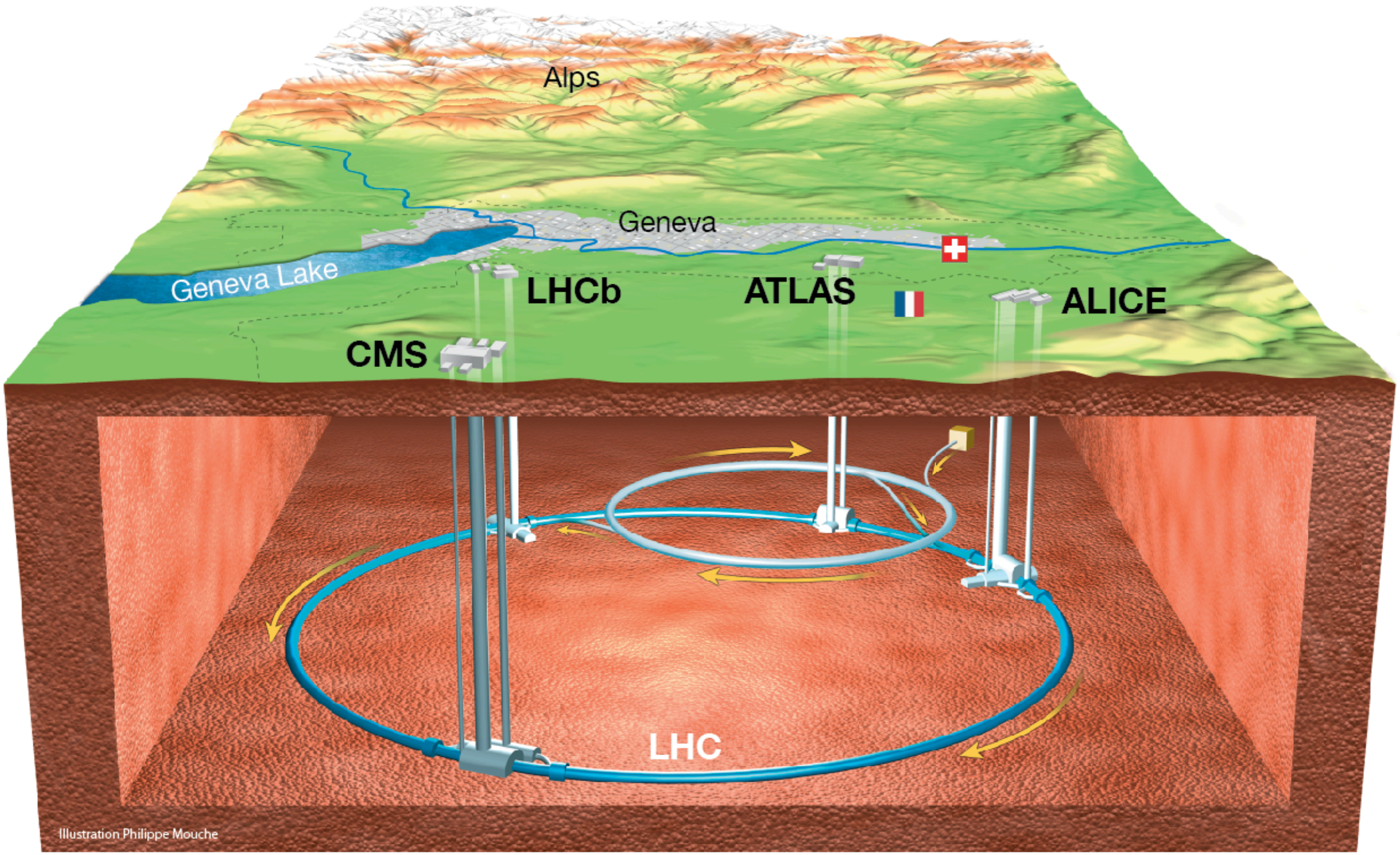
**Based on arXiv:1804.06858[hep-ph] in collaboration with Edmond L. Berger, Jun Gao and Adil Jueid**

# Higgs boson at the LHC



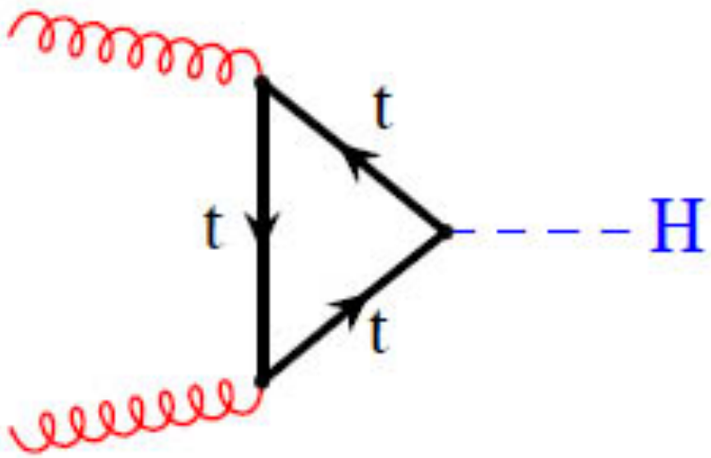
# Higgs boson at the LHC

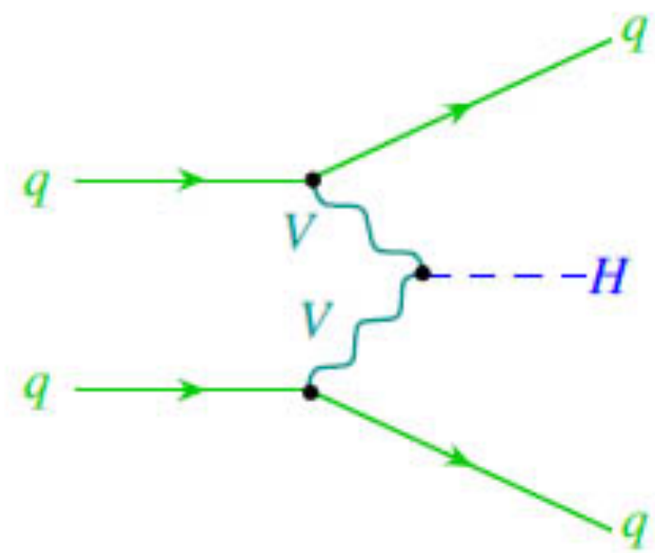
- LHC, the largest high energy collider in the world.

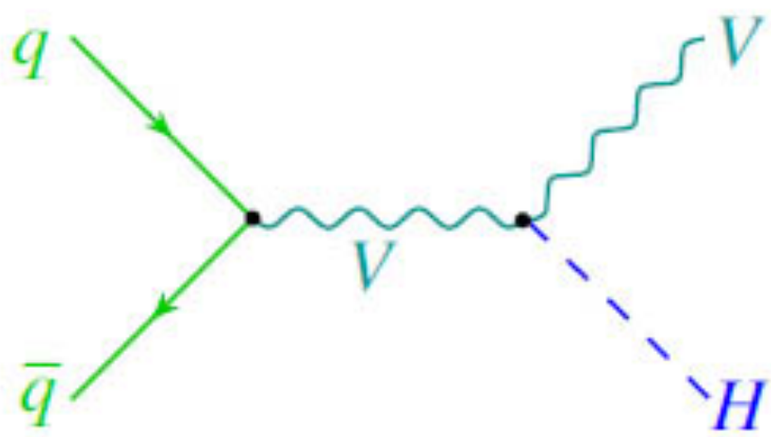


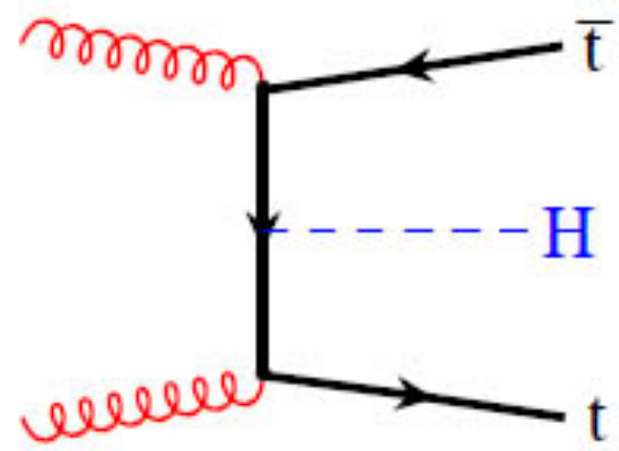
# Higgs boson at the LHC

- The production of the SM-like Higgs boson.



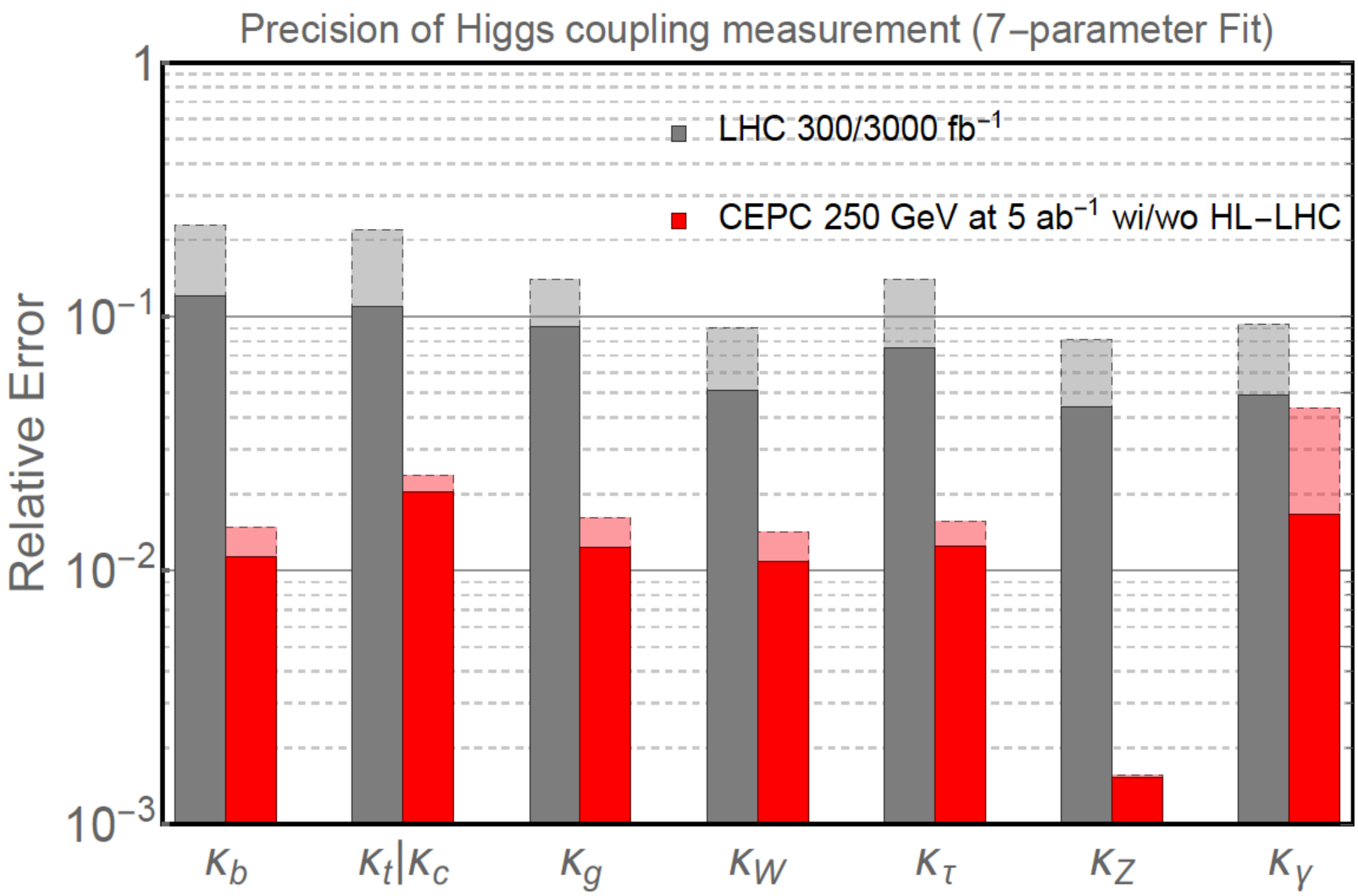



# Higgs boson at the LHC

- The experimentalists work hard to investigate the properties of the 125 GeV SM-like Higgs boson at the LHC.




**From Kaili Zhang's talk.**

# Higgs boson at the LHC

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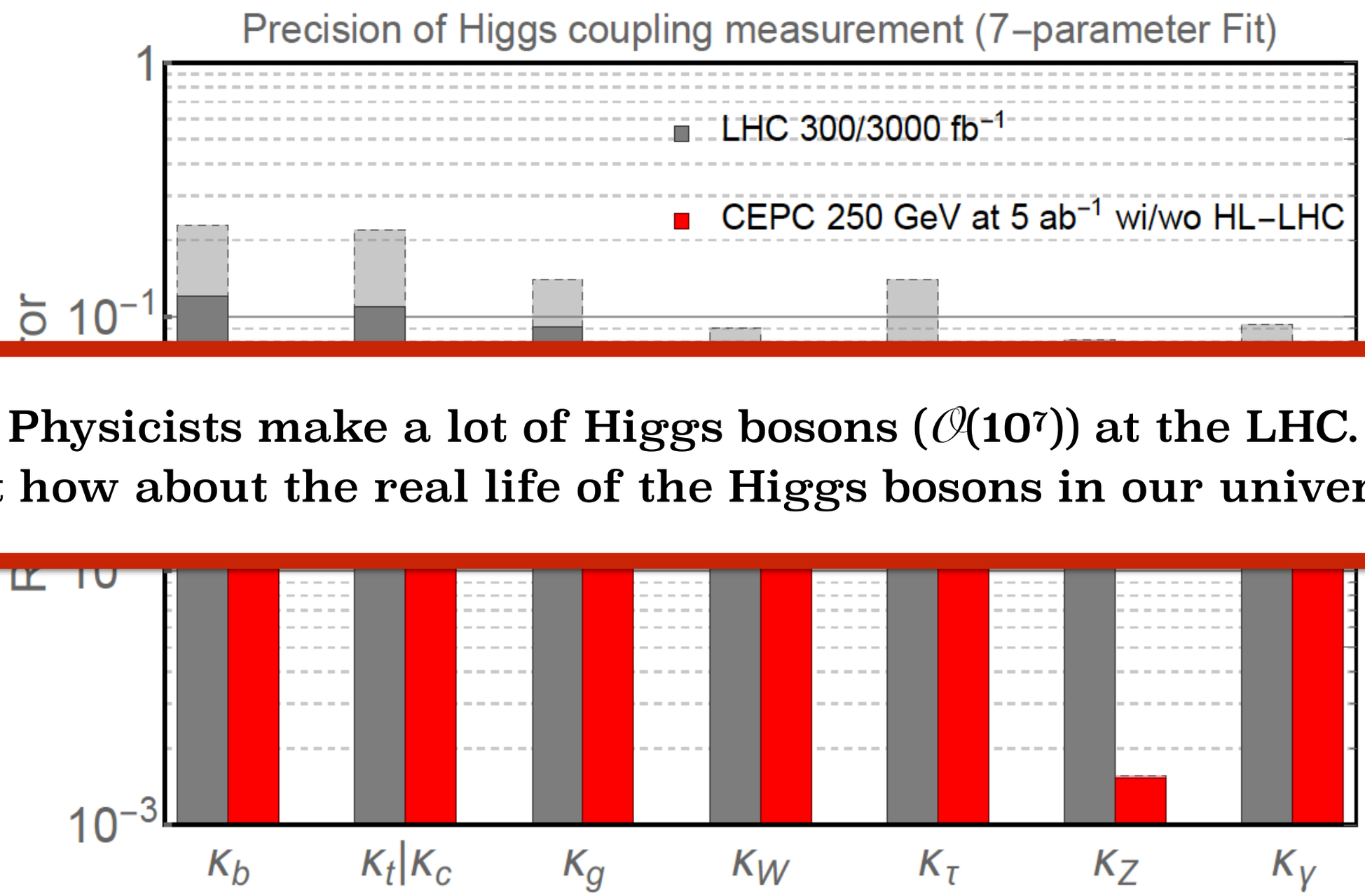
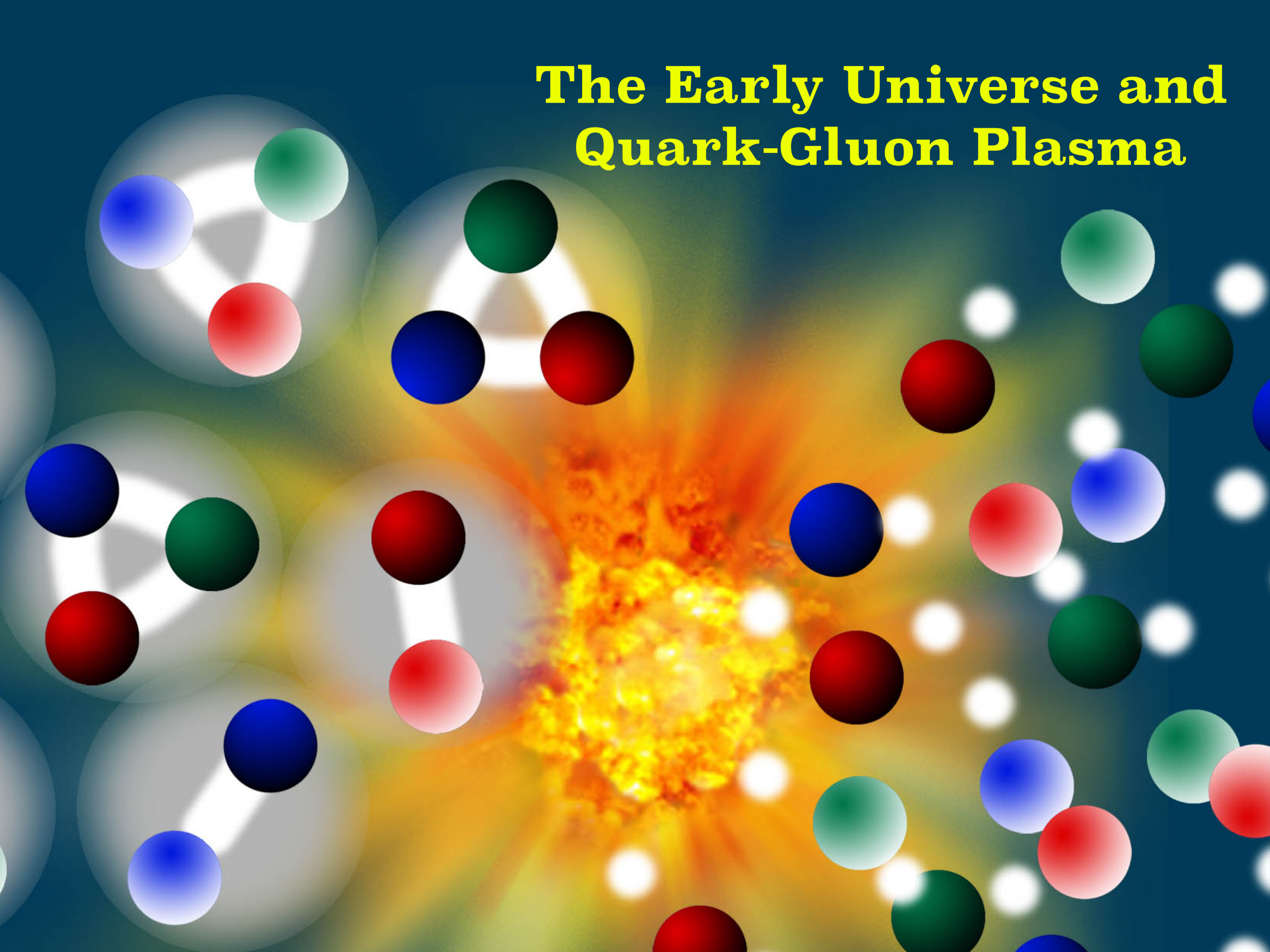


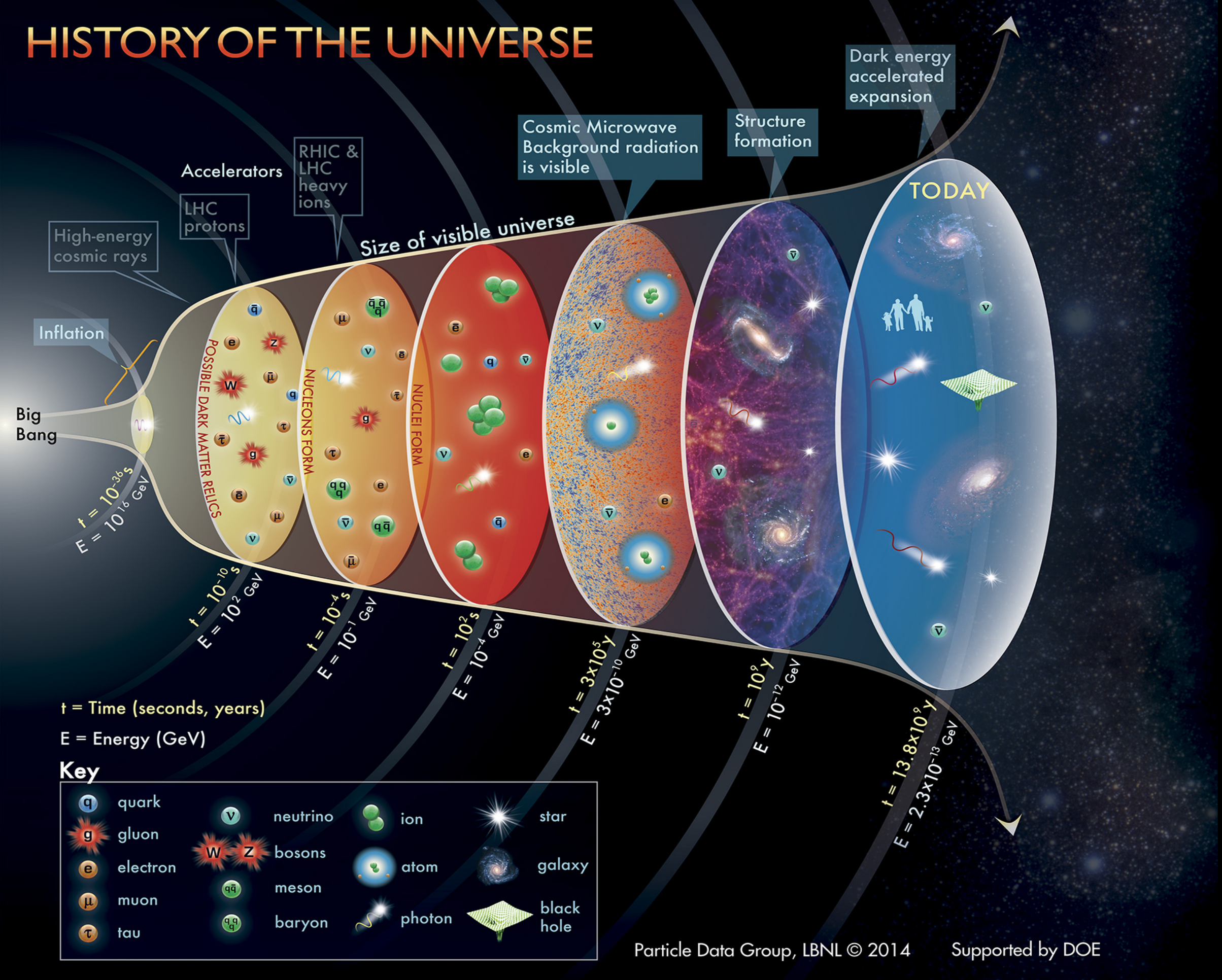

**Physicists make a lot of Higgs bosons ($\mathcal{O}(10^7)$) at the LHC.**
**But how about the real life of the Higgs bosons in our universe?**

From Kaili Zhang's talk.

