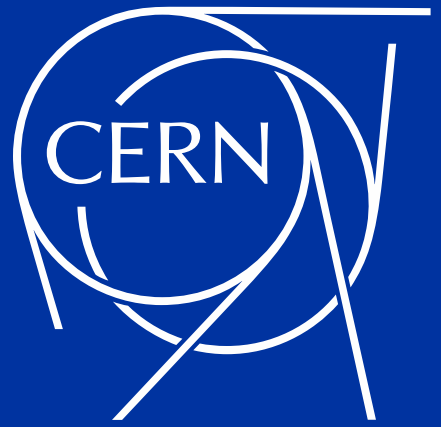


CEP signal to background separation with the CMS Precision Proton Spectrometer at the HL-LHC

Johanna Lömker

Supervisor: Jonathon Hollar, Michael Pitt and Martijn Mulders

11.08.21

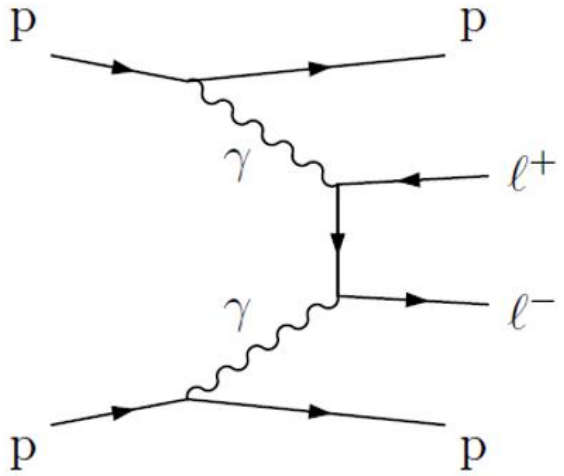
Central exclusion process (CEP)

~ 22% Elastic interactions
~ 78% Minimum bias events

~56 % Non-diffractive: pp → X
~12 % Single-diffractive dissociation: pp → Xp*
~ 9 % Double-diffractive dissociation: pp → XY
~ 1 % Central diffraction: pp → p*Xp*

0.00000001%

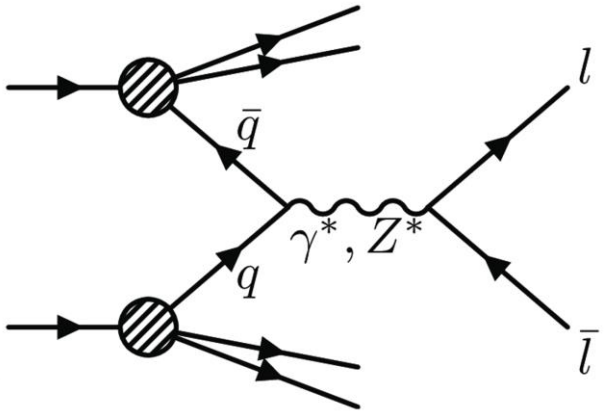
Signal
- Protons remain intact
- Correlations



[1]

vs

Background
- Drell-Yan process
- No correlations



[2]

Goal of the Project

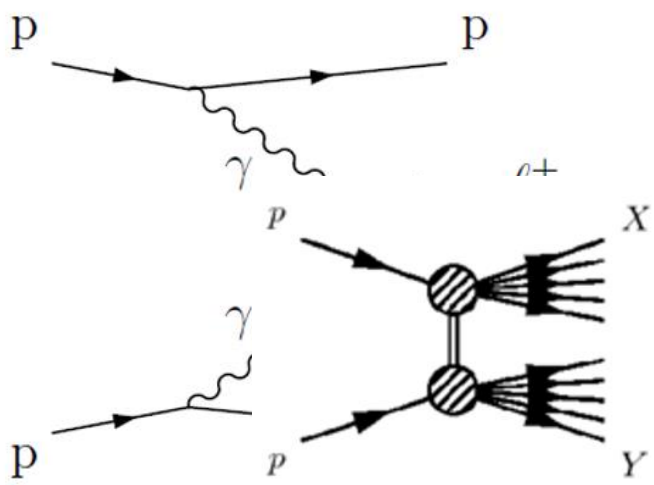
Estimate the CEP signal to background separation at HL-LHC

~ 22% Elastic interactions
~ 78% Minimum bias events

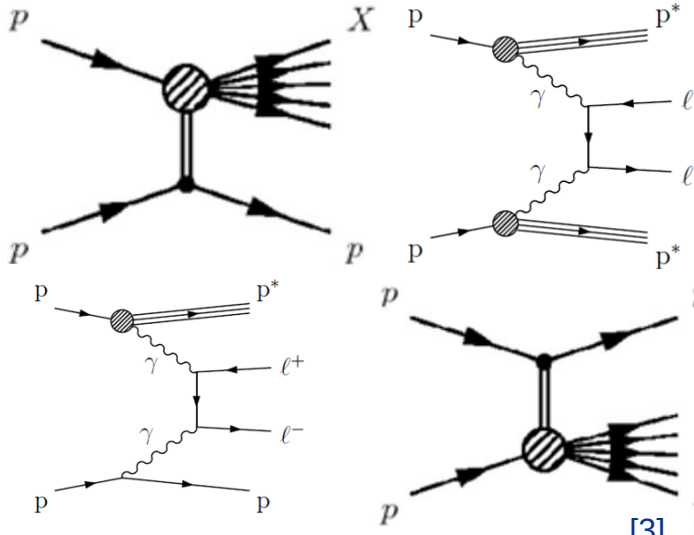
~56 % Non-diffractive: pp → X
~12 % Single-diffractive dissociation: pp → Xp*
~ 9 % Double-diffractive dissociation: pp → XY
~ 1 % Central diffraction: pp → p*Xp*

0.00000001%

Signal
- Protons remain intact
- Correlations

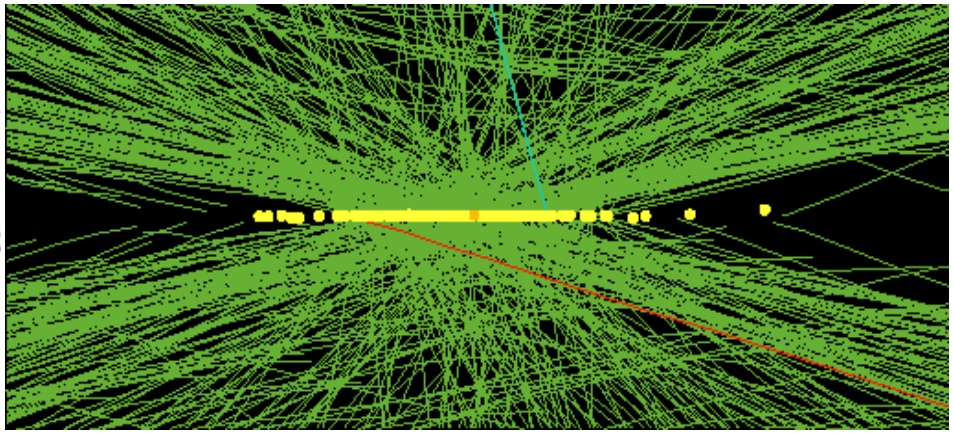


Pile up
- Up to 200 in HL-LHC



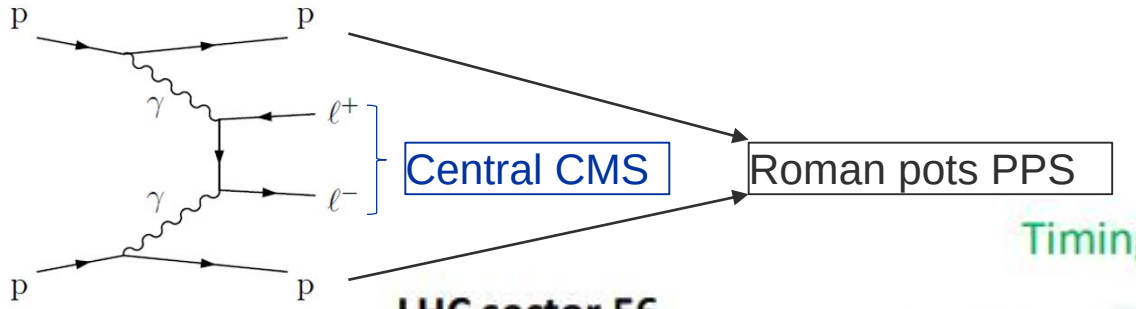
[3]

Background
- Drell-Yan process
  No correlations

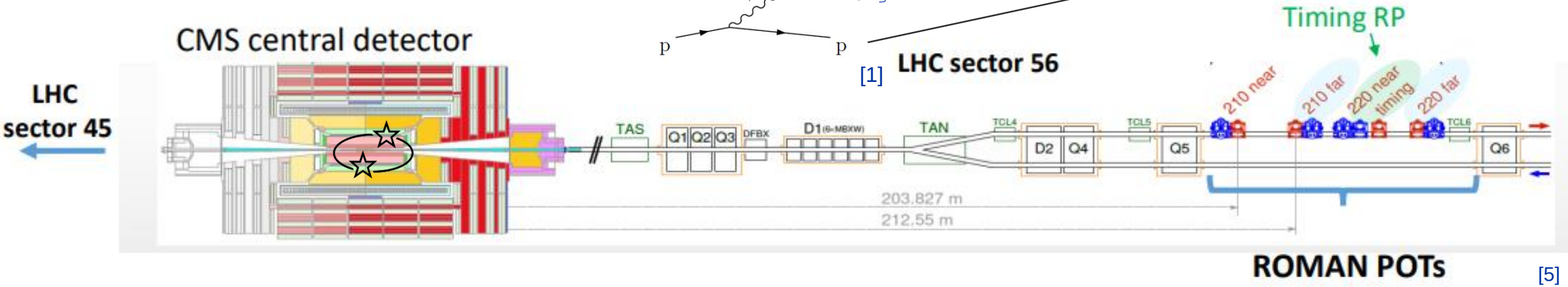


[4]

Experimental Setup



[1]



[5]

Compact Muon Solenoid (CMS)

➢ **Clustering**

- Muon tracks from silicon tracker and muon chambers
- Get 3D primary vertex from detector reconstruction

➢ **Includes the MTD for HL-LHC**

- Time measurement of minimum ionizing particles (MIPs)
- Get 4D primary vertex

Proton Precision Spectrometer (PPS)

➢ **Tracking**

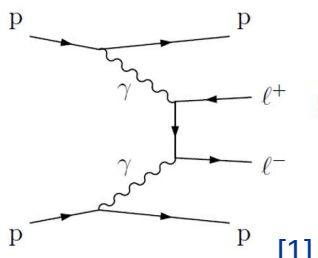
- Proton position in x-y plane relative to the beam
- Deflection related to fractional momentum loss $\xi \rightarrow M_X$, Y_X

