Institute of High Energy Physics Chinese Academy of Sciences

Higgs properties revealed through jet quenching in heavy ion collisions

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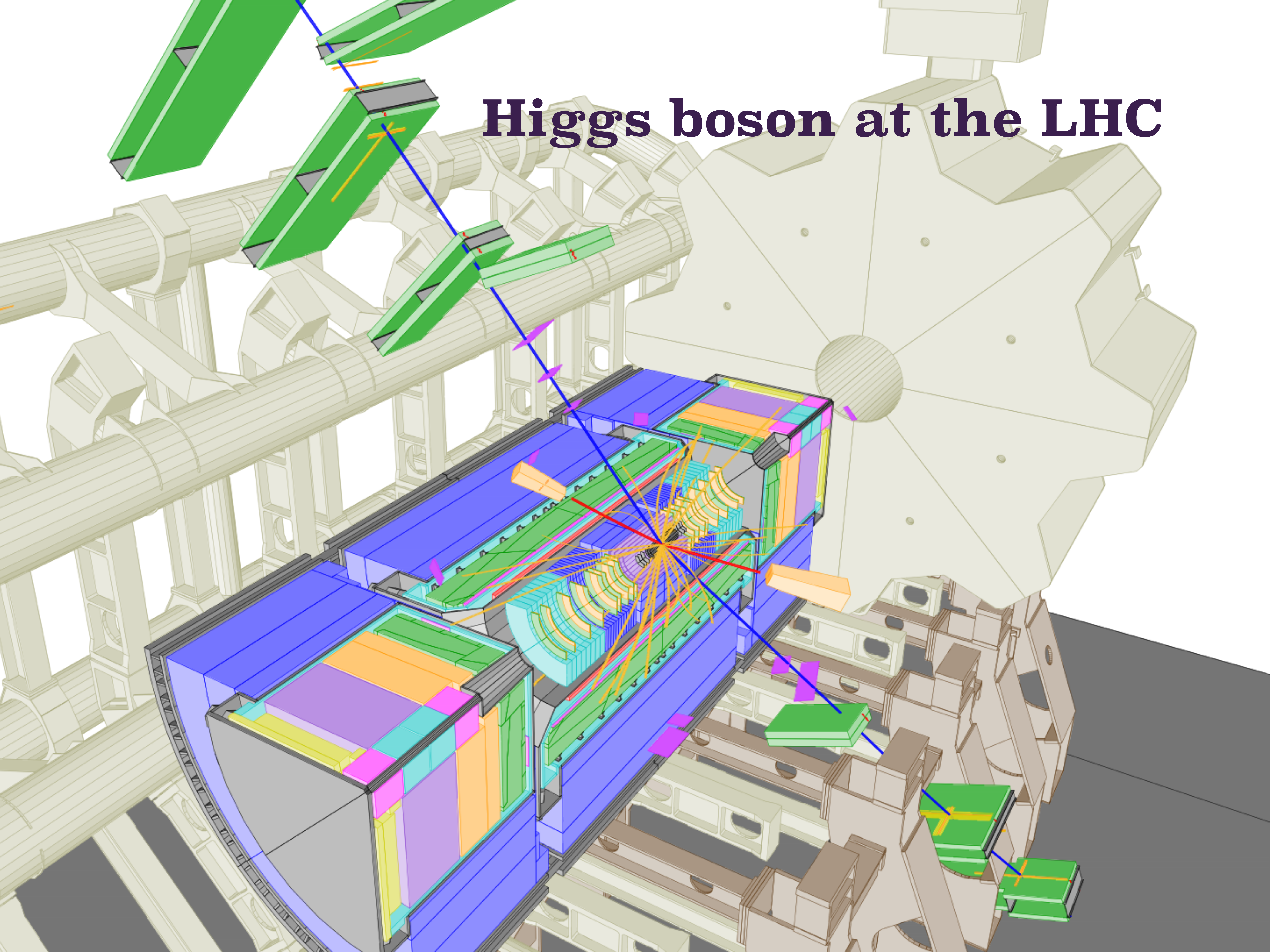
Theoretical Physics Division, Institute of High Energy Physics, Chinese Academy of Sciences

For “第十五届粒子物理、核物理和宇宙学交叉学科前沿问题研讨会”, Aug 22th 2018

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


Higgs boson at the LHC

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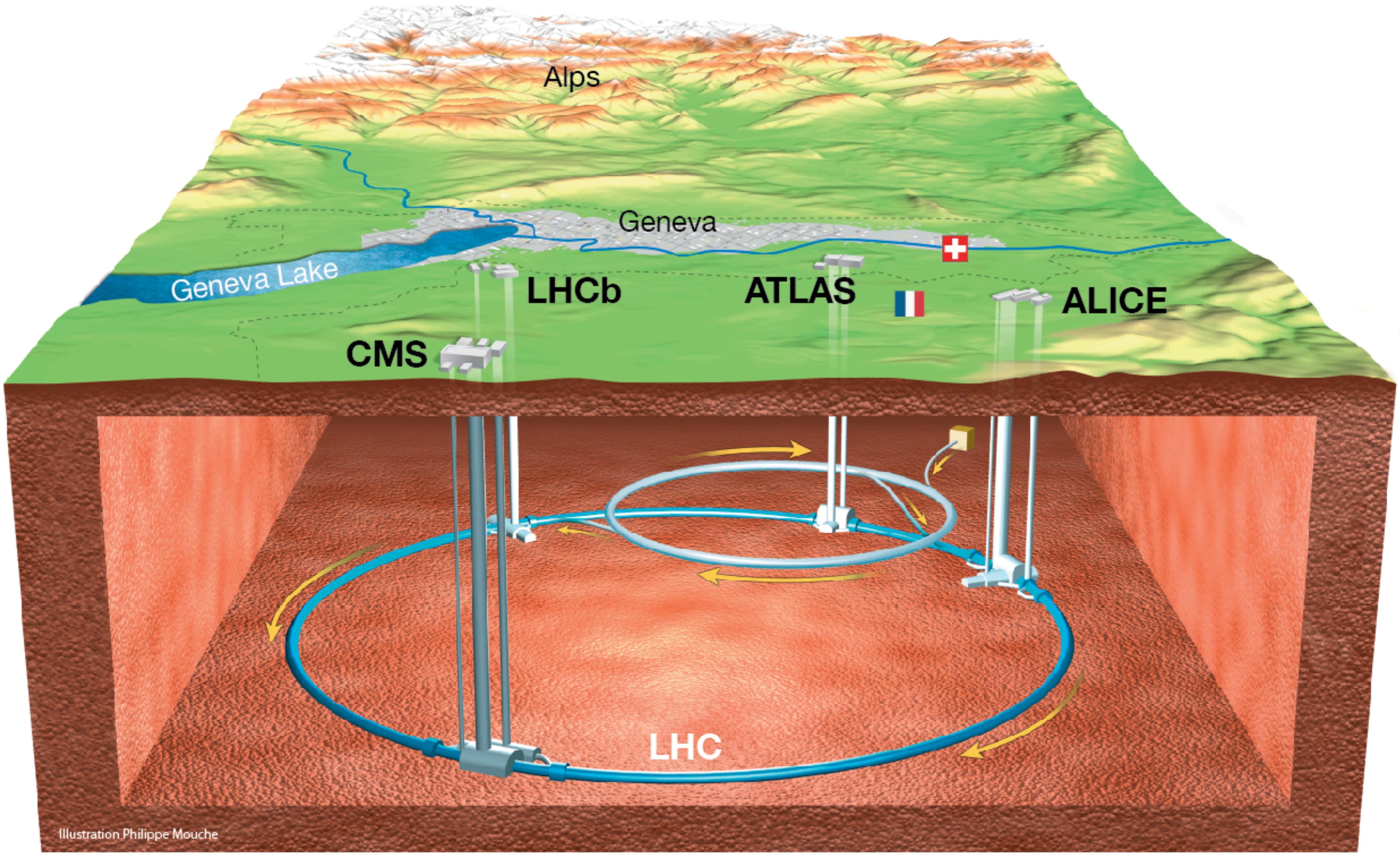
- LHC, the largest high energy collider in the world.



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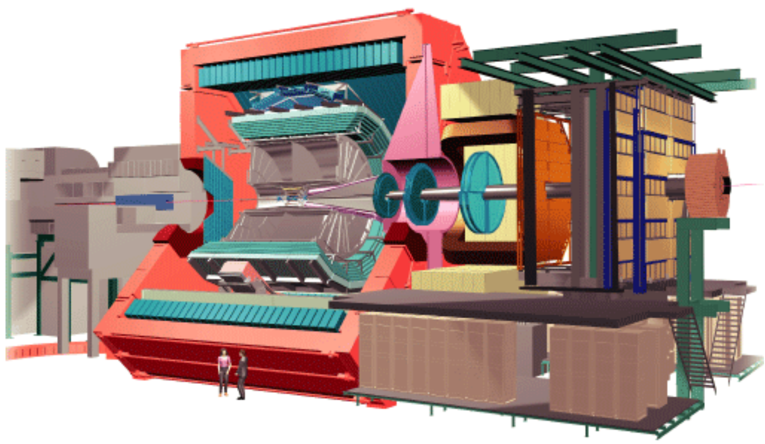
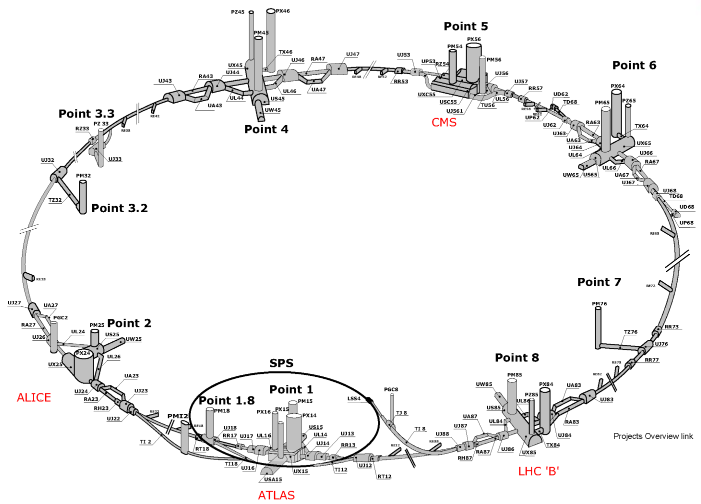
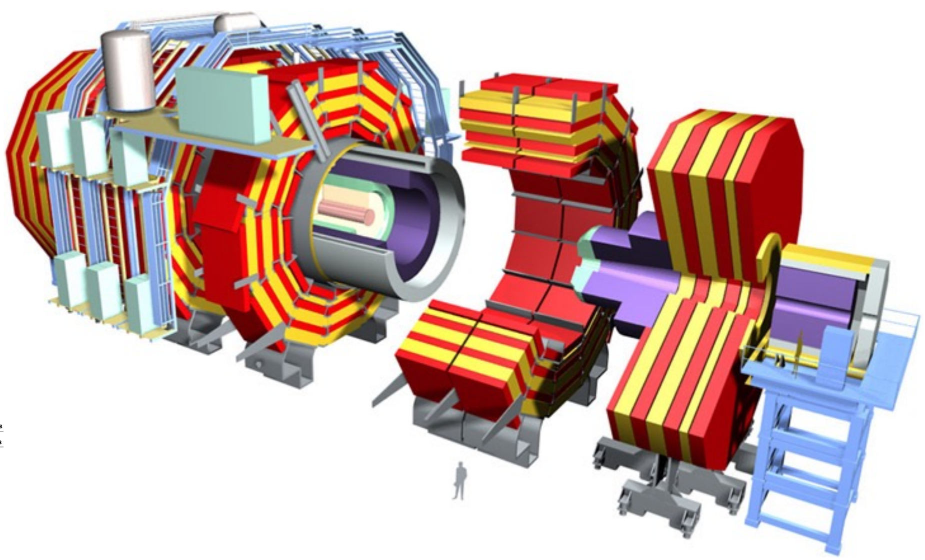
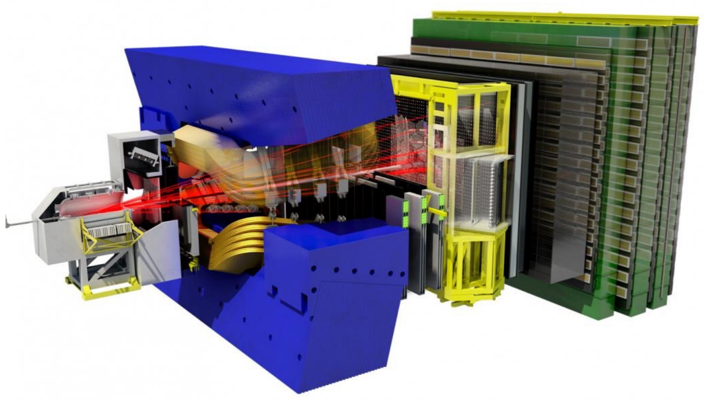
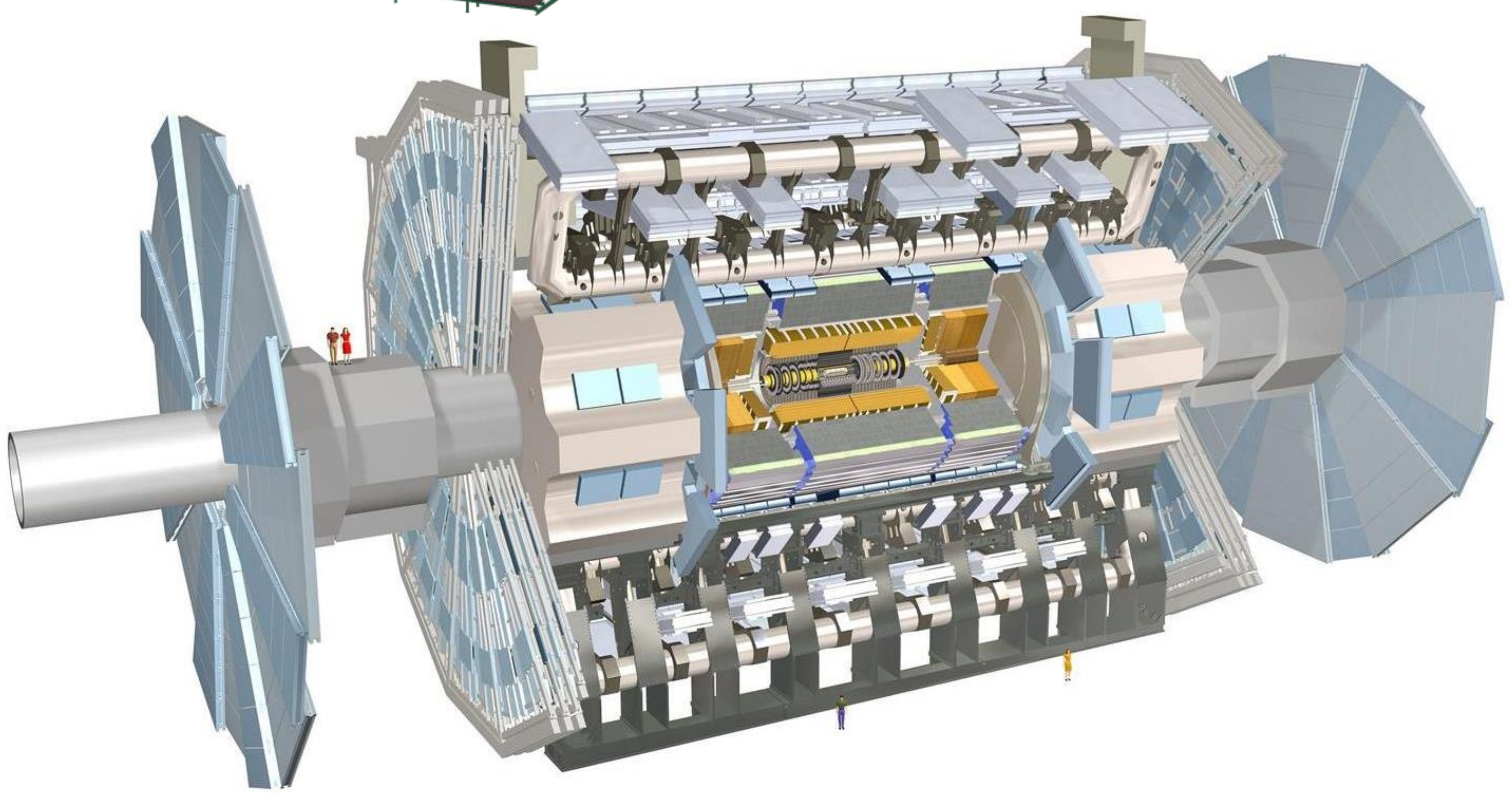