# The Early Universe and Quark-Gluon Plasma



# HISTORY OF THE UNIVERSE



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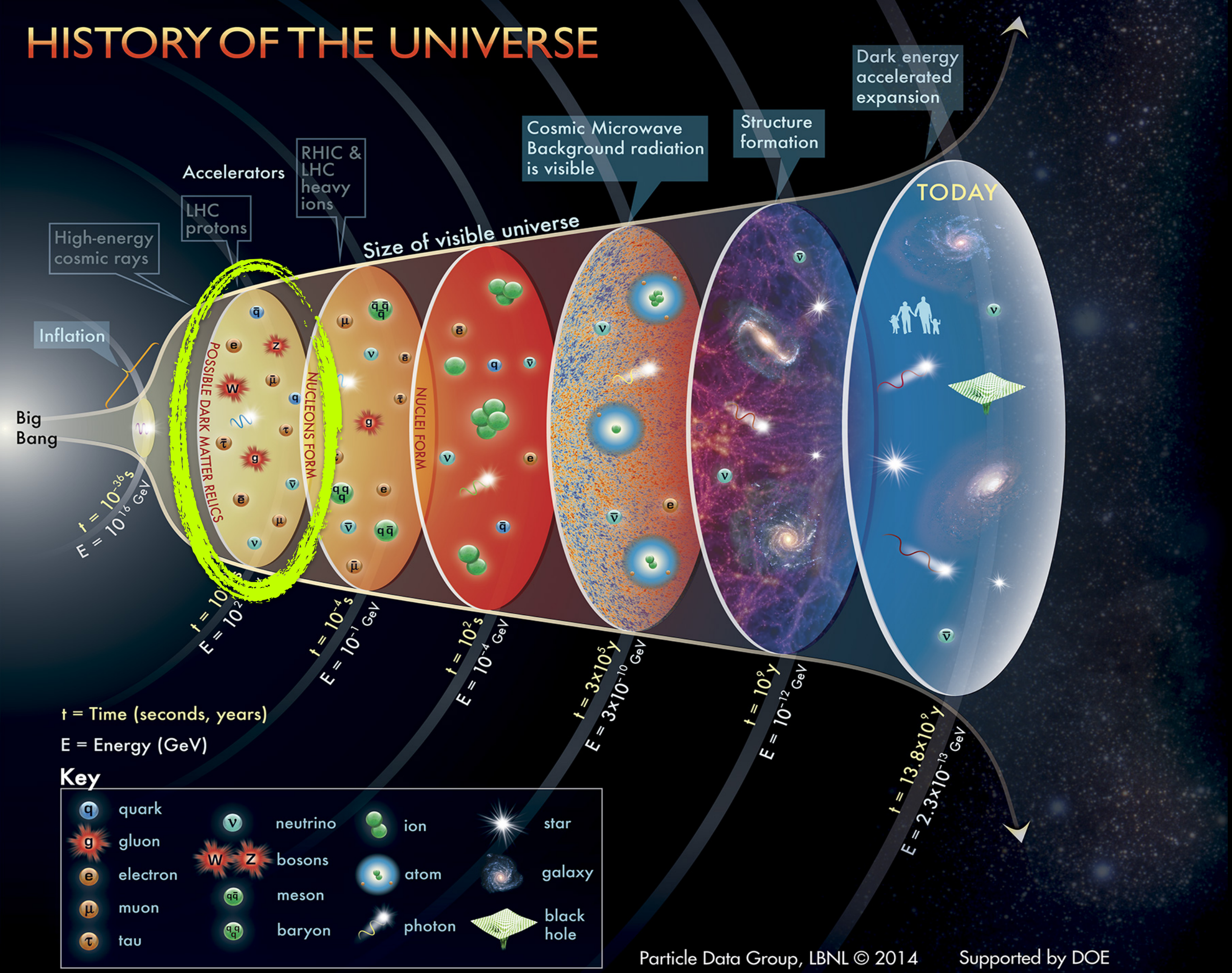
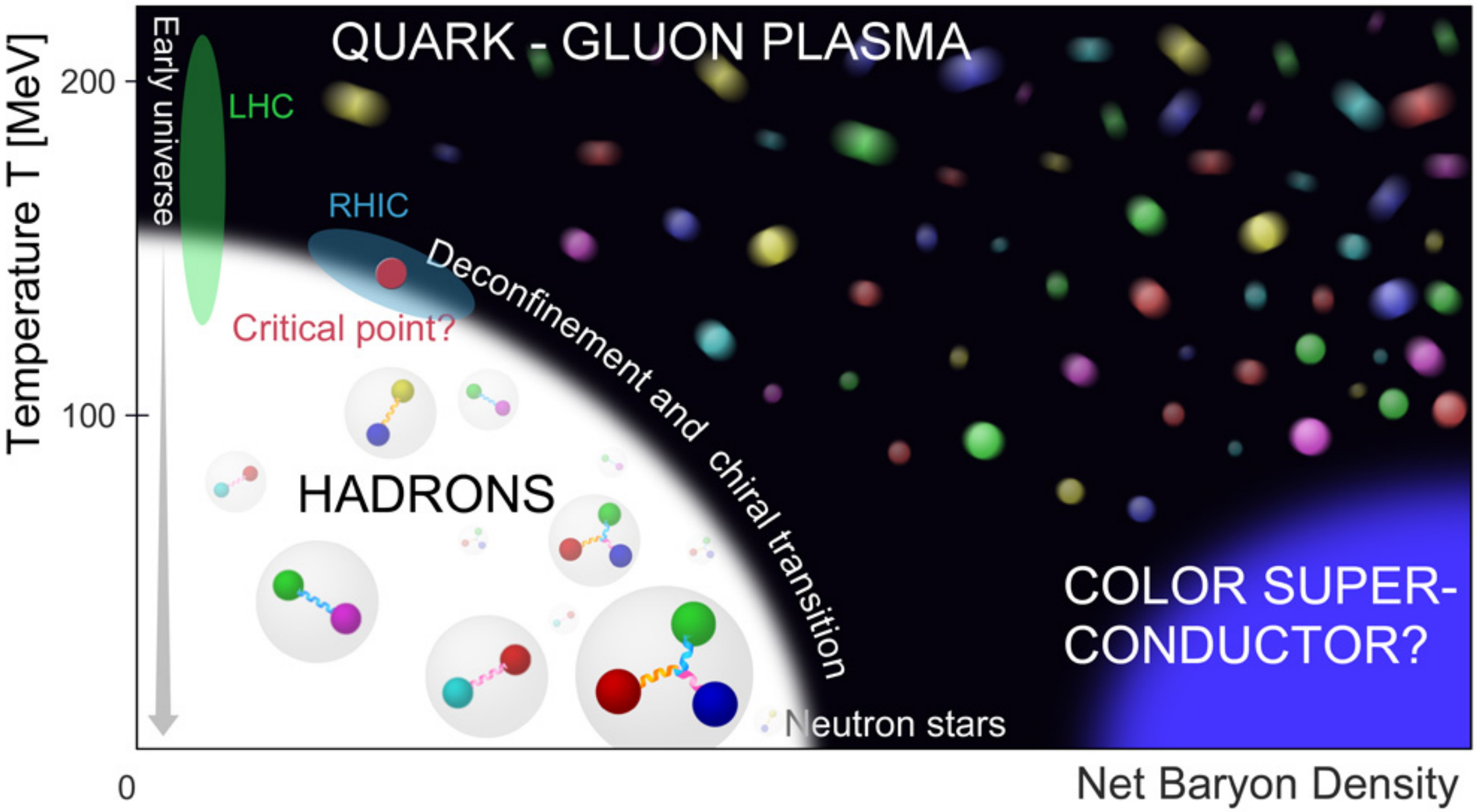
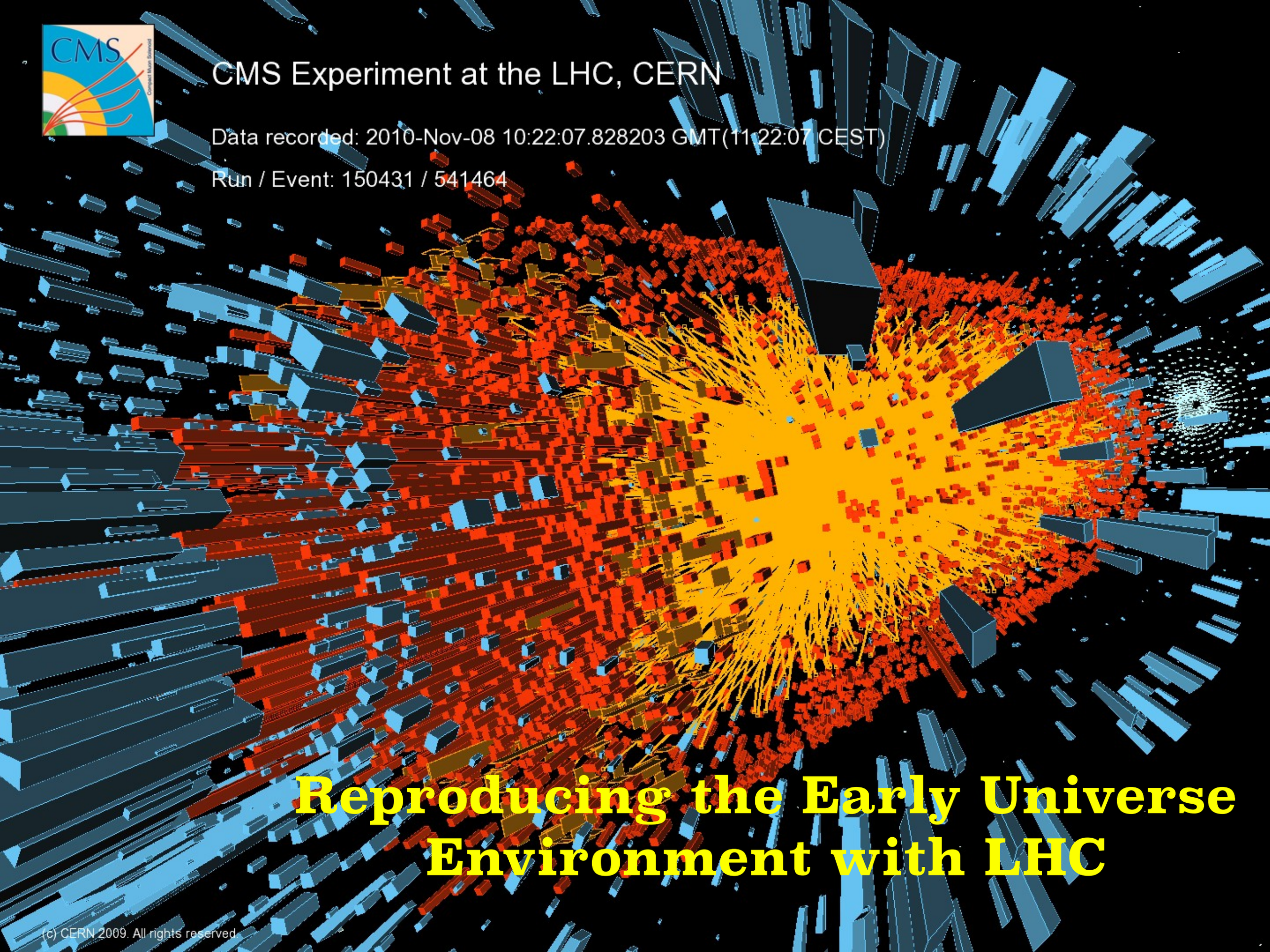



Particle Data Group, LBNL © 2014 Supported by DOE

# The Quark-Gluon Plasma

- The QCD phase diagram.

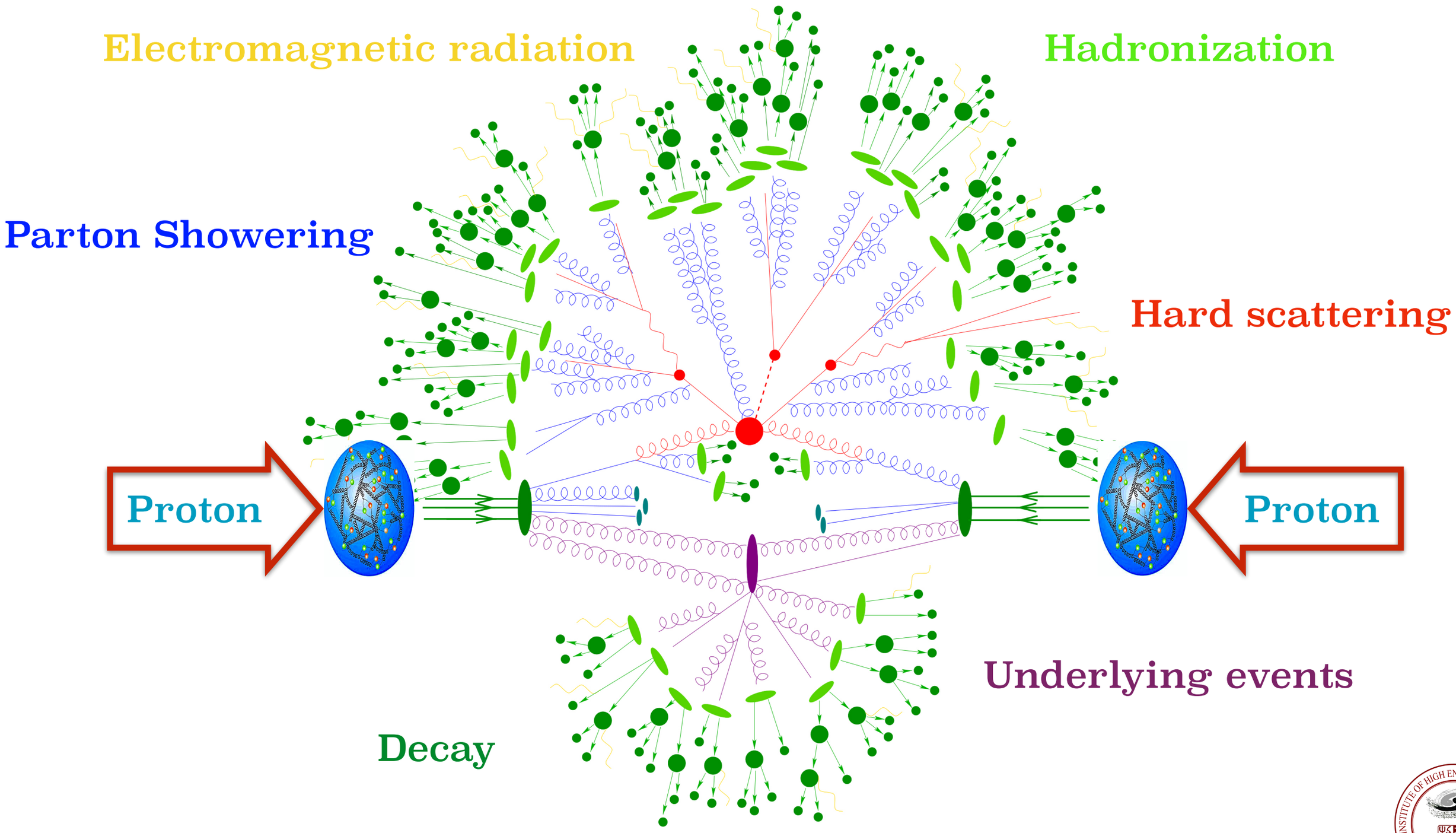





# Reproducing the Early Universe Environment with LHC

# From *pp* Collision to PbPb Collision

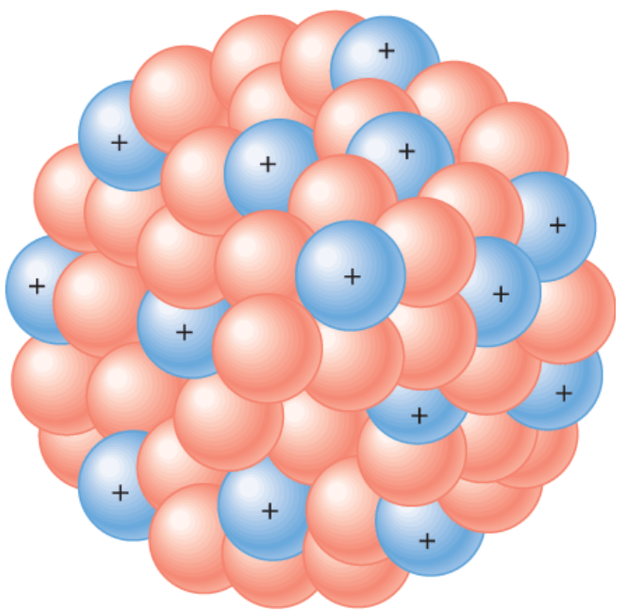
- The proton-proton collision.



# From *pp* Collision to PbPb Collision

- The lead-lead collision.
- The collision energy in the lab frame:

$^{82}Pb_{208}$



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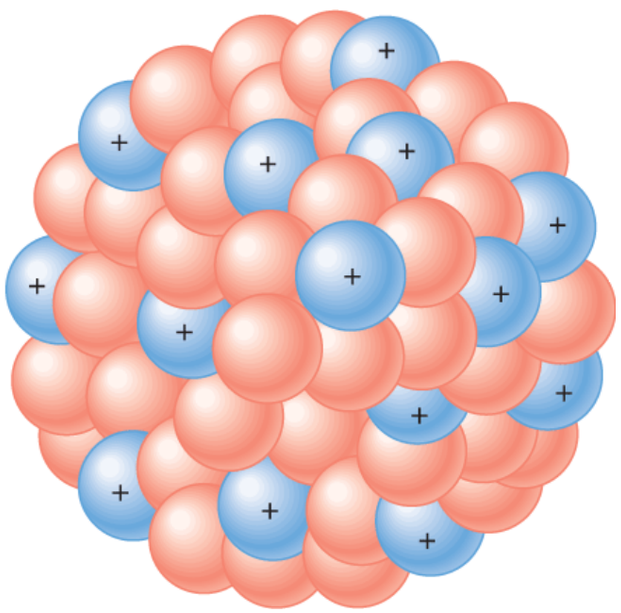

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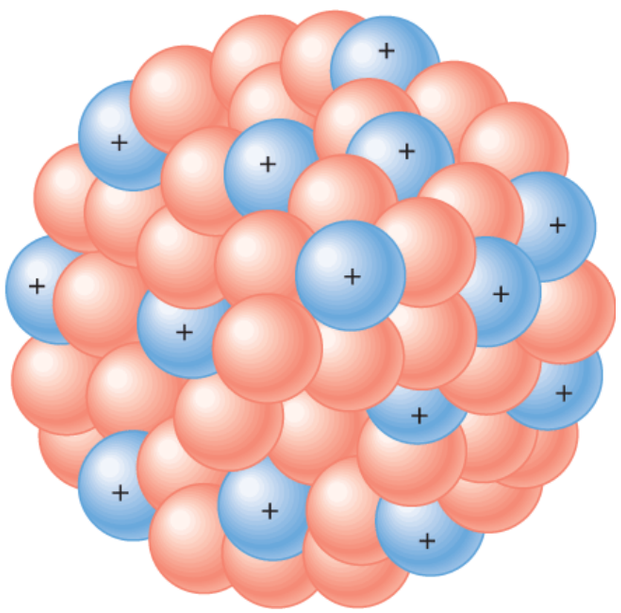

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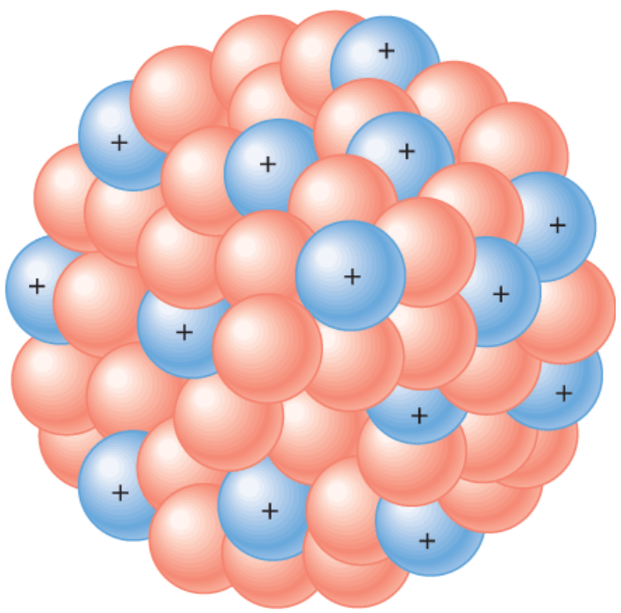

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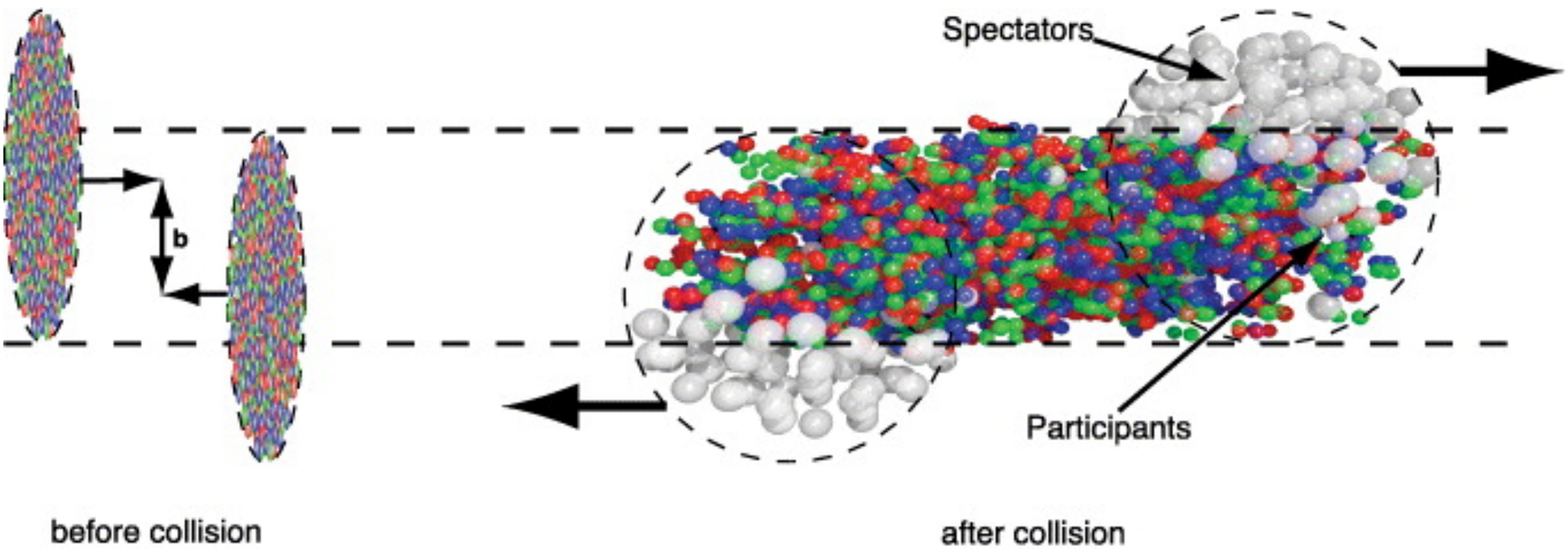
**Determined by the collider!**

$$\sqrt{s_{\mathrm{NN}}} = \frac{Z}{A}\sqrt{s_{pp}} \approx 5.5\mathrm{TeV} \text{ for 14 TeV LHC}$$

# From *pp* Collision to PbPb Collision

- The lead-lead collision.
- Impact parameter (perpendicular distance): Centrality.