➢ **Timing**

- Difference of proton times to find the vertex position

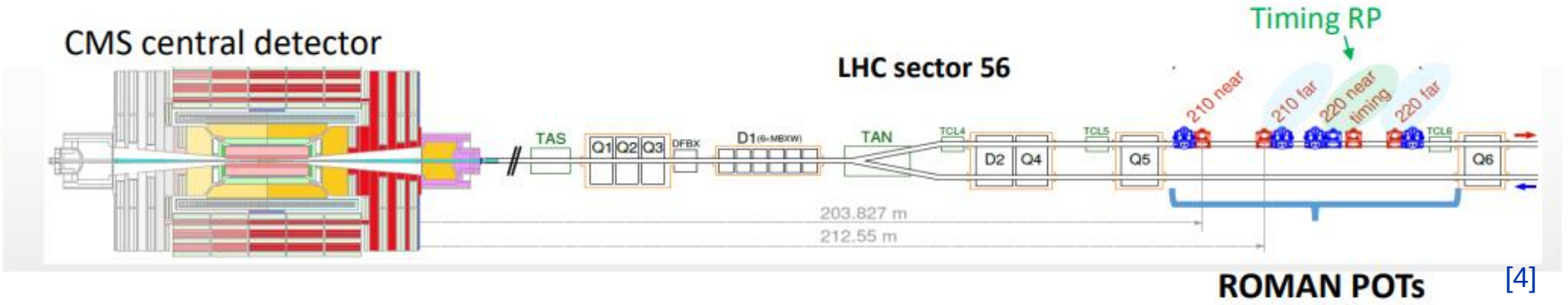
1. Kinematic correlation

$$\xi = \frac{p_z(initial) - p_z(final)}{p_z(initial)} = \frac{dp_z}{p_z}$$



[1]

LHC sector 45



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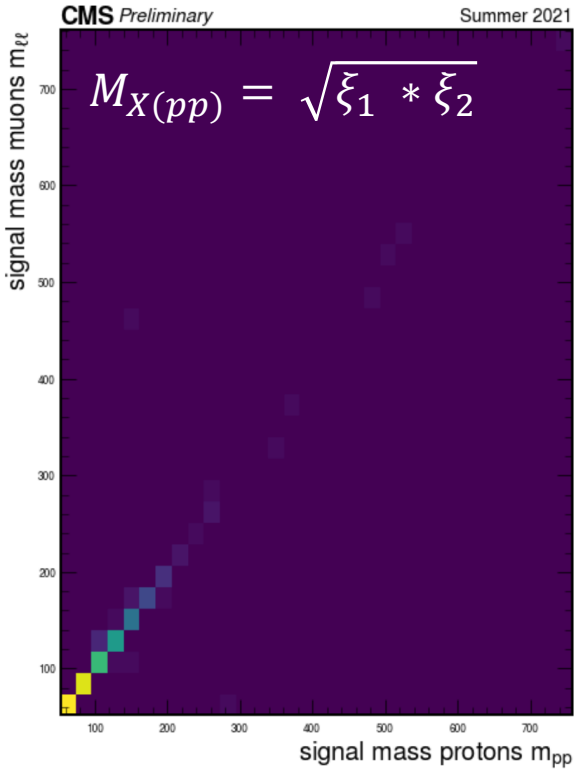
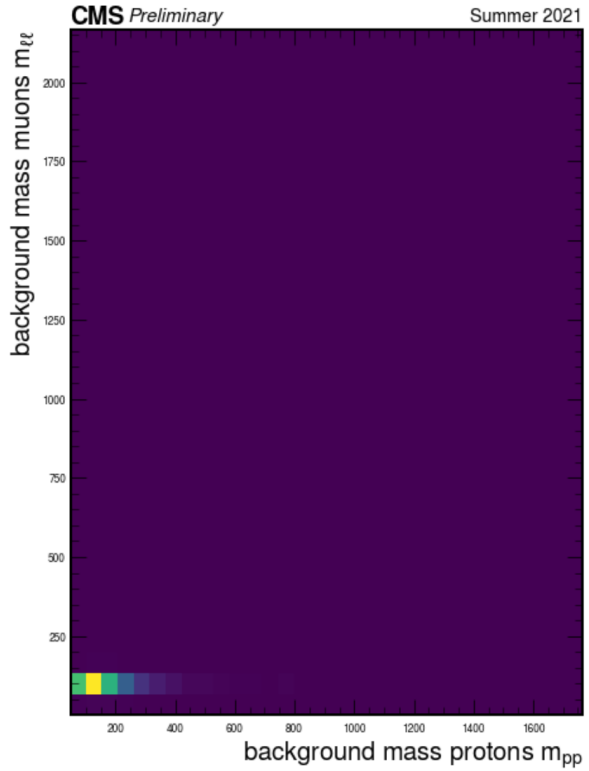
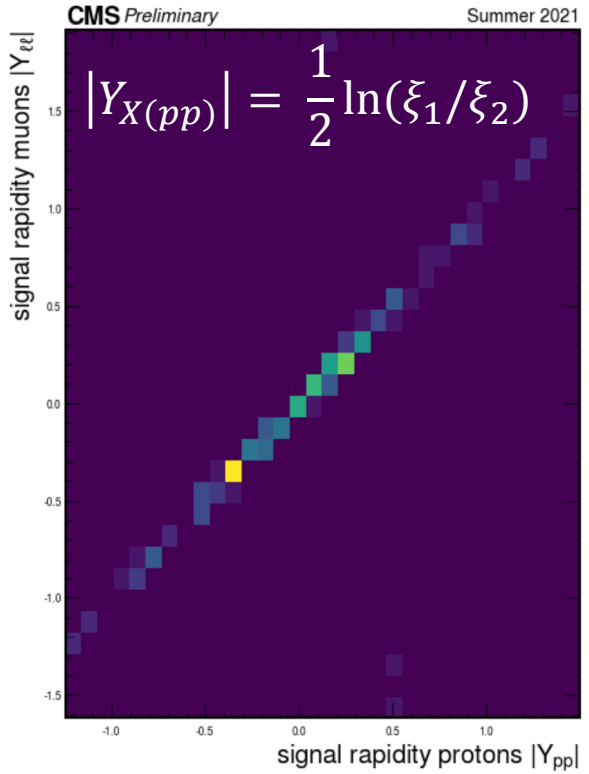
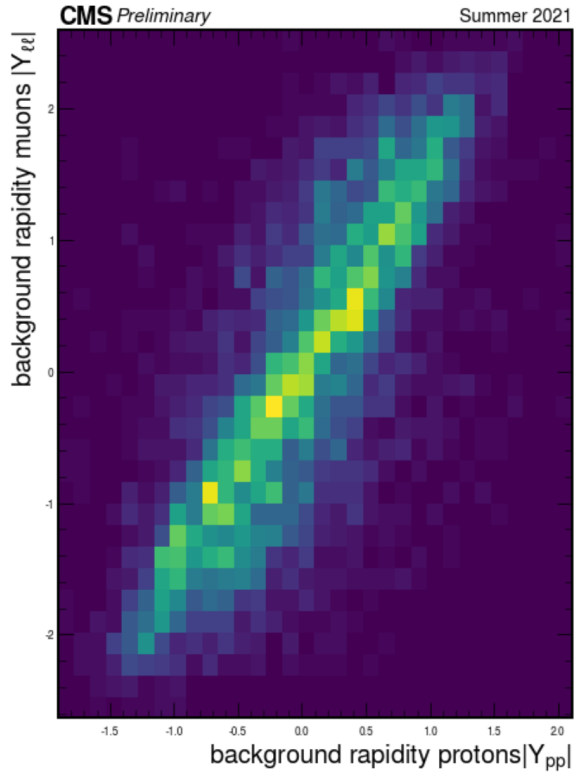
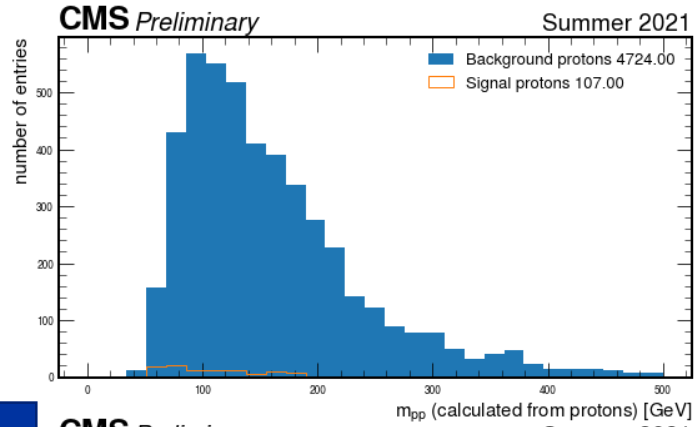
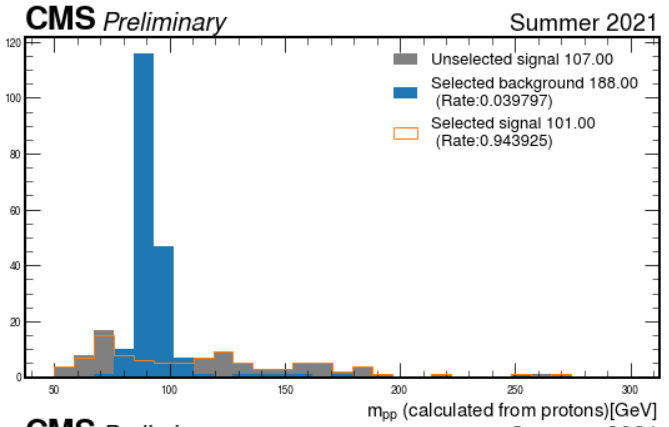


