$t\bar{t}$ as a tool to observe Quark Gluon Plasma

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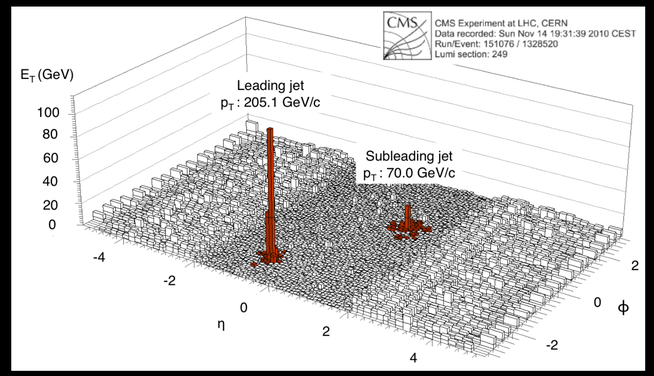
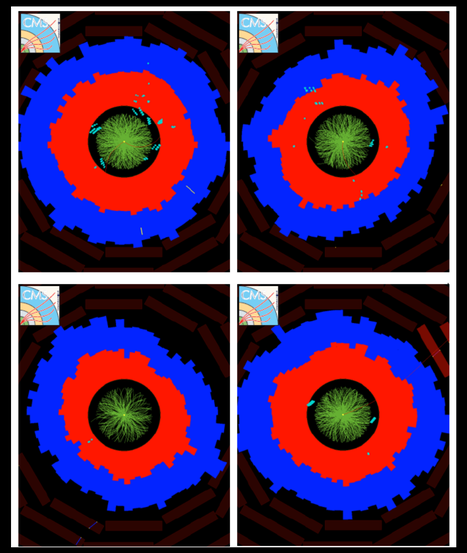
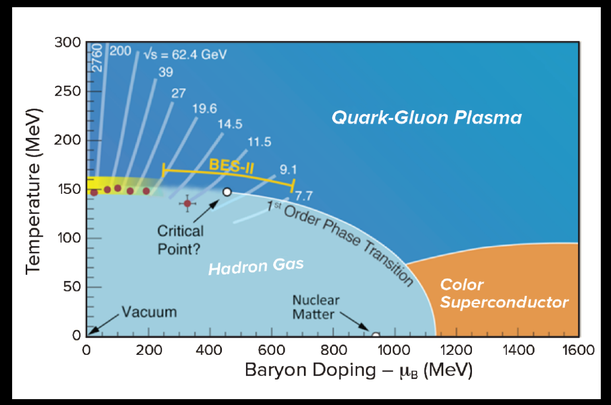
Introduction

- Heavy ion collisions reproduce extreme conditions in temperature and energy density.
- These conditions are similar to the ones prevailing in the very early universe, ~ 10^{-24} sec after the Big Bang.
- QGP is formed: a strongly coupled medium which behaves as a perfect liquid.
- Many questions open:
  - Transition asymptotic freedom → strongly coupled liquid ?
  - QCD phase diagram?
  - What is the smallest droplet of QGP?
  - How the QGP evolves in time?