# From *pp* Collision to PbPb Collision

- The lead-lead collision.
- The differential cross section.

$$d\sigma_{NN\to X}(s_{\mathrm{NN}}) = \langle T_{NN}(b)\rangle N \cdot f_{a/n}(x_a) \otimes N \cdot f_{b/n}(x_b) \otimes d\sigma_{ab\to X}(x_a x_b s_{\mathrm{NN}})$$

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**Parton level hard scattering cross section: from pQCD.**

# From *pp* Collision to PbPb Collision

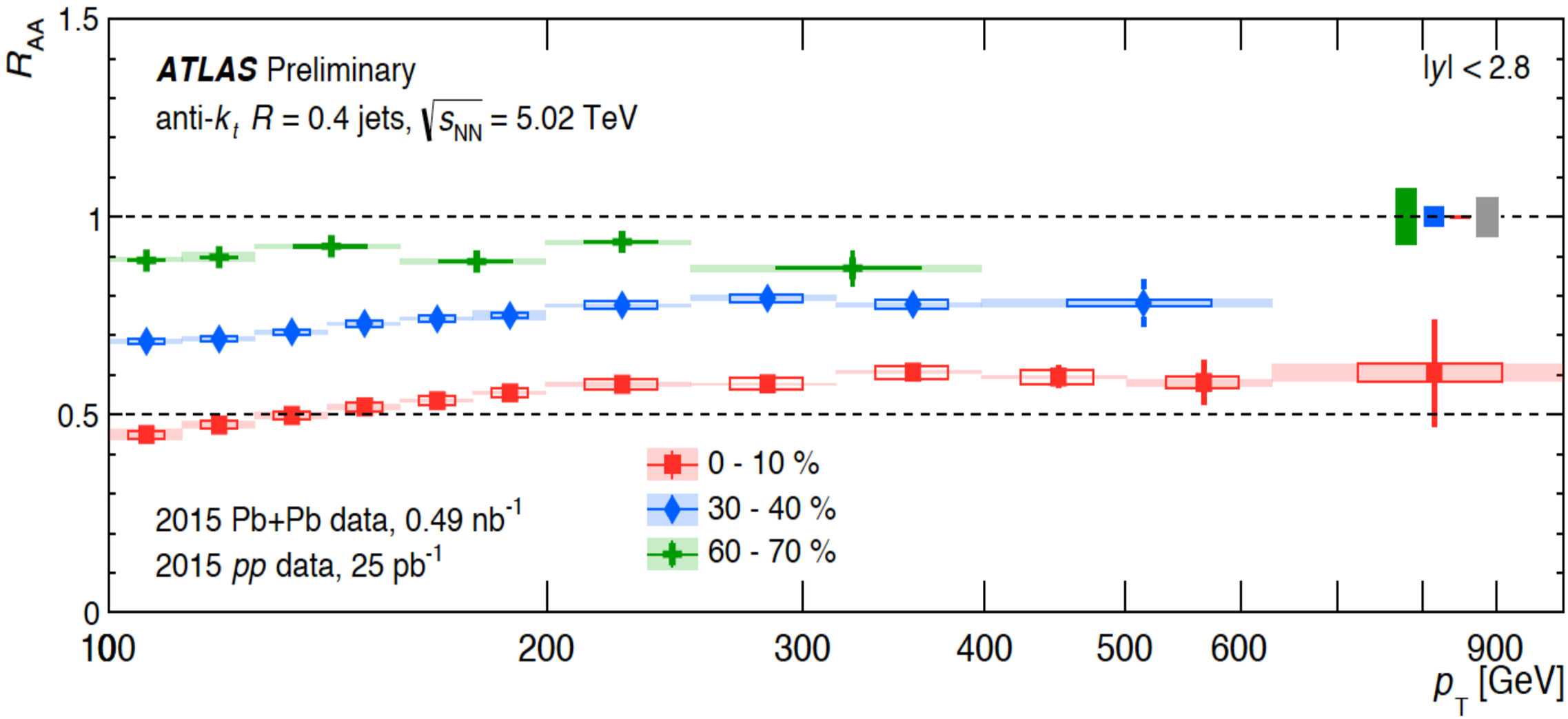
- The lead-lead collision.
- The differential cross section.
- Nuclear modification factor:

$$R_{NN} \equiv \frac{d\sigma_{NN}}{\langle T_{NN}(b)\rangle N^2 d\sigma_{nn}}$$

- If the nuclei-nuclei collision is just the incoherent superposition of nucleon-nucleon collision, $R_{NN} \equiv 1$.

# From *pp* Collision to PbPb Collision

- The lead-lead collision.
- Typical result of $R_{NN}$.




ATLAS Collaboration, ATLAS-CONF-2017-009.

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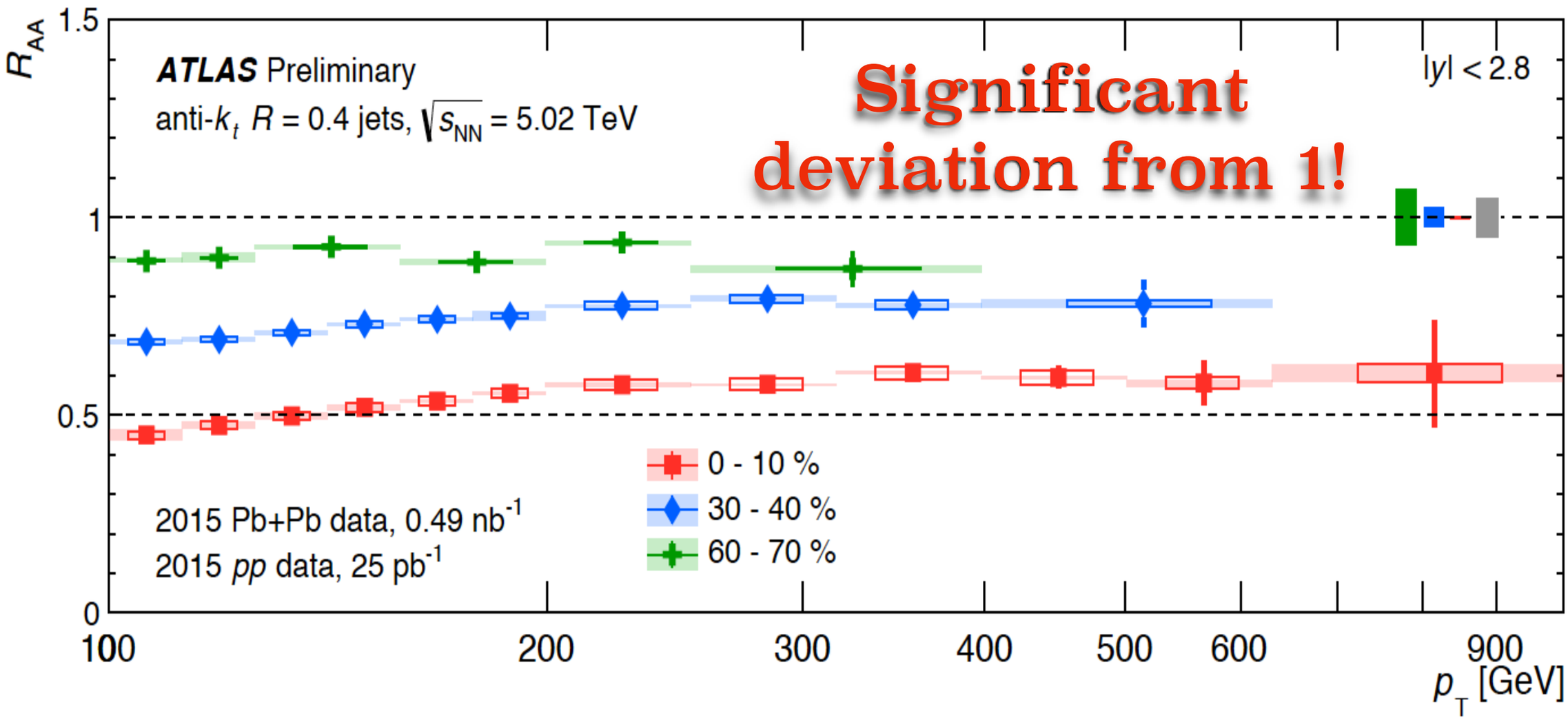
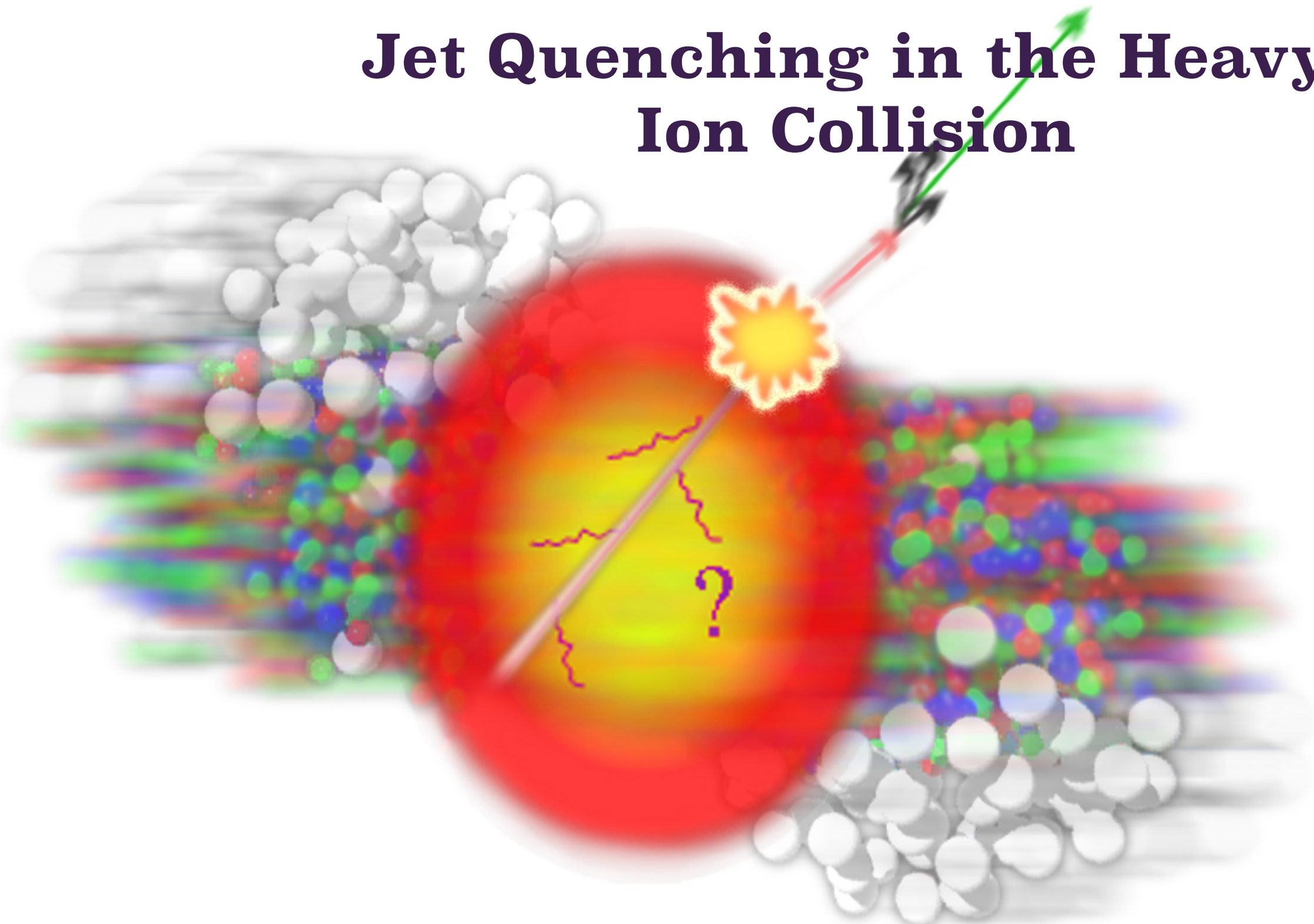


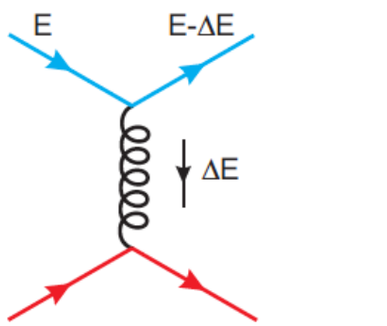

ATLAS Collaboration, ATLAS-CONF-2017-009.

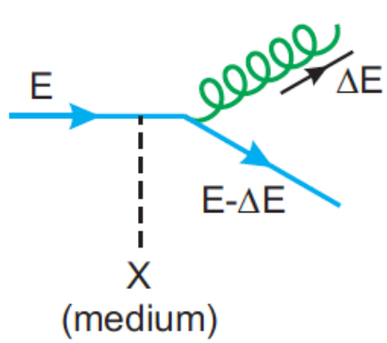
# Jet Quenching in the Heavy-Ion Collision

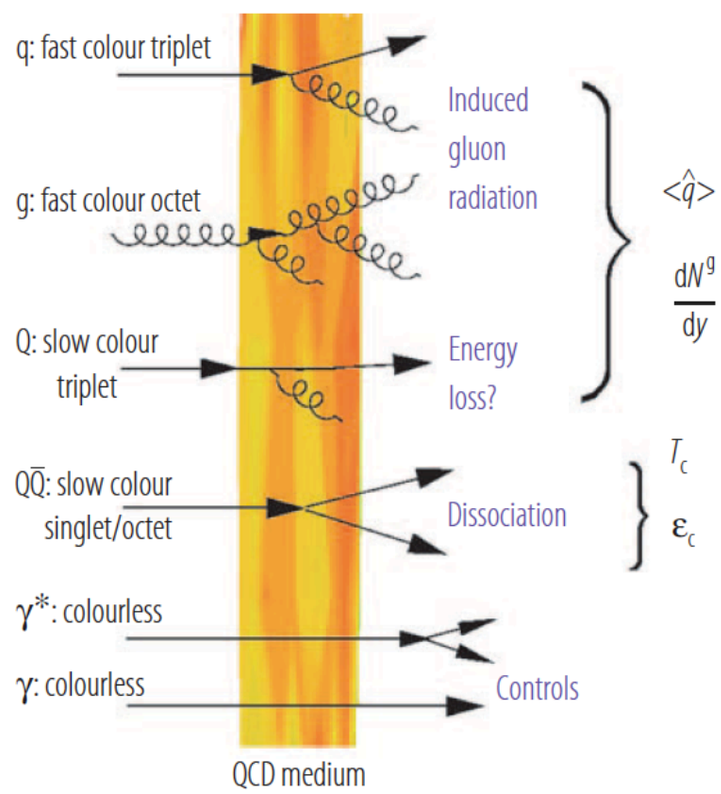


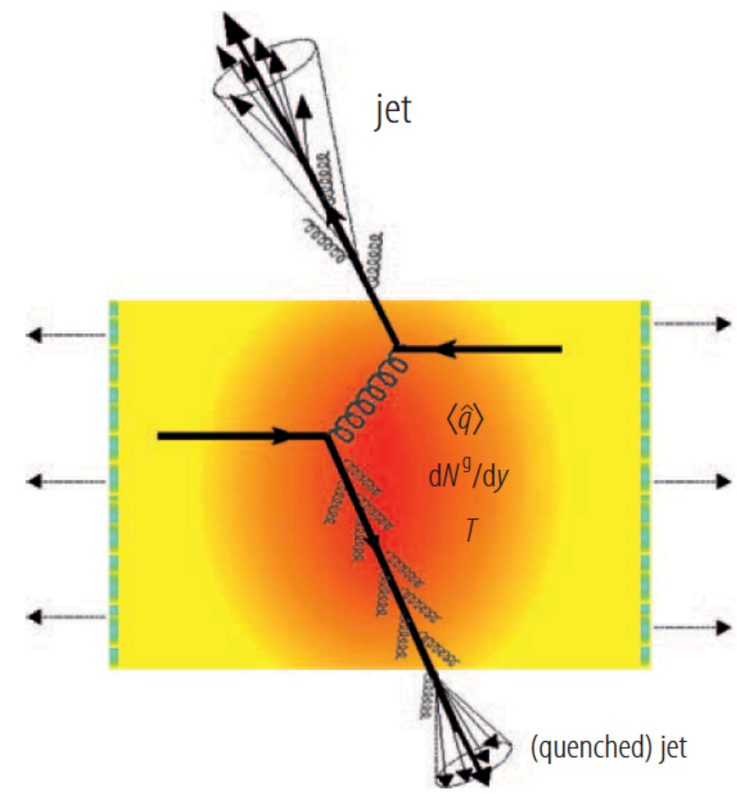
# Heavy-Ion Collision at the LHC

- The discrepancy between the measured $R_{NN}$ and 1 is a strong evidence of the QGP formed in the heavy-ion collision at the LHC in low centrality region.
- The quark and gluon travel in the hot dense phase, the QGP, will lose their energy by collisions and radiations.



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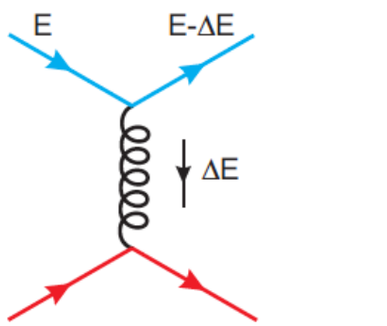
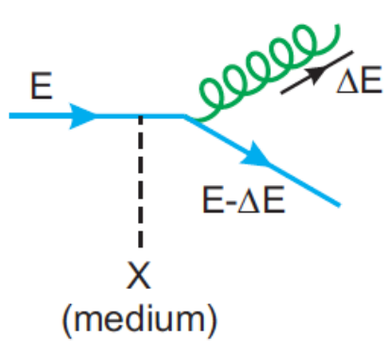
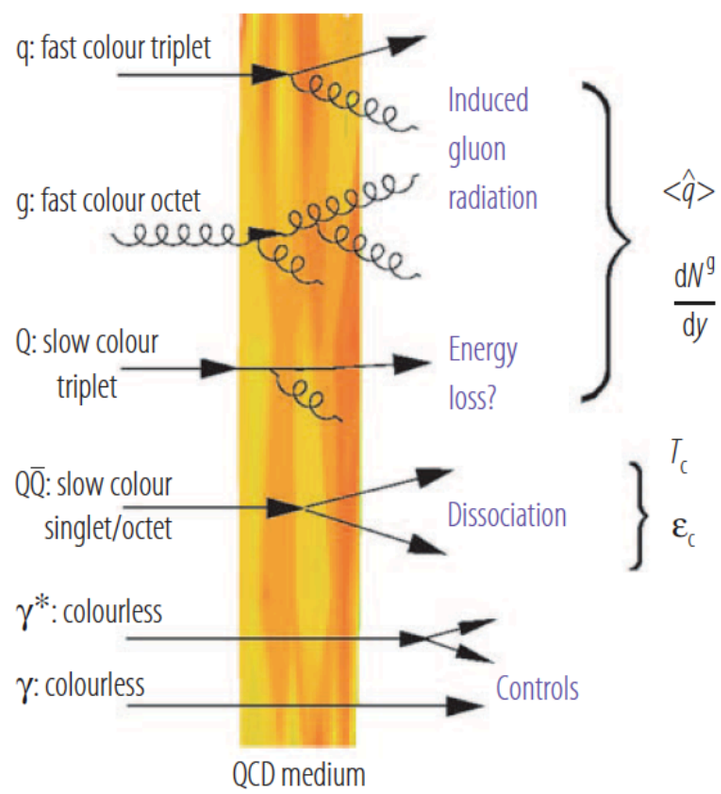
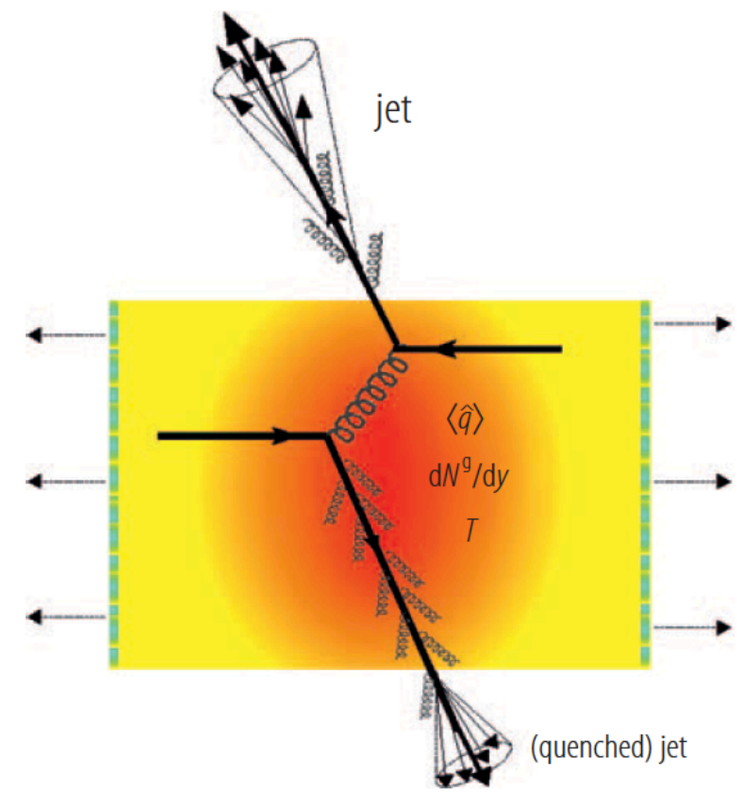
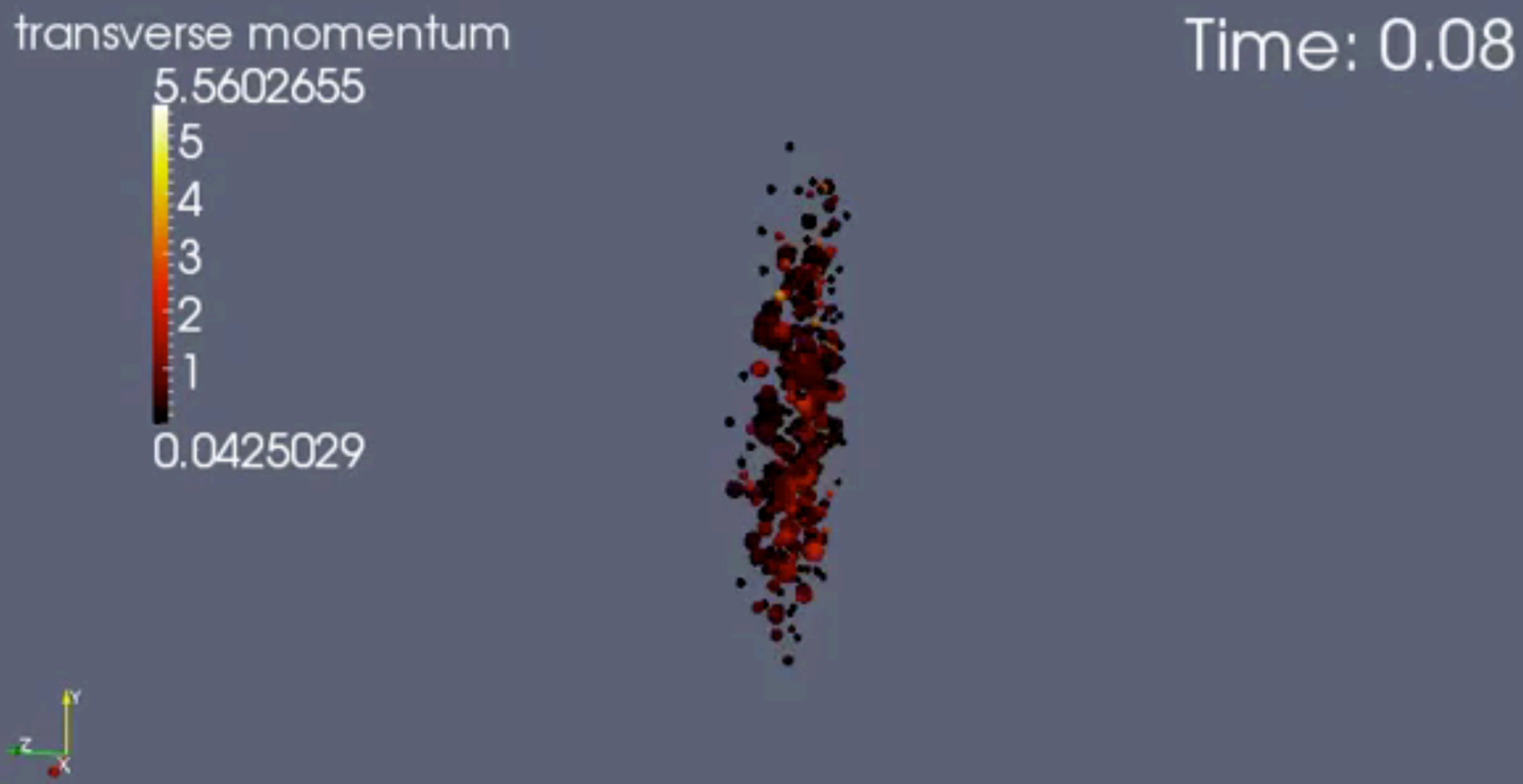