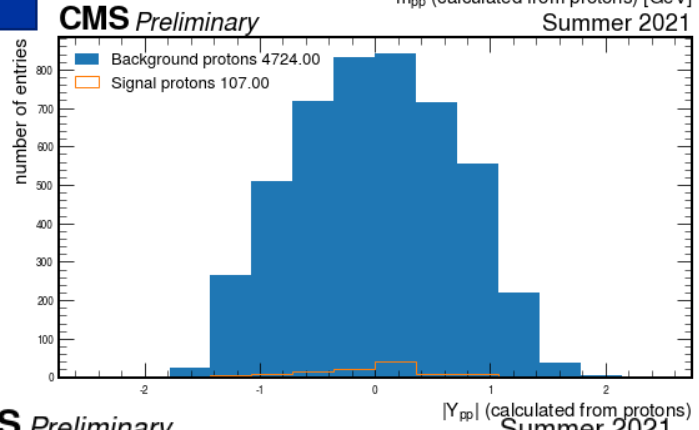


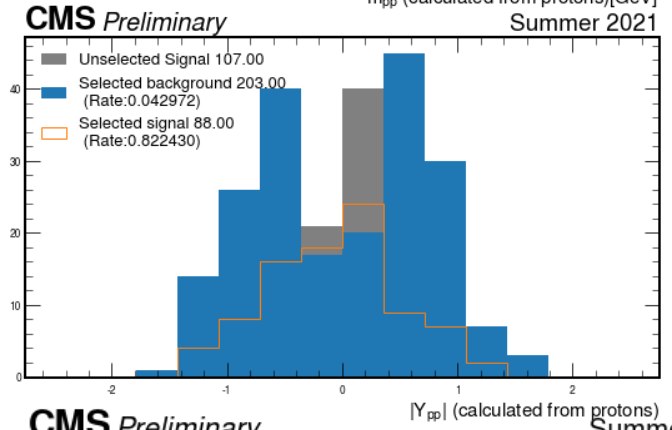


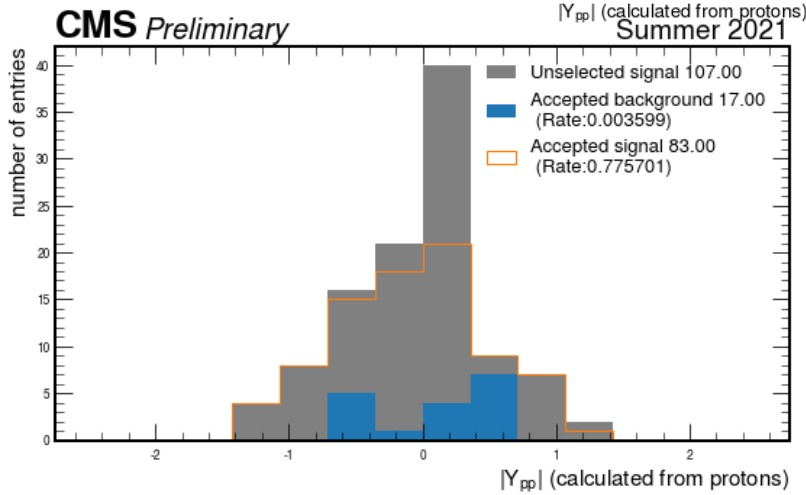


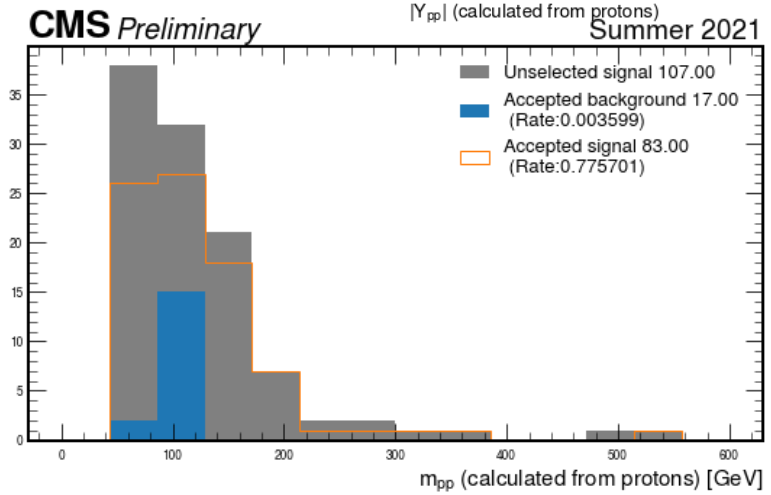












1. Selection cut

Signal mass

$|m_{pp} - m_{ll}| < |2\sigma_m * m_{ll}|$

$\sigma_m \sim 1.62\ \%$

4.0% background acceptance
94.4% signal acceptance

Signal rapidity

$|Y_{pp} - Y_{ll}| < |2\sigma_Y * Y_{ll}|$

$\sigma_Y \sim 3.99\%$

4.3% background acceptance
82.2% signal acceptance

Combined result

0.4% background acceptance
77.6% signal acceptance

2. Timing correlation

Run 2

Vertex position in space

$$\frac{c}{2}[\,t(p_1) - t(p_2)] = rec\_vertex, z_{pp}$$

measured in PPS — 3D reconstruction

HL-LHC

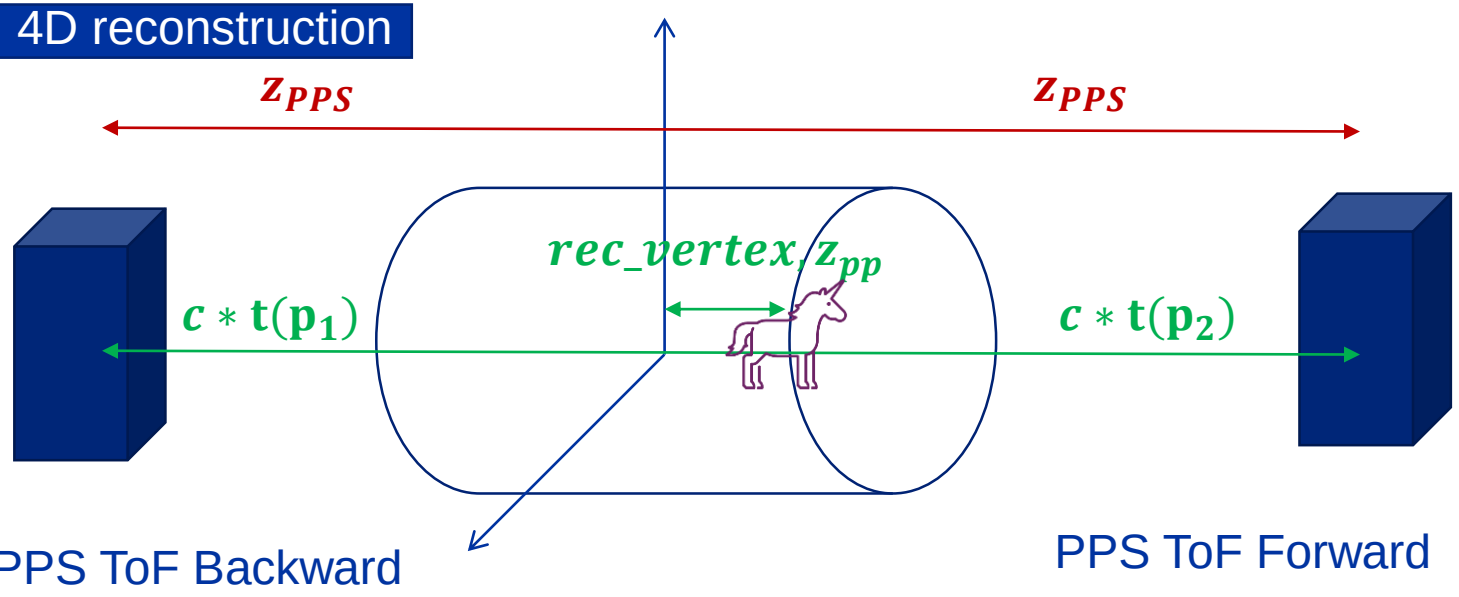
Vertex position in time

$$[\,t(p_1) + t(p_2)]\,c = 2\,z_{PPS} + [t(\mu_1)_{MTD} + t(\mu_2)_{MTD}]\,c$$

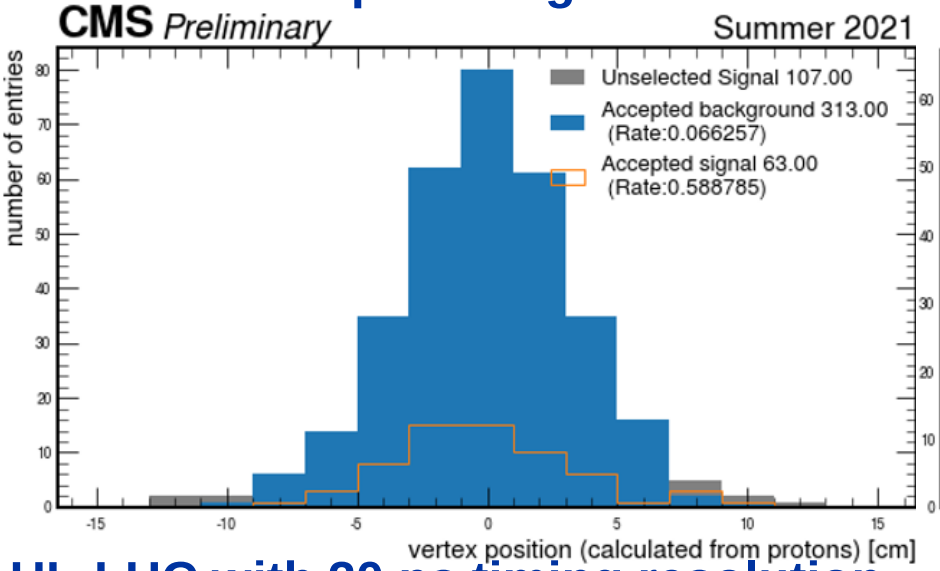
measured in PPS — 234m — measured in MTD

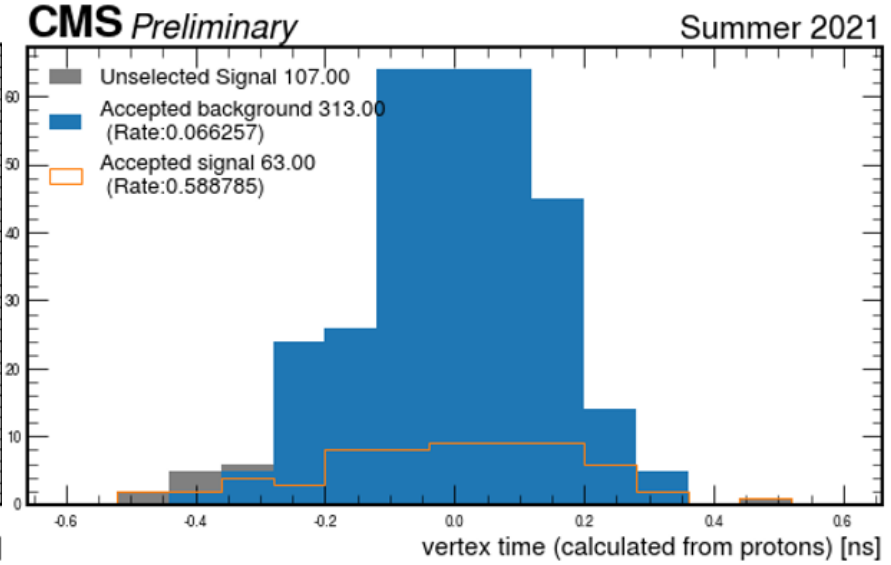
HL-LHC feasibility study — 4D reconstruction