arXiv:1102.1957



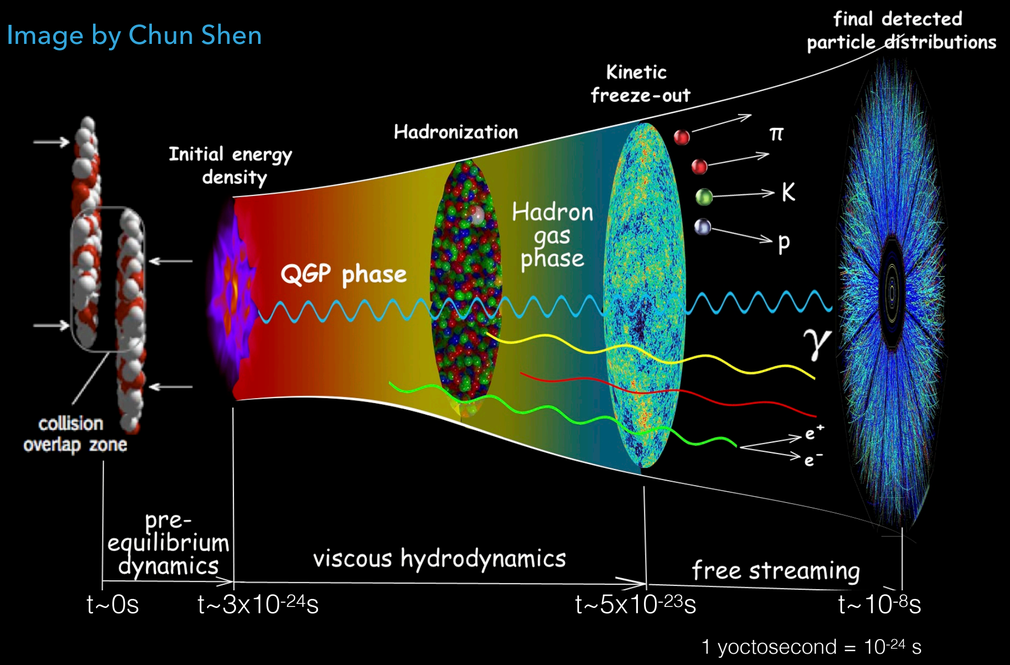


arXiv:1802.04801

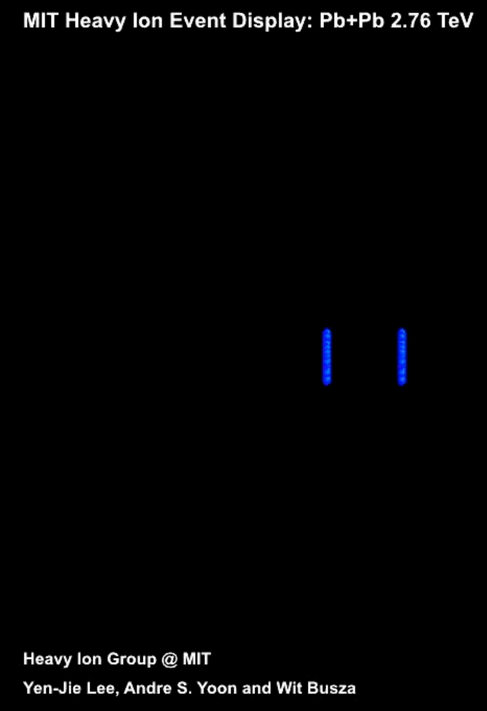
A glimpse of heavy ion physics

- Two Lorentz contracted discs of highly complex systems of partons collide.
- When the discs overlap:
  - soft interactions dominate (small p_T transfer) + tiny amount of hard perturbative processes.
  - High p_T particles production at very early times.
- ~ 1 fm after the collision:
  - $\epsilon_{\text{medium}} \gg \epsilon_{\text{hadron}}$ and enormous entropy.
  - Pressure-driven hydrodynamic expansion builds up p_T

Image by Chun Shen



- As the two discs move apart:
  - QGP is continually producing.
  - Each droplet of QGP hydrodynamically expands, flow and cools down until $\epsilon_{\text{droplet}} \sim \epsilon_{\text{hadron}}$.
  - Mist of hadrons that scatter off each other and then stream away freely.
- The process ends once each participant loses ~ 85% of their energy in particle creation.

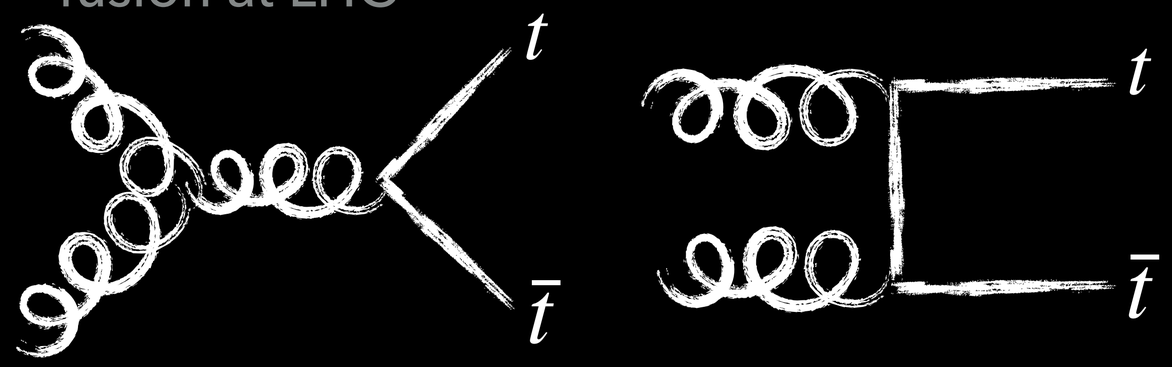


Movie here

Top quark

Top quark:

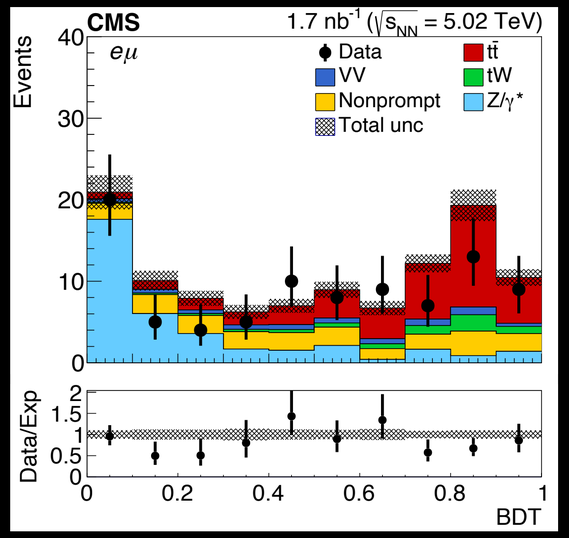
- Discovered in 1995 in Tevatron
- Heaviest particle in the SM: $m_t \sim 173$ GeV
- Decay modes:
  - $t \to bW \to b + \ell\nu$ ($\sim 33\,\%$)
  - $t \to bW \to b + q\bar{q}$ ($\sim 66\,\%$)
- Primarily produced in $t\bar{t}$ pairs by gluon fusion at LHC