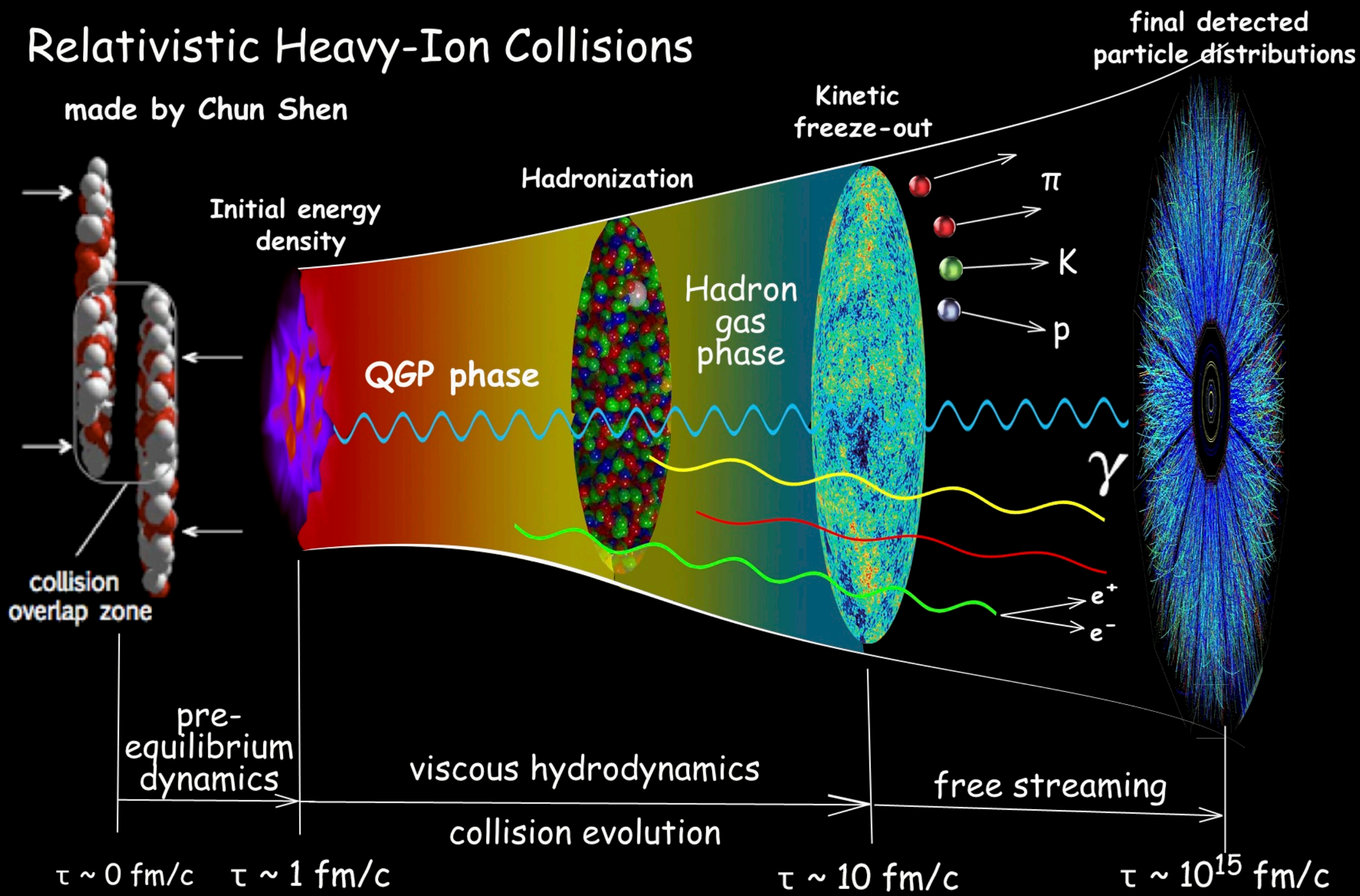




**Jet Quenching**


transverse momentum
5.5602655
5
4
3
2
1
0.0425029
Time: 0.08
Y
Z
X

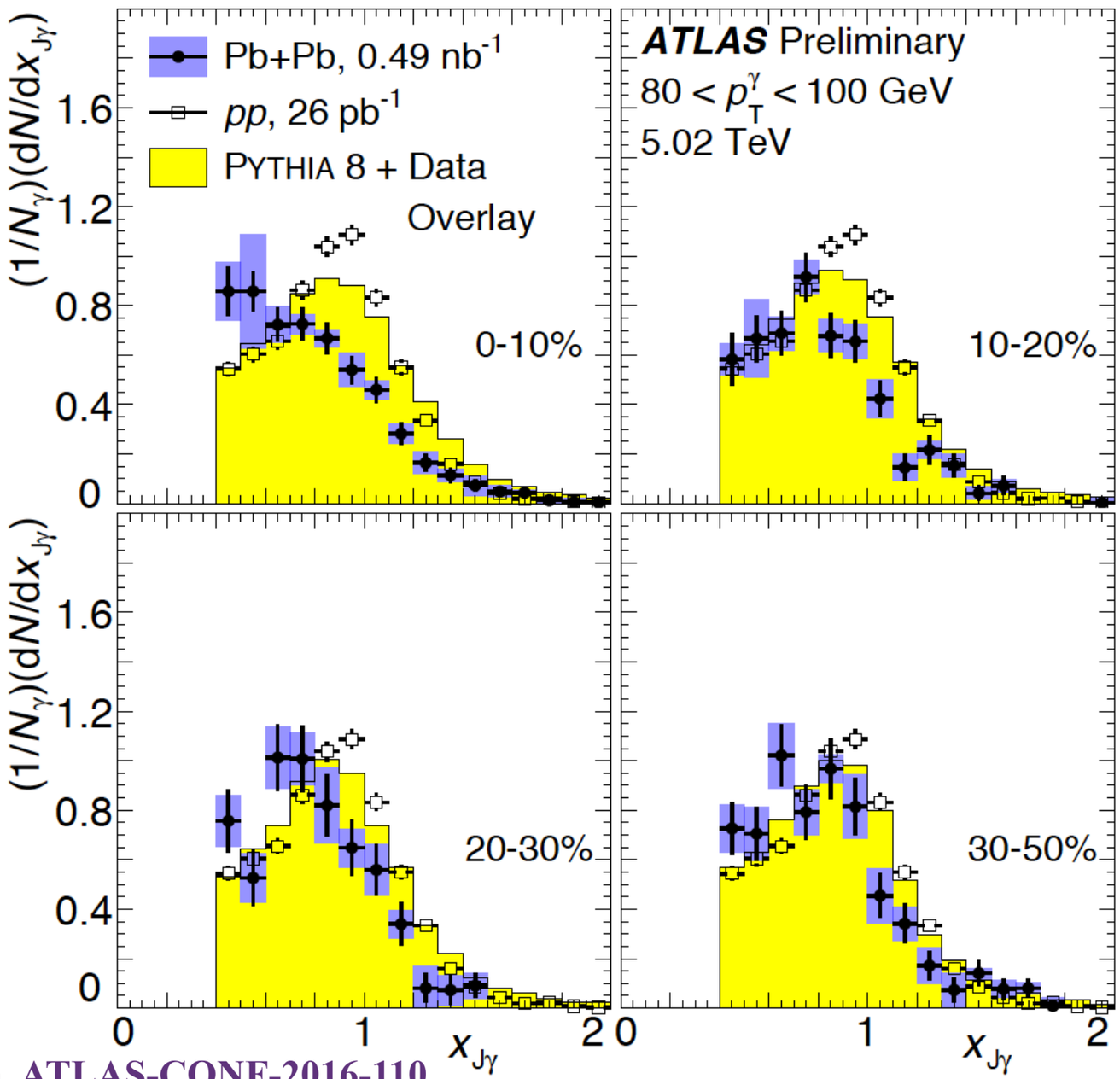
# Relativistic Heavy-Ion Collisions

made by Chun Shen



# Heavy-Ion Collision at the LHC

- Searching evidence of jet quenching in heavy-ion collision.
- Associated production of Objects which does not interact strongly with QGP (photon, leptonic decay $Z$, …) and single hard jet.




ATLAS Collaboration, ATLAS-CONF-2016-110.

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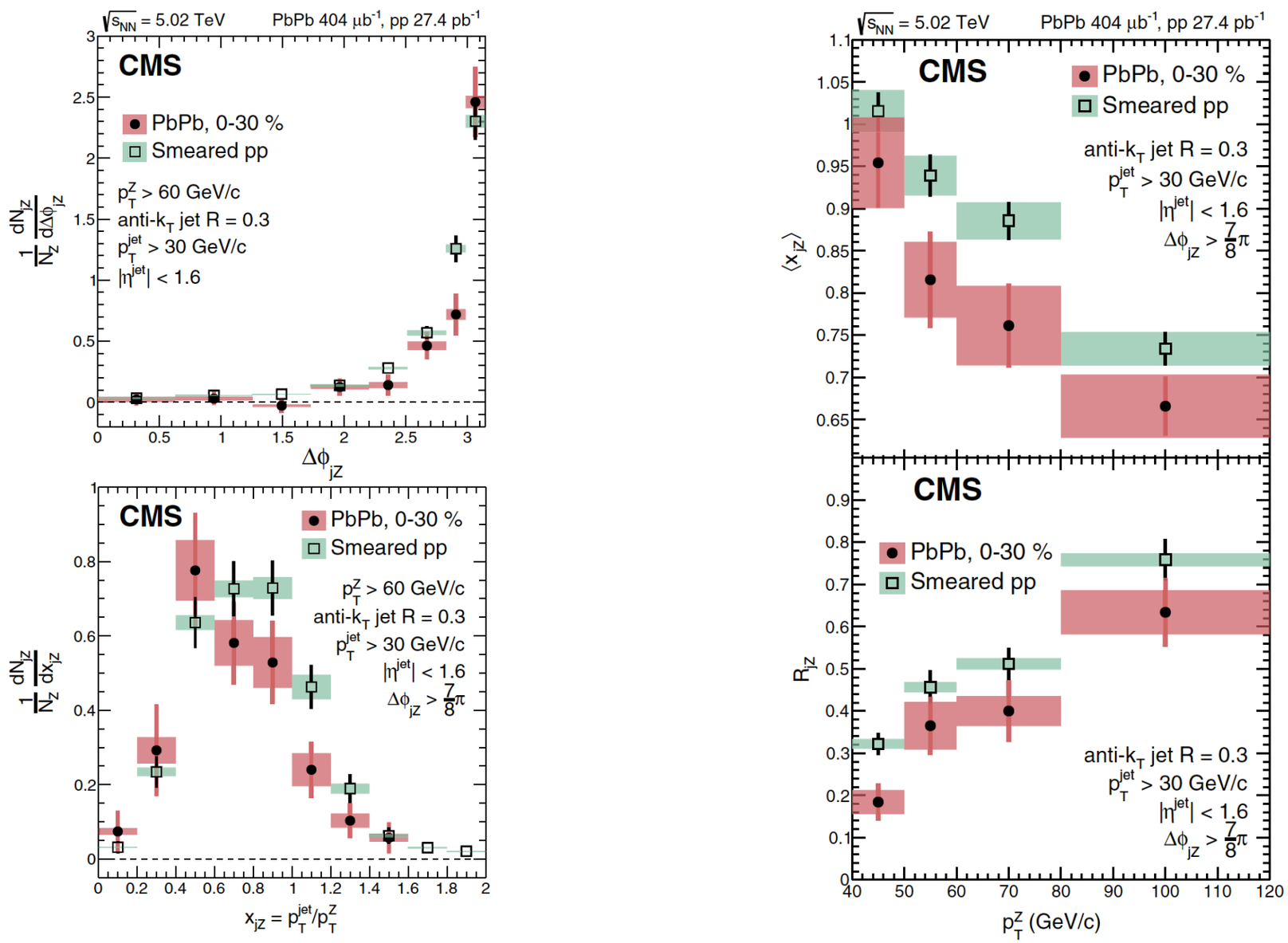


CMS Collaboration, Phys. Rev. Lett. 119 (2017) 082301.

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- But, wait wait wait!

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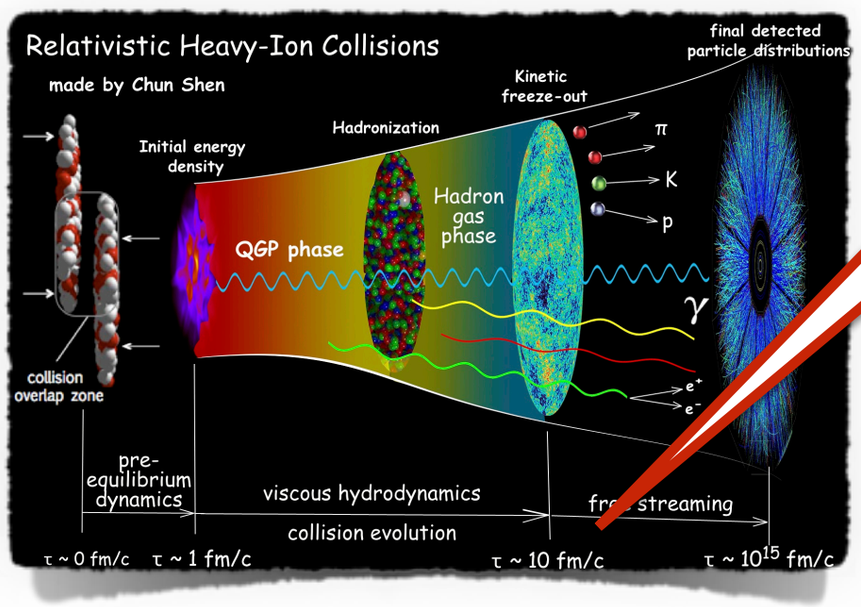


**Lifetime ~ 10fm/c**

How long is it?

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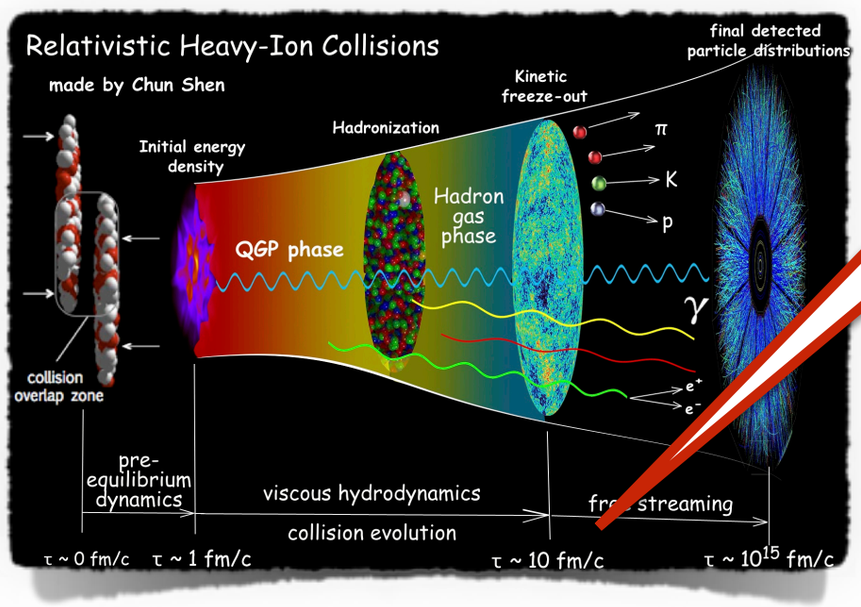


**Lifetime ~ 10fm/c**

$$1\mathrm{fm/c} = \frac{10^{-15}\mathrm{m}}{2.99792458 \times 10^{8}\mathrm{m/s}} = 3.33564 \times 10^{-24}\mathrm{s}$$

$$= \frac{3.33564 \times 10^{-24}\mathrm{s}}{6.58 \times 10^{-25}\mathrm{s} \cdot \mathrm{GeV}} = \frac{1}{197\mathrm{MeV}}$$

# Heavy-Ion Collision at the LHC

- Who is who?

$$\psi \sim \exp\left(-\frac{ip \cdot x}{\hbar}\right) \sim \exp\left(-\frac{i(m - i\Gamma)\tau}{\hbar}\right)$$

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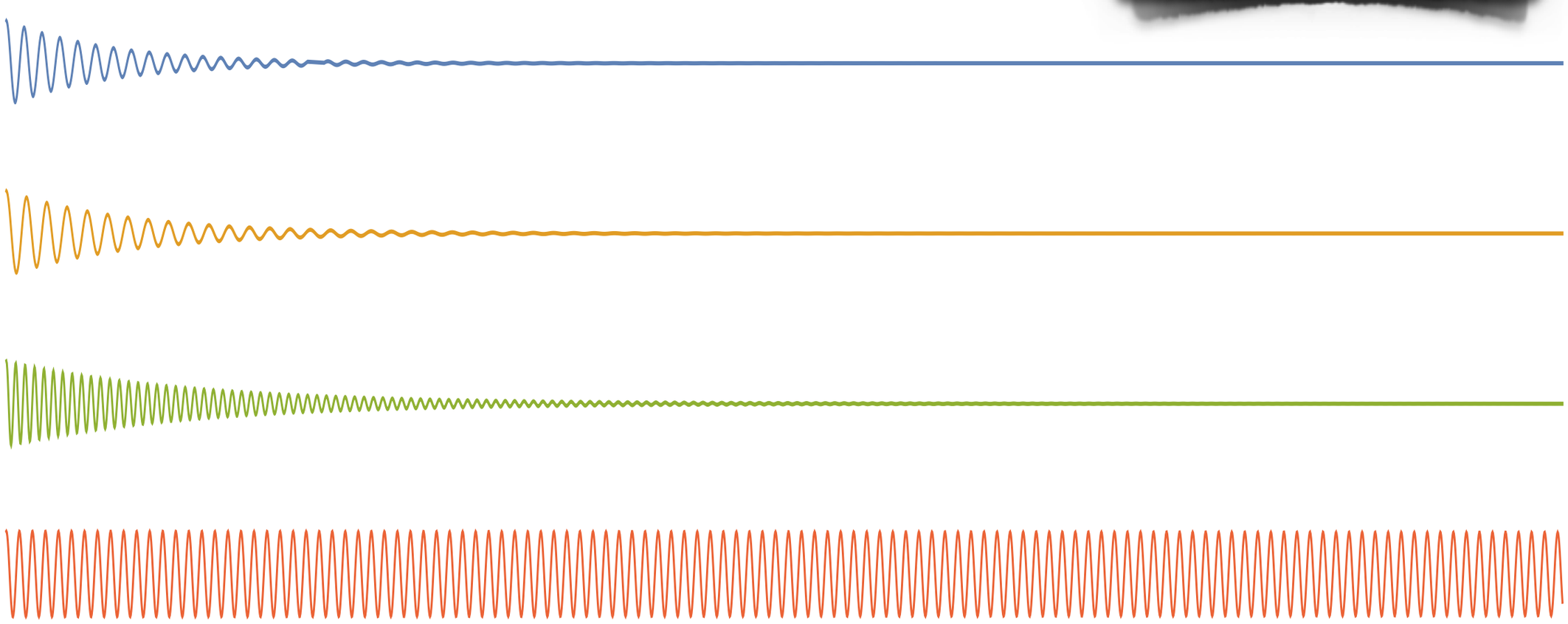
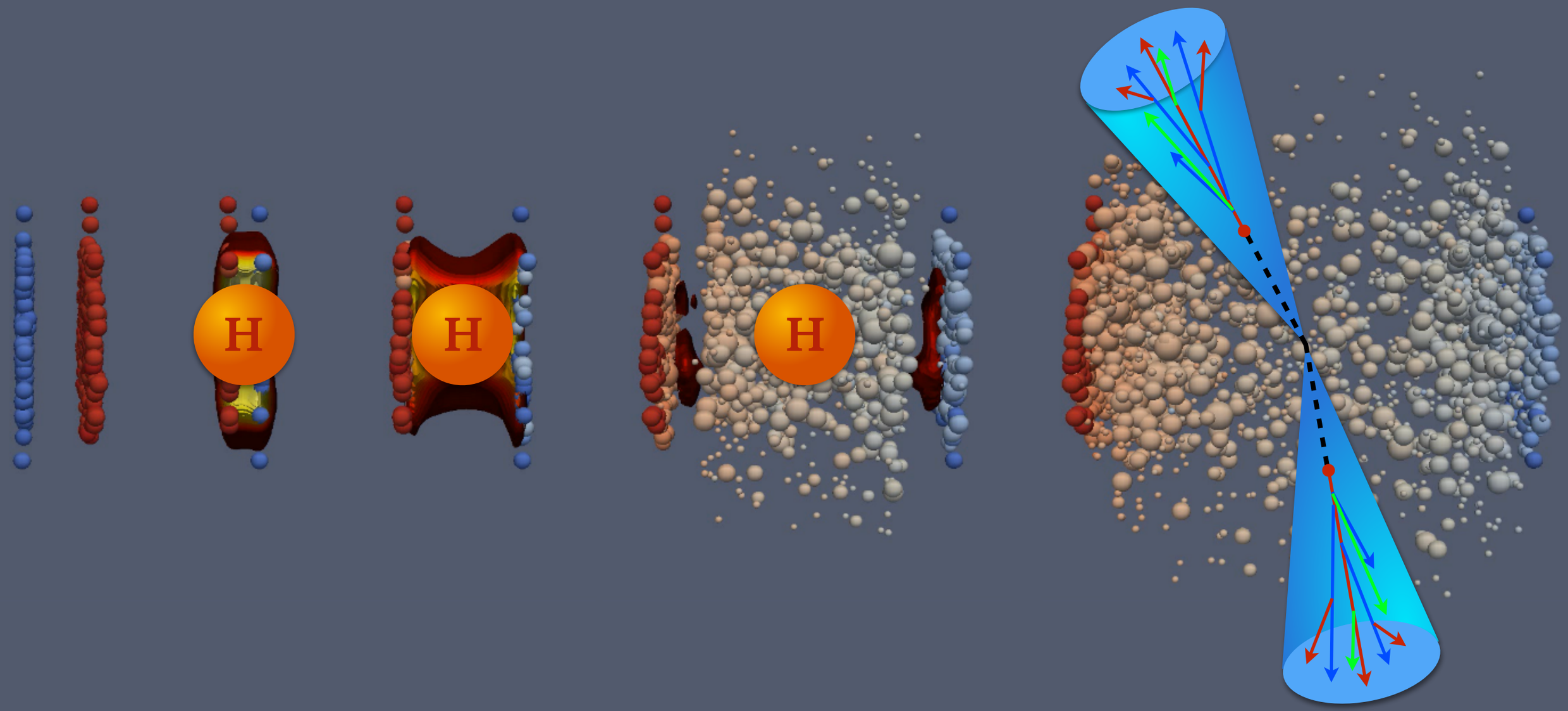


# Heavy-Ion Collision at the LHC

- There is a fundamental particle whose width is smaller than 197MeV!