PPS timing resolution
- ~~Run 2: 100ps~~
- Run 3: 50ps
- HL-LHC: 20ps

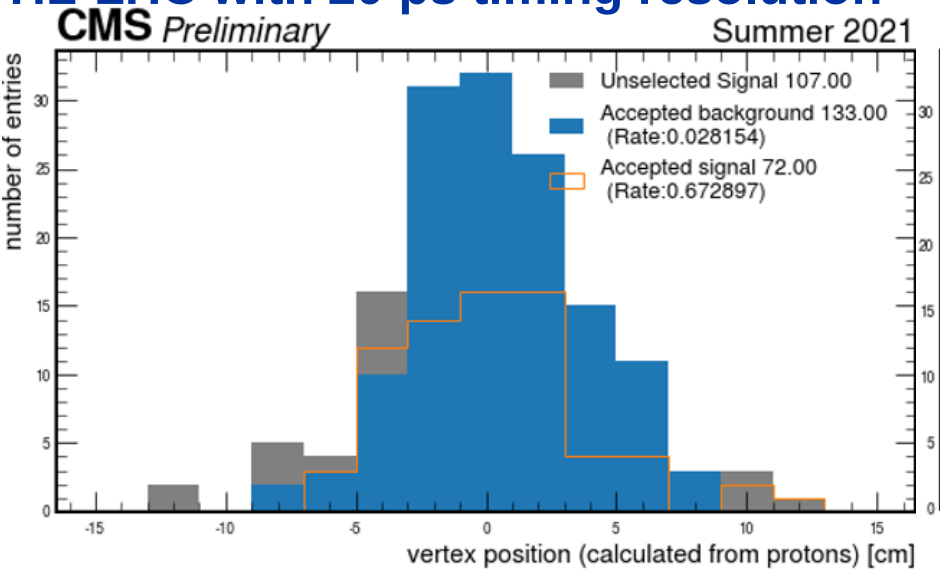


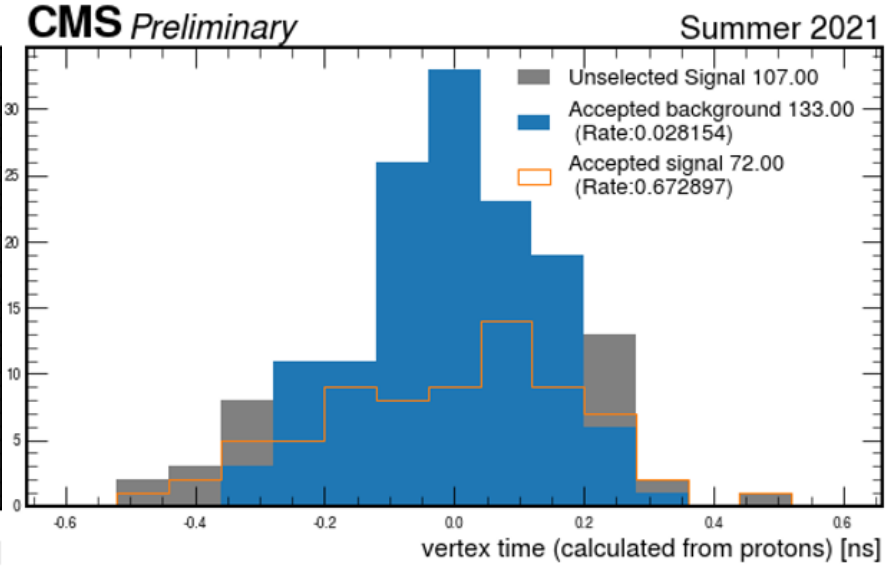
Run 3 with 50 ps timing resolution





HL-LHC with 20 ps timing resolution





2. Selection cut

Signal vertex time

$$|vertex, t_{pp} - vertex, t_{ll}| < |2\sigma_{vertex,t}|$$

Run 3: $\sigma_{vertex,t} \sim 59\ ps$
HL-LHC: $\sigma_{vertex,t} \sim 45\ ps$

Signal vertex position

$$|vertex, z_{pp} - vertex, z_{4D}| < |2\sigma_{vertex,z}|$$

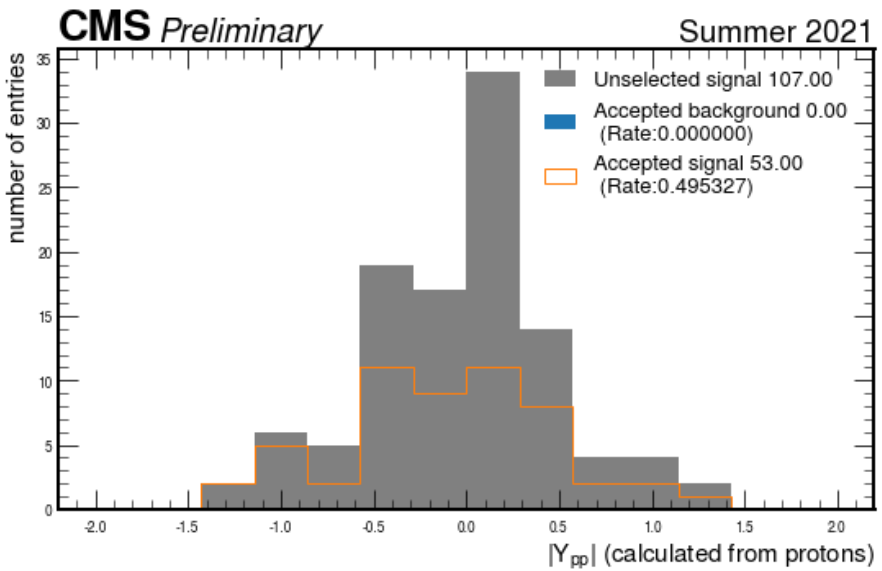
Run 3: $\sigma_{vertex,z} \sim 0.79\ cm$
HL-LHC: $\sigma_{vertex,z} \sim 0.45\ cm$

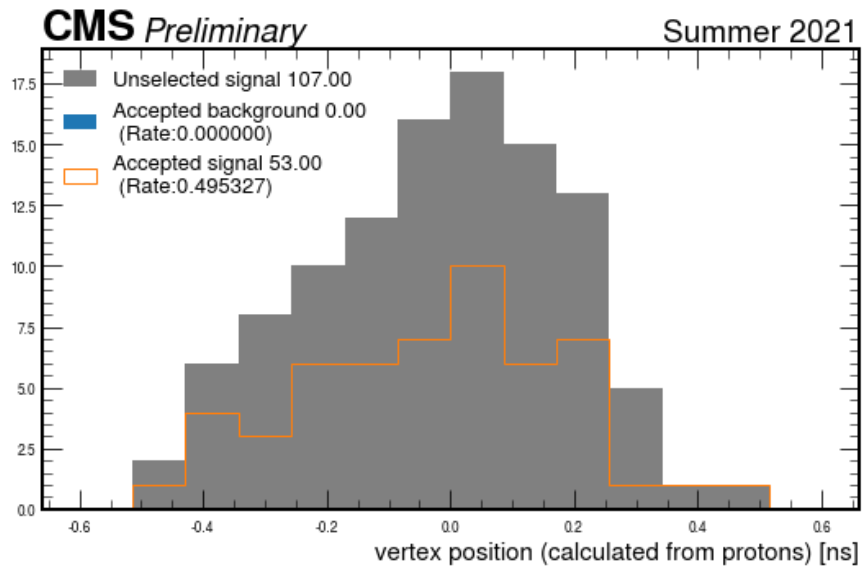
Combined results

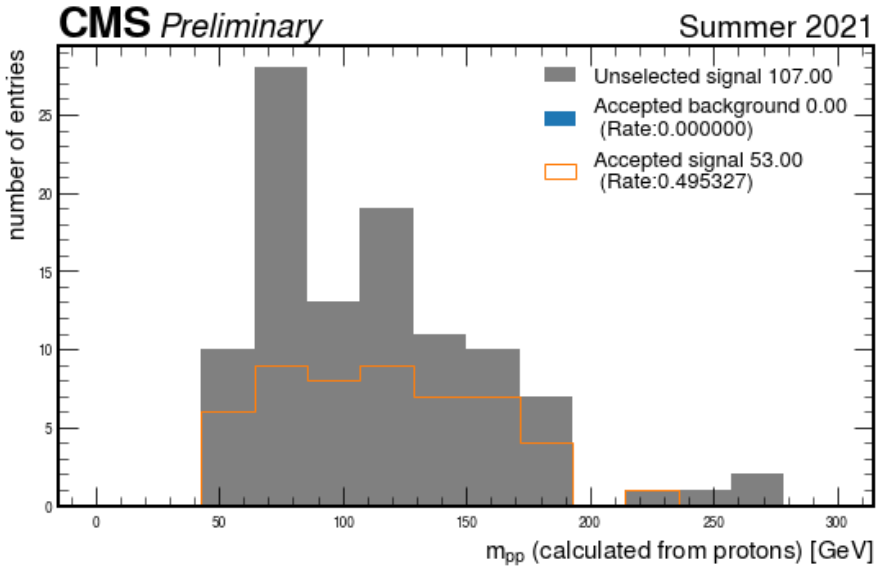
Run 3:
6.6% background acceptance
58.9% signal acceptance

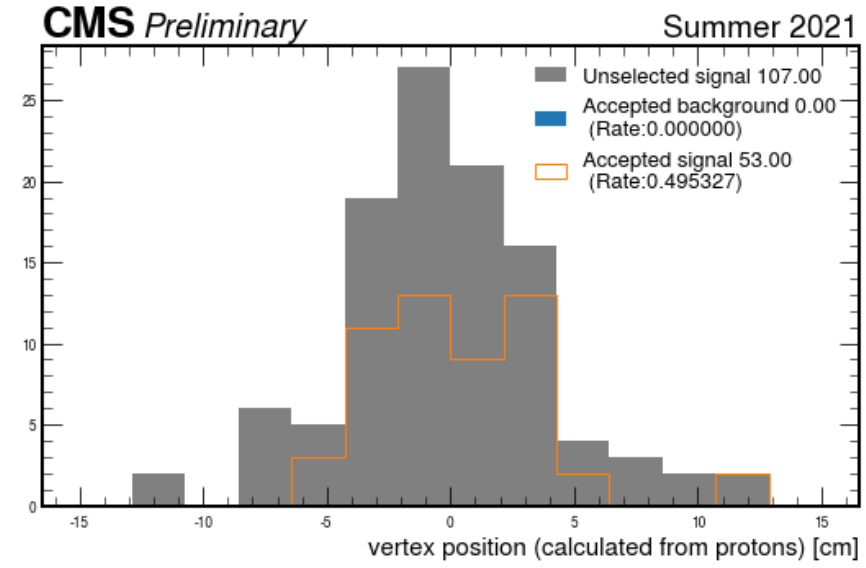
HL-LHC:
2.8% background acceptance
67.3% signal acceptance

Results









Significance of signal events over the background estimate

Run 2

arxiv.org: 1803.04496
without MTD
PPS resolution 100ps
1.49 ± 0.07 (stat) ± 0.53 (syst)

Run 3

"modest" HL-LHC scenario
PPS resolution 50ps
1.04 ± 0.03

HL-LHC

"ideal" HL-LHC scenario
PPS resolution 20ps
1.02 ± 0.02 (stat)

Backup slides

Sources:

PPS HL-LHC upgrade document (arxiv.org: 2004.11068)
CMS expression of interest (arxiv.org: 2103.02752)
Previous study of proton-tagged, central (semi)exclusive production (arxiv.org: 1803.04496)

[1] JHEP07(2018)153
[2] https://www.researchgate.net/figure/Drell-Yan-process-a-quark-of-one-hadron-and-an-antiquark-of-another-hadron-annihilate_fig1_254469235 [accessed 8 Aug, 2021]
[3] 10.1103/PhysRevD.92.012003
[4] https://cds.cern.ch/record/1479324
[5] https://arxiv.org/pdf/2004.11068

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Signal

- 14 TeV $\gamma\gamma \rightarrow \mu^+ \mu^-$
- $p_{\mathrm{T}}(\mu) > 25\ GeV$
- $PU = 200$
- 600 events total
- Generator-level cross section $FPMC = 0.2735\ pb$

Background

- 14 TeV Drell-Yan $Z \rightarrow \mu^+\mu^-$
- $\mathrm{p_T}(\mu) > 2.5$ GeV & $|\mathrm{Y}(\mu) < 4.0|$
- $PU = 200$
- 15296 events total
- Generator-level cross section $\mathrm{Pythia8\ CP5} - \mathrm{TBC} = 2.213\ nb$

Event selection and PPS acceptance

Table 4 and figure 15 (arxiv.org: 2103.02752)

Event selection

- Find two highest pT muons with pT > 25GeV
- Select events with 2 muons that have timing data

Apply dimuon cuts

$$\xi_{\pm\mu} > 0.0032 \sim 31\% \left(\frac{190}{600}\right) \text{events}$$

$$t_\mu > 80 \;\&\; \xi_{\pm\mu} \sim 17\% \left(\frac{106}{600}\right) \text{events}$$

Smearing of proton momentum

Random samples from a normal distribution around 0 with ($\sigma_{res} = 0.02$) 2% resolution

$$\xi_{smear} = Gauss(0;\ \sigma_{\text{res}} * \xi_{proton})$$

$$\rightarrow \xi_{proton} = \xi_{proton} + \xi_{smear}$$

$$\rightarrow p_z(proton) = p_z(proton) + \left(\frac{\sqrt{s}}{2}\right) * \xi_{smear}$$