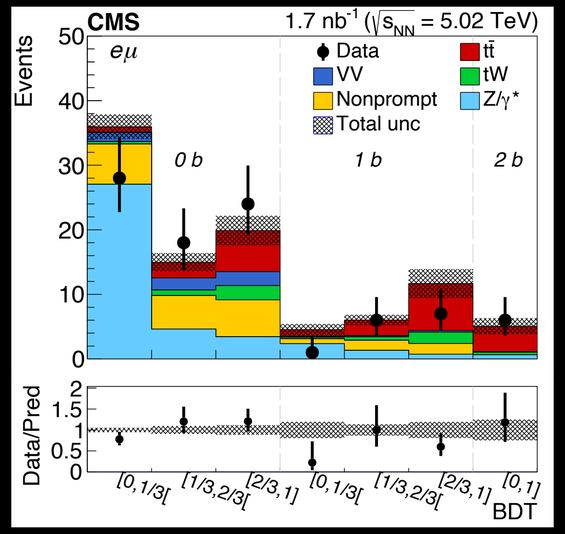
- $t\bar{t}$ in pp
  - Constrain to proton PDF ($x \sim 1/\sqrt{s}$).
  - Determine SM parameters like $|V_{tb}|$
- $t\bar{t}$ in pPb and PbPb:
  - Probe for nuclear PDFs
  - Paves the way for using top to probe QGP.
- Channels:
  - $\ell + jets$ (semileptonic): $t\bar{t} \to bb'W(\to \ell\nu)W'(\to q\bar{q'})$ High BR
  - Dilepton (leptonic): $t\bar{t} \to bb'W(\to \ell\nu)W'(\to \ell'\nu')$ High Purity
  - All jets (hadronic): $t\bar{t} \to bb'W(\to q\bar{q'})W'(\to q''\overline{q'''})$ Dirtiest and more challenging.

$t\bar{t}$ in CMS

- $t\bar{t}$ at $\sqrt{s} = 5{,}7{,}8{,}13$ TeV.
- $t\bar{t}$ in pp, pPb and
- First evidence of $t\bar{t}$ in $PbPb$ by CMS Phys. Rev. Lett. 125, 222001:
  - Channel: purely leptonic
  - Two methods to extract $\sigma_{t\bar{t}}$:



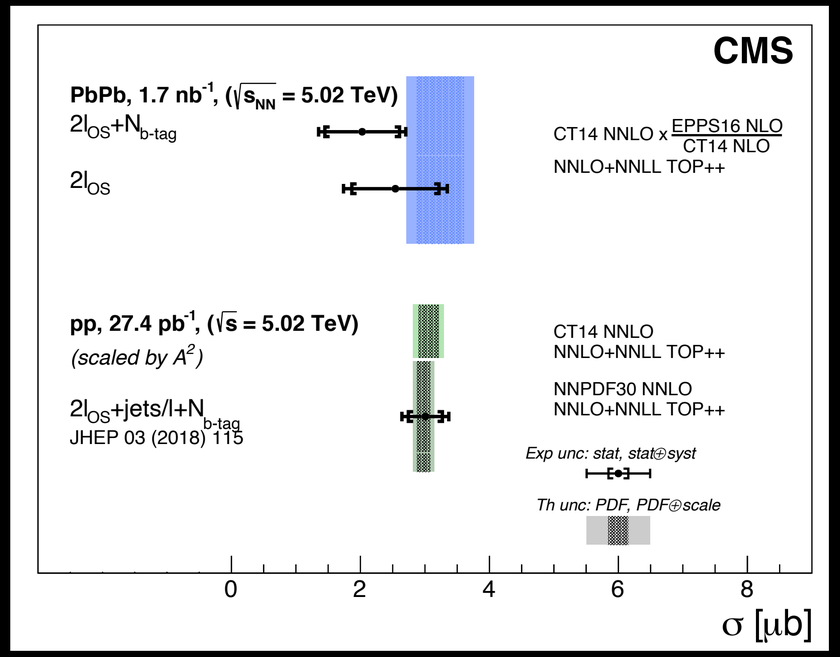
Dilepton



Dilepton + b-jets

Next steps in $t\bar{t}$ in $PbPb$:

- Observation
- $\ell + jets$ channel
- Top as a probe for QGP

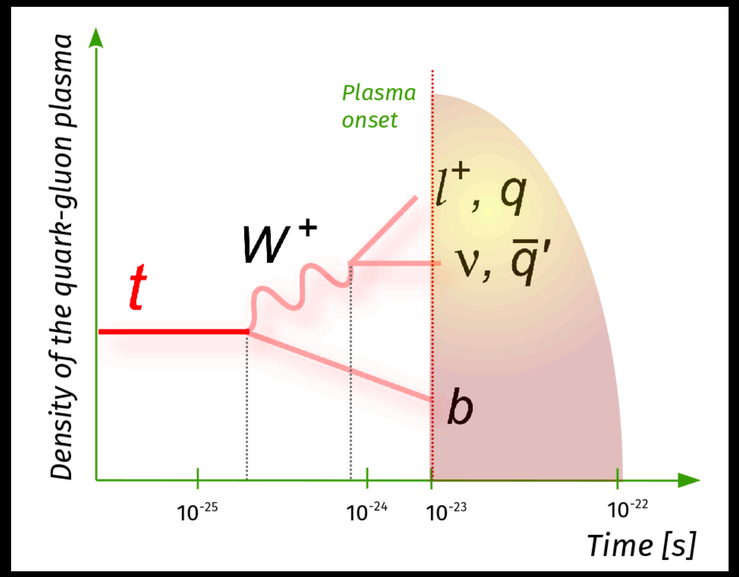


Top quark as a probe for QGP

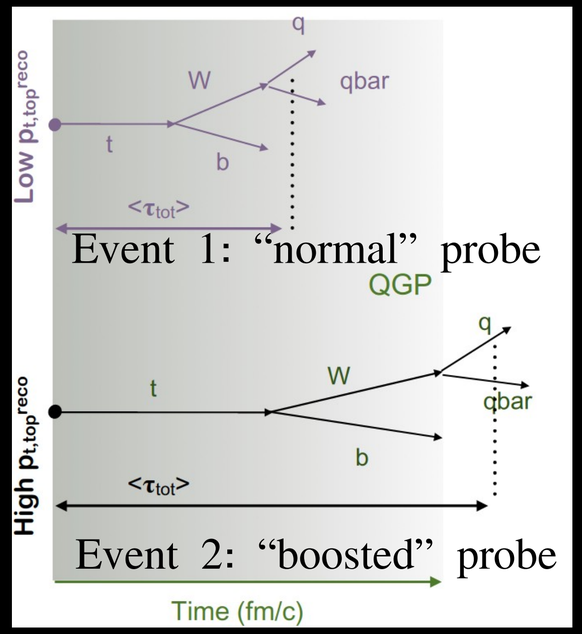
Top quark:

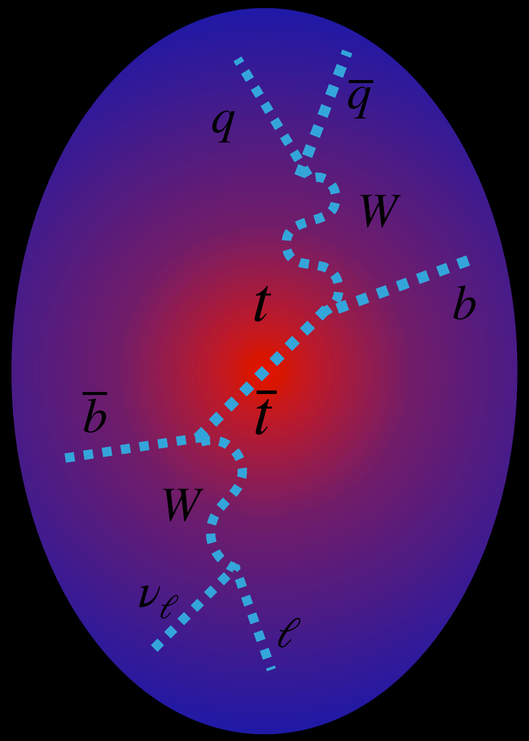
- $\tau_t \sim 10^{-24}$ sec. Does not hadronize and decays before QCD mechanisms start acting.
- Unlike other jet quenching probes (dijets, $Z/\gamma + jets$) which are produced simultaneously with the collision, tops can resolve the time evolution of QGP

- Depending p_t tops can decay before or within QGP.
- Taking "snapshots" at different times (p_t), one could resolve the QGP time evolution.
- Semileptonic $t\bar{t}$ represents a "golden channel":
  - High BR
  - Good S/B
  - "Tag" and "probe"