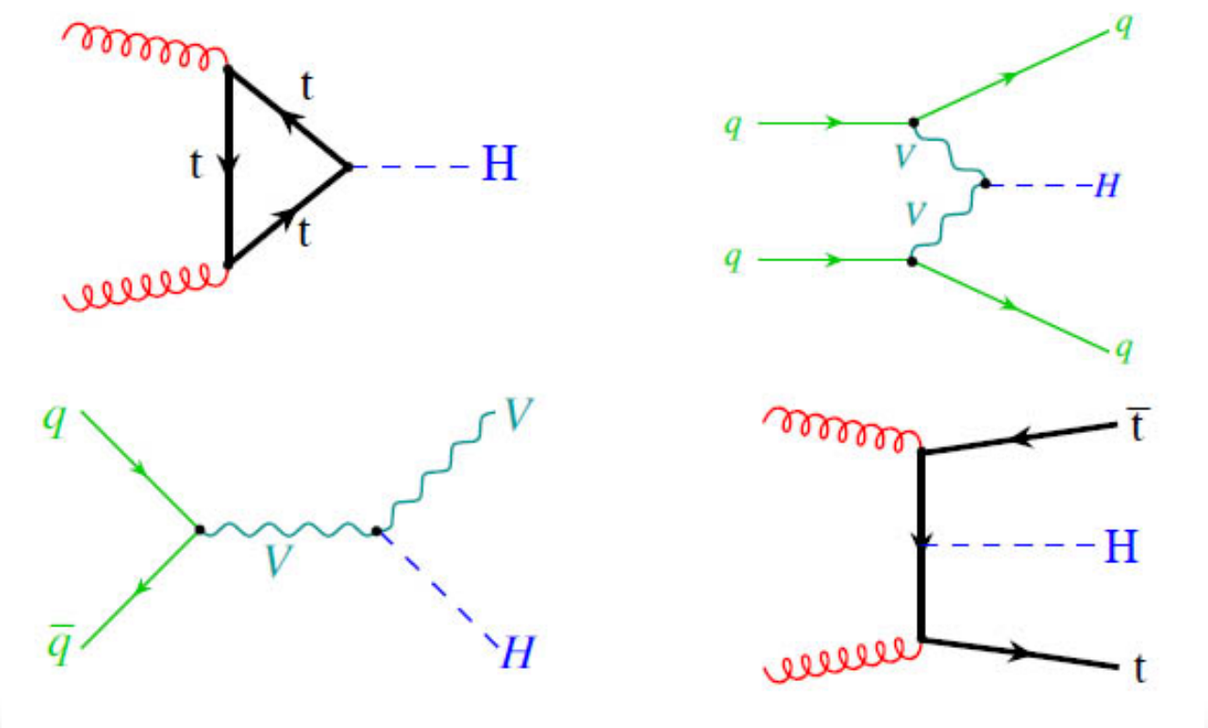
| 姓名 | 出生年月 | 出生地 | 参与相互作用 |  |
|---|---|---|---|---|
| Higgs boson | 2012年 7月 | 日内瓦街道 | 电弱相互作用, 汤川相互作用, … | |
| **宽度** | **体重** | **政治面貌** | **主要衰变道** | |
| 4.07MeV | 125GeV | 基本粒子 | ***bb, WW, gg, cc, ττ, ZZ…*** | |




# Higgs boson —— the Surviver in the QGP Fireball

# Higgs in Heavy-Ion Collision

- The production cross section.




$$d\sigma_{NN\to X}(s_{\rm NN}) = \langle T_{NN}(b)\rangle N \cdot f_{a/n}(x_a) \otimes N \cdot f_{b/n}(x_b) \otimes d\sigma_{ab\to X}(x_a x_b s_{\rm NN})$$

**Nuclear overlap function: for centrality ~ 0-10%, it is ~0.42;**

**Number of nucleons in a nuclear: for $^{208}$Pb, it is 208;**

**Nucleon parton distribution function: nCTEQ15 in our work;**

**Parton level hard scattering cross section: from pQCD.**

# Higgs in Heavy-Ion Collision

- The production cross section (xsec).

| process | PbPb($pp$) in nb(pb) | | |
|---|---|---|---|
| | 5.5 TeV | 11 TeV | 39.4 TeV |
| GF | 480(10.2) | 1556(35.2) | 9580(235) |
| VBF | 15.3(0.316) | 65.6(1.40) | 421(10.02) |
| $Zh$ | 10.2(0.230) | 28.1(0.687) | 147(3.97) |
| $W^+h$ | 8.38(0.162) | 21.8(0.716) | 94.2(3.19) |
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**Largest xsec, but huge background and hard to trigger** 🙁

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**Small xsec, and $W$ decay? Hadronic — large background and trigger, leptonic — missing energy** 🙁

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**Large xsec, two hard forward jets in vacuum, but will be quenched** 🙁

**Small xsec, and $W$ decay? Hadronic — large background and trigger, leptonic — missing energy** 🙁

**Small xsec. But with leptonic decay $Z$ — energetic dilepton with invariant mass ~ $m_Z$, less background and easy to trigger** 🙂

# Higgs in Heavy-Ion Collision

- A successful example of leptonic decay *Z* reconstruction in heavy-ion collision at the LHC.
- Electron-positron trigger:

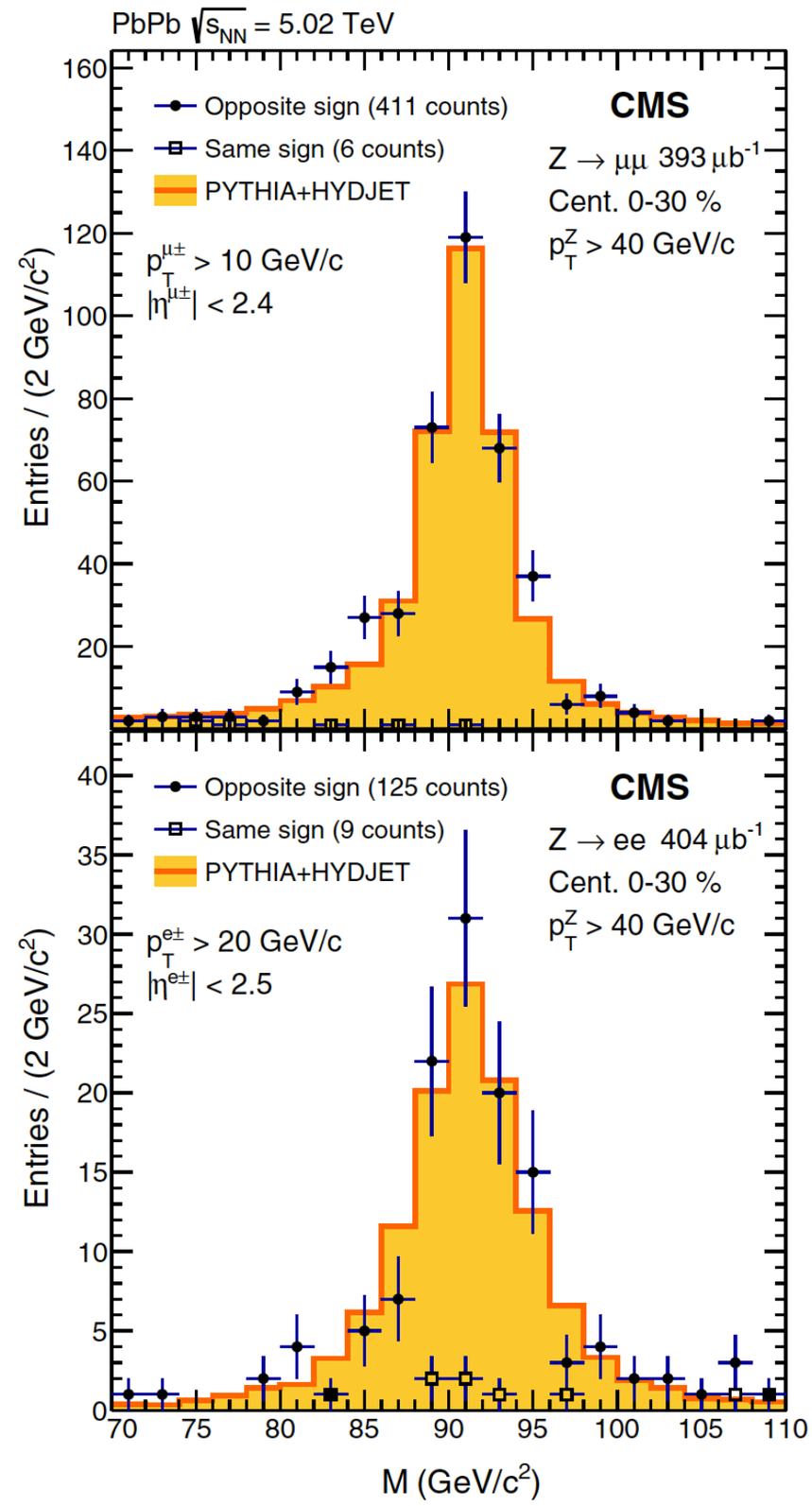
$$e^+ \text{ and } e^-, \quad |\eta| < 2.5, \; E_{\mathrm{T}} > 15\mathrm{GeV}$$

- Single muon trigger:

$$|\eta| < 2.4, \; p_{\mathrm{T}} > 15\mathrm{GeV}$$

- Di-muon trigger:

$$\mu^+ \text{ and } \mu^-, \quad |\eta| < 2.4, \; p_{\mathrm{T}} > 10\mathrm{GeV}$$




CMS Collaboration, Phys. Rev. Lett. 119 (2017) 082301.

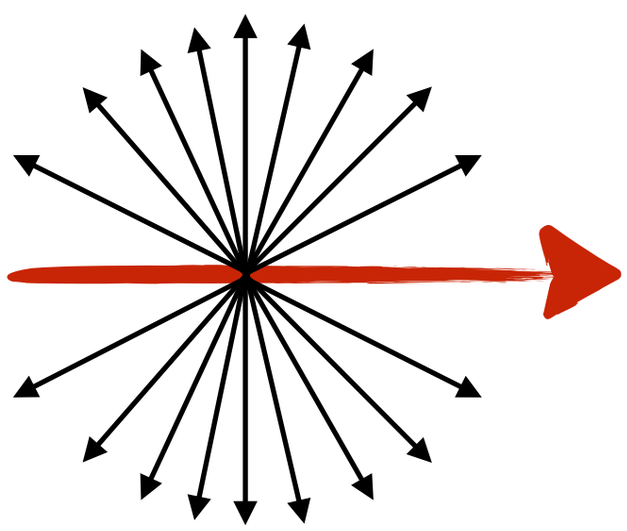
# Higgs in Heavy-Ion Collision

- Hadronic decay Higgs boson.
- Question 1: Is *b*-quark quenched as much as light quarks and gluons?
  - QCD calculation: “dead cone” effect.

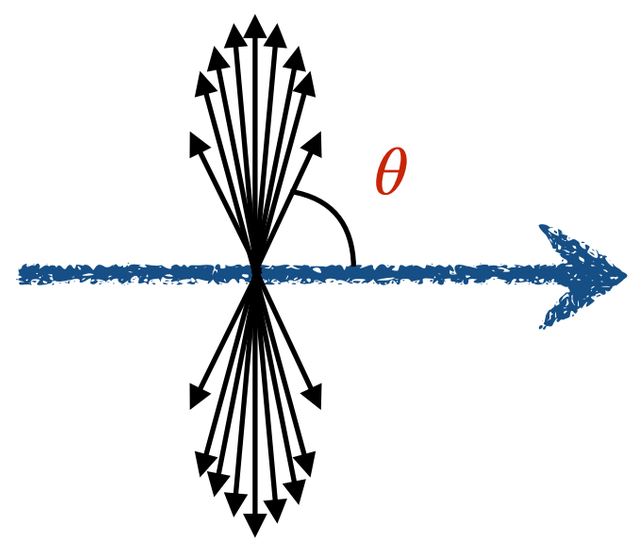
# Higgs in Heavy-Ion Collision

- Hadronic decay Higgs boson.
- Question 1: Is *b*-quark quenched as much as light quarks and gluons?
  - QCD calculation: “dead cone” effect.

$$\omega \frac{dI_{\mathrm{rad},Q}}{d\omega dk_\perp^2} \approx \omega \frac{dI_{\mathrm{rad}}}{d\omega dk_\perp^2} \frac{1}{1+\frac{M_Q^2}{E_Q^2\theta^2}}$$



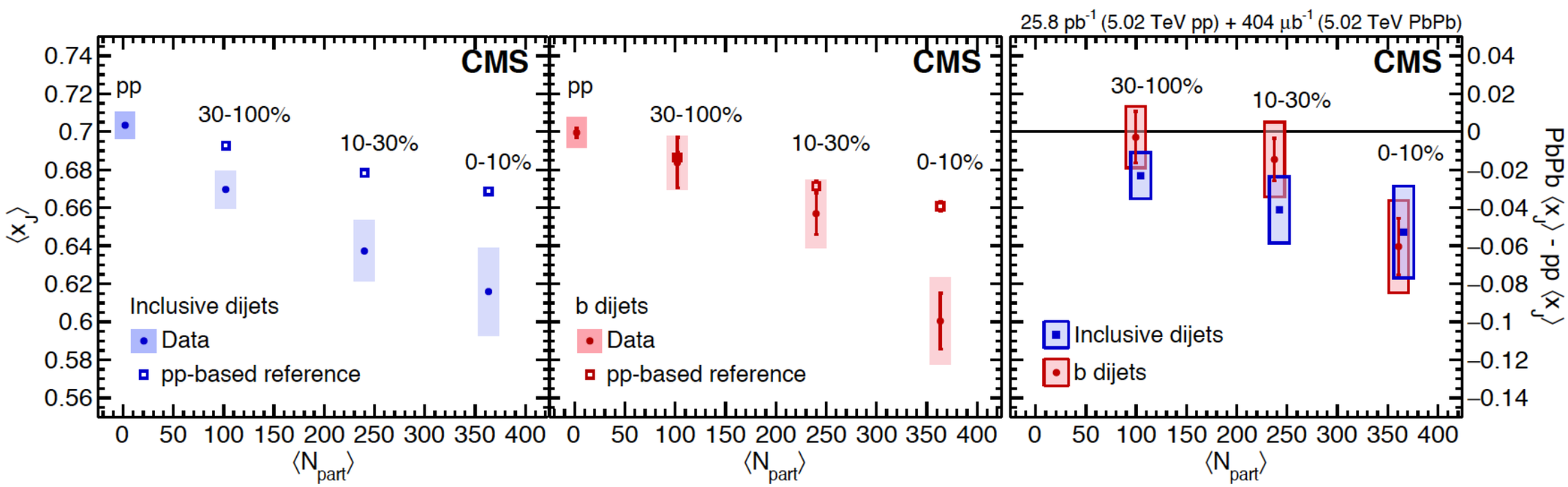
**Gluon, light quarks**




**Heavy quarks**

# Higgs in Heavy-Ion Collision

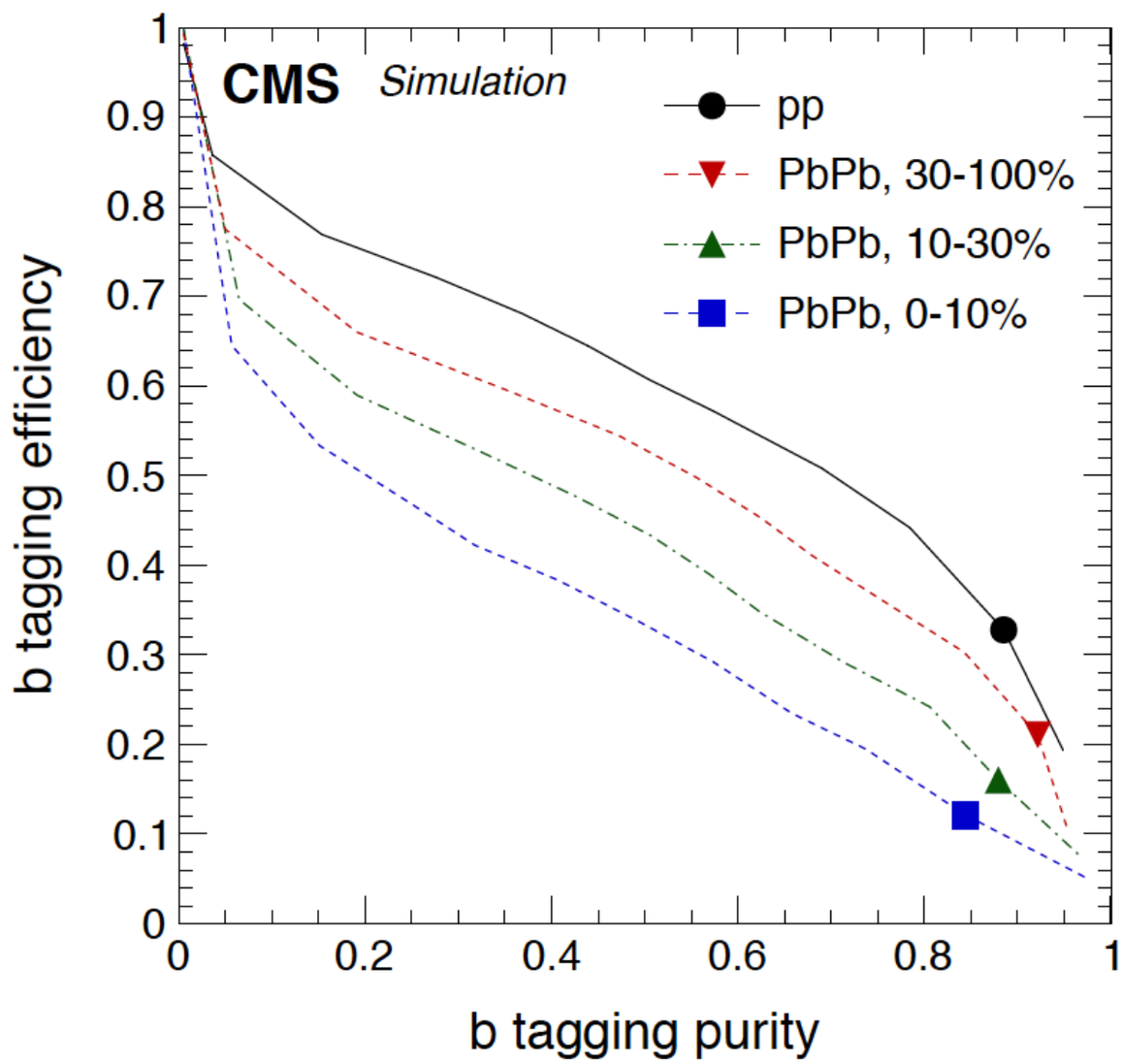
- Hadronic decay Higgs boson.
- Question 1: Is *b*-quark quenched as much as light quarks and gluons?
  - QCD calculation: “dead cone” effect.
  - Experiment (which can be understand theoretically):




CMS Collaboration, arXiv:1802.00707[hep-ex].

# Higgs in Heavy-Ion Collision

- Hadronic decay Higgs boson.
- The *b*-quark jets are quenched as light-quark and gluon jets.
- Question 2: *b*-jet tagging efficiency?

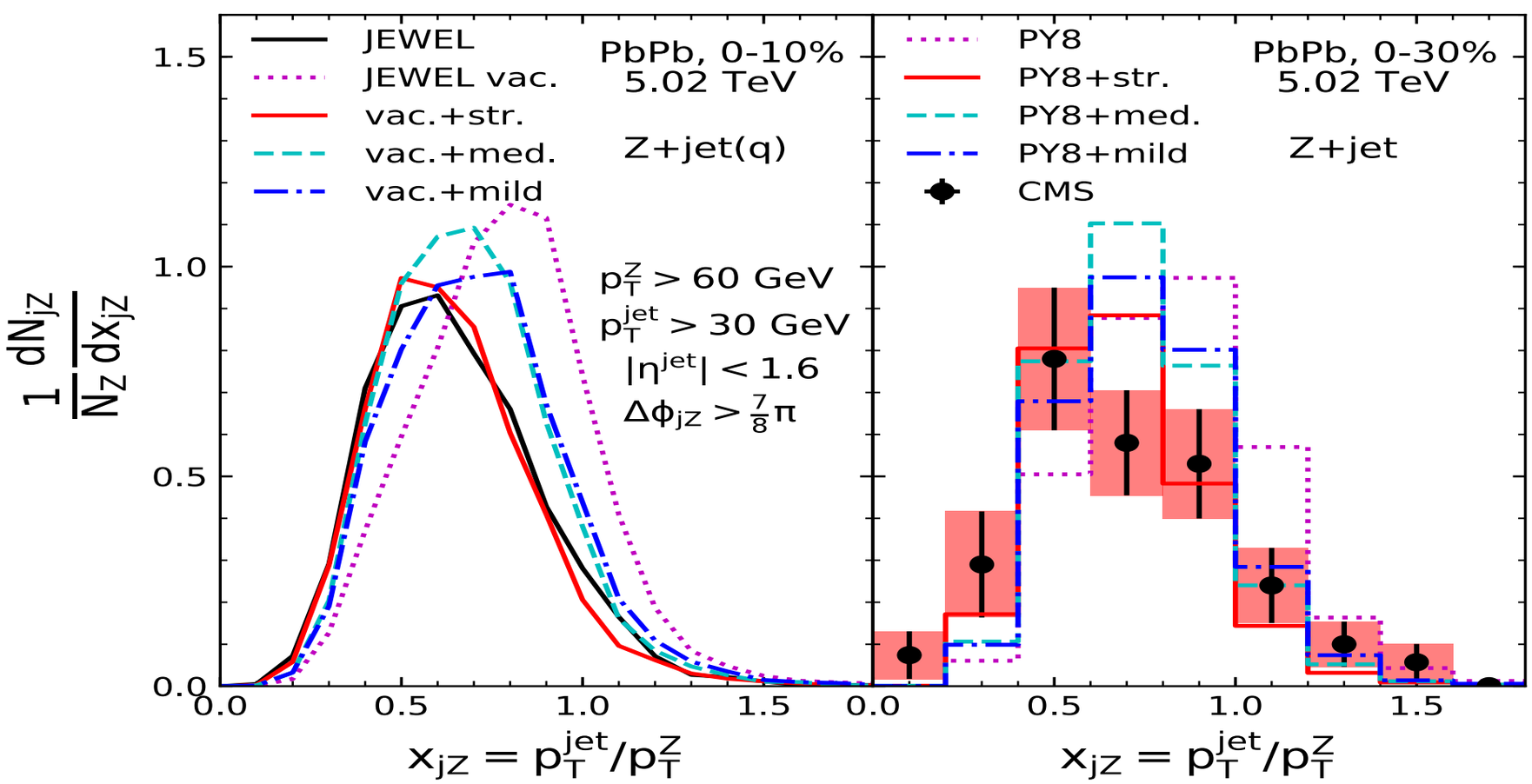



CMS Collaboration, JHEP 03 (2018) 181.