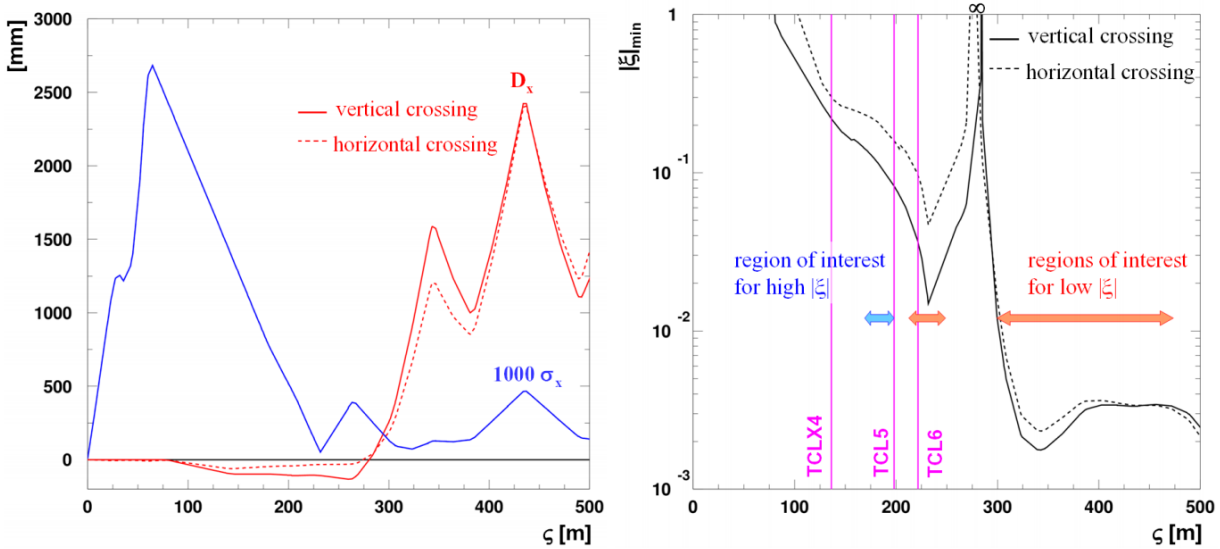
- Apply proton cuts

$$p_z(proton) > 4990\ TeV$$

$$p_z(proton) < (1 - 0.0032) * 7000\ TeV$$

- Take 2 protons with acceptance for scenario 4

$$\xi_{min} = 0.0033\ \&\ \xi_{max} = 0.2871$$



Vertical Crossing-Angle				
Station	$\lvert\xi_{\text{min}}\rvert$	$\lvert\xi_{\text{max}}\rvert$	M_{min} [GeV] @ y = 0	M_{max} [GeV] @ y = 0
196 m	0.0786−0.0856	0.1967	1100.87−1197.80	2754.27
220 m	0.0371−0.0381	0.0688	519.89−533.18	962.70
234 m	0.0189−0.0095	0.0263	264.96−132.80	368.11
420 m	0.0031−0.0034	0.0116	43.38−47.04	162.66
Horizontal Crossing-Angle				
Station	$\lvert\xi_{\text{min}}\rvert$	$\lvert\xi_{\text{max}}\rvert$	M_{min} [GeV] @ y = 0	M_{max} [GeV] @ y = 0
196 m	0.1654−0.1779	0.2871	2316.15−2490.07	4018.94
220 m	0.0984−0.1014	0.1488	1377.48−1419.13	2083.04
234 m	0.0564−0.0312	0.0732	789.48−437.07	1024.60
420 m	0.0032−0.0034	0.0118	44.55−48.20	165.28

Proton time calculation and smearing

Calculation of proton time

$z_{pps} = 23400\ cm, c = 29.979 \frac{cm}{ns}$

- Signal time from real collision time and vertex position

$$t_p = t_{collision} + (z_{pps} \mp z_{vertex,p})/c$$

- Background time from bunch properties:

Proton bunches are gaussian in first order; from the beam width of $\sim 8.3\ cm$ follows the resolution $\sigma_{res} = \frac{0.271\ ns}{\sqrt{s}} = 0.019 \frac{ns}{TeV}$

$$t_{proton} = Gauss(0;\ \sigma_{\mathrm{res}}) + (z_{pps} \mp z_{vertex,p})/c$$

Smearing of proton time

$$t_{p,smeared} = t_{proton} + Gauss(0;\ \sigma_{\mathrm{res}})$$

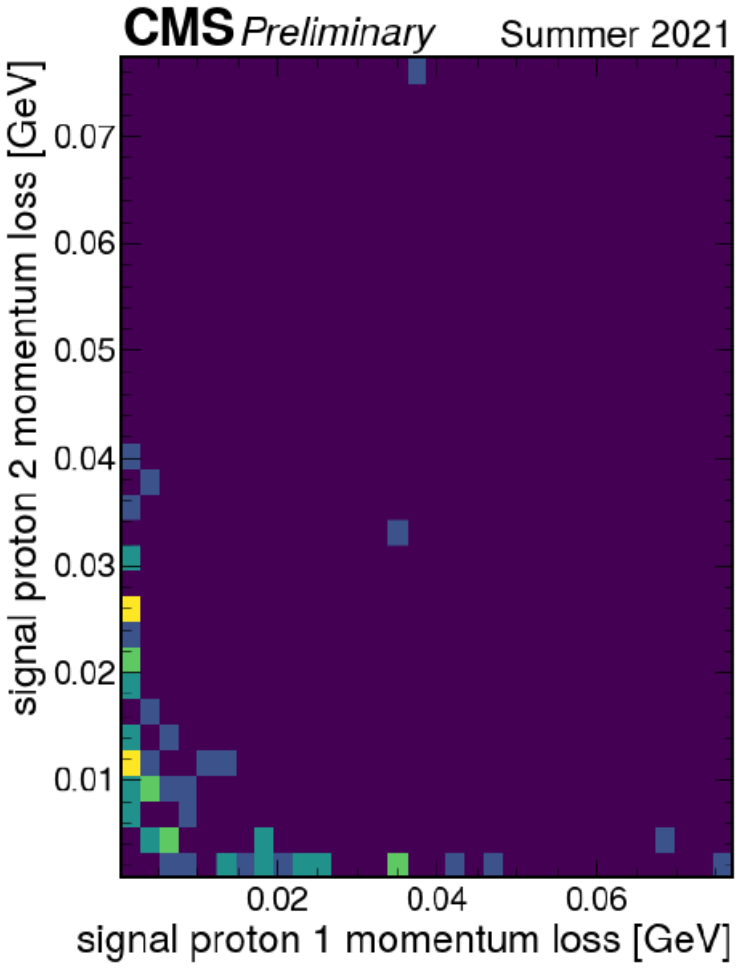
- The expected timing resolution for the HL-LHC

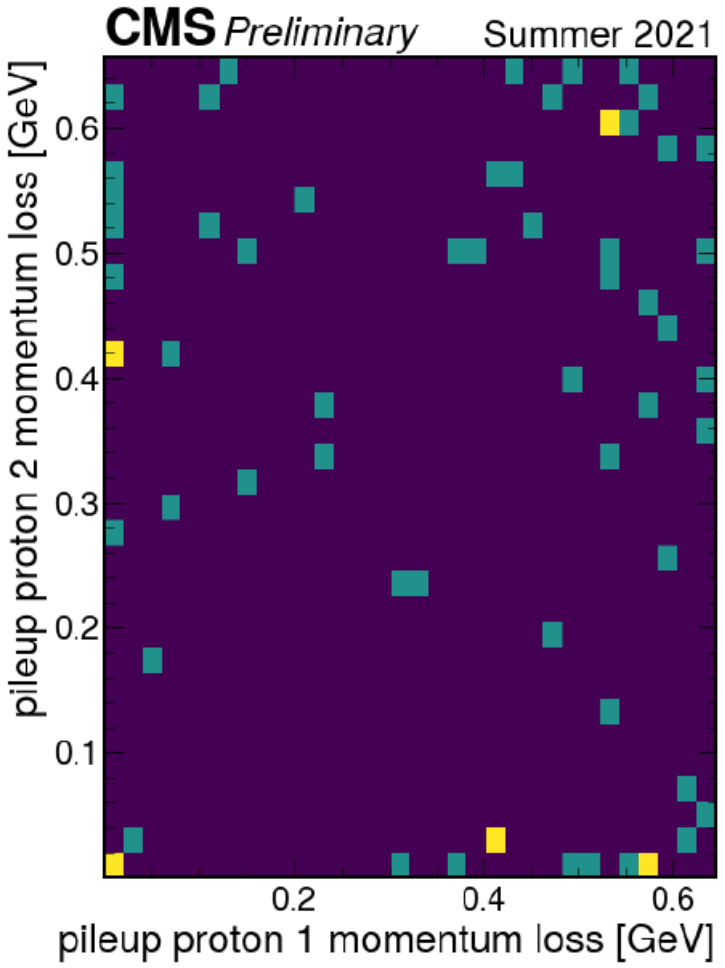
$\sigma_{HL-LHC} = 20ps$

- Scenario where the PPS timing detectors cannot be improved beyond the resolution of Run 3