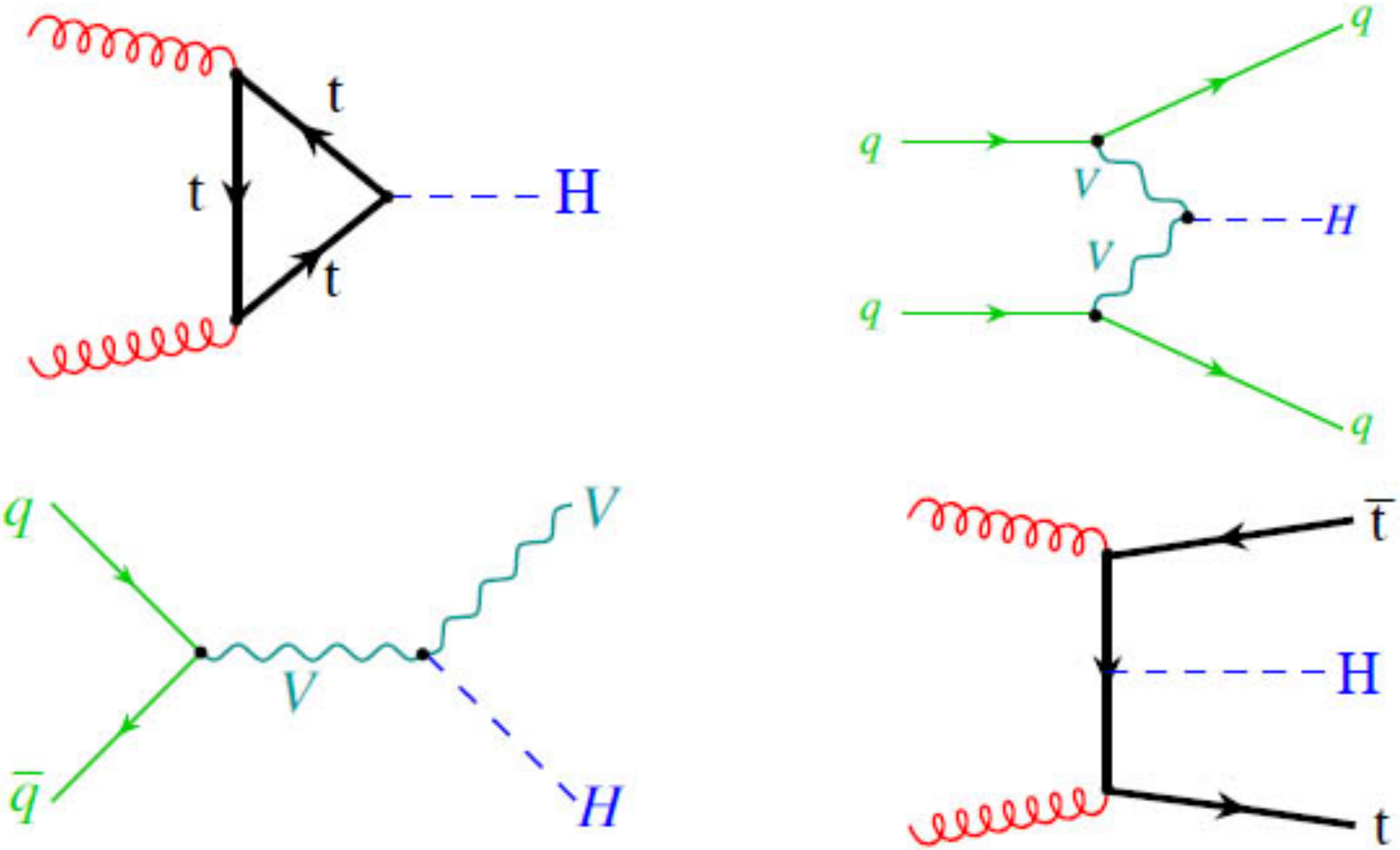






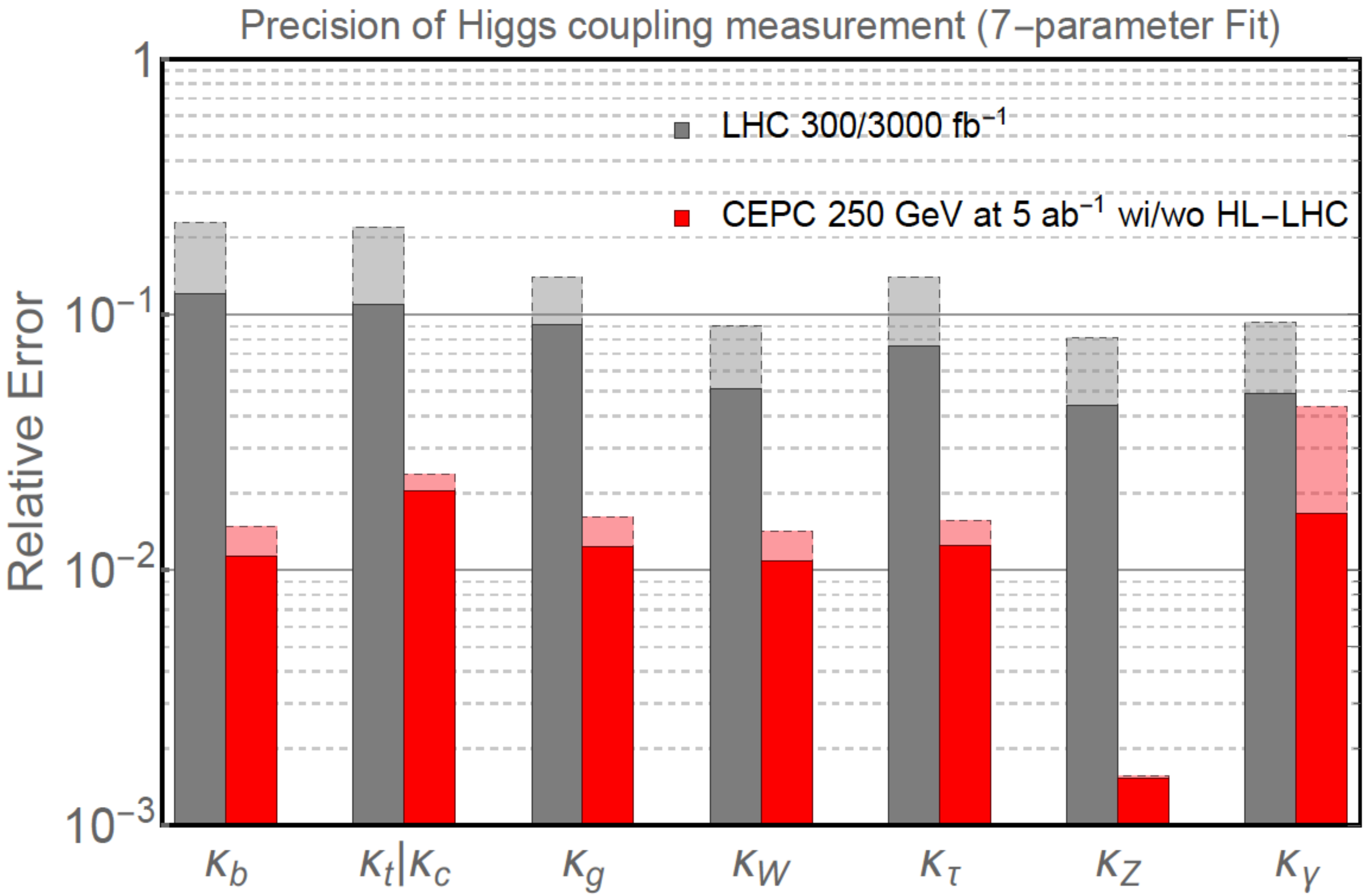
Higgs boson at the LHC

- 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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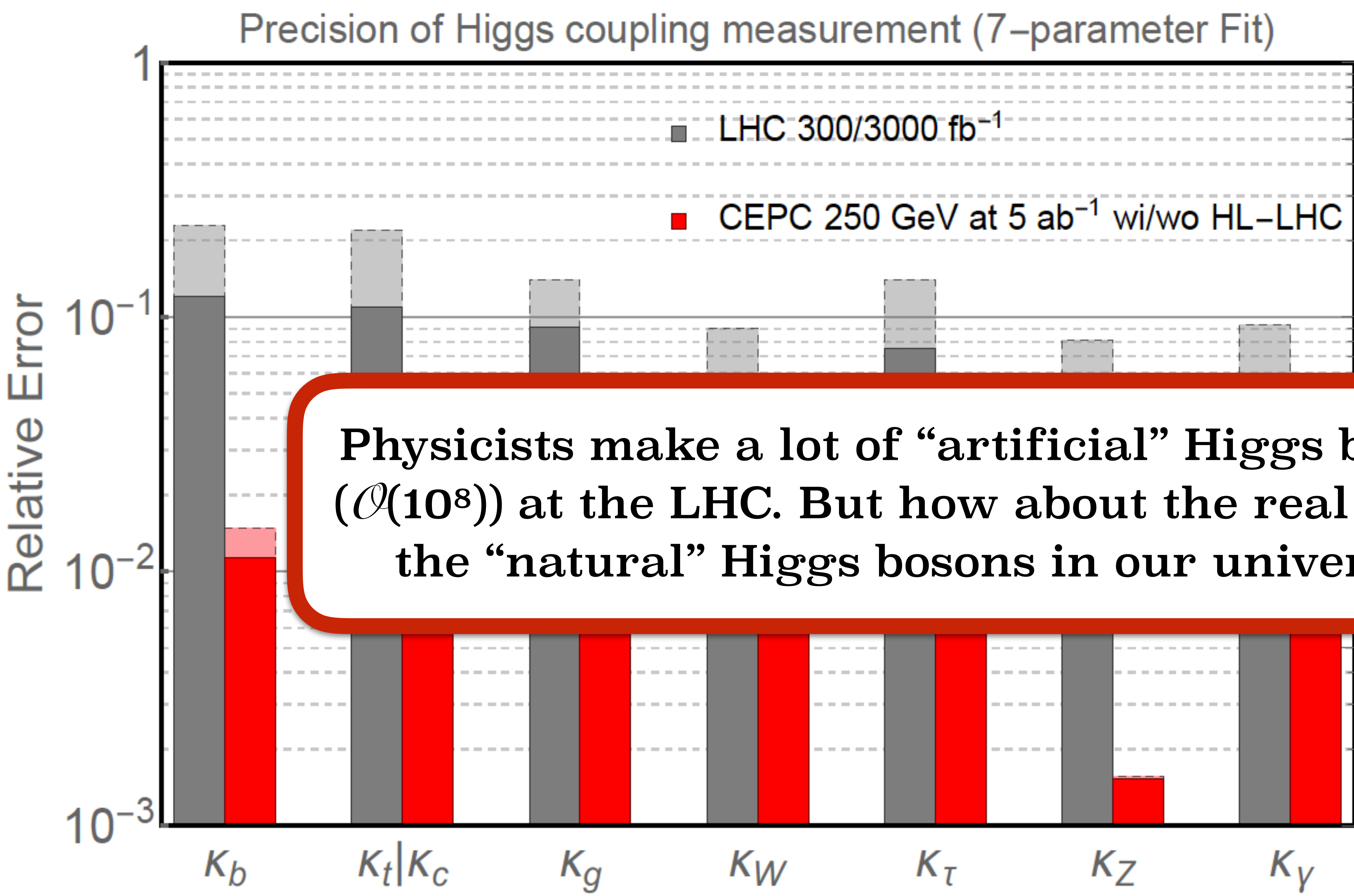
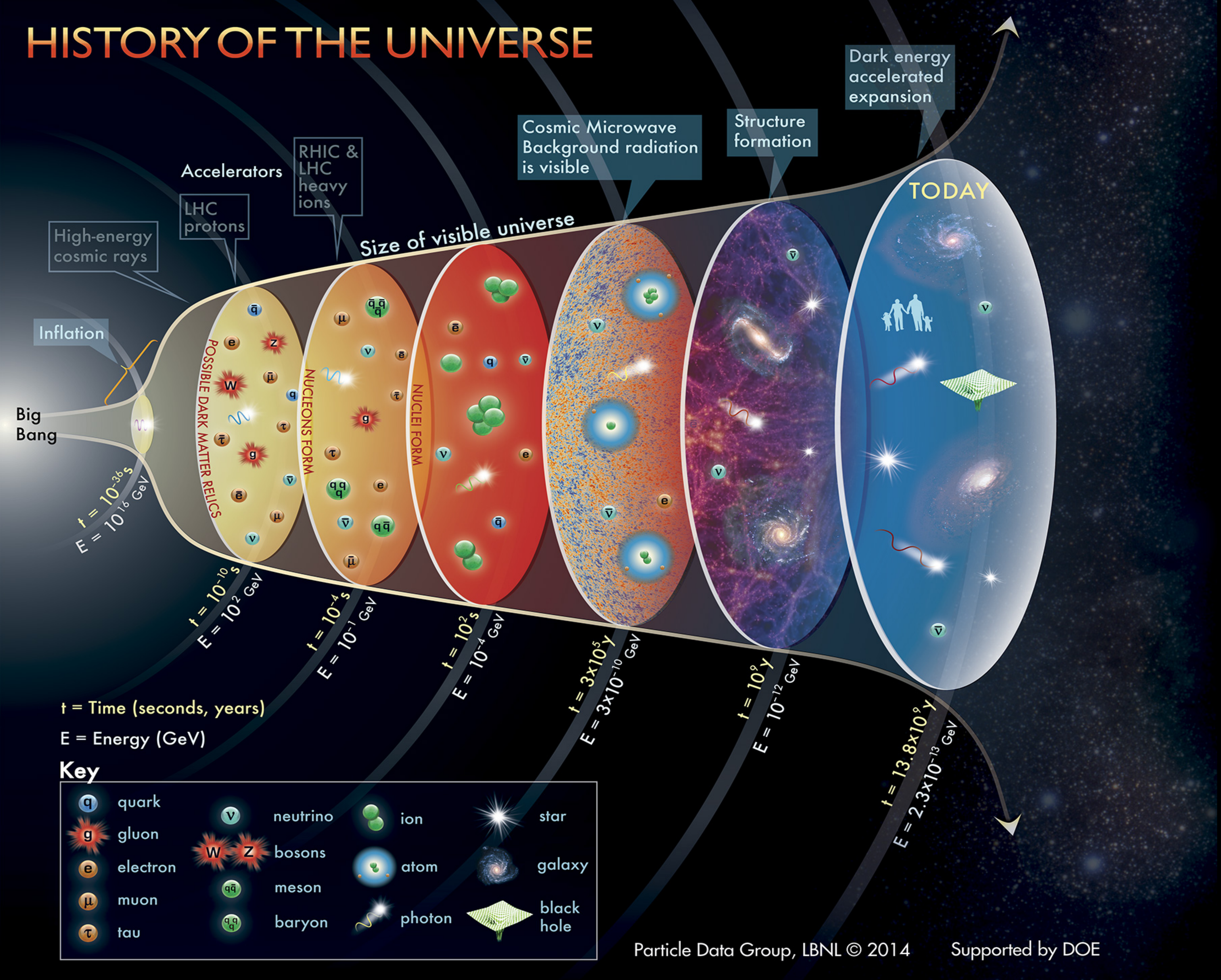


Physicists make a lot of "artificial" Higgs bosons ($\mathcal{O}(10^8)$) at the LHC. But how about the real life of the "natural" Higgs bosons in our universe?

From Kaili Zhang's talk.


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
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t = Time (seconds, years)
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Key
quark
gluon
electron
muon
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neutrino
bosons
meson
baryon
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atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
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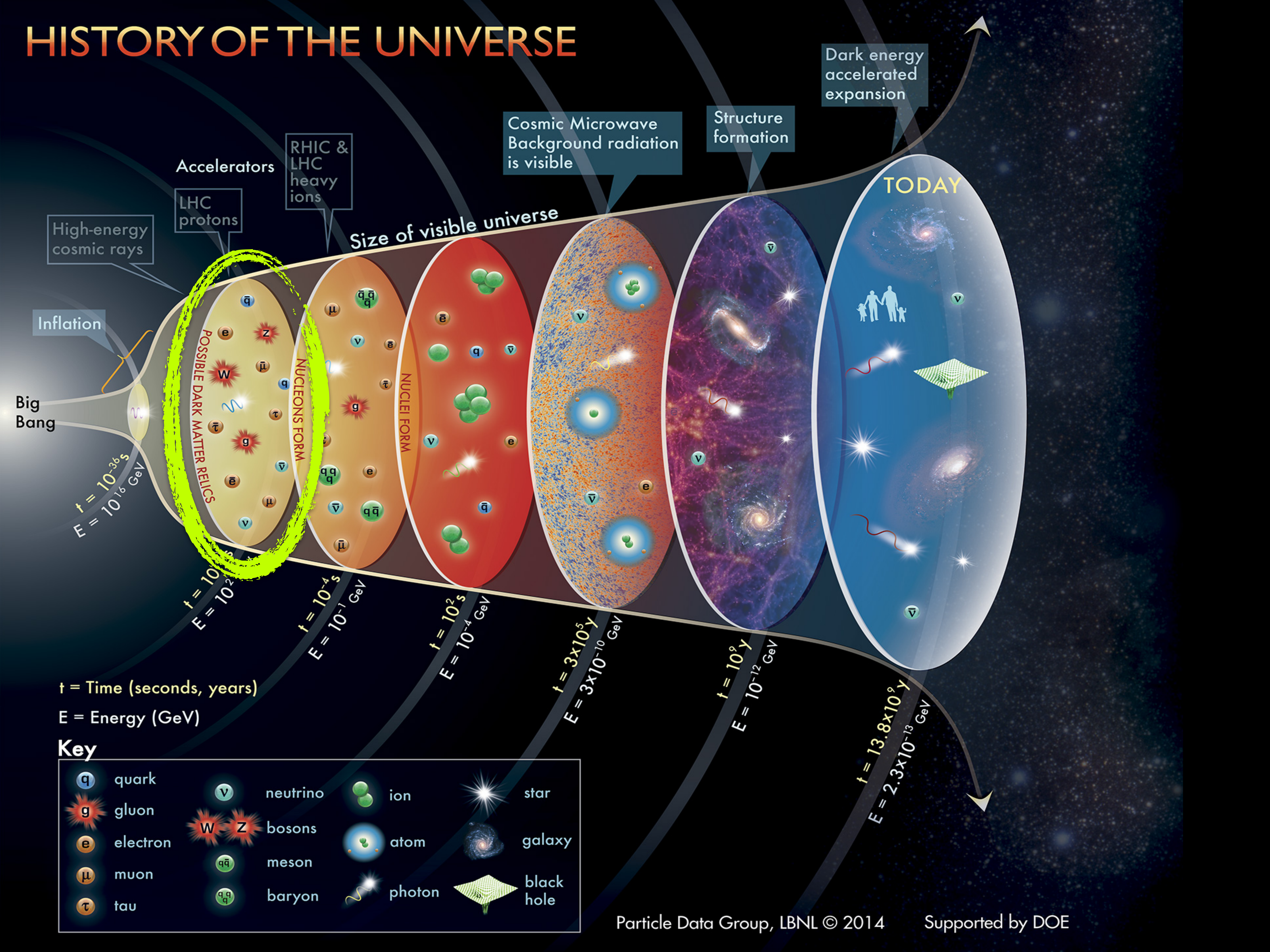

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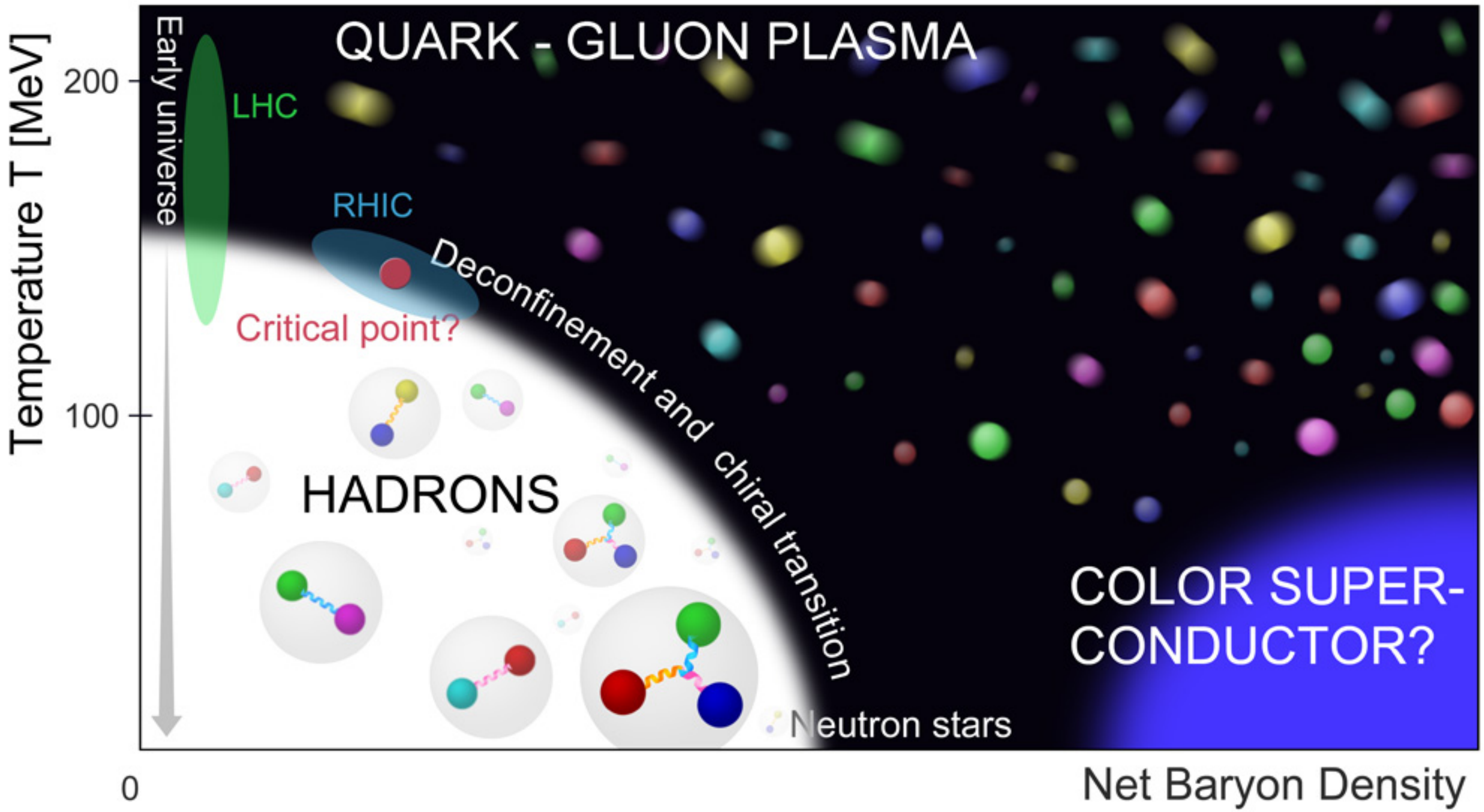
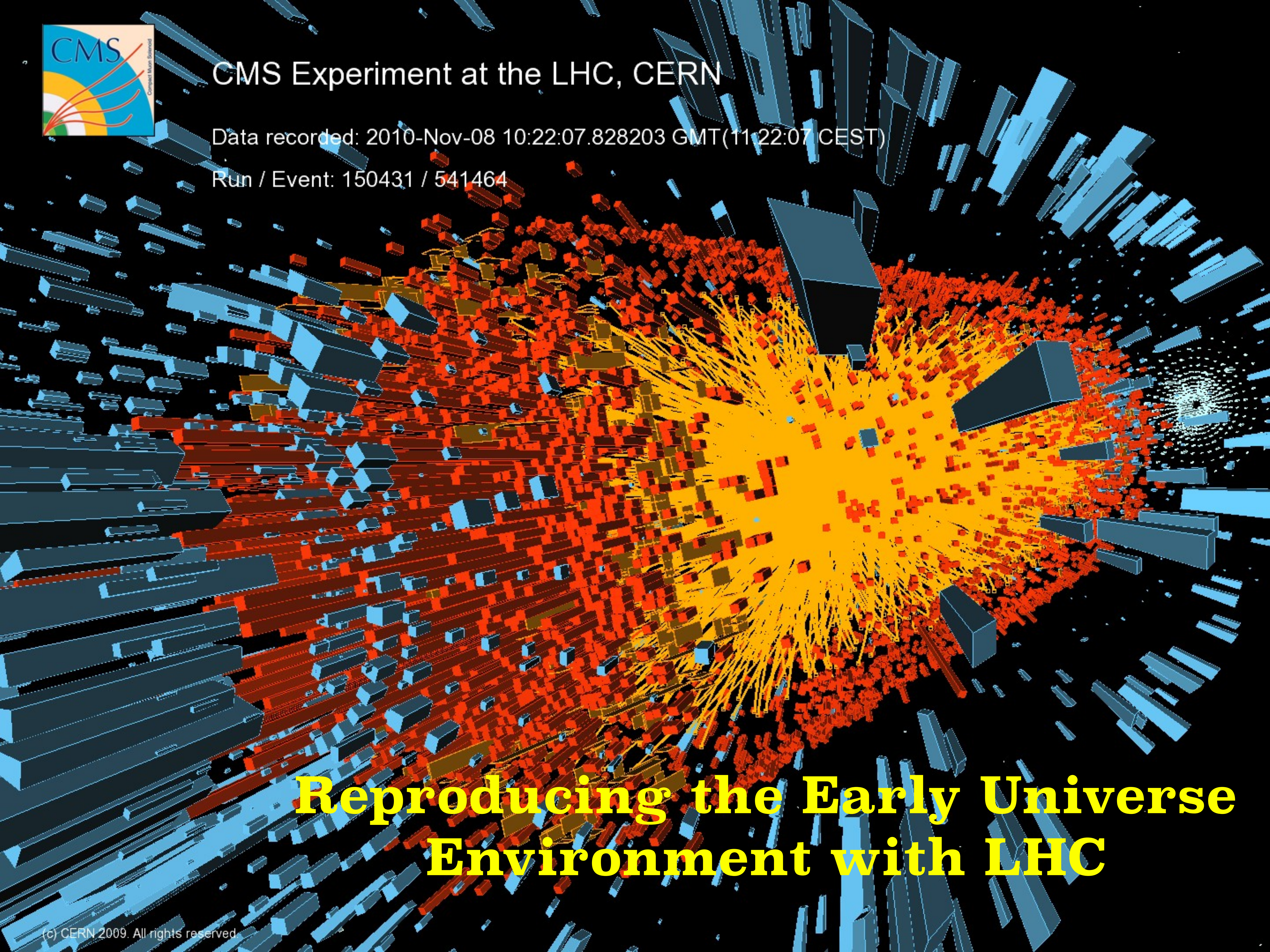
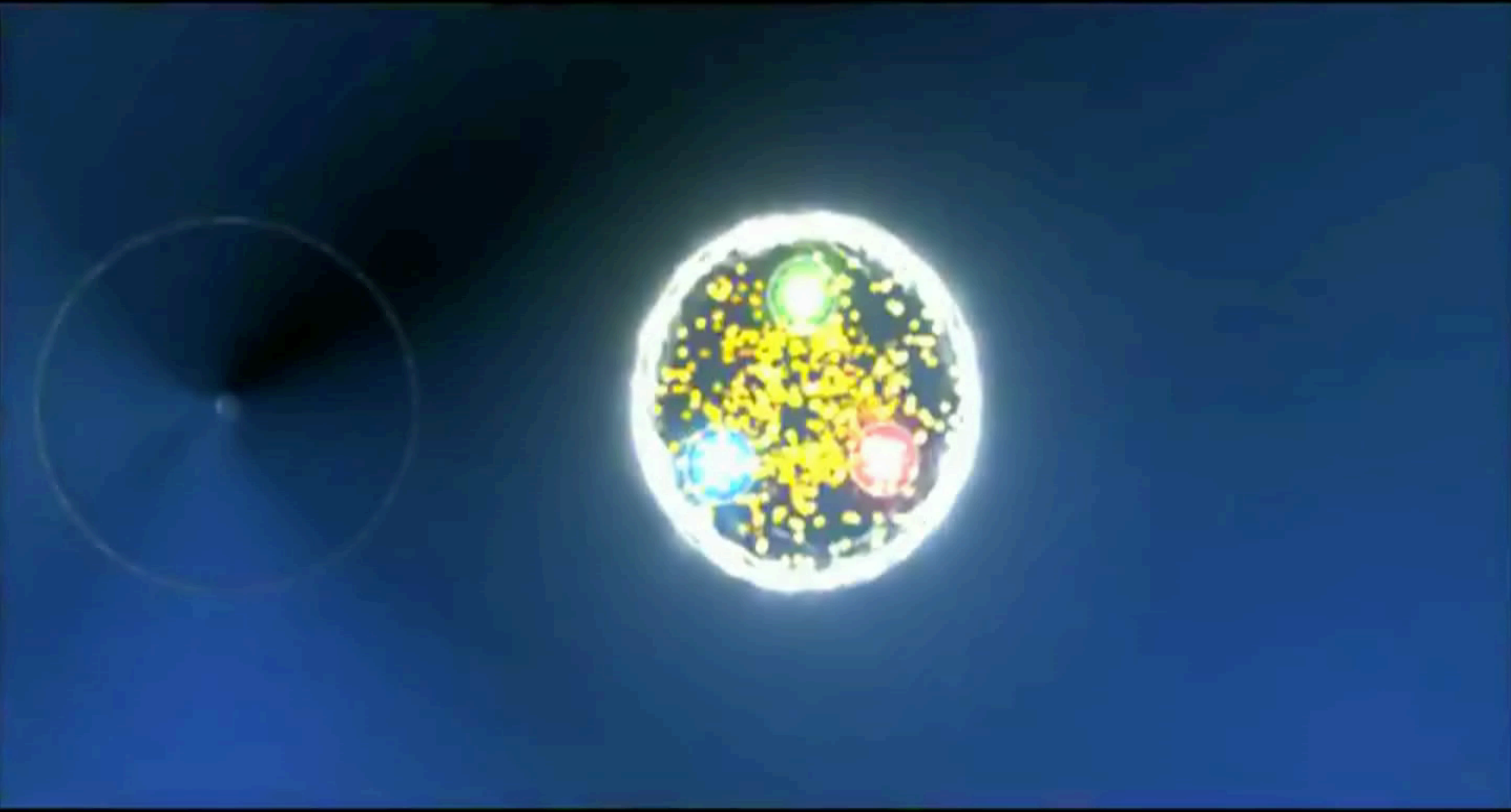
The Quark-Gluon Plasma

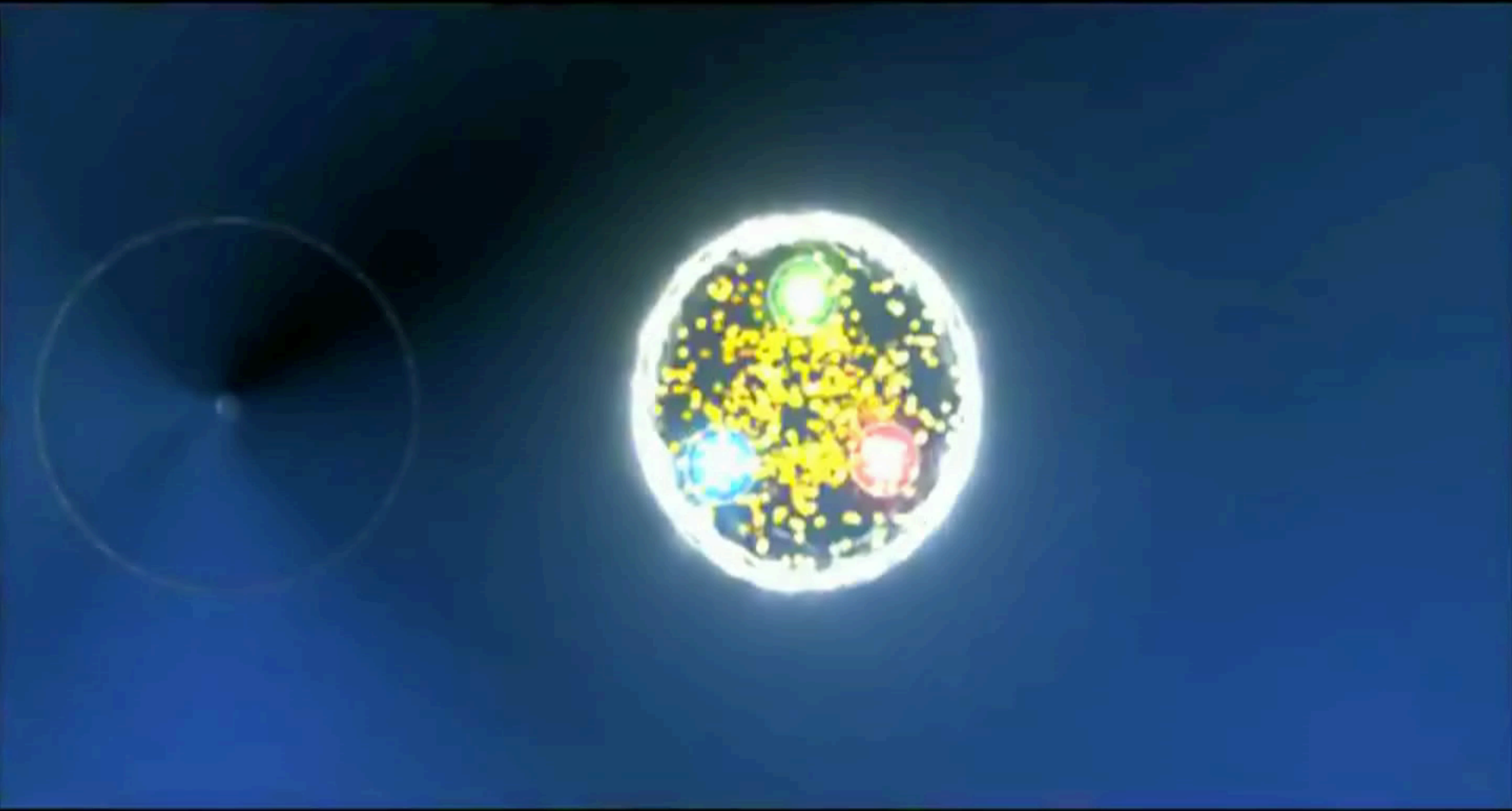
- The QCD phase diagram.