# Higgs in Heavy-Ion Collision

- Hadronic decay Higgs boson.
- The *b*-quark jets are quenched as light-quark and gluon jets.
- We formulate the transverse momentum loss of jet as (see our paper for the values of a, b and c):

$$\langle \delta p_{\mathrm{T}} \rangle = a p_{\mathrm{T}} + b \ln(p_{\mathrm{T}}/\mathrm{GeV}) + c,$$

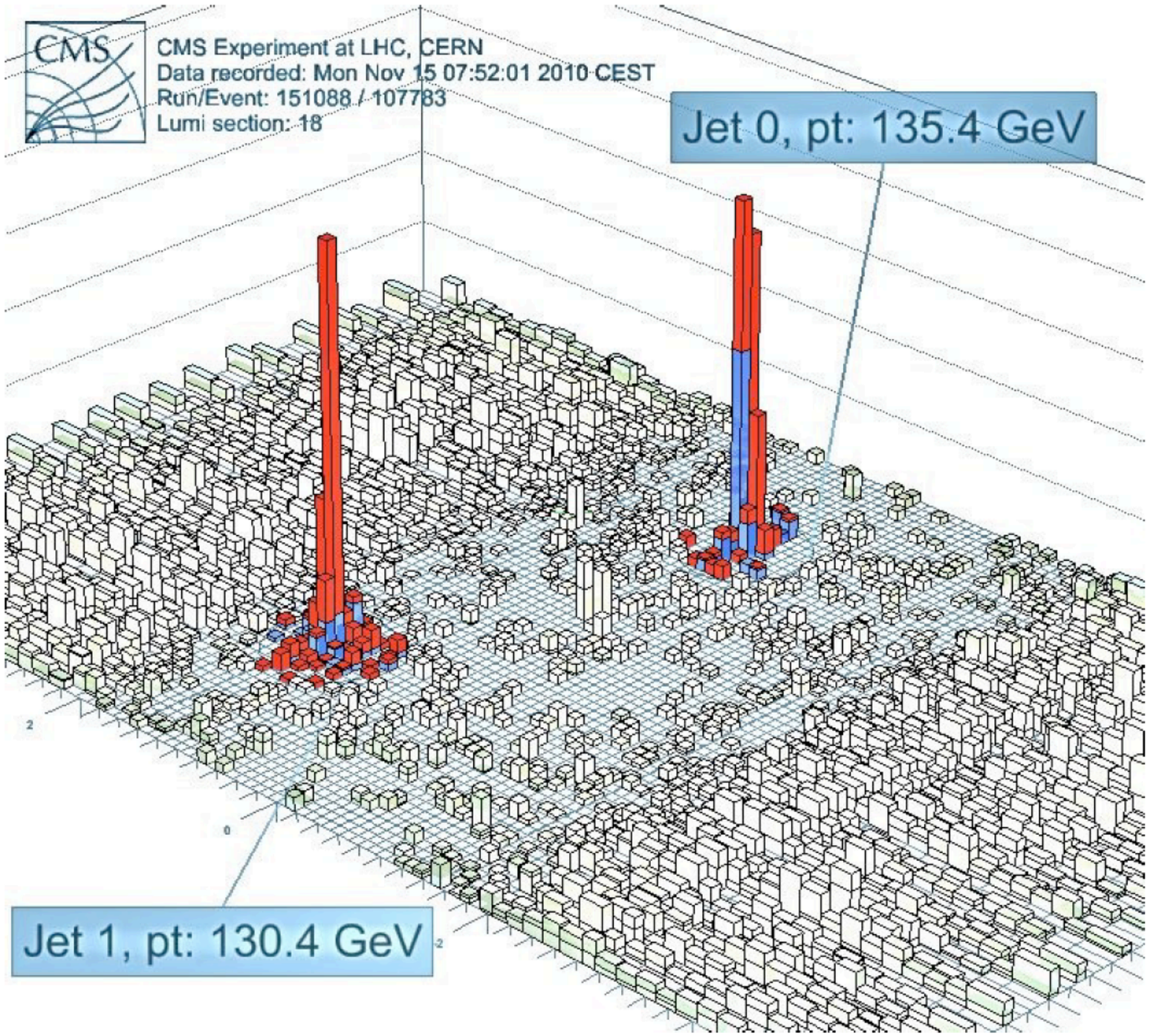


# Higgs in Heavy-Ion Collision

- Hadronic decay Higgs boson.
- The *b*-quark jets are quenched as light-quark and gluon jets.
- The *b*-jet tagging efficiency is hurt by a factor of ~ 0.6.
- However, we will use the same *b*-tagging efficiency as *pp*-collision and believe that our experimentalist colleges can improve it in the future.

# Higgs in Heavy-Ion Collision

- Smearing effect.



# Higgs in Heavy-Ion Collision

- Smearing effect.

$$\sigma(p_{\mathrm{T}}) = \sqrt{C^2 + \frac{S^2}{p_{\mathrm{T}}} + \frac{N^2}{p_{\mathrm{T}}^2}}.$$

$$C = 0.06,\ \ S = 1.0,\ \ N = 14.82 - \mathrm{centrality}(\%)/5.40$$

$p_{\mathrm{T}}$ in GeV

**CMS Collaboration, JHEP 03 (2018) 181.**

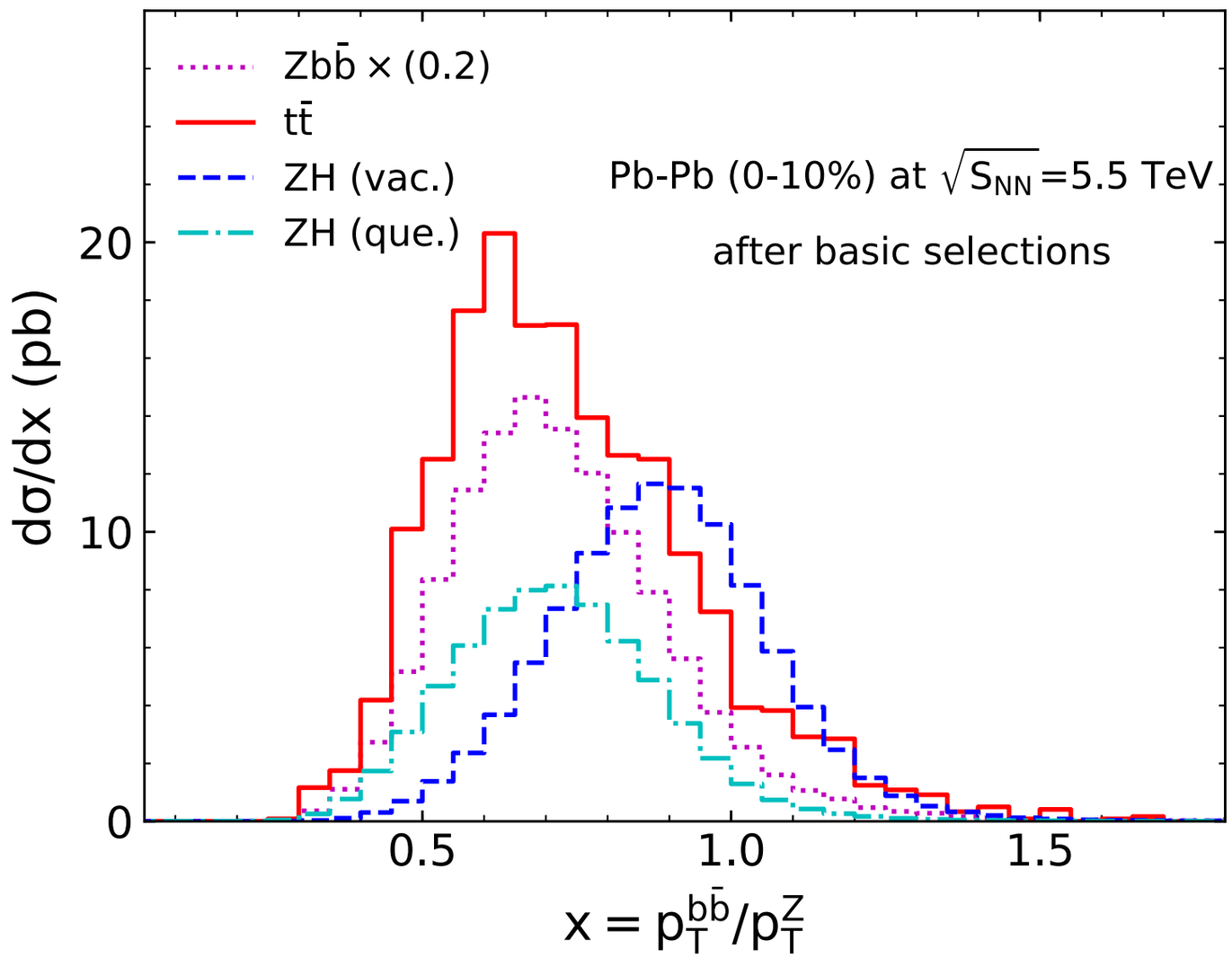
# Higgs in Heavy-Ion Collision

- Dominant SM backgrounds:
  - *Z*+*bb*;
  - *Z*+*bc, Z*+*cc*;
  - Top-pair;
- We simulate the signal and background with MadGraph at parton level and add the smearing and jet quenching effect with the formulas to understand the cuts.

$$p_{\rm T}^{\ell} > 15{\rm GeV},\ |\eta^{\ell}| < 2.5,\ \Delta R_{\ell\ell} > 0.2,$$
$$\text{anti-}k_{\rm T}\ \text{jet}\ ,\ R = 0.3,\ p_{\rm T}^{j} > 30{\rm GeV},\ |\eta^{\ell}| < 1.6,\ \Delta R_{j\ell} > 0.3,$$
$$|m_{\ell\ell} - m_Z| < 10{\rm GeV},\ \Delta R_{bb} < 2.0,\ p_{\rm T}^{Z} \equiv p_{\rm T}^{\ell\ell} > 100{\rm GeV}.$$

# Higgs in Heavy-Ion Collision

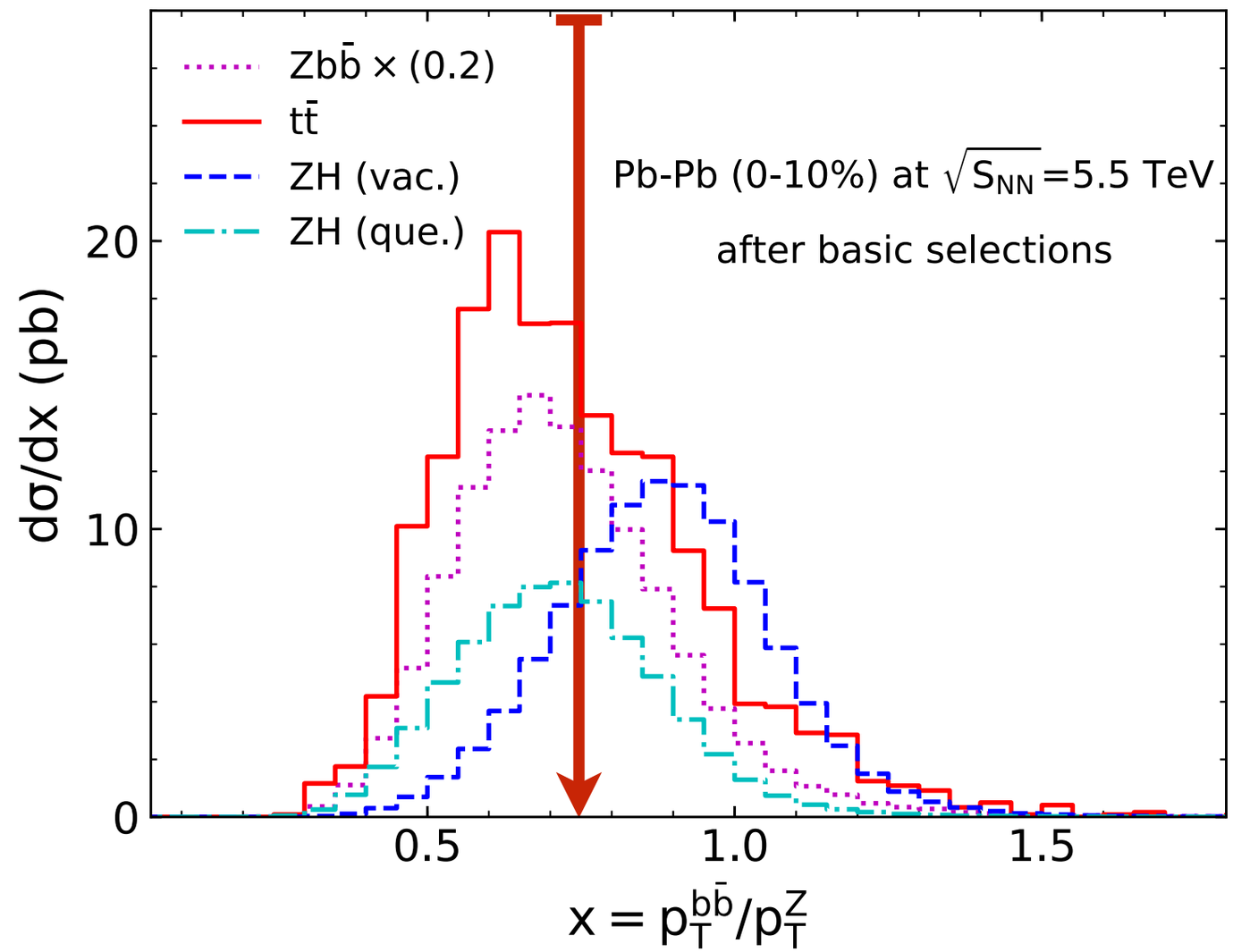
- We simulate the signal and background with MadGraph at parton level and add the smearing and jet quenching effect with the formulas.
- Sherpa is used to generate MC events and shower them. The jets is reconstructed with Fastjet.
- The signal and top-pair backgrounds xsecs are rescaled to NNLO.
- *b*-jet tagging efficiency is chosen to be 80%.



# Higgs in Heavy-Ion Collision

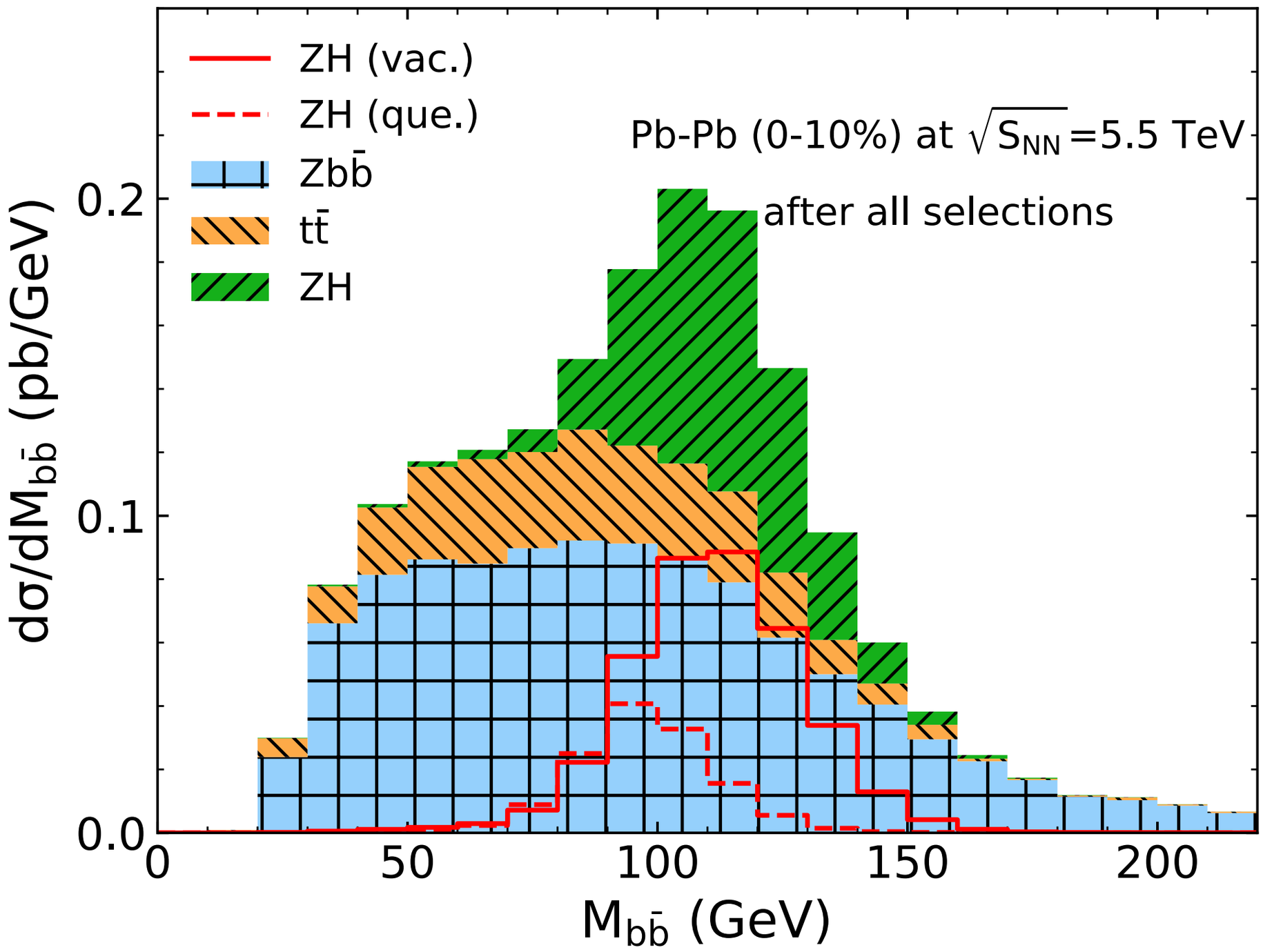
- The jet quenching effect introduces a significant transverse momentum imbalance between the dilepton system and the *b*-jet pair system.
- We can suppress the *Zbb* background with more cuts:

$$p_{\mathrm{T}}^{\text{leading-}b} > 60\mathrm{GeV},$$
$$x \equiv p_{\mathrm{T}}^{bb}/p_{\mathrm{T}}^{\ell\ell} > 0.75.$$



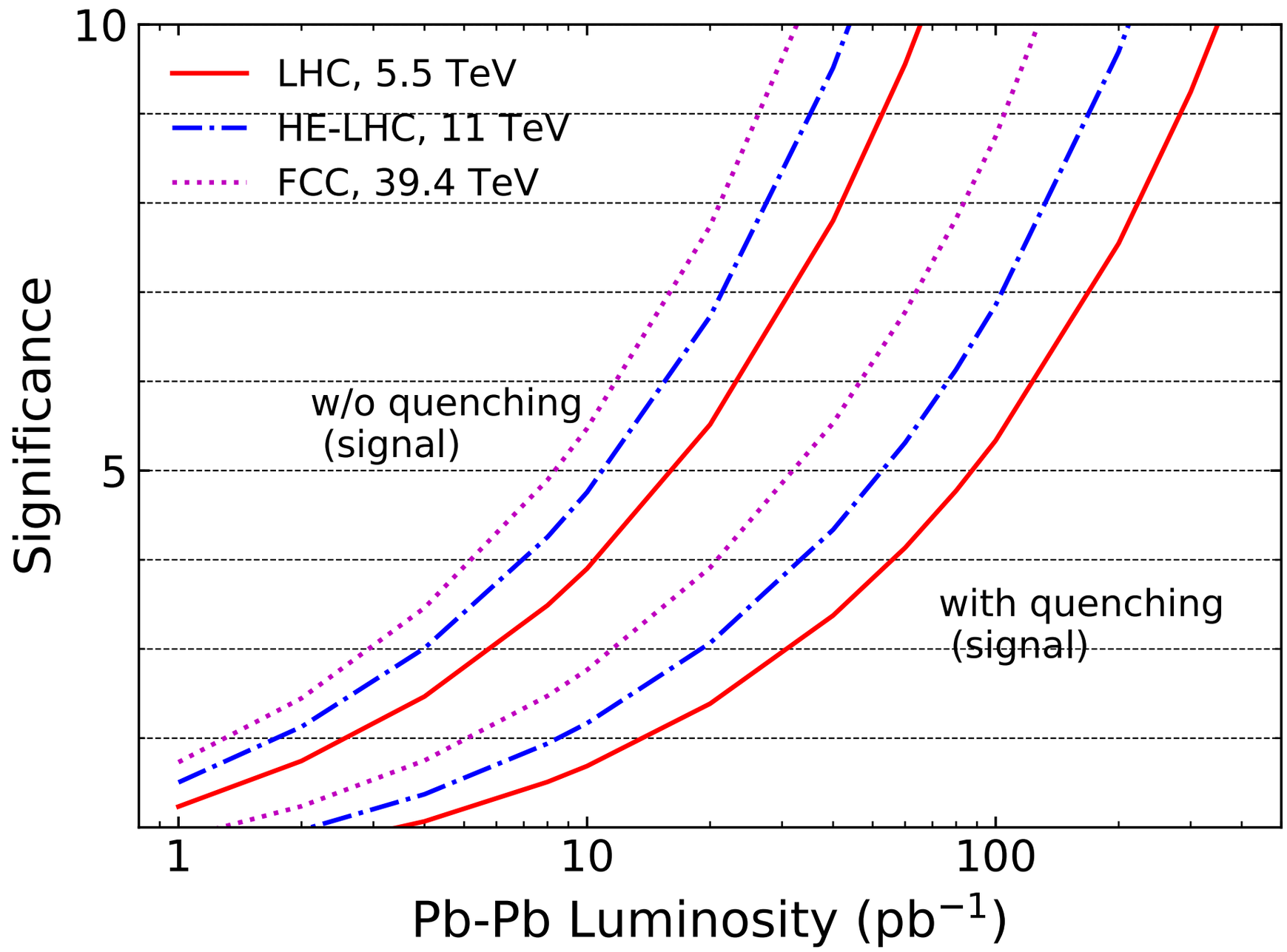
# Higgs in Heavy-Ion Collision

- After all cuts.