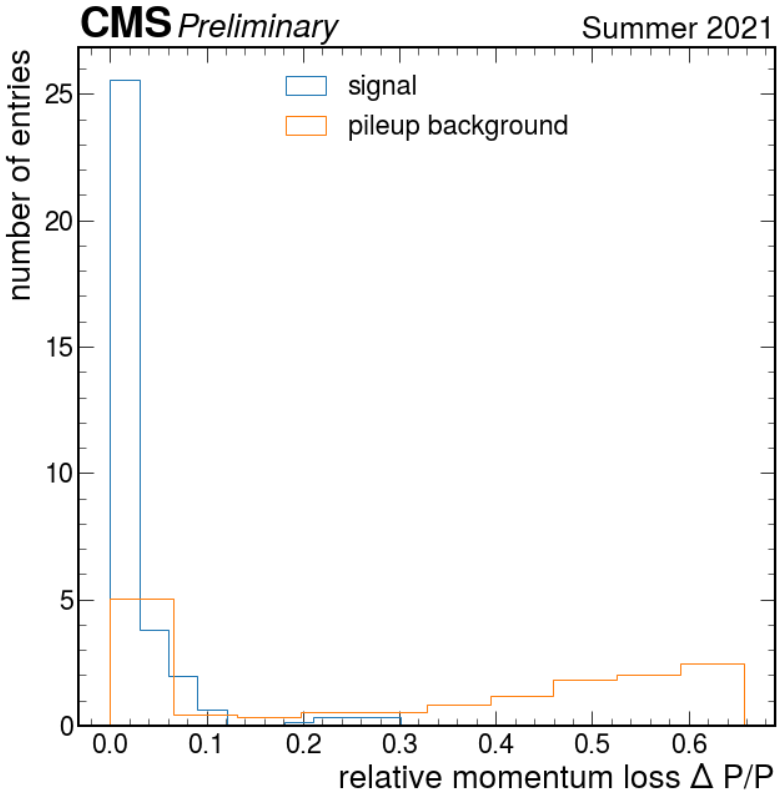
$\sigma_{Run\ 3} = 50ps$

Kinematic correlations: Momentum loss

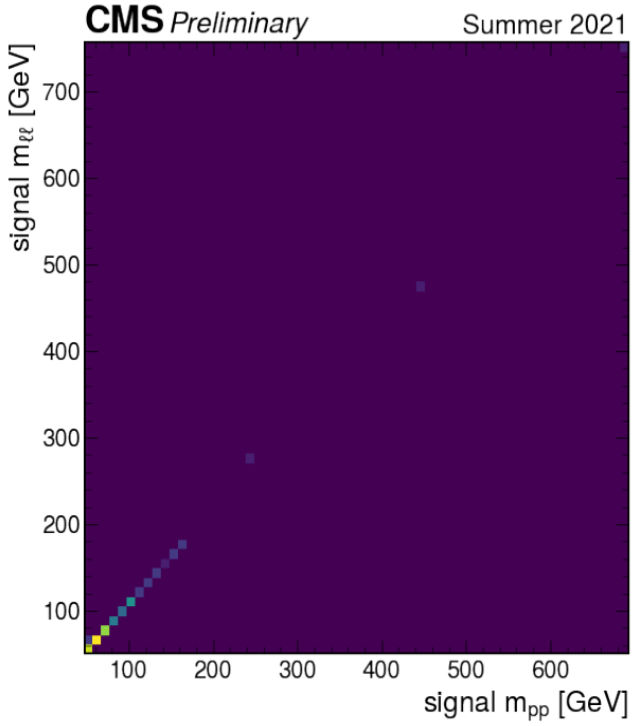


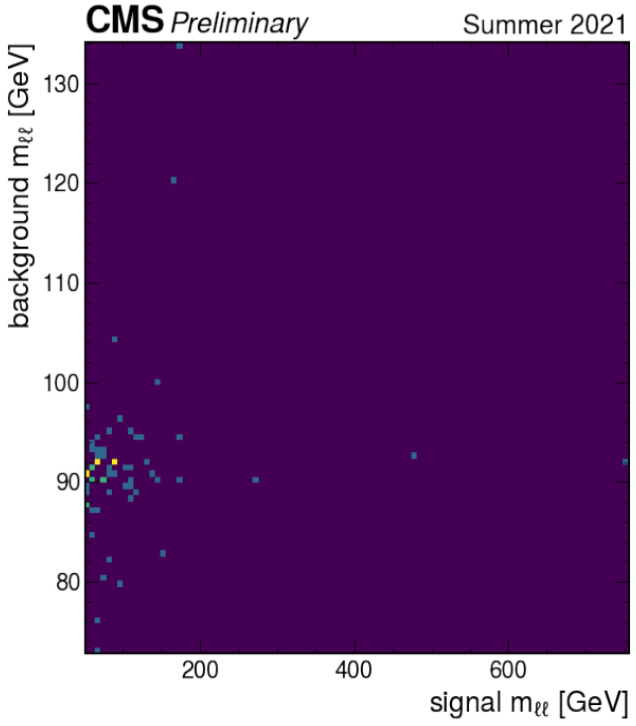


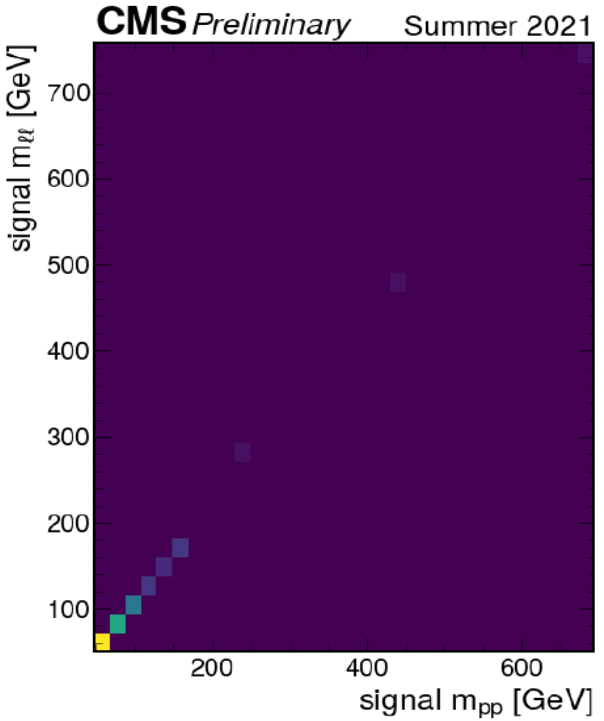
$$\xi = \frac{p_z(initial) - p_z(final)}{p_z(initial)} = \frac{dp_z}{p_z}$$