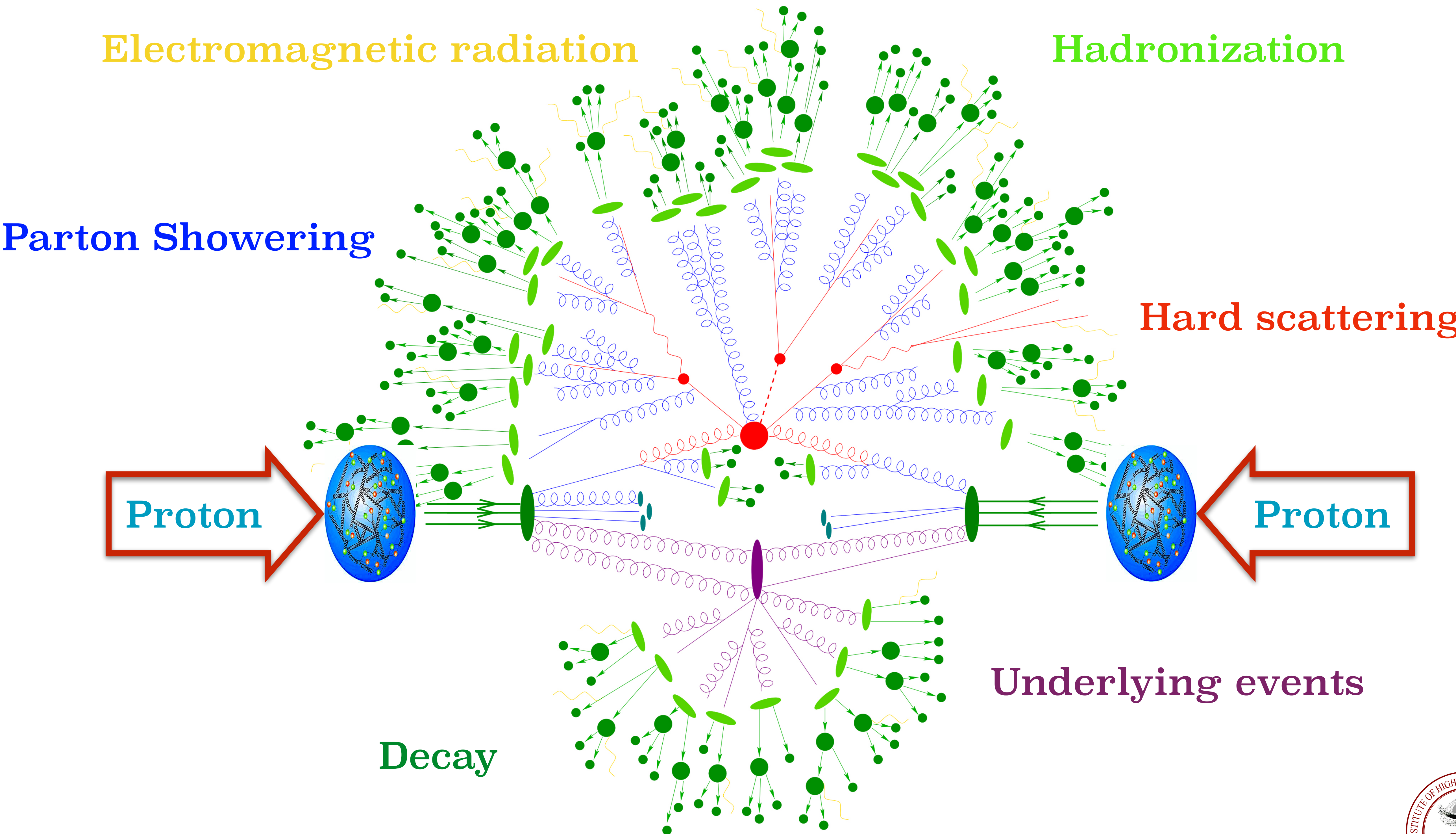
Reproducing the Early Universe Environment with LHC





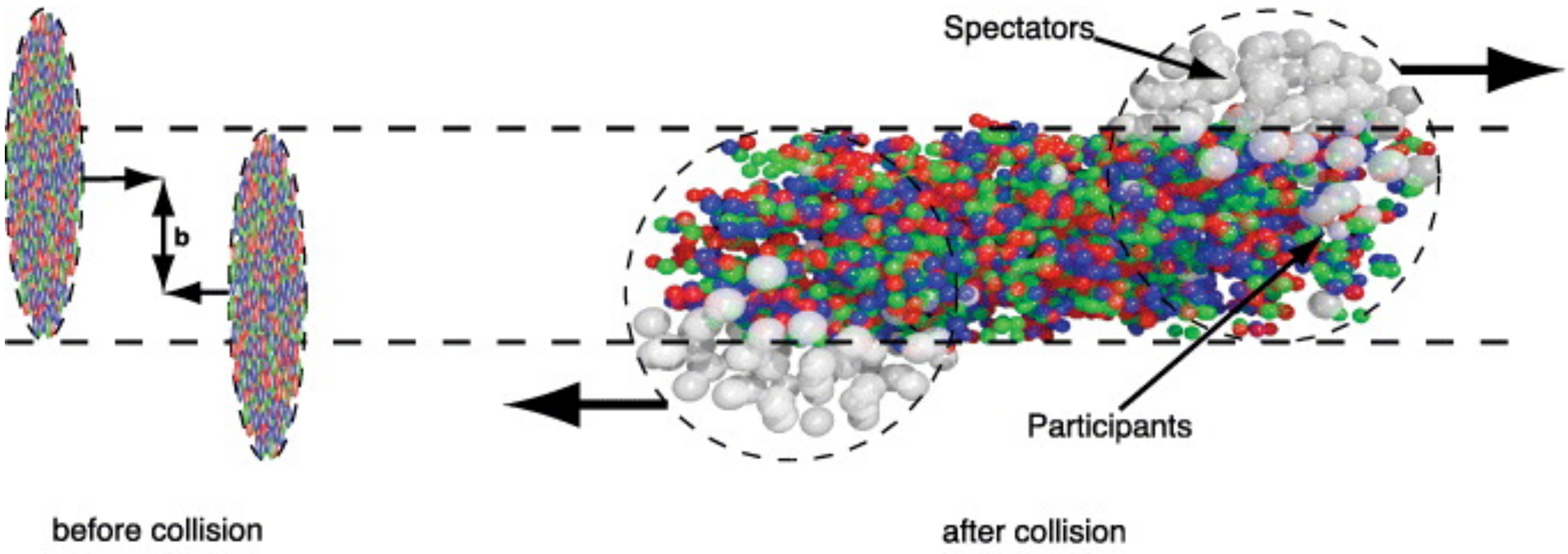
From *pp* Collision to PbPb Collision

- The proton-proton collision.



From *pp* Collision to PbPb Collision

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



From *pp* Collision to PbPb Collision

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

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

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

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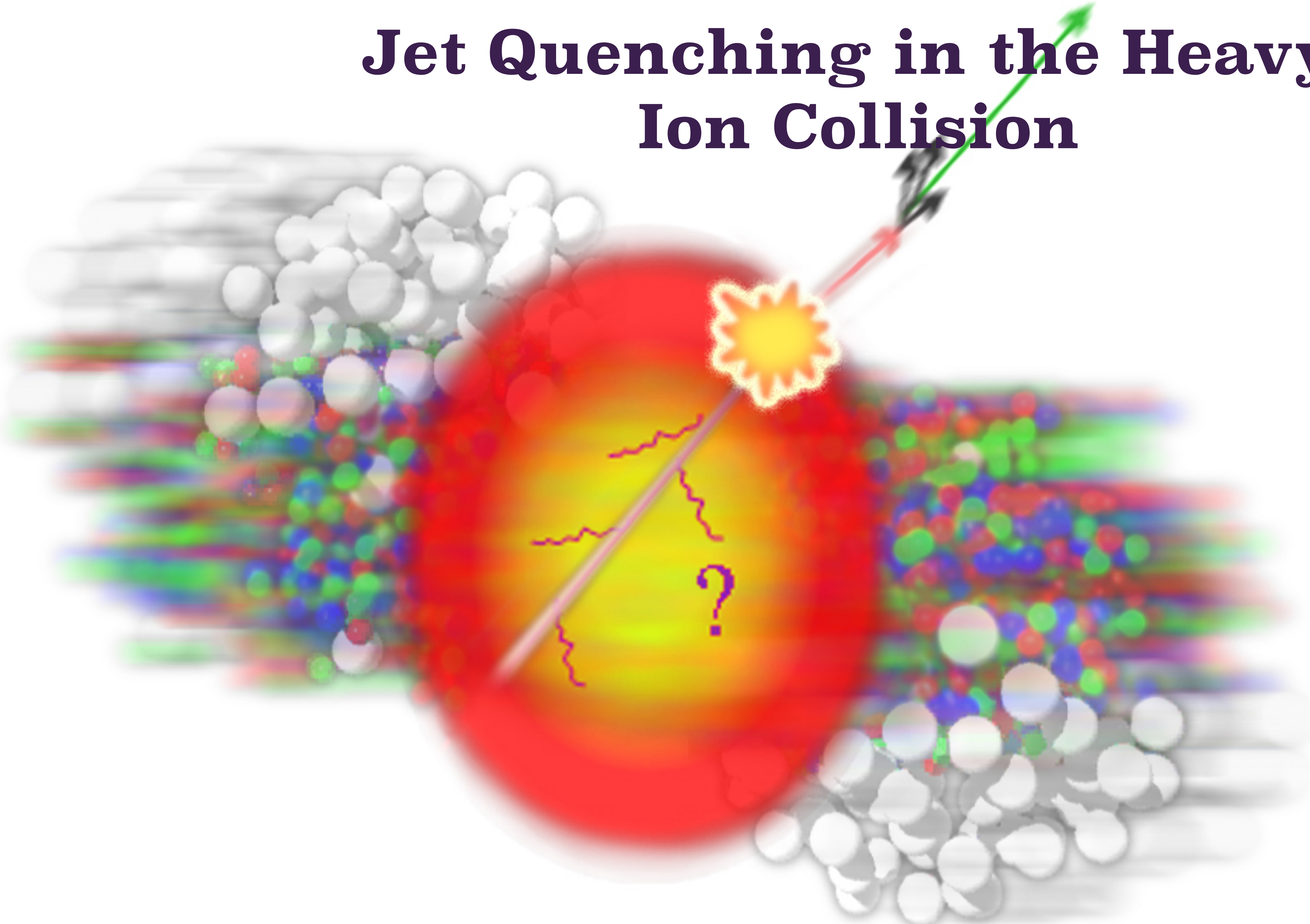
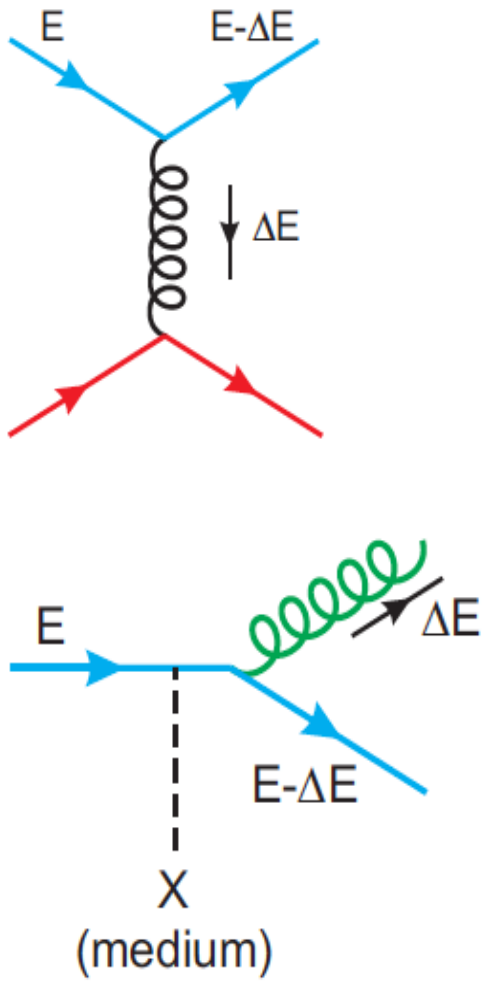
Parton level hard scattering cross section: from pQCD.

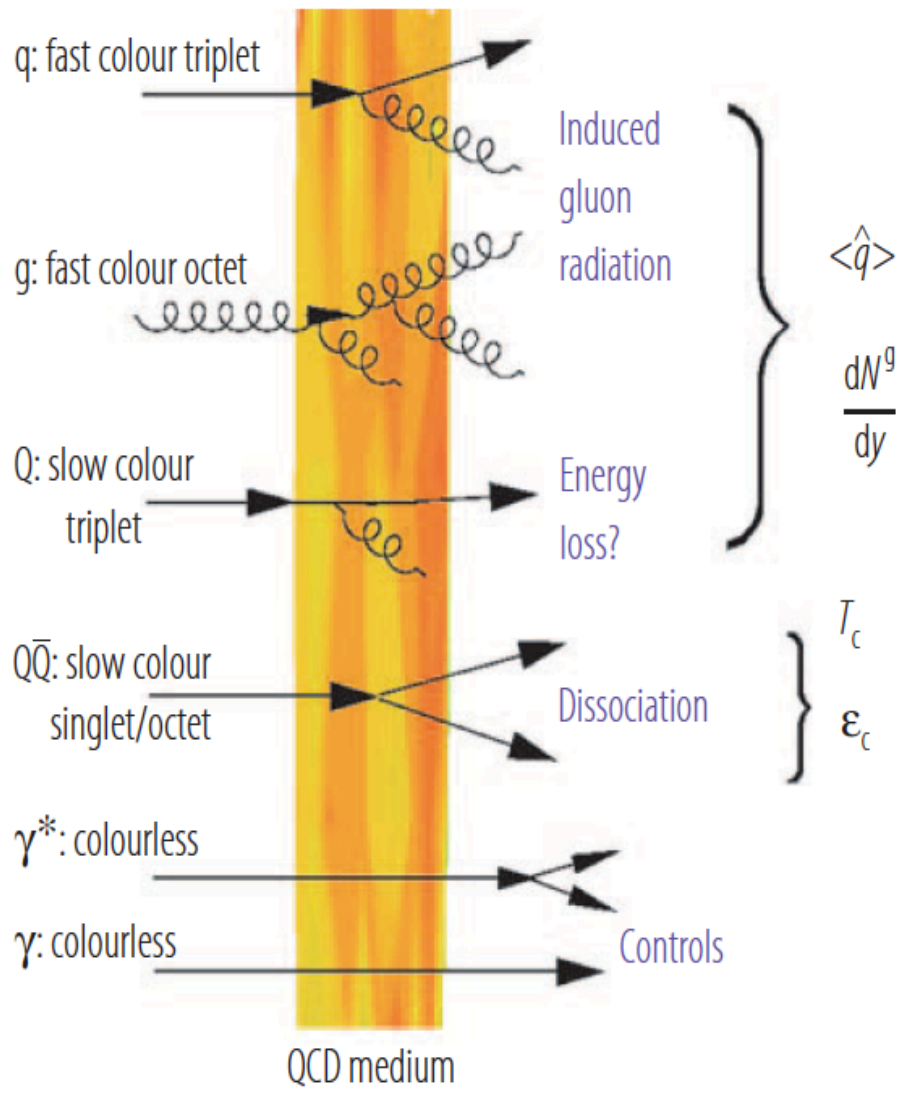
Jet Quenching in the Heavy-Ion Collision

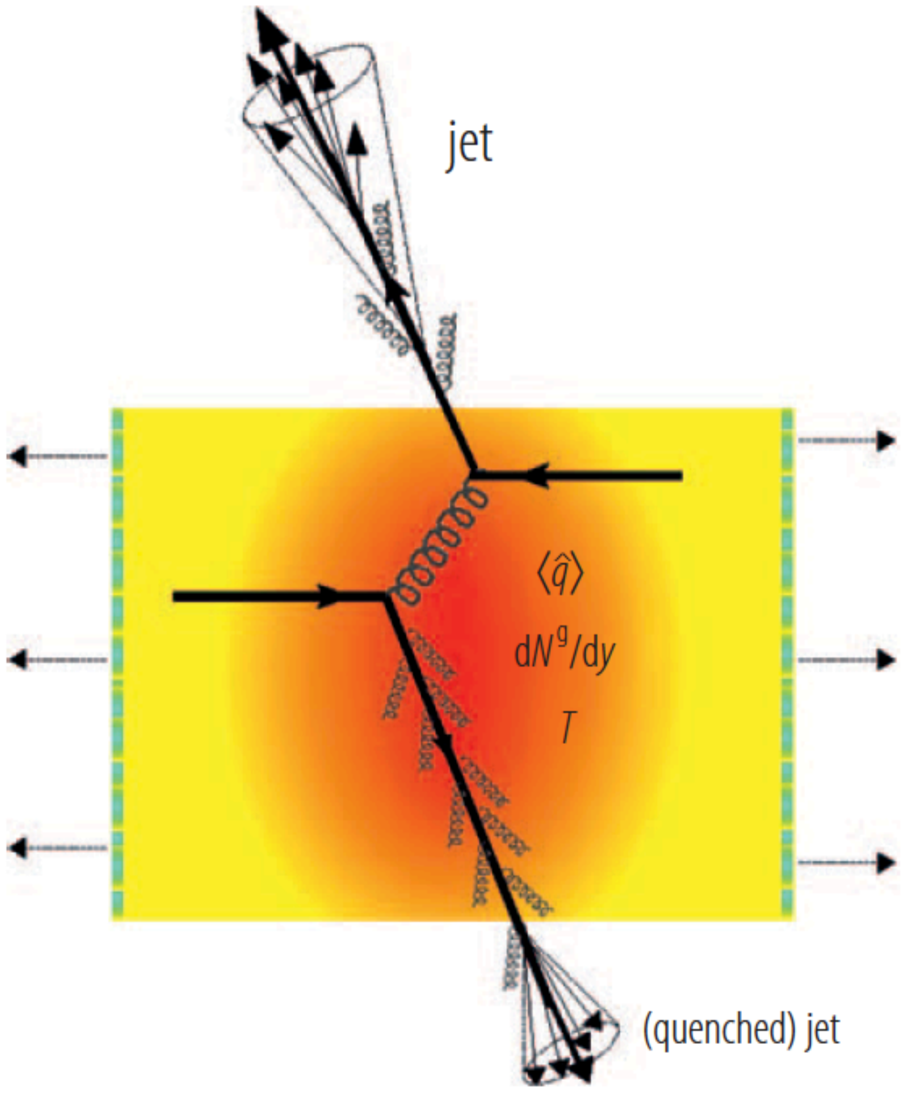


Heavy-Ion Collision at the LHC

- The quark and gluon travel in the hot dense phase, the QGP, will lose their energy by collisions and radiations.







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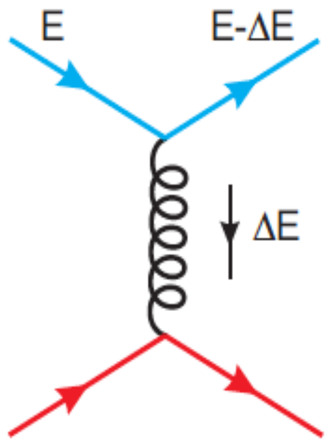
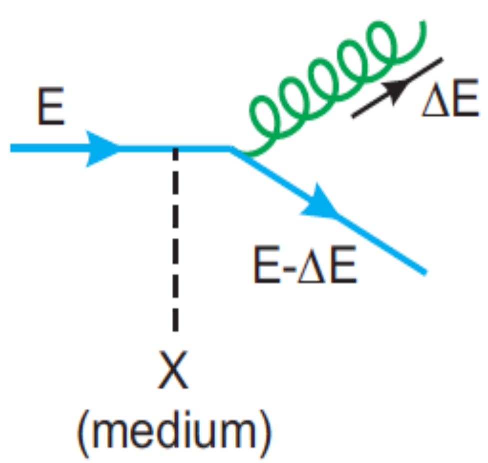
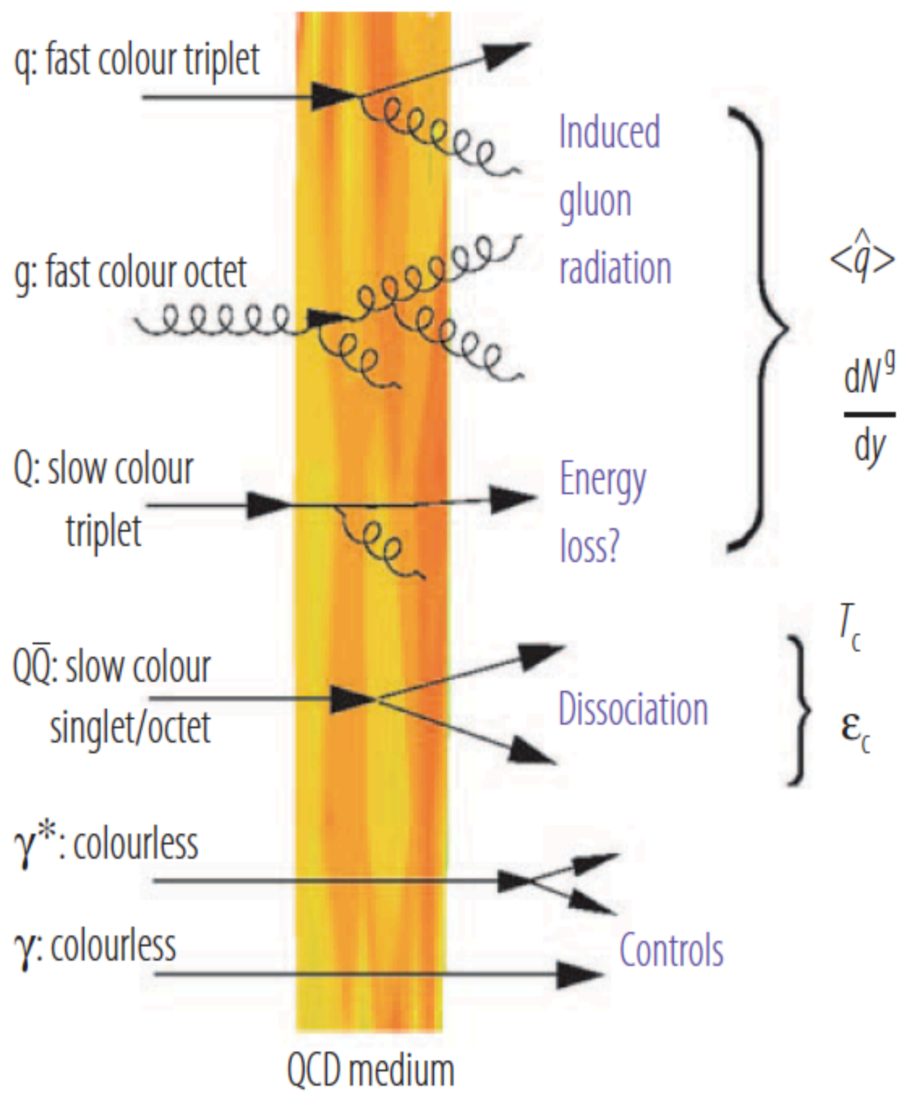
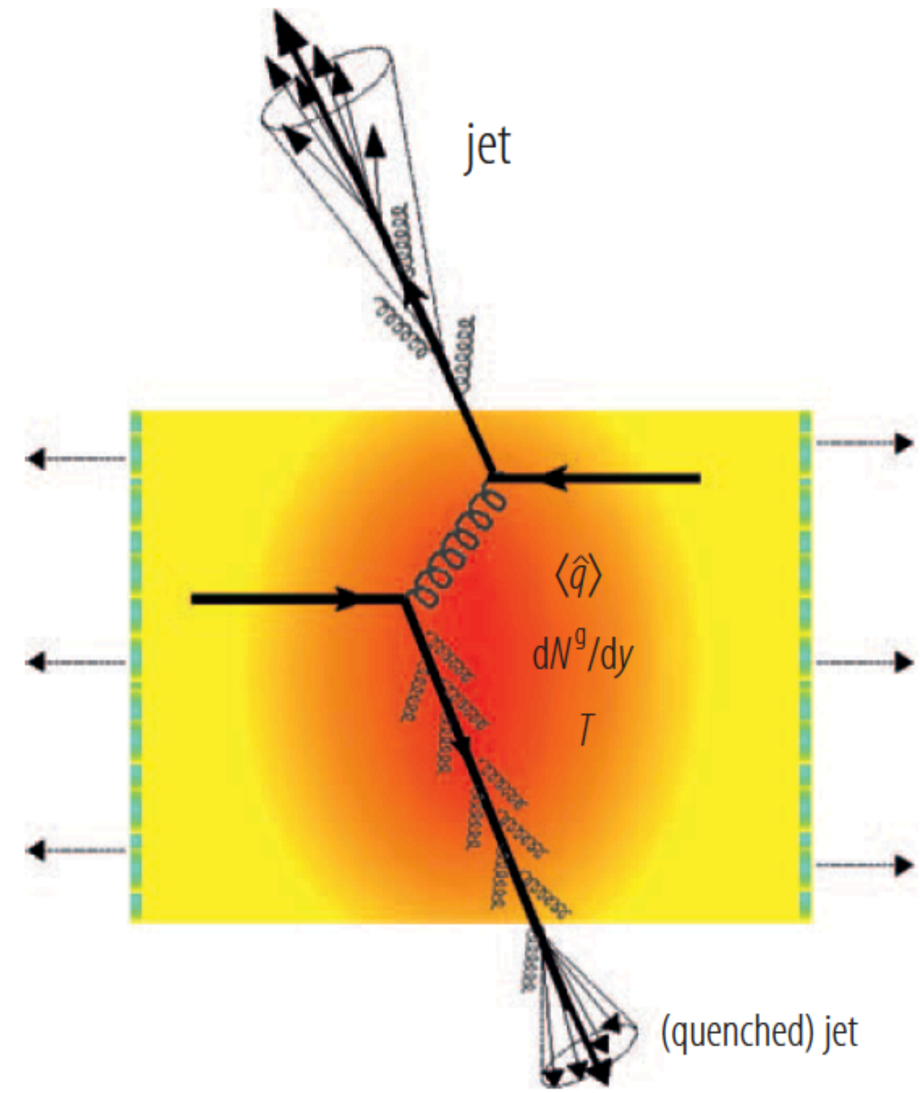
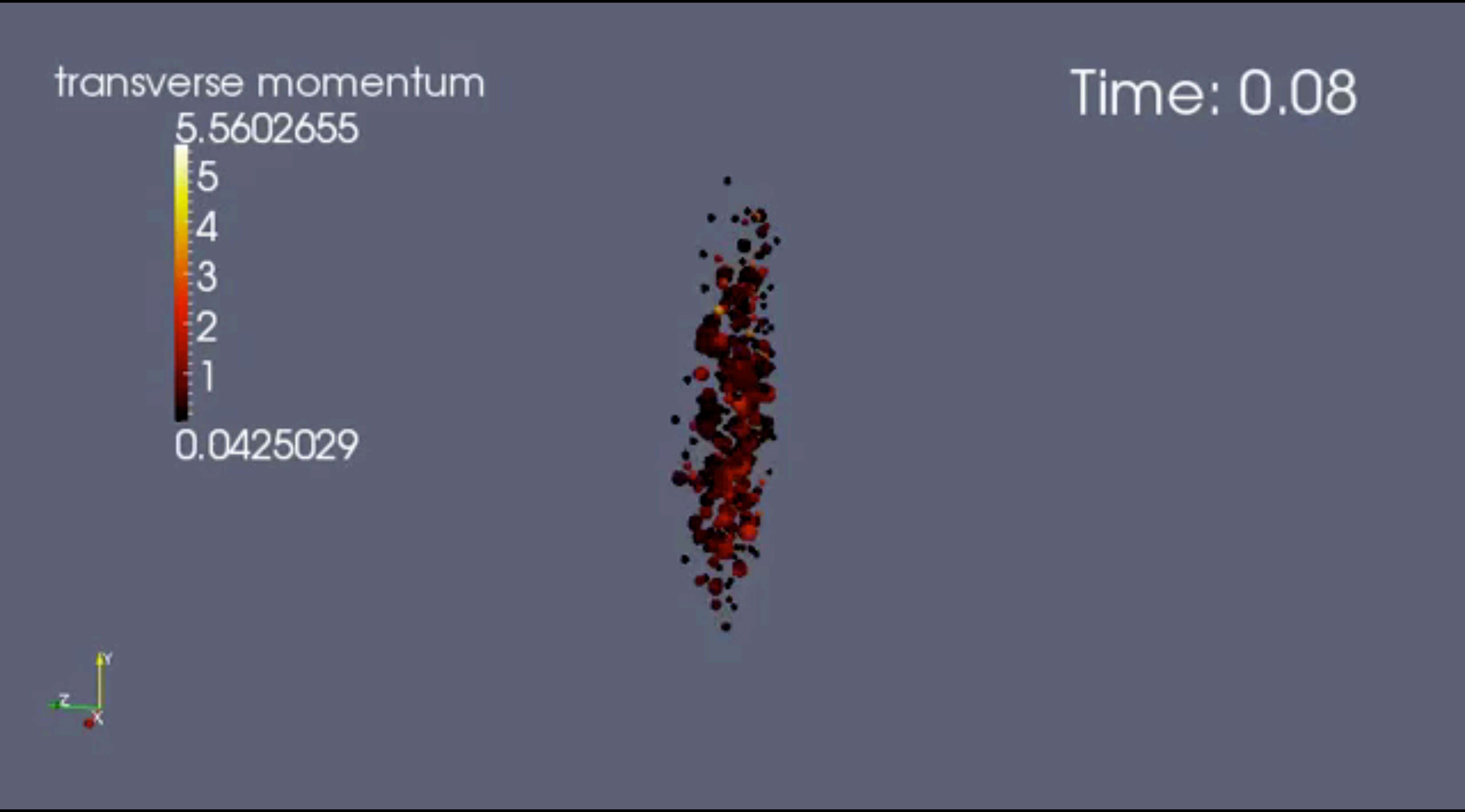