https://cms.cern/news/heavy-metal-hits-top





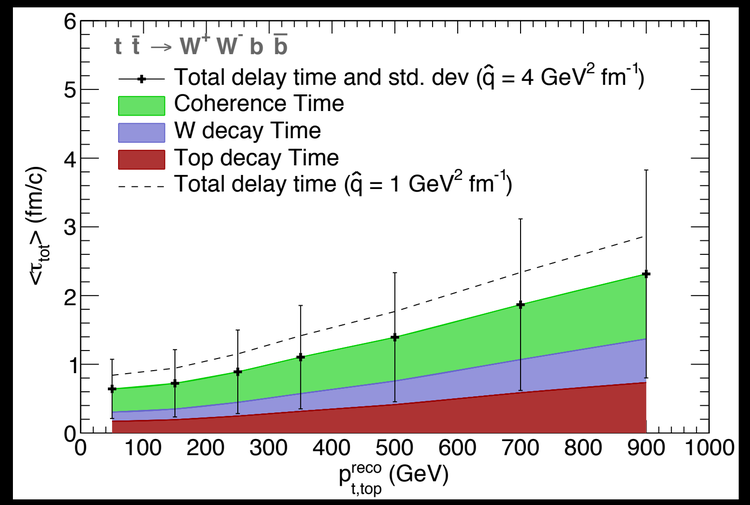
Top quark as a probe for QGP

Pheno study PRL 120 (2018) 232301

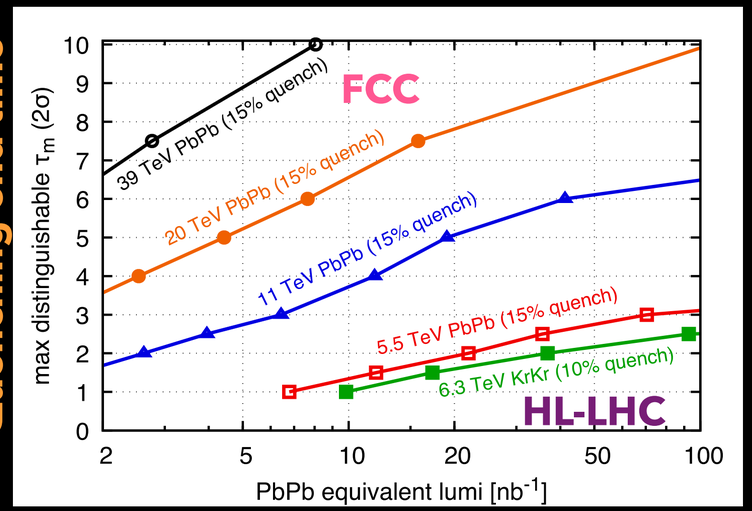
- Channel: Semimuonic $t\bar{t} \to W(\to \mu\nu_\mu)W(\to q\bar{q})$
- The products of $W(\to q\bar{q})$ do not immediately interact with the QGP.
- $q\bar{q}$ propagates a in a certain decoherence time (τ_d) before starts interacting with the medium.
- So $t \to b + W \to q\bar{q}$ does not see the full QGP, only the portion after:

$$\tau_{tot} = \gamma_{t,top}\tau_{top} + \gamma_{t,W}\tau_W + \tau_d$$

- MC for feasibility about using tops to resolve QGP.