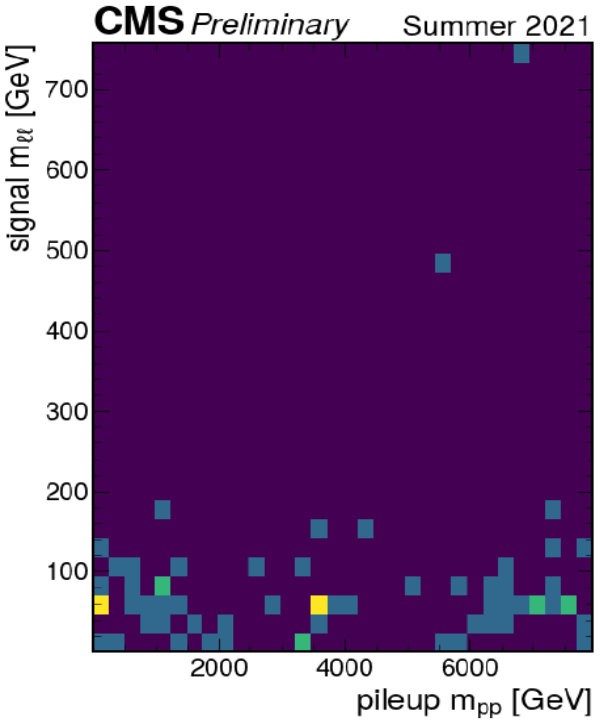


Kinematic correlations: Invariant mass

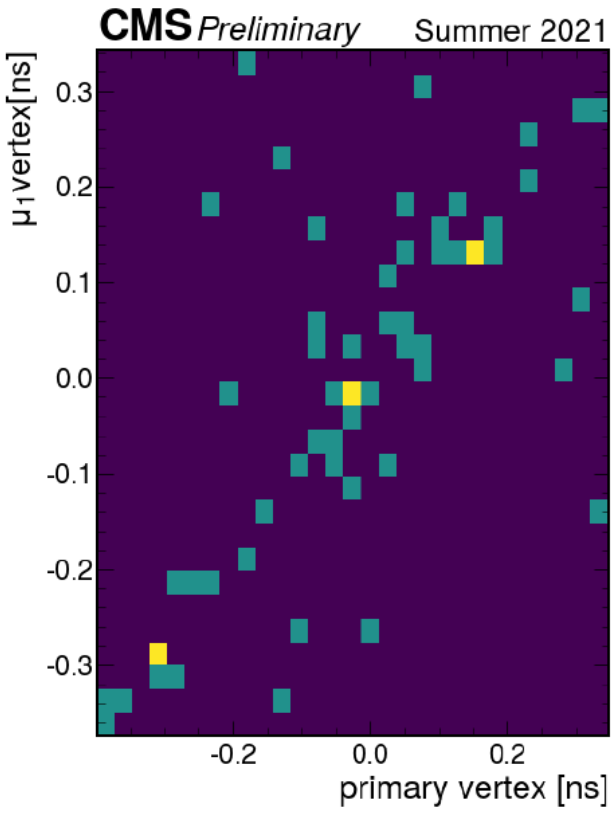


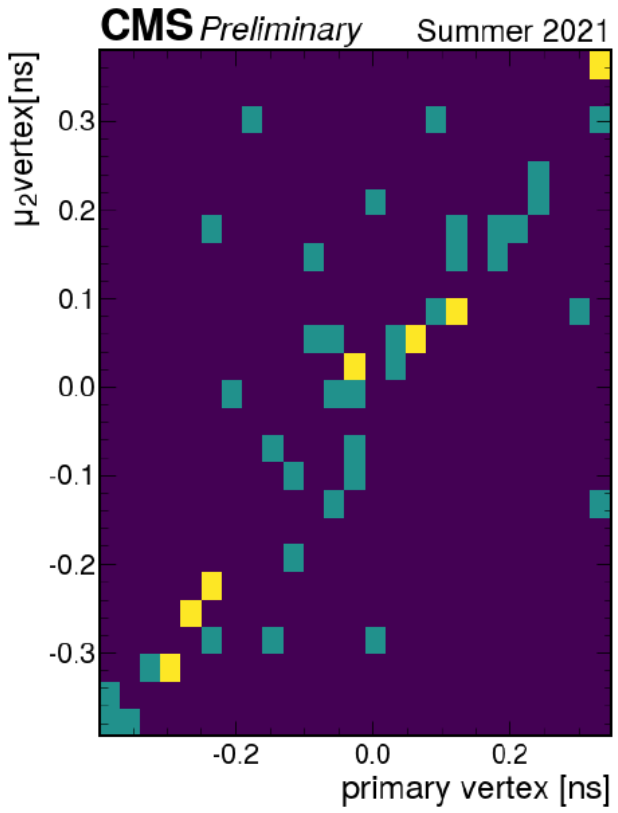


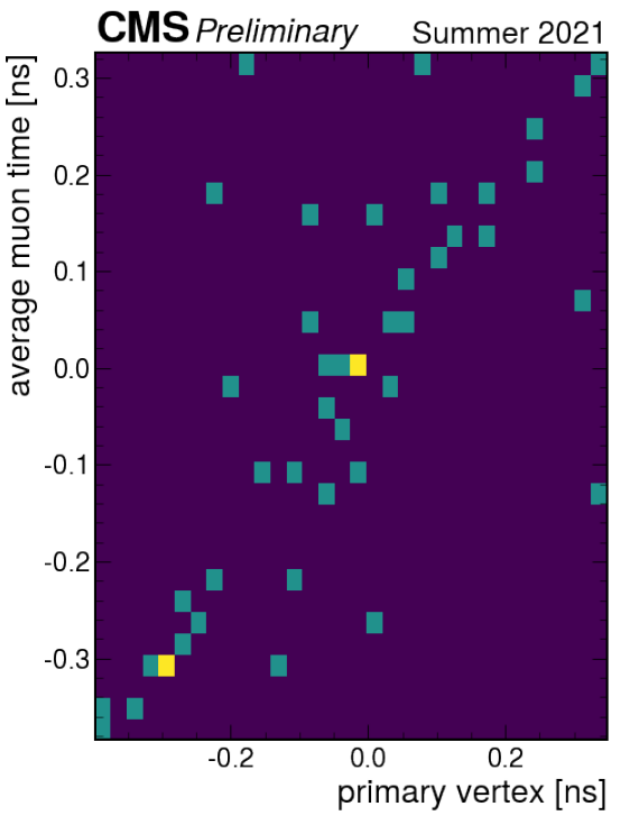


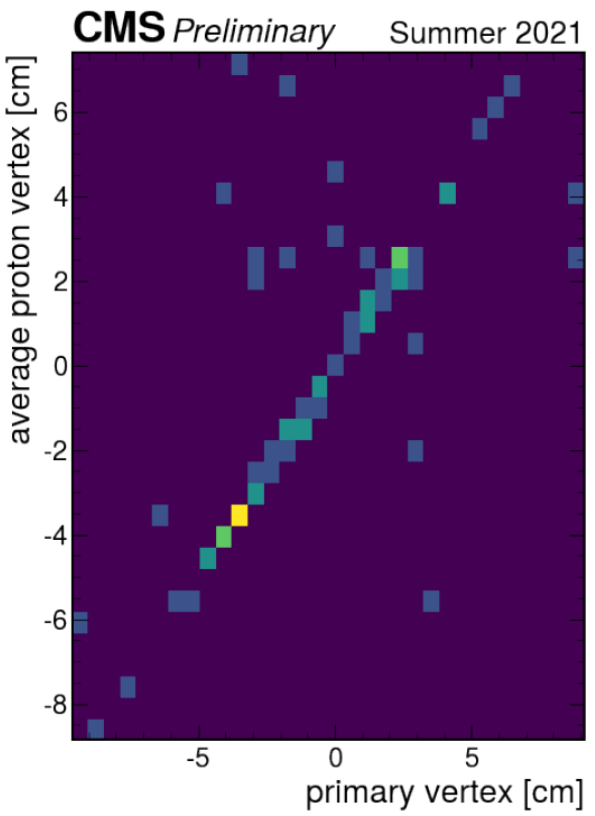


Vertex correlations: Muon vs 4D primary

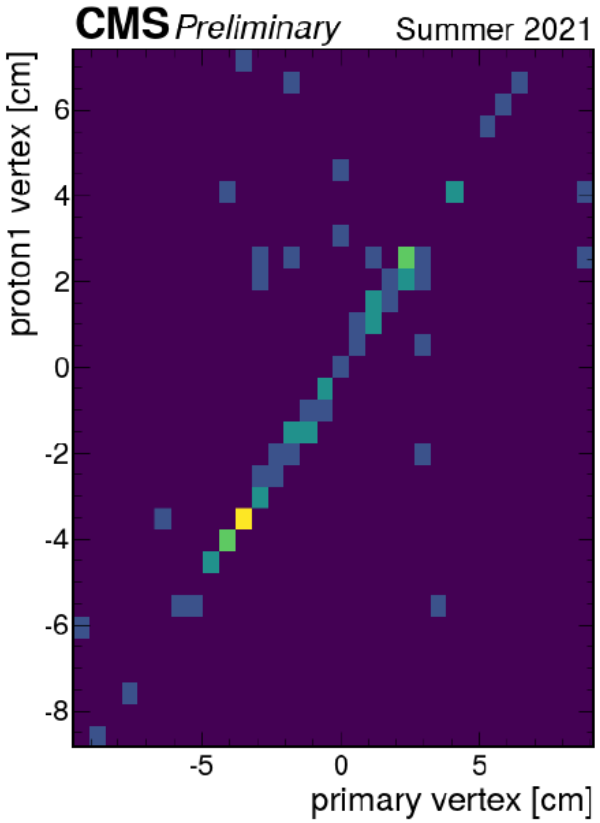


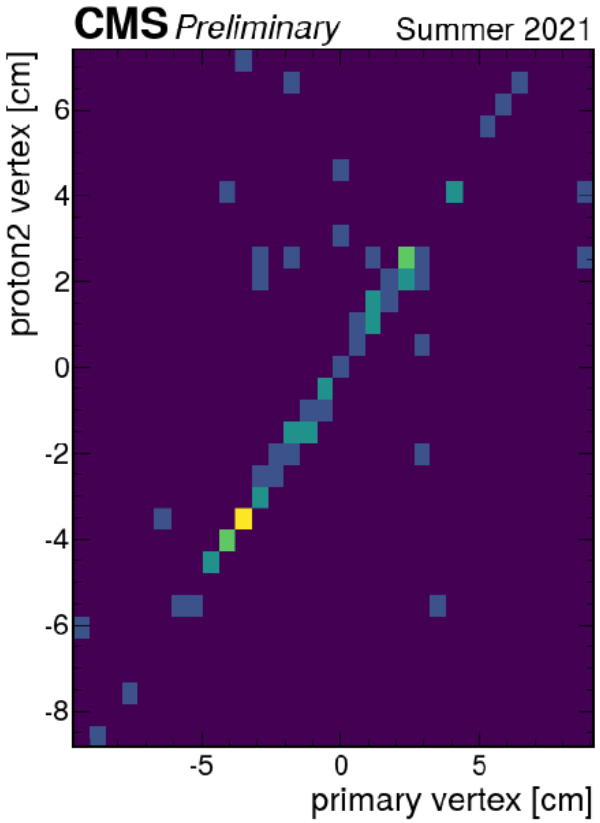


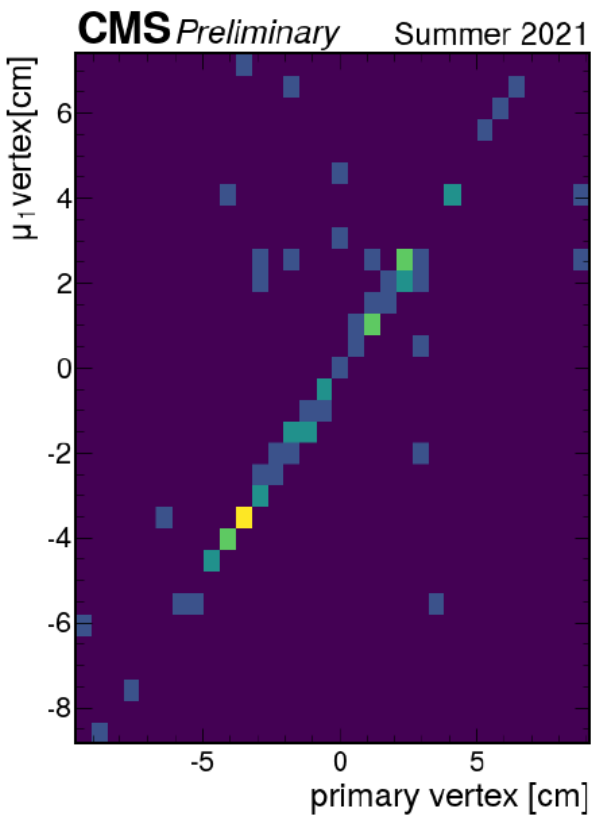


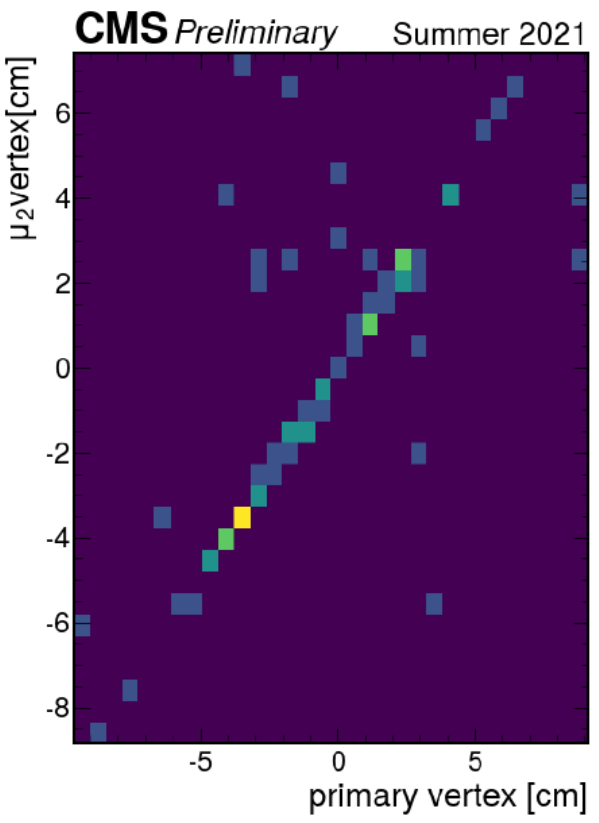


Vertex correlations: Muon vs 4D primary

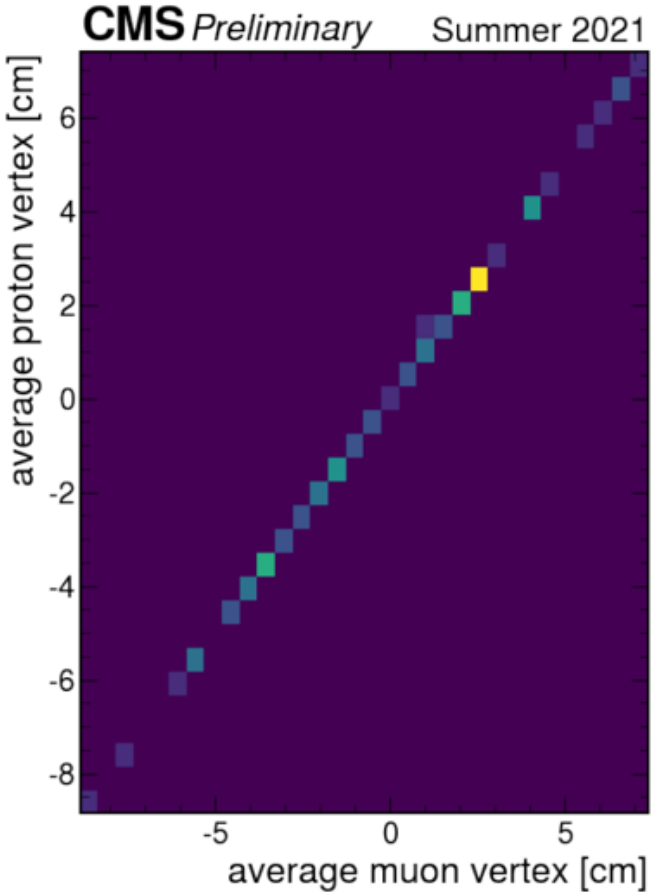


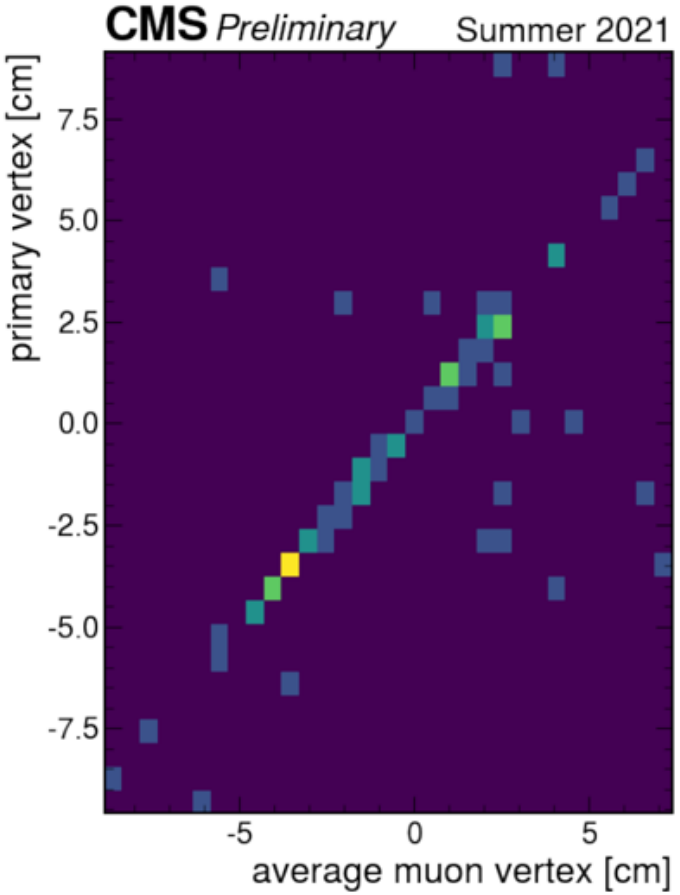


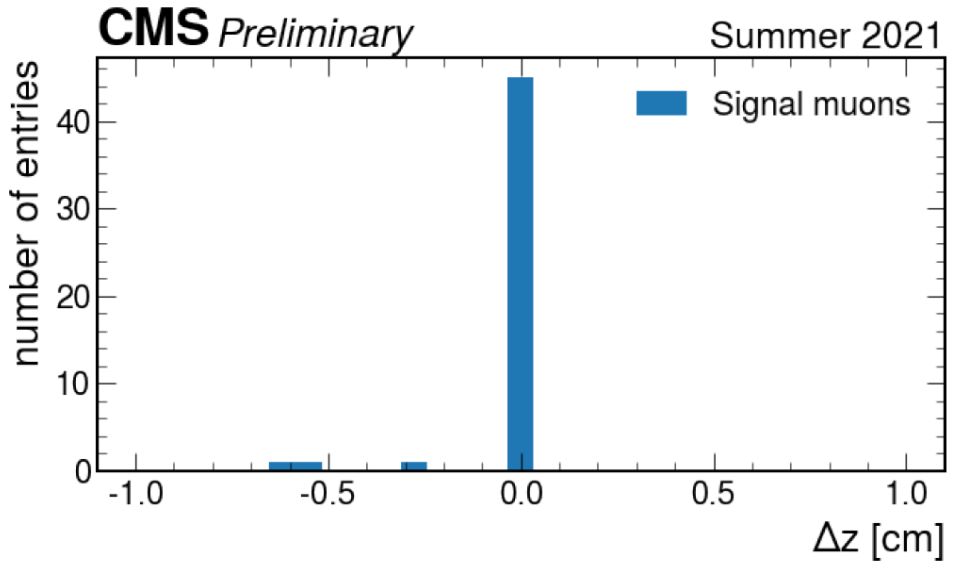


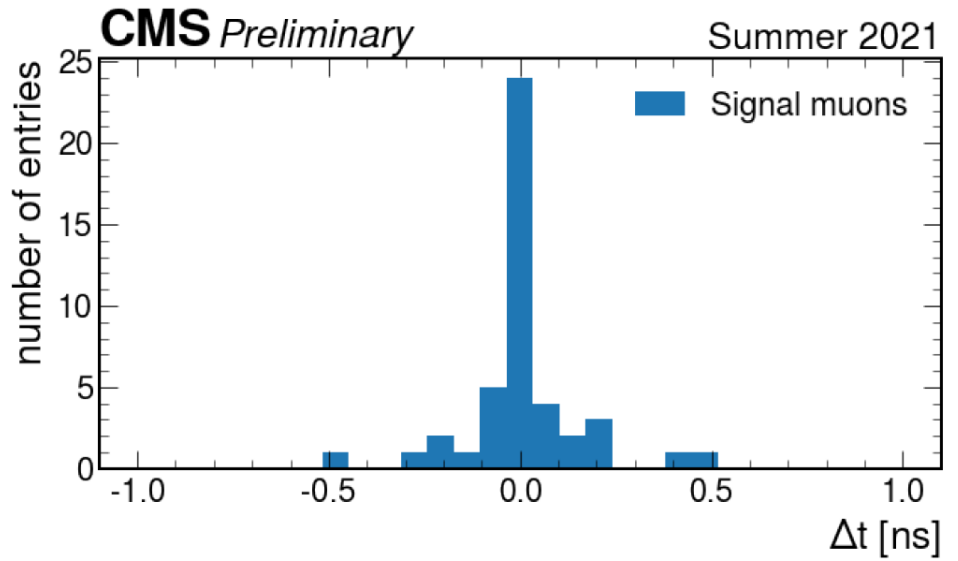