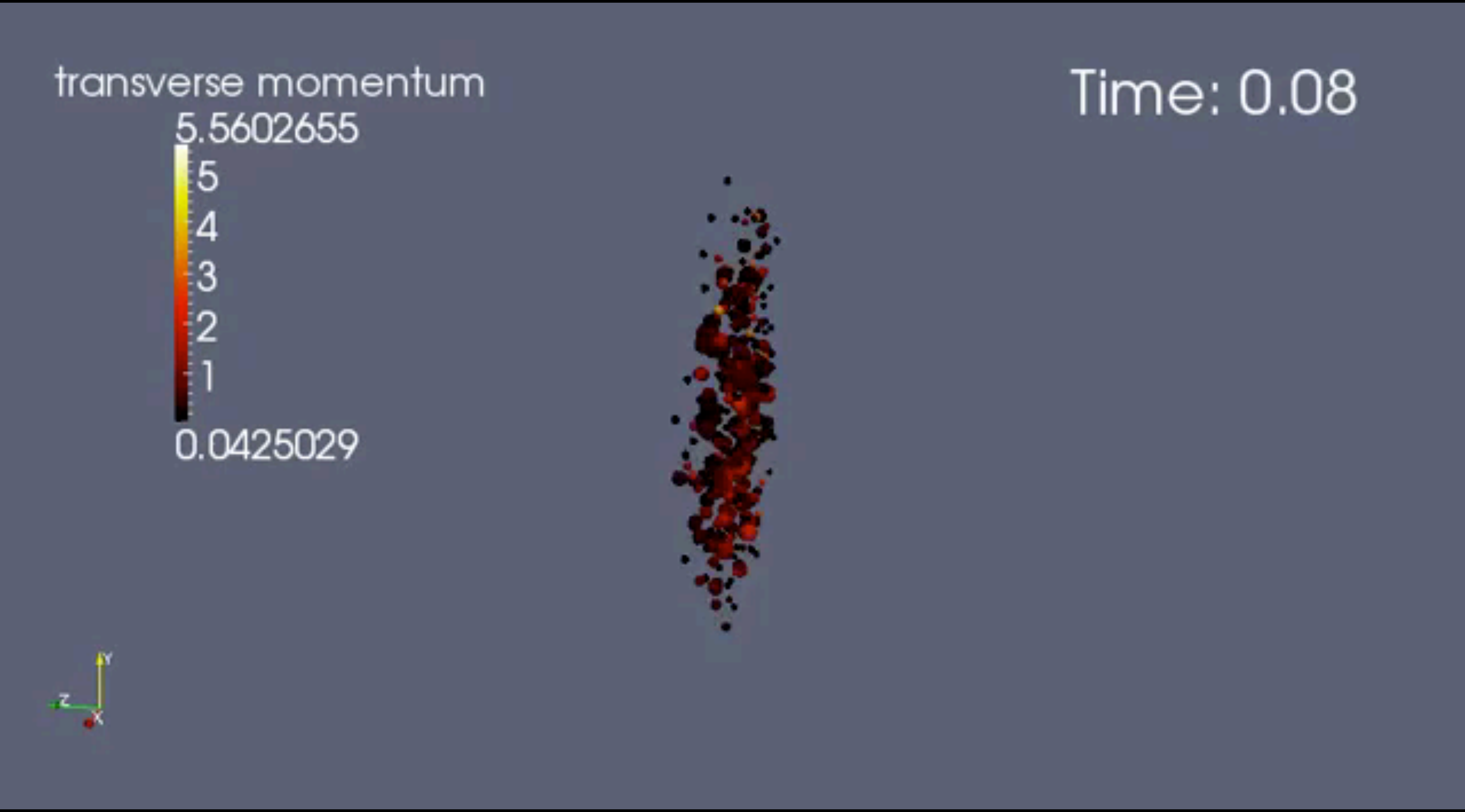






Jet Quenching


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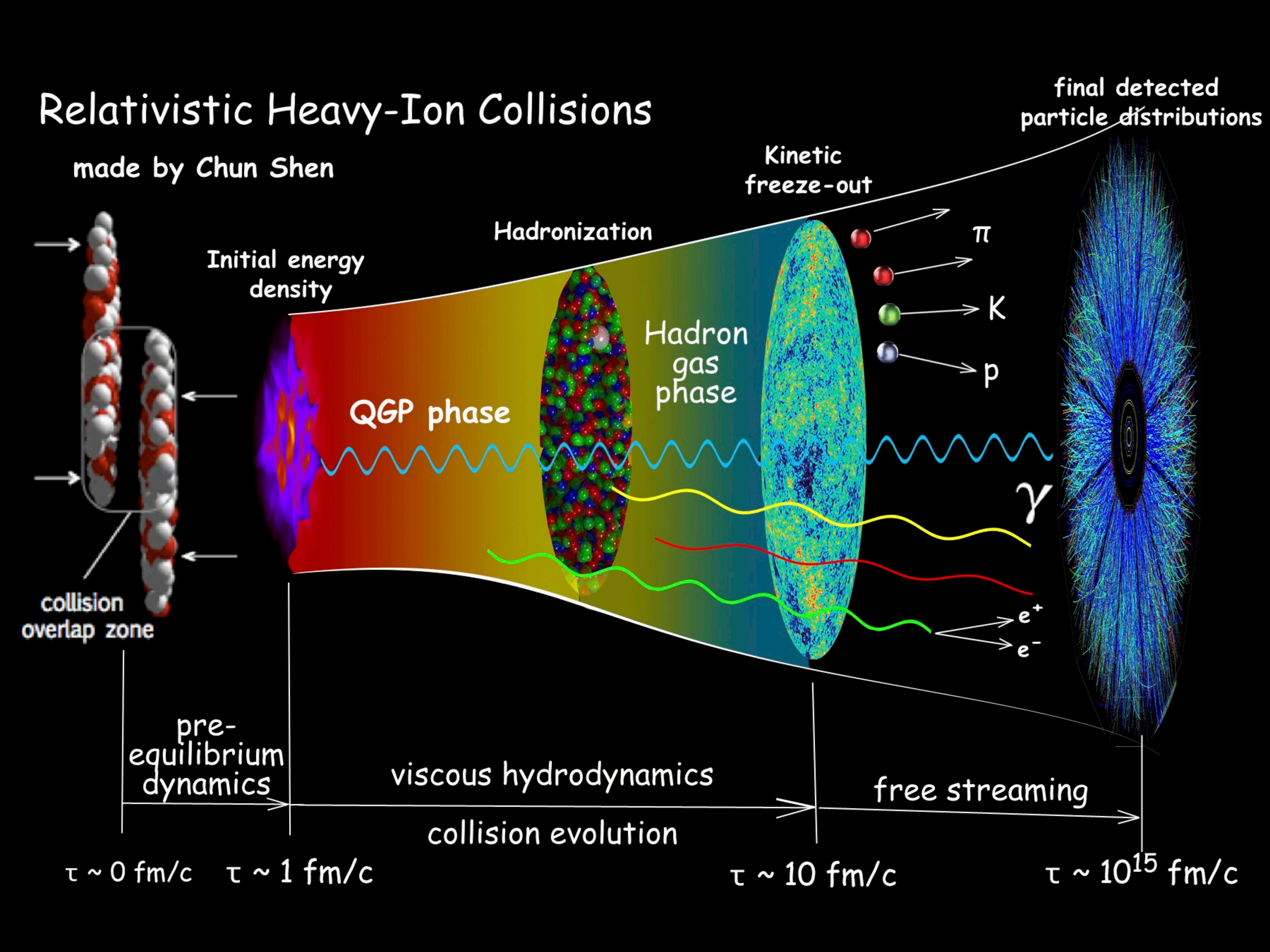
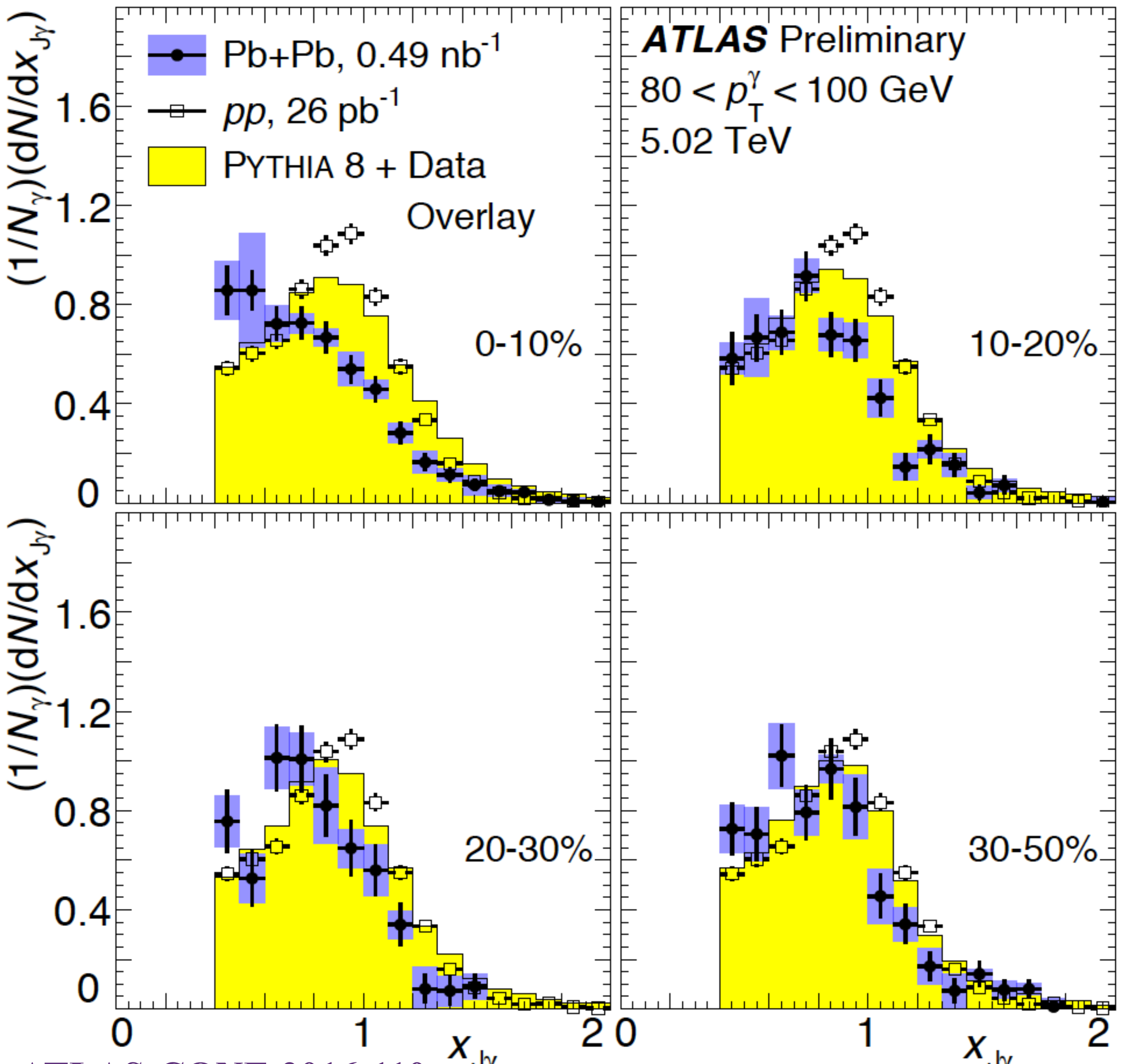

Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
Hadron gas phase
QGP phase
π
K
p
γ
e+
e−
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

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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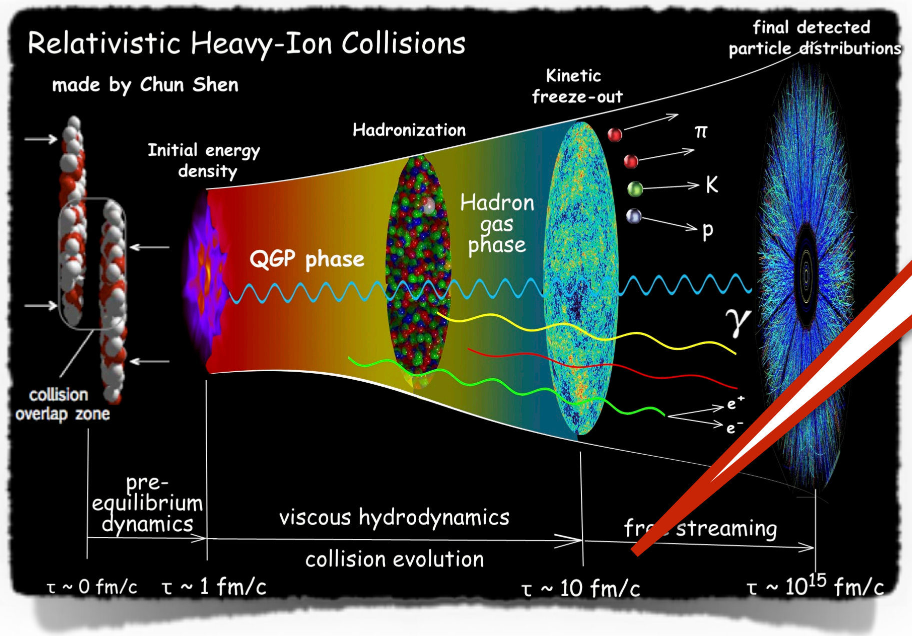

Lifetime ~ 10fm/c

How long is it?

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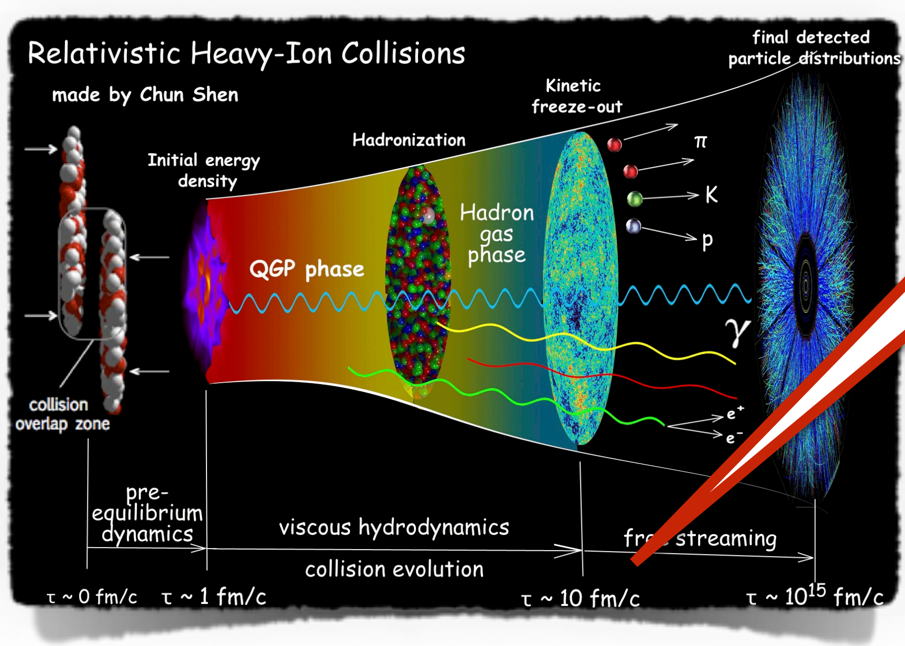


Lifetime ~ 10fm/c

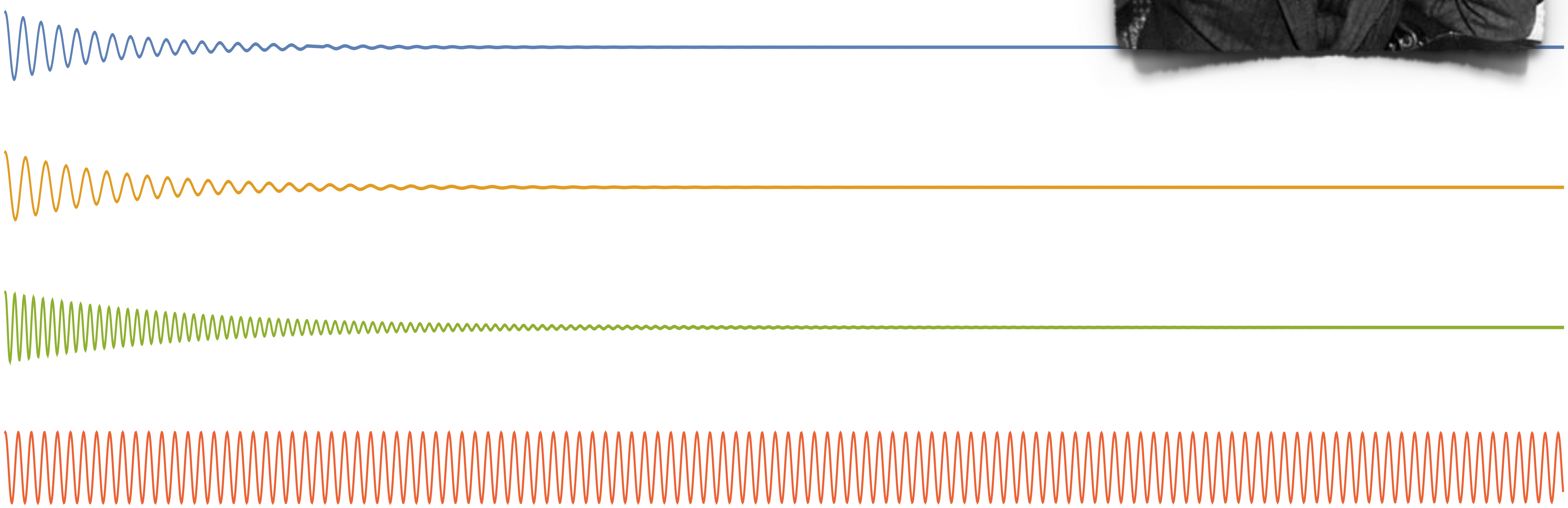
$$1\mathrm{fm/c} = \frac{10^{-15}\mathrm{m}}{2.99792458 \times 10^{8}\mathrm{m/s}} = 3.33564 \times 10^{-24}\mathrm{s}$$

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

Heavy-Ion Collision at the LHC

- Who is who?

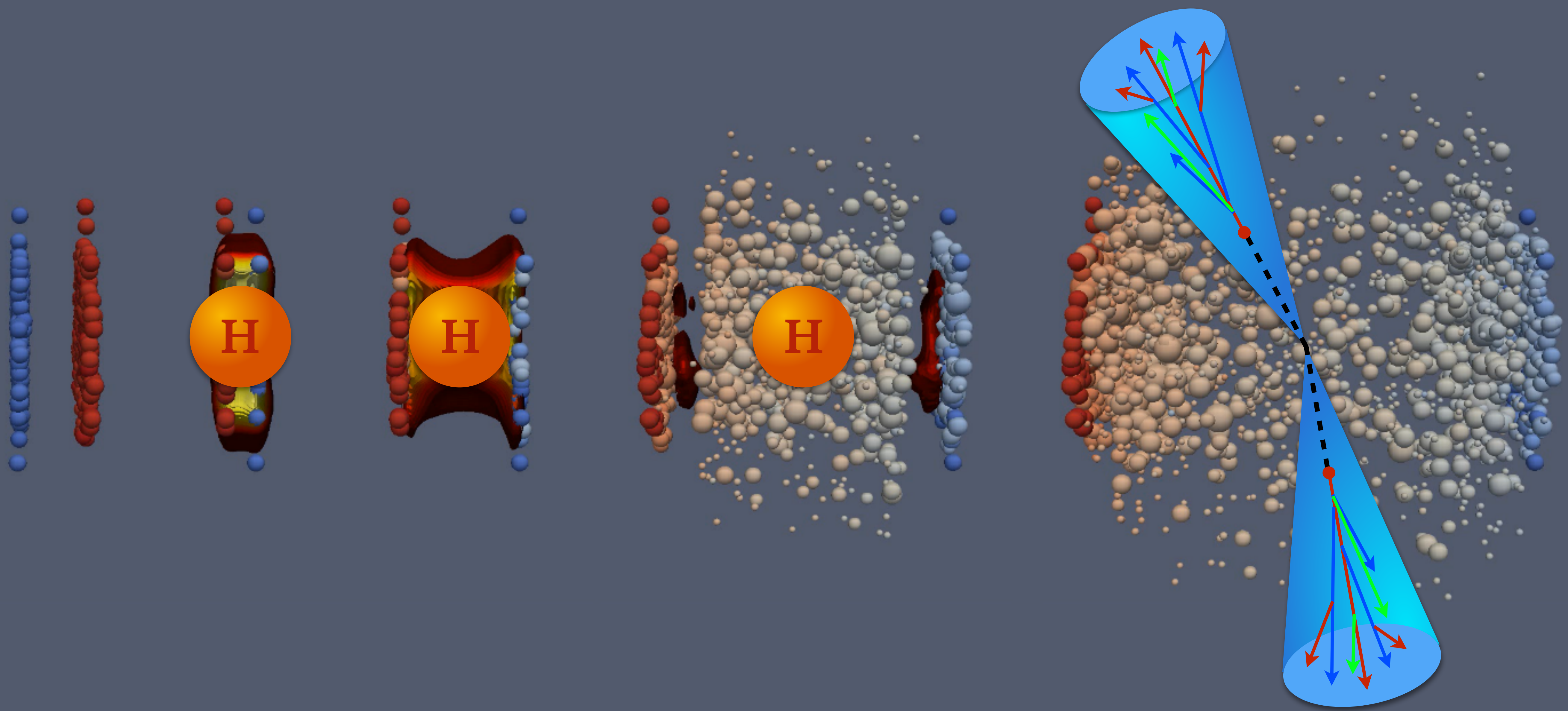
$$\psi \sim \exp\left(-\frac{ip\cdot x}{\hbar}\right) \sim \exp\left(-\frac{i(m-i\Gamma)\tau}{\hbar}\right)$$



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	$bb, WW, gg, cc, \tau\tau, ZZ\ldots$	



Higgs boson —— the Surviver in the QGP Fireball

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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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