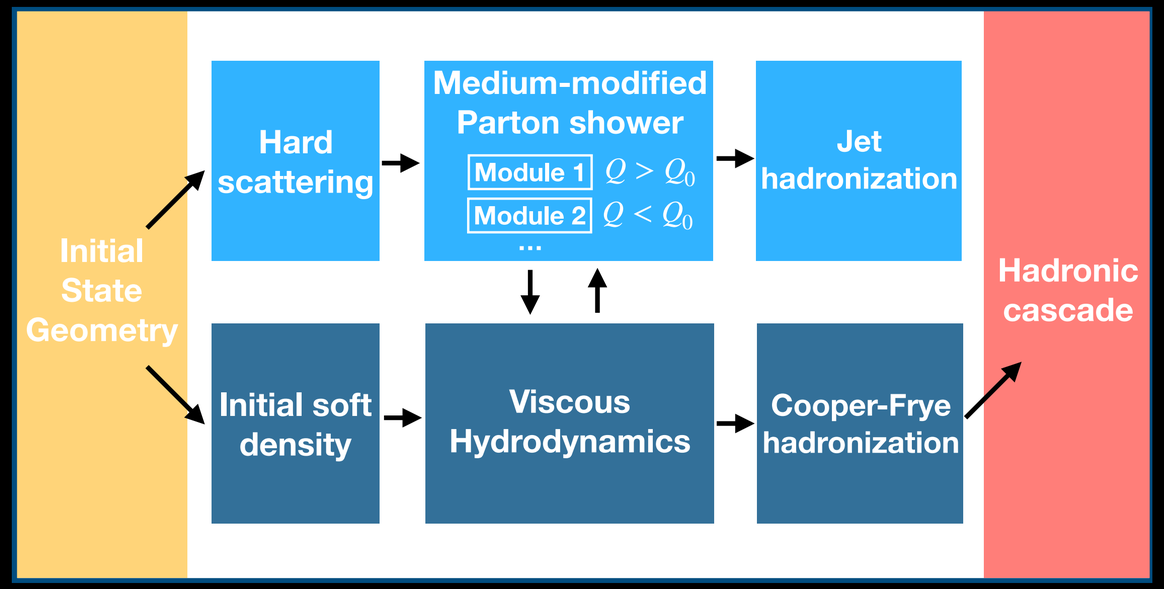
Quenching end time

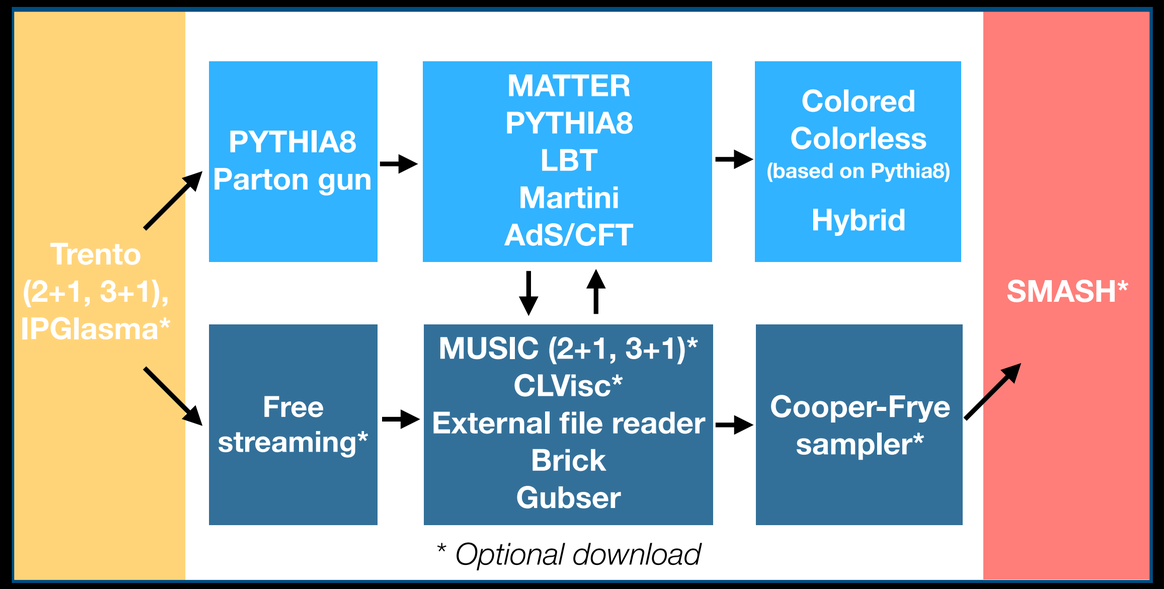


Pheno study

The JETSCAPE framework arXiv:1903.07706

- Computational envelope to perform event generation of heavy ion collision.
- Allows incorporation in a modular way simulating different stages of the collision.
- We are performing phenomenological studies using JETSCAPE.

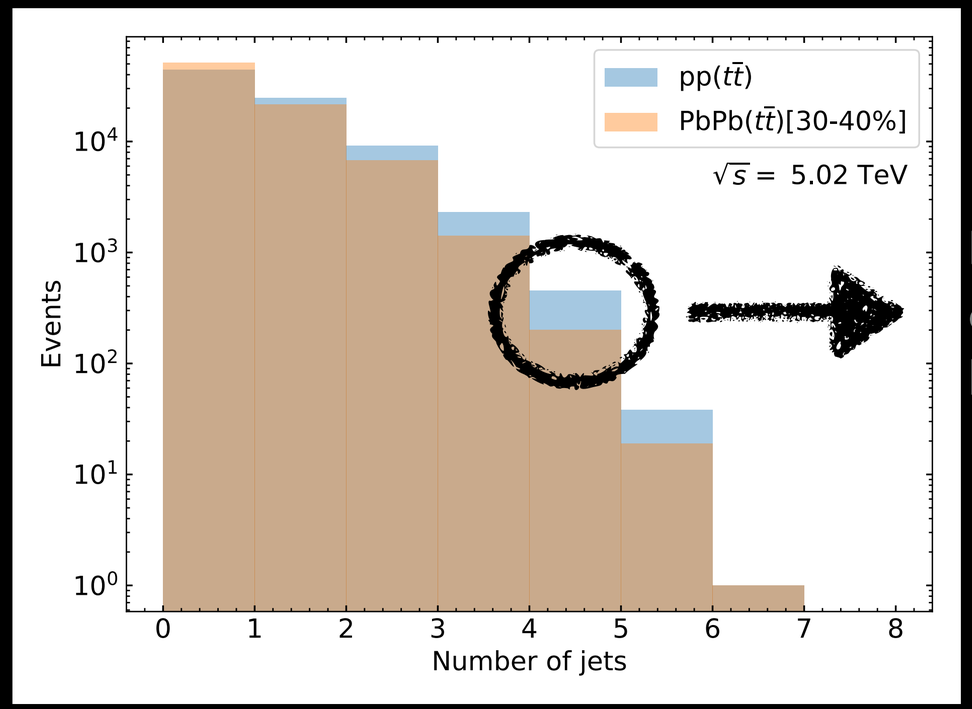




Pheno study

- PbPb and pp simulations:
  - N_{ev} = 76K (81K) for pp and PbPb (pp($t\bar{t}$) and PbPb($t\bar{t}$))
  - $\sqrt{s} = 5.02$ GeV
  - PbPb Centr. = 30-40%
  - $40 \leq \hat{p}_T \leq 160$ GeV
  - Energy loss modules (for PbPb): MATTER+LBT
- Event selection:
  - Jets: anti-k_T R=0.4
  - $p_T^{\text{jet}} > 30$ GeV