Vertex correlations: Muon vs 4D primary



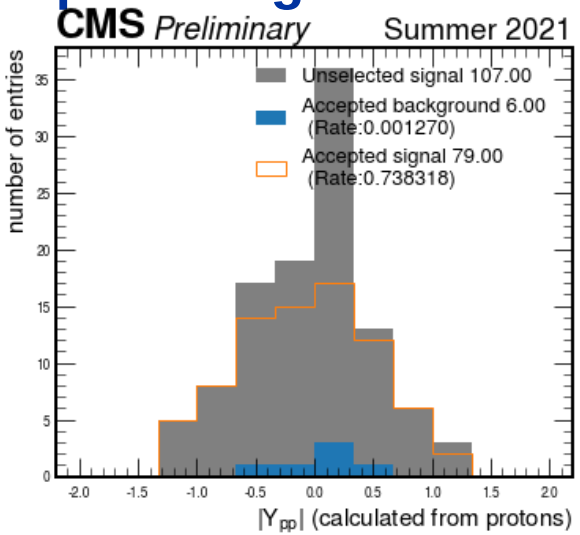


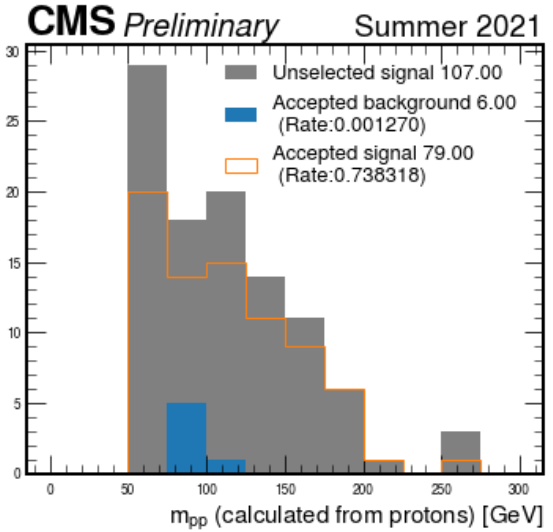


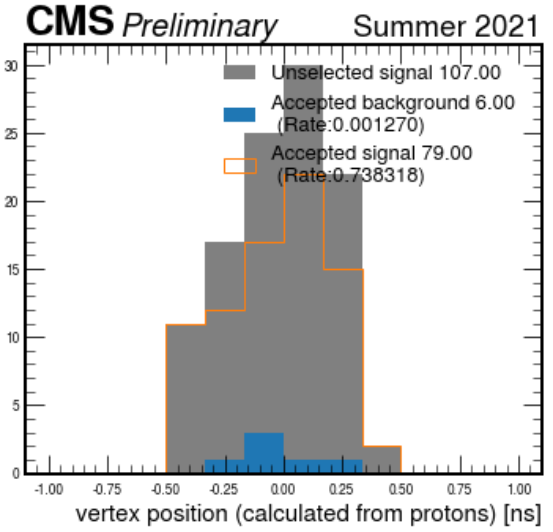


Combine kinematics and vertex timing

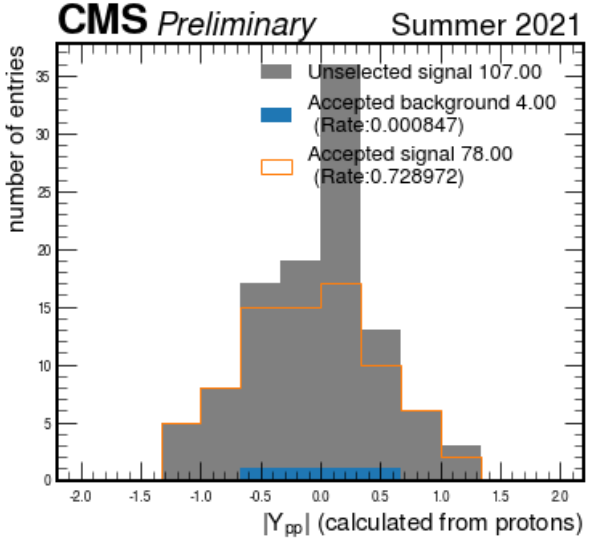
Run 3 with 50 ps timing resolution

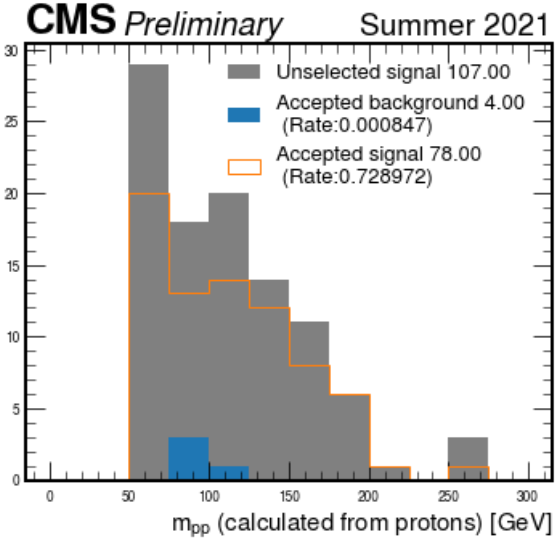


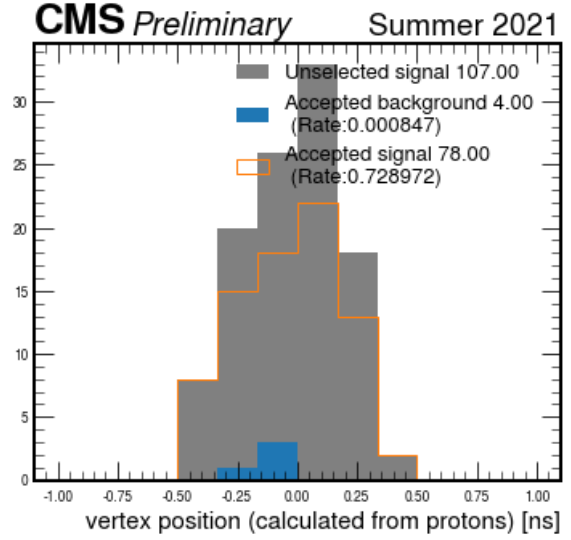




HL-LHC with 20 ps timing resolution

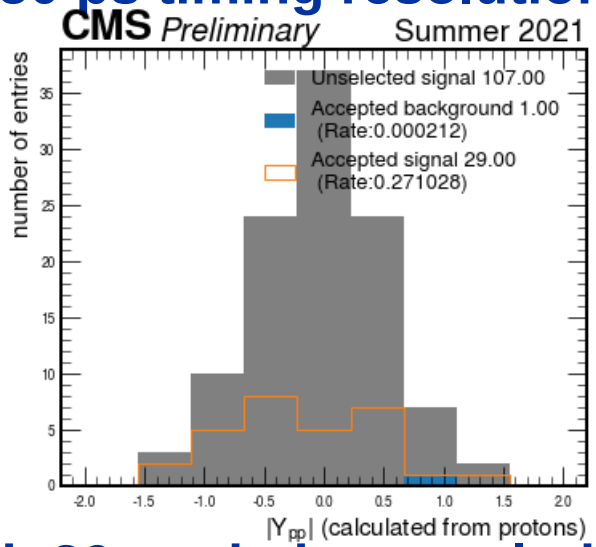


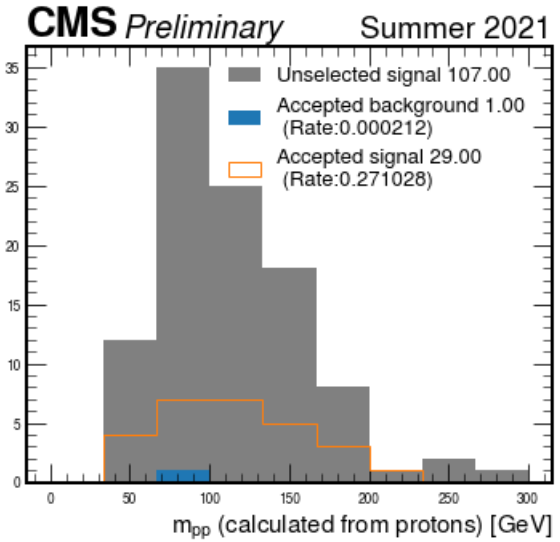


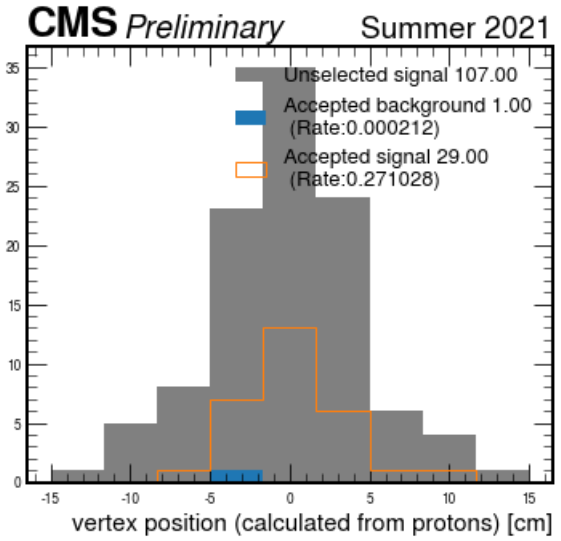


Combine kinematics and vertex position

Run 3 with 50 ps timing resolution







HL-LHC with 20 ps timing resolution