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

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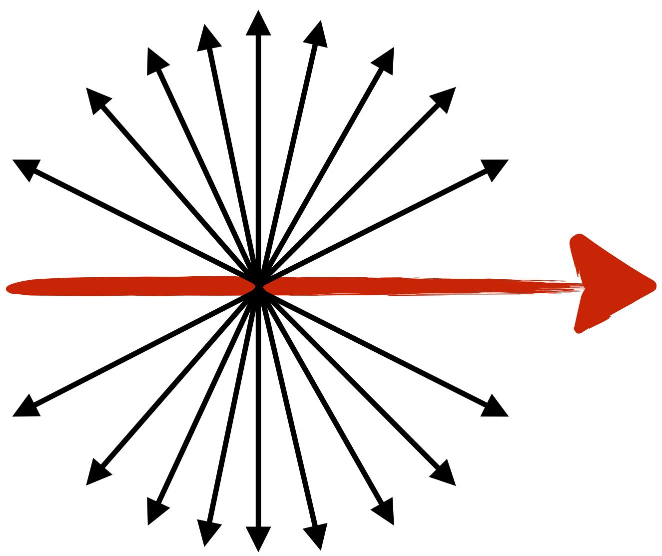
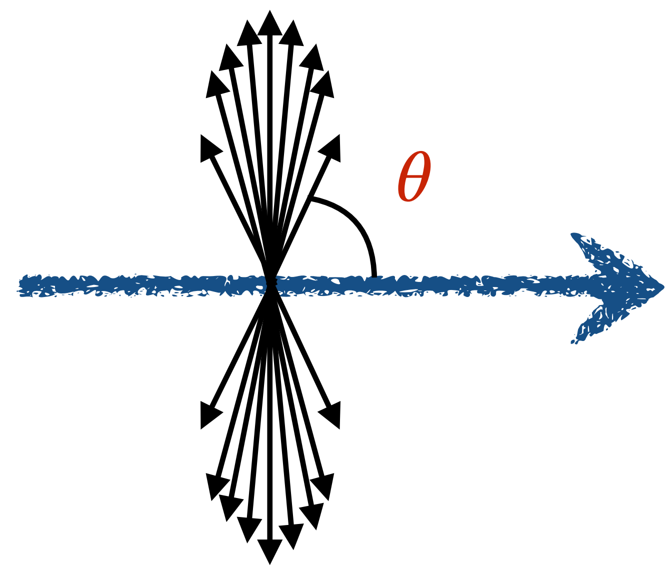
$$\omega \frac{dI_{\mathrm{rad},Q}}{d\omega dk_\perp^2} \approx \omega \frac{dI_{\mathrm{rad}}}{d\omega dk_\perp^2} \frac{1}{1+\frac{M_Q^2}{E_Q^2\theta^2}}$$



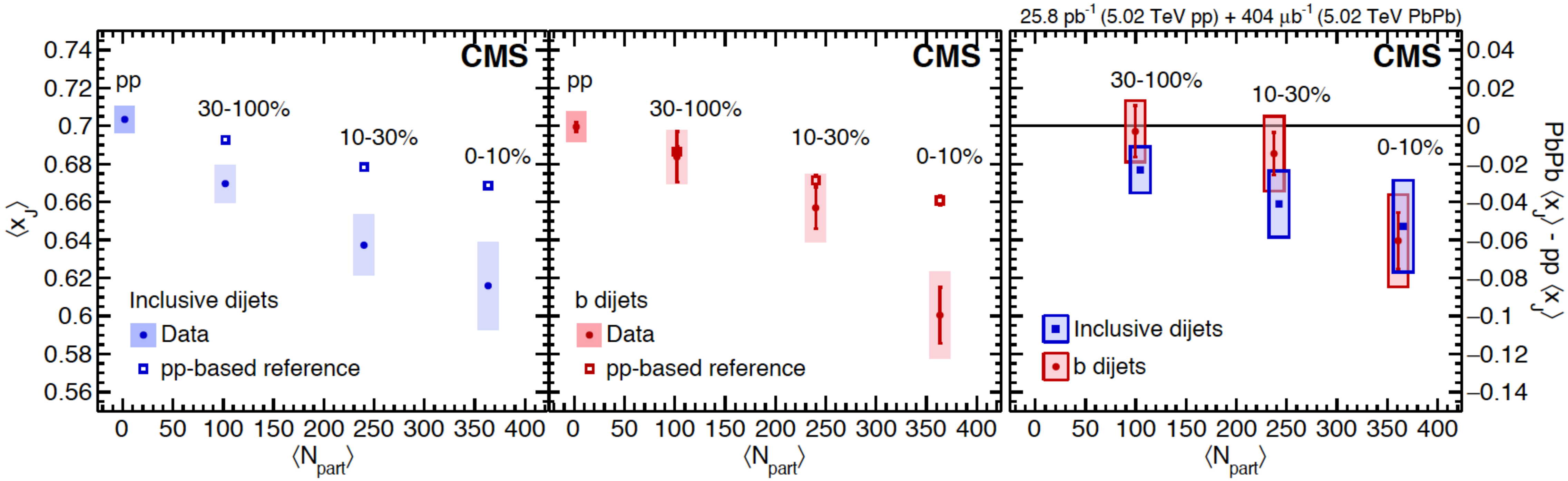
Gluon, light quarks



Heavy quarks

Higgs in Heavy-Ion Collision

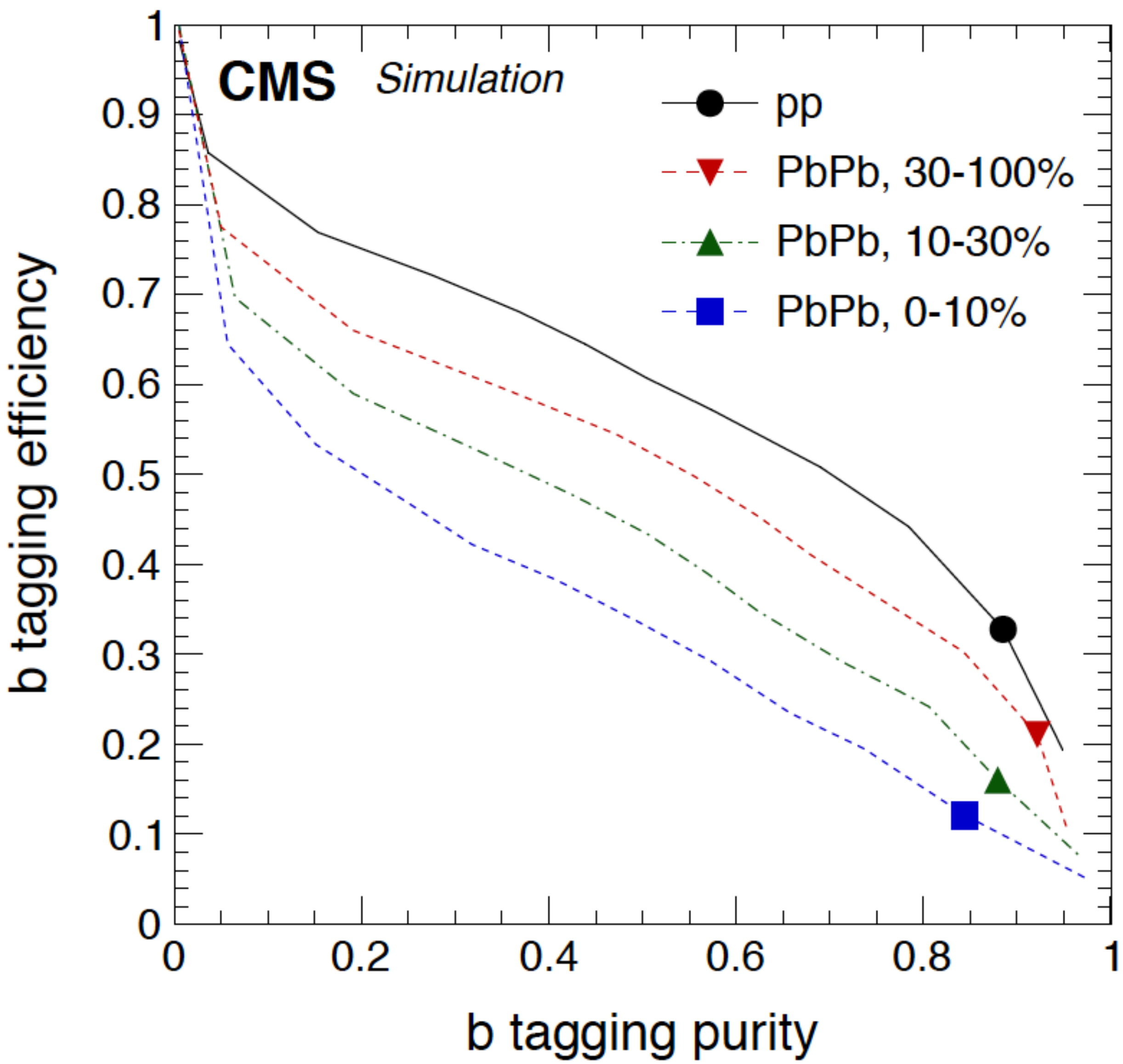
- Hadronic decay Higgs boson.
- Question 1: Is *b*-quark quenched as much as light quarks and gluons?
  - QCD calculation: “dead cone” effect.
  - Experiment (which can be understand theoretically):



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?

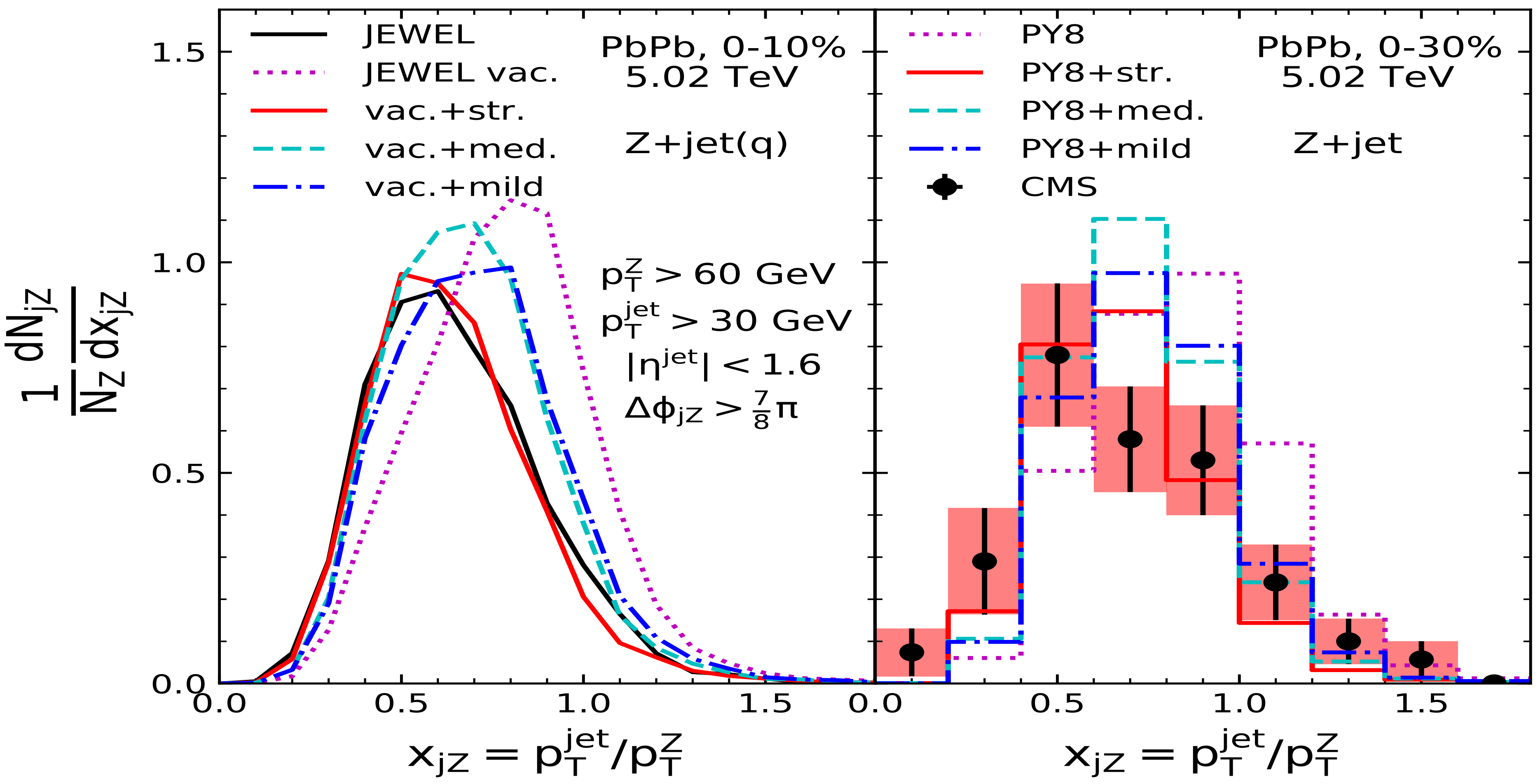


CMS Collaboration, JHEP 03 (2018) 181.

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):

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

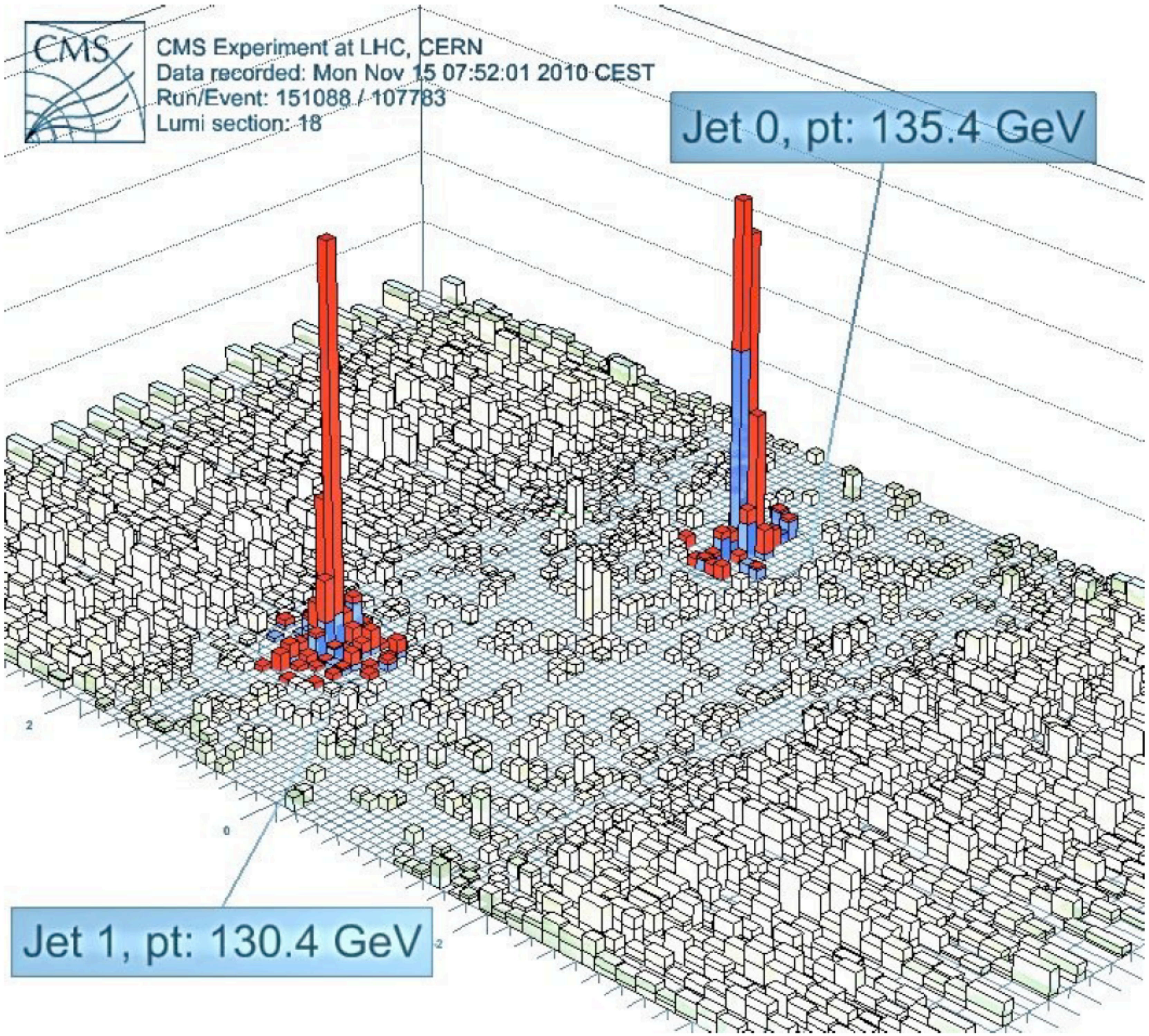


Higgs in Heavy-Ion Collision

- 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

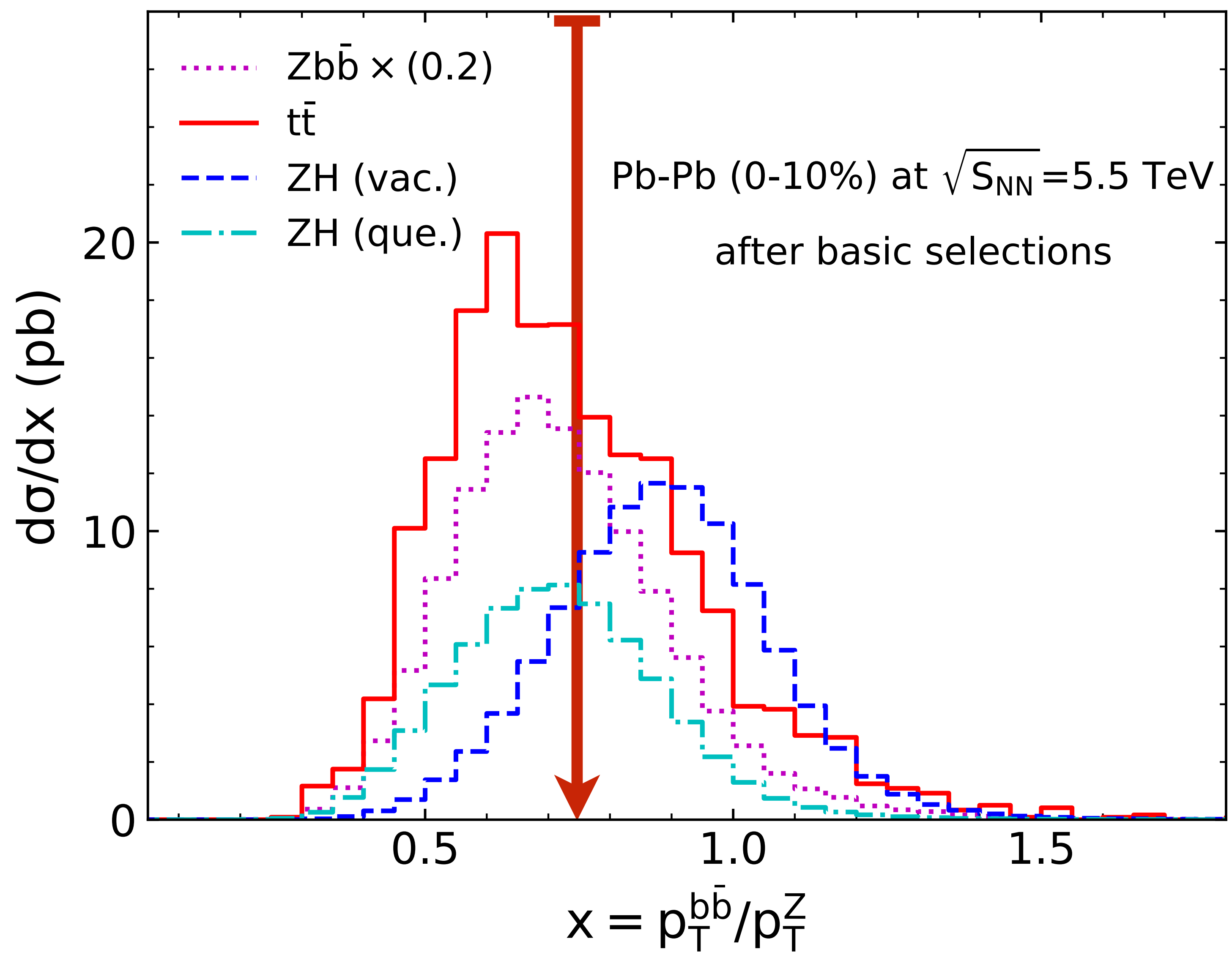
- Dominant SM backgrounds:
  - *Z+bb*;
  - *Z+bc, Z+cc*;
  - Top-pair;
- We simulate the signal and background with MadGraph at parton level and add the smearing and jet quenching effect with the formulas to understand the cuts.

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

Higgs in Heavy-Ion Collision

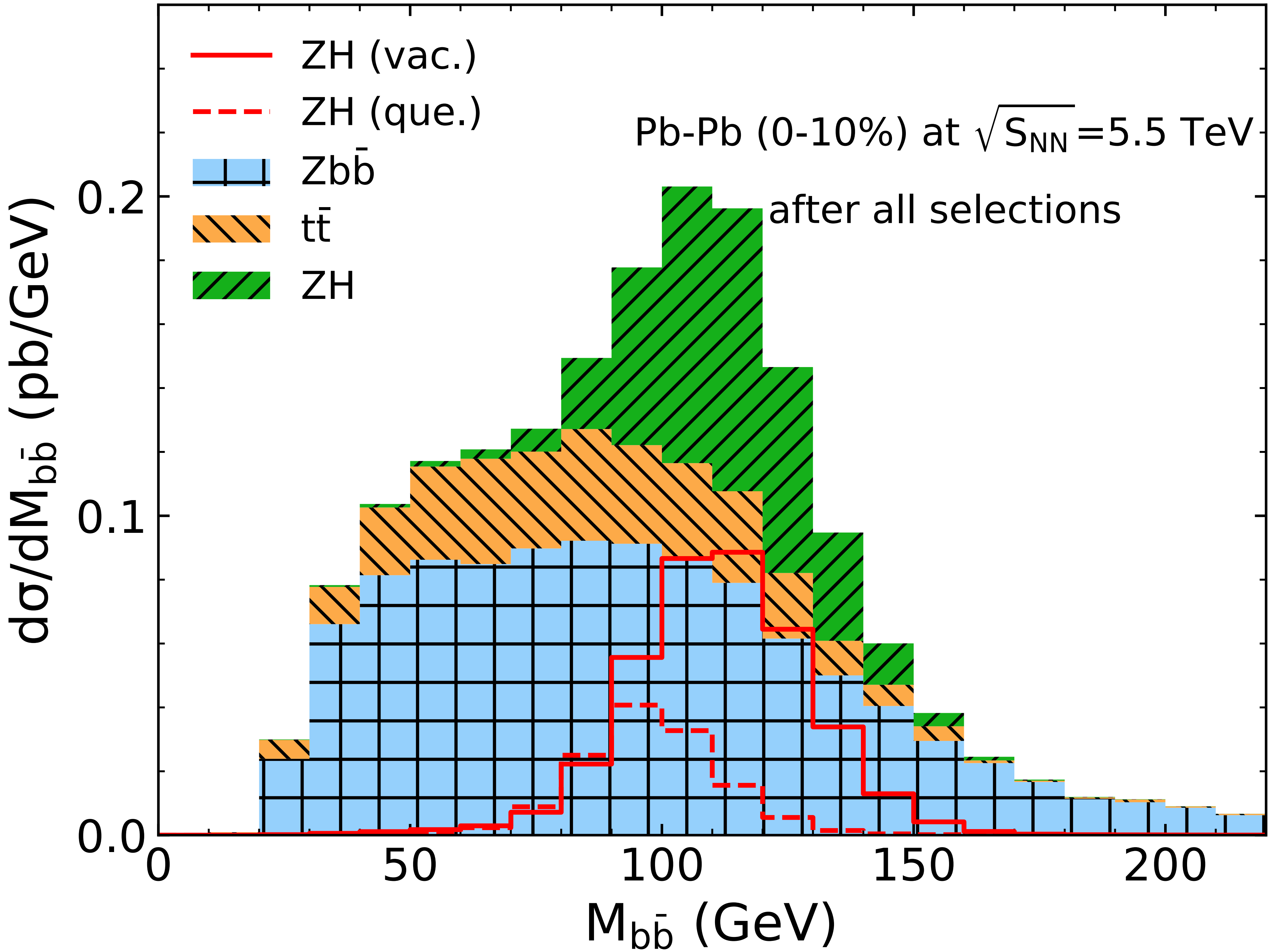
- The jet quenching effect introduces a significant transverse momentum imbalance between the dilepton system and the *b*-jet pair system.
- We can suppress the *Zbb* background with more cuts:

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



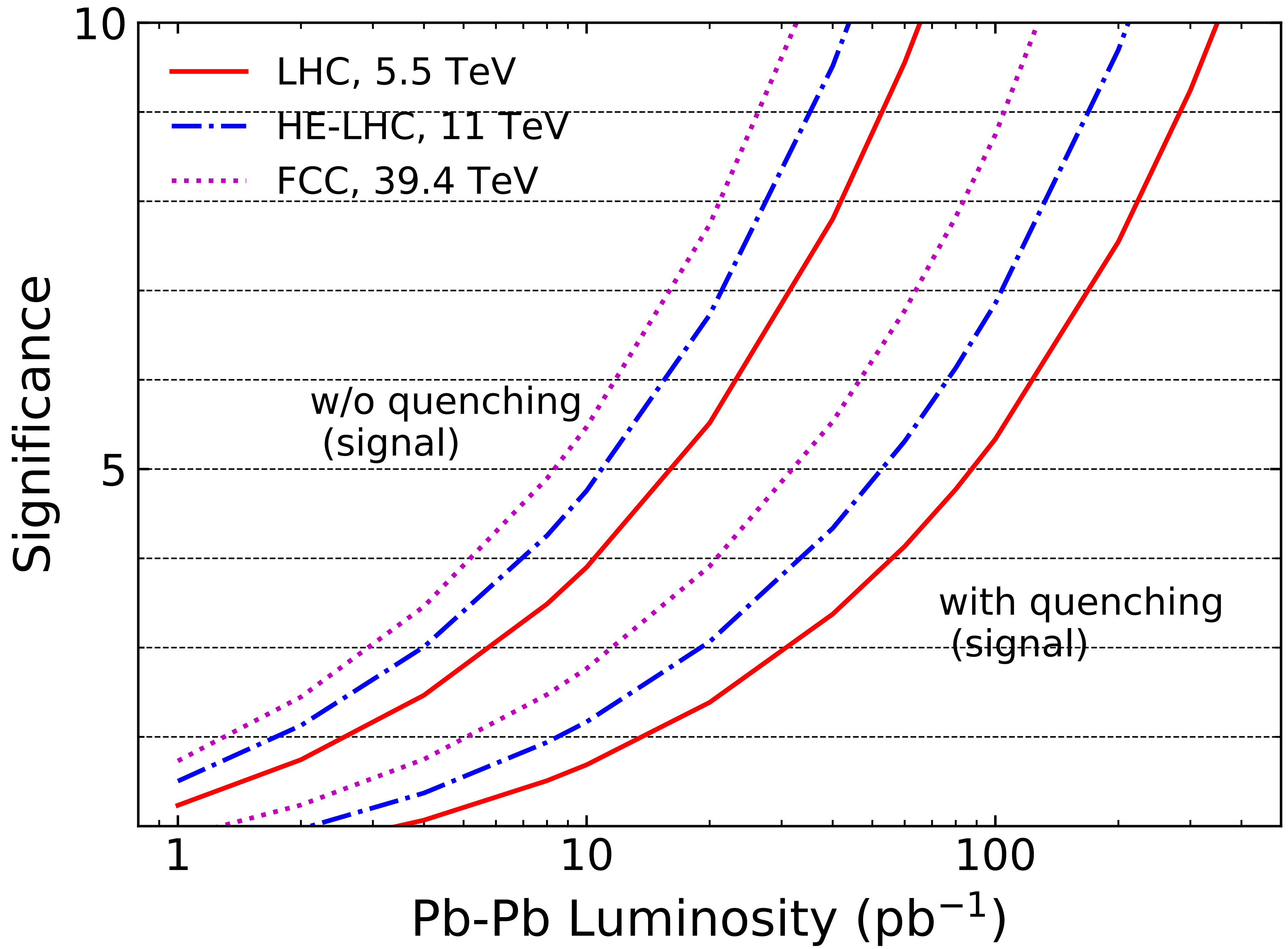
Higgs in Heavy-Ion Collision

- After all cuts.