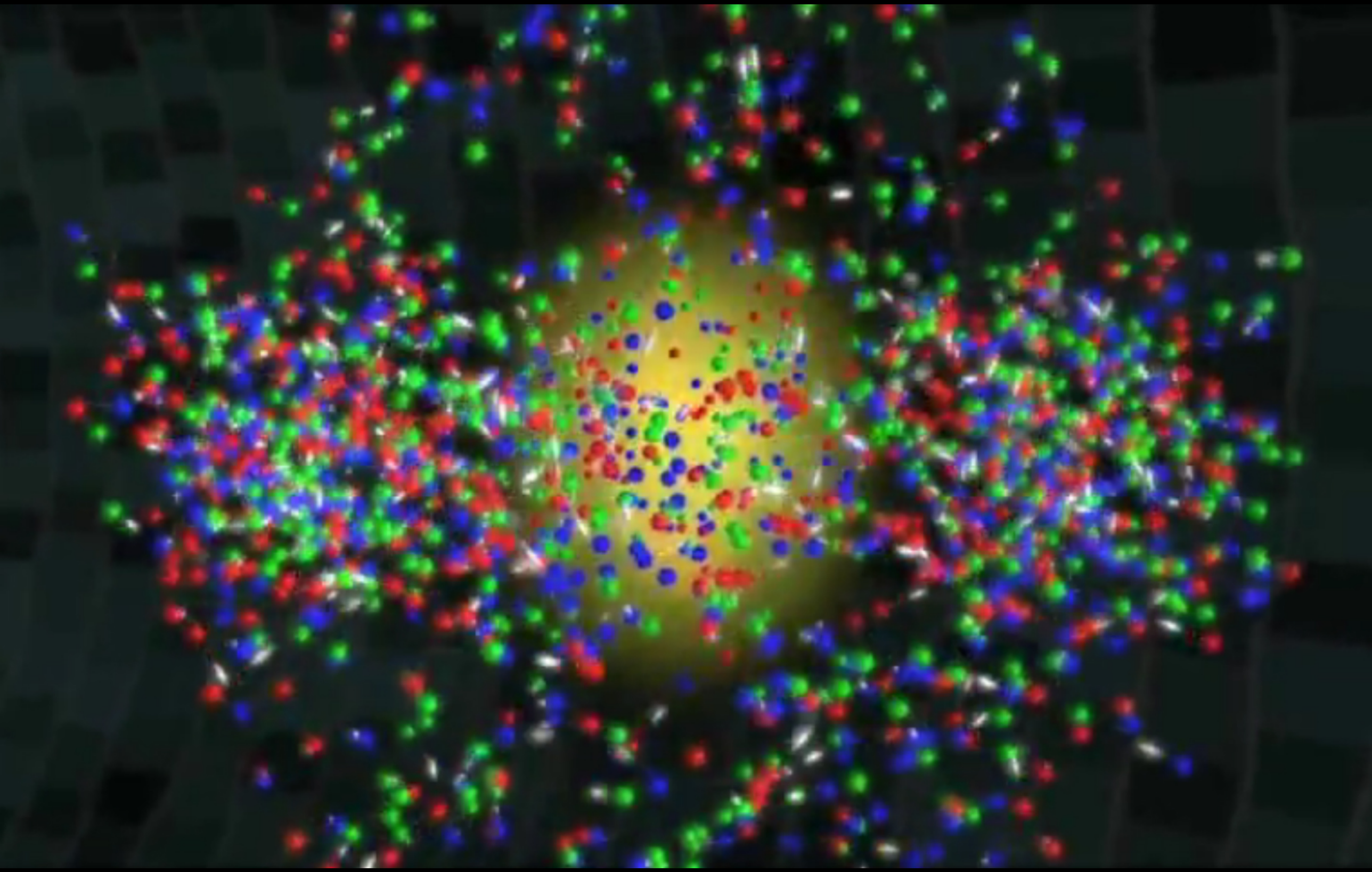


# Higgs in Heavy-Ion Collision

- Significance at the LHC and future hadron colliders.



# Summary and Outlook



# Summary

- We propose to study the production and decays of the Higgs boson in heavy-ion collision.
- It is shown that the screening from QGP on QCD partons serves a natural probe of the lifetime of the Higgs boson and the behavior of the Higgs boson in QGP.

# Outlook

- The luminosity

| | Unit | FCC Injection | FCC Collision | |
|---|---|---|---|---|
| Operation mode | | Pb | Pb–Pb | p–Pb |
| Beam energy | [TeV] | 270 | 4100 | 50 |
| $\sqrt{s_{\mathrm{NN}}}$ | [TeV] | - | 39.4 | 62.8 |
| No. of bunches per LHC injection | - | 518 | 518 | 518 |
| No. of bunches in the FCC | - | 2072 | 2072 | 2072 |
| No. of particles per bunch | [$10^8$] | 2.0 | 2.0 | 164 |
| Transv. norm. emittance | [$\mu$m] | 1.5 | 1.5 | 3.75 |
| Number of IPs in collision | - | - | 1 | 1 |
| Crossing-angle | [$\mu$rad] | - | 0 | |
| Initial luminosity | [$10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$] | - | 24.5 | 2052 |
| Peak luminosity | [$10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$] | - | 57.8 | 9918 |
| Integrated luminosity per fill | [$\mu\mathrm{b}^{-1}$] | - | 553 | 158630 |
| Average luminosity | [$\mu\mathrm{b}^{-1}$] | - | 92 | 20736 |
| Time in collision | [h] | - | 3 | 6 |
| Assumed turnaround time | [h] | - | 1.65 | 1.65 |
| Integrated luminosity/run | [$\mathrm{nb}^{-1}$] | - | 33 | 8000 |

**CERN Yellow Reports, Physics at the FCC-hh, a 100 TeV pp collider, Chapter 4: Heavy Ions at the Future Circular Collider.**

# Outlook

- The luminosity

| | p@LHC | Pb@LHC | p@FCC | Pb@FCC |
|---|---|---|---|---|
| *Extracted beam on an external target* | liq. H / Be / W | liq. H / Be / W | liq. H / Be / W | liq. H / Be / W |
| Extracted flux [$s^{-1}$] | $5 \cdot 10^8$ | $2 \cdot 10^5$ | $1.5 \cdot 10^9$ | $5.8 \cdot 10^5$ |
| $\mathcal{L}(\mu b^{-1}s^{-1})$ | 2000 / 62 / 31 | 0.8 / 0.025 / 0.013 | 6000 / 190 / 93 | 2.32 / 0.072 / 0.036 |
| $\int dt\mathcal{L}(pb^{-1}yr^{-1})$ | 20000 / 620 / 310 | 0.8 / 0.025 / 0.013 | 60000 / 1900 / 930 | 2.32 / 0.072 / 0.036 |
| *Internal gas target* (SMOG type) | ideal gas | ideal gas | ideal gas | ideal gas |
| $\mathcal{L}(\mu b^{-1}s^{-1})$ | 10 | 0.001 | 8.9 | $3.3 \cdot 10^{-3}$ |
| $\int dt\mathcal{L}(pb^{-1}yr^{-1})$ | 100 | 0.001 | 89 | $3.3 \cdot 10^{-3}$ |
| *Internal gas storage-cell target* (HERMES type) | $H_2$ / $D_2$ / Xe | $H_2$ / $D_2$ / Xe | $H_2$ / $D_2$ / Xe | $H_2$ / $D_2$ / Xe |
| $\mathcal{L}(\mu b^{-1}s^{-1})$ | 900 / 1200 / 140 | 0.12 / 0.15 / 0.02 | 800 / 1100 / 120 | 0.3 / 0.4 / 0.05 |
| $\int dt\mathcal{L}(pb^{-1}yr^{-1})$ | 9000 / 12000 / 1400 | 0.12 / 0.15 / 0.02 | 8000 / 11000 / 1200 | 0.3 / 0.4 / 0.05 |

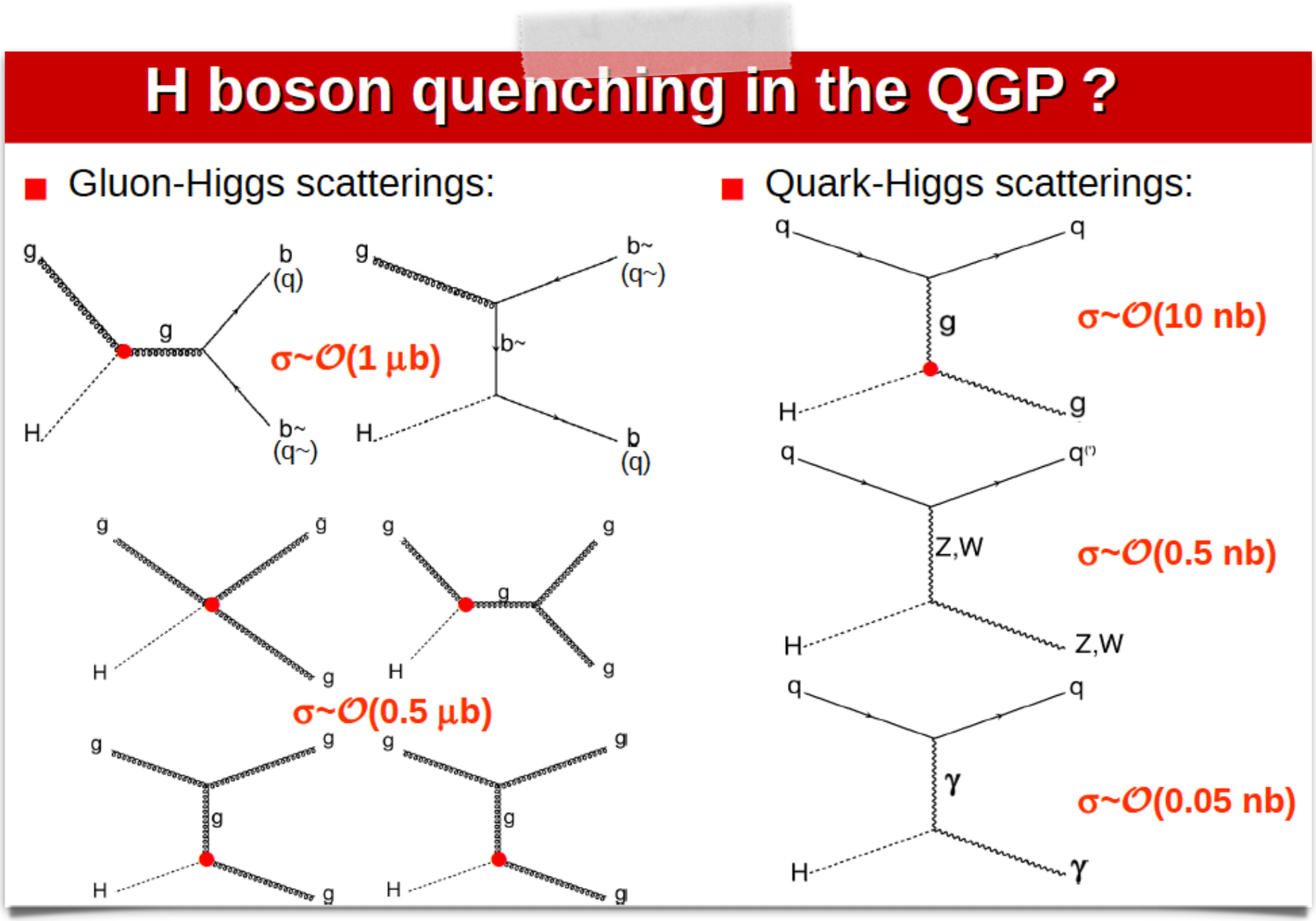
**CERN Yellow Reports, Physics at the FCC-hh, a 100 TeV pp collider, Chapter 4: Heavy Ions at the Future Circular Collider.**

# Outlook

- The luminosity
- More modern analysis methods
- A self-consistent simulation package
- Other channels

# Outlook

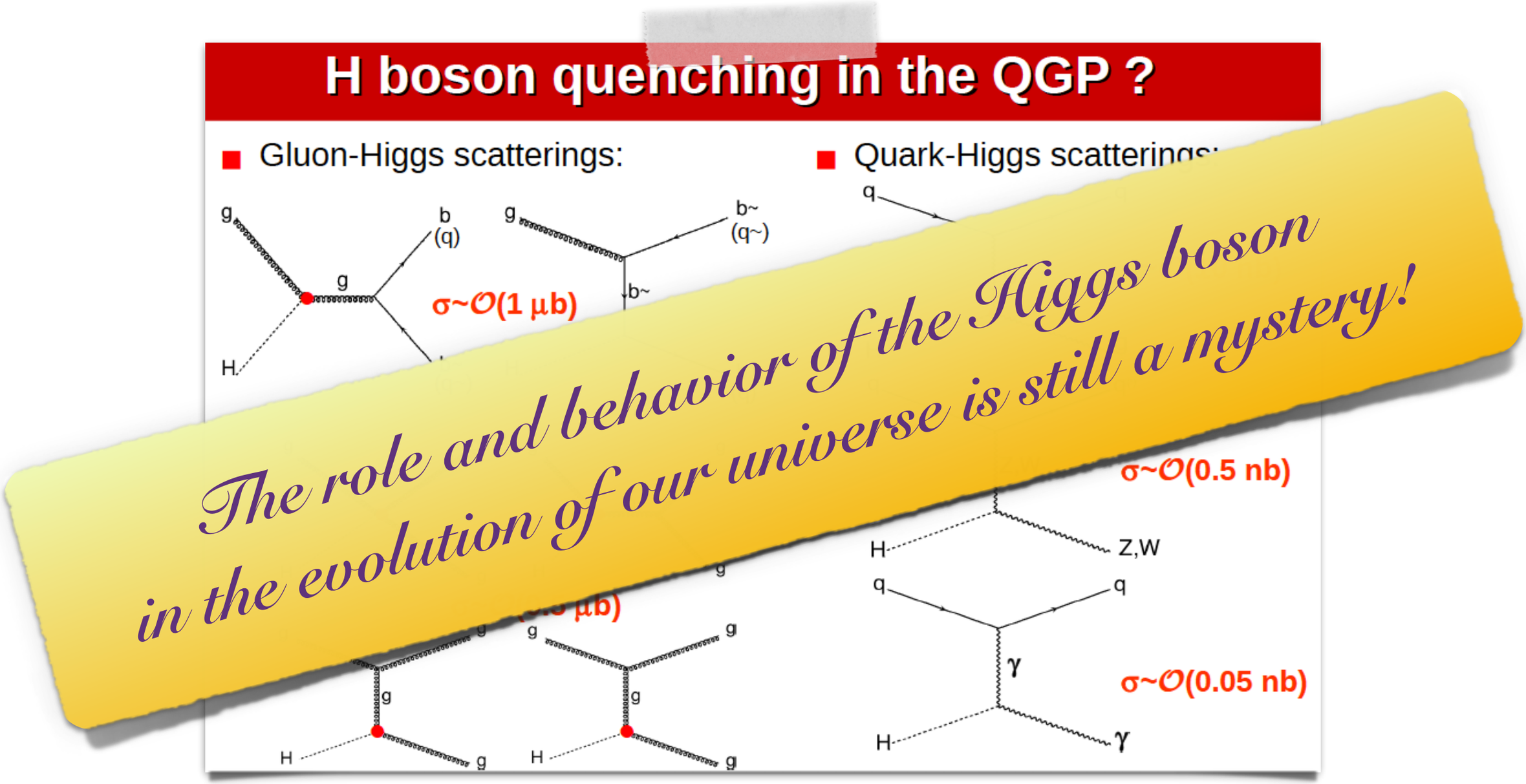
- Higgs quenching?




From David d'Enterria

# Outlook

- Higgs quenching?




From David d'Enterria


Thank you!

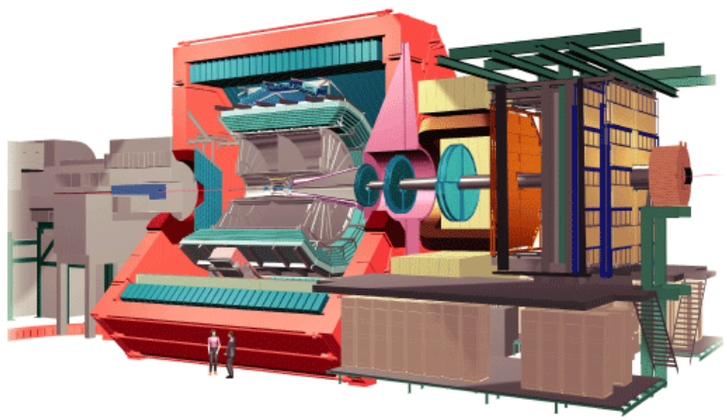
# Backup

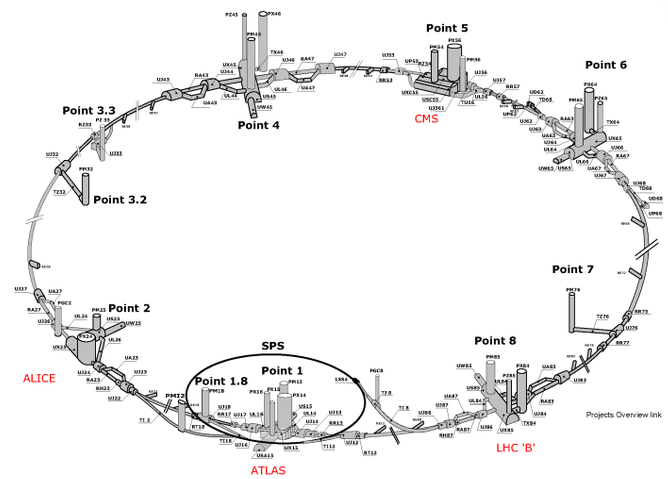
# Outline

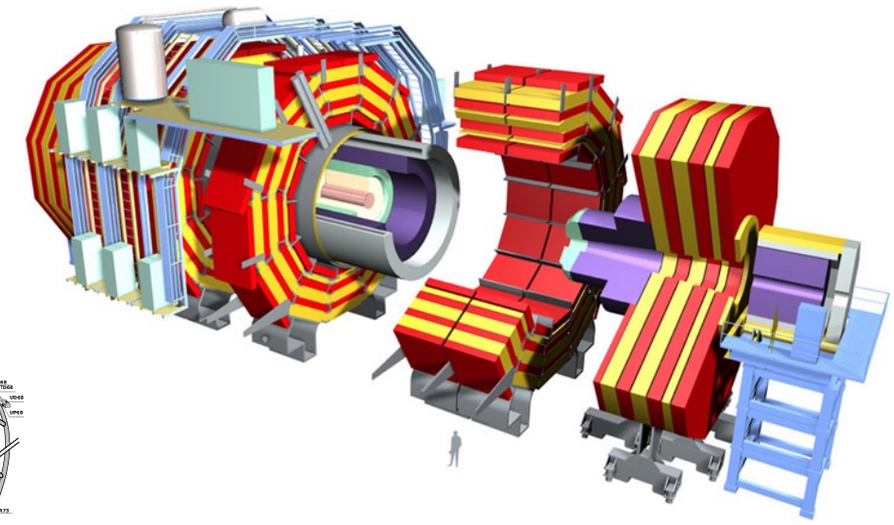
- Higgs boson at the LHC.
- The ABC of early universe, heavy-ion collision and quark-gluon plasma (QGP).
- Why do we look for Higgs boson in heavy-ion collision?
- Searching Higgs boson in QGP.
- Summary and outlook.

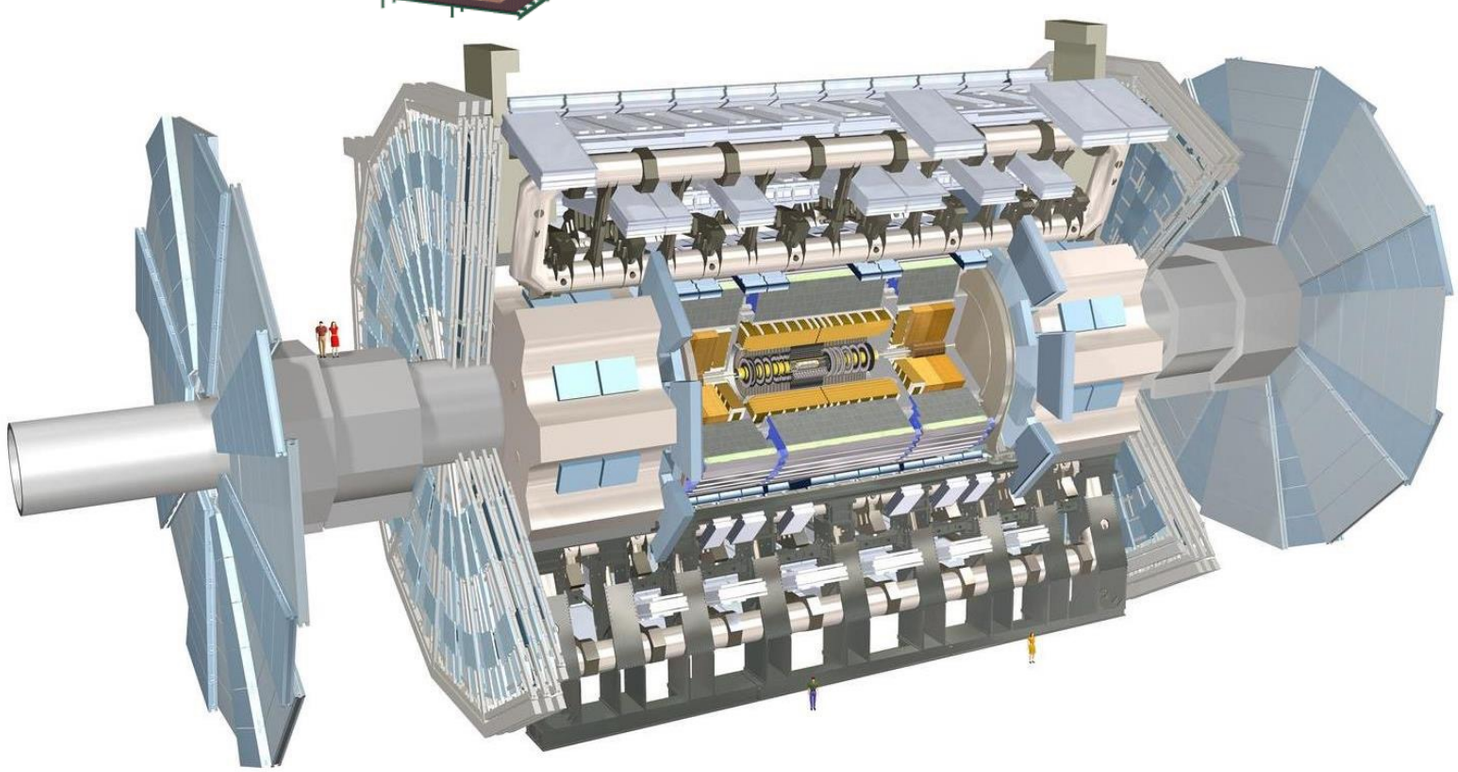
# Higgs boson at the LHC

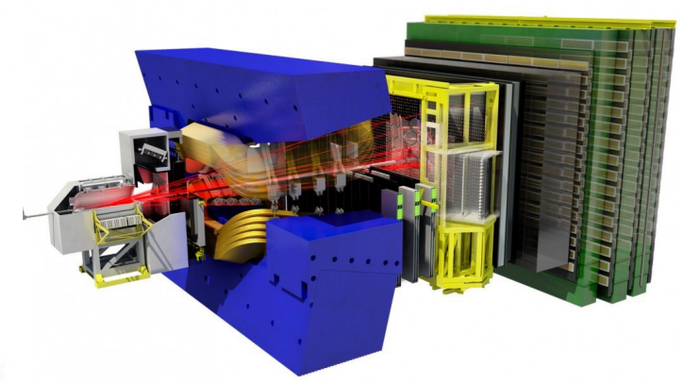
- LHC, the largest high energy collider in the world.