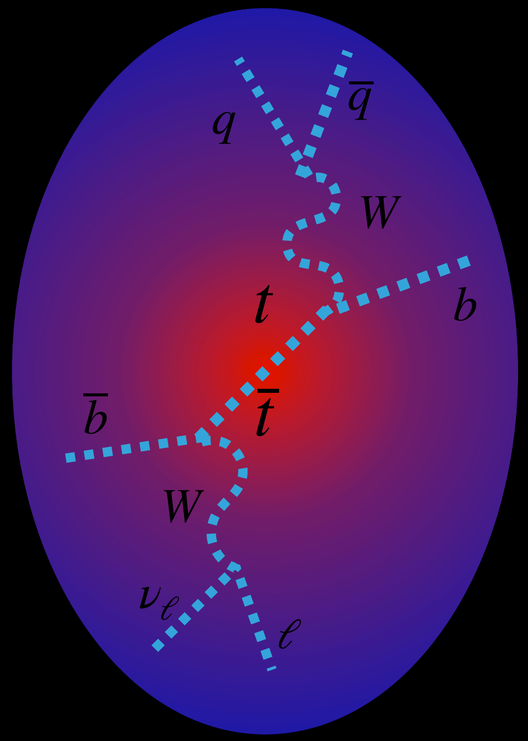
PbPb and pp with $t\bar{t}$



Missing $t\bar{t}$ in PbPb events as we go hadronic

Summary

- It is necessary to perform $t\bar{t}$ pheno studies in view of next runs of LHC and future colliders
- The JETSCAPE framework offers improved modular Eloss models.
- $t\bar{t}$ generated using JETSCAPE
- We are moving to next steps in our pheno study taking advantage of JETSCAPE in the lepton + jets channel.
- We also have perspectives on studies of jet broadening in $t\bar{t}$ in heavy ions.
- $t\bar{t}$ in heavy ions represents a completely new method that would allow us to understand the formation of QGP.



Backup

Identification of b-jets

- Combined Secondary Vertex Algorithm (CSV Run I, CSv2V Run II): combines the info. of displaced tracks and secondary vertices associated with the jet using MVA.

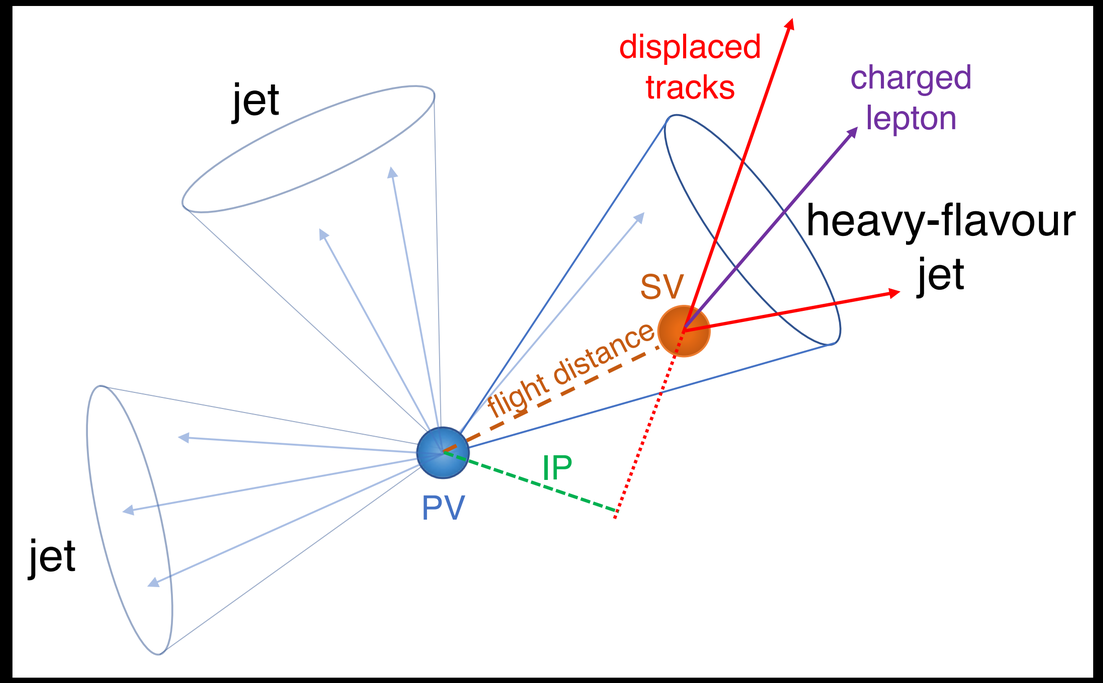


Table 1: Input variables used for the Run 1 version of the CSV algorithm and for the CSVv2 algorithm. The symbol "x" ("—") means that the variable is (not) used in the algorithm