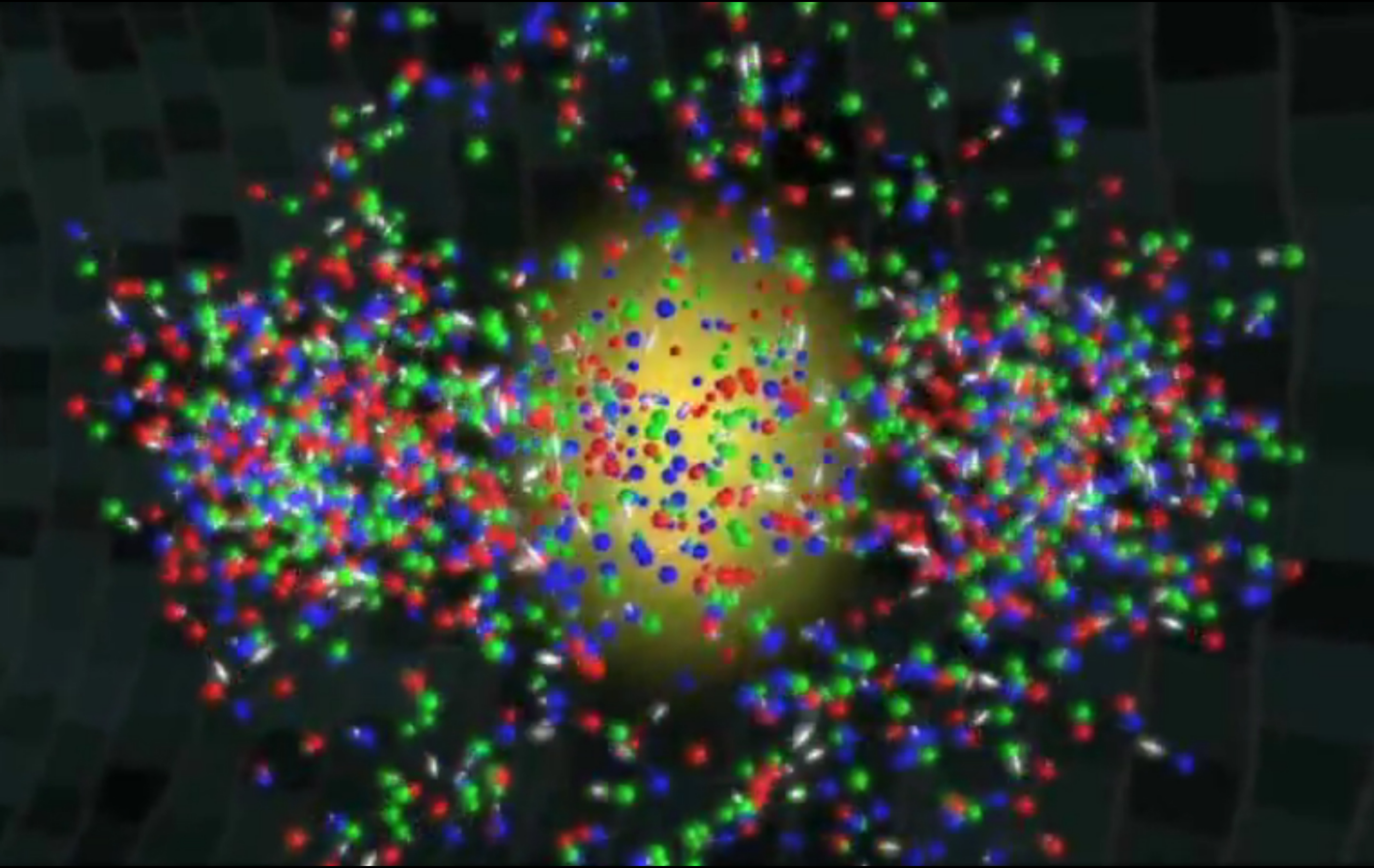


Higgs in Heavy-Ion Collision

- 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	[μm]	1.5	1.5	3.75
Number of IPs in collision	-	-	1	1
Crossing-angle	[μrad]	-	0	
Initial luminosity	[10^{27}cm^{-2}s^{-1}]	-	24.5	2052
Peak luminosity	[10^{27}cm^{-2}s^{-1}]	-	57.8	9918
Integrated luminosity per fill	[μb^{-1}]	-	[illegible]	158630
Average luminosity	[μb^{-1}]	-	92	20736
Time in collision	[h]	-	3	6
Assumed turnaround time	[h]	-	1.65	1.65
Integrated luminosity/run	[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

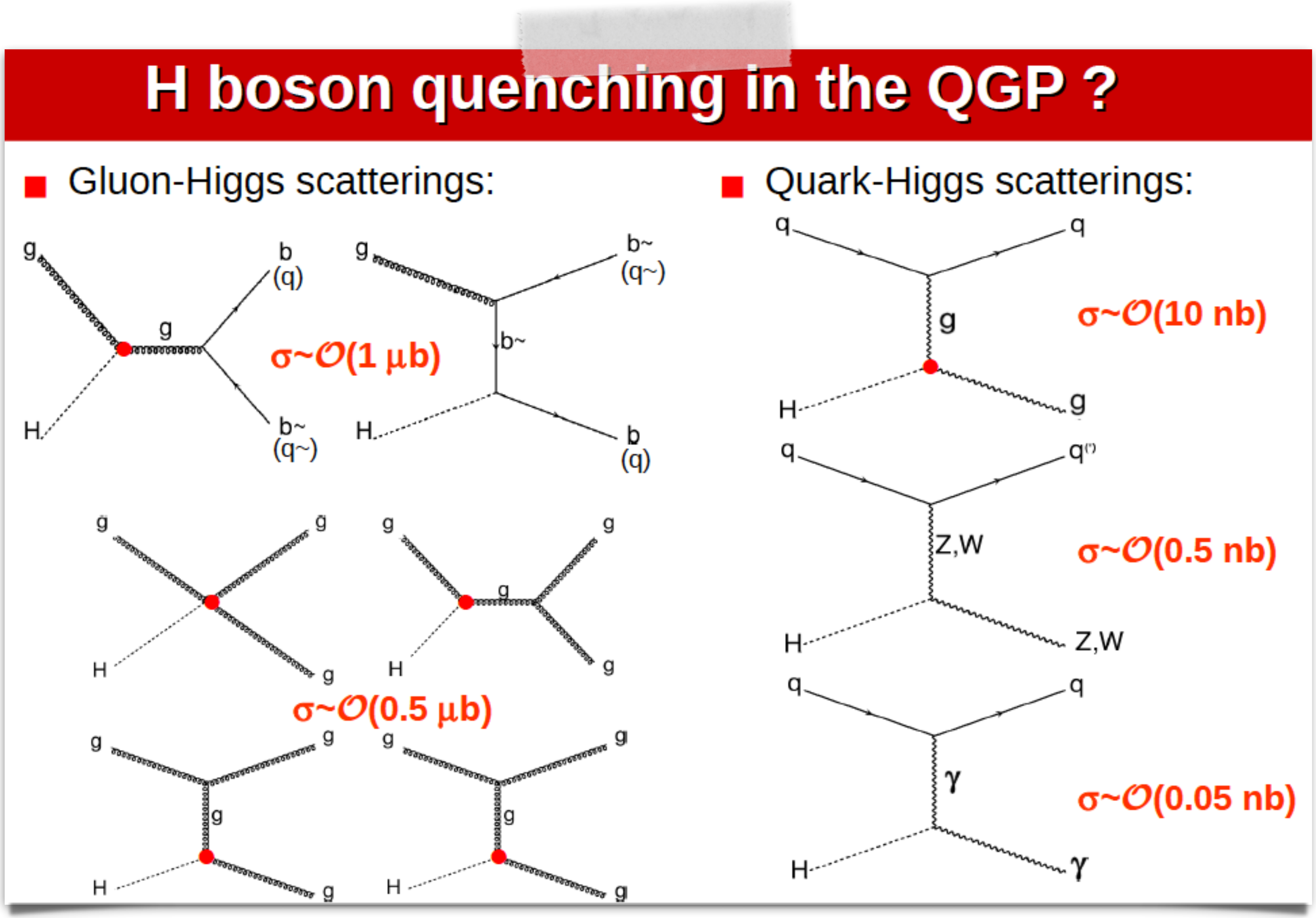
CERN Yellow Reports, Physics at the FCC-hh, a 100 TeV pp collider, Chapter 4: Heavy Ions at the Future Circular Collider.

Outlook

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

Outlook

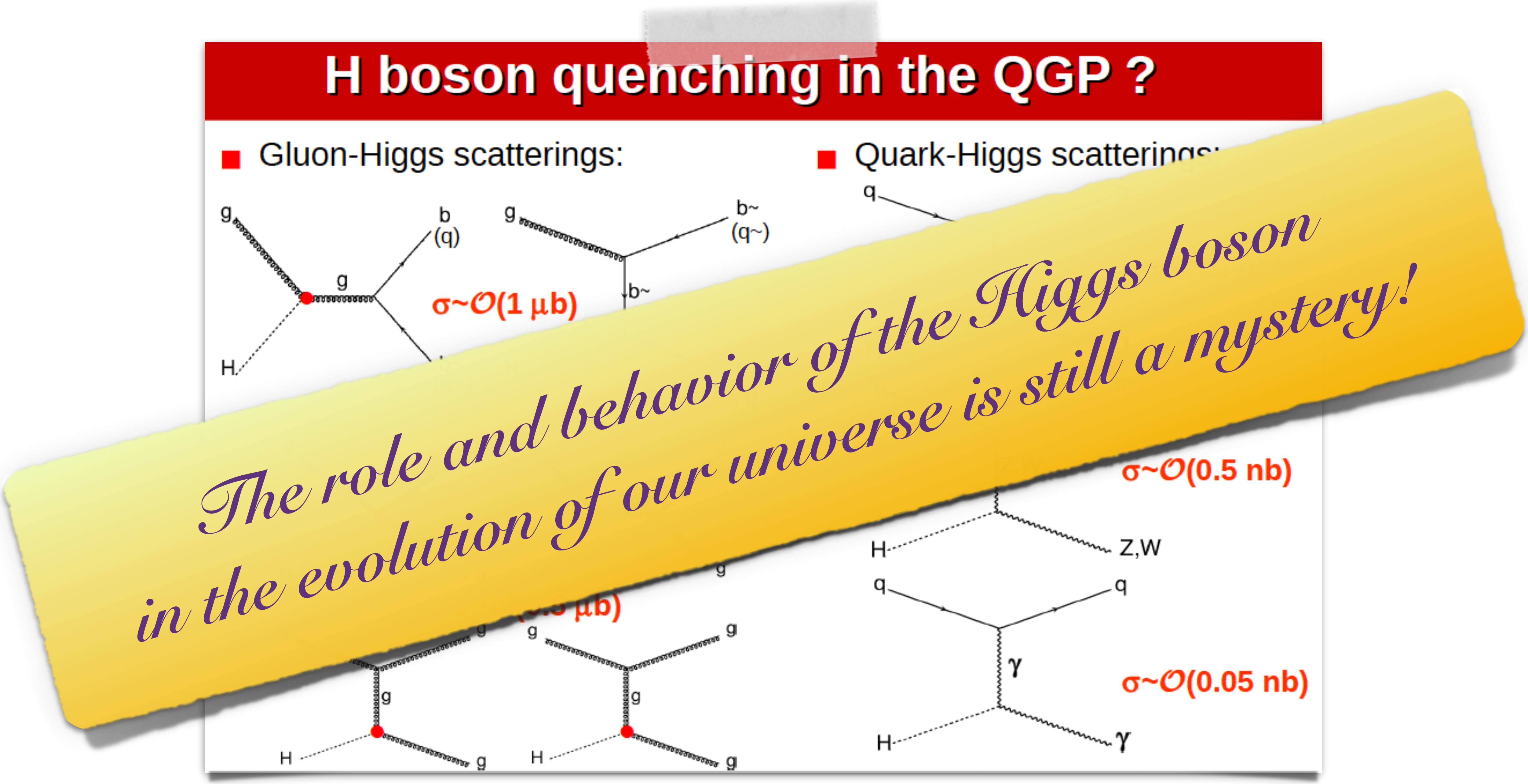
- Higgs quenching?



From David d'Enterria

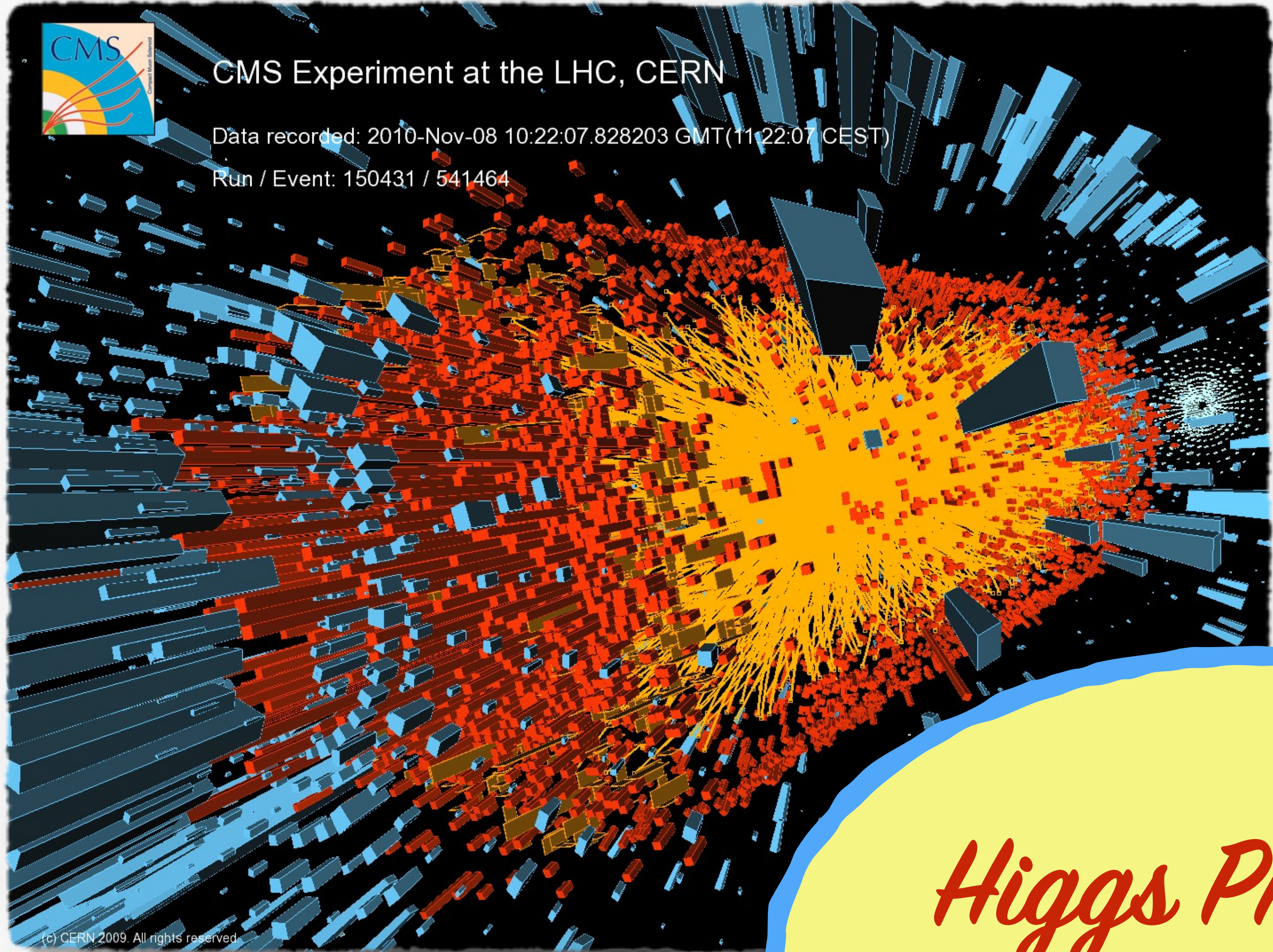
Outlook

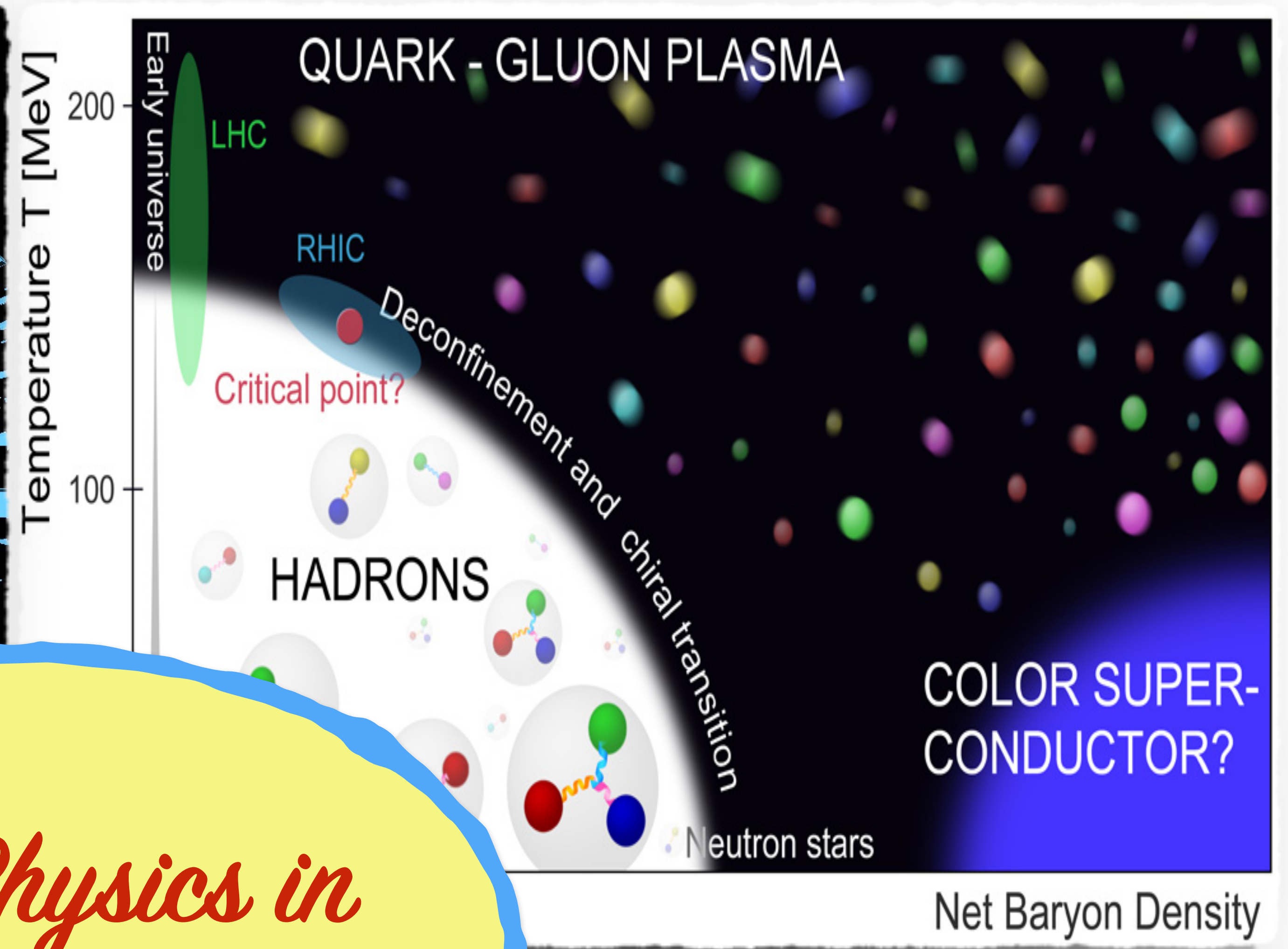
- Higgs quenching?

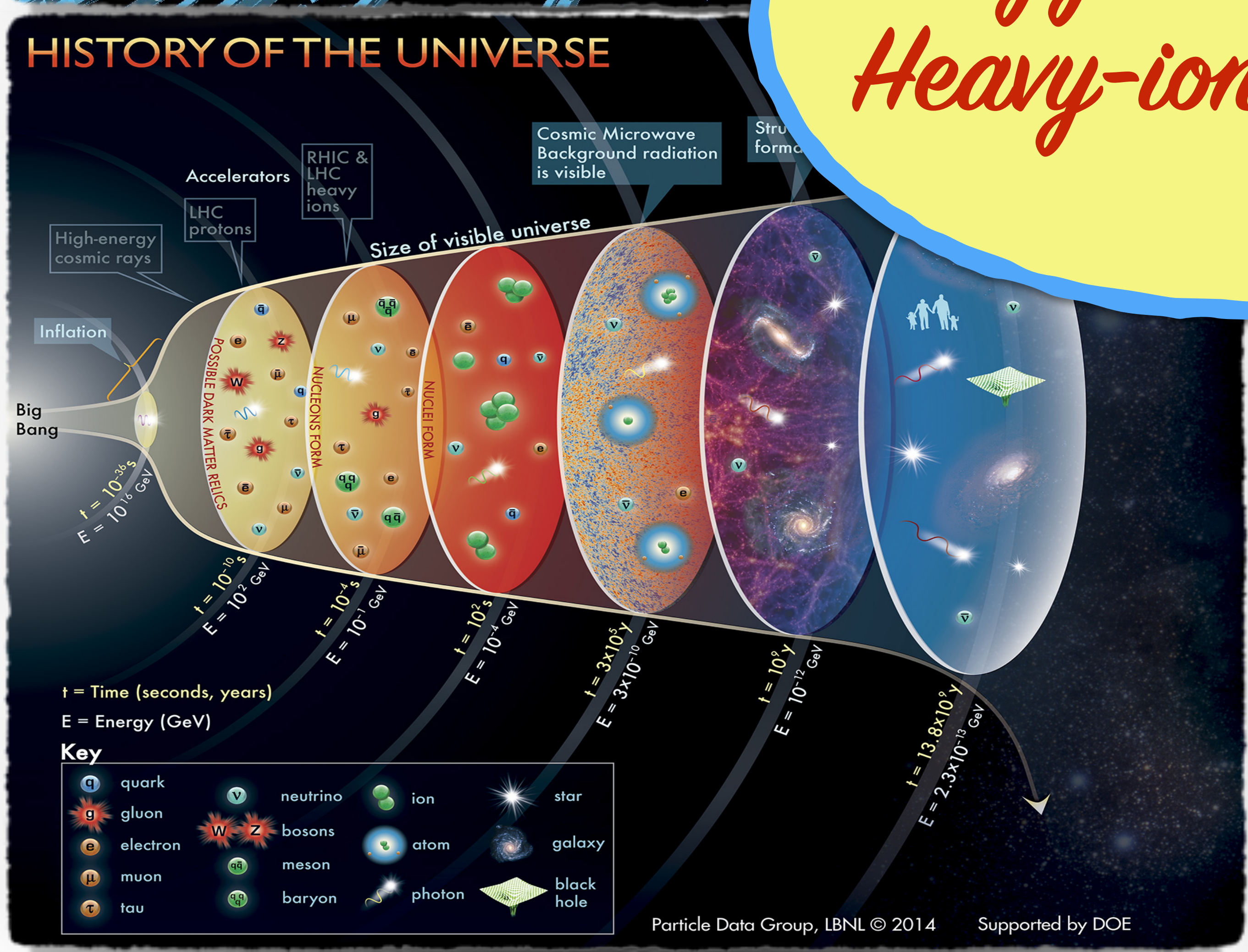


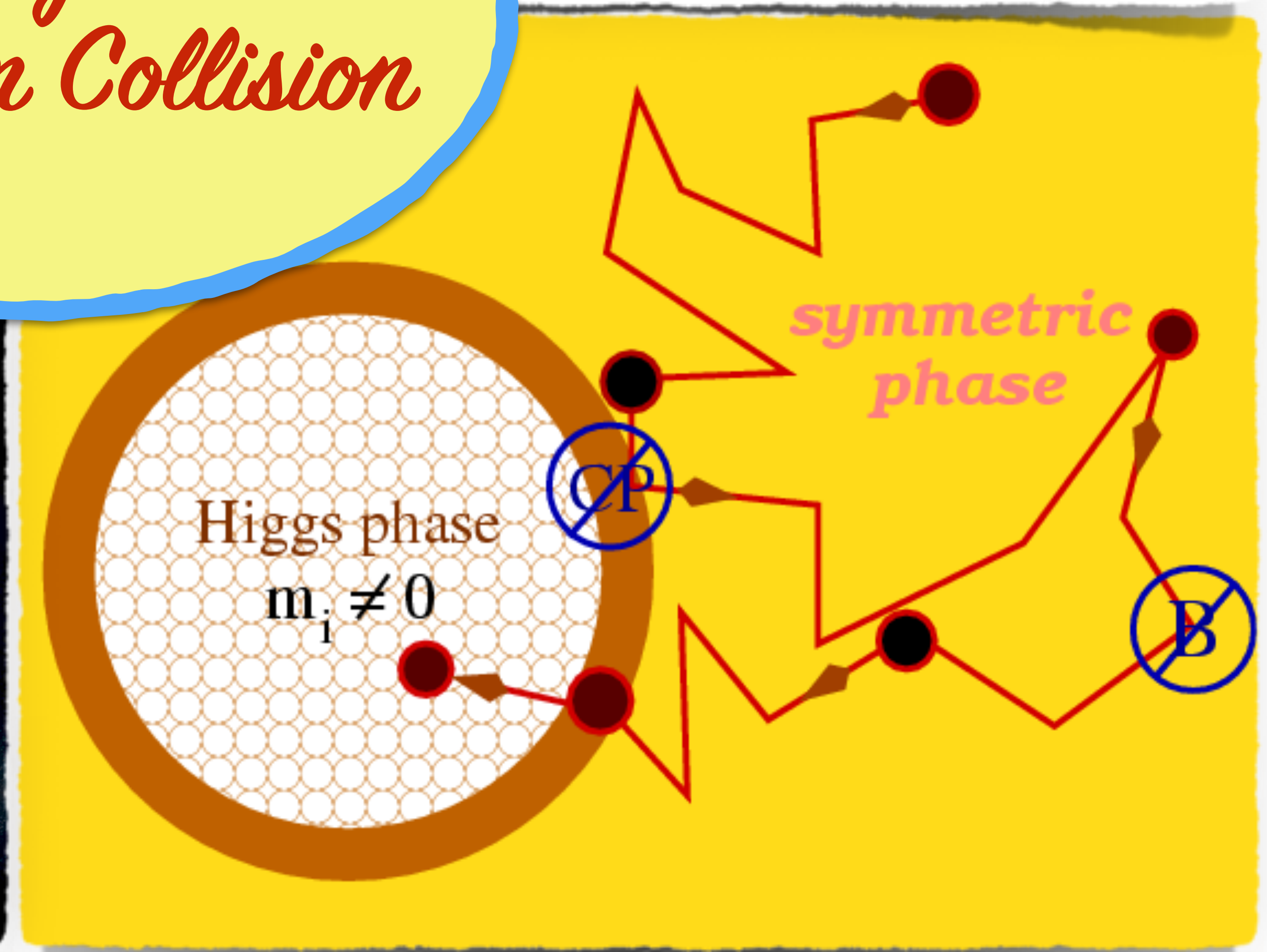
From David d'Enterria

Higgs Physics in Heavy-ion Collision









Thank you!