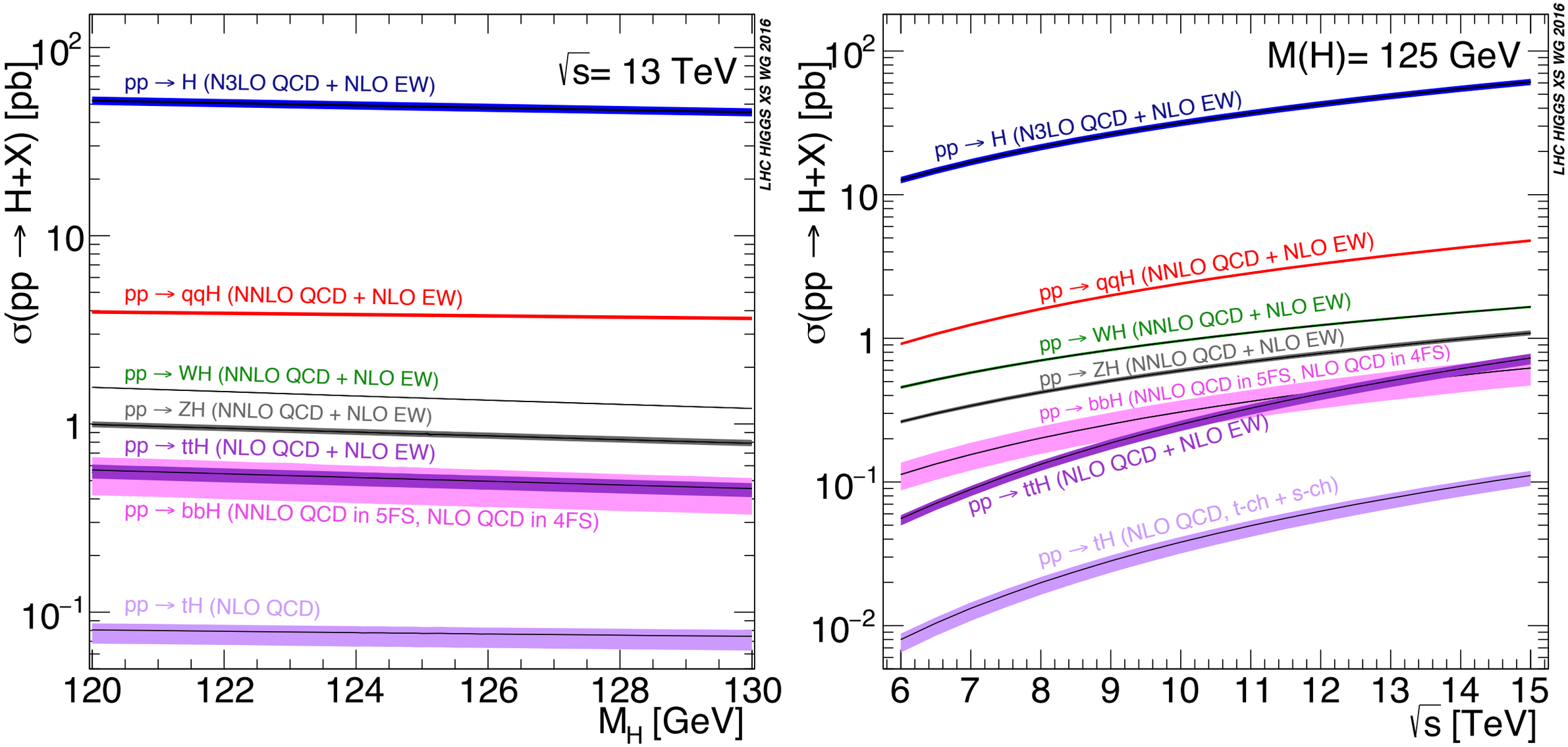







# Higgs boson at the LHC

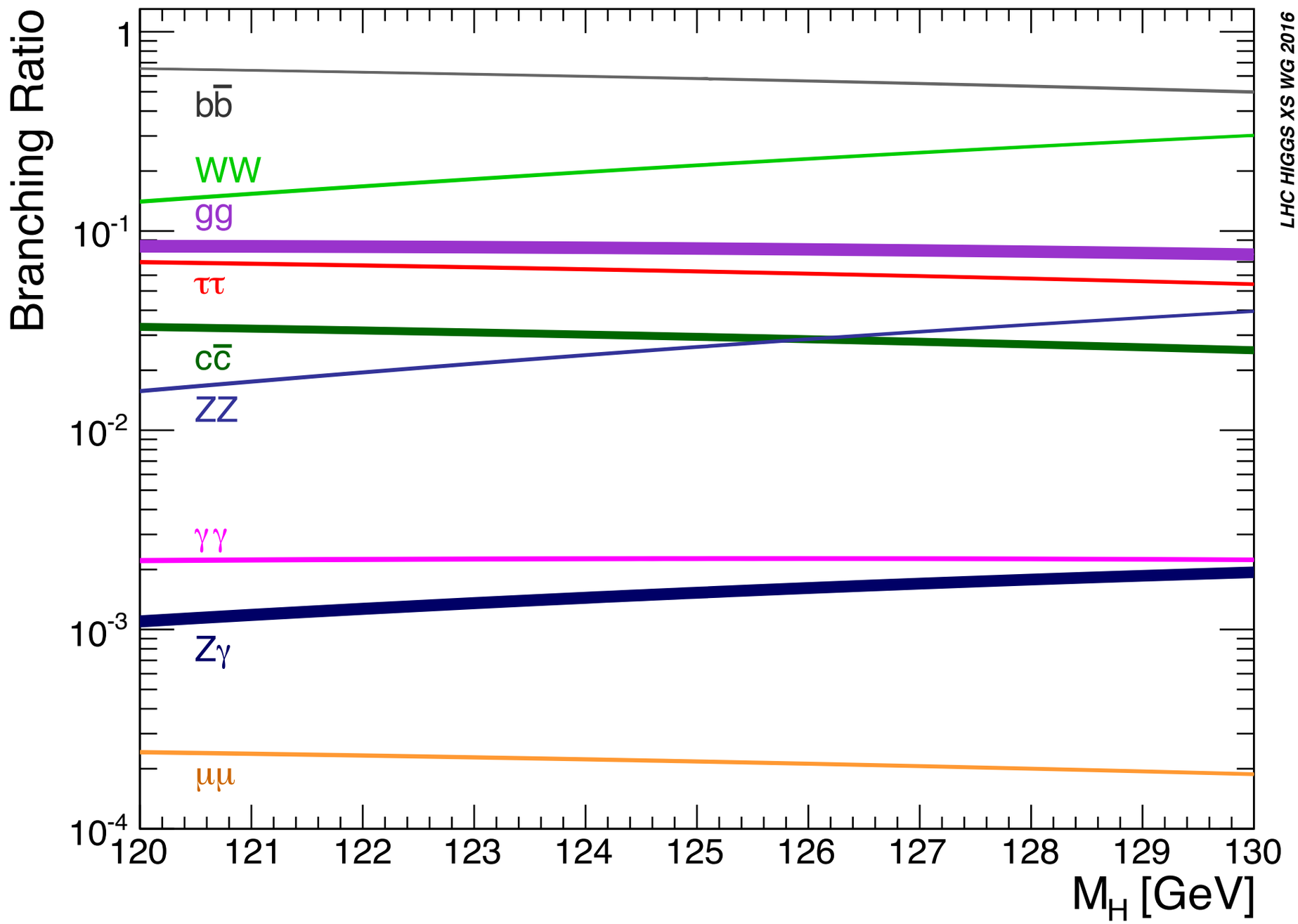
- The production of the SM-like Higgs boson (cross sections).




From LHC Higgs Cross Section Working Group, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

# Higgs boson at the LHC

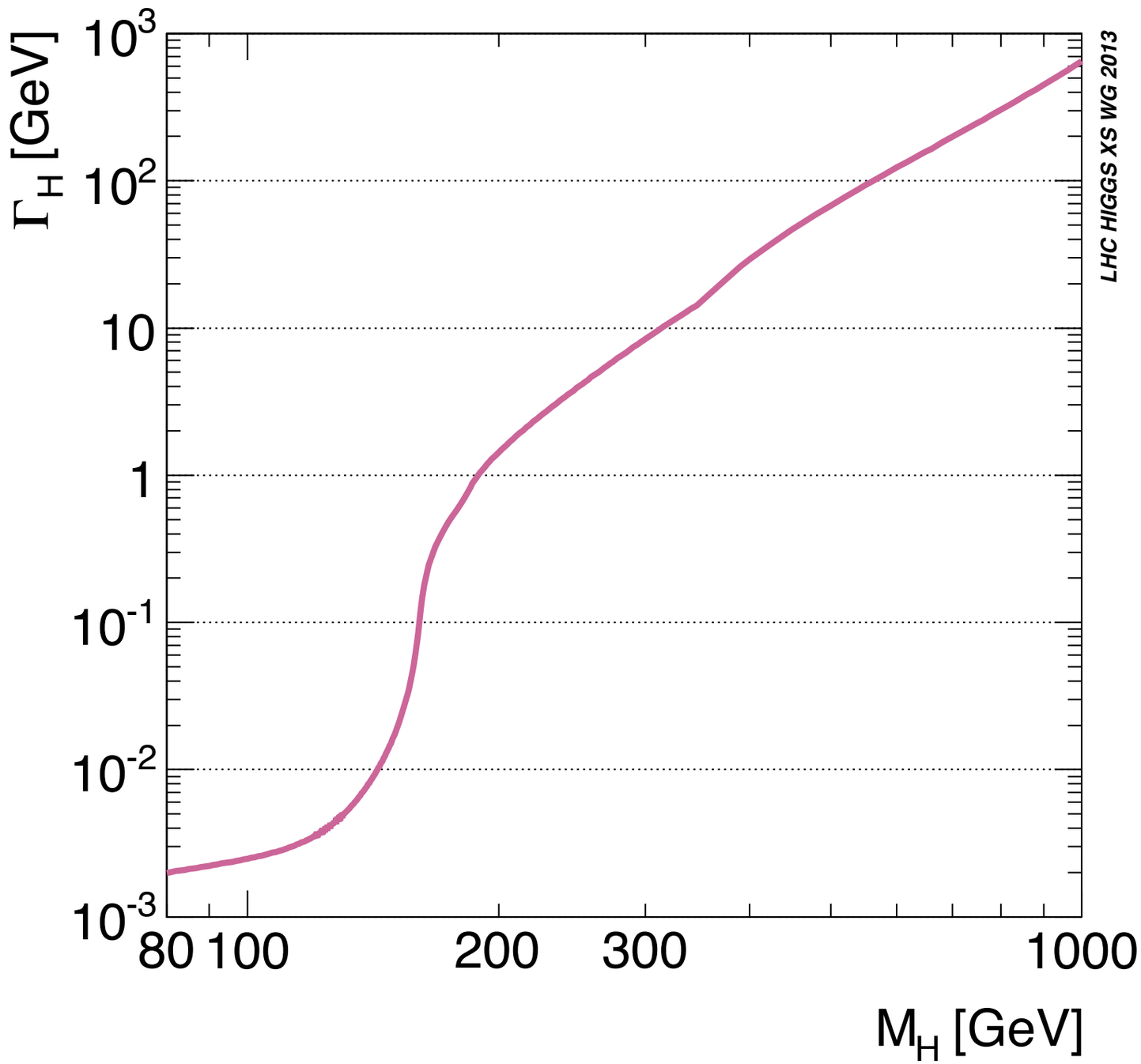
- The decay of the SM-like Higgs boson (branching ratios).



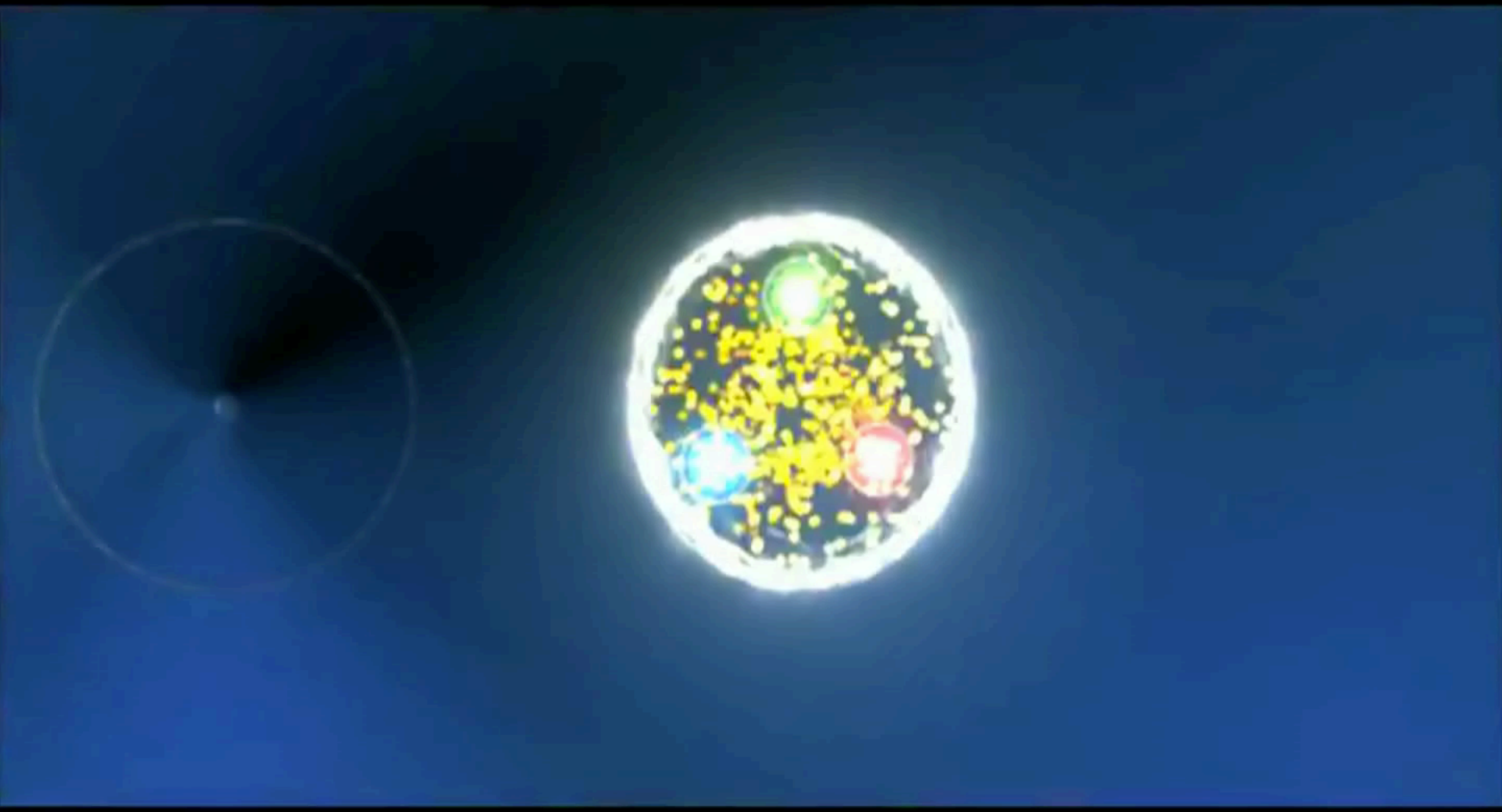

From LHC Higgs Cross Section Working Group, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

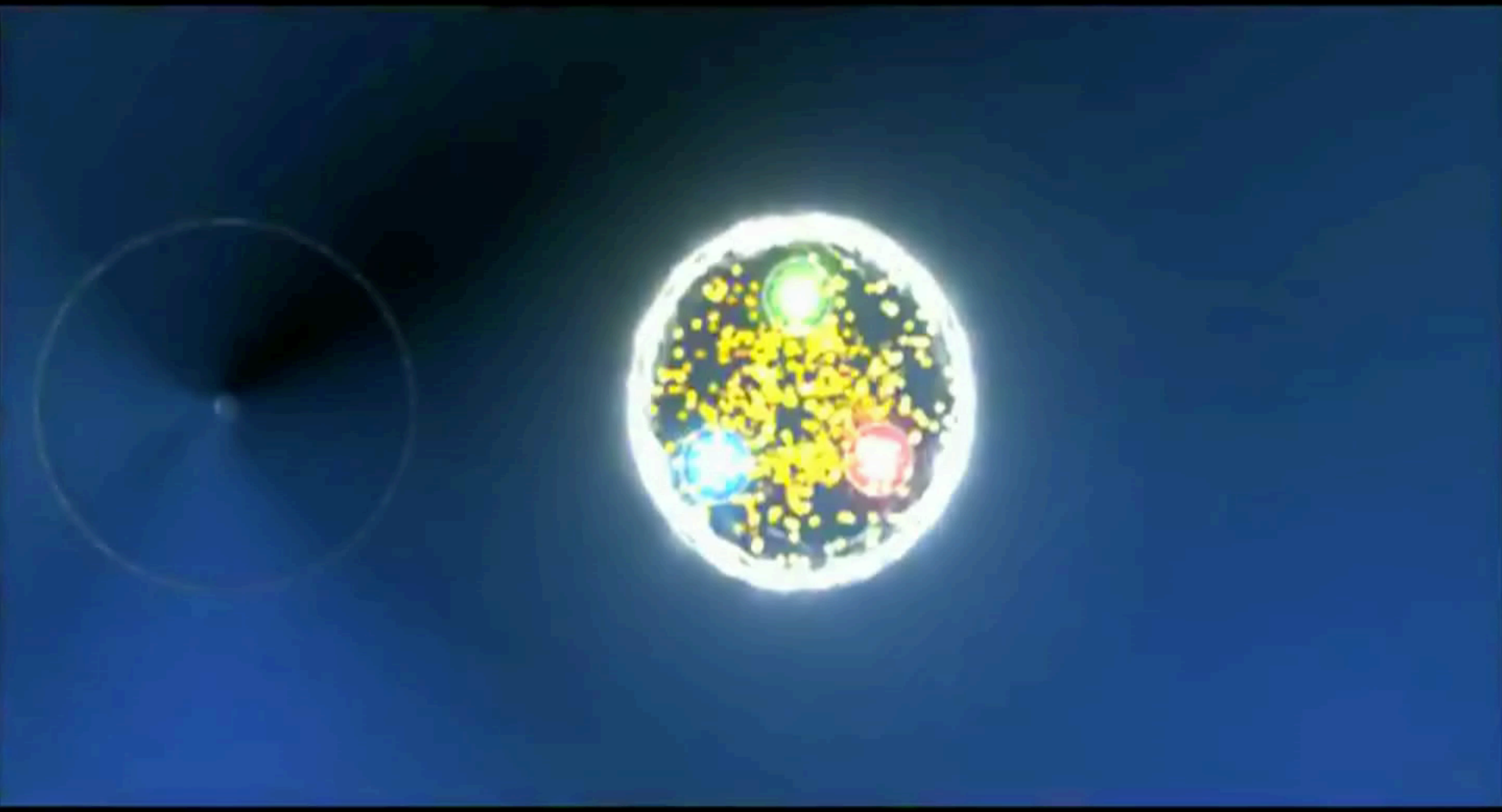
# Higgs boson at the LHC

- The decay of the SM-like Higgs boson (width).



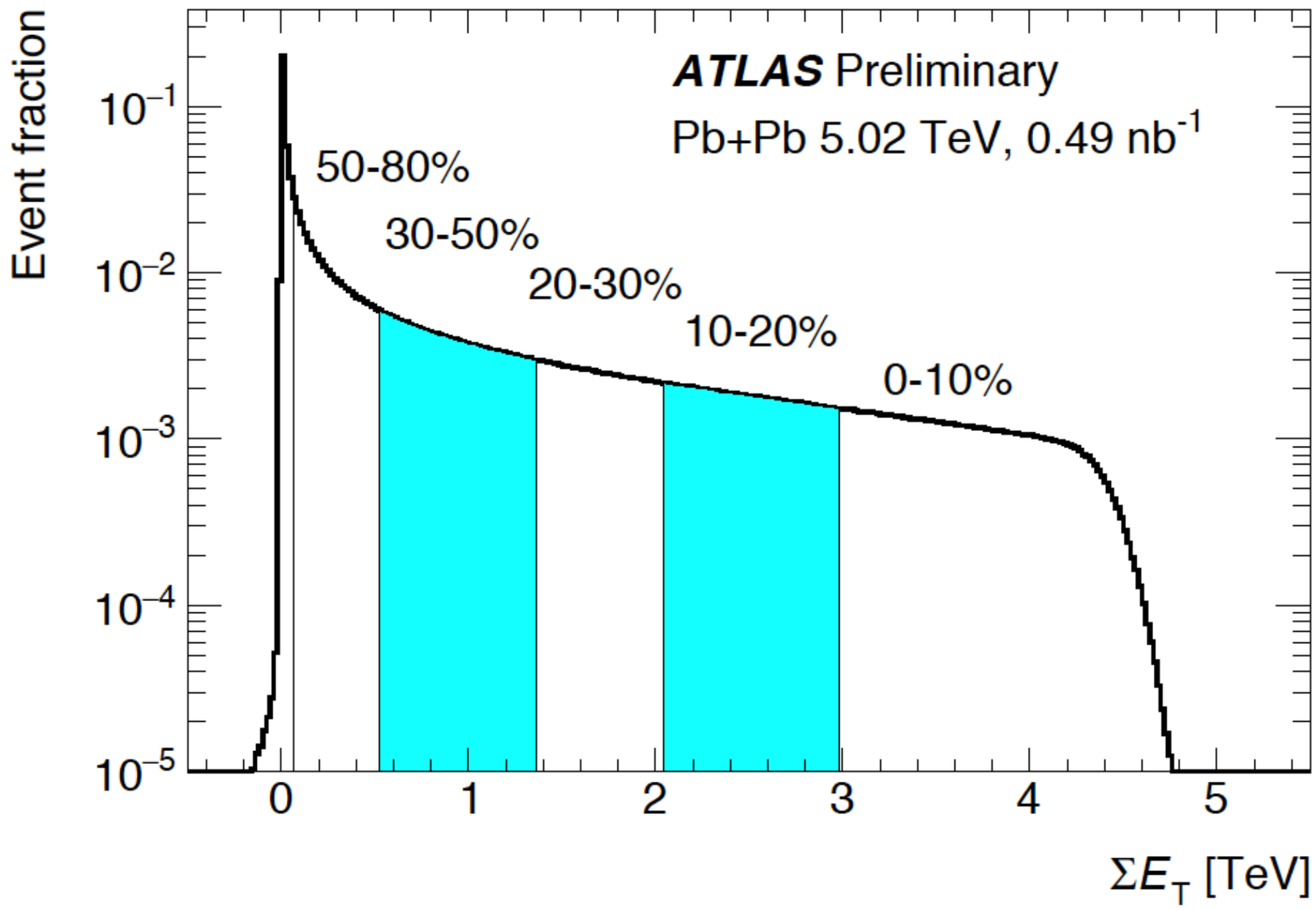

From LHC Higgs Cross Section Working Group, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG





# From *pp* Collision to PbPb Collision

- The lead-lead collision.
- Impact parameter (perpendicular distance): Centrality.




ATLAS Collaboration, ATLAS-CONF-2016-110.

# Heavy-Ion Collision at the LHC

- There is a fundamental particle whose width is smaller than 197MeV!
- The decay products will carry the information of the Higgs boson, and tell us the properties of the Higgs boson in QGP faithfully.
- The QCD and other SM backgrounds of the hadronic decay Higgs boson will be modified and suppressed by the jet quenching effect.
- Verifying these conclusions will give us a double check of the width of the Higgs boson and an upper bound of the width.
- Search for $h \to bb$ in heavy-ion collision at the LHC and future hadron colliders!

# Higgs in Heavy-Ion Collision

- Smearing effect.