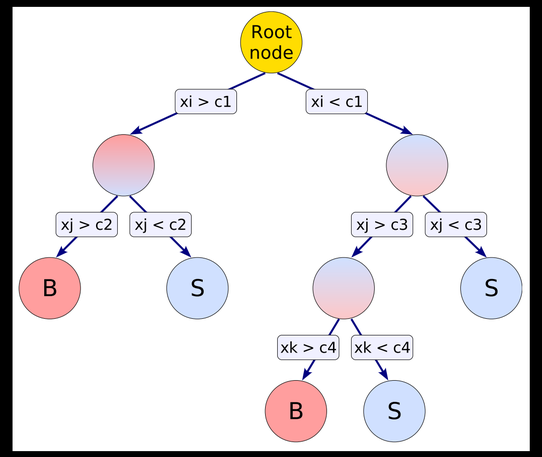
Input variable	Run 1 CSV	CSVv2
SV 2D flight distance significance	x	x
Number of SV	—	x
Track η_{rel}	x	x
Corrected SV mass	x	x
Number of tracks from SV	x	x
SV energy ratio	x	x
ΔR(SV, jet)	—	x
3D IP significance of the first four tracks	x	x
Track $p_{T,rel}$	—	x
ΔR(track, jet)	—	x
Track $p_{T,rel}$ ratio	—	x
Track distance	—	x
Track decay length	—	x
Summed tracks E_T ratio	—	x
ΔR(summed tracks, jet)	—	x
First track 2D IP significance above c threshold	—	x
Number of selected tracks	—	x
Jet p_T	—	x
Jet η	—	x

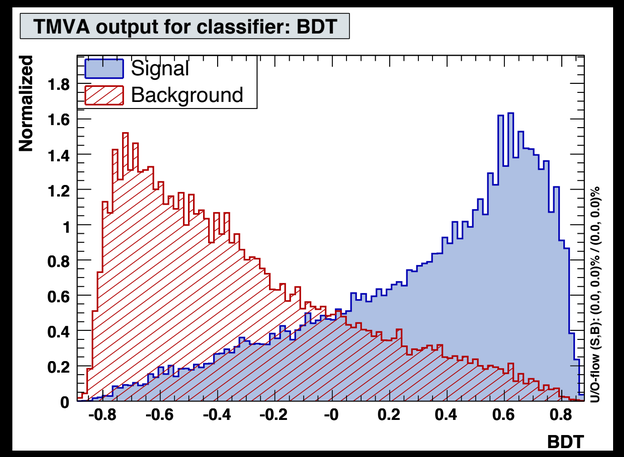
JINST 13 (2018) P05011

Backup

Boosted Decision Trees (BDT)

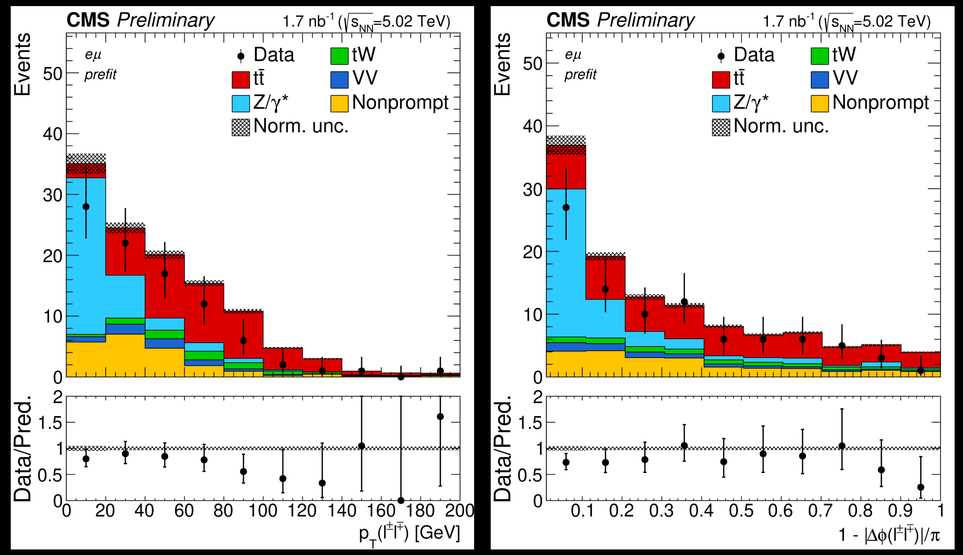
- Decision Tree (DT): binary classifier in which repeated decisions are taken until a stop criterion is reached.
- Boosted DT (BDT): extends the idea from one tree (weak classifier) to several trees (forest)
  - ➔ Better performance classifier
- By convention, signal (background) events accumulate at large (small) BDT score.





CERN-OPEN-2007-007

- $t\bar{t}$ in PbPb: BDT is trained with kinematics of the two leading-p_T leptons.
  - p_T of leading lepton, $p_T(\ell_1)$
  - Asymmetry in lepton-p_T's, $\dfrac{p_T(\ell_1) - p_T(\ell_2)}{p_T(\ell_1) + p_T(\ell_2)}$
  - Dilepton system p_T, $p_T(\ell\ell)$
  - Dilepton system pseudorapidity, $|\eta(\ell\ell)|$
  - Absolute azimuthal separation in ϕ of the two leptons, $|\Delta\phi(\ell\ell)|$
  - Sum of absolute η's of leptons, $\sum_i |\eta_i|$



CMS-PAS-HIN-19-001