Thank you!

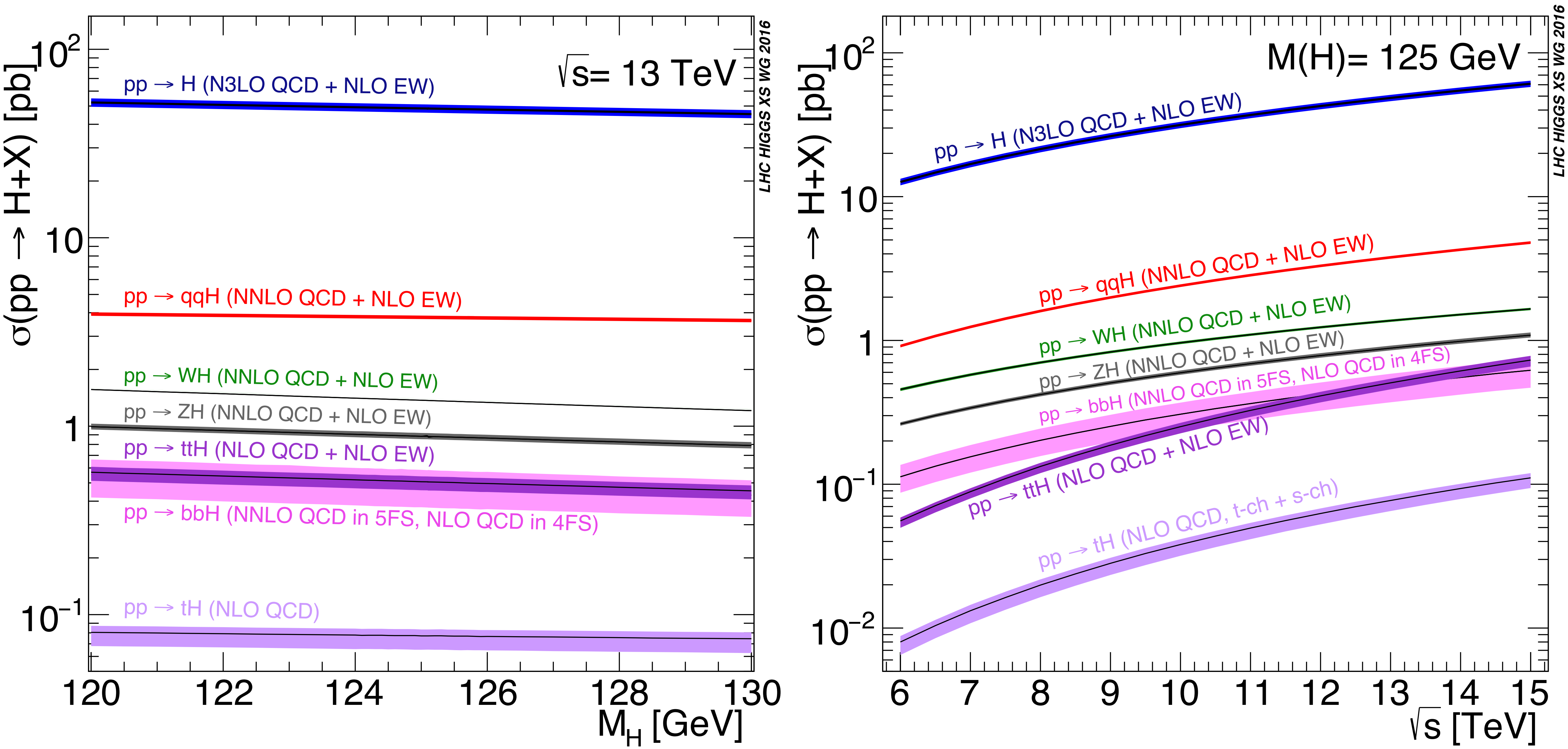
Backup

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

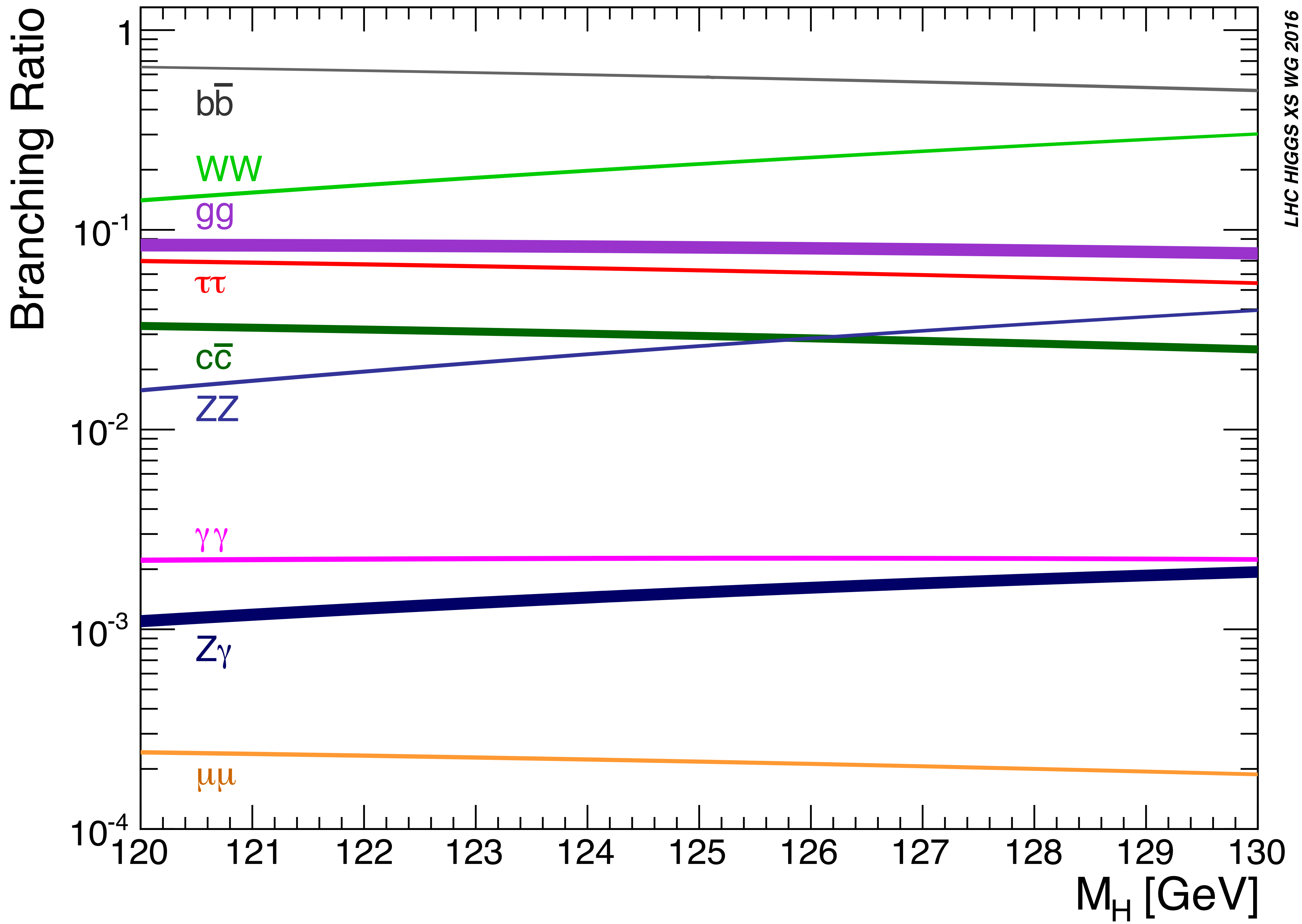
- The production of the SM-like Higgs boson (cross sections).



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

Higgs boson at the LHC

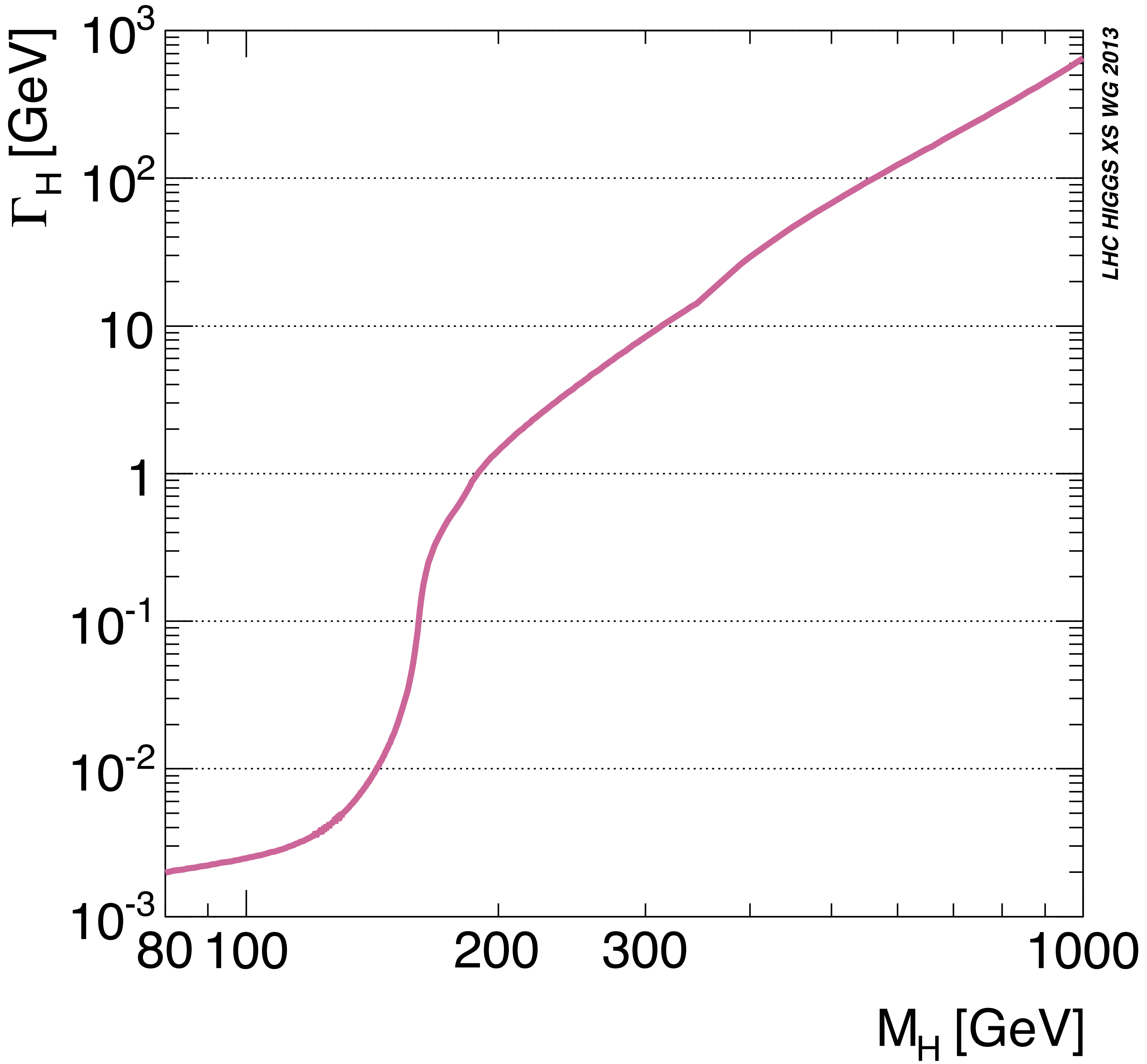
- The decay of the SM-like Higgs boson (branching ratios).



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

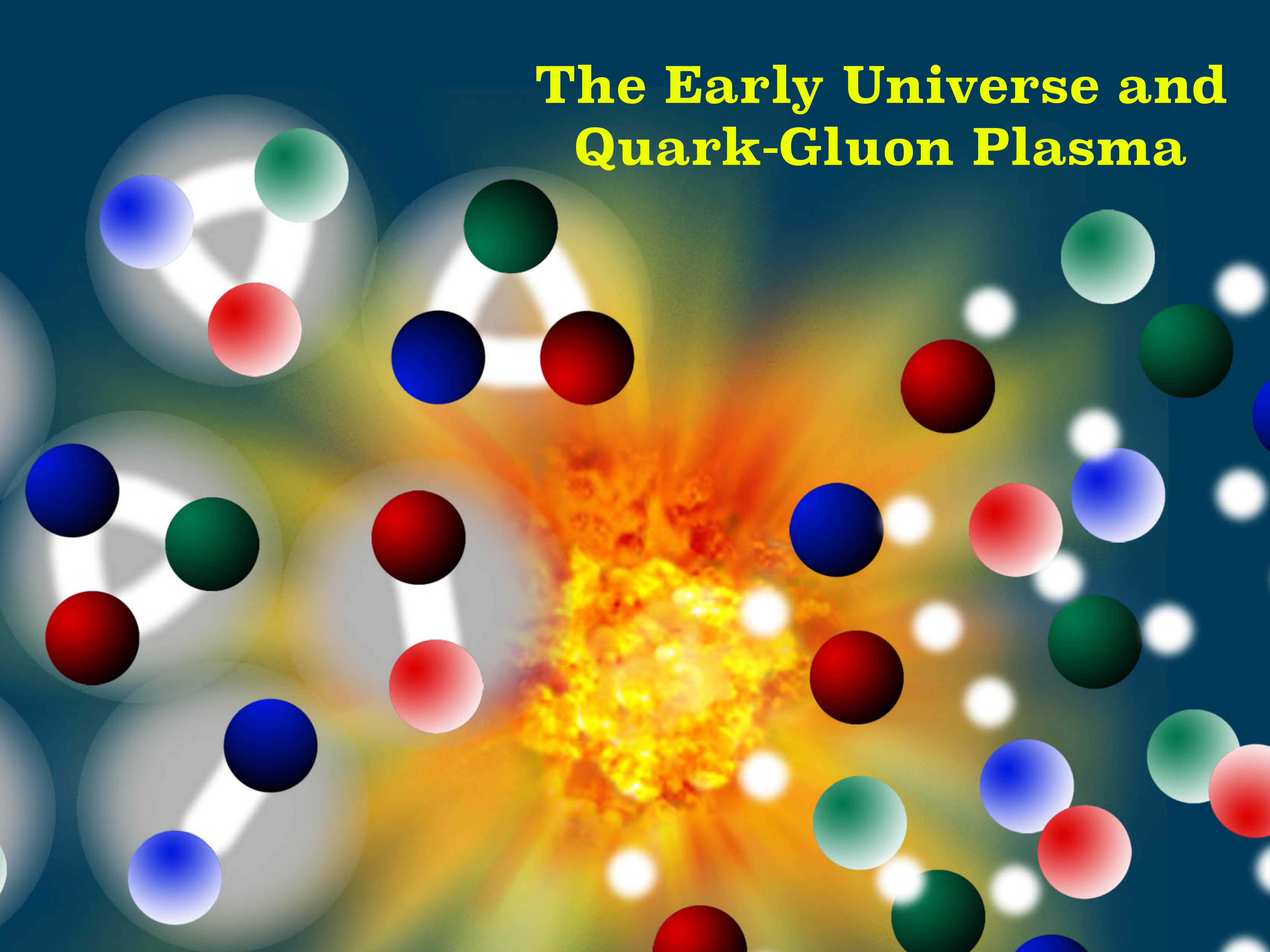
Higgs boson at the LHC

- 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

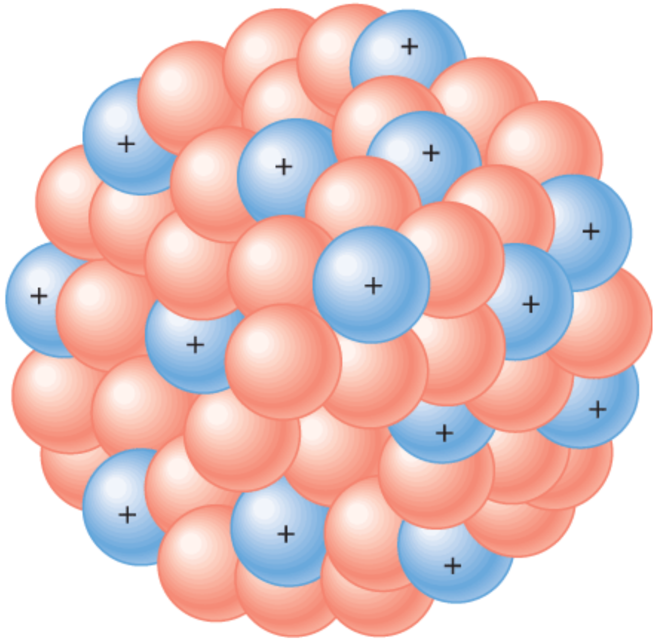
The Early Universe and Quark-Gluon Plasma



From *pp* Collision to PbPb Collision

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

$^{82}\mathrm{Pb}_{208}$



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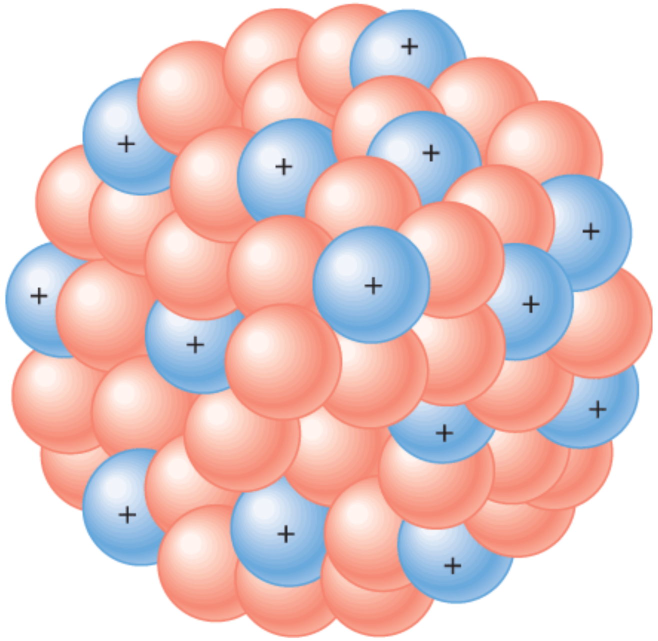

$$m\frac{dU^\mu}{d\tau} = qF^{\mu\nu}U_\nu$$

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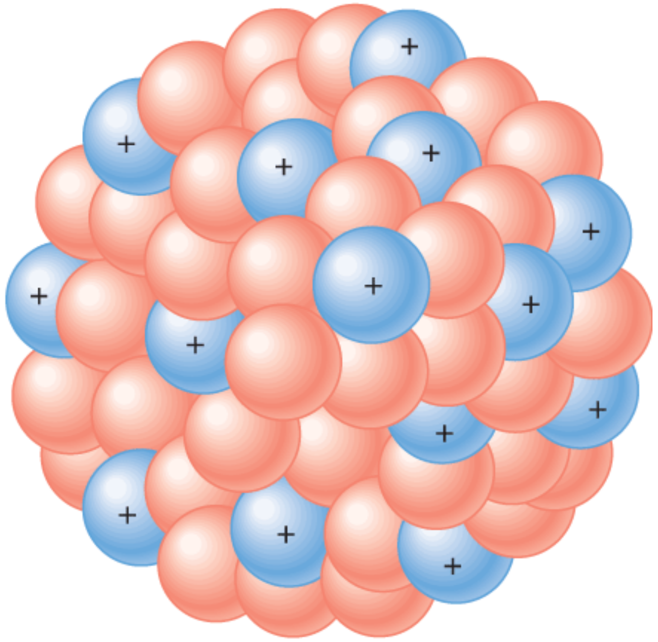

$$m\frac{dU^\mu}{d\tau} = qF^{\mu\nu}U_\nu$$

Determined by the collider!

From *pp* Collision to PbPb Collision

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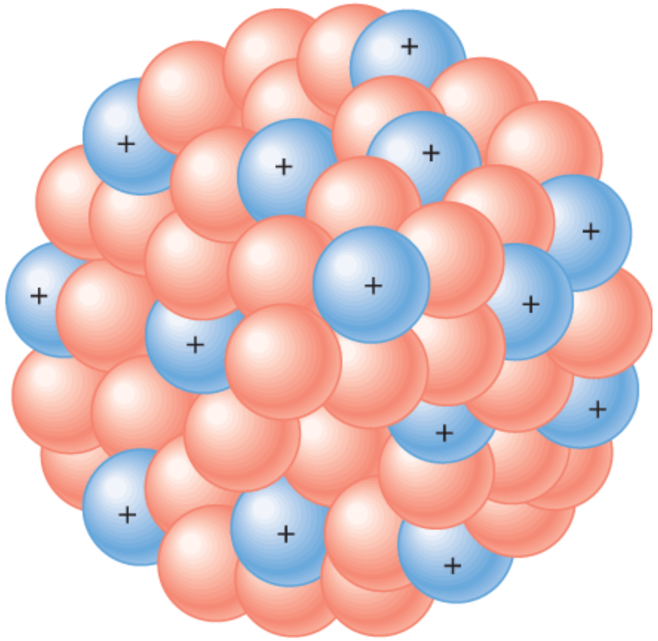


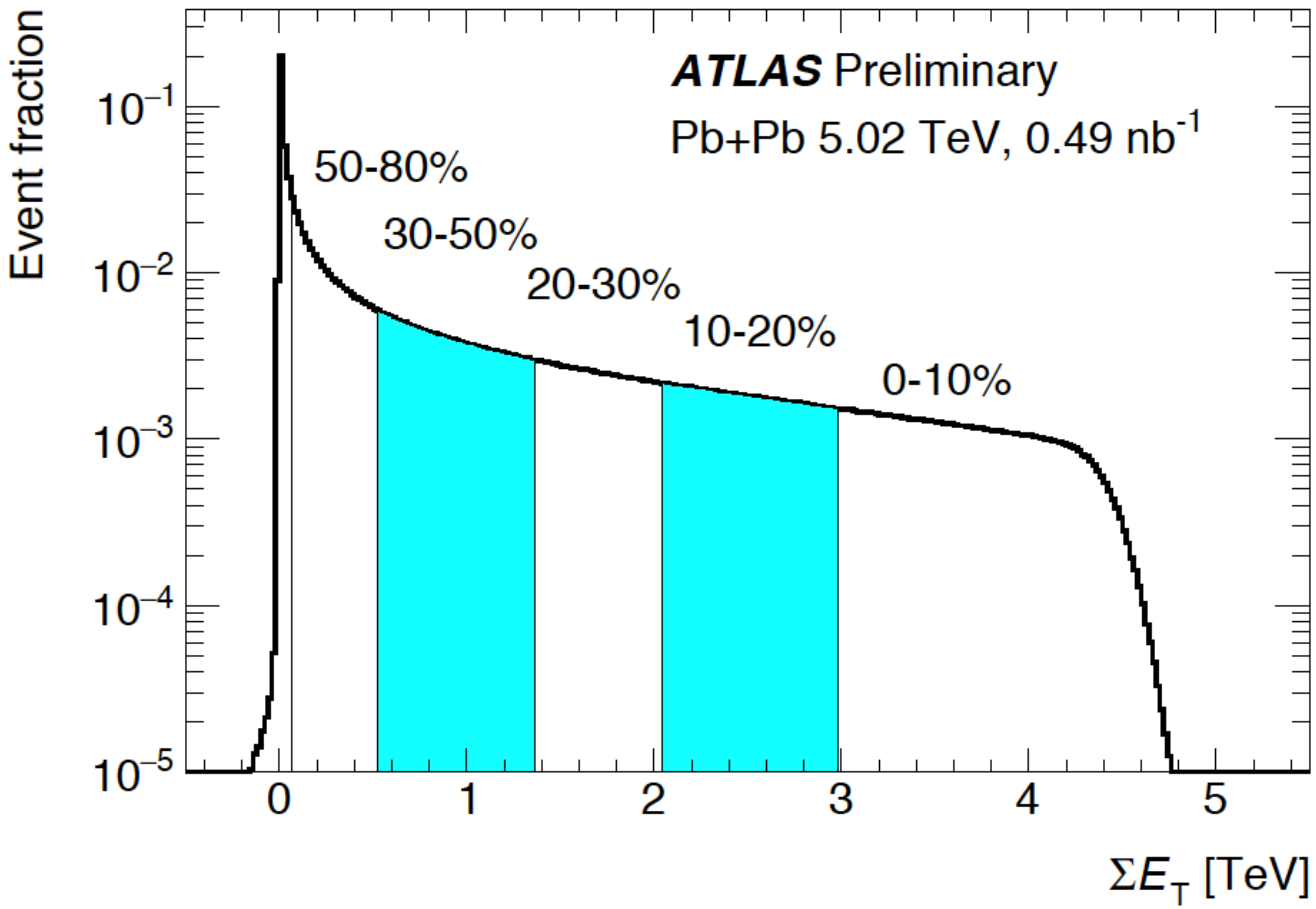
$$m\frac{dU^\mu}{d\tau} = q\boxed{F^{\mu\nu}}U_\nu$$

Determined by the collider!

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

From *pp* Collision to PbPb Collision

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



ATLAS Collaboration, ATLAS-CONF-2016-110.

From *pp* Collision to PbPb Collision

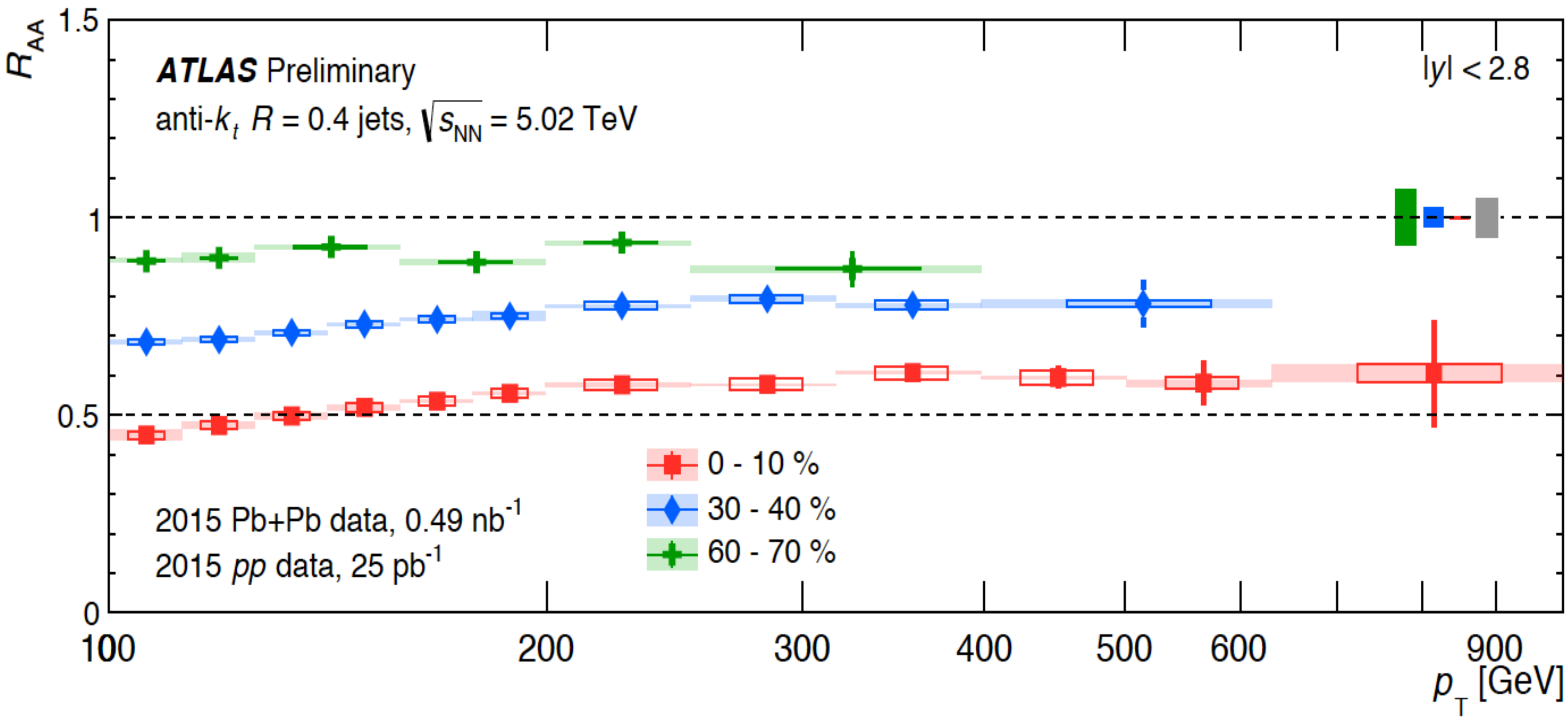
- The lead-lead collision.
- The differential cross section.
- Nuclear modification factor:

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

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

From *pp* Collision to PbPb Collision

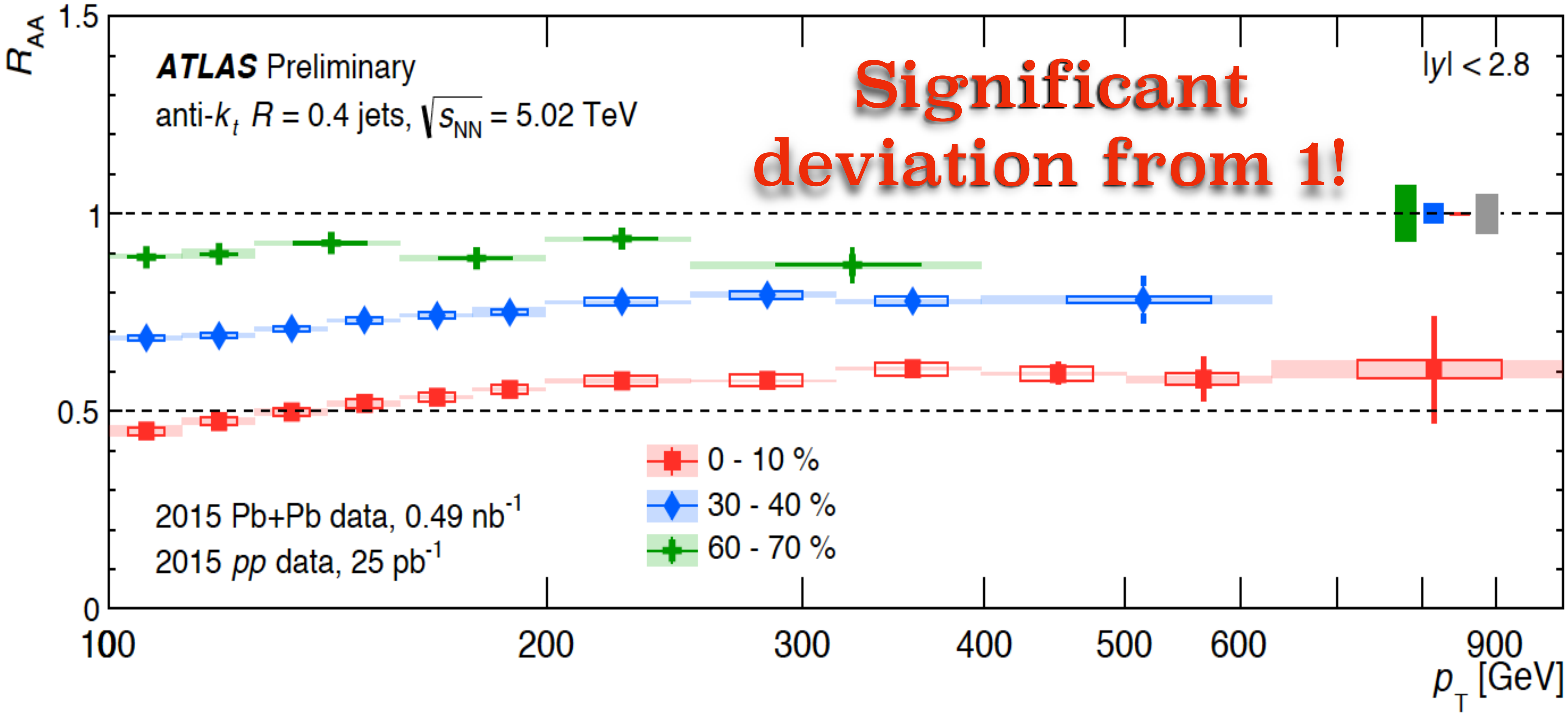
- The lead-lead collision.
- Typical result of R_{NN}.



ATLAS Collaboration, ATLAS-CONF-2017-009.

From *pp* Collision to PbPb Collision

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



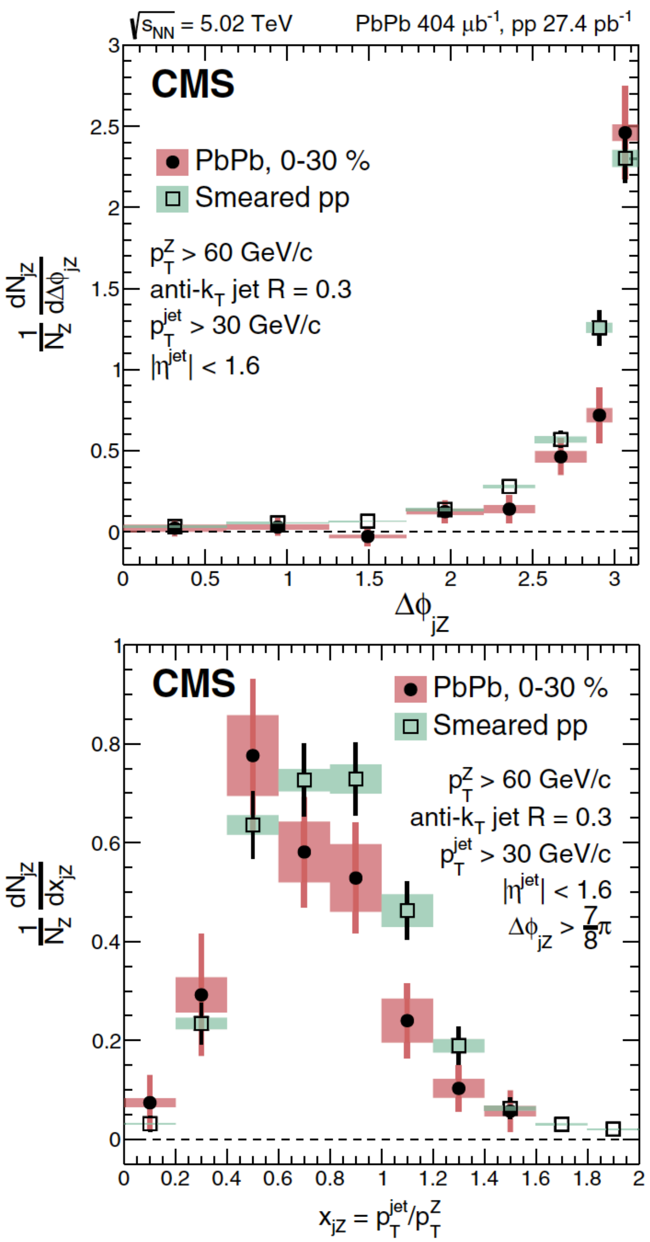
ATLAS Collaboration, ATLAS-CONF-2017-009.

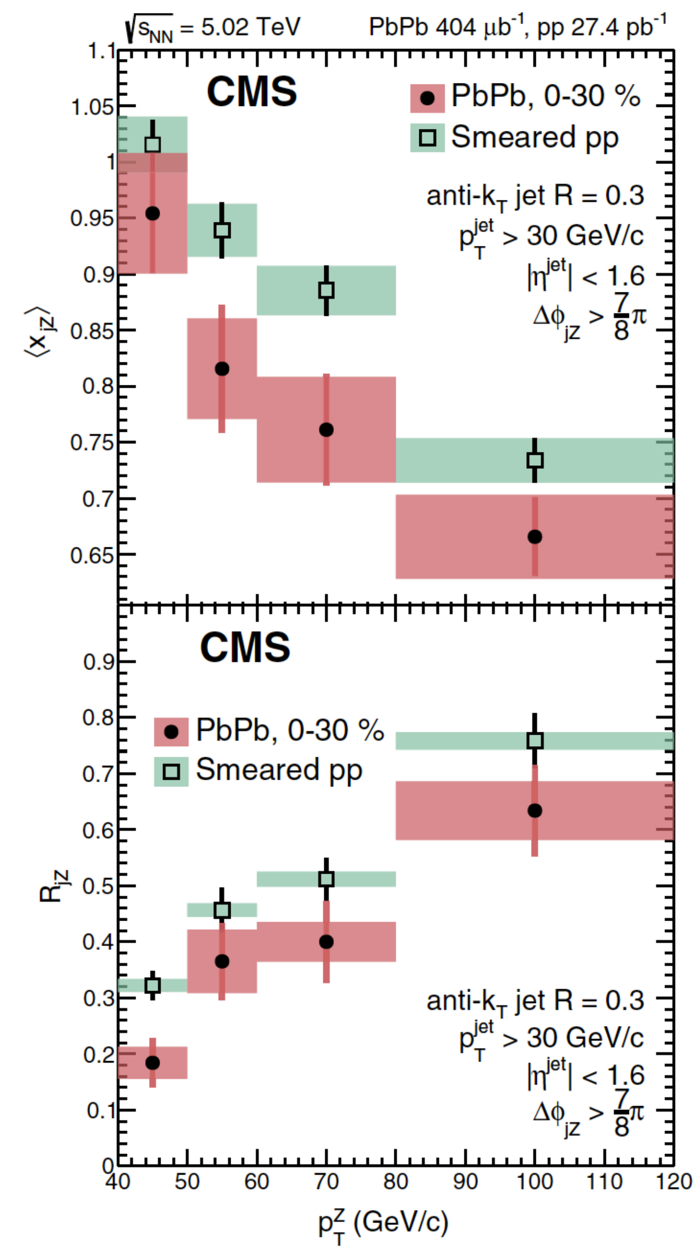
Heavy-Ion Collision at the LHC

- 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!

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.

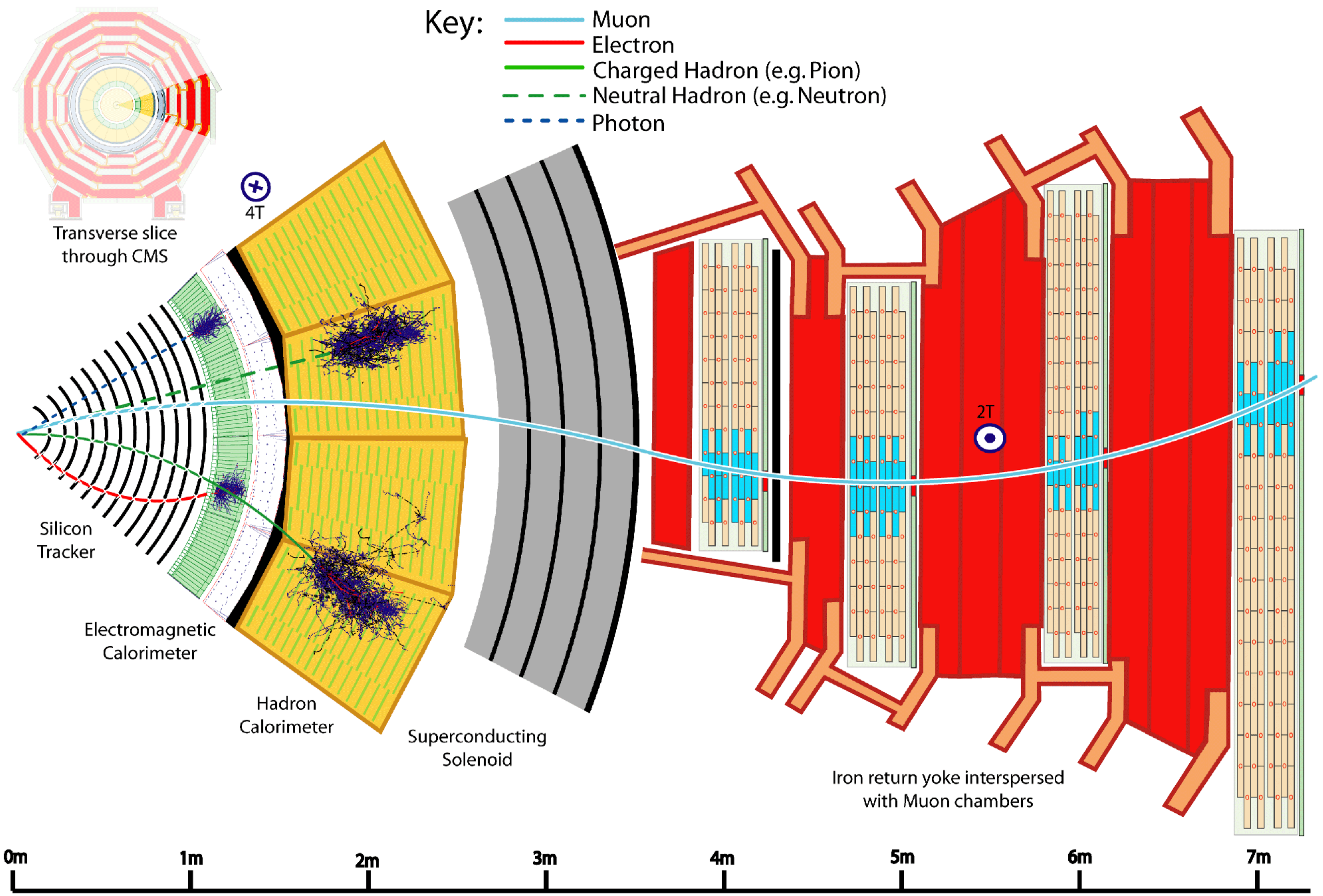




CMS Collaboration, Phys. Rev. Lett. 119 (2017) 082301.

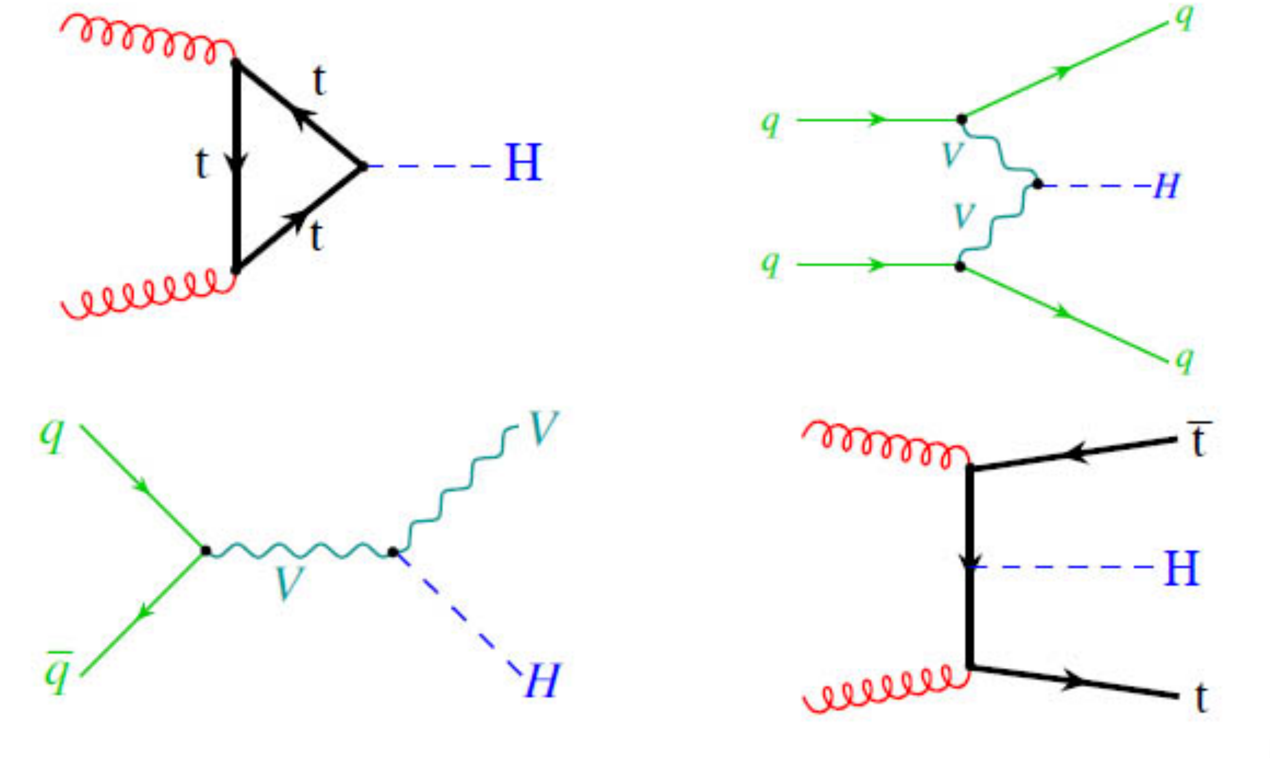
Higgs in Heavy-Ion Collision

- Smearing effect.



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

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

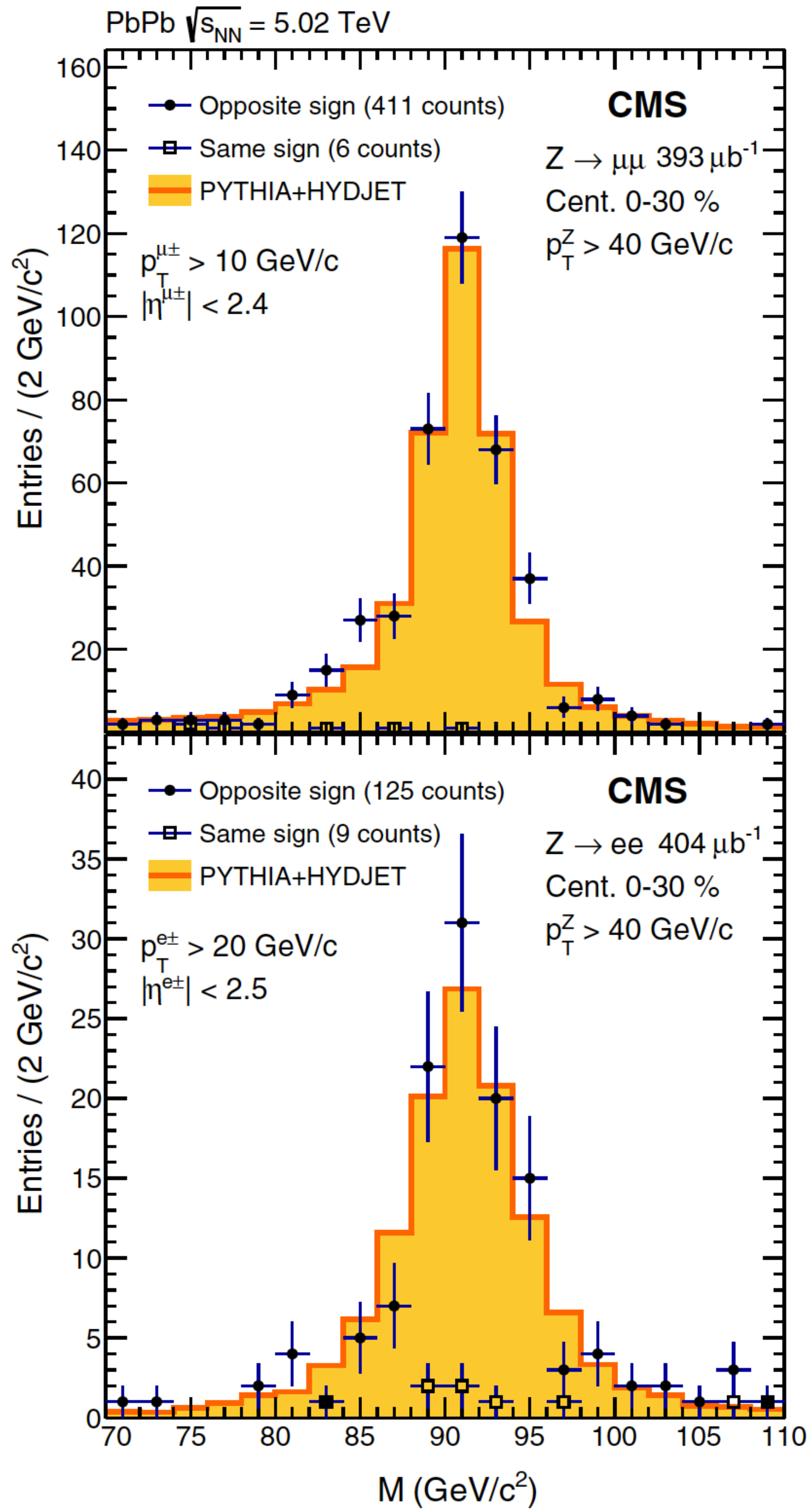
$$e^+ \text{ and } e^-, \quad |\eta| < 2.5, \; E_\mathrm{T} > 15\mathrm{GeV}$$

- 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

- 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_{T} in GeV

CMS Collaboration, JHEP 03 (2018) 181.

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%.